Quark flavor physics
(to overcome the standard model)
— part 1 —

Diego Tonelli (INFN Trieste)
diego.tonelli@ts.infn.it

Jennifer2 School 2021
July 21, 2021 - virtual

```
diegos-mbp-2:~ diego$ whoami
```

Experimental particle physics: indirect searches for non-standard-model particles using weak interactions of quarks (so-called “flavor physics”).

- Born, raised, and educated in Pisa (UniPI/SNS) till completion of my PhD on B physics in the CDF experiment at Fermilab

- 2007-2011: Lederman fellow at Fermilab on CDF physics analysis (charmless B, bottom-strange mixing phase, CP violation in charm)

- 2012-2016: CERN staff scientist on LHCb (track-trigger, D mixing, Bs lifetimes)
- 2016— to date: scientist at INFN Trieste: charmless B decays in Belle II

What

Flavor

In particle physics, flavor is a technical word that identifies the *species* of elementary particles.

Flavor physics is the study of the properties of particles and their interactions that depend on the species.

Early example: in 1932 Chadwick discovered the neutron: mass and behavior under strong-interaction similar to the proton's (but no electric charge). Are neutron and proton "two flavors" of the same kind of particle?

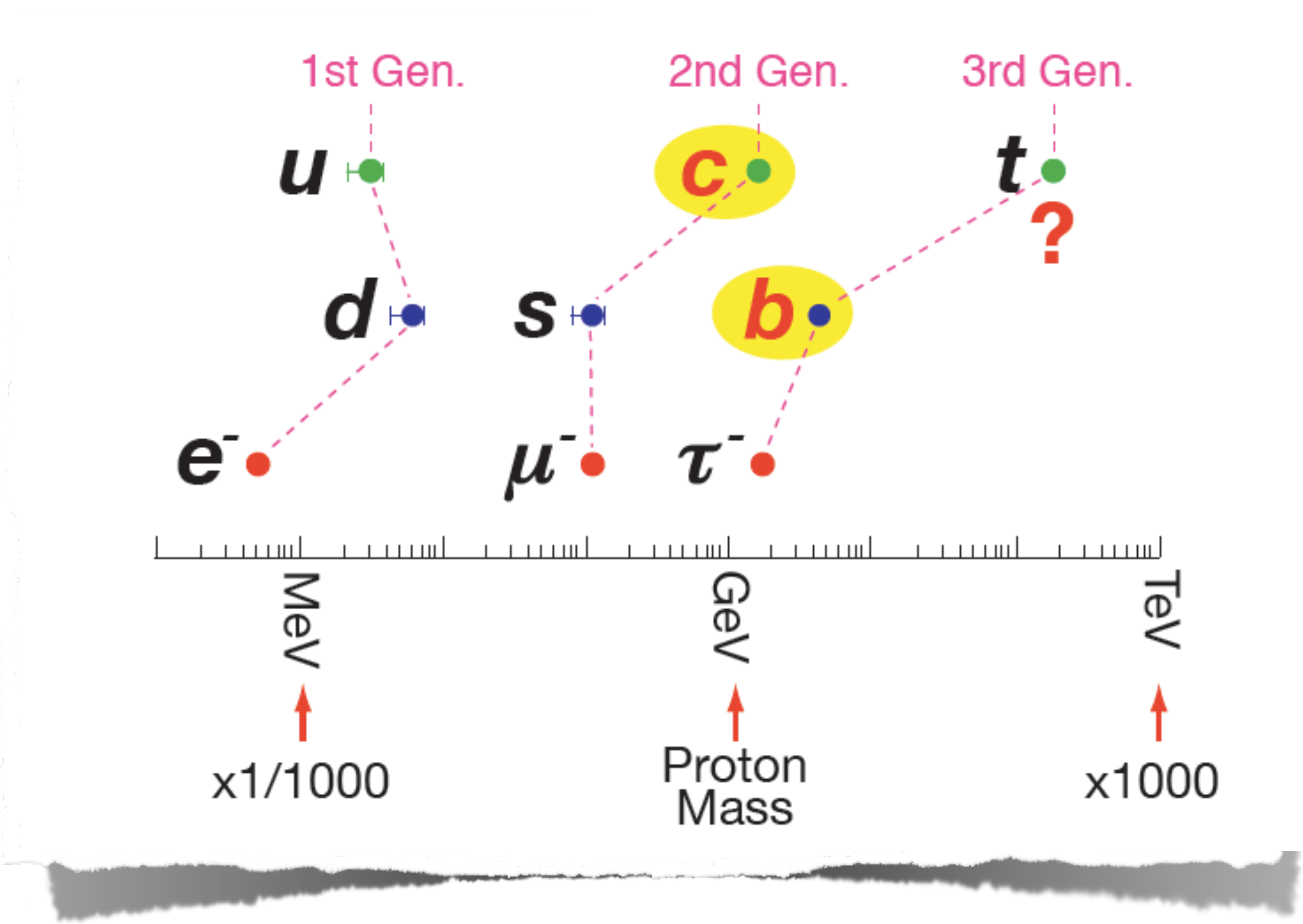
Heisenberg: proton and neutron are two quantum states of the same particle, the nucleon, differentiated by a new quantum number called isotopic spin

$$p: (I, I_3) = (1/2, +1/2) \qquad n: (I, I_3) = (1/2, -1/2)$$

much like a spin-↑ and spin-↓ electrons are two quantum states of the same particle

Flavor

The physics of matter at its most fundamental level. Deals with masses and transitions of fermions



λ=0.22

$$V \approx \begin{array}{cccc} d & s & b & \\ \left(\begin{array}{c} 1 \\ -\lambda \\ -\lambda^3 \end{array}\right. & \begin{array}{c} \lambda \\ 1 \\ -\lambda^2 \end{array} & \left.\begin{array}{c} \lambda^3 \\ \lambda^2 \\ 1 \end{array}\right) & \begin{array}{c} u \\ c \\ t \end{array} \end{array}$$

Added bonuses: CP violation (dynamics not invariant for the mirror reversal of the spatial arrangement and the exchange of all particles with antiparticles); antimatter; flavor mixing (exquisite demonstration of QM at work)…

An important (and messy) part of the SM

- 3 gauge couplings

- 2 Higgs parameters

- 6 quark masses

- 3 quark mixing angles + 1 phase

- 3 charged lepton masses

- (3 neutrino masses)

- (3 neutrino mixing angles + 1 phase)

Flavor parameters

Why

Why we study flavor?

Follow a "reductionist" thinking similar to the one that promoted the concept of atoms as the "fundamental" units of matter aggregation, or of quarks as the fundamental constituents of the "zoo" of hadronic resonances observed in the 60ies:

- ☐ Is such complexity fundamental? Or it suggests a deeper, simpler structure?
- ☐ Any fundamental motivation for the proliferation of fermions? And for their apparent organization into families/generations?
- ☐ Is there any meaning for flavor symmetries and their violations?
- ☐ Why the laws of physics are not invariant if one exchanges all particles with antiparticles and swaps their spatial configuration?
- ☐ Why is the universe made of matter if it started from symmetric conditions?

Understanding them may bring us to a deeper, more predictive understanding of matter and its interactions — but there's more to that.

Where do we stand

Symmetry

- local gauge

Simplicity

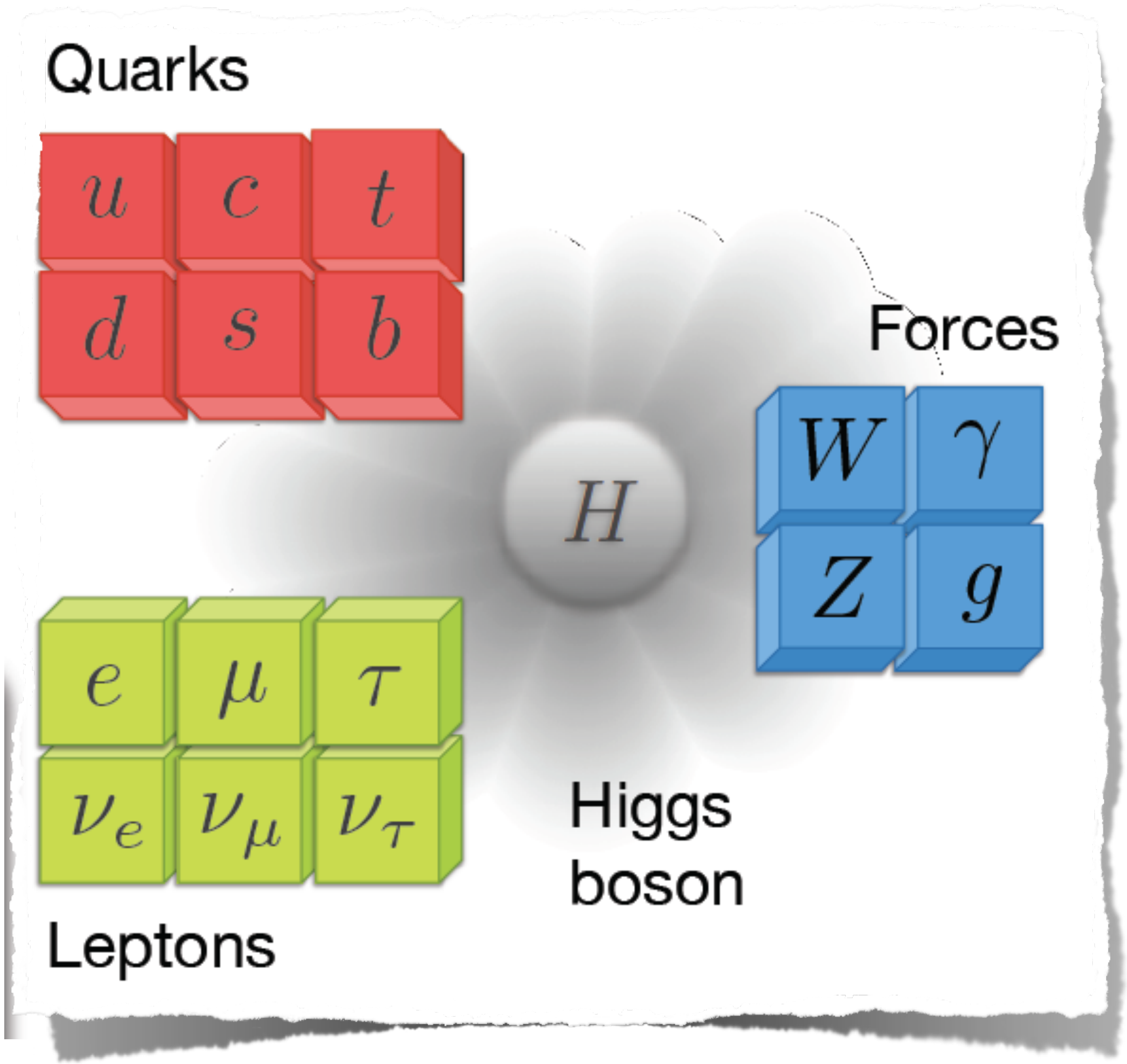
- Few parameters

Naturalness

- Little fine tuning

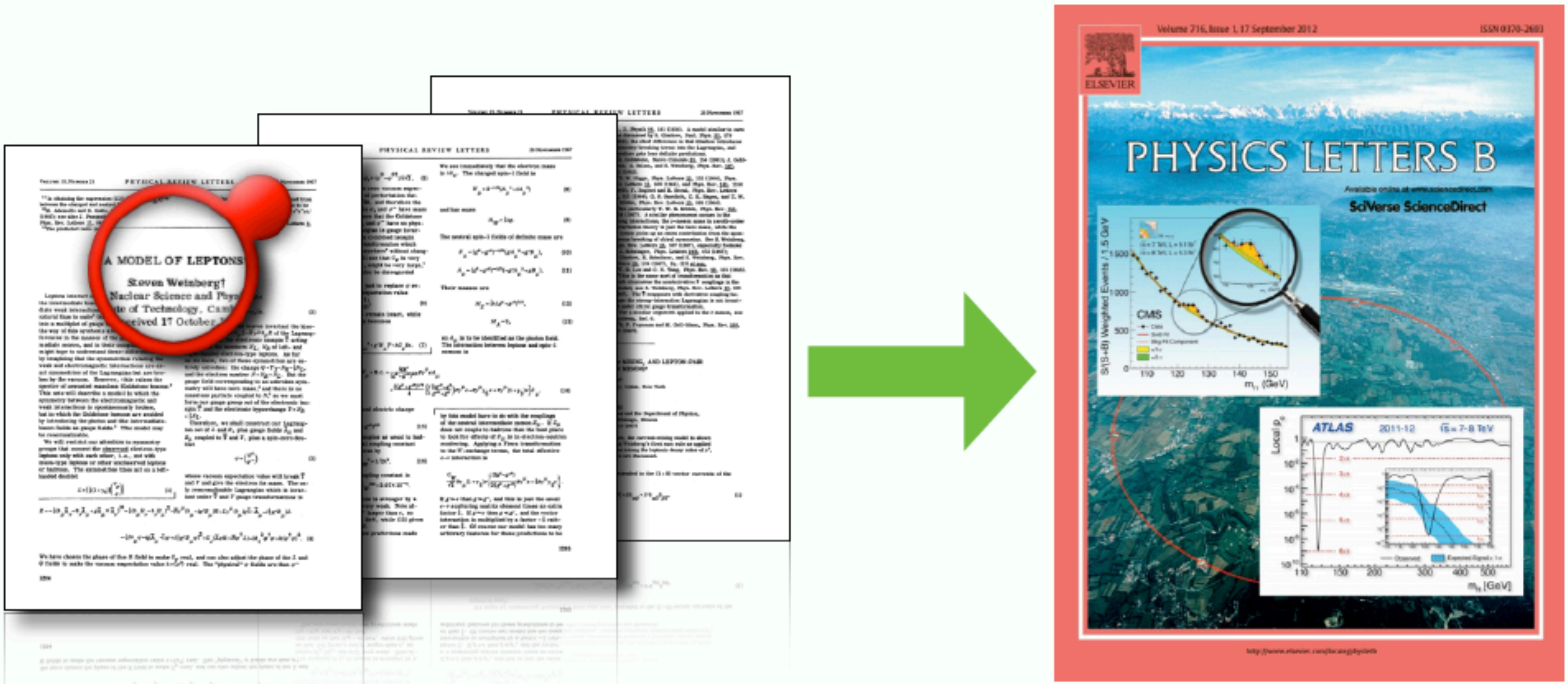
Anarchy

- Whatever isn't explicitly forbidden it's allowed



www.youtube.com/watch?v=UnI1jXFnzgo

1967-2012



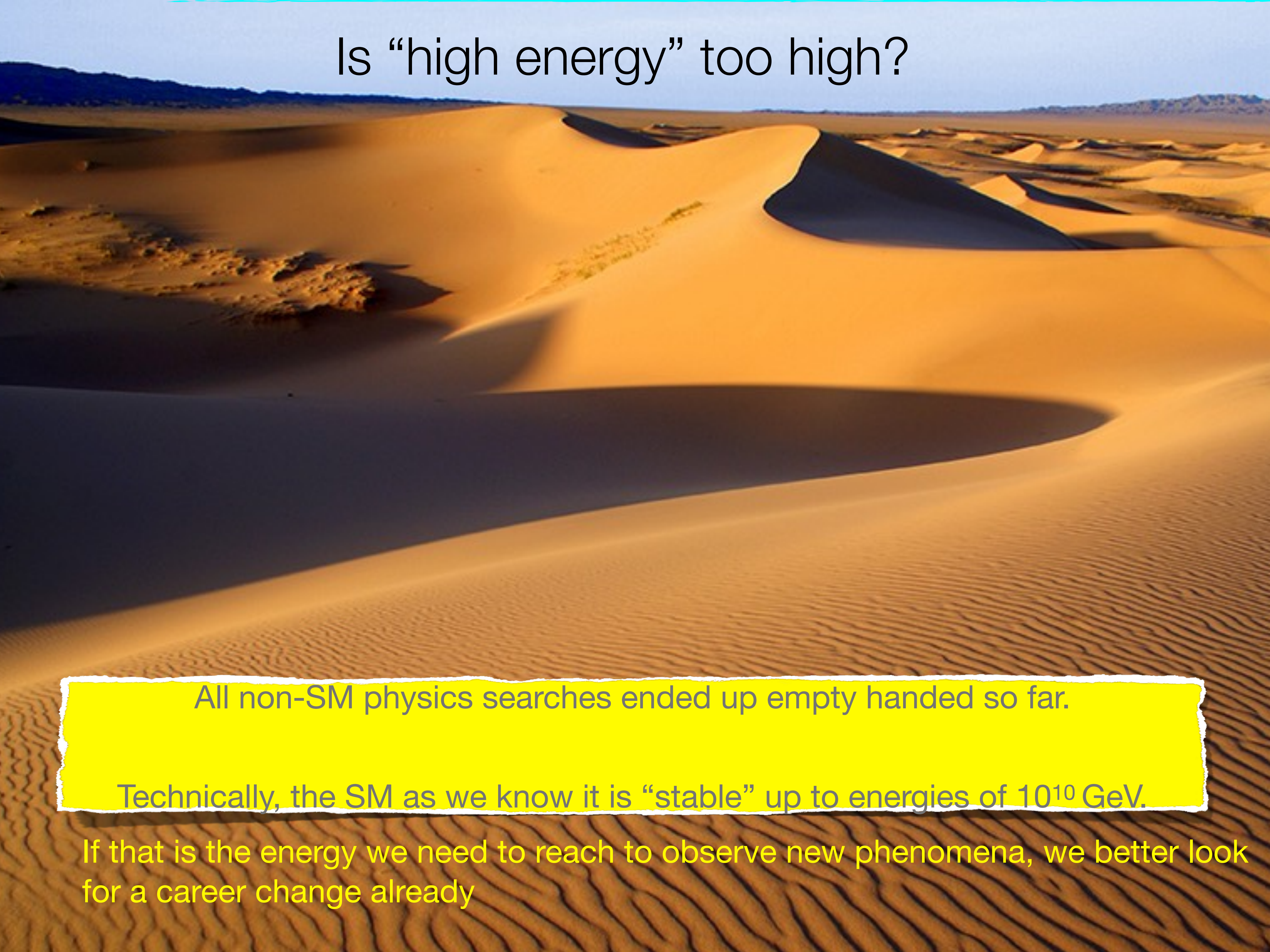
The standard model is now complete. It is robust at the energies explored so far and technically up to 10^{10} GeV.

Are we done?

No. Open questions

These and many other questions fuel the strong and wide-spread prejudice that the SM is completed at high-energy by new particles and interactions

Is “high energy” too high?



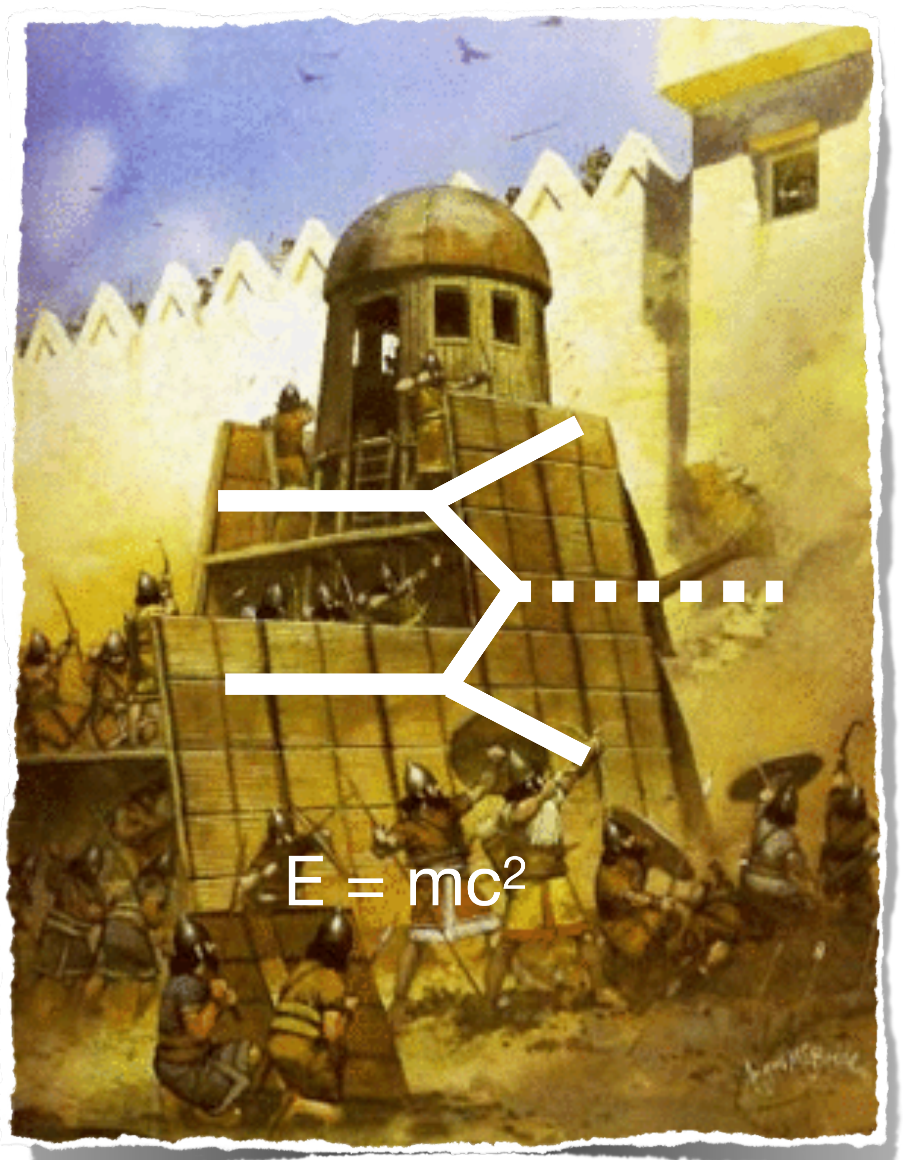
All non-SM physics searches ended up empty handed so far.

Technically, the SM as we know it is “stable” up to energies of 10^{10} GeV.

If that is the energy we need to reach to observe new phenomena, we better look for a career change already

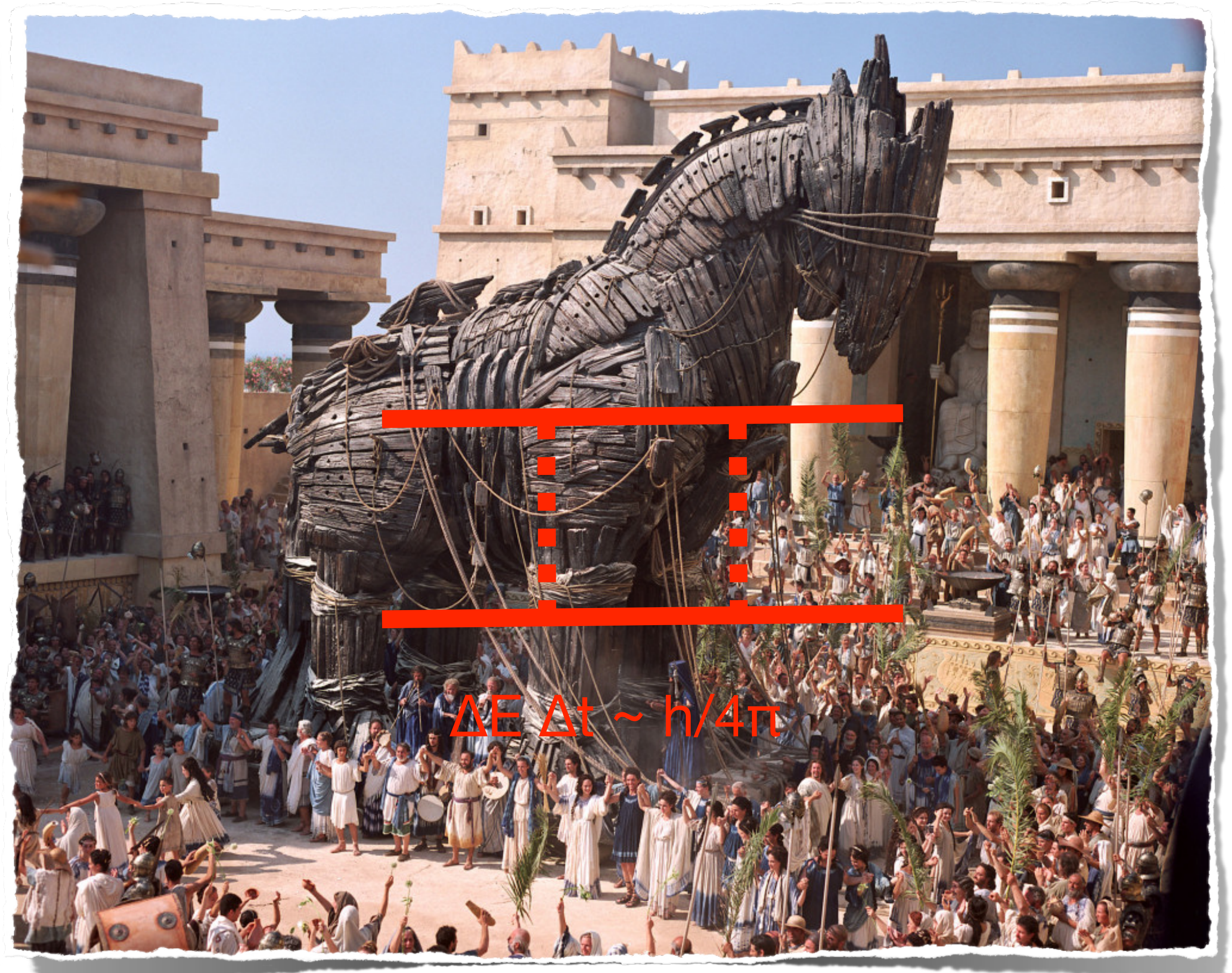
Two ways out

A more powerful collider (not in sight soon)



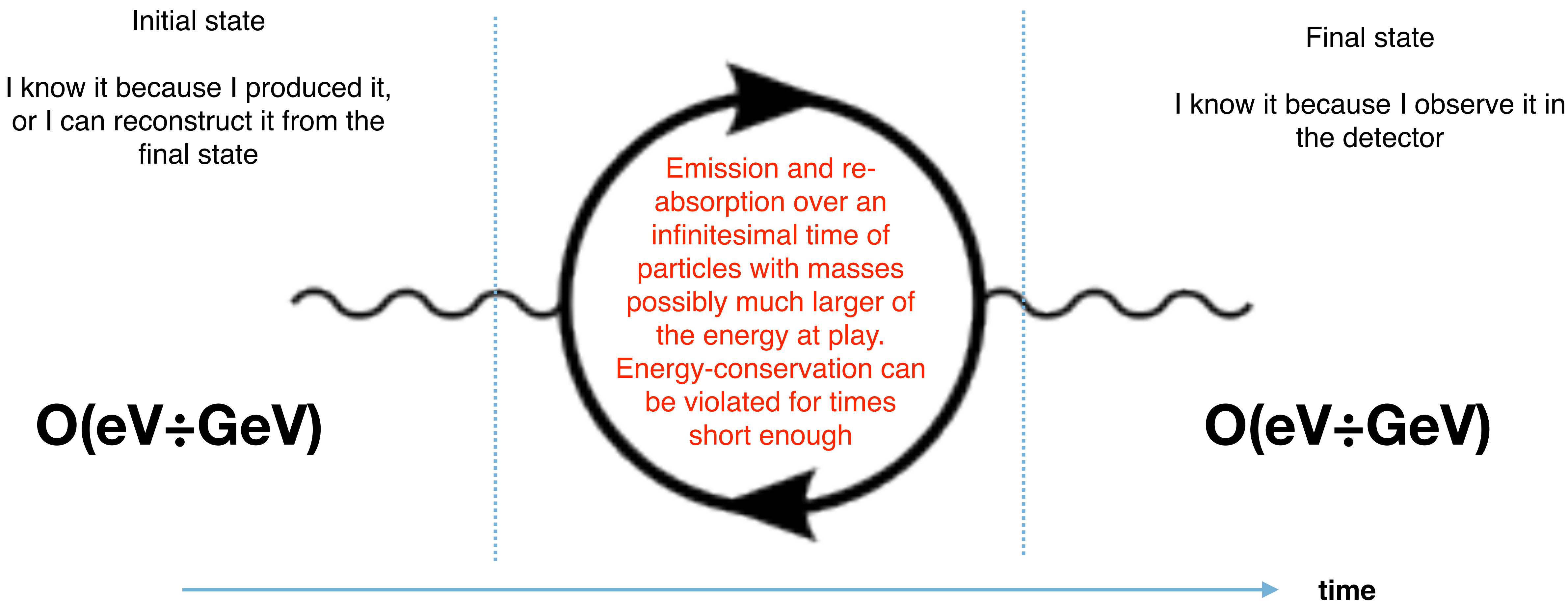
Direct high-energy production of non-SM particles

Get smarter



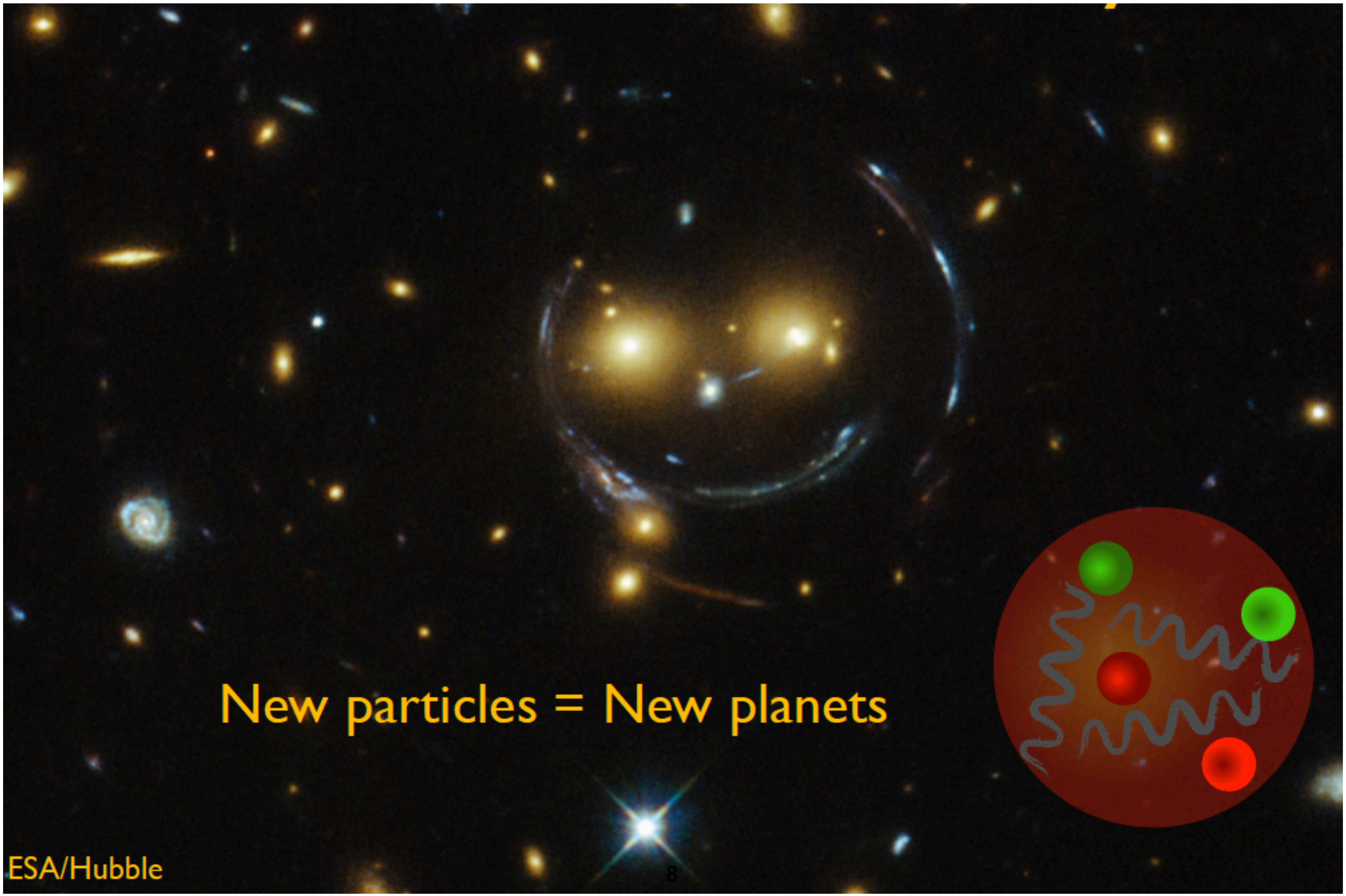
Quantum probing of virtual non-SM particles that contribute to known lower-energy processes

The indirect approach — precision frontier



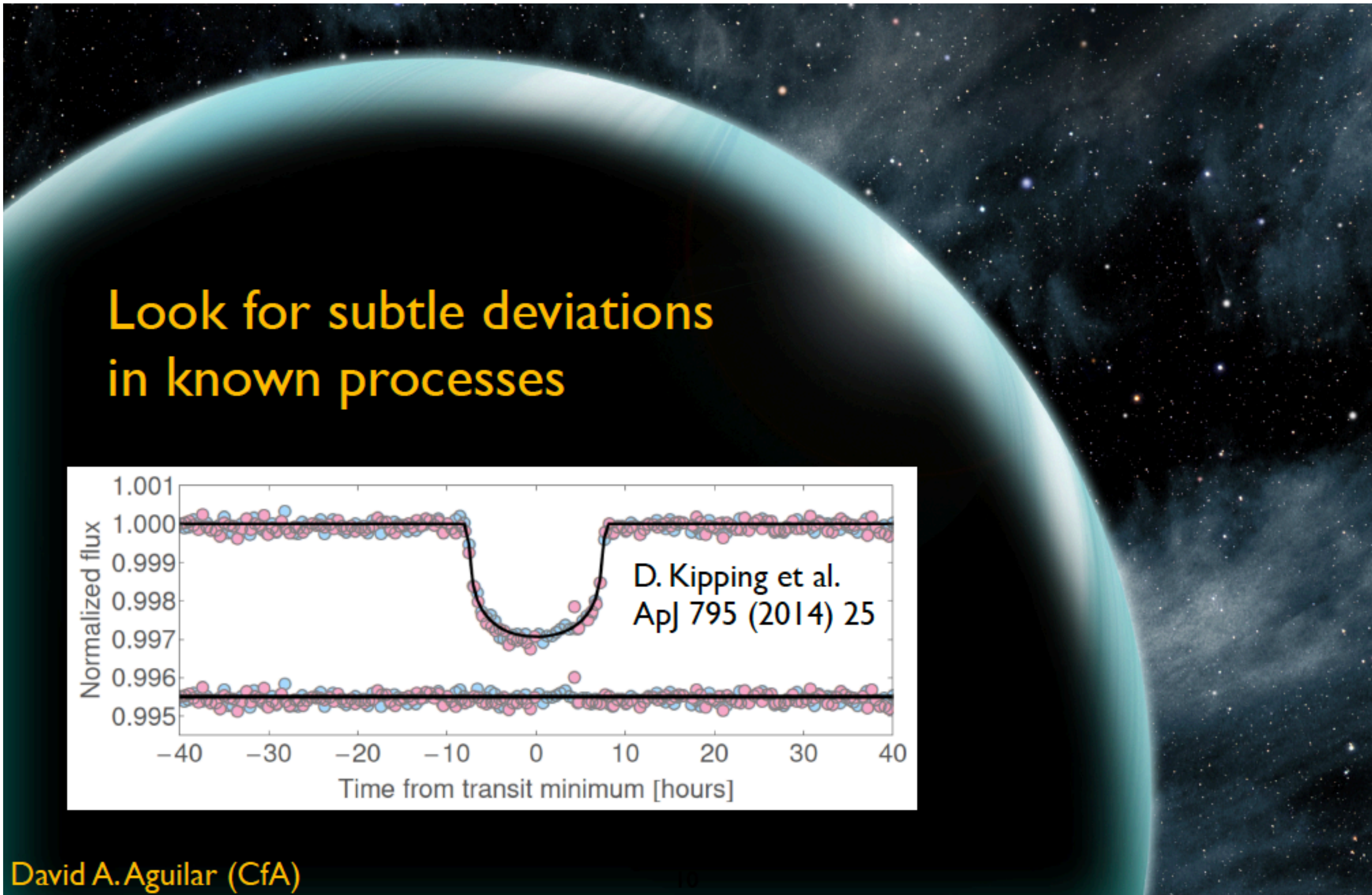
The amplitude that connects initial with final states receives contributions from *all* processes compatible with the symmetries of the dynamics: intermediate states include exchanges of all SM and *non-SM* particles with the right quantum numbers, irrespective of their mass, which can be much higher than the eV÷GeV scale of the process. If measured precisely and compared with equally precise predictions, such amplitudes can show discrepancies, revealing the existence of non-SM particles of masses much higher than directly accessible.

Two roads to discovery



Direct searches

Indirect searches

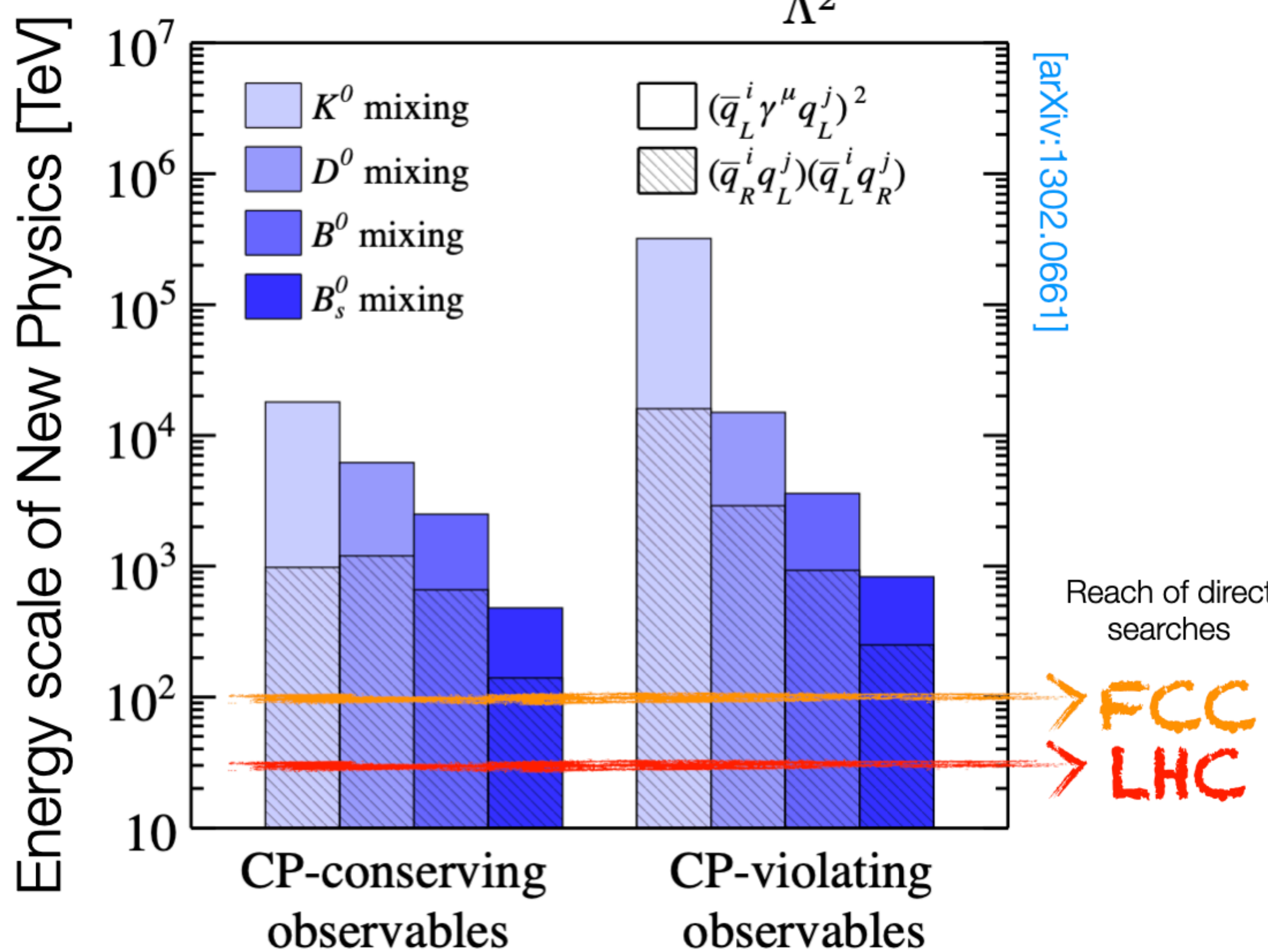


Flavor: a gateway to completing the SM

Flavor offers O(100) processes experimentally accessible and theoretically predictable with similar precision that allow multiple, redundant determinations of a restricted set of few fundamental parameters.

This enables a very large set of precise and reliable consistency checks that probe generically non-SM dynamics at masses of up to 100 000 TeV

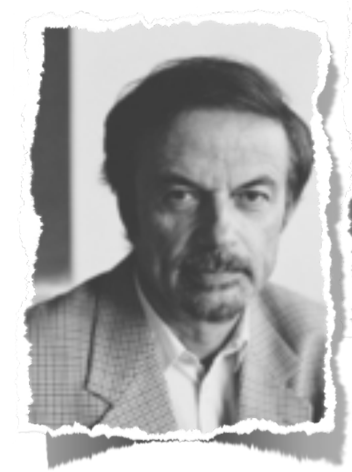
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{O}_{\Delta F=2}$$



Flavor?

The concept of "flavour physics" was introduced in the 1970s [1]

> The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks.



These lectures

- Today: how flavor physics was instrumental in constructing the Standard Model as we know it today (1933–2001)

- Tomorrow: why flavor physics might be our best bet to uncover what lies beyond the SM (2001– to date)

Disclaimer: heavy quark physics is a huge subject. Impossible to efficiently condensate in three hours. In addition, approaches to introduce it are multiple, diverse, and biased by the lecturer's and students' own interests and background.

I attempt an approach that focuses on exposing and consolidating the general concepts building on past history to possibly inspire you toward this field and gloss over the specifics. Please let me know at the end what you did like and what you didn't. In any case, do complement this with the excellent lectures by Karim Trabelsi given in previous installments of the school and others (CERN-Fermilab school etc). (references at the end).

Important caveat

So far and in what follows we talk of “particles”. This facilitate descriptions and helps forming an intuitive mental picture of what’s going on.

However, what is really fundamental are quantum fields, not particles. Fields are quantities that are associated to each point in space-time. They have a resting state. When perturbed, their values start oscillating. These oscillatory states (excitations) have higher energy than the resting state and are called particles.

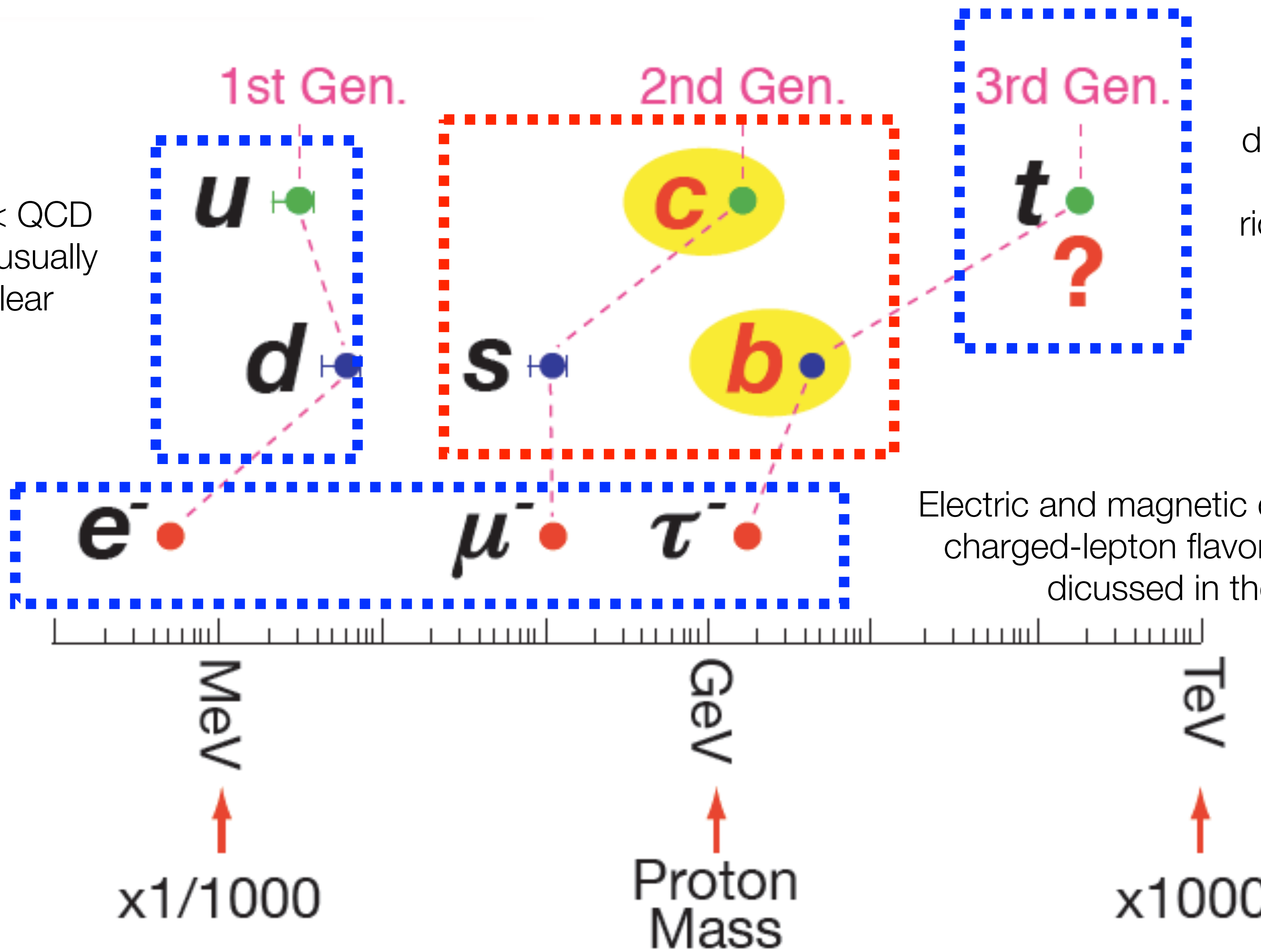
Quantum: one cannot excite arbitrarily *any* oscillatory state, but only states associated with specific quantized values (cannot generate an excitation in the electron field that corresponds to half an electron with half electric charge etc..it’s either one/two/three/… electrons or nothing).

Quantum fields permeate the whole spacetime and overlap at each point. If different fields are coupled, excitation of one propagates an excitation in the others. Couplings of fields are constrained by the symmetries of nature and are studied experimentally with particle interactions

Second caveat

We will focus mostly on the interactions of charm and bottom quarks

light-quark (mass < QCD scale) dynamics is usually the realm of nuclear physics



Top quark is so heavy that it decays before forming hadrons — this limits significantly the richness of the phenomenology for flavor

Electric and magnetic dipole moments and charged-lepton flavor violation won't be dicussed in these lectures

Look at A. Blondel's lectures for neutrino phenomenology

Birth and development of the quark-flavor sector of the SM

Enters antimatter — Arthur Schuster

AUGUST 18, 1898] NATURE 367

LETTERS TO THE EDITOR

[The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, or to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.]*

Potential Matter.—A Holiday Dream.

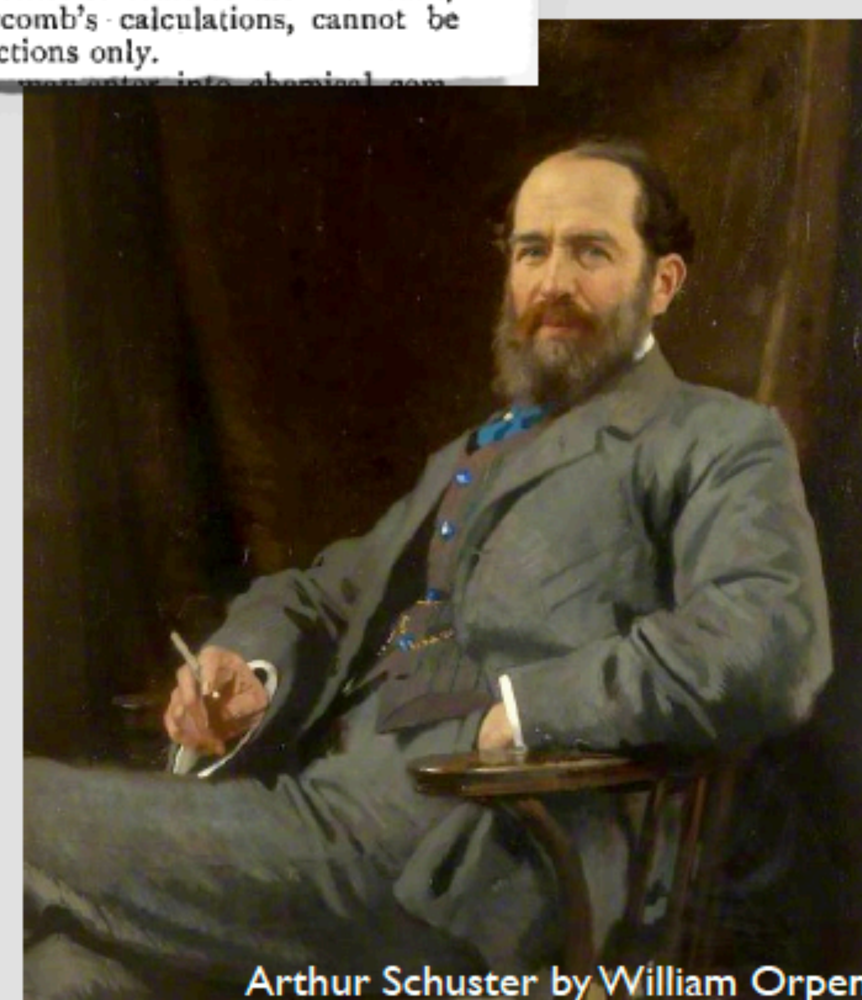
WHEN the year's work is over and all sense of responsibility has left us, who has not occasionally set his fancy free to dream

tional velocity of our solar and of many stellar systems, which cannot be self-generated. Unless we threw our laws of dynamics overboard, or imagine the rotation to have been impressed by creation, we must conclude that some outside body or system of bodies is endowed with an equal and opposite angular momentum. What has become of that outside body, and how could it have parted company with our solar system, if attractive forces only were acting? Another unexplained fact is found in the large velocities of the fixed stars, which, according to Prof. Newcomb's calculations, cannot be explained by gravitational attractions only.

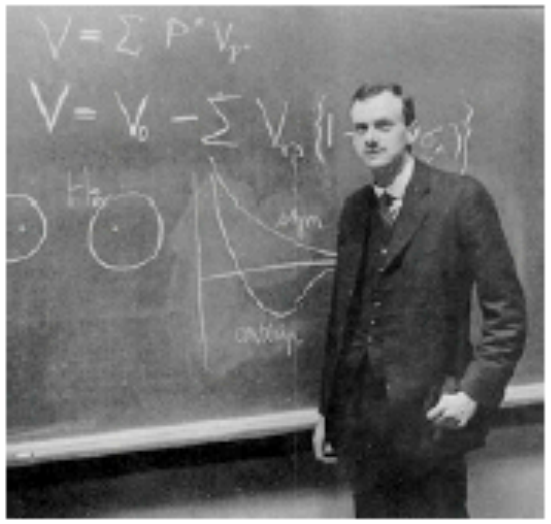
undistinguishable in fact from them until they are brought into each other's vicinity. If there is negative electricity, why not negative gold, as yellow and valuable as our own, with the same boiling point and identical spectral lines; different only in so far that if brought down to us it would rise up into space with an acceleration of 981. The fact that we are not acquainted with such matter does not prove its non-existence; for if it ever

incipient worlds which our telescopes have revealed to us. Astronomy, the oldest and yet most juvenile of sciences, may still have some surprises in store. May anti-matter be commended to its care! But I must stop—the holidays are nearing their end—the British Association is looming in the distance; we must return to sober science, and dreams must go to sleep till next year.

Do dreams ever come true? ARTHUR SCHUSTER.


Arthur Schuster by William Orpen

Antimatter — Dirac



- Combining quantum mechanics with special relativity, and the wish to *linearize* ∂/∂t, leads Dirac to the equation

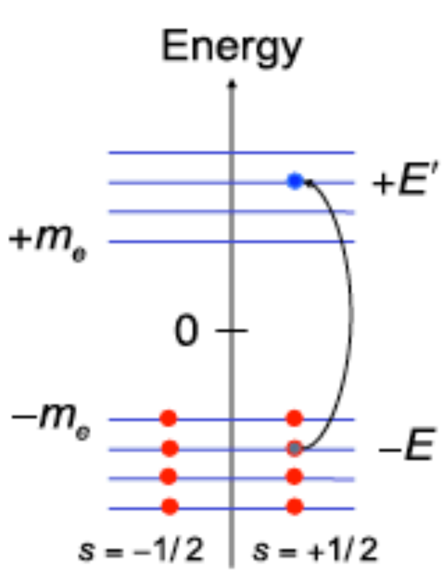
$$(i\gamma^\mu \partial_\mu - m)\,\psi(\vec{x}, t) = 0$$

- Solutions describe particles with spin = 1/2

- But half of the solutions have *negative energy*

$$E = \pm\sqrt{\vec{p}^{\,2} + m^2}$$

But why don't all electrons emit photons and collapse into the (favored) negative-energy states? Because they are all occupied…

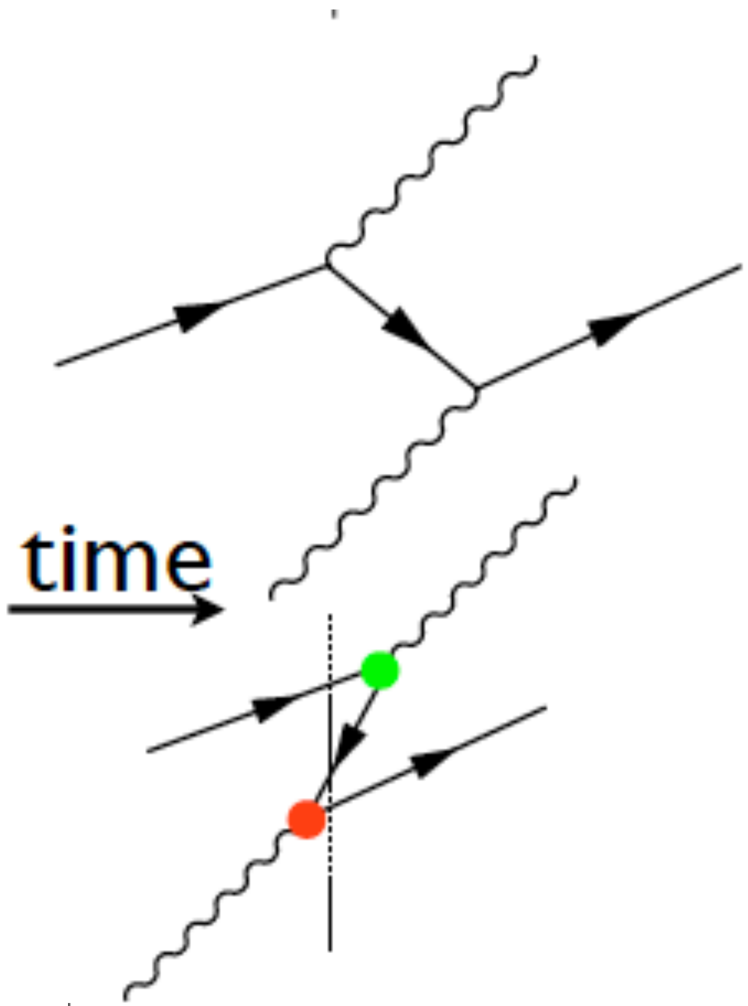


- Vacuum represents a "sea" of such negative-energy particles (fully filled according to Pauli's principle)

- Dirac identified holes in this sea as "antiparticles" with opposite charge to particles … (however, he conjectured that these holes were protons, despite their large difference in mass, because he thought "positrons" would have been discovered already)

- An electron with energy **E** can fill this hole, emitting an energy **2E** and leaving the vacuum (hence, the hole has effectively the charge +e and positive energy).

Antimatter — Stückelberg/Feynman



- consider the negative energy solution as *running backwards in time*
- and re-label it as *antiparticle*, with *positive* energy, going forward in time
- emission of E>0 antiparticle = absorption of particle E<0
- Naturally describes *creation* and *annihilation*...
- ... and that particles and antiparticles must have the same mass, spin, ... and opposite charges

This involves a *CPT* transformation:

- we have flipped Charge (C),
- flipped time (T),
- *and to prevent momentum* from being flipped, must *also* flip the space coordinates (P)

Quantity		C	T	P
Time	t	t	−t	t
Space vector	x	x	x	−x
Momentum	p	p	−p	−p

CPT

"**Any Lorentz-invariant local quantum field theory is invariant under the combined application of *C*, *P* and *T*"**

G. Lüders, W. Pauli (1954); J. Schwinger (1951)

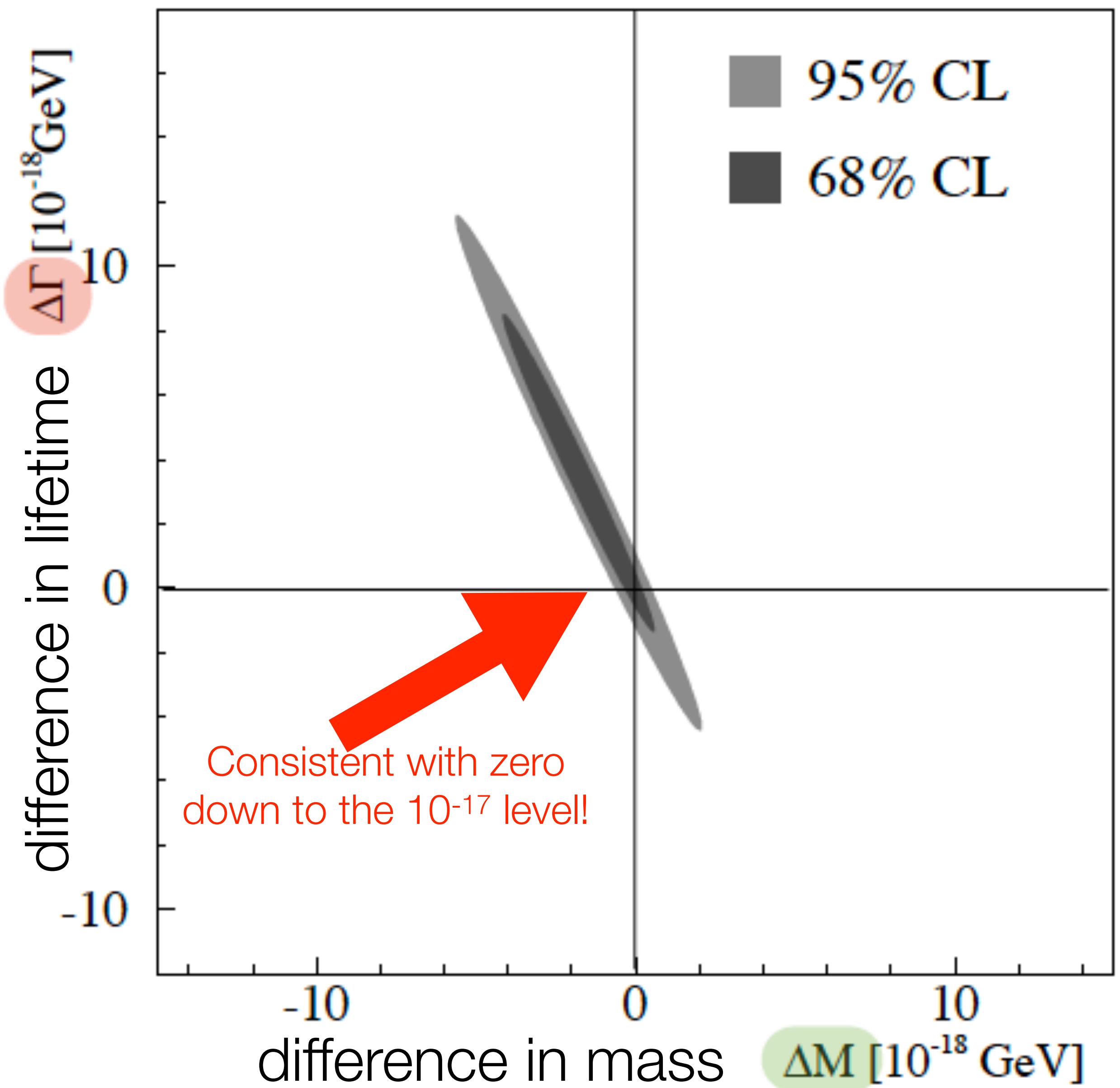
Assumptions:

1. Lorentz invariance
2. "principle of locality"
3. Causality
4. Vacuum lowest energy
5. Flat space-time
6. Point-like particles

Consequences:

1. Relation between spin and statistics: fields with integer spin commute and fields with half-numbered spin anticommute; Pauli exclusion principle
2. Particles and antiparticles have **equal mass and lifetime**, equal magnetic moments with opposite sign, and **opposite quantum numbers**

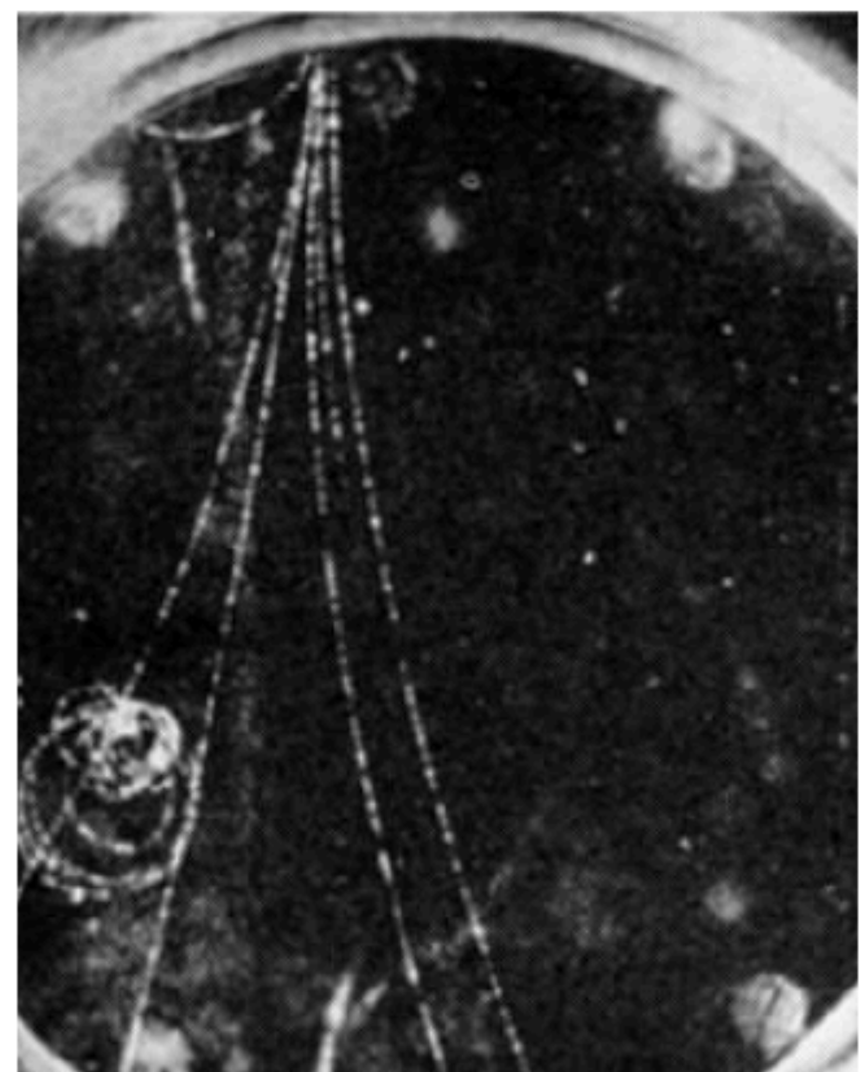
Observed kaon-antikaon differences



Does antimatter exist?

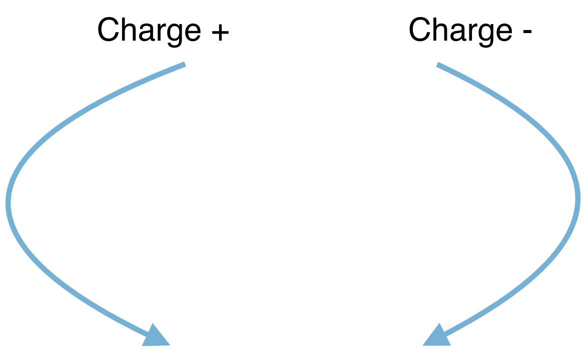
Back to experiment: does antimatter exists, and, if so, where is it?

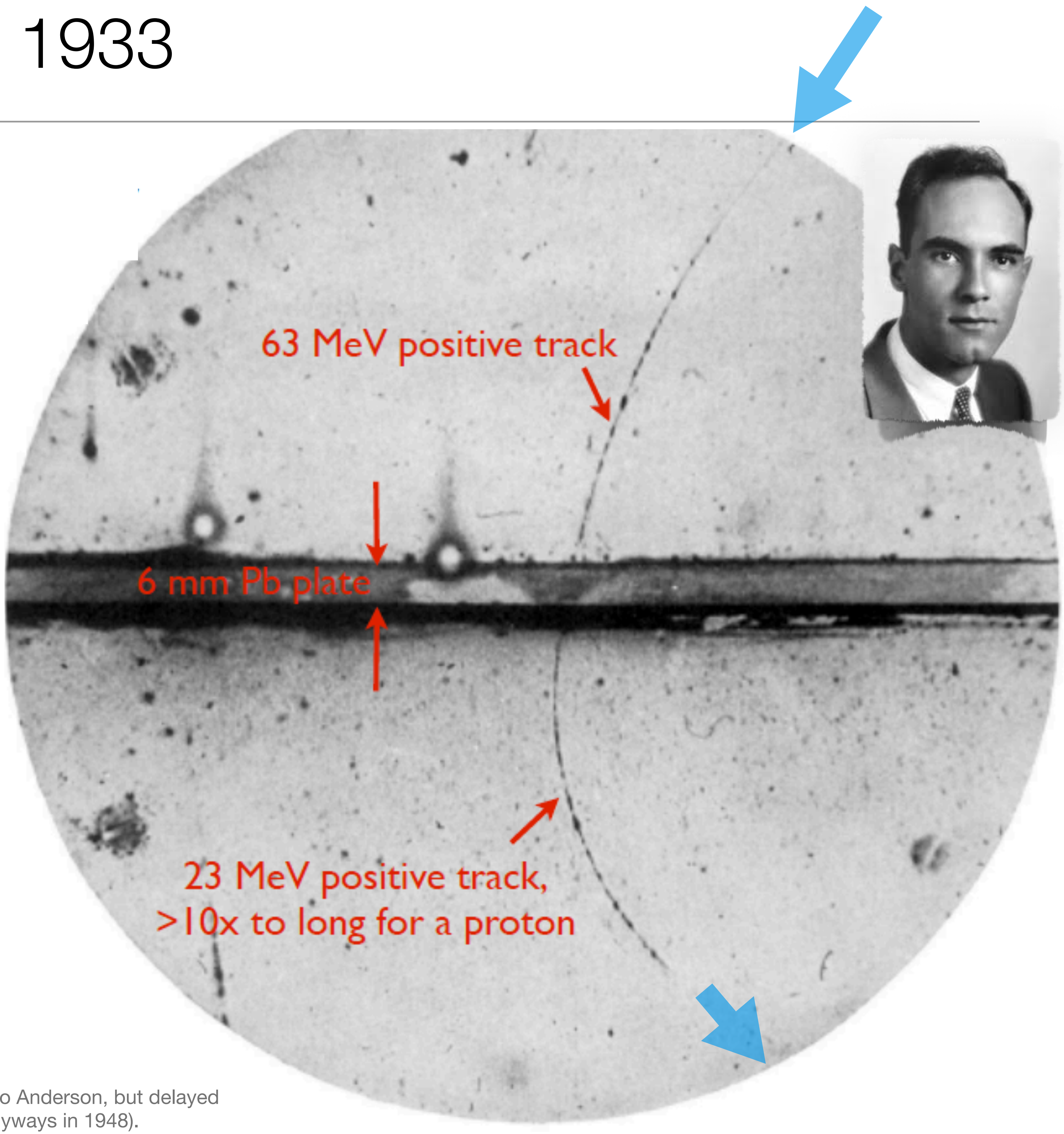
Carl Anderson studies at cosmic rays on Pikes peak, using a Cloud chamber



Particles will show (temporarily) as condensation trail in gas volume (just like condensation trails of airplanes)

Carl D. Anderson - 1933



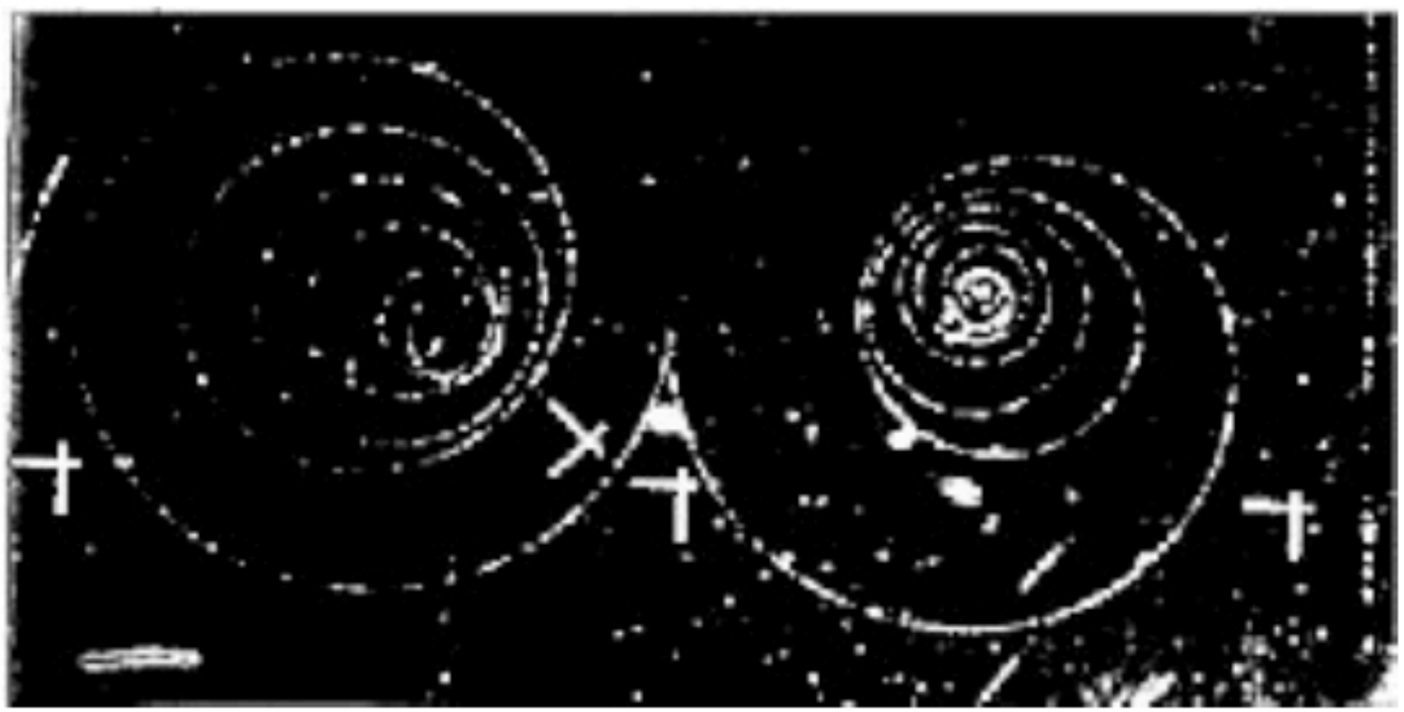


Discovery of a positively charged, electron-like particle. Dubbed “positron”

PS: P. Blackett and G. Occhialini observed positrons simultaneously to Anderson, but delayed publication of the results missing the Nobel Prize — Blackett got it anyways in 1948).

Antimatter is real

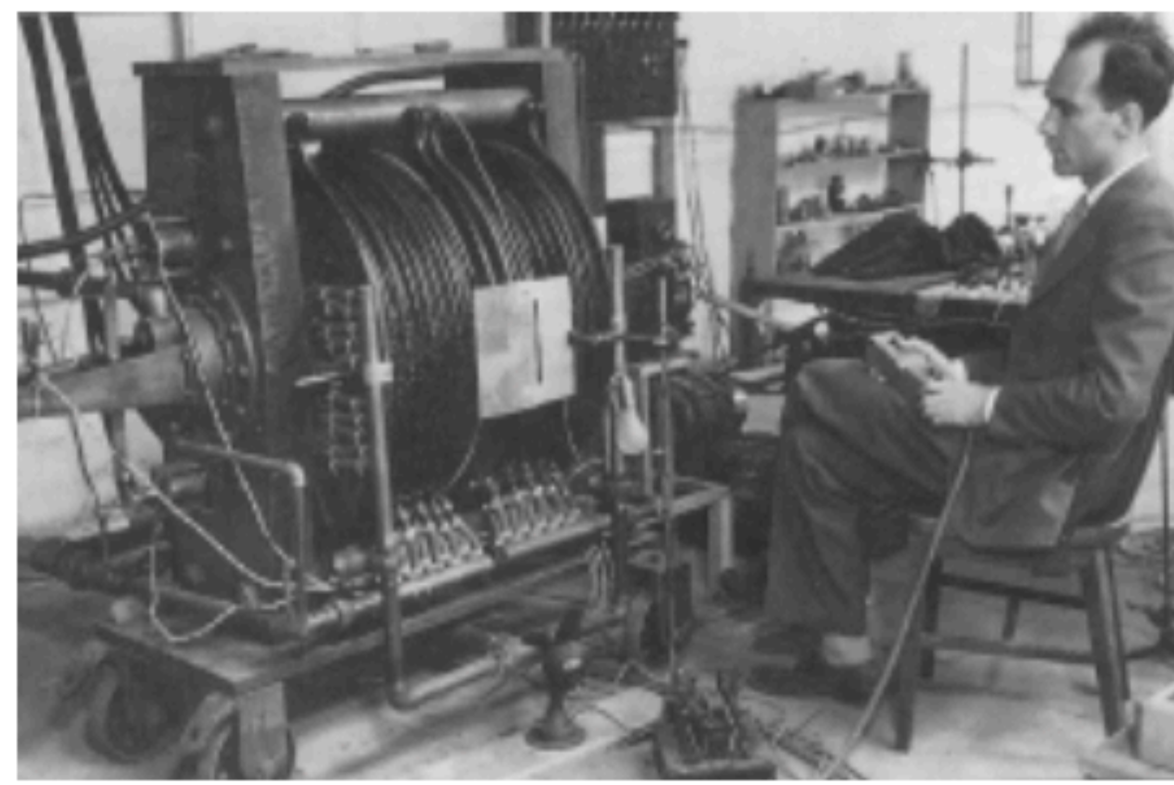
- Confirmed with $\gamma \to e^+e^-$



CARL D. ANDERSON

The production and properties of positrons

Nobel Lecture, December 12, 1936



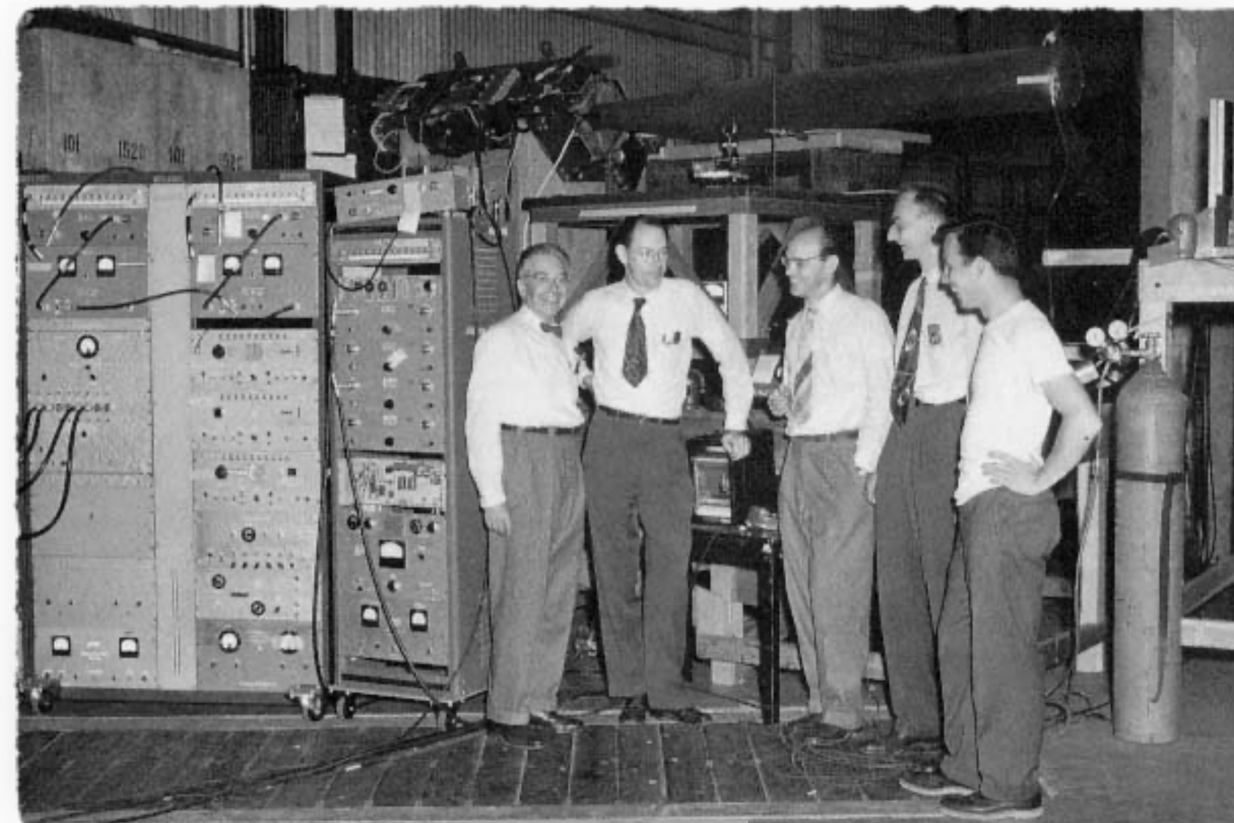
Manufacturing antimatter - Piccioni-Chamberlain-Segré ‘55

The hunt starts for other antimatter particles: antiproton is next.

However, its large mass makes it hard to be observed in cosmic rays.

Need to wait another 20 years and the advent of accelerator physics (generously financed post WWII thanks to the success of the Manhattan project)

Bevatron 1955: protons on protons at high energy produce additional proton-antiproton pair



…to this day: antiatoms

Antimatter research continues to this day. In 1996 the first antiatoms are formed at CERN.

Currently studying if they have the same properties as matter: e.g., are they attracted or repelled by gravity?


CORRIERE DELLA SERA.it

APRE OGGI IL LABORATORIO DEL CERN

Ginevra, nella «fabbrica» dell' anti-materia i segreti del Big Bang

Gli atomi custoditi in una gabbia magnetica per evitare collisioni pericolose

Pagina 16
(10 agosto 2000) - Corriere della Sera

First atoms of antimatter produced at CERN

[Big science question excursus]

(

Big Bang* — G. Gamow 1948

The Universe starts from an initial state at very high density and temperature

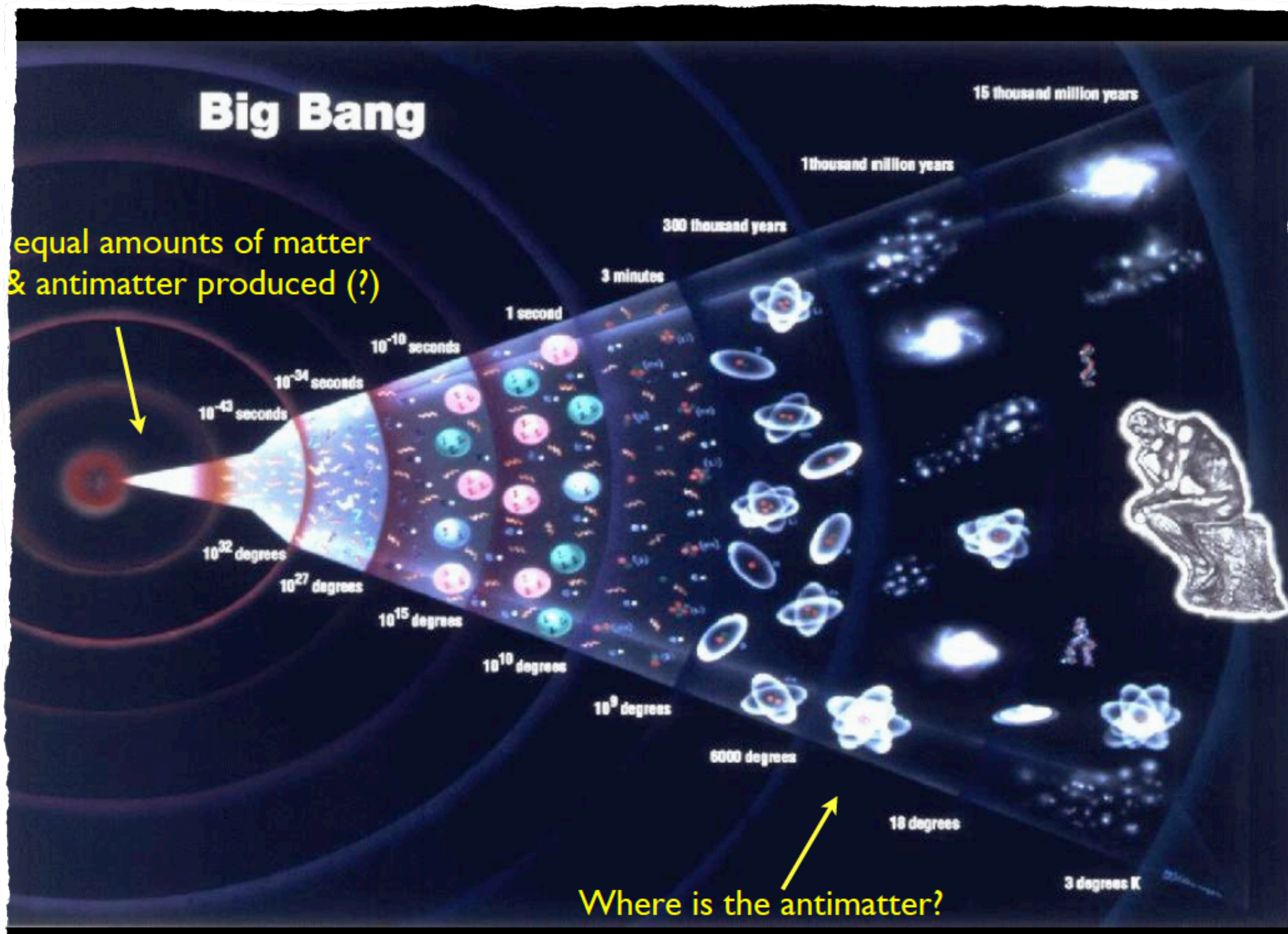
Then it exapnds rapidly and colling off

At the beginning it’s dominated by radiation. During the cooling the various particles form

There has to be an echo of that primordial heat, that we call primordial background radiation

* the process was christened Big Bang by Fred Hoyle in a TV show in 1948 to ridiculize Gamow’s theory, in which he didn’t believe…

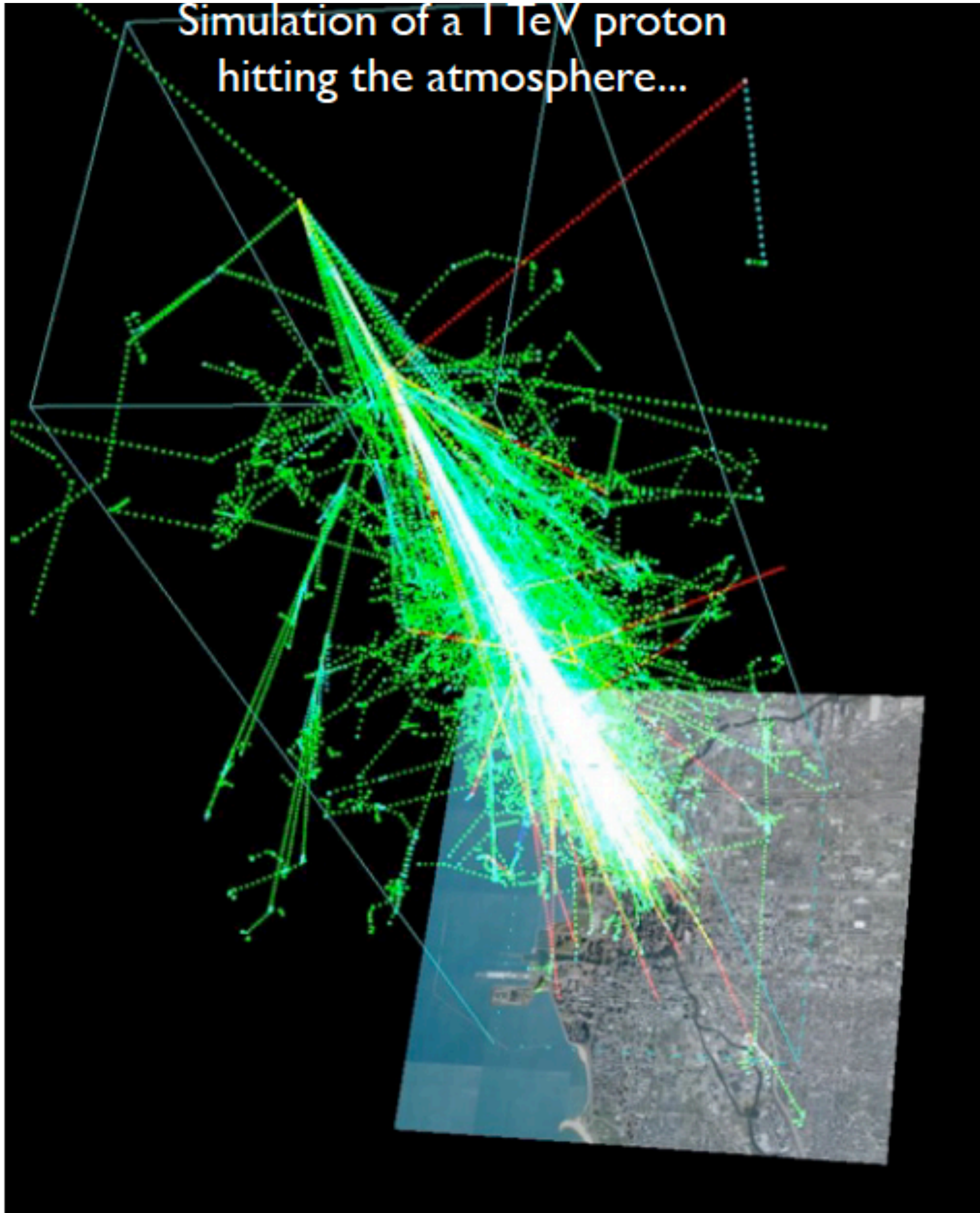
Big bang



Big Bang
equal amounts of matter
& antimatter produced (?)
15 thousand million years
1thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
Where is the antimatter?

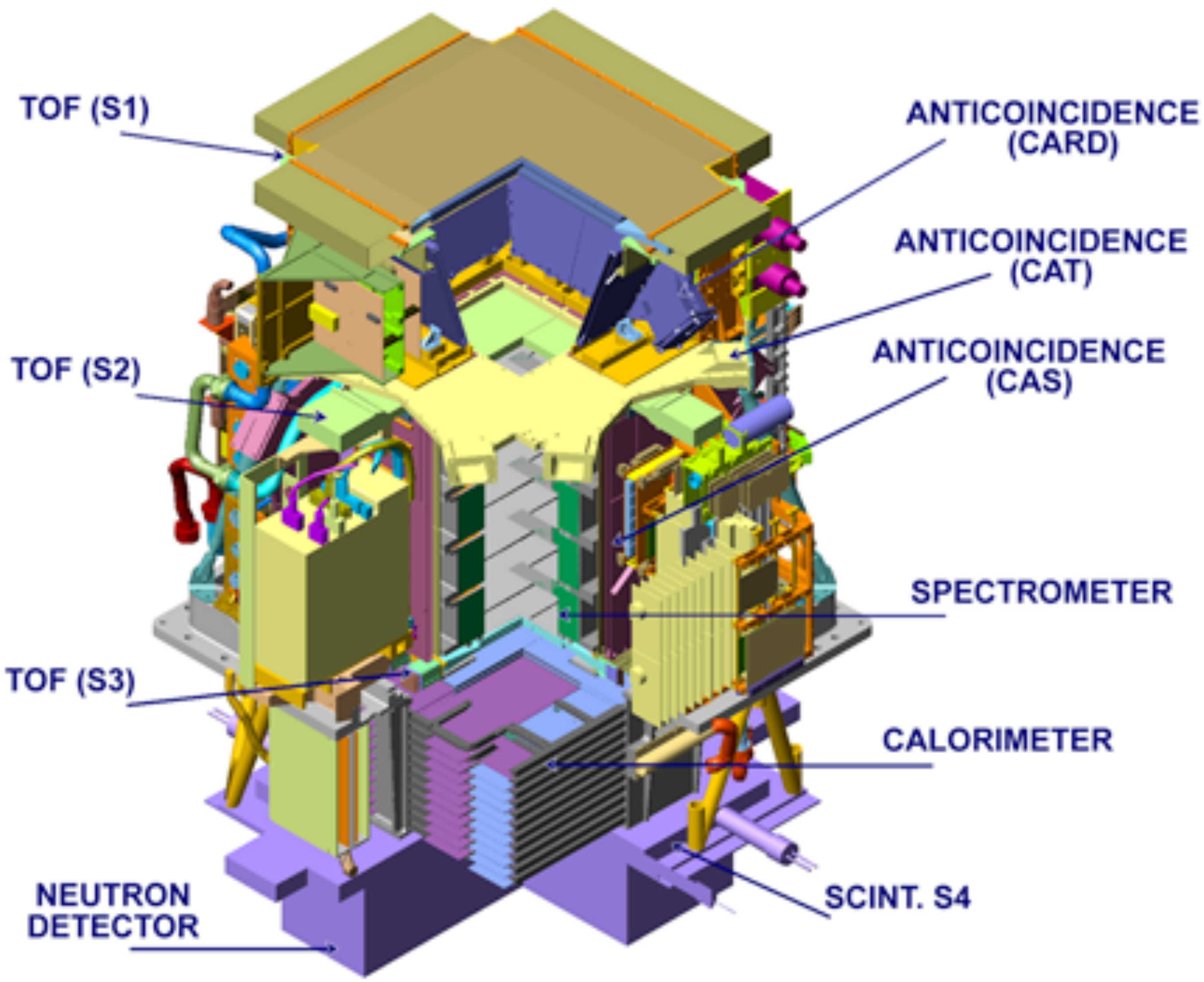
Cosmic antimatter

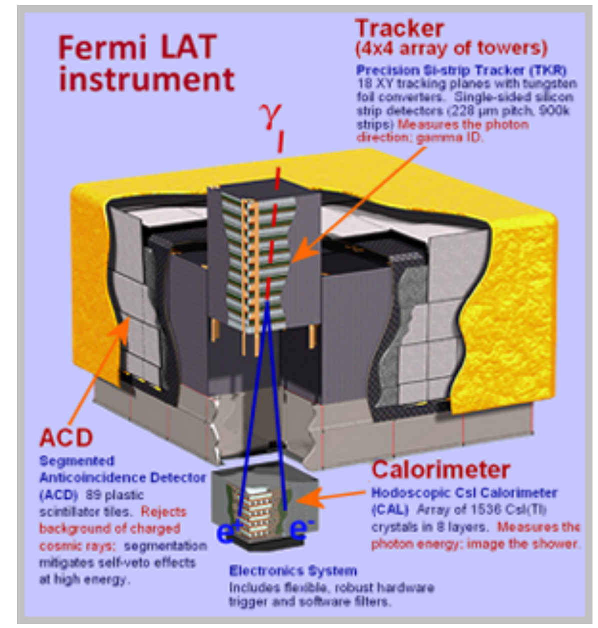
- Antiparticles appear in cosmic ray showers
- But what about the original incoming (anti?)particle
- Must measure before the shower starts, eg. above the atmosphere..

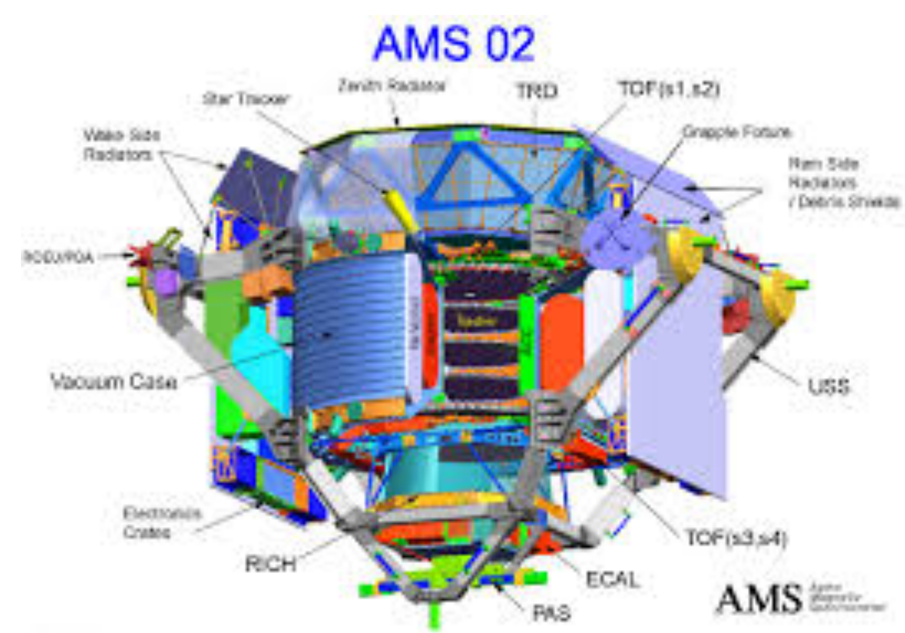


Searching for cosmic antimatter: Pamela, Fermi-LAT, AMS-02

Send “small” particle detectors in **space**







And look for elements, like anti-He, which are unlikely to form in secondary collisions and would be suggestive of primordial antimatter

Searching for cosmic antimatter: bottomline

No evidence for the original, "primordial" cosmic antimatter:

- Absence of anti-nuclei amongst cosmic rays in our galaxy
- Absence of intense γ-ray emission due to annihilation of distant galaxies in collision with antimatter

The big science question

Since vacuum has null baryon number, Big-Bang presumably creates same amounts of matter and antimatter. But somewhere along the evolution matter gets favored and we are left with no antimatter, a bit of matter, and 10^{10} more photons. How did it happen?

Enters CP violation…

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

Andrei Sakharov
"Father" of Soviet hydrogen bomb
& Nobel Peace Prize Winner

Three requirements for a universe with a baryon asymmetry:

1. A process that violates baryon number
2. C and CP violation, i.e. breaking of the C and CP *symmetries*
3. 1 & 2 should occur during a phase which is NOT in thermal equilibrium

[End of big science question excursus]

)

Symmetries in physics

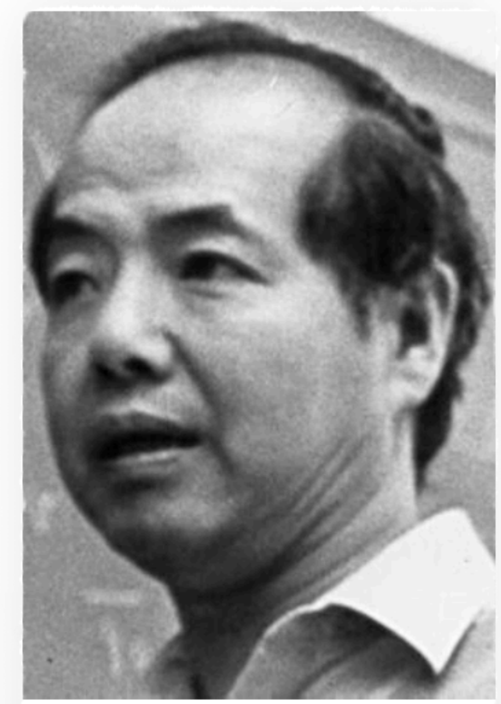
Symmetries have an essential role in bulding a reductionist picture of the fundamental particles and their interactions.

“The root to all symmetry principles relies in the assumption that it is impossible to observe certain basic quantities; the non-observables”

1. Space translation symmetry:
   - Hidden observable: **Absolute position**
   - Conserved quantity: momentum

2. Time shift symmetry:
   - Hidden observable: **Absolute time**
   - Conserved quantity: Energy

3. Rotation symmetry:
   - Hidden observable: **Absolute orientation**
   - Conserved quantity: Angular momentum



T.D. Lee

Discrete symmetries

- Spatial sign flip (x,y,z → -x,-y,-z) : P
- Charge sign flip (Q → -Q) : C
- Time sign flip (t → -t) : T

- Are these discrete symmetries exact symmetries that are observed in nature?
  - Is the assignment of the label (anti) particle a convention or not?
  - Is there a fundamental difference between left-handed and right-handed?

Quantity		P	C	T
Space vector	$\mathbf{x}$	$-\mathbf{x}$	$\mathbf{x}$	$\mathbf{x}$
Time	t	t	t	$-t$
Momentum	$\mathbf{p}$	$-\mathbf{p}$	$\mathbf{p}$	$-\mathbf{p}$
Spin	$\mathbf{s}$	$\mathbf{s}$	$\mathbf{s}$	$-\mathbf{s}$
Electrical field	$\mathbf{E}$	$-\mathbf{E}$	$-\mathbf{E}$	$\mathbf{E}$
Magnetic field	$\mathbf{B}$	$\mathbf{B}$	$-\mathbf{B}$	$-\mathbf{B}$

Conservation of parity - stated in 1928

Über die Erhaltungssätze in der Quantenmechanik.

Von

E. Wigner, Göttingen.

Vorgelegt von Max Born in der Sitzung vom 10. Februar 1928.

1. Durch die „statistische Deutung der Quantenmechanik“ [1]) mußten viele unserer gewohnten physikalischen Begriffe einer weitgehenden Revision unterzogen werden. Ob das Geschehen selber akausal ist, soll hier nicht untersucht werden, es sollen nur die Erhaltungssätze der nunmehr modifizierten Begriffe Energie, Impuls usw. besprochen werden.

Bekanntlich kann man im Sinne der Quantenmechanik niemals die Frage aufstellen: „Wie groß ist die X-Koordinate oder etwa die Energie dieses Körpers?“ Die vernünftige Fragestellung ist: Wie groß ist die Wahrscheinlichkeit, daß ein Versuch zur Bestimmung der X-Koordinate (oder Energie) diesen oder diesen Wert ergibt? In diesem Sinne müssen wir auch die Erhaltungssätze formulieren. Sie lauten dann z. B.: Die Wahrscheinlichkeit, daß die Energie den Wert E hat, ändert sich im Laufe der Zeit nicht. Dies ist also so zu verstehen, daß man bei einer Bestimmung der Energie eines Systems mit derselben Wahrscheinlichkeit den Wert E erhält, gleichgültig, ob man den Versuch zur Zeit 0 oder

E. Wigner

O. Laporte 1924: 1-photon (electric dipole) transitions between energy levels in complex atoms occur only btw states he classified as “even” and “odd” and viceversa (Die Struktur des Eisenspektrums, Zeit. Phys. 23, 135 (1924).) Shortly later, similar results from Russel (H.N. Russell, A New Form of Exclusion Principle in Optical Spectra, Science 49, 512 (1924). First evidence of a parity quantum number. Wigner in 1927 formalized this into the law of conservation of parity using the x → -x invariance of the Schrödinger equation

θ-τ puzzle….

Observation of something(s) which decay to two pions and three pions, but whatever decays (now known as K^+), has, in both decays, the same lifetime, mass, spin=0...

In 1953, Dalitz argued that since the pion has parity of -1,

- two pions (*) would combine to produce a net parity of (-1)(-1) = +1,
- and three pions (*) would combine to have total parity of (-1)(-1)(-1) = -1.

Hence, if conservation of parity holds, there are two *distinct* particles with parity +1 (the 'θ') and parity -1 (the 'τ')(**).

But how to explain the fact that the mass and lifetime are the same?

$\boxed{K^\pm}$ $I(J^P) = \frac{1}{2}(0^-)$

K^+ DECAY MODES

K^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Hadronic modes		
Γ_9	$\pi^+\pi^0$	(21.13 ±0.14) %	S=1.1
Γ_{10}	$\pi^+\pi^0\pi^0$	(1.73 ±0.04) %	S=1.2
Γ_{11}	$\pi^+\pi^+\pi^-$	(5.576±0.031) %	S=1.1

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

(*) produced in the decay of a spin=0 mother

(**) Warning: do not confuse this 'τ' with what is now known as the τ lepton

The "straight experimenter's question"

M. Block

Block proposed that in the weak interactions parity was not conserved, which would then explain the tau/theta puzzle, a subject of great actuality in those days, but he did not dare to formally transmit his view to the participants at the conference.

Richard Feynman, however, communicated Block's idea to the participants,: "Anyway, I was sharing a room with a guy named Martin Block, an experimenter. And one evening, he said to me: 'Why are you guys so insistent on this parity rule? Maybe the tau and theta are the same particle. What would be the consequences if the parity rules were wrong?'

I thought a minute and said: 'It would mean that nature's laws are different for the right hand and the left hand, that there's a way to define the right hand by physical phenomena. I don't know that that's so terrible, though there must be some bad consequences of that, but I don't know. Why don't you ask the experts tomorrow?' He said: 'No, they won't listen to me. You ask.' So the next day, at the meeting … I got up and said, 'I'm asking this question for Martin Block: What would be the consequences if the parity rule was wrong?' Murray Gell-Mann often teased me about this, saying I didn't have the nerve to ask the question for myself. But that's not the reason I thought it might very well be an important idea."

..leds Lee and Yang to postulate P violation

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

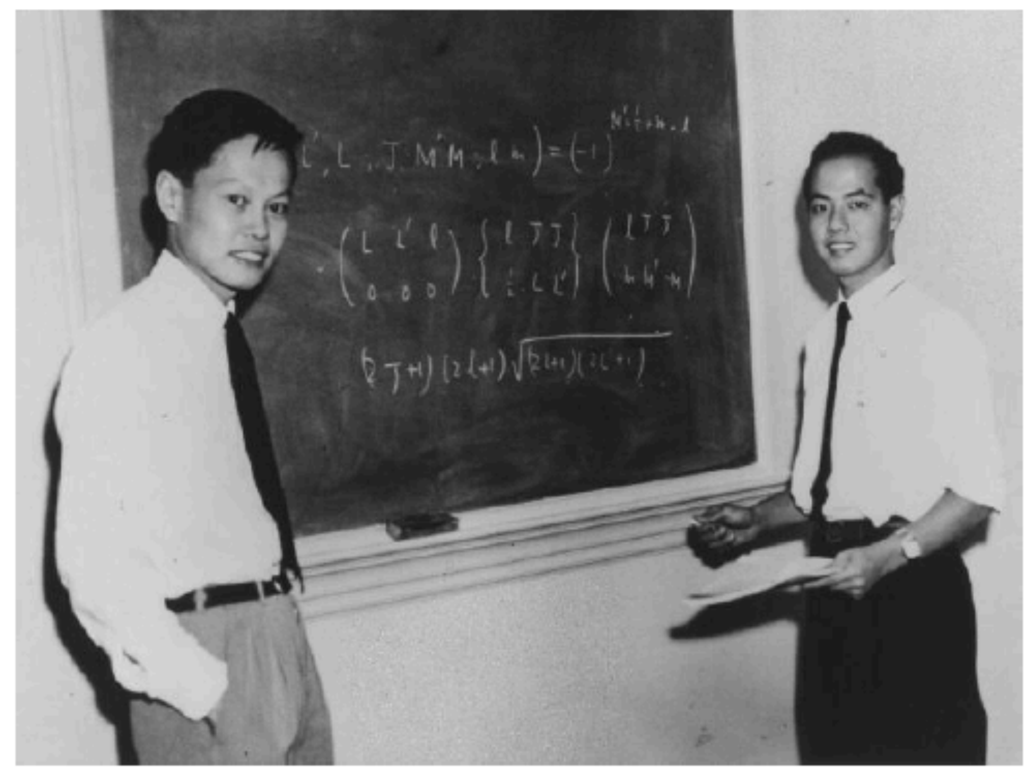
C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper against the background of the existing experimental evidence of parity conservation. It will become clear that existing experiments do indicate parity conservation in strong and electromagnetic interactions to a high degree of accuracy, but that for the weak interactions (i.e., decay interactions for the mesons and hyperons, and various Fermi interactions) parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence. (One might even say that the present $\theta-\tau$ puzzle may be taken as an indication that parity conservation is violated in weak interactions. This argument is, however, not to be taken seriously because of the paucity of our present knowledge concerning the nature of the strange particles. It supplies rather an incentive for an examination of the question of parity conservation.) To decide



Experimental closure test - C.S. Wu

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
National Bureau of Standards, Washington, D. C.

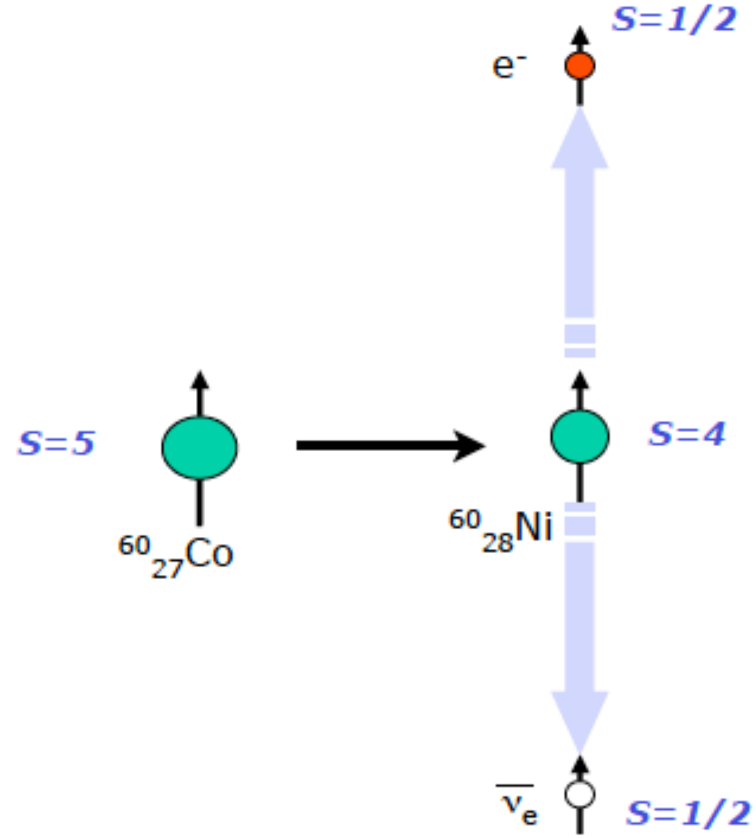
(Received January 15, 1957)

Idea for experiment in collaboration with Lee and Yang: *Look at spin of decay products of polarized radioactive nucleus*

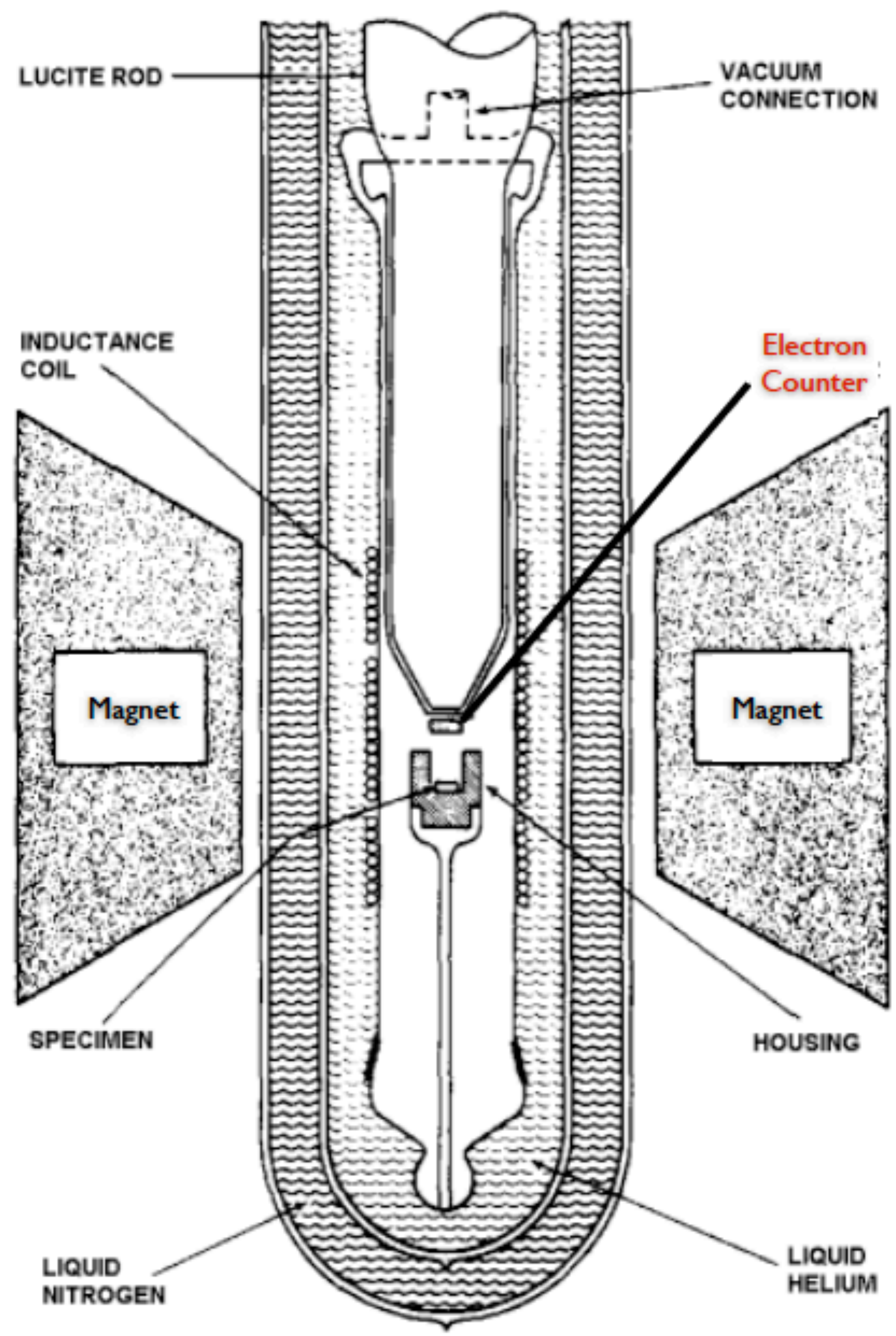
- Production mechanism involves exclusively weak interaction

Mme. Chien-Shiung Wu

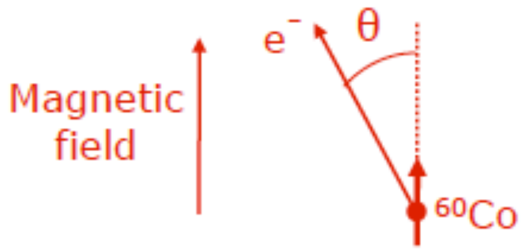
Dr. Wu experimental setup



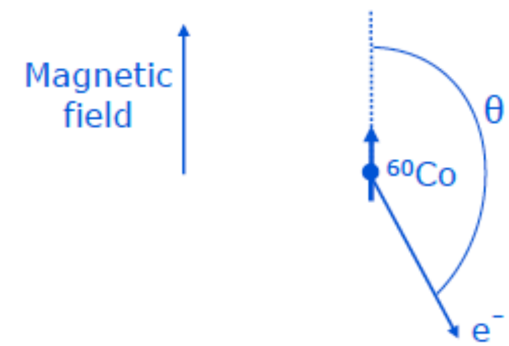
- How do you obtain a sample of ^{60}Co with spins aligned in one direction, and compare to non-aligned case?
- Adiabatic demagnitization of ^{60}Co in a magnetic field at very low temperatures (~0.01 K!). Extremely challenging in 1956!

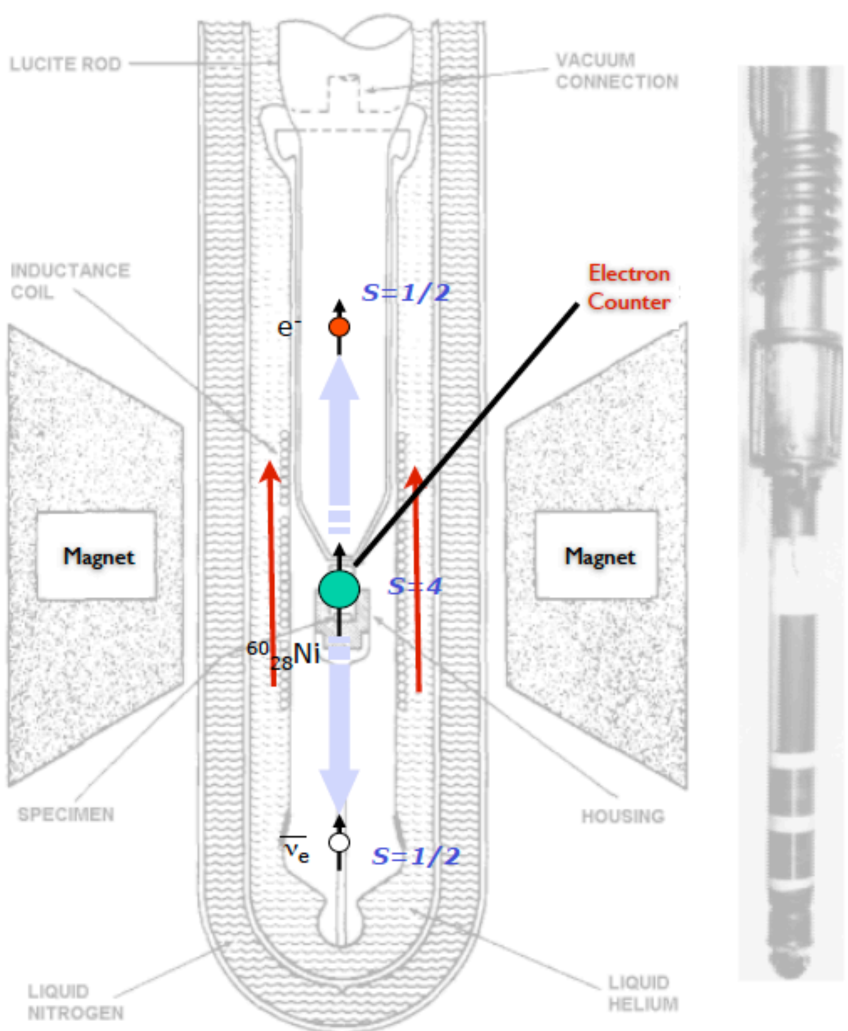


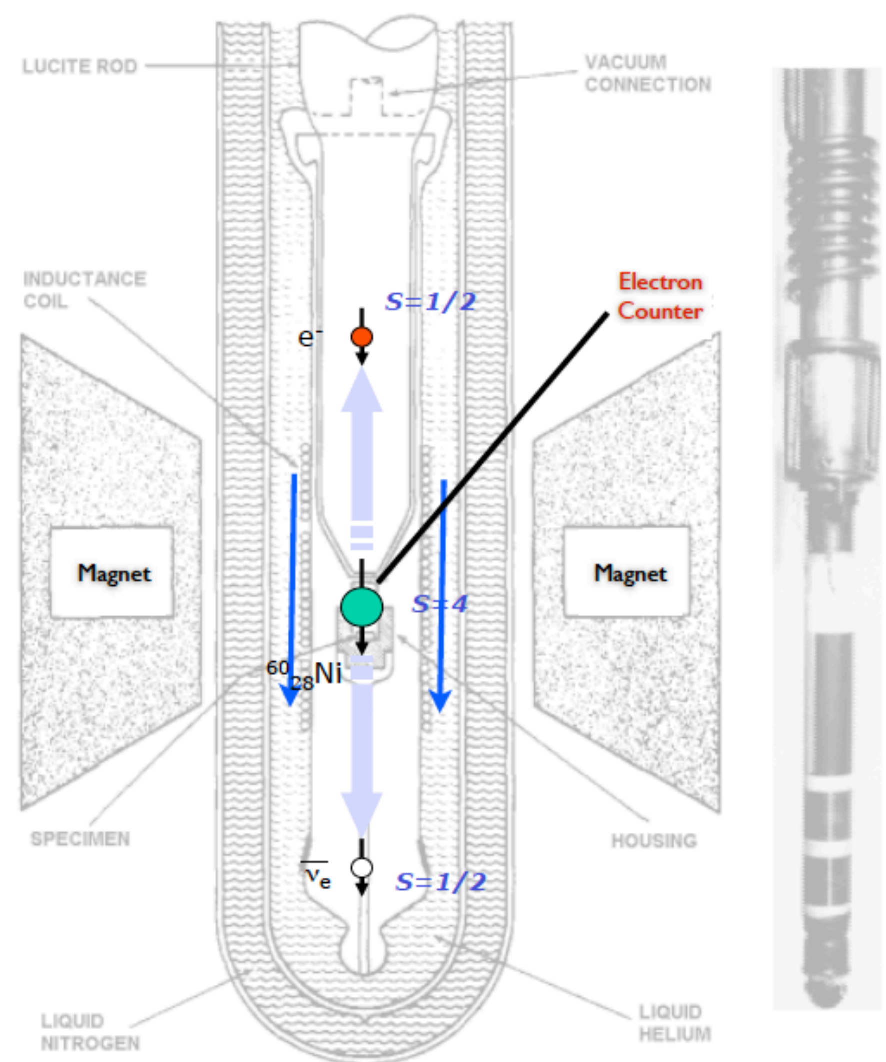
Forward-vs-backward electrons



parity transformation

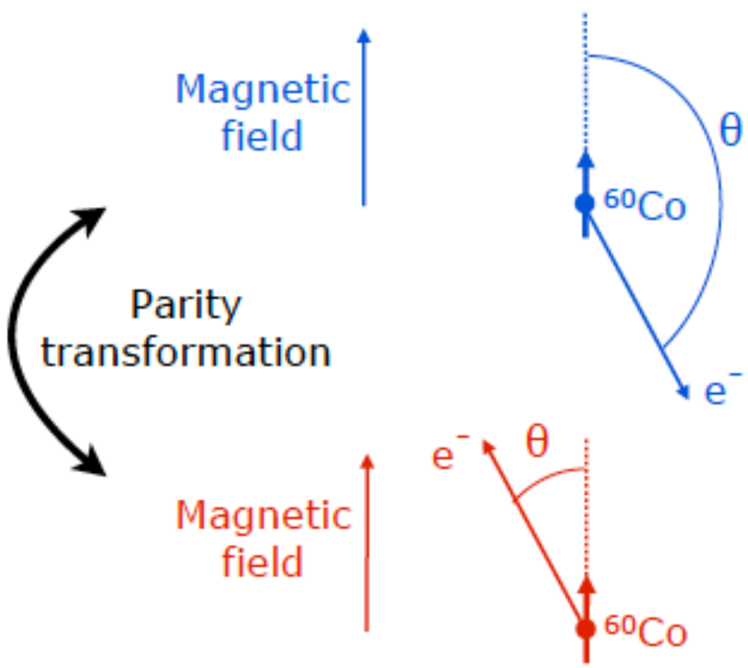


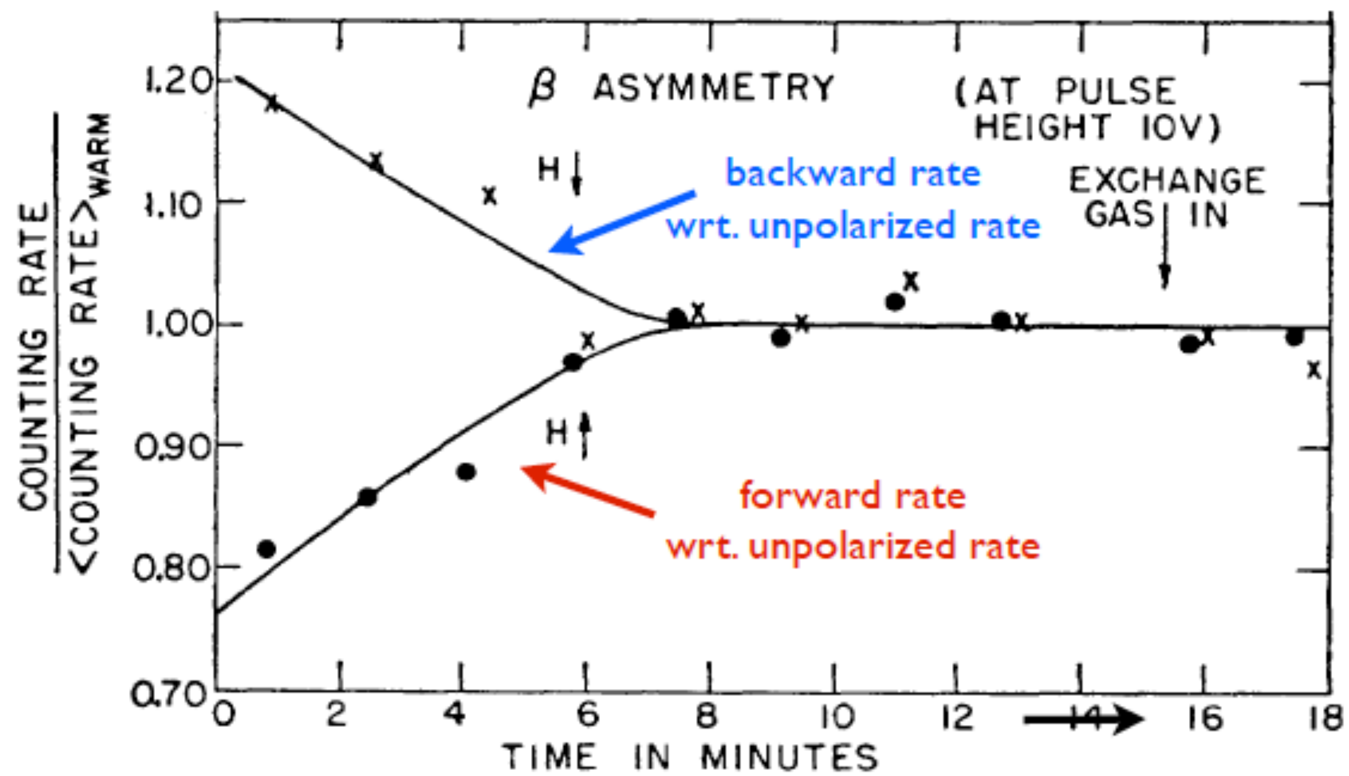




If the interaction is invariant under parity, rates in the two configurations are equal

Rates are *not* equal: parity is maximally violated





^{60}Co polarization decreases as a function of time as the temperature increases

- The counting rate in the polarized case is different from the unpolarized case
- Changing the direction of the B-field changes the counting rate!
- Electrons are preferentially emitted in the direction opposite the ^{60}Co spin!
- Analysis of the results shows that data consistent with the emission of only left-handed (i.e. H = -1) electrons ....
- ... and thus only *right-handed anti-neutrinos*

From another angle

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

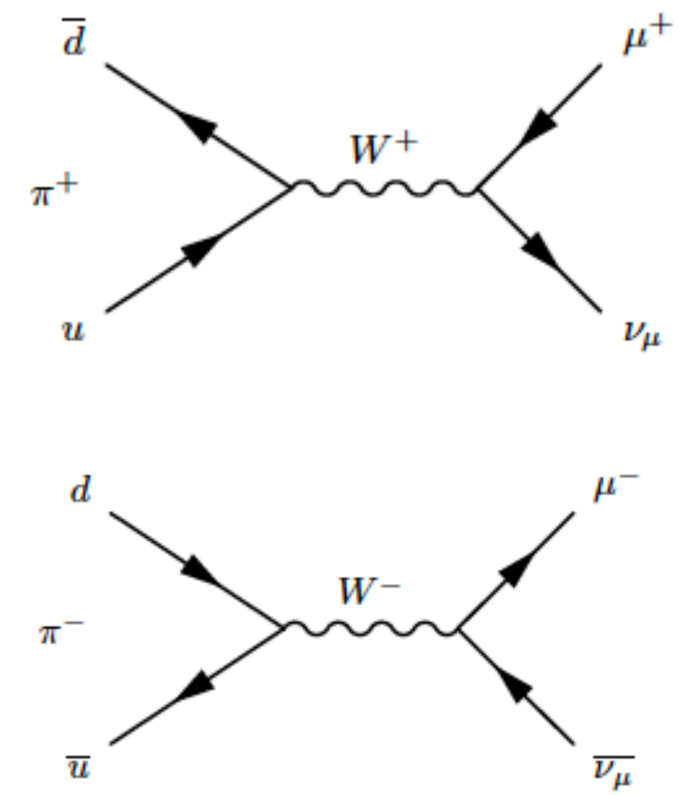
Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)

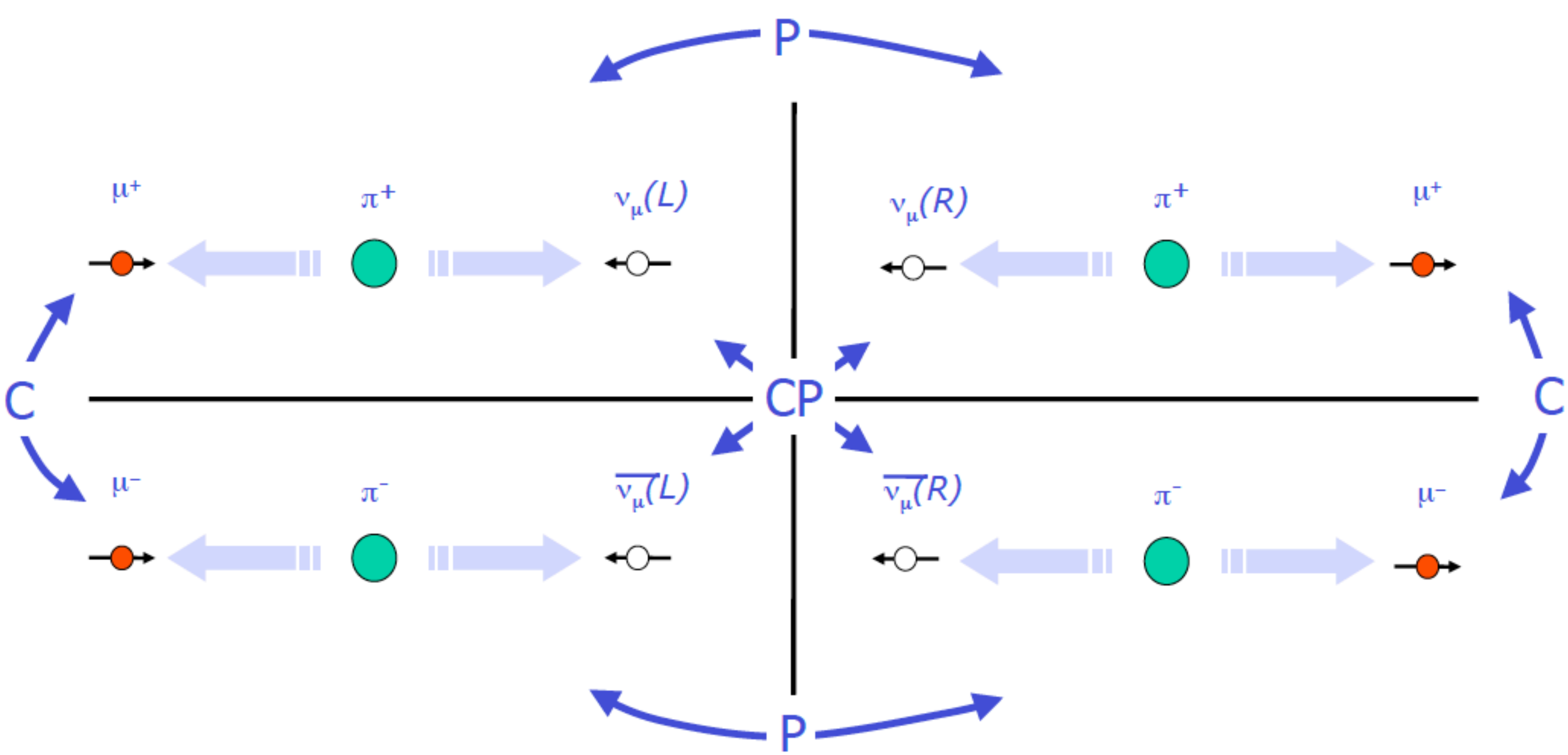
Leon M. Lederman

Concept

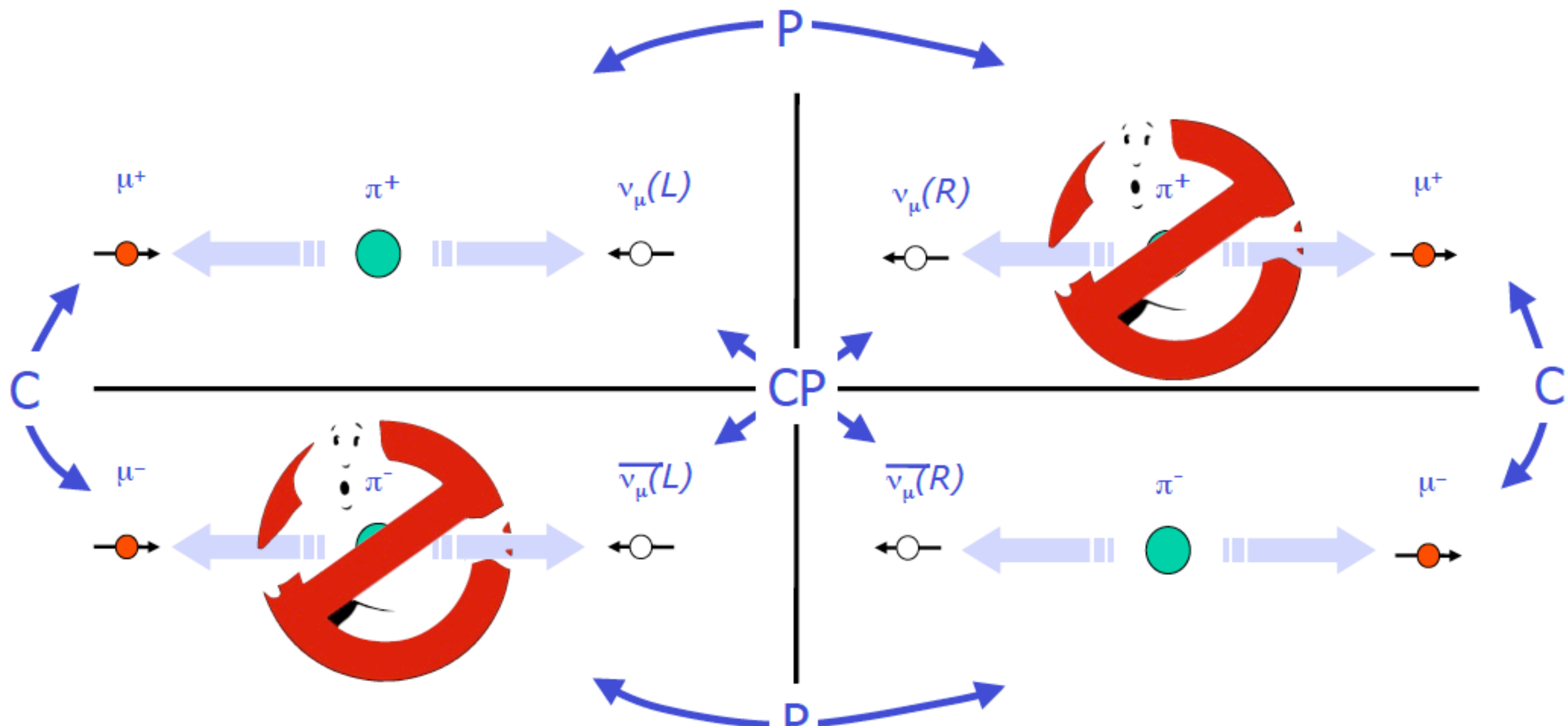
Look at weak decay $\pi^+ \rightarrow \mu^+ \nu$.



Pion has spin zero. μ^+ and ν have both spin 1/2. Spins of μ^+ and ν should be oppositely aligned to conserve angular momentum. There are 4 configurations that satisfy this, related by P and C transformations. Are they all realized?



C is violated too



C broken, P broken, but CP *appears* to be preserved in weak interaction!

Curiosity: this was also the first determination of the magnetic moment of the muon, whose Fermilab result a few months ago attracted lots of attention

Could have been discovered it 25 years earlier…

APPARENT EVIDENCE OF POLARIZATION IN A BEAM OF β-RAYS

By R. T. Cox, C. G. McIlwraith and B. Kurrelmeyer*

New York University and Columbia University†

Communicated June 6, 1928

We have made no attempt at a theoretical treatment of double scattering beyond a consideration of the question whether the results here reported are of an asymmetry of higher order than what might be expected of a spinning electron. The following suggestion is then offered not at all as a

THE SCATTERING OF FAST ELECTRONS BY METALS. II. POLARIZATION BY DOUBLE SCATTERING AT RIGHT ANGLES

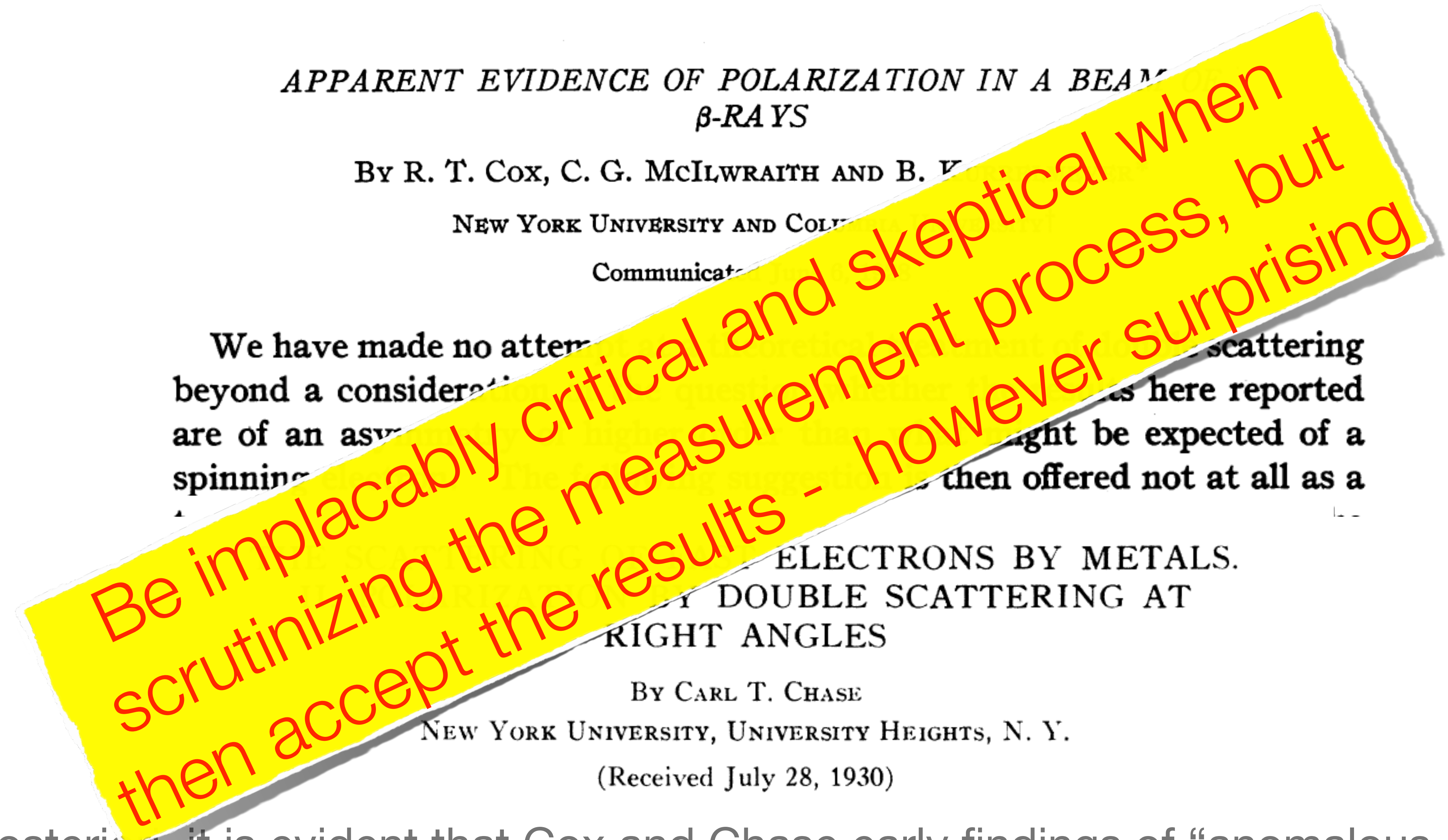
By Carl T. Chase

New York University, University Heights, N. Y.

(Received July 28, 1930)

Cox and Chase early findings of “anomalous polarizations” from β decay were early indications of P violation, but scientists were not yet prepared to the idea that P might be violated and preferred to attribute the results to insufficient understanding of their experiments.

Could have been discovered it 25 years earlier…



A posteriori, it is evident that Cox and Chase early findings of “anomalous polarizations” from β decay were early indications of P violation, but scientists were not yet prepared to the idea that P might be violated and preferred to attribute the results to insufficient understanding of their experiments.

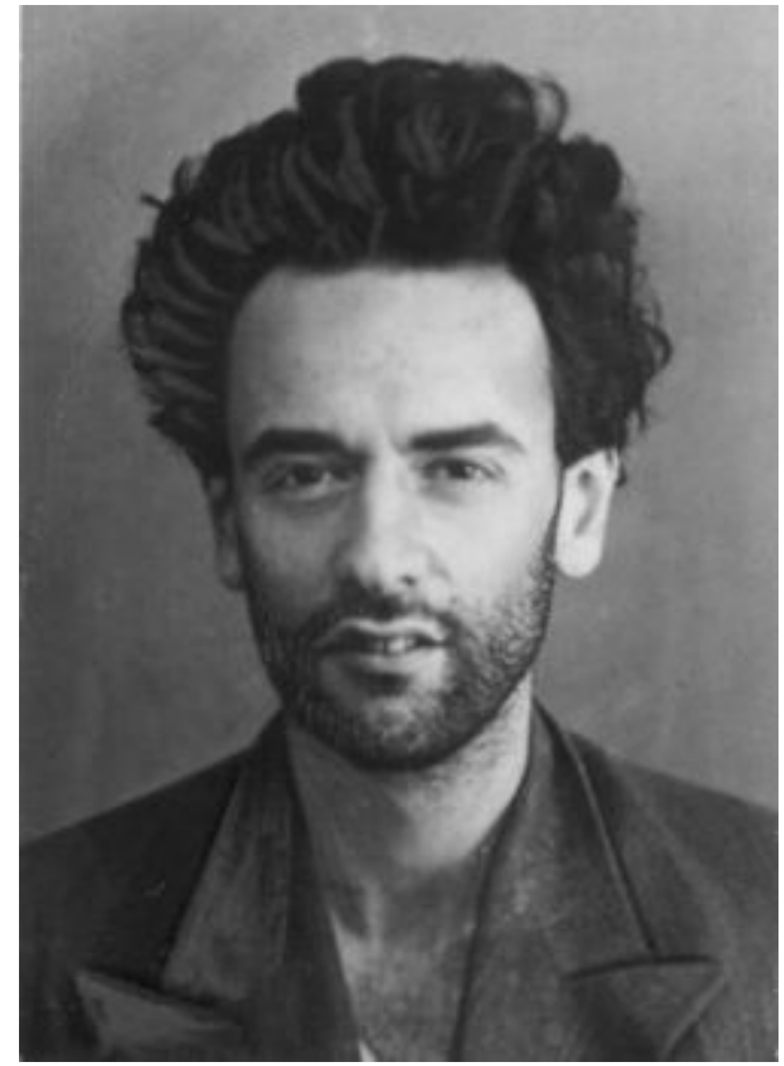
The CP ansatz — Landau

Conservation Laws in Weak Interactions

L. D. LANDAU
Institute for Physical Problems,
Academy of Sciences, USSR

(Submitted to JETP editor December 11,1956)
J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 405–406
(February, 1957)

I wish to point out that there exists a way out of this situation. We know that the strong interactions are invariant not only with respect to space-inversion but also with respect to charge-conjugation. We assume that in weak interactions these two invariance properties do not hold separately. But we can suppose that we still have invariance with respect to the product of the two operations, which we call combined inversion. Combined inversion consists of space reflection with interchange of particles and antiparticles. If all interactions are invariant with respect to combined inversion, space remains completely asymmetrical, and only electric charges are asymmetrical. This asymmetry des-



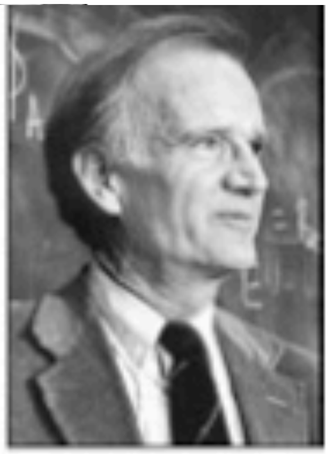
Lev D. Landau reacts to C and P violation by postulating CP conservation for the weak interactions

Cronin and Fitch

Essential idea: if CP is conserved, K_2 cannot decay into two pions, but only to three pions.

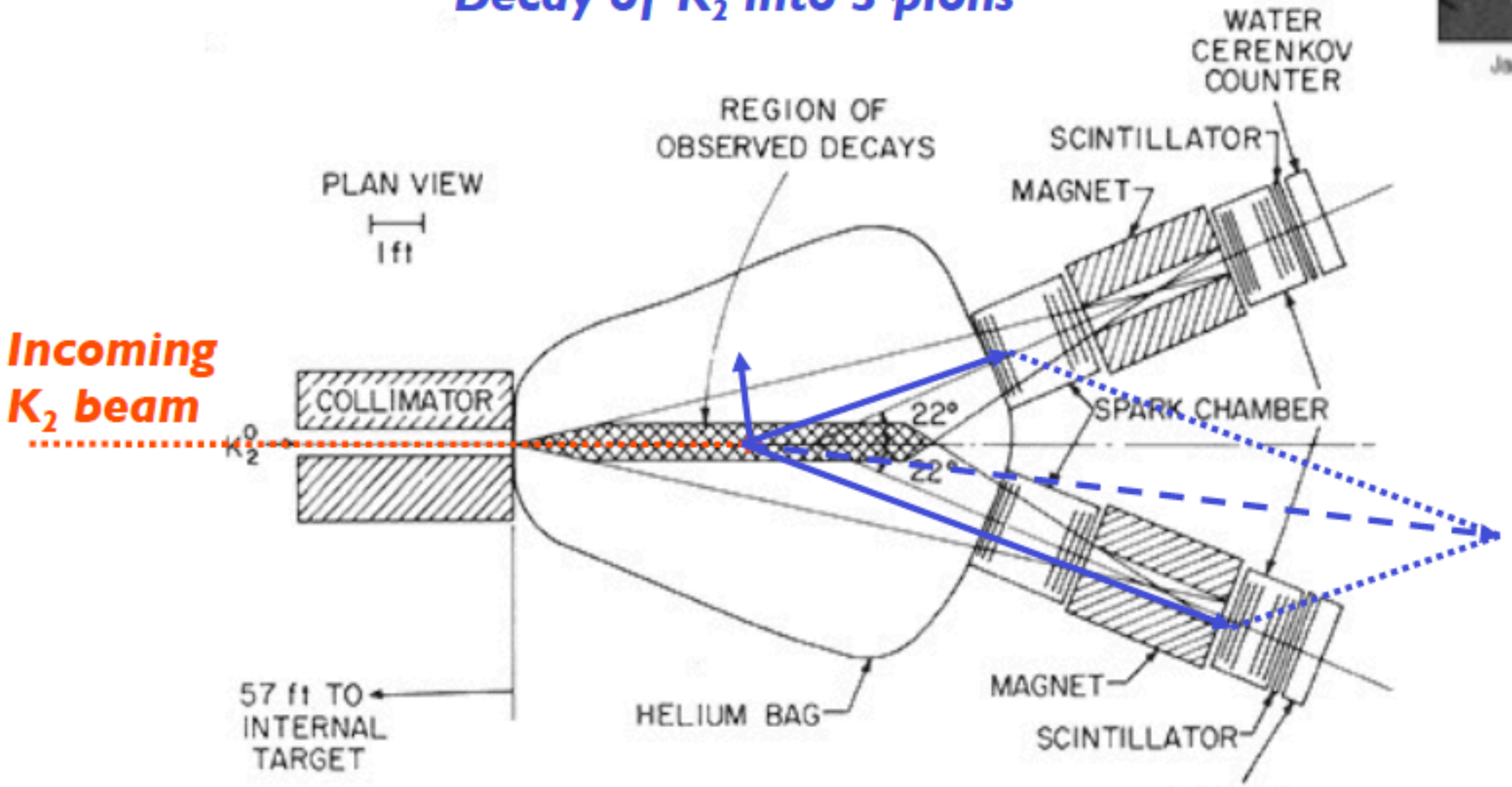
Look for $K_2 \to \pi\pi$ with an ingenuous, low-cost setup

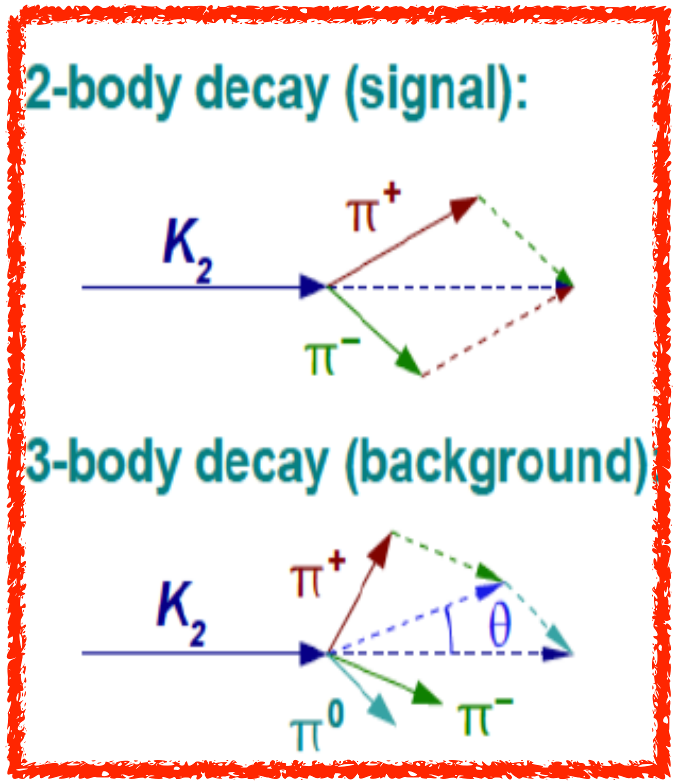
James Cronin



Val Fitch

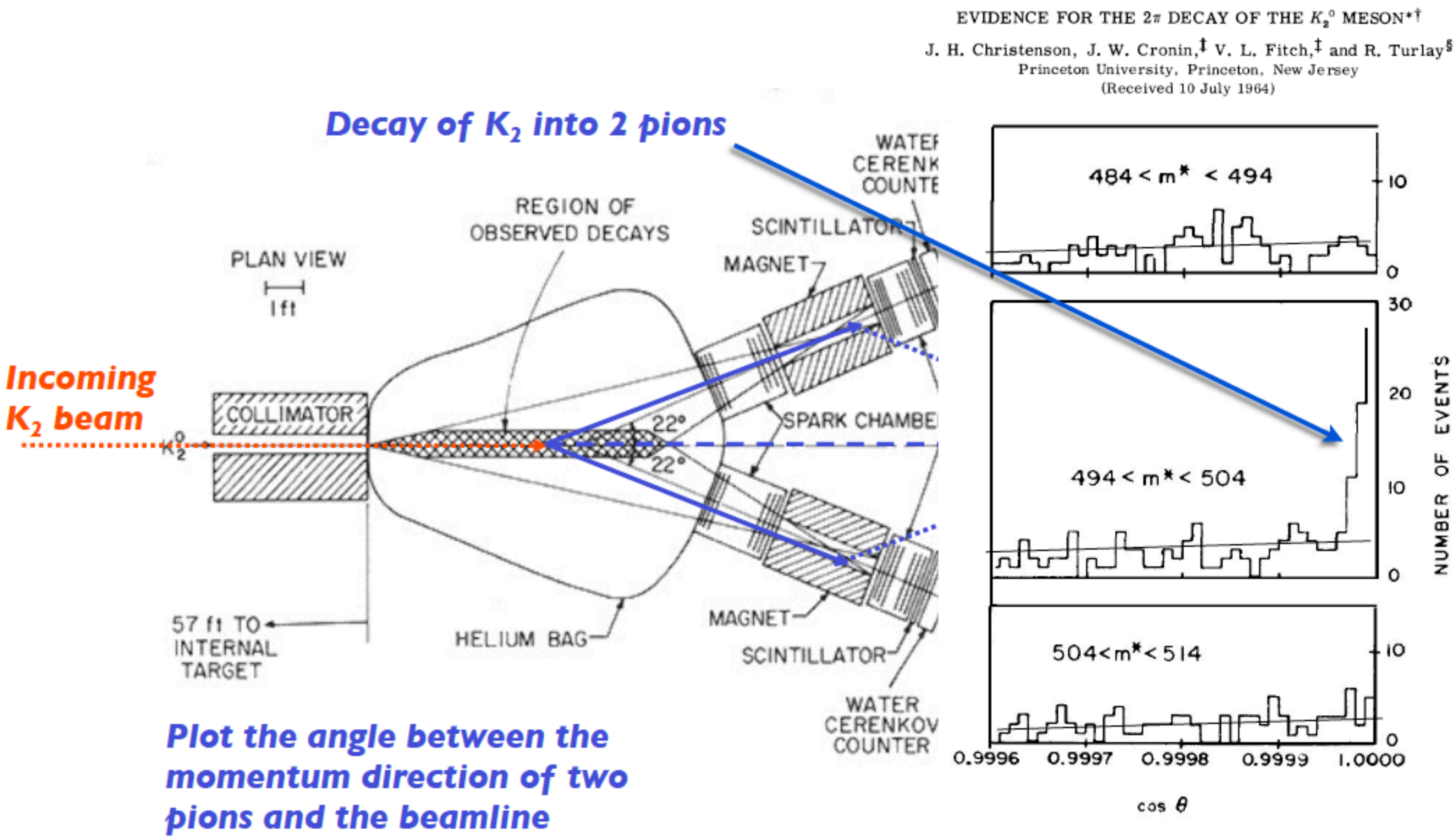
Decay of K_2 into 3 pions



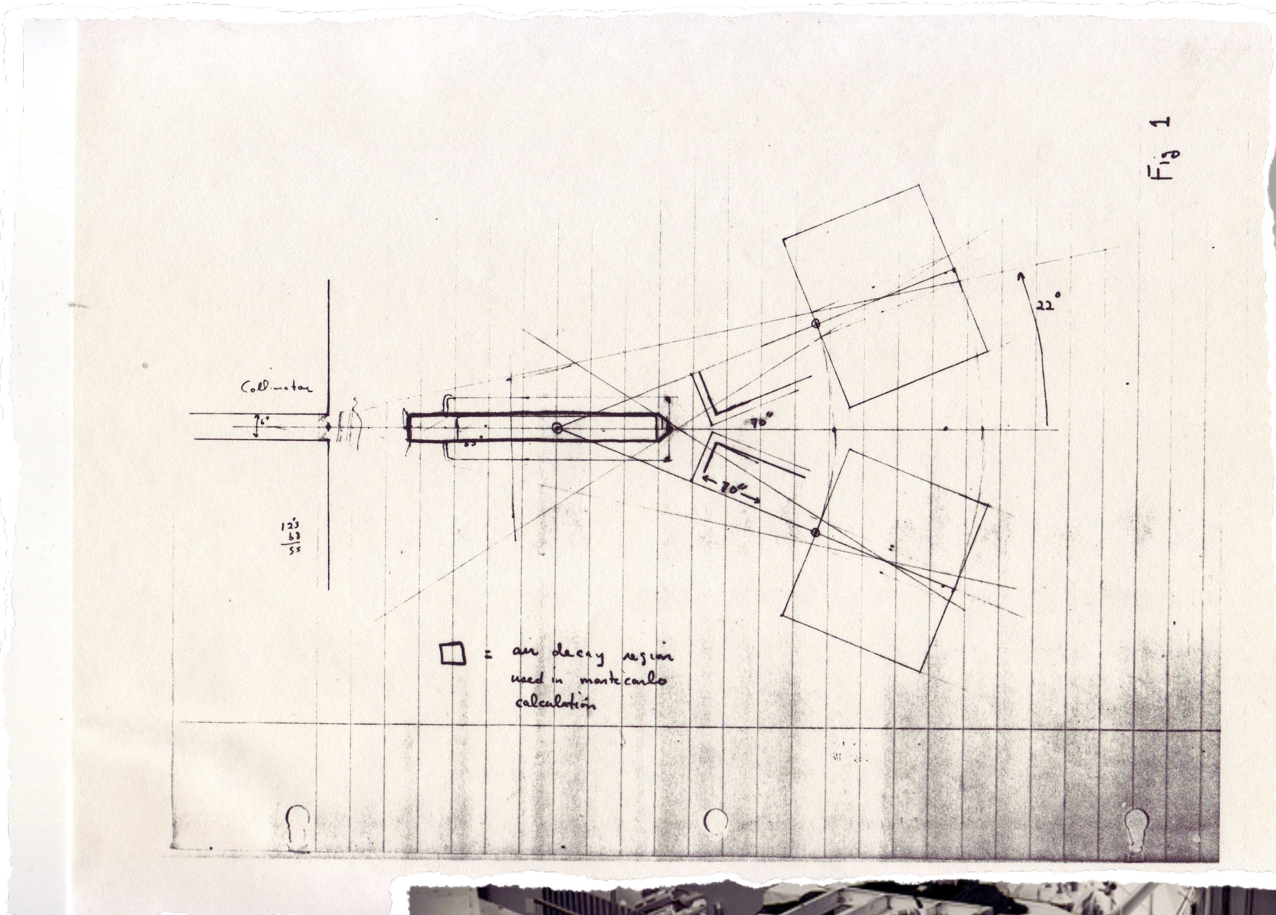


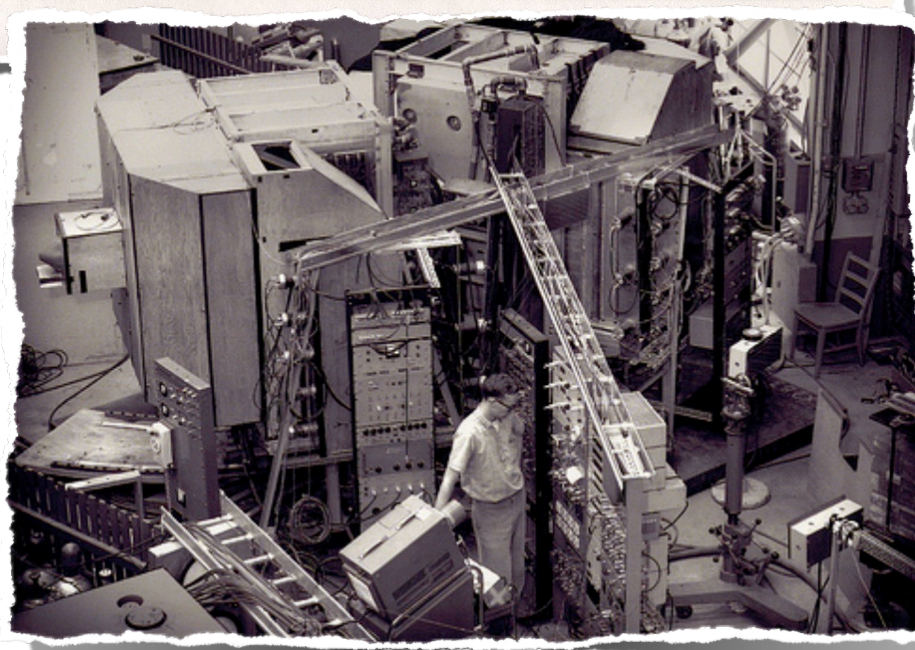
If you detect two out of the three pions of a $K_2 \to \pi\pi\pi$ decay their combined momentum will generally not point along the beam line

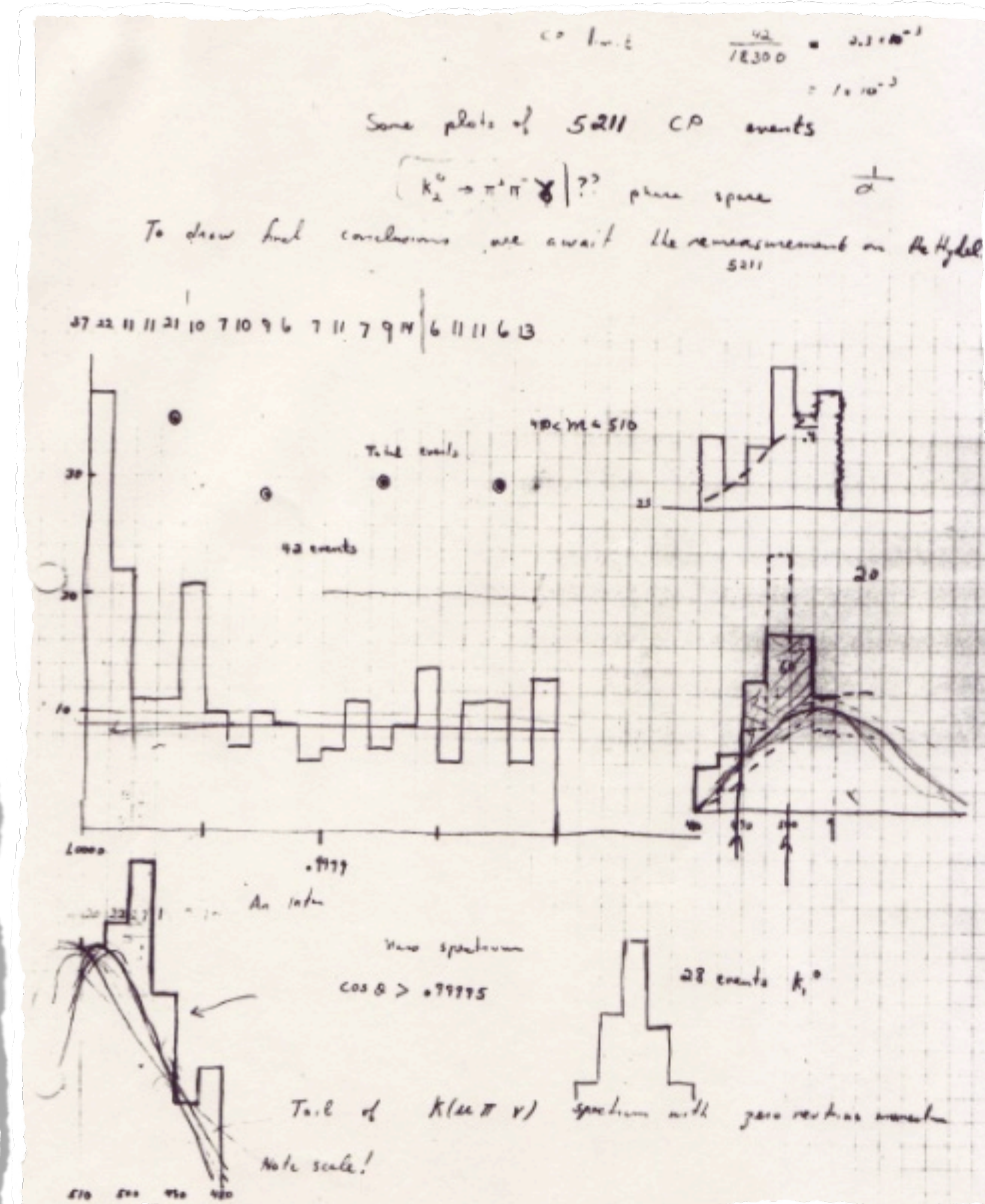
Cronin and Fitch



Old school: paper, pencil, eraser…



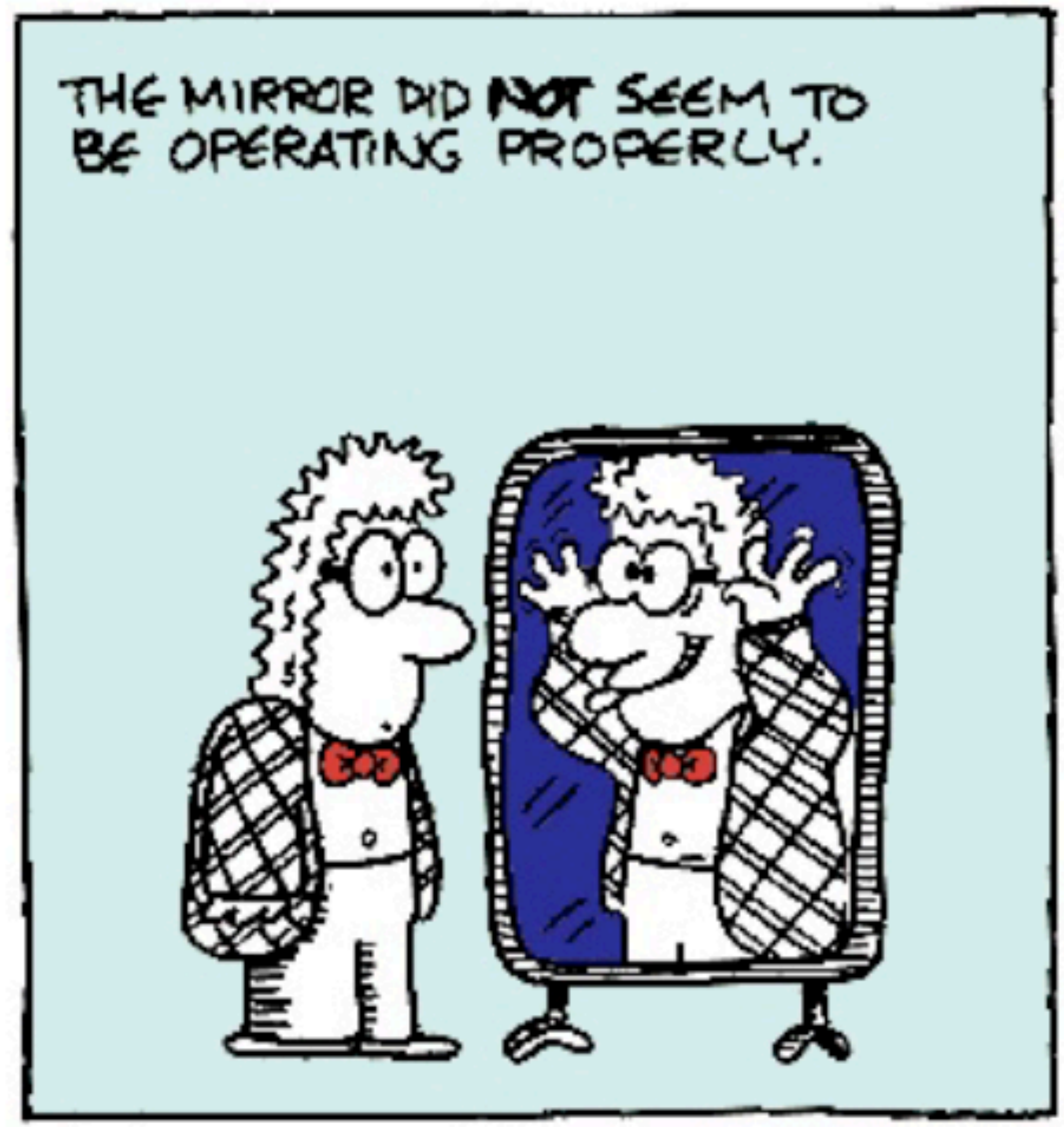




Triumph of experimental skepticism

Nobel prize 1980:

"The discovery emphasizes, once again, that even almost self evident principles in science cannot be regarded fully valid until they have been critically examined in precise experiments."



How to construct a physics law that violates a symmetry just a tiny bit?

- Only 0.2% of K_2 decays violate CP...
- Maximal (100%) violation of P symmetry "easily" interpretable/explained as absence of a right-handed neutrino...

Others had almost gotten there 3 years earlier..

"[…] A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L \rightarrow \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky."
L. Okun, "Spacetime and vacuum as seen from Moscow"

VOLUME 6, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 15, 1961

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.
(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3 % for the relative probability of the decay $K_2^0 \rightarrow \pi^- + \pi^+$. Our results on the charge ratio and the degree of the 2π-decay forbiddenness are in agreement with each other and provide no indications that time-reversal invariance fails in K^0 decay.

Others had almost gotten there 3 years earlier..

"[…] A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L \to \pi^+\pi^-$ event among 600 decay[…] into charged particles (Anikira et al., JETP 1962). At that stage the se[…] terminated by the administration of the lab. The group was u[…]"
L. Okun, "Spacetime and vacuum as seen f[…]ow"

Be persistent! Push precision!

VOLUME 6, NUMBER 10 — P[…]VIEW LETTERS — MAY 15, 1961

[…]Y PROPERTIES OF K_2^0 MESONS*

[…]Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.
(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3 % for the relative probability of the decay $K_2^0 \to \pi^- + \pi^+$. Our results on the charge ratio and the degree of the 2π-decay forbiddenness are in agreement with each other and provide no indications that time-reversal invariance fails in K^0 decay.

How all of this fits in the then-emerging theory?

HEP in the sixties

In the sixties, it seemed that there were

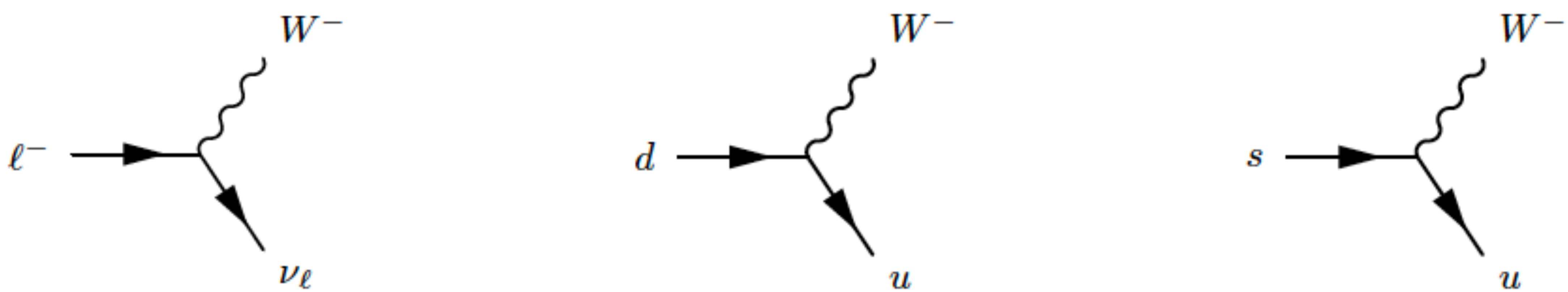
- 4 types of lepton: e, ν_e, μ, ν_μ
- 3 types of quark: u, d, s
    - but many (most!) considered quarks a mathematical trick to explain the zoo of observed particles...

Let's sort them by their electrical charge:

W^-	0: ν_e, ν_μ	+⅔: u	W^+
	-1: e, μ	-⅓: d, s	

Weak interaction strenght is process dependent?

- Problem: using the measured muon lifetime, the *predicted* neutron lifetime is a bit too short -- and the *predicted* lifetime of strange particles way too short...



$$g \quad > \quad g' \quad >> \quad g''$$

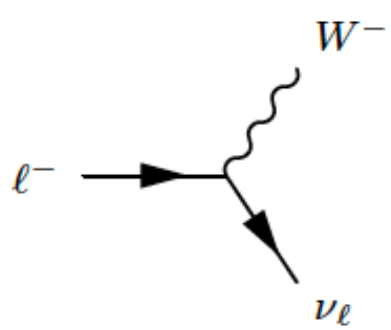
- Conclusion: measured strength (coupling constant) of weak interaction is systematically (!) different when measured in different types of processes???
- Or maybe we just overlooked something?

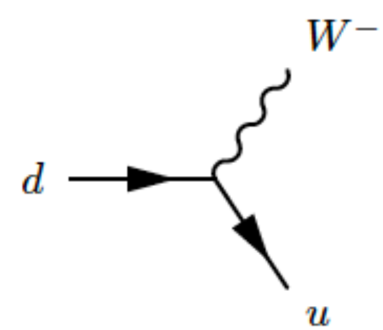
The Cabibbo angle

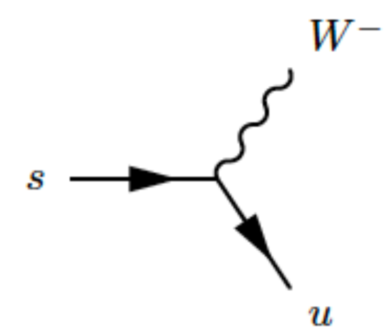
UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

What if, instead of three constants, we have one constant g and one angle?







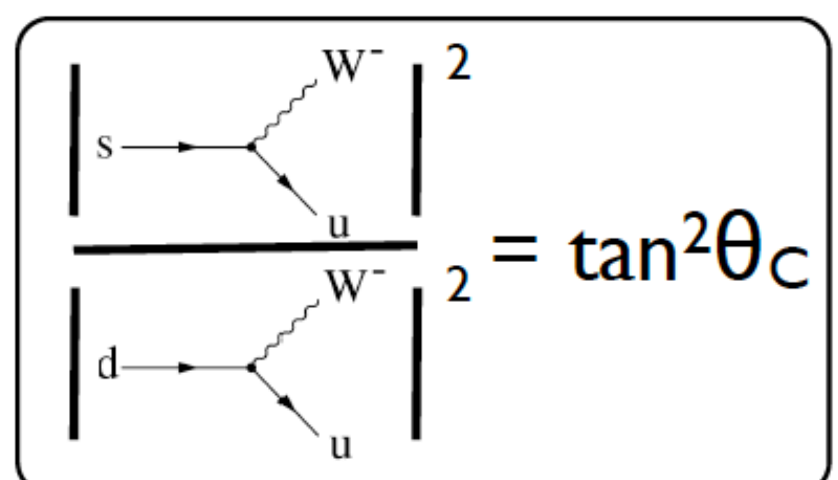
$$g \quad > \quad g\cos\theta_C \quad >> \quad g\sin\theta_C$$

To determine θ, let us compare the rates for $K^+ \to \mu^+ + \nu$ and $\pi^+ \to \mu^+ + \nu$; we find

$$\Gamma(K^+ \to \mu\nu)/\Gamma(\pi^+ \to \mu\nu) = \tan^2\theta M_K(1 - M_\mu{}^2/M_K{}^2)^2/M_\pi(1 - M_\mu{}^2/M_\pi{}^2)^2. \quad (3)$$

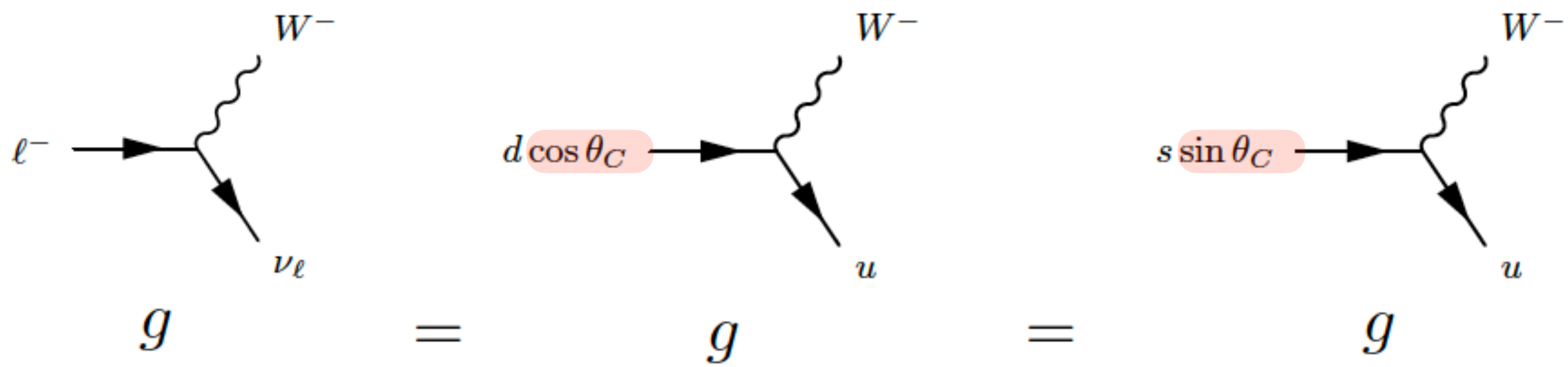
From the experimental data, we then get[5,6]

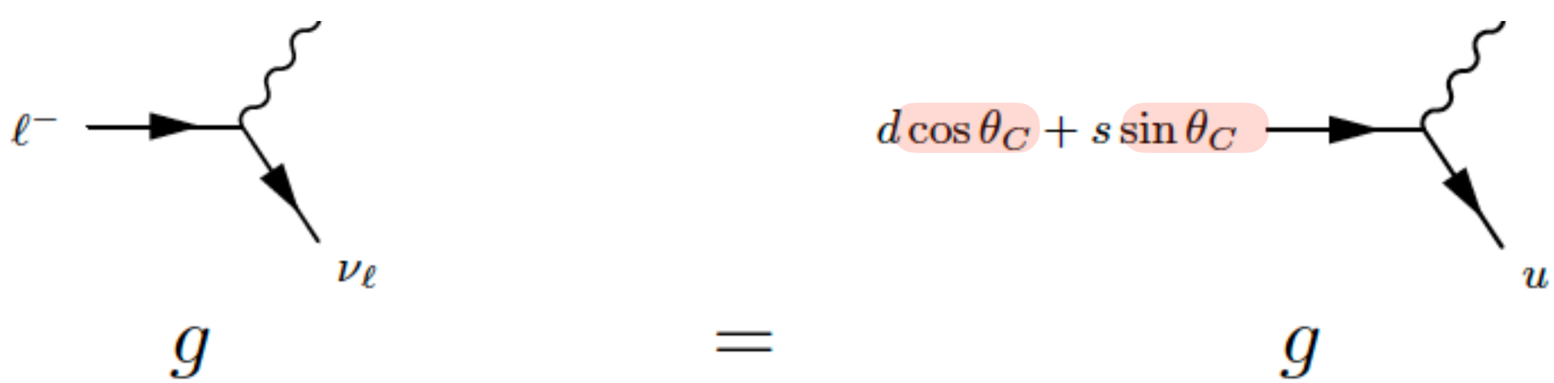
$$\theta = 0.257. \quad (4)$$



Restoring weak-interaction universality

Restore universality by moving the angle from the interaction coupling to the particle fields

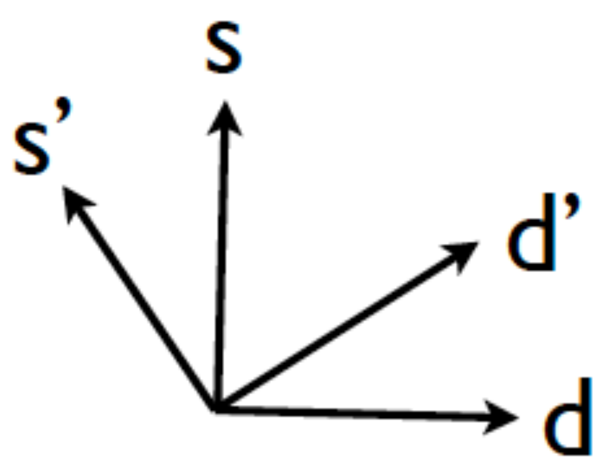




The d quark as 'seen' by the W, the *weak* eigenstate d', is *not* same as the *mass* eigenstate (the d)...

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} u \\ d' \end{pmatrix}_L = \begin{pmatrix} u \\ d\cos\theta_C + s\sin\theta_C \end{pmatrix}_L$$

Restoring weak-interaction universality



The d' seen by the W is a *superposition* of the d and s...

- If d' is a superposition of the d and s, shouldn't there be an s' as well? (*)

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

- If so, we can write d' and s' as *rotated* versions of d and s

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L , \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

- And if there is an s', why no u-like partner for it?

(*) yes: coupling of Z to d' *without* matching s' causes a tree-level flavour changing neutral current, which is incompatible with eg. observed $Br(K_L \rightarrow \mu\mu)$

Is it rather the Gell-Mann-Levy angle?

Three years before the Cabibbo paper, Gell-Mann and Levy had a similar intuition. Not clear if they realize the impact as it’s just mentioned in a footnote of their 1960 paper.

Cabibbo knew and cited that work, but Gell-Mann never got over the discomfort toward acknowledging this as the “Cabibbo angle”

IL NUOVO CIMENTO Vol. XVI, N. 4 16 Maggio 1960

The Axial Vector Current in Beta Decay (*).

M. Gell-Mann (**)
Collège de France and Ecole Normale Supérieure - Paris (***)

M. Lévy
Faculte des Sciences, Orsay, and Ecole Normale Supérieure - Paris (*•*)

(ricevuto il 19 Febbraio 1960)

(*) *Note added in proof.* – Should this discrepancy be real, it would probably indicate a total or partial failure of the conserved vector current idea. It might also mean, however, that the current is conserved but with $G/G_\mu < 1$. Such a situation is consistent with universality if we consider the vector current for $\Delta S = 0$ and $\Delta S = 1$ together to be something like:

$$GV_\alpha + GV_\alpha^{(\Delta S=1)} = G_\mu \bar{p}\gamma_\alpha(n + \varepsilon\Lambda)(1+\varepsilon^2)^{-\frac{1}{2}} + \ldots ,$$

and likewise for the axial vector current. If $(1+\varepsilon^2)^{-\frac{1}{2}} = 0.97$, then $\varepsilon^2 = .06$, which is of the right order of magnitude for explaining the low rate of β decay of the Λ particle. There is, of course, a renormalization factor for that decay, so we cannot be sure that the low rate really fits in with such a picture.

Curiosity: was it rather the Gell-Mann-Levy angle?

Three years before the Cabibbo paper, Gell-Mann and Levy had a similar intuition. Not clear if they realize the impact as it's just mentioned in a footnote of their 1960 paper.

Cabibbo ... work ... got ov... toward ...g this as the "Cab... ...gle"

Having a smart insight is not enough. It should also be identified as such and communicated efficiently

IL NUOVO CIMENTO   Vol. XVI, N ...   16 Maggio 1960

... Decay (*).

...ANN (**)
...Normale Supérieure - Paris (***)

M. LÉVY
...des Sciences, Orsay, and Ecole Normale Supérieure - Paris (*.*)

(ricevuto il 19 Febbraio 1960)

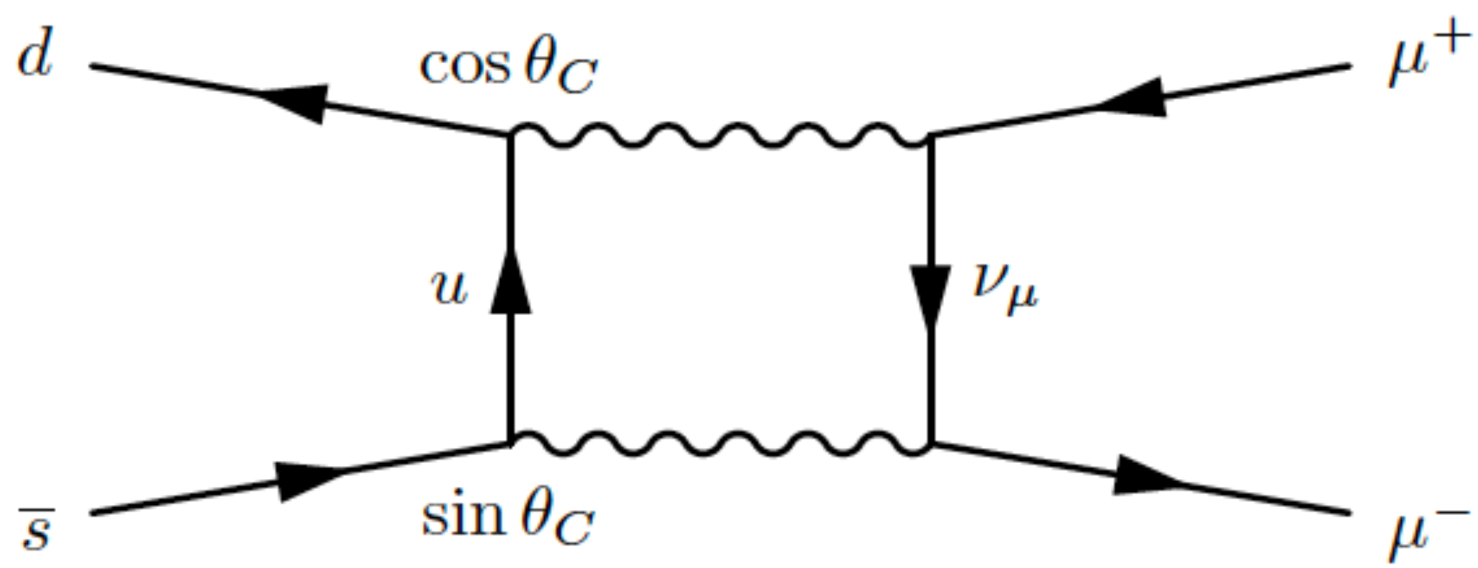
(...) *Note added in proof.* – Should this discrepancy be real, it would probably indicate a total or partial failure of the conserved vector current idea. It might also mean, however, that the current is conserved but with $G/G_\mu < 1$. Such a situation is consistent with universality if we consider the vector current for $\Delta S = 0$ and $\Delta S = 1$ together to be something like:

$$GV_\alpha + GV_\alpha^{(\Delta S=1)} = G_\mu \bar{p}\gamma_\alpha(n + \varepsilon\Lambda)(1+\varepsilon^2)^{-\frac{1}{2}} + \dots ,$$

and likewise for the axial vector current. If $(1+\varepsilon^2)^{-\frac{1}{2}} = 0.97$, then $\varepsilon^2 = .06$, which is of the right order of magnitude for explaining the low rate of β decay of the Λ particle. There is, of course, a renormalization factor for that decay, so we cannot be sure that the low rate really fits in with such a picture.

…a problem

- There was however one major exception which Cabibbo could not describe: $K^0 \rightarrow \mu^+ \mu^-$
    - Observed rate much lower than expected from Cabibbos rate correlations (expected rate $\propto g^8 \sin^2\theta_c \cos^2\theta_c$)



GIM mechanism — predicting charm

Weak Interactions with Lepton-Hadron Symmetry*

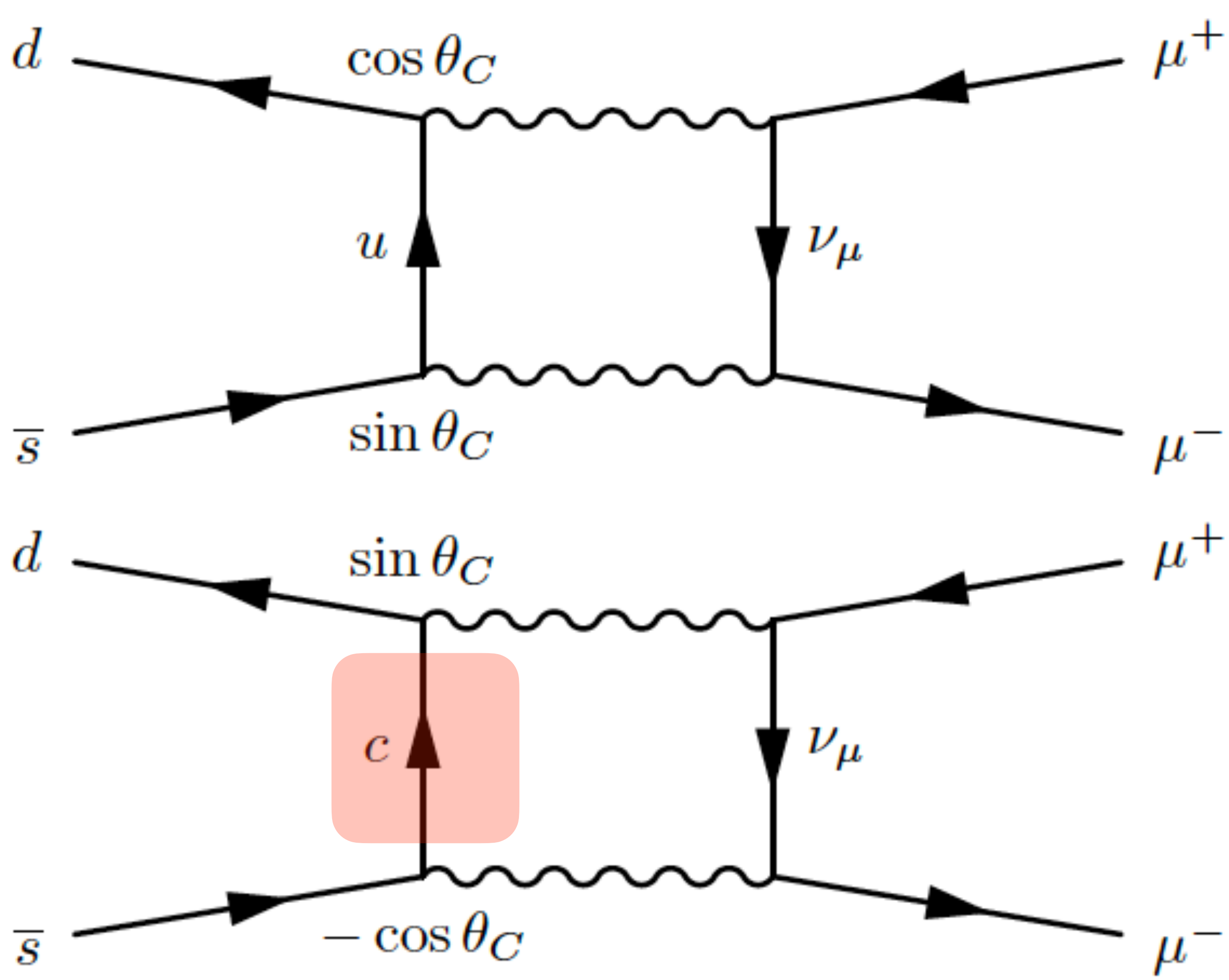
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$$
$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

GIM mechanism — predicting charm

Posited existence of new, 2 GeV quark, called charm — which generates an amplitude almost identical to the original one, but that contributes with a minus sign (destructive interference) thus suppressing the total rate down to the unobservable level



Original amplitude

Additional amplitude

There was just a “minor” problem: no evidence of any charm quark existed then

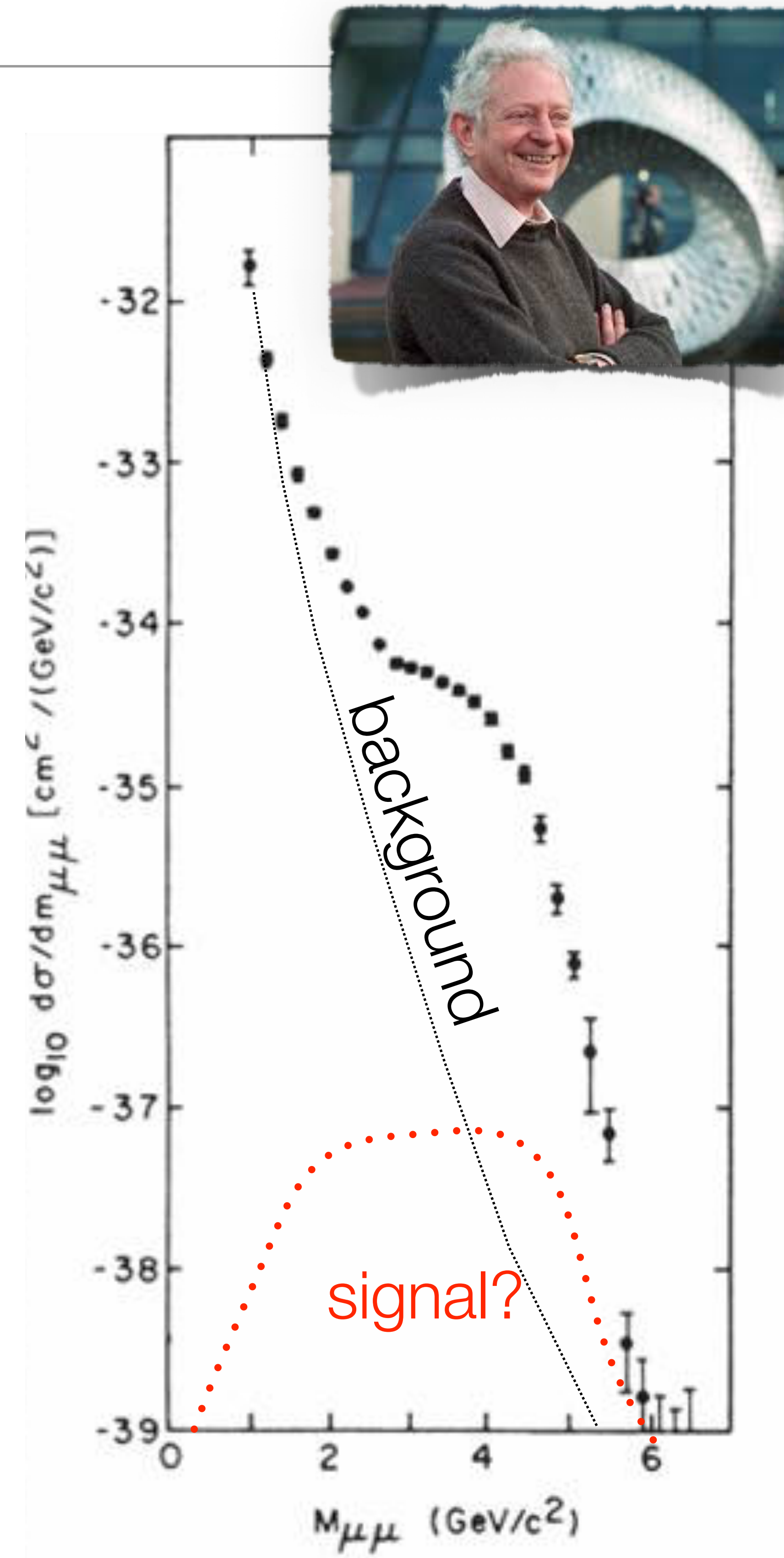
Or was it? The Lederman shoulder

In 1968–1968, Lederman et al studied the dimuon mass spectrum produced by colliding protons on uranium.

The measurement of muon energy was coarse: based on observed range in various meters of steel interspersed with scintillator.

"Indeed, in the mass region near 3.5 GeV, the observed spectrum may be reproduced by a composite of a resonance and a steeper continuum."

The lack of resolution caused the group to miss a Nobel-prize-like discovery



Or was it? The Lederman shoulder

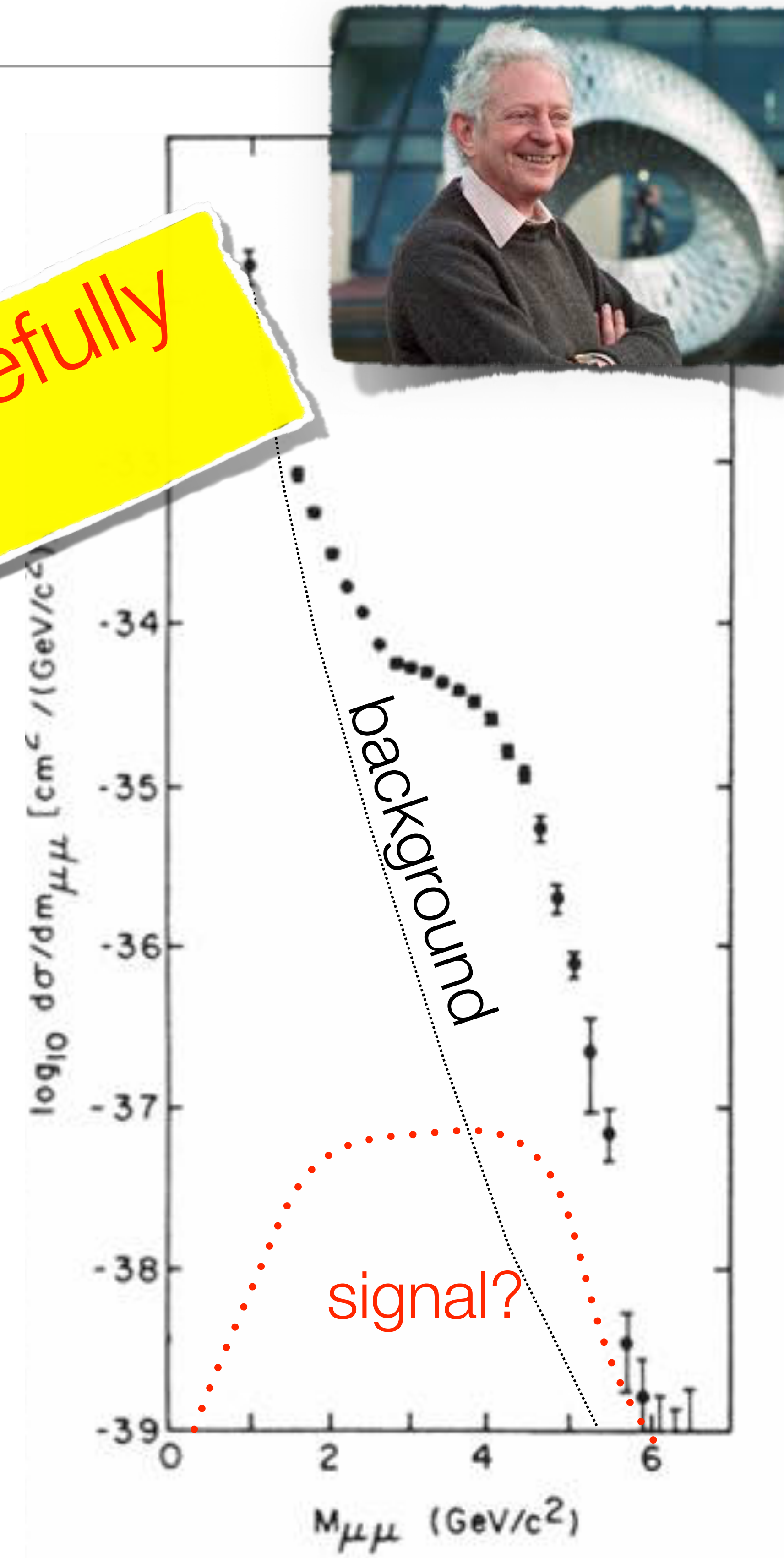
In 1968–1968, Lederman et al studied the dimuon mass spectrum produced by colliding protons on uranium.

The measurement of muon energy was coar... on observed range in various meters of ... interspersed with scintillator.

"Indeed, in the m... GeV, the observed spectrum m... by a composite of a reson... continuum."

Resolution is essential! Design carefully your apparatus

The lack of resolution caused the group to miss a Nobel-prize-like discovery



The first (and unnoticed) discovery of charm

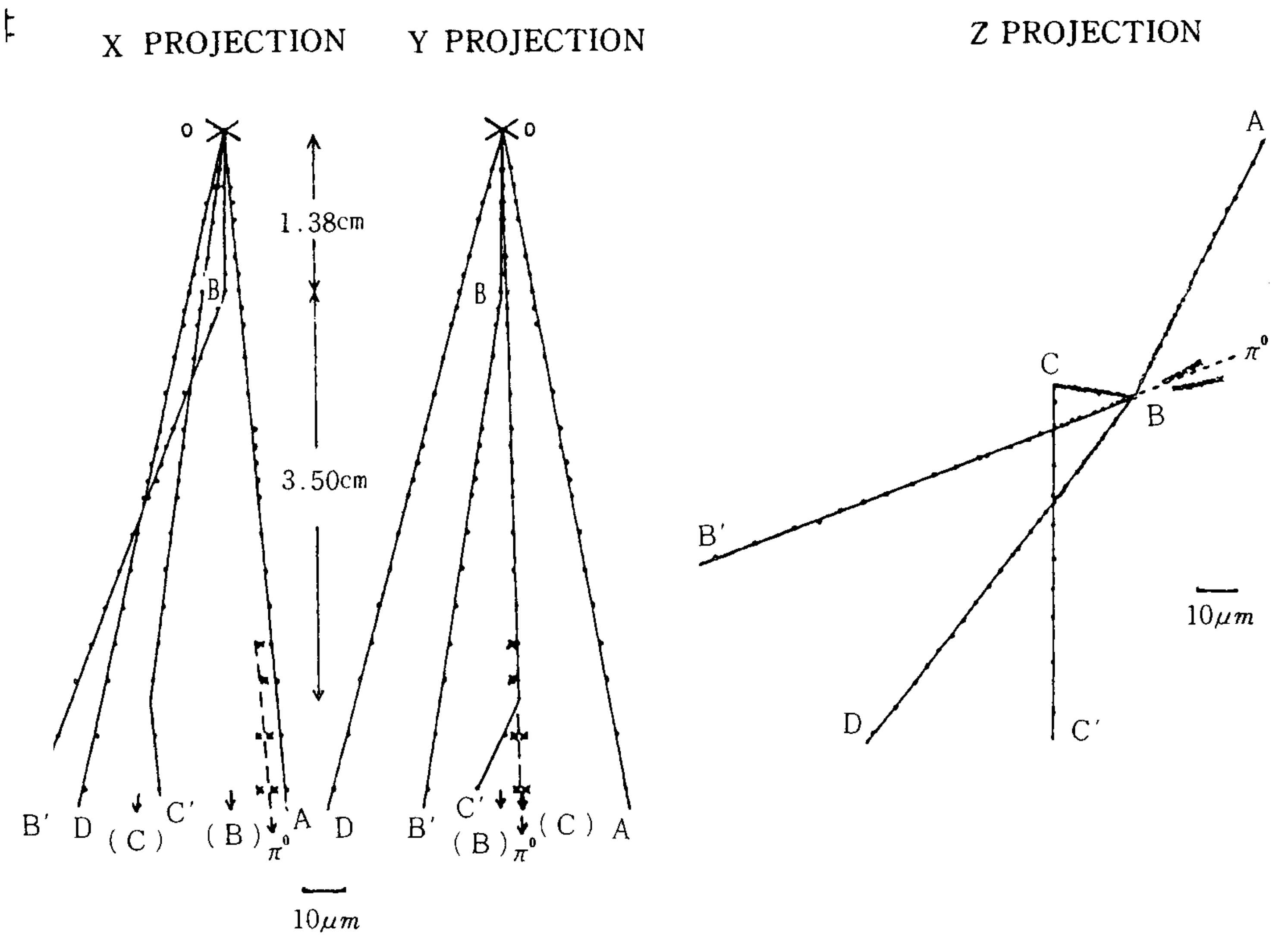
Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study University of Tokyo
**Yokohama National University*

August 9, 1971



1971 — Evidence of kinks from decays of long-lived heavy particles in cosmic rays recorded with emulsions. Went unnoticed in the western world as it was published on a Japanese journal.

The first (and unnoticed) discovery of charm

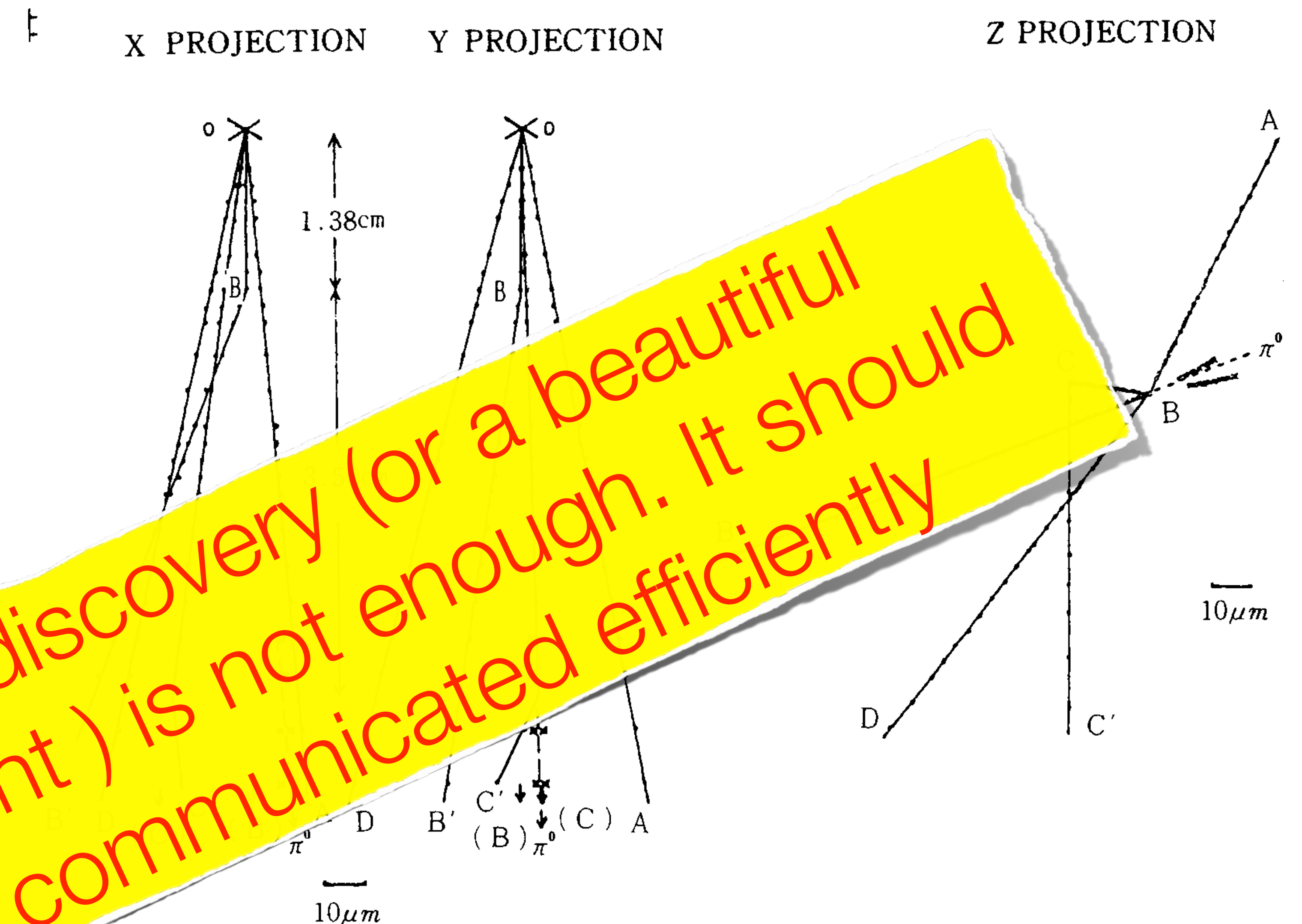
Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study
University of Tokyo
**Yokohama National University*

August 9, 1971

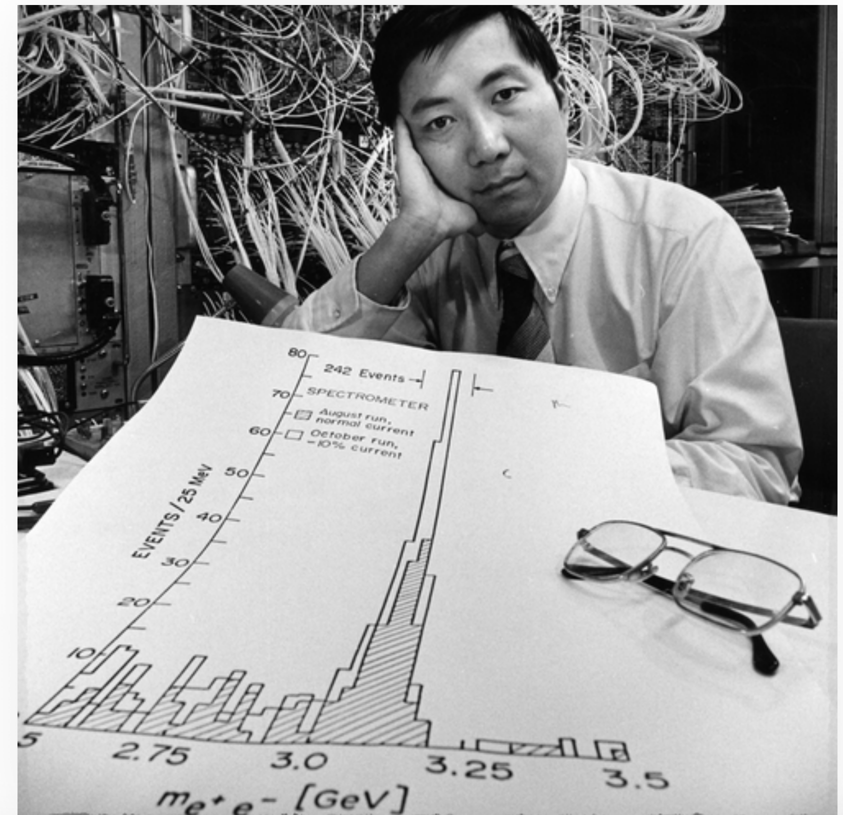


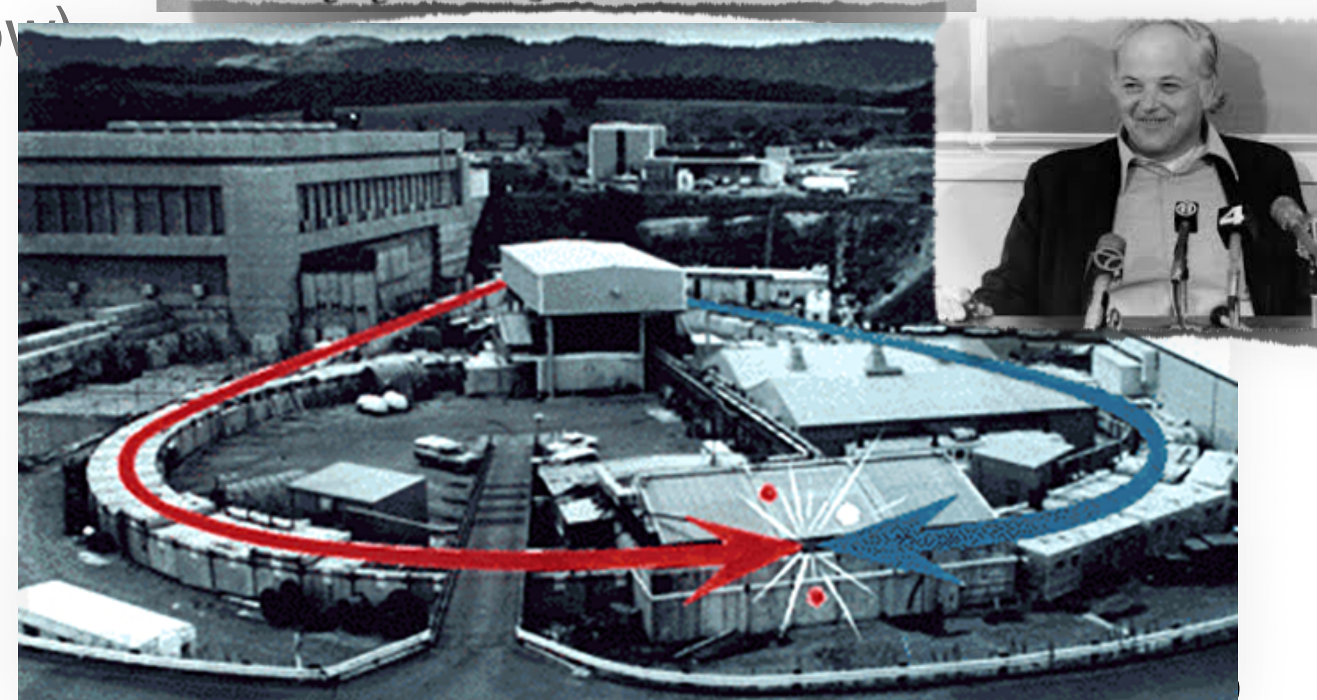
Making a discovery (or a beautiful measurement) is not enough. It should also be communicated efficiently

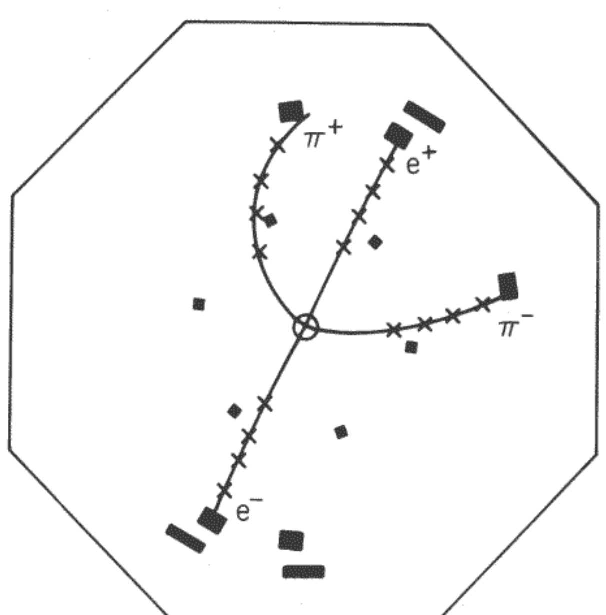
1971 — Evidence of kinks from decays of long-lived heavy particles in cosmic rays recorded with emulsions. Went unnoticed in the western world as it was published on a Japanese journal.

The (second and third) discovery of charm

November 1974 — simultaneous publication (back-to-back) of observation of 3 GeV resonance consistent with a bound c-cbar state by BNL experiment that collided protons on Beryllium pp-> e+e- + anything ("J particle", by S. Ting and collaborators) and SLAC experiment that scanned the e+e- collision energy from 2.4 GeV in 0.2 steps ("psi particle", by B. Richter et al., after the event display below)

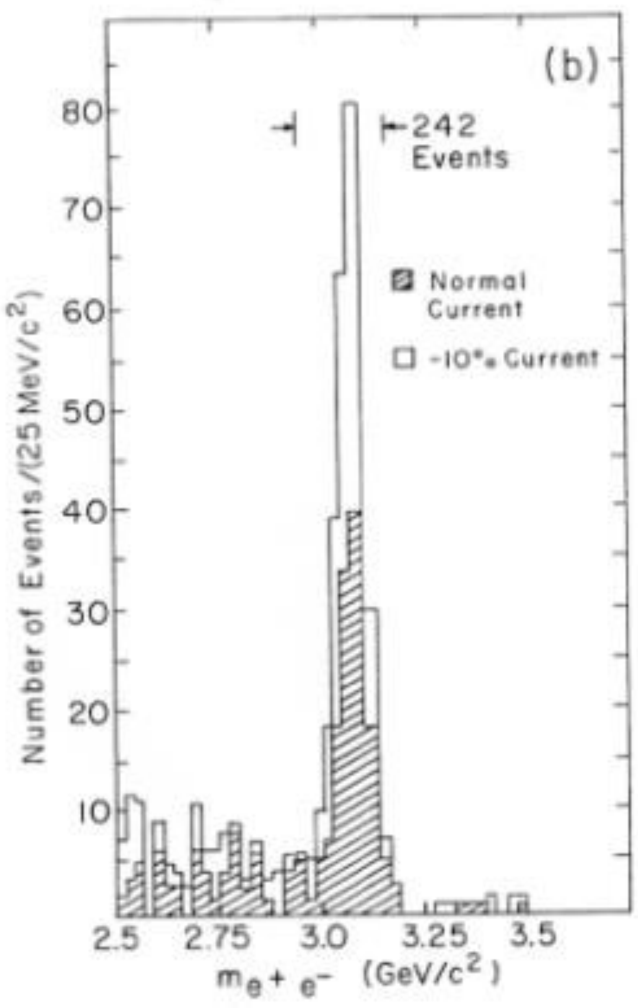




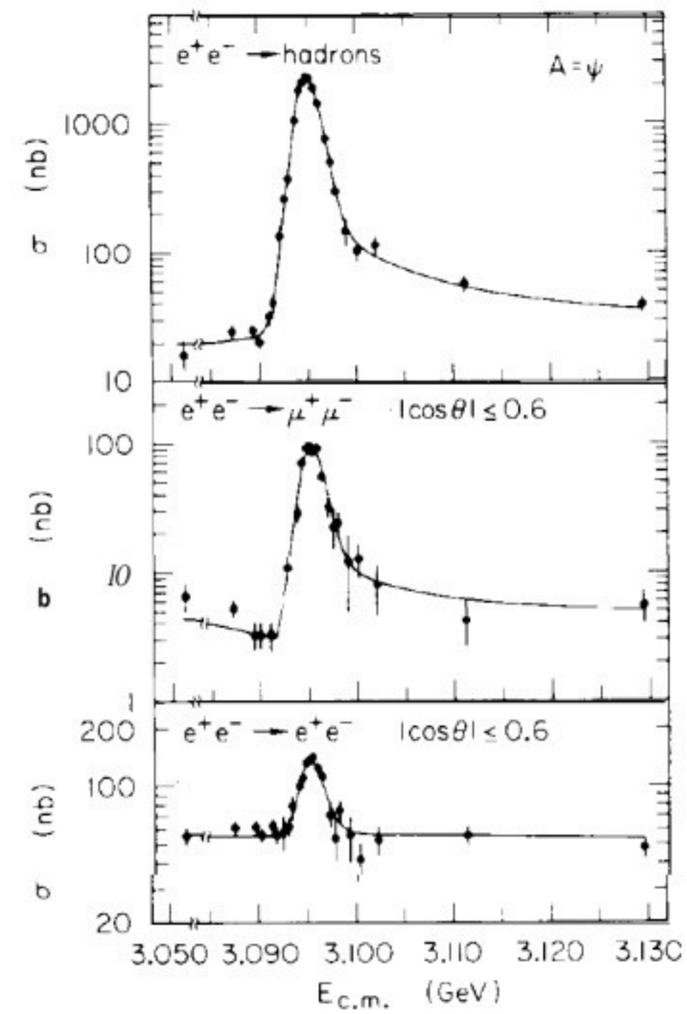


November revolution

BNL's J particle

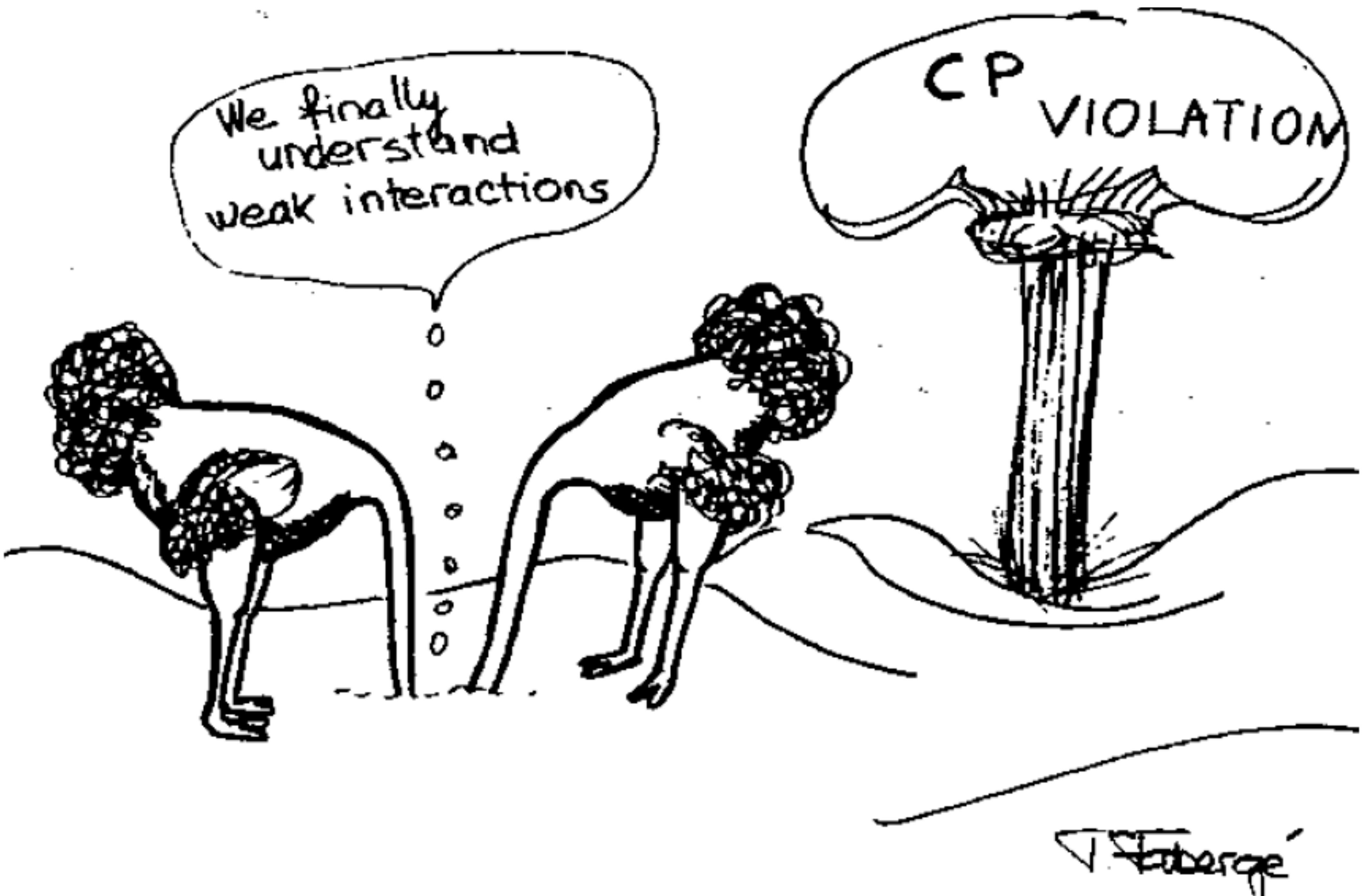


SLAC's psi



The discovery of charm four years after its prediction by GIM was, and still is, one of the most striking examples of the power of the indirect approach in probing physics at higher energy scales before direct detection reaches them.

But CP violation remains a deep mystery

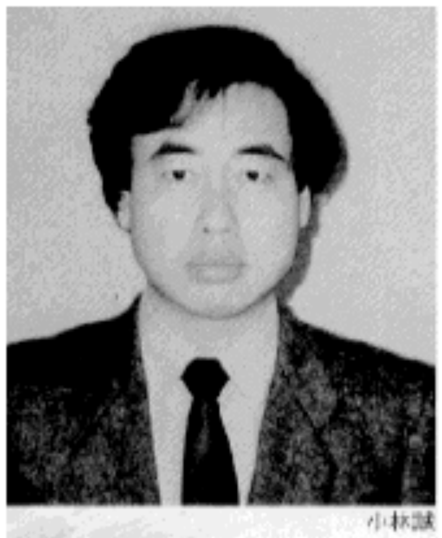


Cartoon shown by N. Cabibbo in 1966...

In the meantime, two young punks in Kyoto, circa 1973

Two young postdocs postulate the existence of a third family of quarks (before even that the charm was discovered!) to accommodate the observed phenomenon of CP violation into the standard model

Made in Japan — postulating 3 generations



Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

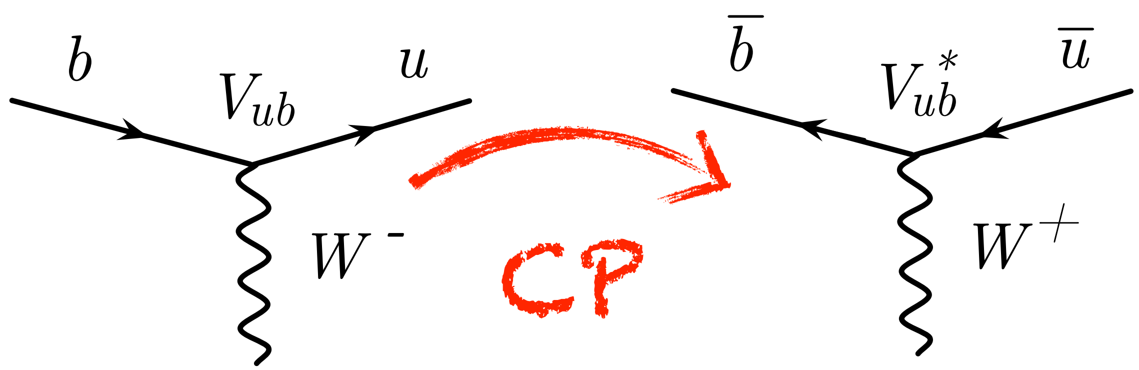
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

The Nobel-prize winning part

For CP violation to occur there needs to be a complex coupling between quarks.



$$V_{ub} \neq V_{ub}^*$$

Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S \neq 0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L \text{ with} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Kobayashi and Maskawa observed that if quark families were three or more such complex coupling could naturally arise without violating any of the global constraints between quark couplings (conservation of probability etc.)

But at the time of the work, only two quark families were known.

Are there really 3 generations? …the first (mistaken) discovery of the fifth quark.

Observation of High-Mass Dilepton Pairs in Hadron Collisions at 400 GeV

D. C. Hom, L. M. Lederman, H. P. Paar, H. D. Snyder, J. M. Weiss, and J. K. Yoh
*Columbia University, New York, New York 10027**

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510†

and

D. M. Kaplan
*State University of New York at Stony Brook, Stony Brook, New York 11794**
(Received 28 January 1976)

We report preliminary results on the production of electron-positron pairs in the mass range 2.5 to 20 GeV in 400-GeV p-Be interactions. 27 high-mass events are observed in the mass range 5.5–10.0 GeV corresponding to $\sigma = (1.2 \pm 0.5) \times 10^{-35}$ cm^2 per nucleon. Clustering of 12 of these events between 5.8 and 6.2 GeV suggests that the data contain a new resonance at 6 GeV.

In 1976, Lederman and collaborators announced the observation of a new particle produced by a beam of protons on Beryllium and decaying into e+ e- pairs, with a mass of about 6 GeV.

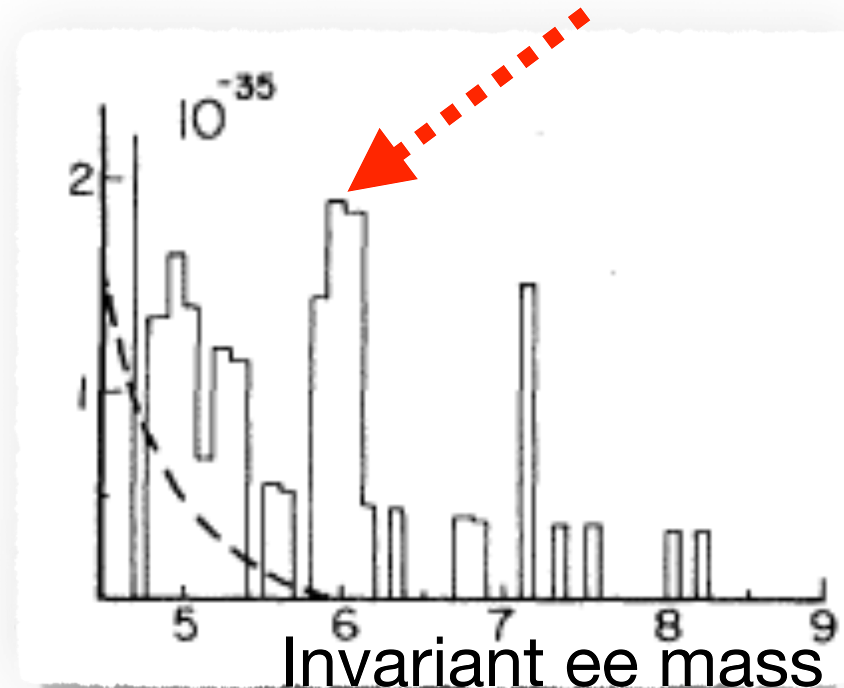
Upsilon? “Ooops-Leon”

This was published and provided a very strong candidate for the Upsilon, the bound state of a (not yet observed) fifth quark.

The experiment took more data. Could not confirm the finding.

The erroneous first claim has been later tracked down to a mistake in the statistical evaluation of the significance of the signal (neglected the *look-elsewhere-effect*)

This, along with other “false discoveries” at those times, contributed to raise the attention toward the need for a proper education in basics statistics for HEP physicists.



a linear A dependence.[7] We have studied the probability for a clustering of events as is observed here to result from a fluctuation in a smooth distribution, e.g., Eq. (3). To avoid the difficult problems involved in the statistical theory associated with small numbers of events per resolution bin, a Monte Carlo method was used. Histograms were generated by throwing events according to a variety of smooth distributions, modulated by the mass acceptance, over the mass range 5.0 to 10.0 GeV. Clusters of events as observed occurring anywhere from 5.5 to 10.0 GeV appeared less than 2% of the time.[8] Thus the statistical case for a narrow (< 100 MeV) resonance is strong although we are aware of the need for confirmation. These data, at a level of

Upsilon? “Ooops-Leon”

This was published and provided a very strong candidate for the Upsilon, the bound state of a (not yet observed) fifth quark.

The experiment took more data. Could not confirm the finding.

The erroneous first claim ... down to a mistake ... the significance ... *look-else...*

This, along w... other "false discoveries" at those times, c...tributed to raise the attention toward the need for a proper education in basics statistics for HEP physicists.

Proper statistical analysis is important (as well as awareness of our unavoidable cognitive biases)

...near A dependence.[7] We have studied the probability for a clustering of events as is observed here to result from a fluctuation in a smooth distribution, e.g., Eq. (3). To avoid the difficult problems involved in the statistical theory associated with small numbers of events per resolution bin, a Monte Carlo method was used. Histograms were generated by throwing events according to a variety of smooth distributions, modulated by the mass acceptance, over the mass range 5.0 to 10.0 GeV. Clusters of events as observed occurring anywhere from 5.5 to 10.0 GeV appeared less than 2% of the time.[8] Thus the statistical case for a narrow (< 100 MeV) resonance is strong although we are aware of the need for confirmation. These data, at a level of

Are there really 3 generations? Yes — the (second and real) discovery of the fifth quark.

- Discovery of 5th quark in 1977
  - Named ‘b’ for beauty/bottom
  - Mass around 4.5 GeV
  - Start of the 3rd generation of quarks!

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

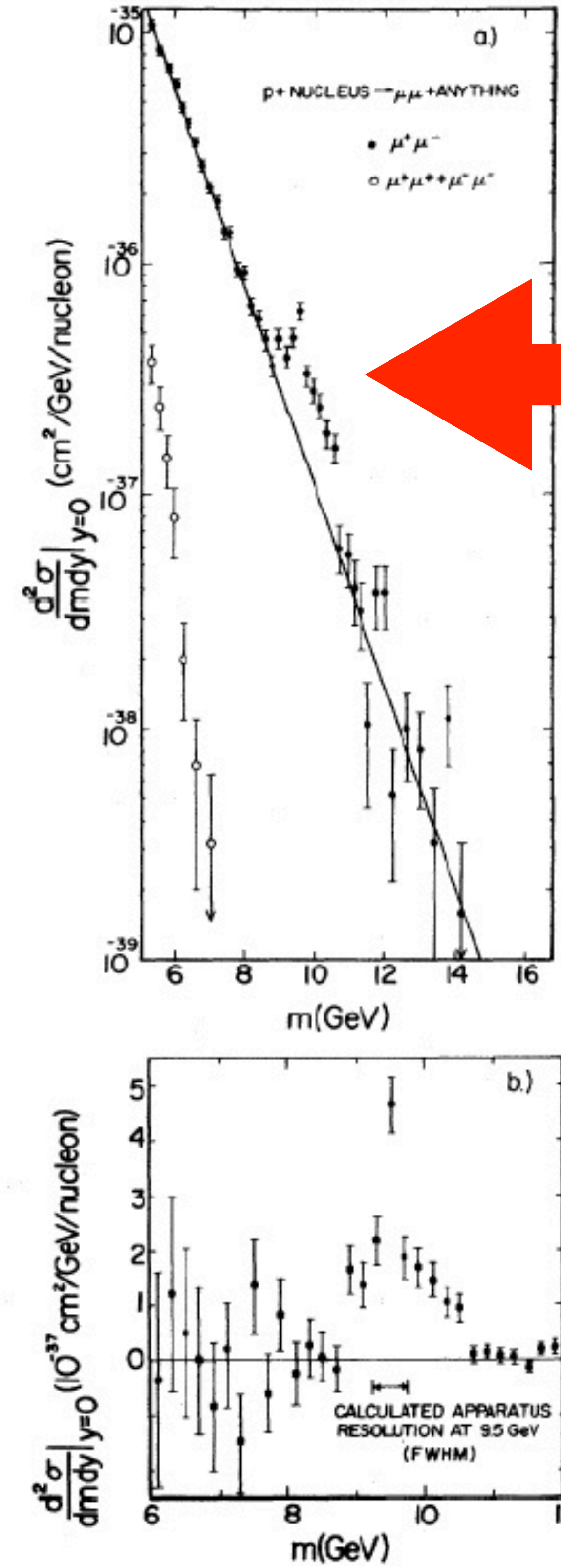
J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974
(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-}$ > 5 GeV.

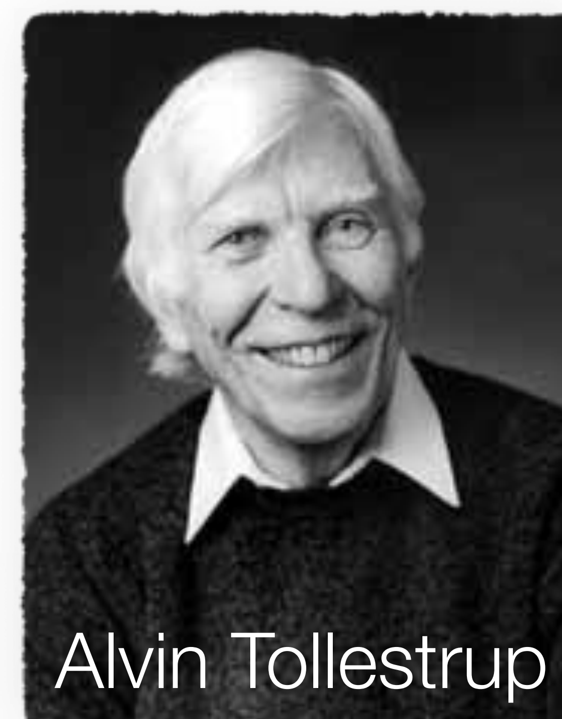


The sixth needed the world's most innovative and powerful collider

In the mid-70ies, Fermilab started planning the construction of the Tevatron proton-antiproton collider to gain the energy frontier:

Extensive use of superconducting magnets (1000 of them) to reach 2 TeV of collision energy (3x CERN's SppbarS energy)

The pioneering work by A. Tollestrup of systematic characterization of superconducting magnets needed for mass production paved the ground for the LHC technology

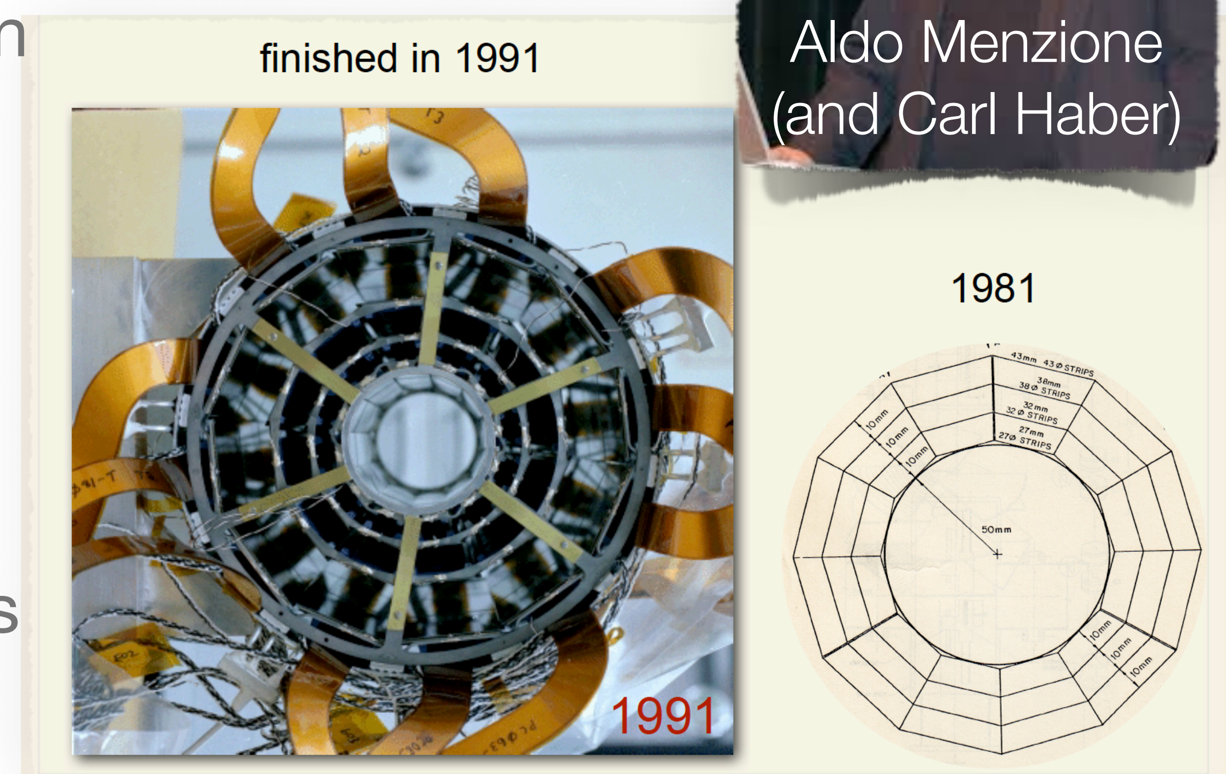


And the world’s most advanced detectors - CDF

World’s first proposal, design, construction and usage of silicon vertex detector in hadron collisions.

Instrumental in identifying the top quark from background.

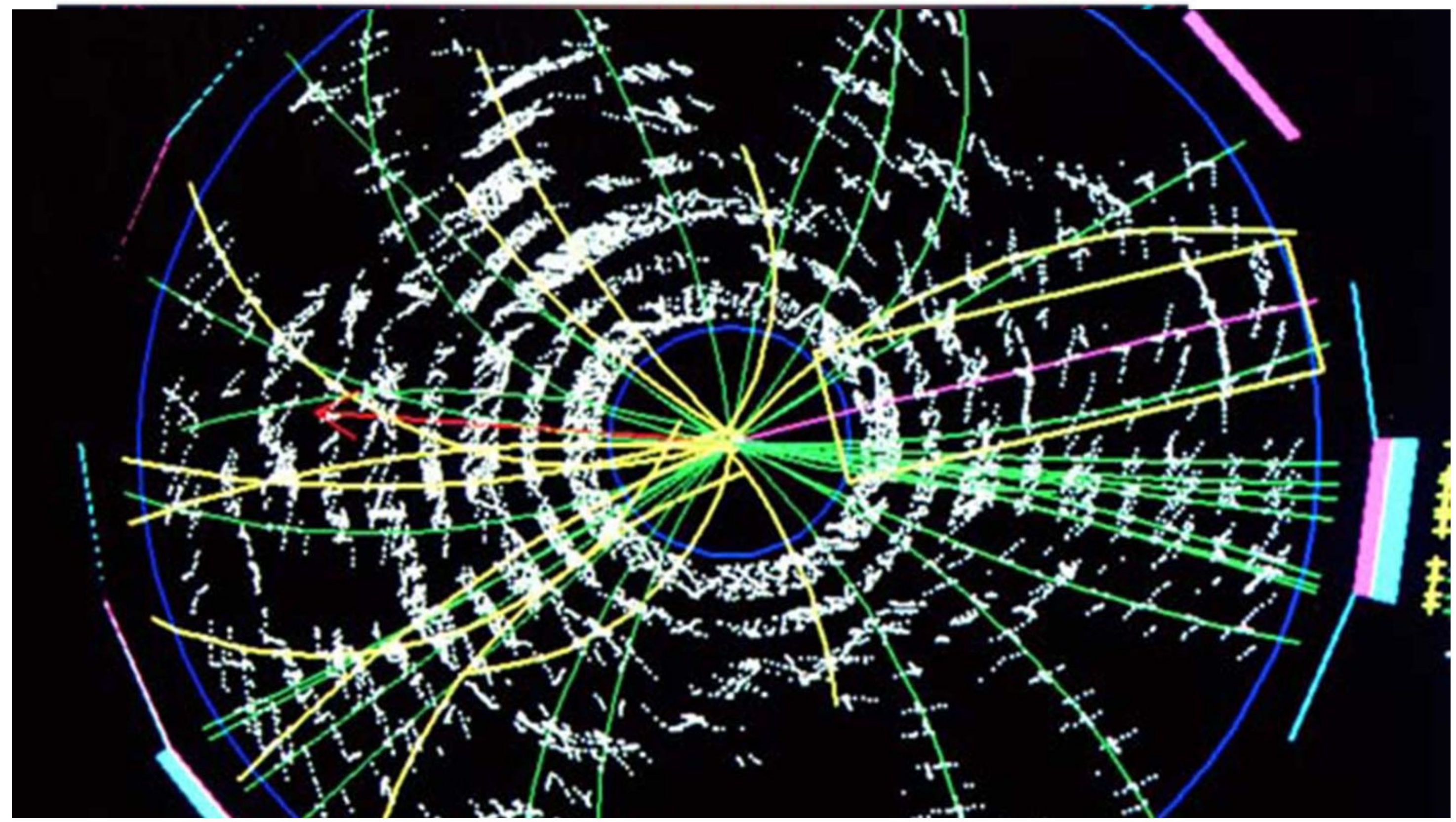
Top always decays in a b quark. Its 1.5 ps lifetime, much longer than light-quark bckg, induces a displacement of its decay products that is observed in the silicon microvertex detector.



And then the sixth…

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s}$ = 1.8 TeV

- Discovery of top quark complete 3-generation picture
- Took a long time (1994) because t quark is *very* heavy: ~175 GeV/c^2!

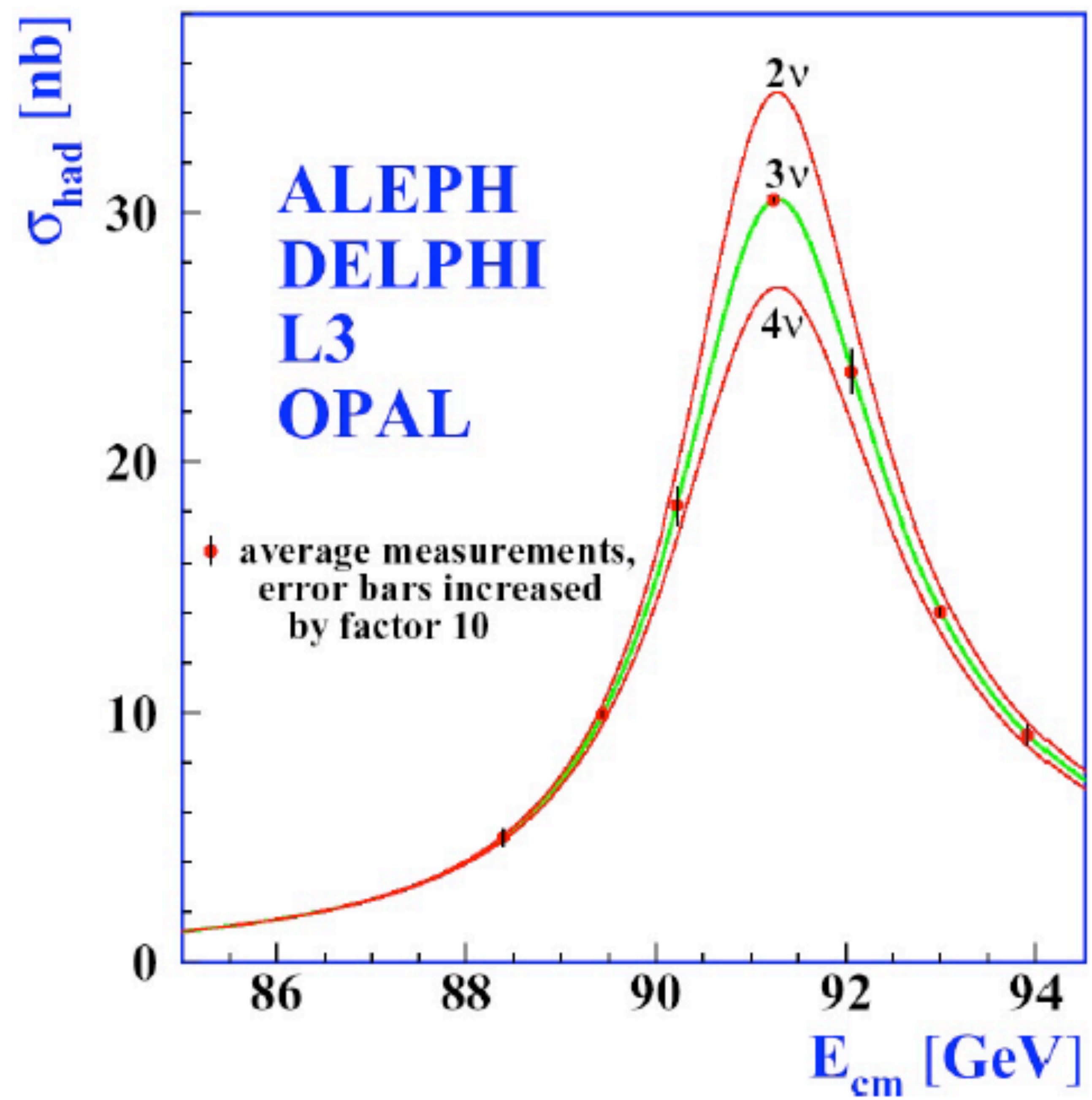


We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV with an integrated luminosity of 19.3 pb^{-1}. We find 12 events consistent with either two W bosons, or a W boson and at least one b jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.

PACS numbers: 14.65.Ha, 13.85.Ni, 13.85.Qk

Are there more than 3 generations? No…

- Surprisingly, you can actually say something about that…
  - Measure decay rate of Z boson into all quarks, compare to total Z boson decay rate
  - Because Z can decay into $\nu\bar{\nu}$ each additional generation with a light neutrino increases the *fraction* of Z decaying to $\nu\bar{\nu}$, and thus decreases the *fraction* of hadronic decays....
  - Shows conclusively that there are only 3 generations (of neutrinos, of the type we know, with mass < $M_Z/2$)



Kobayashi-Maskawa idea remains an ansatz

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The KM structure with 3 families would certainly accommodate into the SM the 1964 observation of CP violation — but no further experimental validation that this was genuinely the picture realized in Nature was available for 30+ years

We simply do not know enough about *CP* violation. Our experimental knowledge is limited to its observation in only one extraordinarily sensitive system that nature has provided us.
At present our experimental understanding of *CP* violation can be summarized by the statement of a single number. If this is all the information nature is willing to provide about *CP* violation it is going to be difficult to understand its origin.

J. Cronin (1980)

After I submitted my paper to Physical Review Letters I received a reluctant acceptance from the referee who objected that my paper made no predictions. What he really meant was that the superweak theory predicted nothing; that is, nothing else would be found beyond the parameter ε in the K° system. Unfortunately, this prediction has proven all too true.

L. Wolfenstein (1989)

Observing CP violation in B decays was the last missing piece to establish KM

Theory pushes for studying CP violation in b-quark

THE PHENOMENOLOGY OF THE NEXT LEFT-HANDED QUARKS

J. ELLIS, M.K. GAILLARD *, D.V. NANOPOULOS ** and S. RUDAZ ***
CERN, Geneva

Received 14 July 1977

Charmed particles should appear in most decays of bottom particles, if the latter are lighter than tops.
Lifetimes $\gtrsim 10^{-13}$ sec for bottom or top particles with masses O(5) GeV.
The possibility of substantial $B^0 (\equiv b\bar{d}) - \bar{B}^0 (\equiv \bar{b}d)$ meson mixing if $m_t > m_b$.
CP violating effects in the $B^0 - \bar{B}^0$ and $T^0 - \bar{T}^0$ systems which are considerably larger than in the $K^0 - \bar{K}^0$ system.

PHYSICAL REVIEW D VOLUME 23, NUMBER 7 1 APRIL 1981

CP violation in *B*-meson decays

Ashton B. Carter and A. I. Sanda
The Rockefeller University, New York, New York 10021
(Received 27 June 1980)

The pattern of *CP* violation in the bottom sector is discussed. We introduce general techniques to expose new *CP*-violating effects in the cascade decays of *B* mesons. In the Kobayashi-Maskawa (KM) model, the *CP* asymmetries so obtained range from 2–20 % for plausible values of the model parameters. This is to be compared with the small effects, of order 10^{-3}–10^{-4}, previously exhibited within this model. Effects of this size should be observable in upcoming experiments. Our approach stresses the on-shell transitions which make up the cascade decays of heavy mesons to ordinary hadrons, as opposed to the off-shell transitions which occur in the analogs of K°-$\bar{K}^\circ$ mixing. The *CP* asymmetries generated by our techniques are of order $\sin\delta$, where δ is the KM phase angle, and thus represent the maximum effects obtainable in this model.

Nuclear Physics B193 (1981) 85–108

CP Noninvariance in the Decays of Heavy Charged Quark Systems

Myron Bander, D. Silverman, and A. Soni
Department of Physics, University of California, Irvine, California 92717
(Received 9 May 1979)

Within the context of a six-quark model combined with quantum chromodynamics we study the asymmetry in the decay of heavy charged mesons into a definite final state as compared with the charge-conjugated mode. We find that, in decays of mesons involving the *b* quark, measurable asymmetries may arise. This would present the first evidence for *CP* noninvariance in charged systems.

NOTES ON THE OBSERVABILITY OF *CP* VIOLATIONS IN B DECAYS

I.I. BIGI
Institut für Theor. Physik der RWTH Aachen, D-5100 Aachen, FR Germany

A.I. SANDA[1]
Rockefeller University, New York 10021, USA

Received 16 June 1981

We describe a general method of exposing *CP* violations in on-shell transitions of B mesons. Such *CP* asymmetries can reach values of the order of up to 10% within the Kobayashi–Maskawa model for plausible values of the model parameters. Our discussion focuses on those (mainly non-leptonic) decay modes which carry the promise of exhibiting clean and relatively large *CP* asymmetries at the expense of a reduction in counting rates. Accordingly we address the complexities encountered when performing *CP* tests with a high statistics B meson factory like the Z^0 (and a toponium) resonance.

All say large CPV plausible in B decays!

CPV in *decay* of kaons show that CPV is instrinsic to the weak force

Volume 206, number 1 PHYSICS LETTERS B

FIRST EVIDENCE FOR DIRECT *CP* VIOLATION

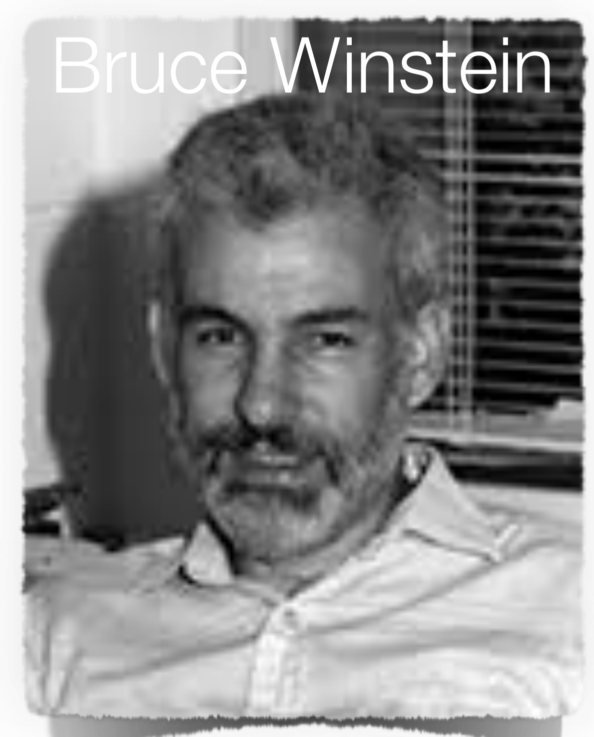
CERN–Dortmund–Edinburgh–Mainz–Orsay–Pisa–Siegen Collaboration

1.1) $\times 10^{-3}$. This is the first time that evidence of *CP*-violating effects is seen in the decay of the *CP*-odd K_2 into two pions, as implied by a non-zero value of ϵ'. It is at the level predicted recently by several evaluations of the standard model for a t-quark mass in the range 50–100 GeV [14] and does not agree with the superweak model [8].

VOLUME 83, NUMBER 1 PHYSICAL REVIEW LETTERS

Observation of Direct *CP* Violation in $K_{S,L} \to \pi\pi$ Decays

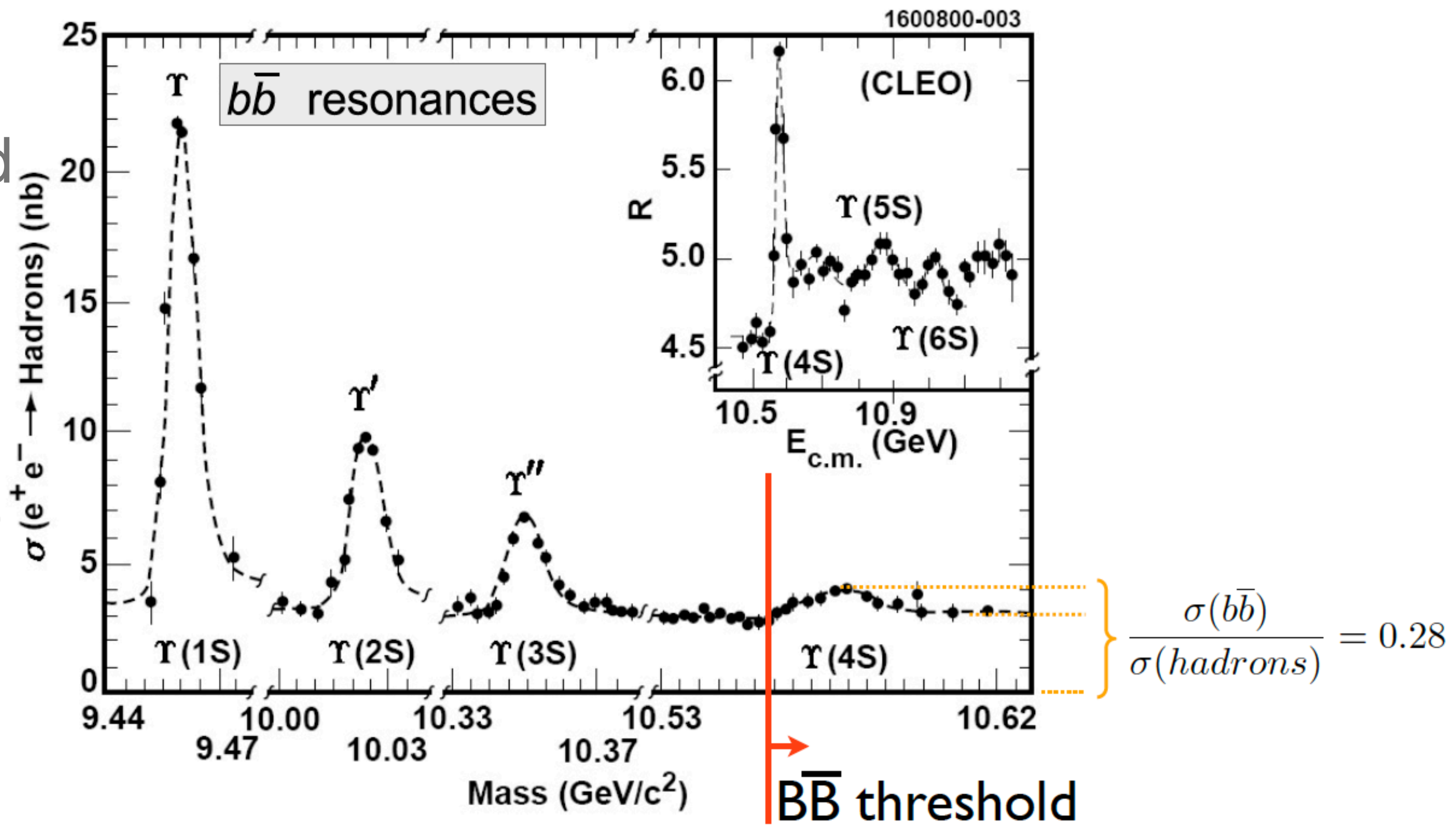
In conclusion, we have measured $\mathrm{Re}(\epsilon'/\epsilon)$ to be $[28.0 \pm 3.0(\mathrm{stat}) \pm 2.8(\mathrm{syst})] \times 10^{-4}$; combining the errors in quadrature, $\mathrm{Re}(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4}$. This result definitively establishes the existence of *CP* violation in a decay process, agreeing better with the earlier measurement from NA31 than with E731 [22], and shows that a superweak interaction cannot be the sole source of *CP* violation in the *K* meson system. The



B factories

Produce B-Bbar pairs from the decays of Y(4S) mesons produced in e+e- collisions

Y(4S) mass just above the B-Bbar kinematic threshold: 96% of Y(4S) decay strongly into B^0anti-B^0 or B^+B^- pairs (and nothing else, low background)

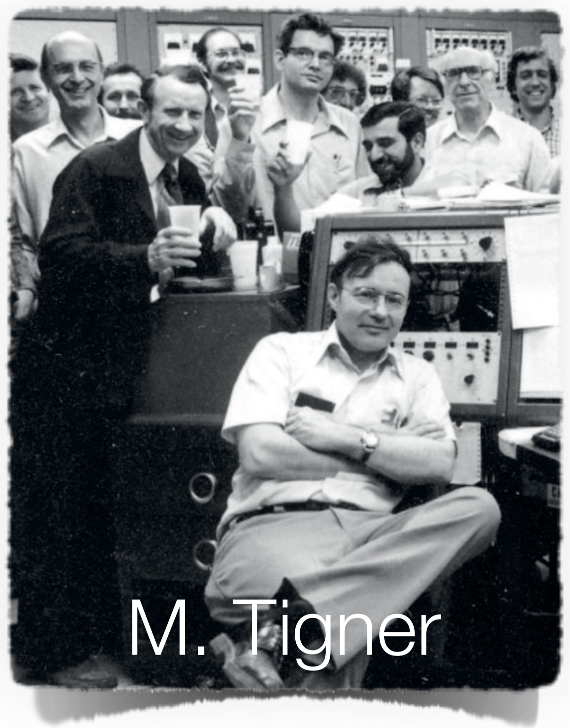


Coherence: Y(4S) is spin-1. B mesons are spin-0, hence L=1 (antisymmetric two-particle state) to conserve angular momentum. Simultaneous presence of two B or two Bbar forbidden as two identical bosons in an antisymmetric state violate Bose statistics. B and Bbar evolve as a particle-antiparticle pair until one decays, allowing flavor identificatio.

Low-background production of BBbar pairs that evolve coherently as particle-antiparticle until one decays.

CLEO at CESR (and DORIS II) showed that it worked

The CESR collider exploited the concept and the associated CLEO experiment pioneered many of the techniques later used and perfected at BaBar/Belle



But there was a problem.

- ☑ Produce and reconstruct large samples of B^0 mesons
- ☑ Identify if a B^0 or anti-B^0 had decayed
- ☐ Have them fly a measurable distance

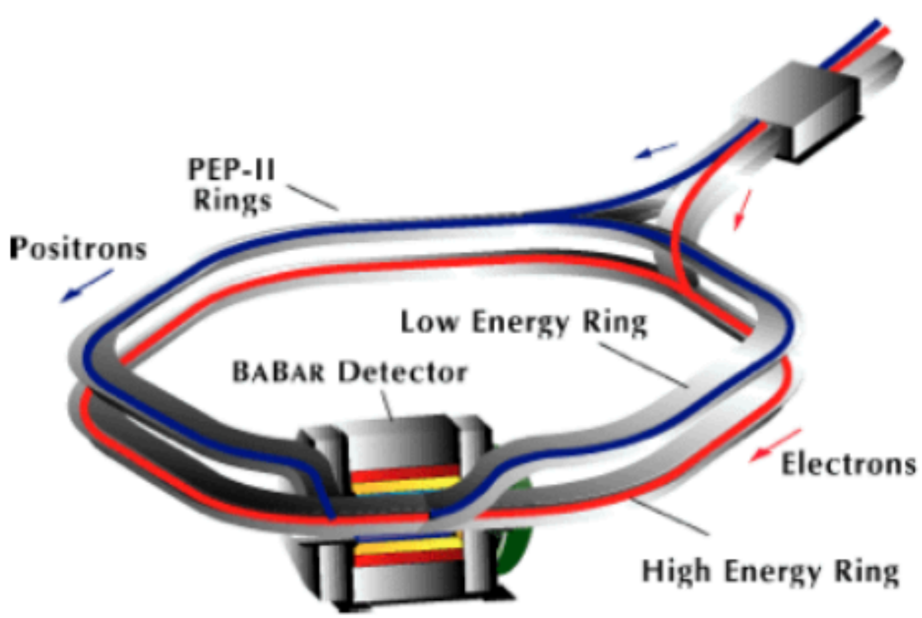
Production at BBbar threshold is efficient and low-background, but the Y(4S) is nearly at rest, which means that B mesons are slow: m(Y(4S)) = 10.56 GeV and m(B) = 5.28 GeV. Hence, p*(B) = 340 MeV, which means $(\beta\gamma)^* = 0.064$ yielding 30 micron decay length for 1.5 ps lifetime. This is hardly measurable.

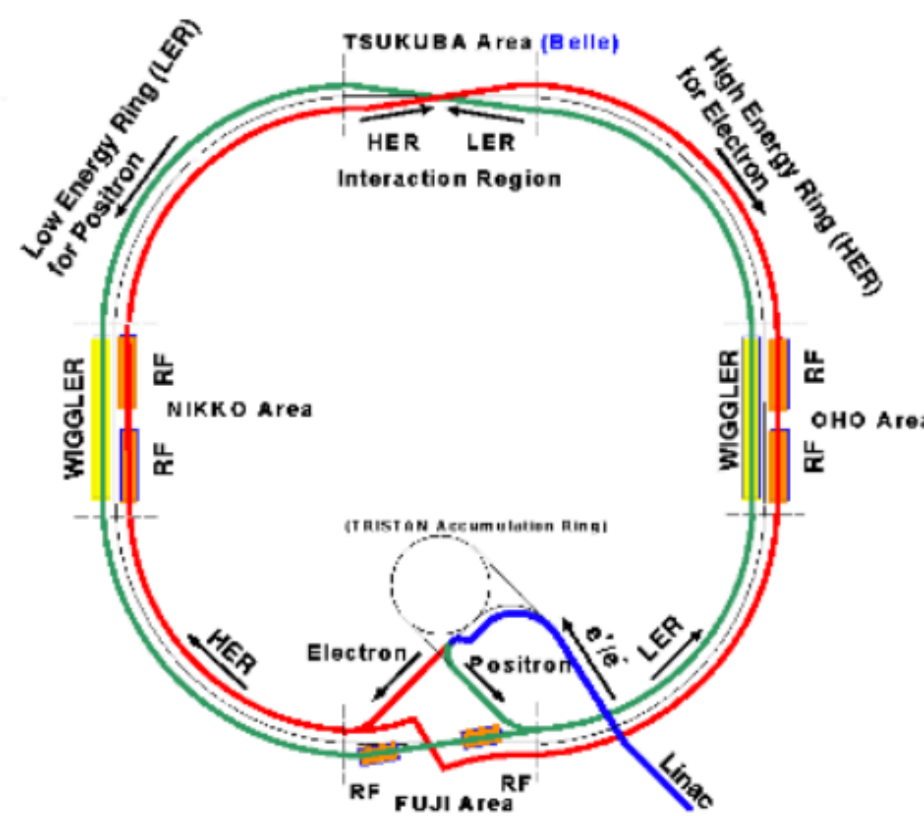
Asymmetric beam energy

1988: Pier Oddone proposes using energy-asymmetric electron-positron beams so that the Υ(4S) is not at rest and B decay lengths are dilated from (unmeasurable) 20 microns to 200 microns, which is measurable with typical 30 micron resolution of silicon detectors

PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

KEKB at KEK
8.0 GeV e^- on 3.5 GeV e^+





CP violation happens in the B meson system

VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

Belle

Observation of Large CP Violation in the Neutral B Meson System

We conclude that there is large CP violation in the neutral B meson system. A zero value for $\sin 2\phi_1$ is ruled out at a level greater than 6σ. Our result is consistent with the higher range of values allowed by the constraints of the KM model as well as with our previous measurement.

VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

BaBar

Observation of CP Violation in the B^0 Meson System

The measurement of $\sin 2\beta = 0.59 \pm 0.14(\text{stat}) \pm 0.05(\text{syst})$ reported here establishes CP violation in the B^0 meson system at the 4.1σ level. This significance is com-

Epilogue

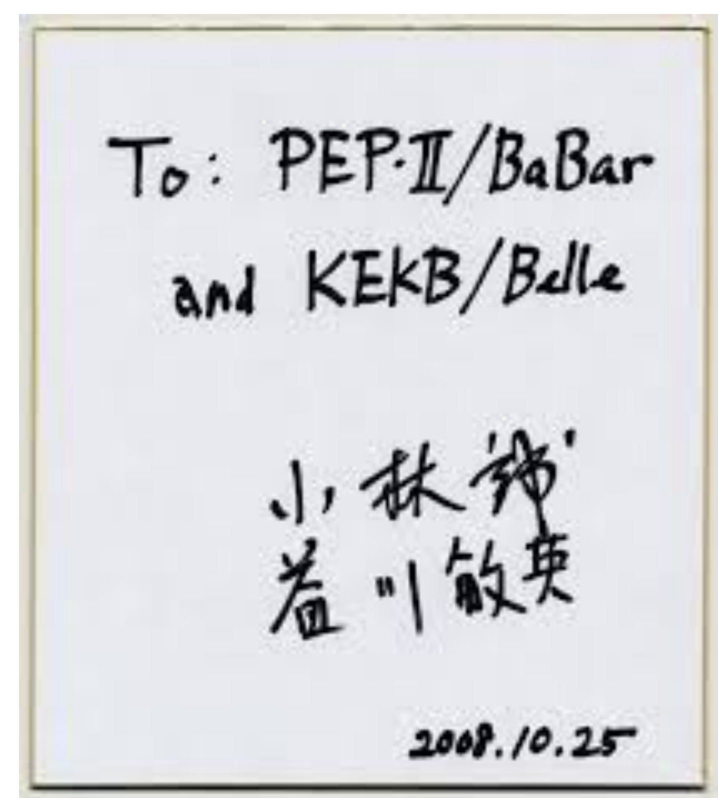
The Nobel Prize in Physics 2008

Photo: University of Chicago
Yoichiro Nambu
Prize share: 1/2

© The Nobel Foundation
Photo: U. Montan
Makoto Kobayashi
Prize share: 1/4

© The Nobel Foundation
Photo: U. Montan
Toshihide Maskawa
Prize share: 1/4

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.




THE
MATRIX


THE
MATRIX