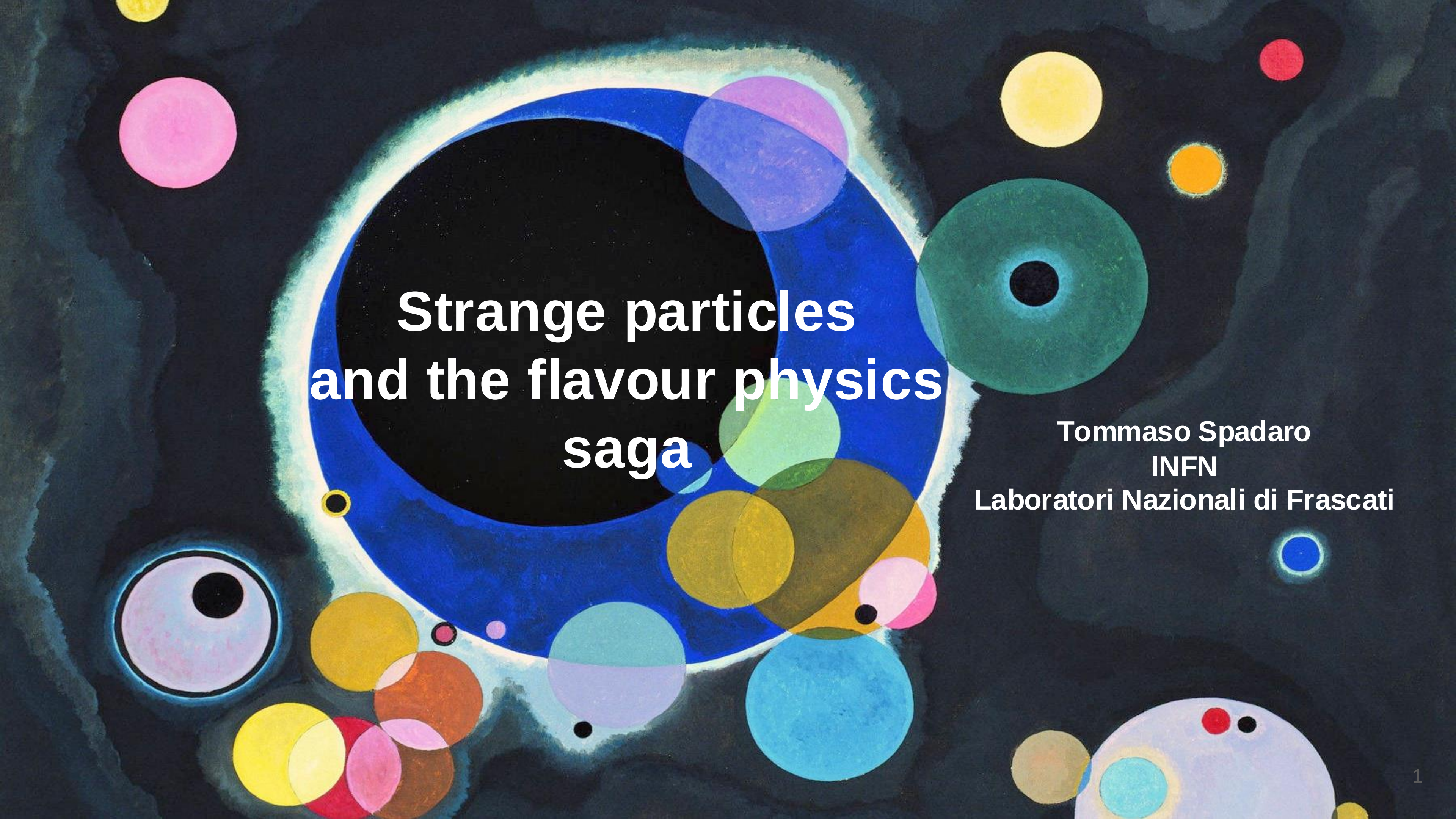

Strange particles and the flavour physics saga

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INFN
Laboratori Nazionali di Frascati

Intro

Anyone who has ever tried to present a rather abstract scientific subject in a popular manner knows the great difficulties of such an attempt.

Either he succeeds in being intelligible by concealing the core of the problem […] or else he gives an expert account of the problem, but in such a fashion that the untrained reader is unable to follow the exposition and becomes discouraged from reading any further” [Einstein, 1948].

Spoiler alert

There are 3 different "replicas" of conventional material, gradually heavier

We don't know why

There is no exact symmetry between matter and antimatter

OK, but we cannot explain the asymmetry observed in the universe

We probed the existence of violations of the structure of space-time

We have no evidence of distortions

Particles with ”strange" and other “flavours” have continued to provide questions for almost 80 years:

We keep looking for answers

What does it mean “strange”

It depends on the context: "Different from the usual or the common, from the normal, very singular, such as to arouse wonder, amazement, curiosity»

Example: at the end of the 19th century, "everything" seemed clear

- **Electricity, magnetism → electromagnetic fields (Maxwell)**
- **Dynamics of the universe→ Classical mechanics, gravitation (Newton)**
- **Gas, chemical processes→ thermodynamics, kinetic theory (Boltzmann)**

Eminent scientists concluded:

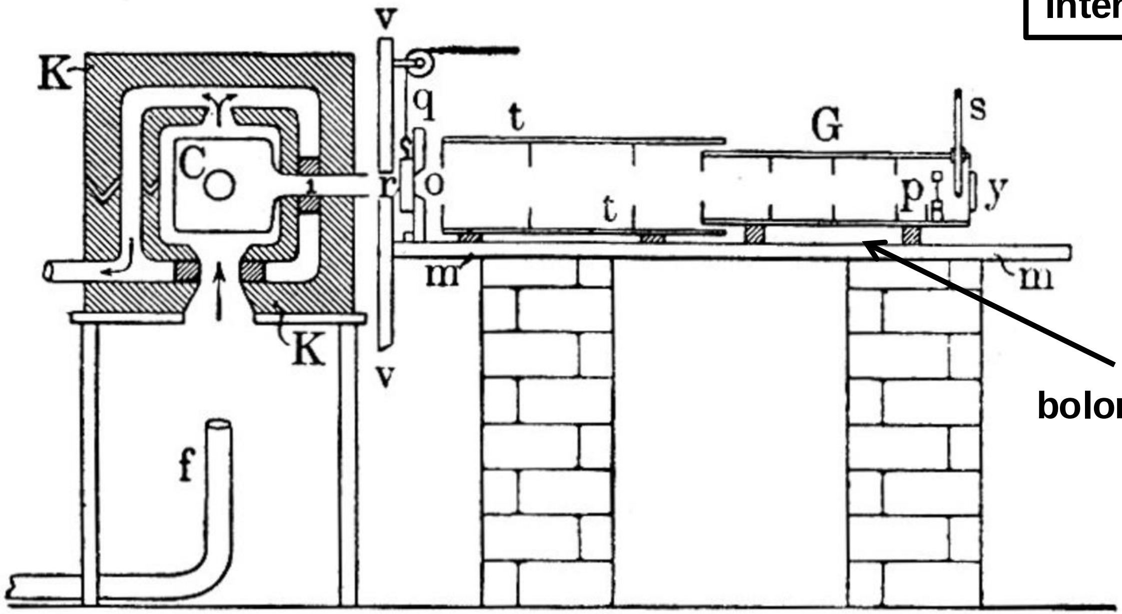
- **“All that remains to do in physics is to fill in the sixth decimal place” (Michelson, 1894)**
- **“There is nothing new to be discovered in physics now. All that remains is more and more precise measurement” (Lord Kelvin, 1900)**

But some "oddities" remained...

Black body radiation (1899-1900)

Fully absorbent ideal body (black) with internal cavity: radiation in the cavity is in equilibrium with the walls, at temperature T

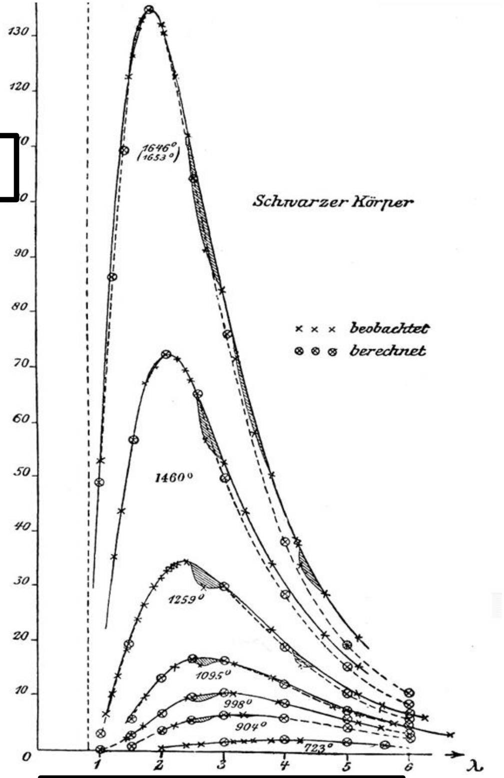
Emittance/absorbance ratio of any body is the blackbody spectrum e_λ



bolometer

Lummer, Pringsheim 1899

Intensity e_λ



Wave length (μm)

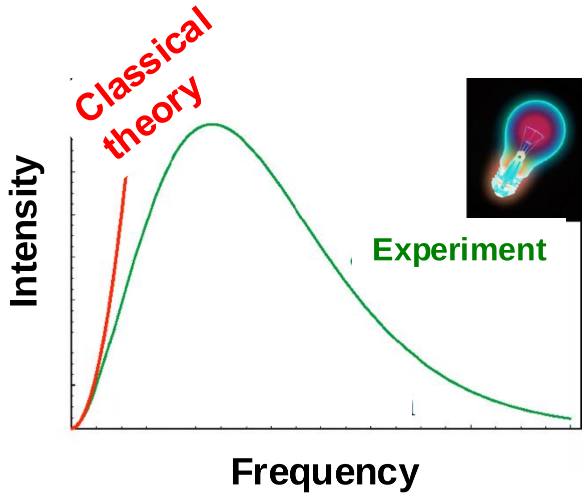
The blackbody spectrum (1899-1900)

Classically, it could be explained that:

$e_\lambda = T^5 F(\lambda T)$ [Stefan-Boltzmann, Wien]

The interpretation [Rayleigh, 1900] of radiation as due to standing waves within the cavity implied: $e_\lambda \sim T^5 \, 1/\lambda T$

Divergence for $\lambda \to 0$



It would have been explainable ("out of desperation") if the oscillators in the container could only emit a finite number of elements of energy proportional to frequency (Planck, 1900), $U = n\,h\nu \to e_\lambda = 8\pi^2 c\, h / \lambda^5 (e^{hc/k\lambda T} - 1)$

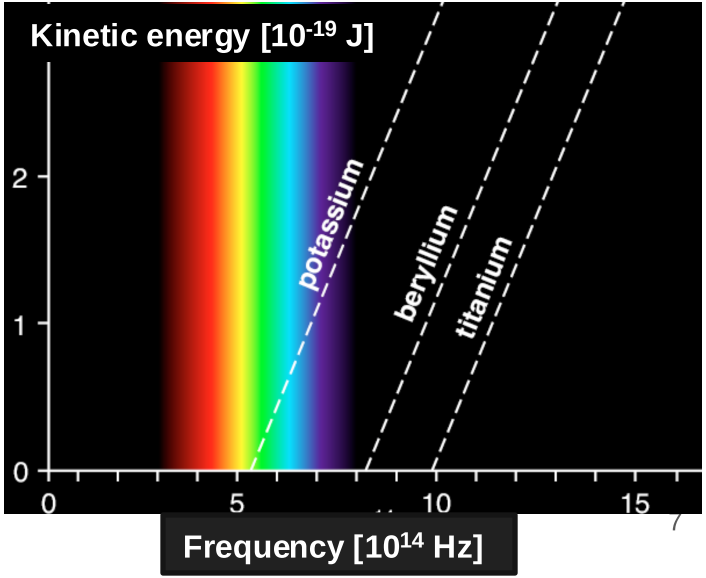
Hydrogen spectrum (1885), photoelectric effect

In the hydrogen emission spectrum, specific frequency values are preferred

$\lambda = h\, m^2 / (m^2 - 2^2)$, for INTEGERS m (3, 4, 5, …) [Balmer, 1885]

By sending light on metals, cathode rays are produced("electrons")

Classically, the kinetic energy of the E electrons is expected to be proportional to the intensity of the light sent, but the observation is E ~ h ν
[Von Lenard, 1902]



In fact, a revolution was upon us...

Cathode rays(e^-) have a defined charge/mass ratio(J.J. Thompson, 1904)

The random motion of small particles in a fluid (Brown, 1827) is due to the bombardment of molecules (Einstein, 1905) → atoms exist (Perrin, 1907)

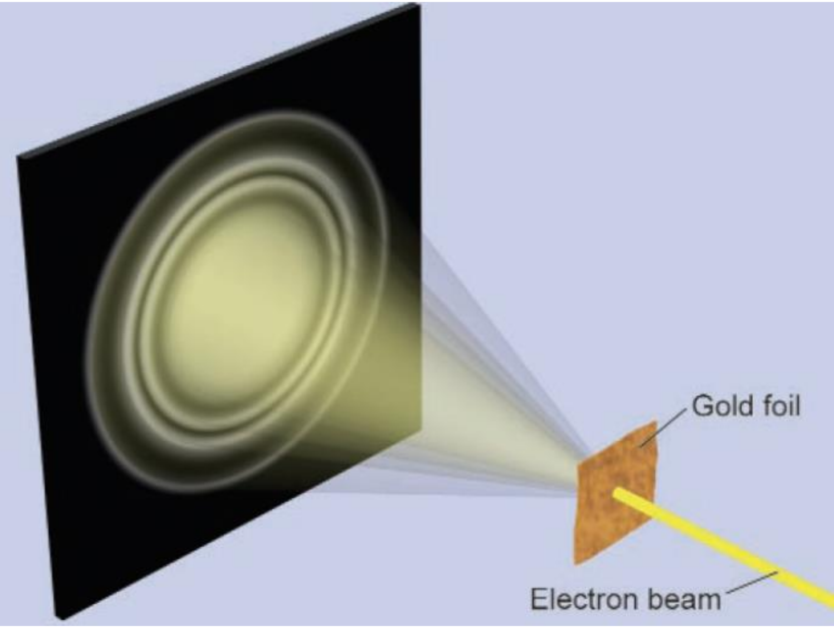
α particles are deflected by a gold foil at large angles (Rutherford, Marsden, 1911) → all the mass of the atom is in a massive and dense nucleus → Rutherford Planetary Model of Atom (1911)

New questions: how do electrons orbit the positive nucleus stably without losing energy by radiation? What components in the core?

Ten years for an explanation

The same particles with mass behave like waves of length l, depending on their pulse p: $\lambda = h / p$ [De broglie, 1924]

Confirmed by Davisson/Germer (1927)



Waves of matter subject to an inescapable principle of position-momentum minimum indetermination [Heisenberg, 1925]: $\delta X \, \delta p > h / 4\pi$

Confirmation, among others, from the Stern-Gerlach experiment [1922]

Ten years for an explanation: Schrodinger, 1926

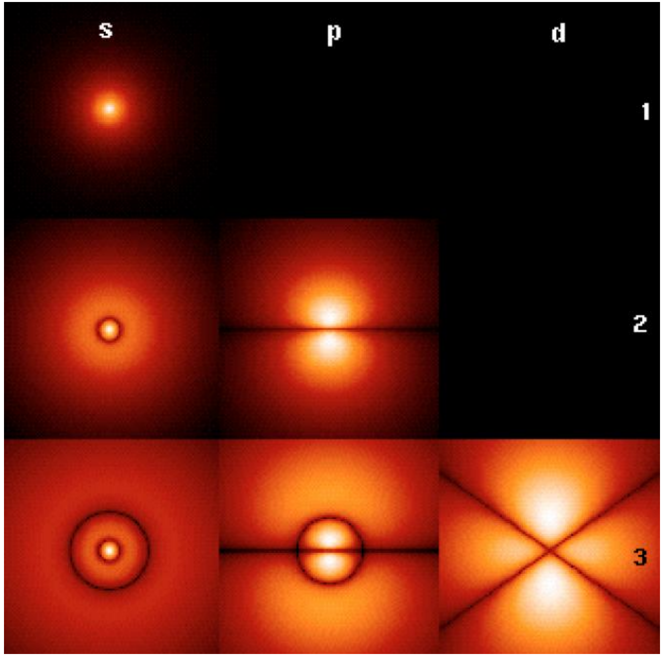
Particles are described by a wave function ψ subject to a dynamic

$$H\psi\left(\mathbf{r},t\right) = \left(T+V\right)\psi\left(\mathbf{r},t\right) = \left[-\frac{\hbar^2}{2m}\nabla^2 + V\left(\mathbf{r}\right)\right]\psi\left(\mathbf{r},t\right) = i\hbar\frac{\partial\psi}{\partial t}\left(\mathbf{r},t\right)$$

Interpretation (Bohr, 1927):

- **ψ is a complex function (interference)**
- **$|\psi|^2$ represents probability**

A large number of observations in chemistry (bonds, molecules) could be explained by these assumptions



Standing waves of the electron in a hydrogen atom

Other quantum interpretations

Balmer spectrum light is emitted during transitions between atomic levels

The angular momentum of the electrons in orbit is quantized, the energy of the light emitted is given by the difference in energy levels (Bohr, 1913)

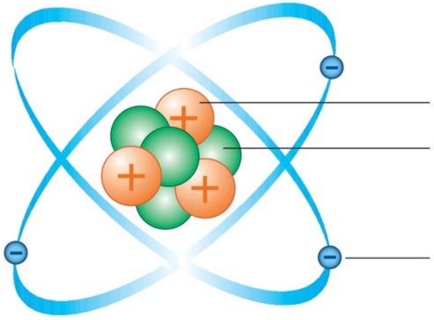
$$\mathbf{L} = n \cdot \hbar = n \cdot \frac{h}{2\pi} \qquad E_n = \frac{-13.6\ \mathrm{eV}}{n^2}$$

Kinetic energy of single electrons in the photoelectric effect due to absorption of single light quanta, of energy E = hν (Einstein, 1905)

Hypothesis initially considered unfounded, later accepted after Millikan's (1915) and Compton's (1917) experiments

The end of this revolution is our beginning

A new vision of "everything" (1932)



The fundamental building blocks of matter are: e, p, n

Interactions are mediated by quantized fields:

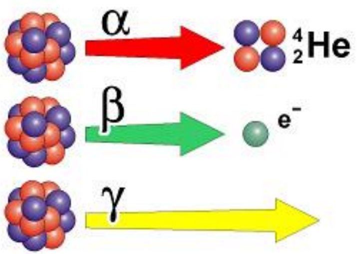
Electromagnetic force → quanta of light called photons

The covariant dynamics of an elementary particle such as the electron implies the existence of an anti-electron (Dirac, 1928) both with spin ½

the anti-electron called "positron": discovered in 1932 by Anderson

End of story? not at all…

The end of this revolution is our beginning



There are other fundamental forces: weak force

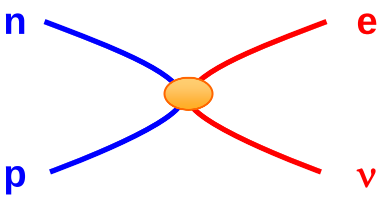
- **responsible for radioactive decays**
- **initiates nuclear fusion in the sun**

1895 discovery of X rays (Röngten)
1896 discovery of radiation from Uranium crystals (Becquerel)
1898 ionizing radiation from Pitchblende, Uranium and Polonium (M. & P. Curie)

Beta rays are made up of electrons emitted in the decay of nuclei

The energy spectrum is continuous → existence of neutrino ν (1930 Pauli)

eg.: n → p e^- $\bar{\nu}$



Quantum field theory for weak interactions (Fermi, 1934)

currents proton-neutron x electron-neutrino

coupling ~ 10^{-5} compared to electromagnetic interaction

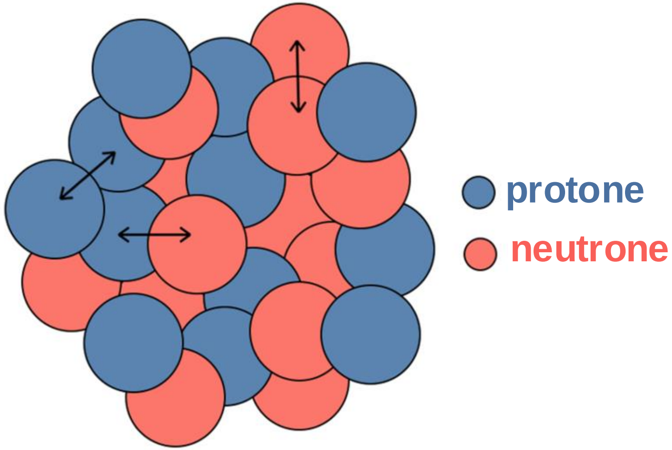
The end of this revolution is our beginning

There are other fundamental forces: strong force → Stability of atomic nuclei

Predicted by Yukawa (1934), short-range potential: $V \sim -g^2 e^{-mr} / r$

A massive quantum force, the "pione" (π): m ~ 140 MeV (1.4 x 10^{-13} cm)

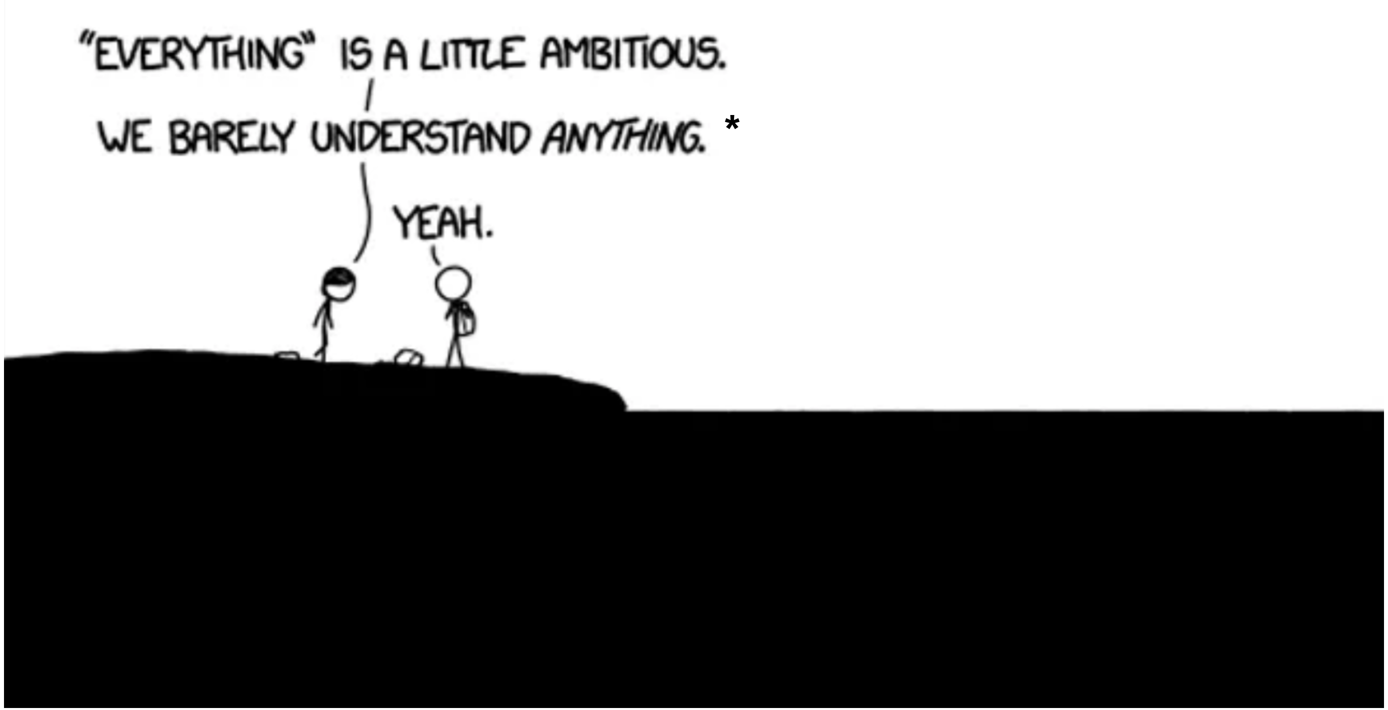
Searches using cosmic rays, the muon μ was found (Neddermayer/Anderson, Street/Stevenson 1936-7)
Famously: "who ordered that?" (I. Rabi)



Later discovered (Lattes, Occhialini, Powell 1947):
$\pi^{\pm} \rightarrow \mu^{\pm} \overset{(-)}{\nu}$

And a neutral pion, too (Panofsky, Aamodt, Hadley 1951): $\pi^{-} p \rightarrow \pi^{0} n$

Pause – Some fundamental concepts



https://en.wikipedia.org/wiki/Time_(xkcd)

Fundamental concepts in the following: spin

A rotation of 2π around an axis can change the wave function

- **eg.: Polarization of an E.M. Wave, analogous to spin = 1**
- **adds up as an orbital angular momentum**

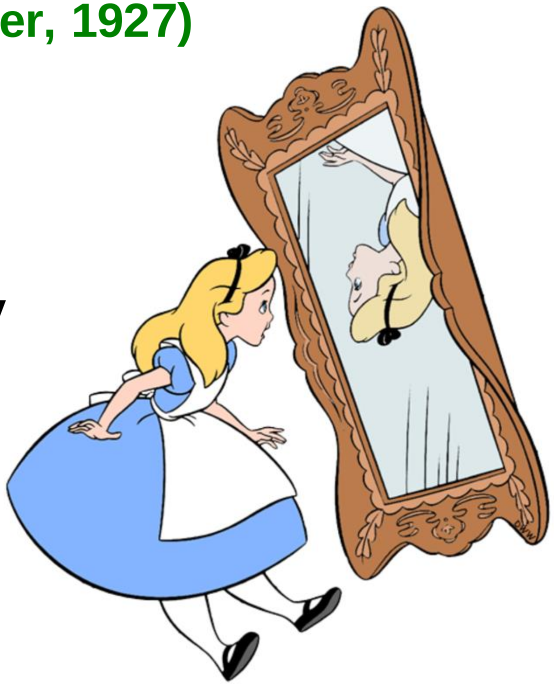
In the quantum case, Spin is quantized, $S = n\hbar$:

- **can be semi-integer, n = 1/2 , 3/2, ecc.**
- **if (S^2, S_z) known → minimum indetermination in $S_{x,y}$**
- **It is an intrinsic characteristic of any type of particle**
- **Particles with (semi)integer spin are in an (anti)symmetric state**

Key concepts below: parity

Parity P is the inversion of spatial coordinates: r → -r

eg.: atomic states divided in 2 classes, P = ±1, Electric dipole transitions proceed from states P = ±1 to states P = ∓1 (Wigner, 1927)



Parity symmetry: one cannot distinguish between a phenomenon in reality and its image in the mirror

"Intrinsic" parity: the wave function changes by P = ±1, by inversion of spatial coordinates

Conventionally, P = +1 for p and n, π have P = -1

- Comparing pp → π^+ d and π^+ d → pp derive: $S_\pi = 0$
- Since π^- d → nn but π^- d $\not\to$ nn π^0, then $J^P(\pi) \neq 0^+$

Parity was considered an exact symmetry of the dynamics

Key concepts in the following: isospin

Nuclear physicists had noticed similar energy levels for nuclei as 13C and 13N

$^{13}C = (6p, 7n)$, $^{13}N = (7p, 6n)$

A symmetry of strong interactions is introduced, “Isospin” (Heisenberg):

(p, n) represent the 2 states of a doublet

(π^+,π^0,π^-) represent the 3 states of a triplet

Isospin adds up as a quantum angular momentum

Slight differences in mass between p and n and between $\pi^\pm$ and π^0 → isospin is an approximate symmetry:

- **$(M_n \square M_p) / M_n \sim 0.13\%$**
- **$(M_{\pi\pm} \square M_{\pi 0}) / M_{\pi\pm} \sim 3.3\%$**

Everything in its place?

Definitely not, it was only the beginning of the discoveries of a "zoo" of particles

Experimental techniques up to the '40s-50s:
Source: Cosmic Rays (High Mountain/Balloons)

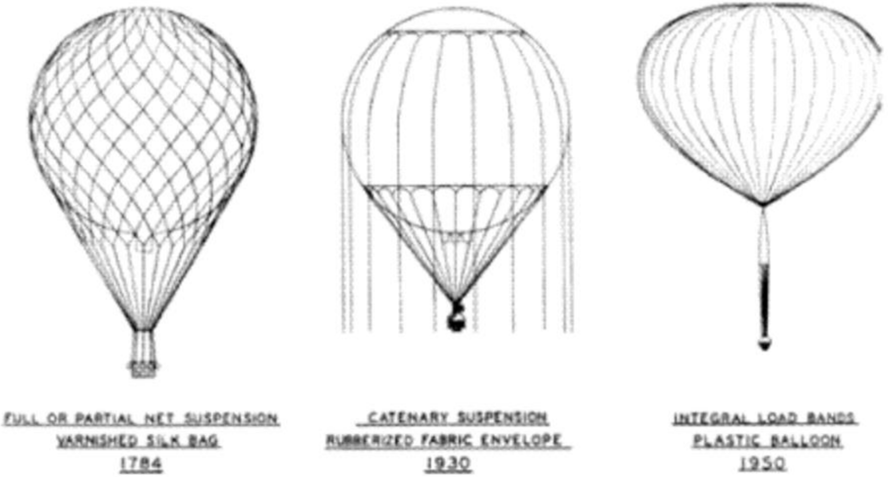


Figure 3. Evolution of balloon designs over almost two centuries.

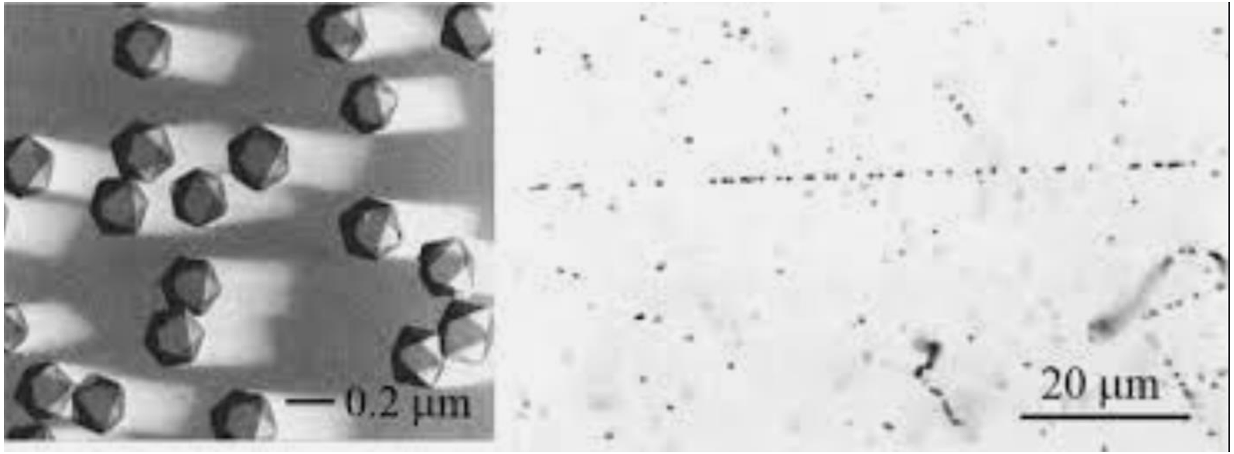
V. Hess, cosmic ray discoverer (1912)

Experimental techniques: nuclear emulsions

Experimental techniques up to the '40s - '50s:

- **source: cosmic rays (High Mountains / Balloons)**
- **detector: Nuclear Emulsions**

AgBr grains in photographic emulsion → Plate development



Already used by Bequerel (1896, charged particles emitted by uranium) and by Kinoshita (1910, from radioactive nuclei) and used on balloons (1935, Explorer II)

Improved by Bristol group and then produced by Ilford and Kodak

Eg.: Discovery of the pion in cosmic rays

C. F. Powell group, Nature 159 (1947) 695

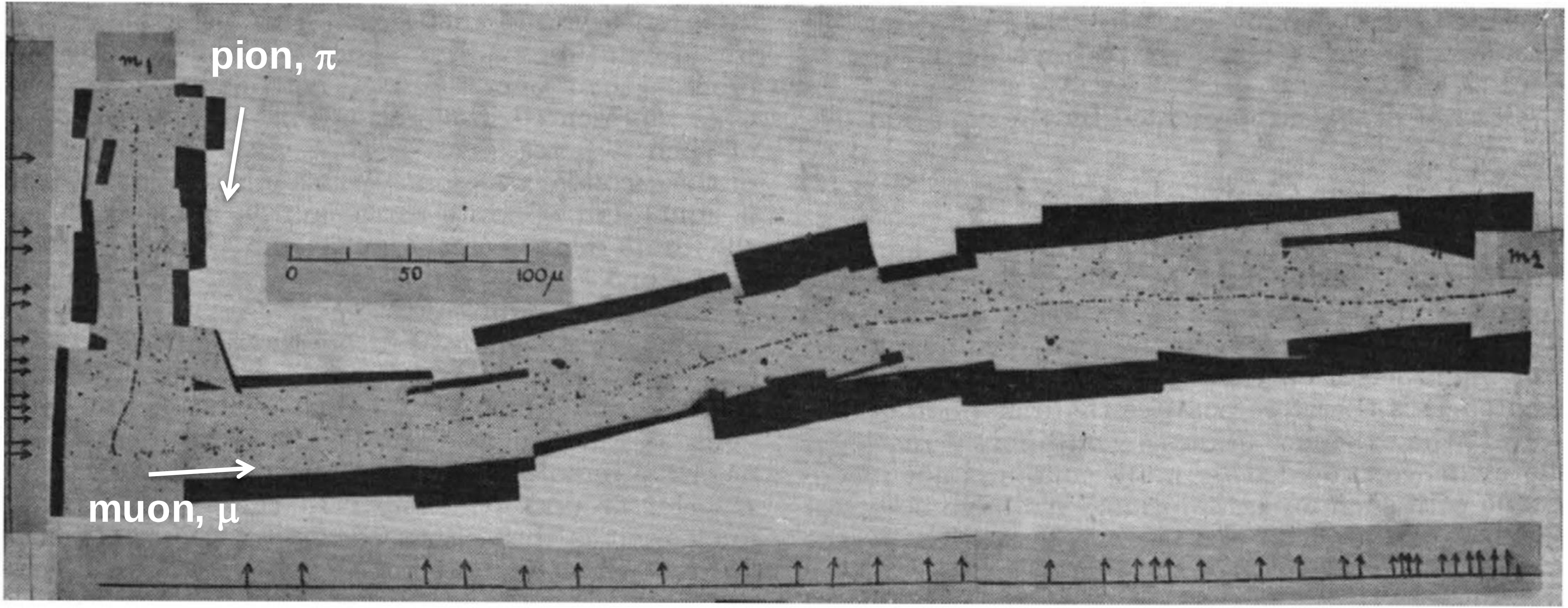


Fig. 1. OBSERVATION BY MRS. I. ROBERTS. PHOTOMICROGRAPH WITH COOKE × 45 'FLUORITE' OBJECTIVE. ILFORD 'NUCLEAR RESEARCH', BORON-LOADED $C2$ EMULSION. m_1 IS THE PRIMARY AND m_2 THE SECONDARY MESON. THE ARROWS, IN THIS AND THE FOLLOWING PHOTOGRAPHS, INDICATE POINTS WHERE CHANGES IN DIRECTION GREATER THAN 2° OCCUR, AS OBSERVED UNDER THE MICROSCOPE. ALL THE PHOTOGRAPHS ARE COMPLETELY UNRETOUCHED

Cloud chambers

Experimental techniques up to the '40s - '50s:

- **source: cosmic rays (High Mountains / Balloons)**
- **detector: Nuclear Emulsions, Cloud chambers (or bubble chambers, mid 50’s)**

Traces of charged particles in supersaturated gas, photographs taken under certain conditions (triggers)

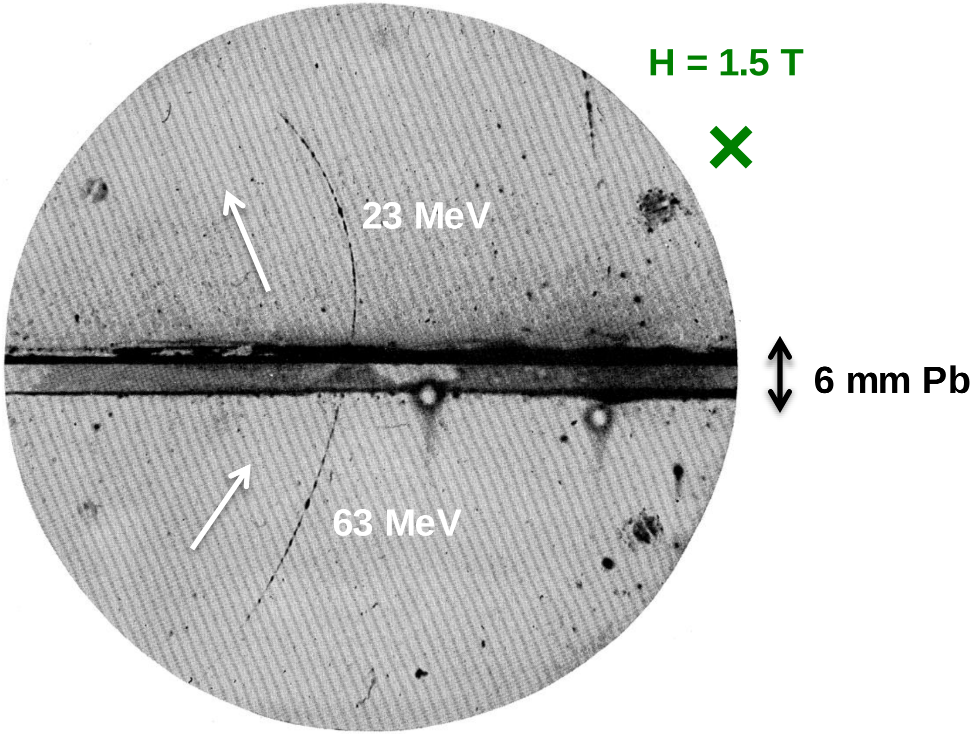
Original chamber invented by Wilson (1899), Cavendish Laboratories, Cambridge (England)

Eg.: Discovery of the positron

C. Anderson Phys. Rev. 43 (1933) 491

- **Magnetic field for momentum measurement, p [GeV/c] ~ 0.3 B [T] R [m]**
- **measurement of dE/dx (Droplet density)**

Charge Ratio Mass ~ as Electron, Opposite Curvature

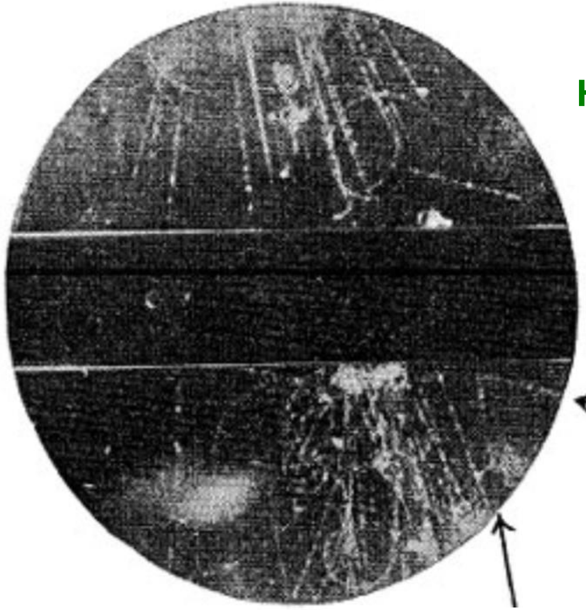


The first “V” particles

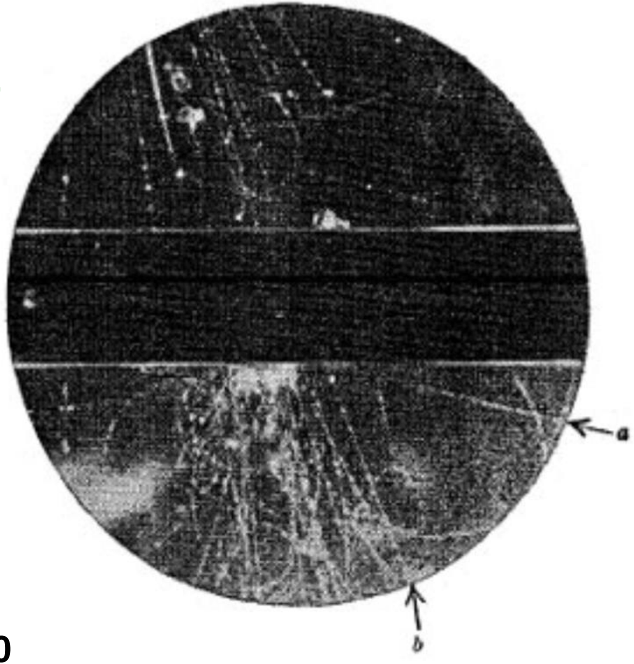
Butler, Rochester [Nature 160 (1947) 855]: spontaneous “V”-shaped decays, 2 observed / 1500 h of exposure

Stereoscopic photographs of event 1: vertex in the gas, opposite charges

30 mm Pb



H = 0.35 T



b, q < 0 **a, q > 0**

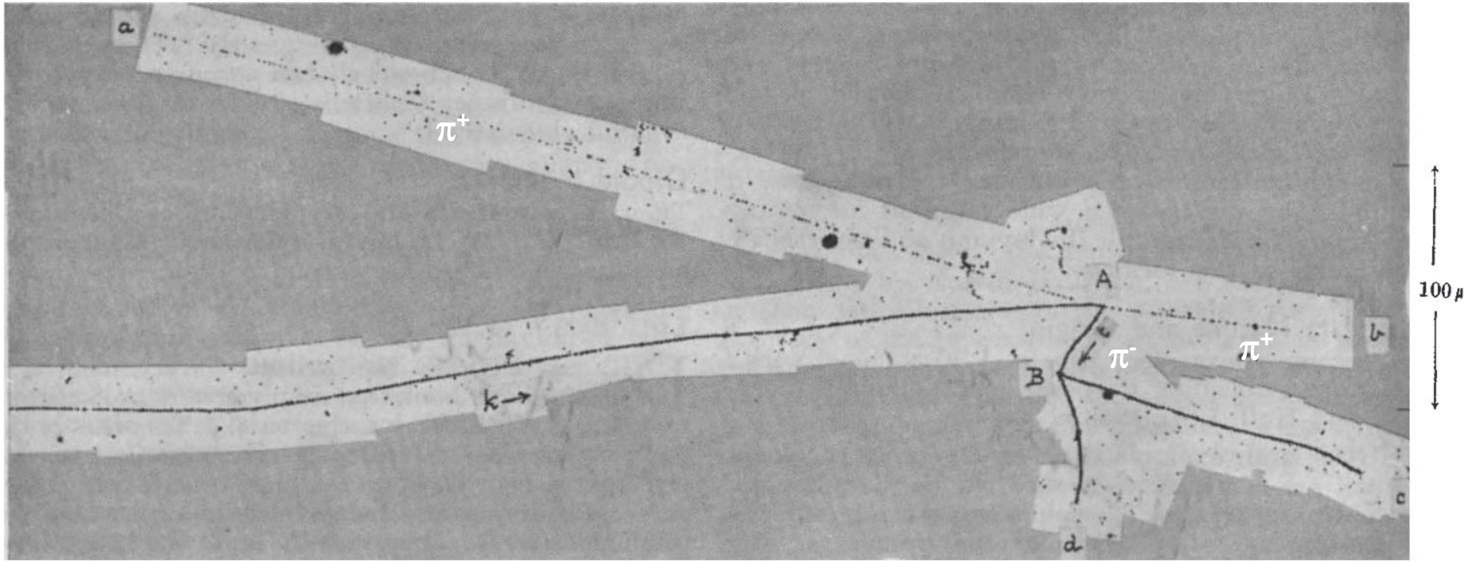
Unstable particles, lifetimes 10^{-9}—10^{-10} s, masses ~ 1000 m_e
They decay into other particles, maybe pions

Other new particles

Powell et al. Nature 163 (1949) 82: the “τ” meson

Emulsions exposed in the Bernese Alps (Jungfraujoch, altitude 3500 m)

Number of grains per 10 μm of path vs range → measure E/m



Observer : Mrs. W. J. van der Merwe

Fig. 8

The trace k produces 3 particles in A, one interacts in B (end range) as π^-
No "star" in A, coplanarity within a few degrees → spontaneous decay

$$m_k \sim 985\ m_e$$

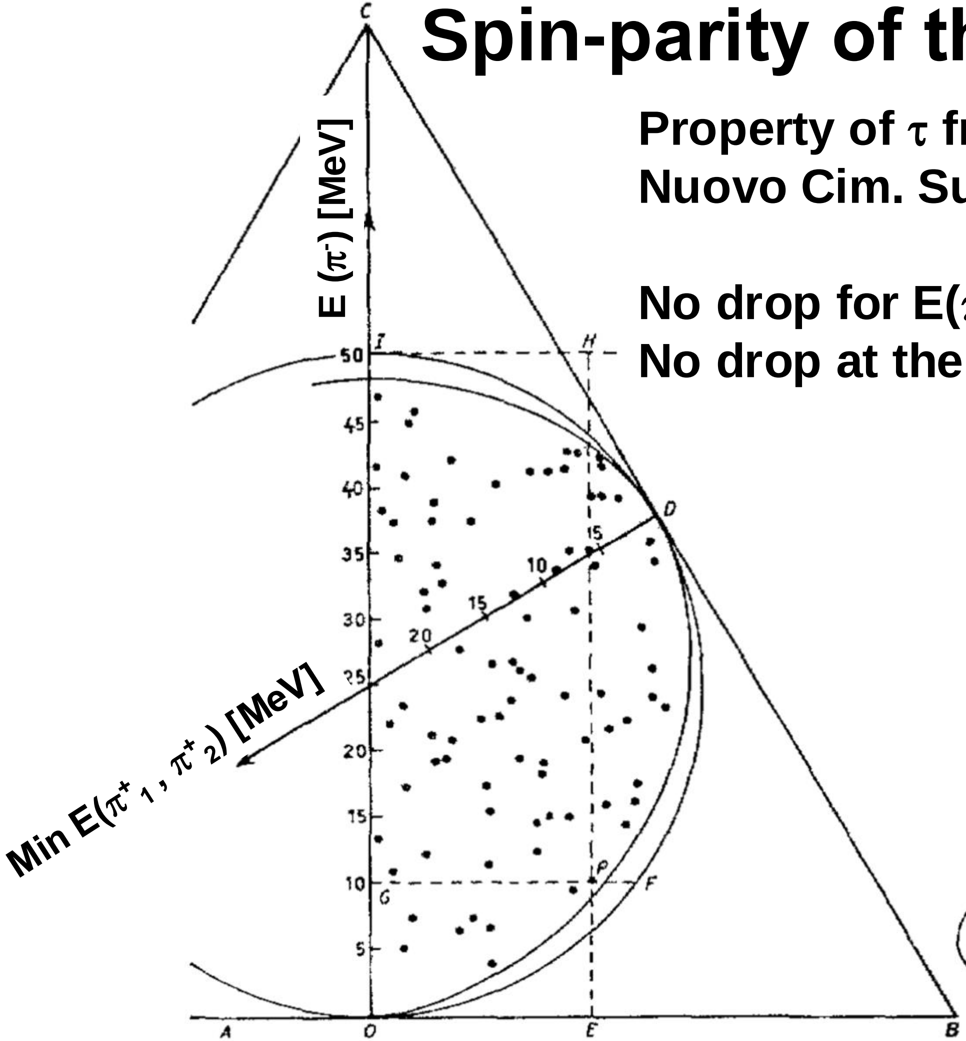
Unexpected behavior: the $\theta^+ - \tau^+$ puzzle

Additional new particles: mass between proton and electron (mesons) or greater than the proton (hyperons)

Original name	Modern name
τ^+	$K^+ \rightarrow \pi^+\pi^+\pi^-$
V^0_1	$\Lambda^0 \rightarrow p\ \pi^-$
V^0_2 (θ^0)	$K_S \rightarrow \pi^+\pi^-$
k	$K^+ \rightarrow \mu^+\nu$
	$K^+ \rightarrow \mu^+\pi^0\nu$
χ (θ^+)	$K^+ \rightarrow \pi^+\pi^0$
V^+, Λ^+	$\Sigma^+ \rightarrow p\ \pi^0$, $n\ \pi^+$

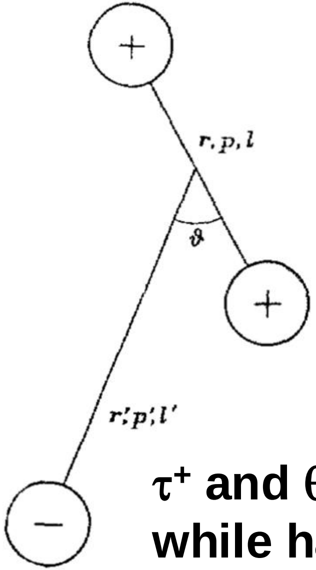
Two particles τ^+, θ^+ very close mass, one decays in 2 pions, one in 3 pions..

Spin-parity of the “τ” meson



Property of τ from π kinematics: Dalitz plot [E. Amaldi, Nuovo Cim. Suppl. IV 206 (1956)]

No drop for E(π^-) ~ 0 → *l'* = 0
No drop at the circle cos(θ)~1 → *l* = 0



$J^P(\tau^+) = (-1)^{J+1}$

But: $\theta^+ \rightarrow \pi^+\pi^0$, $P(\theta^+) = (-1)^J$

So: $J^P(\tau^+) \neq J^P(\theta^+)$

τ^+ and θ^+ are different particles while having compatible masses and lifetimes..?

The solution to the θ-τ puzzle

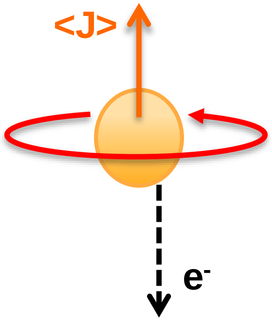
Do weak interactions maintain parity? It had never been tested! [Lee, Yang]

Wu et al.: Asymmetry of ^{60}Co polarized e^- [Phys. Rev. 105 (1957) 1413]

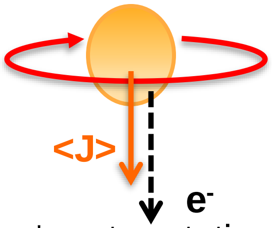
- **Cryogenic apparatus to maintain polarization**
- **The asymmetry vanishes when the temperature increases**

You can distinguish between real space and the mirror

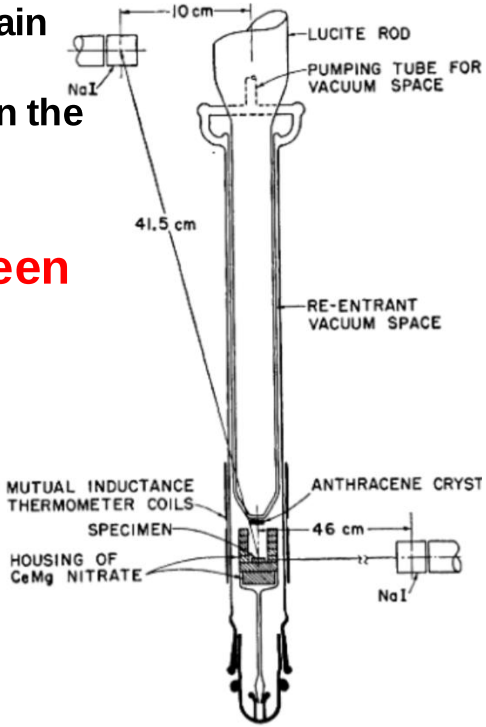
Real space

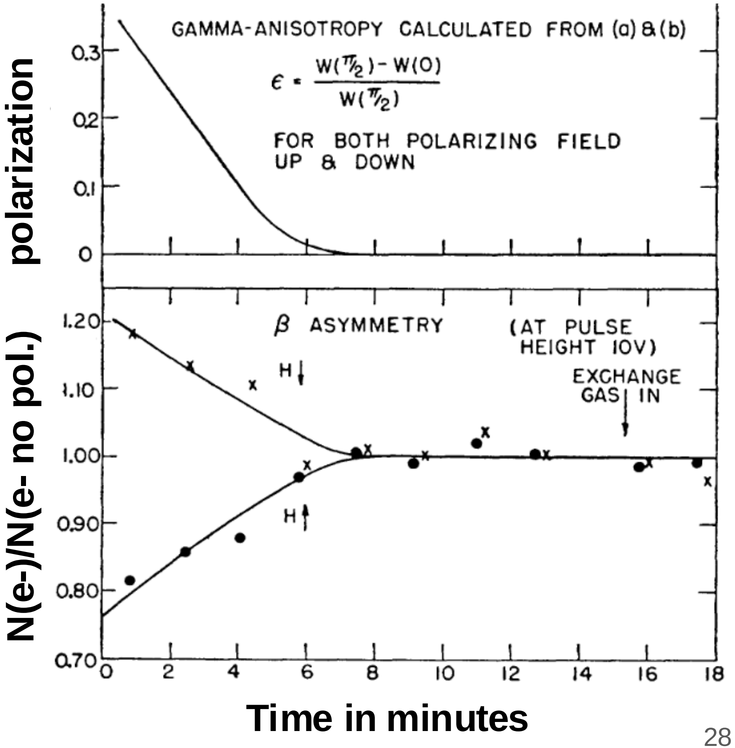


Space in the mirror*



* up to rotations

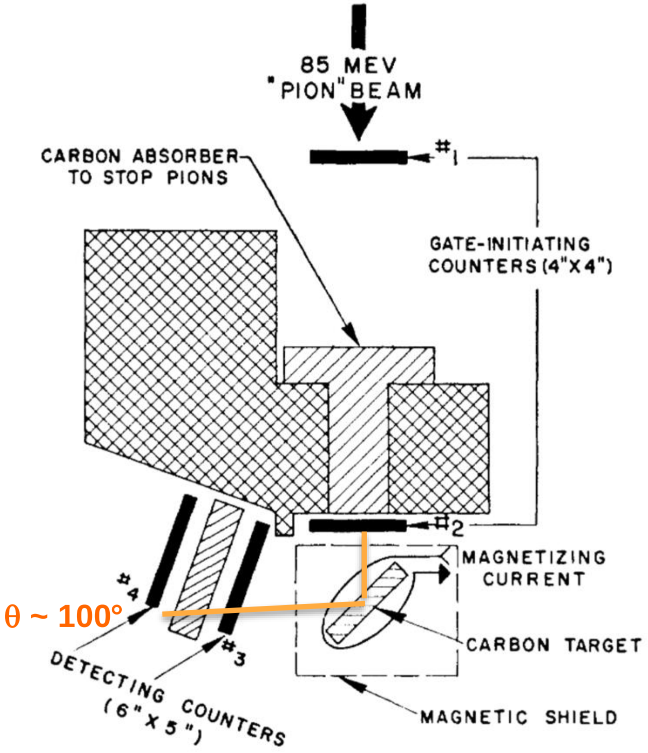


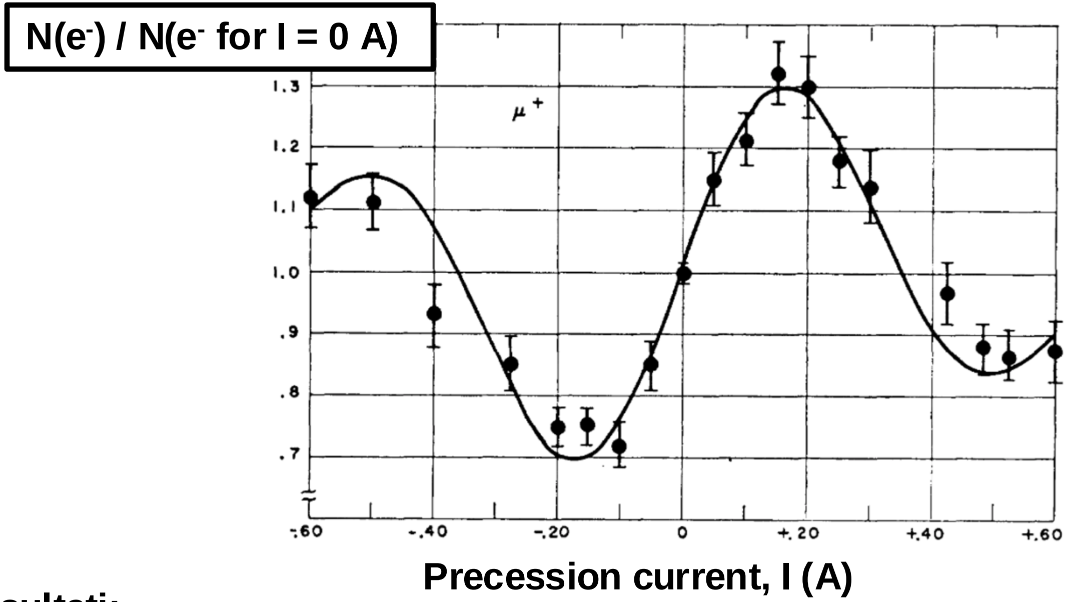


The solution to the θ-τ puzzle

The hypothesis that parity is not preserved in weak interactions is gaining ground

Lederman et al.: asymmetry in $\pi^+ \rightarrow \mu^+\nu$, $\mu^+ \rightarrow e^+ \nu\bar{\nu}$ [Phys. Rev. 105 (1957) 1415]





Risultati:

- μ^+ from $\pi^+ \rightarrow \mu^+\nu$ are polarized, **P violated**
- The distribution of e^+ is sensitive to the direction of the spin of the μ^+, **P violated**
- Gyromagnetic ratio is g ~ 2 (**open problem even today**)

Parity violation

Parity is not conserved in weak interactions


"All the News That's Fit to Print"

The New York Times.

LATE CITY EDITION

FIVE CENTS

PRESIDENT SEEKS 76 MILLION FUND TO FIGHT DROUGHT

Assures Wichita Conference U. S. Will Have Other Plans and Will Solve Problem

Basic Concept in Physics Is Reported Upset in Tests

Conservation of Parity Law in Nuclear Theory Challenged by Scientists at Columbia and Princeton Institute

MACMILLAN GETS EISENHOWER WISH FOR ALL SUCCESS

Briton Responds With Equal Warmth to Greetings on His Appointment

EGYPT TAKES OVER ASSETS OF BANKS OF BRITISH, FRENCH

Insurance Concerns Affected Also by Nasser Regime's 'Egyptianization' Decrees

3.1° Sets 2-Year City Low; Snowfall Imperils Traffic

ELECTRICAL CODE TIGHTENED BY CITY

DULLES SEES PLAN AVERTING A WAR

10 MIG-17 Jet Craft Reported Delivered To Syria by Soviet

ISRAELIS BLOW UP KEY BASE IN SINAI

16 January 1957

Parity violation: a little detour

Parity could be violated even in strong interactions

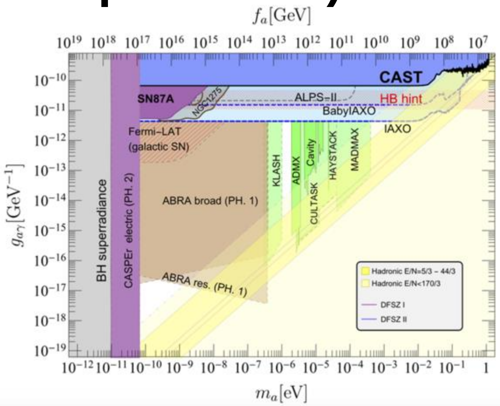
Constructing the theory of strong interactions from symmetry conditions, it is natural to expect components of the dynamics that violate parity

The electromagnetic analogy is having L ~ $|B|^2 - |E|^2 + \theta\,(E \bullet B)$

Some thought they had observed it in the 1960s, but were later disproved

The absence (at the level of sensitivity reached by the experiments) of these components is an open problem

One of the solutions involves adding a new particle, the Axion, even a good dark matter candidate



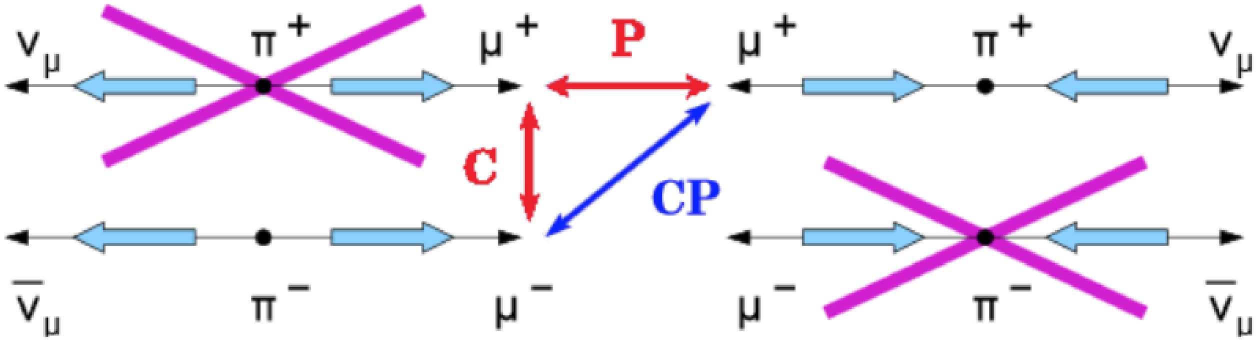
The symmetry of CP

Parity is not conserved in weak interactions

Weak interactions involve:

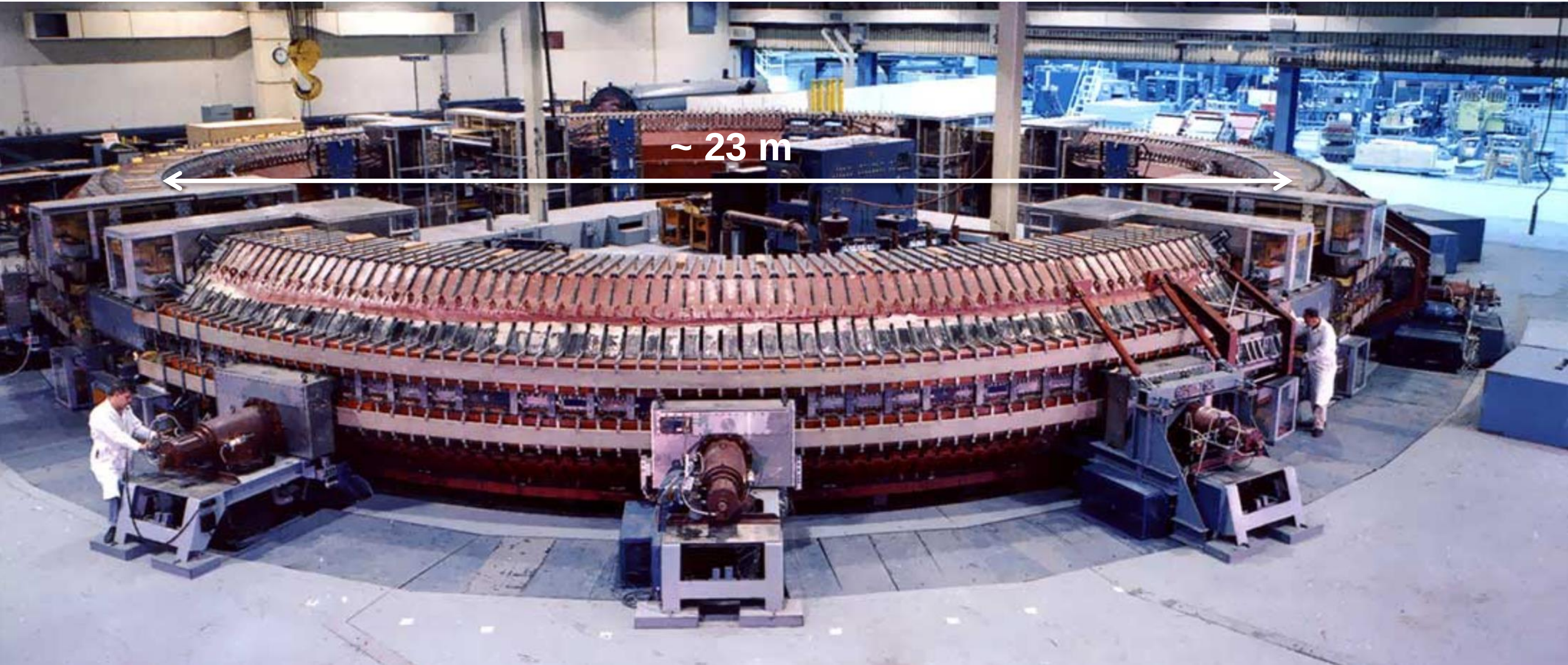
- **semi-integer spin particles with spin antiparallel to momentum (left-handed, L)**
- **semi-integer spin antiparticles w spin parallel to momentum (right-handed, R)**

Apparently, the combined operation of parity (P) e particle-antiparticle swap (C) seemed a symmetry of weak interactions (Landau, 1957)



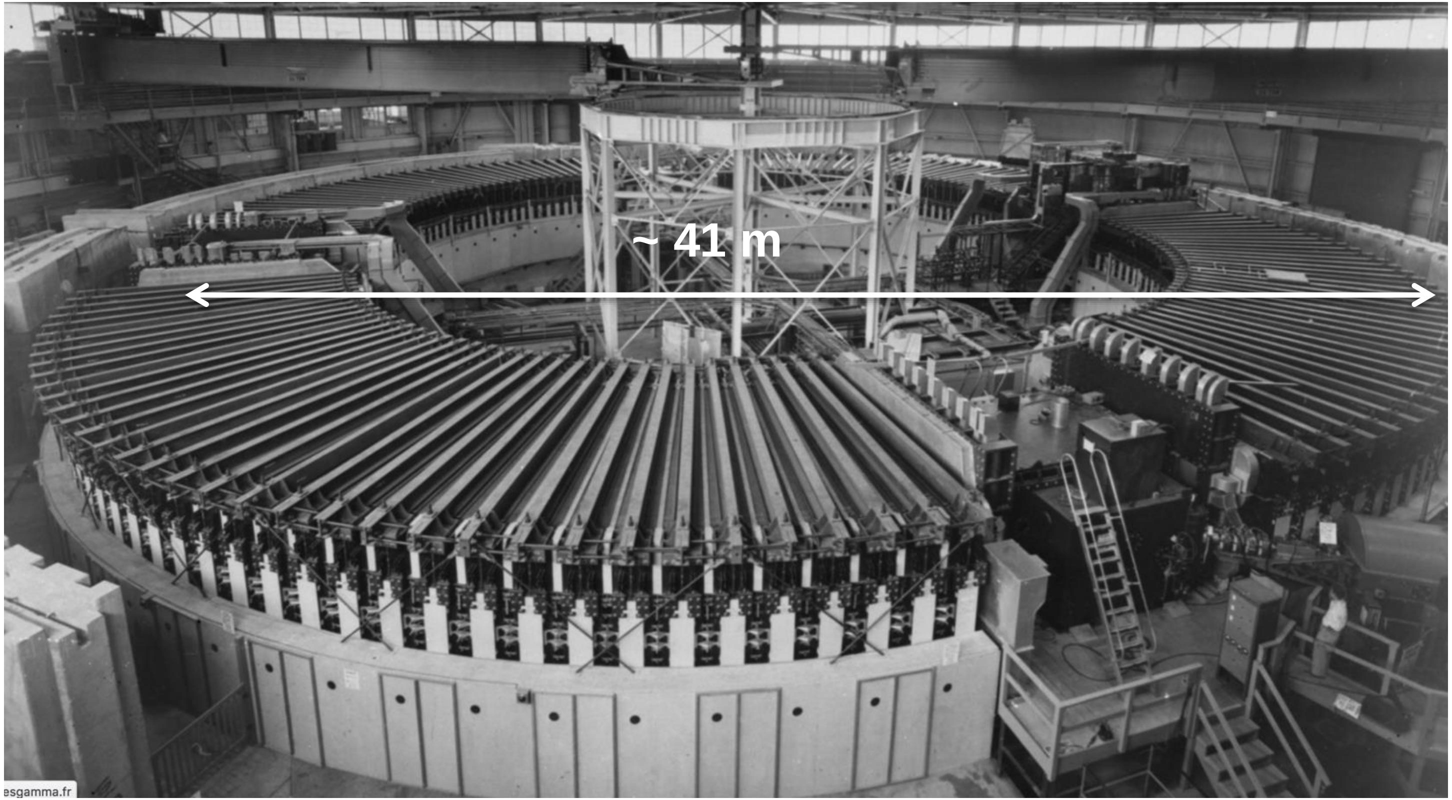
New techniques...

Cosmotron at BNL (NY, USA, 1952-66): protons up to 3.3 GeV, up to 10^{12} / pulse
First extracted beams (p, π^-) and fixed target experiments (nuclear productions)



New techniques...

Bevatron LBNL (CA, USA, 1954-93): synchrotron, p up to 6.5 GeV, 10^{11} / pulse
Fixed target experiments, discovery of anti-proton, anti-neutron, K*(892)



… and further unexpected behaviors

Probability of production (cross section) of "V" particles ~ 1% as for $\pi^{+,-}$

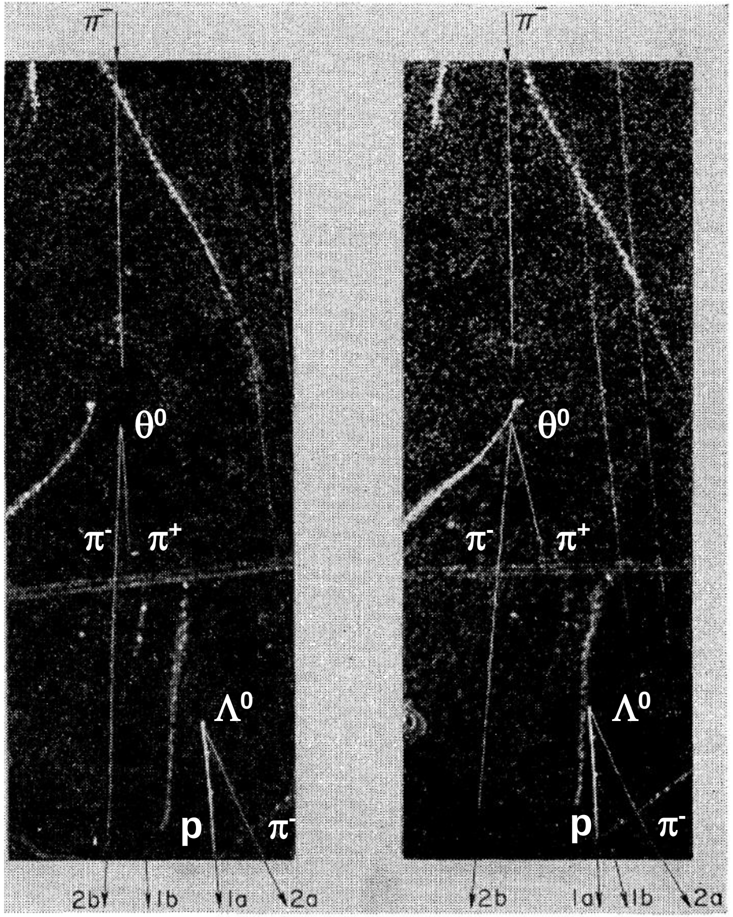
- **"V" decays in π, if accessible p/n + π**
- **Lifetimes of 10^{-9}, 10^{-10} s**

If they would decay with the same interaction producing them → lifetimes of ~ 10^{-21} s

A new quantum number, strangeness S [Pais, Gell-Mann, Nakano e Nijishima]:

- **"V" produced in pairs of opposite strangeness in strong interactions, which conserve S**
- **decay through weak interaction, which violate S**

Associated production observed at Cosmotron



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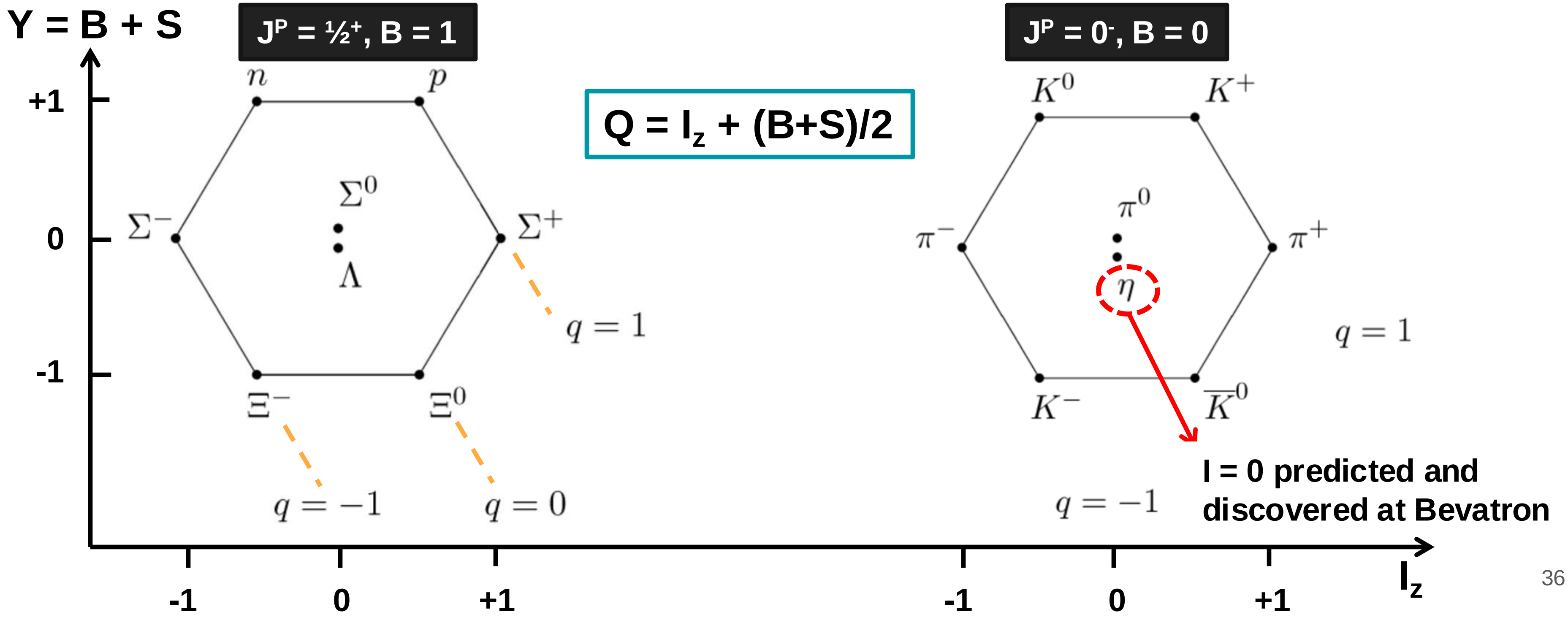
New “periodic tables”

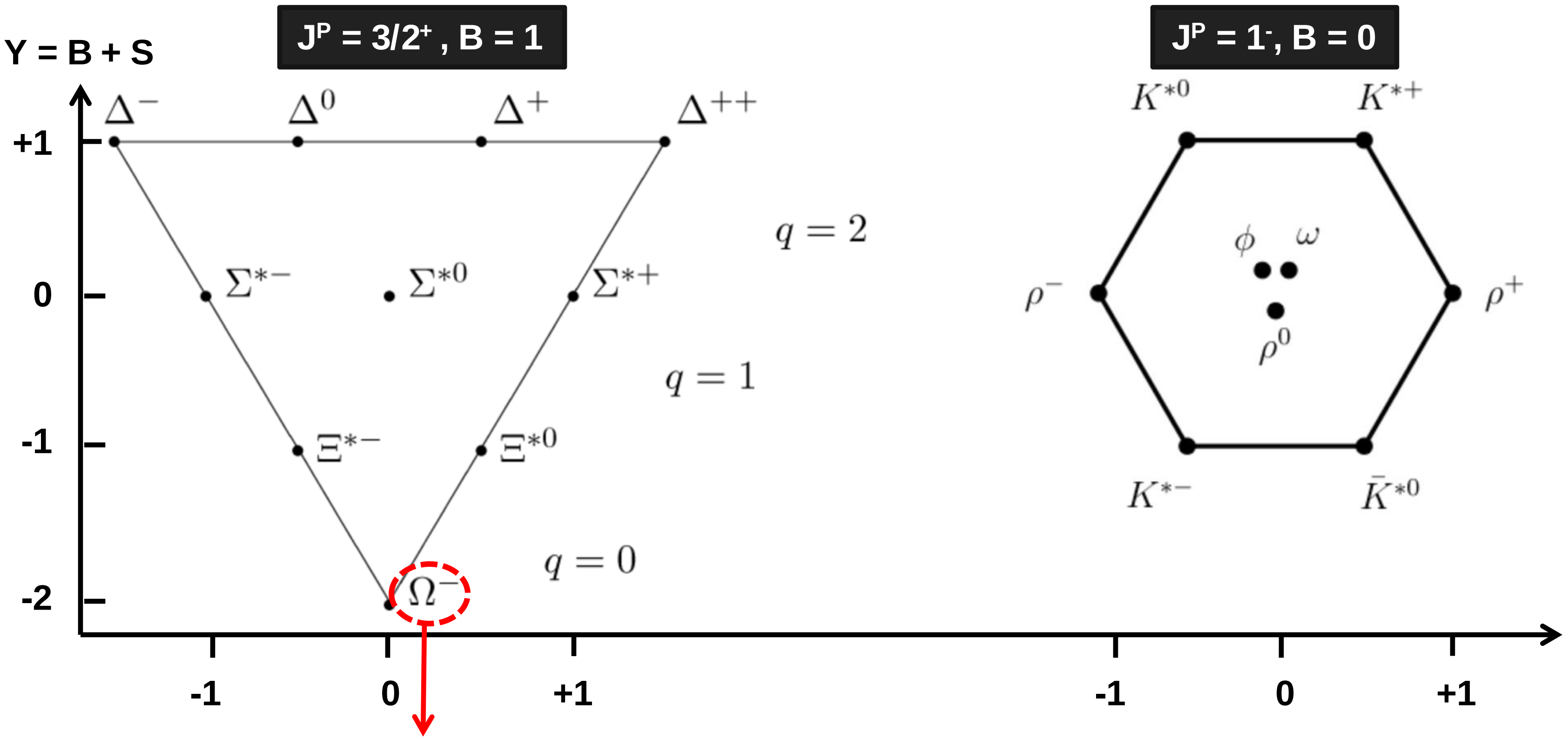
π^{+-} and K^{-} beams (Cosmotron) and photoproduction exp. (Caltech, Cornell): new particles as resonances: maximum in σ and phase shift, lifetimes ~10^{-22} s

New ordering criteria (Gell-Mann, Ne’eman 1962): Isospin, Ipercharge Y



New “periodic tables” for hadrons

Model incorporating particles and resonances



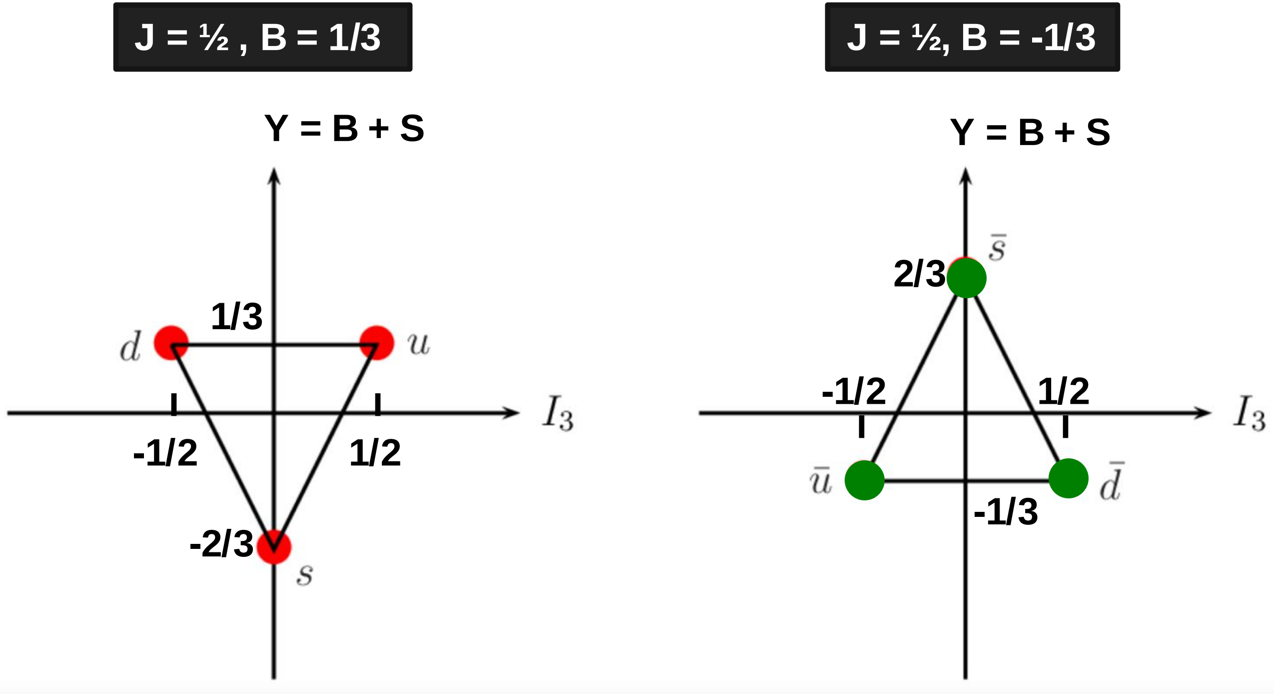
I = 0, S = -3, predicted by the model, found at Cosmotron in 1964

New "periodic tables" and implications

Not a mere classification, but an organization suggesting much more..

Basic building blocks:

- 3 quark (u,d,s)
- 3 anti-quark ($\bar{s}$, $\bar{d}$, $\bar{u}$)

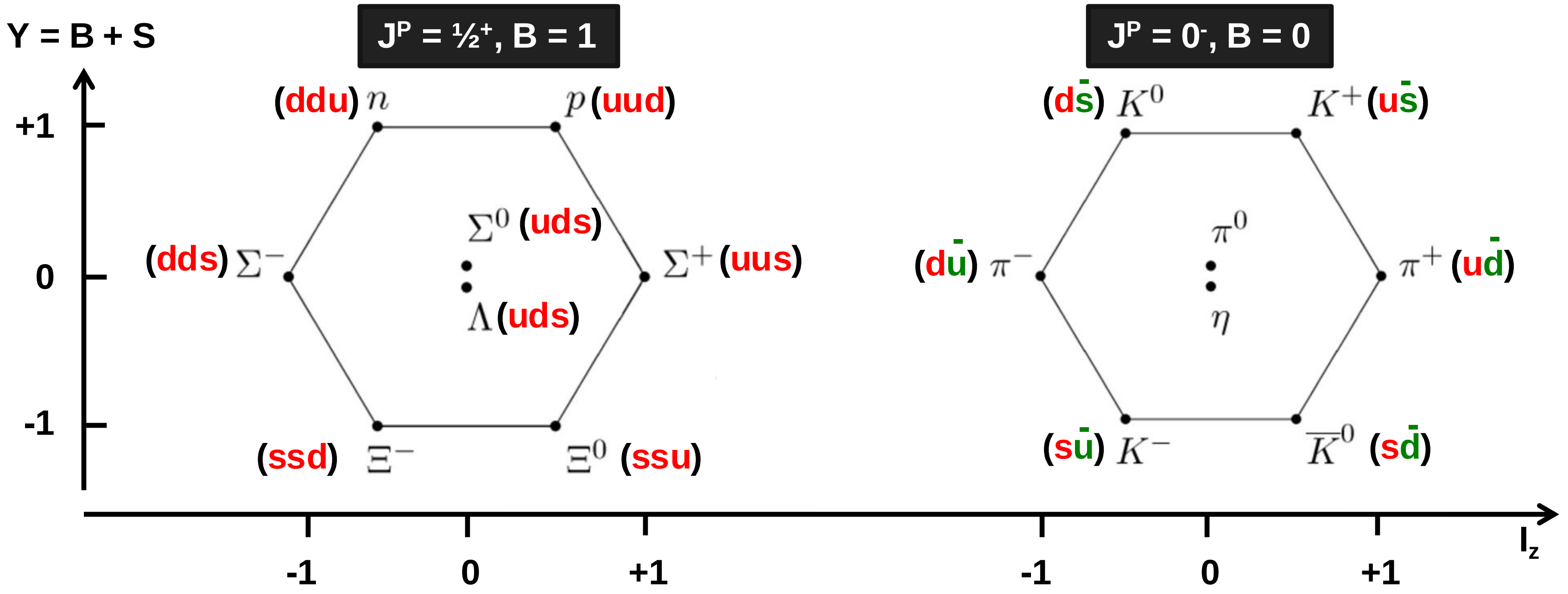


Quarks would have fractional electric charges:

- Up quarks: Q_u = +2/3; down quarks: d, s, …: Q_d = Q_s = -1/3

The quark model (1964)

Baryons: states with 3 quarks; mesons: states of quark anti-quark



Suggestive and very predictive, but quarks had never been seen...
"Discovered" in 1969 at the Stanford linear accelerator (CA, USA): e p → e X

Other oddities…

It was noted that strangeness had an impact on weak interactions:

- **A strangeness variation corresponds to a variation in hadronic charge: $\Delta S = \Delta Q$**

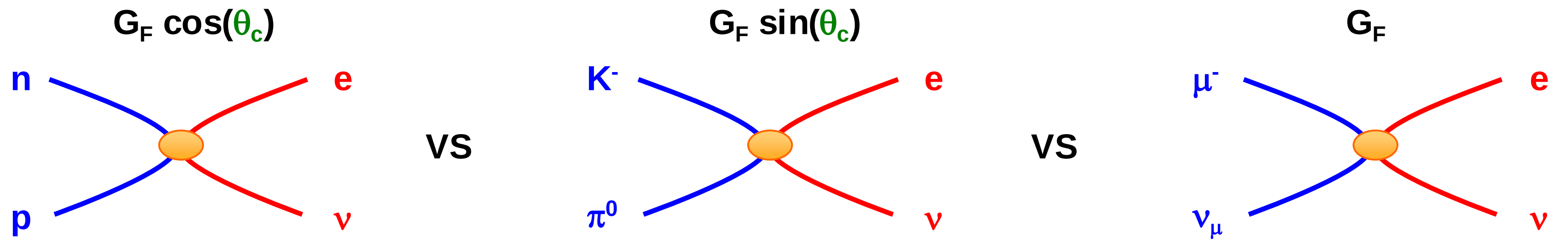
  E.g.: $K^0 \rightarrow \pi^- e^+ \nu$ but NOT $K^0 \rightarrow \pi^+ e^- \nu$

  $\Delta S \neq 0$ e $\Delta Q = 0$ not seen (up to 2024 ☺): ultra-rare $K^+ \rightarrow \pi^+ \nu \nu$, $\pi^+ e^+ e^-$

- **If hadrons are involved, if $\Delta S \neq 0$, the transition is rarer:**

  E.g.: $K^- \rightarrow \pi^0 e^- \nu$ vs $n \rightarrow p\, e^- \nu$

Explained [Cabibbo, PRL 10 (1963) 531] assuming a rotation between interactions with $\Delta S = 1$ (quark s) and $\Delta S = 0$ (quark d), Cabibbo angle $\theta_c \sim 13°$

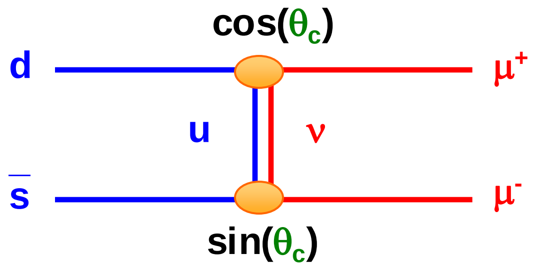


In ⬭ electric charge flows, it's the transition from an up-type to a down-type quark (or lepton)

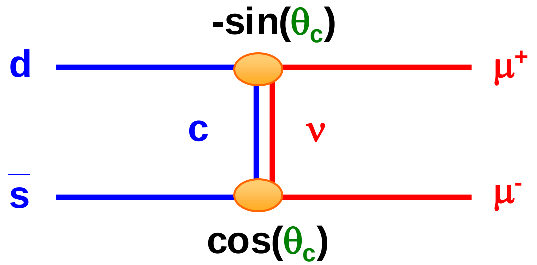
… and intuitions

Transitions $\Delta S \neq 0$ e $\Delta Q = 0$ are possible but inexplicably suppressed, e.g.:

$K \rightarrow \mu^+\mu^-$



Glashow, Iliopoulos e Maiani hypothesized the existence of another up-type quark, the c quark, mass ~ 1.5—2 GeV, partecipating to the rotation as d and s:



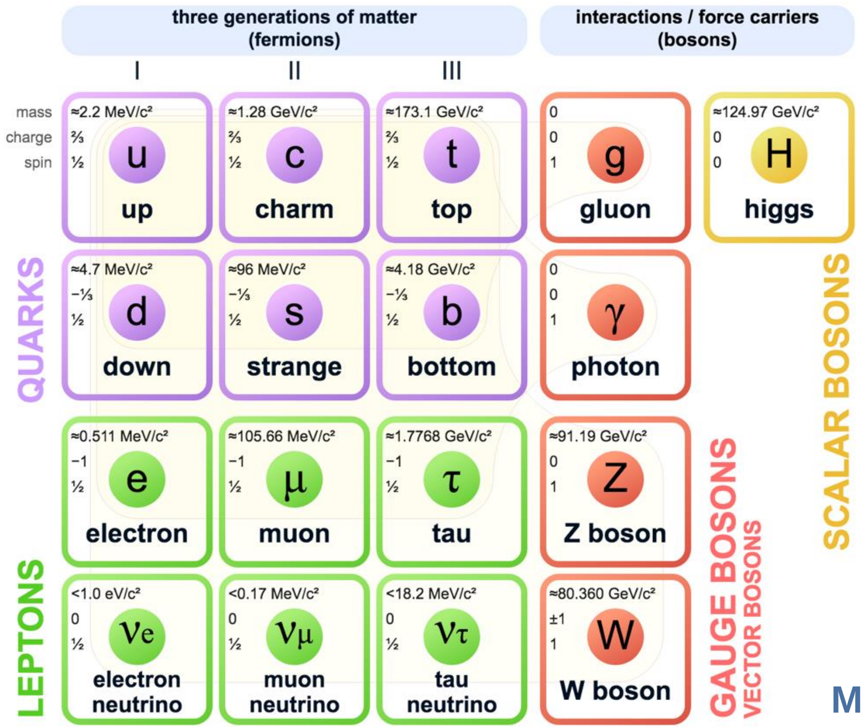
Discovered in the so-called "November revolution" 1974, discovery of J/ψ

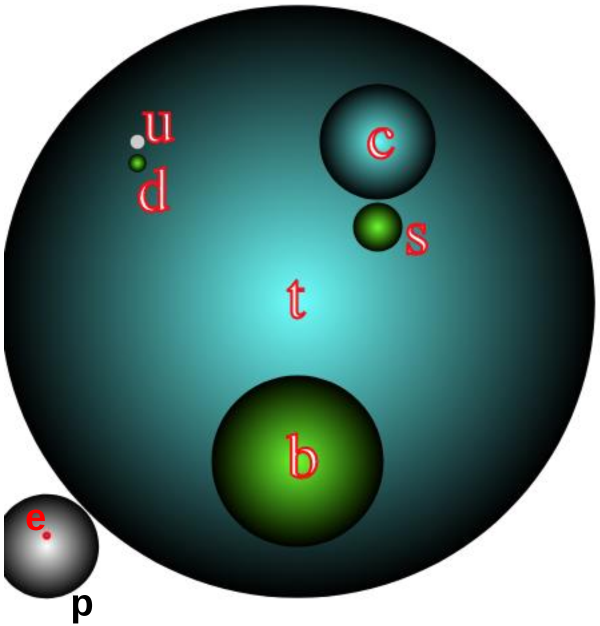
Mass of quark c measured: $m_c \sim 1.28$ GeV

Many questions still open today

3 "generations" of quarks and leptons, the weak interactions mix them up

Masses induced by the Higgs mechanism, but hierarchies are not explained



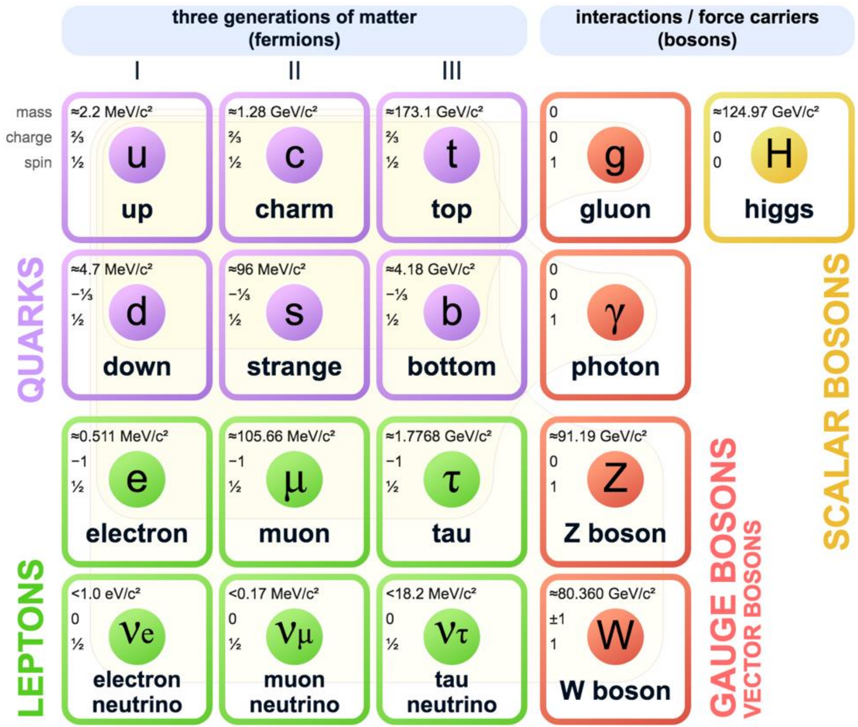


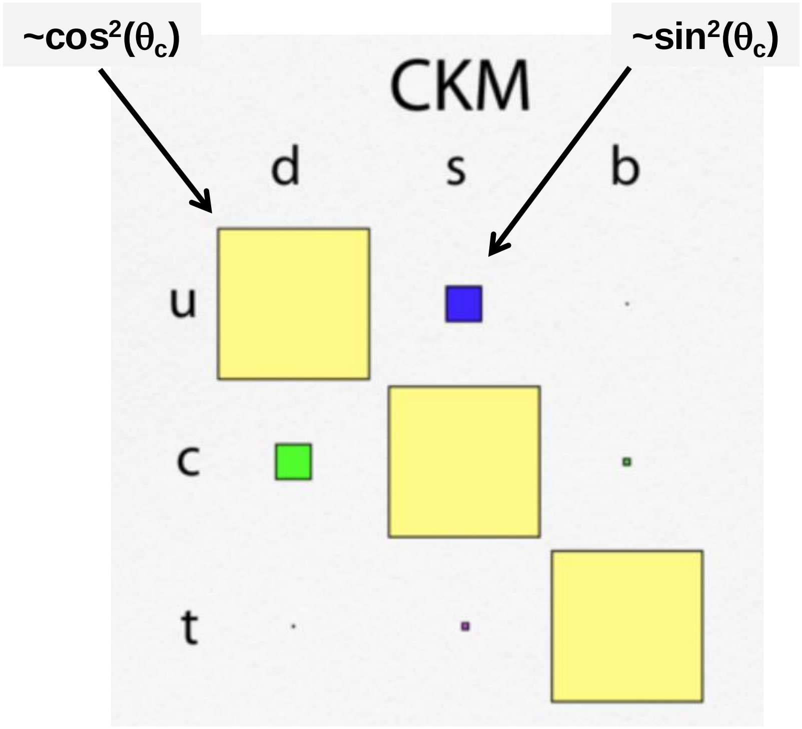
Masses represented as volumes. quarks have no internal structure at the level of 10^{-19} m

Many questions still open today

3 "generations" of quarks and leptons, the weak interactions mix them up

Quark mixing also has a hierarchy, which is also unexplained

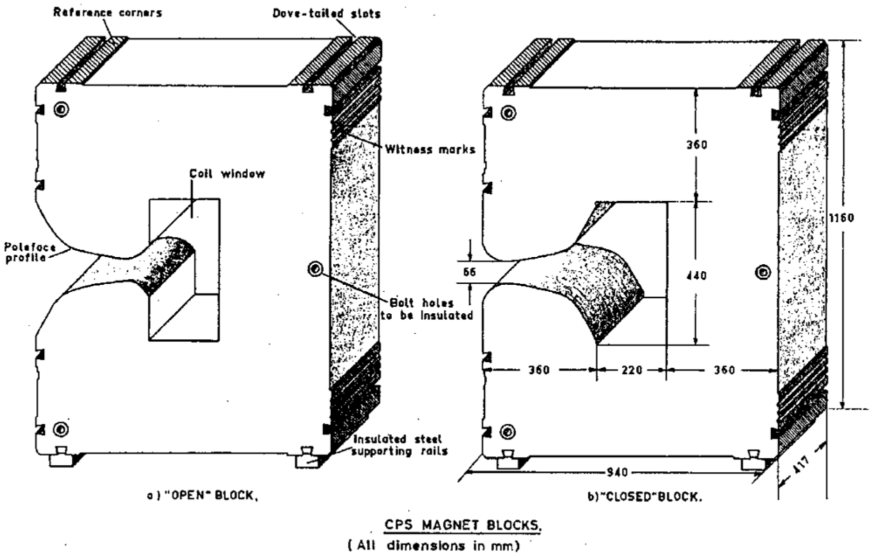


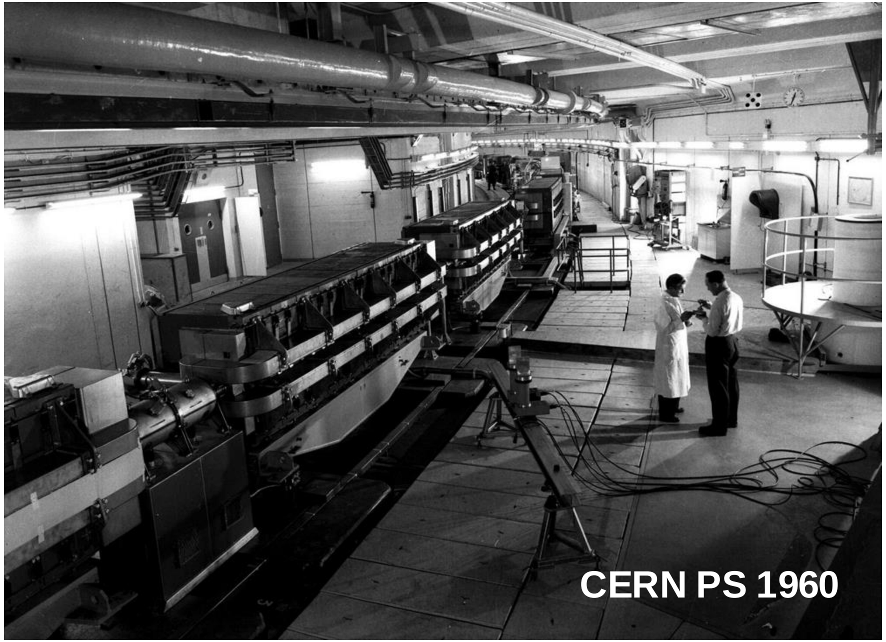


couplings^2 represented as area

New technological developments

Strong focusing with alternate gradients, invented at BNL: a more compact accelerator, higher energies achievable





CERN PS (1959-today) E ~ 28 GeV, 3×10^{11} p / pulse in 1960, up to 4×10^{13} p/pulse

BNL AGS (1960-today) E ~ 33 GeV, 3×10^{13} p / pulse achieved

The peculiar $K^0 - \bar{K}^0$ system: the Gell-Mann Pais prediction

K^0 and $\bar{K}^0$ differ by strangess only, decay in $\pi^+\pi^-/\pi^0\pi^0$ or $\pi^+\pi^-\pi^0/\pi^0\pi^0\pi^0$

Without weak interactions, K^0 and $\bar{K}^0$ degenerate in mass and stable

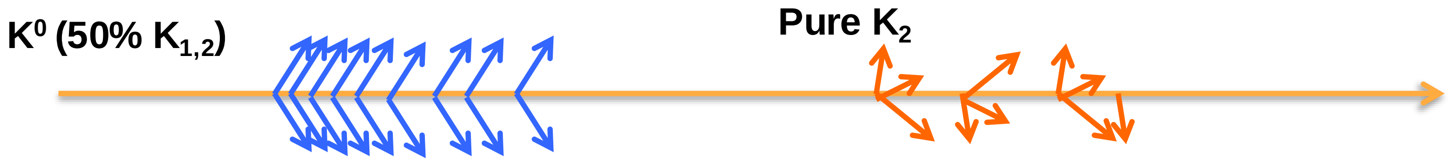
With weak interactions, particles with a given CP are distinct:

CP = +1: $K_1 = K^0 - \bar{K}^0$, CP = -1: $K_2 = K^0 + \bar{K}^0$

K_2 cannot decay in 2π, but only in 3π → longer lifetime

When produced (strong interactions) K^0 o $\bar{K}^0$ are created

In evolution, the K_1 component vanishes and the K_2 remains (τ_{K2}/τ_{K1} ~ 500!)

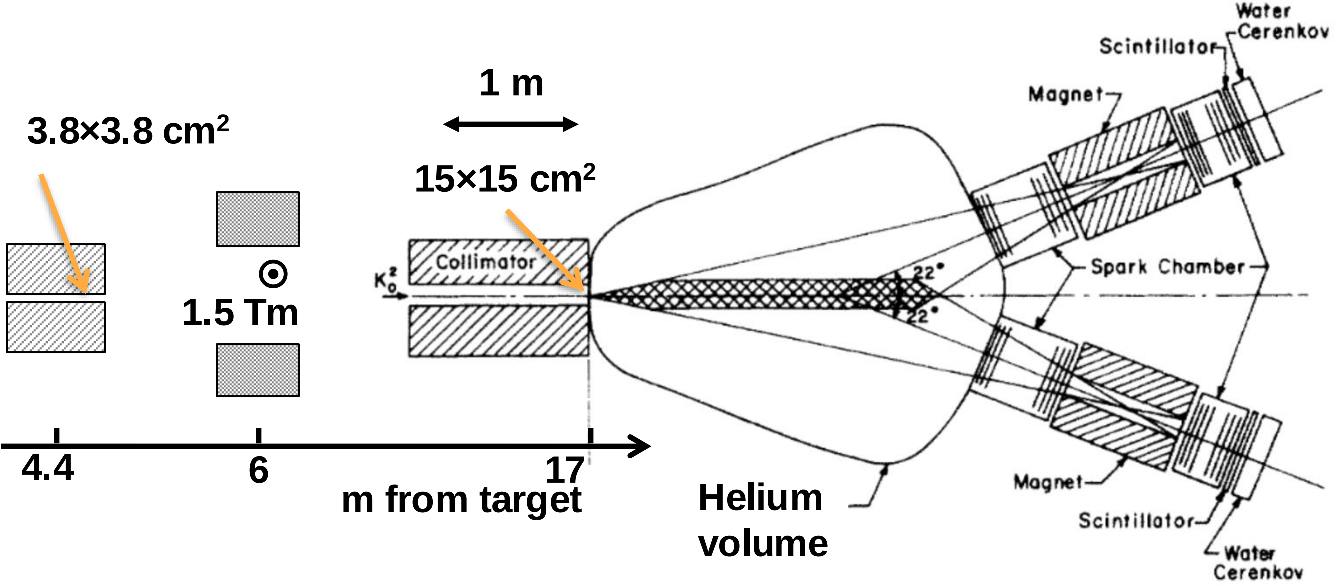


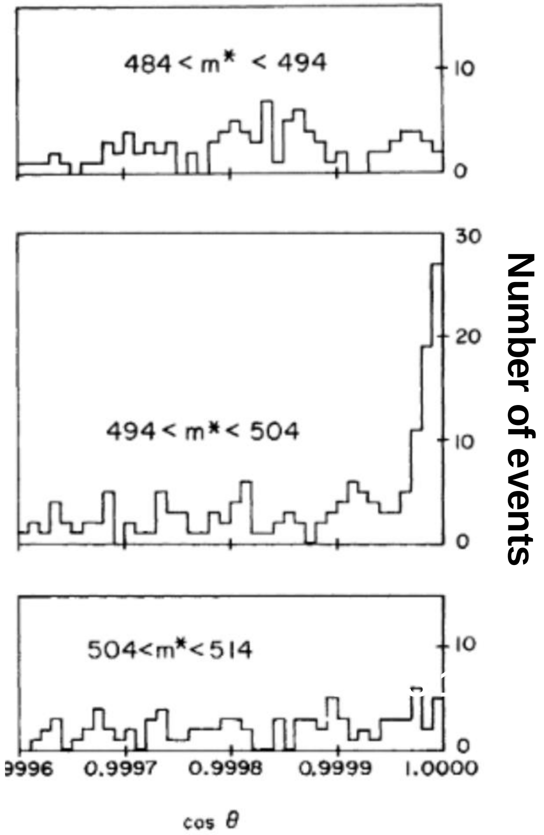
Experimentally confirmed by discovery of K_2 (Lande, 1956)…

… until it is disproved (Fitch, Cronin 1964)

30 GeV Protons from AGS onto Be produce K_2 at 30°

0.2% of the times, K_2 decay in $\pi^+\pi^-$





Great care in removing background of "regenerated" K_1

PRL 13, 4 (1964) 138

Why we care about CP violation

There is more matter than antimatter in the universe, but we think that at the big bang there was balance

Ratio between baryonic and photonic density in the cosmic radiation background:

$$(n_b - n_{\bar{b}})/n_\gamma \sim n_b/n_\gamma \sim 6\times10^{-10}$$

The conditions for generating this asymmetry (Sakharov, 1967)

Baryon number violation: Not observed

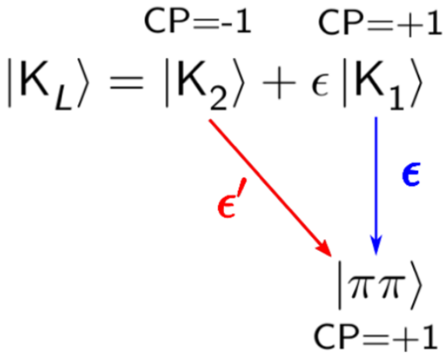
violation of C and CP: observed, CP violation seems insufficient

Non-equilibrium: various scenarios discussed, no consensus

It is still one of the most relevant open problems

How CP violation is realized

Different possibilities: mass mixing and/or "direct" violation



The issue required an experimental effort from the 1980s until the 2000s:

- **CPLEAR at CERN**
- **E731, KTeV a FermiLab (IL, USA)**
- **NA31, NA48 al CERN**

Re(ε'/ε) = (1.66 ± 0.23) × 10^{-3}

A tiny "direct" CPV: need theoretical improvements to make it a new-physics test

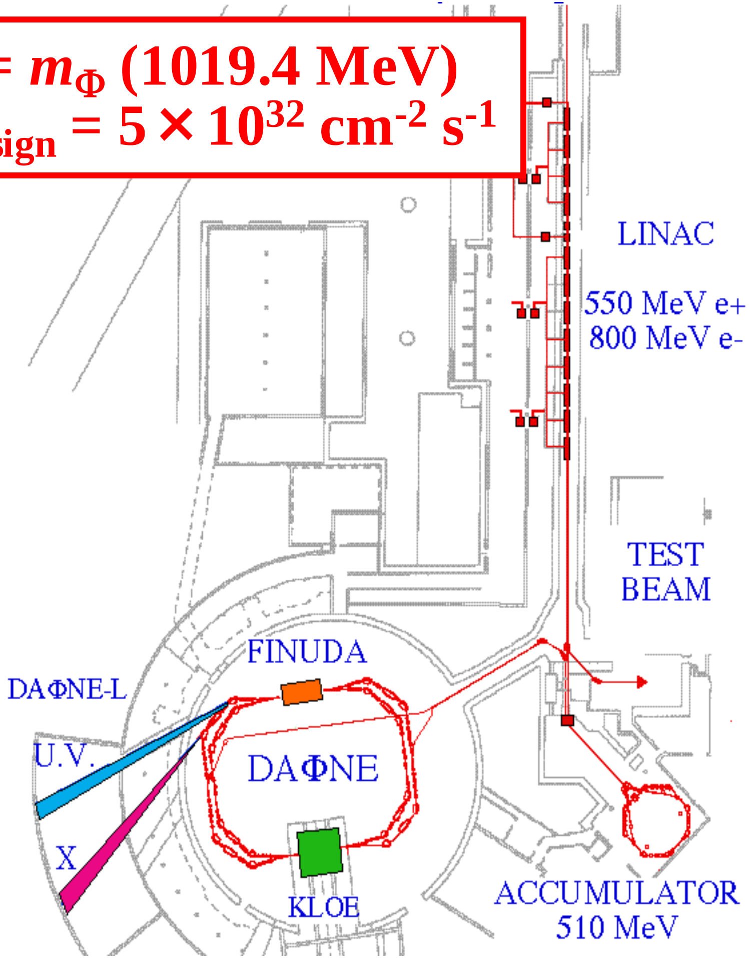
Without (at least) 3 quark families, we could not understand the violation

Experiments to explore CPV: KLOE at Frascati

Produzione in $e^+e^- \rightarrow \Phi \rightarrow K_S K_L$

$W = m_\Phi$ (1019.4 MeV)

$\mathcal{L}_{design} = 5 \times 10^{32}\ cm^{-2}\ s^{-1}$



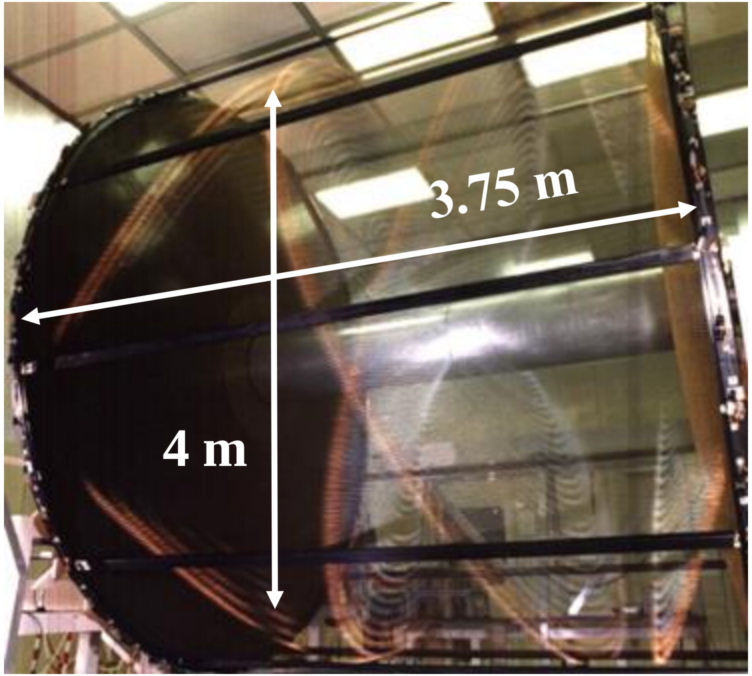
IP crossing angle: ~12.5 mrad

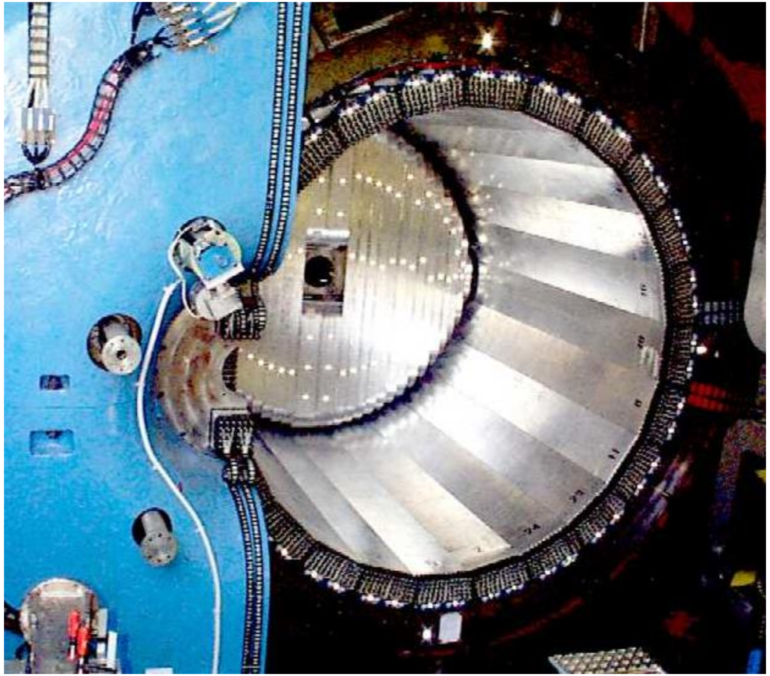
Φ meson momentum ~ 13 MeV

Peak production cross section 3.1 μb

New Rounds of Experiments to Explore CPV: KLOE

Helium drift chamber, Pb/fiber sampling calorimeter, magnet with superconducting coils with field 0.52 T

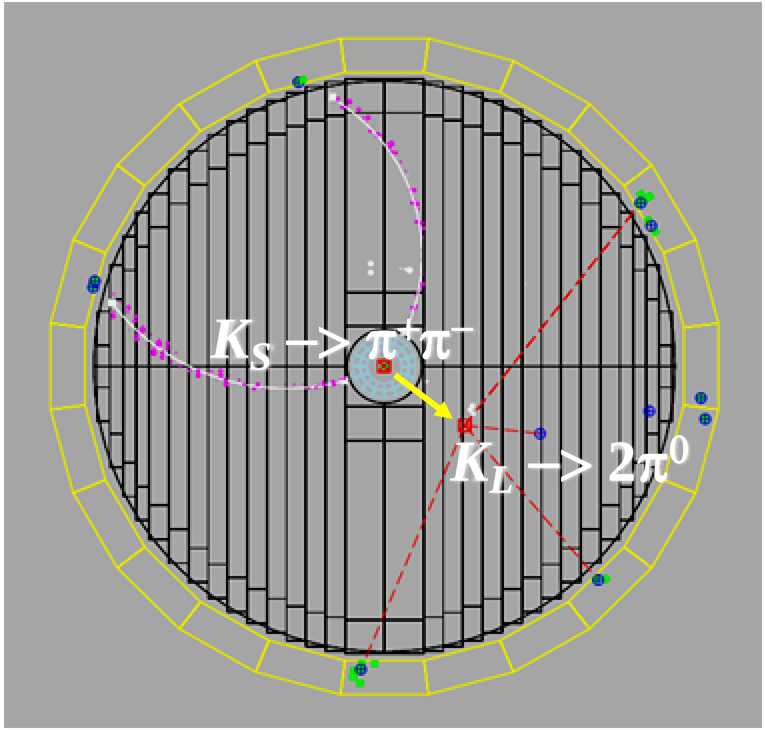




New Rounds of Experiments to Explore CPV: KLOE

KK pairs emitted in almost opposite directions, p ~ 110 MeV

Identification of a $K_{S,L}(K^{+,-})$ tags the presence of a $K_{L,S}(K^{-,+})$



Ability to exploit quantum coherence for symmetry testing, CPT violation search (Lorenz symmetry), quantum-mechanical coherence

Similar approach used at the B-factories (BaBar experiment at SLAC USA, Belle experiment at KEK-B Japan)

New Rounds of Experiments to Explore CPV: KLOE

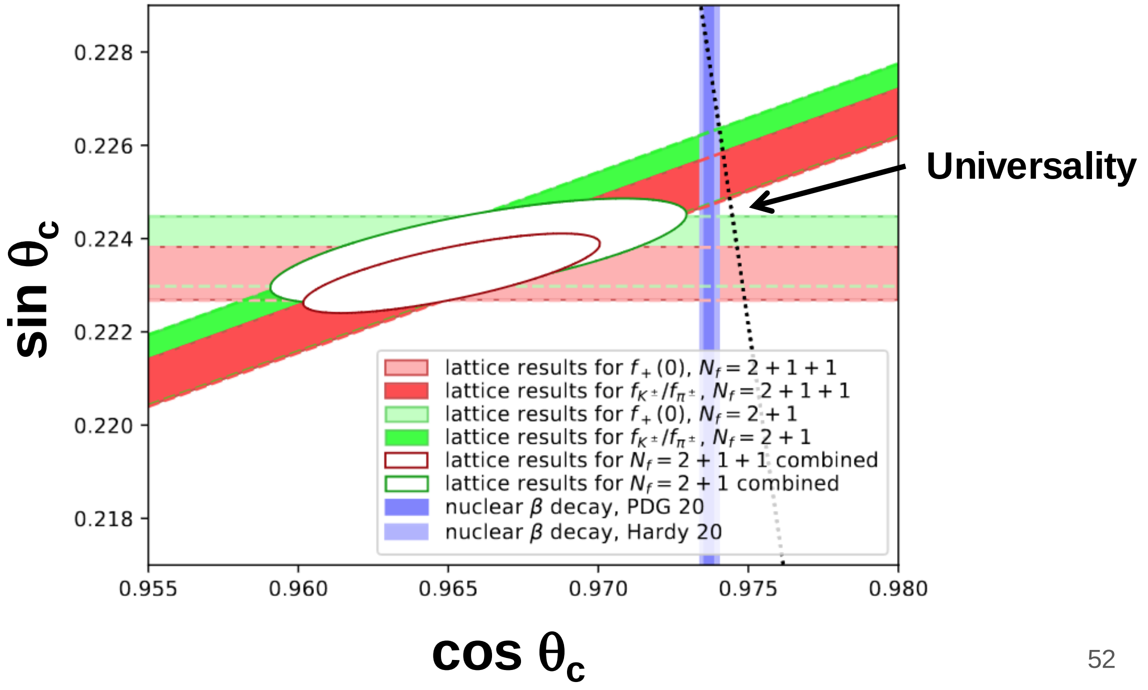
A wide range of interesting results (e.g., lepton flavor violation test, hadronic cross section, lepton universality test, and many others)

KLOE measurements are essential for precise sin θ_c determination

Precision is equivalent to probing scales of 1—10 TeV!

The agreement with theory (standard model) is an open question

Testing universality of weak interactions



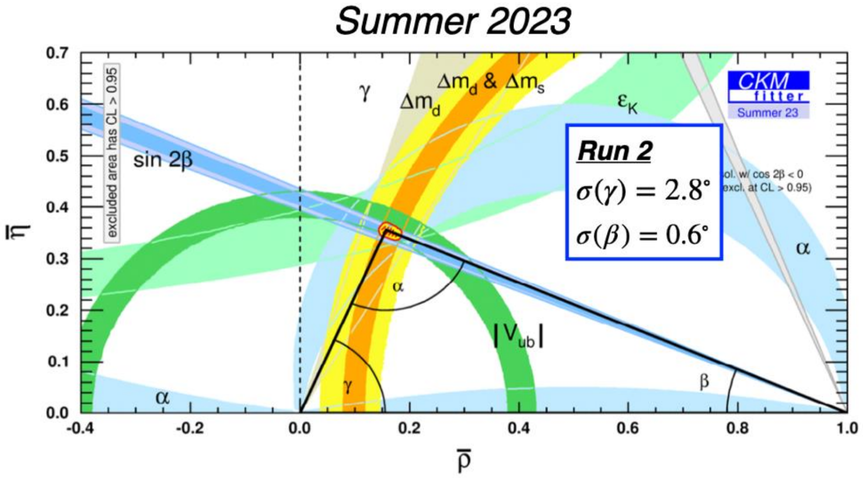
New Rounds of Experiments to Explore CPV: LHCb et al.

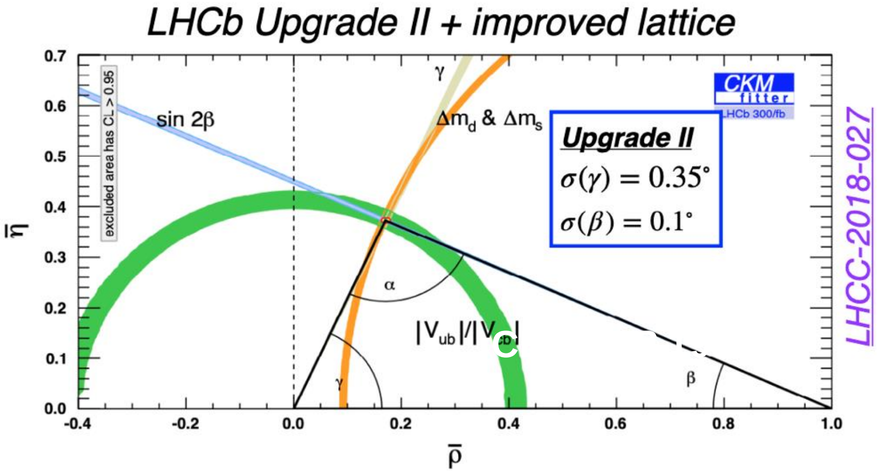
Quark mixing is graphically represented by a triangular relation

$$\begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

Testing the universality of weak interactions means including all flavour transition observables to verify the underlying mechanism

Main actors in the field: LHCb (CERN), Belle-II (SuperKEKB), BES-III (BEPC-II)





ρ and η non zero due to CP violation

KLOE and CPT tests

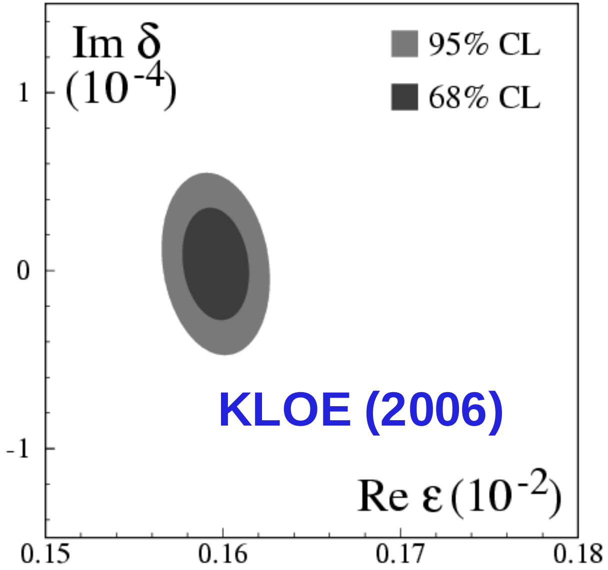
T is called "time inversion": symmetry between a process and the same with inverted motion

A (local) quantum theory respects Lorenz invariance → no CPT violation [Lüders 1954, Pauli 1955]

A CPT violation can generate mass (or half-life) differences between the particle and the antiparticle:

$$\delta = \frac{1}{2}\frac{\left(m_{\overline{K}^0} - m_{K^0}\right) - (i/2)\left(\Gamma_{\overline{K}^0} - \Gamma_{K^0}\right)}{\Delta m + i\Delta\Gamma/2}$$

$\mathrm{Im}(\delta) = (\ 0.4 \pm 2.1) \times 10^{-5}$



CPTV can be achieved with non-commutative geometries, theories integrating gravity (Kaluza-Klein), extra-dimensions etc.

The most stringent limits come from the study of K, possible at D and B as well

$$2\frac{|m_{K^0} - m_{\overline{K}^0}|}{(m_{K^0} + m_{\overline{K}^0})} < 6 \times 10^{-19}$$

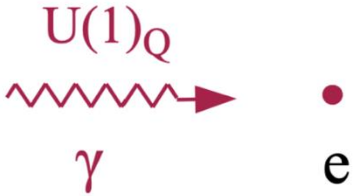
$$2\frac{|\Gamma_{K^0} - \Gamma_{\overline{K}^0}|}{(\Gamma_{K^0} + \Gamma_{\overline{K}^0})} = (8 \pm 8) \times 10^{-18}$$

A historical parallel

In 1861, physics seemed "understood"

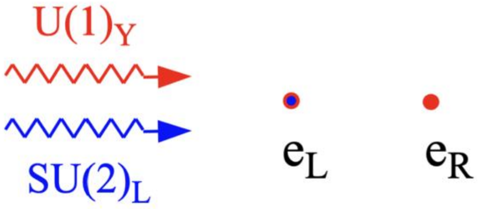
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

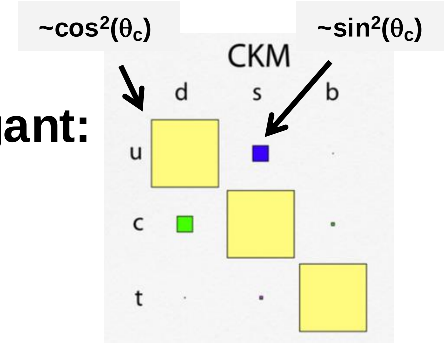
in terms of fields and symmetries:



Probing higher energies, ew unification is seen to be less elegant:

- **Photon is not the fundamental field at high energies**
- **In terms of fields and symmetries:**





couplings^2 represented as area

What if at further higher energies, the flavour scheme is seen to be even different?

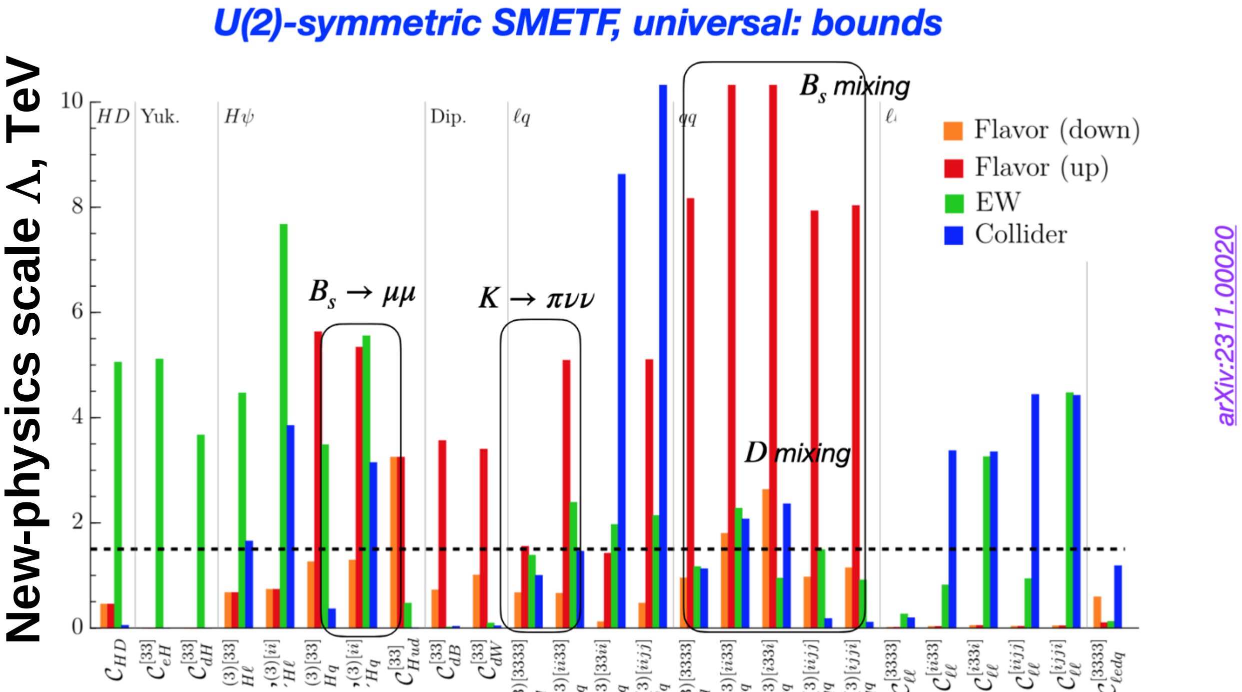
Future of the flavor physics

What if at further higher energies, this is seen to be even different?

NP @ UV scale of SM suggested by cosmology, Higgs mass instability

At lower energies we might observe indirect effects of this

NP parameterized as SMEFT dimension-6 Wilson coefficients [WC]:



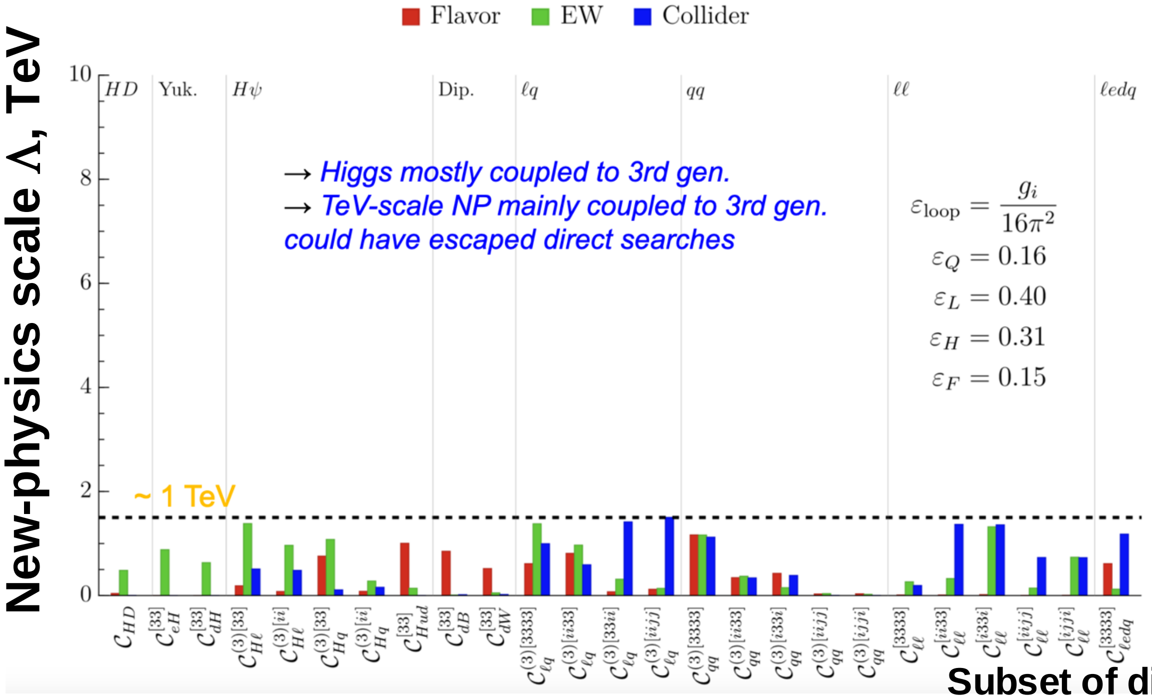
Subset of dim. 6 operator WC

Future of the flavor physics: a possibility

Huge value of m_{top} + tiny mixing within family 1-2 → special role of third family?

New flavor violation can be induced: presently escaped all SM tests but might be behind the corner: new physics scale of 1.5 TeV possible!

$$U(2)^5 \equiv U(2)_q \times U(2)_u \times U(2)_d \times U(2)_\ell \times U(2)_e$$



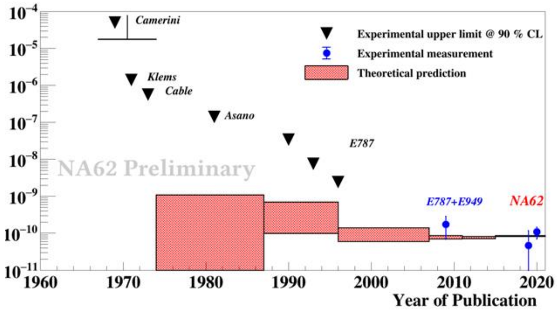
Scale aligns between high-energy collider searches and high-intensity frontier

Subset of dim. 6 operator WC

Further present and future developments

The search for $\Delta S = 1$, $\Delta Q = 0$ decays continues since 50 years, e.g.: $K \rightarrow \pi\nu\bar{\nu}$

Branching ratio
$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$



Highly suppressed in SM, theoretically clean $BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$

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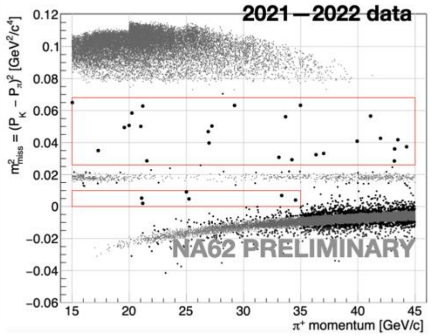


Expected SM signal: $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

Expected background: $N_{bg} = 11.0^{+2.1}_{-1.9}$

Observed: $N_{obs} = 31$

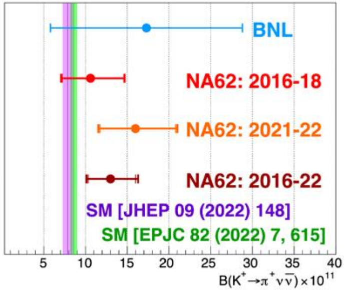
All data so far (2016—22):

$N_{bg} = 18^{+3}_{-2}$, $N_{obs} = 51$

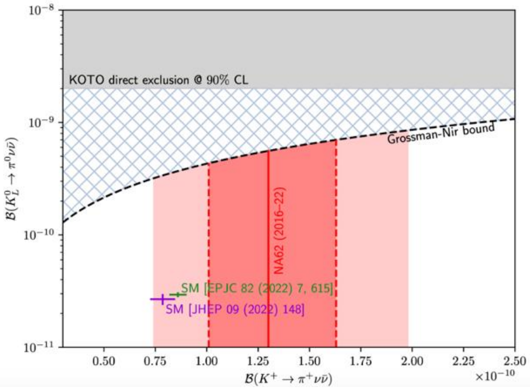
First observation of with significance $> 5\sigma$

$\mathscr{B}^{16-22}_{\pi\nu\bar{\nu}} = (13.0^{+3.3}_{-2.9}) \times 10^{-11}$

25% BR precision

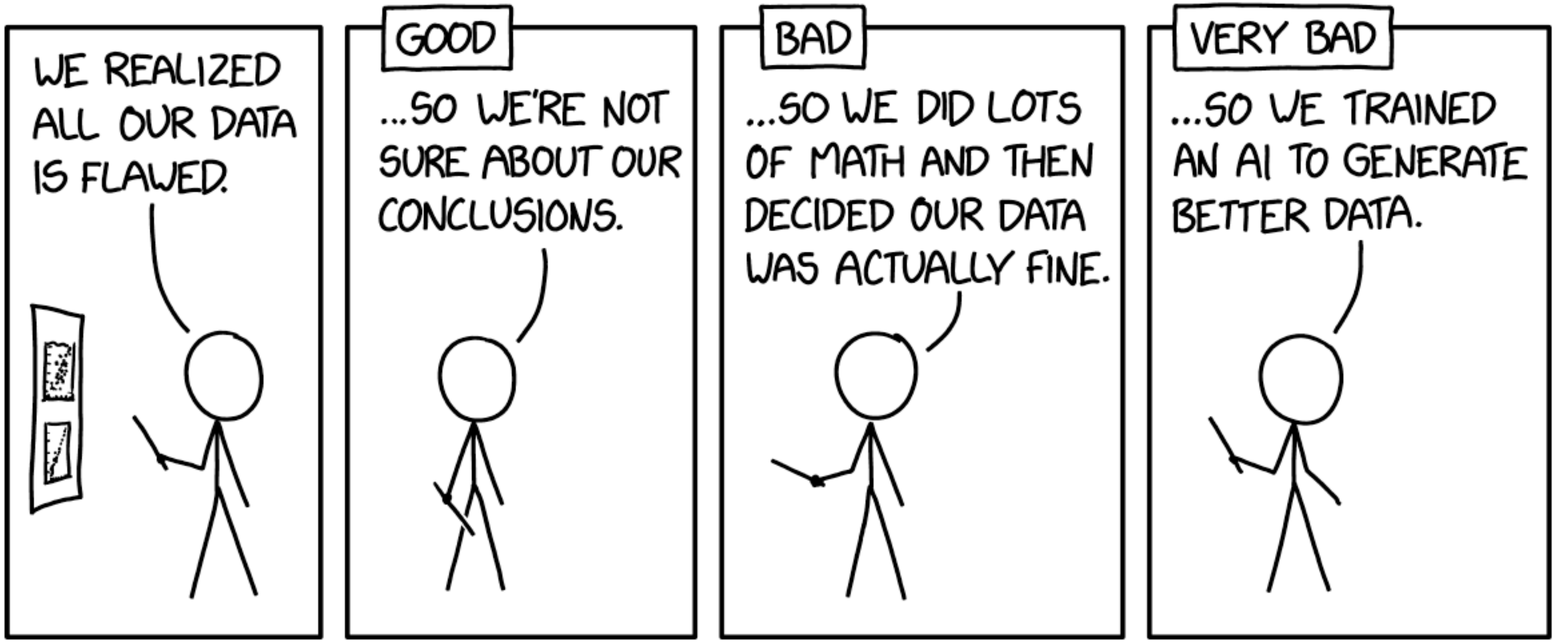


Compatible with SM within 2σ **but need full NA62 sample to clarify level of agreement!**



Present result (Oct. 2024) equivalent to probe scales of ~5 TeV in universal NP

Conclusions



https://xkcd.com/2494/

Conclusions

The peculiar behavior of "strange" particles has generated a good part of the progress made in particle physics since their discovery:

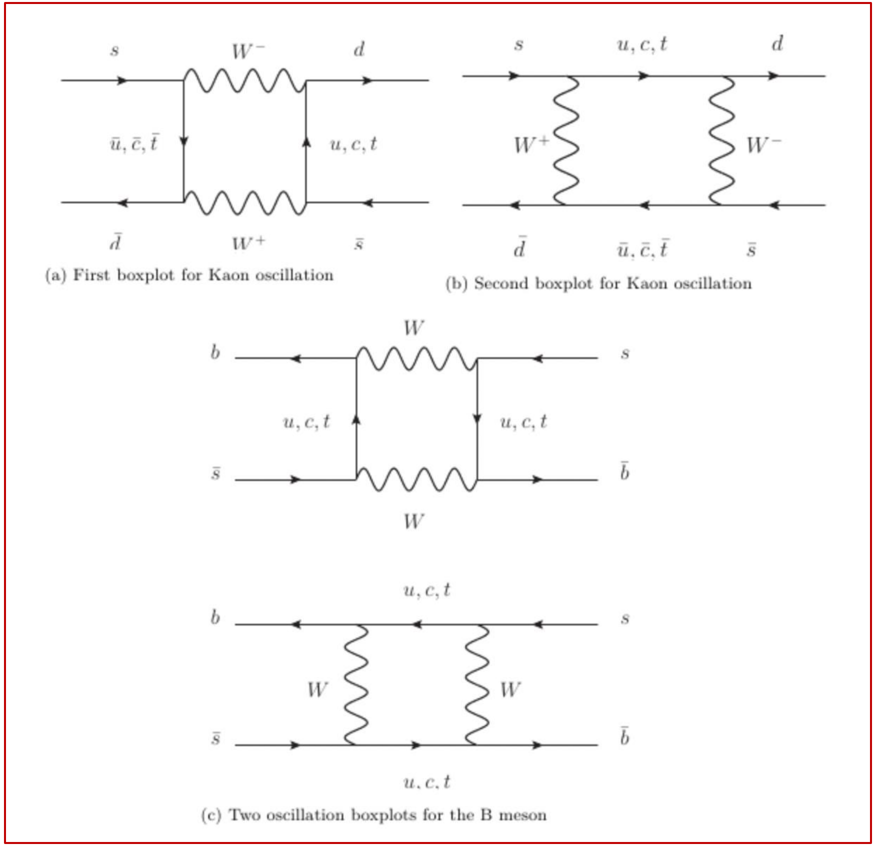
- **Strangeness → Quark model**
- **The θ^{+}--τ^{+} puzzle → Parity violation**
- **Strangeness-changing currents → The c quark**
- **Strangeness oscillation → CP violation, CPT tests**
- **The suppression of flavor-changing neutral currents → The Higgs mechanism**

Flavour physics is still a "laboratory" potentially able to dramatically change our interpretation of nature and provide answers to open questions:

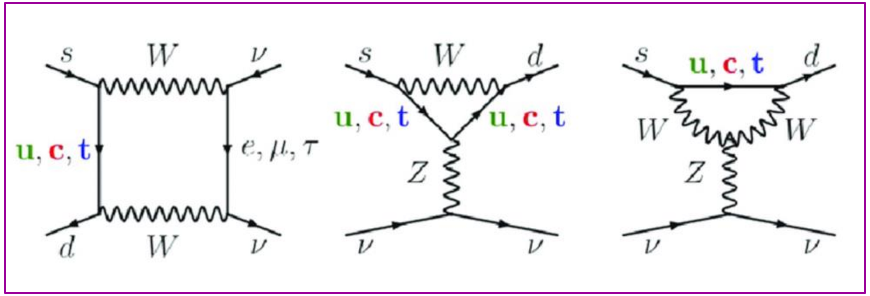
- **Asymmetry between matter and anti-matter in the universe**
- **Hierarchy between matter generations**
- **The role of gravity in quantum theory and dark matter**

Sample two-loop diagrams from flavour physics

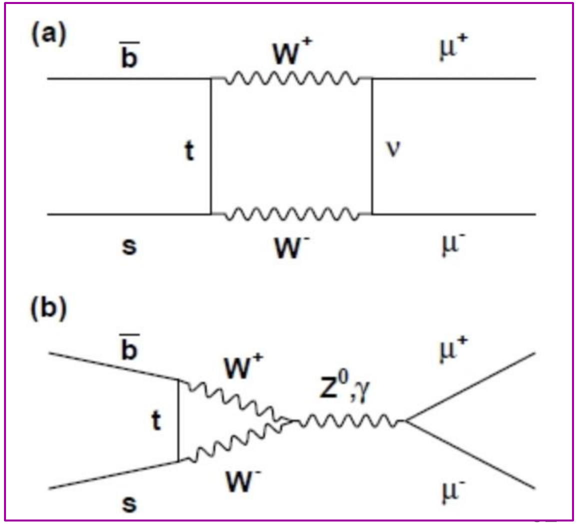
ΔS = 2 and ΔB = 2: K and B oscillations



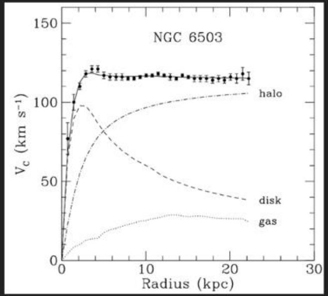
FCNC: K → πνν

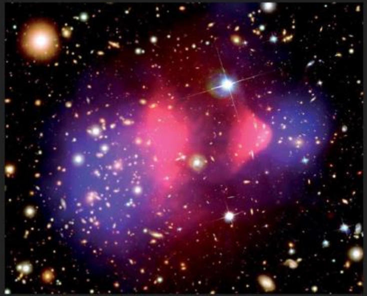


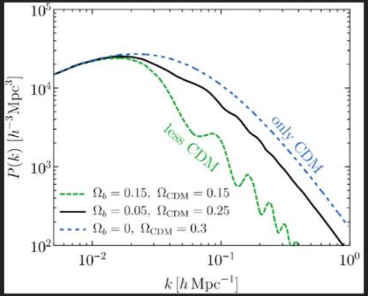
FCNC: Bs → μμ



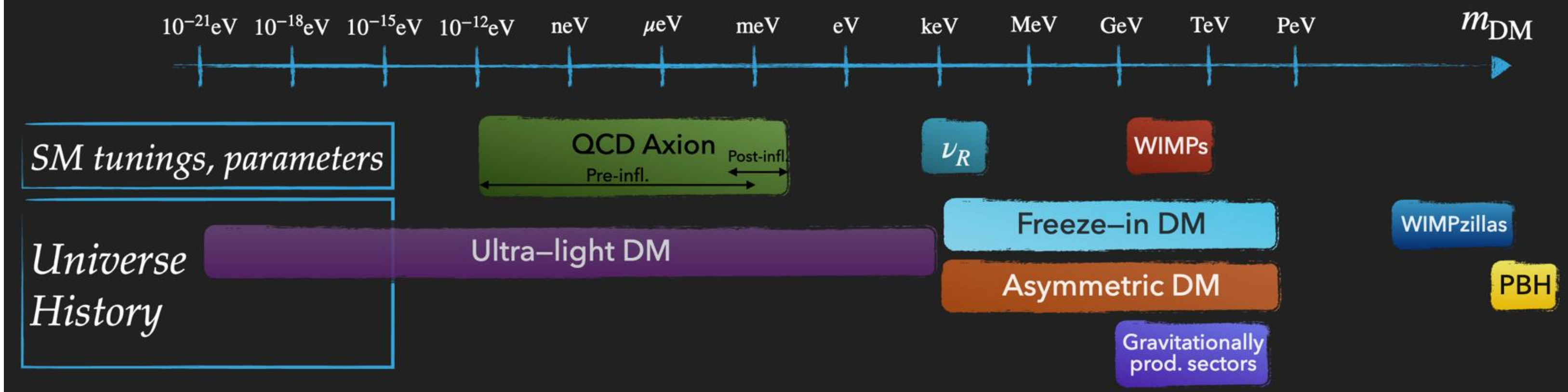
The DM problem





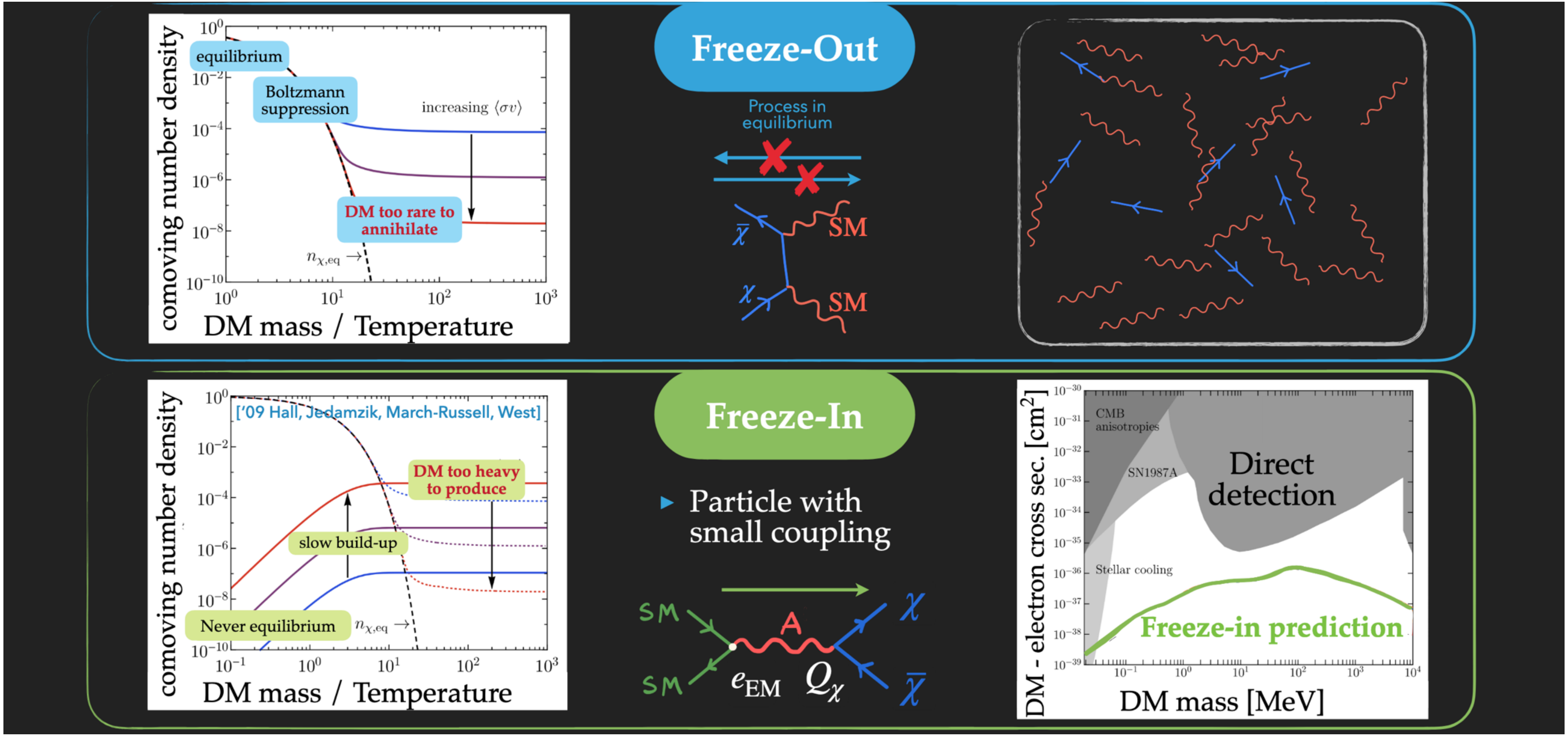


- All evidence from *gravitational* interactions
- Exp. searches look for other interactions with us



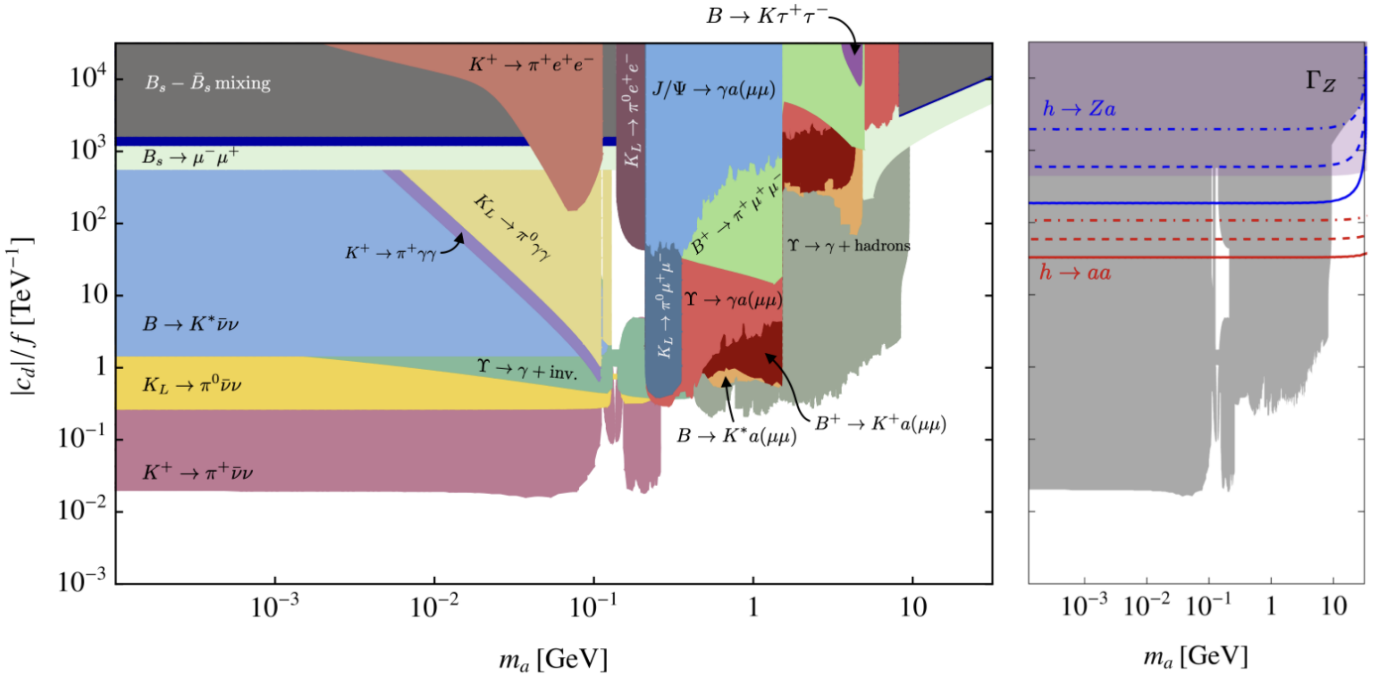
From D. Racco [here]

Possible solutions to the DM problem



From D. Racco here

An example for DM candidate: ALPs



https://arxiv.org/pdf/2110.10698

Figure 24: Left; Flavor bounds on universal ALP couplings to down-type quarks with $\boldsymbol{c_d} = c_d \mathbb{1}$, with all other Wilson coefficients set to zero at $\Lambda = 4\pi f$ and $f = 1\,\text{TeV}$. Right: Constraints from flavor observables (light gray) are compared to the constraint on $Z \to a\gamma$ decays from the LEP measurement of the Z boson width. Contours of constant $\text{Br}(h \to aa) = 10^{-1}, 10^{-2}$ and 10^{-3} are depicted as red dotted, dashed and solid lines, respectively. Contours of constant $\text{Br}(h \to Za) = 10^{-1}, 10^{-2}$ and 10^{-3} are shown as blue dotted, dashed and solid lines, respectively.