Particles, Strings and Cosmology 2025

Introduction

Elisabetta Gallo

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

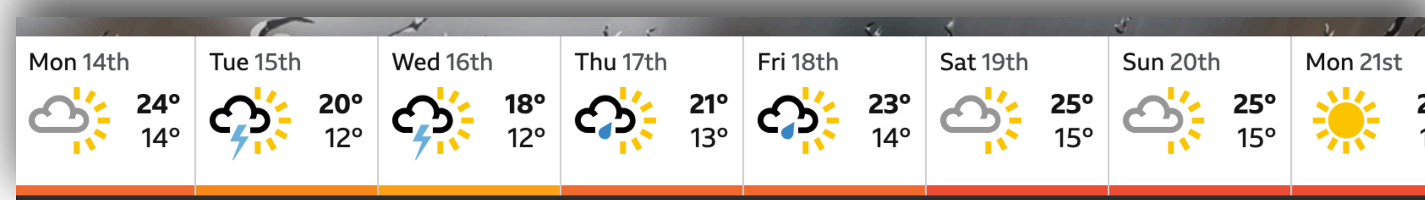
DESY.

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Welcome!

We hope you arrived well in Hamburg !

And that you are not disappointed about the summer weather



The school and who we are

This is the 5th edition of this school, this time organized by myself and Henriette Ullmann

Lecturers:

Katharina Behr

Elisabetta Gallo

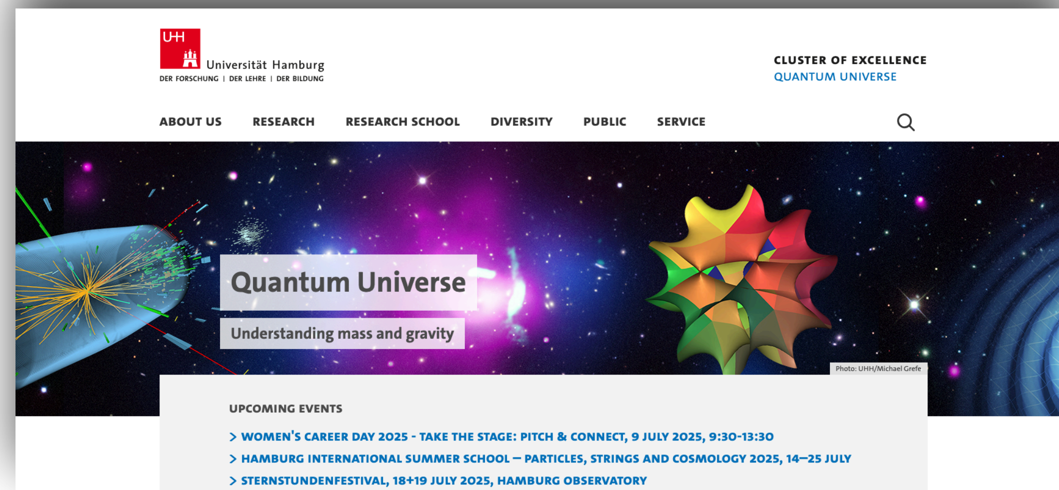
Gregor Kasieczka

Timo Weigand

Alexander Westphal

Quantum Universe Excellence Cluster

Visit our web page https://www.qu.uni-hamburg.de/



About 300 researchers at the University of Hamburg and DESY, our goal:

"understanding of mass and gravity at the interface between quantum physics and cosmology"

Program at a glance

Sign each day to get the final school certificate

Lectures start sharp at the time in the Timetable (e.g. 9:00 in the morning), not 15 minutes later

Fridays it will be in SR IV, ML ex. in HS61, otherwise always here

Group Picture: Tuesday 22/July, just before lunch at 12:30

Wifi: eduroam and Science Hotspot available

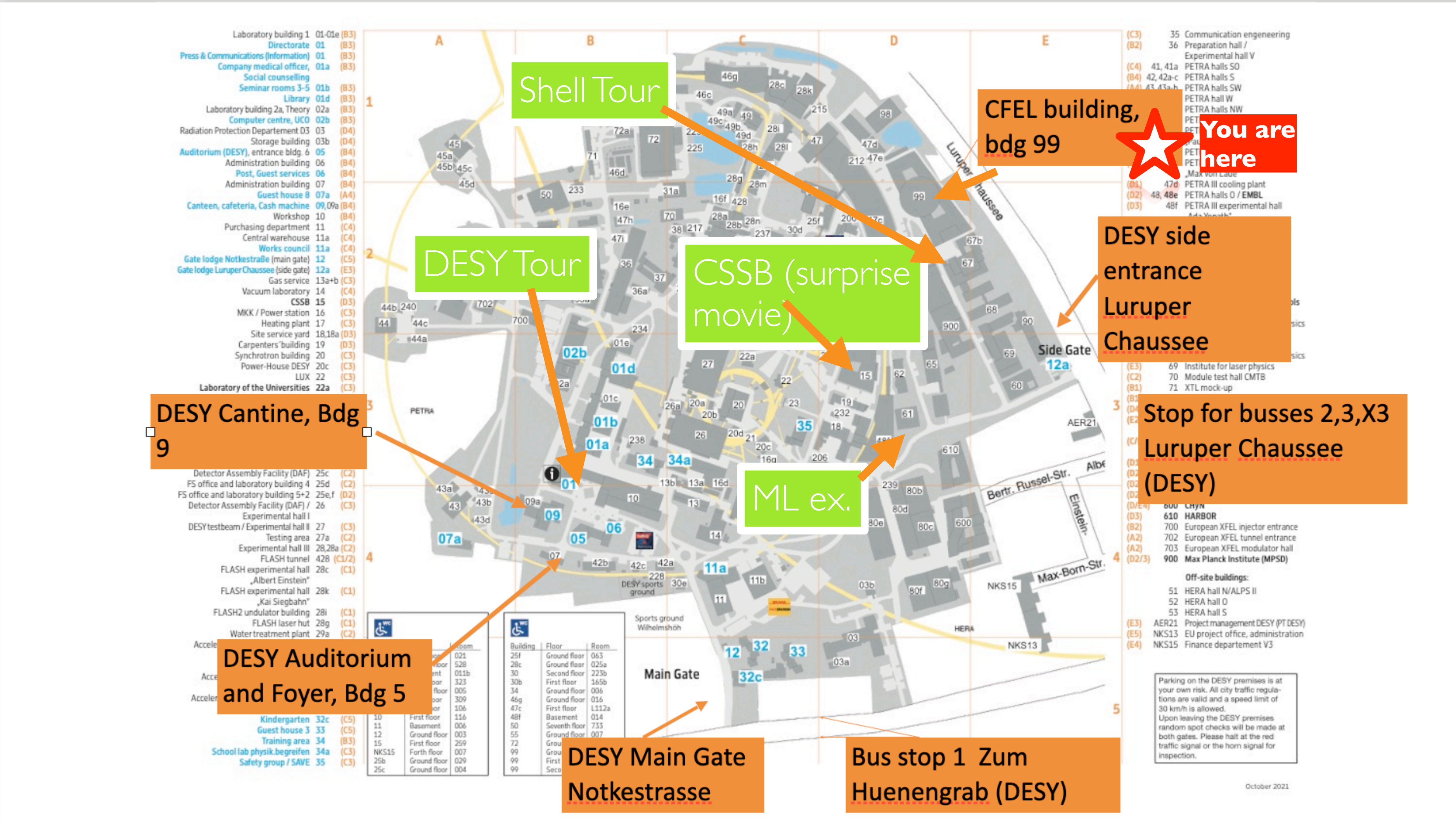
14-18 July 2025	Monday	Tuesday	Wednesday	Thursday	Friday
2 hours	Particles	Particles	Higgs	Higgs	Beyond SM
2 hours	Particles	Higgs	Machine Learning	Machine Learning	Beyond SM
Exercises 2h	Particles	Particles	Machine Learning	Machine Learning	Beyond SM
Particles (30h)					
Extra	Reception			Walking Tour in Hamburg	Surprise movie
	Poster session tbc				
	Meet the QU professor				

21-25 July 2025	Monday	Tuesday	Wednesday	Thursday	Friday
2h	Strings	Strings	Cosmology	Cosmology	Cosmology
2h	Strings	Strings	Cosmology	Cosmology	Cosmology
Exercises 2h	Exercises	Exercises	Exercises	Exercises	Exercises
Strings (12 hours)					
Cosmology (18h)					
Extra	DESY Tour	SHELL Tour	Surprise movie		Dinner

For the DESY Tour:
https://indico.desy.de/event/48195/contributions/182888/attachments/97995/135064/Information_about_your_DESY_visit.pdf

Timetable: https://indico.desy.de/event/48195/timetable/#all

DESY map



Shell Tour
CFEL building, bdg 99
You are here
DESY Tour
CSSB (surprise movie)
DESY side entrance Luruper Chaussee
DESY Cantine, Bdg 9
Stop for busses 2,3,X3 Luruper Chaussee (DESY)
ML ex.
DESY Auditorium and Foyer, Bdg 5
DESY Main Gate Notkestrasse
Bus stop 1 Zum Huenengrab (DESY)
Side Gate
Main Gate
Luruper Chaussee
Bertr.-Russel-Str.
Max-Born-Str.
Einstein-
PETRA
HERA
October 2021

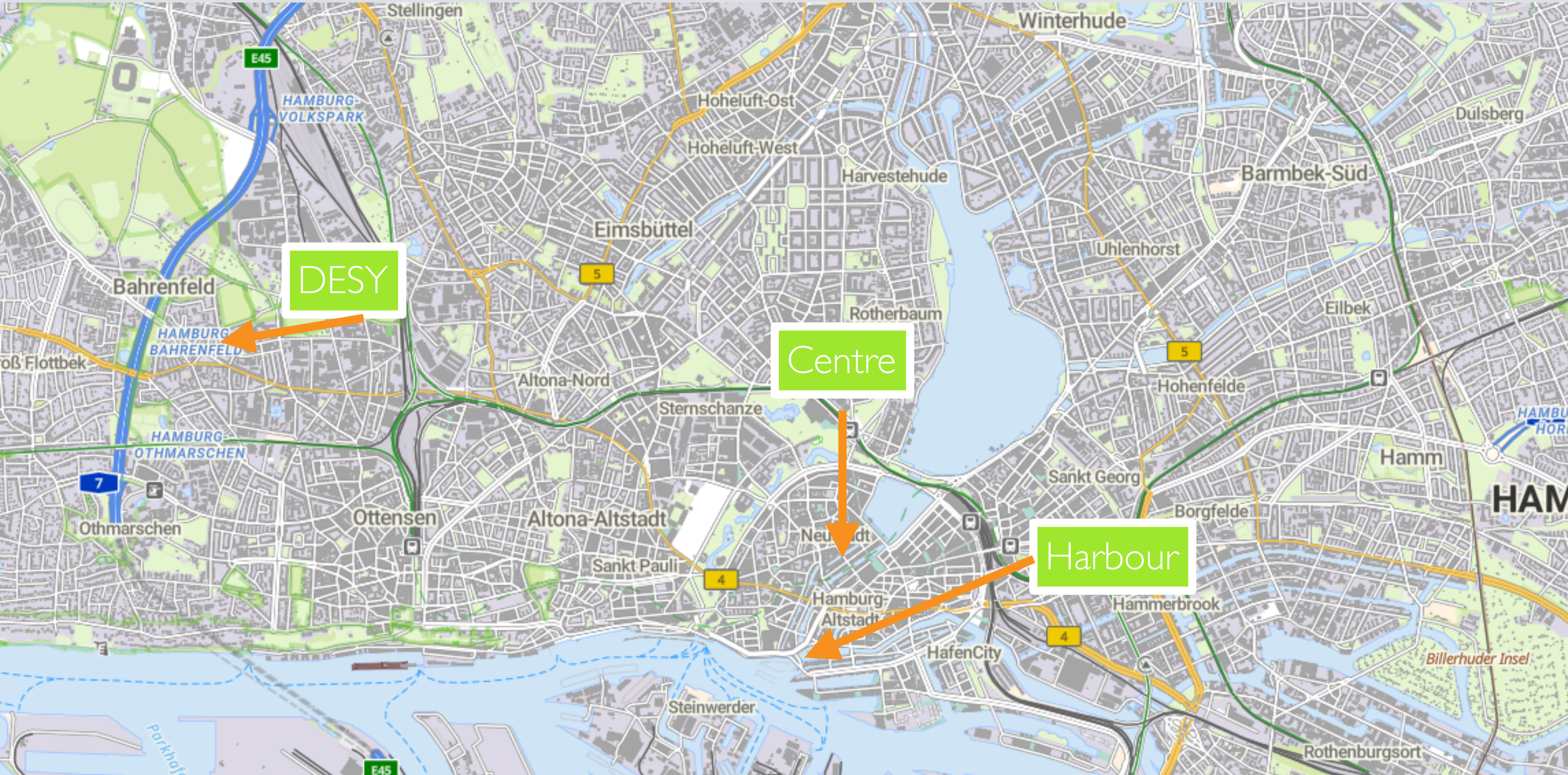
Social program

A particular walking Tour in Hamburg Thursday this week. We will take the bus number 2 all together

Farewell dinner the last day: a menu to choose your main dish will be made available before

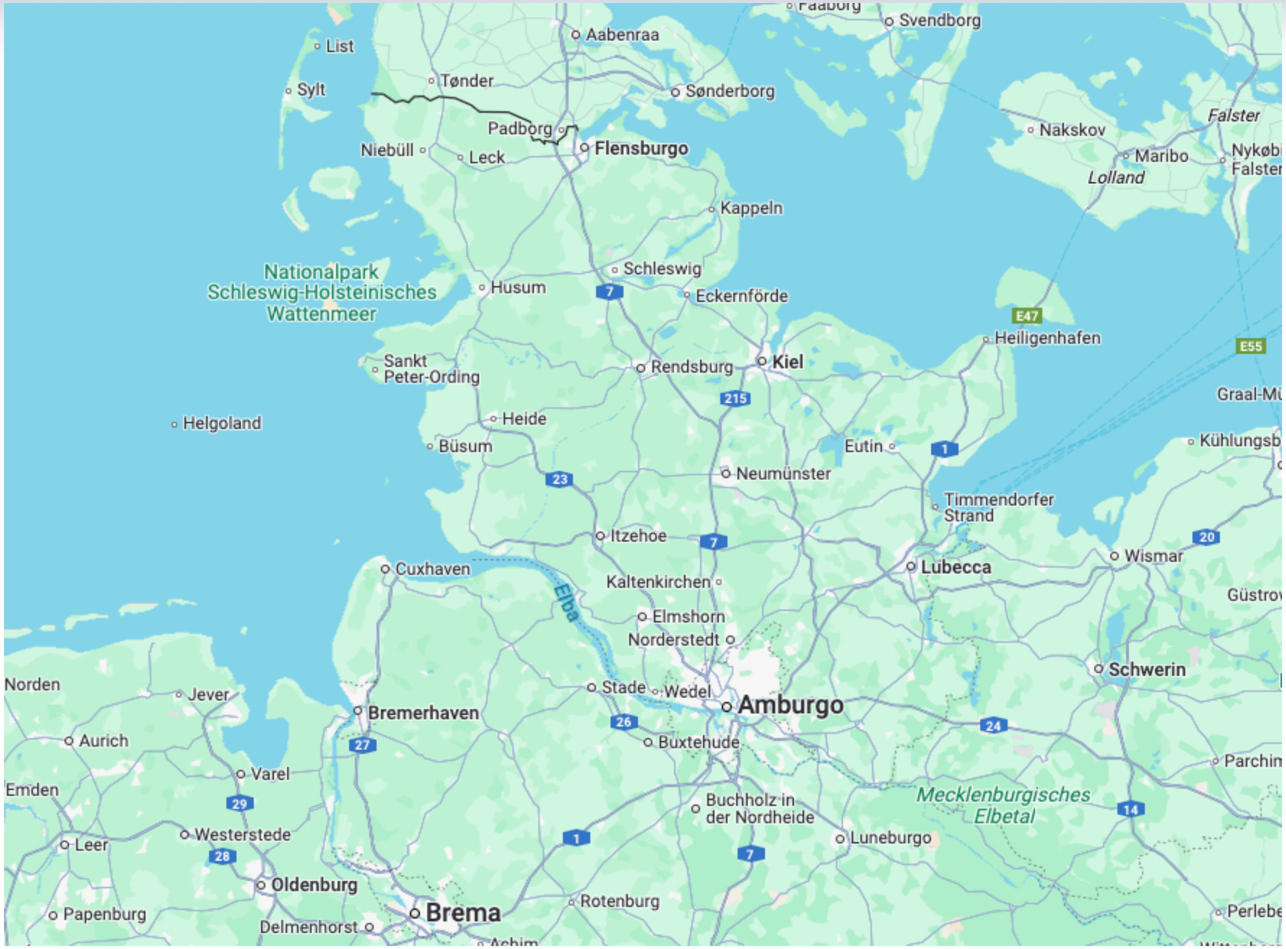
The weekend is free, but we are happy to give you tips

Hamburg die schönste Stadt der Welt



Recommended: Boat Tour in the Harbour, Elbphilarmonie Plaza, Miniaturwunderland (book before!), Michael Kirche, Kunsthalle, sailing or paddling on the AussenAlster, dinner at Sternschanze or Altona, walk in Planten und Blomen, drink in Ottensen/Strandperle, Dom in St Pauli/ Karolinenviertel, StadtPark, Fischmarkt Sunday morning early (use hvv.de for public transports)

Around Hamburg, for the weekend

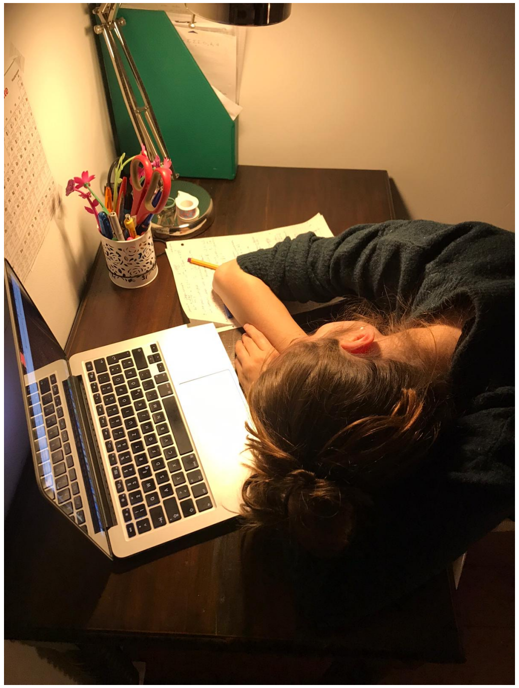


Recommended: Luebeck, Timmendorfer Strand, Schwerin, Lueneburg, Bremen, Husum, Sankt Peter Ording, Sylt. All reachable in a day trip via regional trains (Sylt may be more expensive)
Use https://www.deutschebahn.com/de to buy the ticket

Enjoy the school and Hamburg!

Have you studied particle physics already?

- A) yes, I followed few courses already
- B) I have just limited knowledge
- C) I have no knowledge
- D) Do not like to say



I will use polls for asking few questions and wake you up
Download the letters https://indico.desy.de/event/48195/contributions/182888/attachments/97995/135384/Letters.pdf

Units

Note: I will use natural units most of the times and eV as energy unit:

1 eV = 1,60218e-19 Joule

Quantity	Natural units	Translation	SI units	Remark
Energy E	MeV, GeV, TeV		MeV, GeV, TeV	e.g. LHC: 14 TeV
Momentum p	MeV	$\cdot\frac{1}{c}$	$\frac{\text{MeV}}{c}$	
Mass M	MeV	$\cdot\frac{1}{c^2}$	$\frac{\text{MeV}}{c^2}$	$E = mc^2$
Time t	MeV^{-1}	$\cdot\hbar$	s	$\Delta E \cdot \Delta t \gtrsim \hbar$
				$1\ \text{MeV}^{-1} = 6.5 \cdot 10^{-22}\text{s}$
Length l	MeV^{-1}	$\cdot\hbar c$	m	$1\ \text{MeV}^{-1} = 200$ fm
				$1\ \text{GeV}^{-1} = 0.2$ fm
Velocity β	1	$\cdot c$	$\frac{\text{m}}{\text{s}}$	$\beta = \frac{v}{c} \leq 1$
Angular momentum $\vec{L}$	1	$\cdot\hbar$	J s	

This first lecture

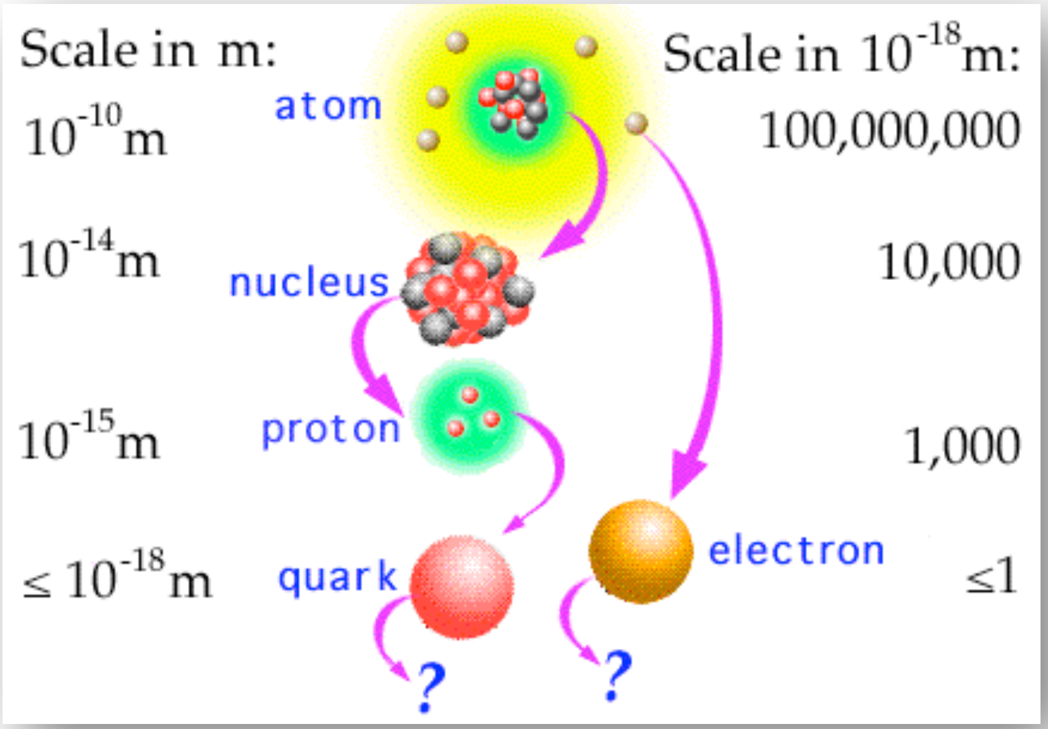
- An historical introduction on particle physics and the Standard Model

Question to you for discussion will be in yellow boxes

Feel free to interrupt and ask questions at any point!

Elementary particles

Democritus
(From Wikipedia)

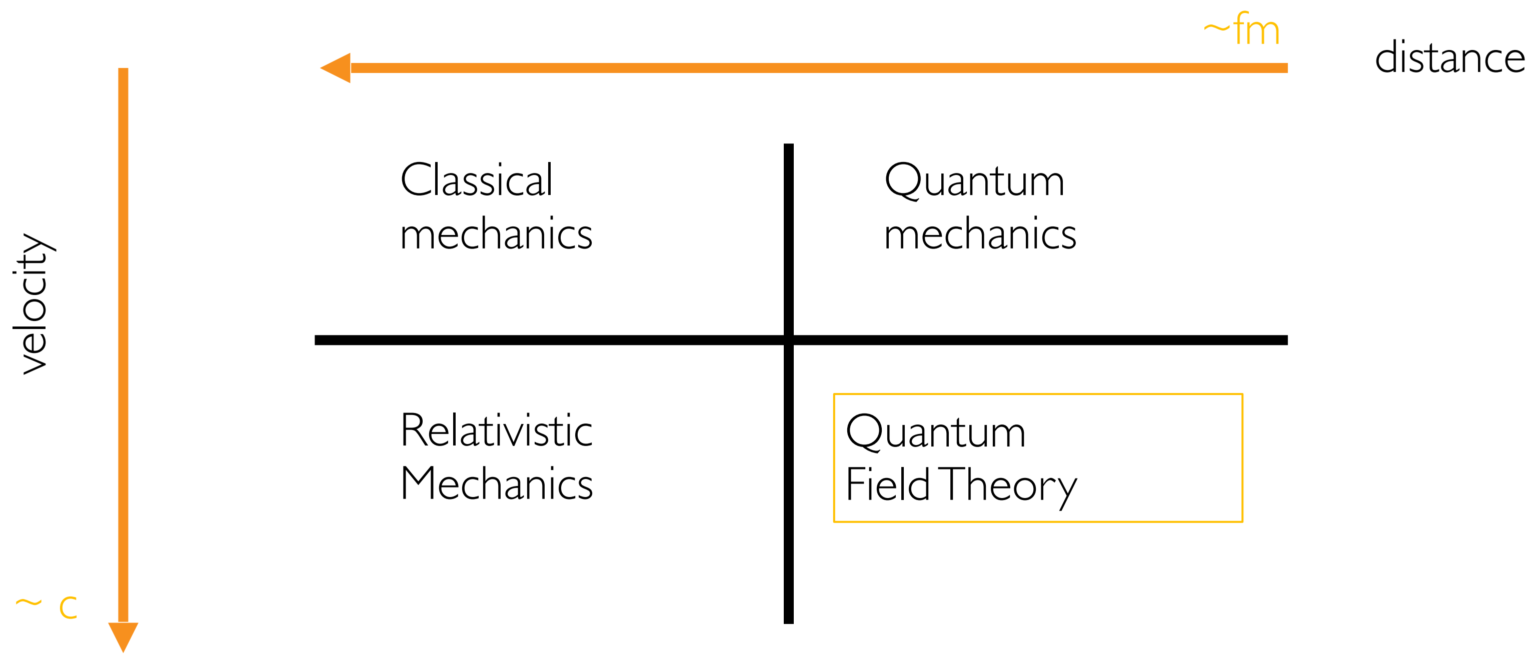


Today we have a quantum field theory describing elementary particles and their interactions, very well verified, which is the "Standard Model" (SM)

Quantum Field Theory

Small distances $<$ fm (10^{-15} m)

Relativistic kinematics $\beta = \frac{v}{c} \lesssim 1$

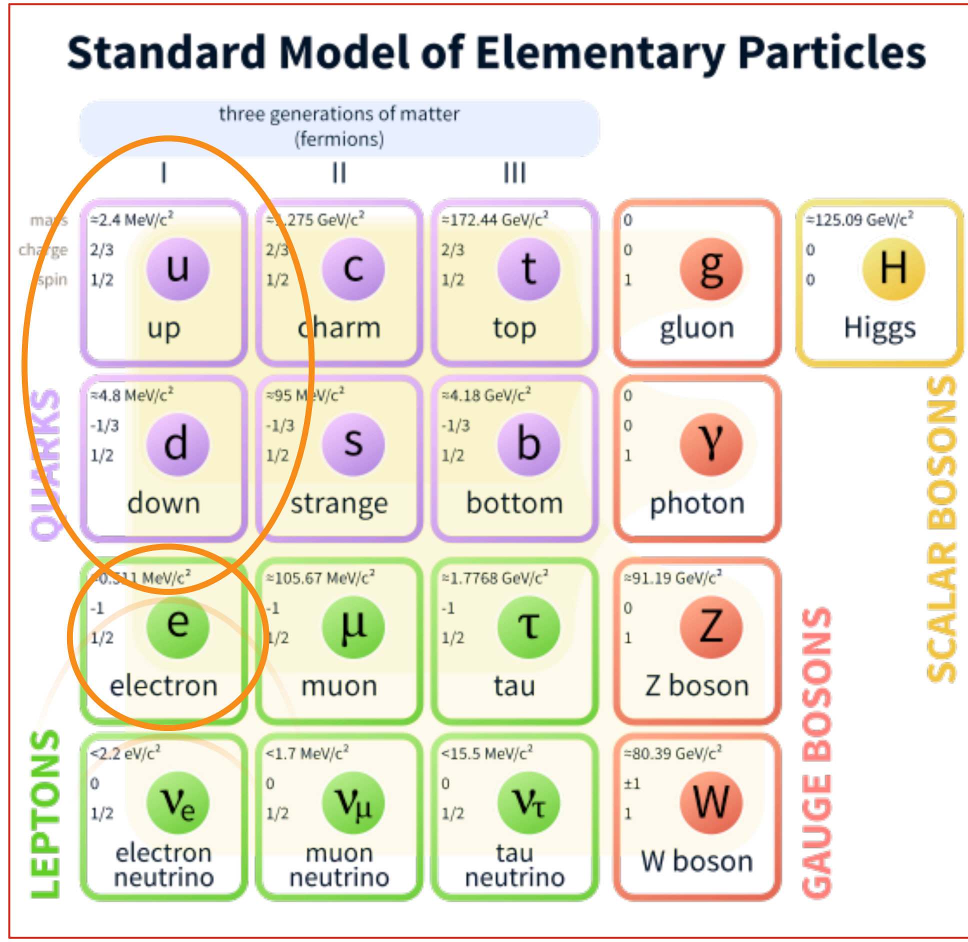


The SM of elementary particles

- Matter is composed of 3 generations of leptons and quarks (and relative anti-particles) which are fermions (spin 1/2)

- Forces are mediated by gauge bosons (spin 1)

- The scalar Higgs boson (spin 0) is responsible of the mechanism that generates mass. It was discovered at the LHC in 2012 and its mass is already known with a precision of ~1 per mille.

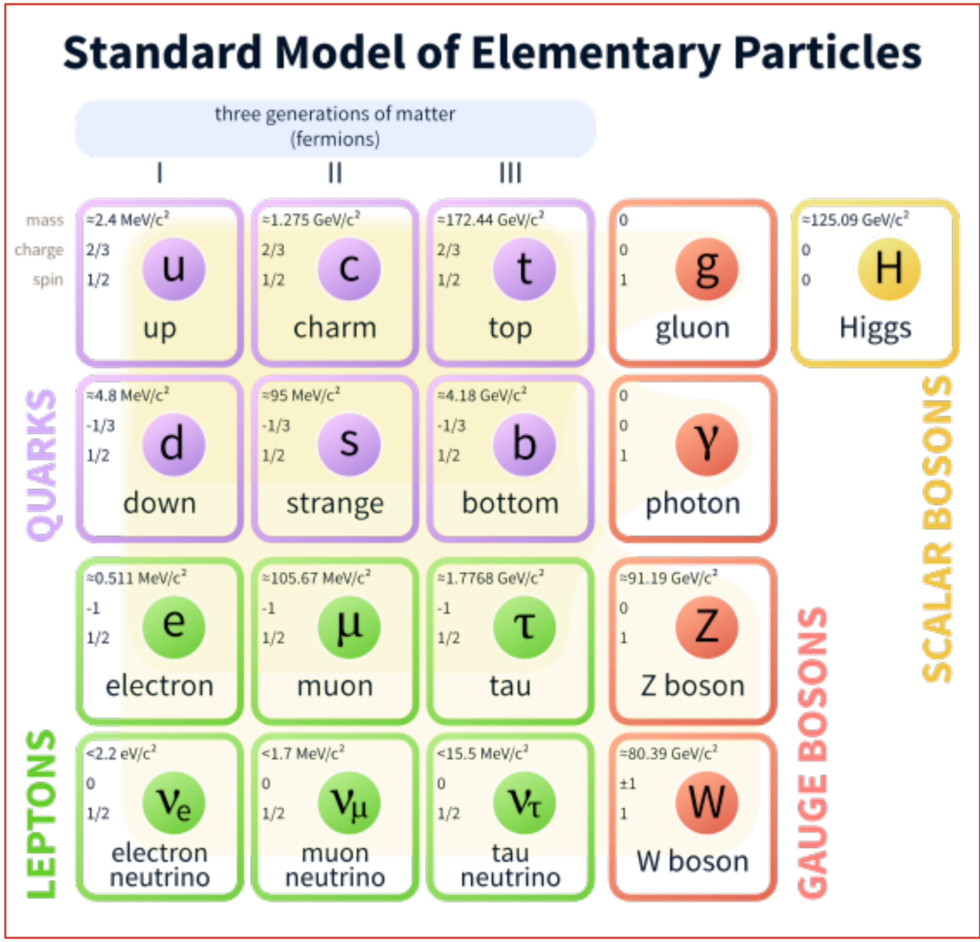


Font: Wikipedia

The SM of elementary particles

A success history in the last century, however still many questions:

- Why 3 generations, why so different masses?
- Why asymmetry matter-antimatter?
- Ordinary matter is only 5% of the energy content in the Universe, origin of dark matter and dark energy?
- Hierarchy problem
- Origin of neutrino mass?
- Gravitation is not included in the SM



Font: Wikipedia

Why 3 generations?

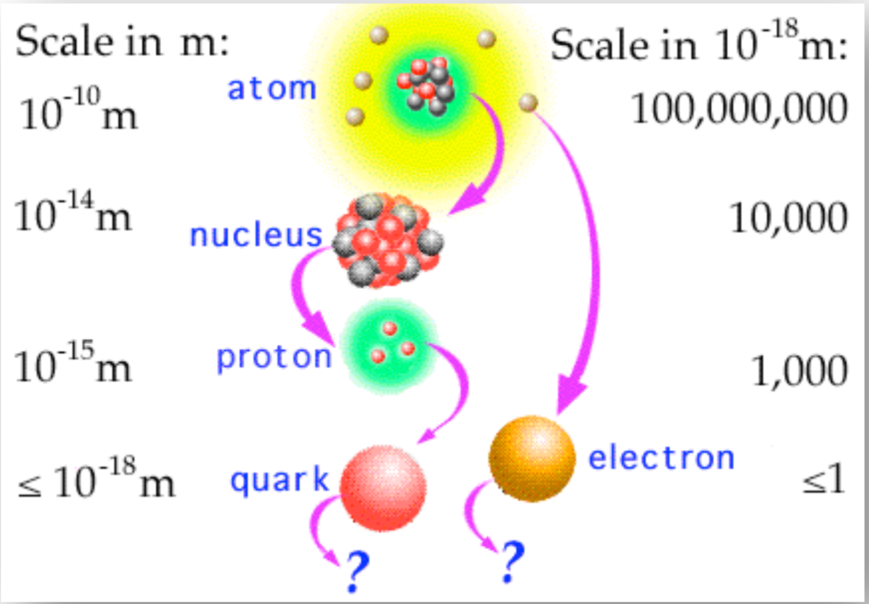
A) There is no reason of only 3 generations

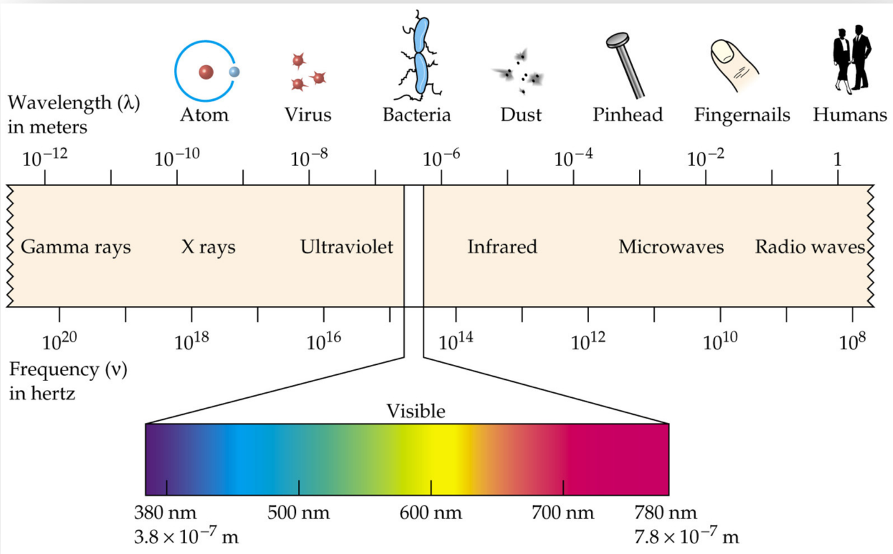
B) There are 3 colours for quarks

C) There is experimental evidence from the Z width measurement

D) I did not understand the question

Scales in the SM

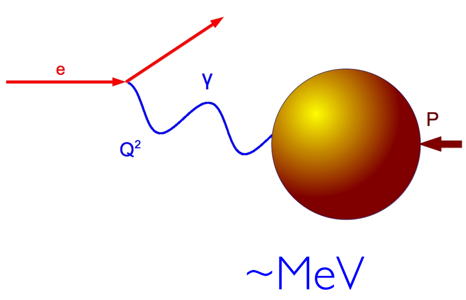


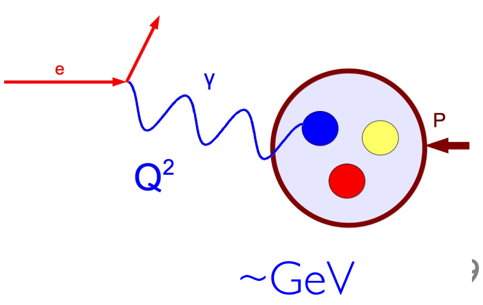


d ~ hc/Q ~ 197 MeV fermi/Q

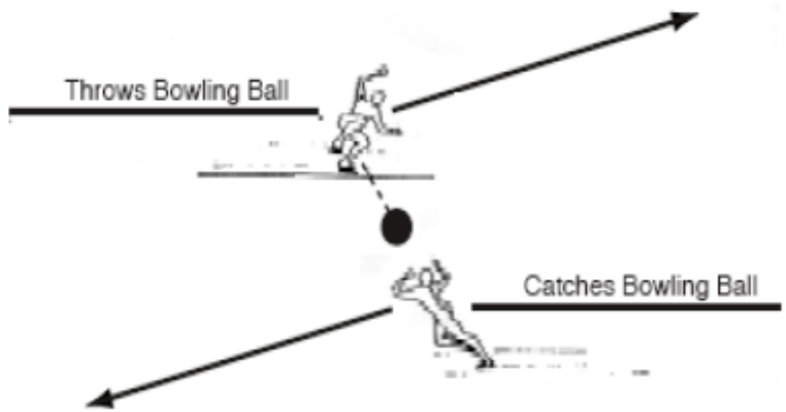
To see distances of the order of 10^{-18} m, values of Q around ~100 GeV are needed -> particle accelerators (or cosmic rays)

Now: LHC, √s= 7-8 TeV, 13 TeV from 2015, 13.6 TeV from 2022.

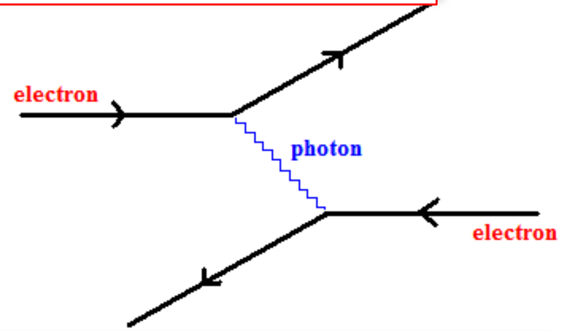


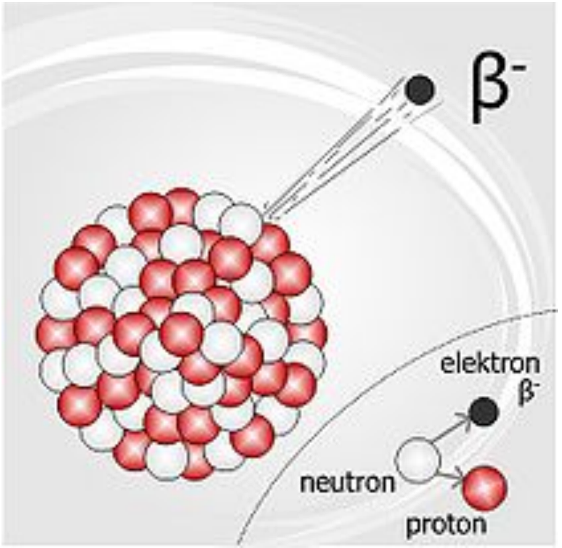


Interactions



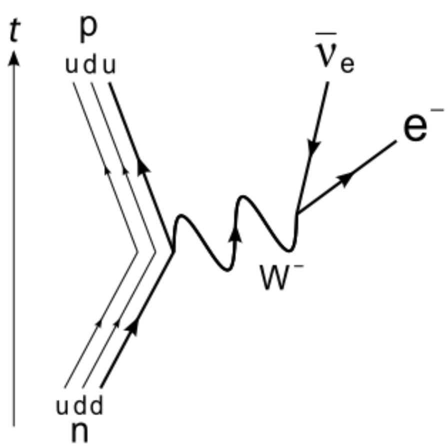
Electromagnetic interaction, mediated by the photon



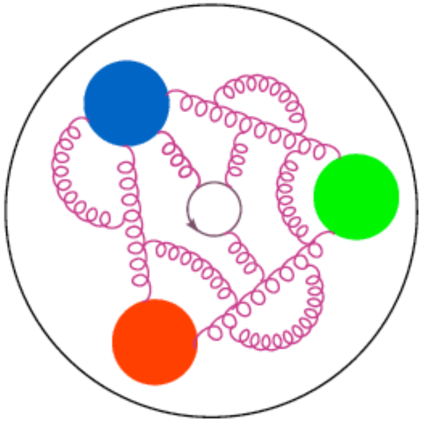


$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

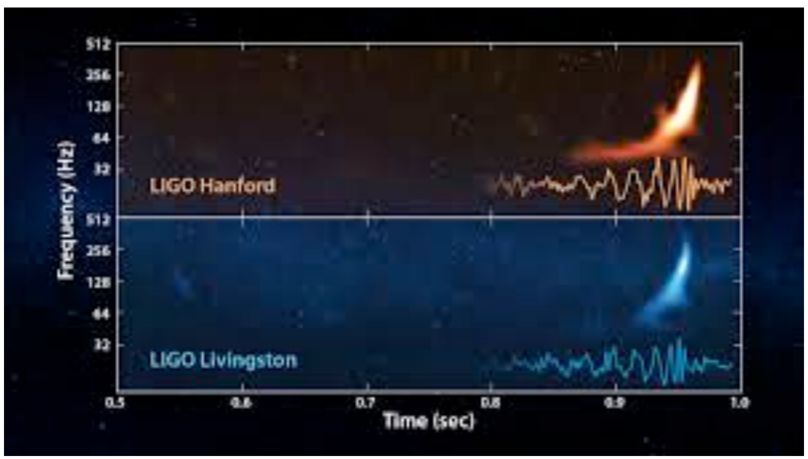
Weak interaction, mediated by W,Z



Interactions



Strong interaction,
Mediated by the gluon g



Gravitation

What is this picture?

Force	strong	e.m.	weak	Grav.
relative strength	0.1-1	~1/137	$\sim 10^{-5}$	10^{-39}

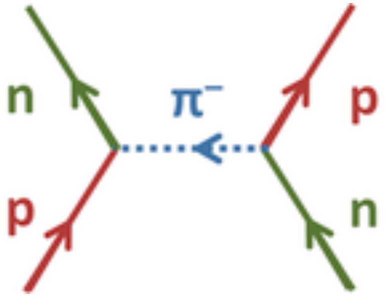
Particle Physics in the 30's

Life was simple in the 30's:

- atoms were composed of electrons and nuclei (protons and neutrons).
- Yukawa postulated a „strong" interaction between proton and neutron mediated by a **„meson"**.
- From the short range of the interaction he calculated a mass of the meson ~ 300X the mass of the electron.
- In 1937 effectively two groups observed in cosmic rays a particle matching that mass.
- In 1947 Powell discovered the pion and clarified that there were two particles with similar mass, the **muon** – weakly interacting („*Who Ordered that?*" - Rabi)– and the **pion**

Isidor Rabi

Earlier picture from Powell, π->μυ decay



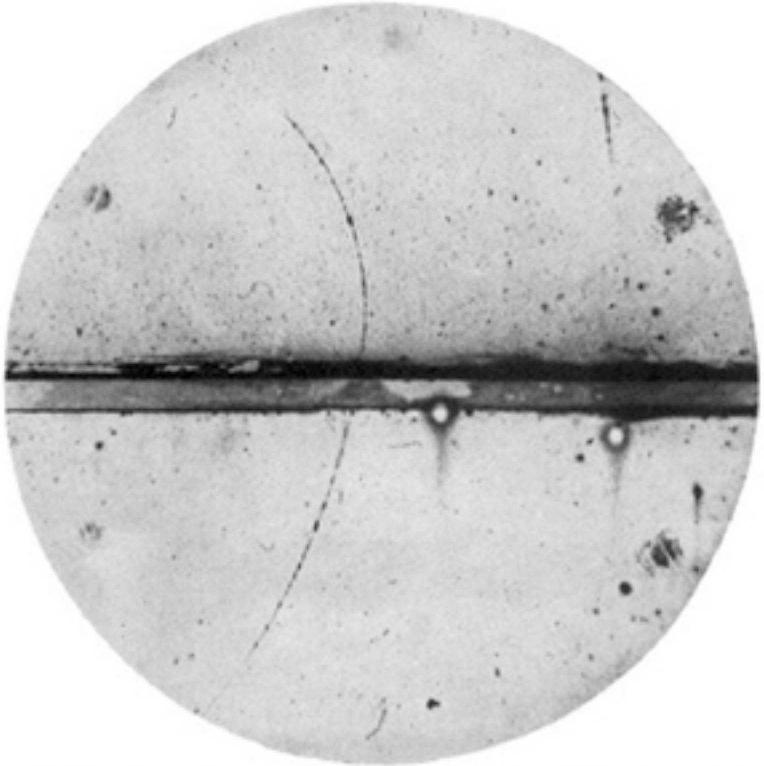
Yukawa interaction

Antimatter (1932)

Discovery of the positron (i.e. antielectron) by Anderson in 1932.

Supported Dirac's equation which admitted positive and negative energy solutions.

$$E = +/- \sqrt{(p^2c^2 + m^2c^4)}$$



• Antiparticles have the same mass as particles and opposite charge and quantum numbers
• Dominance of matter over antimatter is one of the main questions to answer (i.e. LHCb or B-factories experiments)

How did Anderson established that it was a positive charged particle with the electron mass?

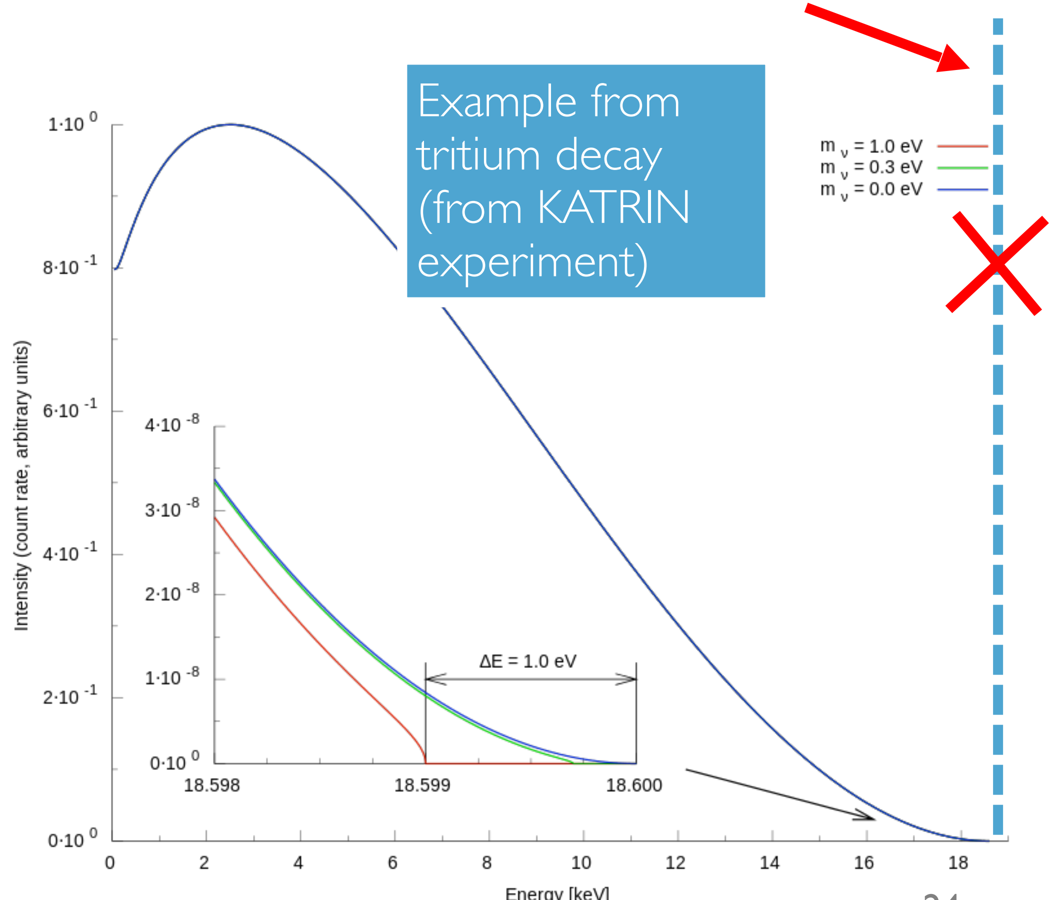
Neutrinos (~1930)

Problem observed in β decays of radioactive nuclei, A -> B + e-
If A is at rest, the two decay particles B and electron are back-to-back and the electron should be monocromatic

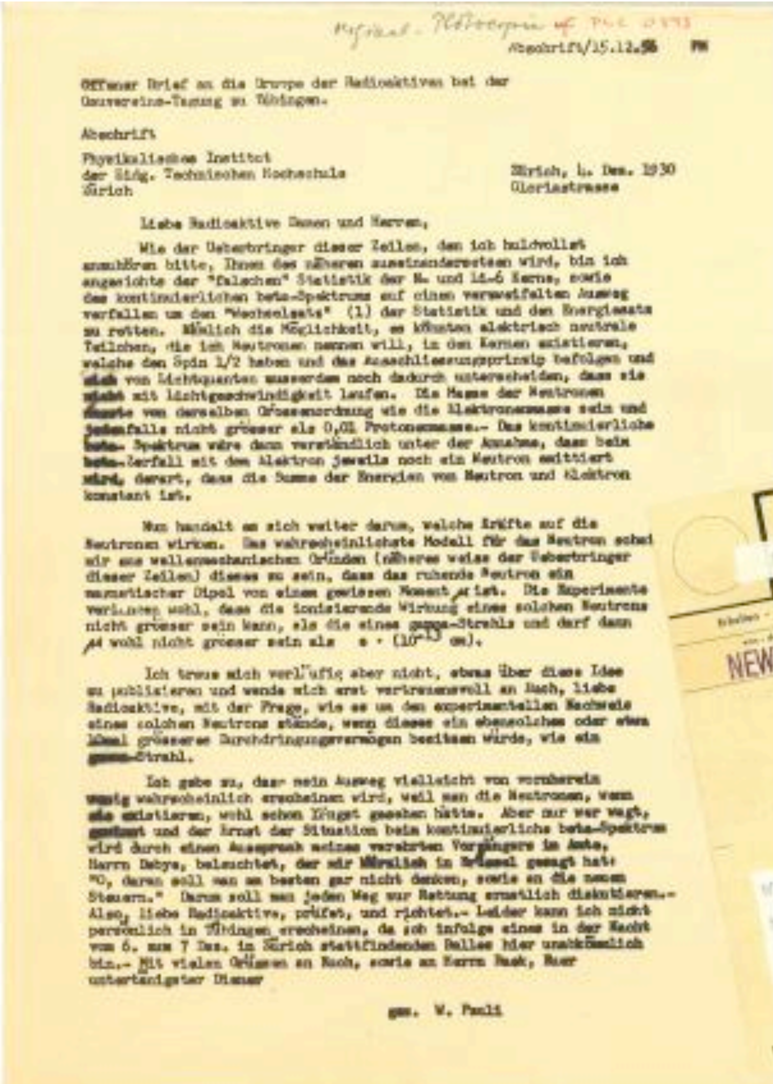
$$E = \left(\frac{m_A^2 - m_B^2 + m_e^2}{2m_A} \right) c^2$$

However a continous spectrum was observed and Pauli postulated the existence of a neutral weakly interacting particle (called later **neutrino** by Fermi)

$$n -> p + e^- + \overline{\nu}_e$$



Neutrino's discovery



Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

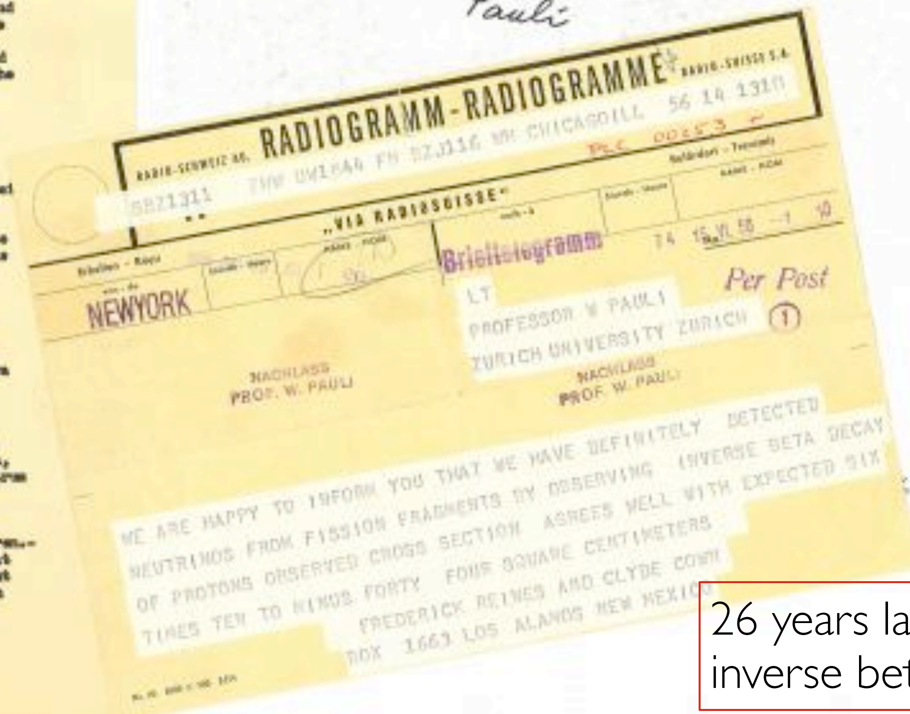
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als e · (10^-13 cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli



RADIOGRAMM-RADIOGRAMME

NEWYORK

Brieftelegramm

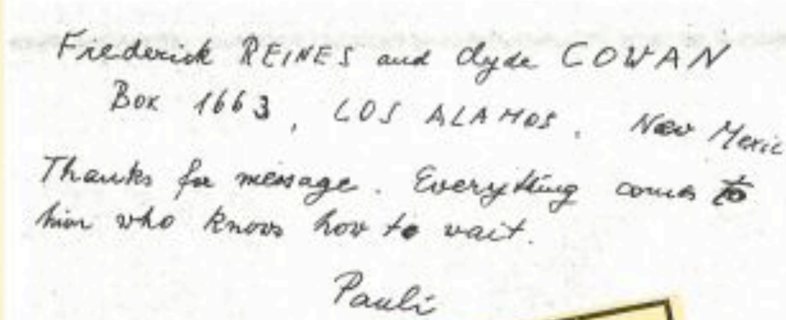
Per Post

LT PROFESSOR W PAULI ZURICH UNIVERSITY ZURICH

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

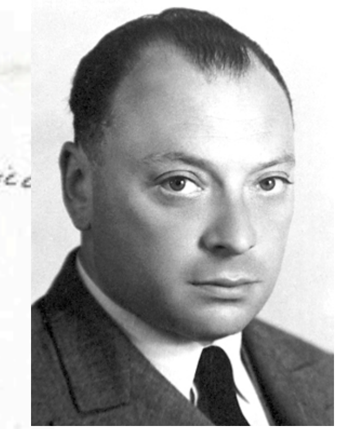
FREDERICK REINES AND CLYDE COWAN BOX 1663 LOS ALAMOS NEW MEXICO



Friedrick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli



Wolfgang Pauli was professor in Hamburg (Photo: Wikipedia)

26 years later in the inverse beta decay

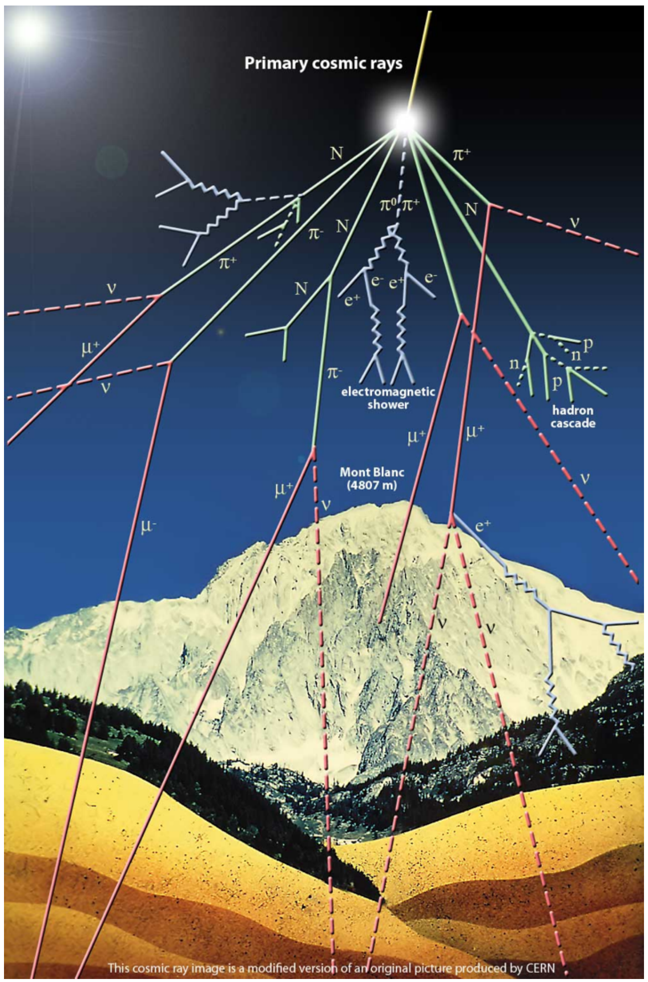
$$\bar{\nu} p \rightarrow n + e^{+}$$

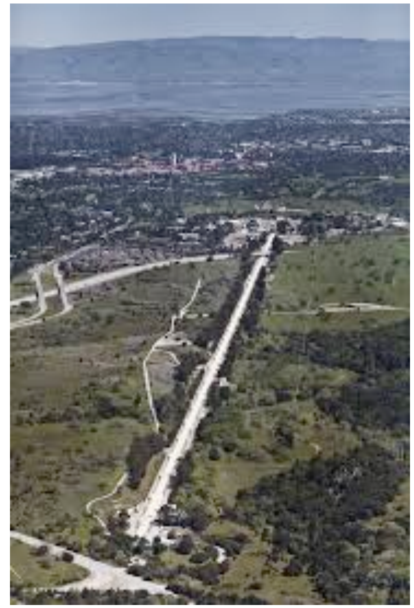
Why did it take so long?

Font: CERN

Particle accelerators

Cosmic rays





Accelerators

SLAC, 1967,
Linac
2 miles long

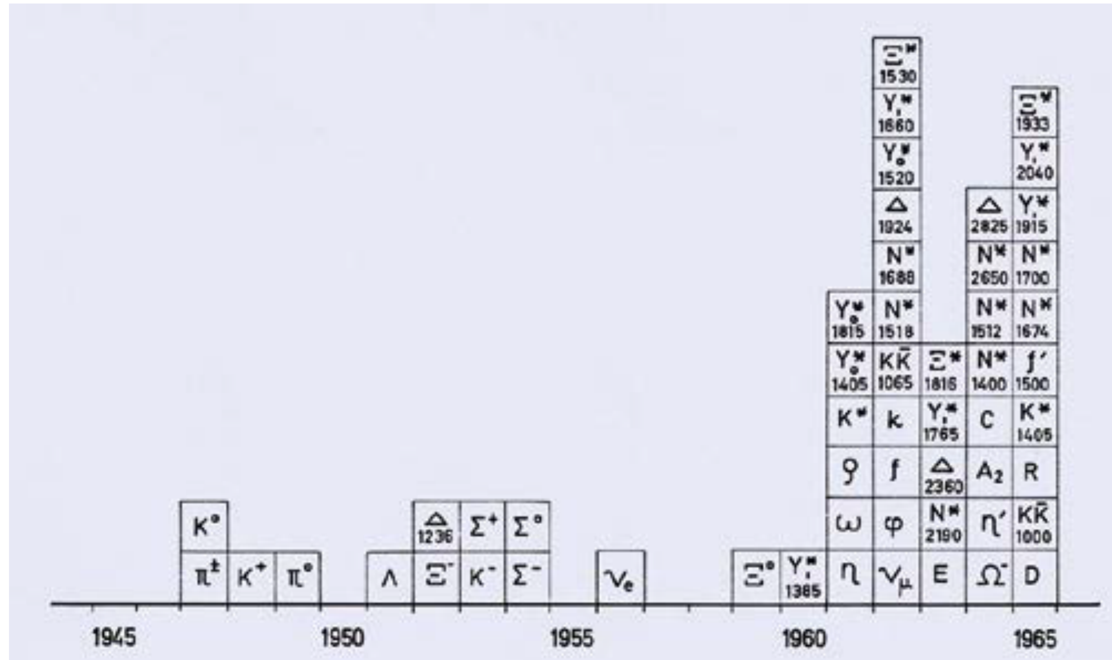
ADA (Frascati, first $e^+ e^-$ collider)

A “zoo“ of particles

In the ‘60 there was a “zoo” of ~100 particle (and anti-particles) discovered at accelerators or cosmic rays.

Somehow particle physics was not attractive and elegant anymore.

The intuition and geniality of few people (i.e. see Gell-Mann together with Feynman in the photo) helped putting “order”.



Font: CERN Courier

Strange particles

Some of these particle were denominated „strange“.
In 1947, in cosmic rays, a new neutral particle, heavier than the pion, was discovered:

$$K^0 \rightarrow \pi^+ + \pi^-$$

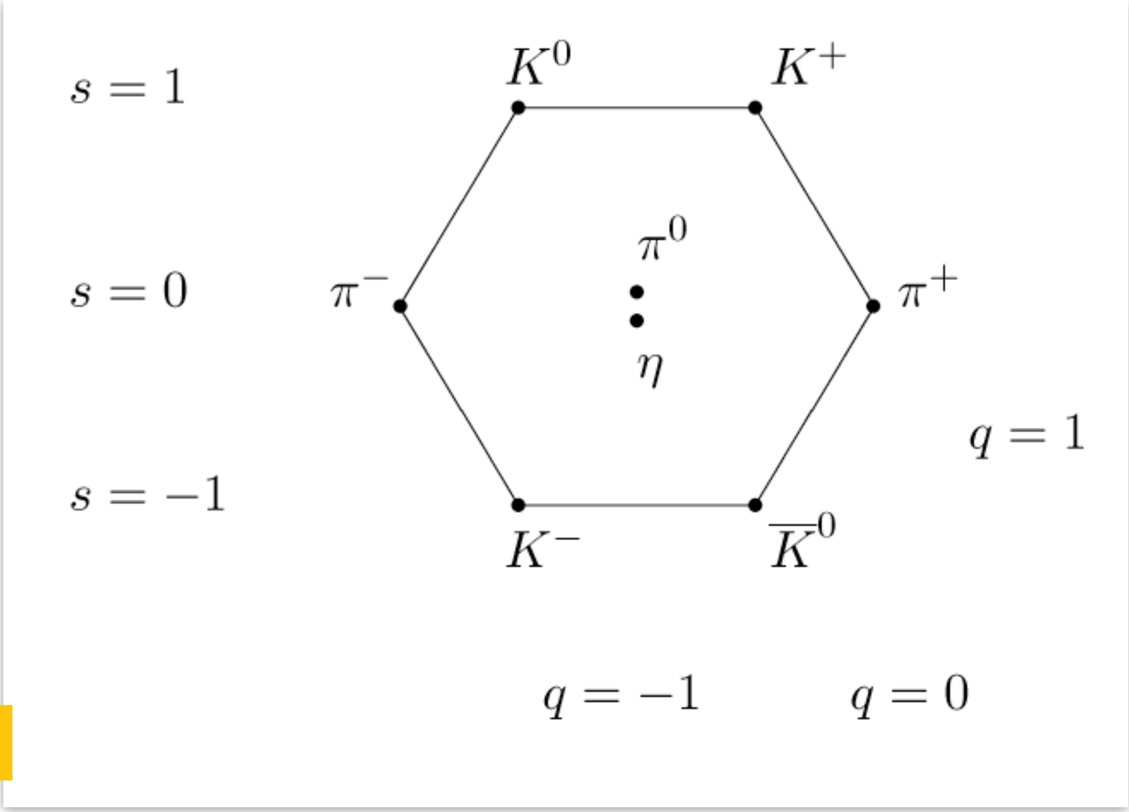
- And in the following years many more particles were discovered in cosmic rays or at accelerators: ρ, ϕ, ω,...., Λ, Σ, ...

- Some of these new particles, like the Λ, were produced in a timescale of 10^{-23} sec, typical of the strong interaction, but decayed slowly in p+π, with typical lifetime of 10^{-10} sec („weak“ interaction). Gell-Mann and Nishijma assigned a new quantum number, the strangeness, conserved in strong but not in weak interactions.

The Eightfold Way

In 1961 Gell-Mann introduced a classification of mesons and baryons, to put order in the jungle of particles, according to charge and strangeness

The Eightfold way is the basis of the quark model (Gell-Mann and Zweig 1964)

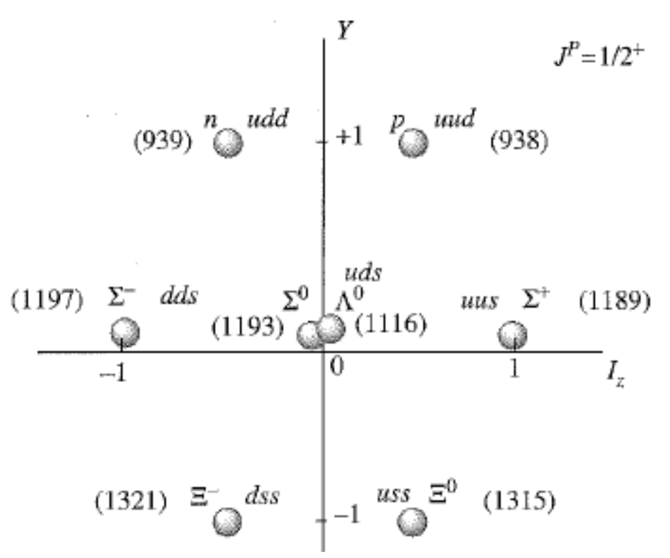


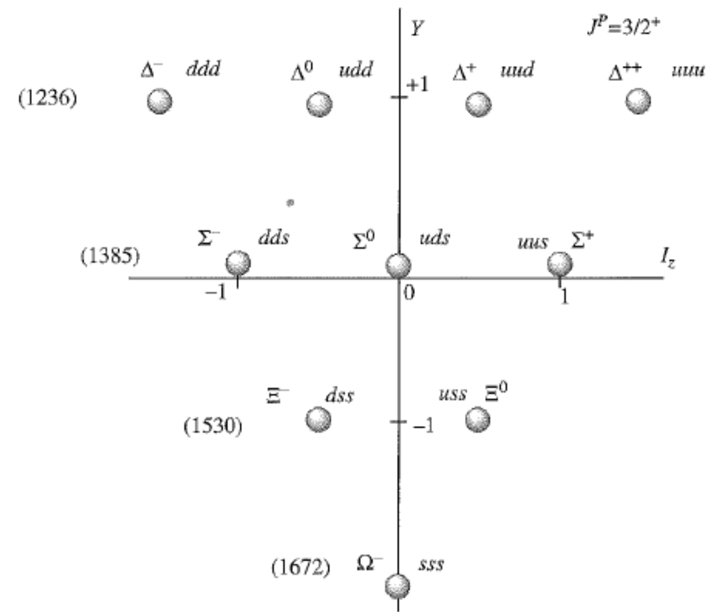
mesons

Font: Wikipedia, Bettini

The Eightfold Way

baryons





Gell-Mann predicted the Ω state (sss) which was effectively found later in 1964.

What is special about the Δ++ and Ω particles?

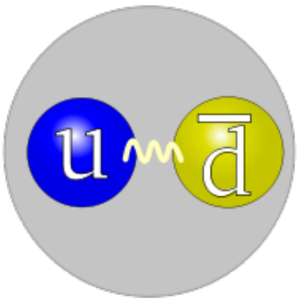
Font: Wikipedia, Bettini

The quark model

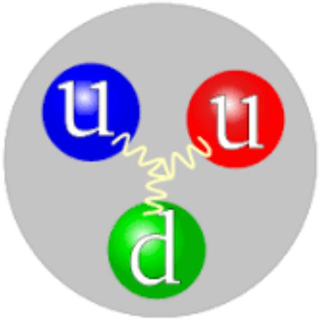
Hadrons are composite particles of quarks:

- up of charge 2/3 and d,s of charge -1/3
- mesons are quark-antiquark states
- baryons are 3-quark states
- Quarks have an additional quantum number (the color), mesons and hadrons are colorless

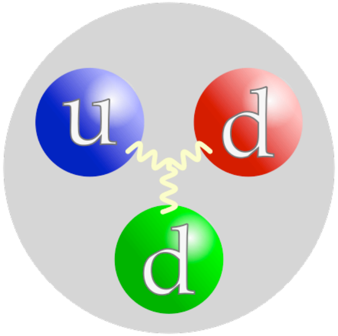
"Three quarks for Muster Mark!" (Finnegans Wake by James Joyce)



pion



proton



neutron

antiproton

Font image: Wikipedia

The proton is the lightest baryon and is stable. Which quantum number is conserved in baryon decays?

The quark model

The meson nonet

$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	π^0
$u\bar{d}$	1	0	π^+
$d\bar{u}$	−1	0	π^-
$d\bar{d}$	0	0	η
$u\bar{s}$	1	1	K^+
$d\bar{s}$	0	1	K^0
$s\bar{u}$	−1	−1	K^-
$s\bar{d}$	0	−1	$\bar{K}^0$
$s\bar{s}$	0	0	??

The baryon decuplet

qqq	Q	S	Baryon
uuu	2	0	Δ^{++}
uud	1	0	Δ^+
udd	0	0	Δ^0
ddd	−1	0	Δ^-
uus	1	−1	Σ^{*+}
uds	0	−1	Σ^{*0}
dds	−1	−1	Σ^{*-}
uss	0	−2	Ξ^{*0}
dss	−1	−2	Ξ^{*-}
sss	−1	−3	Ω^-

See QCD lectures for confirmation of the quark parton model

Font: Griffiths

Are there bound states of 4 or 5 quarks?

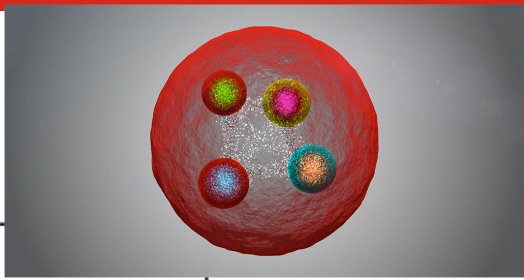
A) No, only 2 or 3 quark bound states exist

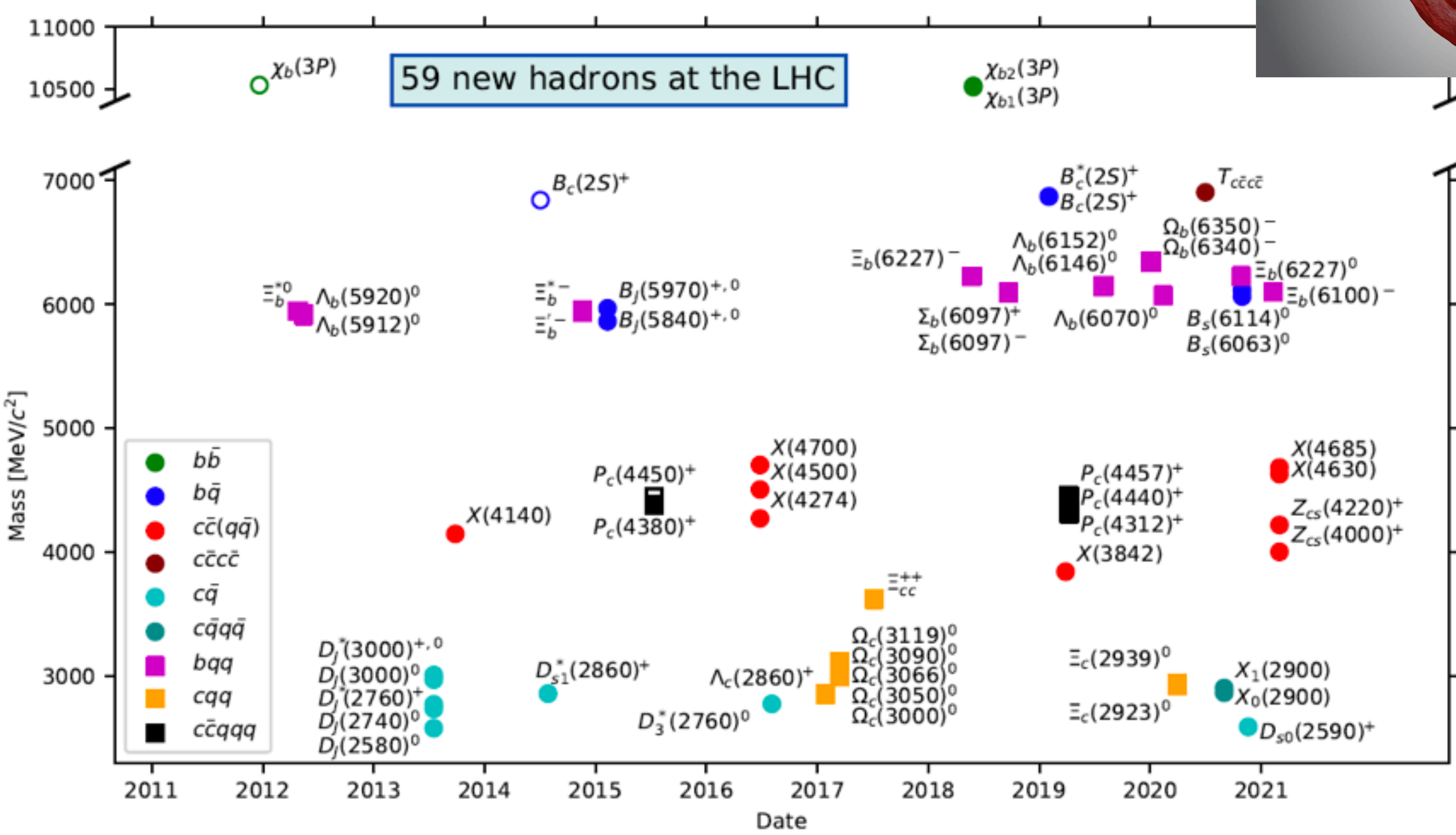
B) Recently 4 or even 5 quarks states have been observed

C) No, but bound states of leptons have been observed

D) I did not understand the question, can you explain better

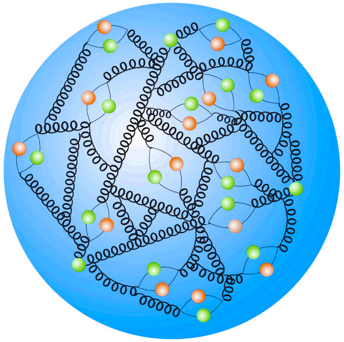
Recently discovered particles



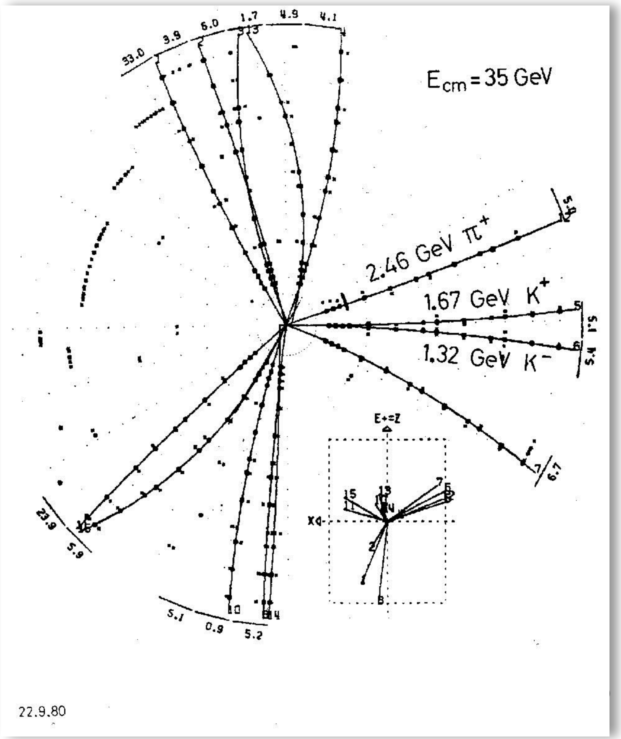


Font=CERN 2021

The quark model



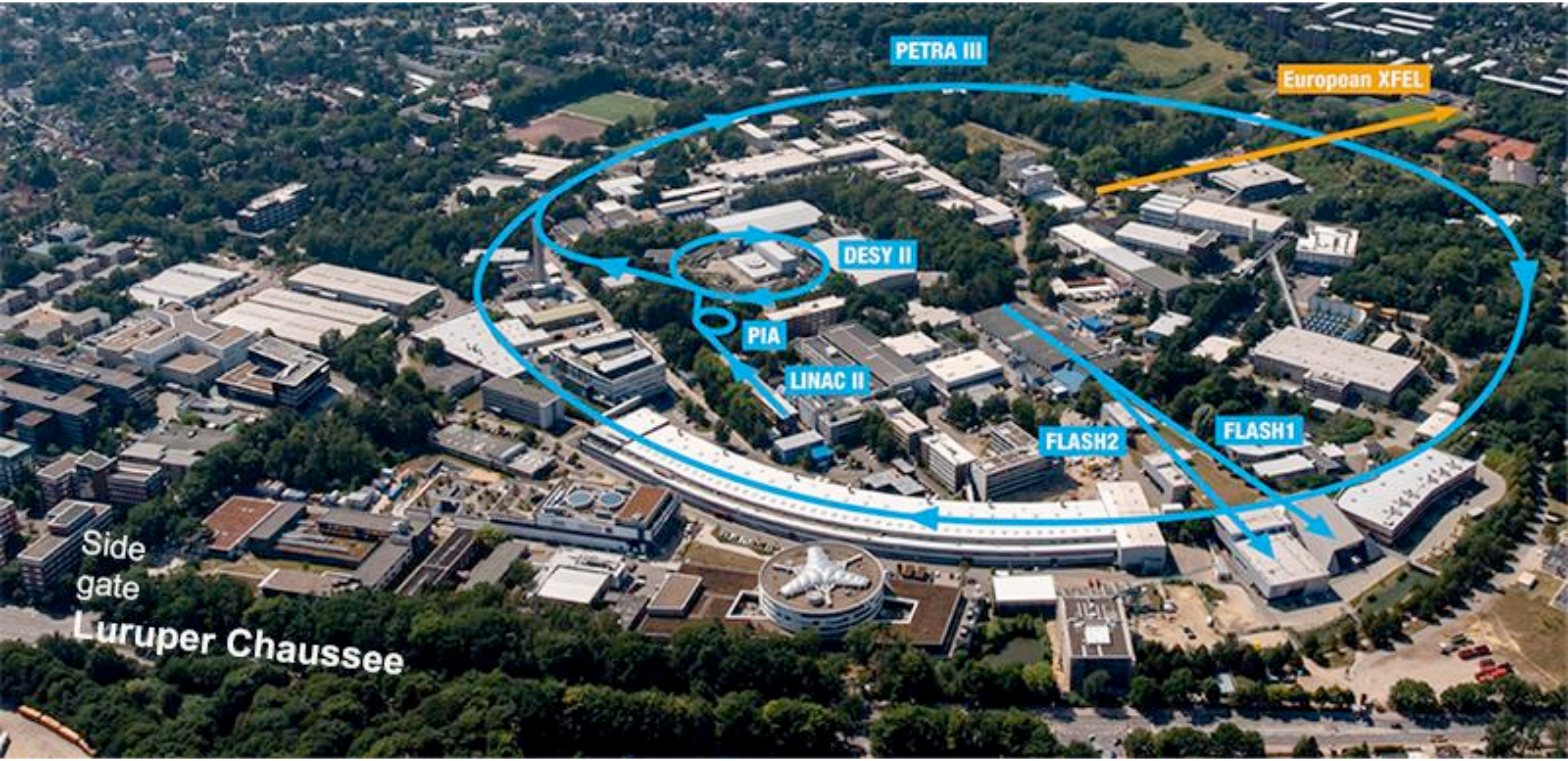
Took a lot of time to be confirmed as quarks had not been observed "free".



Few important results in the "70s":

- Discovery of bound states with "heavy" quarks, like the J?psi
- Deep inelastic scattering experiments, i.e. ep scattering and study of the proton structure, how is a proton made? Can the theory describe this behavior?
- Development of Quantum Chromodynamics (QCD), the theory of strong interactions.
- Discovery of 3-jet events at PETRA/DESY.

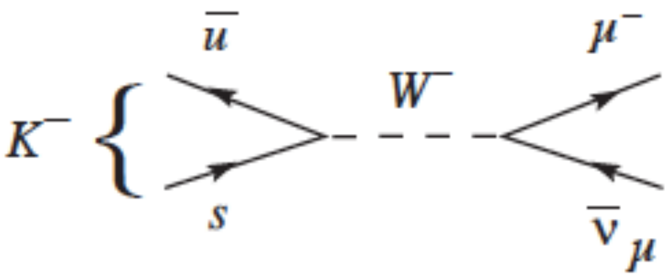
(The DESY campus)

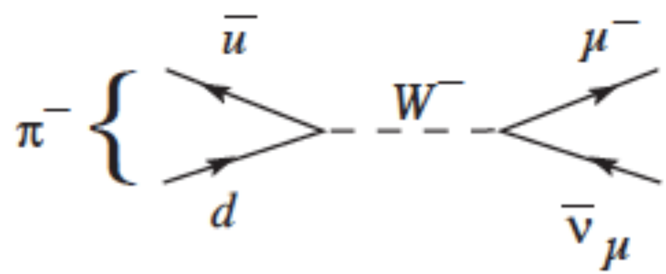


Cabibbo angle (1963)

- Measuring the decay rates of π(ud)->μυ (without change of strangeness ΔS=0) and K(us)->μυ (with ΔS=1) it was found that they were different.
- Was weak interaction not universal, dependent on the quark flavour?

Cabibbo hypothesis: Let's suppose a weak eigenstates of quarks d' as a combination of the mass eigenstates d,s, with mixing given by an angle θ_C





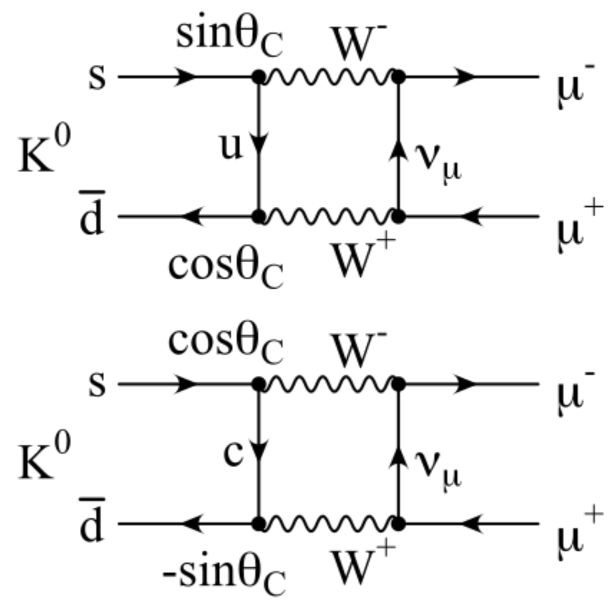
$$|d'\rangle = \cos\theta_c\,|d\rangle + \sin\theta_c\,|s\rangle$$

Then the
Transitions d->u ~ $g_W{}^2\cos^2(\theta_C)$
Transitions s->u ~ $g_W{}^2\sin^2(\theta_C)$

Experimentally this angle was found to be 13 degrees

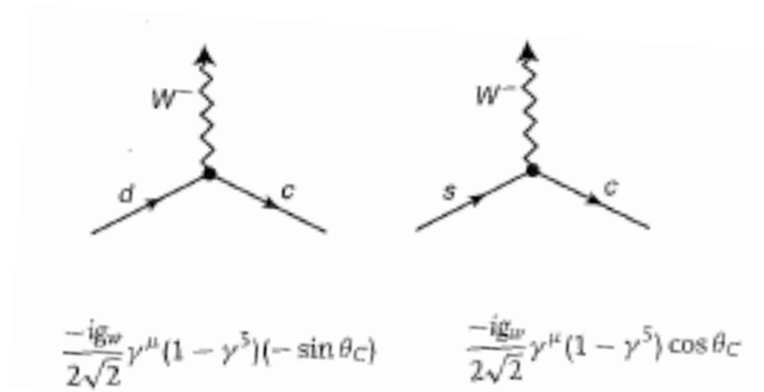
GIM mechanism (1974)

- The Cabibbo angle was explaining very well decays with ΔS=0 or ΔS=1. But there was still a problem, the very low BR of K^0 mesons in two muons.
- **Glashow, Iliopoulos and Maiani** introduced a 4th quark, to explain it, the second diagram almost cancels the first one



$$\begin{pmatrix} u \\ d' = d\cos\vartheta_c + s\sin\vartheta_c \end{pmatrix} \begin{pmatrix} c \\ s' = -d\sin\vartheta_c + s\cos\vartheta_c \end{pmatrix}$$

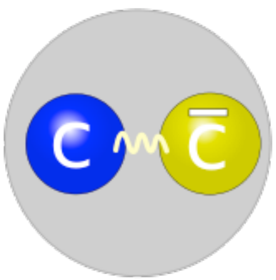
In summary, the W does not couple directly to d,s, but to the rotated weak (isospin) eigenstates d', s'



What happens for 3 quarks? Is there an analogy in the lepton sector?

The J/Psi particle

The success of the Cabibbo+GIM mechanism culminated with the discovery of **charm**, i.e. the J/Psi during the November 1974 revolution



$J/\psi(1S)$ $\qquad I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 3096.900 \pm 0.006$ MeV
Full width $\Gamma = 92.9 \pm 2.8$ keV $\quad (S = 1.1)$
$\Gamma_{ee} = 5.53 \pm 0.10$ keV
$\Gamma_{ee} < 5.4$ eV, CL = 90%

$J/\psi(1S)$ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
hadrons		(87.7 ± 0.5) %		–
virtual $\gamma \to$ hadrons		(13.50 ± 0.30) %		–
ggg		(64.1 ± 1.0) %		–
γgg		(8.8 ± 1.1) %		–
e^+e^-		(5.971 ± 0.032) %		1548
$e^+e^-\gamma$	[a]	$(8.8 \pm 1.4) \times 10^{-3}$		1548
$\mu^+\mu^-$		(5.961 ± 0.033) %		1545

HTTP://PDG.LBL.GOV $\qquad$ Page 2 $\qquad$ Created: 6/1/2020 08:28

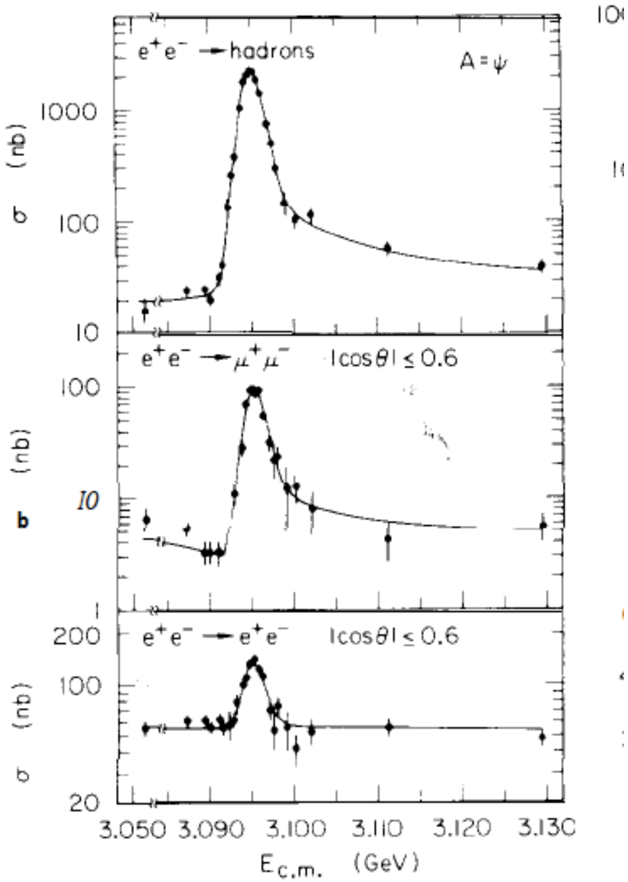
Font= PDG: do you know the PDG?

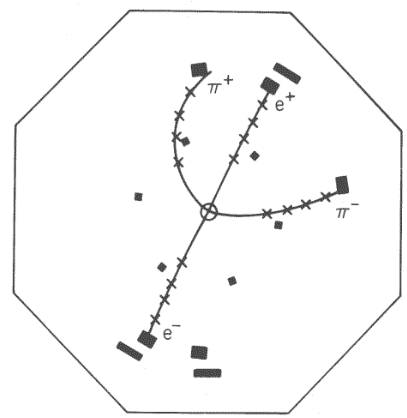
The discovery of the J/Psi was a big success for the quark model

Discovery of the J/Psi (1974)

Richter et al. Observation of a resonance around 3 GeV in scanning the energy in e^+e^- collisions at SPEAR (SLAC)

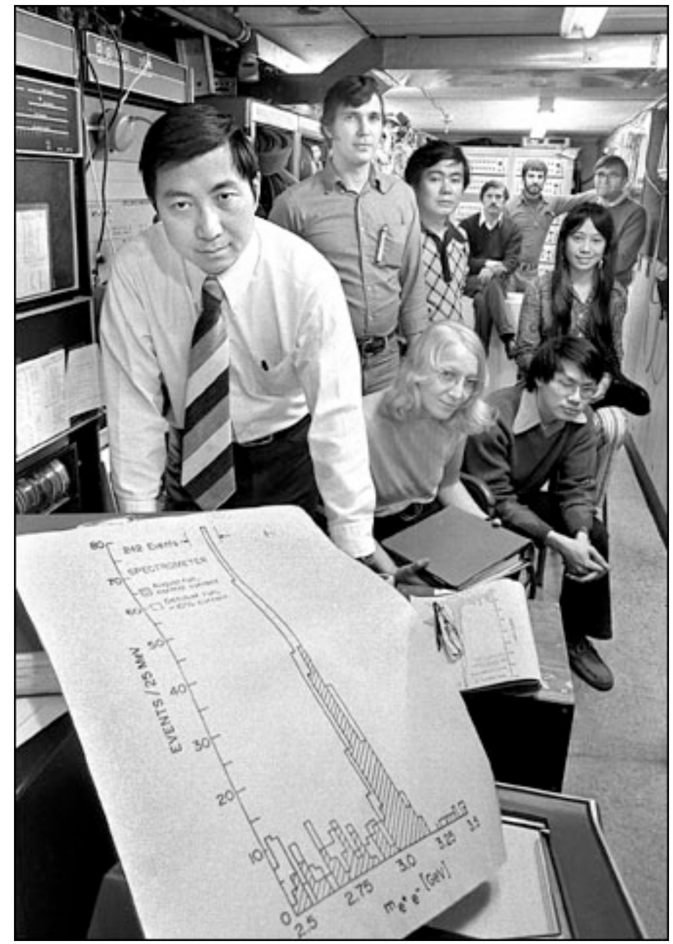
Ting et al. at the same time in fixed target at BNL, he called it J





Ten days later at SLAC they discovered the next excited state, the Psi' (November revolution)

The J/Psi discovery established the quark model



Fonts: SLAC, BNL

Charmonium

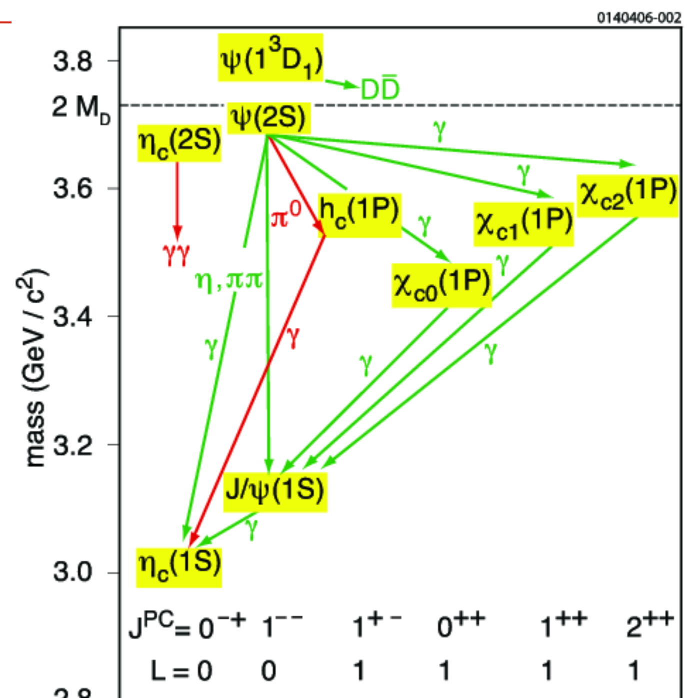
• The J/Psi a bound state of quark-antiquark, $J^{PC}=1^{--}$
• A testbed for the strong interaction: charm is heavy, spectrum of excited states similar to positronium bound state - but with binding force at the ~MeV scale (positronium at the eV scale)
• First states are narrow (Γ(J/psi)=86 KeV). Psi(3770) is the first state that can decay in D mesons, so large width- weak decay

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + F_0 r$$

Short range potential with colour factor

Speculative potential describing confinement

What is confinement? (More in the QCD lectures)



Font: Griffiths, arXiv:0710.1884

Discovery of the 3rd generation

$$e^+ e^- \rightarrow \tau^+ \tau^-$$

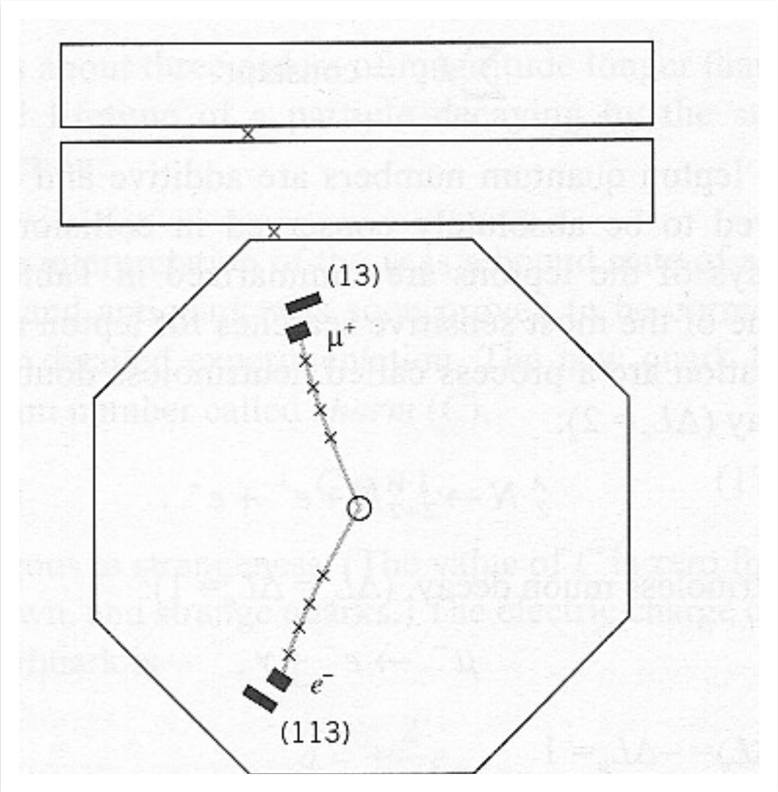
$$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$$

$$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$$

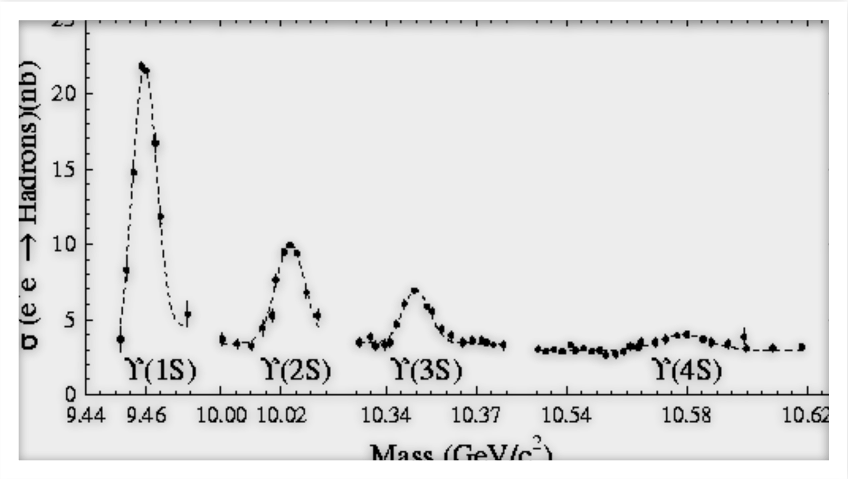
Discovery of the Tau lepton (1975)

In acoplanar electron-muon candidates

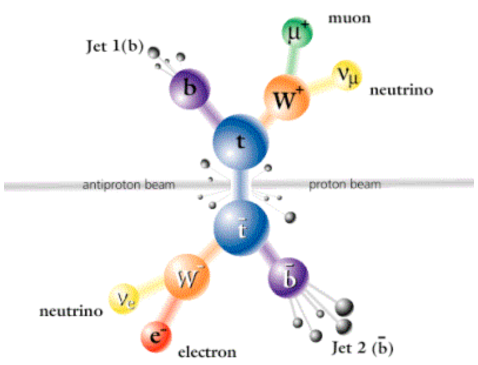
Which quantum numbers are involved?

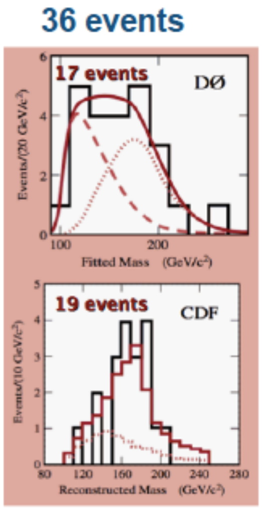


Discovery of the 3rd generation



Discovery of the 5th quark with the observation of the Upsilon ($b\bar{b}$) resonance (1977)



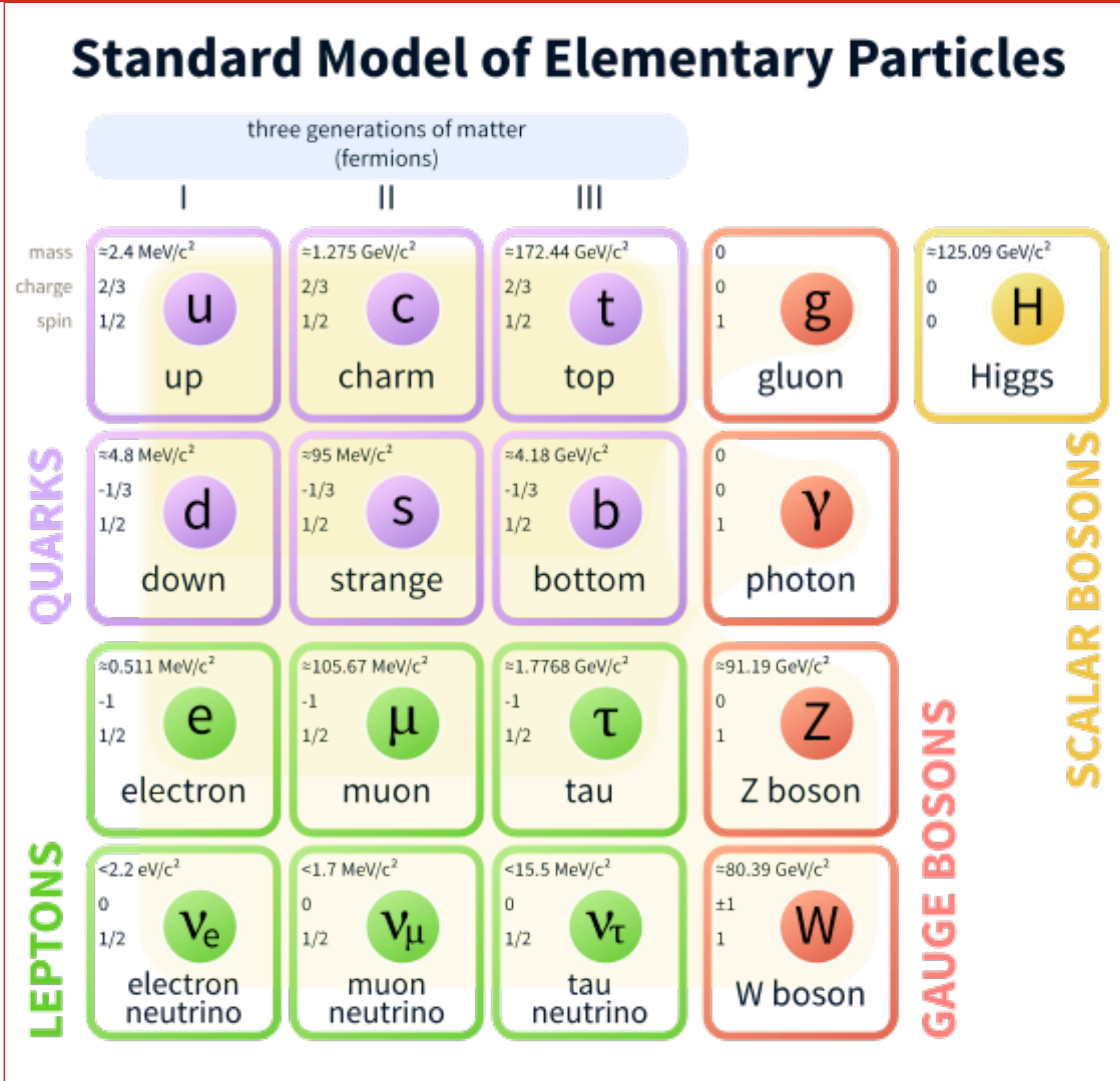


Discovery of the top quarks at the Tevatron (1995)

Why is the top special?

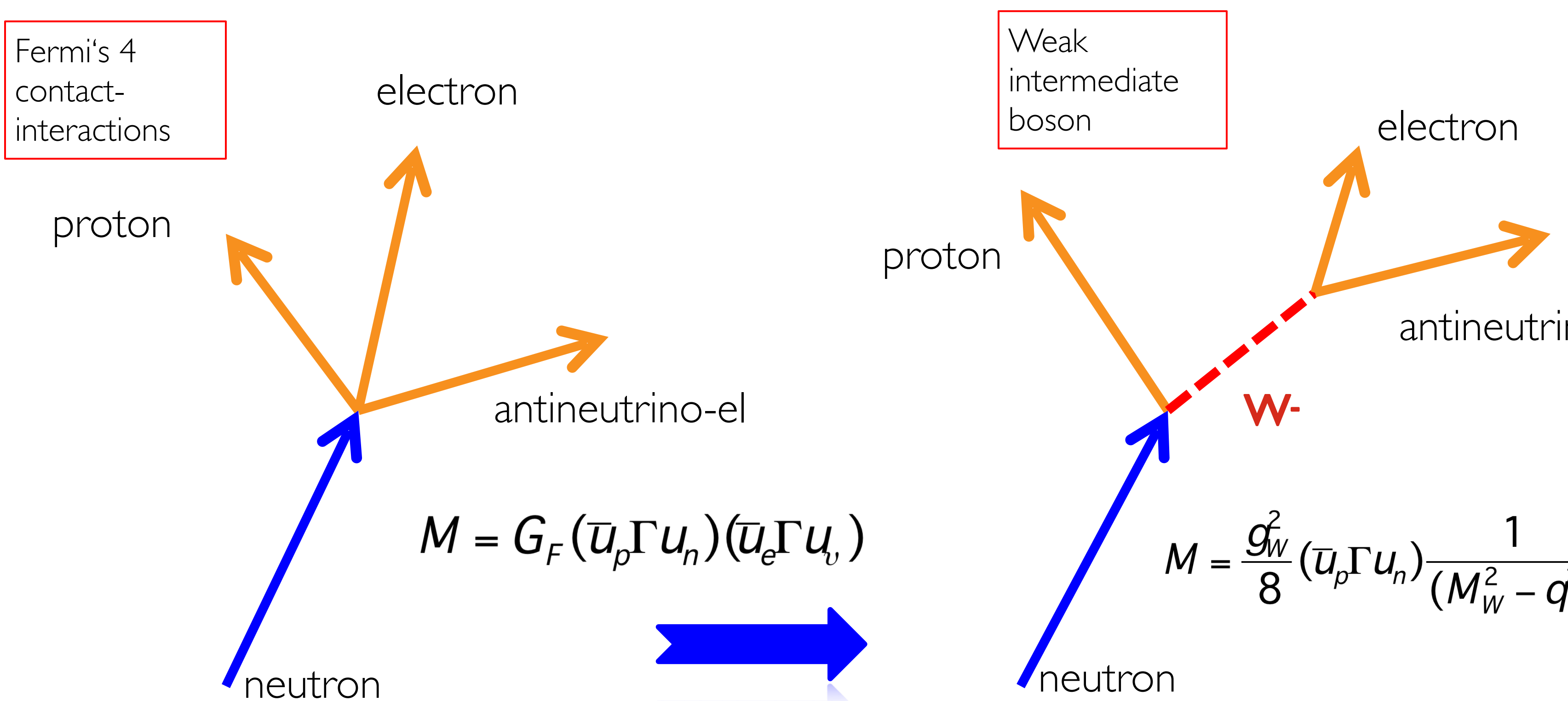
Is there a toponium?

Summary of particles



Weak interactions

The first theory of beta decay is from **Fermi** (1933), a contact interaction with coupling G_F^2, which was describing the decay well at low energy. However the theory would fail at higher energy, predicting a cross section rising infinitely to high $\sqrt{s}$ -> a theory with an intermediate vector boson was proposed

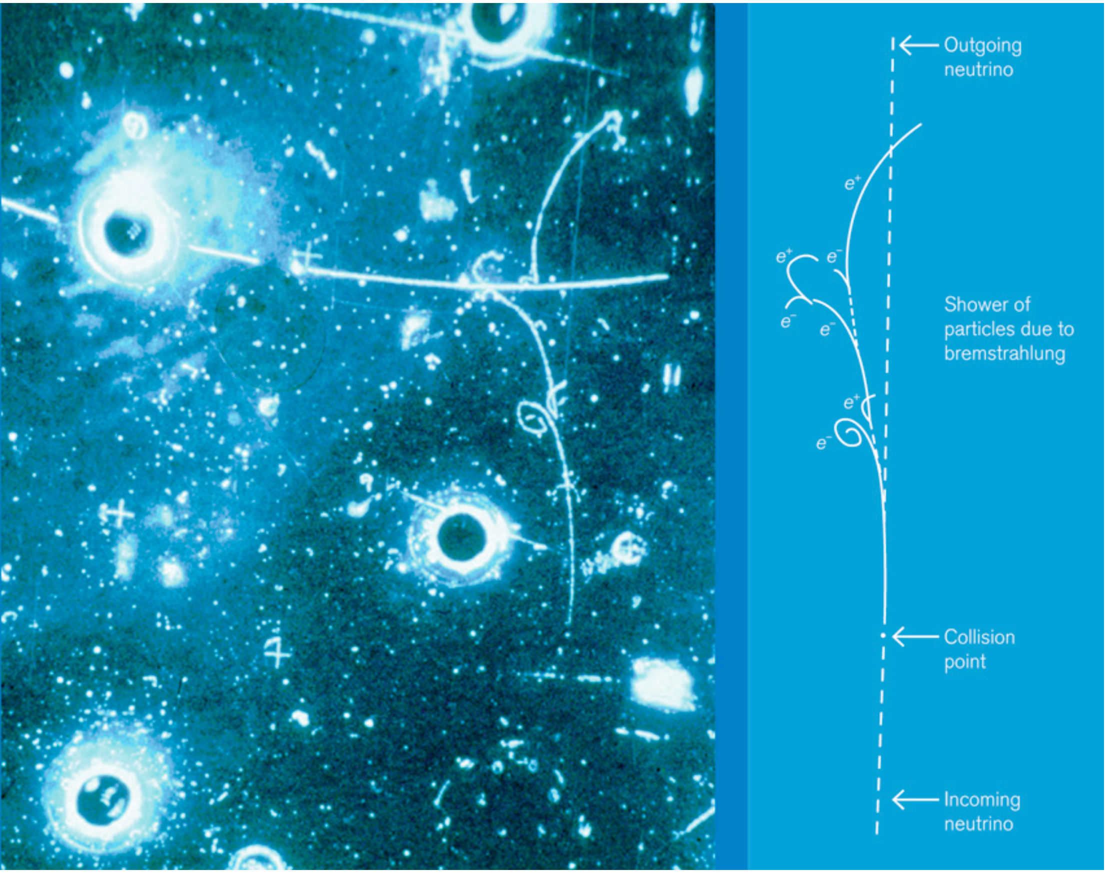


$$M = G_F (\bar{u}_p \Gamma u_n)(\bar{u}_e \Gamma u_\nu)$$

$$M = \frac{g_W^2}{8} (\bar{u}_p \Gamma u_n) \frac{1}{(M_W^2 - q^2)} (\bar{u}_e \Gamma u_\nu)$$

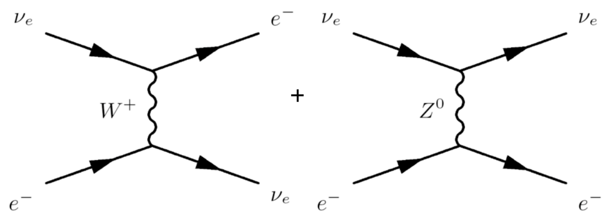
Note: EFT theories today, which similarities are there?

Discovery of neutral currents



Gargamelle bubble chamber, 1973
A very large heavy liquid (freon) chamber, 4m long, in 2T B field

- First milestone in weak interactions



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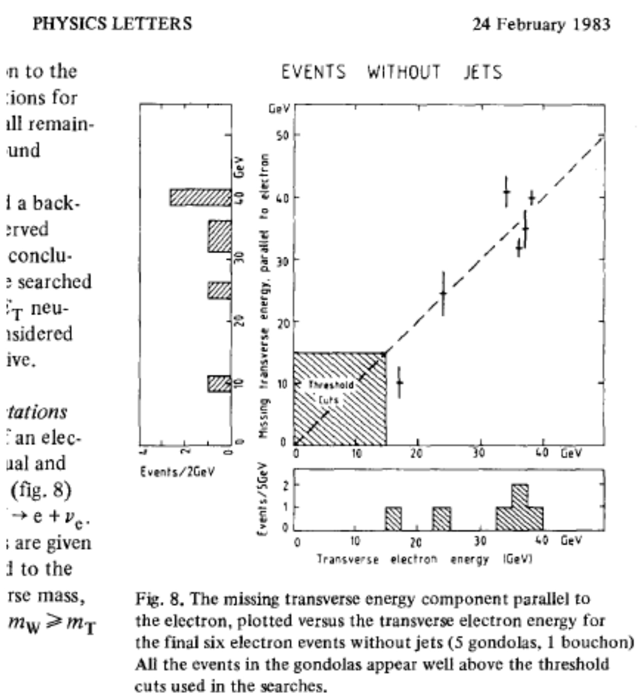
Font: CERN

Discovery of W and Z (1983)


PHYSICS LETTERS 24 February 1983

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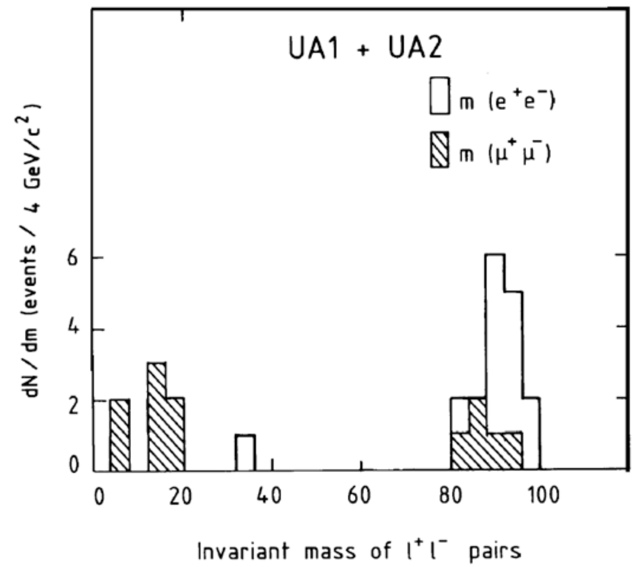
$m_W \geq m_T$

Fig. 8. The missing transverse energy component parallel to the electron, plotted versus the transverse electron energy for the final six electron events without jets (5 gondolas, 1 bouchon) All the events in the gondolas appear well above the threshold cuts used in the searches.

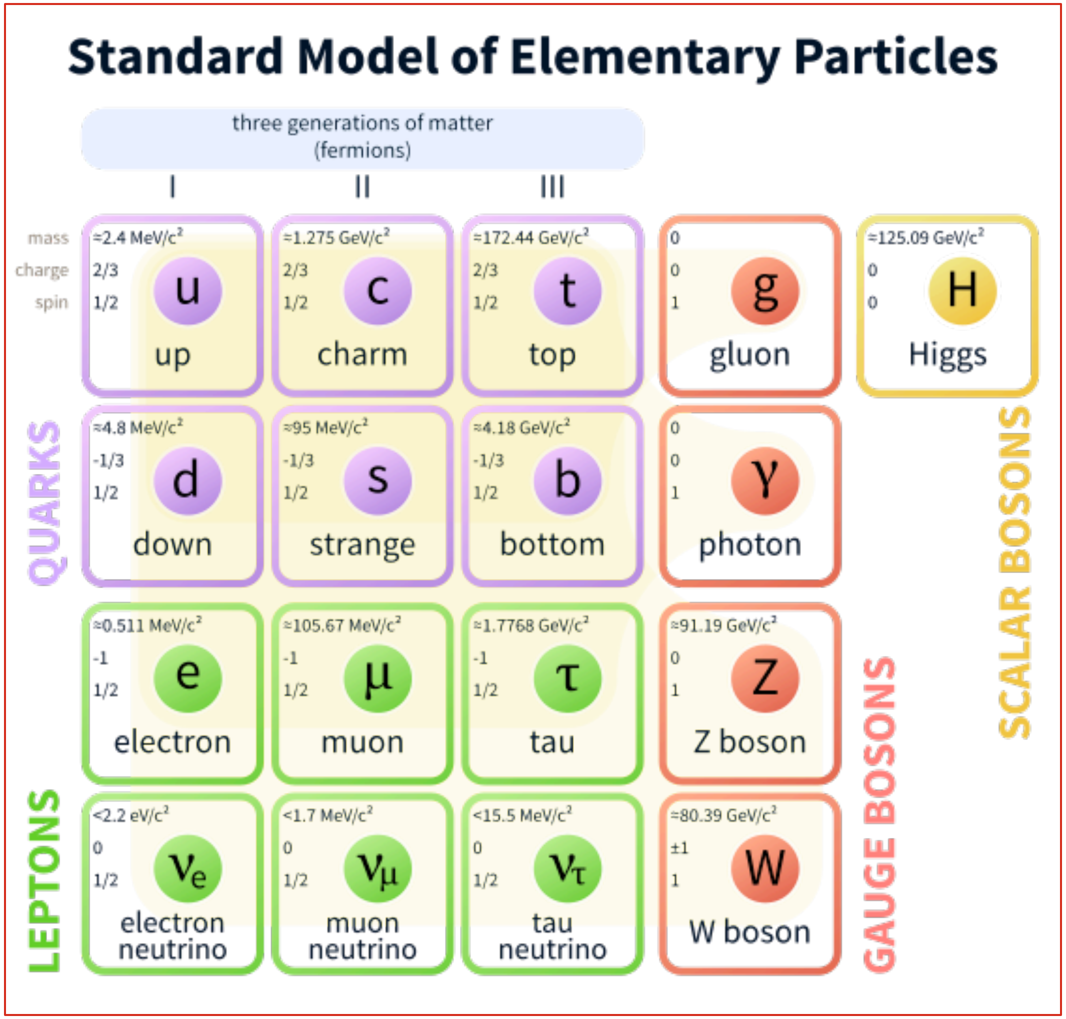


Second milestone in weak interaction

UA1+UA2 at CERN

Font: CERN

Intermediate bosons



But no mechanism to generate W, Z mass in the SM theory

Mass

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.[3] In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.[4-6] A those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce both vector and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local γ_5-phase transformations. In this model the gauge fields themselves may break the γ_5 invariance leading to a mass for the original Fermi field. We shall show in this case that the pseudovector field acquires mass.

In the last paragraph we sketch a simple argument which renders these results reason-

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson[3] has drawn attention: that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged.

about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \qquad (2a)$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \qquad (2b)$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \qquad (2c)$$

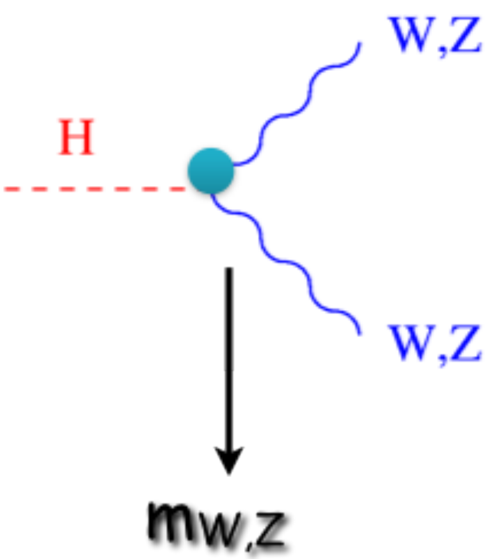
Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

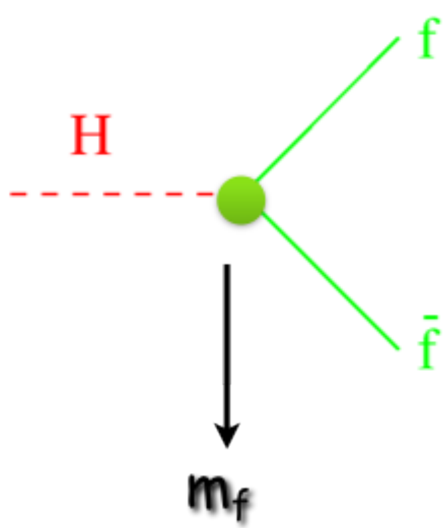
$$B_\mu = A_\mu - (e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

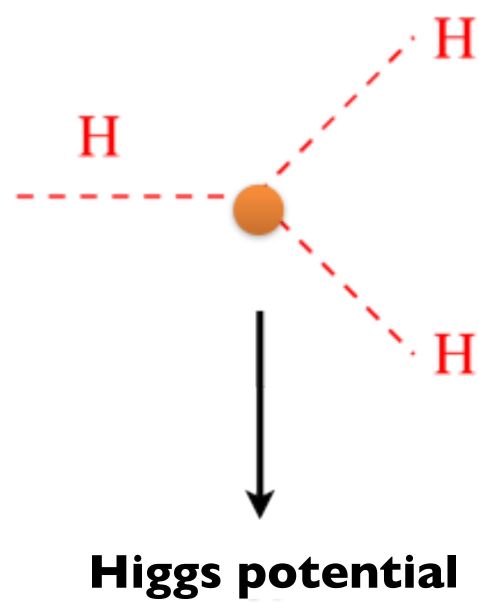
$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \qquad (3)$$

into the form

$$\partial_\mu B^\mu = 0, \quad \partial_\nu G^{\mu\nu} + e^2\varphi_0^2 B^\mu = 0. \qquad (4)$$

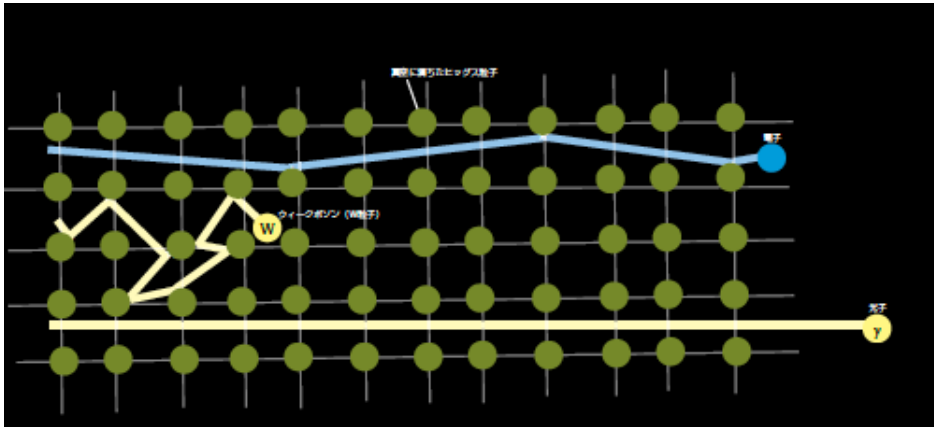






Mass

We are immersed in a field, the Higgs field, of which the H boson is the excitation, and gives mass to all particle, (electron, quarks, ….we would not exist without the H boson). Short film at https://www.youtube.com/watch?v=QVMQ3_somZc



Font: Hitoshi Murayama

How the Higgs affects us

Particle whose mass is set by the interaction with the Higgs field	Role of the particle masses	Impact on everyday life	Has the Higgs-particle interaction been experimentally confirmed?
Up quark (m_{up} ~2.2 MeV/c^2) Down quark (m_{down} ~4.7 MeV/c^2)	Affects the mass of the proton and neutron	Differences in quark masses ($m_{up} < m_{down}$) contribute to protons (made of two up and one down quarks) being lighter than neutrons (made of one up and two down quarks). As a result, protons are stable, as required for the existence of hydrogen.	No
Electron	Atomic radius ~ $1/m_e$	A different value of the electron mass would modify the energy levels and chemical reactions of all known elements.	No
W boson	Radioactive beta decay rate ~ $1/m_W^4$	Many radioactive decays, and the fusion reactions that power the sun, involve the W boson. The W mass affects the rate of all of these reactions.	Yes

More in the lectures of Katharina Behr

Font: Nature theory paper for 10th Higgs anniversary

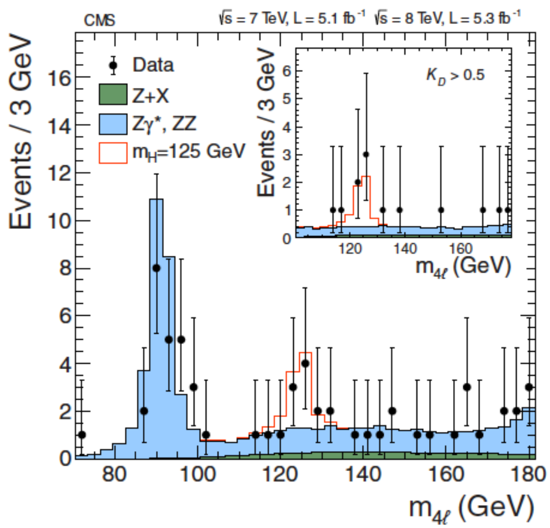
4th July 2012 and 2022 at CERN

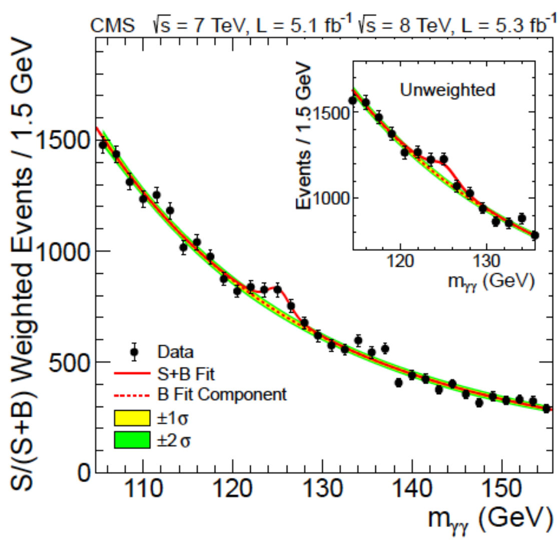
2012, Announcement of the Higgs discovery by ATLAS and CMS

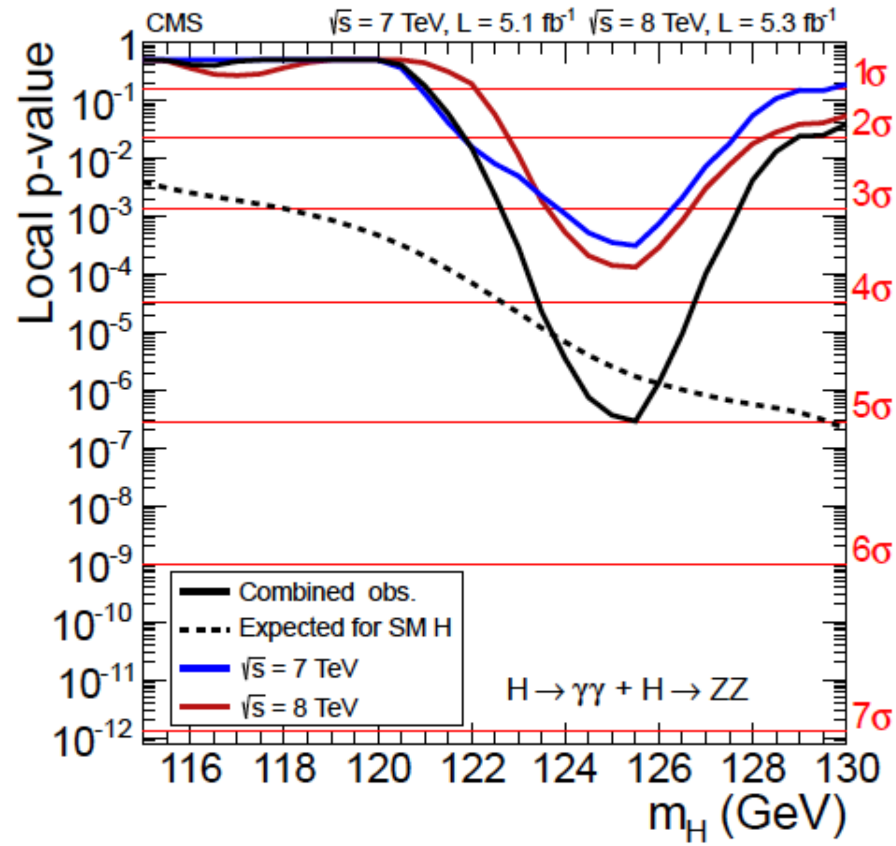
ATLAS 10 years paper
CMS 10 years paper
Theory 10 years paper (I advice this!)

10 years later Auditorium still full

A new boson at m_H~125 GeV

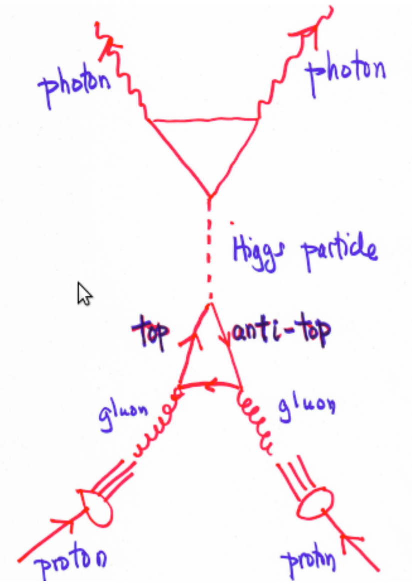


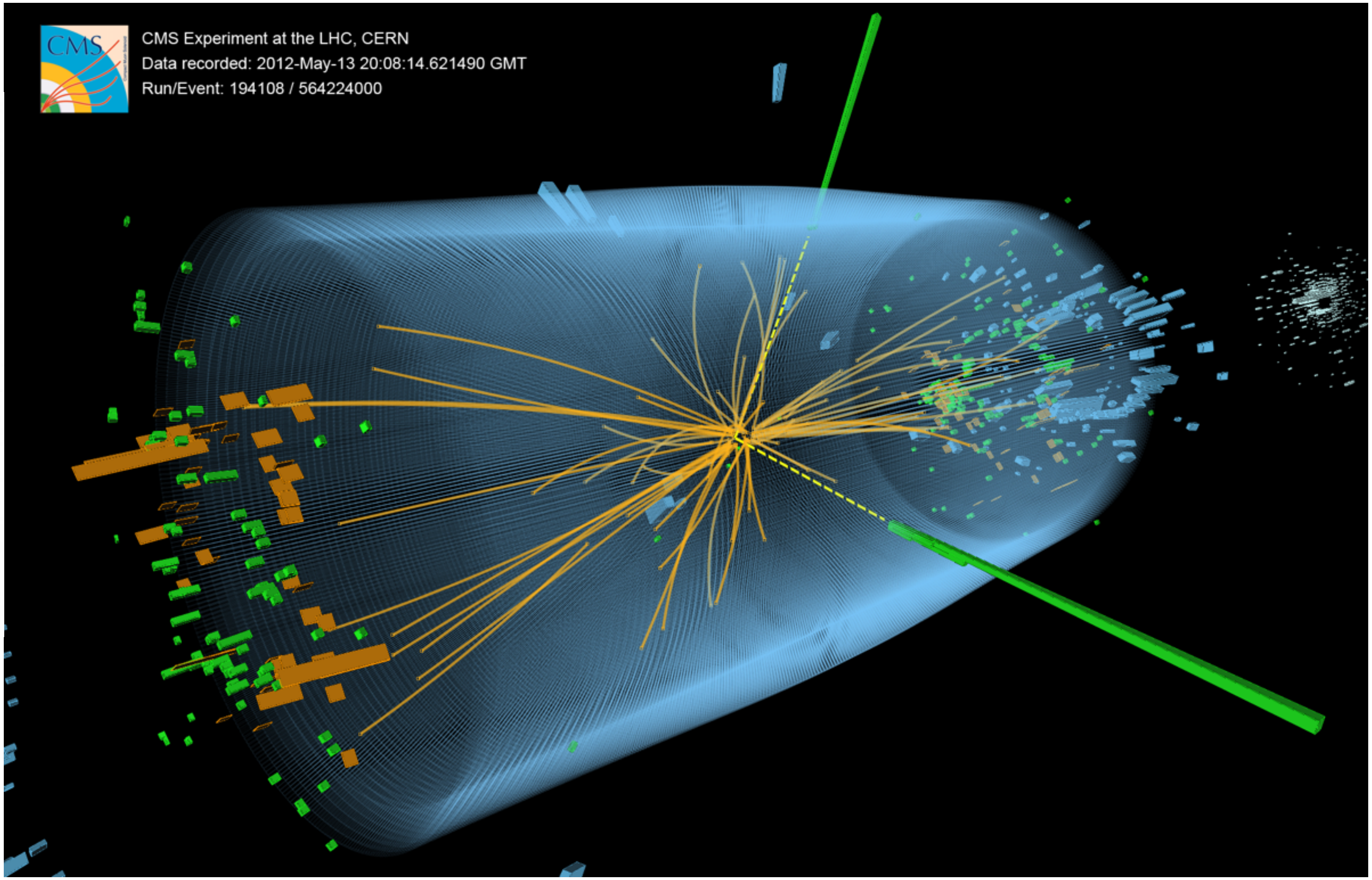




p-value, probability to have >= Nevents as those effectively observed, under the hypothesis of no signal.

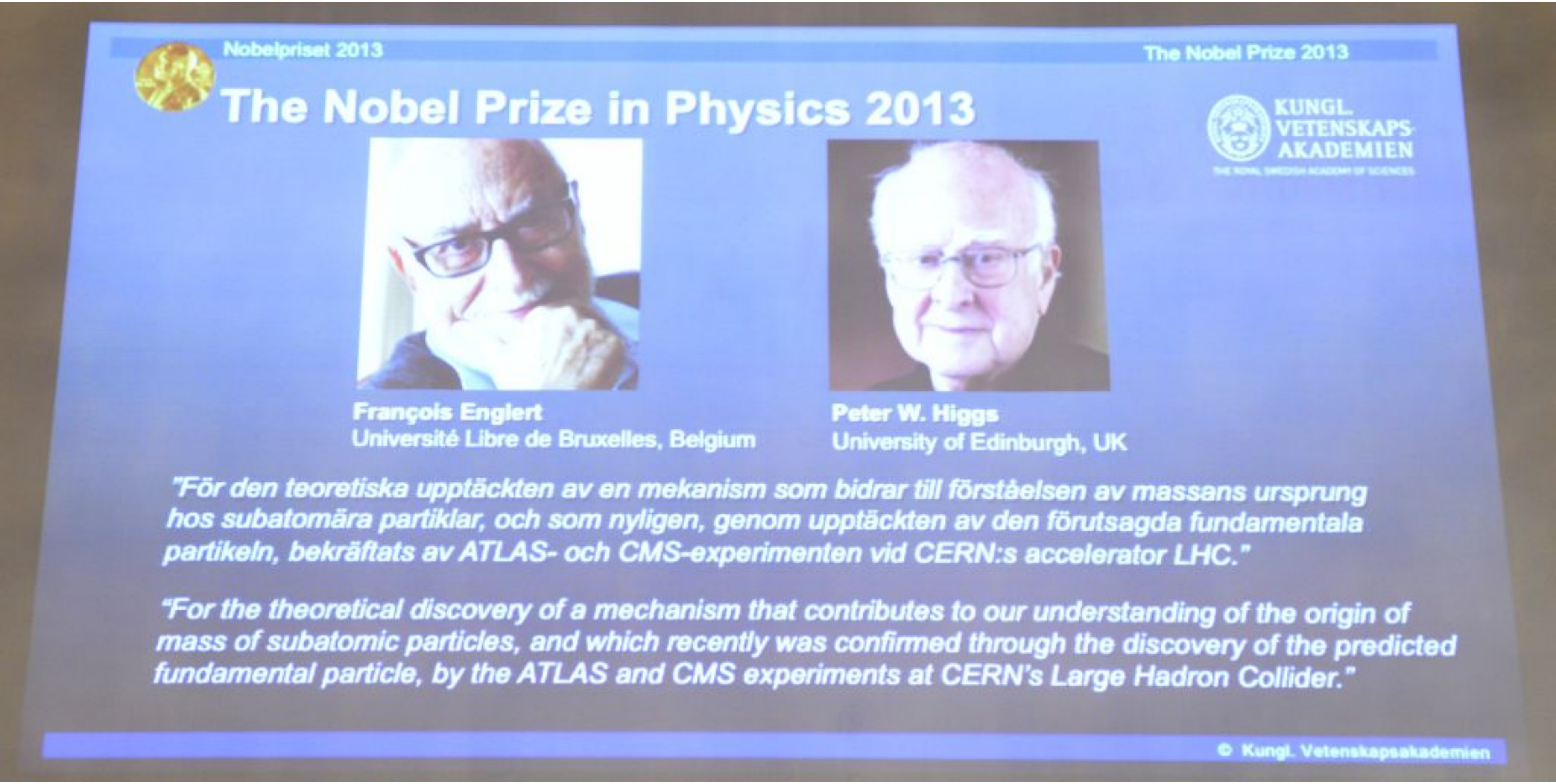
a Higgs -> γγ event



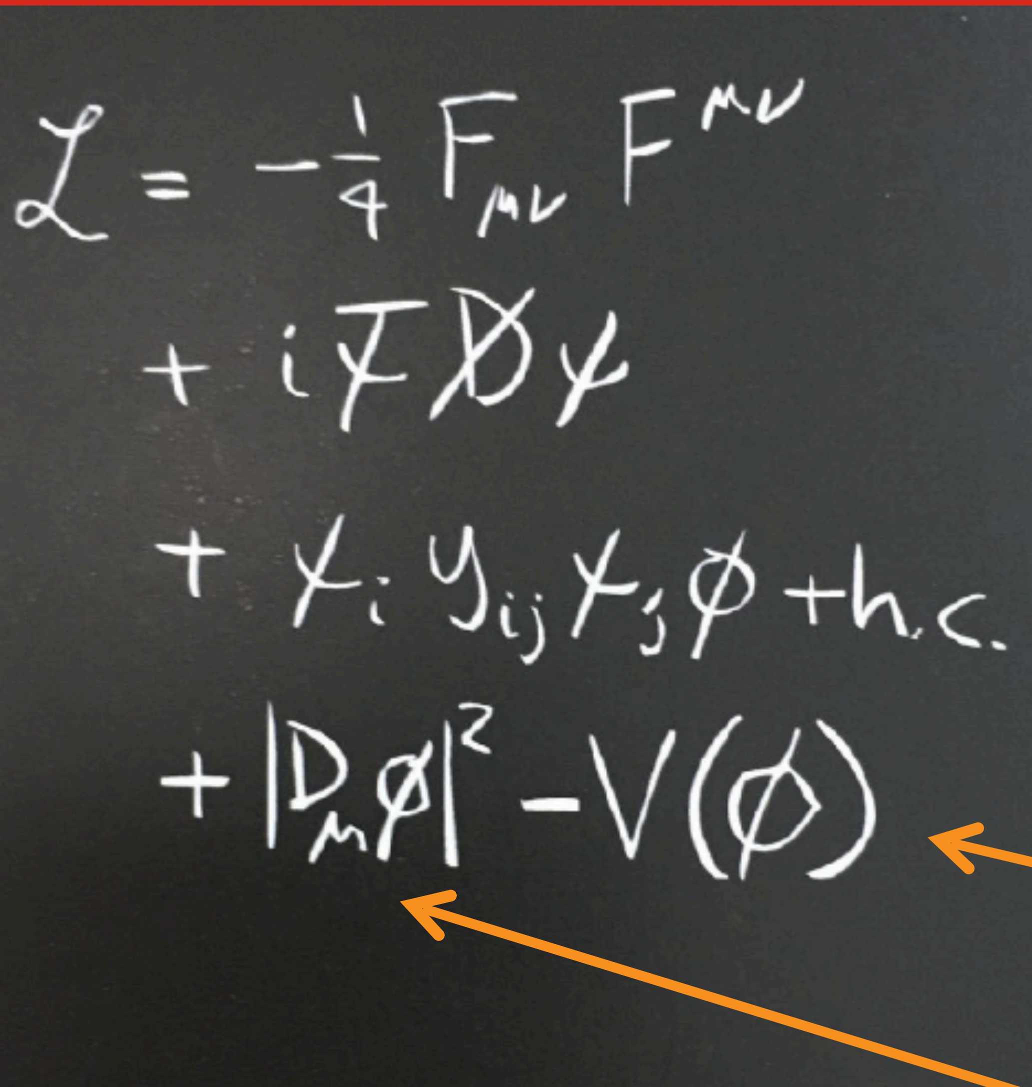


Higgs: only scalar (spin=0) elementary boson known up to now

2013 Nobel prize



The SM Lagrangian



Gauge sector (80s-90s)

Interaction of gauge fields with fermions (80s-90s)

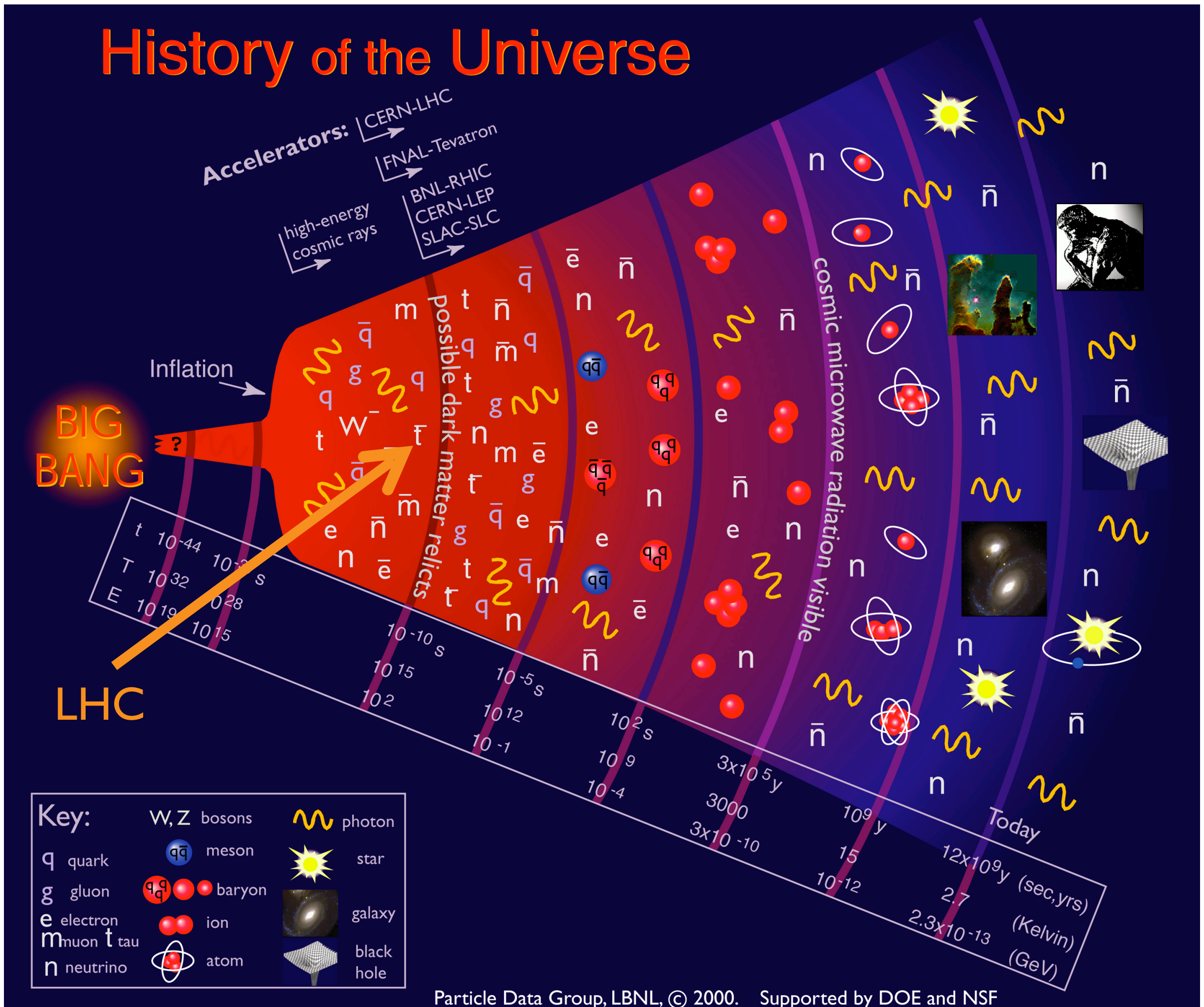
Higgs field interaction with fermions (observed 2017-2018 ~ 10% precision)

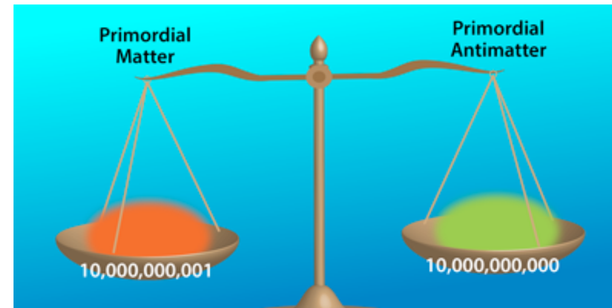
Higgs potential (not yet measured!)

Gauge-Higgs interaction (observed 2012 ~ 5-8% precision)

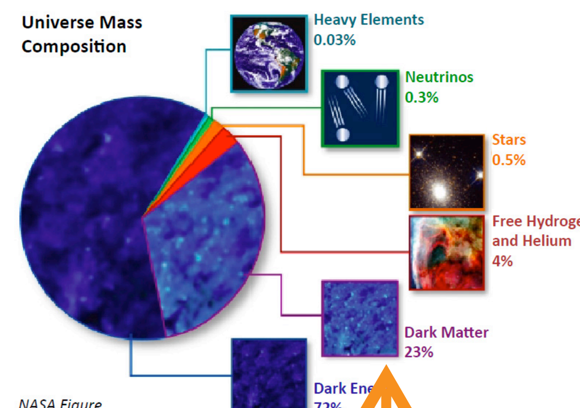
Font: Gavin Salam's talk, CMS meeting, CERN T-shirt

Particle physics in the Universe





CP violation



WIMP at the LHC

Font:APS, DOE, NSF, Nasa