Introduction to particle physics

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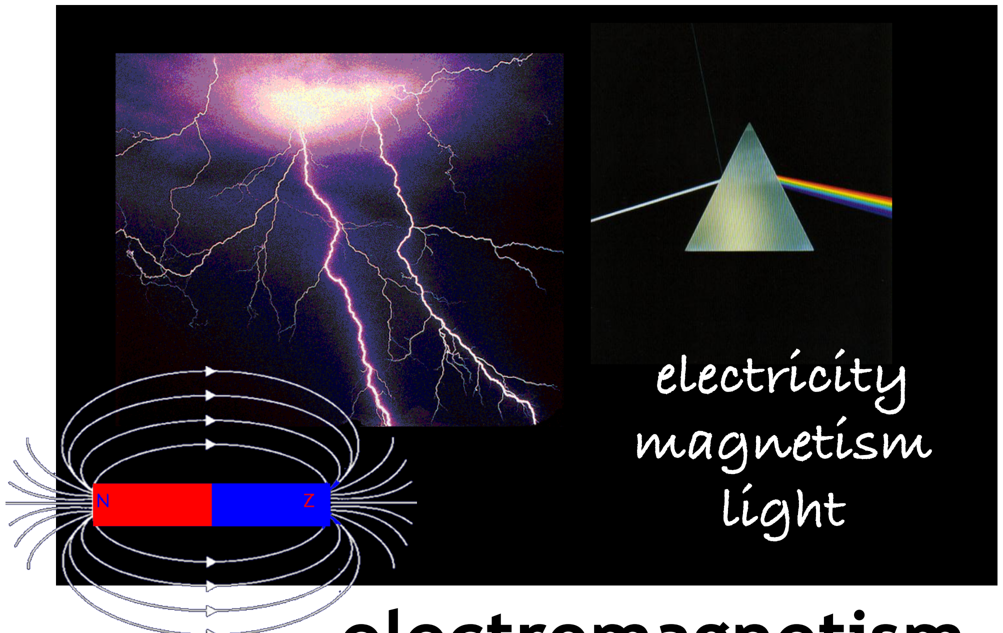
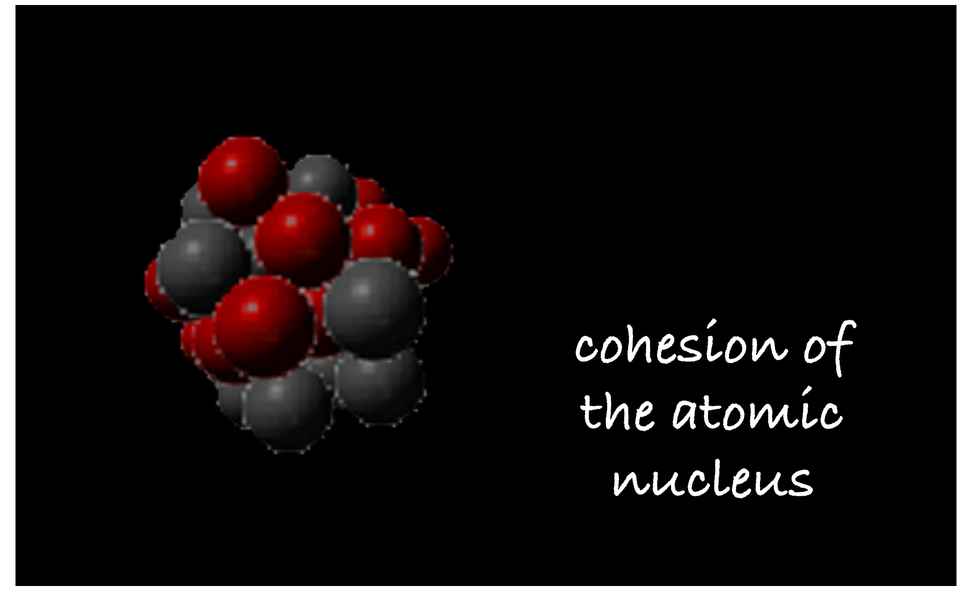
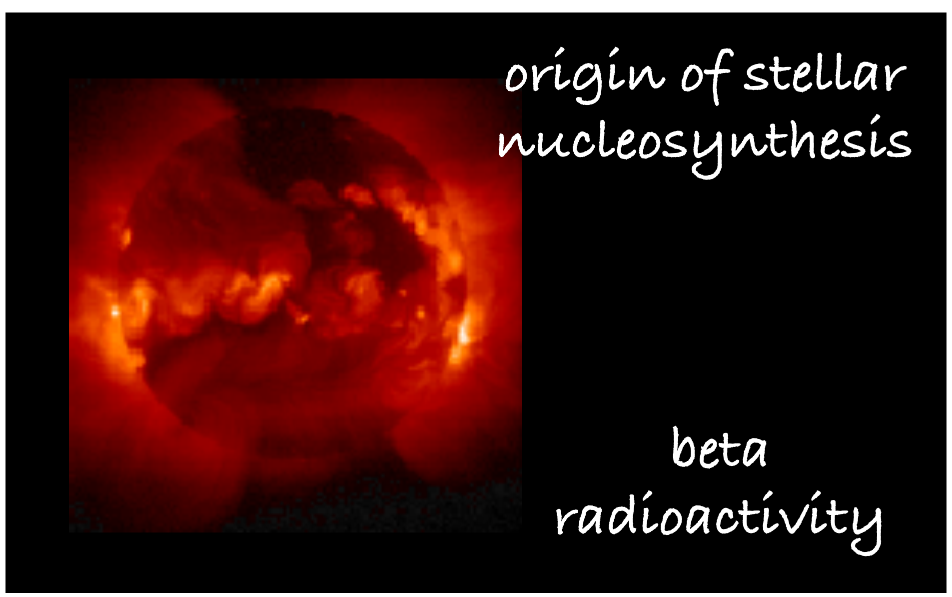
Four fundamental interactions



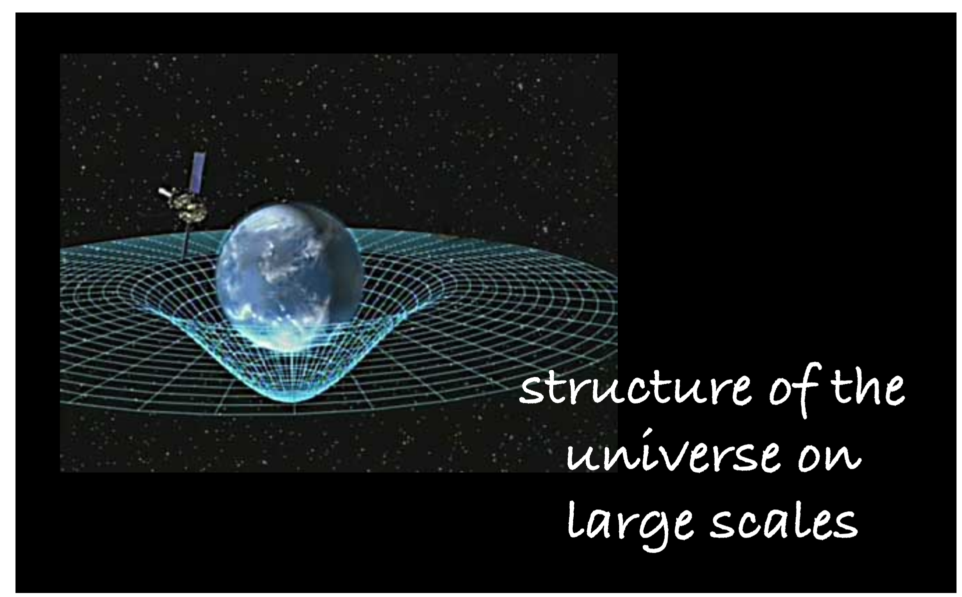
electromagnetism



strong nuclear force



weak nuclear force



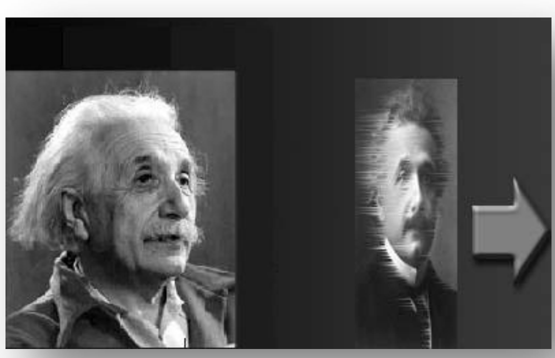
gravitational

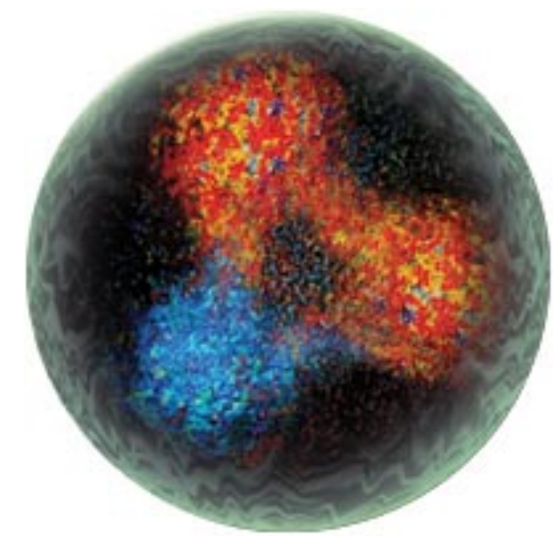
The theories of physics

small →

fast ↓

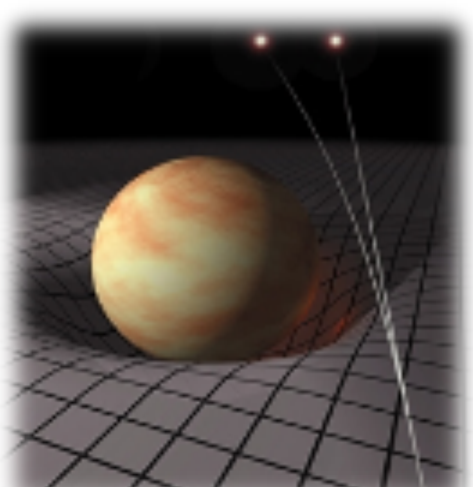
Classical Physics	**Quantum Mechanics**
Special Relativity	**Quantum Field Theory**





on very large scales

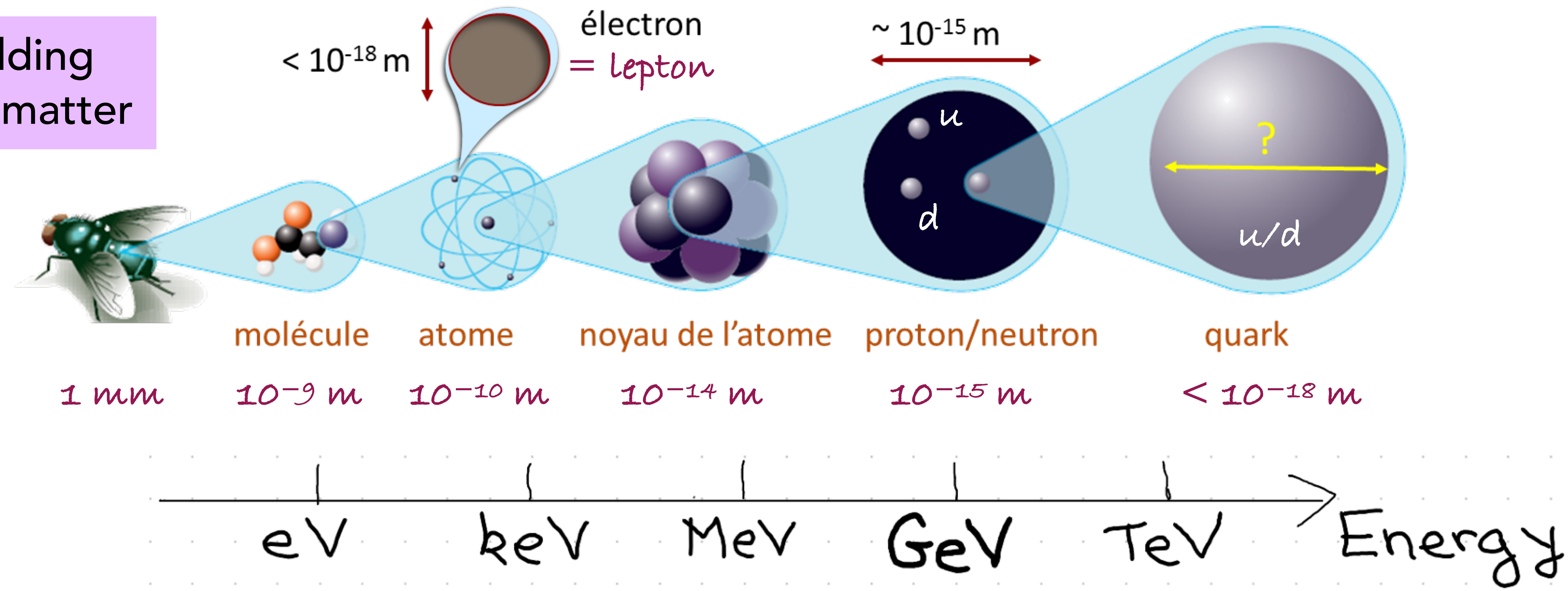
General Relativity



Quantum field theory is the theoretical framework of particle physics

Elementary particles

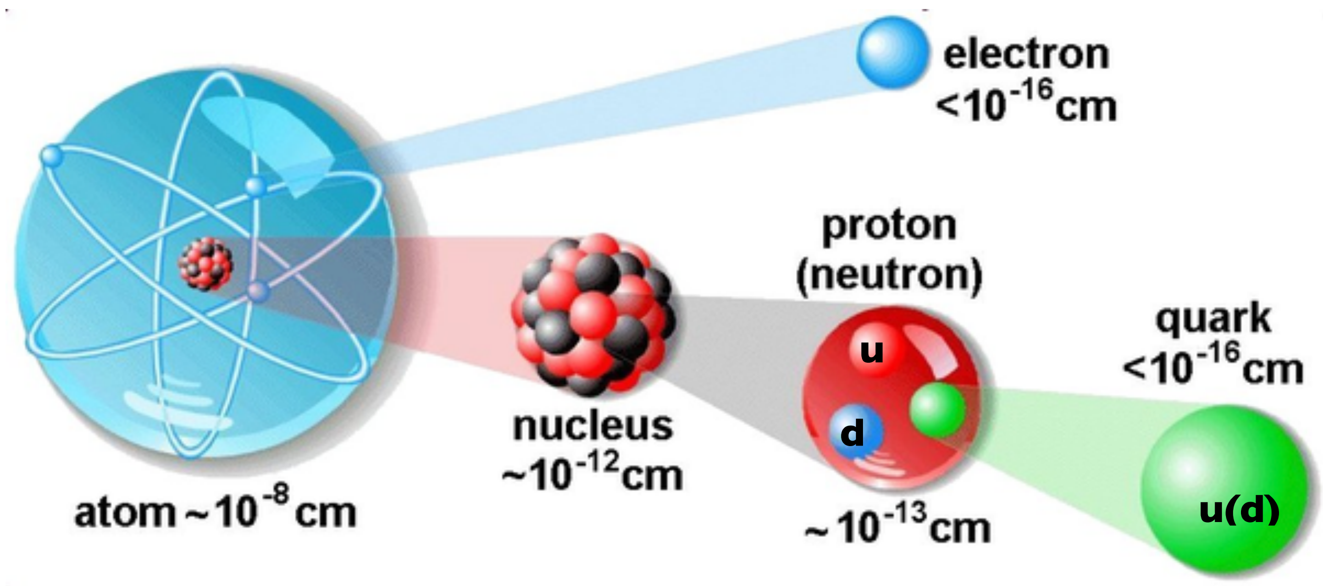
The building blocks of matter



Elementary particles

Spin 0	Spin 1/2	Spin 1	Spin 3/2	Spin 2
Higgs	leptons	photon		graviton ?
	quarks	Z W^+ W^-	?	
		gluons		
	matter	forces		gravitation

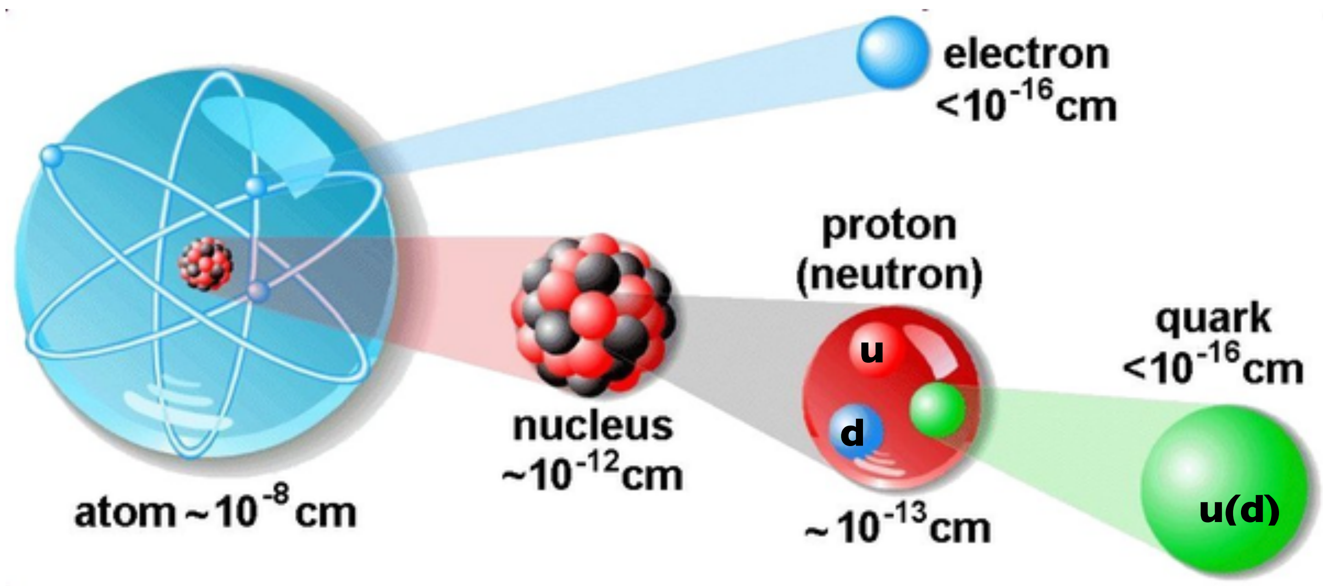
Particles and Interactions



The Standard Model (SM) of particle physics describes elementary particles and their interactions:

- Quarks and leptons
- Force vectors = gauge bosons

Particles and Interactions



The Standard Model (SM) of particle physics describes elementary particles and their interactions:

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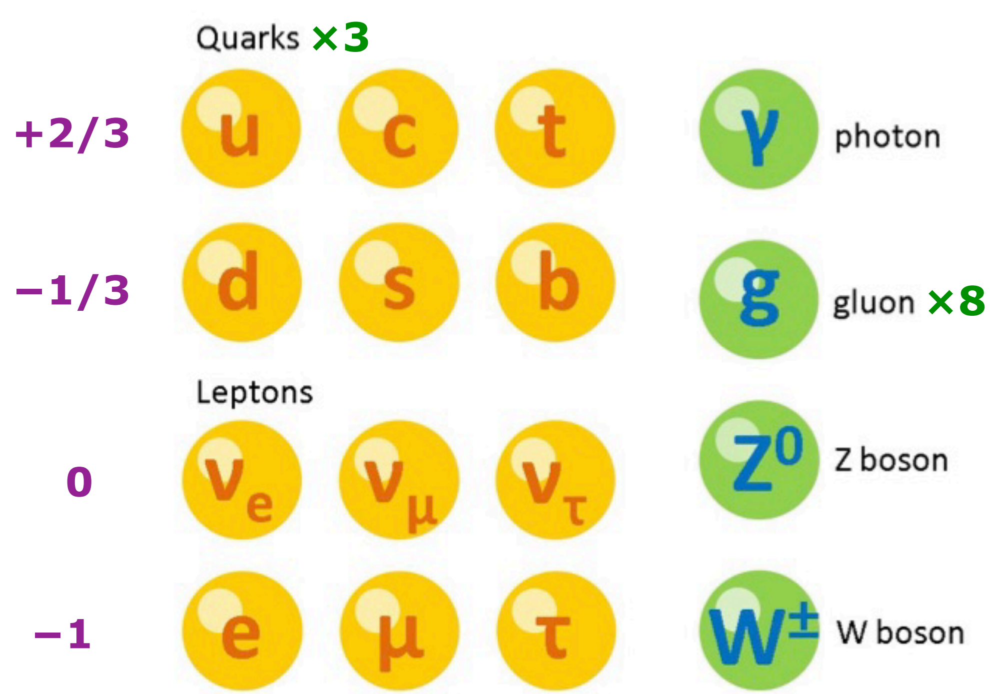
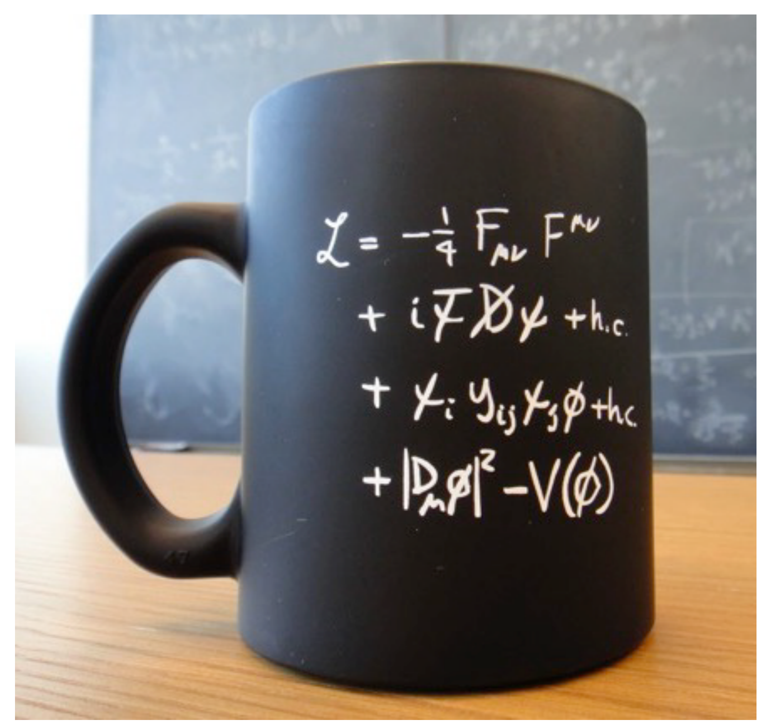
matter *(fermions)*	forces *(vector bosons)*



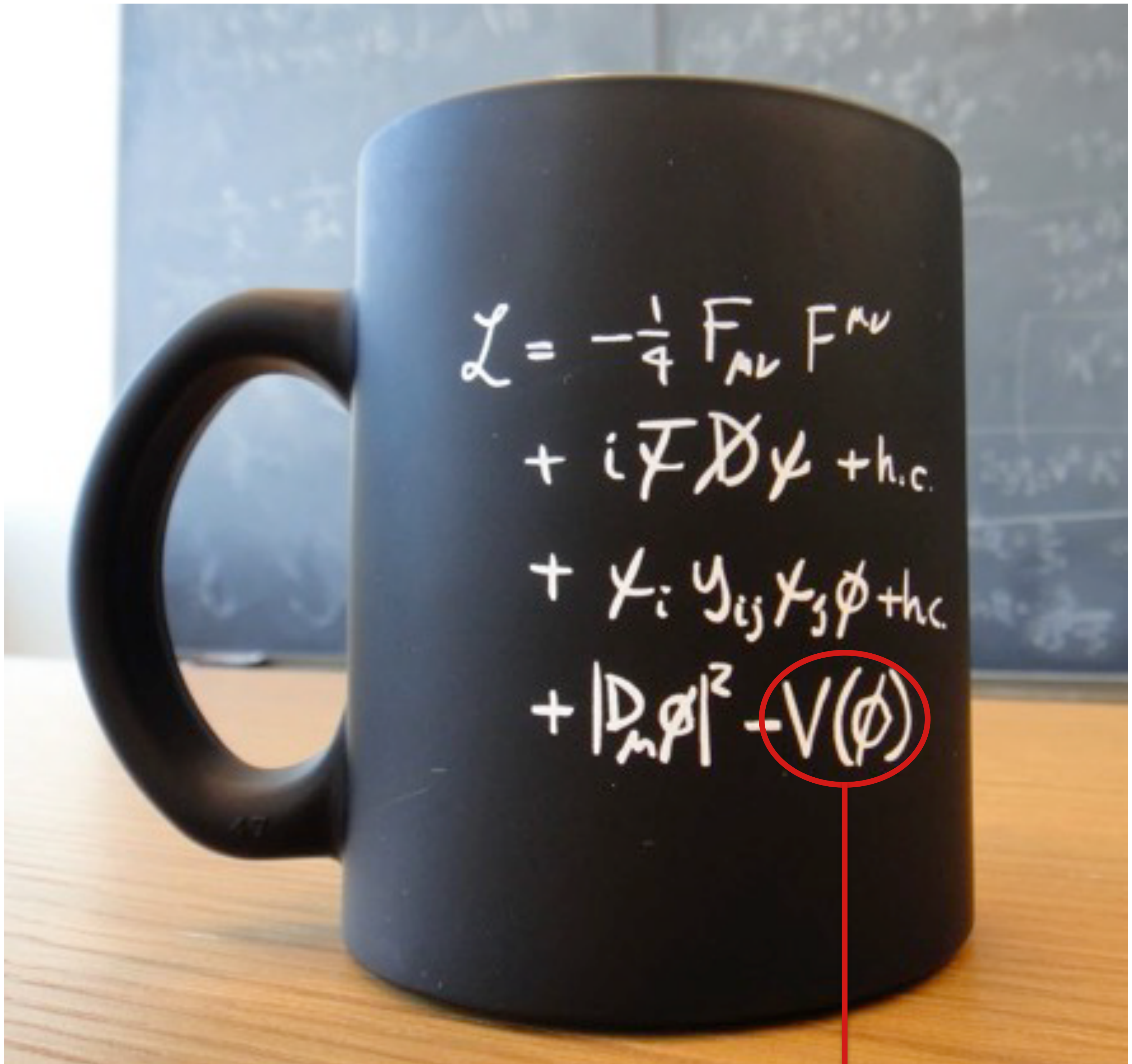
3 "families" of
Quark & leptons

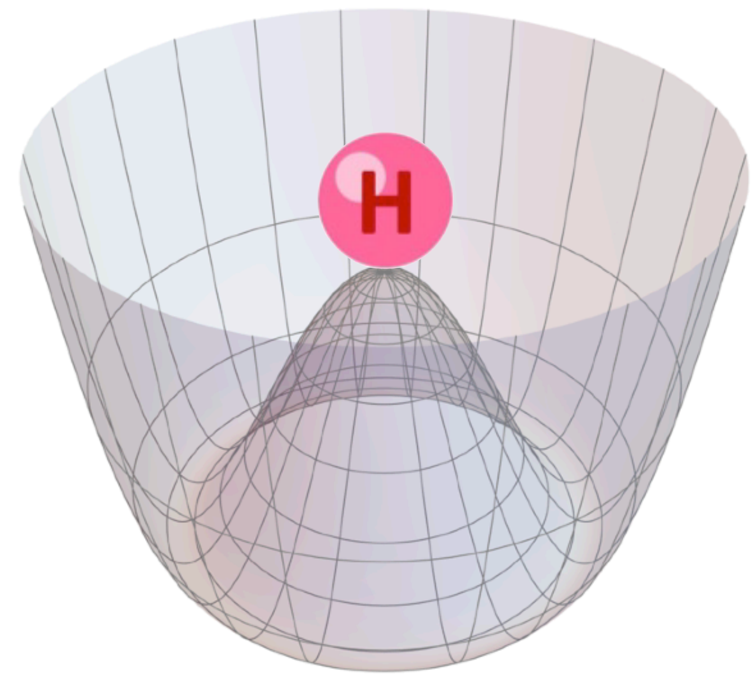


... and the
Higgs boson

Higgs boson

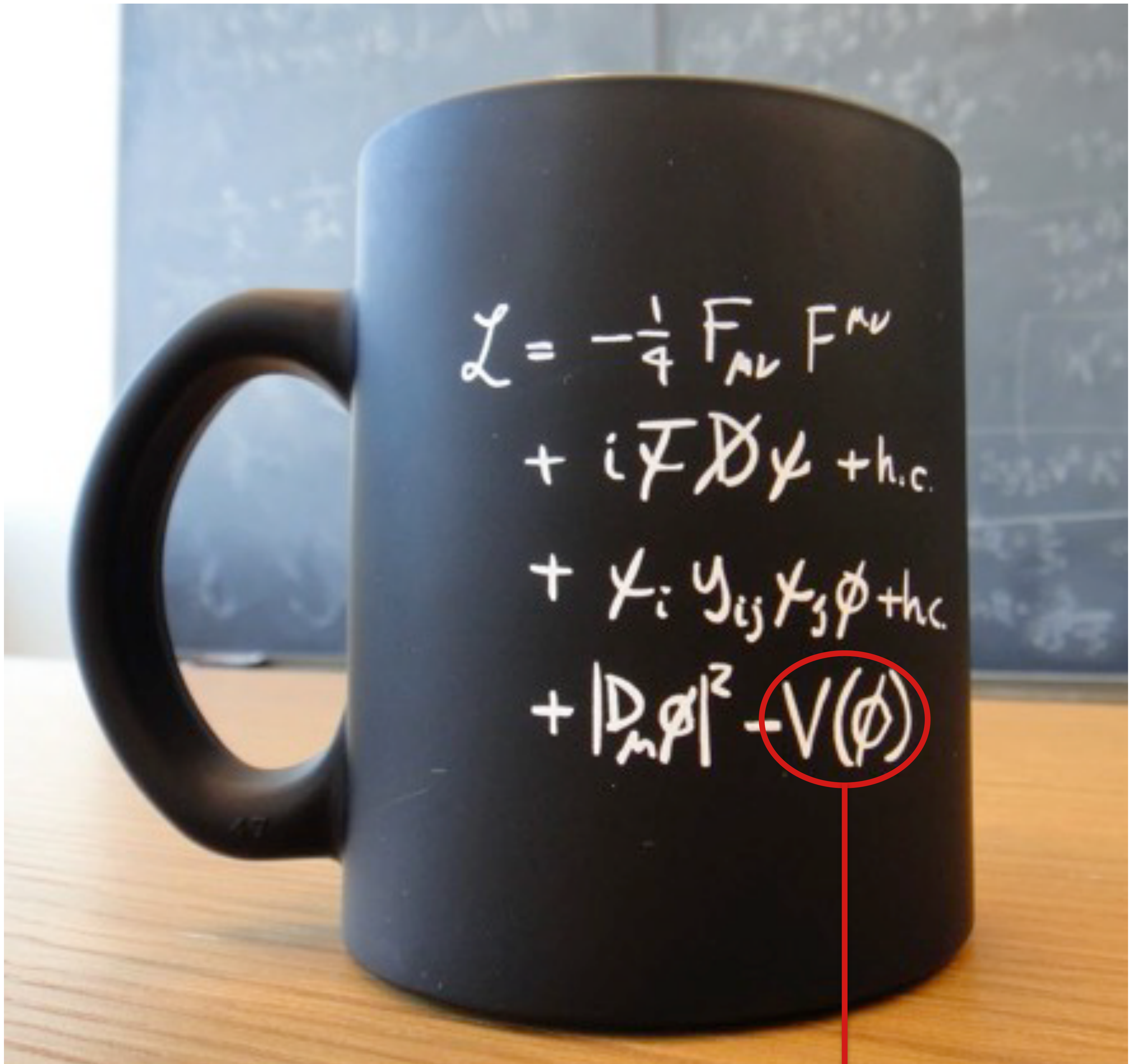
Electroweak Symmetry Breaking

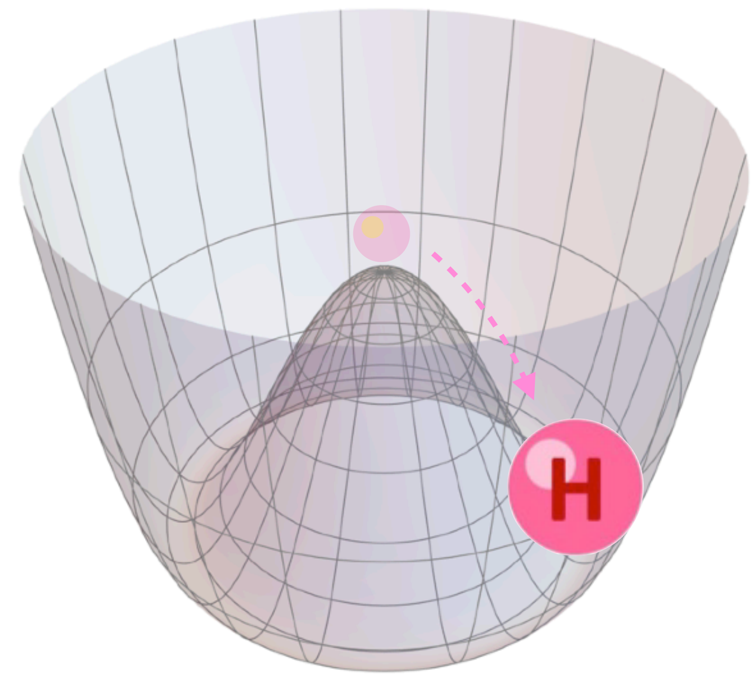




$V(\phi)$ = the Higgs field *potential*

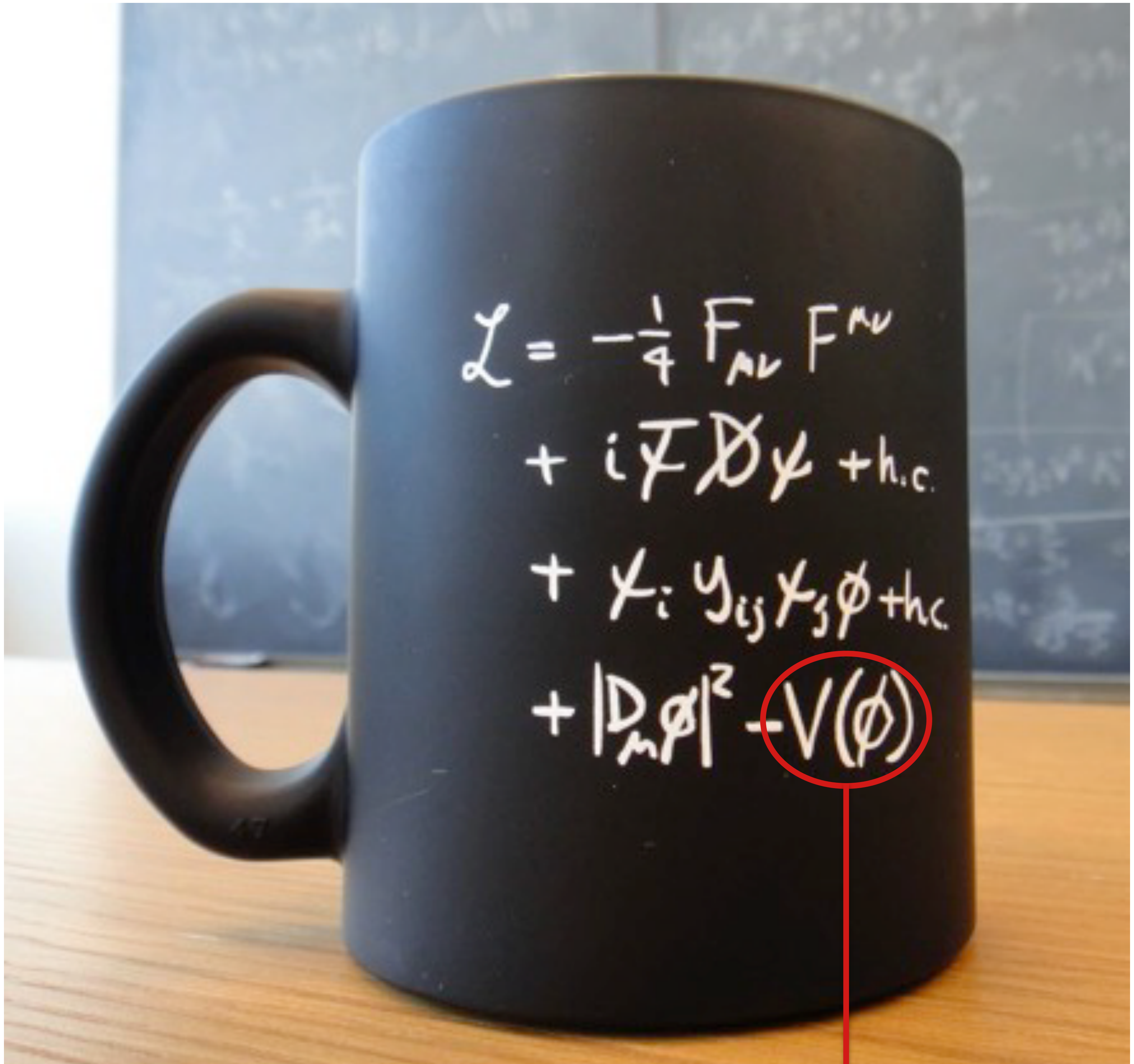
Electroweak Symmetry Breaking





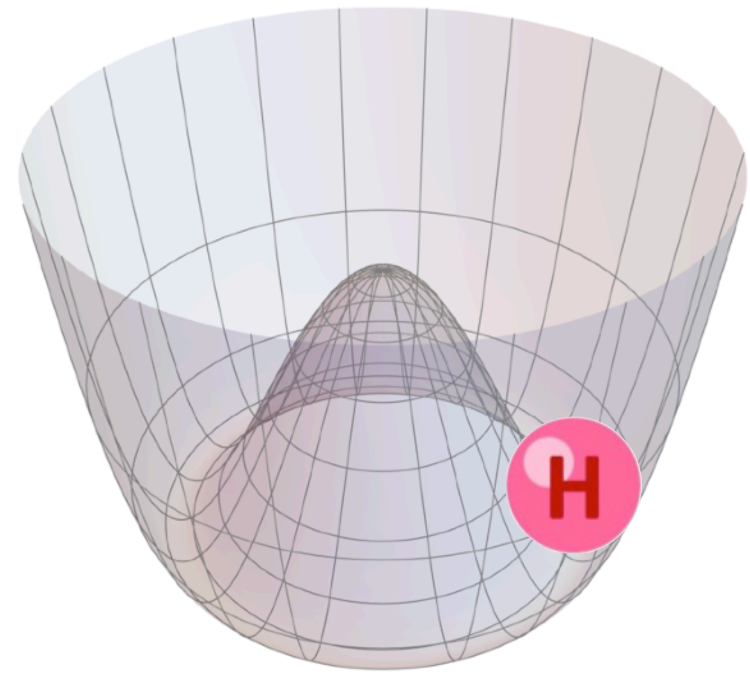
$V(\phi)$ = the Higgs field *potential*

Electroweak Symmetry Breaking



$V(\phi)$ = the Higgs field *potential*

- The ground state (also called electroweak vacuum) is not invariant under symmetry of the theory



- This is a situation of spontaneous symmetry breaking, seen in many fields of physics (ferromagnetism, Bose-Einstein condensation of Cooper pairs, etc.)

But here, we deal with the whole Universe!

The Origin of Matter

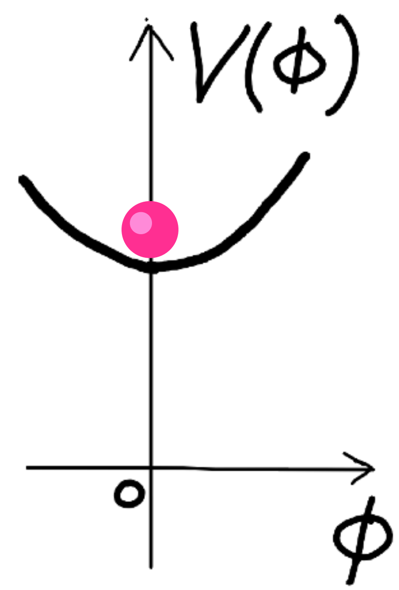
Electroweak Symmetry Breaking (EWSB)

Electroweak phase transition

- $T_{\text{crit}} \simeq 10^{15}\,\text{K}, \quad E \simeq 100\,\text{GeV}$
- second order

Before

$T > T_{\text{crit}}$

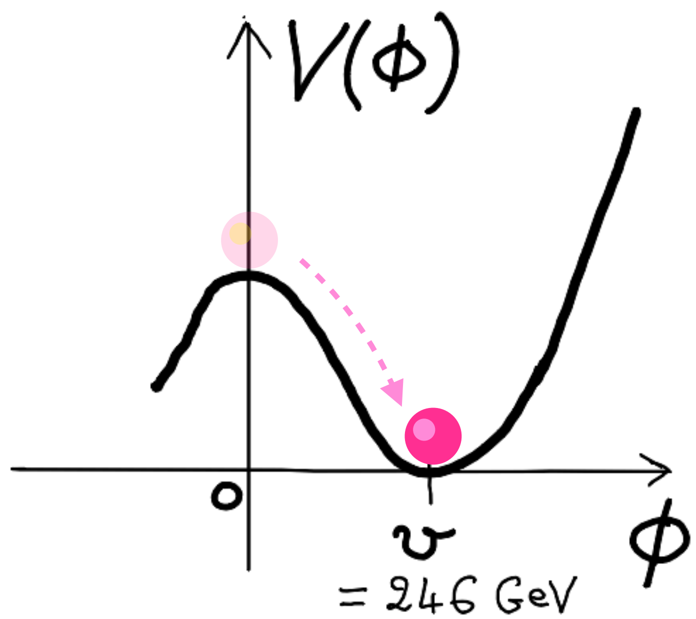


No mass

$v = c$

After

$T < T_{\text{crit}}$



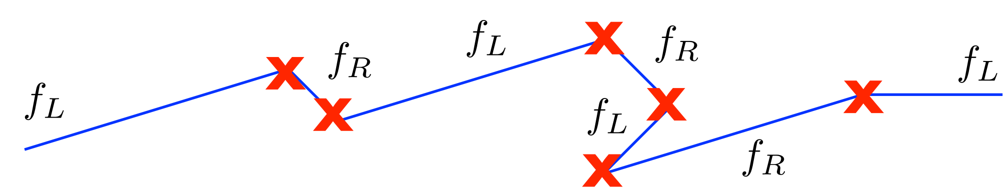
Massive particles

$v < c$

$V(\phi)$ = the Higgs field *potential*

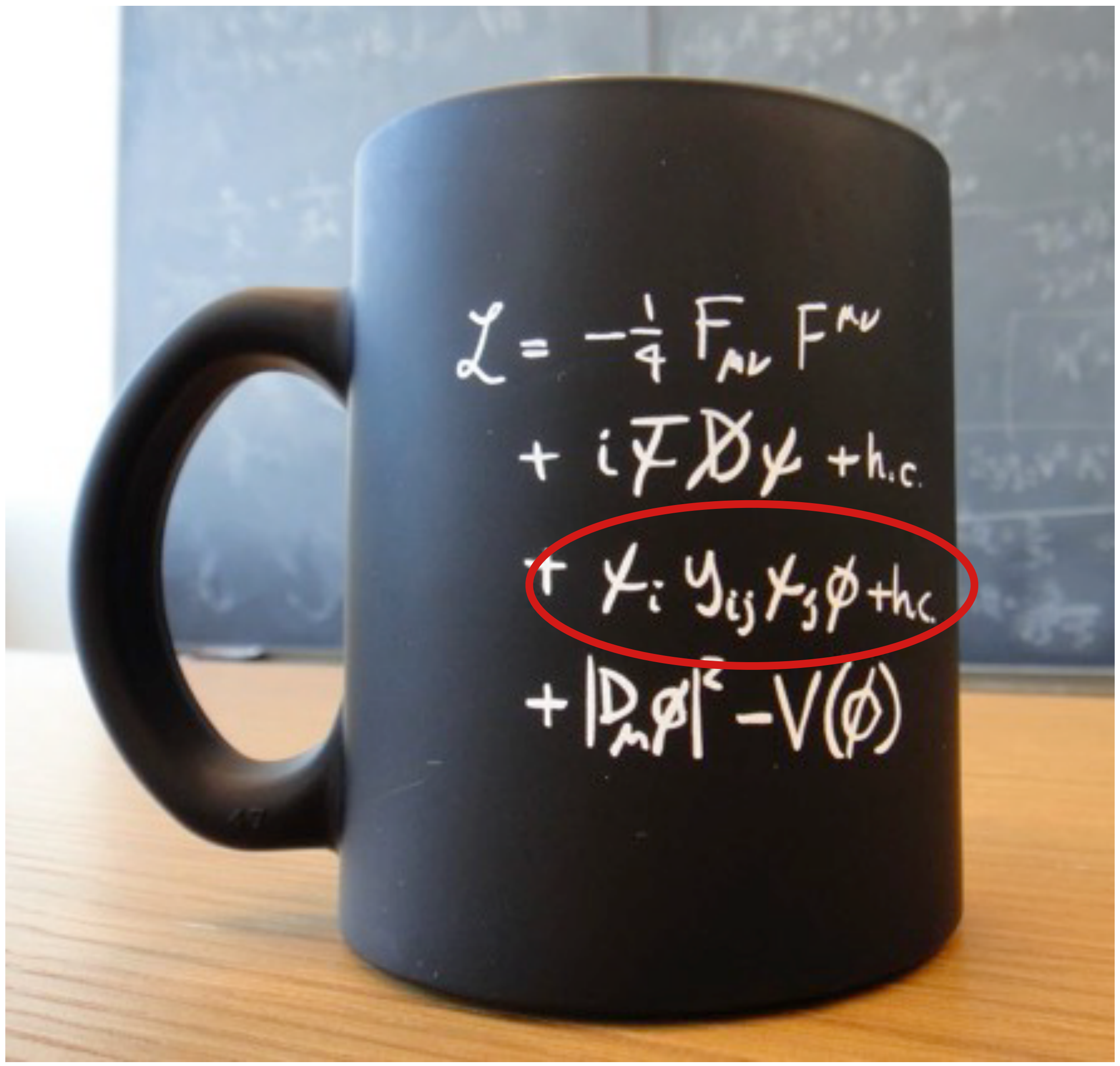
After the electroweak transition

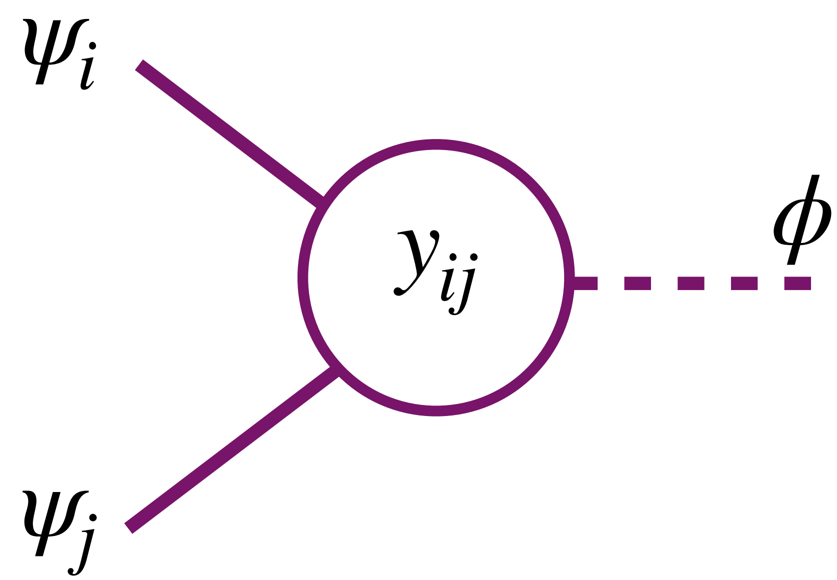
- The W and Z bosons acquire a very large mass ($\simeq 100$ GeV)
- The photon remains massless
- The electromagnetic and weak forces decouple



- Matter particles (quark and leptons) interact with the Higgs condensate in the electroweak vacuum → they are slowed down: $v < c$
  → particle acquire (inertial) mass!

Link between Higgs and Flavour





- In the SM, fermion masses are the result of Yukawa interactions with the Higgs field
- As opposed to gauge interactions, which result from the *gauge symmetries*, the Higgs-fermion couplings are <u>not universal</u> among generations

Strong hierarchical pattern:

$$y_u = \sqrt{2} m_u / v \simeq 10^{-5} \qquad y_t = \sqrt{2} m_t / v \simeq 1$$

- Yukawa interactions give rise to fermion masses, mixing and CP violation

The Flavour Puzzle

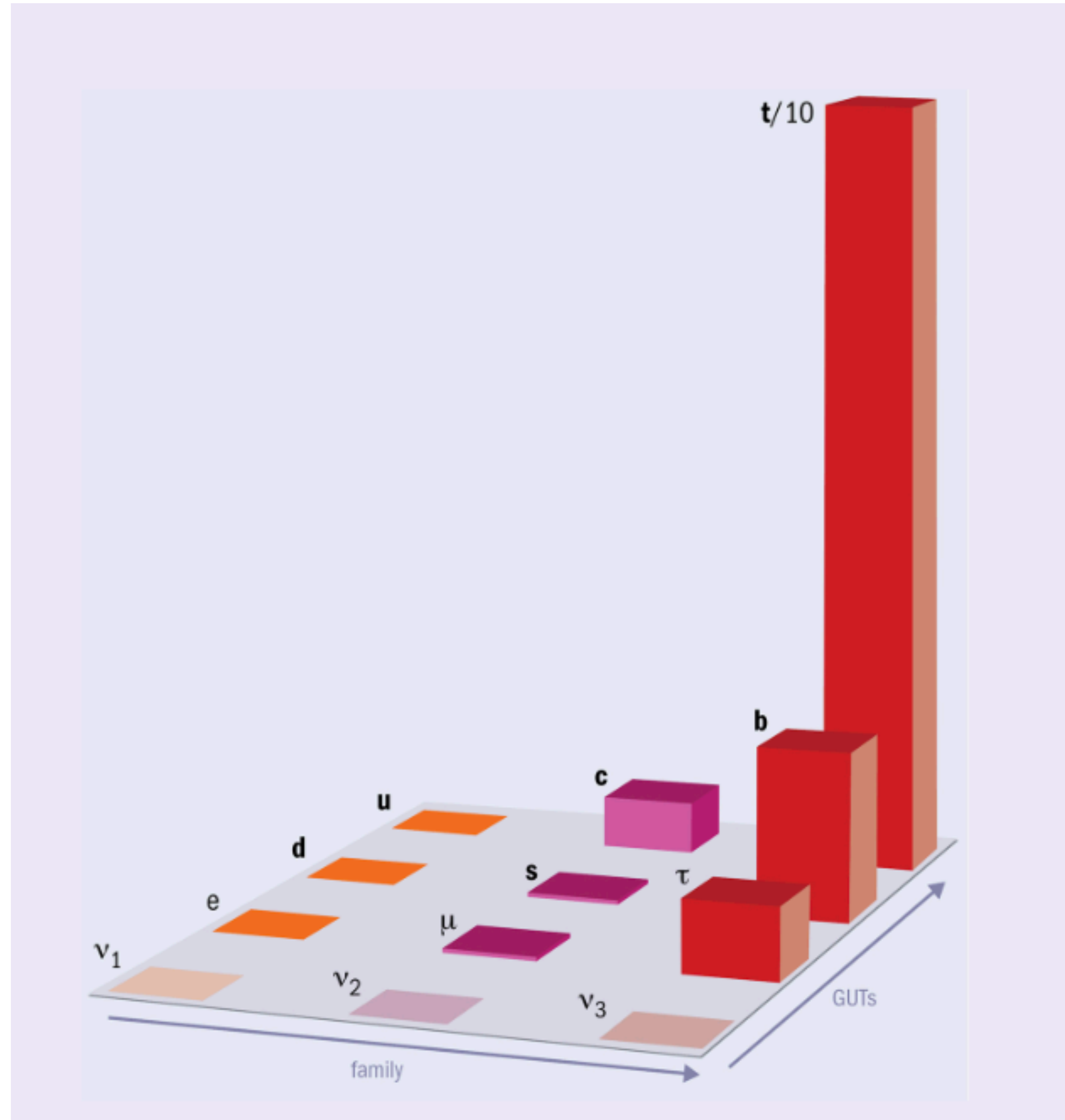
- Why 3 copies of fermions with identical quantum numbers?
- What is the dynamics determining their highly non-trivial mass hierarchy?

E.g.:

$$Y_U \sim \begin{pmatrix} \multicolumn{2}{c}{< 0.01} & 0.003 \\ & & 0.04 \\ & & 1 \end{pmatrix}$$

Y_U in the basis where Y_D is diagonal

$$y_u = \frac{\sqrt{2}\, m_u}{\langle H \rangle} \approx 10^{-5} \qquad y_t = \frac{\sqrt{2}\, m_t}{\langle H \rangle}$$



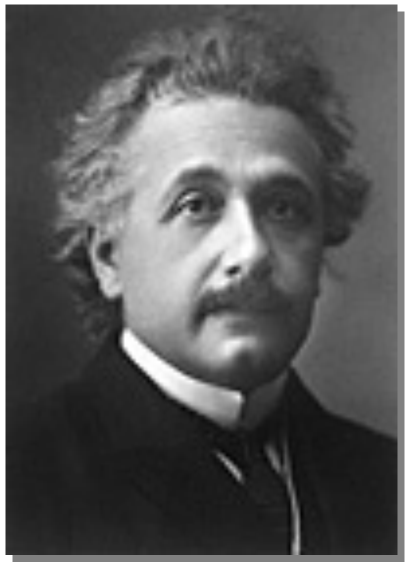
The flavour puzzle is an old problem, that emerged well before the Standard Model was conceived

A bit of History

1927, the founding fathers of quantum mechanics gathered around Einstein

The birth of antimatter

A. Einstein



1905: special relativity

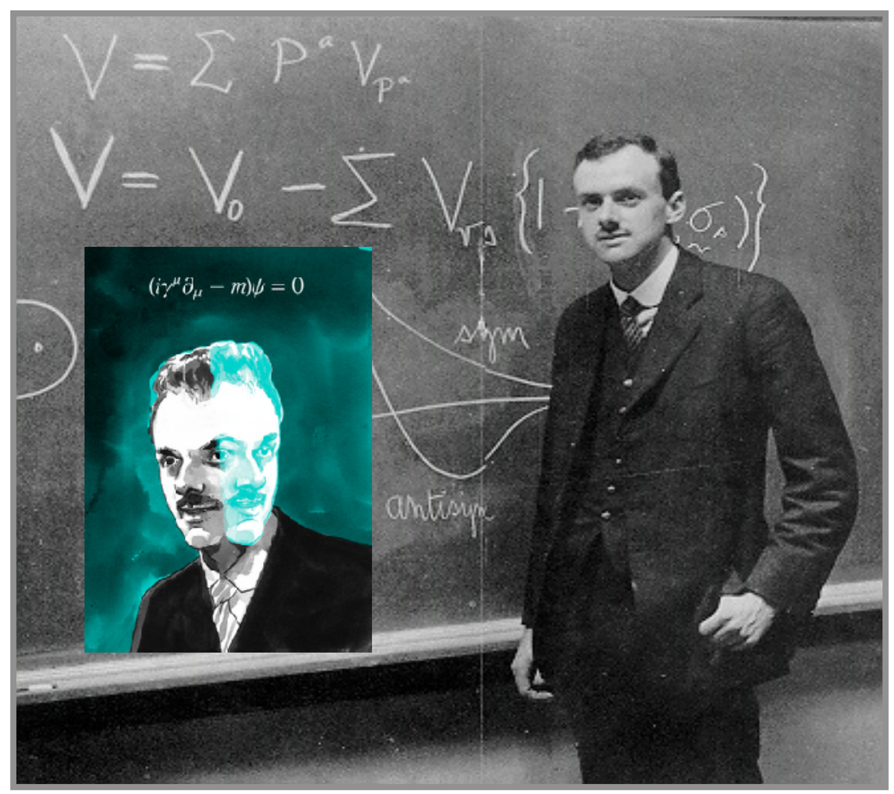
Dirac equation

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

E. Schrödinger

1926: quantum mechanics

P.A.M. Dirac



1928: equation of motion for the relativistic electron...

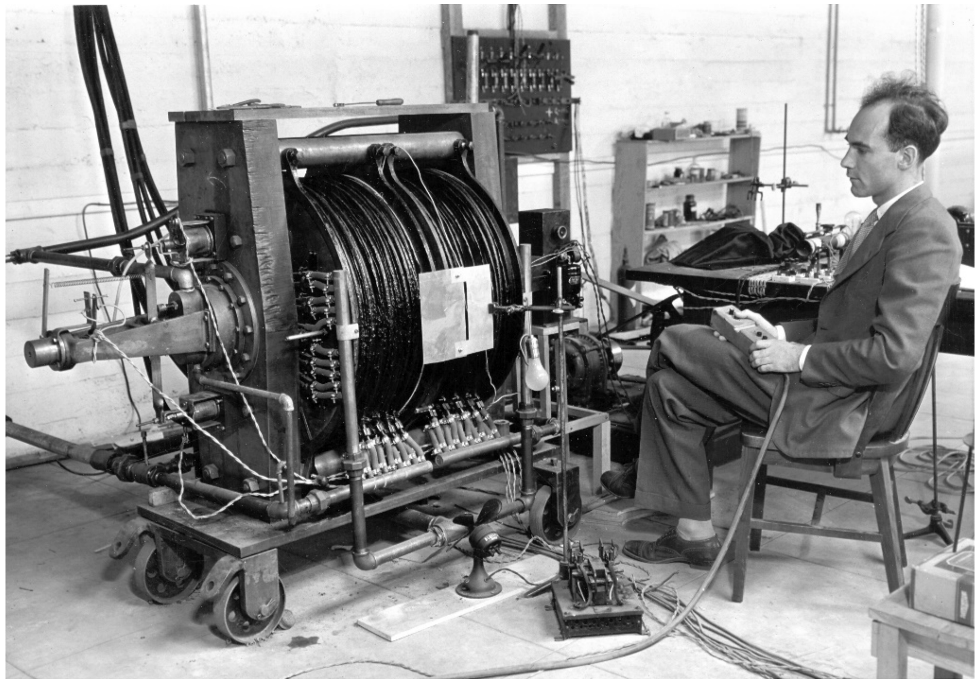
... with spin

1930: Dirac formulates the hypothesis of the positive electron, or positron

Positron discovery

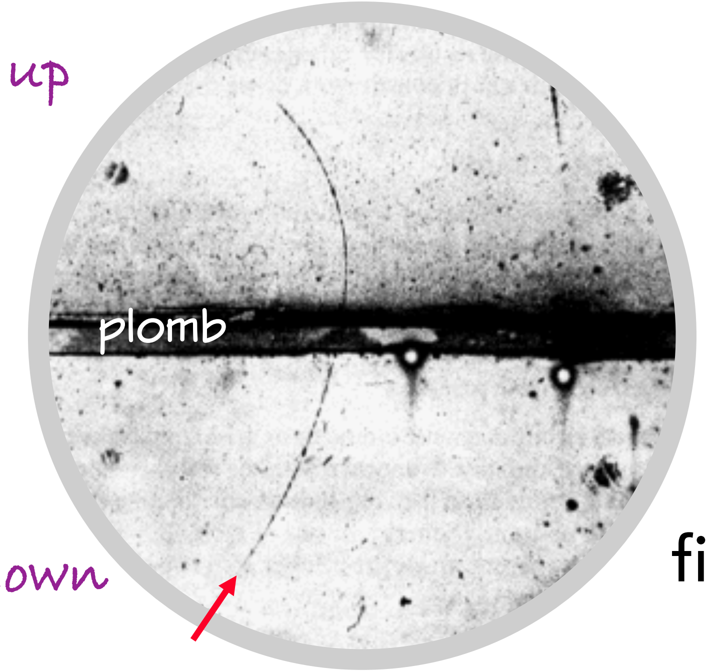
Caltech,1932: C. Anderson discovers the positron in cosmic rays

C. Anderson

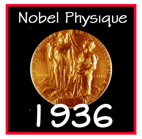


Anderson studies cosmic rays with a Wilson chamber in a magnetic field

up



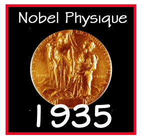
down



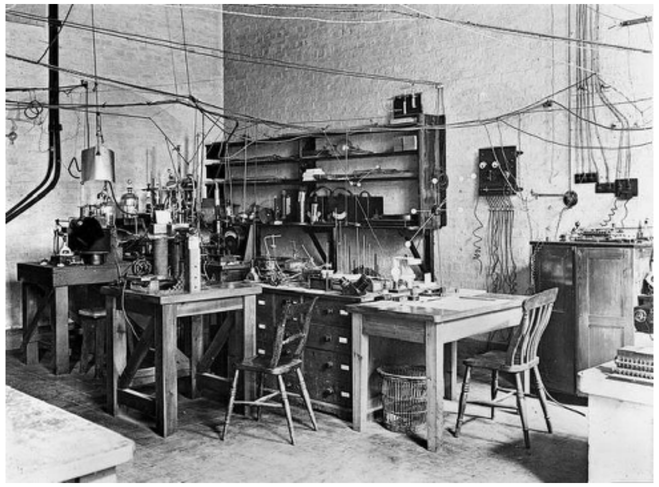
first observation of antimatter

he observes an electron with a positive electric charge

Cambridge, 1932: Chadwick's discovery of the neutron



J. Chadwick

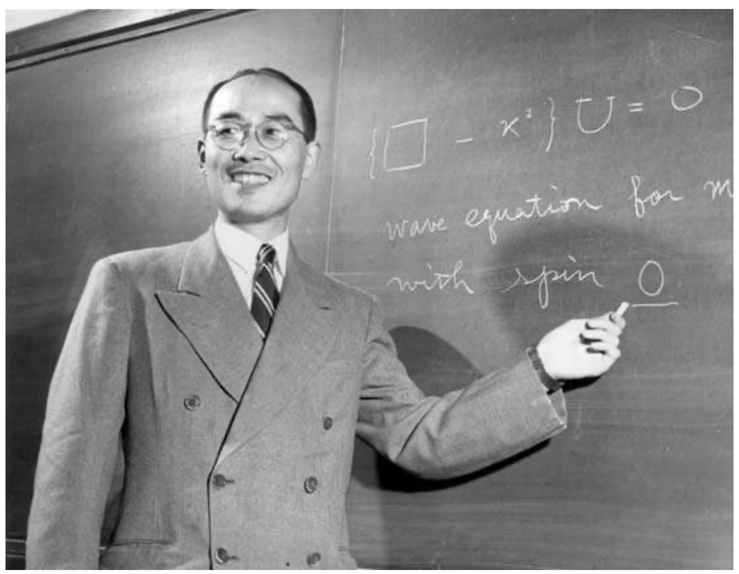


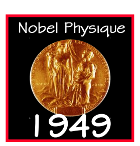
Meson theory

After the discovery of the neutron, nuclear physics takes off

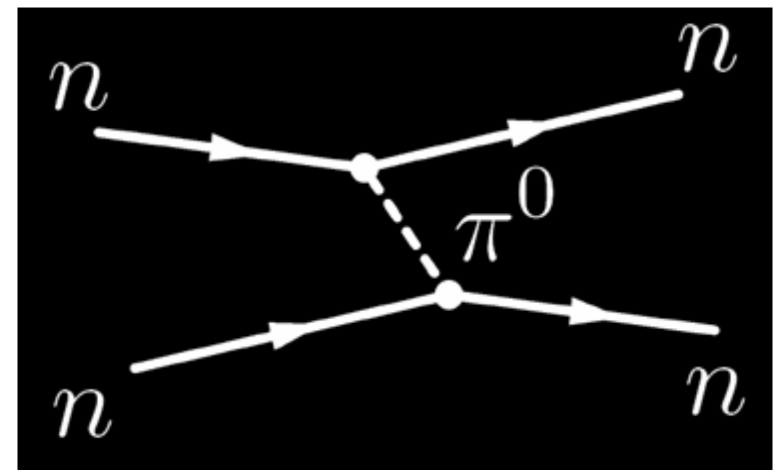
... but from a fundamental point of view, how can one ensure the cohesion of the atomic nucleus? A strong interaction capable of overcoming electrical repulsion is needed..

H. Yukawa

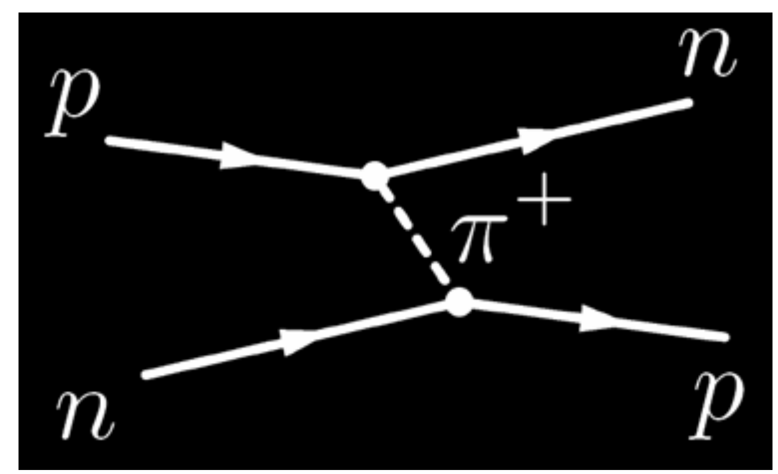




1935: theory of strong nuclear interactions



Cohesion of the atomic nucleus by exchange of π mesons ("pions") between "nucleons

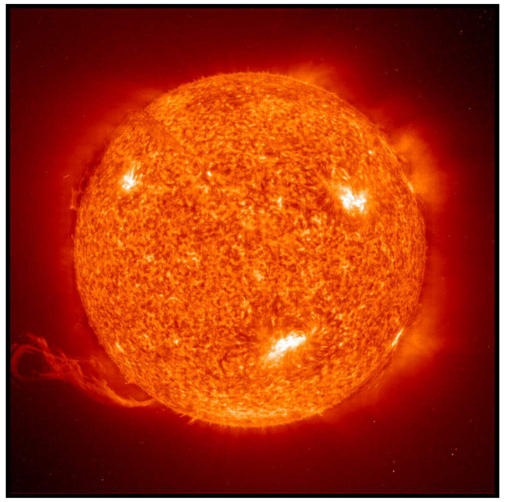


"triplet" of spin 0 particles: the pions.

range : $R \sim 2 \times 10^{-15}$ m ➠ $M(\pi) \sim 1/R \sim 100$ MeV

prediction of a new particle, the pion

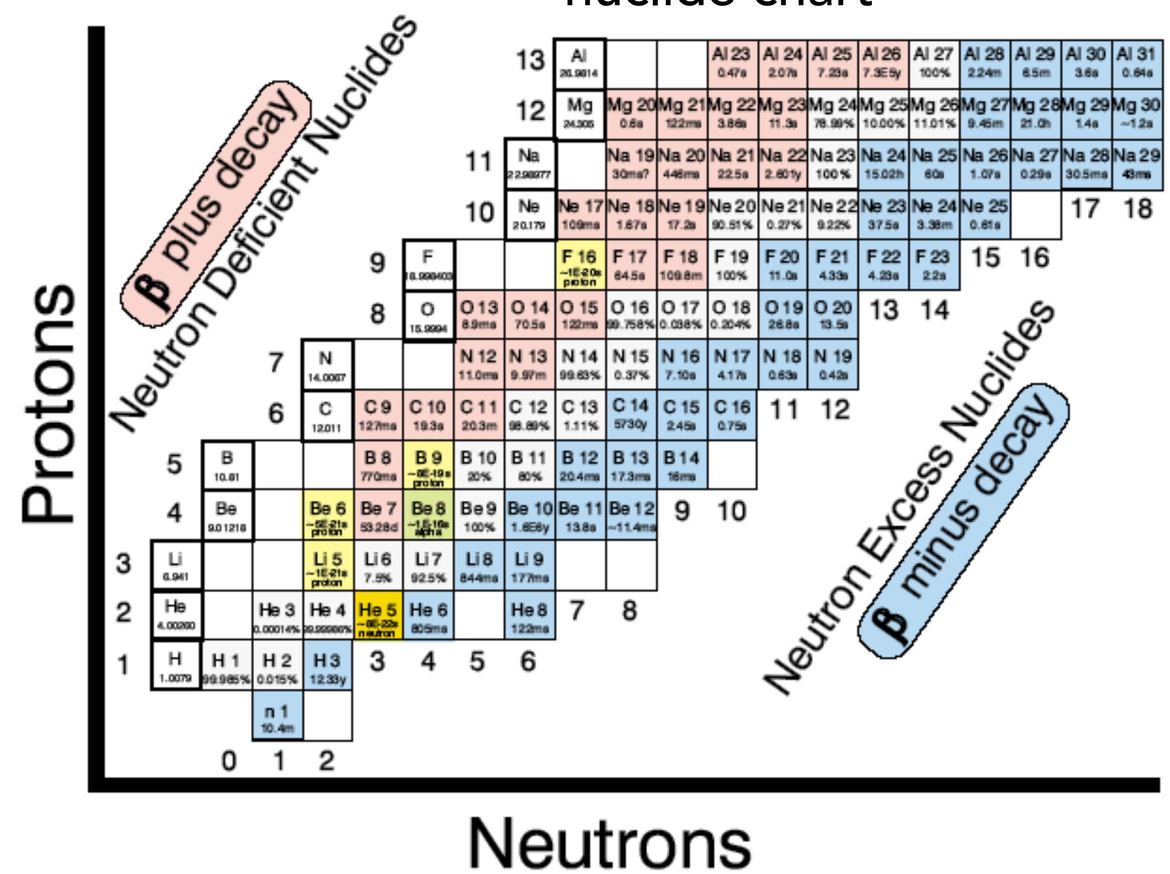
The weak nuclear interaction



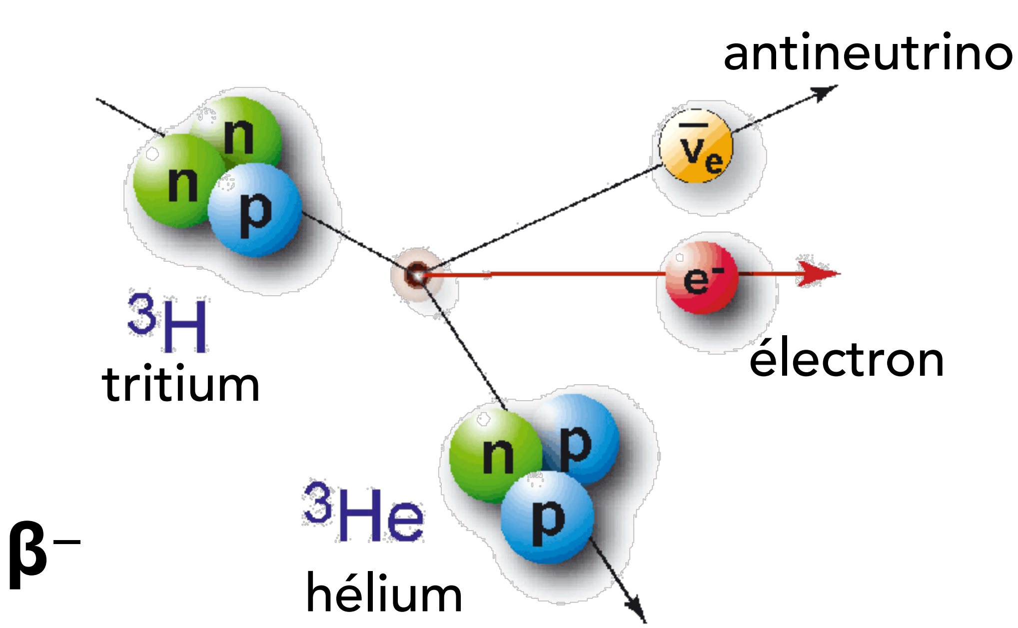
H. Becquerel (1896)
E. Rutherford (1898)
P&M Curie (1899) ...

A. Eddington (1920)
Von Weizsäcker,
H. Bethe (1938) ...

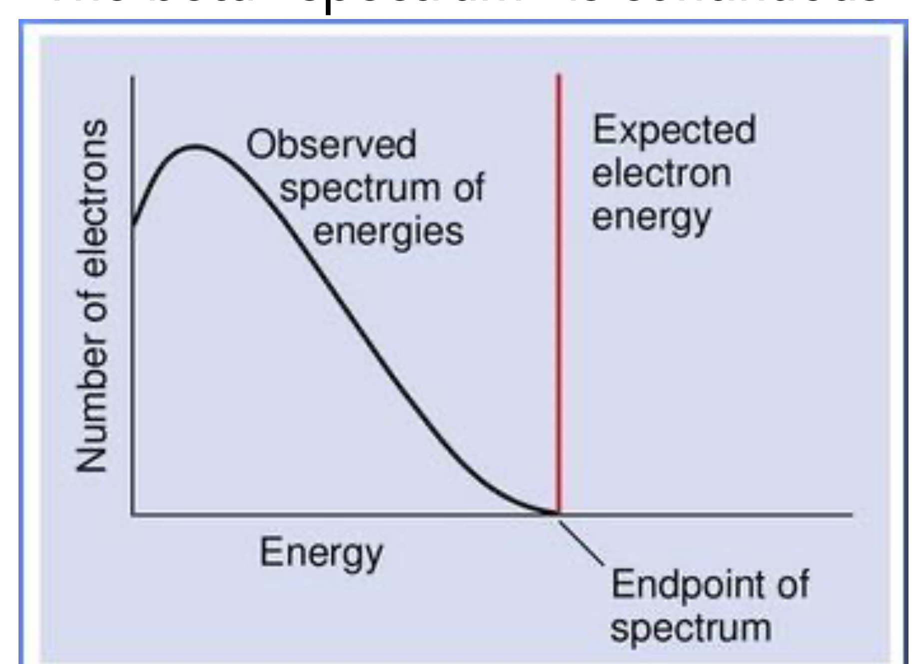
nuclide chart



The weak interaction is responsible for the radioactive **β** decay of certain nuclei and is involved in thermonuclear fusion at the center of stars.



The beta "spectrum" is continuous

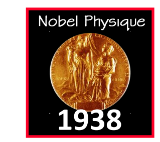


The invention of the neutrino

Dear Radioactive Ladies and Gentlemen,

I've found a desperate solution to save...
the law of conservation of energy.
...let's imagine that there are electrically
neutral particles, which I'll call neutrons,
in nuclei...
The continuous beta spectrum would then
be logical, assuming that in beta decay, in
addition to the electron, a neutron is
emitted so that the sum of the neutron and
electron energies is constant ... nothing
ventured, nothing gained ...
So, dear radioactives, take a look at my
idea and judge for yourselves!

W. Pauli (1930)



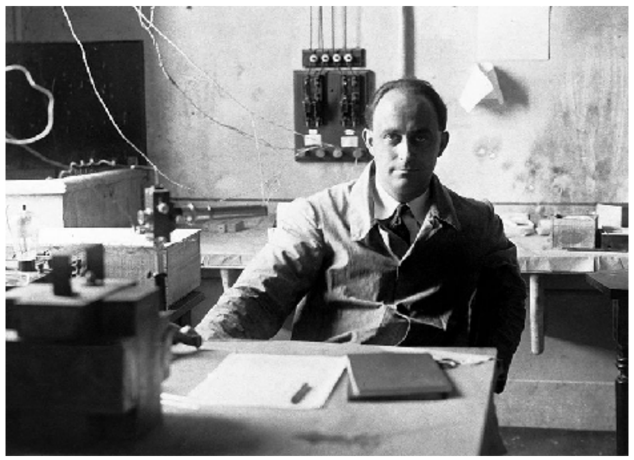
The ~~neutron~~ neutrino :

- subatomic particles of the same type as the electron (spin ½)
- electrically neutral
- of zero mass (or very small)
- extremely penetrating (as it interacts only through weak interactions)

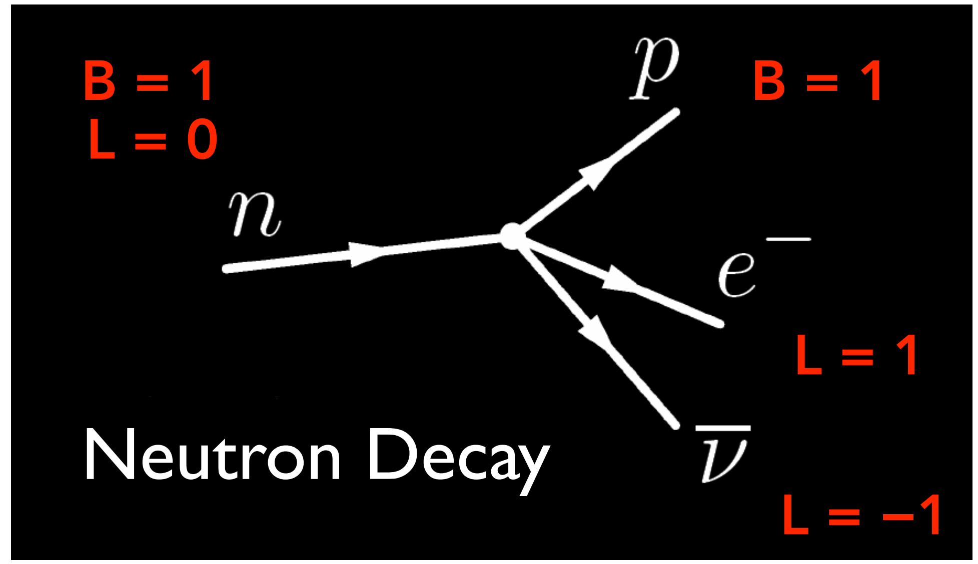
... unfortunately, I can't make it to
Tübingen myself because I'm busy here
in Zürich with a ball...

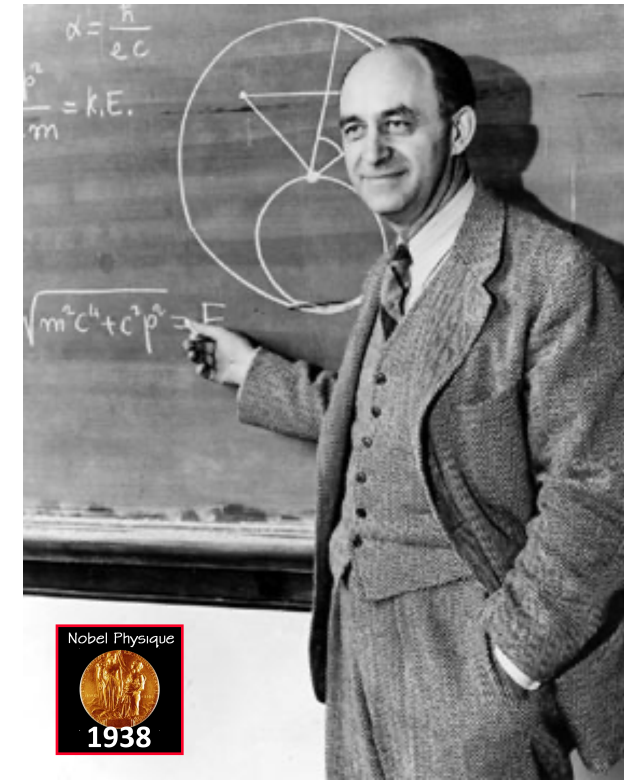
The Fermi Theory

Fermi proposed the name neutrino = "the little neutron".



E. Fermi





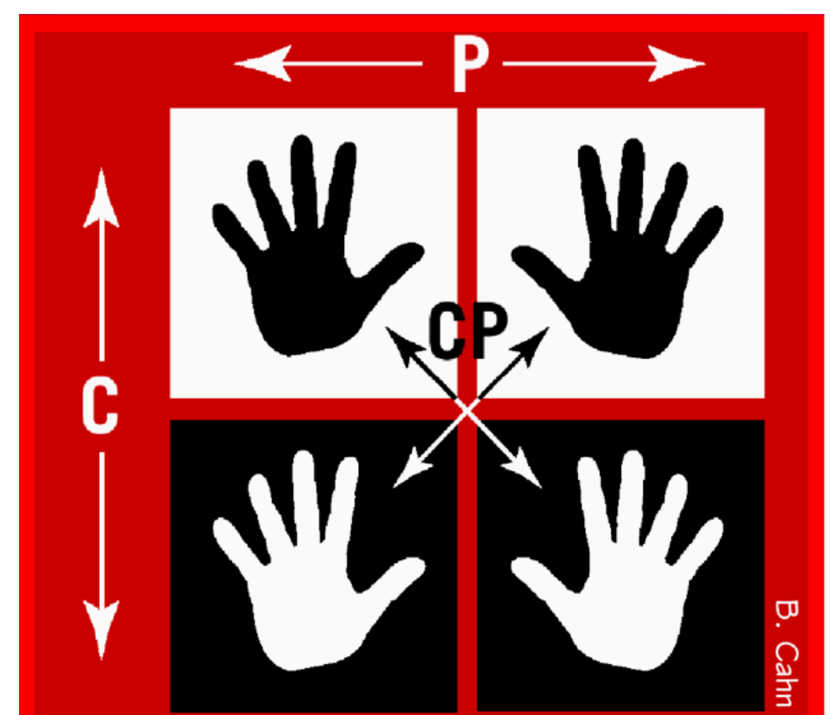
Isospin symmetry
proton ⟷ neutron
electron ⟷ neutrino

1934: theory of the weak nuclear interaction, which perfectly describes beta decay

- Fermi constant G_F
- conserved quantum numbers: baryonic, leptonic
- notion of isospin symmetry
- later (1956) will include maximal violation of parity by weak interactions, and conservation of CP

problems

- a "point" theory is only valid at "low" energies
- CP is only approximately conserved (1964)!

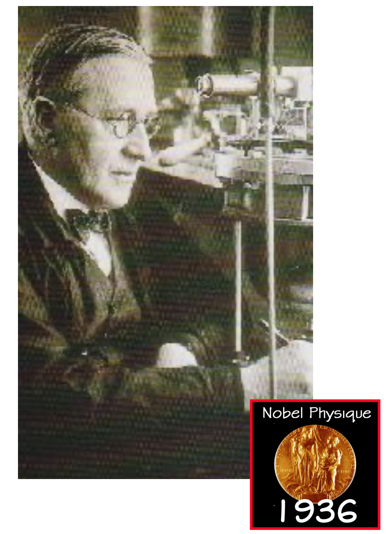


Discovery of pion and muon

Cosmic rays bombard the Earth
100,000 pass through us every hour

V. Hess (1912): they come from outer space!

V. Hess

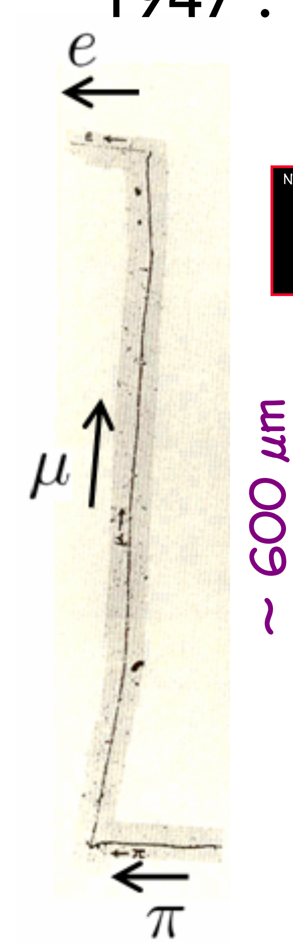


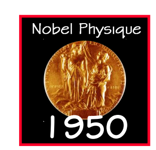
In 1936, C. Anderson and S. Neddermeyer discovered a particle 200 times more massive than the electron in cosmic rays

They identify this new particle with Yukawa's π meson

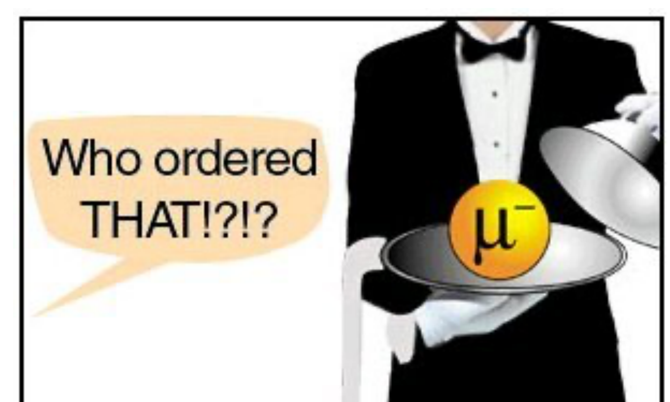
Problem: it doesn't react with protons and neutrons as expected...

1947 : découverte du pion par C. Powell



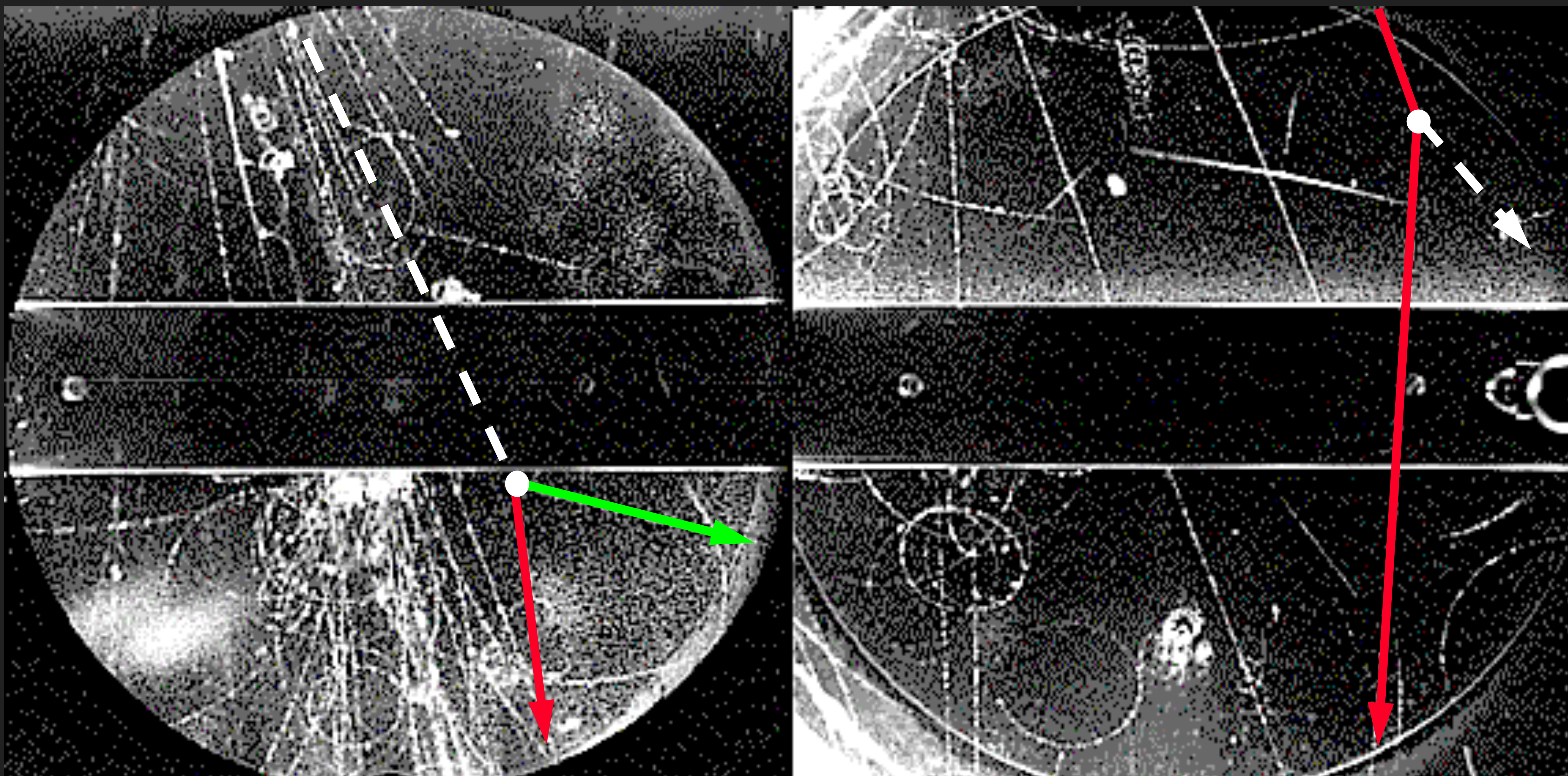


the particle discovered in 1936 will then be called μ meson, or muon.



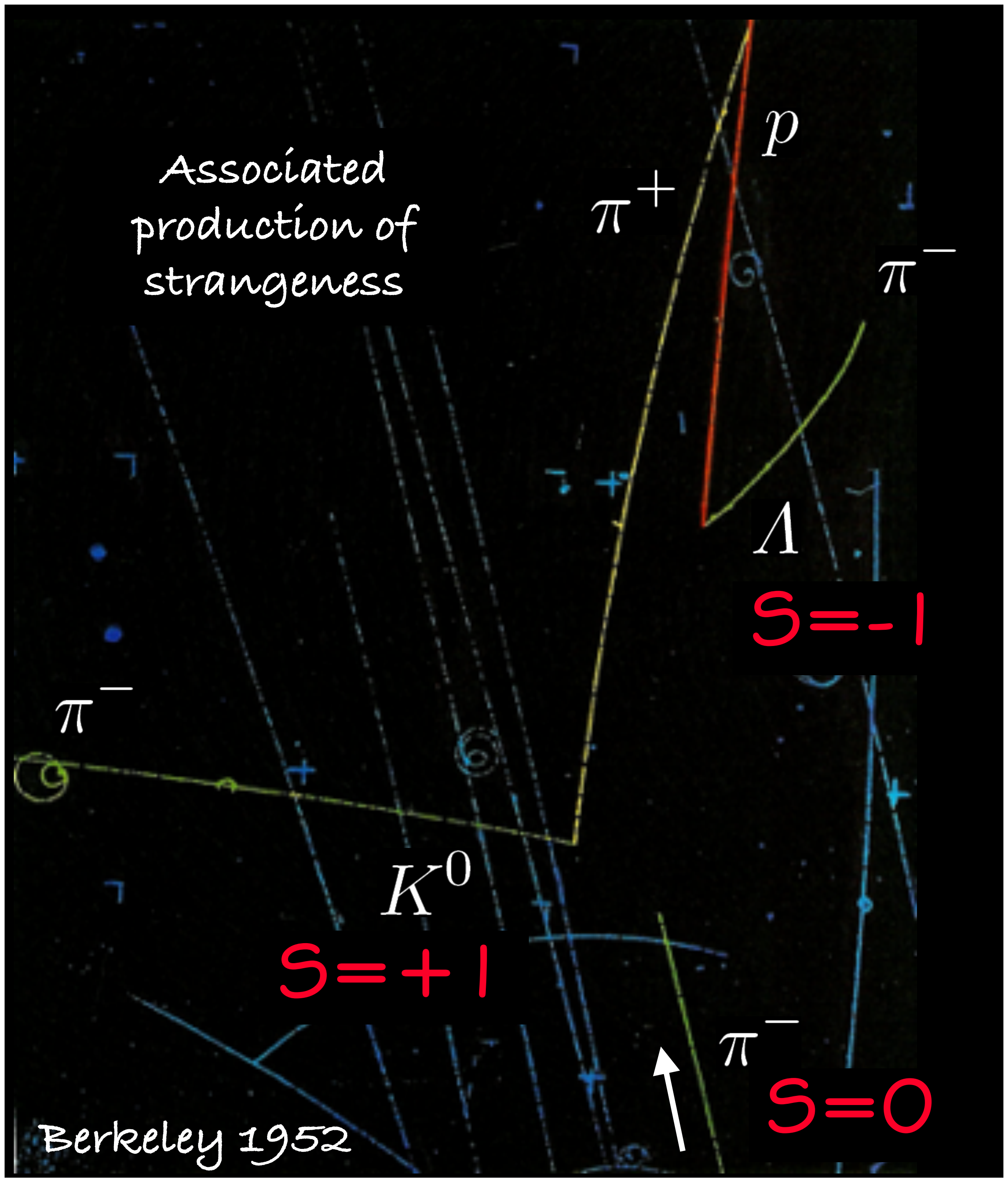
I. Rabi

The Strange Particles



Butler & Rochester, cosmic rays, 1946

Strangeness



1950s: physicists discover dozens of "elementary" particles, hadrons, some of which are "strange"

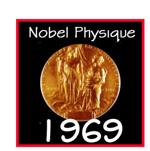
A new quantum number, strangeness, denoted S

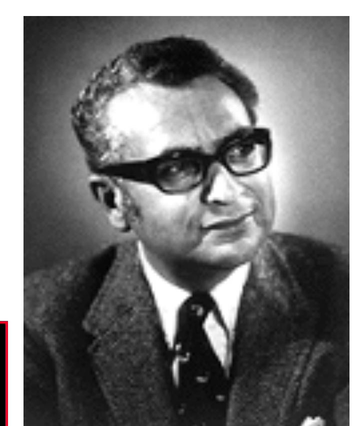
Strangeness is preserved by the strong interaction

Strangeness is not preserved by the weak interaction

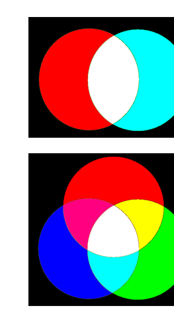
M. Gell-Mann, K. Nishijima (1953)

M. Gell-Mann





1964: symmetry and the quark model



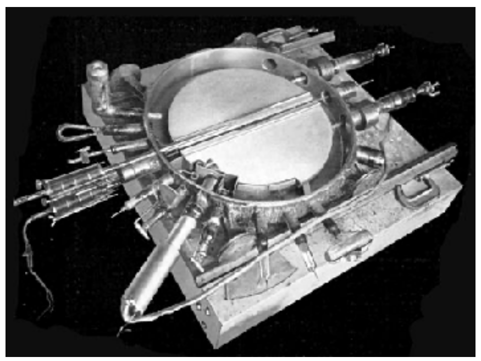
up, down, strange

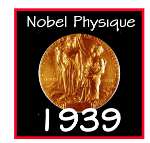
Quarks discovered at SLAC in the late 60s

The First Accelerators

L. Szilard: first linear accelerator (1928) and cyclotron (1929)

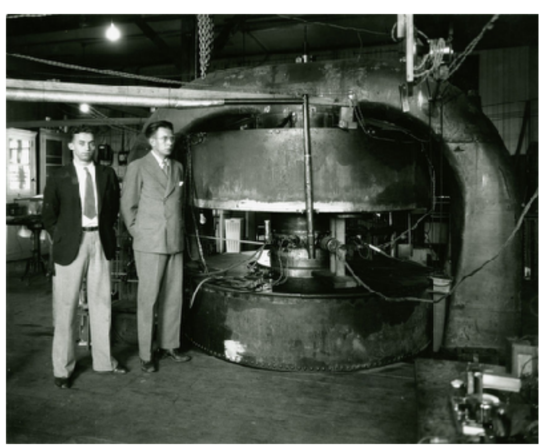
E. Lawrence :





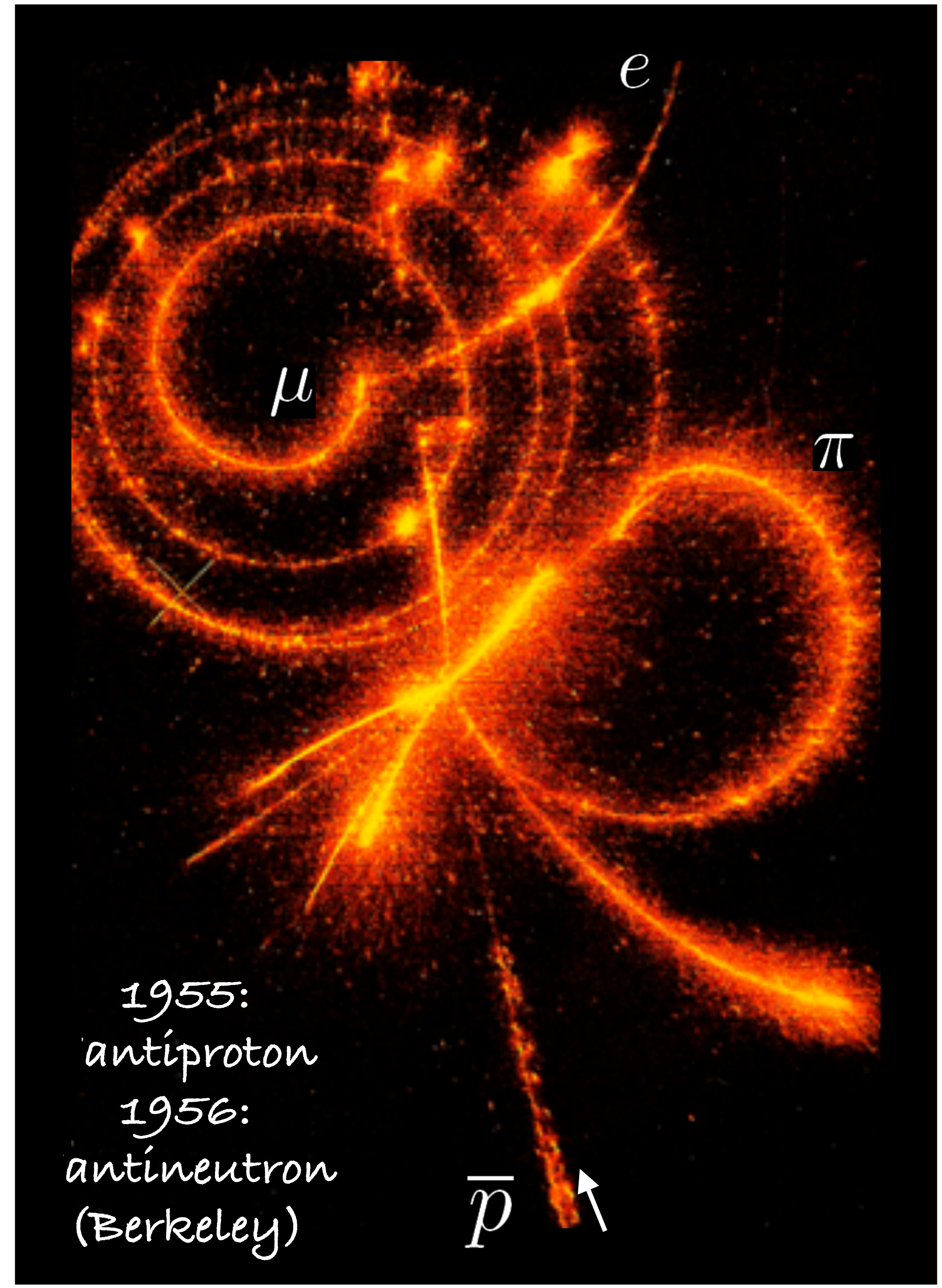
Berkeley, 1932 : 27″ cyclotron, 4.8 MeV

War years: Manhattan Project



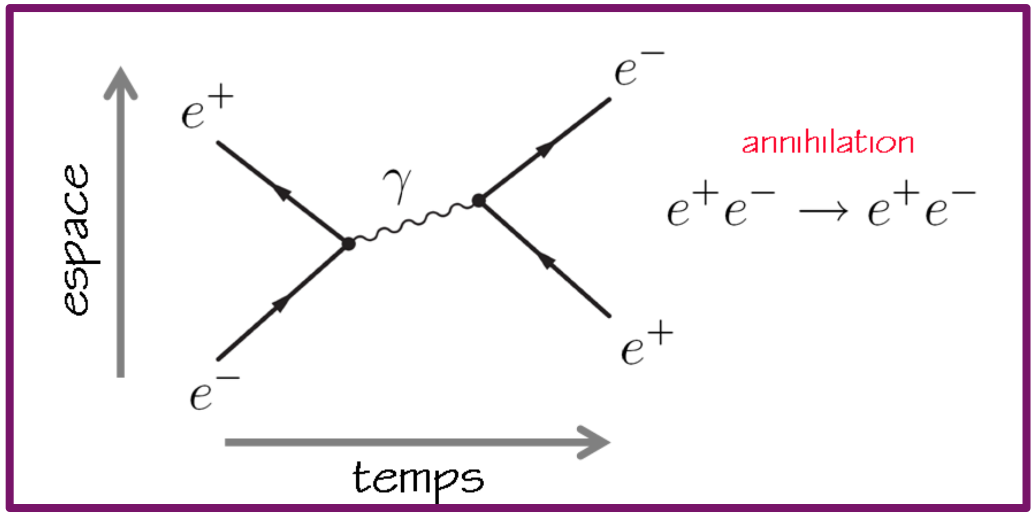
1945 : synchrocyclotron 730 MeV

1954 : BeVatron, synchrotron 6.2 GeV

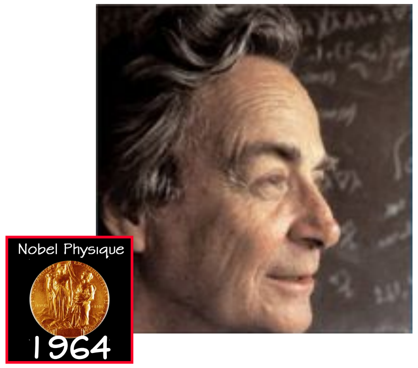


Gauge Theories

Gauge Symmetry Principle
- geometric origin of fundamental interactions
- gauge bosons associated with symmetries



RP Feynman



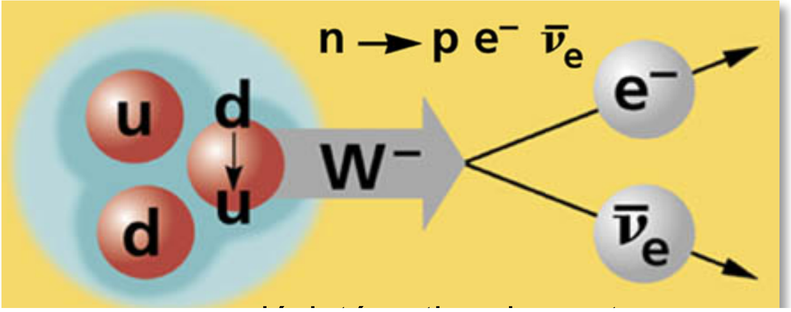
gauge bosons have a mass of rigorously zero

40s-50s: quantum electrodynamics (QED)
1 zero-mass gauge boson = the photon

one of the most successful theories in the history of physics

60s-70s: weak isospin symmetry
4 gauge bosons = photon, W^+, W^- and Z

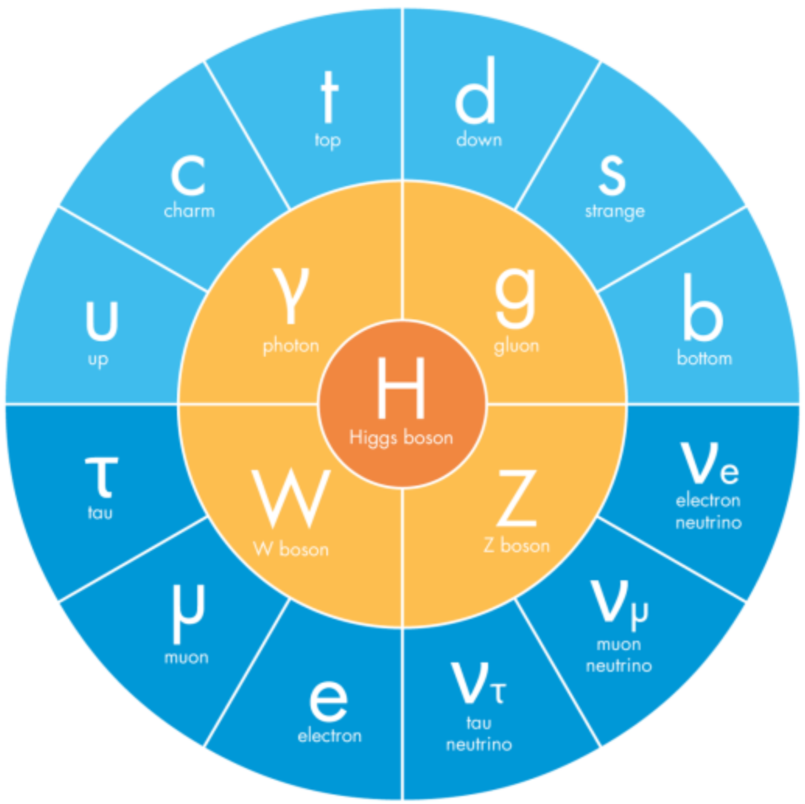
Problem: the weak interaction is very short-range (~10^{-17} m), so the W bosons must be extremely massive (~100 GeV).



If one introduces massive bosons (or fermions) into the theory "by hand", one explicitly breaks the symmetry... the theory loses its mathematical coherence!

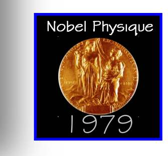
The Standard Model

A fabulous theoretical epic that culminated in the mid-70s



Electroweak theory: unification of electromagnetic and weak interactions

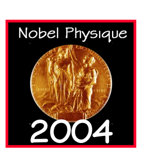
Glashow, Salam, Weinberg

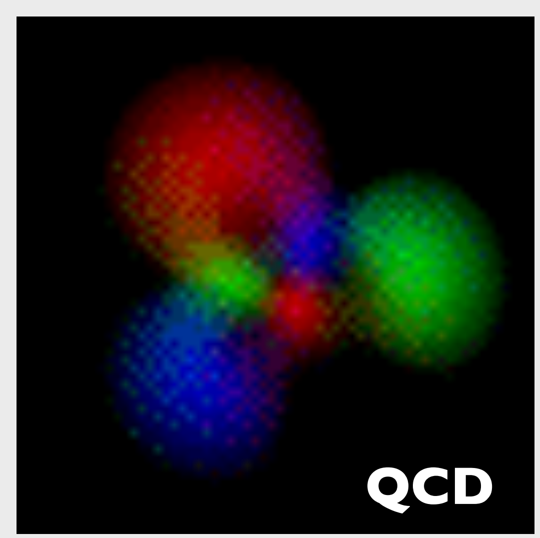


Veltman, 't Hooft

Strong Interaction Theory: Quantum Chromodynamics (QCD)

Wilczek, Politzer, Gross



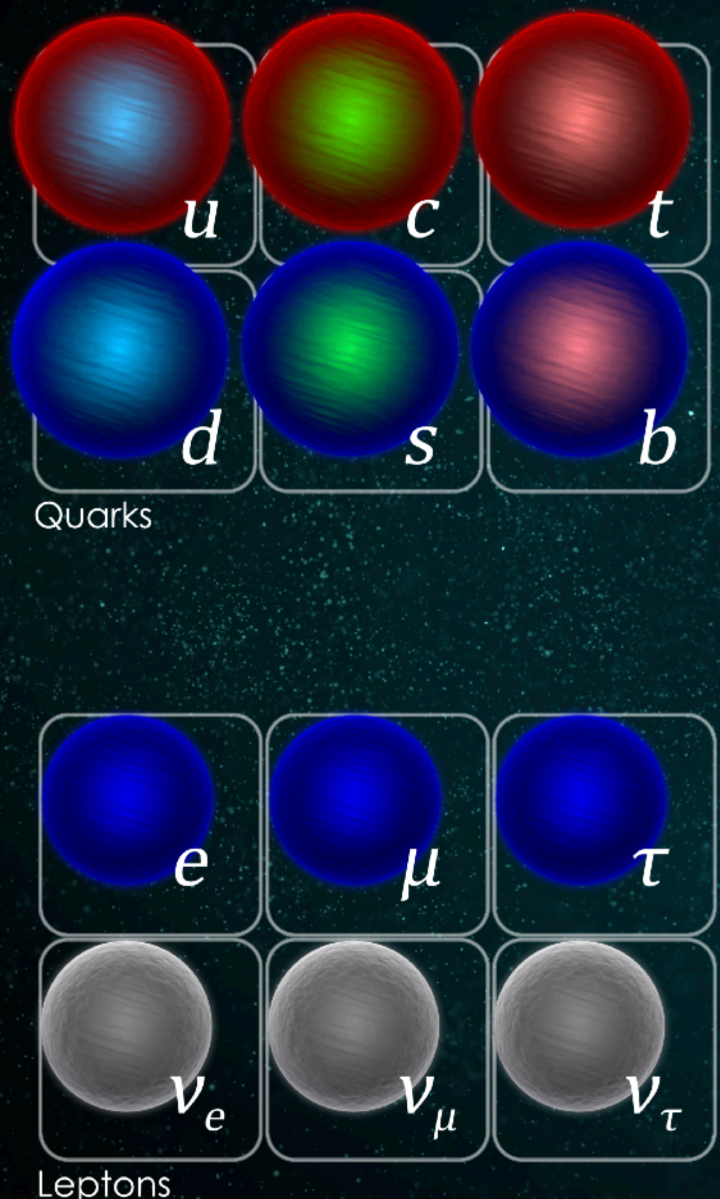


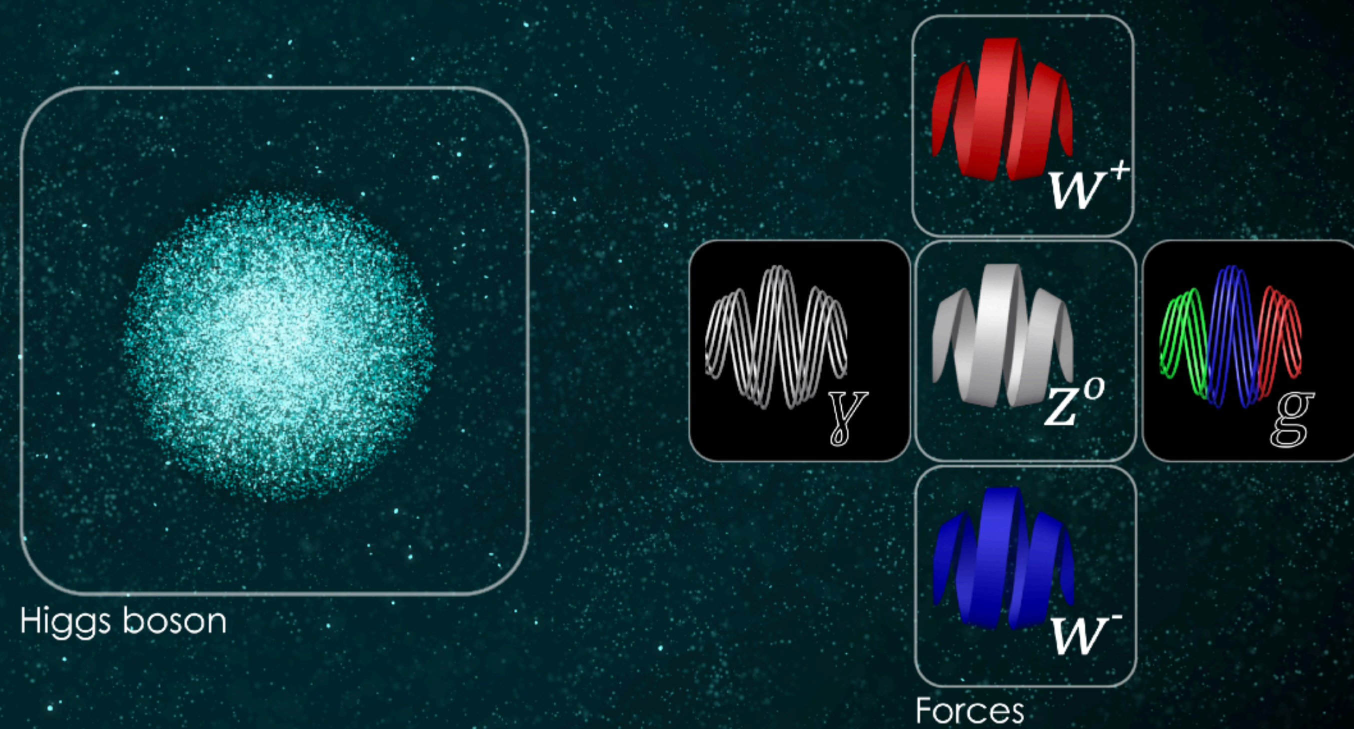
Contribution of quark mass to proton mass <10%

The bulk of a proton's mass comes from the binding energy that holds it together (gluons)

The Standard Model is a renormalizable theory

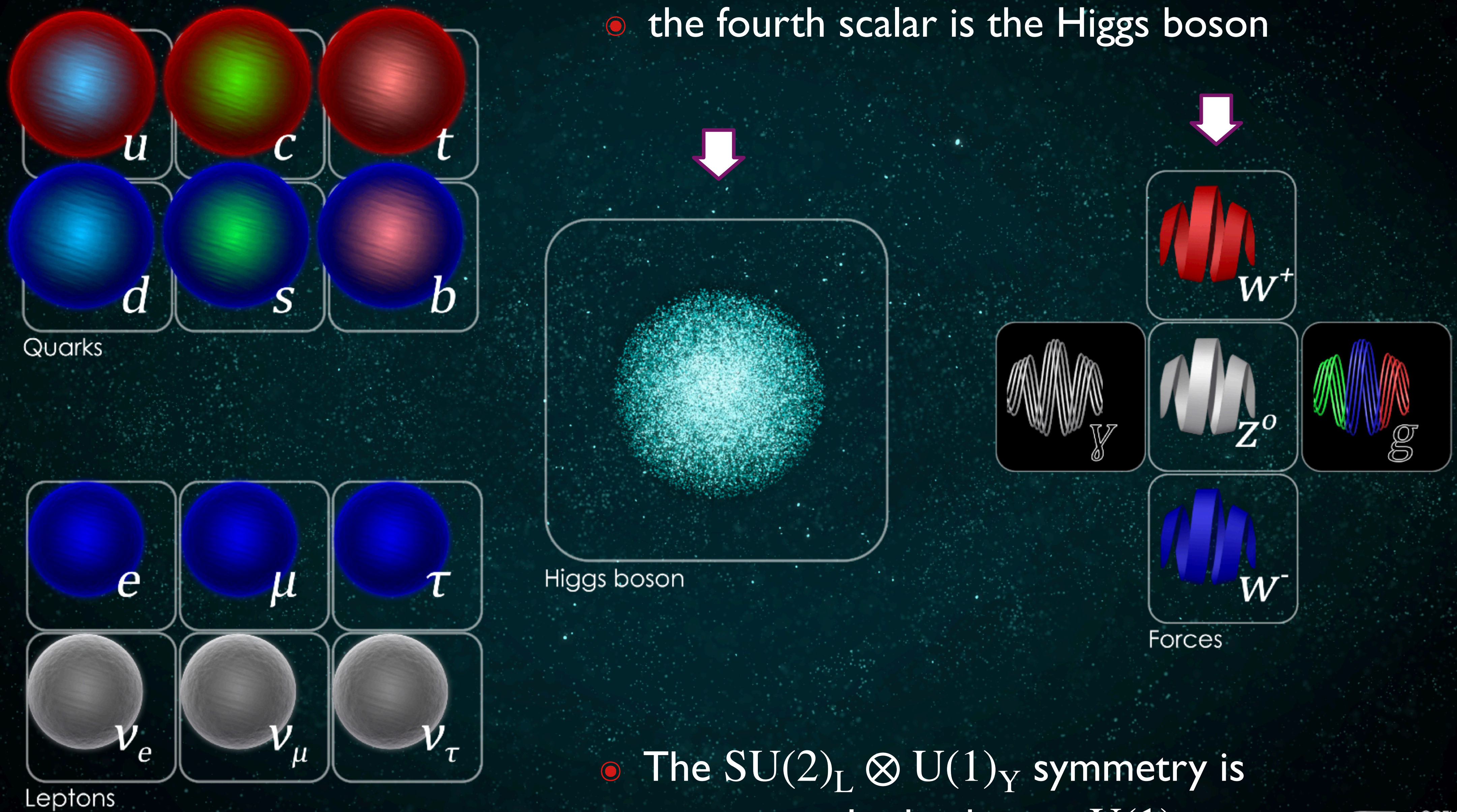
- $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry
- Matter is arranged in chiral multiplets





The Standard Model contains 4 scalar fields

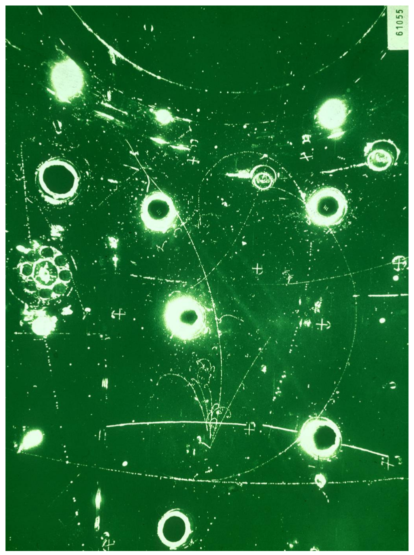
- 3 of these scalars were seen as part of the W^+, Z and W^- boson masses
- the fourth scalar is the Higgs boson



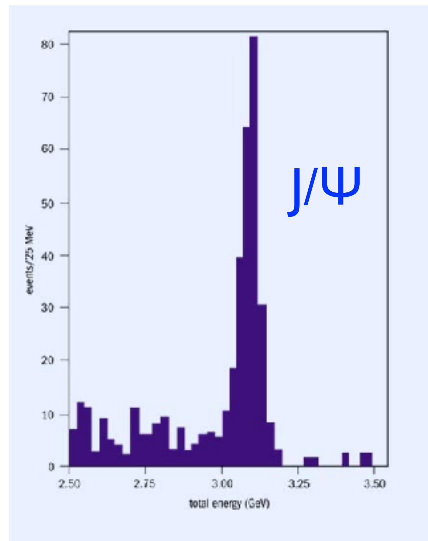
- The $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ symmetry is spontaneoulsy broken to $\mathrm{U}(1)_{EM}$

Three decades of discoveries

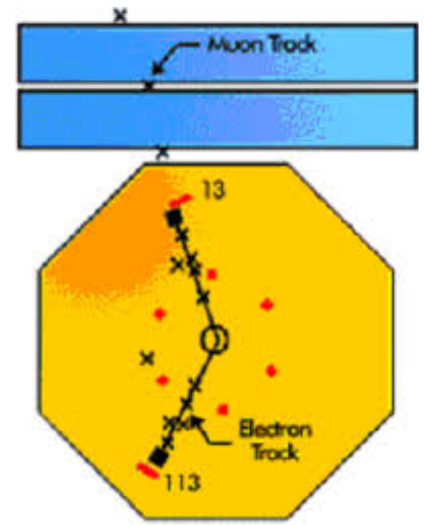
1972 — CERN
neutral currents



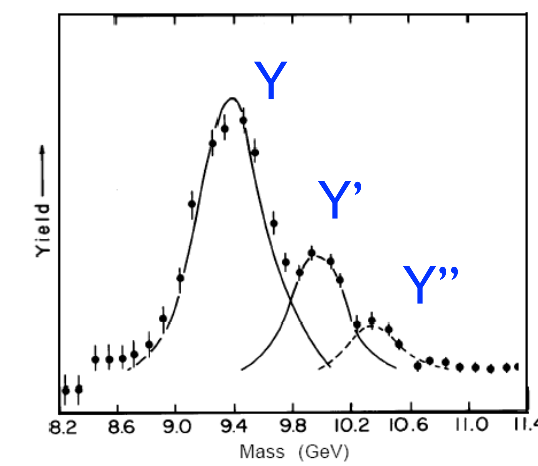
1974 — BNL, SLAC
charm quark



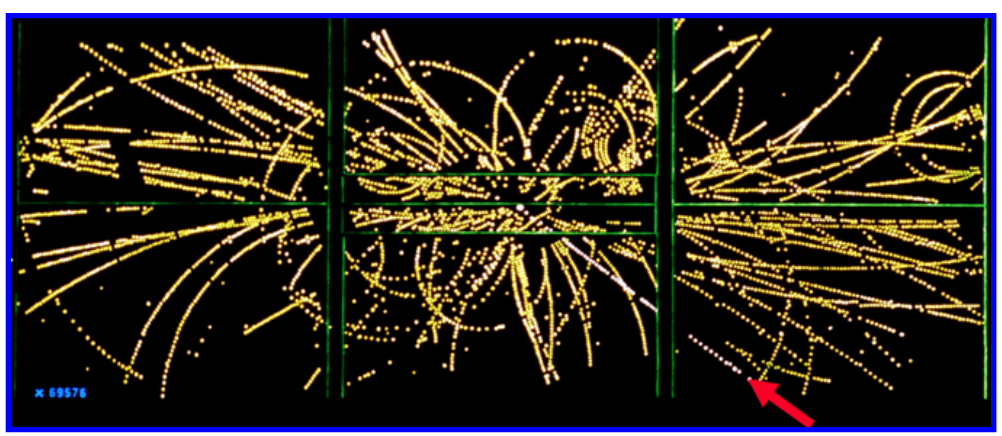
1976 — SLAC
tau lepton



1979 — Fermilab
bottom quark

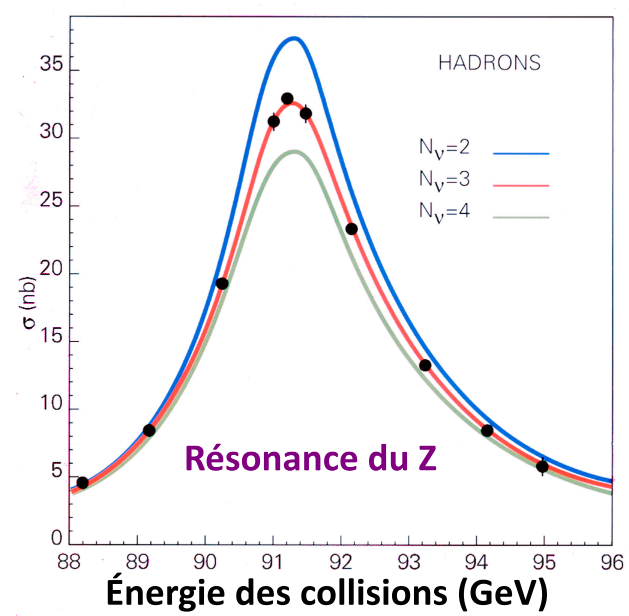


1983 — CERN/SppS
W et Z bosons



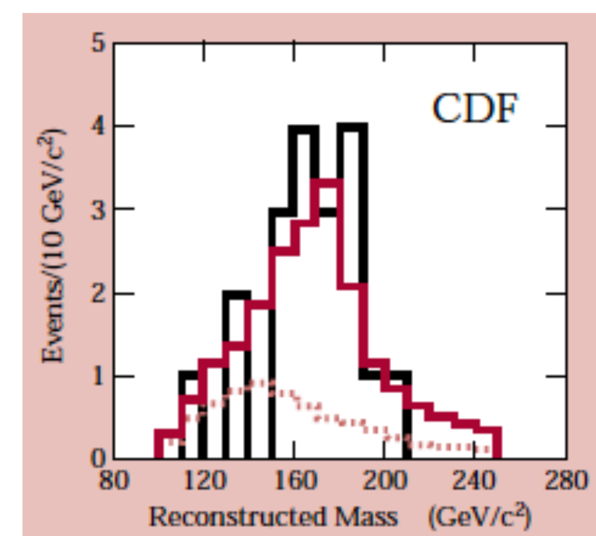
UA1, UA2

1990 — CERN/LEP
3 families of neutrinos



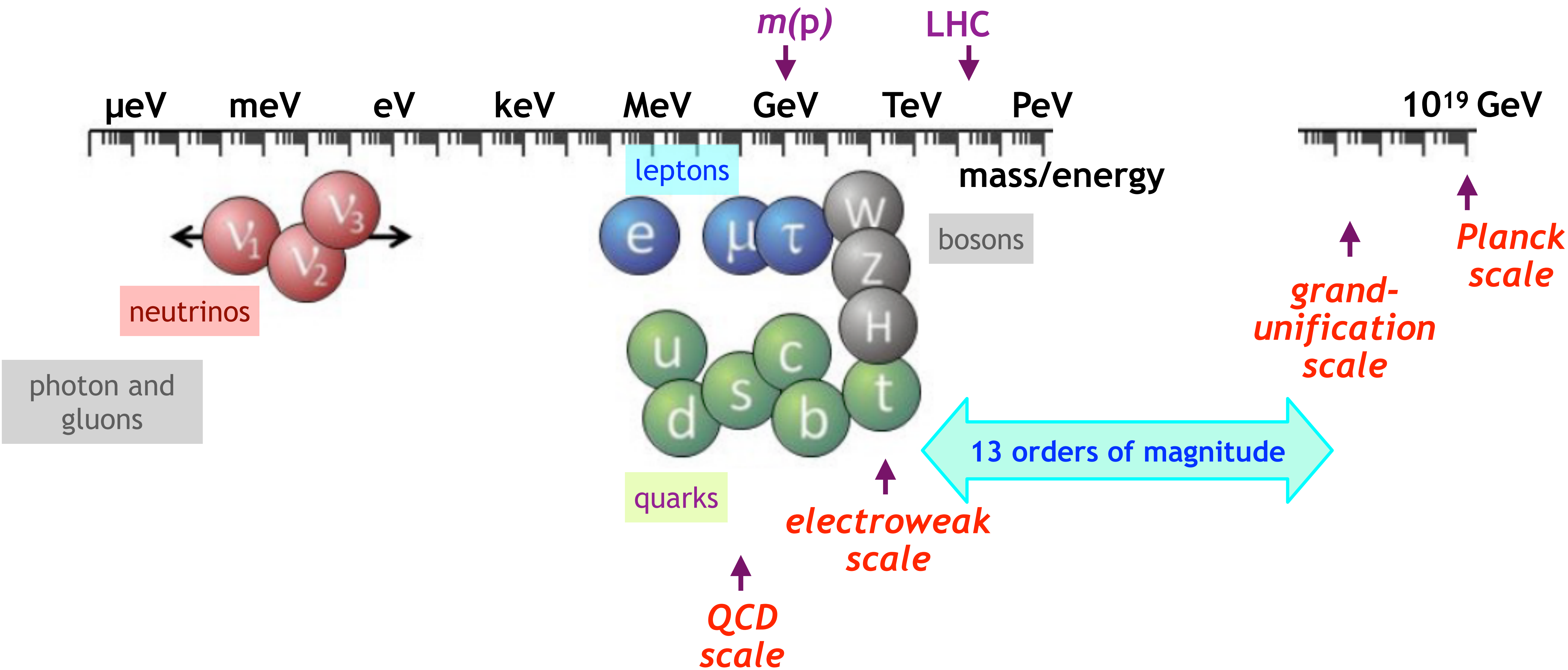
ALEPH, DEPHI, L3, OPAL

1994 — Fermilab/TeVatron
top quark

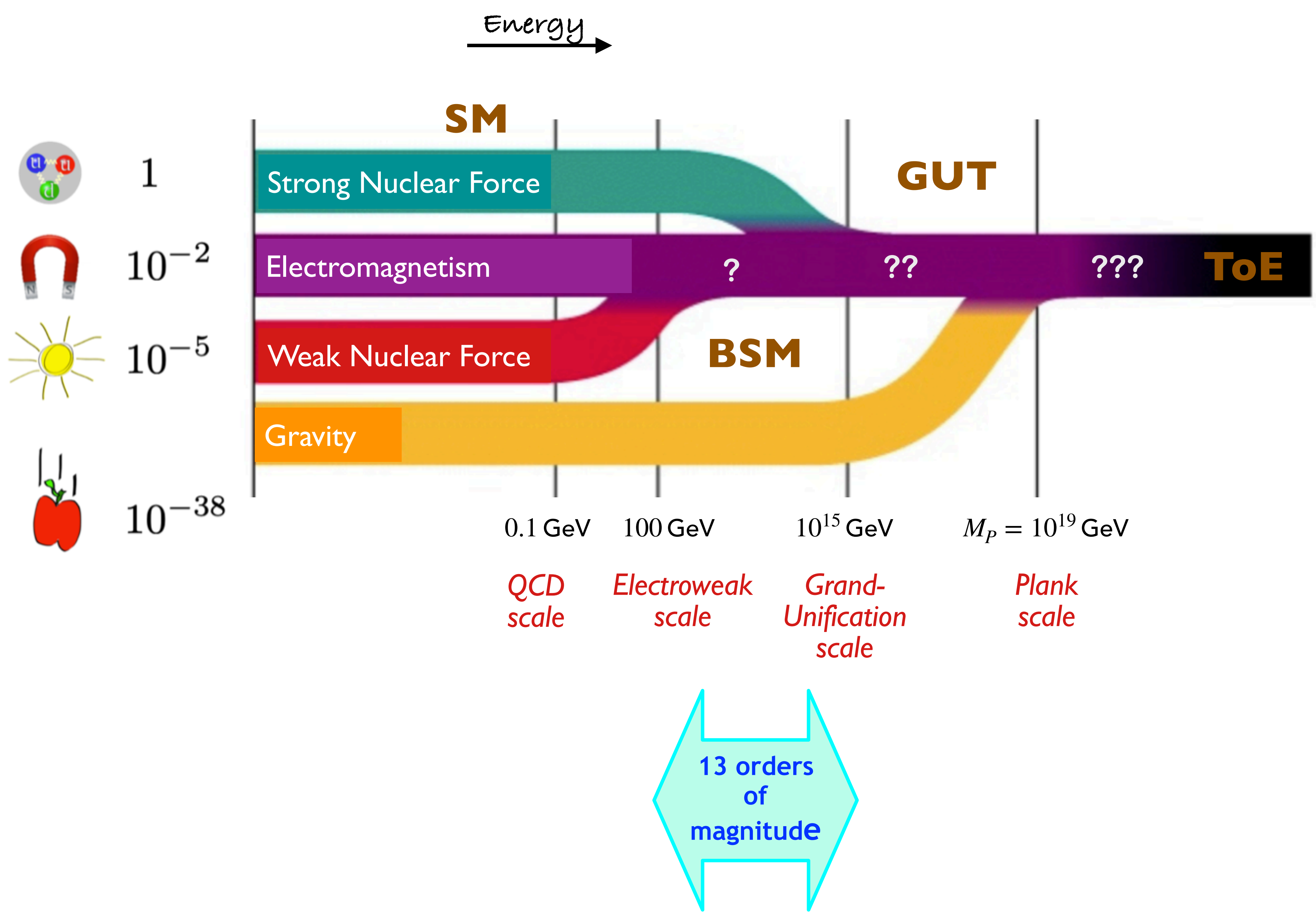


CDF, D0

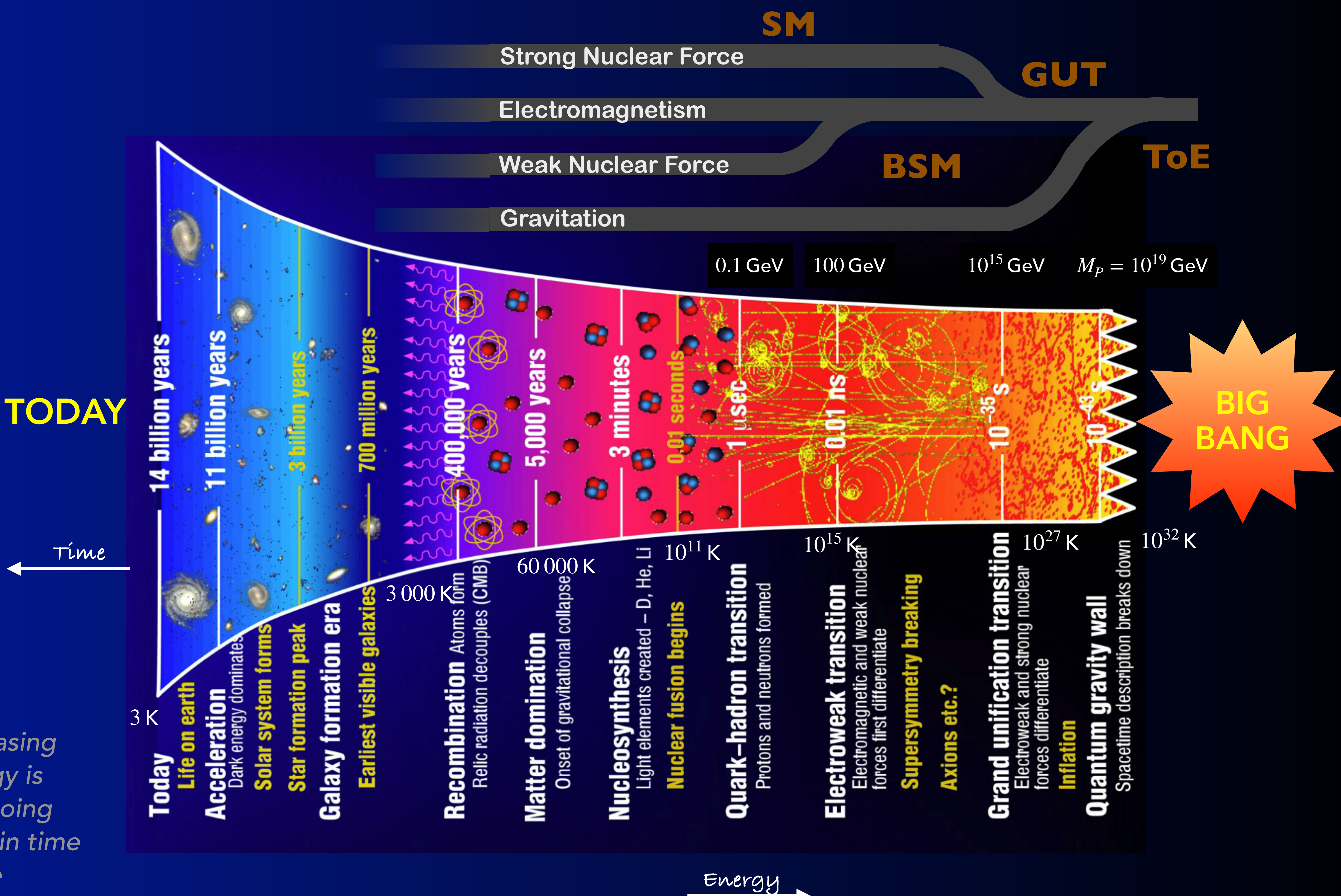
Particle Masses and Energy Scales



Interactions and Energy Scales



Cosmology and Energy Scales

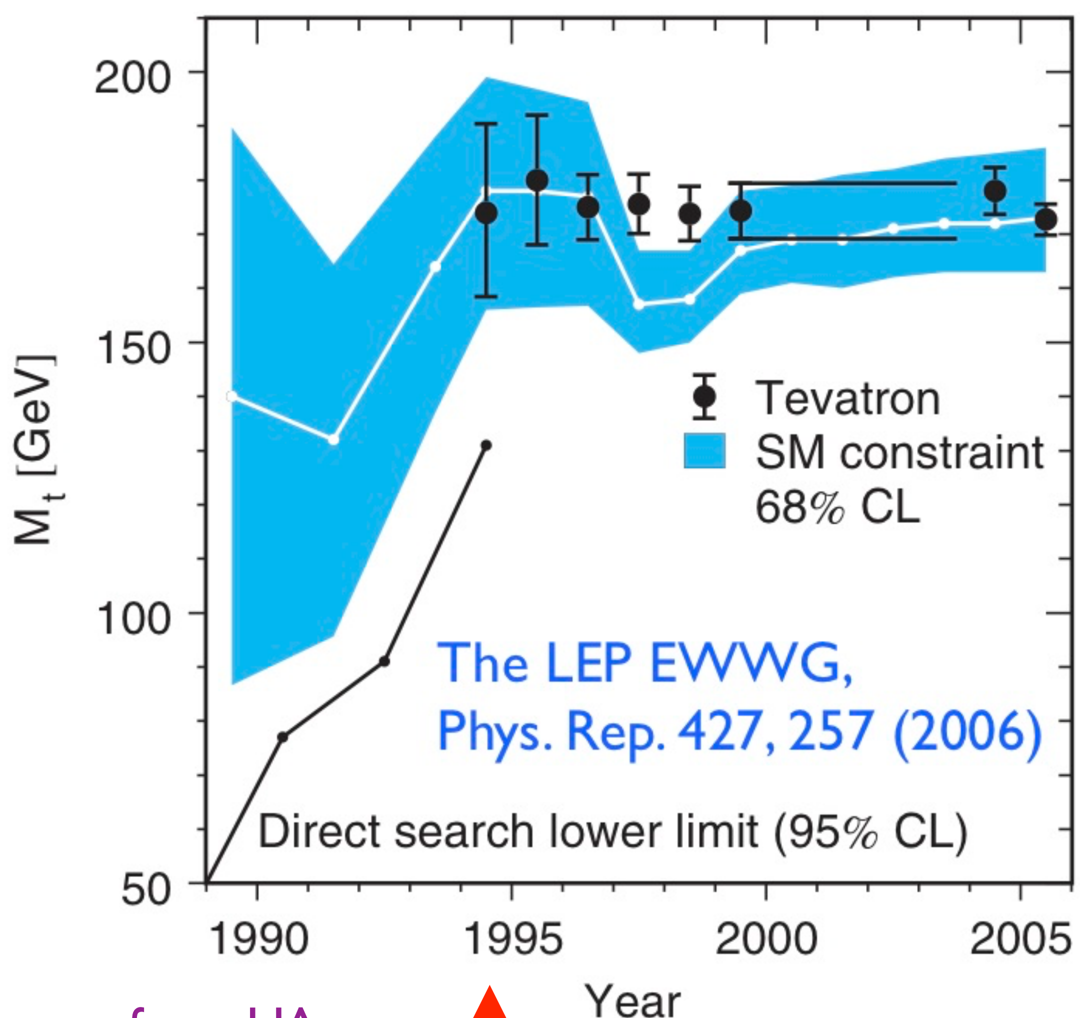


Increasing energy is like going back in time in the history of the Universe

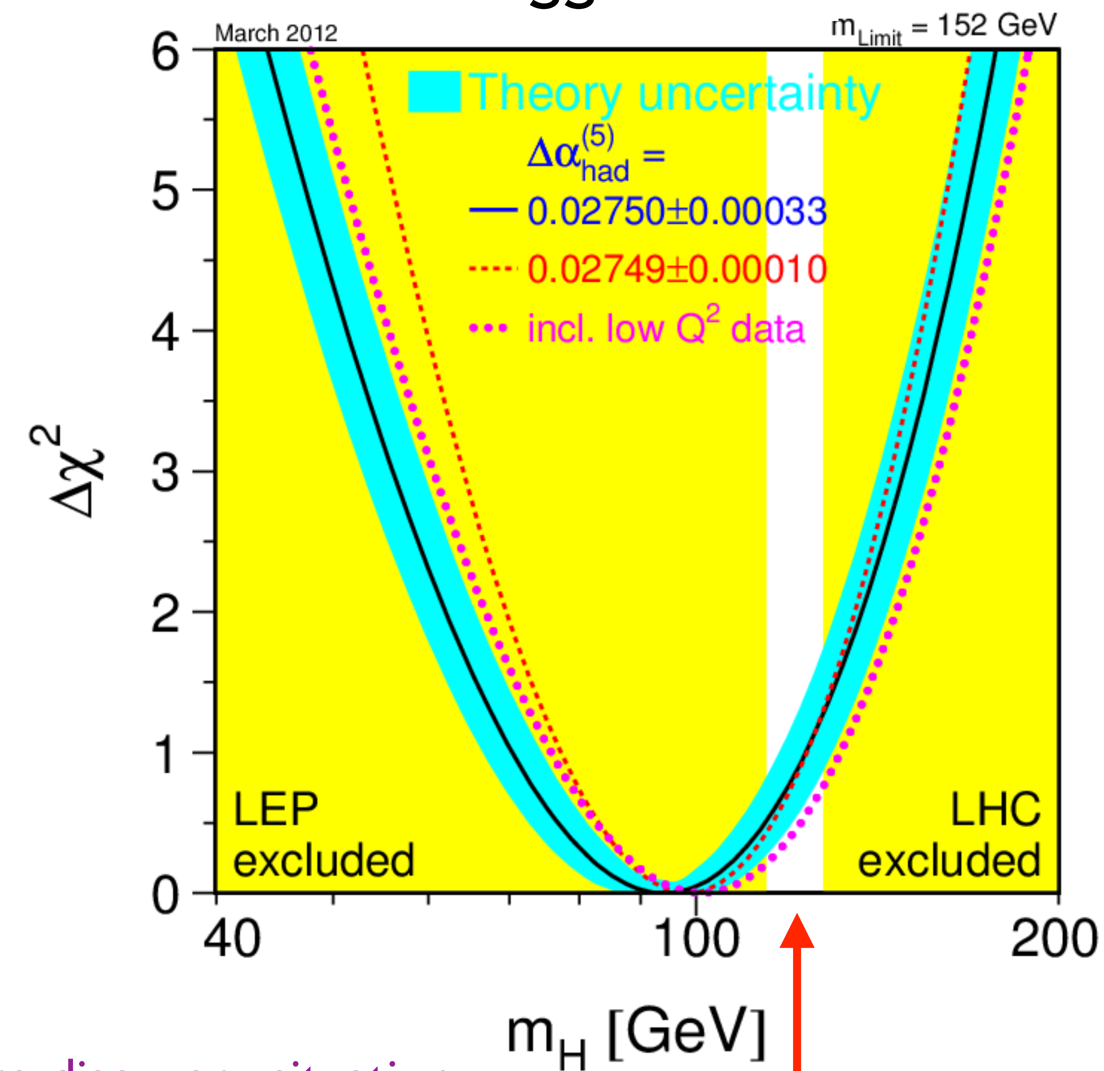
https://www.ctc.cam.ac.uk/outreach/origins/big_bang_three.php

Predictive Power of the SM

The Top Quark



The Higgs Boson



mW from UA
+ precision EW
from LEP/SLD

discovery
Tevatron
1994

W mass
from LEP-II

pre-discovery situation
(March 2012)

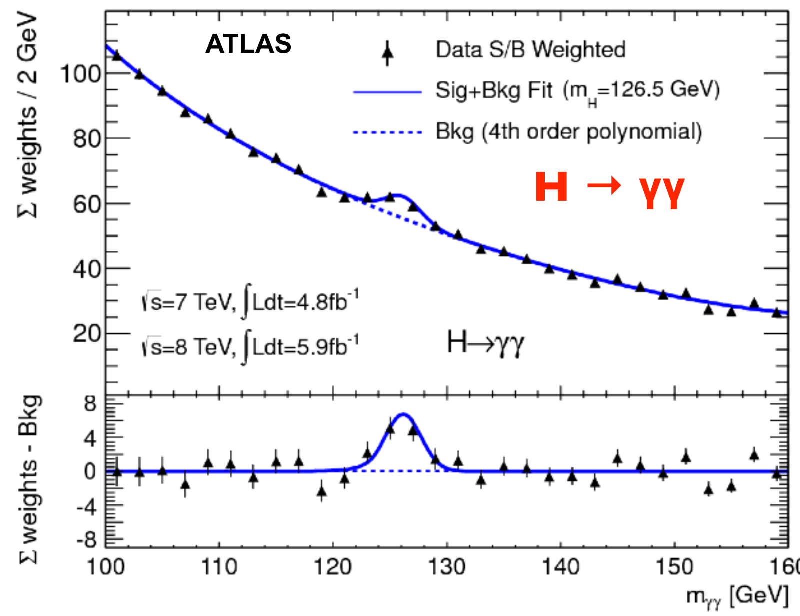
discovery LHC
2012

Successful experimental strategy

- precision at lepton machines
- discovery at hadron machines

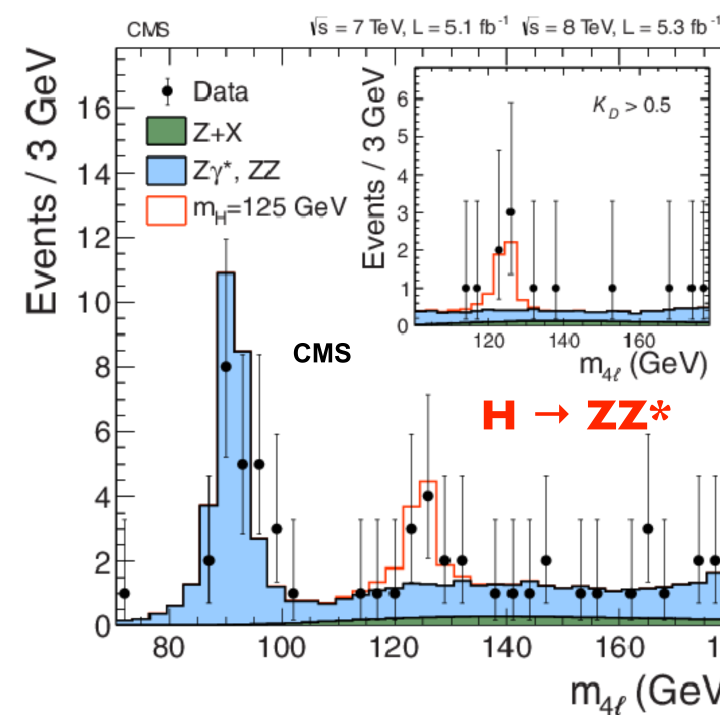
2012: Discovery of the Higgs Boson

CERN 4 July 2012



ATLAS

CMS



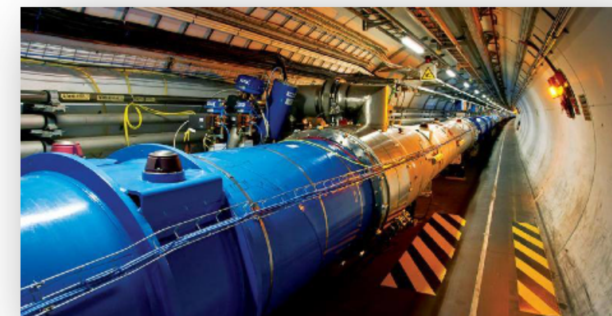
Discovery of a new scalar boson with a mass of 125 GeV,
later unambiguously identified
as the long-sought Higgs boson

The discovery of the Higgs boson proves the physical existence of the scalar Higgs field


The LHC: A Marvel of Technology

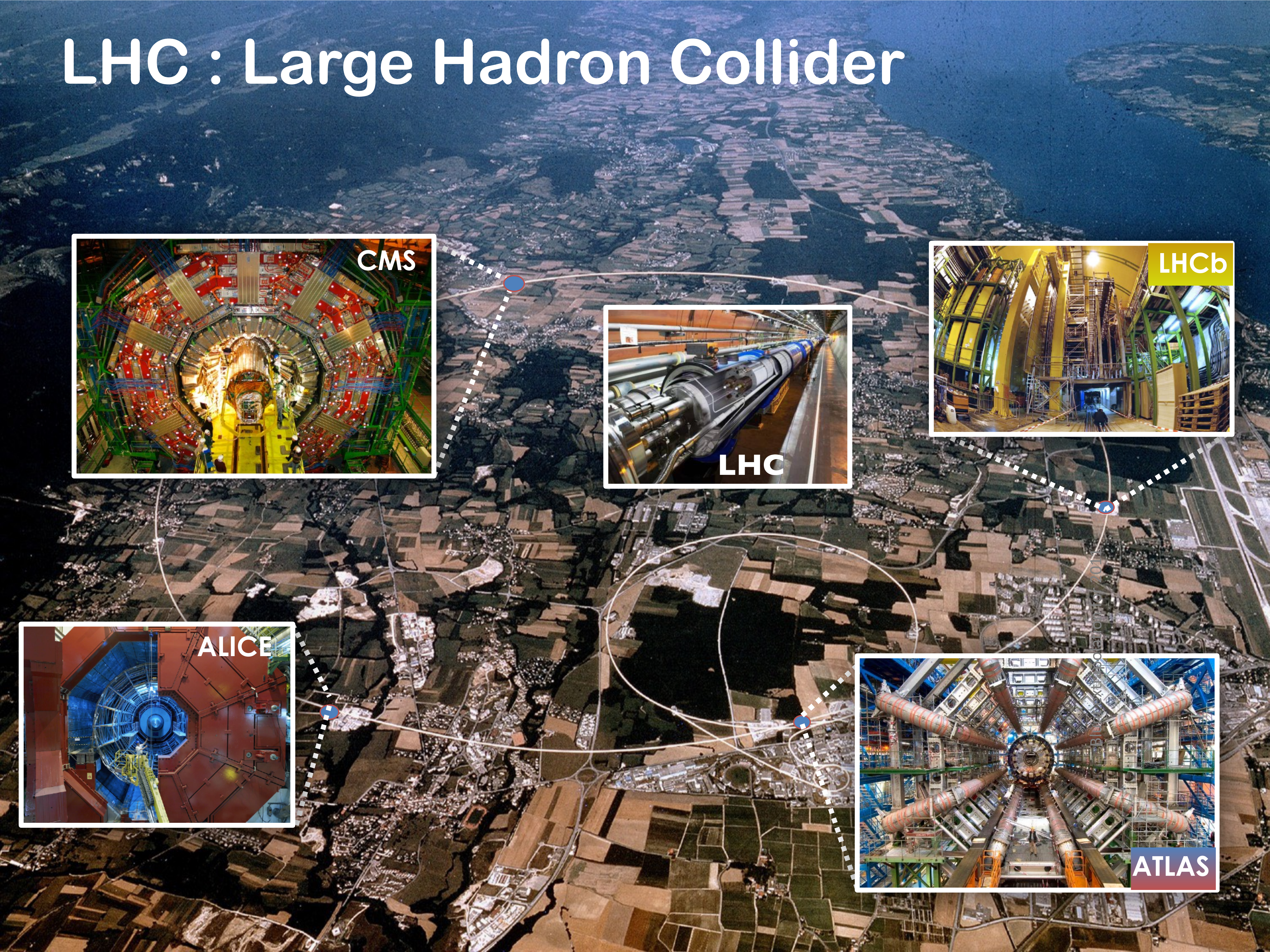
The Large Hadron Collider

A high-energy proton-proton and heavy ion collider

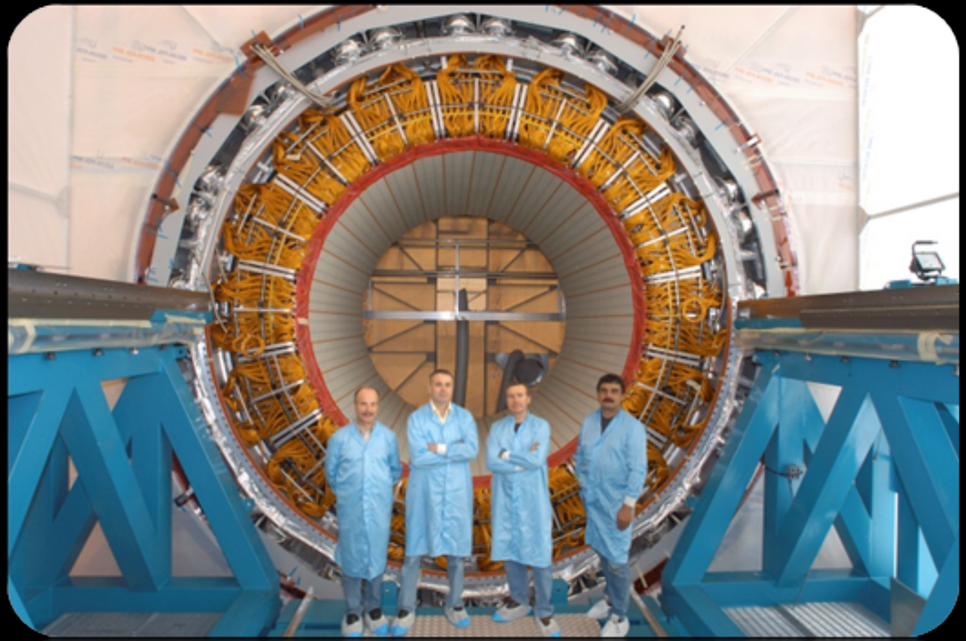


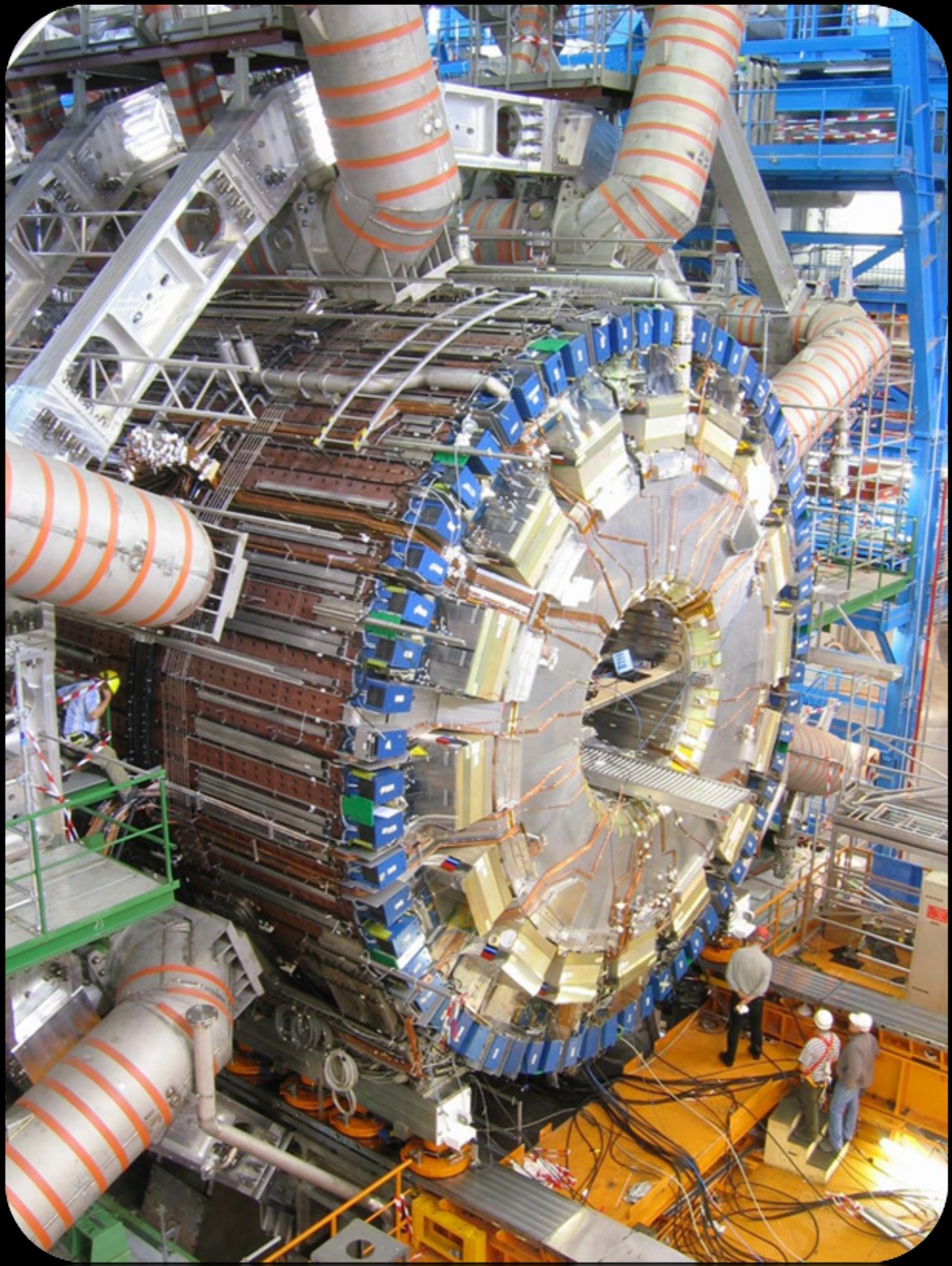
- 1232 superconducting 15-m-long dipoles (8.3 T)
- 10,000 superconducting magnets
- 150 t of superfluid helium (1.9 K)
- cryogenic vacuum (10^{-13} atm)
- stored magnetic energy > 10 GJ
- stored energy in beams > 1 GJ

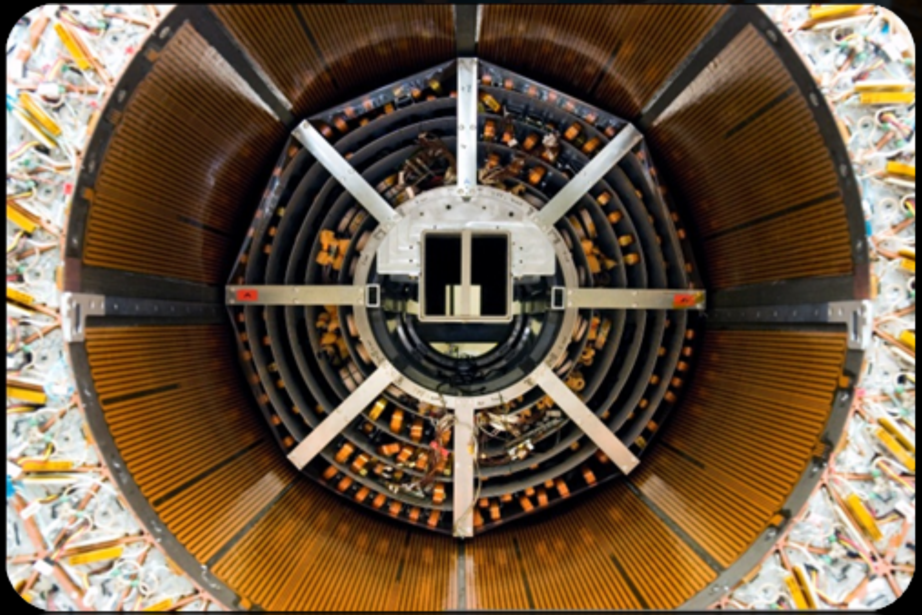
LHC : Large Hadron Collider

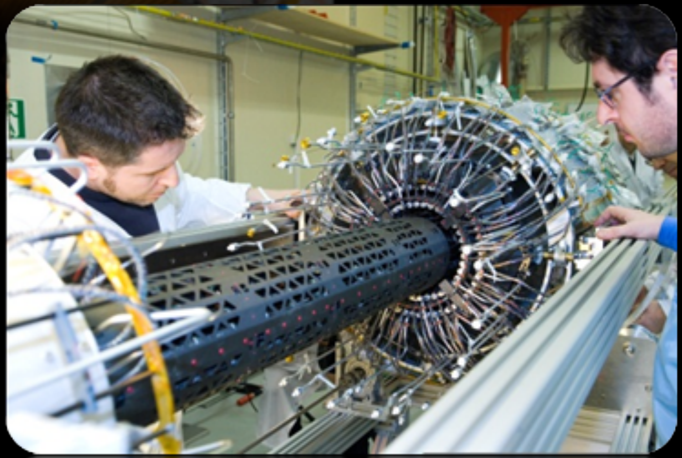


ATLAS

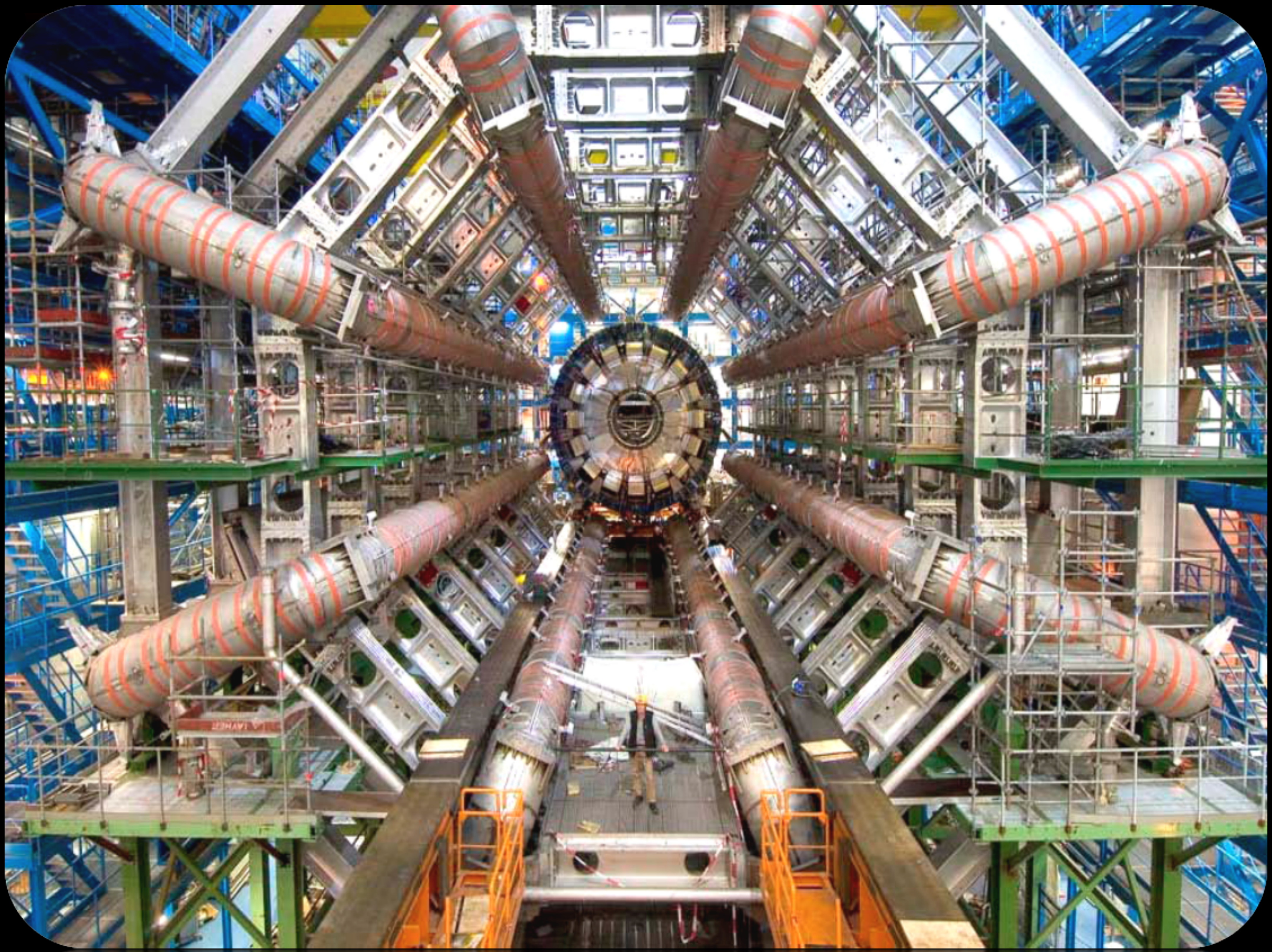




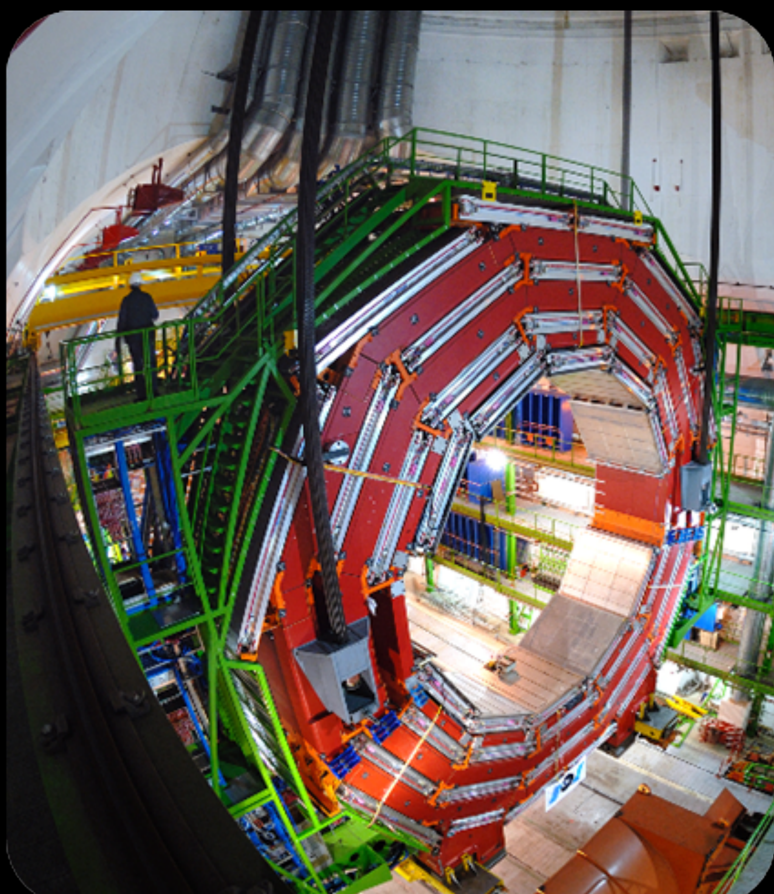


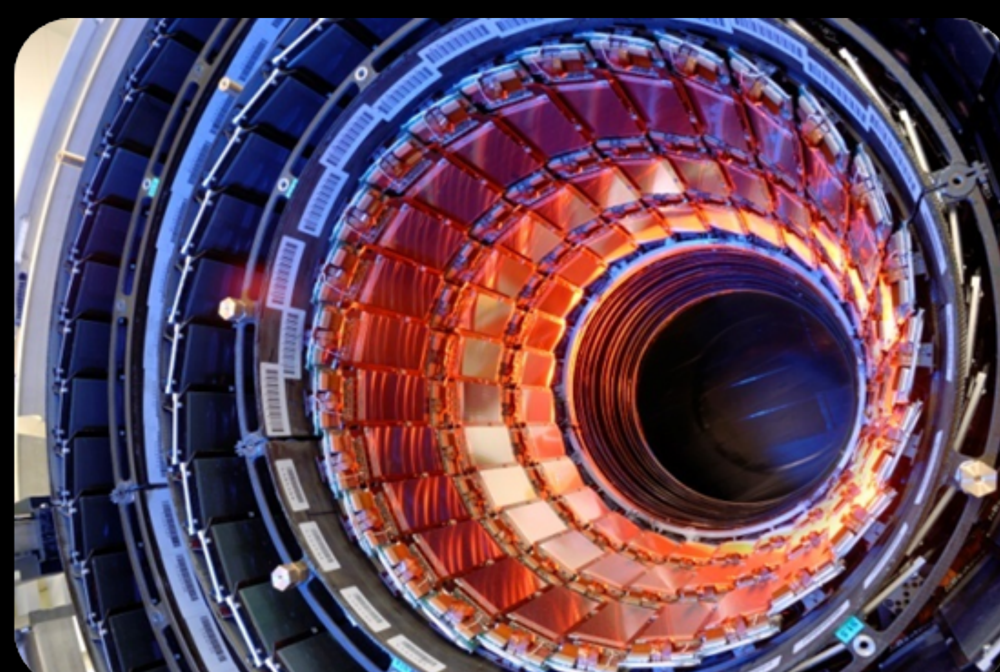


ATLAS

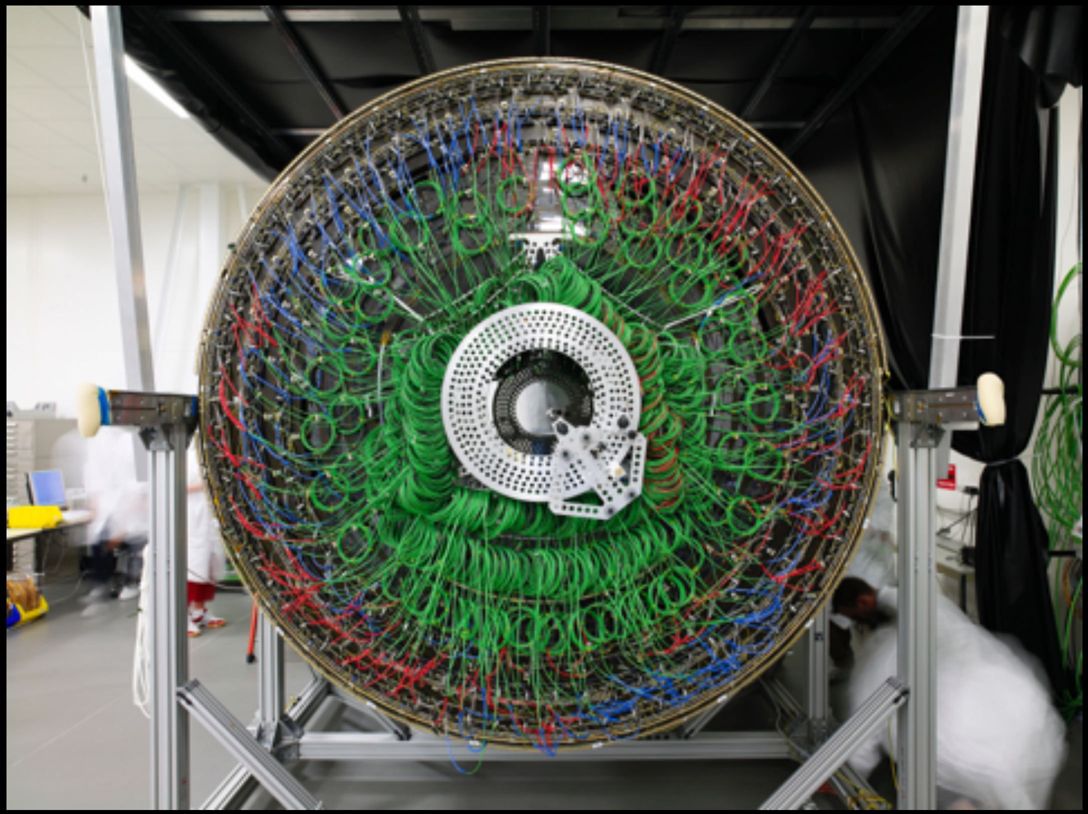


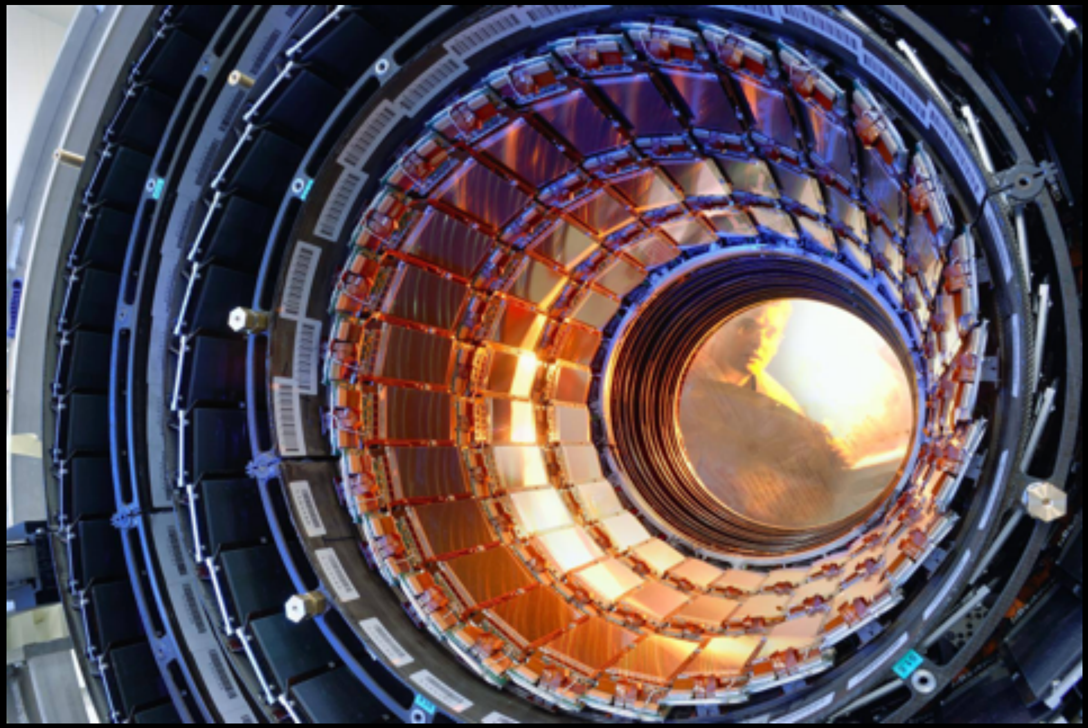
CMS

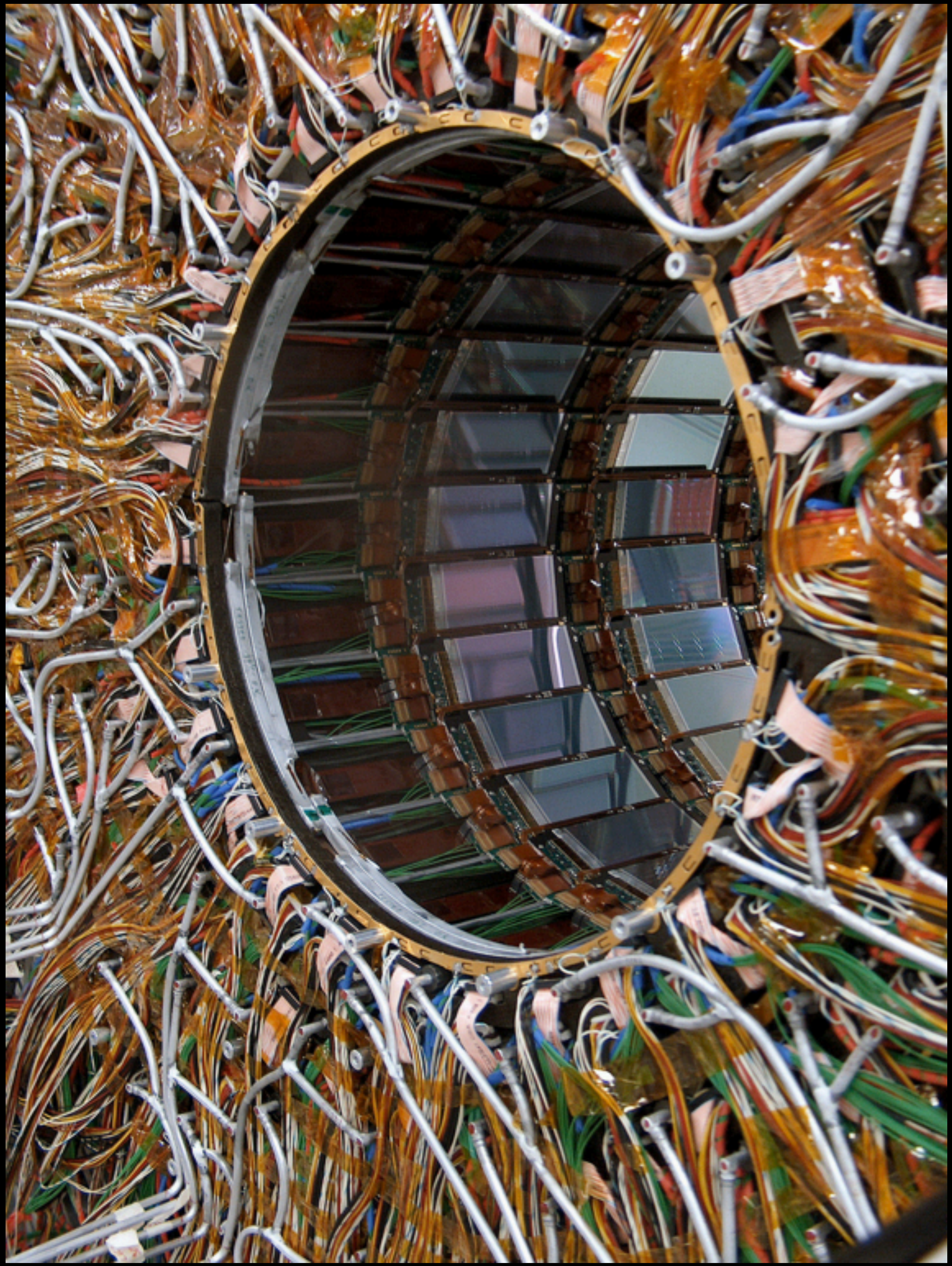




High Technologies







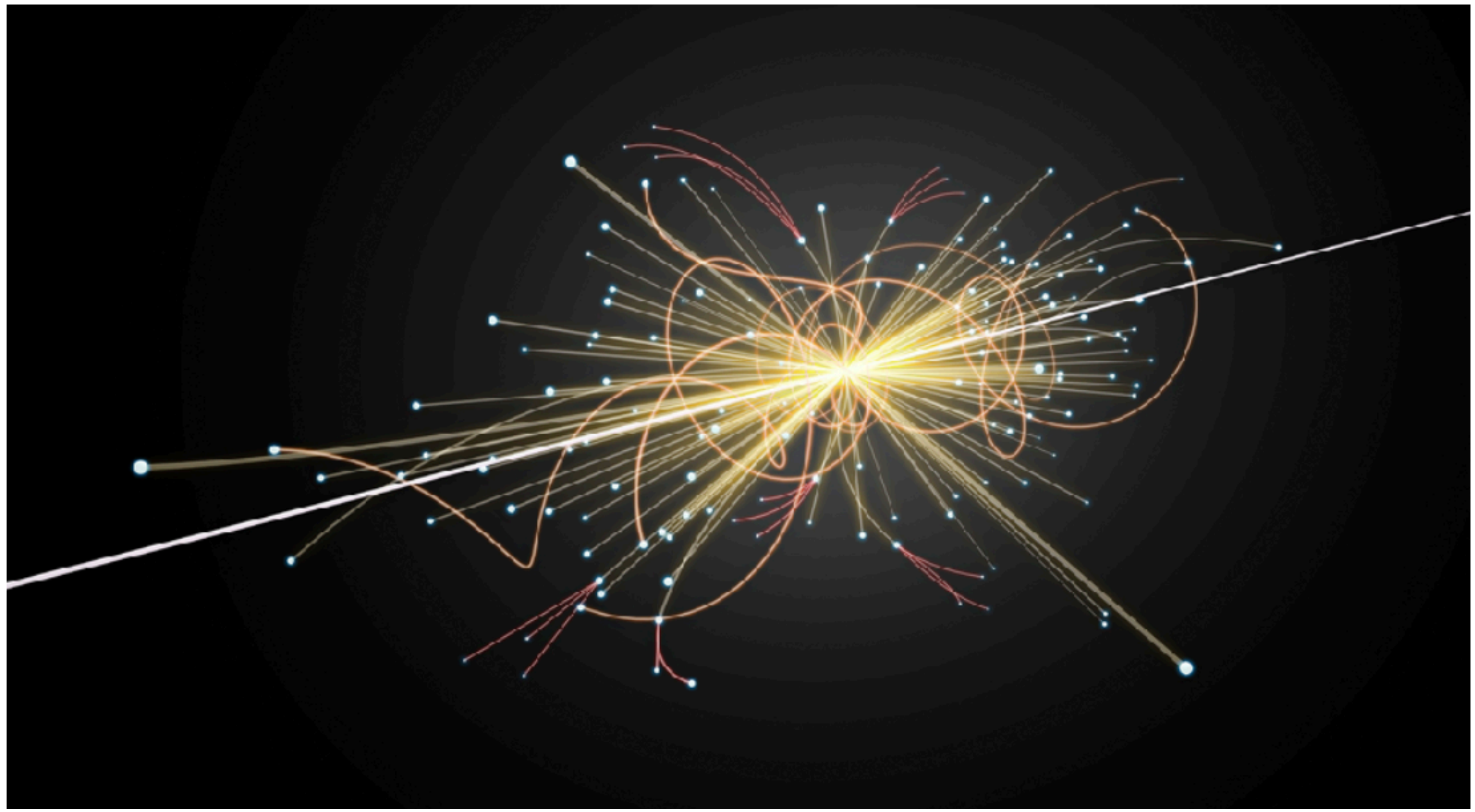
Digital Cameras

- 100 millions “pixels”
- 40 millions “3D photos 3D” per sec.

Phenomenal Quantities of Data

Computer farms to process hundreds of millions of Giga bytes a year

Physics of the Quantum Vacuum

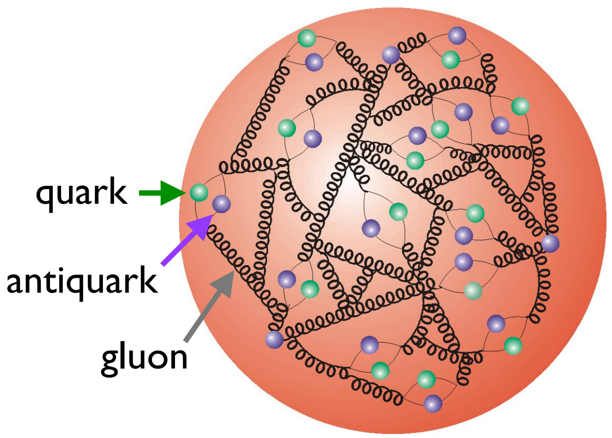


In particle colliders, matter is created from pure energy by locally exciting the quantum vacuum

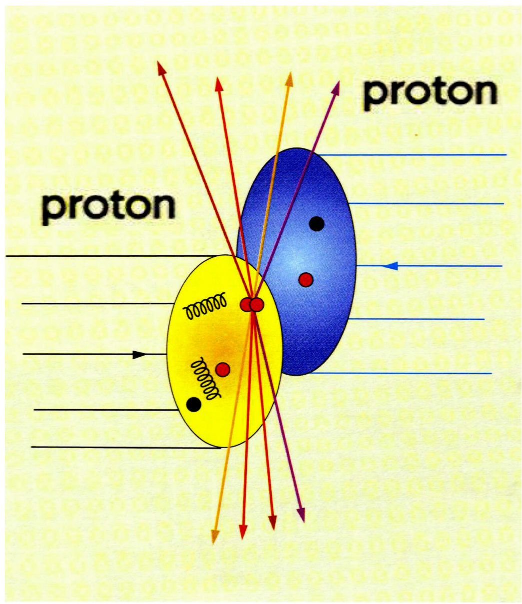
$$m = E/c^2$$

The ultimate goal: to study the vacuum and arrive at the Theory of Everything

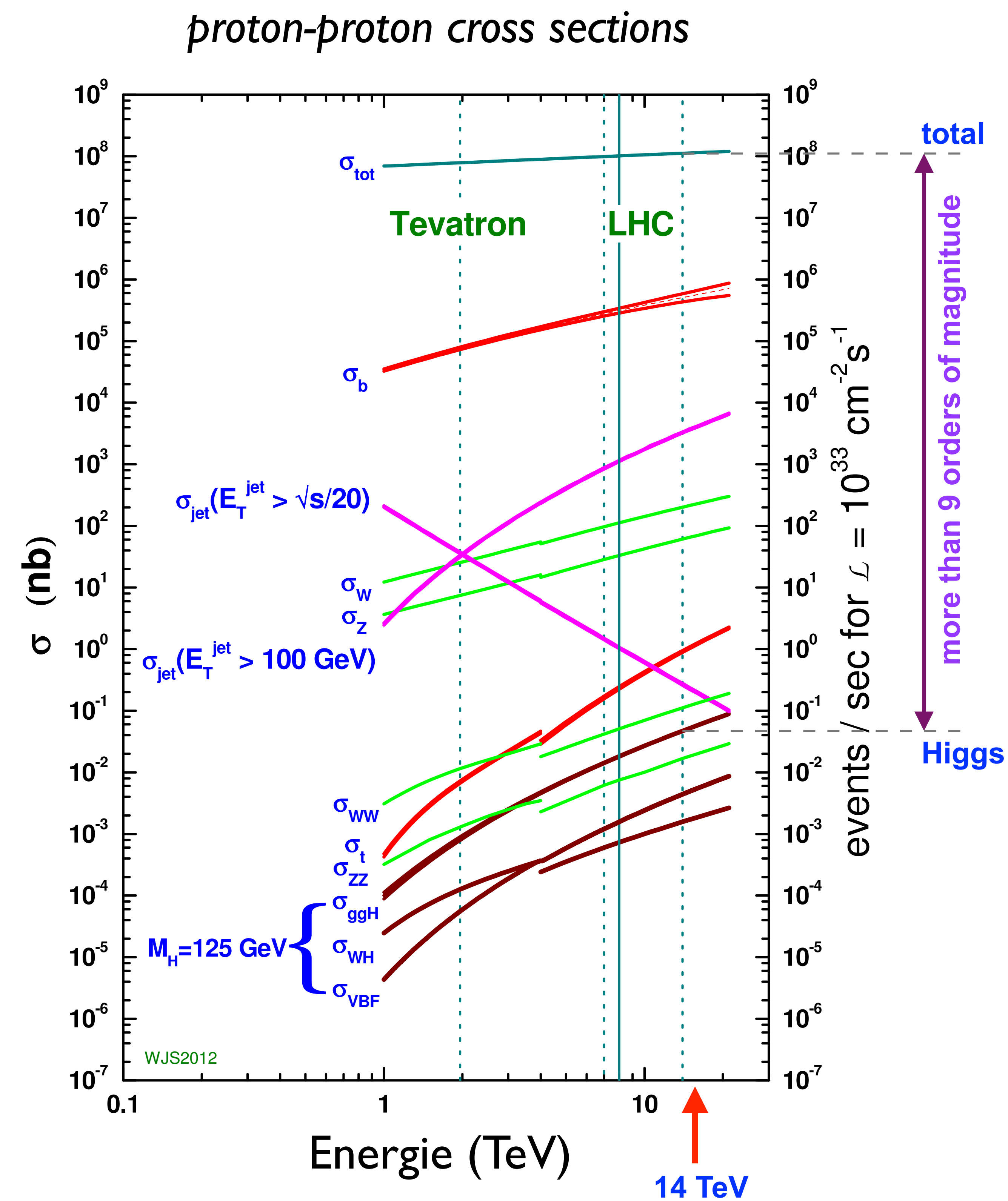
A Quark and Gluon Collider



the proton "seen"
at short distance
(= high energy)



Study of hard interactions
- gluon & gluon *(dominant)*
- quark & antiquark
- (anti)quark & gluon
- etc.



Cross sections in nanobarn (nb)
- ☛ 1 nb = 10^{-33} cm^2
- ☛ at 14 TeV : **$\sigma_{tot} = 10^8$ nb, $\sigma_H = 0.05$ nb**

Instantaneous luminosity LHC : **$\mathcal{L} = 2\times10^{34}$ cm^{-2}s^{-1}**
- ☛ 2 billion inelastic collisions per second
- ☛ 1 Higgs boson every second

A Dantesque Environment

Integrated luminosity expressed in **inverse-femtobarn** (fb^{-1})
☛ at 14 TeV : 1 fb^{-1} corresponds to one hundred thousand billion proton collisions

pile-up (PU) = number of inelastic interactions per bunch crossing (every 25 ns)

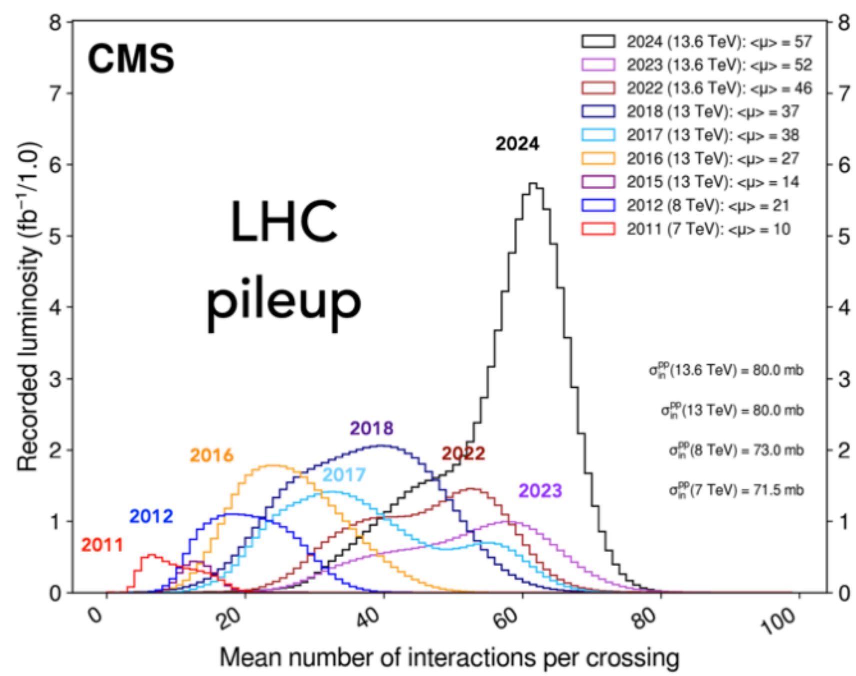
Integrated luminosities at ATLAS and CMS

Run-1
- ✓ 5 fb^{-1} at 7 TeV (2011)
- ✓ 20 fb^{-1} at 8 TeV (2012)

Run-2
- ✓ 140 fb^{-1} at 13 TeV (2015-2018)

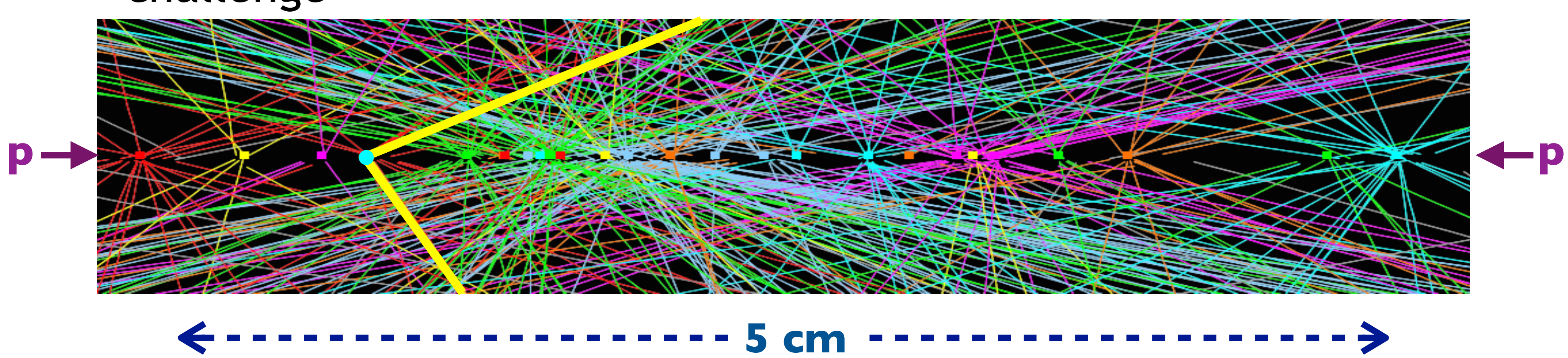
Run-3
- 500 fb^{-1} at 13.6 TeV (2022-2026)

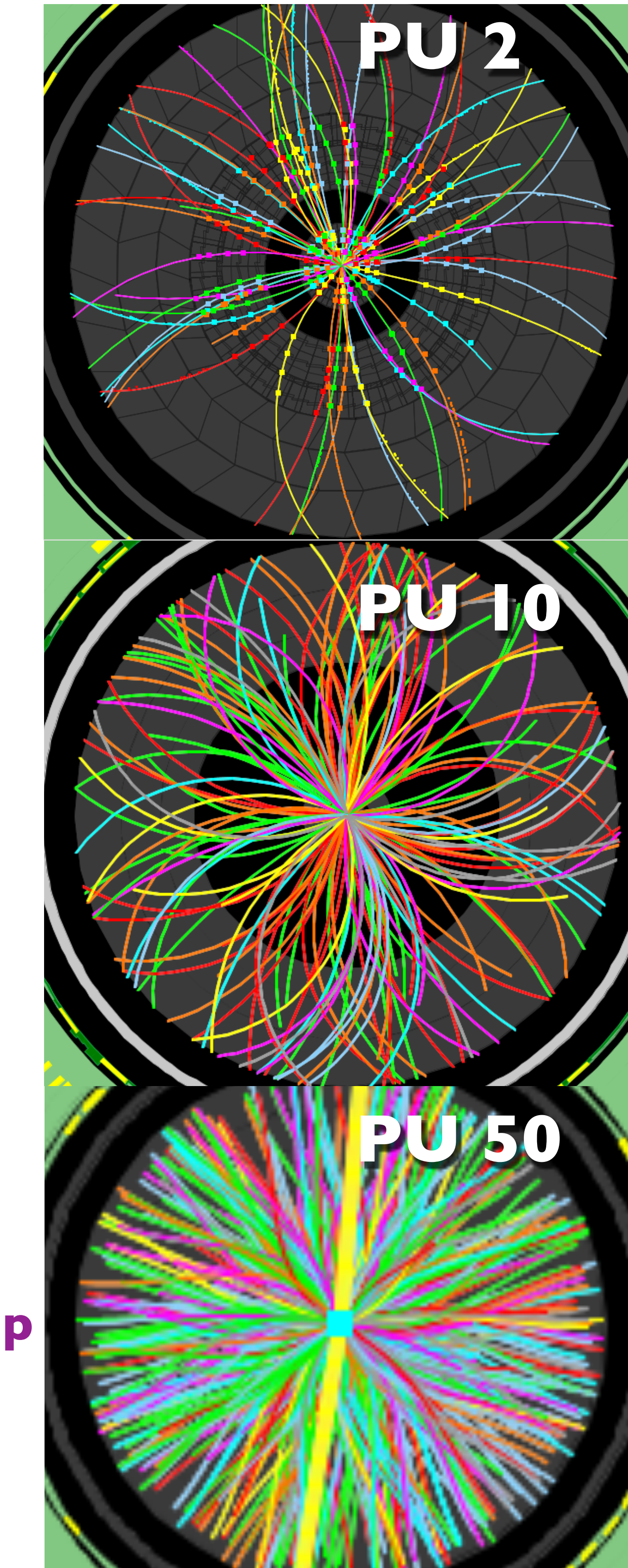
HL-LHC
- 3000 fb^{-1} at 14 TeV (2030-2042)

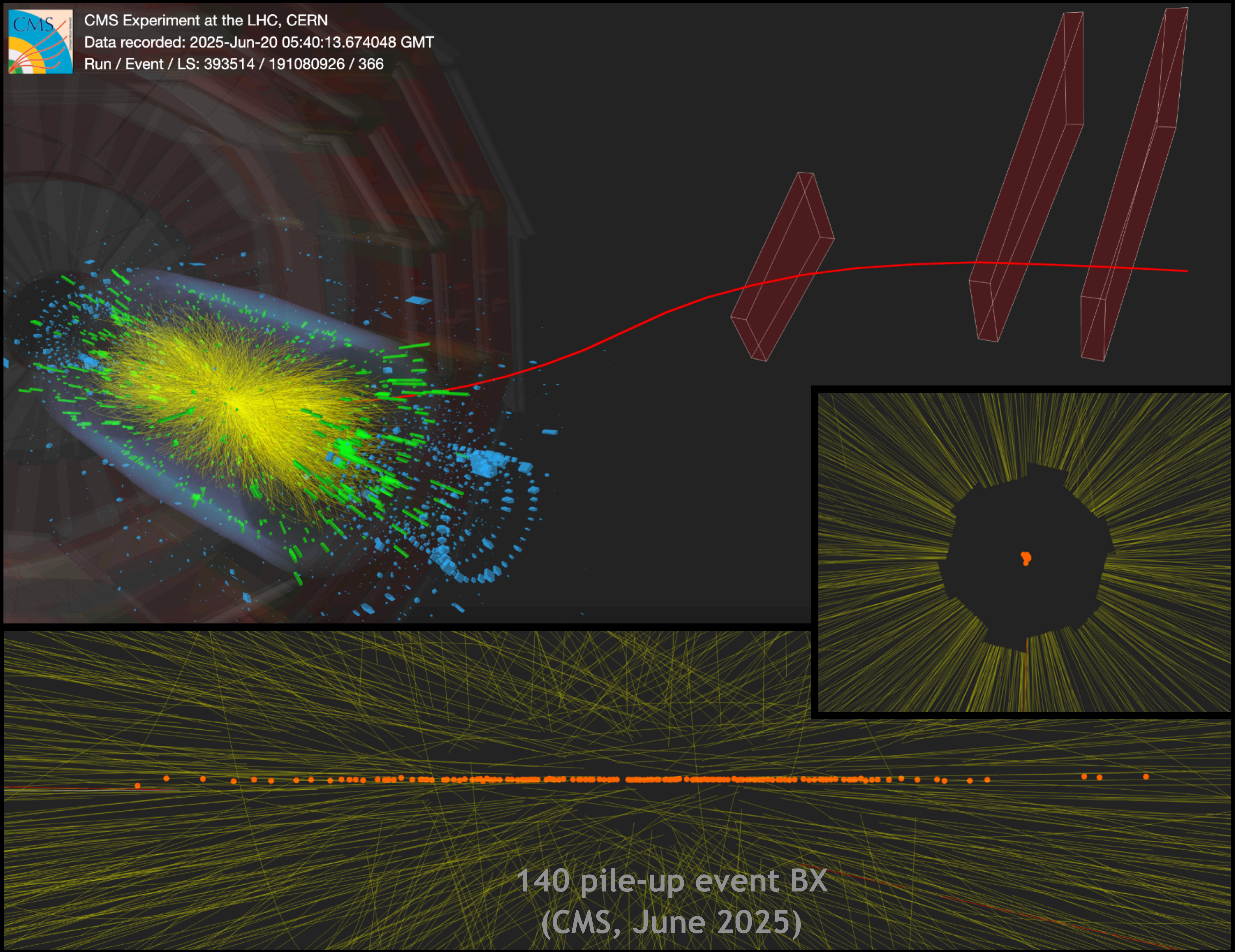


PU at HL-LHC: 200 !

A tremendous experimental challenge





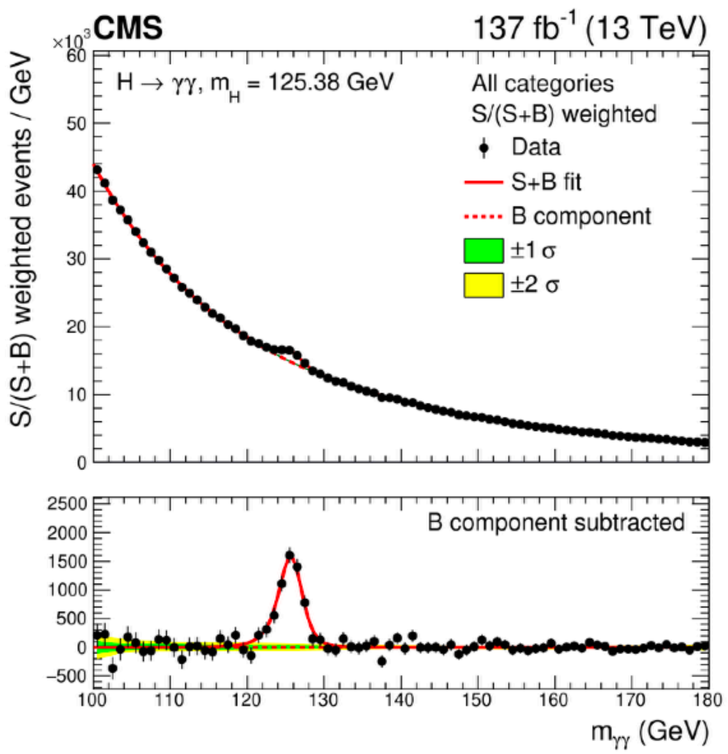

CMS Experiment at the LHC, CERN
Data recorded: 2025-Jun-20 05:40:13.674048 GMT
Run / Event / LS: 393514 / 191080926 / 366
140 pile-up event BX
(CMS, June 2025)

Ten Years After the Discovery

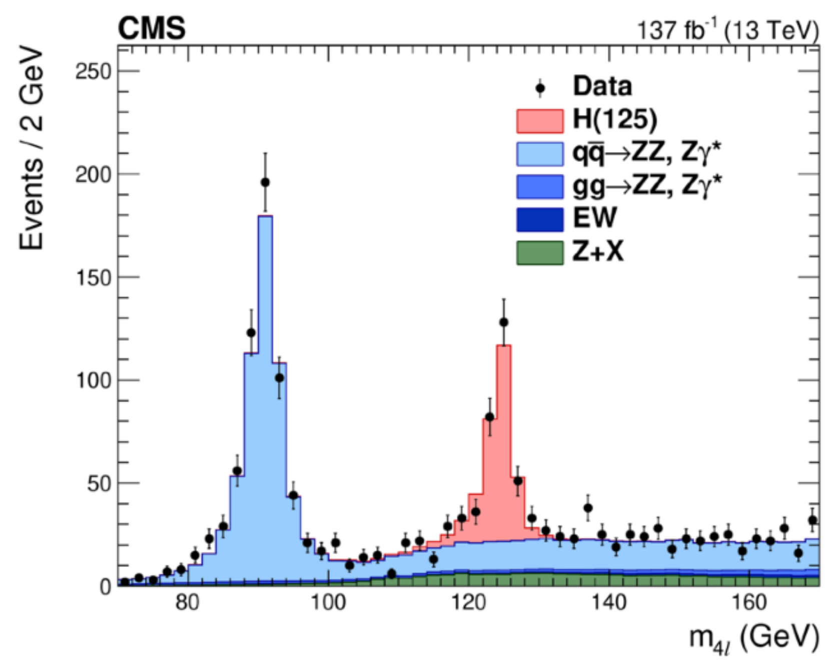
years HIGGS boson discovery

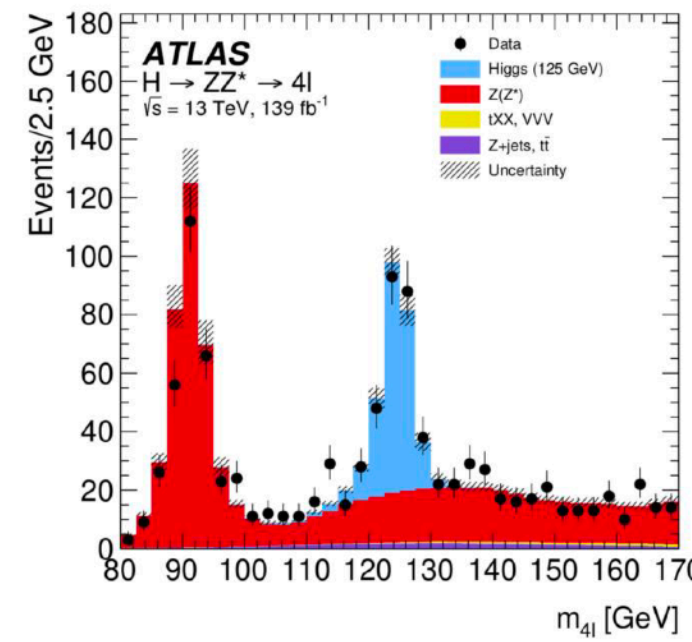
July 4 2022

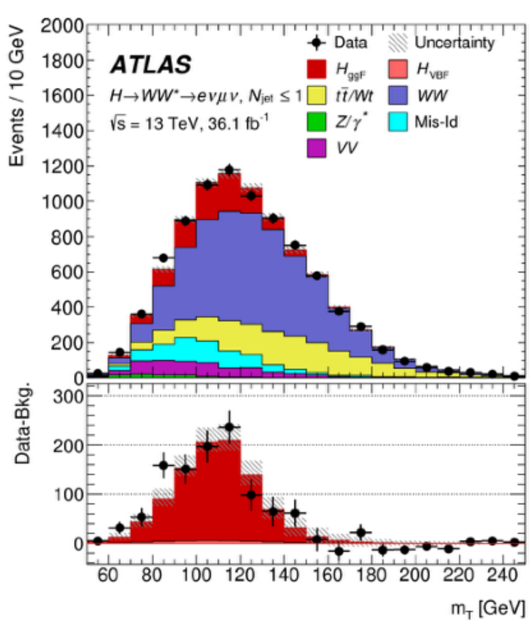
H → γγ

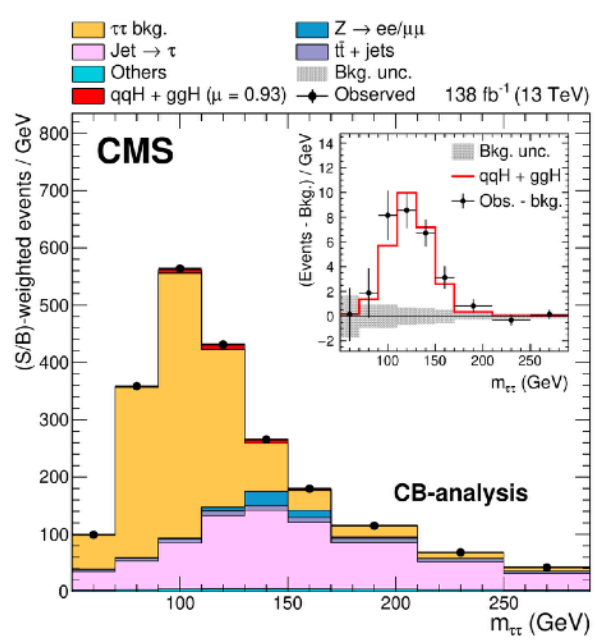


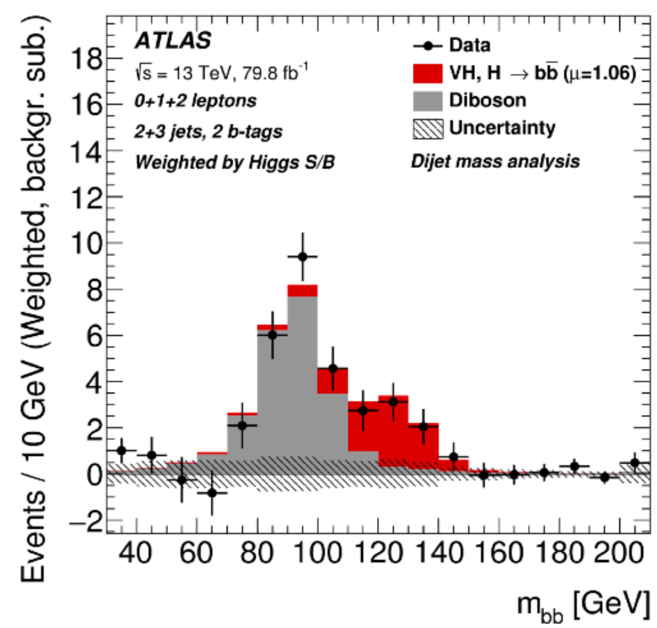
H → ZZ*









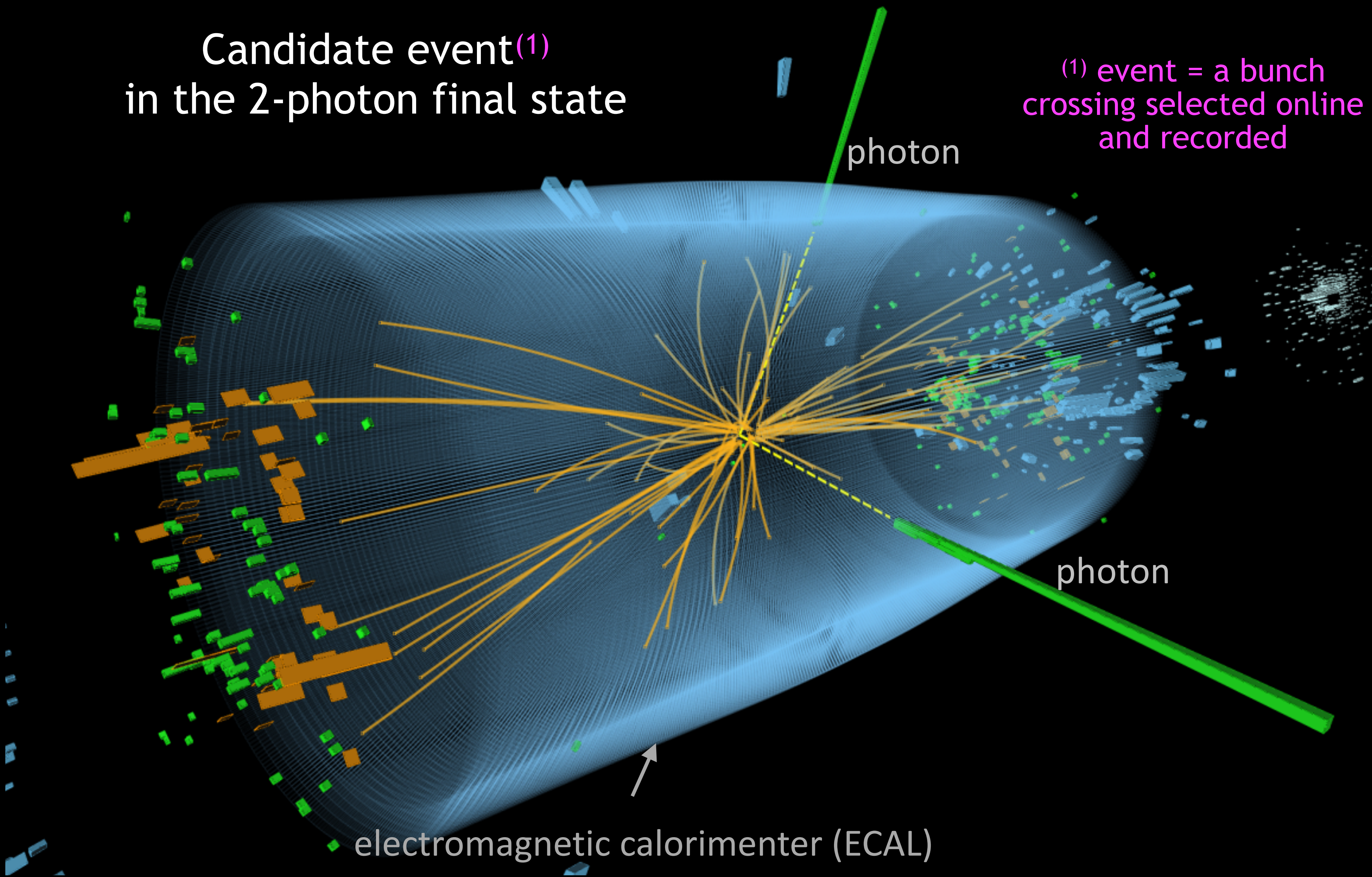


H → WW*   H → ττ   H → bb

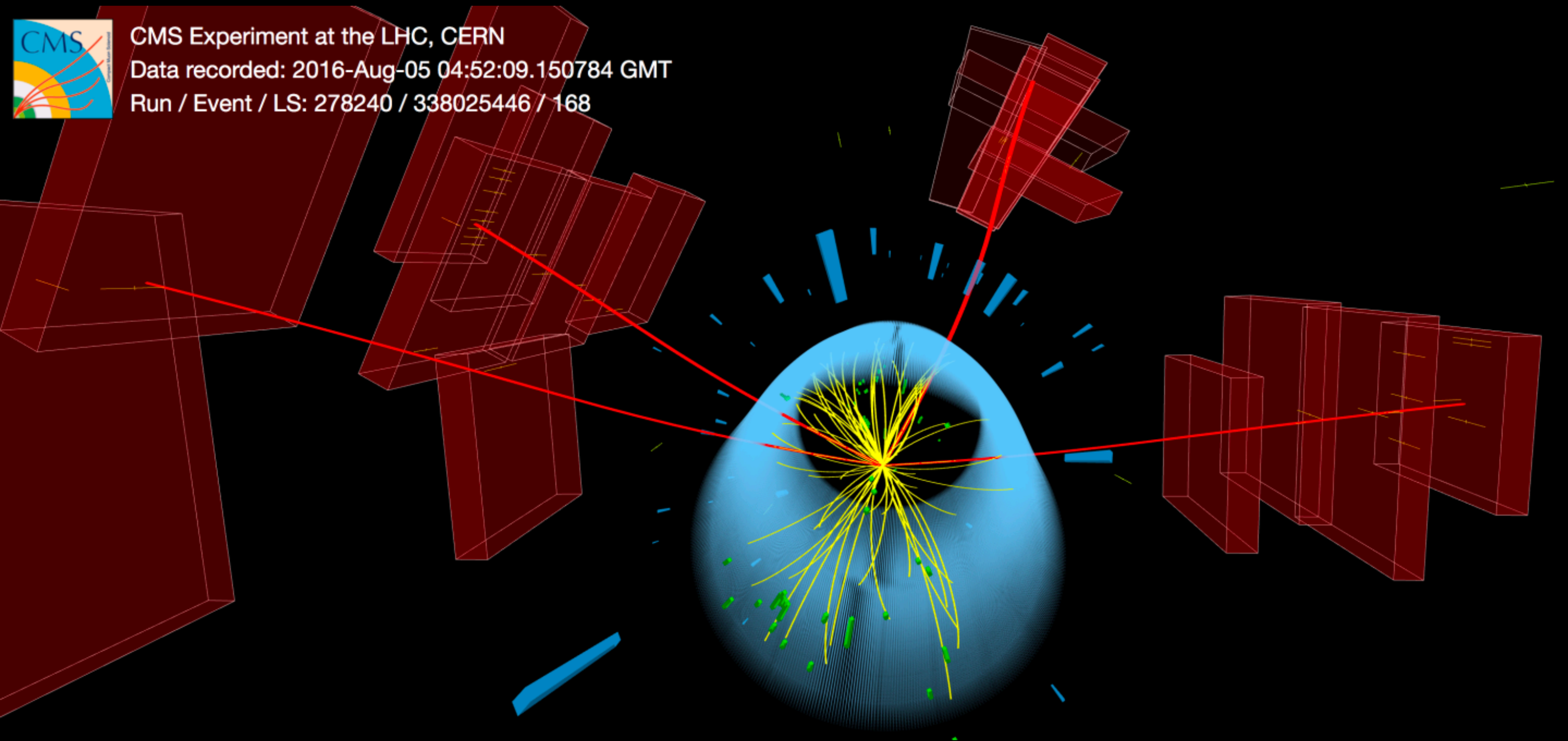
m_H = 125 GeV
±120 MeV
(±0.1%)

- Observation independently in 5 decay modes

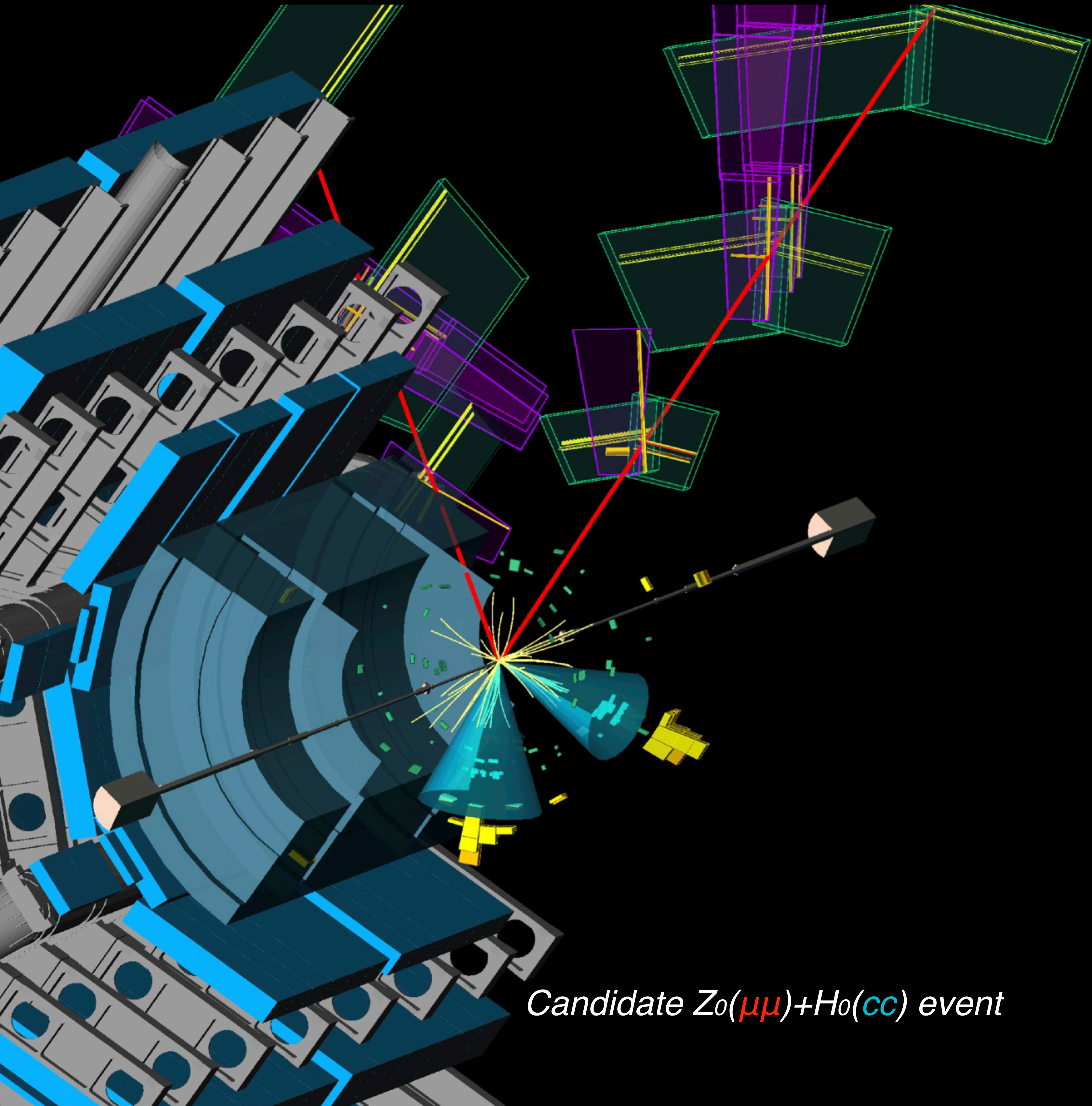
Two-Photon Final State

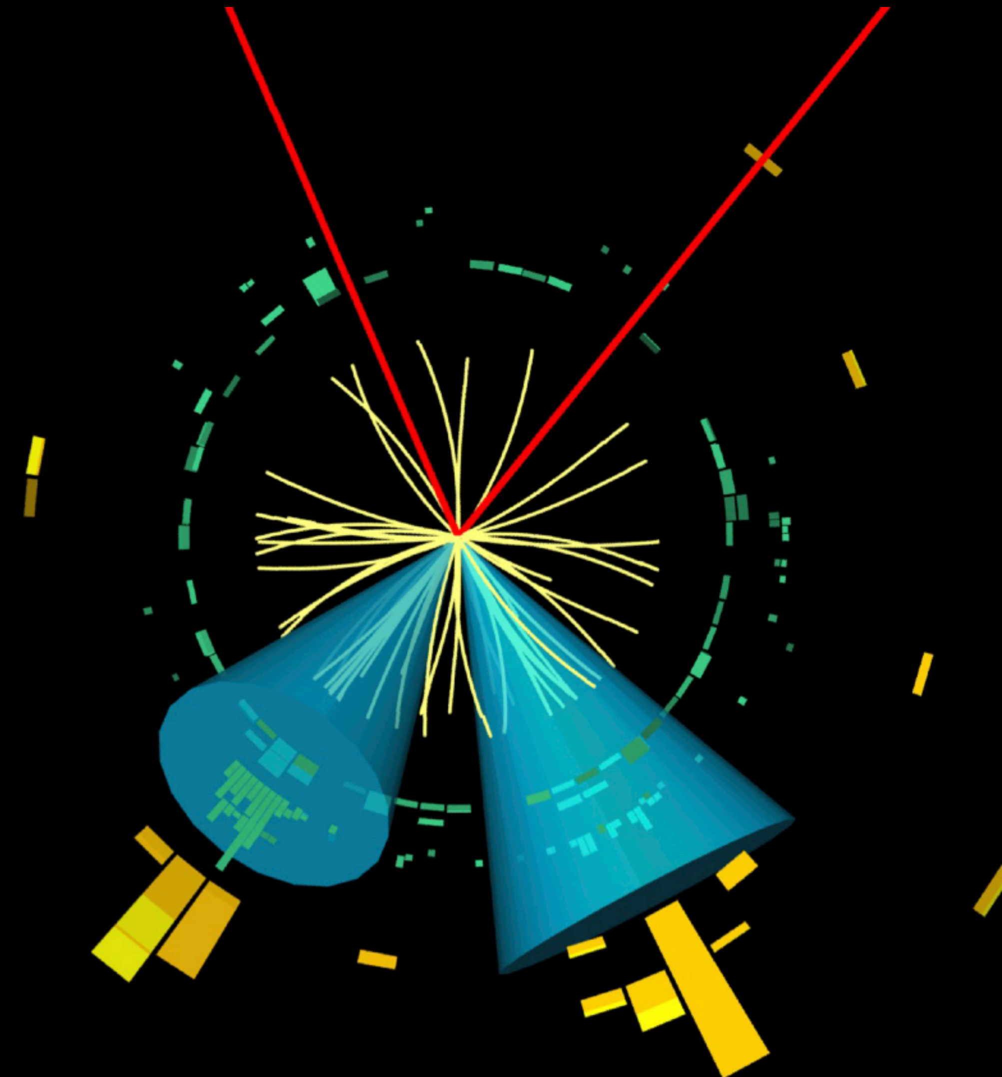


Four Muon Final State



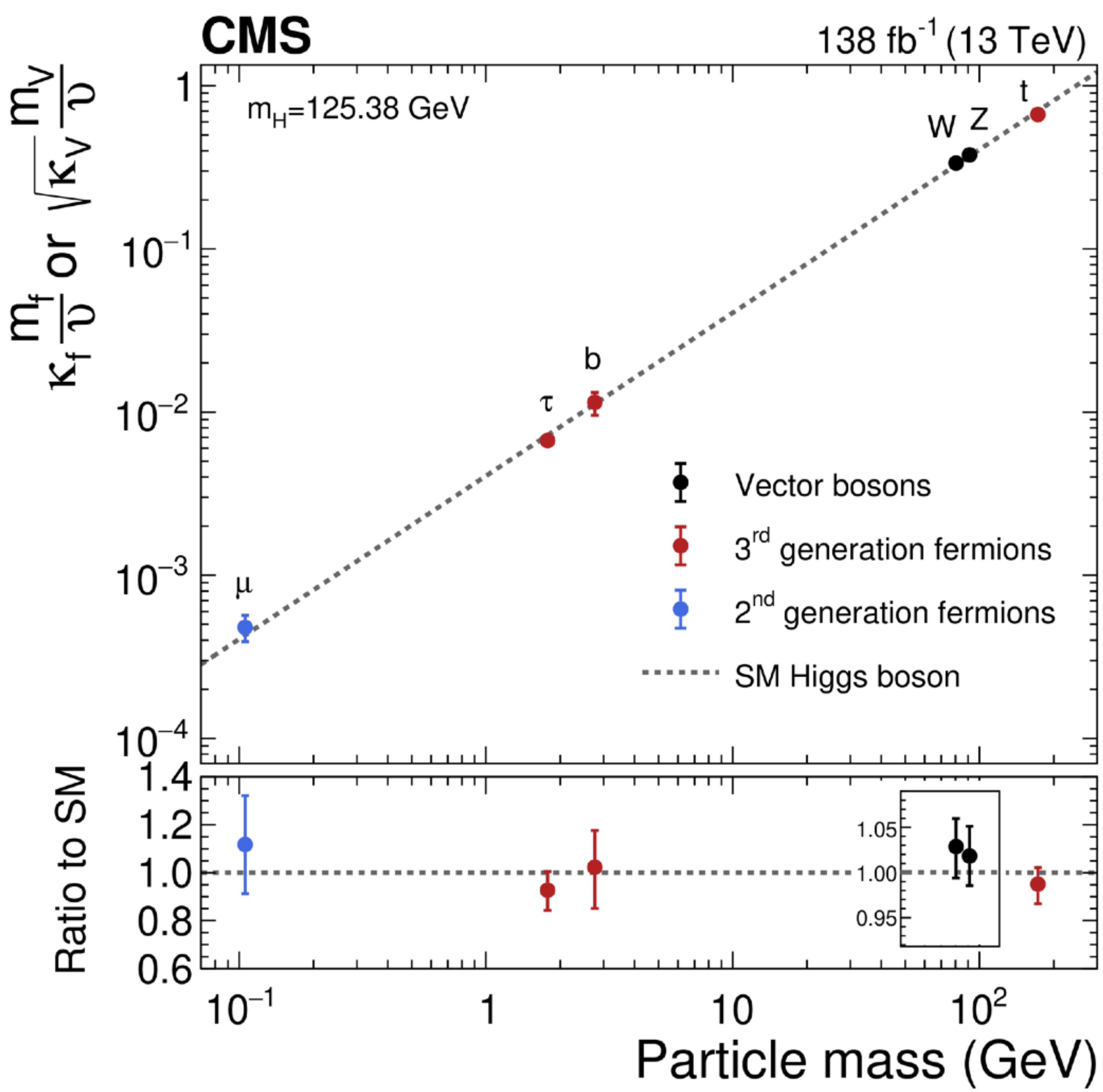
Z+jets Final State





Run: 309892
Event: 4866214607
2016-07-16 06:20:19 CEST

Higgs Boson at the Origin of Mass



Really a "new" force, but a non-universal one, as opposed to gauge interactions

A force which depends on mass!

Striking confirmation of a prediction that originates from seminal theoretical work by several groups in the early 1960s…

[CMS-HIG-22-001](#)
[Nature 607 (2022) 60](#)

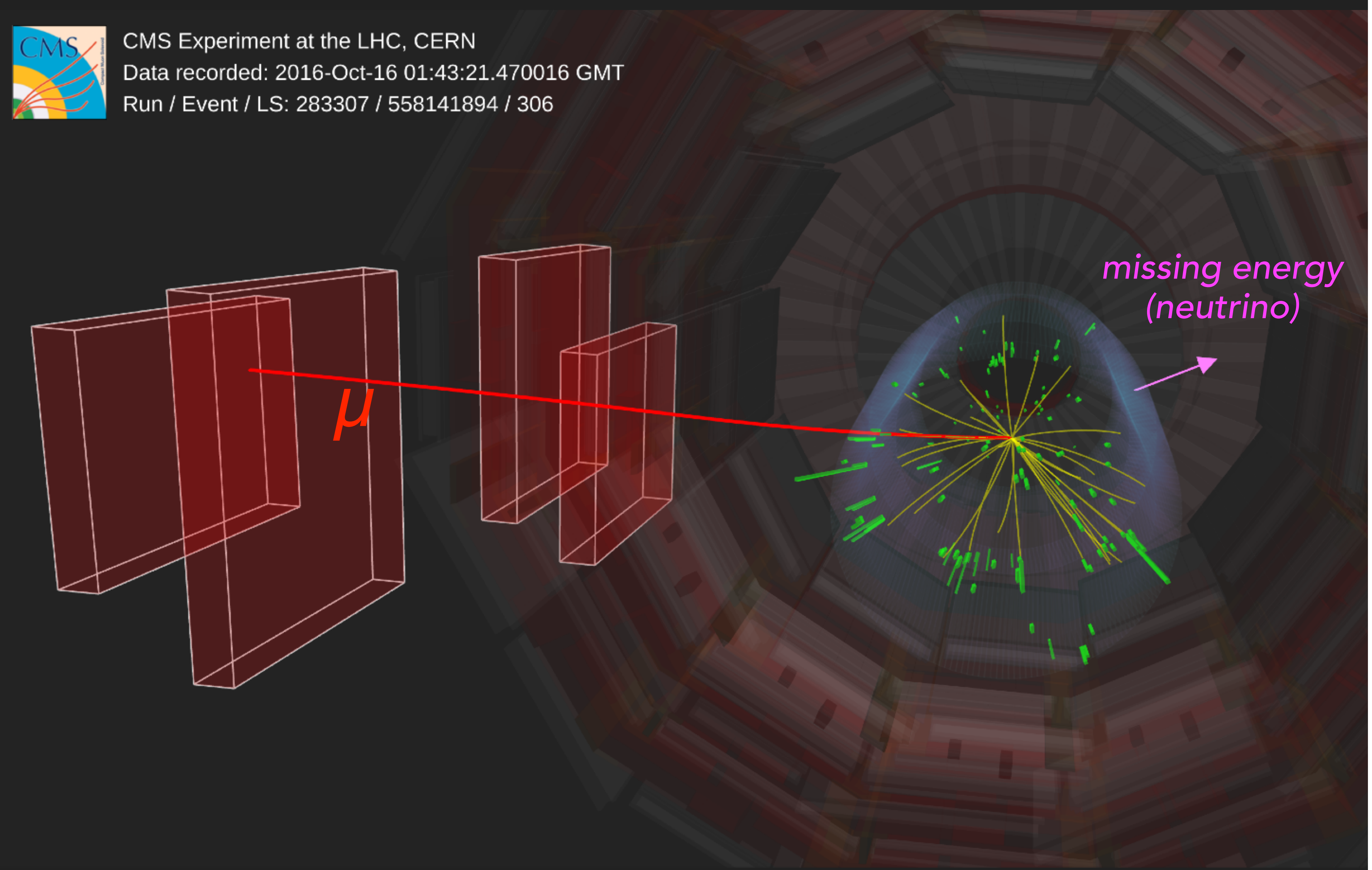
And the Nobel Prize goes to...

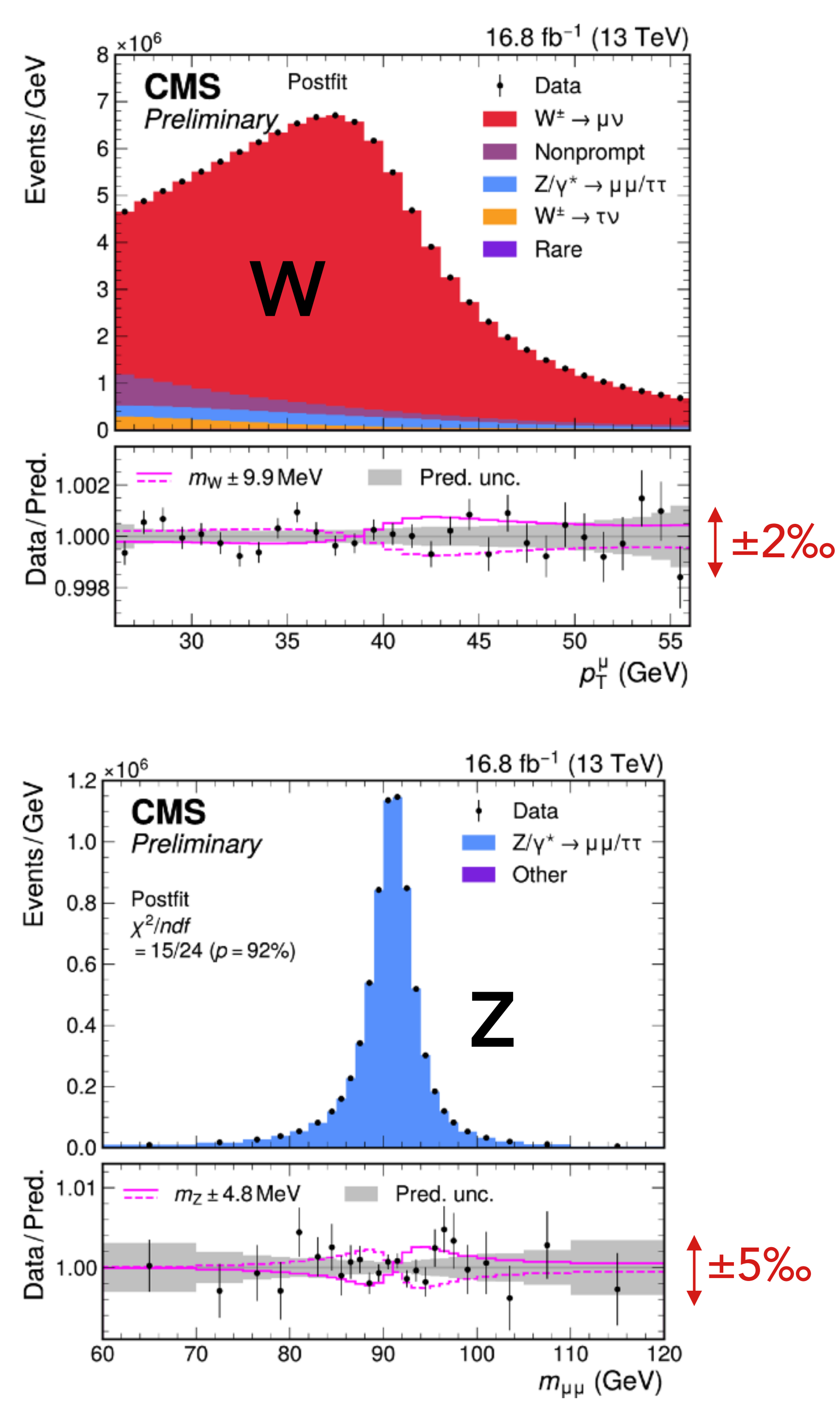
François Englert and Peter Higgs

2013

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of subatomic particle mass, and which was recently confirmed by the discovery of the predicted fundamental particle by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

W Mass Measurement





- 100M $W \to \mu\nu$ events
- 7.5M $Z \to \mu\mu$ events

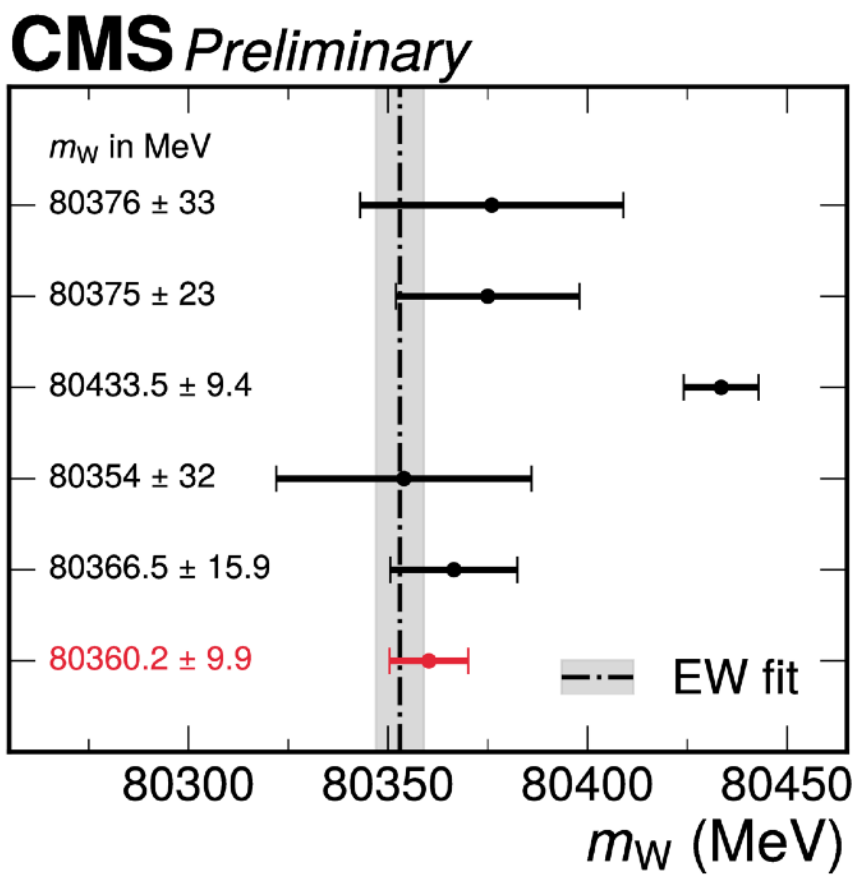
W Mass Measurement

One of the most challenging precision measurement at the LHC

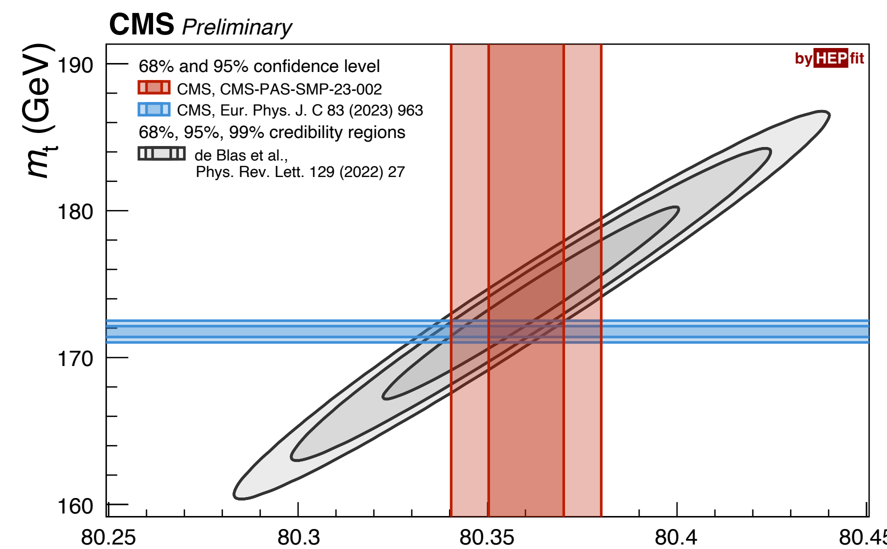
- incredible precision of better than 10 MeV (= 0.012%)

electroweak fit

LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
arxiv:2403.15085, subm. to EPJC
CMS
This Work

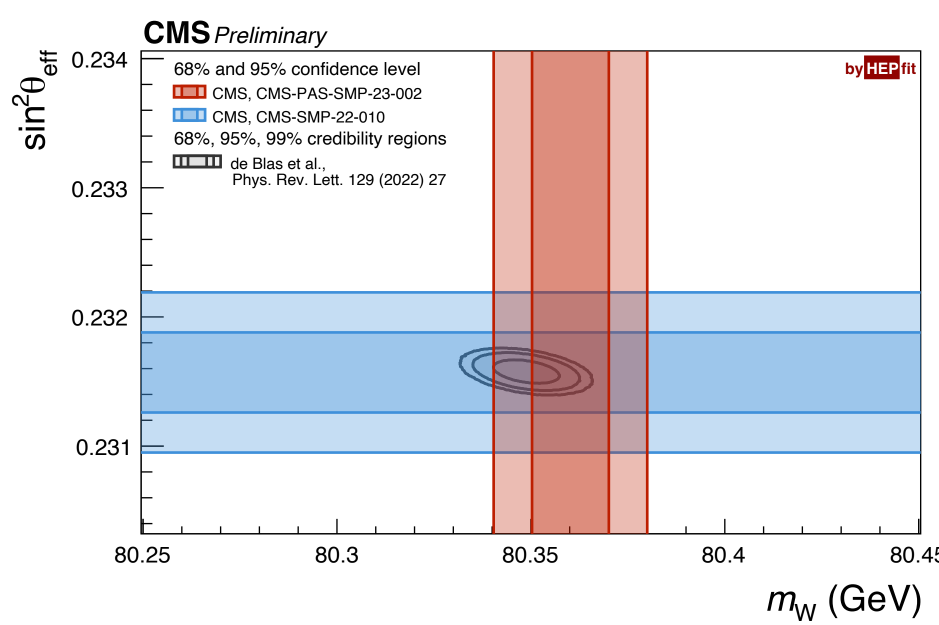


(±0.01%)



(±0.2%)

m_t



$\sin^2\theta_{eff}{}^{\ell}$

m_W

- quantum corrections

$$M_W{}^2 = (1+\Delta\rho) M_Z{}^2 (1-\sin^2\theta_{eff})$$

avec $\Delta\rho = f(M_{top}{}^2, \ln M_H)$

(de l'ordre de 1%)

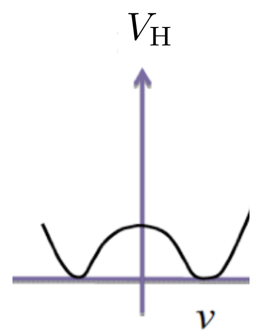
CMS-PAS-SMP-23-002

submitted to Nature

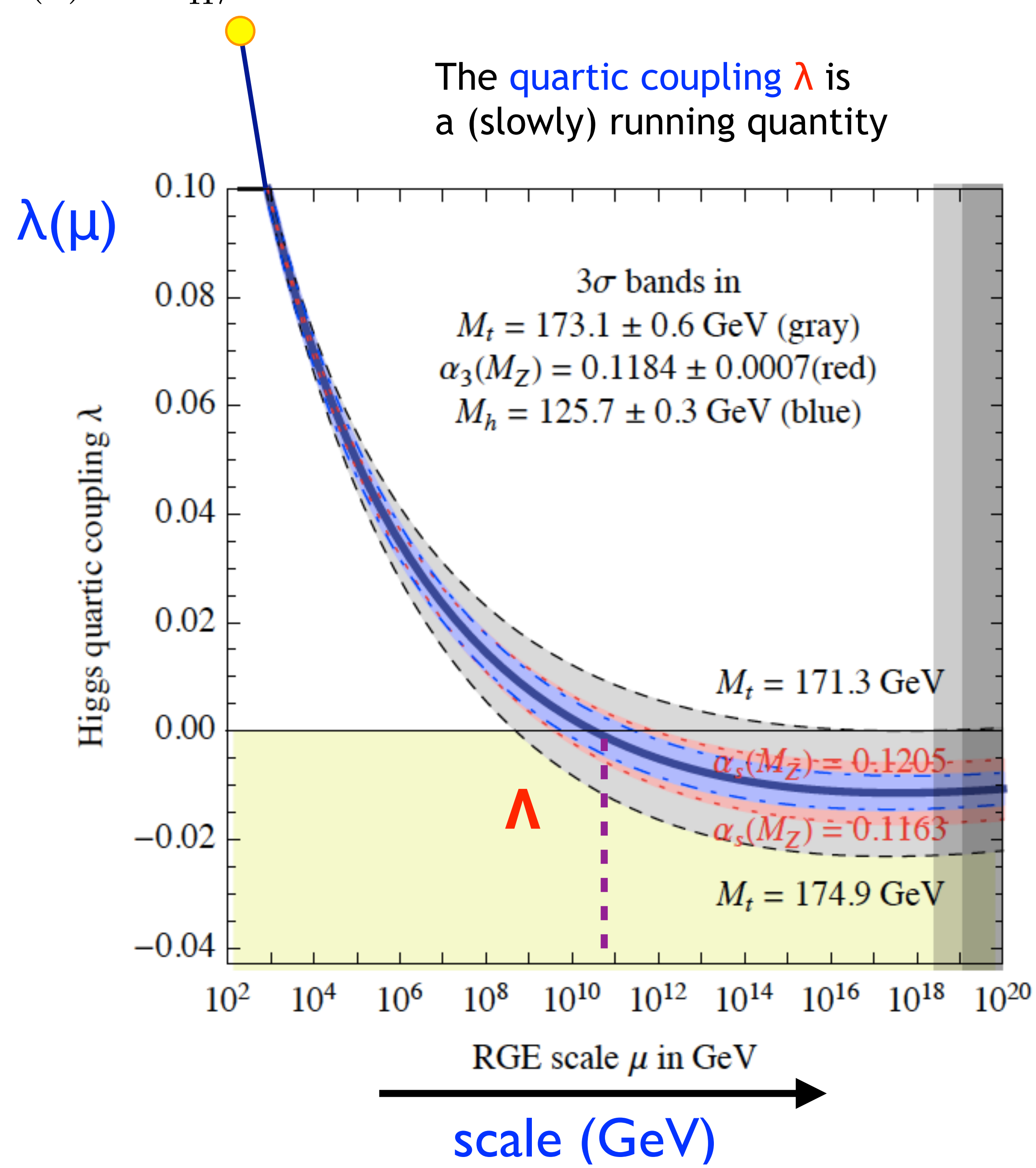
EW Vacuum Stability

Higgs potential

$$V_{\rm H} = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



$$\lambda(v) = M_{\rm H}^2/2v^2$$

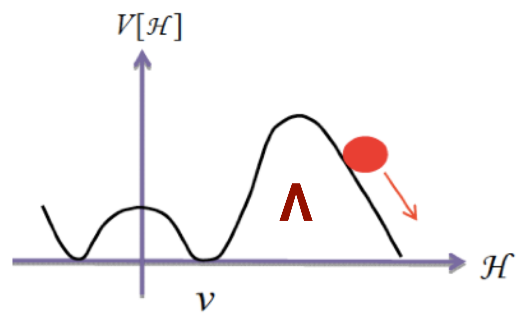


The *instability scale* of the SM, which depends on m_t, M_H, and α_s is of order $\Lambda \approx 10^{11}$ GeV !

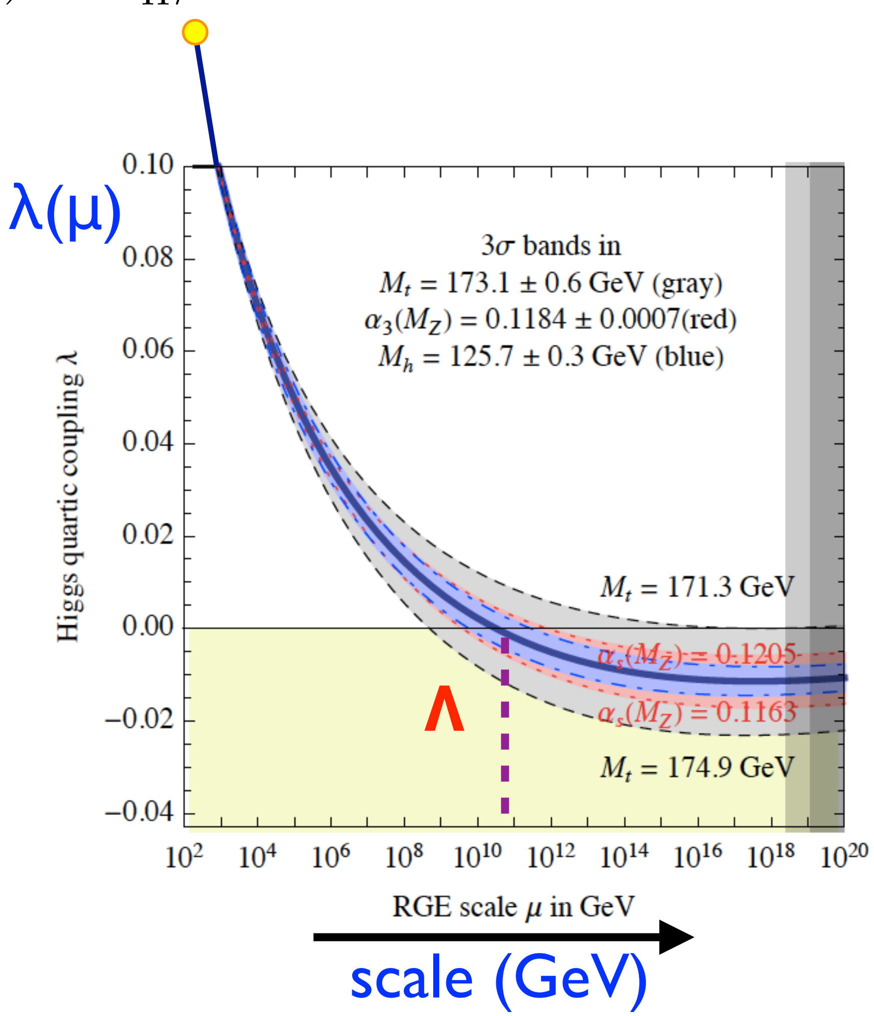
EW Vacuum Stability

Higgs potential

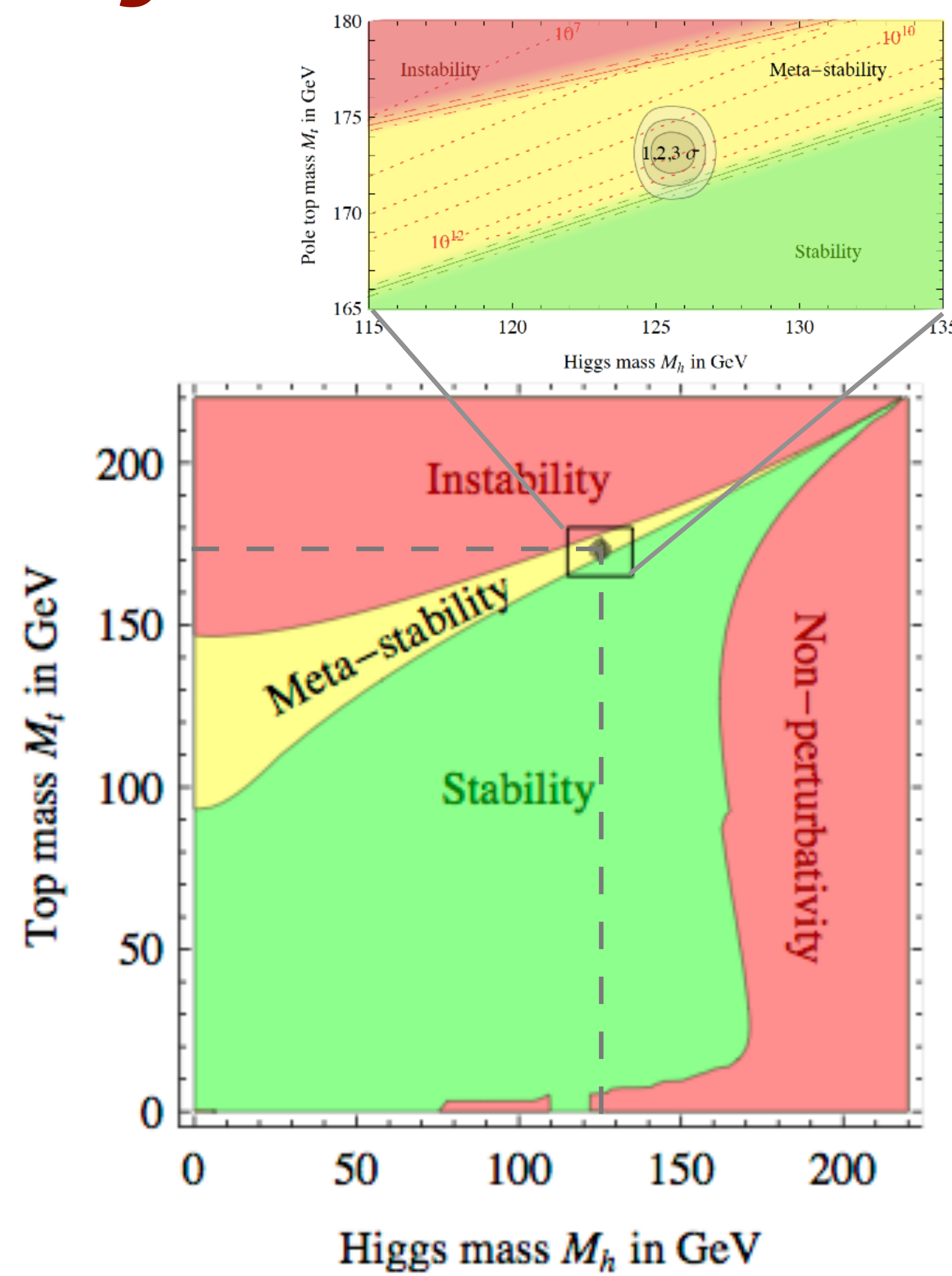
$$V_{\rm H} = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



$$\lambda(v) = M_{\rm H}^2/2v^2$$



Instability scale $\Lambda \approx 10^{11}$ GeV



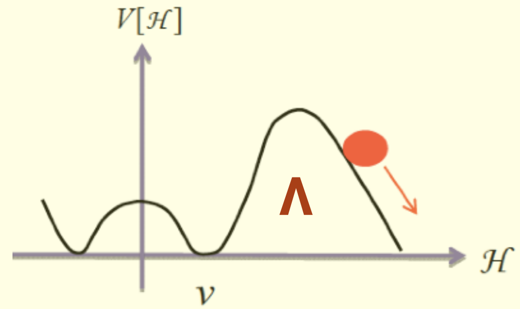
Our universe lives on the edge of the precipice

Numerical coincidence
or fundamental feature ?

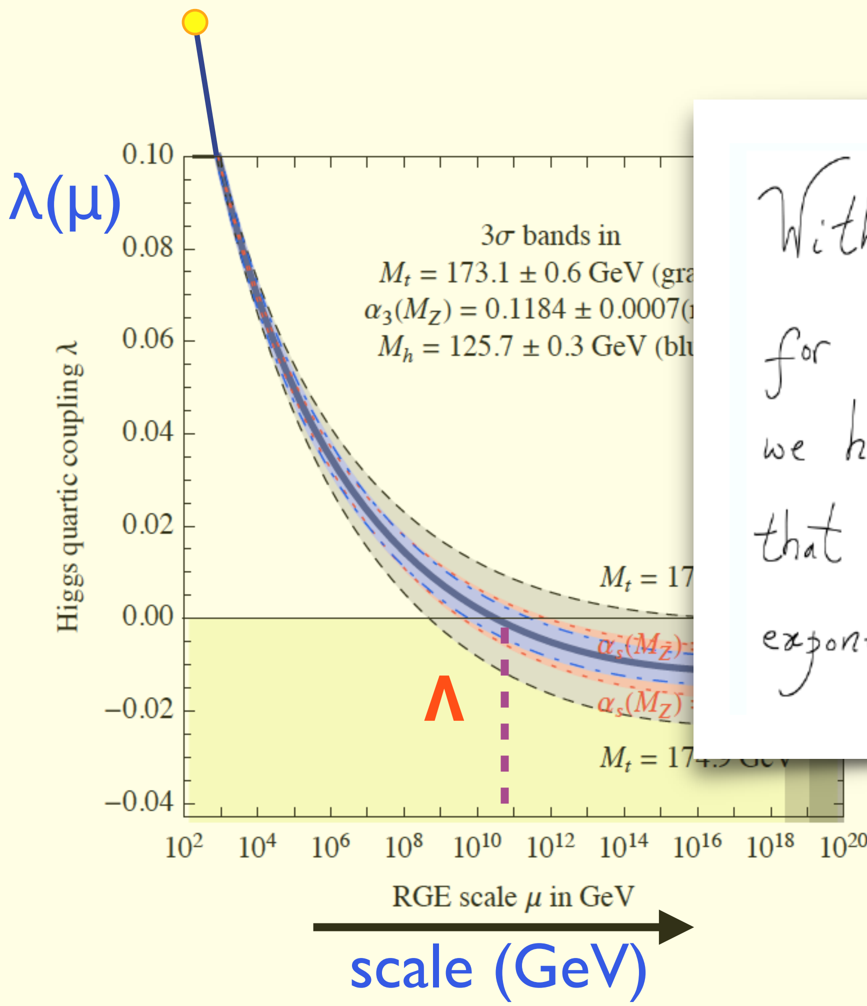
EW Vacuum Stability

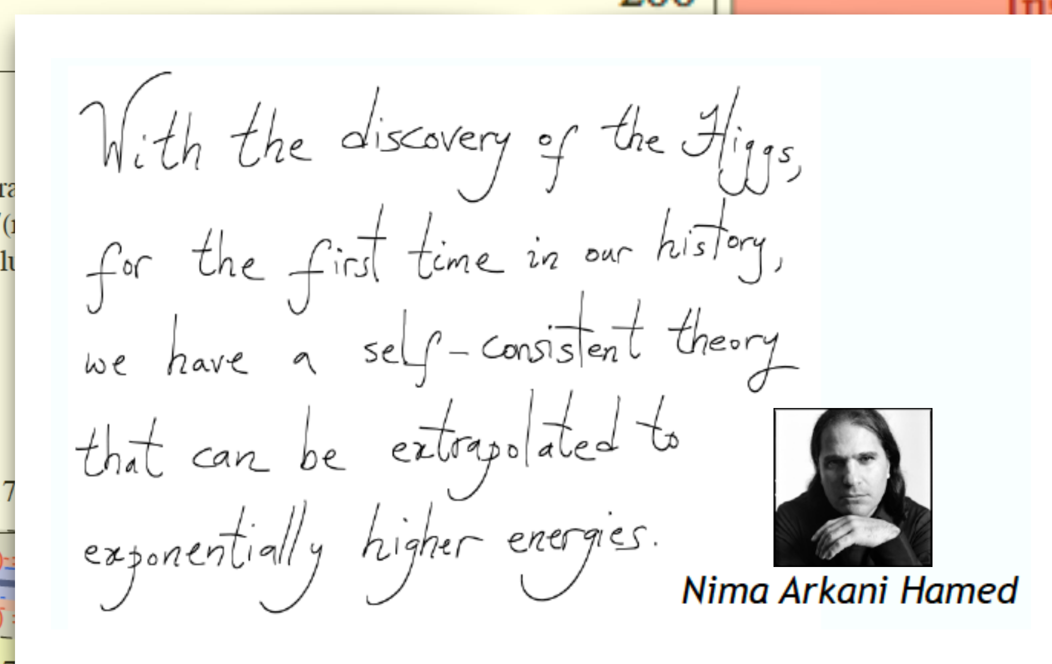
Higgs potential

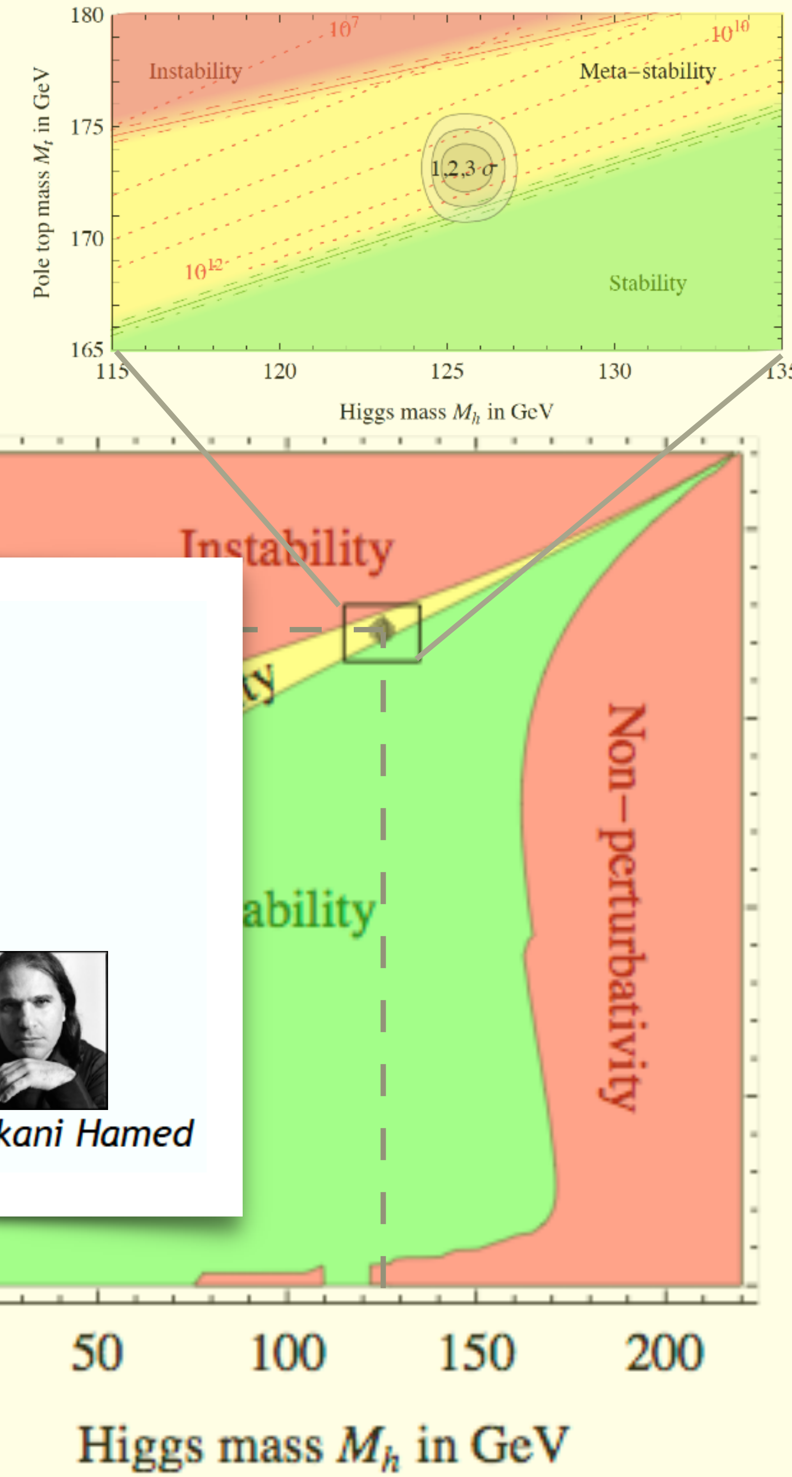
$$V_H = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



$\lambda(v) = M_H^2/2v^2$







Instability scale Λ ≈ 10^{11} GeV

Our universe lives on the edge of the precipice

Numerical coincidence
or fundamental feature ?

The Unbearable Lightness of the Higgs

The SM of particle physics is theoretically consistent and incredibly successful at

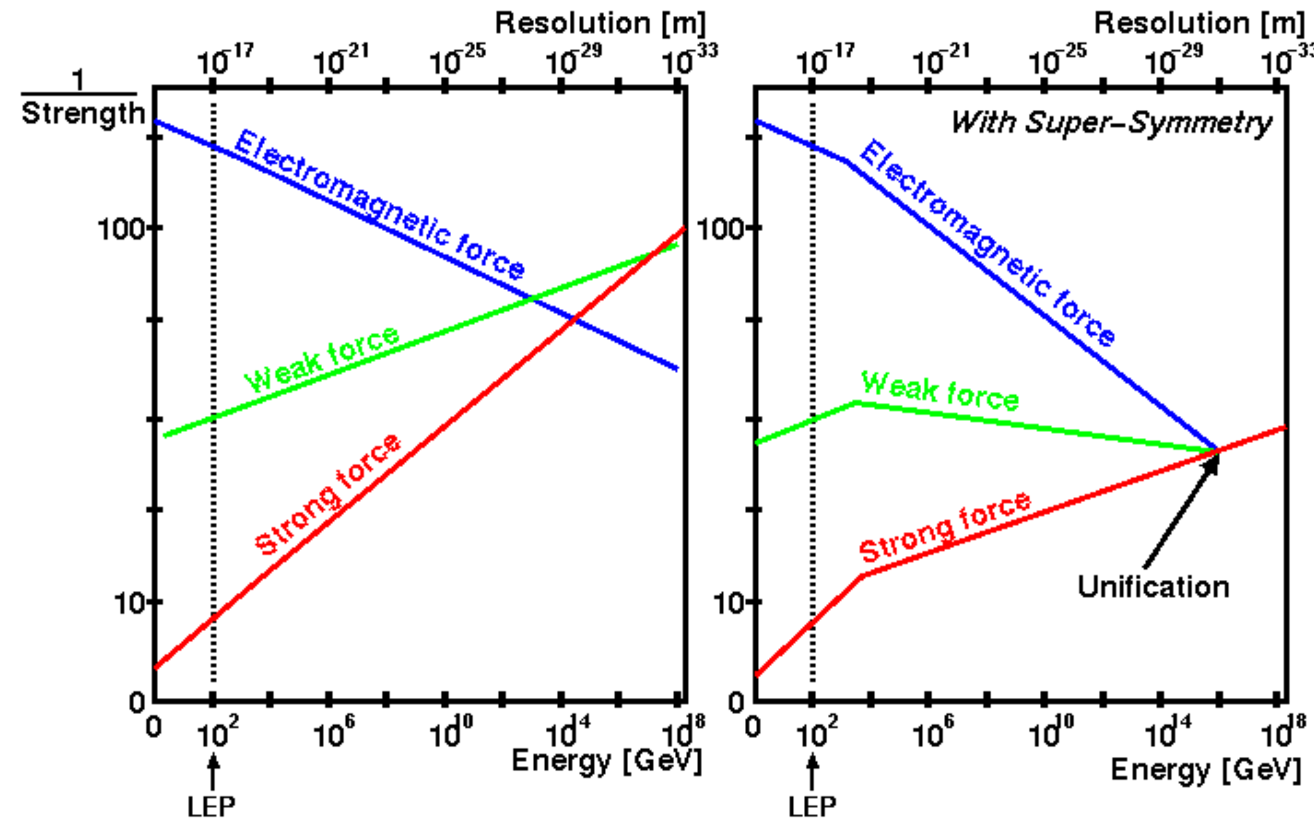
- describing all experimental facts
- making non-trivial falsifiable predictions

Still, the SM has problems, including

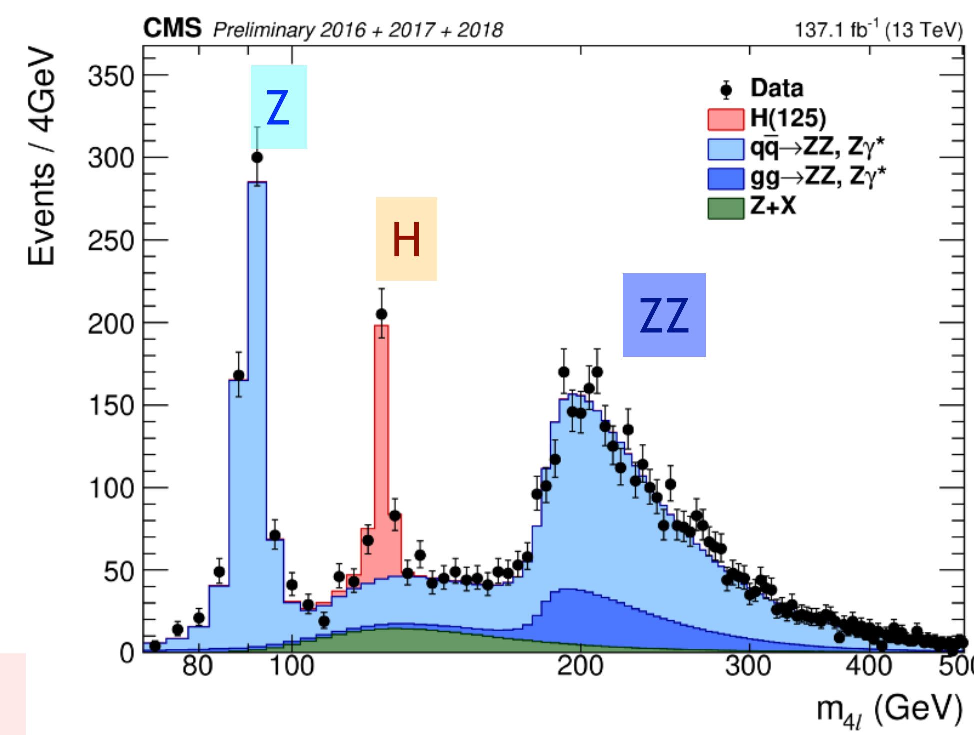
☛ Failure at unifying gauge couplings at high energy

☛ The hierarchy/naturalness problem

- radiative corrections to M_H^2 in the SM with cut-off $\Lambda \gg M_H$ of order Λ^2
- mind-blowing fine tuning for $\Lambda = M_{Plank}$

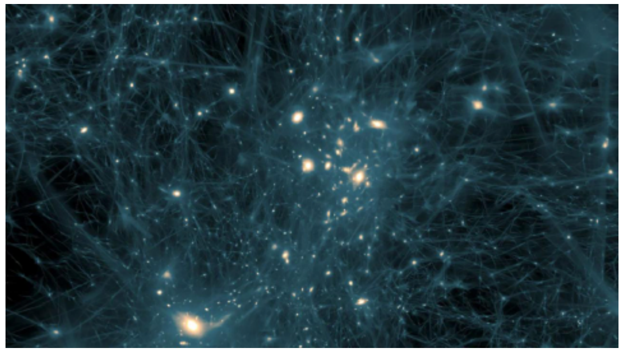


How much fine tuning can we bear?
→ HL-LHC (no NP) ≈1%
→ FCC-hh (no NP) ≈ 0.01%

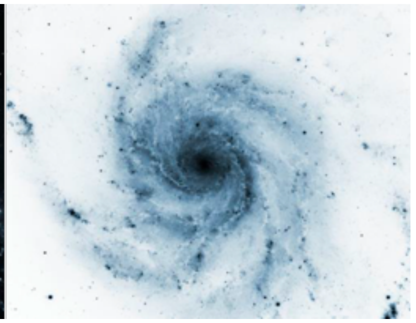


Is there a fundamental symmetry protecting the Higgs mass?

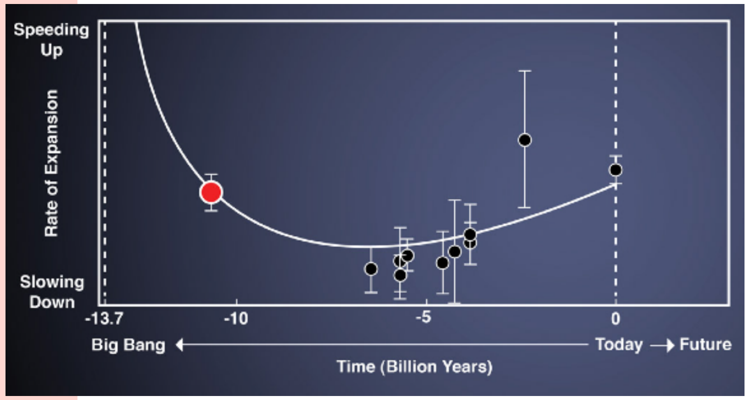
What the SM cannot explain

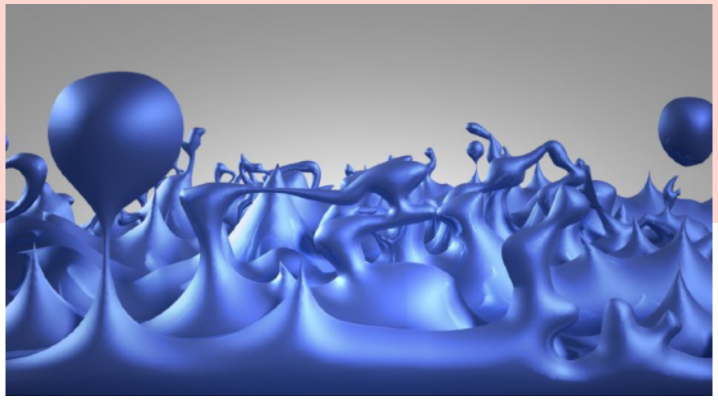


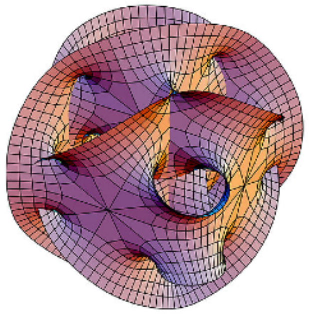
- the origin of Neutrino Masses
- the nature of Dark Matter
- the Baryonic Asymmetry of the Universe



- the Accelerated Expansion of the Universe
- the dynamics of the Primordial Inflation
- Gravitation

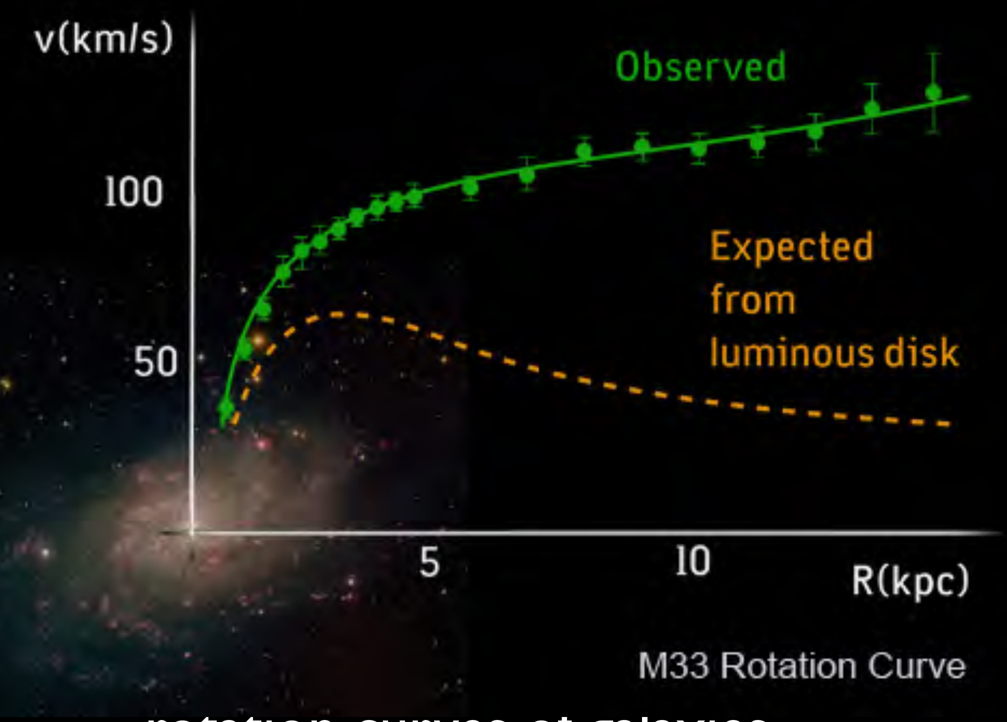






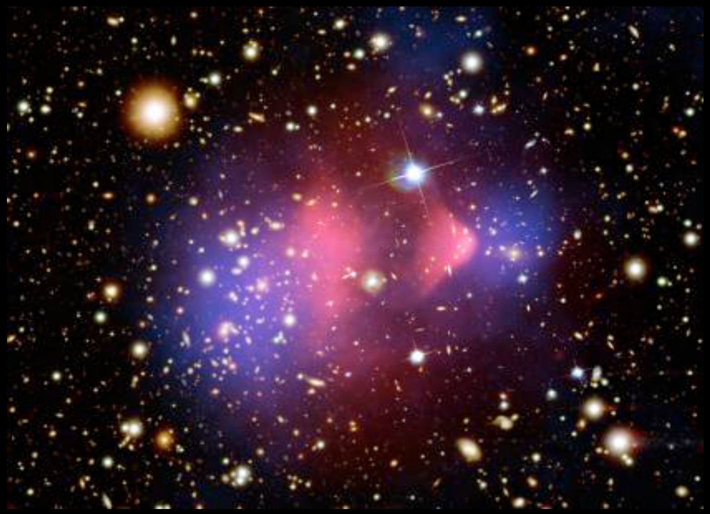
Dark Matter

Astrophysical Indications
all scales

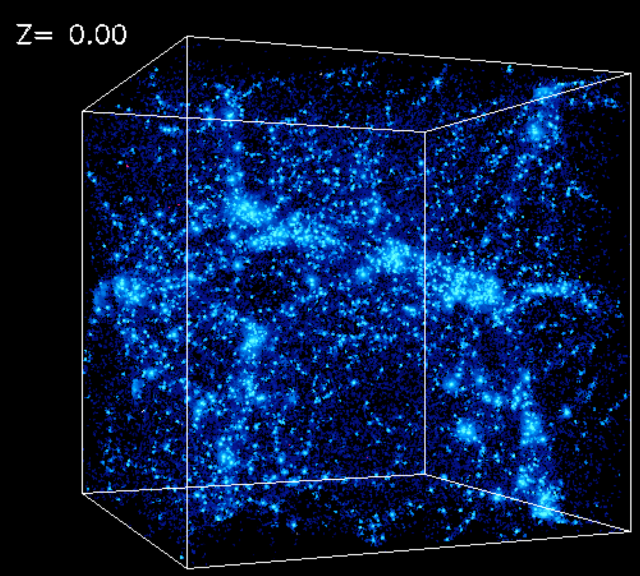


rotation curves of galaxies

galaxy clusters
gravitational lensing

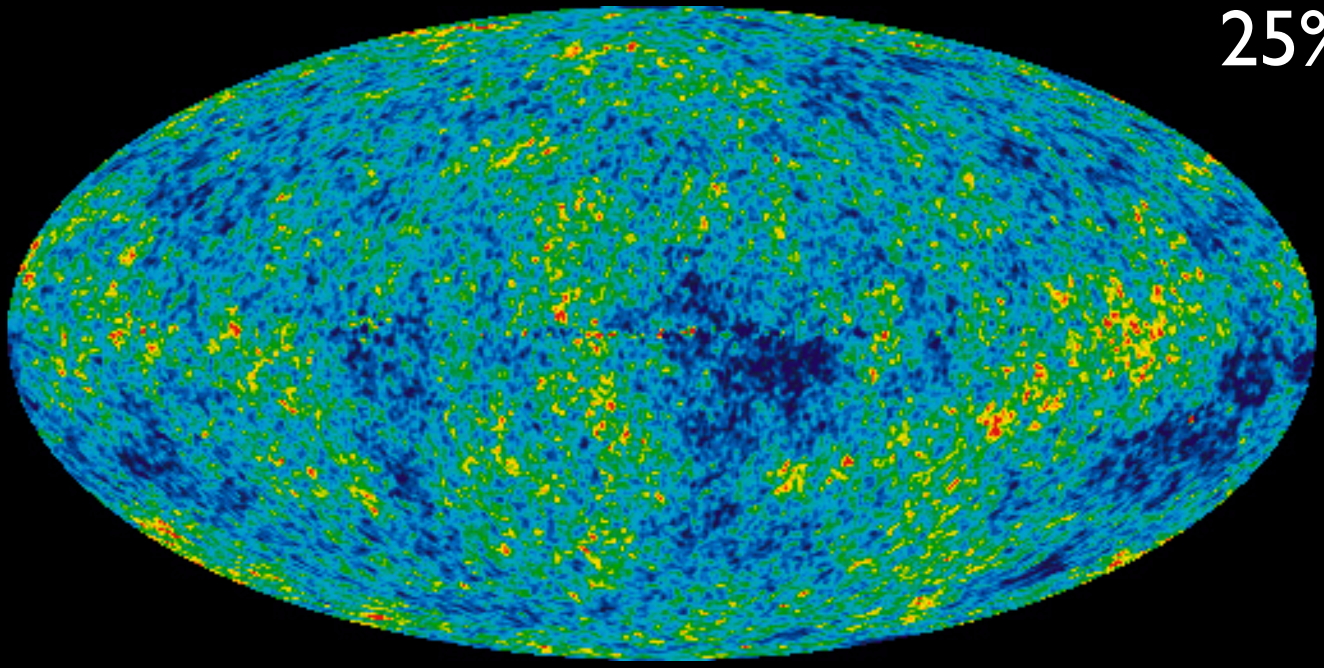


colliding galaxy clusters
(here: *bullet cluster*)



structure formation
at large scale

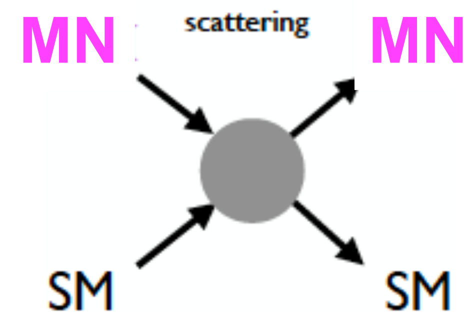
25%

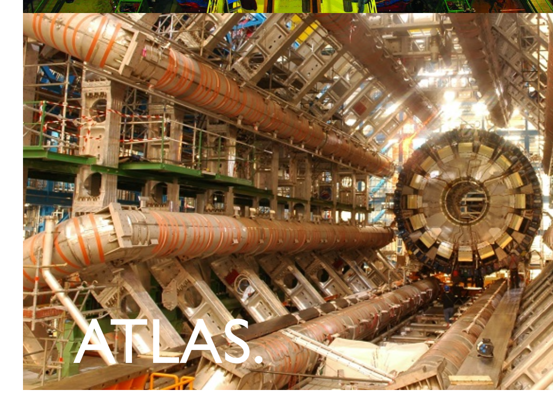


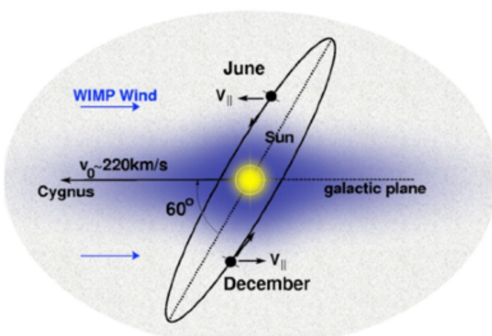
anisotropies in the cosmic microwave radiation (CMB)

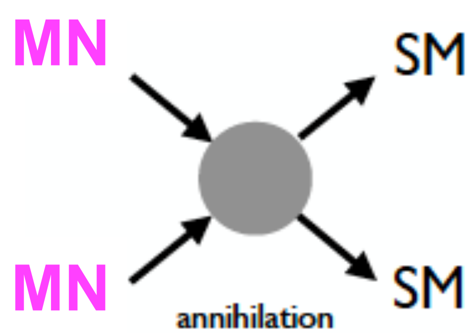
Search for Dark Matter

direct

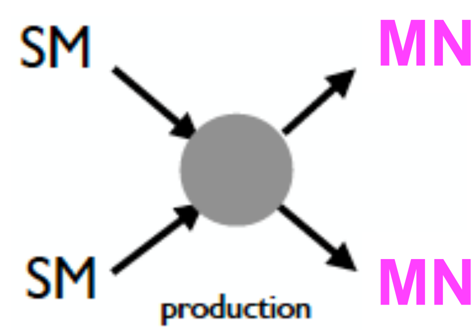








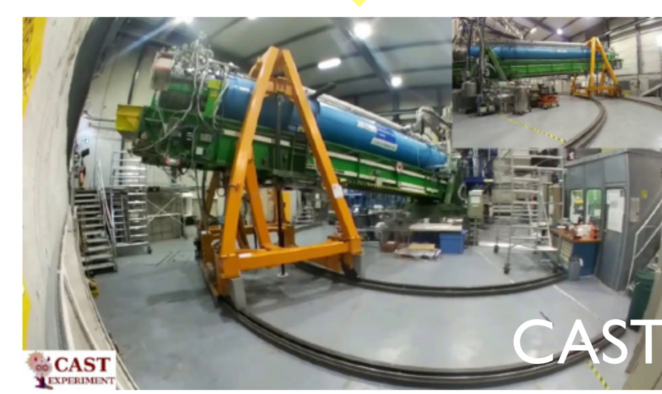
at the LHC



from Galactic Halo

indirect

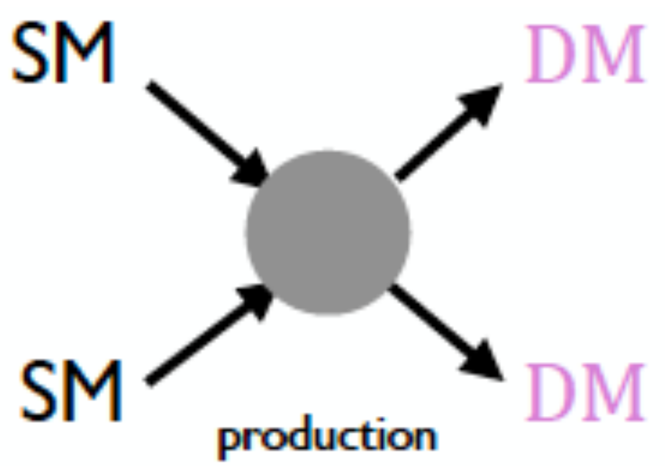
produced in the Sun

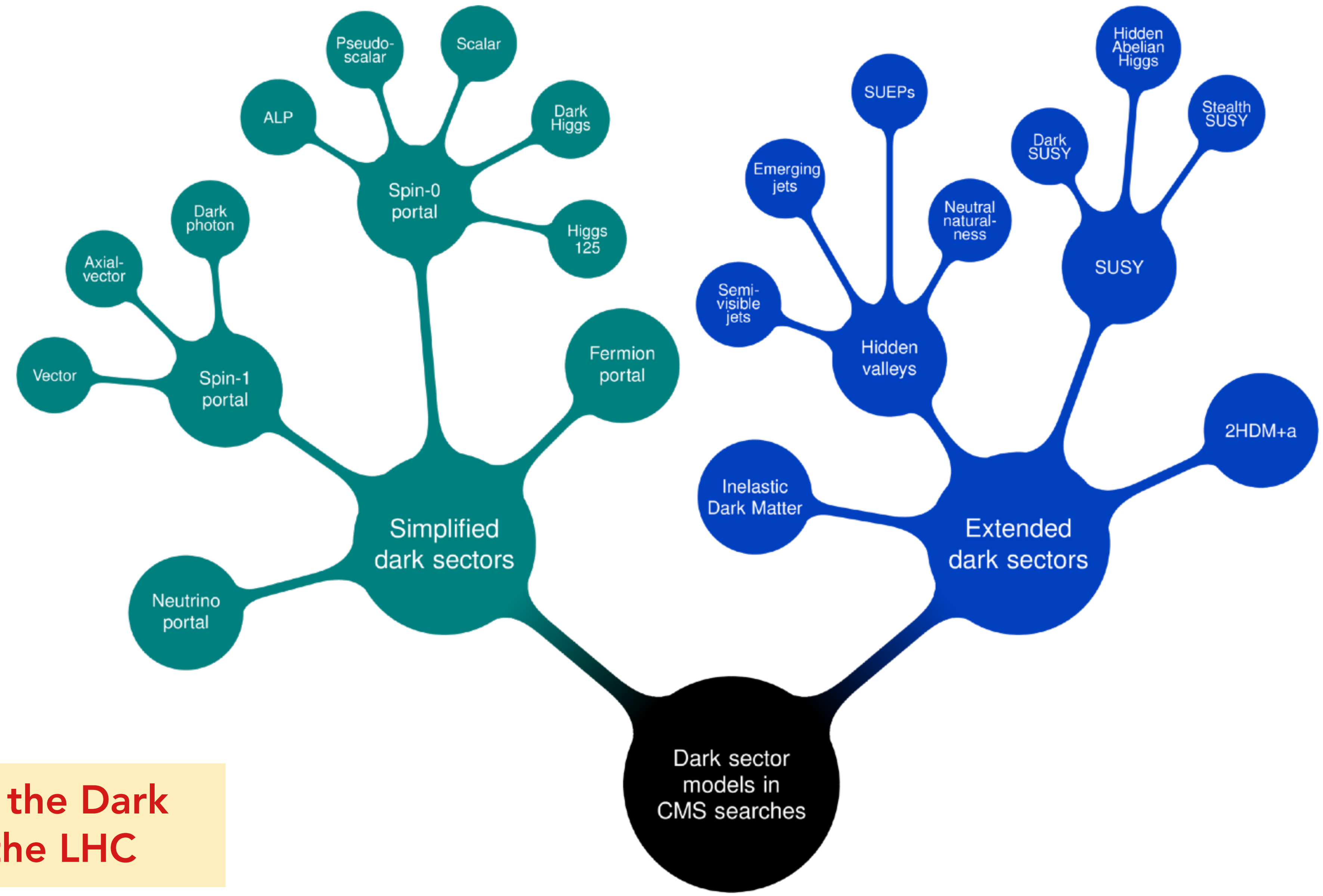


recherche d'*axions*

Dark Matter at the LHC

If Dark Matter (DM) is constituted of massive particles weakly interacting with SM particles (such as massive neutrinos), then it can be produced at the LHC

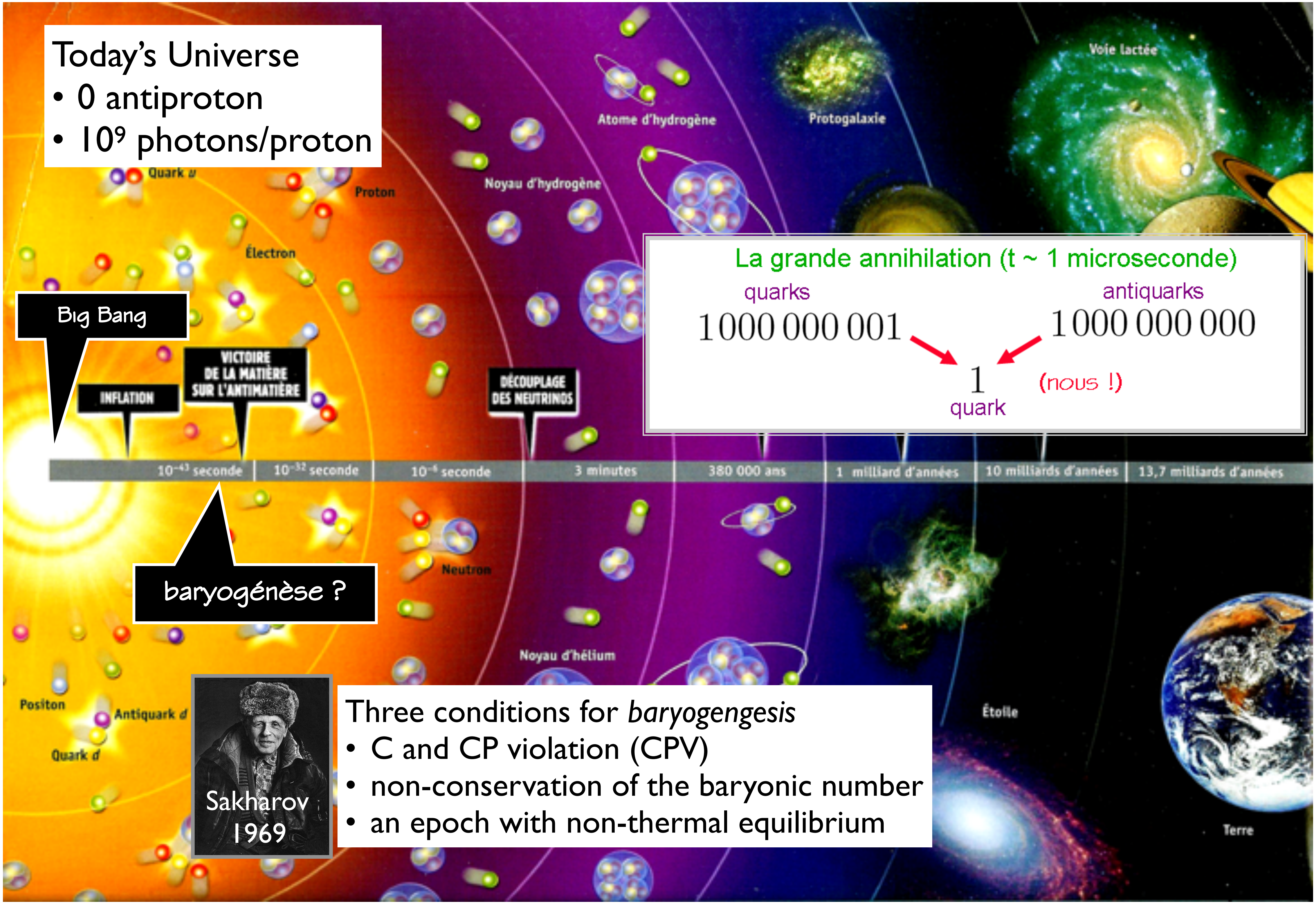




Various scenarios to probe the Dark Sector are considered at the LHC

DM cannot be detected: it would appear as excess of "missing energy" in ATLAS and CMS

Baryonic Asymmetry of the Universe



Today's Universe
- 0 antiproton
- 10^9 photons/proton

Big Bang

baryogénèse ?

La grande annihilation (t ~ 1 microseconde)

quarks	antiquarks
1 000 000 001	1 000 000 000

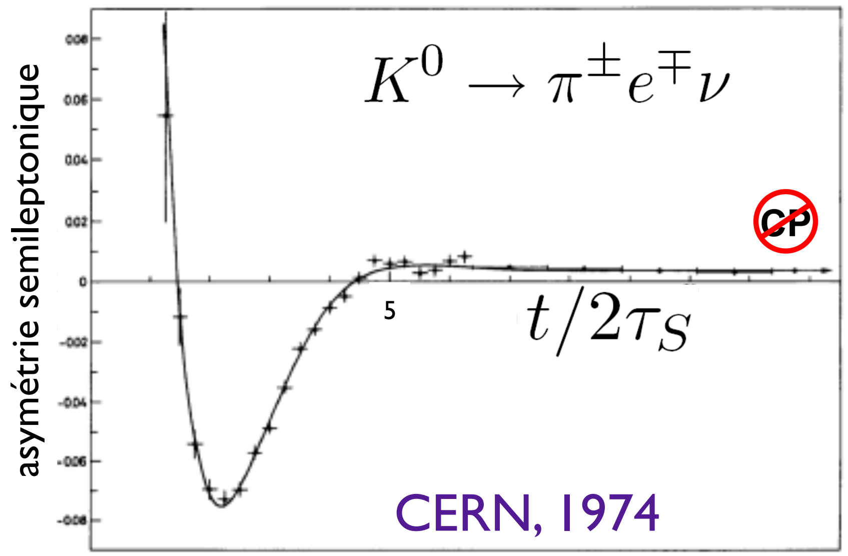
→ 1 quark (nous !)

Sakharov 1969

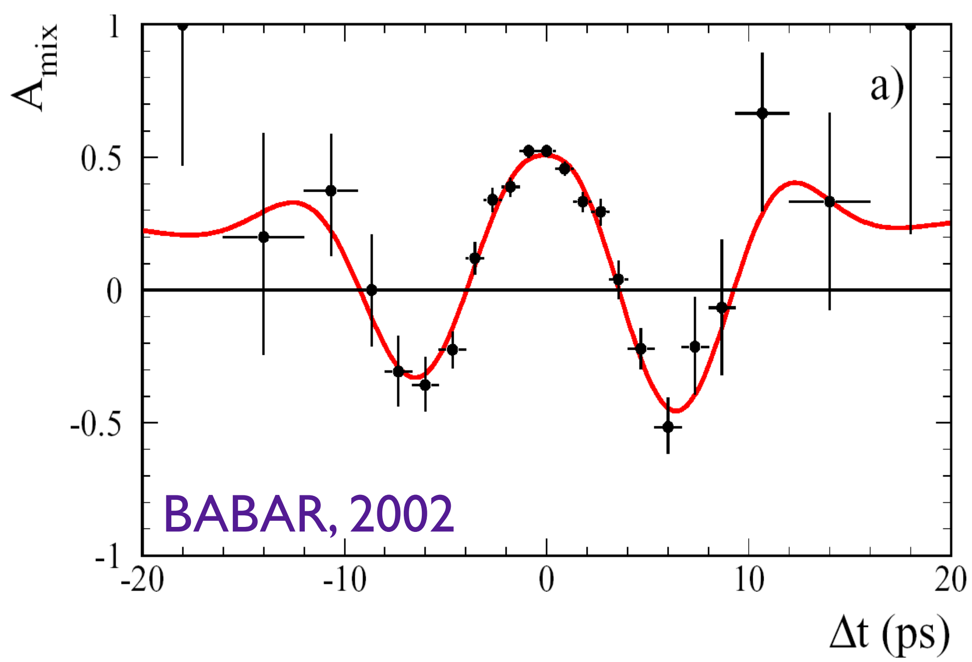
Three conditions for *baryogengesis*
- C and CP violation (CPV)
- non-conservation of the baryonic number
- an epoch with non-thermal equilibrium

Flavor oscillations

☛ in the neutral kaon system

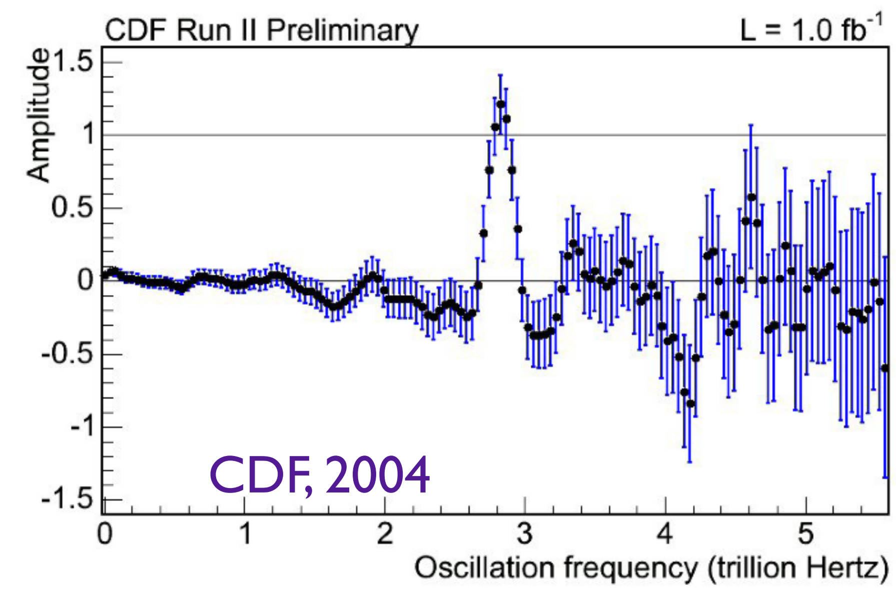


☛ in the B^0 meson system

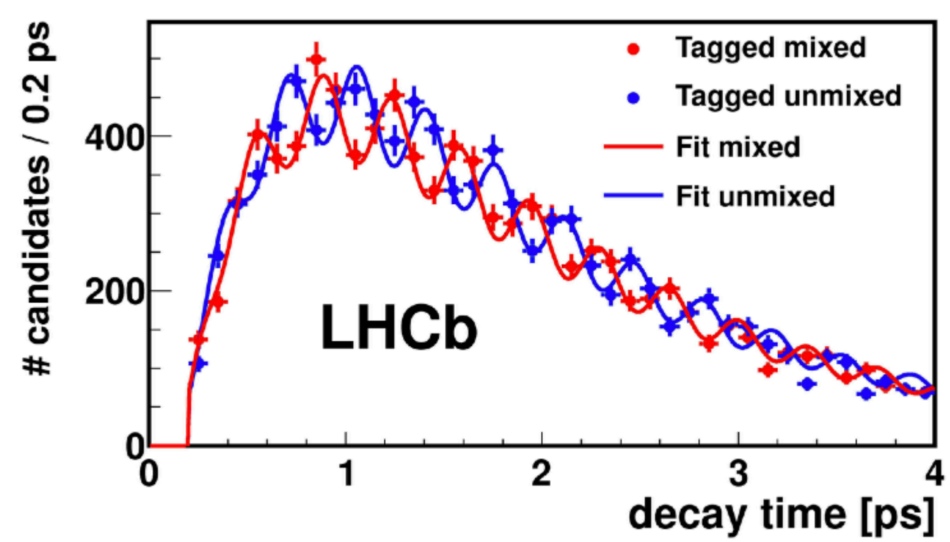


☛ in the B_s^0 meson system

• observation



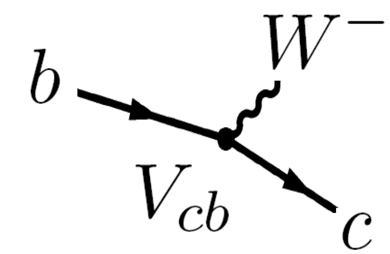
• étude précise

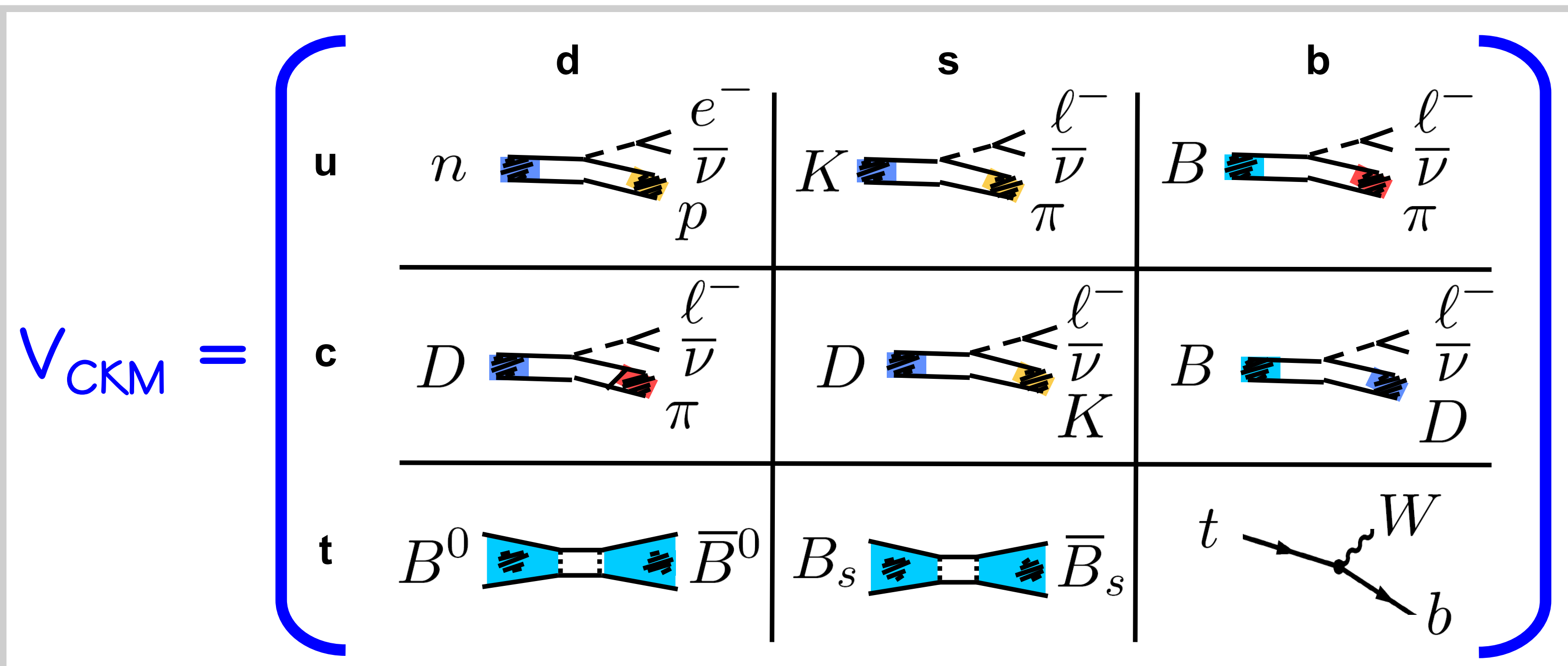


Quark Flavour Mixing

Matrice Cabibbo, Kobayashi-Maskawa (CKM)

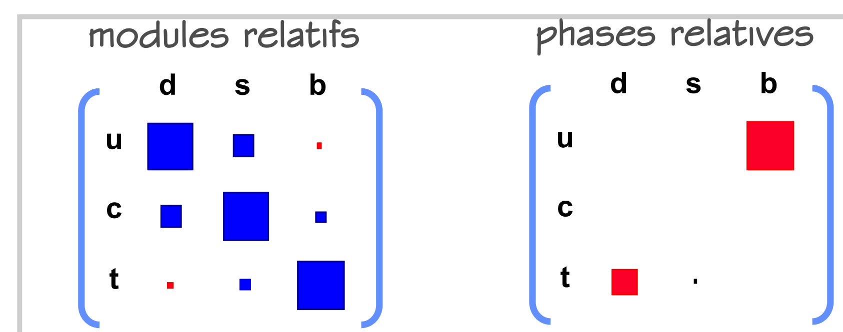
- complex, unitary of dimension 3 (3 families of quarks)
- elements = couplings between up-type quarks and down-type quarks





The CKM matrix is

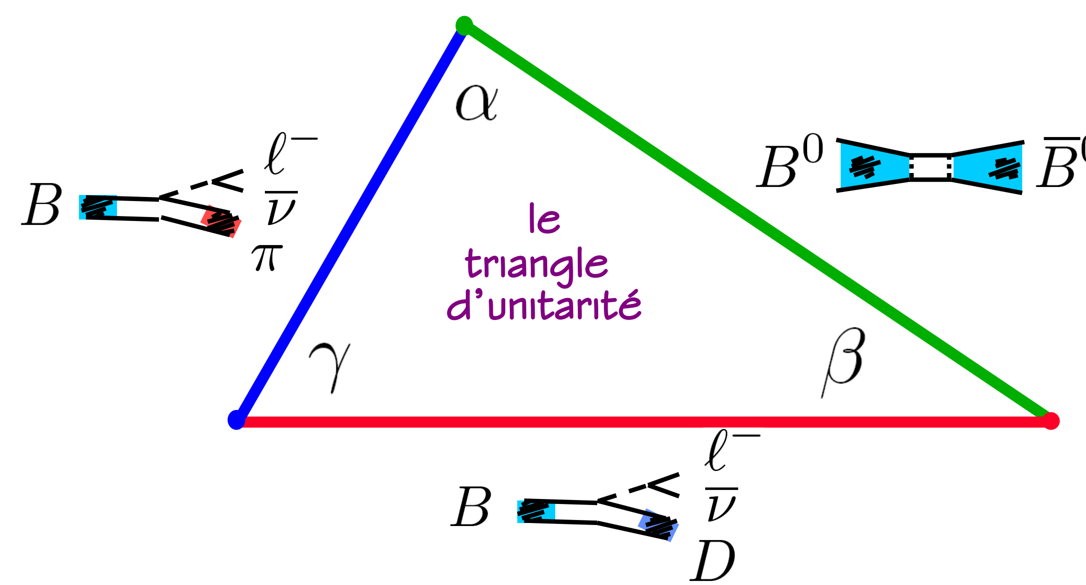
- almost diagonal
- quasi real



Unitarity = "conservation of probabilité"

➪ relations between elements of the CKM matrix

➪ equation of a triangle : the Unitarity Triangle (UT)

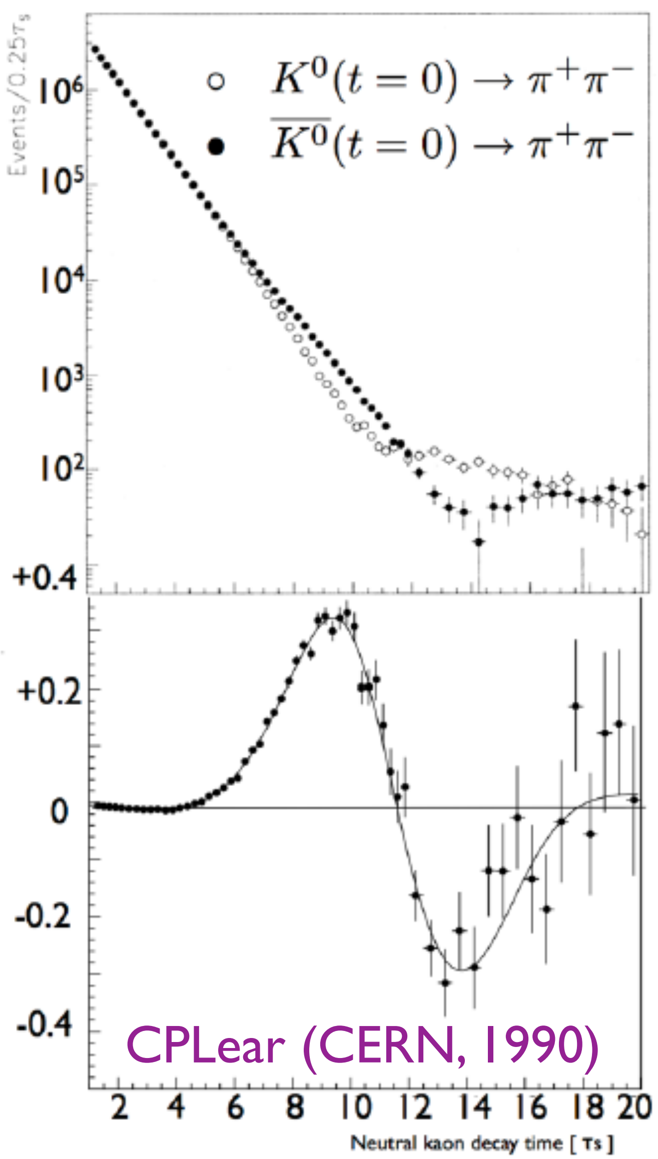


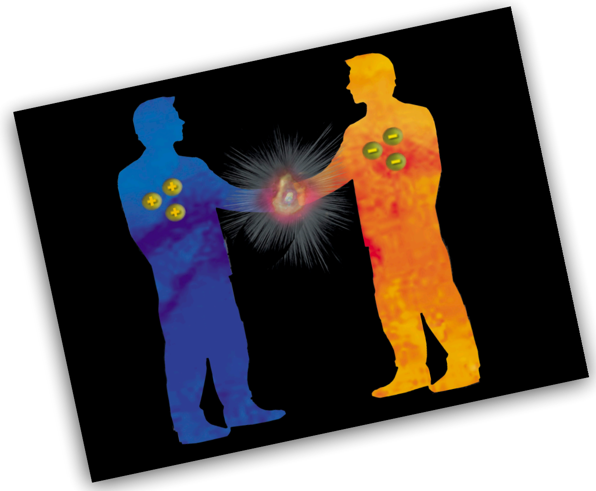
Origin of CPV in the SM

CP Violation

☛ Neutral kaon system
(discovery:1964)

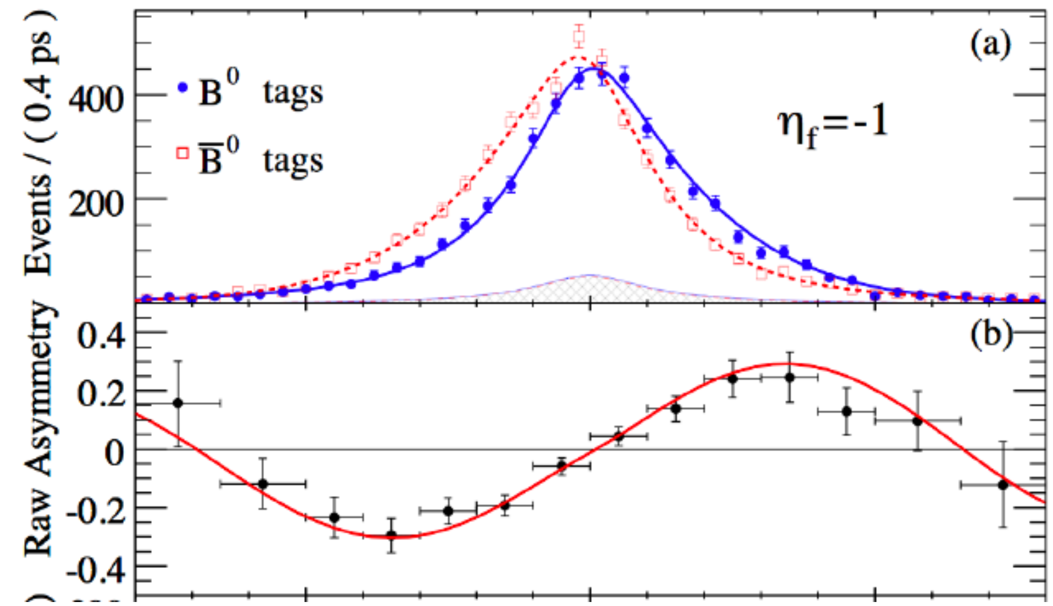
- in flavour mixing
  (indirect CP violation)





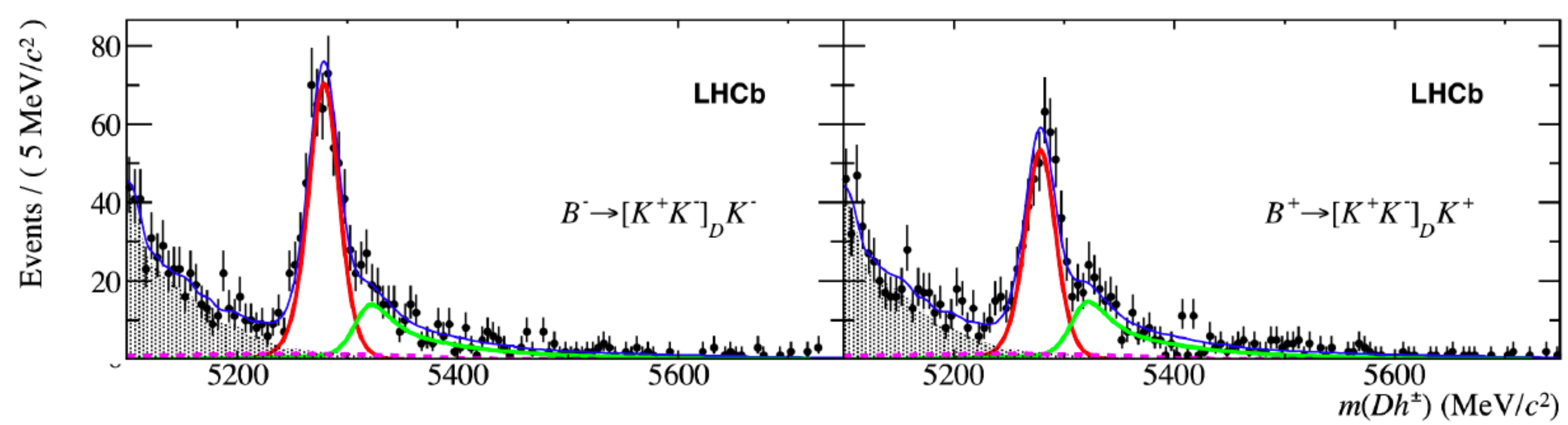
☛ B meson system
BABAR/Belle (years 2000), LHCb

- in interference mising/decay
  (mixing induced CP violation)



- in decay
  (direct CP violation)

neutral kaons: NA48 (CERN, 1998)
B mesons: BABAR/Belle, LHCb



◉ EW baryogenesis impossible in SM due to too small CP violation and no first order phase transition

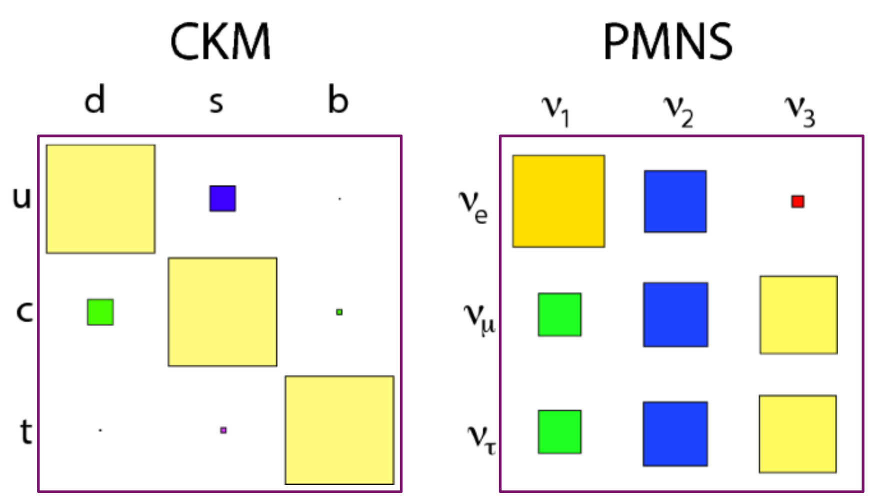
Neutrino Physics

Flavour oscillations in the neutrino sector (SK/SNO, 1998) prove that neutrinos have mass and establish the 3-neutrino paradigm ν_1, ν_2, ν_3

Pontecorvo, Maki-Nakagawa-Sakata (PMNS) Matrix

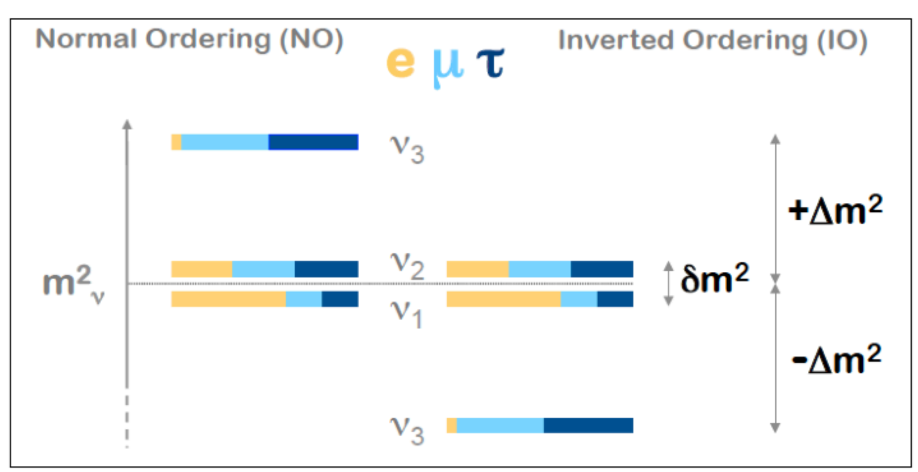
- δm^2 Δm^2
- θ_{12} θ_{23} θ_{13}
- δ

unlike CKM, mixing angles are large



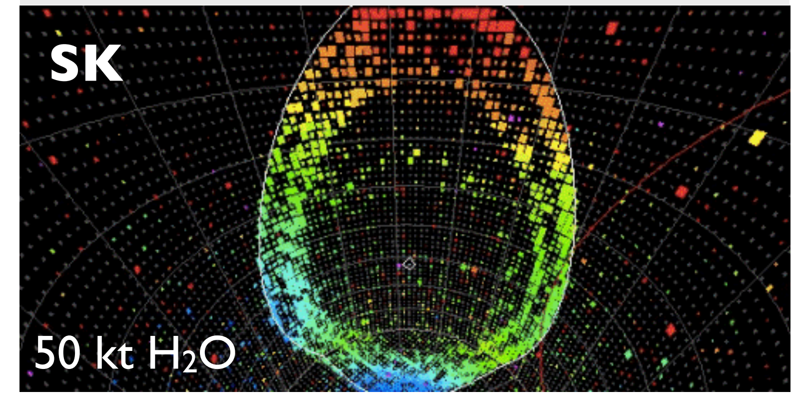
Questions

- absolute scale and mass order
- CP violation?
- θ_{23} octant?
- Dirac ou Majorana?
- sterile neutrinos?

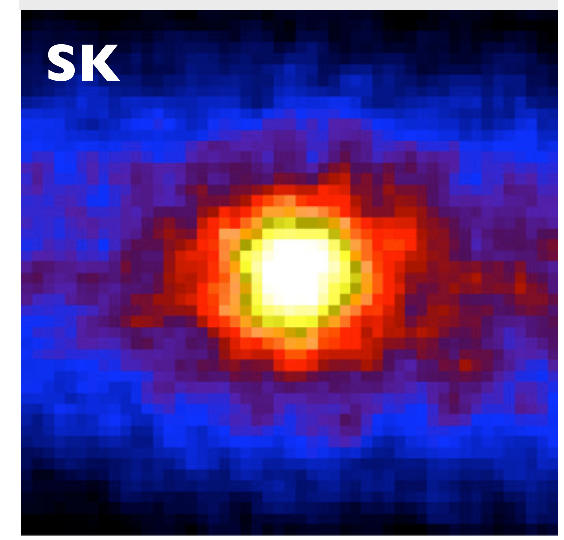


Normal Order (ON) Inverse Order (OI)

A neutrino interaction



The Sun in neutrinos



One hundred billion ν solar per cm^2 per second

Detection : one kilo-tonne of water → one ν solar per day

Neutrinos play a fundamental role in the history of the Universe. Can they shed light on cosmic baryonic asymmetry?

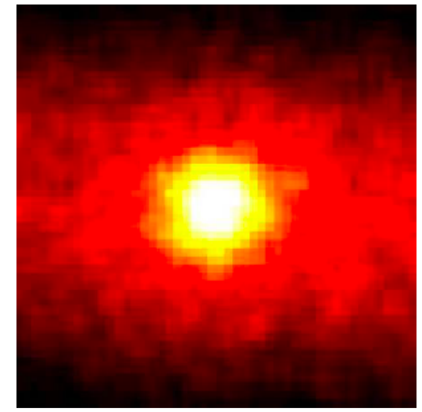
Neutrino Sources

Neutrino sources are
- natural: Sun, Earth, cosmic rays, supernovæ, …
- artificial: reactors, accelerators

Reactors

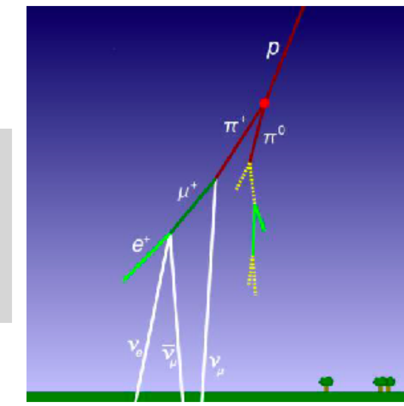
KamLand
Double-Chooz
Daya Bay
Reno…

Solar



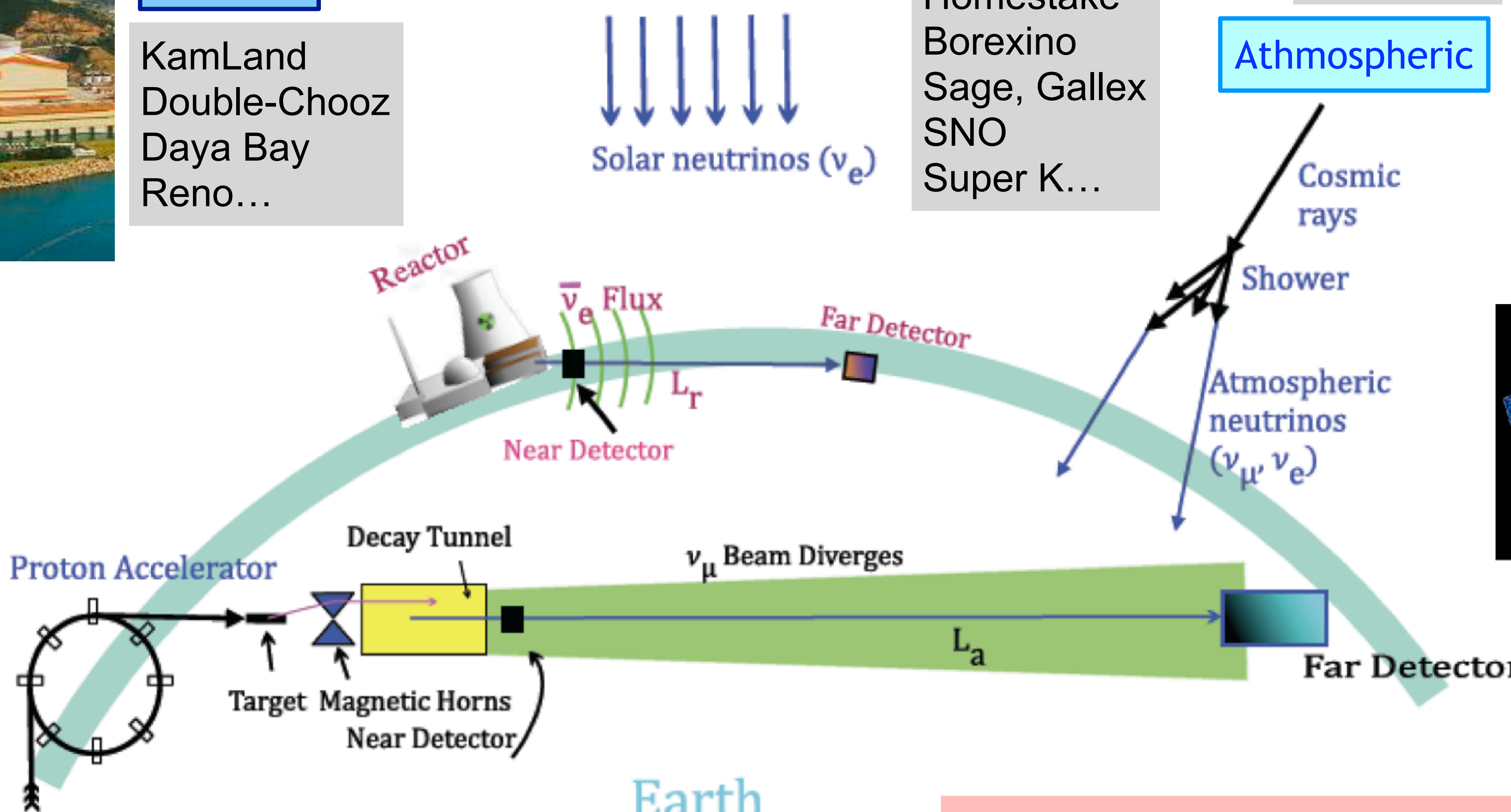
Homestake
Borexino
Sage, Gallex
SNO
Super K…

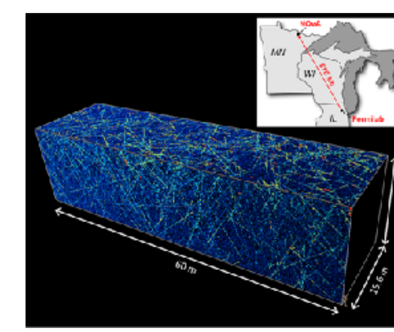
Super K
Minos
IceCube…



Athmospheric

Accelerators



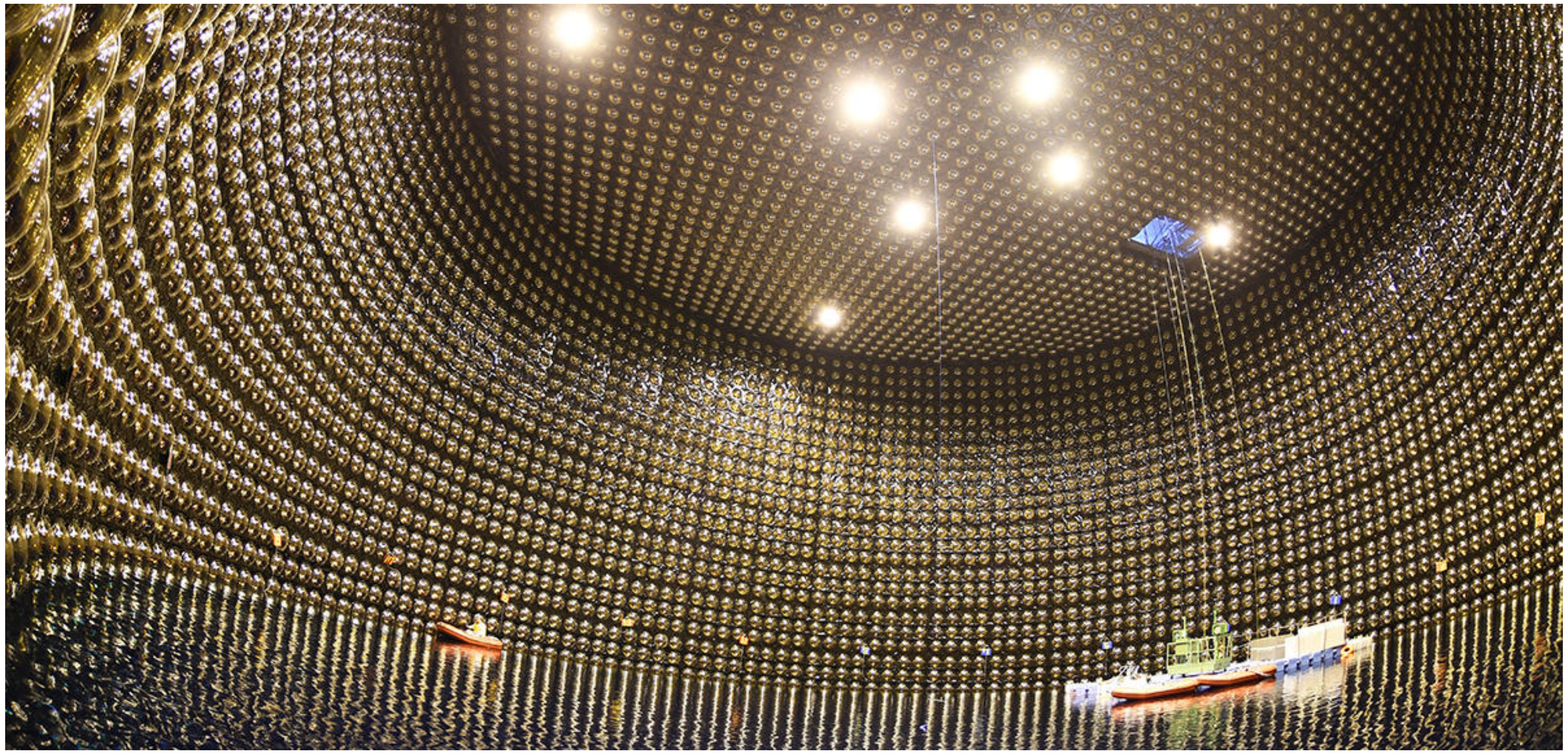


K2K, T2K
Minos, NOvA
Opera…

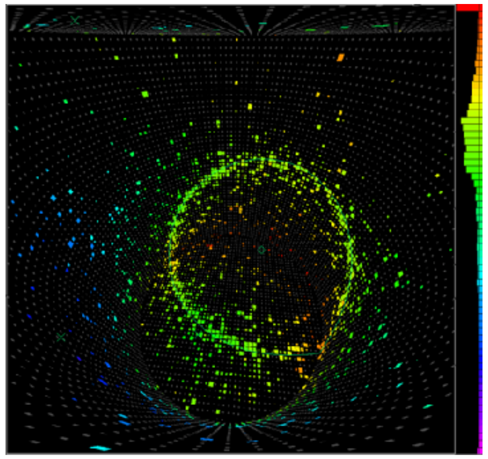
one hundred billion solar neutrinos per cm² per sec

Detection:
1 kilo-ton of water → 1 solar neutrino per day

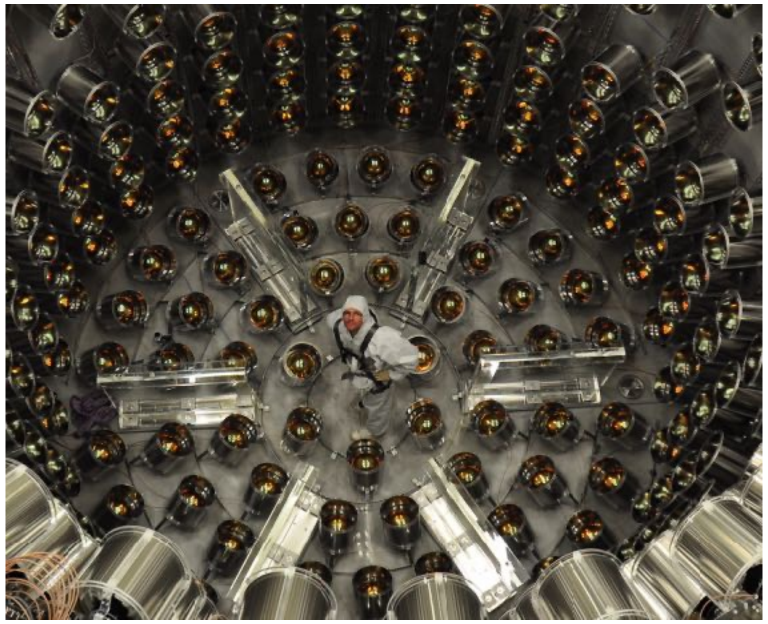
Neutrino Detection



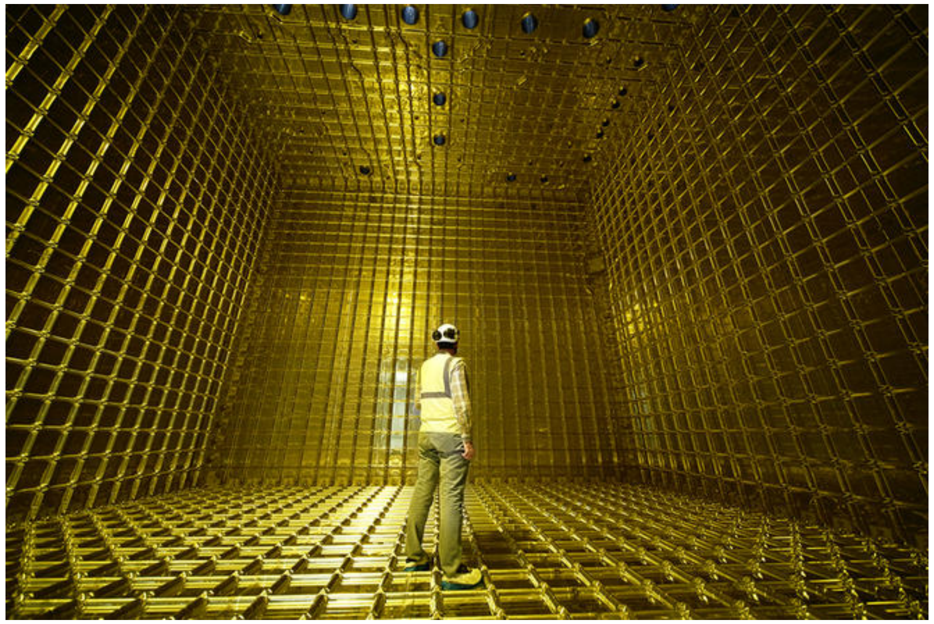
Super K, Japan
(water)



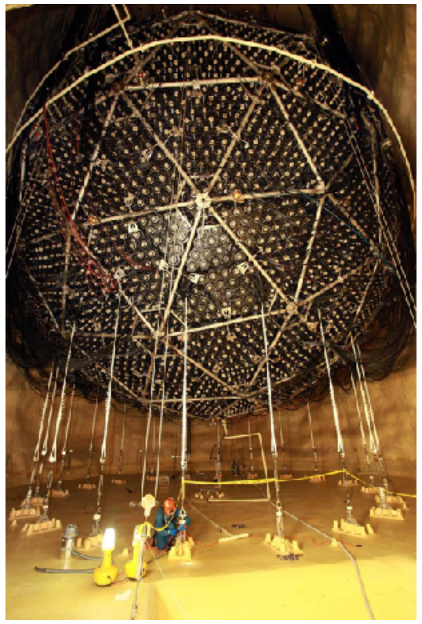
- solar
- atmospheric
- accelerator (T2K)



Double Chooz, France
(scintillating liquid)
- reactor



DUNE prototype, CERN
(liquid argon)

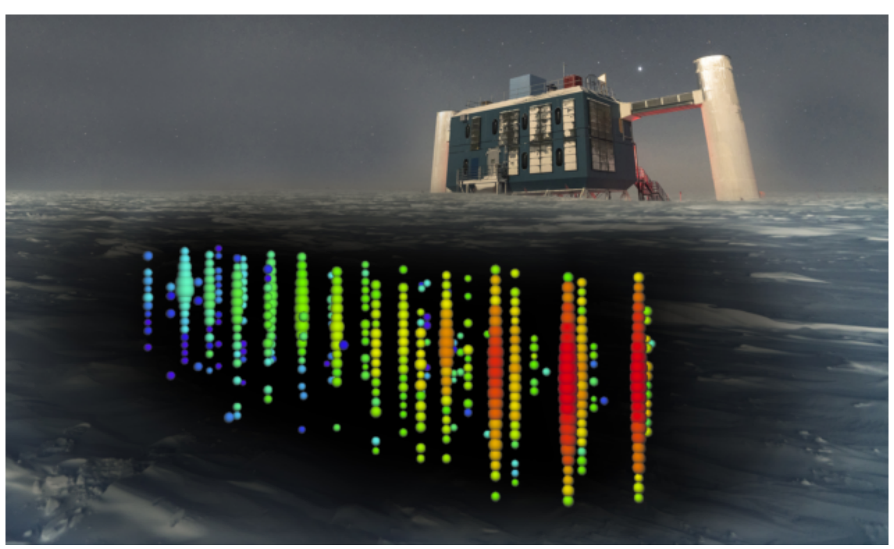


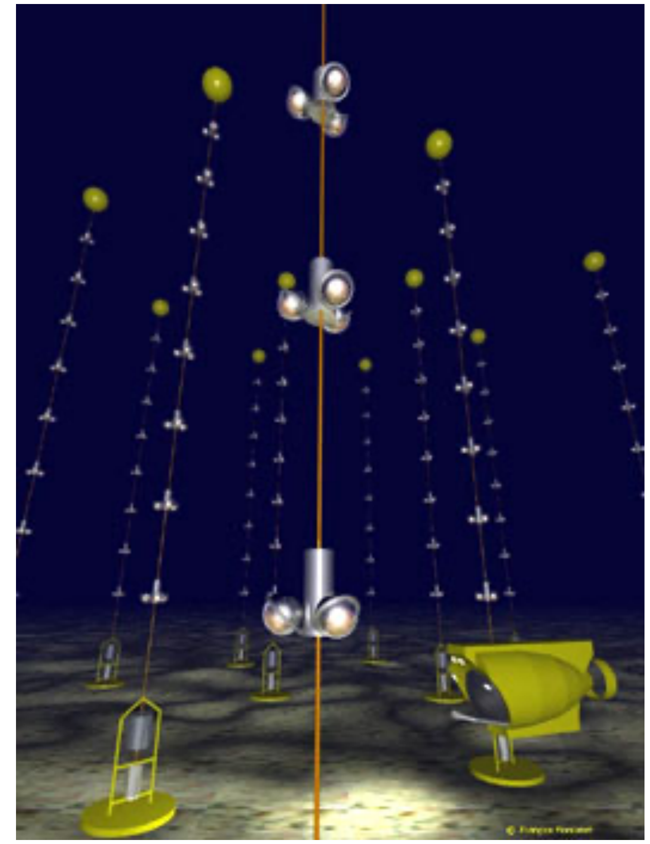
SNO, Canada
(heavy water)
- solar

Ultra-High Energy Neutrinos

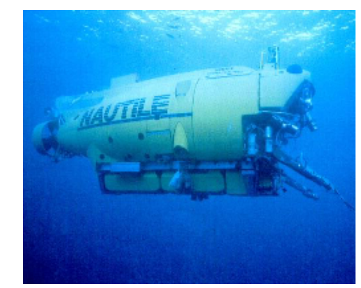
Huge volumes (of the order of cubic km) are needed to detect neutrinos from the cosmos.

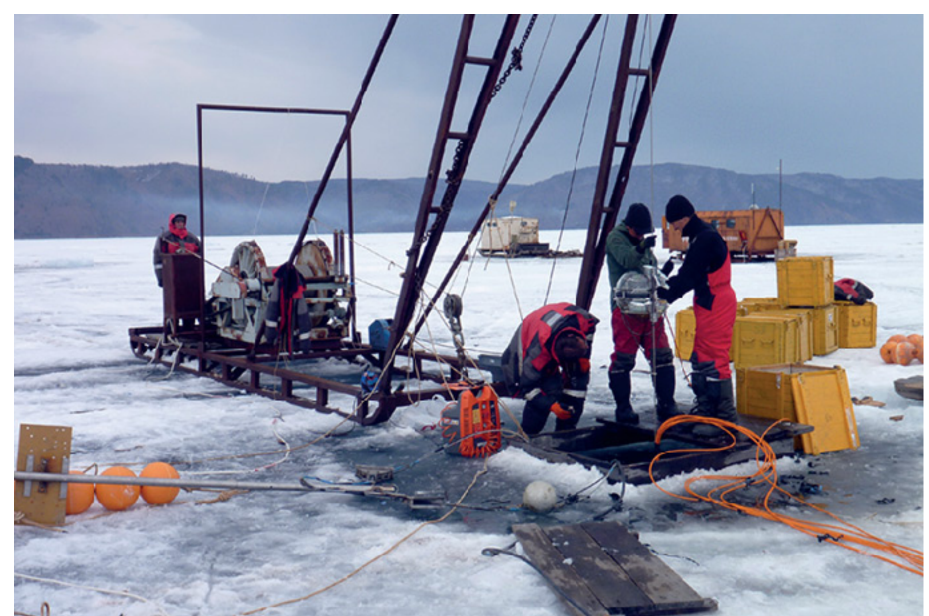
In Antartic: IceCube





In the Mediterranean: Antares and Km3Net



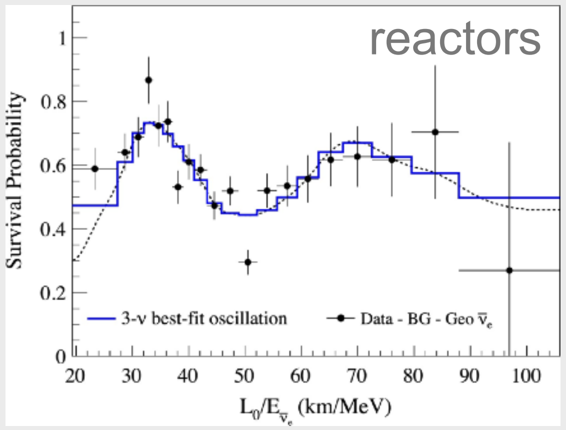


In lake Baïkal: BNO

Neutrino Oscillations

Disparitions and … apparitions

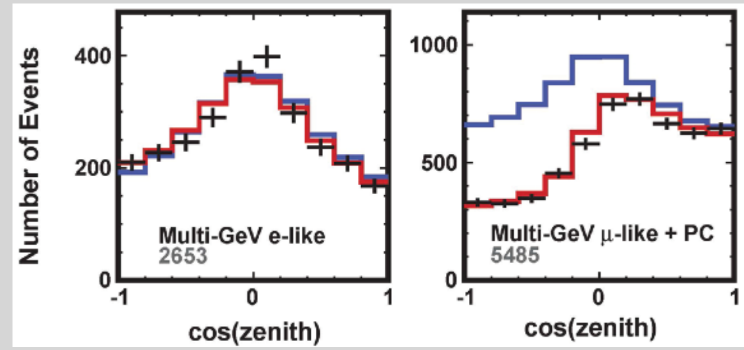
e → e δm^2 θ_{12}



KamLand

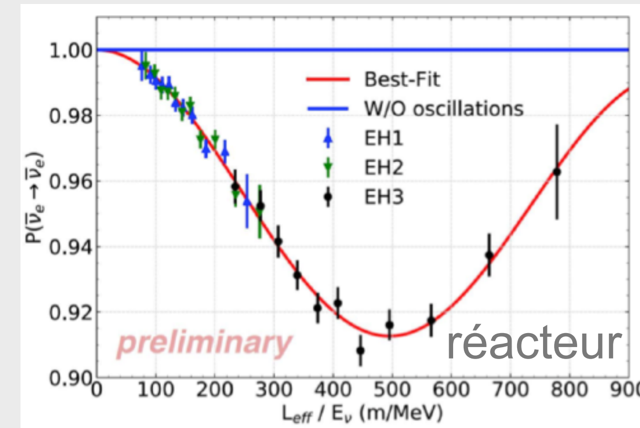
μ → μ Δm^2 θ_{23}

atmospheric



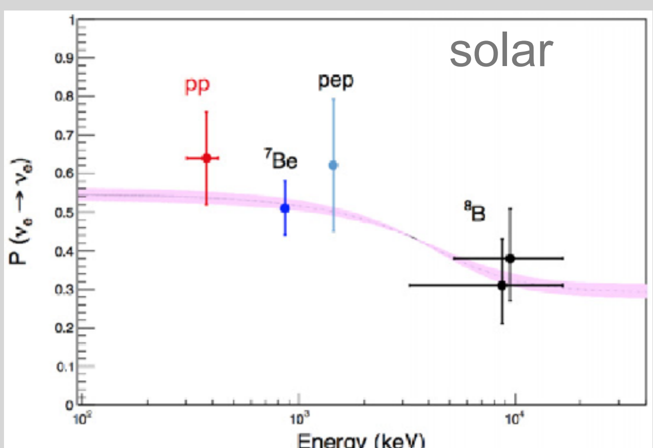
Super K

e → e Δm^2 θ_{13} θ_{23}



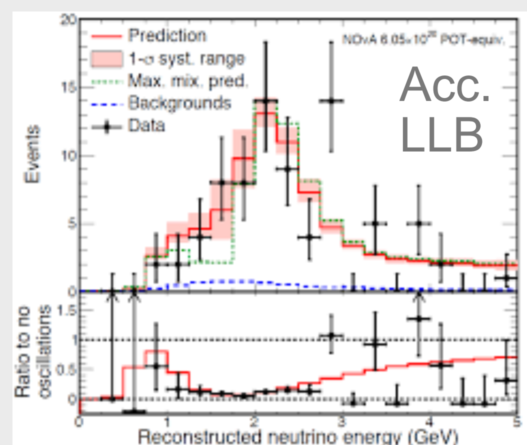
Daya Bay

e → e δm^2 θ_{12}



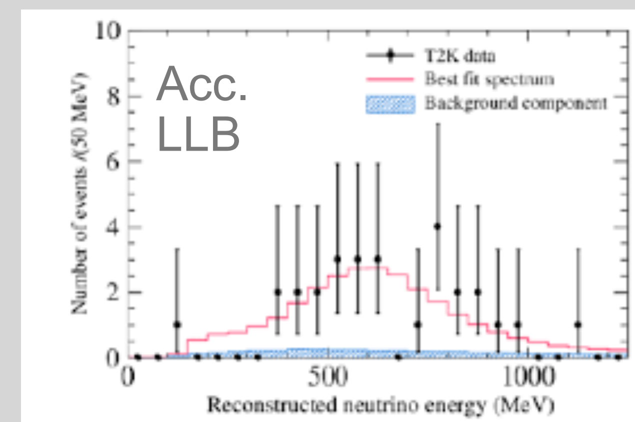
Borexino

μ → μ Δm^2 θ_{23}



NOvA

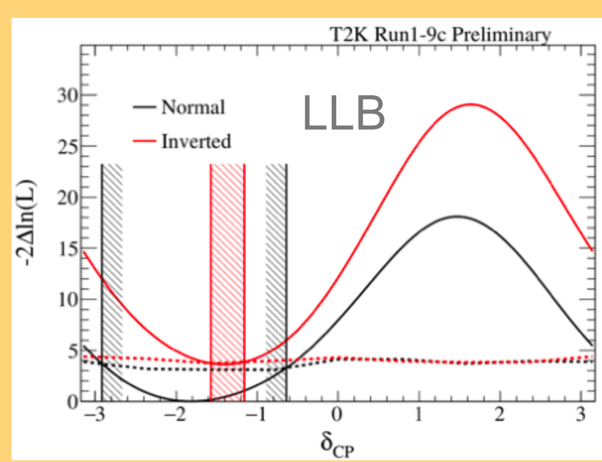
μ → e Δm^2 θ_{13} θ_{23}



T2K

T2K/Nova

- the "normal" order hypothesis (NO) is favored (at 3σ)
- the CP conservation hypothesis is unfavored (at more than 2σ)



Δm^2

θ_{13}

θ_{23}

δ

Observation of CP violation in the ν sector could consolidate models of baryogenesis arising from leptogenesis

Future: DUNE and HK

New Collider to the Rescue?

...there is no experiment/facility, proposed or conceivable (...) which can guarantee discoveries beyond the SM, and answers to the big questions of the field.

M. L. Mangano

Energy

Top Yukawa coupling

Direct NP searches

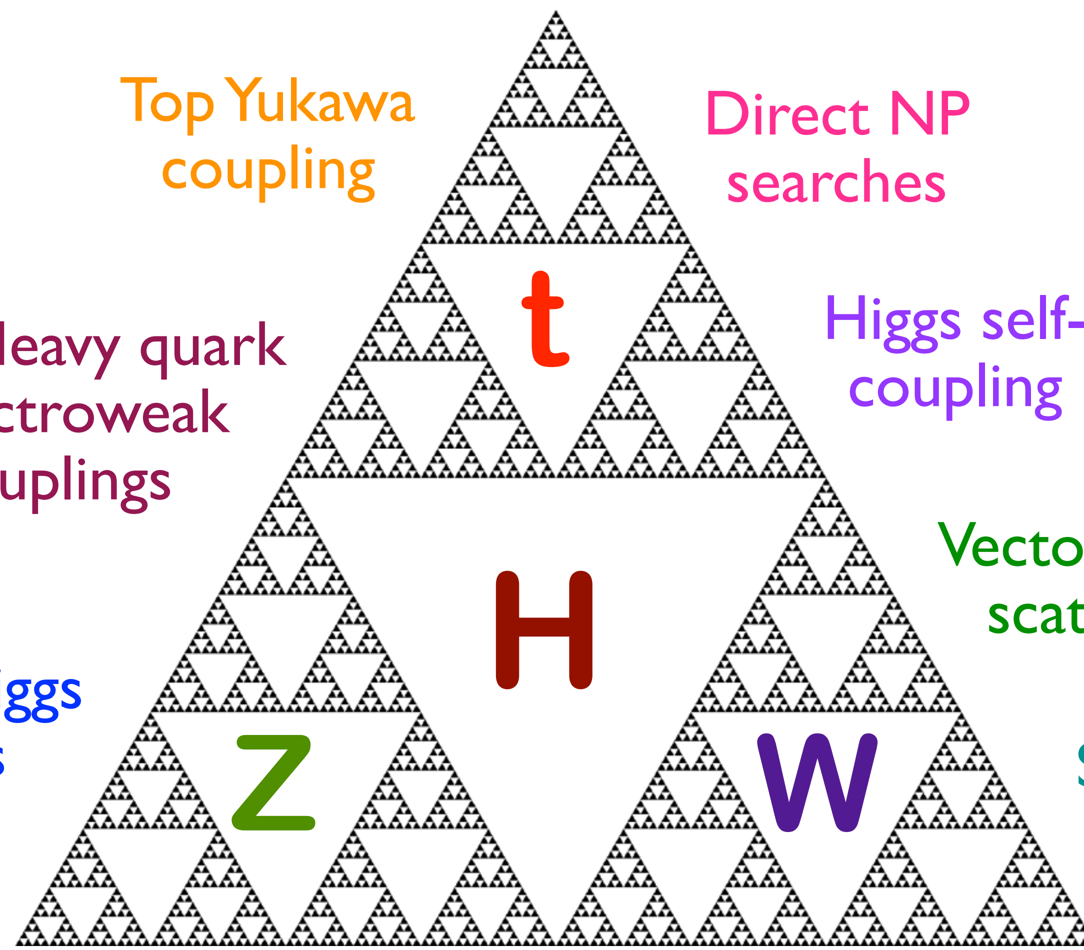
Heavy quark electroweak couplings

Higgs self-coupling

Vector boson scattering

Precision Higgs couplings

Suppressed decays



Precision

Electroweak precision observables

Flavour physics, neutrino physics, and CP violation

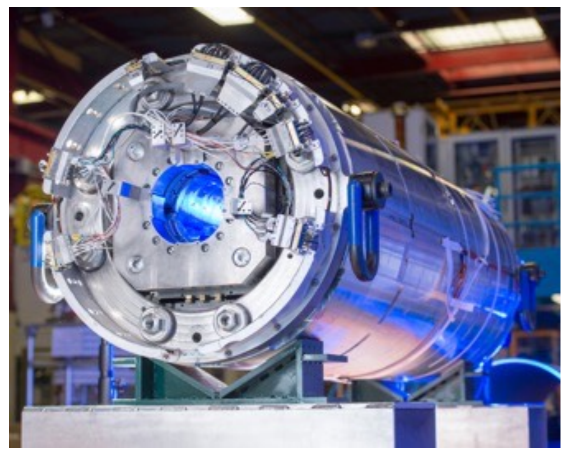
Sensitivity

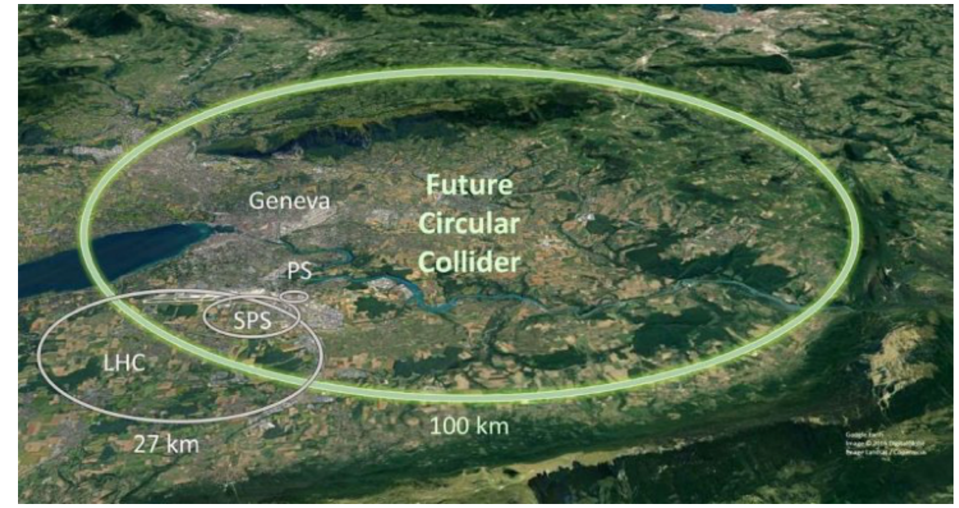
Which Collider after HL-LHC?

High-Luminosity LHC

In construction

- luminosity×5 starting 2030
- 3000 fb^{-1} per experiment in 10 years





Project

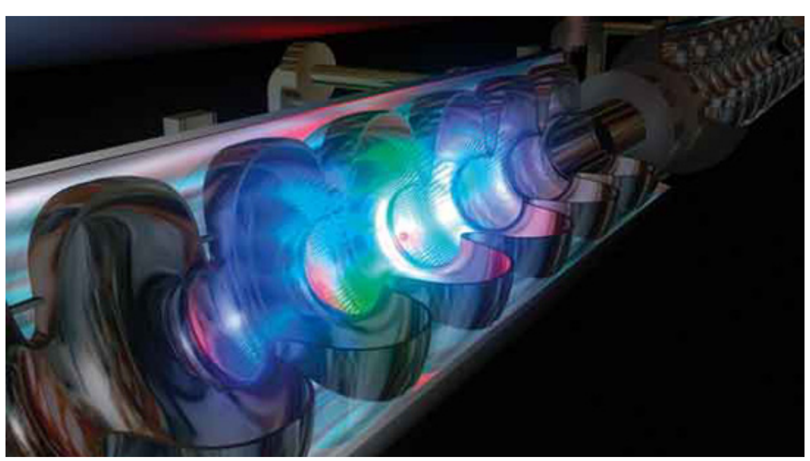
FCC	CM energy	collisions	tunnel
FCC-ee	90-365 GeV	e^+e^-	90-km
FCC-hh	75-100 TeV	pp	

Project

Update of the European Strategy in Particle Physics (EPPSU) in progress (2025-2026)

ILC in Japan / LCF

- e^+e^- linear collider
- 250 GeV → 550 GeV



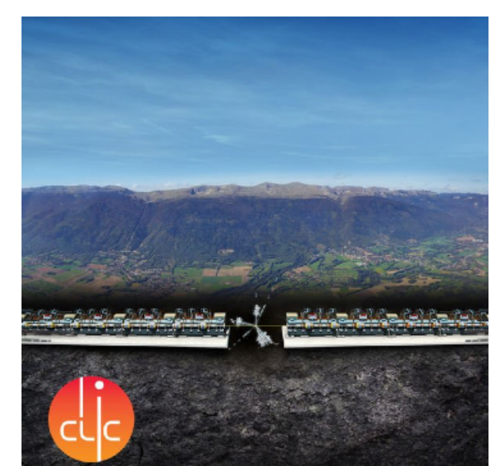
CEPC in China

- e^+e^- circular collider
- tunnel 100 km
- 90-365 GeV

Project

CLIC

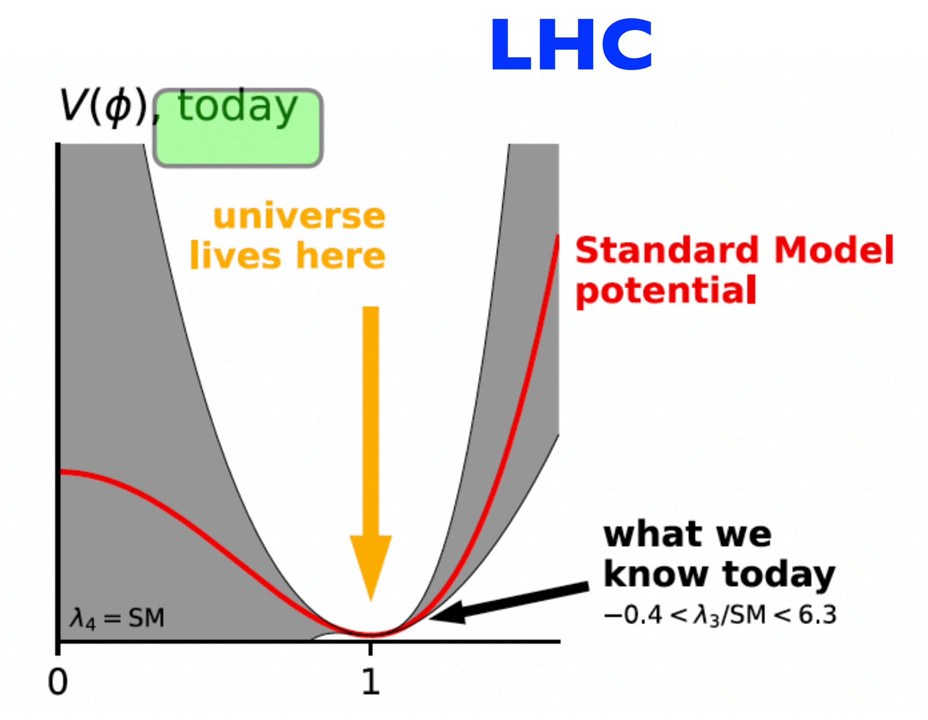
- e^+e^- linear collider
- 380 GeV → 3 TeV

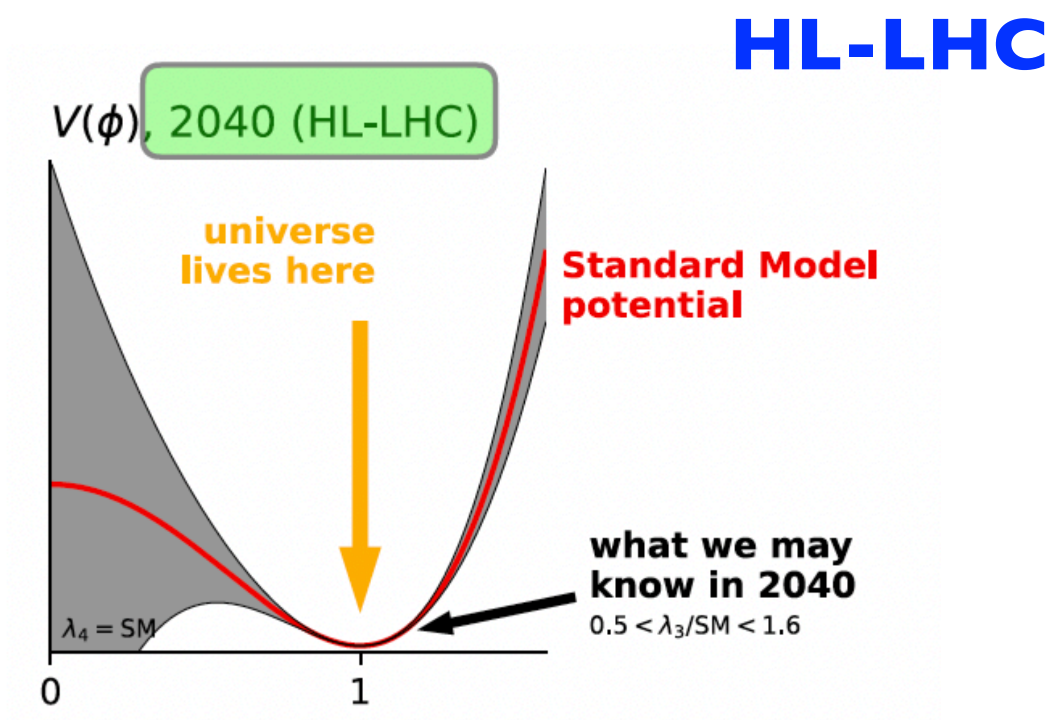


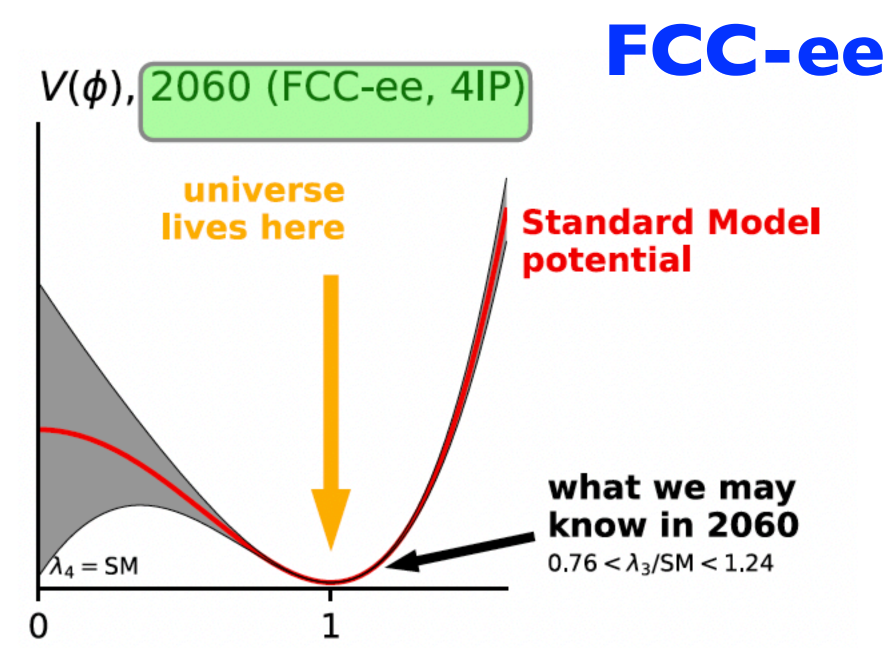
Project

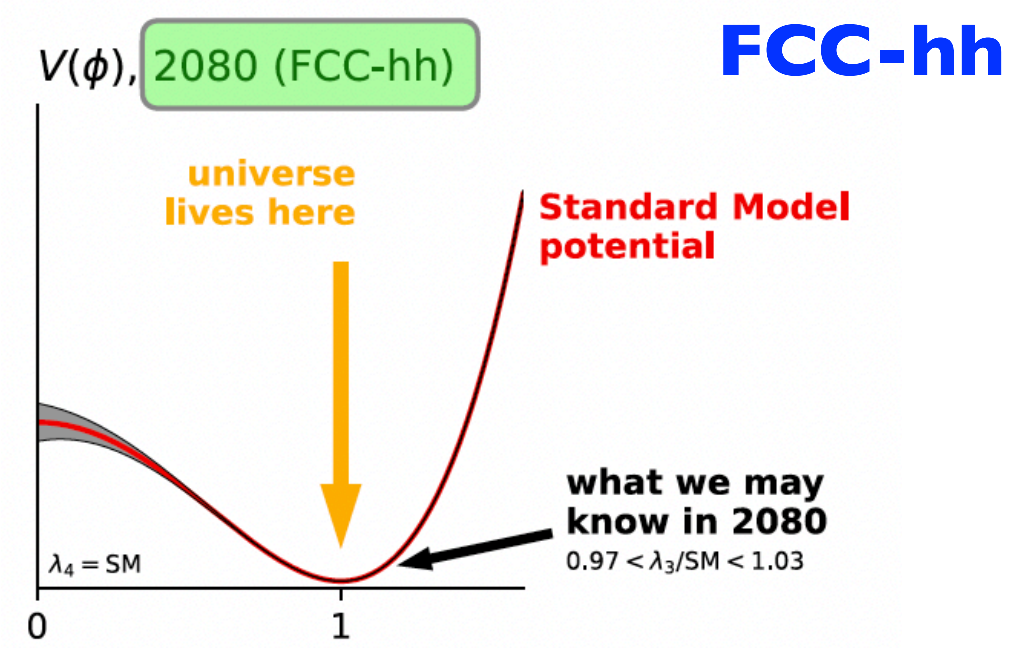
Maximilien Brice, CERN

Unraveling the Higgs Potential?









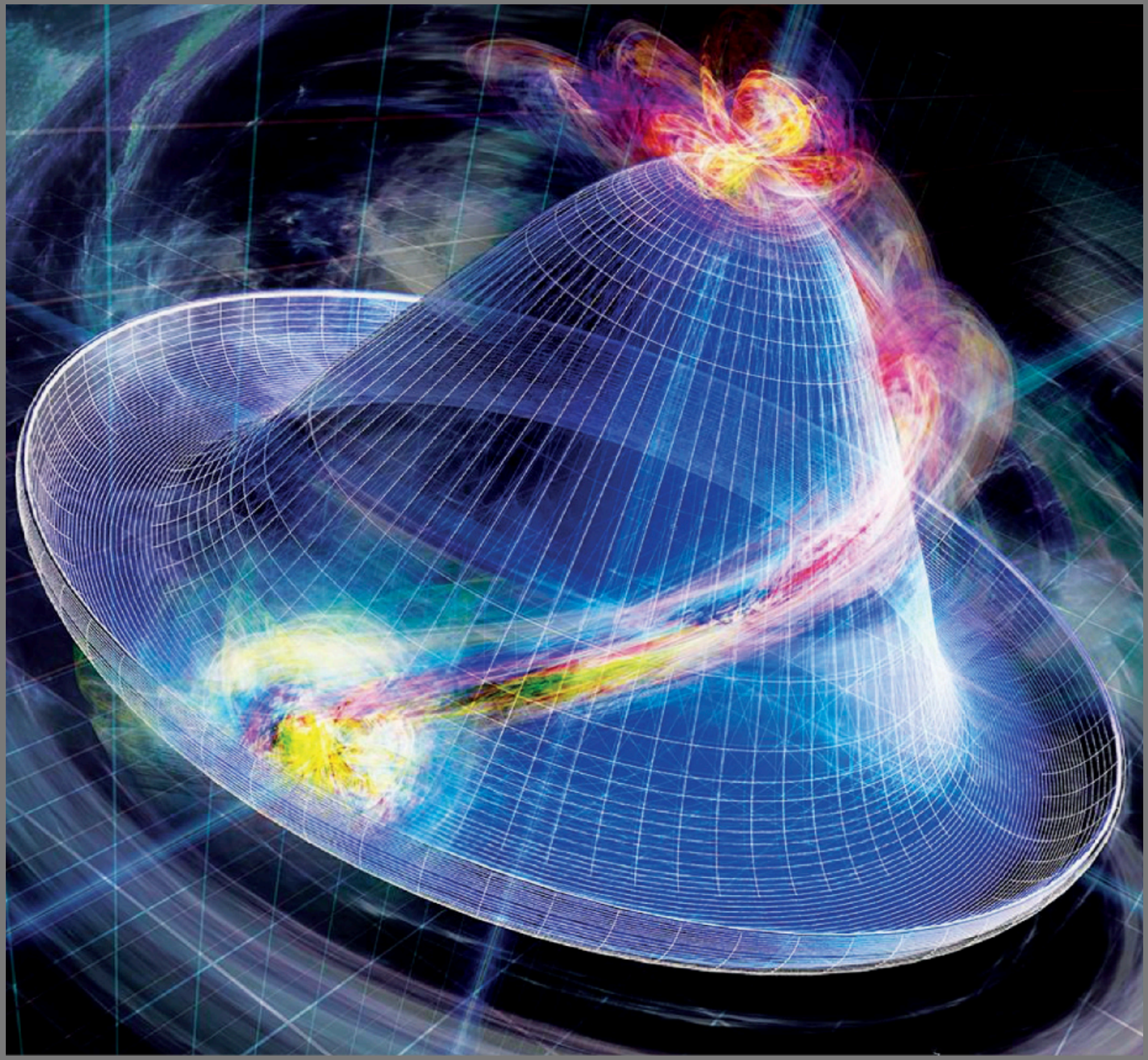
Conclusion

We are living a golden age of particle physics!

LHC : Reinforced standard model
- discovery and study of the Higgs boson
- electroweak precision measurements
- physics of flavour and CP violation

Neutrinos
- 3 neutrino paradigm
- 3 mixing angles measured
- Normal Order favoured by the data
- Program to observe CP violation

Yet the absence of direct observations of dark matter and the discovery of new physics at the LHC on the TeV scale poses a challenge to theoretical physics

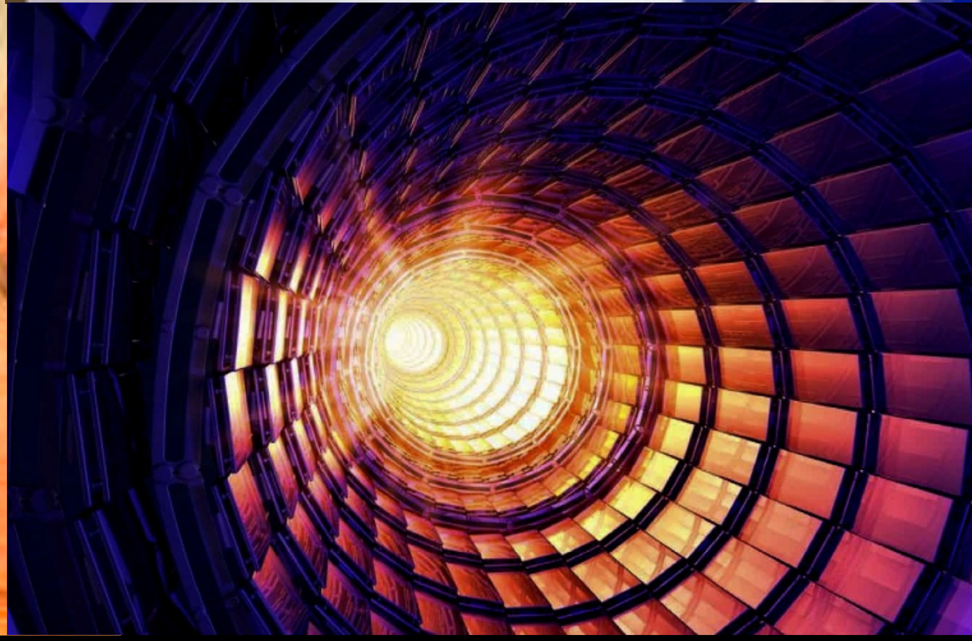


The experimental program is particularly rich for the next twenty years (HL-LHC, Belle-2, DUNE, HK, etc.)

The post-LHC program must be built now, hence the importance of the discussions underway as part of the European Strategy Update 2025-26

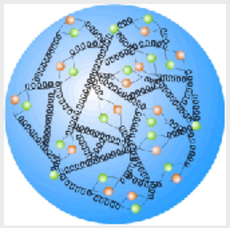
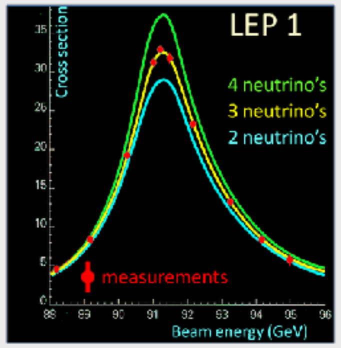
DE LA RECHERCHE À L'INDUSTRIE cea Irfu

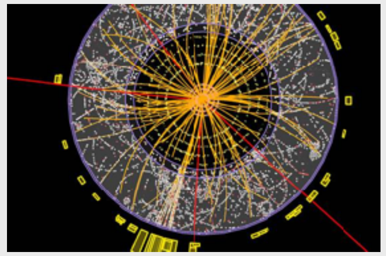
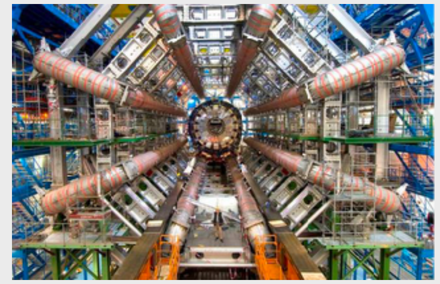
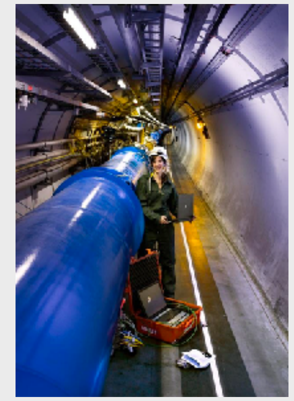
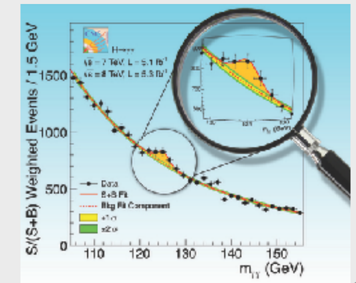
université PARIS-SACLAY

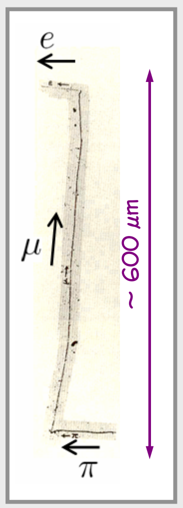


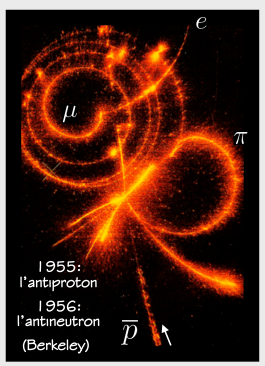
Gautier Hamel de Monchenault

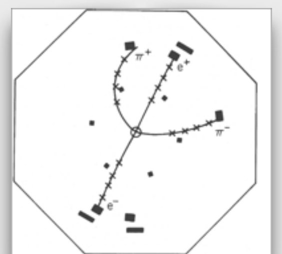
Un siècle de découvertes

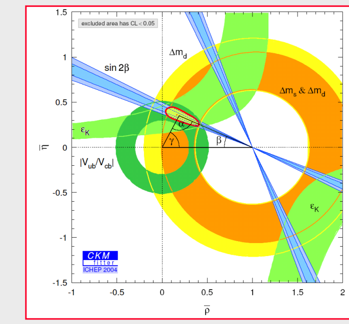



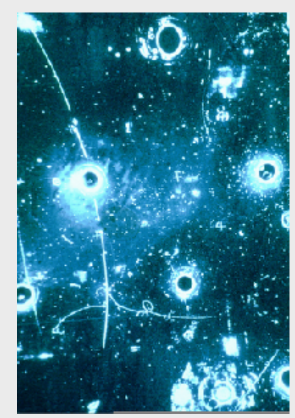
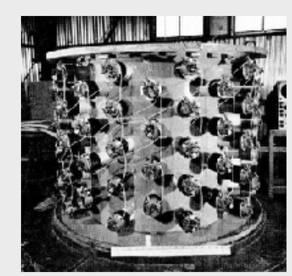
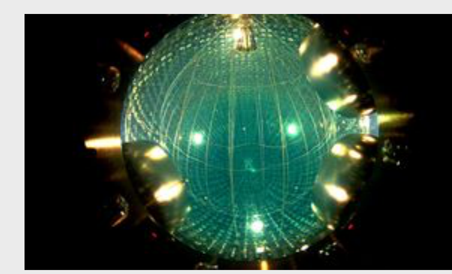
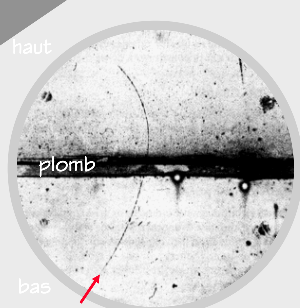



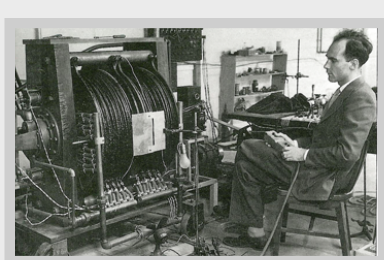
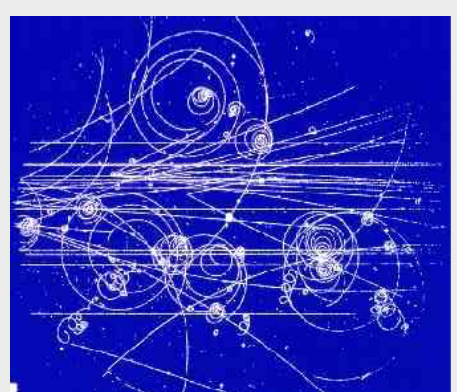


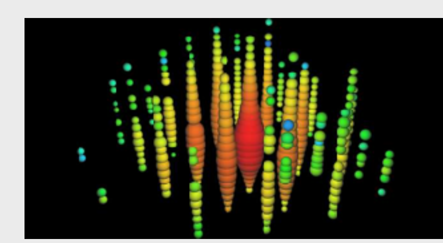




2012	**boson de Higgs**
2001	violation de CP (mésons B)
2000	neutrino tau
1995	**quark top**
1983	**bosons W et Z**
1970-1979	gluon mésons *beaux* (quark b) lepton tau mésons *charmés* (quark c) courants neutres
1968	structure du proton (quarks u, d et s)
1964	violation de CP
1962	neutrino muonique
1956	neutrino électronique
1947	kaon, particules *étranges*
1937	pion et muon
1932	positron

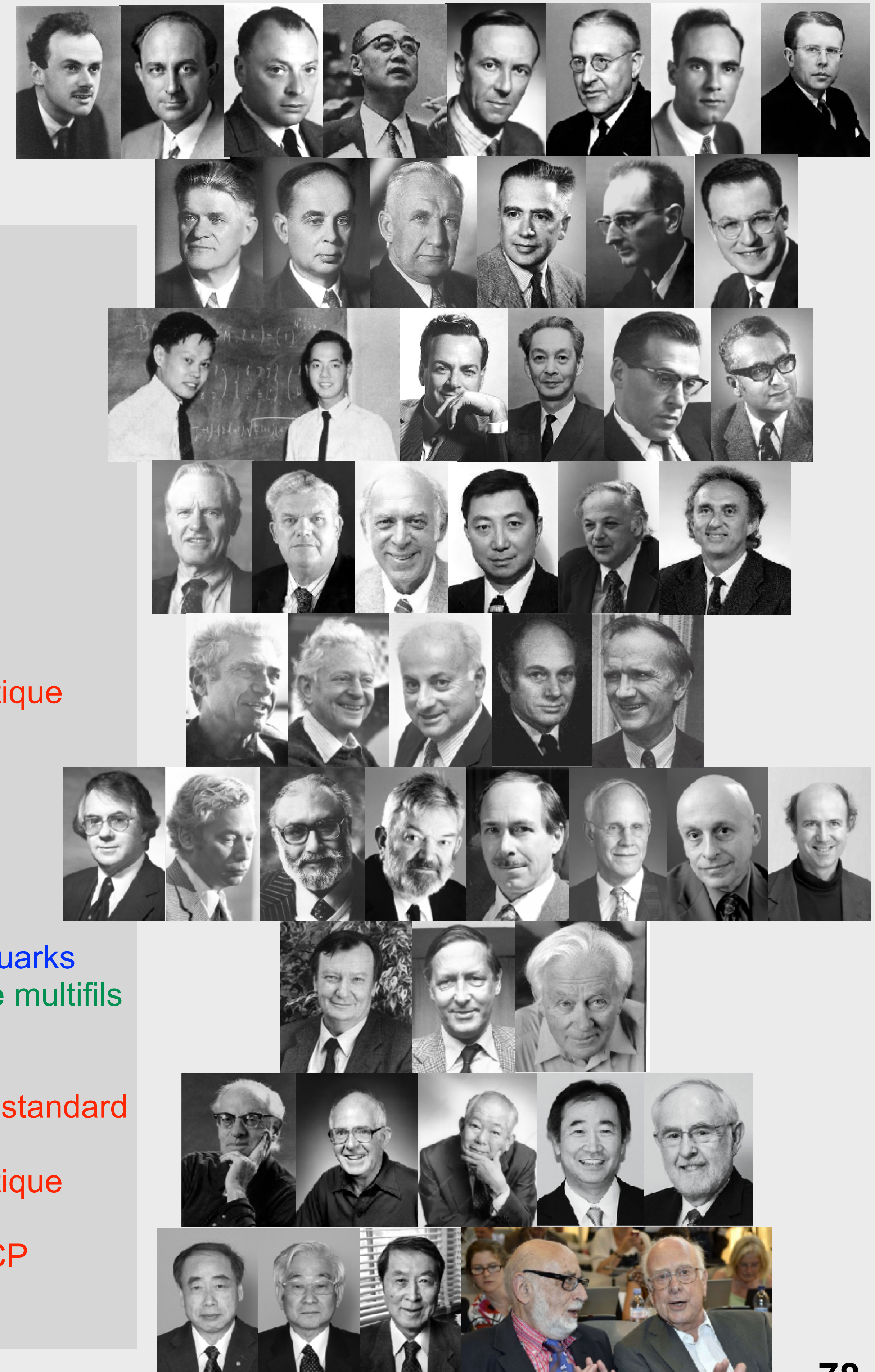







… jalonné de
quelques Prix Nobel

1933	**Dirac***	[antimatière]
1935	**Chadwick**	neutron
1936	**Hess**	rayonnement cosmique
1936	**Anderson**	positron
1938	**Fermi***	[interactions faibles]
1939	**Lawrence**	cyclotron
1945	**Pauli***	[neutrino]
1949	**Yukawa**	interactions fortes
1957	**Yang, Lee**	violation de la parité
1958	**Tcherenkov, Franck, Tamm**	effet Tcherenkov
1959	**Segrè, Chamberlain**	antiproton
1960	**Glaser**	chambre à bulles
1965	**Tomonaga, Schwinger, Feynman**	électrodynamique quantique
1969	**Gell-Mann**	modèle des quarks
1976	**Richter, Ting**	méson J/ψ
1979	**Glashow, Salam, Weinberg**	unification électrofaible
1980	**Cronin, Fitch**	violation de CP
1984	**Rubbia, van der Meer**	bosons W et Z
1988	**Lederman, Schwartz, Steinberger**	neutrino muonique
1990	**Friedman, Kendall, Taylor**	mise en évidence des quarks
1992	**Charpack**	chambre proportionnelle multifils
1995	**Perl**	lepton tau
1995	**Reines**	neutrino électronique
1999	**’t Hooft, Veltman**	renormalisation modèle standard
2002	**Davis, Koshiba**	neutrinos solaires
2004	**Gross, Politzer, Wilczek**	QCD et liberté asymptotique
2008	**Nambu**	brisure de symétrie
2008	**Kobayashi, Maskawa**	familles et violation de CP
2013	**Englert, Higgs**	origine de la masse
2015	**Kajita, Mc Donald**	oscillation des neutrinos



Le CERN

Organisation européenne pour la recherche nucléaire (= Laboratoire européen de physique des particules)
- créé en 1954 sous l'impulsion de la France
- près de Génève

Aujourd'hui le plus grand laboratoire de physique des particules au monde
- 22 états membres
- 2 500 employés (40% de Français)
- 12 300 scientifiques de 110 nationalités (France : 800 scientifiques)
- budget annuel : 1.1 milliard de CHF (France : 14.6%)

fort retour industriel en France

Les grandes missions du CERN
1. la **science**
2. la **technologie** et l'**innovation**
3. la **formation** et l'**éducation**
4. rapprocher les scientifiques de **différentes nations** et **différentes cultures**

La "coopétition"

Le modèle du CERN s'appuie
sur l'**excellence scientifique** et la **coopération internationale**

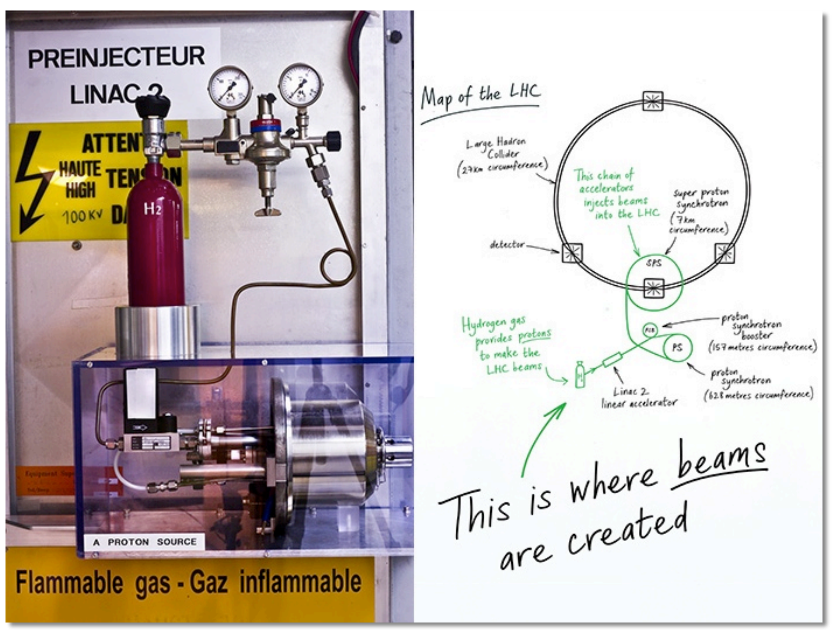
*"Dans toutes les grandes collaborations du CERN, les techniciens, ingénieurs, expérimentateurs et théoriciens travaillent de concert, représentants tous les pays, tous œuvrant passionnément pour un **idéal de science désintéressée et universelle**.*
*Au CERN, le fonctionnement exemplaire de **coopétition**, stimulant les équipes tout en les faisant collaborer, fait avancer la science, mais aussi **la science pour la paix**."*
Michel Spiro, ancien président du conseil du CERN

Mais n'est-ce pas trop coûteux pour le contribuable européen ?

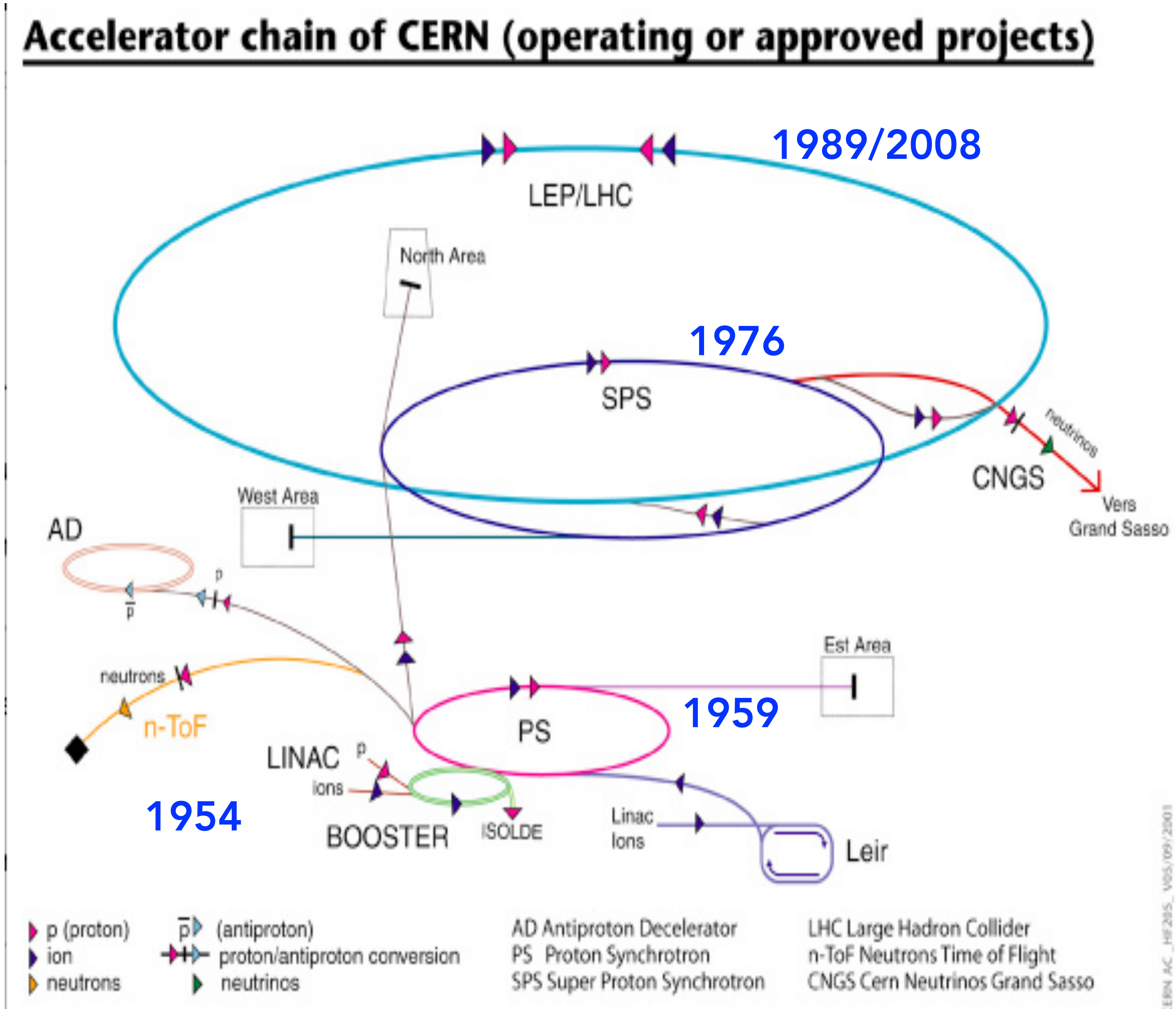
*"Le budget du CERN, c'est **un cappuccino** par citoyen européen et par an."*
Fabiola Gianotti, directrice générale du CERN

Le complexe d'accélérateur du CERN

Ce complexe est formé d'une succession d'accélérateurs d'énergies croissantes



- LINAC2 : 50 MeV
- PS Booster : 1.4 GeV
- PS : 25 GeV
- SPS : 450 GeV
- LHC : 6.5 TeV



- 2x1900 paquets de 10^{11} protons (0,5 ng de H^+) espacés de 25 ns (= 7 m)
- 11 100 tours par seconde

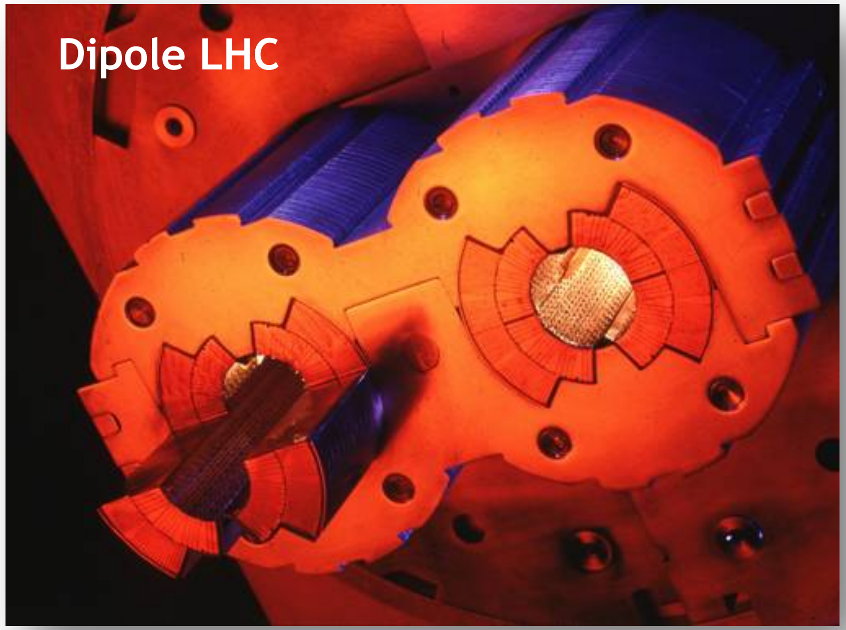
Le LHC

27 kilomètres de circonférence, 100 mètres sous terre (en moyenne)

L'accélérateur a coûté environ 5 milliards de francs suisses
financés sur 15 ans à budget CERN constant

Le LHC

- 1232 dipôles supraconducteurs de 15 m (8.3 T)
- 10 000 aimants supraconducteurs
- 150 tonnes d'hélium superfluide (1.9 K)
- ultravide cryogénique (10^{-13} atm)



- énergie magnétique stockée > 10 GJ
- énergie stockée dans les faisceaux > 700 MJ

HL-LHC Physics in a Nutshell

Higgs, Top and Electroweak

- ☛ precision H coupling measurements
- ☛ m_H, m_W et m_t
- ☛ H properties: width, CP
- ☛ aTGC and aQGC constraints
- ☛ differential measurements
- ☛ rare processes (VBS, VVV, 4-tops)

Top Quark Factory

- ☛ 2 × 3 billion $t\bar{t}$ pairs

Higgs Boson Factory

- ☛ 2 × 150 million H
- ☛ 2 × 120 thousand HH

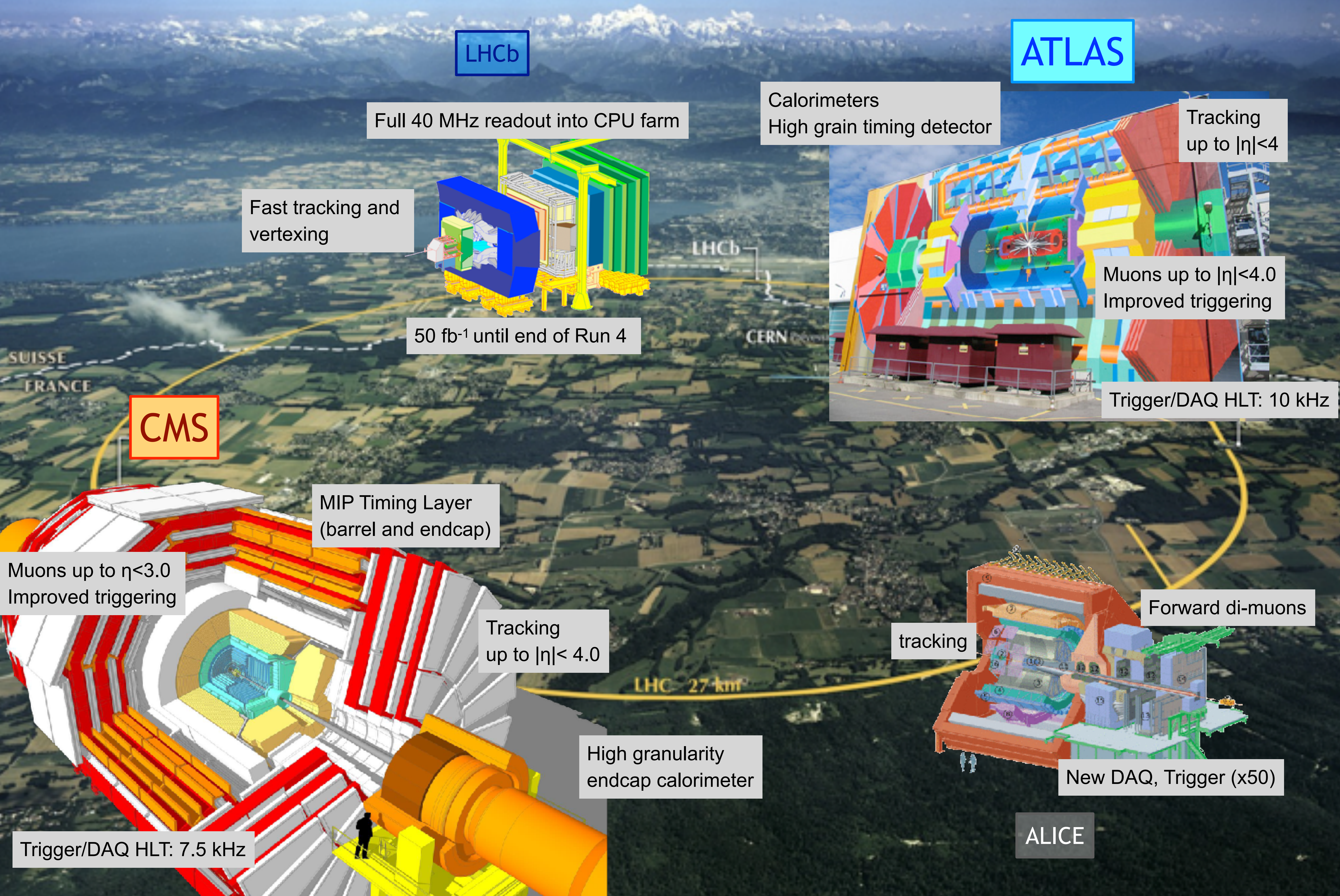
New Particles and Supersymmetry

- ☛ direct searches of heavy resonances
- ☛ searches for new Higgs bosons
- ☛ stringent tests of BSM scenarios
- ☛ novel techniques allowed
  by high statistics and better detectors
- ☛ new trigger strategies
- ☛ better sensitivity to long-lived particles
- ☛ new topologies for Dark Matter searches

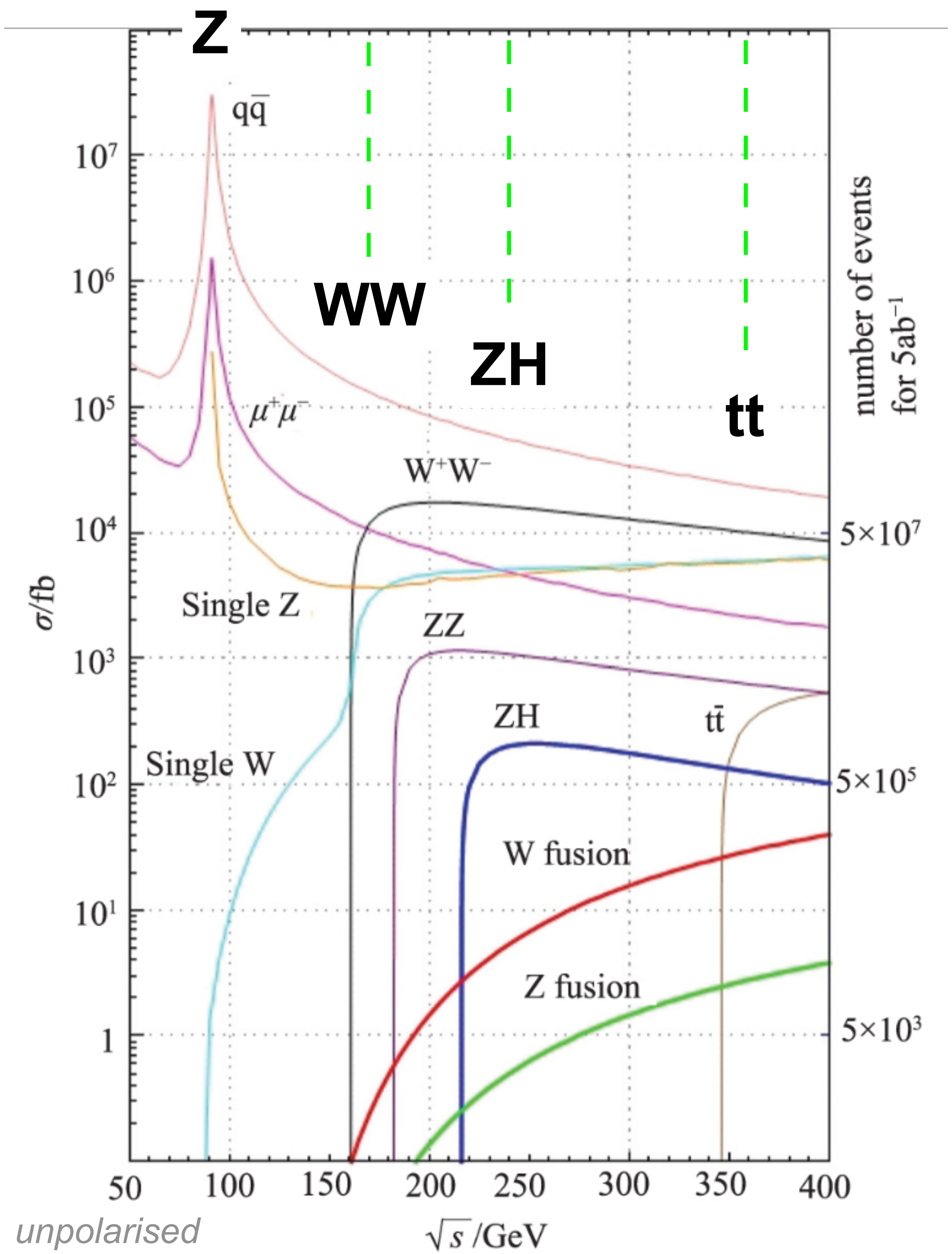
Flavour Physics

- ☛ rare suppressed decays
- ☛ QCD spectroscopy
- ☛ CKM metrology
- ☛ flavour anomalies

LHC Phase 2 Detector Upgrades



SM Cross Sections at e^+e^- Colliders



At $\sqrt{s}$ = 250 GeV

- $e^+e^- \to ZH$ **200 fb** *(Higgsstrahlung)*
- $e^+e^- \to H\nu\nu$ **8 fb** *(W fusion)*

Cross sections decreasing as 1/s:

- $e^+e^- \to qq(\gamma)$ **60 pb** *(incl. Z return)*
- $e^+e^- \to W^+W^-$ **16 pb**
- $e^+e^- \to ZZ$ **1 pb**

Slowly increasing cross sections:

- $\gamma\gamma \to qq, \ell\ell$ **30 pb** *(m > 30 GeV)*
- $e\gamma \to Ze$ **3.8 pb**
- $e\gamma \to W\nu$ **1.5 pb** *(WWγ)*
- $ee \to Z\nu\nu$ **32 fb** *(WWZ)*

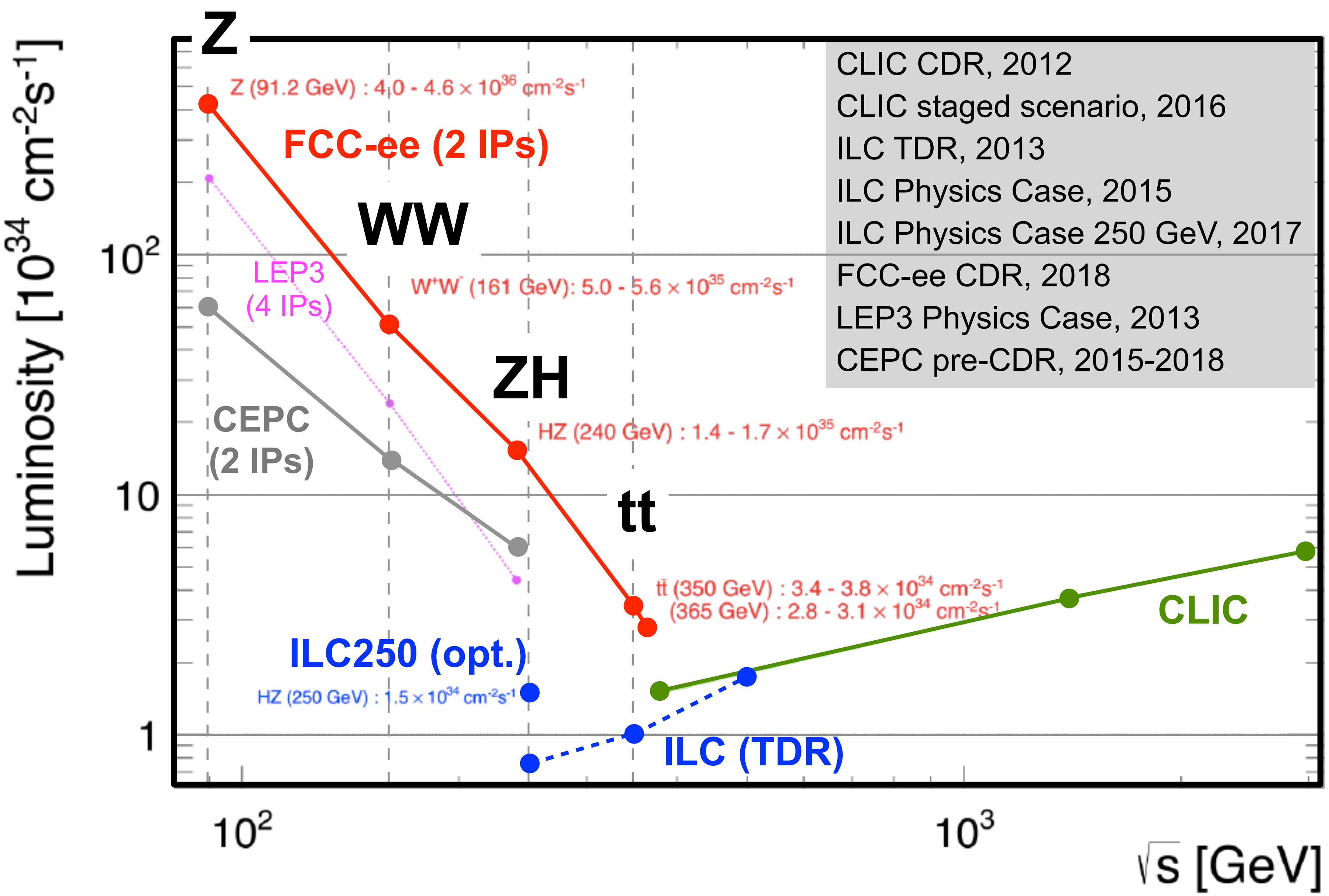
At $\sqrt{s}$ = 380 GeV

- $e^+e^- \to tt$ **500 fb**
- $e^+e^- \to ZH$ **100 fb**
- $e^+e^- \to H\nu\nu$ **40 fb**

SM Physics at e^+e^- Colliders

$\sqrt{s}$	Processes	Physics Goals	Observables
91 GeV	• $e^+e^- \to Z$	ultra-precision EW physics	$\sin^2\theta_{eff}$ M_Z, Γ_Z, N_ν α, α_S
125 GeV	• $e^+e^- \to H$	*limit on s-channel H production?*	y_e
160 GeV	• $e^+e^- \to W^+W^-$	ultra-precision W mass	M_W, Γ_W
>160 GeV	• $e^+e^- \to W^+W^-$ • $e^+e^- \to qq, \ell\ell\ (\gamma)$	precision W mass and couplings precision EW (incl. Z return)	M_W, aTGC N_ν
250 GeV	• $e^+e^- \to ZH$	ultra-precision Higgs mass precision Higgs couplings	M_H κ_V, κ_f, Γ_H
360 GeV	• $e^+e^- \to tt$	ultra-precision top mass	m_t
>360 GeV	• $e^+e^- \to tt$ • $e^+e^- \to ZH$ • $e^+e^- \to H\nu\nu$	precision top couplings precision Higgs couplings	
500+ GeV	• $e^+e^- \to ttH$ • $e^+e^- \to ZHH$ • $e^+e^- \to Z' \to ff$ • $e^+e^- \to \chi\chi$ • $e^+e^- \to AH, H^+H^-$	Higgs coupling to top Higgs self-coupling search for heavy Z' bosons search for Supersymmetry search for new Higgs bosons	y_{top} λ_{HHH}

Luminosity of e⁺e⁻ Colliders



Circular colliders

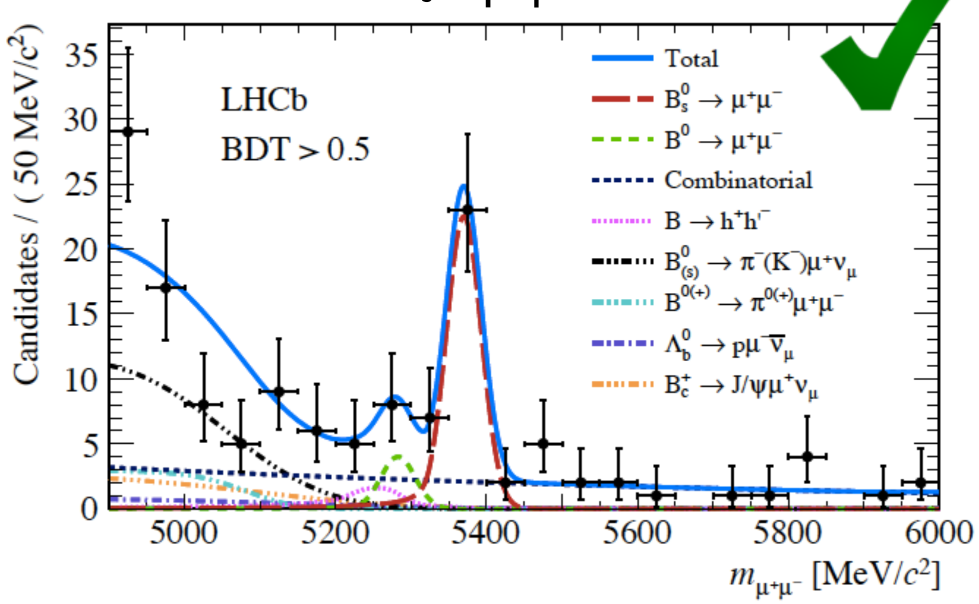
☛ high-luminosity from Z peak to top pair threshold

Linear colliders

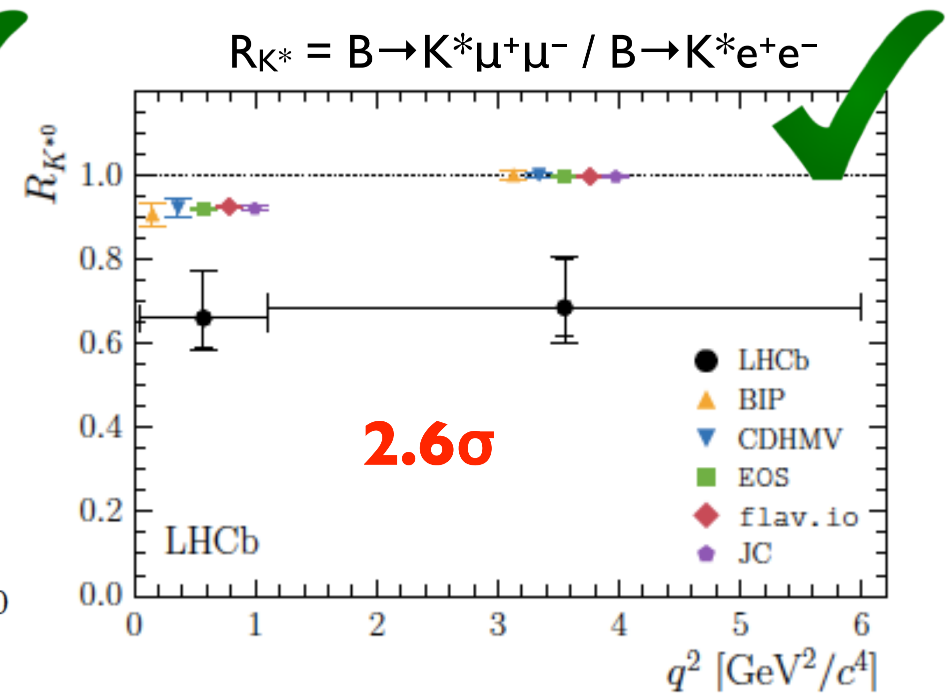
☛ extendability at high energy and beam L-polarisation

Anomalies in Favour Physics

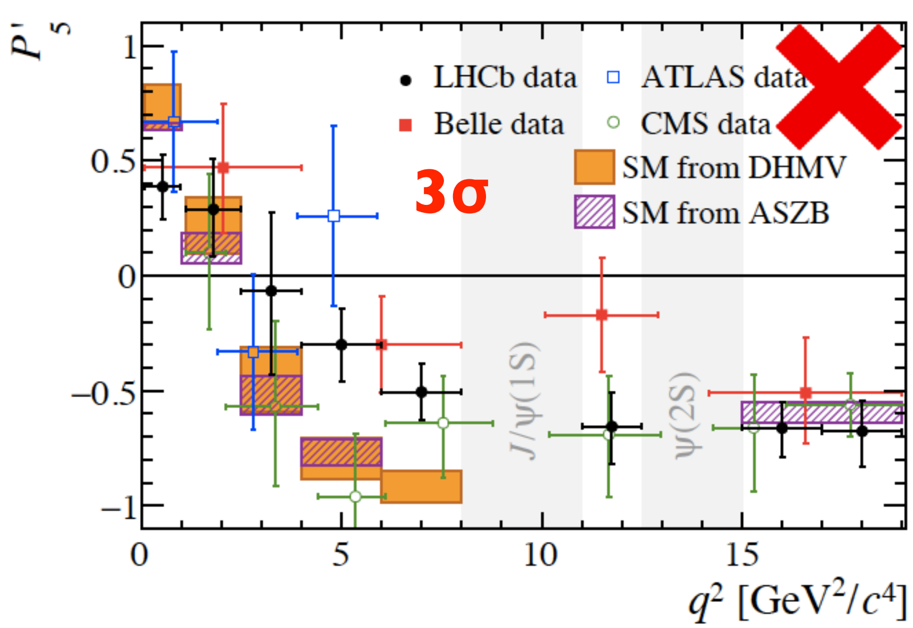
$B_s \to \mu^+\mu^-$



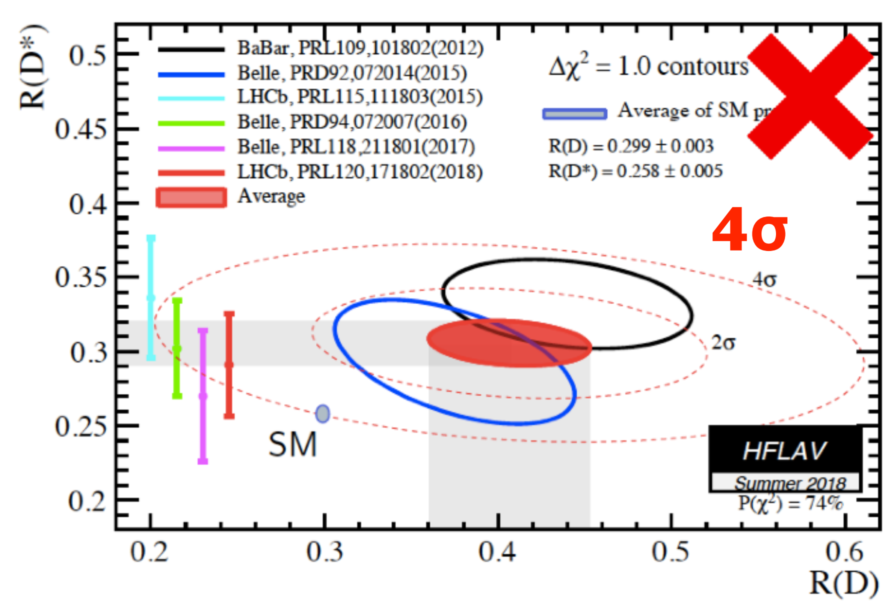
$R_{K^*} = B \to K^*\mu^+\mu^- / B \to K^*e^+e^-$



Distribution angulaire (P'_5) dans $B \to K^*\ell^+\ell^-$



$R(D^{(*)}) = B \to D^{(*)}\tau\nu / B \to D^{(*)}\mu\nu$



New Physics (NP) in flavor-changing neutral currents (FCNC)?

Violation of leptonic universality?

Ancient anomalies:

- tension entre SLD/LEP LR/FB asym. (2.5σ)
- tension dans N_ν (2σ)

And:

- anomaly μ(g-2) (4σ)
- suppression of $B_s \to \phi\ell^+\ell^-$ (3σ)
- tensions between inclusif and exclusif $|V_{ub}|$ and $|V_{cb}|$ (3σ)

Flavor anomalies will be tested with high confidence in LHCb and BELLE-2

The SM as an Effective Theory

- The Standard Model is by essence an effective field theory (EFT)
- It is valid up to a certain energy scale Λ above which a New Physics prevails: this is called the ultraviolet (UV) completion of the SM
- When energies probed by experiment are smaller than Λ, it is in principle possible to observe (small) effects of the UV dynamics, as deviations from the purely SM predictions
- Conversely, null deviations allow to constrain the scale Λ for a given kind of interaction (= an operator in the Lagrangian)

Operators

- In the SM (with null neutrino masses), all operators are dimension 4 except for the Higgs mass term, which is of dimension 2

SM

$$\mathscr{L}_{\mathrm{BSM}} = \boxed{\Lambda^2 \mathscr{L}^{(2)} + \mathscr{L}^{(4)}} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \ldots$$

The "smallness" of the Higgs boson mass points to a small value of the UV scale, $\Lambda \simeq 10^3$ GeV

The Gauge Sector

Gauge fields before SSB (massless)

- $SU(2)_L$ (coupling = g) W^1, W^2 and W^3
- $U(1)_Y$ (coupling = g') B

Physical boson fields after SSB

- weak bosons (massive) W^+, W^- and Z
- photon (massless) γ

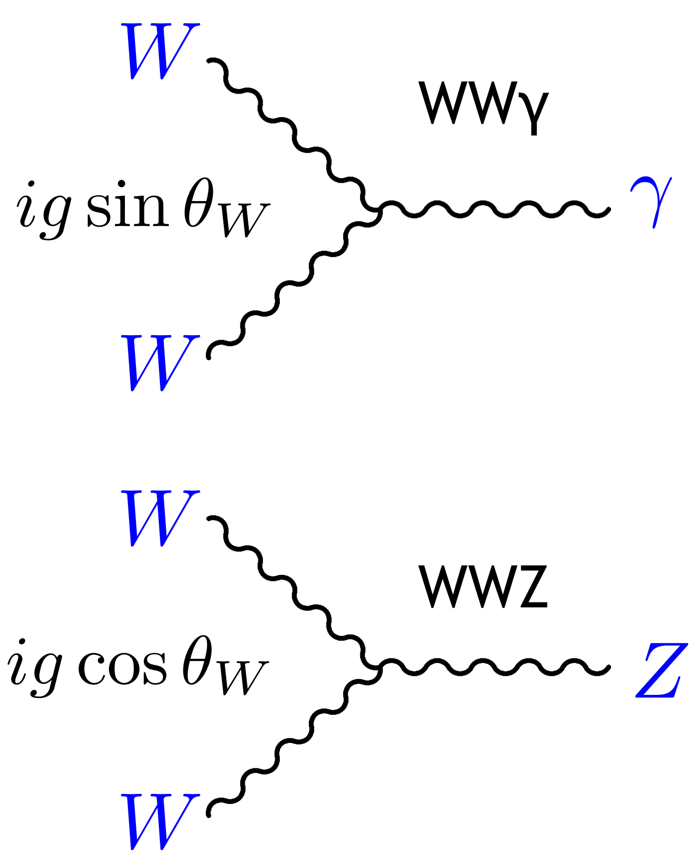
Weak mixing angle

$$\tan\theta_W \equiv g'/g$$

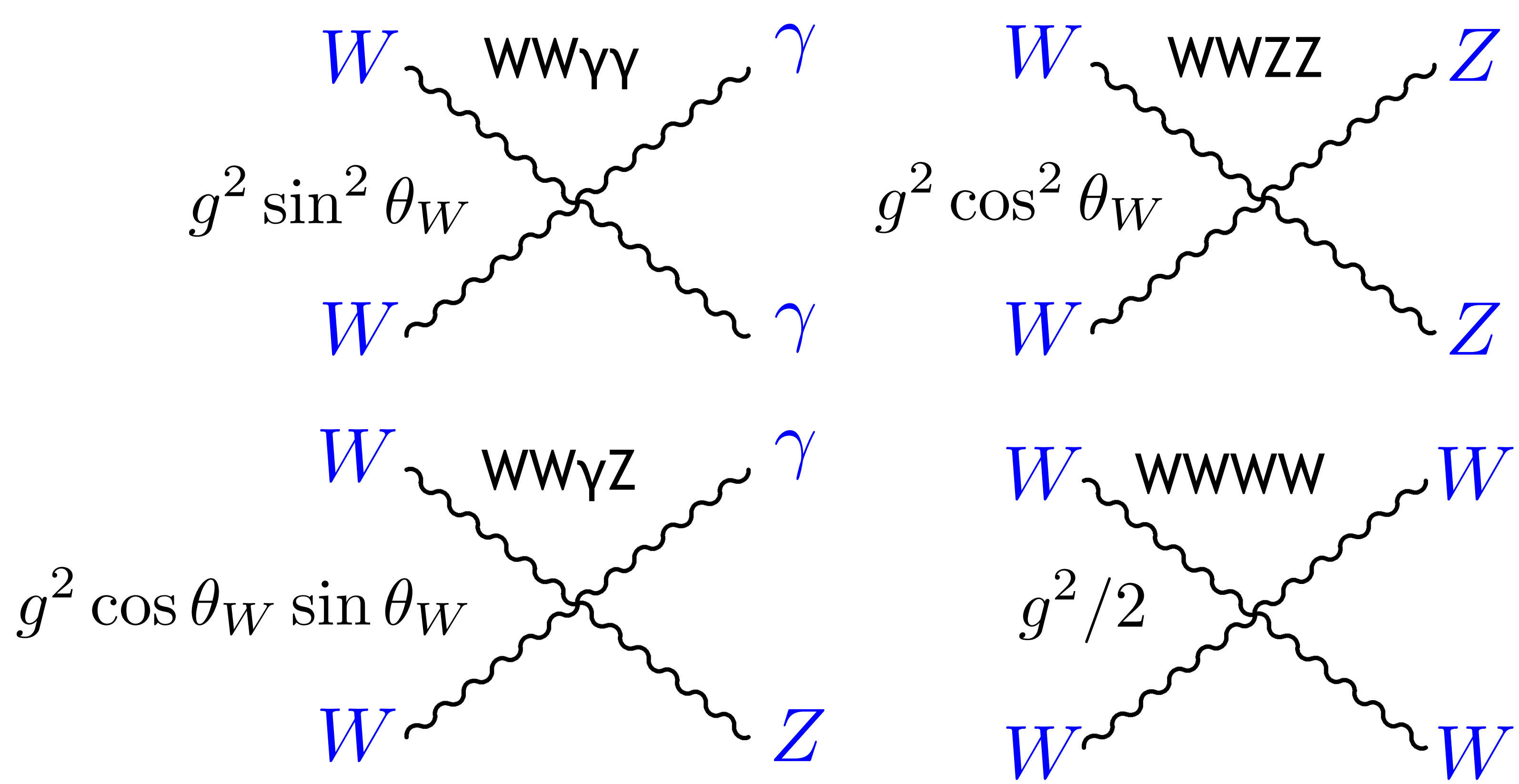
Unit of electric charge

$$e \equiv g \ \sin\theta_W$$

Triple gauge couplings



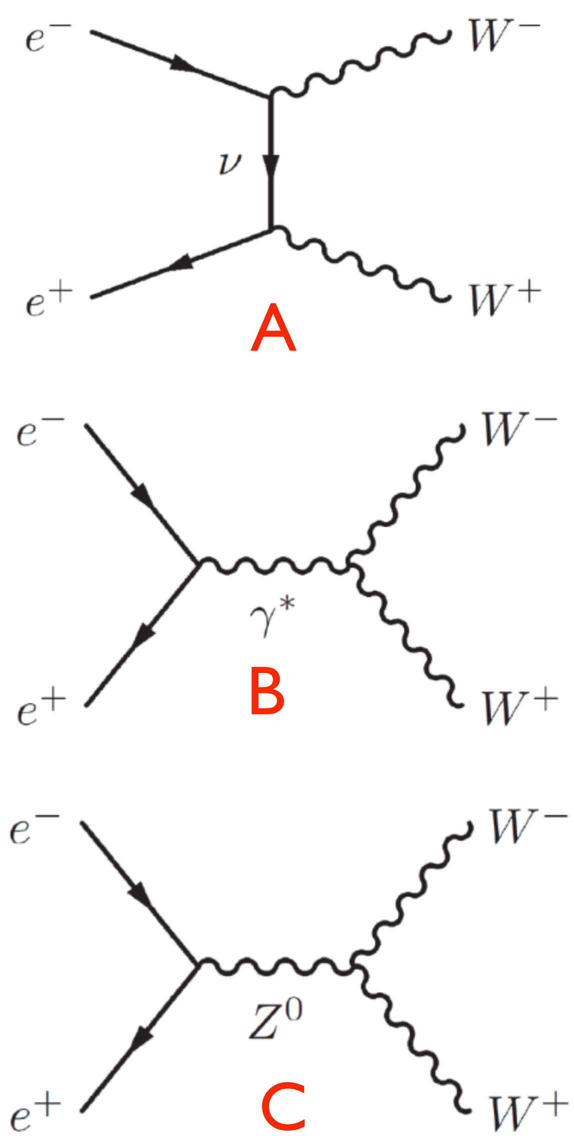
Quartic gauge couplings

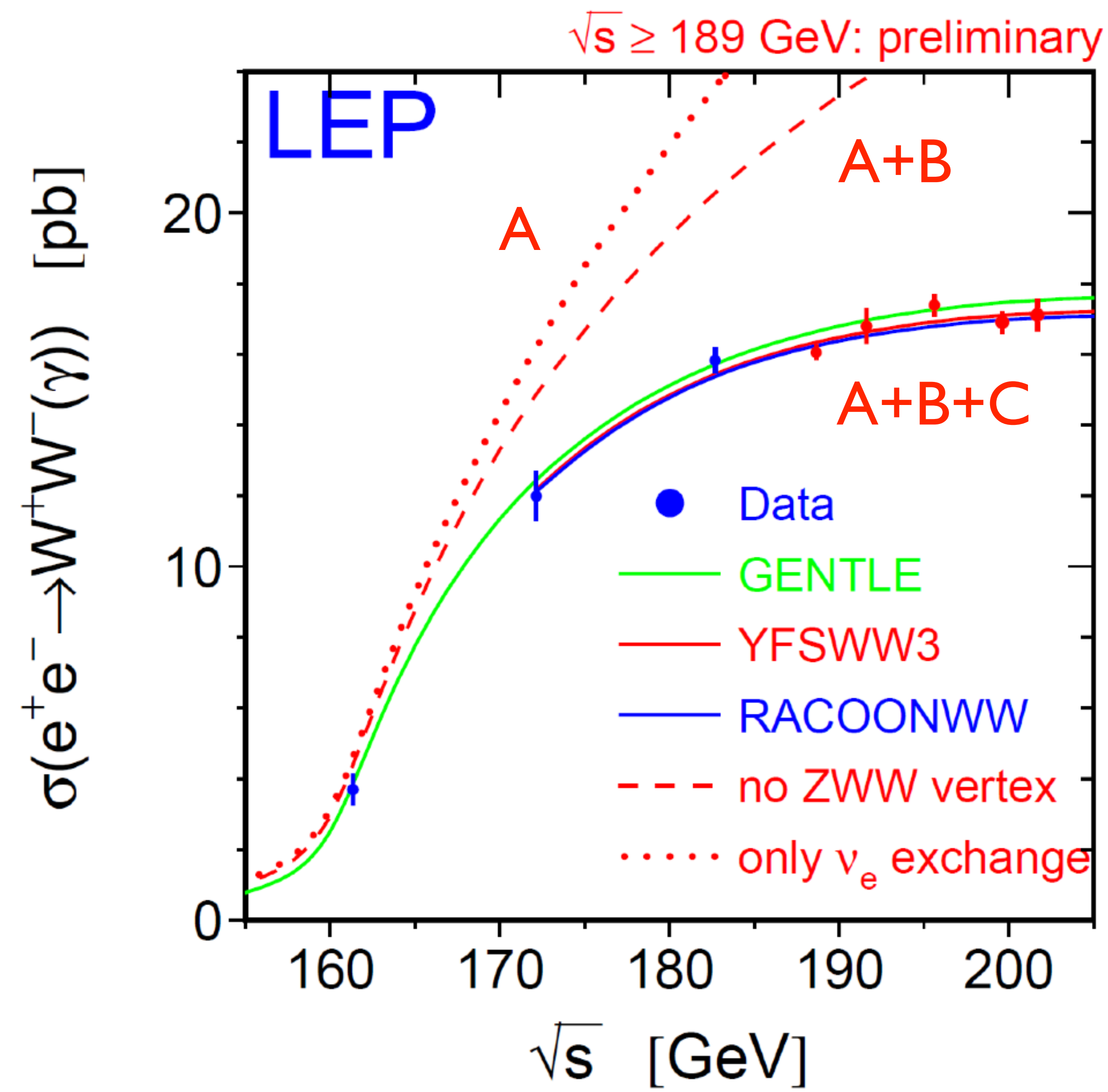


Triple and quartic gauge couplings
are central predictions of the Electroweak theory

LEP-2 : W Pair Production

W-pair production in e^+e^- collisions:





amplitudes B & C are essential to avoid an high-energy catastrophe (violation of unitarity)

Clear observation of triple gauge couplings (circa 2000 @ CERN)

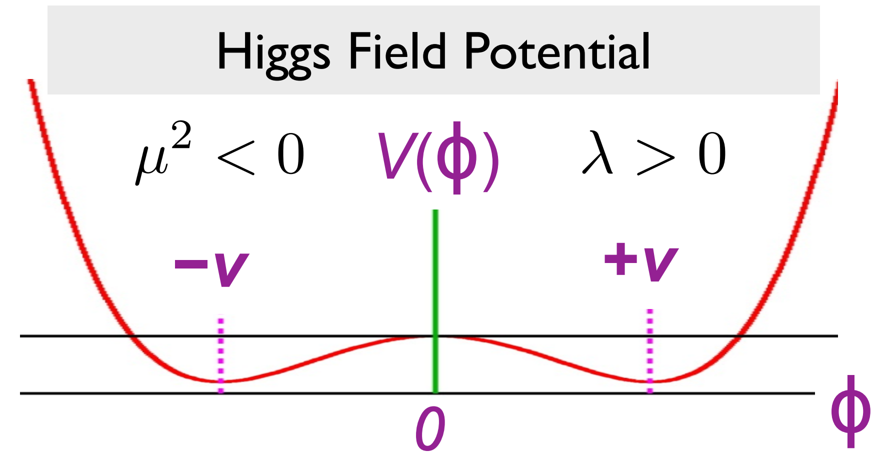
The Higgs Sector

Higgs field v.e.v. $v = \sqrt{-\mu^2/2\lambda}$

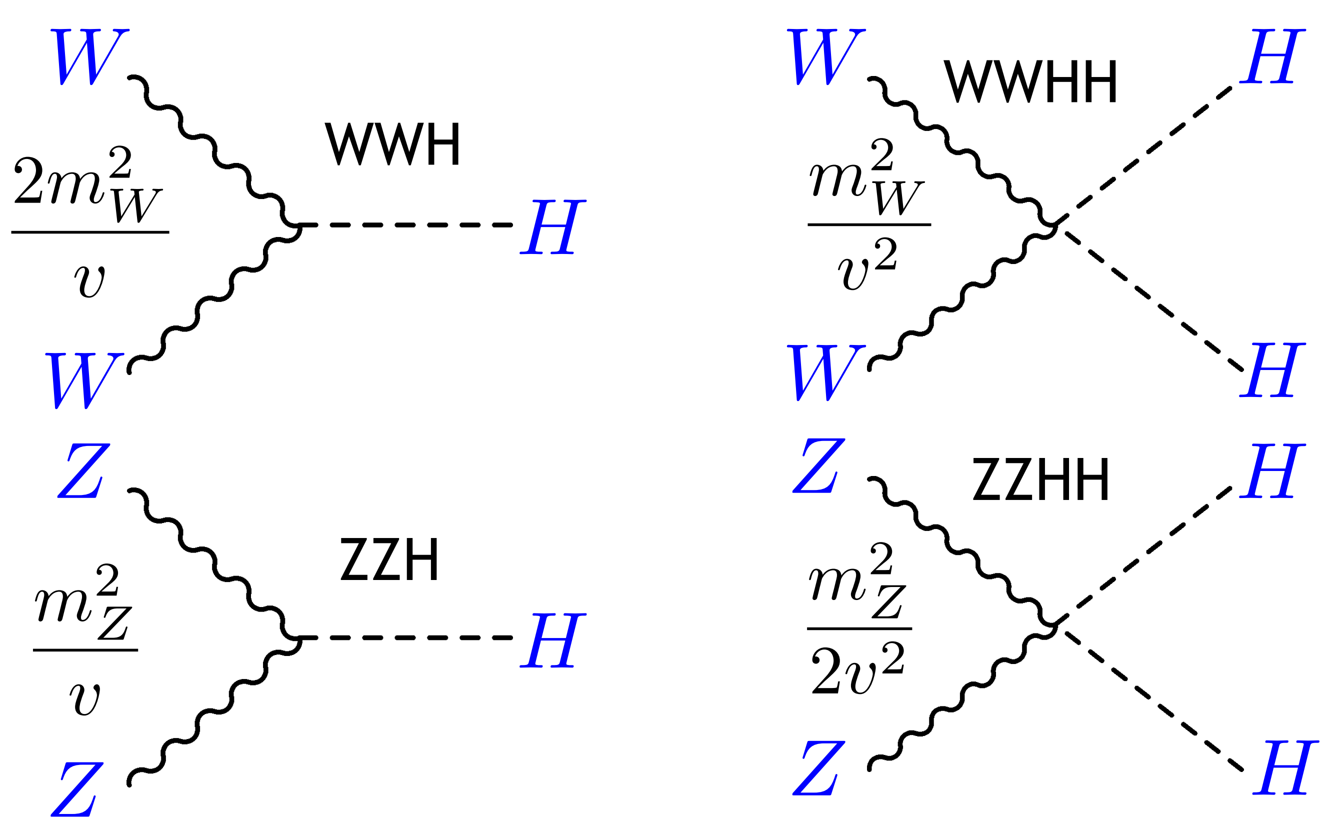
Higgs boson mass $m_H = \sqrt{2\lambda}v$

Weak boson masses

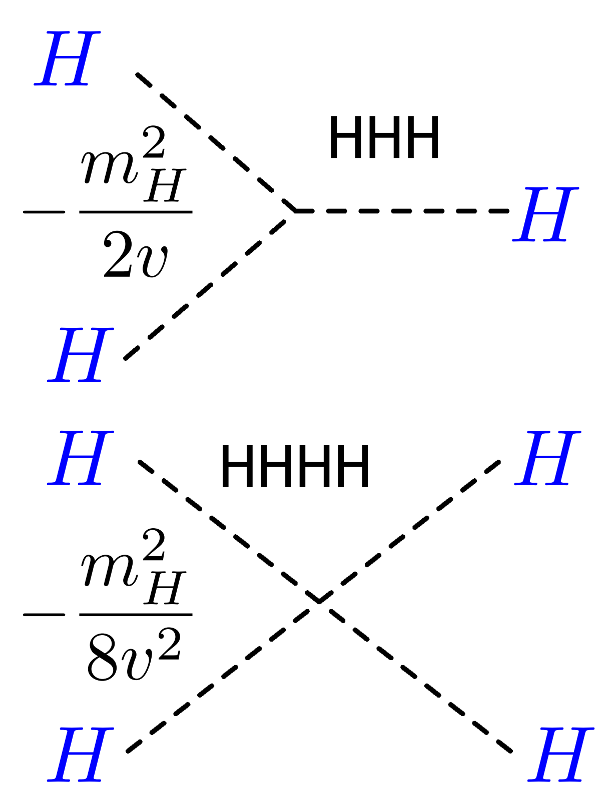
$$m_W \equiv \frac{gv}{2} \quad \text{and} \quad m_Z \equiv \frac{gv}{2\cos\theta_W}$$



Couplings to gauge bosons



Self couplings



EWK Radiative Corrections

Observables can be calculated in the SM in term of a finite number of parameters to be determined experimentally (coupling constants, masses of fermions, CKM and M_H)

Link with Fermi theory

$$m_W^2 = \frac{\pi}{\sqrt{2}G_F}\frac{\alpha}{\sin^2\theta_W}$$

☛ Electroweak parameters (= at classical level)

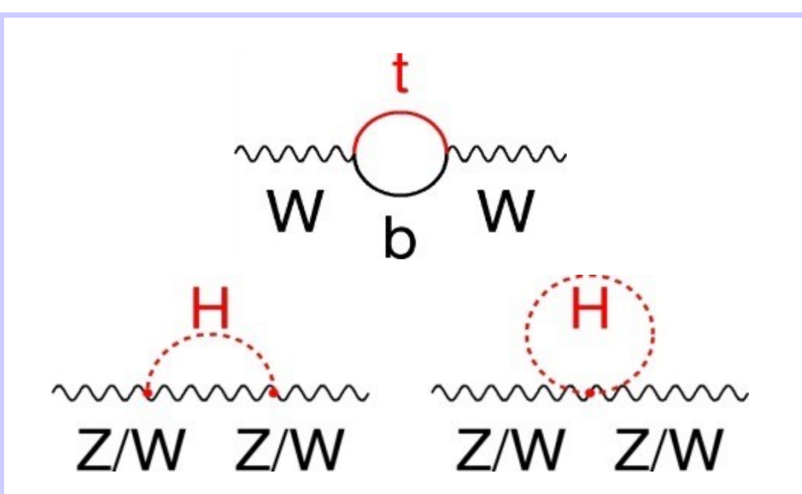
$$\rho \equiv \frac{m_W^2}{m_Z^2\cos^2\theta_W} \quad (= 1) \qquad s_W^2 \equiv 1 - \frac{m_W^2}{m_Z^2} \quad (= \sin^2\theta_W)$$

☛ Physical quantities

$$\bar{\rho} = 1 + \Delta\rho$$

$$M_W^2 = m_W^2\,(1+\Delta r) \quad \text{and} \quad \sin^2\theta_W^{\text{eff}} = s_W^2\,(1+\Delta\kappa)$$

with $\Delta r, \Delta\rho, \Delta\kappa = f(\,m_t{}^2, \ln(m_H), \ldots\,)$



$$\Delta\rho_t \simeq 0.01 \times [\,m_t/(175\ \text{GeV})\,]^2$$

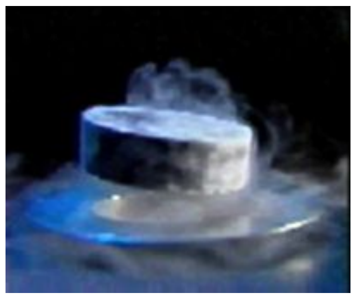
$$\Delta\rho_H \simeq -0.0015 \times \log(\,m_H/M_W\,)$$

the electroweak radiative correction parameters are of the order of the percent and involve contributions from top quark and Higgs boson loops

L'origine de la masse

Comment générer la masse des bosons tout en préservant la symétrie de la théorie ?

Nambu ; Goldstone, 1960
Anderson, 1962
Higgs ; Brout & Englert, 1964
Guralnik, Hagen, Kibble, 1964



Y. Nambu

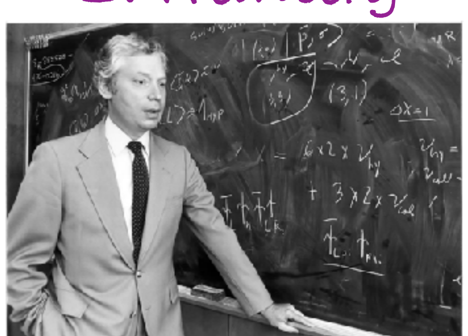
1960-64 : la solution vient de la physique du solide (analogie avec la supraconductivité)

Brisure spontanée de la symétrie
- la théorie respecte rigoureusement la symétrie
- c'est l'état du vide qui brise la symétrie

1967 : théorie électrofaible

On introduit un champ (le champ de Higgs)
- à 4 composantes (une par élément de symétrie)
- de valeur non nulle dans le vide (246 GeV)

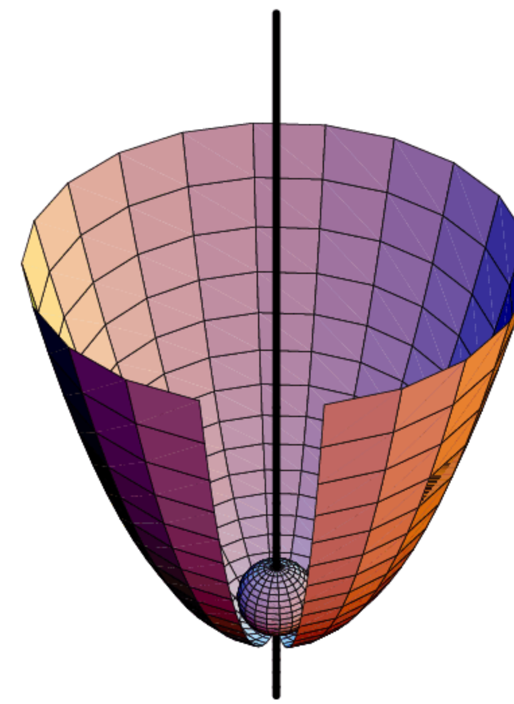
S. Weinberg



Les bosons W^+ et W^- acquièrent une masse, ainsi que le boson Z

Le photon reste sans masse

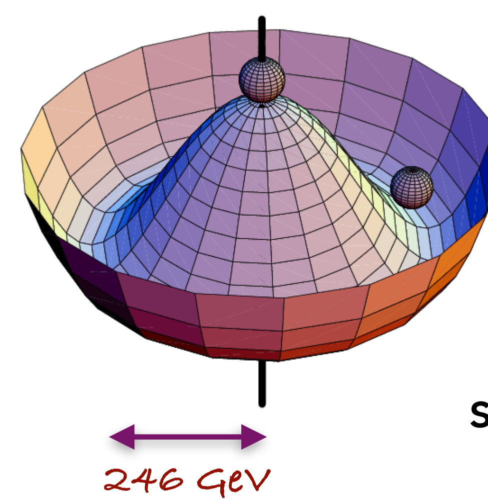
Le champ de Higgs



phase symétrique

$T > 10^{15}$ K

transition de phase cosmique
$t = 10^{-12}$ s



$T < 10^{15}$ K

phase à symétrie spontanément brisée

Et le boson de Higgs ?

- 3 composantes du champ de Higgs sont absorbées pour donner leur masse aux bosons W^+, W^- et Z
- la 4ème composante est un champ scalaire dont le quantum est un boson de spin 0 : le boson de Higgs

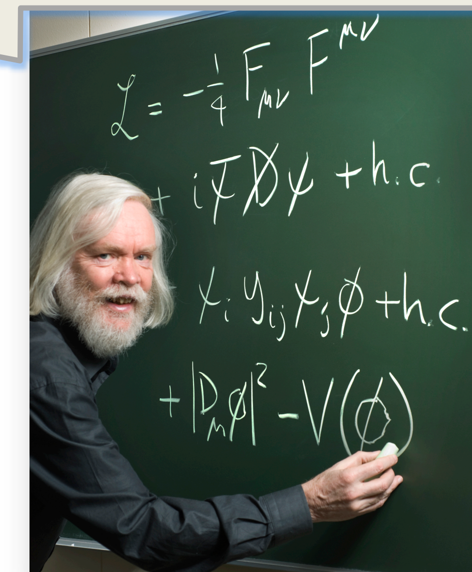
L'existence du boson de Higgs est une prédiction centrale de la théorie électrofaible

La théorie électrofaible spécifie toutes les propriétés du boson de Higgs…

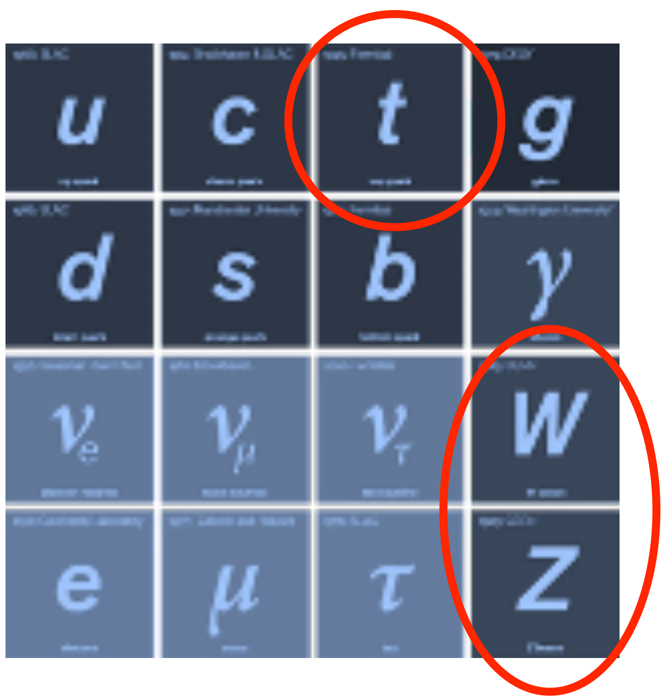
… sauf sa masse !

"nous nous excusons auprès des expérimentateurs de n'avoir aucune idée de la masse du boson de Higgs [...] Nous n'encourageons pas de grands projets expérimentaux pour la recherche du boson de Higgs"

J. Ellis et al (1976)



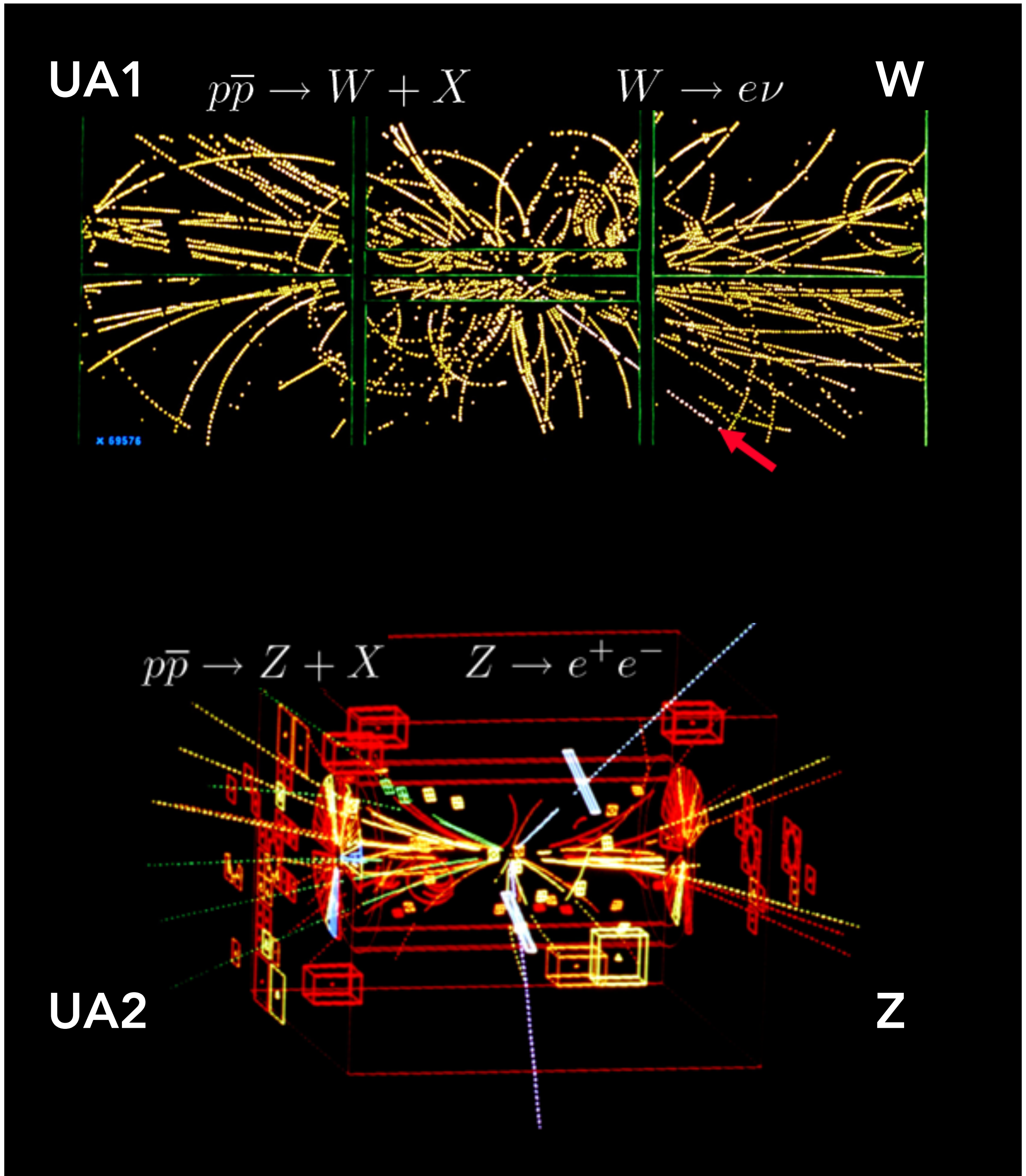
Le couplage du boson de Higgs aux autres particules élémentaires est proportionnel à leurs masses



Le boson de Higgs se couple principalement aux particules les plus massives :
- le quark top
- les bosons W et Z

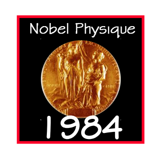
Sur la base de principes premiers : l'existence du boson de Higgs est inéluctable et sa masse doit être inférieure à 600 GeV

Découverte des bosons W et Z



CERN, 1982, collisionneur Sp$\bar{p}$S

C. Rubbia (UA1) H. Schopper P. Darriulat (UA2)



S. van der Meer E. Gabathuler

Un prix Nobel 100% CERN !

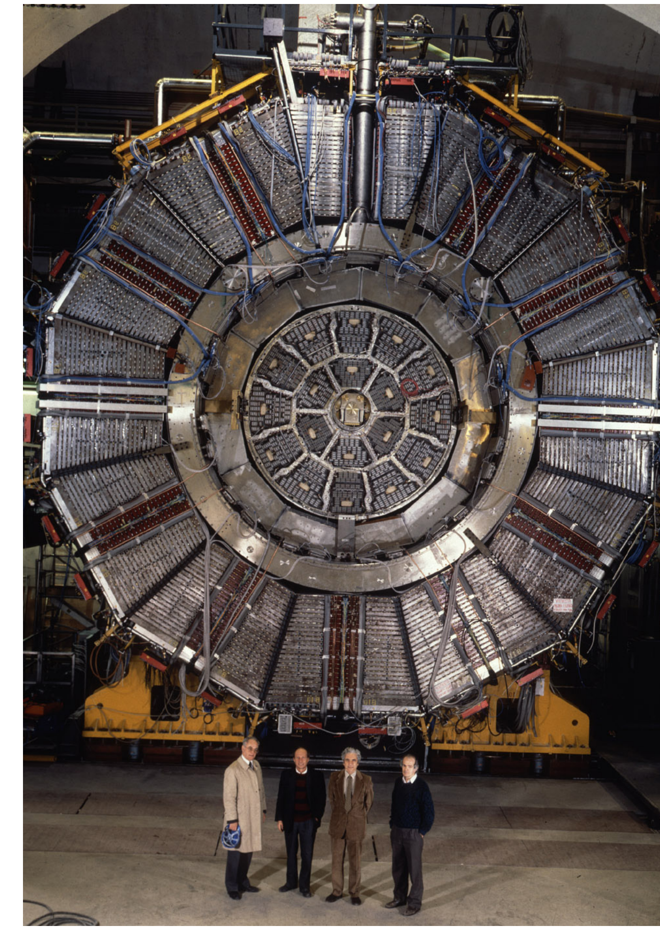
et un bel exemple de coopétition…

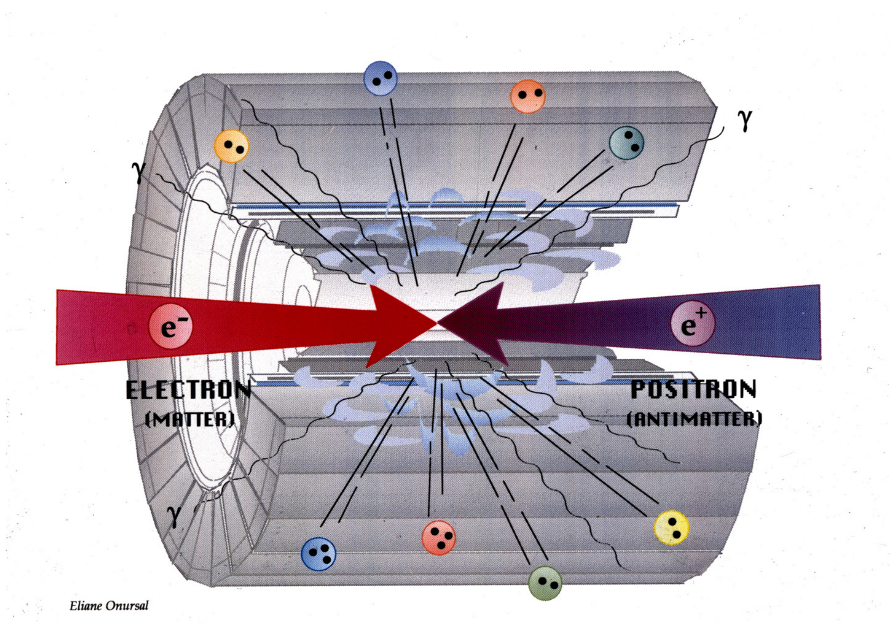
Le LEP

Un tunnel de 27 km de circonférence à 100 m de profondeur, creusé en quelques années dans le pays de Gex pour abriter le “Large electron positron collider”, le LEP !

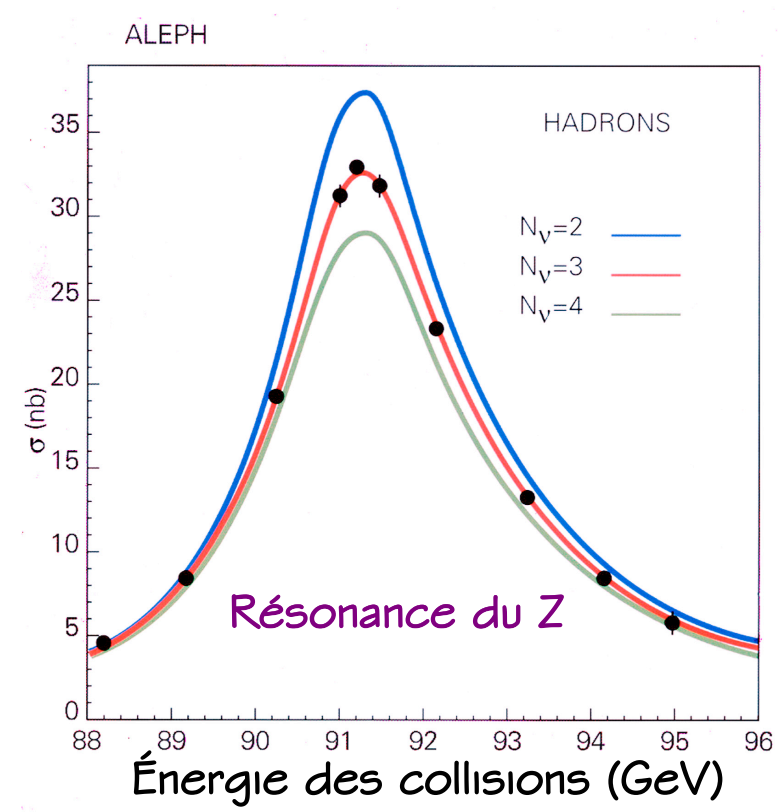
4 grandes expériences : ALEPH, DEPHI, L3 et OPAL

Des collaborations de plusieurs centaines de physiciens !





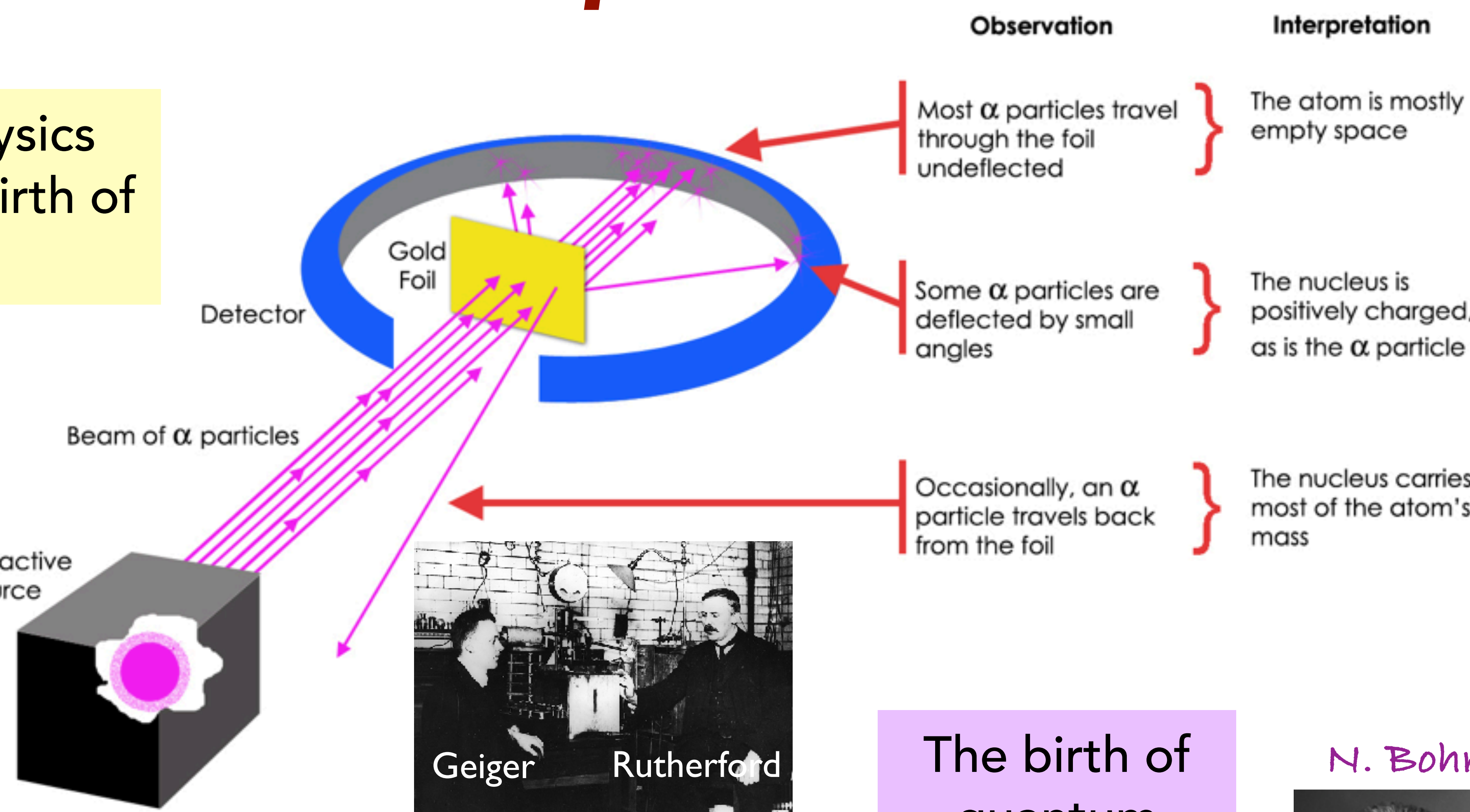
Un des premiers résultats (1990) : la détermination du nombre de familles de neutrinos



The Rutherford experiment

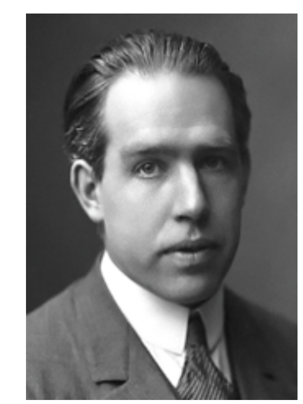
The first particle physics experiment and the birth of nuclear physics

E. Rutherford

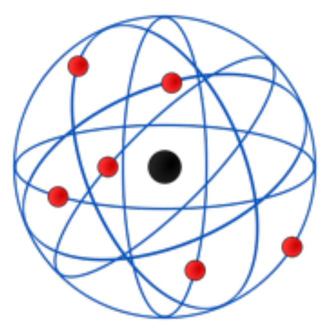


The birth of quantum mechanics

N. Bohr



1911: Rutherford's nuclear model



1913: Bohr's atomic model

The atom is made up of a dense, massive nucleus (essentially point-like) surrounded by an electron cloud

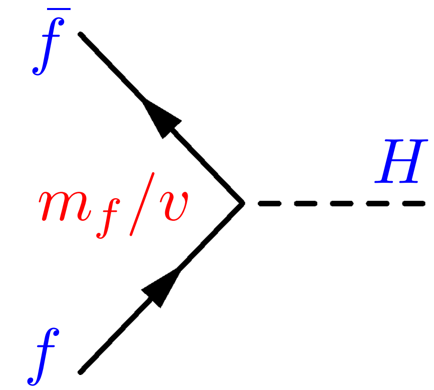
The atom behaves like a planetary system in which electrons occupy quantized energy levels

Fermion and Boson Masses

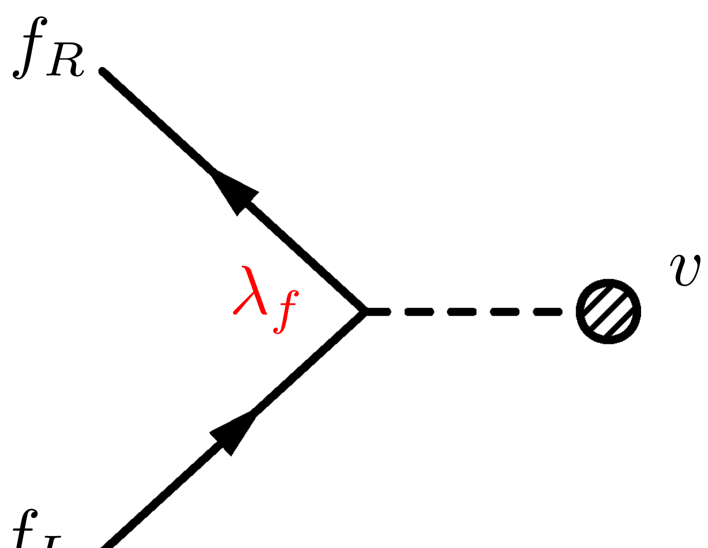
Yukawa interaction terms between fermions and the Higgs field

- Lorentz scalar
- gauge invariant

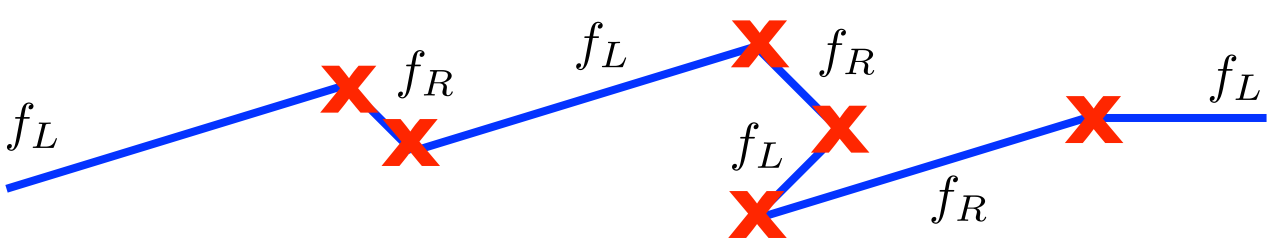
$$\lambda_f (\overline{F_L}\phi) f_R + \text{h.c.} \xrightarrow{\text{SSB}} m_f \bar{f} f + m_f/v \, \bar{f} f h$$



Fermions acquire mass

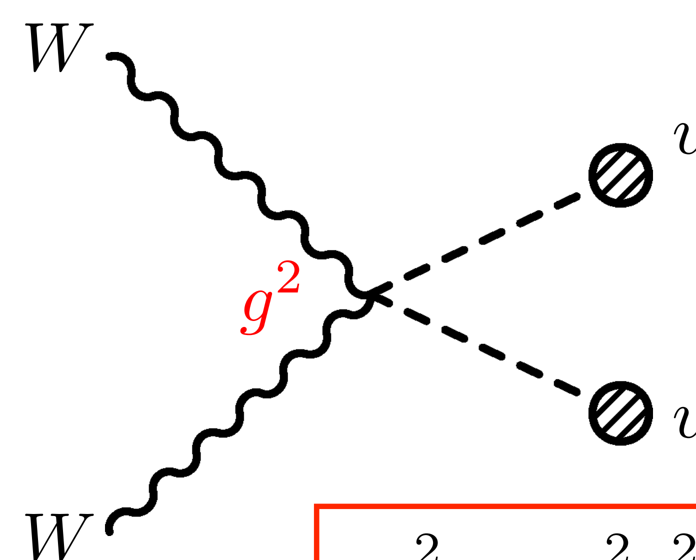


$$m_f = \lambda_f \, v/\sqrt{2}$$



Higgs condensate *connects* left- and right- components

Bosons acquire mass



$$m_W^2 = g^2 v^2/4$$

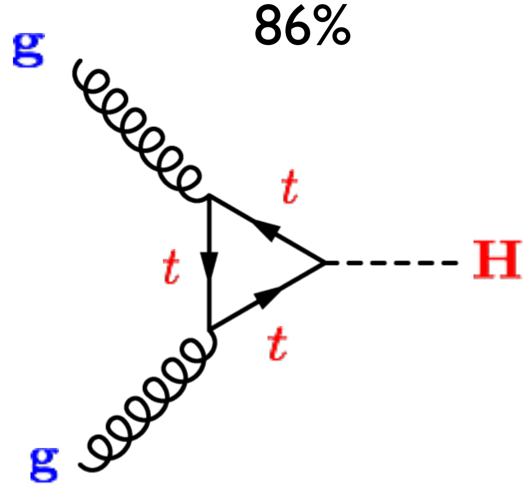
W and Z Bosons acquire a longitudinal polarisation through interaction with the Higgs condensate

Le boson de Higgs au LHC

Cinq modes de production

ggH

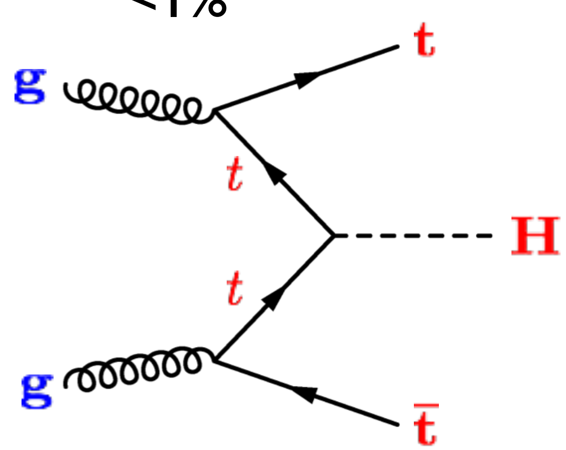
86%



« fusion de gluons »

ttH

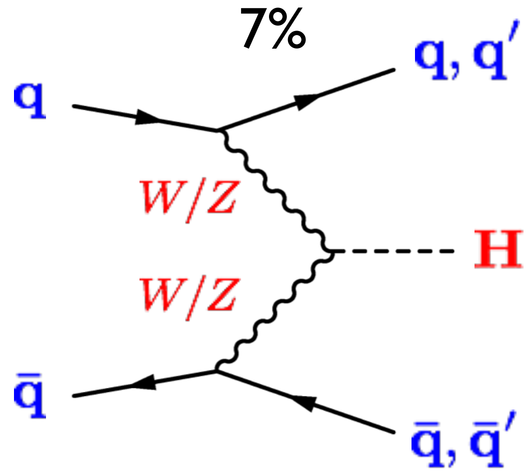
<1%



« en association avec une paire de quarks top »

VBF

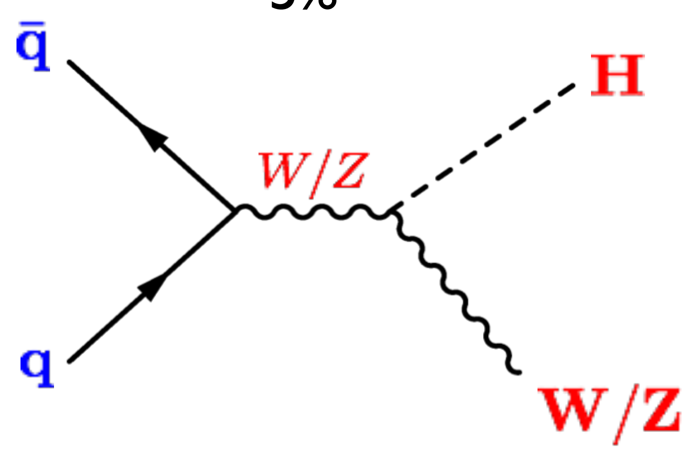
7%



« fusion de bosons vecteurs »

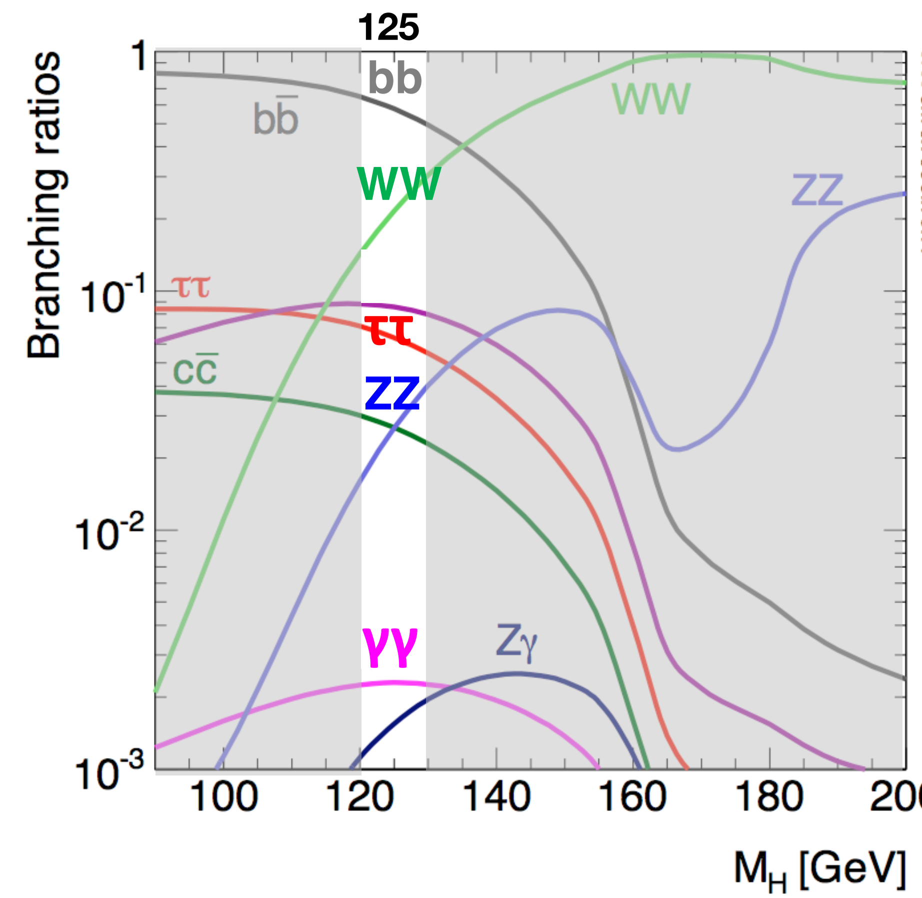
WH, ZH

5%



« en association avec un boson W ou Z »

Cinq modes principaux de désintégration



H → bb	**58%**
H → WW*	**21%**
H → ττ	**6.4%**
H → ZZ*	**2.7%**
H → γγ	**0.2%**

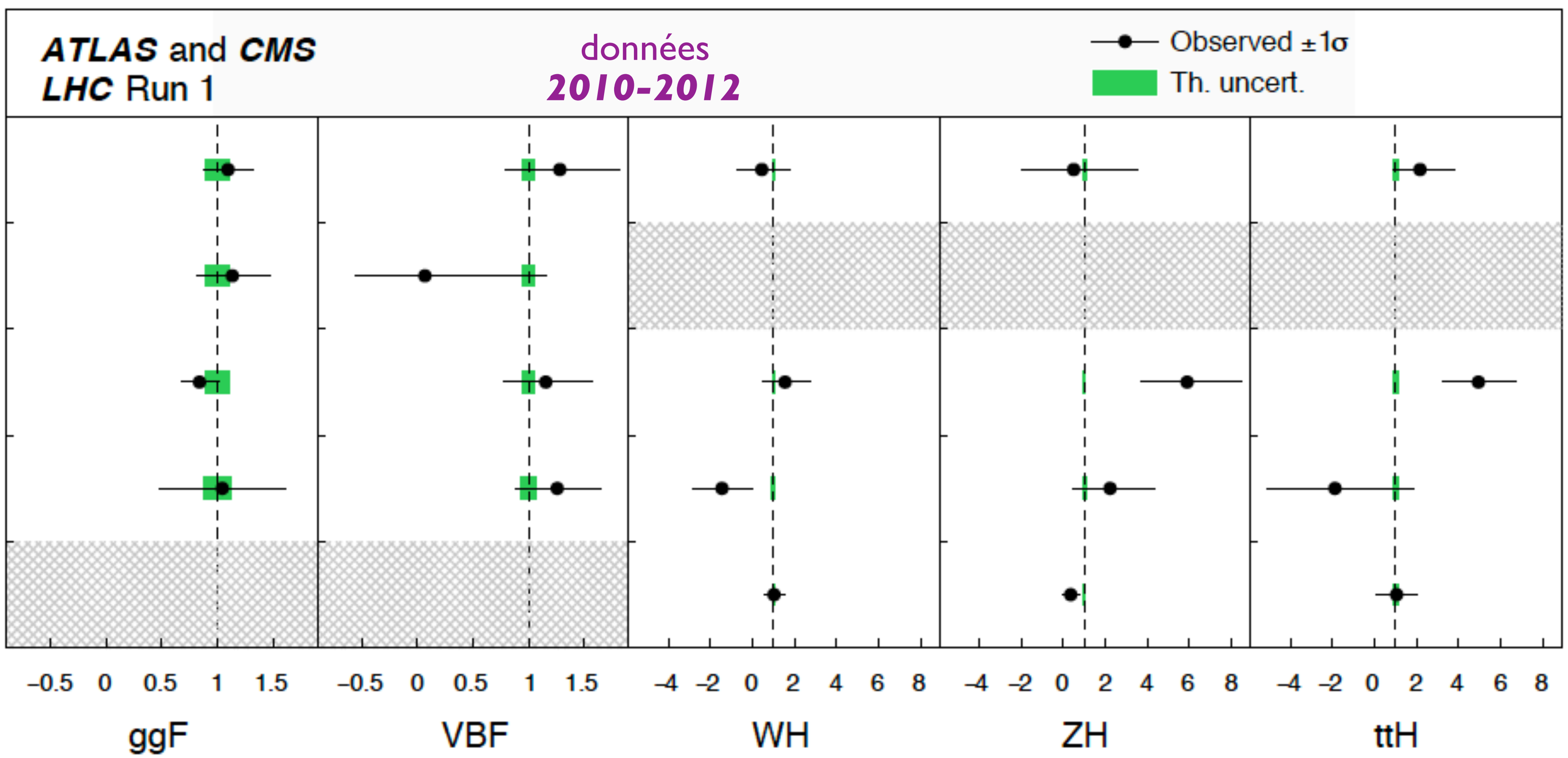
Production et désintégration

Compilation des résultats du Run 1

mesures rapportées aux prédictions théoriques (MS = 1)

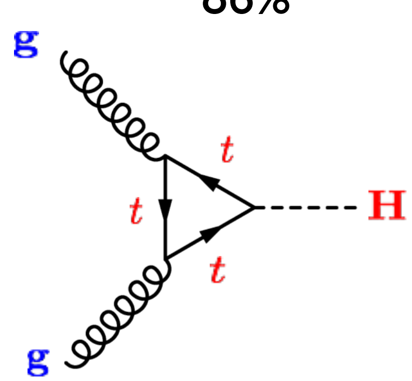
modes de production

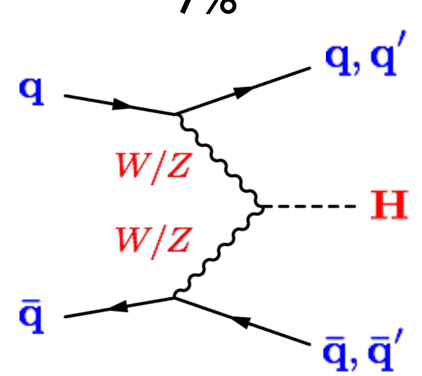
canaux de désintégration

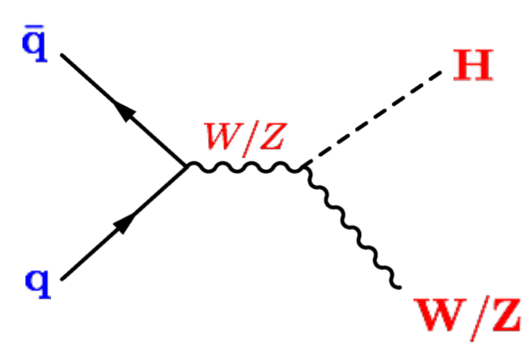


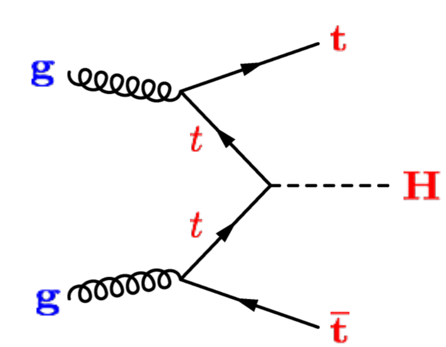
0.2%
2.7%
21%
6.4%
58%

86% 7% 5% <1%









incertitudes théoriques

ggH	15 %
VBF	5 %
VH	5 %
ttH	15 %

ggH : observation (>5σ) en γγ, ZZ et WW

VBF : forte indications (>3σ) en γγ, WW et ττ

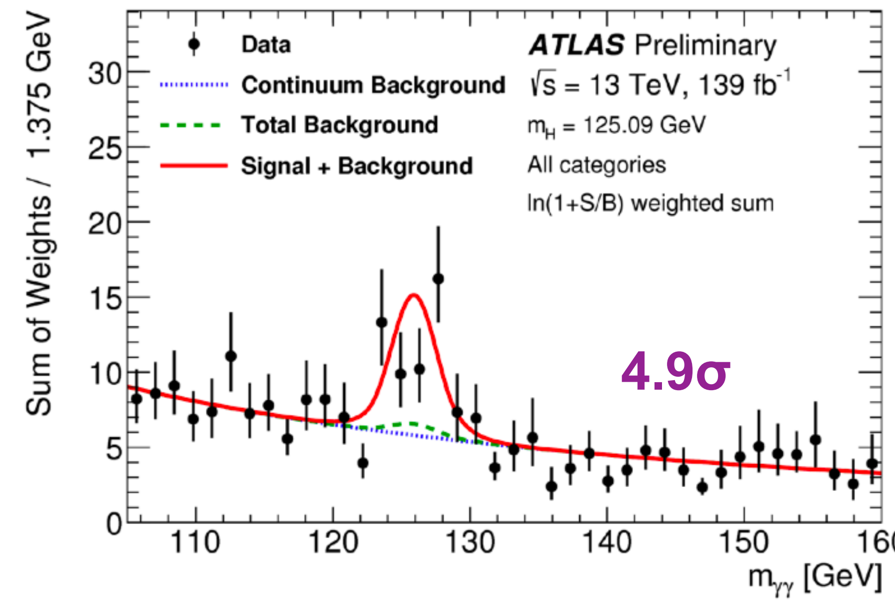
VH : premières indications (3σ) en bb

ttH : des indices non concluants

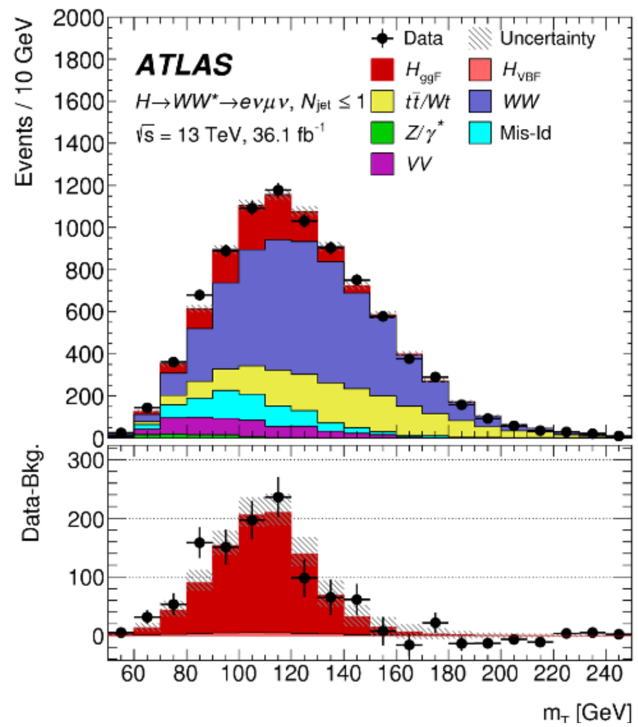
Le boson de Higgs à 13 TeV

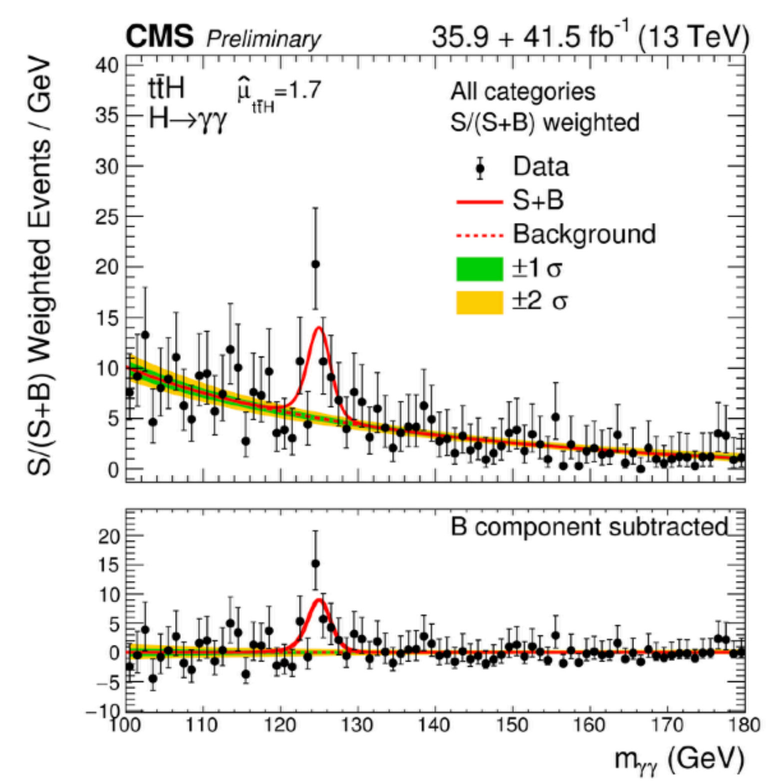
Pas encore de combinaison mais des résultats préliminaires

ttH(→γγ)

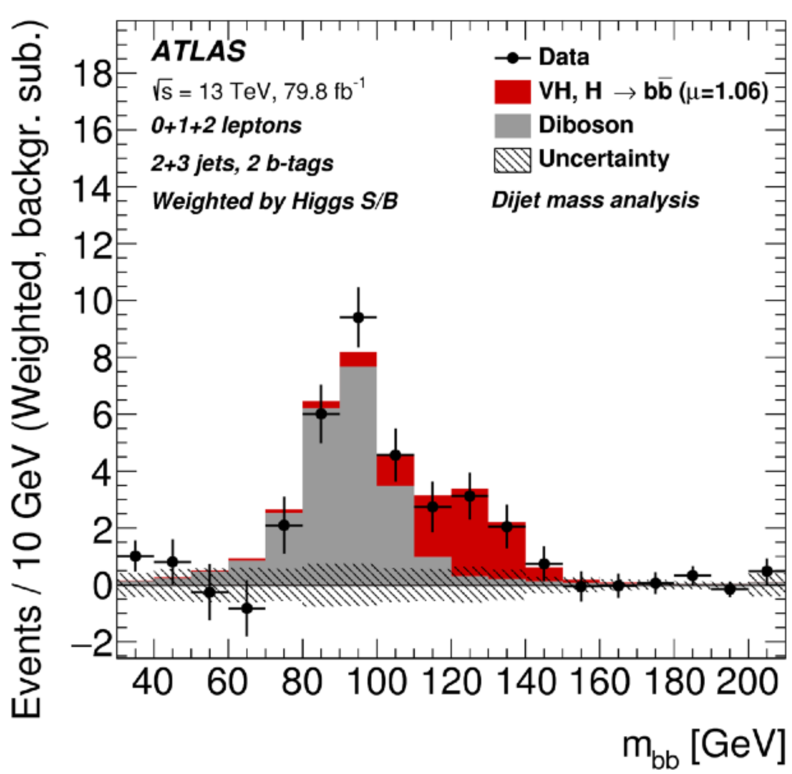


H → WW*



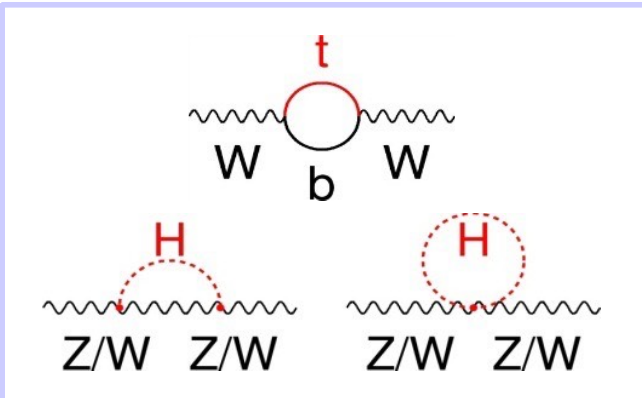


H → bb



observations en accord avec les prédictions

Cohérence du MS



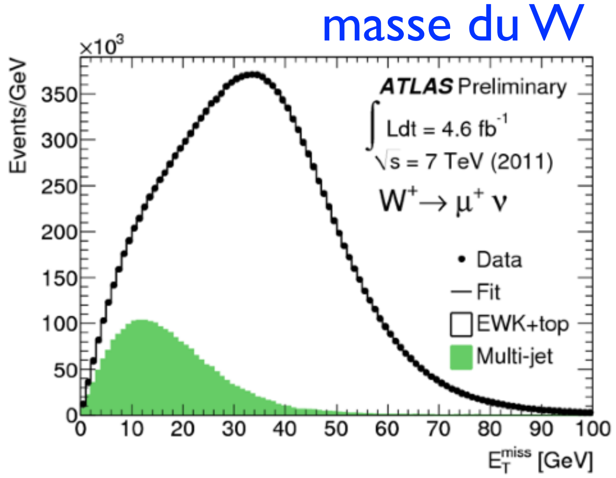
Par le biais de corrections quantiques, la théorie permet d'établir des relations entre paramètres mesurables

$$M_W{}^2 = (1 + \Delta\rho) M_Z{}^2 (1 - \sin^2\theta_{\text{eff}})$$

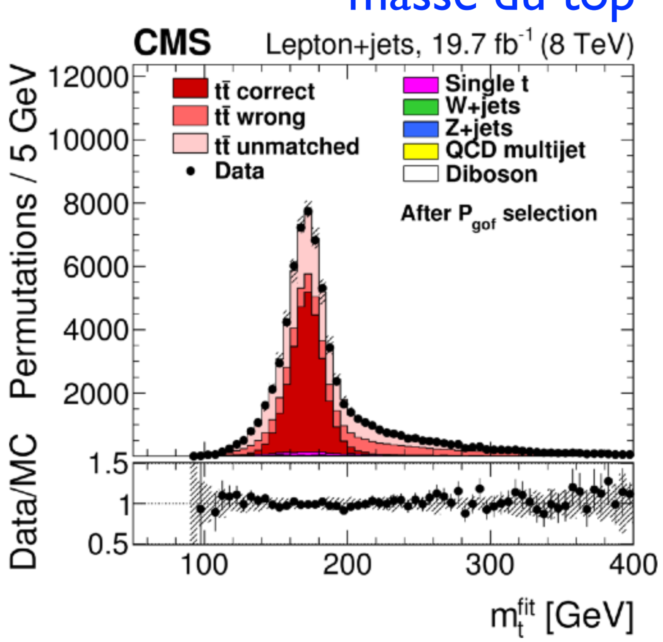
avec $\Delta\rho = f(M_{\text{top}}{}^2, \ln M_H)$

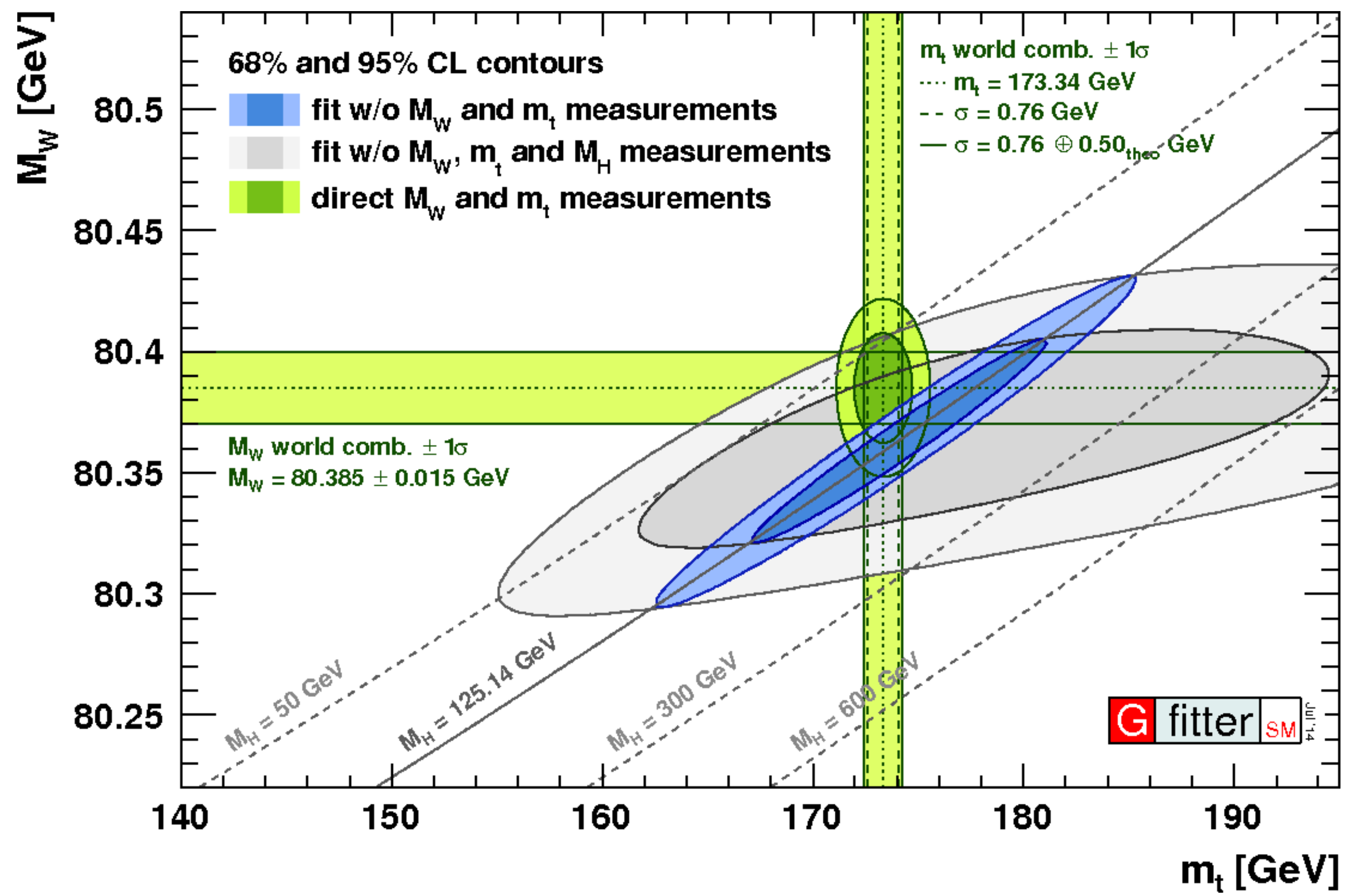
(de l'ordre de 1%)

masse du W

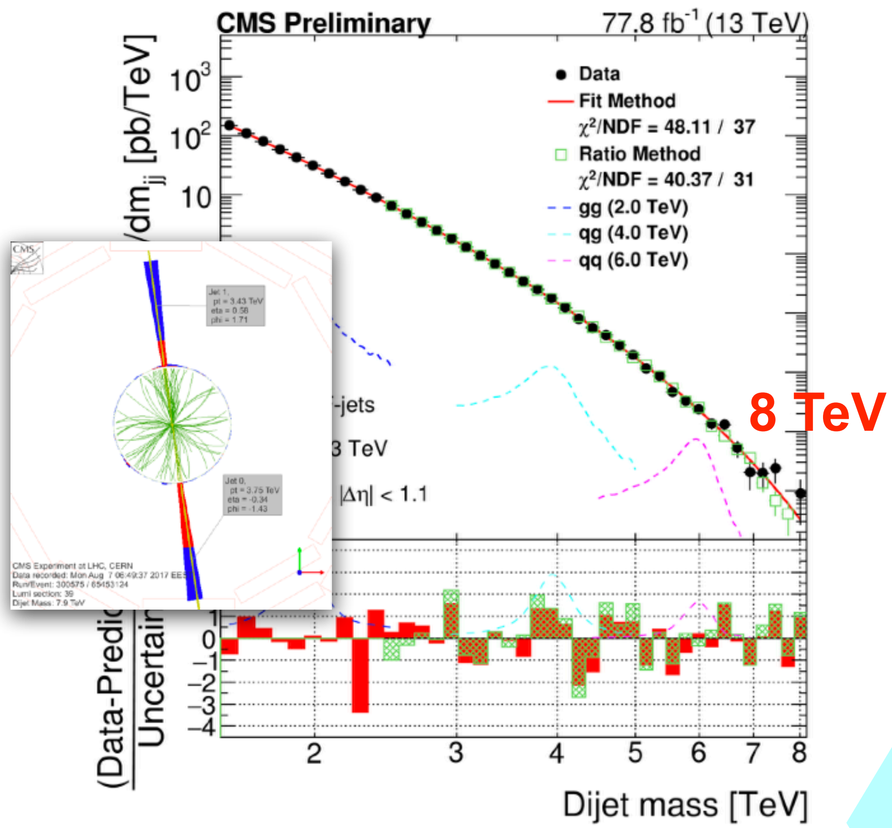


masse du top

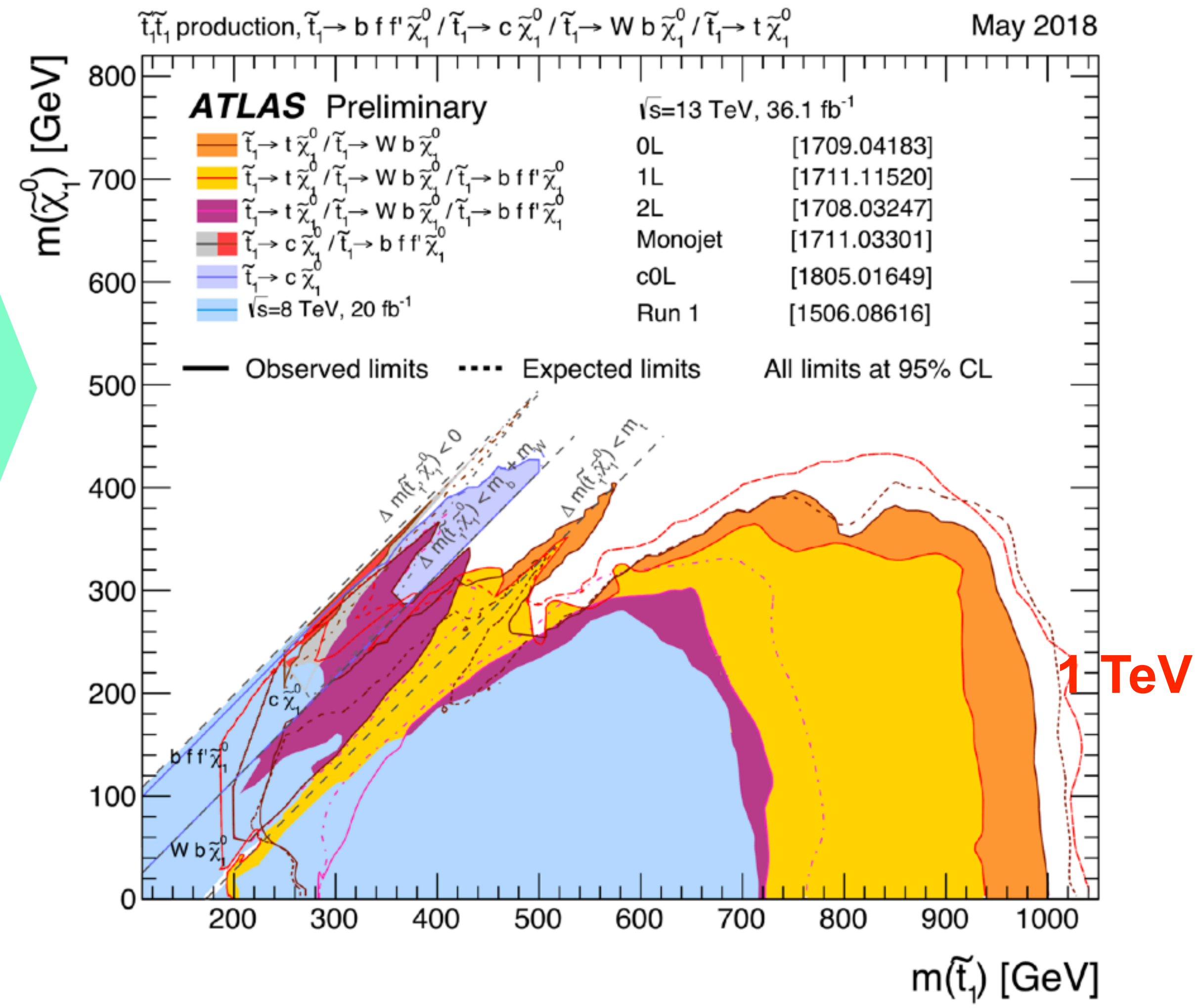




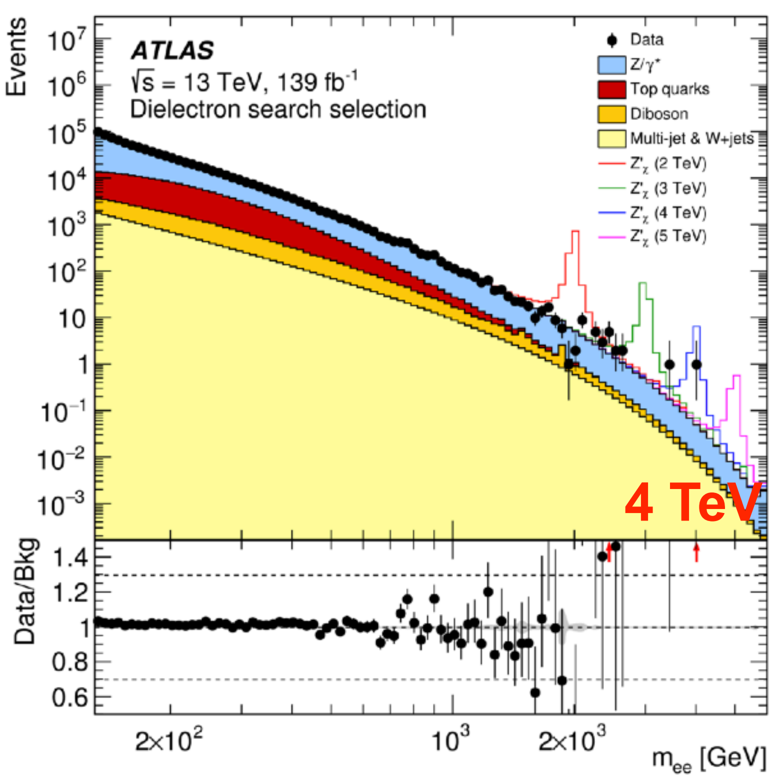
Recherche de nouvelle physique



recherche de supersymétrie (ici : *stops*)



recherche de résonances



Résultat le plus marquant du LHC (après le Higgs)
☛ les recherches de nouvelles particules n'ont pas permis de mettre en évidence de la physique au-delà du MS

pas de signe de SUSY à l'échelle du TeV au LHC

Environ 900 publications par expérience (ATLAS/CMS) dont la moitié sont des recherches