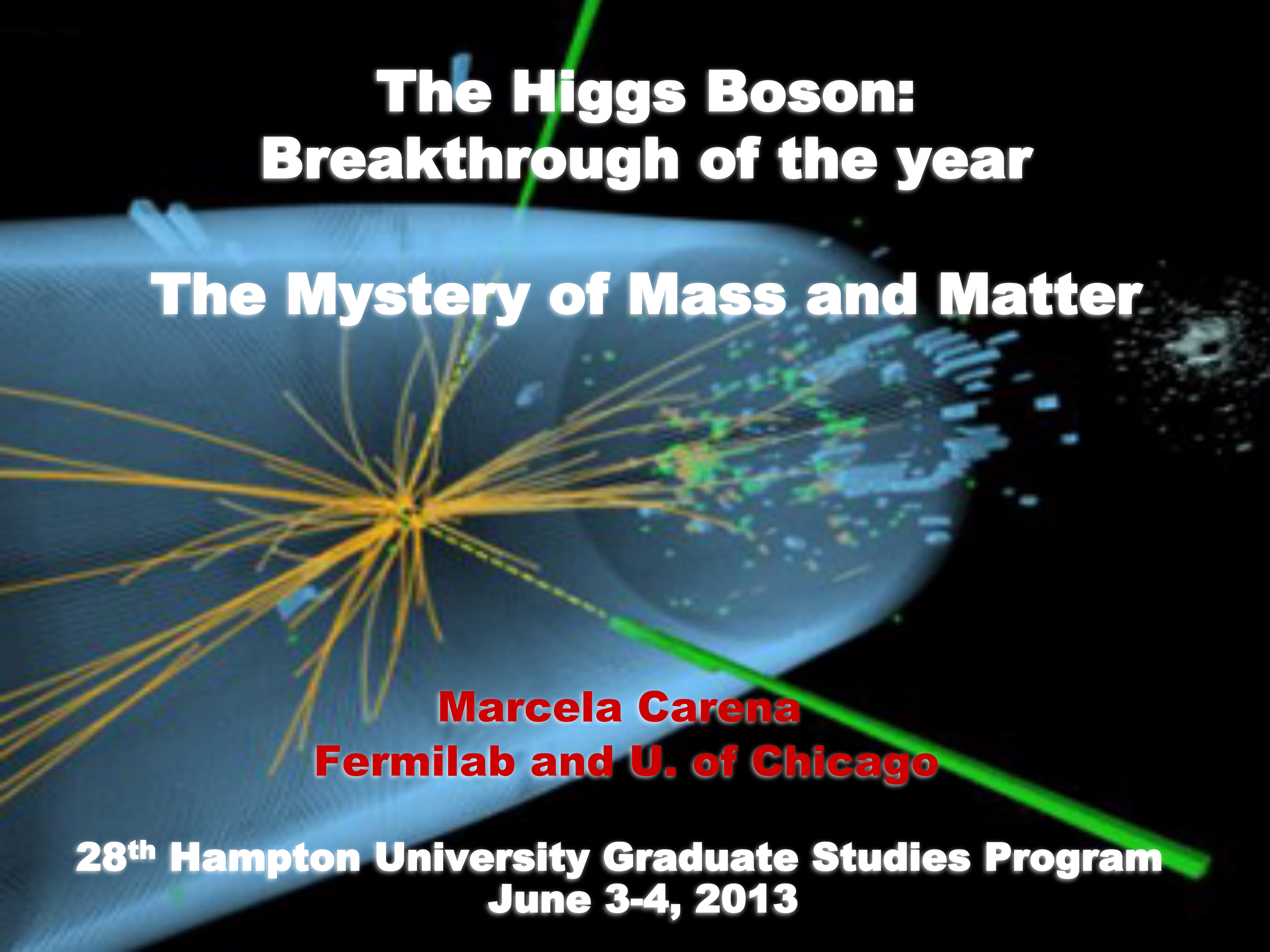


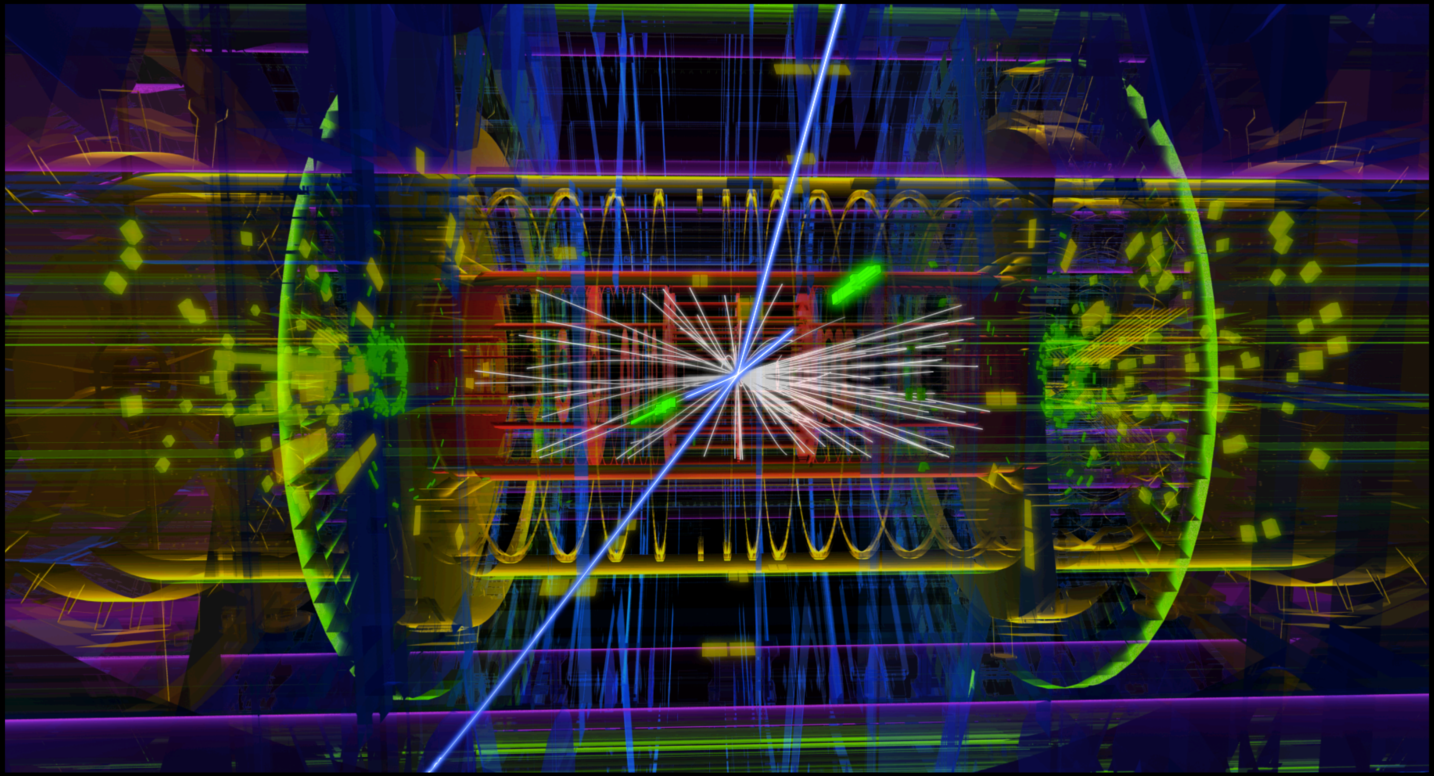
The Higgs Boson: Breakthrough of the year

The Mystery of Mass and Matter

Marcela Carena
Fermilab and U. of Chicago

28th Hampton University Graduate Studies Program
June 3-4, 2013

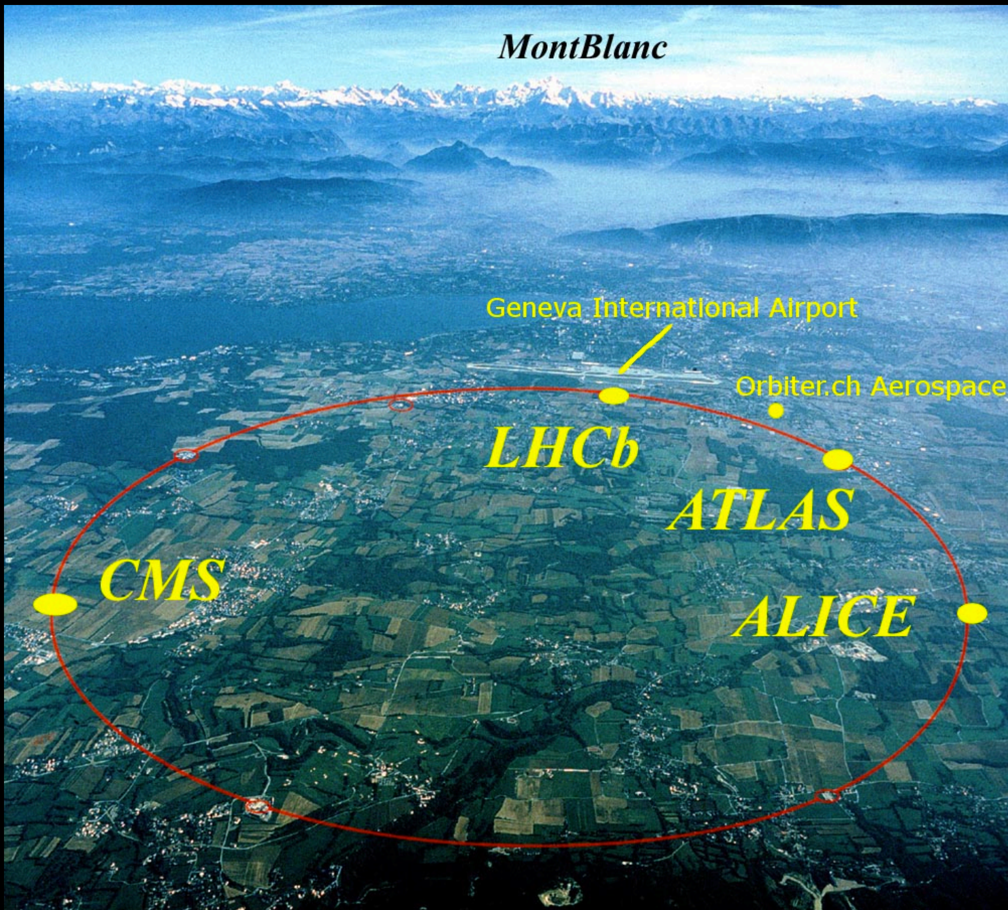
Fireworks on 4th July 2012



- Discovery of a new particle, of a type never seen before
- Confirmation of a new type of interaction among particles

A new era of particle physics and cosmology

The Large Hadron Collider (LHC) @ CERN



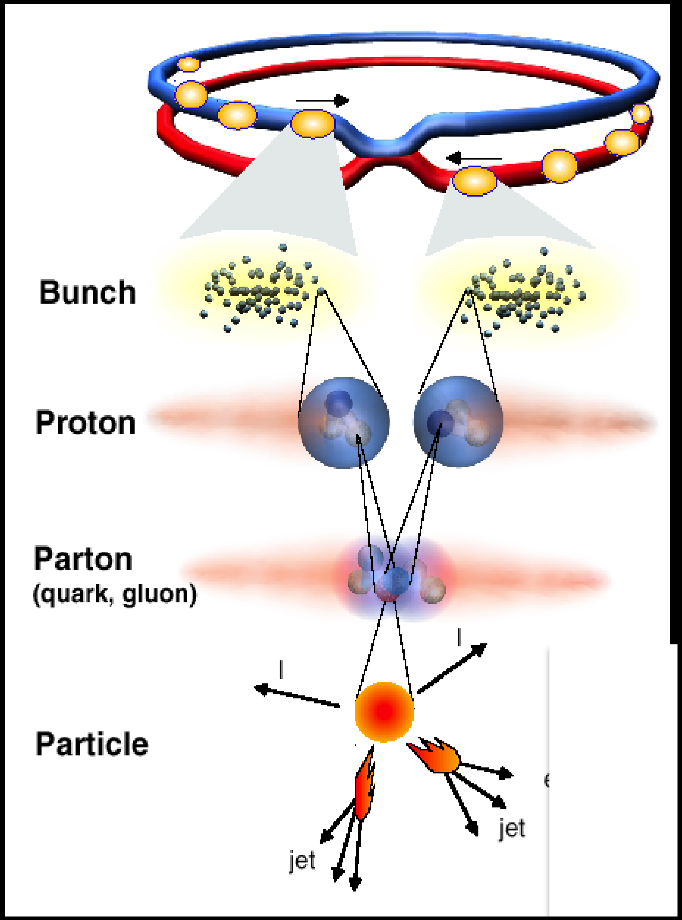
So much energy…
proton–proton collisions
at E_{cm} = 8TeV (14 TeV)

that it is like we transport ourselves to instants after the BIG BANG

A 17 mile long vacuum pipe
300 ft below ground

LHC:
why so huge and why circular ?

- Charged particles are accelerated by electric fields
- A linear accelerator would be prohibitively long
- Instead protons are sent in a circular path and they get several "kicks" with electric fields every time they come around
- Protons are bent in a circular path with magnets
- The higher the energy the harder it is to bend the protons



The size of the ring is set by the strongest magnets we can build

About a Billion proton-proton collisions per second

About 100 particles produced per collision

To look at the new particles we have powerful detectors

- Equivalent of a camera to take “pictures” of the collisions

- They are not ordinary cameras:

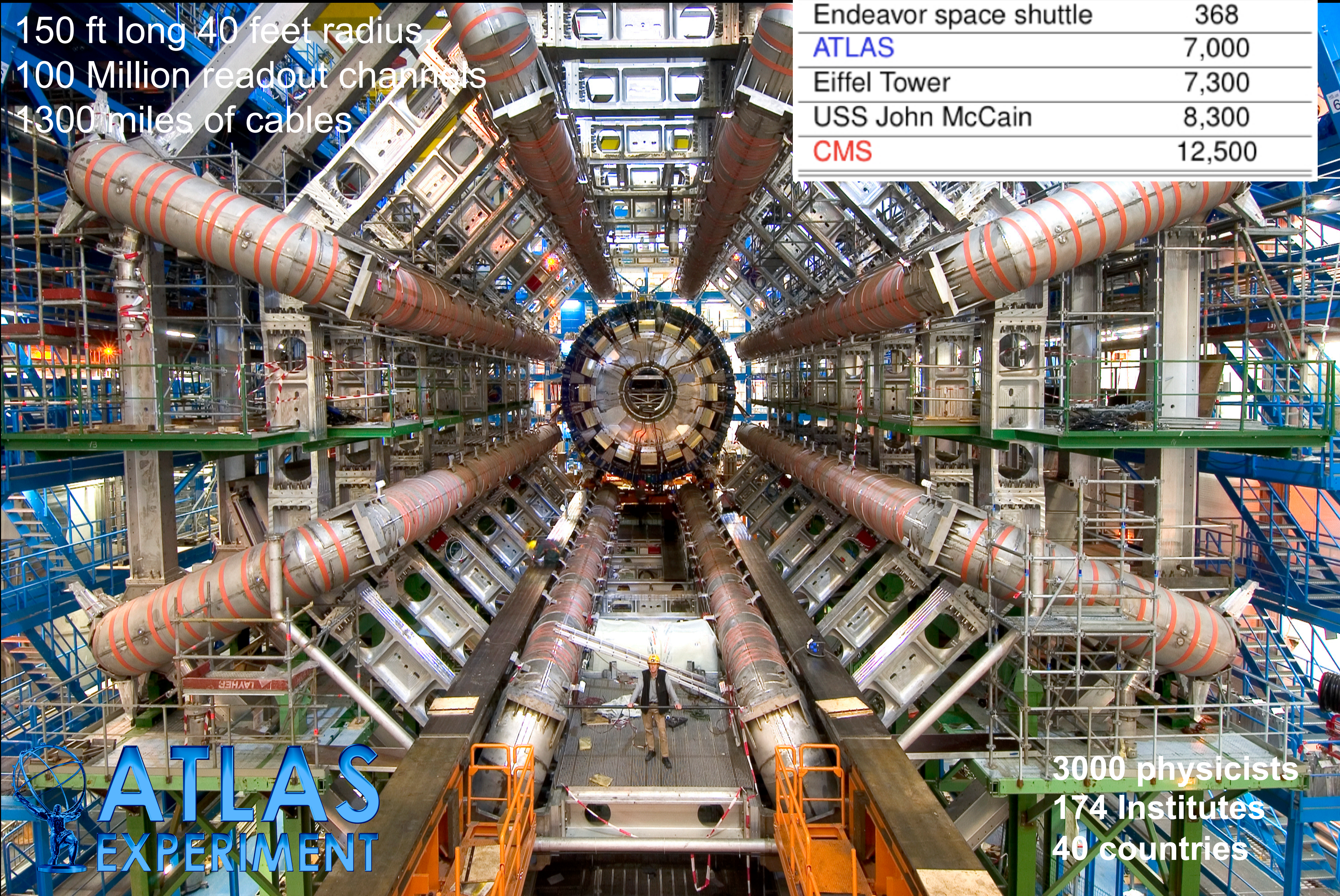
  80 Million pixels
  40 million pictures per second
  Three dimensional picture

- They are huge, complex objects with cutting-edge technology

ATLAS Detector :

150 ft long 40 feet radius.
100 Million readout channels
1300 miles of cables

Object	Weight (tons)
Boeing 747 [fully loaded]	200
Endeavor space shuttle	368
ATLAS	7,000
Eiffel Tower	7,300
USS John McCain	8,300
CMS	12,500

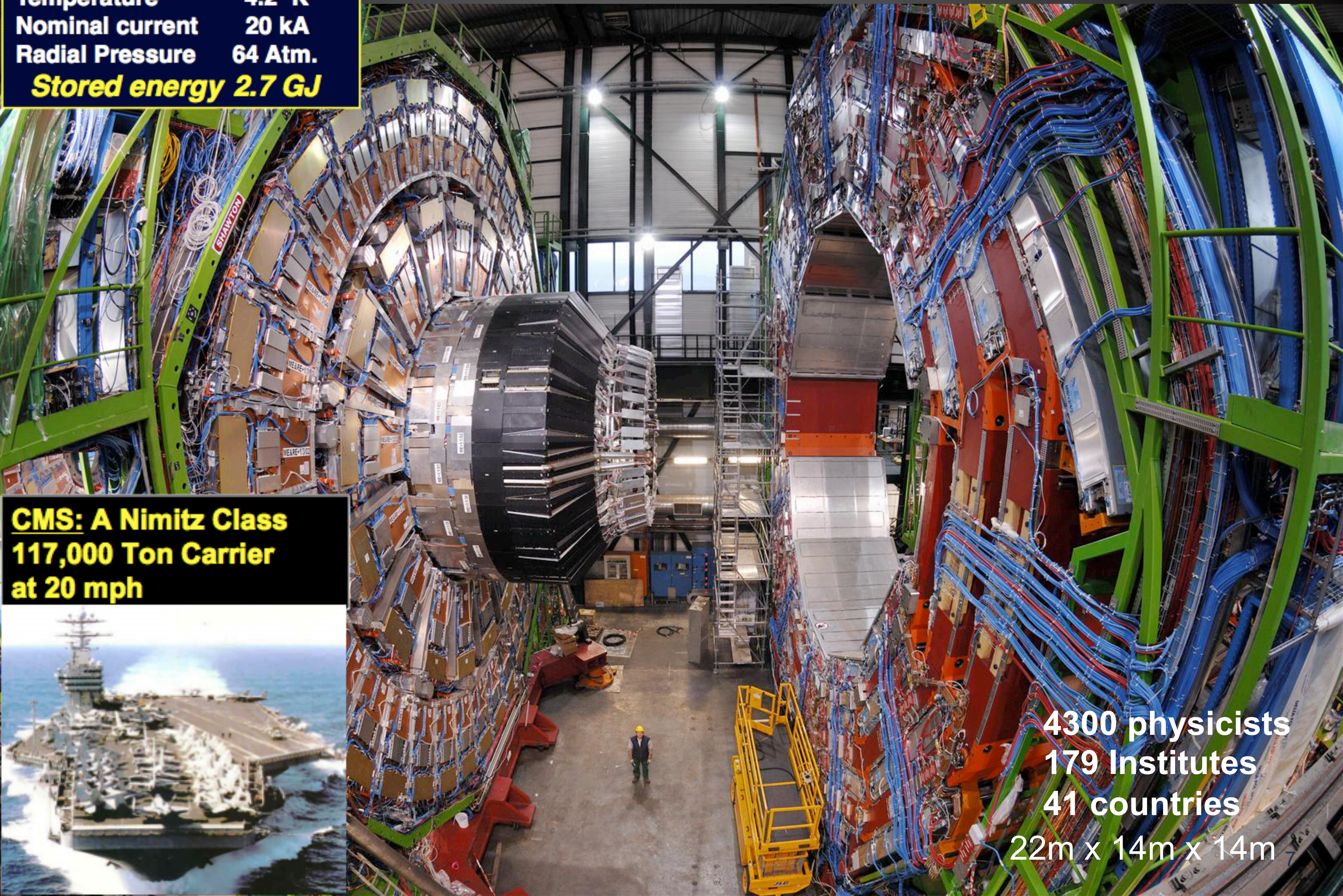


3000 physicists
174 Institutes
40 countries

CMS Detector :

Magnetic length	12.5 m
Free bore diameter	6 m
Central B Field	3.8 Tesla
Temperature	4.2º K
Nominal current	20 kA
Radial Pressure	64 Atm.

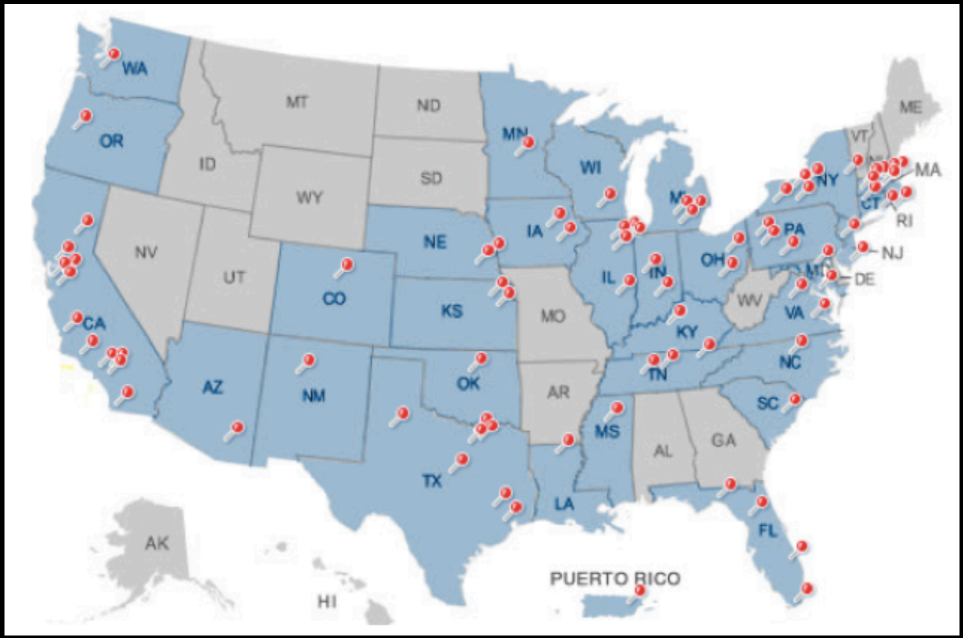
Stored energy 2.7 GJ



CMS: **A Nimitz Class 117,000 Ton Carrier at 20 mph**

U.S. plays a leading role in LHC discovery

- U.S. = 1/3 of CMS, the largest contingent
- U.S. = 1/5 of ATLAS
- CMS/ATLAS leadership: spokesperson, upgrade coordinator, deputy spokespersons, physics coordinators, managers, critical hands-on roles in discovery analyses, hardware, computing
- 1,700 scientists, students, engineers and technicians
- 93 universities,
  7 national labs, 32 states



July 4, 2012

“I think we have it!”

-Rolf Heuer,
CERN director general

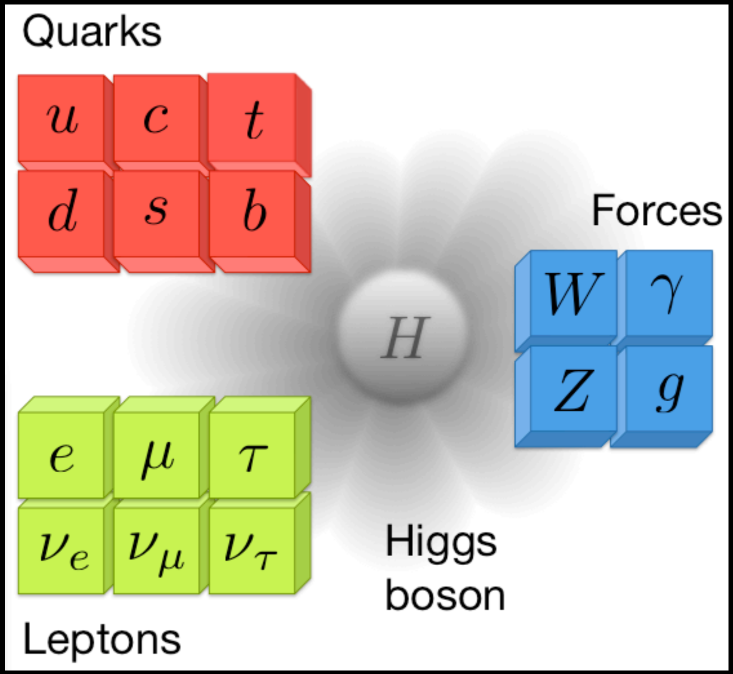
Reactions from CERN

“I never expected this to happen in my lifetime” - Peter Higgs

The first time that the entire NYT Science section is devoted to a single story

Why is the Higgs so important ?

Sub-atomic particles of the Standard Model of Particle Physics



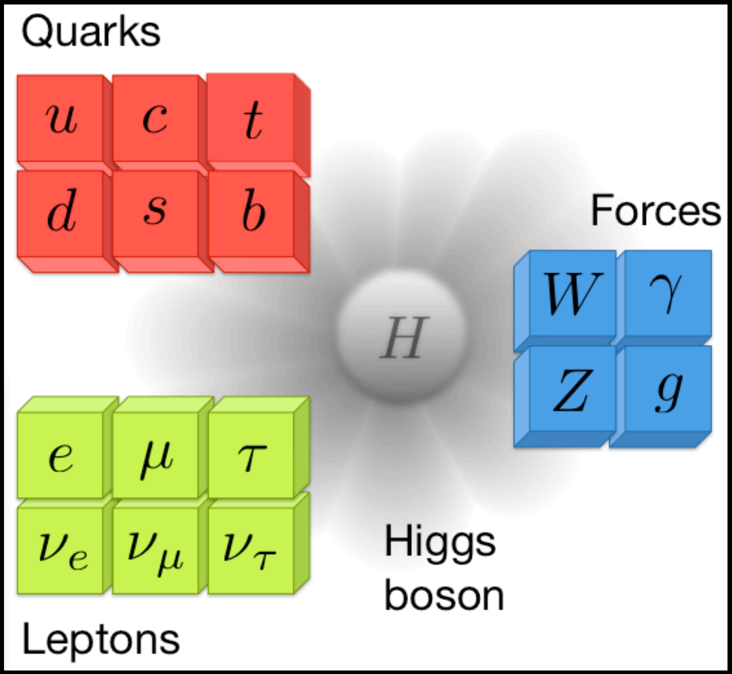
They have all been produced in the laboratory

They have very different masses

What causes fundamental particles to have mass?

The Standard Model

A quantum theory that describes how all known fundamental particles interact via the strong, weak and electromagnetic forces



based on a gauge field theory with a symmetry group

$$G = SU(3)_c \times SU(2)_L \times U(1)_Y$$

Force Carriers:

12 fundamental gauge fields:
8 gluons, 3 Wμ 's and Bμ

and 3 gauge couplings: g3, g2, g1

Matter fields :

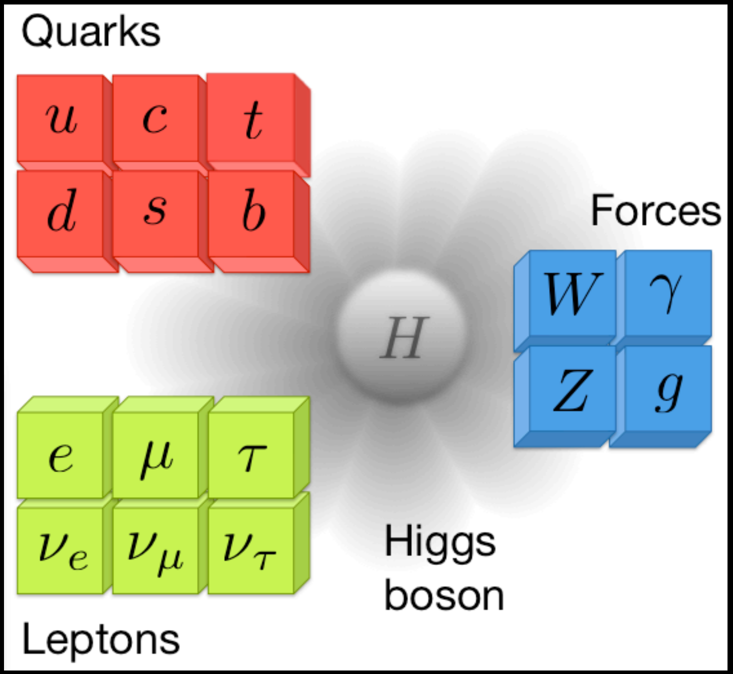
3 families of quarks and leptons with the same quantum numbers under the gauge groups

Quarks come in three colors ($SU(3)_C$)

The Standard Model

SM particle masses and interactions have been tested at Collider experiments

→successful description of nature up to energies ~ a few hundred GeVs



ELECTROWEAK gauge group is product of $SU(2)_L \times U(1)_Y$

Symmetry spontaneously broken to $U(1)_{em}$

3 $W\mu$'s + $B\mu$ → W^{+-}, Z, massless γ

Strong SU(3)c is unbroken

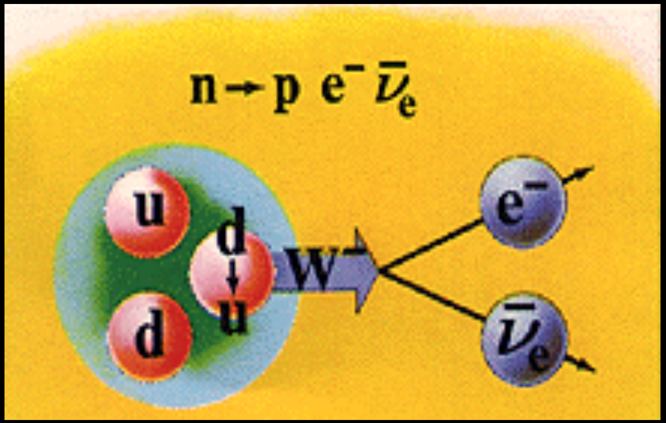
→ massless gluons

At large distances: confinement (no free quarks in nature)

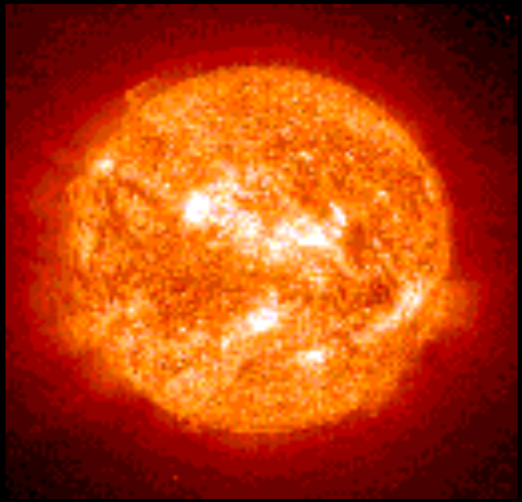
Weak Force

- **Short ranged force**
  (based on SU(2) group)
  exists only inside the protons and neutrons,
  requires massive force carriers (W & Z)

$$F_W \approx e^{-M_W d}/d$$



Observation of Beta decay
demands a novel interaction



Explains nuclear fusion in the Sun!
and ultimately, Sunlight

Very different from infinite ranged QED,
(based on U(1) group), , **with massless photon**

$$F = \frac{k\, e_1 e_2}{d^2}$$

Weak Interactions (cont'd)

- **They have a chiral structure:**

  in the massless fermion limit only left handed quarks and leptons are coupled to the weak interaction messengers

- **They come in two types**:

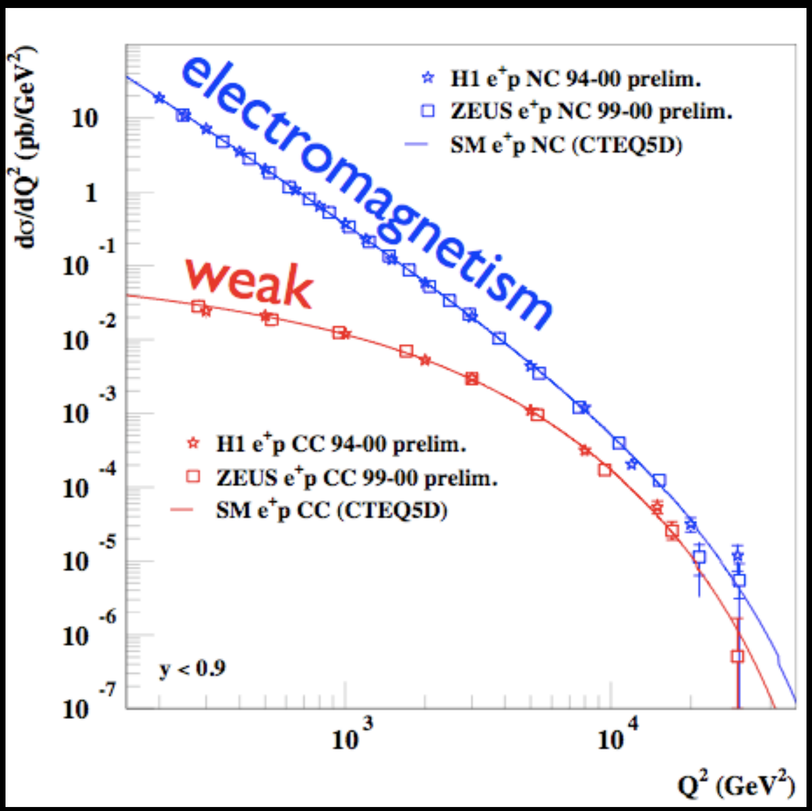
  charged and neutral current-current interactions

  * Charged current interactions mediated by W+- bosons and can change flavor: charged leptons into neutrinos; up-type quarks into down-type quarks

  * Neutral currents do not allow for flavor changing processes at tree level

Hard to think about a unified theory of EW interactions

The SM electroweak theory



HERA ep collider

The electromagnetic and weak forces are unified
=> electroweak theory

EW Symmetry Breaking occurs at a scale of O(100 GeV)

what breaks the symmetry?

and gives mass to W, Z and fermions?

Matter Fields:

3 families of quarks and leptons have very different masses !

m_3/m_2 and $m_2/m_1 \cong$ a few tens or hundreds

$m_e \approx 0.5\ \ 10^{-3}\, GeV$ $\quad m_\mu/m_e \approx 200$ $\quad m_\tau/m_\mu \approx 20$

Largest Hierarchies: $m_t \approx 175\ \text{GeV}$ $\quad m_t/m_e > 10^5$

neutrino masses as small as $10^{-10}\,\text{GeV}$

Crucial Problem:

Due to the chiral nature of the model, fermion mass term

$L = m\ \overline{\psi_L}\psi_R + h.c.$ is not invariant under gauge group

Also, how to give mass to $SU(2)_L$ gauge bosons?

$m_W = 80.449 \pm 0.034\, GeV$ $\quad m_z = 91.1875 \pm 0.0017\, GeV$

The symmetries of the model do not allow to generate mass at all!

A Brief Review on Gauge Theories (GT): definition, structure and rules of construction

To build a GT, start from a global symmetry and promote it to a gauge one
➔ demand invariance of the Lagrangian under local transformations

$L[\phi,\partial_\mu\phi]$ ==> Invariant under D dimensional continuous group Γ

of transformations: $\boxed{\phi' = U(\theta^A)\phi \quad \text{with } A = 1,2,\ldots,D}$

$$\theta^A \text{ infinitesimal} \rightarrow U(\theta^A) = 1 + ig\sum_{A}\theta^A T^A$$

T^A are matrices indep. of space- time coordinates and normalized such that

$$tr(T^A T^B) = \frac{1}{2}\delta^{AB} \qquad \text{and satify } \left[T^A, T^B\right] = iC_{ABC}T^C$$

For each quantity V^A we define $V = \sum_A V^A T^A$

If now $\theta^A \to \theta^A(x_\mu) \quad \Rightarrow \quad L[\phi, \partial_\mu \phi]$ is no longer gauge invariant under $U\left[\theta^A\left(x_\mu\right)\right]$ due to derivative terms

Gauge invariance is recovered if ordinary derivative replaced by covariant derivative

$$\mathcal{D}_\mu = \partial_\mu + igV_\mu$$

V_μ^A are a set of D gauge fields in correspondence with the group generators and

$$V'_\mu = UV_\mu U^{-1} - (1/ig)\,(\partial_\mu U)\,U^{-1}$$

Then, the covariant derivative has the same transformation properties as Φ

$$(\mathcal{D}_\mu \phi)' = U(\mathcal{D}_\mu \phi)$$

$\Rightarrow \quad L[\phi, D_\mu \phi]$ is invariant under gauge transformations.

In order to construct a gauge invariant kinetic term
for the gauge fields V^A
we construct **the field strength tensor $F_{\mu\nu}$**

$$F^A_{\mu\nu} = \partial_\mu V^A_\mu - \partial_\nu V^A_\mu - gC_{ABC} V^B_\mu V^C_\nu$$

transforms as a tensor in the adjoint representation

$$\boxed{F'_{\mu\nu} = U F_{\mu\nu} U^{-1}}$$

$$\Rightarrow \text{ invariant quantity: tr } (\mathrm{UF^2U^{-1}}) = \text{tr } (\mathrm{UU^{-1}F^2}) = \text{tr } (F_{\mu\nu} F^{\mu\nu}) = \frac{1}{2} F^A_{\mu\nu} F^{A\mu\nu}$$

The complete Yang Mills Lagrangian invariant under gauge transformations:

$$L_{YM} = -\frac{1}{4} F^A_{\mu\nu} F^{A\mu\nu} + L\left(\phi, D_\mu \phi\right)$$

An Abelian theory like QED ==> $U[\theta(x)] = \exp[ieQ\theta(x)]$

the photon field transforms as

$$V'_\mu = V_\mu - \partial_\mu \theta(x) \quad \text{and} \quad F_{\mu\nu} \quad \text{is linear in } V_\mu$$

In the absence of matter fields ==> It is a free theory (no self interactions)

Non-Abelian theories like QCD,

field strength tensor $\mathbf{F}_{\mu\nu}$ has both linear and quadratic terms in the gauge fields

Kinetic term $\mathbf{F}_{\mu\nu}\ \mathbf{F}^{\mu\nu}$ induces self interactions (3 &4 gluon vertices)

Matter fields: fermion and scalars transform like:

$\Psi' = U\Psi$ and $\varphi' = U\varphi$,

Hence they may be massive (only if U(1))

$$L_{mass} \propto m^2 \varphi^* \varphi \qquad L_{mass} \propto m\, \overline{\psi}\psi = m(\overline{\psi}_R \psi_L + \overline{\psi}_L \psi_R)$$

$\overline{\psi} = \psi^+ \gamma^0 \quad \psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$ and Dirac matrices $\gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix} \quad \gamma^0 = \begin{pmatrix} 0 & \mathrm{I} \\ \mathrm{I} & 0 \end{pmatrix}$ $\gamma_5^2 = \mathrm{I}$

Mass Terms for the SM gauge bosons and matter fields

- Gluons and photons are massless and preserve gauge invariance
- Z and W bosons are not, but a term $m^2 V_\mu V^\mu$ is forbidden for gauge invariance
- Mass term for fermionic matter fields only possible for vector – like fermions, not for the SM *chiral* ones, *when Left and Right handed fields transform differently*

SM gauge bosons and fermions should be massless,

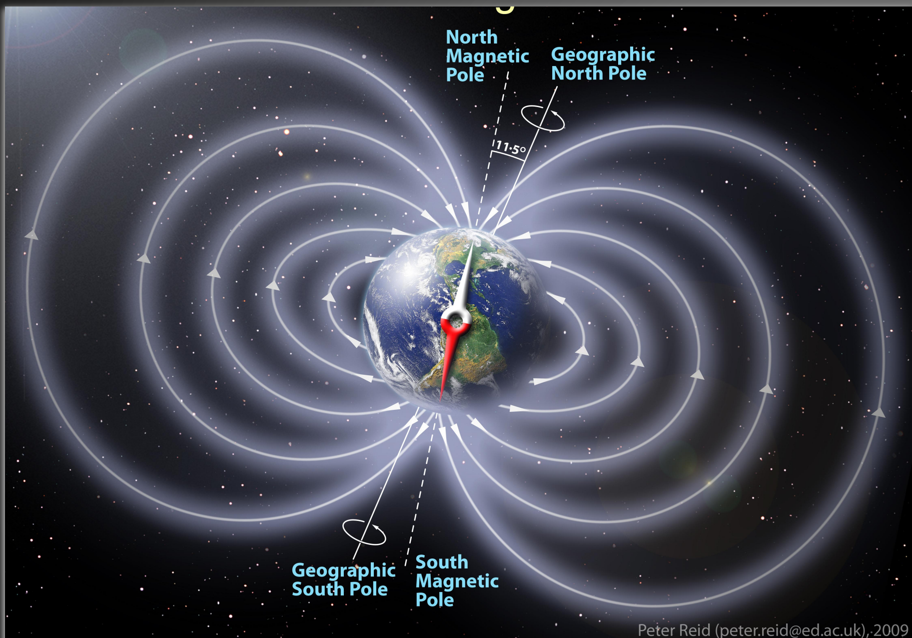
THIS contradicts experience!!

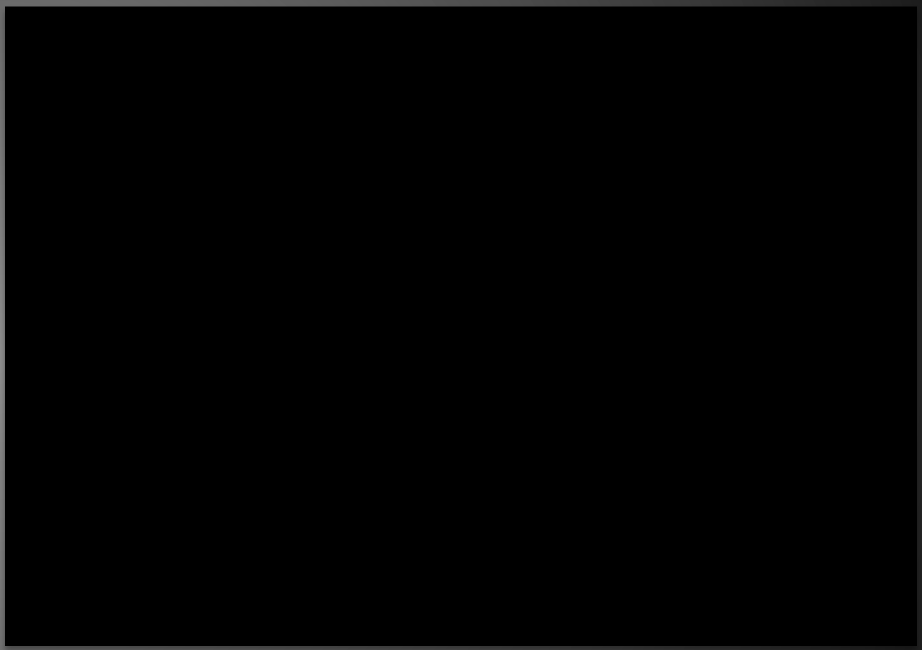
What causes fundamental particles to have mass?

$E=mc^2$

A field of Energy that permeates all of the space

Invisible Force Fields





The Earth’s Magnetic Field

sourced by the Earth permeates nearby space

The Higgs Field

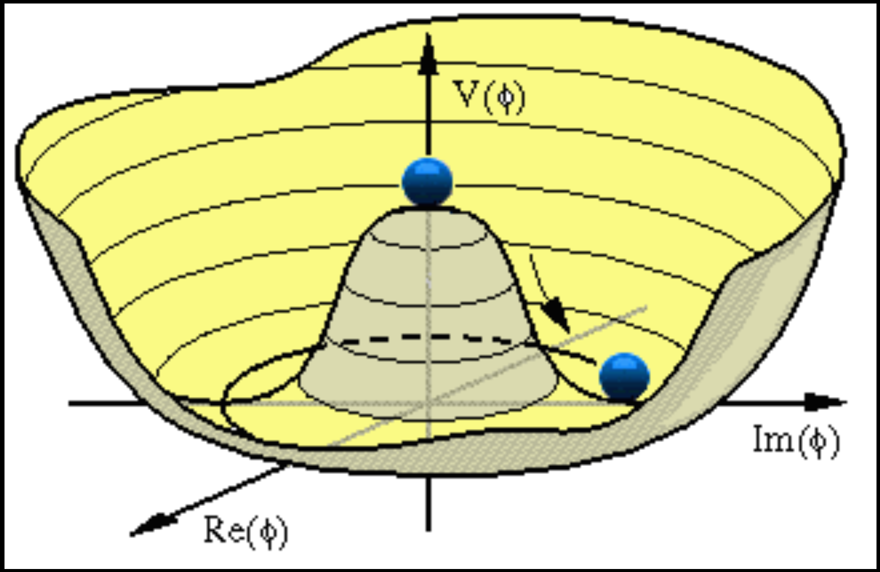
sourced by itself permeates the entire universe

What turns the Higgs field on?

The Higgs field is self-sourcing

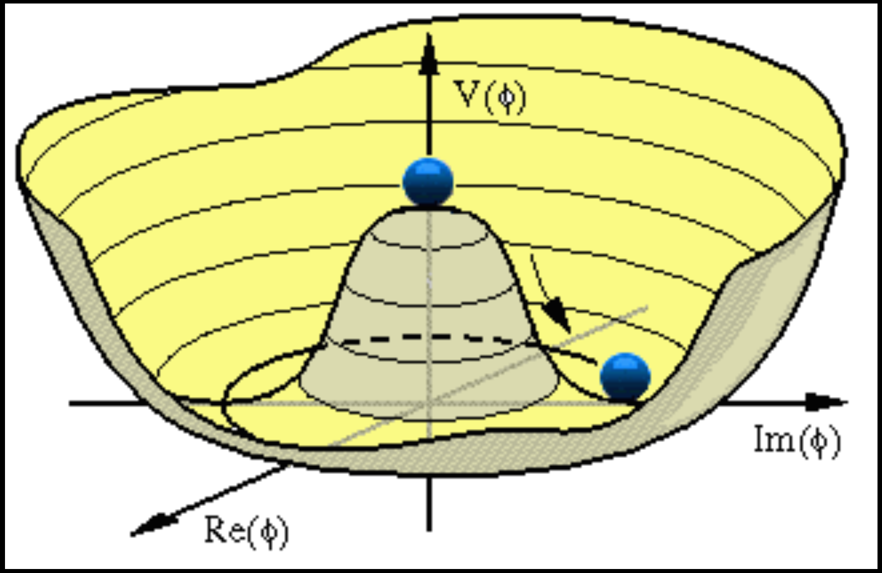
$$V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

The Higgs potential describes the energetics of turning on the Higgs field
The global minimum defines the vacuum state



Spontaneous Symmetry Breaking

Spontaneous Symmetry Breaking

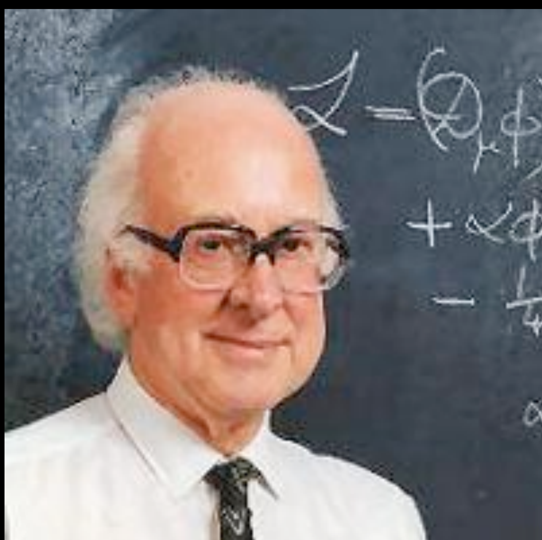


Whose plate is this ?

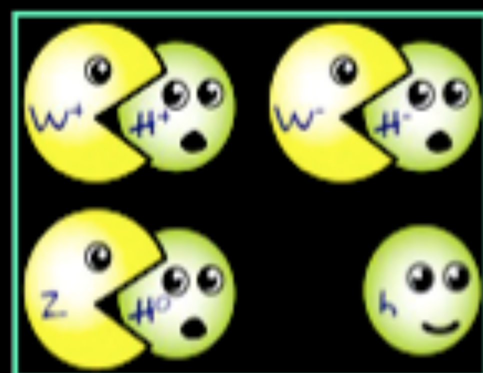
Prof. Yoichiro Nambu (U.of Chicago)
Nobel Prize in Physics 2008

The Higgs Mechanism and the Higgs Boson

A fundamental scalar field with self-interactions can cause spontaneous symmetry-breaking in the vacuum without picking a preferred frame or direction, and can give gauge bosons mass



Higgs et al (1964)



Matter fields also get mass from new type of interactions with the Higgs field

A new massive scalar particle appears

Heavier particles interact more with the Higgs

The Standard Model of Particle Physics

Weinberg-Salam (1967)

The origin of mass : the Higgs mechanism

A simple example: the abelian Higgs model [U(1) gauge theory]

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \qquad F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$$

- Local U(1) gauge invariance: Lagrangian invariant under the transformation

$$A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu \eta(x) \quad \forall \eta$$

- Suppose we add a mass term: $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2 A_\mu A^\mu$

==> this term violates local gauge invariance

- **Adding also a single complex scalar field:** $\phi = \frac{1}{\sqrt{2}} (\phi_1 + i \phi_2)$

$$\Rightarrow \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + |D_\mu \phi|^2 - V(\phi)$$

with $D_\mu = \partial_\mu - ie A_\mu$ and

$$V(\phi) = \mu^2 |\phi|^2 + \lambda (|\phi|^2)^2$$

the most general renormalizable potential allowed by U(1) invariance

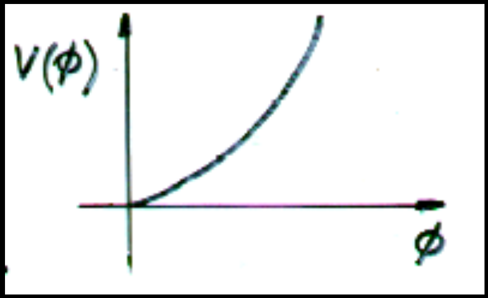
$\mathcal{L}$ ==> inv. under U(1) rotations $\phi \rightarrow e^{i\theta}\phi$ and under local transformations

$$A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu \eta(x) \qquad \phi(x) \rightarrow e^{-ie\eta(x)} \phi(x)$$

Given $V(\phi) = \mu^2 |\phi|^2 + \lambda \left(|\phi|^2 \right)^2$ assuming $\lambda > 0$ ==> two solutions

i) $\mu^2 > 0$

The potential has the shape ➔



and preserves the symmetry of the Lagrangian.

The state of lower energy is for $\langle\Phi\rangle=0$ ➔ vacuum state

$$\partial V/\partial\phi = \mu^2 \phi^\dagger + 2\lambda |\phi|^2 \phi^\dagger = 0 \Rightarrow \phi^\dagger = 0 \text{ sol.}$$

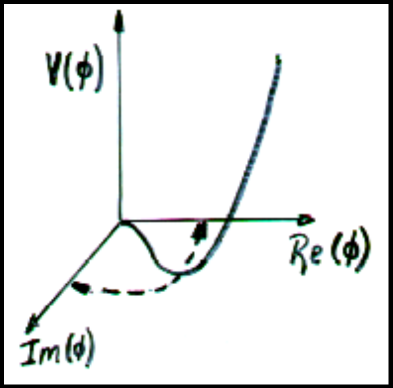
$$\partial^2 V/\partial\phi^2 \Big|_{\langle\phi\rangle=0} = \mu^2 = m_\phi^2$$

The theory is QED with a massless photon and

a charged scalar field Φ with mass μ

ii) $\mu^2 \equiv -|\mu|^2 < 0$

$$\Rightarrow \partial V / \partial \phi^+ = 0 \longrightarrow \langle \phi \rangle_{min} = |\mu| / \sqrt{2\lambda} \equiv v$$



The direction in which the vacuum is chosen is arbitrary
<but one usually chooses it to lie along the real part of Φ >

It is convenient to write: $\phi = \frac{1}{\sqrt{2}} e^{i\chi/v} (v + H)$

$\chi, \ H$ => real fields with no v.e.v.'s

Substituting in the Lagrangian:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - ev A_\mu \partial^\mu \chi + \frac{e^2 v^2}{2} A_\mu A^\mu + \frac{1}{2}\left(\partial_\mu H \partial^\mu H + 2\mu^2 H^2\right) + \frac{1}{2} \partial_\mu \chi \partial^\mu \chi + (H, \chi \text{ interac.})$$

Describes a photon of mass $m_{A\gamma} = ev$, a scalar field H => $m_H^2 = -2\mu^2 \equiv 4\lambda v^2$

and a massless field χ => rotated away by $A'_\mu \equiv A_\mu - \frac{1}{ev} \partial_\mu \chi$

χ is the Goldstone boson "eaten" by the gauge field to give the photon mass

In the unitary gauge: $A'_\mu \equiv A_\mu - \frac{1}{ev}\partial_\mu \chi$ the particle content is clear

1 massive gauge field A'_μ
1 massive scalar field H

Summarizing:

The spontaneous breakdown of the gauge theory by a non-zero v.e.v
= The Higgs mechanism
➔ disappearance of a Goldstone boson which transforms into the longitudinal component of a massive gauge boson

Number of degrees of freedom:

Before Spontaneous Symmetry Breaking (SSB) =>

1 massless γ = 2
1 complex scalar = 2

Total: 4

After SSB =>

1 massive γ → 3
1 real scalar → 1

Total: 4

The Standard Model Electroweak Lagrangian

$$L = L_{kin.}^{gauge} + L_{kin.}^{fermions} + L_{Higgs}$$

The chiral SU(2)W x U(1)Y Yang Mills Lagrangian with massless left- and right-handed fermions reads:

$$L_{kin.}^{gauge} + L_{kin.}^{fermions} = -\frac{1}{4}\sum_{A=1}^{3} F_{\mu\nu}^{A} F^{A\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \overline{\psi}_L i\gamma^{\mu} D_{\mu}\psi_L + \overline{\psi}_R i\gamma^{\mu} D_{\mu}\psi_R$$

The gauge antisymmetric tensors ==>

$$B_{\mu\nu} = \partial_{\mu} B_{\nu} - \partial_{\nu} B_{\mu} \rightarrow U(1)_Y$$

$$F_{\mu\nu}^{A} = \partial_{\mu} W_{\nu}^{A} - \partial_{\nu} W_{\nu}^{A} - g\varepsilon_{ABC} W_{\mu}^{B} W_{\nu}^{C} \rightarrow SU(2)_W$$

The fermion fields: $\psi_{L,R} = \left[(1 \mp \gamma_5)/2\right]\psi \equiv \mathrm{P_{L,R}}\ \psi \qquad \mathrm{P_{L,R}}$ are projectors

Dirac matrices in the chiral/Weyl rep.

$$\gamma^{i} = \begin{pmatrix} 0 & \sigma^{i} \\ -\sigma^{i} & 0 \end{pmatrix} \qquad \gamma^{0} = \begin{pmatrix} 0 & \mathrm{I} \\ \mathrm{I} & 0 \end{pmatrix}$$

$$\left\{\gamma_{\mu}, \gamma_{\nu}\right\} = 2g_{\mu\nu}; \quad g_{\mu\nu} = diag(+,-,-,-)$$

$$\gamma_5^2 = \mathrm{I}; \quad \gamma_5^{+} = \gamma_5$$

Quantum number assignments for the SM matter fields

Non-Abelian $SU(2)_W$ => chargeless one dim. Singlet (1) representation
charged two dim. Doublet (2) representation

Abelian $U(1)_Y$ => only one dimensional representation ==> can give different hypercharges to SU(2) singlets and doublets

Non-Abelian $SU(3)_C$: Singlets => Leptons and Triplets ==> Quarks

- Quarks and leptons cannot mix, since weak interactions do not change color, nor left and right handed fields (would violate Lorentz symmetry)
- Charged Currents => connect up- and down-type quarks as well as charged leptons and neutrinos and W+- bosons couple only to left handed fermions

Hence ==> form Left-handed doublets and Right-handed singlets

For one generation of SM particles ==> **seven chiral spinors: $u_{L,R}$, $d_{L,R}$, $e_{L,R}$ and v_L.**
For the moment we will treat neutrinos as massless, we omit the right-handed one.

For the $SU(2)_W$ multiplets: $q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R d_R $l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R

For the hypercharges: $q_L : \frac{1}{3}$ $u_R : \frac{4}{3}$ $d_R : -\frac{2}{3}$ $l_L : -1$ $e_R : -2$

We can now write the covariant derivatives

$$D_\mu \psi_L = \left(\partial_\mu + igW_\mu + ig'\frac{1}{2}YB_\mu \right) \psi_L \quad \text{where} \quad W_\mu = \frac{1}{2}\sigma^A W_\mu^A$$

While the right-handed fields are singlets under $SU(2)_W$, hence do not couple to W's

$$D_\mu \psi_R = \left(\partial_\mu + ig'\frac{1}{2}YB_\mu \right) \psi_R$$

From the explicit form of the Pauli matrices:

$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$W^{1,2}_\mu$ mix up- and down-type quarks, while W^3_μ ,the same as B_μ , does not.

The Higgs Mechanism

So far: Gauge bosons are massless, implying long range forces, because a mass term $m^2 W_\mu W^\mu$ would violate gauge invariance

Fermions are massless, again because of gauge invariance

Mass term $m\bar{\psi}\psi = m\left(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L\right)$ is forbidden because it would mix left- and right-handed fermions which have different quantum numbers

Adding a complex scalar field Φ, doublet under $SU(2)_W$ and with Y= 1 with a potential

$$V(\Phi) = \mu^2\Phi^+\Phi + \lambda\left(\Phi^+\Phi\right)^2 \qquad (\lambda > 0)$$

or

$$V(H,\phi_o) = \frac{\mu^2}{2}\left(H^2 + \phi_0^2\right) + \frac{\lambda}{4}\left(H^2 + \phi_0^2\right)^2 \quad \textbf{with} \quad \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1^+ + i\phi_2^+ \\ H + i\phi_0 \end{pmatrix}$$

The Higgs Lagrangian, with the covariant derivative as previously defined

$$L_{Higgs} = \left(D_\mu\Phi\right)^+ D^\mu\Phi - V(\Phi)$$

As in the Abelian simple example, for $\mu^2 < 0$ there is a minimum at $\langle\Phi\rangle_{\min} = \begin{pmatrix} 0 \\ \mathbf{v} \end{pmatrix}$

Minimization condition only fixes the modulus $\Phi^+\Phi$ ==> no fixed direction since

$$V(\Phi) \propto \Phi^+\Phi = \frac{1}{2}\left(\phi_1^2 + \phi_2^2 + H^2 + \phi_0^2\right)$$

Hence,

$$V(H,\phi_0) = -\frac{|\mu|^2}{2}\left(H^2 + \phi_0^2\right) + \frac{\lambda}{4}\left(H^2 + \phi_0^2\right)^2$$

$$\partial V/\partial H = -|\mu|^2 H + \frac{\lambda}{4} 2\left(H^2 + \phi_0^2\right) 2H = 0 \quad \Rightarrow \quad \left\langle H^2 \right\rangle_{\min} = \frac{|\mu|^2}{\lambda} = 2\mathbf{v}^2$$

$$\partial V/\partial \phi_0 = 0 \quad \Rightarrow \quad \langle \phi_0 \rangle = 0$$

and

$$m_H^2 = \partial^2 V/\partial H^2 |_{\langle H\rangle_{\min} \langle \phi_0 \rangle_{\min}} = 2|\mu|^2 = 4\lambda \mathbf{v}^2$$

$$m_{\phi_0}^2 = \partial^2 V/\partial \phi_0{}^2 |_{\langle H\rangle_{\min} \langle \phi_0 \rangle_{\min}} = 0 \quad \Rightarrow \quad \textbf{Goldstone Boson}$$

same for $m_{\phi_1}^2$ **and** $m_{\phi_2}^2 \rightarrow$ **Charged Goldstone bosons**

W and Z gauge boson masses

In the unitary gauge the Higgs Lagrangian becomes

$$H \to \sqrt{2}\mathbf{v} + H$$

$$\langle H \rangle = 0$$

$$L_{Higgs} = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\underbrace{4\lambda \mathbf{v}^2}_{\mathbf{m_H^2}} H^2 + \sqrt{2}\lambda \mathbf{v} H^3 + \frac{\lambda}{4} H^4$$

$$+\frac{1}{4}\left(\mathbf{v} + \frac{1}{\sqrt{2}}H\right)^2 \begin{pmatrix} W_\mu^1 & W_\mu^2 & W_\mu^3 & B_\mu \end{pmatrix} \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & -gg' \\ 0 & 0 & -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W^{1\mu} \\ W^{2\mu} \\ W^{3\mu} \\ B^\mu \end{pmatrix}$$

Last term contains the physical photon, W+- and Z bosons boson masses !!

The mass matrix has one zero eigenvalue and three others: g^2, g^2 and $g^2+g'^2$

==> it describes a massless particle, two of equal non-zero mass and one heavier

The massless eigenstate $\rightarrow A_\mu = \sin\theta_W W_\mu^3 + \cos\theta_W B_\mu$

The Z boson eigenstate $\rightarrow Z_\mu = \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu$

The W boson eigenstate $W^\pm = (W_1 \pm W_2)/\sqrt{2}$

With the Weinberg angle: $\sin\theta_W = g' \Big/ \sqrt{g'^2 + g^2}$ $\cos\theta_W = g \Big/ \sqrt{g'^2 + g^2}$

Summarizing: the theory has the following mass eigenstates:

- Two charged vector boson W+- with mass $M_W^2 = g^2 \mathbf{v}^2 / 2$
- Two neutral ones with masses $M_Z^2 = \left(g^2 + g'^2\right)\mathbf{v}^2/2 = M_W^2/\cos^2\theta_W$ **and** $M_\gamma = 0$
- One neutral Higgs boson with mass $m_H^2 = 4\lambda \mathbf{v}^2$

The Higgs mechanism and the diagonalization of the vector boson mass matrix

Rewrite the interaction Lagrangian of fermions and gauge bosons in term of the physical fields, separating into Charged and Neutral Currents:

$$L_{CC} = -\frac{g}{\sqrt{2}} \sum_{i-1,2,3} \left(\bar{u}_{L_i} \gamma^\mu d_{L_i} + \bar{\nu}_{L_i} \gamma^\mu e_{L_i} \right) W_\mu^+ + h.c.$$

$$e = g \sin\theta_W = g' \cos\theta_W$$

$$L_{NC} = -g\, J_\mu^3\, W^{3\mu} - g' J_{Y,\mu}\, B^\mu = -e\, J_\mu^{em} A^\mu - \left(e/\sin 2\theta_W\right) J_\mu^Z Z^\mu$$

With the Electromagnetic and Z currents:

$$J_\mu^{em} = \sum_{i=u,d,c,s,t,b,e,\mu,\tau} \bar{\psi}_i \gamma_\mu Q_i \psi_i \quad \text{with the electric charge } Q_i = T_i^3 + Y_i/2$$

$$J_\mu^Z = \sum_{\substack{i=u,d,c,s,t,b,\\ e,\mu,\tau,\nu_e,\nu_\mu,\nu_\tau}} \bar{\psi}_i \gamma_\mu \left(v_i - a_i \gamma^5\right) \psi_i \quad \text{where } \psi_i = \psi_{L_i} + \psi_{R_i}$$

About the Neutral Currents:

- The coupling to the photon ==> $Q = T_L^3 + Y/2 = T_R^3 + Y/2$,
  with the weak isospin T_L^3 = +-1/2 for doublets, and T_R^3=0 for singlets
  ==> defines the hypercharge Y assignments to reproduce the known electric charges of quarks and leptons

- The photon couples only vector like, i.e., it does not distinguish chiralities
- The Z boson couples to axial and vector fermion currents differently

==> $a_i = T_L^3$ and $v_i = T_L^3 - 2Q\sin^2\theta_W$ and it couples universally to all families

Number of degrees of freedom

The EWSB reshuffles the degrees of freedom of the theory

Before:

1 complex scalar double	= 4
1 massless SU(2) Wμ	= 6
1 massless U(1) Bμ	= 2
	12

After:

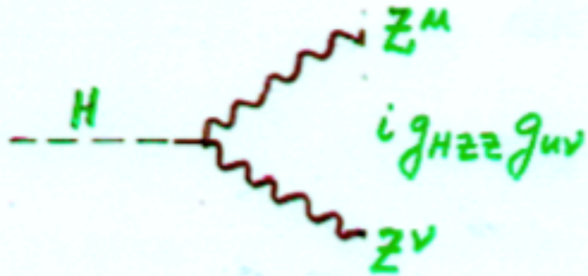
1 charged W+-	= 6
1 massive Z	= 3
1 massless photon	= 2
1 massive scalar	= 1
	12

Higgs neutral under strong and em interactions ==> massless photon and gluons
Massless gauge bosons ==> Exact symmetry:

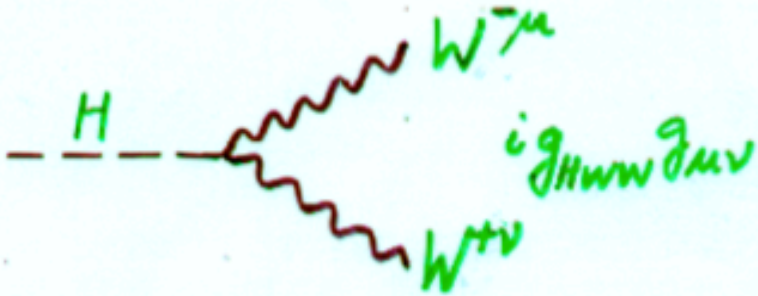
$$SU(3)_C \times SU(2)_W \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{em}$$

Higgs-Vector Boson Couplings

from $$\mathcal{L}_{H-W/Z} = \left(v + H/\sqrt{2}\right)^2 \left[\frac{g_2^2}{2} W_\mu^+ W^{-\mu} + \frac{g_1^2 + g_2^2}{4} Z_\mu Z^\mu\right]$$



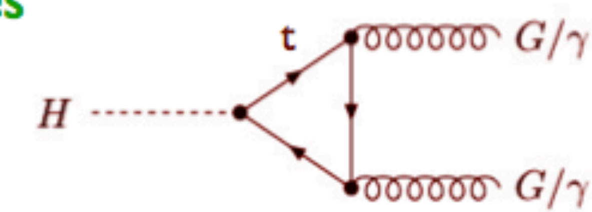
$$g_{HZZ} = 2!\,\frac{(g_1^2 + g_2^2)}{4}\frac{2v}{\sqrt{2}} = \frac{M_Z^2}{v}\sqrt{2}$$



$$g_{HWW} = \frac{g_2^2}{2}\, v\sqrt{2} = \frac{M_W^2}{v}\sqrt{2}$$

Tree level couplings are proportional to masses

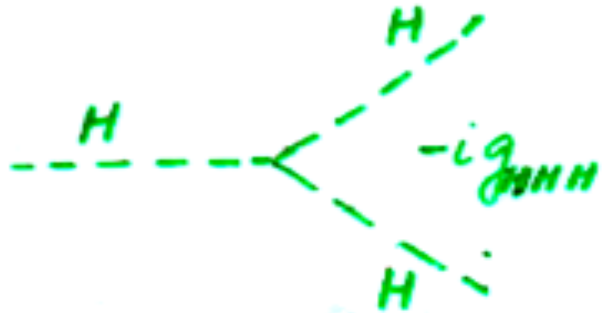
There are also loop induced couplings into massless gauge bosons ===>



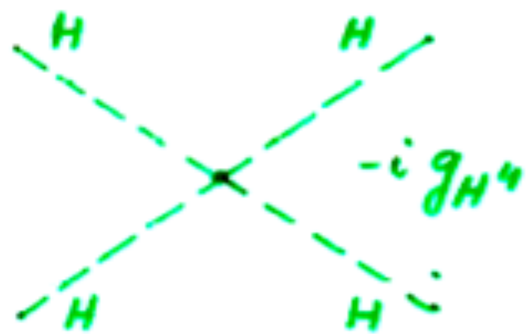
The $H\gamma\gamma$ coupling is dominated by the W boson loop

Higgs Self-Interactions

From: $V(\phi) = -|\mu|^2/2 \, H^2 + \lambda \left(v + H/\sqrt{2}\right)^4$



$g_{HHH} = 3! \, \lambda \sqrt{2} \, v = \dfrac{3 \, m_H^2}{\sqrt{2} \, v}$



$g_{H^4} = 4! \, \lambda/4 = \dfrac{m_H^2}{v^2} \cdot 3/2$

Higgs potential has two free parameters :

$|\mu|$ and λ $\rightarrow$ trade by $v^2 = -|\mu|^2/2\lambda; \; m_H^2 = 4\lambda v^2$

Fermion Masses and Mixings

Higgs mechanism generates masses also for the fermions through Yukawa couplings of the Higgs doublet to two fermions:

-- Higgs couplings to quark doublets and either up or down-type singlets

-- Higgs couplings to lepton doublet and charged lepton singlets

- Each term is parametrized by a 3x3 matrix in generation space

$$L_{Hf\bar{f}} = -(h_d)_{ij}\bar{q}_{L_i}\Phi\, d_{R_j} - (h_u)_{ij}\bar{q}_{L_i}\Phi^C u_{R_j} - (h_l)_{ij}\bar{l}_{L_i}\Phi\, e_{R_j} + h.c$$

$$\text{recall: } \Phi = \begin{pmatrix} (\phi_1 + i\phi_2)/\sqrt{2} \\ \mathrm{v} + (H + i\phi_0)/\sqrt{2} \end{pmatrix} \quad \text{and } \Phi^C = -i\sigma_2\Phi^*$$

Once the electroweak symmetry is spontaneously broken $\langle\Phi\rangle = \mathrm{v}$

$$L_{m_f} = (m_d)_{ij}\bar{d}_{L_i}\, d_{R_j} + (m_u)_{ij}\bar{u}_{L_i}\, u_{R_j} + (m_e)_{ij}\bar{e}_{L_i}\, e_{R_j} + h.c$$

with $m_f = h_f \mathrm{v}$ and u_L, d_L and e_L the quark and lepton doublet components

- These mass matrices are not diagonal in the same basis as the charged currents,, but can be diagonalized by bi-unitary transformations

$$V^{u\dagger} m_u \tilde{V}^u = diag(m_u, m_c, m_t)$$
$$V^{d\dagger} m_d \tilde{V}^d = diag(m_d, m_s, m_b)$$
$$V^{e\dagger} m_e \tilde{V}^e = diag(m_e, m_\mu, m_\tau)$$

with unitary matrices V $\rightarrow$ $V^\dagger V = I$

We change the basis from weak eigenstates $(i, j, \ldots)$ to mass eigenstates $(\alpha, \beta, \ldots)$

$$u_{Li} = V^u_{i\alpha}\, u_{L\alpha}, \qquad d_{Li} = V^d_{i\alpha}\, d_{L\alpha}, \qquad u_{Ri} = \tilde{V}^u_{i\alpha}\, u_{R\alpha}, \qquad d_{Ri} = \tilde{V}^d_{i\alpha}\, d_{R\alpha}$$

The up and down matrices V^u and V^d are not identical, hence, the charged current couplings are no longer diagonal

$$L_{CC} = -\frac{g}{\sqrt{2}} V^{CKM}_{\alpha\beta}\, \bar{u}_{L_\alpha} \gamma^\mu d_{L_\beta} W^+_\mu + h.c.$$

with the CKM matrix $V^{CKM}_{\alpha\beta} = V^{u\dagger}_{\alpha i} V^d_{i\beta}$

The CKM mass matrix is almost the identity ==> flavor changing transitions suppressed

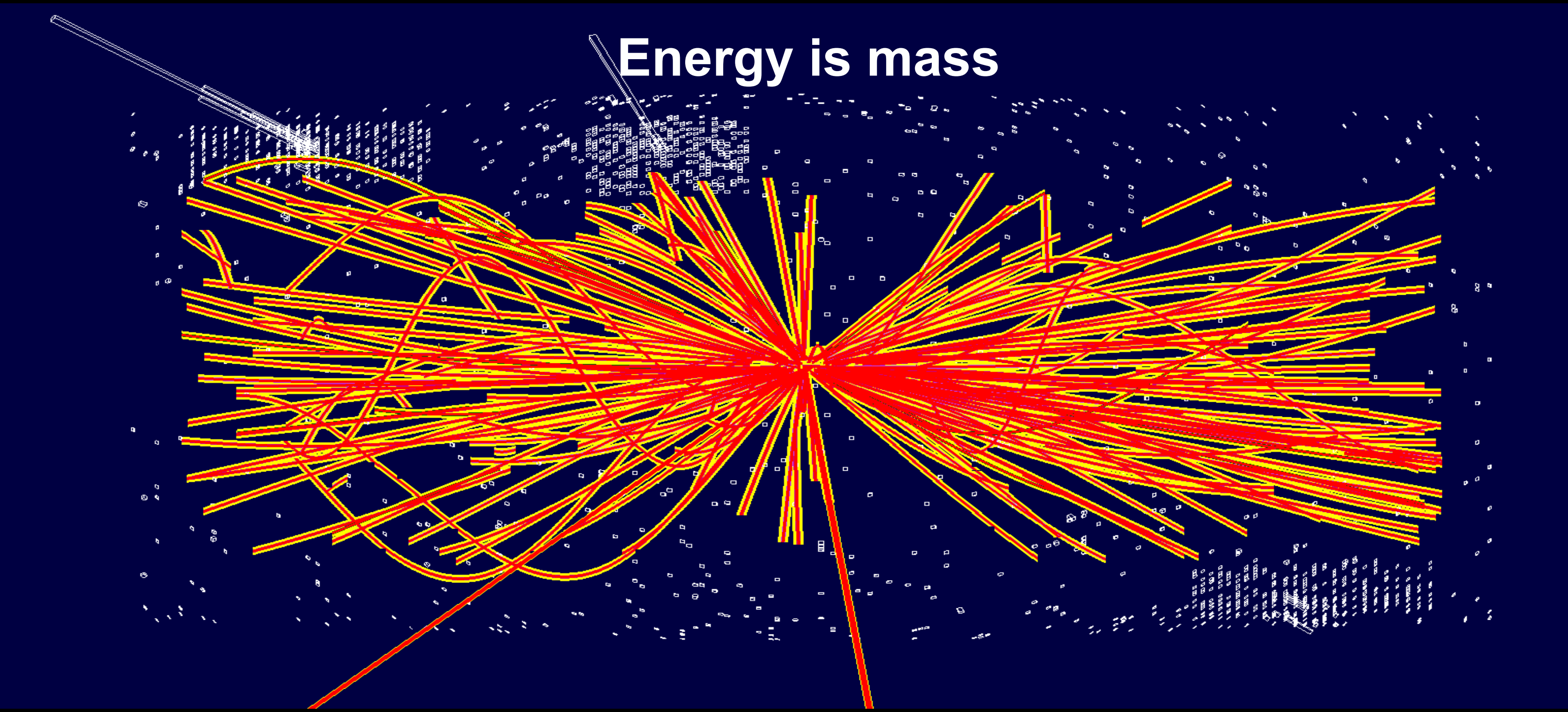
Due to the unitarity of the transformations ==> no FCNC in the neutral gauge sector

The Higgs-fermion interactions are flavor diagonal in the fermion mass eigenstate basis

given $\bar{d}_i\,(m_{ij} + h_{ij} H)\, d_j$, since $m_{ij} = h_i j v$ they are diagonalised together

How do we search for the Higgs?

Smashing Particles at High Energy Accelerators to create it



And searching for known particles into which the Higgs transforms (decays) almost instantly

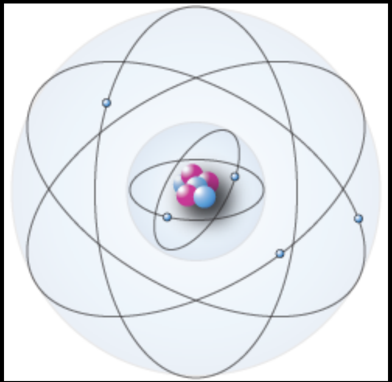
At huge Particle Accelerators,

Shouldn't we expect to find particles consisting of the initial particle constituents?

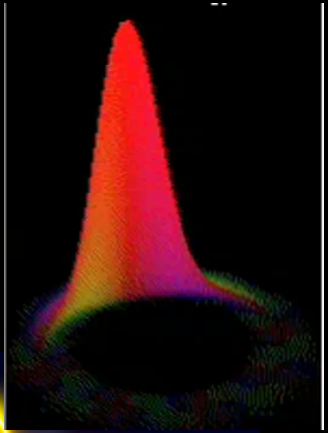
An element of chance in the microscopic world

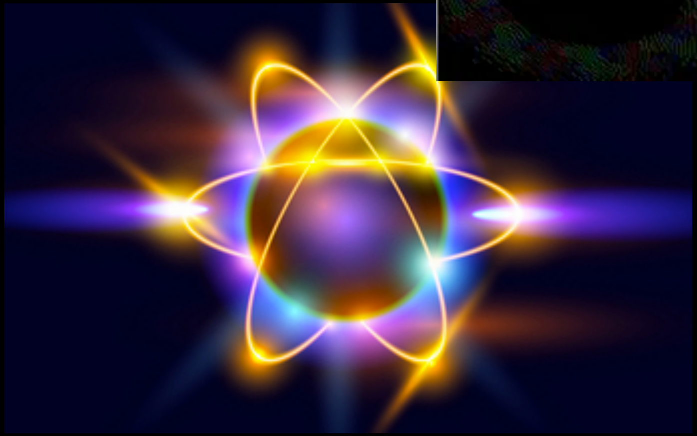
$\Delta x \cdot \Delta p \sim h$

Werner Heisenberg



Classical model of atoms



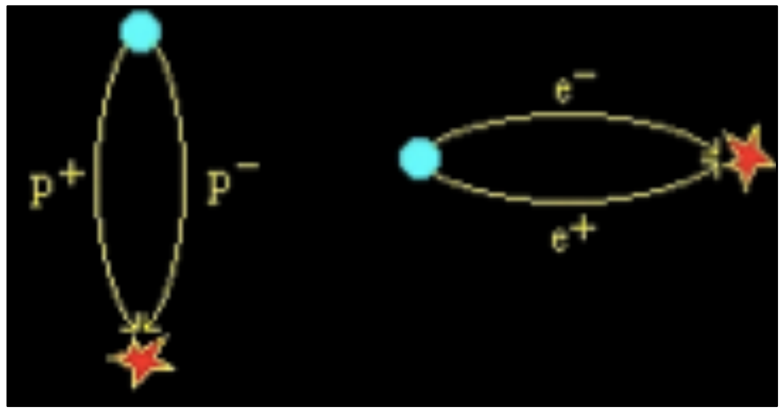


Quantum mechanical model of atoms

Quantum Vacuum

“Nothingness” is the most exciting medium in the cosmos!

Quantum fluctuations create and annihilate “virtual particles” in the vacuum



$\Delta t \cdot \Delta E \sim h$

virtual particles + energy → real particles

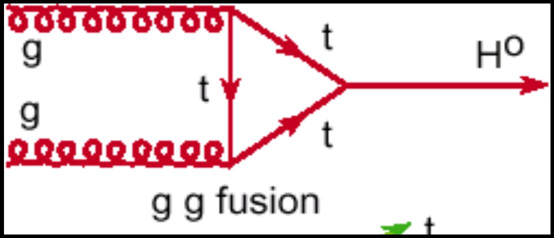
quantum vacuum

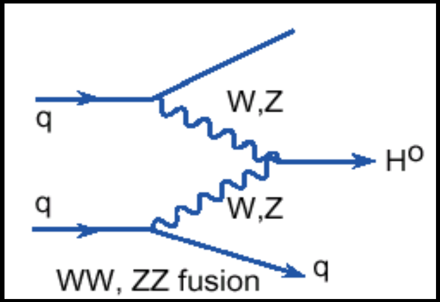
accelerator

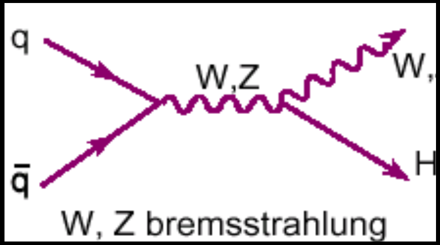
production of new particles

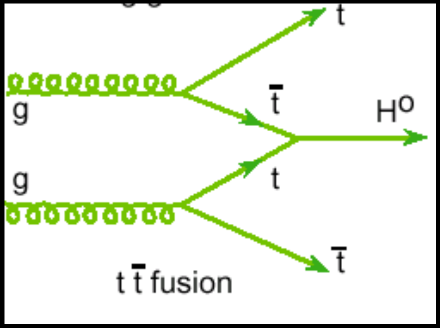
Quantum Fluctuations can produce the Higgs at the LHC

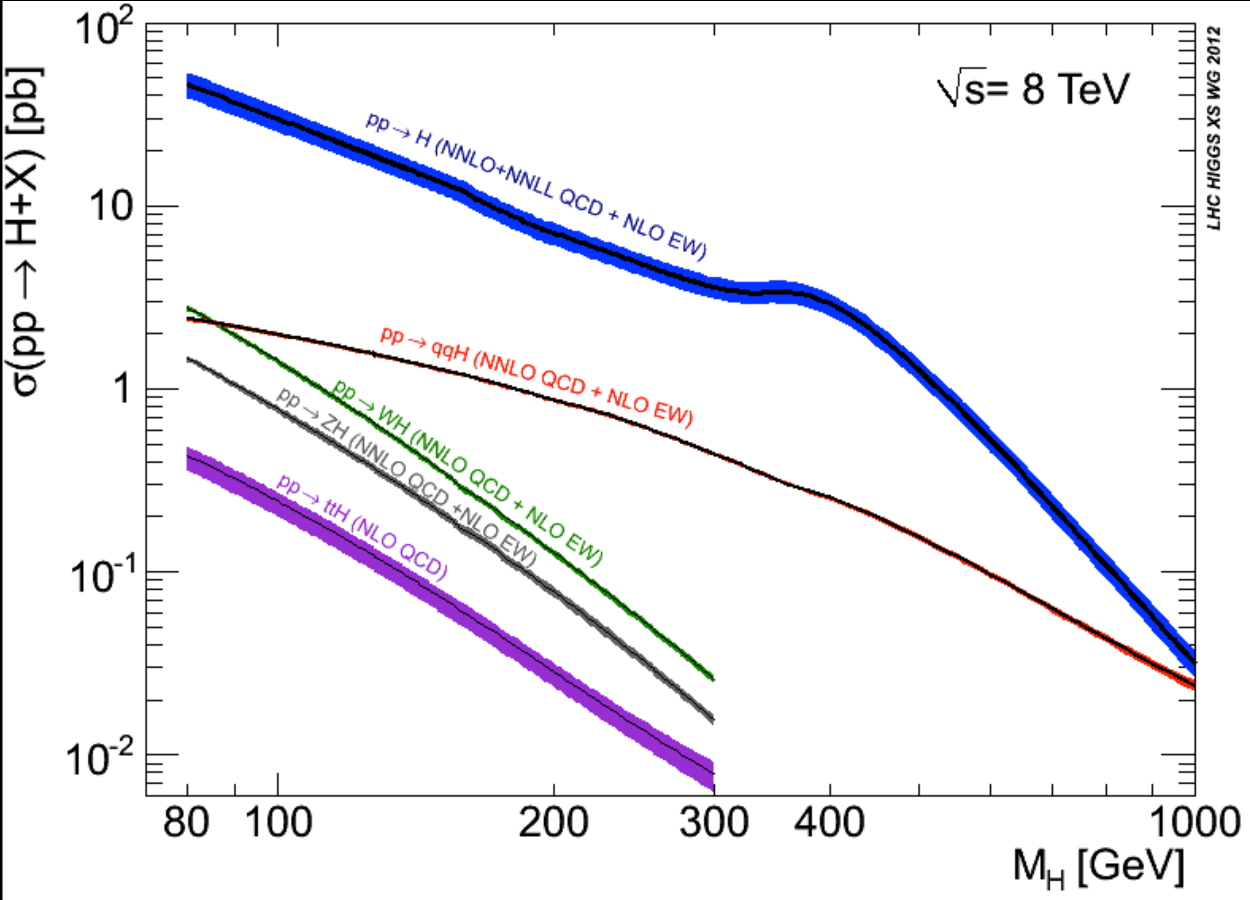
The SM Higgs at the LHC







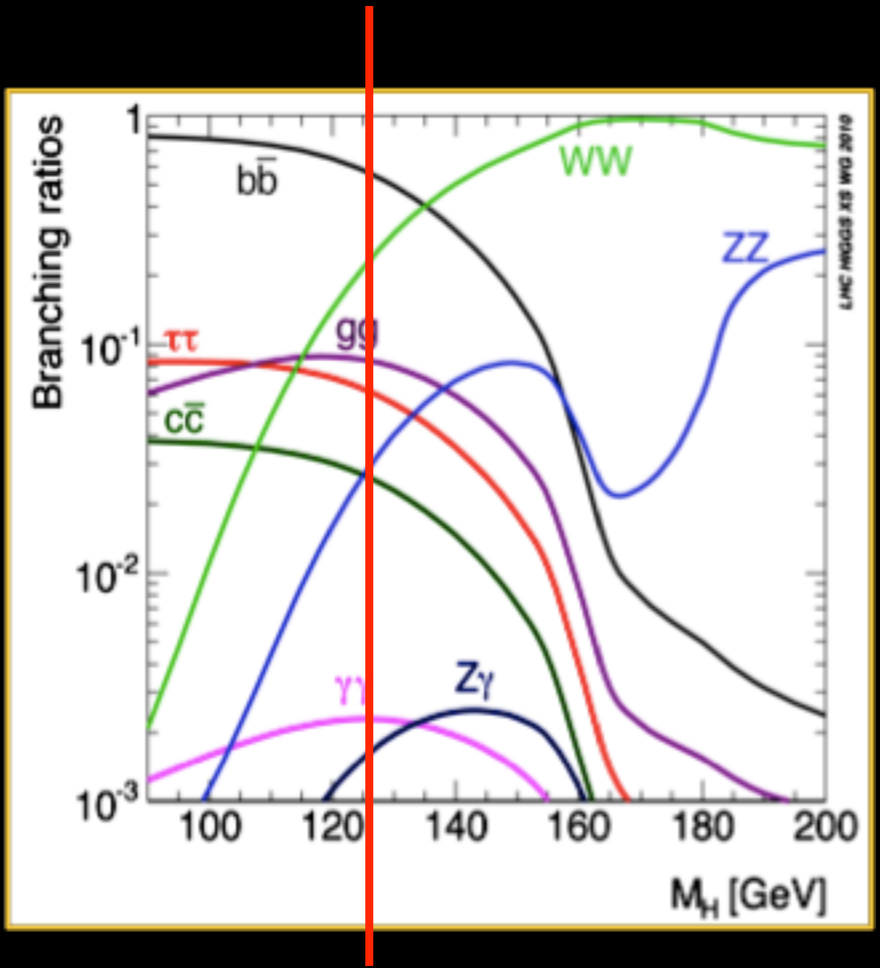


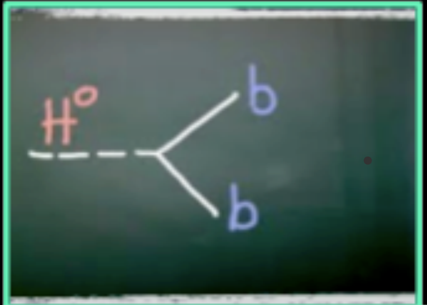


Much progress recently in computing NLO and NNLO QCD corrections

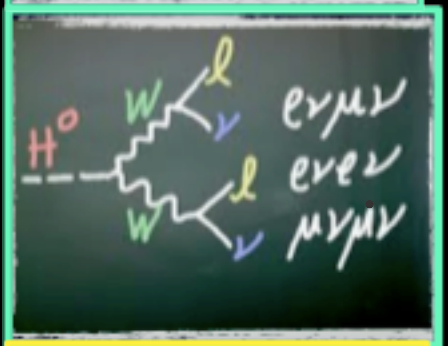
Higgs decays:

Higgs decays after about 100 yocktoseconds into various pairs of lighter particles

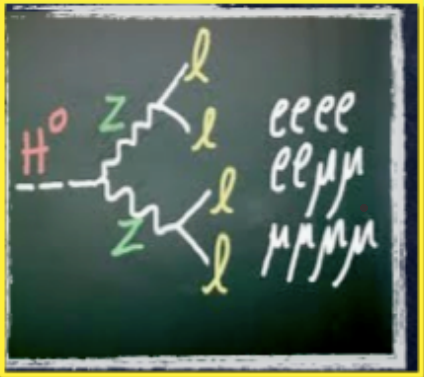




Lots of background



Neutrinos not detected

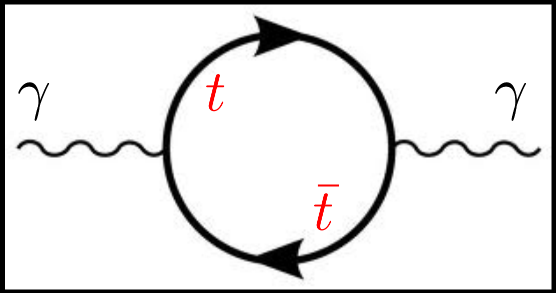


Rare but “Golden” channel

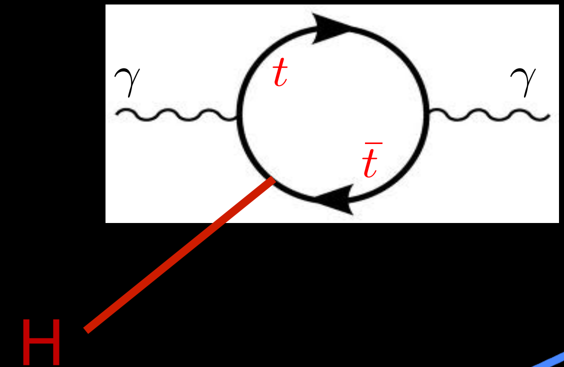
Rare but relatively clean

Virtual particles facilitate Higgs discovery

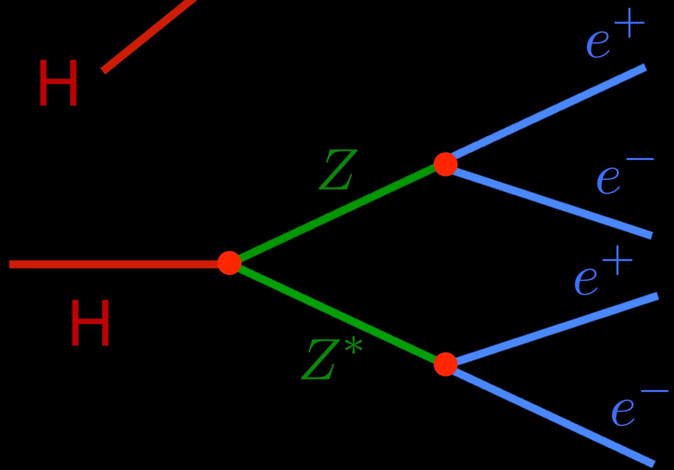
Photon propagates in Quantum Vacuum



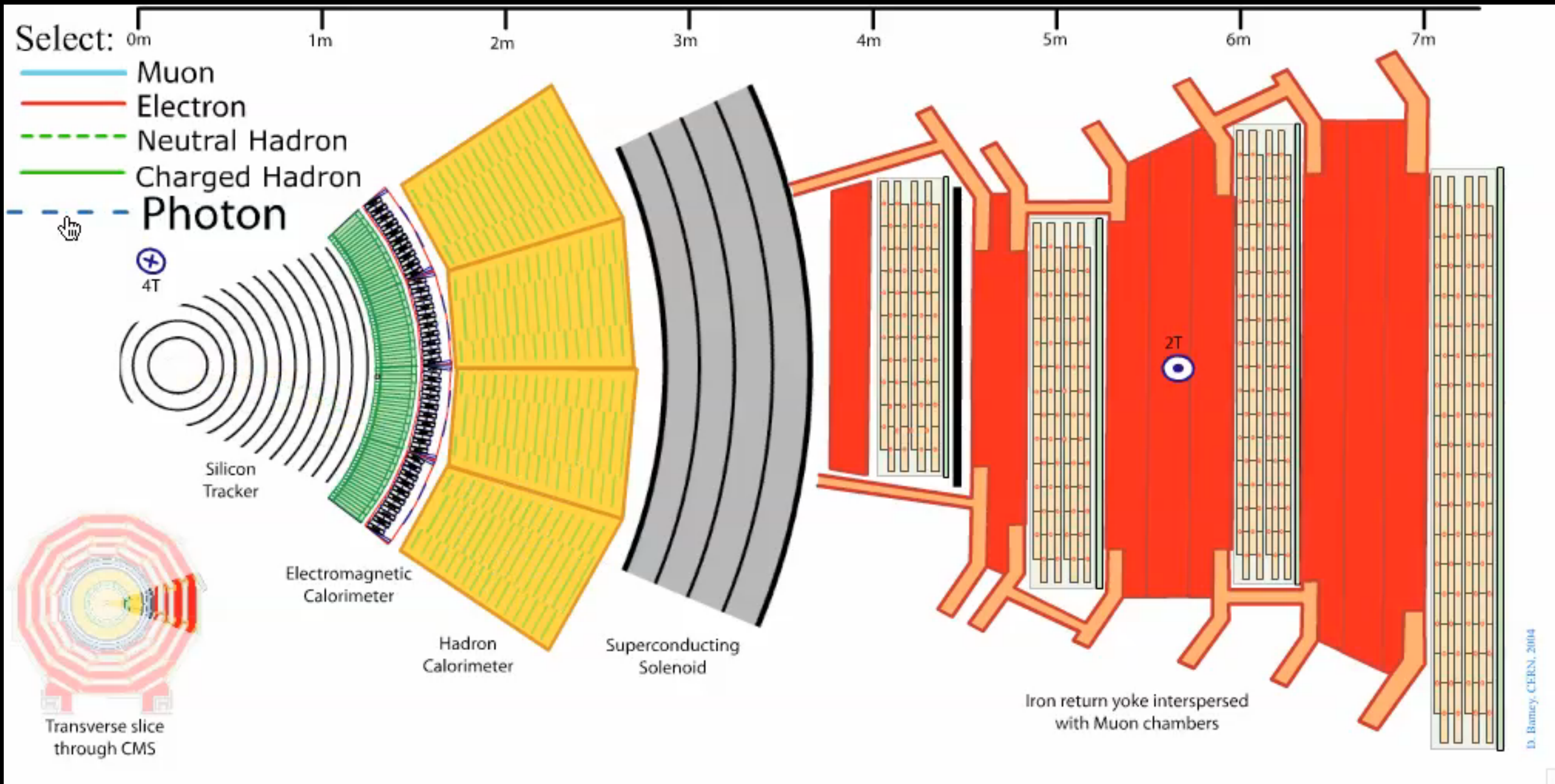
Higgs decays into 2 Photons



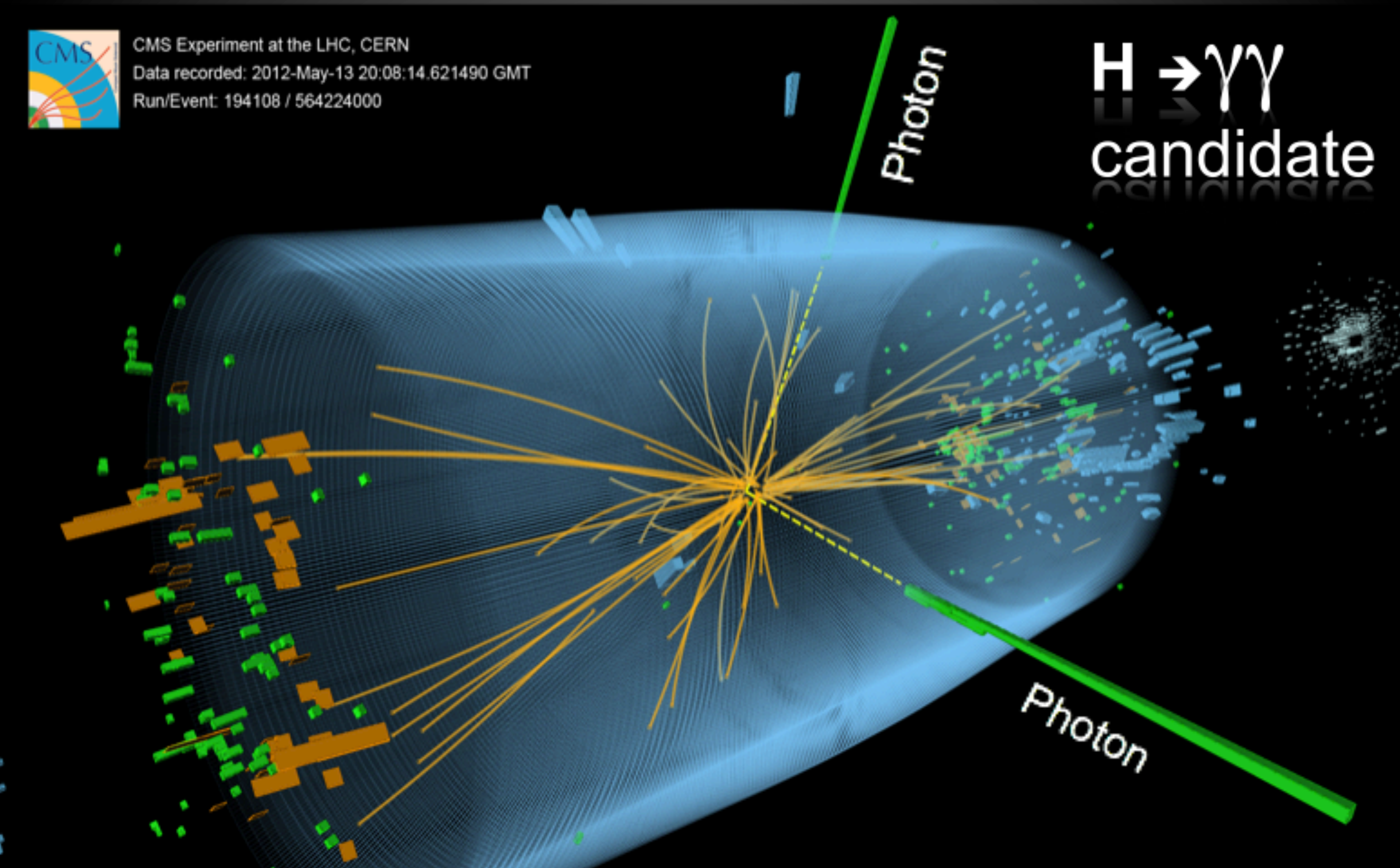
Higgs decay into 4 leptons via virtual Z bosons



What the detectors detect

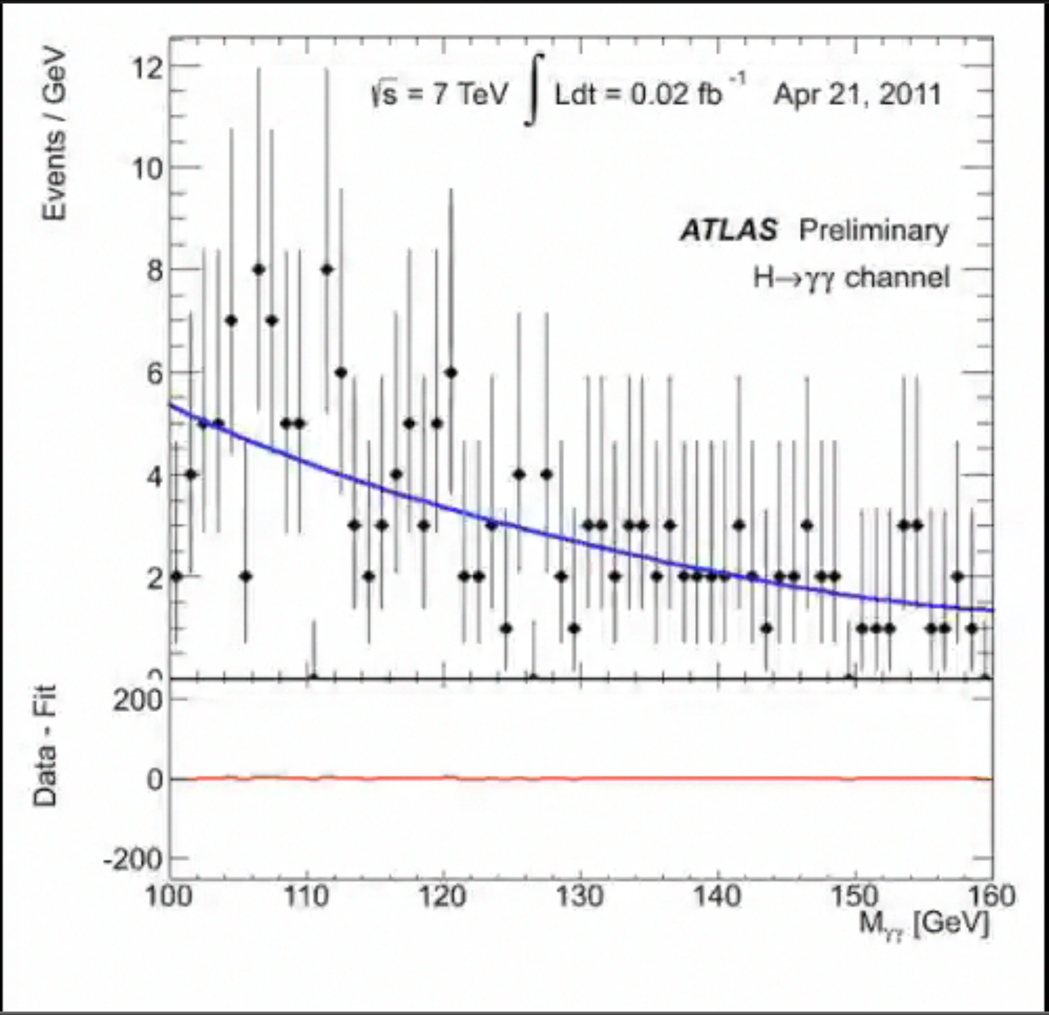


We look for the tracks that a particle leaves behind

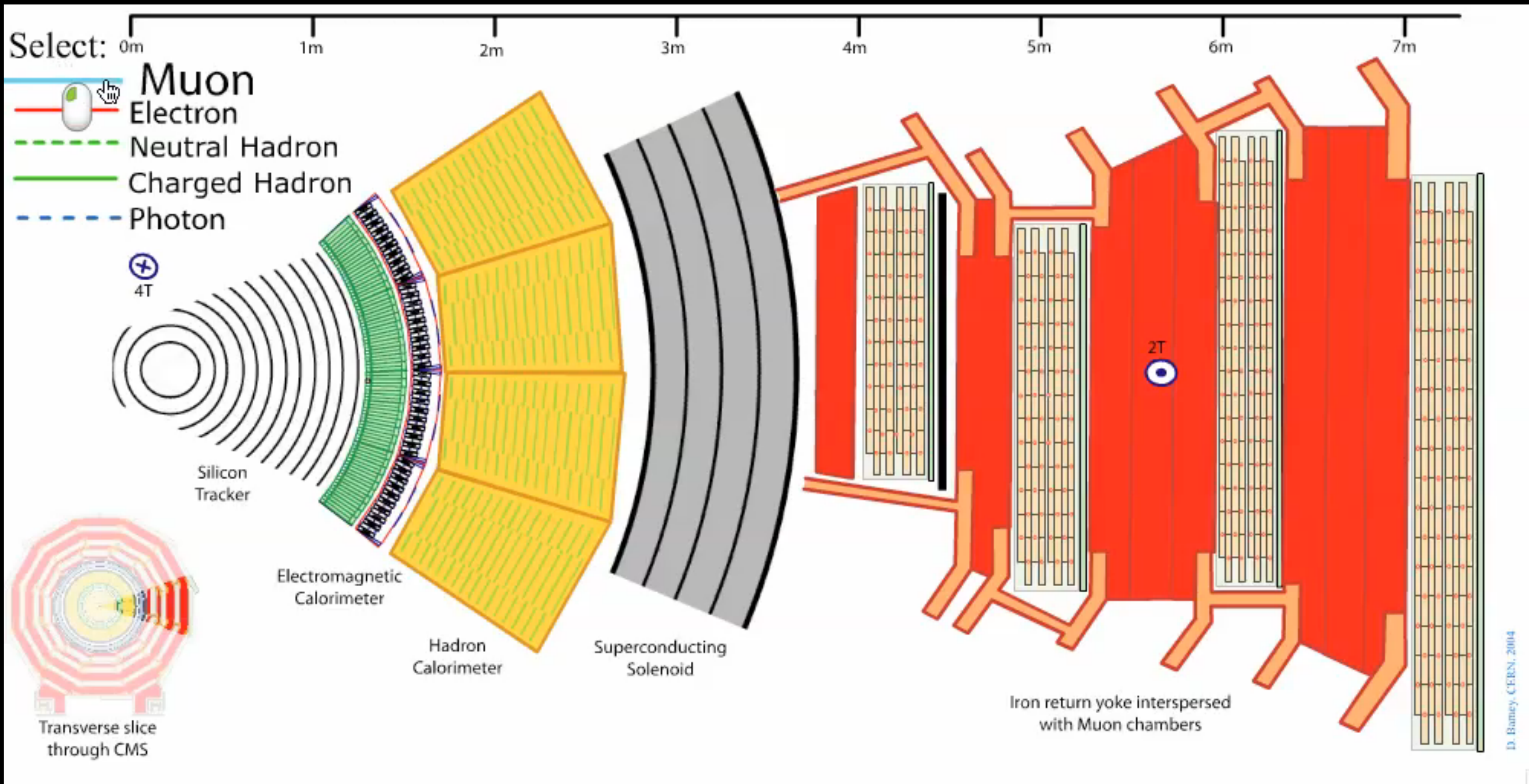


Search for a narrow mass peak with two isolated high E_T photons on a smoothly falling background

The Discovery: Higgs → two photons

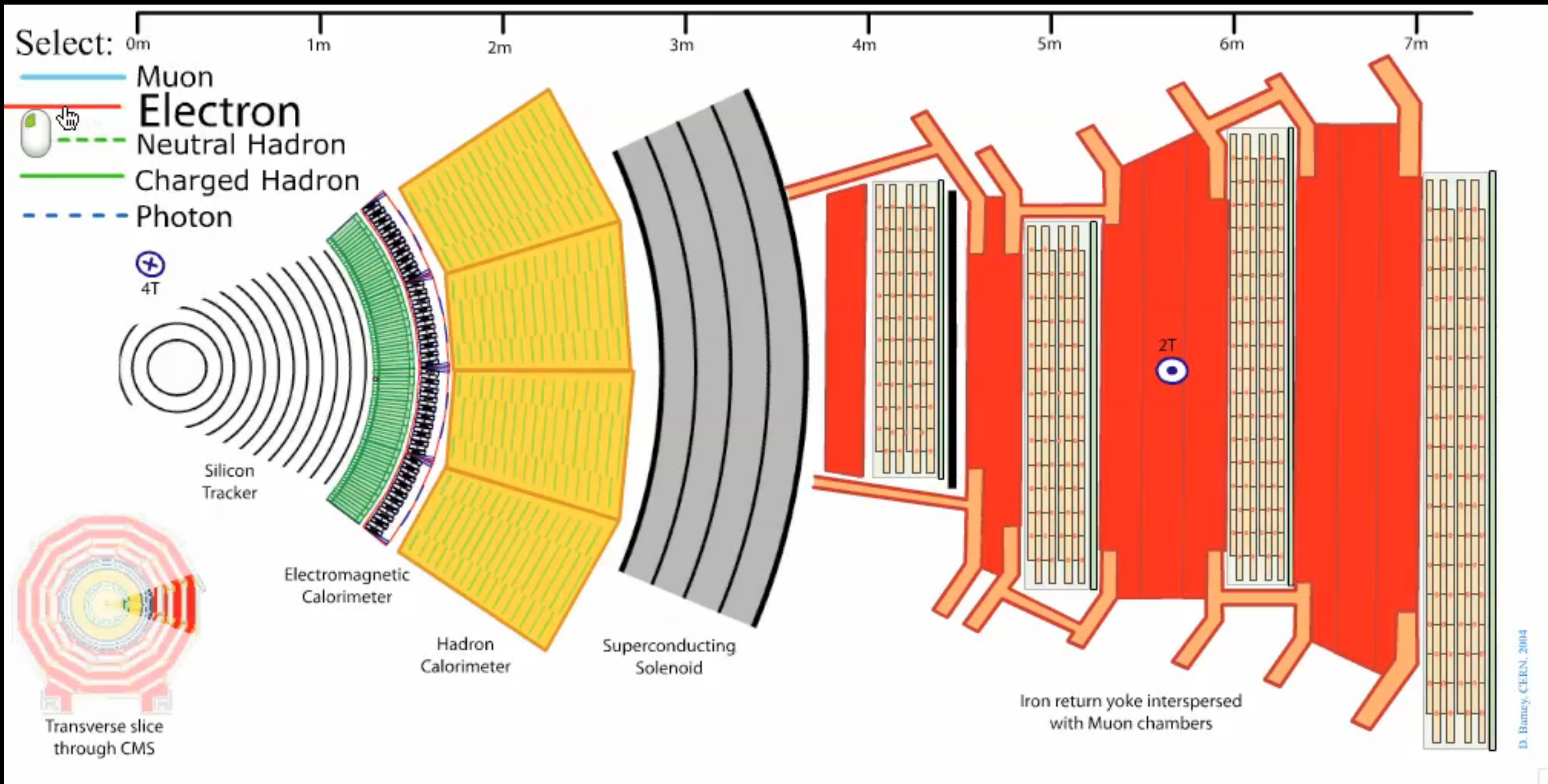


What the detectors detect



We see signals when the layers of the detector stop the particles as they fly out

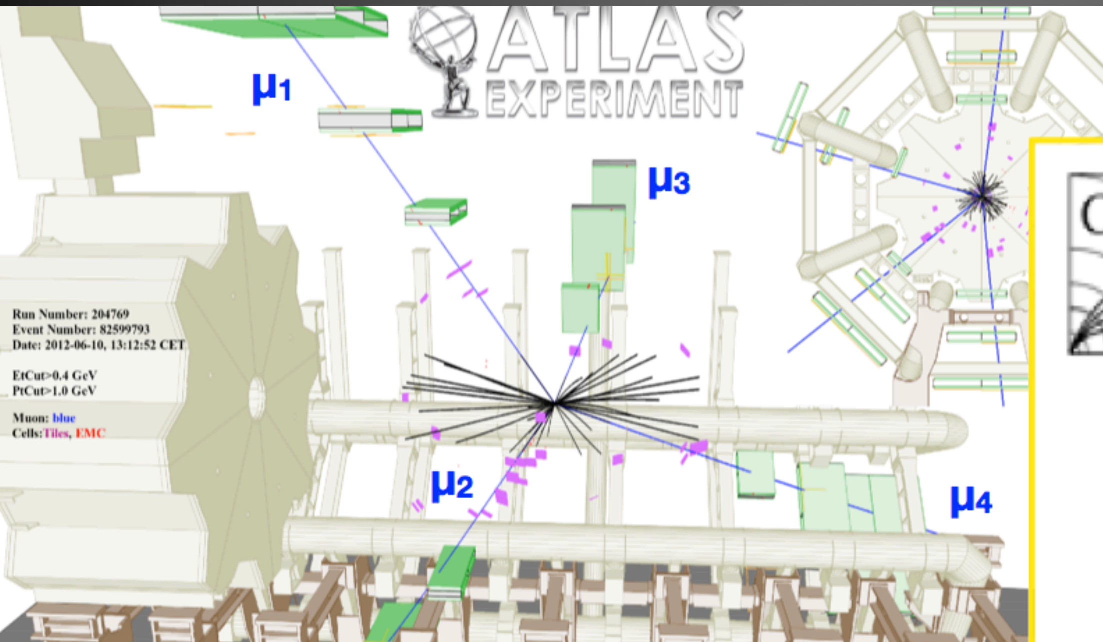
What the detectors detect

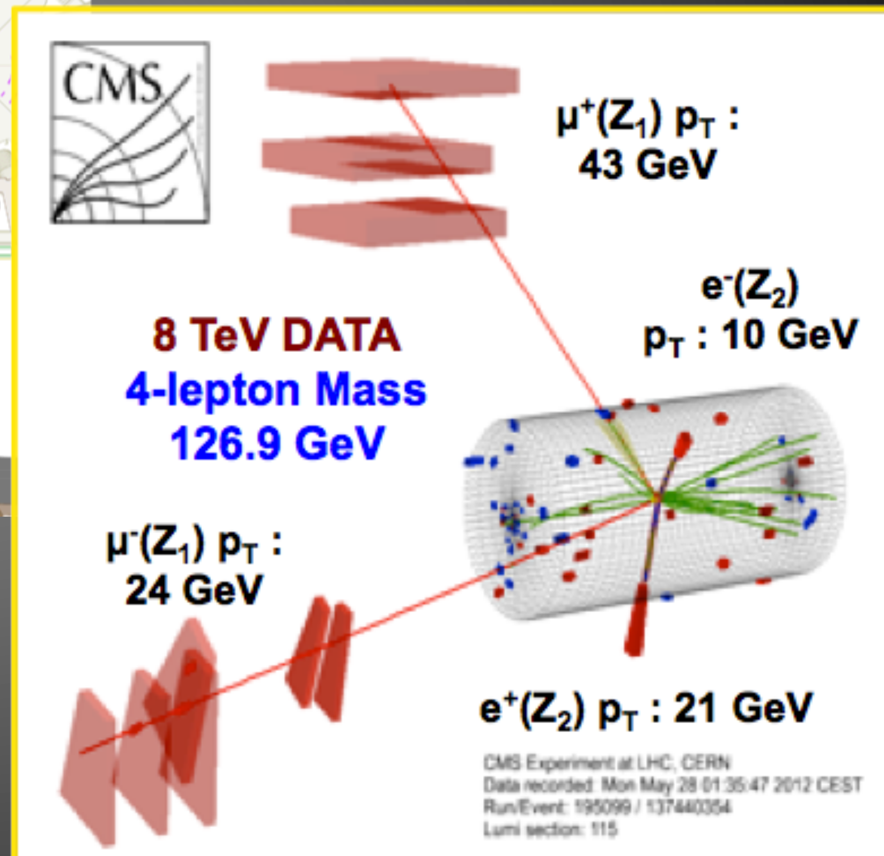


We see signals when the layers of the detector stop the particles as they fly out

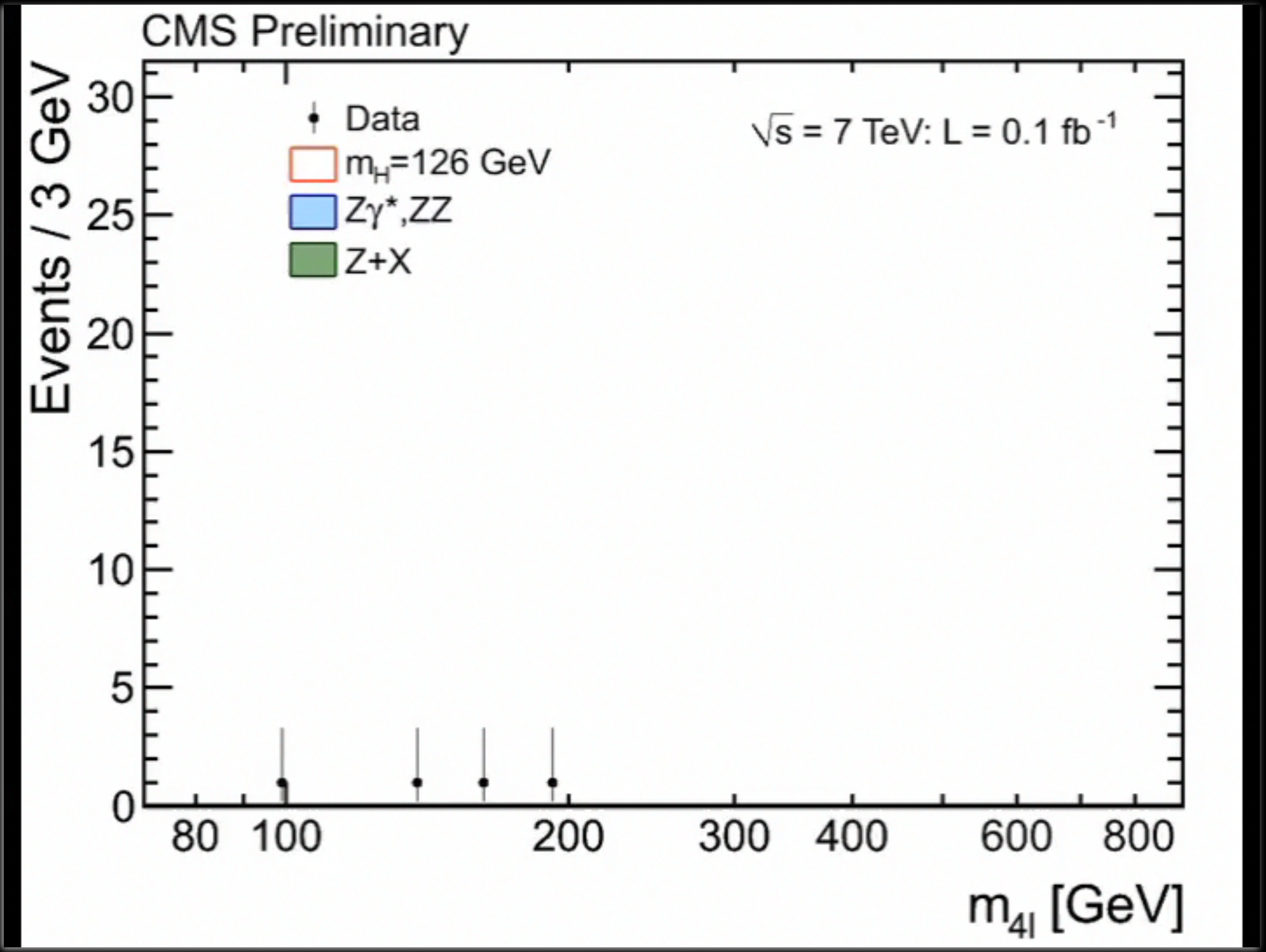
$\mathbf{H \to ZZ \to 4\ell}$

The Golden channel





The Discovery: Higgs → 4 Leptons with virtual Z bosons



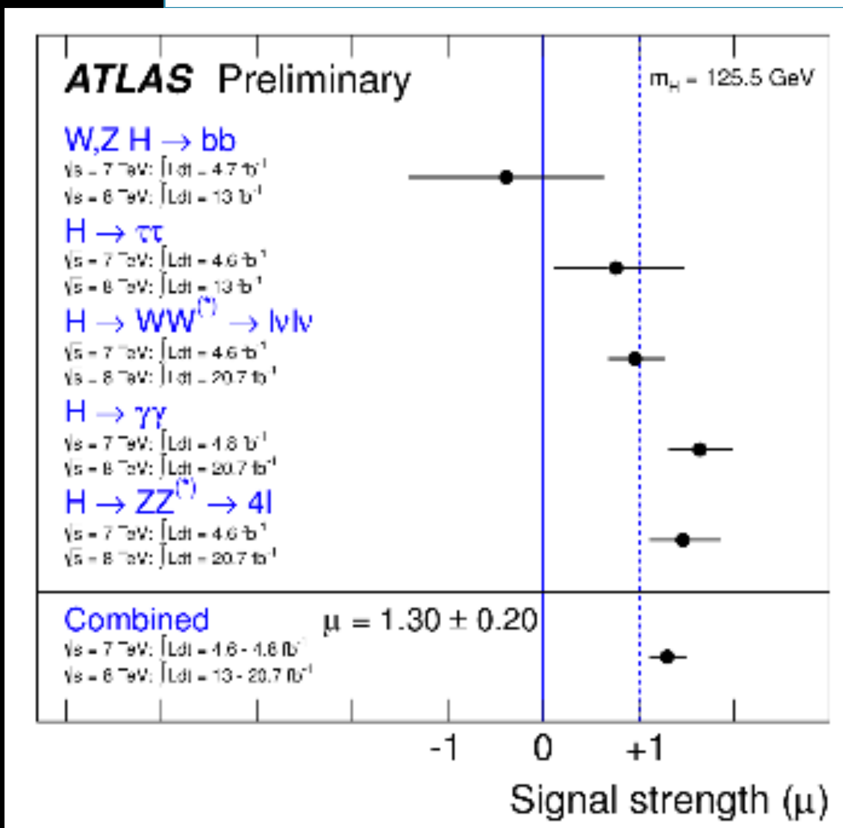
2012-2013: a revolutionary year for Physics

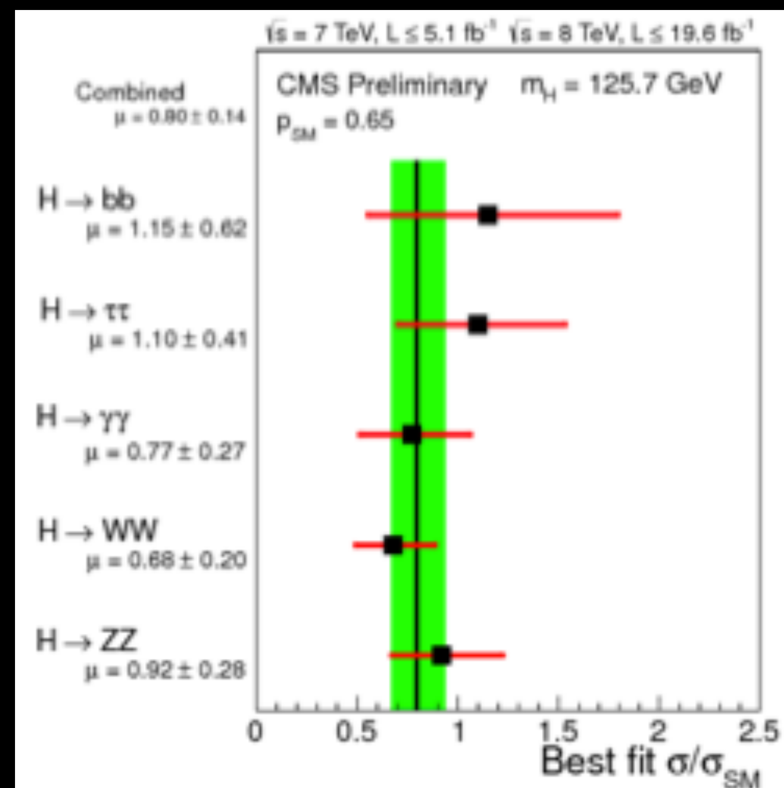
No doubt a new particle has been discovered

CMS: $m_h \sim 125.8$ GeV (in ZZ); $m_h = 124.9.$ GeV (in $\gamma\gamma$)

ATLAS: $m_h = 124.3$ GeV (in ZZ); $m_h = 126.8$ GeV (in $\gamma\gamma$)

Observation with a significance > 5 σ



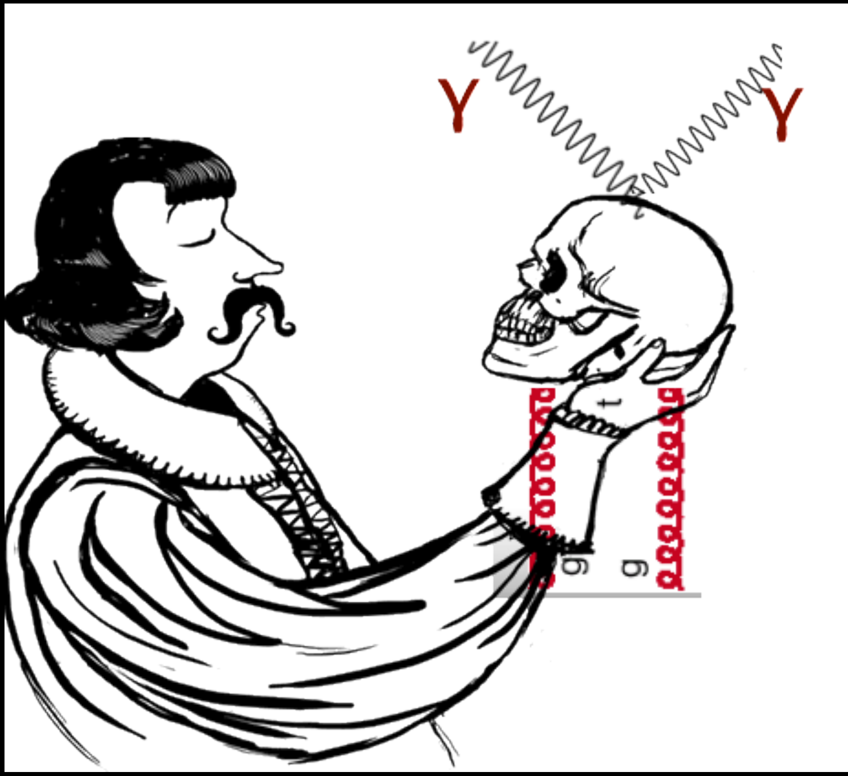


2012-2013: a revolutionary year for Physics

"The" Standard Model Scalar Boson, or not ....

- The PARTICLE of the July 4 discovery: is it THE Higgs boson that explains the mass of fundamental particles?

  ~1% of all the visible mass



- Is it THE STANDARD MODEL HIGGS , just a close relative or an impostor?

The Discovery of a Scalar boson like particle puts the final piece of the Standard Model in place

and marks the birth of the hierarchy problem: one of the main motivations for physics beyond the SM

The SM works beautifully,
no compelling hints for deviations

But many questions remain unanswered:

Dynamical Origin of electroweak symmetry breaking

Origin of generations and structure of Yukawa interactions

Matter-antimatter asymmetry

Unification of forces

Neutrino masses

Dark matter and dark energy

Hence, the "prejudice" (the hope) that there must be "New Physics"

What if the newly discovered particle is not *the SM Scalar?*

it can still be the scalar boson responsible for EWSB -

The SM Scalar Boson:

Spin 0

Neutral CP even component of a complex $SU(2)_L$ doublet with Y=1

Singlet under the residual SU(2) custodial symmetry after EWSB

==> $g_{WWH}/g_{ZZH} = m_W^2/m_Z^2$ at tree level

Couplings to SM fermions proportional to fermion masses

Self-coupling strength determined in terms of its mass

and v = 246 GeV

It could have non- Standard properties and still be “The Higgs”

Could be a mixture from more than one Higgs
[SUSY or other new forces in nature]

Could be a mixture of CP even and CP odd

Could be a composite particle

Could be partly a singlet or a triplet instead of an SU(2) doublet

Could have enhanced/suppressed coupling to photons or gluons if there are exotic heavy charged or colored particles

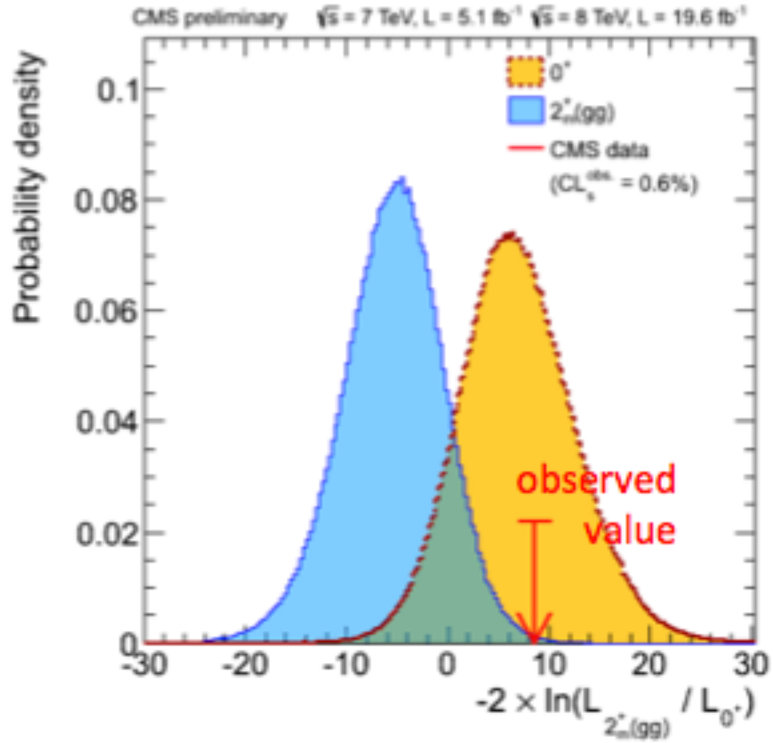
Could decay to exotic particles, e.g. dark matter

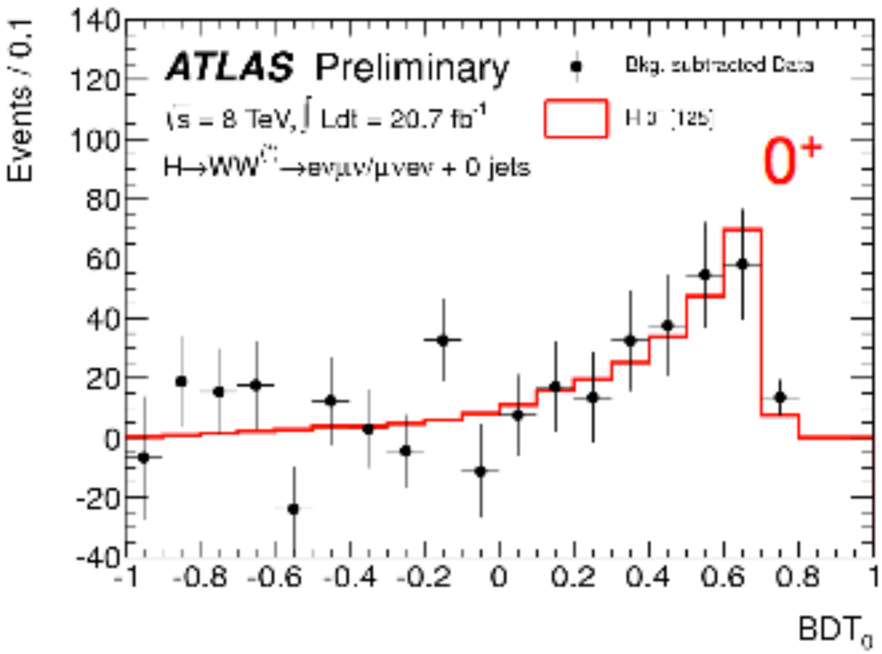
May not couple to matter particles proportional to their masses

Experiments are starting to answer these questions,
more data at higher energy needed (2015)

SPIN: Comnbined WW and ZZ results

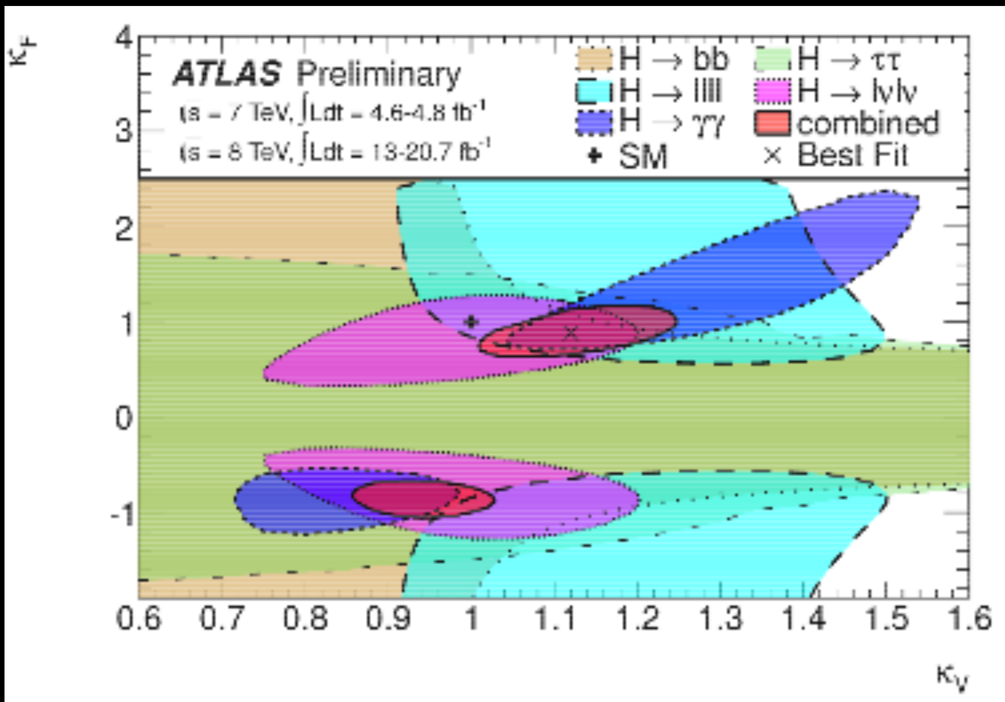
Test statistic comparing the signal J^P hypotheses 0^+ and $2^+_m(gg)$ in the best fit to the data.

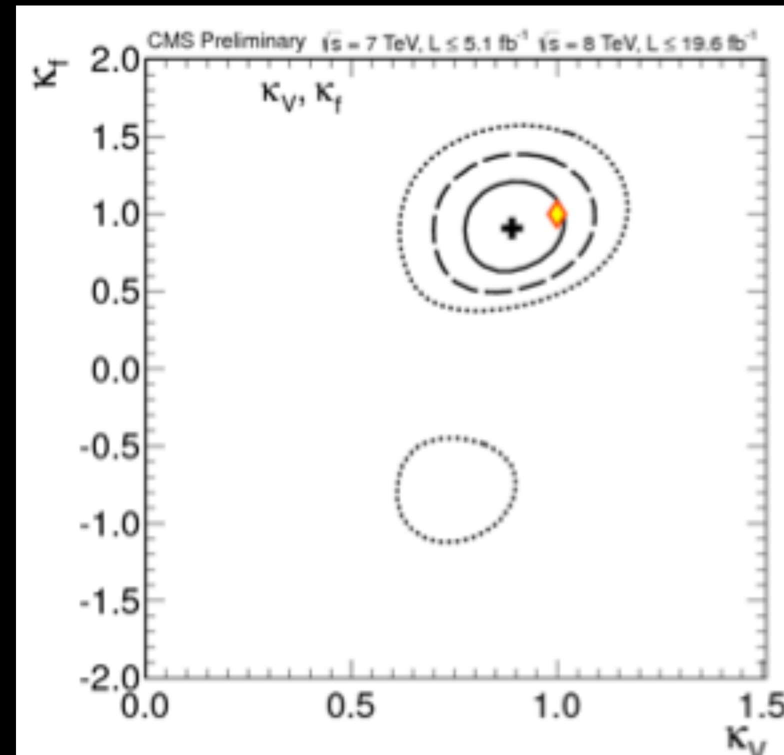




Fermion and Vector Couplings

non-zero and consistent with SM.





Vector coupling (κ_V) measured indirectly & directly in many channels

Fermion coupling (κ_F) measured:

-directly in H→bb and H→ττ – not well measured yet --

- indirectly via loop gg→H

The Generation of big hierarchy of scales:

- The hierarchy problem of the SM Higgs sector -

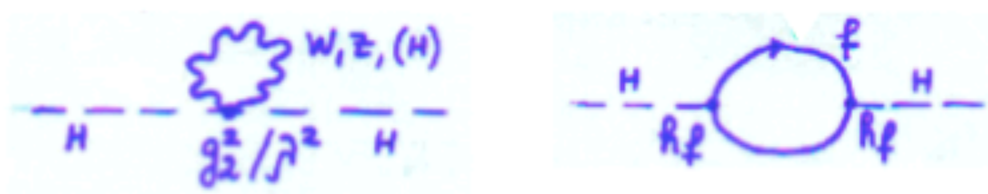
Why v $\ll$ M_{Pl}?

Quantum Corrections to the Higgs mass parameter diverge quadratically with the scale at which the SM is superseded by New Physics

$$\mu^2 = \mu^2(\Lambda_{eff.}) + \Delta\mu^2 \longrightarrow \Delta\mu^2 \approx \frac{n_W g_{hWW}^2 + n_h \lambda^2 - n_f g_{hf\bar{f}}^2}{16\pi^2} \Lambda^2_{eff.}$$

to explain v $\approx O(m_W)$

either $\Lambda_{eff.} \leq$ 1 TeV or extreme fine tuning to give cancellation

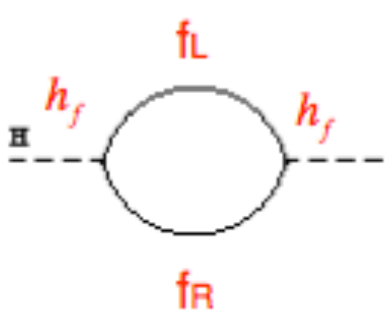


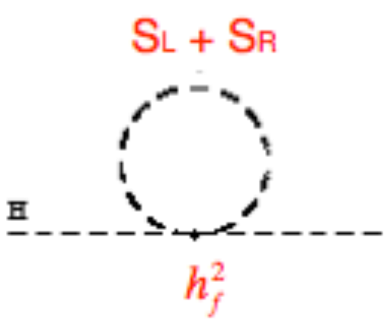
Quantum Corrections to the Higgs Mass Parameter

Quadratic Divergent contributions:

One loop corrections to the Higgs mass parameter cancel if the couplings of bosons and fermions are equal to each other

$$\delta m_H^2 = \frac{N_C h_f^2}{16\pi^2}\left[-2\Lambda^2 + 3m_f^2 \log\left(\frac{\Lambda^2}{m_f^2}\right) + 2\Lambda^2 - 2m_s^2 \log\left(\frac{\Lambda^2}{m_f^2}\right)\right]$$





If the mass proceeds from a v.e.v of H, cancellation of the log terms is ensured by the presence of an additional diagram induced by trilinear Higgs couplings. The fermion and scalar masses are the same in this case: $m_f = m_s = h_f\, \boldsymbol{v}$

Supersymmetry is a symmetry between bosons and fermions that ensures the equality of couplings and masses

Automatic cancellation of loop corrections to the Higgs mass parameter

The Existence of the Higgs Boson

- Creates a mathematical challenge

that calls for a new symmetry of nature

SUPERSYMMETRY

LHC experiments search for SUSY particles

SUSY predicts at least five kinds of Higgs bosons,

differing in their mass and other properties

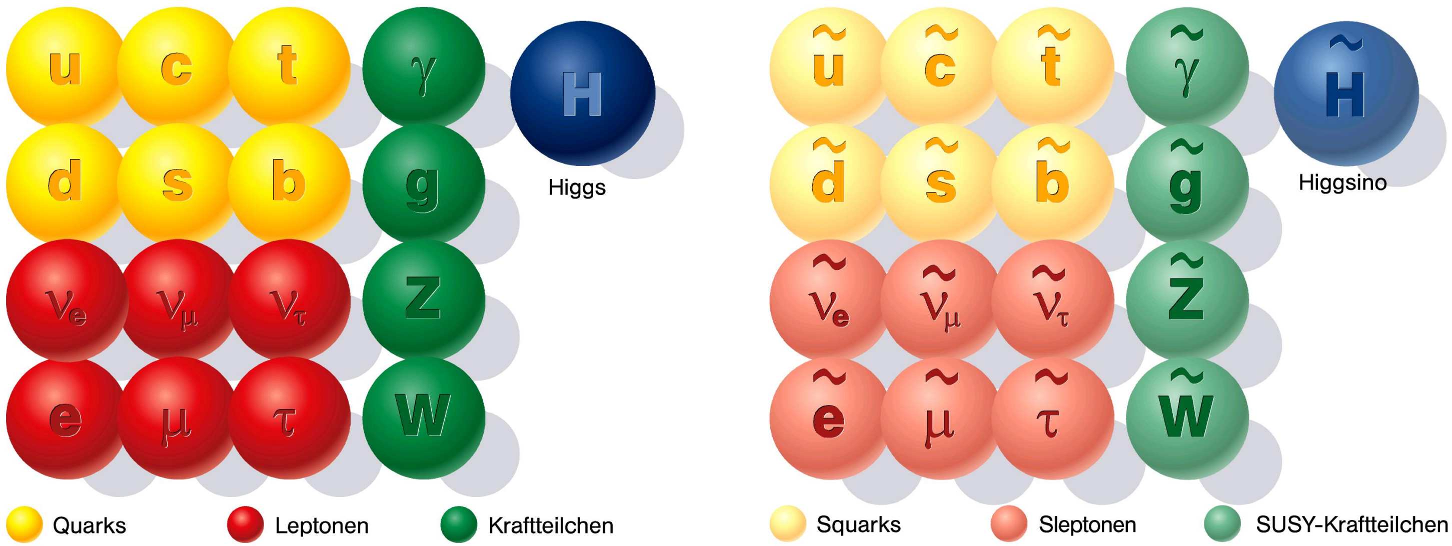
No discovery, YET

SUPERSYMMETRY

lesson from history: electron self energy ⟶ fluctuations of em fields generate a quadratic divergence but existence of electron antiparticle cancels it

Will history repeat itself? Take SM and double particle spectrum

New Fermion-Boson Symmetry: SUPERSYMMETRY (SUSY)



No new dimensionless couplings

Couplings of SUSY particles equal to couplings of SM particles

For every fermion there is a boson of equal mass and couplings

Why Supersymmetry?

- Helps stabilize the weak scale-Planck scale hierarchy
- SUSY algebra contains the generator of space translations
  $\longrightarrow$ necessary ingredient of theory of quantum gravity
- Allows for Gauge Coupling Unification at a scale ~ 10^{16} GeV
- Starting from positive Higgs mass parameters at high energies, induces electroweak symmetry breaking radiatively.
- Provides a good Dark matter candidate:
  The Lightest SUSY Particle (LSP)
- Provides possible solutions to the baryon asymmetry of the universe.

SUSY Lagrangian

$$\mathcal{L}_{\rm SUSY} = (\mathcal{D}_\mu A_i)^\dagger \mathcal{D} A_i + \left(\frac{i}{2}\bar\psi_i \bar\sigma^\mu \mathcal{D}_\mu \psi_i + \text{h.c.}\right)$$
$$- \frac{1}{4}(G^a_{\mu\nu})^2 + \left(\frac{i}{2}\bar\lambda^a \bar\sigma^\mu \mathcal{D}_\mu \lambda^a + \text{h.c.}\right)$$
$$- \left(\frac{1}{2}\frac{\partial^2 P(A)}{\partial A_i \partial A_j}\psi_i\psi_j - i\sqrt{2} g A_i^* T_a \psi_i \lambda^a + h.c.\right) - V_{scalar}$$

SM fermion superpartners + Higgs

SM fermions + Higgsinos

Gauginos

Yukawa interactions

Novel gaugino-scalar-fermion interaction

Gauge bosons in covariant derivatives and in $G_{\mu\nu}$

$$V_{scalar} = \sum_i \left|\frac{\partial P(A)}{\partial A_i}\right|^2 + \frac{1}{2}\sum_a \left(g \sum_i A_i^* T^a A_i\right)^2$$

Quartic couplings governed by gauge couplings crucial for Higgs sector

The Superpotential: $P(A) = \frac{m_{ij}}{2} A_i A_j + \frac{\lambda_{ijk}}{6} A_i A_j A_k$

The superpotential parameters determine the matter field masses and give equal masses to fermions and scalars when the Higgs acquires a v.e.v

$$m_f^2 = m_s^2 = \lambda_{ffh}^2 \, \text{v}^2$$

SUSY Generators

Supersymmetric transformations relate bosonic to fermionic degrees of freedom

the operator Q that generates that transformation acts, schematically

$$Q|B>=|F> \quad Q|F>=|B> \qquad Q^\dagger|B>=|F> \quad Q^\dagger|F>=|B>$$

The SUSY generators, Q and $Q^\dagger$, are two-component anti-commuting spinors satisfying:

$$\{Q_\alpha, Q^\dagger_\alpha\} = 2\sigma^\mu_{\alpha\dot{\alpha}} P_\mu \qquad \{Q_\alpha, Q_\beta\} = \{Q^\dagger_\alpha, Q^\dagger_\beta\} = 0 \qquad [Q_\alpha, P^\mu] = [Q^\dagger_{\dot{\alpha}}, P^\mu] = 0$$

$$\text{where } \sigma^\mu = (I, \vec{\sigma}), \quad \bar{\sigma}^\mu = (I, -\vec{\sigma}), \text{ and } \sigma^i \text{ are Pauli Matrices}$$

$P^\mu = (H, \vec{p})$ is the generator of spacetime translations: part of the SUSY algebra

The Minimal SUSY extension of the Standard Model (MSSM)

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(×3 families)	U	$\widetilde{u}^*_R$	$(u^C)_L$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	D	$\widetilde{d}^*_R$	$(d^C)_L$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	E	$\widetilde{e}^*_R$	$(e^C)_L$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \;\; H_u^0)$	$(\widetilde{H}_u^+ \;\; \widetilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \;\; H_d^-)$	$(\widetilde{H}_d^0 \;\; \widetilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

Matter Superfields

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^{\pm} \;\; \widetilde{W}^0$	$W^{\pm} \;\; W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Gauge Superfields

The winos and bino are not mass eigenstates, they mix with each other and with the Higgs superpartners, called higgsinos, of the same charge

The Higgs Sector: two Higgs fields with opposite hypercharges

2 Higgs doublets necessary to give mass to both up and down quarks and leptons in a gauge/SUSY invariant way

2 Higgsino doublets necessary for anomaly cancellation

Names		spin 0	spin 1/2	$SU(3)_C,\, SU(2)_L,\, U(1)_Y$
Higgs, higgsinos	H_u	$(H_u^+ \;\; H_u^0)$	$(\widetilde{H}_u^+ \;\; \widetilde{H}_u^0)$	$(\,\mathbf{1},\, \mathbf{2}\,,\, +\frac{1}{2})$
	H_d	$(H_d^0 \;\; H_d^-)$	$(\widetilde{H}_d^0 \;\; \widetilde{H}_d^-)$	$(\,\mathbf{1},\, \mathbf{2}\,,\, -\frac{1}{2})$

- Both Higgs fields acquire v.e.v. New parameter, $\tan\beta = v_2/v_1$.

Both Higgs fields contribute to the superpotential and give masses to up and down/lepton sectors, respectively

$H_1 \equiv H_d$
$H_2 \equiv H_u$

$$P[\phi] = h_u Q U H_2 + h_d Q D H_1 + h_l L E H_1$$

With two Higgs doublets, a mass term may be written $\delta P[\phi] = \mu H_1 H_2$

Interesting to observe:

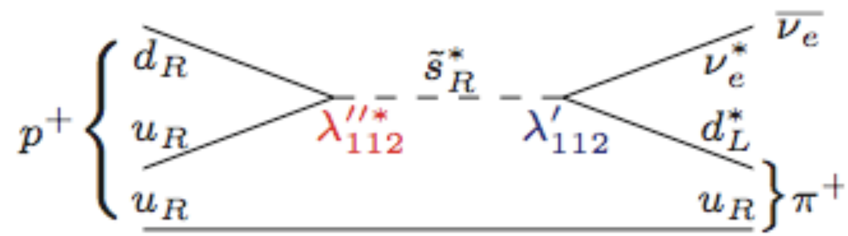
The quantum numbers of H_1 are the same as those of the lepton superfield L. One can add terms in the superpotential replacing H_1 by L

Dangerous Baryon and Lepton Number Violating Interactions

$$P[\Phi]_{new} \rightarrow \begin{array}{l} P_{\Delta L=1} = \frac{1}{2}\lambda_{ijk}L_iL_jE_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \mu'_iL_iH_u \\ P_{\Delta B=1} = \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k \end{array}$$

If both types of couplings were present, and of order 1, then the proton would decay in a tiny fraction of a second through diagrams like this:

Proton Decay



One cannot require B and L conservation since they are already known to be violated at the quantum level in the SM.
Instead, one postulates a new discrete symmetry called **R-parity.**

$$P_R = (-1)^{3(B-L)+2S}$$

All SM particles have $P_R = 1$

All Supersymmetric partners have $P_R = -1$

Important Consequences of R-Parity Conservation

Since SUSY partners are R-parity odd (have $P_R = -1$)

every interaction vertex must contain an even number of SUSY particles

- All Yukawa couplings induced by $P(\Phi)_{new}$ are forbidden (have and odd number of SUSY particles)

- The Lightest SUSY Particle (LSP) must be absolutely stable

If electrically neutral, interacts only weakly with ordinary matter

LSP is a good Dark Matter candidate

- In collider experiments SUSY particles can only be produced in even numbers (usually in pairs)

- Each sparticle eventually decays into a state that contains an LSP
==> Missing Energy Signal at colliders

Supersymmetry Breaking

If SUSY were an exact symmetry, the SM particles and their superpartners would have the exactly same masses

$m_{\tilde{e}_L} = m_{\tilde{e}_R} = m_e = 0.511$ MeV

$m_{\tilde{u}_L} = m_{\tilde{u}_R} = m_u$

$m_{\tilde{g}} = m_{\text{gluon}} = 0 +$ QCD-scale effects

etc.

- No supersymmetric particle have been seen: Supersymmetry is broken in nature
- Unless a specific mechanism of supersymmetry breaking is known, no information on the spectrum can be obtained.
- Cancellation of quadratic divergences:
  - Relies on equality of couplings and not on equality of the masses of particle and superpartners. →
- Soft Supersymmetry Breaking: Give different masses to SM particles and their superpartners but preserves the structure of couplings of the theory.

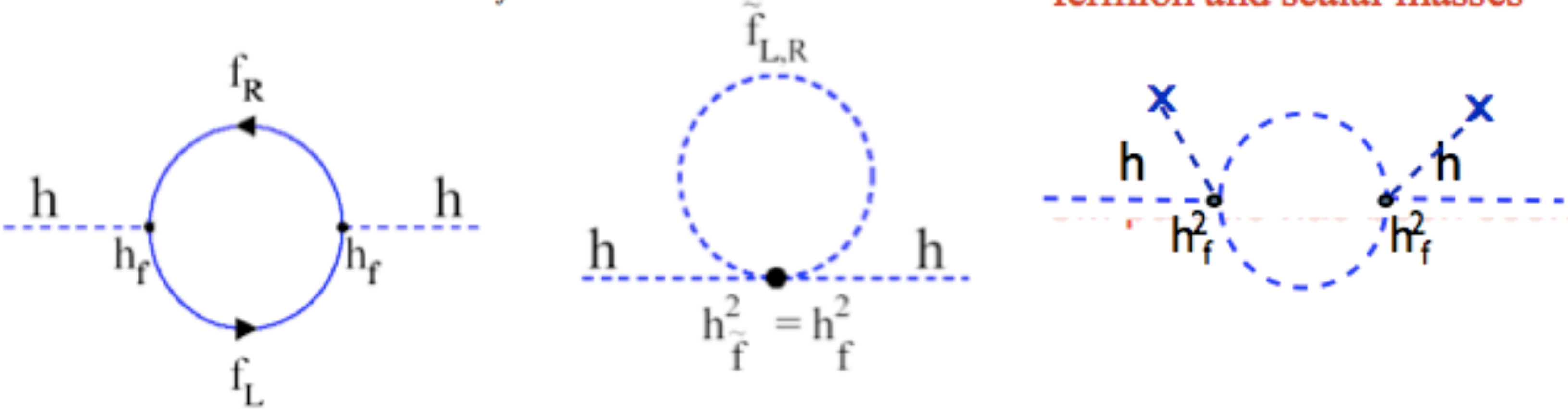
SUSY must be broken in nature

Back to SUSY corrections to the Higgs mass parameter:

Cancellation of quadratic divergences in Higgs mass quantum corrections has to do with SUSY relation between couplings and bosonic and fermionic degrees of freedom

$$\Delta\mu^2 \approx g^2_{hf\bar{f}}[m_f^2 - m_{\tilde{f}}^2]\ln(\Lambda^2_{eff} / m_h^2)$$

not with the exact equality of fermion and scalar masses



In low energy SUSY: quadratic sensitivity to Λ_{eff} replaced by quadratic sensitivity to SUSY breaking scale

The scale of SUSY breaking must be of order 1 TeV, if SUSY is associated with the scale of electroweak symmetry breaking

Soft Supersymmetry Breaking:

Give different masses to SM particles and their superpartners, but preserves the structure of couplings of the theory

Gaugino masses, squark/slepton squared mass terms and trilinear/biliniar terms prop. to scalar superpotential do not spoil cancellation of quadratic divergences

$$\mathcal{L}_{soft} = -\frac{1}{2}(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B})$$
$$-m_Q^2\tilde{Q}^\dagger\tilde{Q} - m_U^2\tilde{U}^\dagger\tilde{U} - m_D^2\tilde{D}^\dagger\tilde{D} - m_L^2\tilde{L}^\dagger\tilde{L} - m_E^2\tilde{E}^\dagger\tilde{E}$$
$$-m_{H_1}^2H_1^*H_1 - m_{H_2}^2H_2^*H_2 - (\mu BH_1H_2 + cc.)$$
$$-(A_uh_u\tilde{U}\tilde{Q}H_2 + A_dh_d\tilde{D}\tilde{Q}H_1 + A_lh_l\tilde{E}\tilde{L}H_1) + c.c.$$

Trilinear terms are proportional to the Yukawa couplings

→ induce L-R mixing in the sfermion sector once the Higgs acquire v.e.v. mixing proportional to fermion masses: relevant for 3rd generation

B → SUSY breaking parameter to be determined from condition of proper EWSB

MSSM: 105 new parameters not present in the SM

Most of what we do not really know about SUSY is expressed by the question: "How is SUSY broken?"

The specific pattern of SUSY sparticle masses depend on the SUSY breaking scenario. The crucial question is how much can we learn about it from collider and astroparticle physics experiments

The SUSY Particles of the MSSM

Names	Spin	P_R	Mass Eigenstates	Gauge Eigenstates
Higgs bosons	0	+1	$h^0\ H^0\ A^0\ H^\pm$	$H_u^0\ H_d^0\ H_u^+\ H_d^-$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	" "
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	" "
			$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$	$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	" "
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	" "
			$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$
charginos	1/2	−1	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$
gluino	1/2	−1	$\widetilde{g}$	" "

What does a 125 GeV Scalar Boson mean for SUSY Models?

2 CP-even h, H with mixing angle α

1 CP-odd A and a charged pair $H^{\pm}$ with mixing angle β

$\tan\beta = v_2/v_1$

$v = \sqrt{v_1^2 + v_2^2}$

$$m_A^2 = m_1^2 + m_2^2 = m_{H_1}^2 + m_{H_2}^2 + 2\mu^2$$

$m_{H_1}^2 + m_{H_2}^2$ → Soft SUSY breaking Higgs mass parameters

$$m_{H^\pm}^2 = m_A^2 + M_W^2 \qquad m_H^2 \simeq m_A^2$$

$$m_h^2 \cong M_Z^2 \cos^2 2\beta$$ (tree level)

- Quartic couplings determined by SUSY as a function of the gauge couplings

  -- lightest (SM-like) scalar boson strongly correlated to Z mass (naturally light!)

  -- other scalar bosons can be as heavy as the SUSY breaking scale

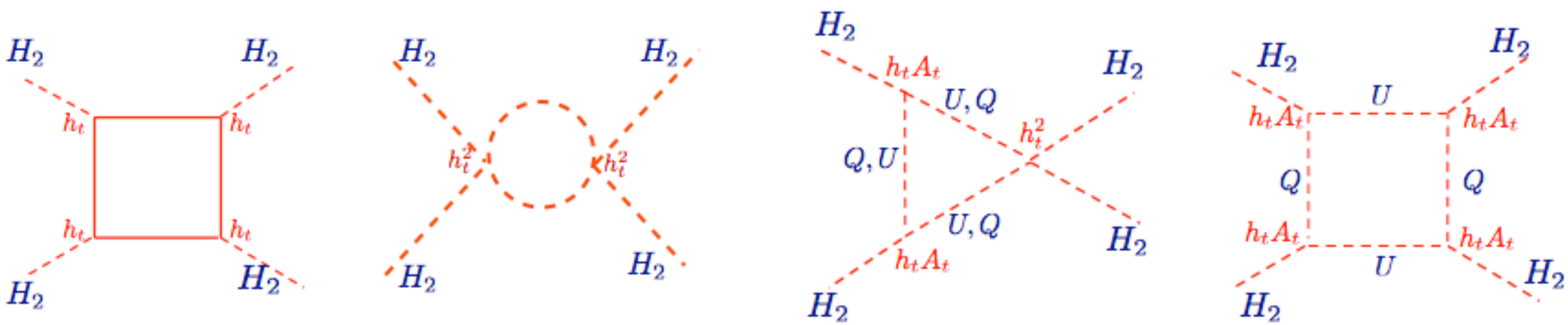
- Important quantum corrections to the lightest Scalar boson mass due to incomplete cancellation of top and stop contributions in the loops

Lightest SM-like Scalar boson mass strongly depends on:

CP-odd mass m_A, $\tan\beta$,

M_{top}

Stop masses and mixing → $M^2_{\tilde{t}} = \begin{pmatrix} m^2_Q + m^2_t + D_L & m_t X_t \\ m_t X_t & m^2_U + m^2_t + D_R \end{pmatrix}$

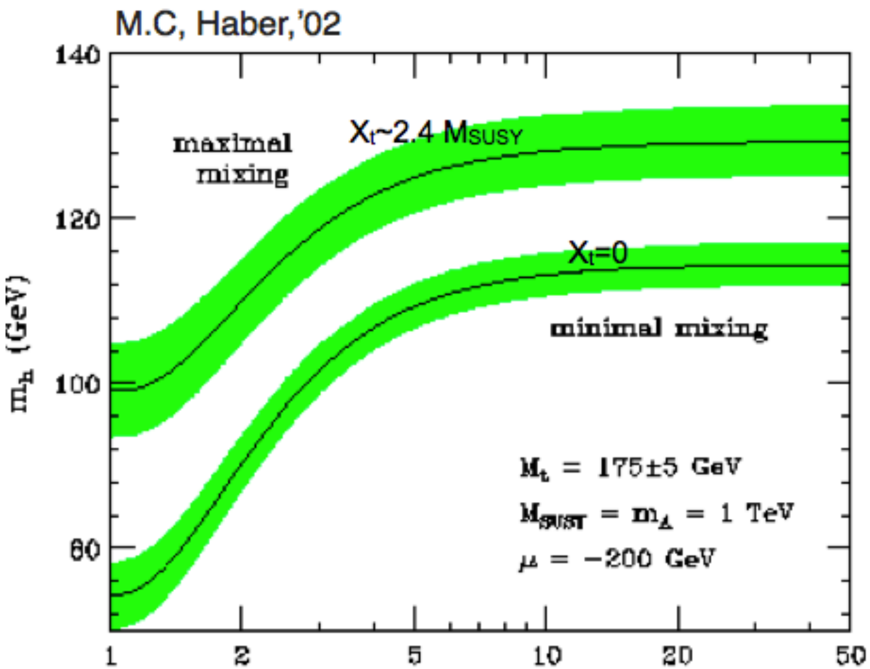


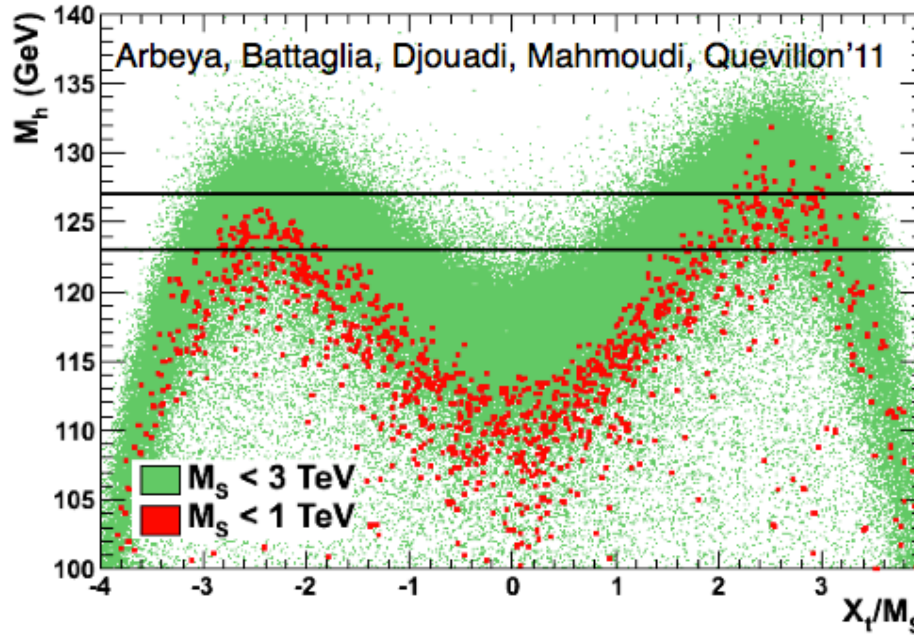
For moderate to large values of tan beta and large non-standard Scalar boson masses

$$m_h^2 \simeq M_Z^2 cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left[log\left(\frac{M^2_{SUSY}}{m_t^2}\right) + \frac{X_t^2}{M^2_{SUSY}}\left(1 - \frac{X_t^2}{12 M^2_{SUSY}}\right)\right]$$

$t = \log(M^2_{SUSY}/m_t^2)$ **$M_{SUSY} \sim m_Q \sim m_U$** $X_t = A_t - \mu/\tan\beta$ → LR stop mixing

SM-like MSSM Scalar Boson Mass:





$$m_h \leq 130\ \text{GeV}$$

(for sparticles of ~ 1 TeV)

Many contributions to two-loop calculations
Brignole, M.C., Degrassi, Diaz, Ellis, Haber, Hempfling, Heinemeyer, Hollik, Espinosa, Martin, Quiros, Ridolfi, Slavich, Wagner, Weiglein, Zhang, Zwirner, …

Given the Discovery of a SM-like Scalar boson particle with mass ~ 125 GeV

- Do we still expect SUSY (some type of low energy SUSY) ?

- If yes, what does it imply for SUSY models?

large mixing in the stop sector

or

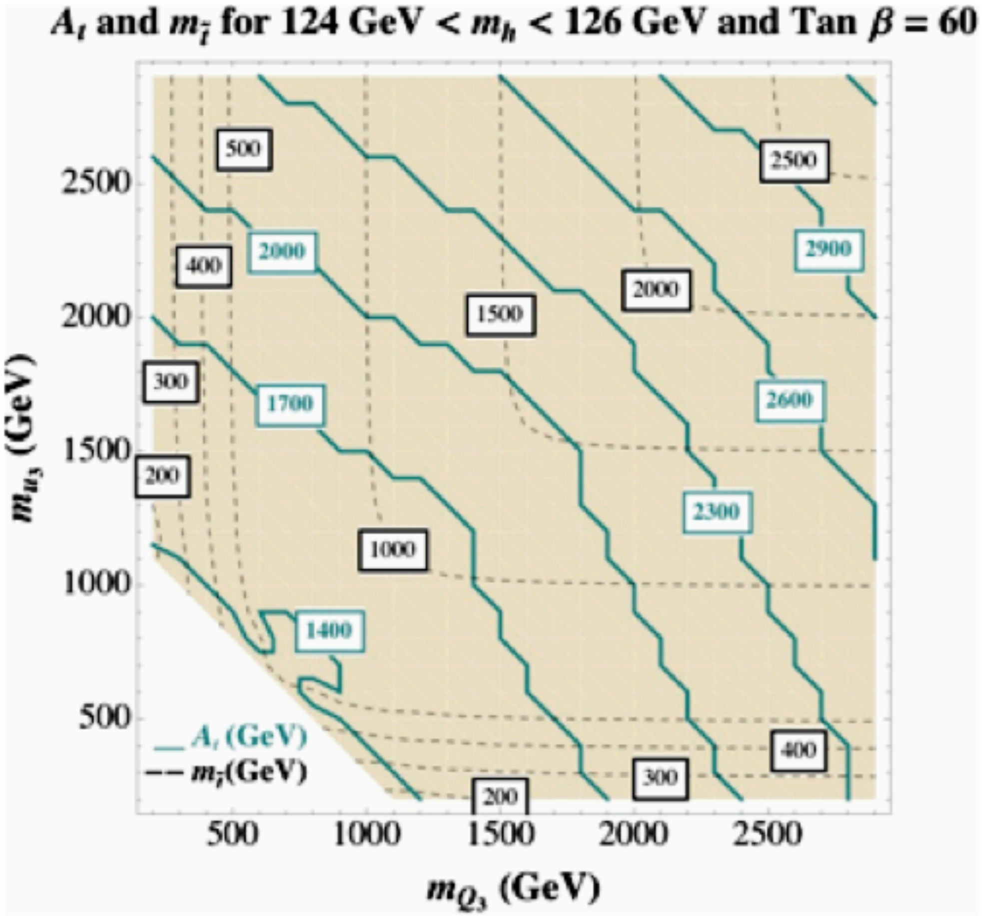
new matter or gauge superfields

Both alternatives have important implications for the Higgs production and decay rates

They also have implications for the flavor-Higgs connection within assumption of MFV at the SUSY breaking scale

Soft supersymmetry Breaking Parameters

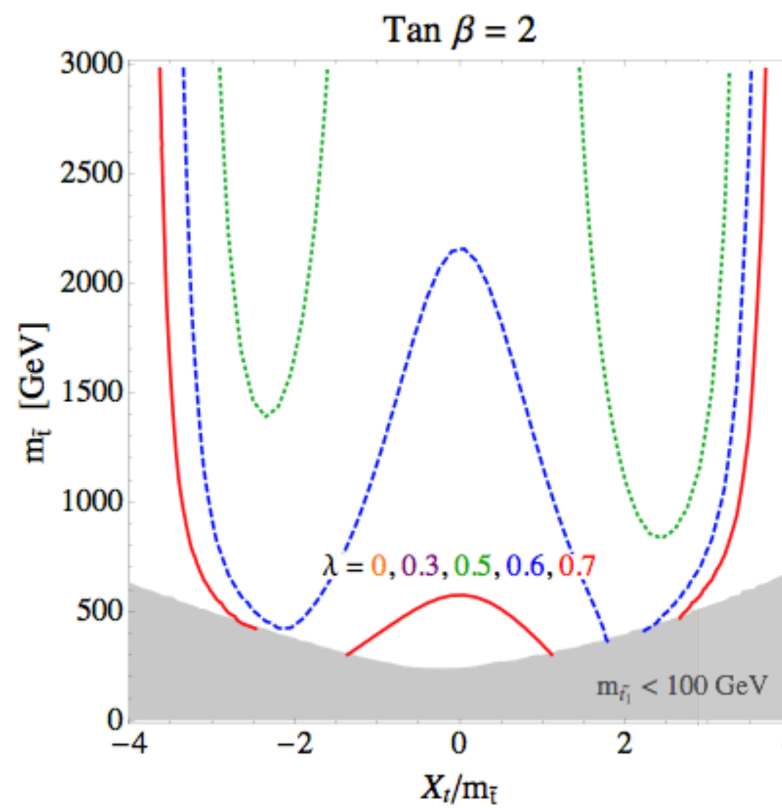
MSSM



M. C., S. Gori, N. Shah, C.Wagner '11 +L.T.Wang '12

Similar results from
Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon '11
Draper Meade, Reece, Shih'11

NMSSM



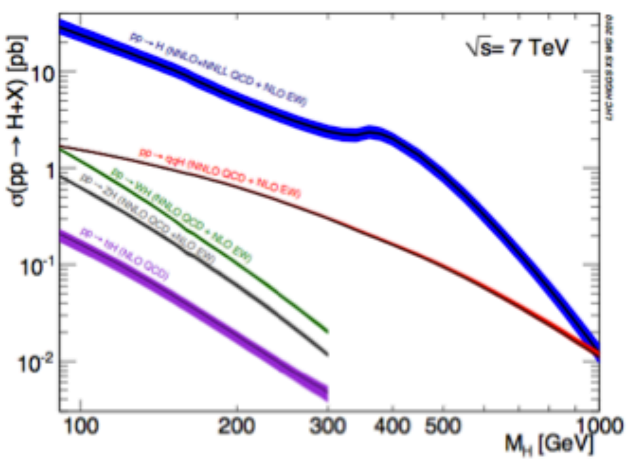
Hall, Pinner, Ruderman'11

Ellwanger. 12
Benbrik, Bock, Heinemeyer, Stal, Weiglein, Zeune'12
Gunion, Jiang, Kraml '12

Can departures from the SM in the production/decay rates at the LHC disentangle among different SUSY spectra?

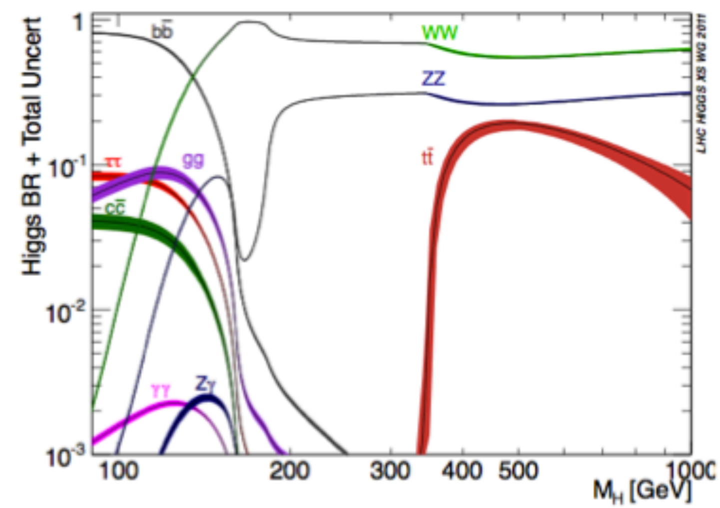
The event rates: $B\sigma(p\bar{p} \to h \to X_{\rm SM}) \equiv \sigma(p\bar{p} \to h) \dfrac{\Gamma(h \to X_{\rm SM})}{\Gamma_{\rm total}}$

- All three quantities may be affected by new physics.
- If one partial width is modified, the total width is modified as well, modifying all BR's.



Main production channel:
Gluon Fusion

Main/first search modes:
decay into γγ/ZZ/WW



How much can we perturb the gluon production mode?

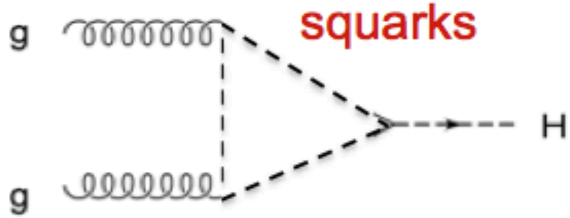
Is it possible to change WW and ZZ decay rates independently?

Can we vary the Higgs rate into di-photons independently from the rate into WW/ZZ?

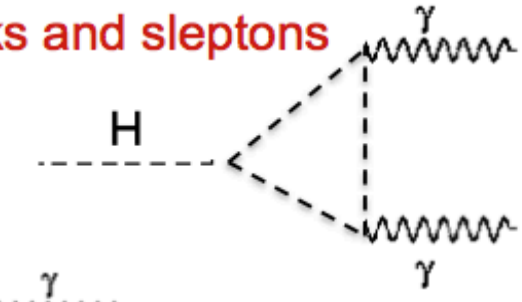
Can we change the ratio of b-pair to tau pair decay rates?

Possible departures in the production and decay rates at the LHC

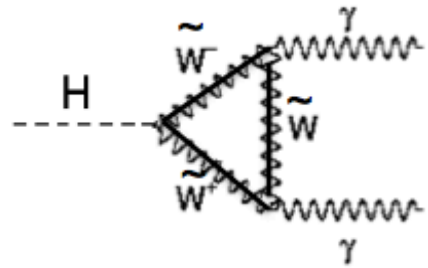
- Through SUSY particle effects in loop induced processes



squarks



squarks and sleptons



charginos

❖ Through enhancement/suppression of the Hbb and Hττ coupling strength via mixing in the scalar boson sector :
This affects in similar manner BR's into all other particles

❖ Through vertex corrections to Yukawa couplings: different for bottoms and taus
This destroys the SM relation $BR(h \to bb)/BR(h \to \tau\tau) \sim m_b^2/m_\tau^2$

❖ Through decays to new particles (including invisible decays)
This affects in similar manner BR's to all SM particles

- MSSM ==> Large stop mixing necessary ($A_t/M_Q \sim 1$) (figs.)
  No lower bound on lighter stop

Implications of light 3rd generation scalars on loop induced processes:

** light stops with the required mixing tend to slightly suppress gluon fusion

** light staus with sizeable mixing (large tan beta) may enhanced $\gamma\gamma$ up to 50 %
with SM-like ZZ/WW ;

**possible variation on Higgs-bb/$\tau\tau$ couplings due to Higgs mixing (A_τ induced
can further enhance di-boson rates,

** additional radiative corrections to fermion-Higgs couplings can suppress $\tau\tau$/
Higgs couplings ratio (a few % in bb and 15-20 % in tau tau)

- **Large mixing also constrains SUSY breaking model building**

NMSSM :At low tan beta, trade requirement on large stop mixing by sizeable trilinear Higgs-Higgs singlet coupling $\lambda \longrightarrow$ more freedom on gluon fusion production

- **Higgs mixing effects can be also triggered by extra new parameter λ**
- Higgs-Singlet mixing ==> wide range of ZZ/WW and Diphoton rates
- Light staus cannot enhance the di-photon rate (at low tanβ stau mixing is negligible)
- Light chargino at low tanβ can contribute to enhance the di-photon rate

Extensions with extra gauge groups: 125 GeV Higgs mass from D terms plus chargino contribution to the quartic (plus usual top-stop)

Enhancement of $\gamma\gamma$ rate from new (strong) charginos (~60% max. to avoid too large Higgs mass)

Models with mixtures of singlets, W' Z', triplets:

Higgs mass = 125 GeV easy to achieve for light stops, **small mixing**
Enhancement of h to di-photons due to bb suppression or light staus
Higgs cascade decays from large splitting in masses : h/H to AA

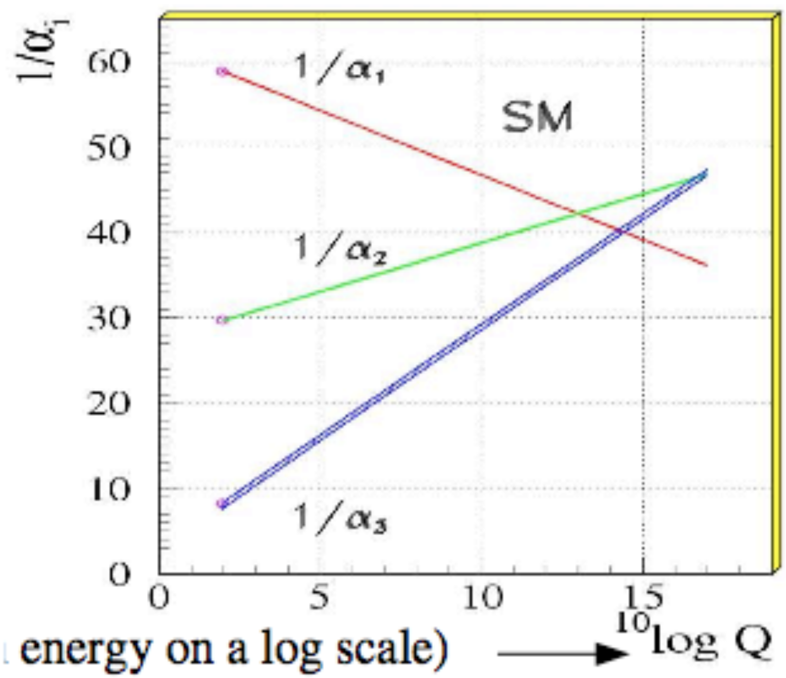
Split SUSY: (no extra light scalars below 100-1000 TeV)
$\longrightarrow$ diphoton rate constrained to be about the SM value

Low Energy Supersymmetry

If SUSY exists, many of its most important motivations demand some SUSY particles at the TeV scale

SUSY particles at the TeV scale allow Unification of Gauge Couplings

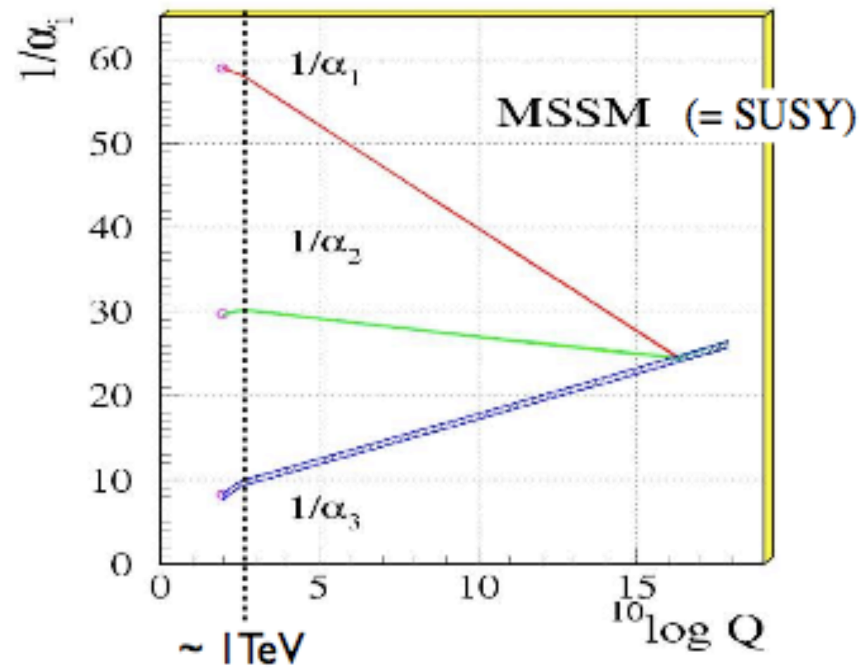
SM: couplings tend to converge at high energies but unification is quantitatively ruled out



MSSM:

Unification at $\alpha_{GUT} \simeq 0.04$

and $M_{GUT} \simeq 10^{16}$ GeV



Experimentally, $\alpha_3(M_Z) \simeq 0.118 \pm 0.004$ — Bardeen, M.C., Pokorski & Wagner

in the MSSM: $\alpha_3(M_Z) = 0.127 - 4(\sin^2\theta_W - 0.2315) \pm 0.008$

Remarkable agreement between Theory and Experiment!!

EWSB IN SUSY: radiatively generated

mSUGRA (CMSSM) example:

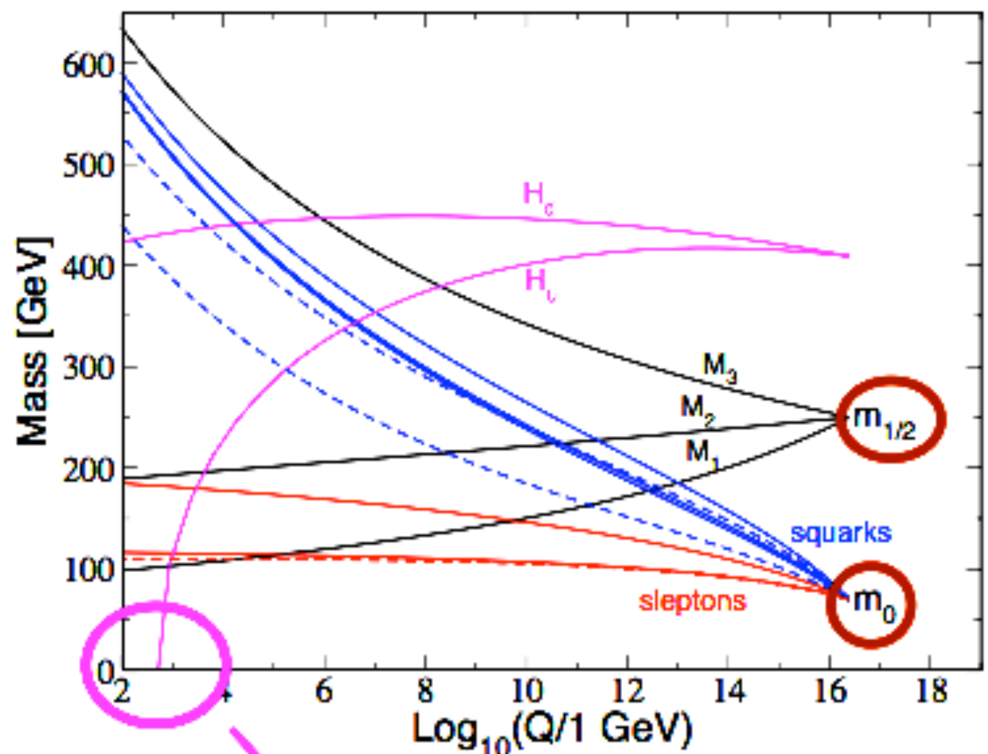
Renormalization group running of the soft SUSY breaking parameters starting with common values m_0 and $M_{1/2}$ for sfermion and guagino masses, respectively

Gaugino masses M_1, M_2, M_3

Slepton masses (dashed=stau)

Squark masses (dashed=stop)

Higgs: $(m_{H_u}^2 + \mu^2)^{1/2}$, $(m_{H_d}^2 + \mu^2)^{1/2}$



Electroweak symmetry breaking occurs because $m_{H_u}^2 + \mu^2$ runs negative near the electroweak scale. This is due directly to the large top quark Yukawa coupling.

SUSY & particle physics

- Stabilization of the weak scale – Planck scale hierarchy
- Super-space algebra contains the generator of space-time translations

  → possible ingredient for SUPERGRAVITY

- Starting from positive masses at high energies:

  electroweak symmetry breaking is induced radiatively

- Minimal SUSY extension of the Standard Model

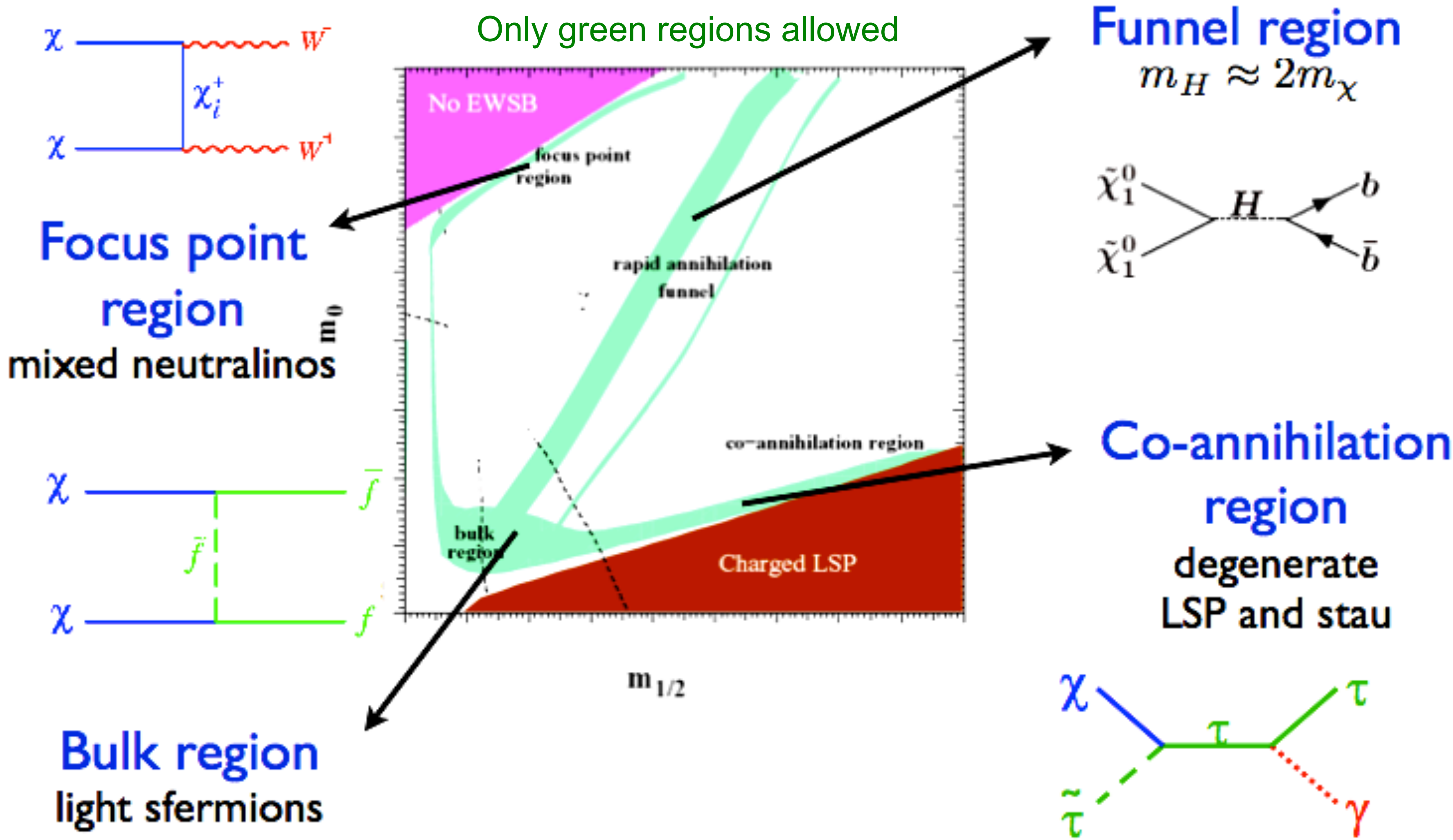
  leads to Unification of Gauge Couplings

SUSY & COSMOLOGY

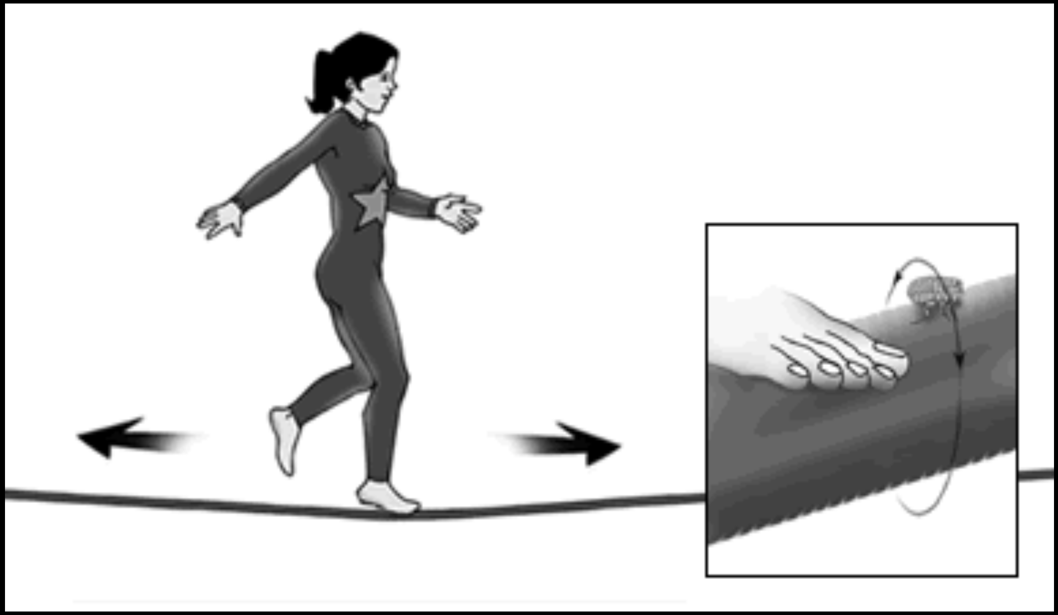
- Dark Matter
- Baryon Asymmetry

Dark Matter density strongly restricts viable models

LSP annihilation cross section is typically suppressed for most regions of SUSY spectrum → too much relic density



Extra Dimensions of Space



- **A Higgs**
- **Dark Matter**

How would we "see" them at colliders?

- Missing Energy: copies of the graviton disappearing in ED
- New particles with masses in an ascending ladder
- Black Holes

Deep Connections

The Higgs

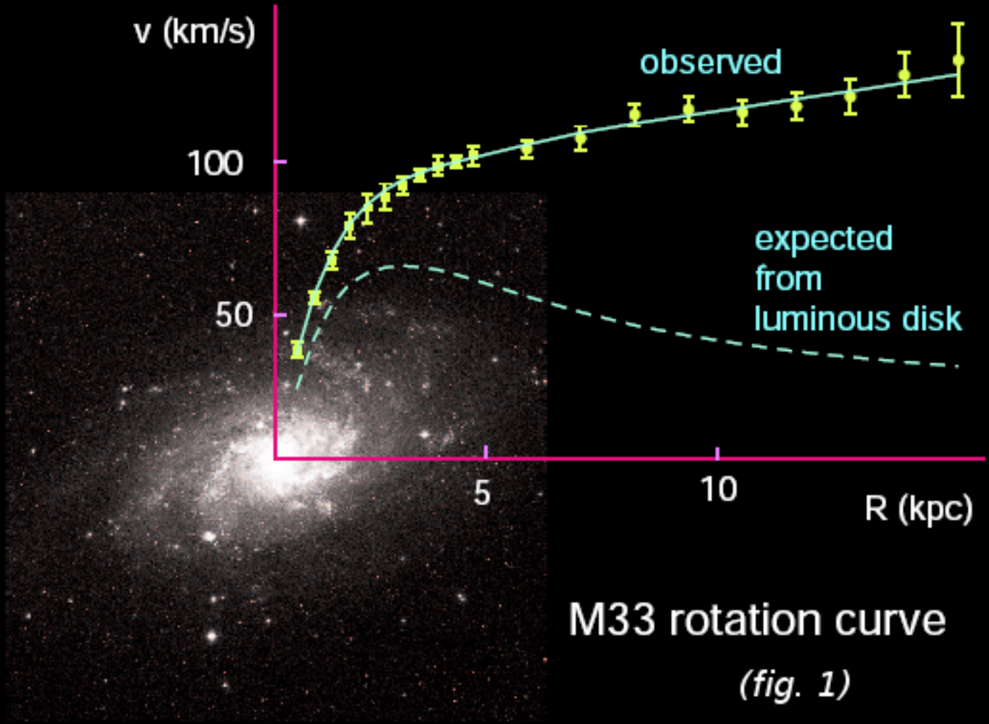
and the Mysteries of Matter

The Dark Universe

Fritz Zwicky

Vera Rubin

The rotational velocity of galaxies



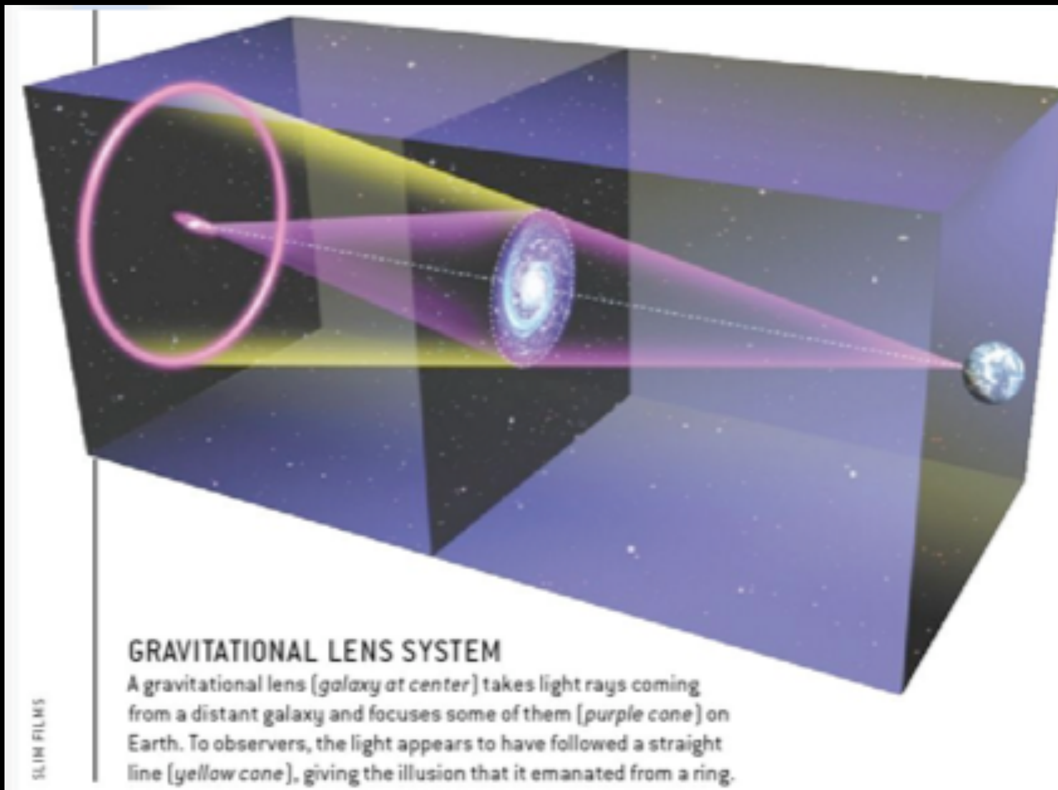
M33 rotation curve

(fig. 1)

There must be a lot of matter that we cannot see

Dark Matter ~ 85% of all the matter in the universe!

How to see Dark Matter?



Light deflection due to warping of space near massive objects: gravitational lensing

The power of the dark side

Holds the Universe Together

What is dark matter?

What are its properties?

Does it have substructure?

How will we find it?

The power of the dark side

Holds the Universe Together

Astrophysics and Cosmology taught us

- Not atoms (non-baryonic)
- moves slow (cold dark matter)

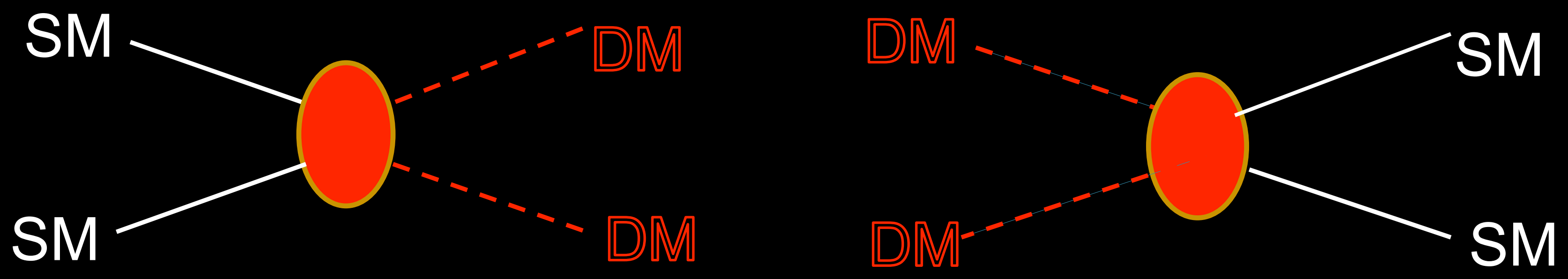
Interacts very weakly
(not charged)

→ **Gravity**

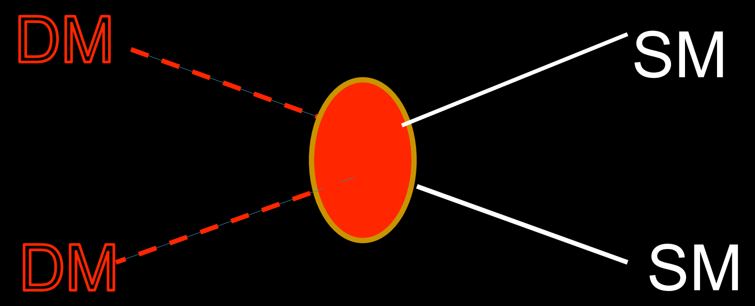
→ **Higgs-like Interactions?**

The History of the Dark Matter Abundance

- Dark matter produced in the hot early Universe can pair-wise annihilate (thermal equilibrium)



- Dark Matter density decreases as the Universe expands



- ***<u>Finally DM annihilation stops</u>***

The *smaller* the rate for pair annihilation,

the *larger* is the Dark Matter abundance (relic) observed today

Dark Matter Relic

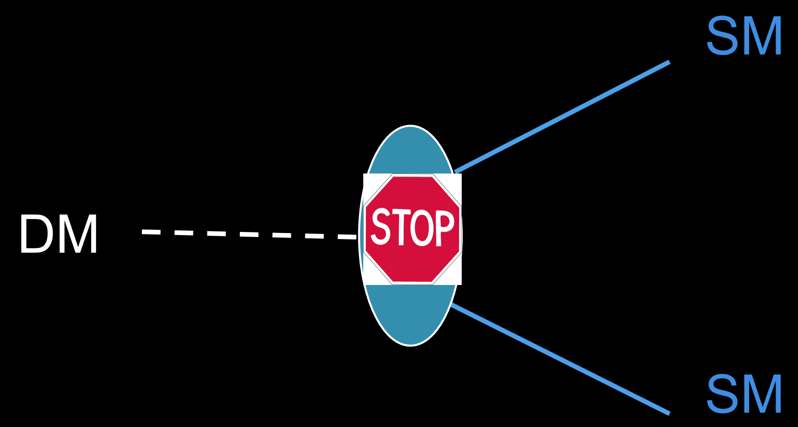
- DM = yet unknown, heavy, neutral elementary particle/s

- Mass estimate (model dependent) from observed dark matter abundance:

M_{DM} ~ 100 – 1000 proton masses

and fits well with a weakly interacting particle = **WIMP**

CAVEAT: To avoid decay of a WIMP to lighter visible matter, theorists invented a symmetry: "dark matter charge" such that



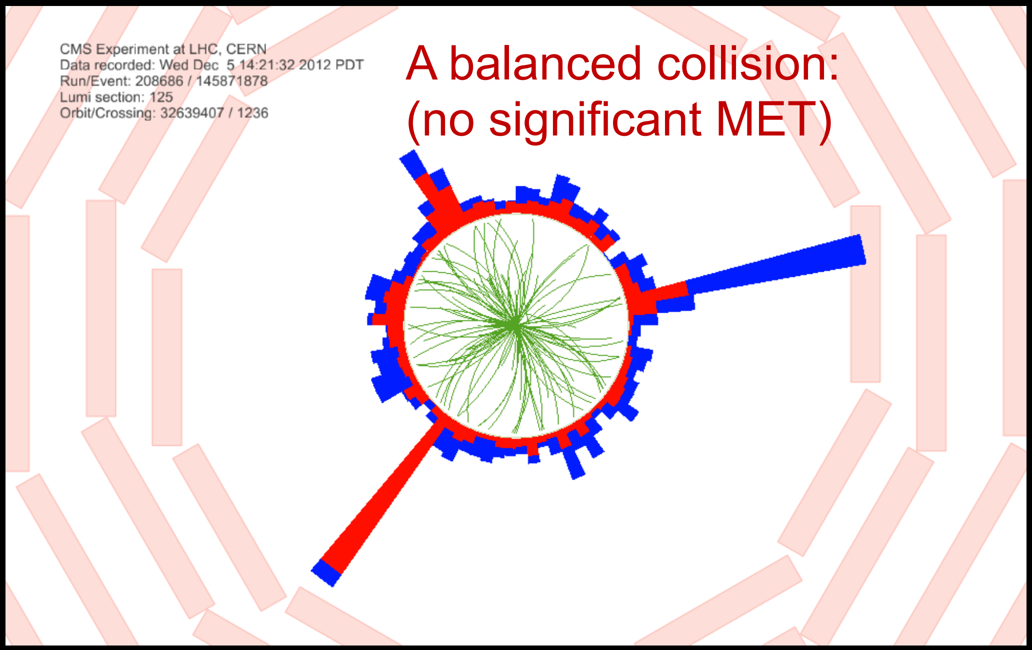
We are testing the outrageous idea

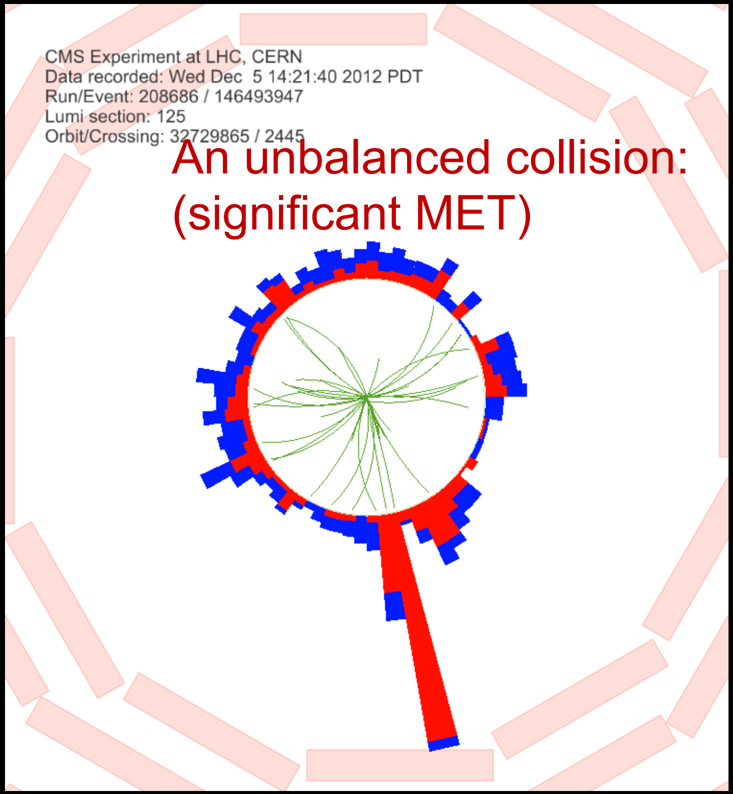
of Dark Matter using

accelerators, telescopes and specialized detectors!

A priority for Particle Physics and Cosmology

We can create Dark Matter at the LHC





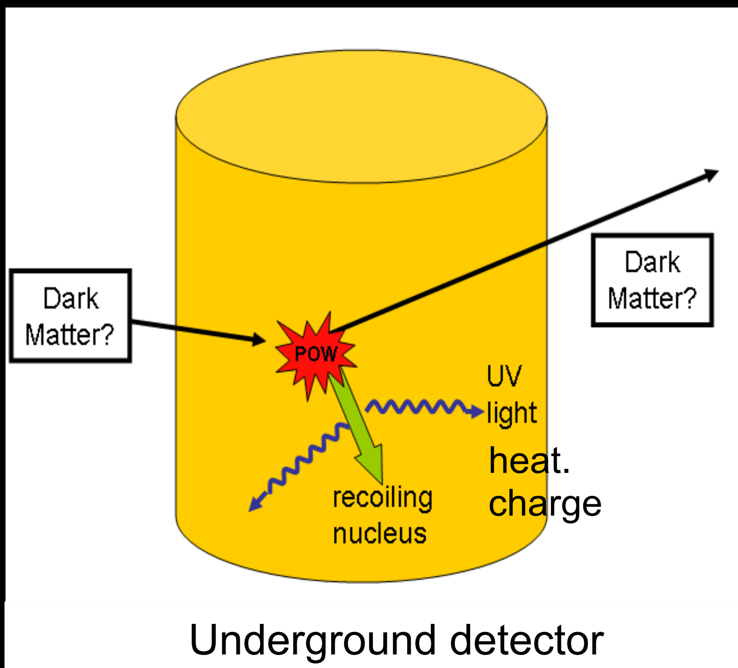
We count the energy we put in and the energy that comes out

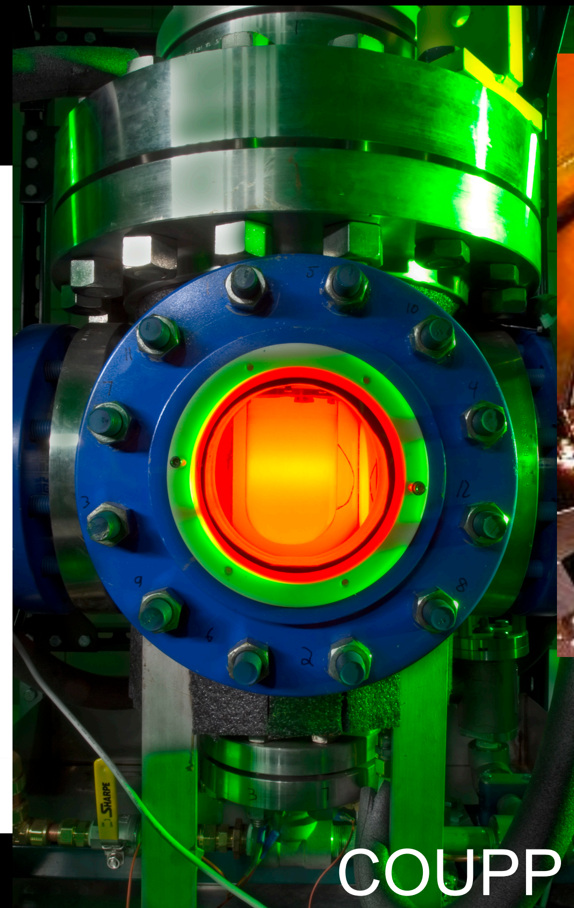
if a lot is missing we created Dark Matter

Rely on *excellent* understanding of detector response
<u>and</u> standard model processes at collider

Dark Matter Search in Direct Detection Experiments

It can *collide with a single nucleus in your detector (which you observe)*

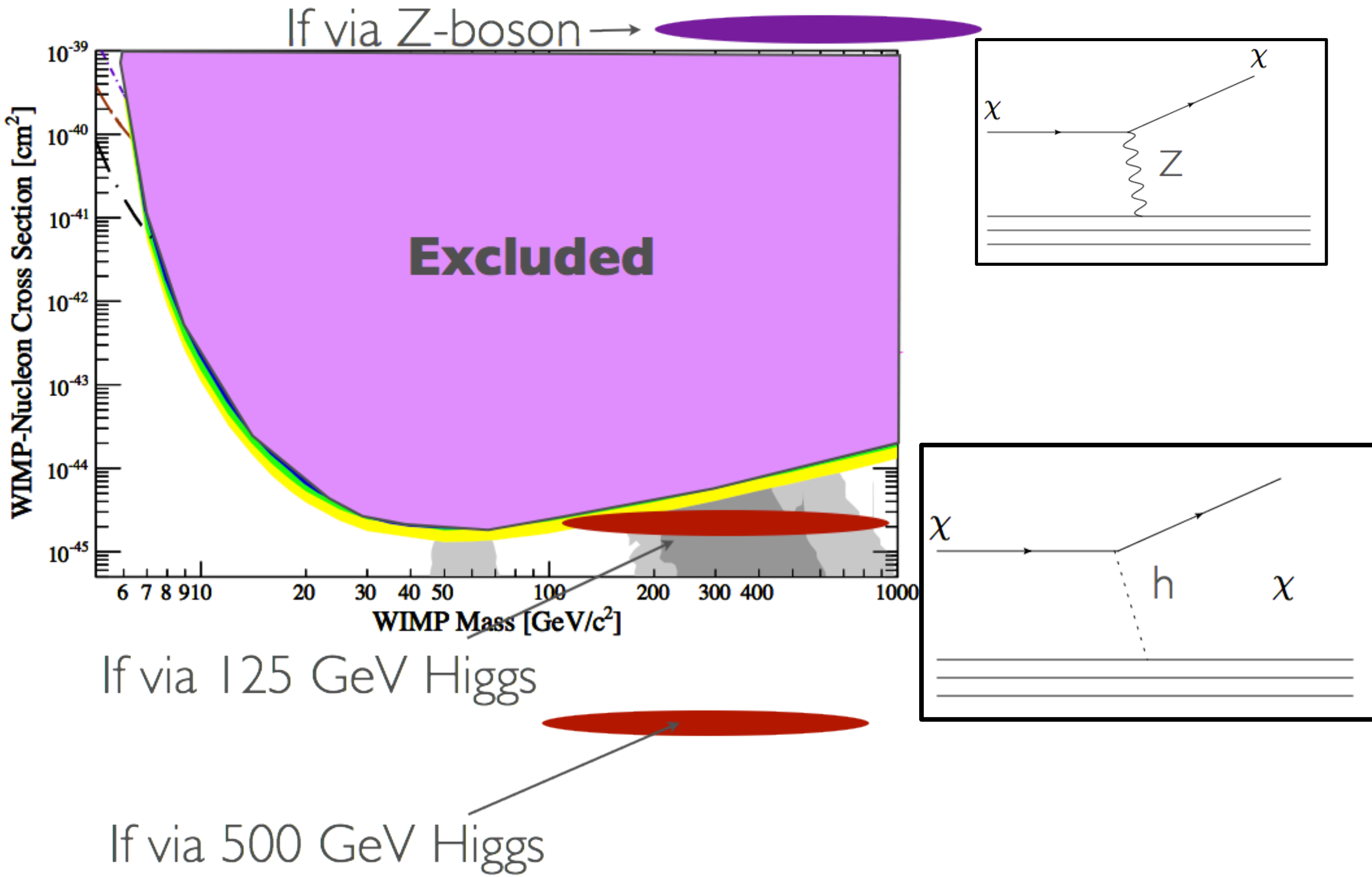




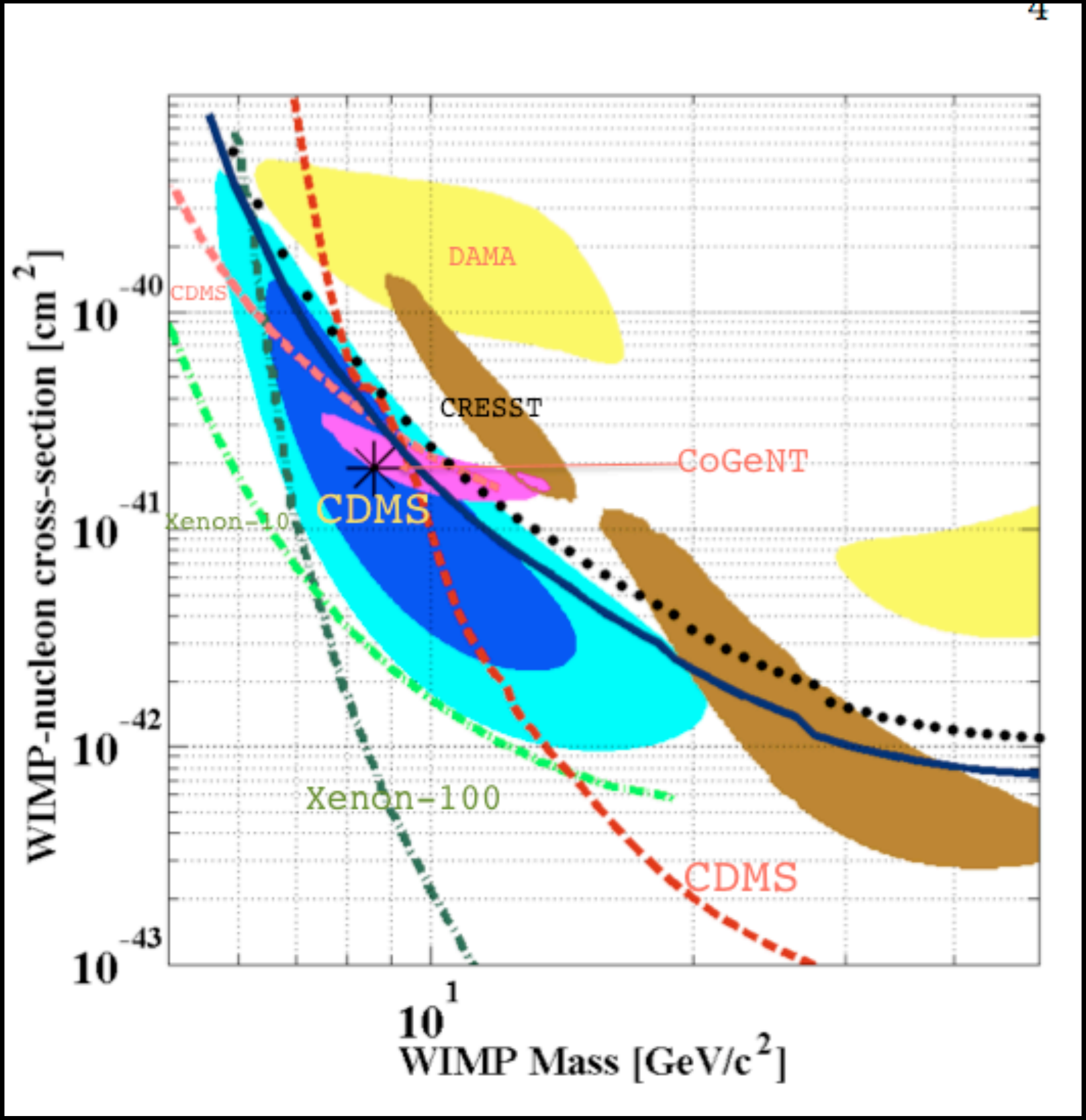
also GoGeNT
DAMIC
DarkSide

Leading World efforts in Chicago

Starting to probe the Higgs Portal



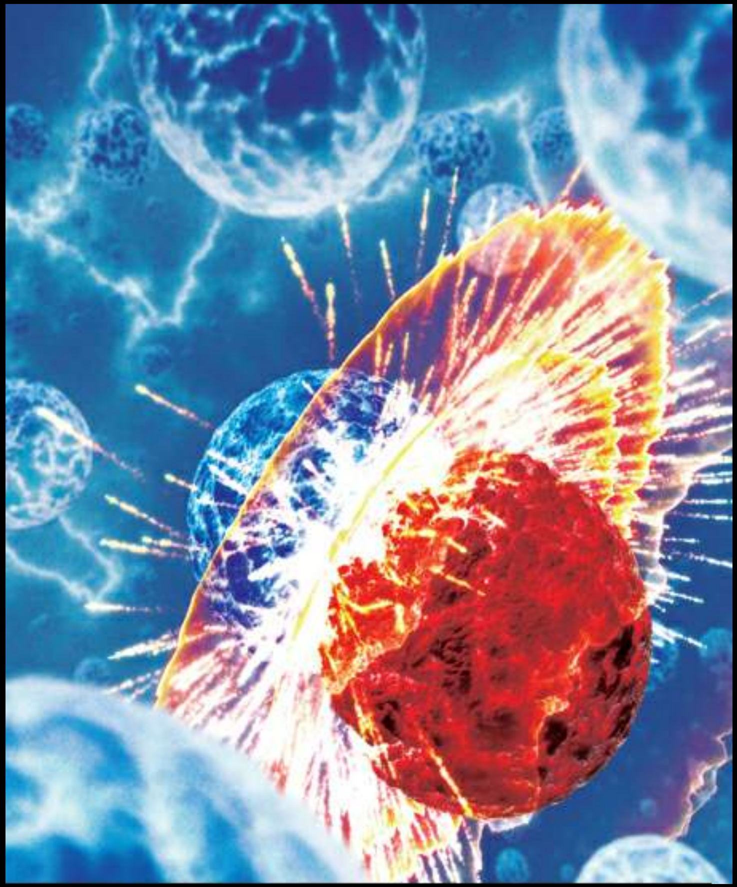
There are some signals in the "excluded" region that could be Dark Matter



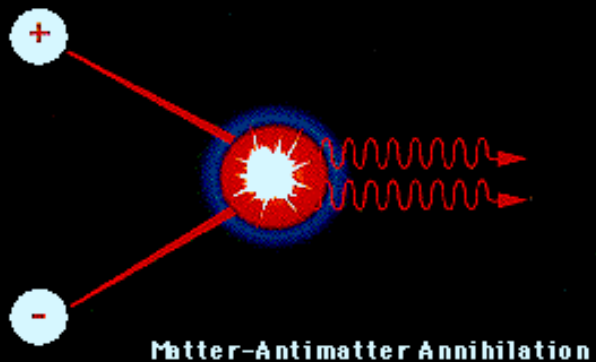
The Mystery of our Existence

We are made of Matter but there is also Anti-Matter

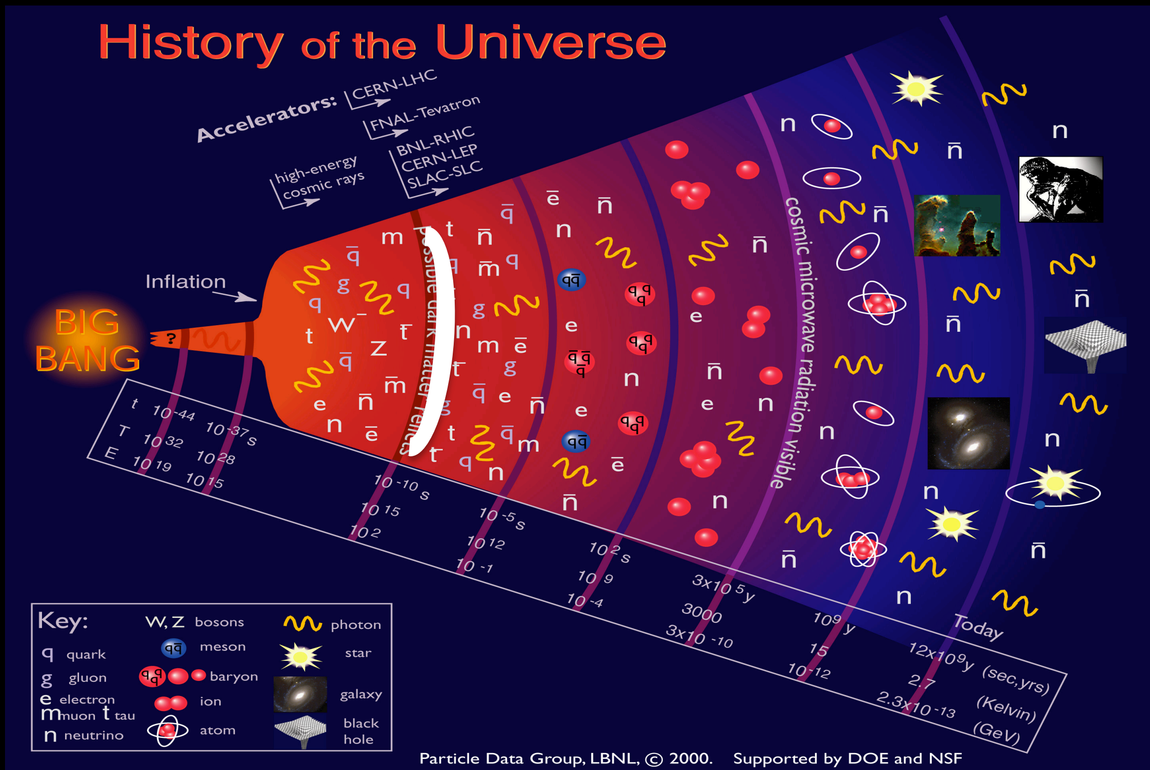
Each matter particle has an anti-particle: an exact copy but…
with opposite electric charge



When matter meets anti-matter...



It annihilates into em radiation

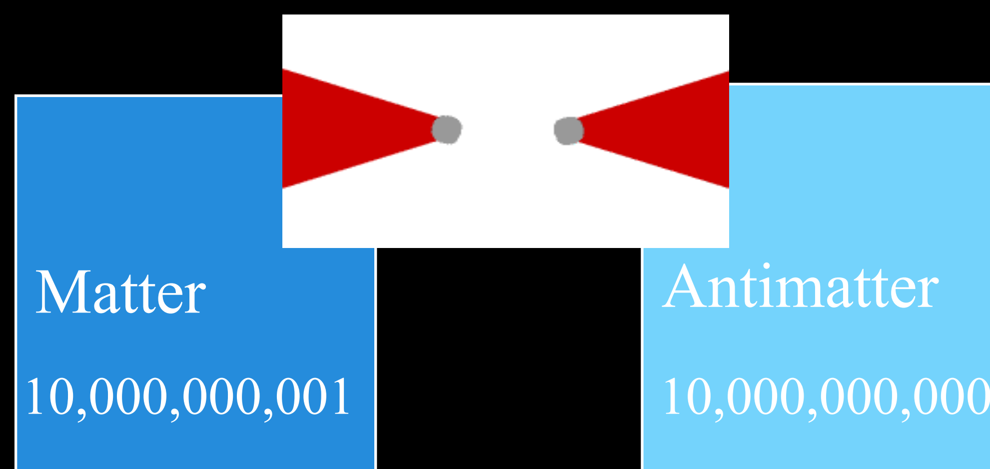


At the BIG BANG :

Equal amounts of Matter and Anti-matter

There was a big matter-antimatter battle…

A tiny amount of matter survived …

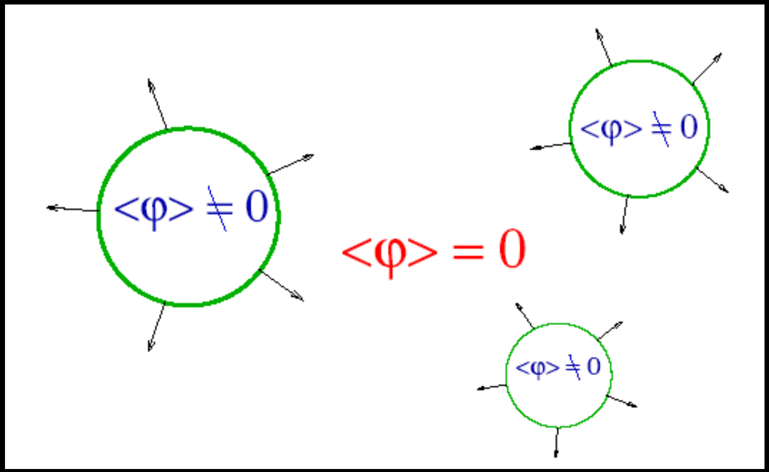


Baryogenesis

What generated the small imbalance between matter and antimatter? How did it happen? When?

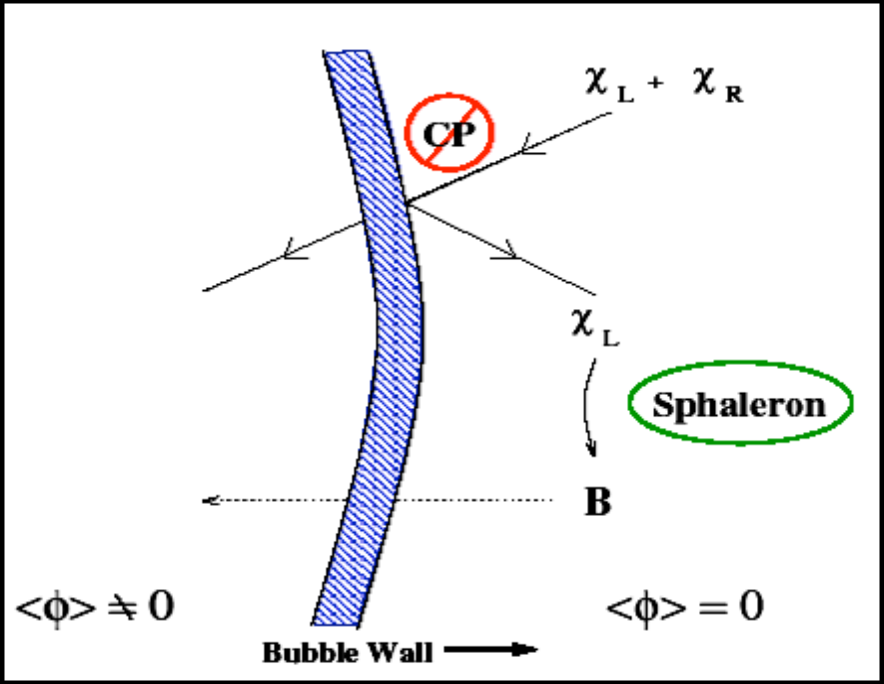
- Out of Equilibrium processes
- Violation of Charge-Parity Symmetry that relates matter with antimatter
- Baryon number violation
- At the scale at which the Higgs field becomes relevant

At the temperature at which the Higgs becomes active



- Bubbles of true vacua start to form and expand
- CP violating currents are generated at the bubble walls
- Quantum configurations generate a net matter-antimatter asymmetry

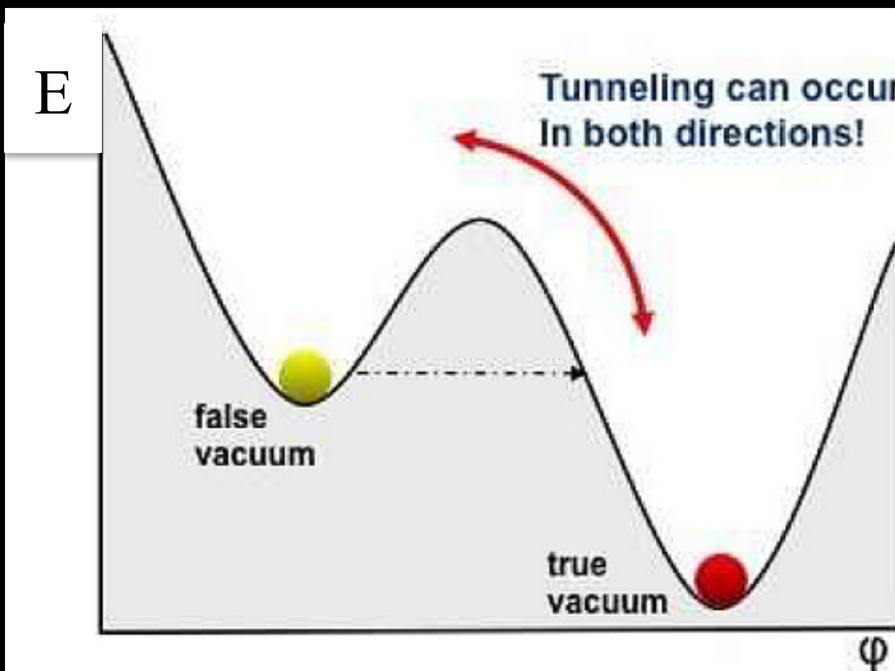
The Higgs field needs to behave such that the transition to the true vacuum is abrupt and the created Matter-antimatter Asymmetry stays frozen until today



- In the Standard Model the Higgs we have discovered does not allow for this mechanism
- In the Standard Model we know there are not enough CP violating currents
- In Supersymmetry, new particles at the reach of LHC can make this work
- Baryogenesis at the Electroweak Scale can explain our existence and can be tested at the LHC

The Higgs and the fate of our universe

We live in a
Meta-stable vacuum



If the SM is all what it is eventually fireballs of doom will form spontaneously and expand to destroy the universe

Scaling of the Higgs Quartic Coupling with Energy

recall: $V(\phi) = -|\mu|^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$

with v= 174 GeV

The quartic coupling determines the Higgs boson mass: $m_h^2 = 4\lambda v^2$ and is not asymptotically free

$$\frac{d\lambda}{d\ln Q^2} = \frac{6}{16\pi^2}\left(\underbrace{\lambda^2 + \lambda h_t^2} - \underbrace{h_t^4}\right) + \text{elw. correc.}$$

•There is the usual situation of non-asymptotic freedom for sufficiently large Q²

↓

λ becomes too large
(strongly interacting, close to Landau pole)

From requiring perturbative validity of the model up to scale Λ or M_{pl}

$$\lambda^{max}(\Lambda)/4\pi = 1 \Rightarrow m_h^{max} = 2\sqrt{\lambda^{max}}\,v$$

•The part of the β_λ independent of λ can drive $\lambda(Q)$ to negative values ==> destabilizing the electroweak minimum

↓

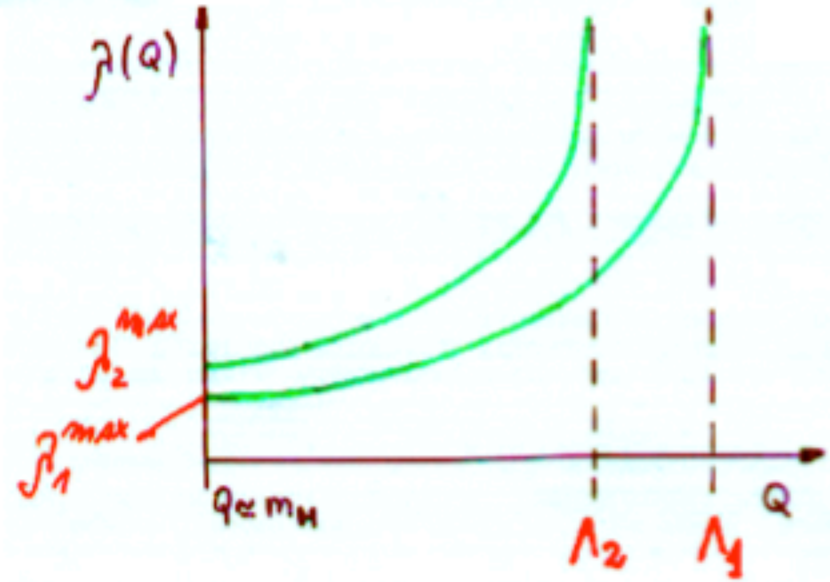
Lower bound on $\lambda(m_h)$ from stability requirement

m_h^{min} strongly dependent on m_t

• $\lambda(Q)$ becomes strongly interacting ($\simeq$ has a Landau pole) at $Q = \Lambda$

$\Rightarrow$ determines $\lambda^{max.}(Q \simeq m_H)$

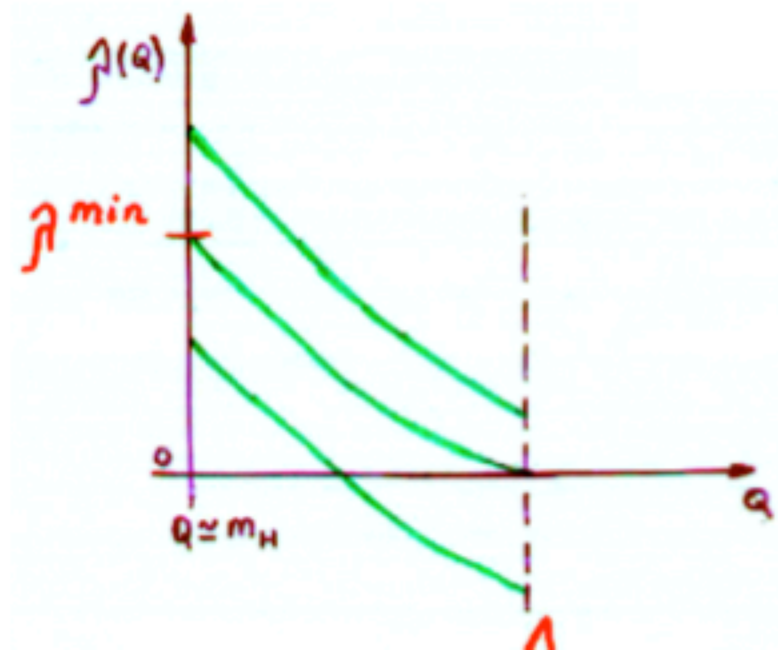
$$m_h^{\max} = 2\sqrt{\lambda^{\max}}\, \mathrm{v} \quad \rightarrow$$



• $\lambda(Q) = 0$ for $Q = \Lambda$

$\Rightarrow$ determines $\lambda^{min.}(Q \simeq m_H)$

$$m_h^{\min} = 2\sqrt{\lambda^{\min}}\, \mathrm{v} \quad \rightarrow$$



Maximum and minimum conditions of the Higgs potential far away from the electroweak minimum

this page only $\lambda \to 2\lambda$

$$\beta_\lambda = d\lambda / d\ln\phi^2 = \phi^2 \cdot d\lambda / d\phi^2$$

$$V(\phi) \sim -|\mu|^2 \phi^2 + \frac{\lambda(\phi)}{2} \phi^4$$

$$\partial V / \partial \phi^2 = -|\mu|^2 + \lambda(\phi)\,\phi^2 + \beta_\lambda/2\,\phi^2$$

$$\partial^2 V / (\partial \phi^2)^2 = \beta_\lambda + \lambda(\phi) + \beta_\lambda/2 + \frac{1}{2}\frac{\partial \beta_\lambda}{\partial \ln \phi^2}$$

$\Rightarrow$ Extreme: $\phi^2 (\lambda(\phi) + \beta_\lambda/2) = |\mu|^2$

if $\phi^2 \sim |\mu|^2 \Rightarrow \phi^2 \simeq |\mu|^2 / \lambda(\phi^2)$

if $\phi^2 \gg |\mu|^2 \Rightarrow \lambda(\phi) \sim -\beta_\lambda/2 \to$ h.o. in pert. theory $\Rightarrow \lambda(\phi) \sim 0$

$\to \partial^2 V / (\partial \phi^2)^2 \sim \beta_\lambda$

Extremes for $\lambda(\phi) \sim 0$

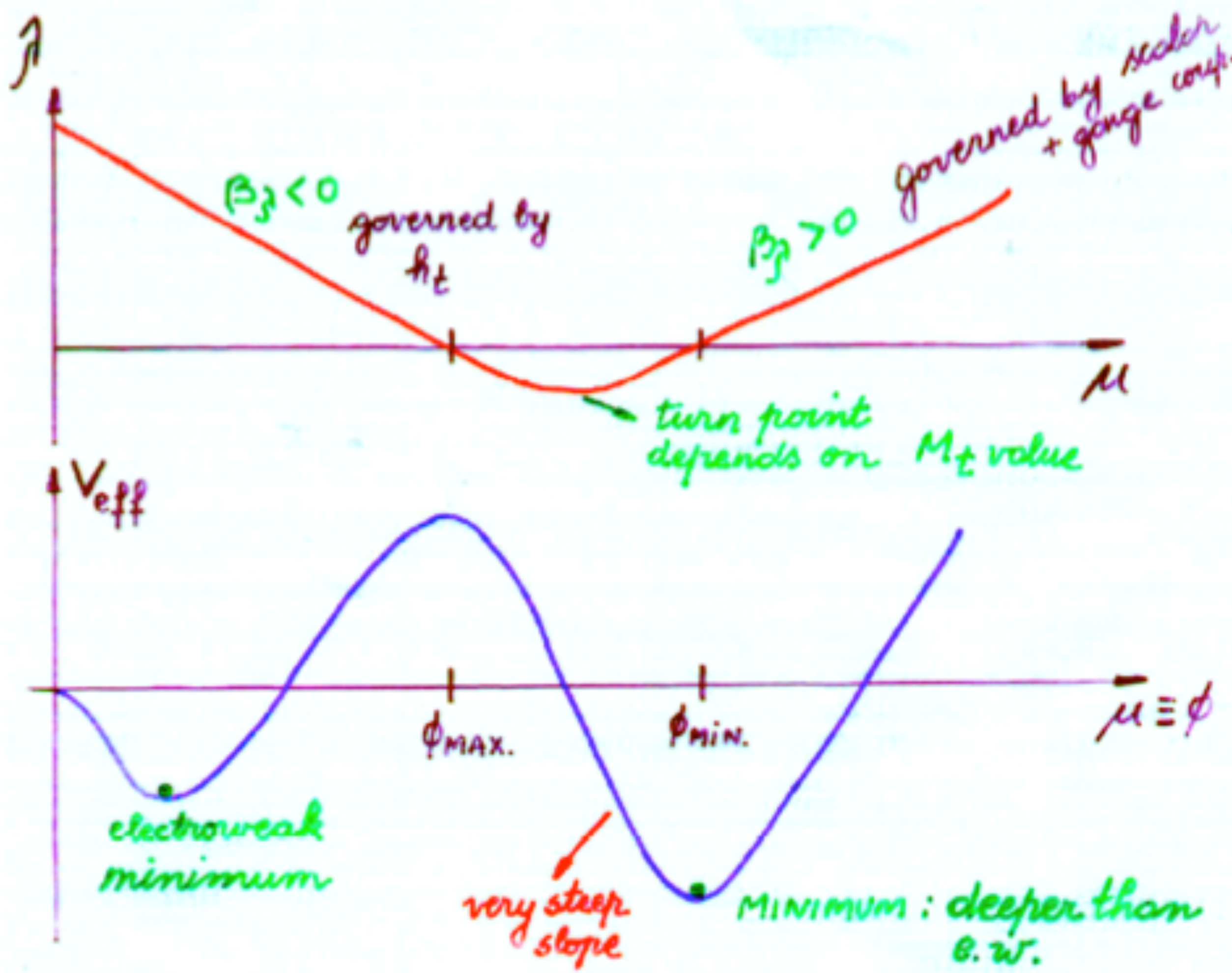
Maximum at $\beta_\lambda < 0$; Minimum at $\beta_\lambda > 0$

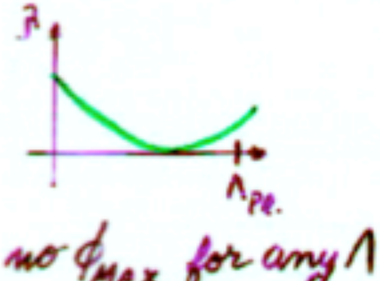
The stability m_h lower bound comes from defining for a given top quark mass the lower value m_h for which

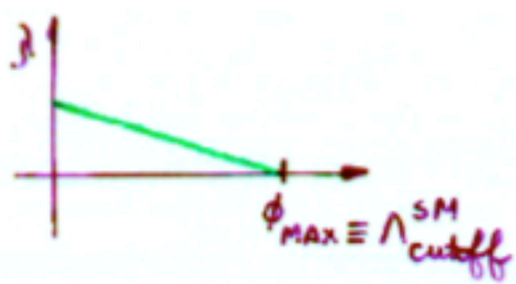
→no Maximum for

$\phi < \Lambda^{SM}_{cutoff}$

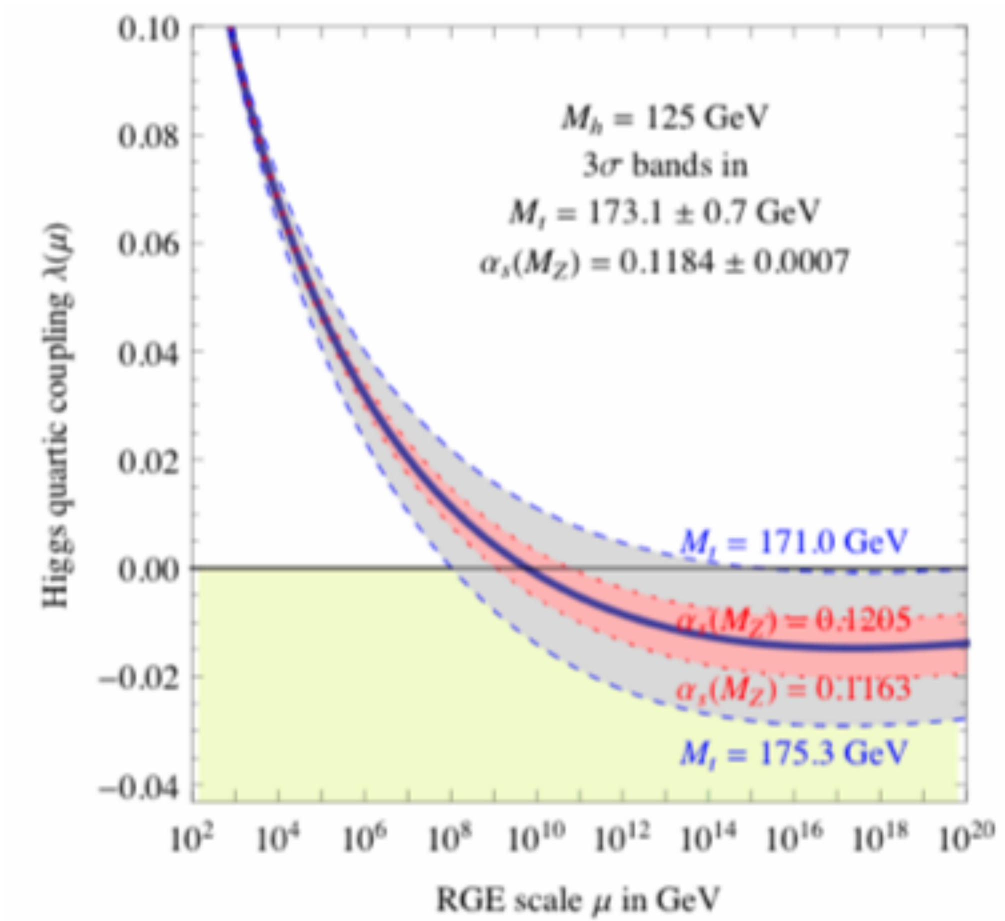
$(\equiv \lambda(\phi) \geq 0$ for $\phi < \Lambda^{SM}_{cutoff}$.



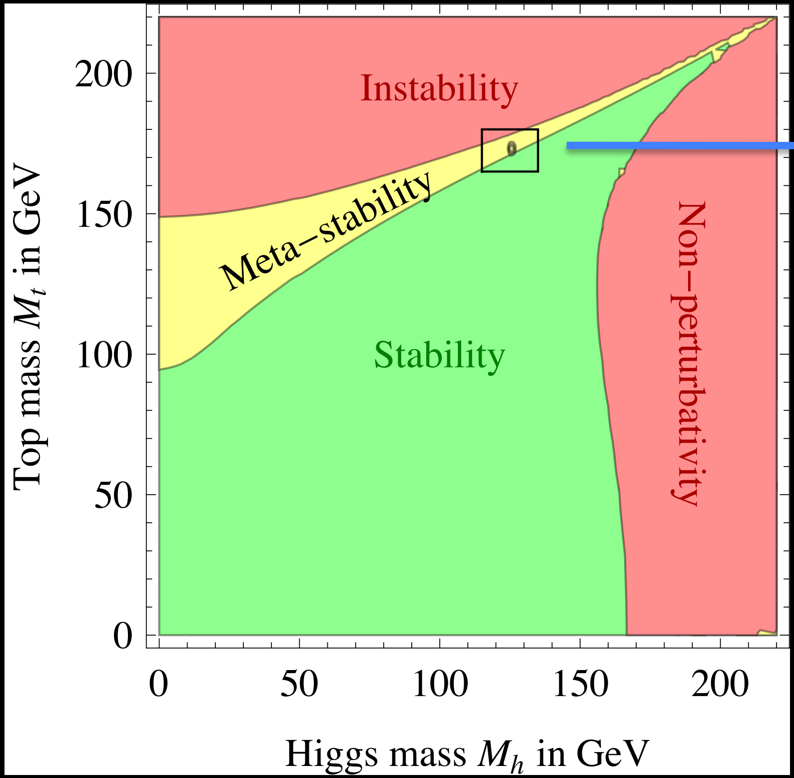


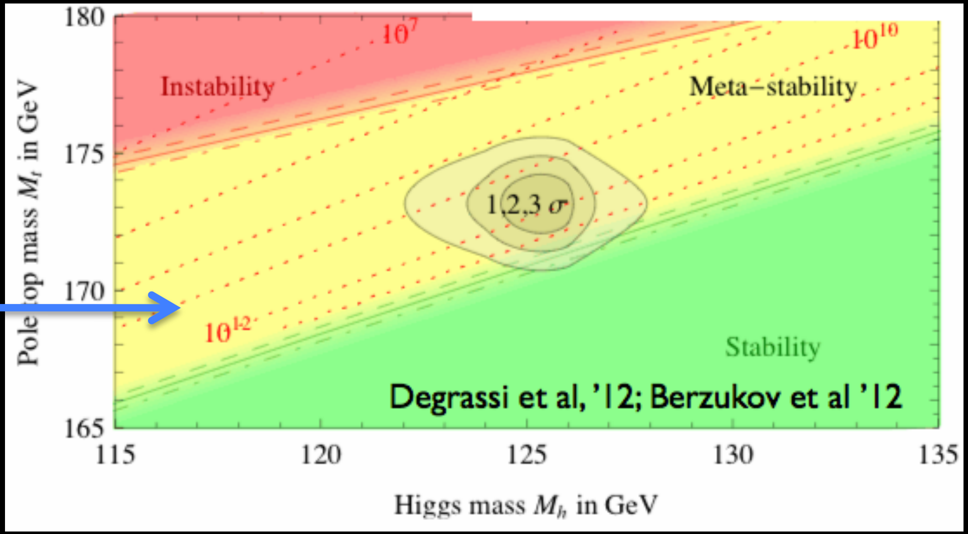


The stability of our universe, given th evalue of m_H, prefers new physics at a scale below MPl.

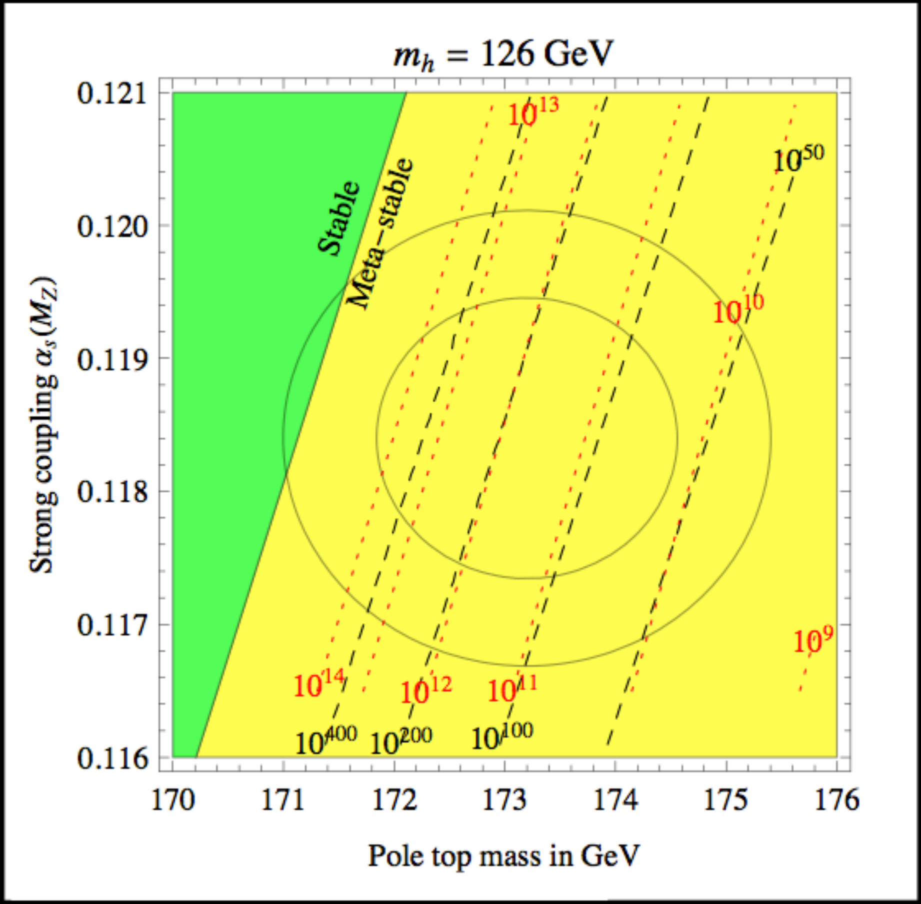


The Higgs and the fate of our universe



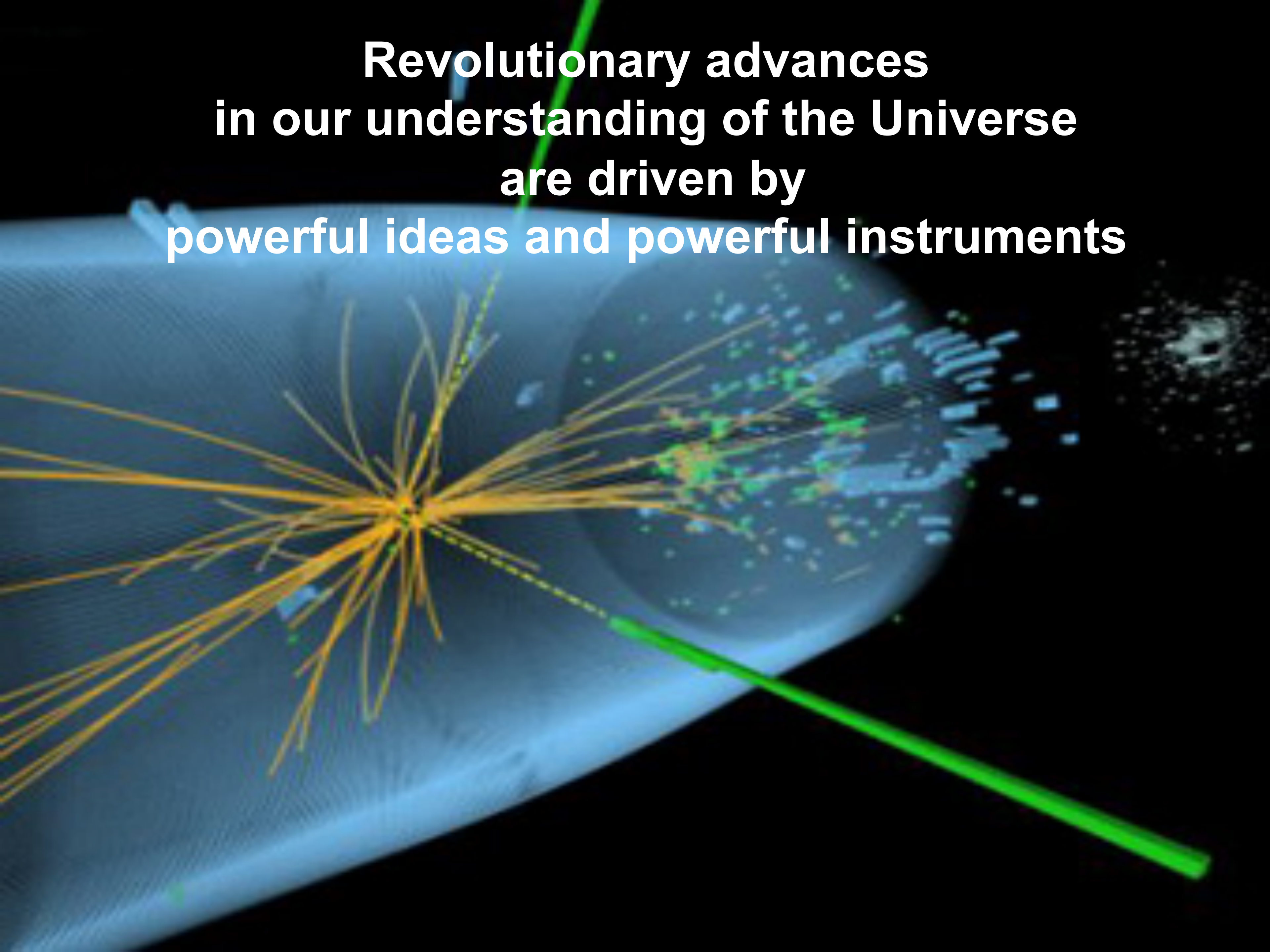


The Higgs and the fate of our universe



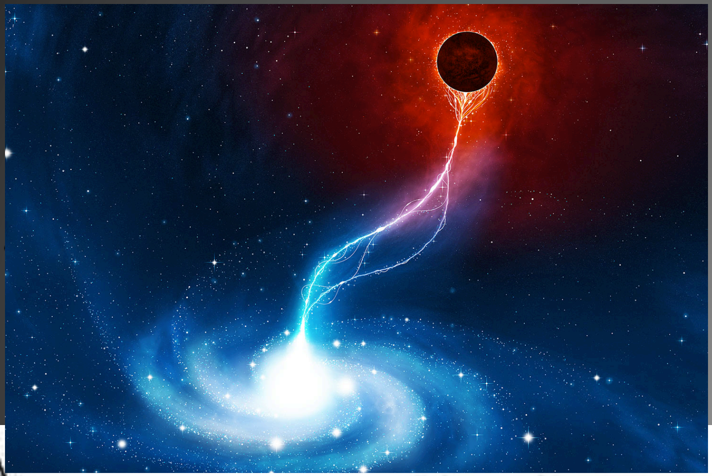
It might be 10^{100} years before the fatal bubble forms or, we may be very unlucky…

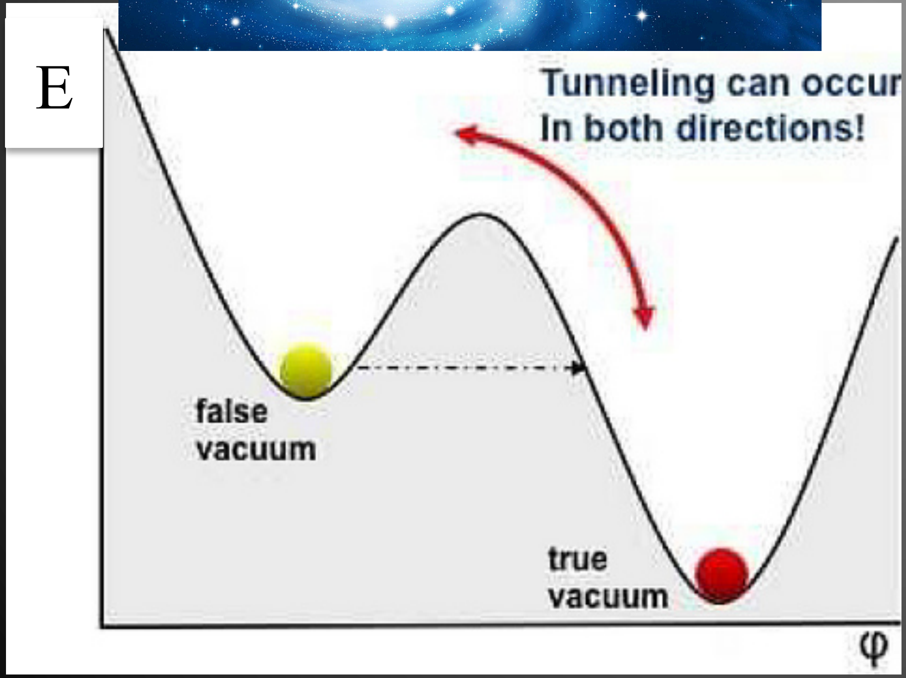
Or a new symmetry of nature may stabilize the universe


Revolutionary advances
in our understanding of the Universe
are driven by
powerful ideas and powerful instruments

EXTRAS

How does the measured Higgs mass fit in our modeling of the universe?





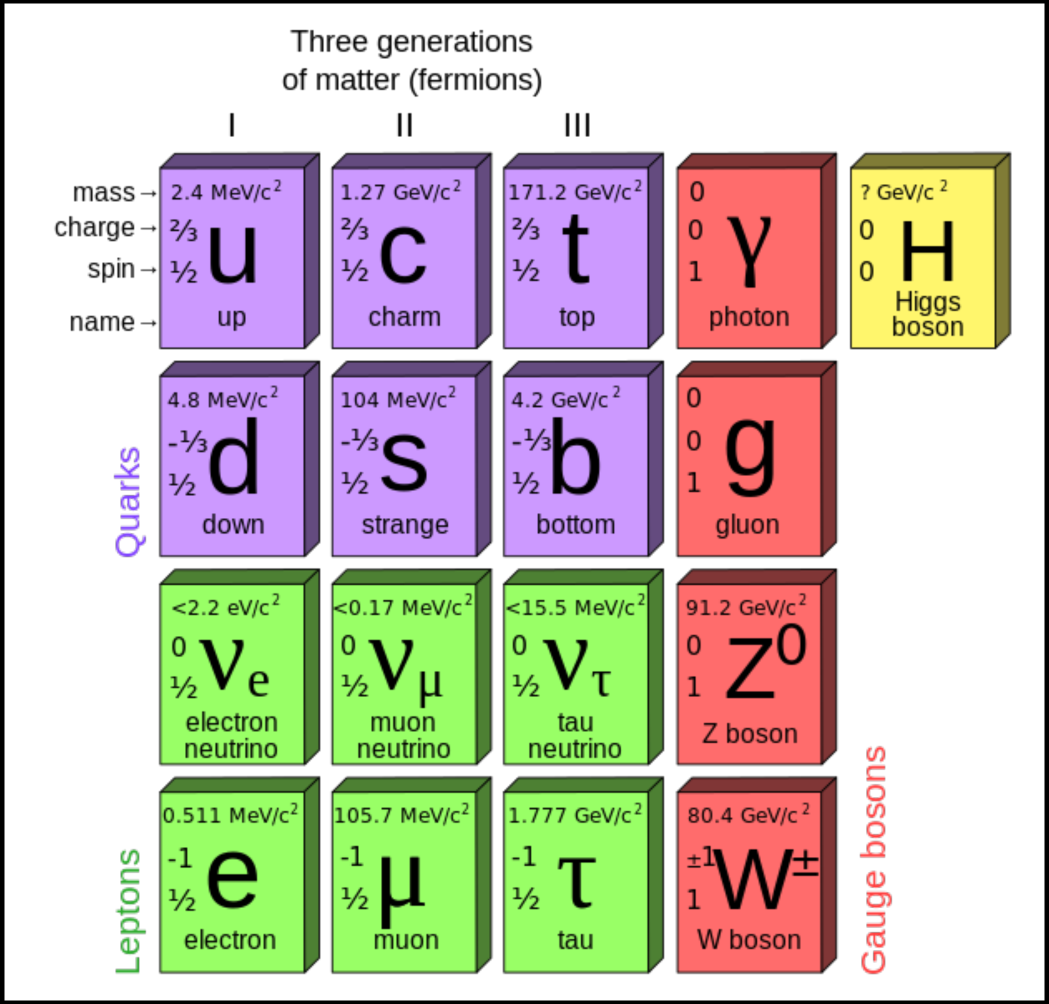
We live in a Meta-stable vacuum

Or

A new symmetry of nature may stabilize the universe

Why is the Higgs so important ?

Sub-atomic particles of the Standard Model of Particle Physics



They have all been produced in the laboratory

They have very different masses

$M_p = 0.938\ GeV/c^2 = 938\ MeV/c^2$

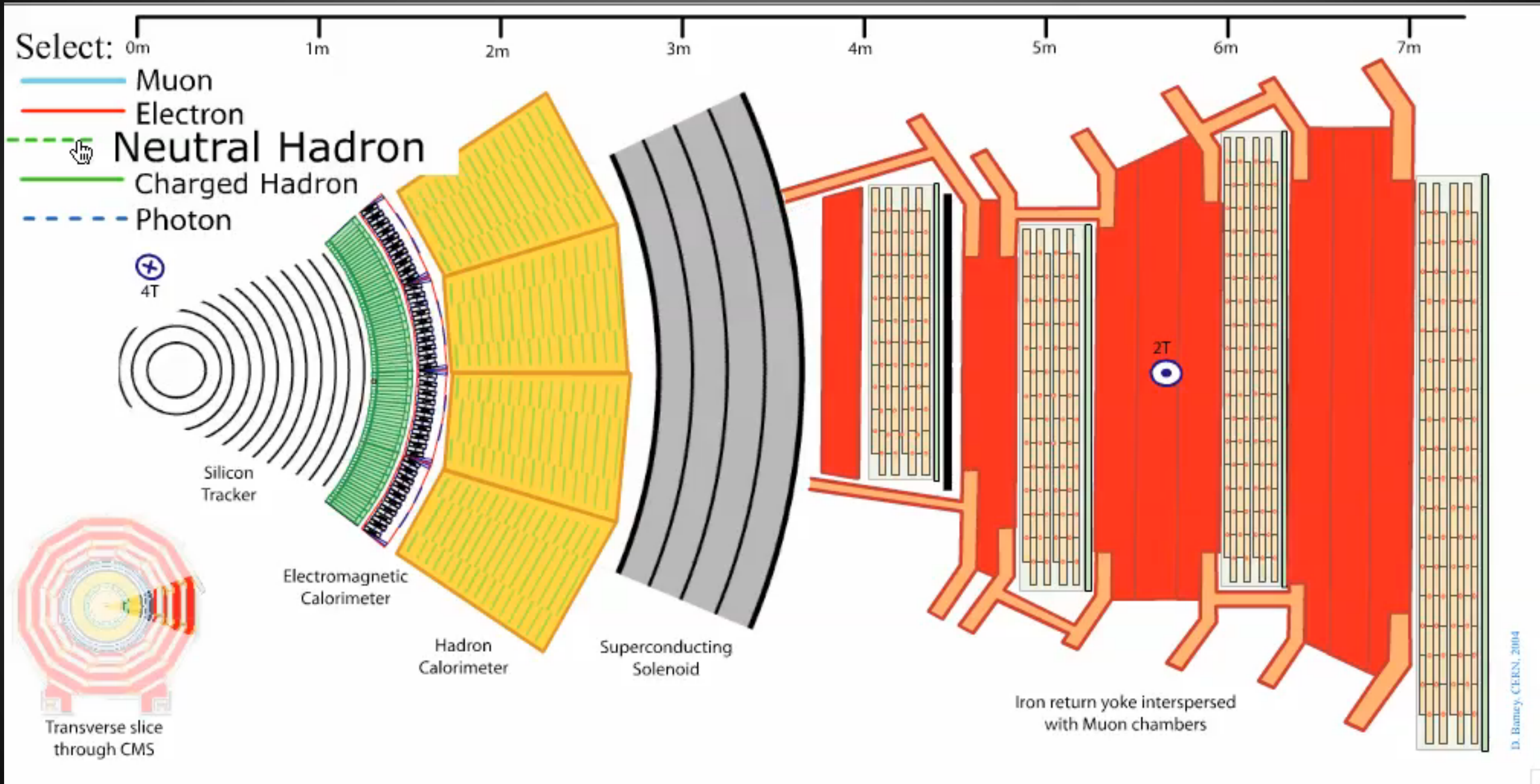
Nature does not forget

The equations governing the fundamental laws of physics contain everything possible:

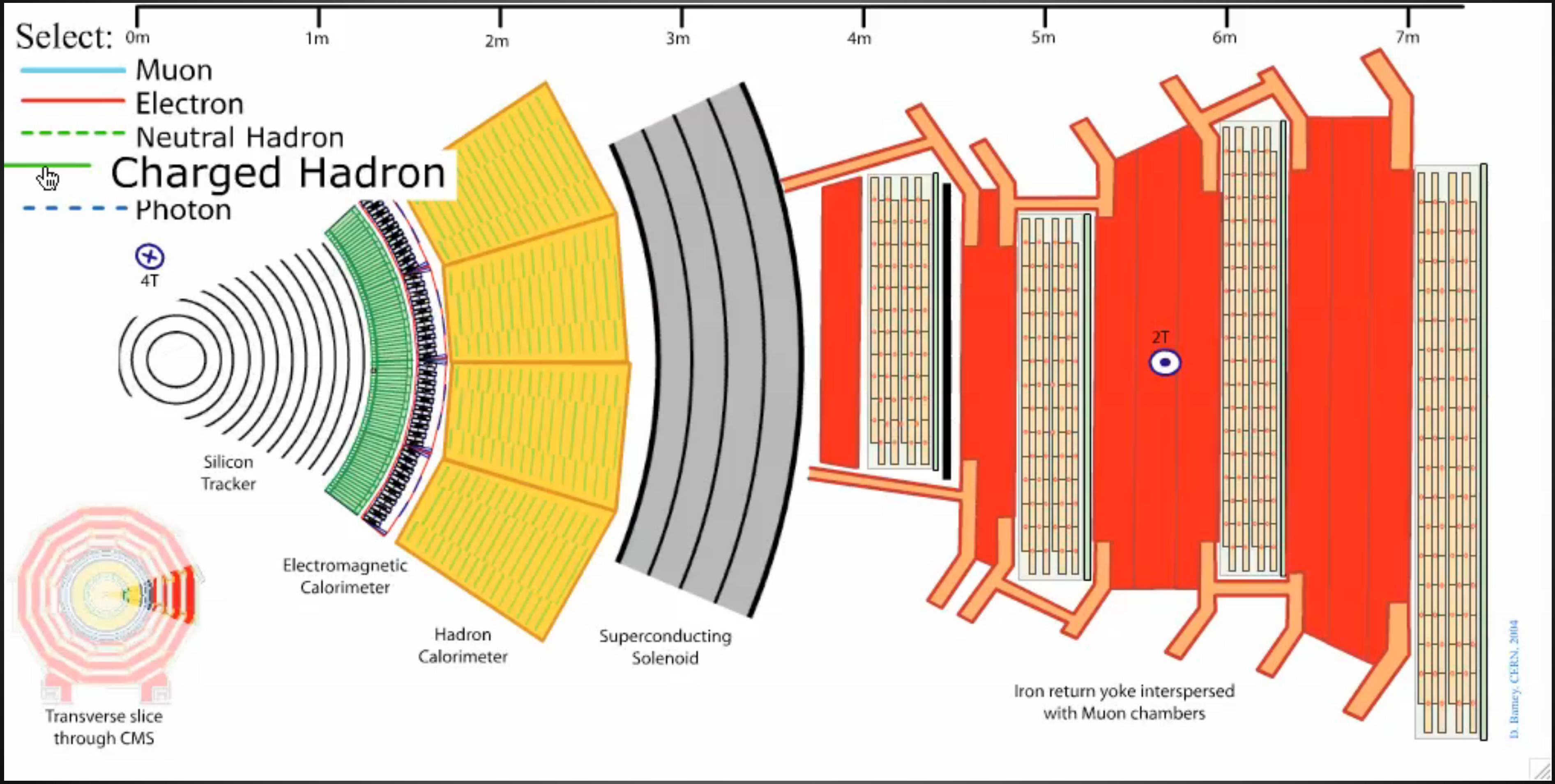
$$\mathcal{L} = \sum_{\text{particles}} \bar{\psi}\, i \not{D}\, \psi + \sum_{\text{forces}} F^2$$

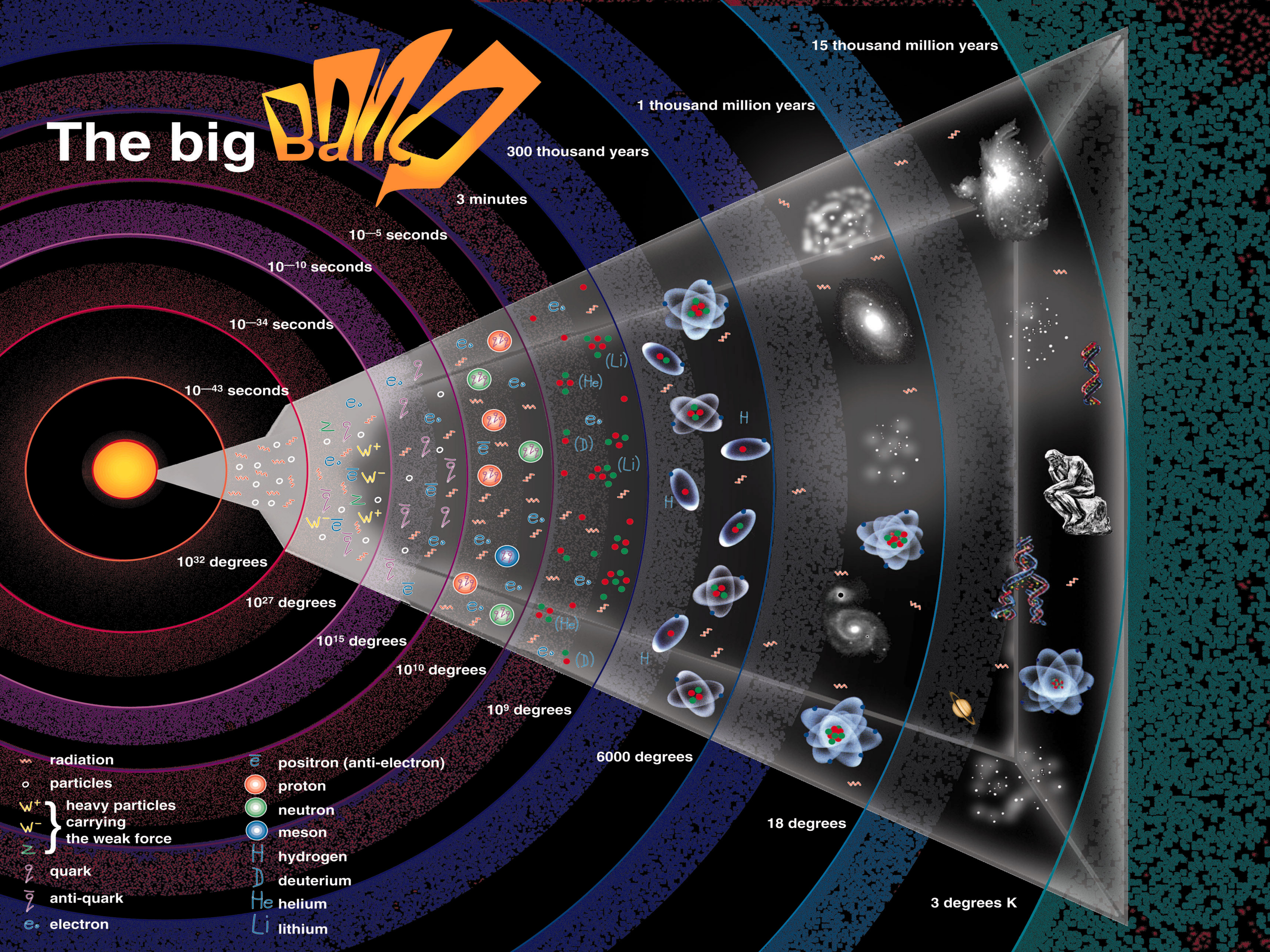
This is why we can search for particles that only existed shortly after the Big Bang using high-energy particle colliders!

What the detectors detect

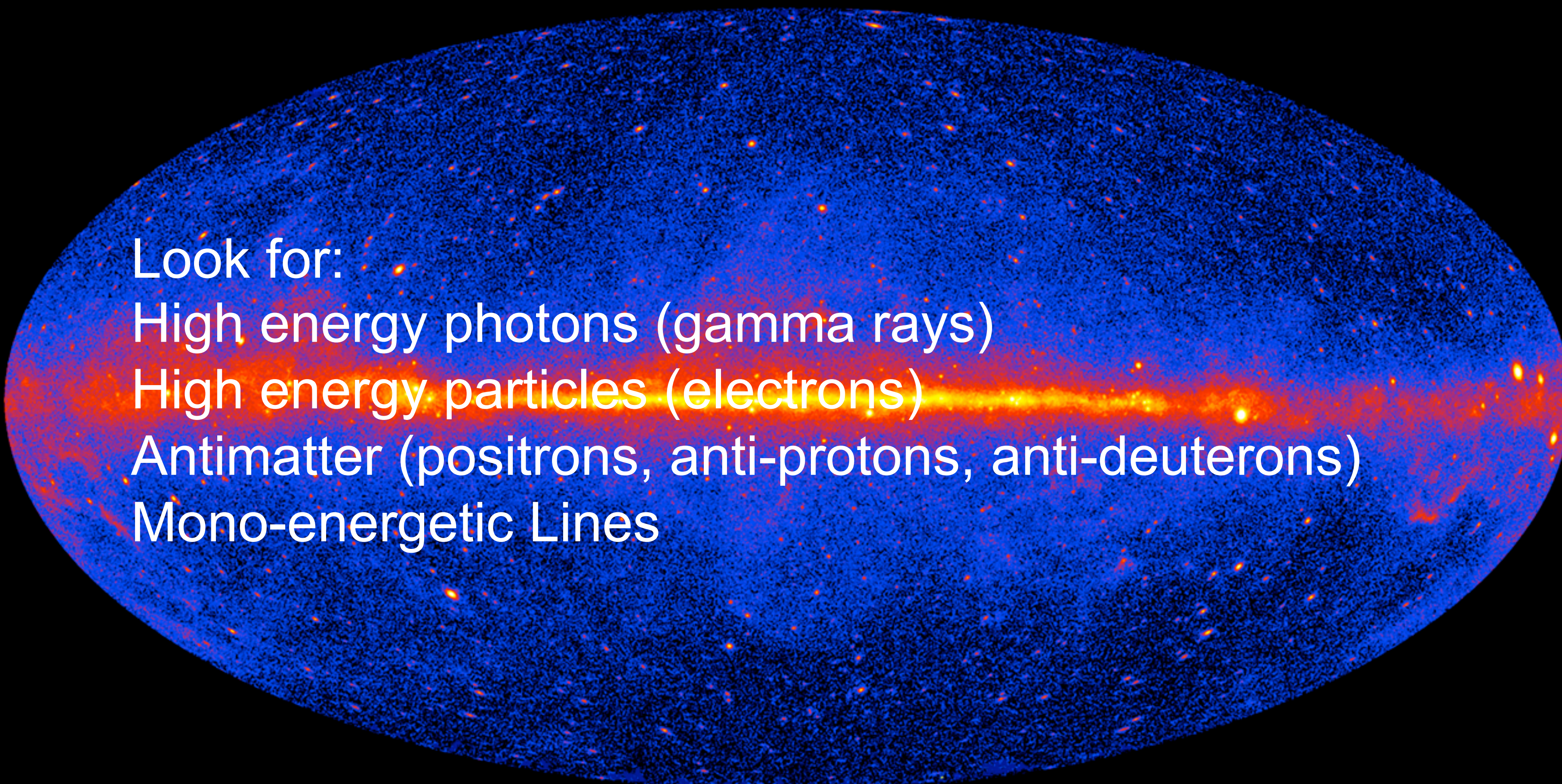


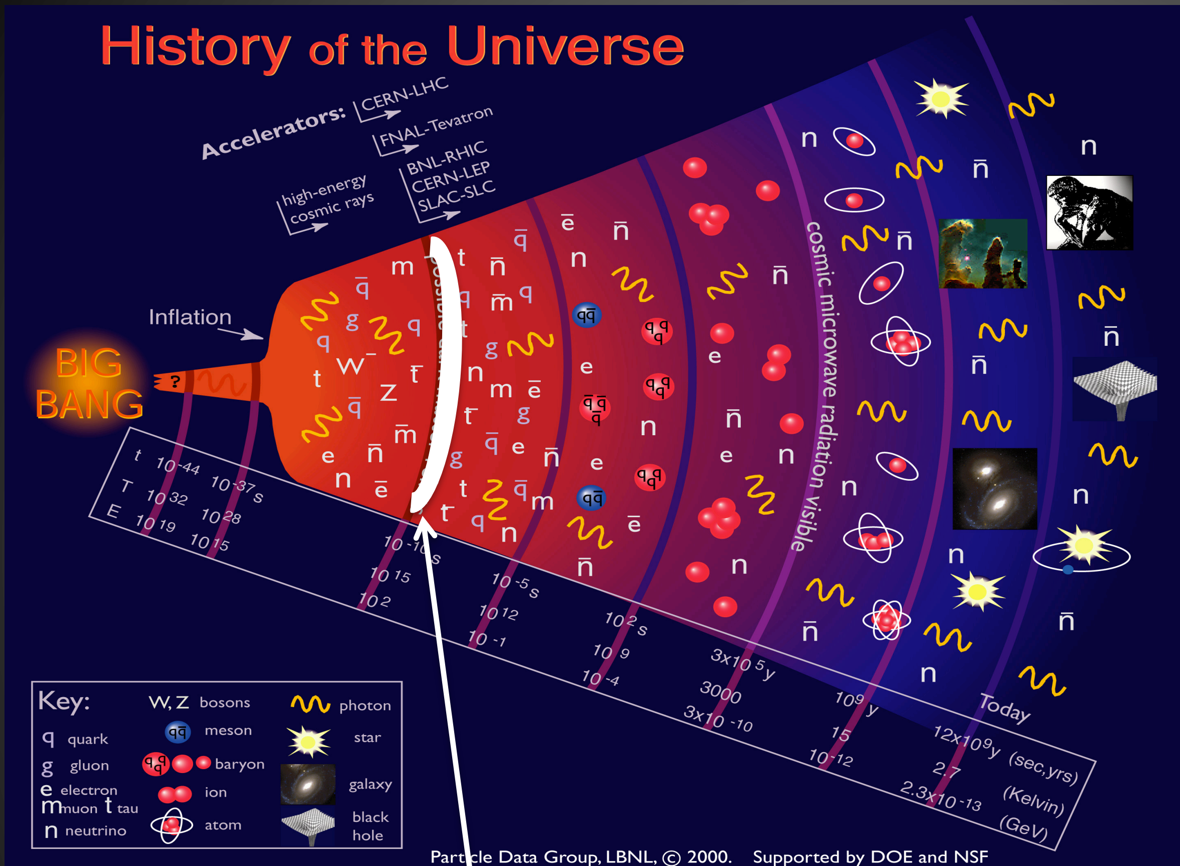
What the detectors detect




The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10—5 seconds
10—10 seconds
10—34 seconds
10—43 seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

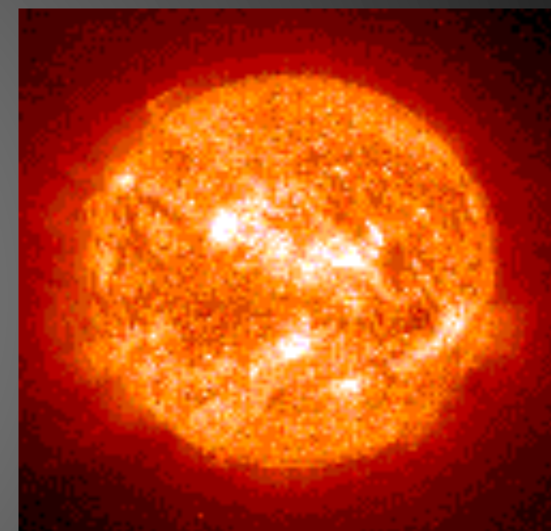
Indirect Dark Matter Detection
The Universe becomes the experiment





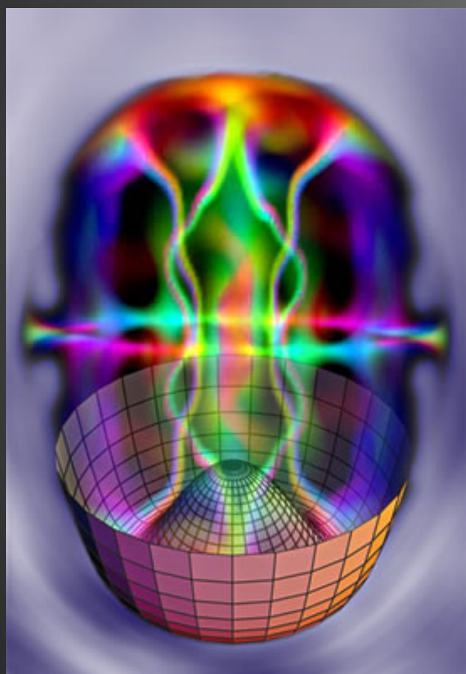
Spontaneous electroweak
Symmetry breaking

Solar Fusion



Sun still burning!

What generated the matter-antimatter imbalance?



God Mechanism ?

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

Are both Symmetry breaking mechanisms related, happening at the same time?