The Standard Model and Beyond

Paris Sphicas
CERN & University of Athens
CERN Accelerator School
Chavannes de Bogis, February 6, 2017

- **The Standard Model of Particle Physics**
  - **And the Higgs boson…**
- **Looking for the Higgs**
  - **A new boson at ≈ 126 GeV!**
  - **Studying its properties**
- **Is this all there is to Nature?**
  - **Searching for New Physics; e.g. Supersymmetry?**
- **Outlook**

Standard Model of Particle Physics

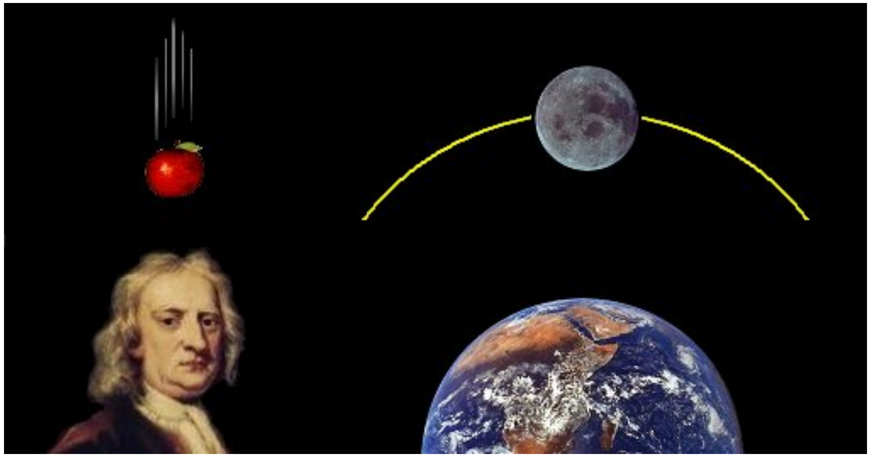
The main ideas

Intermediate vector bosons and their masslessness

The Higgs mechanism

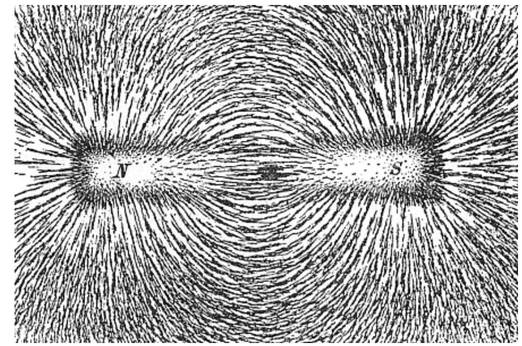
Nature: “forces” between particles?

- Gravity == action-at-a distance: separated objects, in the vacuum, act on each other!
- The “charge” of gravity: mass – the substance of matter!



- What about electricity and magnetism? Same as gravity; except two charges (like ones repel, opposite ones attract). But same spooky “action-at-a-distance, through the vacuum”

Nature: "forces"?!?



- Maxwell and electromagnetism: the concept of a field; charges generate fields which (can) permeate all of space… Other "charges" feel this field – and thus they feel a force.
- The incredible discovery: the E/B fields can exist alone – they propagate in waves in the vacuum! Thus are radio, TV and cell-phones made possible.

20^{th} century: two more forces at work

But nuclei are held together – against the electrostatic repulsion.

So there is yet another type of force!

It must be very, very strong.

But nuclei also "break"! Radioactivity! Neutrons become protons.

So there is yet another type of force!

And it is very, very weak.

There are, in total FOUR different forces in nature:
Gravity, Electromagnetism, Weak Force, Strong Force

FOUR???

What makes them different?

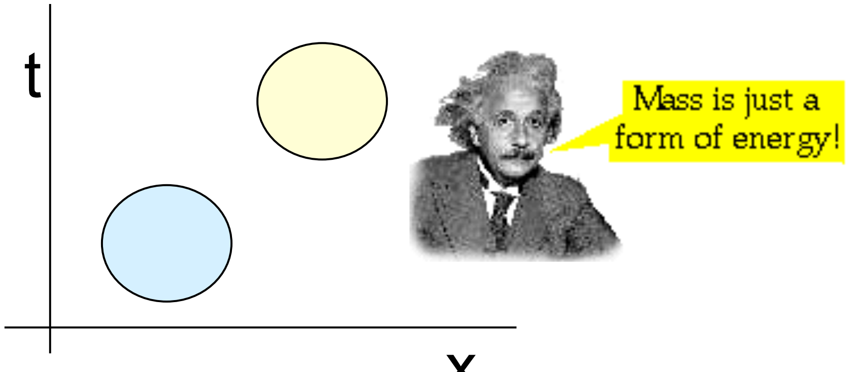
Are all of them "needed"?

Why not just one?

The two scientific revolutions of the 20th century (Relativity and Quantum mechanics) provide (most of) the answers

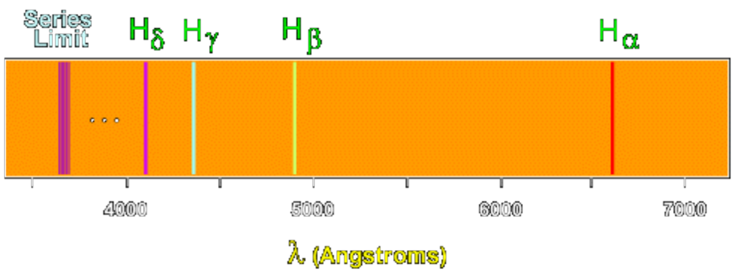
20th century physics: quantum mechanics and relativity

- **Relativity: action can only travel at speed c**
  - Localization



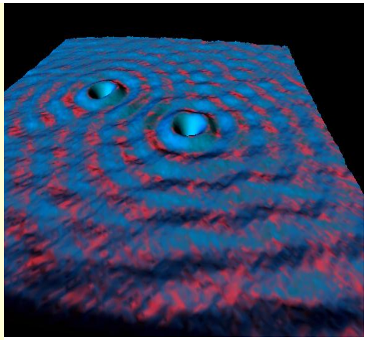
  - Communication between space-time points only as long as within light-cone
- **Thus: operators (that finally yield obser-vables) are a function of x,t; i.e. they are fields**

- **Quantum Mechanics**
  - Dicretization
    - e.g. of absorption or emission



  - Wave-particle duality
    - demonstrated beyond all doubt:

Electron density waves are seen breaking around two atom-size defects on the surface of a copper crystal



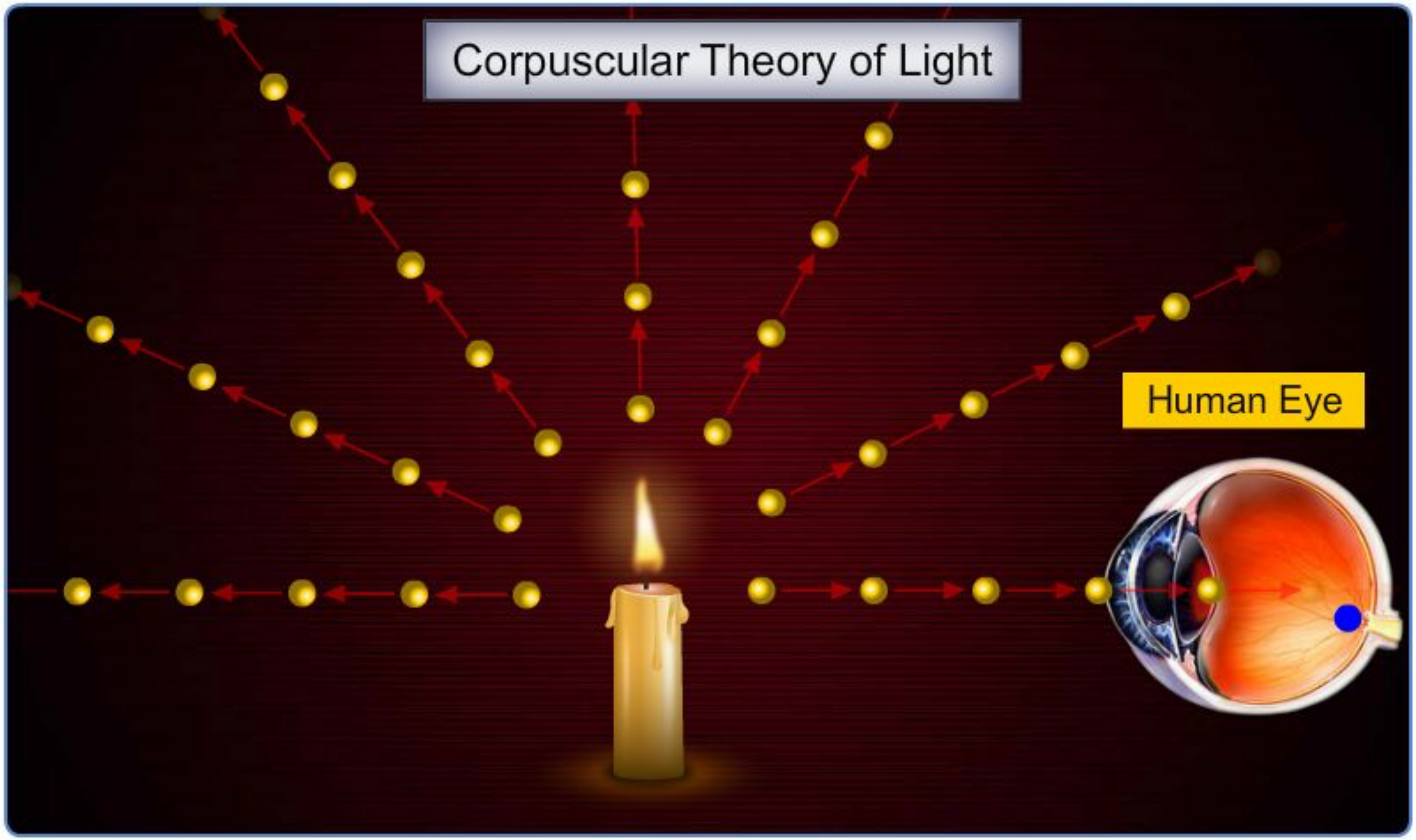
Classical Mechanics: light waves

- **Apparent continuity of light rays.**

But: when “zooming in” on light...

Quantum Mechanics: discreteness

- **"Zooming in" on light... Light "comes" in discrete units → corpuscules → particles!**

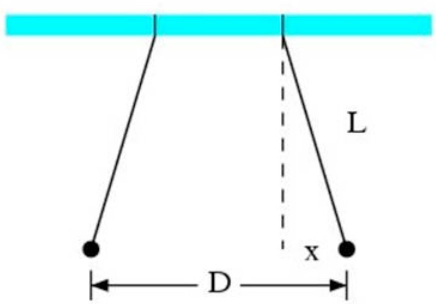


Quantum Field Theory

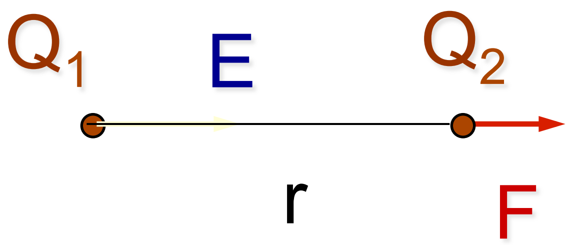
Relativity Theory + Quantum mechanics: a new picture of what is a "force"

$$L_{\text{int}} = -q\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

FORCE IS THE EXCHANGE OF PARTICLES!

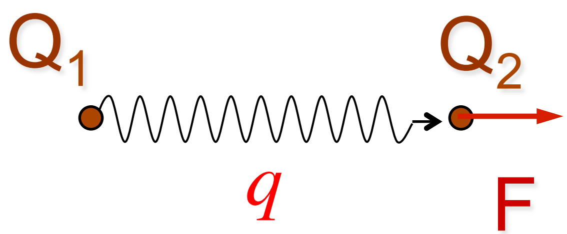


Classical and Quantum picture of "force"



Classical Field E(r)

$$\vec{F} = \vec{E}(r)\cdot Q_2 = \frac{Q_1}{r^2}\hat{r}\cdot Q_2 = \frac{Q_1 Q_2}{r^2}\hat{r}$$

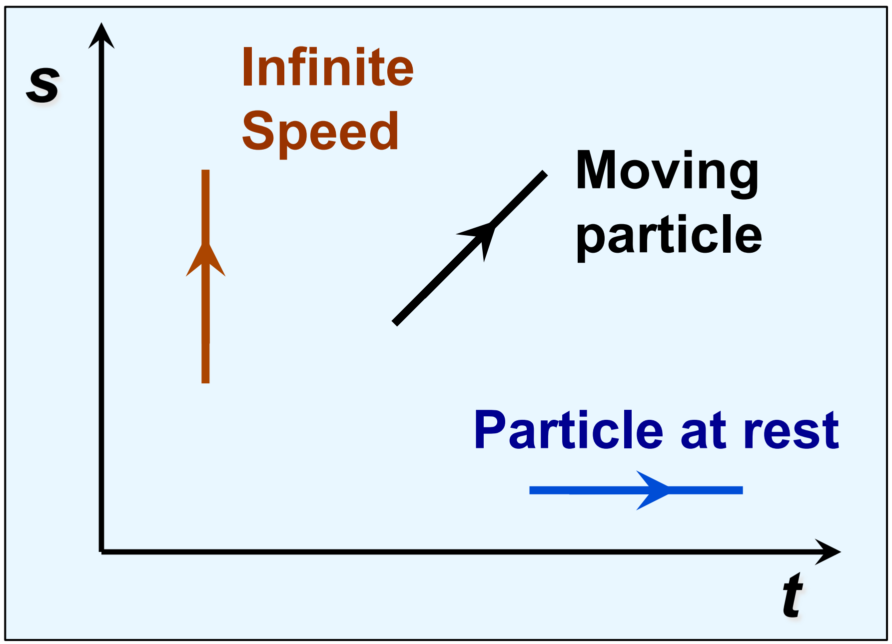


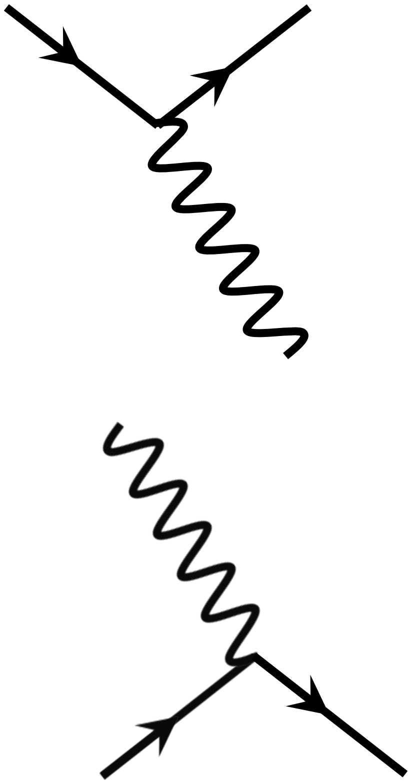
Exchange of a virtual particle of momentum *q*:

$$qr \approx \hbar \Rightarrow q \approx \frac{\hbar}{r} \Rightarrow q \approx \frac{\hbar}{ct} \Rightarrow \frac{dq}{dt} \approx \frac{\hbar}{ct^2} \Rightarrow \frac{dq}{dt} \approx \frac{\hbar c}{r^2}$$

Force = exchange of particle

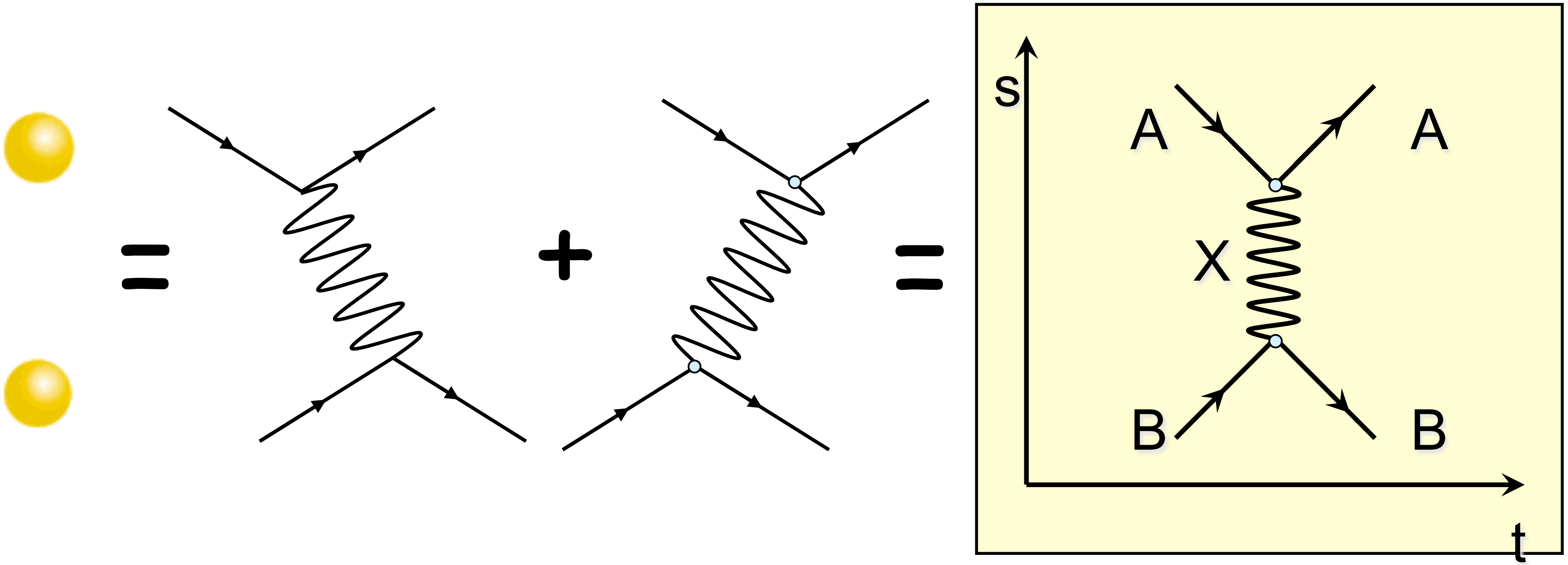
- **The most basic process: a fermion (matter particle) emits/absorbs a boson (force particle)**





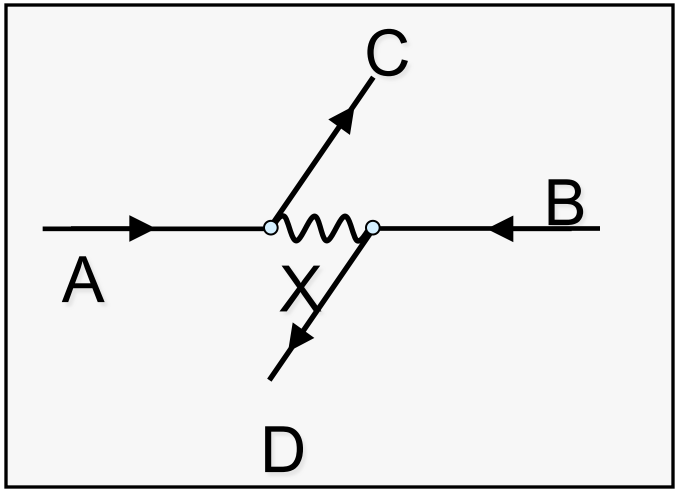
Feynman diagrams (I)

- **Have to draw all possibilities**
  - **We do not know whether X was emitted by A and absorbed by B or the opposite**
  - **So: X is drawn vertically [though it does not have infinite v]**

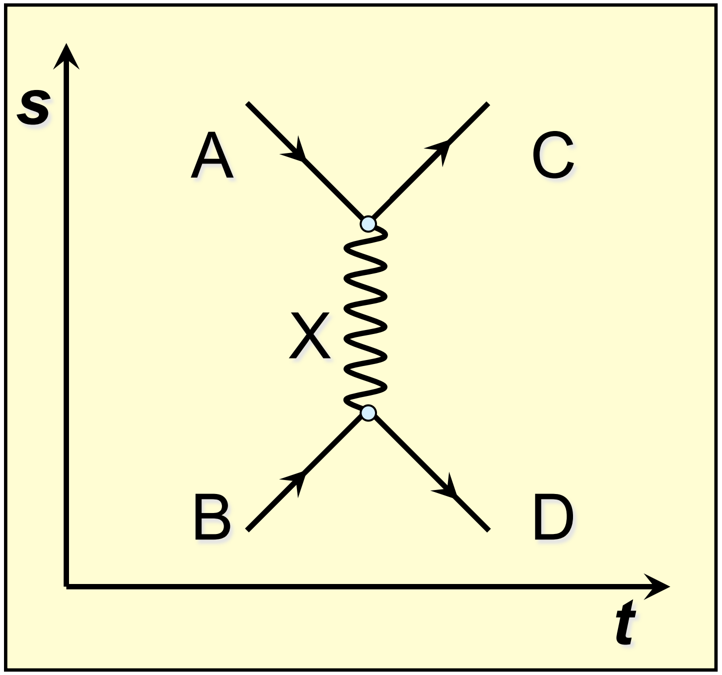


Feynman diagrams (II)

- **Exchange Diagrams**
  - Particle A scatters off of particle B by exchanging intermediate particle X. If X is a photon, then the final particles C and D are the same as A and B.



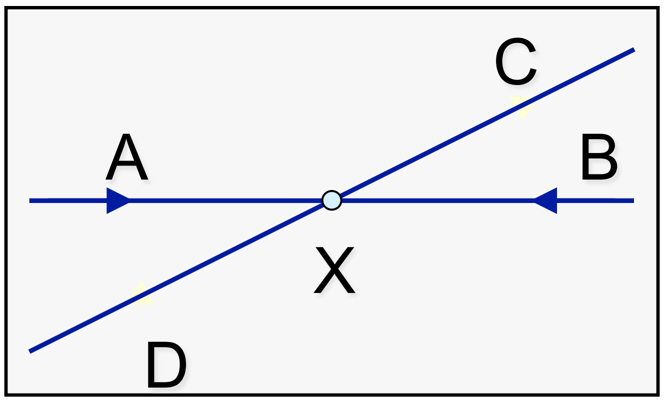
The interaction, as seen in the laboratory frame



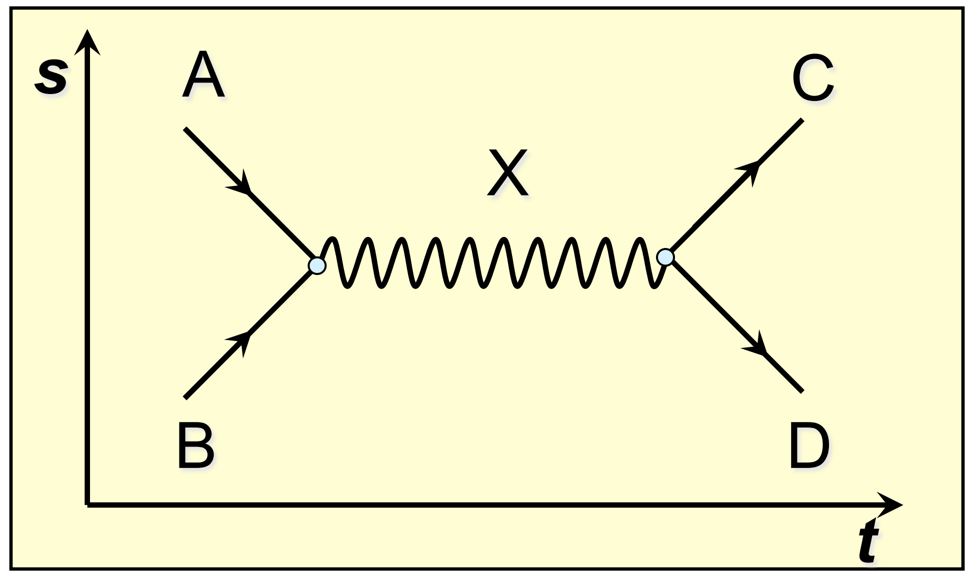
Schematic representation of the collision in terms of a Feynman diagram.

Feynman diagrams (III)

- **Annihilation and Creation (Formation) diagrams**
  - Incoming particles A and B collide, forming an intermediate particle X, which in turn decays into particles C and D

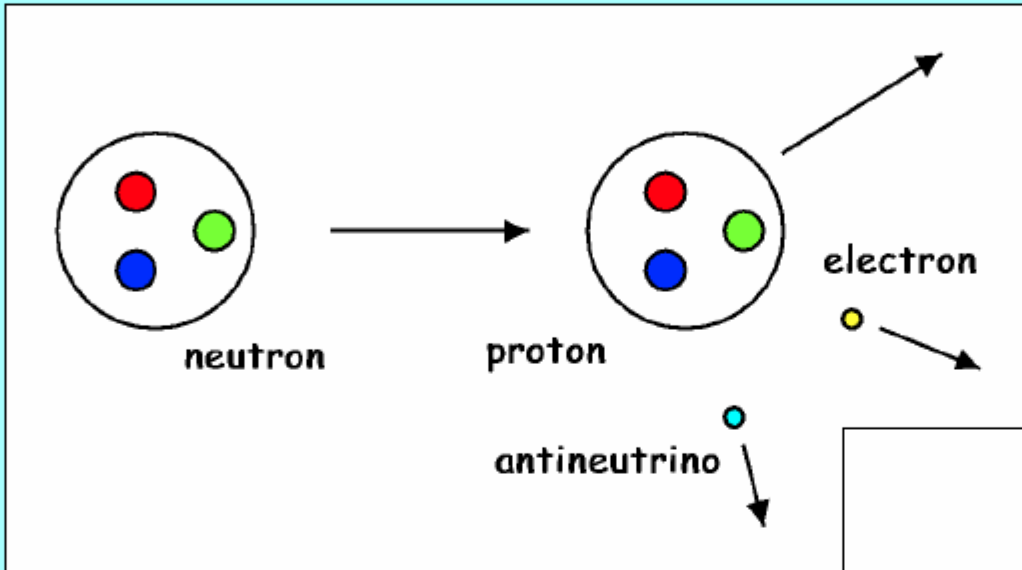


The interaction, as seen in the laboratory frame



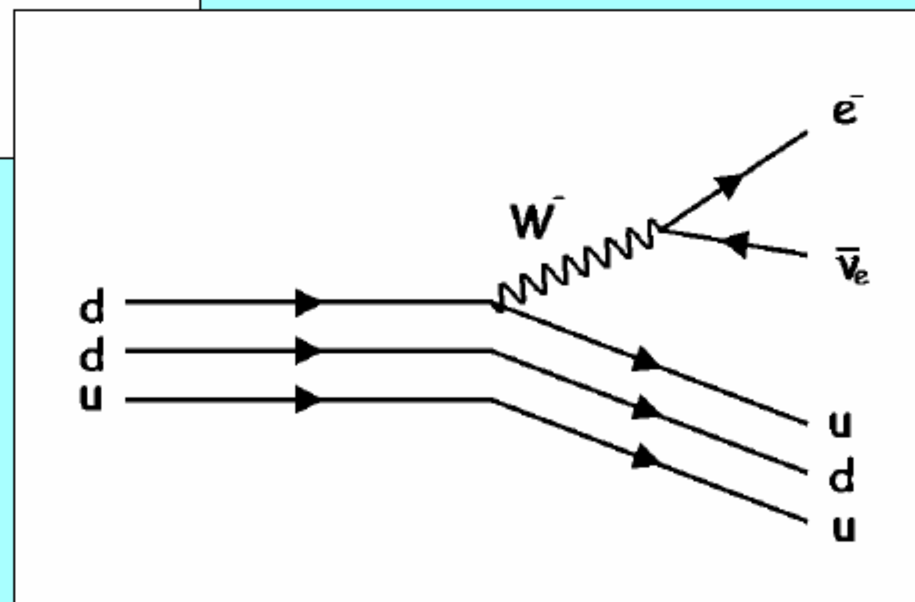
Schematic representation of the collision in terms of a Feynman diagram. Note that vertices conserve charge/momentum

Weak interaction



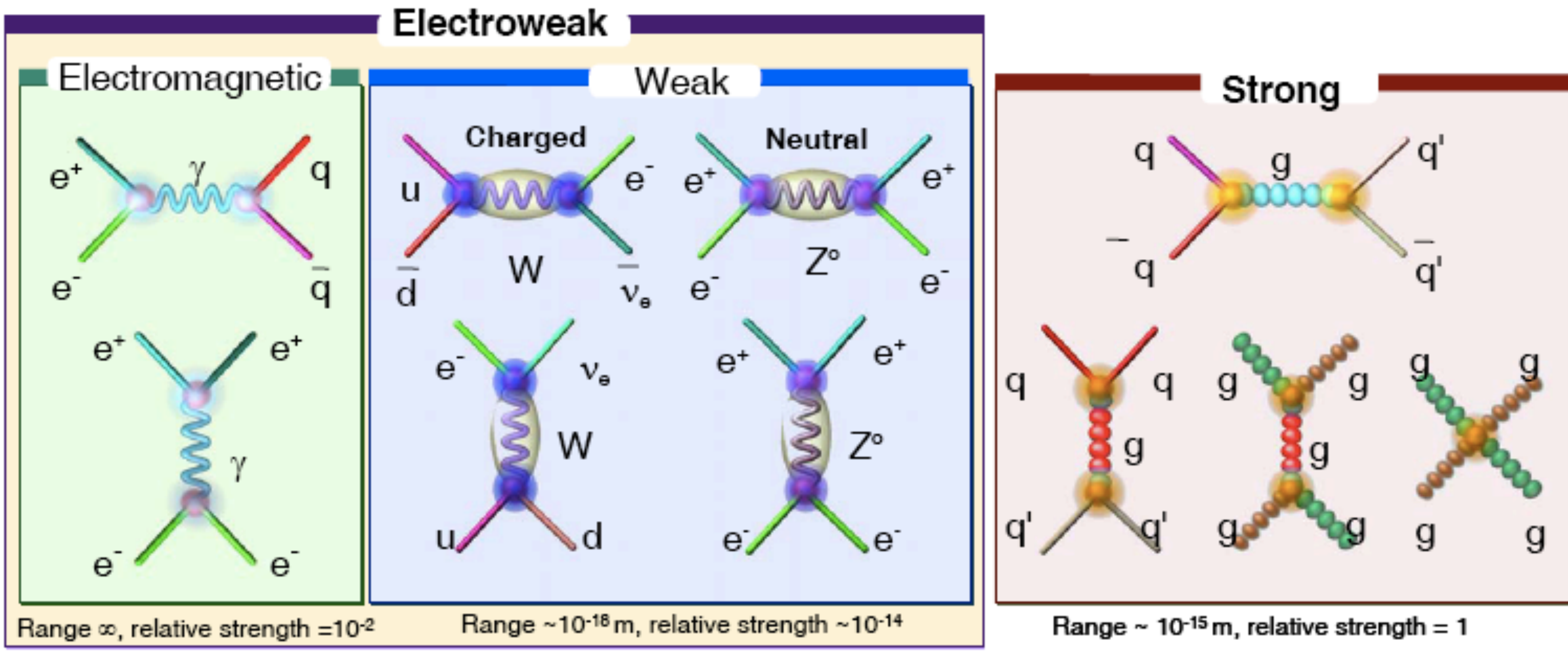
Beta decay $n \rightarrow p + e^- + \bar{\nu}_e$

Mediated by charged W exchange



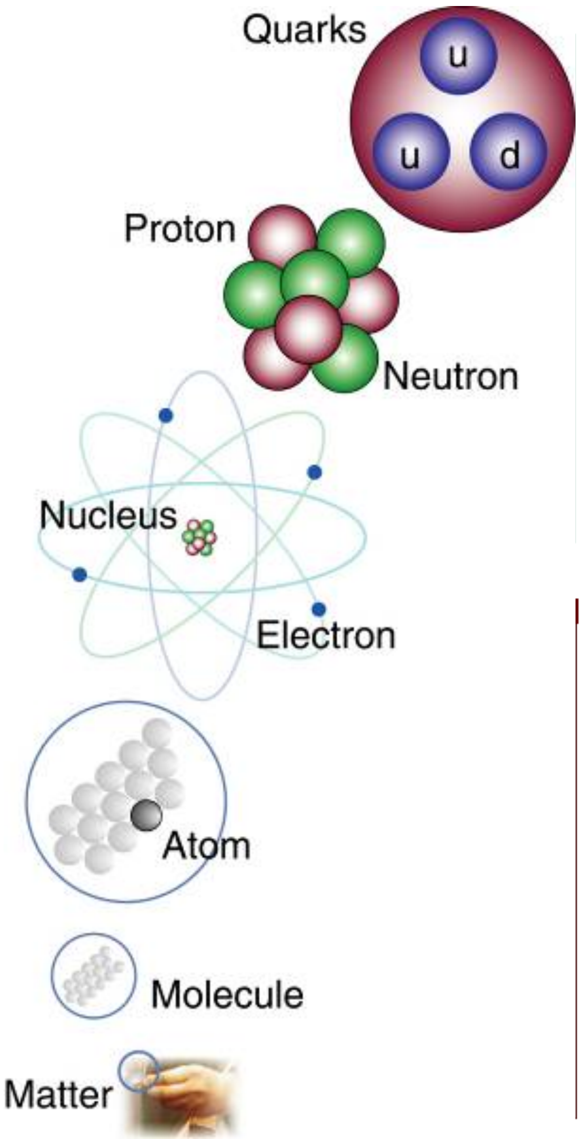
Standard Model of Particle Physics

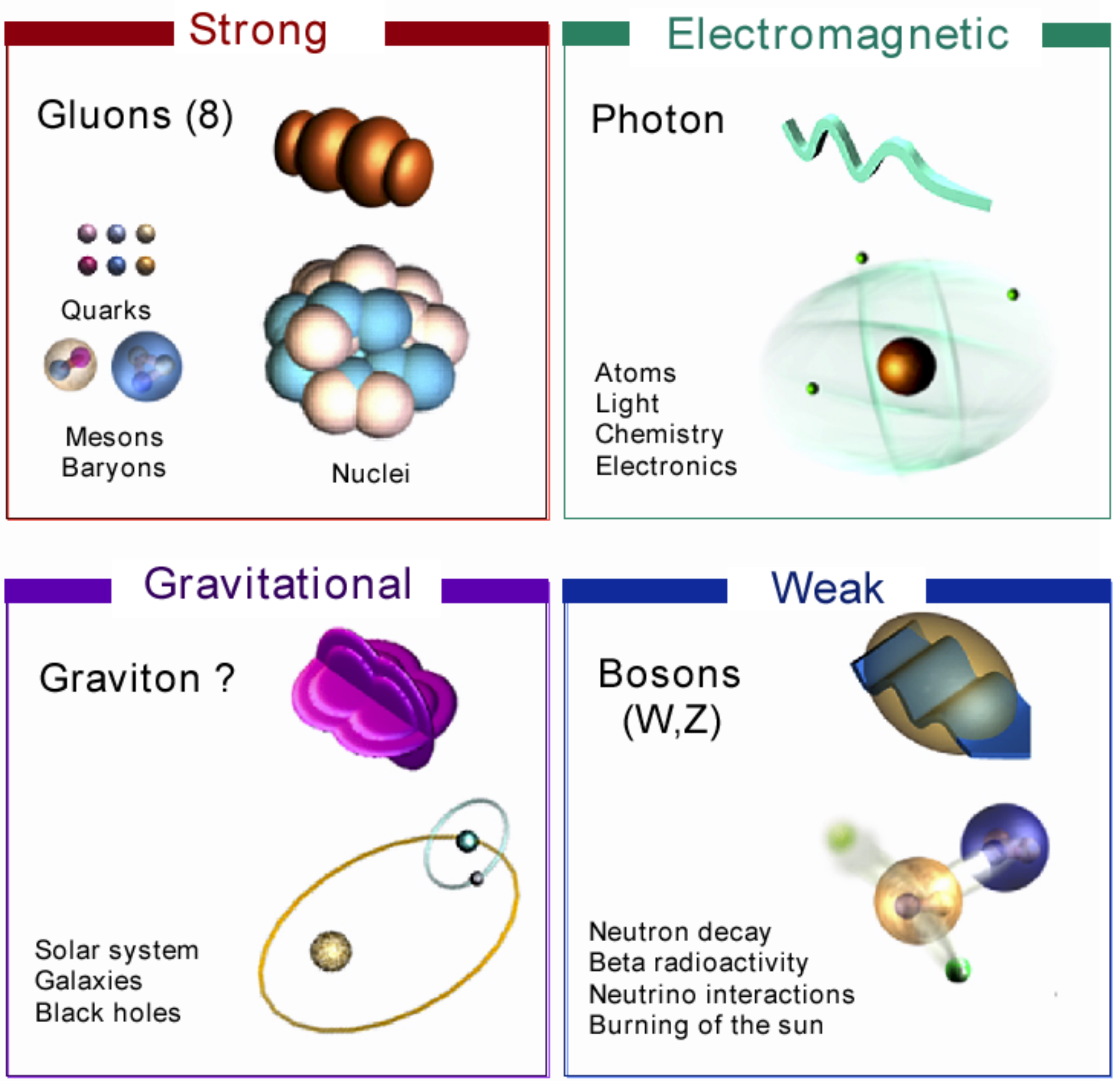
- **Quantum Field theory: matter particles (spin-1/2) interact via the exchange of force particles (spin-1)**



- **Interactions → need charges. Which should be conserved. Implies some new symmetry…**
  - **Internal symmetry (SU(3)xSU(2)xU(1)) → massless bosons**

FAQ: how to make a universe





Except... We got a basic issue wrong.

Because the range of the weak force
is very small.

Which means the carrier must be massive.
Very massive!

Mathematical Interlude

Quantum mechanics and Relativity

- **Classical Energy ⇒ Schrodinger's equation:**

$$E = \frac{p^2}{2m} + V(\vec{r}) \quad \Longrightarrow \quad -\frac{\hbar^2}{2m}\nabla^2\psi + V(\vec{r})\psi = i\hbar\frac{\partial\psi}{\partial t}$$

- **Klein-Gordon equation:**

$$E^2 = p^2c^2 + m_0^2c^4 \quad \Longrightarrow \quad -\hbar^2\frac{\partial^2}{\partial t^2}\phi = -\hbar^2c^2\nabla^2\phi + m^2c^4\phi$$

- **Static potential (forgetting time dependence)**

$$\Longrightarrow \quad \nabla^2 V(r) = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial V}{\partial r}\right) = \frac{m^2c^2}{\hbar^2}V(r)$$

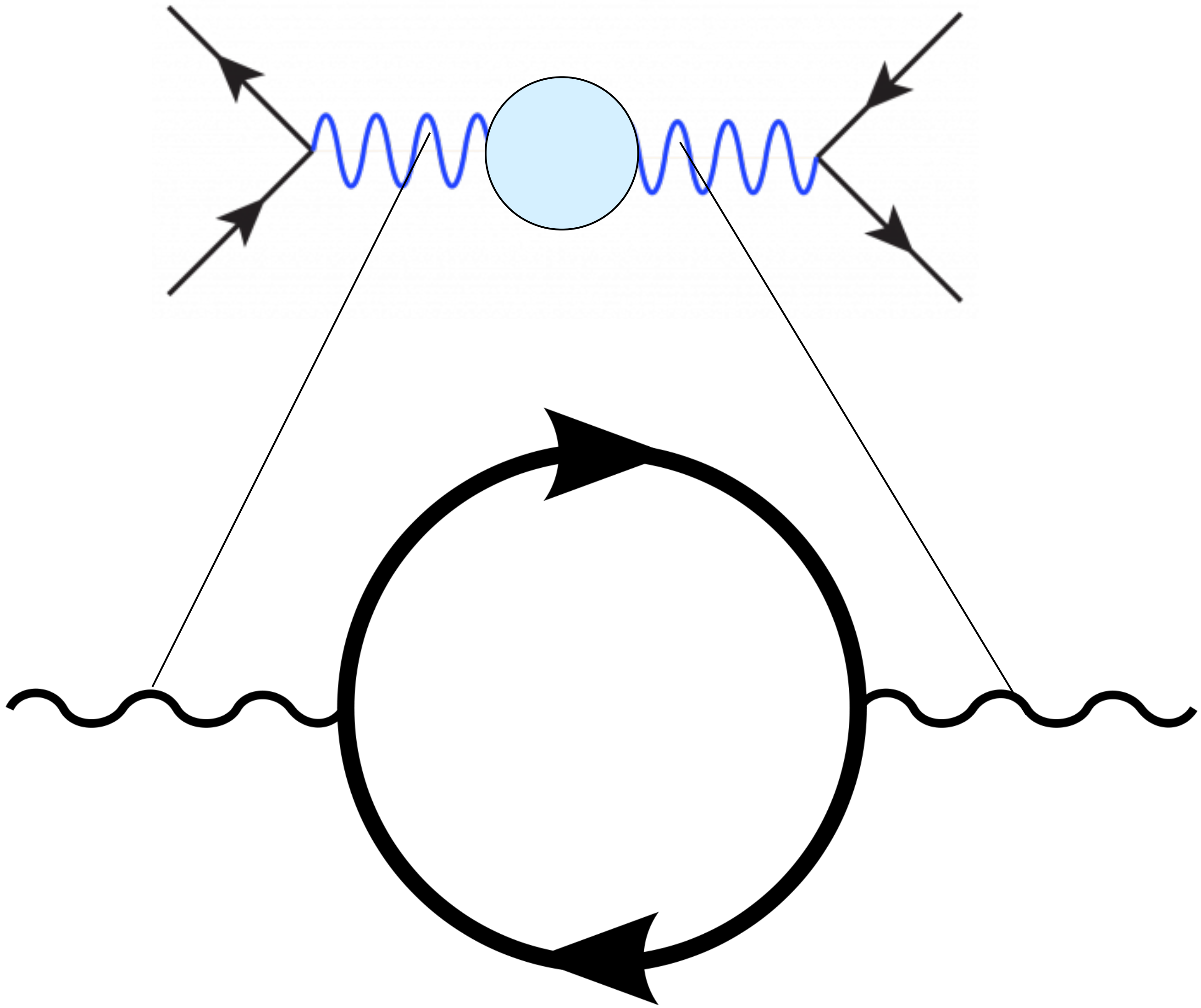
$$U(r) = \frac{g}{4\pi r}e^{-r/R} \;, \; R = \frac{\hbar}{mc}$$

What IS mass?

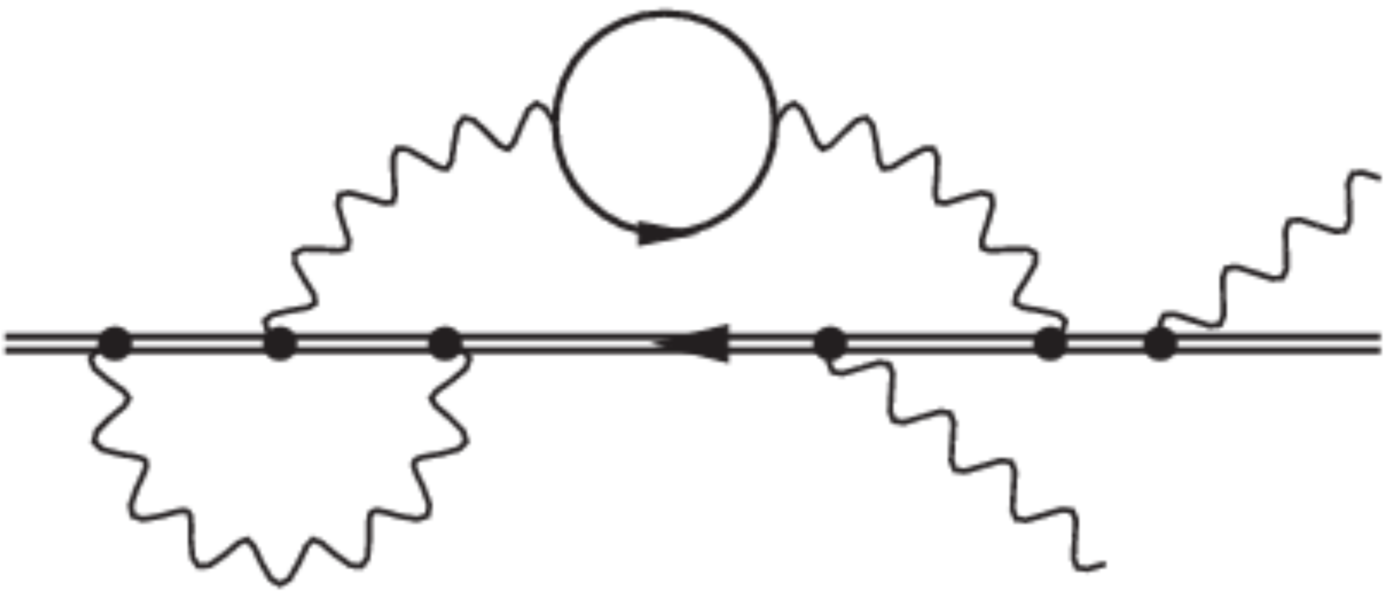
Newton: mass is the property of a particle – the one that makes it resist changes in its motion.

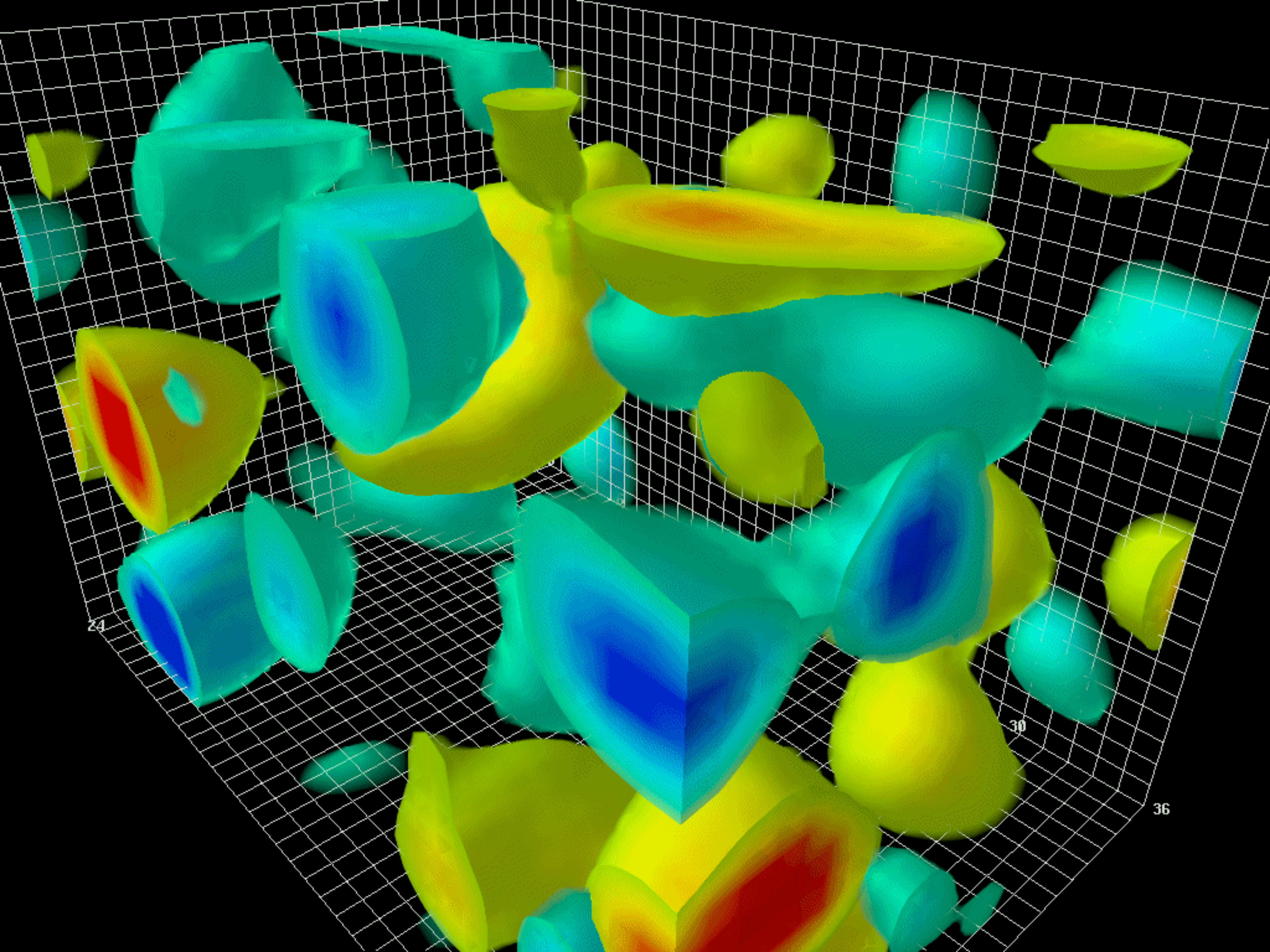
A particle travelling in empty space continues travelling in a straight line (“forever”)

Quantum Vacuum: anything but "empty"



The full quantum vacuum...



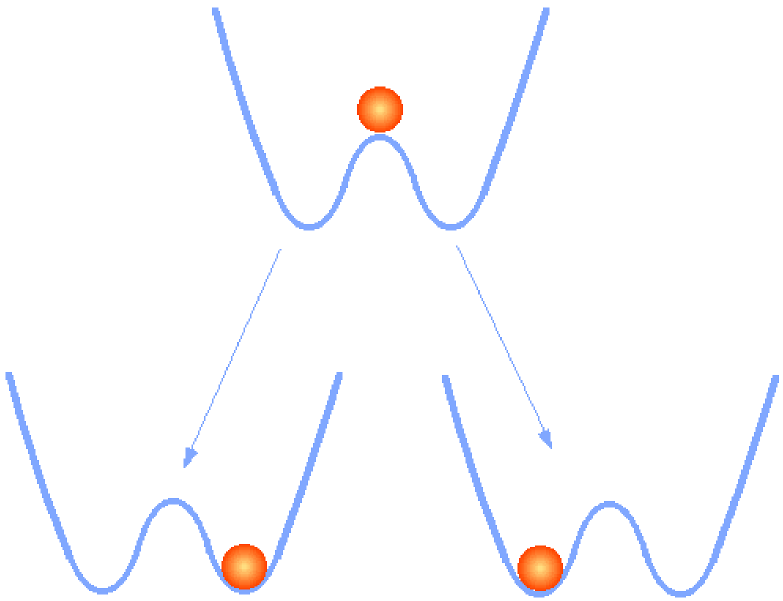

24
30
36

Brout-Englert-Higgs mechanism

- Generate masses for the fundamental particles (some of the bosons of the EWK interaction AND the fermions that make up matter)
  - $M(\gamma)=0$; $M(W)=80\ GeV/c^2$; $M(Z)=90\ GeV/c^2$
- BUT: this has to take place starting from an overall symmetric "universe" in which there is "no difference" in the way the photon and the W/Z appear
  - We cannot add mass terms by hand (due to the original symmetry "gauge invariance")
  - How can we end up with an asymmetric world [in which $M(W)\neq M(\gamma)$] when the laws are symmetric?

Standard Model & Symmetry Breaking

- **Potential with two minima**
  - "Law of nature": potential.
    (V(x)→Lagrangian →eqns of motion)
    Can be Left-Right symmetric while equilibrium state is not
  - Ball chooses one of the two minima → Left-Right symmetry is "broken"



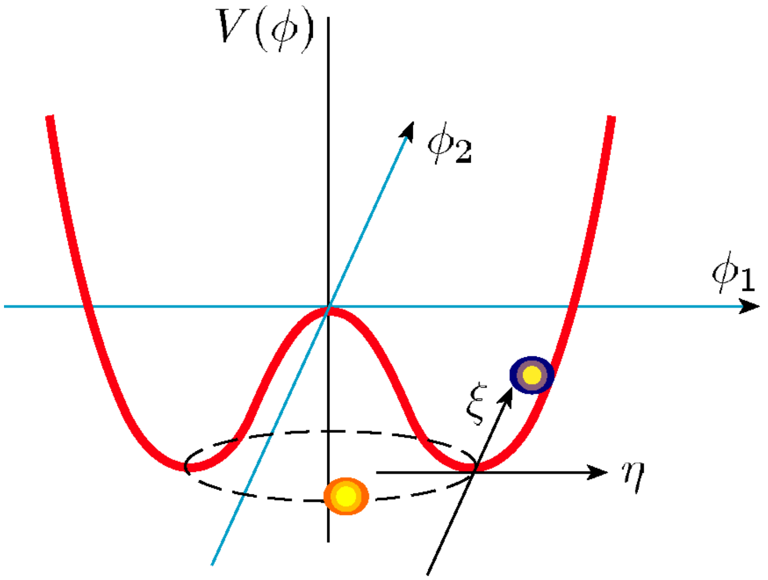
Laws: LR symmetric; but low-energy world need not be!

BEH mechanism in words

- There is a new field – which is different from ALL others: it has no spin at all (so, not a matter field, and not a boson that transmits a force)
- It's everywhere – filling up all space. It's in the vacuum – and interacts with anything that travels in the "vacuum".
- Thus: point particles, travel in a "sea" made by the Higgs Field. They meet resistance... Inertia... Mass.
- Quantum Mechanics: particle (a boson) corresponding to the field. The Higgs boson.

The Higgs Mechanism: mathematics

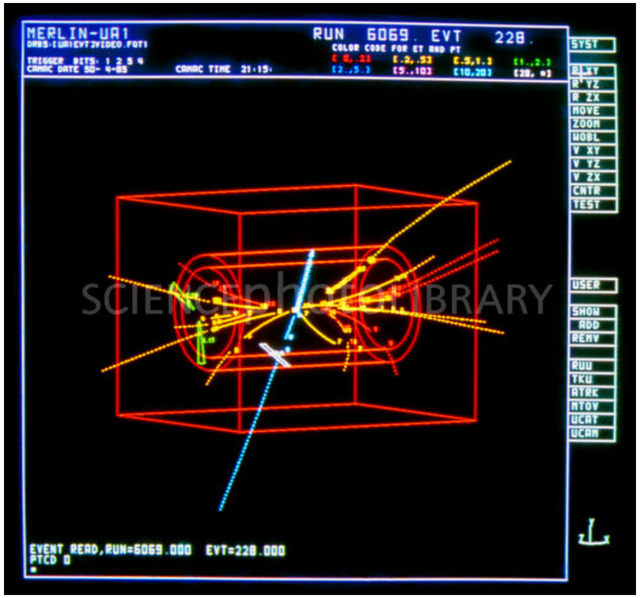
- **With two independent (complex) fields (4 DoFs)**
- **Two "motions" in the potential**
  - One on the plane; "massless" mode that is lost (once a direction is chosen). Each degree of freedom appears as additional degree of freedom of a gauge boson
    - Extra polarization state
    - The boson becomes massive!
  - One up/down on potential; massive
    - Higgs boson; for which we know everything, except one parameter: its mass!

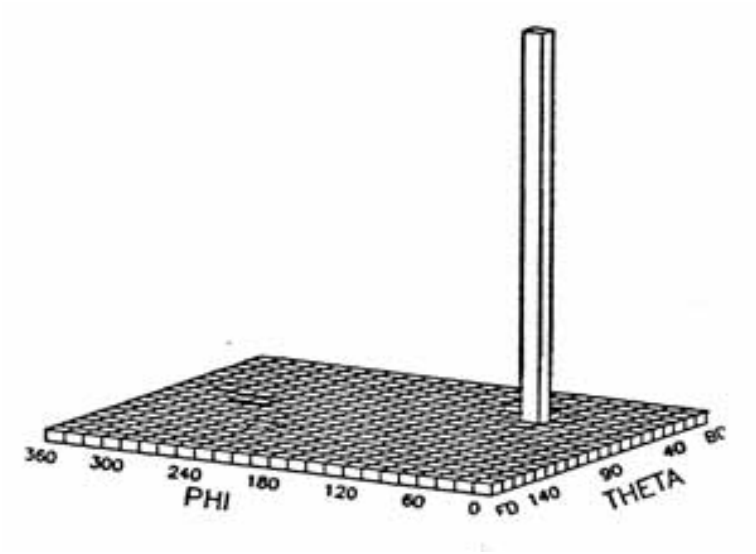


Thus were the W/Z masses born in theory; and discovered (at the right value) @ CERN in 1984.

W and Z discovery

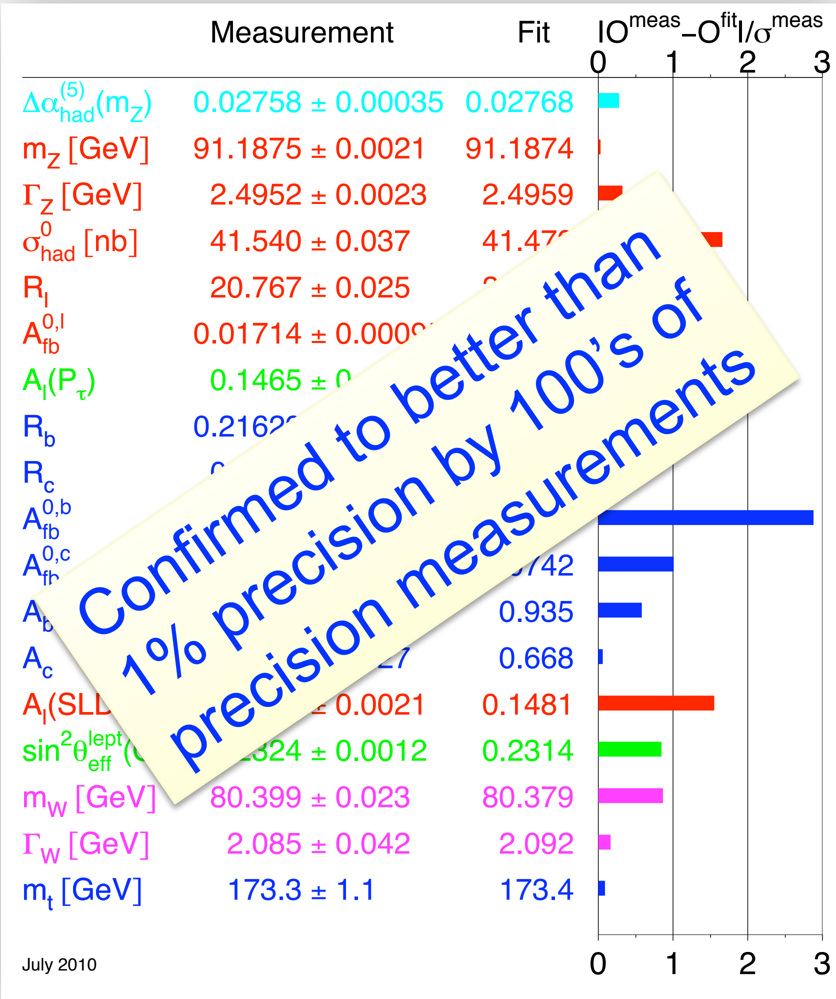
- **In 1983, the *W* and *Z* particles were discovered at CERN (UA1 and UA2)**
  - **1984 Nobel Prize to Simon van der Meer and Carlo Rubbia**

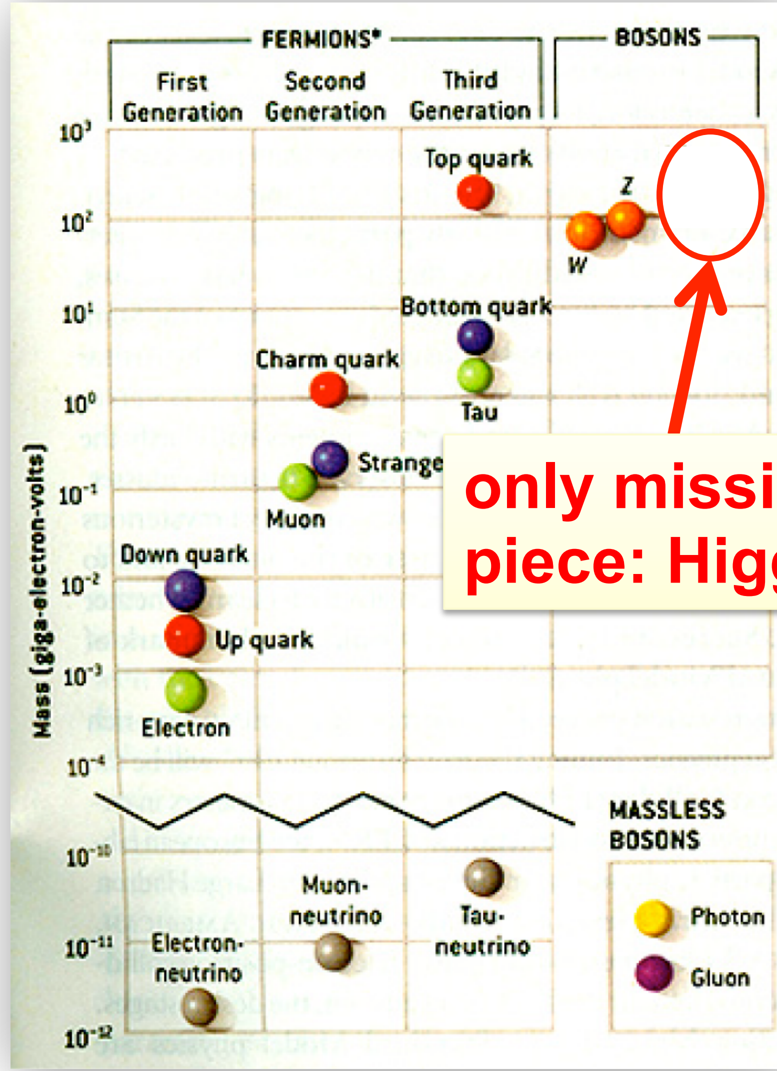




- ***Sneak preview:* at that point, the Higgs boson became the last important missing piece of SM!**

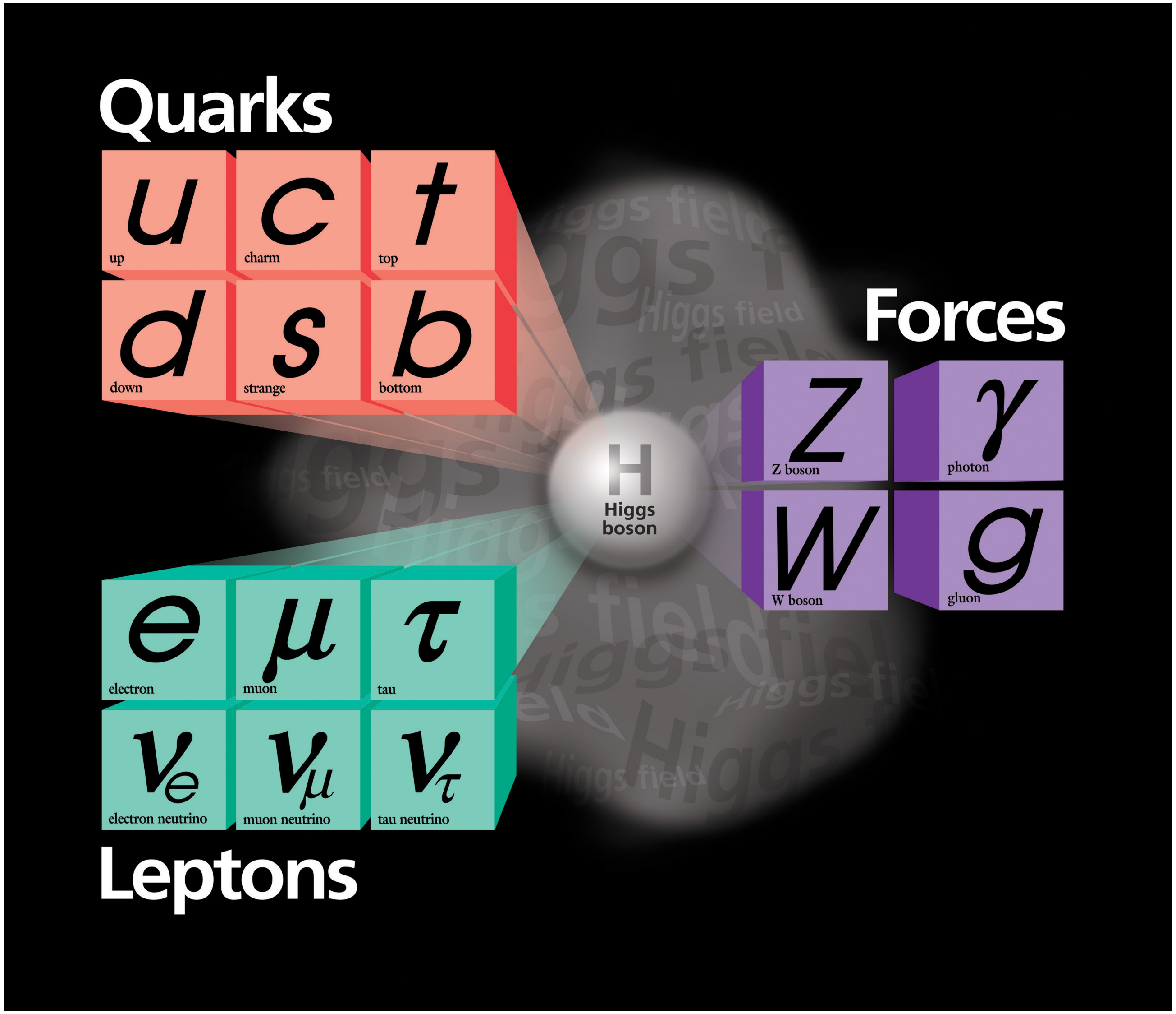
The Standard Model up until 2012





only missing piece: Higgs

Standard Model of Particle Physics



LHC($t_0+\Delta t$=2.5yrs):

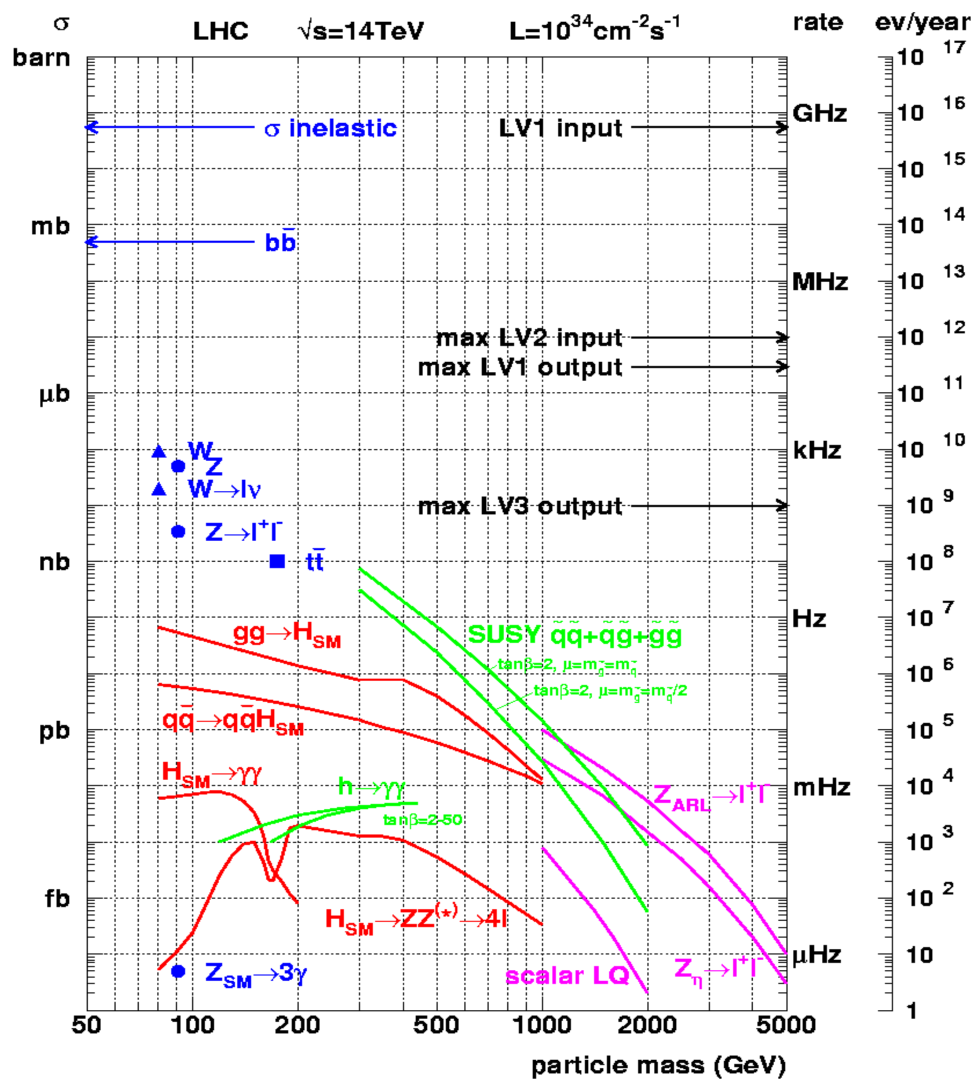
Foundations established
a "tour de force" of SM measurements

and, of course,
the hunt for the Higgs boson…

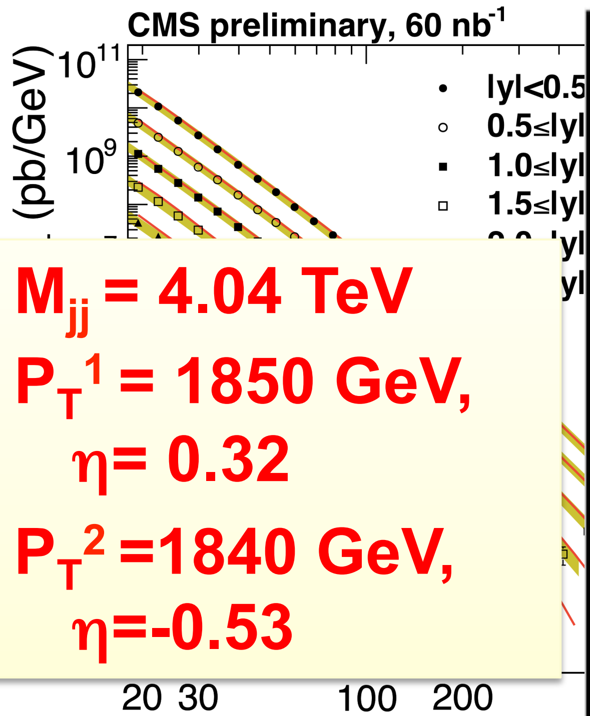
The problem: the background

The LHC: signals much smaller than "bkg"

- **General event properties**
- **Heavy flavor physics**
- **Standard Model physics**
  - QCD jets
  - EWK physics
  - Top quark
- **Higgs physics**
- **Searches for SUSY**
- **Searches for 'exotica'**



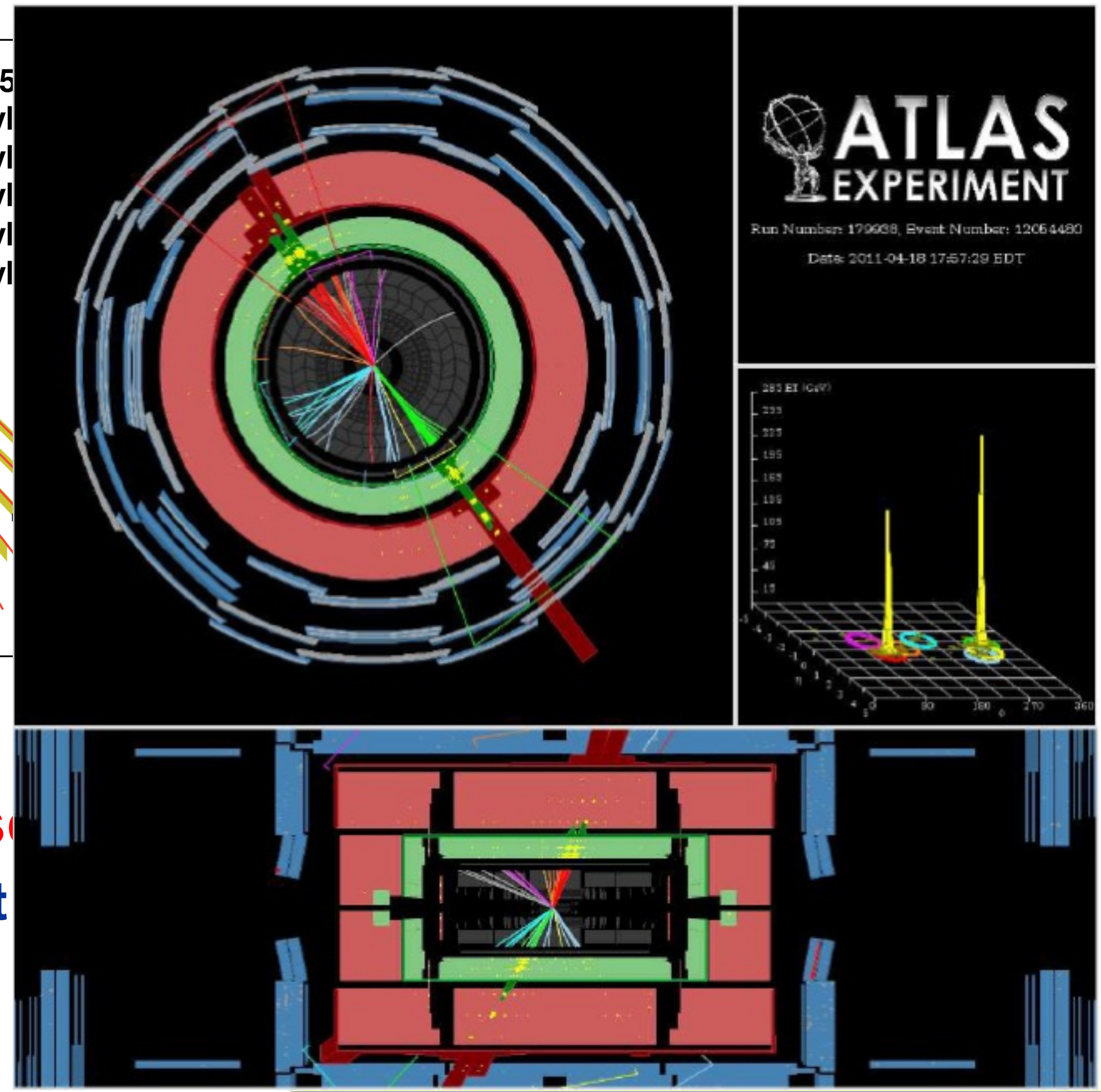
Jets



M_{jj} = 4.04 TeV

P_T^1 = 1850 GeV, η= 0.32

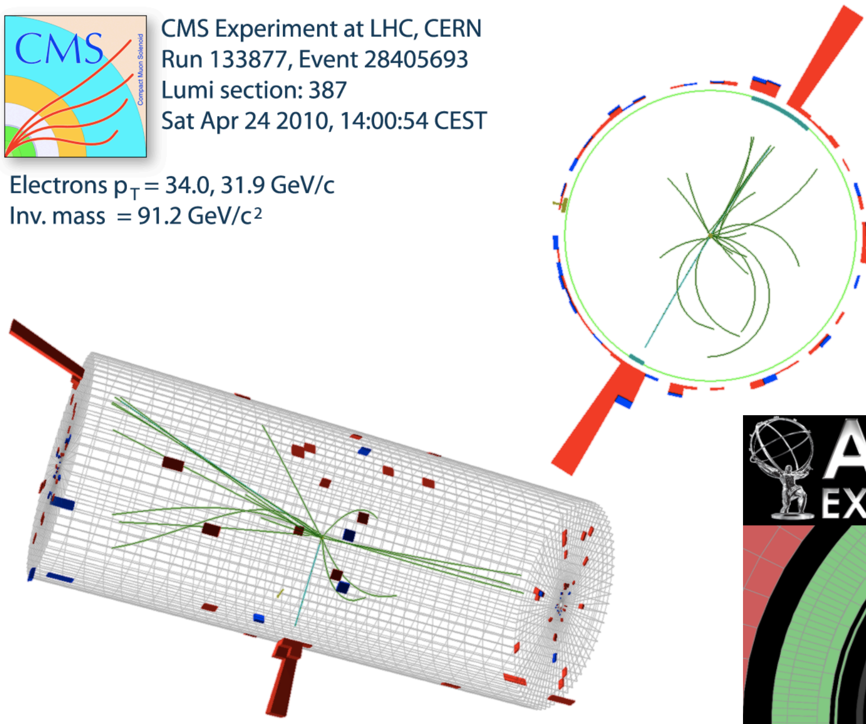
P_T^2 =1840 GeV, η=-0.53



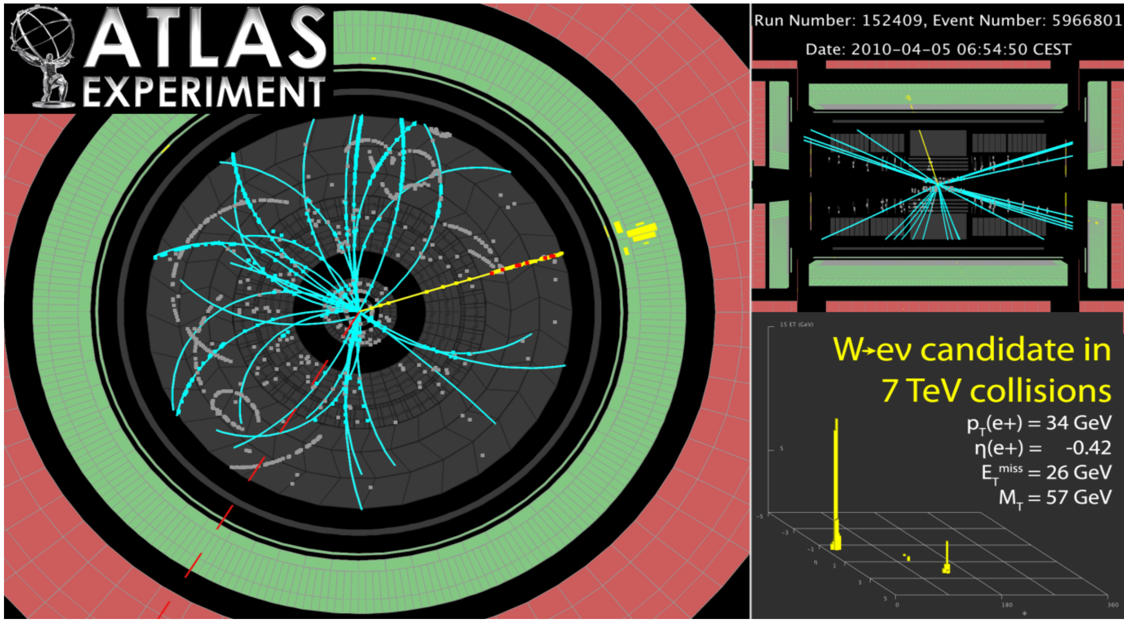
- To probe the hard s
  - The hard scatter: jet

W/Z at 7 TeV: (still) clean & beautiful

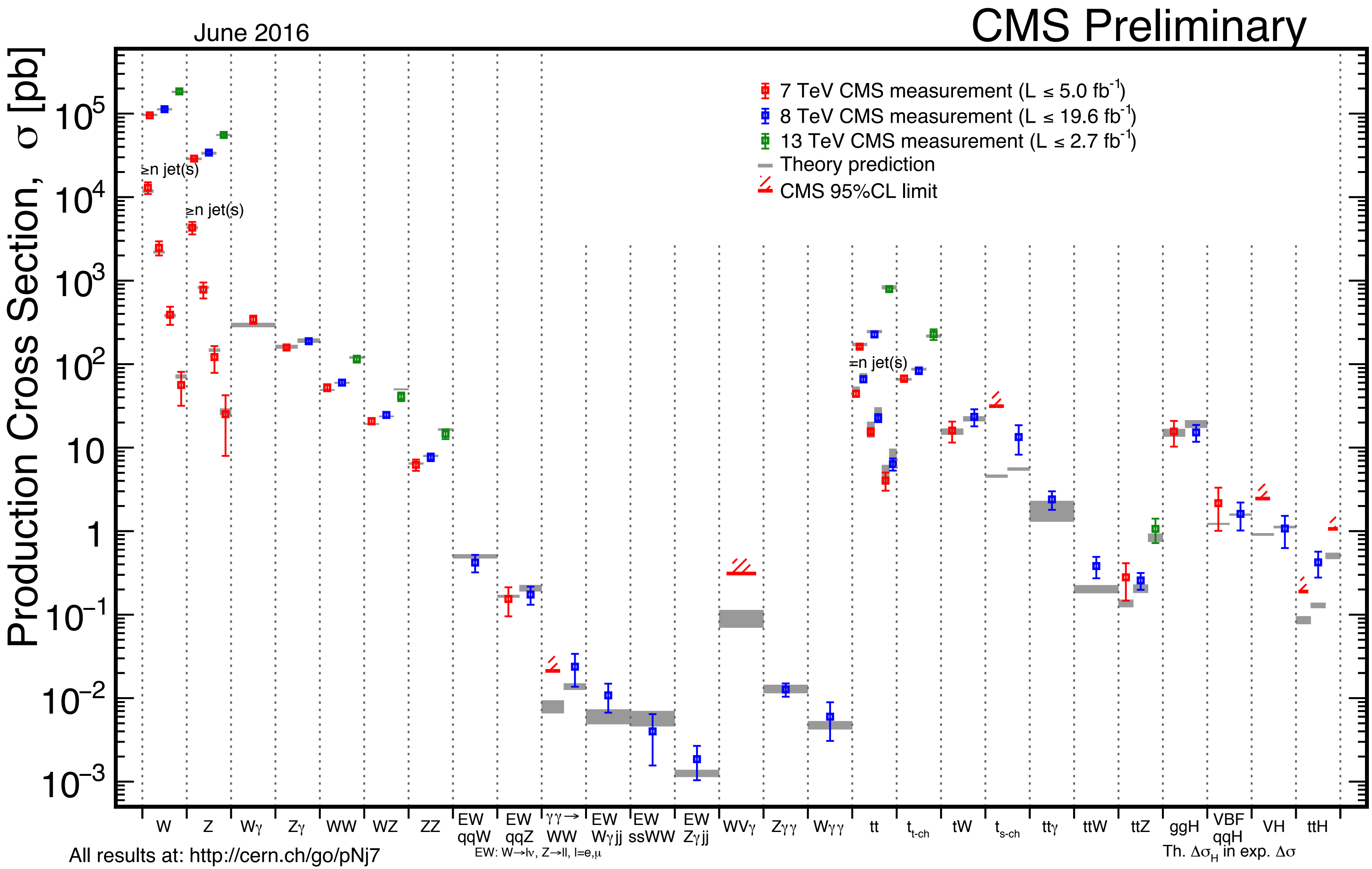
Z → electron + positron



W → electron + neutrino

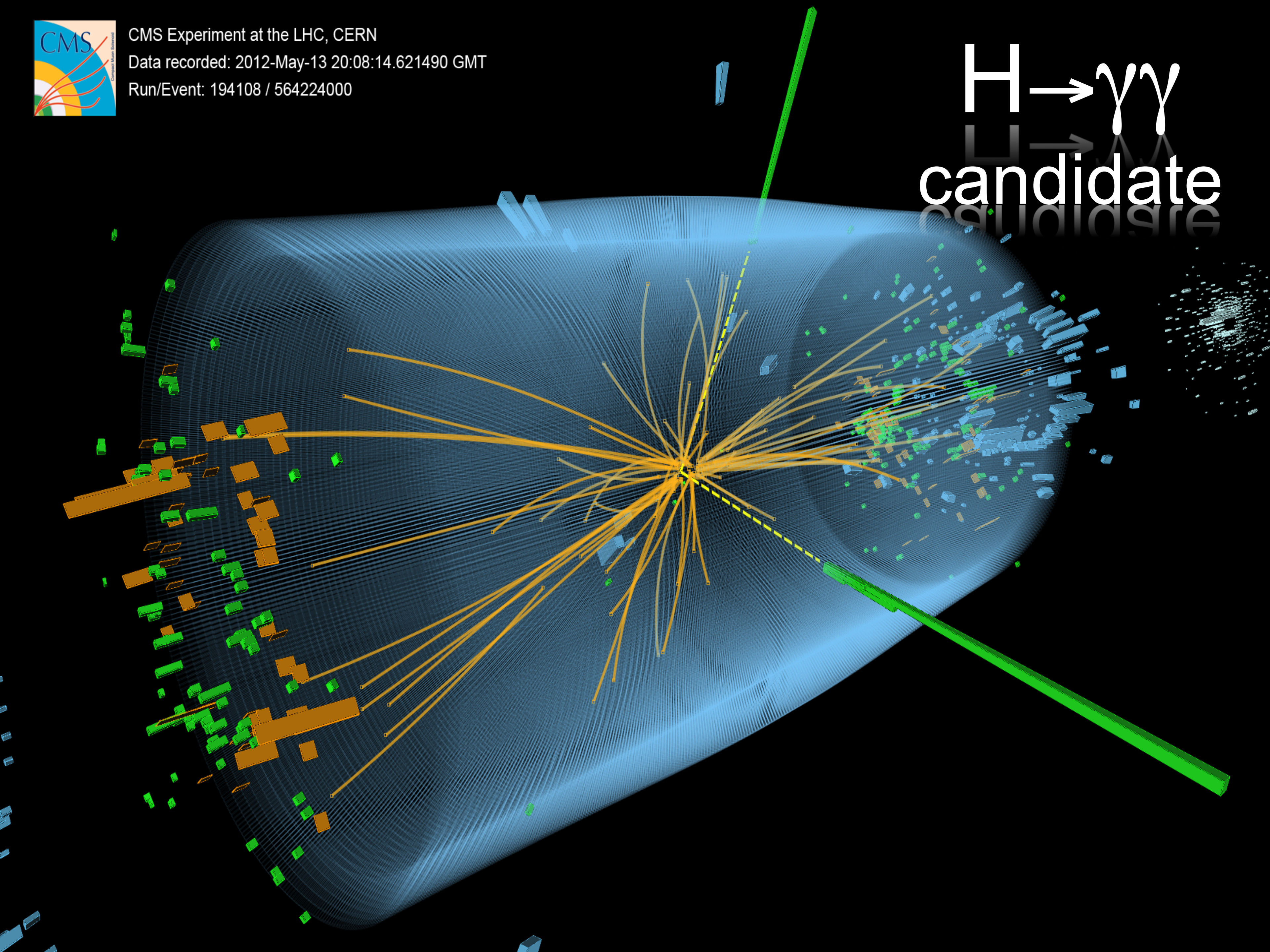


Standard Model Measurements



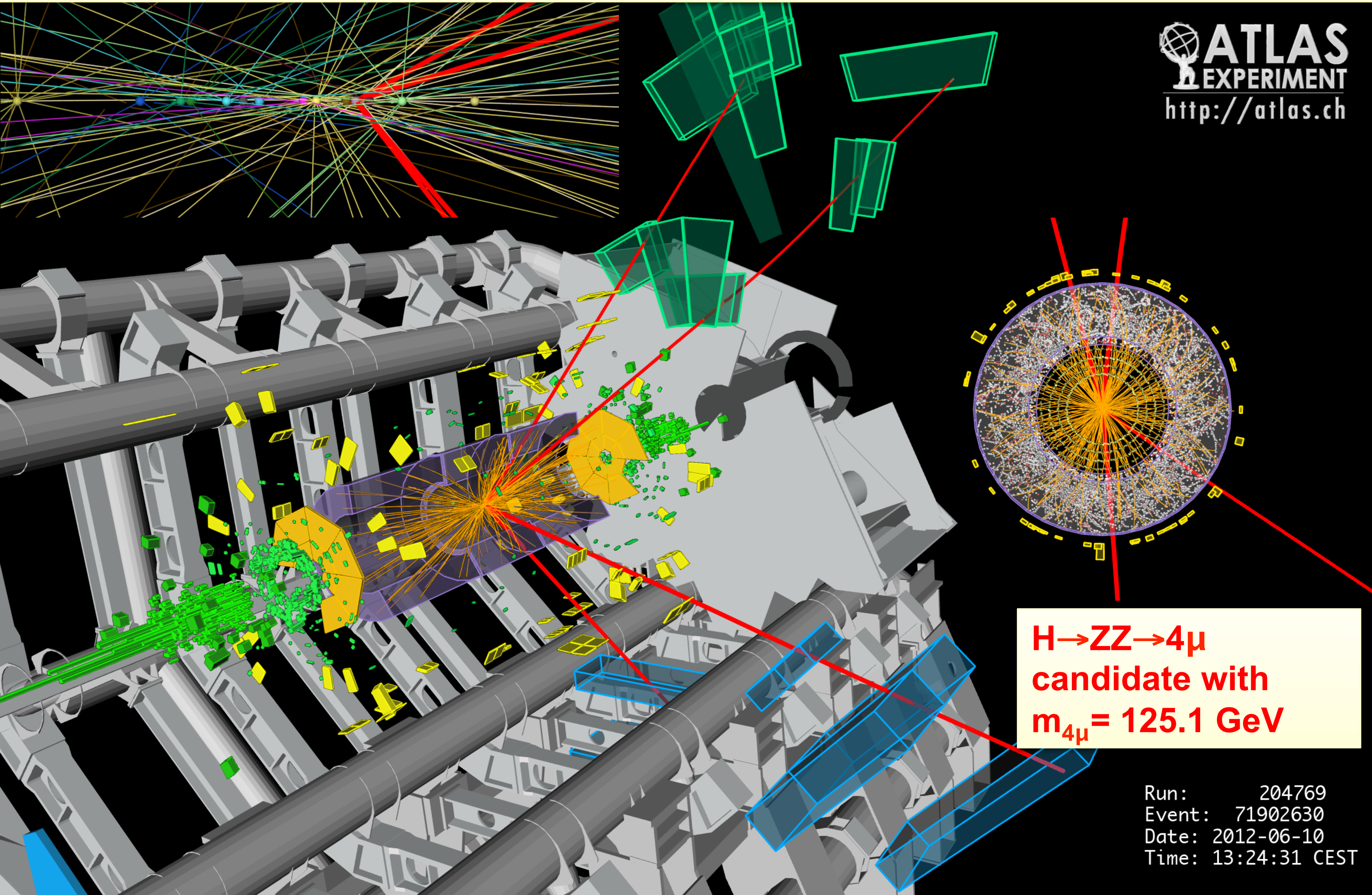
What about the Higgs boson?

Some “signatures”


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H→γγ
candidate

$p_T(\mu)$= 36, 48, 26, 72 GeV; m_{12}= 86.3 GeV, m_{34}= 31.6 GeV

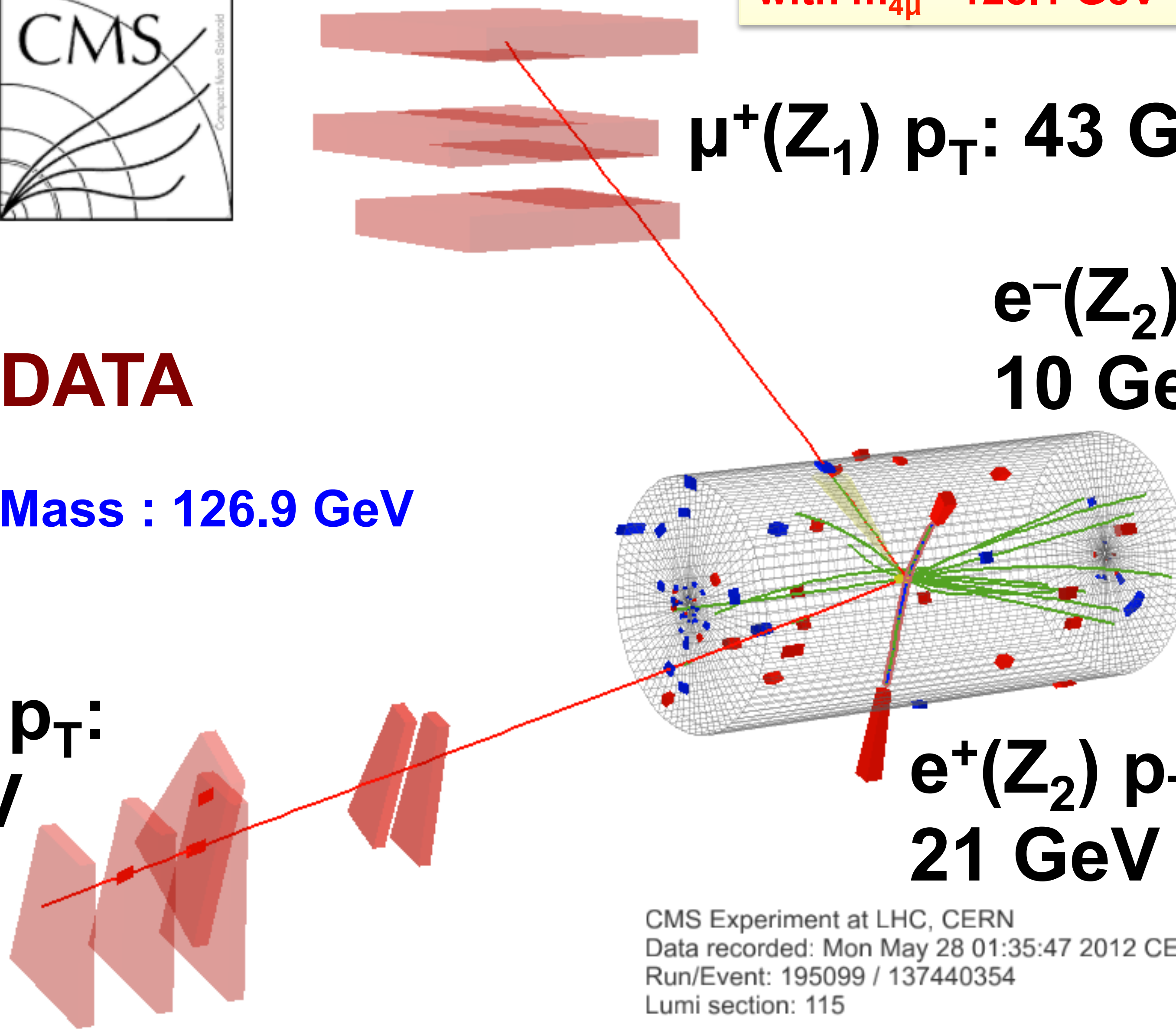
15 reconstructed vertices



H→ZZ→μμee candidate with $m_{4\mu}$= 125.1 GeV

8 TeV DATA

4-lepton Mass : 126.9 GeV

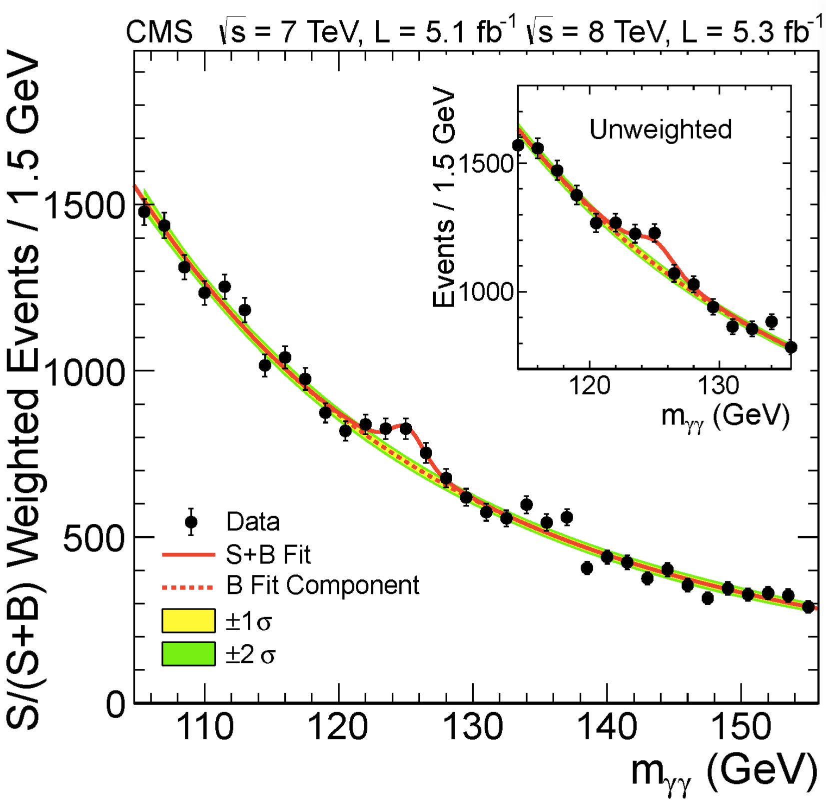


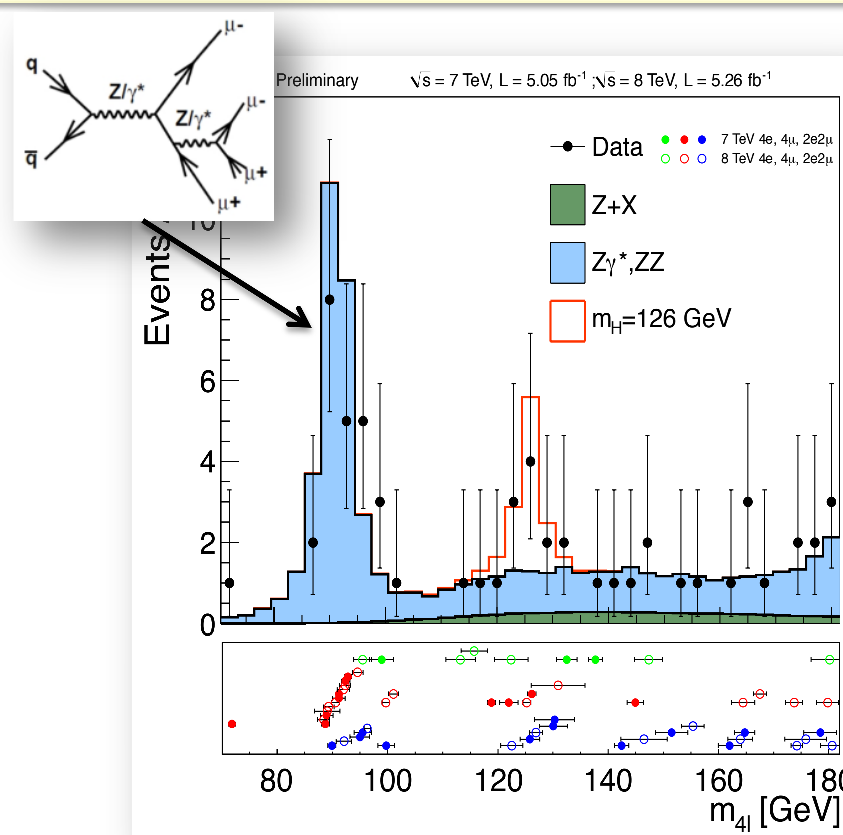
Are these events “significant”?

Discovery of a new boson

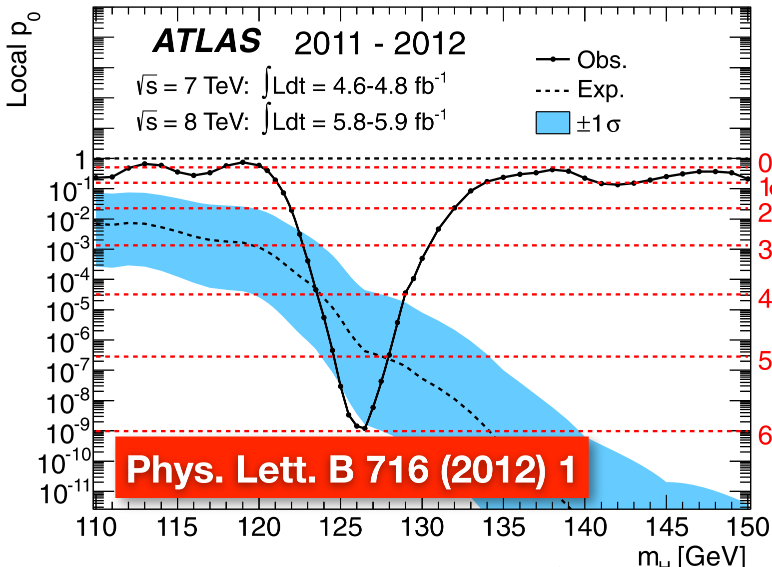
Mass peaks: H(?)→γγ & H(?)→ZZ→4leptons

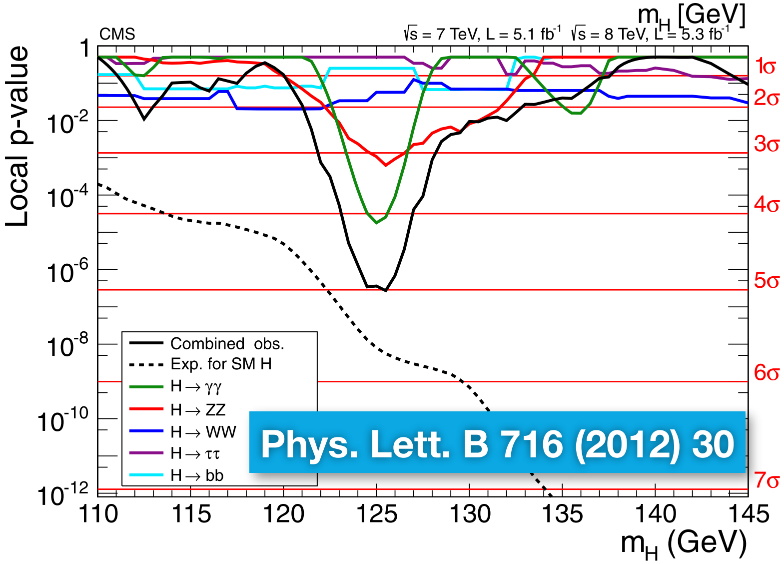
Despite the low branching fraction to the final state, the mass resolution of these two channels enables the siting of a “peak”. The ZZ peak has a Z calibration as well(!)

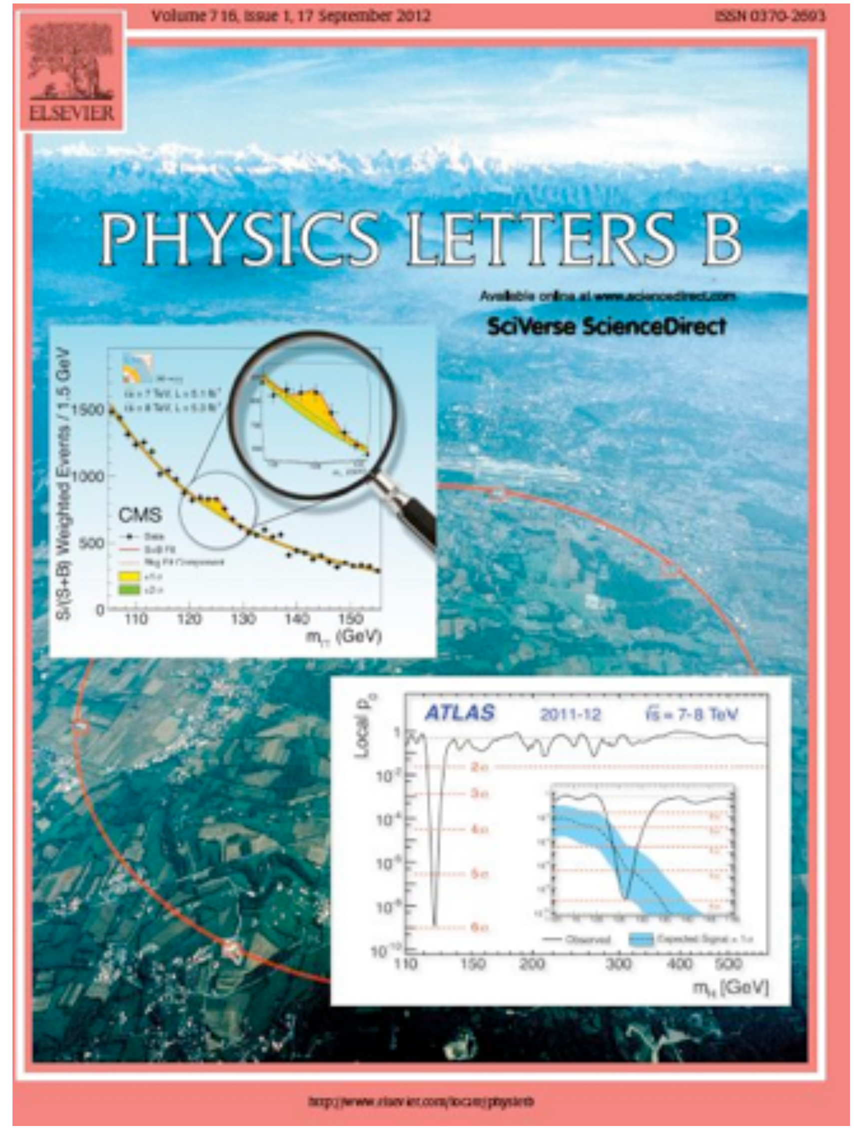




Putting it all together…







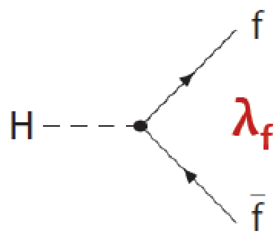
And thus was born,
on July 4^{th} 2012,
“a new boson with mass ~126 GeV”:

it decayed to two bosons
(two γ; two Z; two W)

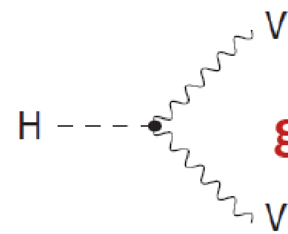
It is not spin-1: it decays to two photons (Landau-Yang theorem)

It is either spin-0 or spin-2 (could also be higher spin, but this is really disfavored)

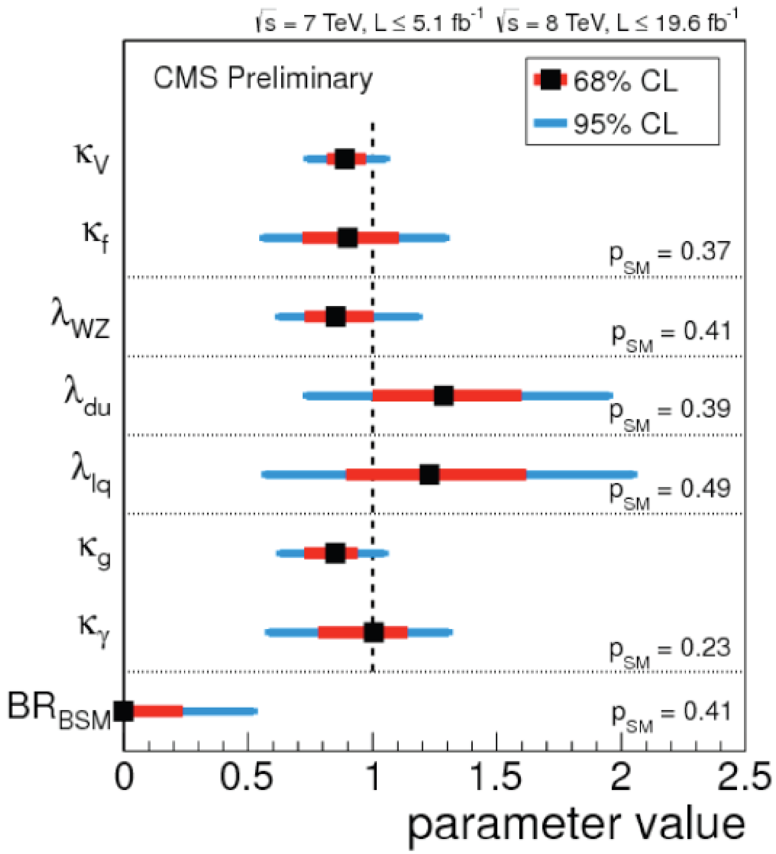
Couplings to particles

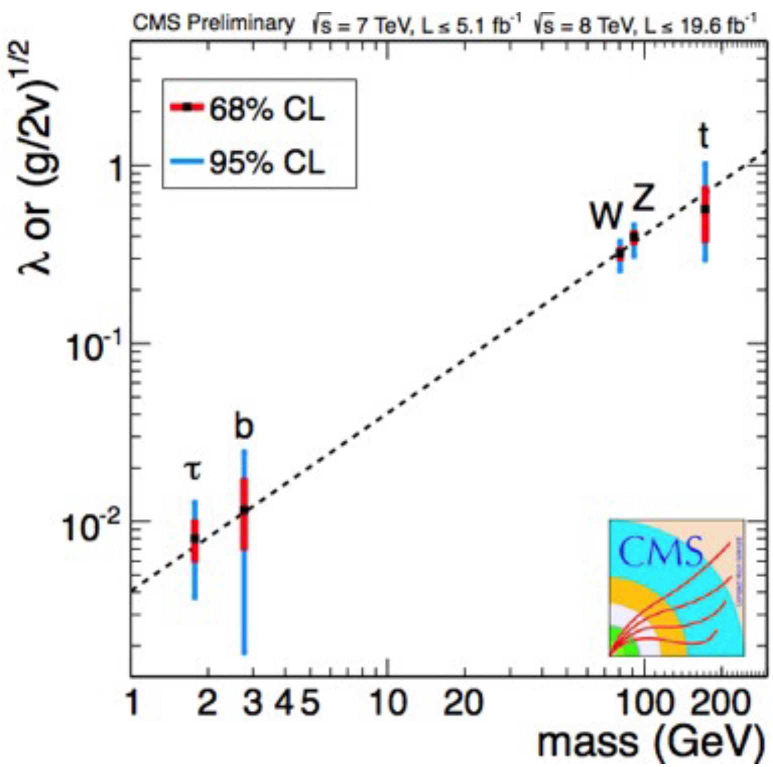


$\lambda_f = m_f / v$

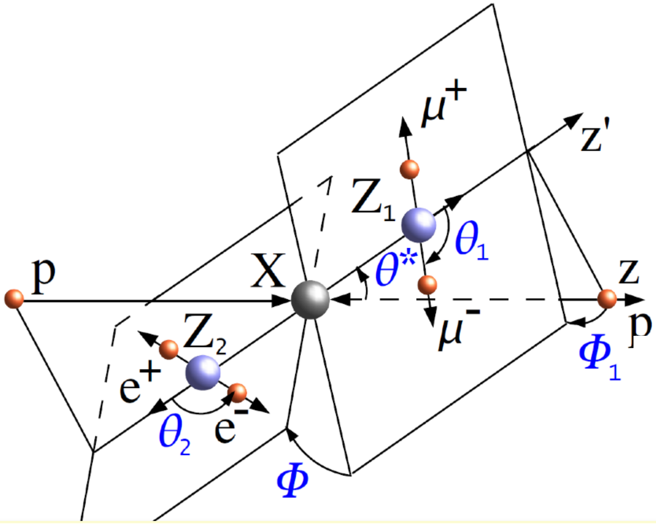


$g_V = 2\, m_V^2 / v$





H→ZZ→4leptons: angular analysis

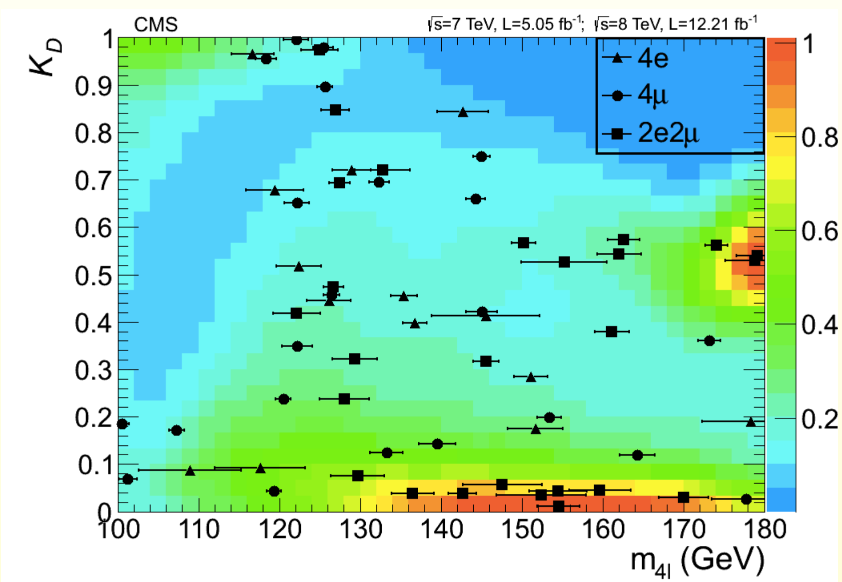


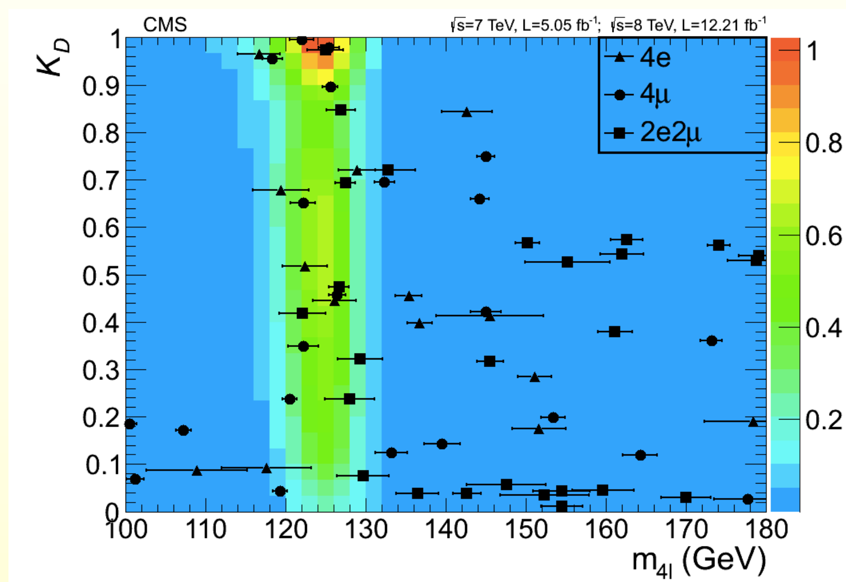
Matrix Element Likelihood Analysis:

uses kinematic inputs for signal to background discrimination

$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

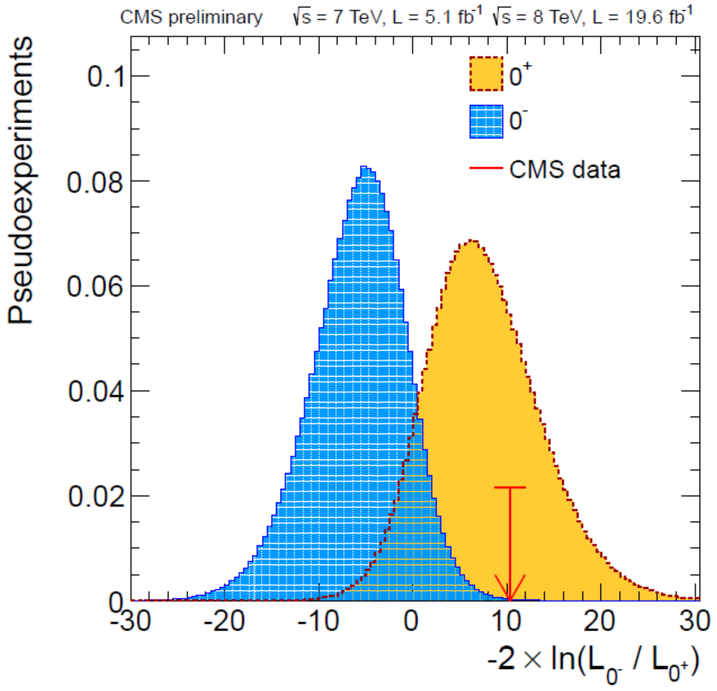
$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$



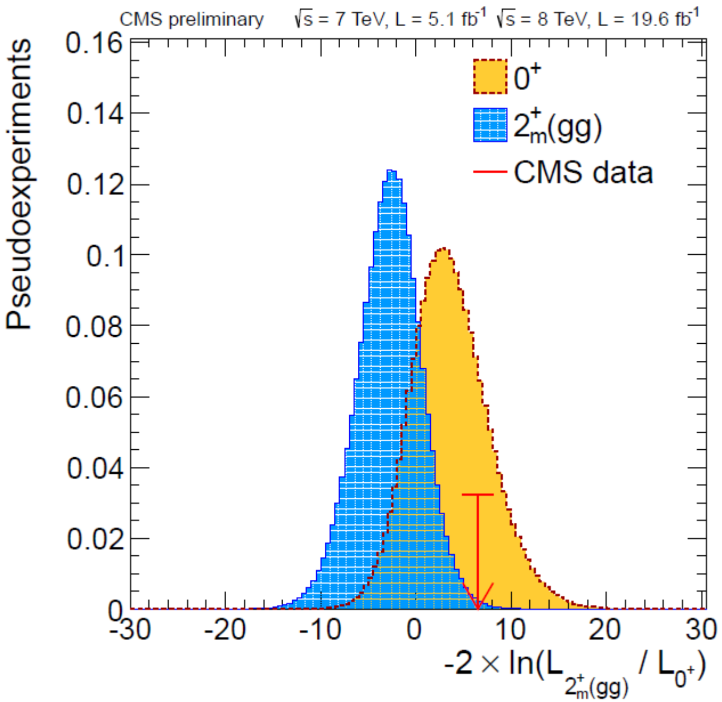


Scalar or pseudoscalar? Spin 2 or 0?

- **Test angular distributions under both the 0^+ and 0^- hypotheses**



- **Test angular distributions under both the 2^+ and 0^+ hypotheses**



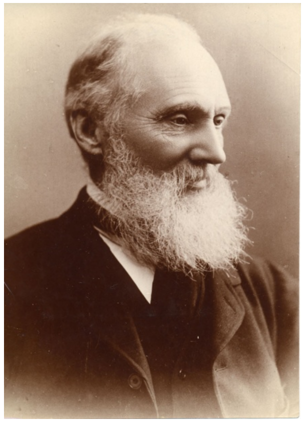
$$CLs\left({}^{0^-}\!/_{0^+}\right) = 0.16\%,\ CLs\left({}^{2^+}\!/_{0^+}\right) = 1.5\%$$

So is this it?

In a world of an SM Higgs, is there any room for new physics?

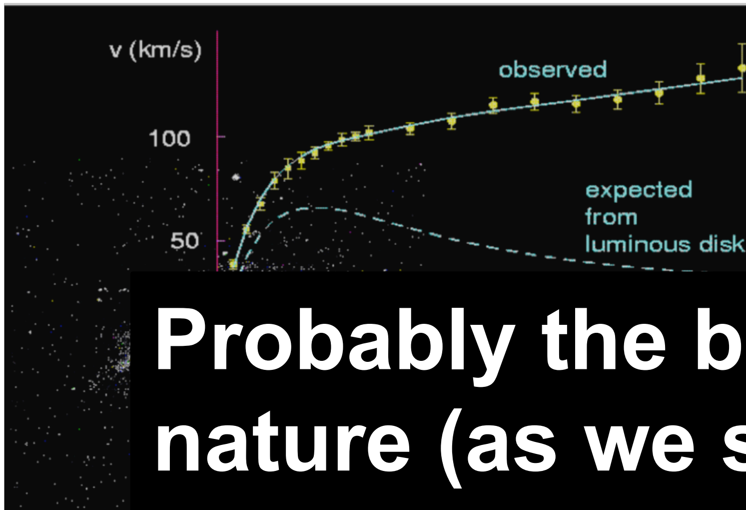
Learning from history

- **With the discovery of the Higgs boson, the Standard Model (SM) is now complete**
  - **The SM provides a remarkably accurate description of experiments with and without high-energy accelerators.**
- **With the physics of the very small [thought to be] understood at energy scales of at least 100 GeV, the situation is reminiscent of previous times in history when our knowledge of nature was deemed to be "complete".**



Lord Kelvin (1900):
There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

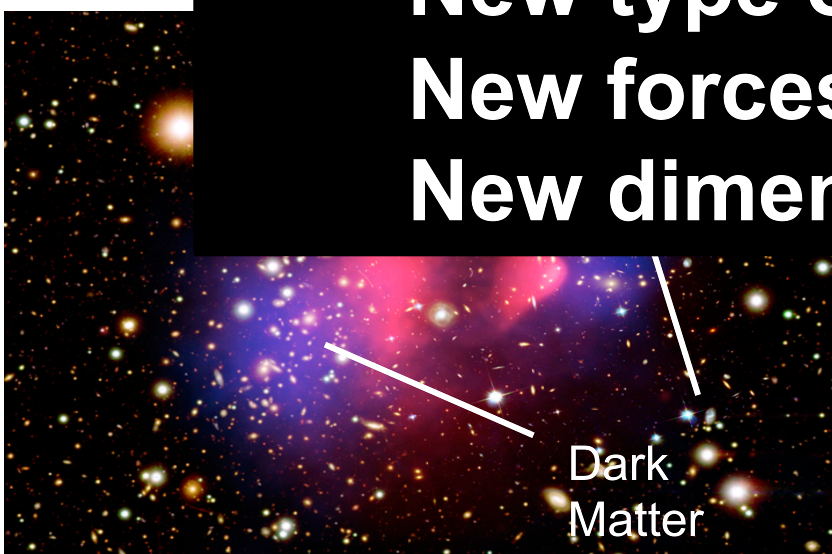
Dark matter

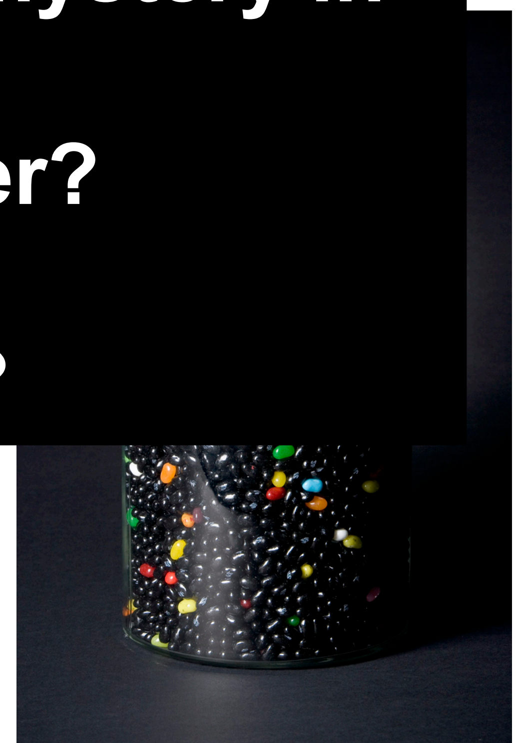


Dark (invisible) matter!

Probably the biggest mystery in nature (as we speak)

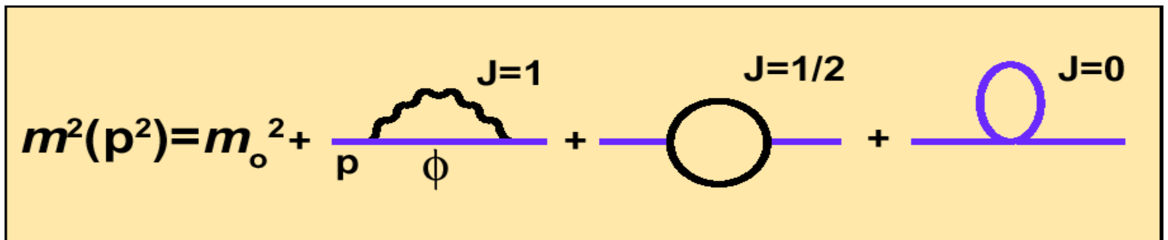
- **New type of matter?**
- **New forces?**
- **New dimensions?**





The magic of the Higgs boson mass

- **Quantum Mechanics: ultimate destructor of small numbers (in nature) not protected by some symmetry (thus "law")**
- **Higgs boson: the ultimate example.**



$$m^2\left(p^2\right) = m^2\left(\Lambda^2\right) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2$$

  - If no new physics up to Planck scale, then $\Lambda \sim 10^{19}$ GeV
  - m^2 = 1234567890123456789012345675432189012 – 1234567890123456789012345675432173136 = 15876 GeV^2

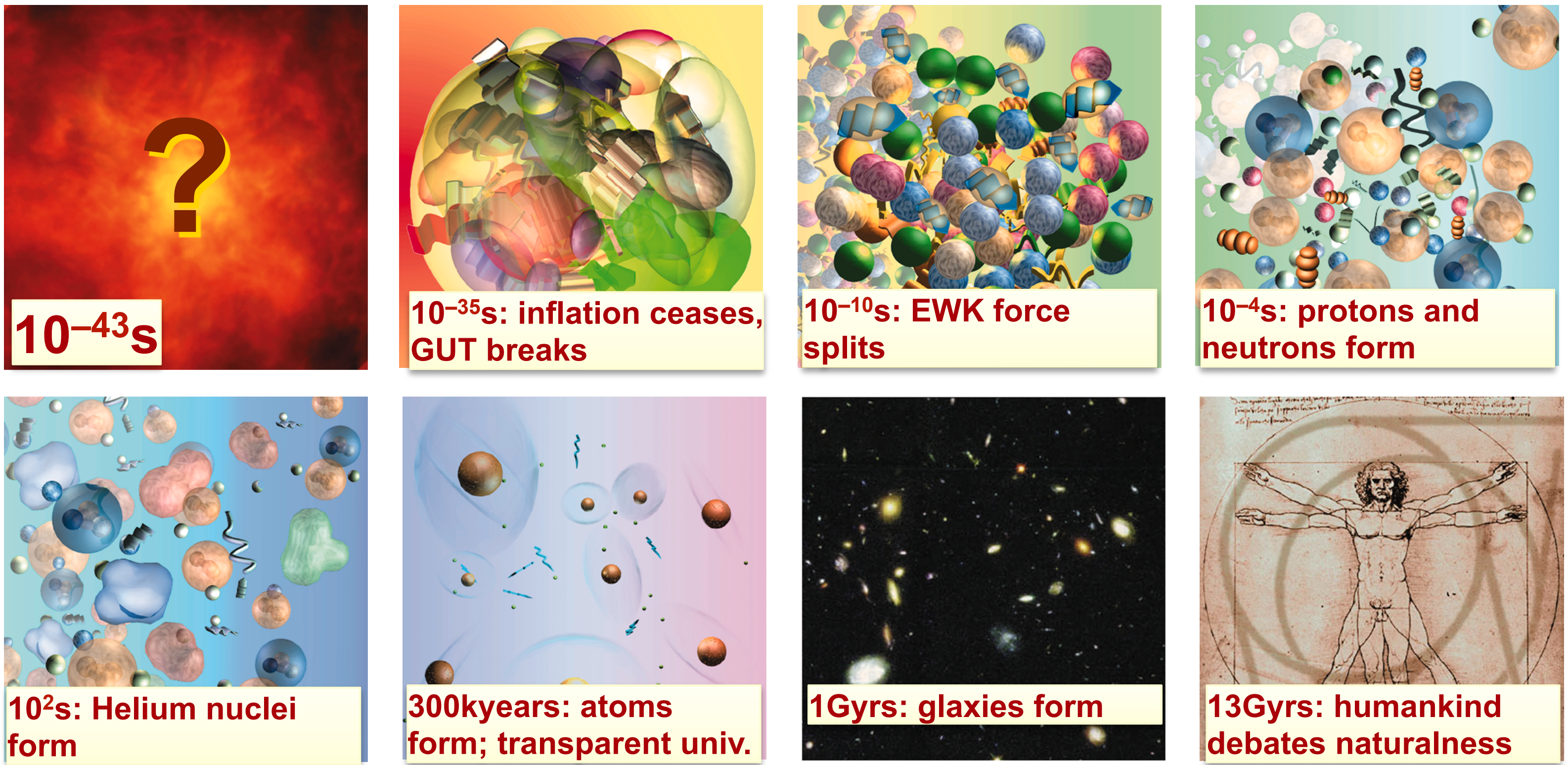
- **Two possible explanations for this:**

(a) The A word (b) New Physics

P.A.M Dirac

The A word: anthropic [aka "accident"*]

- **Extreme fine-tuning (ETF) of parameters: no problem!**

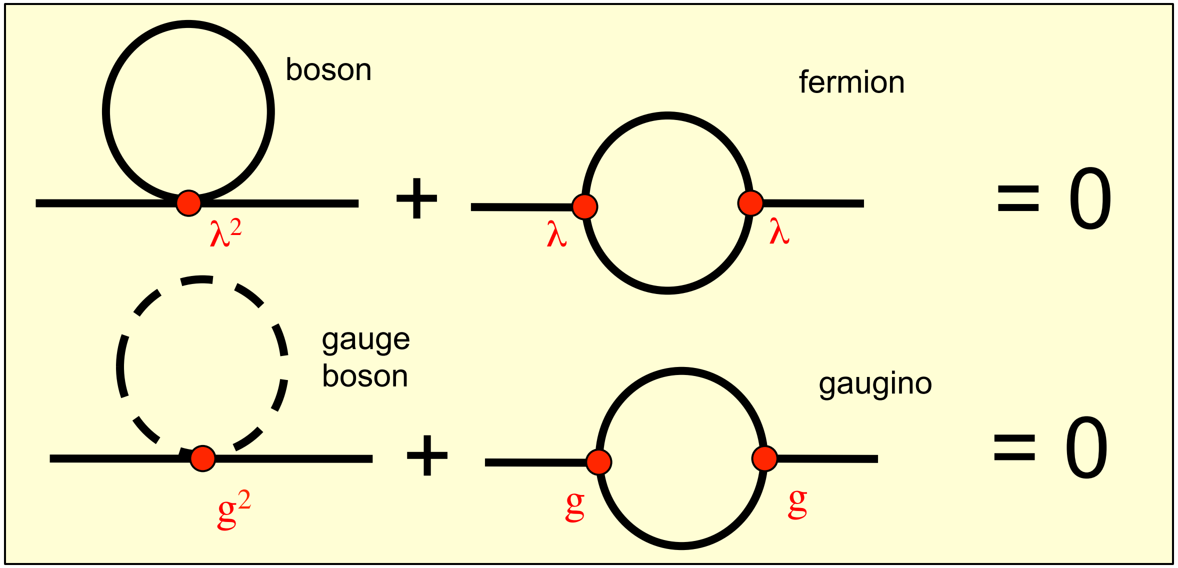


- **Of the 10^{500} possible ways of making a universe, we live in the one that has this cancellation – so as to ensure that we end up with a "livable" universe as we know it**

*Oxford dictionary: an unfortunate incident that happens unexpectedly and unintentionally, typically resulting in damage or injury

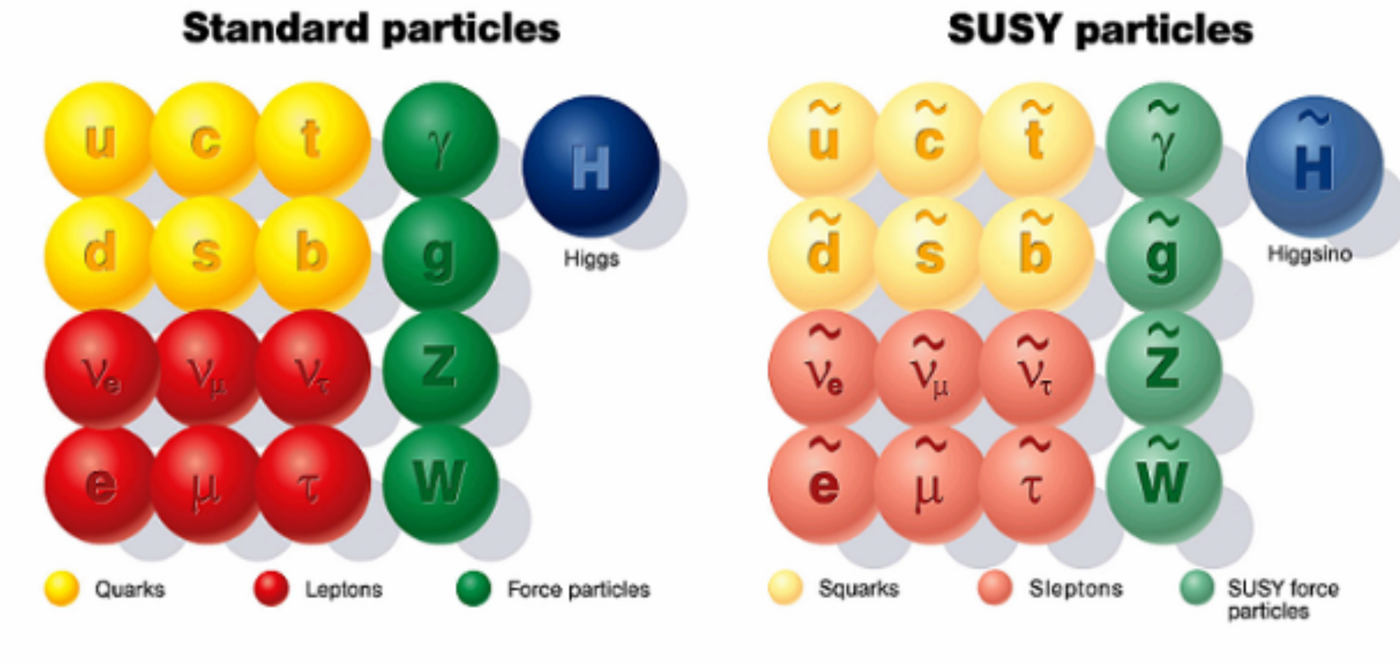
The NP word(s): this is no accident

- **Strong dependence of Physics(Λ_{EWK}) on Physics(Λ_{PL})?**
  - **It's like saying that to describe the Hydrogen atom one needs to know about the quarks inside the proton (not true!)**
- **No way. There must be some physics that cancels these huge corrections. A straightforward way:**



Supersymmetry (SUSY)

- **SUSY (super-symmetry) premise: for every particle in the SM, there is a super-partner with spin-½ difference**



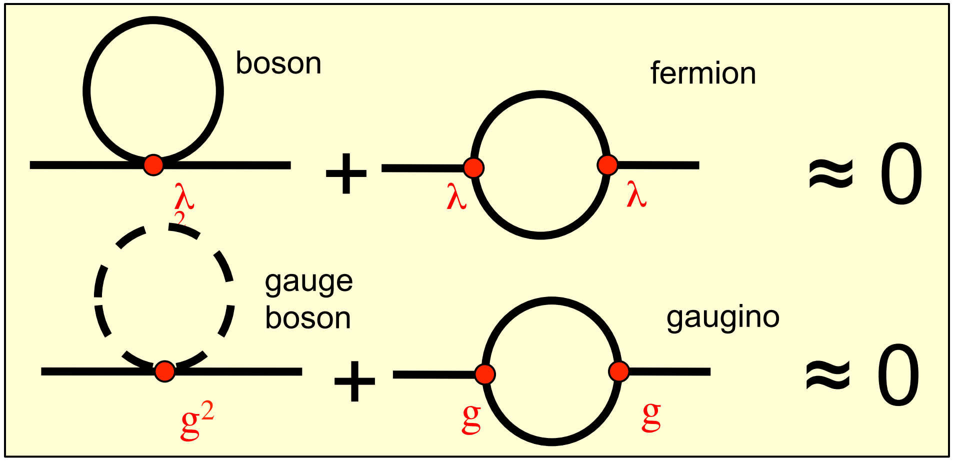
- **Before proceeding, need to explain:**
  - **Why we have not observed spin–0 electrons (or muons…) up to now [simple: spartners are heavy; not produced thus far…]**
  - **Lack of other new phenomena, e.g. why proton does not decay**

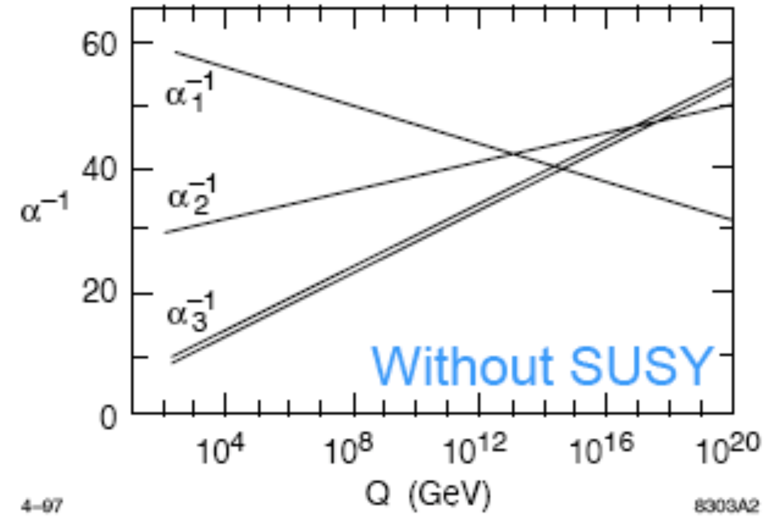
Supersymmetry: TO“AE” at the Weak Scale

- **SUSY is a broken symmetry!**
- **SUSY partners do not have the same mass as their Standard Model counterparts.**
  - **Though they are the same in (essentially) every other aspect.**

- **Make/keep the mass split at ~TeV and nature’s choice of the Higgs boson mass is… “natural”**

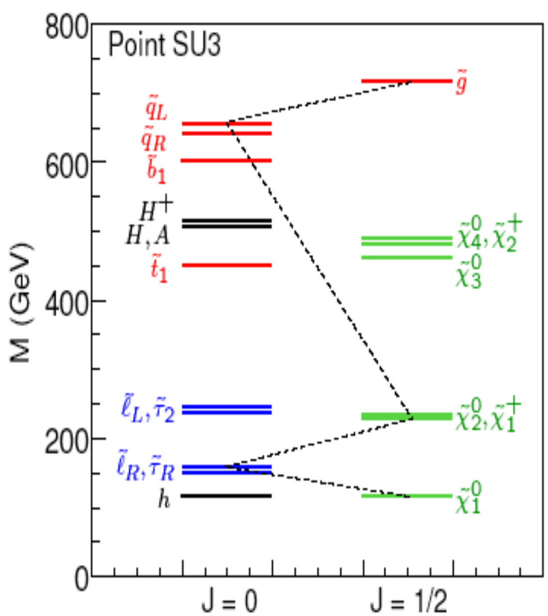
Higgs (mass) is natural ?!



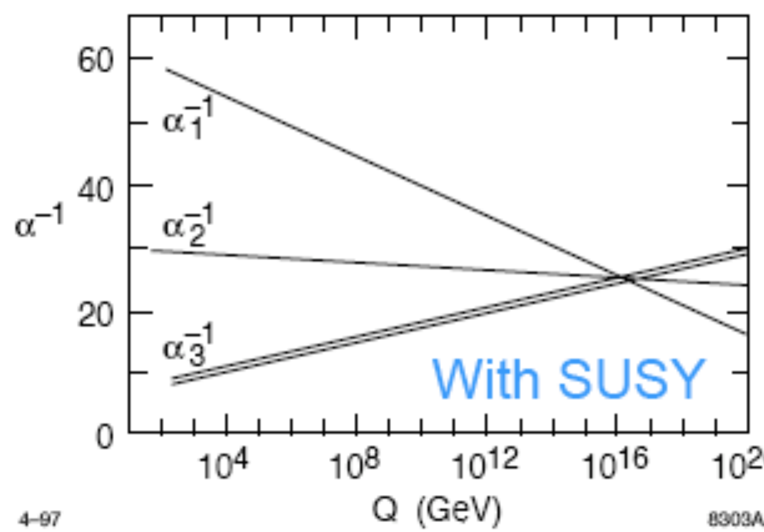


A super(b) symmetry!

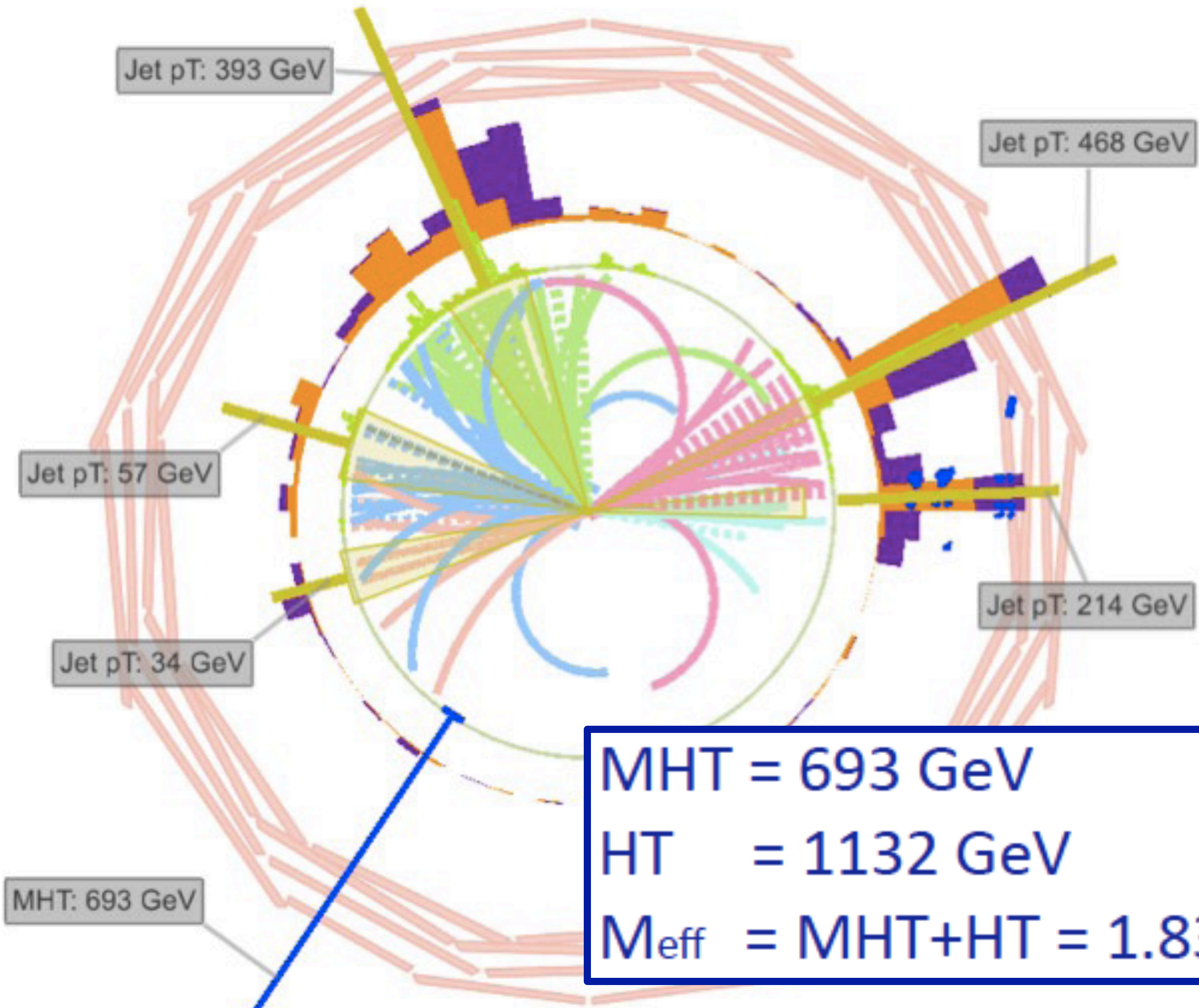
Grand Unifier?



Dark Matter candidate



SUSY? What it could look [looks?] like

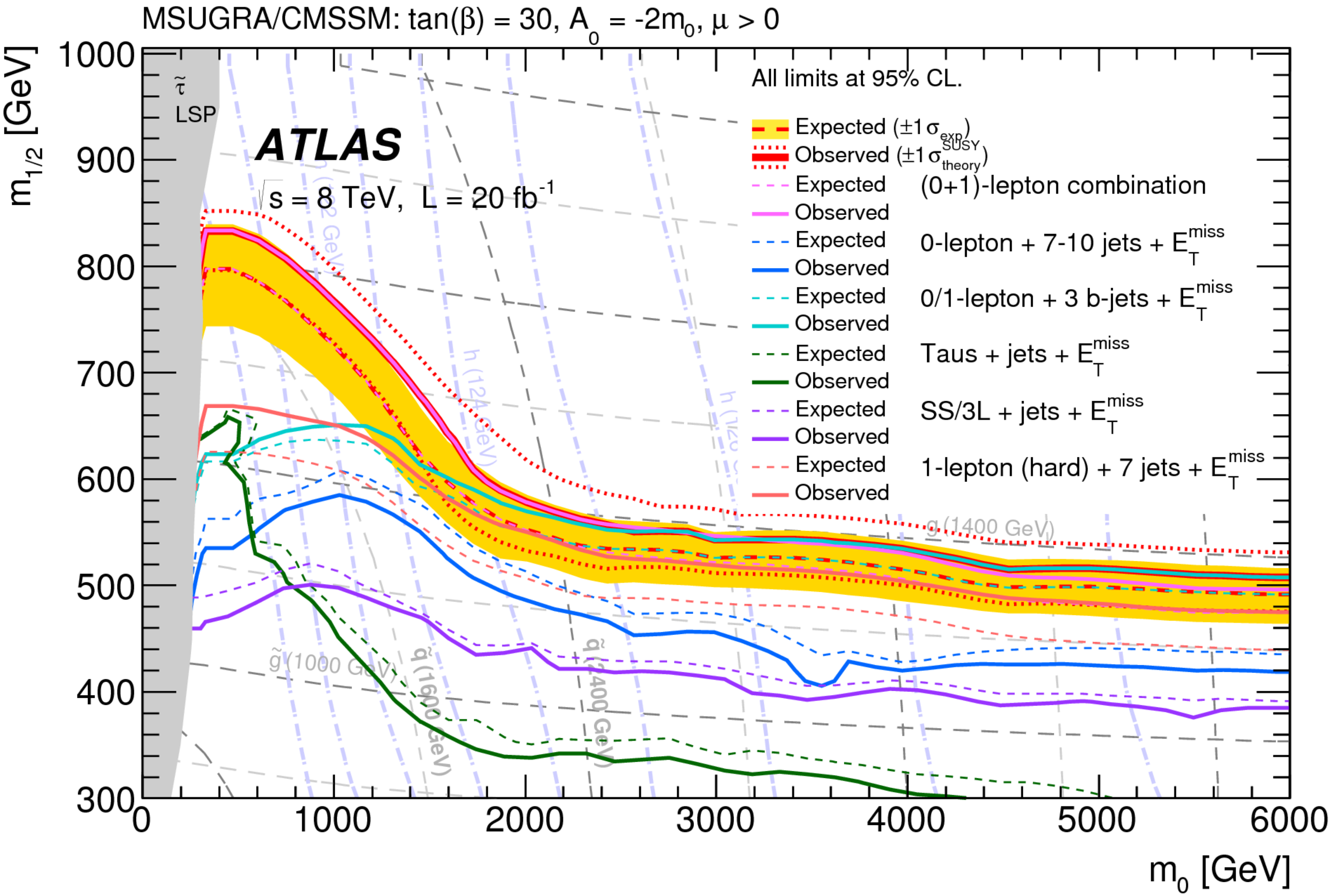


MHT = 693 GeV

HT = 1132 GeV

M_{eff} = MHT+HT = 1.83 TeV

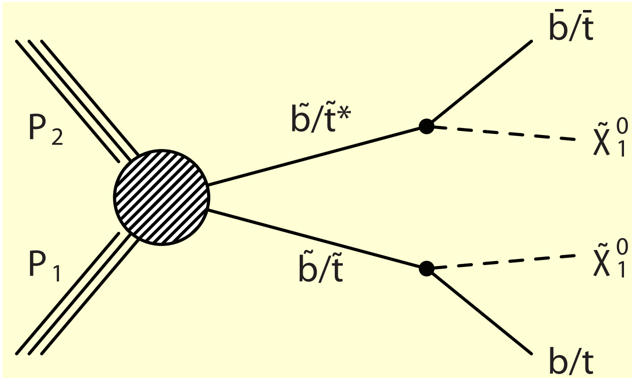
Constrained MSSM: Highly Constrained...

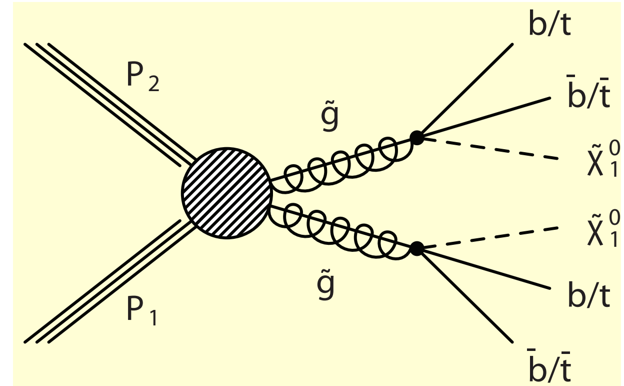


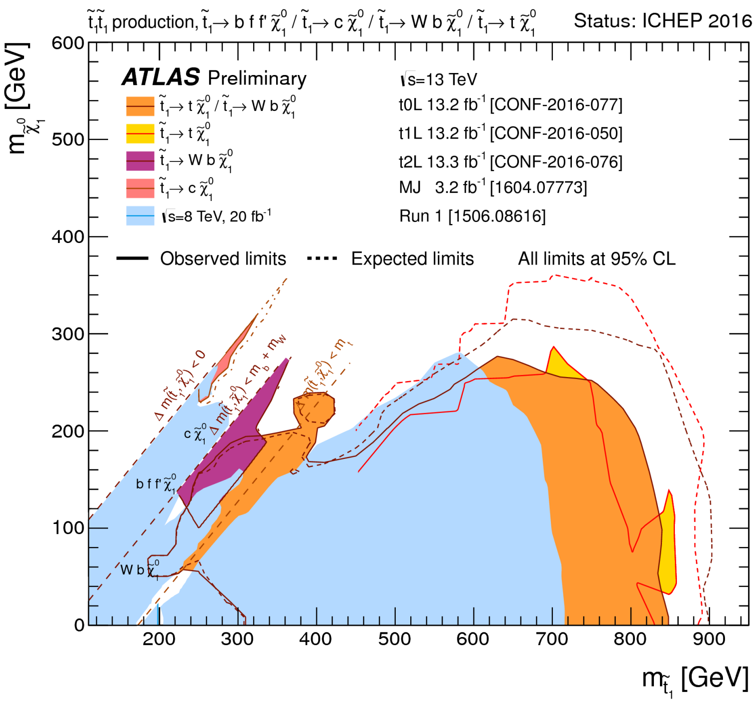
Supersymmetry

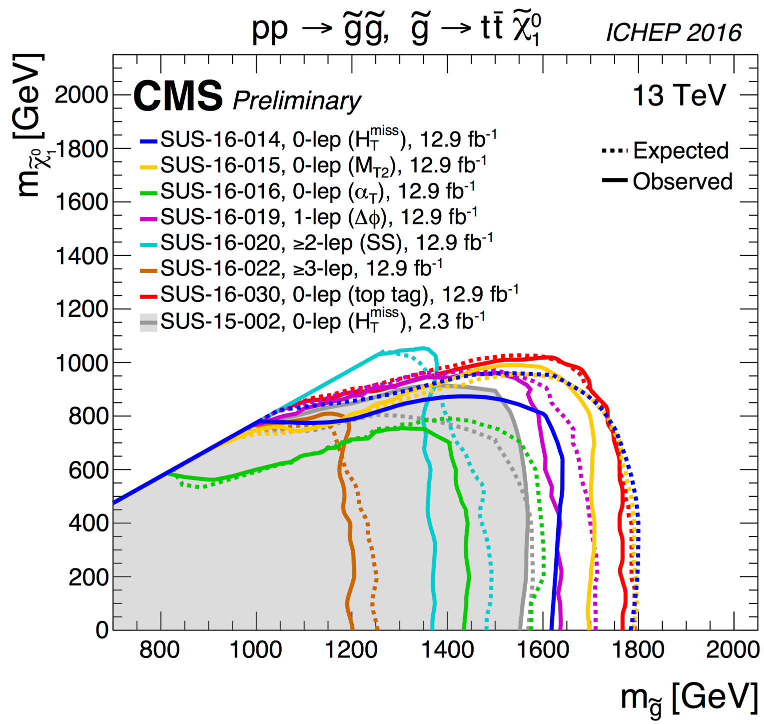
- **The LHC has placed very severe constraints on Supersymmetry**
  - In fact, the more "constrained" models of SUSY are now almost excluded
  - So, is it dead? [it seems the press loves to declare this…]
- **There is a lot of room still left. But if SUSY is the answer to the "naturalness" problem, then there must exist light colored particles**
  - Leading hypothesis: a relatively light (~TeV) top squark (partner of the top quark)
  - Second-to-leading: compressed spectra

SUSY: searching for the top squark

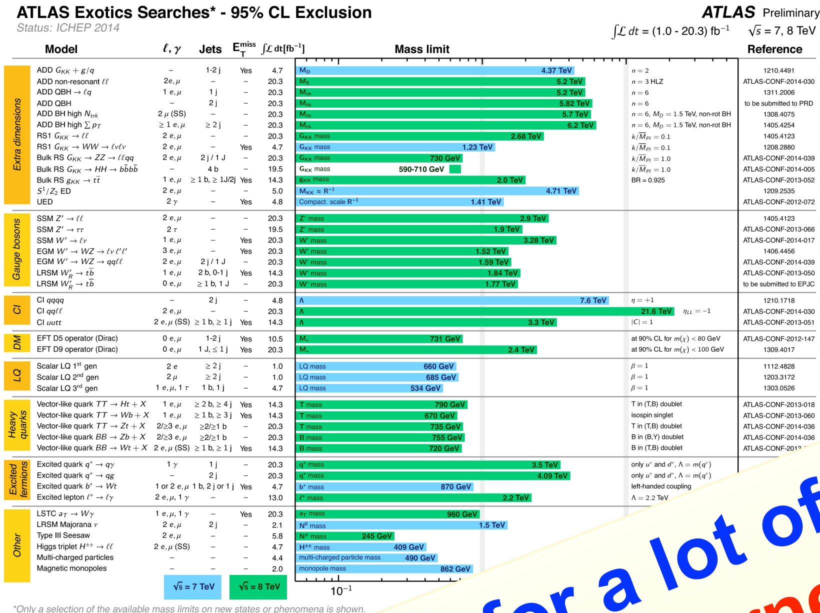


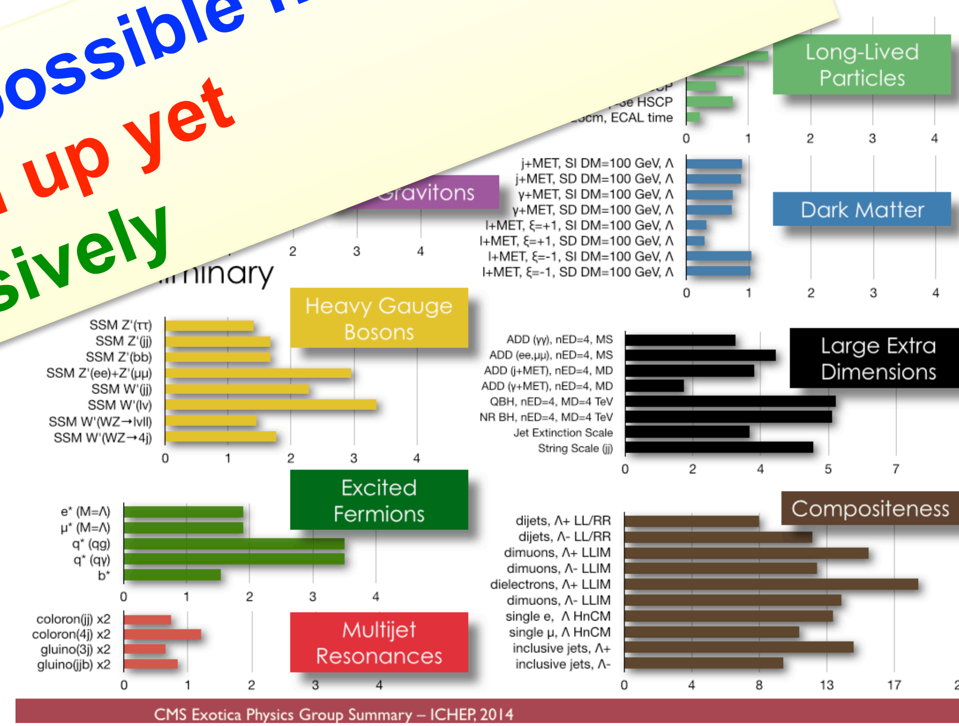






A dizzying exclusion map



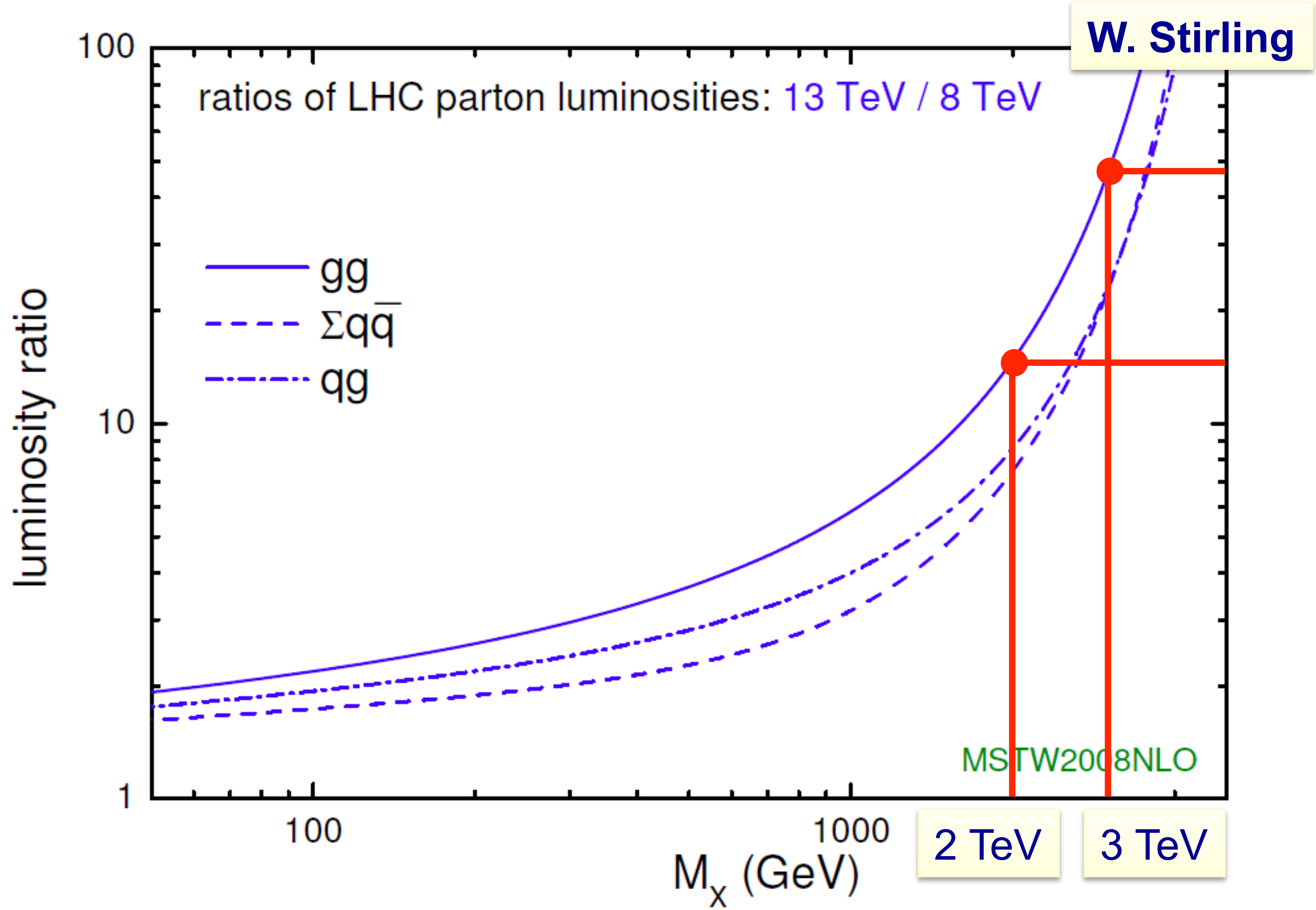


Looked for a lot of possible new things

Nothing has turned up yet

Still looking intensively

The LHC at 13 TeV vs 8 TeV



Outlook
(LHC at 13-14 TeV & at very high luminosity)
&
Summary

Summary

- **The Standard Model of particle physics is actually much more: it's the Standard Theory of particle physics**
  - **An elegant description of "interactions", based on Quantum Field Theory (special relativity and quantum mechanics)**
  - **One tricky issue: symmetry breaking. Needed a truly new mechanism – BEH? There should be a left-over boson**
    - **For decades: missing element – the Higgs boson**
- **A new boson with mass 125 GeV has been found**
  - **We are probing its properties. It IS a Higgs boson! Is it the SM Higgs boson? Need to study it in more detail.**
- **Even if this turns out to be the very Higgs boson of the Standard Model, there are huge reasons to believe that new physics is within reach;**
  - **A gigantic amount of work on searches for SUSY, extra dimensions, etc…; Null so far, but, the best has yet to come!**