The Standard Model and Beyond

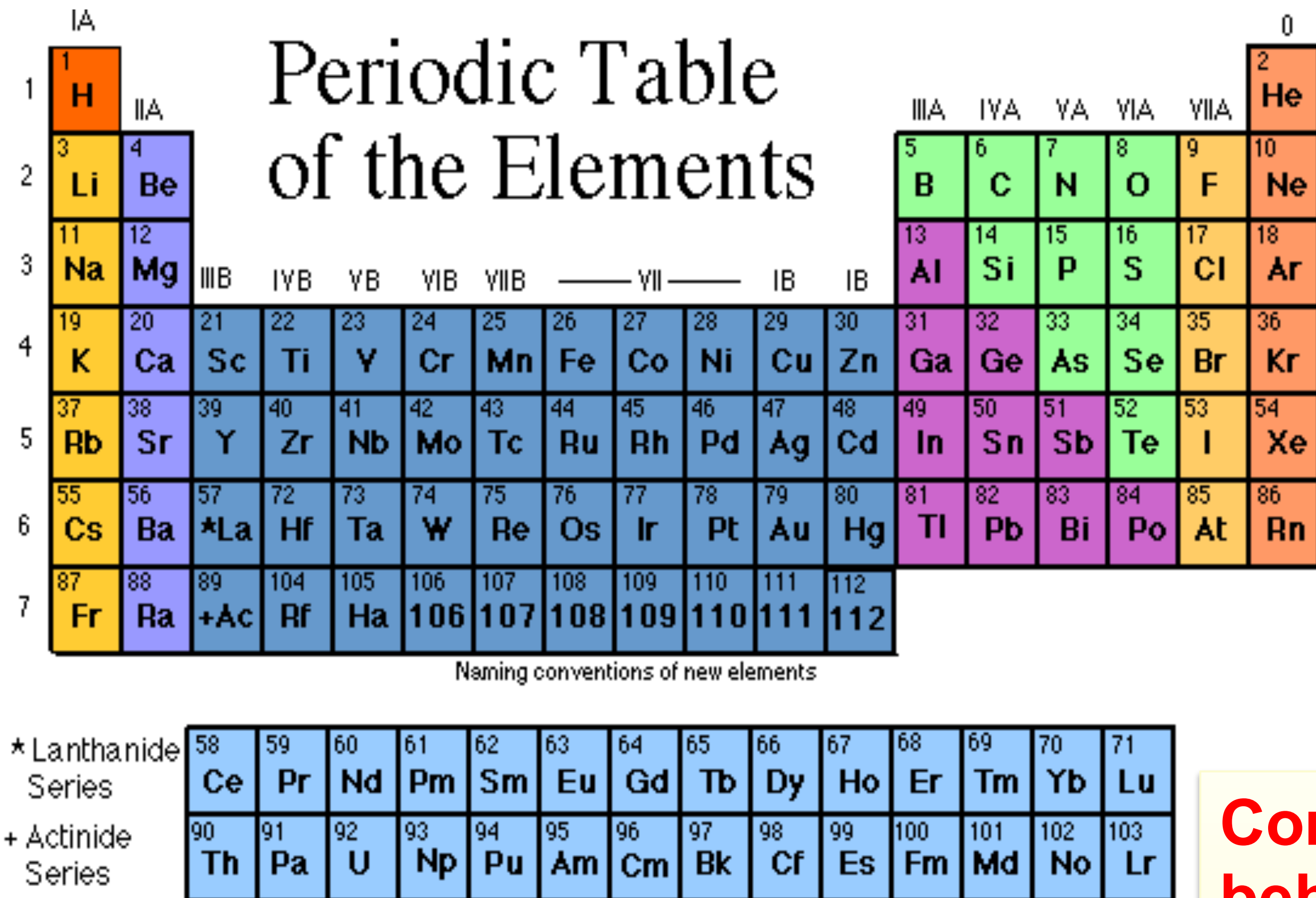
Paris Sphicas
CERN & University of Athens
CERN Accelerator School
Archamps, June 26, 2018

- **The Standard Model of Particle Physics**
  - **What is everything made of?**
  - **And how do these things interact?**
  - **And how do they get their substance – mass?**
- **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**

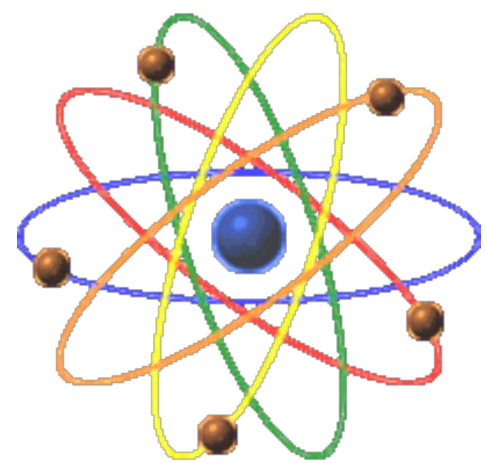
Nature...

What is everything made of?
And what is there in between?

What everything is made of



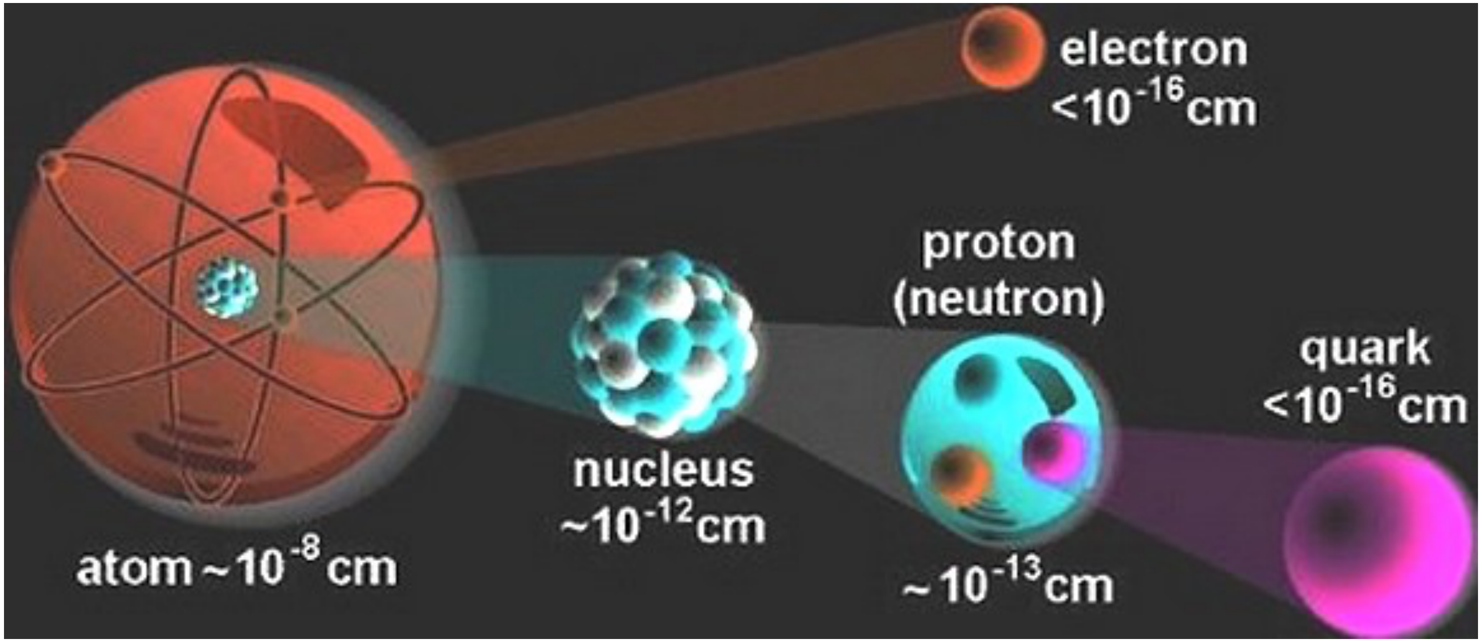
All elements are made of a-toms



Complexity of behavior: one parameter: the number of electrons!

Zooming (entering) into the atom

20st century: everything is made of four particles (u, d, e, ν_e)*



These are pointlike!

* Plus two copies…

Forces...

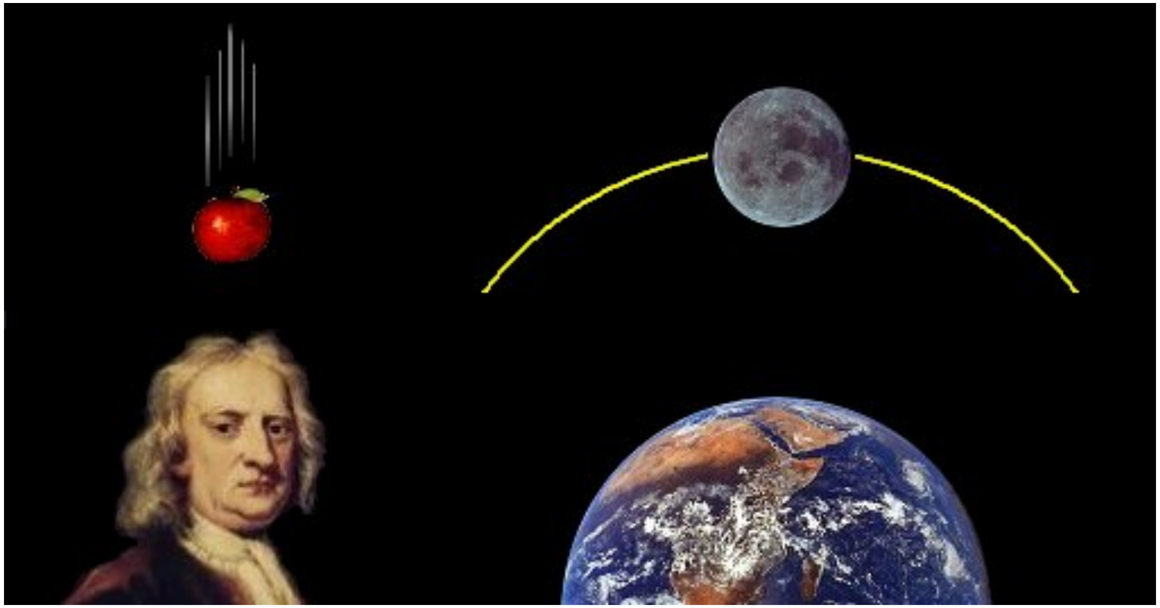
How does one particle "act" on another?

Do they have to "touch" each others, or can they act at a distance?

Nature and forces in the vacuum

Gravity :== action-at-a distance: separated objects, in the vacuum, act on each other!

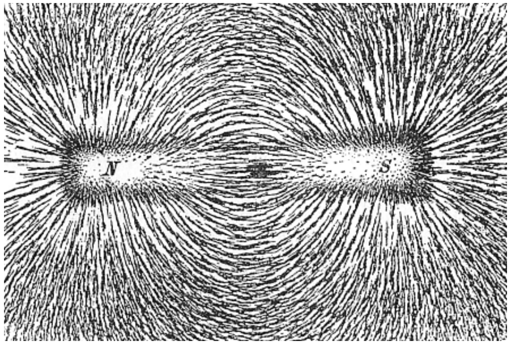
Mass: the "substance" of matter



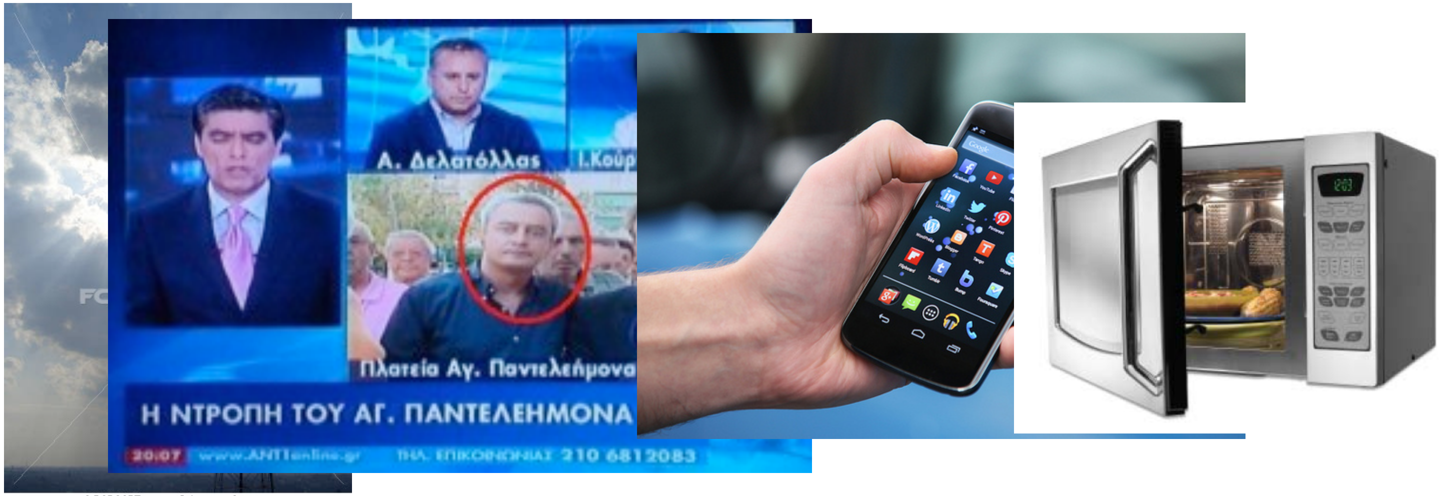
Bodies in the vacuum acting on each other!

Introduction of "fields"

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.



Fields travel through matter and in the vacuum!



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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???

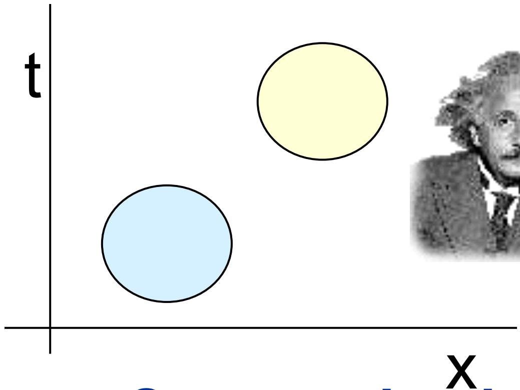
What makes them different?

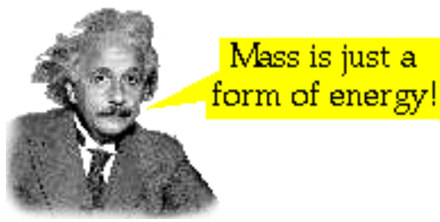
Are all of them "needed"?

Why not just one?

20th century physics: quantum mechanics and relativity

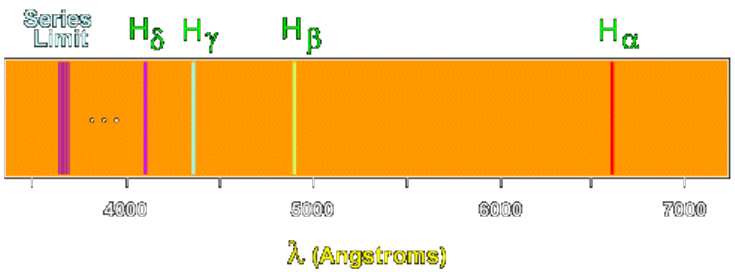
- **Relativity: action can only travel at speed c**
  - Localization





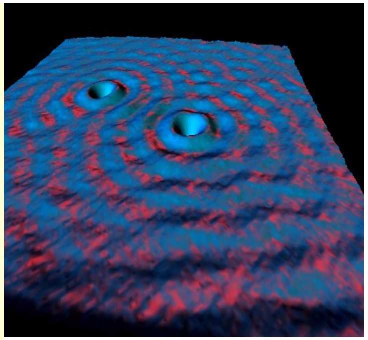
  - Communication between space-time points only as long as within light-cone
- **Thus: operators (that finally yield obser-vables) are a function of x,t; i.e. they are fields**

- **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



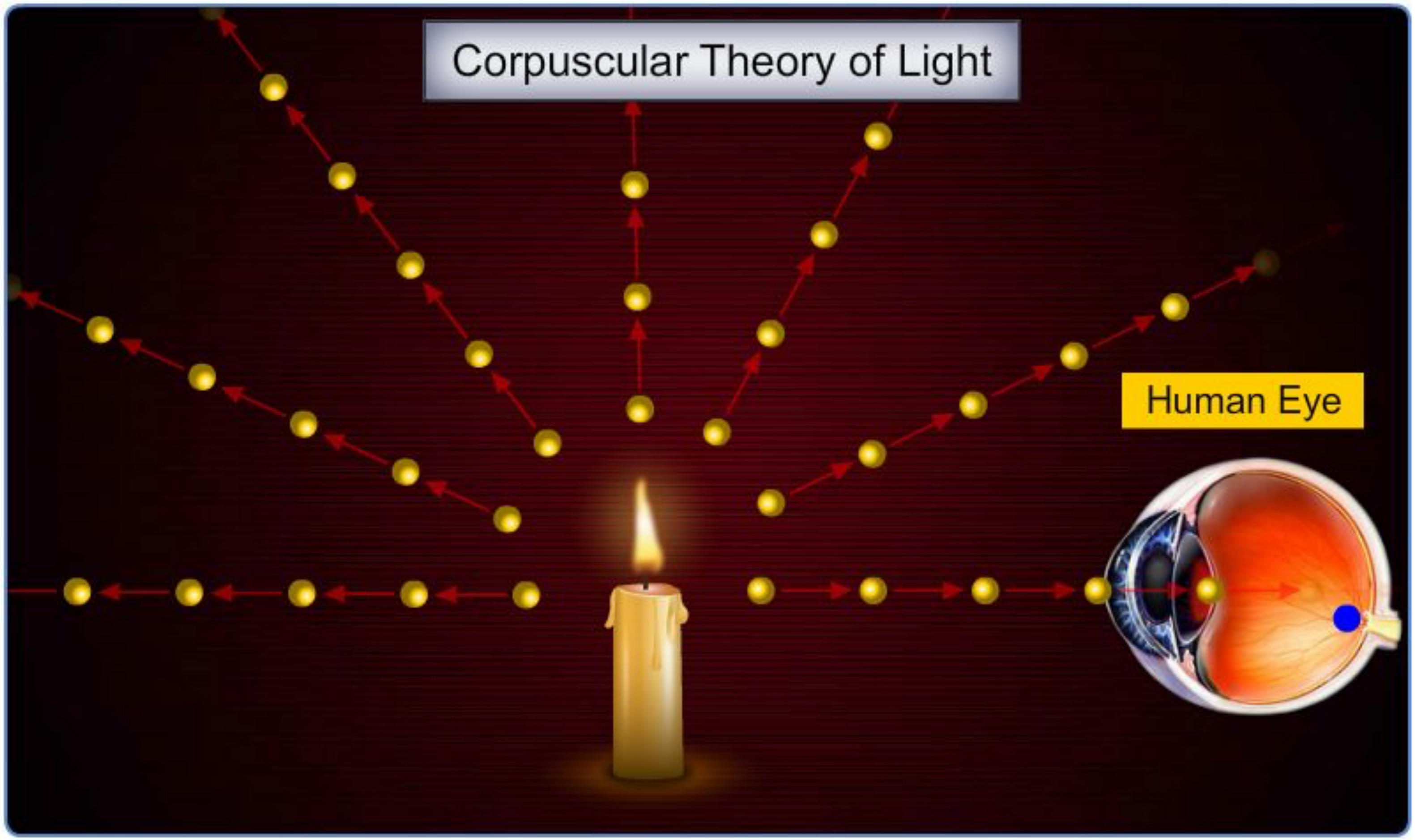
Classical Mechanics: light waves

- **Apparent continuity of light rays.**

But: when “zooming in” on light...

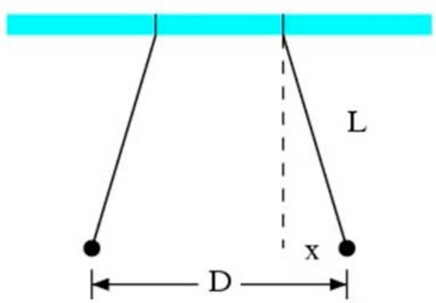
Quantum Mechanics: discreteness

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

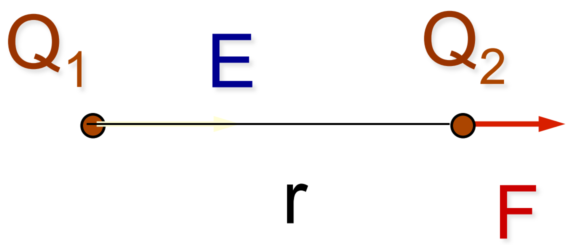


Theory of Relativity + Quantum Mechanics: New picture of a force:

Force is the exchange of particles

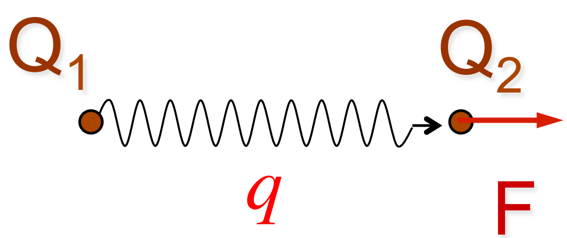


Classical and Quantum picture of "force"



Classical Field E(r)

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

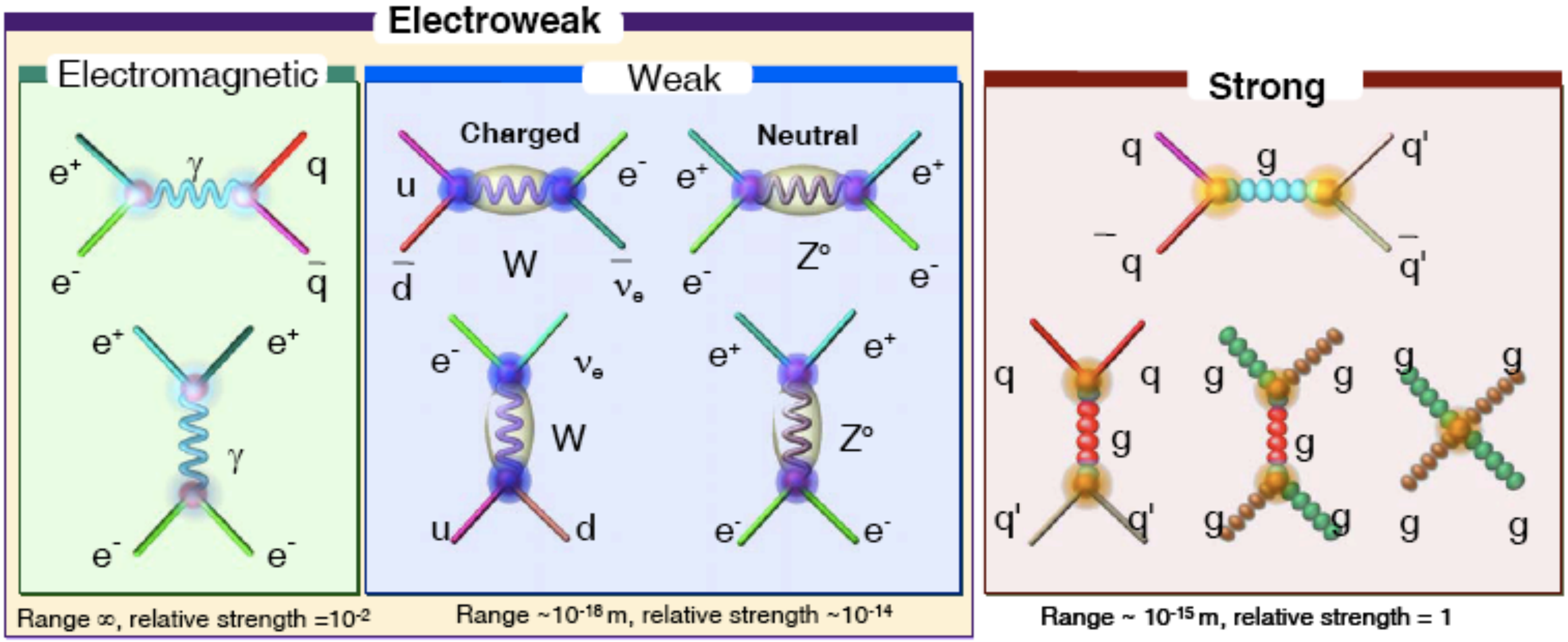


Exchange of a virtual particle of momentum *q*:

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

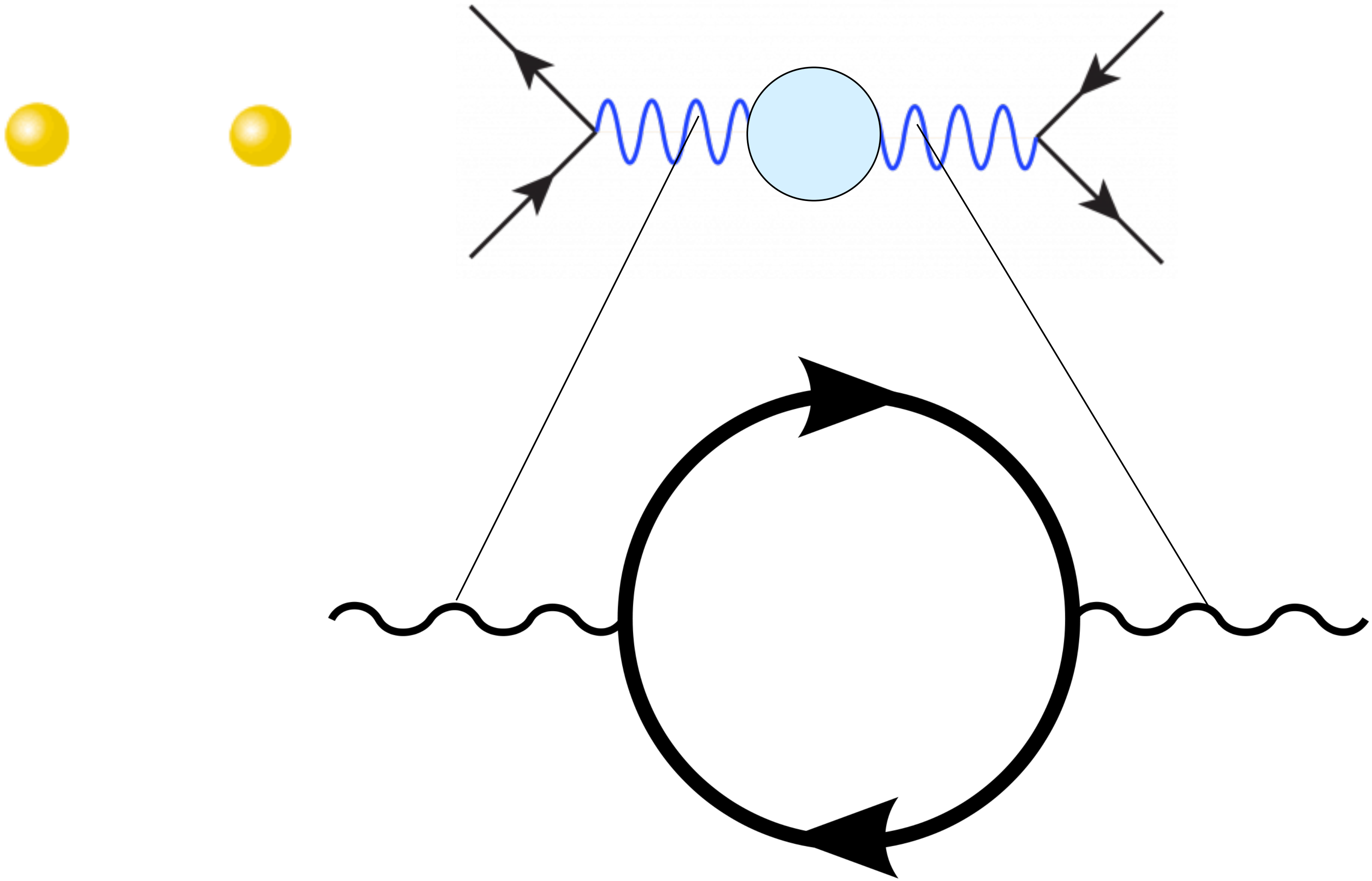
Standard Model of Particle Physics

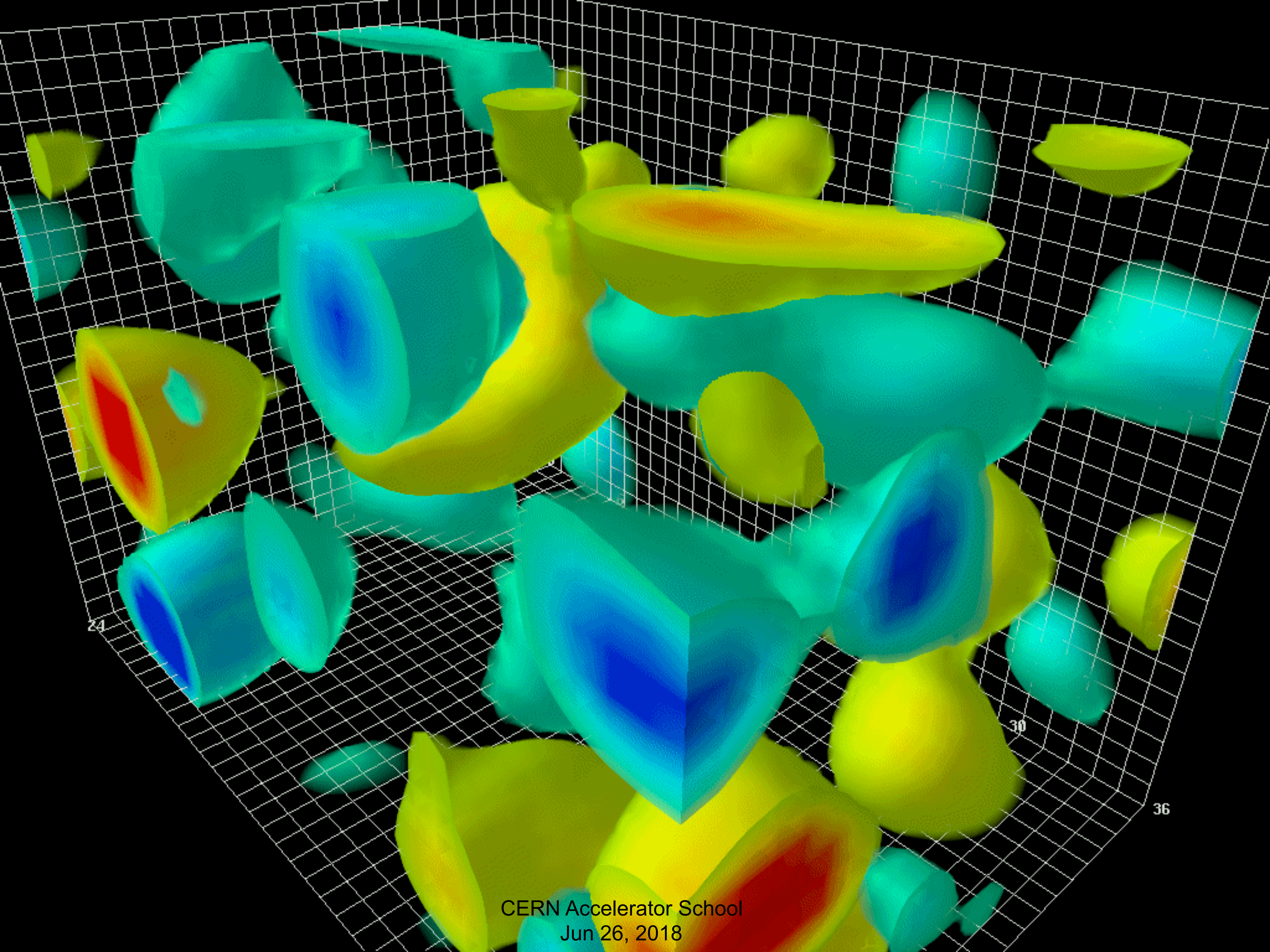
- Quantum Field theory: matter particles (spin-1/2) interact via the exchange of force particles (spin-1)



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

And the vacuum is now full




24
30
36

Brout-Englert-Higgs mechanism: there is a new field that permeates all of space. It fills up the "vacuum".

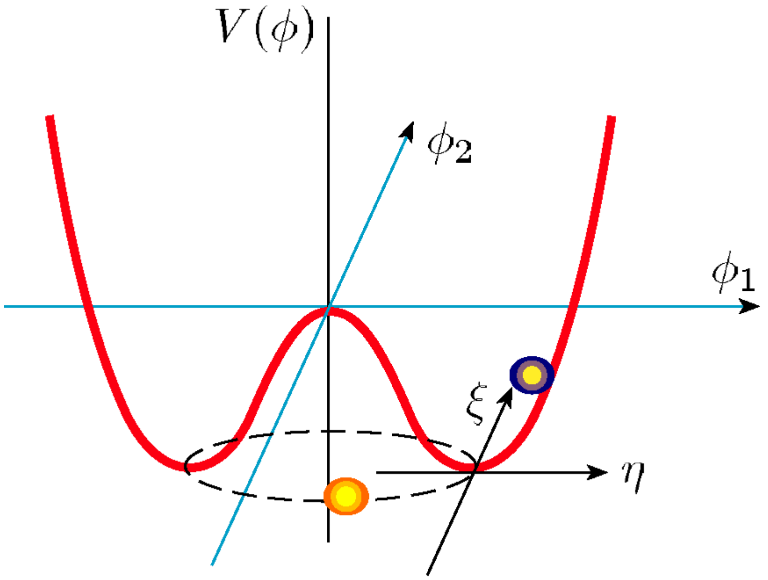
Particles travel ("swim") through it – so they feel resistance

Inertia...

They acquire mass!

The Higgs Mechanism: mathematics

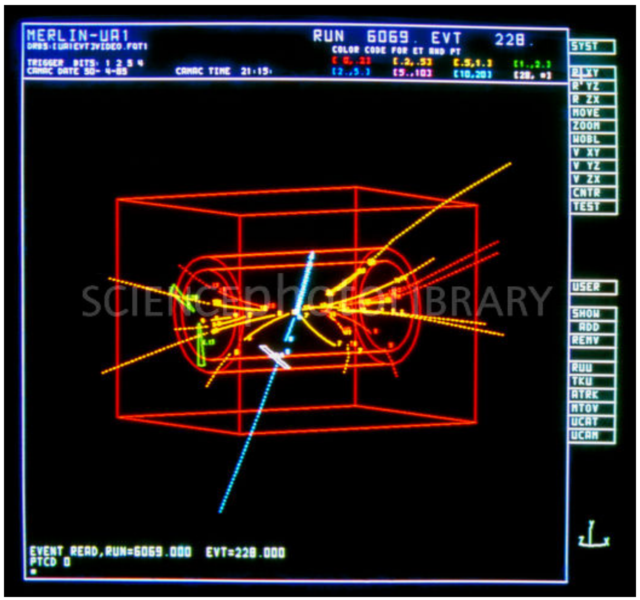
- **With two independent (complex) fields (4 DoFs)**
- **Two "motions" in the potential**
  - One on the plane; "massless" mode that is lost (once a direction is chosen). Each degree of freedom appears as additional degree of freedom of a gauge boson
    - Extra polarization state
    - The boson becomes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

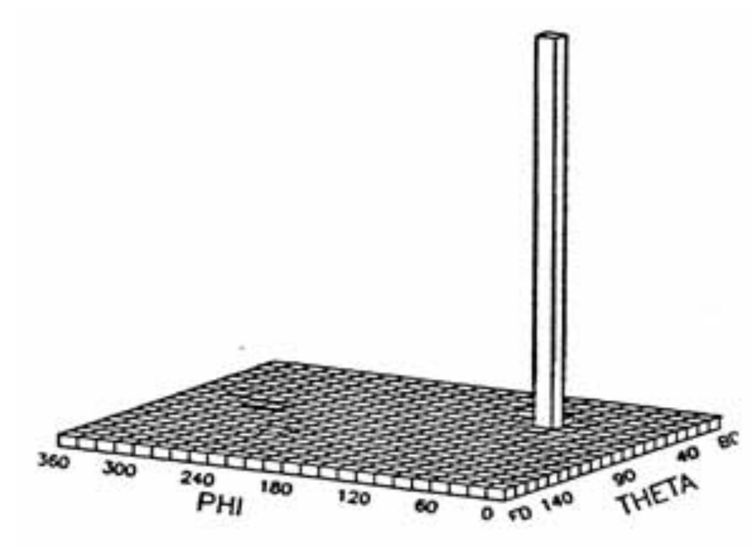


Thus were the W/Z masses born in theory; and discovered (at the right value) @ CERN in 1984.

W and Z discovery

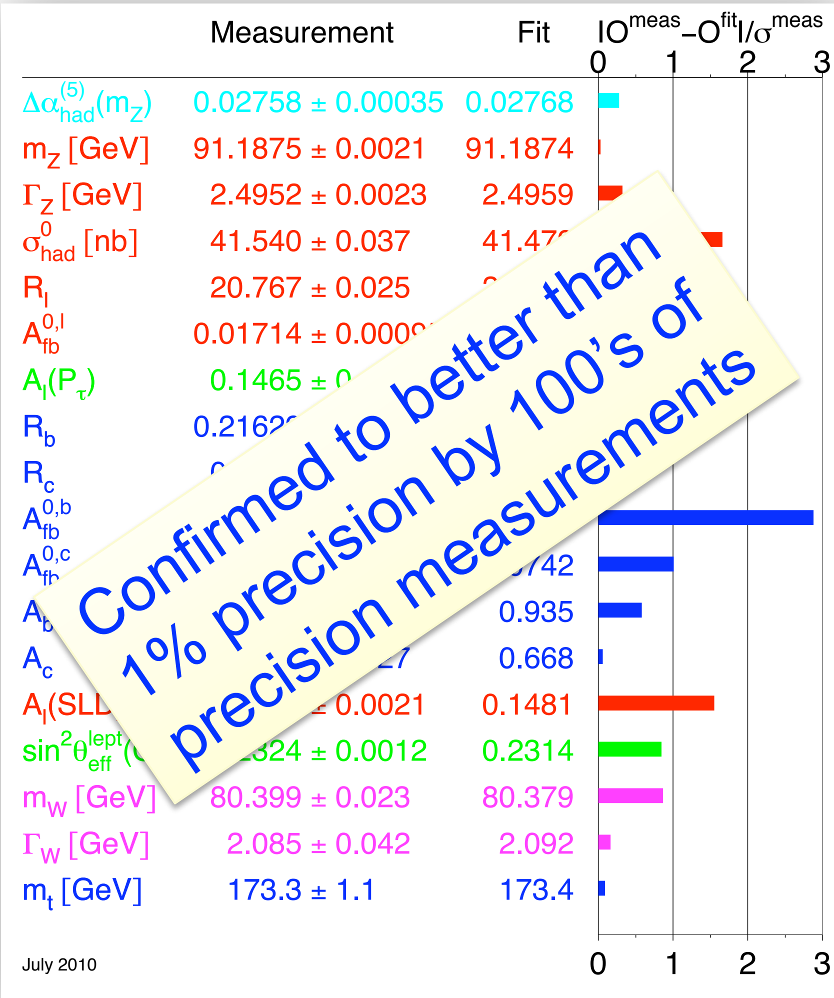
- **In 1983, the *W* and *Z* particles were discovered at CERN (UA1 and UA2)**
  - **1984 Nobel Prize to Simon van der Meer and Carlo Rubbia**



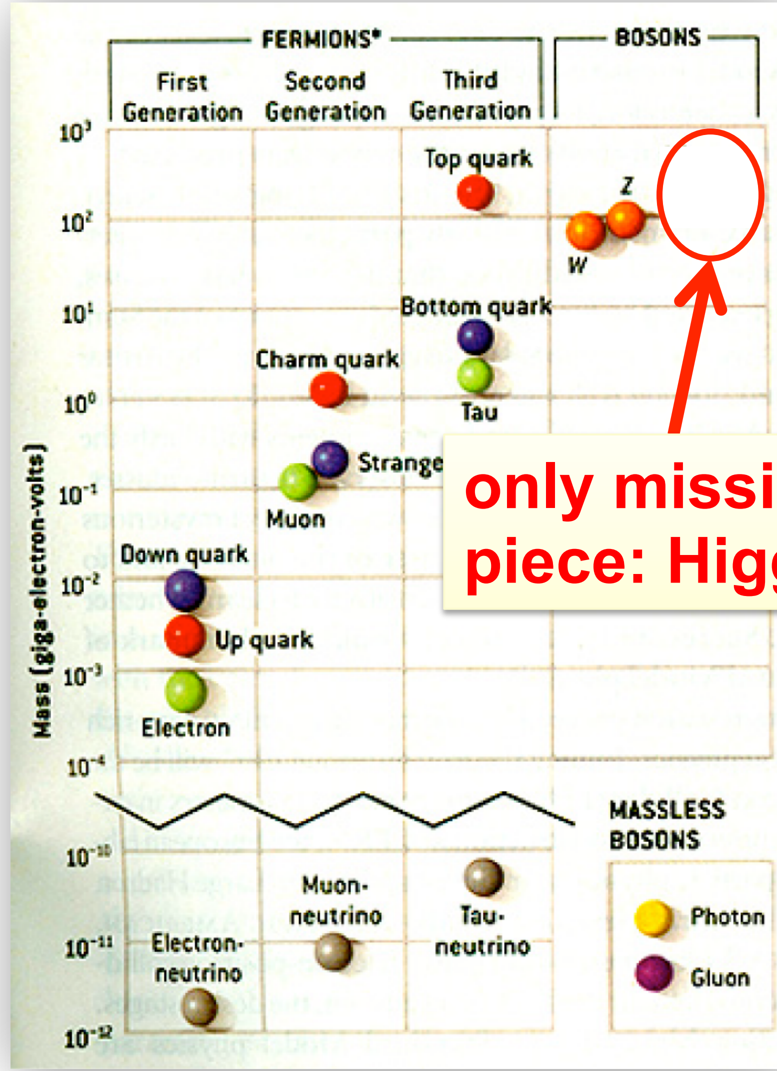


- ***Sneak preview:* at that point, the Higgs boson became the last important missing piece of SM!**

The Standard Model up until 2012



Confirmed to better than 1% precision by 100's of precision measurements



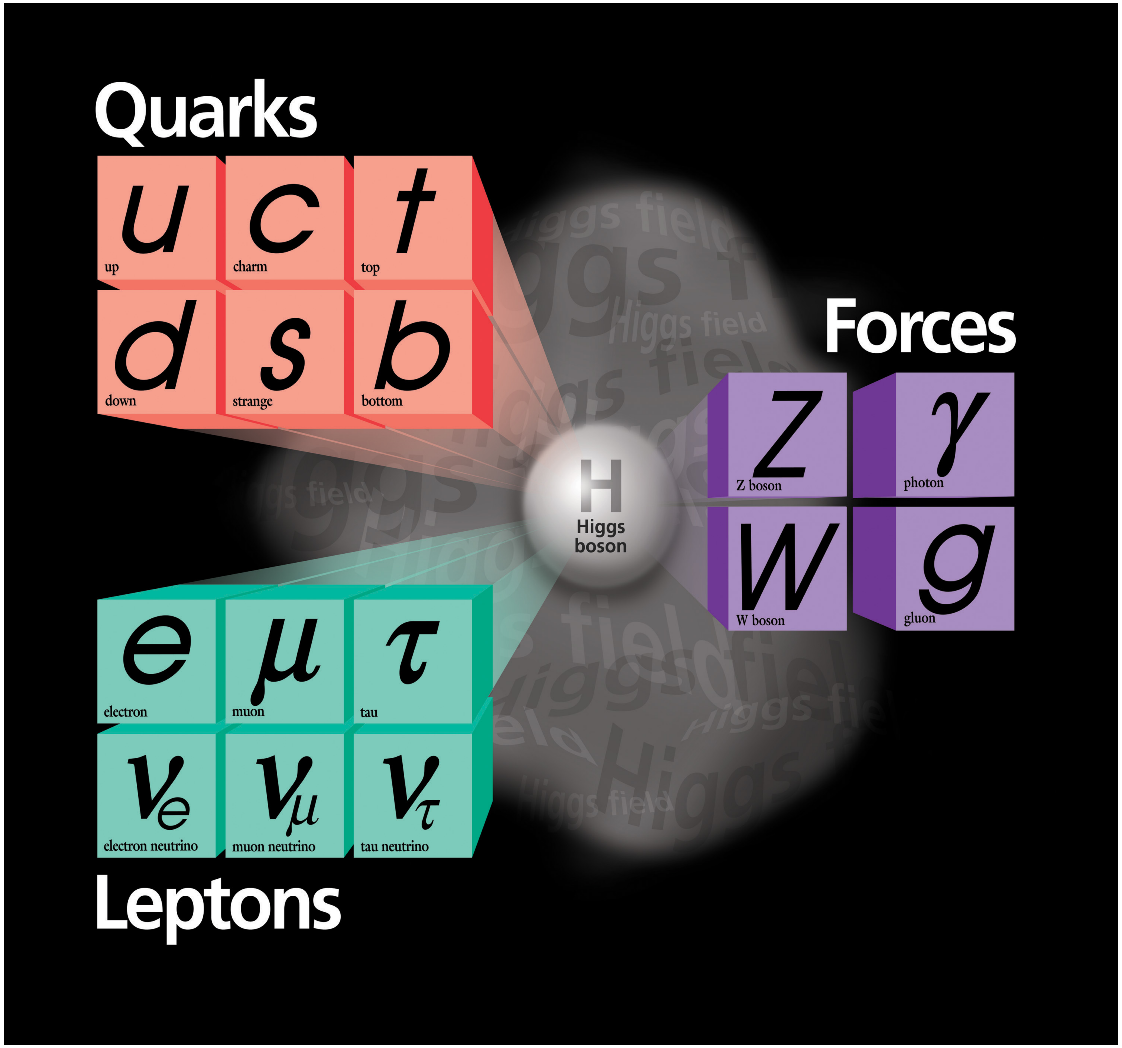
only missing piece: Higgs

New field, the BEH field

- **But, like any other field, in quantum mechanics, there much be a particle that corresponds to it!**
  - **The Higgs boson!**
- **Why can't we just observe it if "it's everywhere", "in the vacuum"?**
  - **Because we need to supply the energy needed to produce it ($E=mc^2$)**
  - **Theory dictated that its mass could be as high as 1 TeV (10^{12} eV! Or 1000 times the proton!)**

Summary: the "Standard Model"

Matter particles



Force particles

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}}_{\text{kinetic energies and self-interactions of the gauge bosons}}$$

$$+ \underbrace{\bar{L}\gamma^{\mu}(i\partial_{\mu} - \frac{1}{2}g\tau\cdot\mathbf{W}_{\mu} - \frac{1}{2}g'YB_{\mu})L + \bar{R}\gamma^{\mu}(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu})R}_{\text{kinetic energies and electroweak interactions of fermions}}$$

$$+ \underbrace{\frac{1}{2}\left|(i\partial_{\mu} - \frac{1}{2}g\tau\cdot\mathbf{W}_{\mu} - \frac{1}{2}g'YB_{\mu})\,\phi\right|^{2} - V(\phi)}_{W^{\pm},Z,\gamma,\text{and Higgs masses and couplings}}$$

$$+ \underbrace{g''(\bar{q}\gamma^{\mu}T_{a}q)\,G^{a}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{(G_{1}\bar{L}\phi R + G_{2}\bar{L}\phi_{c}R + h.c.)}_{\text{fermion masses and couplings to Higgs}}$$

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$

$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$

$$\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$

$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu -$$

$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu -$$

$$W_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W_\mu - W_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W_\mu W^+_\nu W_\nu +$$

$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$

$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W_\mu) - 2A_\mu Z^0_\mu W^+_\nu W_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi] -$$

$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] -$$

$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$

$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$

$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi - W_\mu\phi^+) +$$

$$igs_w MA_\mu(W^+_\mu\phi - W_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi - \phi\partial_\mu\phi^+) +$$

$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$

$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi - W_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi +$$

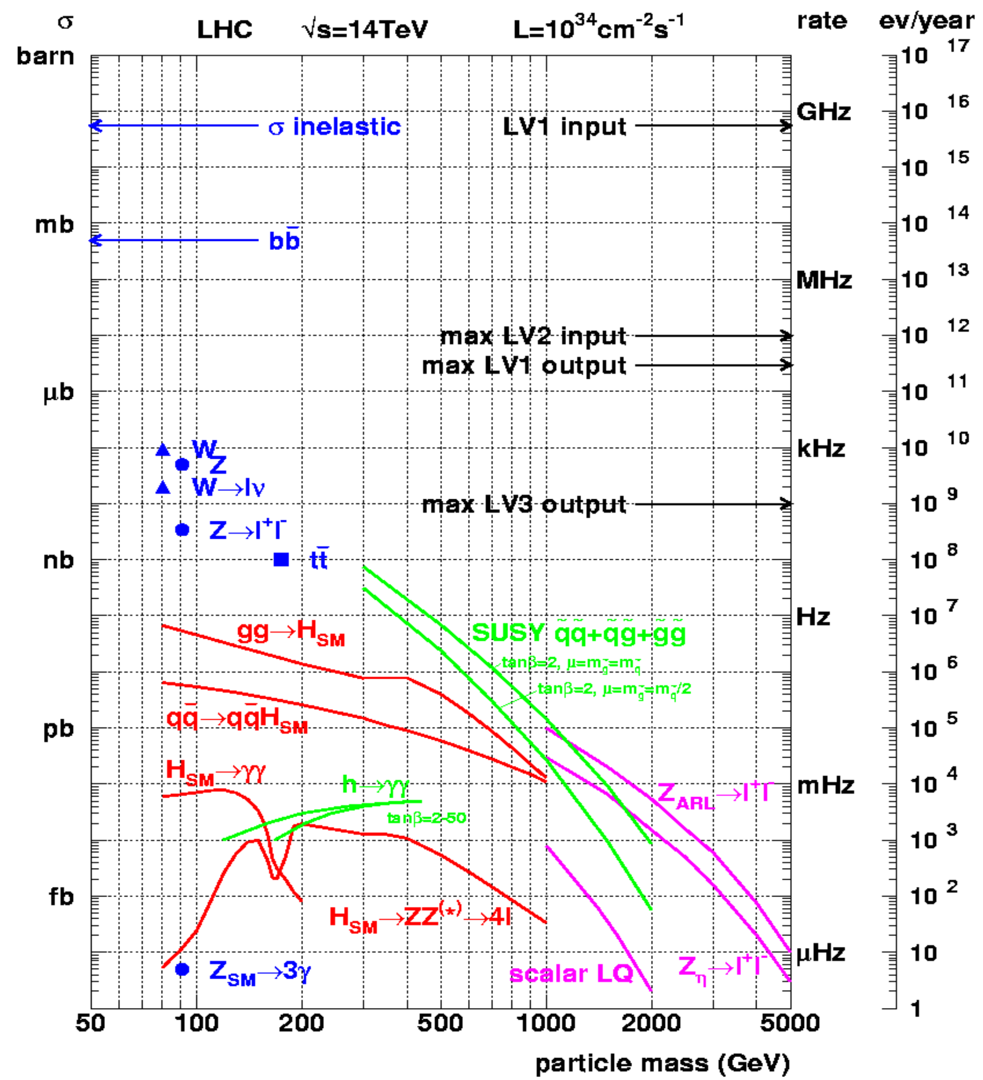
LHC($t_0+\Delta t=3$yrs):

Foundations established
a “tour de force” of SM measurements

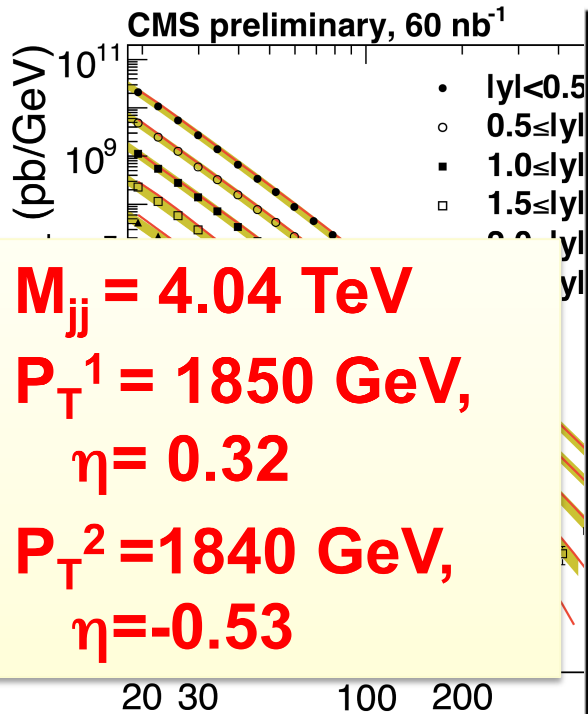
and, of course,
the hunt for the Higgs boson…

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’**



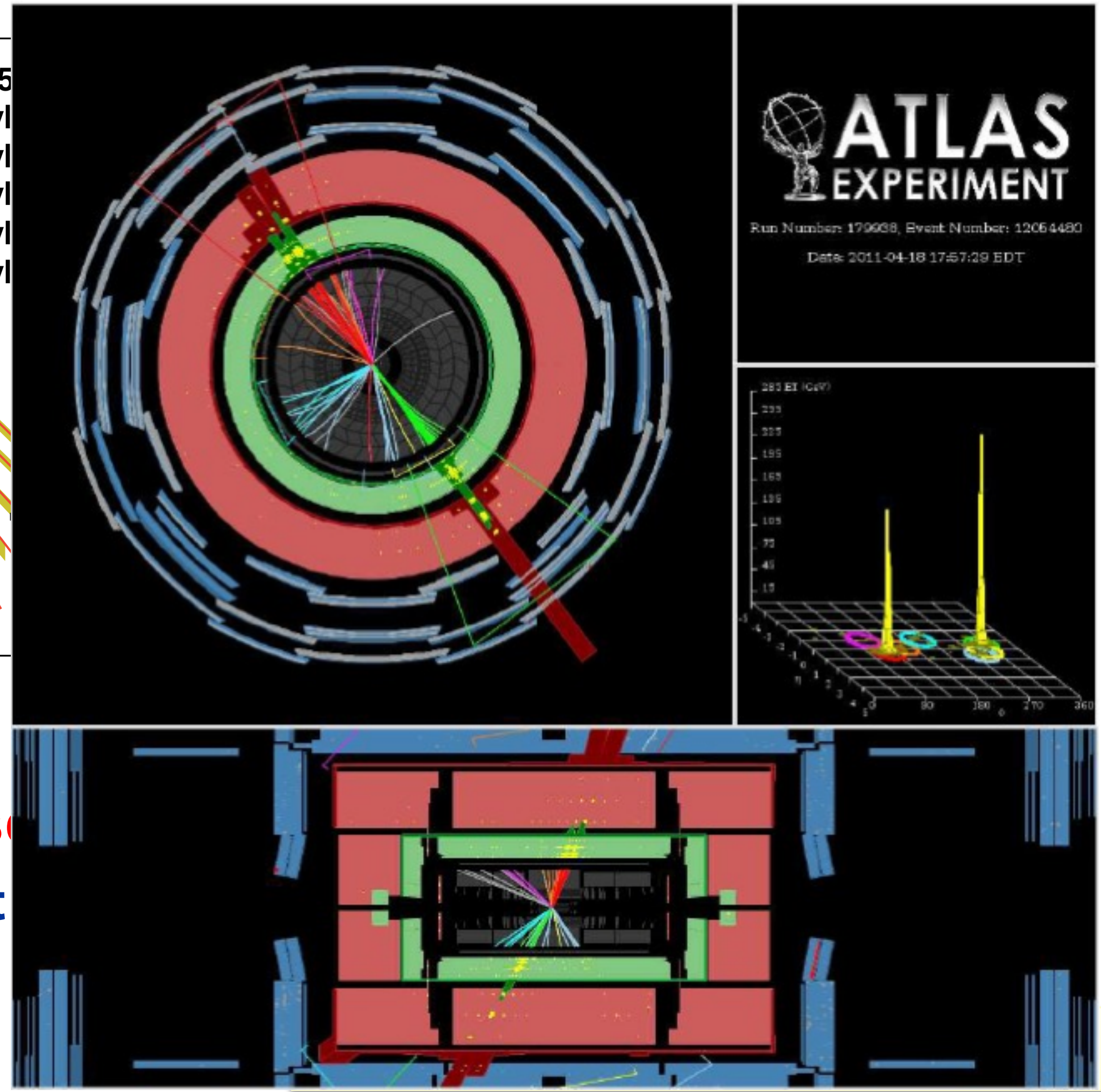
Jets



M_{jj} = 4.04 TeV

$P_T{}^1$ = 1850 GeV,
η= 0.32

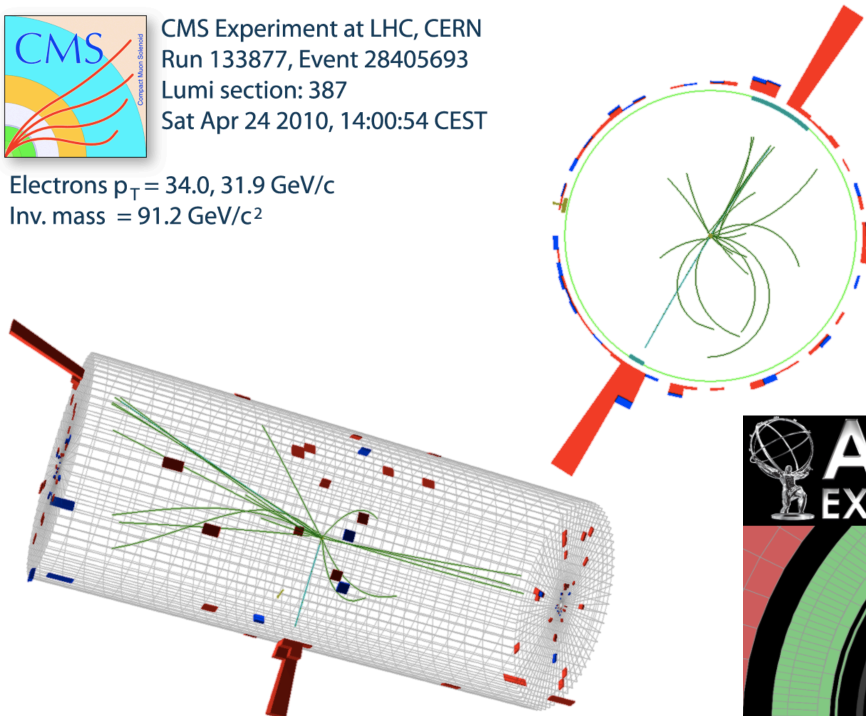
$P_T{}^2$ =1840 GeV,
η=-0.53



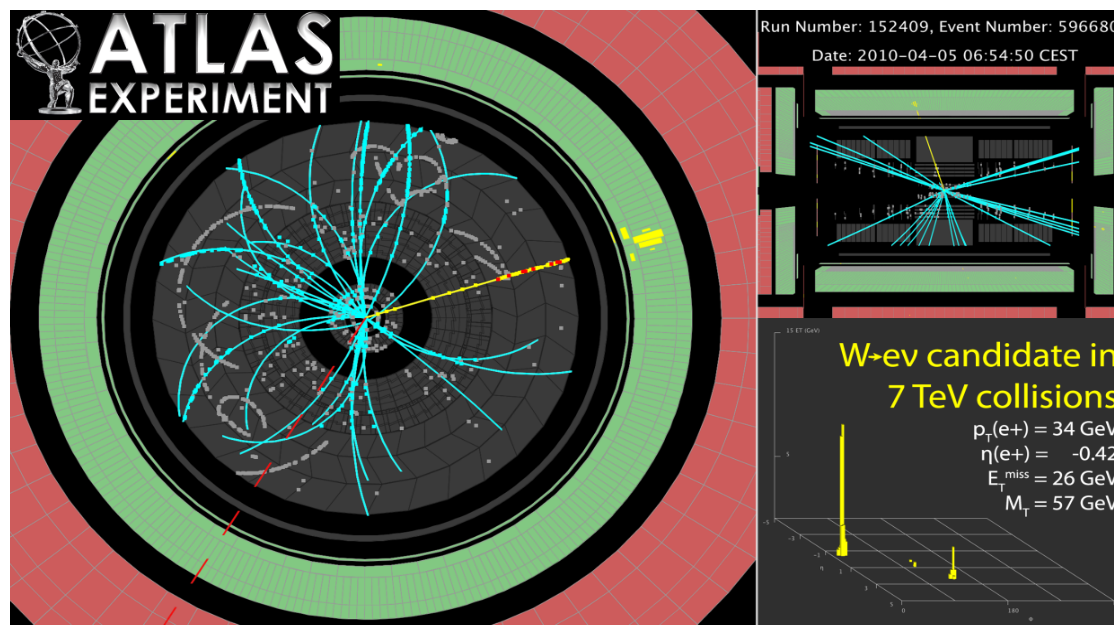
- To probe the hard s
  - The hard scatter: jet

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

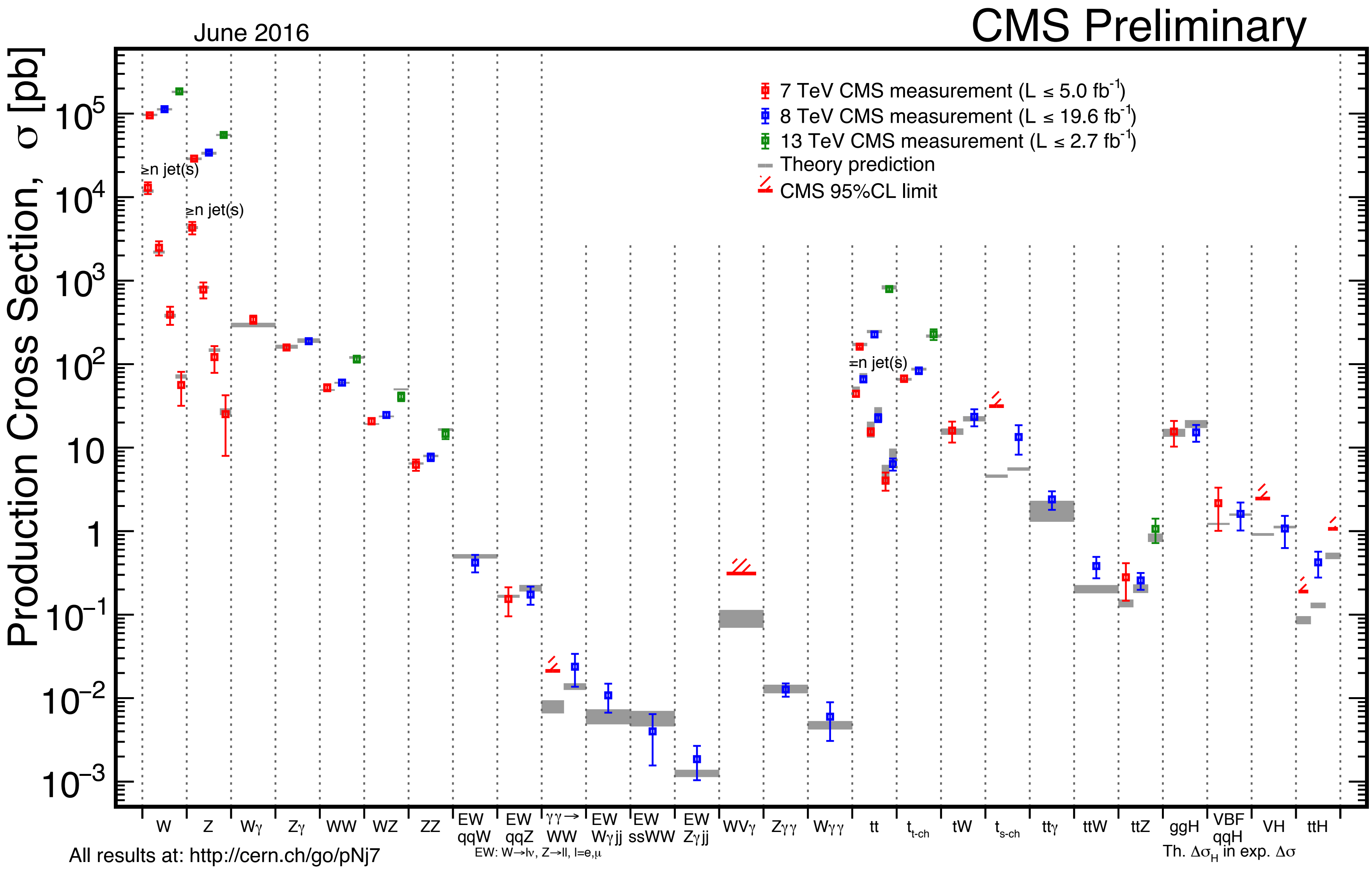
Z → electron + positron



W → electron + neutrino

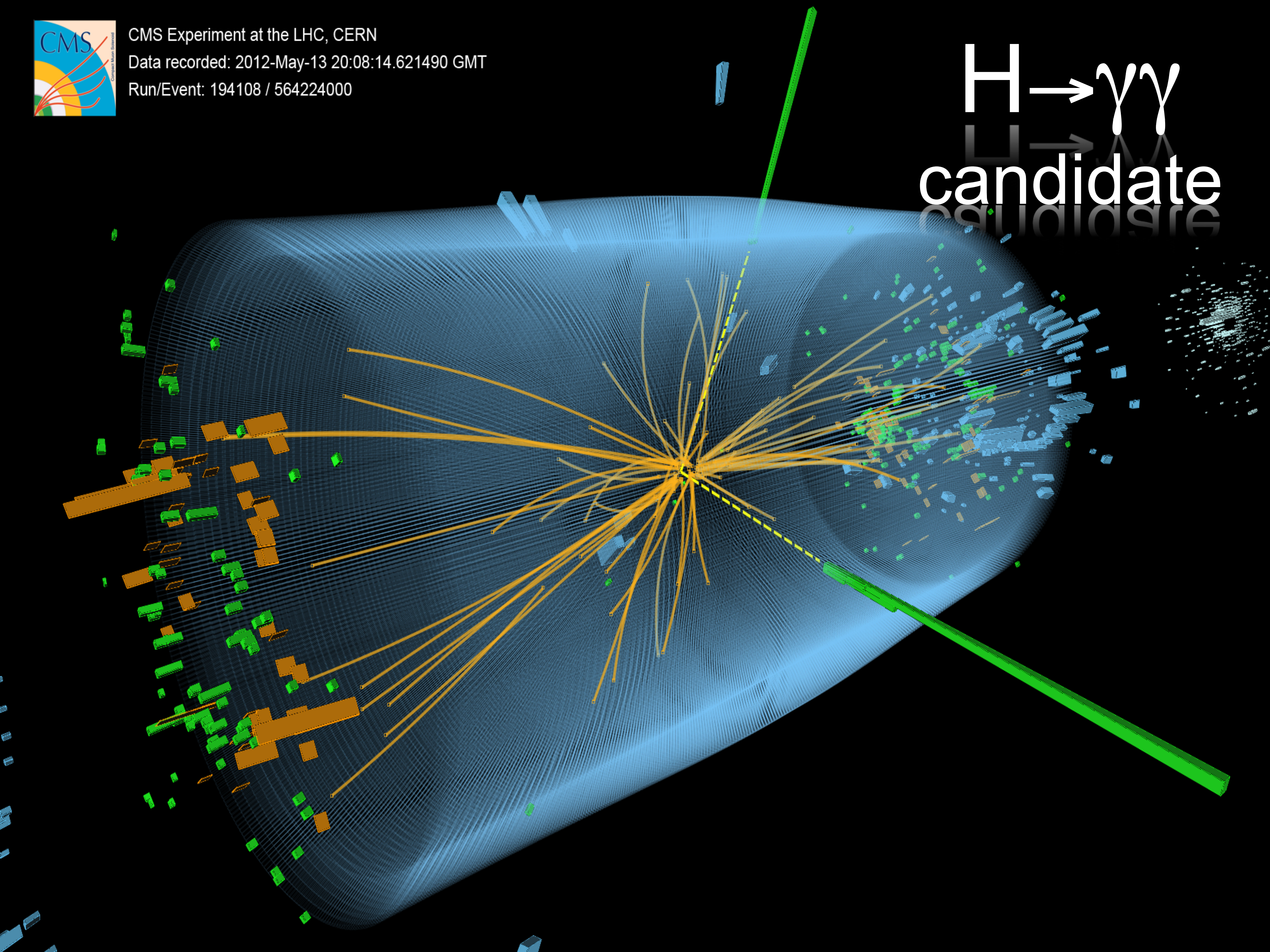


Standard Model Measurements



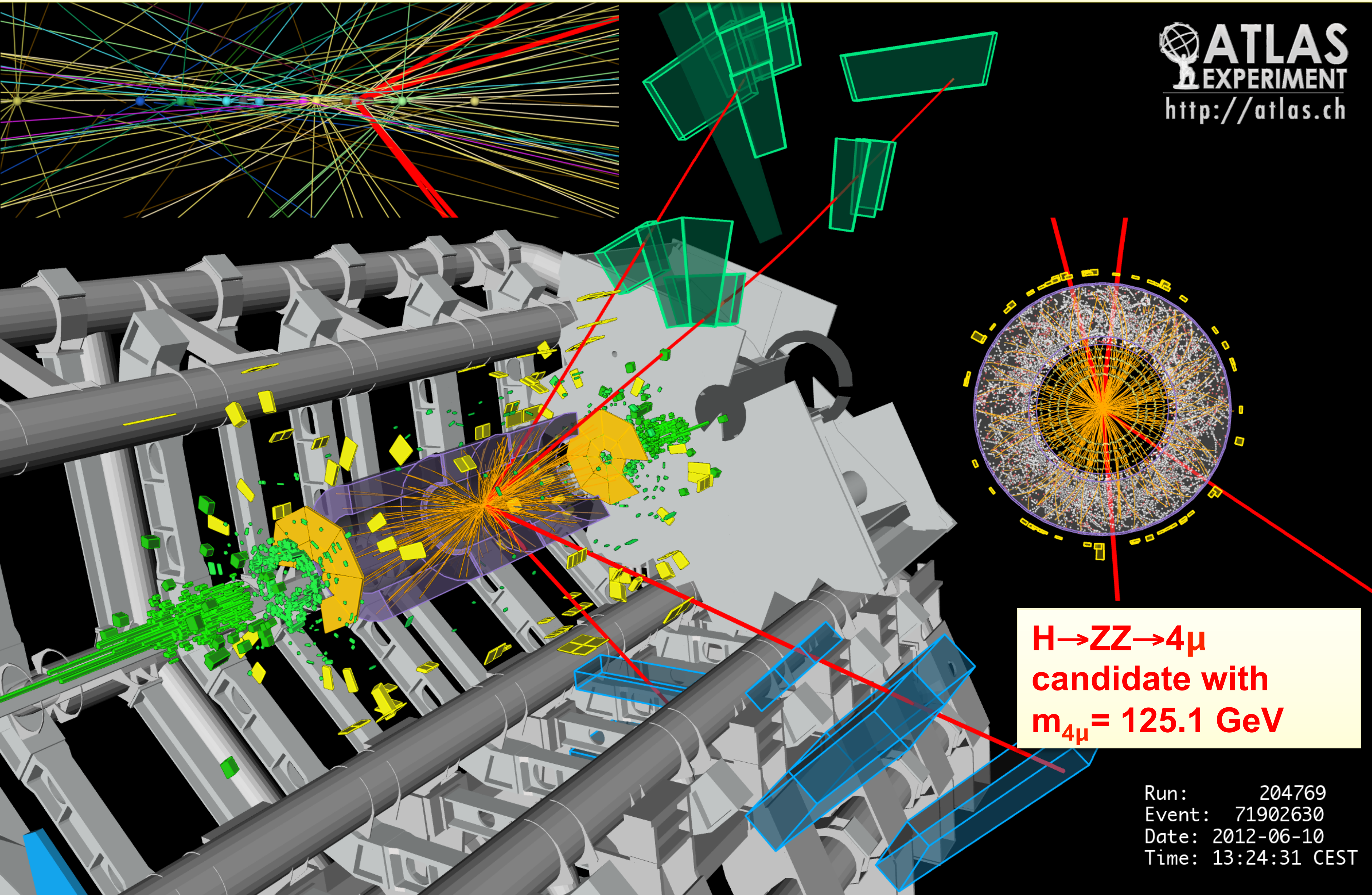
What about the Higgs boson?

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

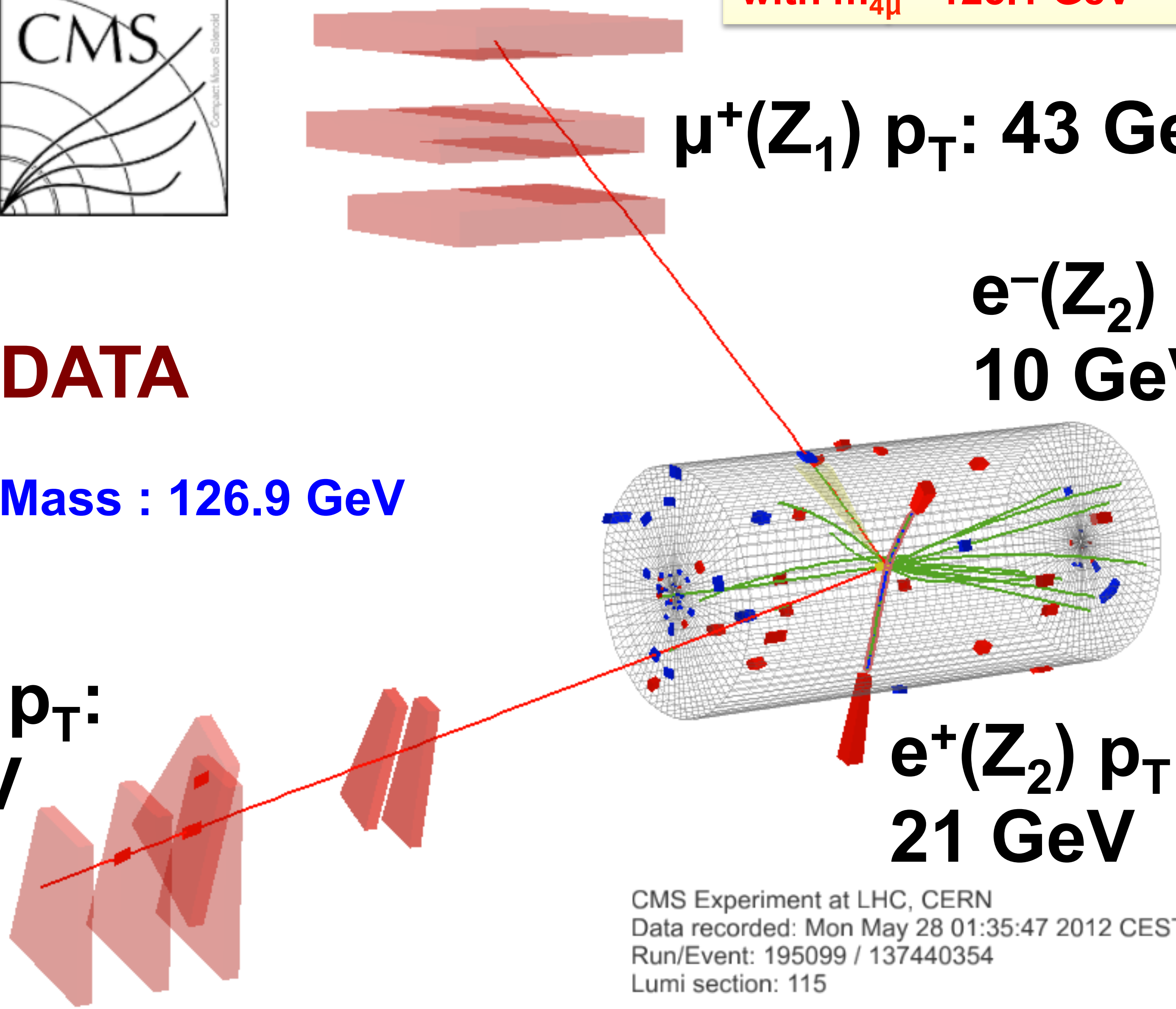
15 reconstructed vertices



$H \to ZZ \to \mu\mu ee$ candidate with $m_{4\mu}$= 125.1 GeV

8 TeV DATA

4-lepton Mass : 126.9 GeV



$\mu^+(Z_1)$ p_T: 43 GeV

$e^-(Z_2)$ p_T: 10 GeV

$m^-(Z_1)$ p_T: 24 GeV

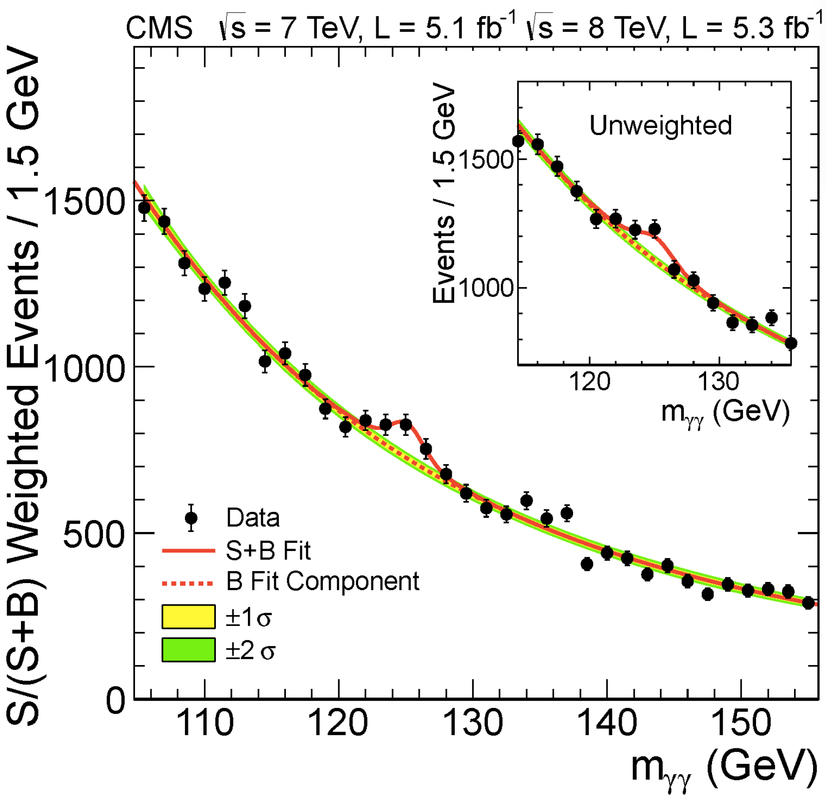
$e^+(Z_2)$ p_T: 21 GeV

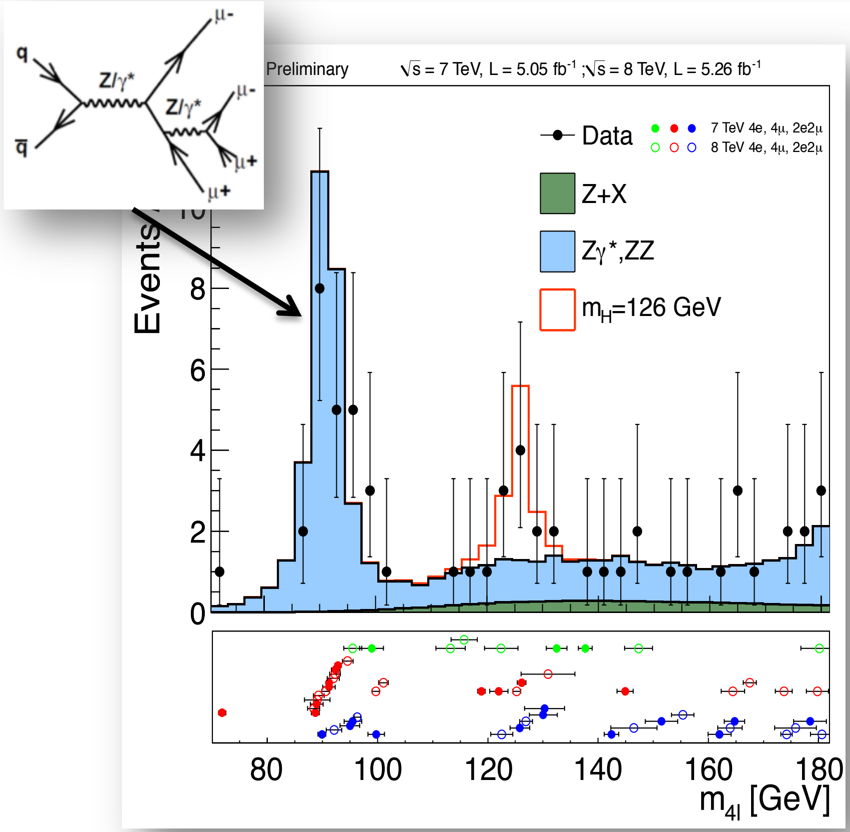
Are these events “significant”?

Discovery of a new boson

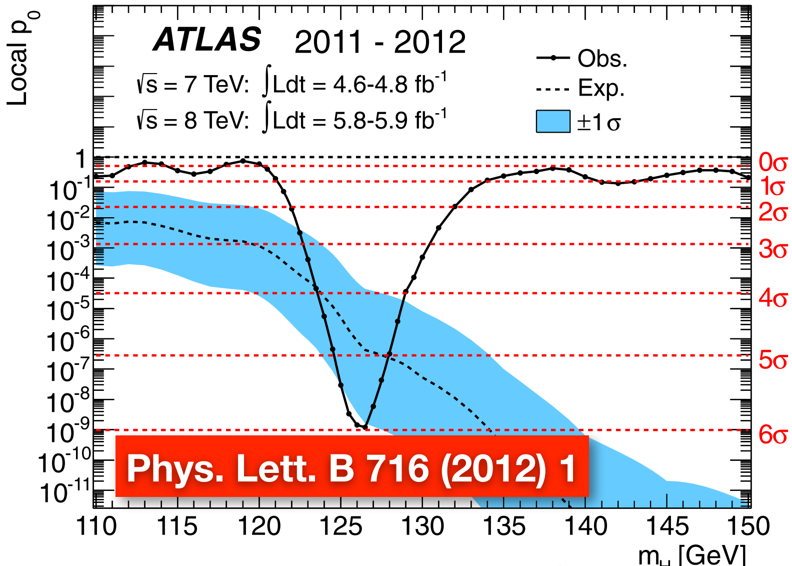
Mass peaks: H(?)→γγ & H(?)→ZZ→4leptons

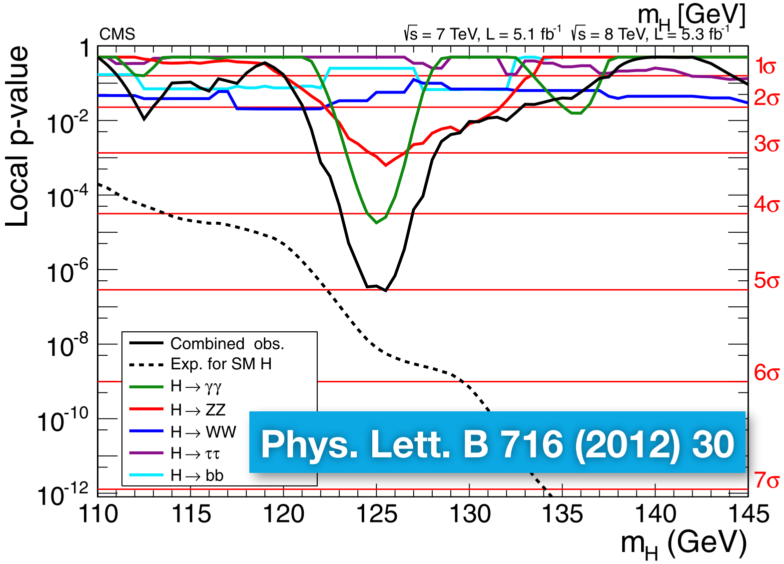
Despite the low branching fraction to the final state, the mass resolution of these two channels enables the siting of a "peak". The ZZ peak has a Z calibration as well(!)

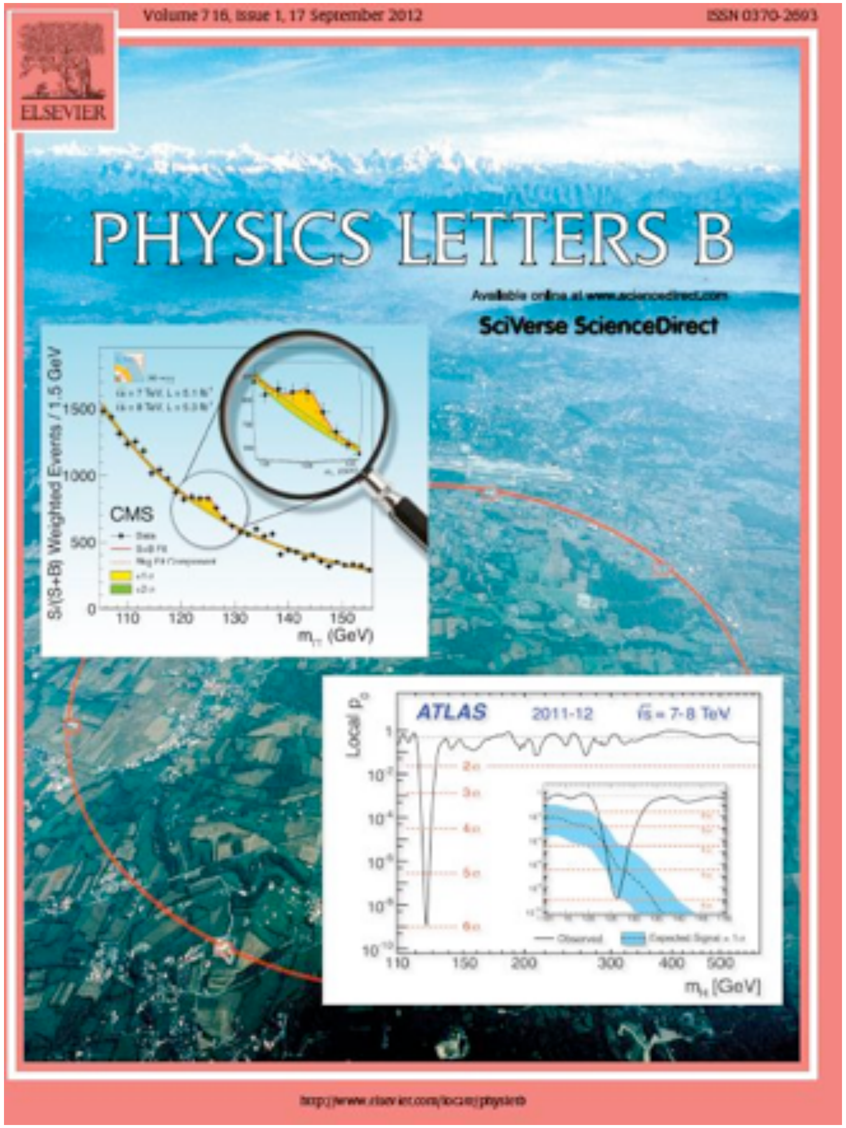




Putting it all together…







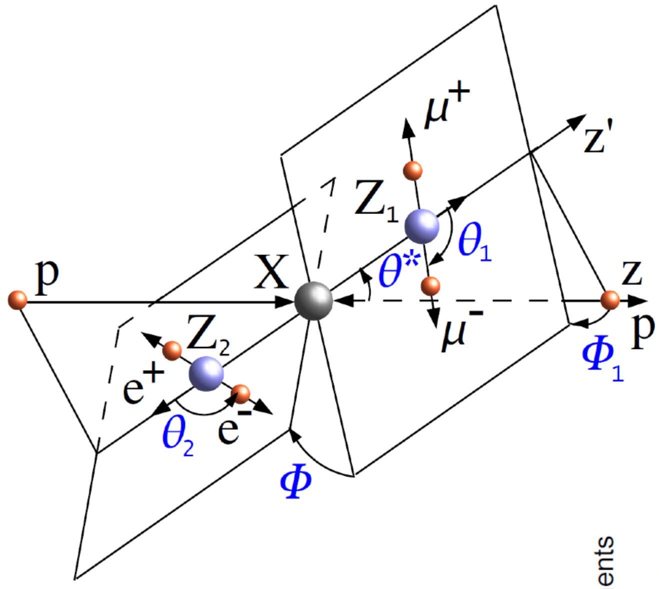
And thus was born,
on July 4th 2012,
“a new boson with mass ~126 GeV”:

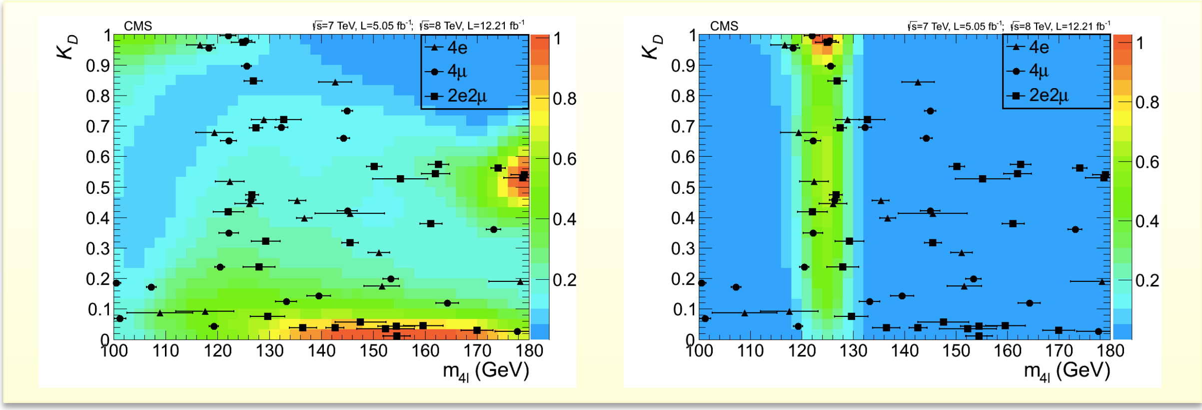
it decayed to two bosons
(two γ; two Z; two W)

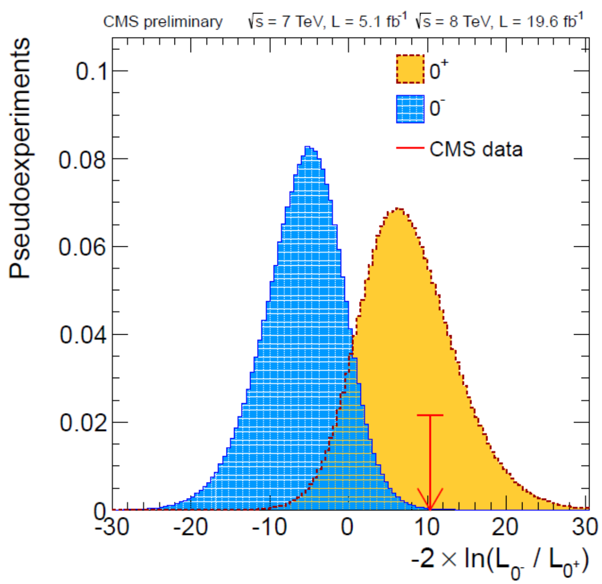
It is not spin-1: it decays to two photons (Landau-Yang theorem)

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

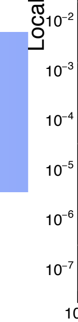
H→ZZ→4leptons: angular analysis



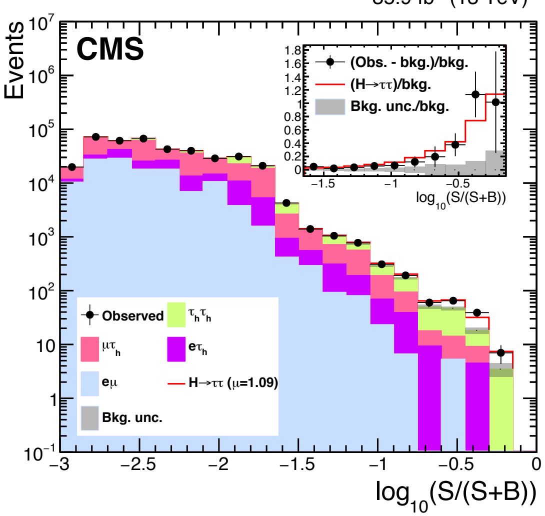


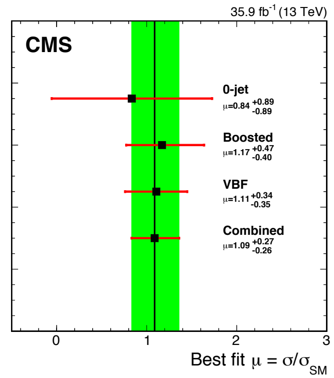


EWSB/H sector: coupling to fermions



H→ττ: established

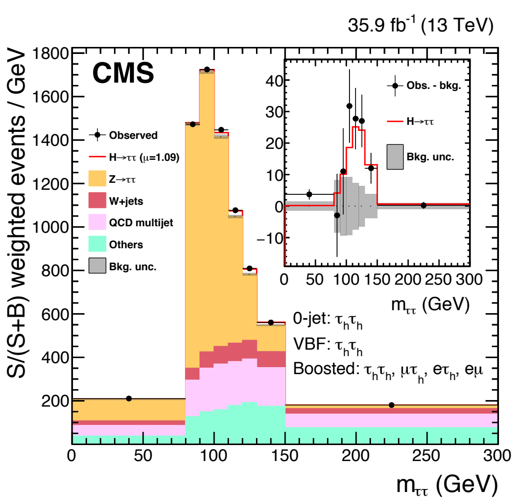


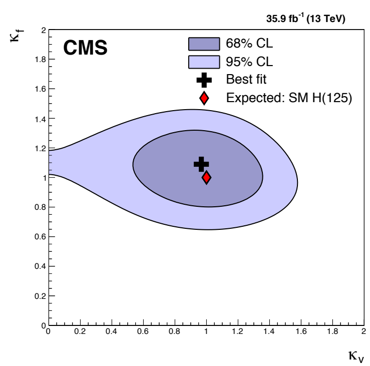


$$\mu = 1.09^{+0.27}_{-0.26} \quad (4.9\sigma)$$

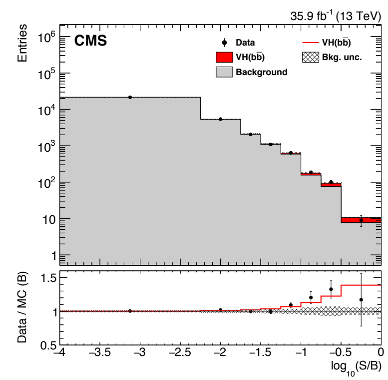
Comb. 7+8+13 TeV:

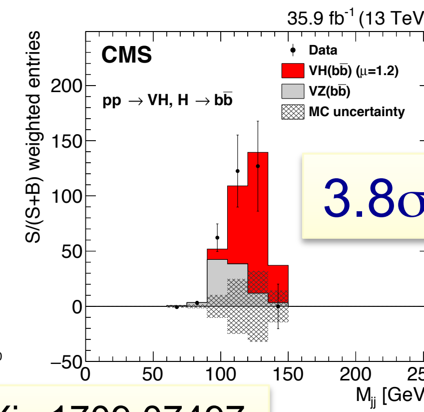
$$\mu = 0.98 \pm 0.18 \quad (5.9\sigma)$$





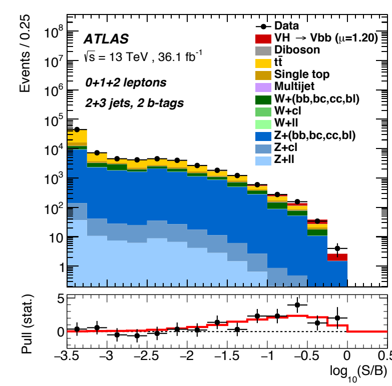
H→bb: evidence (>3σ)

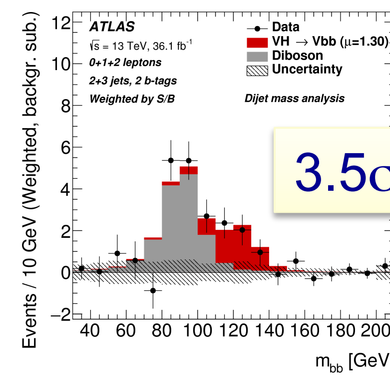




3.8σ

CMS arXiv:1709.07497

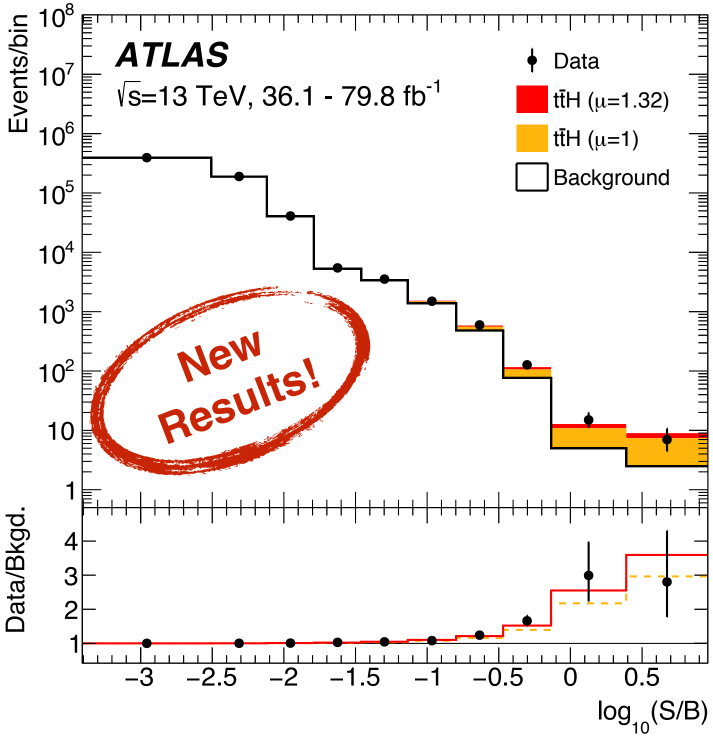


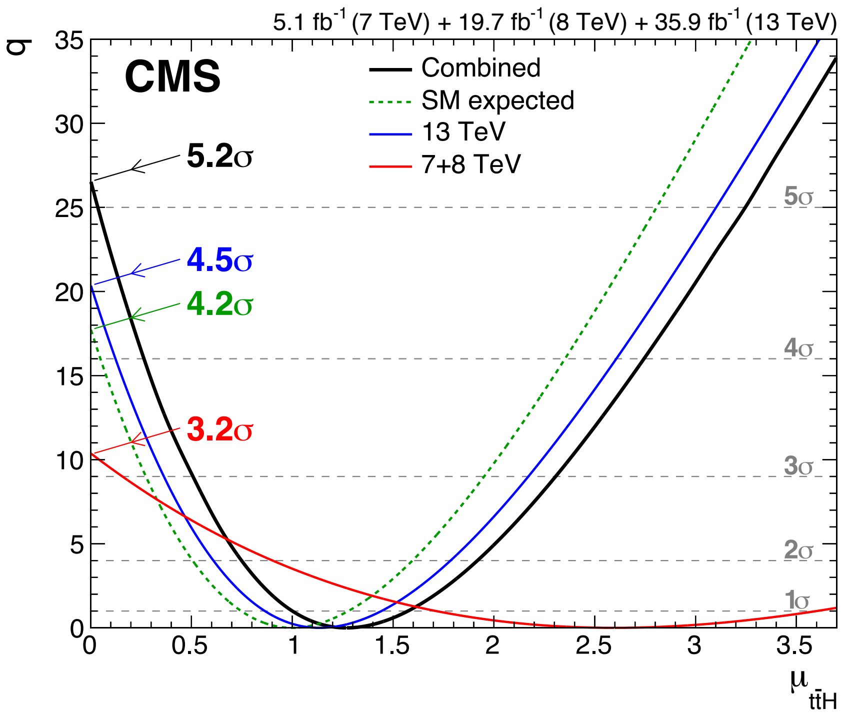


3.5σ

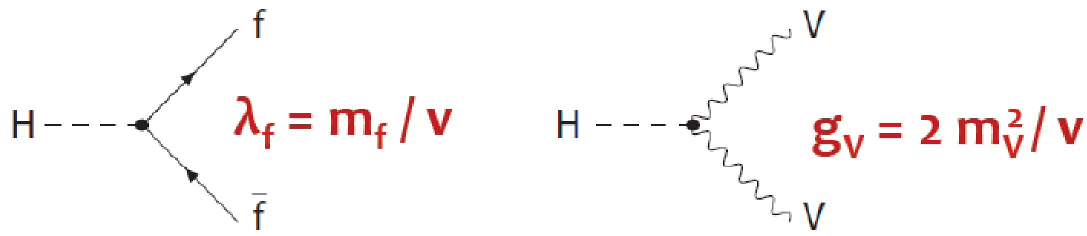
ATLAS arXiv:1708.03299

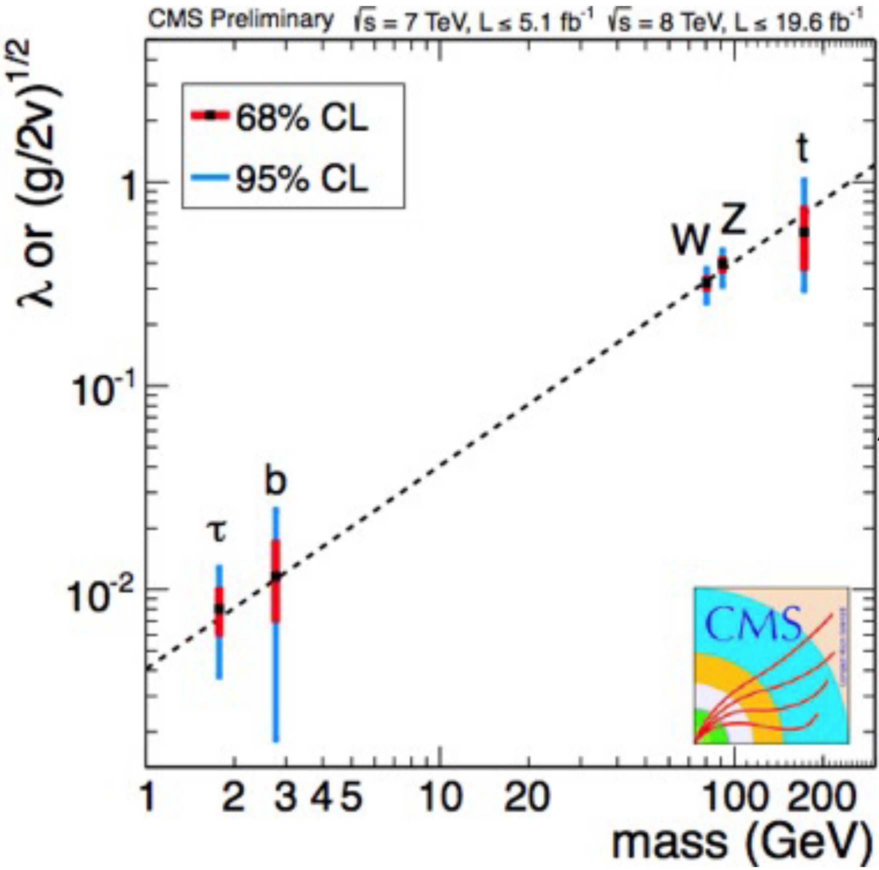
Top-Higgs "Yukawa" coupling





It couples to Mass!

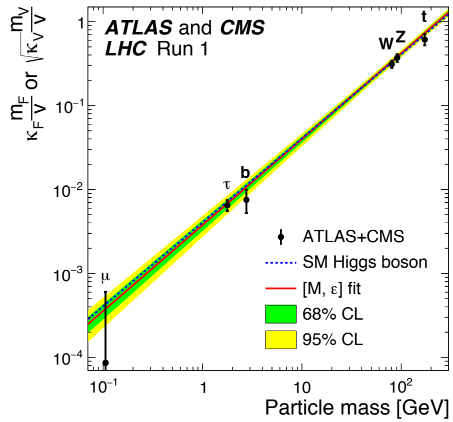




And has SPIN 0(!)

It's a Higgs boson!

(a) $J^P=0^+$ (b)



Is it *the* Higgs?
→ establish production and decay (AMAP)

SM: EWSB/Higgs sector

Higgs couplings to fermions (τ, b and t)

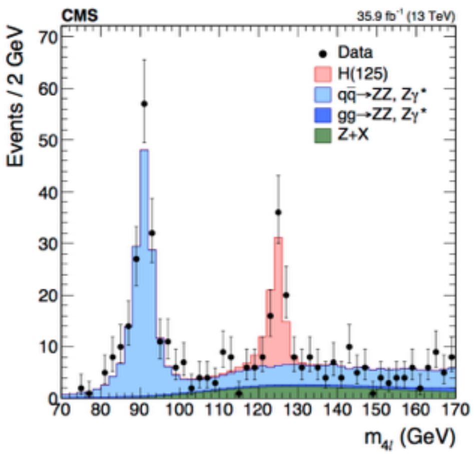
Couplings to 2nd-gen fermions

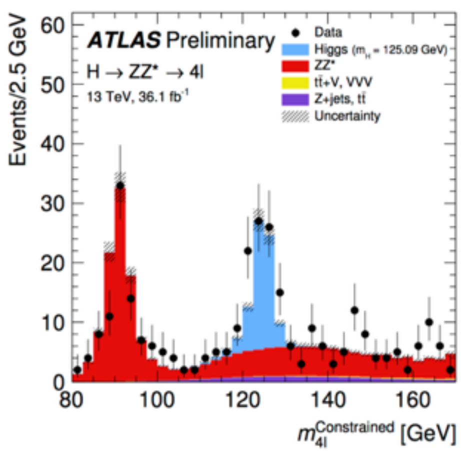
Measurements enabled by high stats

H self-coupling; long-term future

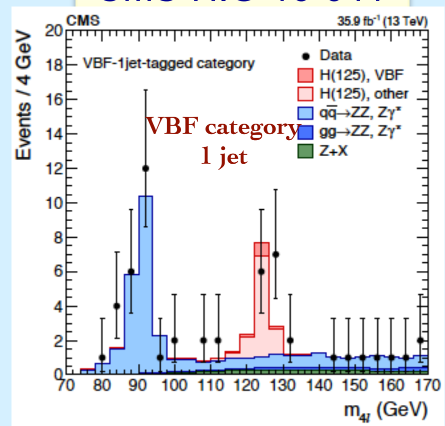
EWSB/H sector: increasing statistics

- With increased stats: Observation channels → measurement channels

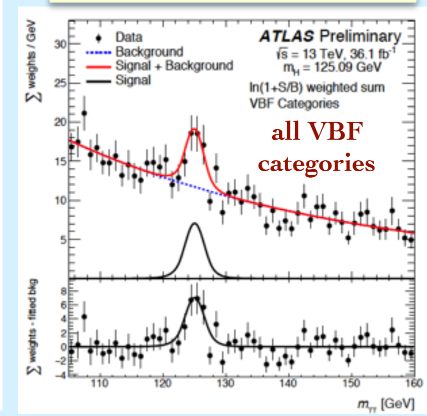




CMS-HIG-16-041

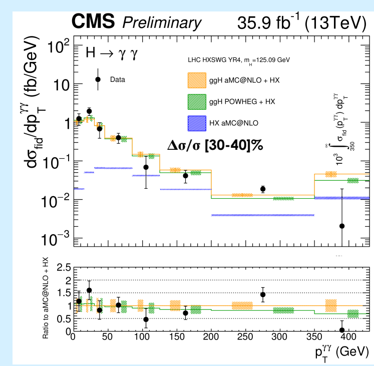


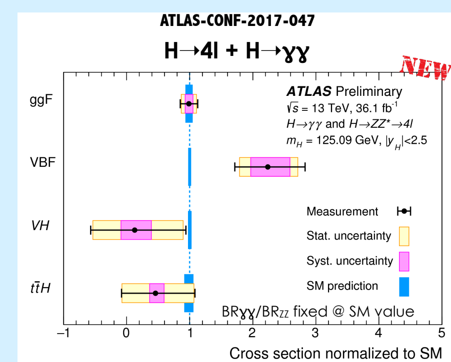
ATLAS 1708.03299



σ/σ_{SM}=1.2±0.2

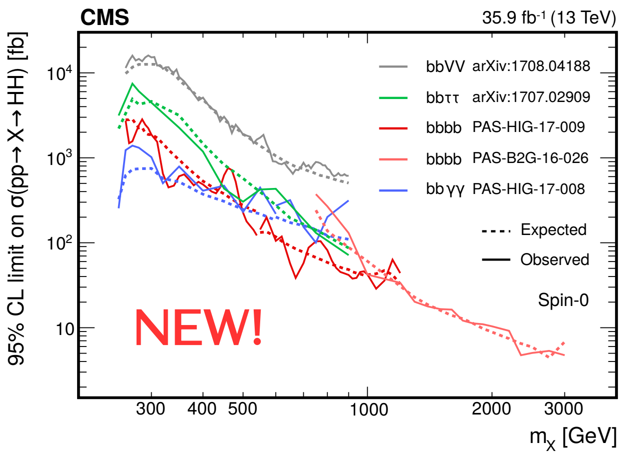
VBF clearly seen

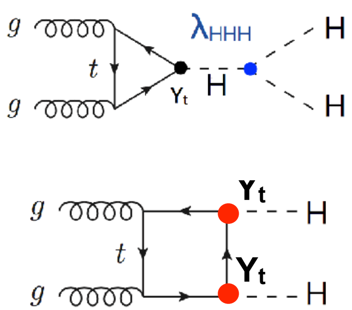




SM EWSB/H sector: for the future

HH; today, within 20xSM
→ need HL-LHC



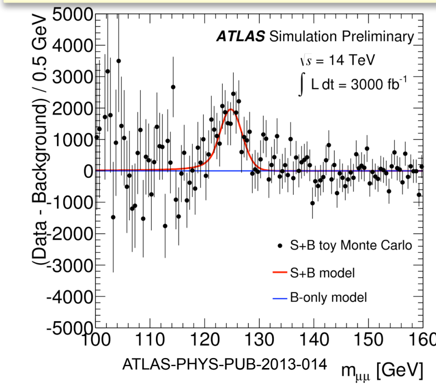


Final state	ATLAS	CMS
$b\bar{b}\gamma\gamma$	177 (162)	19 (16)
$b\bar{b}\tau\tau$		30 (25)
$b\bar{b}b\bar{b}$	29 (38)	342 (308)
$b\bar{b}WW^*$		79 (89)
$\gamma\gamma WW^*$	750 (386)	

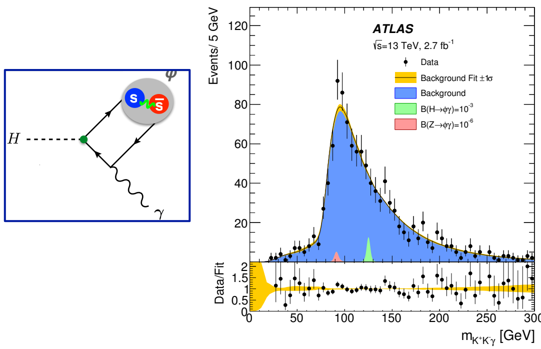
2015 (2.3-3.2 fb^{-1})
2015+2016 (13.3 fb^{-1})
2016 (35.9 fb^{-1})

S. Wertz,
Higgs Coupling 2017

H→μμ @ HL-LHC:
7σ (/exp)



Rare decays…



ATLAS-CONF-2017-057

Process	σ/σ_{SM} (95% CL)
H→Zγ (ATLAS) 36fb-1 @ 13 TeV	<6.6
H→Zγ (CMS) Run1	<9
H→γ*γ (CMS) Run1	<7.7
H→J/Ψγ (ATLAS) Run1	<540
H→J/Ψγ (CMS) Run1	<540
H→ργ (ATLAS) 36 fb-1 @ 13 TeV	<52
H→φγ (ATLAS) 36 fb-1 @ 13 TeV	<208
H→ee (CMS) Run1	<~10^5

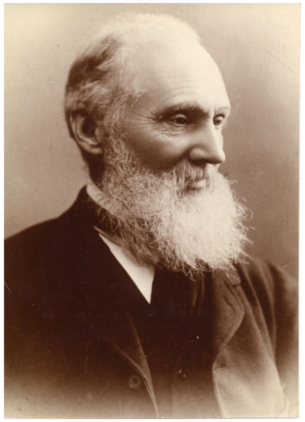
Run1
Run2 36 fb^{-1}

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 ≥ 100 GeV, the situation is reminiscent of previous times in history when our knowledge of nature was deemed to be "complete".**

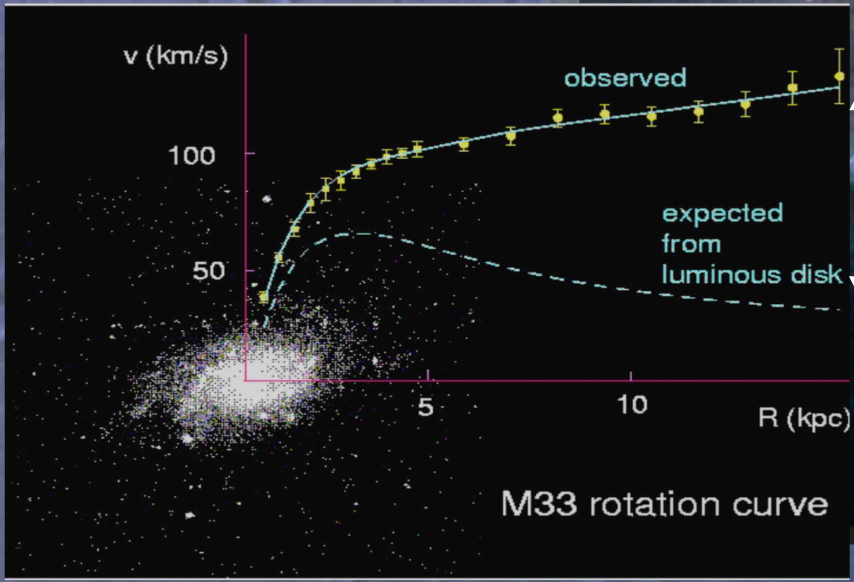


Lord Kelvin (1900):
There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

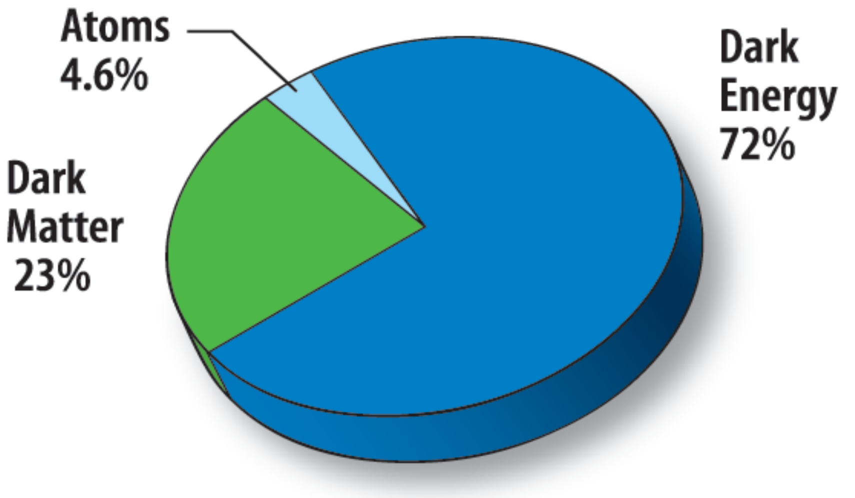
1905-1920: Relativity, Quantum mechanics

Dark matter in the universe

Hubble: we have probed the universe to distances of 13,5 billion years



Dark Matter



Perhaps the biggest mystery in nature (as we speak)

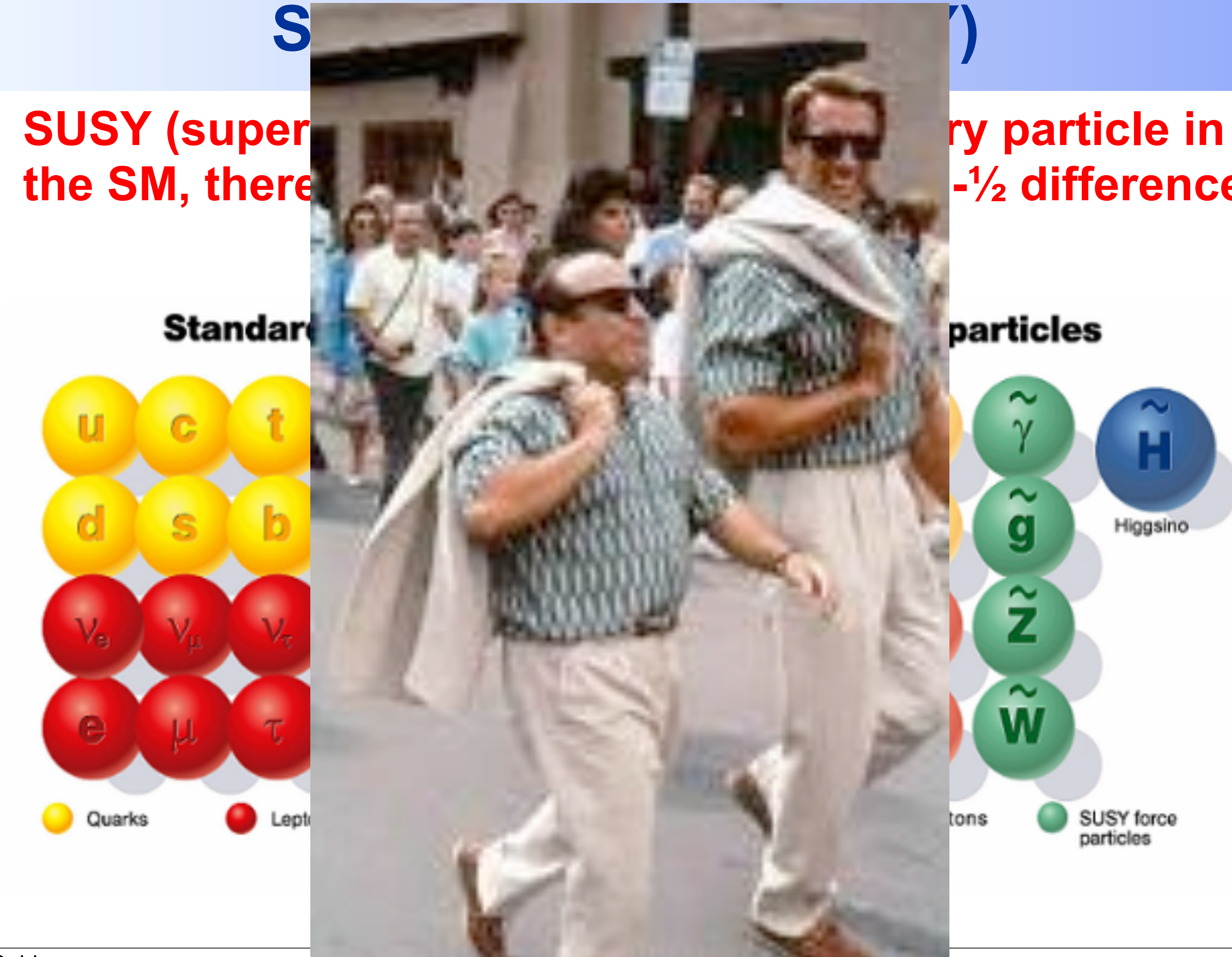
New type of matter?
New forces?
New dimensions?

And now that the Higgs is found: questions

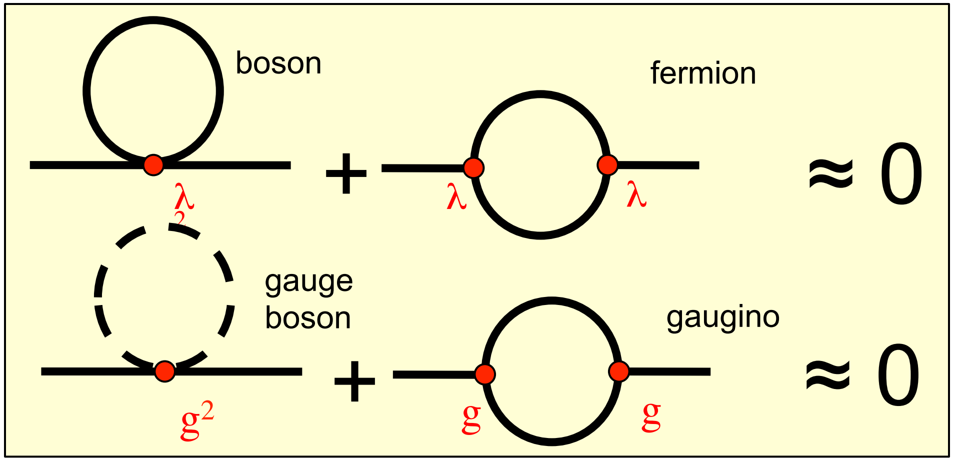
- **Foremost: how can its mass be anything "small"?**
  - It should resist itself (since it couples to mass, it should couple to itself as well). A cascade/avalanche…
  - Its mass should be almost infinite!
- **Where is all this vacuum energy?**
  - We would expect a tremendous energy density, >Googol (10^{100}) times larger than observed! ("Cosmological constant too small")
  - Size of the universe if the Higgs was there (ALONE): a football (soccer ball)

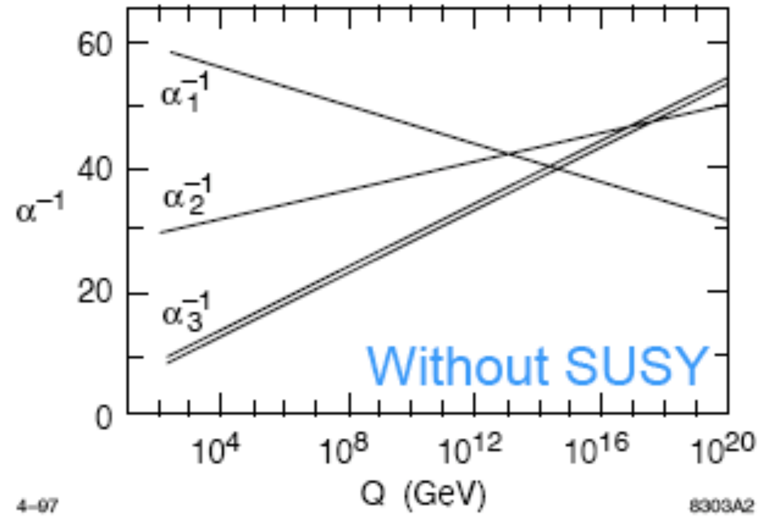
S … Y)

- **SUSY (super … ry particle in the SM, there … -½ difference**



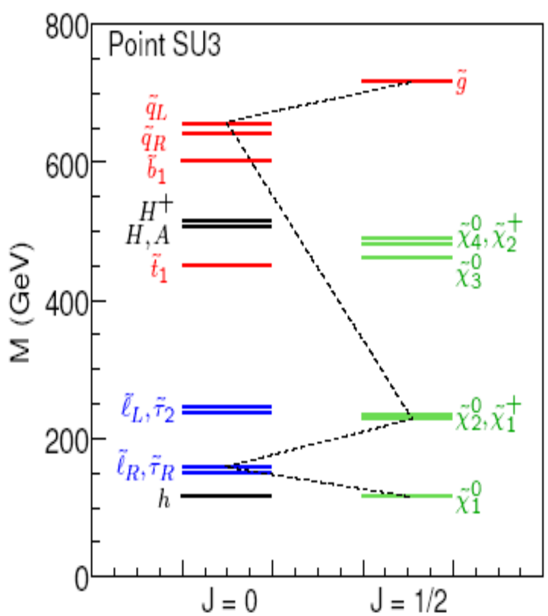
Higgs (mass) is natural ?!



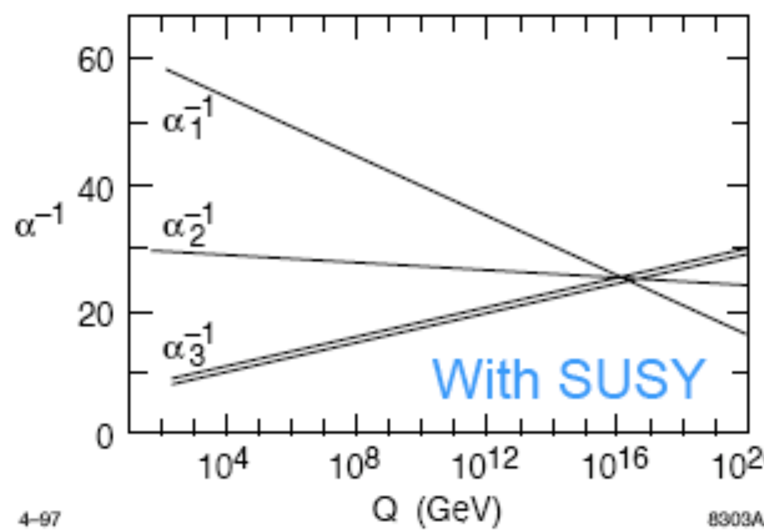


A super(b) symmetry!

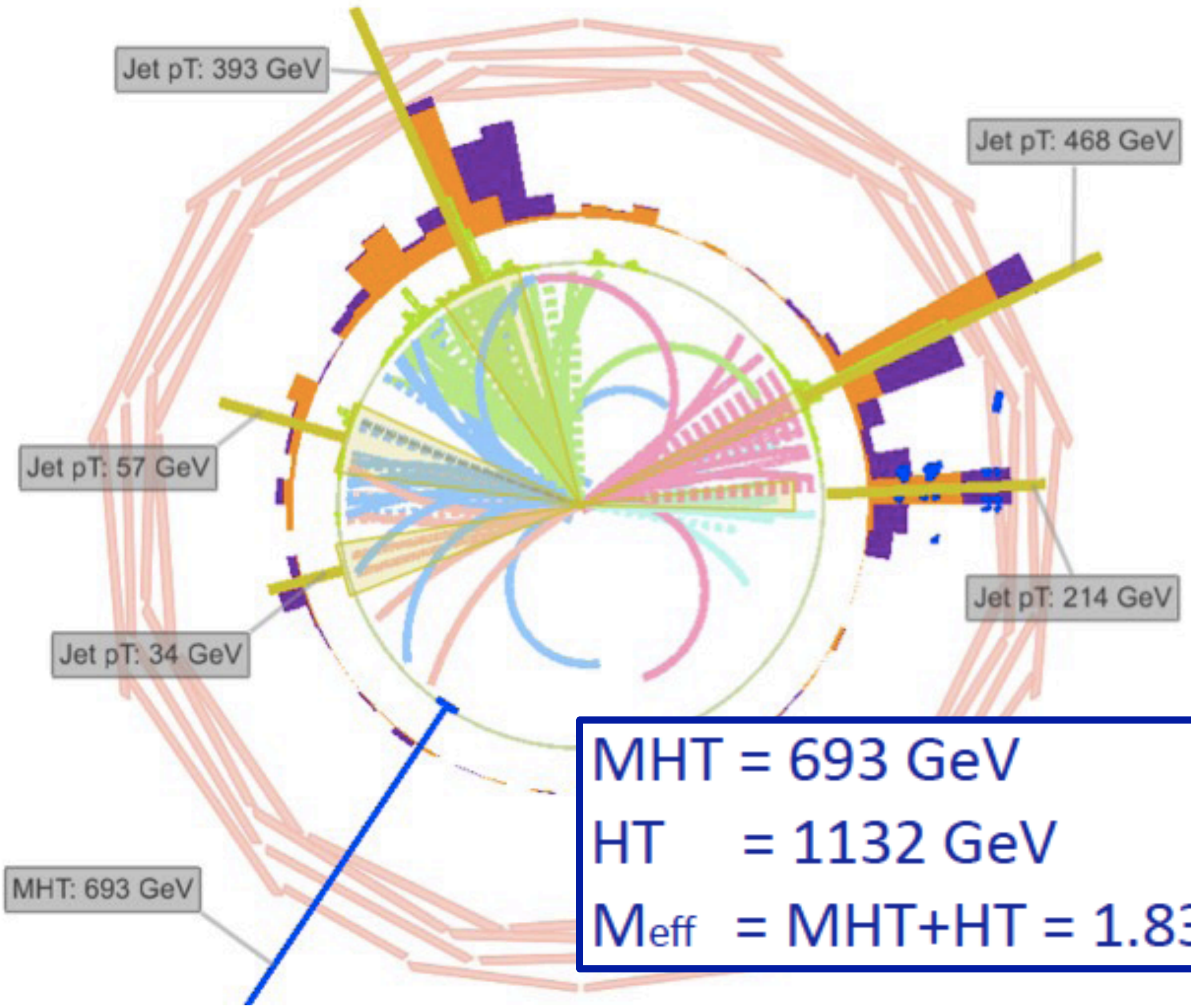
Grand Unifier?



Dark Matter candidate



SUSY? What it could look [looks?] like



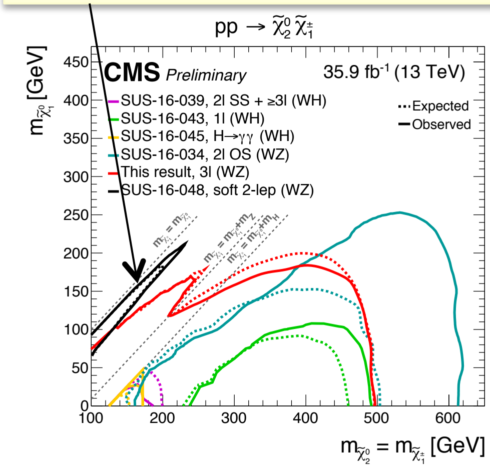
MHT = 693 GeV
HT = 1132 GeV
M_{eff} = MHT+HT = 1.83 TeV

Supersymmetry

- **The LHC has placed very severe constraints on Supersymmetry**
  - In fact, the more "constrained" models of SUSY are now almost excluded (M>~2 TeV)
  - 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

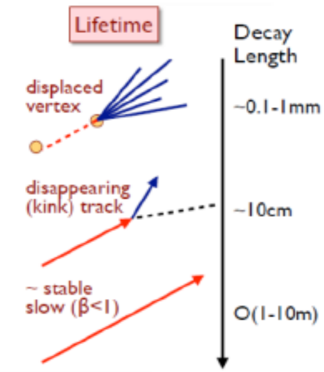
Supersymmetry: what to do next

Compressed spectra

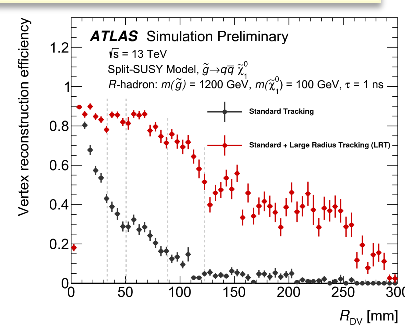


Long Lifetimes

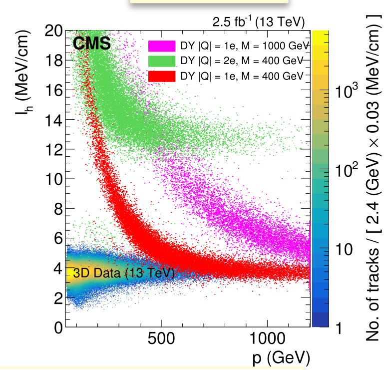
- Small couplings: RPV decays, dark sector coupling
- Small Δm: almost degenerate NLSP heavy messenger: Z', split SUSY
- Hidden valleys…



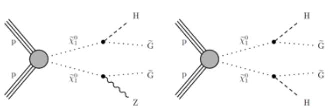
Dedicated (re)tracking

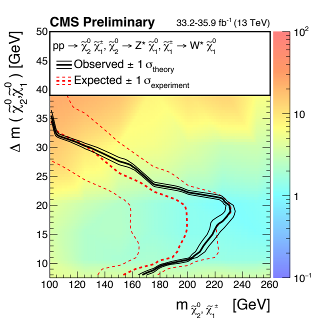


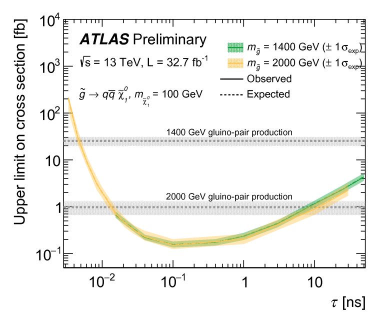
dE/dx



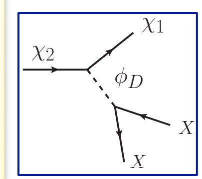
We will always have Higgsinos… μ term must be ~O(M_H)







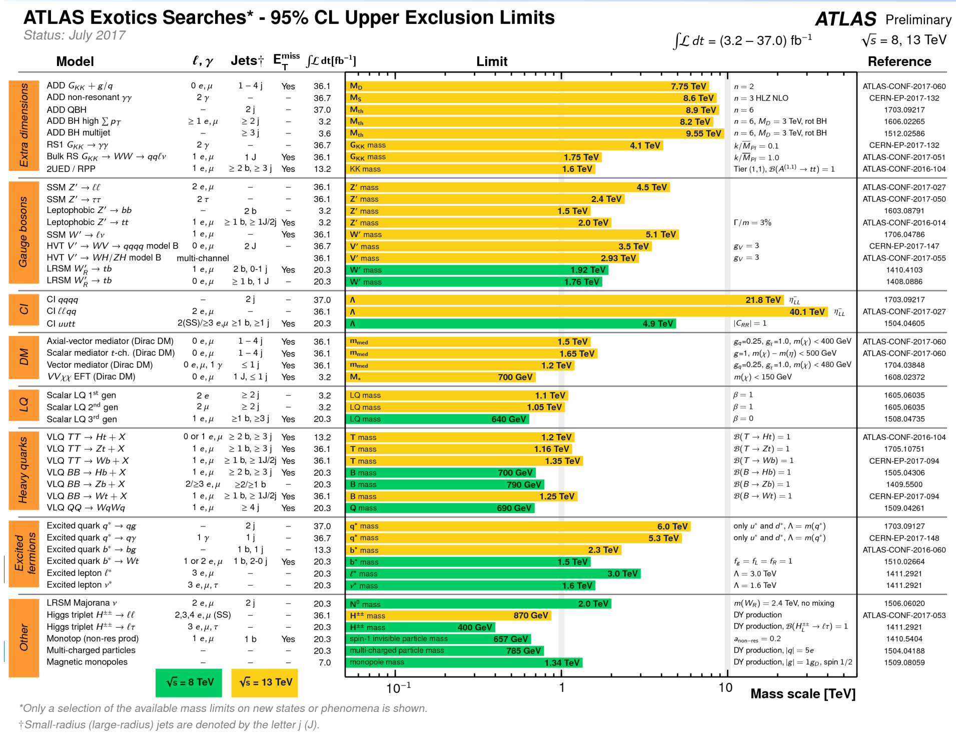
What is really needed: Systematic study of all SUSY and DM space under long-τ hypothesis

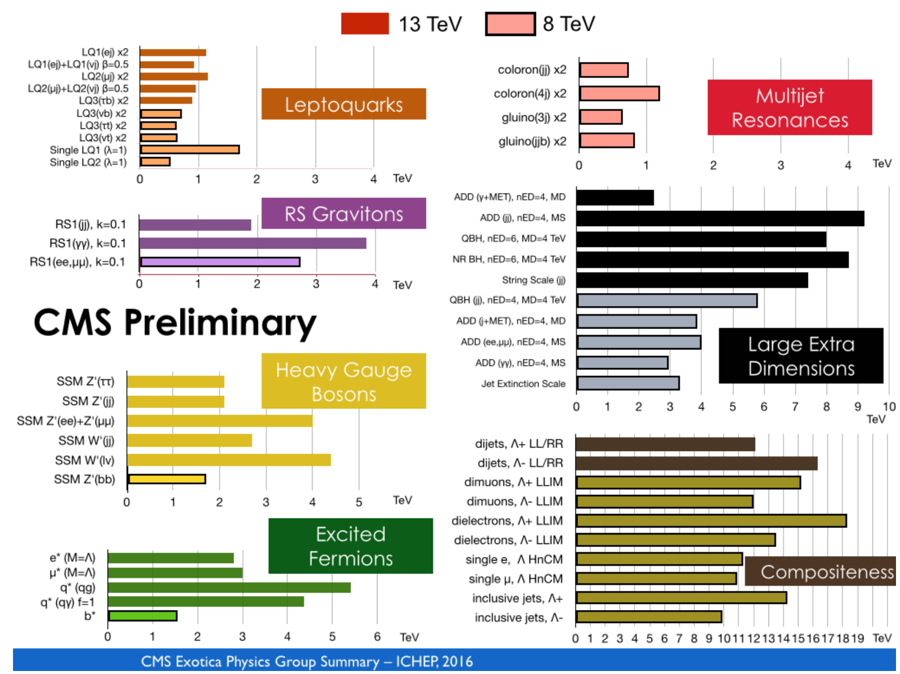


CERN LLP Workshop

arXiv:1704.06515

Non-SUSY BSM: vast, simply vast…





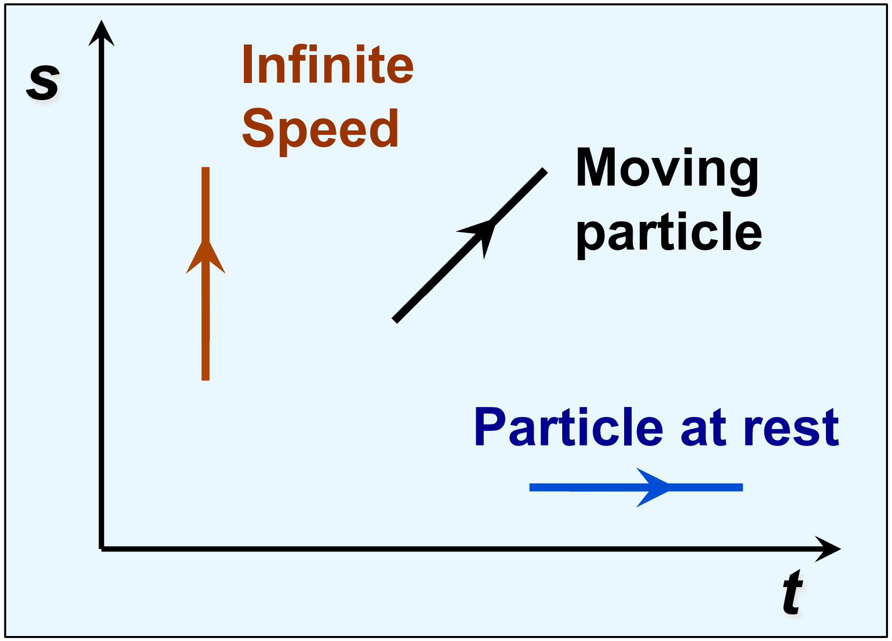
Summary

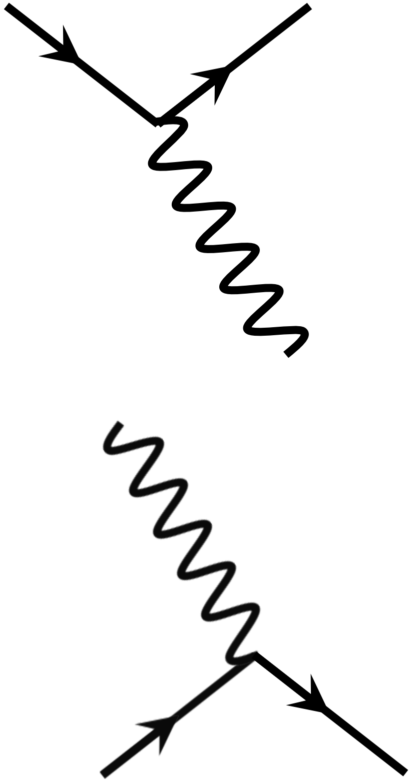
Summary

- 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)
  - For decades, it had only one missing element the Higgs boson
- LHC and experiments: a 20-year "Odyssey"
  - And we found a Higgs boson at 125 GeV! Is it the very Higgs boson of the SM?
  - Now need to study the Higgs boson in detail!
- Still, huge reasons to believe in new physics
  - Dark Matter; the finiteness of the Higgs; history!
  - There is still plenty of room where SUSY and other new physics may be hiding
- Stay tuned! The best may well be ahead!

Force = exchange of particle

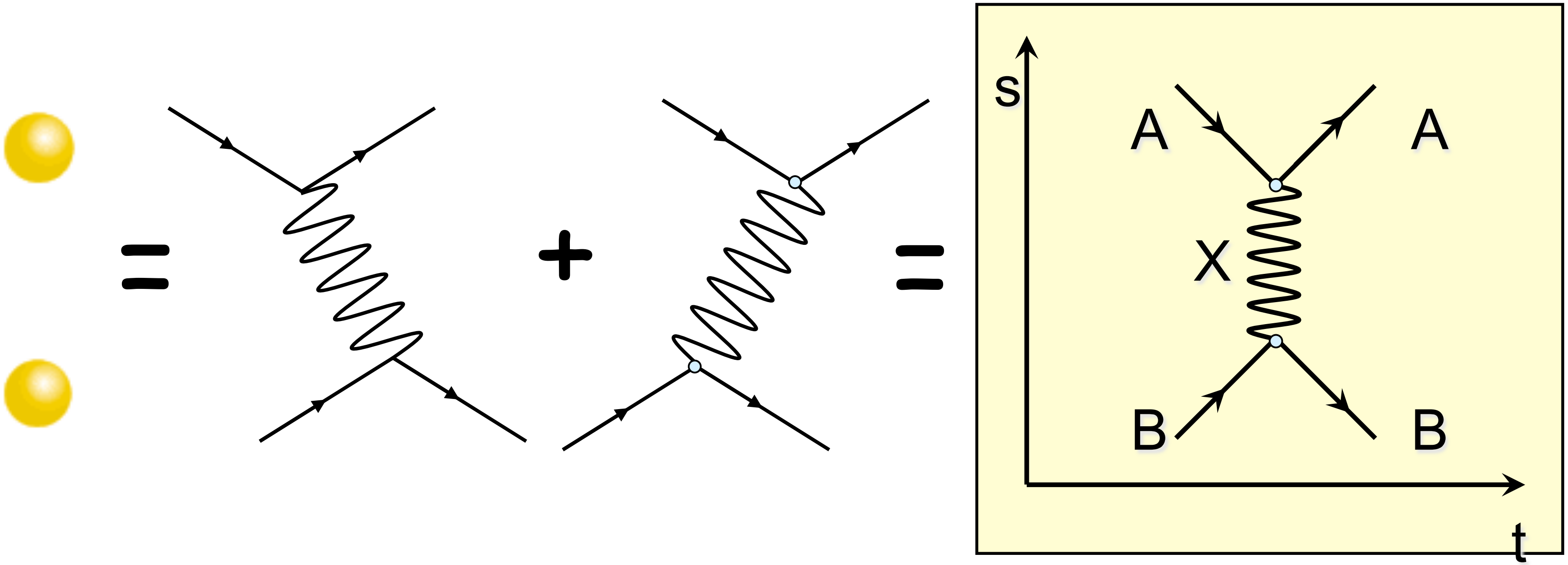
- **The most basic process: a fermion (matter particle) emits/absorbs a boson (force particle)**





Feynman diagrams (I)

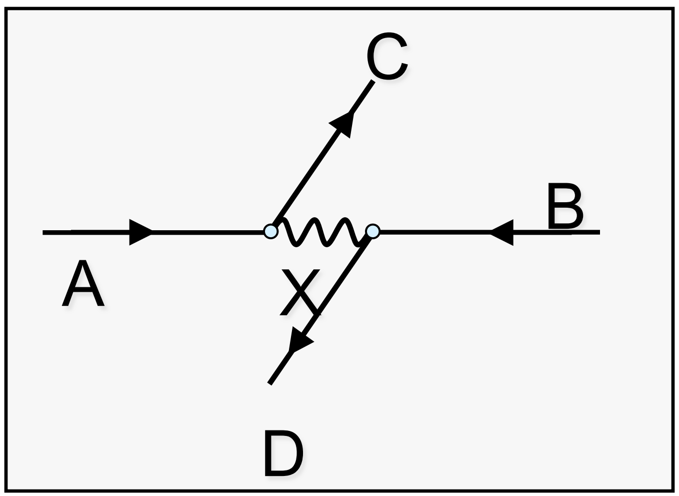
- **Have to draw all possibilities**
  - We do not know whether X was emitted by A and absorbed by B or the opposite
  - So: X is drawn vertically [though it does not have infinite v]



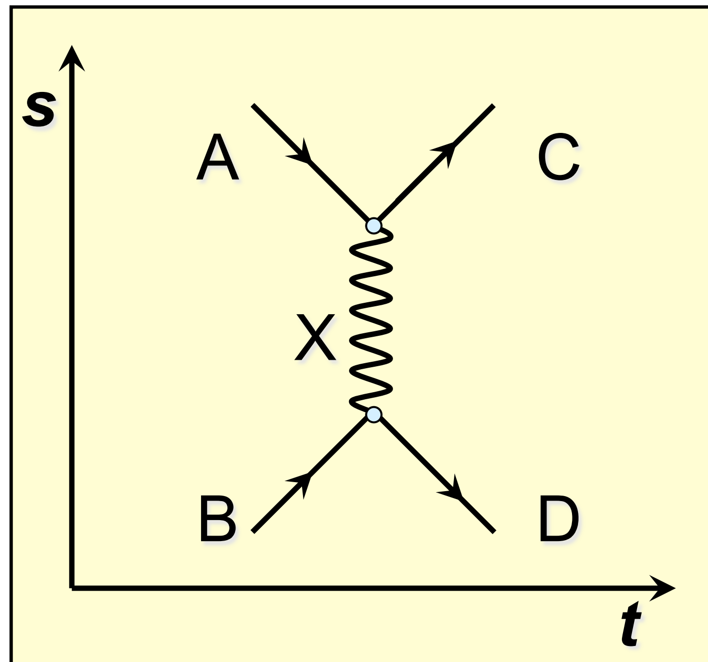
Feynman diagrams (II)

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.



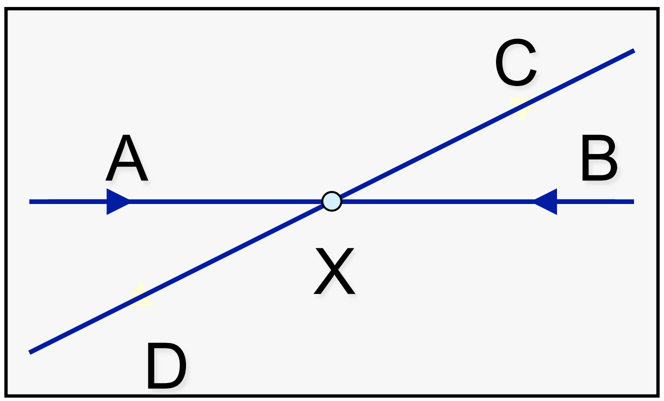
The interaction, as seen in the laboratory frame



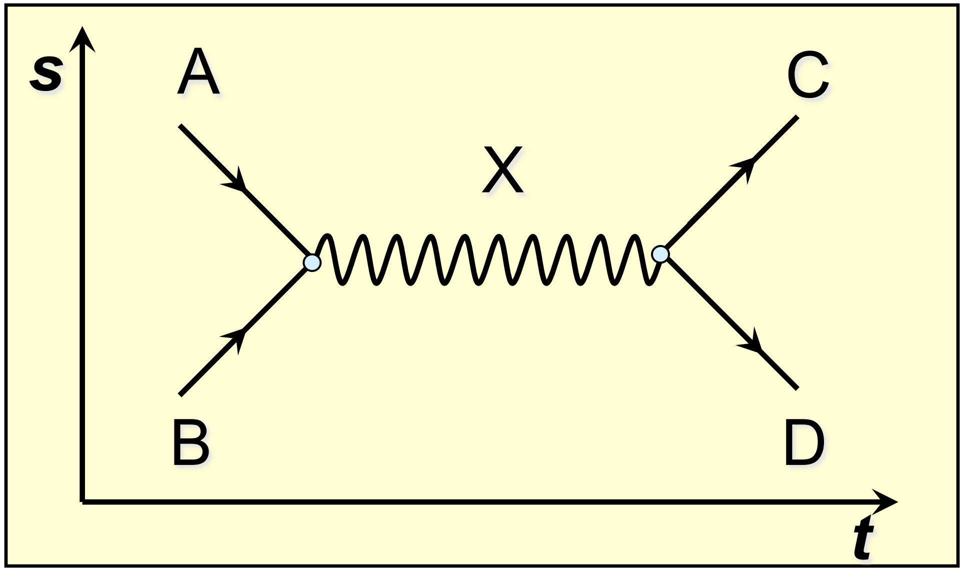
Schematic representation of the collision in terms of a Feynman diagram.

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

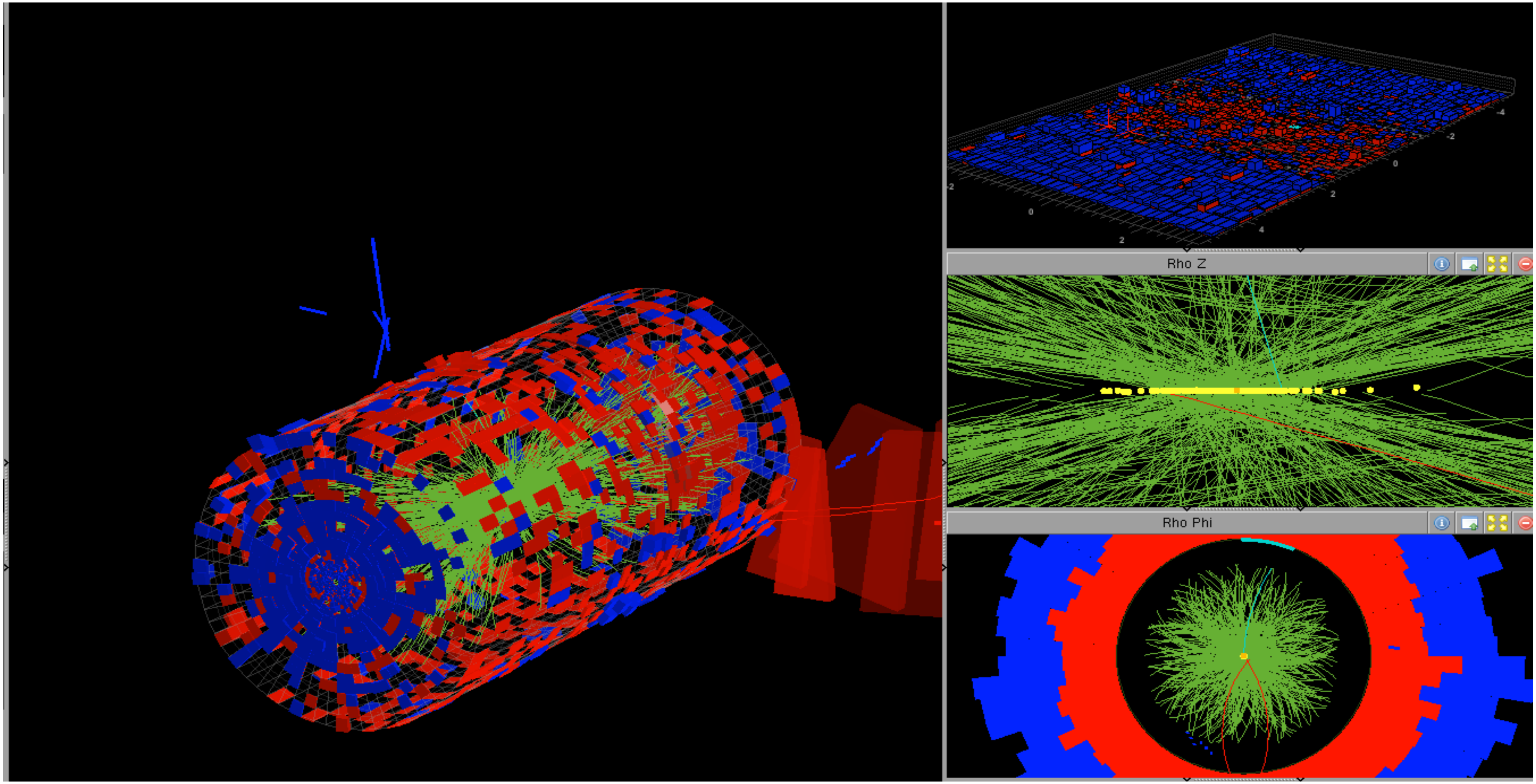
Summary

- **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!

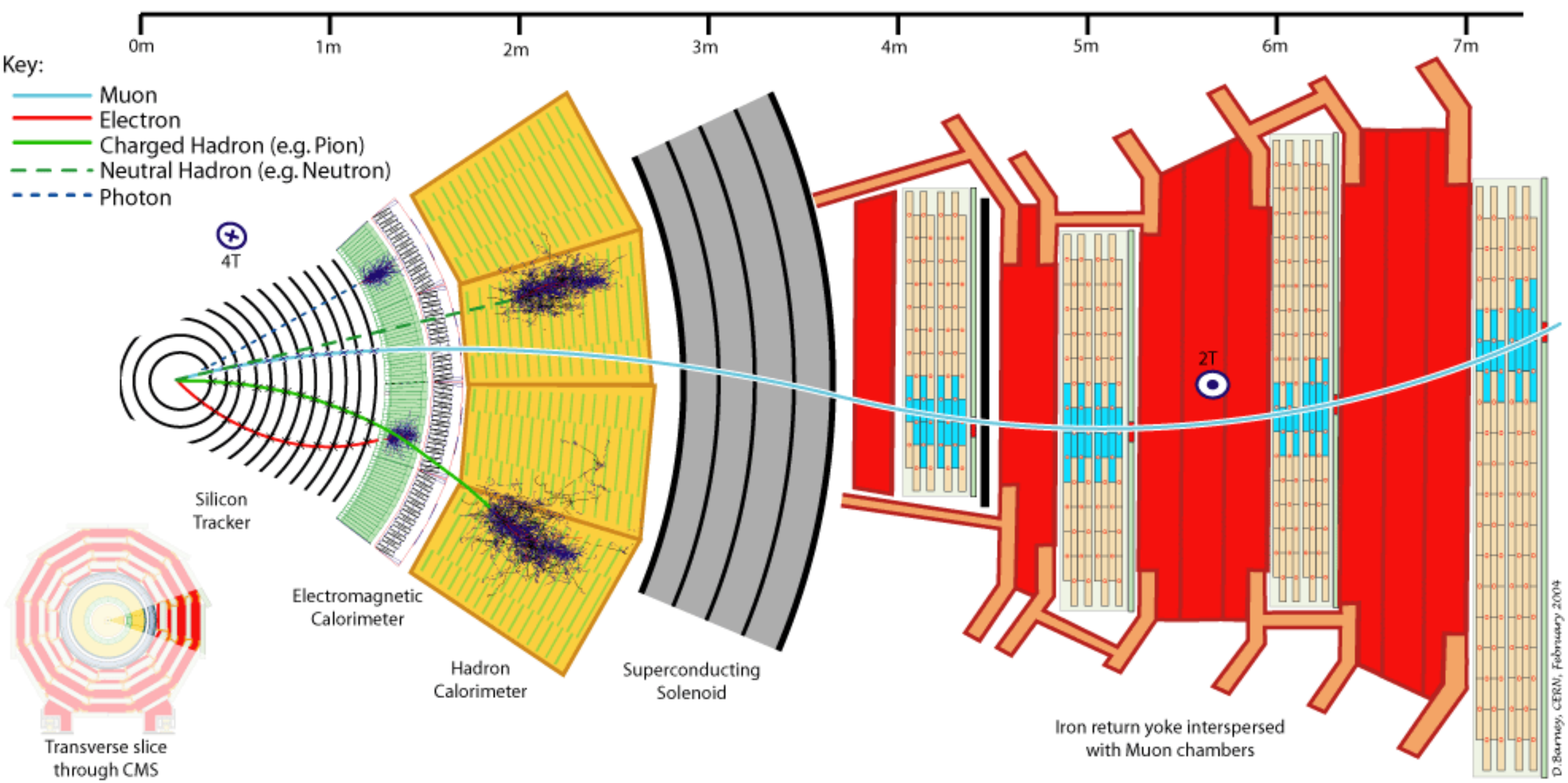
Backups

Going beyond design conditions

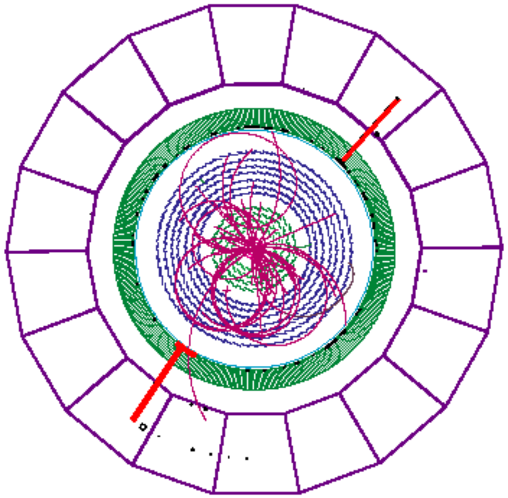
CMS event with 78 reconstructed vertices and 2 muons…

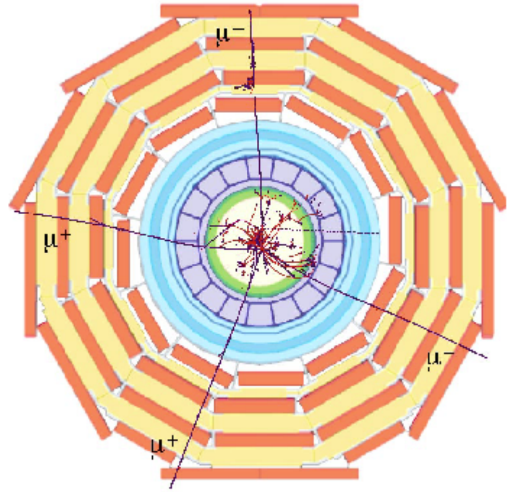


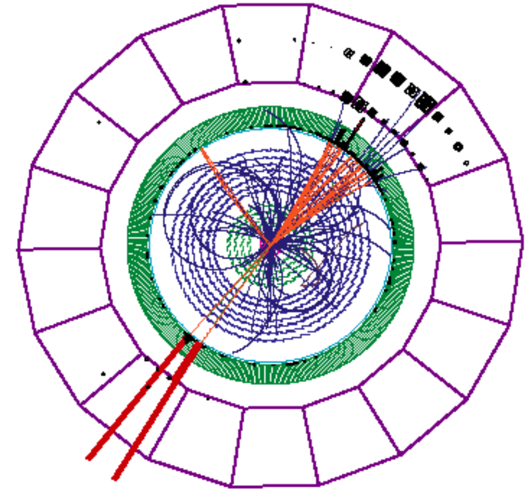
Particle detection/identification in CMS

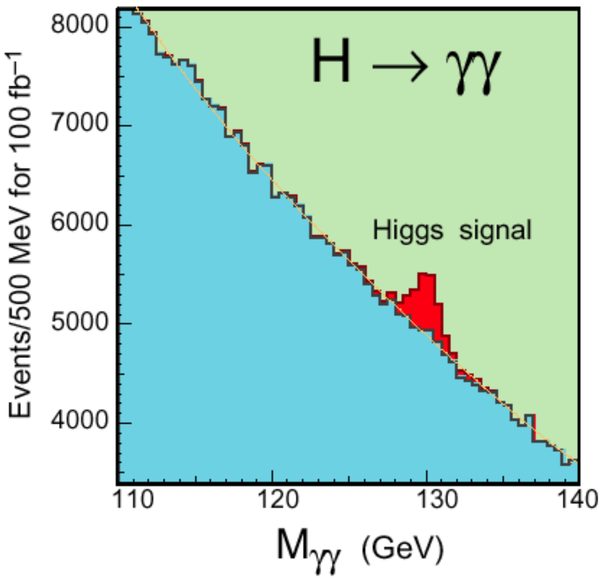


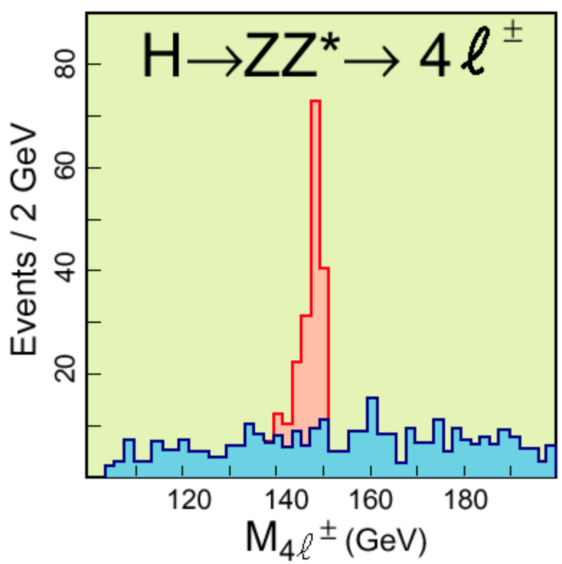
The (SM) Higgs in the detector

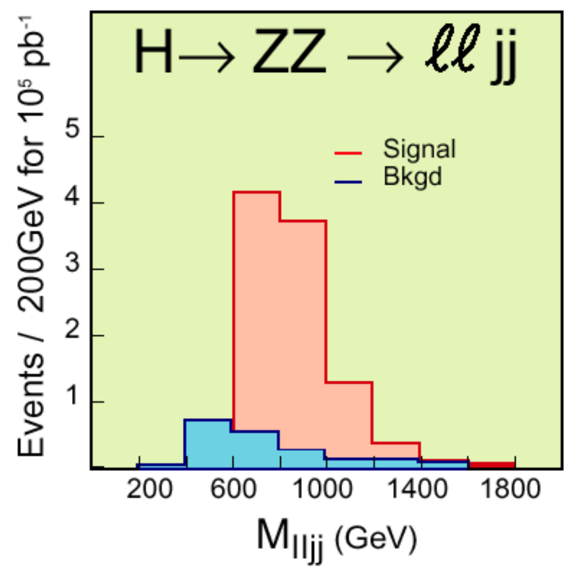




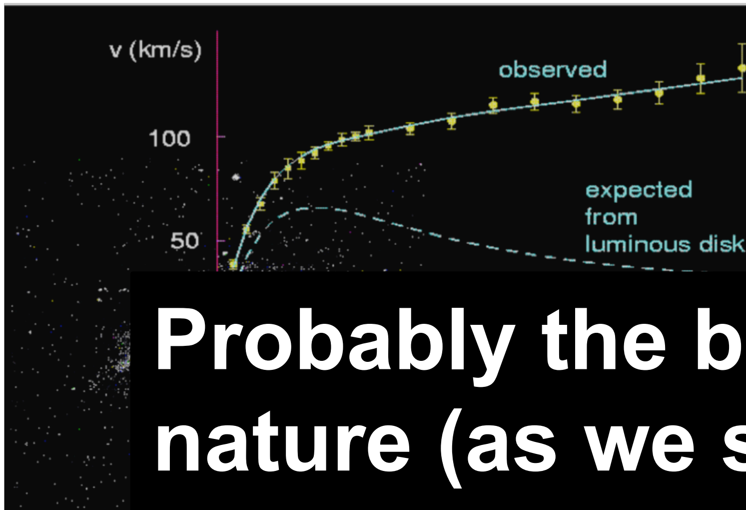




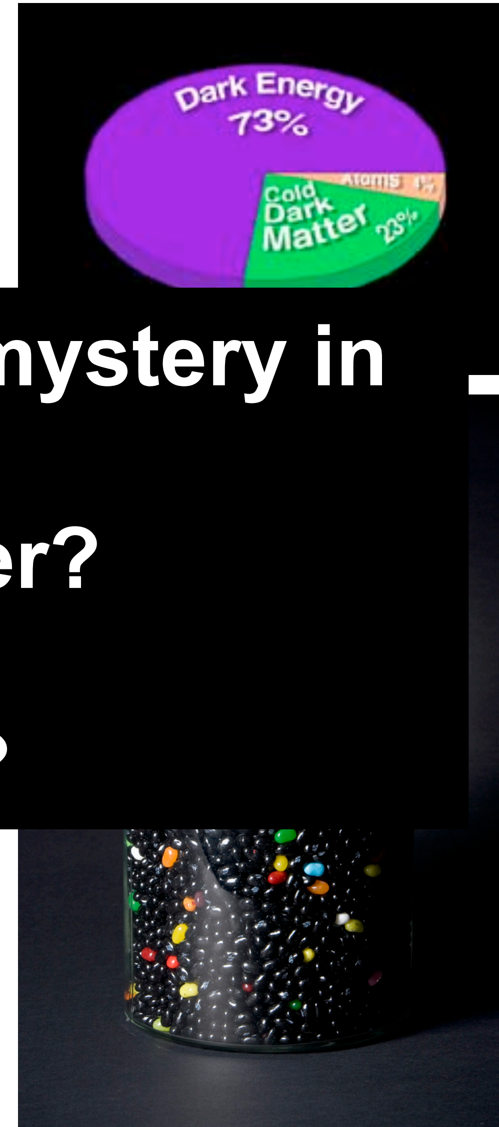




Dark matter

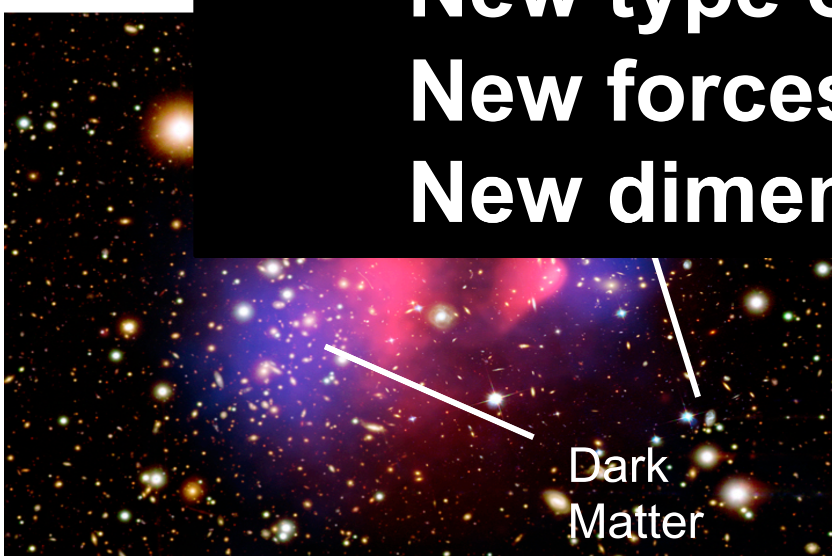


Dark (invisible) matter!



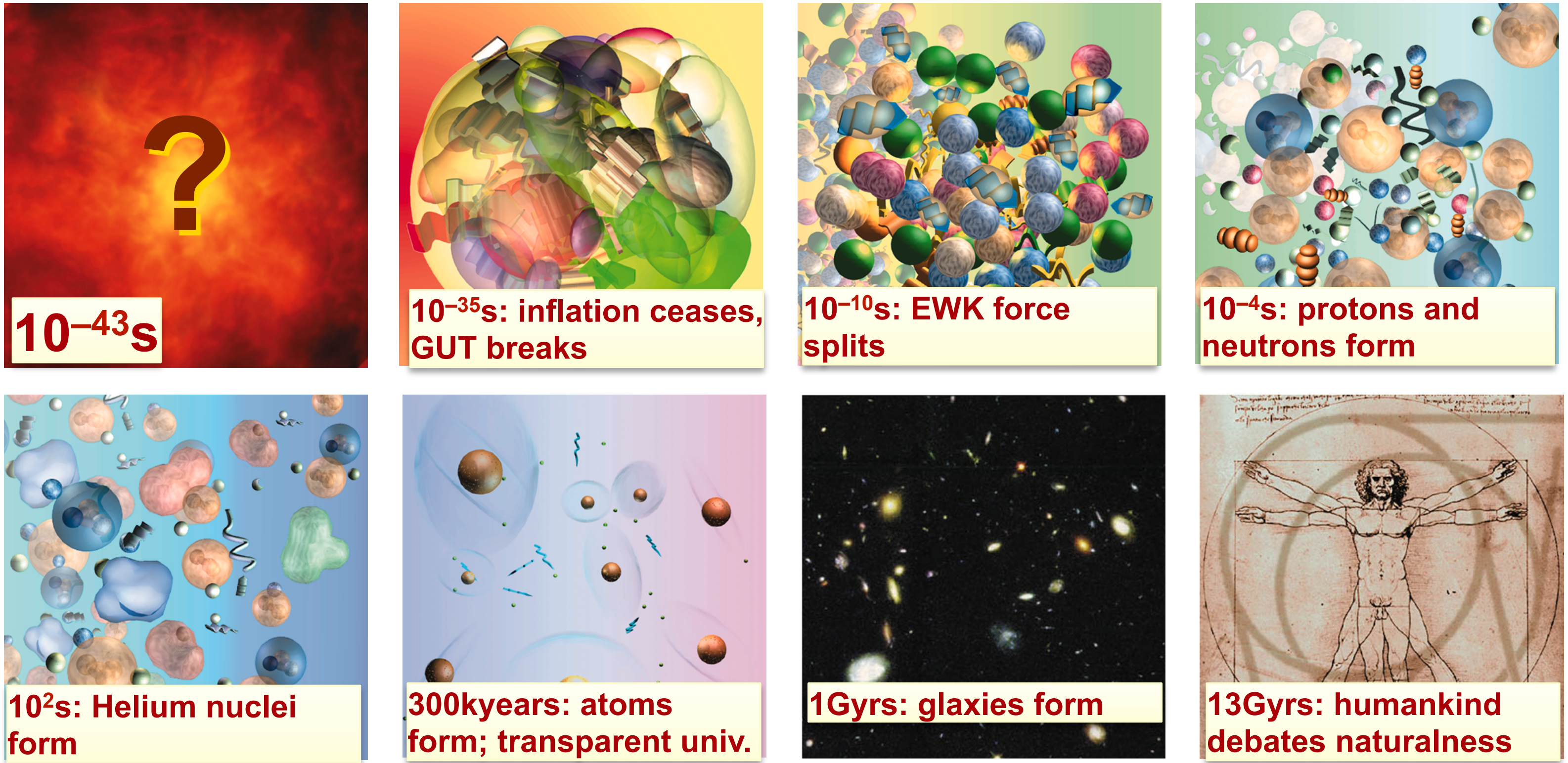
Probably the biggest mystery in nature (as we speak)

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



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

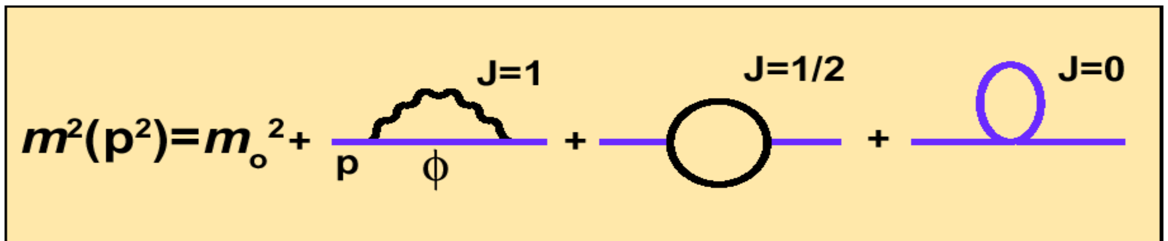
Supersymmetry: TO"AE" at the Weak Scale

- 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"

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.**



P.A.M Dirac

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

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

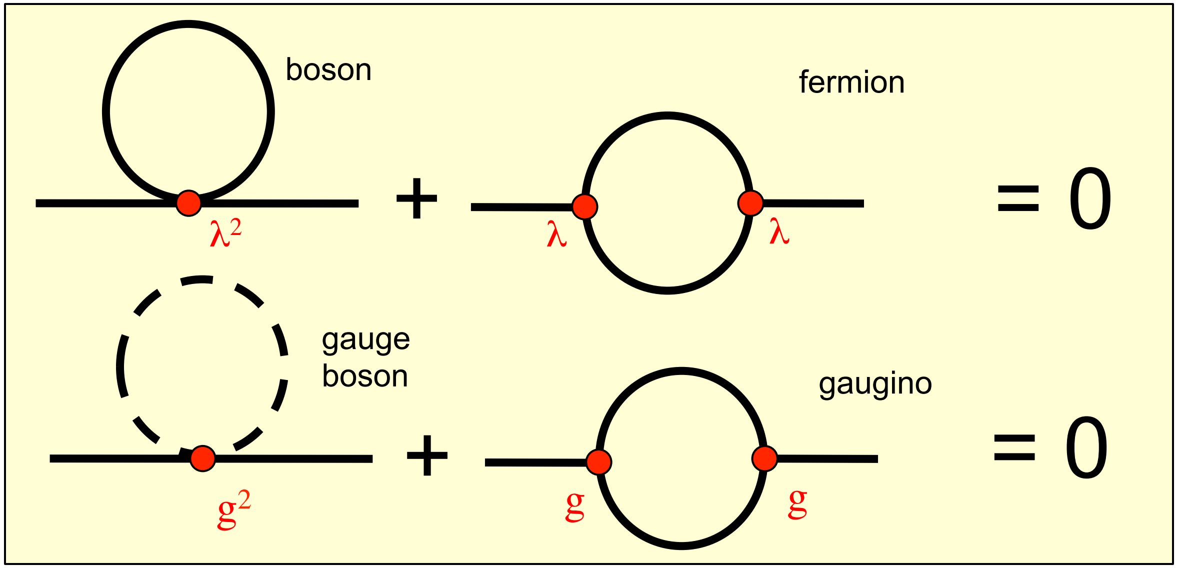
- **Two possible explanations for this:**

  (a) The A word (b) New Physics

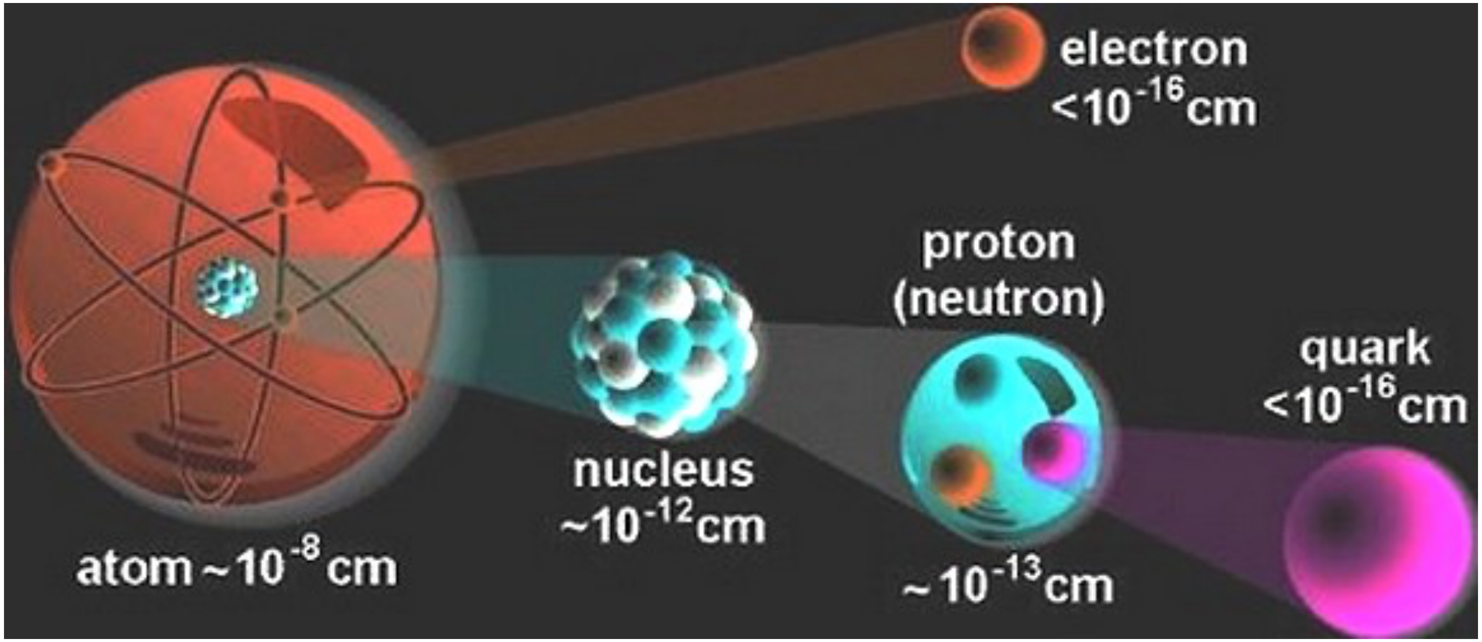
The NP word(s): this is no accident

- 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:



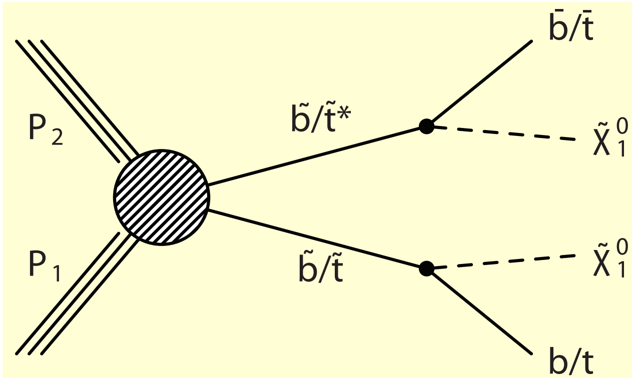
20^{st} century: everything is made of four particles (u, d, e, ν_e)*

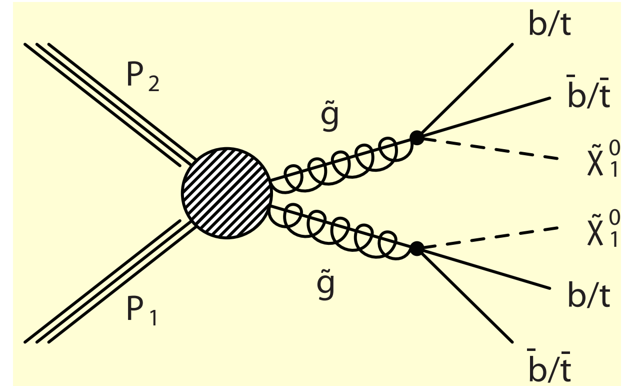


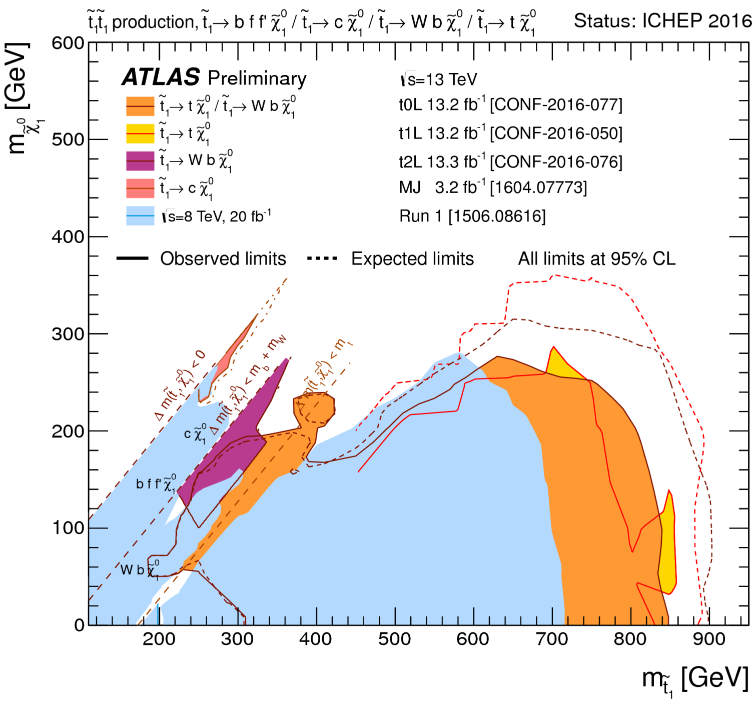
These are pointlike!

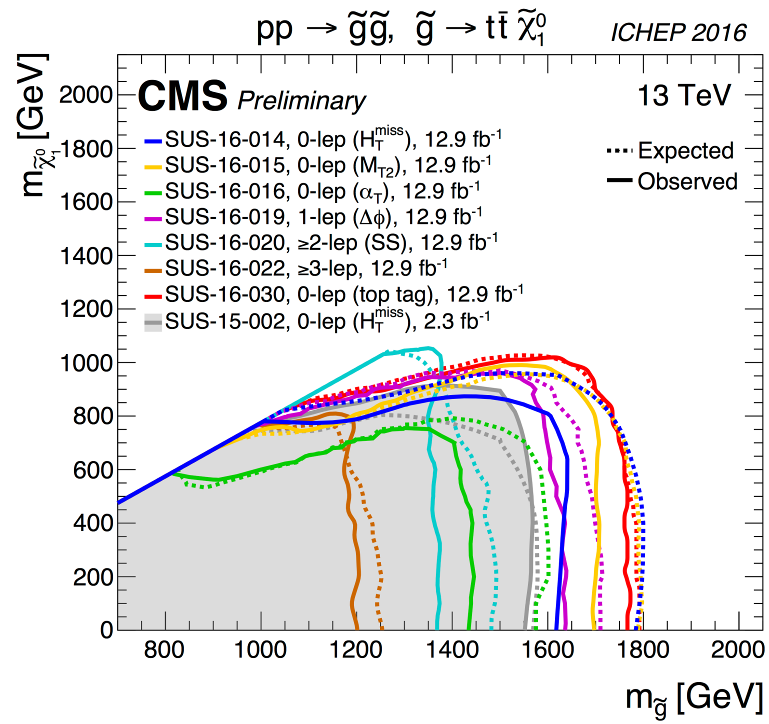
The problem: the background

SUSY: searching for the top squark









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