The Standard Model and Beyond

Paris Sphicas
CERN & University of Athens
CERN Accelerator School
Chavannes de Bogis, November 04, 2013

- **The Standard Model of Particle Physics**
  - **And the Higgs boson…**
- **Looking for the Higgs**
  - **A new boson at ≈ 126 GeV!**
  - **Update since the discovery (properties)**
- **Searching for New Physics**
  - **Supersymmetry?**
- **Outlook**

Standard Model of Particle Physics

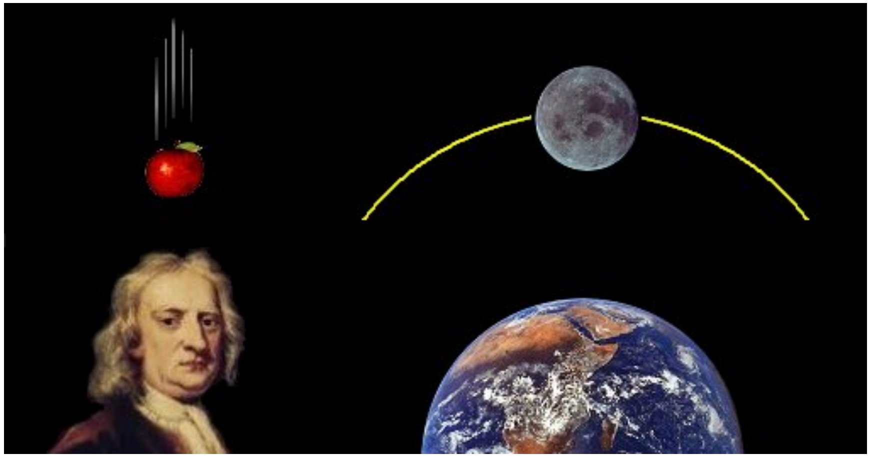
The main ideas

Intermediate vector bosons and their massleness

The Higgs mechanism

Nature: "forces" between particles?

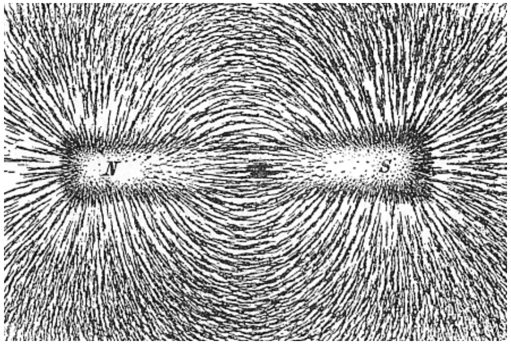
- Gravity == action-at-a distance: separated objects, in the vacuum, act on each other!
- The "charge" of gravity: mass – the substance of matter!



- 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.

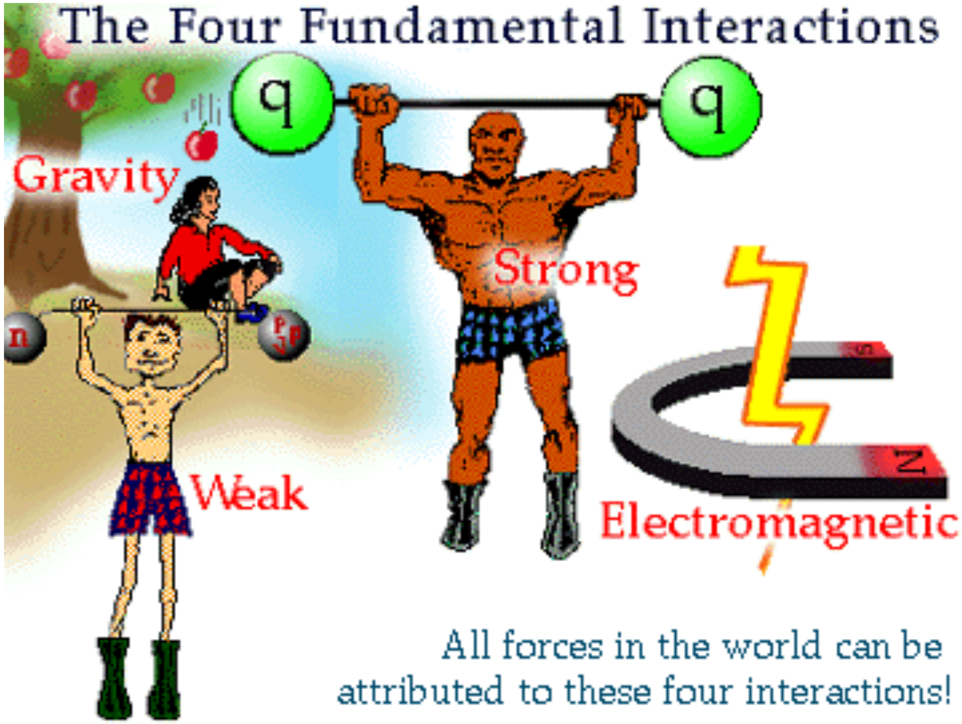


- The incredible discovery: the E/B fields can exist alone – they propagate in waves in the vacuum! Thus are radio, TV and cell-phones made possible.

20th century: two more forces at work

- **But nuclei are held together – against the electrostatic repulsion.** So there is yet another type of force! And it must be very, very strong.
- **And nuclei break up! 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



FOUR???

What makes them different?

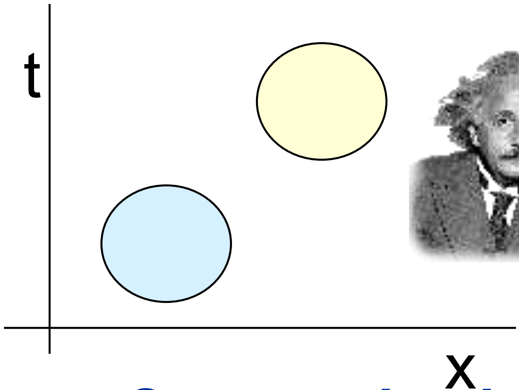
Are all of them "needed"?

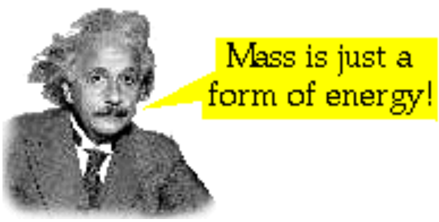
Why not just one?

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

20^{th} century physics: quantum mechanics and relativity

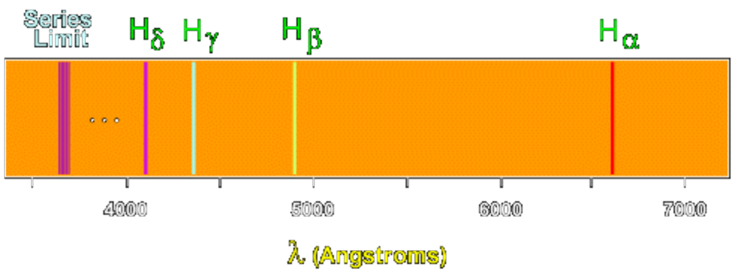
- **Relativity: action can only travel at speed c**
  - Localization





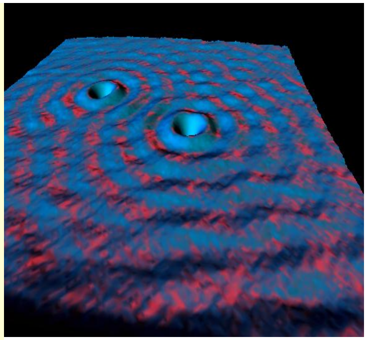
  - Communication between space-time points only as long as within light-cone
- Thus: operators (that finally yield obser-vables) are a function of x,t; i.e. they are fields

- **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



Quantum mechanics + Relativity

- **A system is described by a wavefunction $\psi(x,t)$**
  - Wavefunction: a complex number
    - Probability ~ $|\psi(x,t)|^2$
  - Changing the phase of the wavefunction by some angle ω, changes nothing:
    - $\psi(x,t) \rightarrow \psi(x,t)e^{i\omega}$ still means $|\psi(x,t)e^{i\omega}|^2=|\psi(x,t)|^2$
  - We are thus free to select this phase freely. [As long as it is the same phase everywhere…]
- **Relativity: we should, in principle, be able to do locally, i.e. $\omega \rightarrow \omega(x)$!!!**
  - For it takes a while to communicate to other points that we have changed this phase!

Quantum Electrodynamics (I)

- **The "derivation" of electromagnetism:**
  - e^+e^- interactions: spin-1/2 fields. Dirac Lagrangian:

$$L = \bar{\psi}\left(i\gamma^{\mu}\frac{\partial}{\partial x^{\mu}} - m\right)\psi = \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi$$

  - It is NOT invariant under "rotations in U(1)", i.e. under $\psi(x) \rightarrow \psi(x)\, e^{iq\theta(x)}$…
    - because of the derivative
  - Insist on invariance! So restore it.
  - Requires adding a field $A_{\mu}(x)$ that cancels derivatives, i.e.

$$L = \bar{\psi}\left[i\gamma^{\mu}\left(\partial_{\mu} + iqA_{\mu}\right) - m\right]\psi; \quad A_{\mu} \rightarrow A_{\mu} - \partial_{\mu}\theta$$

Quantum Electrodynamics (II)

- **The fields A and ψ now interact:**

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

  - **Which is precisely the interaction term in the Maxwell Lagrangian:**

$$L = -\frac{1}{16\pi}F^{\mu\nu}F_{\mu\nu} - J^{\mu}A_{\mu} \quad (\text{with } J^{\mu} = q\bar{\psi}\gamma^{\mu}\psi)$$

  - **Thus: matter-A-matter interaction with Force Law:**

$$\vec{F} = q\left(-\vec{\nabla}A^{0} + \frac{\partial\vec{A}}{\partial t}\right) + q\vec{v}\times\left(\vec{\nabla}\times\vec{A}\right)$$

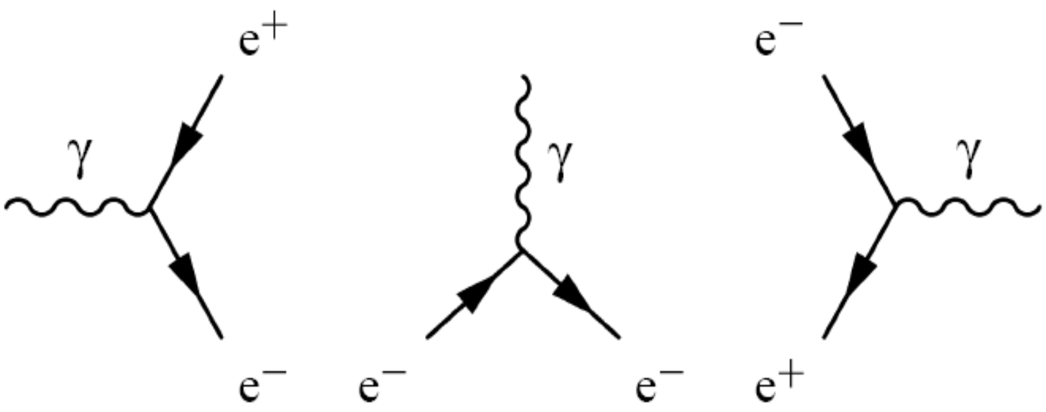
- **"Discovery" of electro-magnetism (!) from the demand that the phase can be set locally**

Quantum Electrodynamics (III)

- **The interaction:**

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

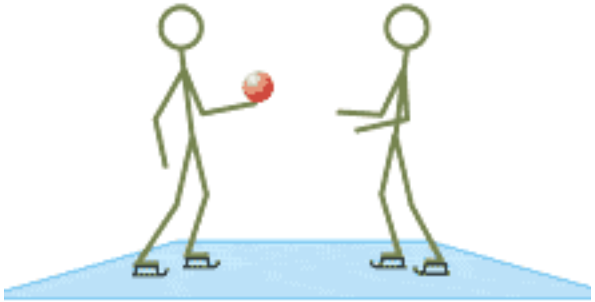
- **And the quantum excitation of the A field will be particles (photons!)**



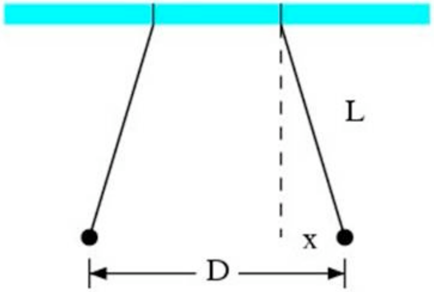
Quantum Field Theory

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

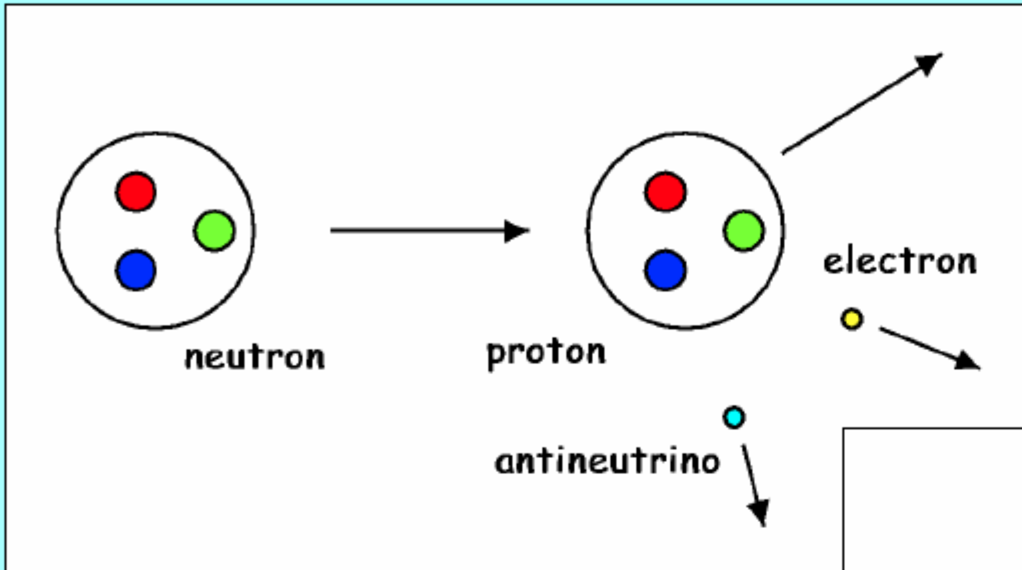
$$L_{\text{int}} = -q\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$



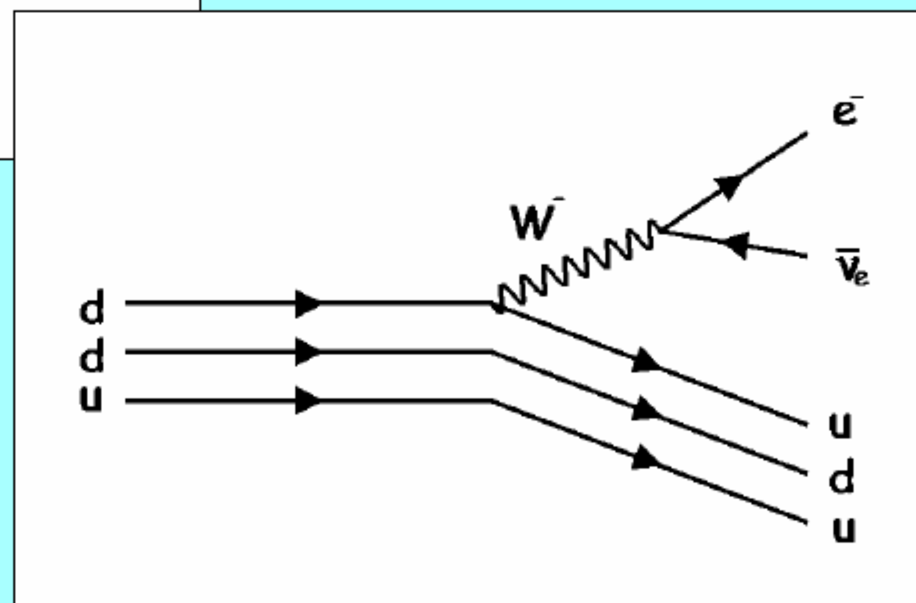
FORCE IS THE EXCHANGE OF PARTICLES!



Weak interaction



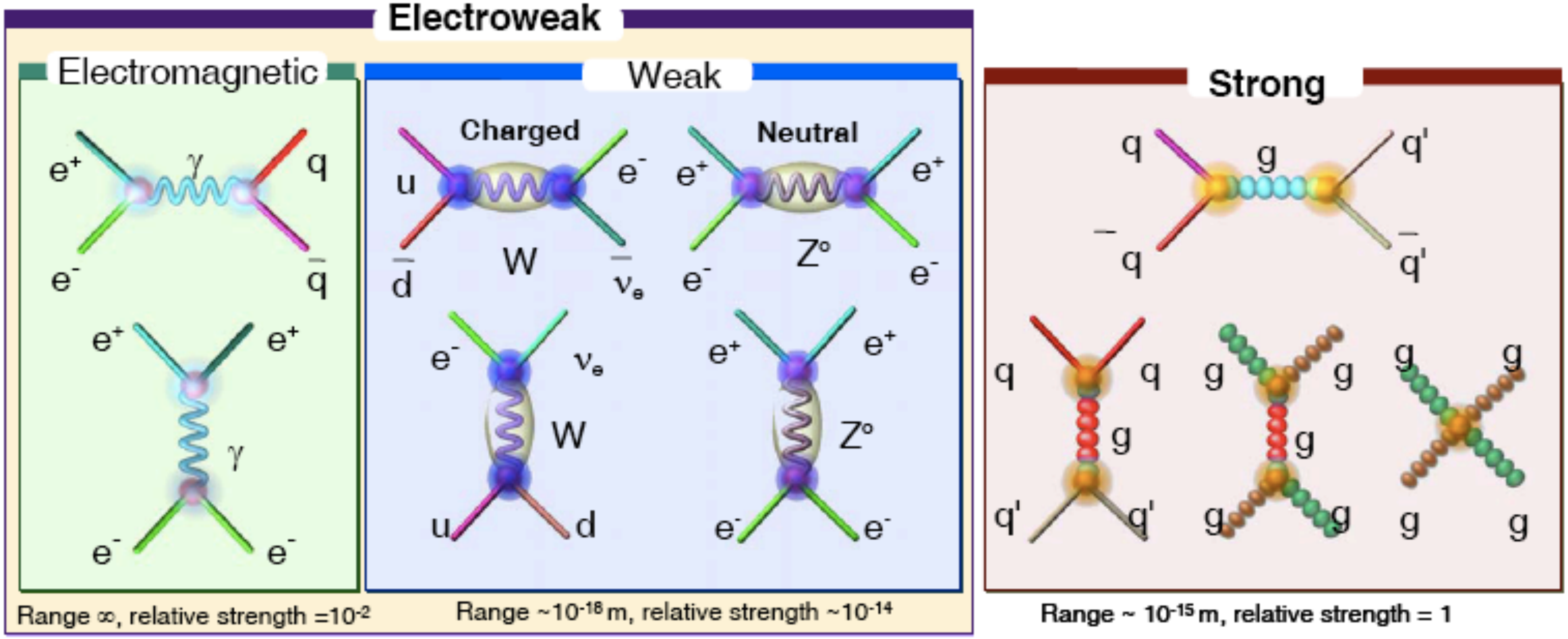
Beta decay $n \rightarrow p + e^{-} + \bar{\nu}_e$



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)**



- **Forces: interactions, so need (a) charge(s). Which should be conserved. Which implies some new symmetry…**
- **Standard Model: internal symmetry (SU(3)xSU(2)xU(1))**

Invariance of the world under phase changes in *SU(2)⊗U(1)* results in four bosons, $W^{\pm}$, Z, γ

Thus the unification of Electromagnetism and the Weak interaction into the "Electroweak"

Except that it gets a basic issue wrong.

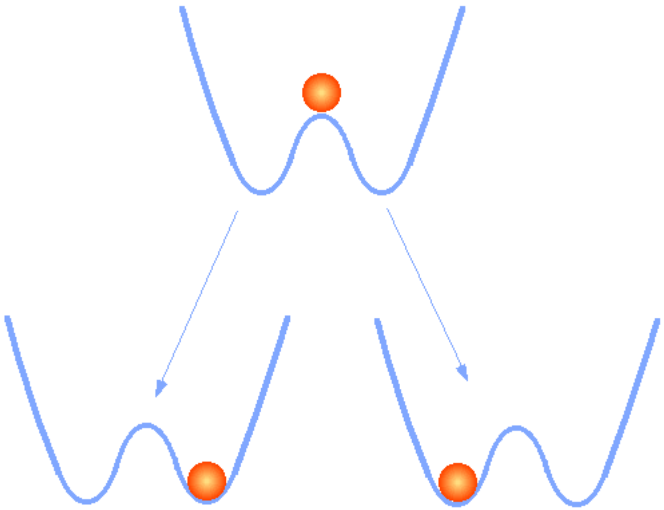
Because the range of the weak force is very small.

Which means the carrier must be massive.

Very massive!

Standard Model & Symmetry Breaking

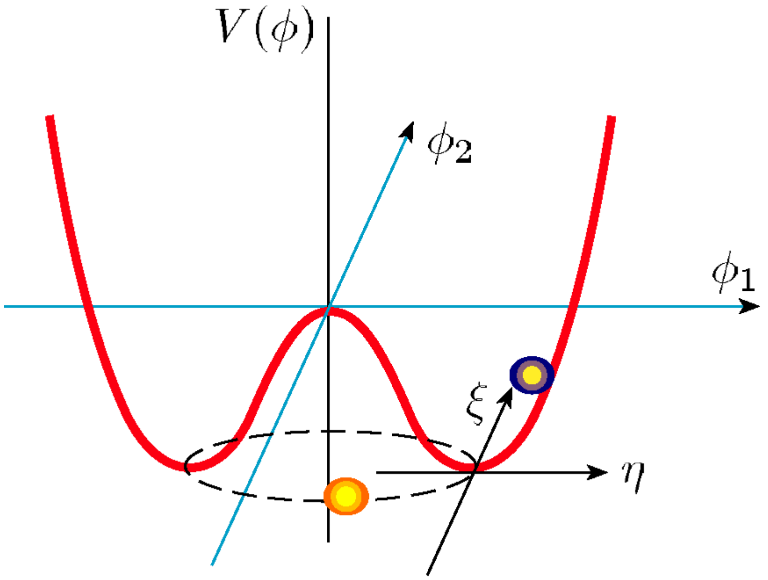
- **Yet, the Standard Model symmetry (SU(2)xU(1)) MUST be broken:**
  - $M(\gamma)=0$; $M(W)=80$ GeV/c^2; $M(Z)=90$ GeV/c^2
    - And we cannot add mass terms by hand (gauge invariance)
  - How can we end up with an asymmetric world when the laws are symmetric?
- **Take potential with two minima**
  - "Laws of nature" (potential→Lagrangian →equations of motion) right-left symmetric
  - Equilibrium state is not
  - Particle chooses one of the two minima → left-right symmetry is "broken"



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

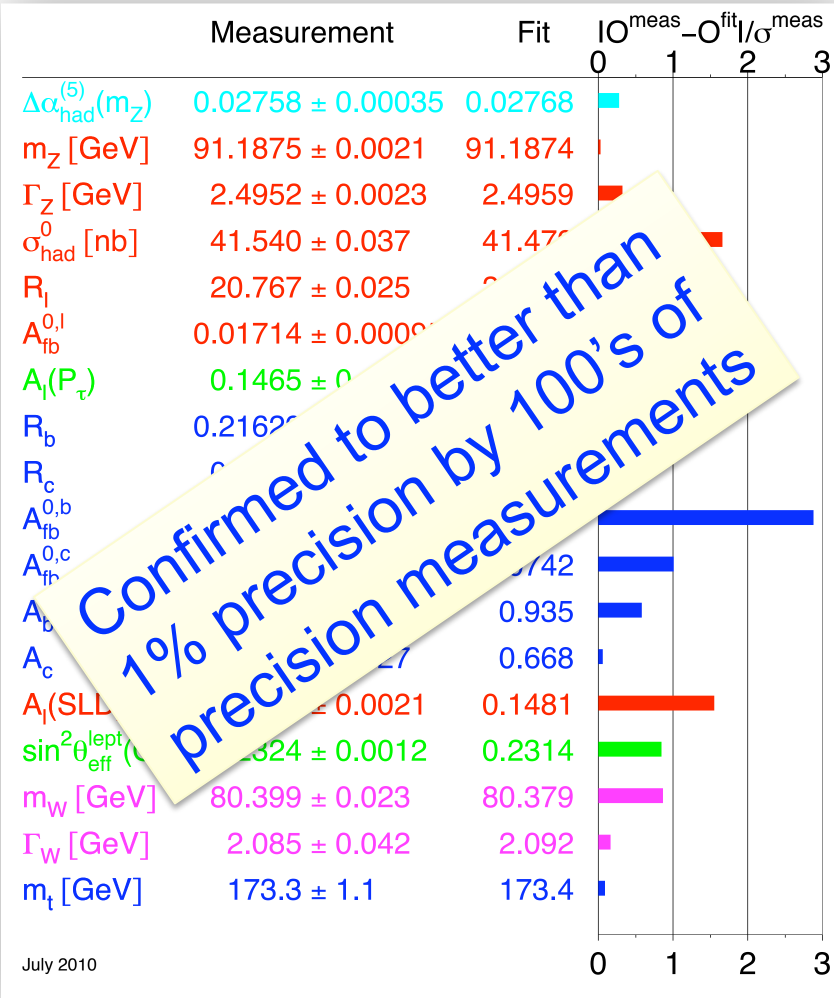
The Higgs Mechanism

- With two independent (complex) fields
- Two "motions" in the potential
  - One on the plane; "massless" mode that is lost (once a direction is chosen). The degree of freedom appears as additional degree of freedom of the 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!

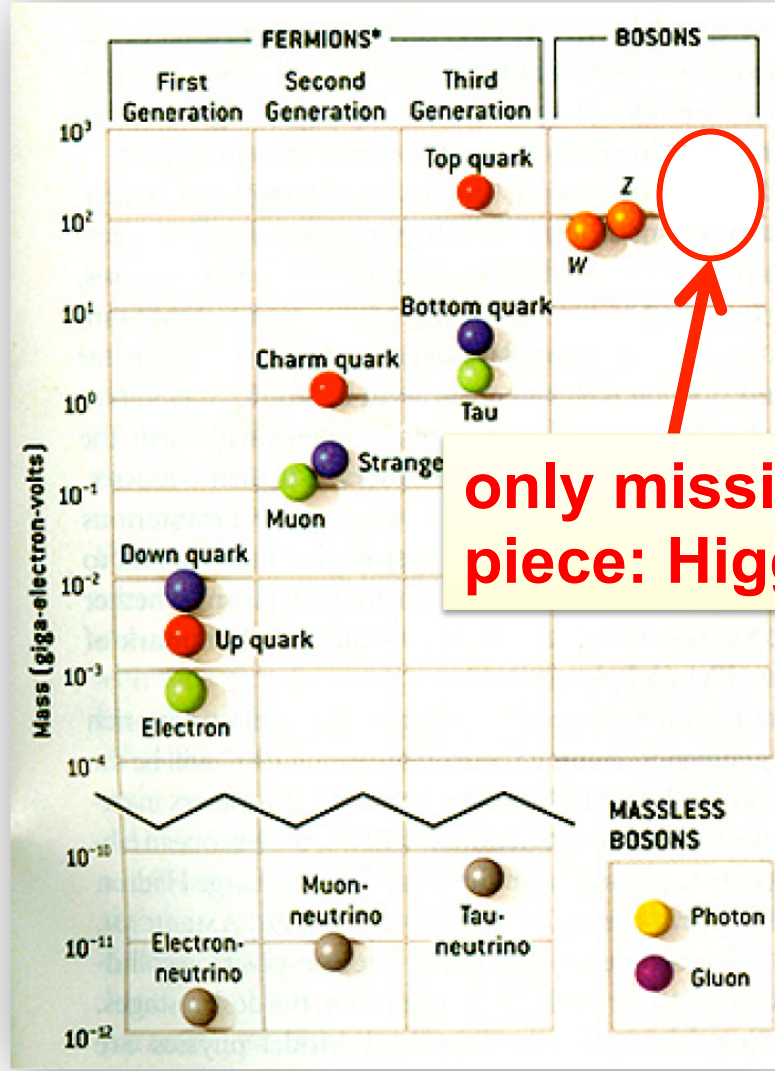


Thus were the W/Z masses born in theory; and discovered (at the right value) @ CERN in 1984.

The Standard Model up until 2012



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



only missing piece: Higgs

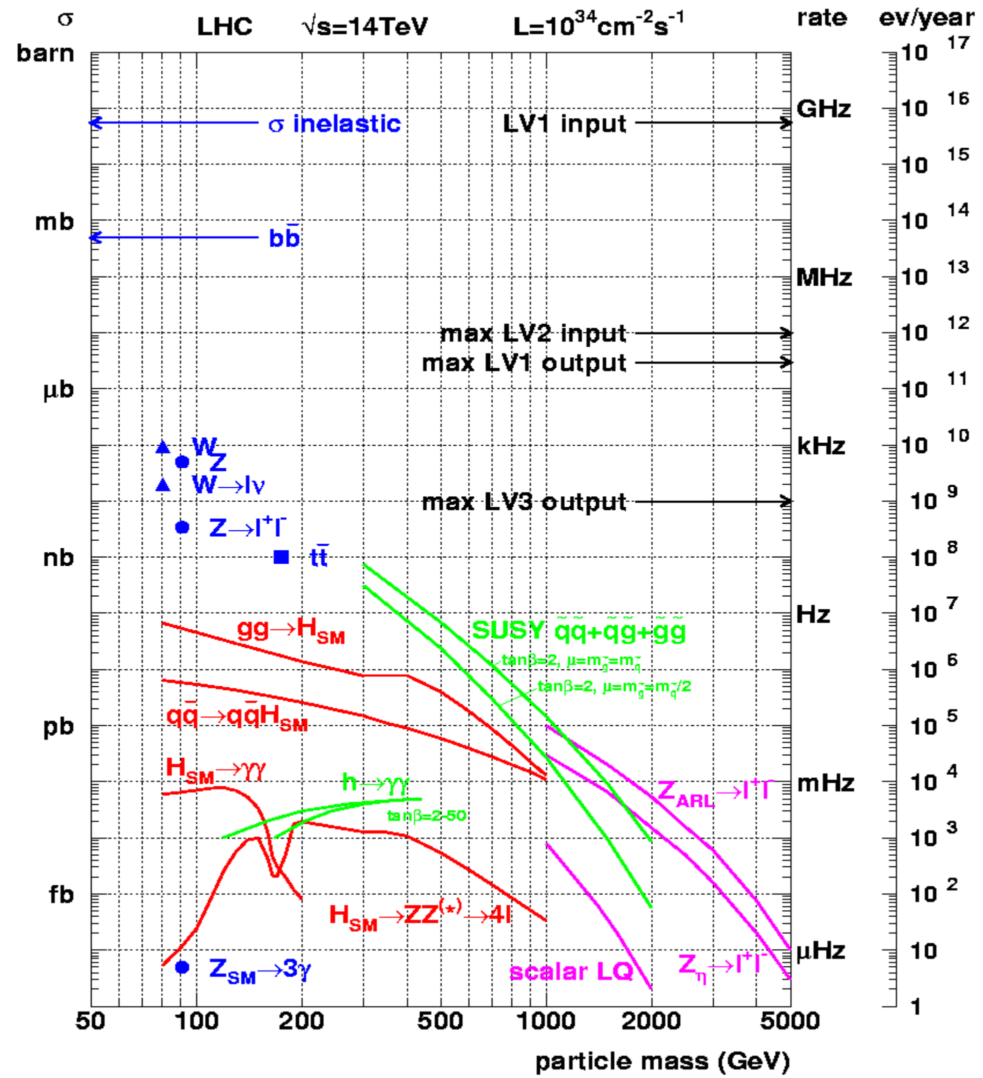
LHC($t_0+\Delta t$=2.5yrs):

Foundations established
a “tour de force” of SM measurements

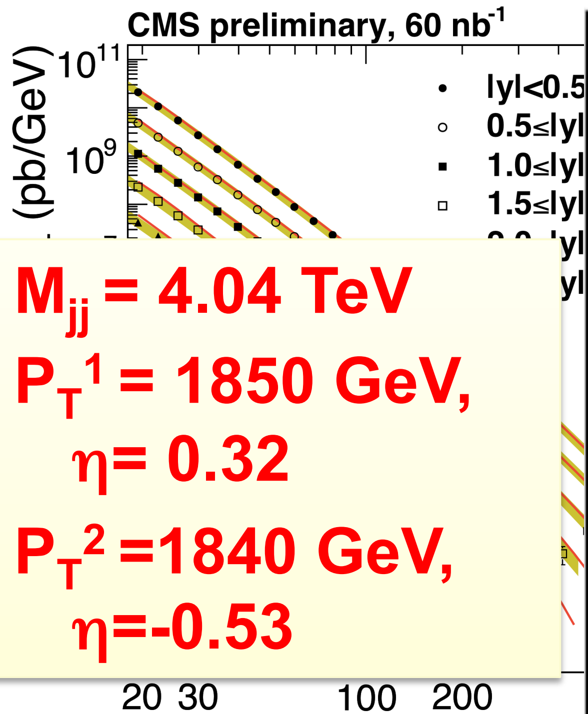
and, of course,
the hunt for the Higgs boson…

The 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'



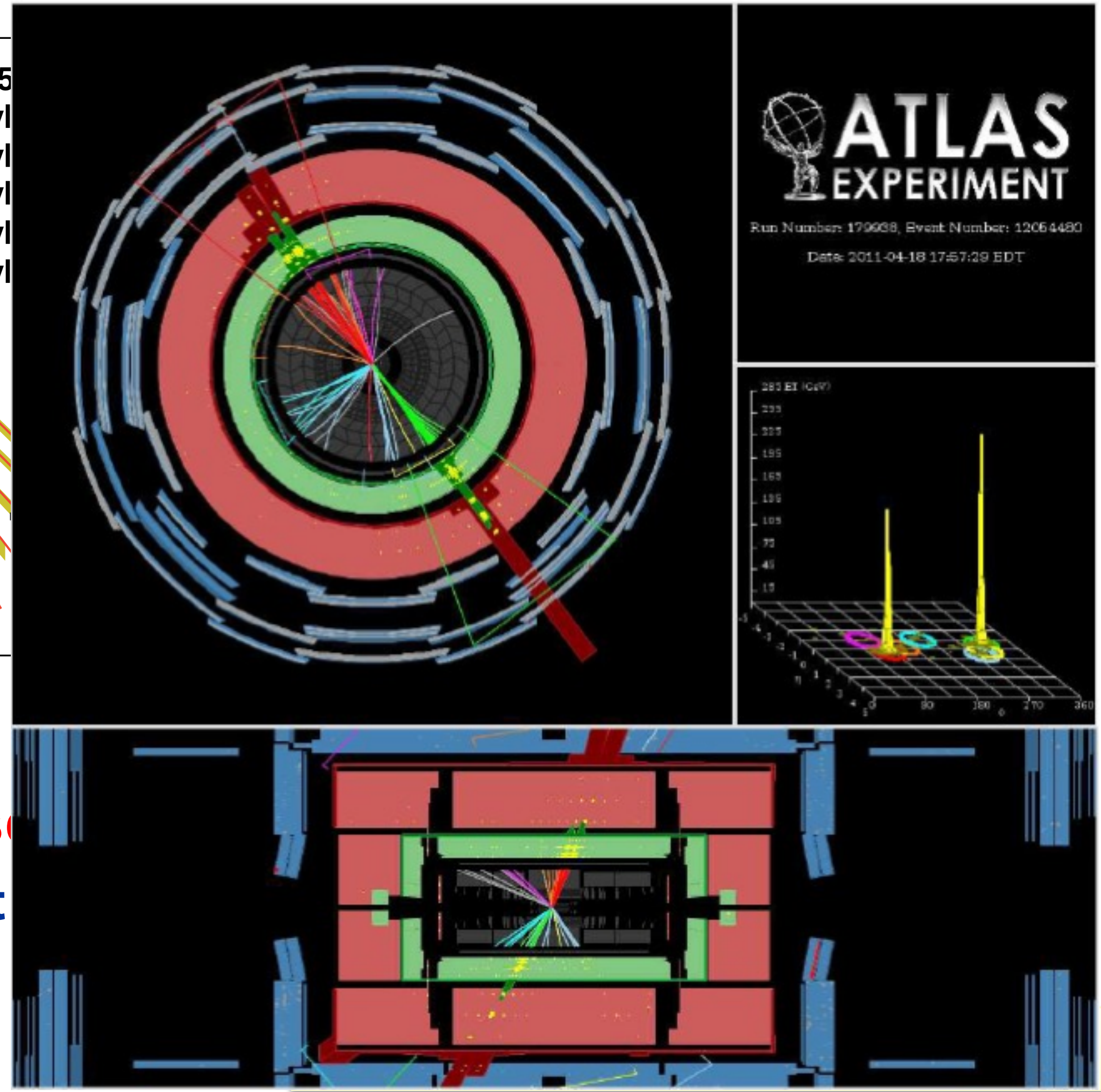
Jets



M_{jj} = 4.04 TeV

P_T^1 = 1850 GeV, η= 0.32

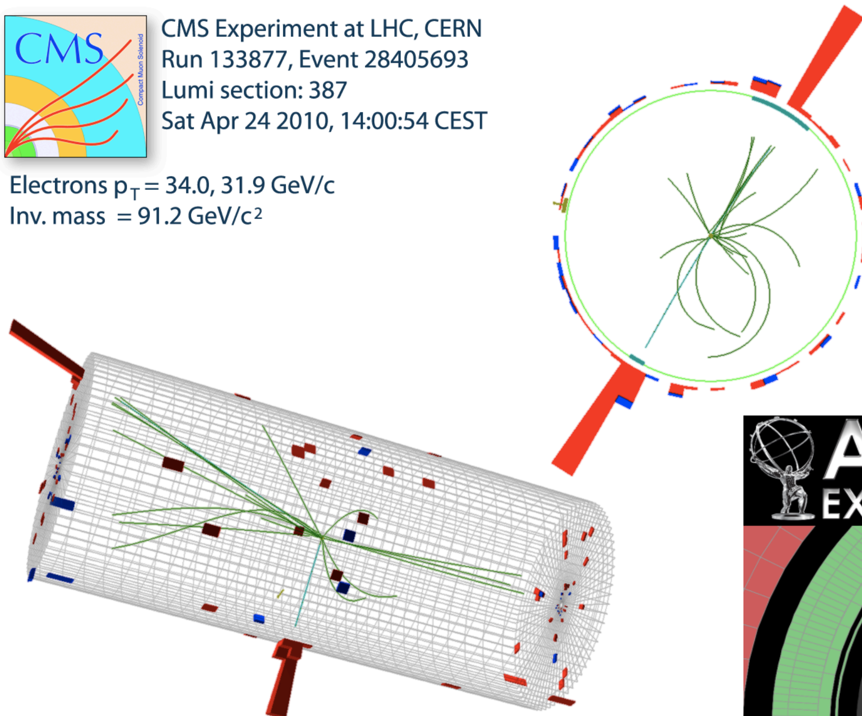
P_T^2 =1840 GeV, η=-0.53



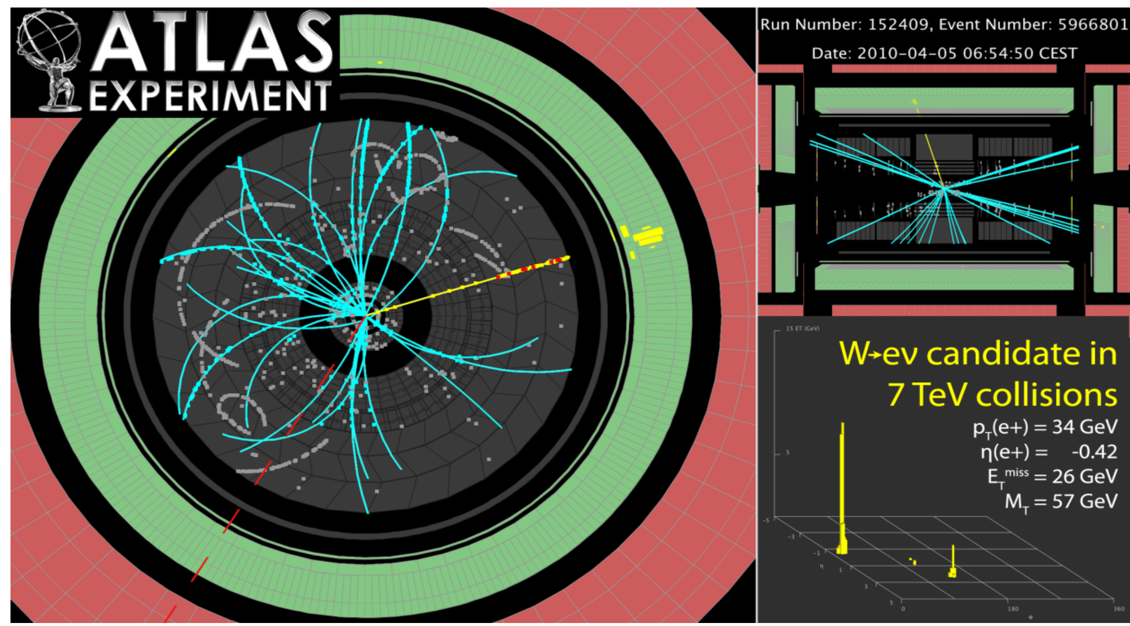
- To probe the hard s
  - The hard scatter: jet

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

Z → electron + positron

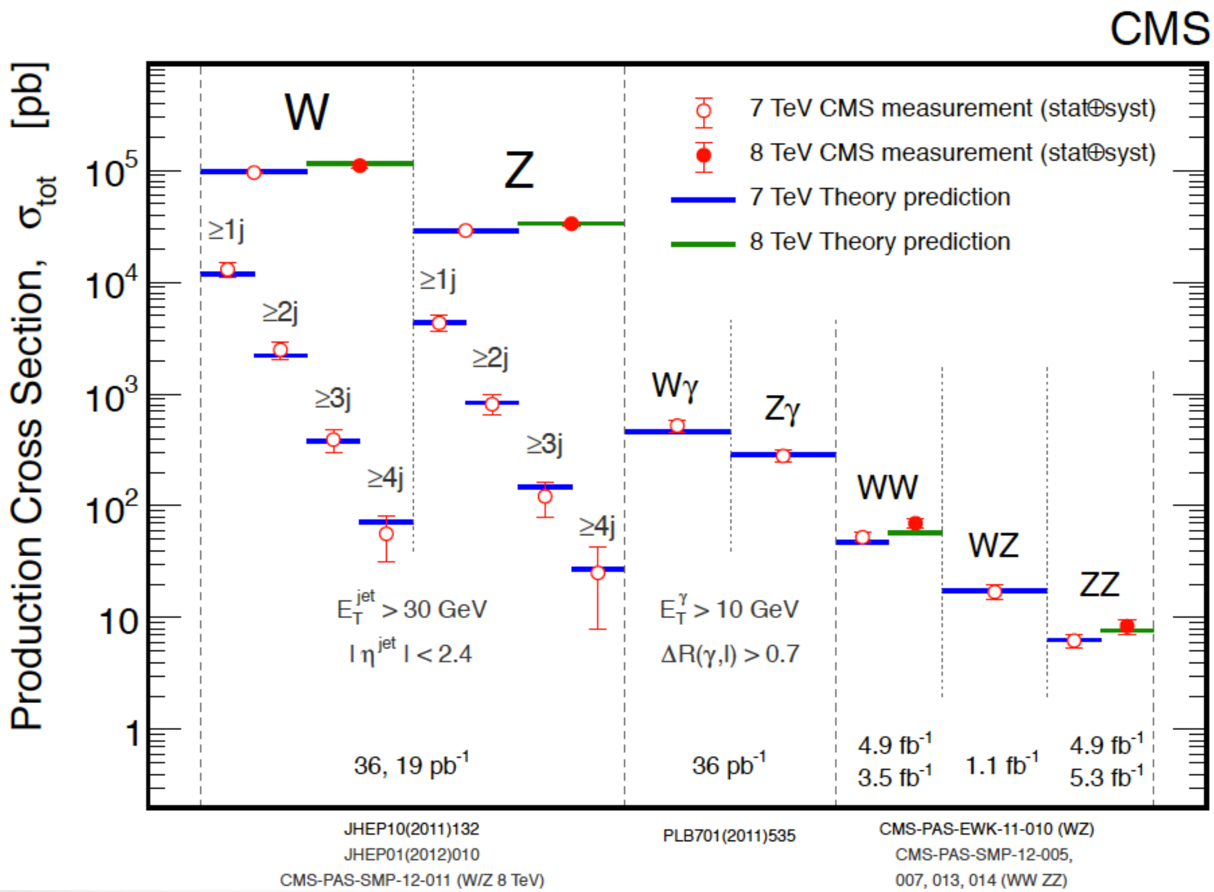


W → electron + neutrino



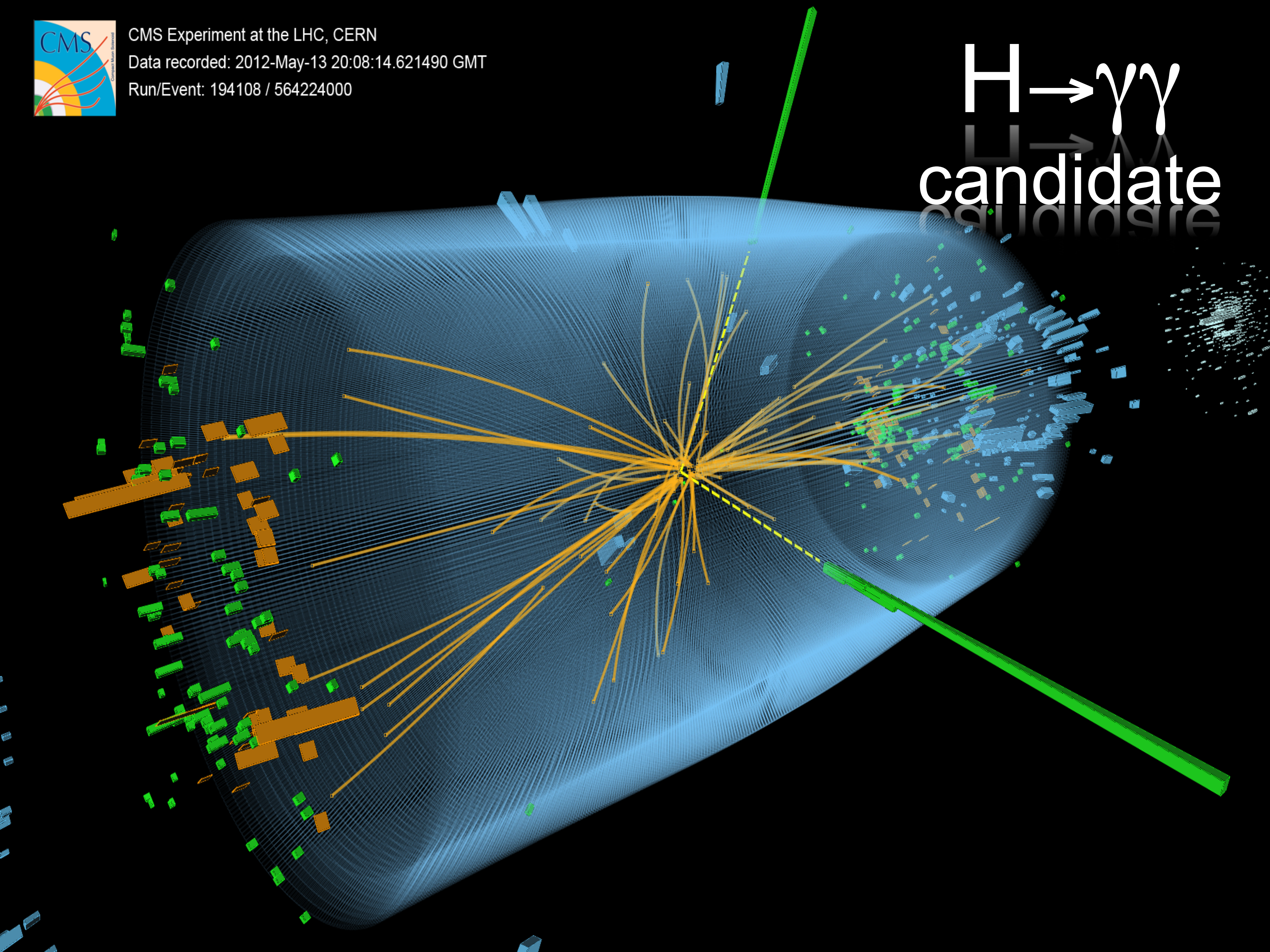
Standard model in pp collisions @ 7 TeV

- **Understanding of SM processes at level of Tevatron experiments – and beyond.**
  - **Let the search begin.**



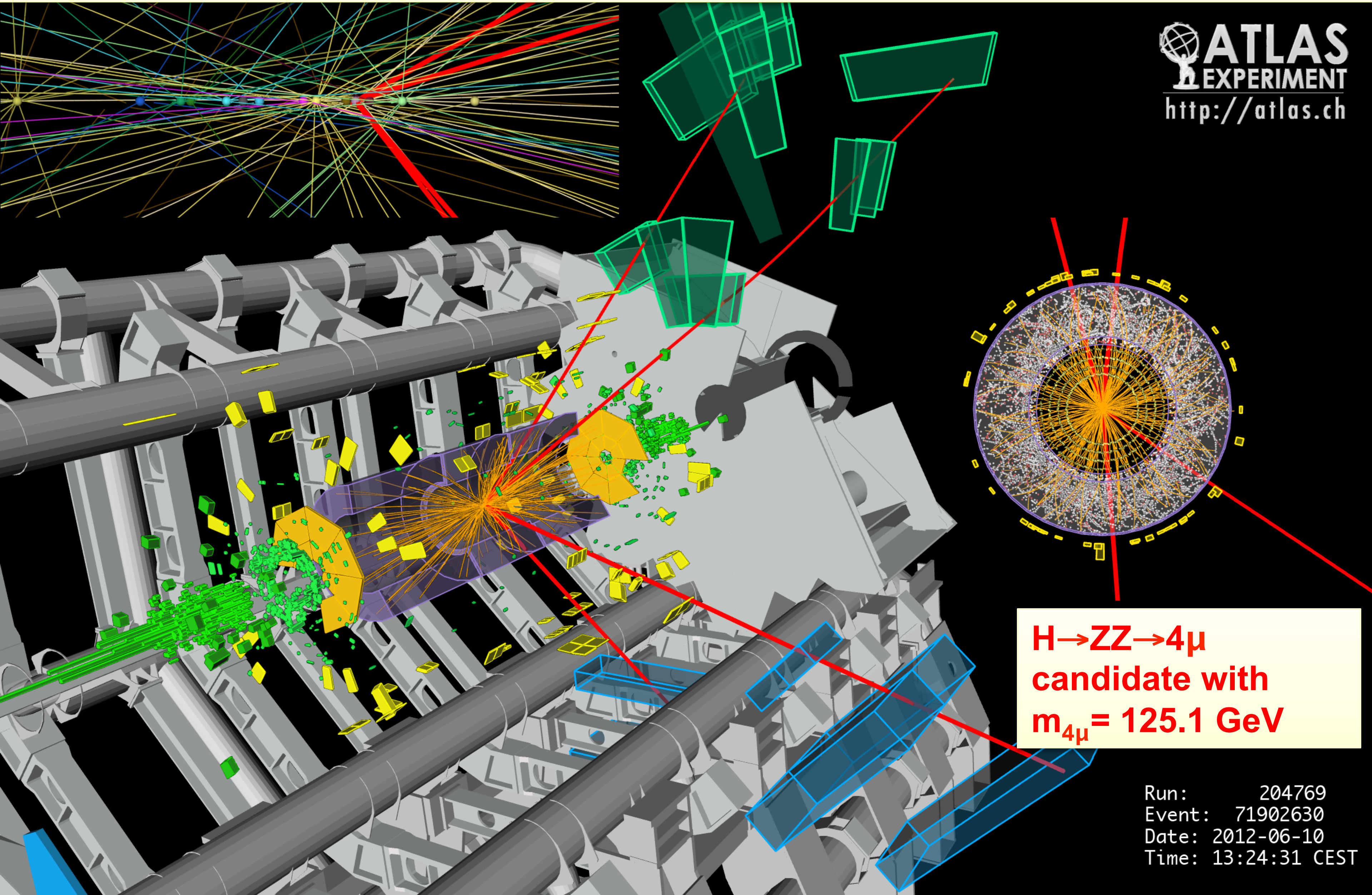
What about the Higgs boson?

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

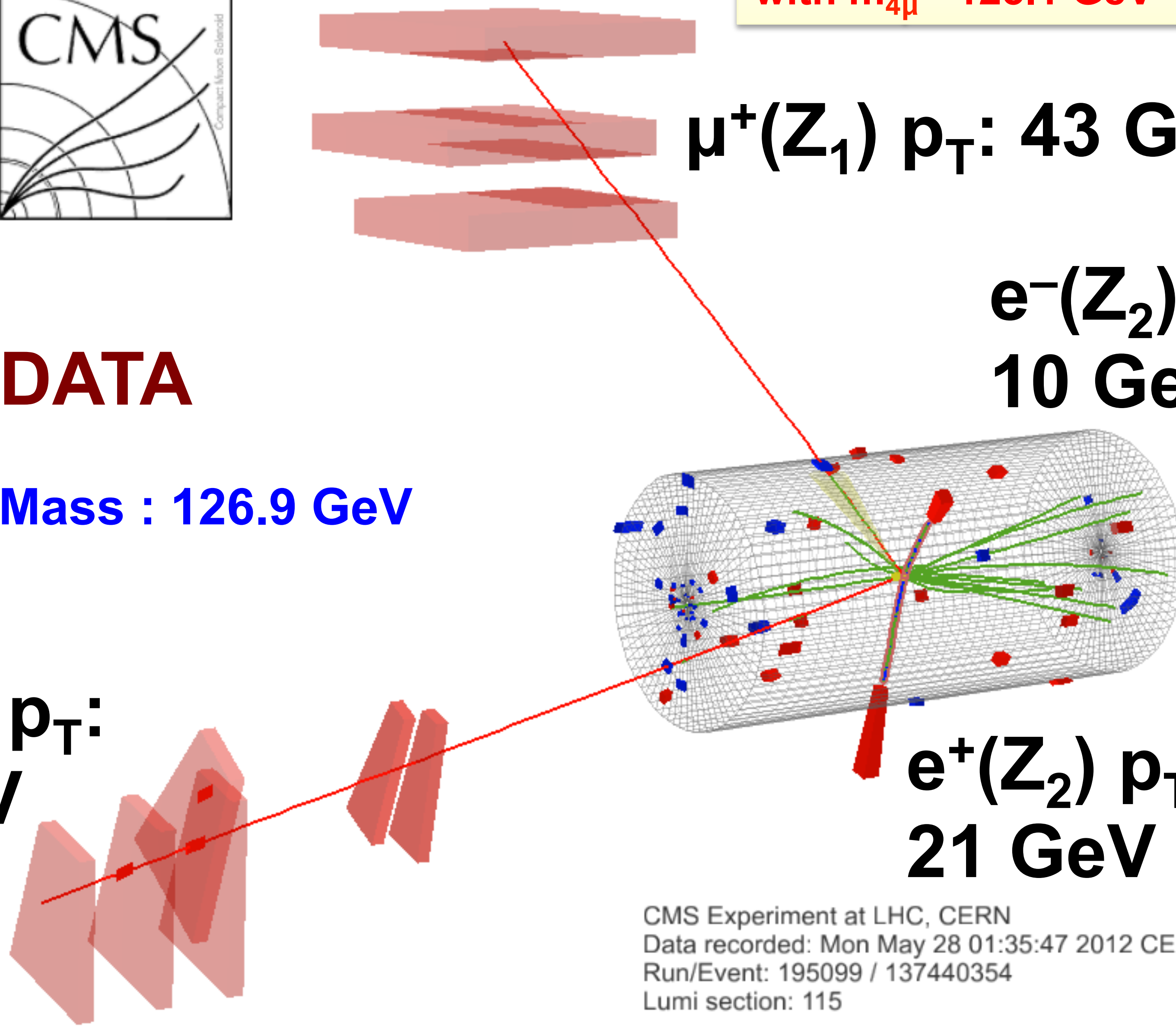
15 reconstructed vertices



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

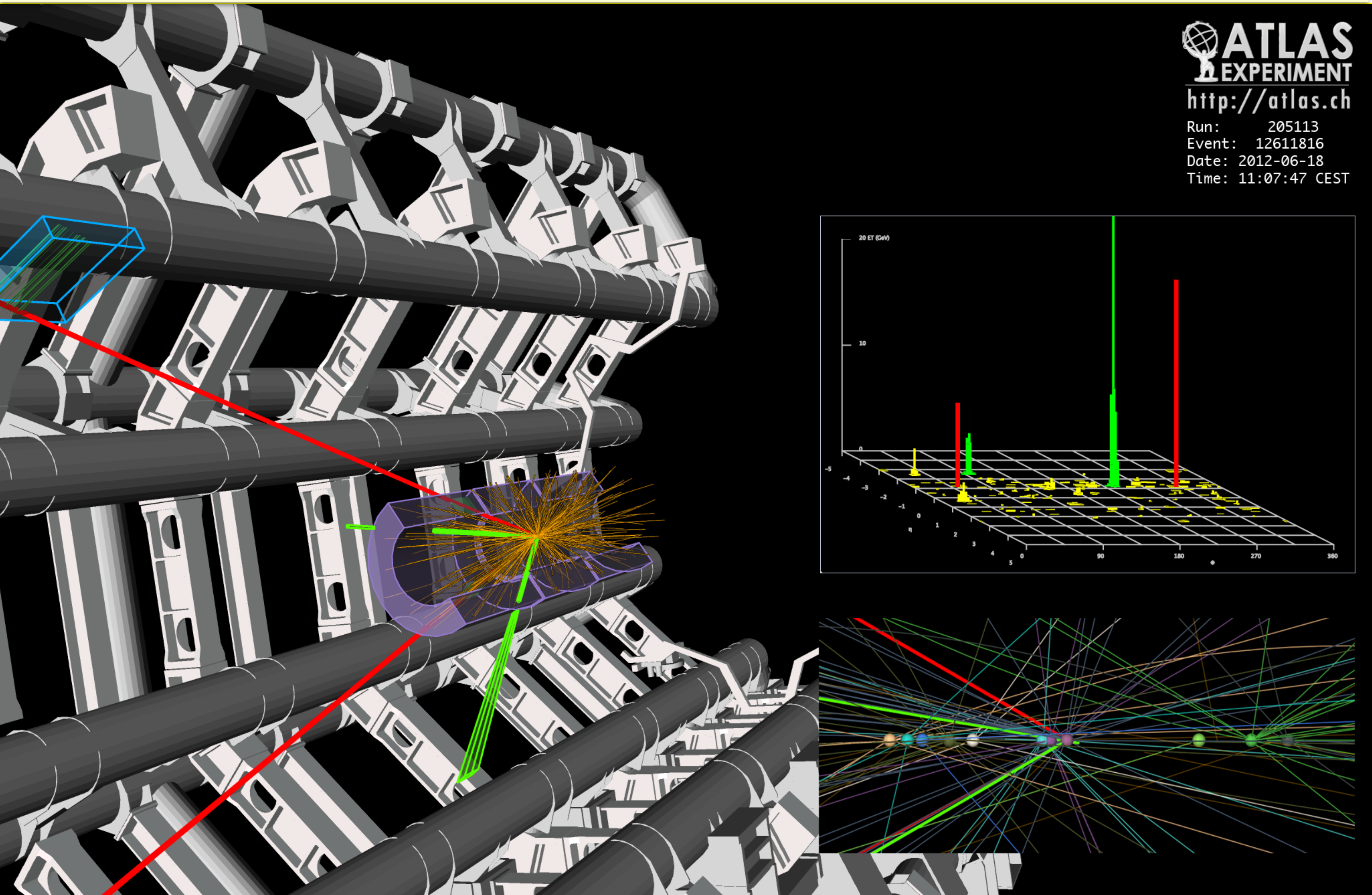
8 TeV DATA

4-lepton Mass : 126.9 GeV



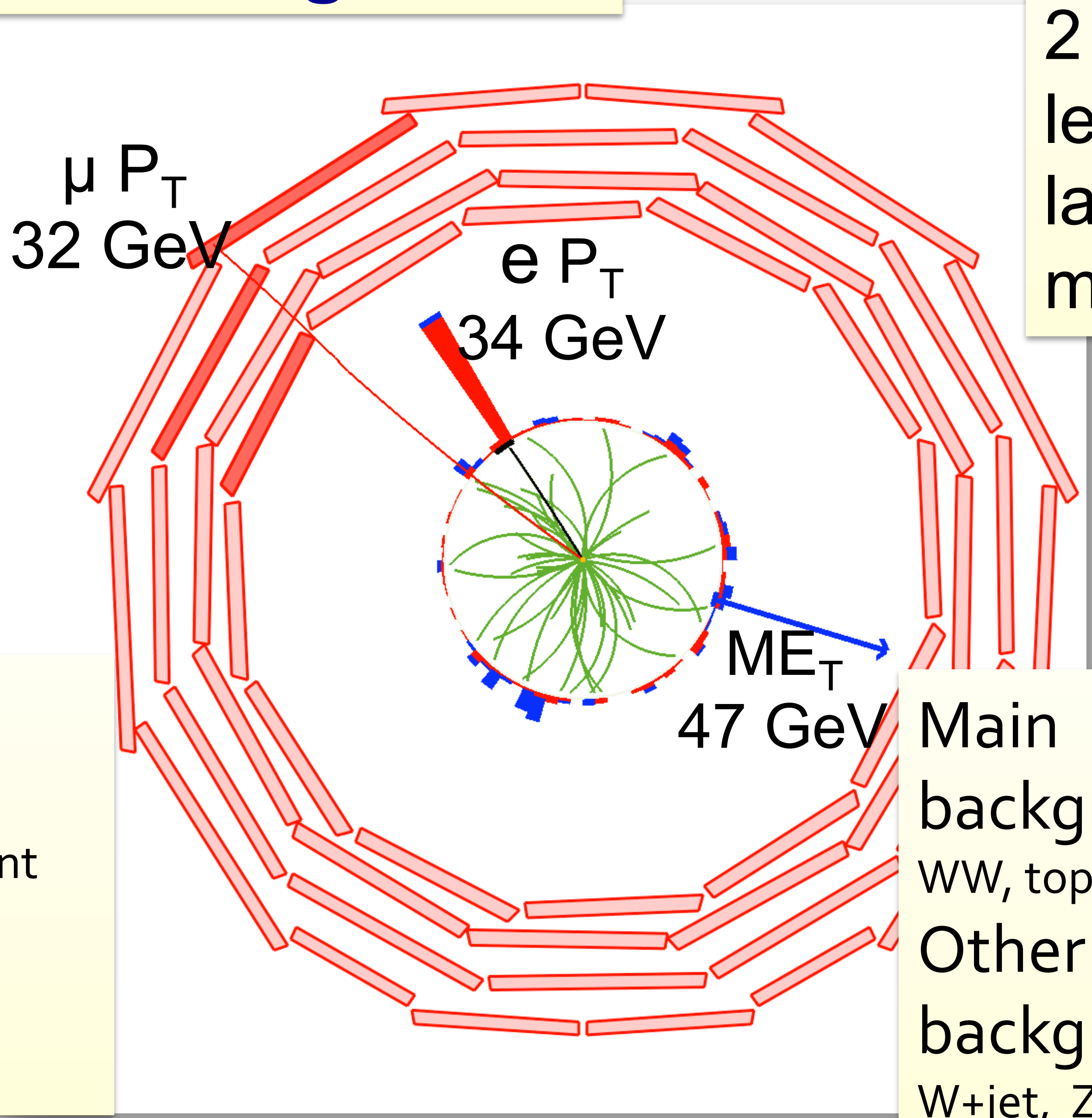
$p_T(e,e,\mu,\mu)$: 19, 76, 20, 8 GeV; m_{e+e-} = 88 GeV, $m_{\mu+\mu-}$ = 20 GeV

12 reconstructed vertices



H→WW→lνl'ν signature

Signature:
2 high p_T leptons
large missing E_T



qq→WW + gg→WW
- Non-resonant

H→WW
- Large BR
- Small Δϕ(ll)

Main backgrounds: WW, top

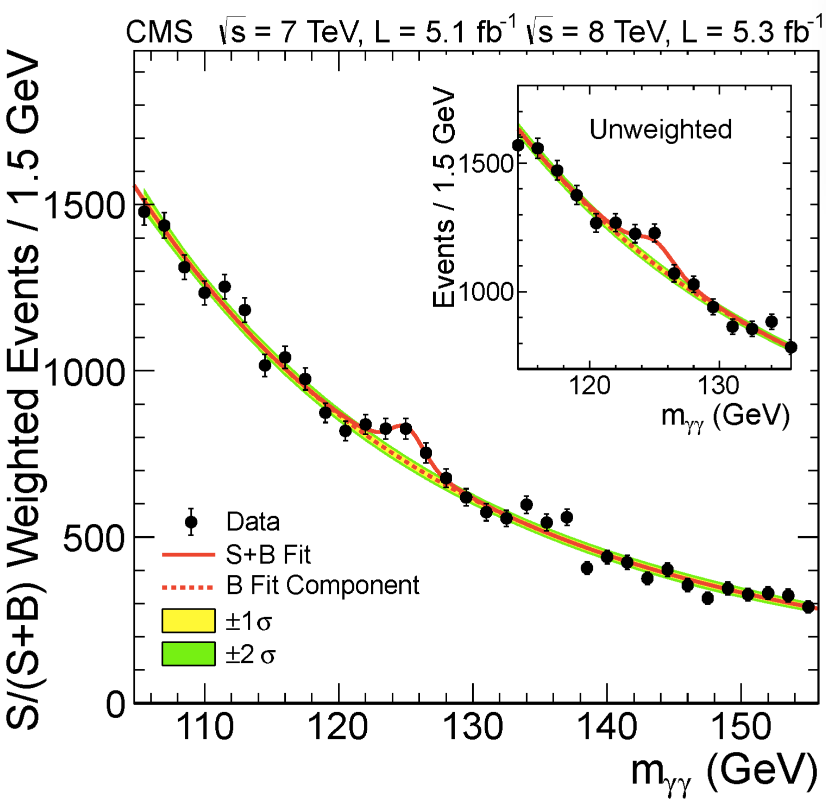
Other backgrounds: W+jet, Z/γ*, WZ, ZZ, Wγ

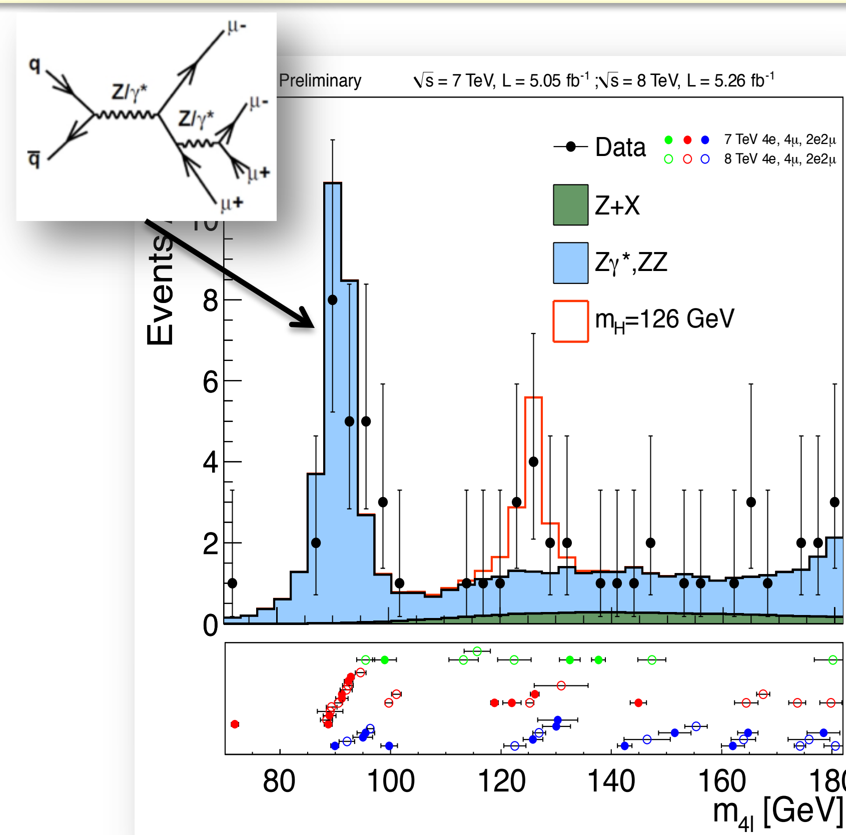
Are these events "significant"?

Searches for the SM Higgs boson
Discovery of a new boson

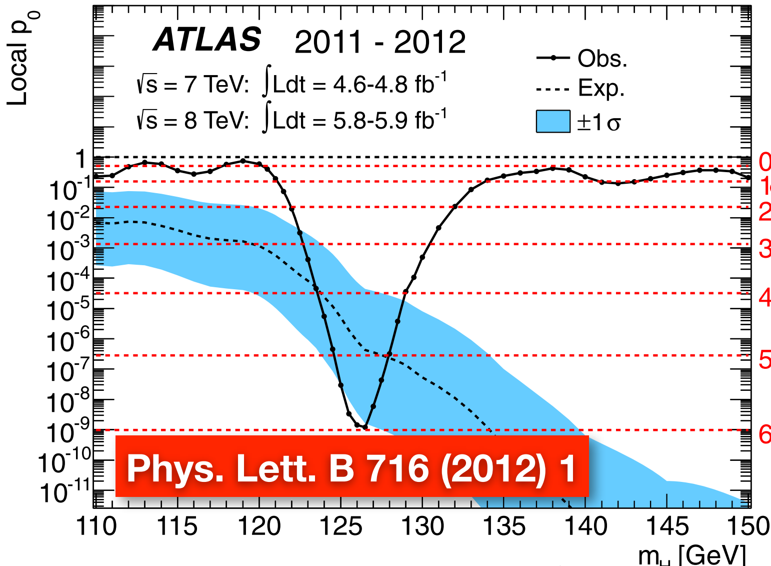
Mass peaks: H(?)→γγ & H(?)→ZZ→4leptons

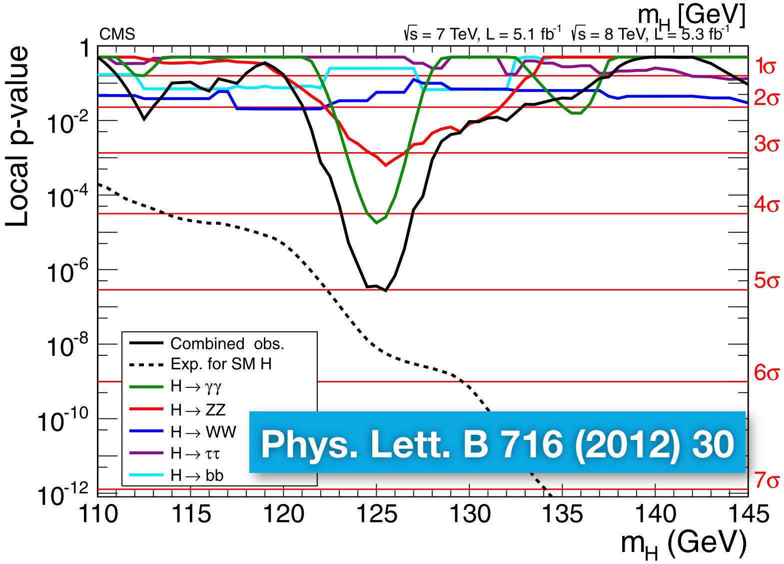
Despite the low branching fraction to the final state, the mass resolution of these two channels enables the siting of a "peak". The ZZ peak has a Z calibration as well(!)

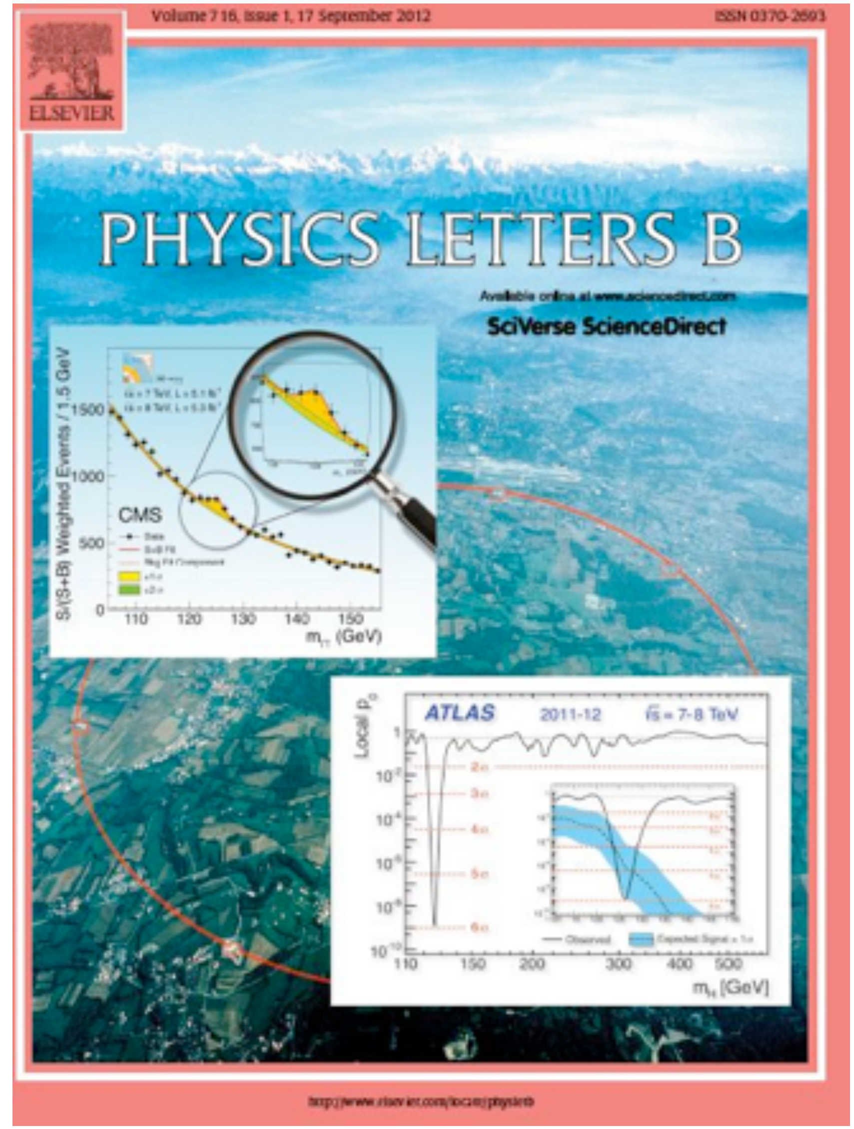




Putting it all together…







And thus was born,
on July 4th 2012,
"a new boson":
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)

So, is it THE Higgs boson?

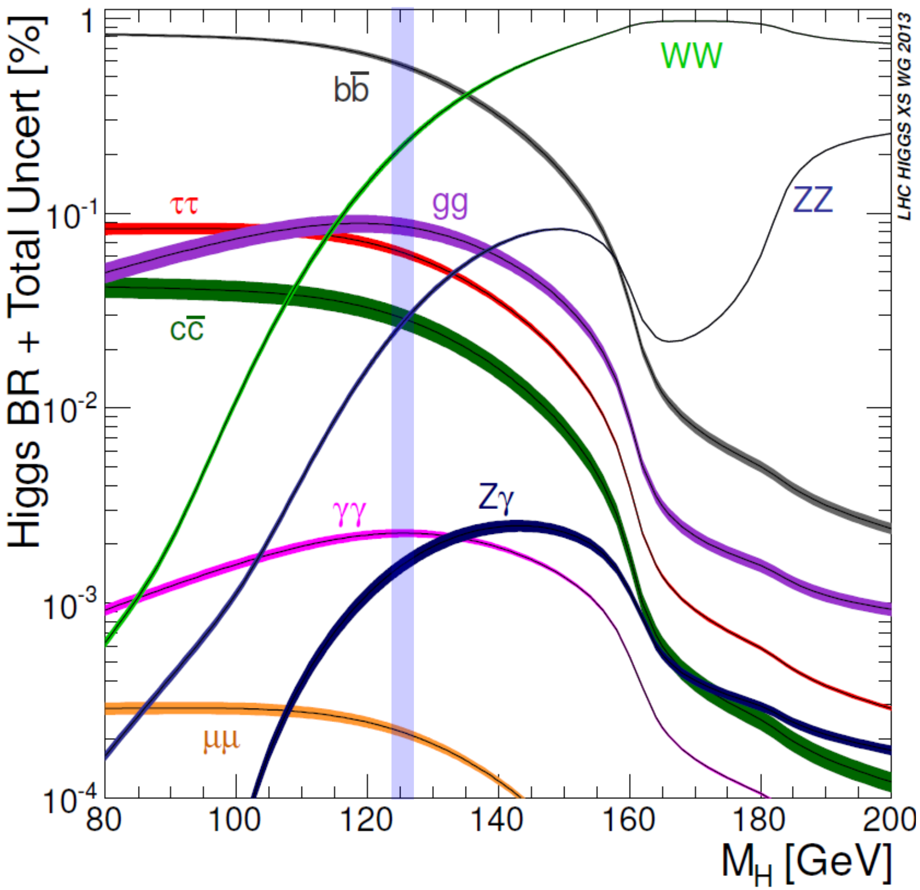
- **Can we call the "new boson" the "Higgs boson"? Let alone a "Standard Model Higgs boson"…**
  - Foremost: it must have spin 0 (to call it a "Higgs boson")
  - Also:
    - neutral CP-even component of complex $SU(2)_L$ doublet with Y=1
    - couplings to SM fermions proportional to masses
- **The "new boson" can have many non-SM properties and still be the Higgs boson of electroweak symmetry breaking:**
  - CP mixture, mixture of two or more weak doublets!
  - Composite!
  - Nonstandard decay to gg or γγ from other colored/charged exotic particles in loops

Does it behave like the Higgs boson?

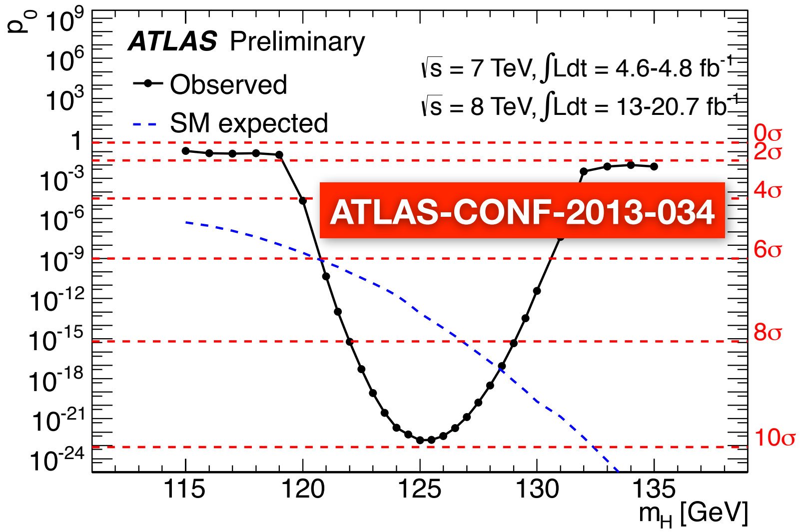
- **Does it couple like a H-boson? (i.e. to mass?)**
  - **Measure couplings to fermions and bosons, and see if they come out right**
- **What is its spin & CP?**

Decay Modes available

	Exp Sig (CMS) @125.7	σ_M/M
• bb	2.2σ	10%
• ττ	2.7σ	10%
• WW	5.1σ	20%
• ZZ	7.1σ	1-2%
• γγ	4.2σ	1-2%

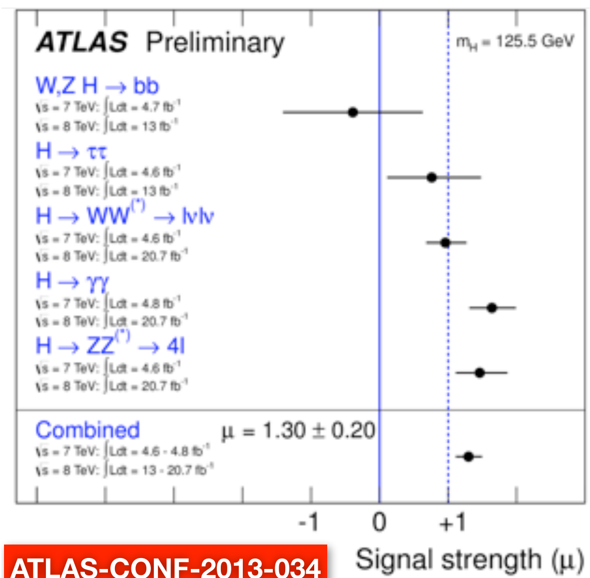


Since the discovery…



	Significance (m_H = 125.7 GeV)		
Combination	Expected (pre-fit)	Expected (post-fit)	Observed
H→ZZ	7.1 σ	7.1 σ	6.7 σ
H→γγ	4.2 σ	3.9 σ	3.2 σ
H→WW	5.6 σ	5.3 σ	3.9 σ
H→bb	2.1 σ	2.2 σ	2.0 σ
H→ττ	2.7 σ	2.6 σ	2.8 σ
H→ττ and H→bb	3.5 σ	3.4 σ	3.4 σ

CMS PAS HIG-13-005



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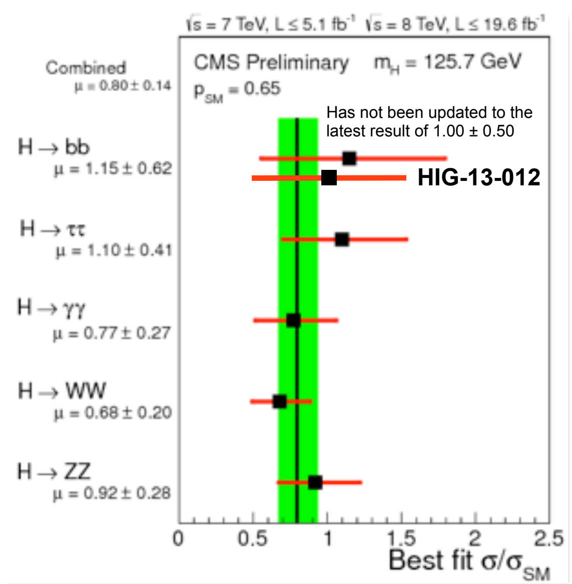
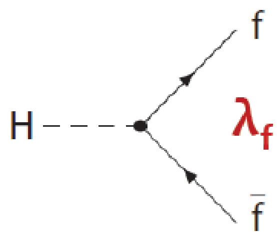
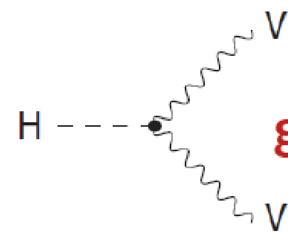


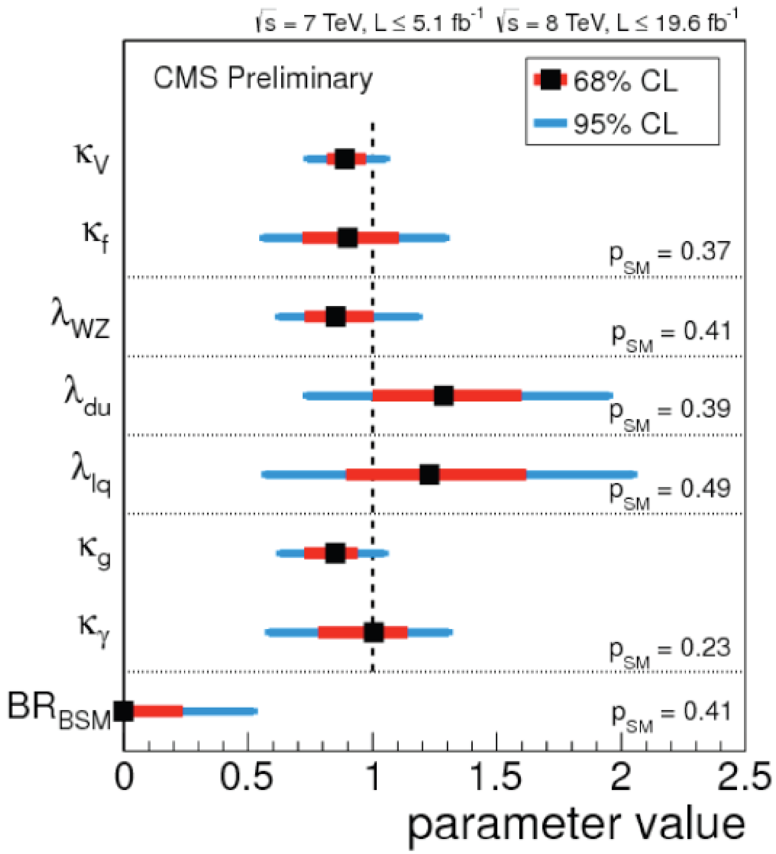
Couplings to particles

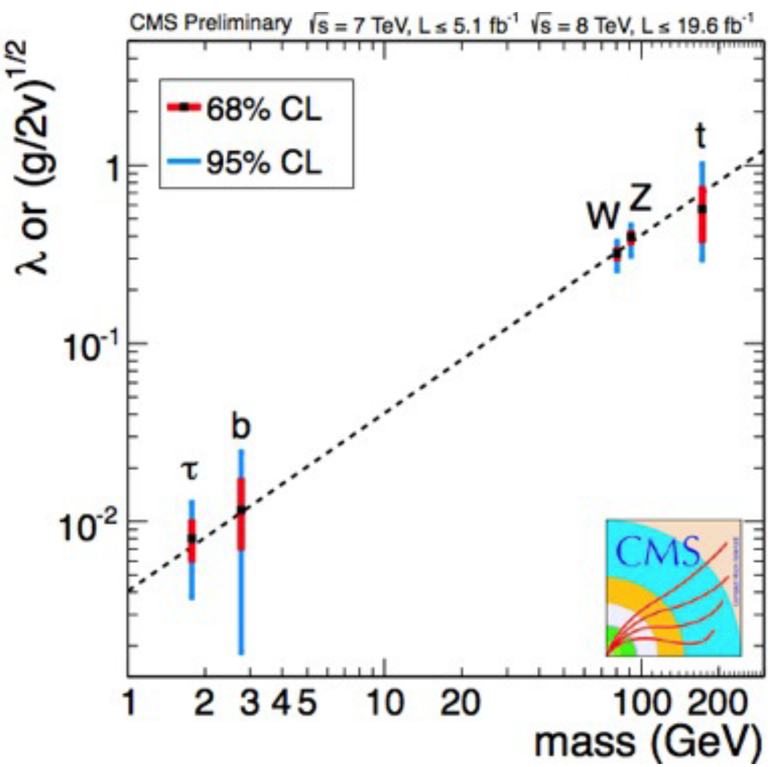


$\lambda_f = m_f / v$

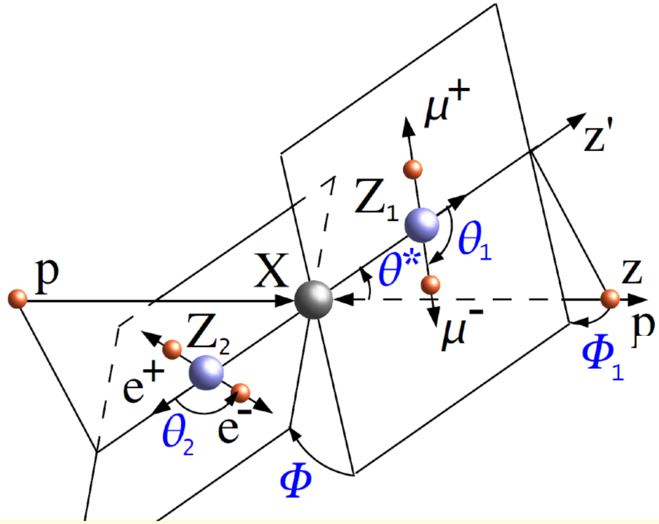


$g_V = 2\, m_V^2 / v$





H→ZZ→4leptons: angular analysis

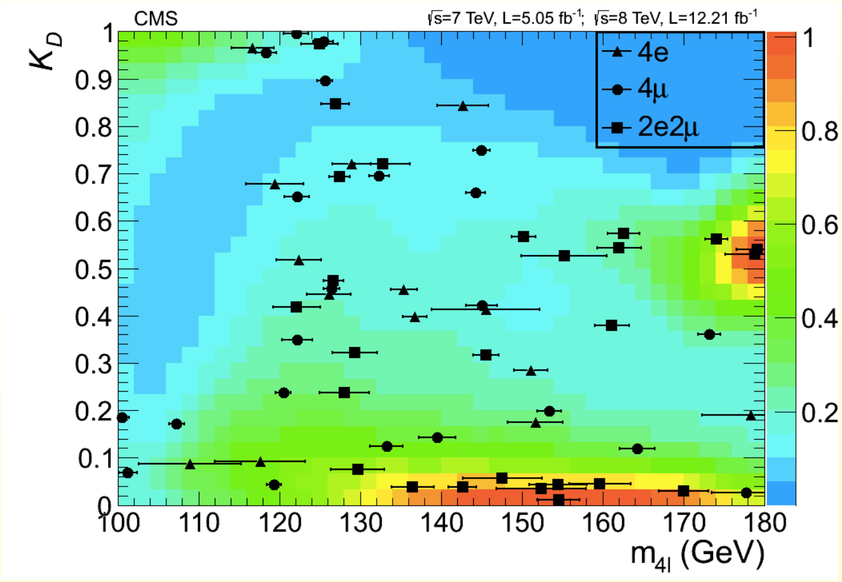


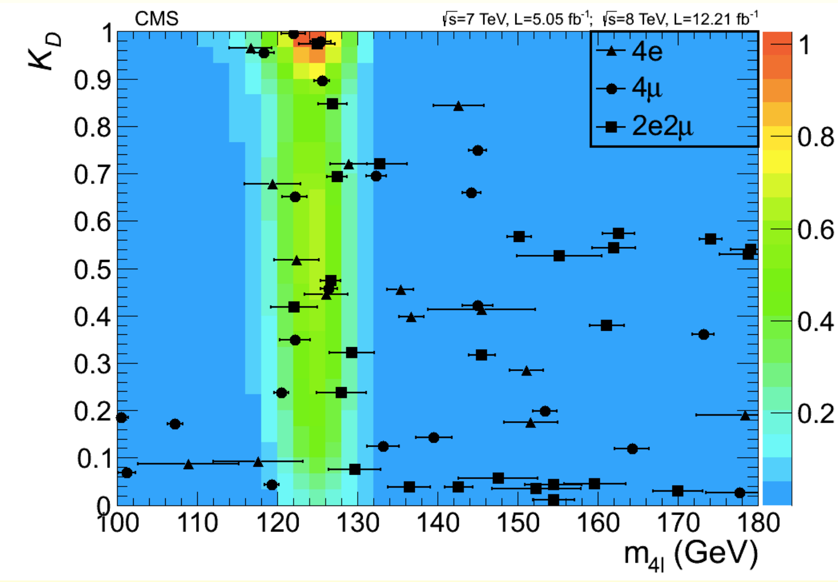
Matrix Element Likelihood Analysis:

uses kinematic inputs for signal to background discrimination

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

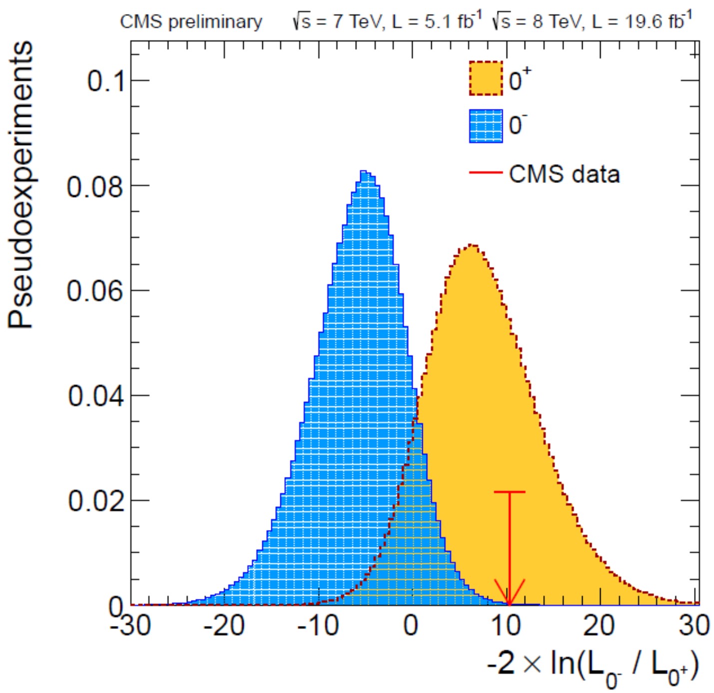
$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$



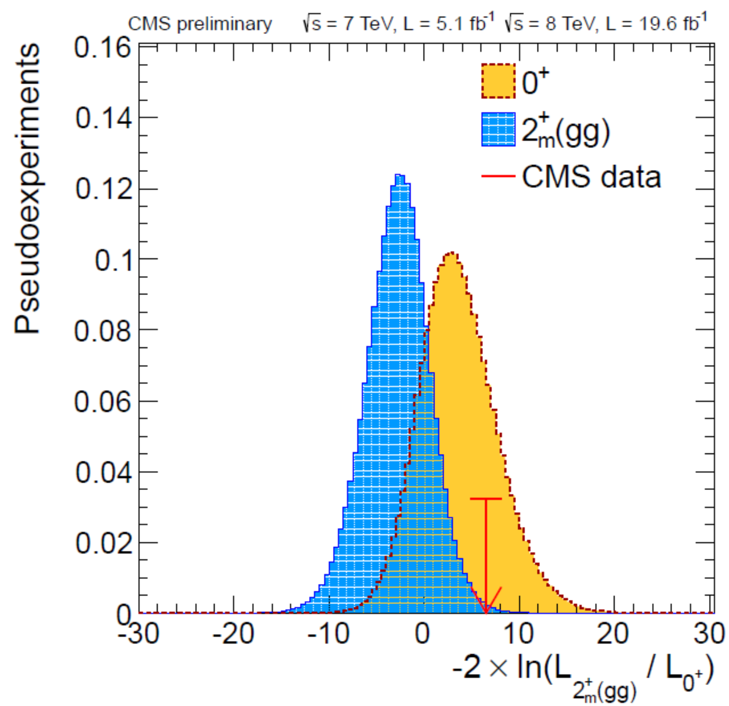


Scalar or pseudoscalar? Spin 2 or 0?

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



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



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

Summary (and where it was – in mass…)

- **So it is a Higgs boson; and in fact one that looks very (as in very) much like the one of the Standard Model**
- **And its mass? That "one unknown parameter"?**

Collaboration	channel	mass (GeV)
ATLAS	$\gamma\gamma$	$126.8 \pm 0.2 \pm 0.7$
CMS	$\gamma\gamma$	$125.4 \pm 0.5 \pm 0.6$
ATLAS	4ℓ	$124.3^{+0.6+0.5}_{-0.5-0.3}$
CMS	4ℓ	$125.8 \pm 0.5 \pm 0.2$
ATLAS	combination	$125.5 \pm 0.2^{+0.5}_{-0.6}$
CMS	combination	$125.7 \pm 0.3 \pm 0.3$

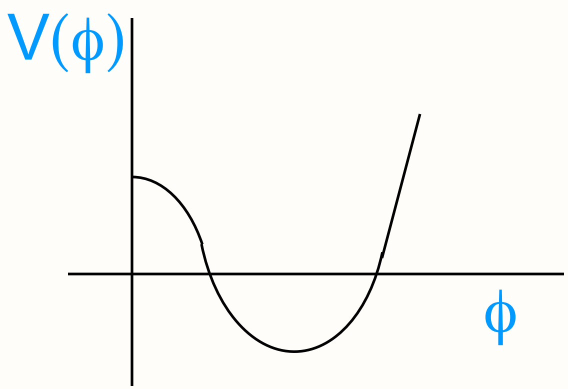
$M_H \approx 126$ GeV! A farce?

So is this it?

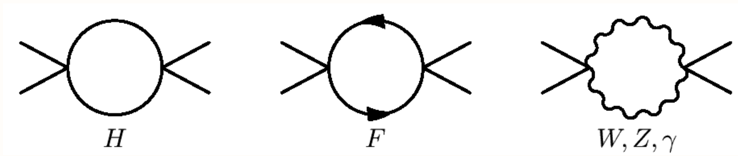
What about new physics?

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

Scale of New Physics = F(M_H)



+



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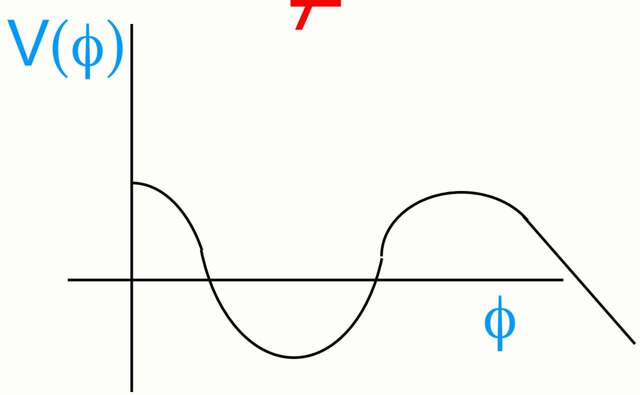
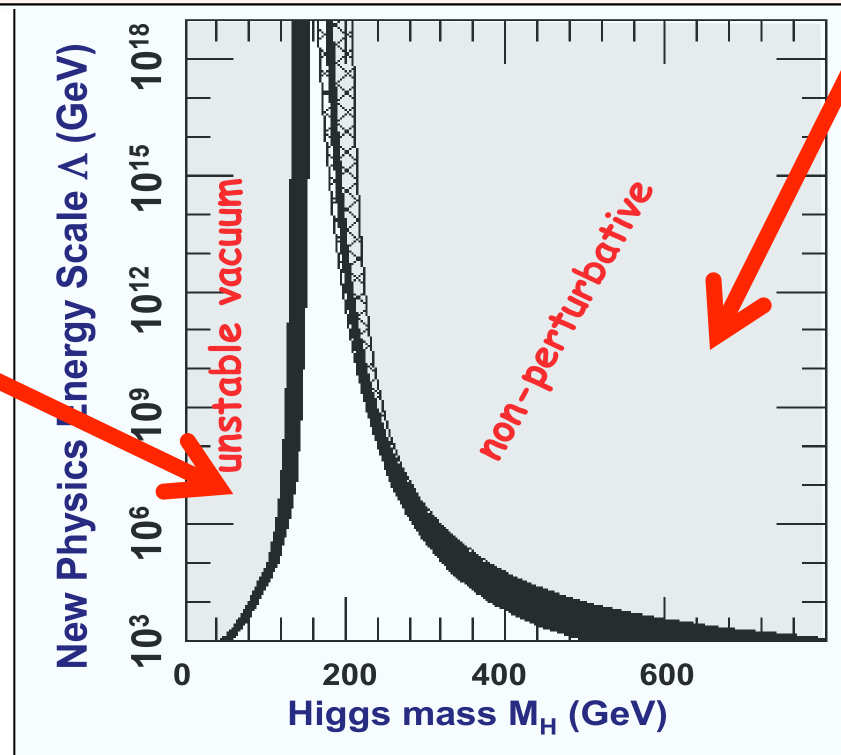


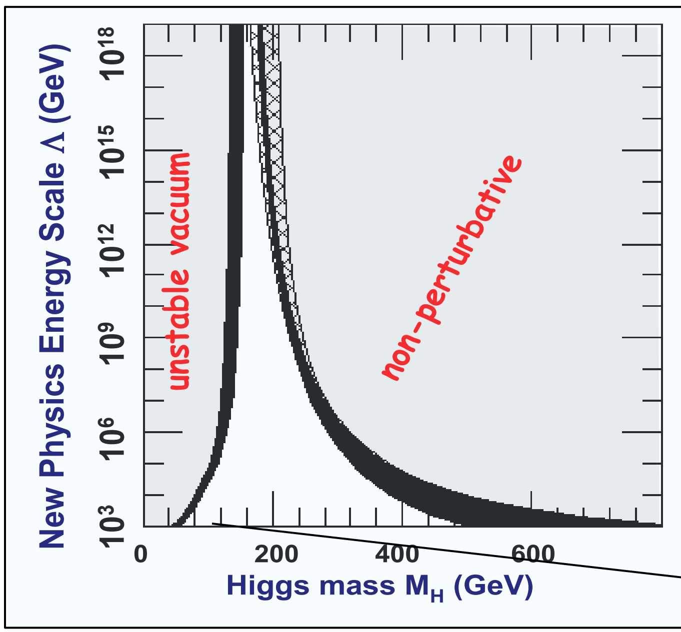
$$\lambda\left(Q^2\right) = \frac{\lambda\left(Q_0^2\right)}{1-\lambda(Q_0^2)/16\pi^2 \log\left(Q^2/Q_0^2\right)}$$

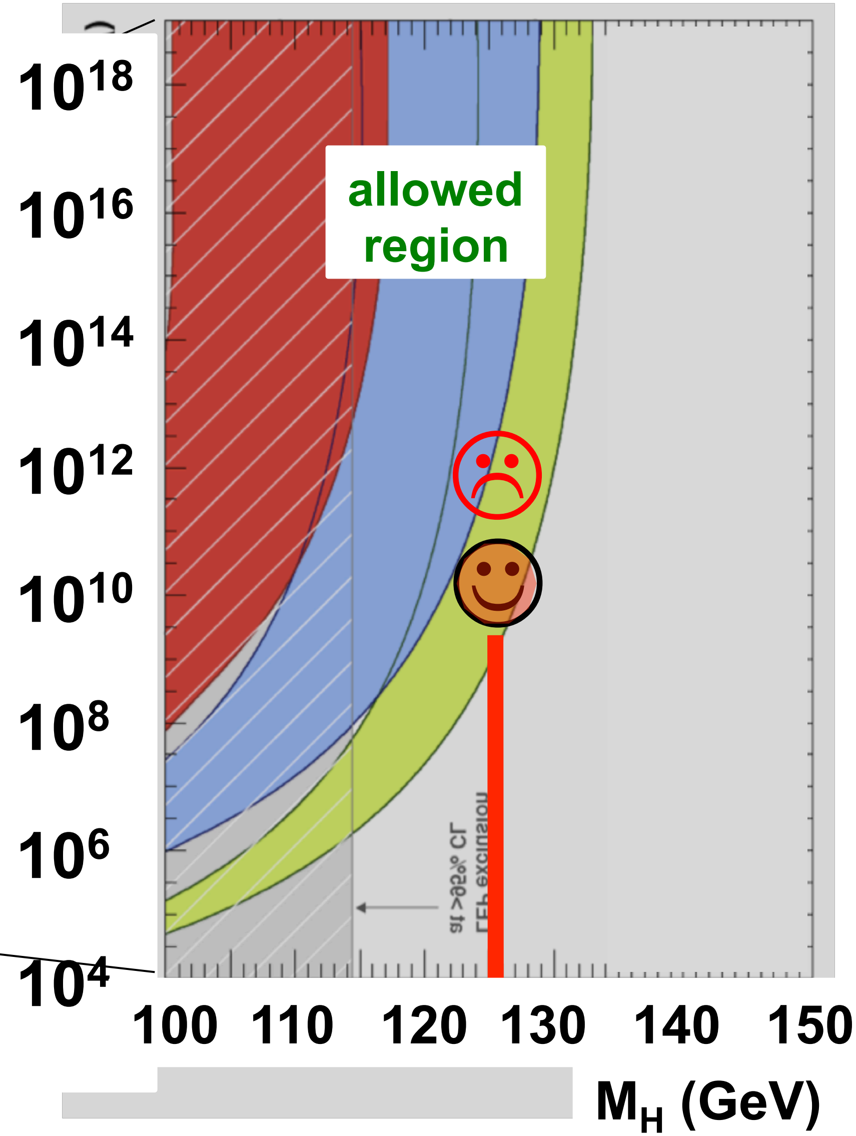
$Q^2 \to \infty,\ \lambda \to \infty!$ $\quad \Lambda \le M_H \exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$



Zooming in: some good (?) news

- **At 95% CL: there is new physics at a scale below the GUT scale ☺**
  - Or vacuum is not stable…

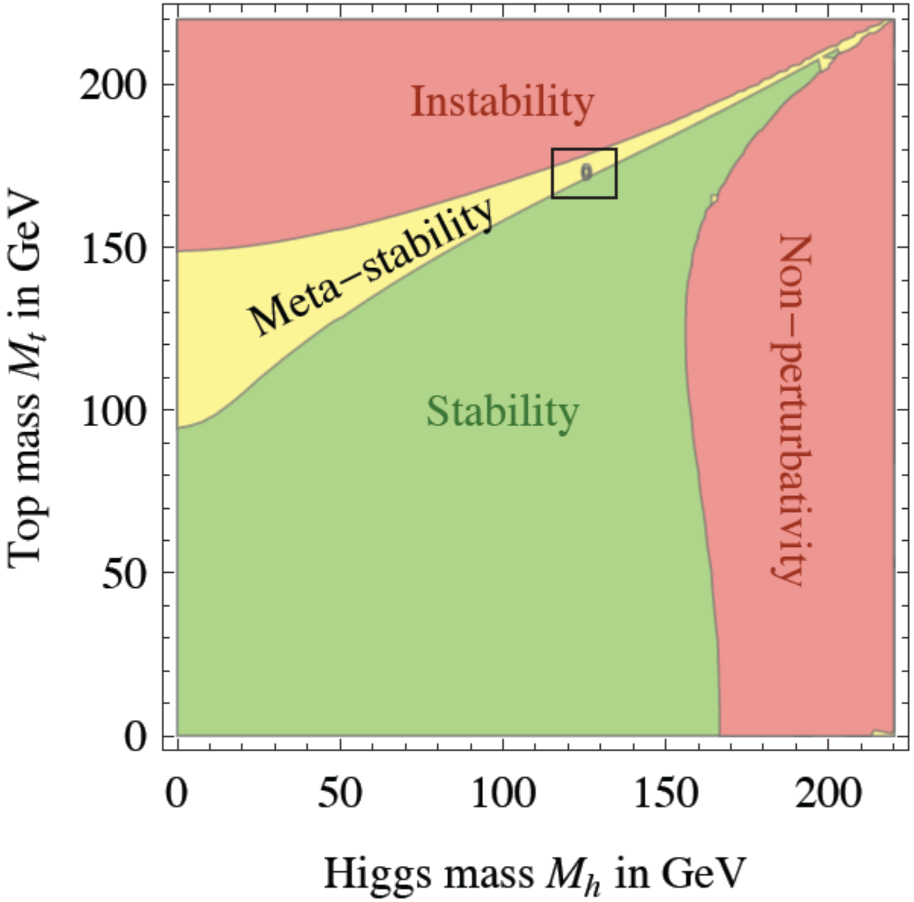


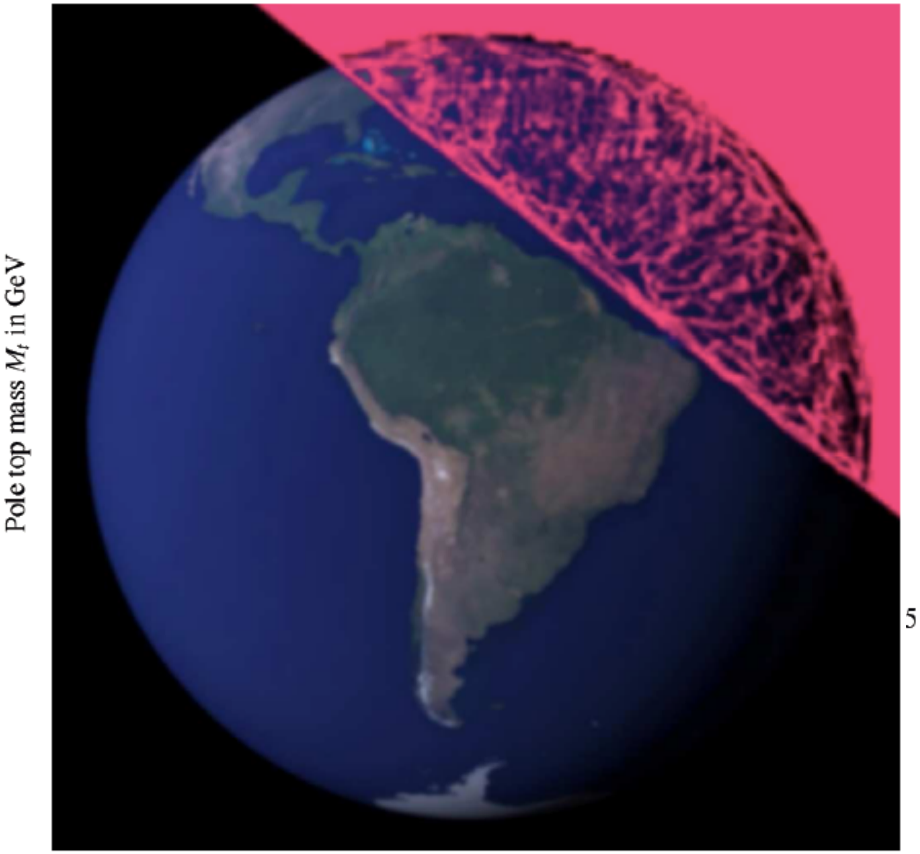


Thankfully, best estimate of time we still have ~15 Gyr!

Living at the edge…

- **Perhaps even more important than originally thought**



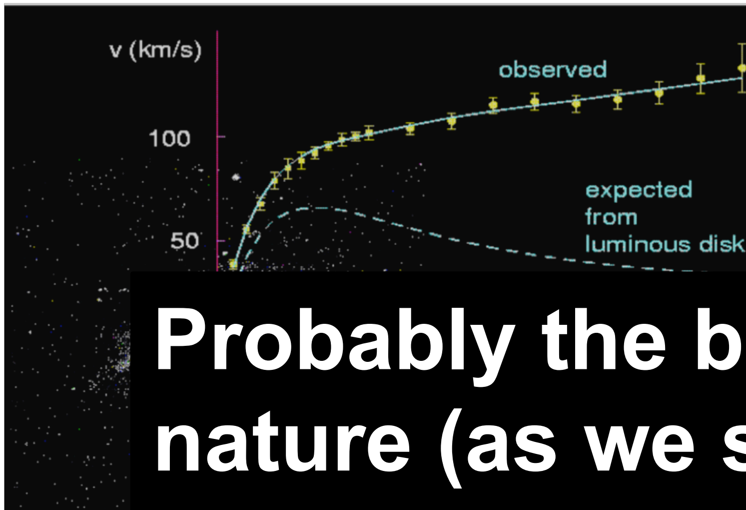


Plenty of room for new physics

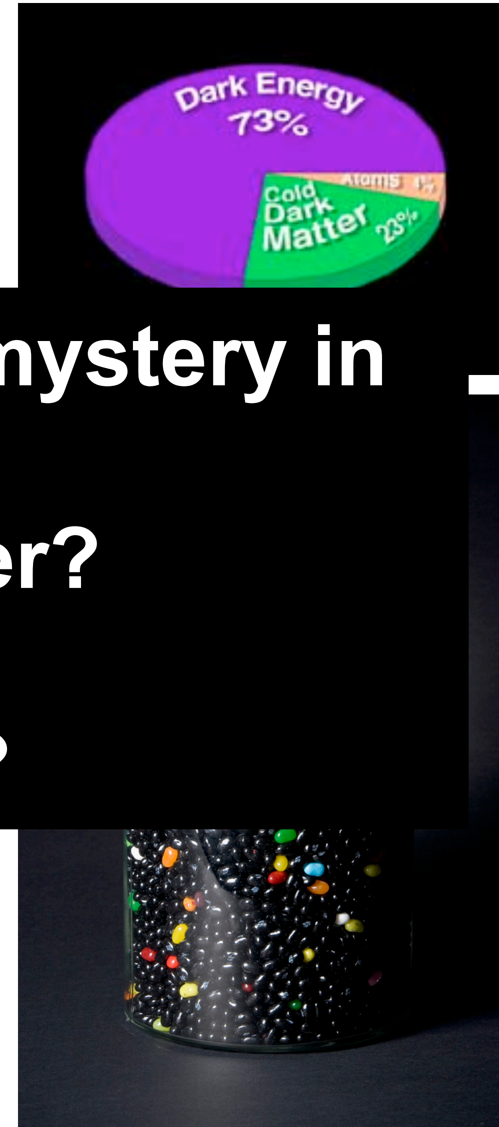
Some real and some virtual reasons to believe in new physics

Real reasons: dark matter & ν masses
Virtual reasons: naturalness

Real reason(s): dark matter

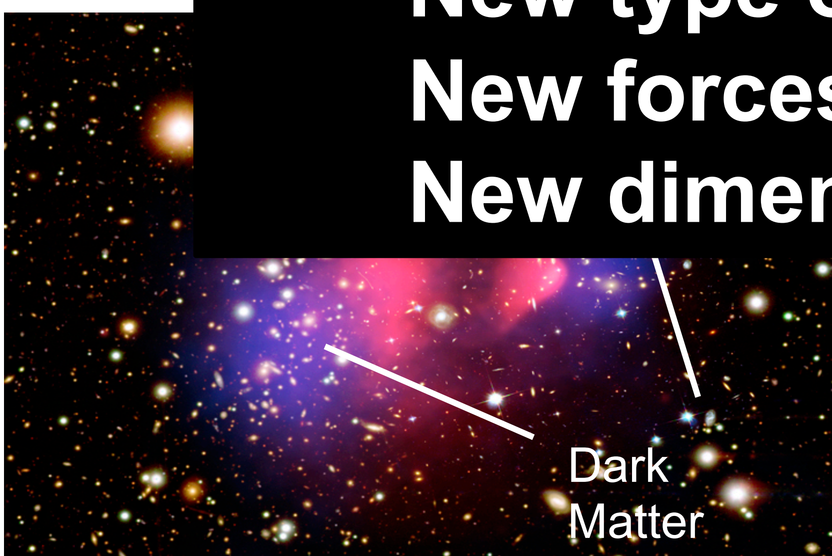


Dark (invisible) matter!



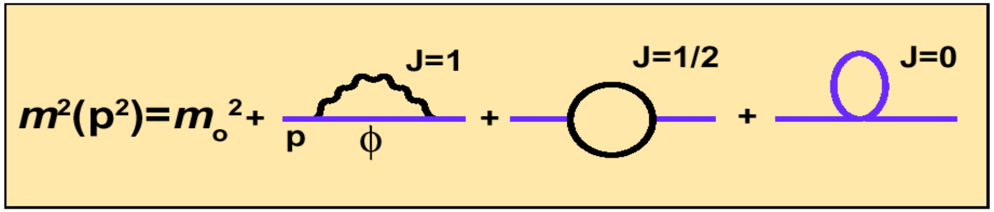
Probably the biggest mystery in nature (as we speak)

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



Virtual reasons: Higgs mass

- **Foremost, the issue of "naturalness": how can the mass of the Higgs boson be anything "small"?**
  - **It should "resist" itself (since it couples to mass, it should couple to itself as well); Its mass should be almost infinite:**



  - **Quadratic divergence in the Higgs mass**

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

  - **Why is the Higgs mass so low? What is the mechanism?**
  - **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!)**
    - **Implies extreme fine-tuning (ETF) of parameters**

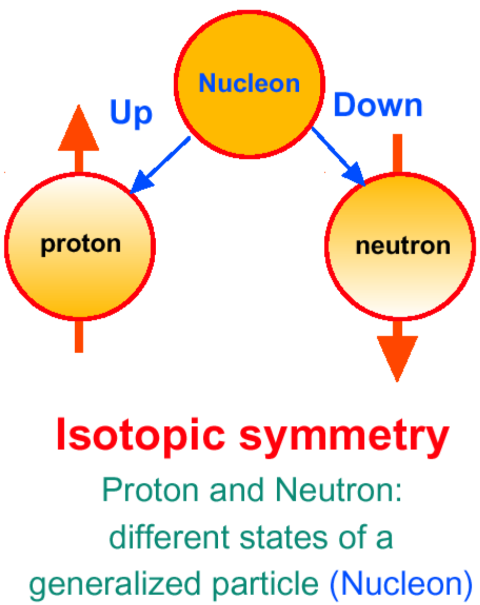
Bringing gravity into the game…

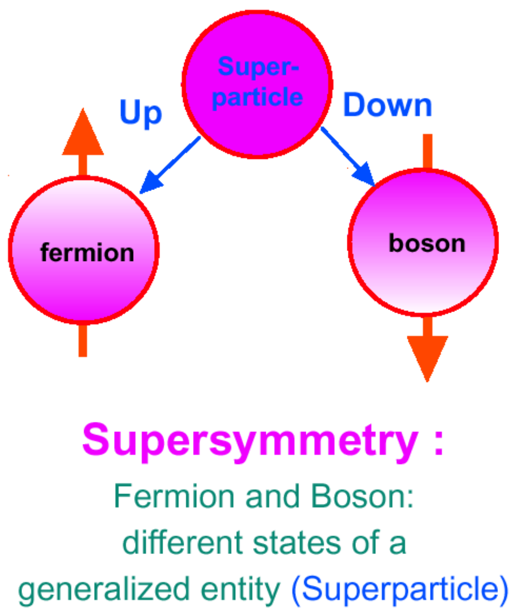
- **If cut off at Λ_{PL}, why $m_W \ll M_{Pl}$? Or, why is gravity ($G \sim 1/M_{Pl}$) so very very weak?**
  - And by the way, the mighty SM ignores gravity (too weak)
- **Interestingly, beyond the Higgs, the biggest problems come from gravity-related measurements:**
  - Dark matter, Dark Energy, and a non-matter-dominated universe
- **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, as we expect it was there (ALONE): a football (soccer) ball)

Supersymmetry
(and Naturalness)

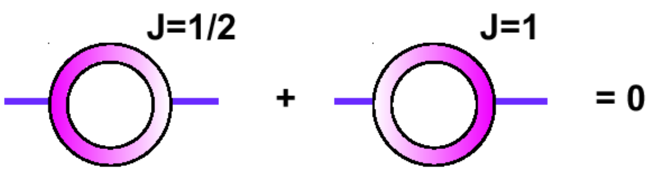
Supersymmetry (SUSY)

- **SUSY (super-symmetry) premise: for every particle in the SM, there is a super-partner with spin-½ difference**
  - Can now speak of a "super-particle" which has two possible states: fermion and boson – much like the proton and the neutron can be seen as two isospin states of one particle, the "nucleon"!



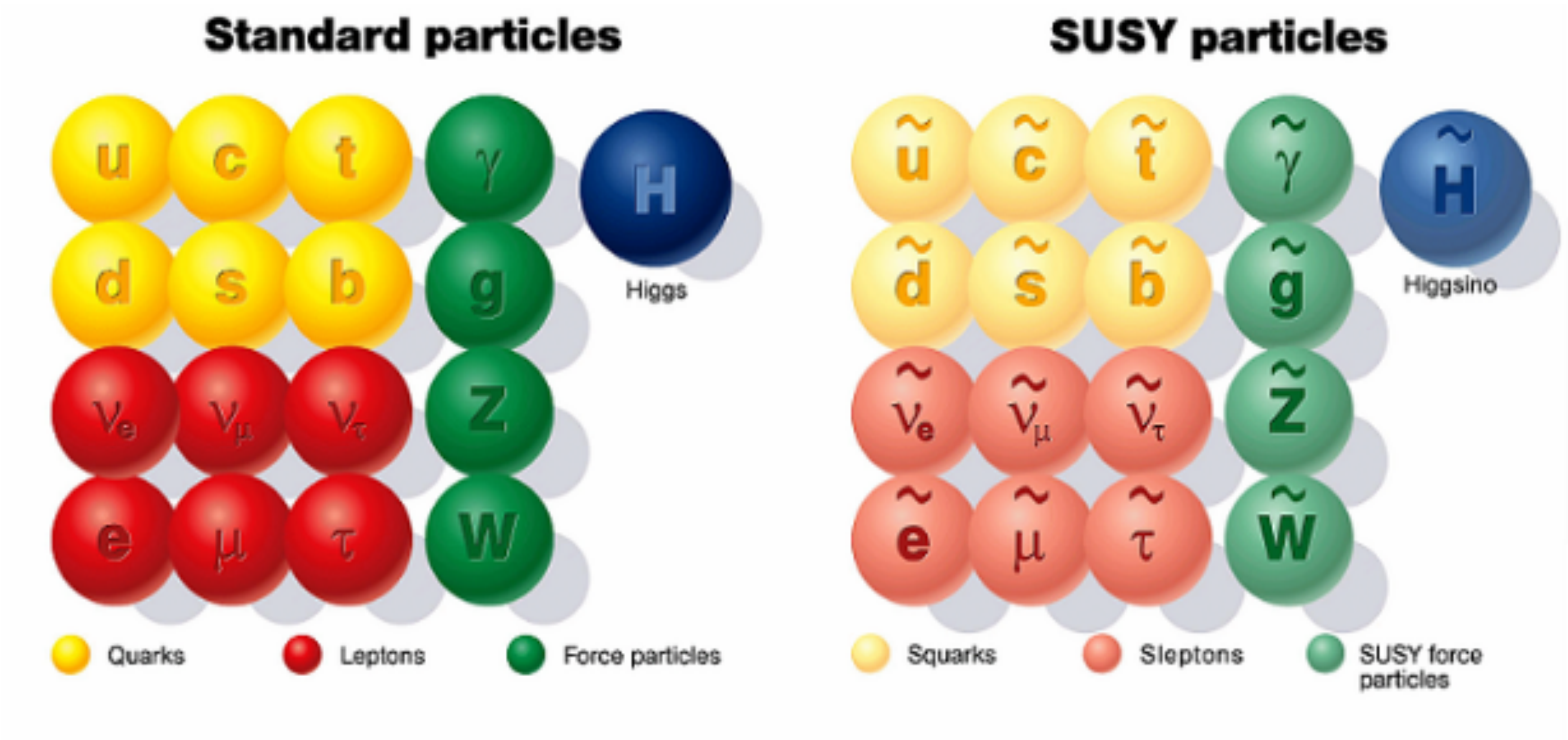


With SUSY, infinities disappear:
As long as $M_p = M_{sp}$

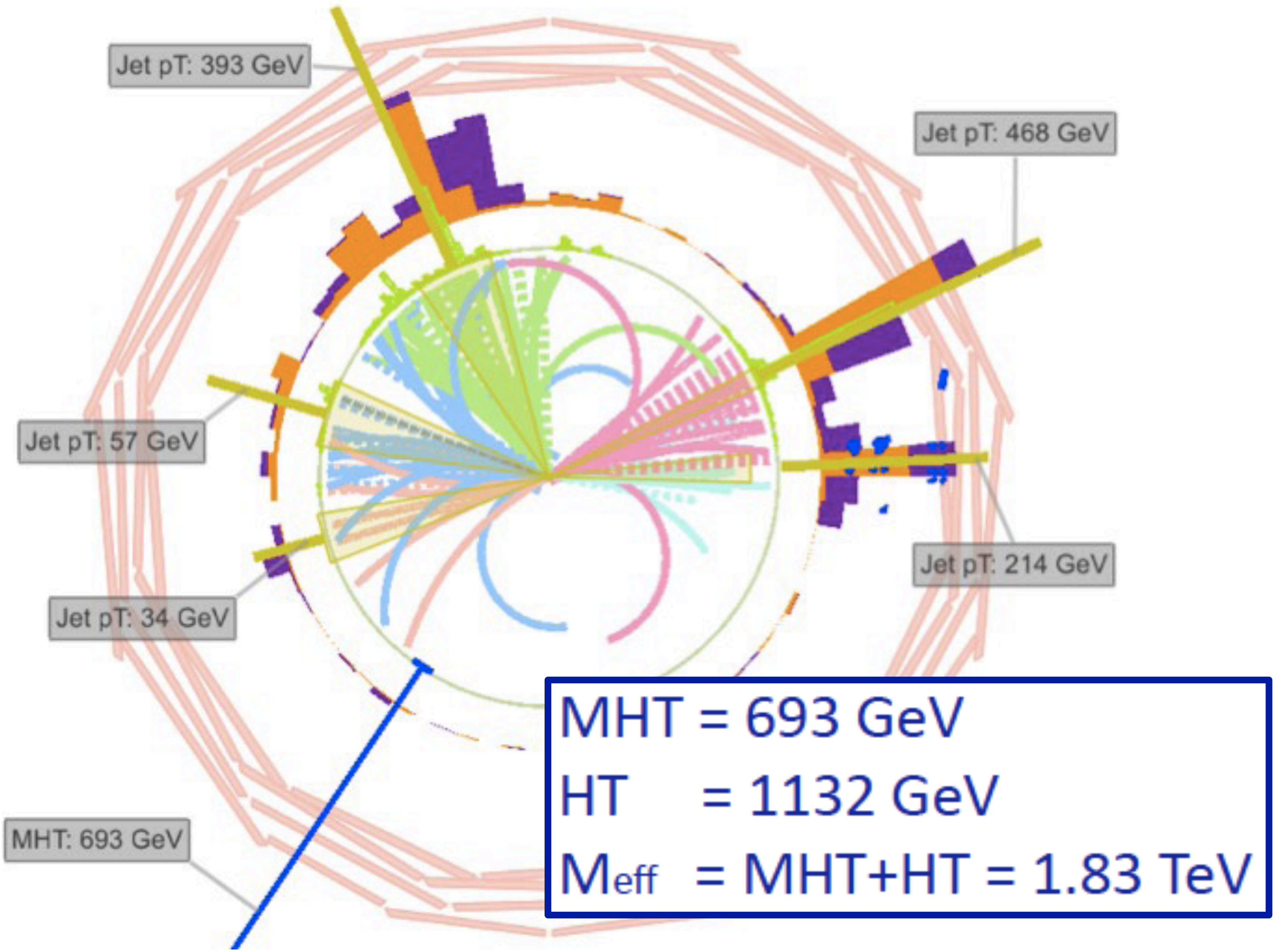


Supersymmetry (SUSY)

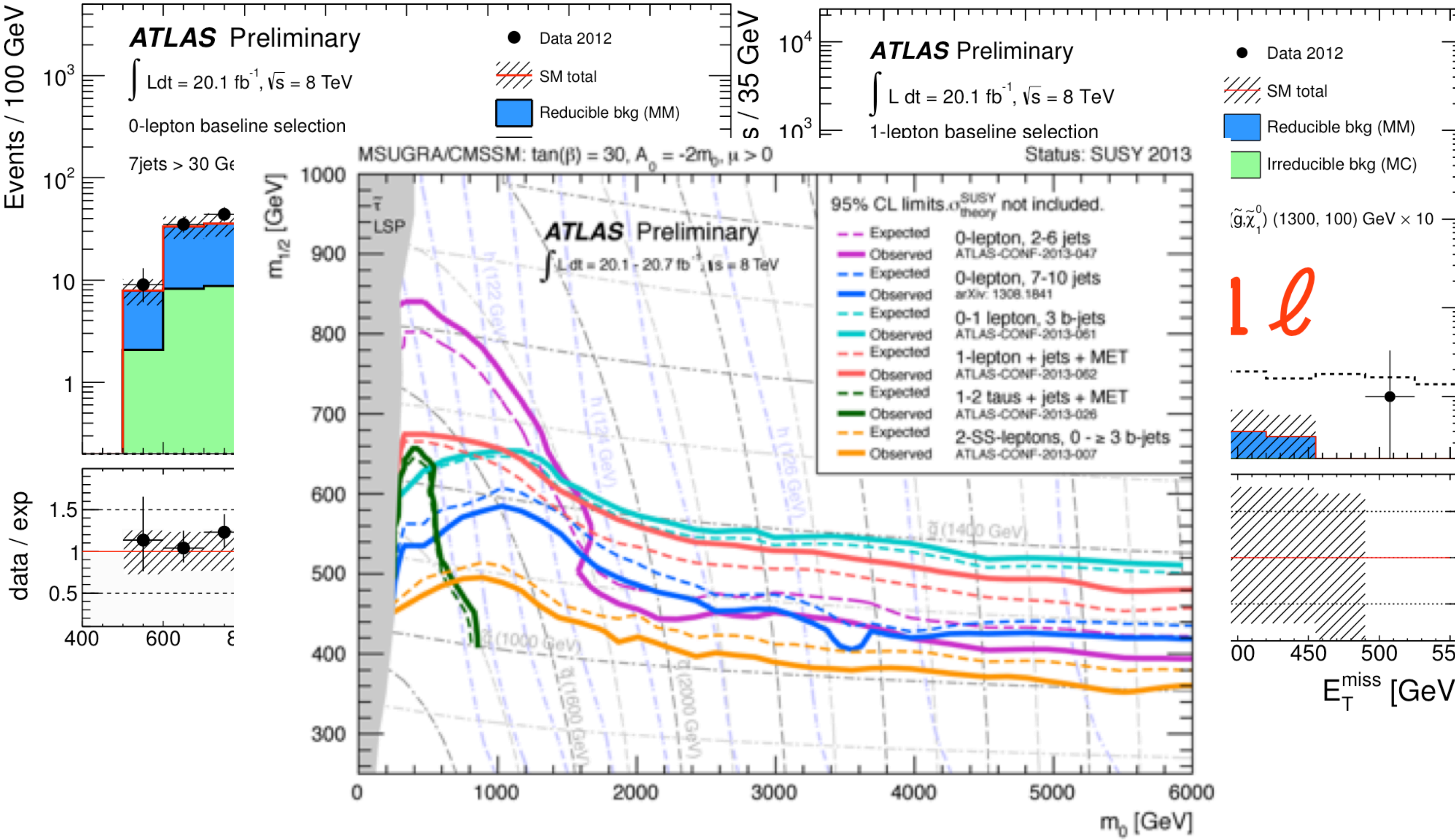
- **SUSY (super-symmetry) premise: for every particle in the SM, there is a super-partner with spin-½ difference**



SUSY? What it could look [looks?] like

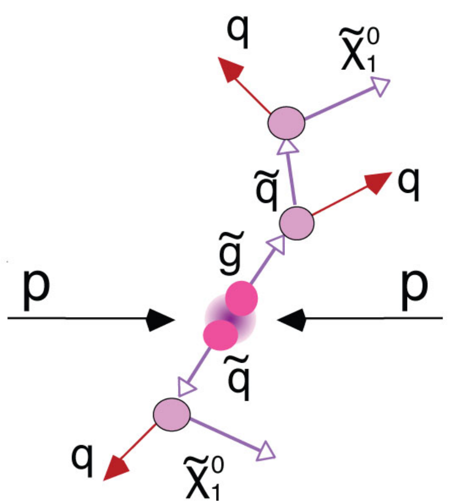


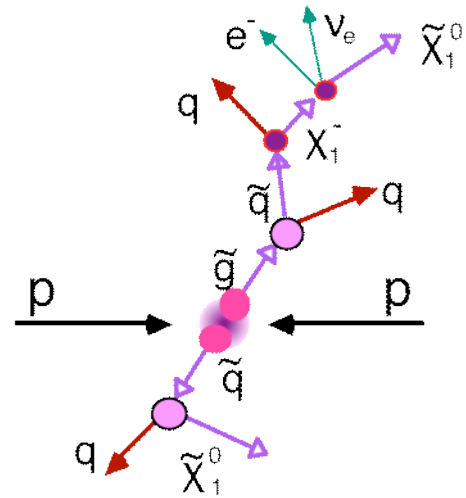
No signs of SUSY yet

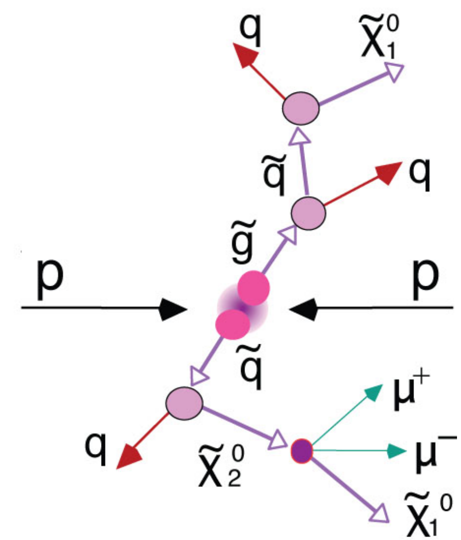


SUSY with ME_T: signatures and bkgs

- **Searches distinguished by the number of leptons**
  - In all cases, demand “(high-P_T) jets + (high) ME_T”
  - 0ℓ (all-hadronic); 1ℓ; 2ℓ (and break down into OS and SS)



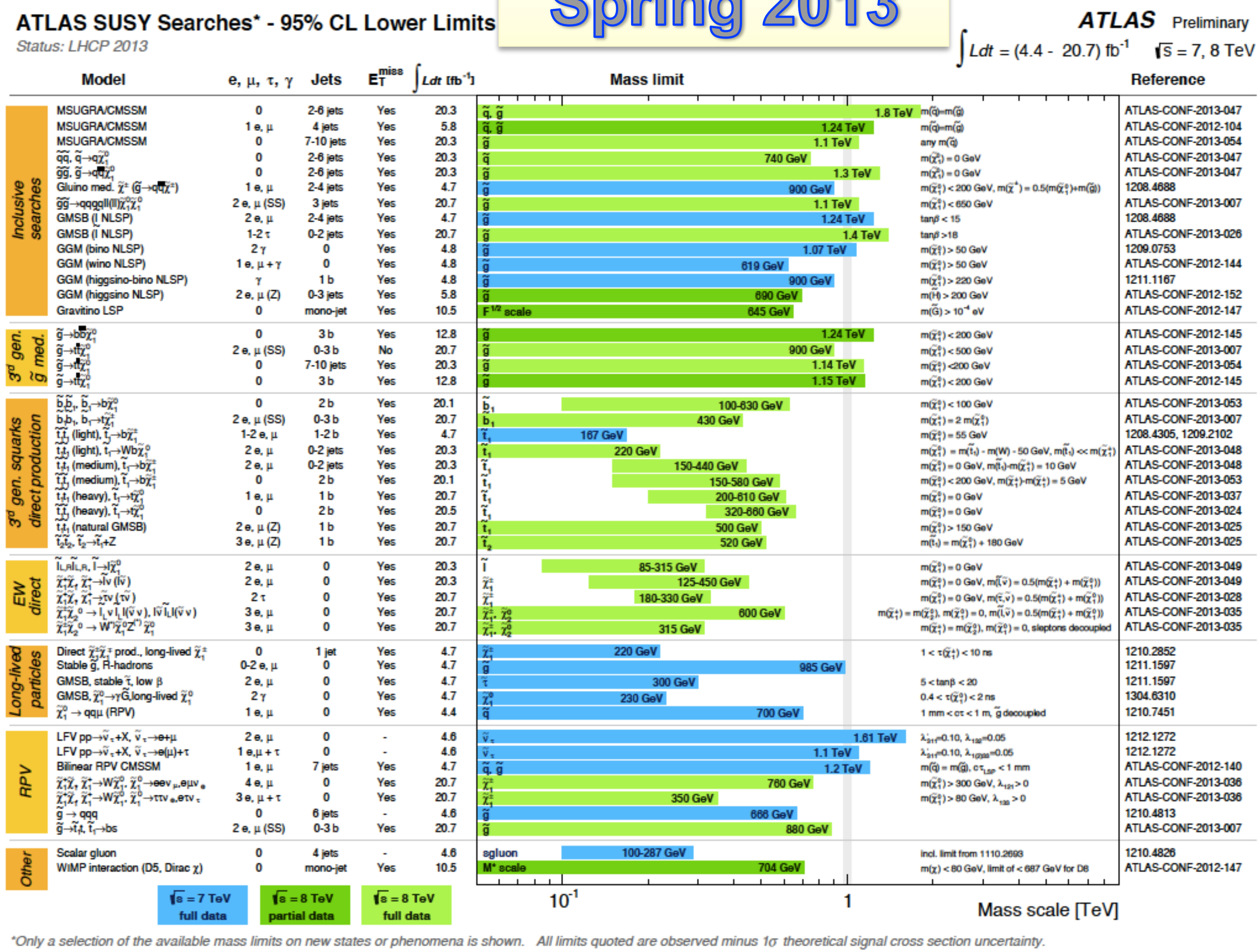




0ℓ	1ℓ	2ℓ
QCD multijets	QCD: small	W/Z($\rightarrow \ell\nu$)+jets
Z($\rightarrow\nu\nu$)+ jets	W/Z($\rightarrow \ell\nu$)+jets	WW, WZ
(W,t)+jets; W$\rightarrow\tau\nu$	t($\rightarrow \ell\nu$)+jets	tt($\rightarrow \ell\ell\nu$)+jets

A dizzying exclusion map

Spring 2013



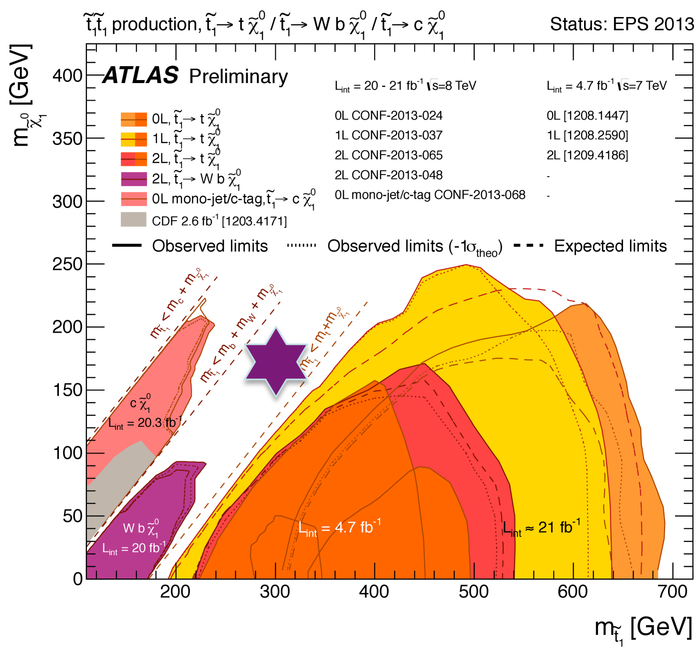
Supersymmetry

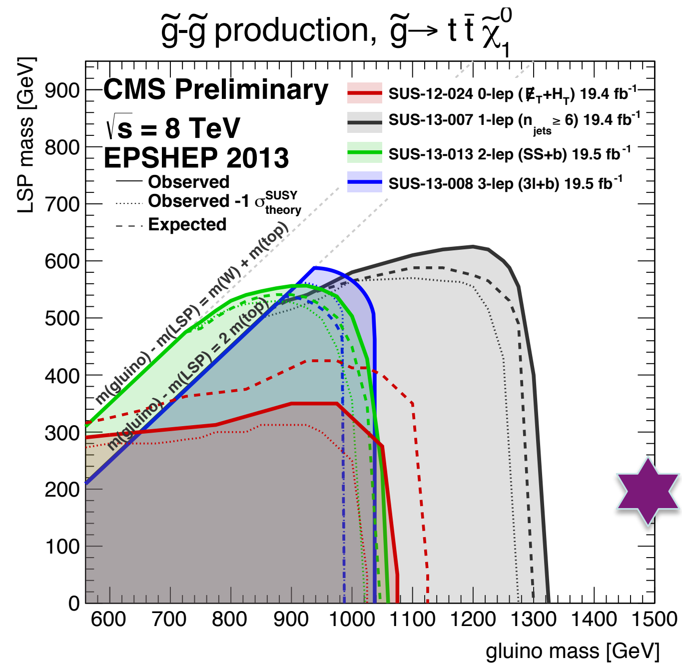
- **The LHC has placed very severe constraints on Supersymmetry**
  - **In fact, the more “constrained” models of SUSY are now almost excluded**
  - **So, is it dead? [it seems the press loves to declare this…]**

- **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)**

Searches for top squarks

- Dedicated searches for both direct and indirect production of top squarks; no signs of them (yet):





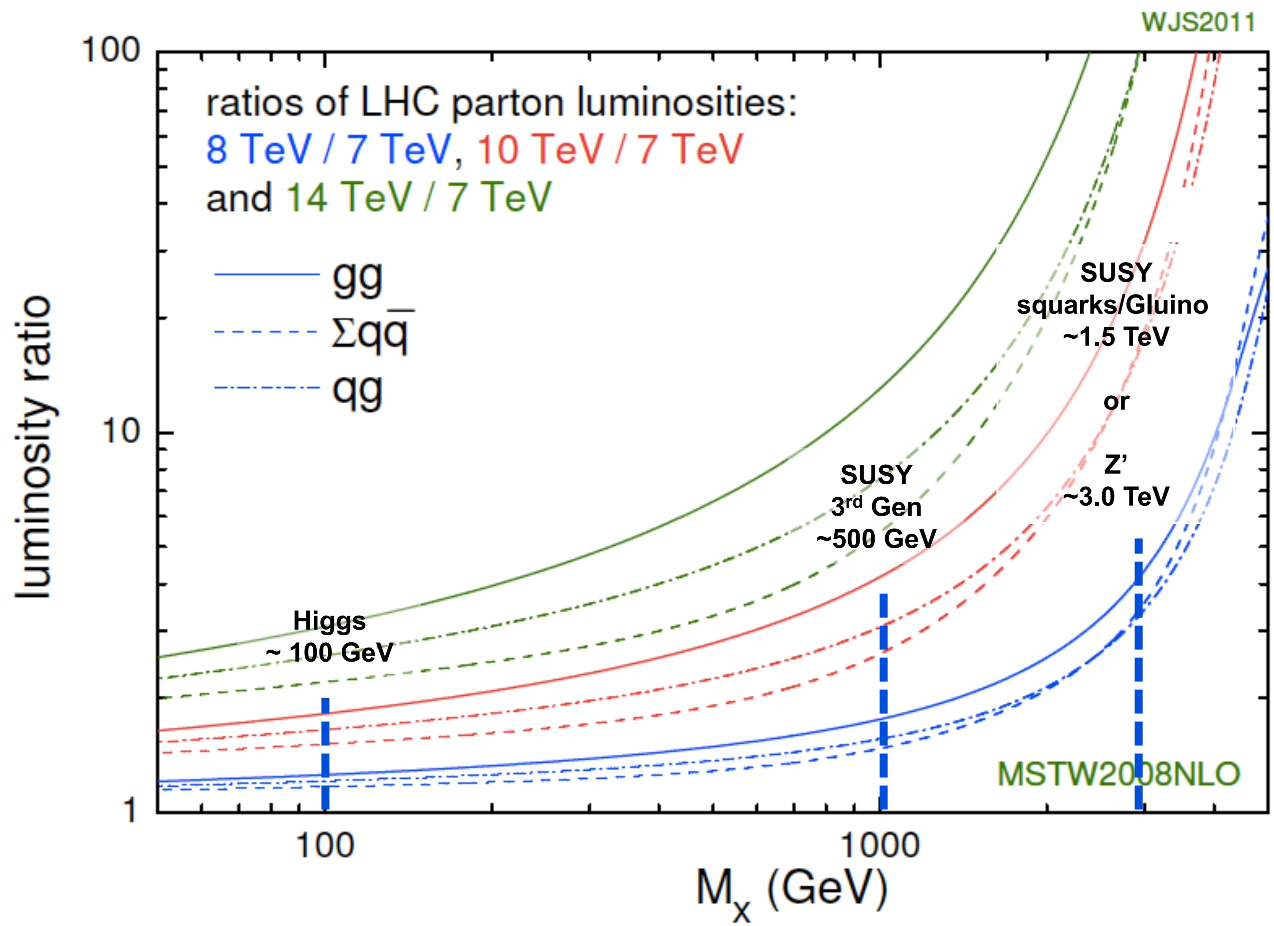
  - But still room left for naturalness: e.g. M(gluino)~1.5 TeV; m(stop)~300 GeV; m(LSP)~150 GeV

- Really need more energy!

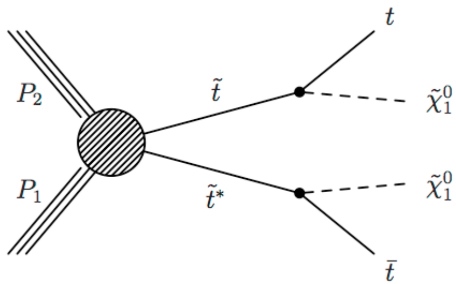
Outlook
(LHC at 13-14 TeV & at very high luminosity)
&
Summary

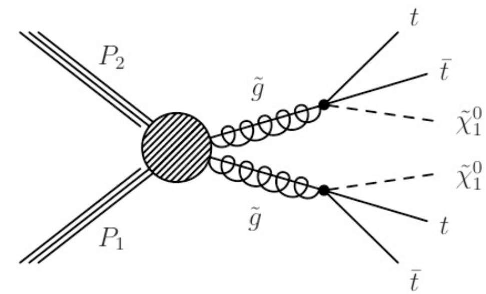
LHC running in at higher energy

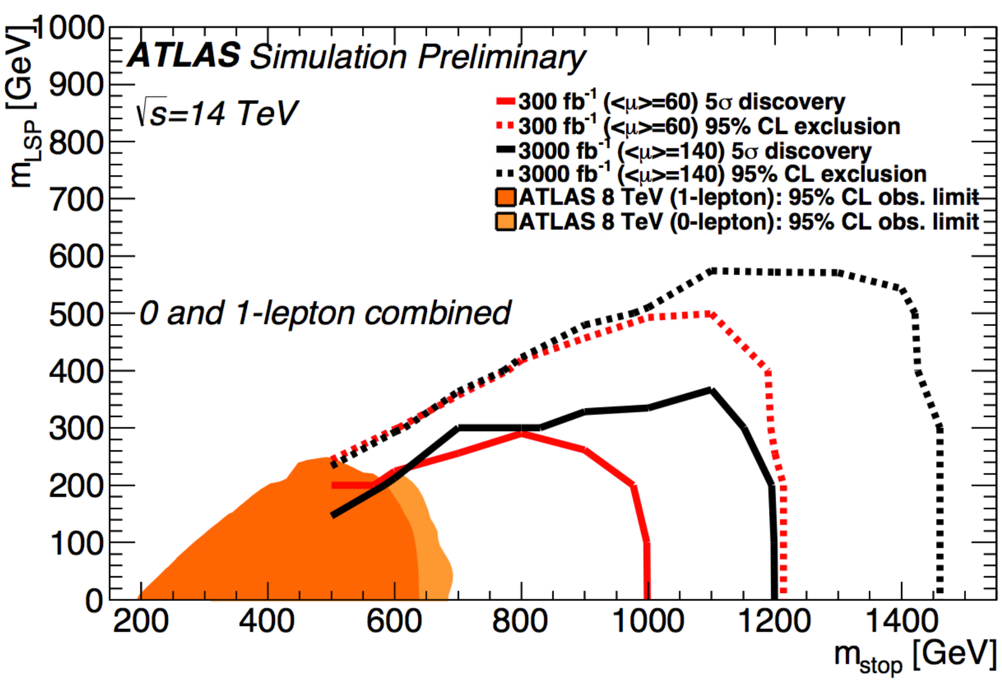
- **Enhances physics reach in two ways:**
  - **Higher cross sections for new physics over full mass range**

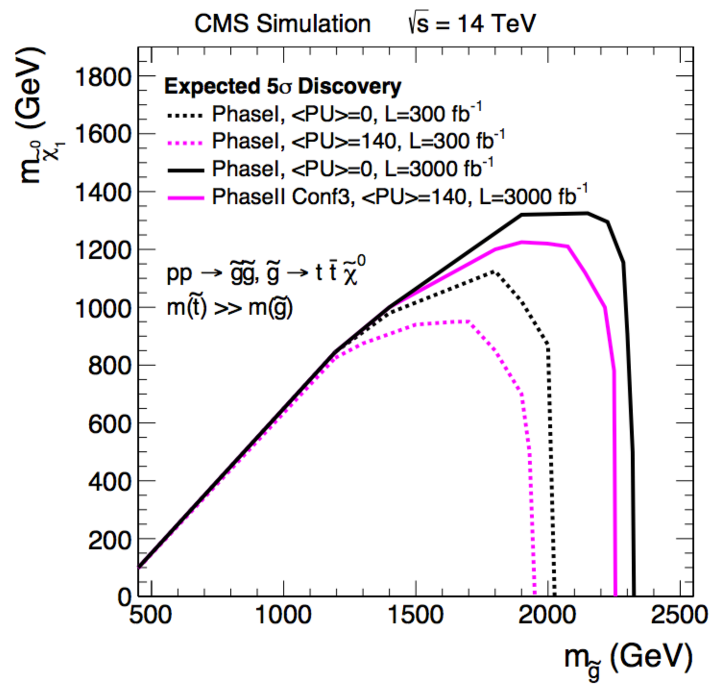


Very significant new reach to SUSY (stop)









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, one missing element – the Higgs boson
- **A new boson with mass 125-126 GeV has been found**
  - We are probing its properties. It's 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!
- **The increase in energy in 2015 will give very significant new physics reach to the experiments. Stay tuned!**

Backups

FAQ: how to make a universe