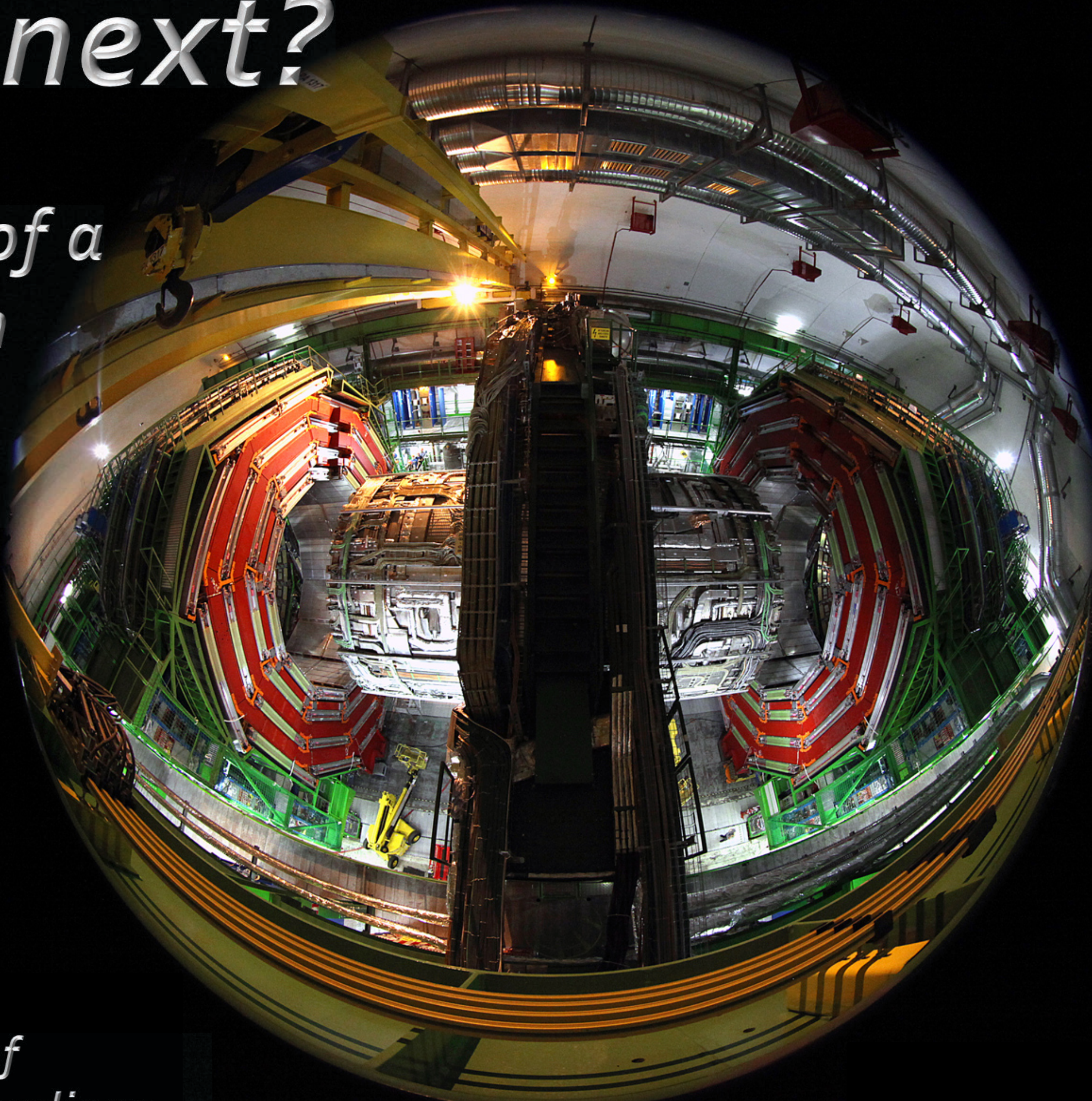
What next?

Aftermath of a Higgs boson discovery at the LHC

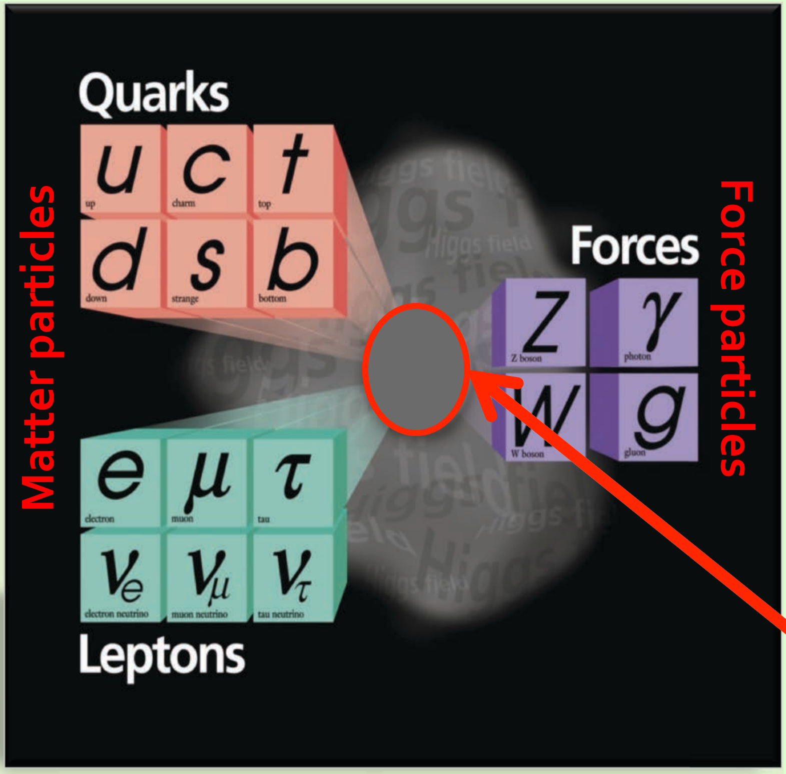


The inauguration of
the Pat and Joe Yzurdiaga
chair in experimental science

August 23, 2013
Prof. J. Incandela

The Standard Model

- Over the last ~100 years: Advances in theoretical physics and the discovery of many sub-atomic particles has led to
  The Standard Model of Particle Physics
- A new "Periodic Table" of fundamental elements



Fermions

Bosons

One of the greatest achievements of 20th Century Science

1 Missing piece: Higgs

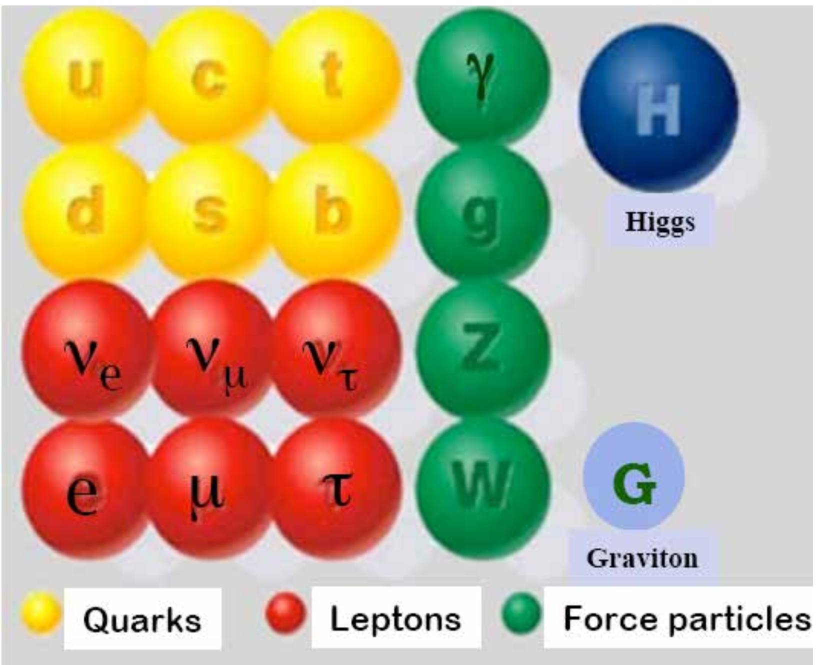
A problem?

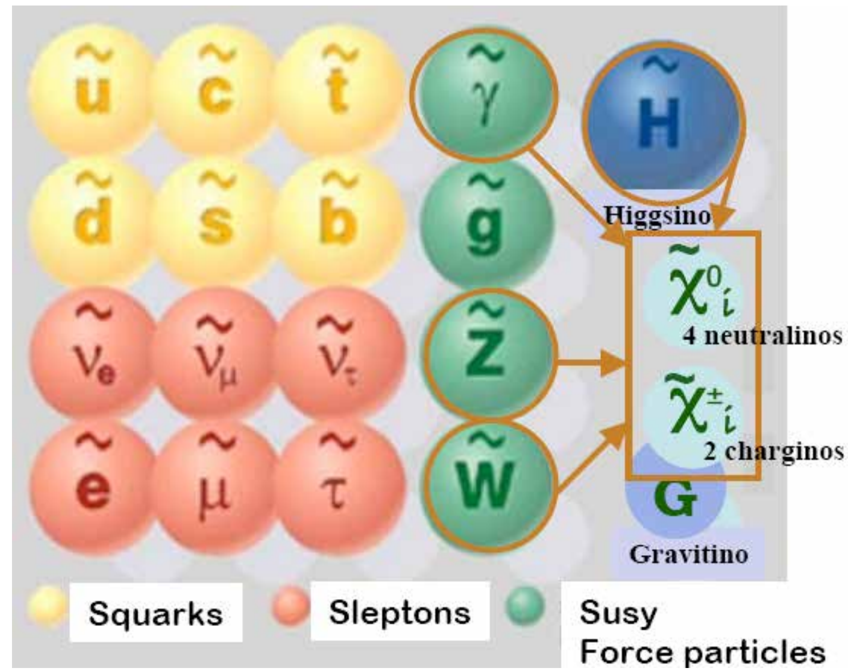
- The Higgs mass:
  - Quantum Field theory predicts that other Standard Model particles should contribute a huge amount to the Higgs mass
    - As much as 10^{19} times the mass of the proton (Planck scale)
  - This is a problem
    - Is the universe 'impossibly' balanced -> **fine-tuned**?
    - Is there something that provides a '**natural**' balance ?
- New 'partner particles' can provide a natural balance
  - They cancel the effects of Standard Model particles
- How do you get partner particles?
  - The most compelling way is to invoke a symmetry transformation that connects each known particle to a new one that is very much, but not exactly, like it.
- Supersymmetry (SUSY) is the 'natural' choice

Supersymmetry

Extension of the Standard Model: Introduce a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles **SUSY particles**





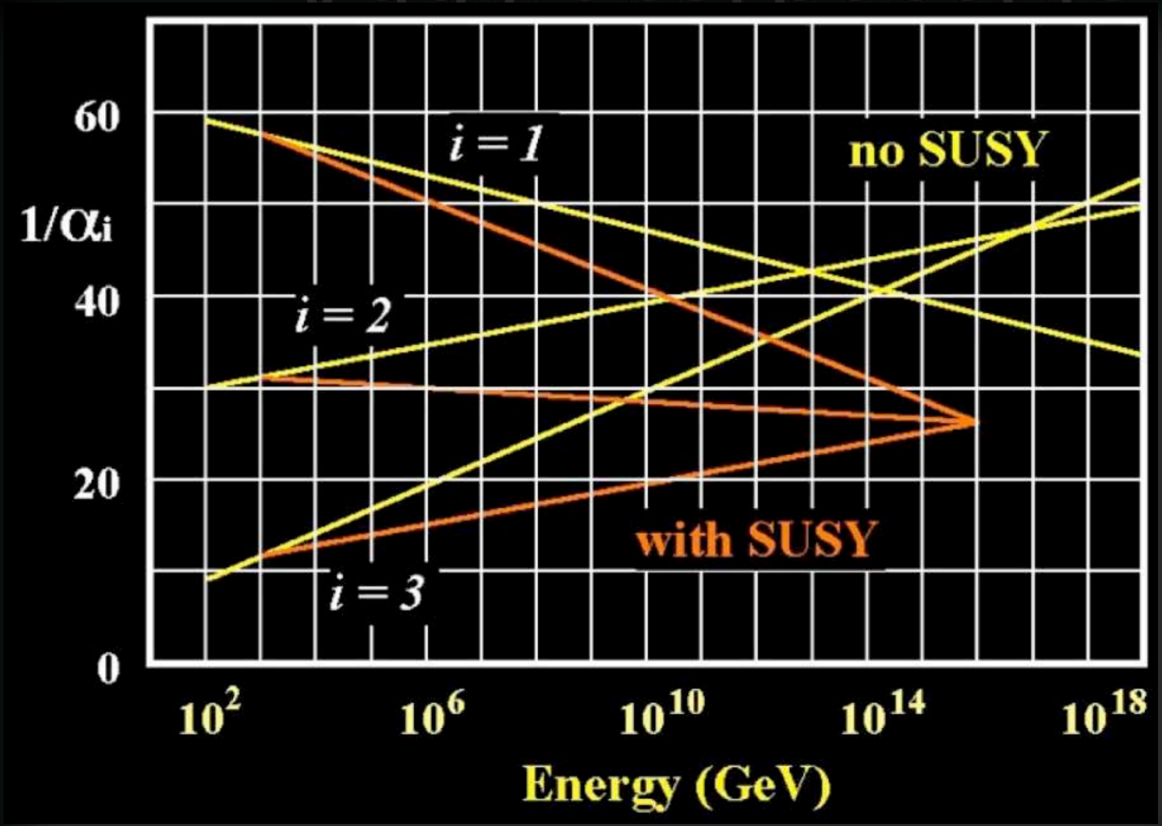
New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles
- 1 SUSY particles

<u>R-parity conservation</u>:

- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable

Courtesy Oliver Buchmueller, EPS 2013

Additional benefits of SUSY



- Unifies the strengths of all forces at ~10^{16} GeV
- Predicts a "Standard Model-like" Higgs h with m_h < 130 GeV
- Provides clues to the dark side of the universe

The Dark Side

- We now know that only ~5% of the energy in the universe is ordinary matter (remember $E=mc^2$).

- 27% is "Dark Matter"
  - SUSY theories can happily predict this amount

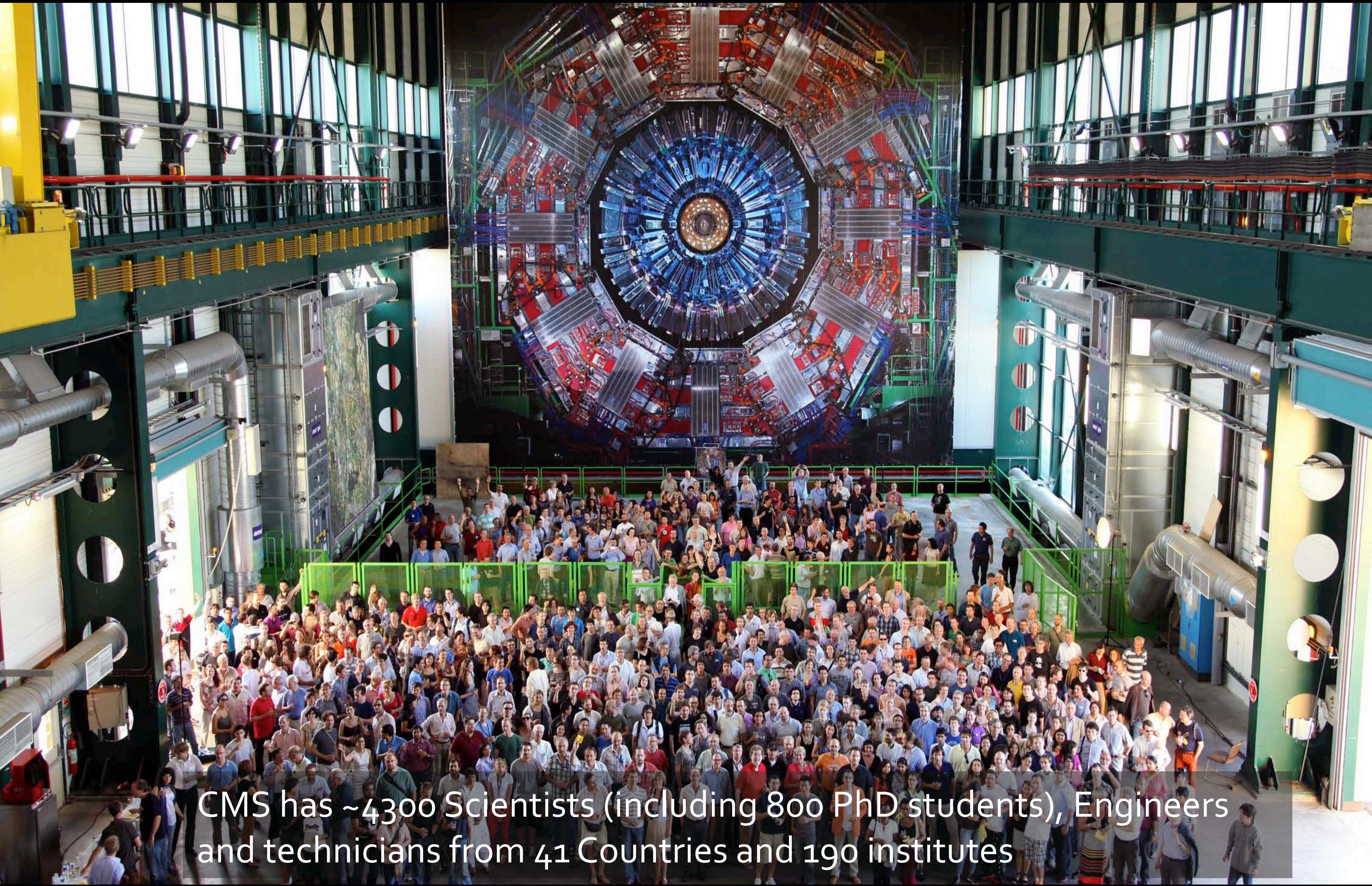
- The remaining 68% is "Dark Energy"
  - We have few good ideas about what this could be
  - It will probably be taxed someday
    - Dept. of Dark Energy?

- There are other possibilities but SUSY is a favorite
    - *Can explain dark matter*
    - *Leads to remarkable unification of field strengths*
    - *Fixes the Higgs mass problem (while predicting a Higgs with $m_h < 130$)*

- ***What does it take to look for these particles?***


Jörg Wenninger
The LHC Accelerator Complex
Courtesy of Jorg Wenninger

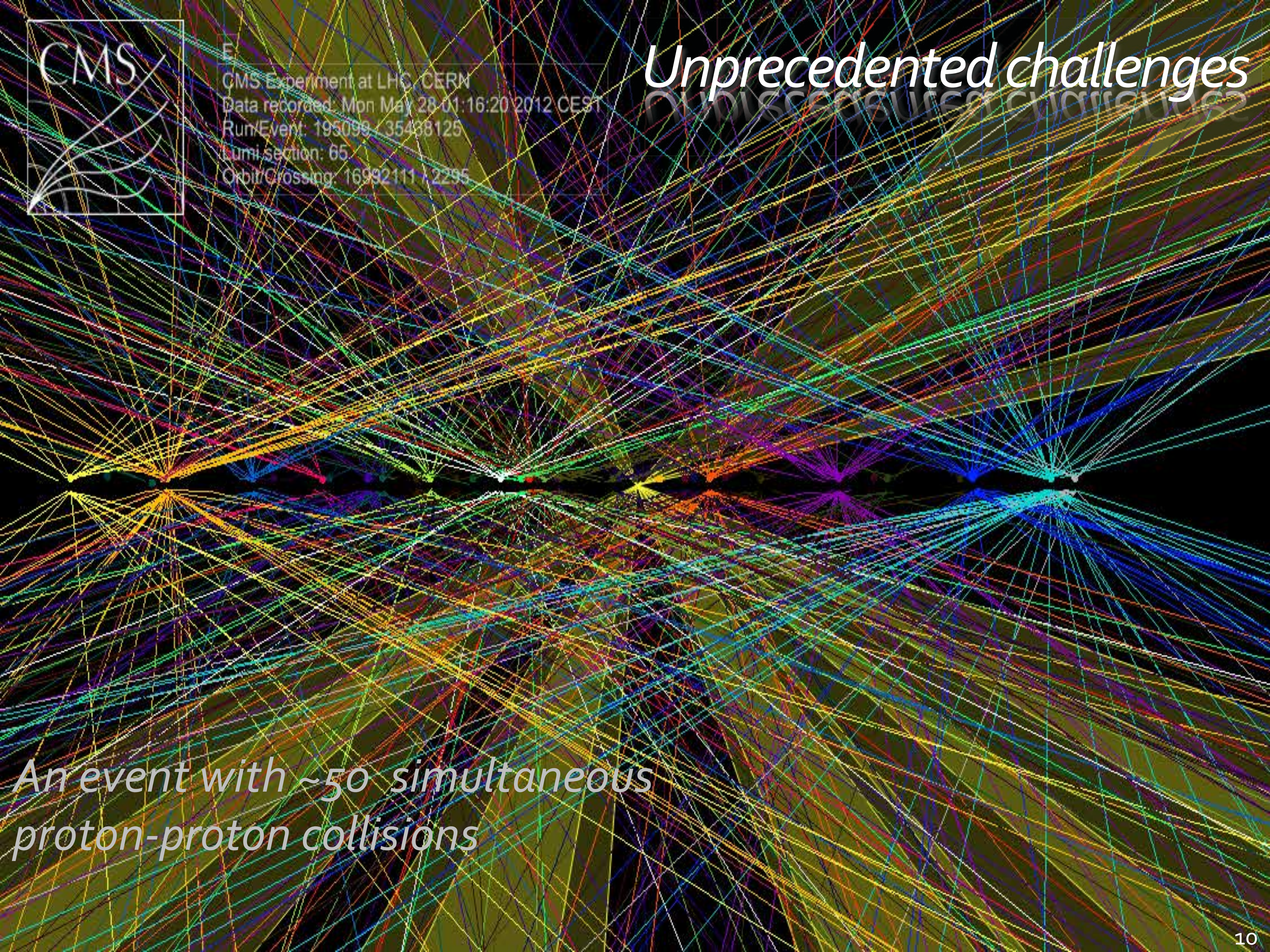
Some of those who made CMS possible



CMS has ~4300 Scientists (including 800 PhD students), Engineers and technicians from 41 Countries and 190 institutes

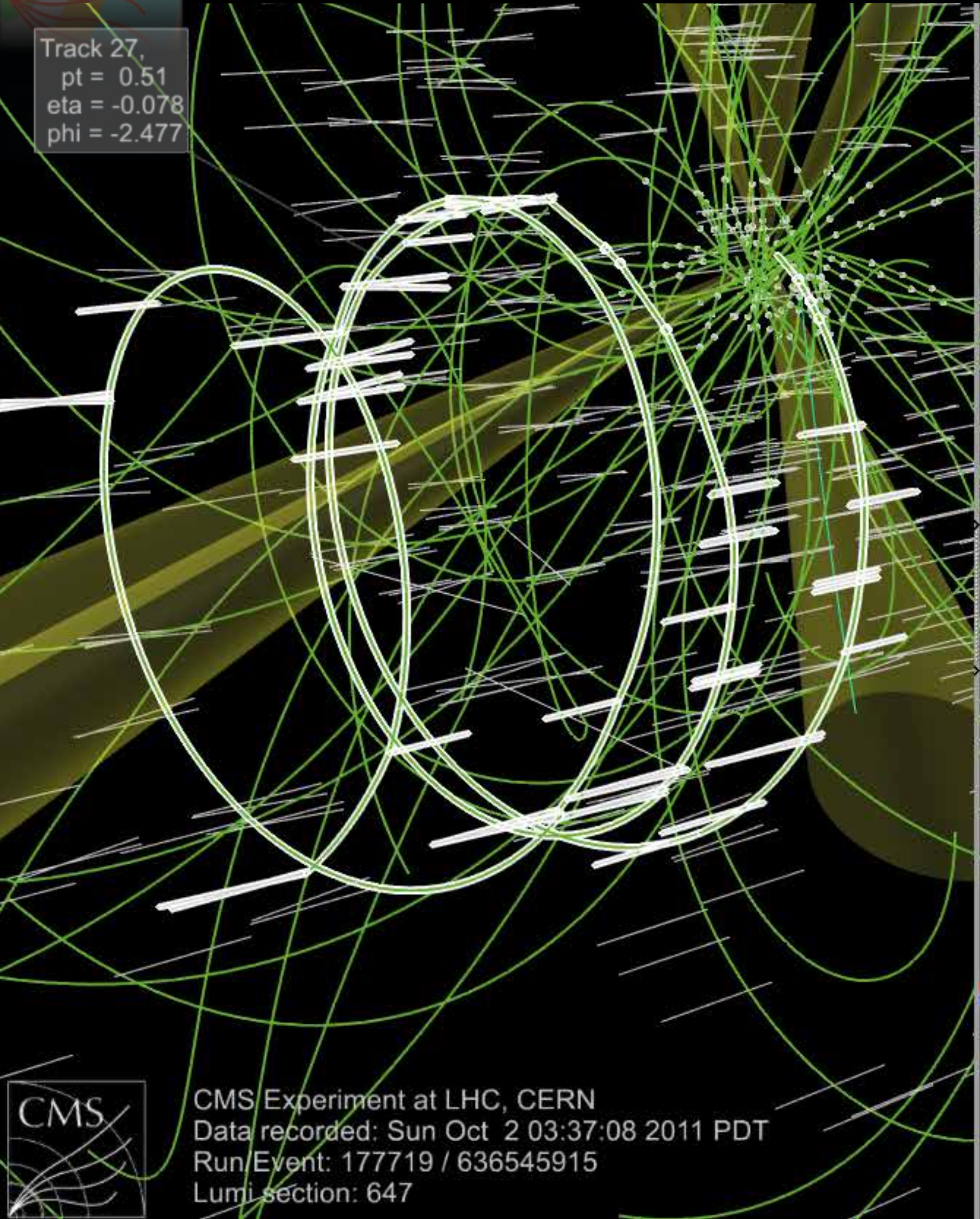
CMS Data distribution

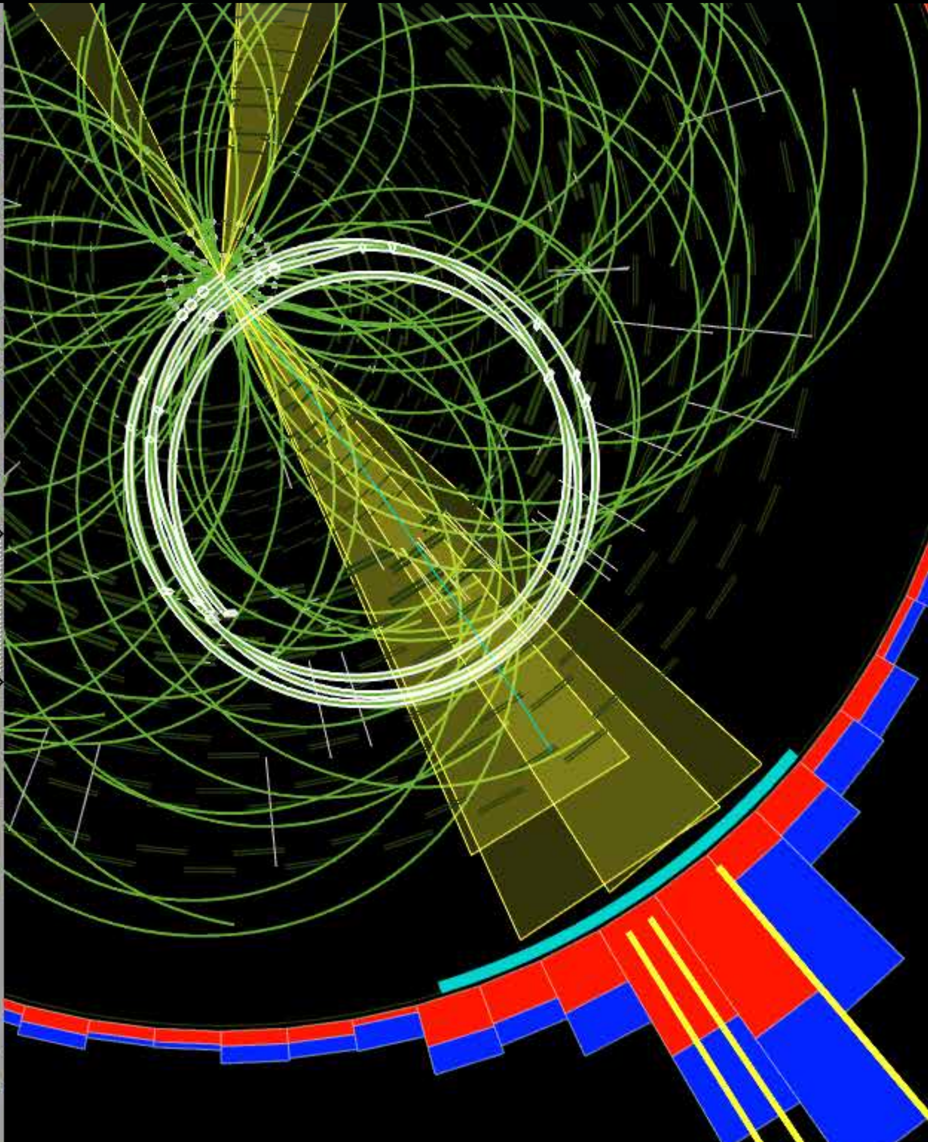
Unprecedented challenges



An event with ~50 simultaneous proton-proton collisions

Unprecedented capabilities





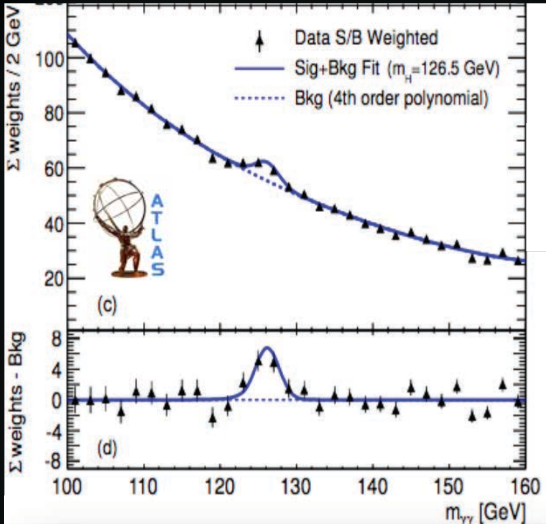
CMS particle tracking: UCSB built more of this than any other institute

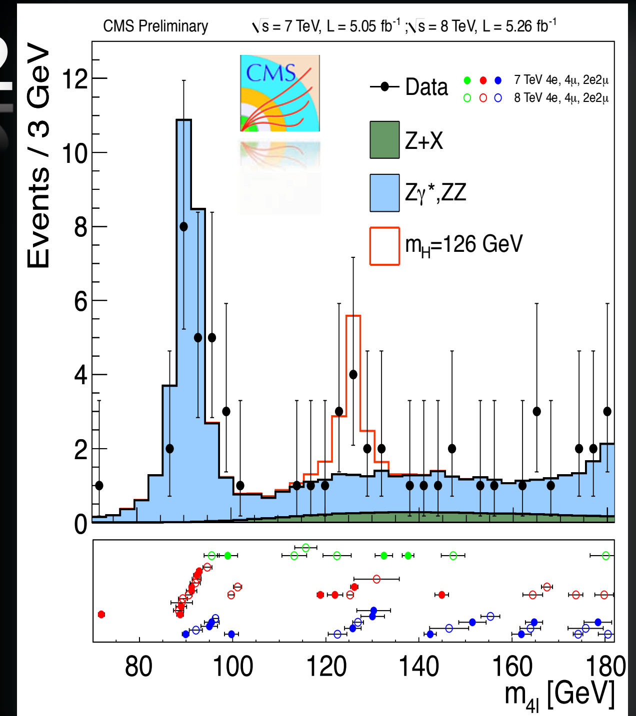
J. Incandela UCSB

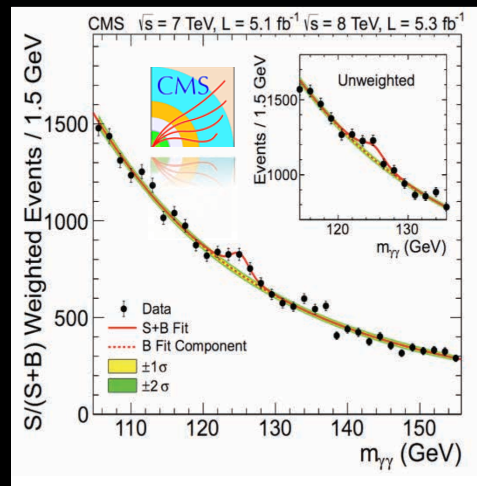
UC Santa Barbara
August 13, 2013 Yzurdiaga Chair Inauguration

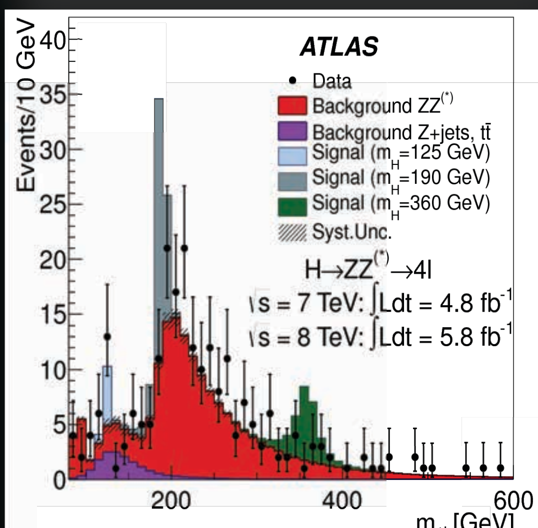
July 4th 2012

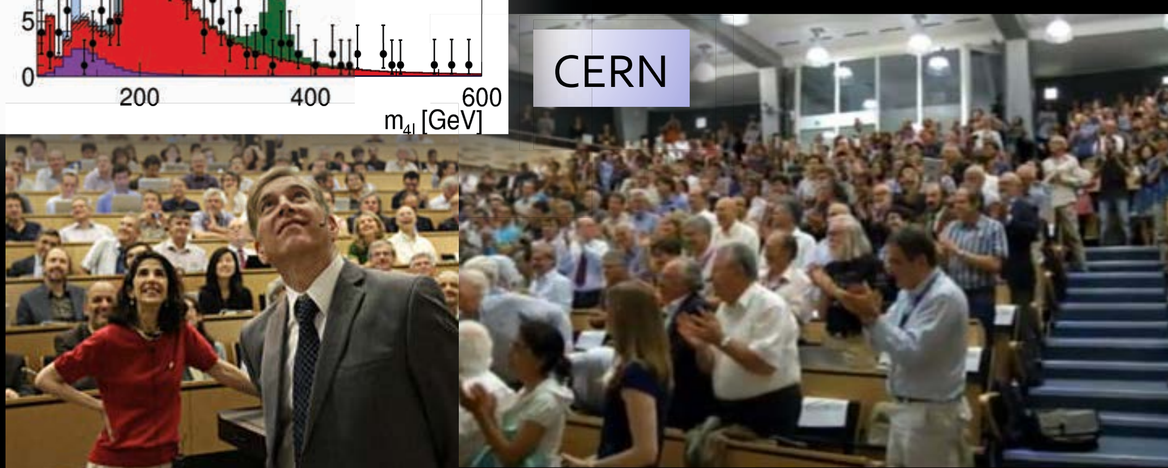
Discovery of a 'Higgs-like'

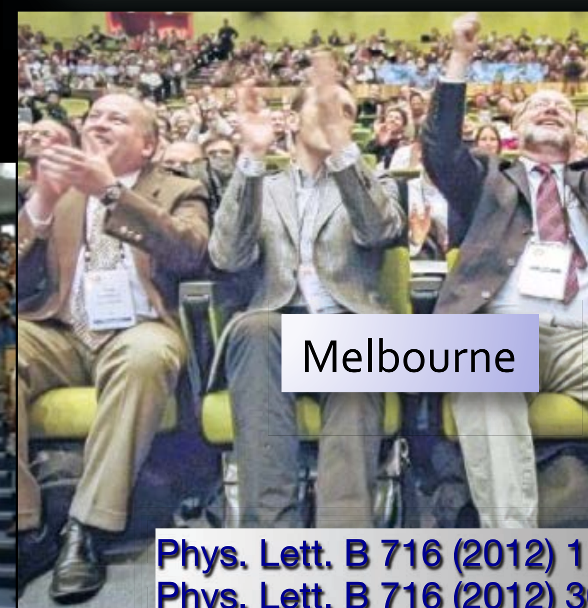










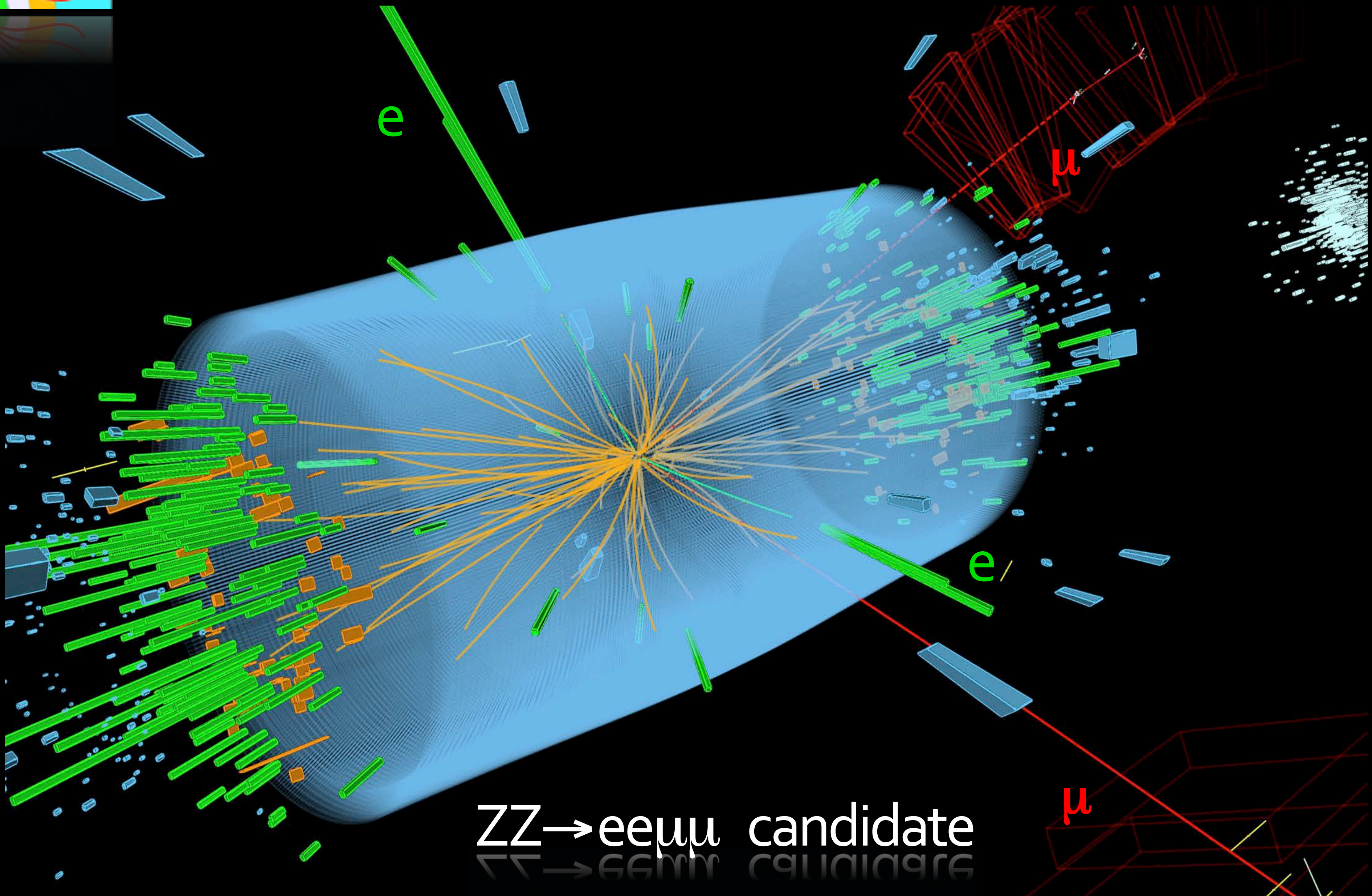


Phys. Lett. B 716 (2012) 1
Phys. Lett. B 716 (2012) 30

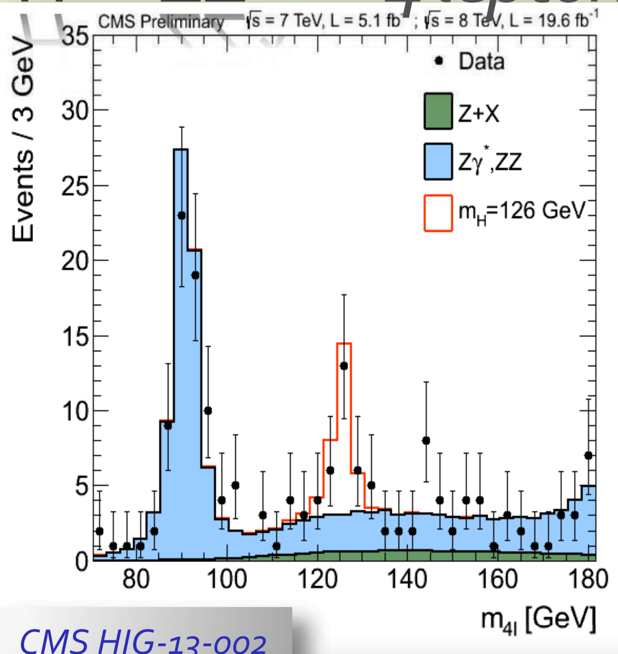
17,000
news articles in
108
countries in
2
days

> 1 billion
people saw TV footage
1,034
TV stations
5,016
Broadcasts

CMS Higgs Results Since 4th July 2012



$H \rightarrow ZZ^* \rightarrow 4$ leptons

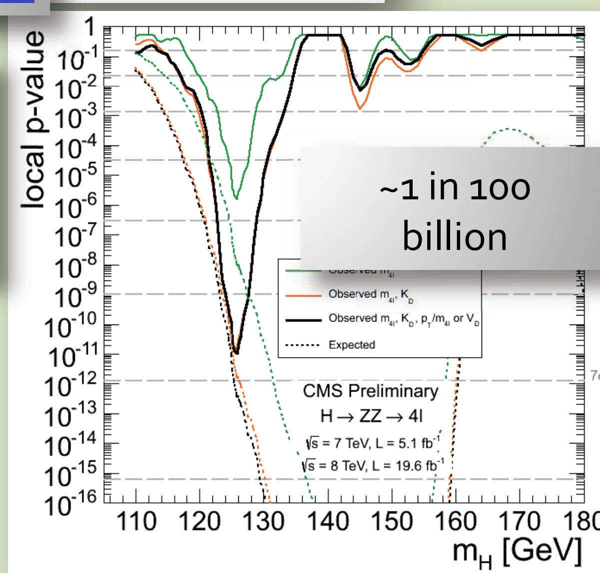


CMS HIG-13-002

6.7 σ (expect 7.1)

Signal strength relative to the Standard Model:

$\mu = 0.92 \pm 0.28$



~1 in 100 billion

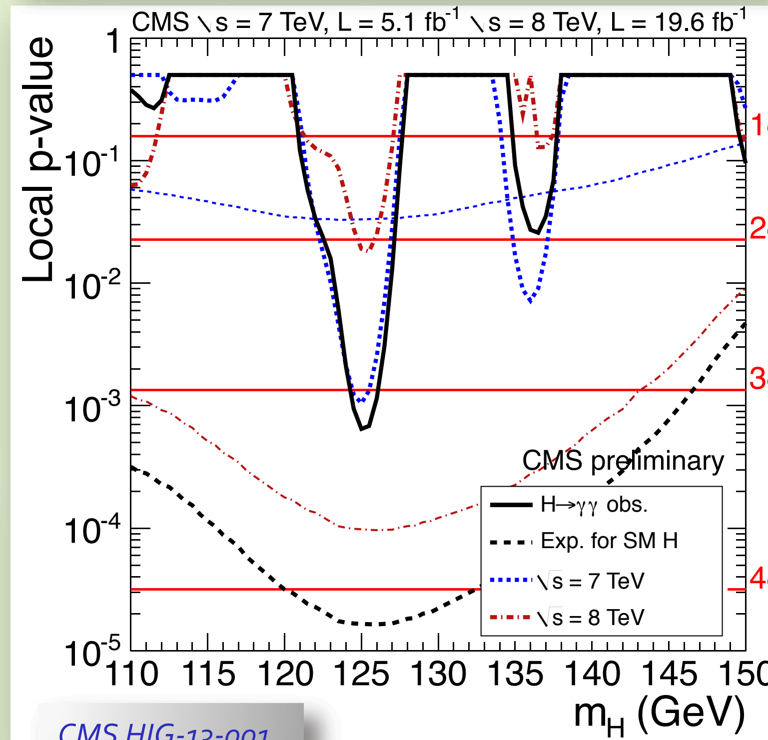
$m_H = 125.8 \pm 0.5 \pm 0.2$ (sys.)

$H \rightarrow \gamma\gamma$

Moriond 2013

CMS 3.2σ (expect 4.2σ)

$m_H = 125.4 \pm 0.5$ (stat.) ± 0.6 (syst.)

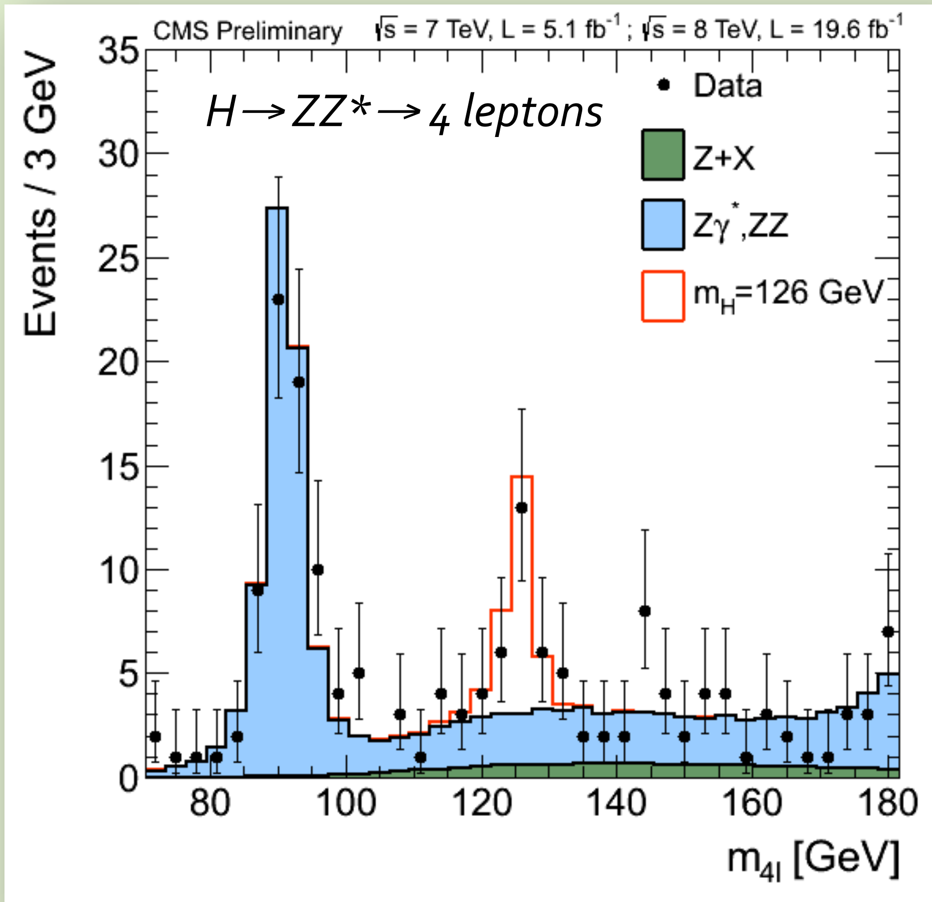


CMS HIG-13-001

$m_H = 125.4 \pm 0.5 \pm 0.6$ (syst.)

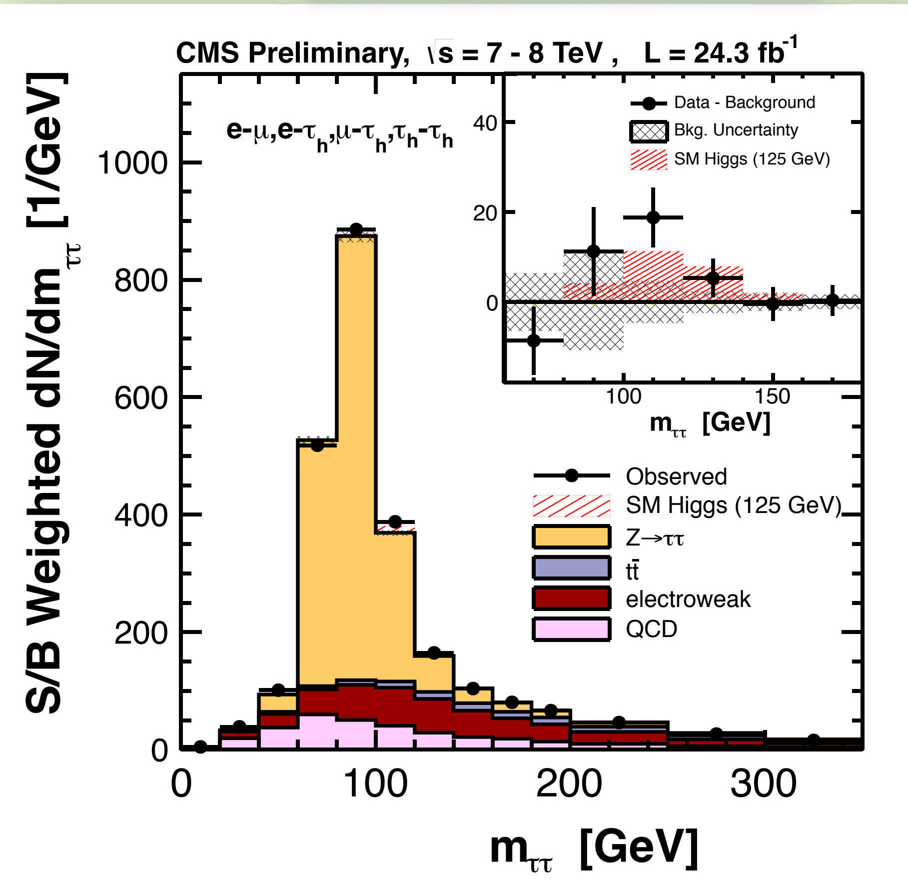
With additional data, significance decreased relative to 4th of July!!

$\mu = 0.77 \pm 0.27$

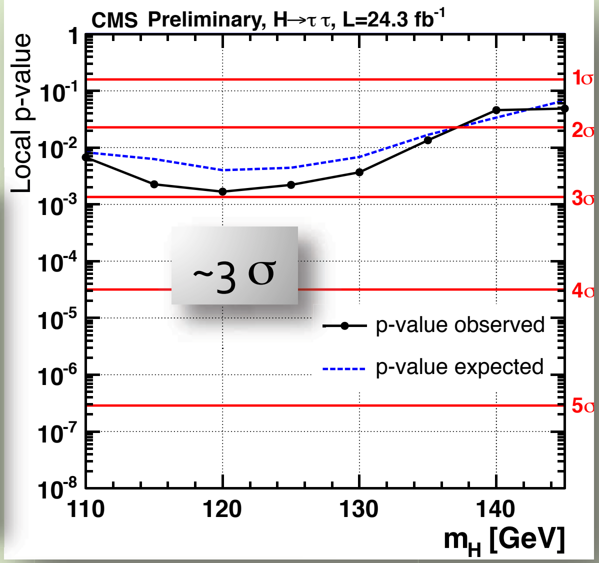

CMS Preliminary
√s = 7 TeV, L = 5.1 fb^{-1} ; √s = 8 TeV, L = 19.6 fb^{-1}
$H \to ZZ^* \to 4$ leptons
Data
Z+X
$Z\gamma^*$,ZZ
m_H=126 GeV
Events / 3 GeV
m_{4l} [GeV]
0
5
10
15
20
25
30
35
80
100
120
140
160
180

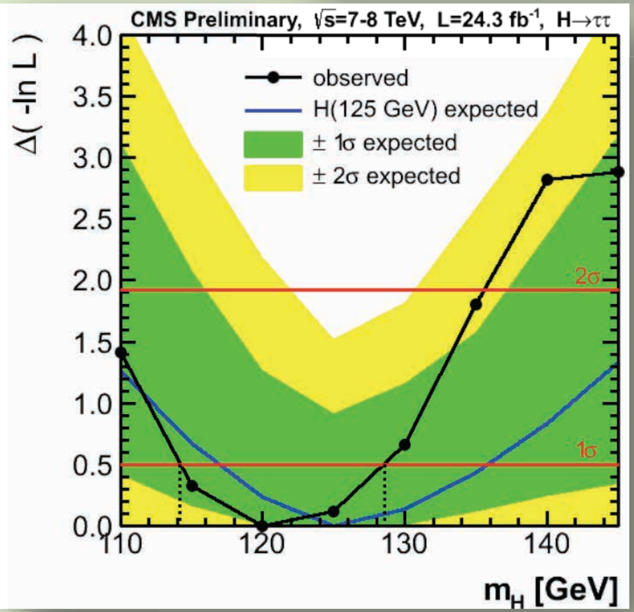
$H \rightarrow \tau\tau$

$\mu\tau_h$, $e\tau_h$, $e\mu$, $\tau_h\tau_h$, $\mu\mu$



First strong indication of decay to spin ½ particles



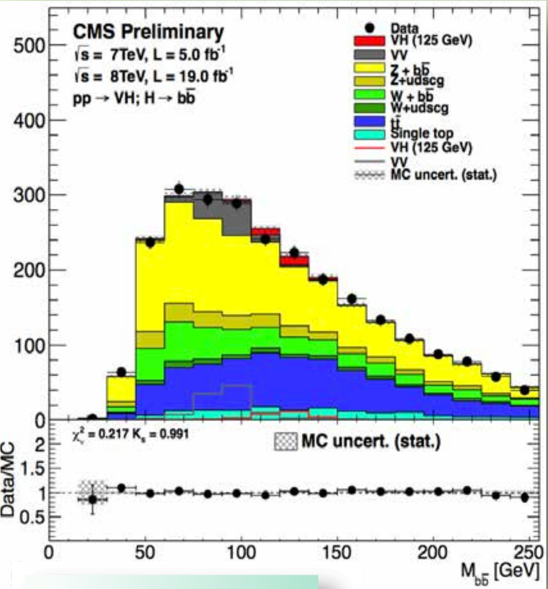


$m = 120^{+9}_{-7}$ GeV

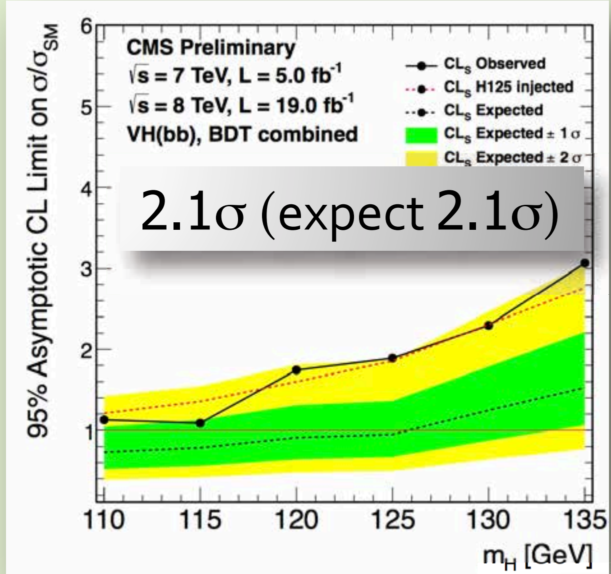
[CMS HIG-13-004](CMS HIG-13-004)

VH, H→$b\bar{b}$

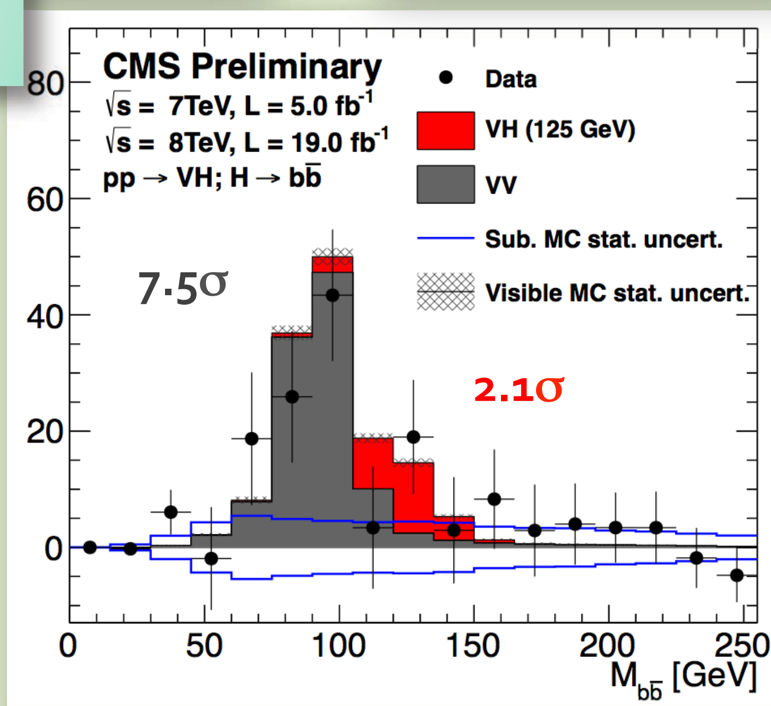
V = W or Z decaying to Electrons, muons, taus, and neutrinos

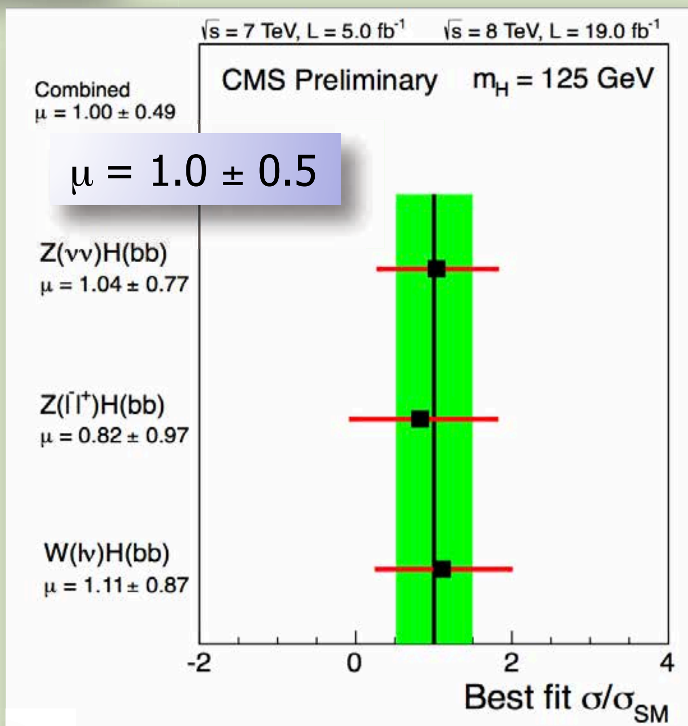


$M_{b\bar{b}}$ all subchannels



2.1σ (expect 2.1σ)

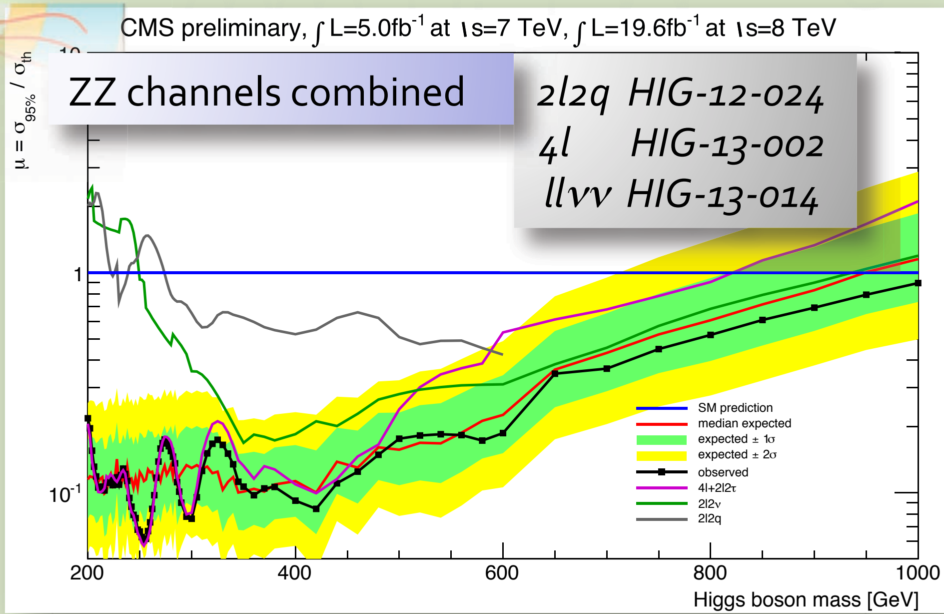


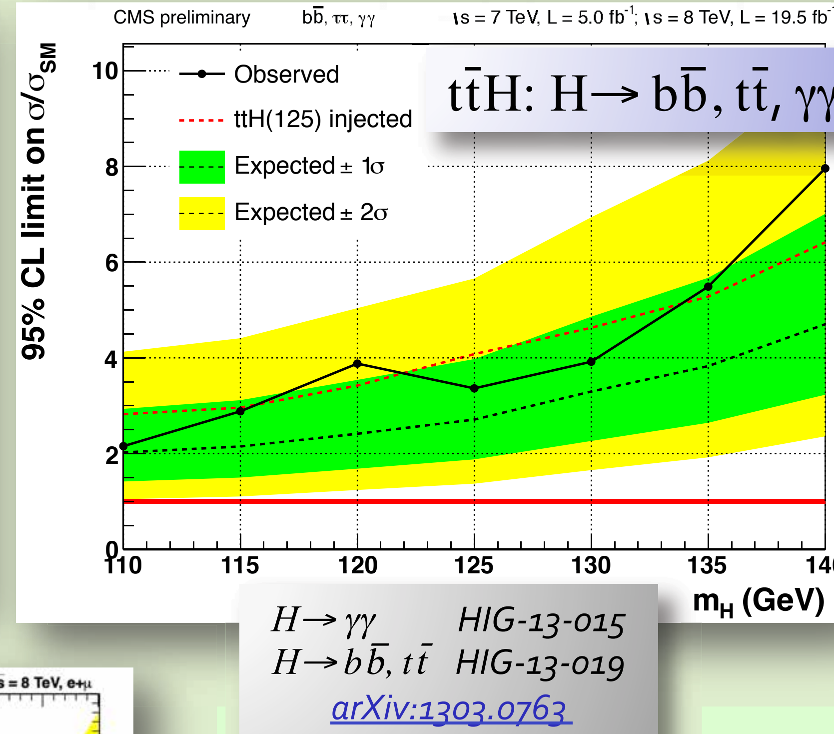


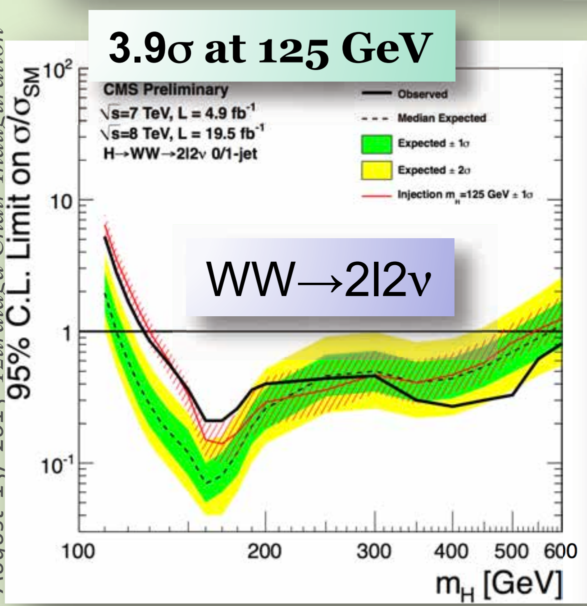
μ = 1.0 ± 0.5

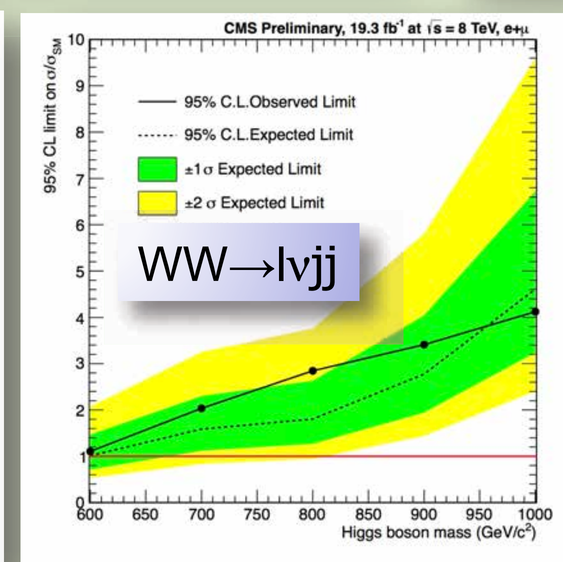
W($\mu\nu$)H, W($e\nu$)H, W($\tau\nu$)H, Z($\mu\mu$)H, Z(ee)H and Z($\nu\nu$)H

WW, High Mass Searches and $t\bar{t}H$ results









Interpretation in EW-singlet models and LHC XS WG benchmark models:

lνjj HIG-13-008

2l2ν HIG-13-014

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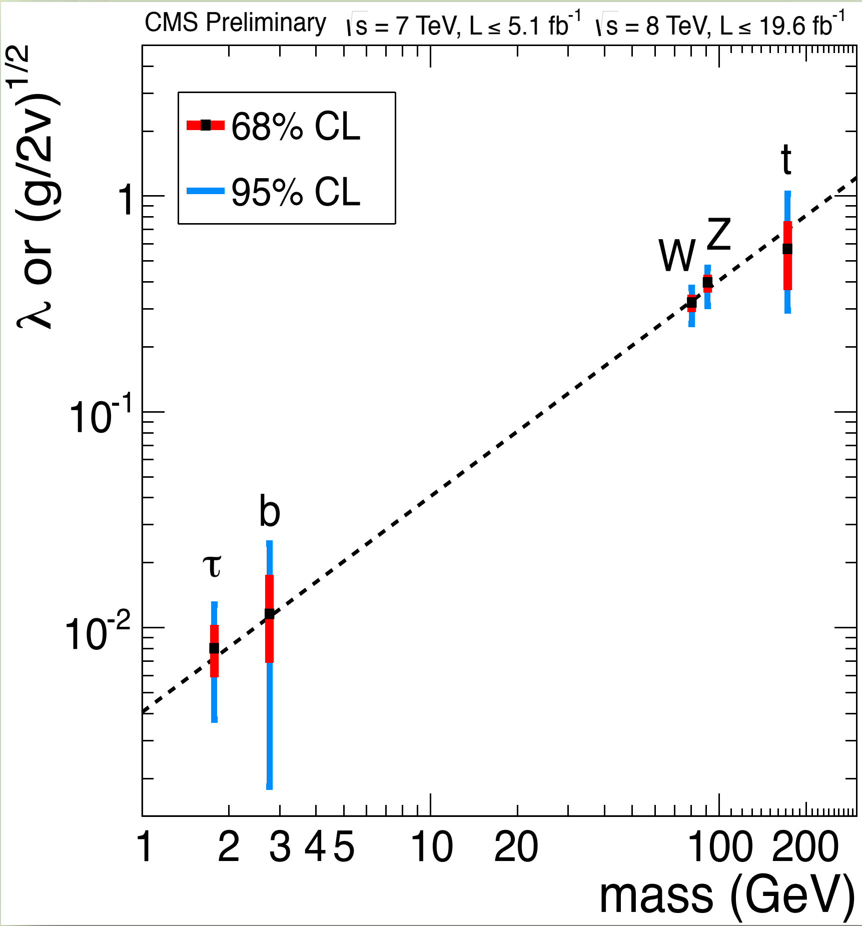
Measured properties



Br(H→χχ) < 75% (91% exp.) @ 95% CL

HIG-13-005

Decay	Expected	Observed
ZZ	7.1 σ	6.7 σ
γγ	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.1 σ
ττ	2.6 σ	2.8 σ

bb + ττ combined: 3.4 σ

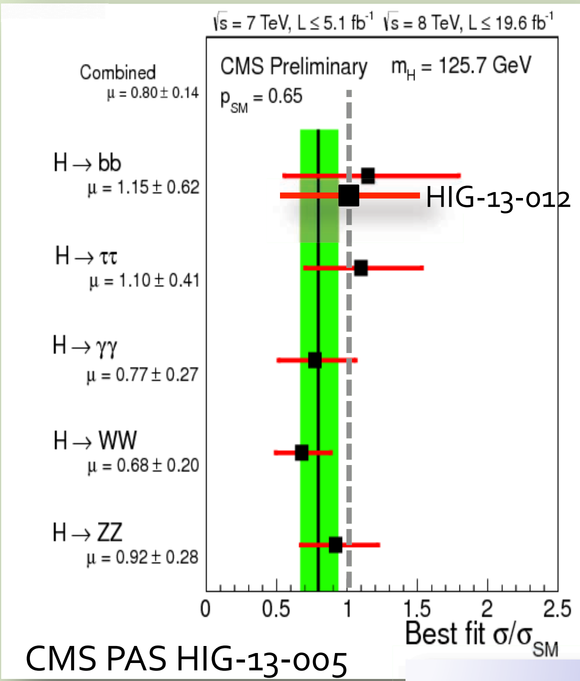
m_H = 125.7

$b\bar{b}$: VH ⊕ VBF
WW: ggF⊕VH⊕VBF

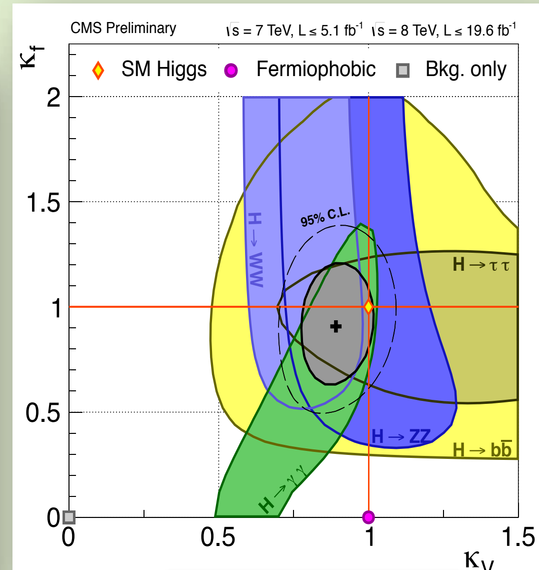
3.4σ Evidence for H→ $f\bar{f}$

σ/σ_{SM}, Mass ($\gamma\gamma \oplus ZZ$), Couplings, J^{PC}

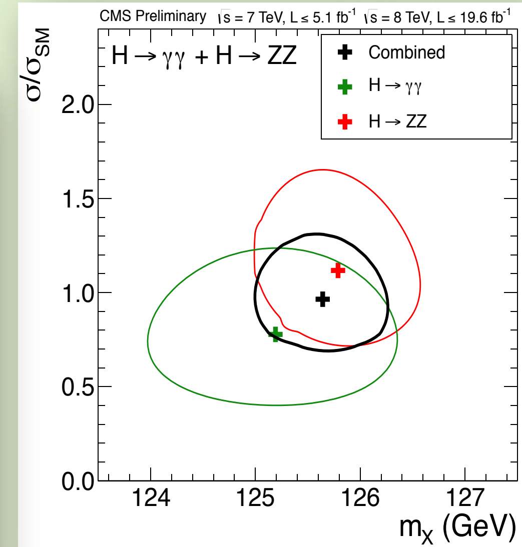
CERN April 15, 2013



μ=0.80±0.14



HIG-13-005



m = 125.7 ± 0.3 ± 0.3 GeV

$\mu = 0.80 \pm 0.14$

- *Negligible change for new VH(bb) result: $\mu = 1.15 \pm 0.62 \rightarrow 1.00 \pm 0.50$*

m = 125.7 ± 0.3 ± 0.3 GeV

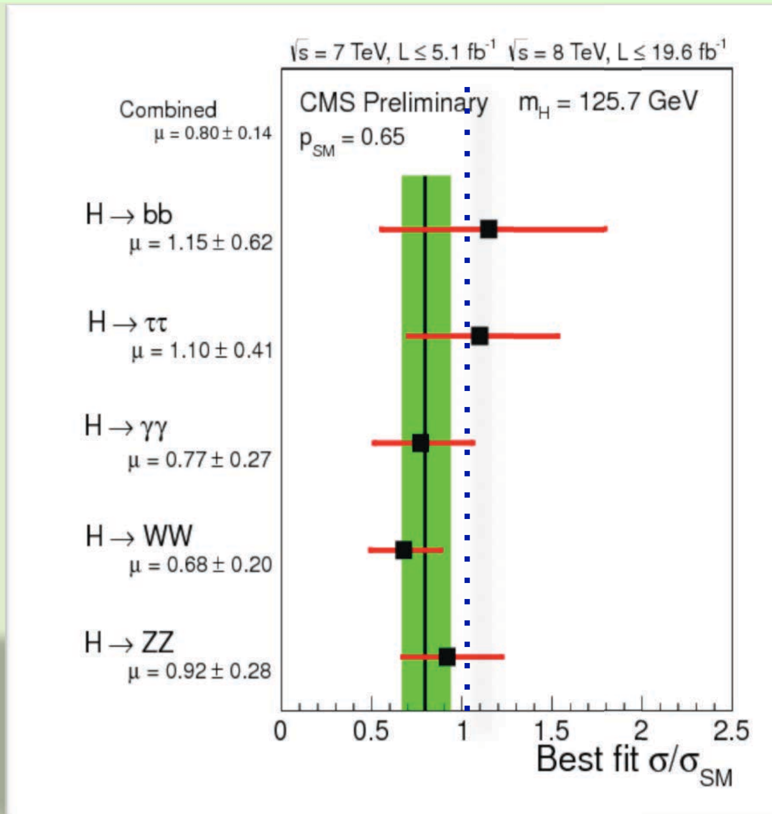
- 0.5% precision already

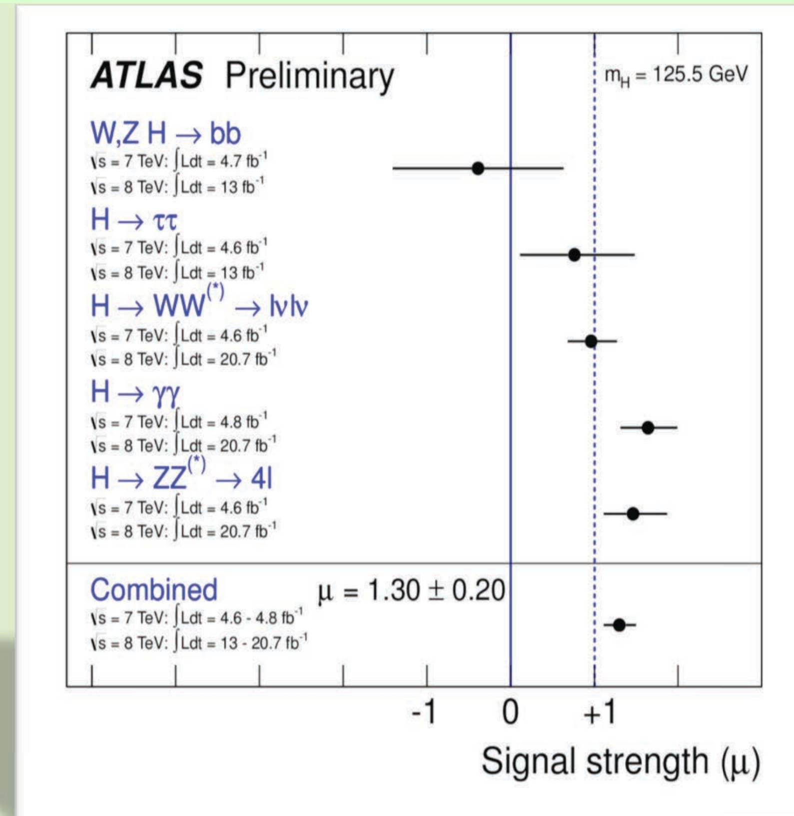
0^{++} is preferred over 2^{++}, 0^{-+} at 2.8, 3.3σ, respectively

ATLAS consistent with CMS and the SM

μ=0.80±0.14

μ=1.30±0.20





m = 125.7 ± 0.3$^{(stat)}$ ± 0.3$^{(syst)}$ GeV

m = 125.5 ± 0.2 $^{+0.5}_{-0.6}$ GeV

A big news week!

Where do we stand now?

The Higgs:
so simple yet so unnatural

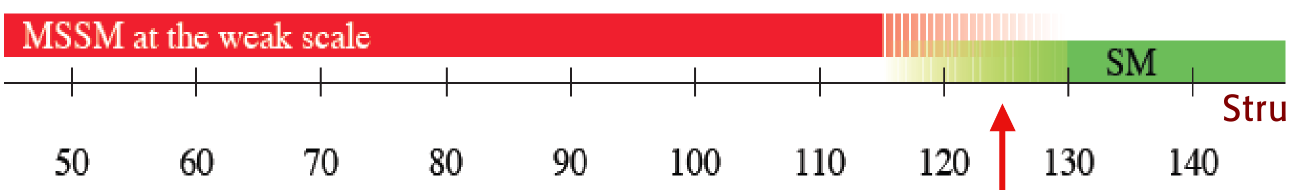
Guido Altarelli

Presentations/discussions *(Nobel Symposium, May 12-17 Uppsala)*

*Talk by G. Altarelli**

A malicious choice!

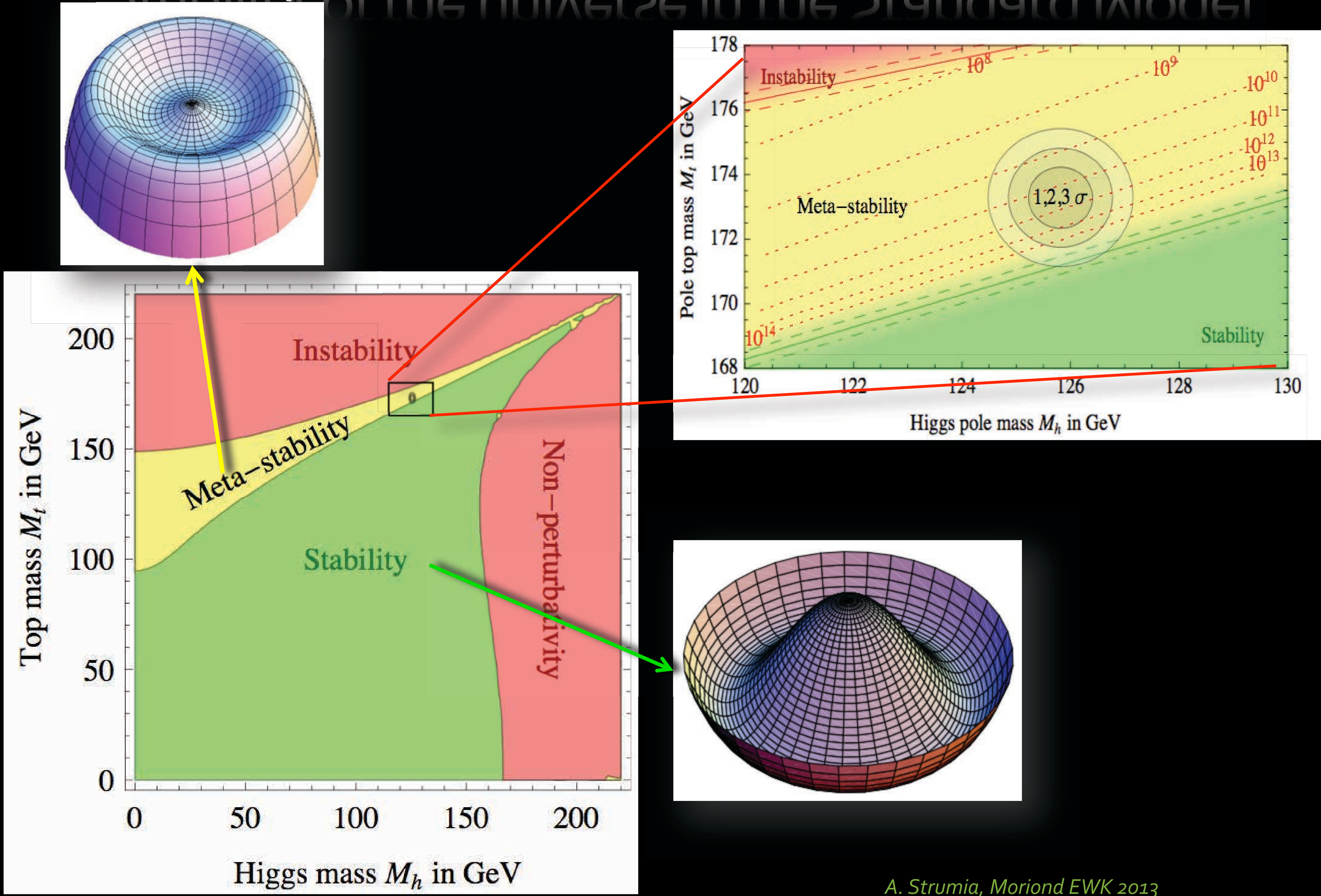
$m_H = 125.6 \pm 0.4$ GeV



Strumia

*G. Altarelli: https://indico.cern.ch/conferenceDisplay.py?confId=239571

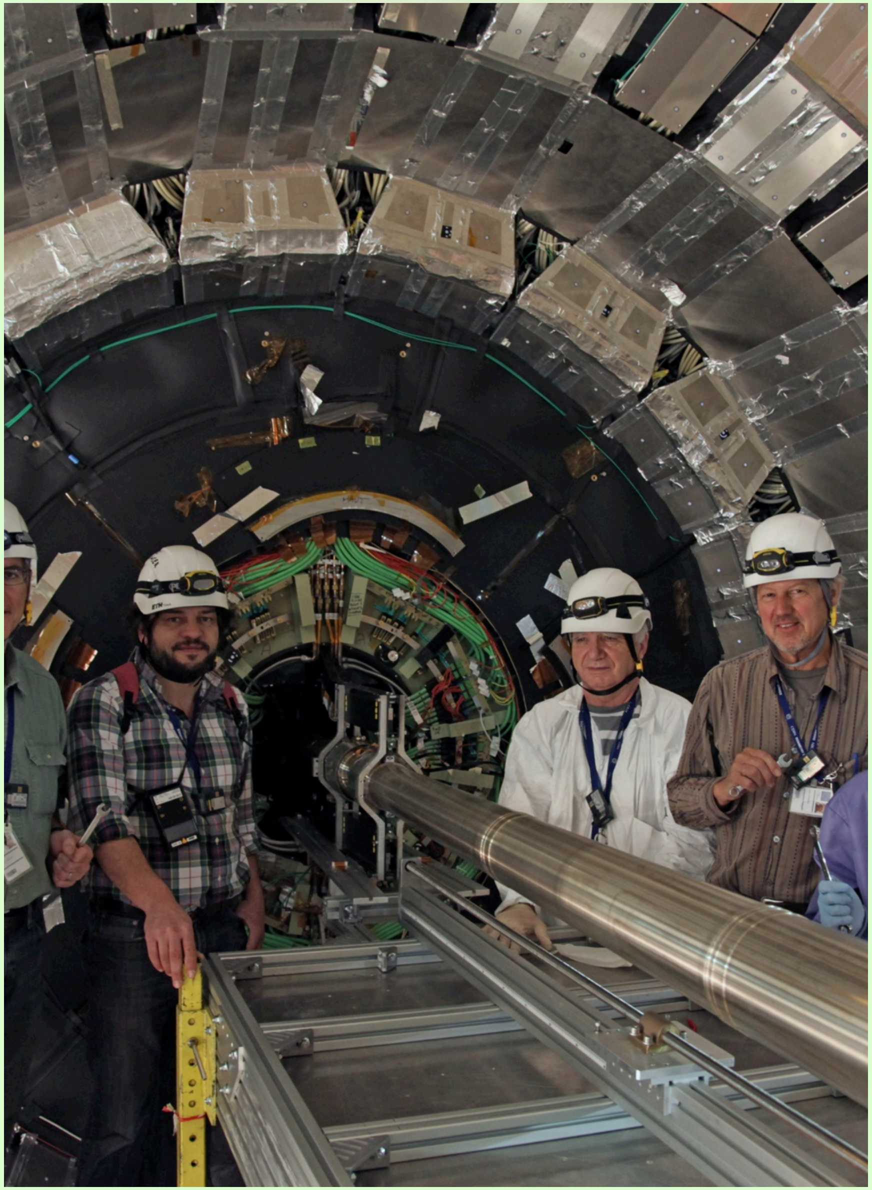
Stability of the universe in the Standard Model



A. Strumia, Moriond EWK 2013

What next?

- H125 is a great discovery
  - More discoveries ahead ?
    - They may just not be quite like we anticipated, just as this scalar boson is not quite where we expected it
- Can only be studied at the LHC
  - It is the only machine left that produce Higgs, (and top and Z and W…) for the next 15+ years.



Getting to know a 'so simple' Higgs…

The precise measurements of Higgs couplings are crucial in order to determine to what extent it is SM

Contino

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 \ldots$$

$$- \left(m_W^2\, W_\mu W_\mu + \frac{1}{2}m_Z^2\, Z_\mu Z_\mu\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right)$$

$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi \frac{h}{v} + c_{2\psi}\frac{h^2}{v^2} + \ldots\right) + \ldots$$

a ~ hVV
c ~ hff

It would really be astonishing if no deviation from the SM is seen!

See talk by G. Altarelli: https://indico.cern.ch/conferenceDisplay.py?confId=239571

...and yet so unnatural

The crisis of the naturalness principle

Has been and is the main motivation for new physics at the weak scale

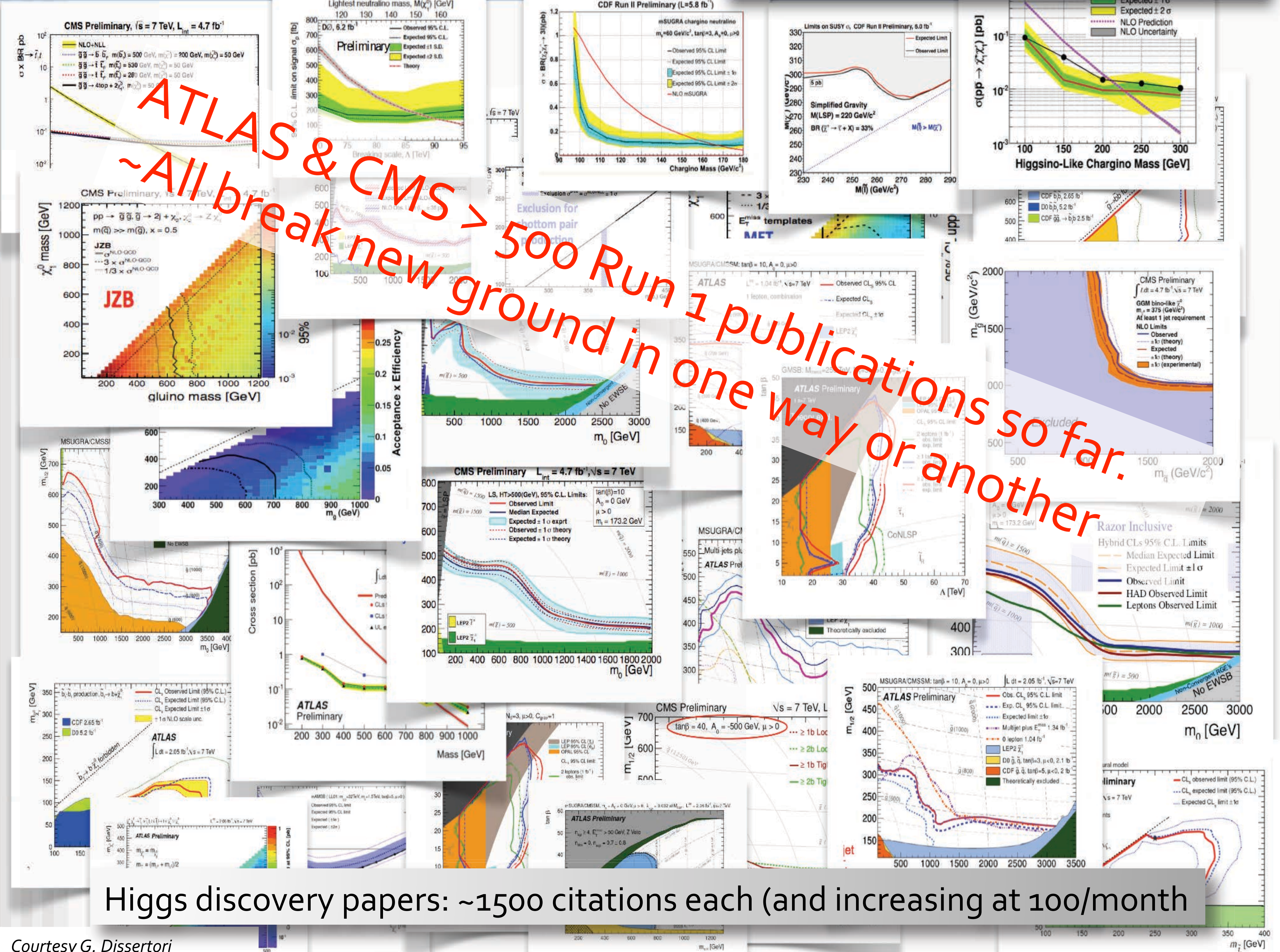
But at present our confidence on naturalness as a guiding principle is being more and more challenged

No indirect evidence of new physics (g-2?)
No direct evidence of new physics at the LHC

Apparently some amount of fine tuning is imposed on us by the data. More now after the LHC7-8 results

Does Nature really care about our concept of Naturalness?
Which form of Naturalness is Natural?

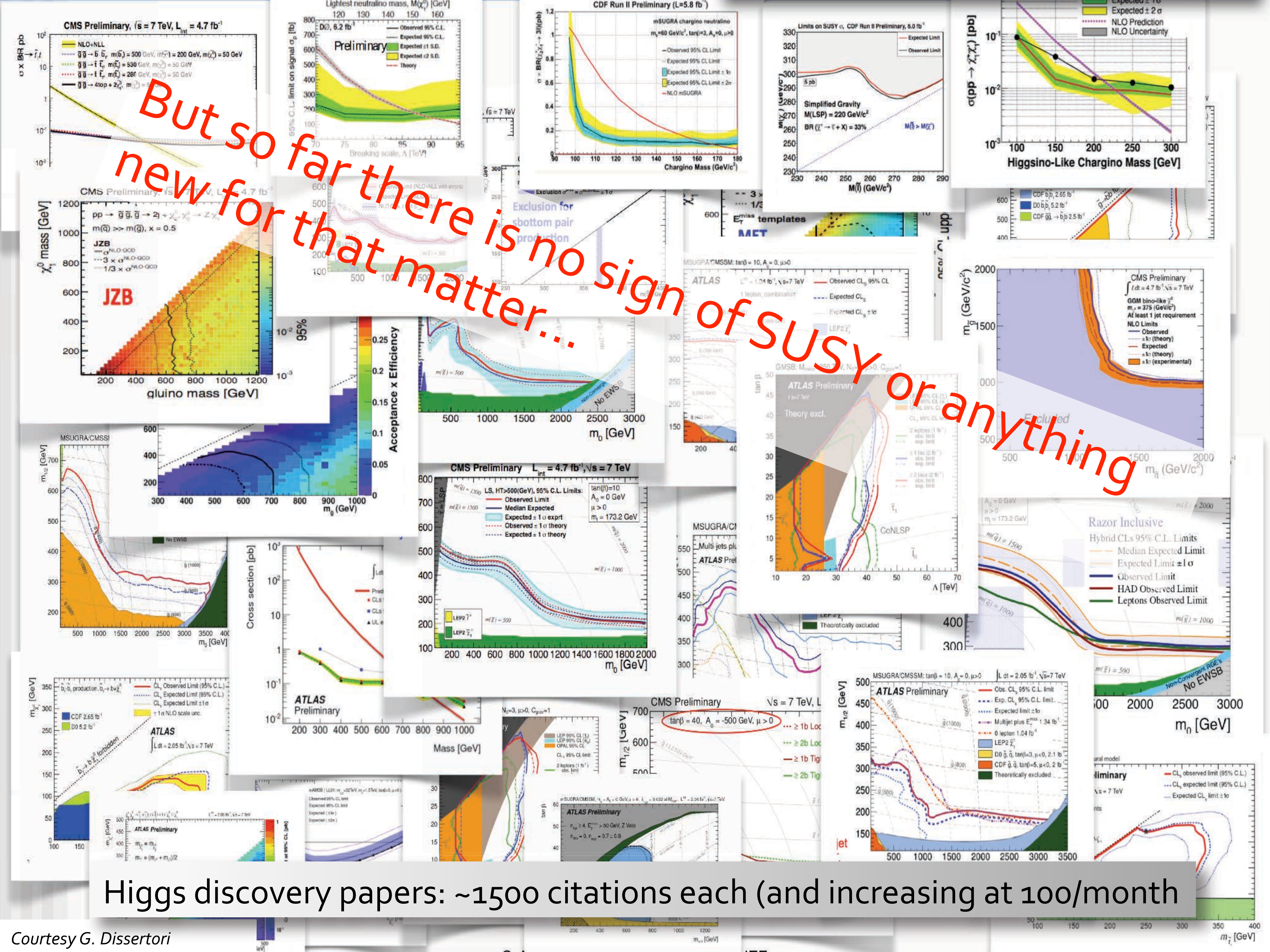
See talk by G. Altarelli: https://indico.cern.ch/conferenceDisplay.py?confId=239571



ATLAS & CMS > 500 Run 1 publications so far.
~All break new ground in one way or another

Higgs discovery papers: ~1500 citations each (and increasing at 100/month

Courtesy G. Dissertori



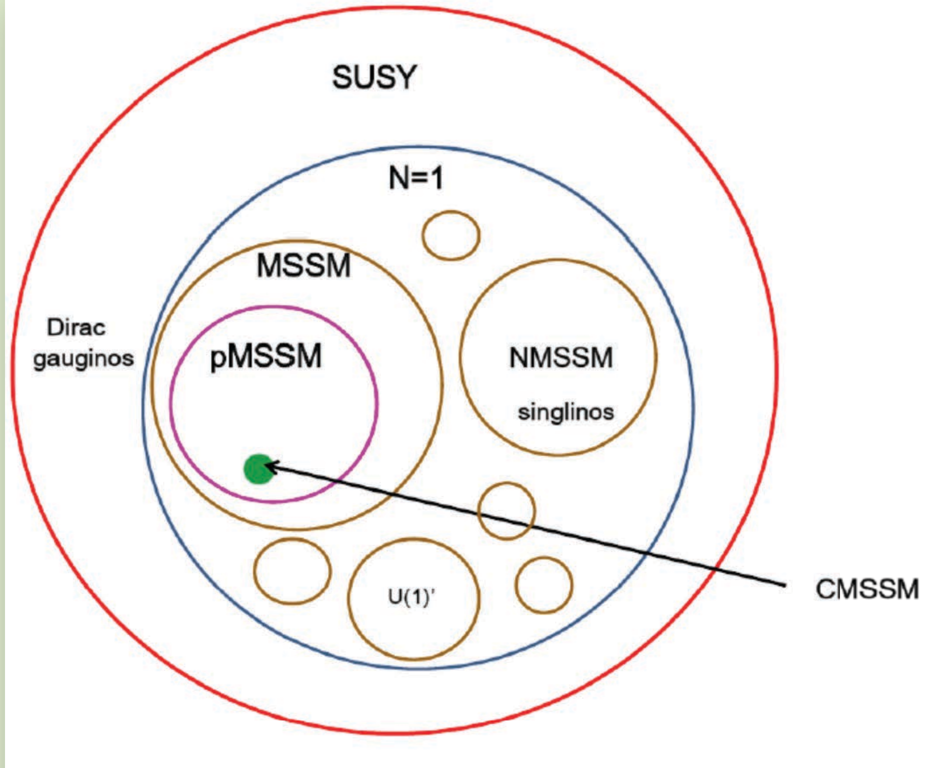
But so far there is no sign of SUSY or anything new for that matter…

Higgs discovery papers: ~1500 citations each (and increasing at 100/month

Courtesy G. Dissertori

Status of SUSY

- Many people thought SUSY would appear early.
  - Instead we excluded SUSY partners of quarks and gluons up to 1 TeV (>1000 times the mass of the proton) and 1.8 TeV, respectively
- Is natural SUSY ruled out?
  - Almost! If you only consider the most *Aristotelean* forms of SUSY
    - E.g. the Constrained Minimal SUSY Model (CMSSM)
- It can still be there but …
  - Maybe at a low mass scale but much more hidden
  - Or at a higher mass scale and still 'natural'



T. Rizzo (SLAC Summer Institute, 01-Aug-12)

What seems "so simple" may just be more complicated…

NMSSM as an example

The Minimal Supersymmetric Model does not explain why the mu parameter in the superpotential term $\mu H_u H_d$ is at the electroweak scale. The idea behind the **Next to Minimal Supersymmetric Model** is to promote the mu term to a gauge singlet, chiral superfield S. Note that the scalar superpartner of the singlino S is denoted by $\hat{S}$ and the spin-1/2 singlino superpartner by $\tilde{S}$ in the following. The superpotential for the NMSSM is given by

$$W_{\mathrm{NMSSM}} = W_{\mathrm{Yuk}} + \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

where W_{Yuk} gives the Yukawa couplings for the Standard Model fermions. Since the superpotential has mass dimension three, the couplings λ and κ are dimensionless, hence the mu problem of the MSSM is solved in the NMSSM – the superpotential of the NMSSM is scale invariant. The role of the λ term is to generate an effective μ term. This is done with the scalar component of the singlet $\hat{S}$ getting a vacuum-expectation value $\langle \hat{S} \rangle$, that is, we have $\mu_{\mathrm{eff}} = \lambda \langle \hat{S} \rangle$. Without the κ term the superpotential would have a U(1)' symmetry, so-called Peccei–Quinn symmetry; see Peccei–Quinn theory. This additional symmetry would alter the phenomenology completely. The role of the κ term is to break this U(1)' symmetry. The κ

What seems "so simple" may just be more complicated…

NMSSM example
- *R. Barbieri**

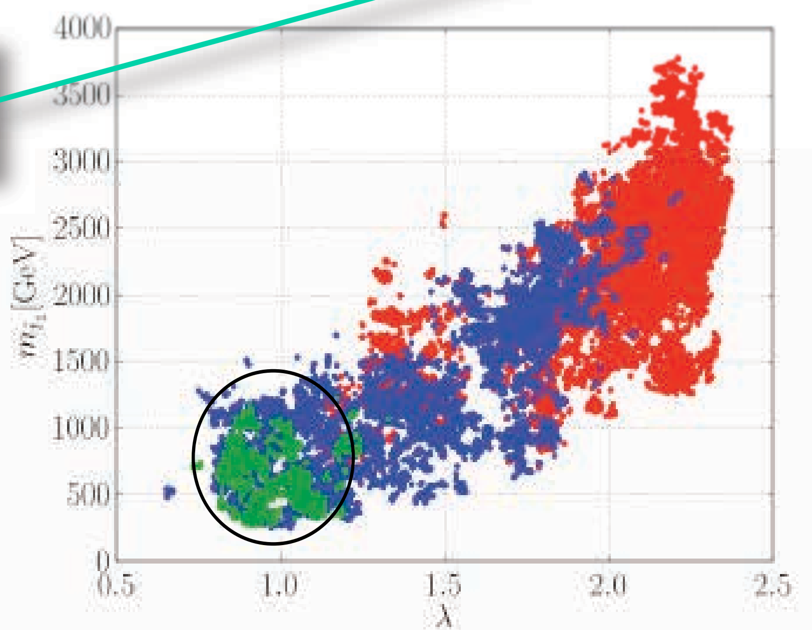
Fayet 1975

Two independent reasons to consider it:

1. Add an extra contribution to $m_{hh}^2 = m_Z^2 c_{2\beta}^2 + \Delta_t^2 + \lambda^2 v^2 s_{2\beta}^2$
   thus allowing for lighter stops
2. Alleviates fine tuning in v for $\lambda \gtrsim 1$ and moderate $\tan\beta$

$$\frac{dv^2}{dm_{H_u}^2}|_{NMSSM} \approx \frac{\kappa}{\lambda^3}\cot 2\beta \quad \text{versus} \quad \frac{dv^2}{dm_{H_u}^2}|_{MSSM} \approx \frac{4}{g^2}$$

2-way balance becomes 3-way



green points have better than 5% "combined" fine-tuning and $\Lambda_{mess} = 20\ TeV$ in the scale invariant NMSSM

$$m_{\tilde{t}_1} < 1.2\ TeV$$
$$m_{\tilde{g}} < 3\ TeV$$

Gherghetta et al 2012

*R. Barbieri: https://indico.cern.ch/conferenceDisplay.py?confId=239571

An obvious gap

Belief in Principles Paid Off

$0, \frac{1}{2}, 1, \frac{3}{2}, 2$

Higgs is first "really new" particle we've seen

An Obvious Gap!

$\{0, \frac{1}{2}, 1, \frac{3}{2}, 2\}$

POSSIBLE, VERY SPECIAL!

SUPERSYMMETRY

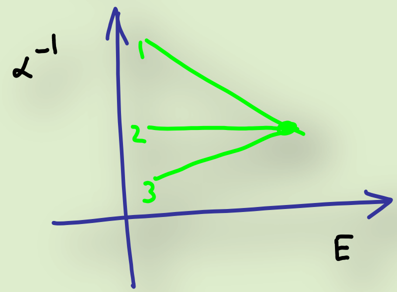
See talk by Nima Arkani-Hamed at Edinburgh Higgs Symposium, January 2013

SUSY is hard to ignore

Supersymmetry

* Last Consistent Possibility
* Dramatic extension of Spacetime

SUSY circa 1990



+ D.M.

SPECTACULAR

See talk by Nima Arkani-Hamed at Edinburgh Higgs Symposium, January 2013

Nature is natural: SPLIT SUSY?

THIS SPECTRUM

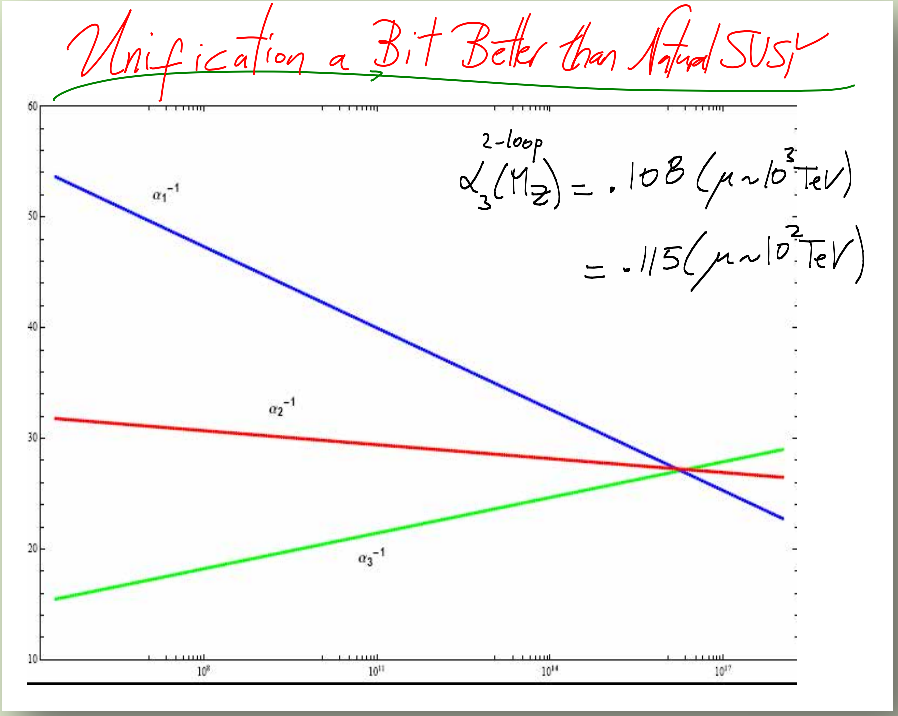
~ 100 TeV scalars

– 1000

~ 10^{-4} – 10^{-6} tuned

~ TeV fermions

IS WHAT SUSY MODELS "WANT TO DO." LET THEM!



See talk by Nima Arkani-Hamed at Edinburgh Higgs Symposium, January 2013

Data is king…

- Experimentation has a critical role now
- Expanding our capabilities is absolutely crucial
- Detectors must be upgraded to have greater capabilities
  - But there is very limited support for R&D in the US
- Accelerators must be upgraded or new ones built
  - Nations need to work together. Europe and Asia are moving forward with strength but the US is not
    - US plans to cut funding for the LHC in the next few years

New physics is out there

But do we have the tools to find it? Will we have the support we need?

EU strategy update document*

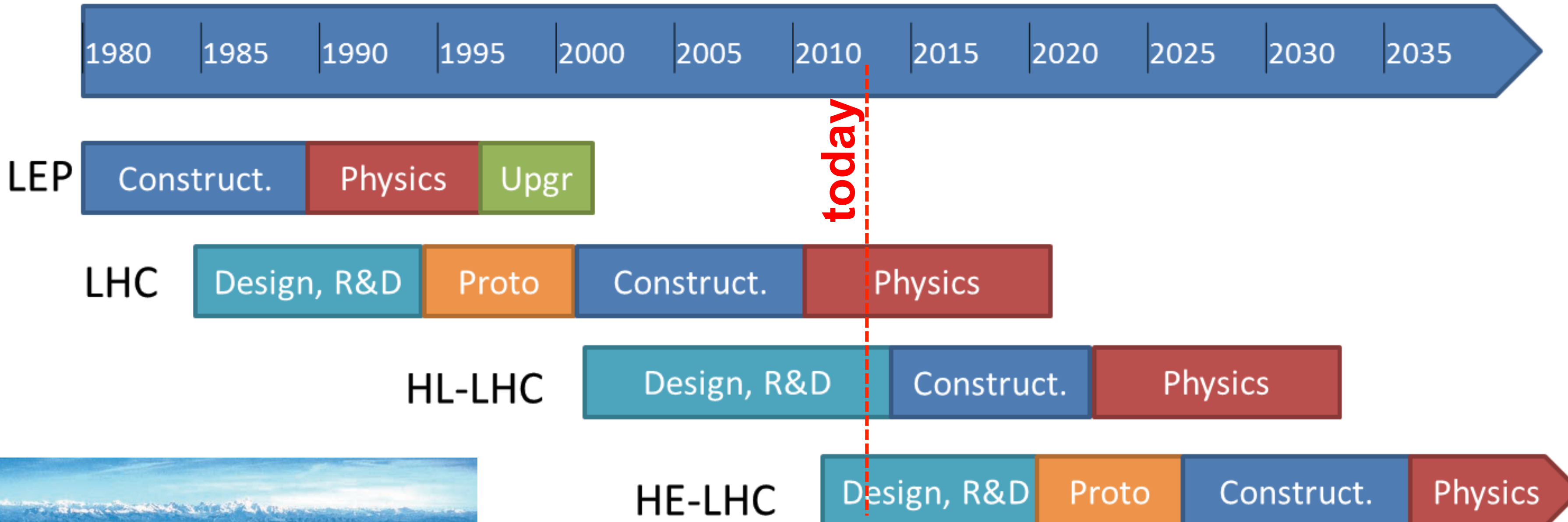
The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. ***Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.*** This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

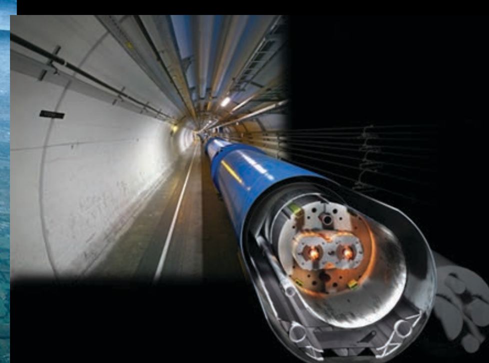
* *Approved May 2013 by Council*

Courtesy L. Rossi

Unprecedented potential

The super-exploitation of the CERN complex:
Injectors, LEP/LHC tunnel, infrastructures





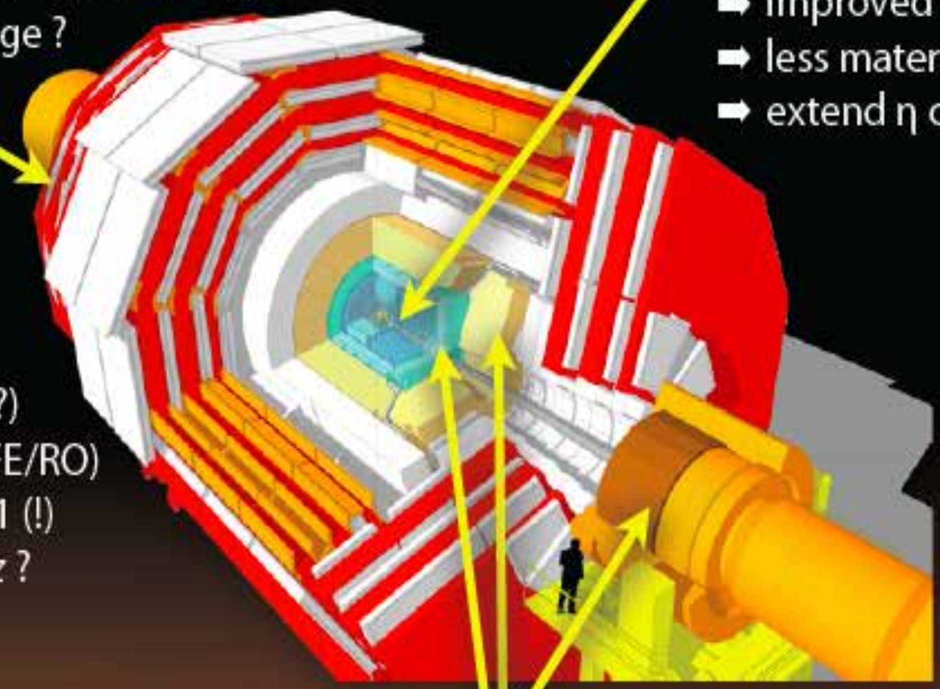
2000 large magnets of 15-20 T
1500 tons of HEP grade Nb3Sn
500 tons of HTS for magnets
100 tons of SC for Sc links

Courtesy L. Rossi

CMS Phase-2 Upgrades

- Muons
  - ➡ complete RPCs in forward region with new technology, GEM or GRPCs
  - ➡ extend η coverage ?

- new Inner Tracker
  - ➡ radiation hardness
  - ➡ better granularity and faster links
  - ➡ improved precision
  - ➡ less material
  - ➡ extend η coverage ?

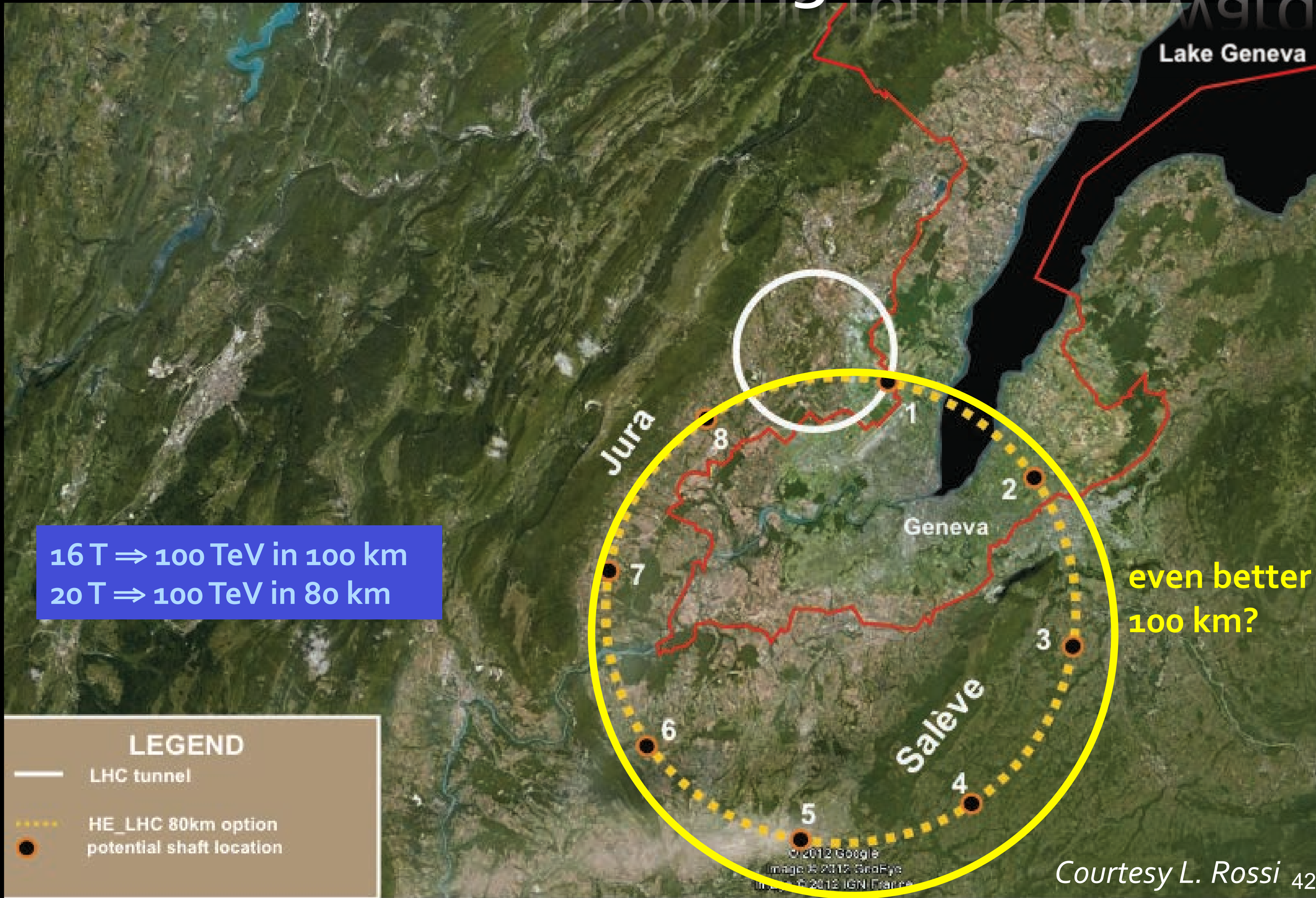


- T/DAQ
  - ➡ Level-1 at 1 *MHz* (?) (requires all new FE/RO)
  - ➡ Tracking at Level-1 (!)
  - ➡ HLT output 10 *kHz* ?

Technical Proposal in 2014

- upgrade/replace Forward Calorimeters
  - ➡ extend η coverage ?
  - ➡ mitigate pileup effects with tracking and precise timing

Looking further forward



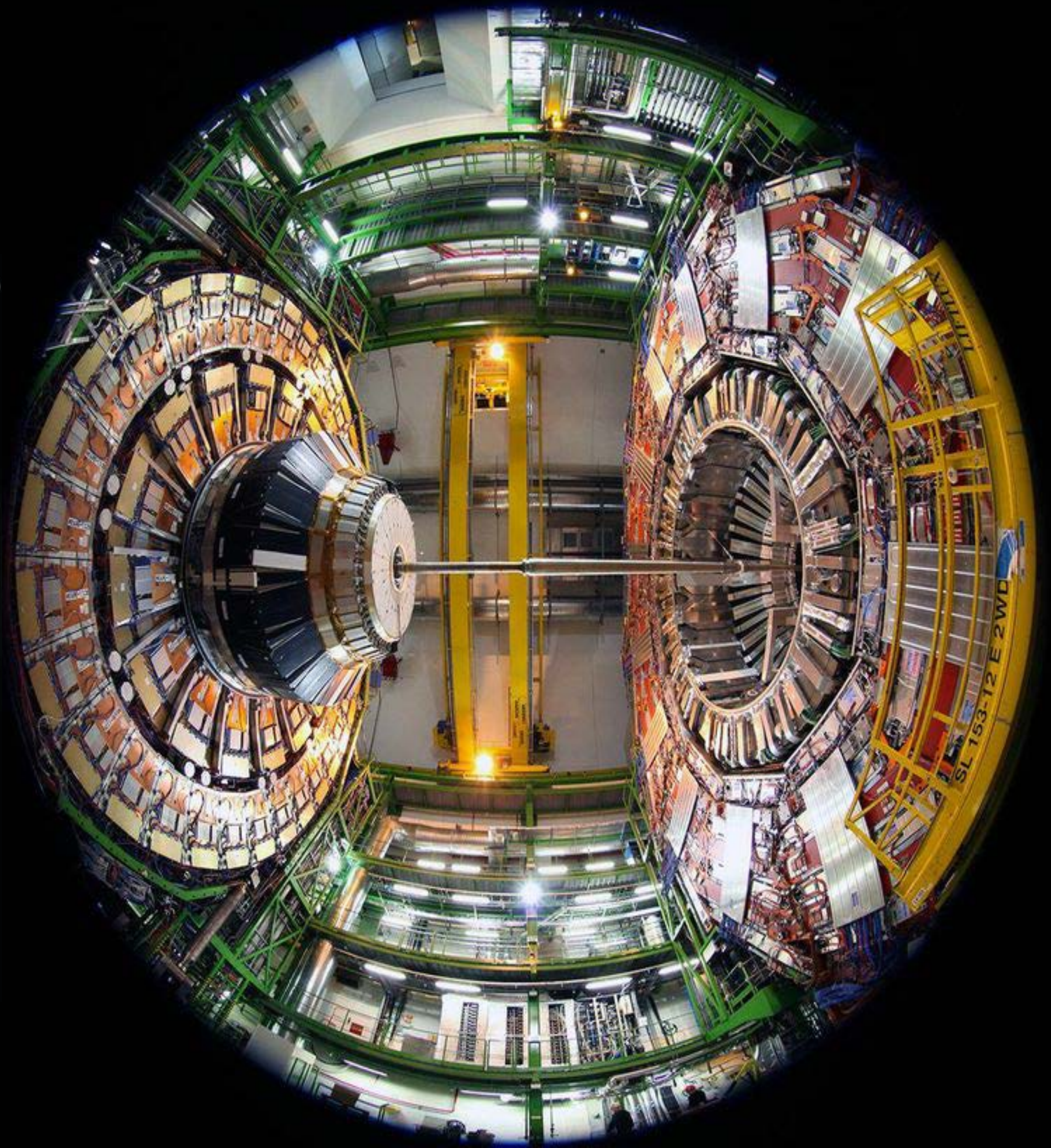
16 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km

even better
100 km?

Courtesy L. Rossi

What will we see next?

- We really don't know
- This is exploration



Many, many thanks to Pat and Joe Yzurdiaga!

Basic research in experimental science is the cornerstone of the greatest scientific legacy of all time.

Their gift provides key support in a key but difficult time