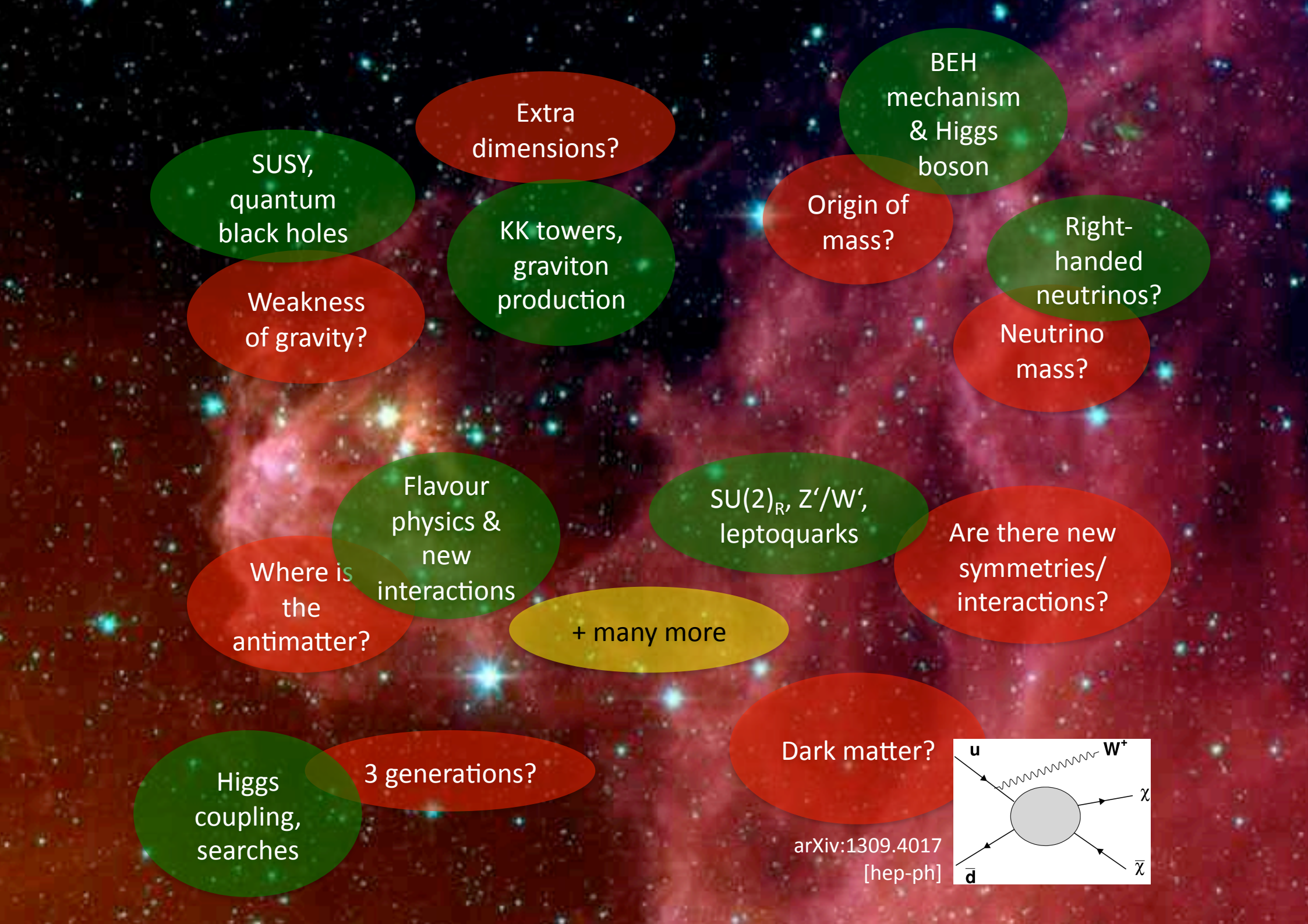
LHC

What has been accomplished?
What lies ahead?

Mike Flowerdew, MPP Munich

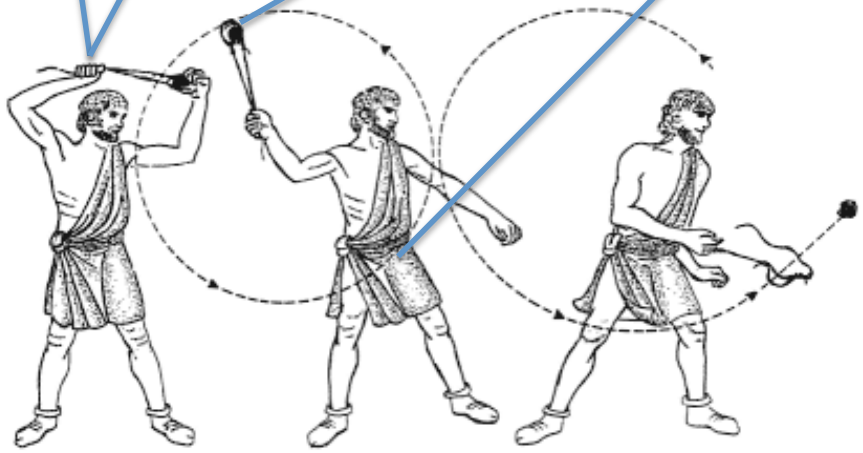
Science week, 04/12/13

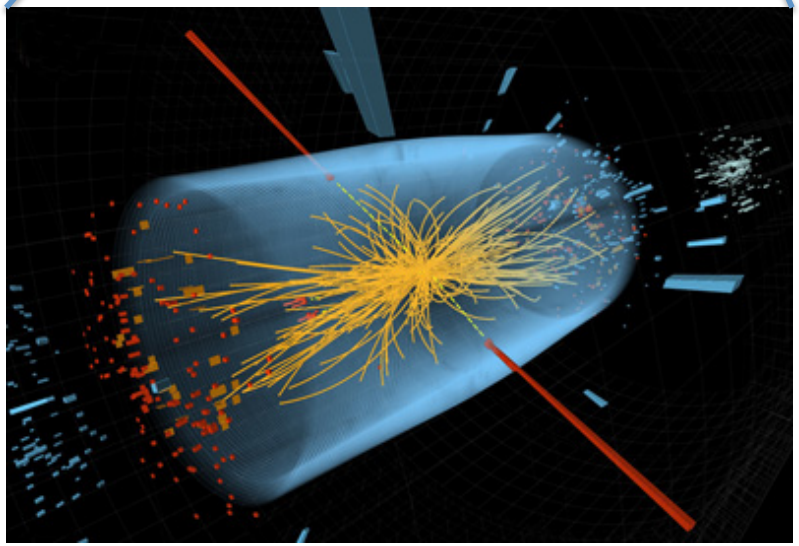

Extra dimensions?
Origin of mass?
Weakness of gravity?
Neutrino mass?
Some big questions
Are there new symmetries/ interactions?
Where is the antimatter?
Dark matter?
3 generations?

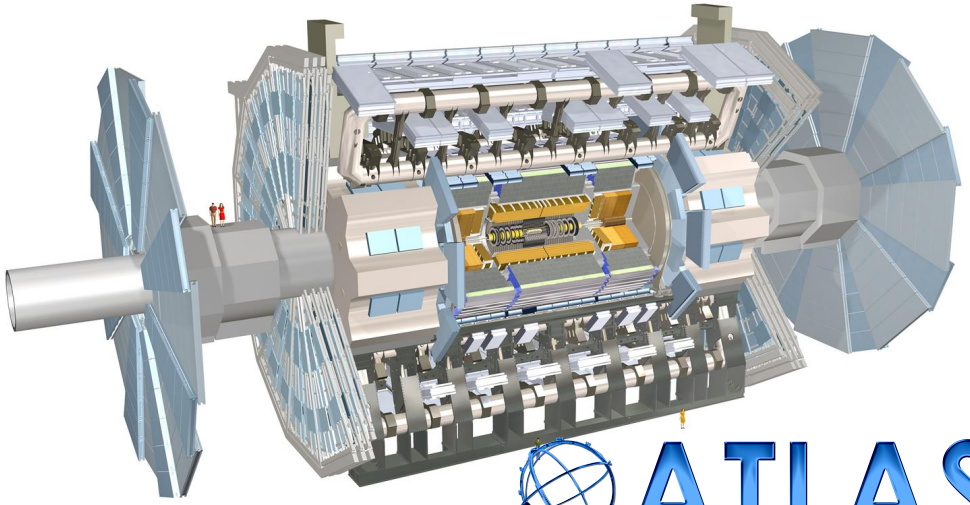


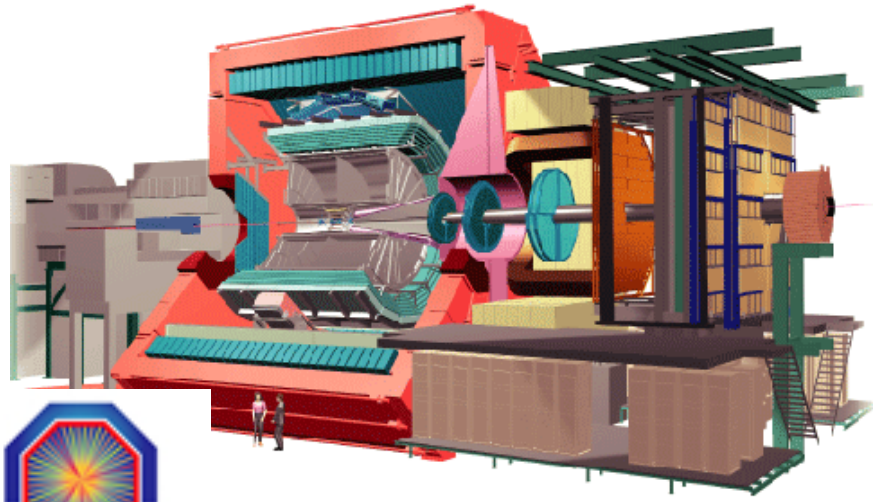
arXiv:1309.4017 [hep-ph]

The Large Hadron Collider







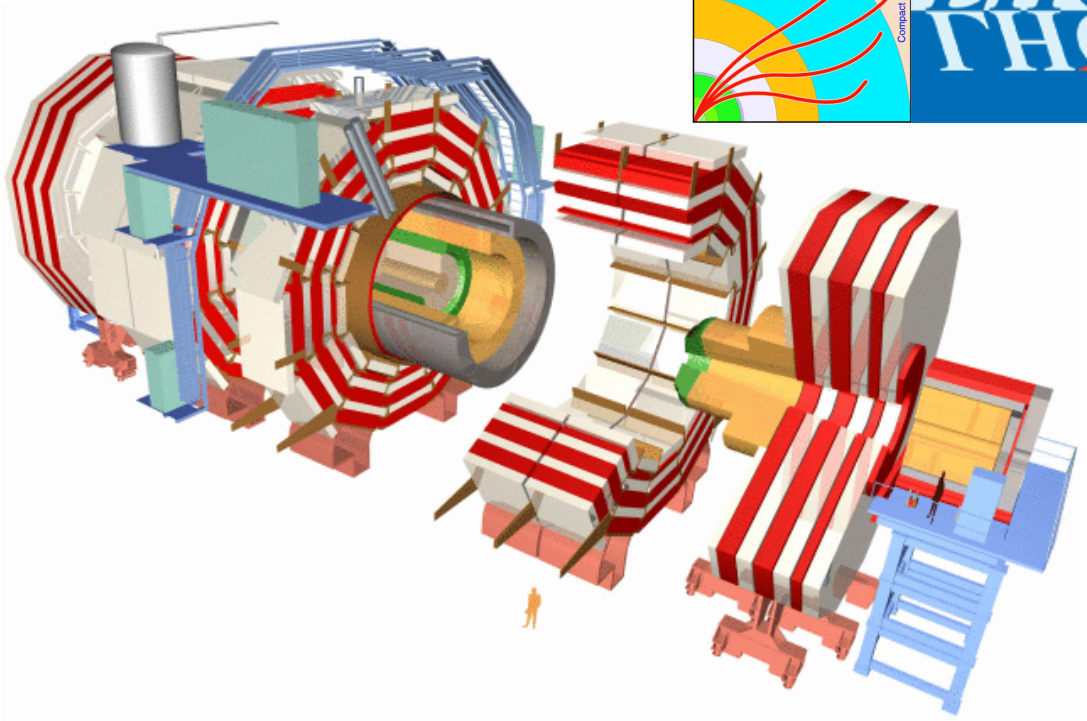


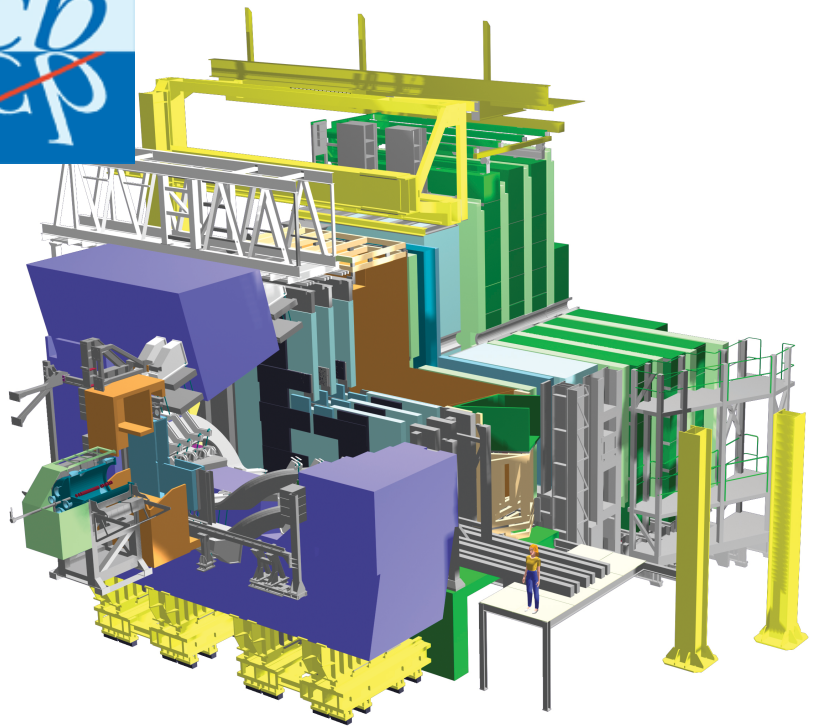
ATLAS EXPERIMENT

ALICE

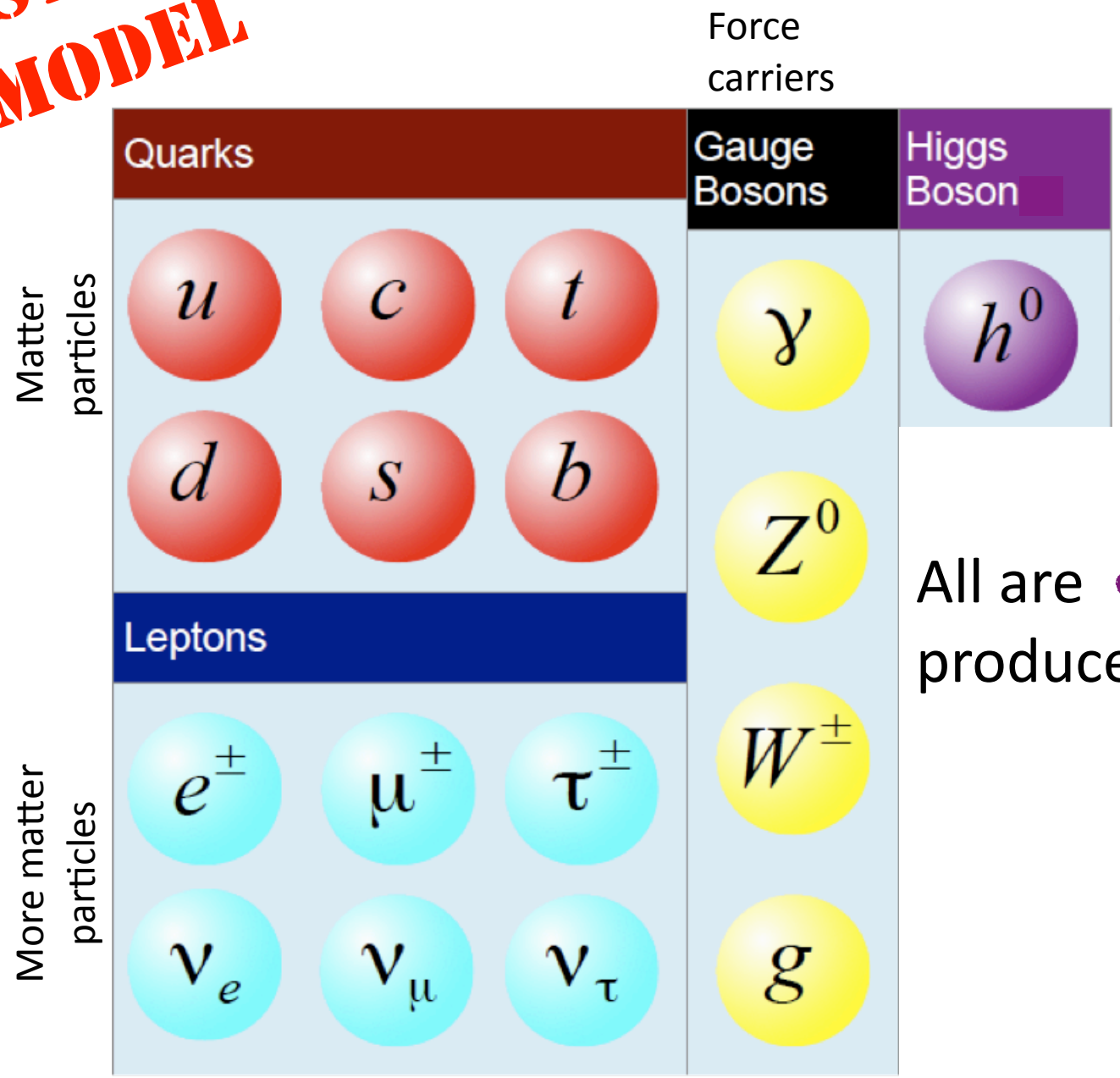
CMS Compact Muon Solenoid

LHCb

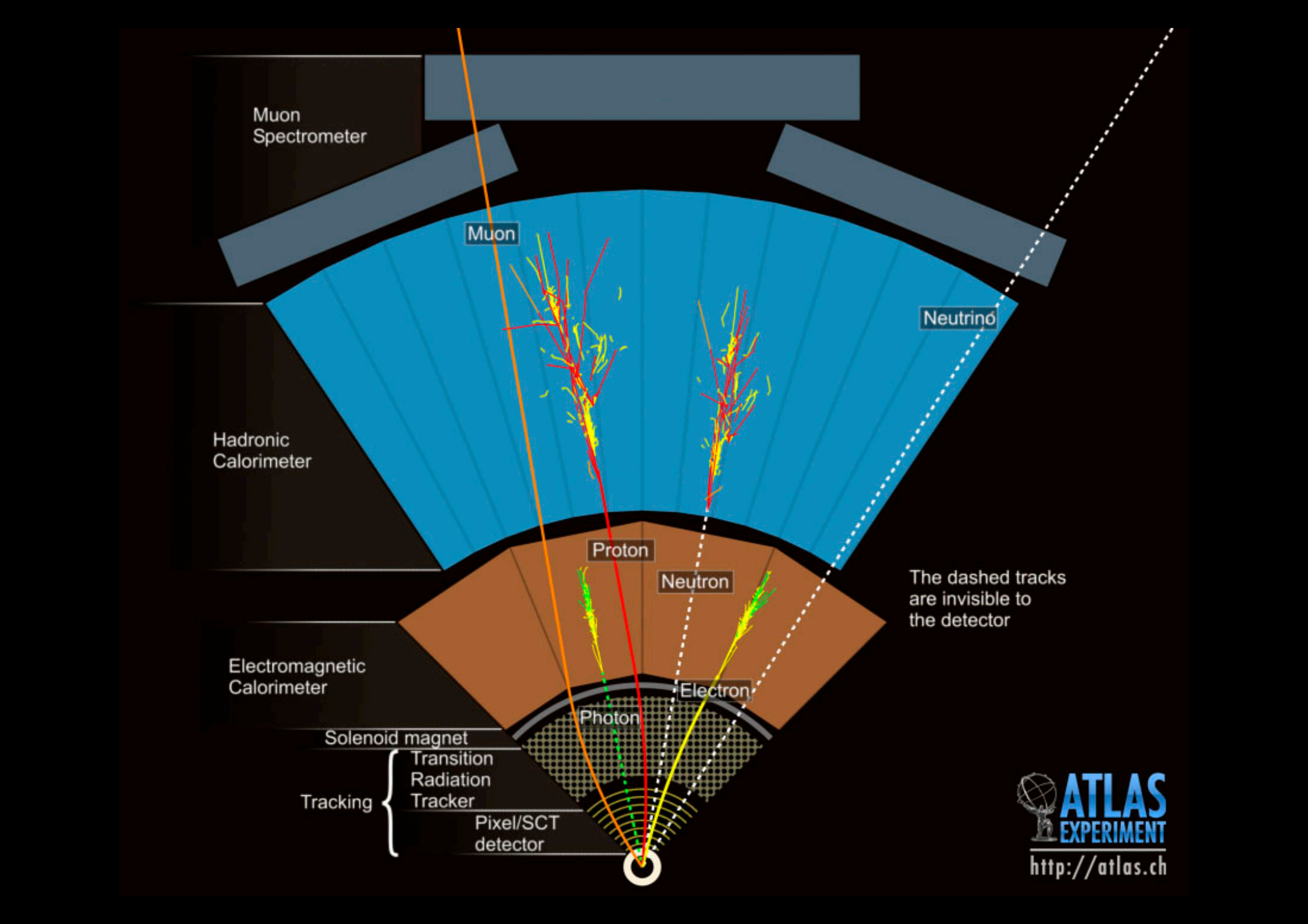




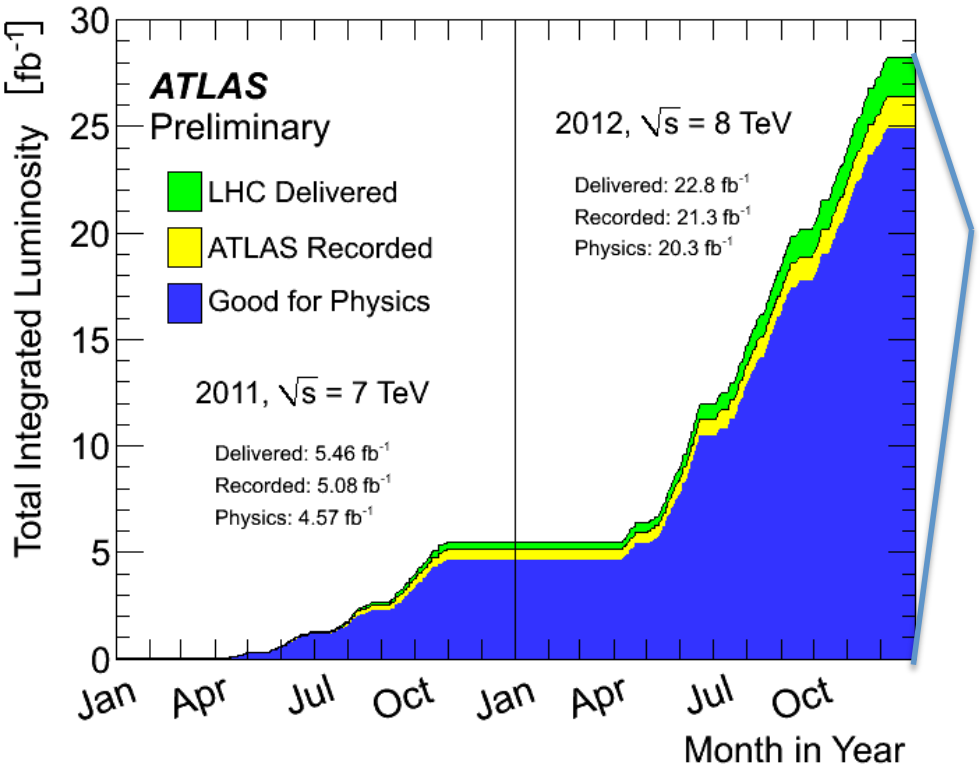
THE STANDARD MODEL℠



All are or should be produced at the LHC


Muon
Spectrometer
Muon
Neutrino
Hadronic
Calorimeter
Proton
Neutron
The dashed tracks
are invisible to
the detector
Electromagnetic
Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
ATLAS
EXPERIMENT
http://atlas.ch

Run I summary



LUMINOSITY

We need data, and lots of it!

2,000,000,000,000,000 p-p collisions per experiment in 2 years

- Lots of chances to produce exceptionally rare processes
- Only about one in a million events recorded

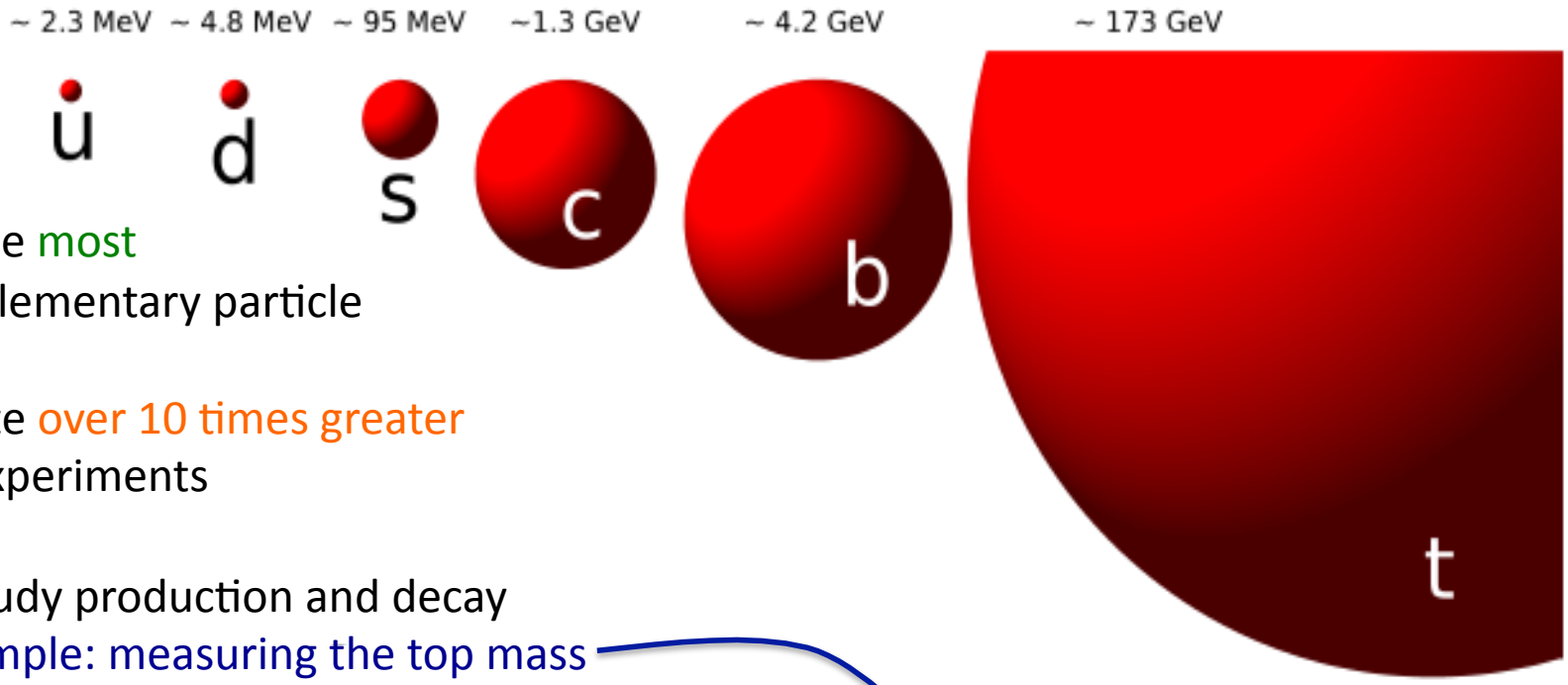
All achieved at reduced collision energy following 2008 incident

- **Full repairs now underway for Run II**

ENERGY

Year	Energy [TeV]
2009	0.9-2.36
2010-2011	7
2012	8
2015-?	13

Precision measurements

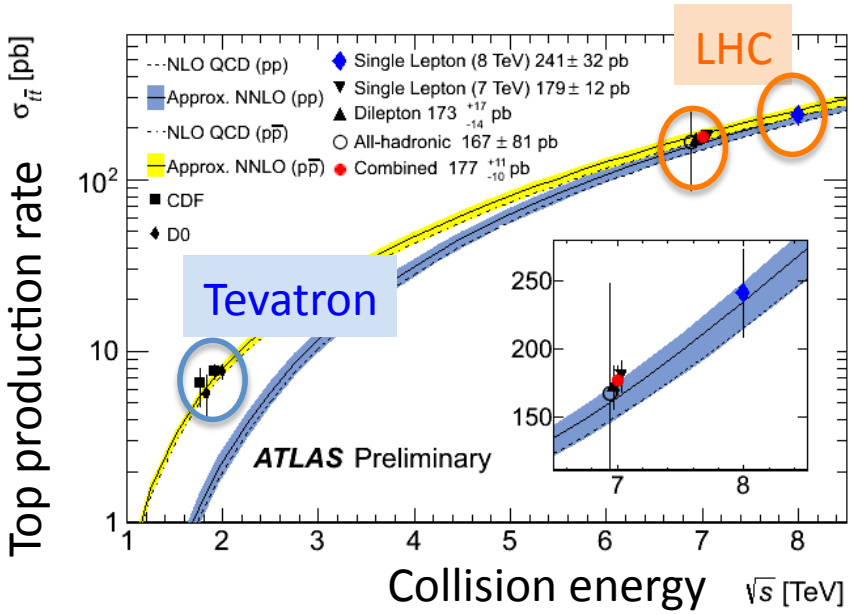


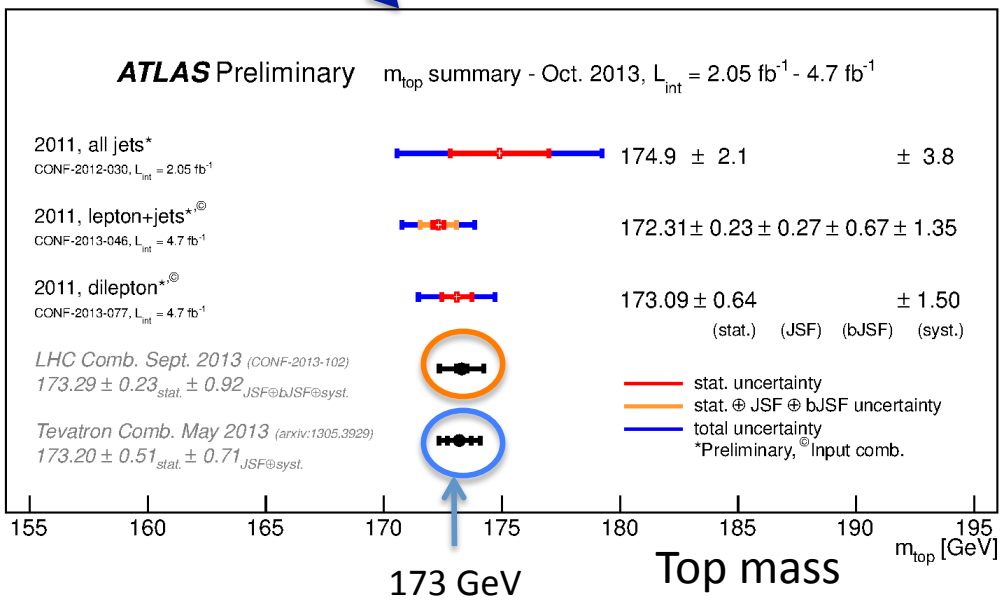
The top quark is the most massive (known) elementary particle

LHC production rate over 10 times greater than in previous experiments

Large sample to study production and decay

Example: measuring the top mass

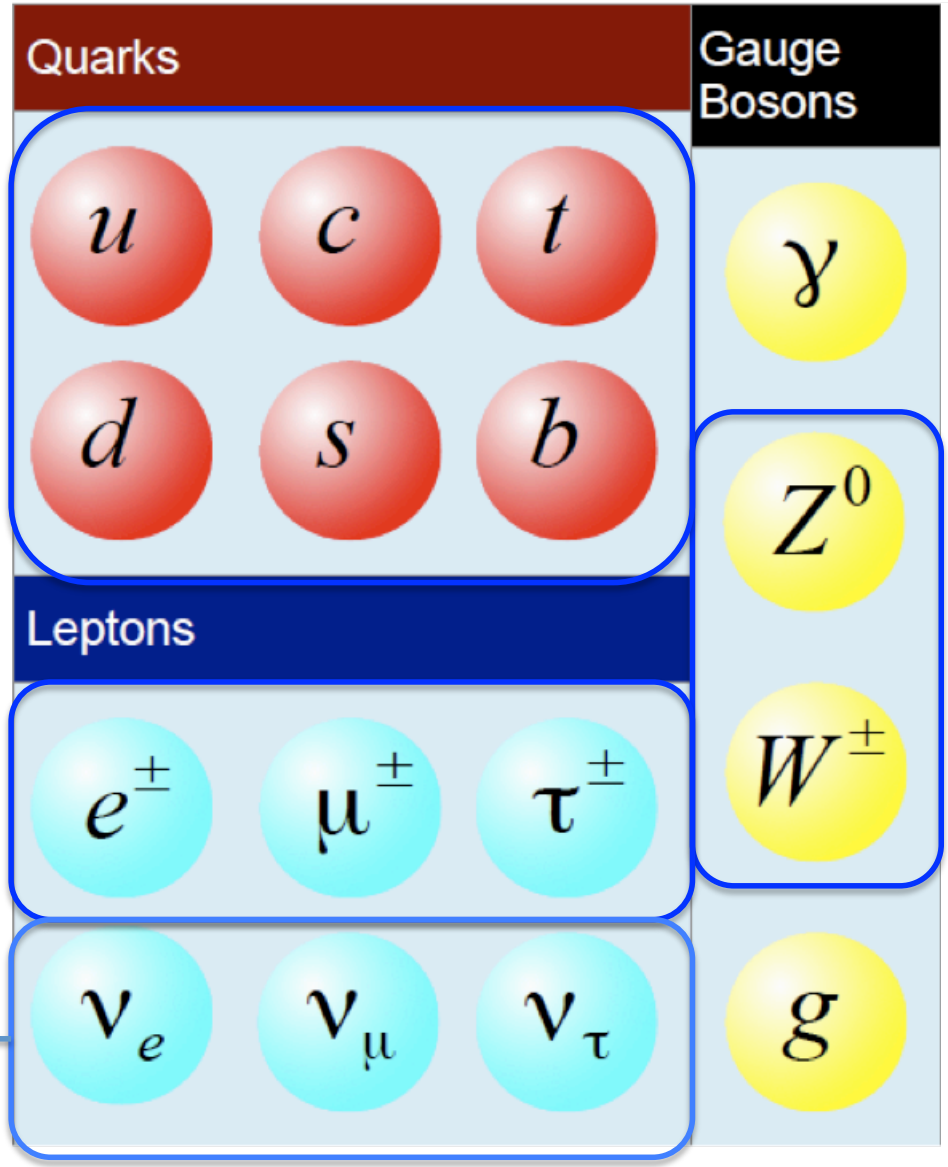




Observed particles (pre-LHC)

Particles with mass

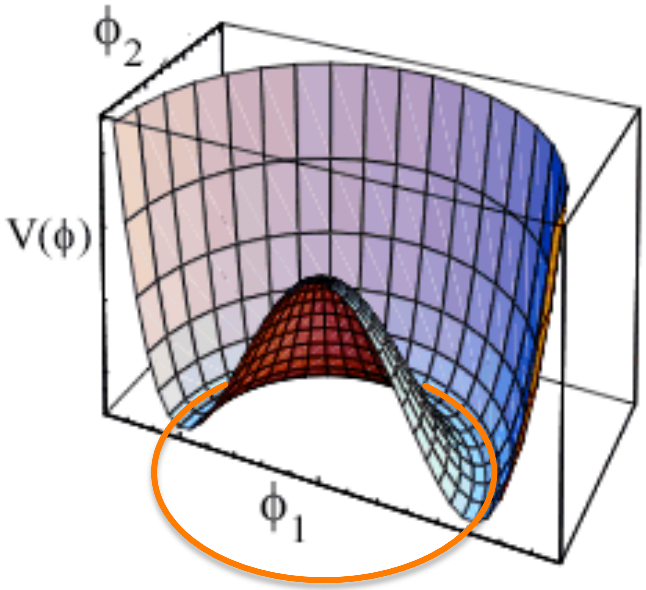
Forbidden by gauge symmetry



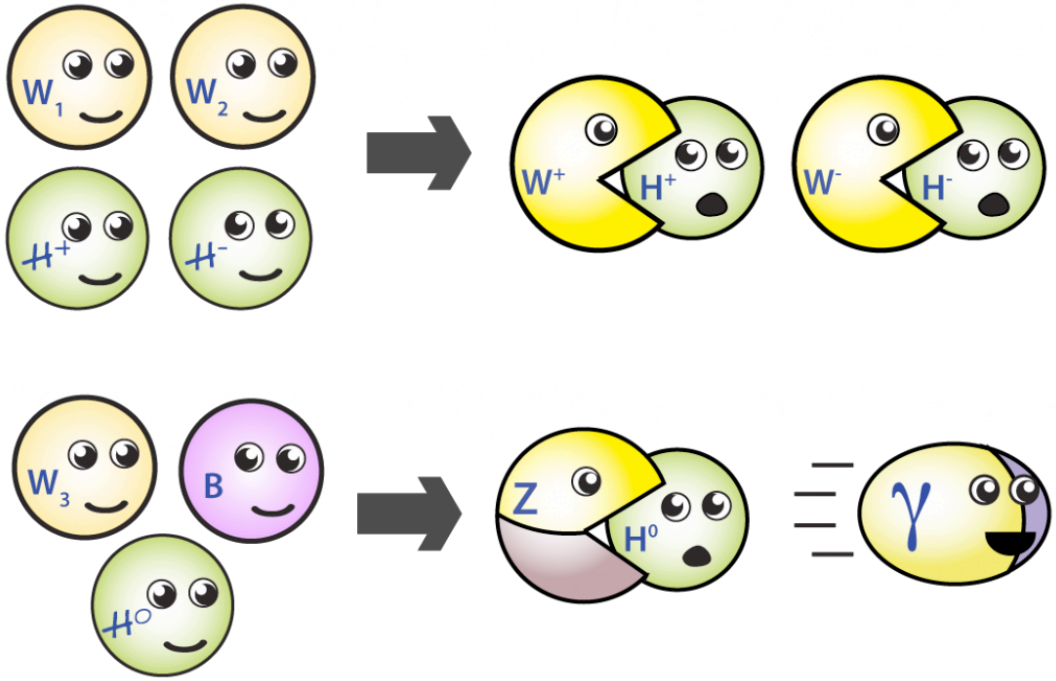
Another story

The BEH mechanism

(Brout-Englert-Higgs)



BEH field: ϕ_1, ϕ_2
4 components overall
Vacuum state breaks gauge symmetry

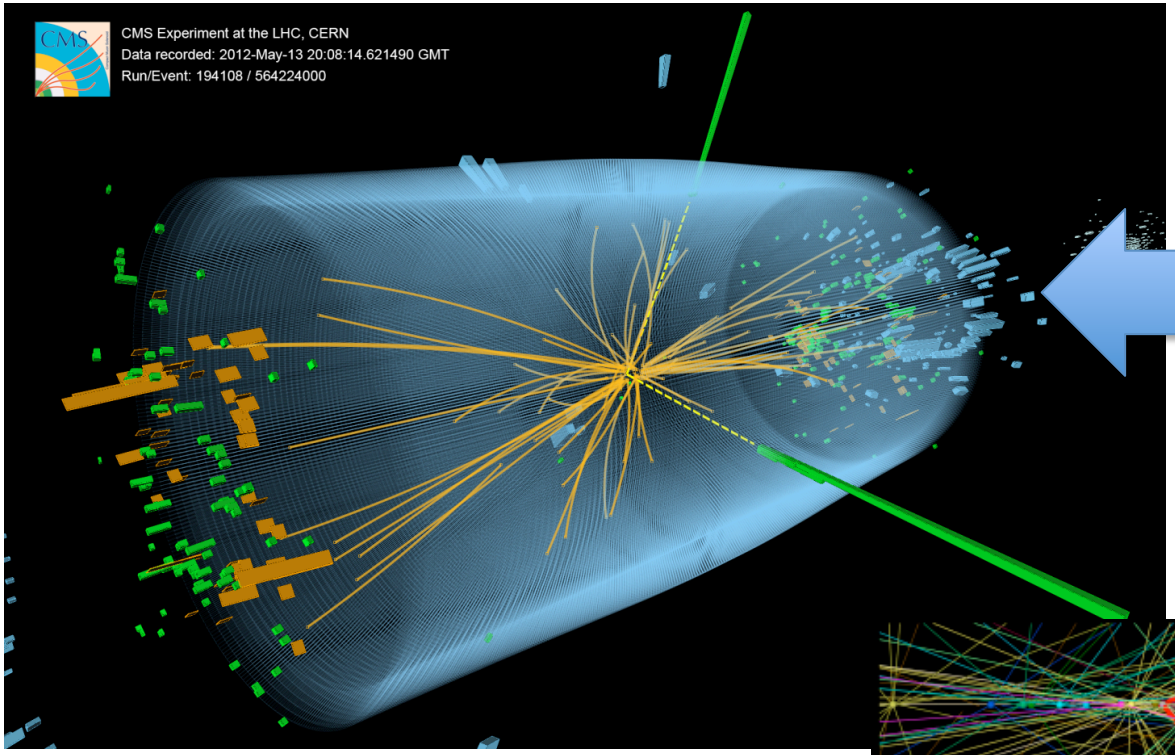


Massless bosons from SM symmetries

Physically observable bosons: $W^{\pm}$, Z, γ

One field left over: **The Higgs Boson**

Higgs detection at the LHC



Precision channels

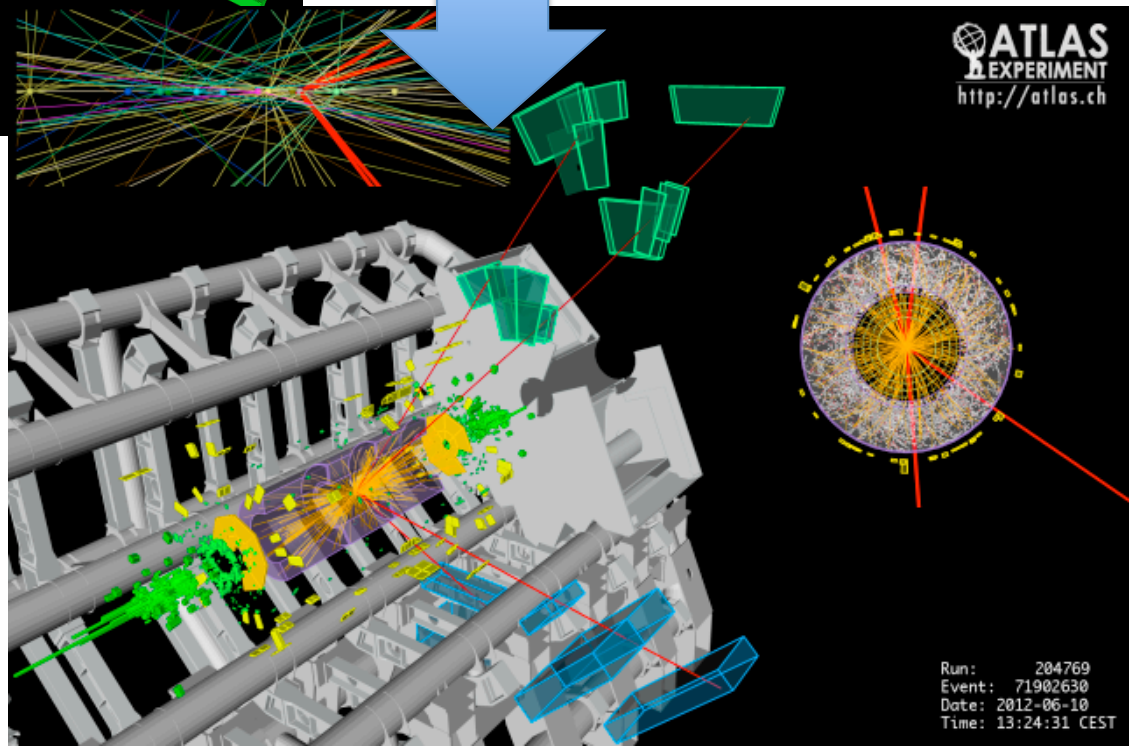
(good mass resolution)

$h \to \gamma\gamma$

High rate, substantial background

$h \to ZZ^* \to 4\ell$

Low rate, but very pure



Other channels

(poor mass resolution)

$h \to WW^* \to 2\ell 2\nu$

$h \to \tau\tau$

$h \to b\bar{b}$

$h \to ZZ^* \to 2\ell 2\nu$

and many more

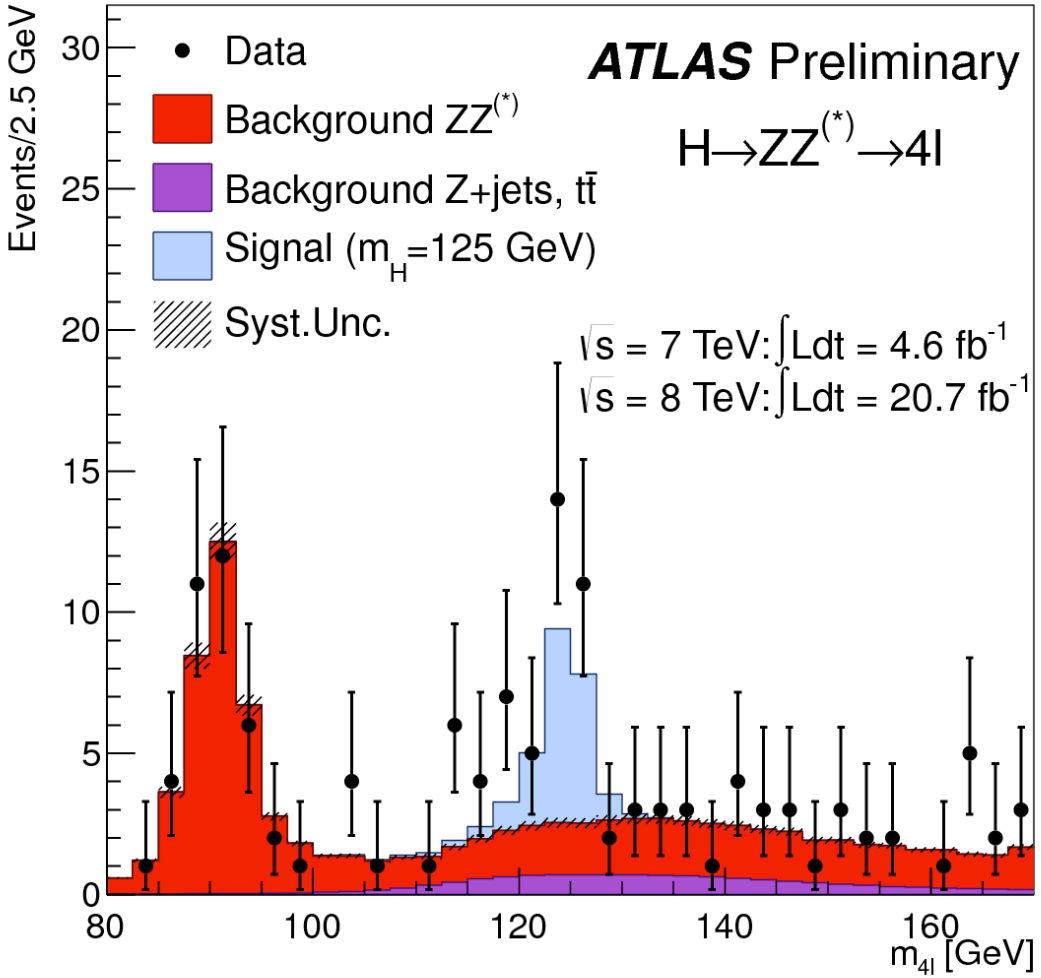
How discoveries are made

$$h \rightarrow ZZ^* \rightarrow 4\ell$$

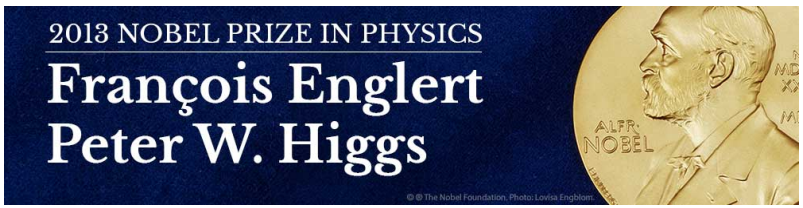
Ongoing measurements:

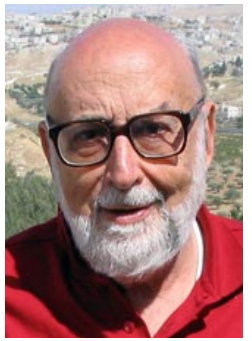
- Mass
- Couplings
- Spin/parity

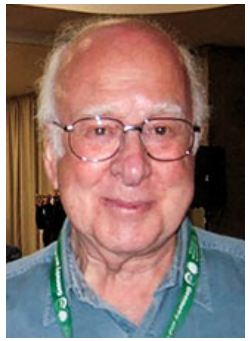
So far consistent with expectations



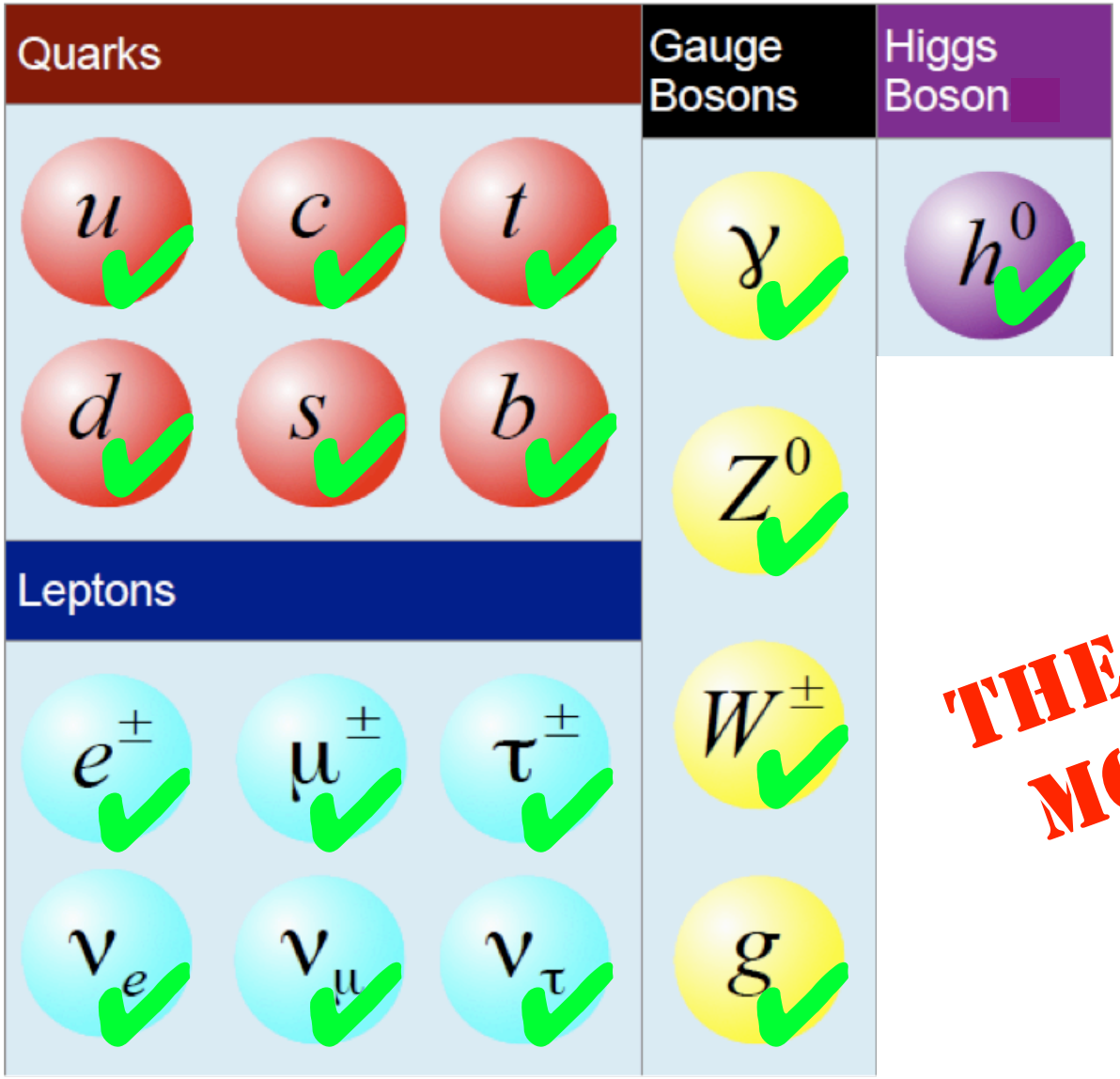
The 2013 Nobel prize honoured this successful prediction







Revenge of the SM



THE STANDARD MODEL WINS!

But is that it?

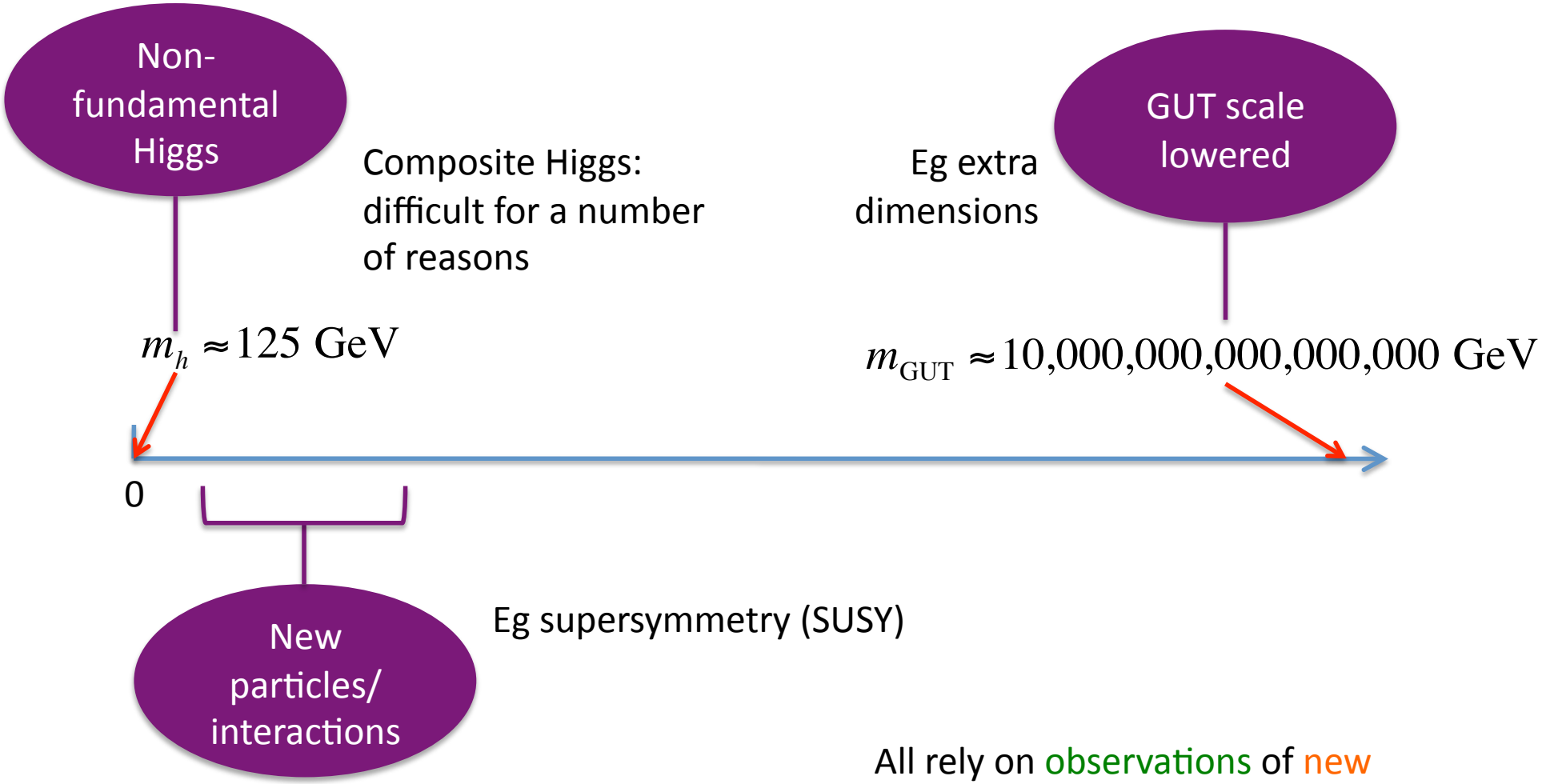
If SM parameters are random, how lucky are we?

Good example: Higgs boson mass should be much, much bigger

It's like winning with odds of 1/**100,000,000,000,000**

What is more believable: that this just happened or **that the game is rigged**?

Three solutions

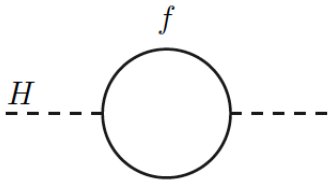


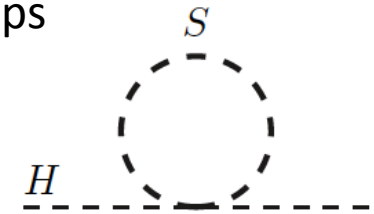
All rely on observations of new phenomena with mass near m_h
ie at most ~1000 GeV = 1 TeV

Supersymmetry @ the LHC

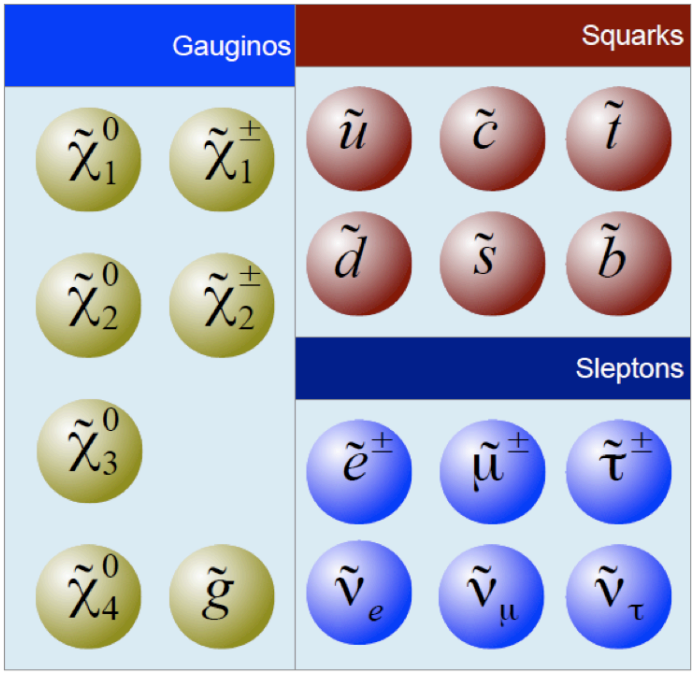
Hypothesis: every SM particle gains a partner, different only by ½ a unit of spin

Solves hierarchy problem via (nearly) exact cancellation of Higgs mass loops





Bonus: potential dark matter candidate (or neutrino masses)



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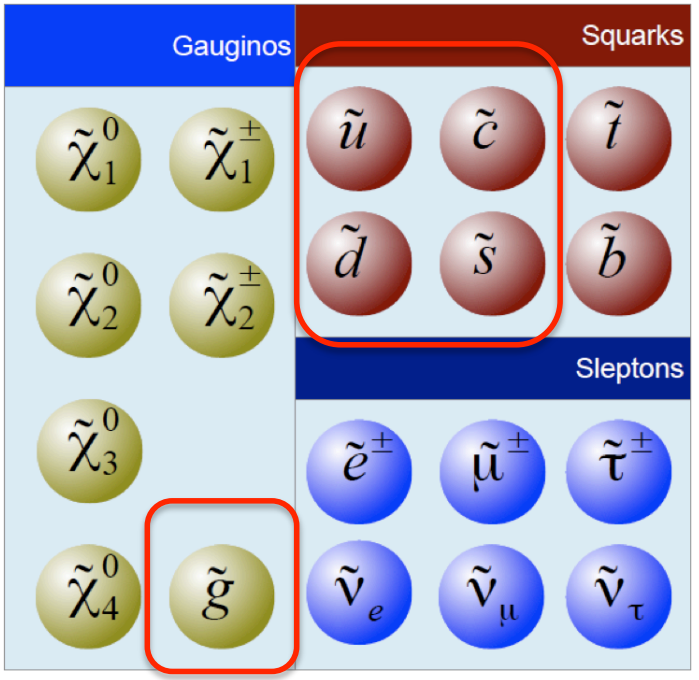

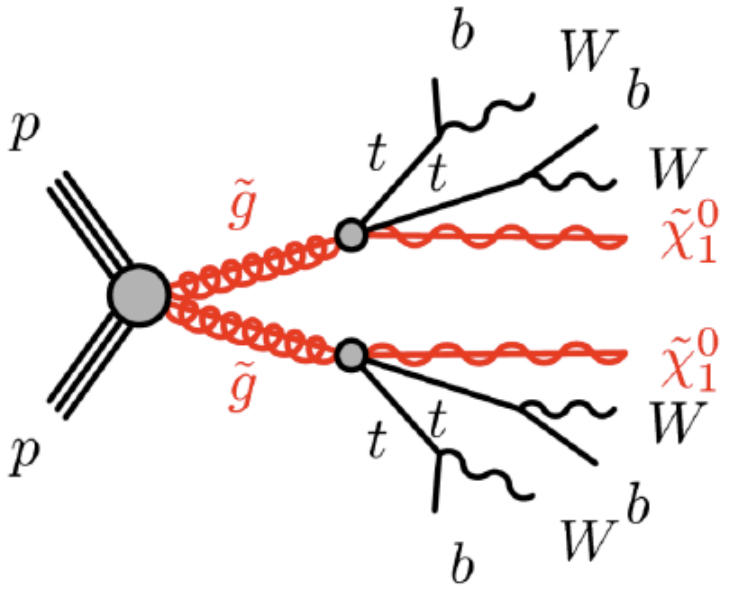

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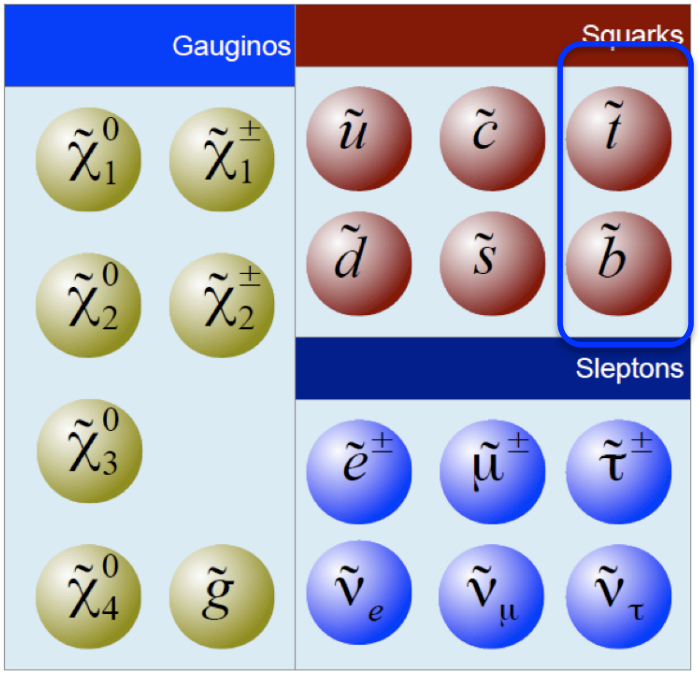
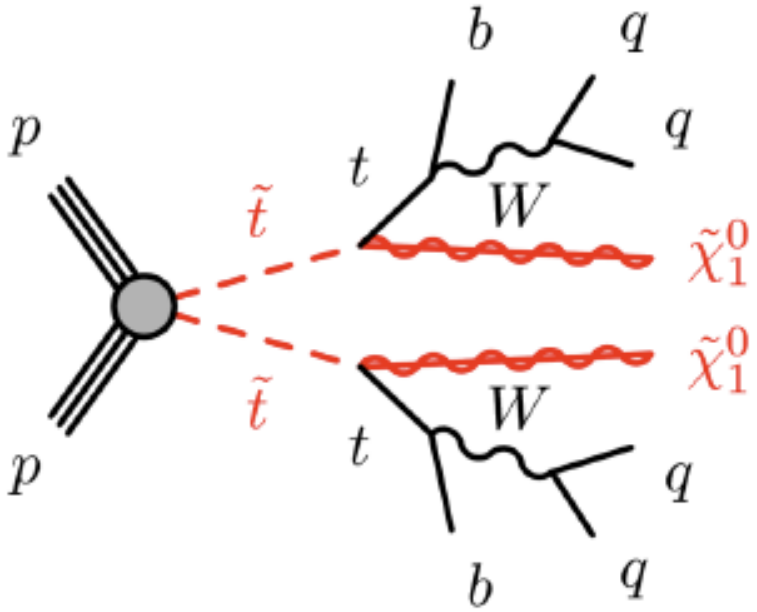
2. Stop/sbottom production: lower rate, must be light for naturalness





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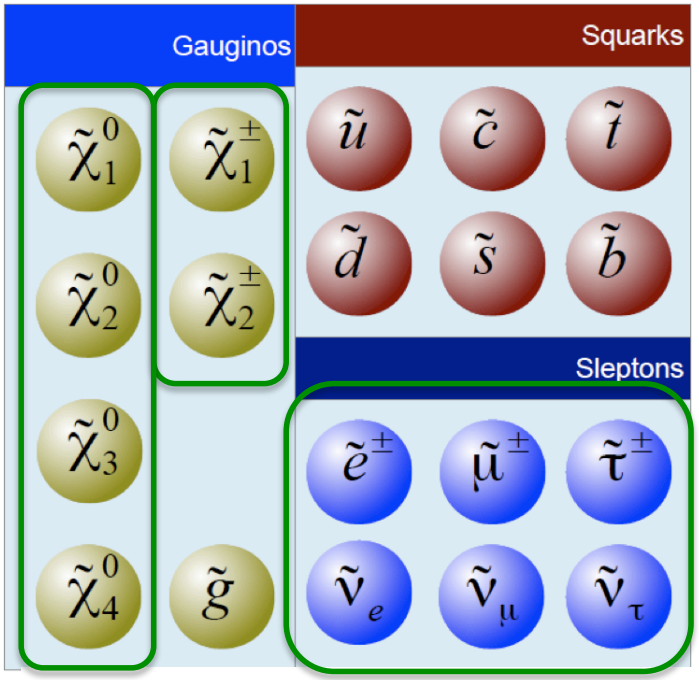
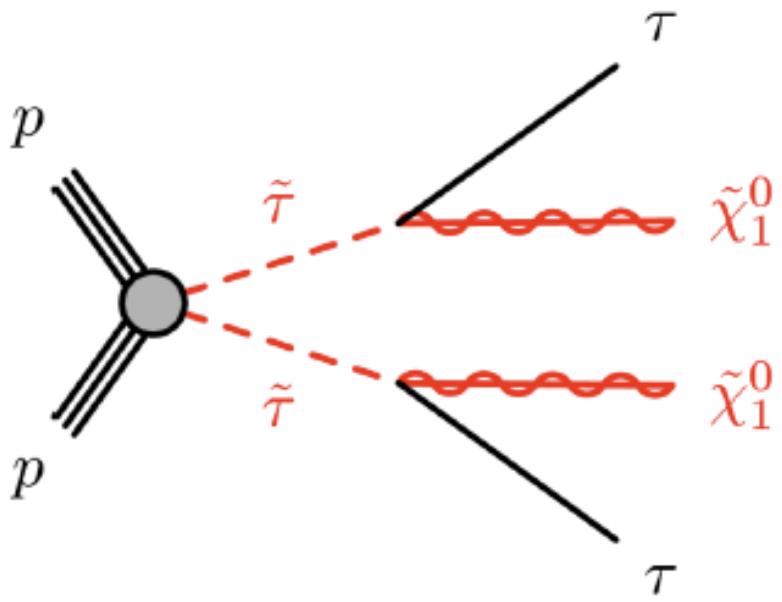
3. Slepton/gaugino production: could still be seen if squarks are very massive





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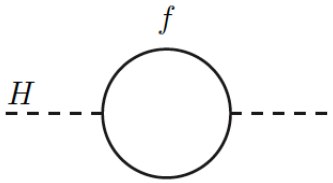

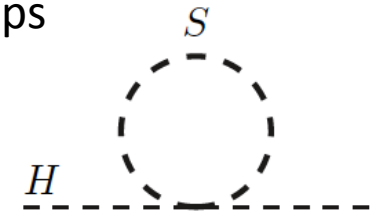

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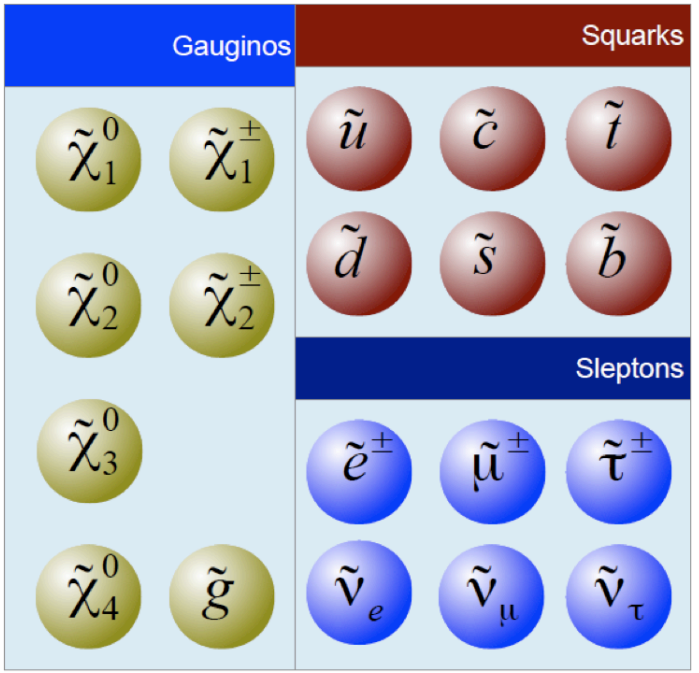
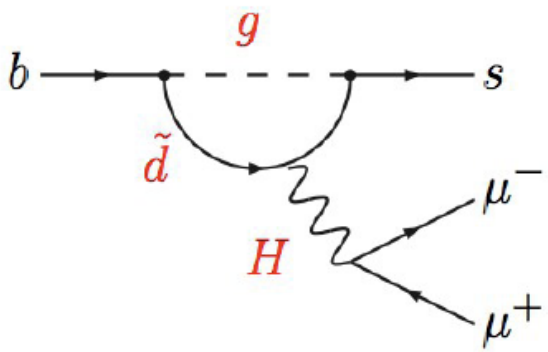
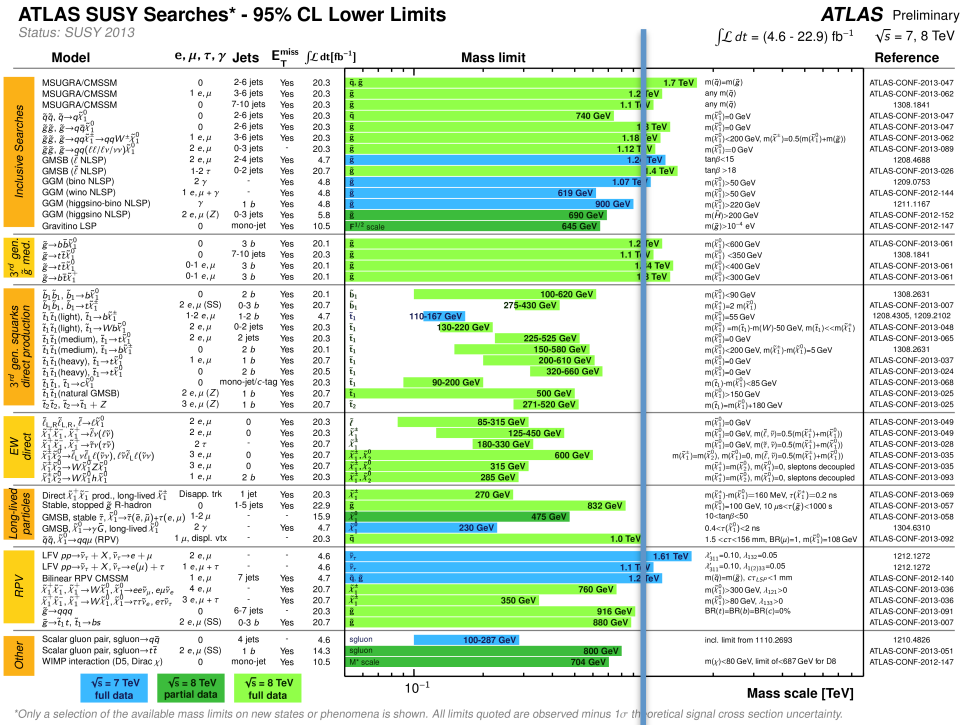
2. Stop/sbottom production: lower rate, must be light for naturalness
3. Slepton/gaugino production: could still be seen if squarks are very massive
4. Indirect effects: usually in flavour physics



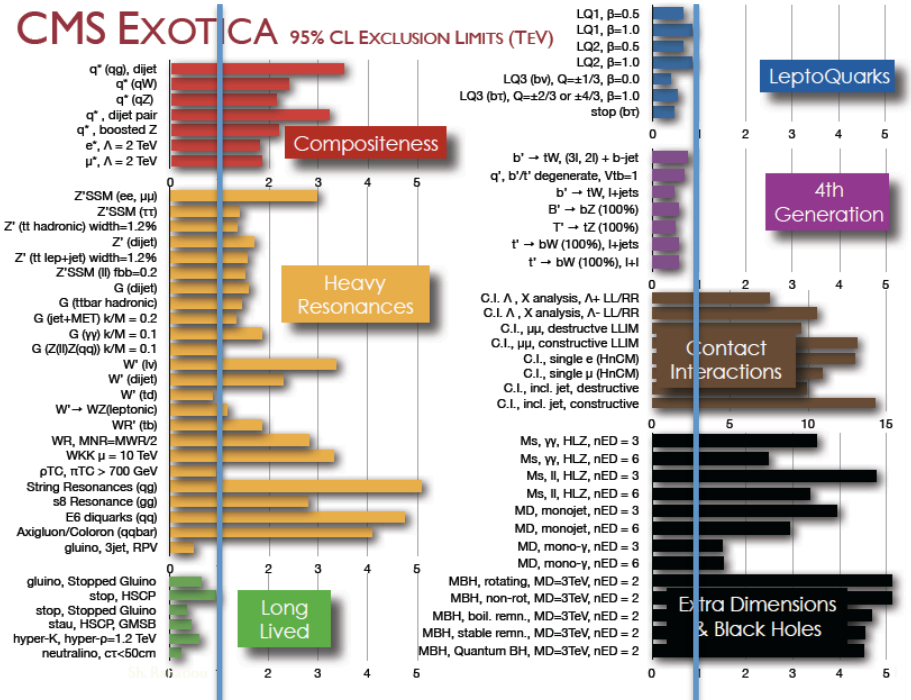


See Alexander Mann's talk yesterday for more

$B_s \to \mu^+\mu^-$ now observed!
No enhancement over SM
LHCb-CONF-2013-012



1 TeV



1 TeV

1 TeV

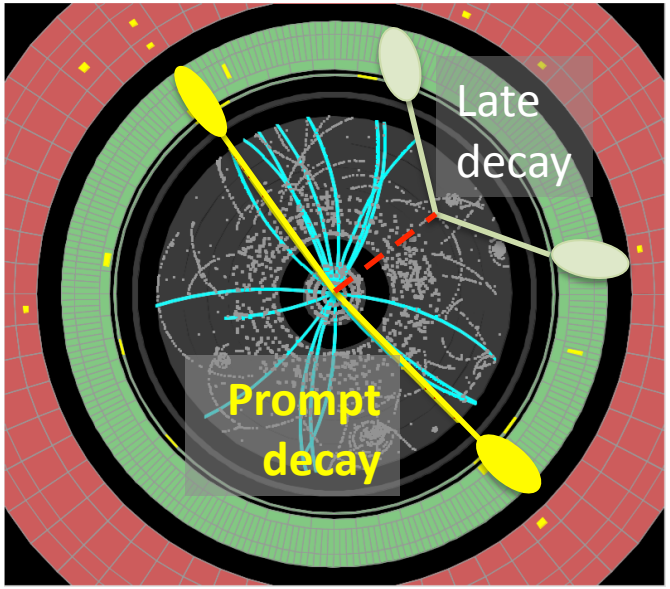
So far, **no significant deviation** from the Standard Model

No evidence for SUSY or other non-SM physics

Precision measurements in agreement with expectation

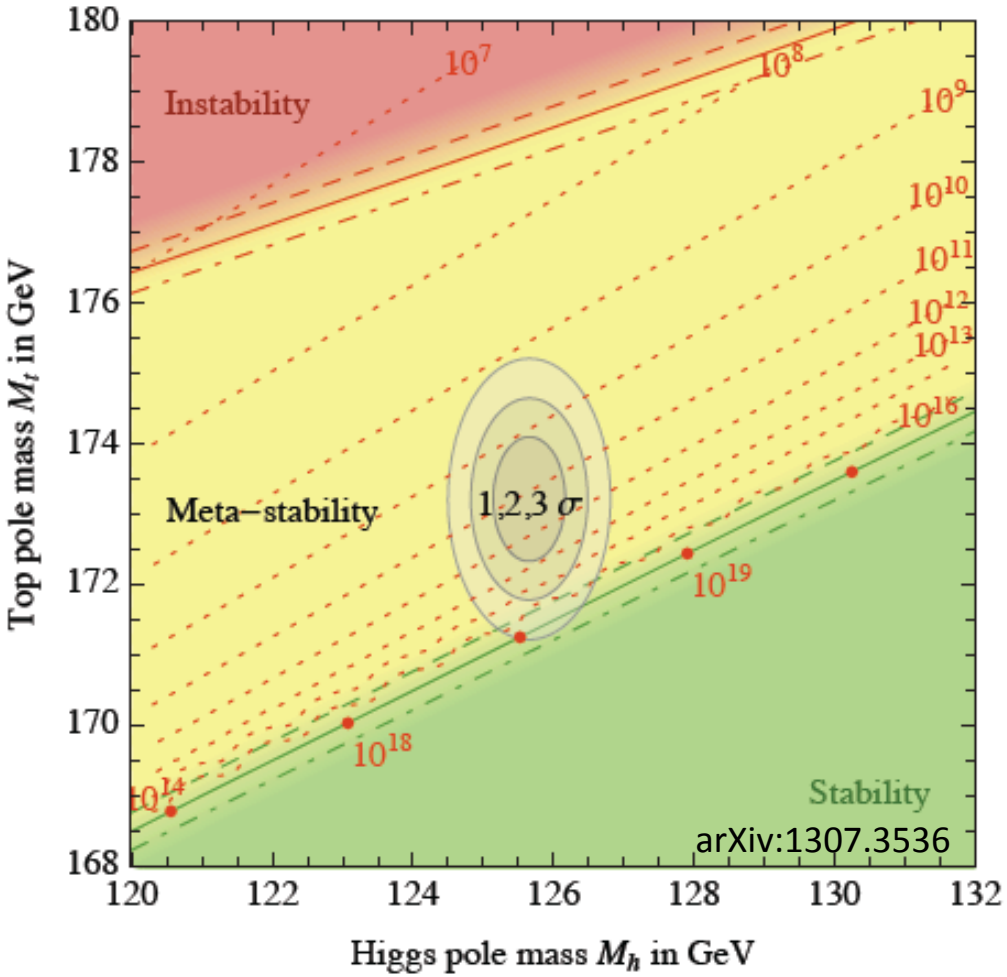
Caution: Many caveats and loopholes

Example: Limited sensitivity to **late-decaying particles**, surprises could still be lurking in the Run I data!




Extra dimensions?
Origin of mass?
Weakness of gravity?
Neutrino mass?
Some big answers?
Are there new symmetries/ interactions?
Where is the antimatter?
Dark matter?
3 generations?

Buttazzo et al, arXiv:1307.3536v2 [hep-ph]



Is that it?

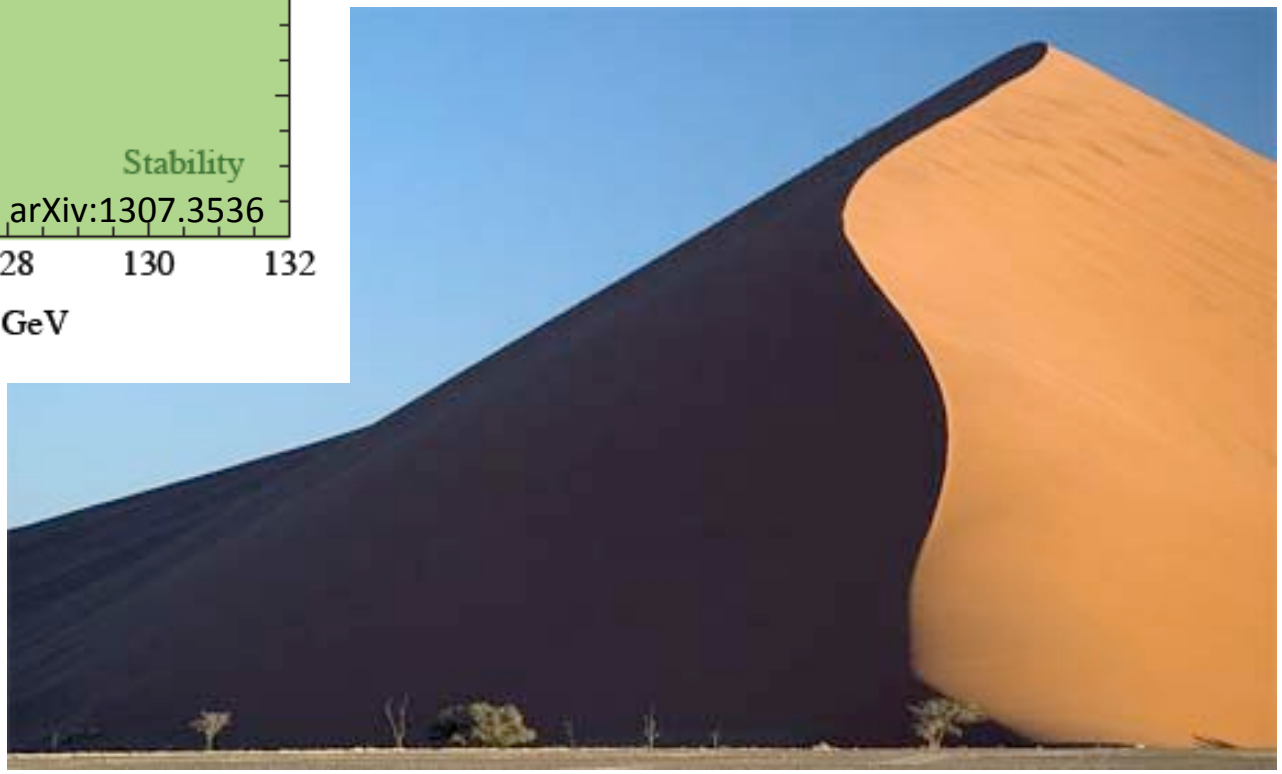
If the SM is all that is,
the universe appears to be
finely tuned and metastable

Finely-tuned: Apparently unlikely selection of fundamental constants

Metastable: Our universe not the „best“ vacuum, but stable for current life of universe

How can this be?
Are we in a multiverse?
Do balancing pressures place us near the critical point?

Maybe



The future

Warning: all simulation past this point!

The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

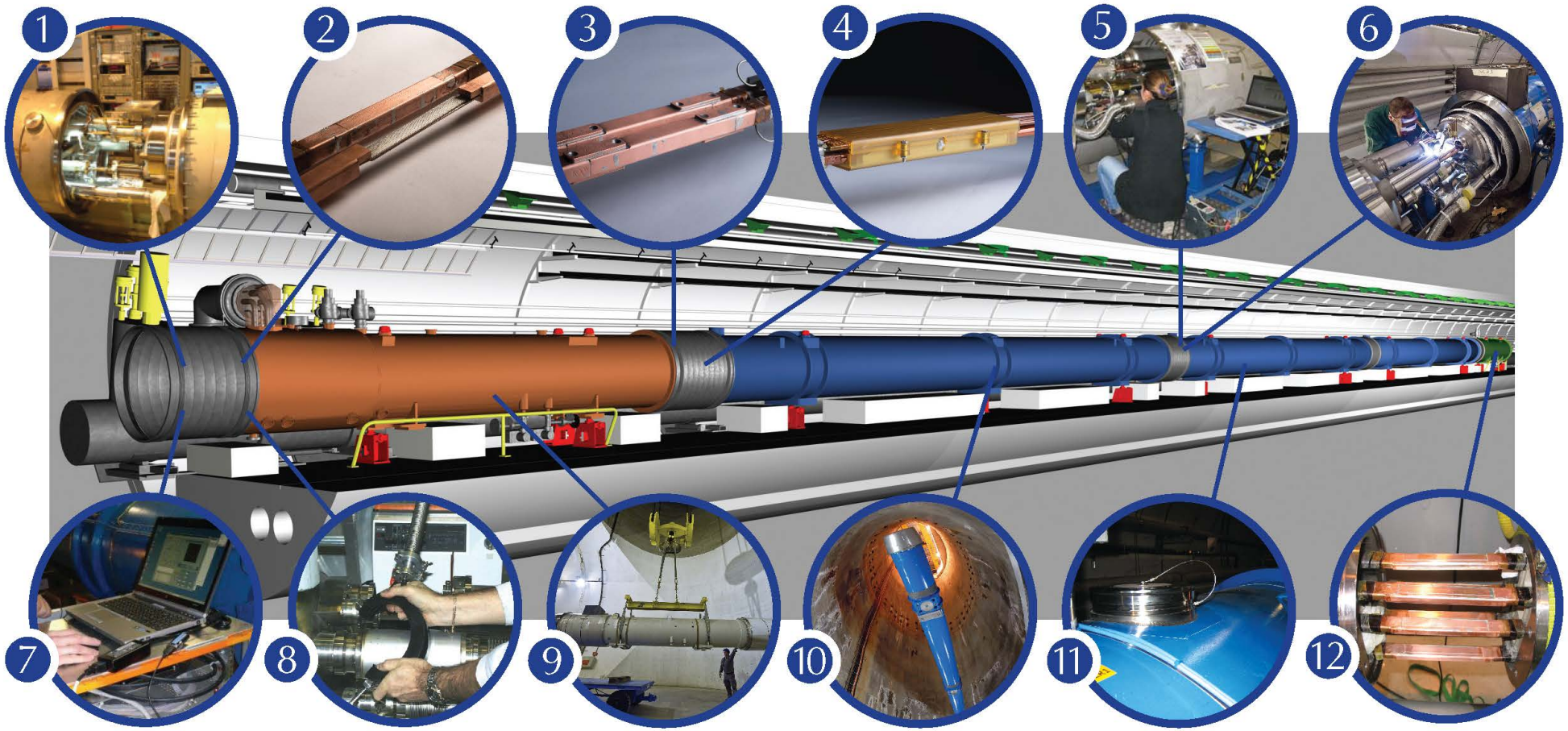
Complete reconstruction of 1500 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines



18 000 electrical Quality Assurance tests

10170 leak tightness tests

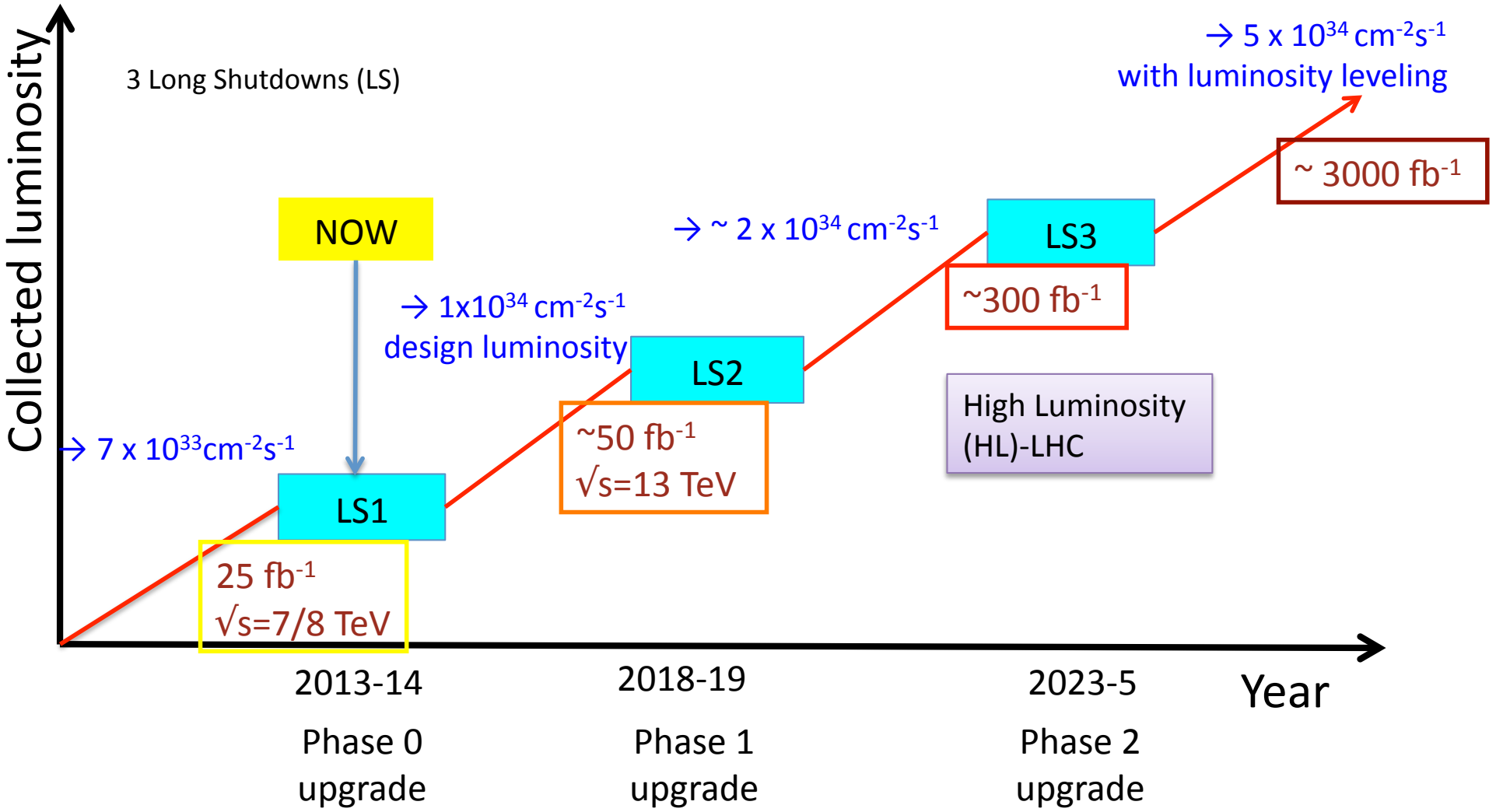
4 quadrupole magnets to be replaced

15 dipole magnets to be replaced

Installation of 612 pressure relief devices to bring the total to 1344

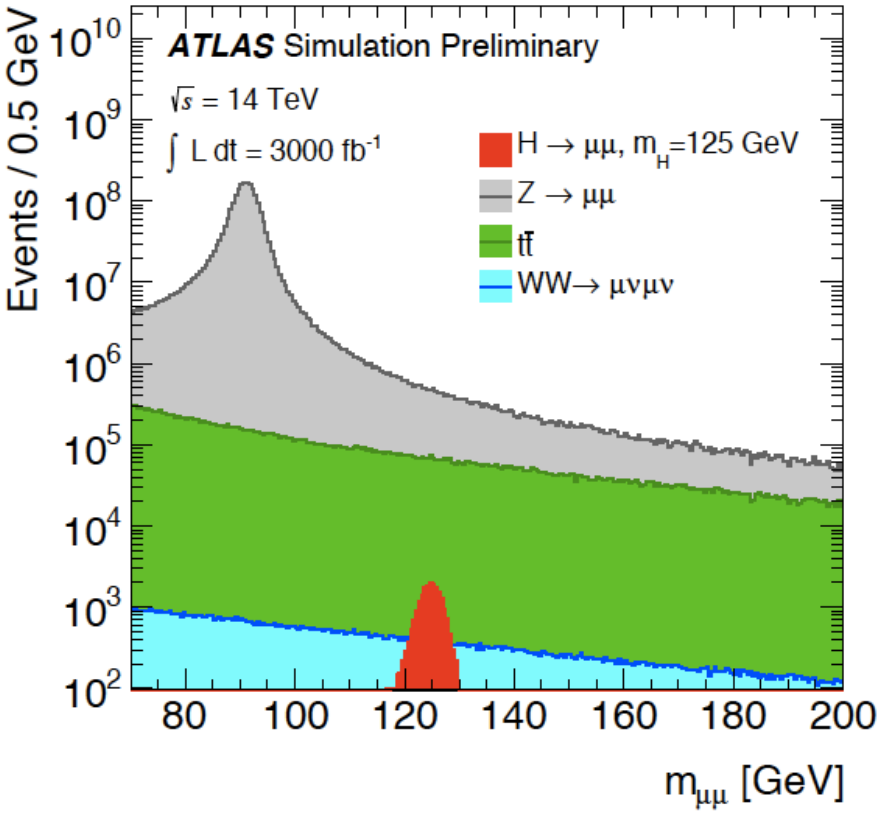
Consolidation of the 13 kA circuits in the 16 main electrical feedboxes

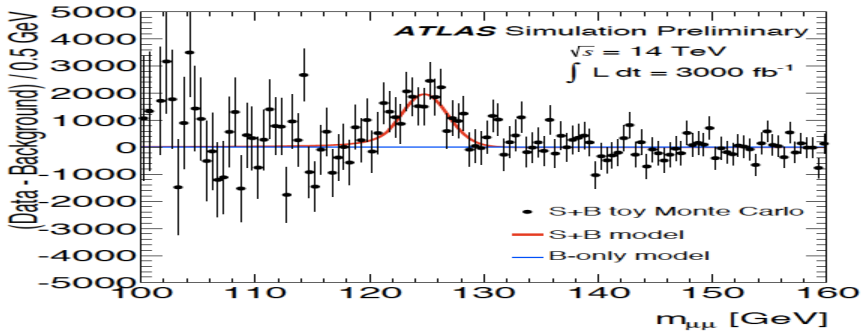
The LHC upgrade plan



At each stage: beam improvements and detector repairs, upgrades
Eventual target: >100 times today's dataset

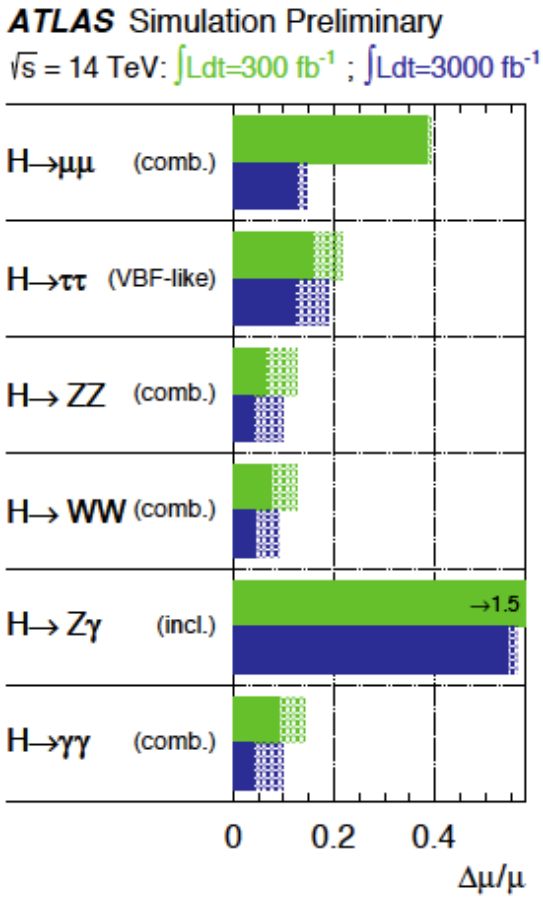
Future prospects: Higgs





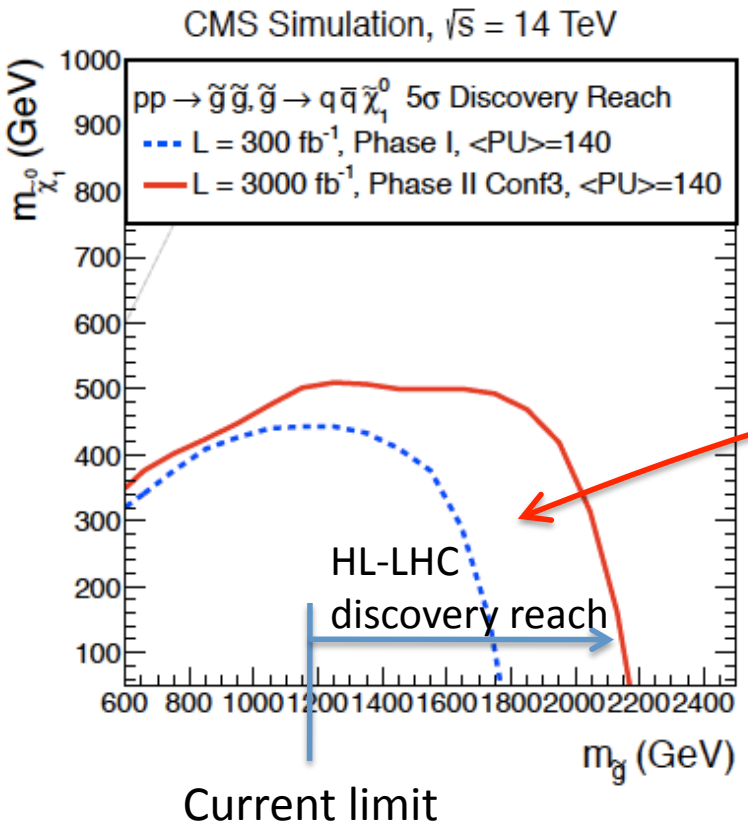
10-100x current dataset will allow rare events to be observed

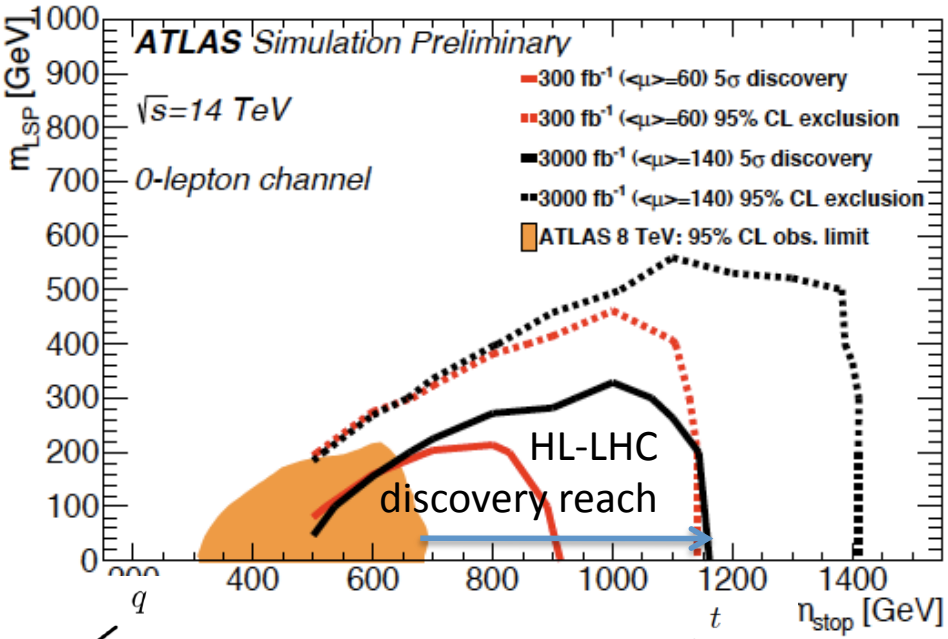
- Eg **h→μμ**: ~1 in 5000 decays
- Probe interaction strengths to O(5%)

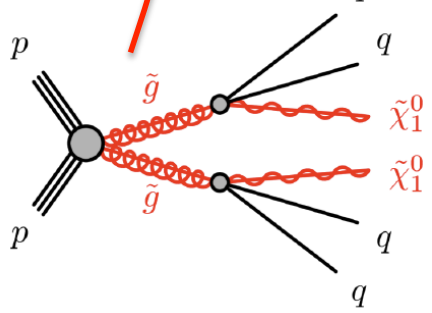


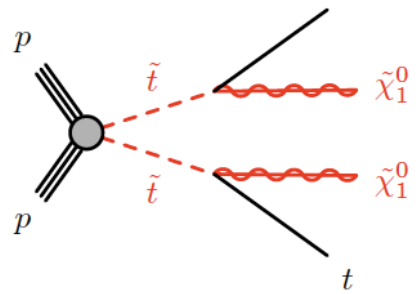
Future prospects: SUSY

- Many searches statistically limited
  - More luminosity improves sensitivity to rarely produced particles
  - Higher energy increases production rate of massive particles
- Maintaining sensitivity to **all** scenarios challenging

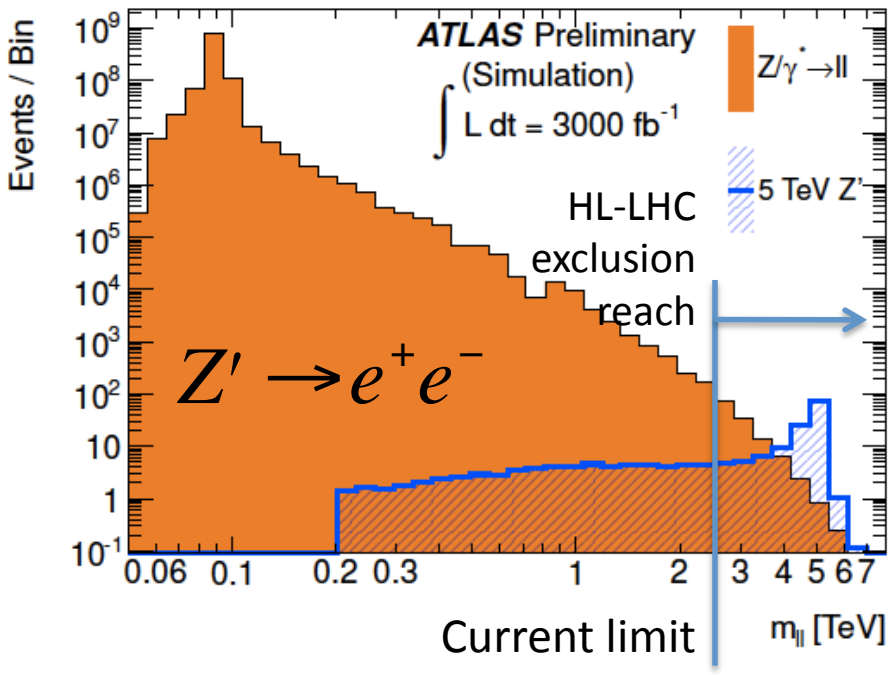


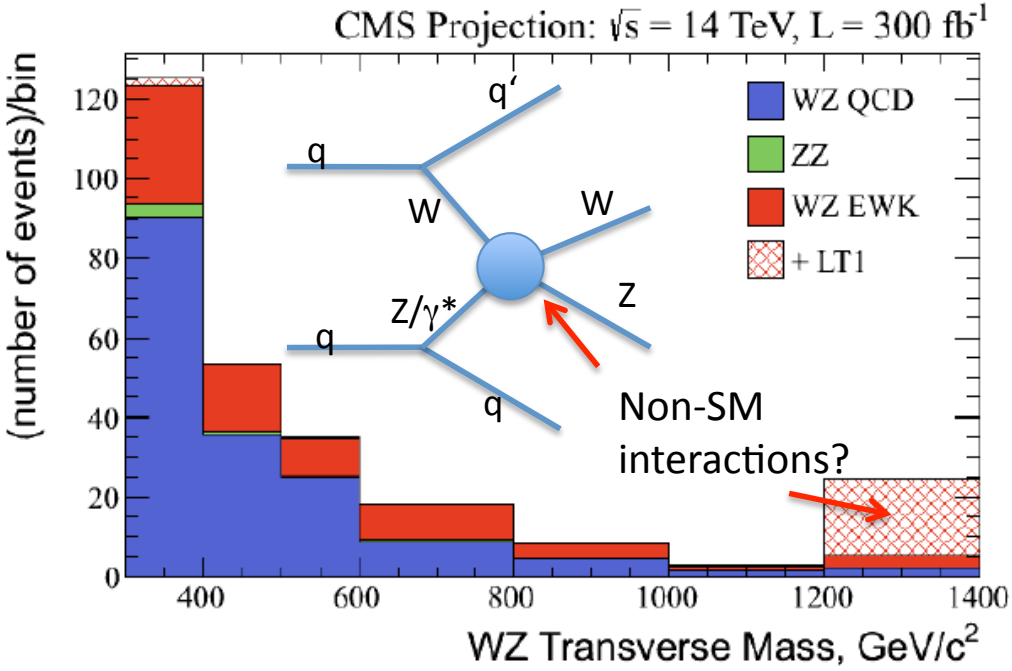






Future prospects: some other examples





New forces would emerge at the LHC through the production of new gauge bosons (Z‘)

Exceptionally clean dilepton signatures are possible

Exclusion sensitivity could reach nearly 8 TeV

The LHC can collide gauge bosons too!

Rare, needs large luminosity to observe

Deviations in diboson kinematic distributions could hint at unexpected processes

Conclusions

- In the first three years of high energy collisions, the LHC and its experiments have really delivered
- Brout-Englert-Higgs mechanism confirmed as the origin of mass
- No sign of anything else, so far, but questions about the Standard Model remain
- Higher energy LHC will help probe even higher mass scales to attempt answer these questions