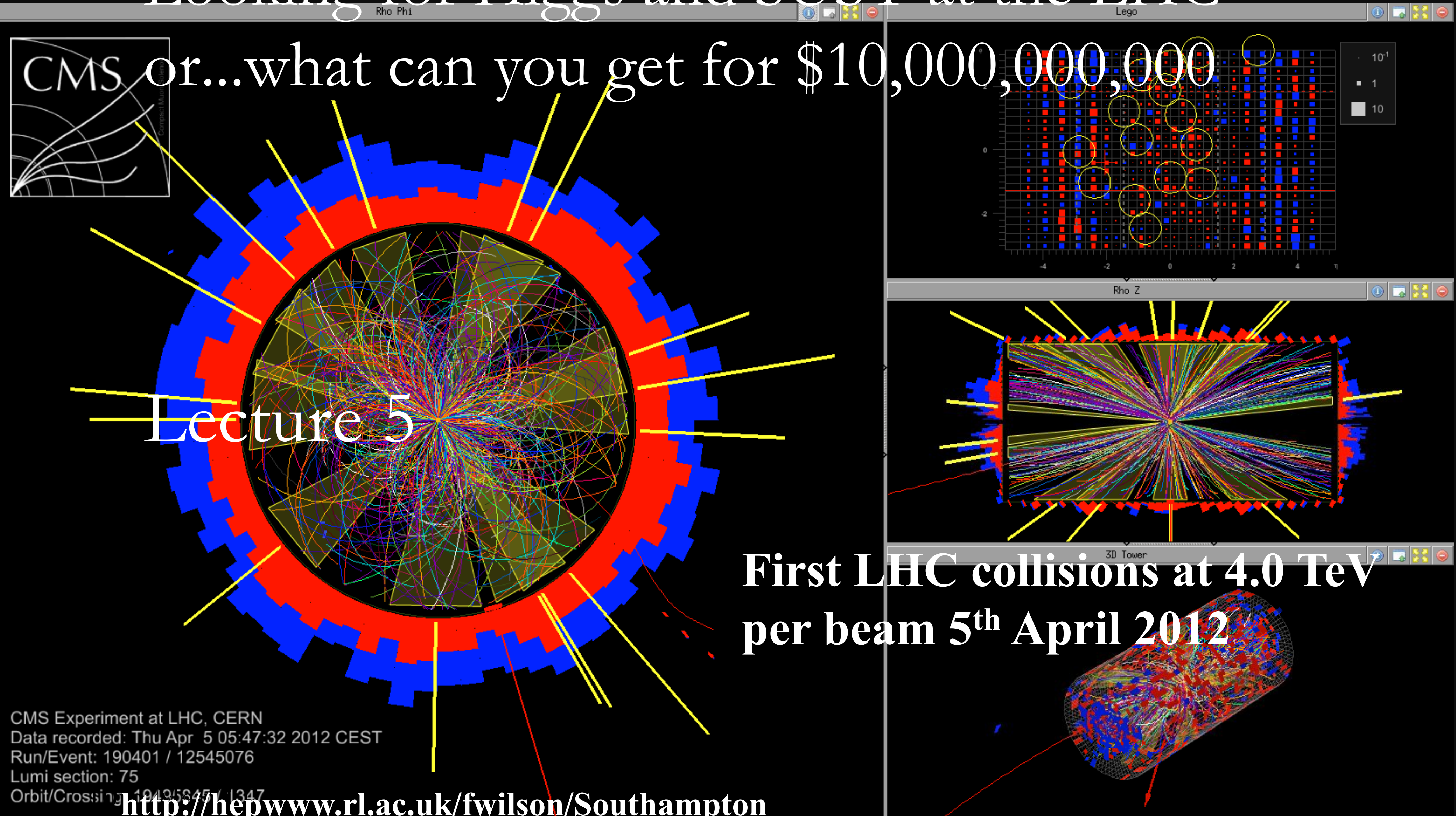
Experimental Particle Physics PHYS6011

Looking for Higgs and SUSY at the LHC

or...what can you get for $10,000,000,000

Lecture 5



First LHC collisions at 4.0 TeV per beam 5th April 2012

http://hepwww.rl.ac.uk/fwilson/Southampton

Search for the Higgs Boson

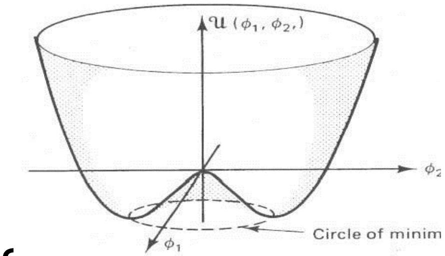
- Missing piece of Standard Model
- Standard Model Higgs theory well understood:
  - Mass is only free parameter
  - Clear predictions to test
- Most "New Physics" models have something equivalent to a Higgs boson ("MSSM Higgs", "little Higgs", etc…).
- Could be more than one type of Higgs boson
- Current limit M_H>115 GeV (LEP)

- Particle masses are generated by interactions with the scalar (Higgs) field.
- Couplings are fixed by the masses.
- Once M_H is known everything is predicted.
- So by measuring the coupling of the Higgs to particles of known mass we can test theory.

Higgs Mechanism in the Standard Model

- Need to accommodate massive gauge bosons
  - Strong and electromagnetism ok (photon, gluon)
  - Weak force has two massive W and a Z

Modified potential $V = \mu^2 |\phi|^2 + \lambda |\phi|^4$ $\qquad \phi_{\min} = \upsilon = \sqrt{\frac{-\mu^2}{\lambda}}$



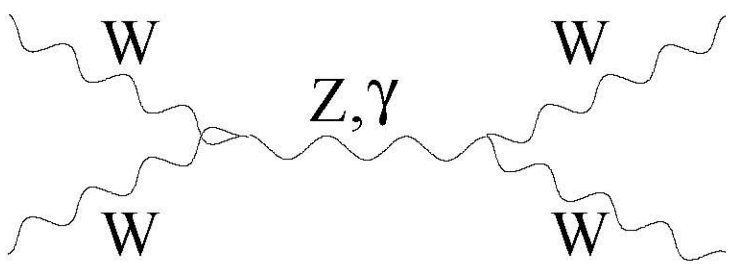
- Step 1: Spontaneous Symmetry Breaking produces one massive and one massless gauge boson (Goldstone Boson).
- Step 2: Introduce local gauge invariance : massive Higgs particle, three massive vector bosons and one massless boson.
- Higgs mass a free parameter $\qquad M_H = \sqrt{-2\mu^2}$
- Gauge couplings of Higgs doublet give gauge boson masses:

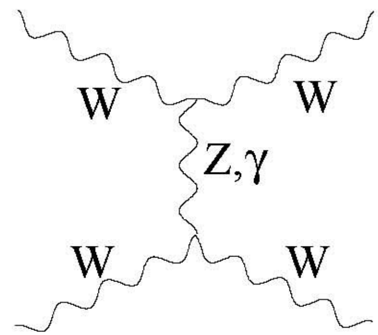
$$M_W = g_W \nu / 2 \quad M_Z = M_W \cos\theta_W \quad \cos\theta_W = 0.8810$$

- Can calculate υ (=246GeV) but not λ before measuring Higgs mass.
- Higgs couplings to fermions depends on their mass and unique coupling for each fermion: $\qquad M_f \propto M_H g_f$

What do we know about the Higgs?

- No useful lower limit from theory.
- Upper limit from WW scattering
  - Above ~1TeV cross-section $\rightarrow \infty$
  - Need Higgs to "regularise" cross-section

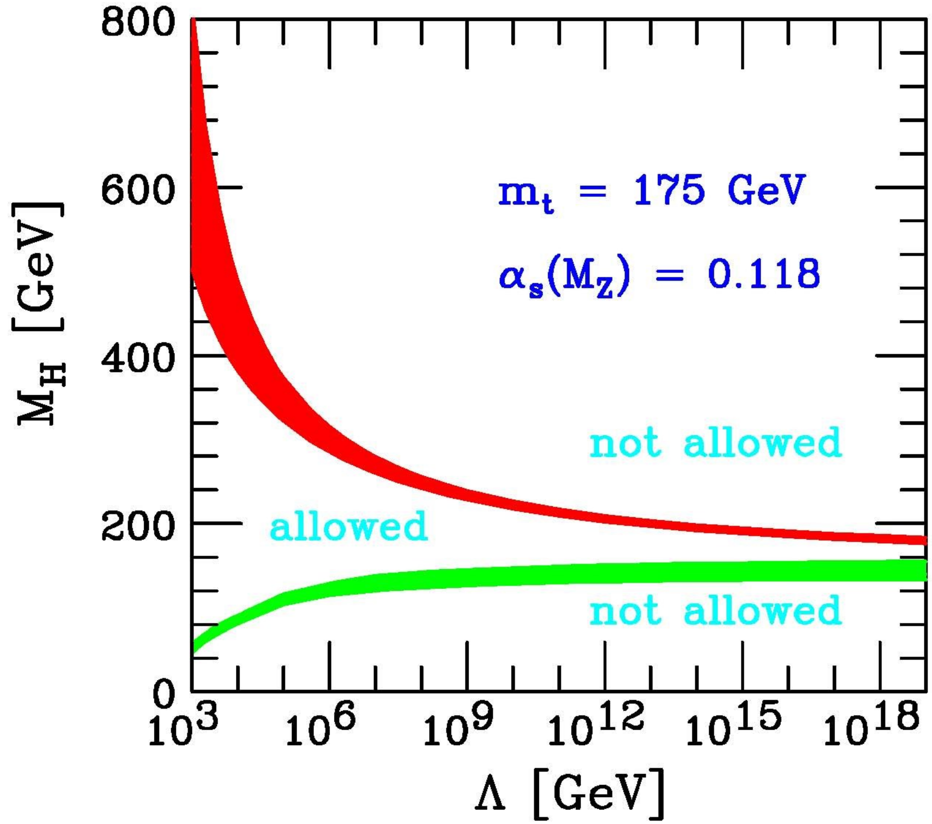




What do we know about the Higgs?

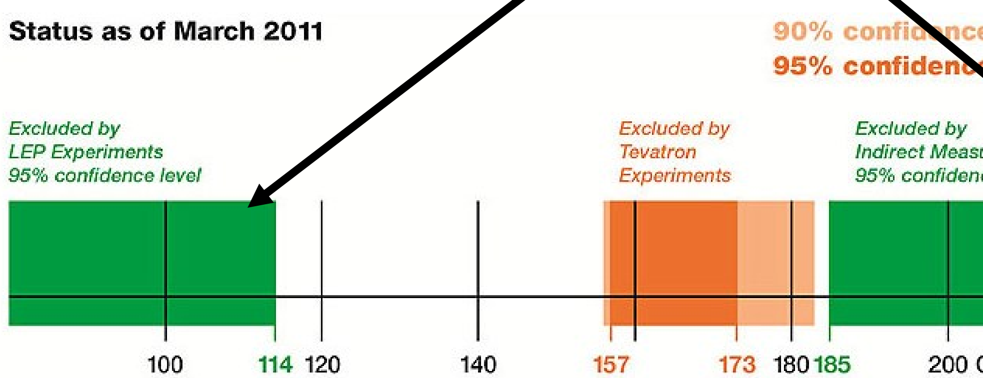
If no new physics up to Planck scale (~10^{19}GeV)
small mass range for Higgs: $130 < M_H < 190$ GeV

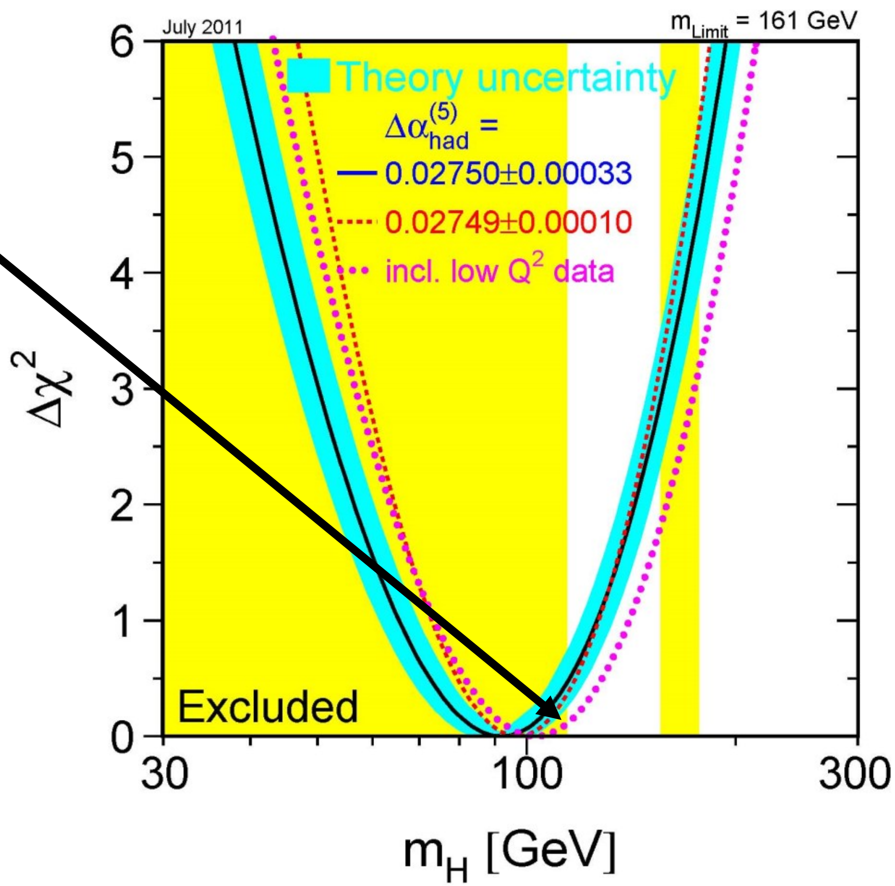
$$M_H^2 \leq \frac{8\pi^2 v^2}{3\log\frac{\Lambda_{QCD}^2}{v^2}} \qquad \upsilon^2 = 246\,\text{GeV}$$



What do we know about the Higgs?

Direct searches
$M_H > 114.4$ GeV
@ 95% C.L.





http://lepewwg.web.cern.ch/LEPEWWG

How to discover a signal?

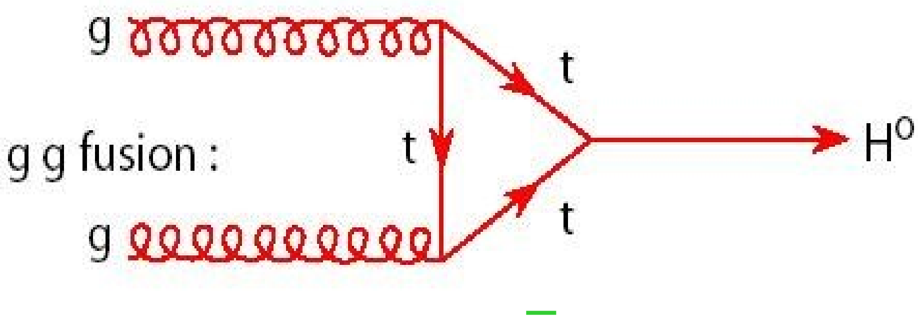
- Total number of events (n_t) will have signal events (n_s) and background events (n_b)
- Number of events follows a Poissonian distribution with σ = sqrt(n).
- Require signal > 5σ above background for "observation".

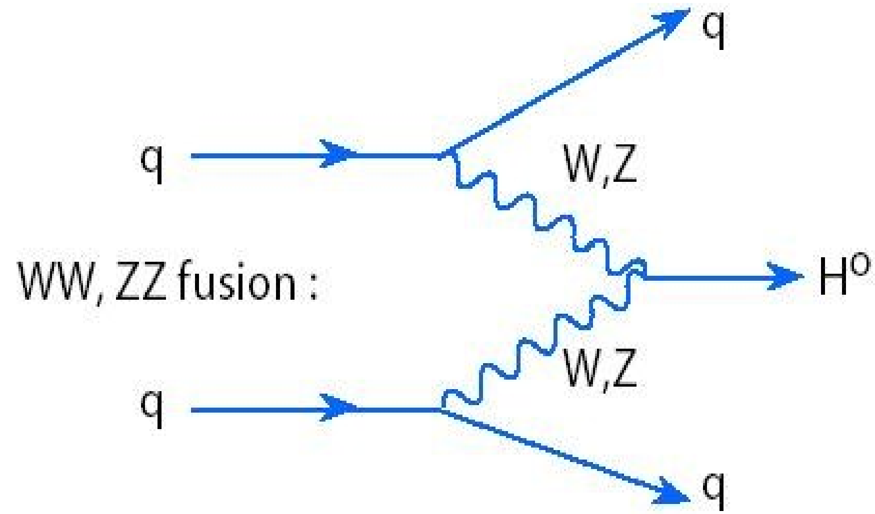
$$\text{Significance S} = n_s \big/ \sqrt{n_b} > 5$$

- Require signal > 3σ above background for "first evidence".
- e.g. Measure 140 events and know 100 come from background: $S = 40 / \sqrt{100} = 4$
- How do you know the background? Monte Carlo or Look in areas where there is no signal.
- Significance depend on how much data you have taken

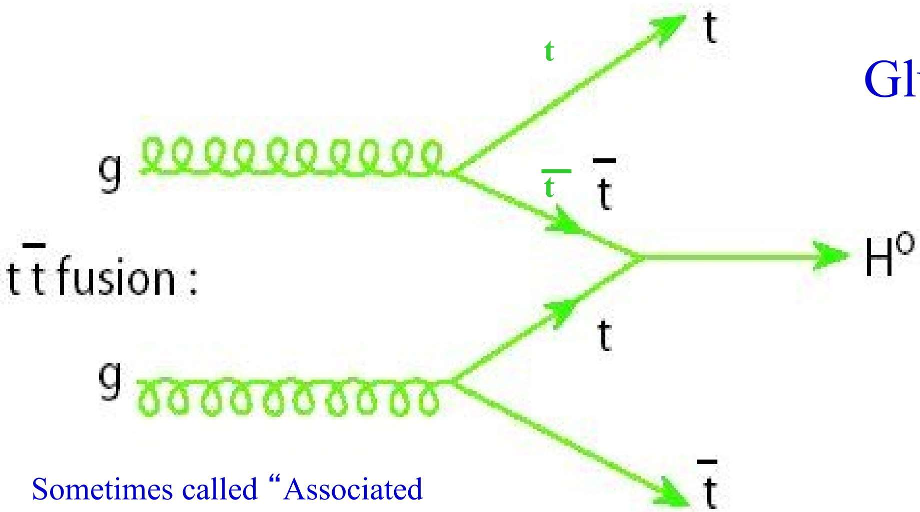
$$S \propto \sqrt{\text{Luminosity}}$$

Higgs Production Mechanisms

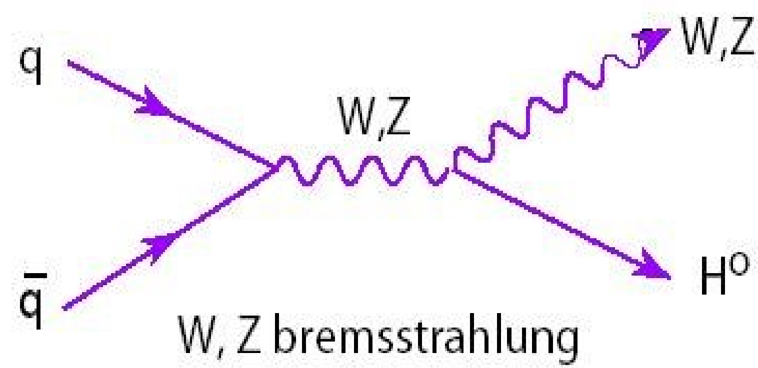




Gluon fusion looks most promising



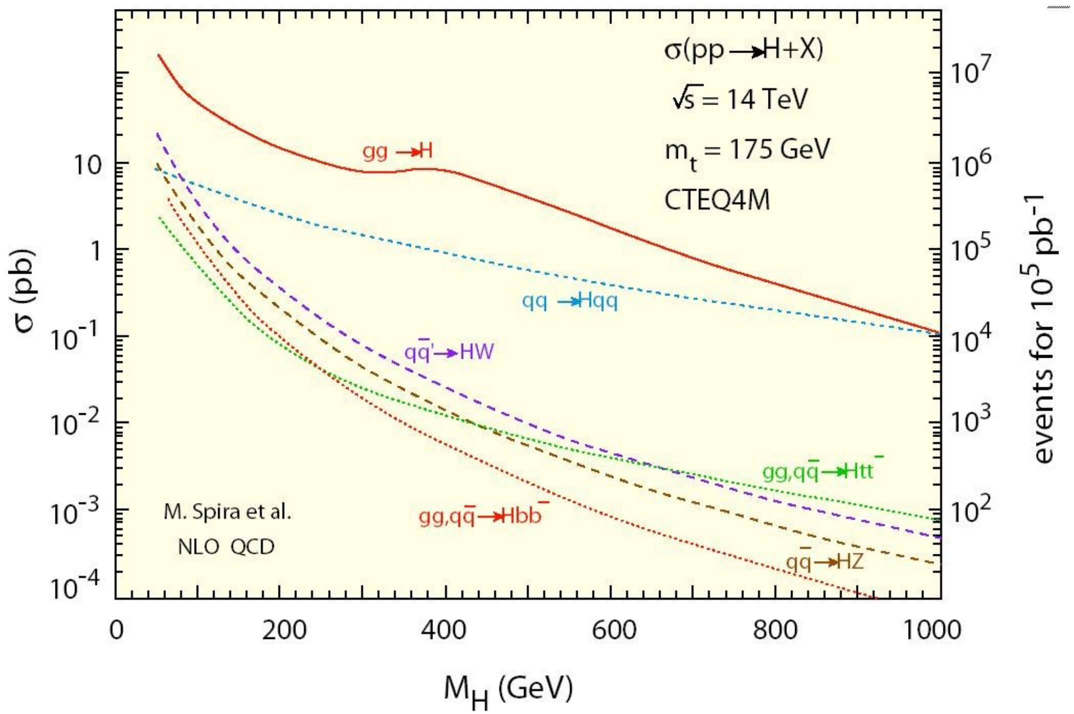
Sometimes called "Associated ttH production"



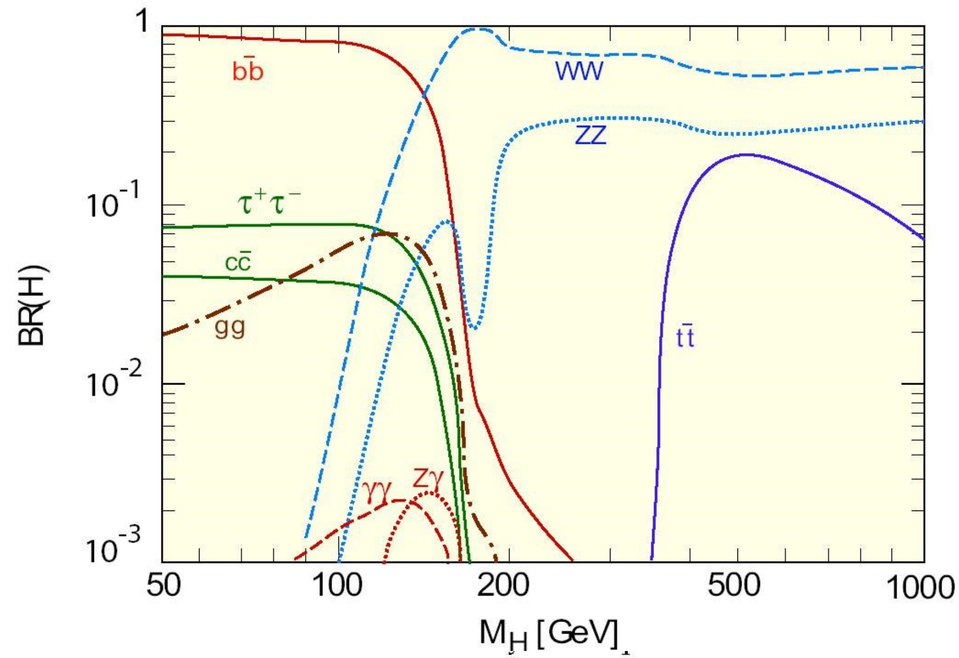
Sometimes called "Associated WH,ZH production"

Higgs production and decay

How often is it produced?



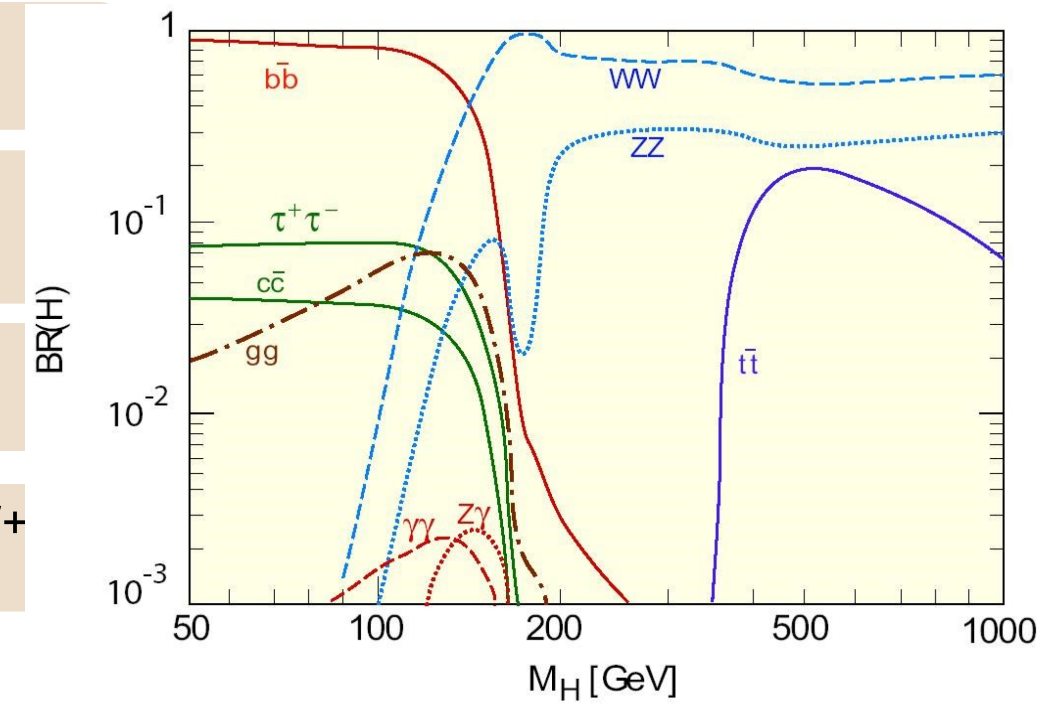
What does the Higgs decay into?



Process	Events/s	Events/year
$W \to e\nu$	40	$4 \cdot 10^8$
$Z \to ee$	4	$4 \cdot 10^7$
$t\bar{t}$	1.6	$1.6 \cdot 10^7$
$b\bar{b}$	10^6	10^{13}
$\tilde{g}\tilde{g}$ (m = 1 TeV)	0.002	$2 \cdot 10^4$
Higgs (m= 120 GeV)	0.08	$8 \cdot 10^5$
Higgs (m= 120 GeV)	0.08	$8 \cdot 10^5$
Higgs (m= 800 GeV)	0.001	10^4
QCD jets $p_T > 200$ GeV	10^2	10^9

Which Higgs decay to look for

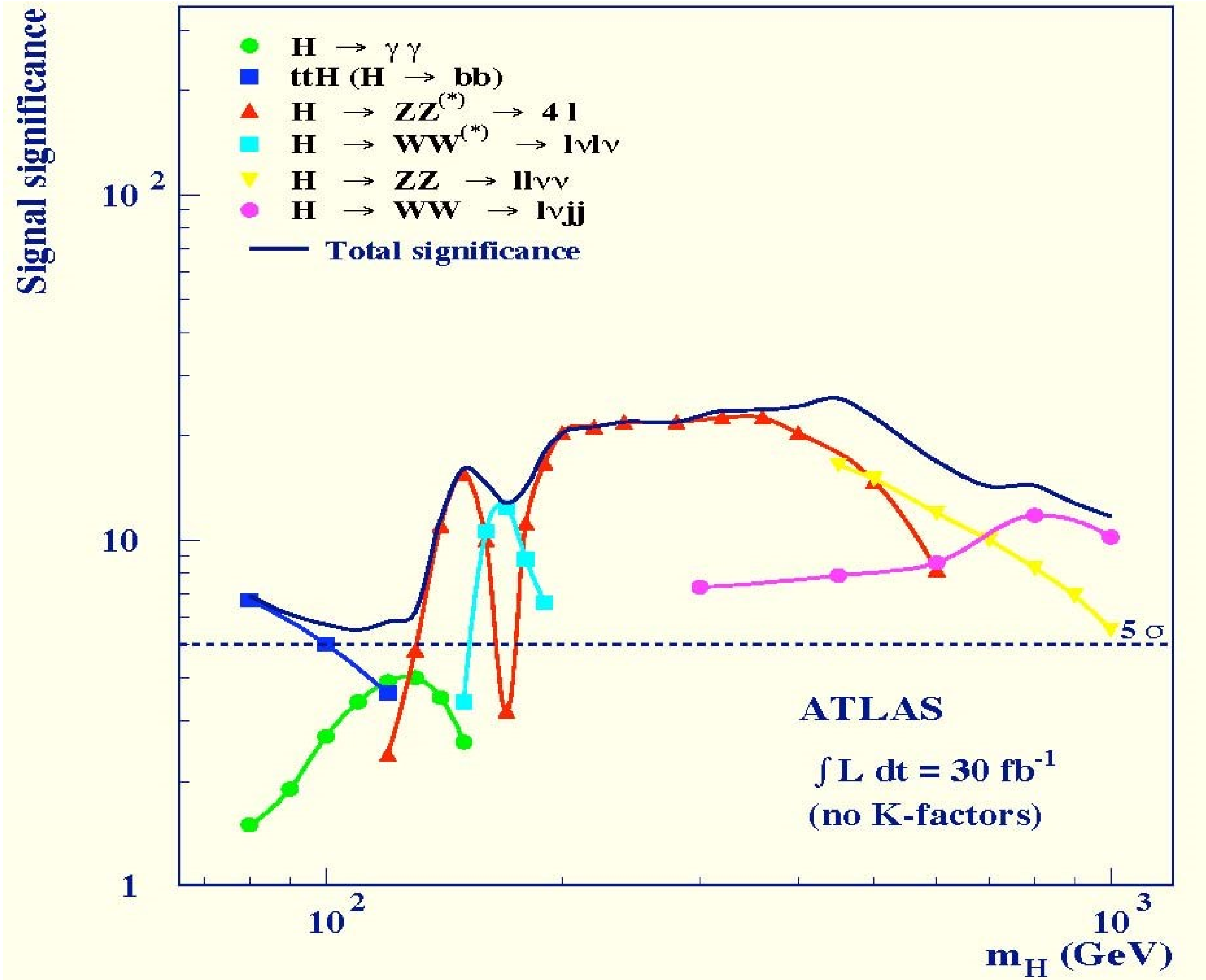
MH < 100 GeV	• H -> γγ
MH < 150 GeV	•H- >ZZ*->4l •H- > bb •H -> WW*-> 2l2υ •H ->τ+τ-
130 < MH < 500 GeV	• H-> ZZ->4l
500< MH < 1000 GeV	• H->ZZ,W+ > jets



Branching Fraction: If produce 10^8 Higgs and measure only 20 decays H→gg with an efficiency of 0.00025% then Branching Fraction:

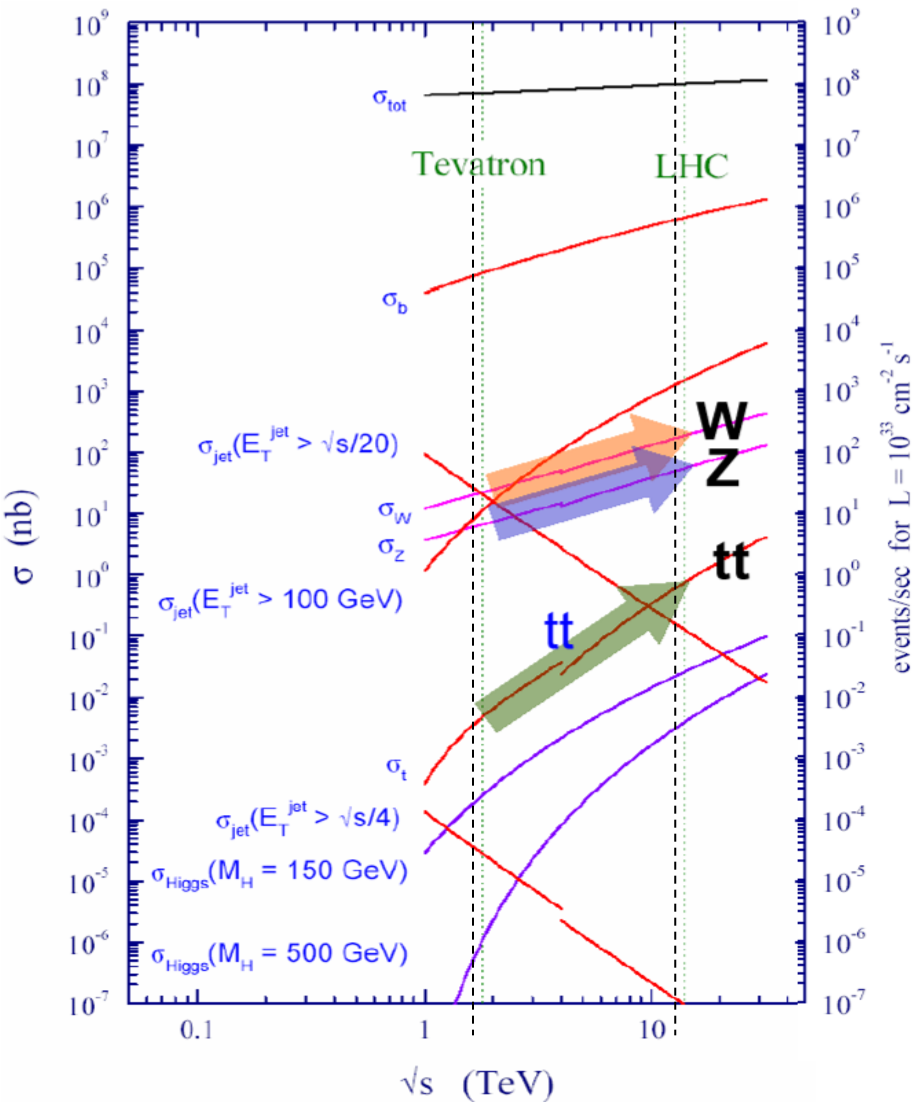
$$BF(Higgs \to gg) = \frac{N_{decays}}{N_H * \eta} = \frac{20}{10^8 * 2.5 \times 10^{-6}} = 0.08$$

Best Modes to look at



Compare to list on previous slides

Backgrounds - Tevatron to the LHC



Huge stats for Standard Model signals. Rates @ $10^{33} cm^{-2} s^{-1}$

~10^9 events/10 fb^{-1} W (200 Hz)

~10^8 events/10 fb^{-1} Z (50 Hz)

~10^7 events/10 fb^{-1} tt (1 Hz)

(10 fb^{-1} = 1 year of LHC running at low luminosity $10^{33} cm^{-2} s^{-1}$)

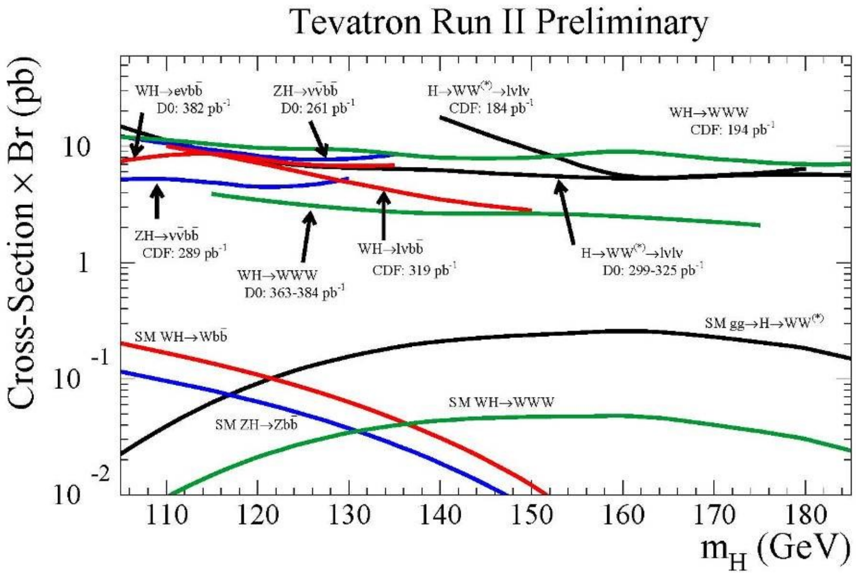
Background is anything with signature similar to signal

- *W+X* (*X* can be *W*, *Z* or just 2 QCD jets)
- *ZZ-> qql+l-* (one lepton not identified)
- $\tau^+\tau^-$
- *b*-tags can be real, charm or fakes

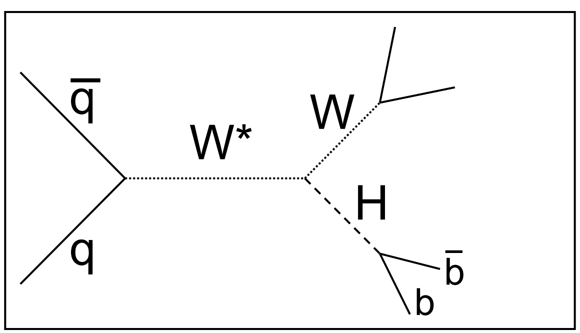
Current Results - Tevatron

- At 120 GeV *H->b$\bar{b}$* dominates
- Signature *gg->H->b$\bar{b}$*:
  - 2 jets
  - One or two *b*-tags
- Swamped by dijet production
  - *b$\bar{b}$* ~ μb
  - *q$\bar{q}$* ~ mb *(fake b-tag rate small but not zero)*
- Have to use *W/Z+H* channel (Associated Production)

Tevatron/CDF - Associated Production



Qq̄->WH with *H->bb̄*



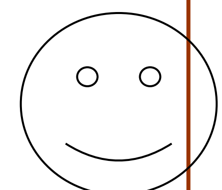
W->qq̄ 70%

- final state *qq̄bb̄*
- Four jet backgrounds still too large

W-> eν$_e$ 10% *W-> μν$_μ$* 10%

- Final state *lνbb̄*
  - One electron or muon
  - Missing transverse momentum
  - Two jets
  - One or two *b*-tags
- Easy to select in trigger and offline

$\sigma \times Br \approx 0.02$ pb



Understanding "Higgs Exclusion Plot"

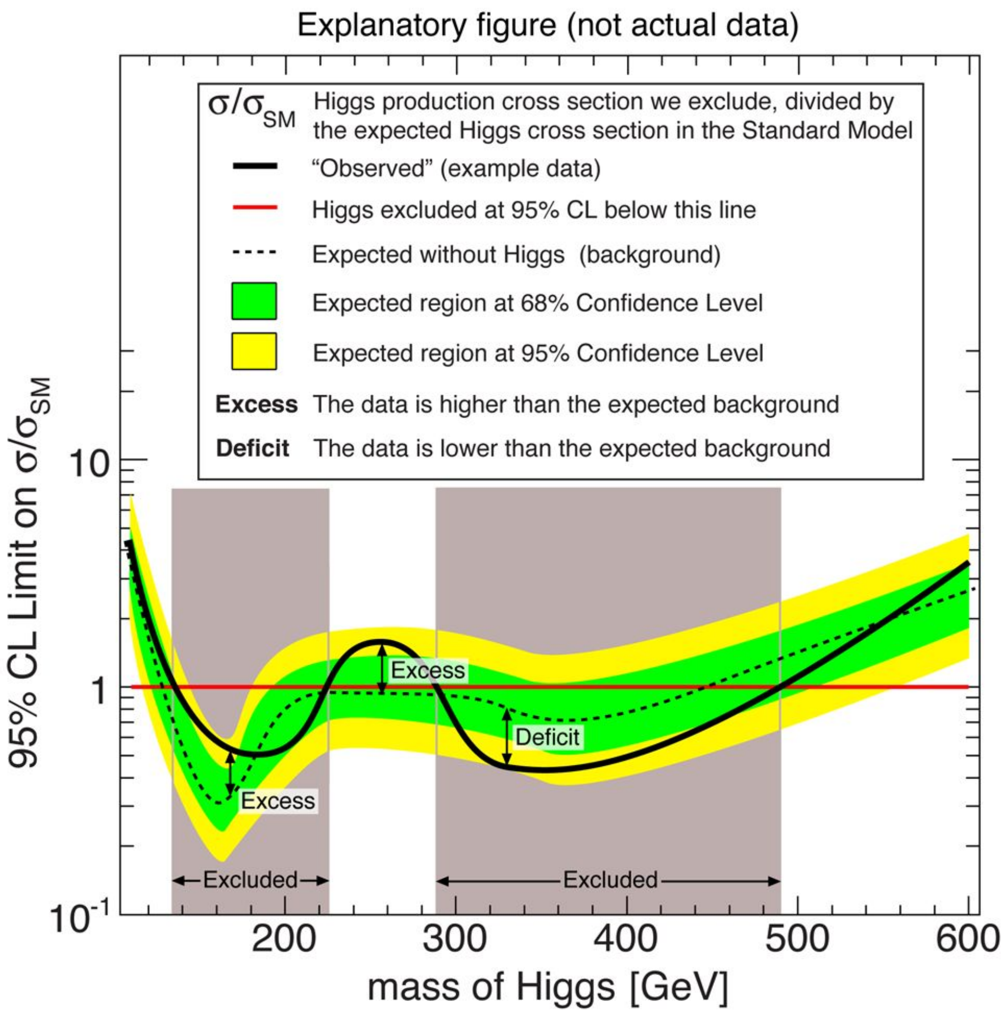
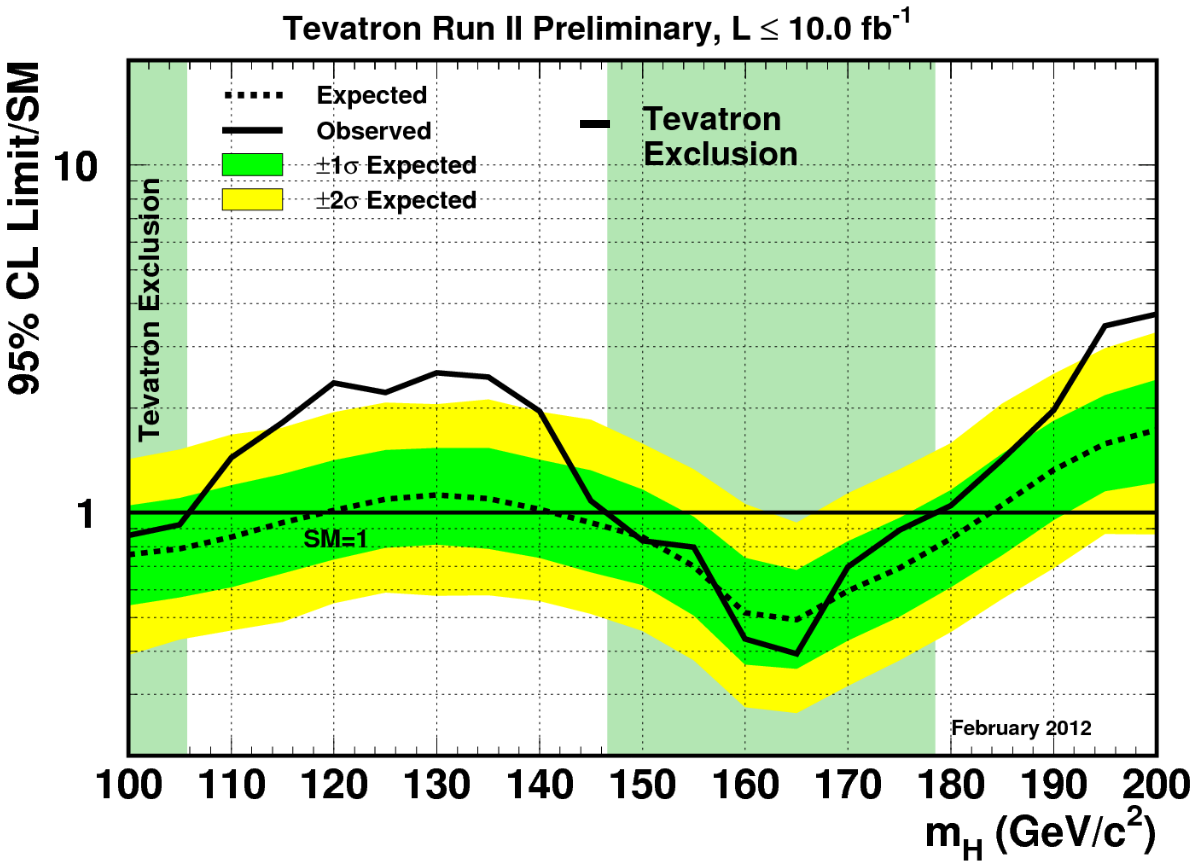


Figure A

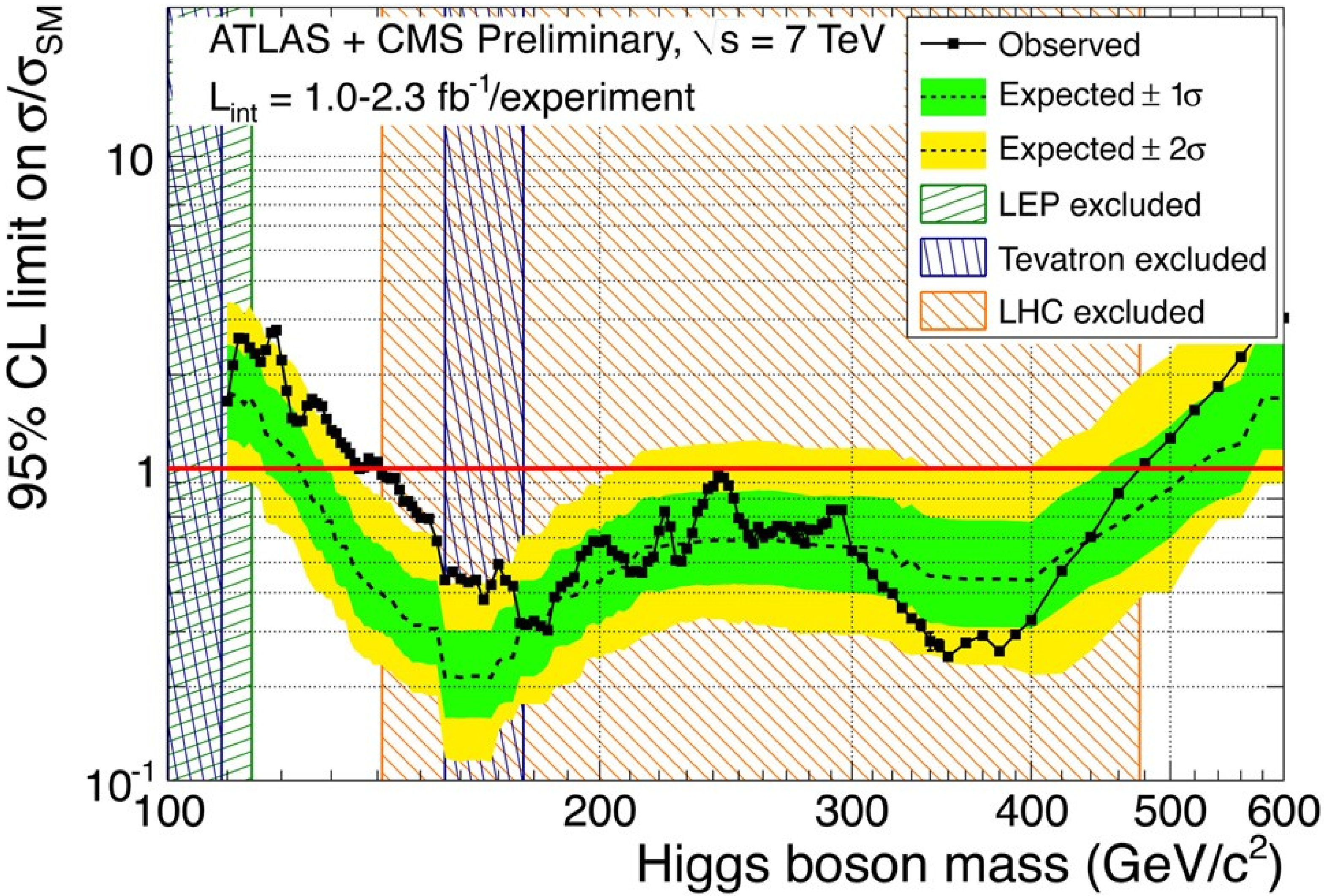
Latest Higgs Results from Tevatron



Combined from many measurements.

10 years of data

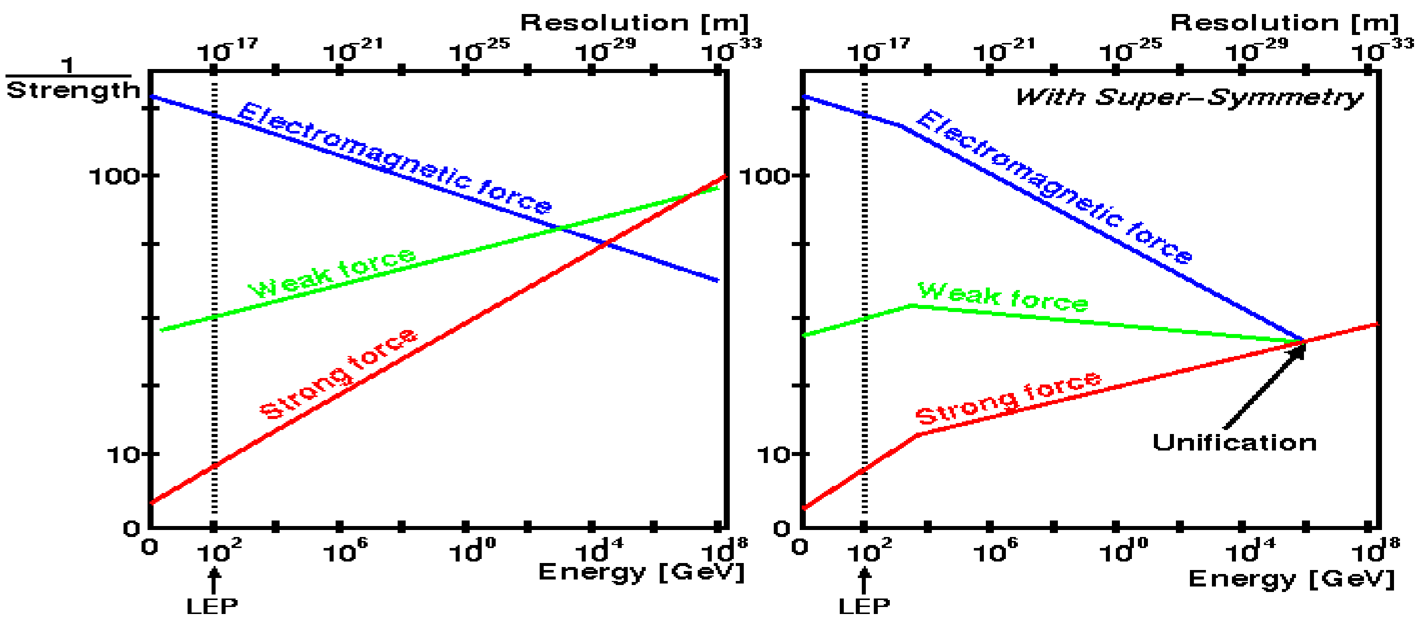
Latest Higgs Results from LHC



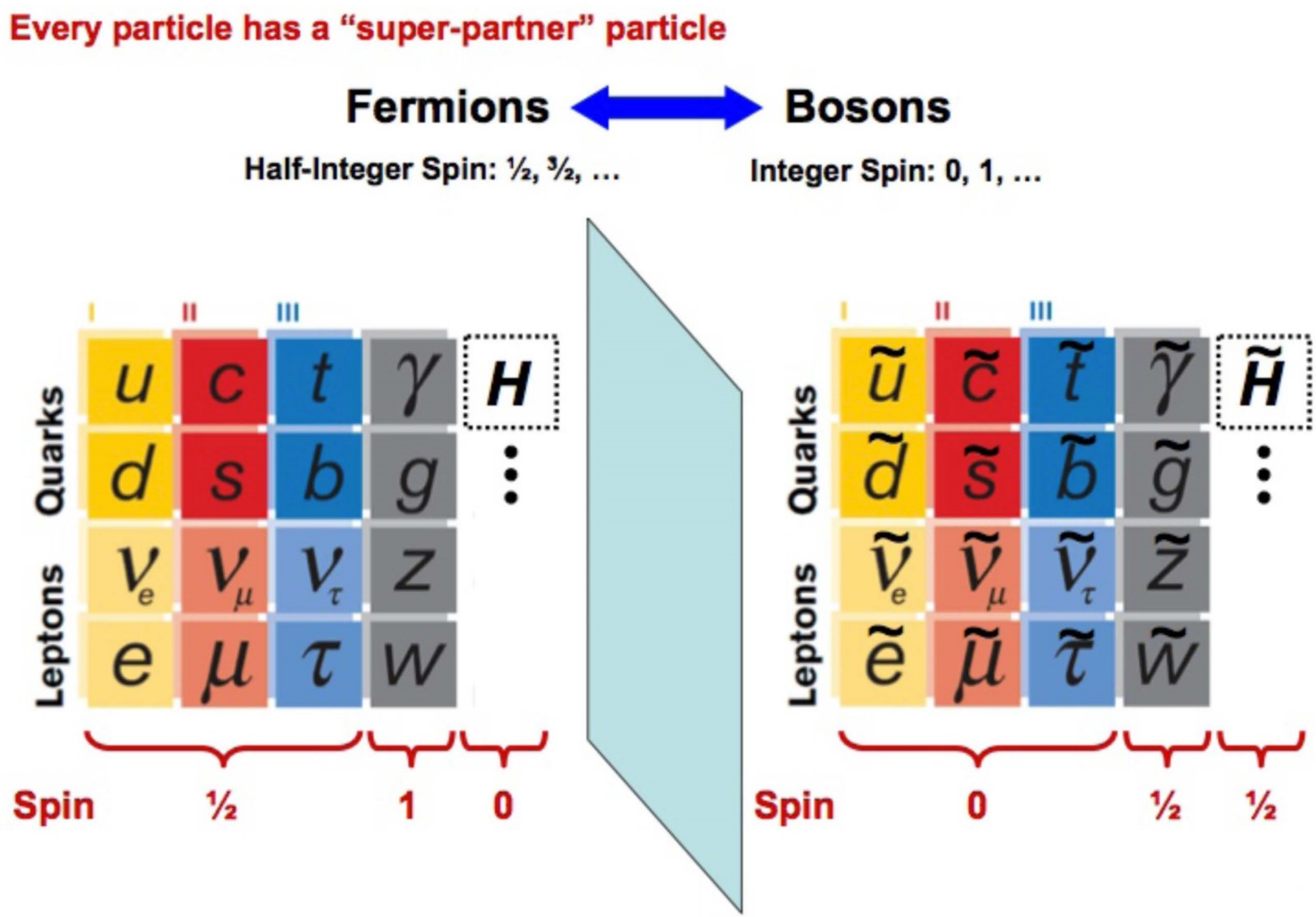
Nov 2011

Is the Standard Model all there is?

- So far we have assumed a Standard Model Higgs but...
  - Does not explain Dark Matter
  - Does not unify electromagnetism, weak and strong forces at high-energies (10^{16} GeV, Planck mass).
  - Do not know the Higgs potential
  - Calculations of Higgs mass using Standard Model produces a mass which is far too high (>1 TeV)
- Need models beyond the Standard Model



Supersymmetry



Supersymmetric Higgs

- Need at least two Higgs doublets (H_1,H_2) to generate down- and up-type particles.
- Physical particles:

$$h = H_2 \cos\alpha - H_1 \sin\alpha \quad (m_h < m_Z)$$
$$H = H_2 \sin\alpha - H_1 \cos\alpha \quad (m_H > m_Z)$$
$$A = \text{CP-odd Higgs}$$
$$\text{H}^{\pm} = \text{charged Higgs} \quad (m_{H^{\pm}} = m_A^2 + m_W^2)$$

- Radiative corrections can change masses.
- Higgs sector now described by two free parameters (m_h and $\tan\beta = \upsilon_2/\upsilon_1$).
- However, the exact SUSY symmetry has to be broken to reconcile the theory with experiment (i.e. the standard model and SUSY particles have different masses).
- The minimal extension to SUSY (MSSM) has 105 parameters!
- Have to assume a specific model e.g. mSUGRA
  - Modifies Higgs mechanism
  - 5 free parameters:
    - $\tan\beta$ (as before)
    - m_0 (universal scalar mass, includes Higgs)
    - $m_{½}$(gaugino mass)
    - plus two others

Looking for SUSY Higgs at the LHC

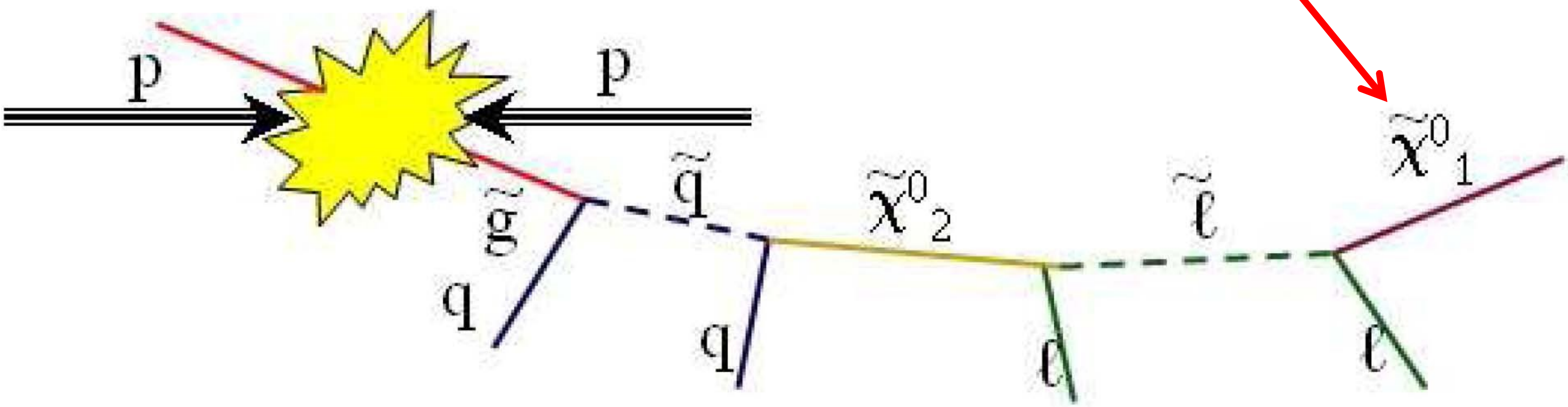
- Small $\tan\beta$
  - $gg \rightarrow H,A$ production is enhanced due to stronger $t\bar{t}H$ coupling.
  - $H,A \rightarrow t\bar{t}$ decay gets enhanced.
- Large $\tan\beta$
  - H, A production is enhanced in $b\bar{b}$-fusion
  - $H \rightarrow \tau\tau$ has a large branching ratio
- Medium $\tan\beta$
  - Only SM-like h visible. We could see a Higgs and not realise we have seen SUSY!
- Charged Higgs
  - Clear signal for new physics (not predicted in Standard Model)

Looking for other SUSY particles

- SUSY predicts that every Standard Model particle has a Super-Symmetric partner
  - Electron ↔ selectron, quark ↔ squark, W ↔ wino, etc...
  - But masses not the same → SUSY not exact symmetry
- SUSY can be a new source of CP-Violation
  - Explain matter/anti-matter asymmetry of the Universe
- A SUSY particle will quickly decay to the Lightest Supersymmetric Particle (LSP).
  - Neutral (no charge)
  - LSP is a candidate for Dark Matter
- LSP will leave detector without interacting
  - Large Missing energy, momentum (because LSP is massive)
- What is the LSP?
  - Don't really know
  - Likely to be a neutralino

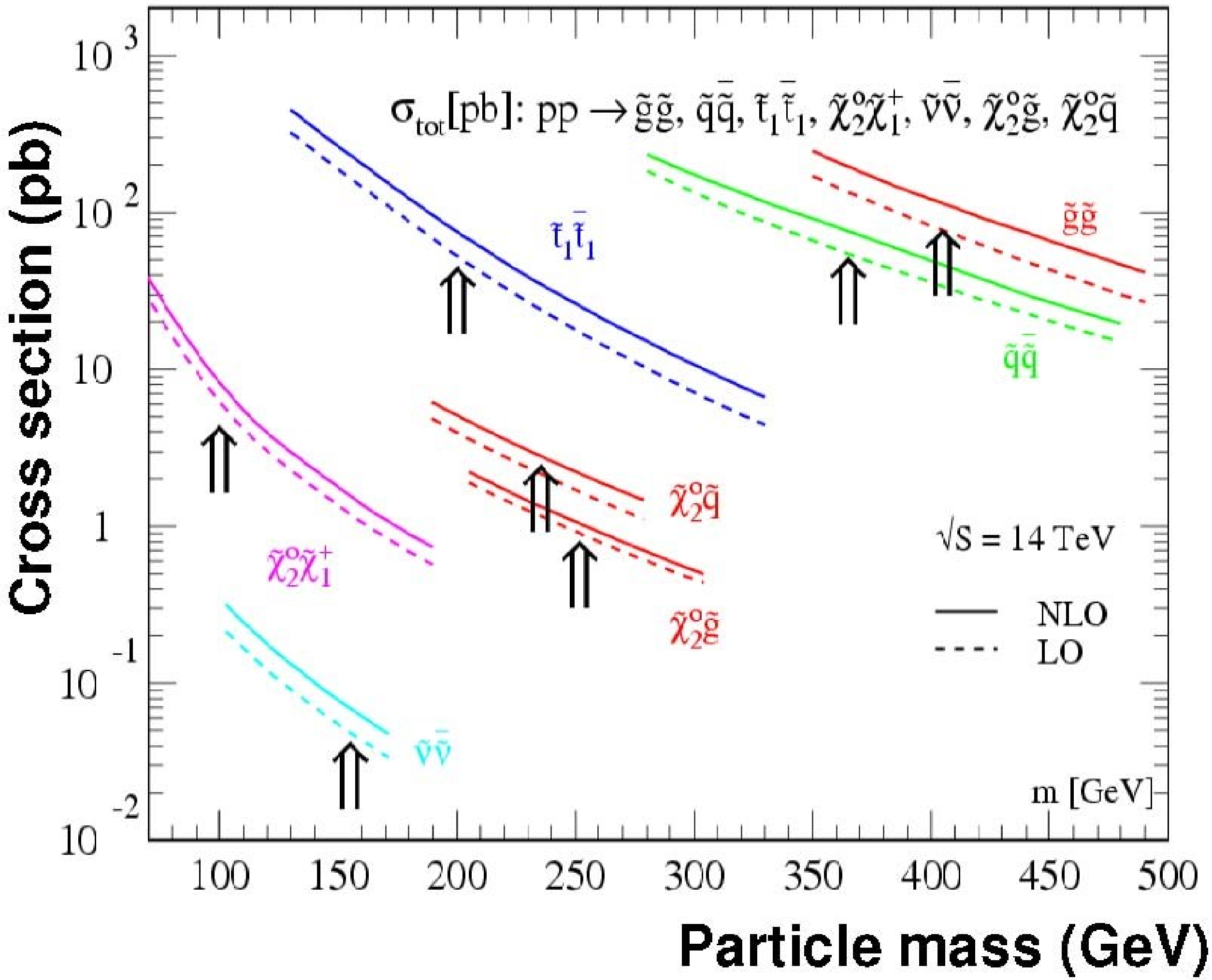
What a SUSY decay looks like

Missing energy

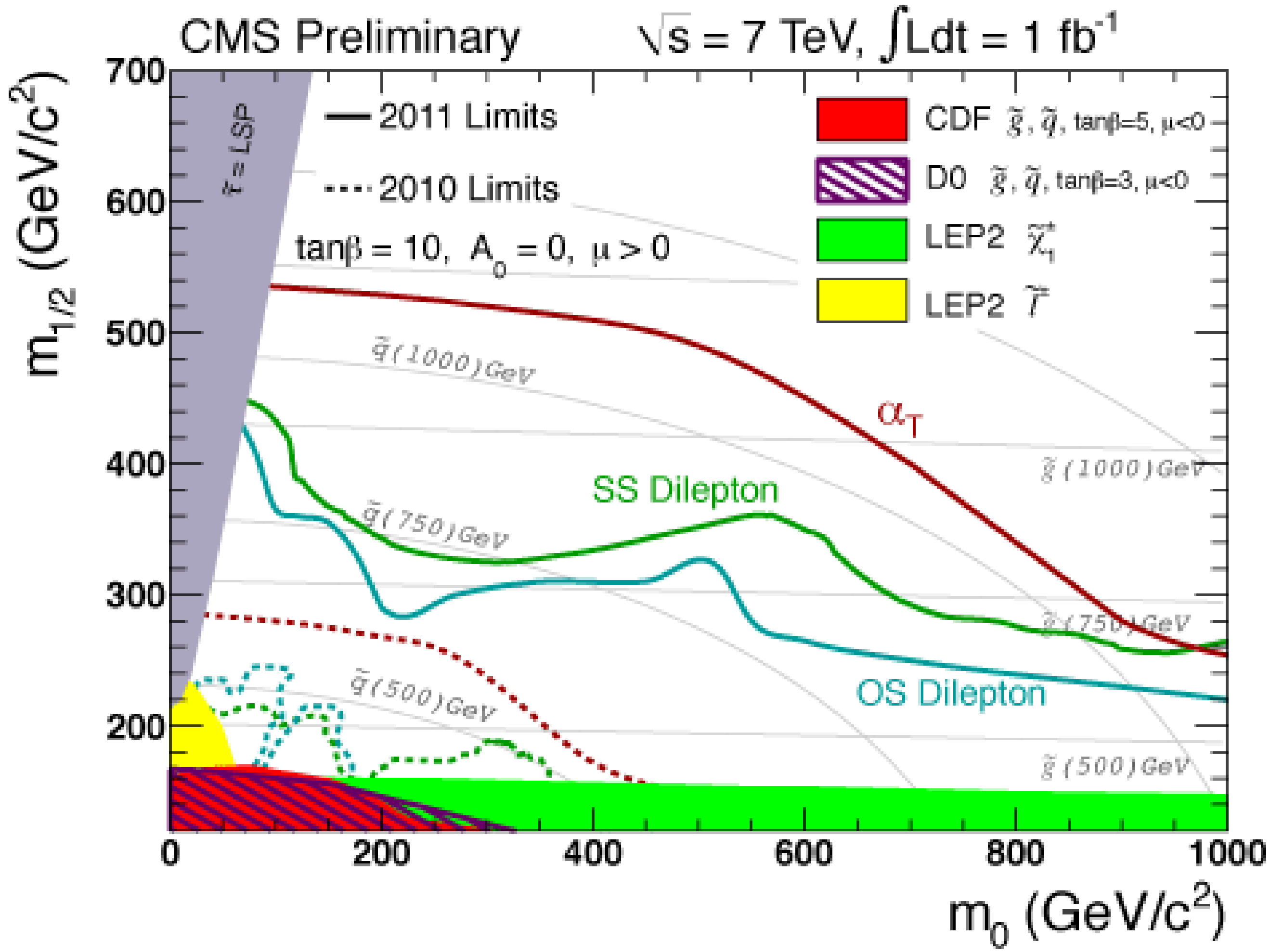


Lots of leptons produced. Easy to see and not produced in background events

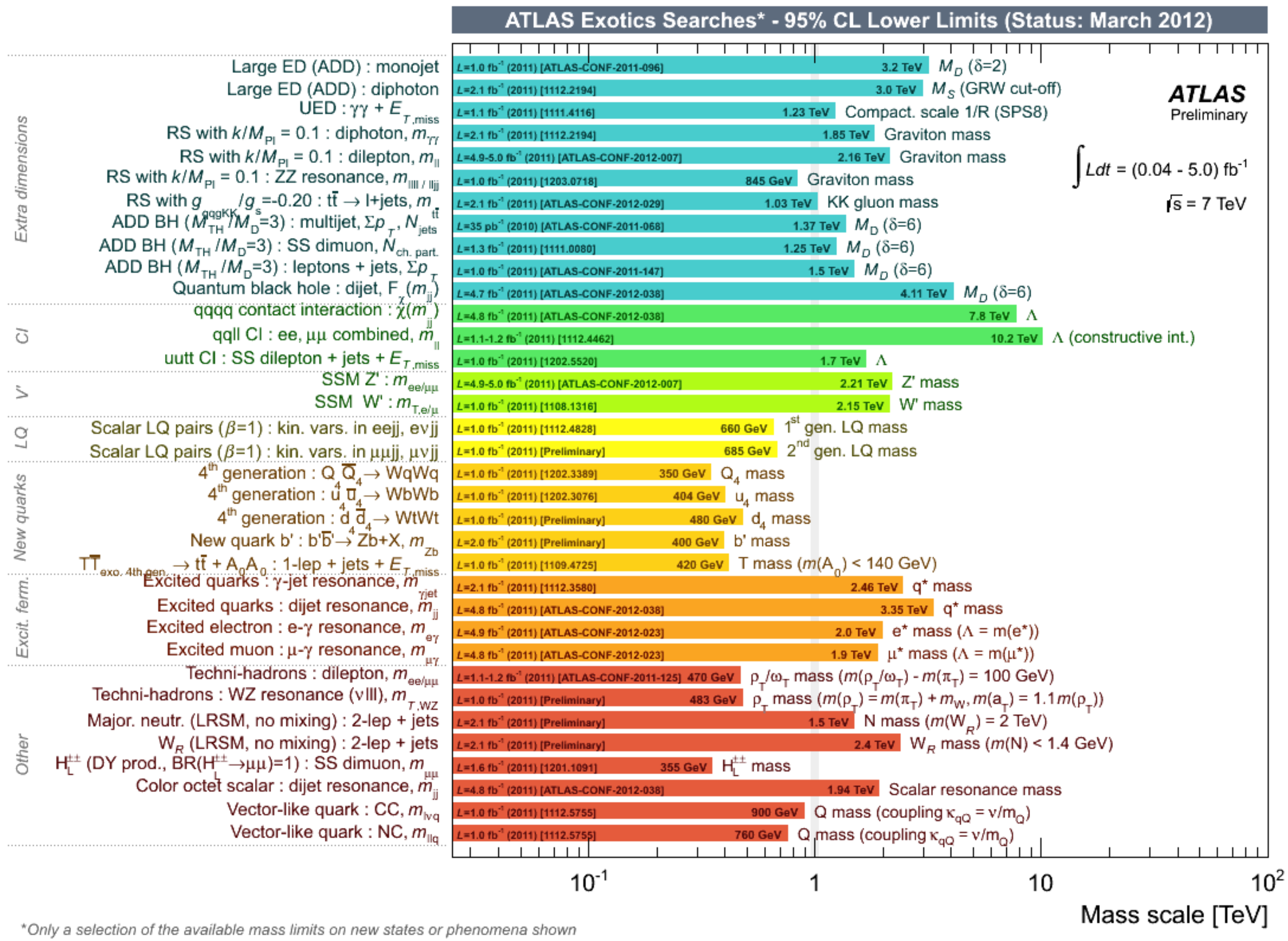
What theory predicts for SUSY at LHC



What we currently (don’t) see (March 2012)



What we currently (don't) see (March 2012)



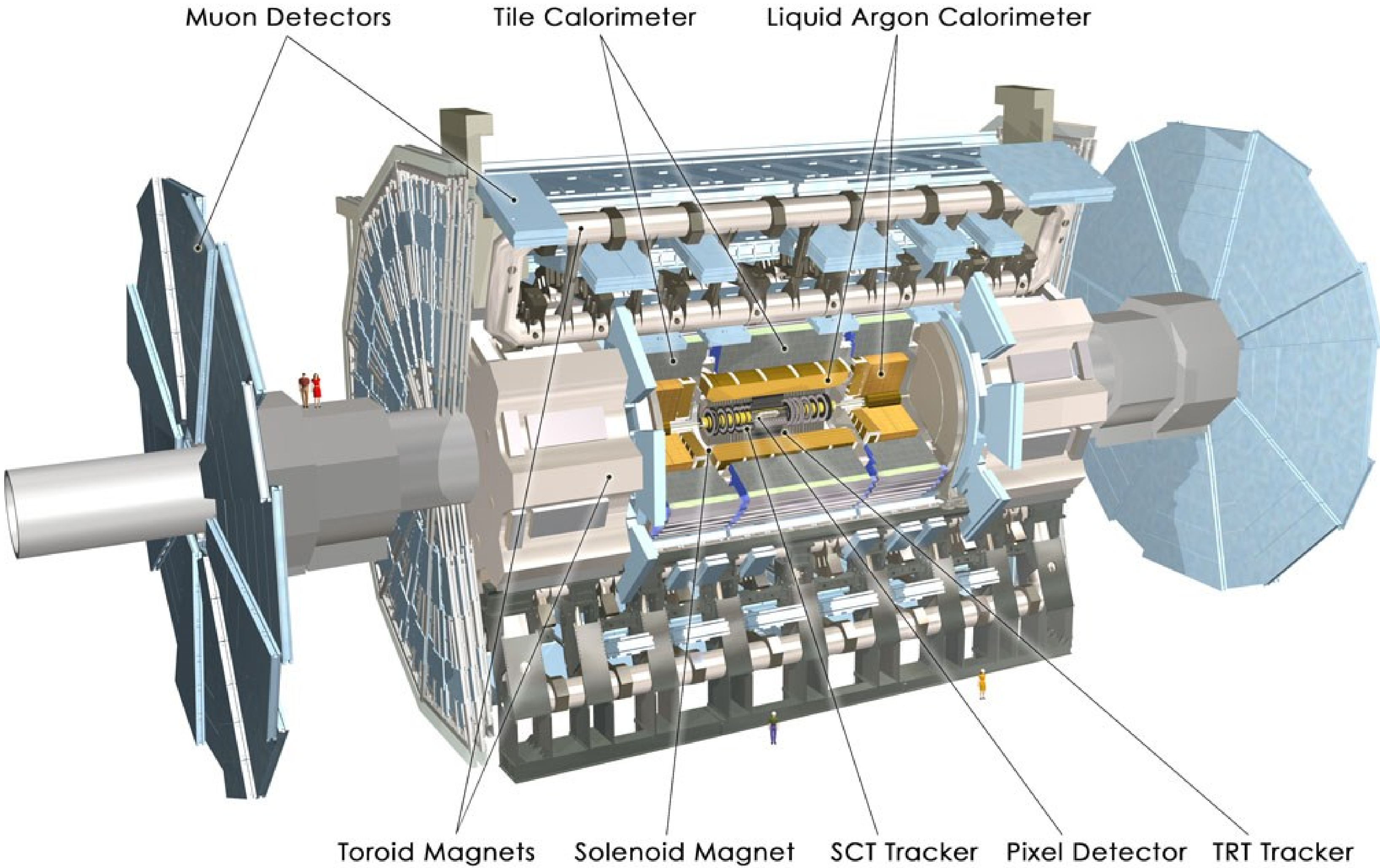
Status of the LHC

- The Higgs mass has not been excluded around ~125GeV
- By the end of 2012, the LHC will be able to confirm/deny presence of a Higgs below ~600 GeV.
- If 125 GeV Higgs confirmed
  - Could be a Standard Model Higgs (good).
  - Could be a SUSY Higgs (also good).
- If no Higgs below ~600 GeV
  - Higgs mechanism (and therefore Standard Model) in big trouble (bad).
- If no SUSY particles found below 1 TeV
  - SUSY models are "wrong" (bad) but theorists always have a back up plan.

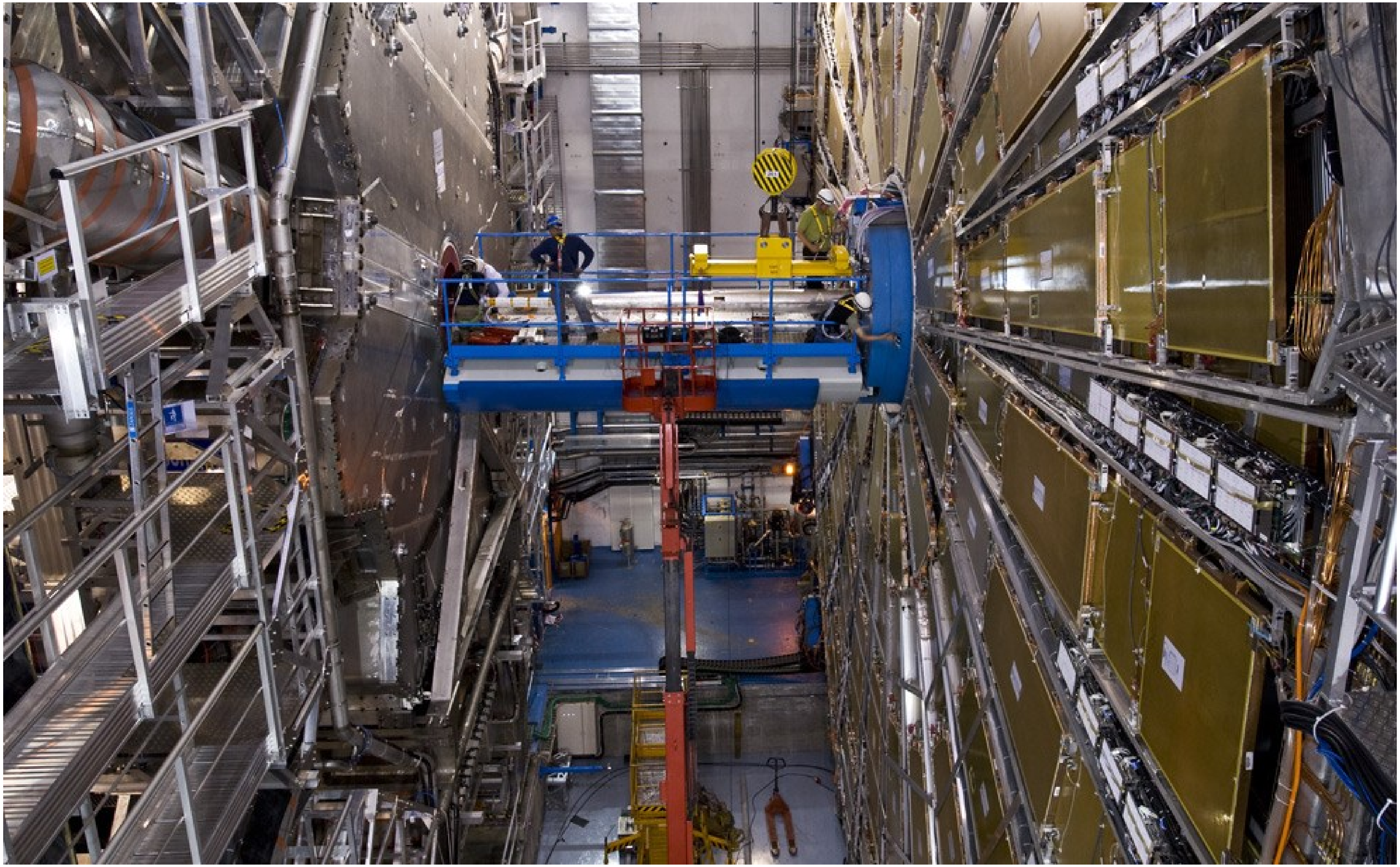
One final thought...

- John Ellis, Nature 481, 24 (2012)
  - "One option is that the evidence from the LHC will be confirmed, and a standard-model Higgs boson exists in the low-mass range below 130 GeV....But there is a catch. Within the standard model, it is possible to calculate the lowest energy state of the Universe. If the Higgs is light, this calculation predicts a lowest energy state totally unlike our current Universe. It implies that our Universe is in some other, unstable state that will eventually flip over to its lowest energy condition — next week, or in a few billion years, we could go down the cosmological tubes...."

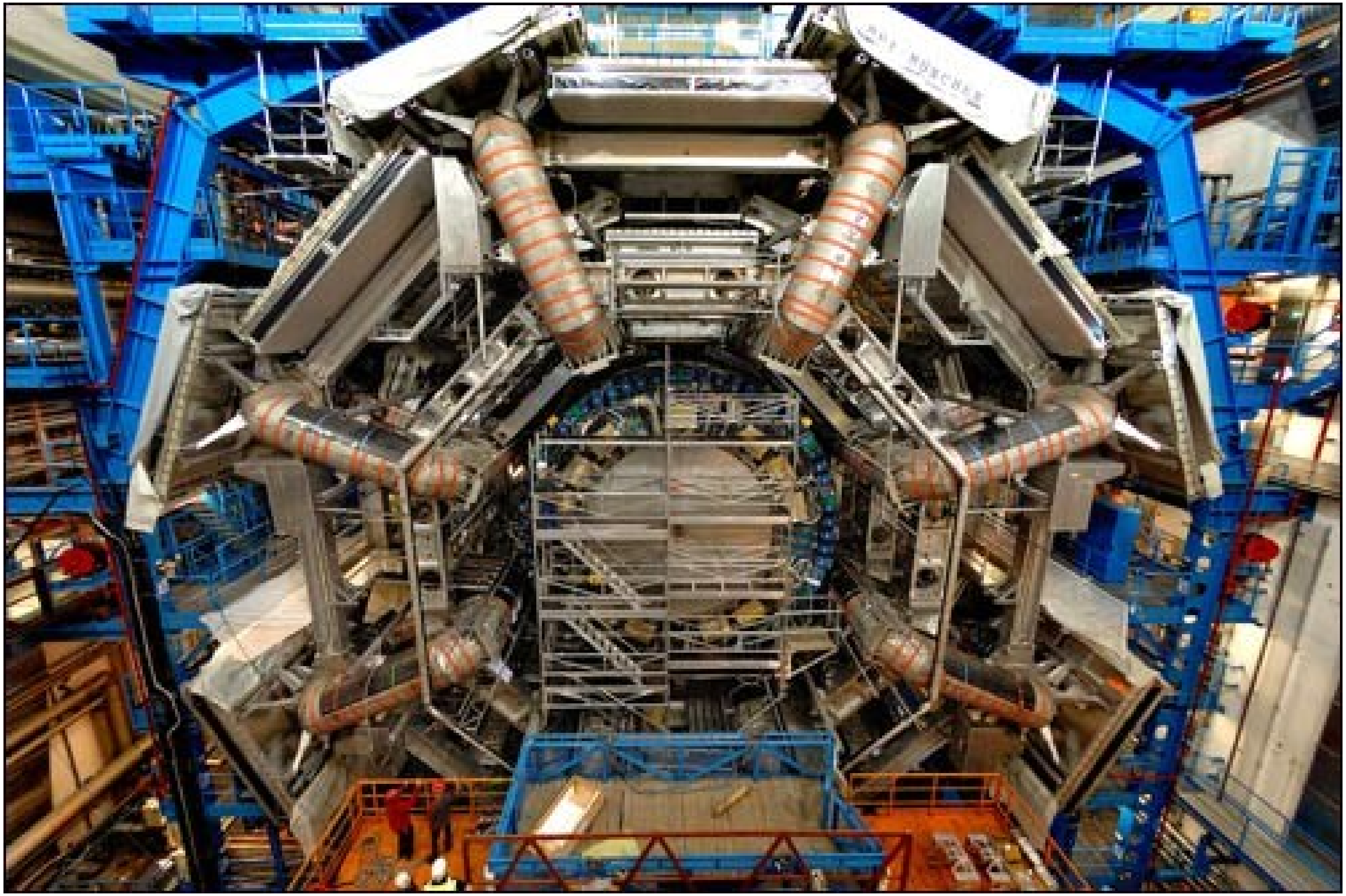
ATLAS detector



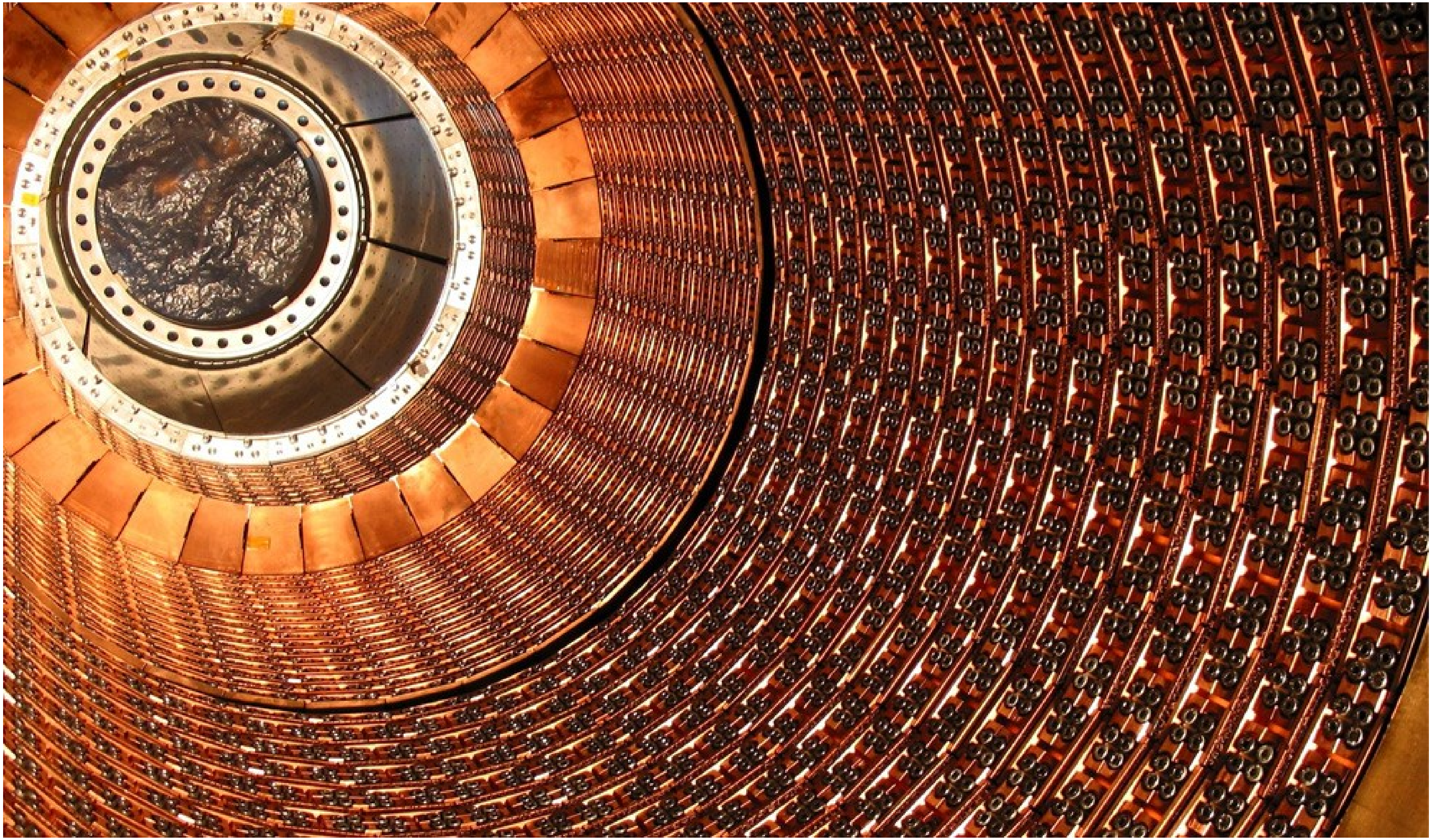
ATLAS beam-pipe



ATLAS construction

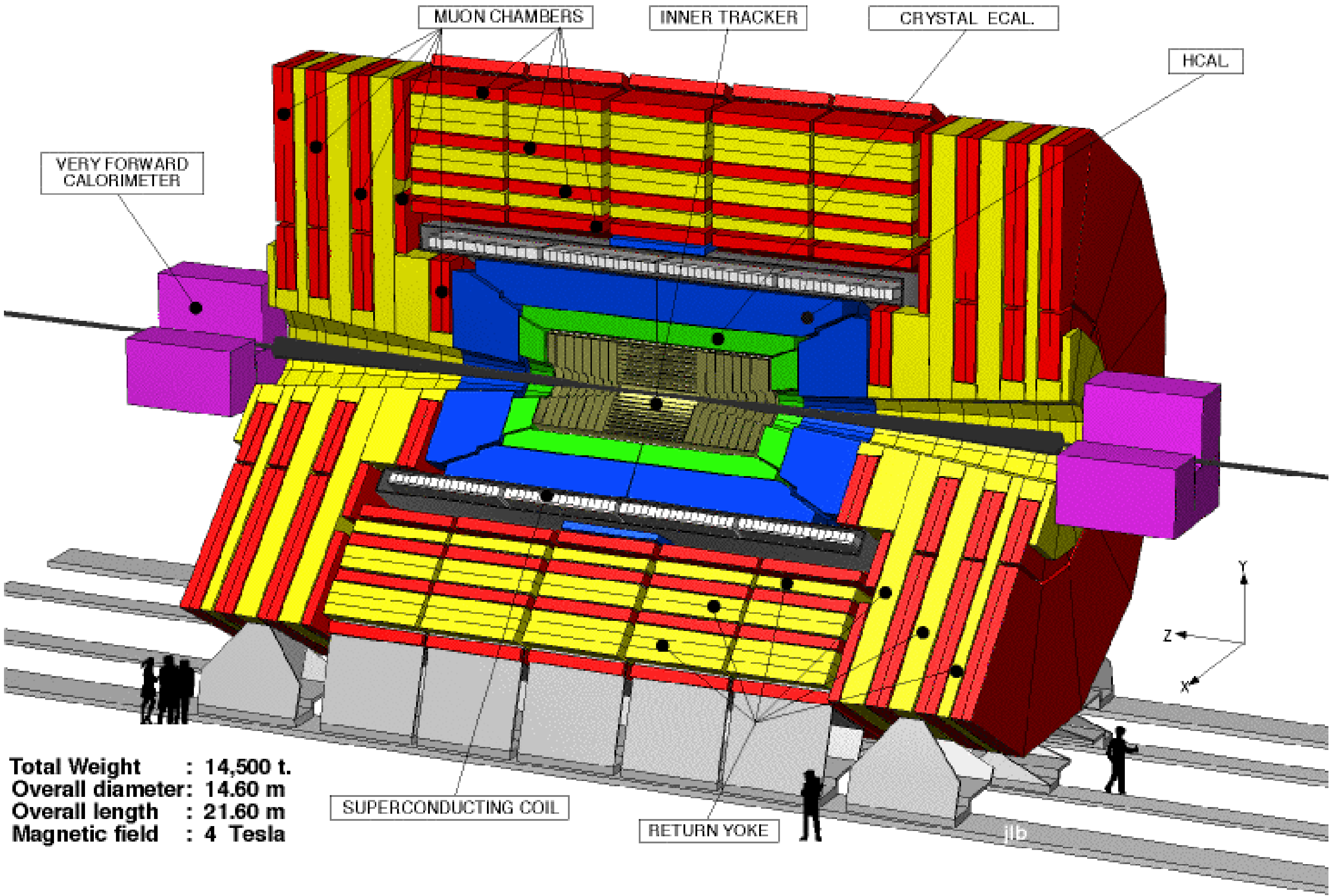


ATLAS Tracker (silicon)

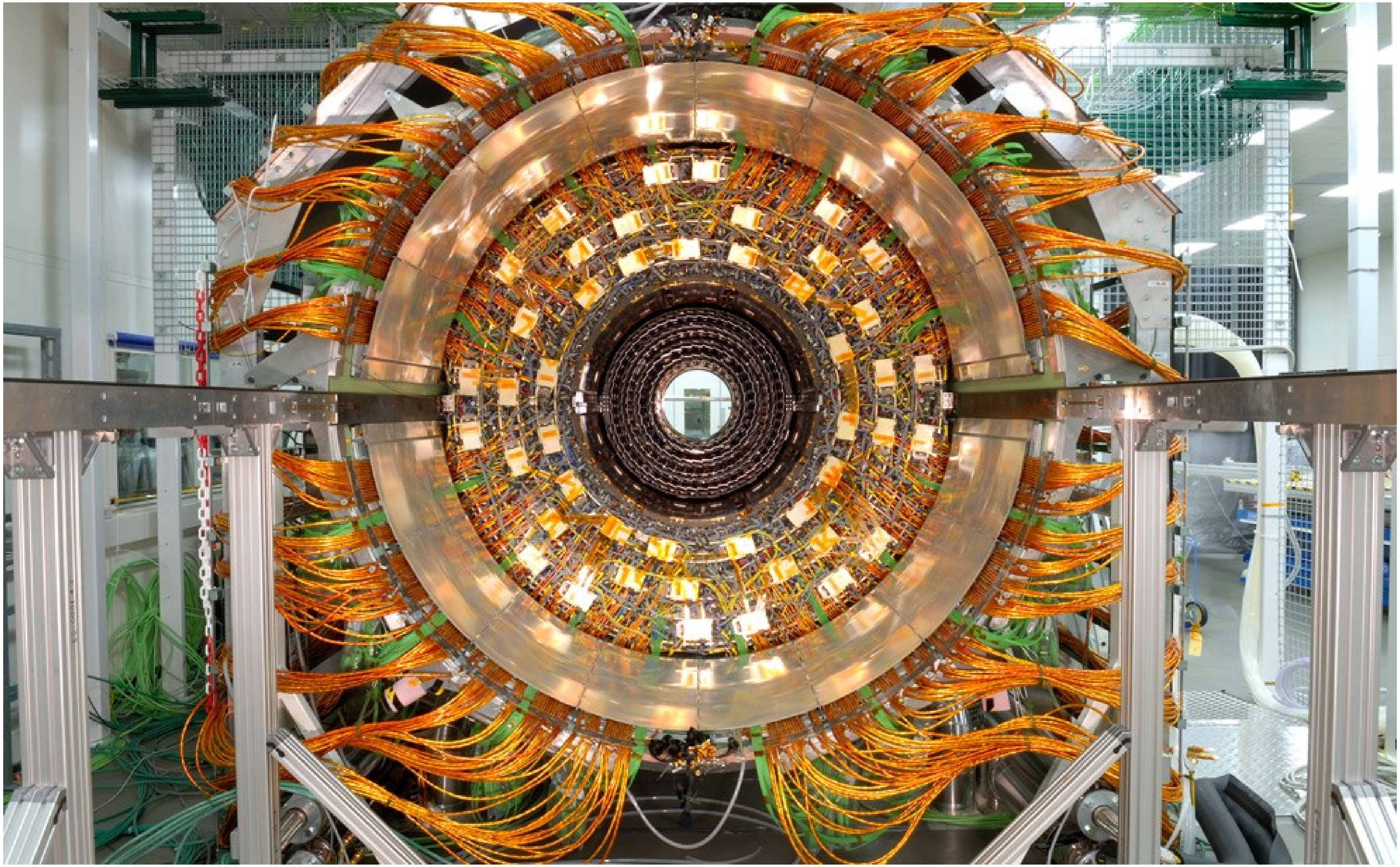


ATLAS toroid magnet

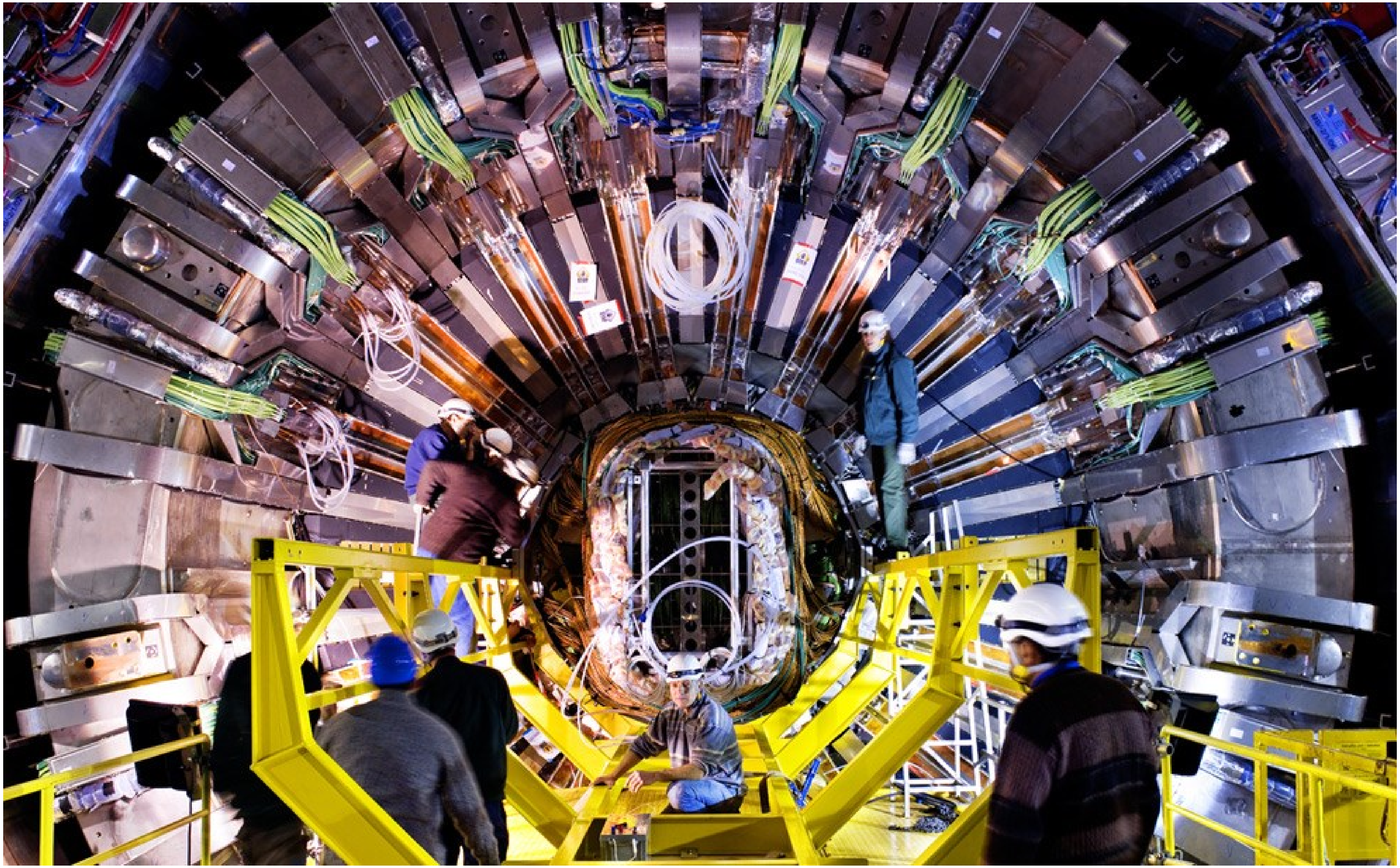
CMS detector



Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla



Inserting CMS tracker



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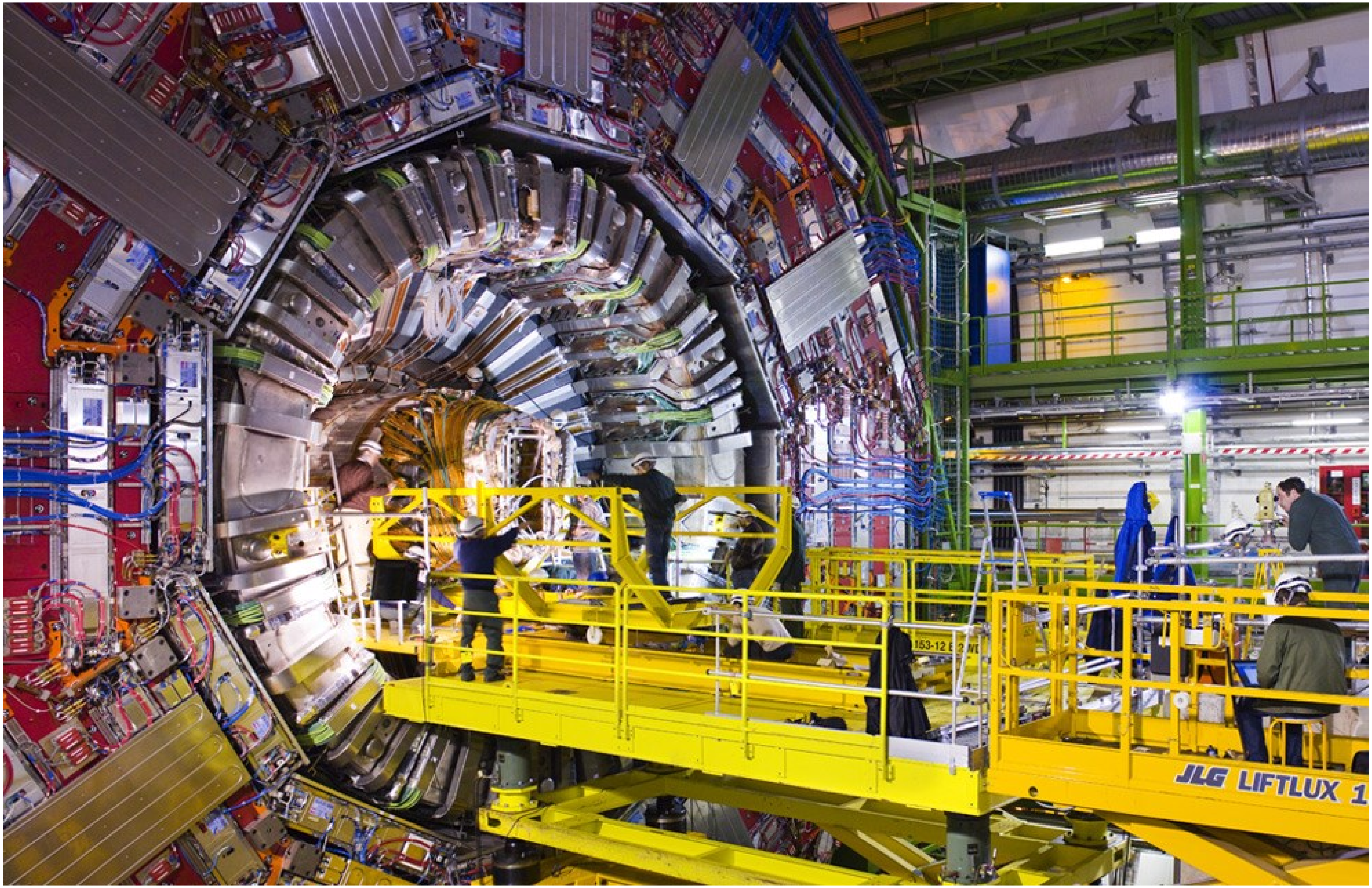
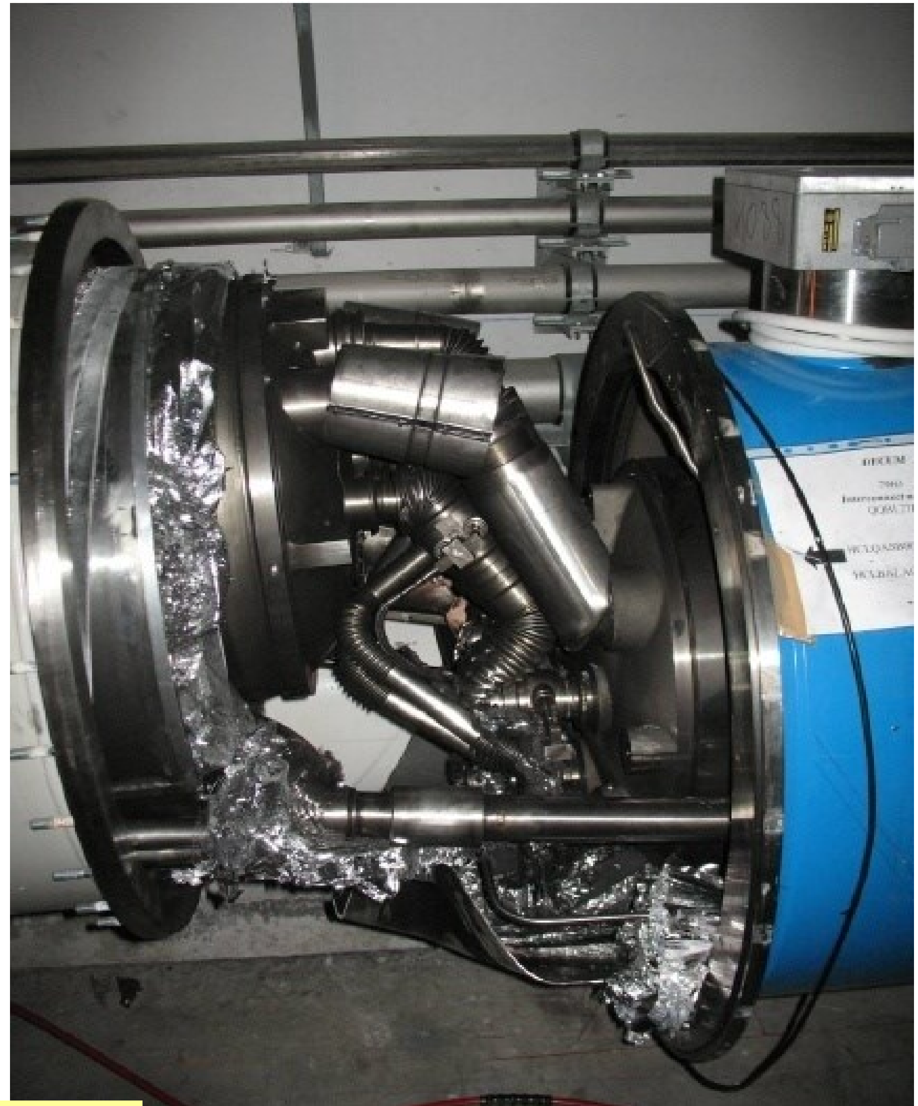


Damaged magnets 2009

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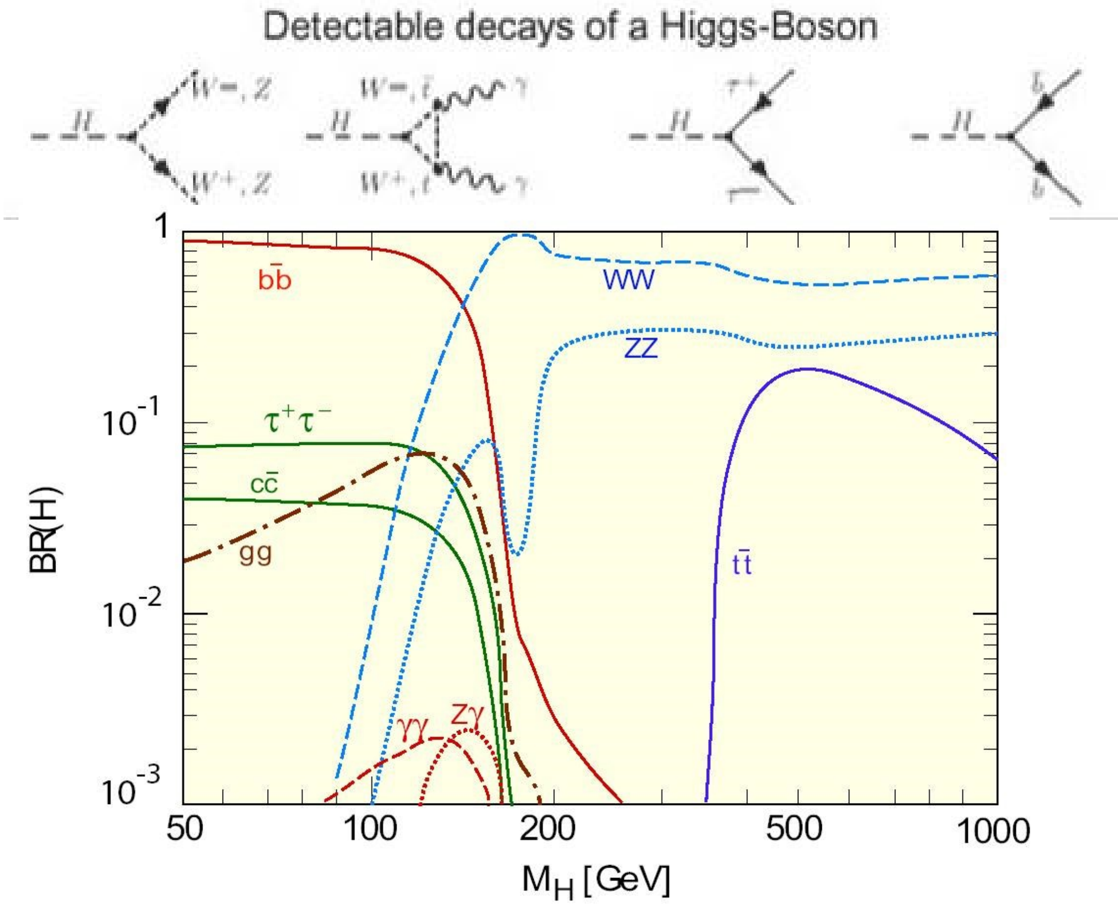
Higgs Decay



- Which decay to look at?
- Depends on Higgs Mass
  - M_H <100 GeV
    - gg → H→$\gamma\gamma$
  - M_H <150 GeV
    - H→ZZ^*→4l
    - H→bb
    - H→WW^*→2l 2ν
    - H →$\tau^+\tau^-$
  - 130 < M_H <500 GeV
    - H→ZZ→4l
  - 600 < M_H < 1000 GeV
    - H→ZZ,WW → jets

Branching Fraction: If produce 10^8 Higgs and measure only 20 decays H→gg with an efficiency of 0.00025% then Branching Fraction:

$$BF(Higgs \rightarrow gg) = \frac{N_{decays}}{N_H * \eta} = \frac{20}{10^8 * 2.5\times10^{-6}} = 0.08$$