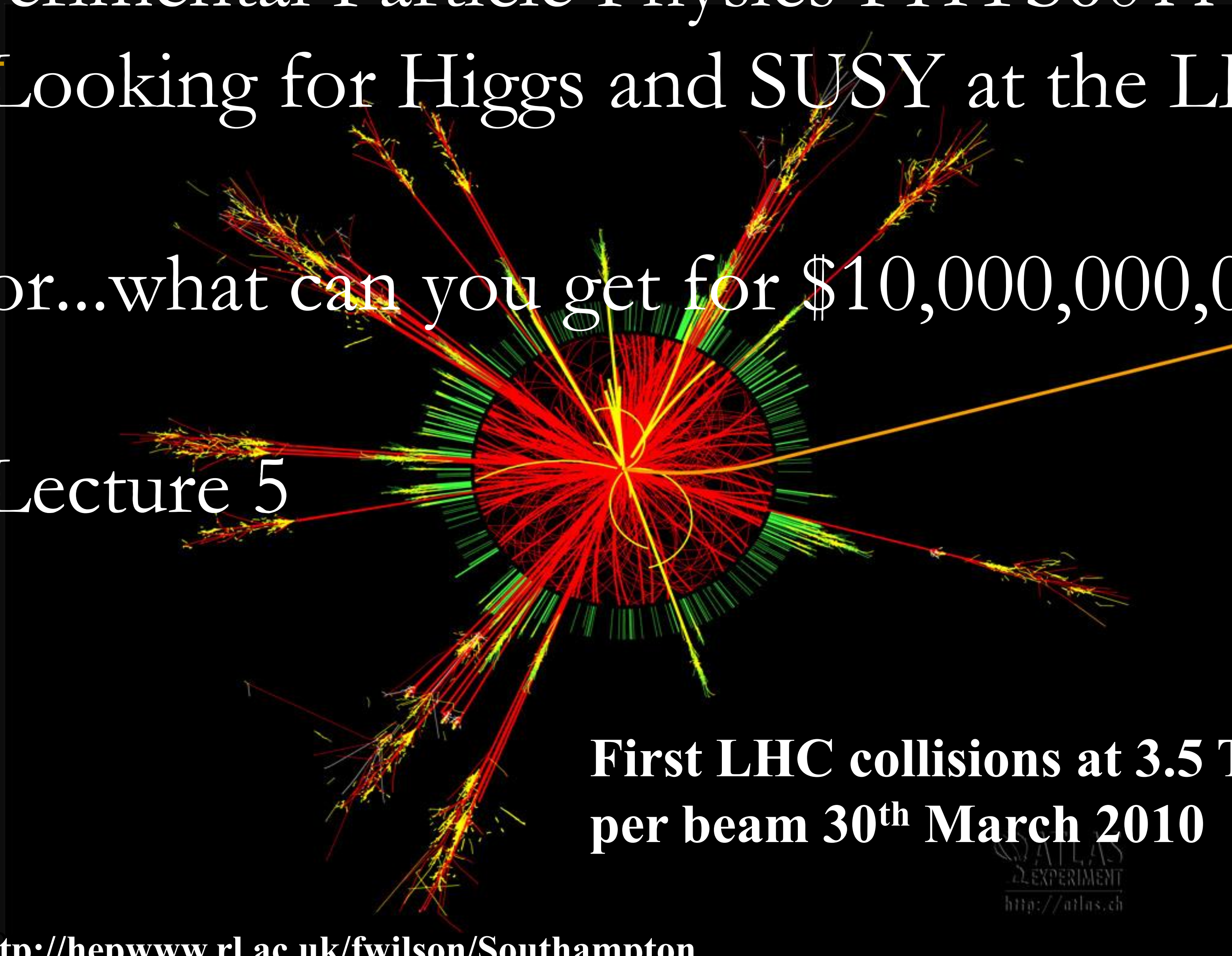
Experimental Particle Physics PHYS6011

Looking for Higgs and SUSY at the LHC

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

Lecture 5



First LHC collisions at 3.5 TeV per beam 30th March 2010

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

Search for the Higgs Boson

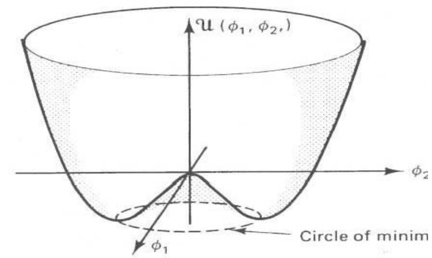
- Missing piece of Standard Model
- Standard Model Higgs theory well understood:
  - Mass is only free parameter
  - Clear predictions to test
- Most "New Physics" models have something equivalent to a Higgs boson ("MSSM Higgs", "little Higgs", etc…).
- Could be more than one type of Higgs boson
- Current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

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



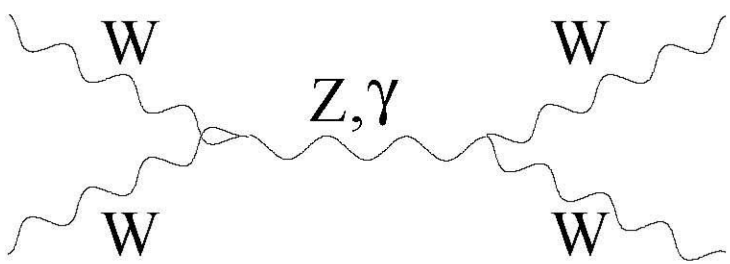
- Step 1: Spontaneous Symmetry Breaking produces one massive and one massless gauge boson (Goldstone Boson).
- Step 2: Introduce local gauge invariance : massive Higgs particle and a massive gauge field.
- Higgs mass a free parameter $M_H = \sqrt{-2\mu^2}$
- Gauge couplings of Higgs doublet give gauge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

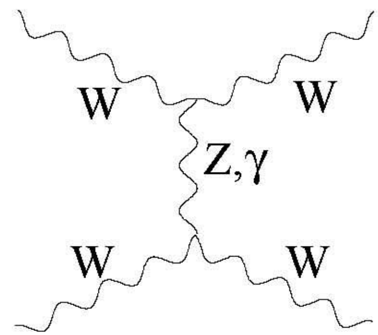
$$M_W = g_W \nu / 2 \quad M_Z = M_W \cos\theta_W \quad \cos\theta_W = 0.8810$$

- Higgs couplings to fermions depends on their mass and unique coupling for each fermion: $M_f \propto M_H g_f$

What do we know about the Higgs?

- No useful lower limit from theory.
- Upper limit from WW scattering
  - Above ~1TeV cross-section → ∞
  - Need Higgs to “regularise” cross-section

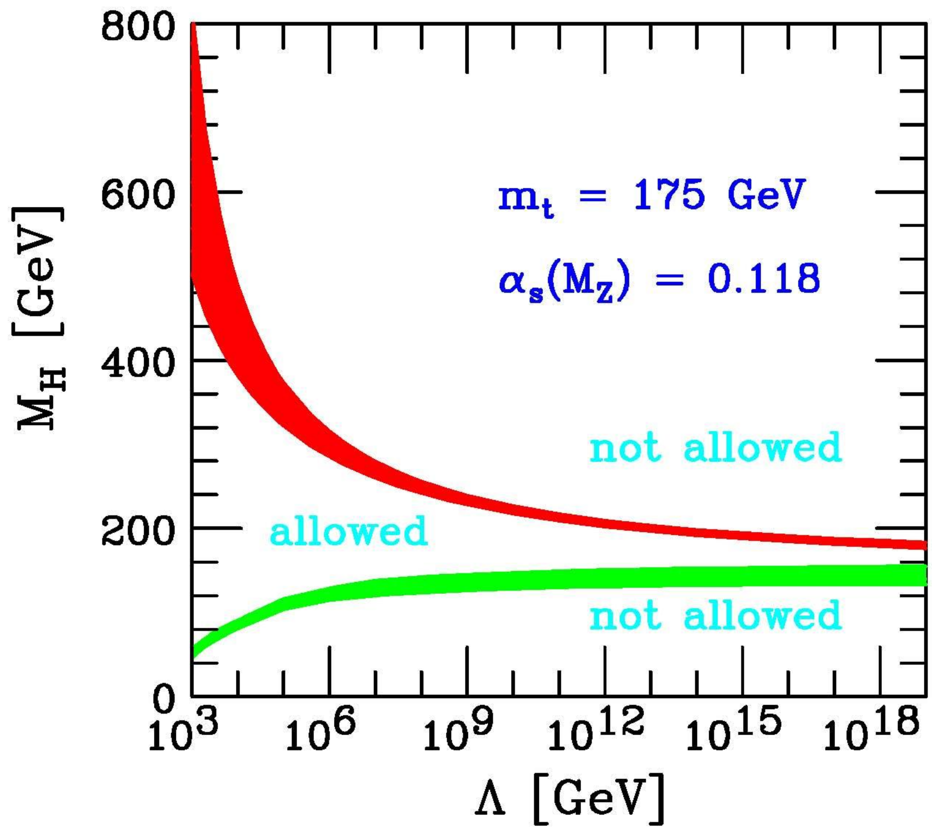




What do we know about the Higgs?

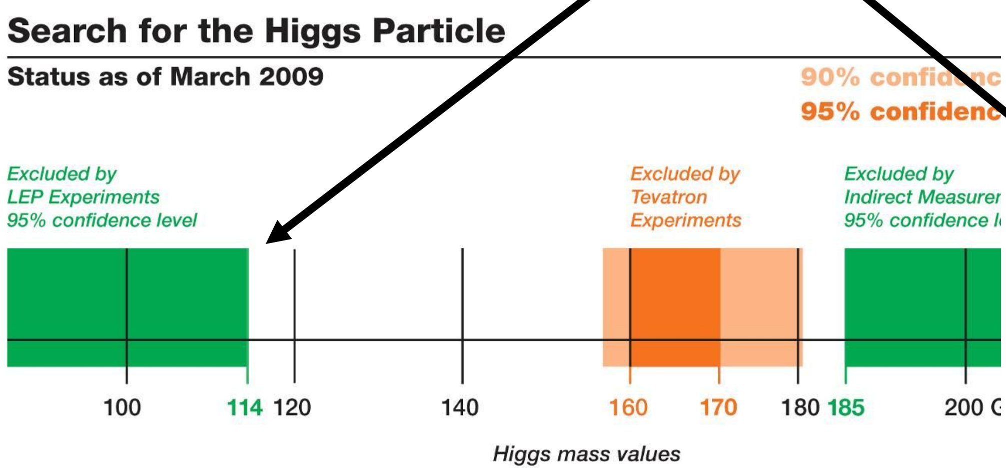
If no new physics up to Planck scale (~10^{19}GeV) small mass range for Higgs: $130 < M_H < 190$ GeV

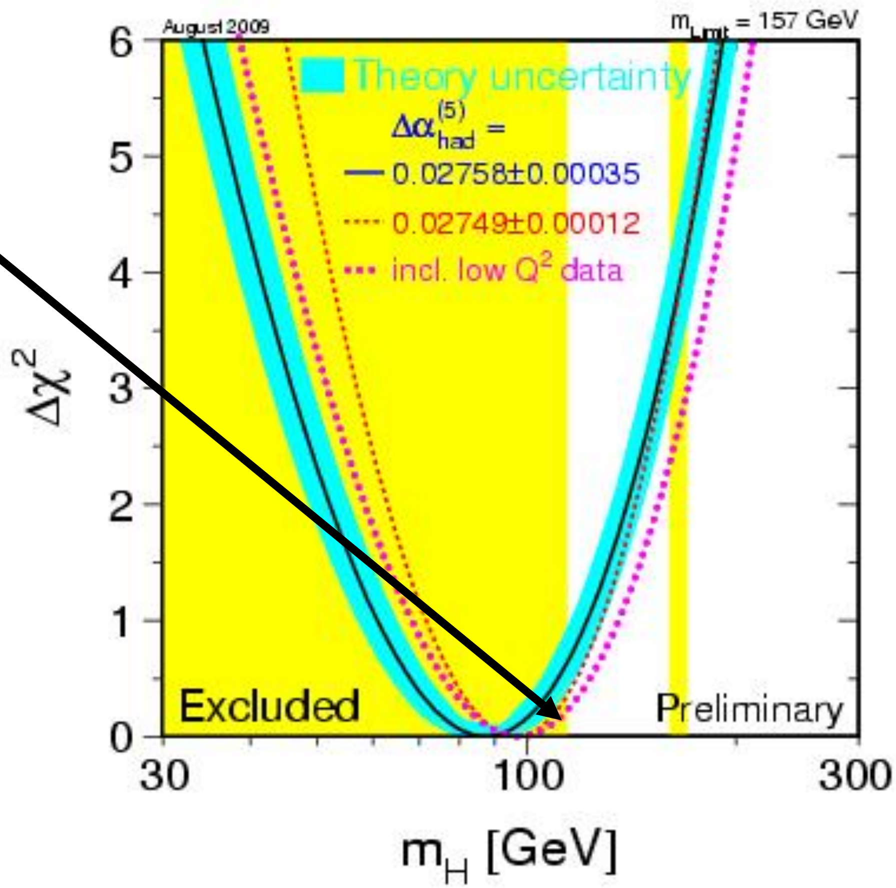
$$M_H^2 \leq \frac{8\pi^2 v^2}{3\log\frac{\Lambda_{QCD}^2}{v^2}} \qquad \upsilon^2 = 246\ \text{GeV}$$



What do we know about the Higgs?

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





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".

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

- Require signal > 3σ above background for "first evidence".
- e.g. Measure 140 events and know 100 come from background:

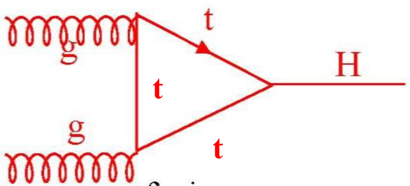
$$S = 40 / \sqrt{100} = 4$$

- 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

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

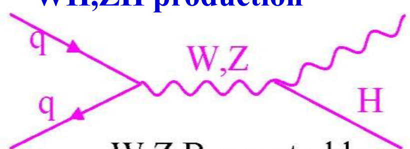
Higgs Production

How is the Higgs produced?

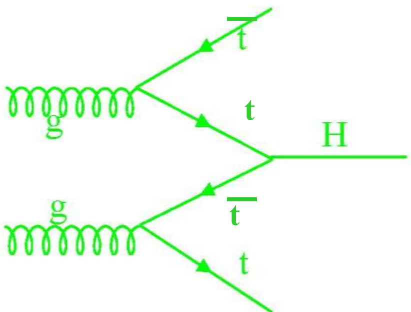


gg fusion

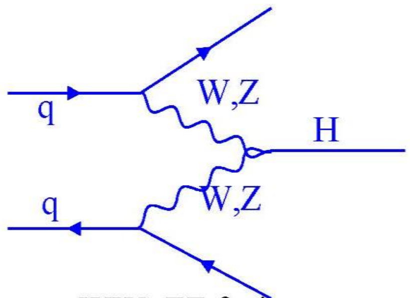
Sometimes called "Associated WH,ZH production"



W,Z Bremsstrahlung



tt fusion

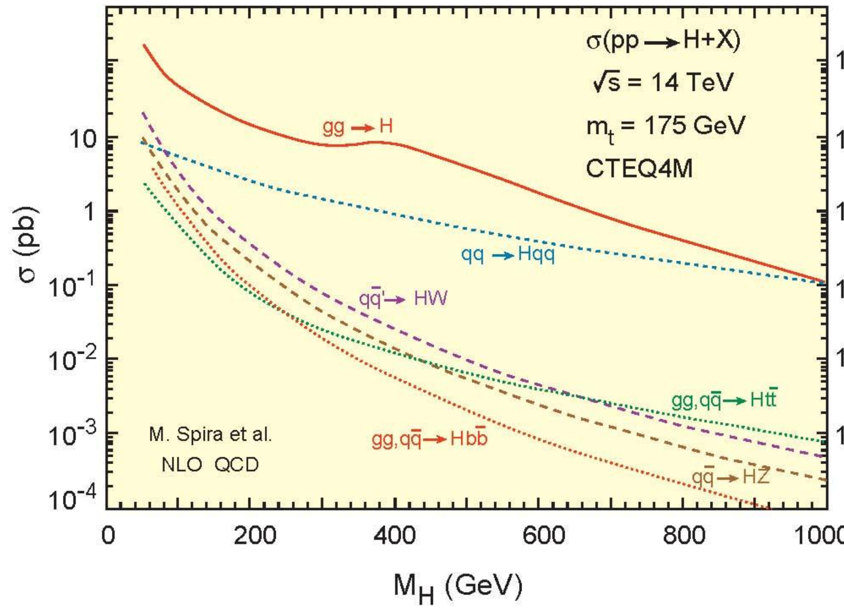


WW, ZZ fusion

Sometimes called "Associated ttH production"

Gluon fusion most promising

How often is it produced?

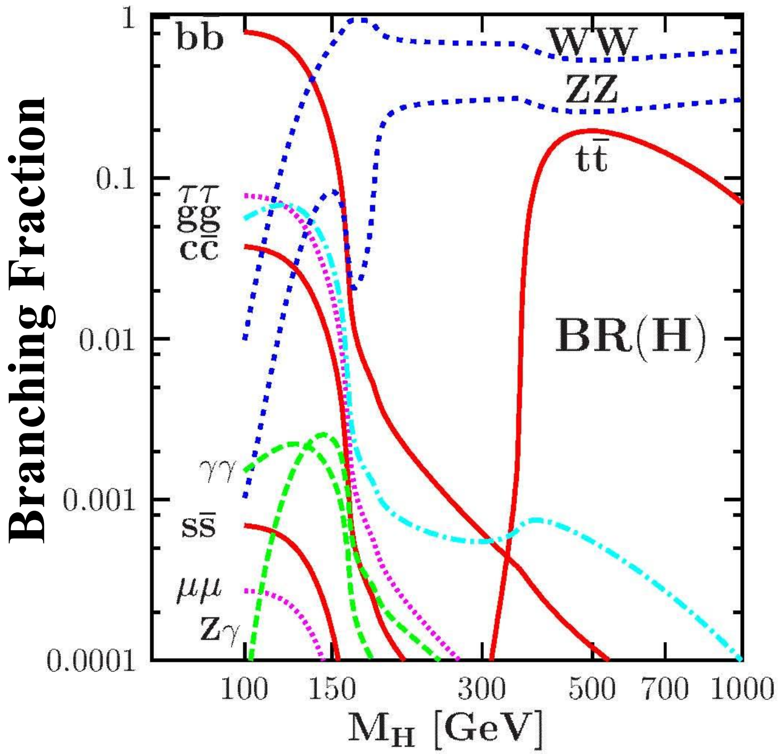


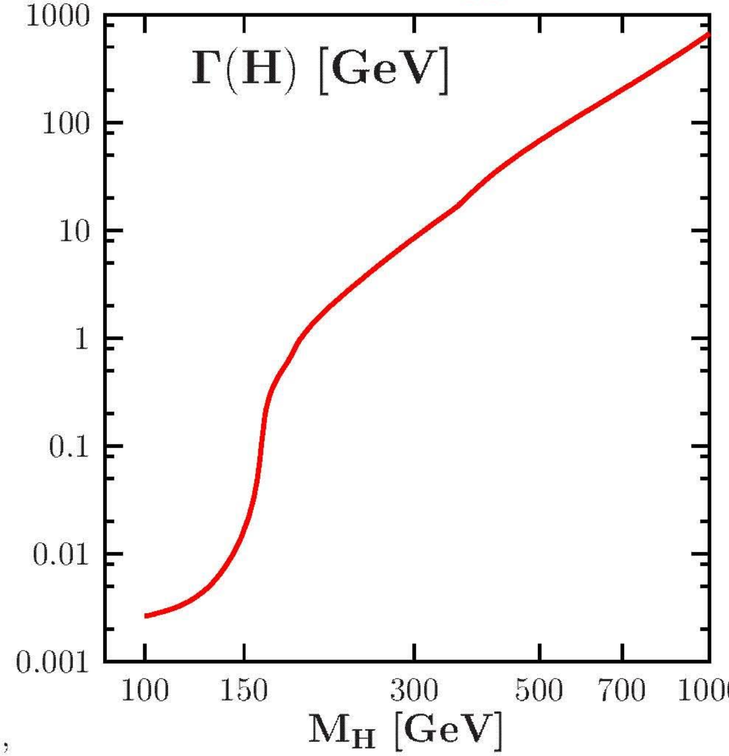
Process	Events/s	Events/year
$W \to e\nu$	40	$4 \cdot 10^8$
$Z \to ee$	4	$4 \cdot 10^7$
$t\bar{t}$	1.6	$1.6 \cdot 10^7$
$b\bar{b}$	10^6	10^{13}
$\tilde{g}\tilde{g}$ (m = 1 TeV)	0.002	$2 \cdot 10^4$
Higgs (m= 120 GeV)	0.08	$8 \cdot 10^5$
Higgs (m= 120 GeV)	0.08	$8 \cdot 10^5$
Higgs (m= 800 GeV)	0.001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

$$L = 2 \times 10^{33} cm^{-2} s^{-1}$$

Higgs decays

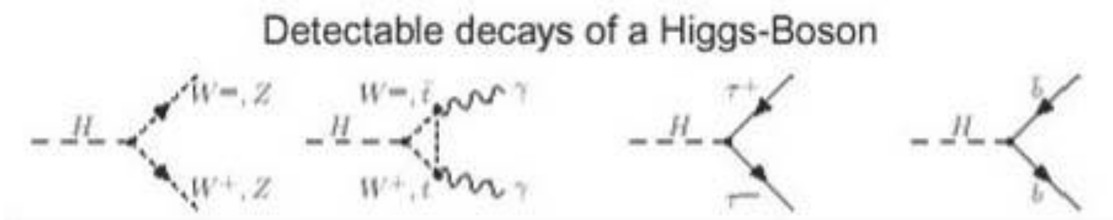
Partial and total widths of a Standard Model Higgs

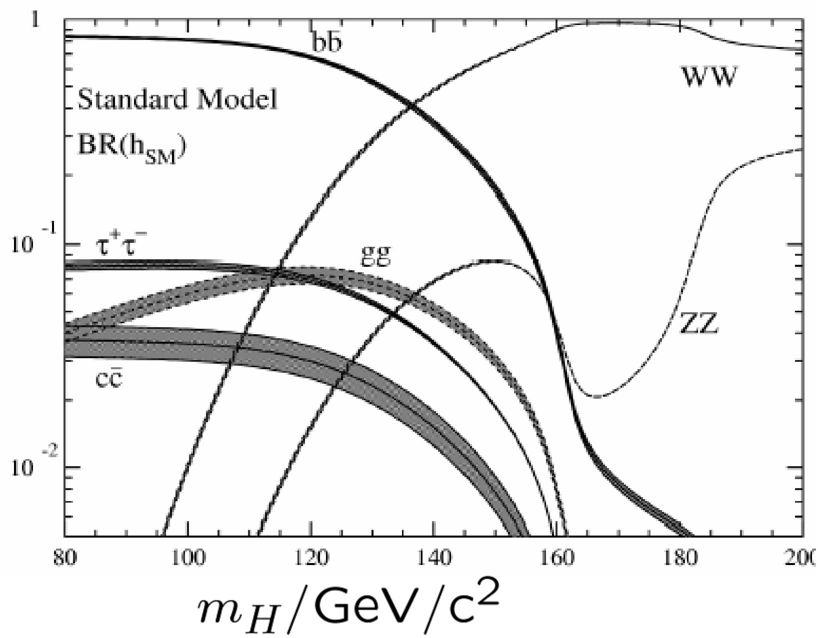




- Light Higgs: $b\bar{b}$ is dominant
- Heavy Higgs: Mostly WW and ZZ
- Higgs width large above WW threshold

Higgs Decay



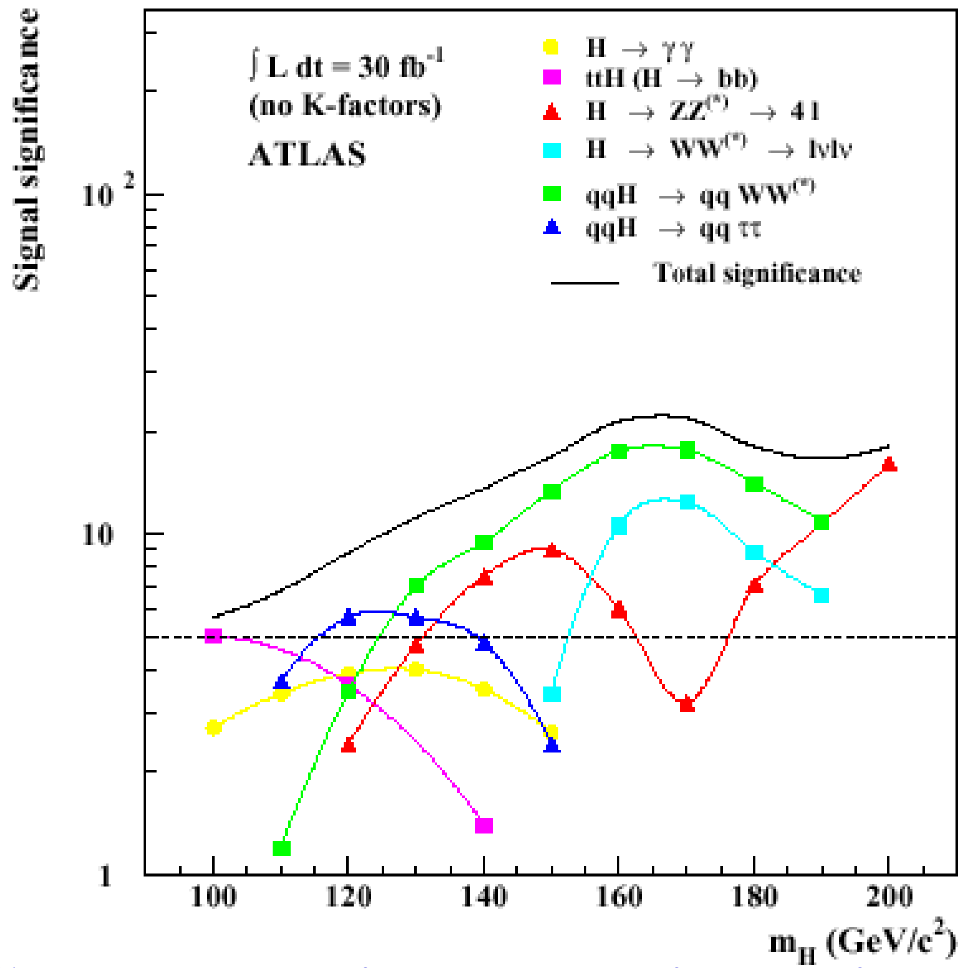


Branching Fraction: If produce 10^8 Higgs and measure only 20 decays H→gg with an efficiency of 0.00025% then Branching Fraction:

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

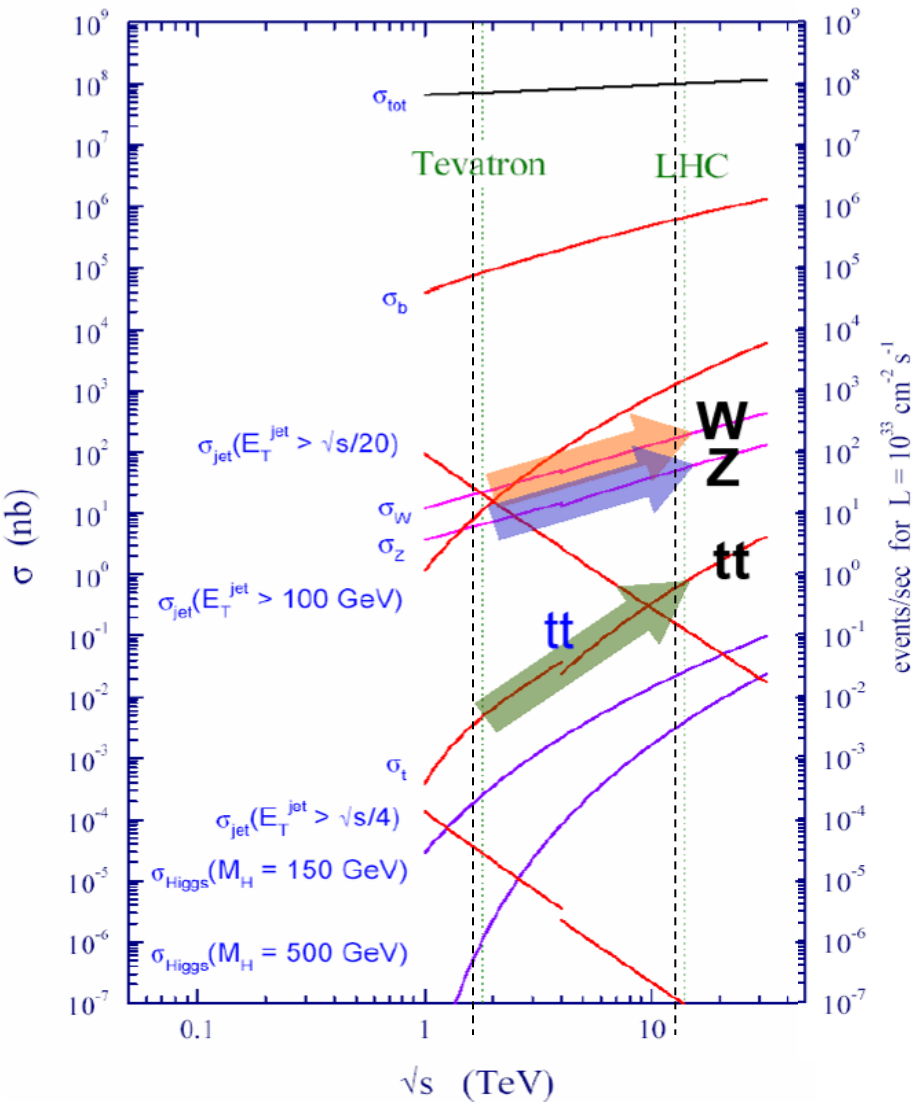
- Which decay to look at?
- Depends on Higgs Mass
  - M_H <100 GeV
    - gg → H→γγ
  - M_H <150 GeV
    - $H\rightarrow ZZ^* \rightarrow 4l$
    - H→bb
    - $H\rightarrow WW^* \rightarrow 2l\ 2\nu$
    - $H \rightarrow \tau^+\tau^-$
  - 130 < M_H <500 GeV
    - $H\rightarrow ZZ \rightarrow 4l$
  - 600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

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})

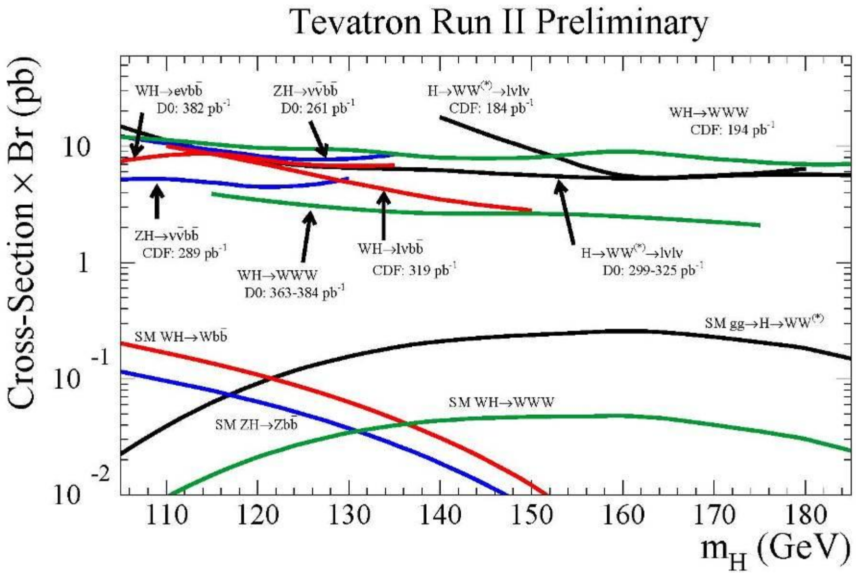
Background is anything with signature similar to signal

- *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

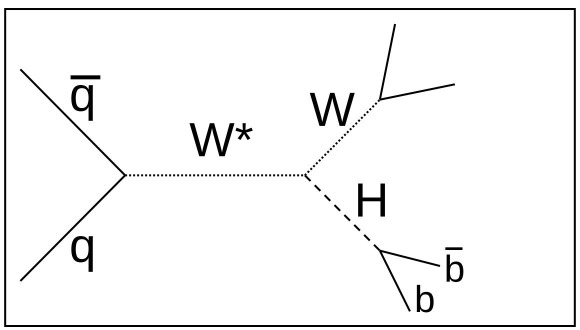
Current Results - Tevatron

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

Tevatron/CDF - Associated Production



$q\bar{q} \rightarrow WH$ with $H \rightarrow b\bar{b}$



$W \rightarrow q\bar{q}$ 70%

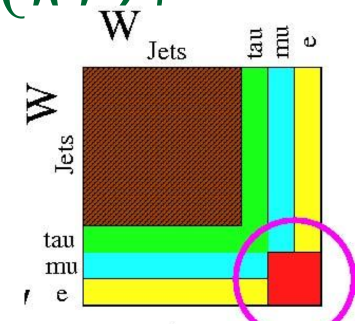
- final state $q\bar{q}b\bar{b}$
- Four jet backgrounds still too large

$W \rightarrow e\nu_e$ 10% $W \rightarrow \mu\nu_\mu$ 10%

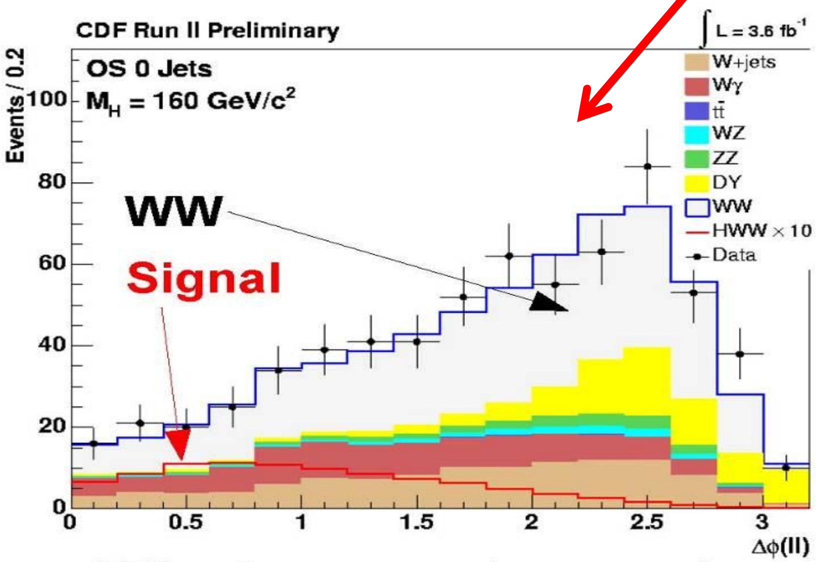
- Final state $l\nu b\bar{b}$
  - One electron or muon
  - Missing transverse momentum
  - Two jets
  - One or two *b*-tags
- Easy to select in trigger and offline

$\sigma \times Br \approx 0.02$ pb

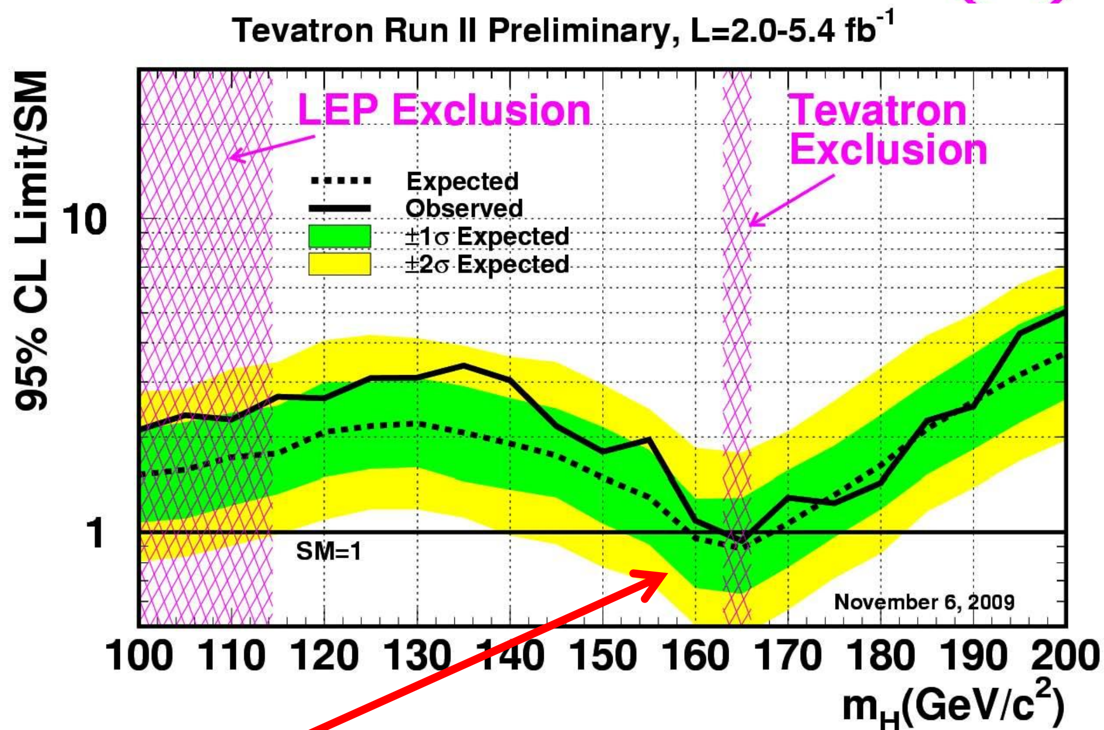
Latest CDF/D0 Higgs Results (Nov 2009)



- Example: Look for H→WW (dominant above 135 GeV) and W→ lυ (W→bb̄ not used as too much background).



Dilepton opening angle strongest background discriminant

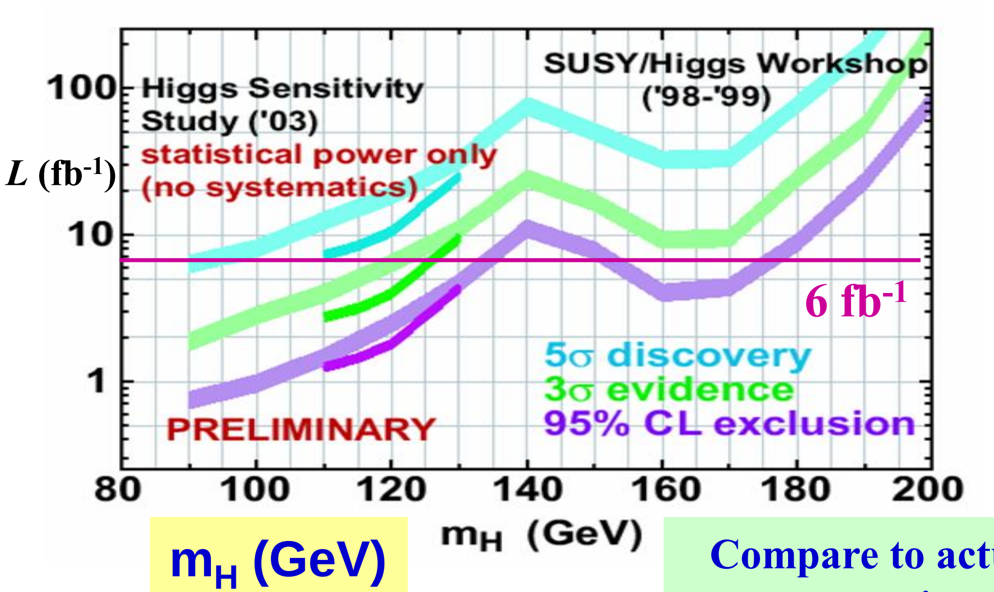


- Combined result from many analyses

Predicted Sensitivity – Tevatron v LHC

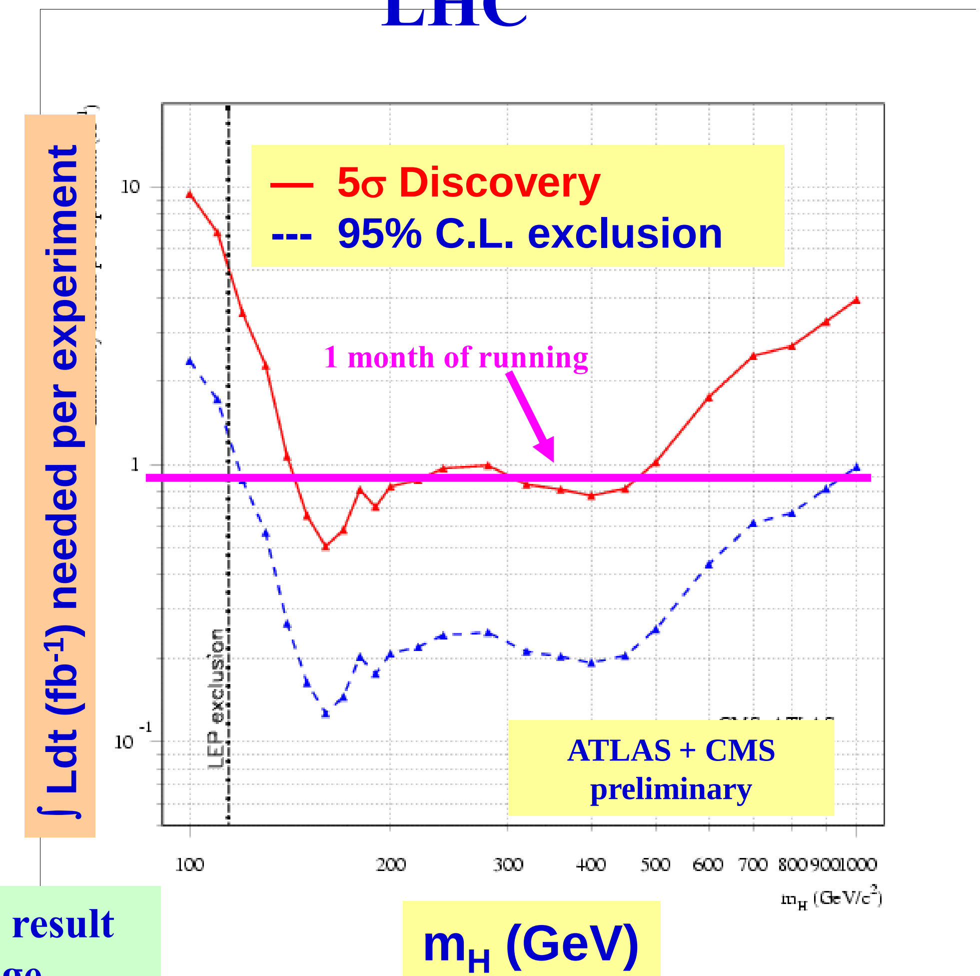
Tevatron

- CDF expects a maximum of 6.5 fb^{-1} by 2009
  - 15-20 signal events
  - 2000 background
  - 8 years of running



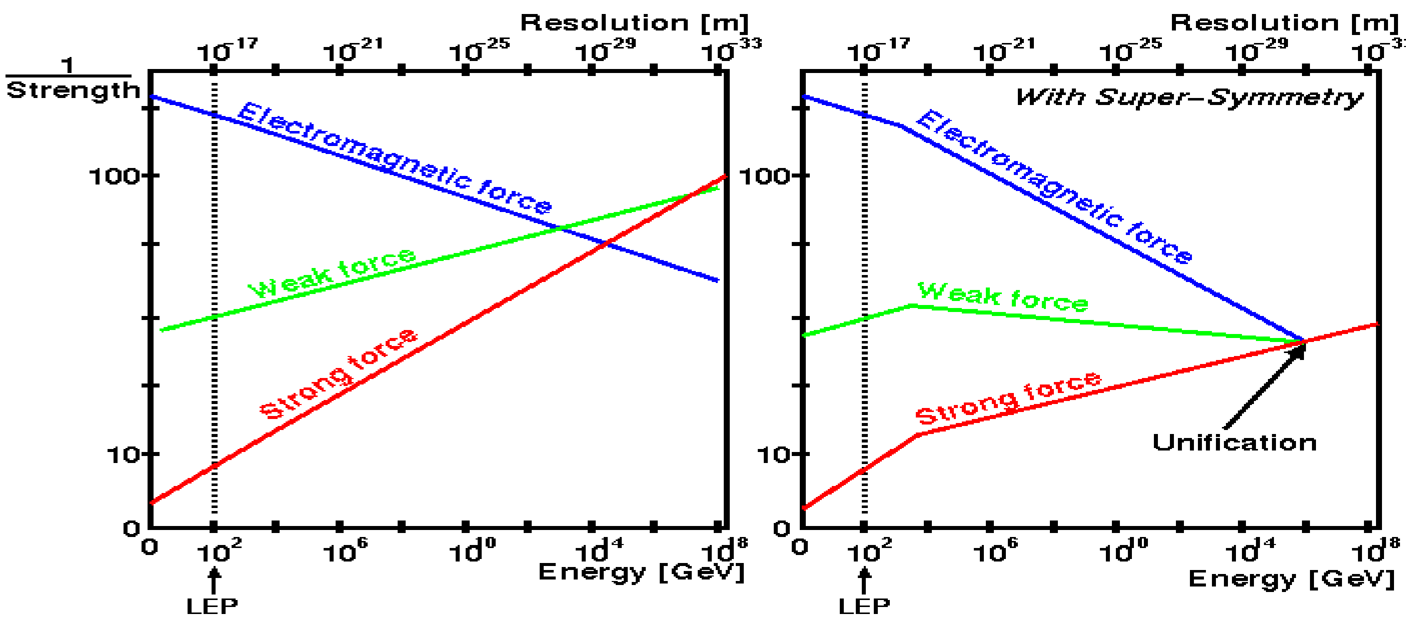
Compare to actual result on previous page

LHC



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



Supersymmetric Higgs

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

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

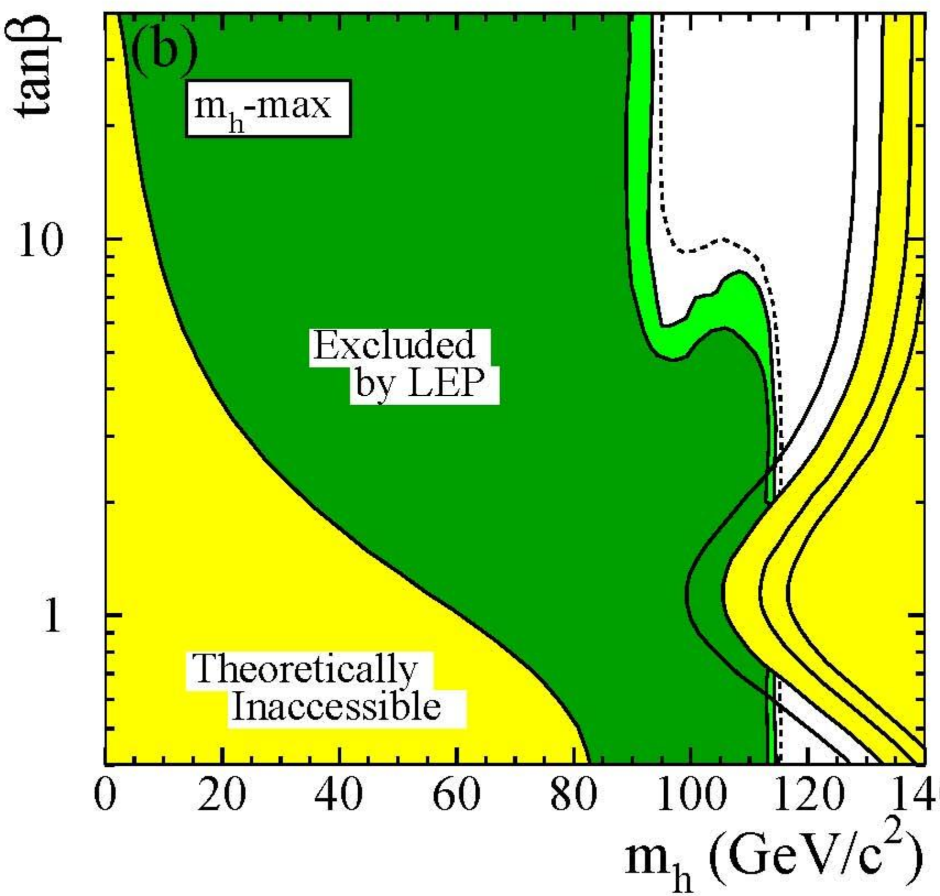
- Radiative corrections can change masses.
- Higgs sector now described by two free parameters (m_h and $\tan\beta = \upsilon_2/\upsilon_1$).
- However, the exact SUSY symmetry has to be broken to reconcile the theory with experiment.
- The minimal extension to SUSY (MSSM) has 105 parameters!
- Have 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)
    - $m_{1/2}$(gaugino mass)
    - plus two others

What to look for at the LHC

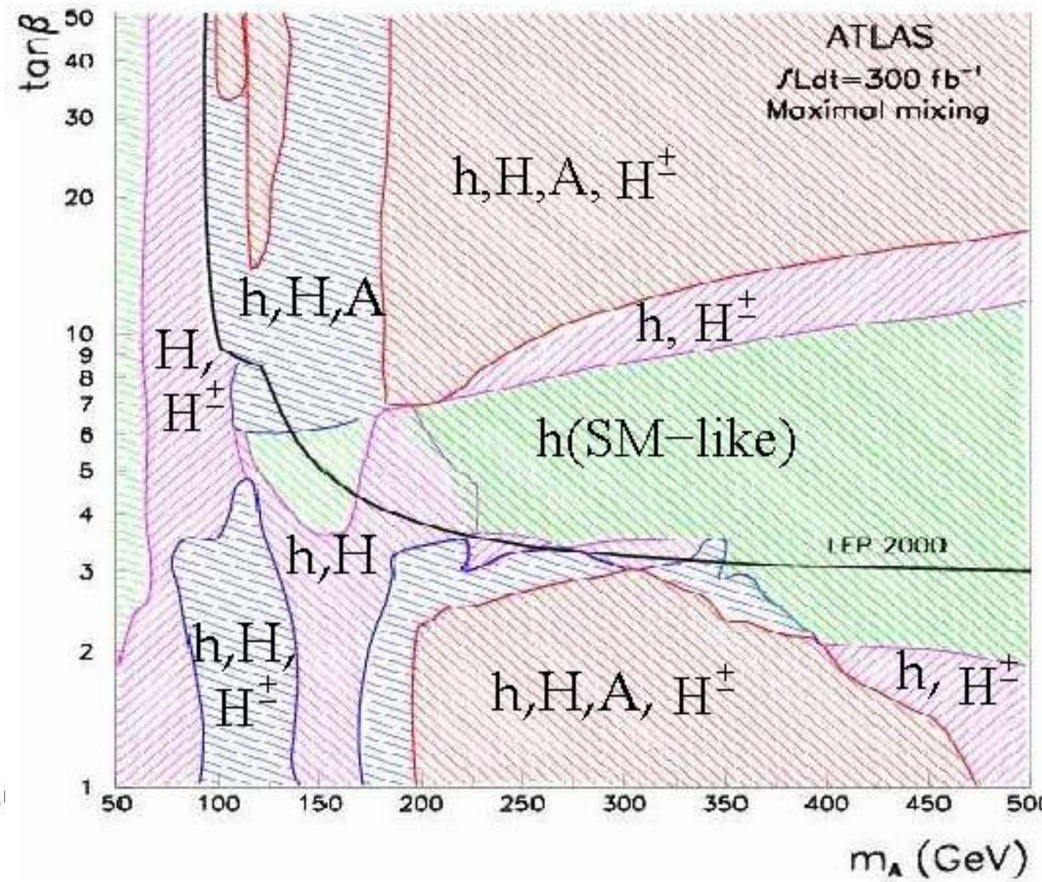
- Small tanβ
  - gg→H,A production is enhanced due to stronger $t\bar{t}H$ coupling.
  - H,A →$t\bar{t}$ decay gets enhanced.
- Large tanβ
  - H, A production is enhanced in $b\bar{b}$-fusion
  - H →ττ has a large branching ratio
- Medium tanβ
  - Only SM-like h visible. We could see a Higgs and not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

What might we see?

What we know now



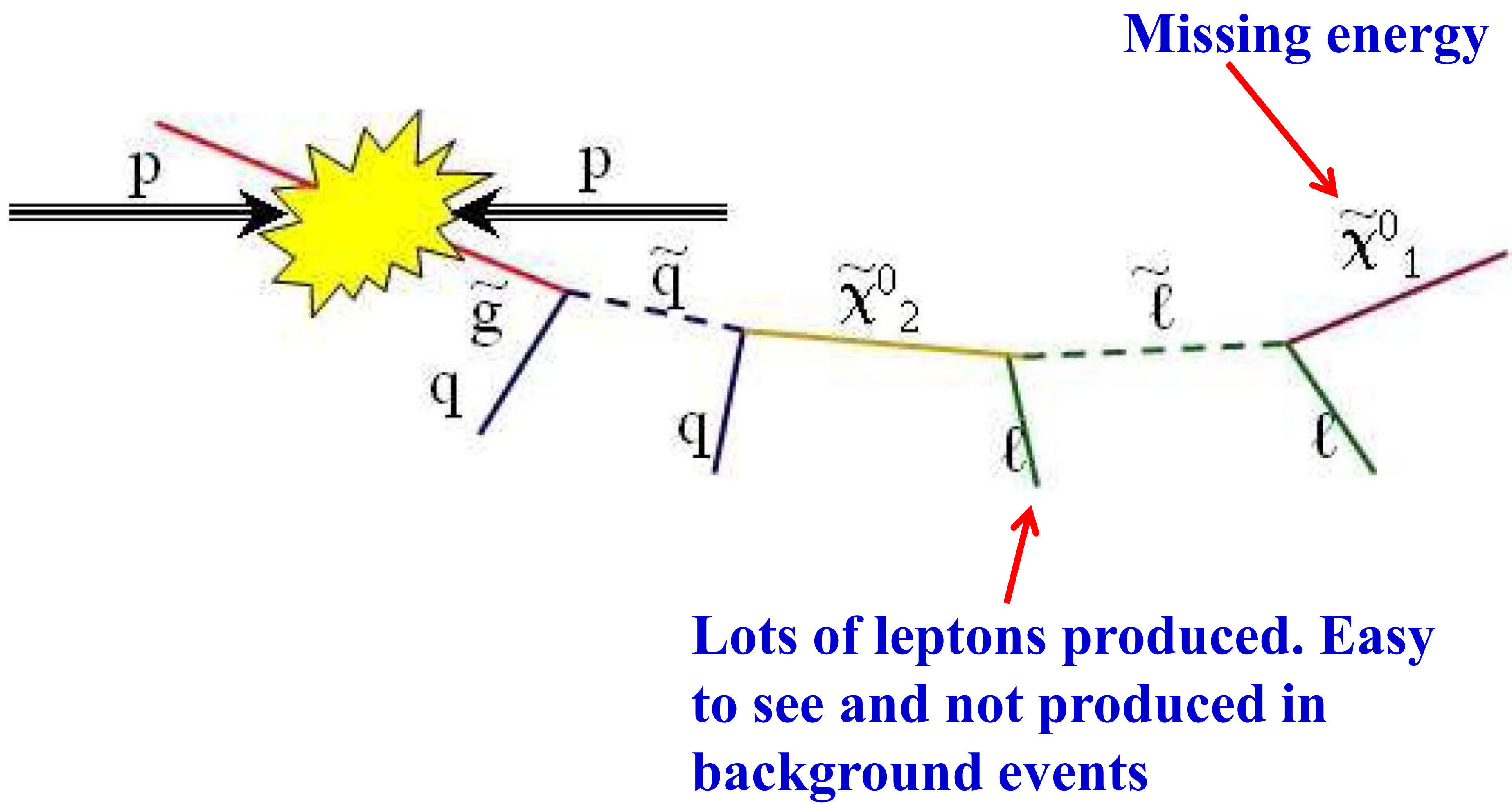
What the LHC might see



Detecting SUSY signals

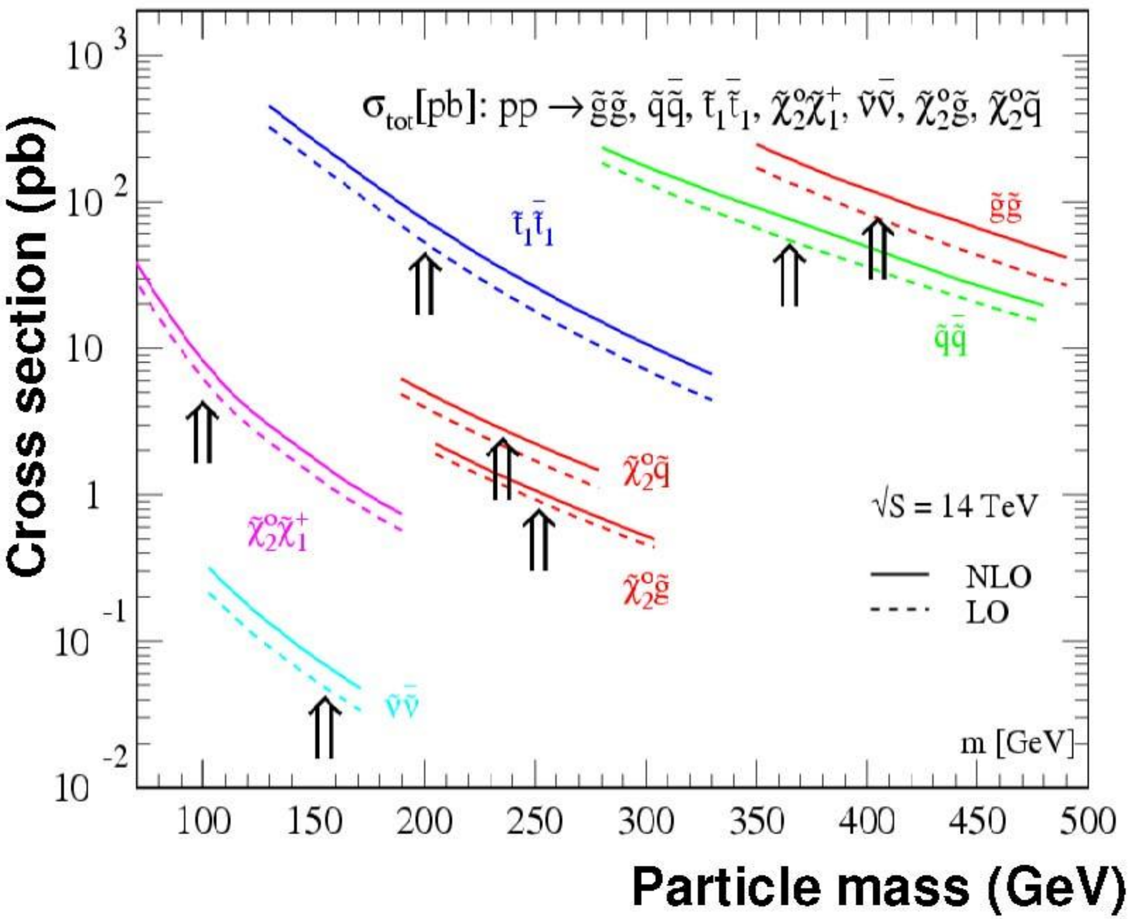
- SUSY predicts that every Standard Model particle has a Super-Symmetric partner
  - Electron ↔ selectron, quark ↔ squark,W ↔ wino, etc...
  - But masses not the same → SUSY not exact symmetry
- SUSY can be a new source of CP-Violation
  - Explain matter/anti-matter asymmetry of the Universe
- A SUSY 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
  - Missing energy, momentum
- What is the LSP?
  - Dont't really know
  - Likely to be a neutralino

What a SUSY decay looks like



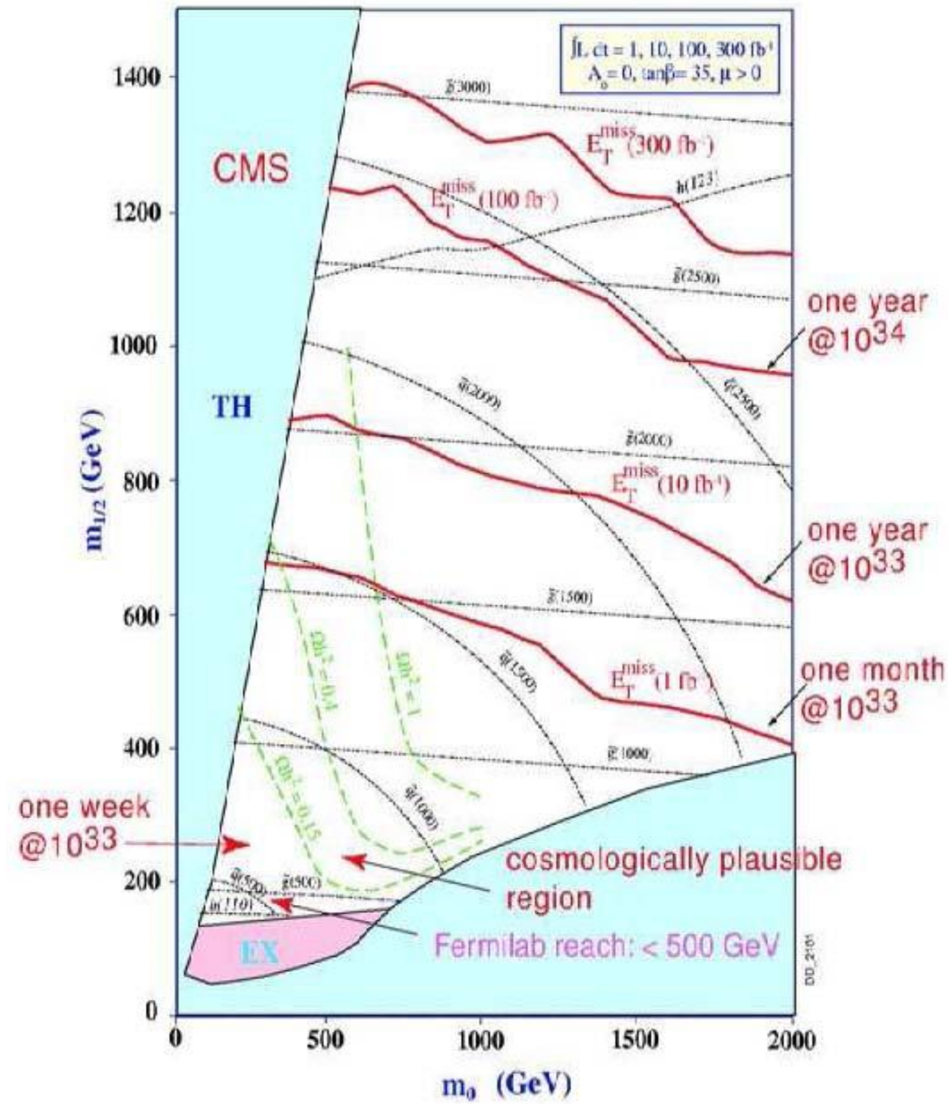
SUSY production at the LHC

- The cross-section is very high even if super-partner masses are very large. Could see SUSY before we see the Higgs



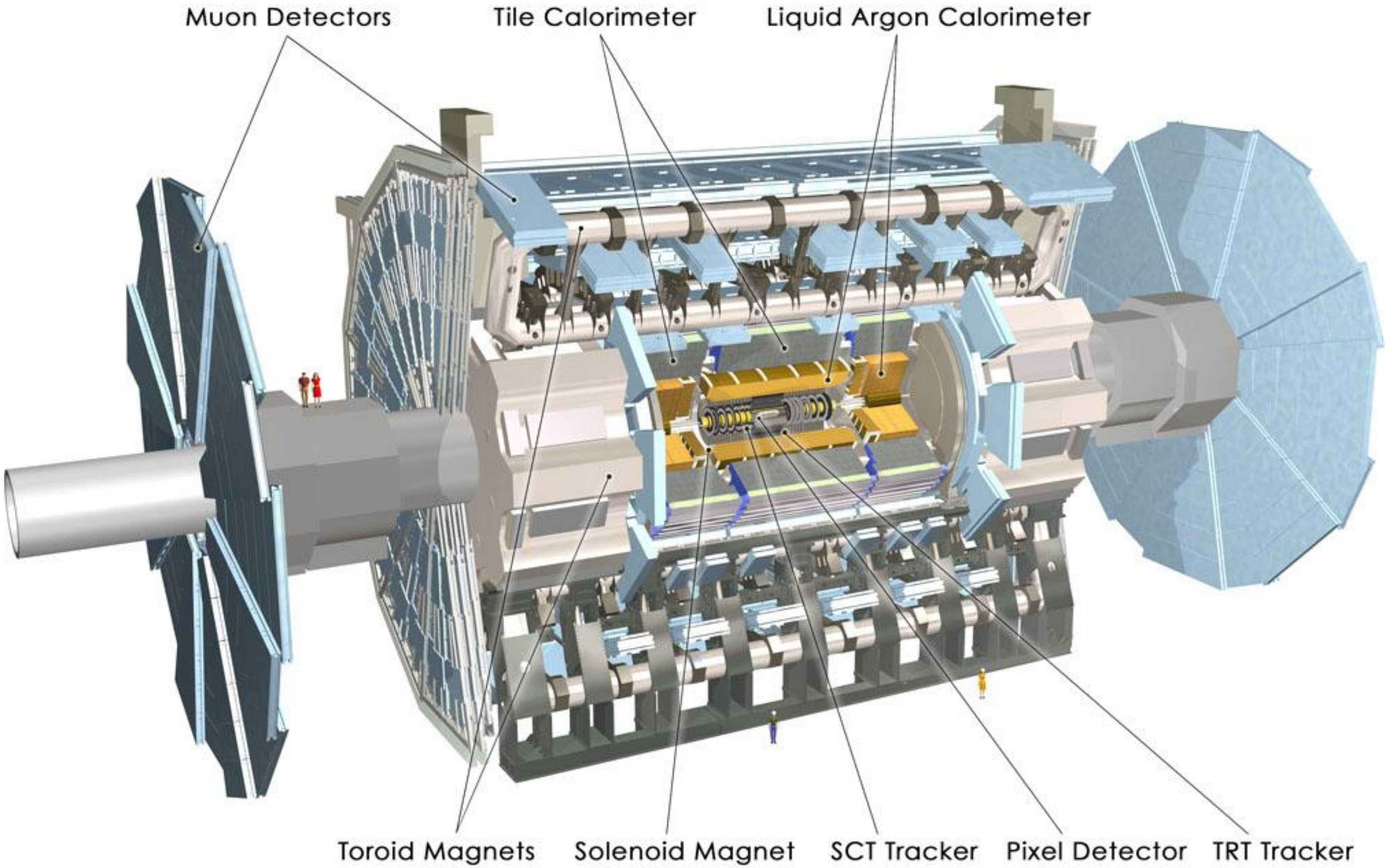
What LHC will see

- This assumes LHC is running at its design luminosity (10^{33} cm^{-2}s^{-1}) and 7 TeV energy.
- In 2010, only running at $3\text{x}10^{31}$ cm^{-2}s^{-1} and 3.5 TeV energy per beam.
- So will take ~50 times longer than in the plot.
- However, luminosity will be increased in 2012

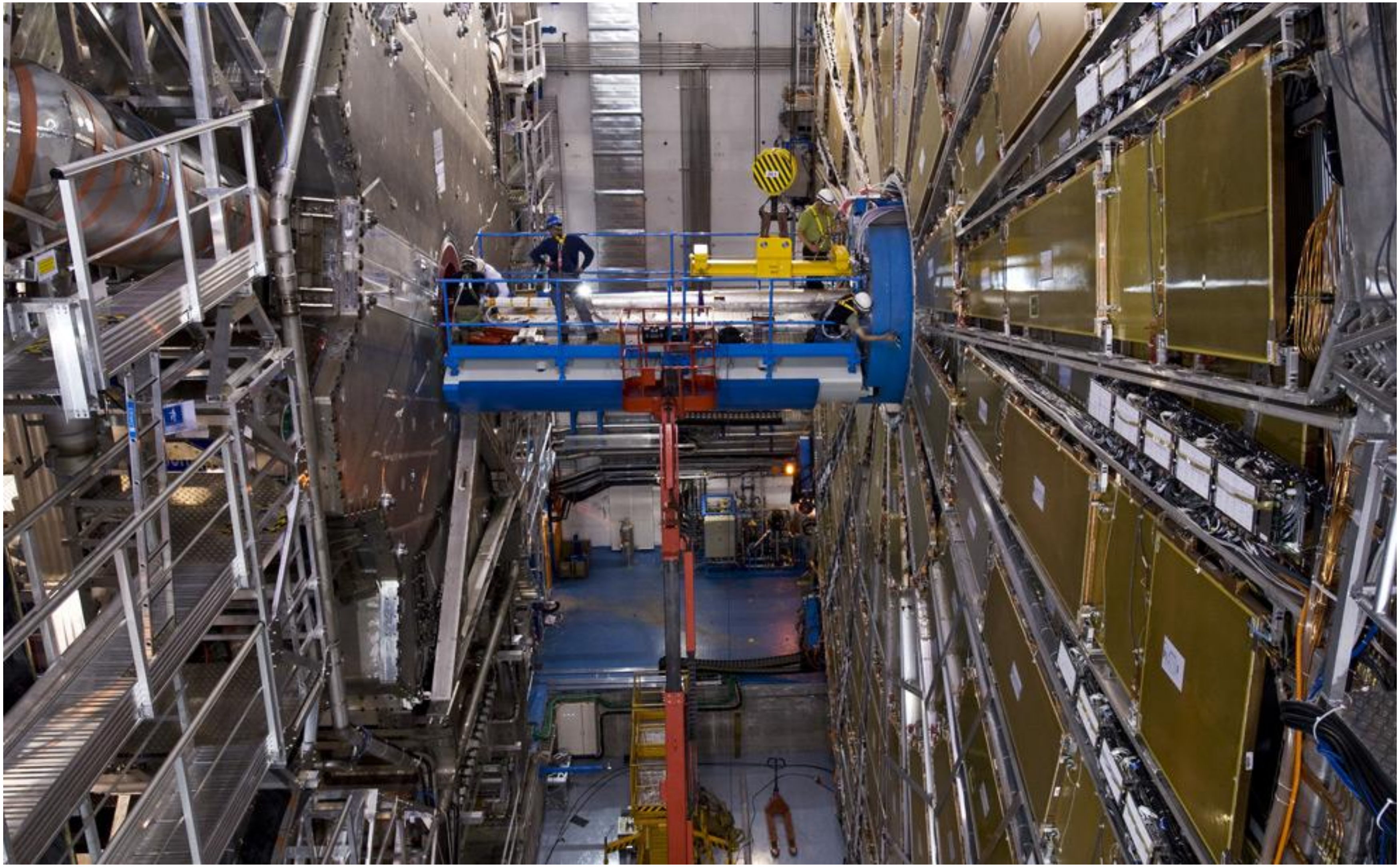


The End

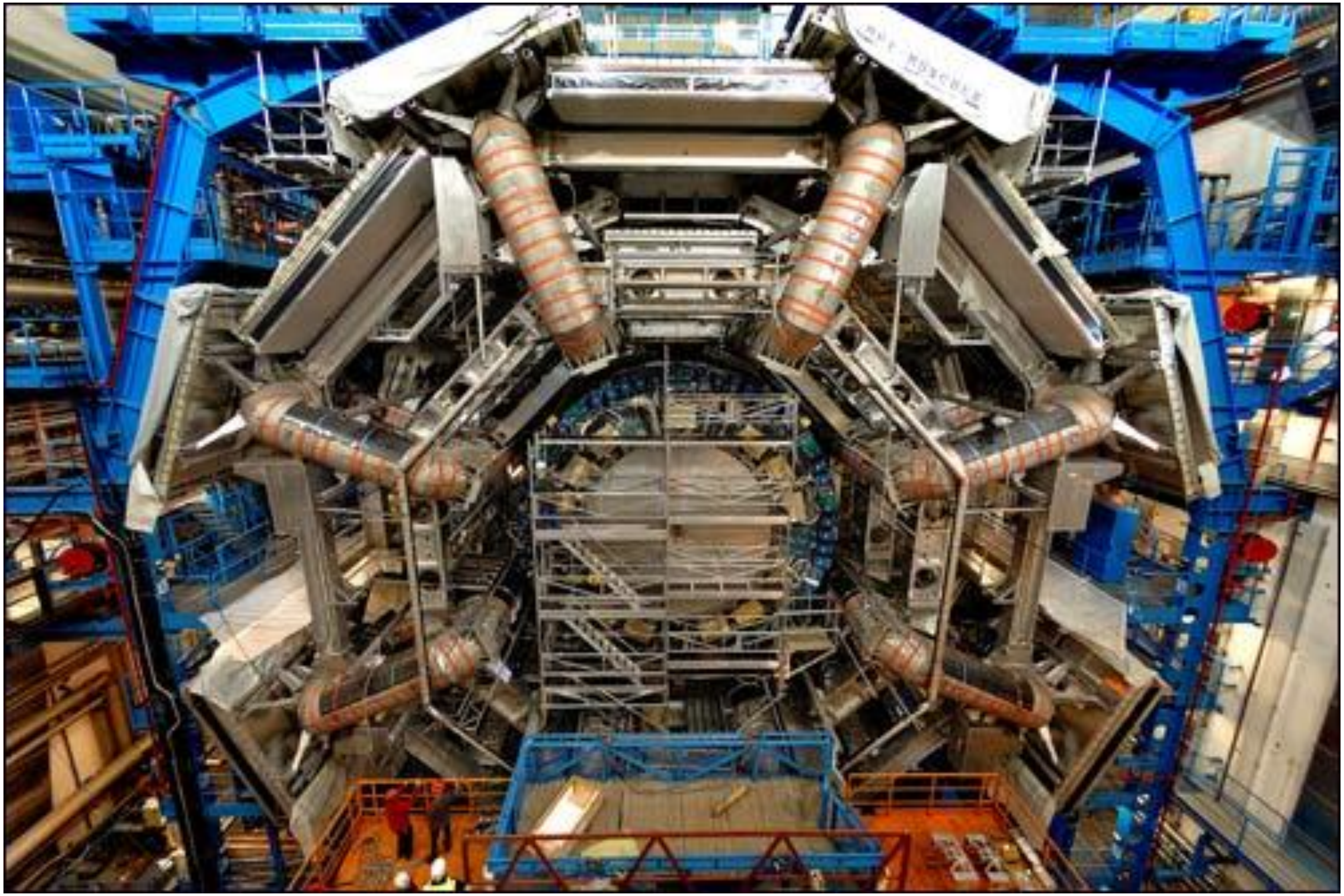
ATLAS detector



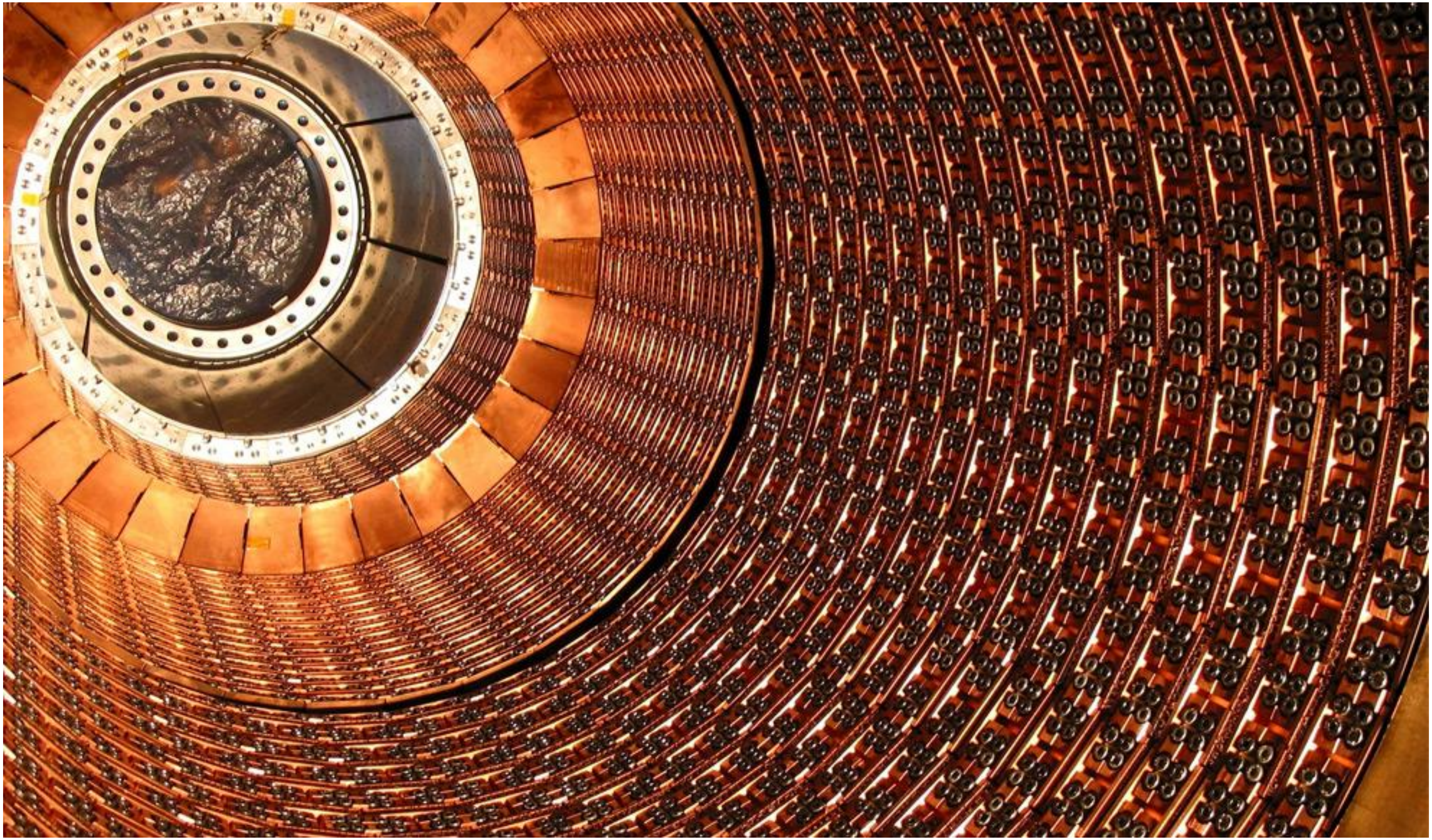
ATLAS beam-pipe



ATLAS construction

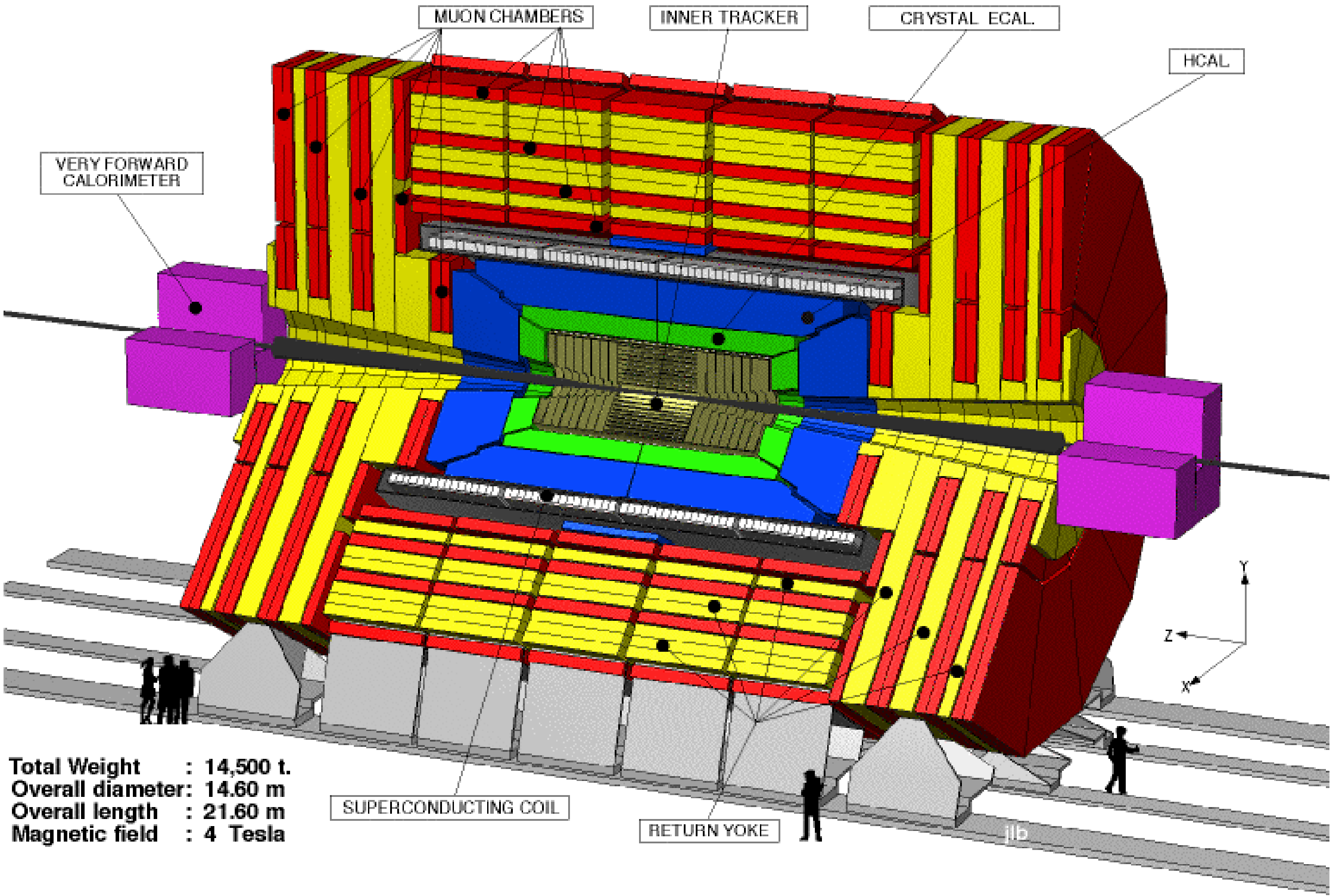


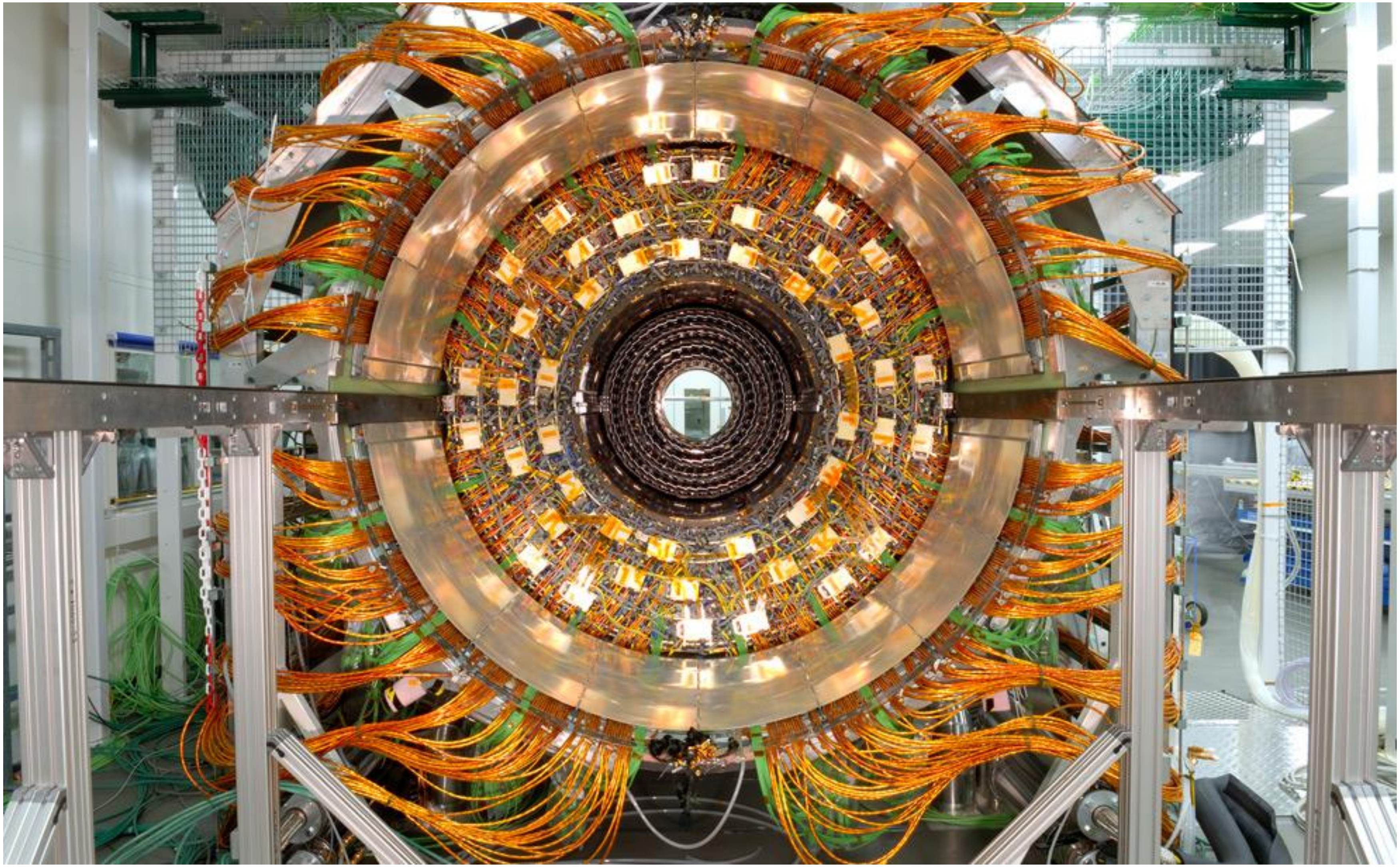
ATLAS Tracker (silicon)



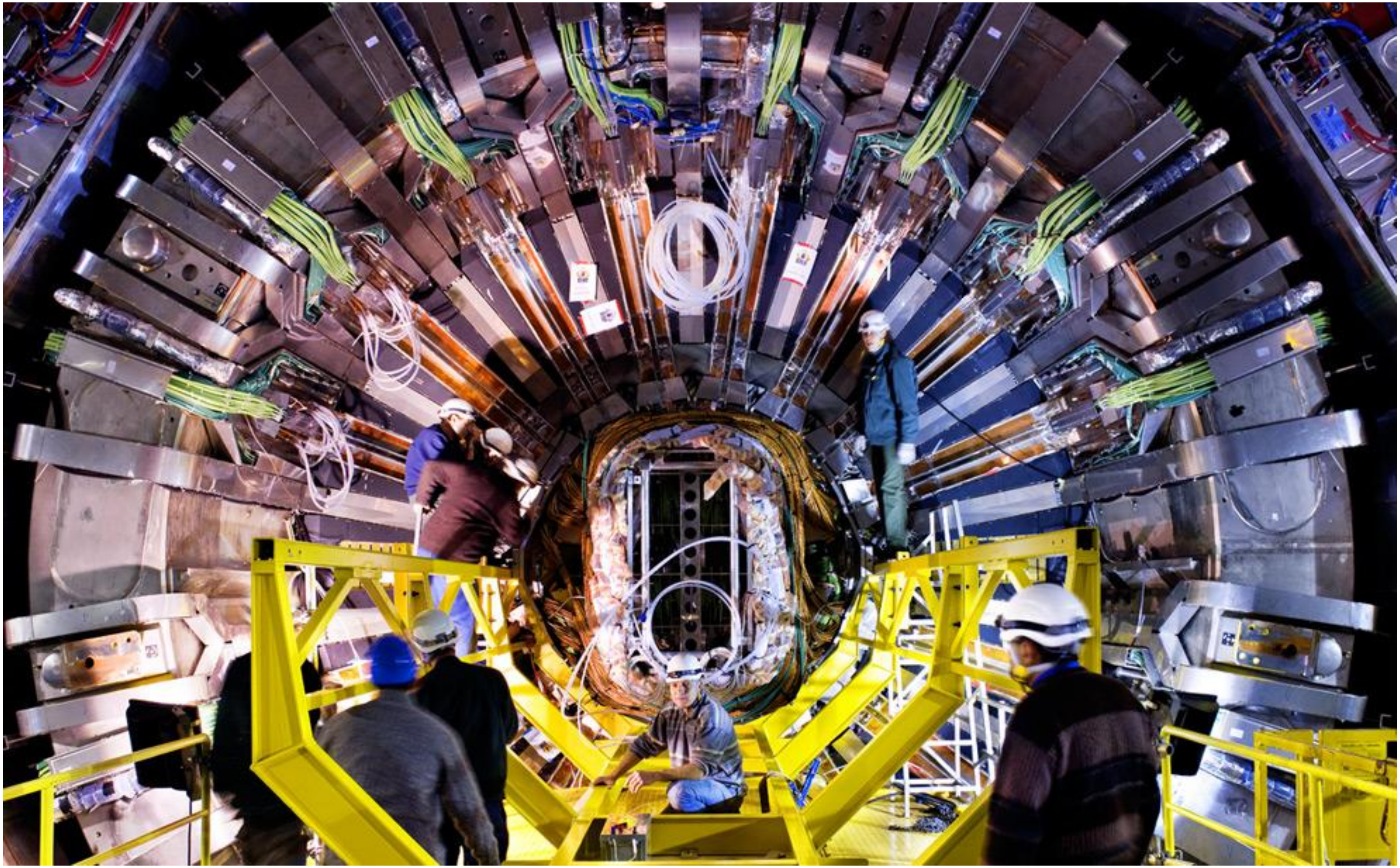
ATLAS toroid magnet

CMS detector





Inserting CMS tracker



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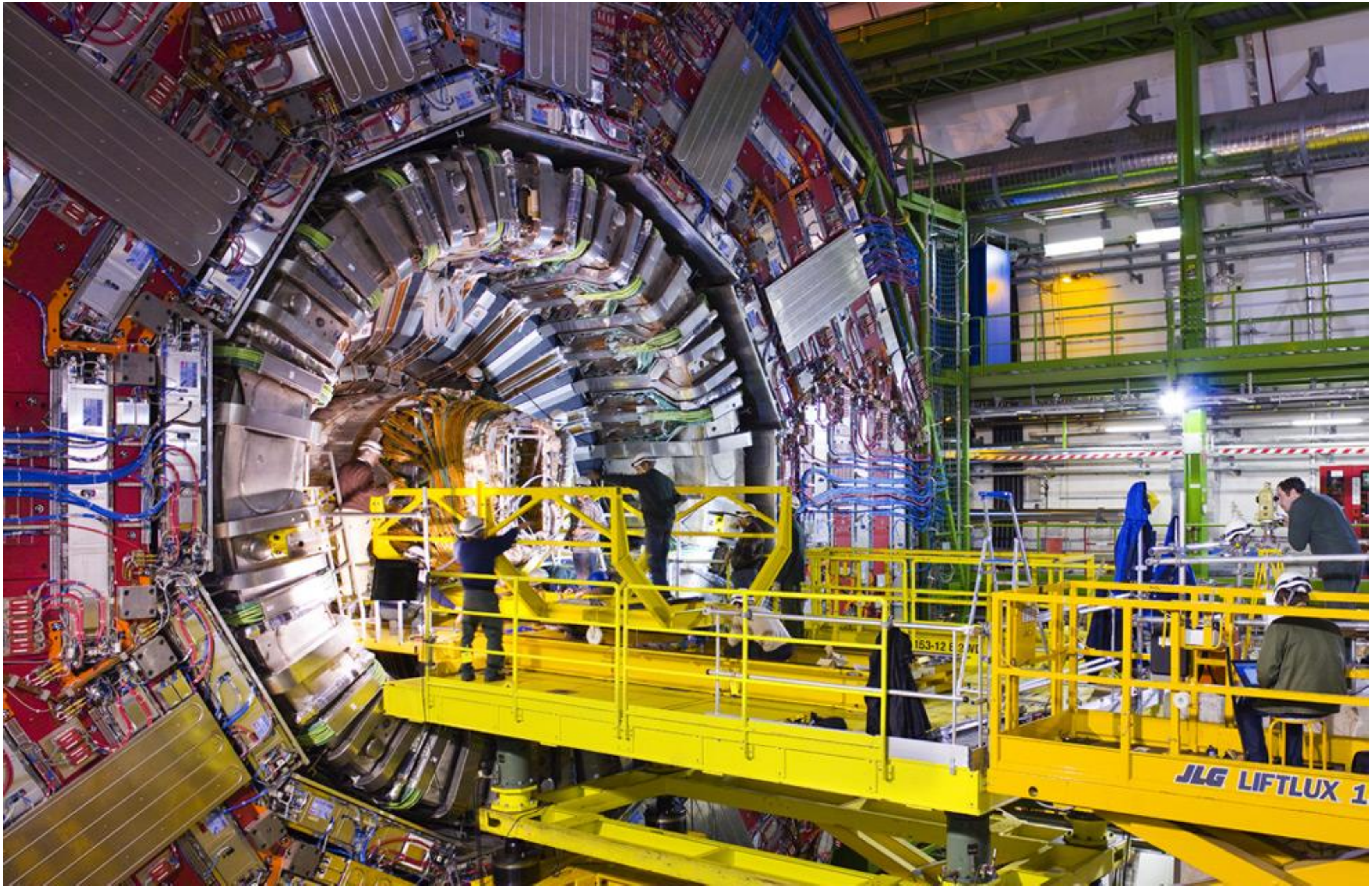
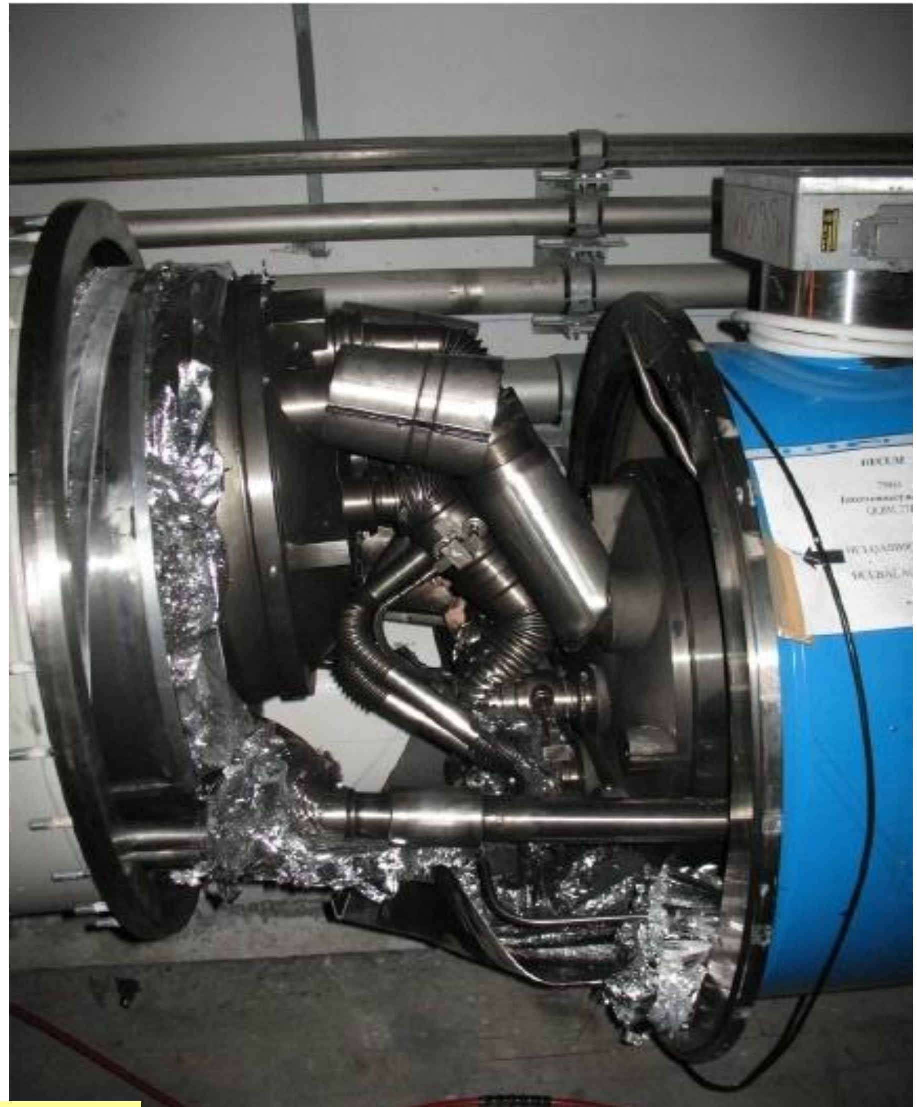


Damaged magnets 2009



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