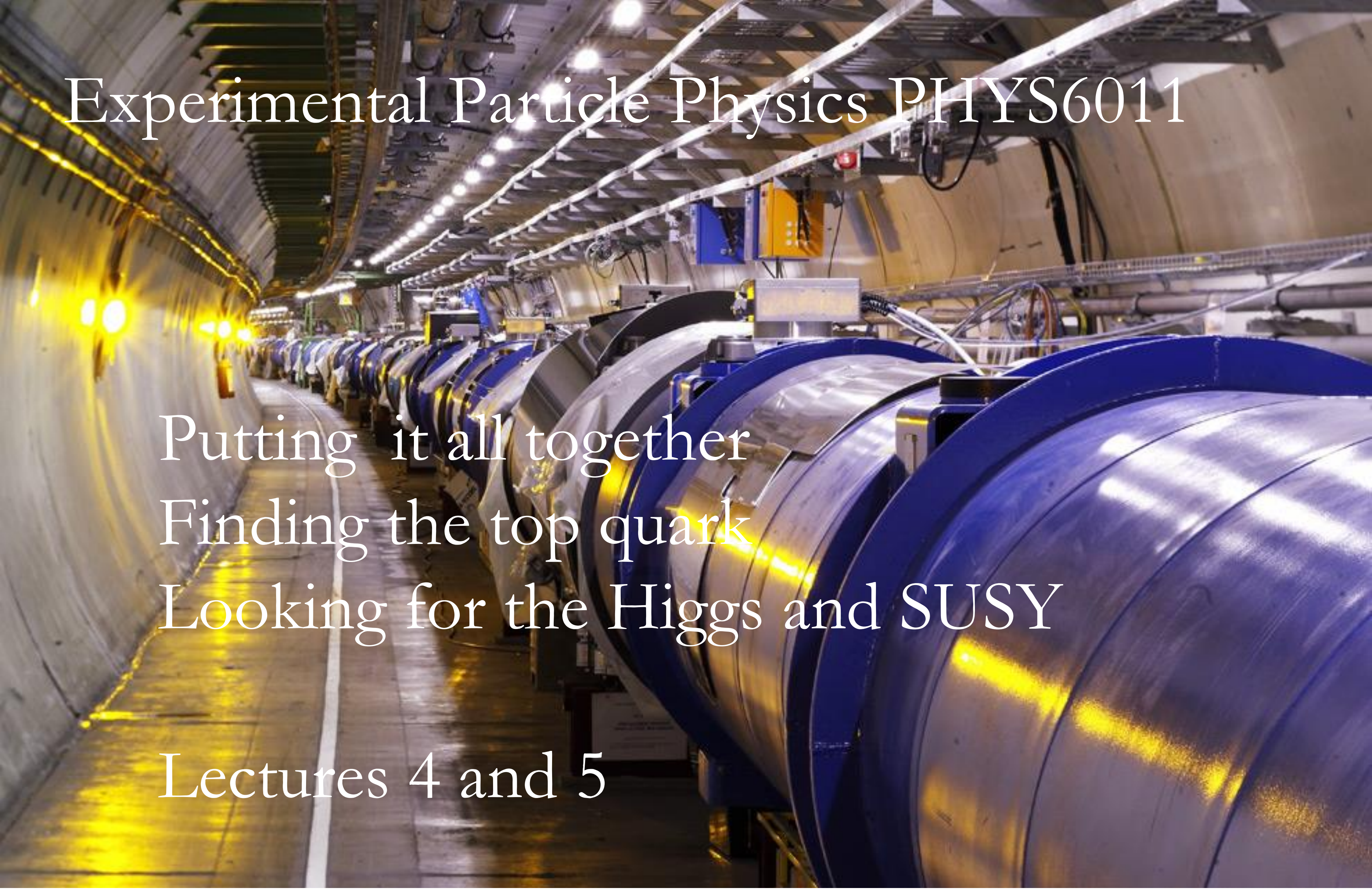


Experimental Particle Physics PHYS6011

Putting it all together
Finding the top quark
Looking for the Higgs and SUSY

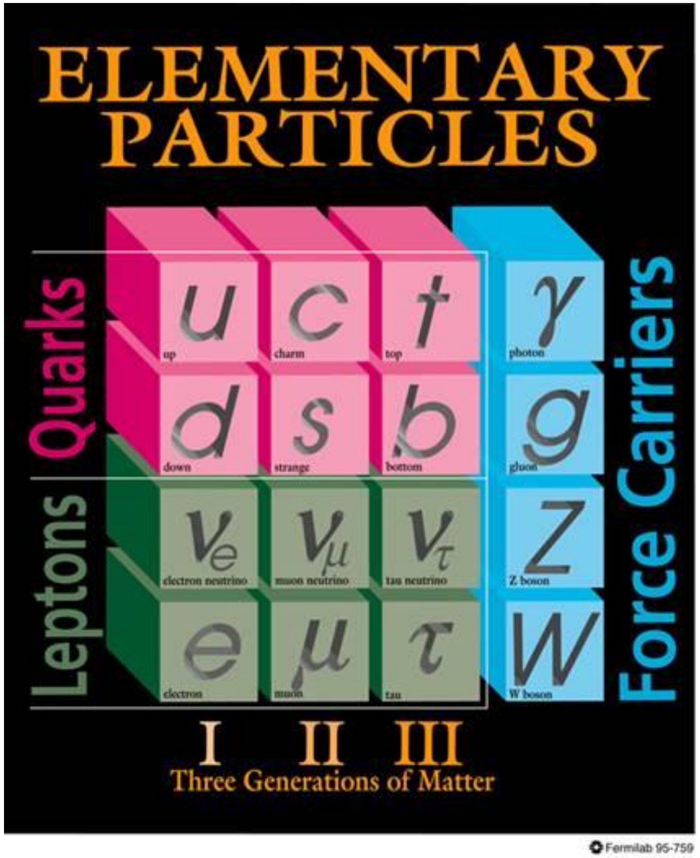
Lectures 4 and 5

Practical questions

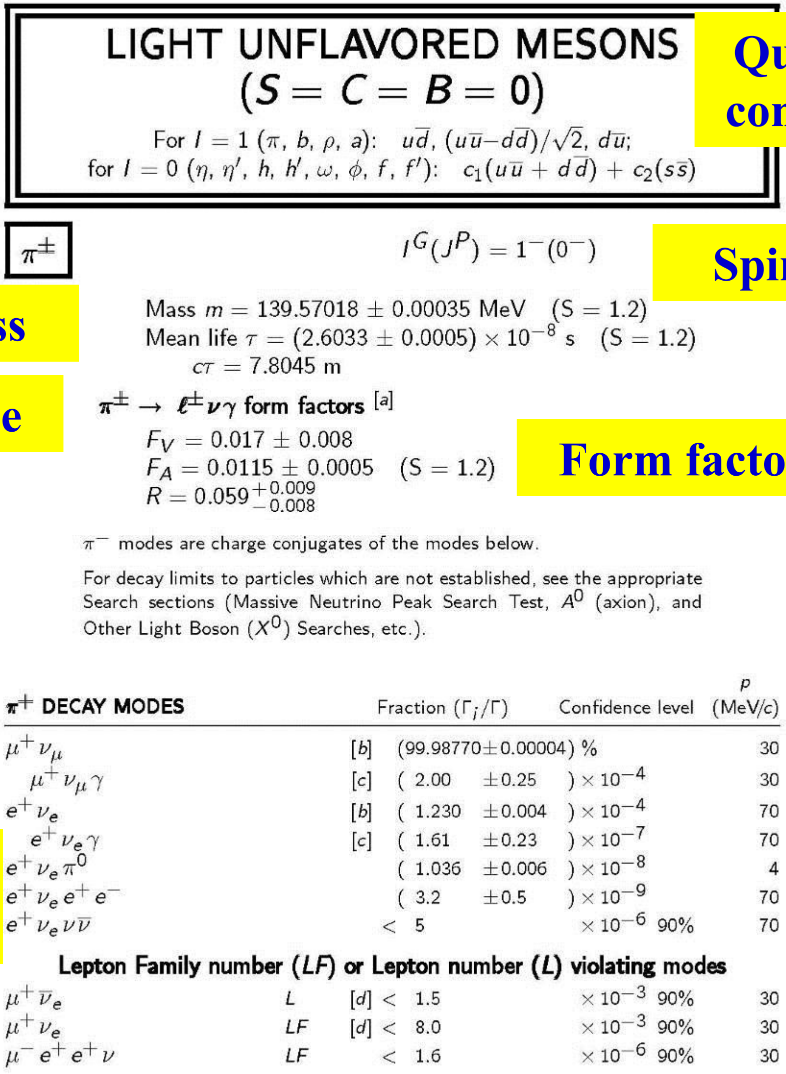
- What do we want to do?
  - Measure a known property e.g. mass of the top quark?
  - Look for new particles e.g. Higgs?
- How to do it?
  - How do you get the information out of the detector?
  - How well is our detector is performing?
  - How do you identify the “true signal”?
  - How do you eliminate the “fake signal”?
  - How confident are you that you really have measured something?

What do we measure?

In principle:



But in reality:



LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

Quark content

$\pi^\pm$ $\qquad I^G(J^P) = 1^-(0^-)$

Spin

Mass

Lifetime

Mass $m = 139.57018 \pm 0.00035$ MeV $\quad$ (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s $\quad$ (S = 1.2)
$c\tau = 7.8045$ m

$\pi^\pm \to \ell^\pm \nu \gamma$ form factors [a]

$F_V = 0.017 \pm 0.008$
$F_A = 0.0115 \pm 0.0005$ $\quad$ (S = 1.2)
$R = 0.059^{+0.009}_{-0.008}$

Form factor

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the appropriate Search sections (Massive Neutrino Peak Search Test, A^0 (axion), and Other Light Boson (X^0) Searches, etc.).

Decay Modes

Branching Fraction

π^+ DECAY MODES			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$		[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$		[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$		[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$		[c]	$(1.61 \pm 0.23) \times 10^{-7}$		70
$e^+\nu_e\pi^0$			$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$			$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\bar{\nu}$			$< 5 \times 10^{-6}$	90%	70
Lepton Family number (*LF*) or Lepton number (*L*) violating modes					
$\mu^+\bar{\nu}_e$	*L*	[d]	$< 1.5 \times 10^{-3}$	90%	30
$\mu^+\nu_e$	*LF*	[d]	$< 8.0 \times 10^{-3}$	90%	30
$\mu^- e^+ e^+ \nu$	*LF*		$< 1.6 \times 10^{-6}$	90%	30

Particle Properties

- Mass
  - Measure momentum and energy: $E^2 = p^2 + m^2$
- Mass width → Lifetime
  - Measure momentum and energy or
  - How many particles exist after t seconds
- Branching Fraction
  - Reconstruct the decays and see how many there are.
- Charge
  - Direction in a magnetic field
- Spin
  - Angular distribution of decays
- Structure e.g. Proton/Neutron/Nucleus
  - Scatter particles off the proton and look at distribution

$$\Delta M = \frac{\Gamma}{2} = \frac{\hbar}{2\tau}$$

e.g. top mass width $\Delta \mathrm{M} = 2GeV$

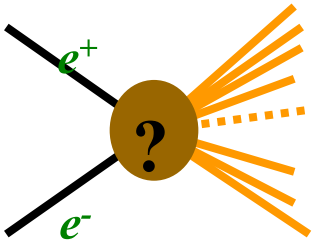
$$\Rightarrow \tau \approx 3x10^{-25} s$$

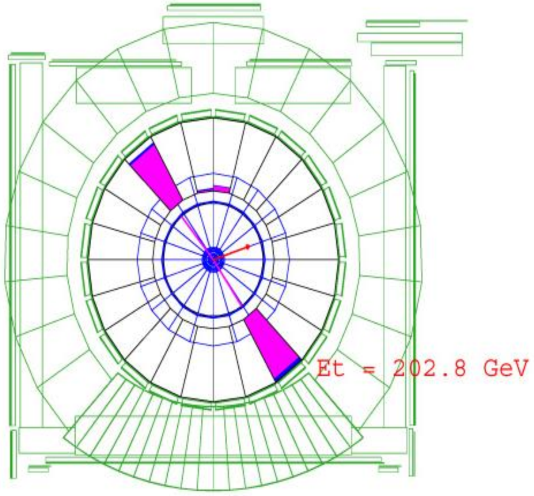
Data Flow

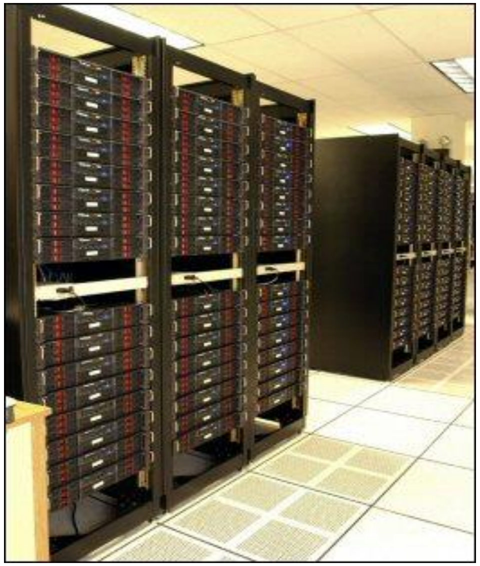
Low Signal: High Background → **High Signal: Low Background**

Collision (10^9 Hz, 800 Tbytes/sec) → Detector → Trigger and DAQ → Storage (200Hz, 2 Gbytes/sec) → Event Selection → Storage again → Analysis

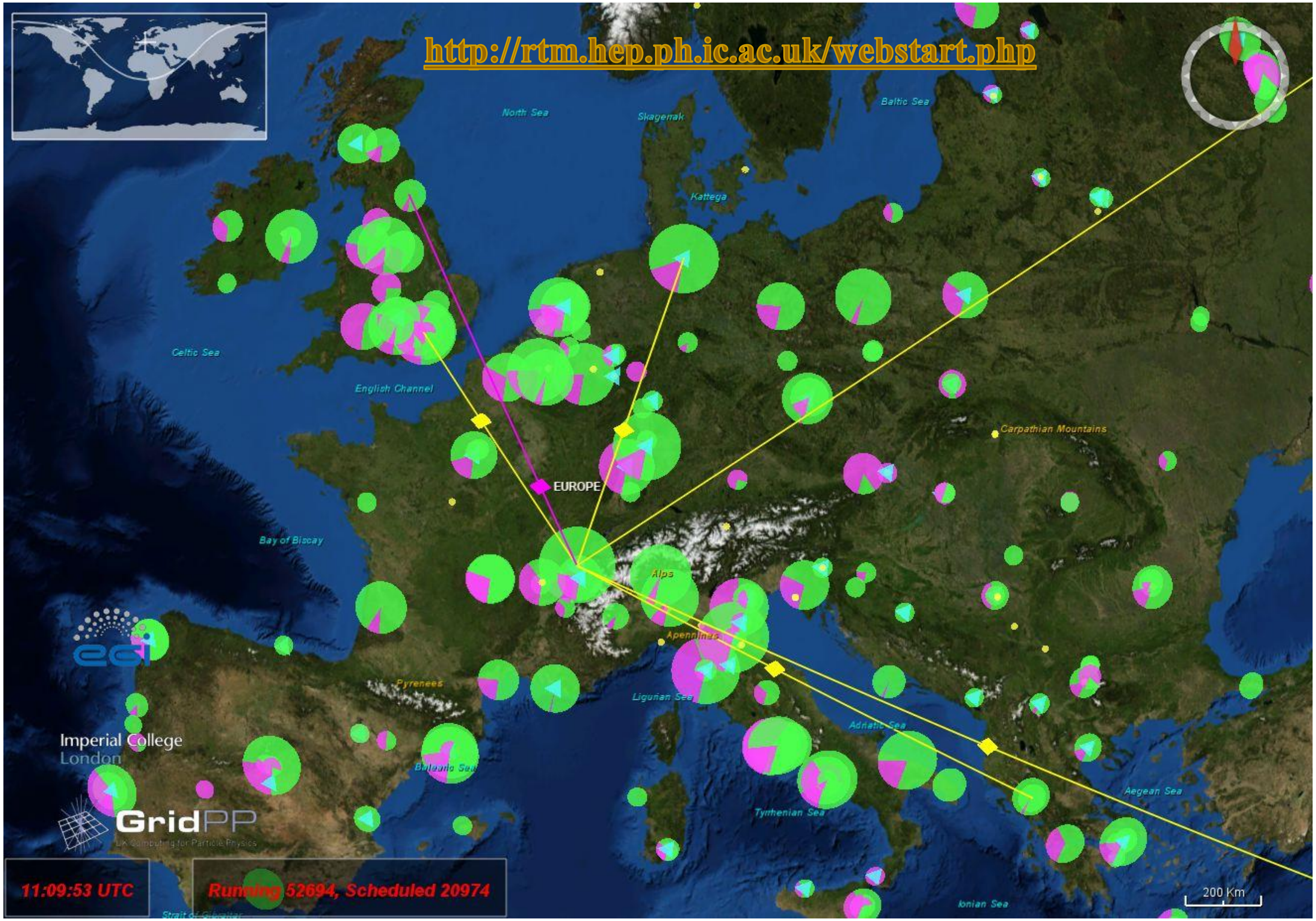
(numbers from an LHC experiment)





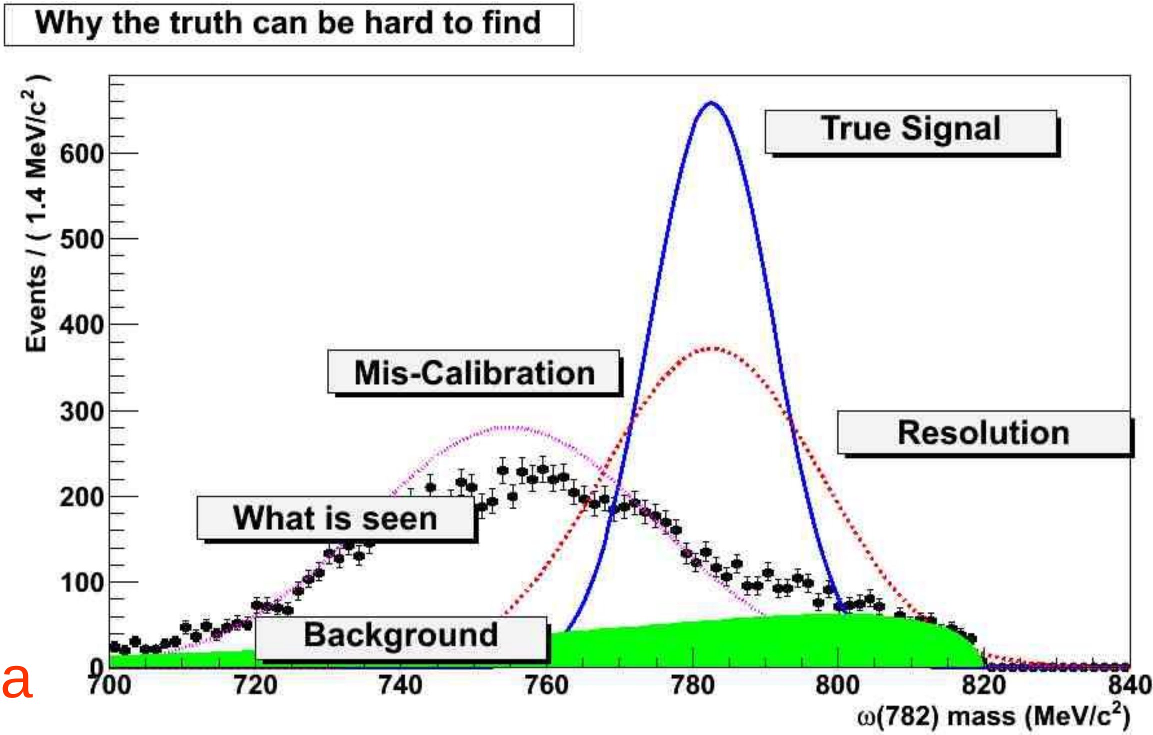


Where is all the LHC data going?



Elements of Analysis

- What you actually measure can be affected by
  - Acceptance (how many events actually enter your detector)
  - Detector Response (not a perfect device)
    - Can smear the distribution
    - Can shift the distribution
  - Errors
    - Statistical
    - Systematic
- How to find the truth?
  - Try and evaluate from the data
  - Create a simulation of your experiment (Monte Carlo)

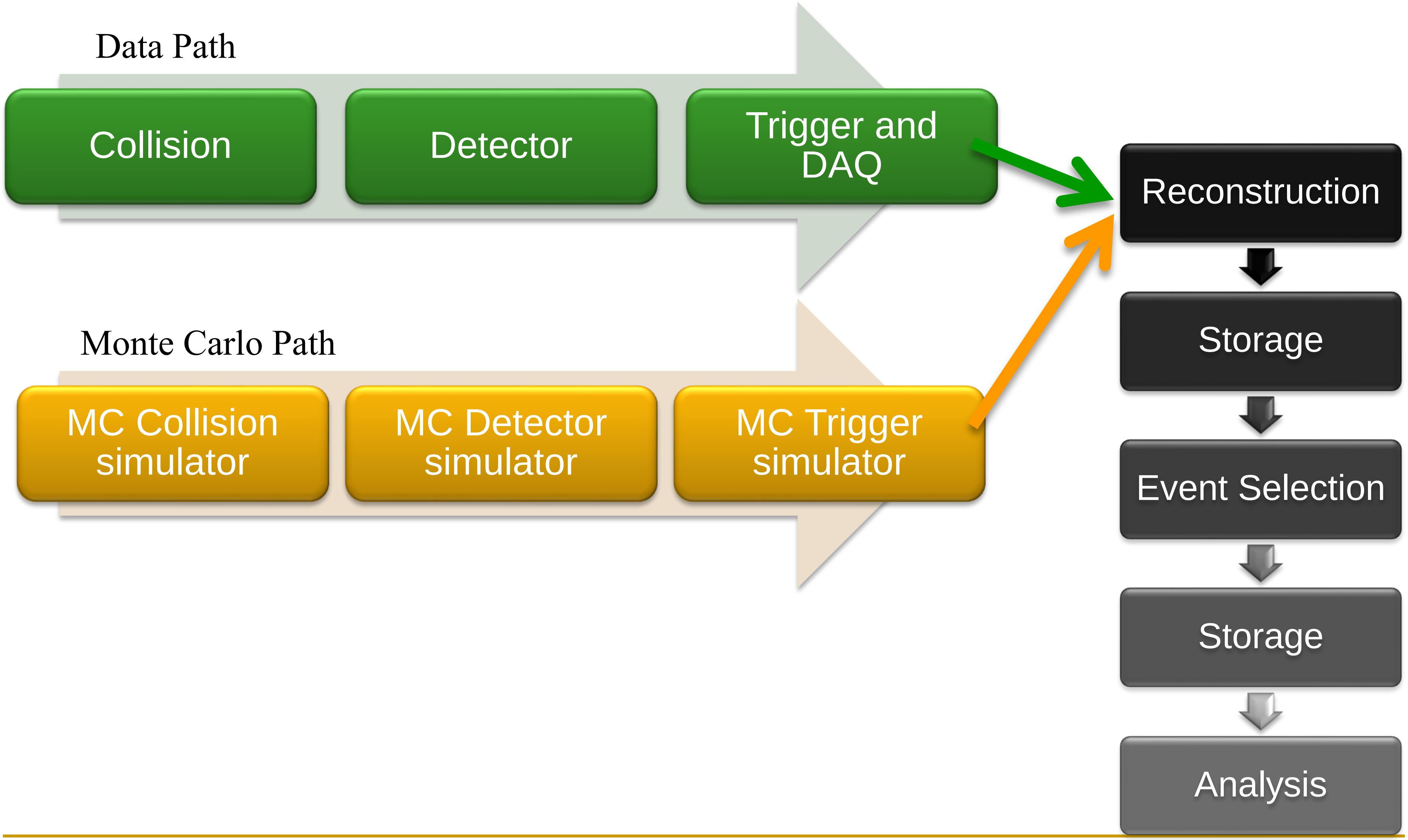


Monte Carlo

- Generate artificial data
- Simulate every component of your detector (from the ~atomic level)
- Analyse the simulated data as though it were real data
  - Response to a known input can be calculated
  - Invert the response to calculate what the input should look like for a given output
- Also used to design the detector
- Very computer intensive

- One LHC event takes 20 minutes to simulate.
- In 20 minutes, LHC creates 250,000 real events.
- So need 250,000 computers to keep up.

Data and Monte Carlo Comparison



Data Path

Collision

Detector

Trigger and DAQ

Monte Carlo Path

MC Collision simulator

MC Detector simulator

MC Trigger simulator

Reconstruction

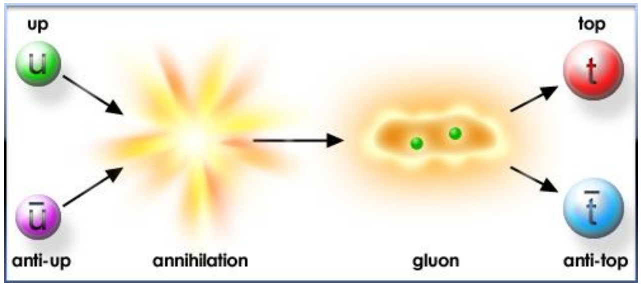
Storage

Event Selection

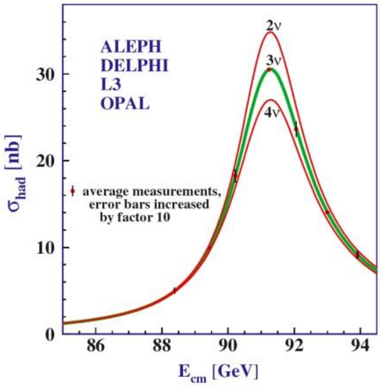
Storage

Analysis

What should we collide?



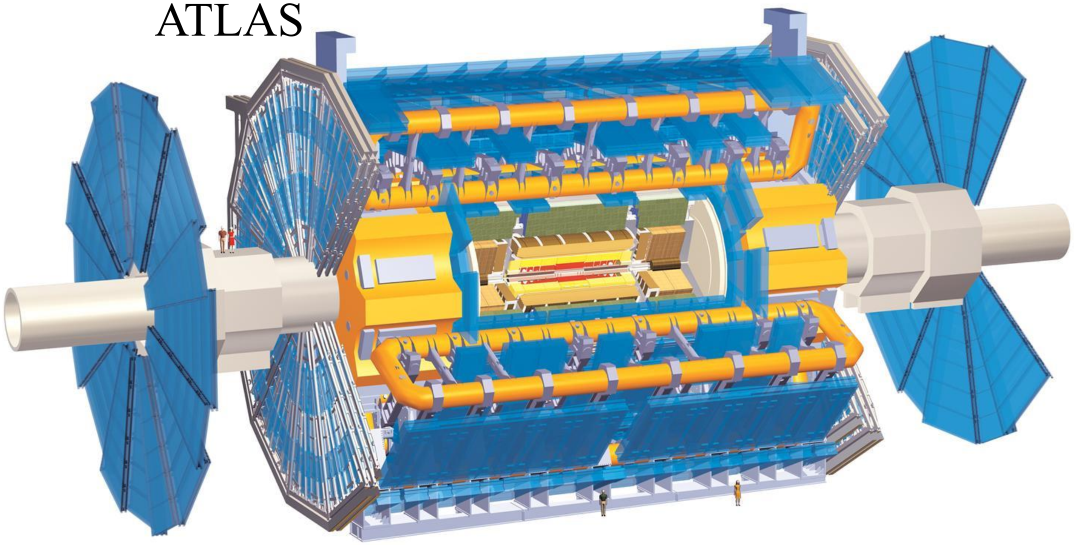
- Generally want to collide particles and anti-particles:
  - They annihilate into energy
  - But anti-particles can be expensive to produce.
- Electron / Positron colliders (e.g. LEP):
  - Point-like with well-known initial energy.
  - All the energy goes into the collision.
  - All decays have roughly the same cross-section so there are no large backgrounds.
  - Lose lots of synchrotron radiation in circular colliders.
  - Need to have good idea of the mass of the particles you want to produce e.g. e+e- →Z^0
- Proton / Anti-proton colliders (e.g. Tevatron):
  - Composite particles so initial energy not known
  - Not all the energy goes into the collision so need to accelerate to higher energies
  - Large cross-sections but large QCD backgrounds
  - Heavy so do not lose lots of energy via synchrotron radiation
  - Useful if you don't know the mass of the particles you want to produce e.g. gg→H



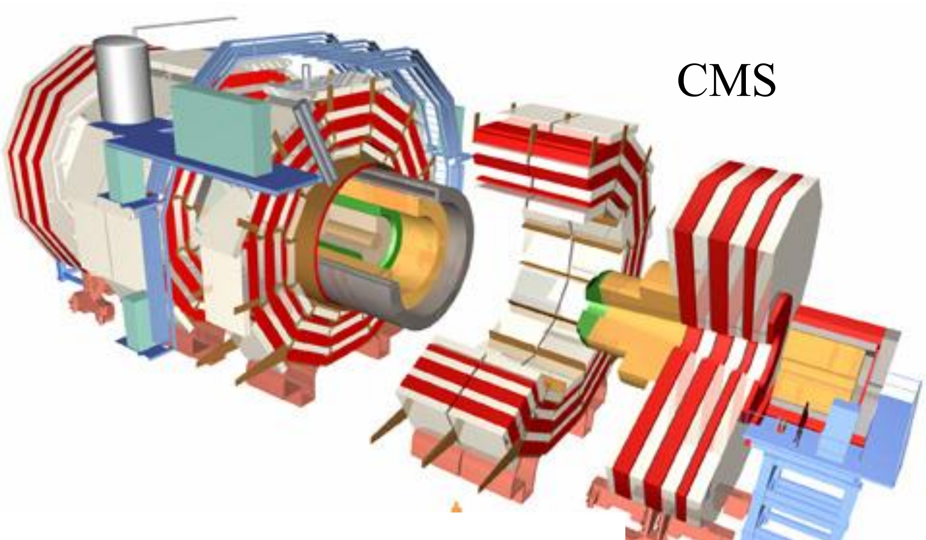
- Proton / Proton colliders (e.g. LHC)
  - At high energies, most interactions involve gluons and sea-quarks so little difference in proton/proton and proton/anti-proton cross-section.
- Neutrino / Nucleon colliders (e.g. T2K)
  - Need a lot of mass to stop neutrinos
- Electron / Proton (e.g. ZEUS and H1 at DESY)
  - A giant electron microscope to probe the structure of the proton.

The (4 out of 6) LHC Experiments

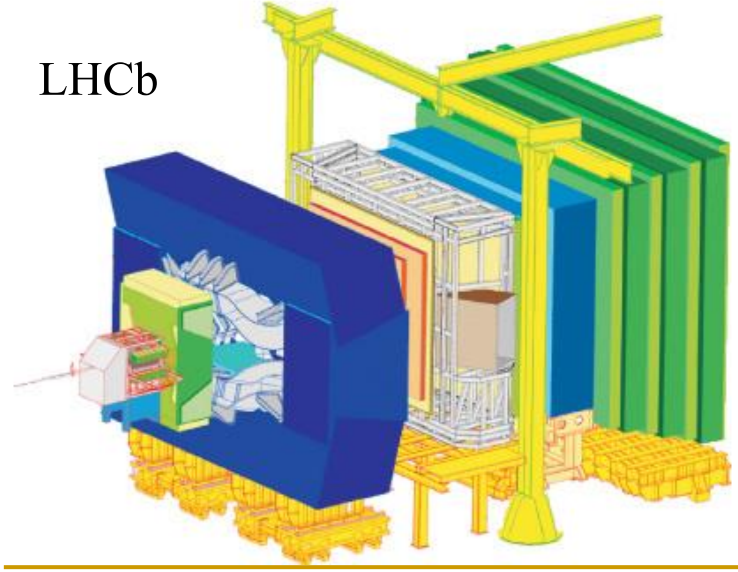
ATLAS

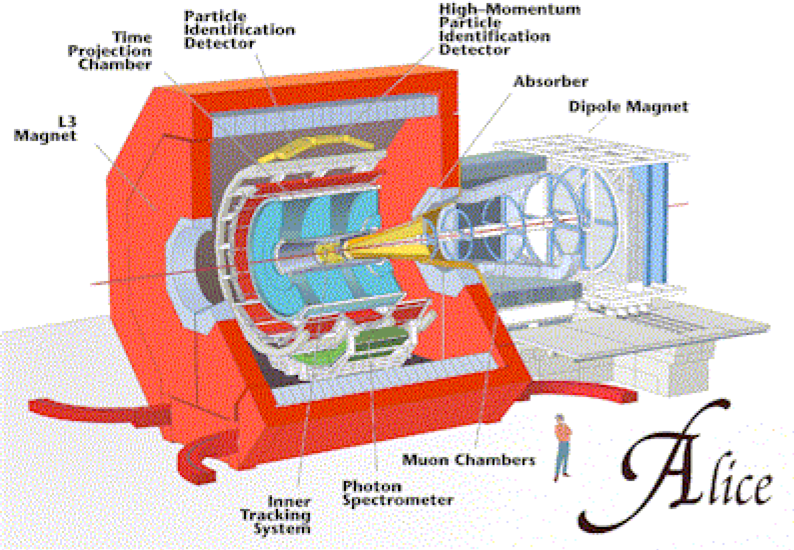


CMS

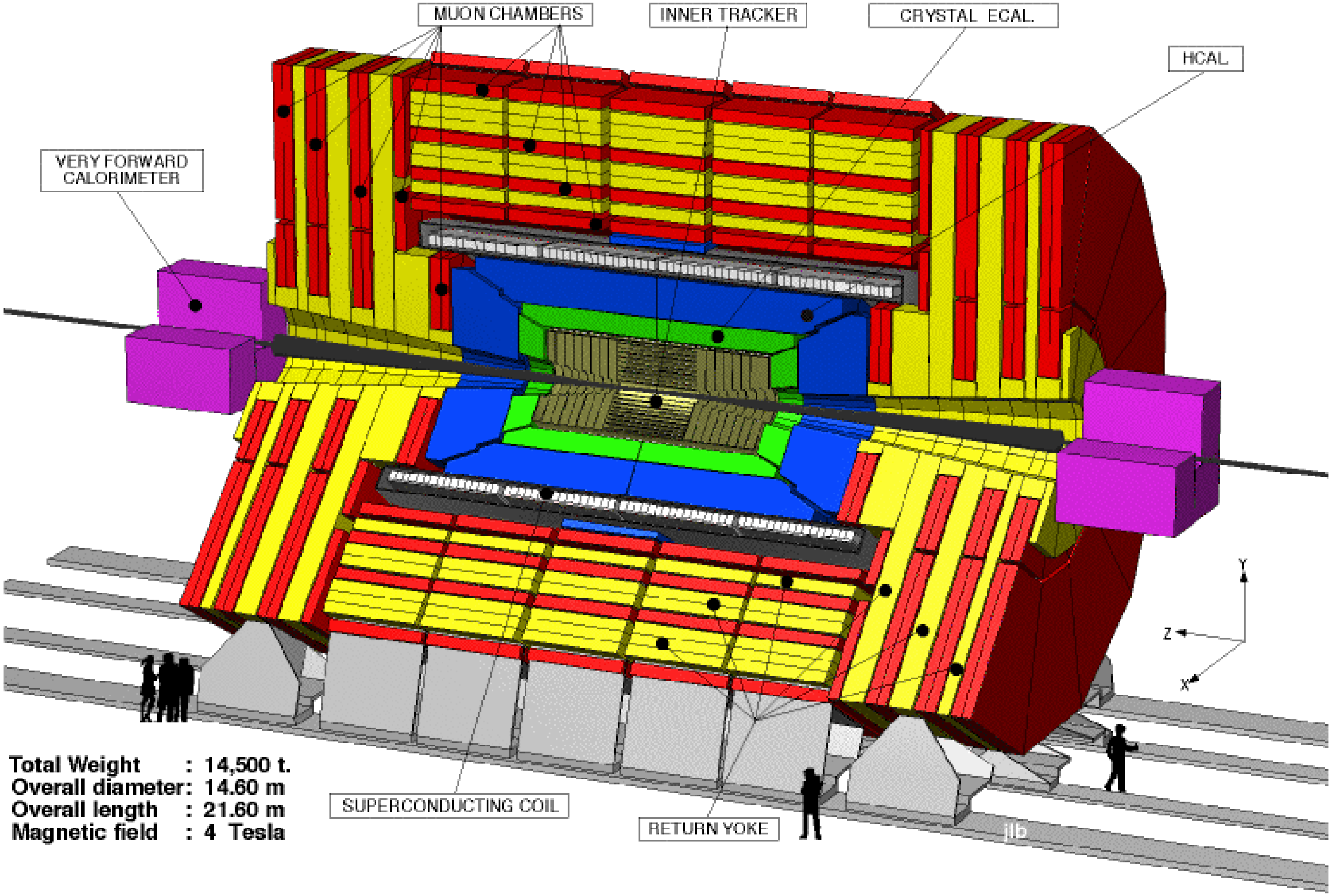


LHCb





The CMS detector



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

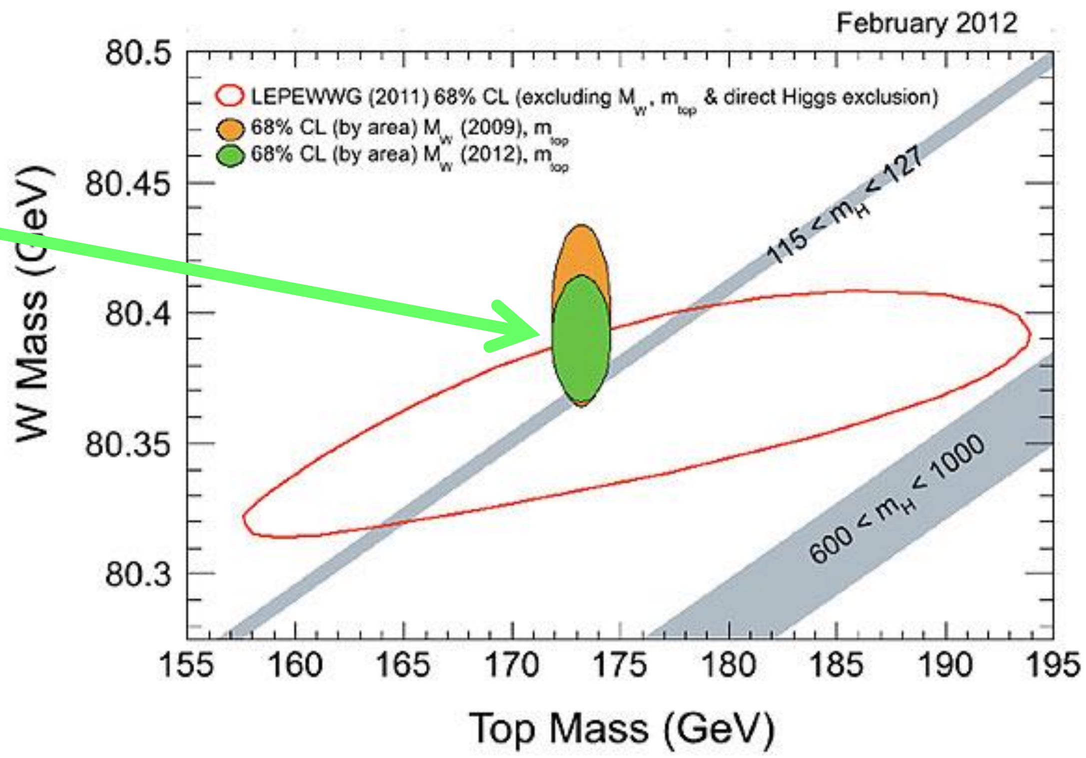
Building the ATLAS detector

Why look for the top quark?

- The top quark and W boson are very heavy
- Their mass is influenced by the Higgs mass
- If we measure both we can “predict” Higgs mass

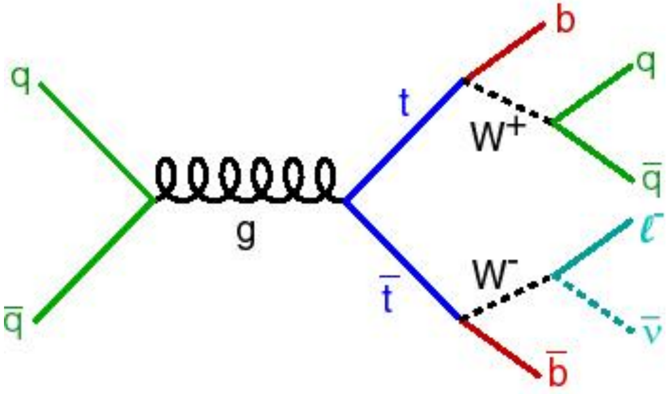
Top mass : 172.6 ± 1.4 GeV

W mass : 80.385 ± 0.0021 GeV

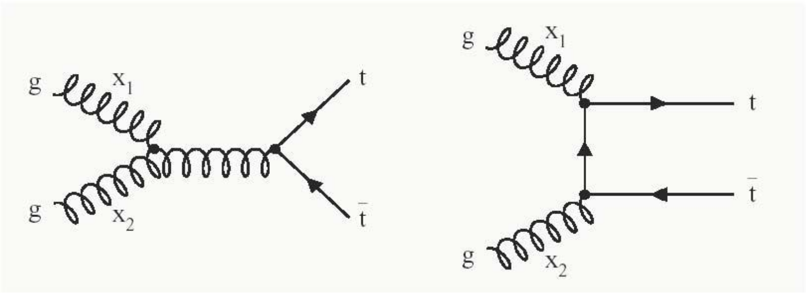


Top Pair Production and decay

- Tevatron



- LHC



$t \rightarrow W^{+} b$ (100%)

$W^{+} \rightarrow q\bar{q}$ (70%)

$W^{+} \rightarrow l^{+}\nu$ (10% per lepton)

Semi-leptonic ($l^{+}\upsilon$) channel is best

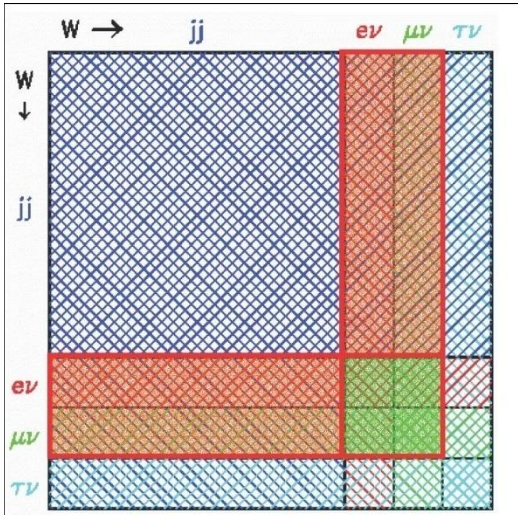
l^{+} is an electron or muon

l^{+} is easy to identify

Only one neutrino

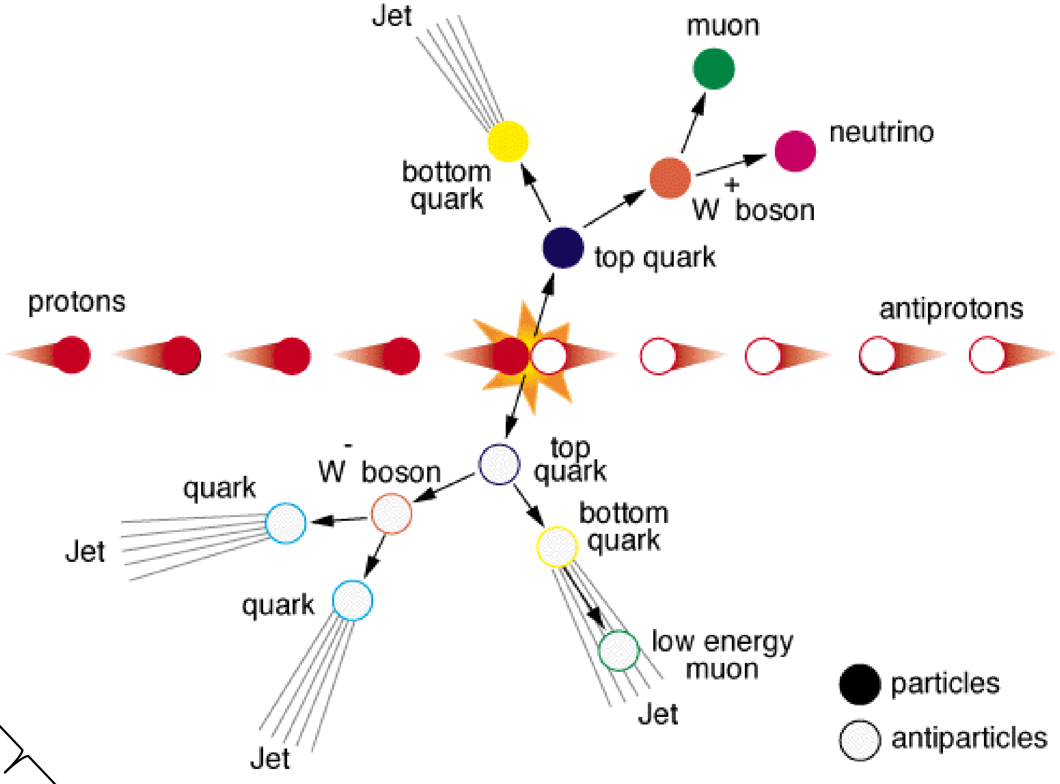
Each b quark decays into a jet

Each q quark decay into another 2 jets



Best decay channel to look for

- Semi-leptonic mode (lepton+neutrino)
- Electron or muon 20% of the time
- Signature:
  - 2 light quark jets
  - 2 bottom jets
  - One electron or muon
  - Missing transverse momentum (because of the neutrino)
- Extras:
  - Underlying event
  - Higher order processes
  - Multiple interactions



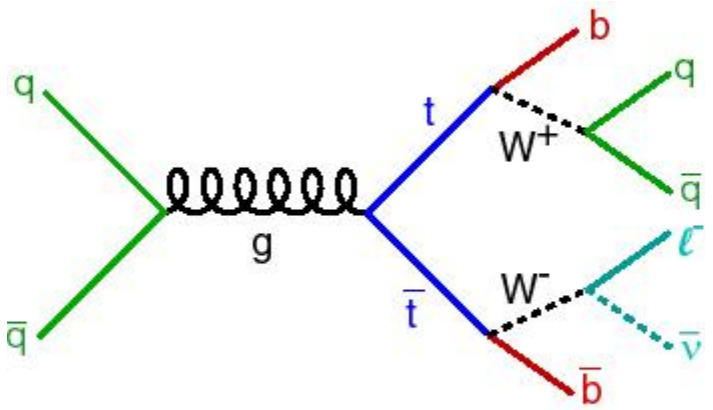
A Top Antitop Quark Event from the D-Zero Detector at Fermilab

These two jets have W^- mass

These three jets have top mass

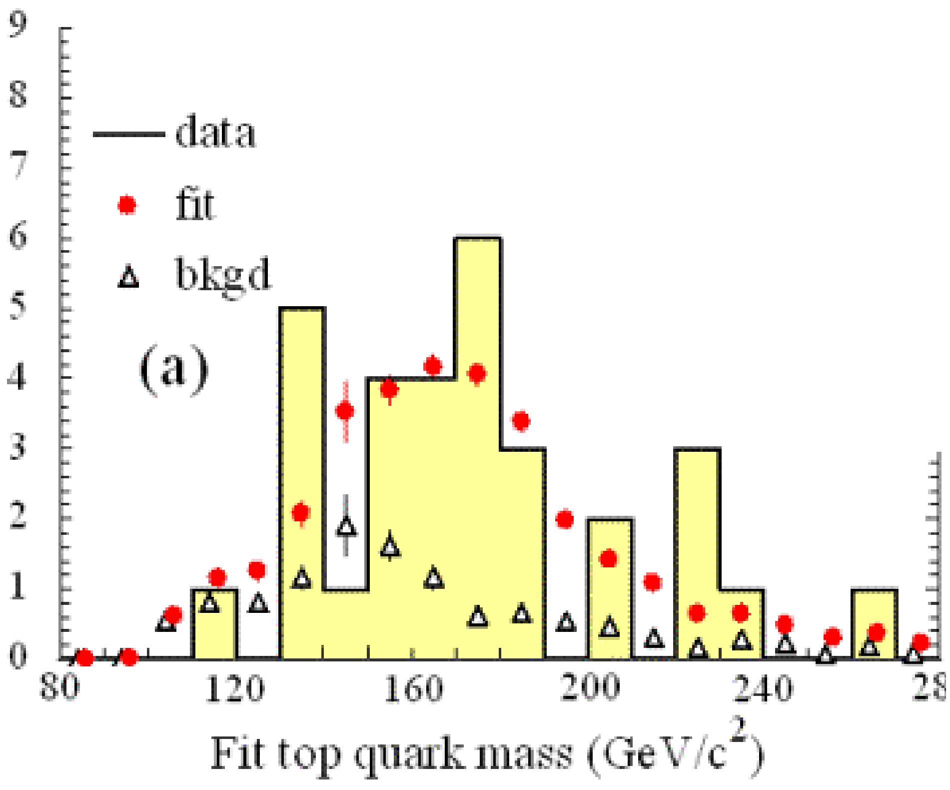
The Top mass

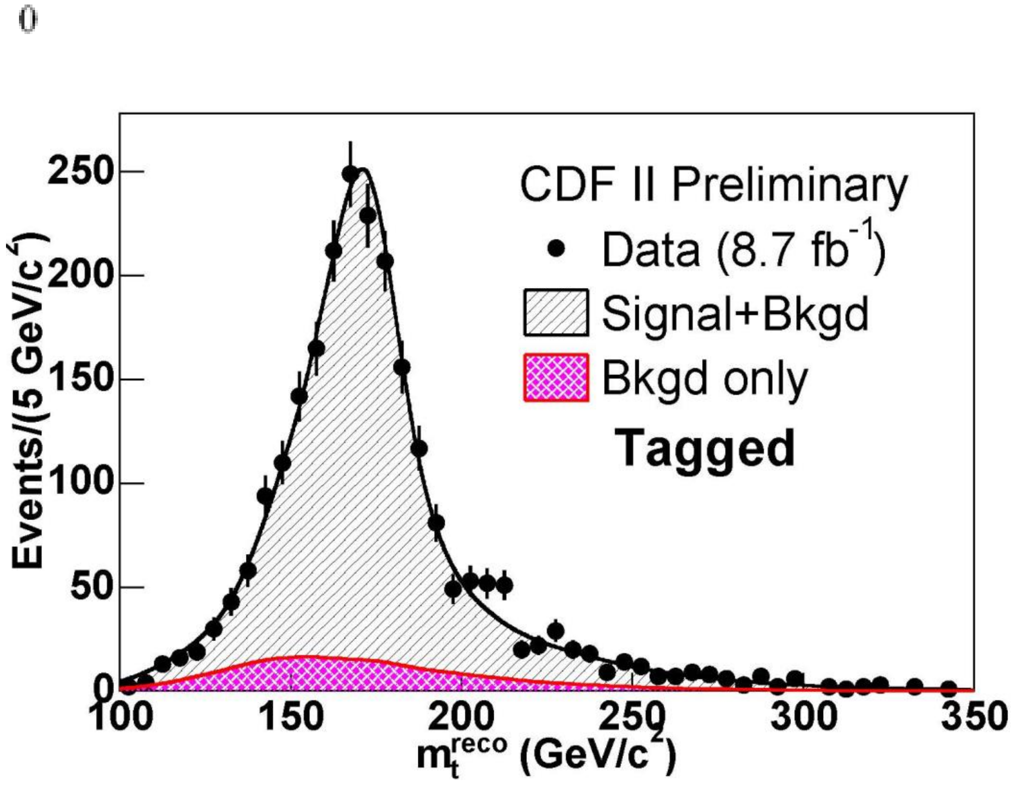
- How do we find the top mass



- Add together the q and anti-q jets to form W^+ mass
- If this is okay, add the b quark jet to get the top mass

An example of the top mass





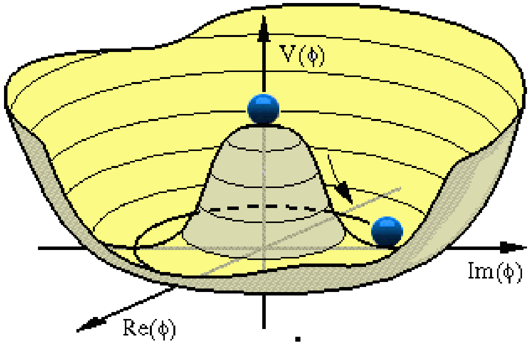
~1999

2011

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
- 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

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

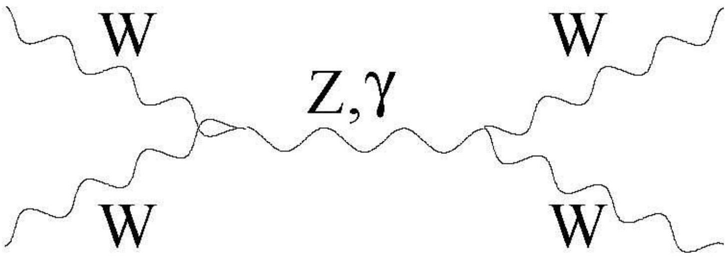
- Step 1: Spontaneous Symmetry Breaking produces one massive and one massless gauge boson (Goldstone Boson).
- Step 2: Introduce local gauge invariance : massive Higgs particle, three massive vector bosons (W/Z) and one massless boson (γ).
- Higgs mass a free parameter $M_H = \sqrt{-2\mu^2}$
- Gauge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

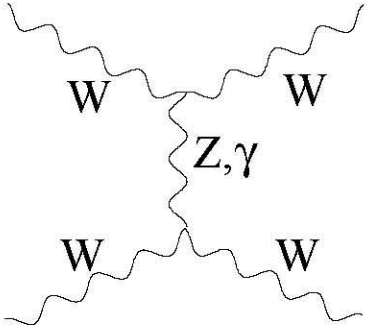
$$M_W = g_W \nu / 2 \quad M_Z = M_W \cos\theta_W \quad \cos\theta_W = 0.8810$$

- 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: $M_f \propto M_H g_f$

What did we know about the Higgs before 2012?

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

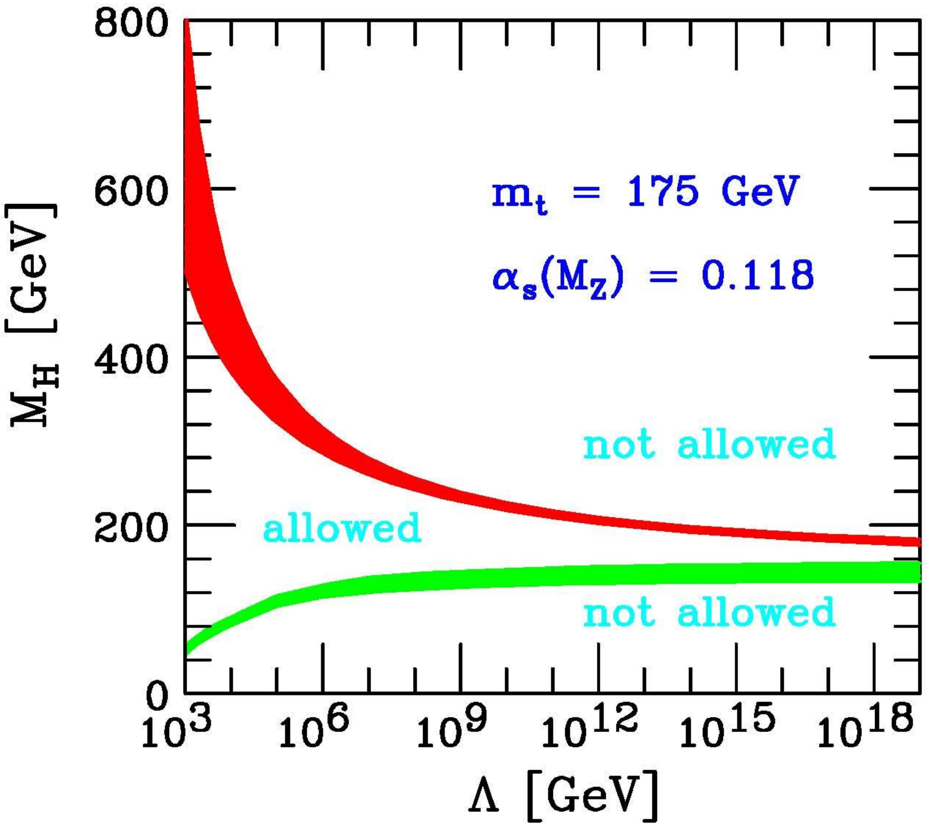




What did we know about the Higgs before 2012?

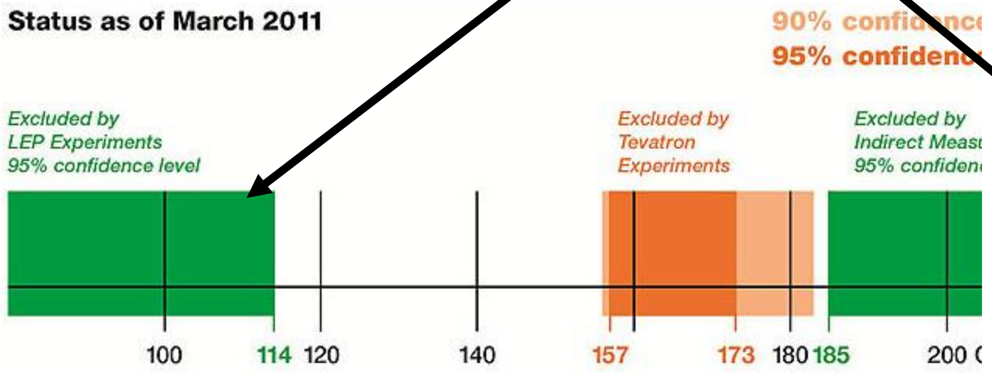
If no new physics up to Planck scale (~10^{19}GeV) small mass range for Higgs: $130 < M_H < 190$ GeV

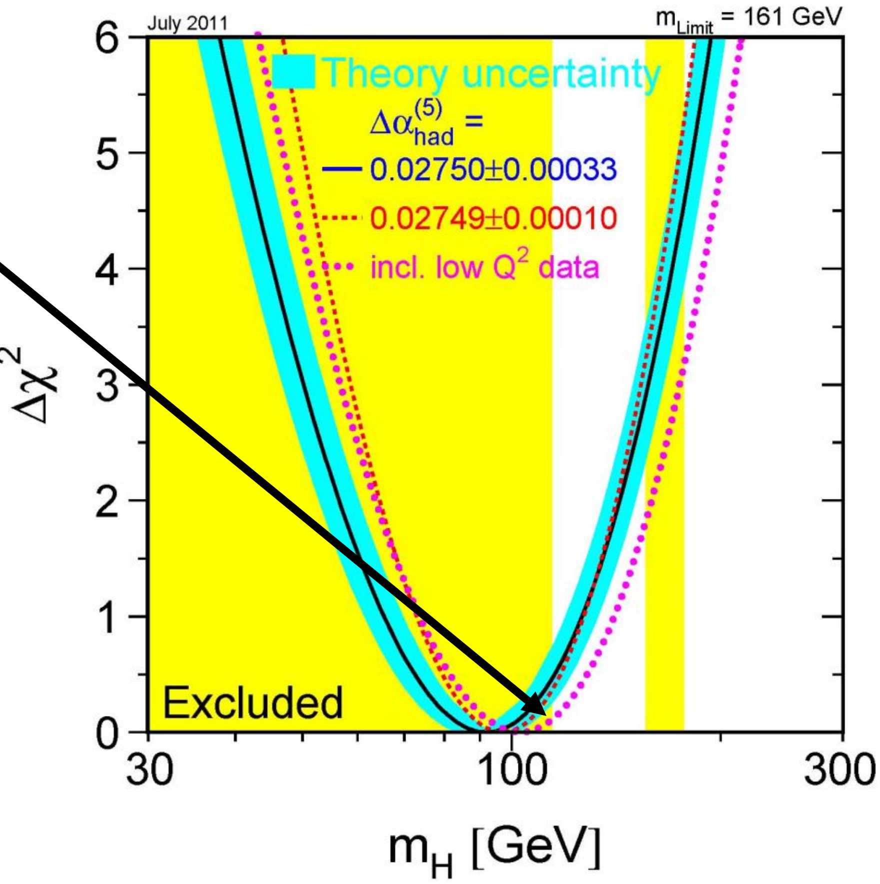
$$M_H^2 \leq \frac{8\pi^2 v^2}{3\log\frac{\Lambda_{QCD}^2}{v^2}} \qquad \upsilon^2 = 246\,\mathrm{GeV}$$



What did we know about the Higgs before 2012?

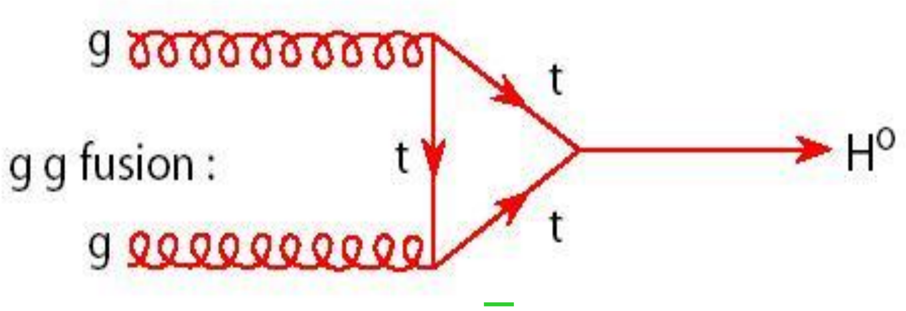
Direct searches
$M_H > 114.4$ GeV
@ 95% C.L.

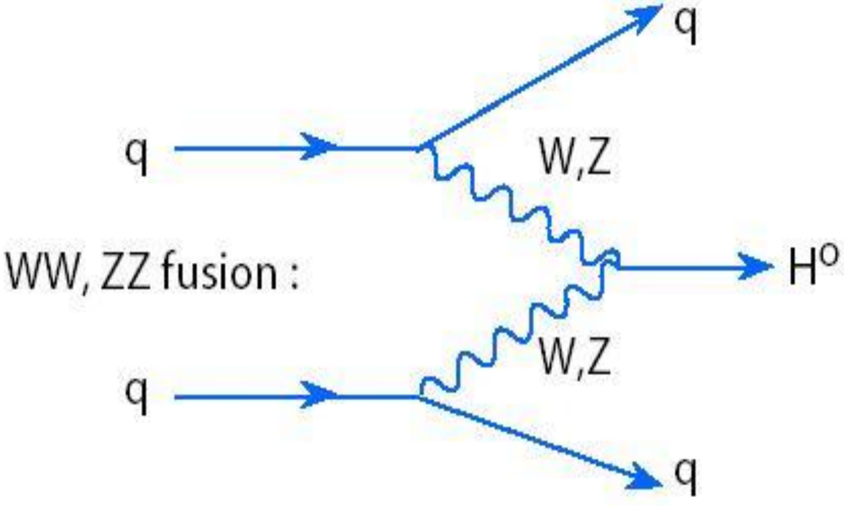




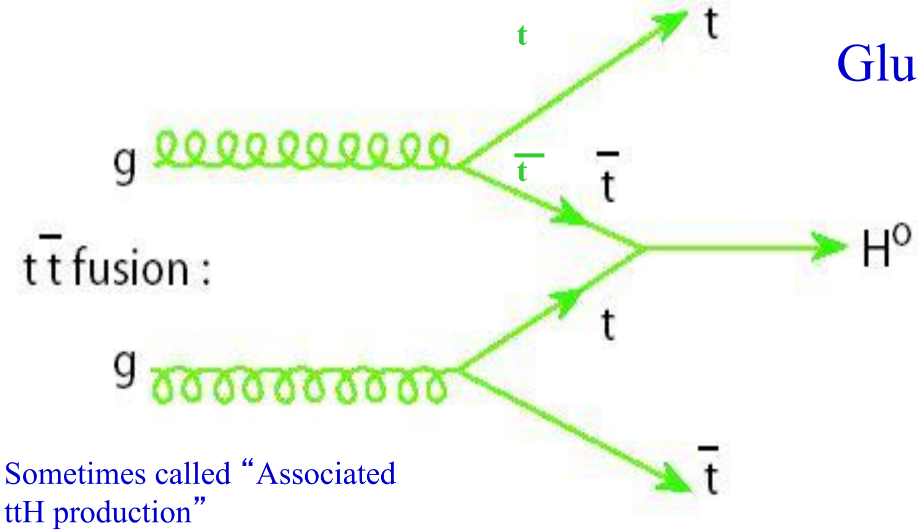
http://lepewwg.web.cern.ch/LEPEWWG

Higgs Production Mechanisms

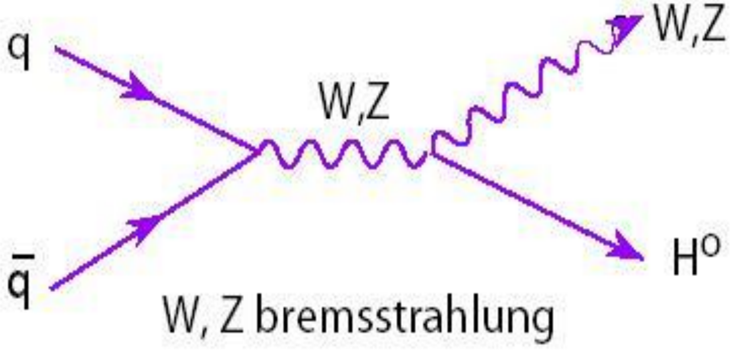




Gluon fusion looks most promising



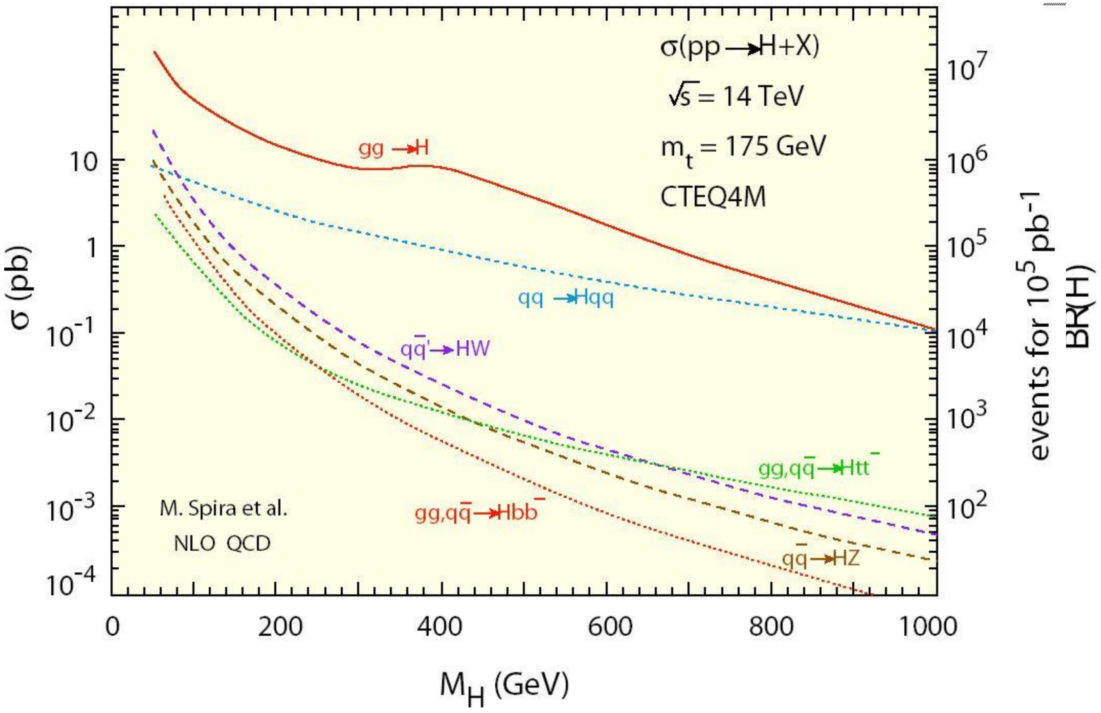
Sometimes called "Associated ttH production"



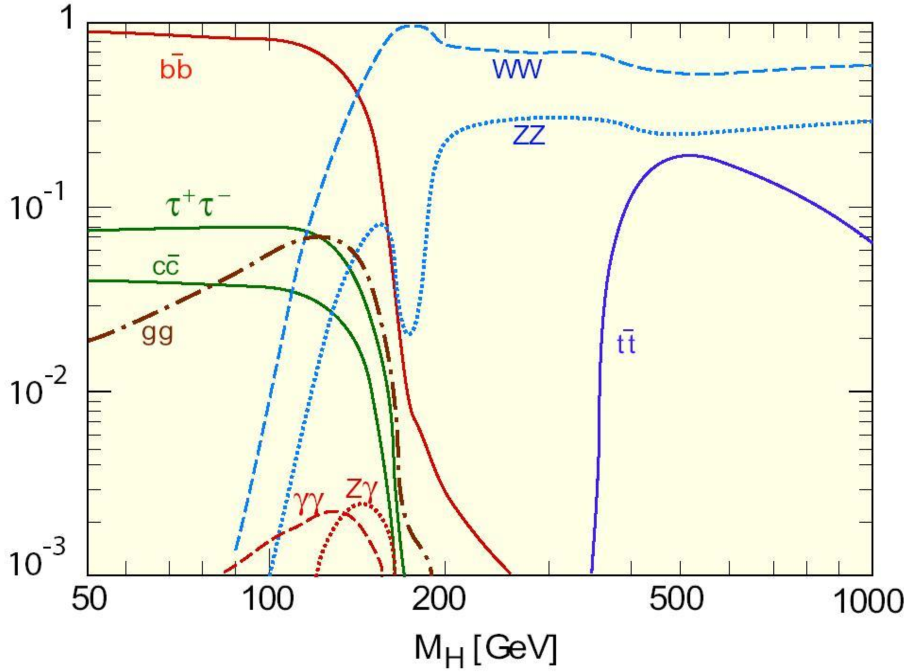
Sometimes called "Associated WH,ZH production"

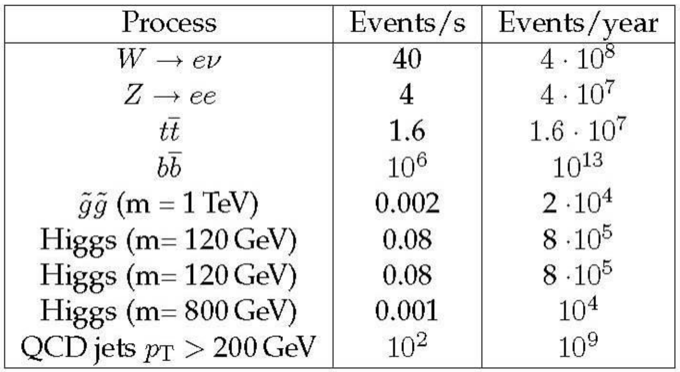
Higgs production and decay

How often is it produced?



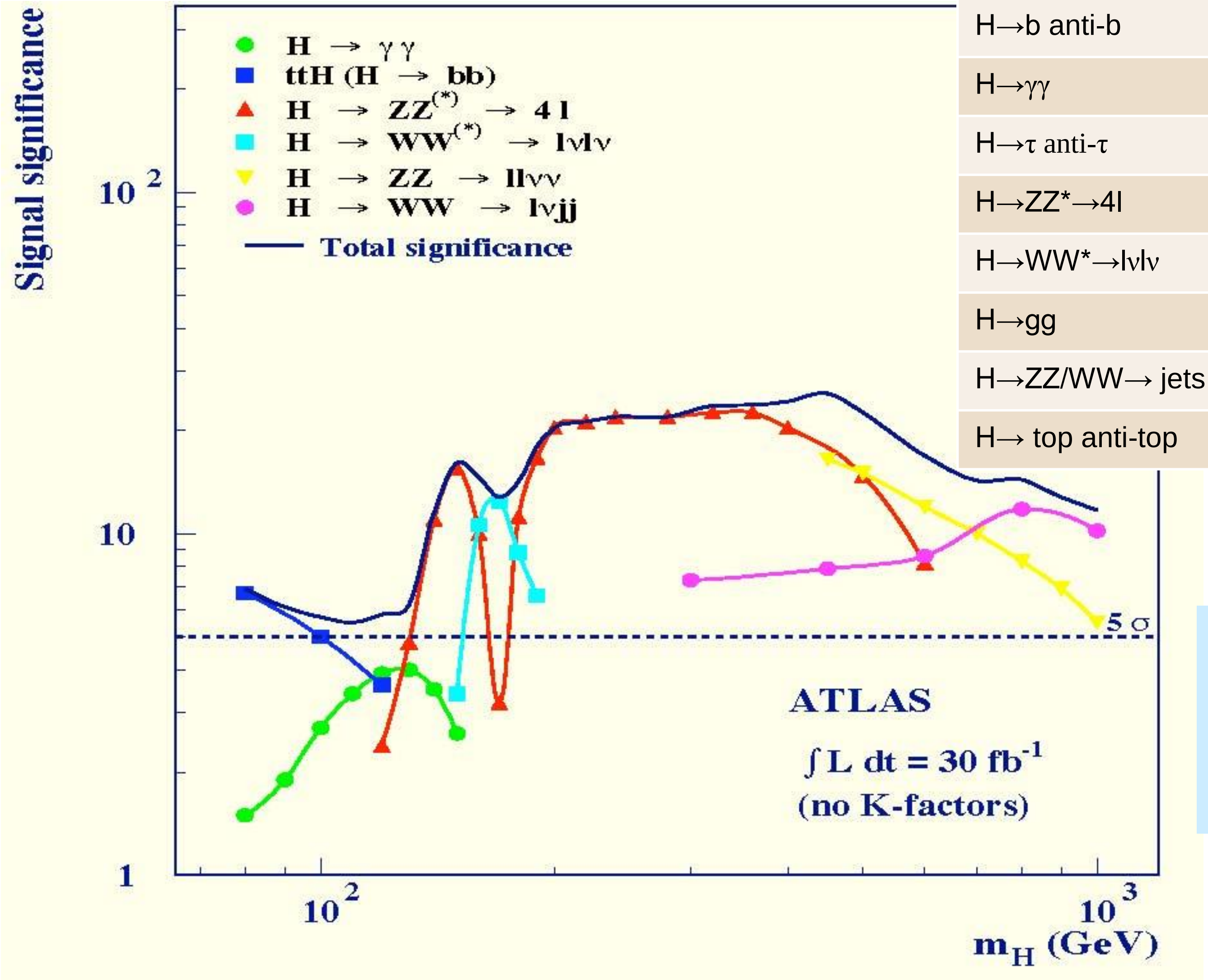
What does the Higgs decay into?





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

Best Modes to look at



Decay	Signal Rate	Background Rate	Best for Higgs mass
H→q anti-q	Low	Large	~100 GeV
H→b anti-b	Large	Large	~100 GeV
H→γγ	Low	Low	~100 GeV
H→τ anti-τ	Low	Large	~100 GeV
H→ZZ*→4l	Large	Low	~250 GeV
H→WW*→lνlν	Large	Low	~150 GeV
H→gg	Low	Large	~100 GeV
H→ZZ/WW→ jets	Large	Large	~500 GeV
H→ top anti-top	Low	Large	~500 GeV

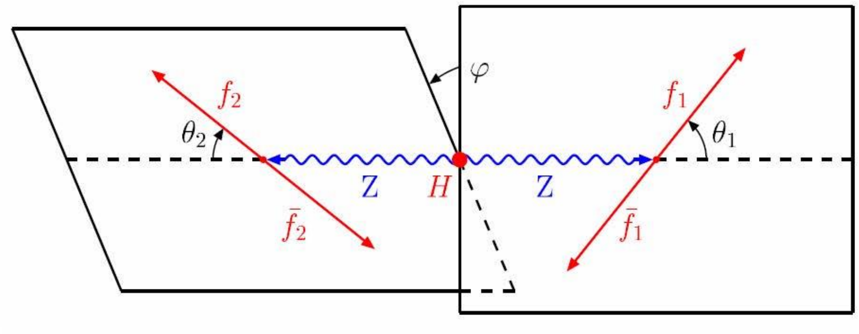
The amount of background affects our ability to see the Higgs.

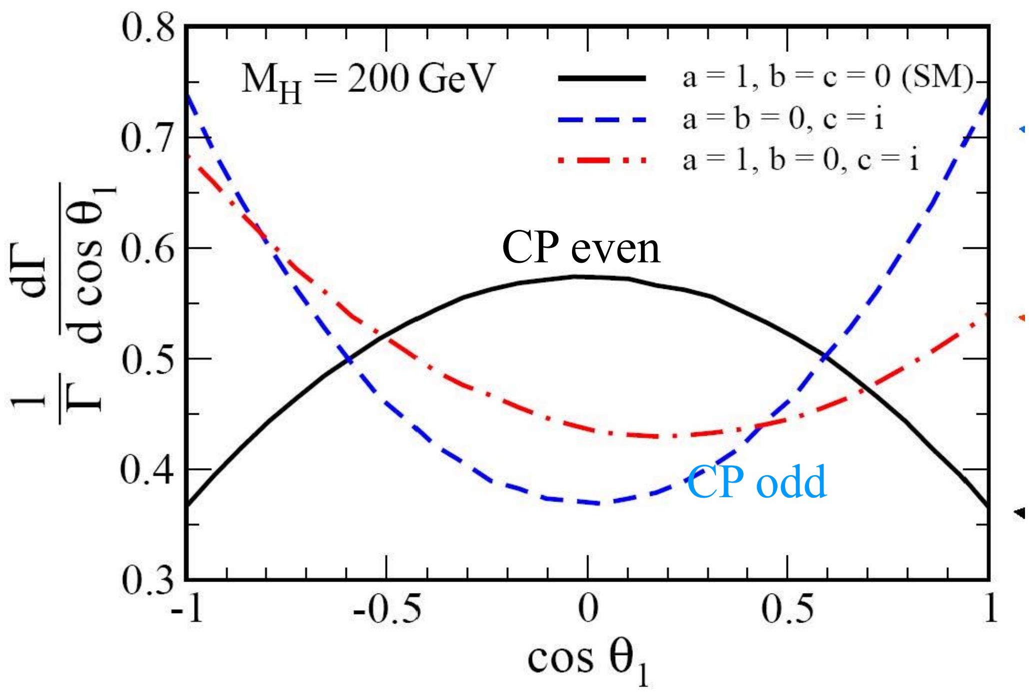
Reconstructing the Higgs properties

- 1) Mass
  - Add up all the 4-moment of its decay particle e.g. $H\to\gamma\gamma$, $H \to ZZ^* \to l^+l^-l^+l^-$ (4 leptons)
  - But sometimes miss particles e.g. $H\to W^+W^-\to l\nu l\nu$
    - Just use 4-momenta in transverse direction “transverse mass” i.e. ignore p_z along beam direction.
- 2) Spin
  - Look at the angle between one of the decay products and the direction of the Higgs in the Higgs centre of mass
    - E.g. $H\to\gamma\gamma$

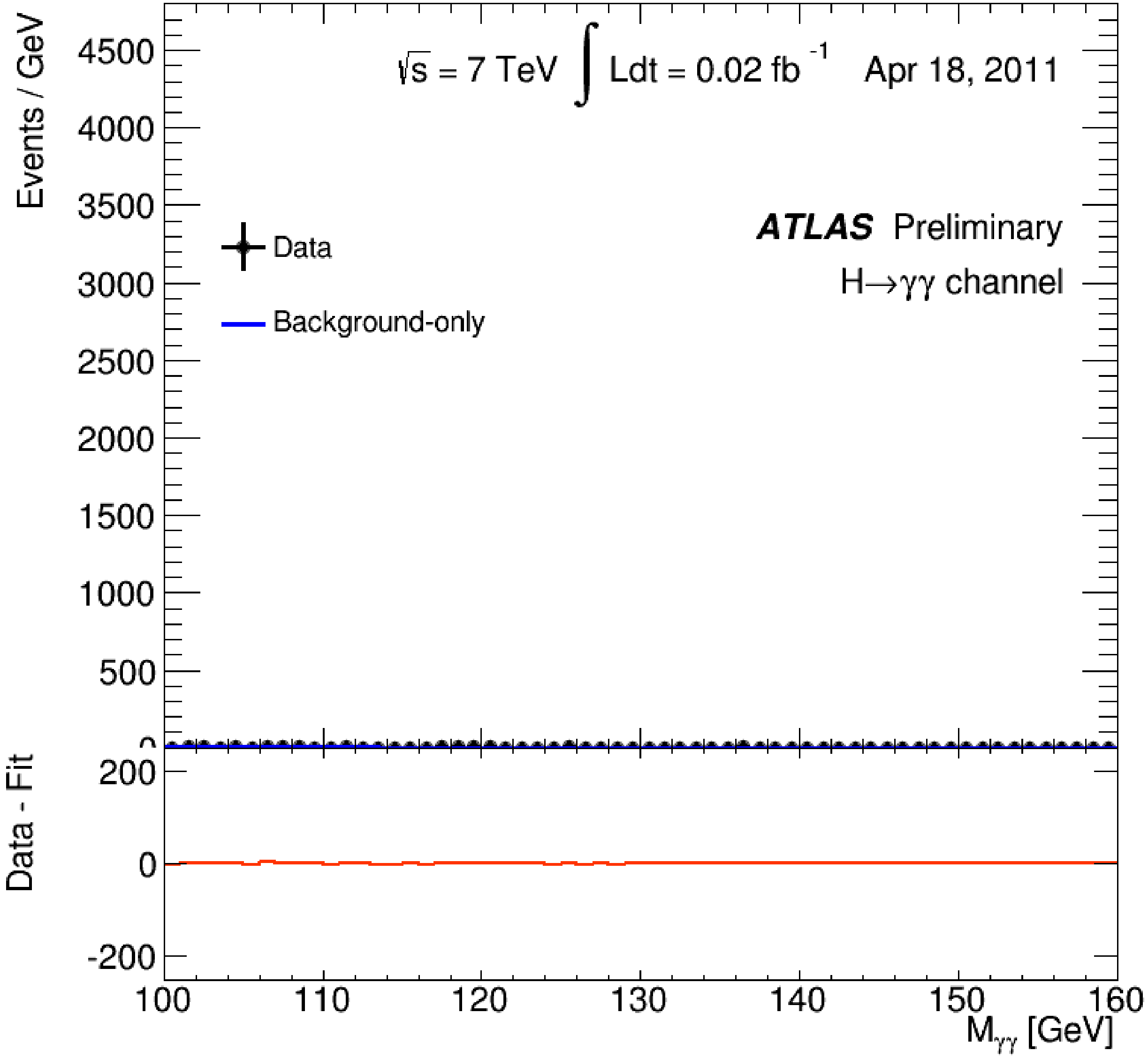
Reconstructing the Higgs properties

- 3) Charge Parity (CP)
  - Look at angles defined by leptons in H →ZZ →$l^+l^-l^+l^-$
  - SM CP=+1 (even); some SUSY models CP=-1 (odd)

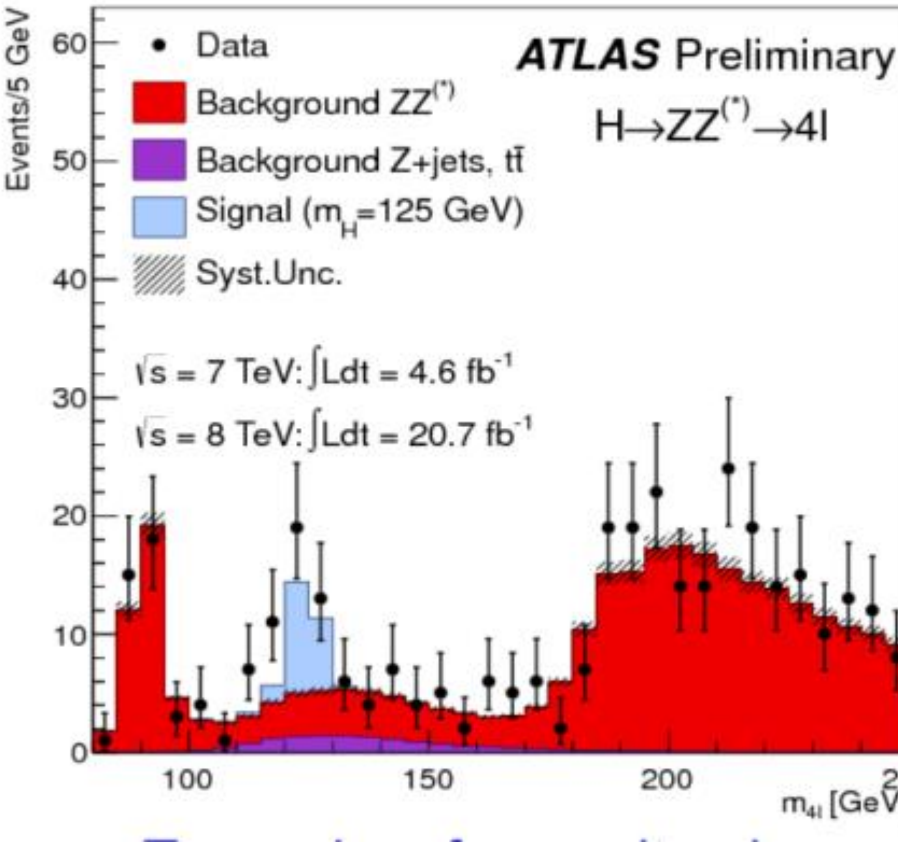


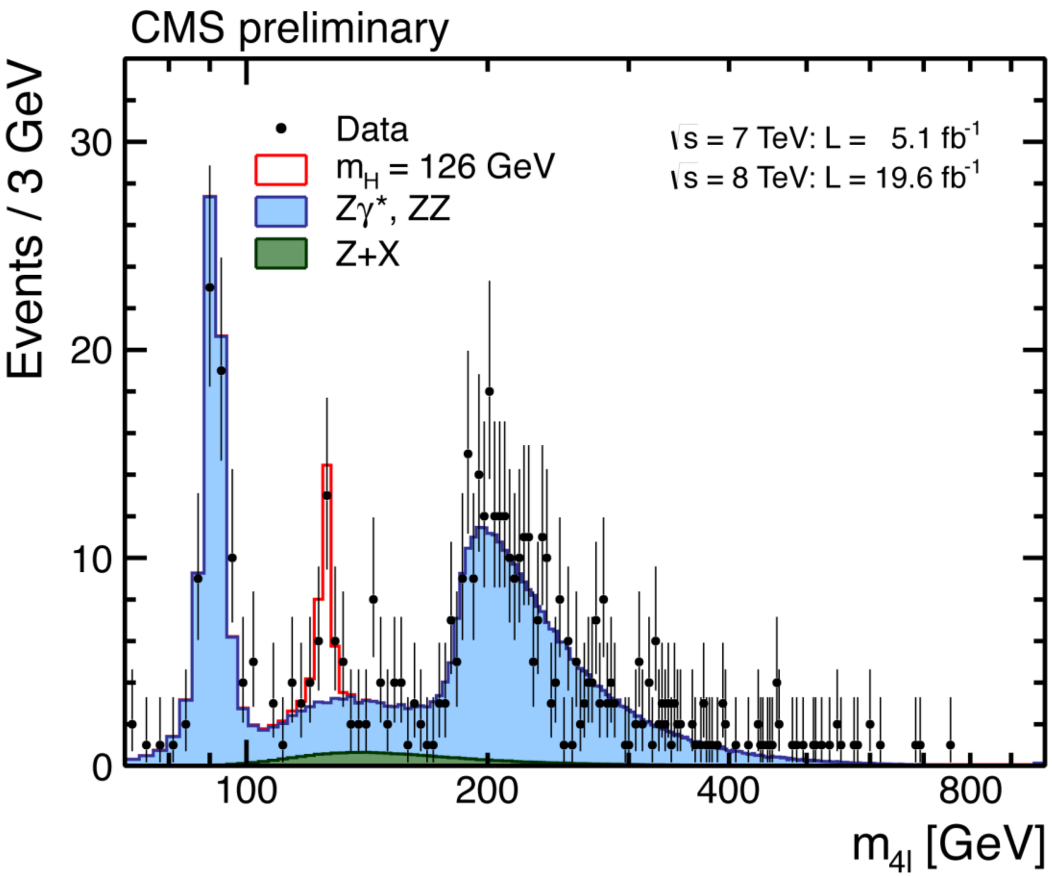


Three of the best Higgs modes: 1/3

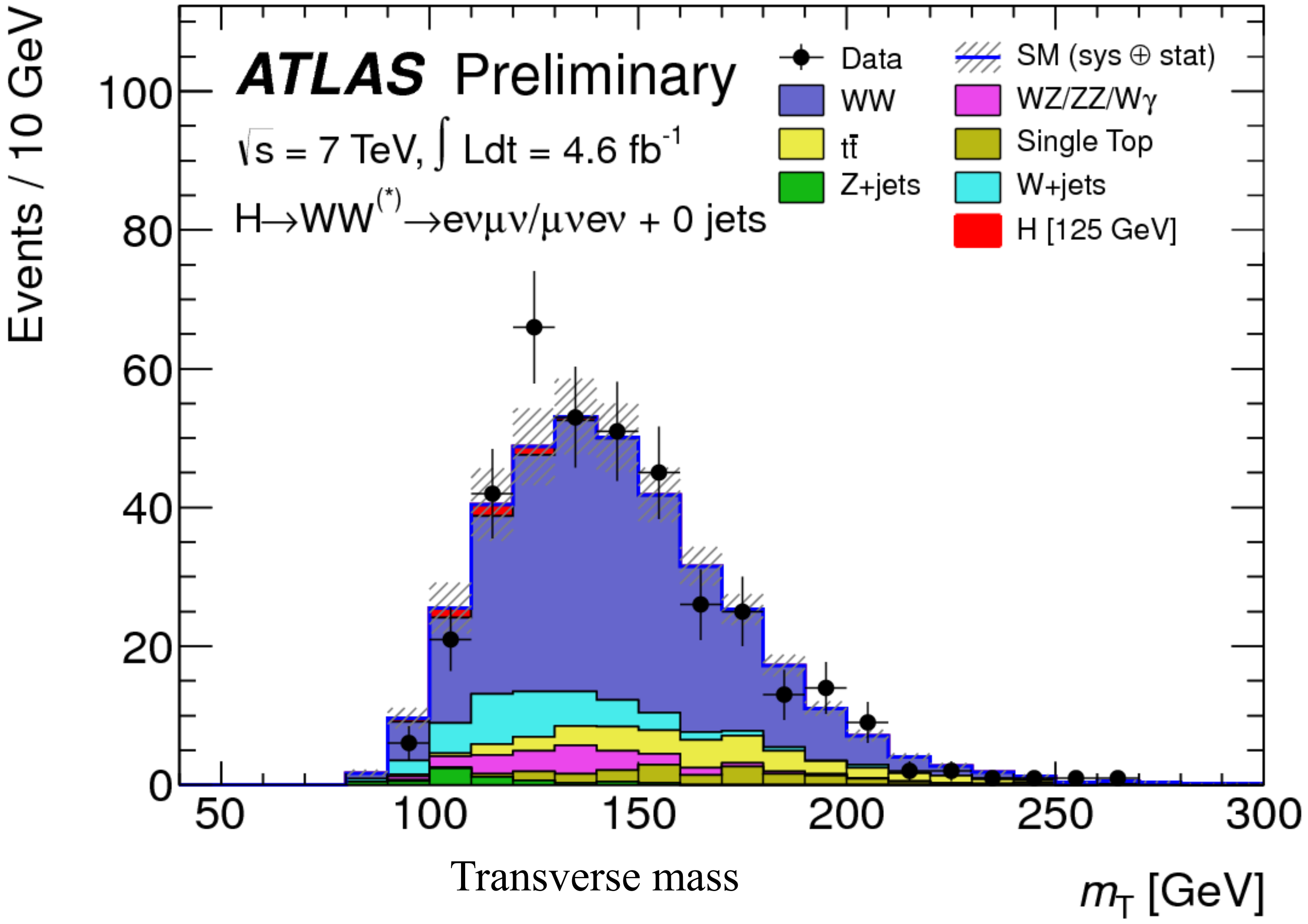


Three of the best Higgs modes: 2/3





Three of the best Higgs modes: 3/3

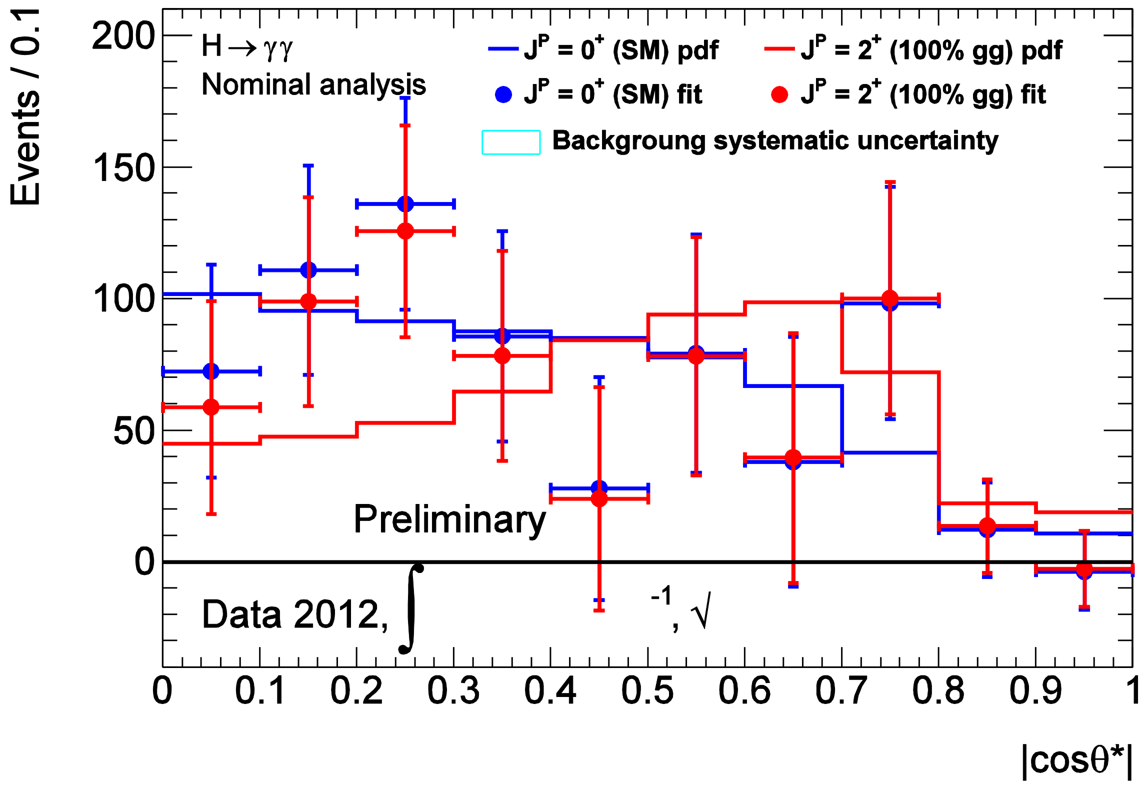


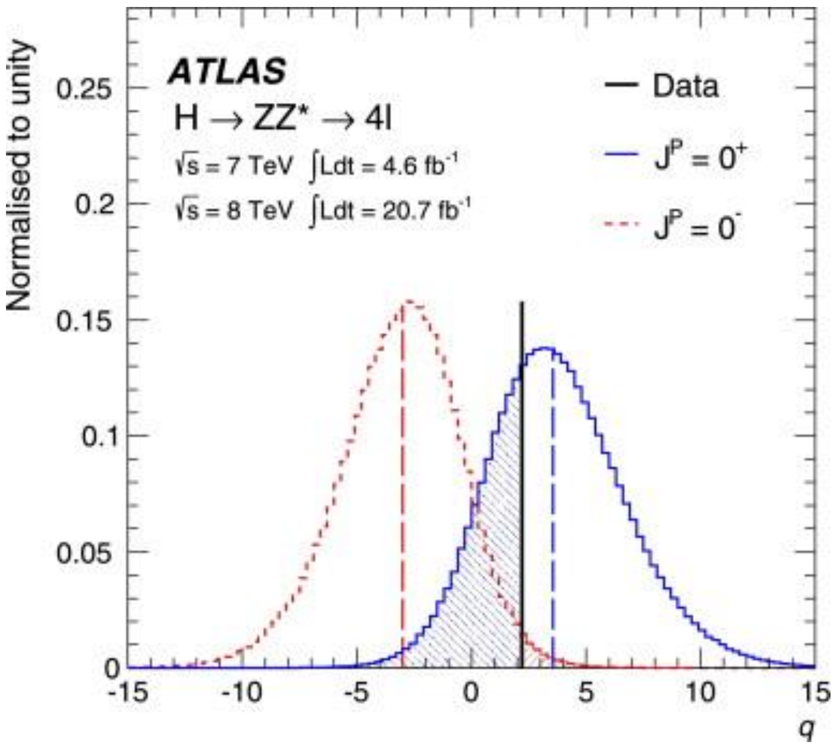
Transverse mass

Higgs Spin

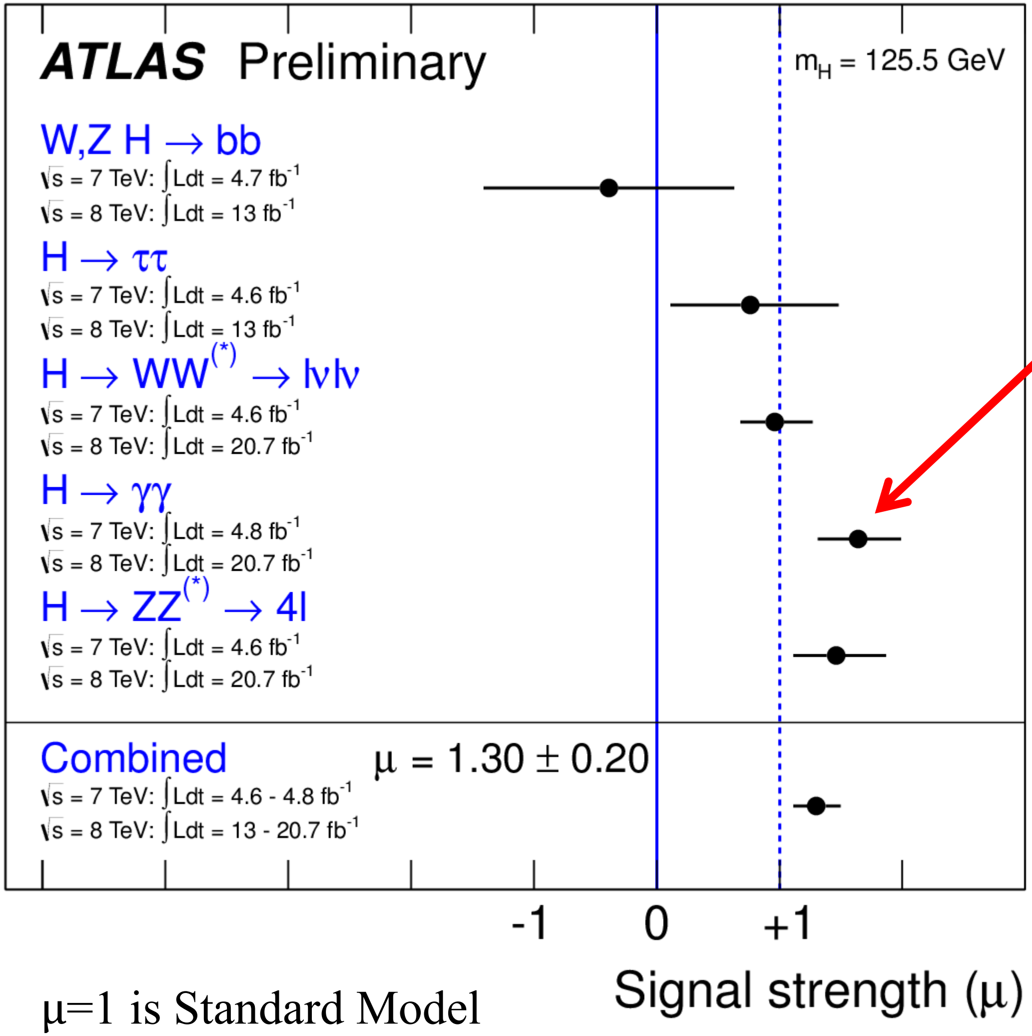
Best fit suggests Higgs is a scalar (J=0) particle.

Don’t yet know CP values but CP=+1 is preferred.





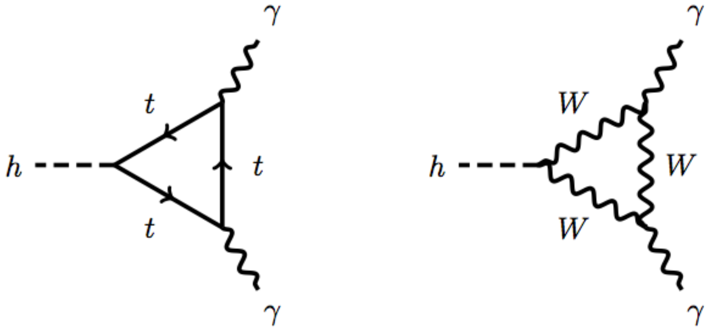
Higgs coupling to different particles



μ=1 is Standard Model

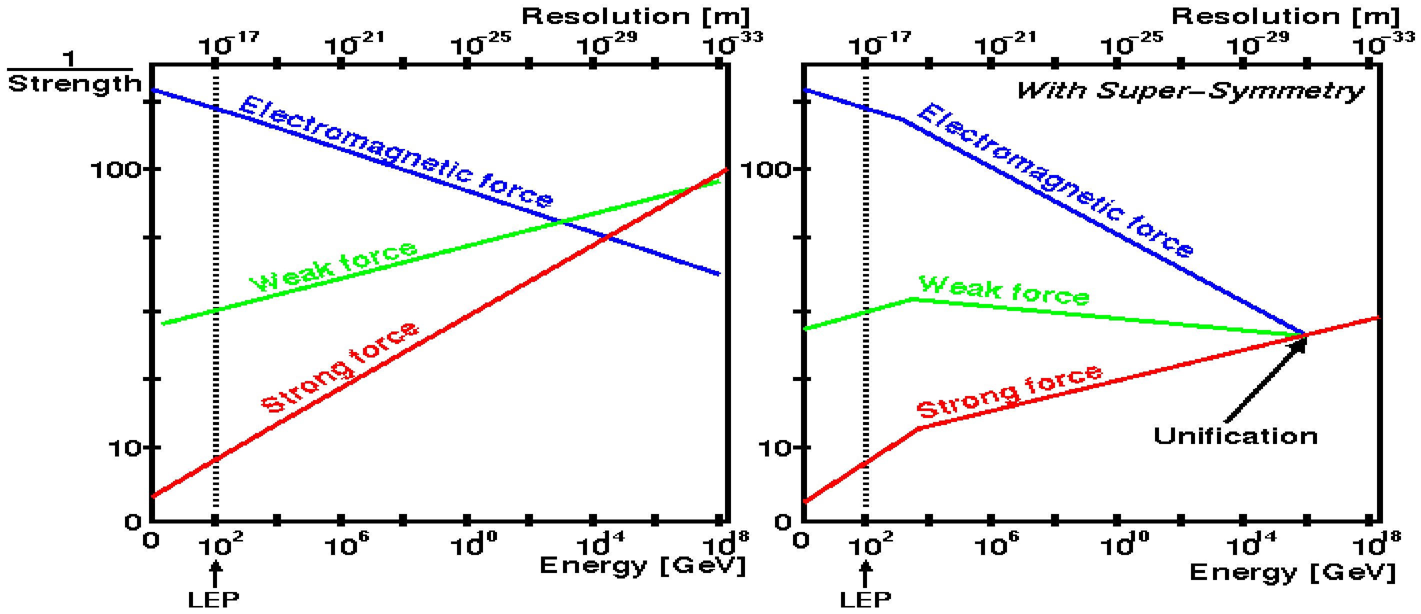
Is this rate too high? Is it a signal of new physics?

- Could be new fermions in the decay or production.
- Could be new charged bosons in the decay loop.
- Could just be statistics !

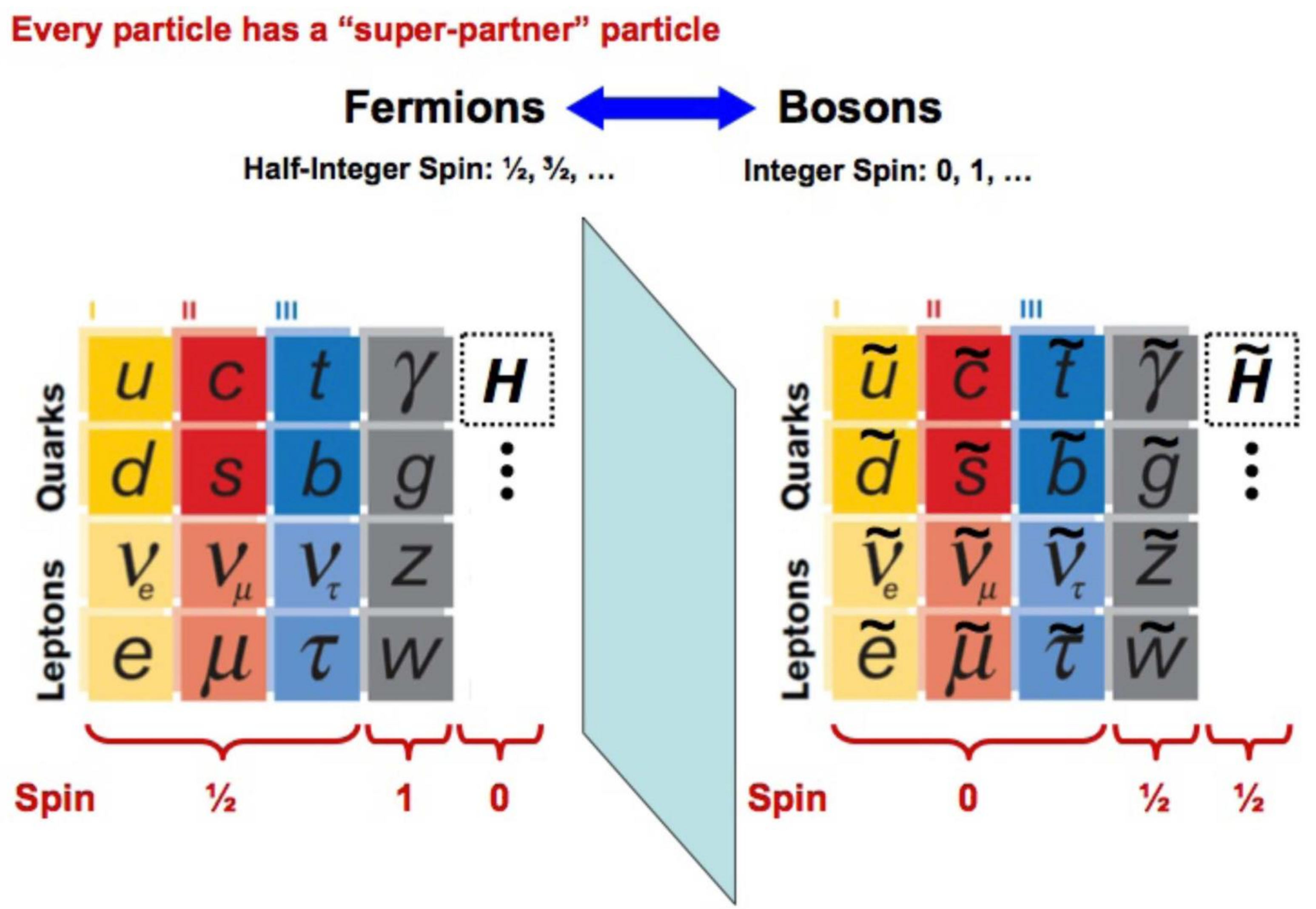


Is the Standard Model all there is?

- 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).
- Need models beyond the Standard Model



Supersymmetry



Every particle has a "super-partner" particle

Fermions ⟷ **Bosons**

Half-Integer Spin: ½, ³⁄₂, …

Integer Spin: 0, 1, …

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 (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:
    - tanβ (as before)
    - m_0 (universal scalar mass, includes Higgs)
    - $m_{½}$(gaugino mass)
    - plus two others

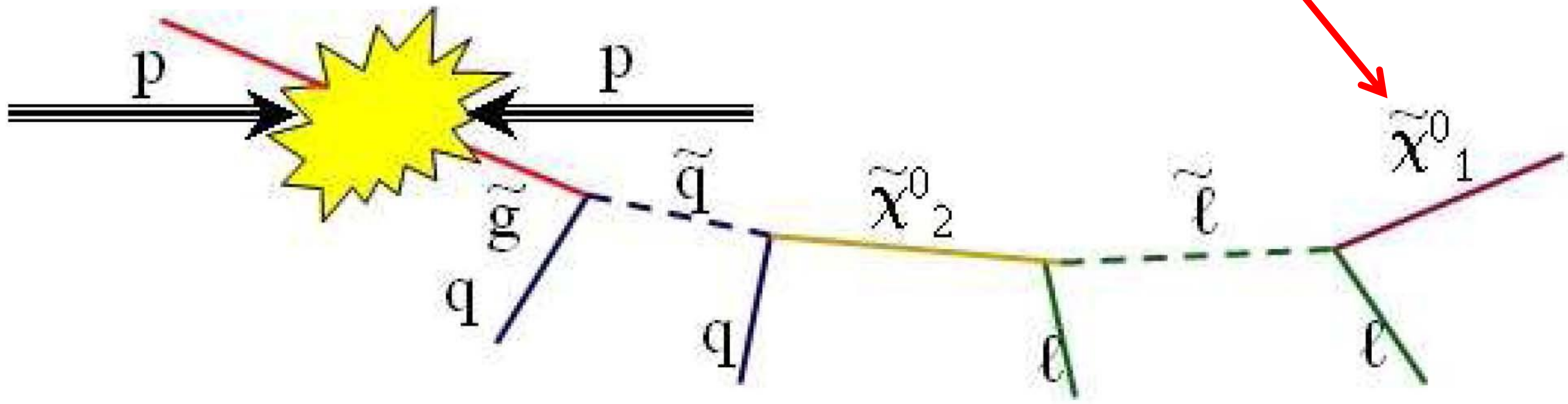
Looking for SUSY Higgs at the LHC

- Small tanβ
  - $gg \to H,A$ production is enhanced due to stronger $t\bar{t}H$ coupling.
  - $H,A \to t\bar{t}$ decay gets enhanced.
- Large tanβ
  - H, A production is enhanced in $b\bar{b}$-fusion
  - $H \to \tau^+\tau^-$ 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)

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
  - But they can not be too massive.
- 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

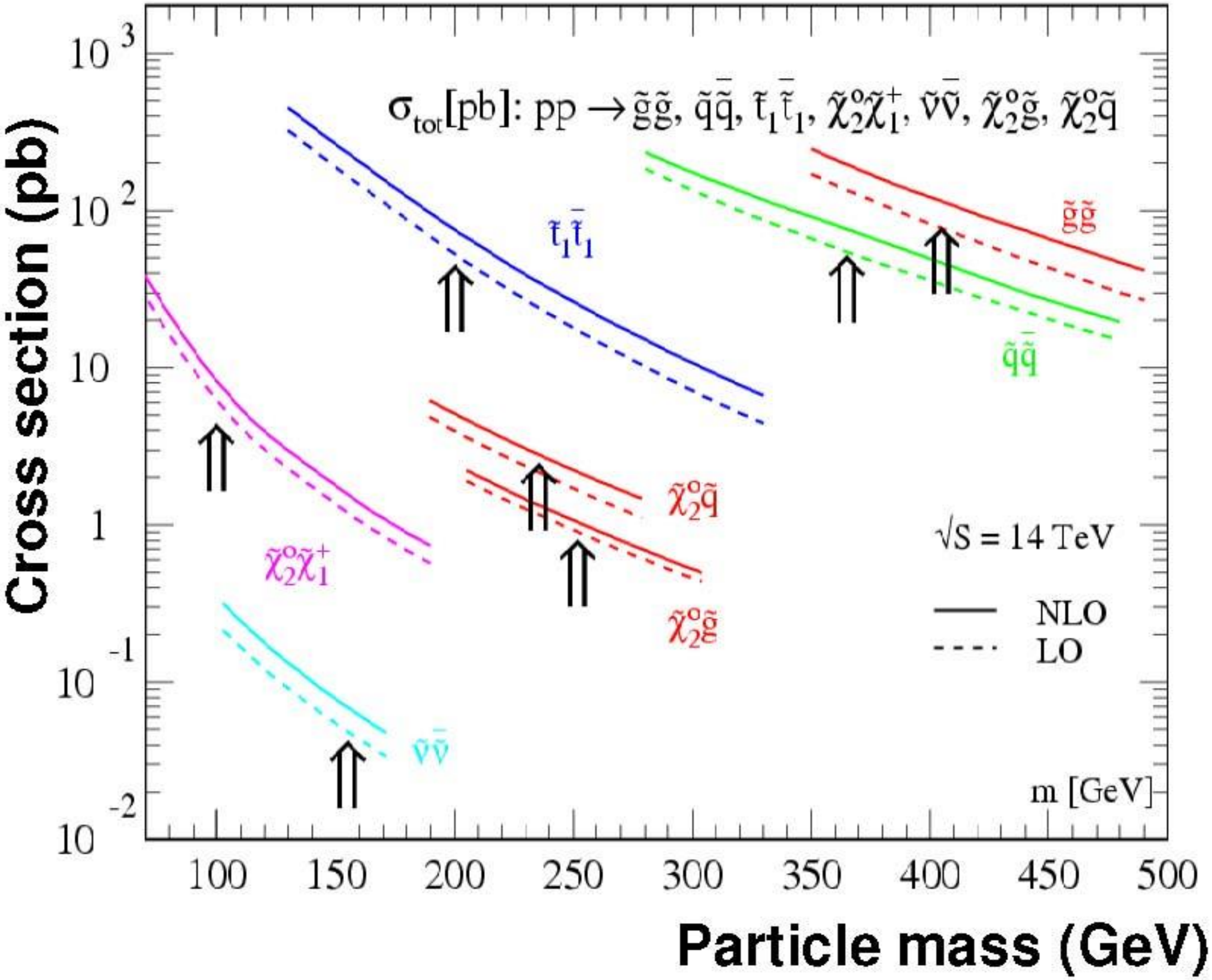
What a SUSY decay looks like



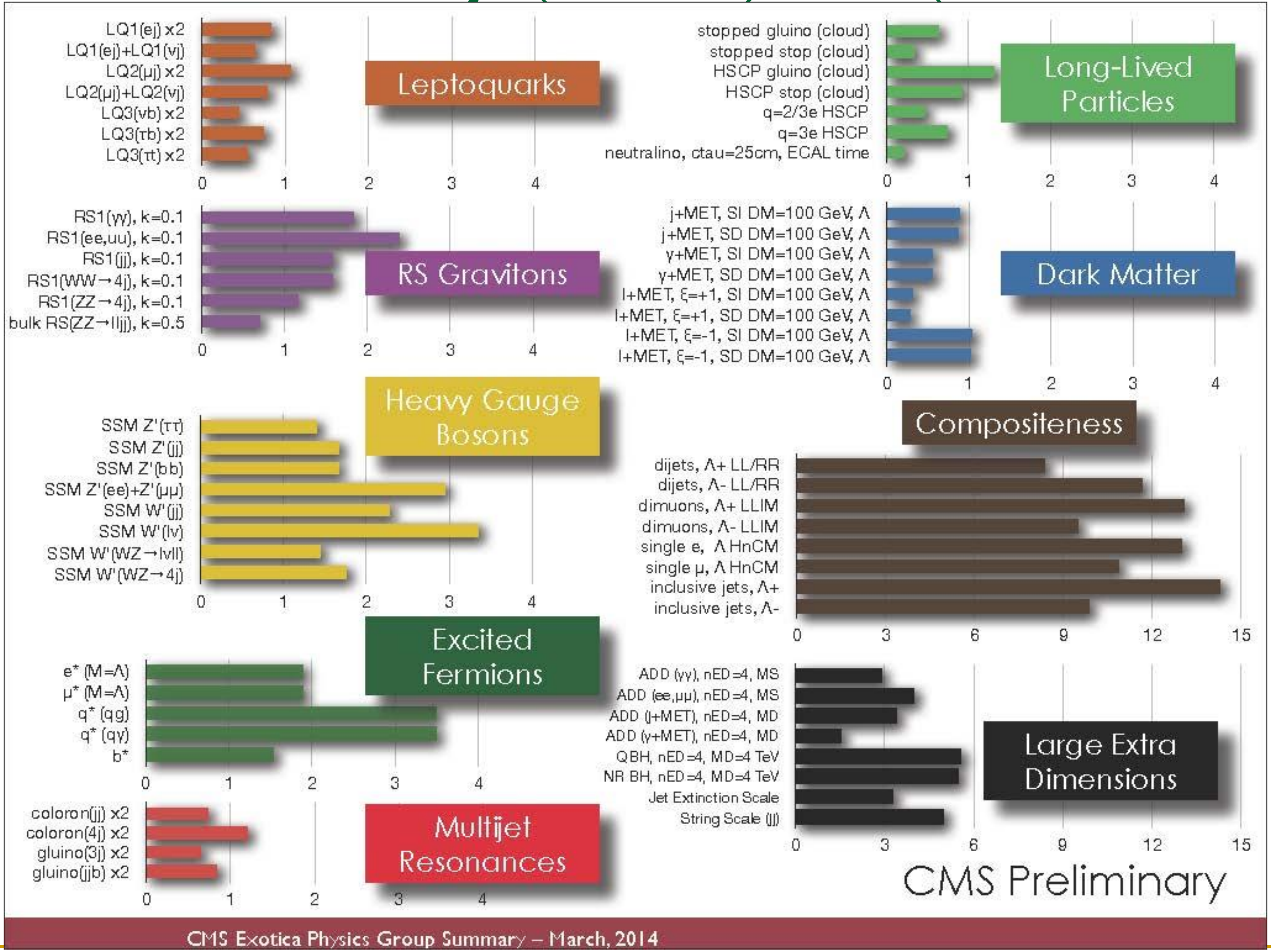
Missing energy

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 2013)



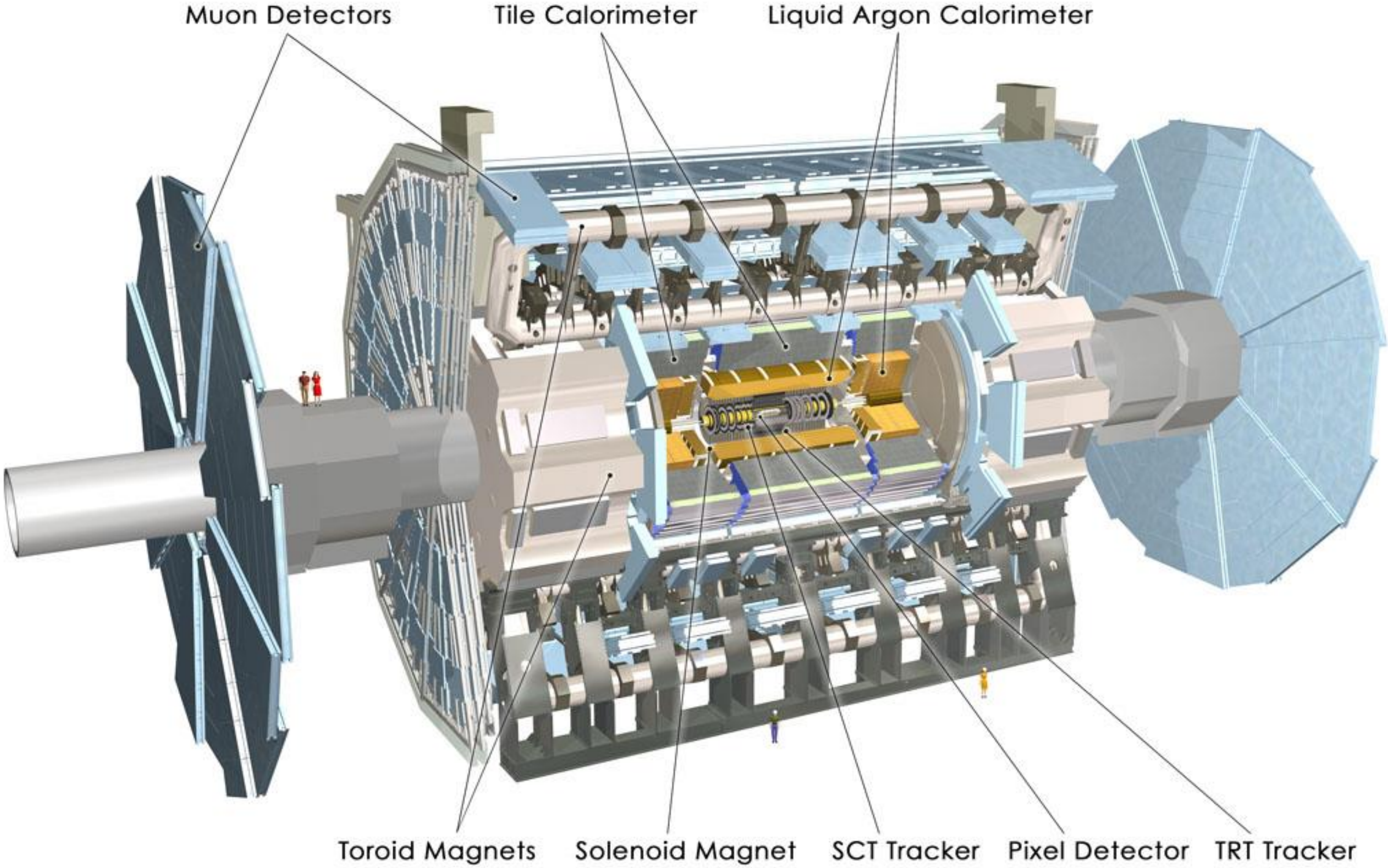
Status of the LHC today

- Higgs
  - Mass ~125 GeV
  - Spin = 0
  - CP probably not -1.
  - Could be a Standard Model Higgs (good).
  - Could be a SUSY Higgs (also good).
  - No sign yet of any other Higgs below ~600 GeV.
- SUSY
  - No particles found below 1 TeV
  - If no SUSY particles found below 1 TeV SUSY models are "wrong" (bad) but theorists always have a back up plan.

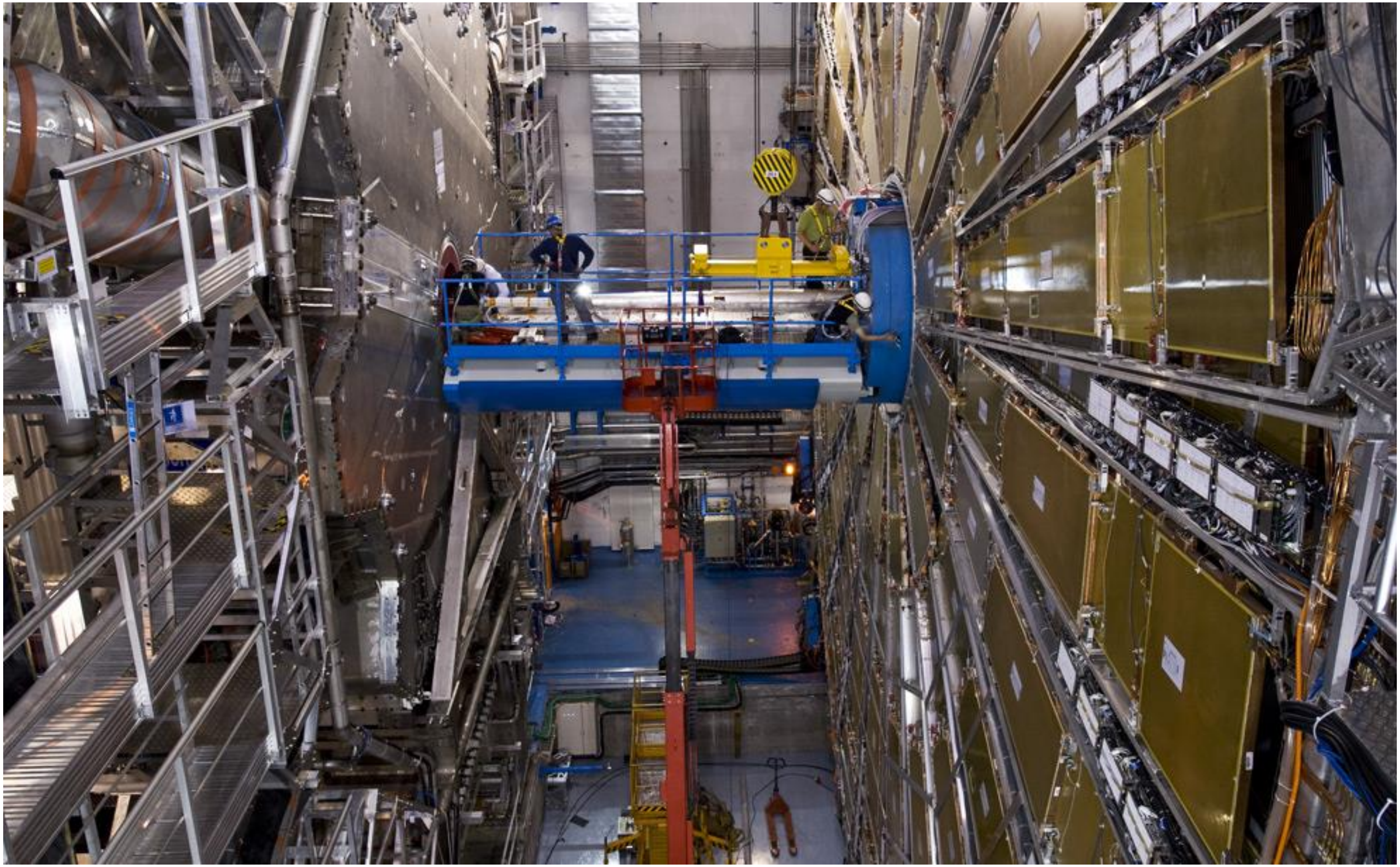
One final thought...

- 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....”

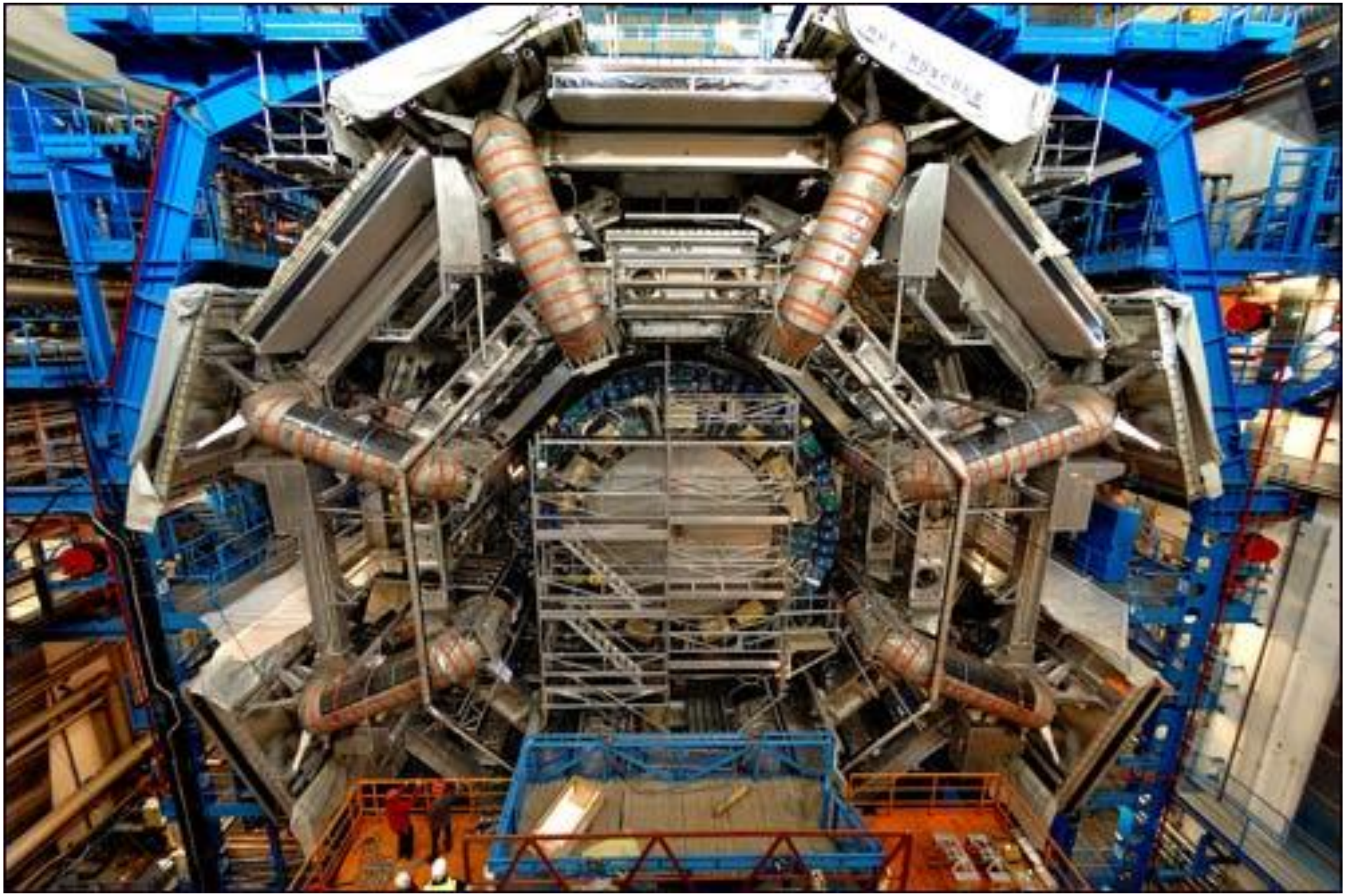
ATLAS detector



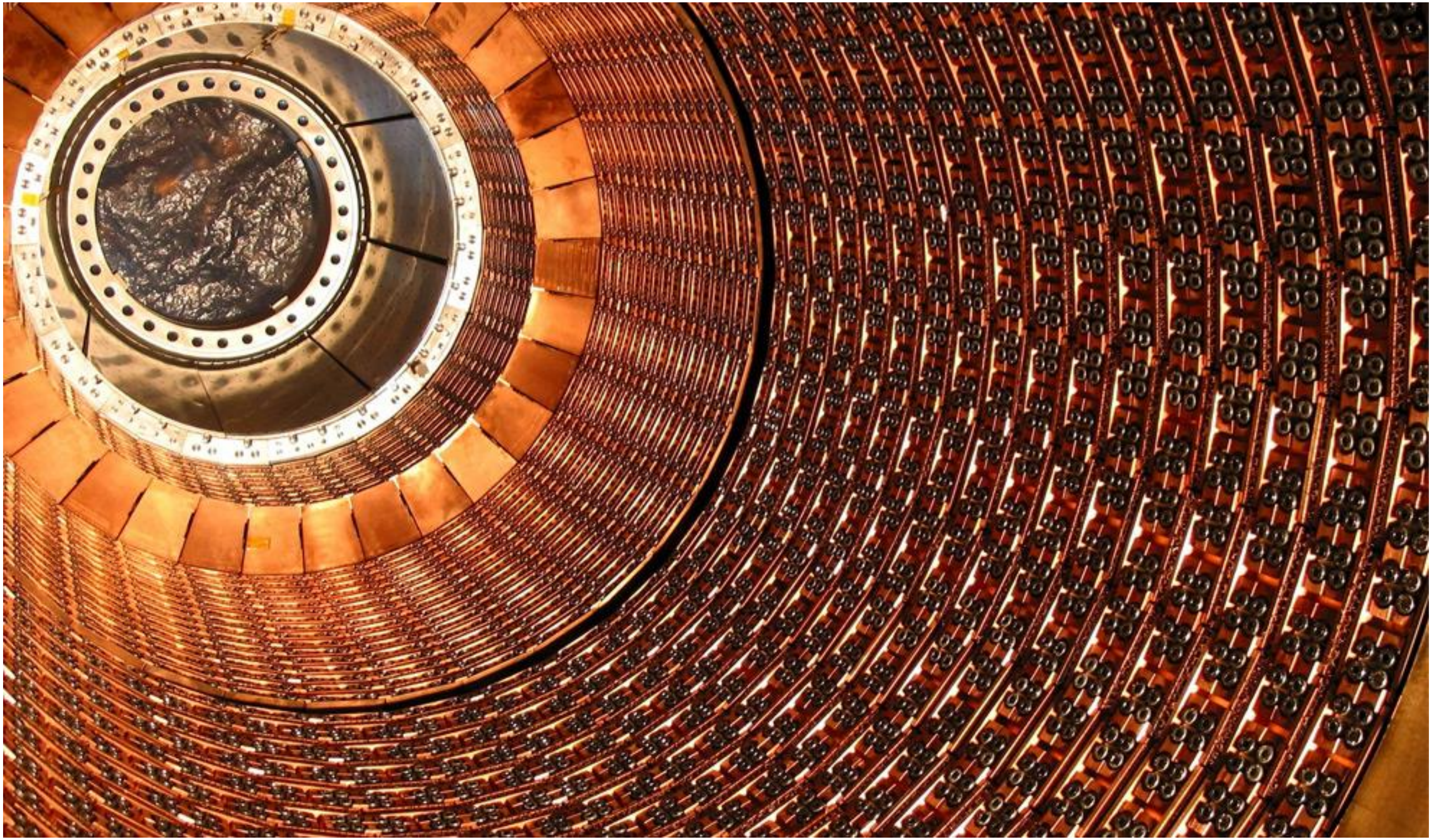
ATLAS beam-pipe



ATLAS construction

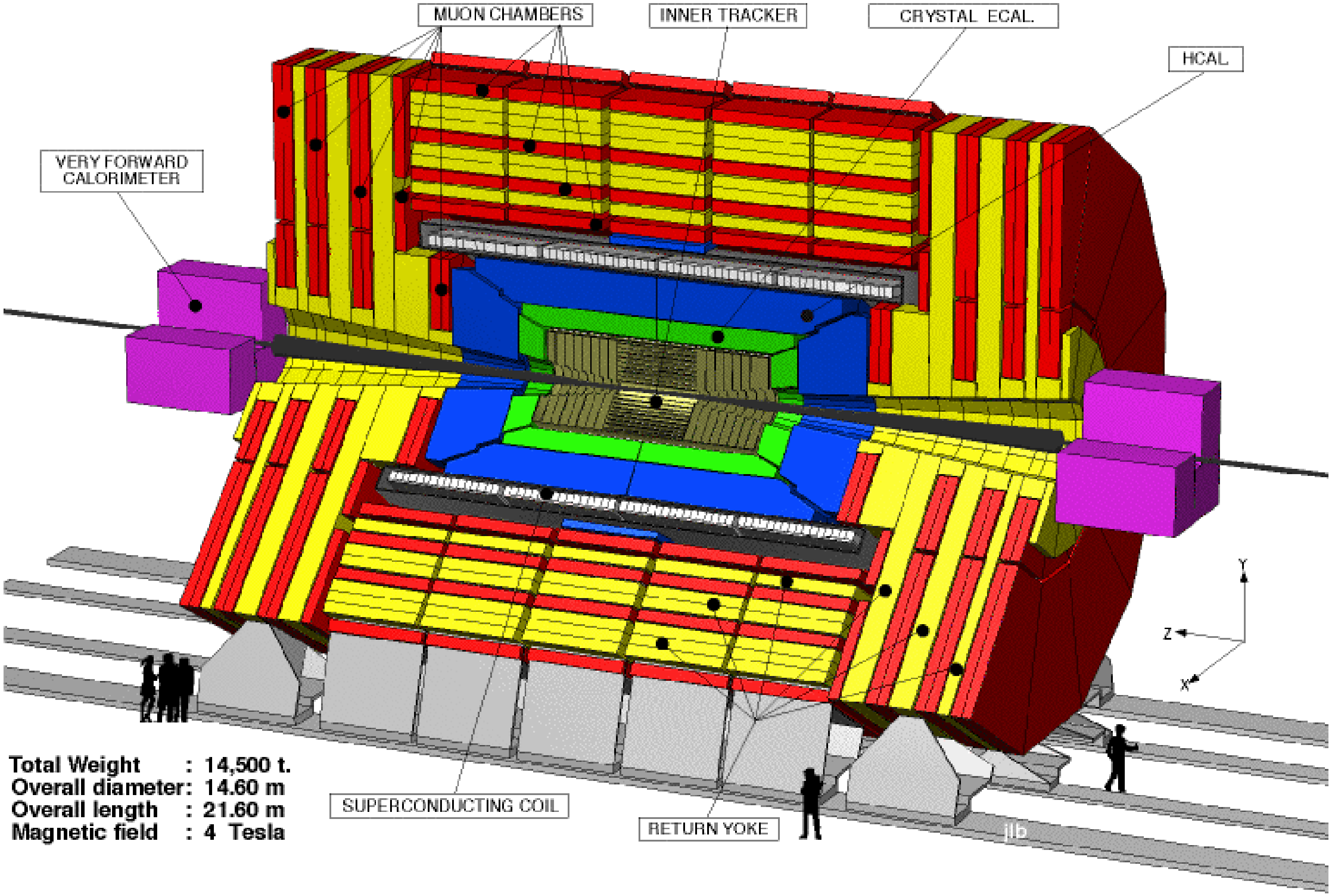


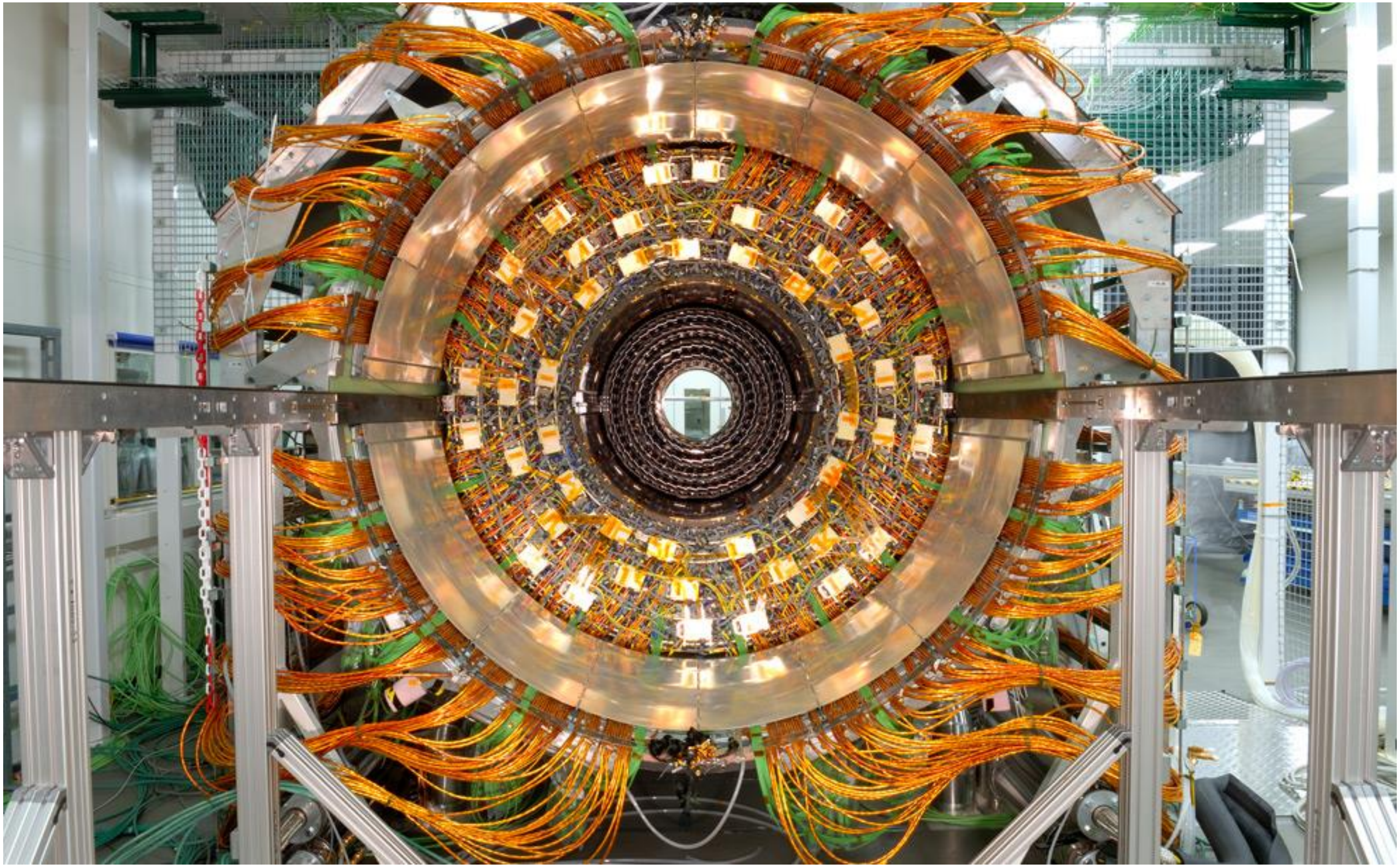
ATLAS Tracker (silicon)



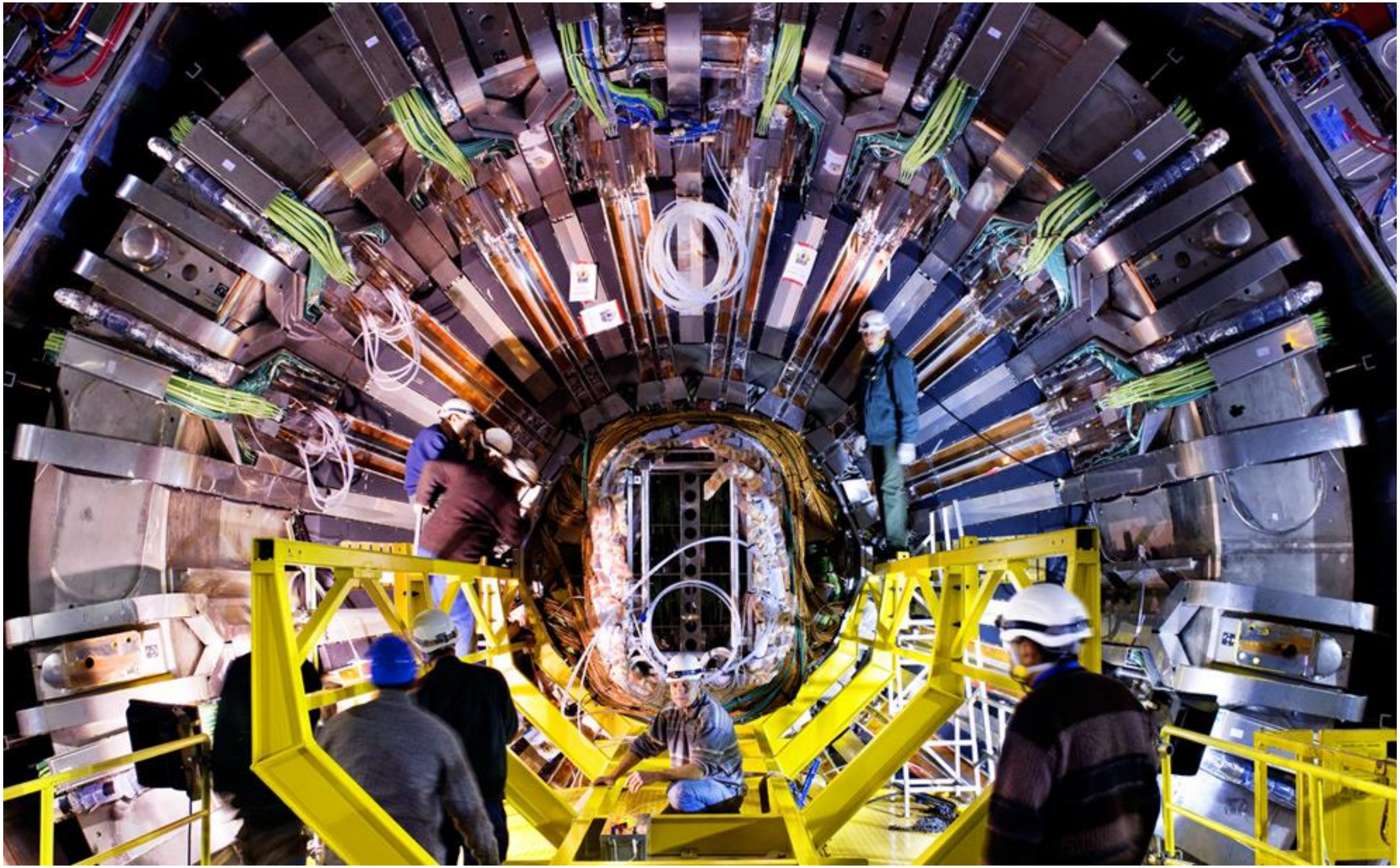
ATLAS toroid magnet

CMS detector

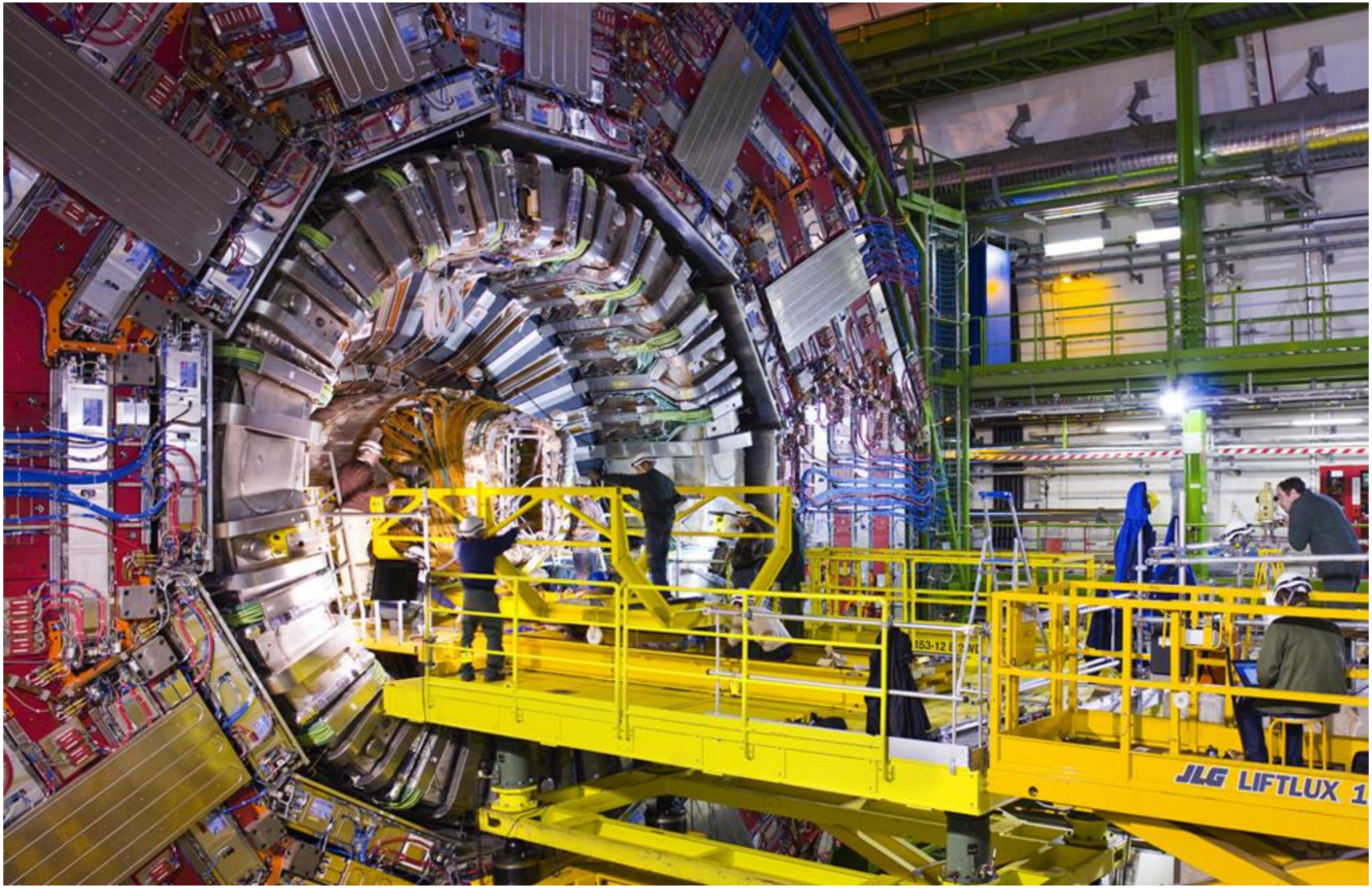




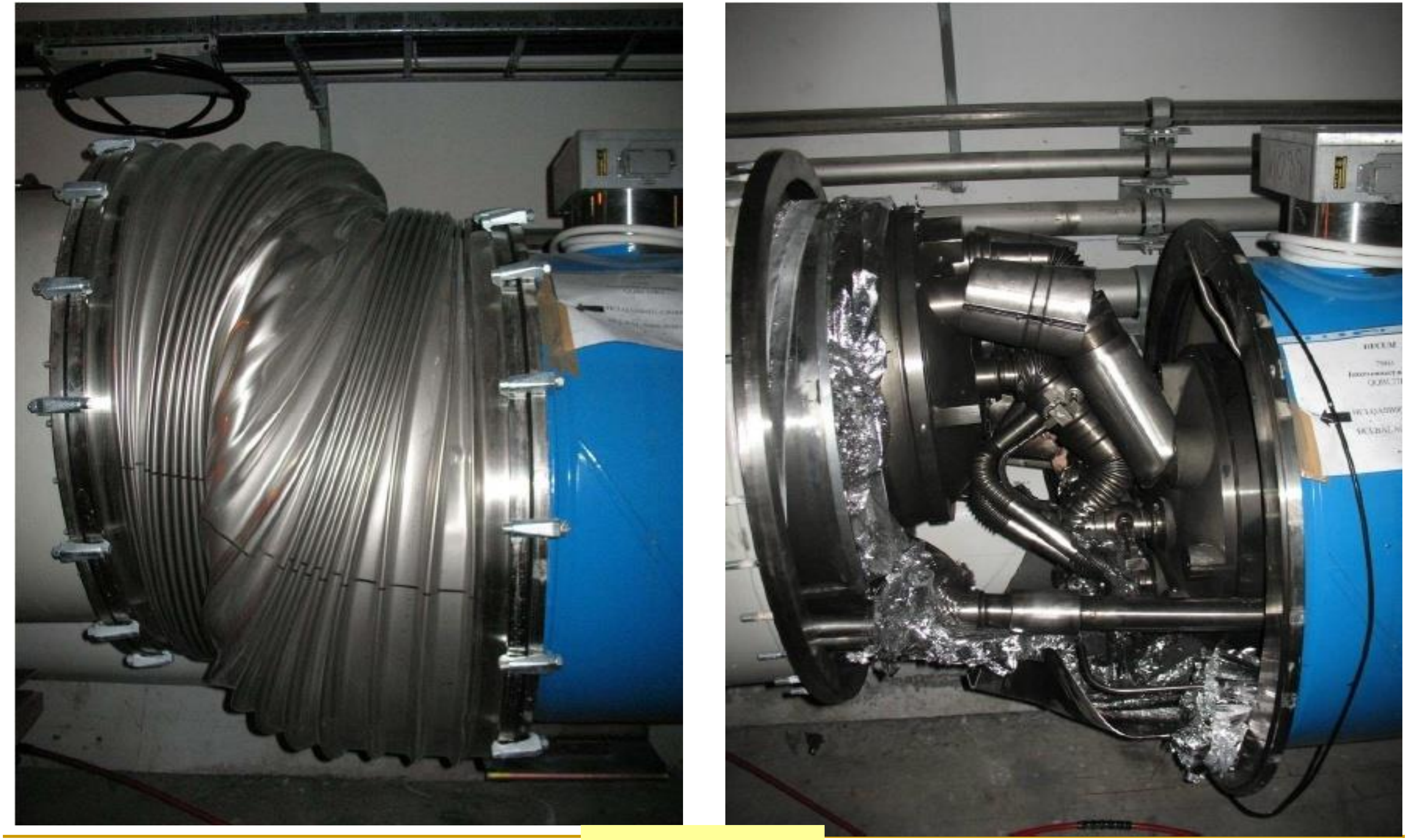
Inserting CMS tracker



Inserting CMS tracker



Damaged magnets 2009



QQBI.27R3