Hunting the Higgs (and Other Animals) at the CERN LHC

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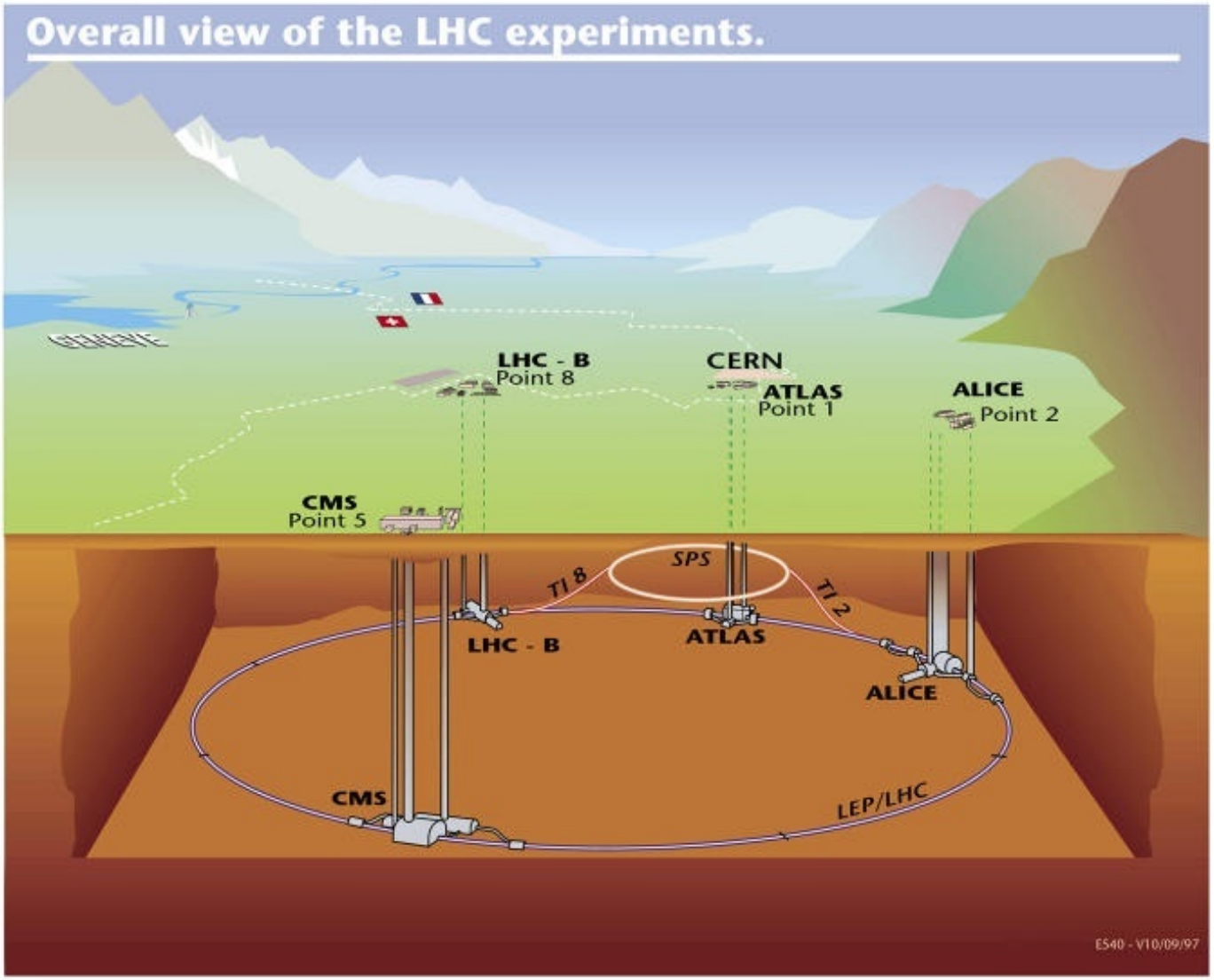
Outline

- Status of the LHC and the ATLAS experiment
- Search for the Standard Model Higgs boson
- Search for Beyond the Standard Model particles decaying into top quark pairs

LHC (Large Hadron Collider)

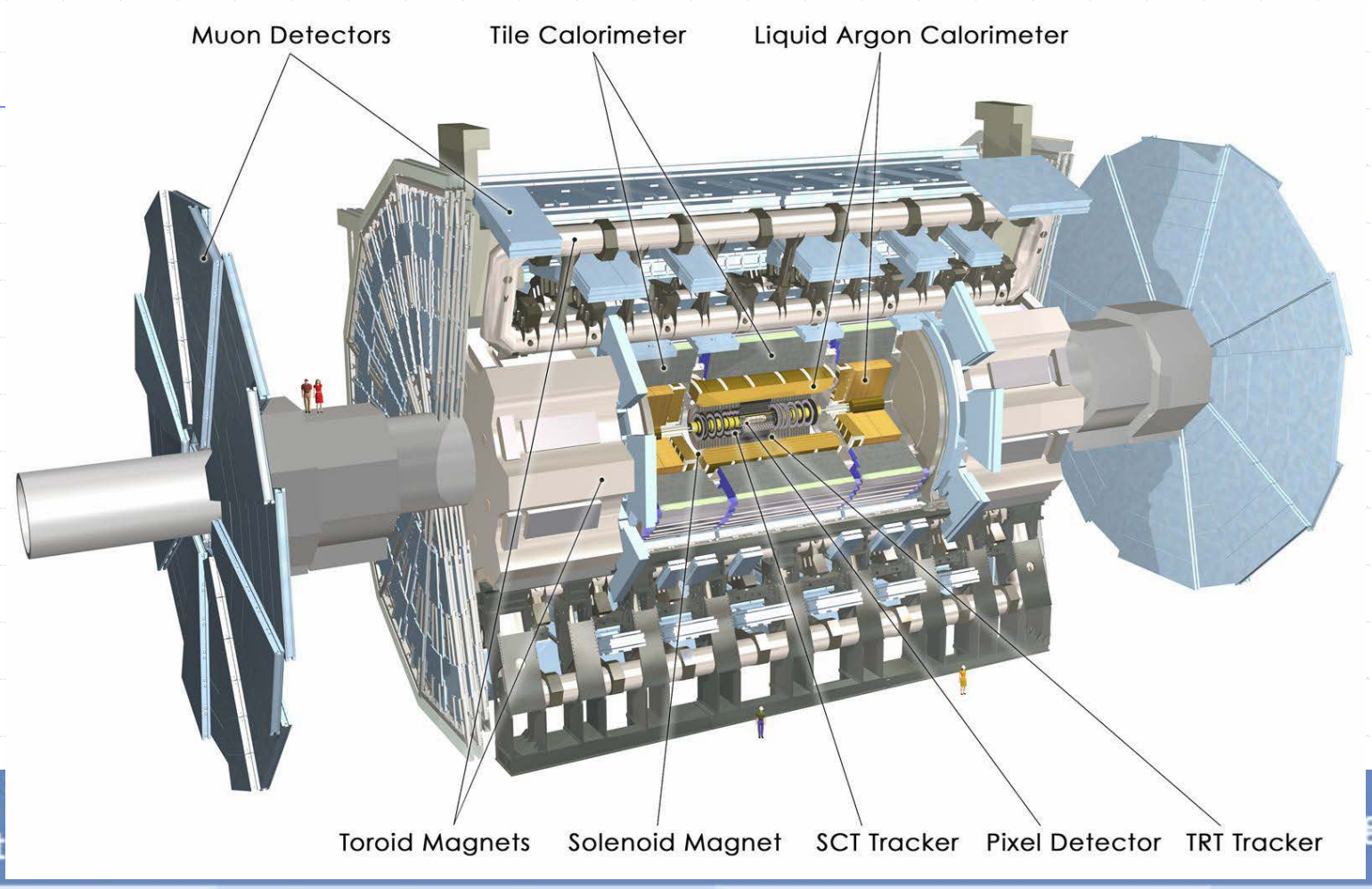
- CERN is located outside Geneva, Switzerland
- The ring circumference is 27 km
- The energy of the LHC is now 7 TeV = 3.5 TeV + 3.5 TeV

LHC (Large Hadron Collider)



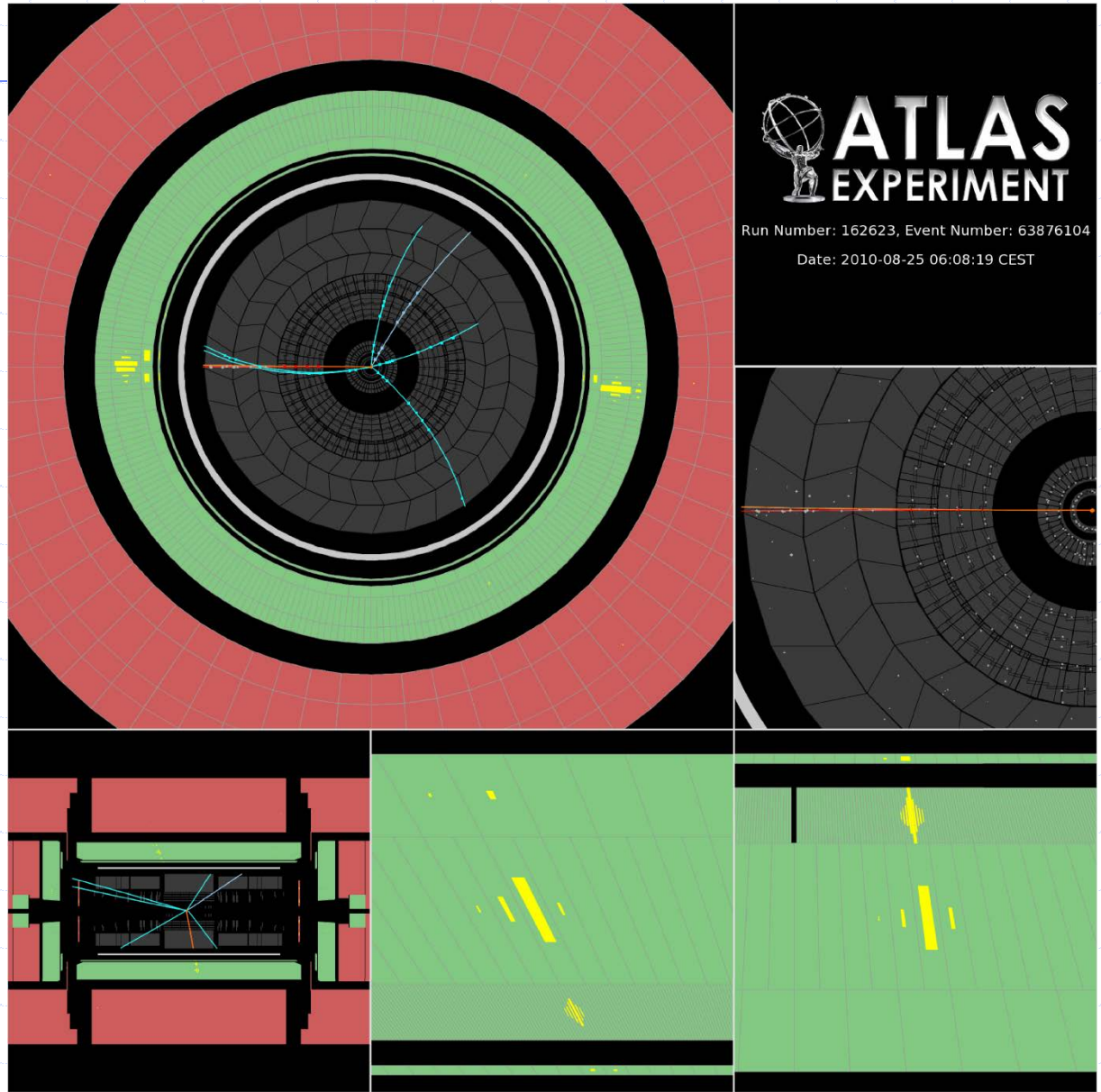
The experiments (detectors) are located 100m underground

ATLAS Detector



Inner Det											gnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.5	100	89.3	92.7	94.3	99.5	100	99.5	100	99.9	98.5	97.9

ATLAS Particle ID



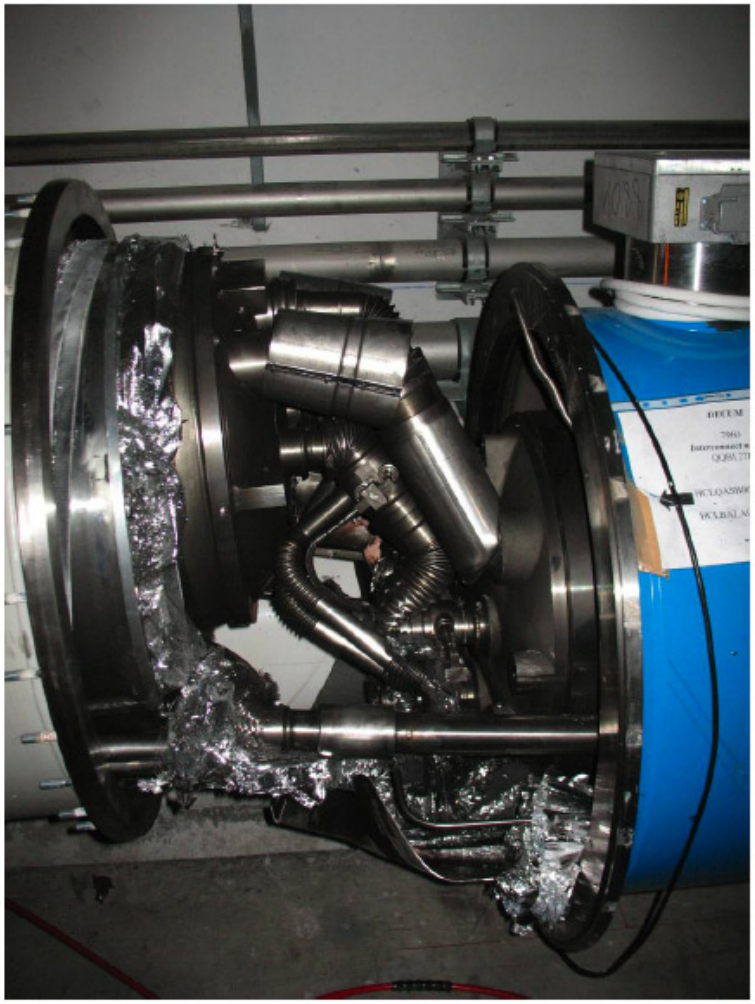
ATLAS CSC (Electronics) by UA

First Beam in the LHC

- September 10, 2008 in the ATLAS control room

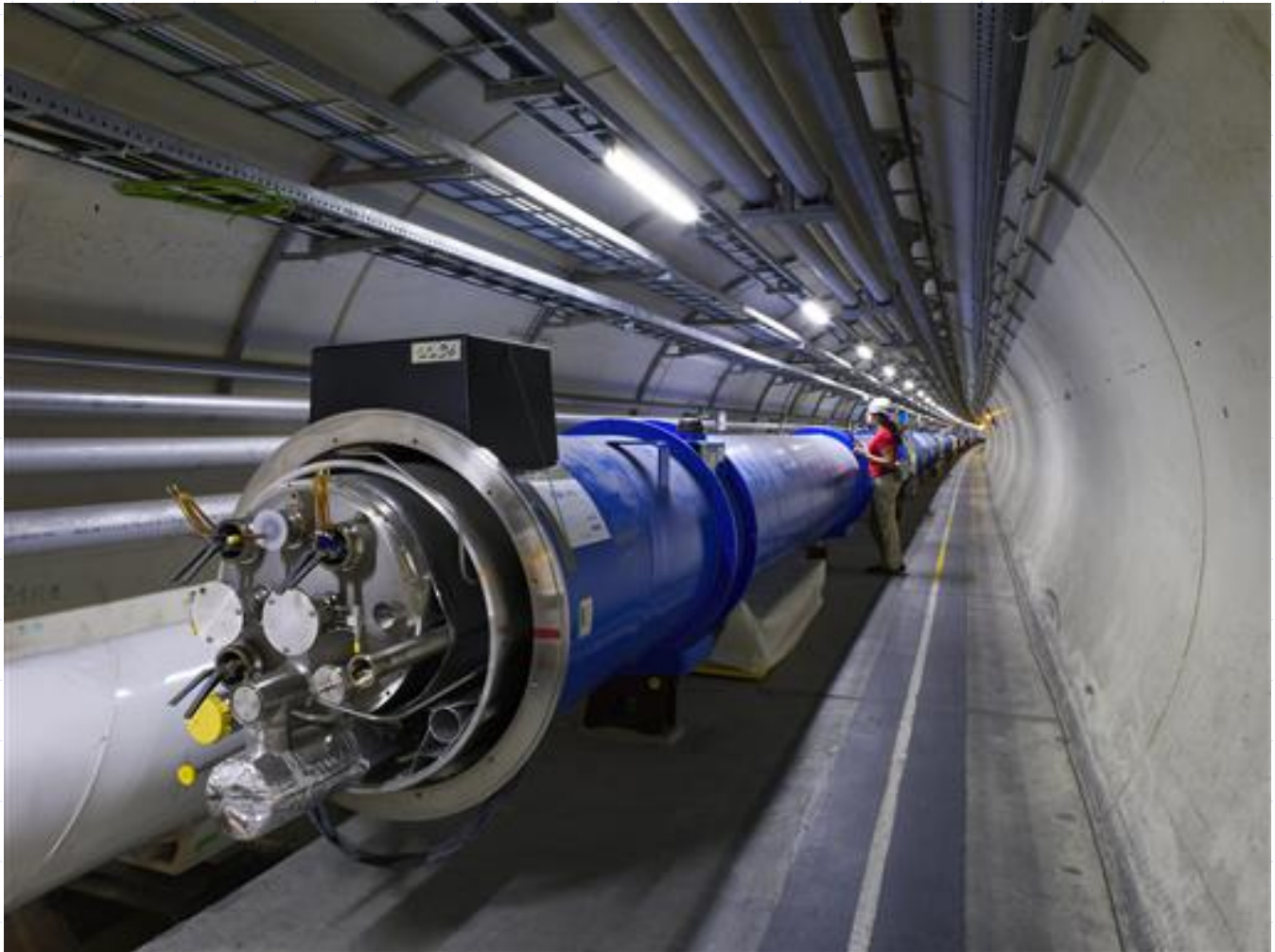
First Malfunction at the LHC

- September 19, 2008 in the LHC tunnel



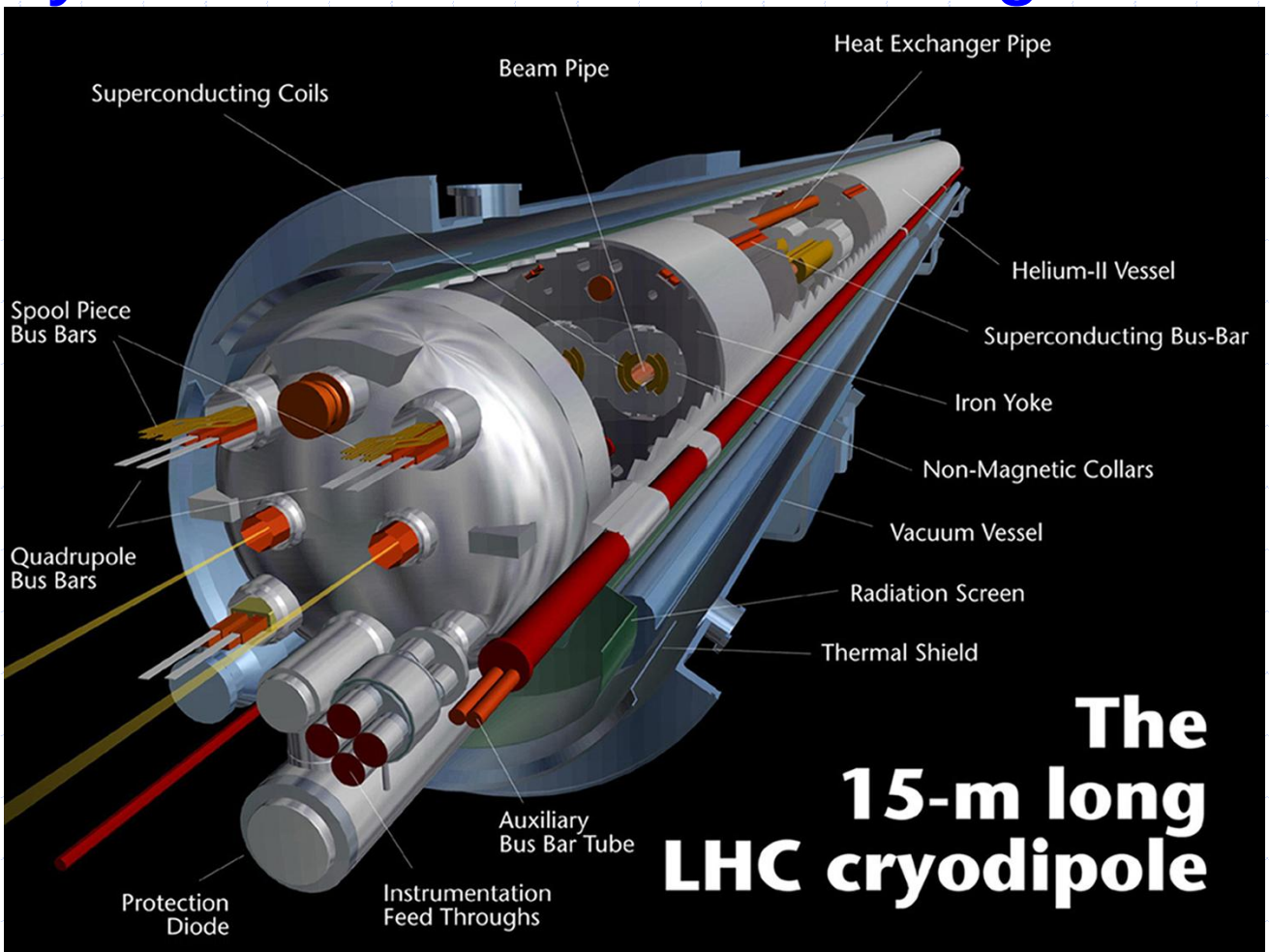
LHC Dipole Magnets

- Bending is provided by 1232 15-m dipoles @ 8.33 T



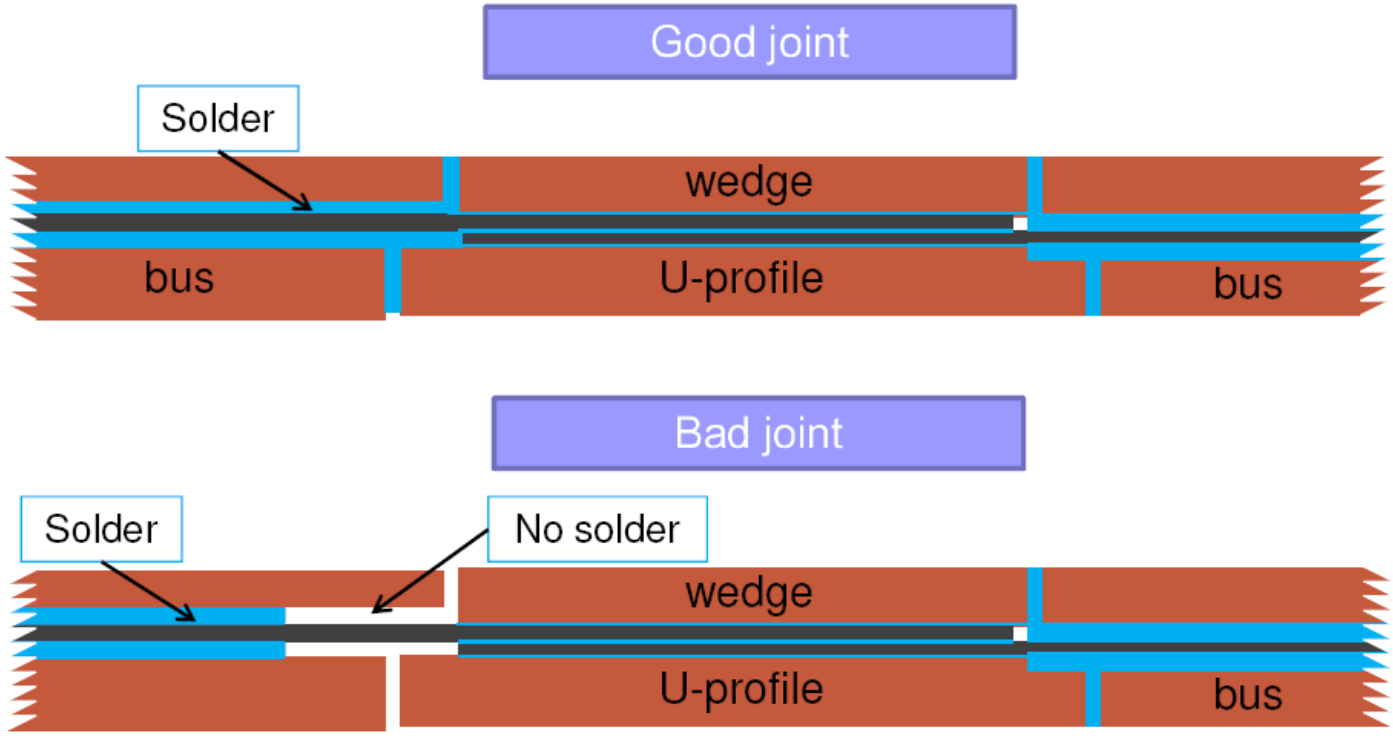
LHC Dipole Magnets

- Busbar interconnections are used to carry the current between magnets



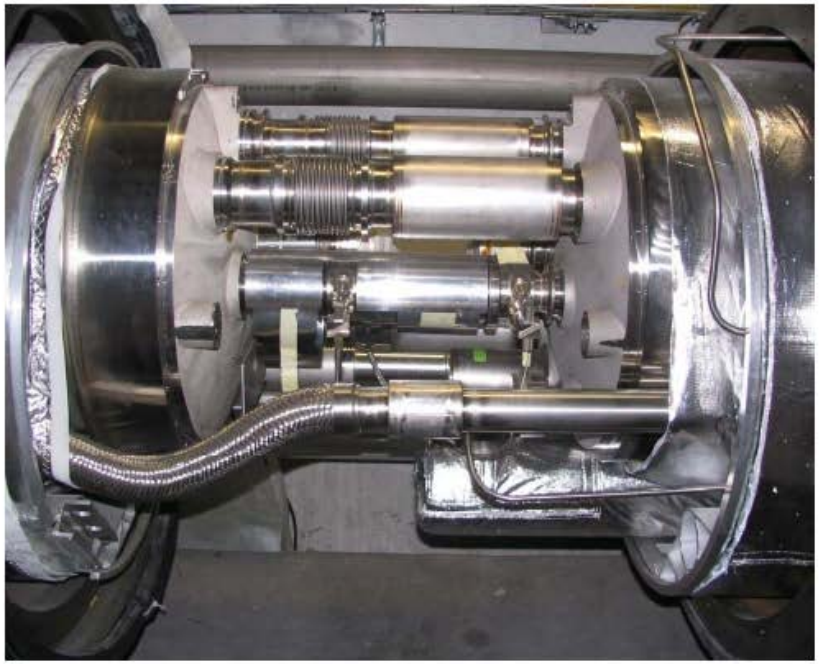
LHC Dipole Busbars

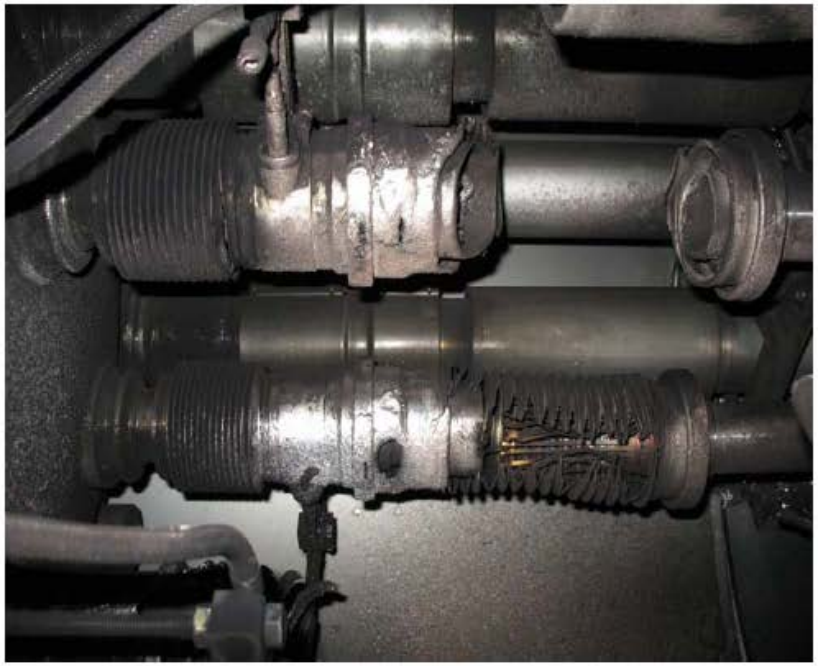
- The copper busbar must take the current during the current decay after a quench



September 2008 Incident

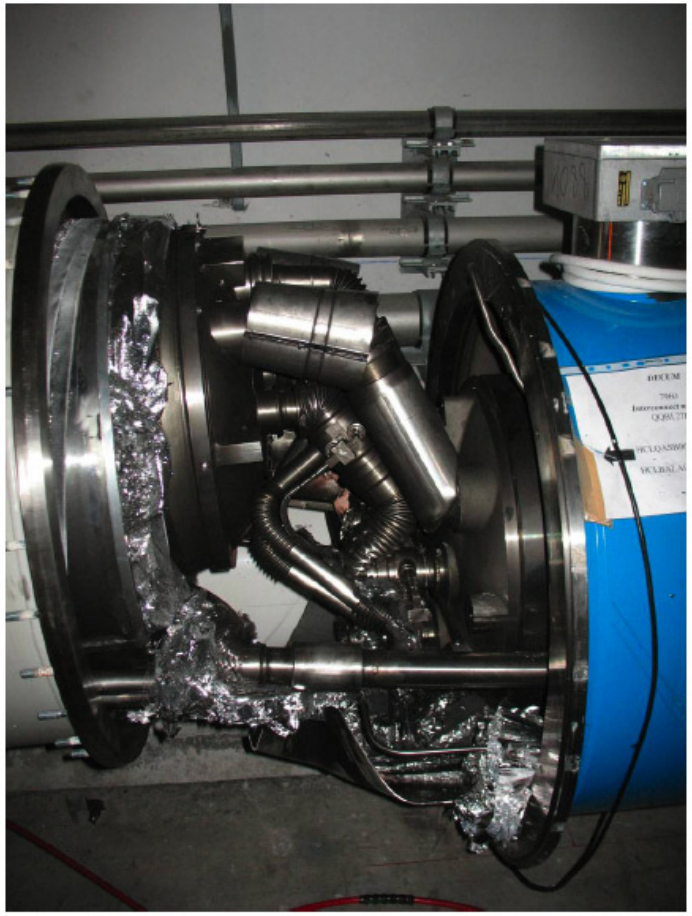
- The electrical arc destroyed the busbars





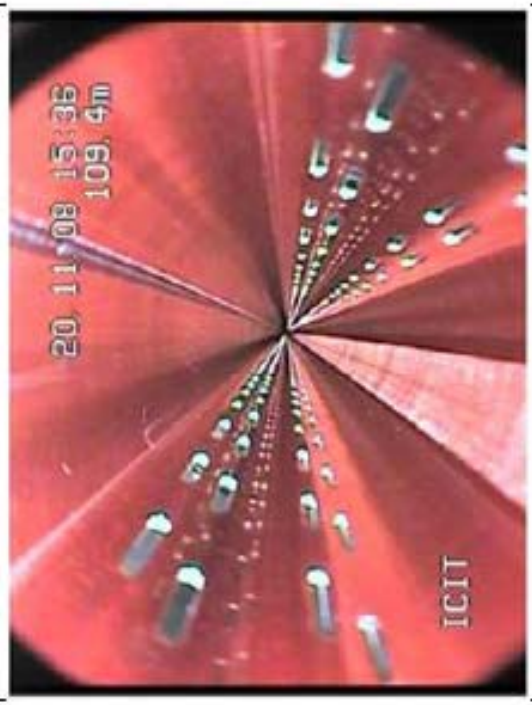
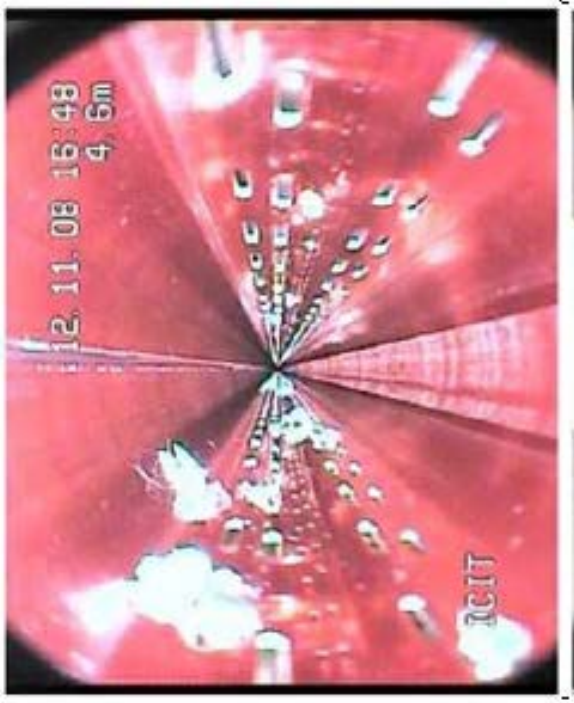
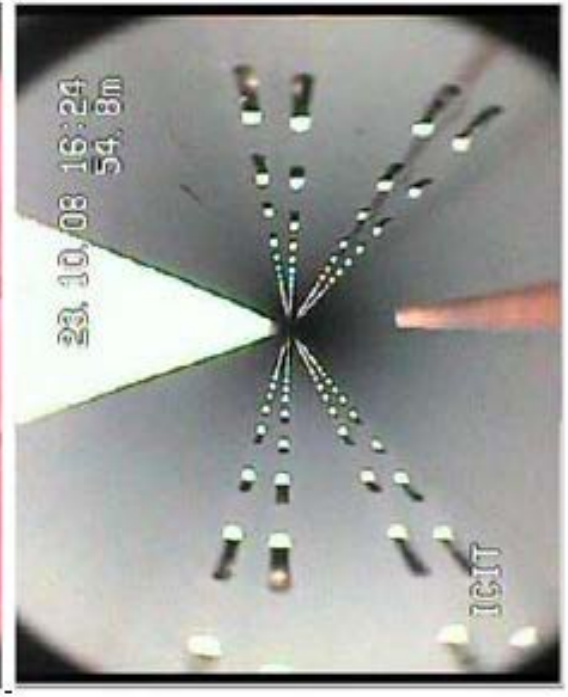
September 2008 Incident

- The large pressure forces from He entering the cryo vacuum resulted in magnet displacements



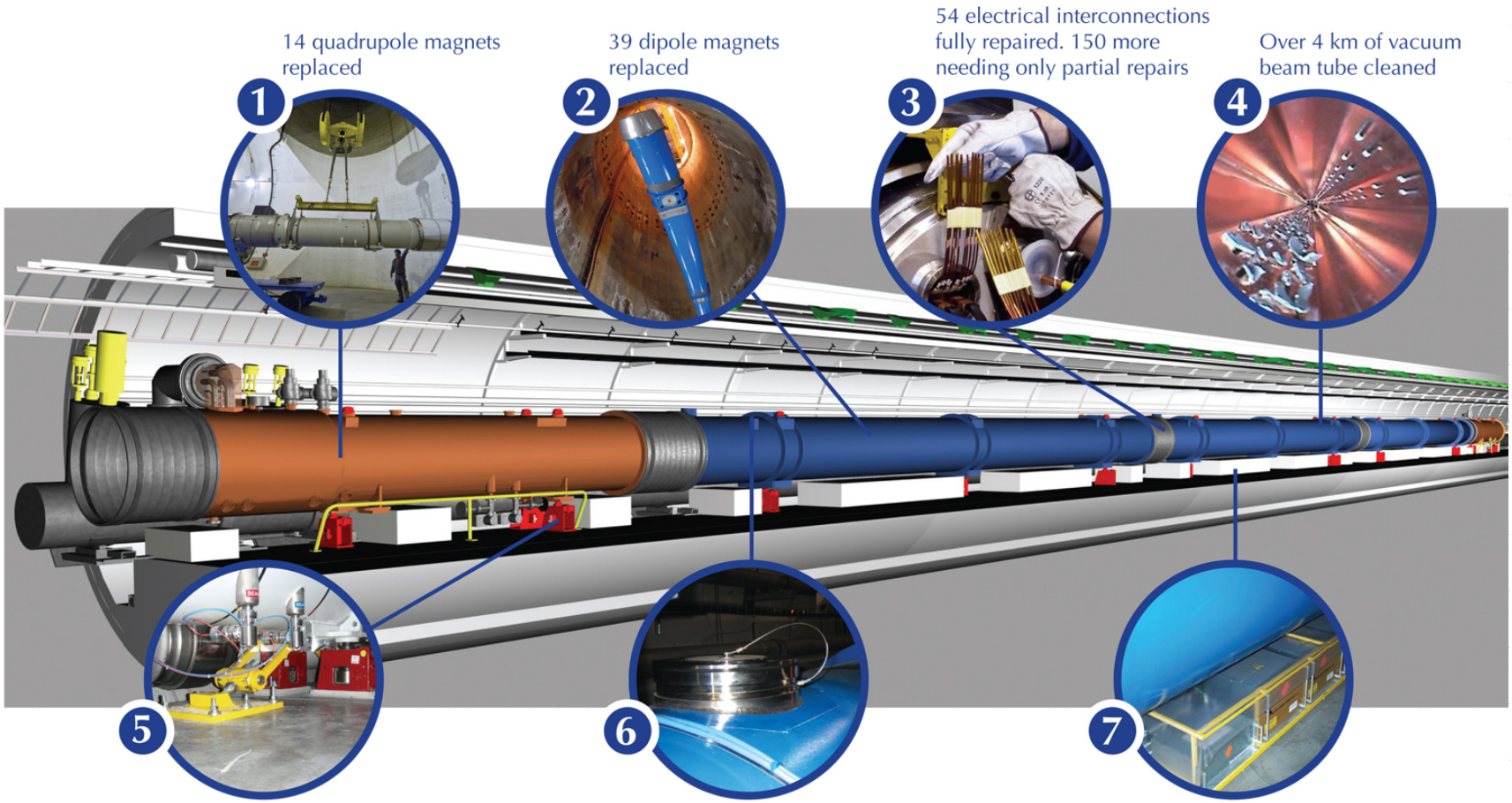
September 2008 Incident

- Beam vacuum contamination

Beam Screen (BS) : The red color is characteristic of a clean copper surface	BS with some contamination by super-isolation (MLI multi layer insulation)	BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.
		

LHC Repairs

The LHC repairs in detail



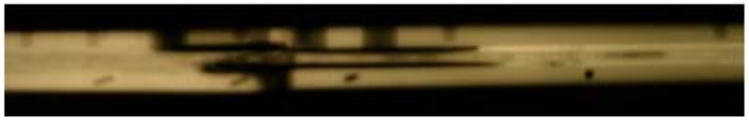
A new longitudinal restraining system is being fitted to 50 quadrupole magnets

Nearly 900 new helium pressure release ports are being installed around the machine

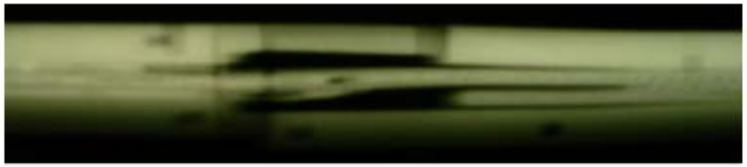
6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid

LHC Dipole Busbars

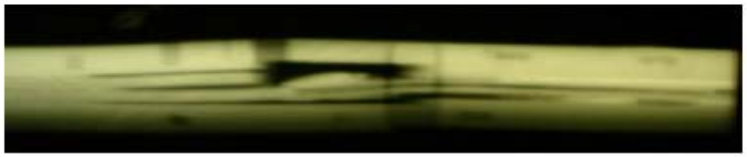
- In the LHC there are
  - 3372 RB interconnect splices
  - 6744 RQ interconnect splices



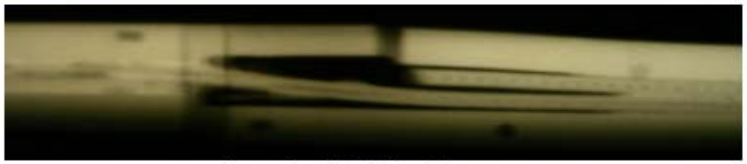
Sample 1 (61 μΩ)



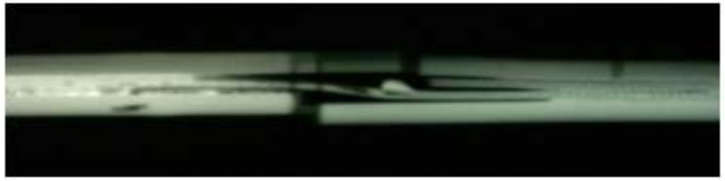
Sample 2A left (32 μΩ)



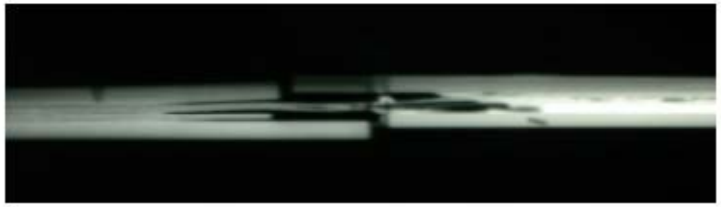
Sample 2A right (43 μΩ)



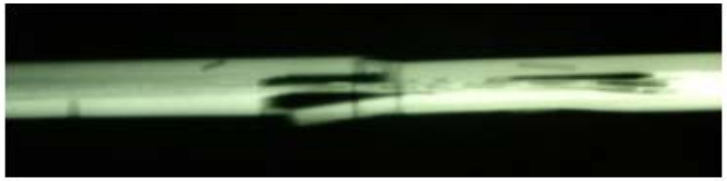
Sample 2B (42 μΩ)



Sample 3A left (26 μΩ)



Sample 3A right (43 μΩ)



Sample 3B (21 μΩ)

Pictures by J.-M. Dalin

LHC Operating Energy

- Of the 10000 such splices in the LHC, some less than perfect splices remain
  - Cannot run at 14 TeV without replacing all splices by new clamped, shunted ones
    - Ditto even for 8 TeV; it's just too risky
  - Present plan is to run through 2012 at 7 TeV
  - Then take the LHC down for one-two years in 2013 to install shunts, repair bad joints, and do accelerator upgrade work such as commission linac4 injector to PS

7 TeV versus 14 TeV

- Must run longer with more limited mass reach to exclude or discover new particles

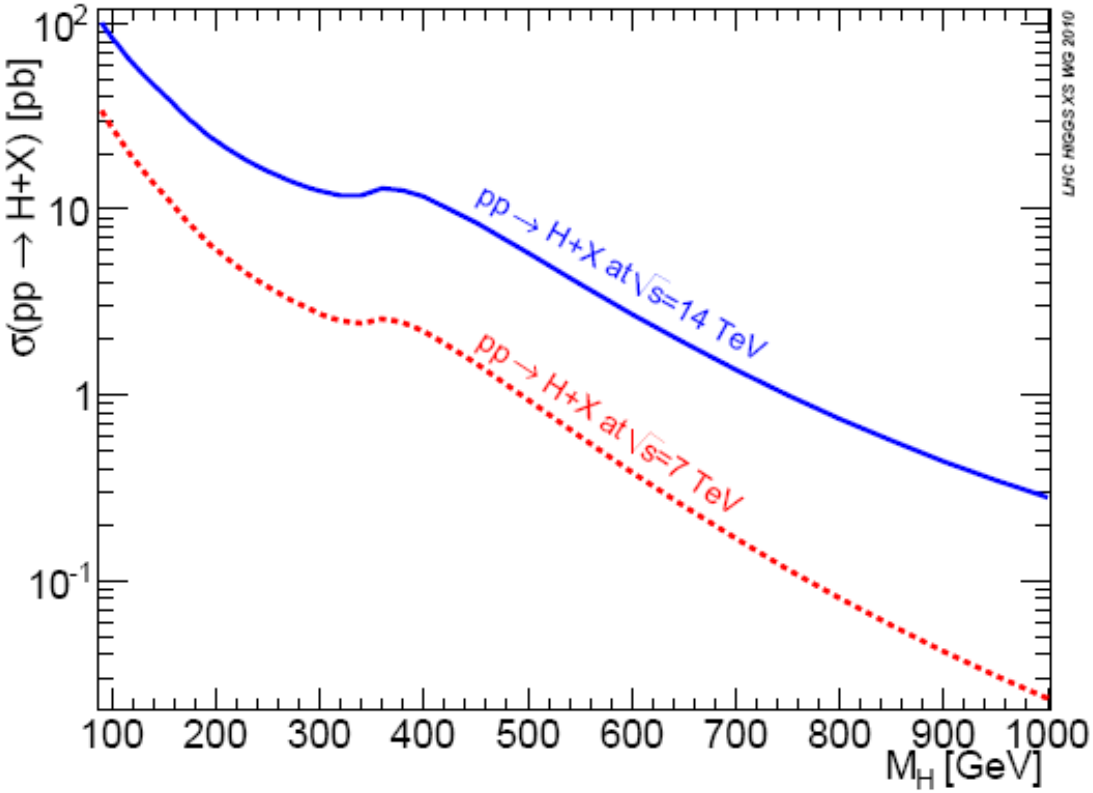
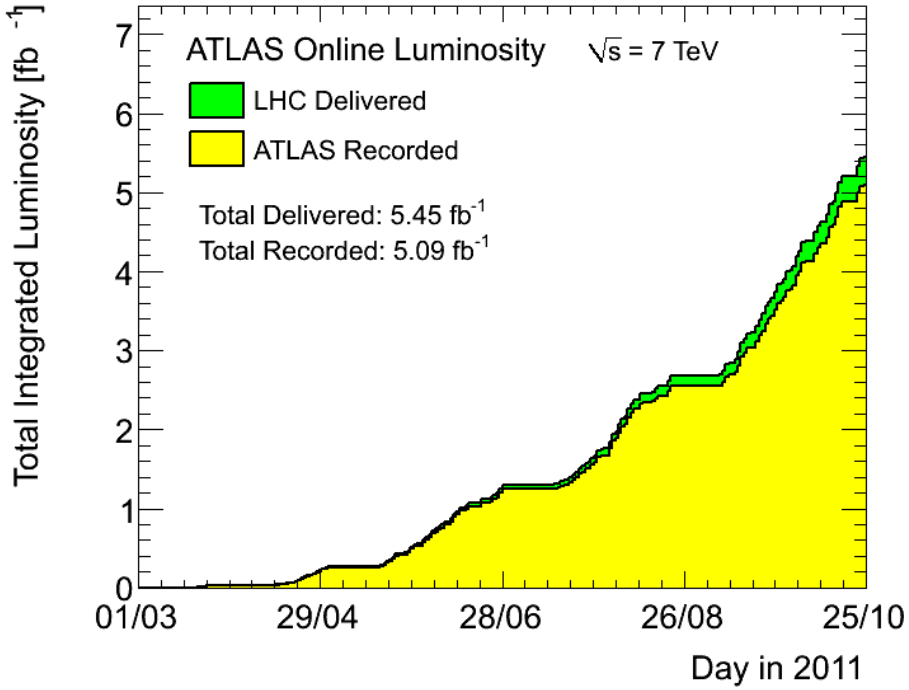
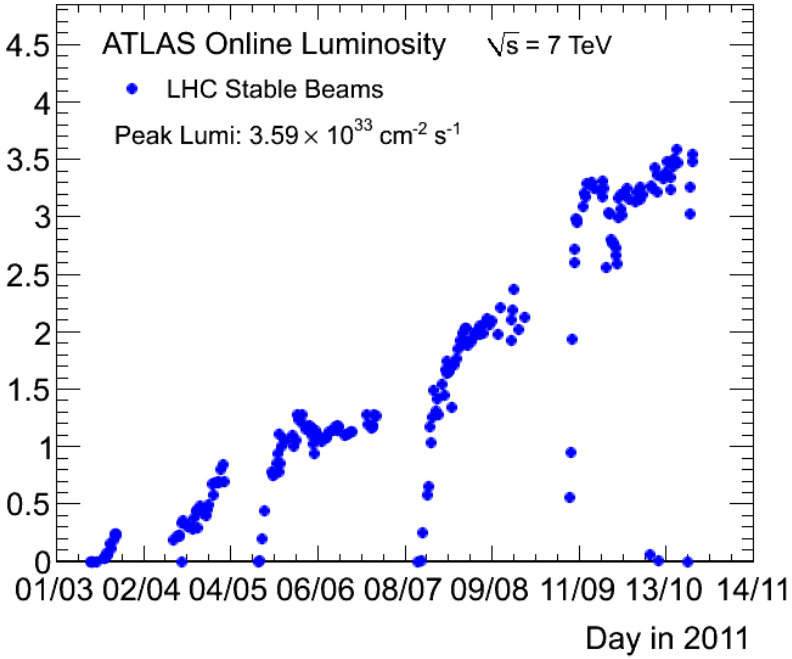


Fig. 40: The total SM Higgs production cross section at $\sqrt{s} = 7$ and 14 TeV.

LHC and ATLAS 2011 Running

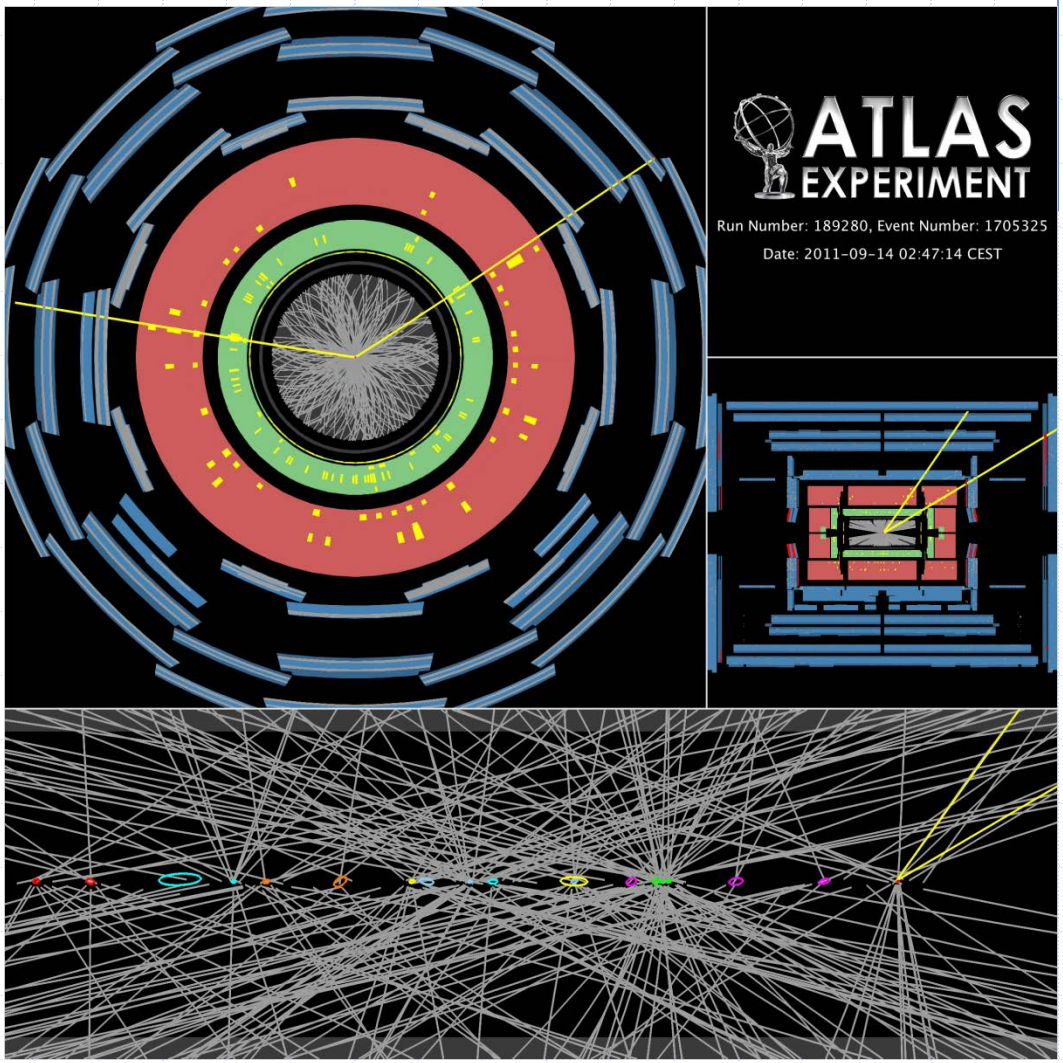
- Fantastic! x5 what we hoped for in 2011



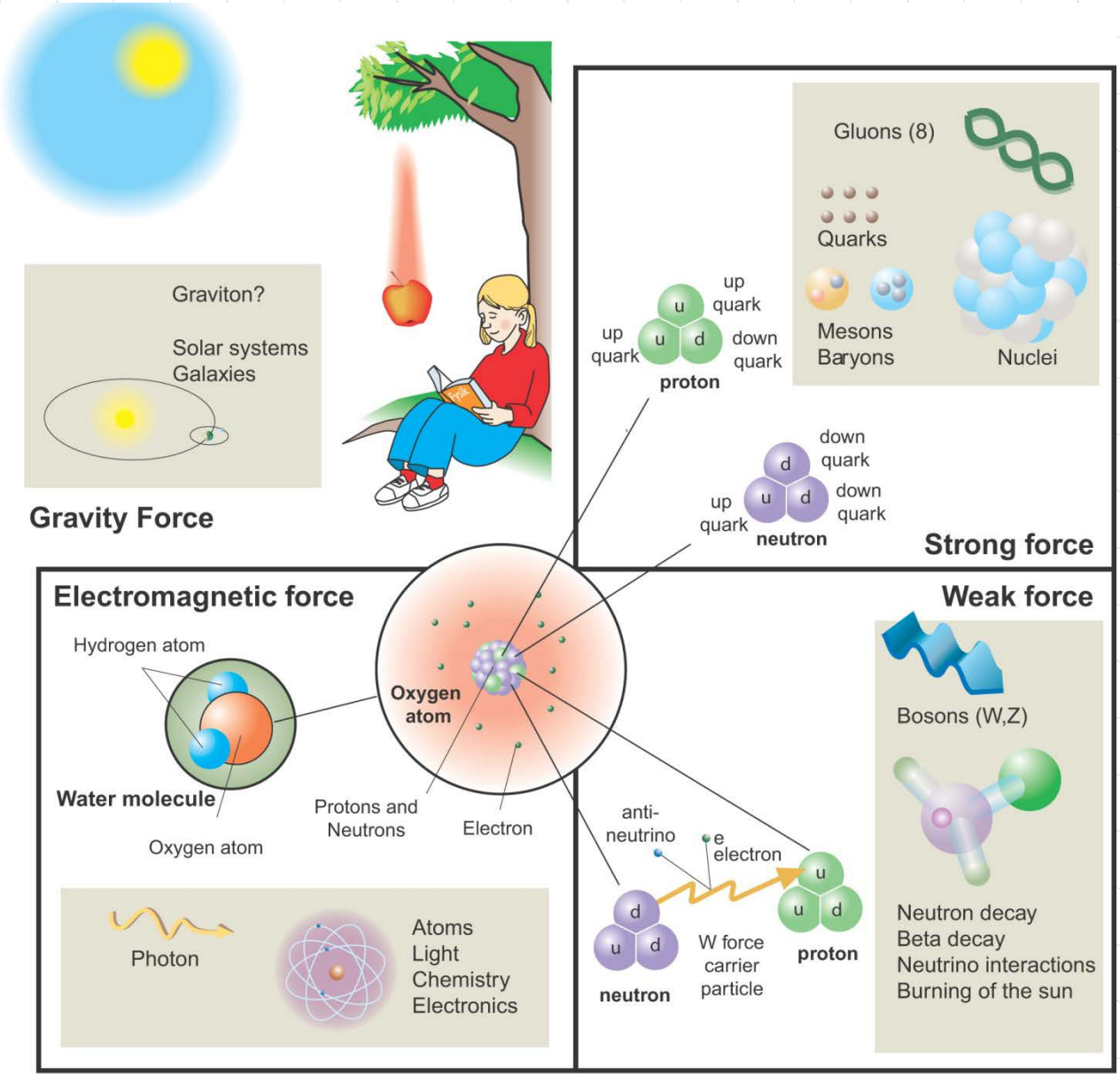


Pileup Problems?

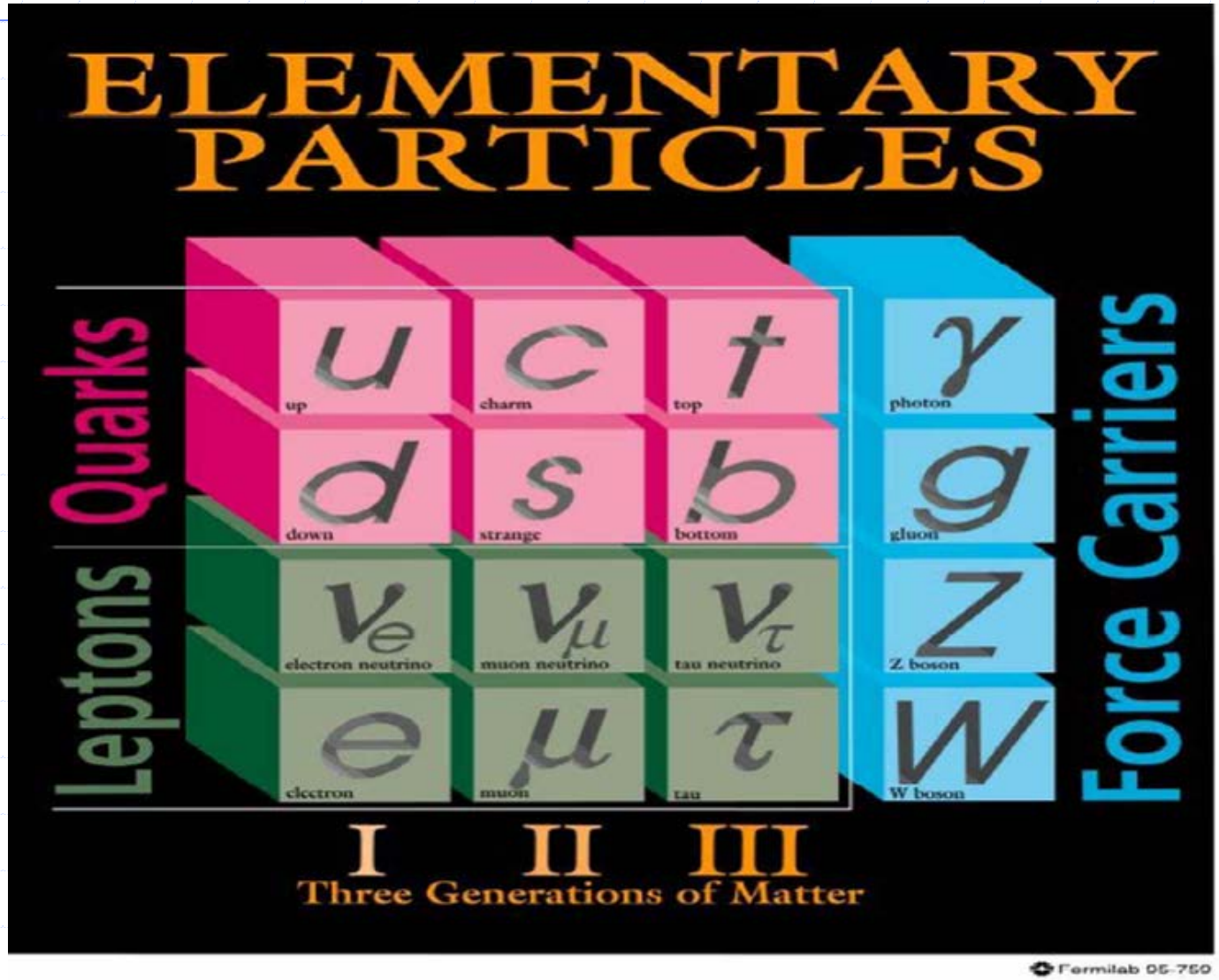
- Running with 50 ns bunch spacing gives an average of 6 pp interactions per crossing



Fundamental Forces

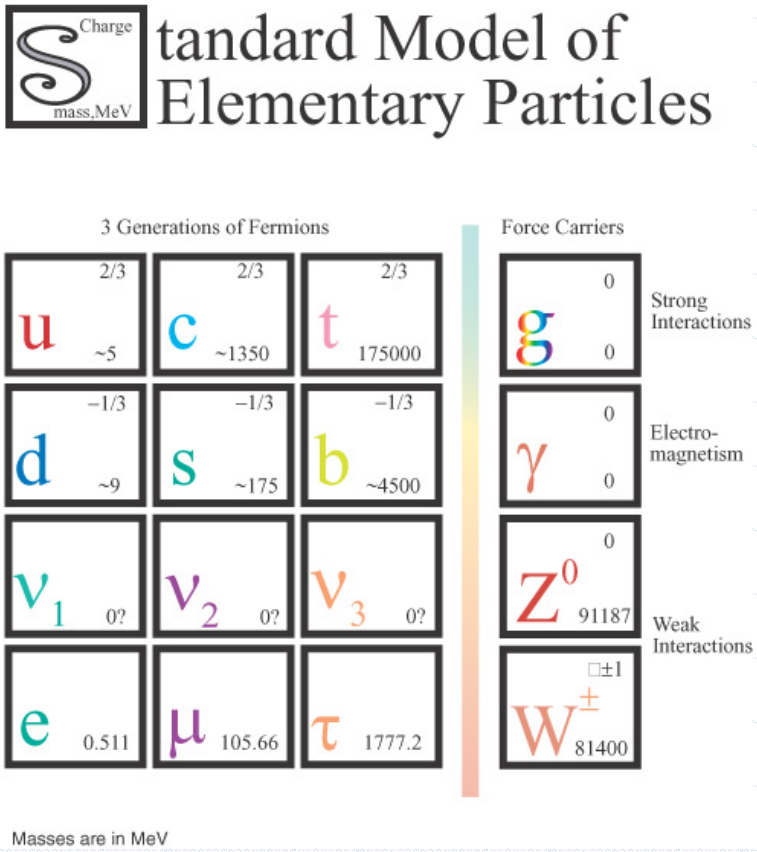


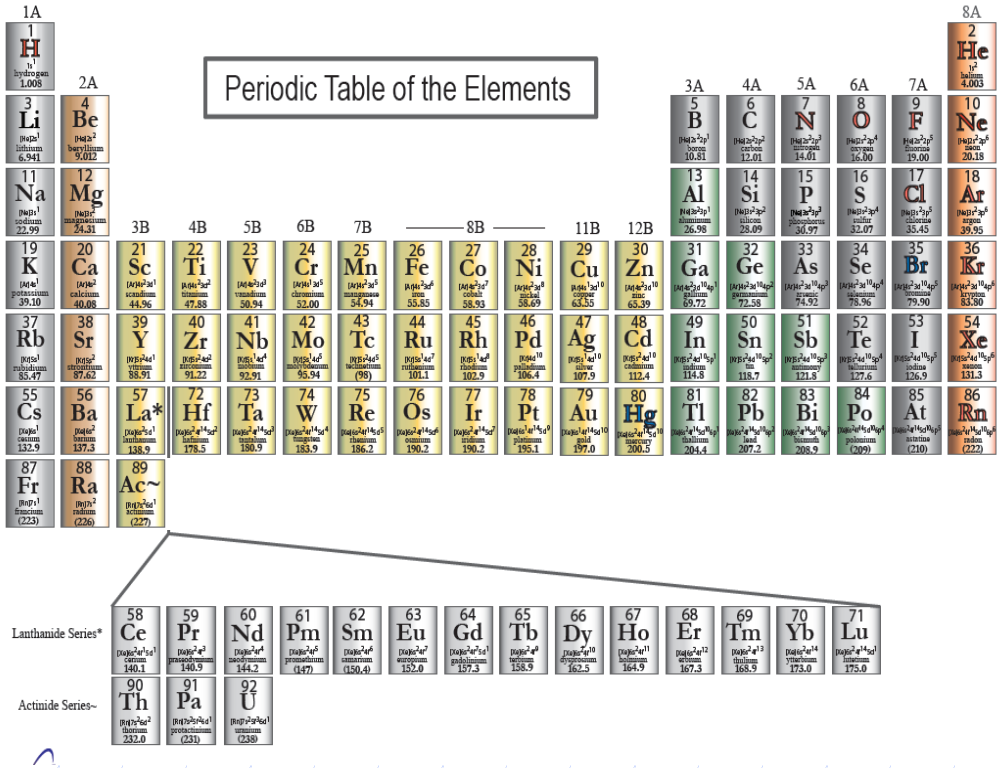
Fundamental Particles



Fundamental Particles

- Or another pattern to unravel?





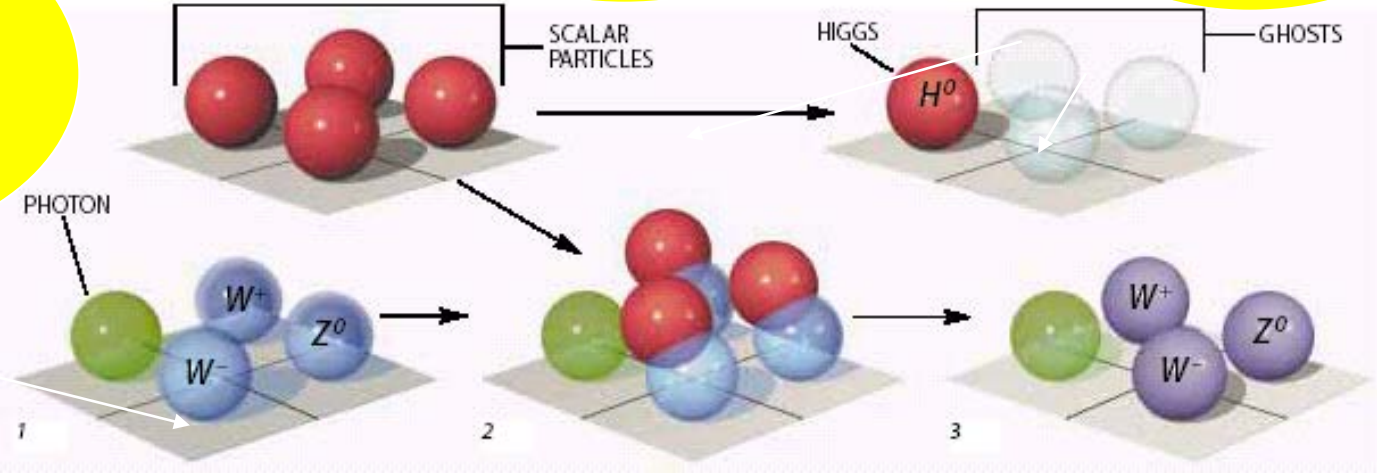
Standard Model

- Summary

SSB and Higgs Mechanism

Massive Higgs Boson

Local Gauge Invariance



Massive Gauge Bosons

Standard Model

- Standard Model Lagrangian

$$\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) +$$

$$+ \frac{g}{\sqrt{2}} \sum_i (\bar{a}_L^i \gamma^\mu b_L^i W_\mu^+ + \bar{b}_L^i \gamma^\mu a_L^i W_\mu^-) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I_f^3 - 2s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z_\mu +$$

$$-\frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 - \frac{1}{2} |\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ +$$

$$-ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu|^2 +$$

$$-\frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 +$$

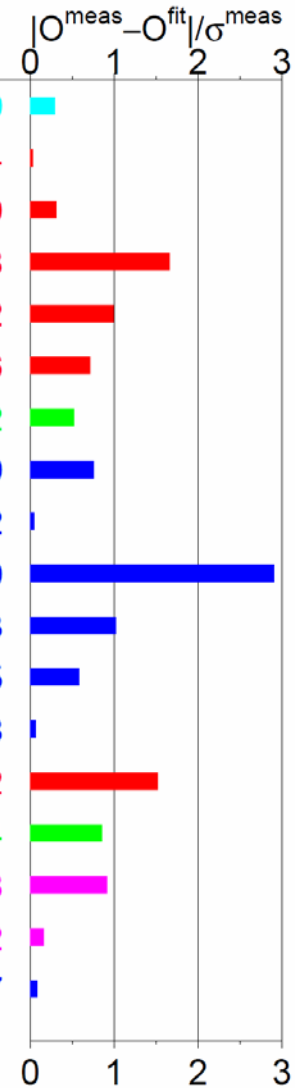
$$-\frac{1}{2} M_\eta^2 \eta^2 - \frac{g M_\eta^2}{8 M_W} \eta^3 - \frac{g'^2 M_\eta^2}{32 M_W} \eta^4 + |M_W W_\mu^+ + \frac{g}{2} \eta W_\mu^+|^2 +$$

$$+ \frac{1}{2} |\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta$$

Standard Model Successes

- The Standard Model is mathematically complete
- There are no significant experimental discrepancies with Standard Model predictions
- But no Higgs boson has been observed either

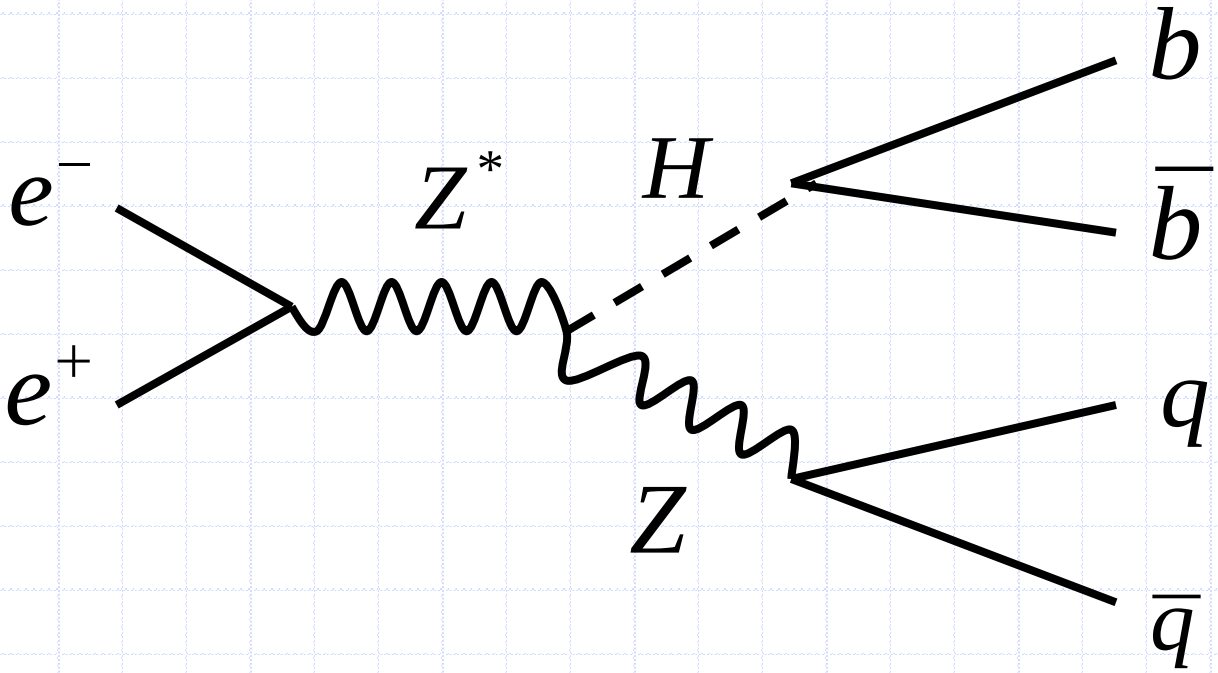
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1039
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27



July 2011

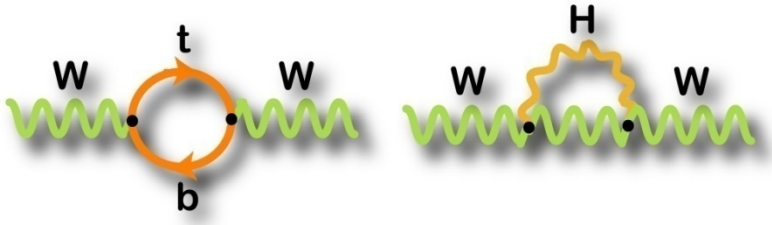
Where to Search for the Higgs

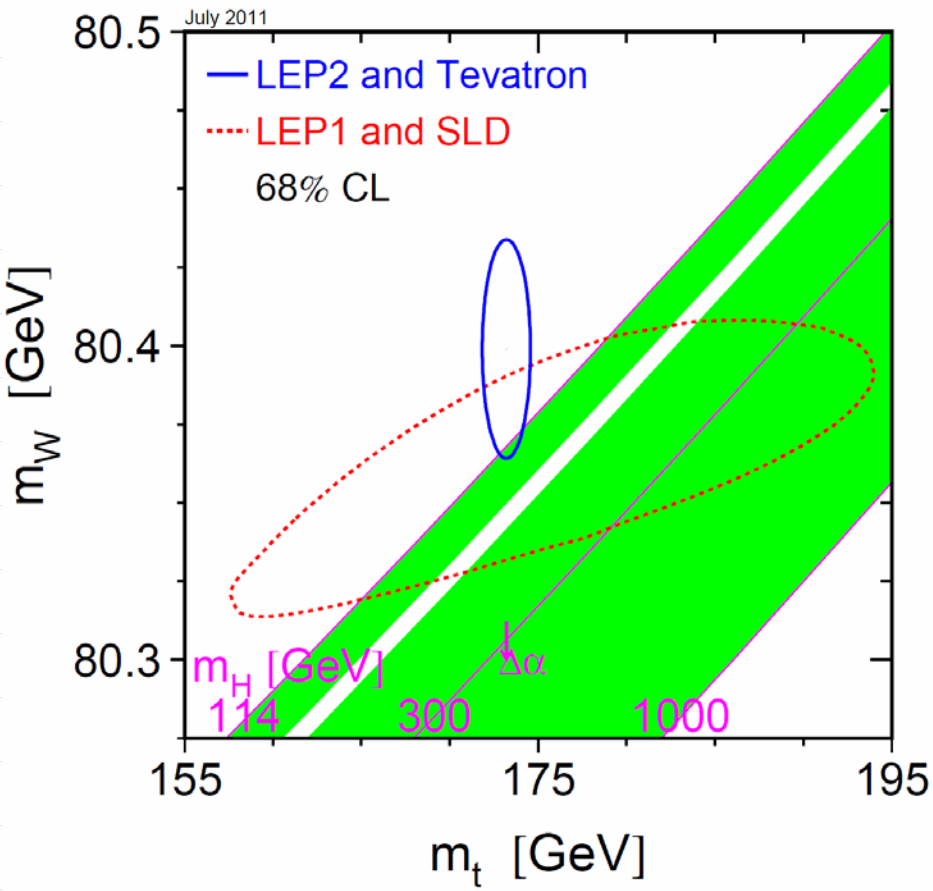
- A direct search for the Higgs was carried out by the four LEP experiments from 1995-2000
  - Center-of-mass energy of 205-208 GeV
  - The production and decay were primarily by



Where to Search for the Higgs

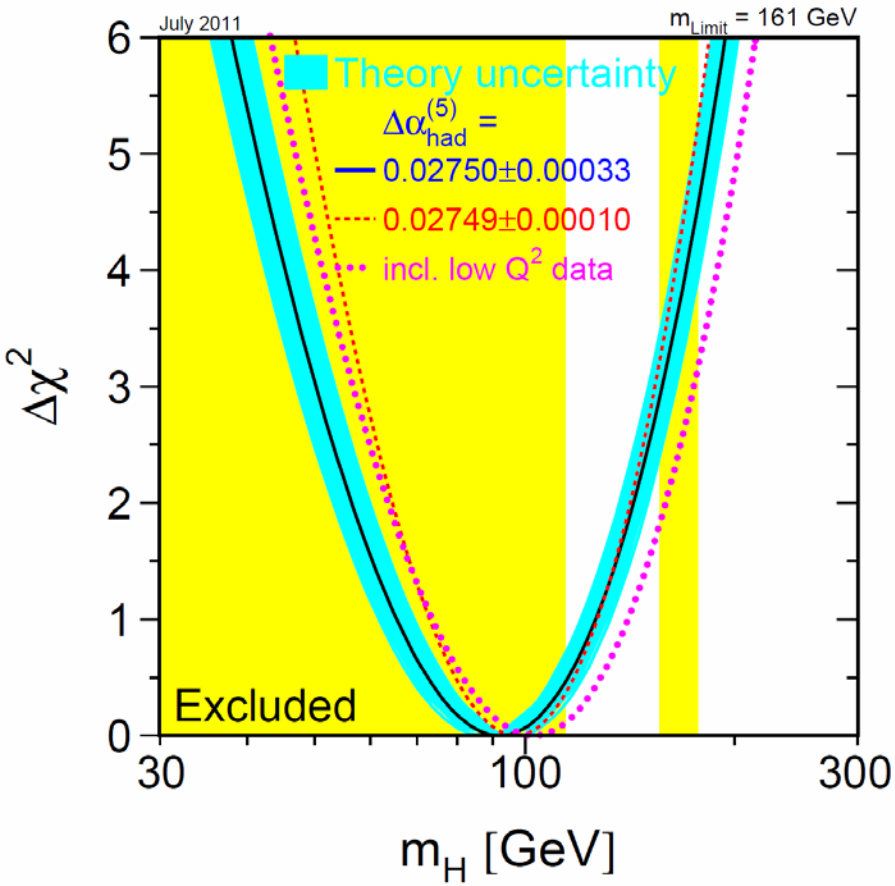
- Indirect constraints on the Higgs mass can be found by considering electroweak radiative corrections like





Where to Search for the Higgs

- Electroweak observables depend quadratically on the top quark mass and logarithmically on the Higgs boson mass



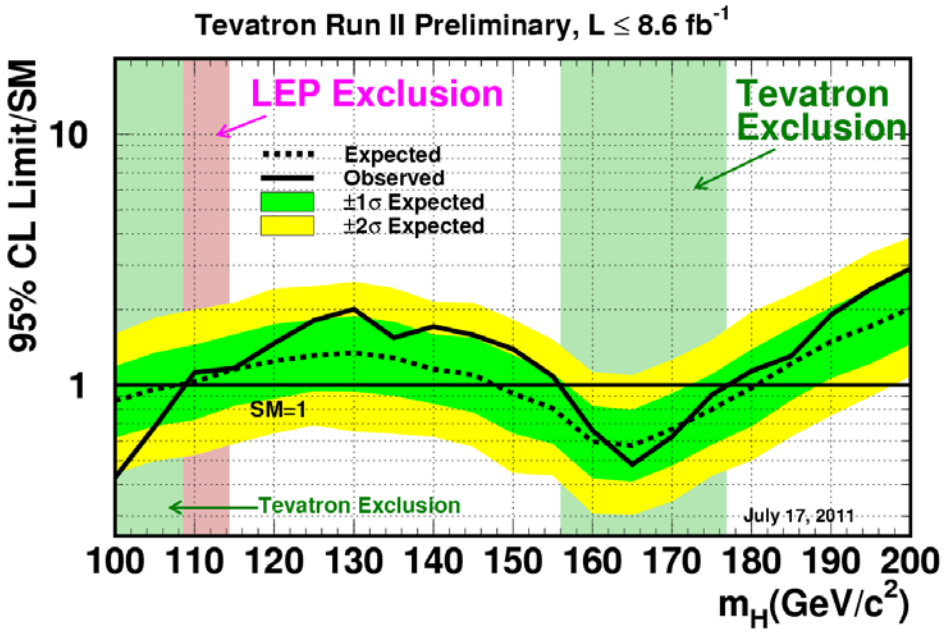
- A global fit yields

$$m_H < 161\,\text{GeV} @ 95\%\,\text{CL}$$

$$m_H < 185\,\text{GeV} @ 95\%\,\text{CL w LEP direct}$$

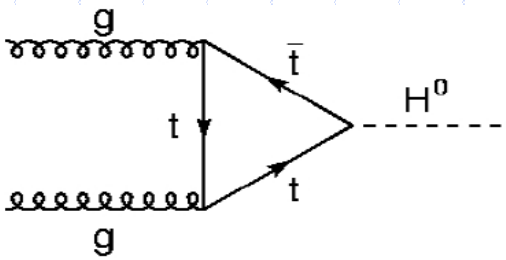
Where to Search for the Higgs

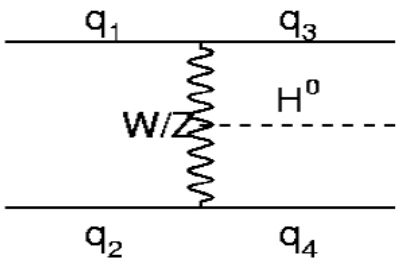
- The DZero and CDF experiments at the Fermilab Tevatron continue to search for the Higgs
  - Many different channels

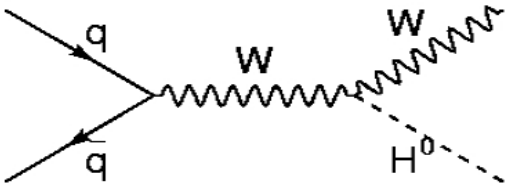


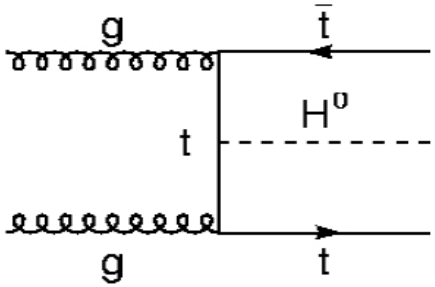
Higgs Production at the LHC

- Gluon Fusion (GGF)
  - Dominant process
- Vector Boson Fusion (VBF)
  - Second largest cross section
  - Distinctive topology useful for small m_H
- Associated W/Z (AW)
- Associated Top (AT)
  - Interesting topologies but smaller cross section









Higgs Production at the LHC

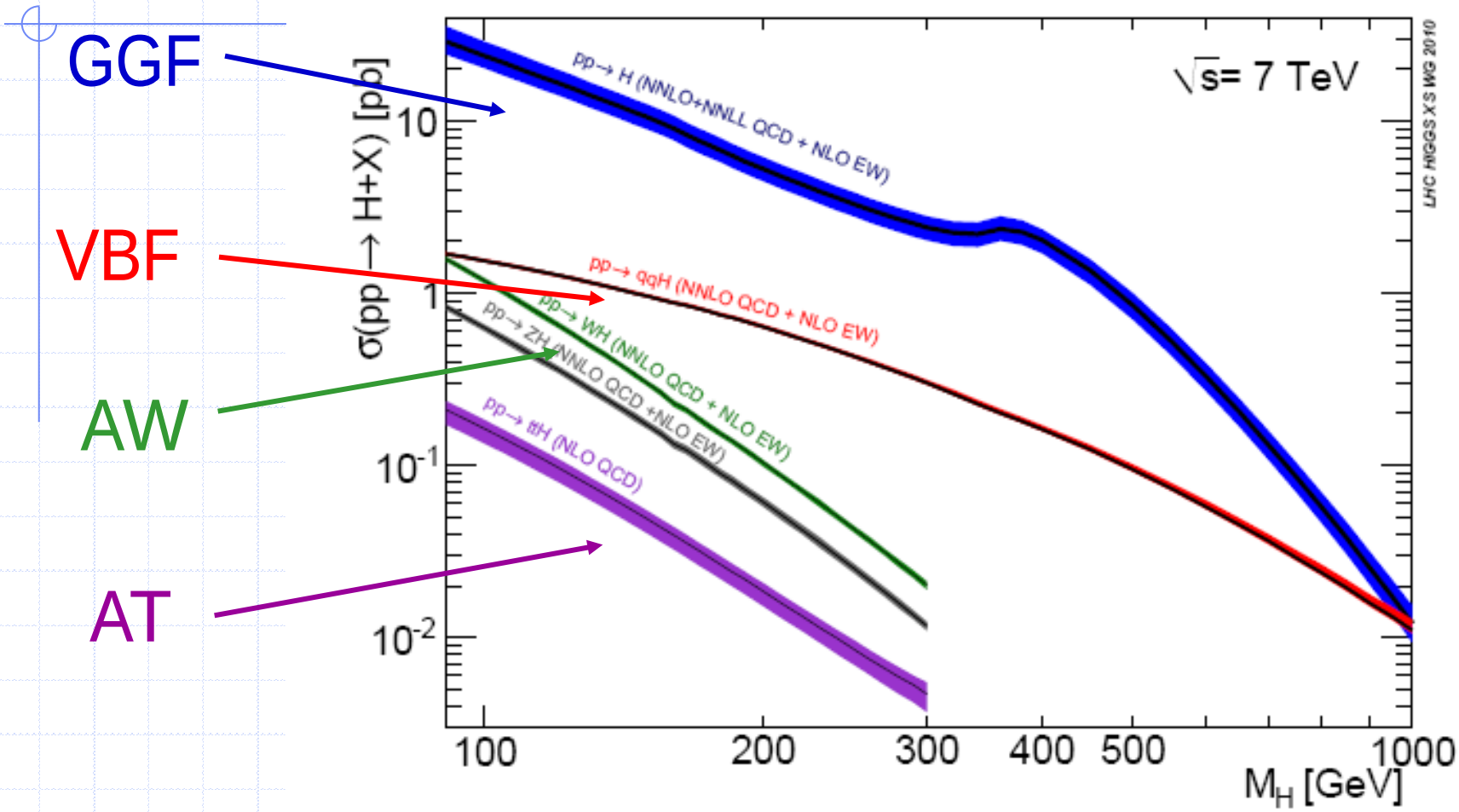
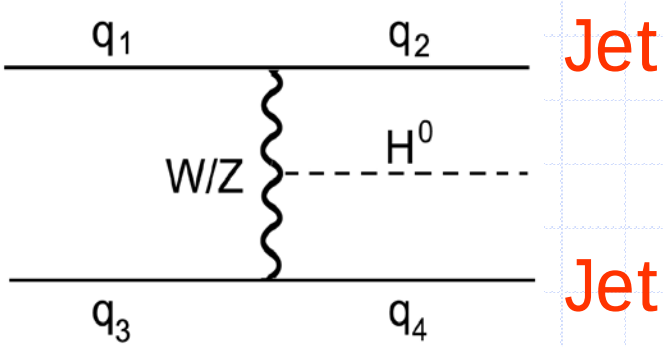
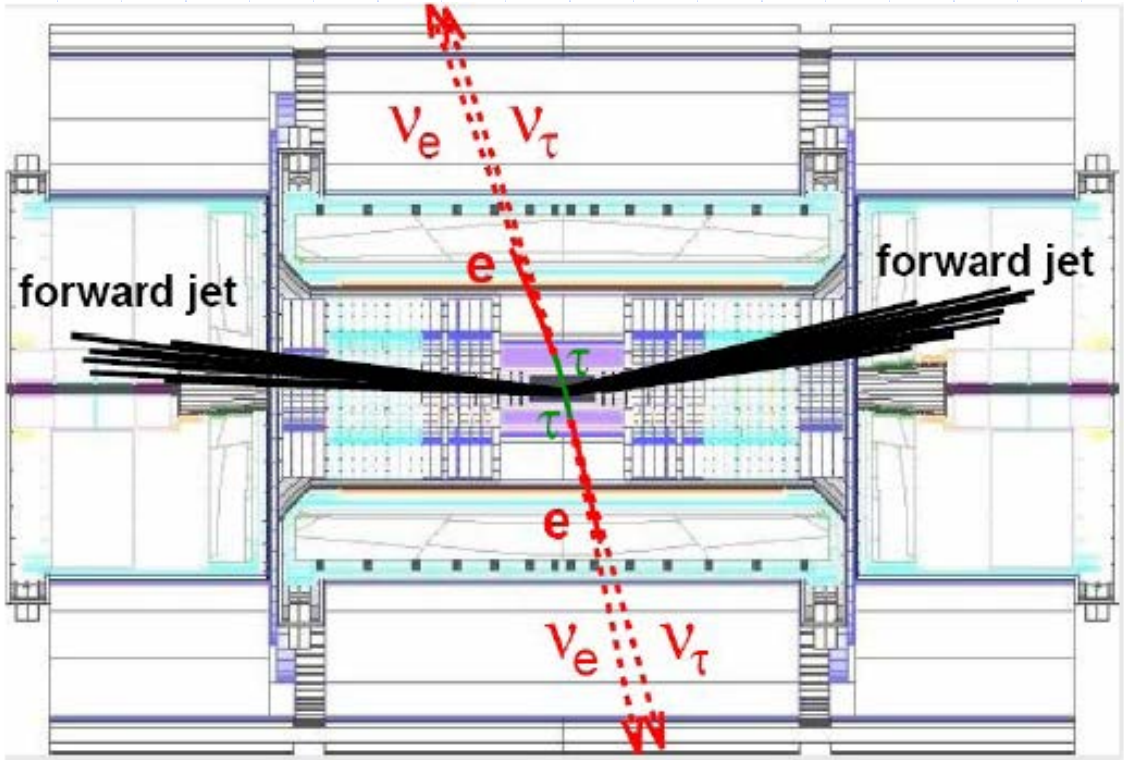


Fig. 41: The SM Higgs production cross section at $\sqrt{s} = 7$ TeV.

VBF (Vector Boson Fusion)

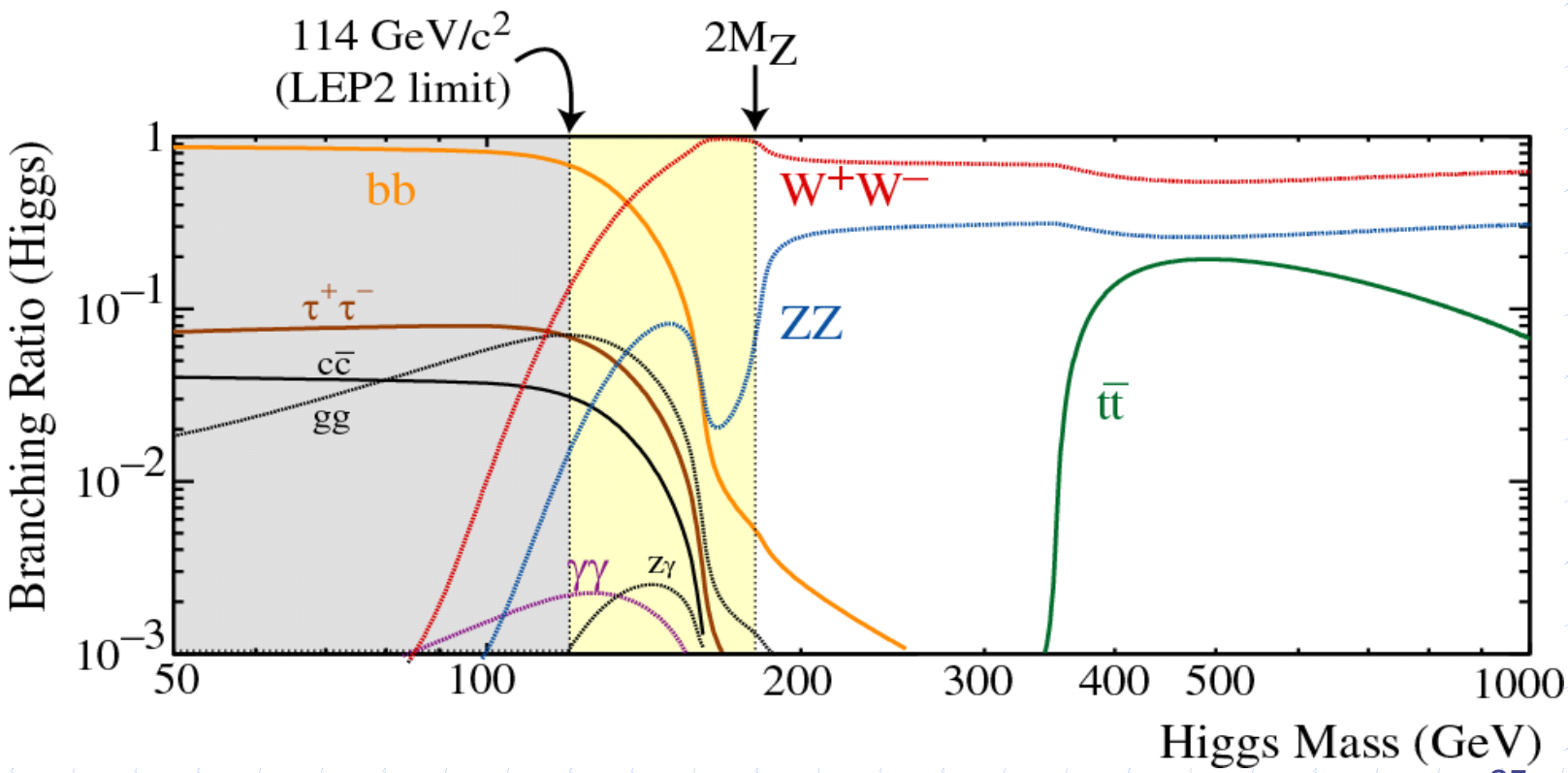
- Higgs production with a distinctive topology
  - Forward jets
  - No central jet activity because no color flow





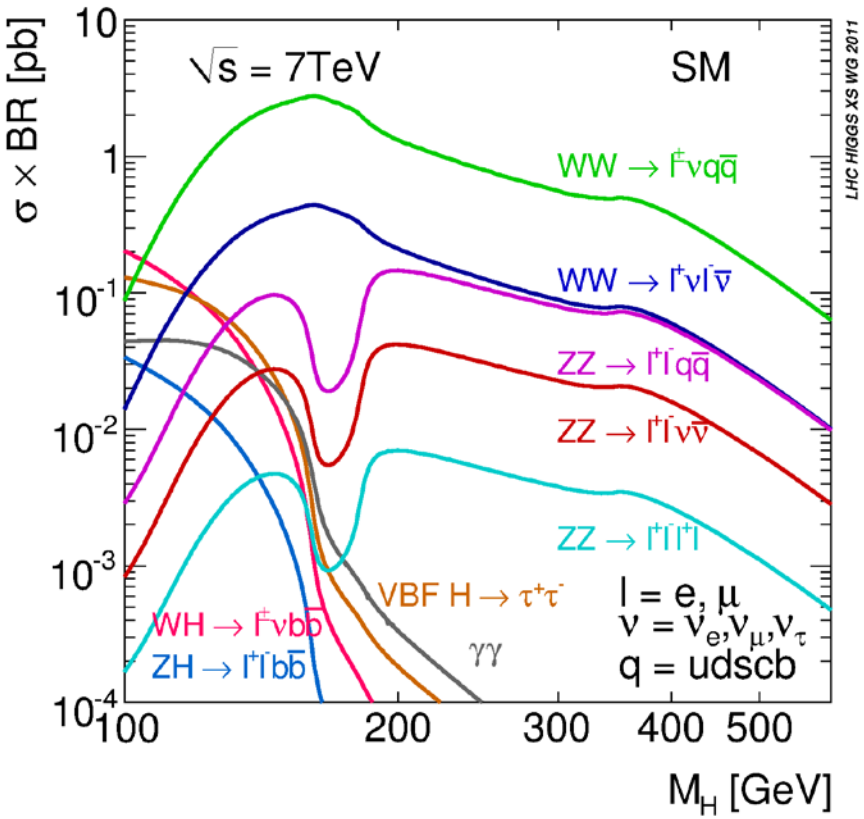
Higgs Decay Modes

- The Standard Model rules say the Higgs decays into the heaviest pair of particles that is kinematically allowed



Higgs Production x Decay

- ATLAS searches for the Higgs using many different decay modes



Number of expected events for 1 fb^{-1}

m_H	WW→lvlv	ZZ→4l	γγ
120 GeV	127	1.5	43
150 GeV	390	4.6	16
300 GeV	89	3.8	0.04

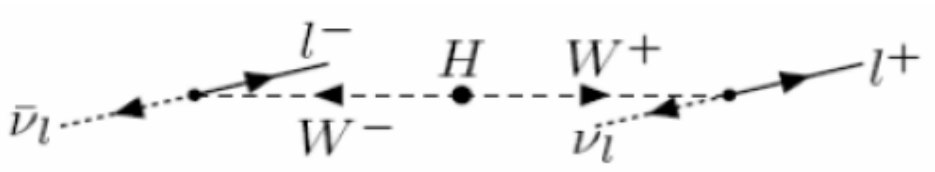
$H \rightarrow WW^* \rightarrow l\nu l\nu$

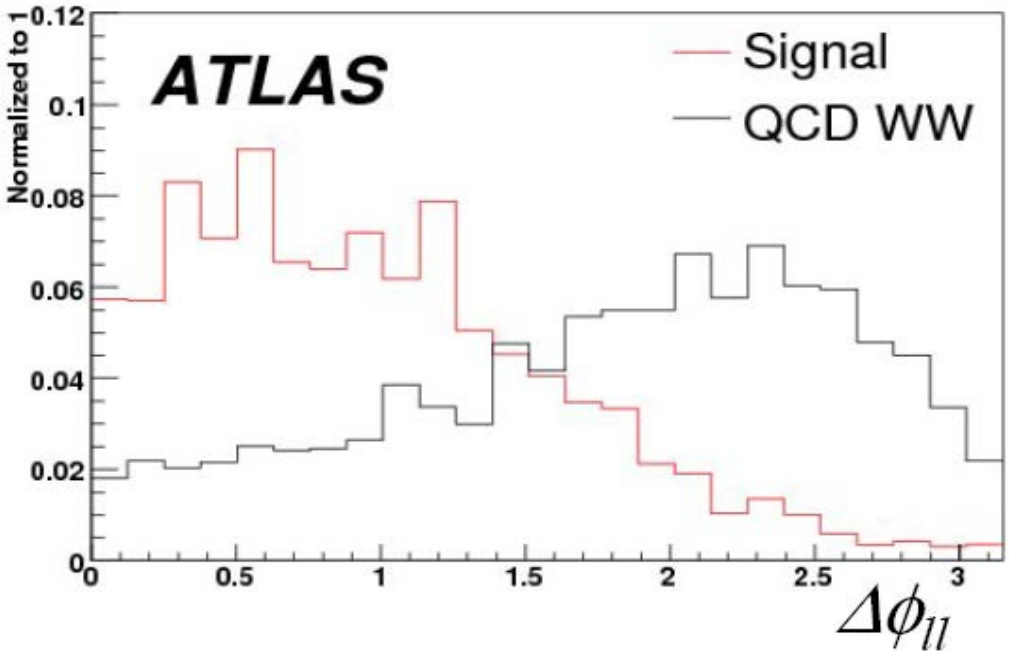
➢ Generalities

- Effective for 120 < m_H < 240 GeV
- All production processes are considered (GGF, VBF, and associated W/Z)
  - Separate search is carried out for H+ 0 jet and H+1 jet events (P_T > 25 GeV)
- Common selection
  - 2 oppositely charged, high P_T (>25, 20 GeV) leptons
  - M_{ll} > 15 GeV and $|M_{ll} - M_Z|$ > 15 GeV
  - Missing E_T > 40 GeV (ee and $\mu\mu$)
- Major backgrounds (determined mostly by data-driven methods)
  - WW, W+jets, top

$H \rightarrow WW^* \rightarrow l\nu l\nu$

- Additional selection criteria
  - Leptons are used to infer the W spin direction
  - $\Delta\phi_{ll}$ < 1.3 radians (m_H < 170 GeV)

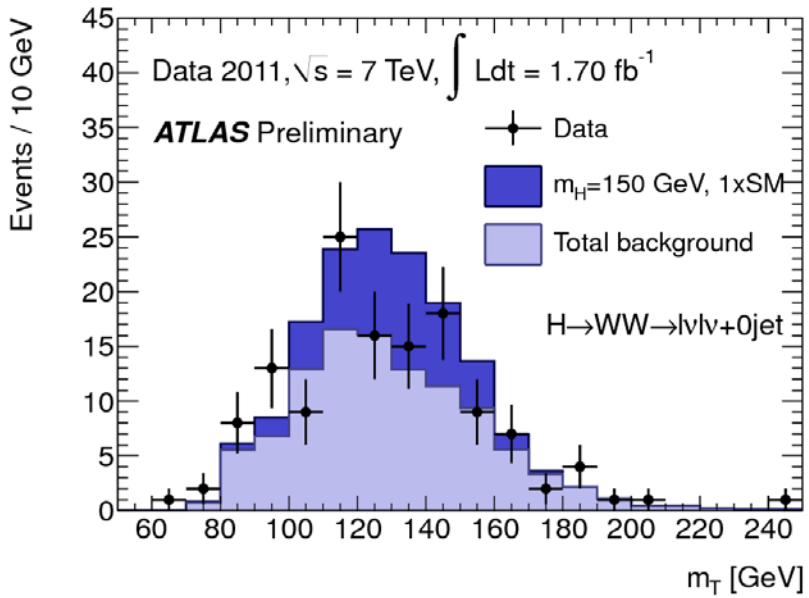


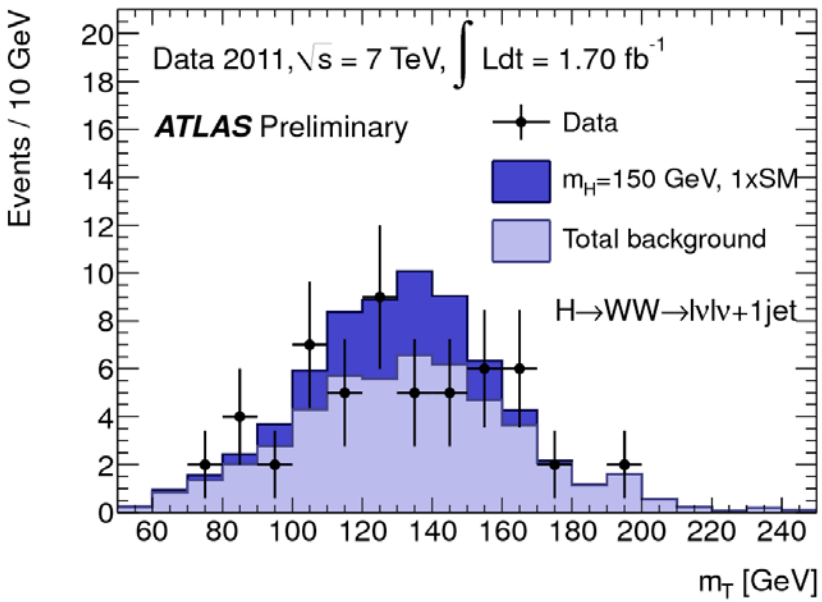


$$H \rightarrow WW^{*} \rightarrow l\nu l\nu$$

➢ Results

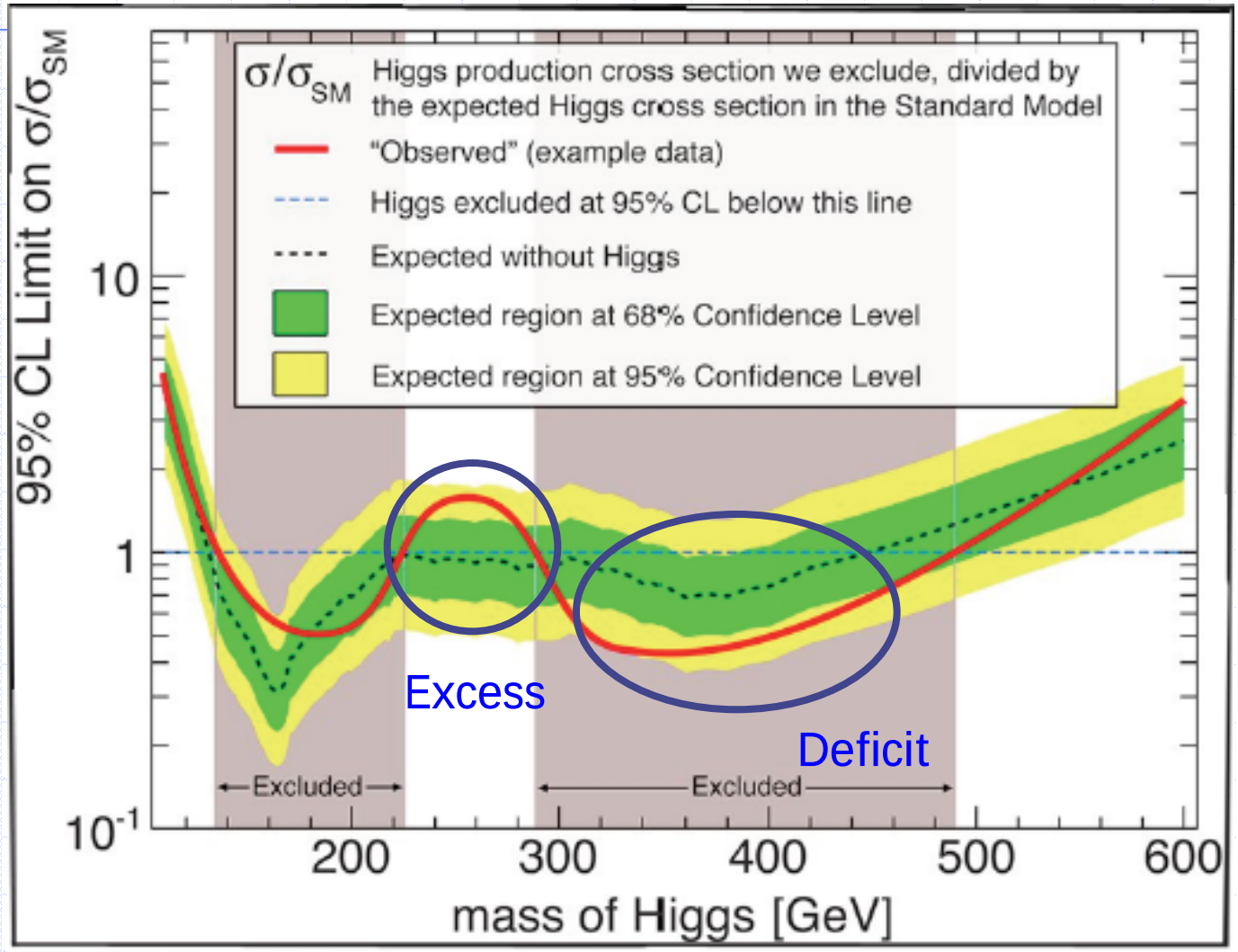
- Additional selection criteria and the background estimates are done separately for H+0 and H+1 jets





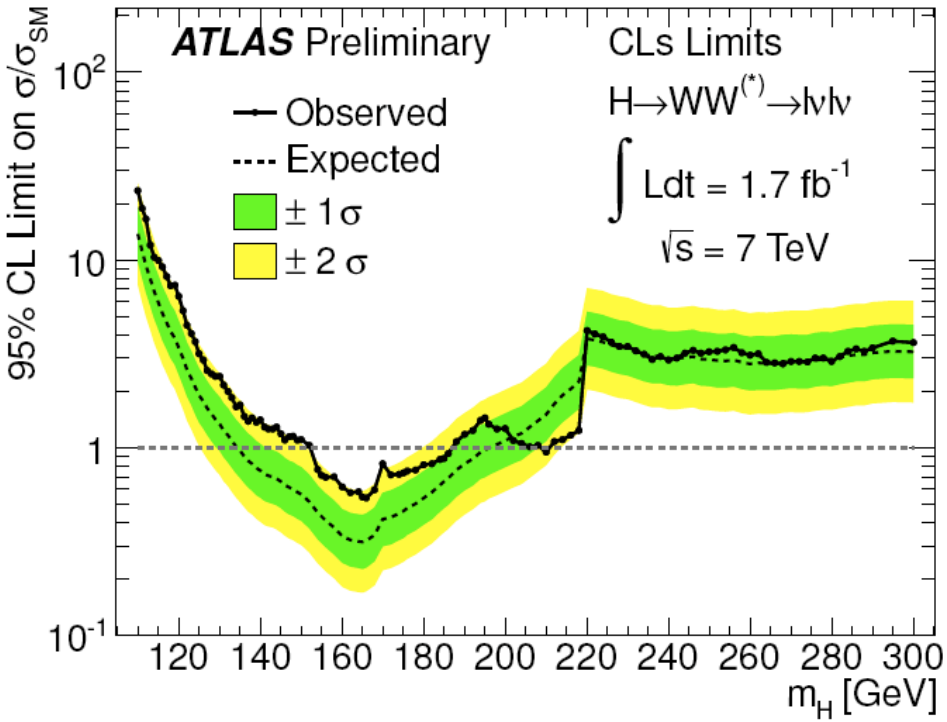
$$m_T = \sqrt{\left(E_T^{ll} + E_T^{miss}\right)^2 - \left(\vec{p}_T^{\,ll} + \vec{p}_T^{\,miss}\right)^2}$$

Limit Plots Explained



$H \rightarrow WW^{*} \rightarrow l\nu l\nu$

- Observed and expected limits

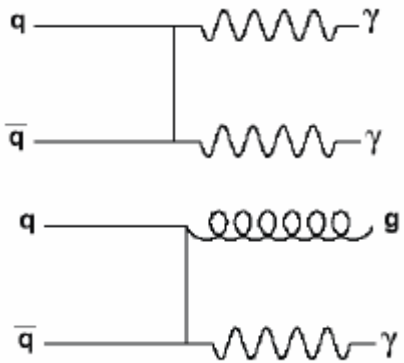


- At 95% CL, the following m_H is excluded
  - 142-186 GeV

$H \rightarrow \gamma\gamma$

Generalities

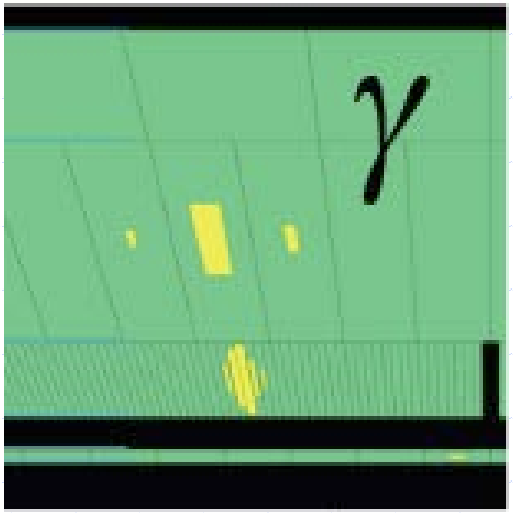
- Effective for 110 < m_H < 140 GeV
- BR ~ 0.002 but possesses a distinctive signature
- Backgrounds
  - Irreducible background: $\gamma\gamma$
  - Reducible background: γ+jet, jet+jet

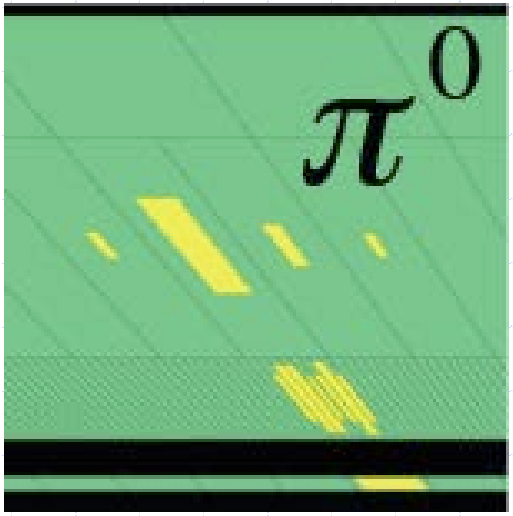


- Selection
  - Two isolated photons > 40 and 25 GeV
  - Photon energies are measured by the calorimeter
  - Photon directions are measured using shower position in the first and second layers of the calorimeter

$H \rightarrow \gamma\gamma$

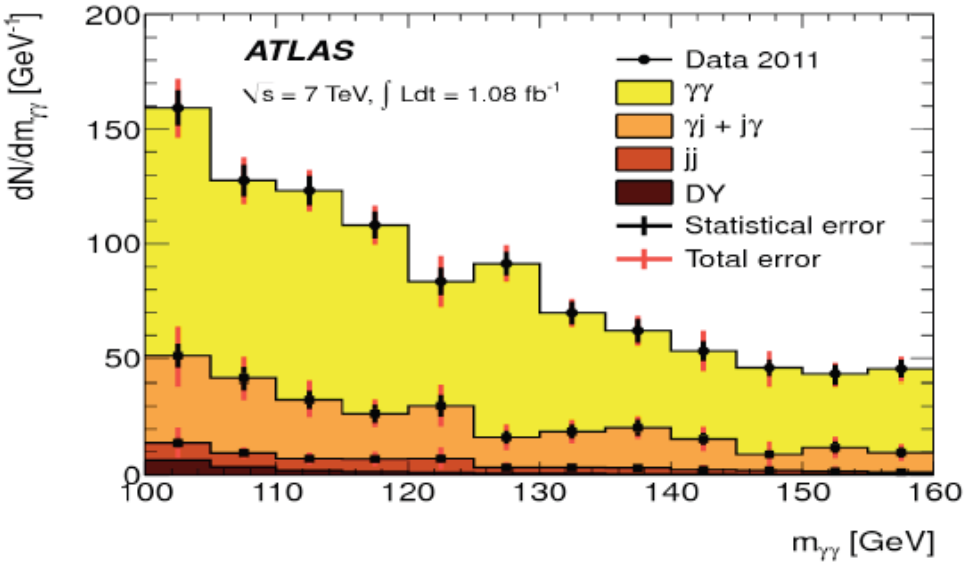
- Photon identification and reconstruction
  - High granularity of the first calorimeter layer can be used to reject photon pairs from neutral meson decays
  - Photon direction (used in the mass reconstruction) is estimated from the shower position in the first and second calorimeter layers

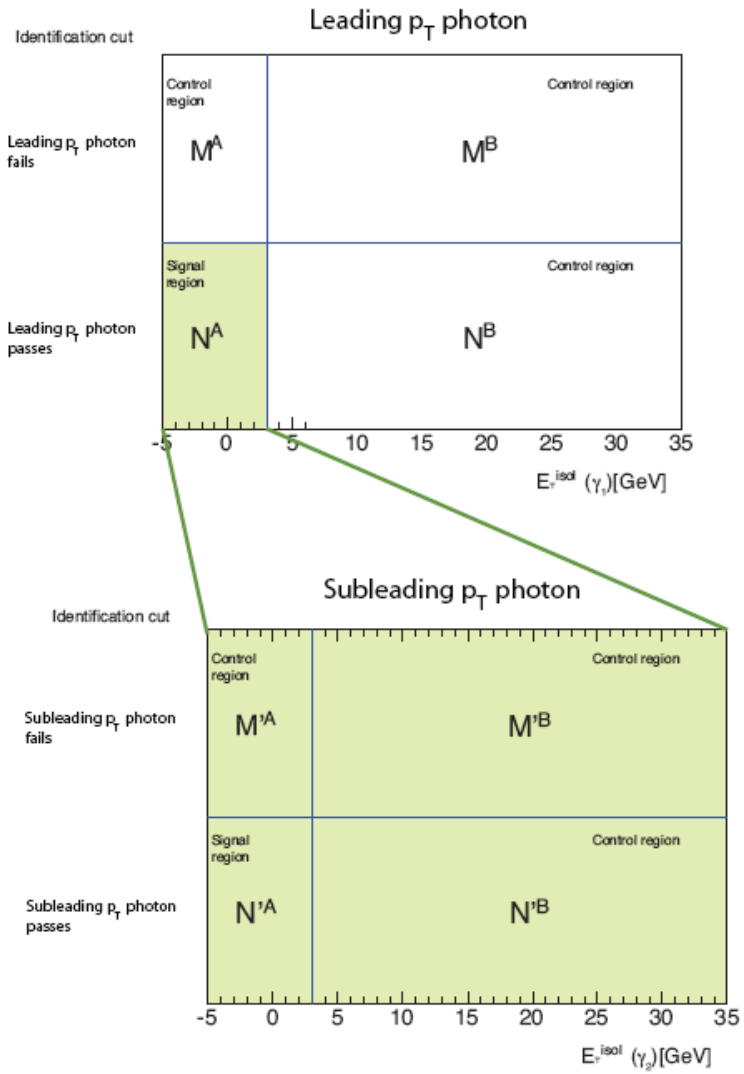




$H \rightarrow \gamma\gamma$

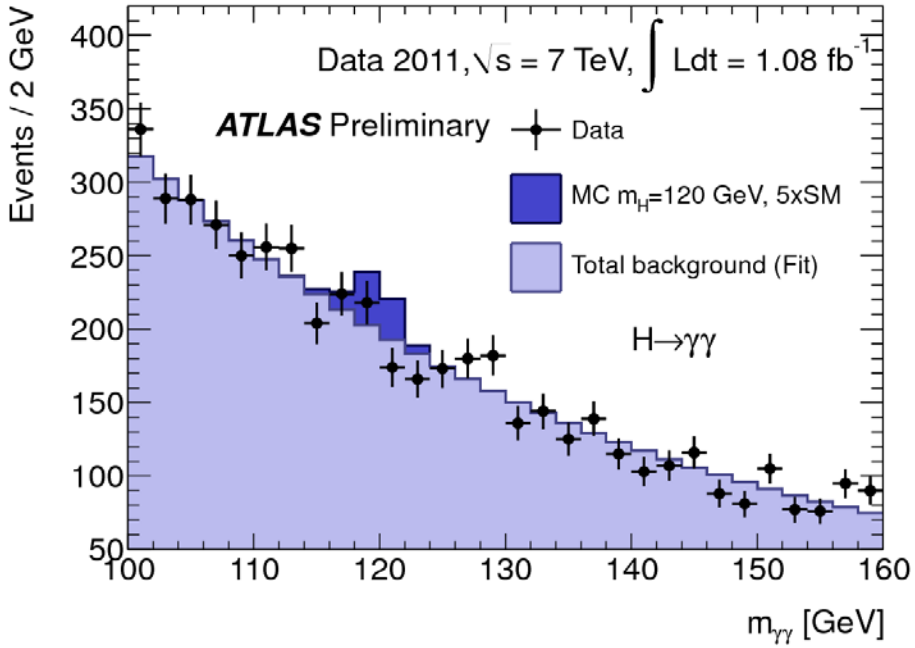
- Data driven methods are used to estimate the background





$H \rightarrow \gamma\gamma$

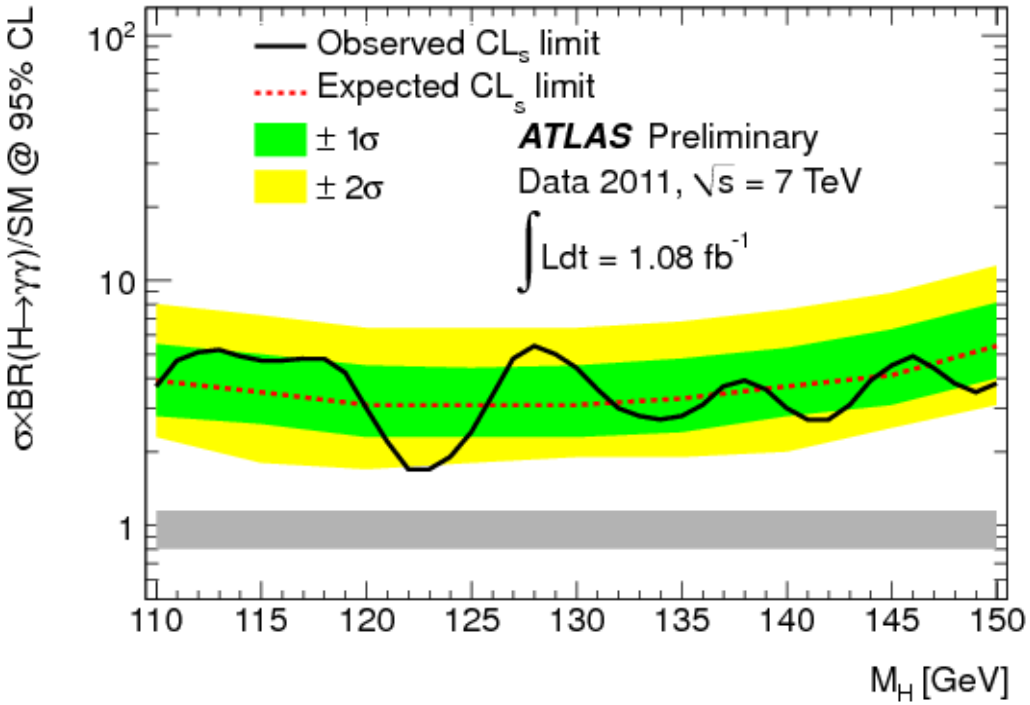
- The resulting diphoton invariant mass
  - No excess is observed



- Currently this channel can only set observed 95% CL limits at ~4 times the SM cross section

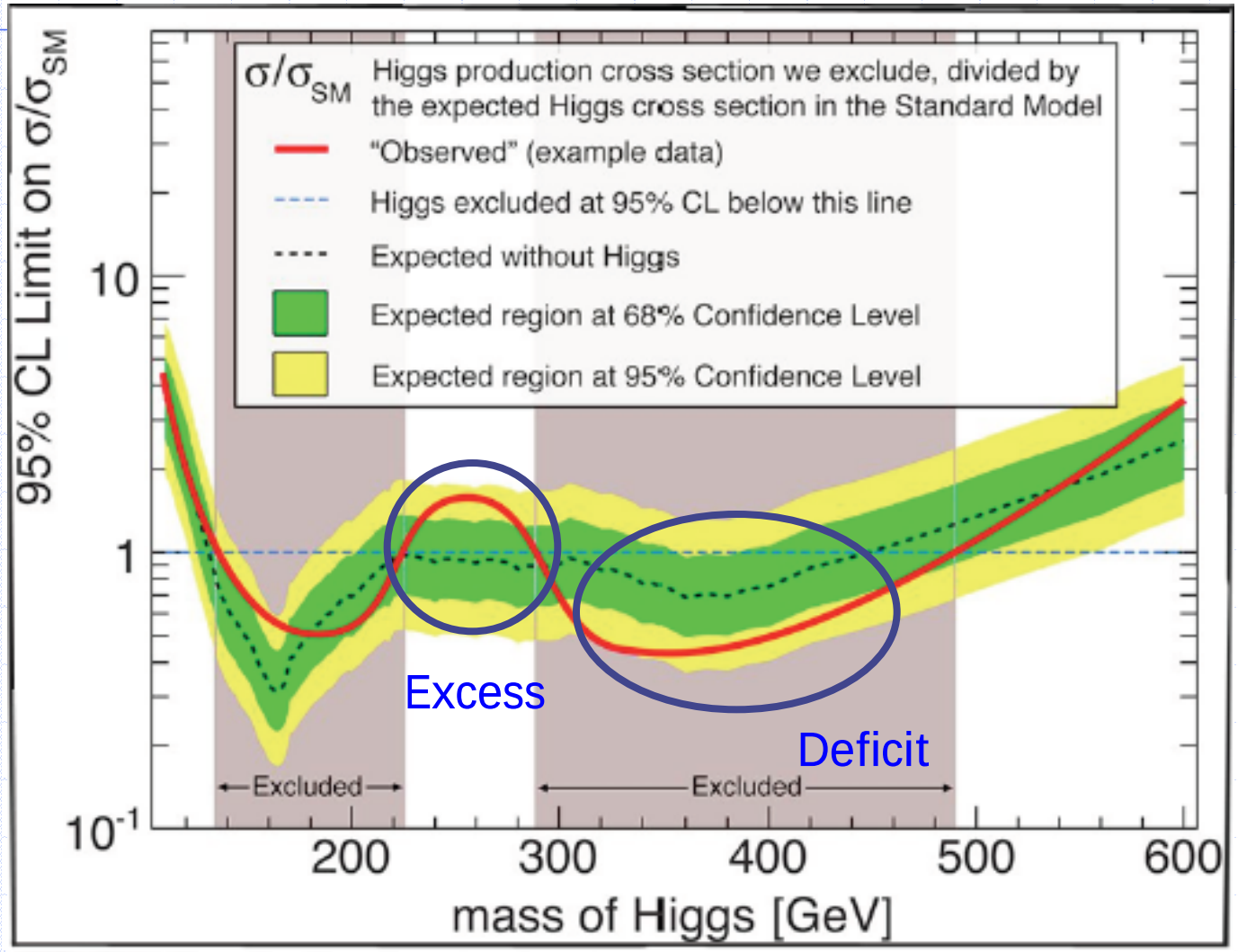
$H \rightarrow \gamma\gamma$

- Combined observed and expected limits



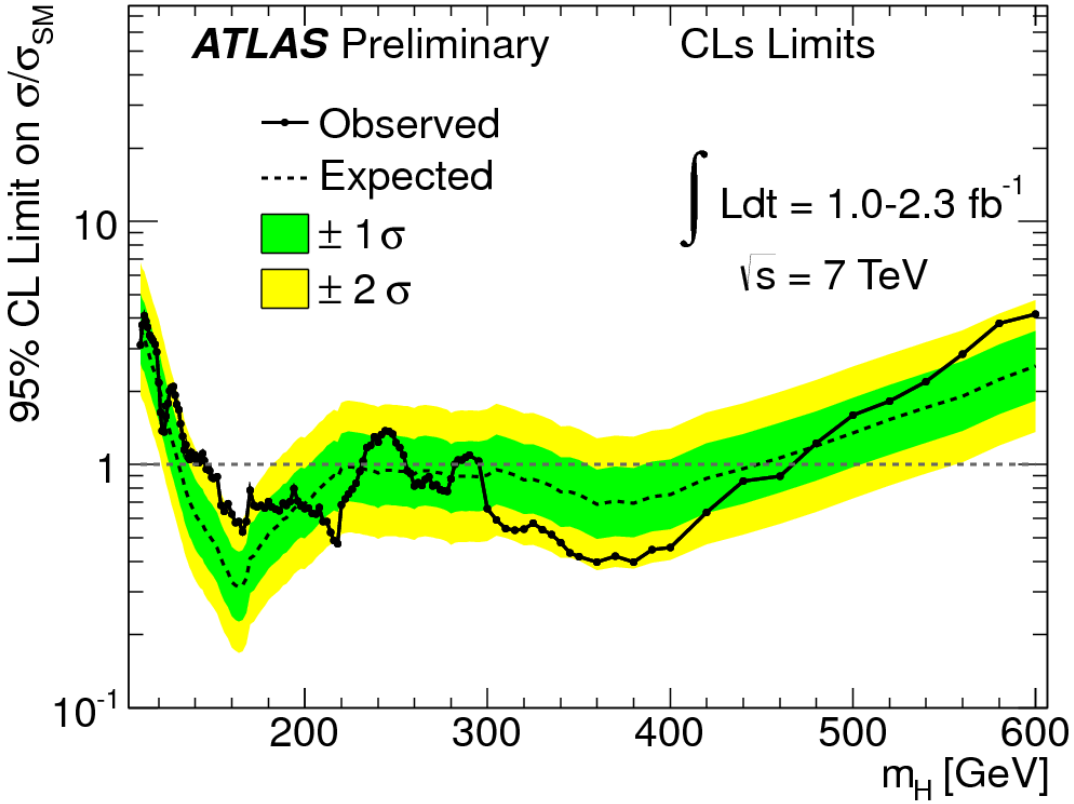
- At 95% CL, can only exclude ~4 x SM production cross section x BR

Limit Plots Explained



Higgs Mass Exclusion Limits

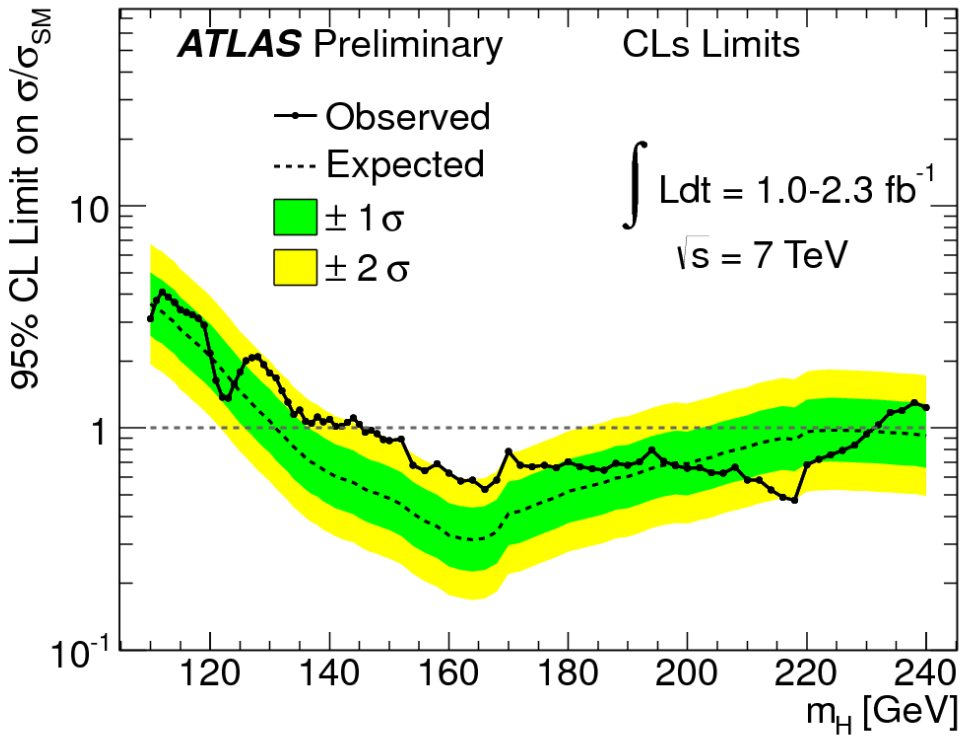
- Combined observed and expected limits



- At 95% CL, the following is excluded
  - 146-242 GeV, 256-282 GeV, 296-466 GeV

Higgs Mass Exclusion Limits

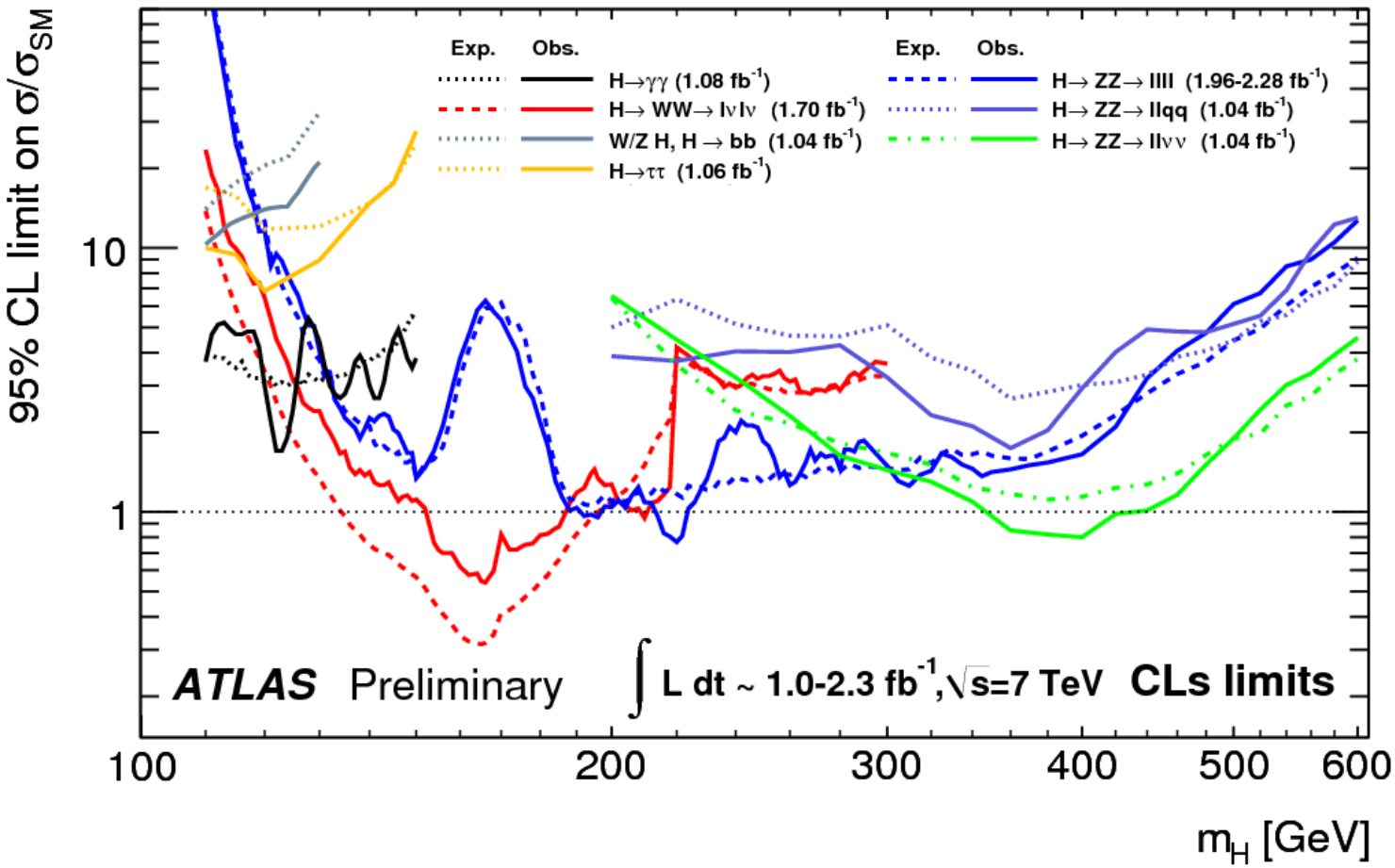
- Combined observed and expected limits



- At 95% CL, the following m_H is excluded
  - 146-242 GeV, 256-282 GeV, 296-466 GeV

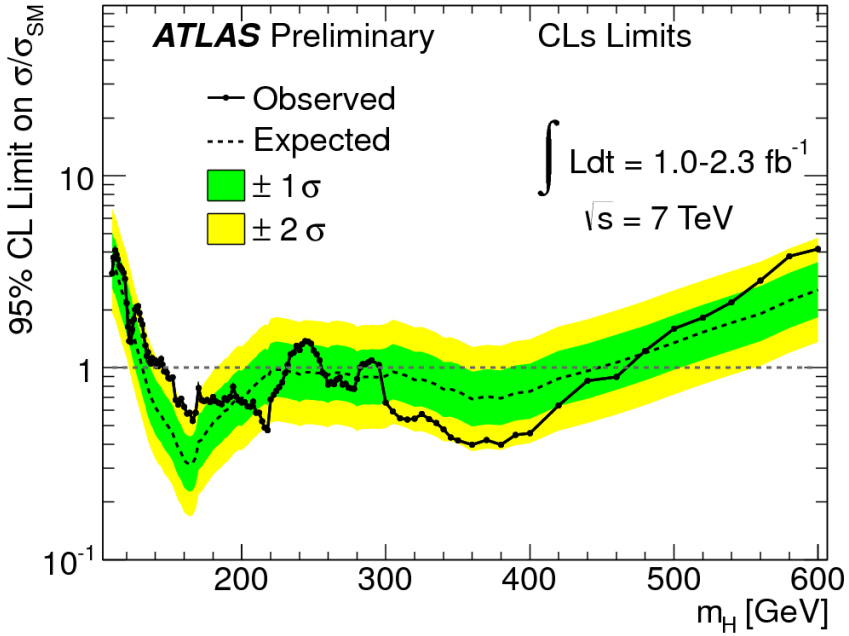
Higgs Mass Exclusion Limits

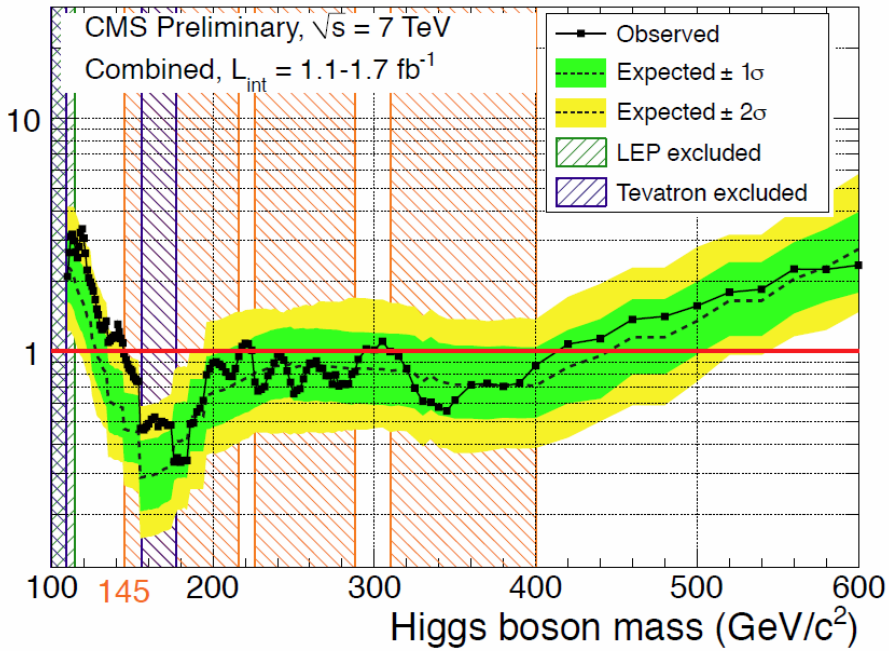
- Combined observed and expected limits for individual channels



ATLAS and CMS Limits

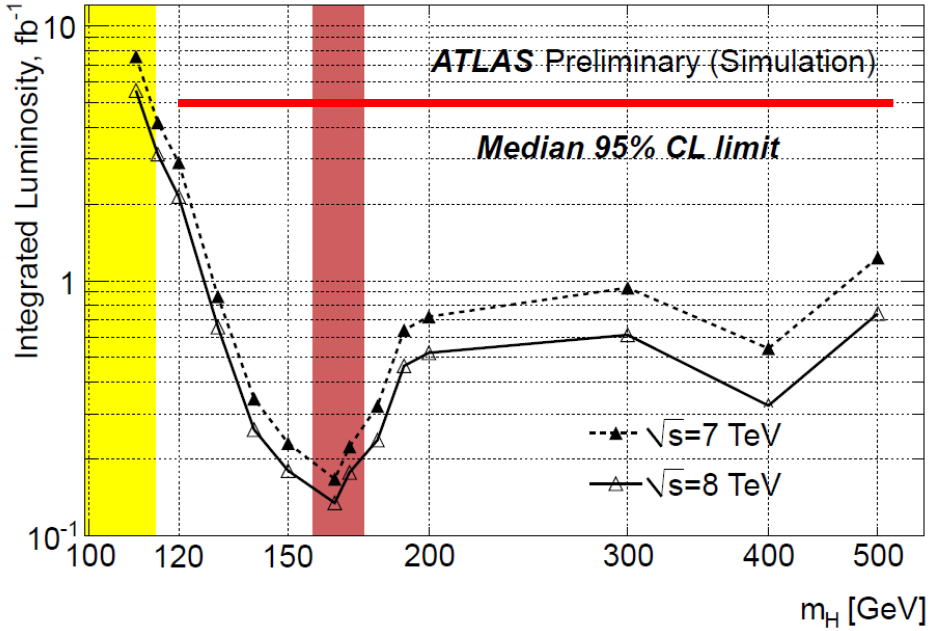
- Combination of both experiments is in progress

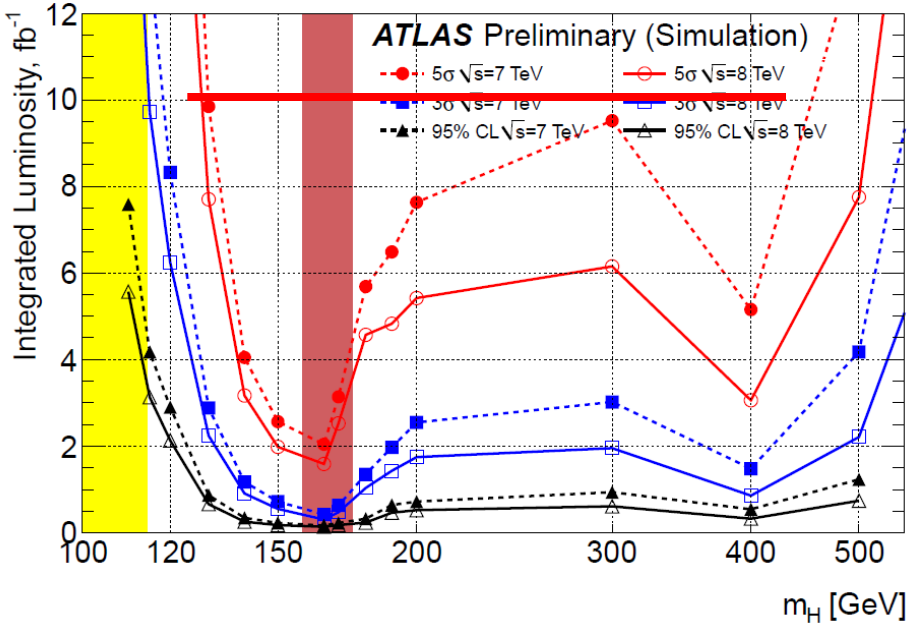




Higgs Search Prospects at 7 TeV

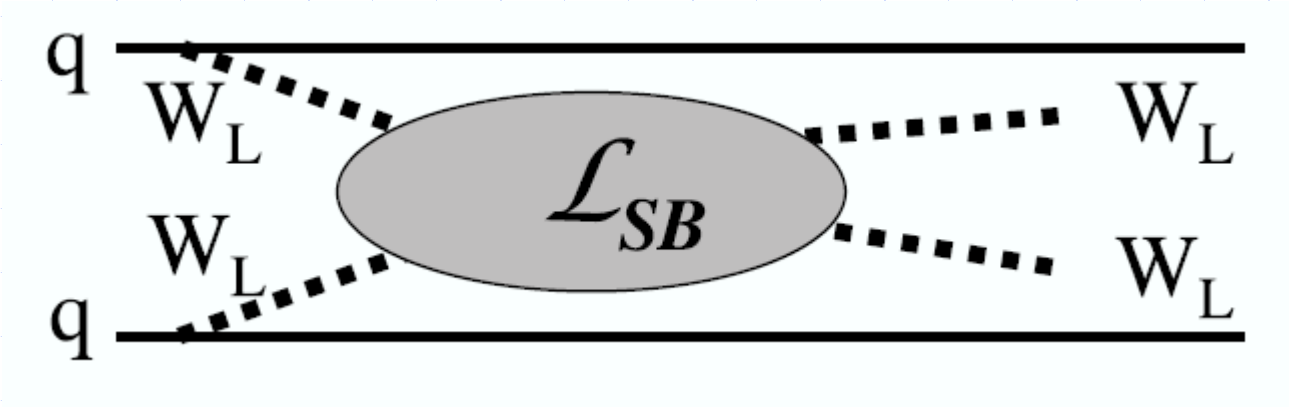
- Exclusion and discovery at 7 TeV
  - Nearly the entire range of Higgs boson masses can be excluded at 95% CL with 5 fb^{-1}
  - Discovery of a SM Higgs boson will require more data - masses between 130 and 450 GeV could be discovered with 10 fb^{-1}





What If We Don't Find the Higgs?

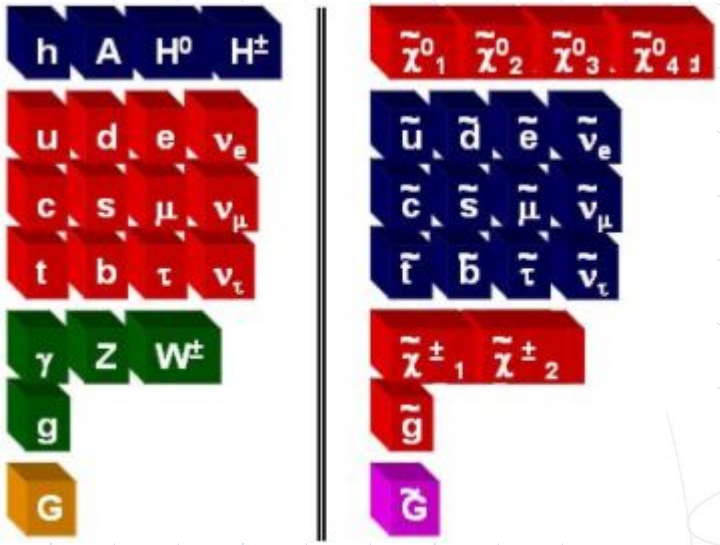
- The Higgs is needed for perturbative unitarity in $W_L W_L \to W_L W_L$ scattering

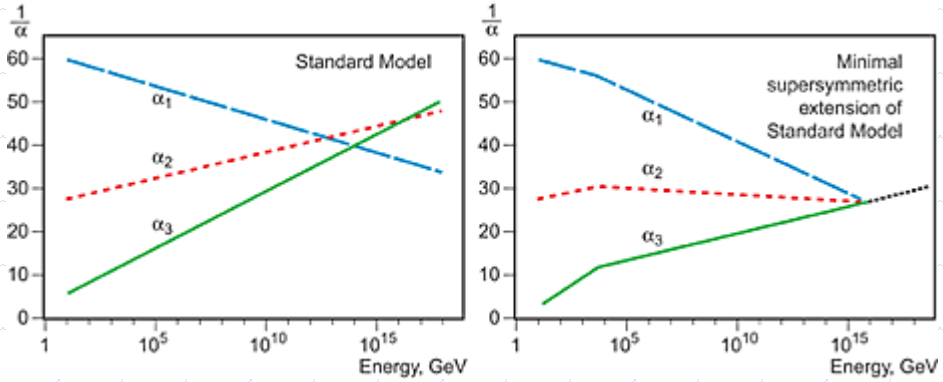


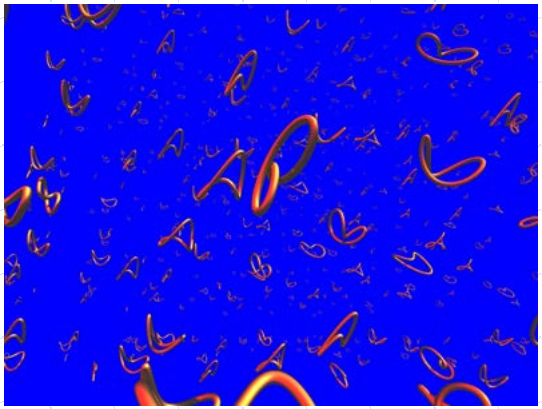
- At ~ 1 TeV
  - Strong WW scattering (resonances?, ...)
  - If no strong WW scattering, go back and search some more for a light Higgs

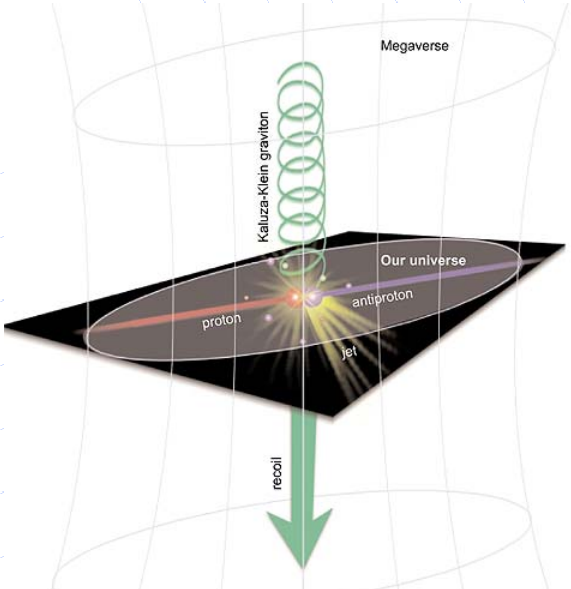
Beyond the Standard Model (BSM)

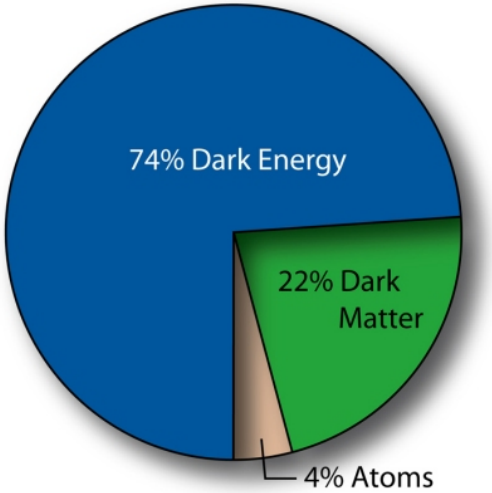
- Supersymmetry, string theory, extra dimensions, dark matter, ...





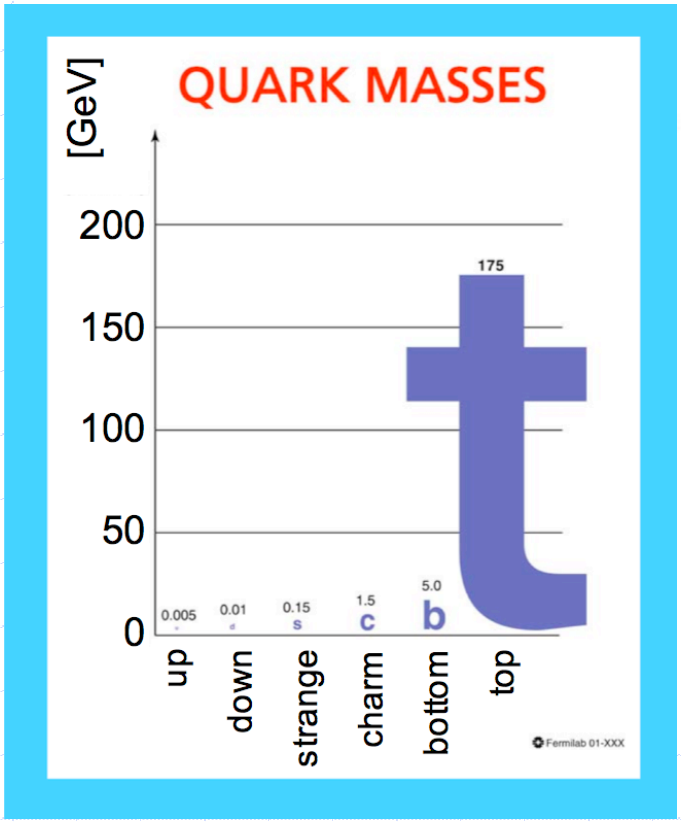


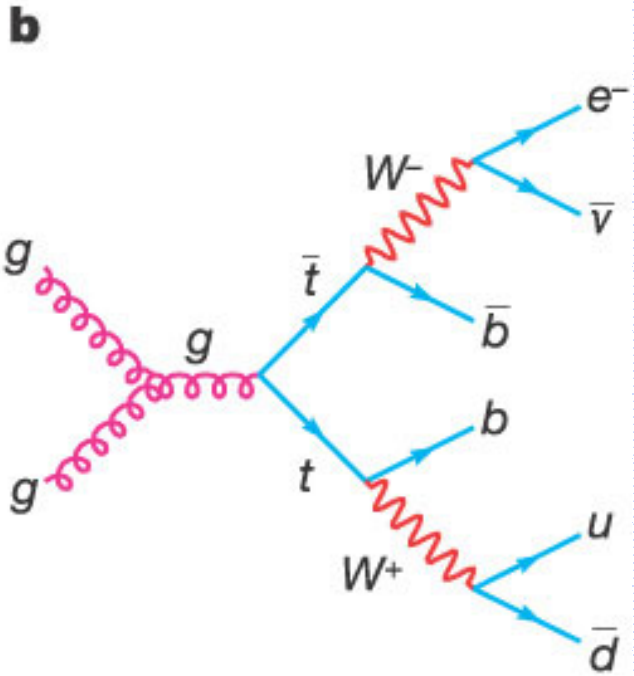




SM Top Quark Pair Production

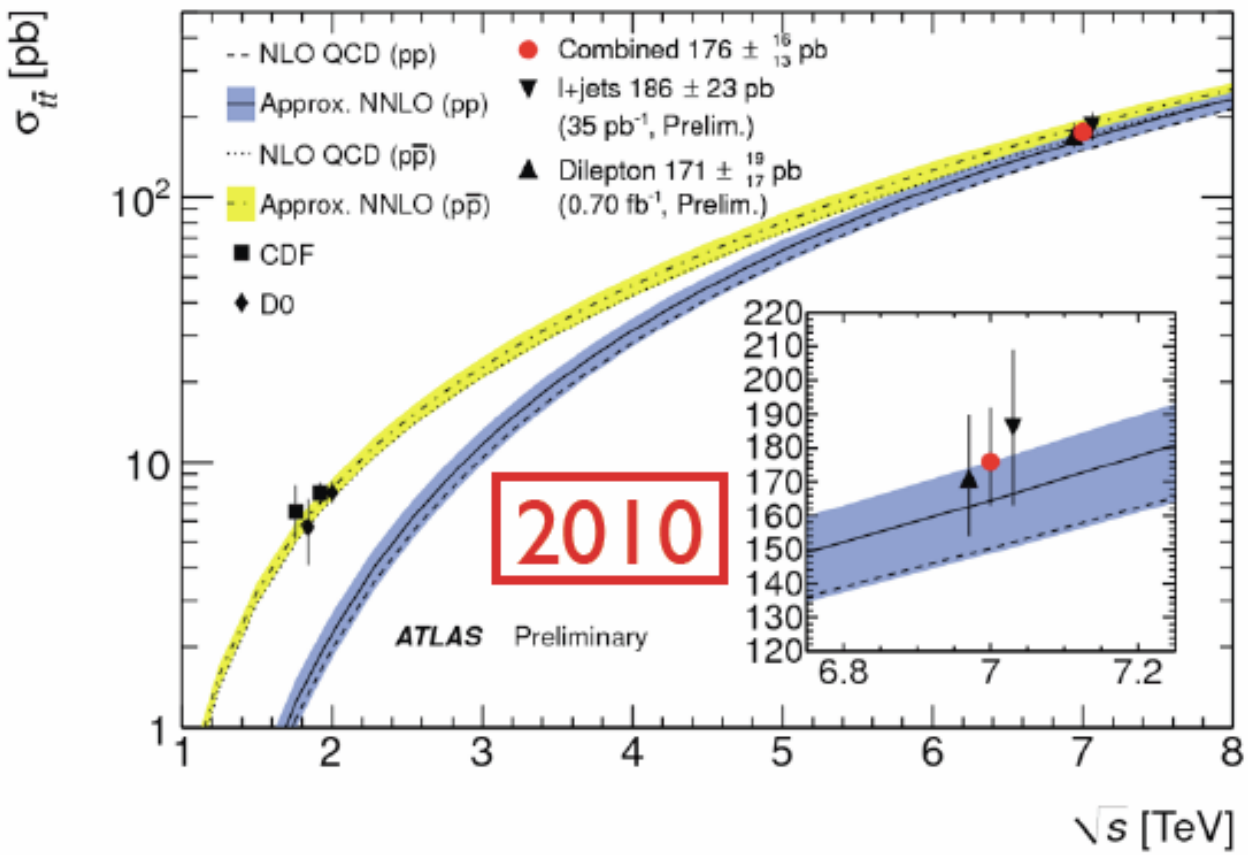
- SM top quark production and decay are measured and understood





SM Top Quark Pair Production

- Cross section at 7 TeV



Search for Top Quark Pair Resonances

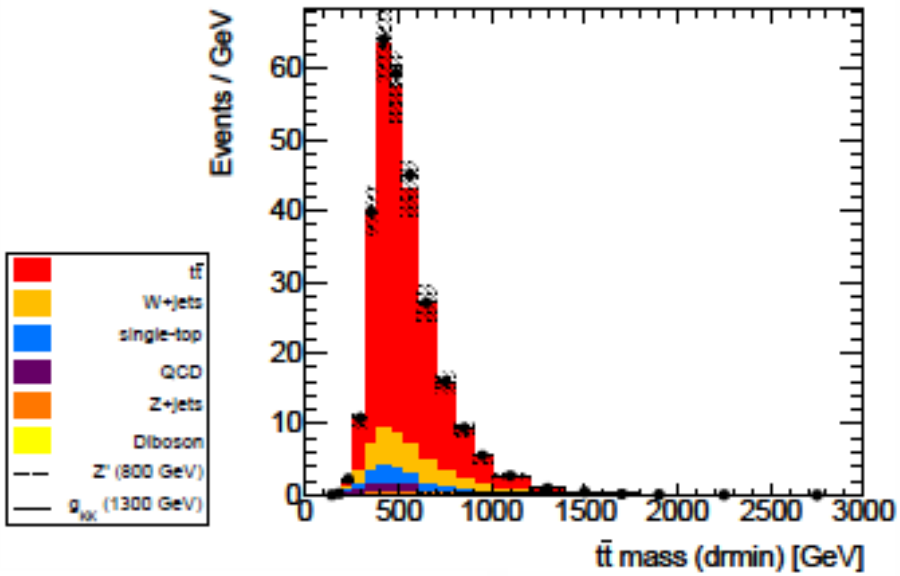
- New particles that decay into pairs of top quarks are predicted in a number of models including
  - New Z' boson (associated with Sequential SM models)
  - Topcolor Z' (found in models of dynamical electroweak symmetry breaking)
  - Kaluza-Klein gluons (found in models with warped extra dimensions)
  - Randall-Sundrum graviton (also found in models with warped extra dimensions)
  - Randall-Meade quantum black holes (resulting from two colliding partons with impact parameter less than the Schwarzschild radius)

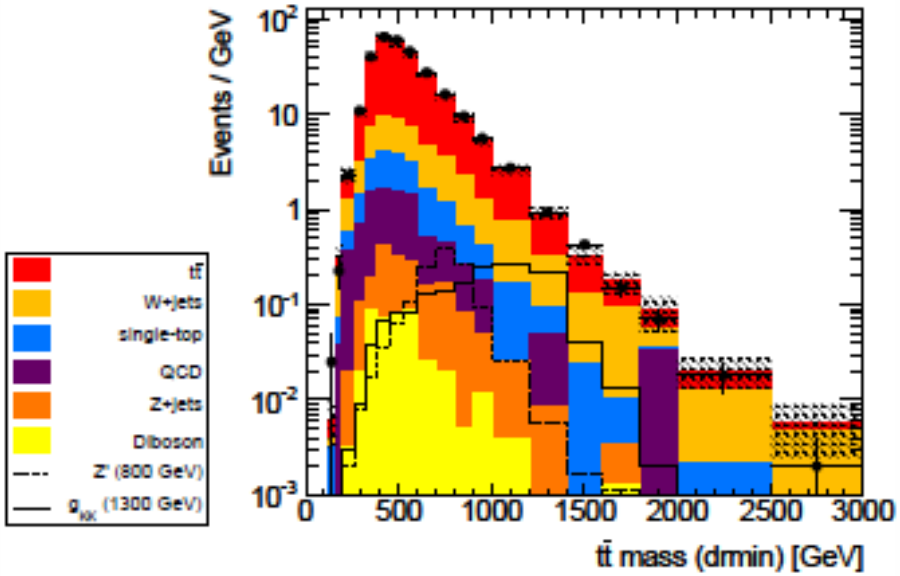
Search for Top Quark Pair Resonances

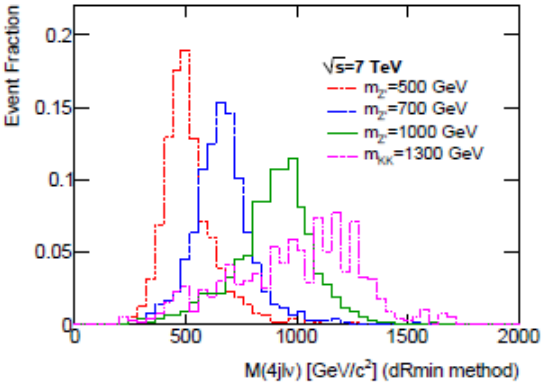
- Strategy
  - Identify top quark pairs as in a cross section measurement
    - Optionally remove jets that are too far from other jets or leptons in the event
  - Plot the invariant mass of the top quark pairs
  - Search for excess pairs above SM predictions
    - Proceed to set upper limits in the absence of any signal
  - Complications begin to arise for top quark pair resonances > 1 TeV because boosted top quarks may be reconstructed as a single fat jet rather than the usual three distinct jets

Search for Top Quark Pair Resonances

- The $t\bar{t}$ invariant mass spectrum after all selection criteria







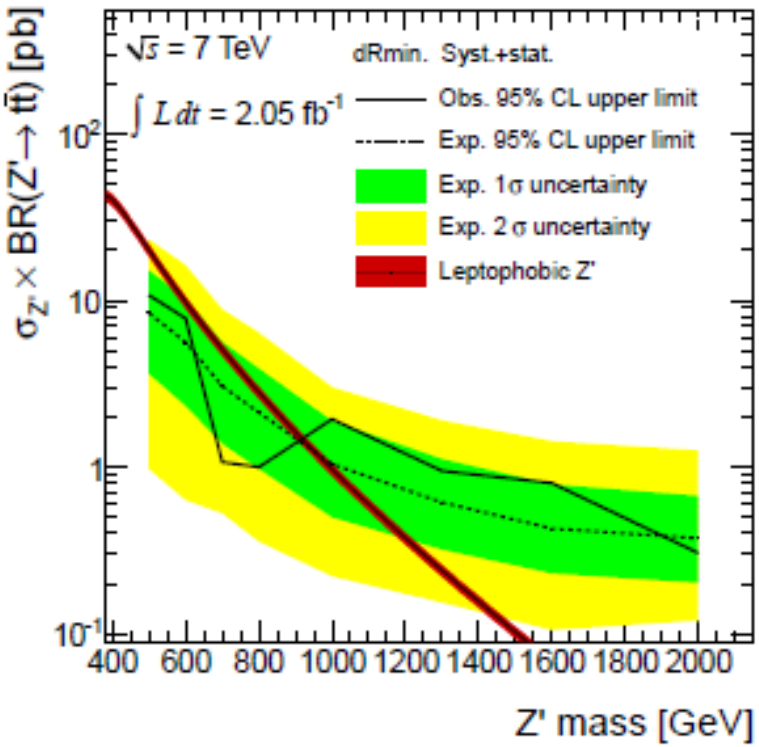
Search for Top Quark Pair Resonances

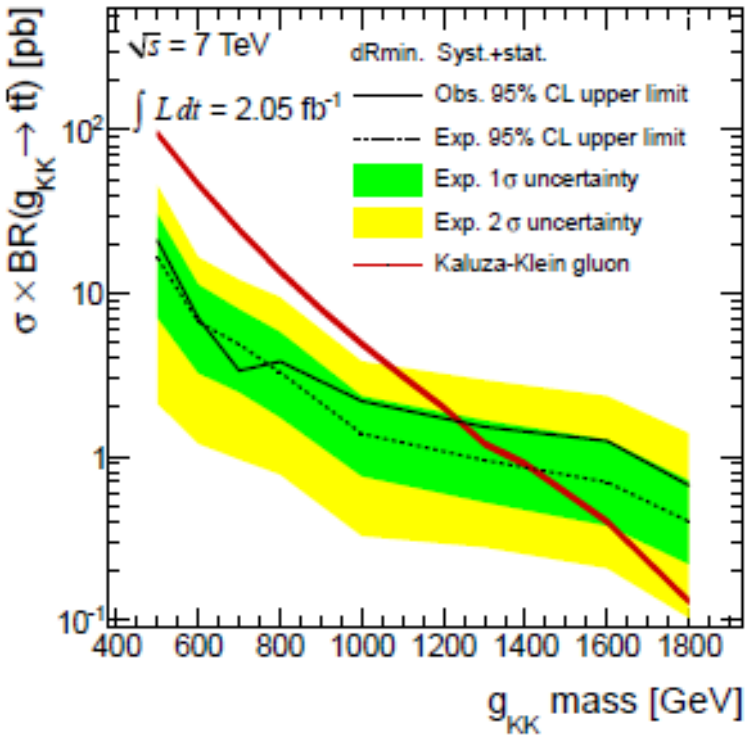
- Systematic errors to consider

Source	$t\bar{t}$	W+jets	All MC	Z', $m_{Z'}$ = 1000 GeV
Jet energy scale	+10.6% -11.5%	+73% -34.8%	+18.7% -14.5%	+4.8% -5.1%
Jet energy resolution	±0.9%	±9%	±2.2%	±0.1%
Jet reconstruction efficiency	< 1%	< 1%	< 1%	< 1%
b-tagging efficiency (incl. mistag rate)	+15.1% -13.4%	+5.9% -5.2%	+12.8% -11.2%	+18.8% -16.4%
Muon p_T resolution	< 1%	< 1%	< 1%	< 1%
Muon efficiency	< 1%	< 1%	< 1%	< 1%
Electron energy scale	< 1%	< 1%	< 1%	< 1%
Electron energy resolution	< 1%	< 1%	< 1%	< 1%
Electron ID efficiency	±1.1%	±1.1%	±1.1%	±1.2%
E_T^{miss}	< 1%	< 1%	< 1%	< 1%
$m_{t\bar{t}}$ shape	±0.6%	–	–	–
Parton shower & fragmentation	±4.1%	–	–	–
ISR	+4.3% -10.4%	– –	– –	+1% -8.5%
Wc normalization	–	± 3.5%	–	–
Wbb/Wcc normalization	–	± 20.4%	–	–
W modeling: iqopt3	–	± 3.9%	–	–
W modeling: ptjmin	–	< 1%	–	–
LAr hole	< 1%	< 1%	< 1%	< 1%
Pile-Up	< 1%	< 1%	< 1%	< 1%

Limits for Topcolor Z' and KK Gluon Resonances

- 95% CL upper limits including stat. and sys. errors

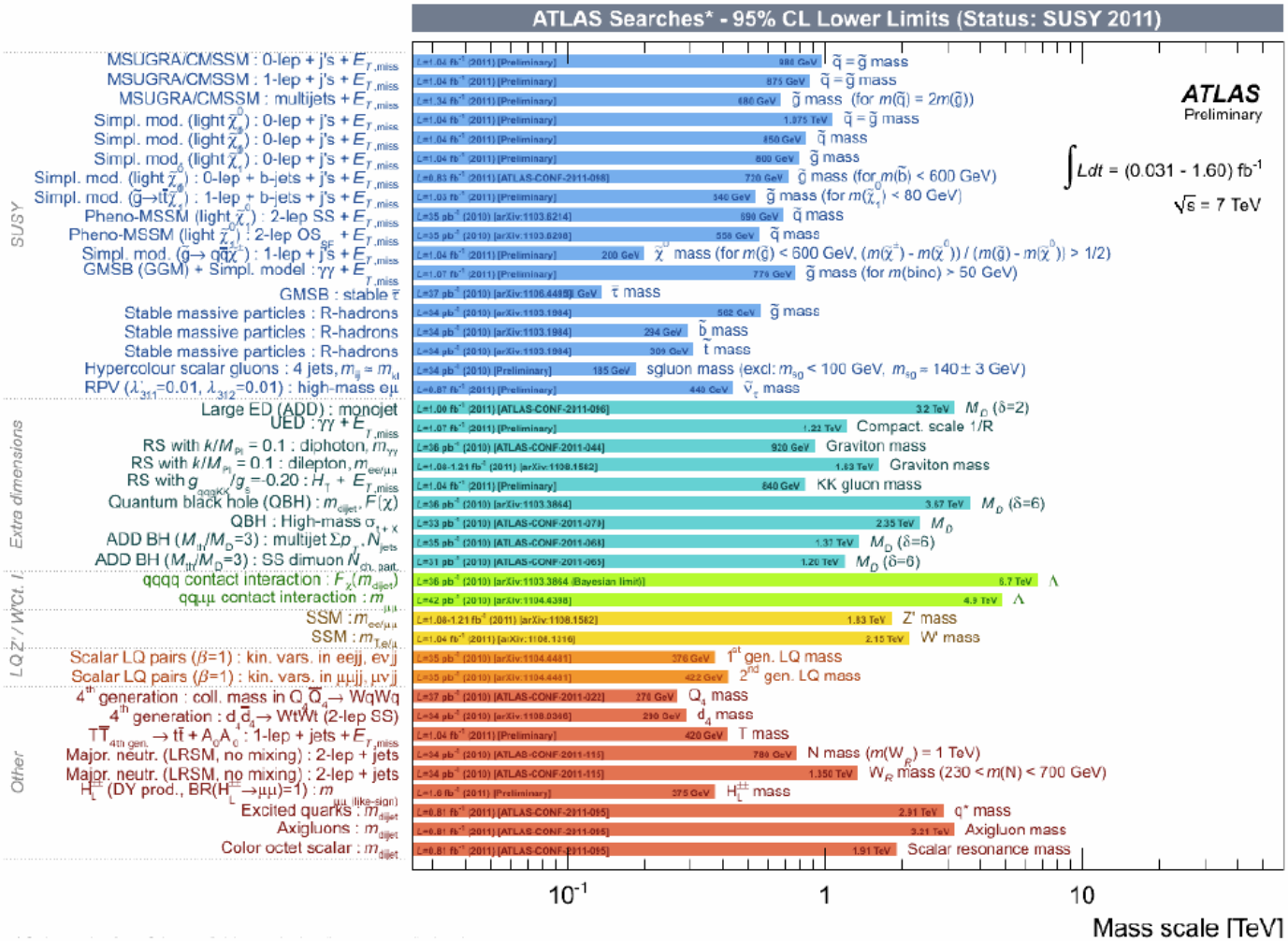




- Z' with m < 9xx GeV is excluded at 95% CL
- KKg with m < 1xxx GeV is excluded at 95% CL

ATLAS BSM Searches

- Many other searches to talk about another day

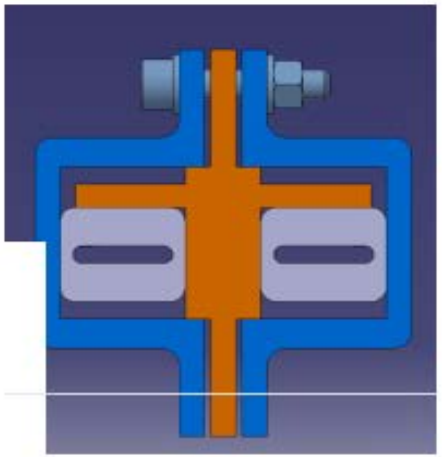


Conclusions

- The LHC and ATLAS experiment performed exceedingly well in 2011, with > 5 fb^{-1} of data recorded
- A wide range of Higgs masses have been excluded using ~half of the 2011 data
- Increased integrated luminosity may allow us to discover the new animals that await beyond the SM landscape

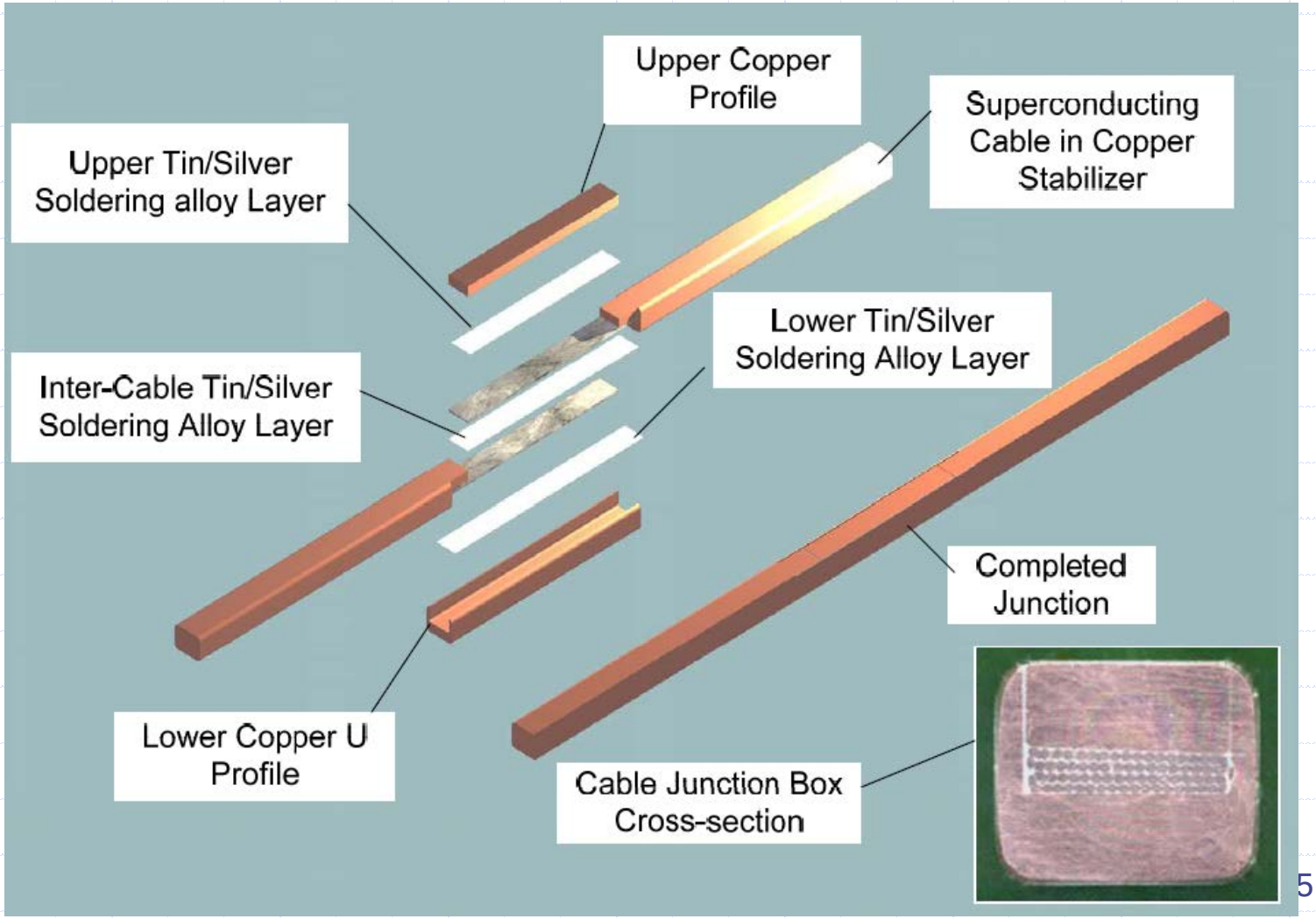
LHC Interconnect Busbars

- For safe running at 14 TeV, all 10k interconnect splices must be repaired



LHC Dipole Busbars

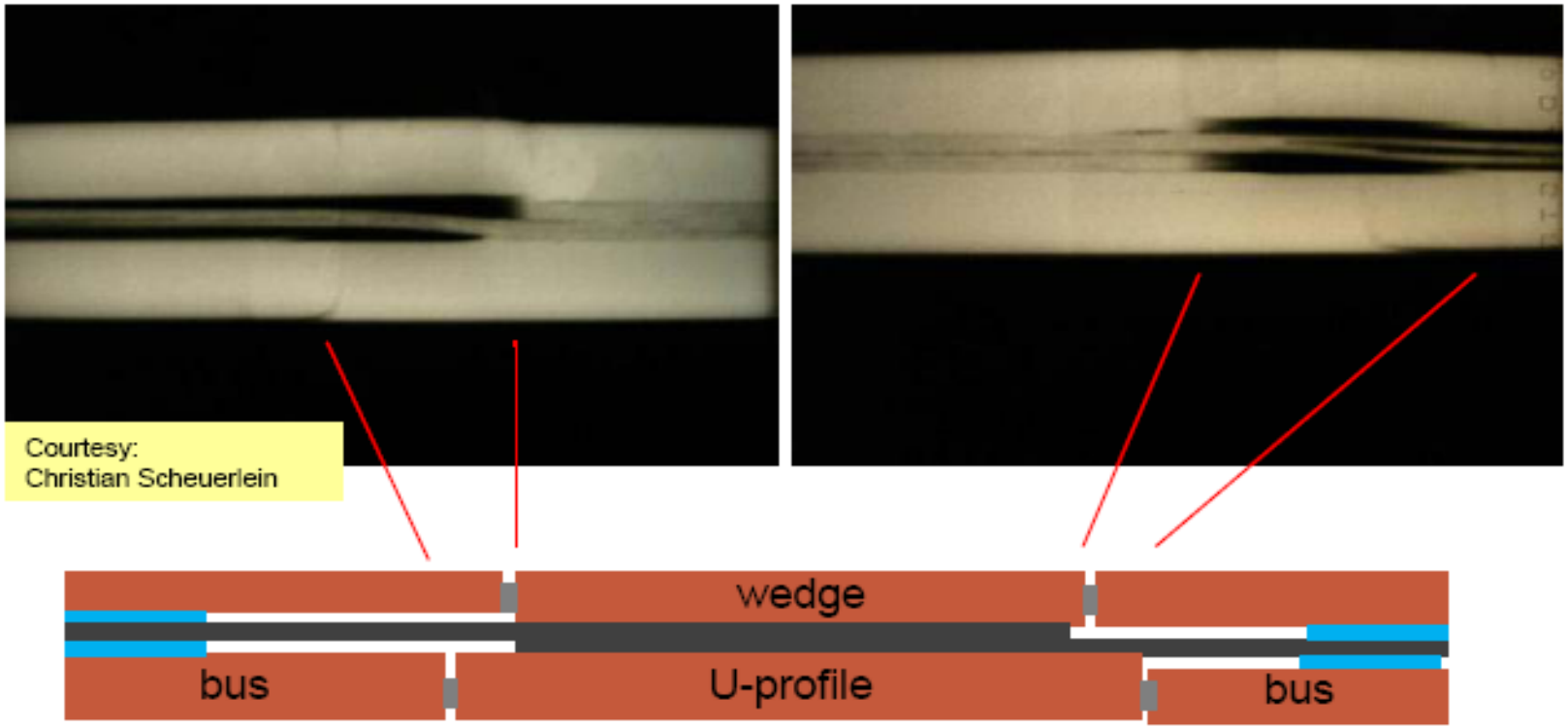
- Carrying up to 13 kA



LHC Dipole Busbars

- Unfortunately conceptual mistakes plus design errors plus execution errors =

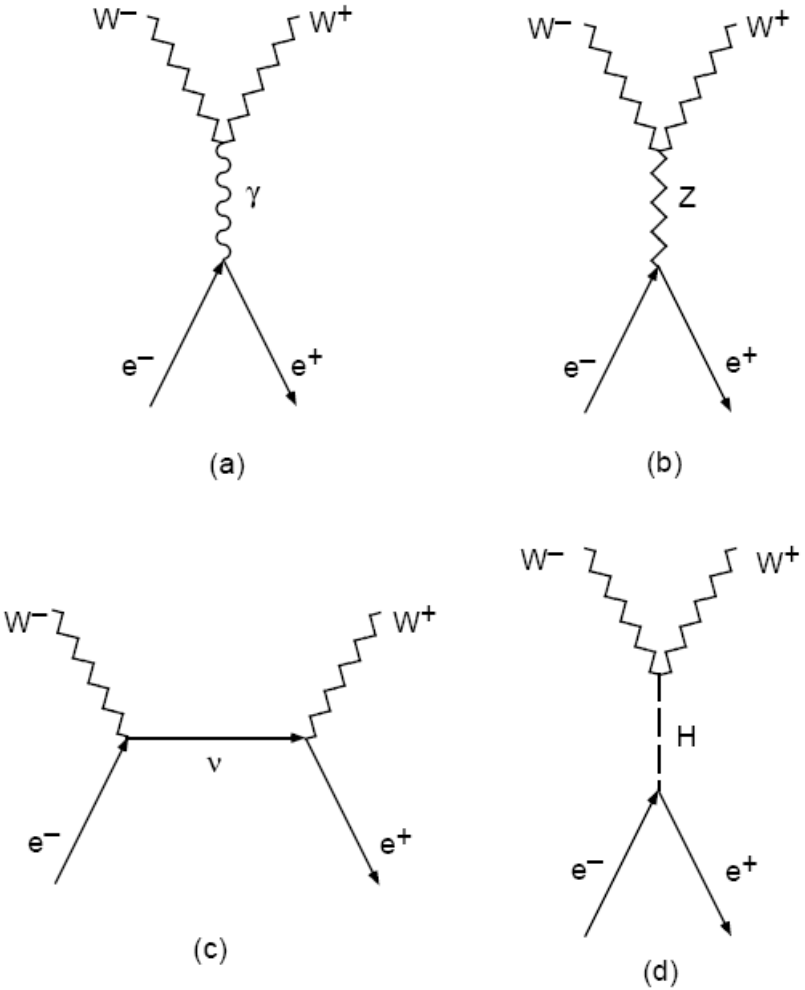
Gamma rays QBBI.B25R3-M3 before disconnection (QRL connection & QRL lyra sides)



Where to Search for the Higgs

- An upper limit can be found by considering the scattering amplitudes for
  - Partial wave unitarity yields

$$m_H \leq 1 TeV$$



Standard Model

- One of the goals in physics is to understand complex phenomena in terms of a few simple principles
- The Standard Model joins the strong, weak and electromagnetic interactions in the sense that they all arise from a common symmetry principle
  - The symmetry is called local gauge invariance
  - It is the breaking of this symmetry (electroweak symmetry breaking) that provides us with an opening to formulate a general mechanism for mass generation

Standard Model

- Requiring the electromagnetic and weak interaction Lagrangians to be locally gauge invariant necessitates the introduction of 1 + 3 gauge fields
  - These we'd like to identify as the photon, W^+, W^-, and Z
- Unfortunately any mass term associated with these gauge fields would spoil the local gauge symmetry
  - Thus in this theory the photon, W^+, W^-, and Z are massless

Standard Model

- Local gauge invariance
  - One can easily imagine that quantum field theories are invariant under global gauge (phase) transformations

$$\psi(x) \rightarrow \psi'(x) = e^{i\alpha}\psi(x)$$

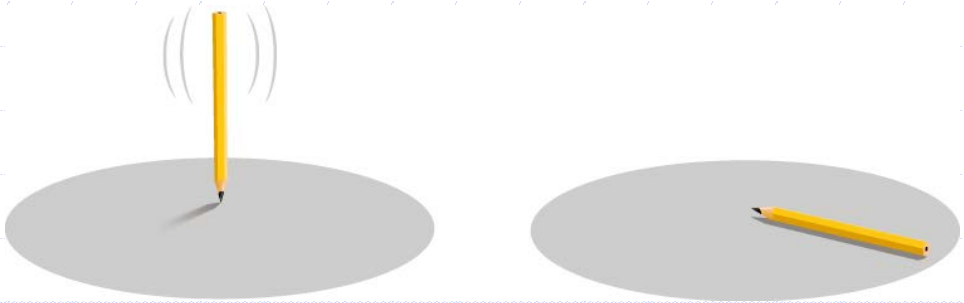
  - One could ask whether they are also invariant under local gauge transformations

$$\psi(x) \rightarrow \psi'(x) = e^{i\alpha(x)}\psi(x)$$

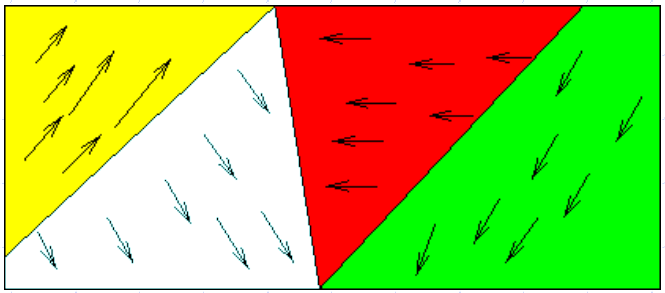
  - The answer turns out to be yes if we introduce a gauge covariant derivative that includes a gauge boson field – the photon

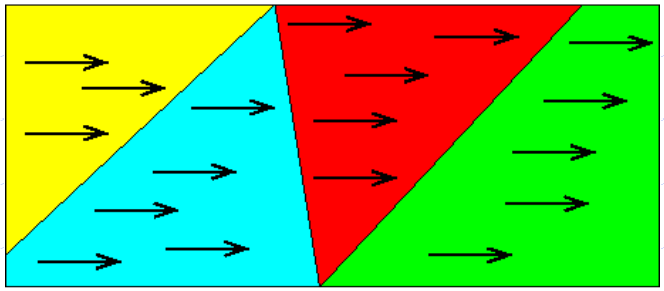
Standard Model

- Spontaneous Symmetry Breaking (SSB) occurs when a Lagrangian is invariant under some symmetry but the ground state (vacuum) is not
  - Pencil falling



  - Heisenberg ferromagnet





- 2008 Nobel Prize to Nambu for discovering SSB

Standard Model

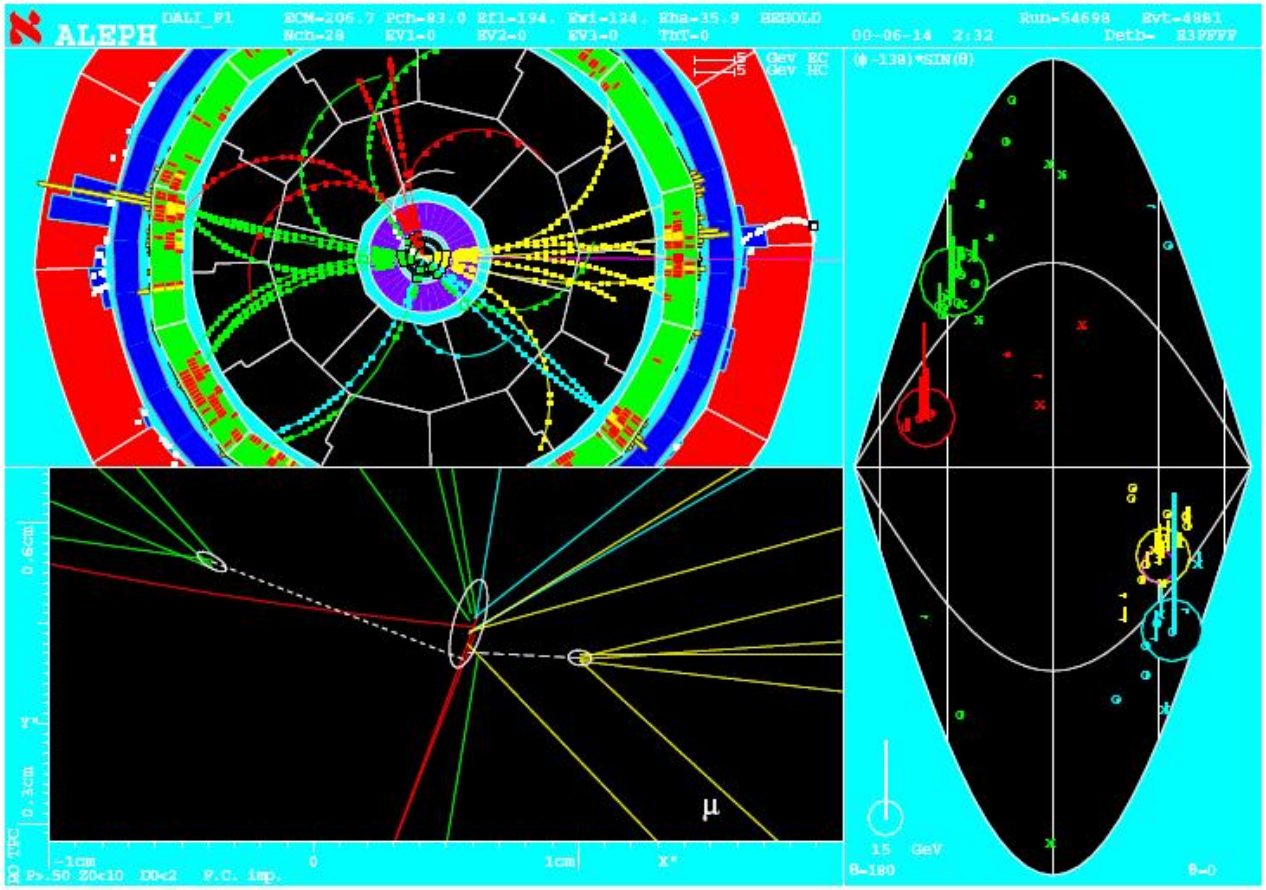
- Higgs mechanism
  - We have SSB when a Lagrangian is invariant under some symmetry but the ground state (vacuum) is not
  - If the broken symmetry is a continuous symmetry, then there necessarily exists one or more massless spin 0 particles (Goldstone bosons)
  - If the broken symmetry is a local gauge symmetry, then the Goldstone bosons get absorbed (eaten) by the massless gauge bosons thereby acquiring mass

Where to Search for the Higgs

- The combined result was

$$m_H > 114.4\,\text{GeV} \;@\; 95\%\,\text{CL}$$

- Of course there were interesting events

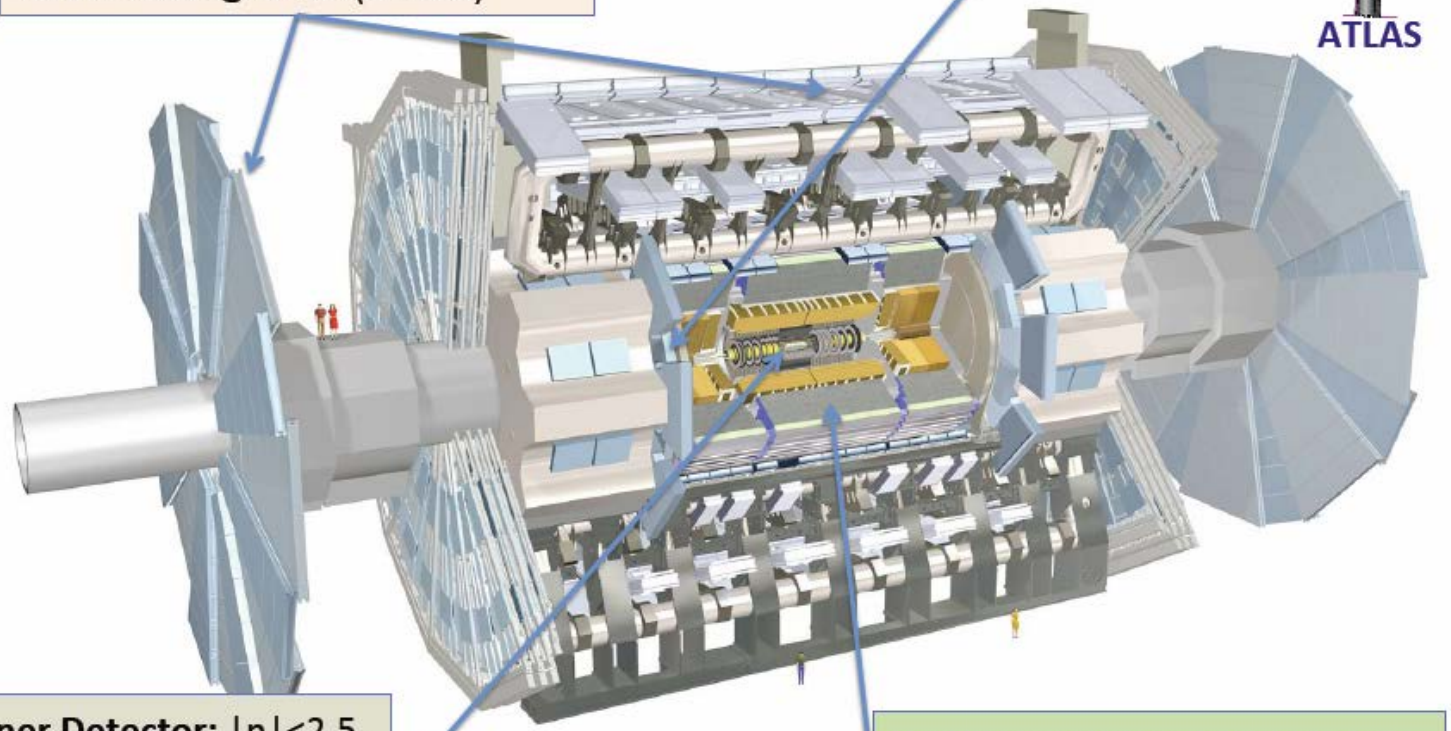


The ATLAS detector

Muon Spectrometer: |η|<2.7
Air-core toroids and gas-based muon chambers σ/p_T = 2% @ 50 GeV to 10% @ 1TeV (ID+MS)

EM Calorimeter: |η|<3.2
Pb-LAr Accordion $\sigma/E=10\% \sqrt{E} \oplus 0.7\%$

ATLAS



Inner Detector: |η|<2.5, B=2T, Si pixels/strips and Trans. Rad. Det.; σ/pT = 0.05% pT (GeV) ⊕ 1%

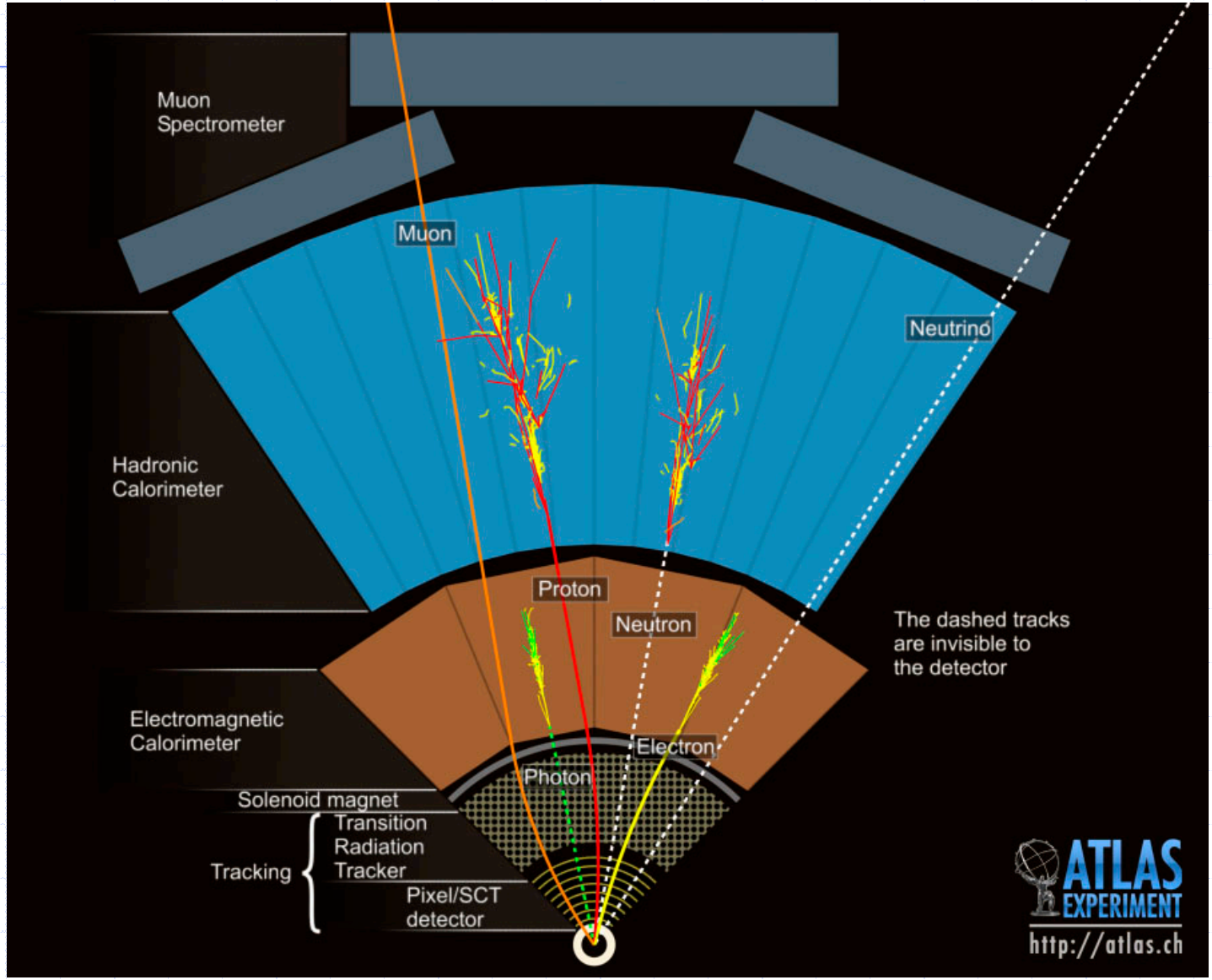
Hadronic calorimeter: |η|<1.7 Fe/scintillator 1.3<|η|<4.9 Cu/W-LAr; $\sigma/Ejet= 50\%/\sqrt{E} \oplus 3\%$

Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.5	100	89.3	92.7	94.3	99.5	100	99.5	100	99.9	98.5	97.9

Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.5	100	89.3	92.7	94.3	99.5	100	99.5	100	99.9	98.5	97.9

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at $\sqrt{s}$=7 TeV between March 13th and June 6th (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future. The magnets were not operational for a 3-day period at the start of the data taking.

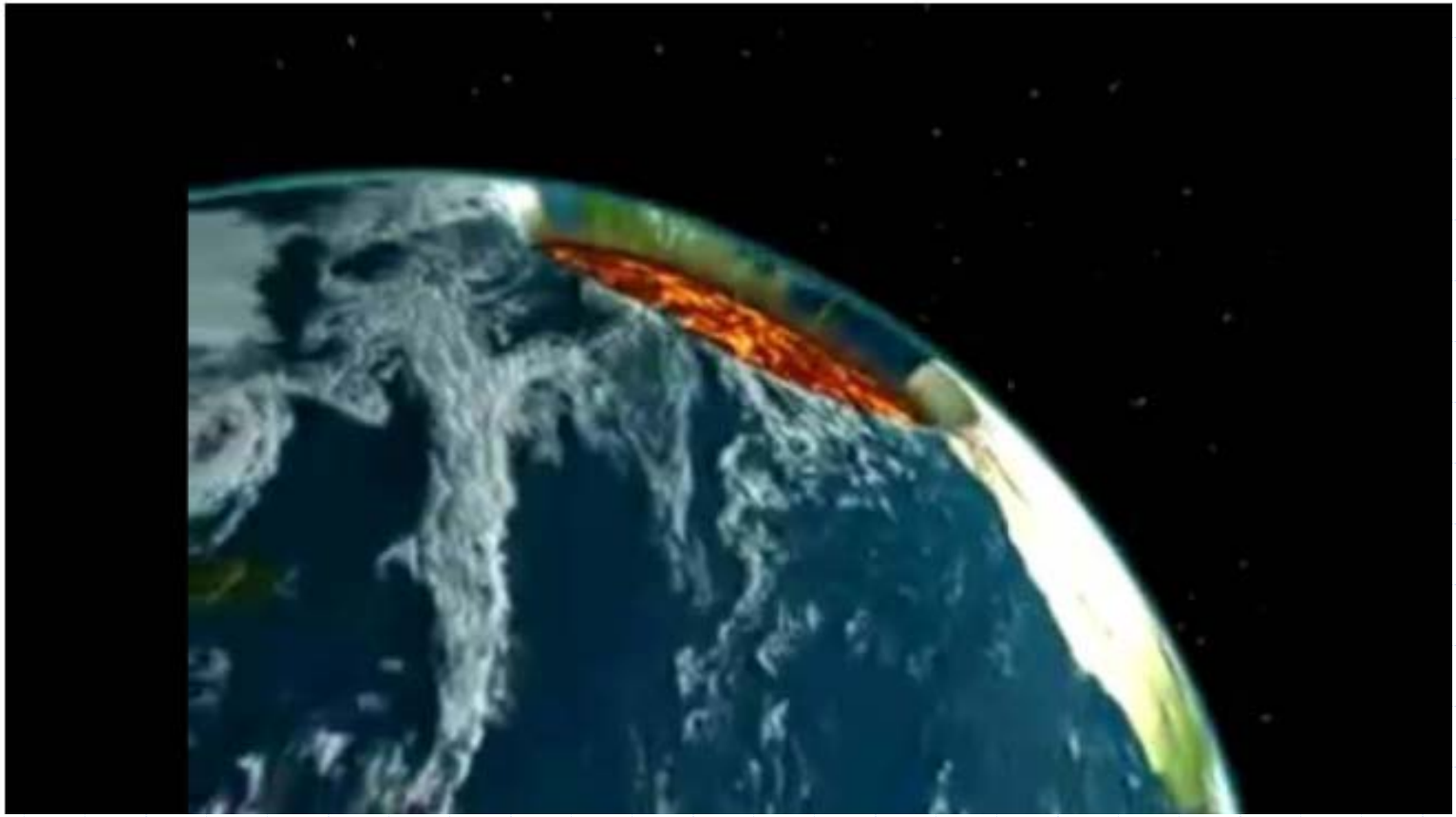
Particle Identification in ATLAS



First Beam in the LHC

- No black hole or stranglet production

The CERN black hole



Beam Re-established in the LHC

- November 20, 2009 - 14 months later in the ATLAS control room

Pb-Pb Physics at 2.76 TeV (per nucleon)

- November 8, 2010