Title: Collider Experiments 1

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Abstract:

Argonne NATIONAL LABORATORY

Colliders

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Before We Take Off

STOP ME if I go too fast or you have questions!!

I know I talk too fast, so please interrupt me – my goal is not to cover as much material as possible: it's to *uncover* as much material as possible

Syllabus

These lectures will be backwards. I plan to start with something specific and then work my way to the more general.

- Higgs Discovery
- Hadron Colliders and Detectors
- Electron Colliders
- What Did We Learn from the LHC?
- Future Colliders

Thanks to the Organizers

- Thanks for the opportunity to talk about physics near and dear to my heart, and…
- Thanks for the opportunity to return to the land of my ancestors

The part where the LeComptes are from

The part with a sensible climate

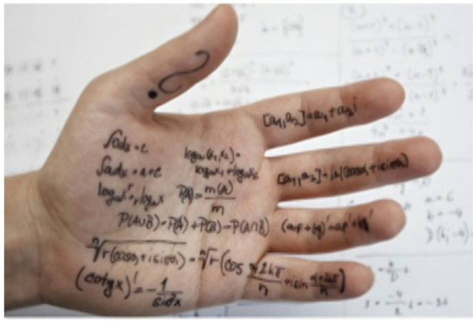
4

Who Is This Guy?

- This is a picture of a small, round-faced, adorable creature.
- Holding a koala.

- I got my PhD in 1992 on E-705, a Fermilab fixed target charmonium experiment.
- I then moved into hadron collider physics, and have worked at pretty much every such collider:
  - CDF at the Tevatron
  - STAR at RHIC
  - ATLAS at the LHC
- Recently I was the physics coordinator of ATLAS
- I have worked on QCD/Heavy Flavor Production, SUSY and Higgs.

Cheating Already? On Slide 6?



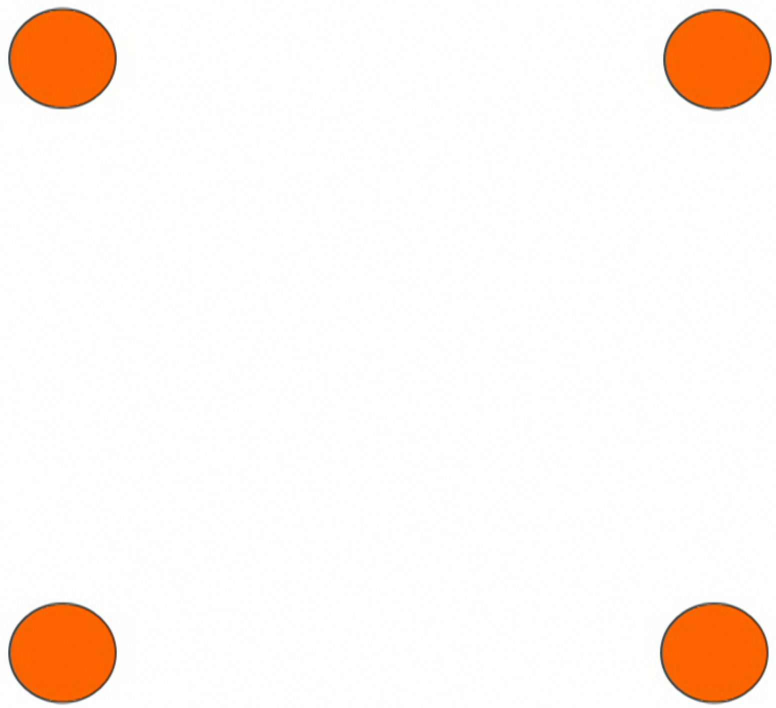
- I was charged with talking about colliders, and will use the Higgs discovery as a framework

- I'm actually going to do this!

- But not as a death march through a jungle of plots and tables. Instead I want to highlight
  - What we know and how we know it
  - What we would like to know
  - How we might go about doing this
  - With examples from ATLAS, CMS and elsewhere when appropriate

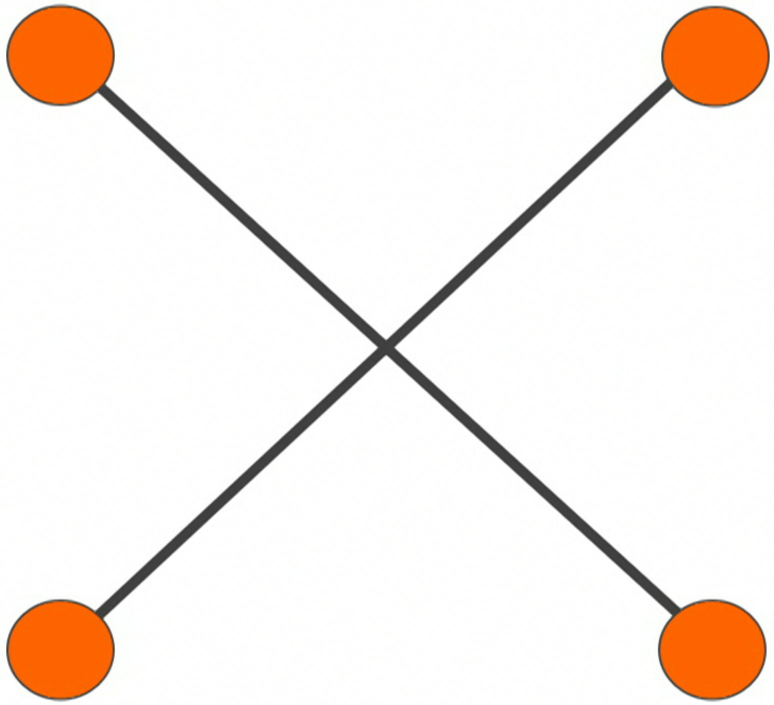
- With only four lectures, there will inevitably be some omissions and oversimplifications

Spontaneous Symmetry Breaking



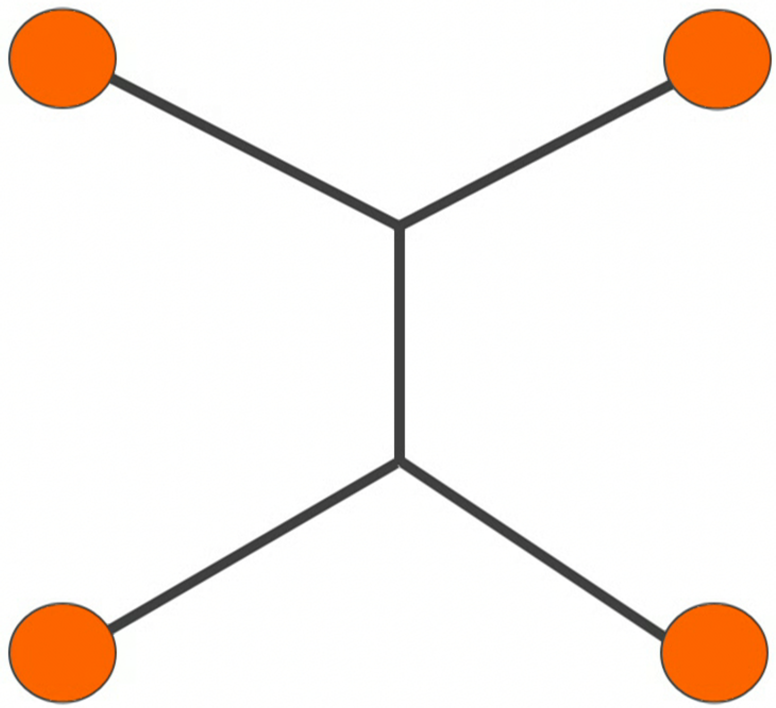
What is the least amount of railroad track needed to connect these 4 cities?

Option Three



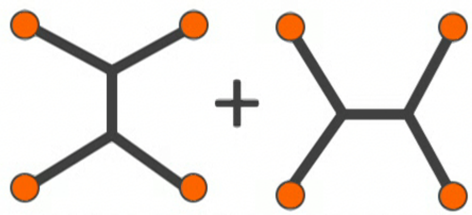
This requires only $2\sqrt{2}$

The Real Optimal Solution



This requires $1+\sqrt{3}$

Note that the symmetry of the solution is lower than the symmetry of the problem: this is the definition of *Spontaneous Symmetry Breaking*.

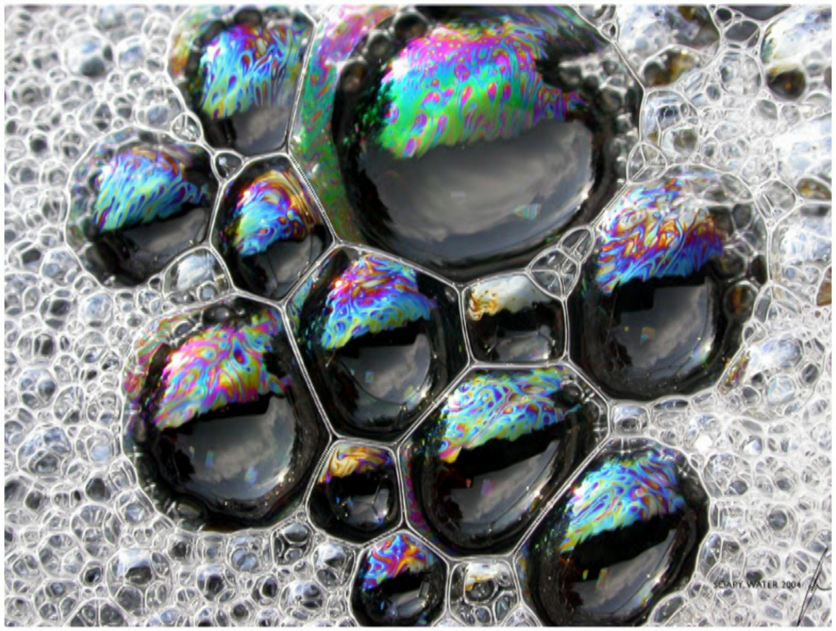


n.b. The sum of the solutions has the same symmetry as the problem.

A Pointless Aside

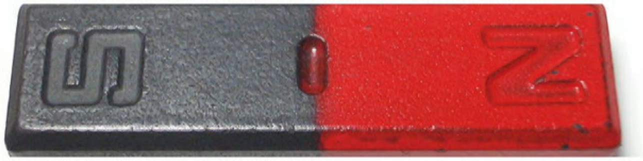
One might have guessed at the answer by looking at soap bubbles, which try to minimize their surface area.

But that's not important right now…



Another Example of Spontaneous Symmetry Breaking

Ferromagnetism: the Hamiltonian is fully spatially symmetric, but the ground state has a non-zero magnetization pointing in some direction.



The Higgs Mechanism

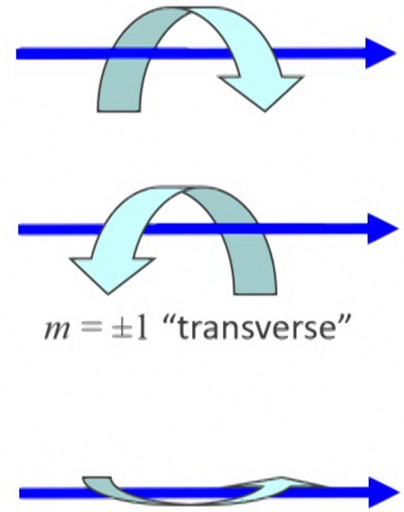
- Write down a theory of massless weak bosons
  - The only thing wrong with this theory is that it doesn't describe the world in which we live
- Add a new doublet of spin-0 particles:
  - This adds *four* new degrees of freedom (the doublet + their antiparticles)

$$\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \begin{pmatrix} \varphi^- \\ \varphi^{*0} \end{pmatrix}$$

- Write down the interactions between the new doublet and itself, and the new doublet and the weak bosons in just the right way to
  - Spontaneously break the symmetry: i.e. the Higgs field develops a non-zero vacuum expectation value
    - Like the magnetization in a ferromagnet
  - Allow something really cute to happen

The Really Cute Thing

- The massless w^+ and ϕ^+ mix.
  - You get one particle with *three* spin states
    - Massive particles have three spin states
  - The W has acquired a mass
- The same thing happens for the w^- and ϕ^-
- In the neutral case, the same thing happens for one neutral combination, and it becomes the massive Z^0.
- The other neutral combination doesn't couple to the Higgs, and it gives the massless photon.
- That leaves one degree of freedom left, and because of the non zero v.e.v. of the Higgs field, produces a massive Higgs.



$m = \pm 1$ "transverse"

$m = 0$ "longitudinal"

How Cute Is It?

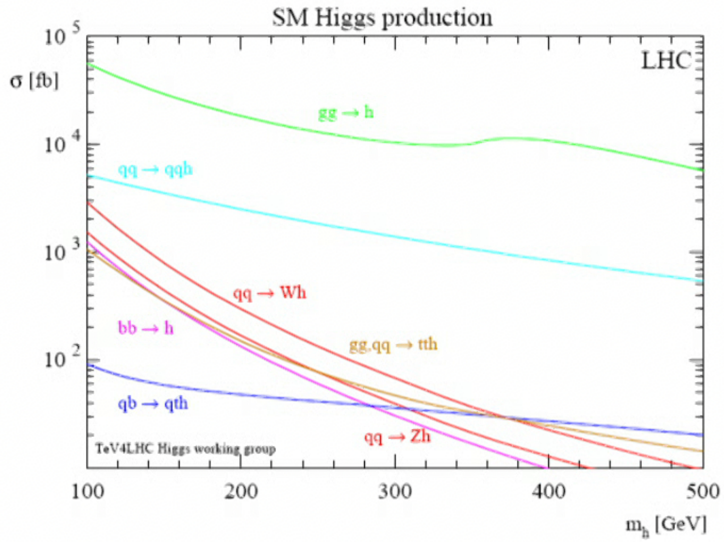
- There's very little choice involved in how you write down this theory.
  - There's one free parameter which determines the Higgs boson mass
  - There's one sign which determines if the symmetry breaks or not.

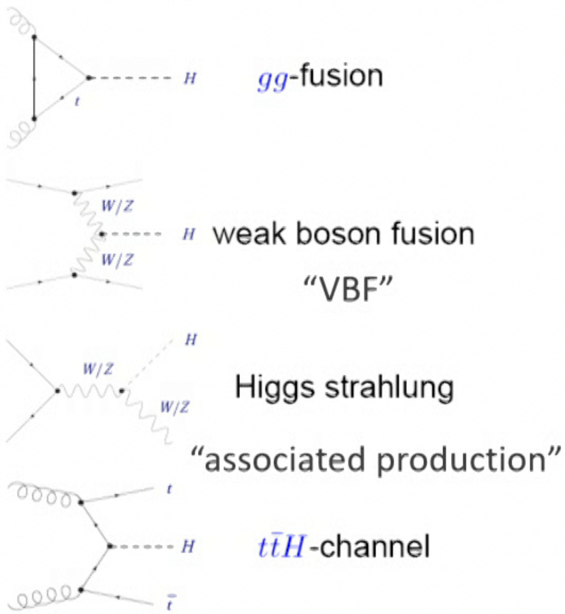
- The theory leaves the Standard Model mostly untouched
  - It adds a new Higgs boson – **which we can look for**
  - It adds a new piece to the WW → WW cross-section
    - This interferes destructively with the piece that was already there and restores unitarity

- In this model, the v.e.v. of the Higgs field ***is*** the Fermi constant
  - This shows the deep connection between the Higgs and the weak interaction

Onto the Higgs Boson Discovery

Higgs Production

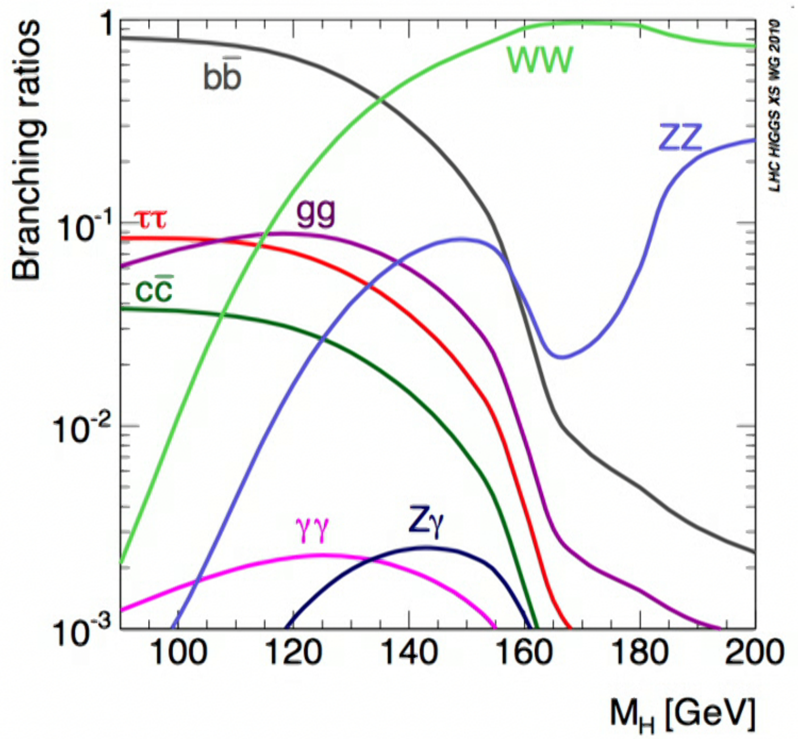




- Glue-glue initiated production dominates
- VBF is a ~10% contribution:
  - Can be larger or smaller than this depending on the analysis
- Associated production is a small piece, only useful in high background regions

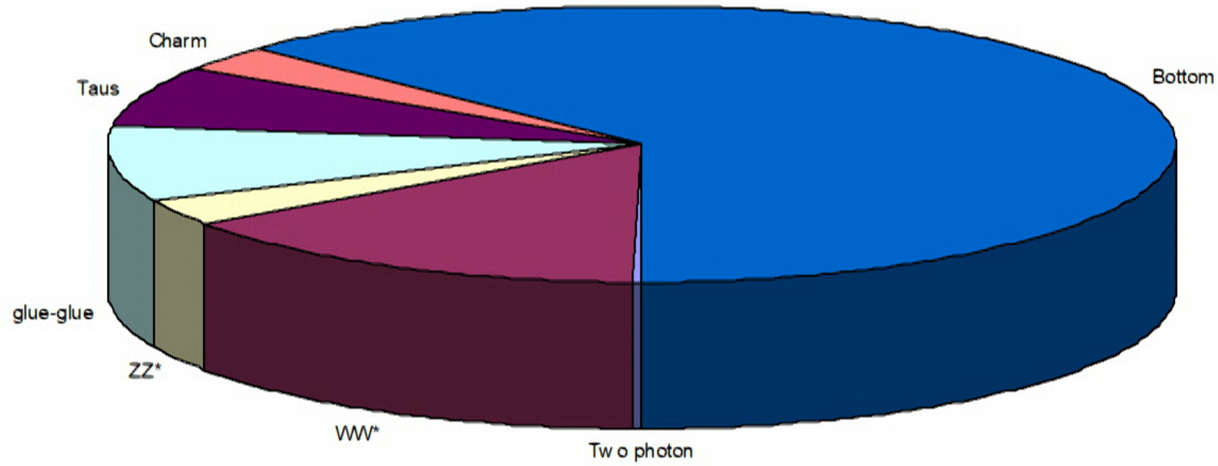
And…

Higgs Decays



- The Higgs wants to decay to heavy gauge bosons if it can. (That's its job)
- Otherwise, it wants to decay into the heaviest fermions it can (That's its other job)
- Modes like γγ occur at one-loop and are suppressed by a factor of ~1000.

More Higgs Decays



- Lesson: Logarithmic plots can be horribly misleading.
  - The above shows the relative decays for a ~125 GeV Higgs.
- Question: Why on earth would anyone design an analysis around this little sliver?

Digression - the Inventor of the "Cut"

Thales of Miletus
(c. 624 BCE – 526 BCE)

- One of the Seven Wise Men of ancient Greece
  - Pre-Socratic (and thus pre-Aristotle) philosopher
  - Pre-Euclid mathematician
  - First to predict a solar eclipse
  - Early speculator in commodities
    - According to Aristotle, predicting a strong harvest, he rented all the olive presses at a discount early in the season and re-rented them at a premium when the olives came in.
- Measured the height of the Pyramids
  - Without Euclidian geometry (which wouldn't be invented for centuries)
  - Thales recognized that twice a day this measurement is easy; twice a day an object's shadow is the same length as the object.

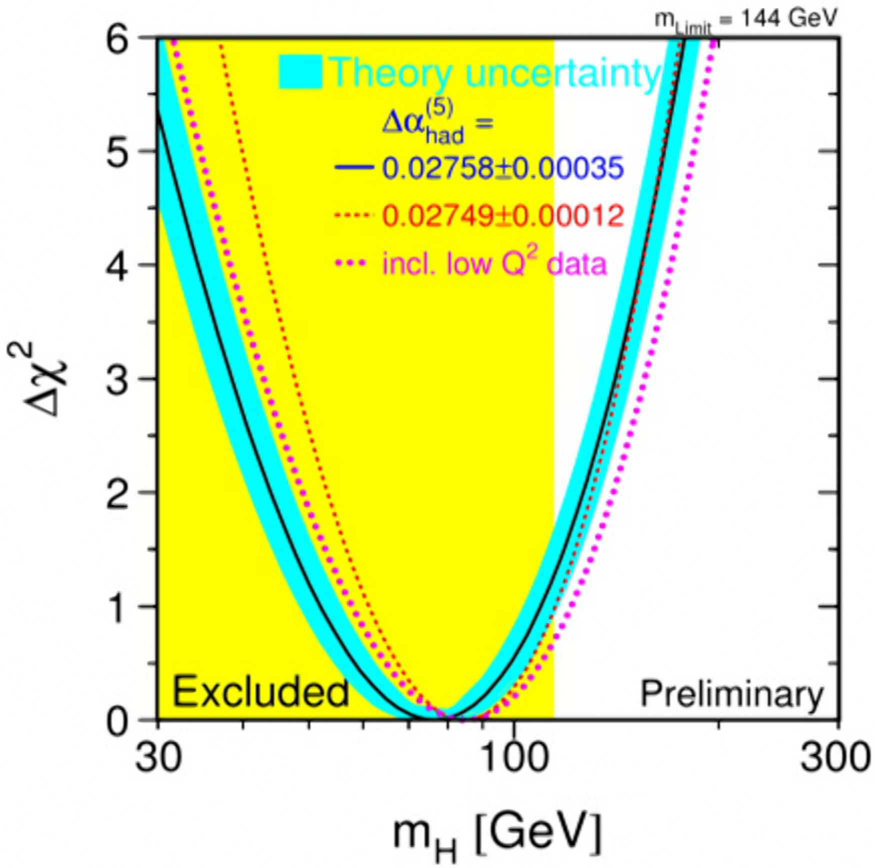
Higgs Decays

Decay Mode	Branching Fraction	Useful Branching fraction	Background Level
Bottom quarks	60%	30%	Tens of thousands:1
WW*	15%	~2%	Few:1
ZZ*	4%	0.014%	Comparable
gluons	10%	10%	Millions:1
taus	8%	6%	A long story
Charm quarks	6%	3%	Tens of thousands:1
Two photons	0.2%	0.2%	Few:1

For a ~125 GeV Higgs

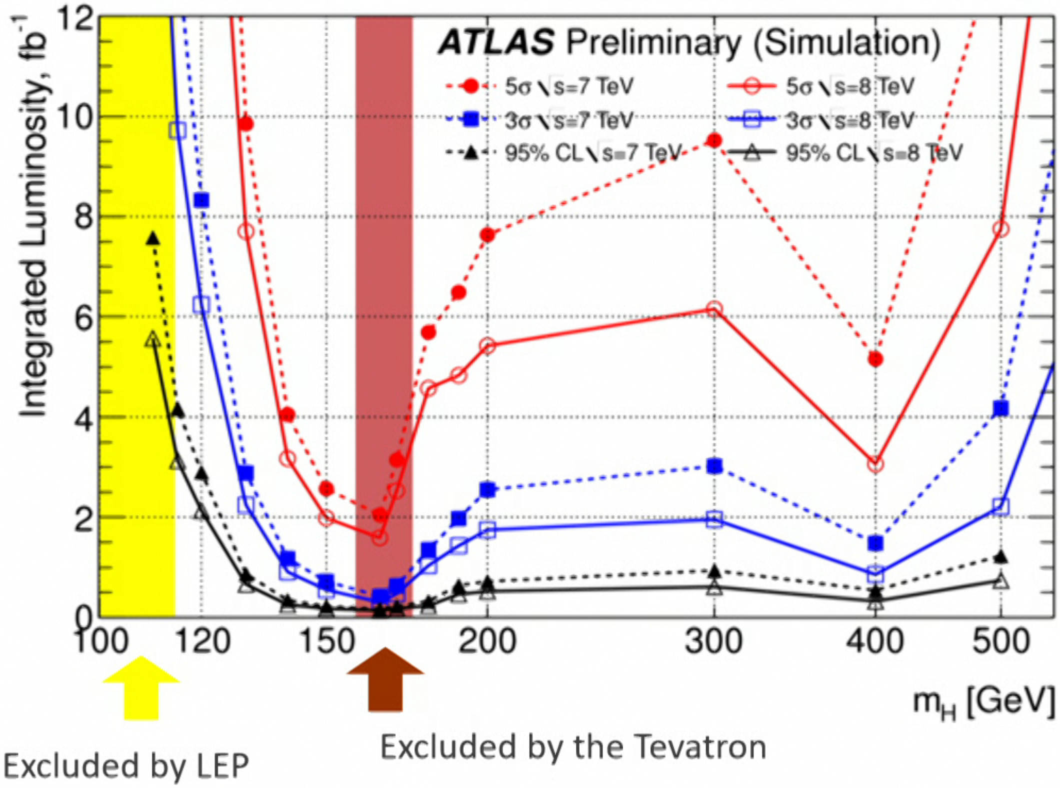
The quantity of signal is but one element in designing an analysis. The level of background is at least as important. While I will only barely touch on it at the moment, so is triggerability: you cannot analyze an event that you didn't record.

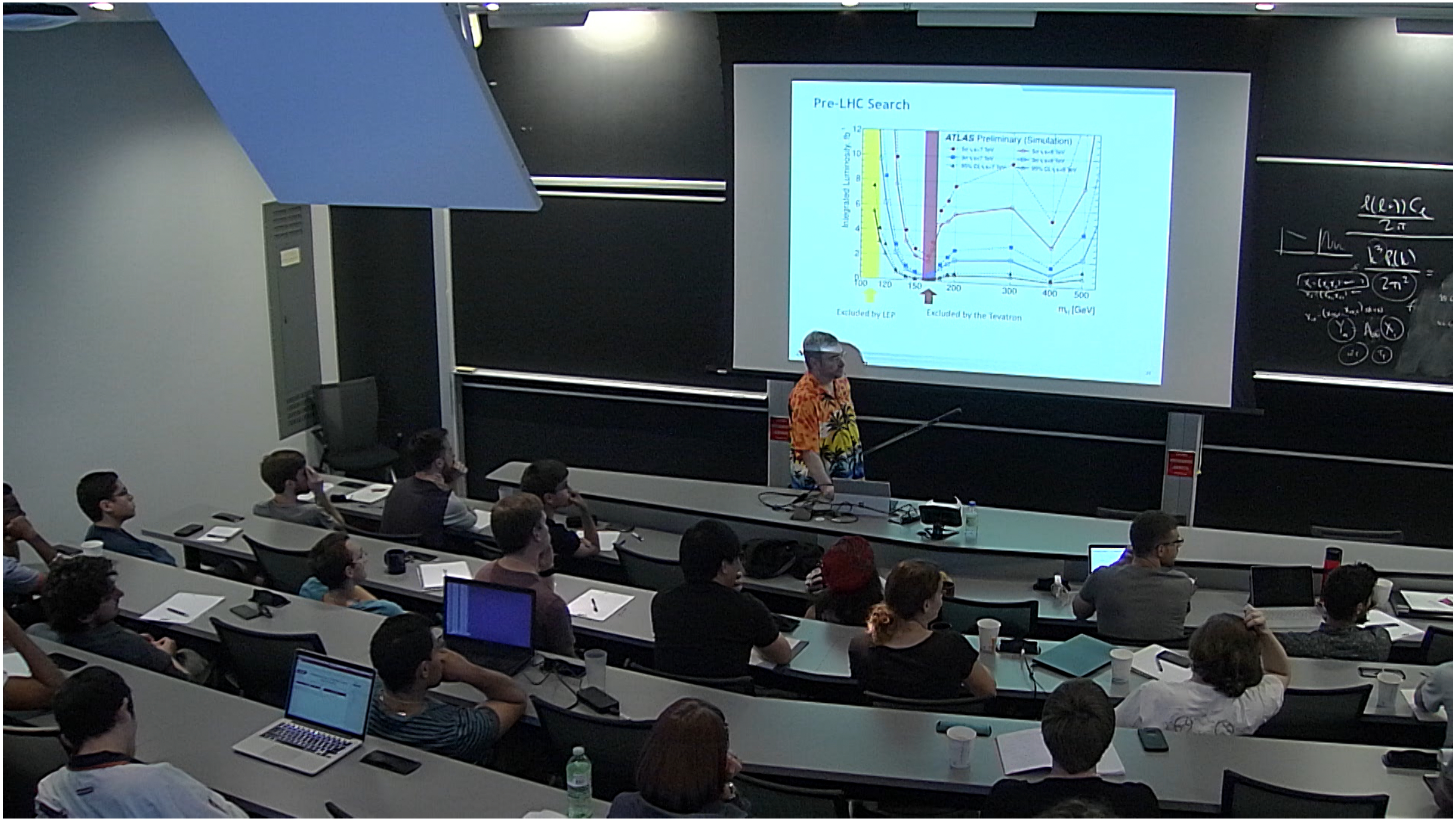
Pre-Search



- Indirect measurements (loop contributions to m_W and m_t) suggest the Higgs is light.
- The assumption in these plots is that there are no other particles (e.g. supersymmetric ones) that also contribute to these loops.
- My conclusion (not universally held)
  - The Higgs can be anywhere between 114 GeV (experimental limit) and ~1 TeV (theoretical limit)

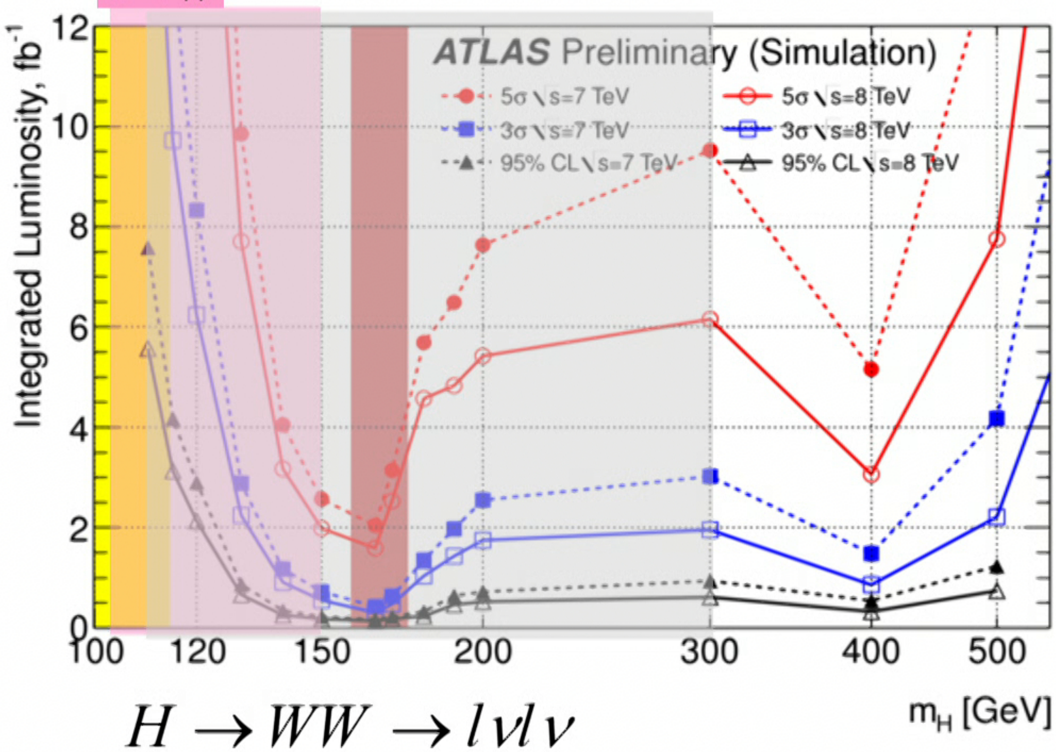
Pre-LHC Search




Pre-LHC Search
ATLAS Preliminary (Simulation)
Integrated Luminosity
Excluded by LEP
Excluded by the Tevatron
m_t [GeV]

Channel-by-Channel

$H \rightarrow \gamma\gamma$



$H \rightarrow WW \rightarrow l \nu l \nu$

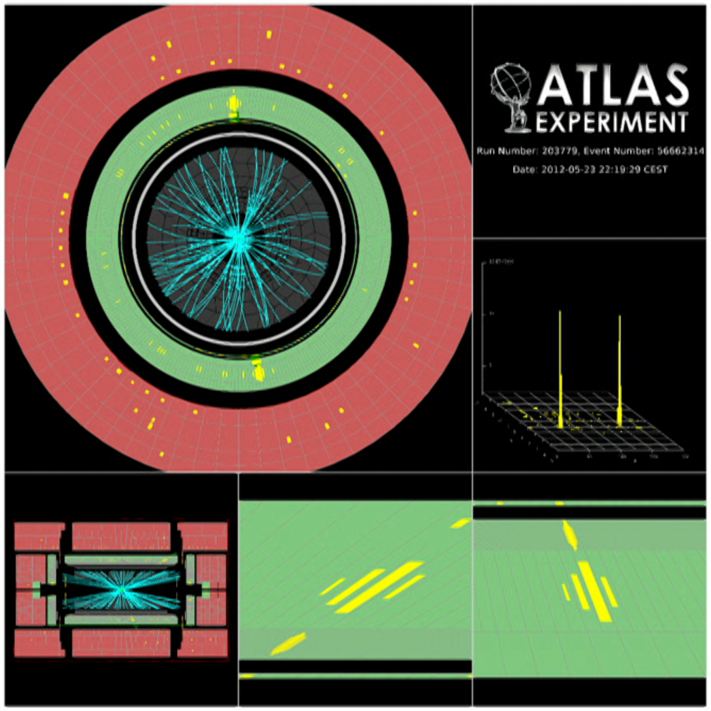
Where Are We After Step #0?

- We will look at H → $\gamma\gamma$.
  - This favors the lowest possible range of Higgs masses.
  - It's produced 90% through gg-fusion and 10% through VBF
  - Tiny branching fraction, but reasonable S/B ratio

- Other people will look at H → WW*
- Still other people will look at H → ZZ*
- And still other people will look for "specialized" Higgs decays
  - Heavy Higgs
  - Charged Higgs
  - Supersymmetric Higgs

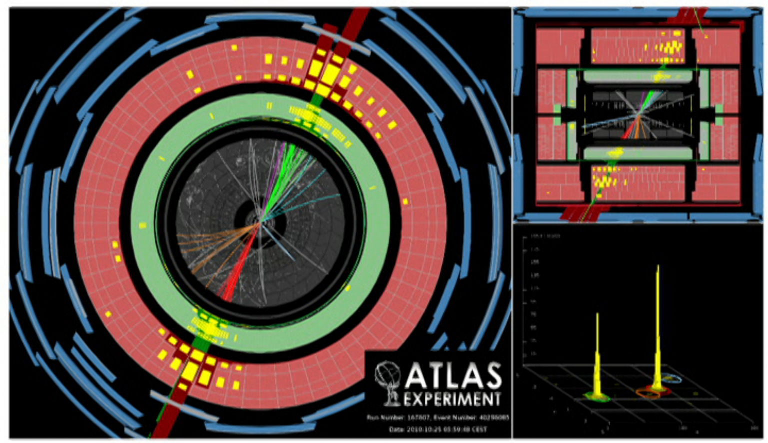
Step #0 is a critical part to an analysis – doing the spadework of thinking about what one is doing, why one is doing, what the strategy is, how that strategy is informed by what we already know (sometimes mistakenly called "theory").

Identifying Photons



We need to separate this...

From this...

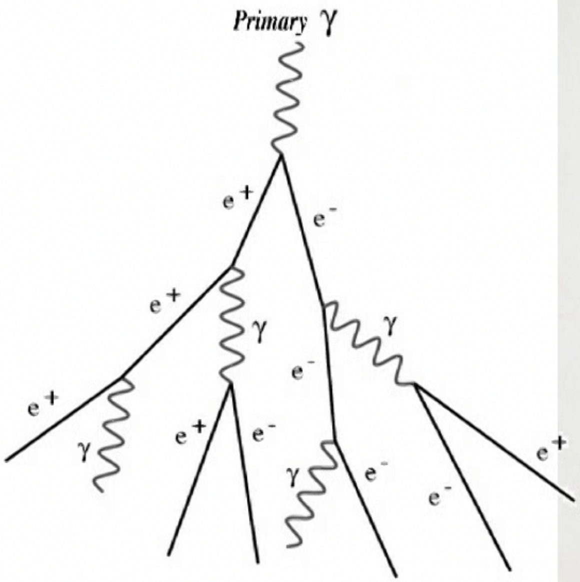


Only a small fraction of jets* can mimic a photon – but there are a lot of jets!

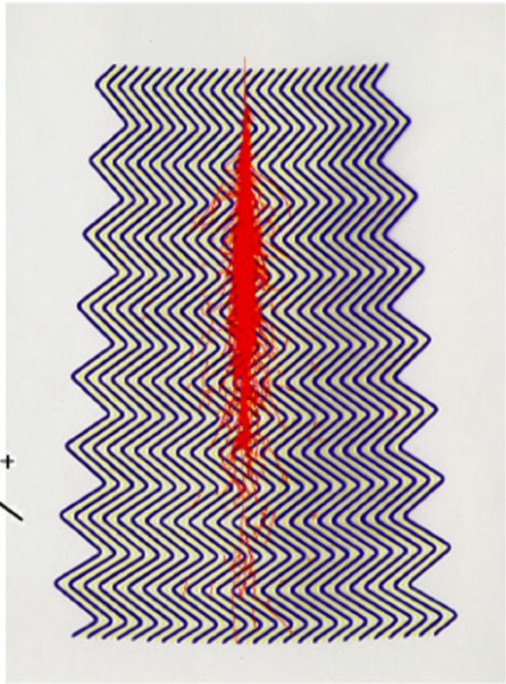
* A jet is a collimated "spray" of hadrons – more later

Identifying Photons – Basics of Calorimeter Design

n.b. these are the very same showers Francis was talking about Monday



A schematic of an electromagnetic shower



A GEANT simulationof an electromagnetic shower

Not too much or too little energy here.

You want exactly one photon – not 0 (a likely hadron) or 2 (likely π^0)

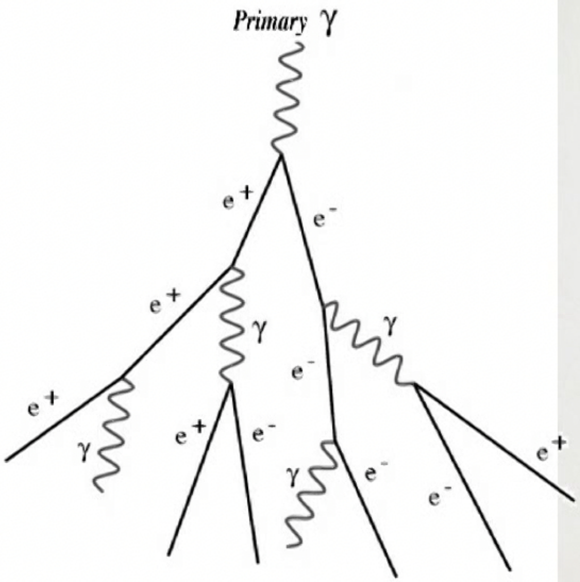
Not too wide here.

One photon and not two nearby ones (again, a likely π^0)

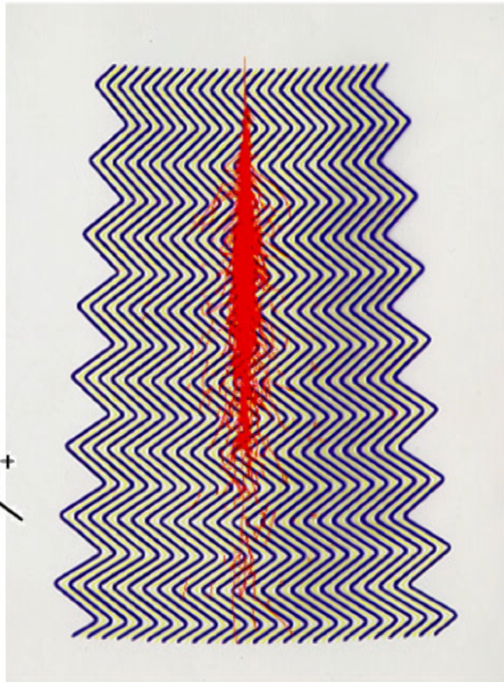
Not too much energy here.

Indicative of a hadronic shower: probably a neutron or K_L.

Identifying Photons – Basics of Calorimeter Design



A schematic of an electromagnetic shower

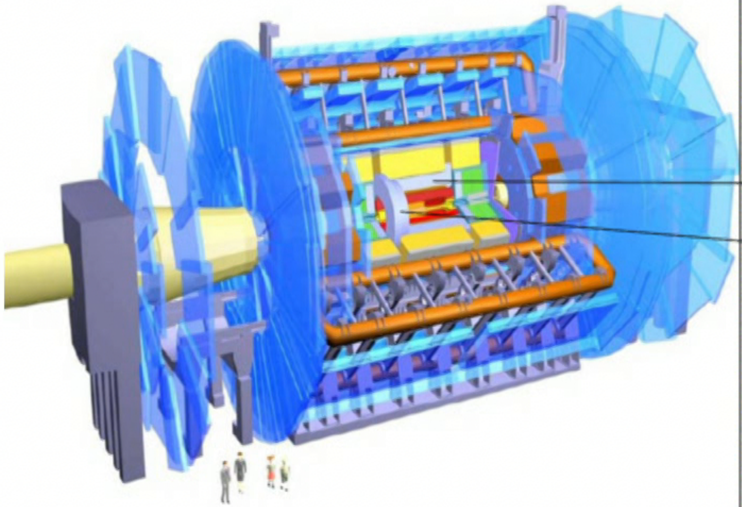


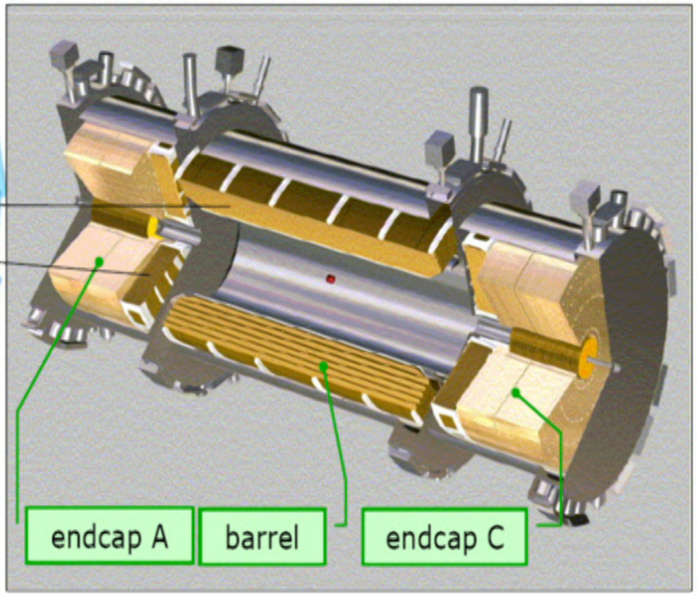
A GEANT simulationof an electromagnetic shower

- EM showers all look the same

- Hadronic showers – and jets - are like snowflakes
  - Every one is unique

ATLAS Electromagnetic Calorimeter





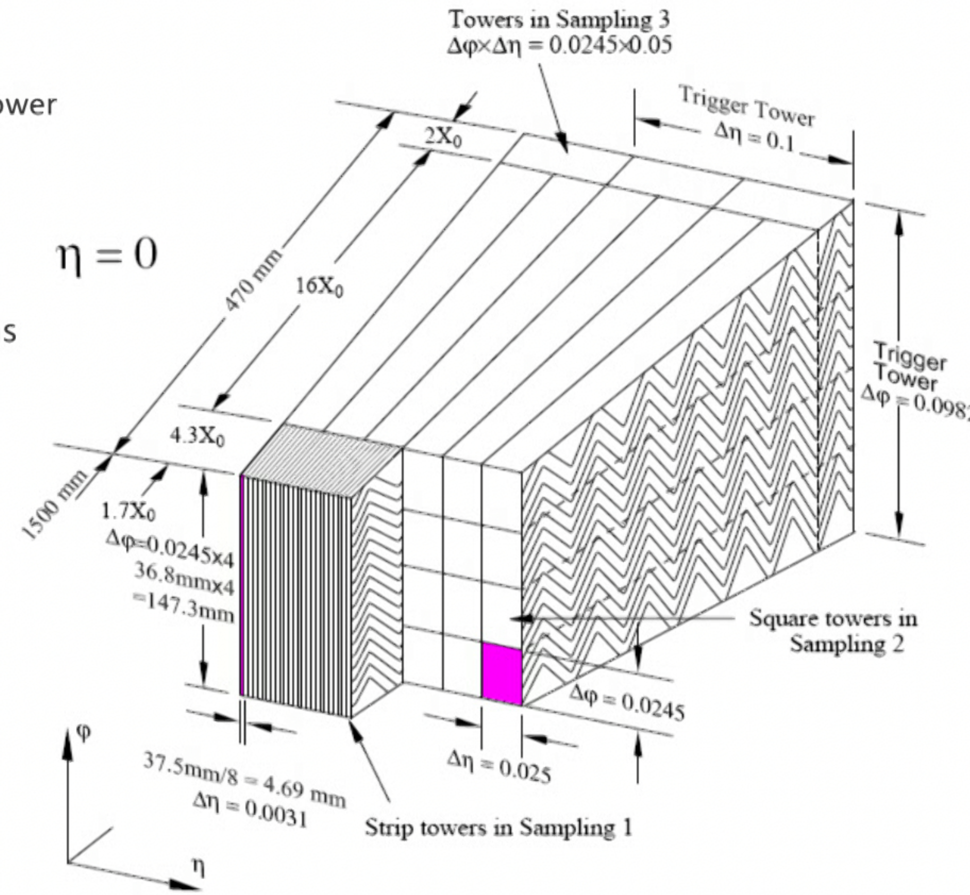
Design resolution:

$$\frac{\delta E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\% \oplus \frac{0.2\,\mathrm{GeV}}{E}$$

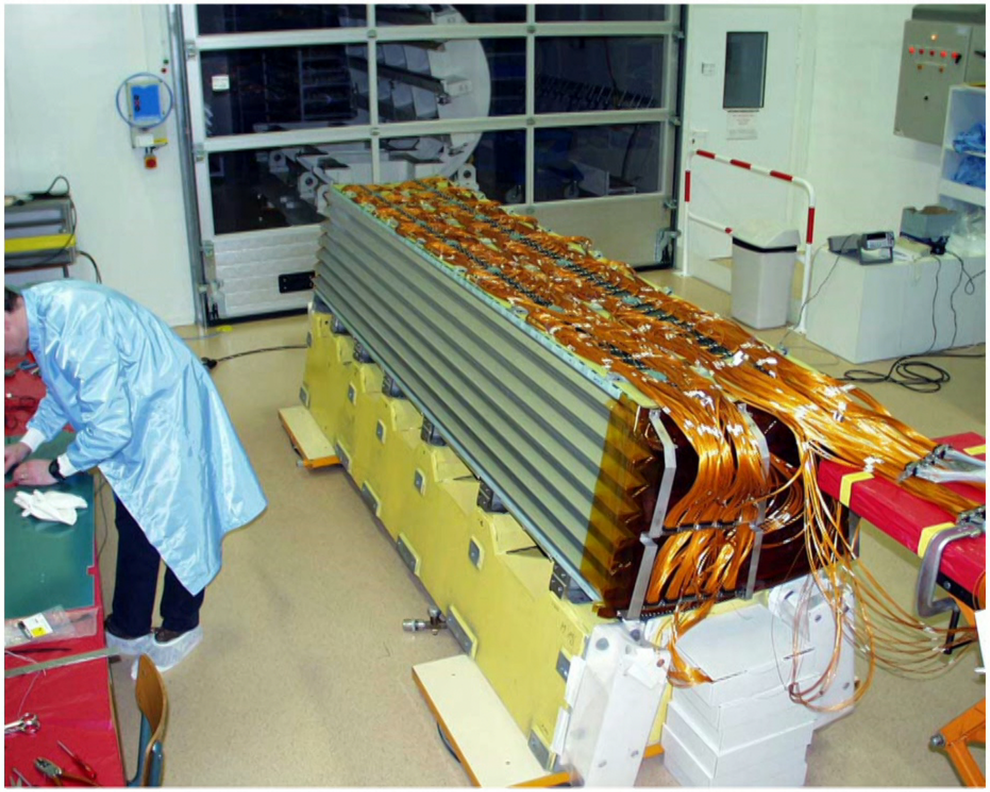
Technology: uses lead as an absorber and liquid argon as an ionization medium. Energy deposited in the calorimeter is converted to an electrical signal.

ATLAS Liquid Argon Calorimeter Module

- Highly segmented
  - Allows measurement of shower development
    - Rejects background
  - Has some pointing ability
- Very good (but not as good as CMS) energy resolution
- "Accordion" faster than other LAr calorimeters
  - Still slower than crystals



ATLAS Calorimeter in Real Life



Before installation – it's now in a cryostat and impossible to see.

CMS Calorimeter Crystals

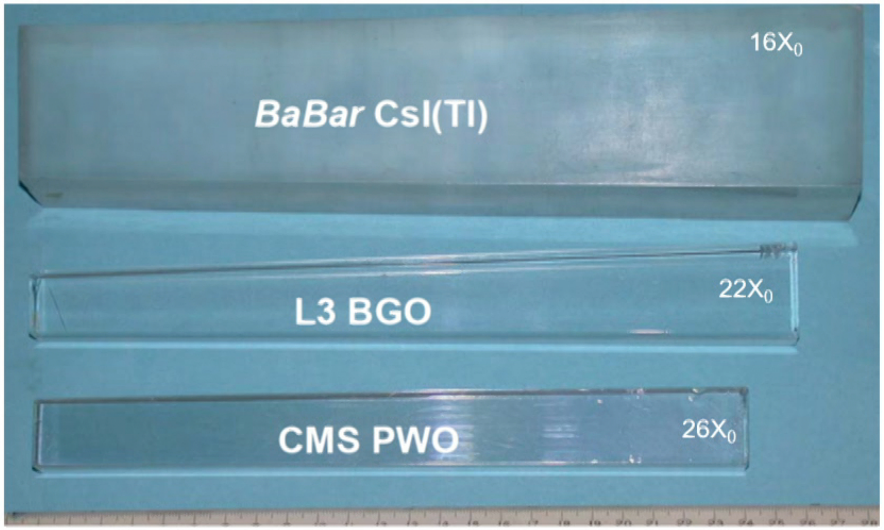


Photo: Ren-yuan Zhu, Caltech

Design resolution:

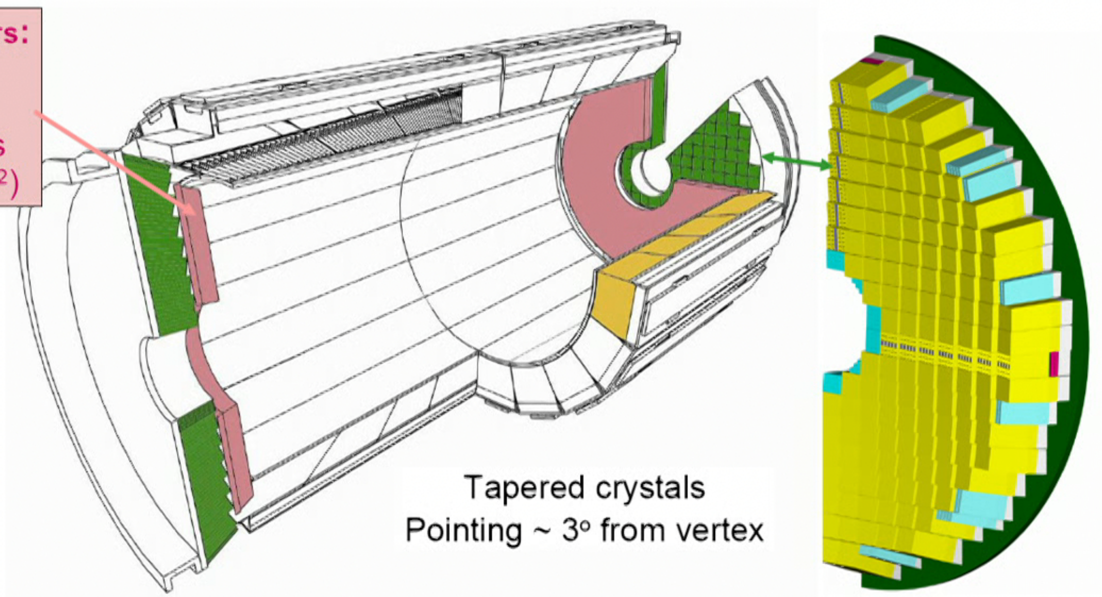
$$\frac{\delta E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.55\% \oplus \frac{0.16\,\mathrm{GeV}}{E}$$

- CMS uses Lead Tungstate crystals
  - Scintillator: energy is converted to light
  - **Exceptional** energy resolution, because there are no inert absorbers
- The focus is to get the best possible energy resolution, no matter what it takes
  - Ultimate energy resolution is ~2x better than ATLAS' in the region where Higgs decay is important

Another nice feature – low noise

CMS EM Calorimeter

Pb/Si Preshowers:
4 Dees
(2/endcap)
4300 Si strips
(~ 63 x 1.9 mm²)



Barrel: 36 Supermodules (18 per half-barrel)
61200 Crystals (34 types) – total mass 67.4 t
Dimensions: ~ 25 x 25 x 230 mm^3 (25.8 X^0)
$\Delta\eta \times \Delta\varphi$ = 0.0175 x 0.0175

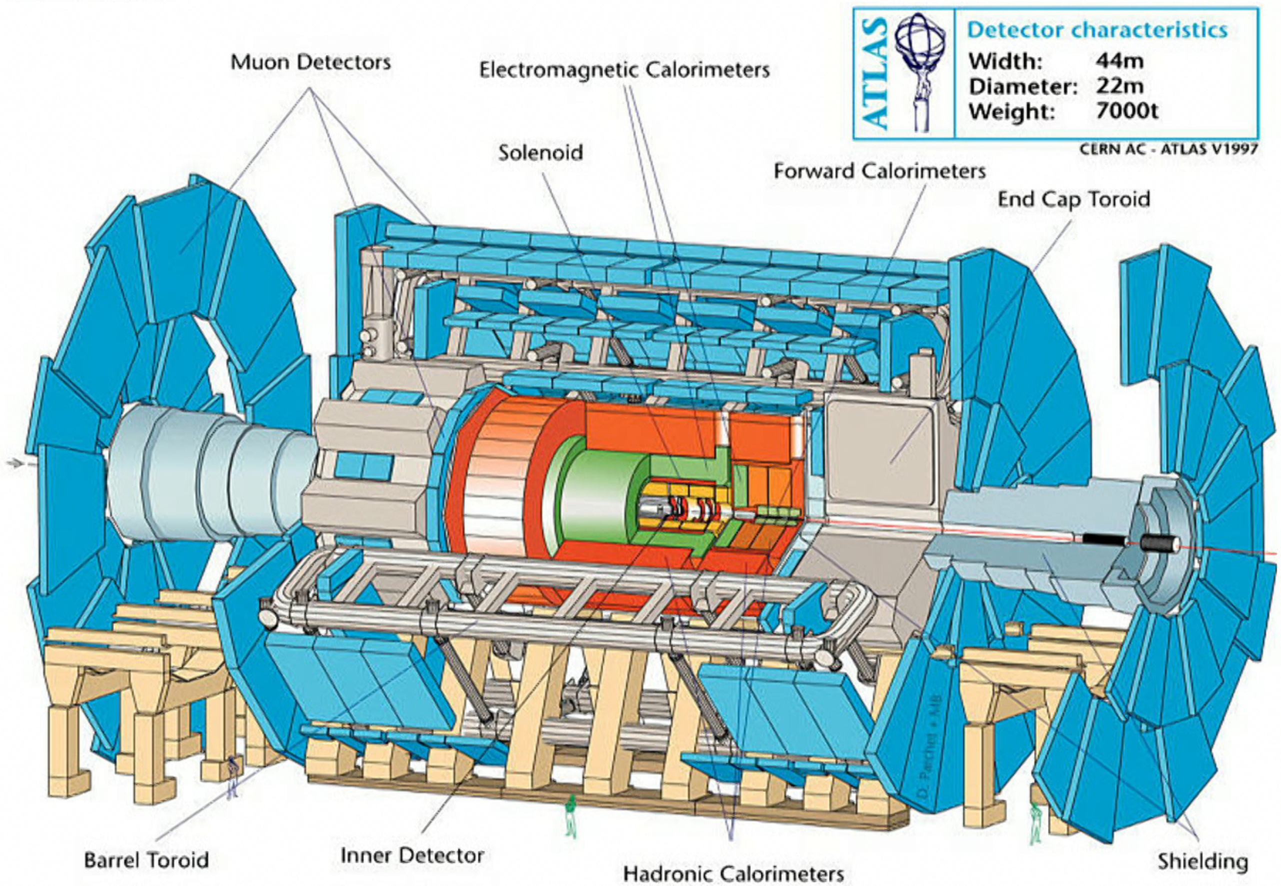
Endcaps: 4 Dees (2 per endcap)
14648 Crystals (1 type) – total mass 22.9 t
Dimensions: ~ 30 x 30 x 220 mm^3 (24.7 X^0)
$\Delta\eta \times \Delta\varphi$ = 0.0175 x 0.0175 ↔ 0.05 x 0.05

Figure: Ren-yuan Zhu, Caltech

Comparing Design Philosophies

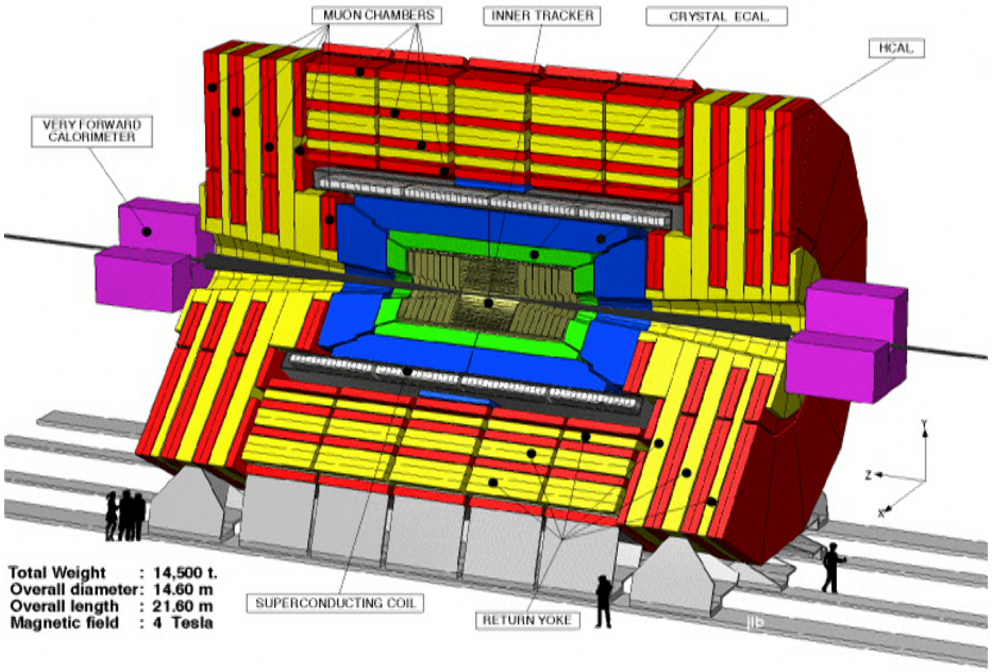
- CMS emphasizes energy resolution
  - Use PWO crystals
    - Expensive – means go to small radius to keep the detector within budget ***and schedule***.
    - Only handful of vendors worldwide
- ATLAS emphasizes background rejection
  - Able to go to larger radius: separates showers better
  - Highly segmented calorimeter allows measurement of shower development
    - One photon? Two? A hadron masquerading as a photon?
- Both calorimeters are quite thick
  - Improves resolution (showers are contained)
  - Degrades electron-hadron separation
    - ATLAS measurement of shower development is intended to compensate

ATLAS



Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

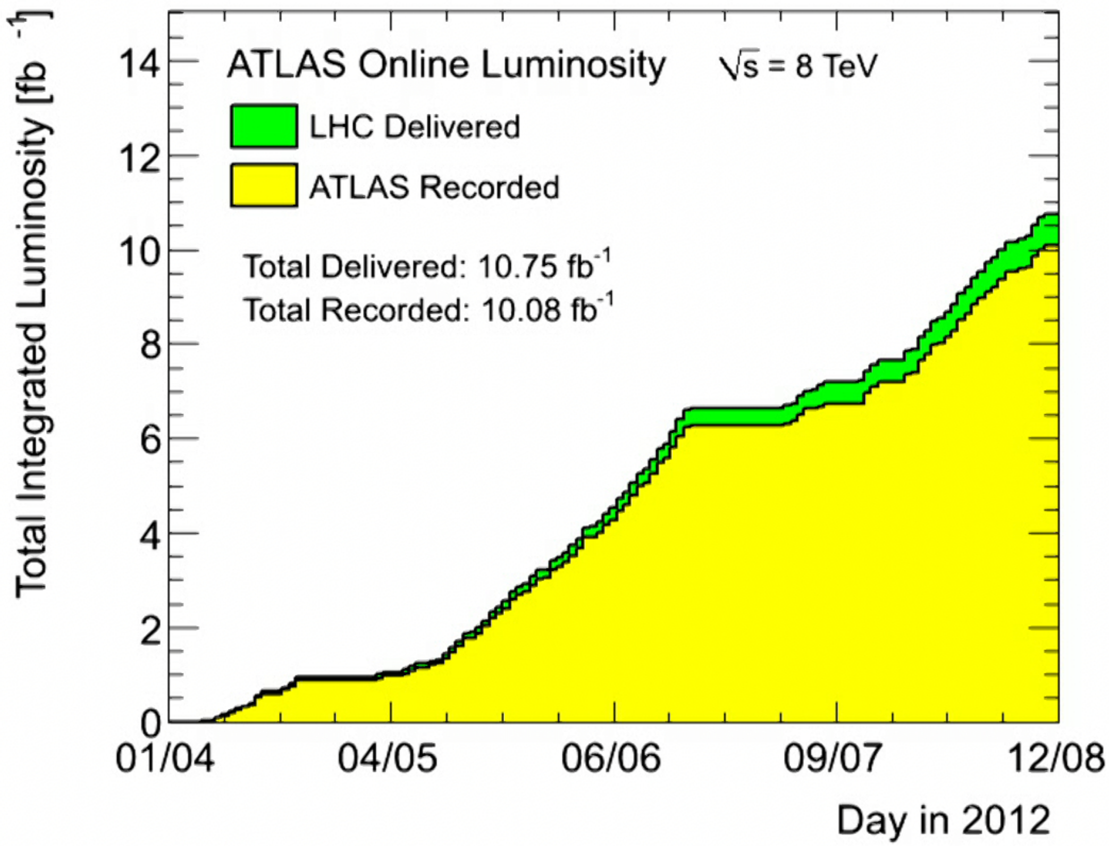
CMS: The Other LHC "Large" Detector



- Different detector technologies
  - e.g. iron core muon spectrometer vs. air core
  - Crystal calorimeter vs. liquid argon
- Different design emphasis
  - e.g. their EM calorimeter is optimized more towards precise measurement of the signal; ATLAS is optimized more towards background rejection

Similar in concept to ATLAS, but with a different execution.

I Like Working at the LHC…



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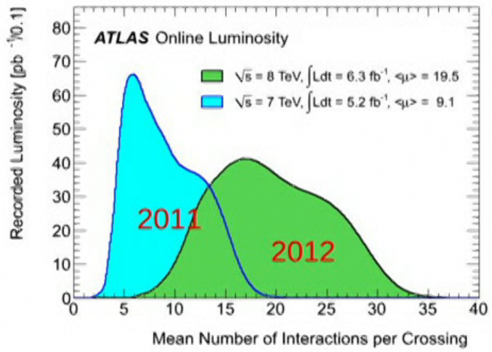
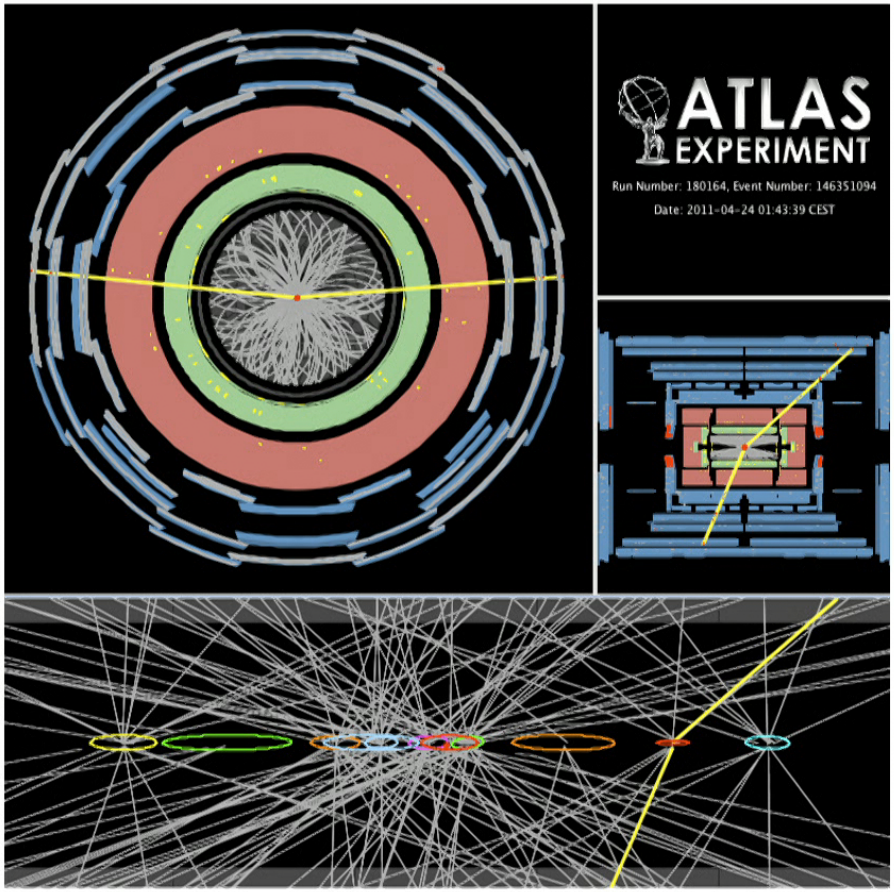
...But I Miss Working At The Tevatron

This is a Z event (into muons) with ***only*** 11 primary vertices.



Not a showstopper, but it is work.



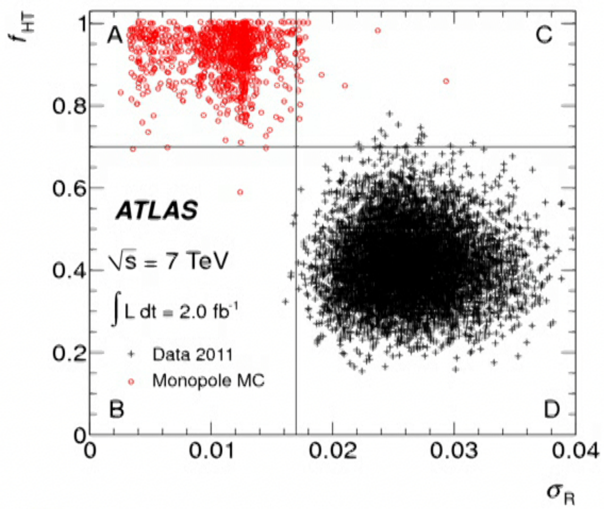
Where Are We After Step #1?

- We've identified the problem:
- We need to identify Higgs $\gamma\gamma$ events over three backgrounds…
  - Other $\gamma\gamma$ events
  - Jet+γ events misidentified as $\gamma\gamma$
    - About 1000x larger
  - Dijet events misidentified as $\gamma\gamma$
    - About 1000000x larger
- … in the face of a large number of pile-up events

QCD kinda-sorta predicts these rates: well enough that we can tell we are on the right path, but nowhere near well enough to discover the Higgs by looking at total rates.

The tool that lest us solve this is the "ABCD Method"

The ABCD Method

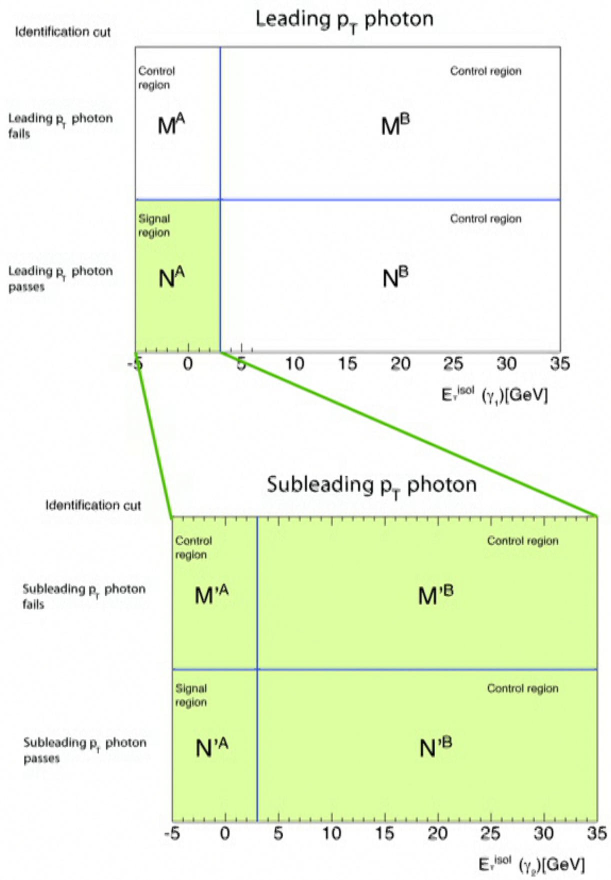


A general method (the above plot has nothing to do with the Higgs) to answer the question "how much background is inside signal region A"?

$$\frac{A}{B} = \frac{C}{D} \Rightarrow A = B\frac{C}{D}$$

- Requires two variables that are *uncorrelated* for the *background*.
  - Signal can be and often is correlated.
  - If the variables are not exactly uncorrelated, this becomes an approximation.
- Requires that regions B,C and D all be dominated by the background
- This doesn't say anything about how much signal "leaks" into B and C
  - Usually this is done with Monte Carlo

ABCD for Diphotons

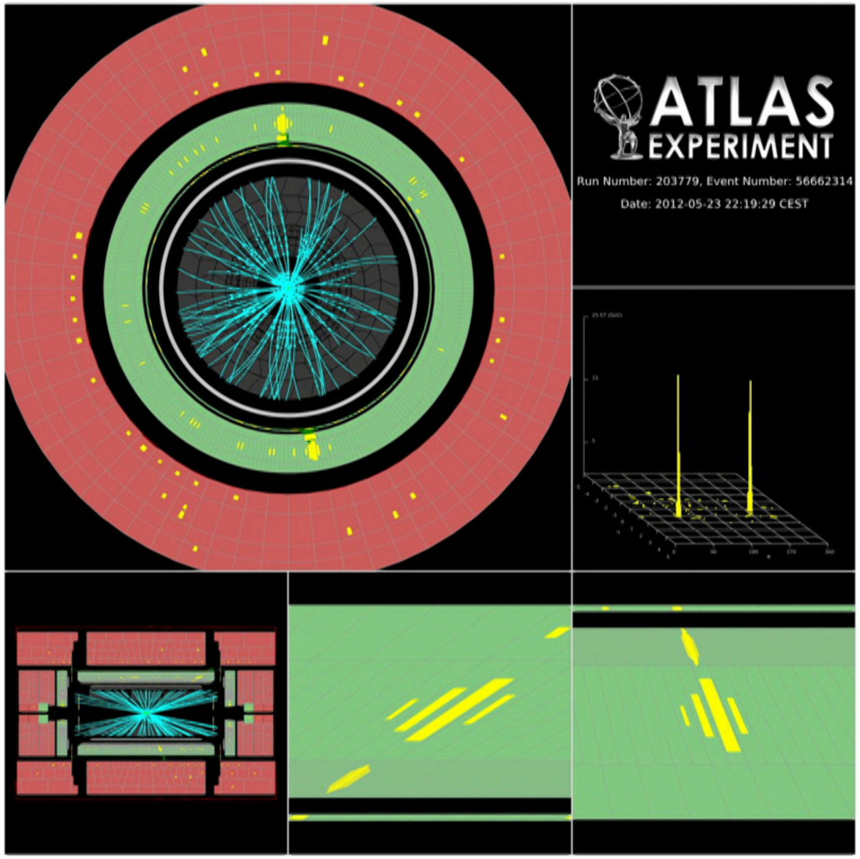


- Here the two uncorrelated variables are:
  - Photon identification: the shower shape variables I discussed ~10 slides back plus the absence of a track pointing at the shower.
  - Isolation: how much energy is around the photon. If the photon came from a jet, odds are that there is some remnant nearby that we can detect.
    - Isolation energy is directly affected by pileup, so we want to make this area as small as possible.
- We can apply this to both photons, so at the end of the process we know how many events have zero, one or two real photons.

What Are We Searching For?

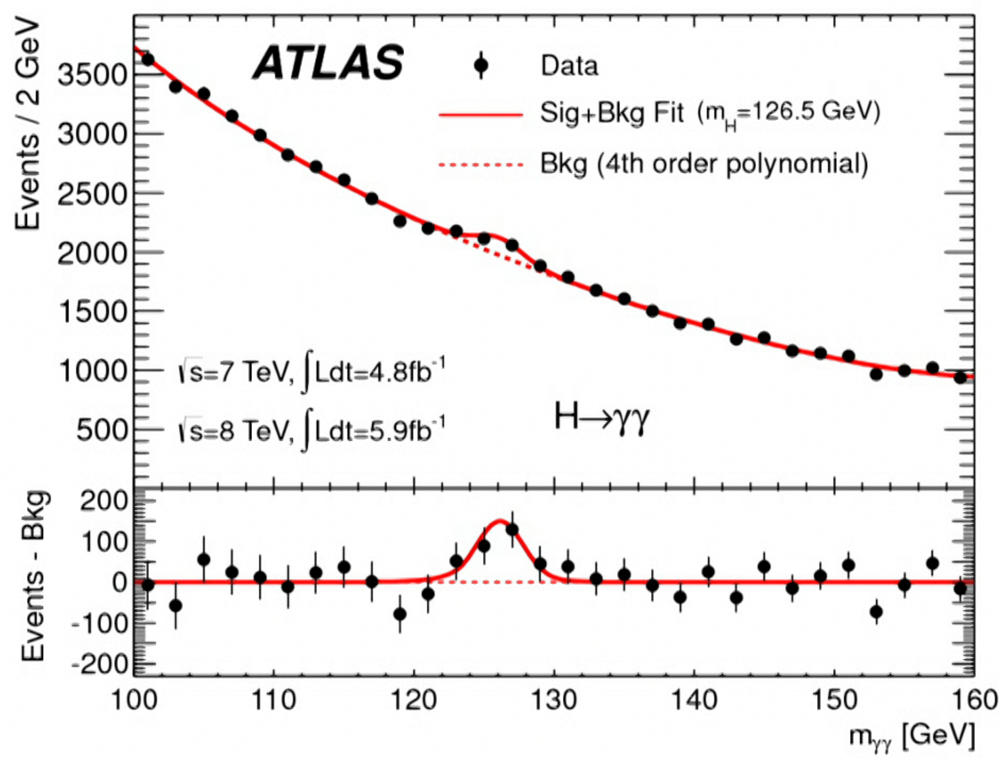
- We cannot avoid this question any more.
  - Are we looking for a generic particle that decays to $\gamma\gamma$?
  - Or are we looking for the SM Higgs?
- This matters:
  - Are we allowed to use Higgs production models in this analysis?
  - What about assuming its spin-0? (Isotropic decays in any frame)
- Both experiments have decided to design the search around the SM Higgs
  - For exclusion, this is obviously the right thing to do
  - For a search, we have decided matching the exclusion strategy was best

A ~~Typical~~ Pretty Two Photon Event



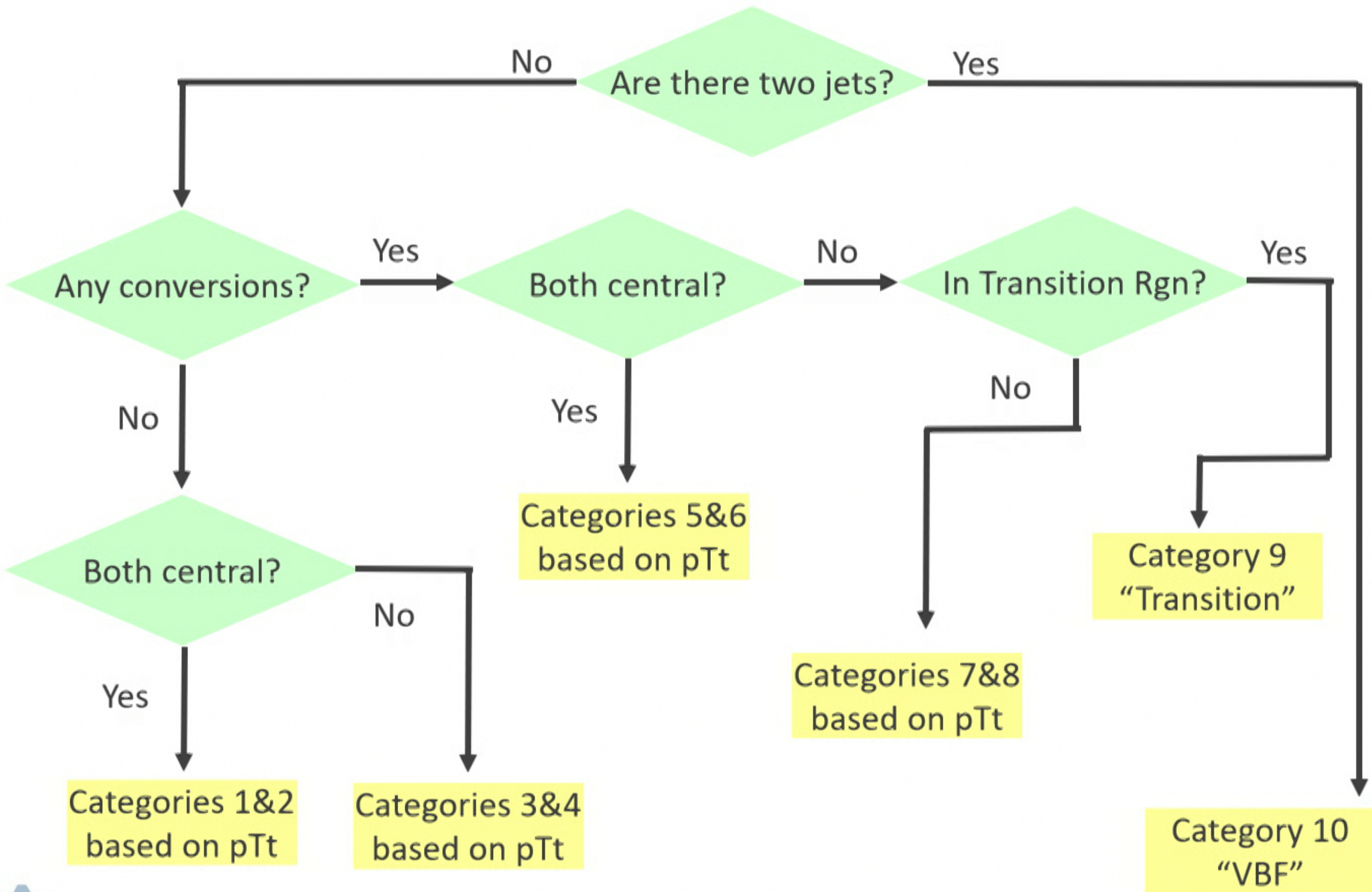
- Photons are obvious, even with pile-up
  - Note that low p_T tracks are suppressed in the display
- One can see how the EM showers can be used to point back to the primary vertex
  - Usually points to within ±1 interaction of the correct vertex
  - This is as good as it needs to be; beyond this it's diminishing returns
- Three photon regions: central, endcap, transition
  - The transition region is difficult

The Data



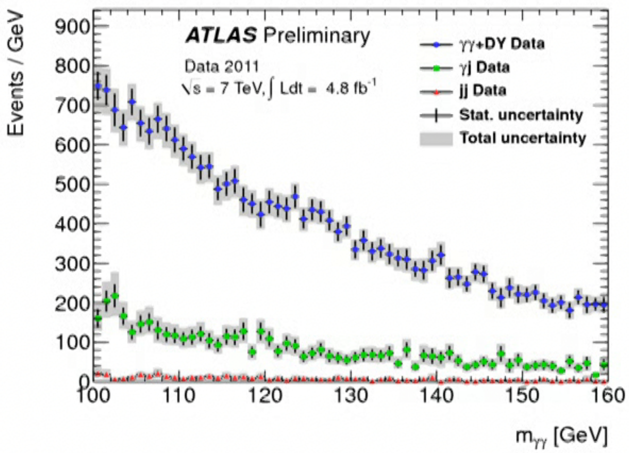
This plot, shown in many places, is actually not really used in the analysis.
Actually, we look at things in ten categories.

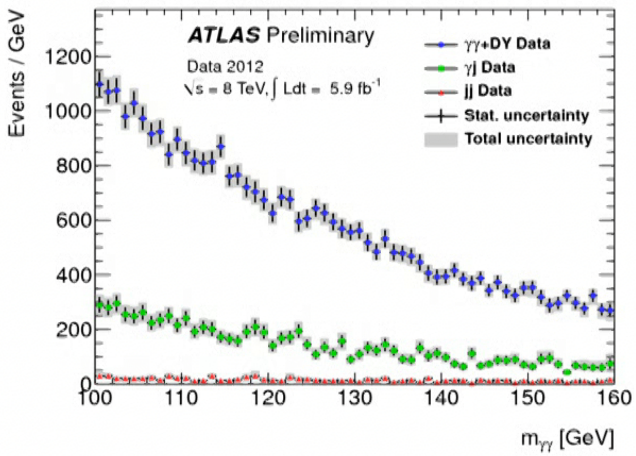
ATLAS $\gamma\gamma$ Categorization



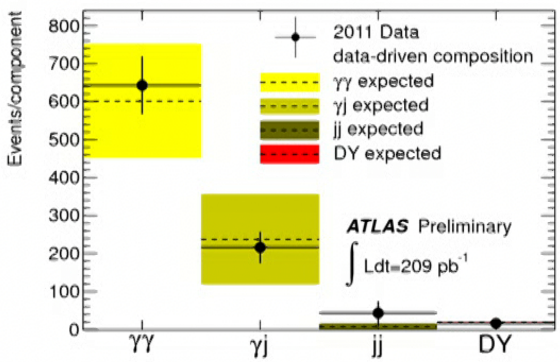
48

Diphoton Background

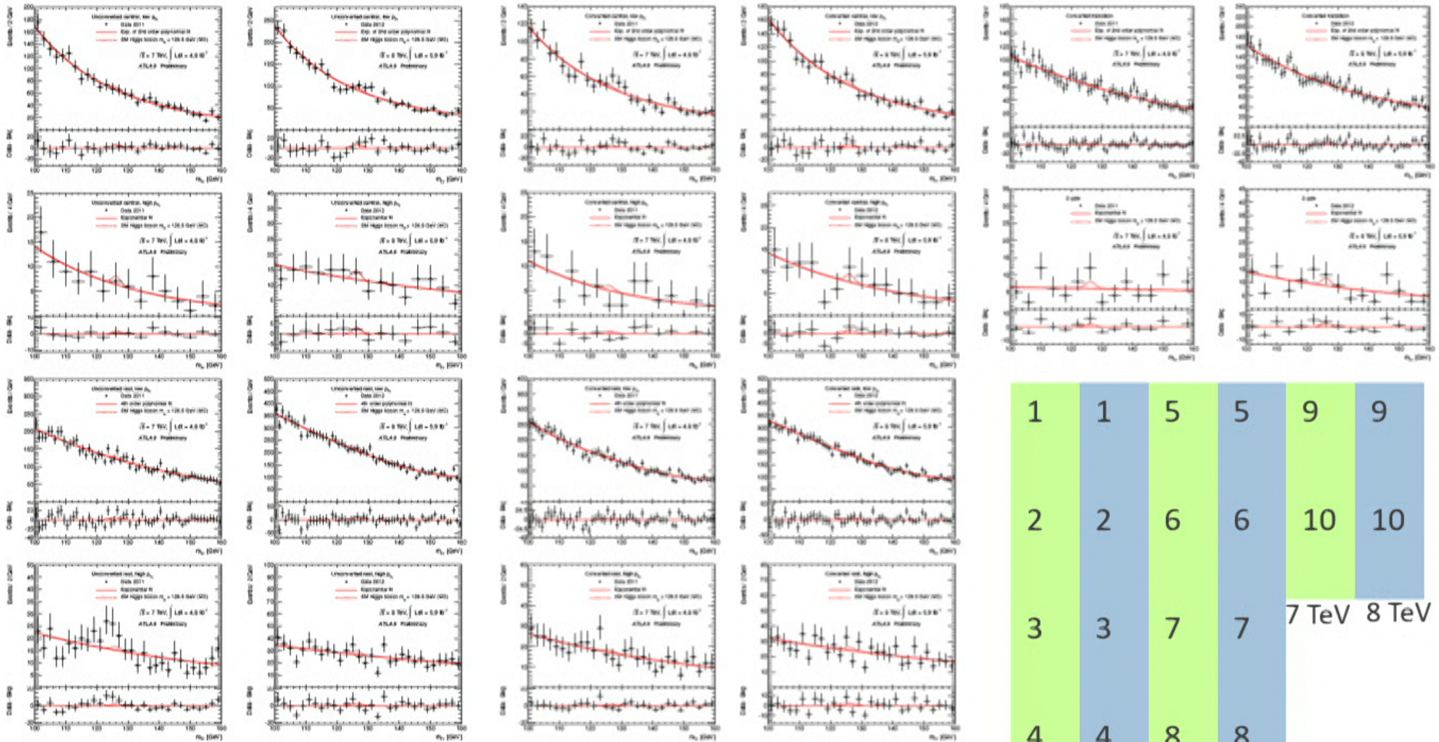




- The background is mostly real diphotons.
  - Improving fake photon rejection will help, but we're past the point of diminishing returns.
- The 7 TeV data and 8 TeV data look similar, but not identical.
  - They can be combined, but they have to be handled separately. This is a royal pain in the wazoozy.
- Although we don't use the absolute QCD predictions anywhere in this analysis, this is about what we would have expected these plots to look like.

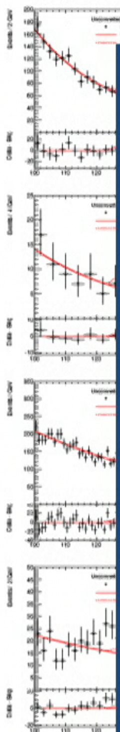


Results in Each Bin



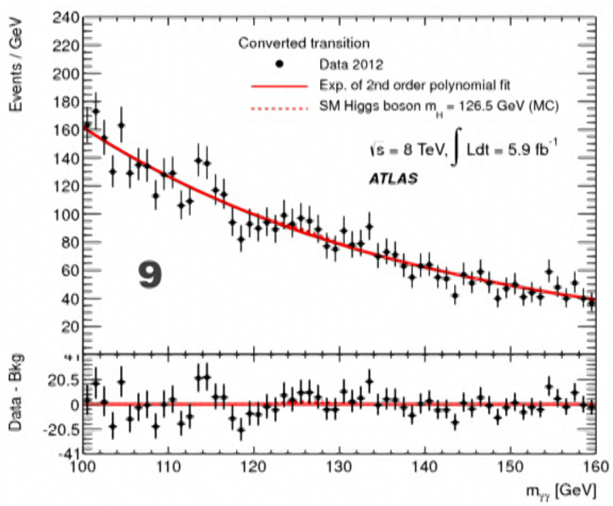
1	1	5	5	9	9
2	2	6	6	10	10
3	3	7	7	7 TeV	8 TeV
4	4	8	8		

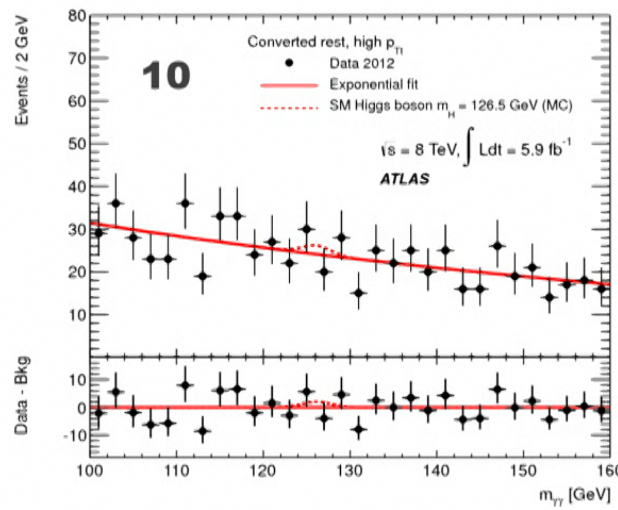
Results in Each Bin



- Obviously, none of the individual bins are significant by themselves
  - This is what one expects for 20 bins (10 x 2 energies) and a ~4σ signal
- You can think of the combination as a sort of MVA
  - Because it is – this is an example of an (unboosted) Decision Tree
  - The statistical test is asking the question "Is there an excess…and is this excess distributed in the way we expect for a SM Higgs?"
  - We could have gotten the same total excess distributed differently – and this would have given us a different total significance
- The fact we are looking for an SM Higgs rather than a generic particle decaying to $\gamma\gamma$ is built into this analysis.
  - For example, the best fit yield for a fermiphobic Higgs would be different
  - This technique adds a little less than 1σ to the significance *for this data set*.

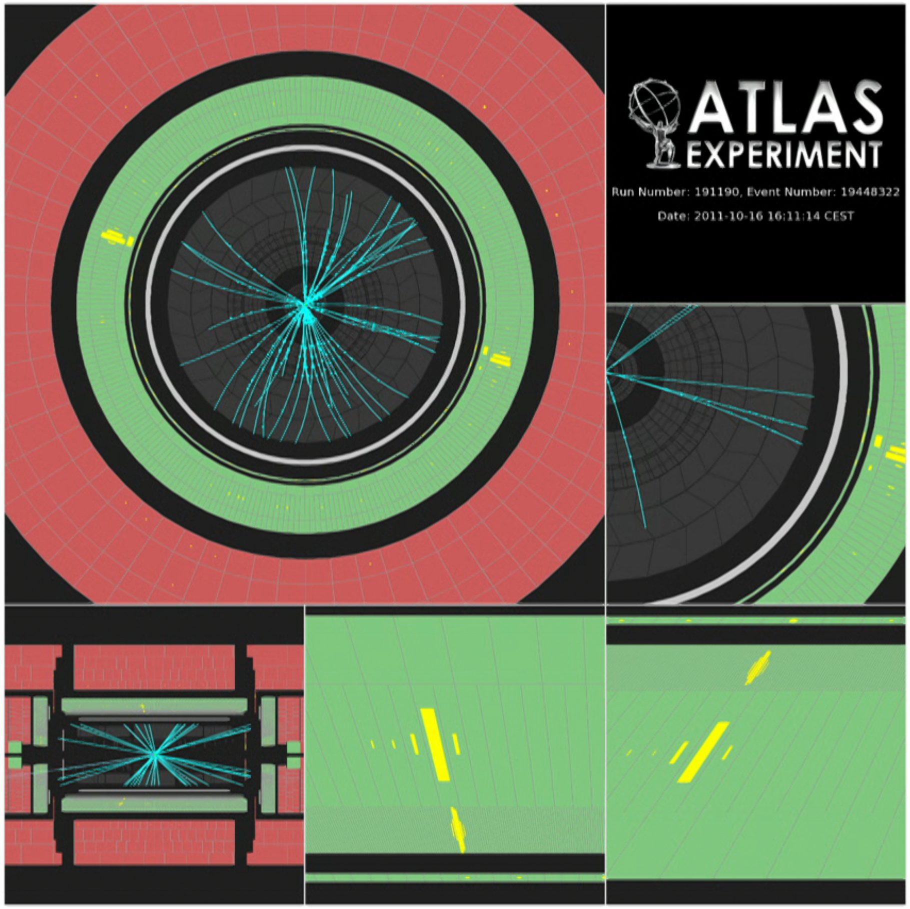
A Close-Up





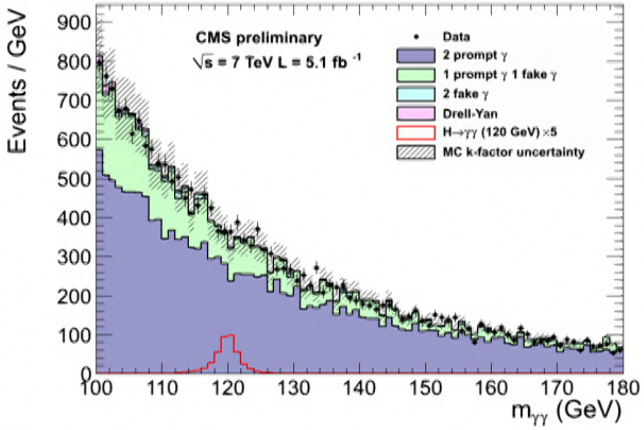
- These regions don't look anything like each other
  - Signal width
  - Signal to noise ratio
  - Background shape (still, it would be nice if the same functional form everywhere. <sigh>)
  - Event yield
- Why lump them together in the analysis?

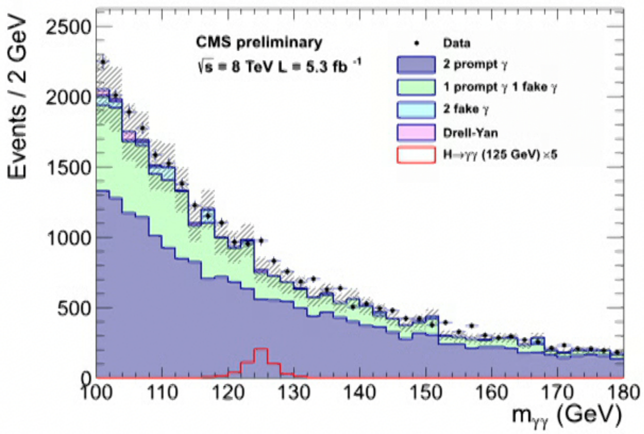
One Particular Event



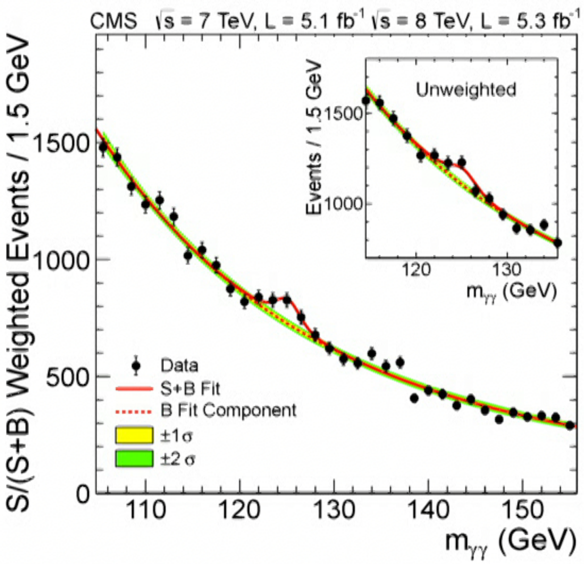
- This event has
  - One central unconverted photon
  - One central converted photon
  - A low pTt (6.5 GeV)
- This places it in Category 5

CMS Results





- The background is ~75% real γ-γ events
  - Ordinary QCD Production
  - Very similar to ATLAS
- This is why I am not going to describe the photon cuts in detail: separating photons from neutral mesons is not the biggest challenge in this measurement.



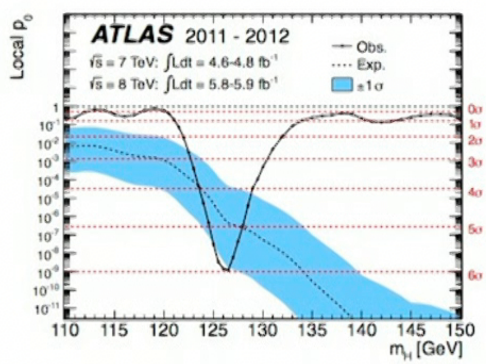
An Observation

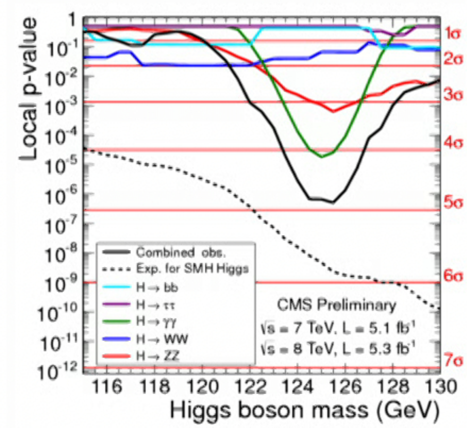
- The CMS calorimeter emphasized resolution – but at the end of the day they got about the same resolution as ATLAS.
- The ATLAS calorimeter emphasized background rejection – but at the end of the day they got about the same signal-to-background as CMS.
- I'm sure there's a lesson in this somewhere.

Anyway, it's time to move on

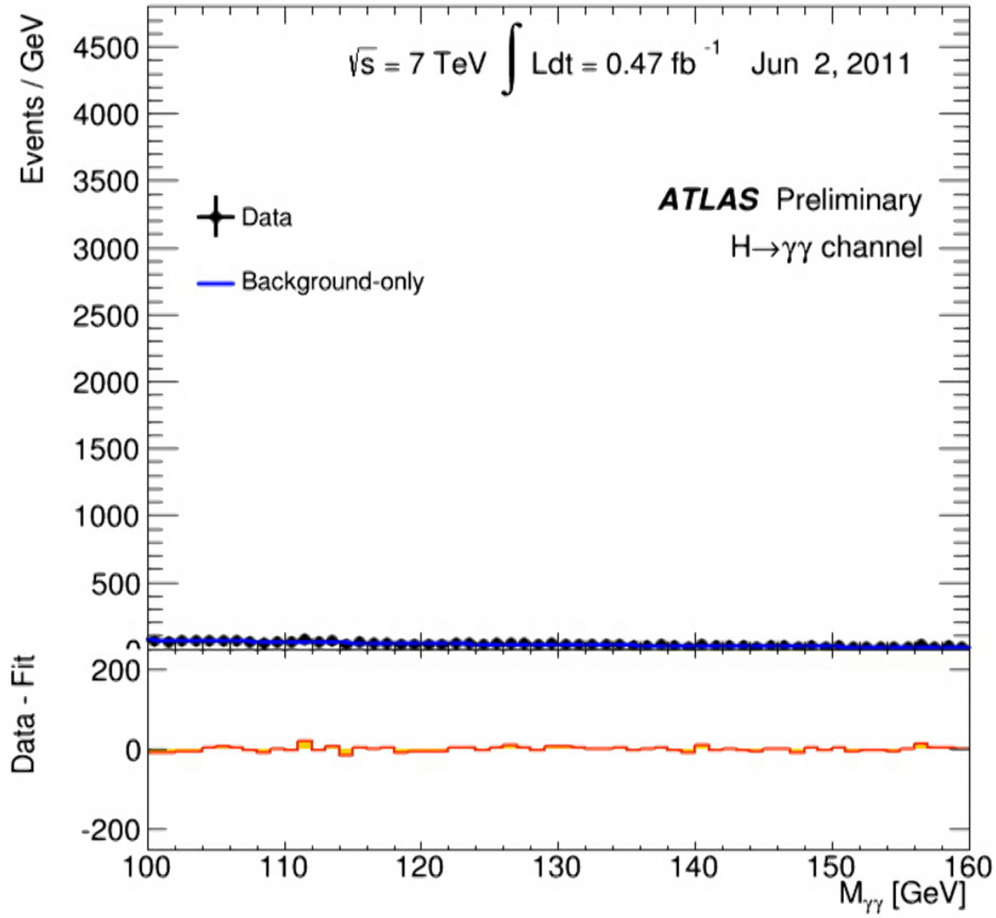
July 4th, 2012

- The ATLAS and CMS experiments reported seeing a new particle
  - At the same mass (~125 GeV)
  - In two decay channels (γγ and ZZ*)
  - With about the same production rate – the same rate as predicted for the SM Higgs
  - With a combined statistical significance of > 6σ: p_0 < 1 in a billion
  - With some minor supporting (at least not impeaching) evidence



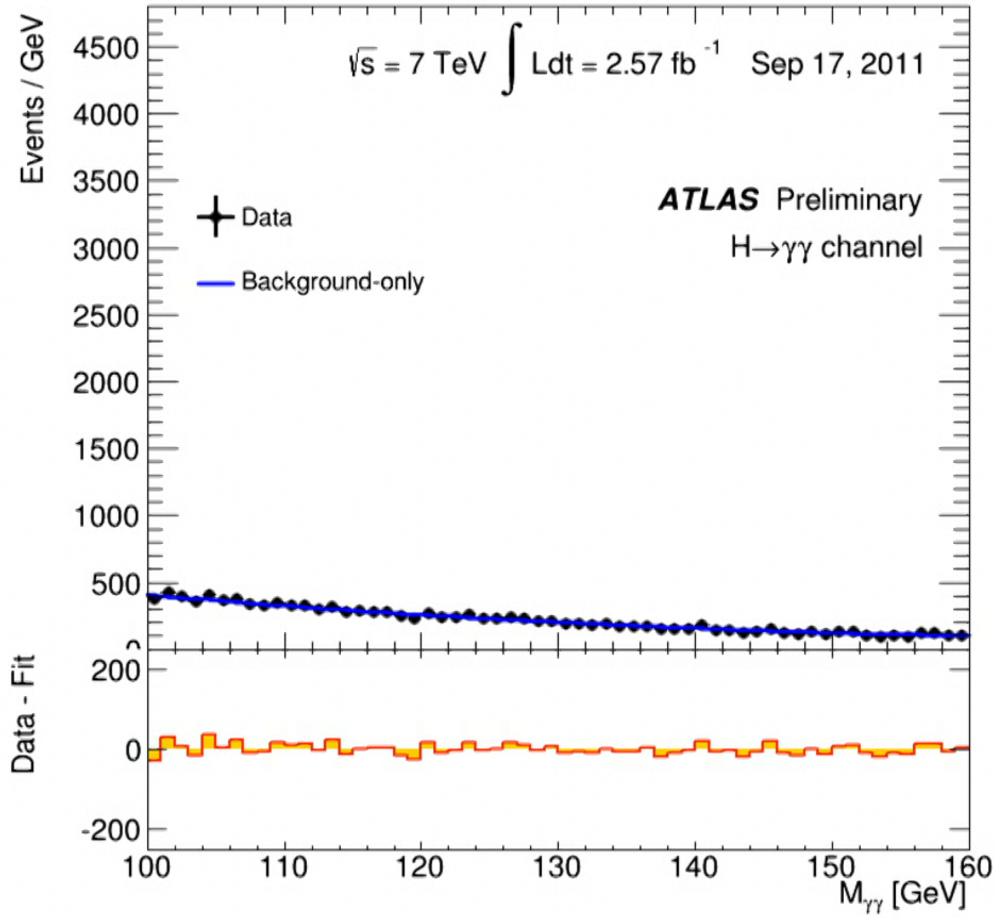


H → γγ



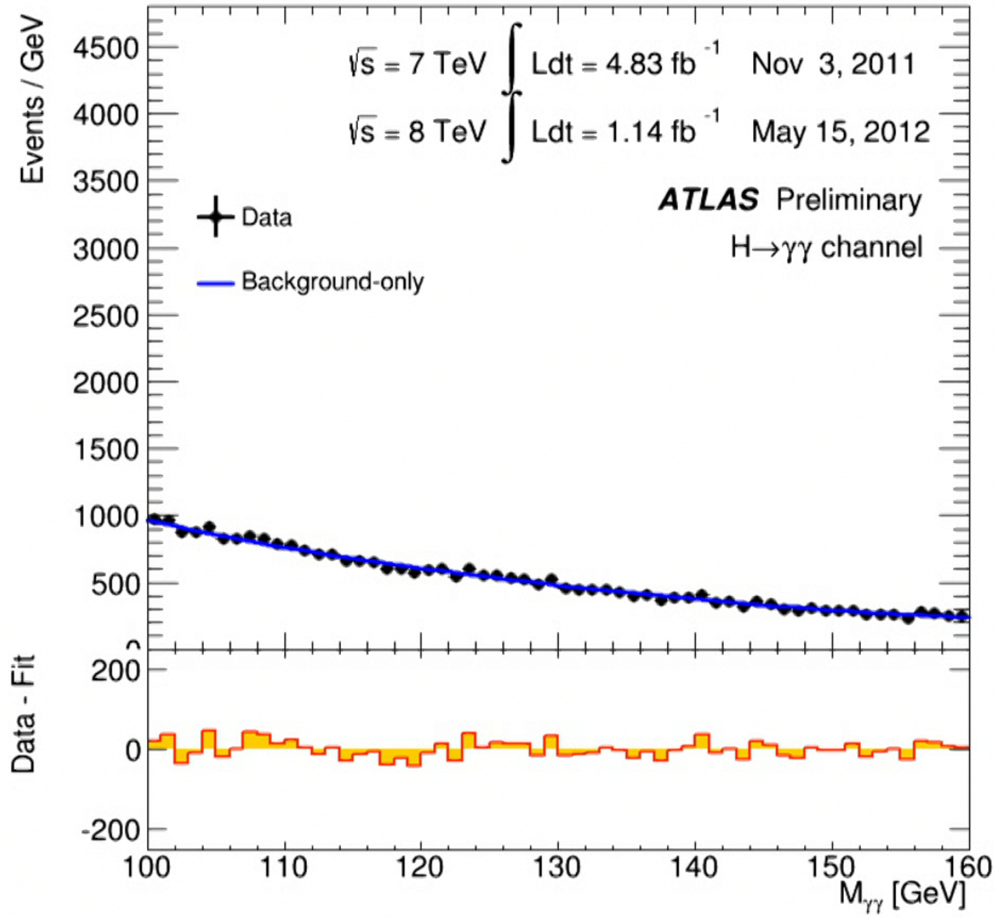
√s = 7 TeV ∫ Ldt = 0.47 fb⁻¹ Jun 2, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
Data - Fit
200
0
-200
100
110
120
130
140
150
160
M_γγ [GeV]

H → γγ



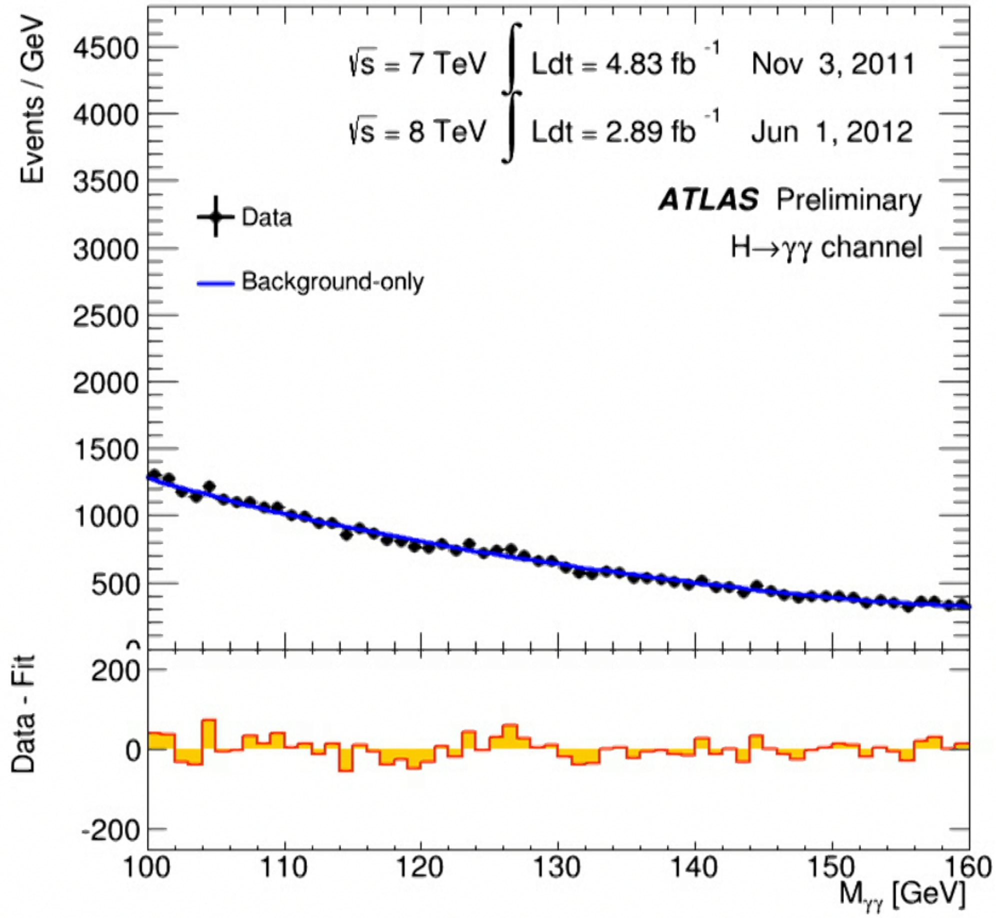
$\sqrt{s}$ = 7 TeV $\int$ Ldt = 2.57 fb^{-1} Sep 17, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
Data - Fit
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]

H → γγ



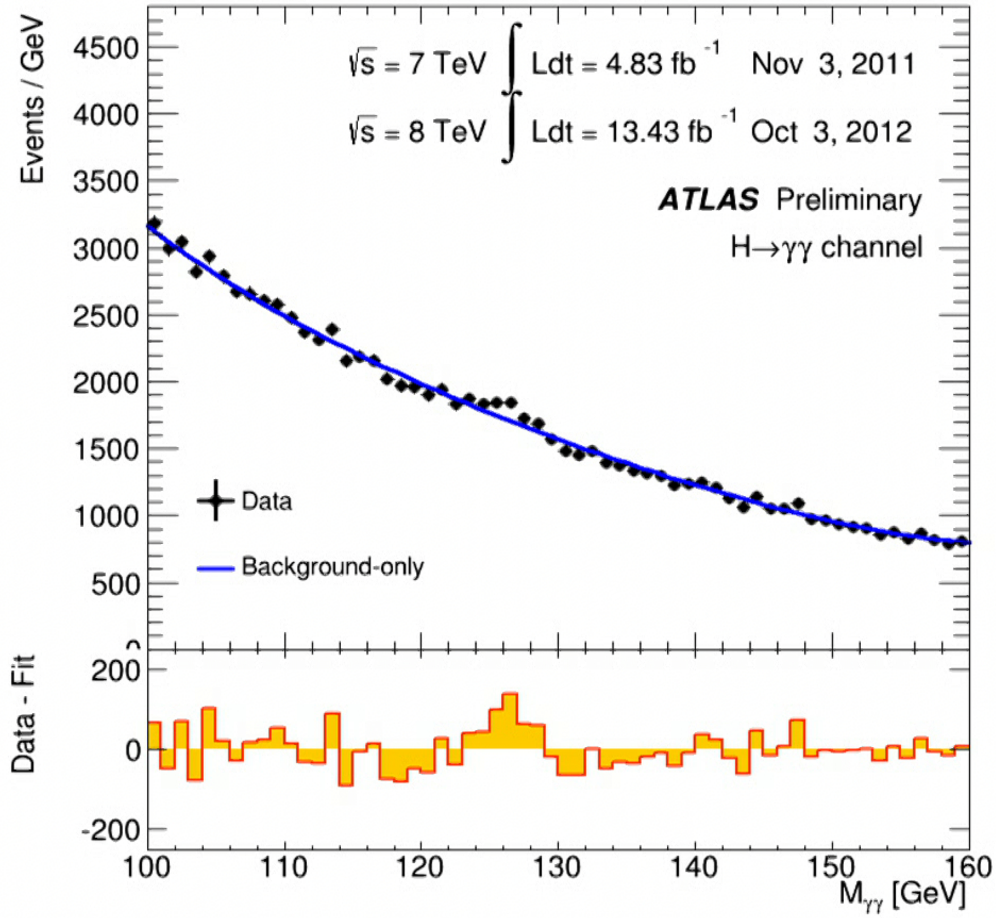
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
√s = 7 TeV ∫Ldt = 4.83 fb⁻¹ Nov 3, 2011
√s = 8 TeV ∫Ldt = 1.14 fb⁻¹ May 15, 2012
ATLAS Preliminary
H→γγ channel
Data
Background-only
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]

H → γγ



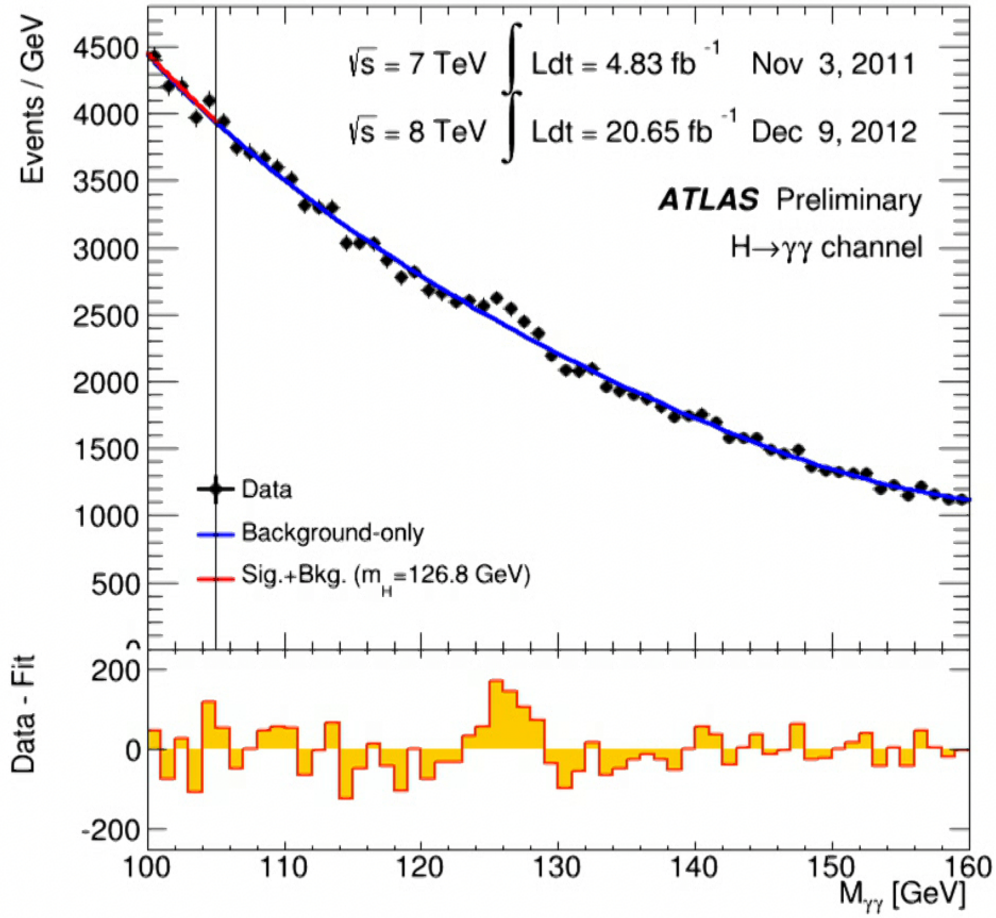
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
√s = 7 TeV ∫ Ldt = 4.83 fb -1 Nov 3, 2011
√s = 8 TeV ∫ Ldt = 2.89 fb -1 Jun 1, 2012
ATLAS Preliminary
H→γγ channel
Data
Background-only
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]

H → γγ



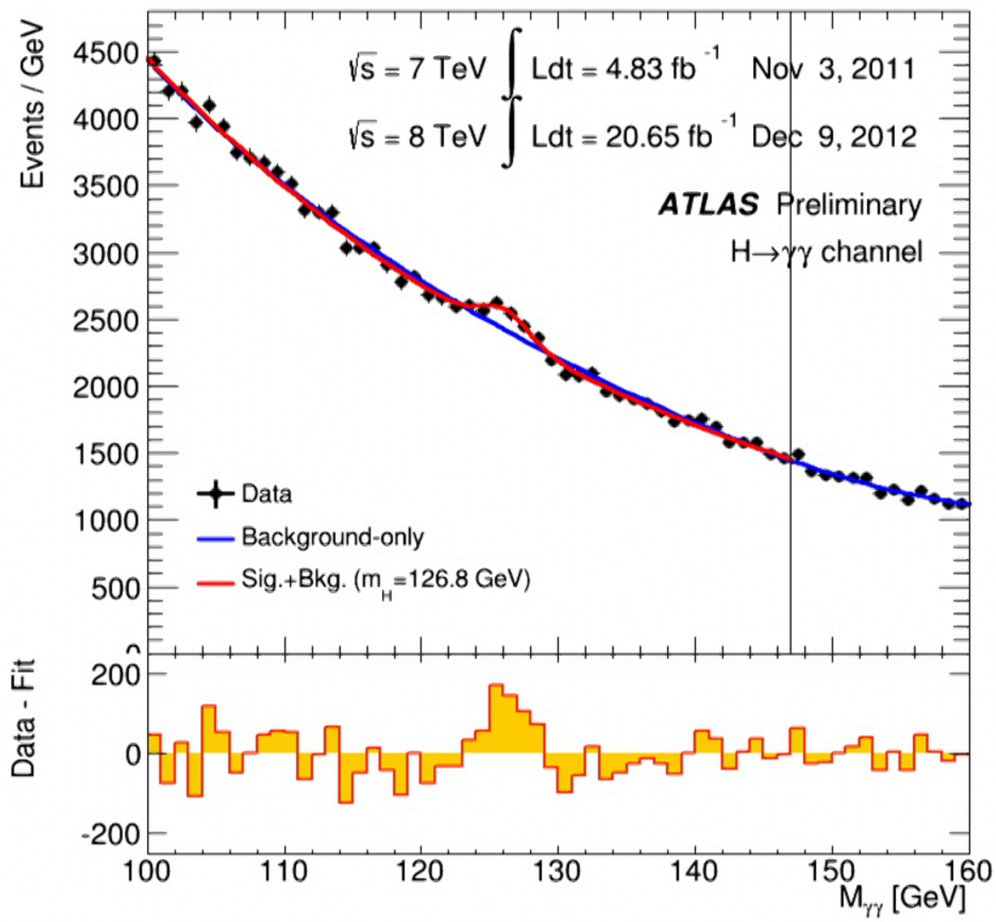
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
√s = 7 TeV ∫Ldt = 4.83 fb -1 Nov 3, 2011
√s = 8 TeV ∫Ldt = 13.43 fb -1 Oct 3, 2012
ATLAS Preliminary
H→γγ channel
Data
Background-only
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]

H → γγ



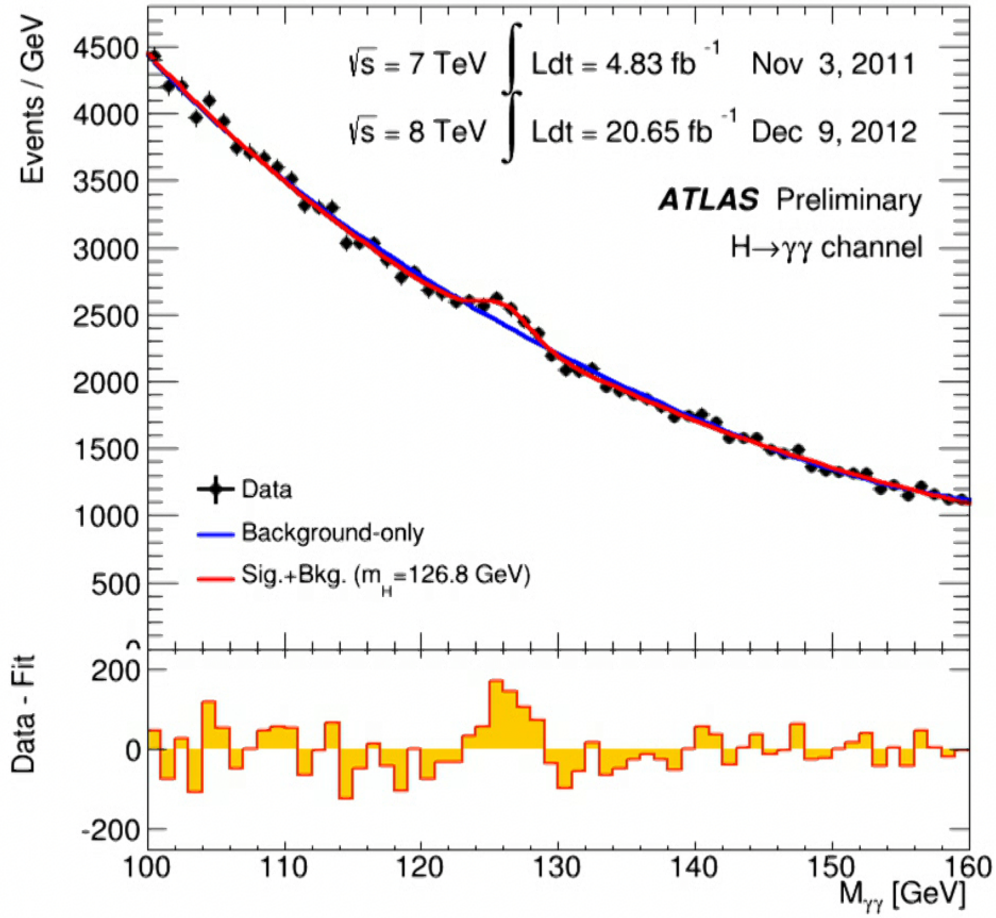
Events / GeV
√s = 7 TeV ∫Ldt = 4.83 fb⁻¹ Nov 3, 2011
√s = 8 TeV ∫Ldt = 20.65 fb⁻¹ Dec 9, 2012
ATLAS Preliminary
H→γγ channel
Data
Background-only
Sig.+Bkg. (m_H=126.8 GeV)
Data - Fit
M_γγ [GeV]

H → γγ



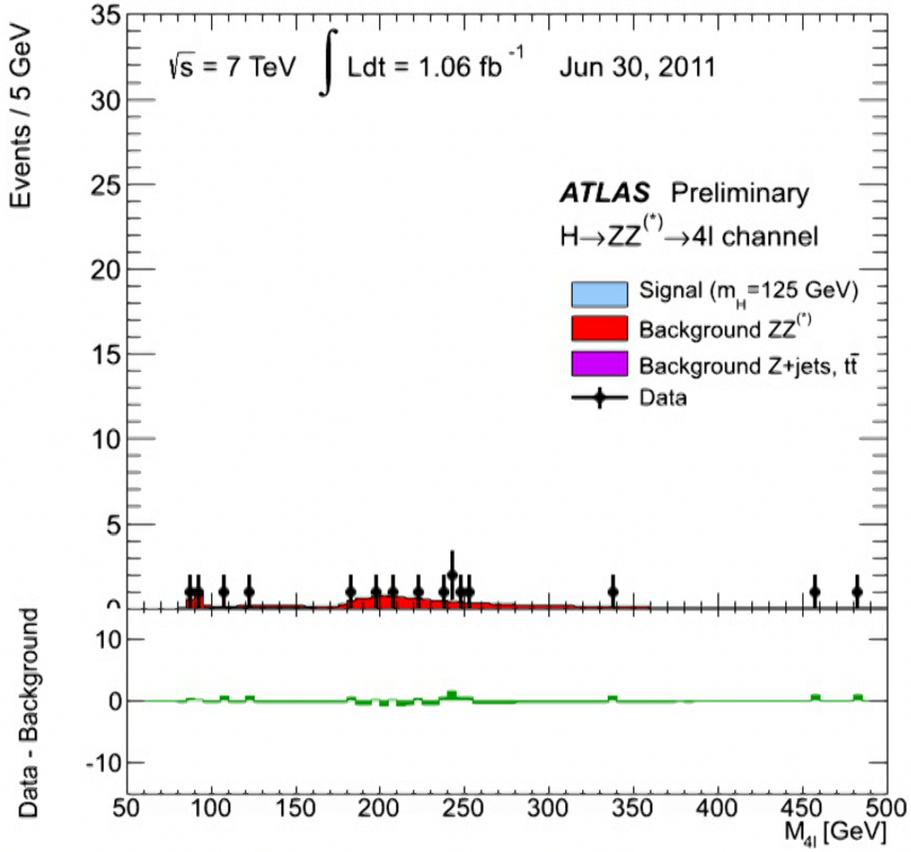
Events / GeV
√s = 7 TeV ∫Ldt = 4.83 fb⁻¹ Nov 3, 2011
√s = 8 TeV ∫Ldt = 20.65 fb⁻¹ Dec 9, 2012
ATLAS Preliminary
H→γγ channel
Data
Background-only
Sig.+Bkg. (m_H=126.8 GeV)
Data - Fit
M_γγ [GeV]

H → γγ



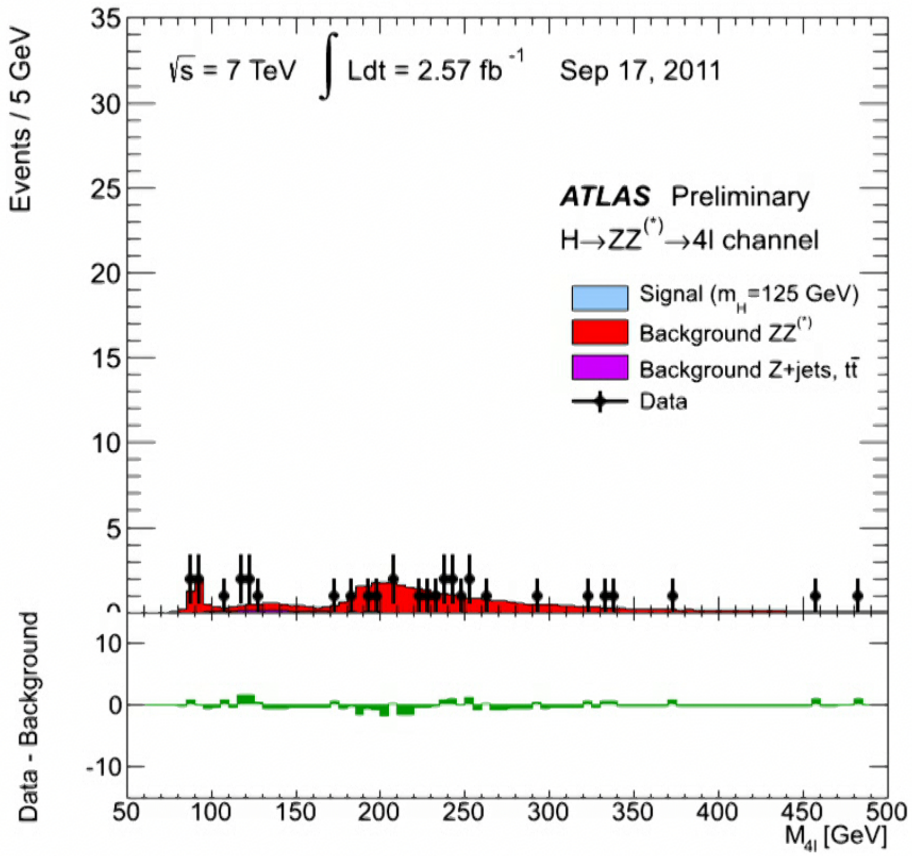
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
√s = 7 TeV ∫Ldt = 4.83 fb⁻¹ Nov 3, 2011
√s = 8 TeV ∫Ldt = 20.65 fb⁻¹ Dec 9, 2012
ATLAS Preliminary
H→γγ channel
Data
Background-only
Sig.+Bkg. (m_H=126.8 GeV)
Data - Fit
200
0
-200
100
110
120
130
140
150
160
M_γγ [GeV]

H → ZZ*



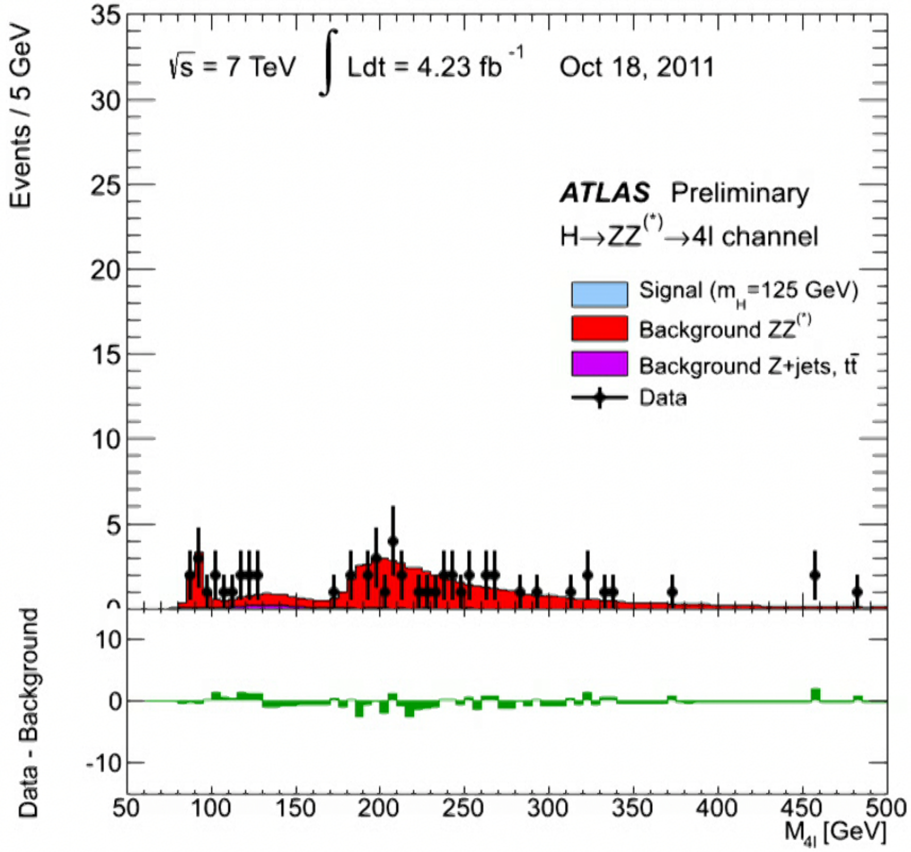
√s = 7 TeV ∫ Ldt = 1.06 fb⁻¹ Jun 30, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M_4l [GeV]

H → ZZ*



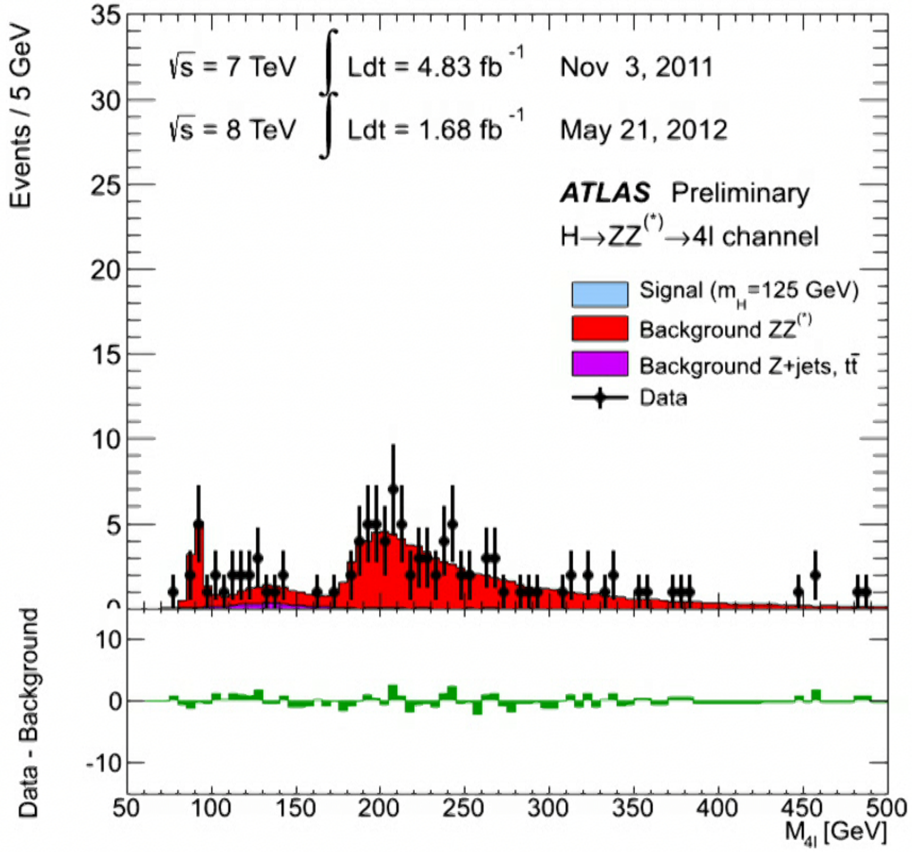
√s = 7 TeV ∫ Ldt = 2.57 fb⁻¹ Sep 17, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]

H → ZZ*



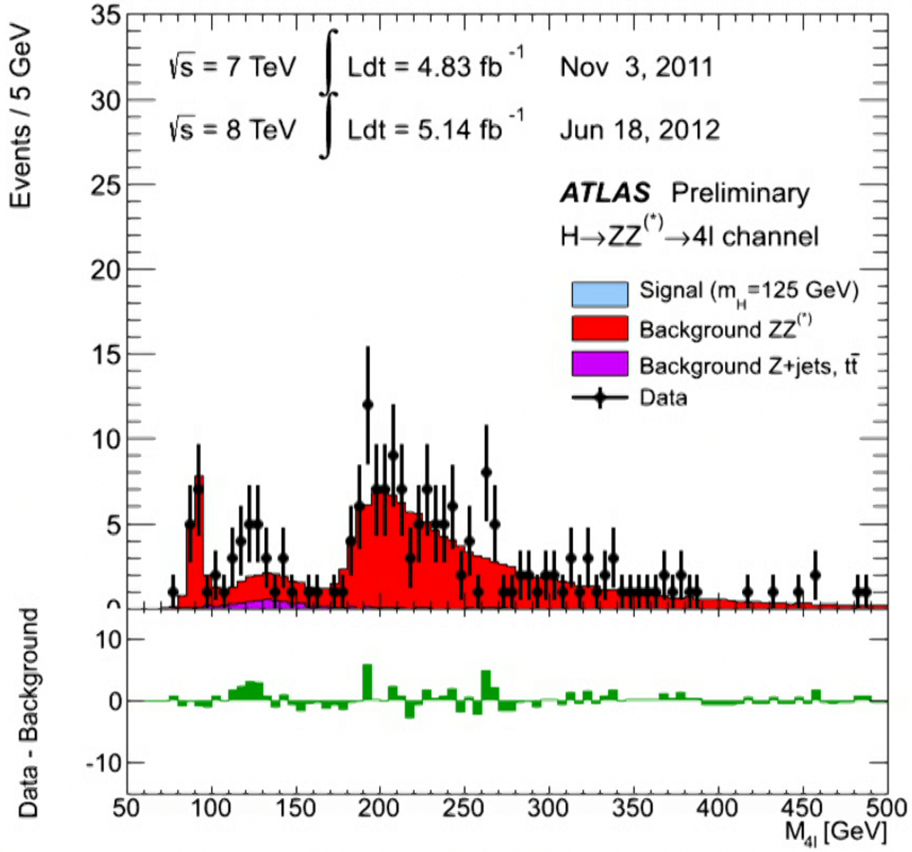
√s = 7 TeV ∫ Ldt = 4.23 fb⁻¹ Oct 18, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M_4l [GeV]

H → ZZ*



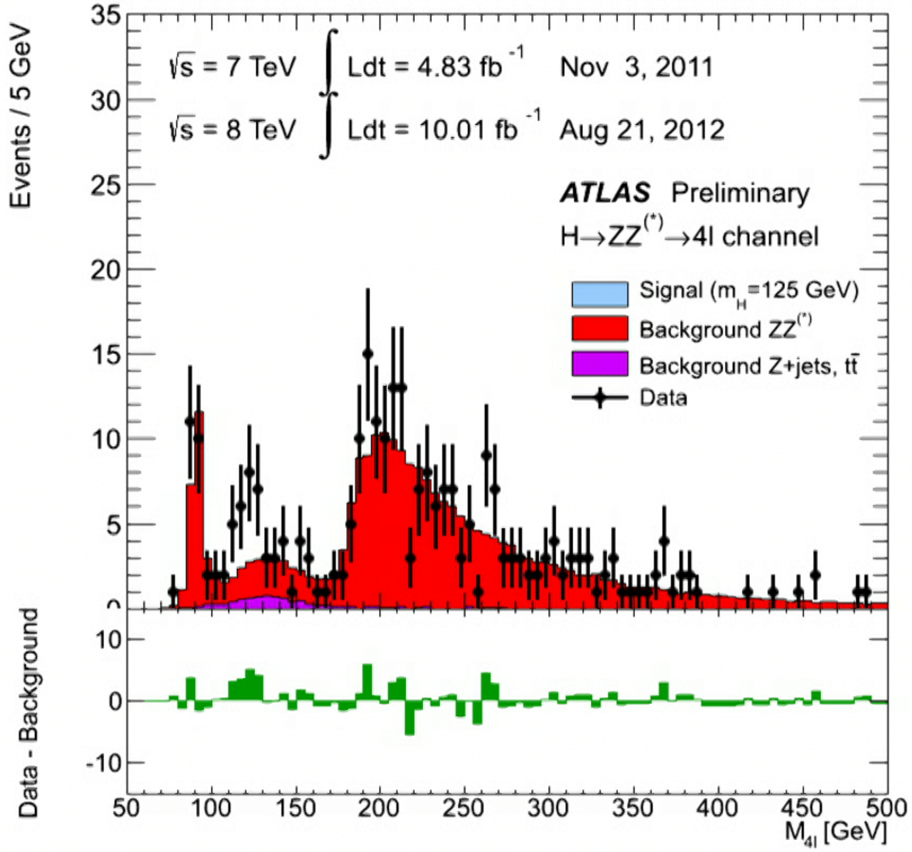
Events / 5 GeV
√s = 7 TeV ∫Ldt = 4.83 fb⁻¹ Nov 3, 2011
√s = 8 TeV ∫Ldt = 1.68 fb⁻¹ May 21, 2012
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M_4l [GeV]

H → ZZ*



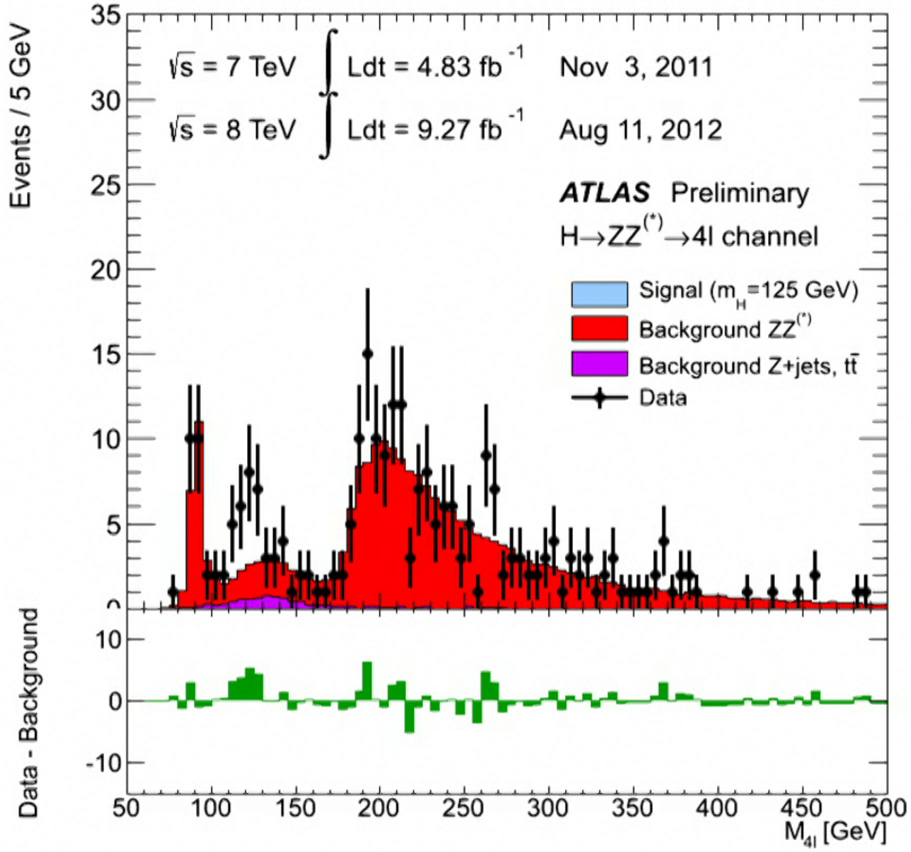
√s = 7 TeV ∫Ldt = 4.83 fb-1 Nov 3, 2011
√s = 8 TeV ∫Ldt = 5.14 fb-1 Jun 18, 2012
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]

H → ZZ*



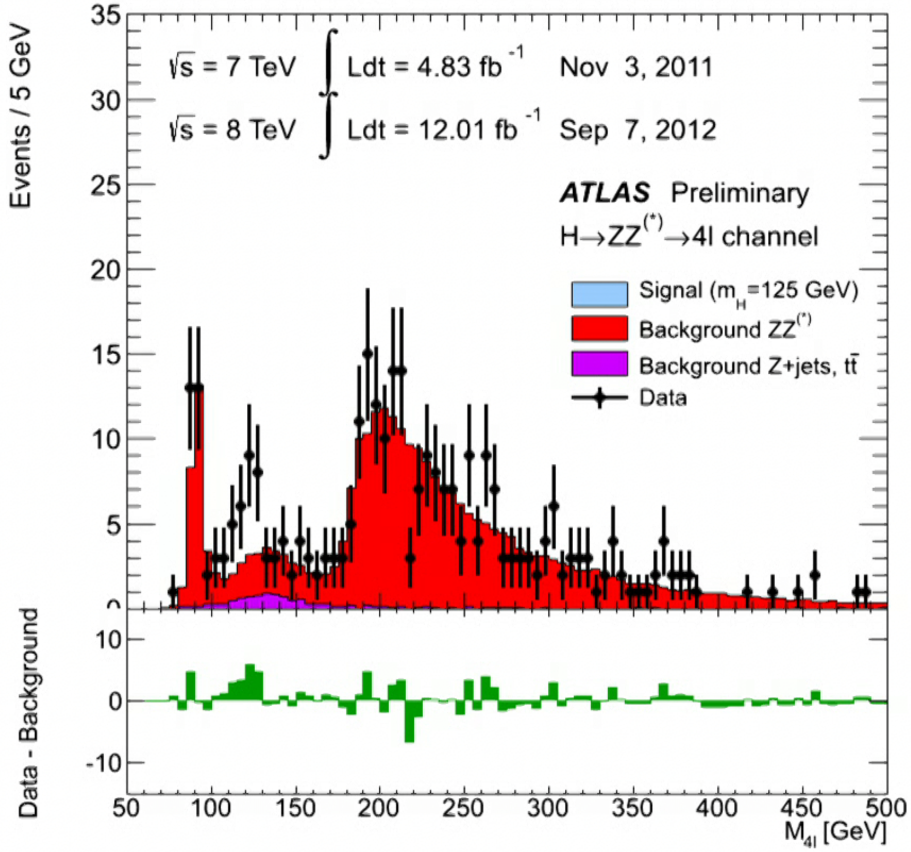
Events / 5 GeV
$\sqrt{s}$ = 7 TeV ∫Ldt = 4.83 fb^{-1} Nov 3, 2011
$\sqrt{s}$ = 8 TeV ∫Ldt = 10.01 fb^{-1} Aug 21, 2012
ATLAS Preliminary
H→ZZ$^{(*)}$→4l channel
Signal (m_H=125 GeV)
Background ZZ$^{(*)}$
Background Z+jets, $t\bar{t}$
Data
Data - Background
M_{4l} [GeV]

H → ZZ*



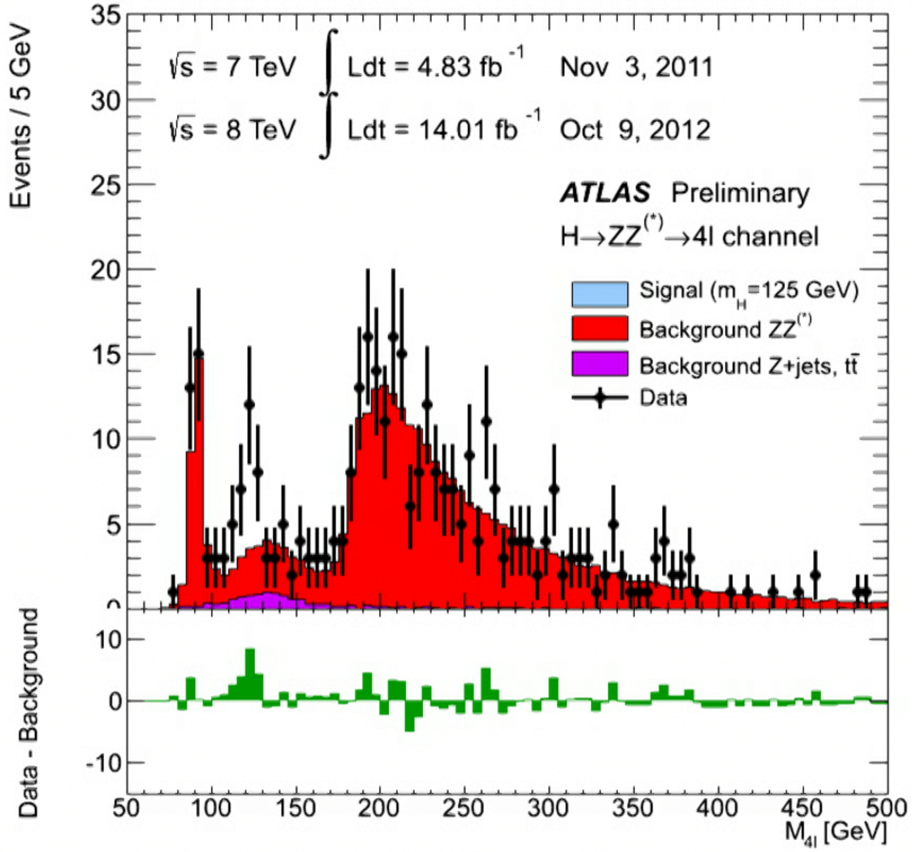
Events / 5 GeV
√s = 7 TeV ∫Ldt = 4.83 fb⁻¹ Nov 3, 2011
√s = 8 TeV ∫Ldt = 9.27 fb⁻¹ Aug 11, 2012
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M4l [GeV]

H → ZZ*



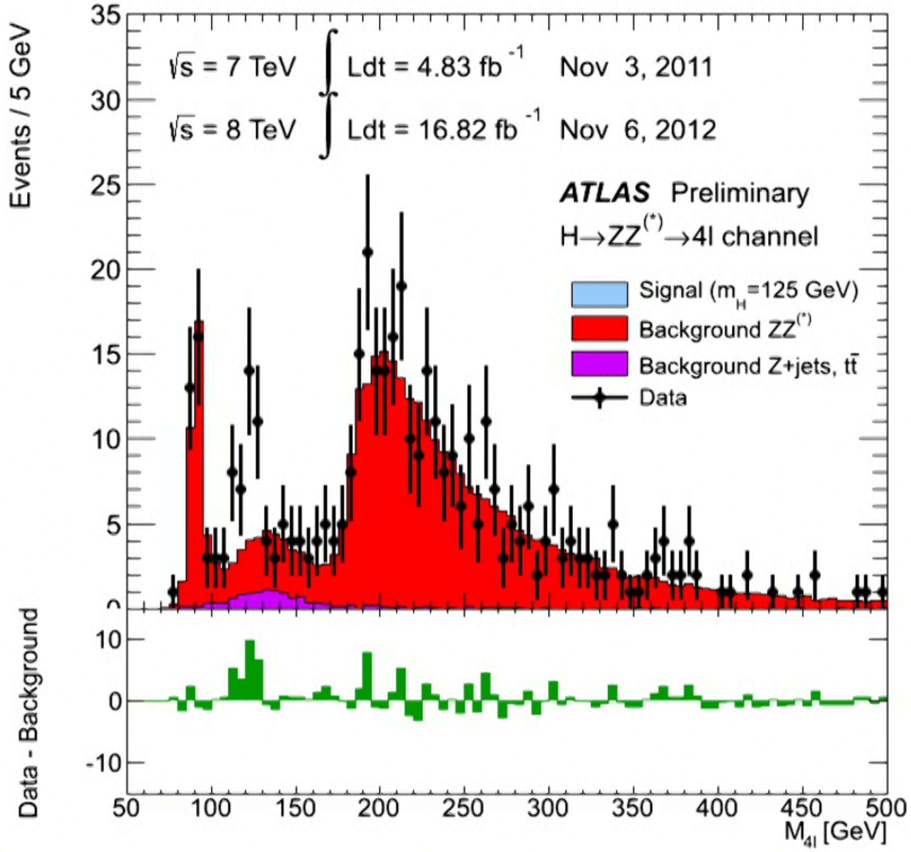
√s = 7 TeV ∫Ldt = 4.83 fb⁻¹ Nov 3, 2011
√s = 8 TeV ∫Ldt = 12.01 fb⁻¹ Sep 7, 2012
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]

H → ZZ*



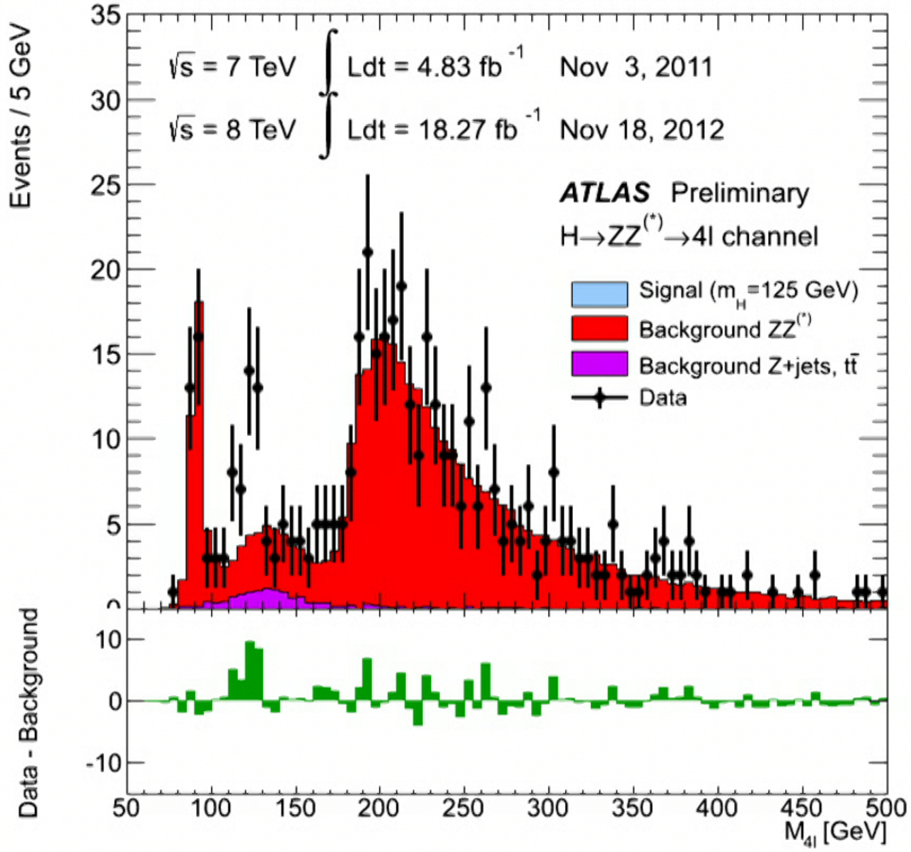
√s = 7 TeV ∫ Ldt = 4.83 fb⁻¹ Nov 3, 2011
√s = 8 TeV ∫ Ldt = 14.01 fb⁻¹ Oct 9, 2012
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M_4l [GeV]

H → ZZ*



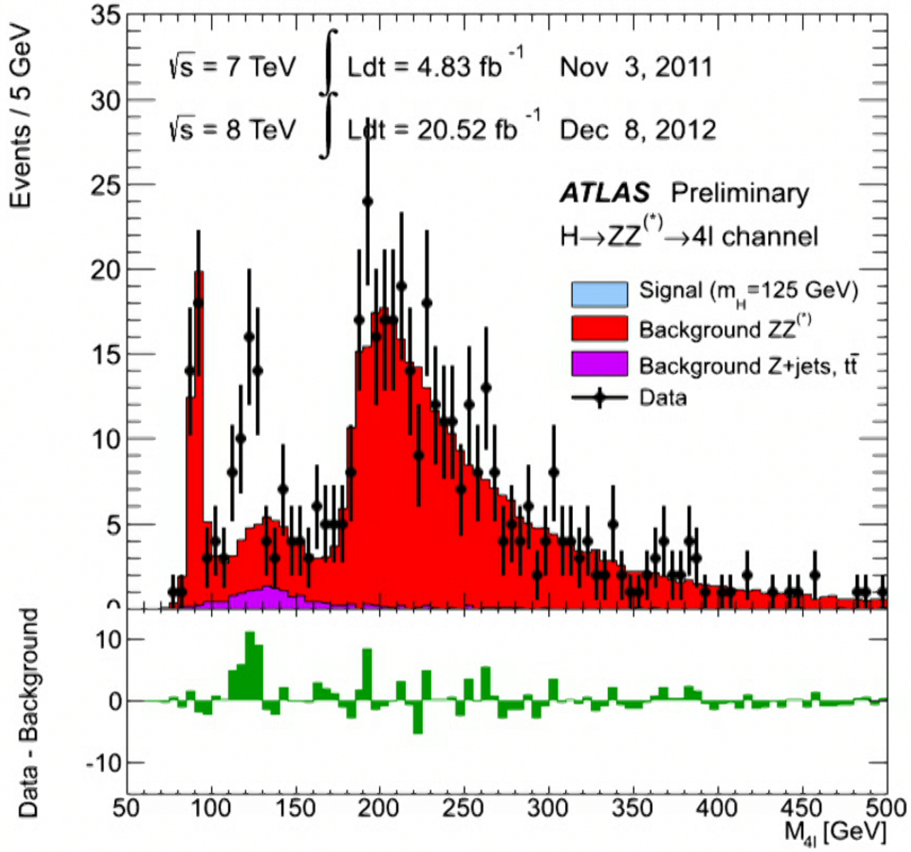
$\sqrt{s}$ = 7 TeV ∫Ldt = 4.83 fb^{-1} Nov 3, 2011
$\sqrt{s}$ = 8 TeV ∫Ldt = 16.82 fb^{-1} Nov 6, 2012
ATLAS Preliminary
H→ZZ$^{(*)}$→4l channel
Signal (m_H=125 GeV)
Background ZZ$^{(*)}$
Background Z+jets, $t\bar{t}$
Data
Events / 5 GeV
Data - Background
M_{4l} [GeV]

H → ZZ*



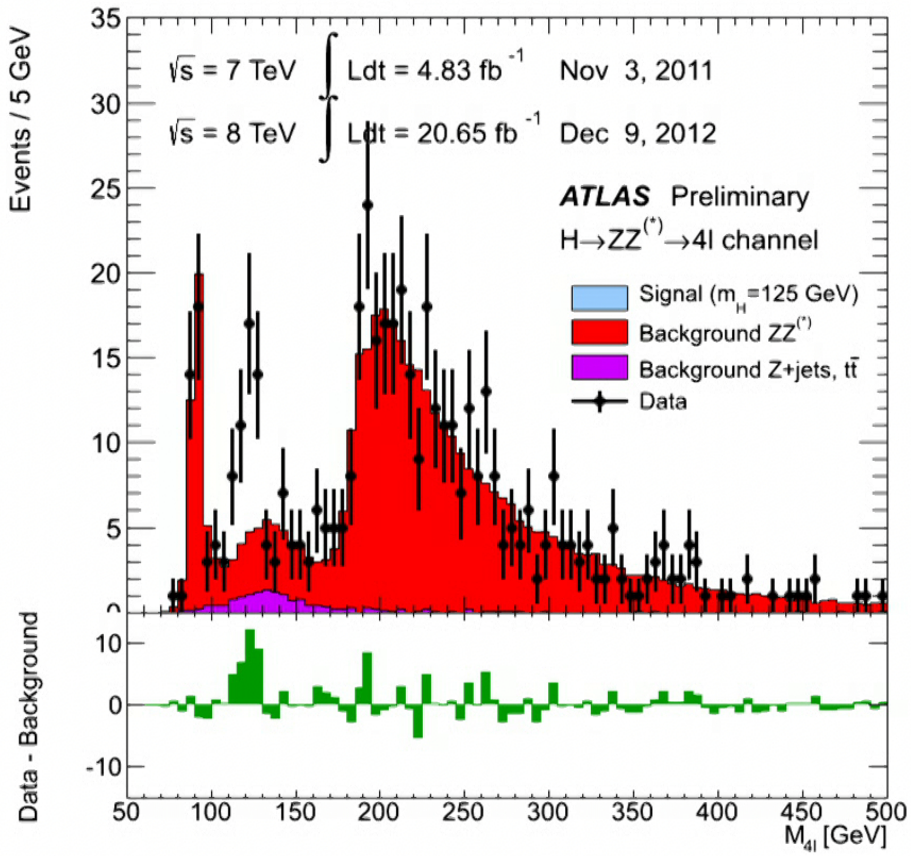
√s = 7 TeV ∫Ldt = 4.83 fb⁻¹ Nov 3, 2011
√s = 8 TeV ∫Ldt = 18.27 fb⁻¹ Nov 18, 2012
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M_4l [GeV]

H → ZZ*



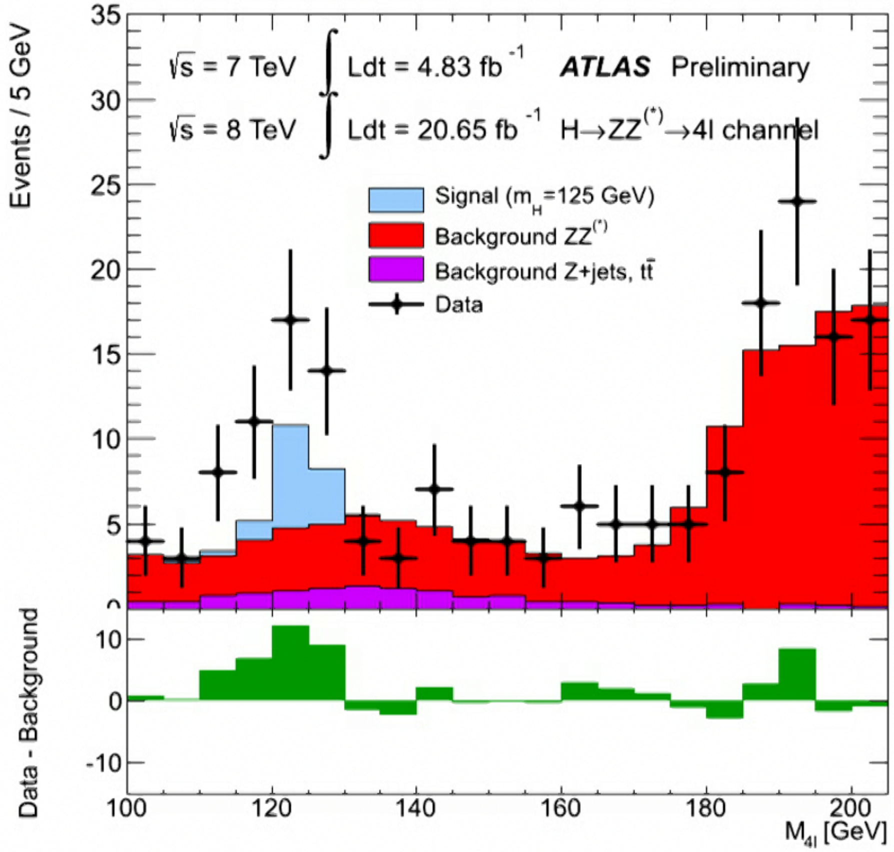
Events / 5 GeV
√s = 7 TeV ∫Ldt = 4.83 fb⁻¹ Nov 3, 2011
√s = 8 TeV ∫Ldt = 20.52 fb⁻¹ Dec 8, 2012
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M_4l [GeV]

H → ZZ*



√s = 7 TeV ∫Ldt = 4.83 fb⁻¹ Nov 3, 2011
√s = 8 TeV ∫Ldt = 20.65 fb⁻¹ Dec 9, 2012
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]

H → ZZ*



√s = 7 TeV ∫Ldt = 4.83 fb^-1 ATLAS Preliminary
√s = 8 TeV ∫Ldt = 20.65 fb^-1 H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M_4l [GeV]

An Immediate Fact and A Mystery

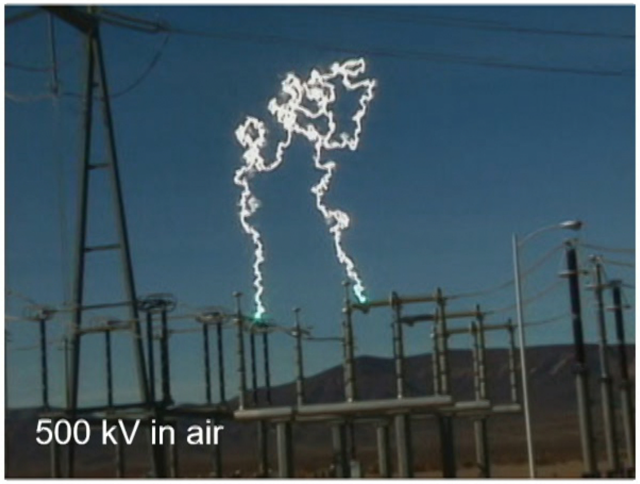
- Fact: whatever the new particle was (we called it "Higgs-like" in those days), it coupled very strongly to the Z
  - The rate of h → ZZ* was ~30x the rate of h → $\gamma\gamma$.
    - Even though the Z* must be off-shell by at least 56 GeV: about 25Γ!
    - Higgs or not, one could not write down a correct theory of electroweak symmetry breaking without including this particle.

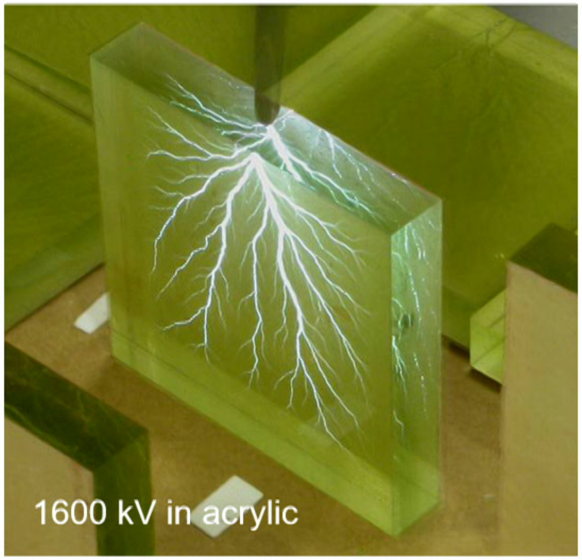
- Mystery: why does it weigh 125 GeV?
  - This makes no sense.
  - At tree level, things are fine.
  - When you impose quantum corrections, they push this mass way, way up – to the GUT or even the Planck scale…
  - …unless you impose a symmetry
    - For example, pair each upward correction with a downward one (SUSY does this)
    - The problem is this mechanism usually works too well, and the Higgs becomes lighter than 125 GeV
  - We don't have a good answer to this

Getting a Beam of 7 TeV Protons

- In principle, this is simple: put 7 trillion volts of potential on a proton and let 'er rip…

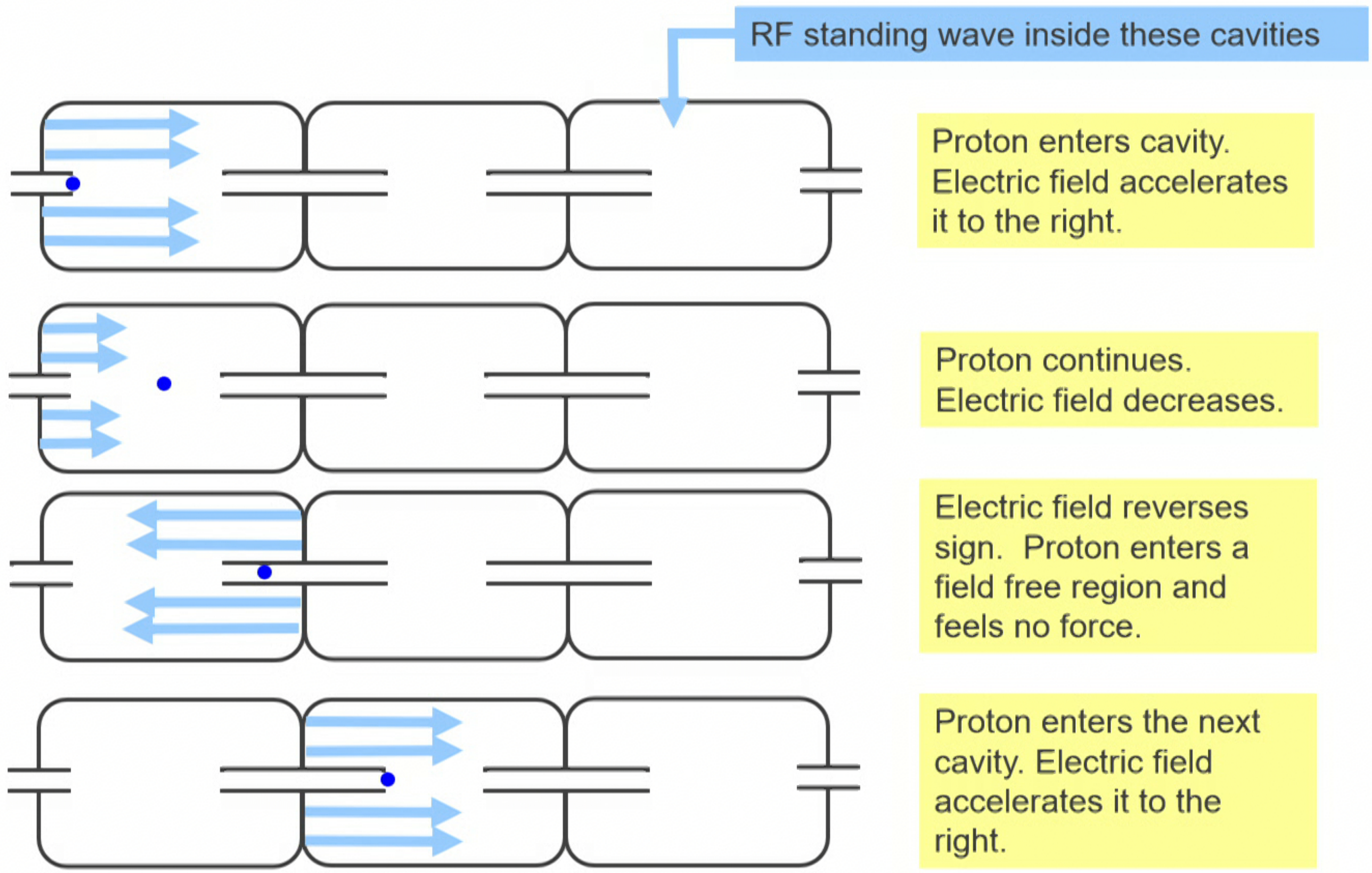
- This may not be the safest course of action – here is what less than one four-millionth of this potential can do:





Even in vacuum this won't work – the electric fields necessary would rip the atoms apart.

How To Build a Linear Accelerator



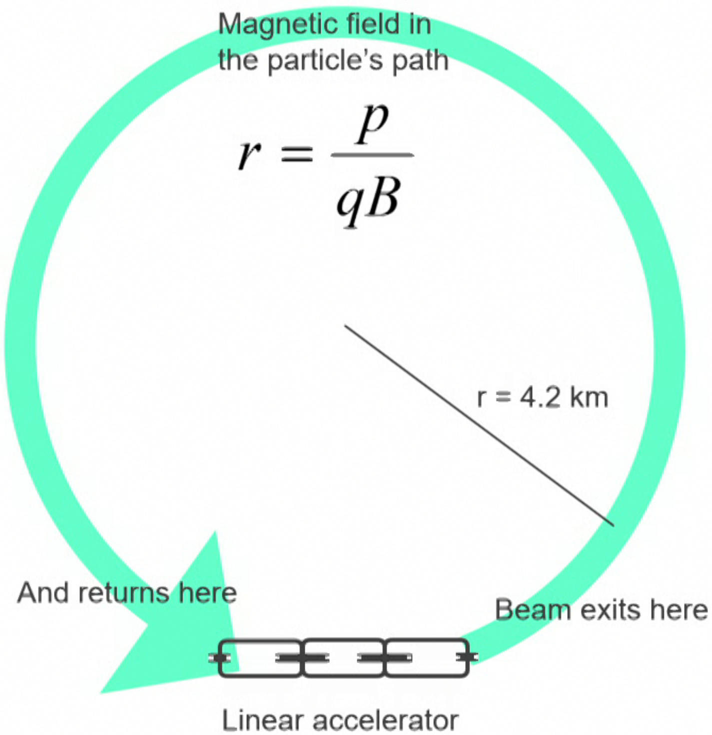
Linear Acceleration

- In principle, our problem is solved: simply build a long enough linear accelerator

- This isn't too practical. Using state of the art cavities, reaching the LHC design energy of 7 TeV on 7 TeV means
  - It would be 150 miles long
  - It would cost $75 billion

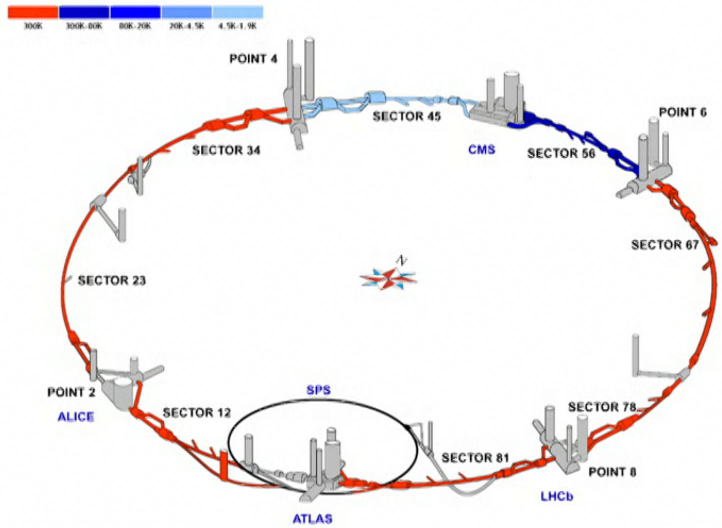
A portion of Fermilab's linear accelerator

Recycling: The Proton Synchrotron



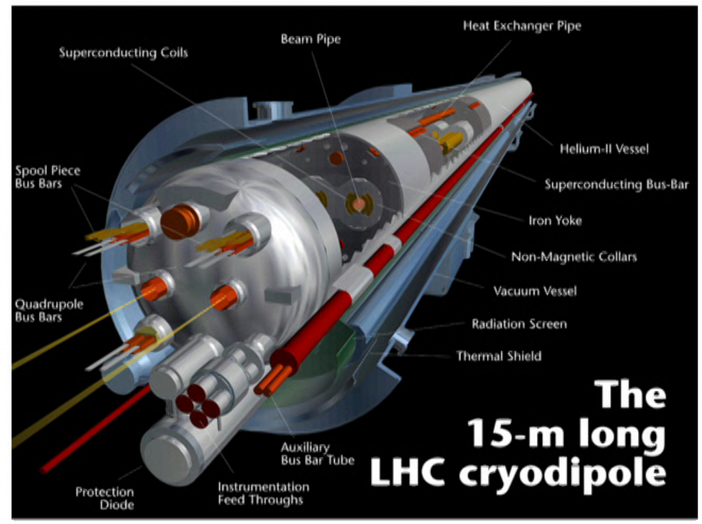
- Accelerating structures are reused ~20 million times during each fill of the LHC
- The cost of such a machine is ~an order of magnitude cheaper than an equivalent linear accelerator
- The energy that can be reached is limited by the strength of the magnetic field in the arcs
  - These are dipole magnets
  - Field direction is into the page
  - LHC dipole fields are 8.36 T

A Less Cartoonish View



The Large Hadron Collider is a 26km long circular accelerator built at CERN, near Geneva Switzerland.

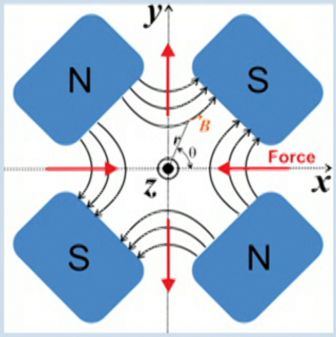
The magnetic field is created by 1232 dipole magnets (plus thousands of focusing and correction magnets) arranged in a ring in the tunnel.



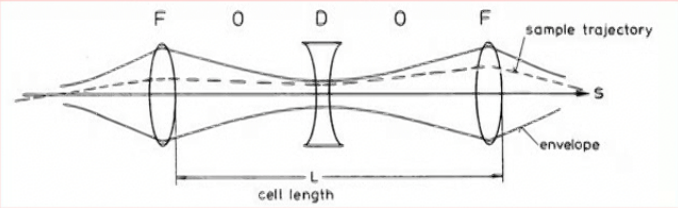
Keeping the Beam from Exploding

A beam has particles all with the same charge – how do we keep them together?

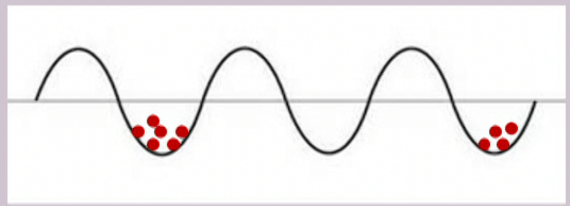
Transverse to the beam, we use quadrupole magnets



A quadrupole in one orientation focuses horizontally and defocuses vertically. The other orientation does the reverse.
From optics*: a combination of focusing and defocusing is net focusing.



Longitudinal to the beam, we use RF, the same RF we used for acceleration.



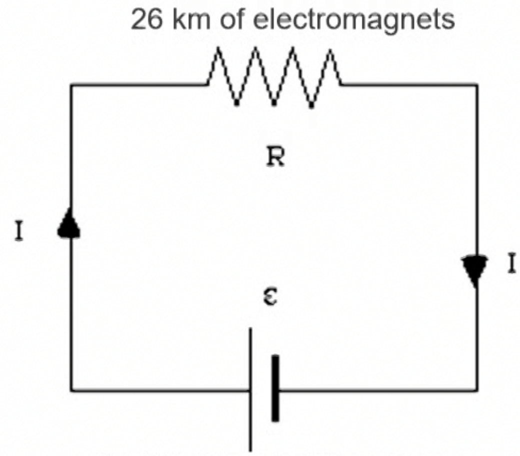
Together this gives us stability in x, y and z.

* Homework: what is the relationship between f and L that makes this true?

Our Next Problem - Resistance

- To generate the field we want, we need to carry about 12000 Amperes.
- US NFPA code says one needs a "wire" that has a diameter of about 35 cm to safely carry this current.
  - This is 000…000 (32 zeros) gauge "wire"
    - In practice one would use a shaped piece of copper.
    - It's probably impossible to control the shape of the current flow accurately enough
- Resistance is only 0.02 Ω
  - This means Joule heating is 3 megawatts

Need to go to superconducting magnets.



LHC Circuit Diagram

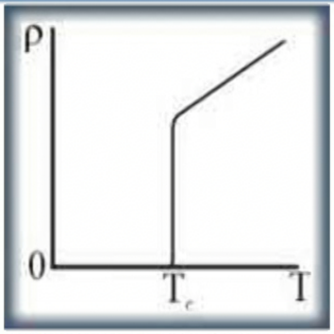
$$E = IR$$

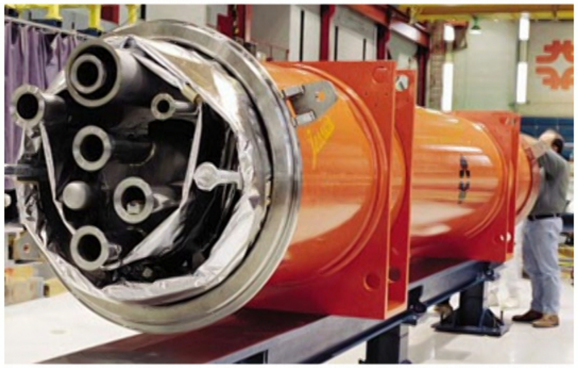
$$P = EI$$

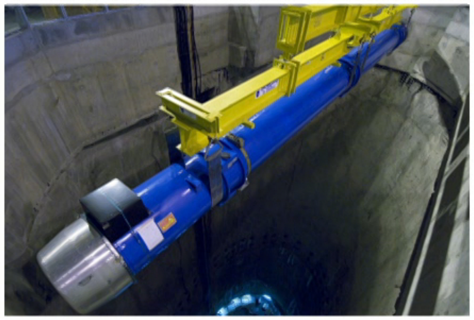
$$P = I^2 R$$

Using Superconducting Magnets

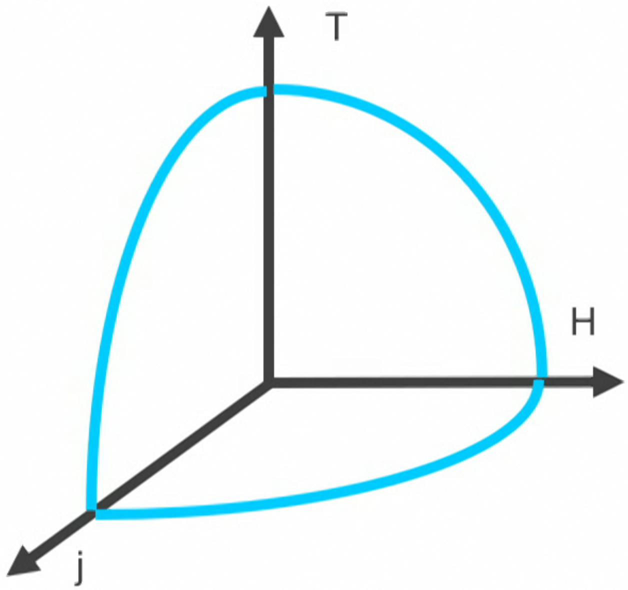
- Zero resistance – a good thing!
- Field is limited to ~9 Tesla (see next slide)
- They have to be kept cold: around 1.9K
  - Carnot efficiency of pumping out any heat that's leaked in is 1.9K/300K < 1%.
  - This is less than 15W per magnet for superconducting magnets to "win"







Superconductivity Facts

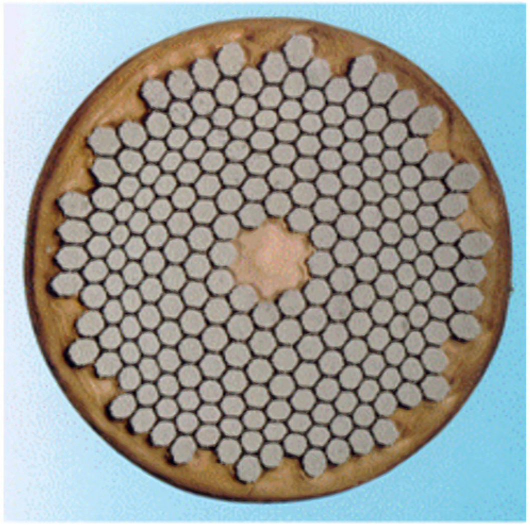


Phase diagram for a superconductor

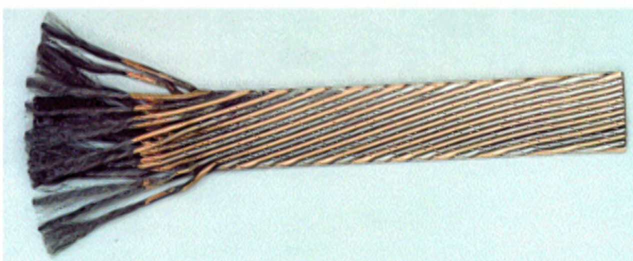
Think "critical surface" instead of "critical temperature"

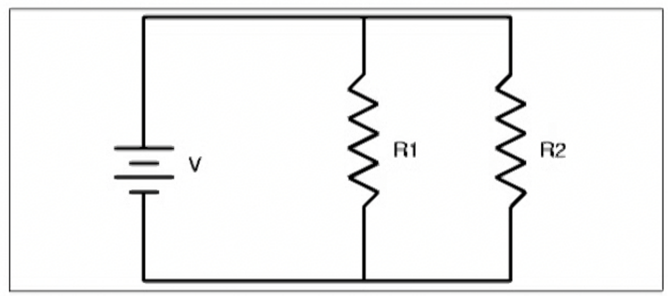
- Superconductivity can be destroyed by:
  - Shaking apart the Cooper pairs (exceeding T_c)
  - Pulling apart the Cooper pairs (exceeding H_c or j_c)
- Because we want to run at high fields/high currents we want a cold magnet
  - T = 1.9K
  - T_c for Ni-Ti is 17.9K
- At 1.9K the small sample limit is ~9T
  - At design LHC magnets operate at 8.36T

Superconducting "Wire"



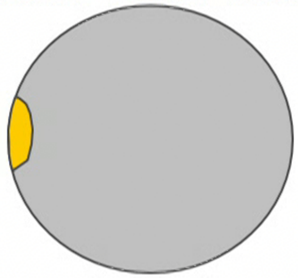
- Nb-Ti has great superconducting properties
  - High T_c, H_c and j_c.
- It has the mechanical consistency of toothpaste.
- It's surrounded by a thin (~ 10% of the radius) copper jacket
  - Provides mechanical strength
  - Carries most (~80%) of the current when the magnet is warm
    - Copper area is 20% of the area of the cable, but copper's resistivity is 40x smaller.



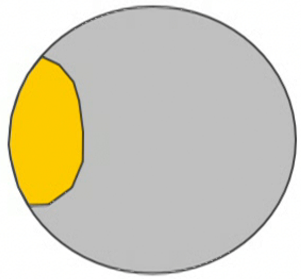


What NOT to Do With Your Magnet

Suppose a small region in your superconducting cable goes normal.



Current will flow around the resistive spot, driving it past j_c; the spot grows



Eventually, the entire cross-section goes normal, and now you have a resistive wire. All the heat is dissipated in that spot.

Stored energy in magnets = 10 GJ, same as a 747 at top speed.)

A magnet undergoing a controlled quench.

2008 "Incident" Timeline

- March 2008 – CERN announces the LHC will start with 5 TeV per beam rather than 7 TeV. This avoids a lengthy magnet retaining process.
- 10 September 2008 – amidst much media hoopla, beams are circulated at 450 GeV (injection energy). At this time, 7 of the 8 sectors are "qualified for 10 TeV collisions", meaning they operate properly at 11 TeV equivalent current.
- 18 September 2008 – a transformer near Point 5 fails. EDF says it will take a couple of days to find and install a replacement. Two sectors start to warm. Decided to return to qualifying the last sector, 3-4, in parallel.
- 19 September 2008 – during one of these tests, a magnet quench led to an electrical arc, which in turn led to a catastrophic loss of helium, which made a great big mess.