Higgstravaganza!

Tom LeCompte

High Energy Physics Division
Argonne National Laboratory

(With thanks to the ATLAS and CMS Collaborations)

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

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 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.

Lecture Plan

- This lecture is in two parts
  - Today: Discovery
  - Tomorrow: Post-Discovery

(unfortunately, not an easy 50-50 split)

- I am going to devote most of the time to walking you through the ATLAS $H \rightarrow \gamma\gamma$ analysis, as it was on July 4 2012.

- However, I also want to show you elements of
  - the corresponding CMS analysis
  - other ATLAS and CMS Higgs analyses

- These talks are often a death march through a jungle of plots and tables. Instead I want to highlight
  - Some of the questions the experiments asked themselves
  - The decisions that they made
  - The decisions other people made
  - The strengths and weaknesses of these choices

- Remember, a month of work can save you an hour of thinking

The Mandatory Theory Slide

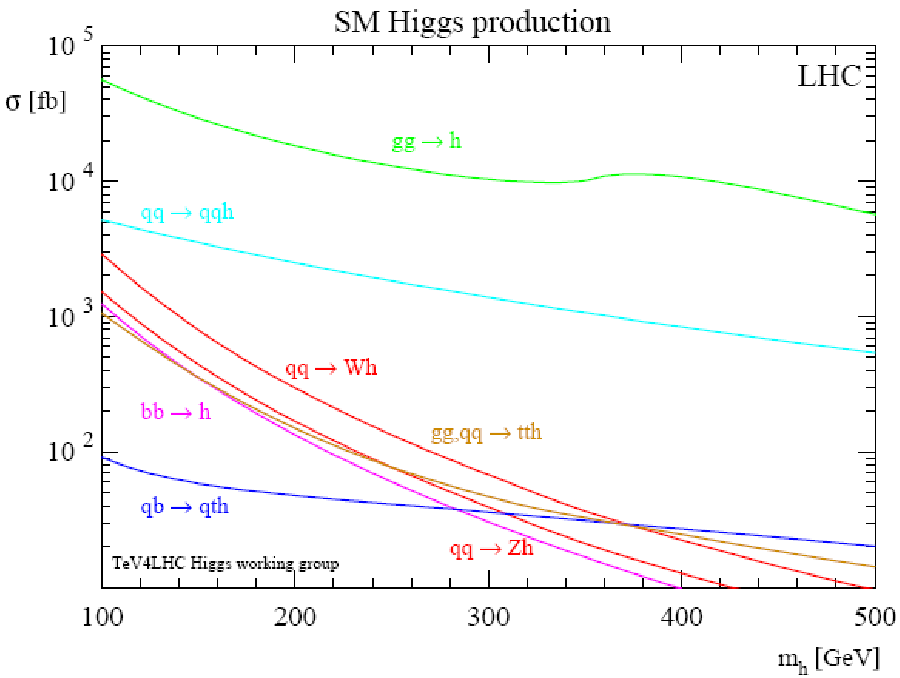
- The Higgs mechanism has three jobs:
  - Give mass to the W and Z (EWSB)
  - Give mass to the U-type fermions
  - Give mass to the D-type fermions

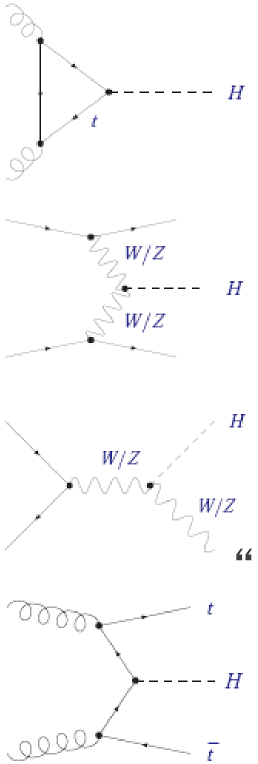
- In the SM, these three jobs are done by a single spin-0 particle
  - Strictly speaking, by a doublet and its conjugate, which leads to one spin-0 particle. It's shorthand to say "one Higgs".

- This is an extremely constrained theory – apart from one free parameter (usually λ, the Higgs self-coupling, but equivalently m_H, its mass) everything is completely determined.

Like…

Higgs Production





gg-fusion

weak boson fusion

"VBF"

Higgs strahlung

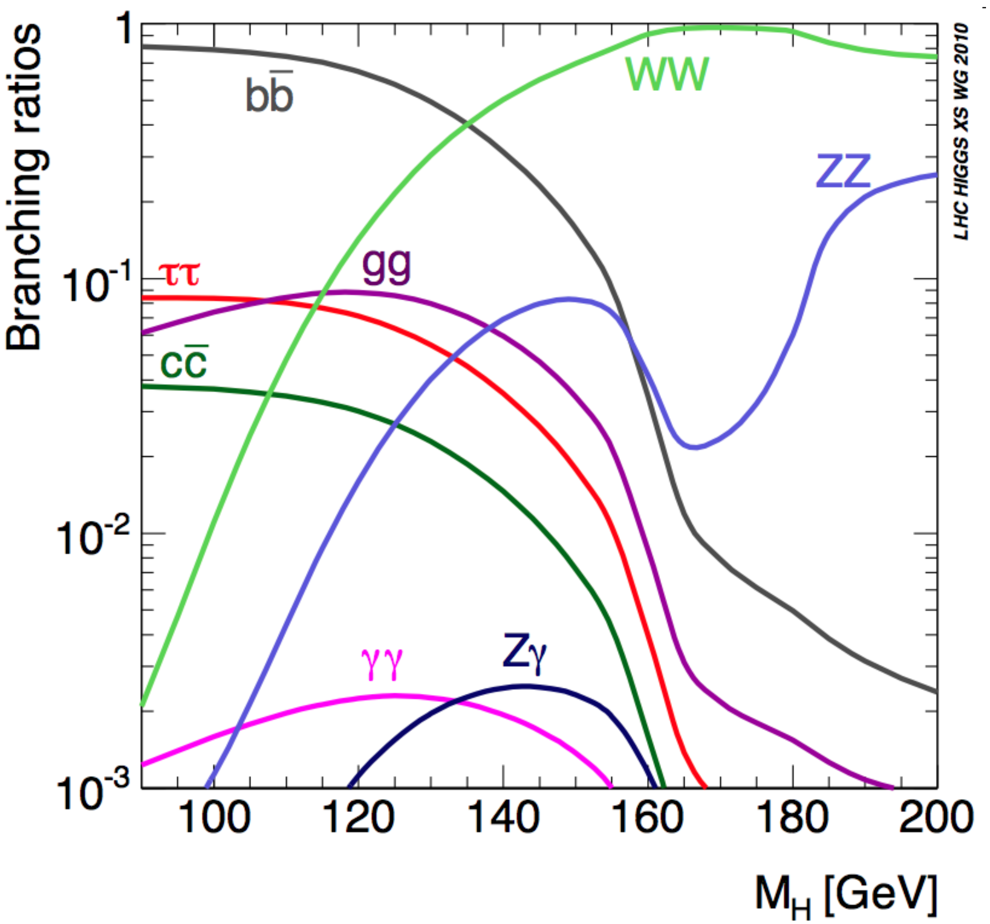
"associated production"

$t\bar{t}H$-channel

- 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

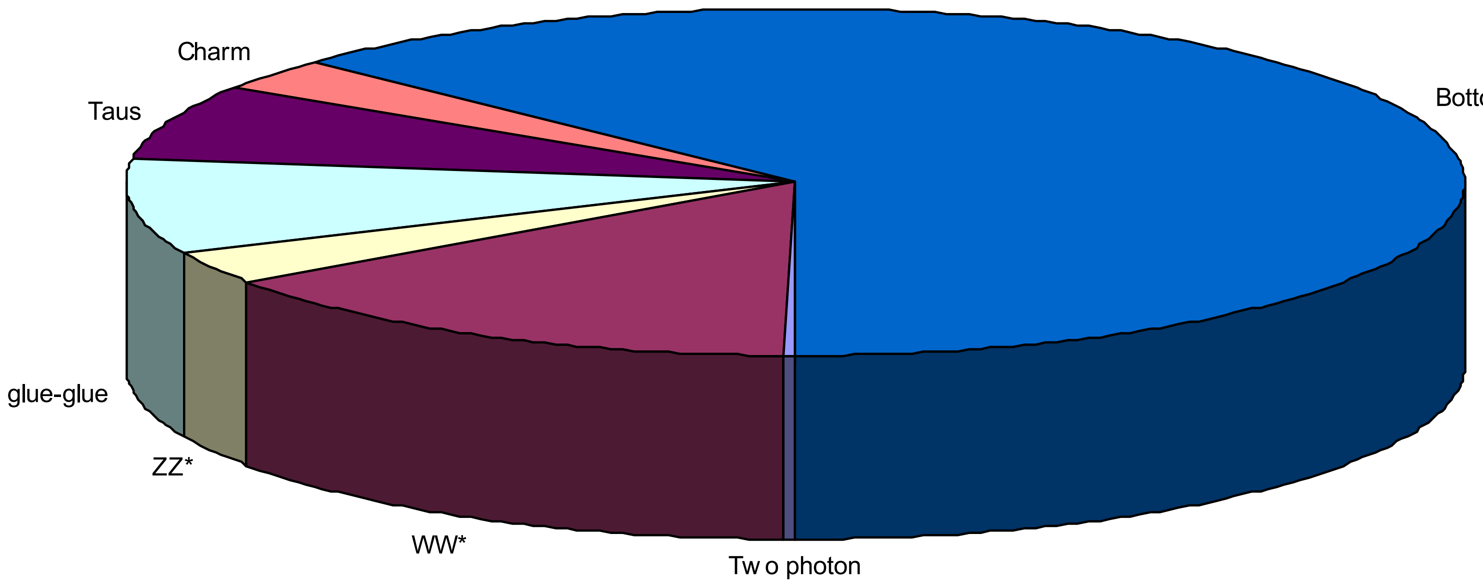
And…

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 $\gamma\gamma$ 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.

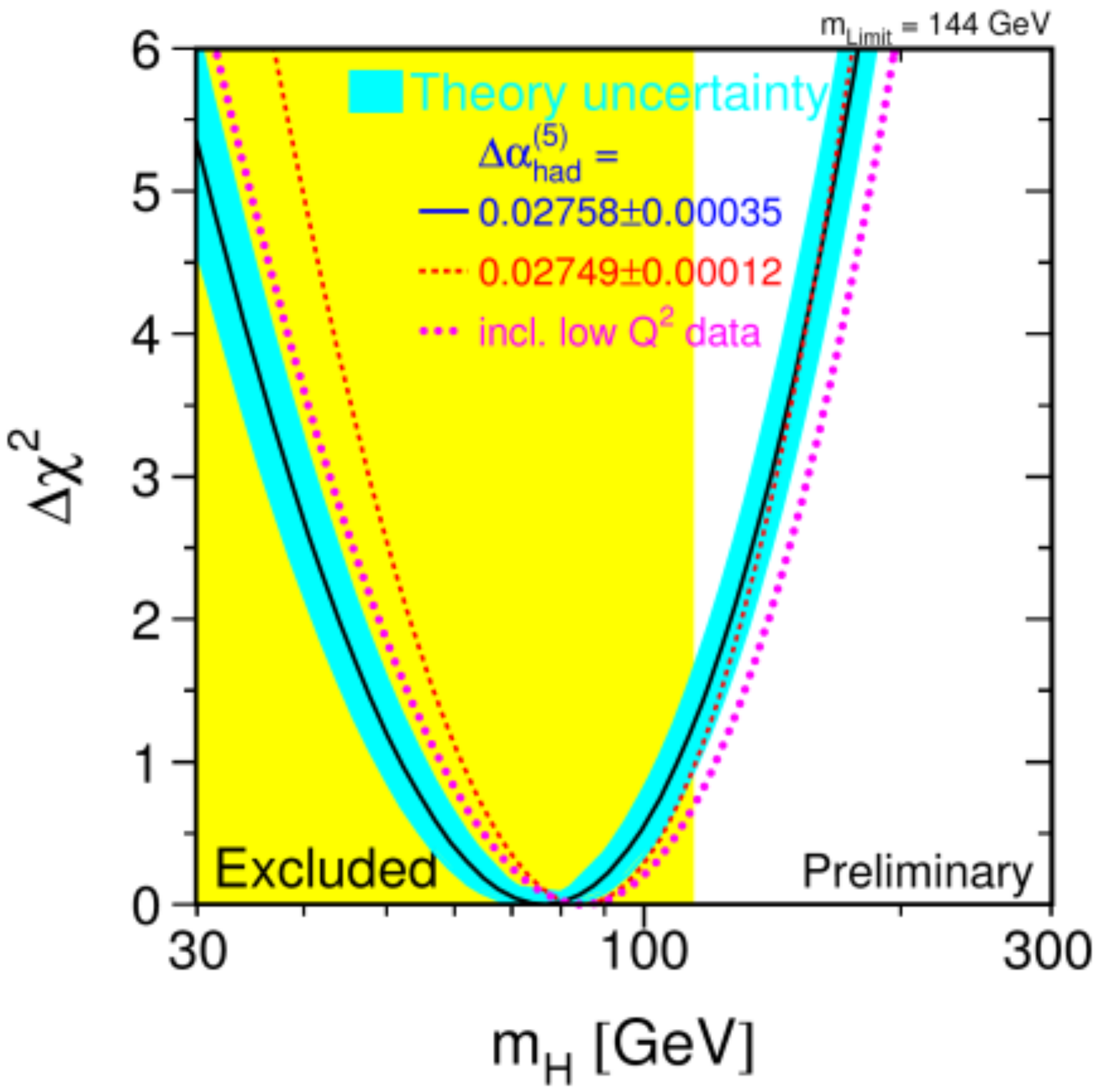
Higgs Decays

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

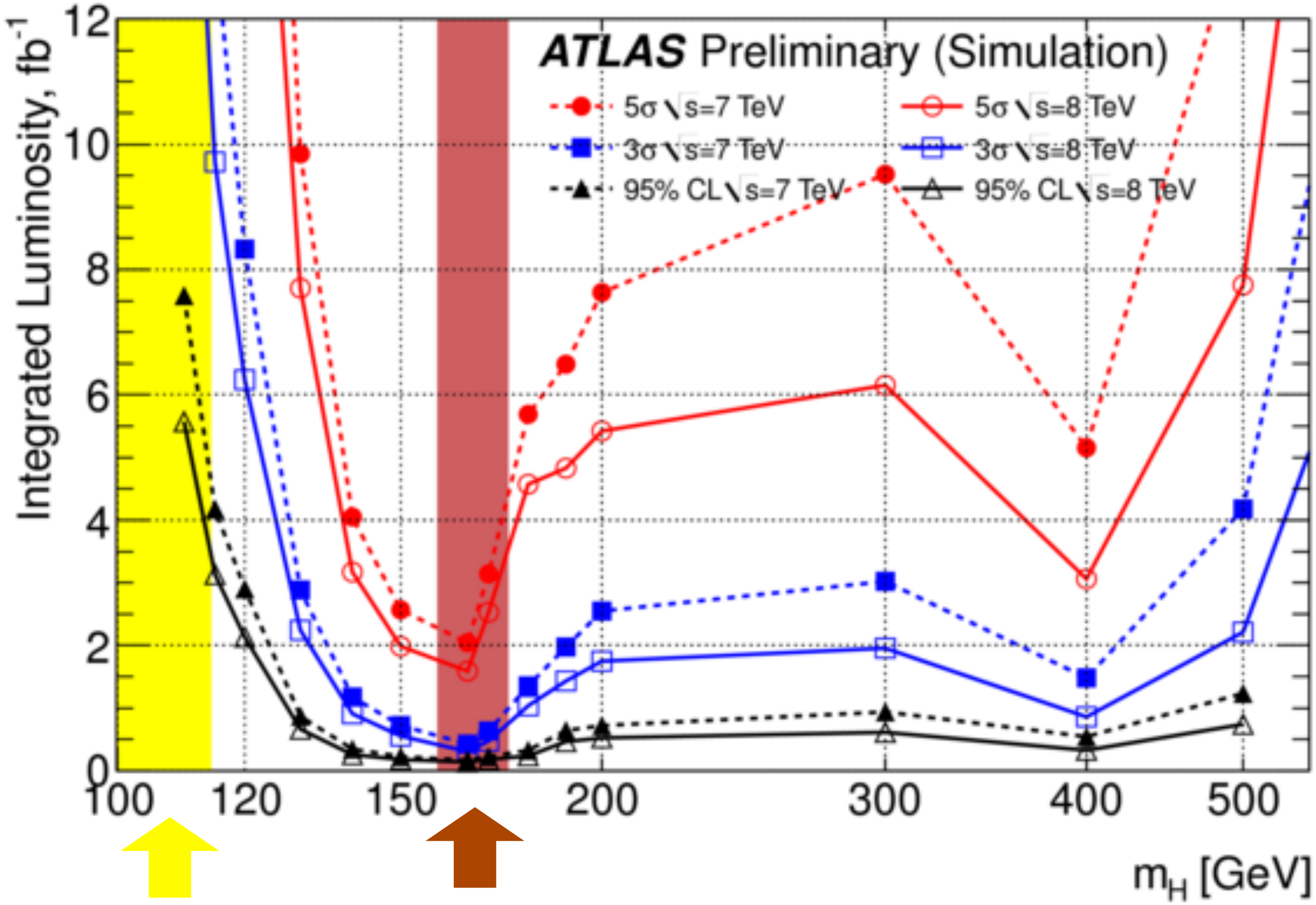
The quantity of signal is but one element in designing an analysis. The level of background is at least as important. While I will only barely touch on it, so is triggerability: you cannot analyze an event that you didn't record.

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)

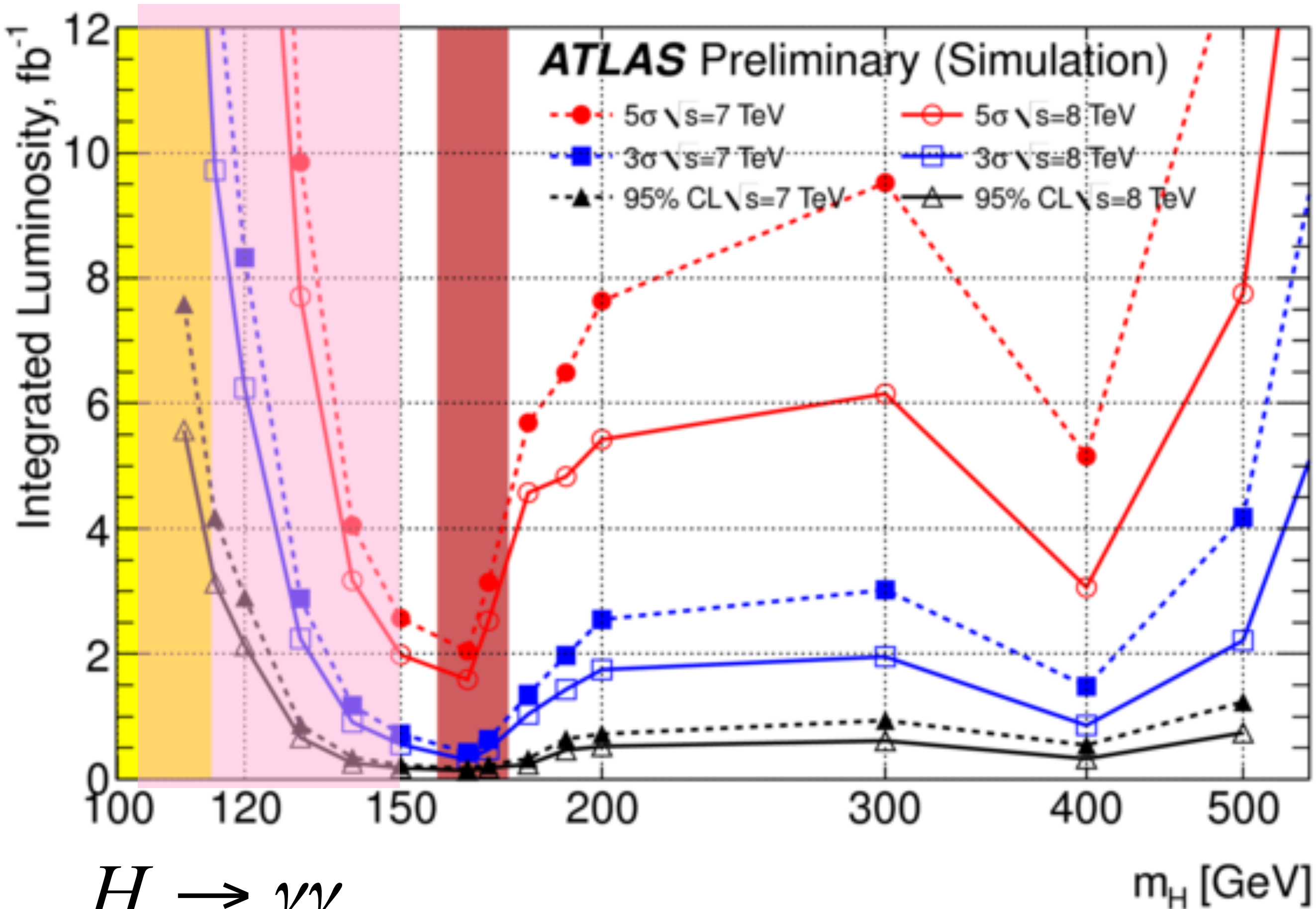
Pre-LHC Search



Excluded by LEP

Excluded by the Tevatron

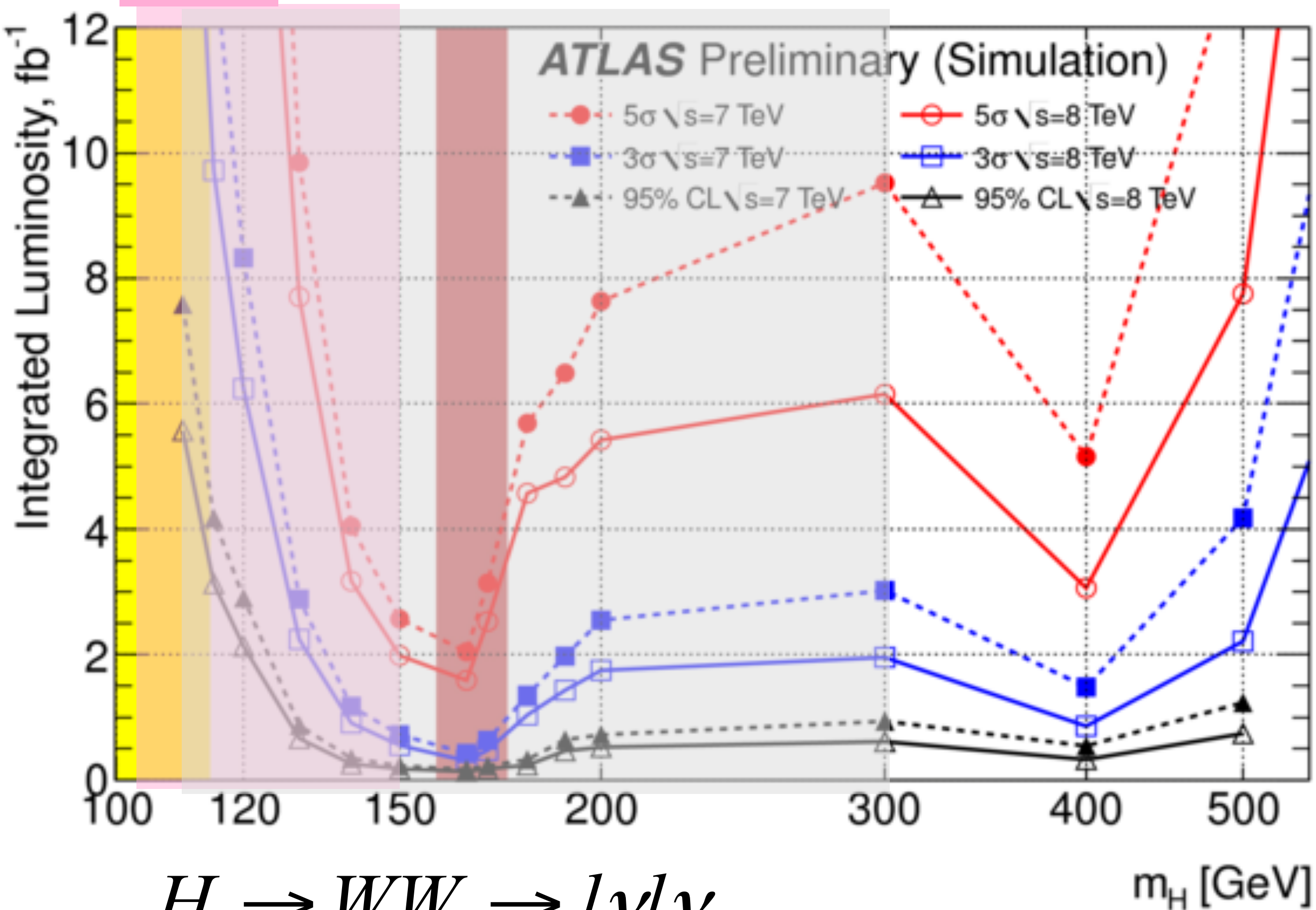
Channel-by-Channel



$H \to \gamma\gamma$

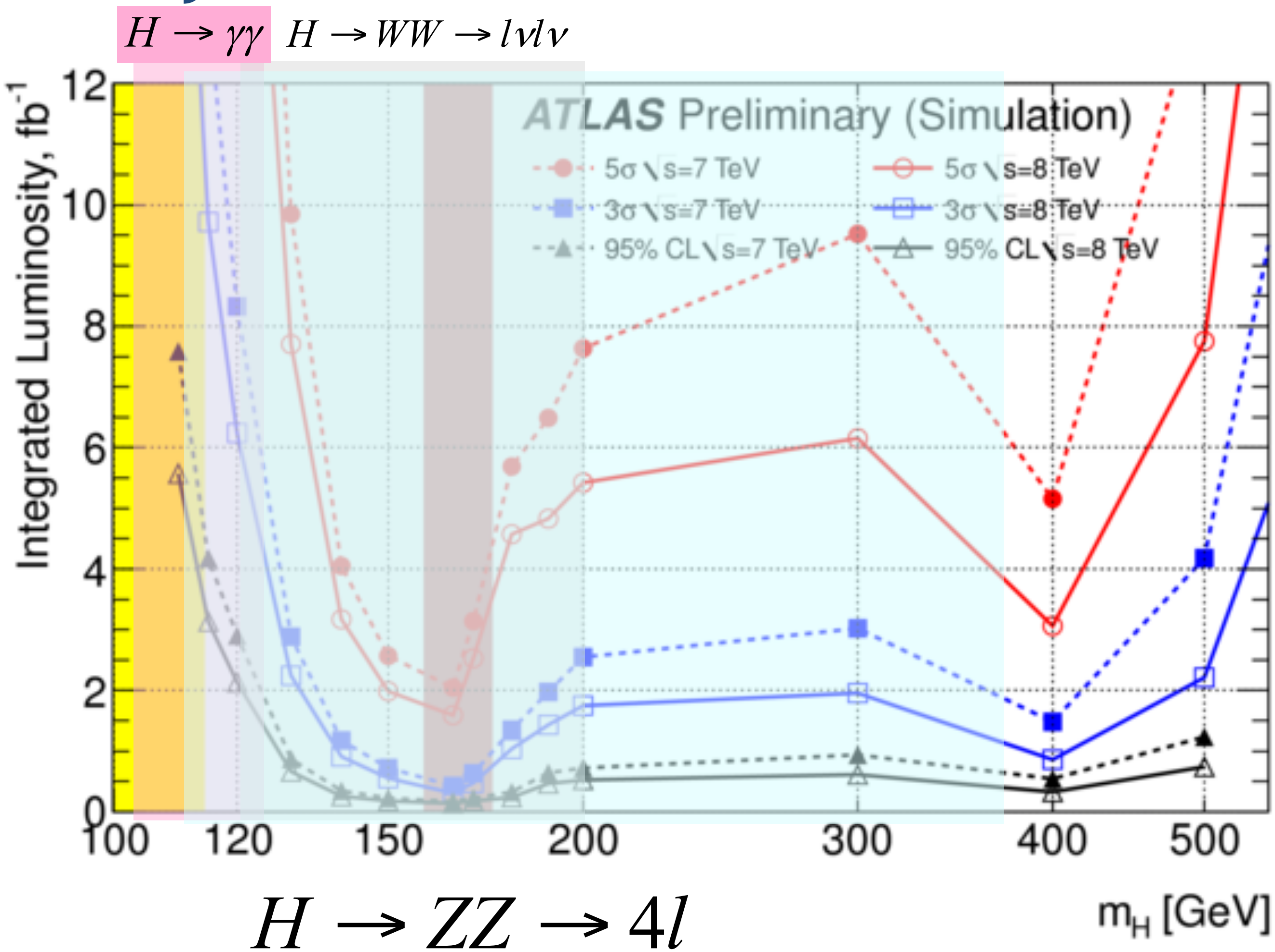
Channel-by-Channel

$H \rightarrow \gamma\gamma$



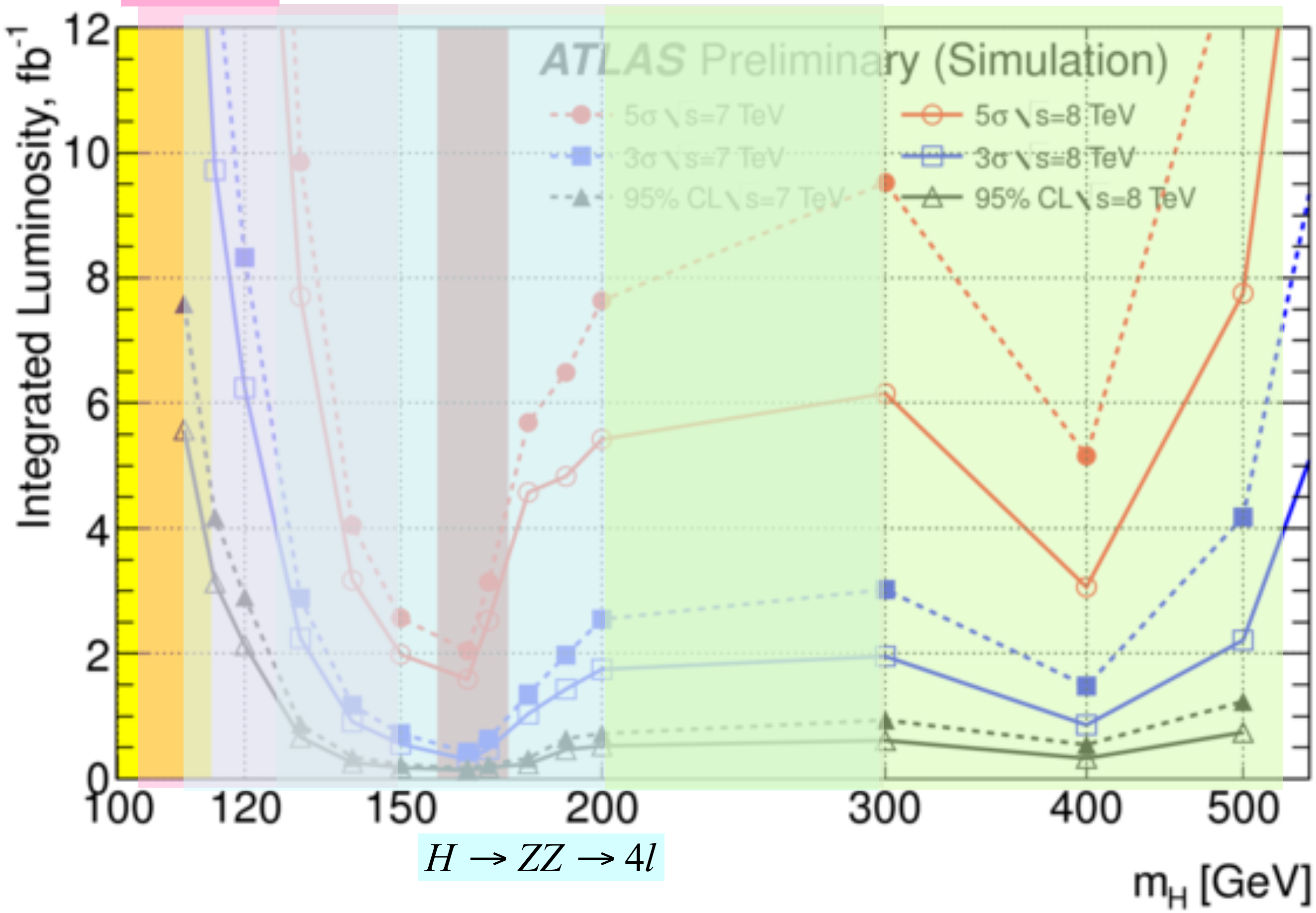
$$H \rightarrow WW \rightarrow l\nu l\nu$$

Channel-by-Channel



Channel-by-Channel

$H \to \gamma\gamma$ $H \to WW \to l\nu l\nu$



$H \to ZZ \to 4l$

$$H \to ZZ \to ll\nu\nu$$

Plus some $H \to WW \to l\nu qq$ $H \to ZZ \to llqq$

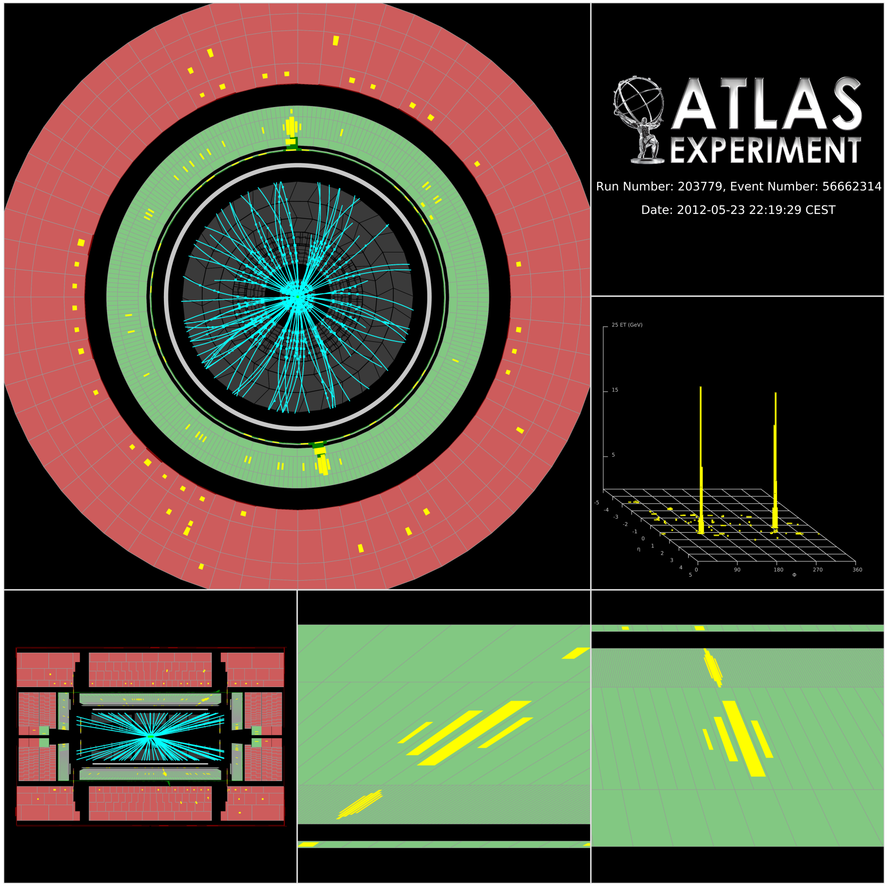
Where Are We After Step #0?

- 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

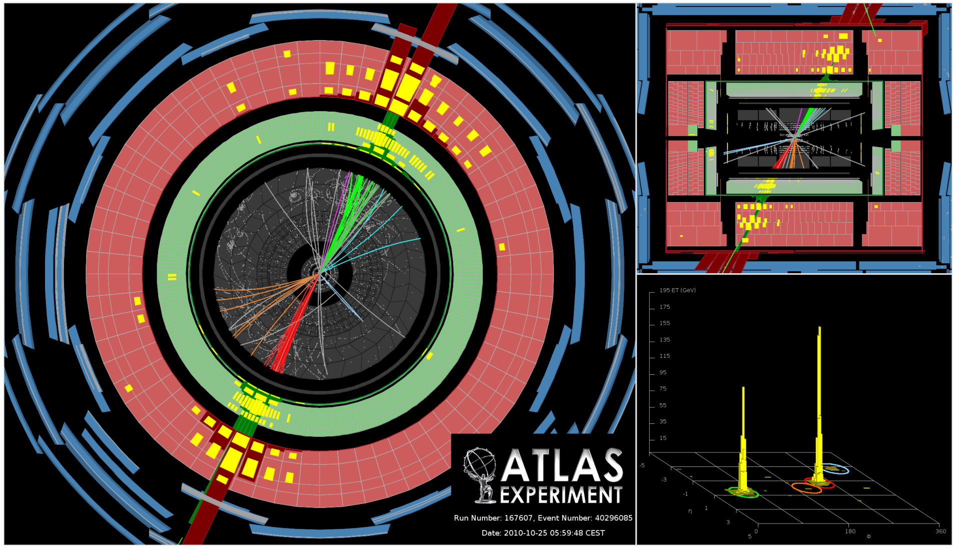
- Other people will look at H → WW*
- Still other people will look at H → ZZ*
- And still other people will look for "specialized" Higgs decays
  - Heavy Higgs
  - Charged Higgs
  - Supersymmetric Higgs

Identifying Photons

We need to separate this…

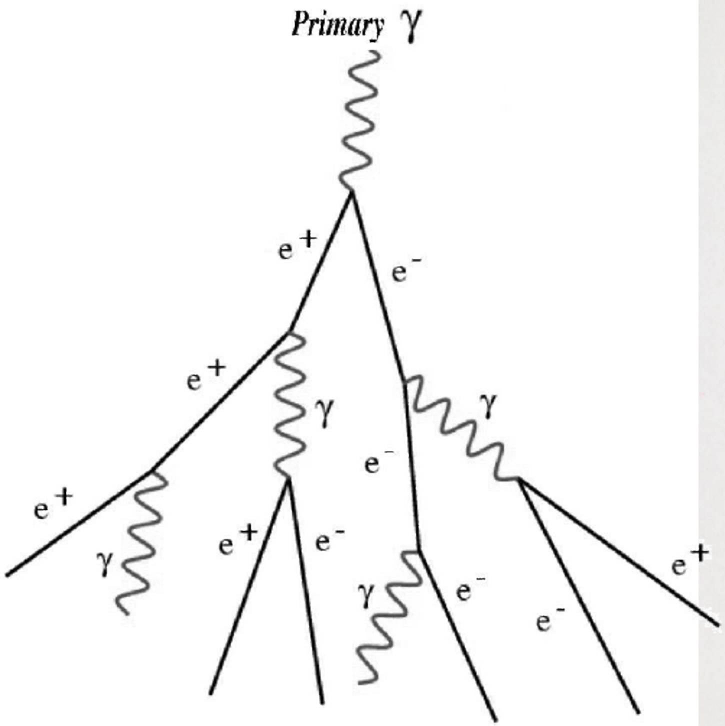


From this…

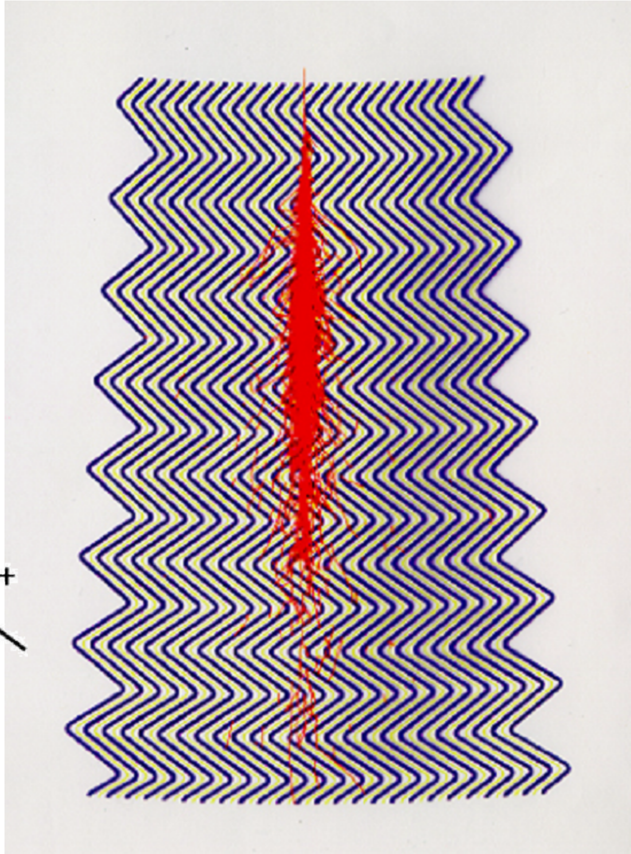


Only a small fraction of jets can mimic a photon – but there are a lot of jets!

Identifying Photons - Basics of Calorimeter Design



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)

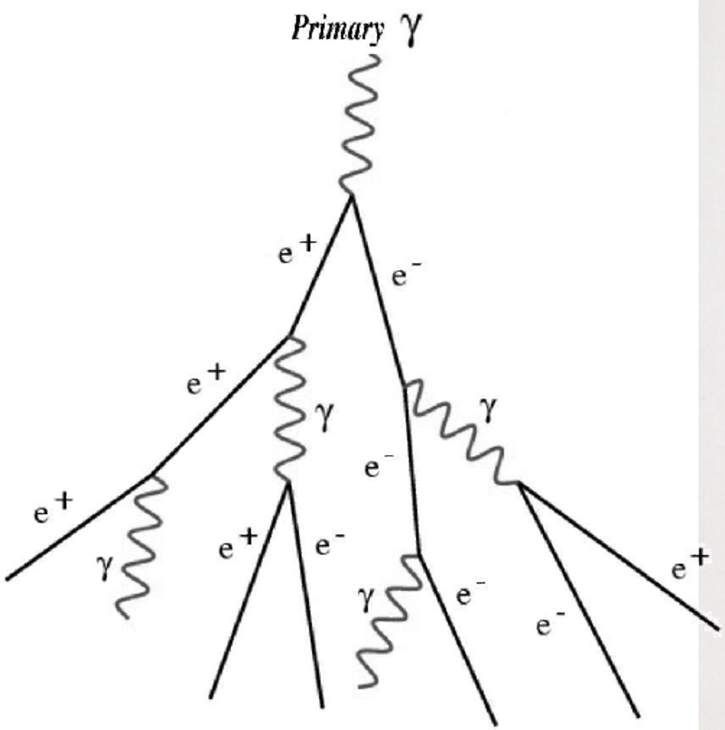
Not too wide here.

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

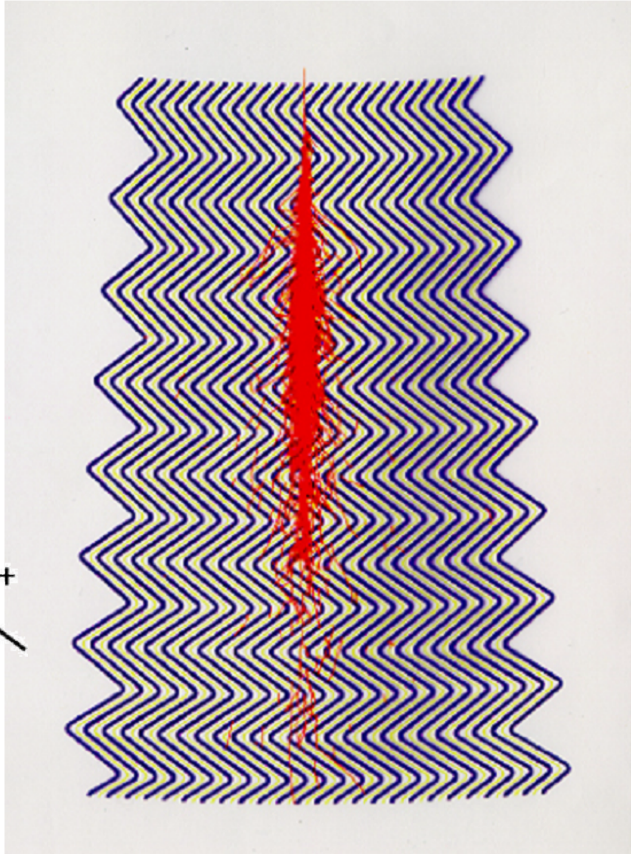
Not too much energy here.

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

Identifying Photons - Basics of Calorimeter Design



A schematic of an electromagnetic shower

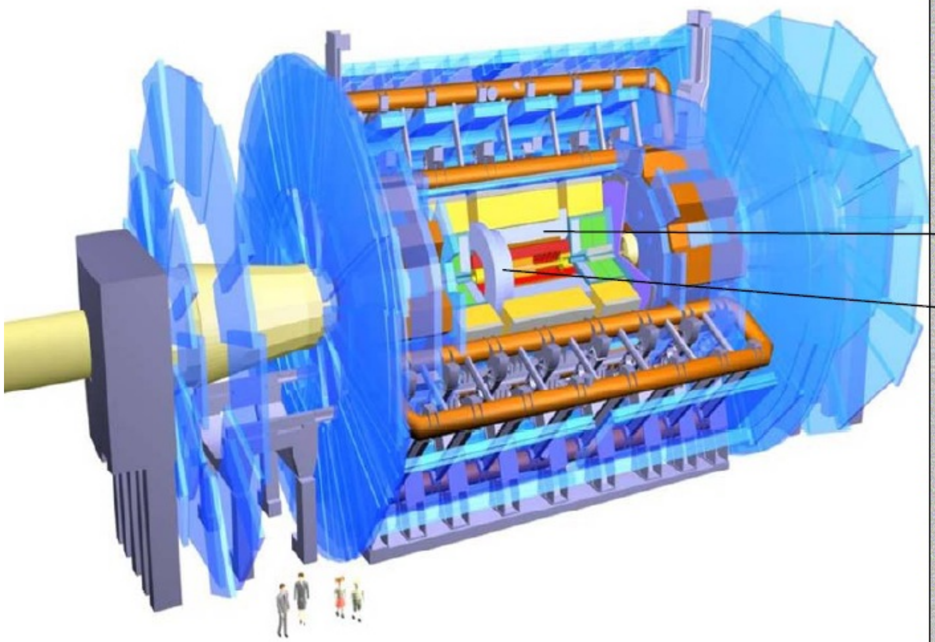


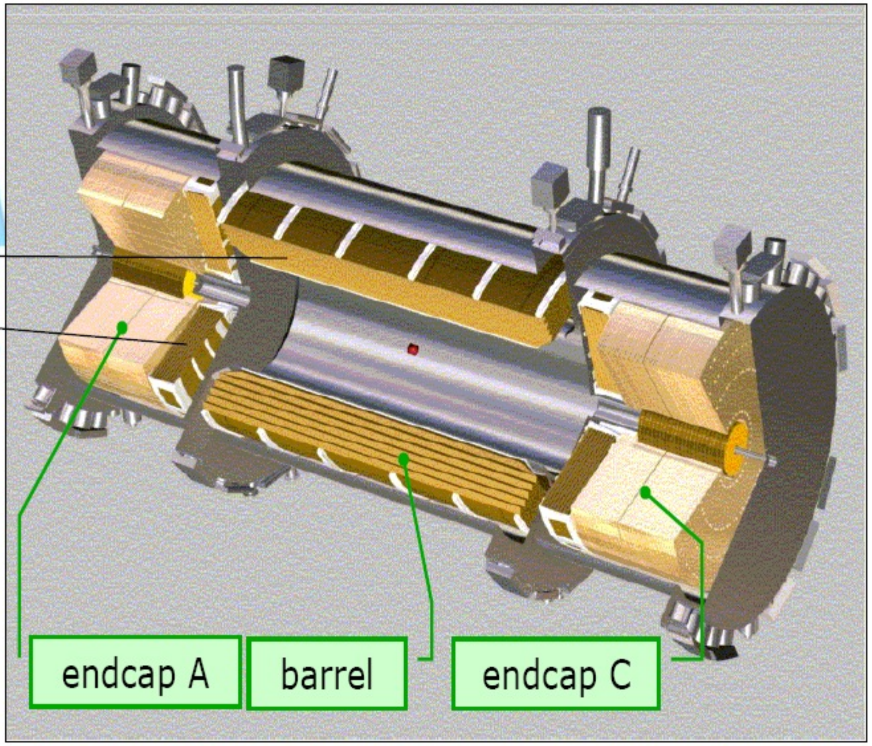
A GEANT simulationof an electromagnetic shower

- EM showers all look the same

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

ATLAS Electromagnetic Calorimeter





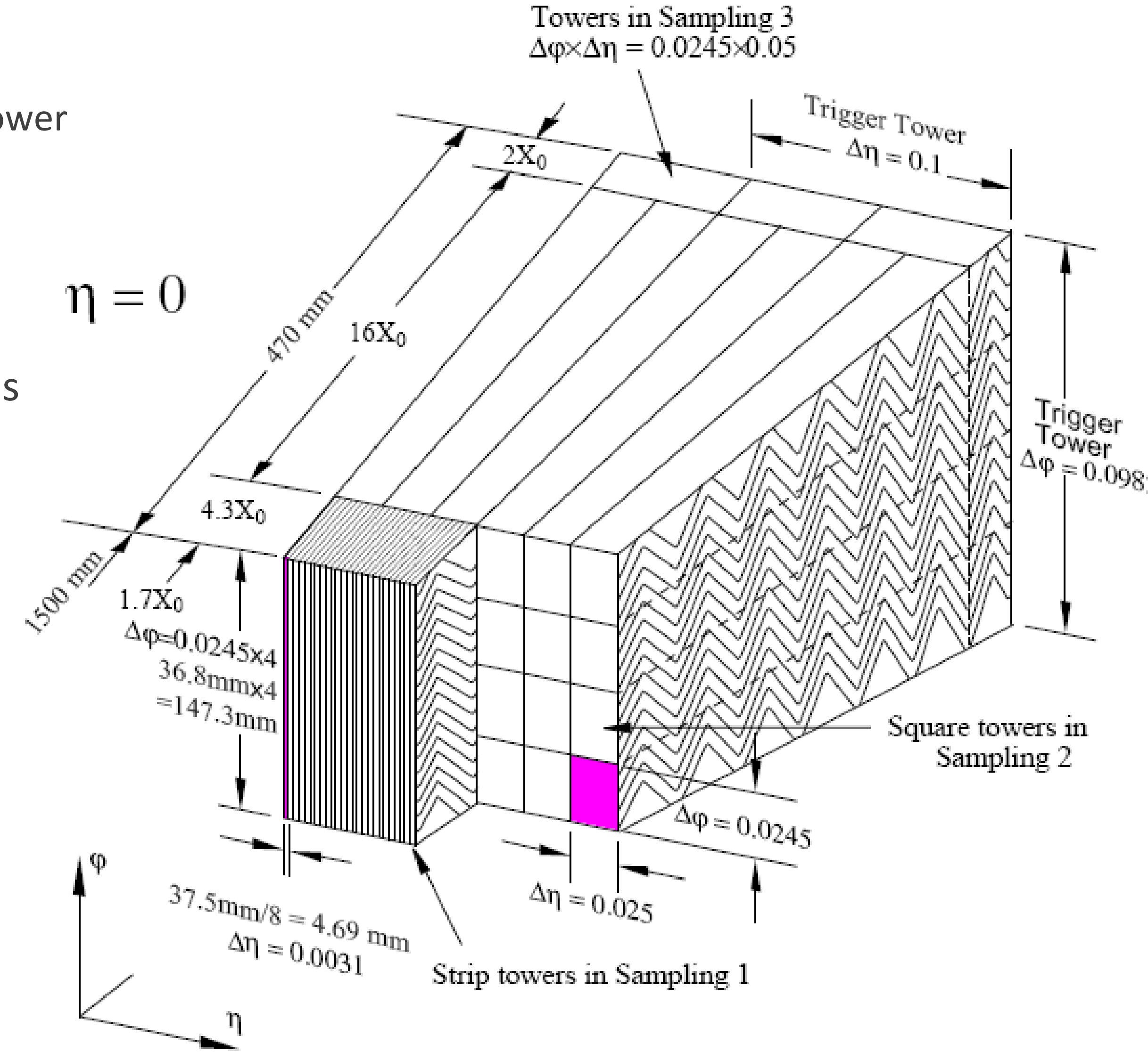
Design resolution:

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

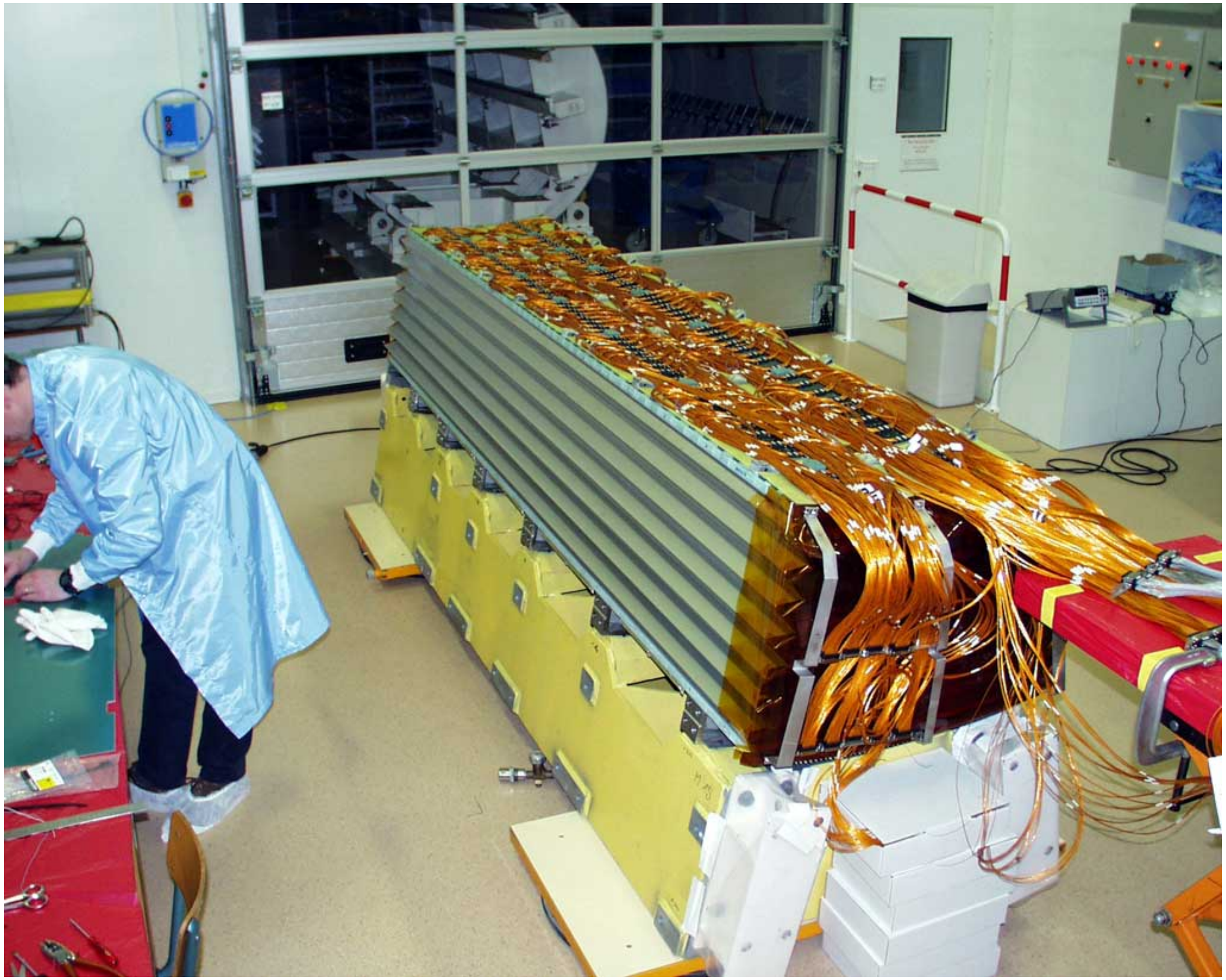
Technology: uses lead as an absorber and liquid argon as an ionization medium. Energy deposited in the calorimeter is converted to an electrical signal.

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

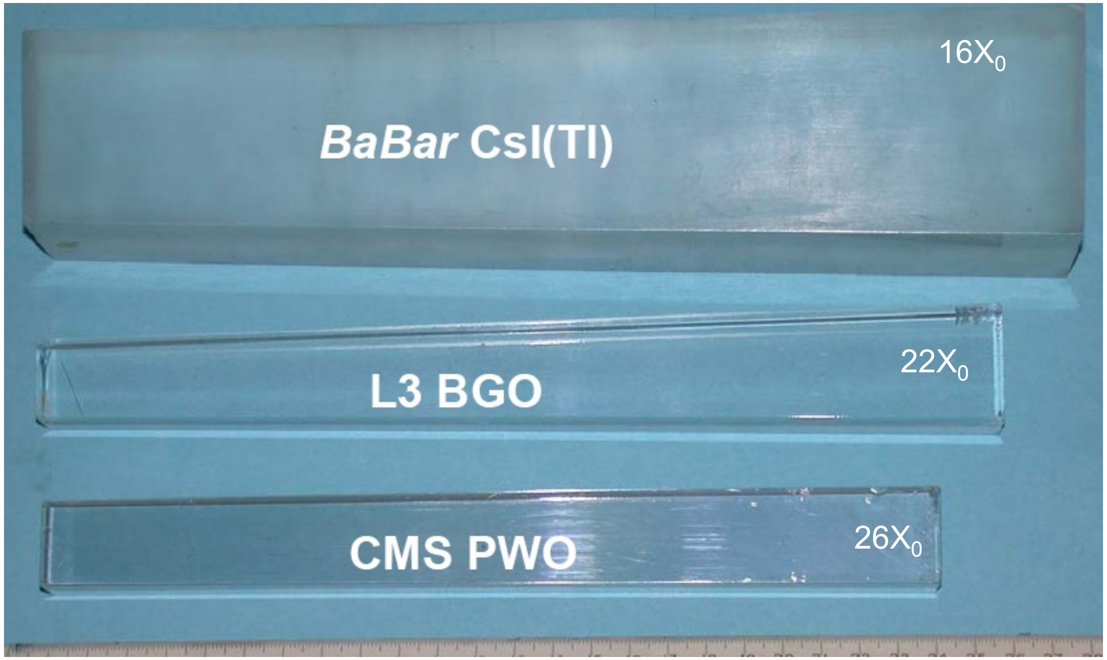


ATLAS Calorimeter in Real Life



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

CMS Calorimeter Crystals



Design resolution:

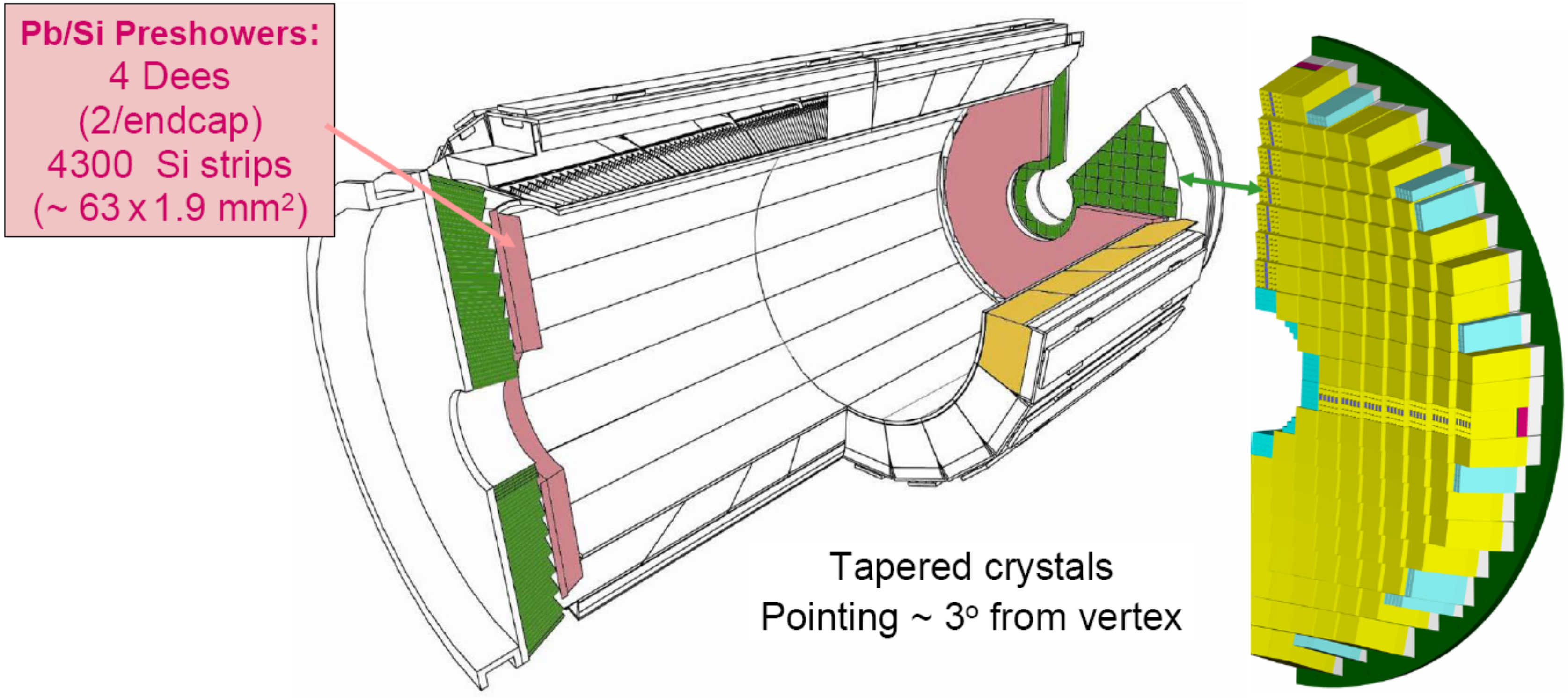
$$\frac{\delta E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.55\% \oplus \frac{0.16\,\mathrm{GeV}}{E}$$

Photo: Ren-yuan Zhu, Caltech

- 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



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)
$\Delta\eta \times \Delta\varphi = 0.0175 \times 0.0175$

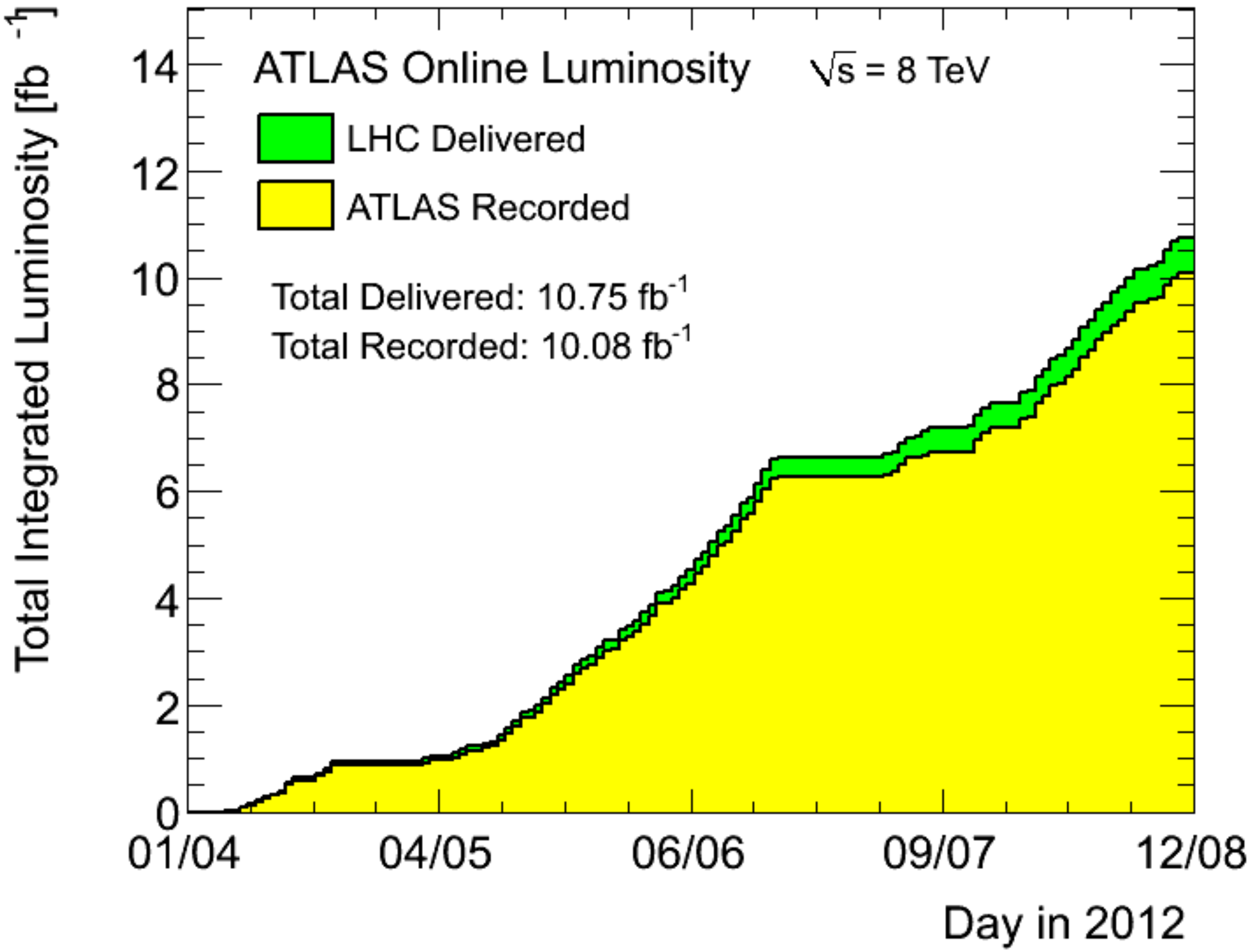
Endcaps: 4 Dees (2 per endcap)
14648 Crystals (1 type) – total mass 22.9 t
Dimensions: ~ 30 x 30 x 220 mm^3 (24.7 X^0)
$\Delta\eta \times \Delta\varphi = 0.0175 \times 0.0175 \leftrightarrow 0.05 \times 0.05$

Figure: Ren-yuan Zhu, Caltech

Comparing Design Philosophies

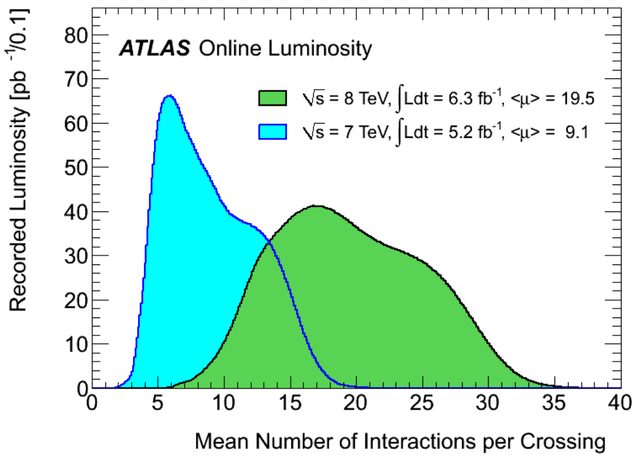
- CMS emphasizes energy resolution
  - Use PWO crystals
    - Expensive – means go to small radius to keep the detector within budget ***and schedule***.
    - Only handful of vendors worldwide
- ATLAS emphasizes background rejection
  - Able to go to larger radius: separates showers better
  - Highly 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

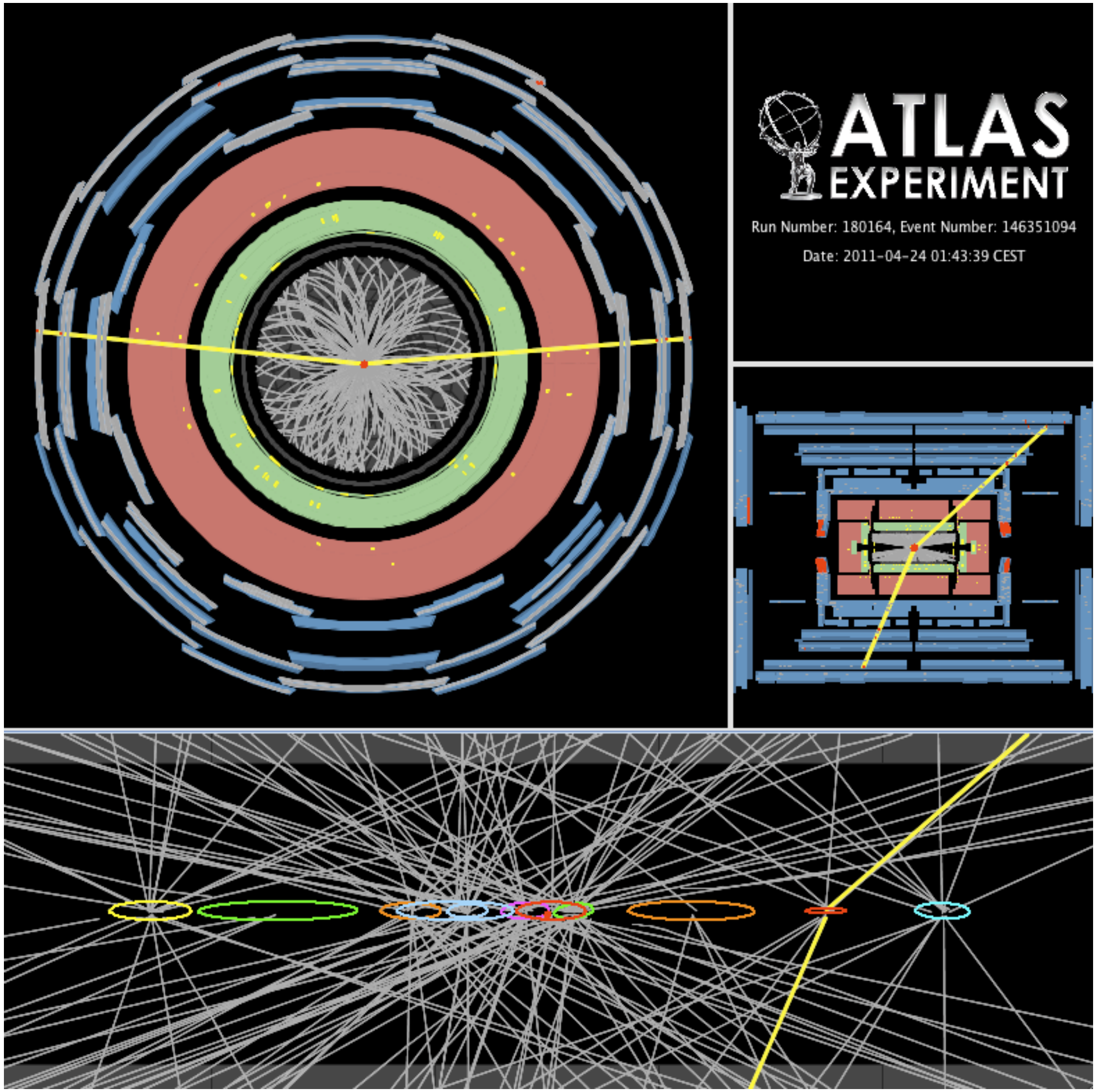
I Like Working at the LHC…



…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.

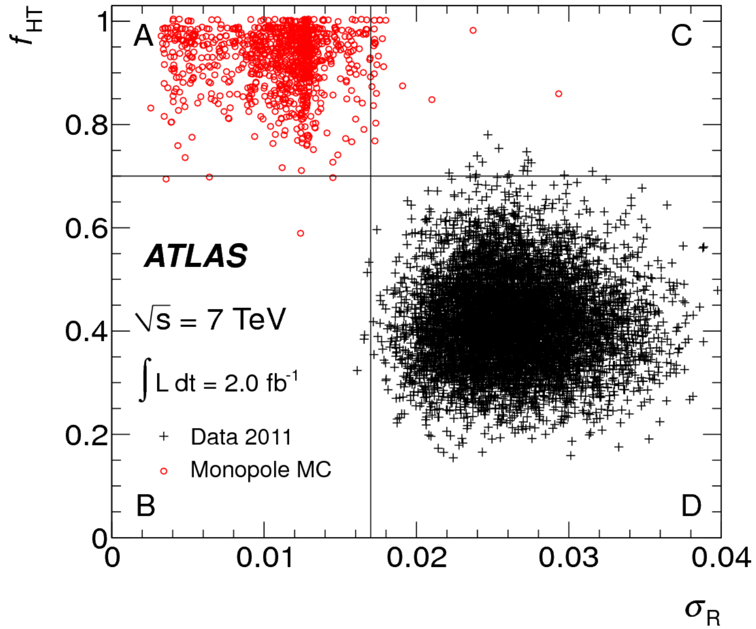
Where Are We After Step #1?

- 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

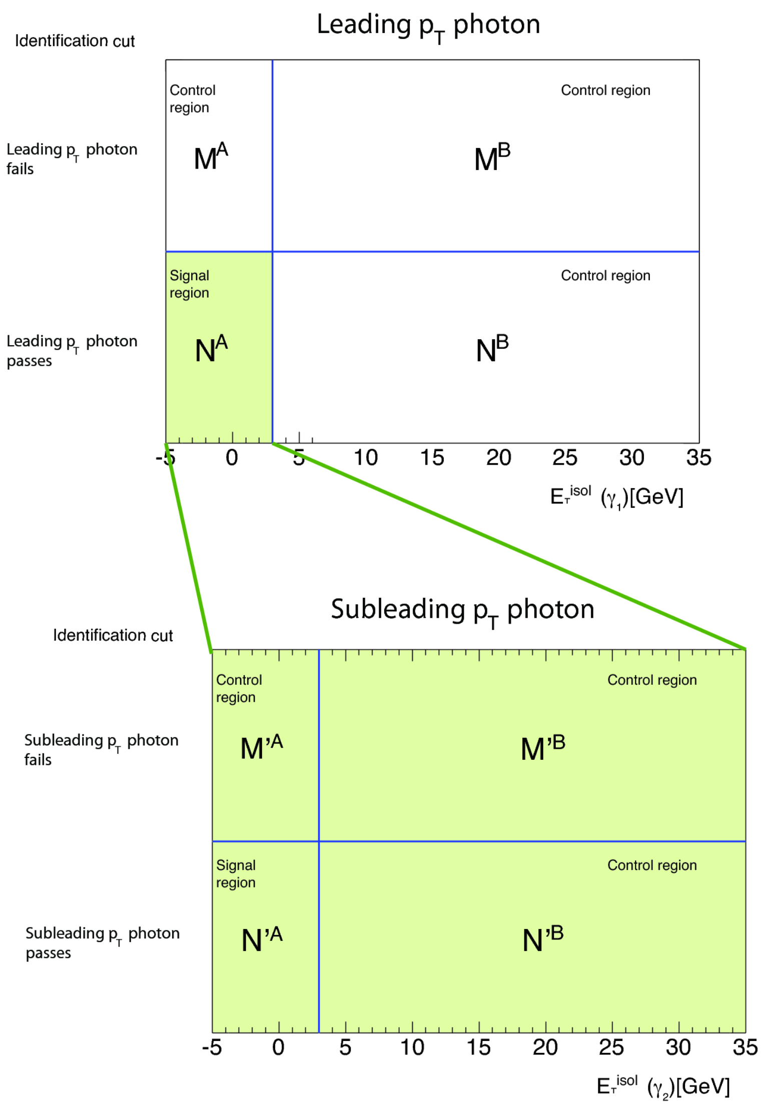


A general method (the above plot has nothing to do with the Higgs) to answer the question "how much background is inside signal region A"?

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

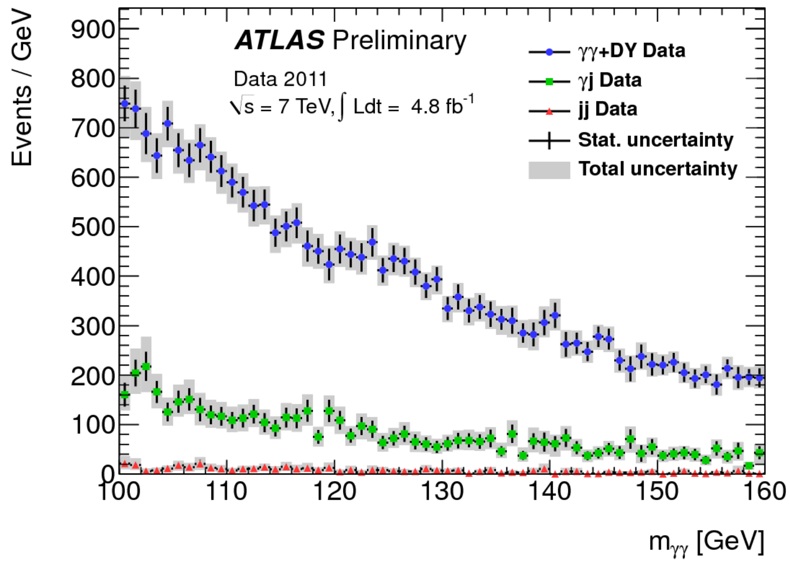
- Requires two variables that are *uncorrelated* for the *background*.
  - Signal can be and often is correlated.
  - If the variables are not exactly uncorrelated, this becomes an approximation.
- Requires that regions B,C and D all be dominated by the background
- This doesn't say anything about how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

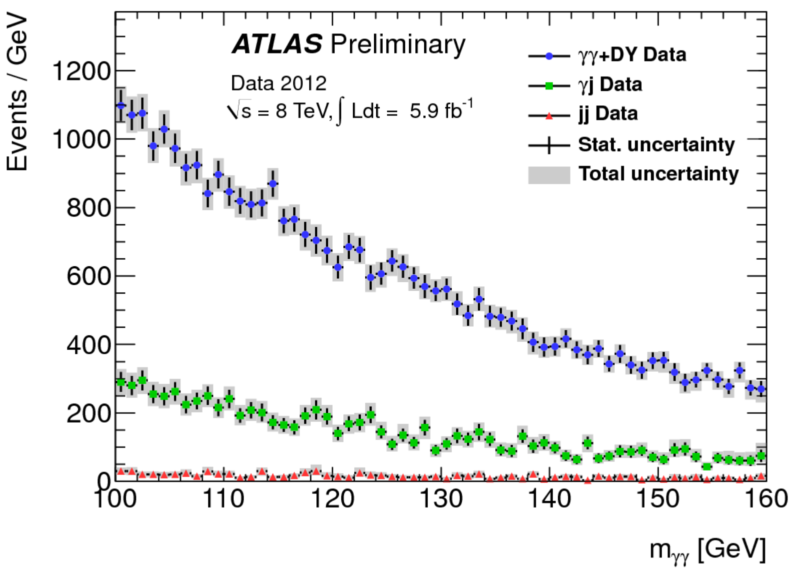
ABCD for Diphotons



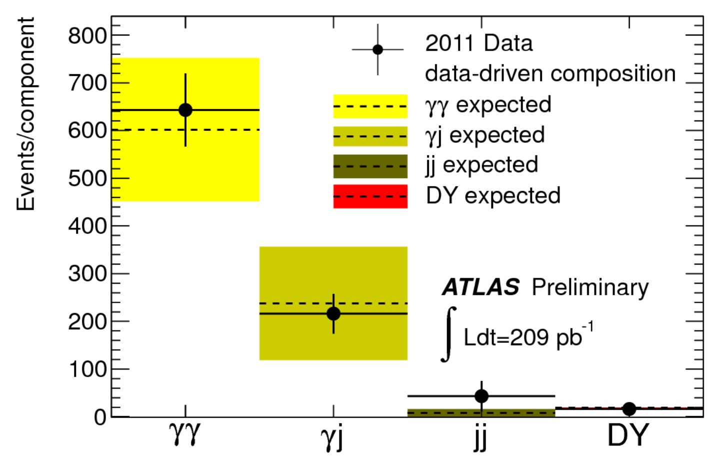
- Here the two uncorrelated variables are:
  - Photon identification: the shower shape variables I discussed ~10 slides back plus the absence of a track pointing at the shower.
  - Isolation: how much energy is around the photon. If the photon came from a jet, odds are that there is some remnant nearby 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.

Diphoton Background





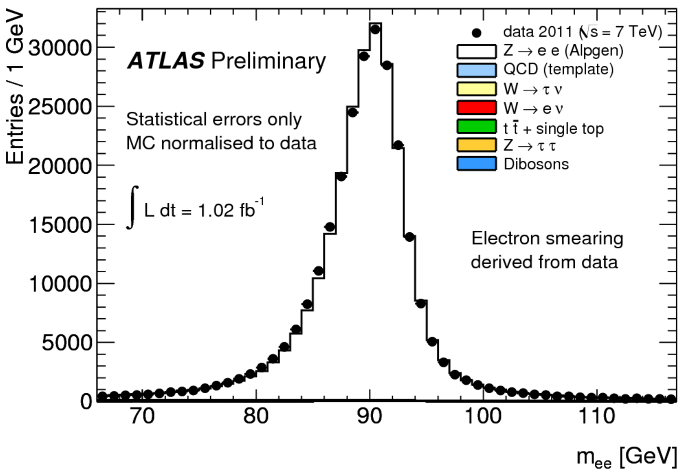
- The background is mostly real diphotons.
  - Improving fake photon rejection will help, but we' re past the point of diminishing returns.
- The 7 TeV data and 8 TeV data look similar, but not identical.
  - They can be combined, but they have to be handled separately. This is a royal pain in the wazoozy.
- 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.



Some Cleanup

- The identification requirements are different for 7 TeV and 8 TeV
  - 7 TeV uses a MVA. If every single shower shape variable is right at the edge of the cut, do you really want to call it a photon?
  - 8 TeV uses a cut based identification. There wasn't time to develop and tune the MVA.
    - Pileup is very different in these samples

- The photon energy scale is also important. Since e and γ showers are nearly indistinguishable (we can quibble about a 7/9ths) we gain confidence that the γ energy is right by looking at Z → ee decays.

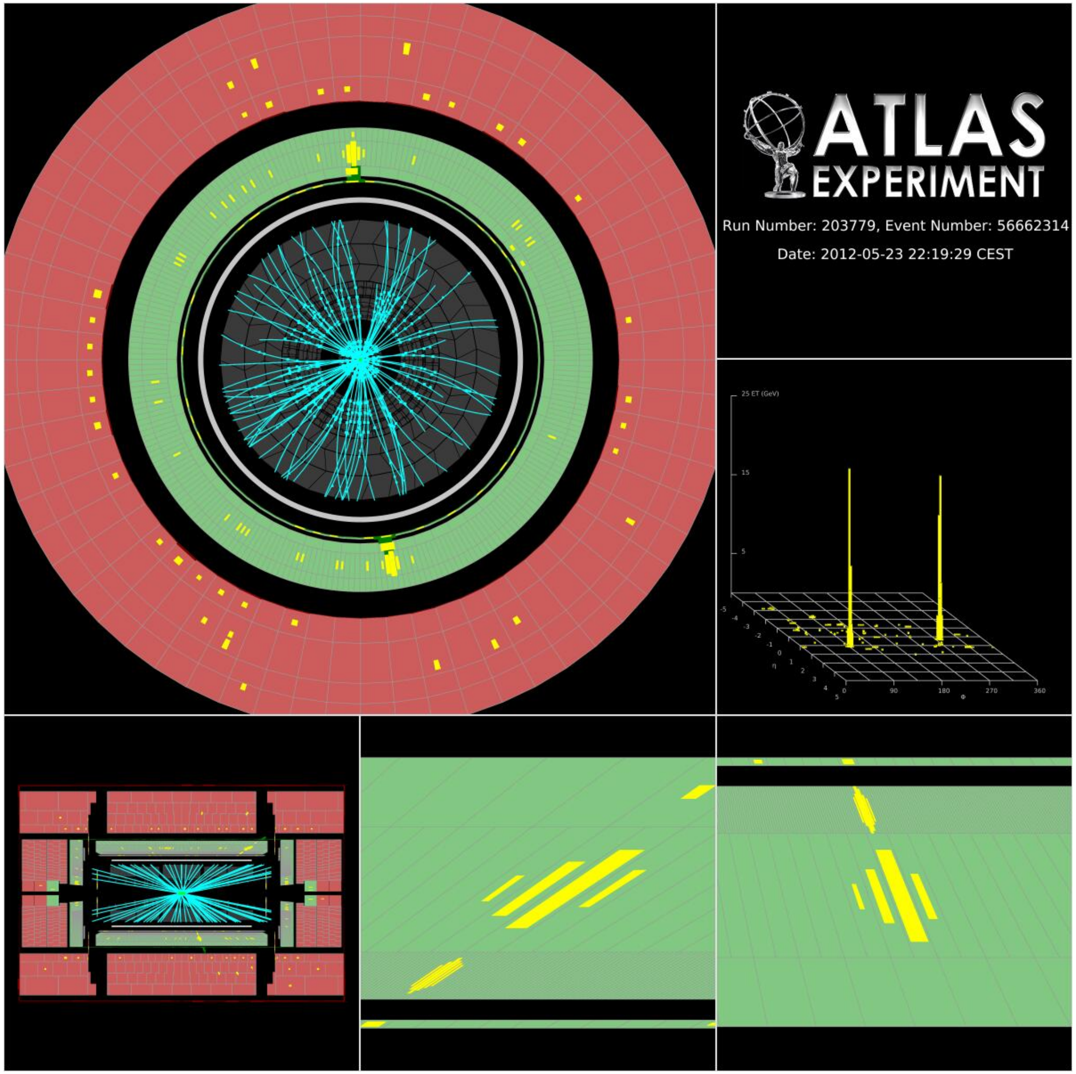


A plot with an very very large number (but only 10% of what we had) of Z's in it.

What Are We Searching For?

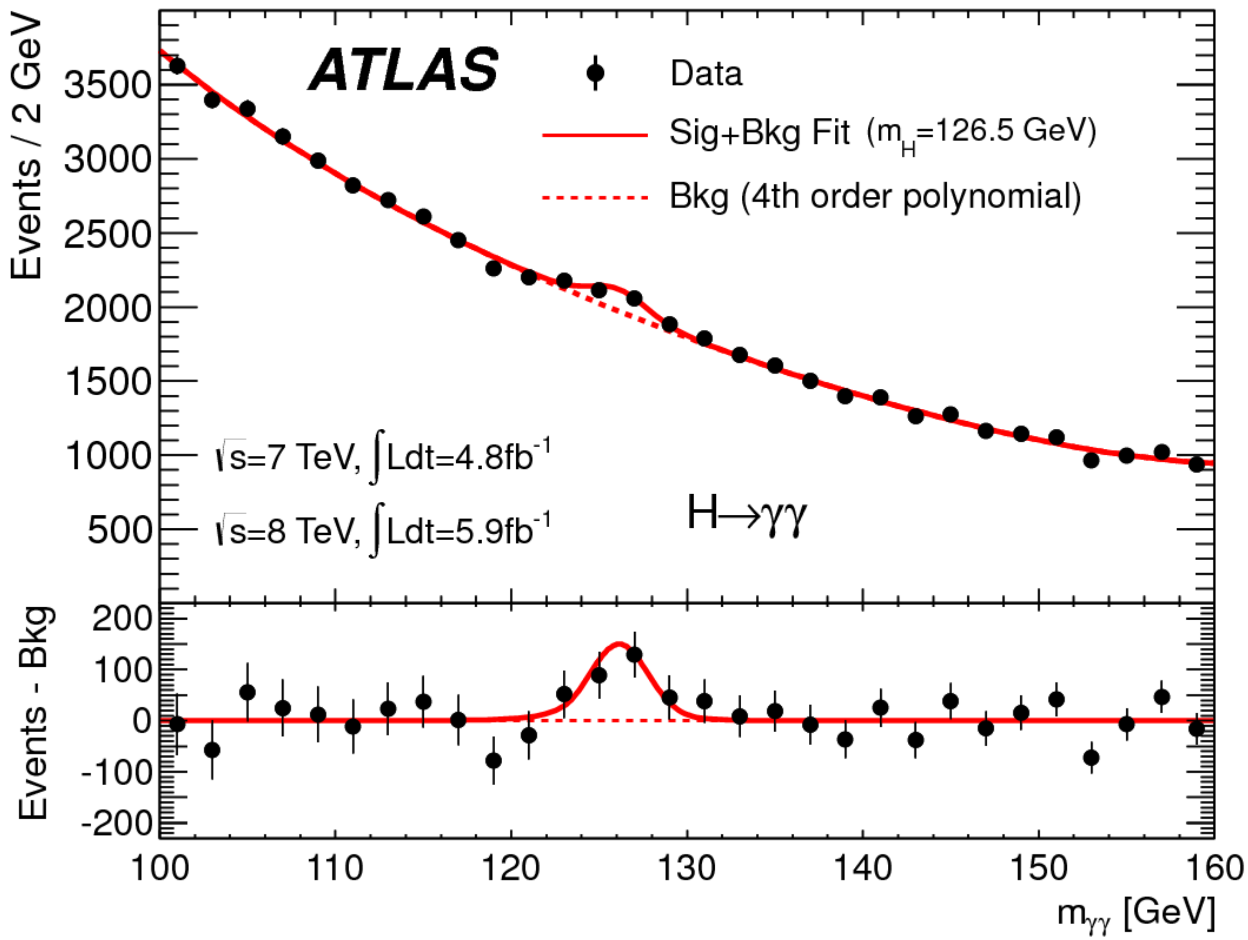
- We cannot avoid this question any more.
  - Are we looking for a generic particle that decays to $\gamma\gamma$?
  - Or are we looking for the SM Higgs?
- This matters:
  - Are we allowed to use Higgs production models in this analysis?
  - What about assuming its spin-0? (Isotropic decays in any frame)
- 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



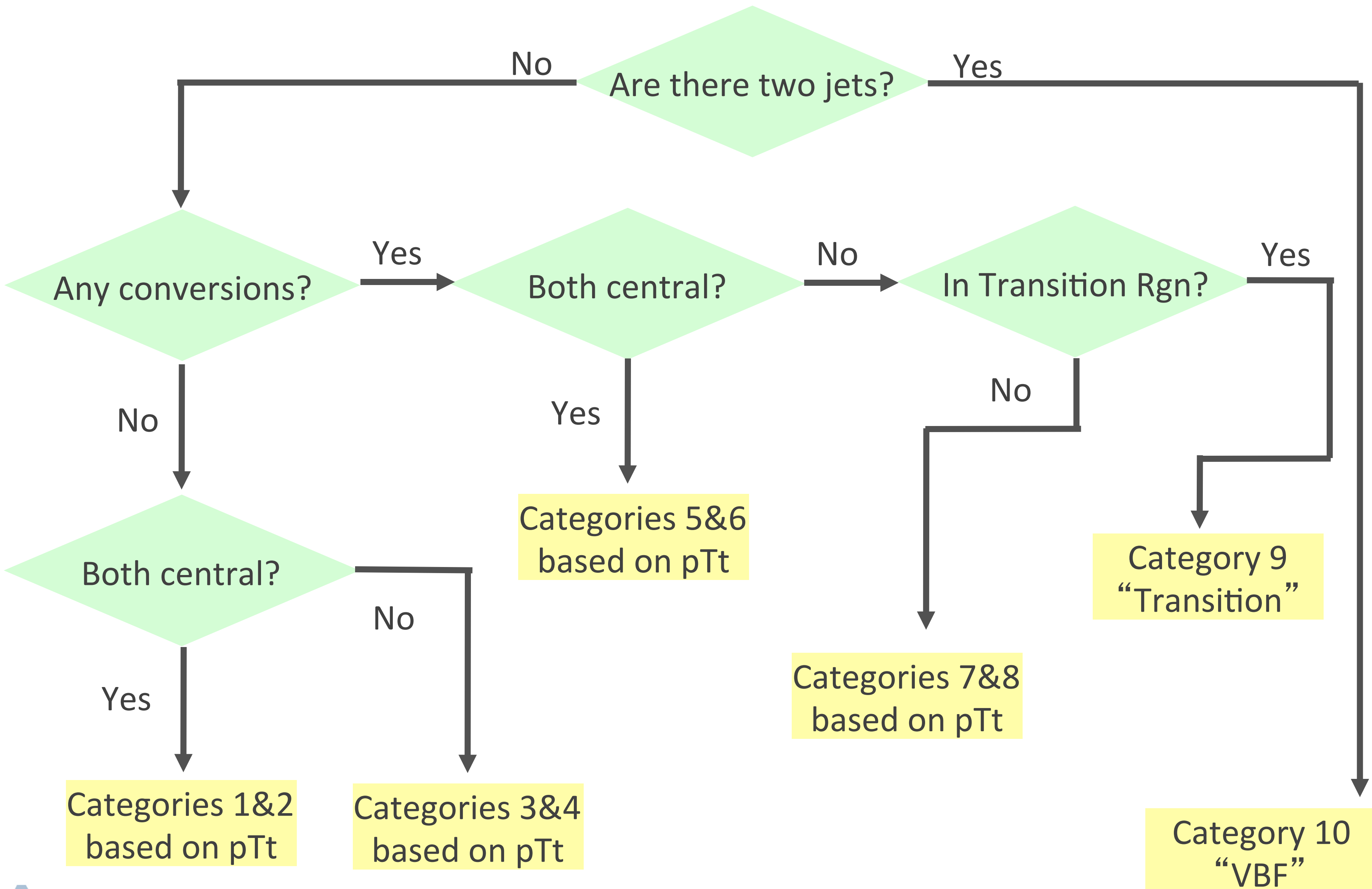
- Photons are obvious, even with pile-up
  - Note that low p_T tracks are suppressed in the display
- One can see how the EM showers can be used to point back to the primary vertex
  - Usually points to within ±1 interaction of the correct vertex
  - This is as good as it needs to be; beyond this it's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

The Data



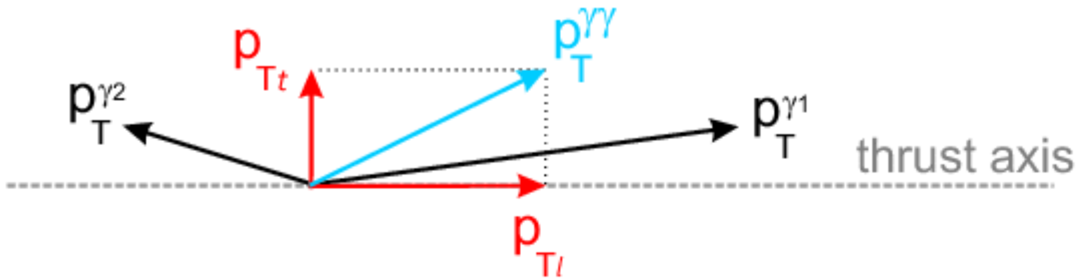
This plot, shown in many places, is actually not really used in the analysis. Actually, we look at things in ten categories.

ATLAS $\gamma\gamma$ Categorization



The Two Obvious Questions

- What is pTt? Why use it?



$$\hat{t} = \frac{\vec{p}_T^{\,\gamma_1} - \vec{p}_T^{\,\gamma_2}}{|\vec{p}_T^{\,\gamma_1} - \vec{p}_T^{\,\gamma_2}|}$$

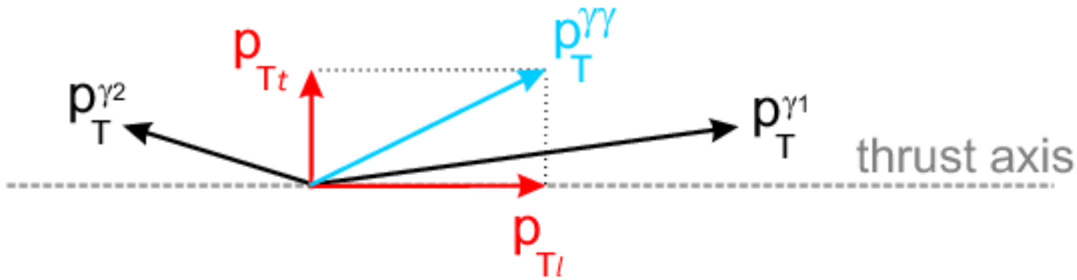
  - This has slightly better separation power than p_T.
  - It leaves a smoother background that p_T.
  - The High/Low threshold is 60 GeV.

In my view, the most important

- Why split things into ten categories?
  - S/B varies from 1:4.6 (Category 10) to 1:72 (Category 9)
  - Peak width (FWHM) varies from 2.3 GeV (Category 2) to 6.2 GeV (Category 9)

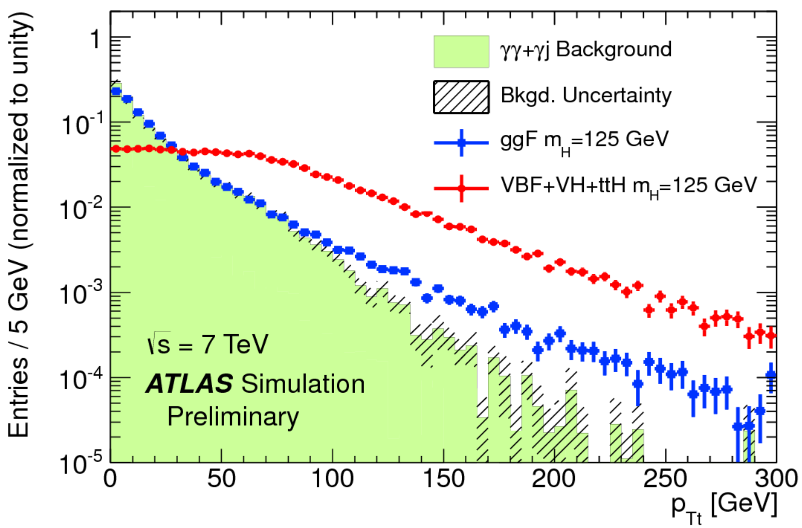
ATLAS assumes a known width and relative yield when dividing into these categories. ATLAS is not searching for a generic particle decaying into $\gamma\gamma$ in this analysis: it is searching for a SM Higgs.

Backgrounds and Kinematics

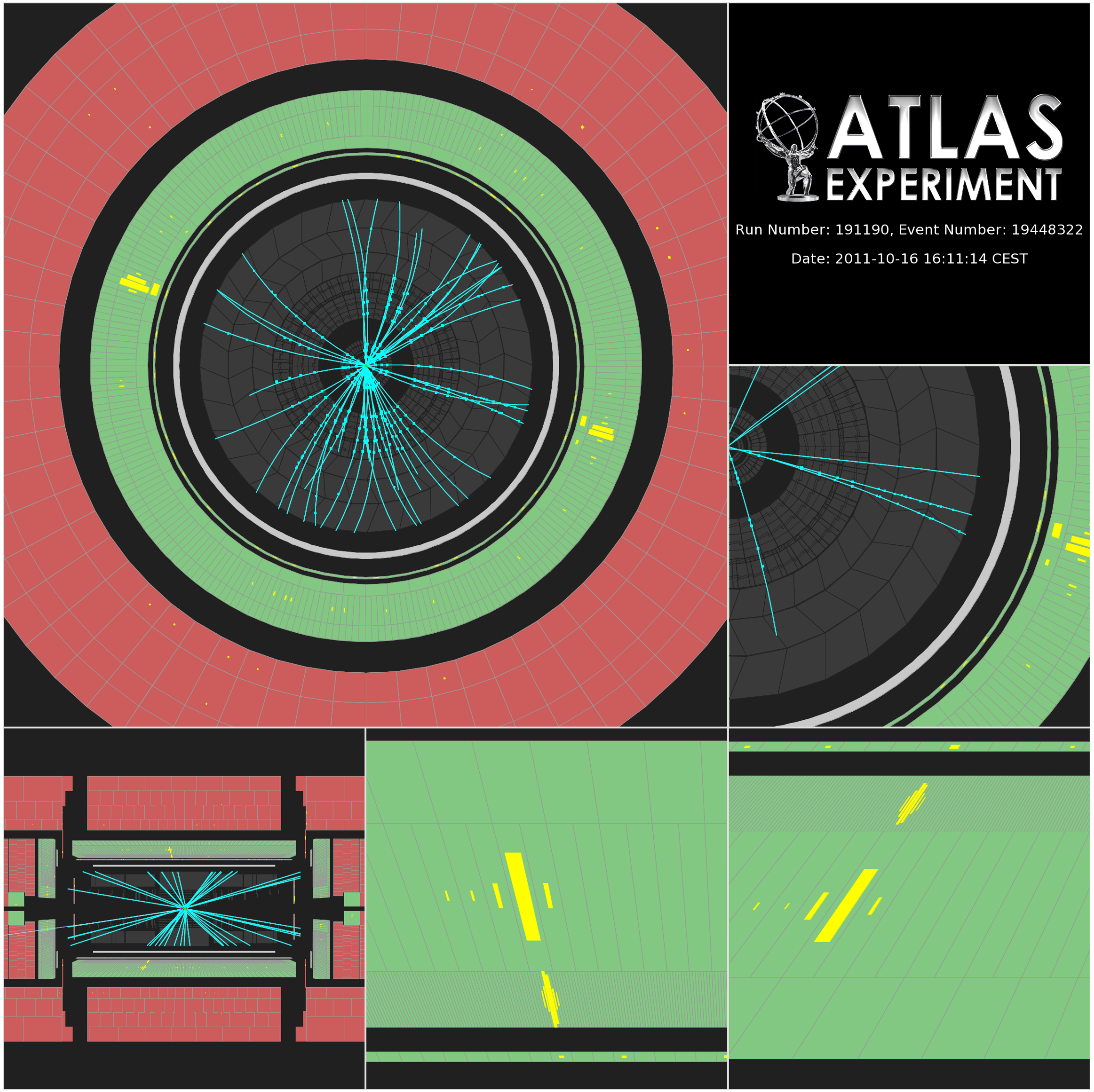


$$\hat{t} = \frac{\vec{p}_{\mathrm{T}}^{\gamma_1} - \vec{p}_{\mathrm{T}}^{\gamma_2}}{|\vec{p}_{\mathrm{T}}^{\gamma_1} - \vec{p}_{\mathrm{T}}^{\gamma_2}|}$$

- **We get the background from the data.**
- The background in pTt is smooth
  - Can be fit with a 4th degree polynomial or an exponential – however, the fits are different for 7 and 8 TeV running.
- The signal for gluon-gluon production is stiffer than the background
- The signal for VBF is stiffer still

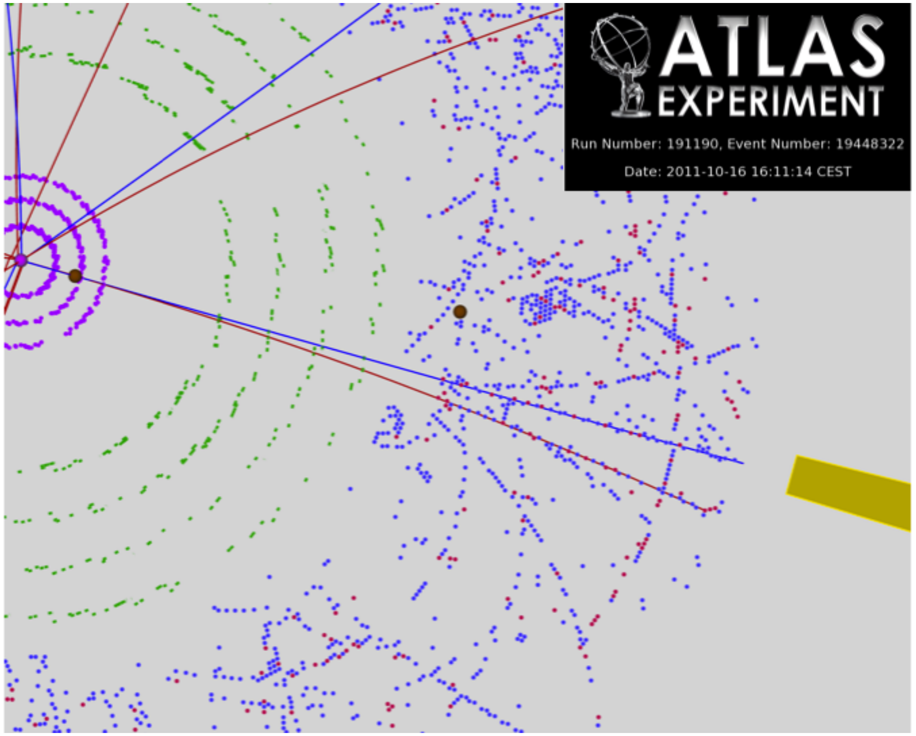


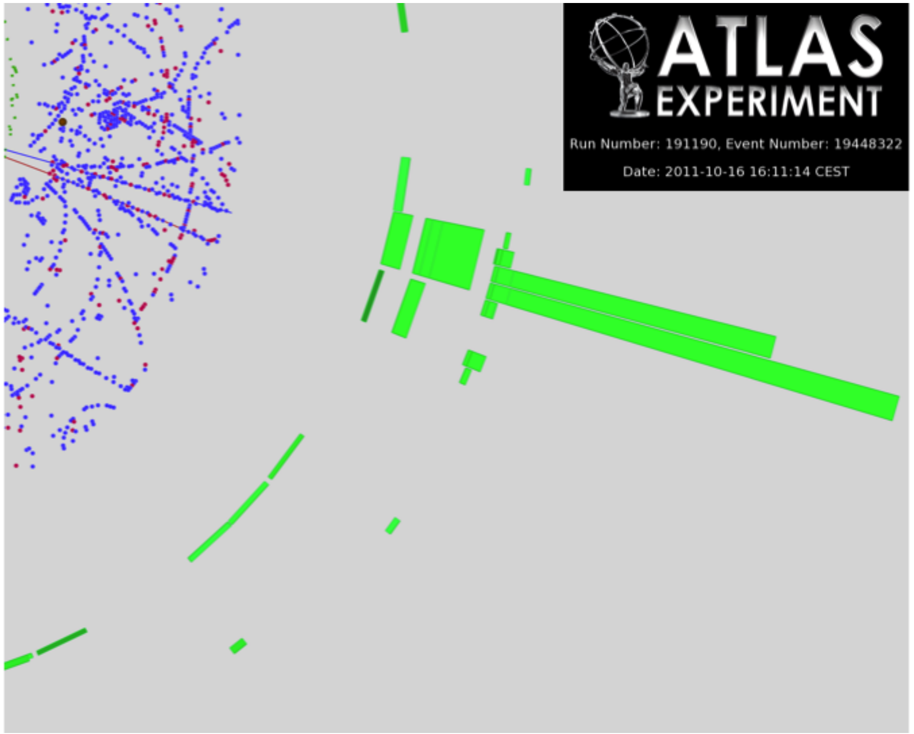
One Particular Event



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

The Conversion in More Detail

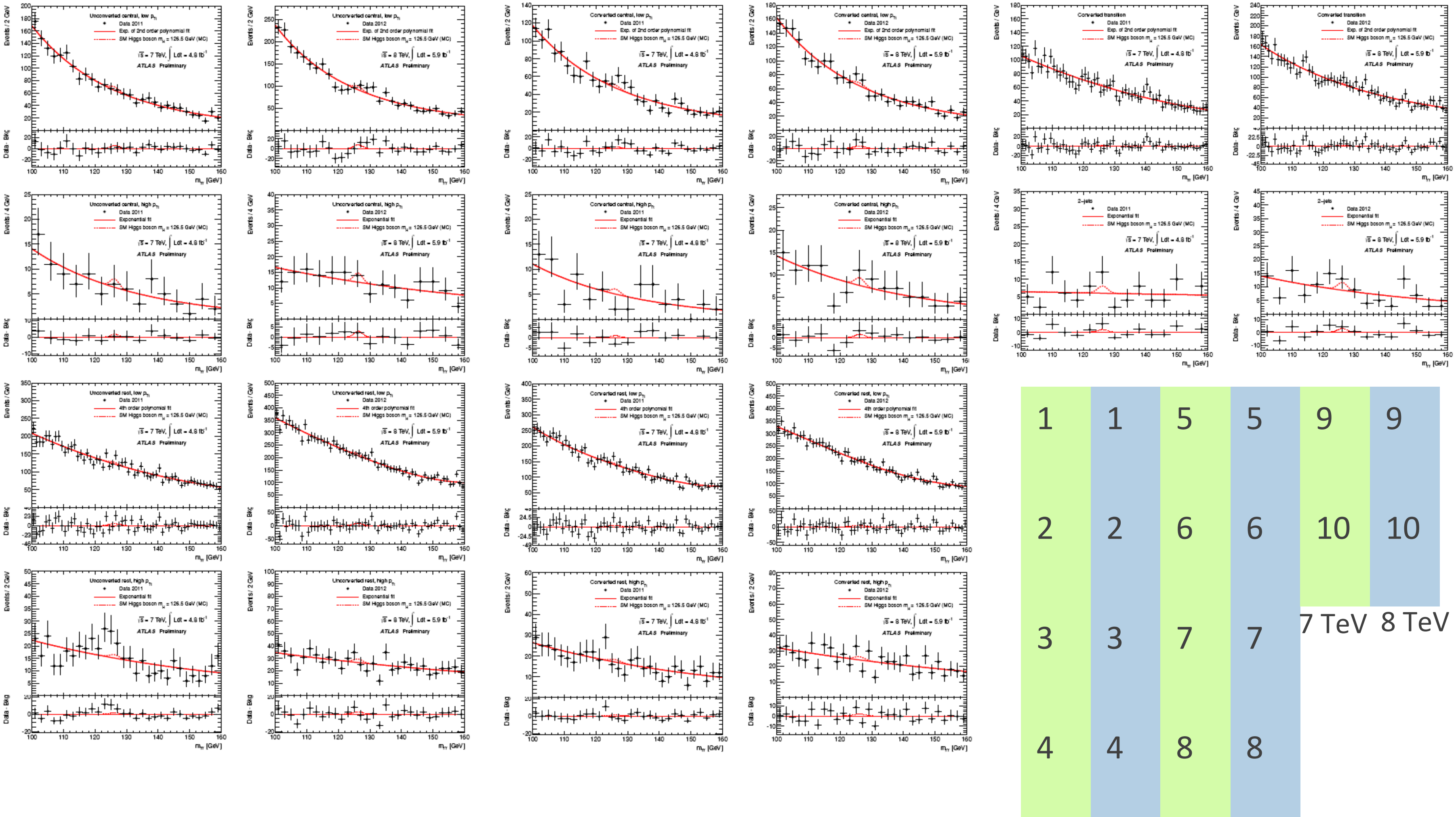




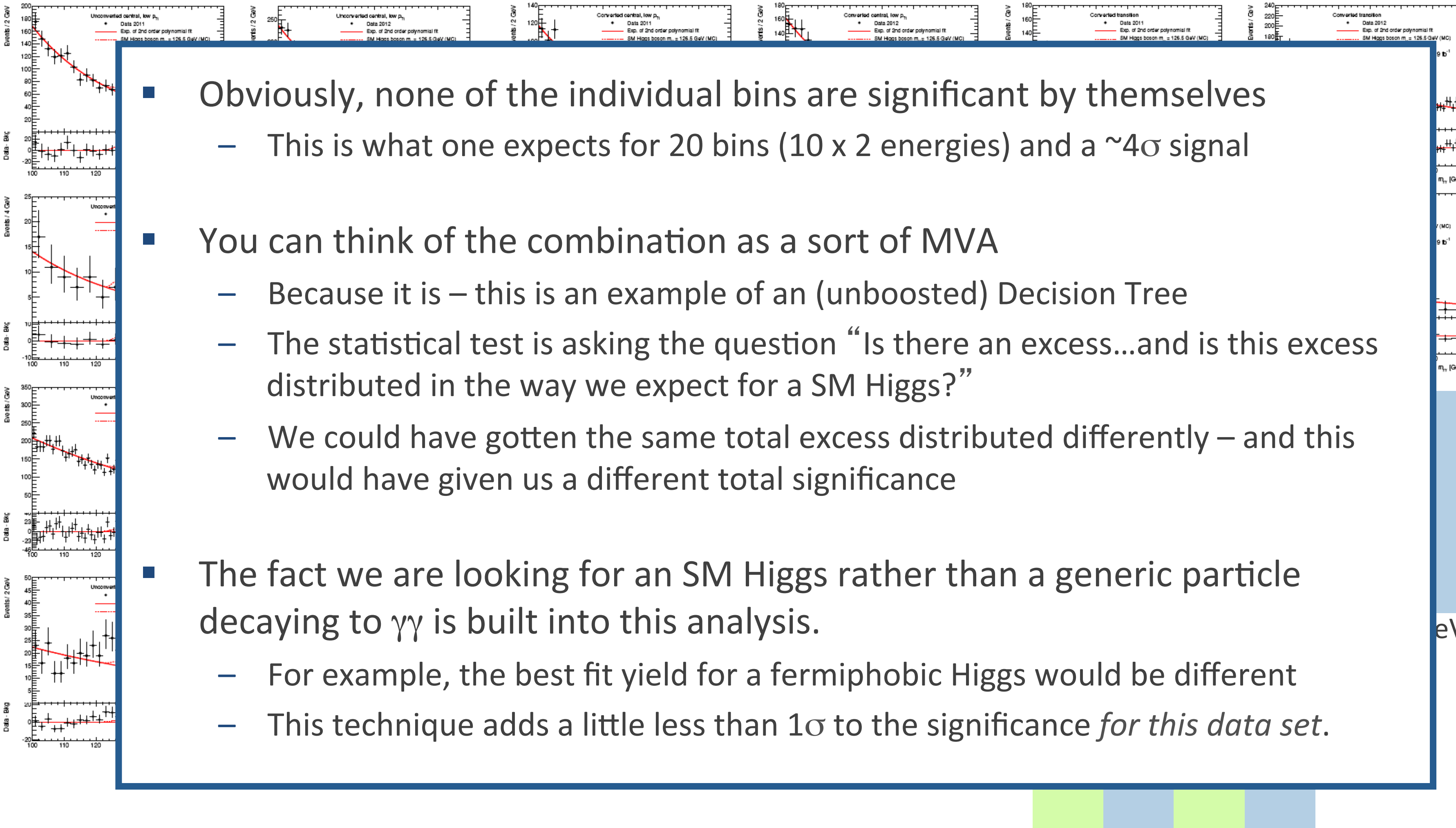
The tracks from $\gamma \rightarrow e^+e^-$ are clear and distinct. Red hits are high threshold TRT hits and confirm that these are in fact electrons.

The shape of the EM cluster in the calorimeter is consistent with two electrons very near each other.

Results in Each Bin

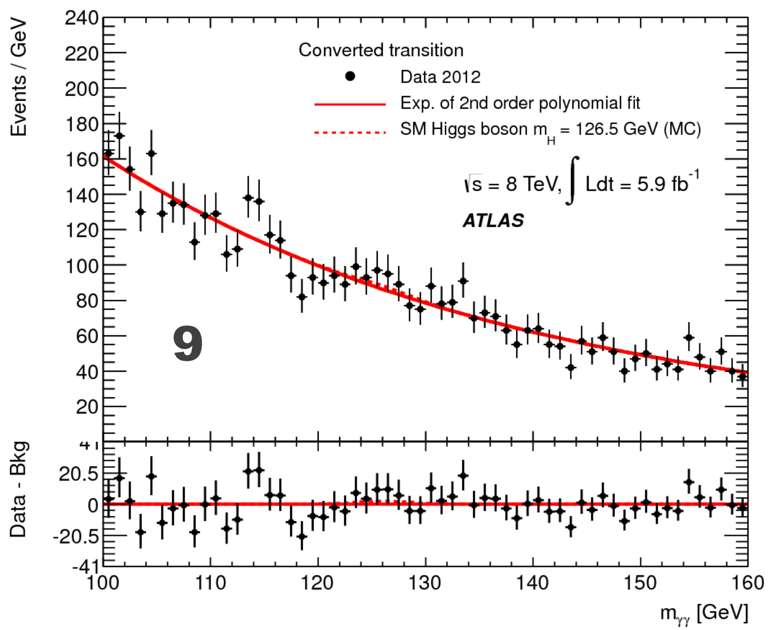


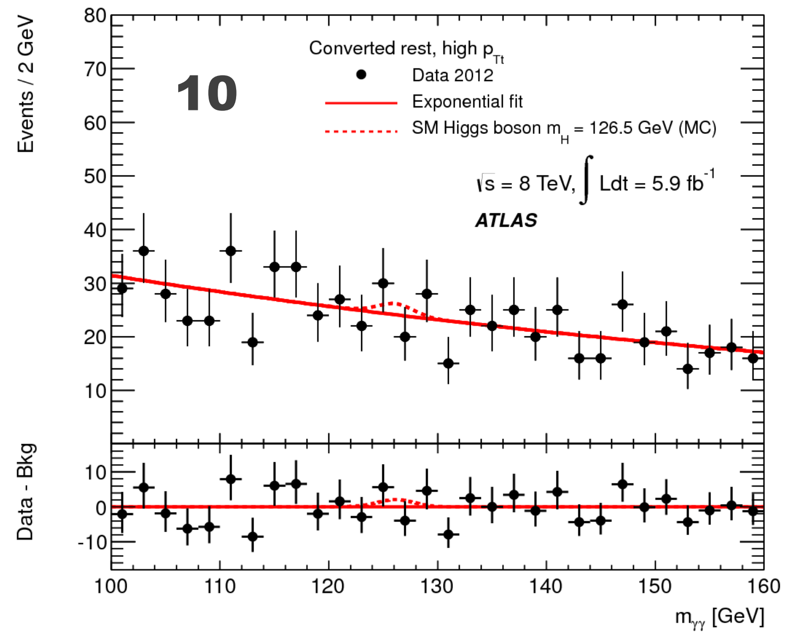
Results in Each Bin



- 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*.

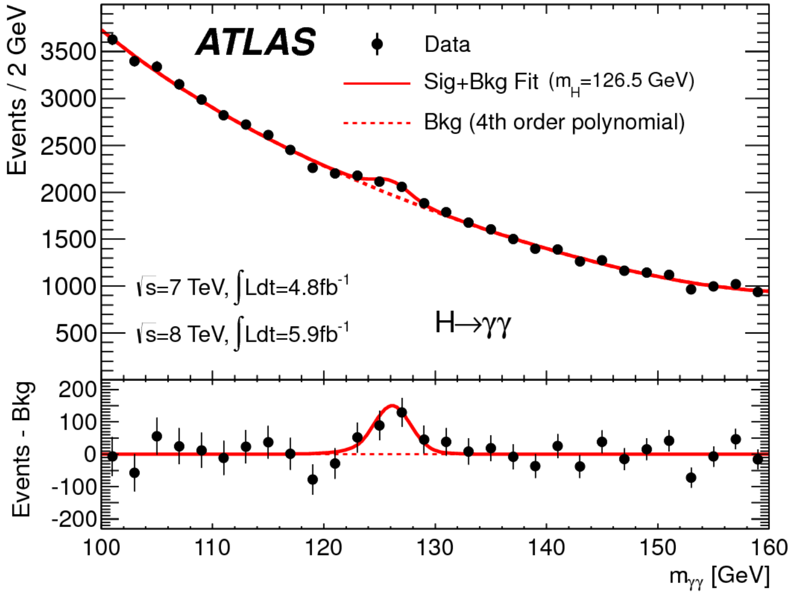
A Close-Up





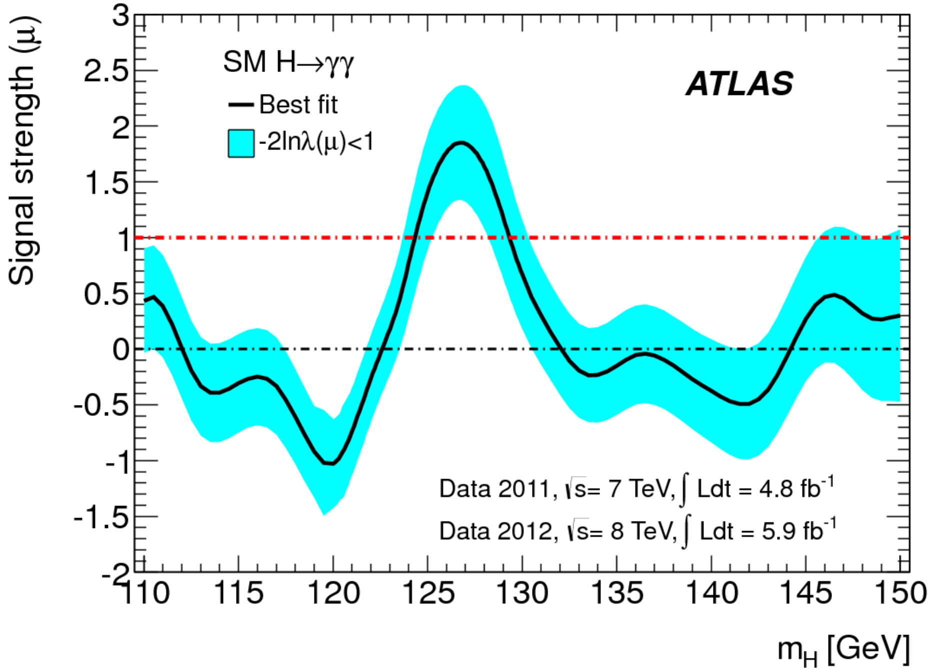
- These regions don’t look anything like each other
  - Signal width
  - Signal to noise ratio
  - Background shape (still, it would be nice if the same functional form everywhere. <sigh>)
  - Event yield
- Why lump them together in the analysis?

Yields



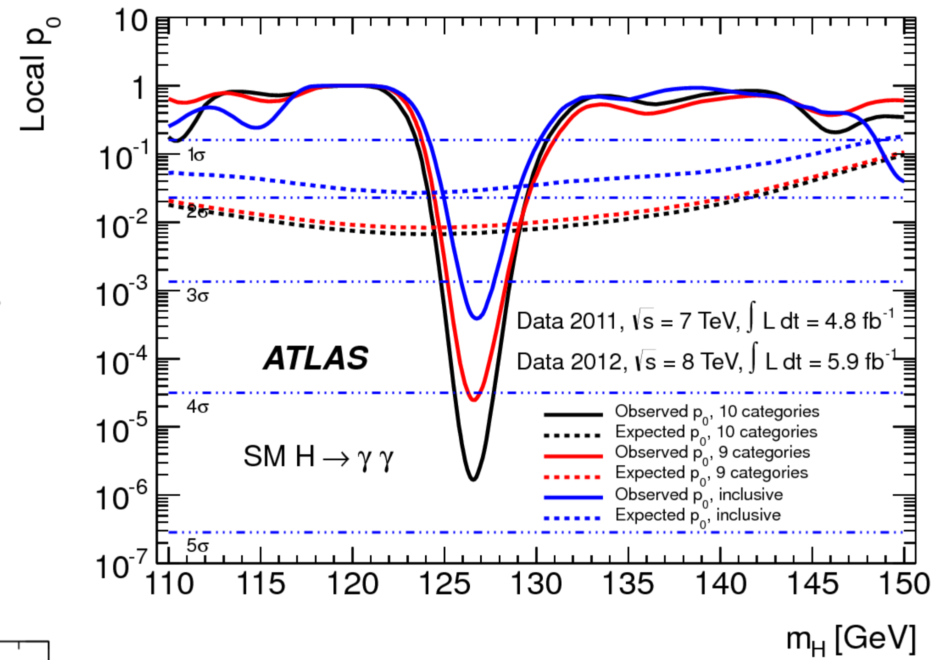
This is not an expected signal plotted over a background. It is the sum of 20 expected signals plotted over the sum of 20 backgrounds.

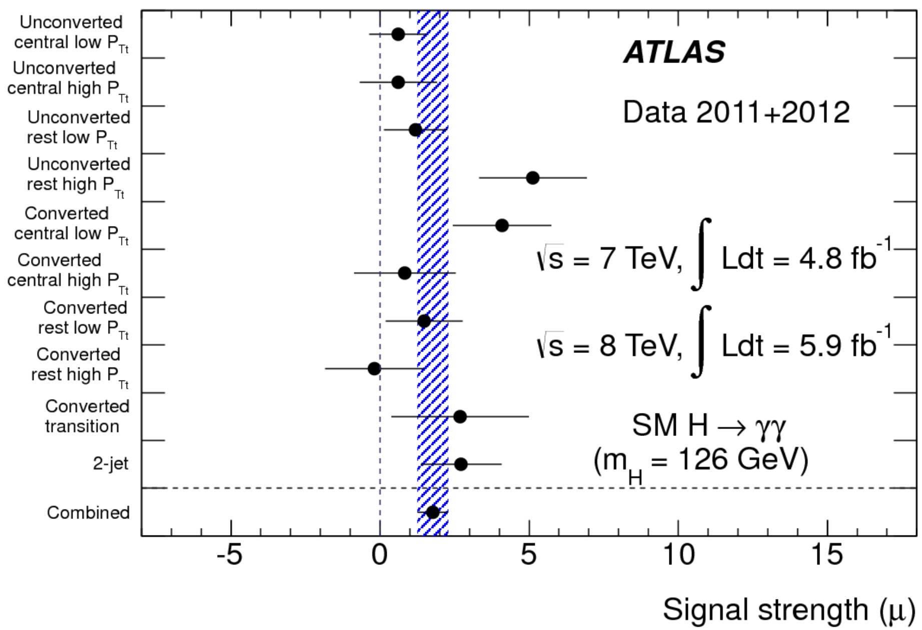
In the blue and white plots, μ is defined as σ/σ_{SM}. ATLAS sees slightly more γγ events than expected (see above), but OK at 2σ. The distribution of events over the 20 bins affects this plot.



More on μ

This plot (the black and white plot) asks the question "Could μ=0?" It shows the (im) probability of this, and also the effect of the categorization.





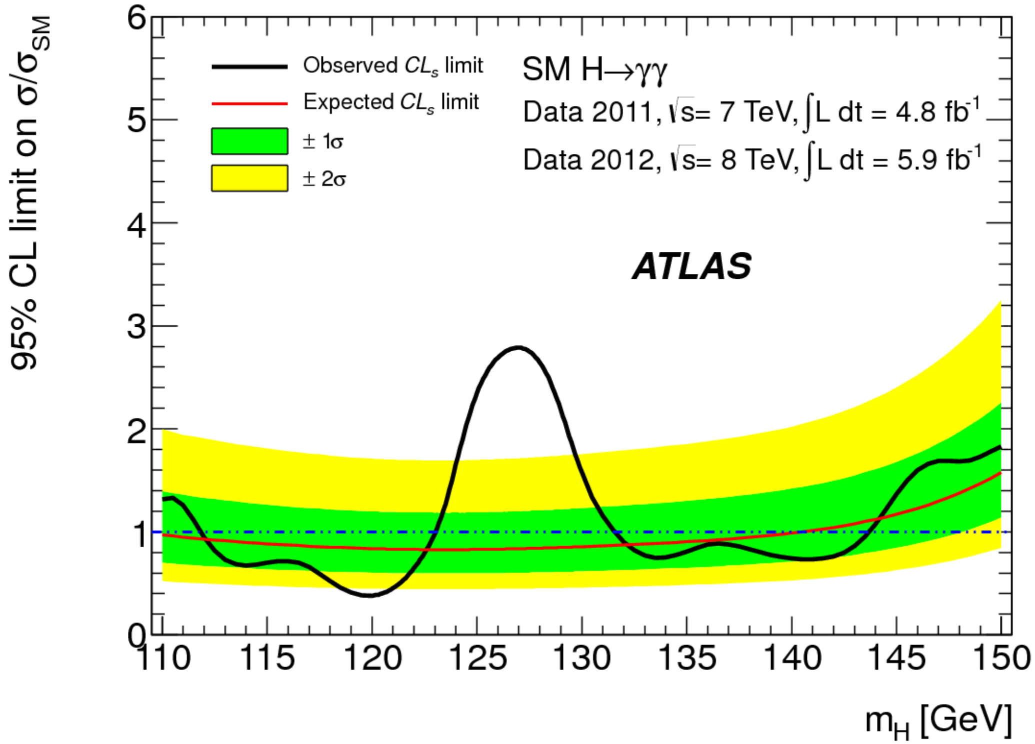
This plot asks the question "Is μ the same for each category?"

While there is some spread, there's nothing obvious in common between the high or low categories.

And For Completeness

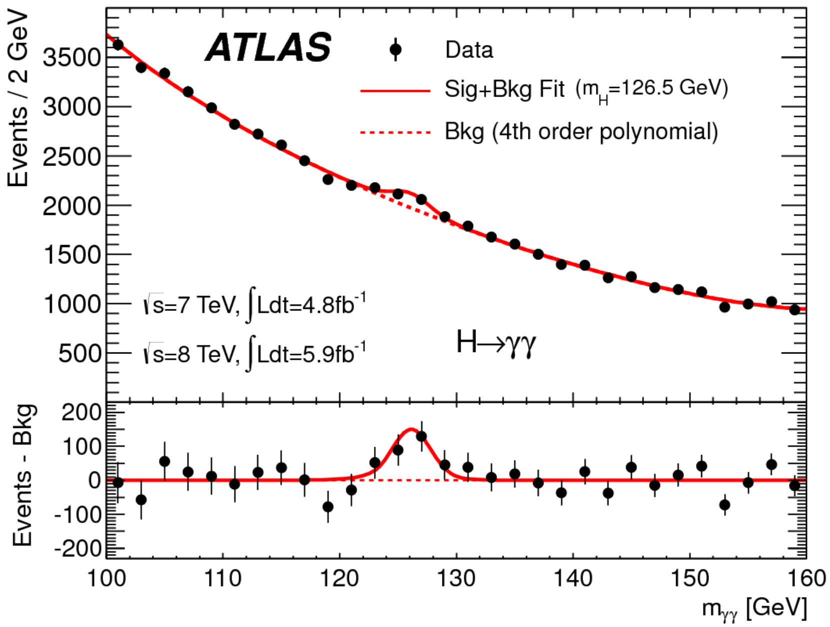
The green and yellow plots address the question "Could μ =1?"

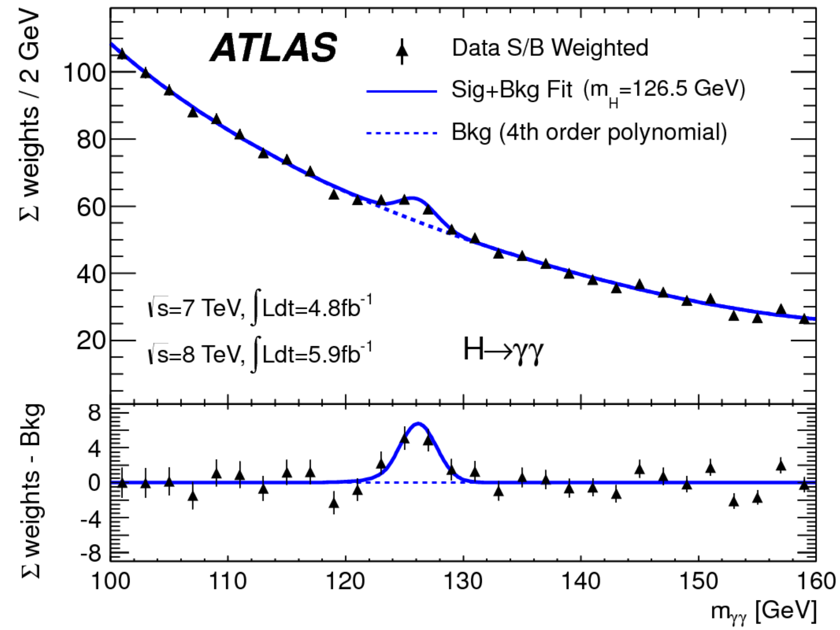
The area of poorest exclusion is (totally unsurprisingly) the region where there is a signal.



Note to self: pause here and make sure everyone understands the meaning of the three plots.

Differently Misleading Ways to Present Data





Here we are plotting events. However, the fact that different events are "worth" more than others is hidden. The effect of dividing into 10 bins is not evident.

Here we are plotting weights. However, it looks like we are plotting events.

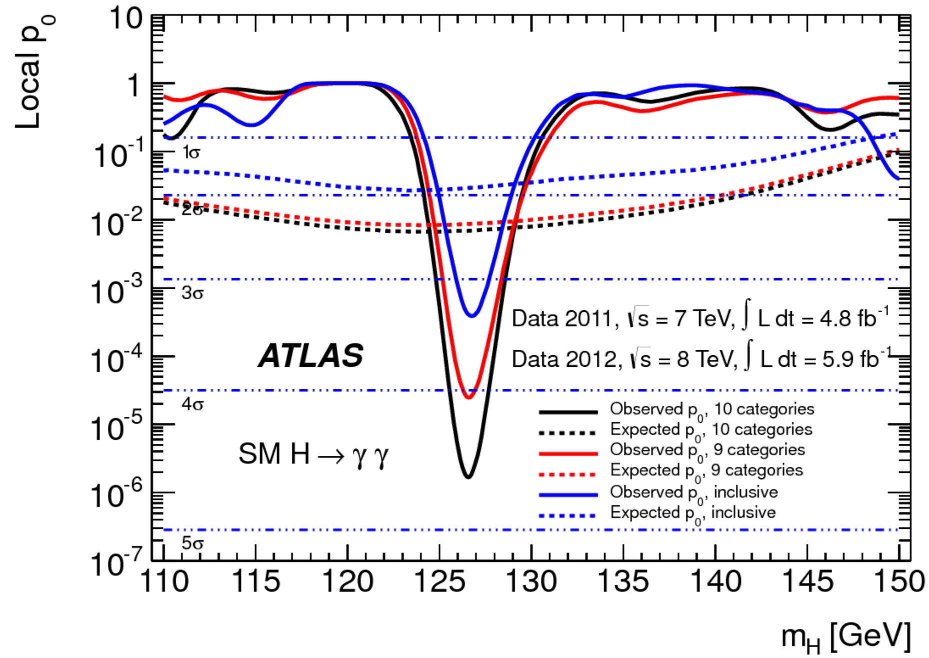
We don't think there is a perfect solution here on how to compress a complex analysis onto one plot. The fact that the peak looks better in the blue over the red is additional support for the Higgs hypothesis.

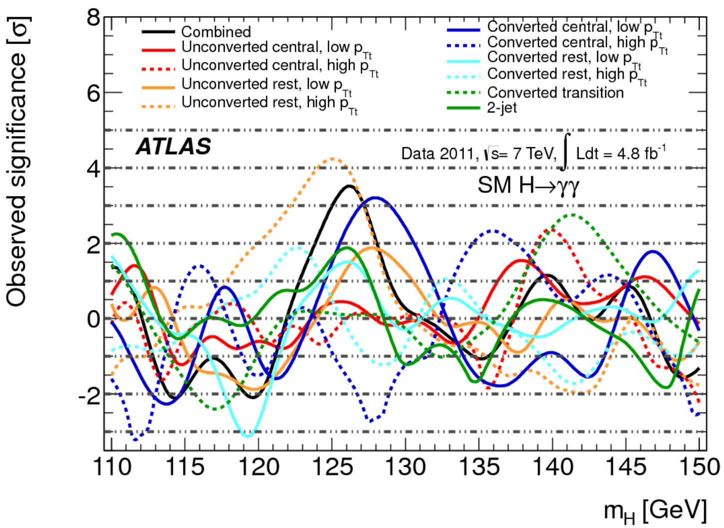
A Comment on Statistical Tests

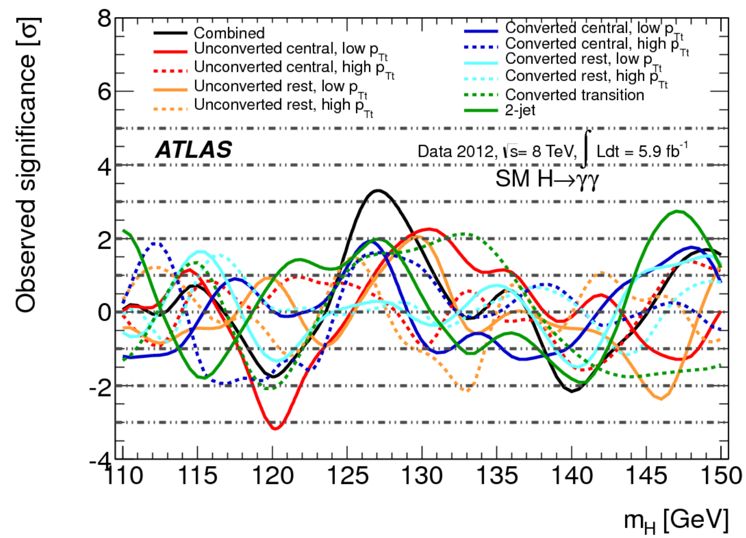
- The null hypothesis is $\mu=0$; i.e. there is no SM Higgs
- In calculating the significance, both ATLAS and CMS use the alternative hypothesis that $\mu > 0$; i.e. there is a Higgs that is produced with some unknown, non-zero rate.
- One could argue that, based on the way this analysis is designed, a better alternative is $\mu=1$; i.e. there is a SM Higgs, produced with the predicted rate.
- We chose not to do this.
  - This may not be *mathematically* the best justified, but *scientifically* it's the right thing to do: we want to be as open as possible to a surprise.

Some Statistics

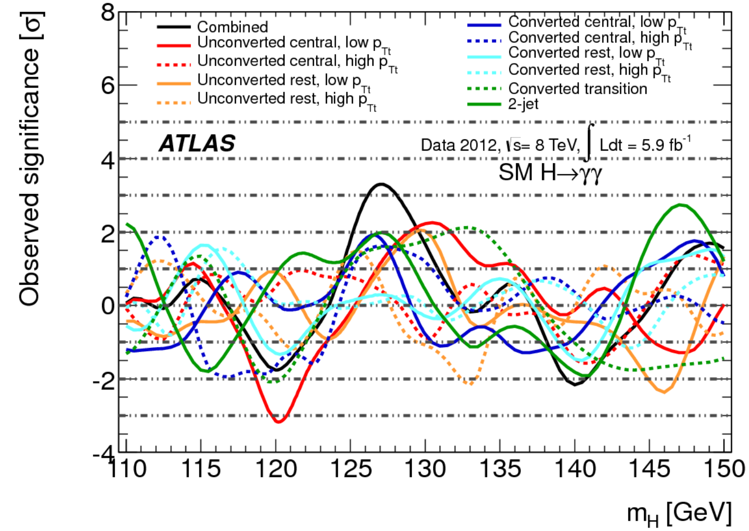
- There is a local significance of about 4.5σ.
- This is about a 1/300,000 of happening by chance alone.
- No individual channel has anything like a significant signal.
  - However 18 of 20 channels show an excess, not a deficit. (p=1/4970)







The Energy Scale Systematic



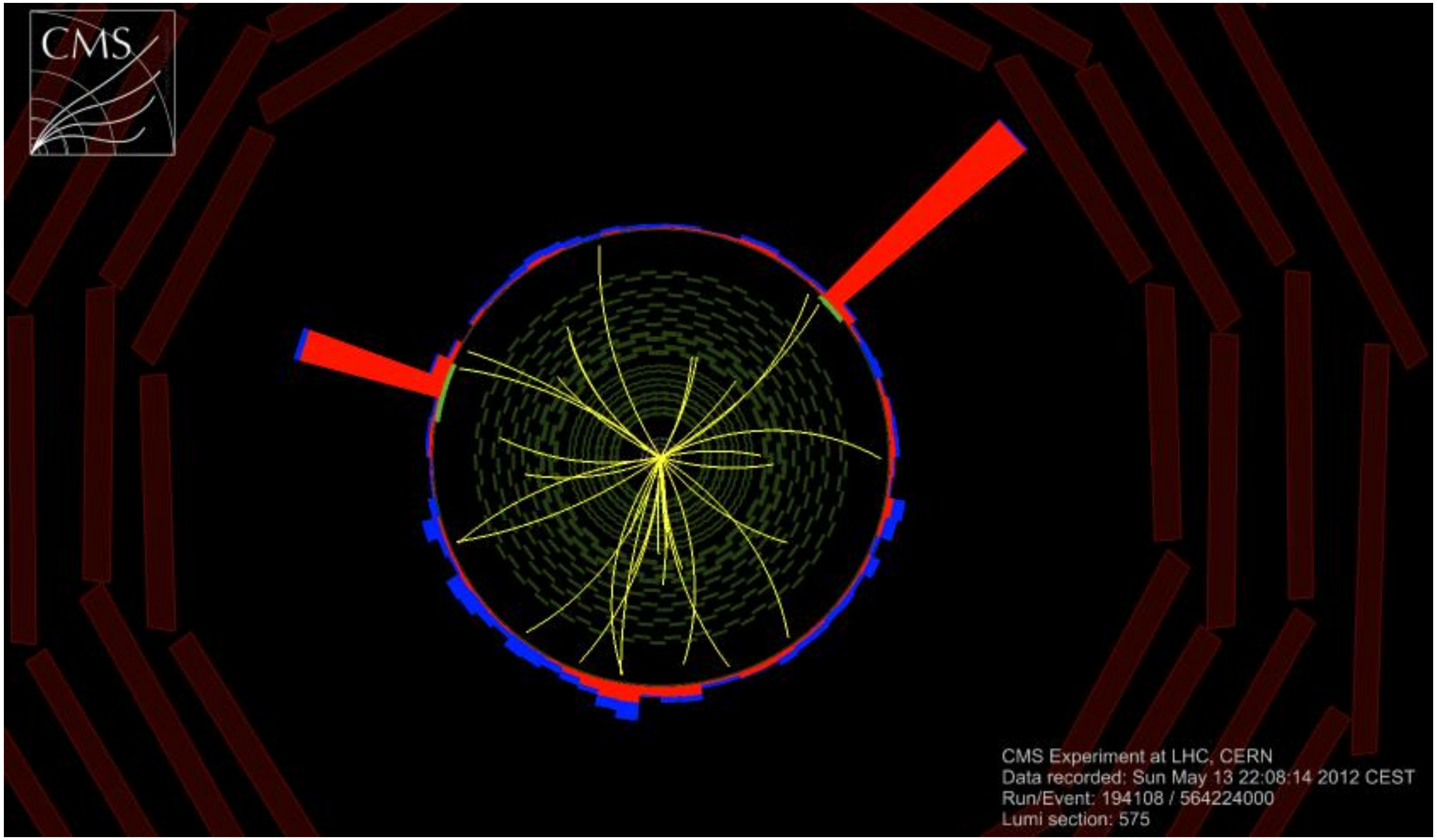
- There is about a 0.6% uncertainty on the energy scale.
  - This comes from the uncertainty on the fraction of the shower energy that ends up in the (thin) presampler layer.
  - This is also the most sensitive layer to upstream material and pile-up
- The energy scale varies with detector geography – and thus Higgs search region
- The fit can then move the curves above along the x-axis by this fraction of a %.
- This in turn increases the significance by about 0.1σ.
- We therefore report a significance 0.1σ lower than what comes out of the fit.

What About Other Systematics?

- Most affect the calculation of μ, not the significance:
  - Photon identification: 8-10%
  - Effect of Pileup: 4%
  - Trigger efficiency: 1%
  - Higgs cross-section: 7-12%
  - Higgs branching fraction: 5%
- The ones that affect the significance have to do largely with:
  - Prediction of the expected width
  - Category migration (e.g. uncertainty in material affects conversion rate)
  - Are included in the fit and make rather little difference

Where Are We Now?

One experiment has a (local) 4.5σ effect in one channel. What do the other channels look like? What do the other guys see?

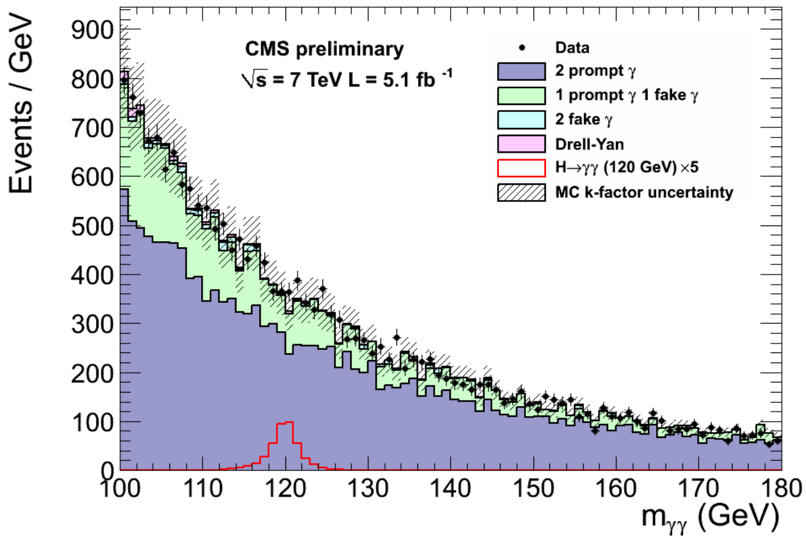


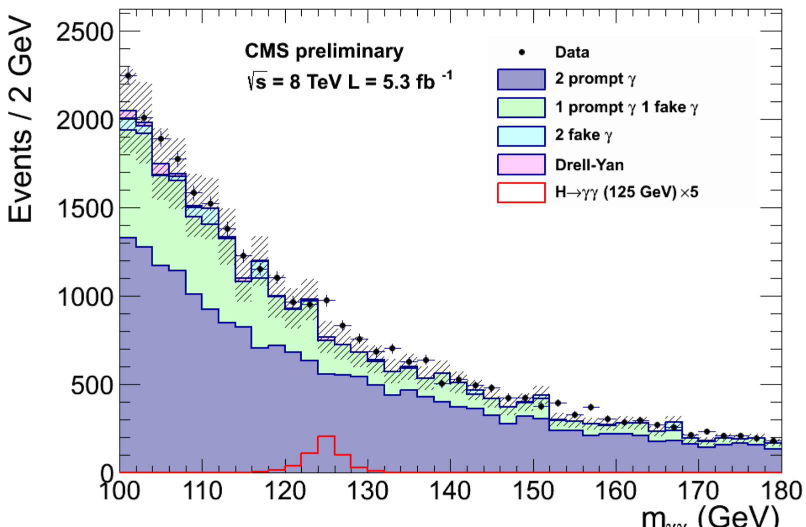
The CMS Analysis

Similar to the ATLAS analysis, but differs in details

- Uses 5 (7 TeV) or 6 (8 TeV) categories instead of 10:
  - One (7 TeV) or two (8 TeV) for VBF-like events (ATLAS uses one)
  - Four assigned via a MVA output (rather than a Decision Tree)
  - As at ATLAS, S/B and mass resolution varies substantially between the categories
- Uses p_T instead of pTt everywhere
- Of course, uses a crystal (lead tungstate) calorimeter rather than liquid argon.

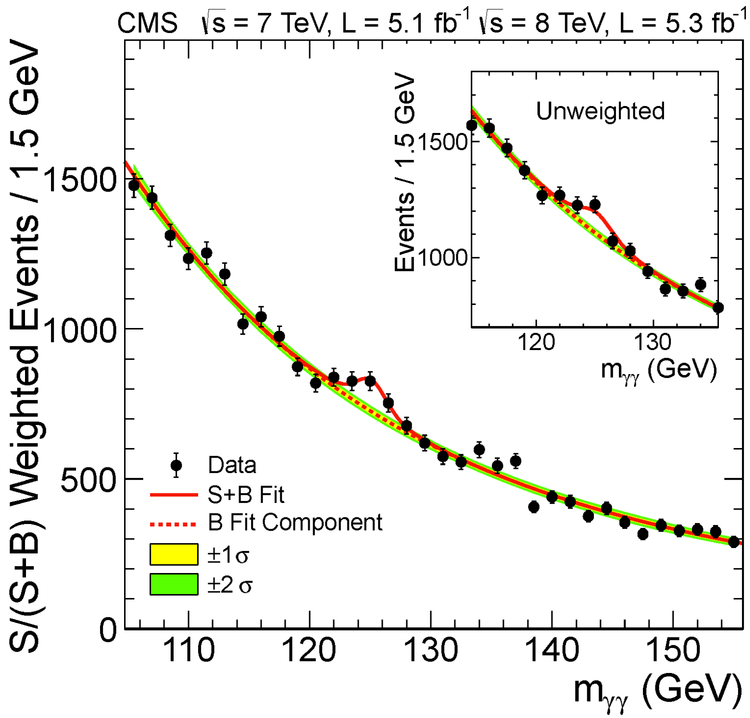
Backgrounds



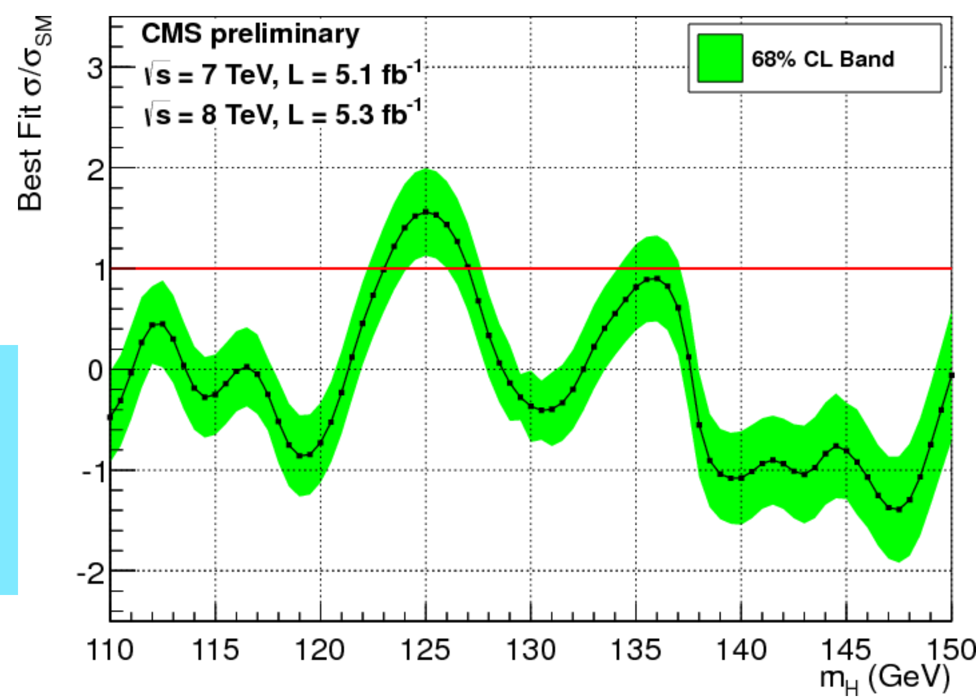


- The background is ~75% real γ-γ events
  - Ordinary QCD Production
  - Very similar to ATLAS
- This is why I am not going to describe the photon cuts in detail: separating photons from neutral mesons is not the biggest challenge in this measurement.
- Note that the 7 and 8 TeV backgrounds, while similar, are not identical.
  - This necessitates treating them separately.

Yields



This is not a mass plot per se. It is a mass plot weighted by category that the event was classified in. The actual mass plot is in the inset.



CMS plots their blue and white plots in green. As before μ is defined as σ/σ_{SM}. CMS also sees slightly more $\gamma\gamma$ events than expected, but OK at 2σ.

More on μ

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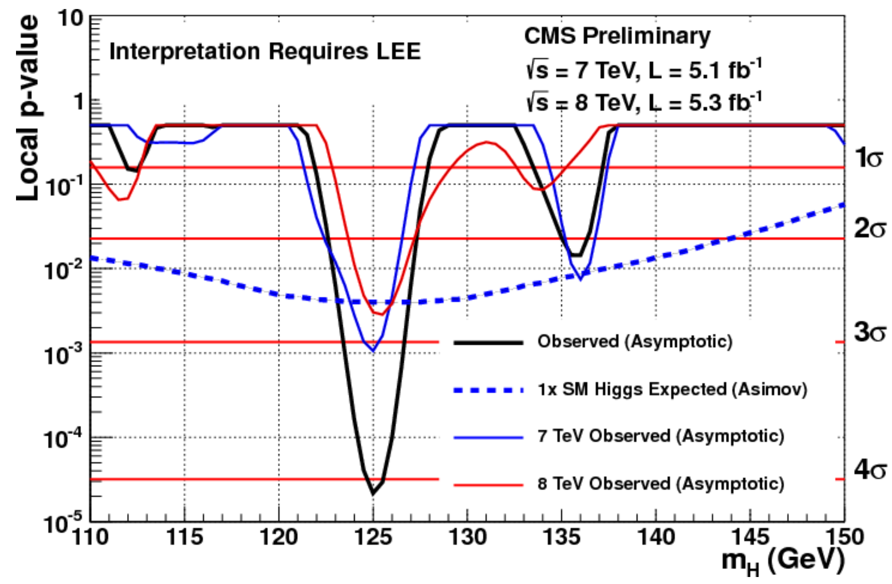

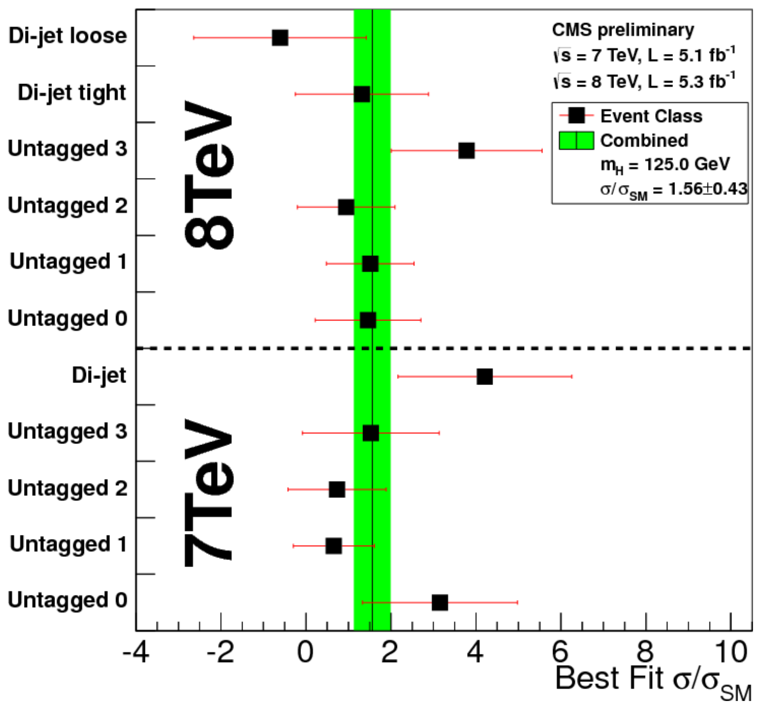

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And For Completeness

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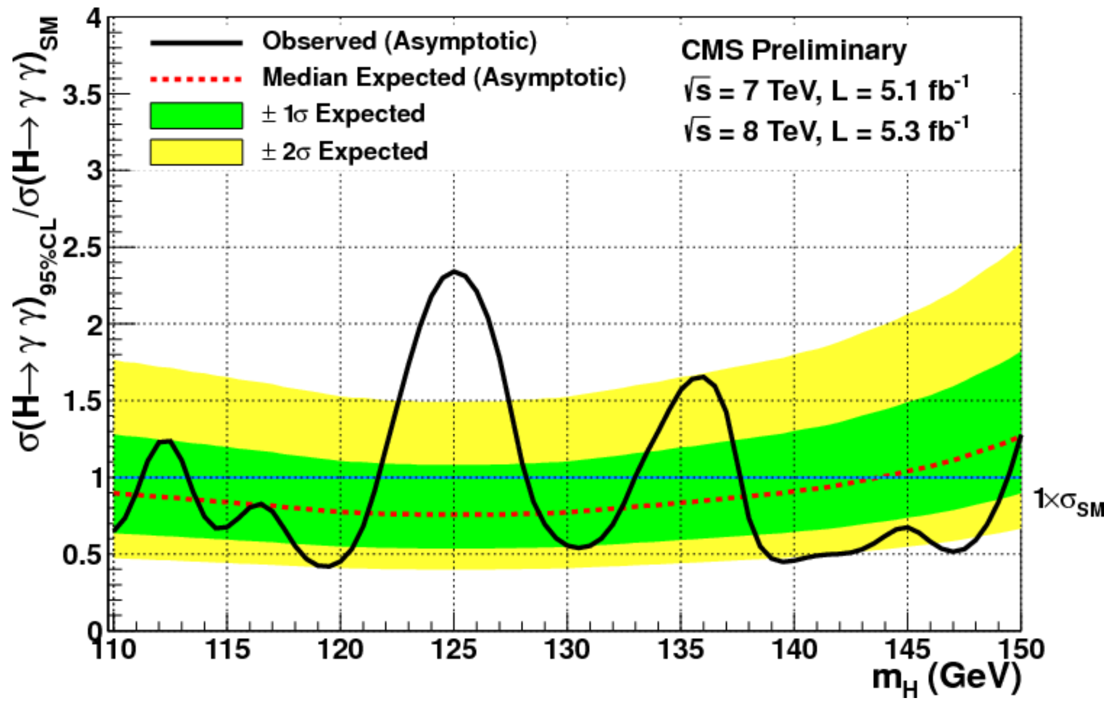
The area of poorest exclusion is (again totally unsurprisingly) the region where there is a signal.

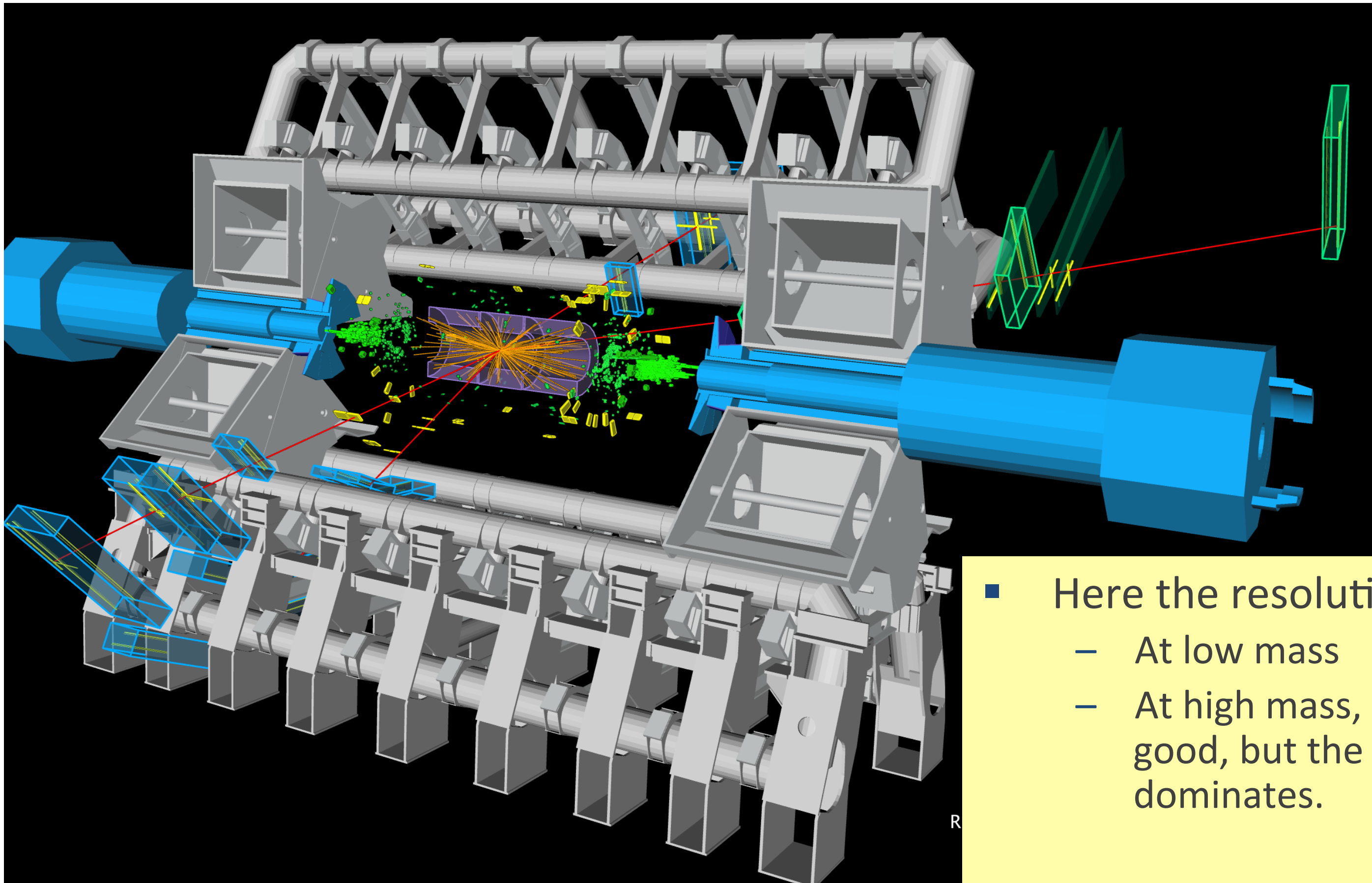


An Observation

- 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 look at the other channels

Higgs to $ZZ^{(*)}$ (4 leptons - e's and μ's)



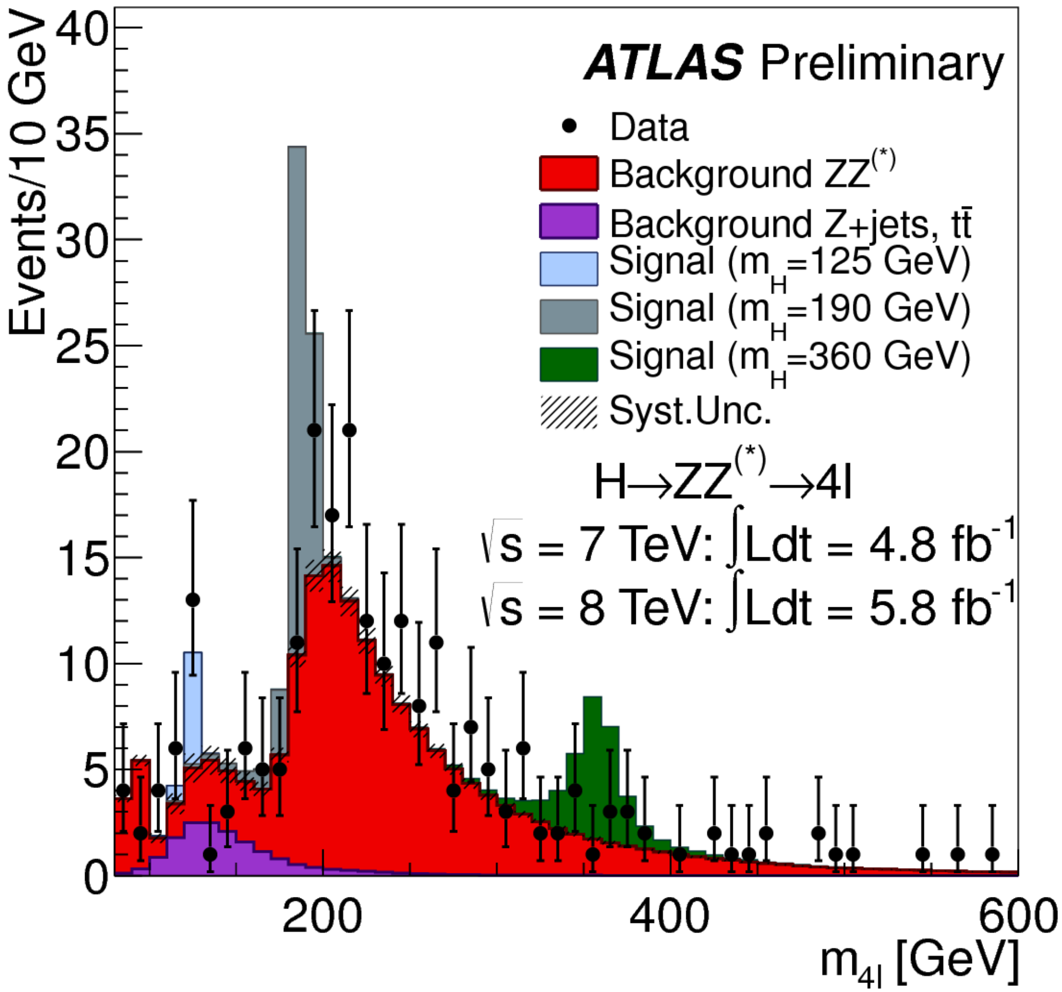
- Here the resolution is very good.
  - At low mass
  - At high mass, the resolution is still good, but the Higgs width dominates.
- The branching fraction hurts. $(.06)^2 = .004$
- Background is largely real $ZZ^{(*)}$

Backgrounds

	4μ		$2e2\mu/2\mu2e$		$4e$	
	Low mass	High mass	Low mass	High mass	Low mass	High mass
$\sqrt{s} = 8$ TeV						
Int. Luminosity	5.8 fb^{-1}		5.8 fb^{-1}		5.9 fb^{-1}	
$ZZ^{(*)}$	6.3±0.3	27.5±1.9	3.7±0.2	41.7±3.0	2.9±0.3	17.7±1.4
Z + jets, and $t\bar{t}$	0.4±0.2	0.15±0.07	3.9±0.9	1.4±0.3	2.9±0.8	1.0±0.3
Total Background	6.7±0.3	27.6±1.9	7.6±1.0	43.1±3.0	5.7±0.8	18.8±1.4
Data	4	34	11	61	7	25
$m_H = 125$ GeV	1.4±0.2		1.7±0.2		0.8±0.1	
$m_H = 150$ GeV	4.5±0.6		5.9±0.8		2.7±0.4	
$m_H = 190$ GeV	8.2±1.0		12.5±1.7		5.3±0.8	
$m_H = 400$ GeV	3.9±0.5		6.6±0.9		2.9±0.4	
$\sqrt{s} = 7$ TeV						
Int. Luminosity	4.8 fb^{-1}		4.8 fb^{-1}		4.9 fb^{-1}	
$ZZ^{(*)}$	4.9±0.2	18.1±1.3	3.1±0.2	27.3±2.0	1.6±0.2	10.2±0.8
Z + jets, and $t\bar{t}$	0.2±0.1	0.07±0.03	2.1±0.5	0.7±0.2	2.3±0.6	0.8±0.2
Total Background	5.1±0.2	18.2±1.3	5.1±0.5	28.0±2.0	3.9±0.6	11.0±0.8
Data	8	25	5	28	4	18
$m_H = 125$ GeV	1.0±0.1		1.0±0.1		0.37±0.05	
$m_H = 150$ GeV	3.0±0.4		3.4±0.5		1.4±0.2	
$m_H = 190$ GeV	5.1±0.6		7.4±1.0		2.8±0.4	
$m_H = 400$ GeV	2.3±0.3		3.8±0.5		1.6±0.2	

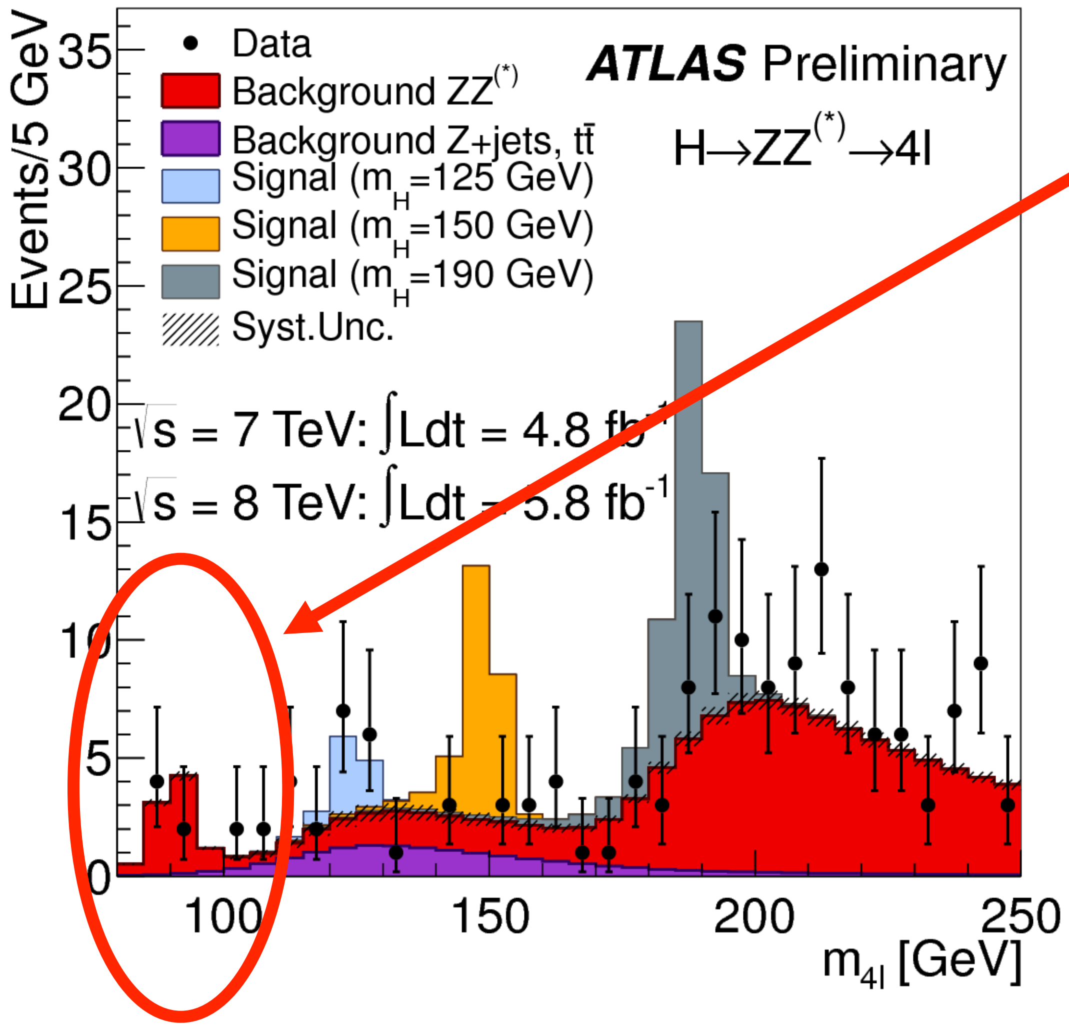
- Key ideas:
  - Most of the background is real (and irreducible) ZZ and ZZ*.
  - The yields are small, so we'll be dealing with the statistics of small numbers of events
  - ATLAS treats "high mass" (ZZ) and "low mass" (ZZ*) separately – a four-lepton mass of 160 GeV is the dividing line.

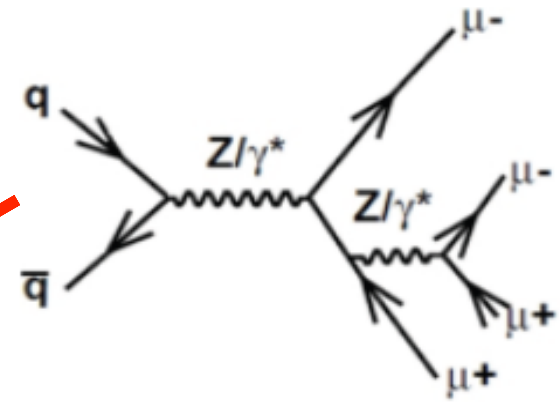
The ATLAS Data



- We're obviously dealing with small statistics.
  - At 125 GeV, it's 13 events over a predicted background of 5
- The background is almost entirely ZZ and ZZ*
  - Except under the peak at 125 GeV: more on that later.
- There are some interesting features in this plot.

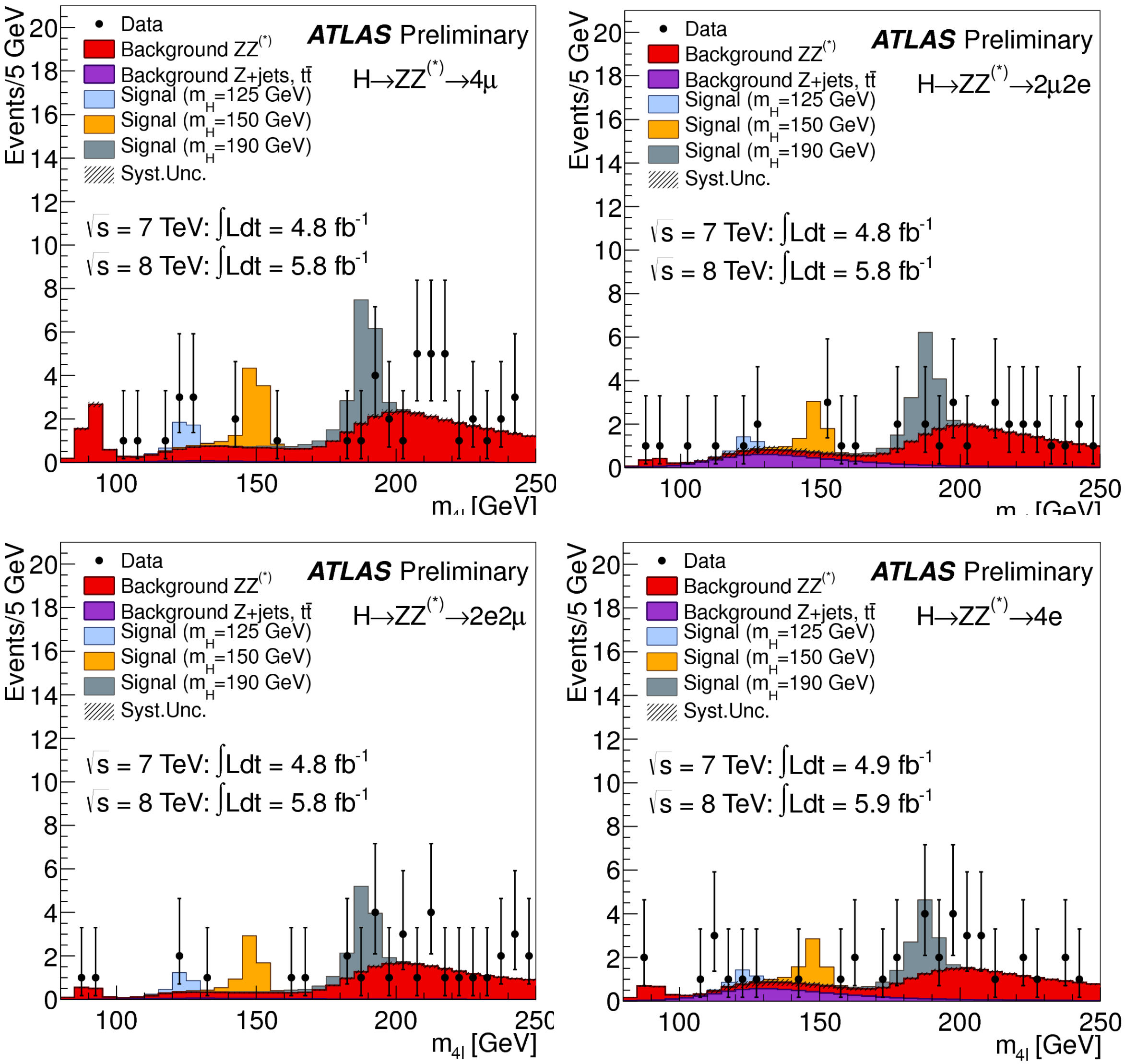
Interesting Feature #1: Z →4 leptons





- There are 6 events that are radiative + internal conversion (i.e. 4 lepton) Z decays.
  - Two each in the 4e, $2e2\mu$ and $2\mu 2e$ categories.
  - ATLAS considers a "Z" to be between 50-106 GeV
- These events occur with about the same frequency as a SM Higgs.

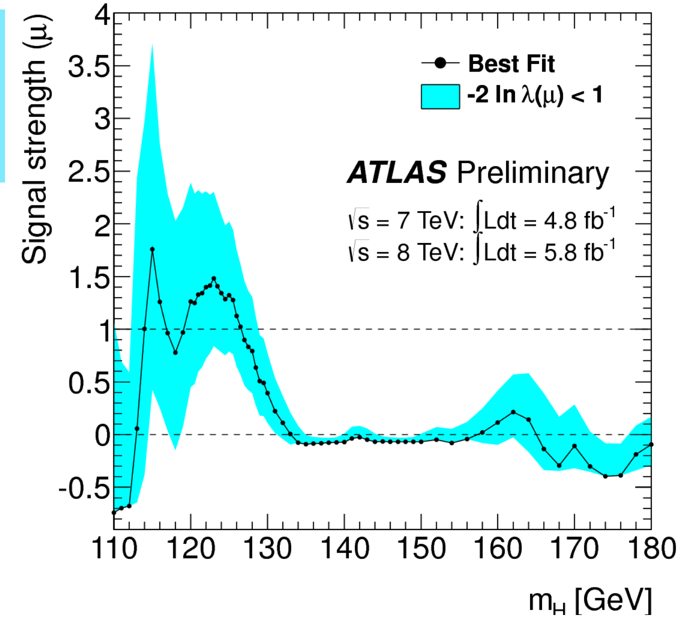
Interesting Feature #2: Decay Modes



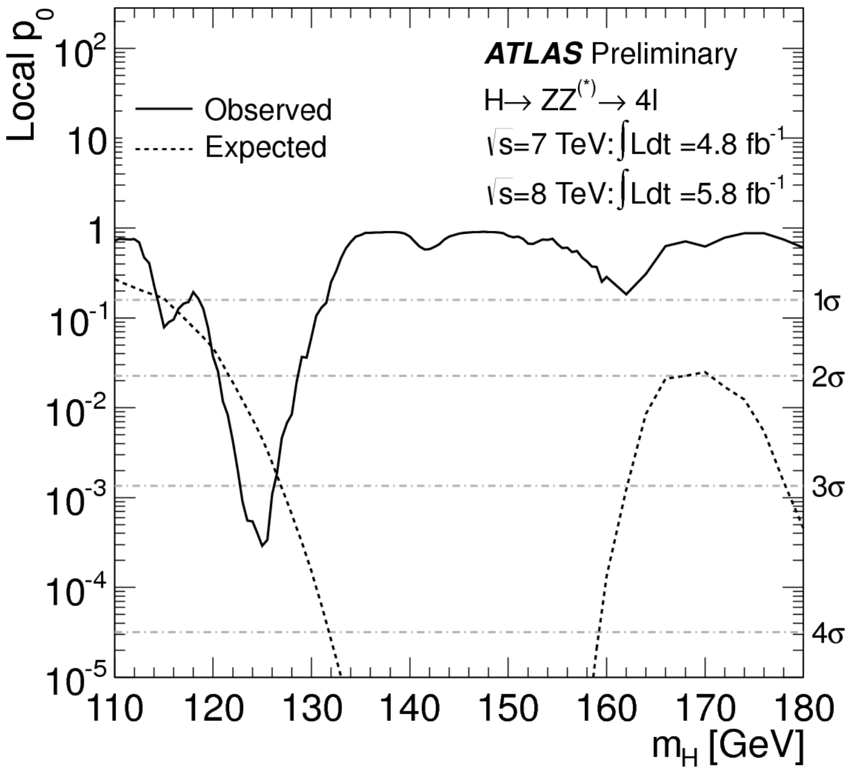
- The excess is not coming from a single channel.
  - Not much more to say with this level of statistics.
- The only channels with significant non ZZ* background are the ones where the off-shell Z* decays to electrons.
  - The higher probability for a jet to fake an isolated electron over an isolated muon comes into play.
  - The mass constraint for the on-shell pair removes most of this.
  - Much of the note concerns itself with the proper assessment of this background.

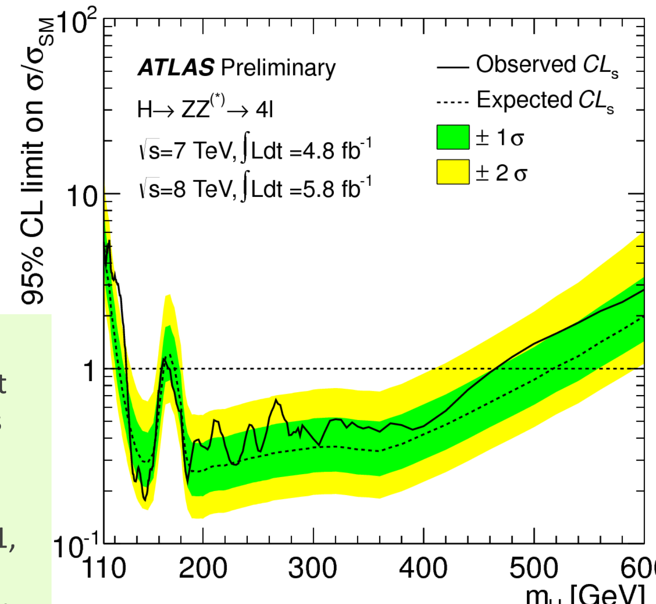
Yields and Limits

In the blue and white plots, μ is defined as σ/σ_{SM}. ATLAS sees slightly more ZZ* events than expected, but OK at 1σ.



In the black and white plots, we test how compatible μ is with 0. At 125 GeV, the answer is "not very" (3.4σ). Everywhere else is OK.

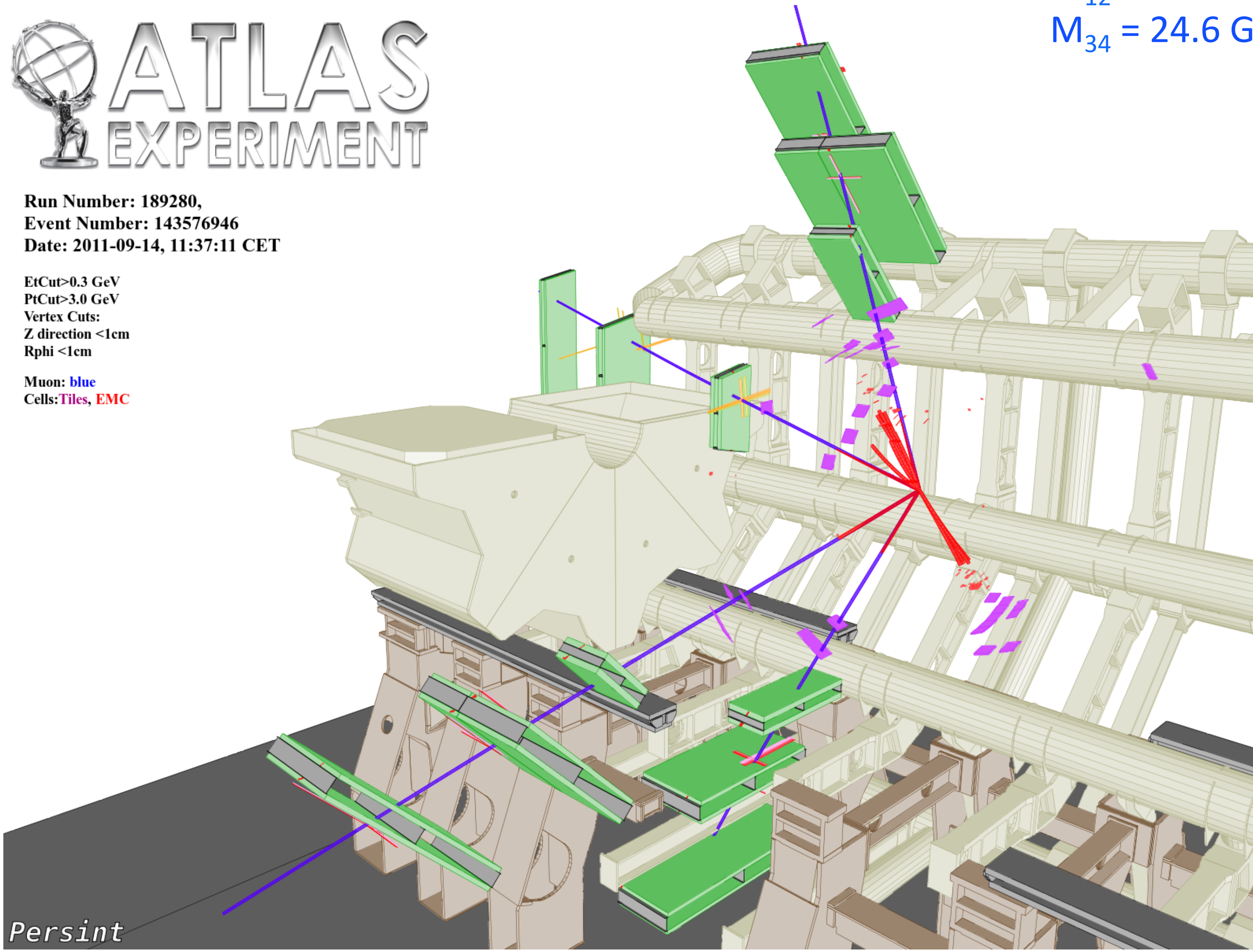




In the green and yellow plots, we test how compatible μ is with 1. Below ~130 GeV, the data are compatible with μ=1, but just about everywhere else up to 460 GeV is excluded.

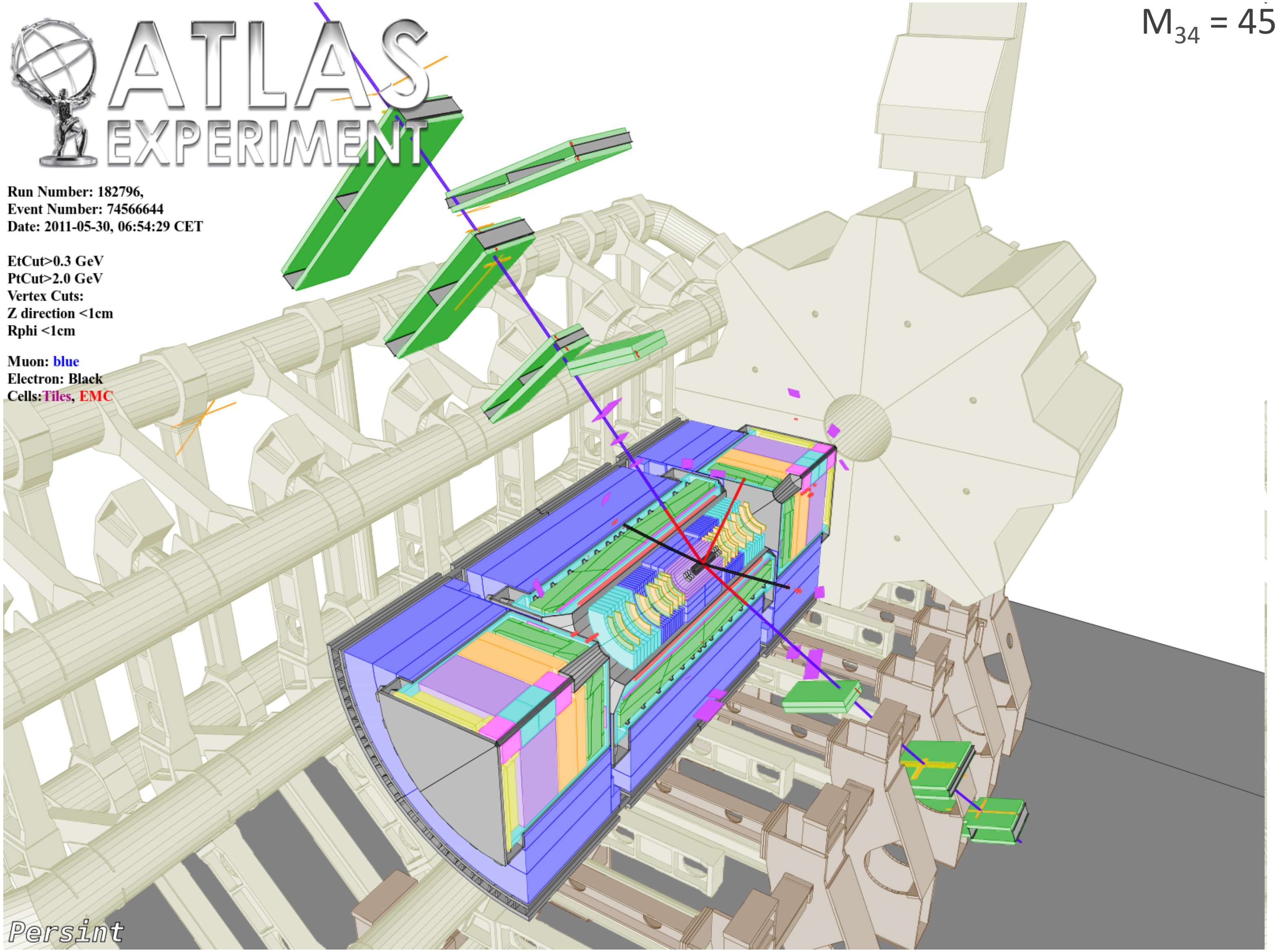
Event 1 - 4μ

M_{12} = 89.7 GeV
M_{34} = 24.6 GeV



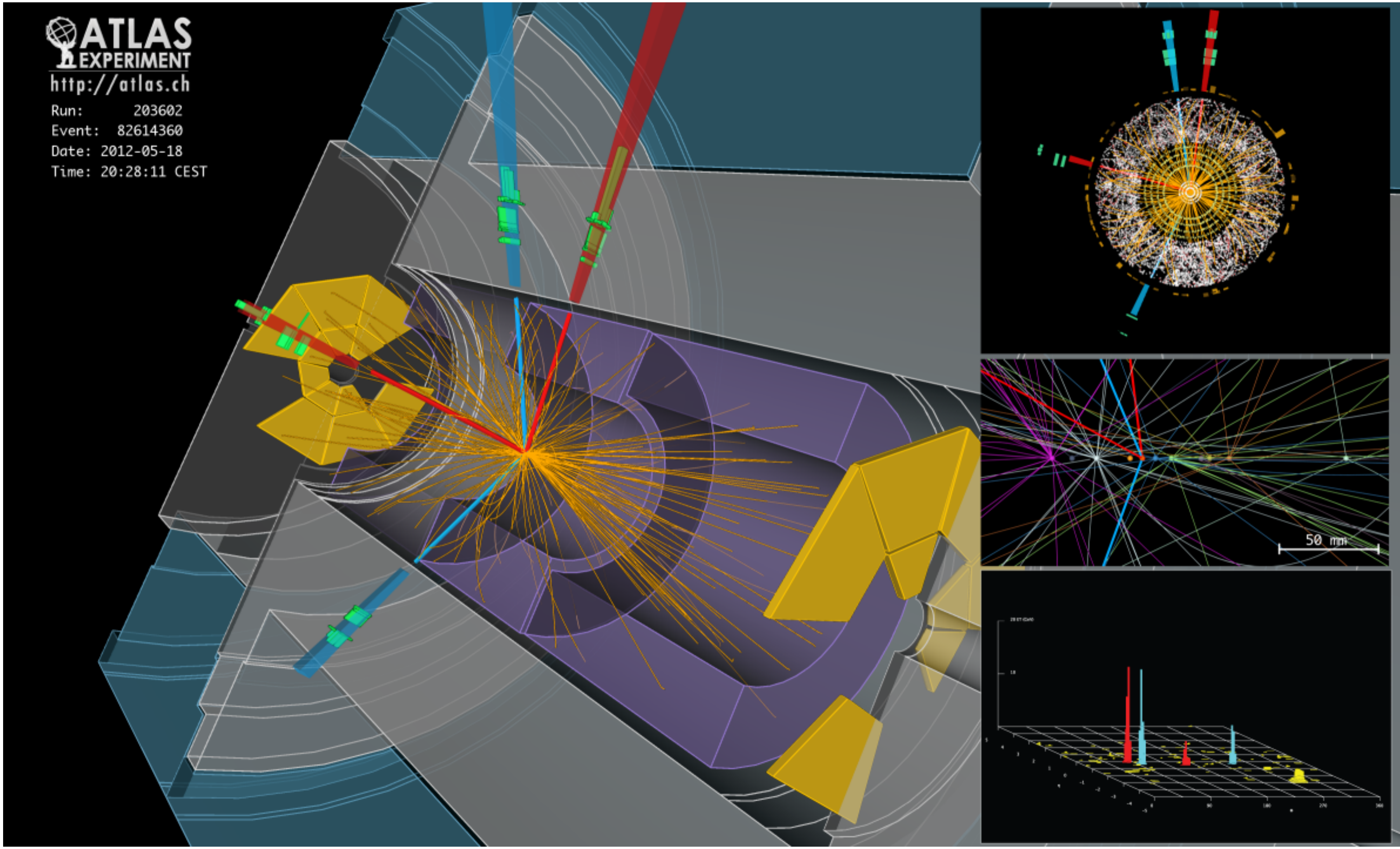
Event 2 - 2μ2e

M_{12} = 76.8 GeV
M_{34} = 45.7 GeV



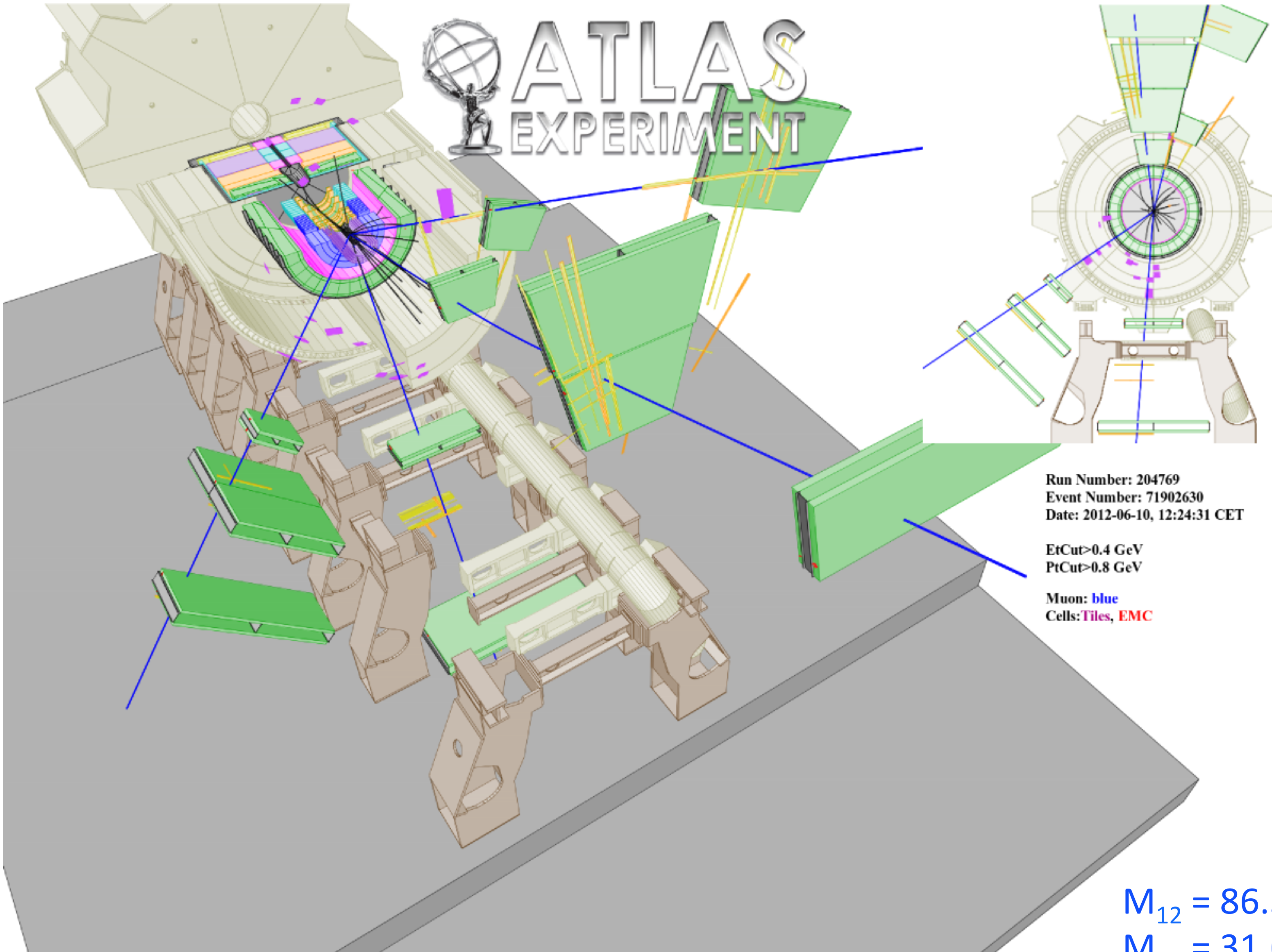
Event 3 - 4e

M_{12} = 70.6 GeV
M_{34} = 44.7 GeV



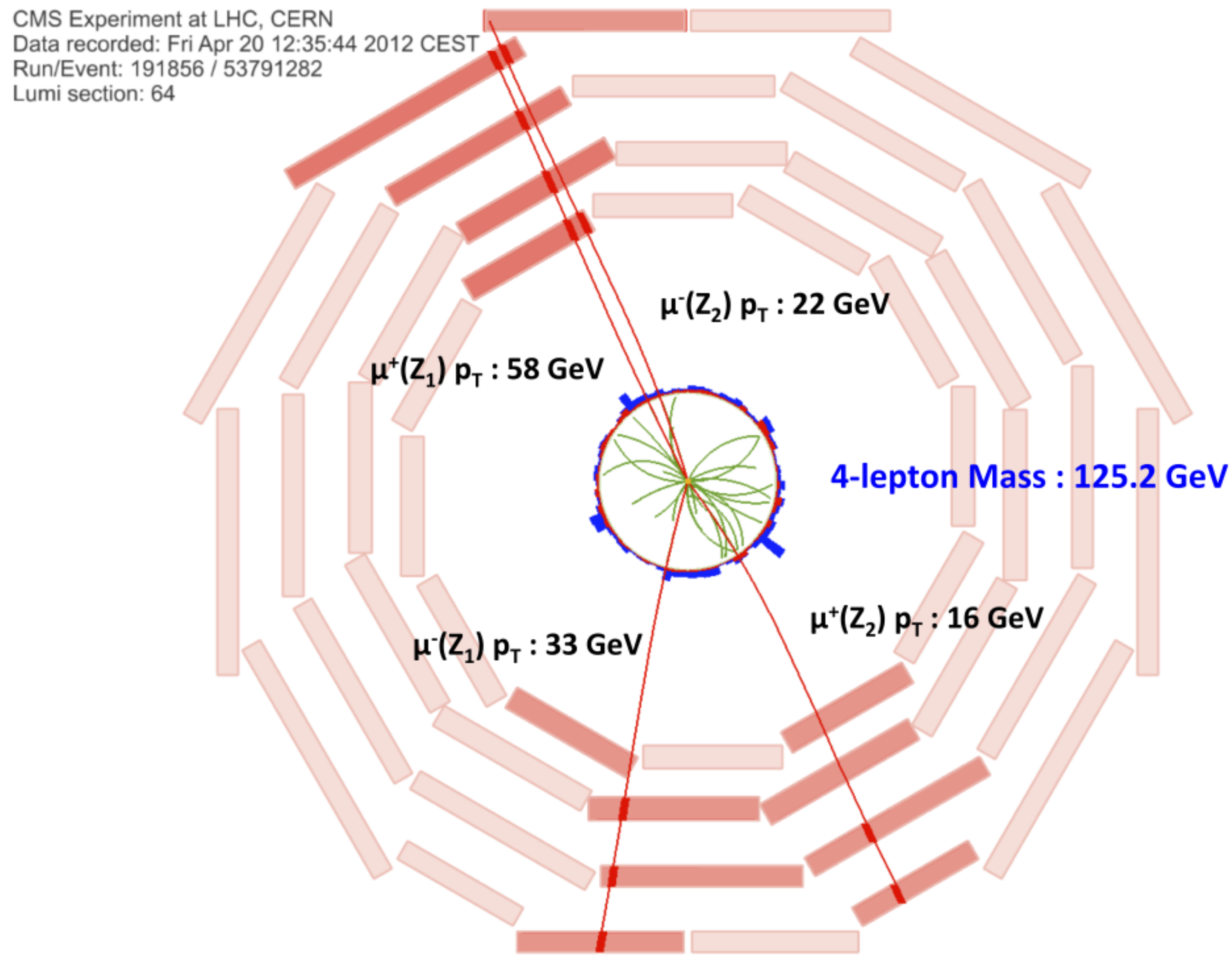
Event 4 - 4μ

(Everything goes forward)



M_{12} = 86.3 GeV
M_{34} = 31.6 GeV

Higgs to ZZ$^{(*)}$ at CMS

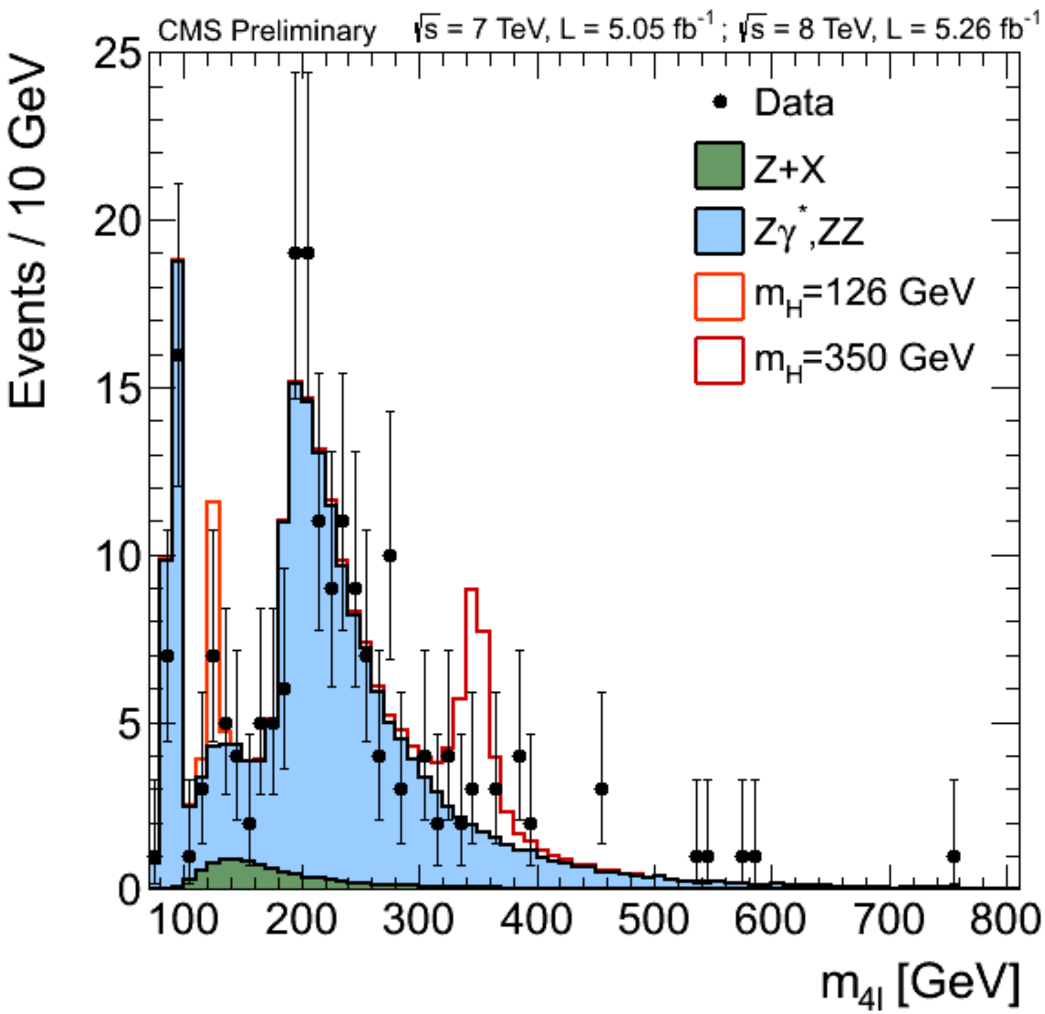


Backgrounds

Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.5 ± 1.0
Z+X	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds	$3.9^{+1.1}_{-0.8}$	$6.6^{+0.9}_{-0.8}$	$9.5^{+2.0}_{-1.6}$	$19.9^{+2.4}_{-2.0}$
$m_H = 120\,GeV$	0.8 ± 0.2	1.6 ± 0.3	1.9 ± 0.5	4.4 ± 0.6
$m_H = 126\,GeV$	1.5 ± 0.5	3.0 ± 0.6	3.8 ± 0.9	8.3 ± 1.2
$m_H = 130\,GeV$	2.1 ± 0.7	4.1 ± 0.8	5.4 ± 1.3	11.6 ± 1.6
Observed	6	6	9	21

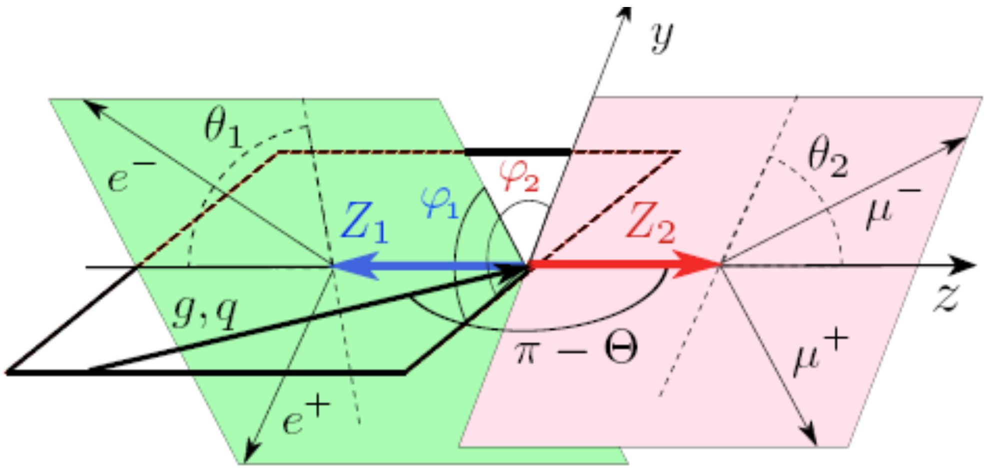
- Key ideas:
  - Most of the background is real (and irreducible) ZZ and ZZ*.
  - The yields are small, so we' ll be dealing with the statistics of small numbers of events
  - The CMS definition of a Z is somewhat looser than ATLAS' : 40-120 GeV

The CMS Data



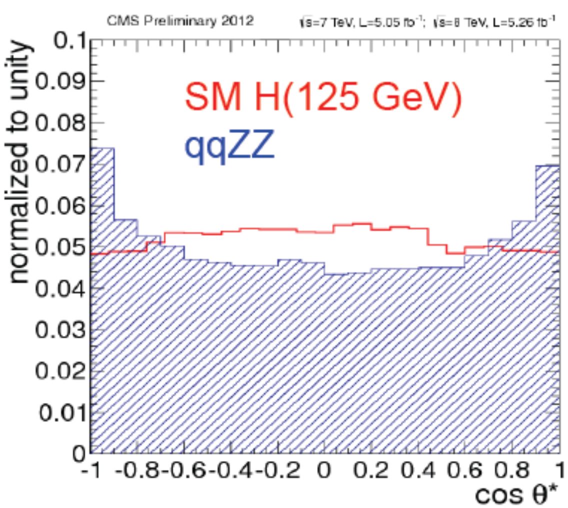
- We' re obviously dealing with small statistics.
  - At 125 GeV, it' s 12 events over a predicted background of 9
- The background is almost entirely ZZ and ZZ*
  - Like it ATLAS, the Z* to electron channel has some additional background
- CMS goes beyond counting events

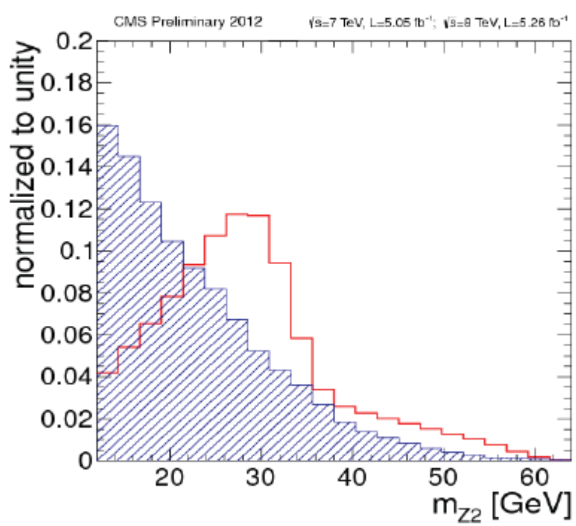
MELA – Matrix Element Likelihood Analysis

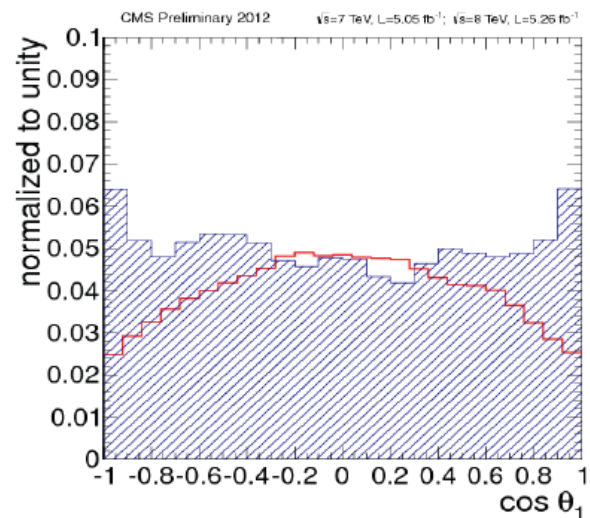


The idea: incorporate the angular information into a single variable (based on a likelihood ratio) that separates signal from background.

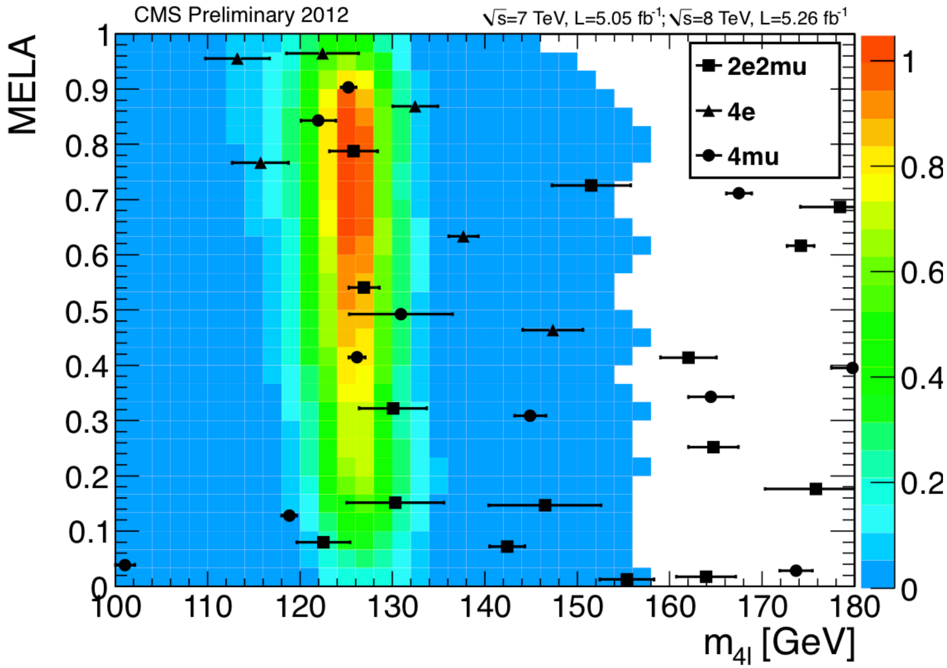
This happens to be relatively insensitive to the spin of the Higgs; this depends mostly on the character of the background – not the signal.

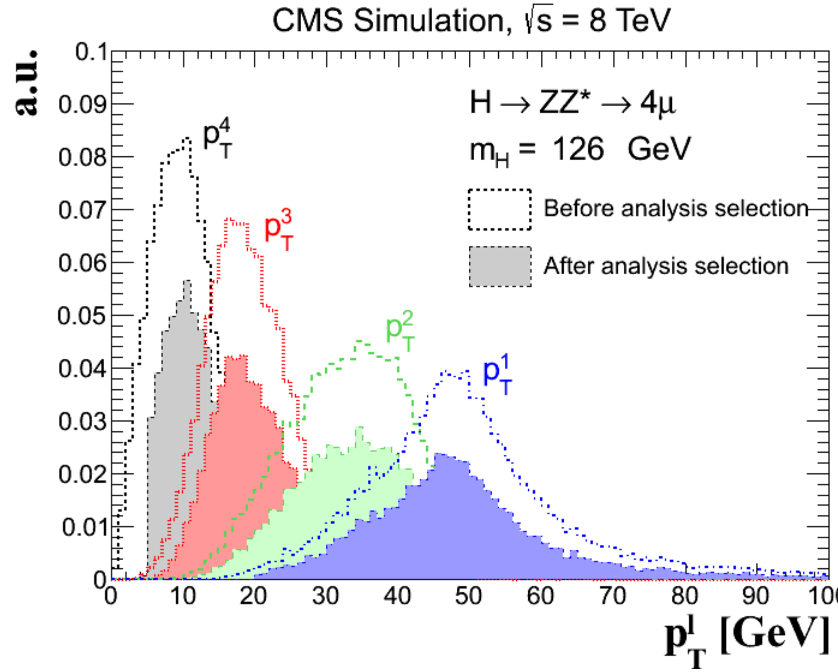






Outcome of the Process





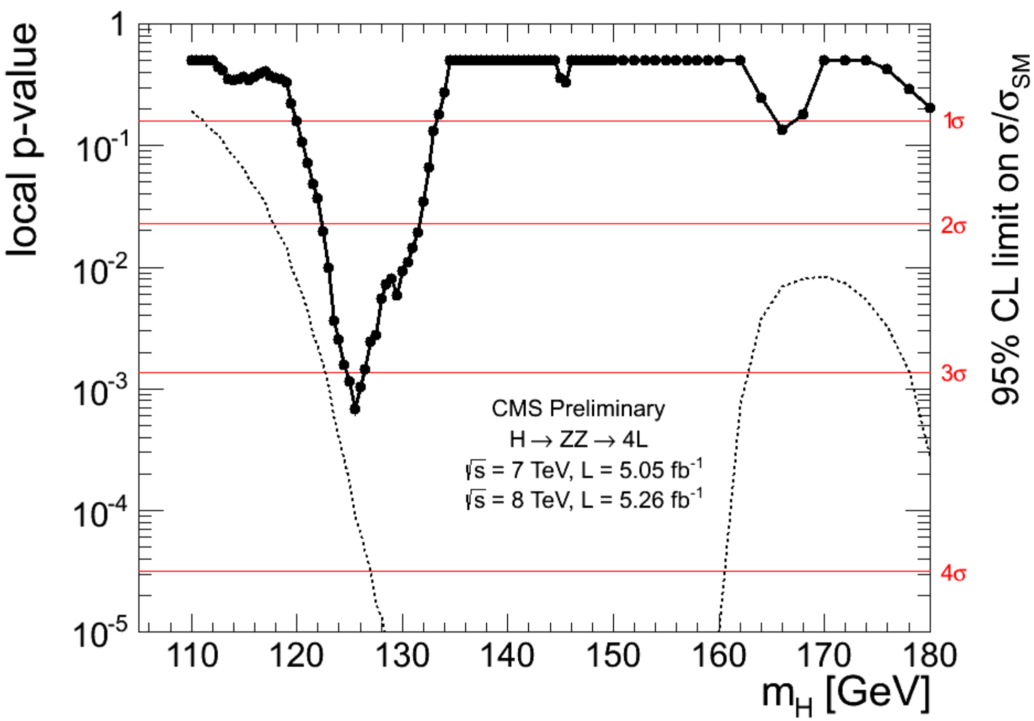
- Not all events at 125 GeV are equal; some look much more Higgs-like, and some look much more background-like.
- A 2-D fit tells you much more than just counting events, even with just the handful that we have.
- This shows why gaining signal cannot be done with p_T cuts, and why something like MELA is needed to improve S/B instead.
  - The lowest p_T lepton is a high background region.
- I wish ATLAS had a similar plot.

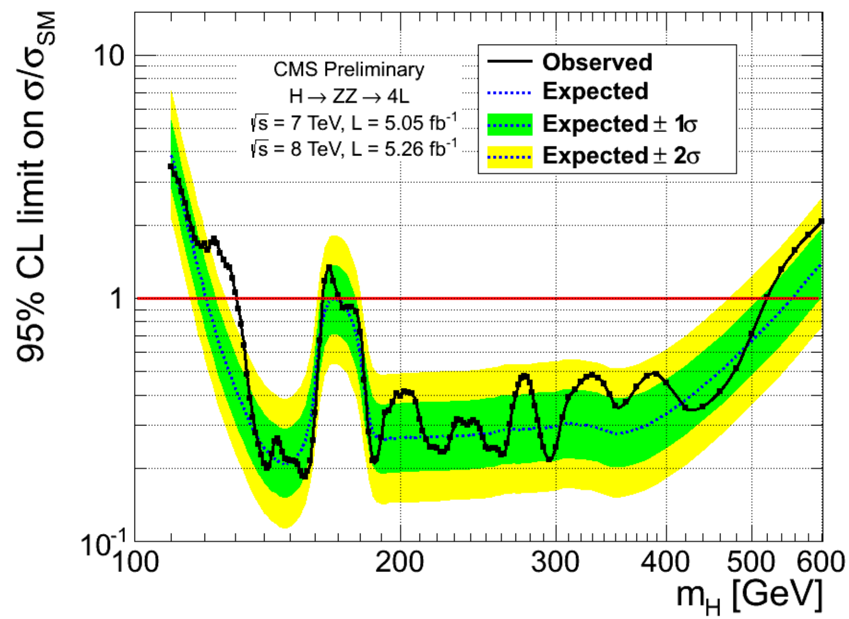
CMS Limits

CMS did not provide a blue and white plot; they see slightly fewer ZZ* events than expected, but OK at 1σ.

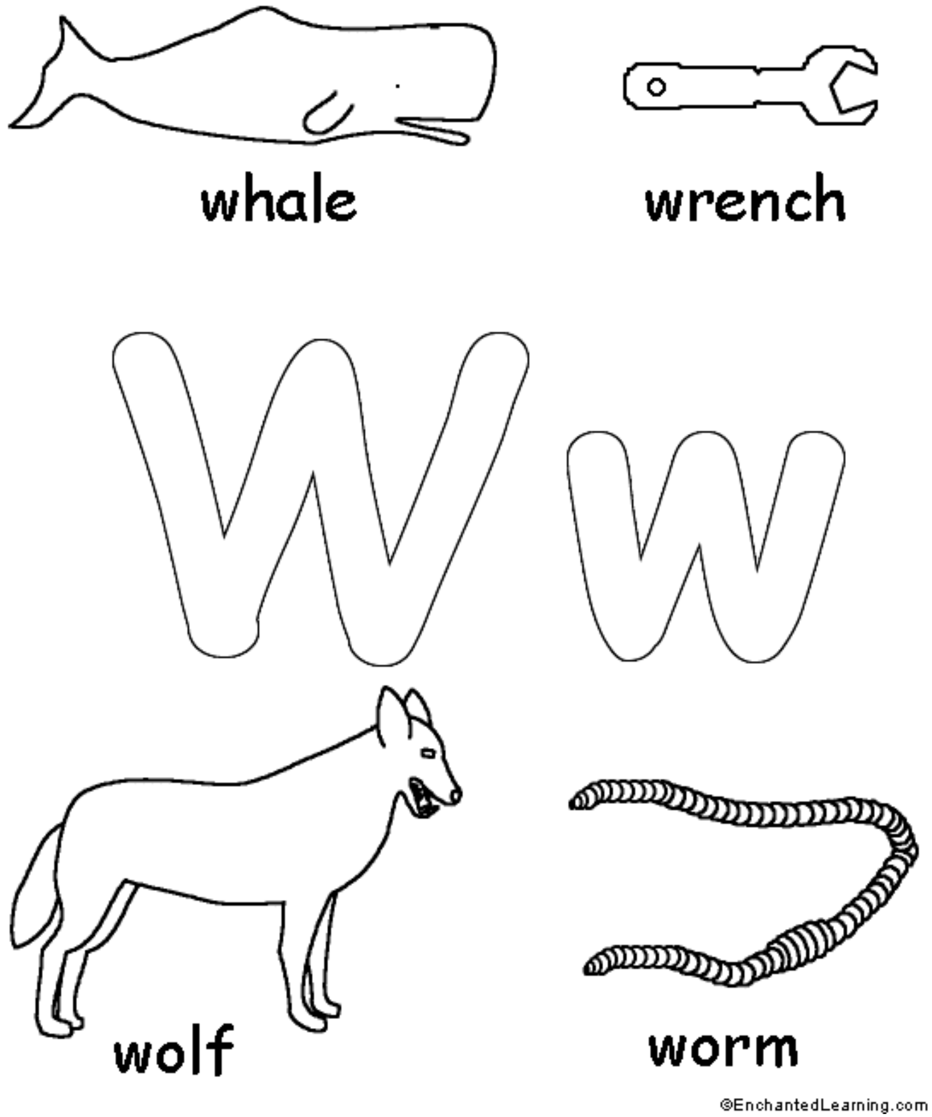
In the black and white plots, we test how compatible μ is with 0. At 125 GeV, the answer is "not very". Everywhere else is OK.

In the green and yellow plots, we test how compatible μ is with 1. The difficult region near 180 is OK, as is m < 130 GeV or so.

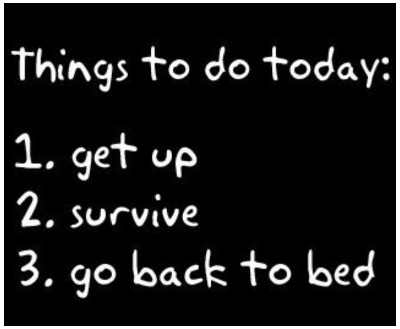




Higgs to WW$^{(*)}$ ($l\nu l\nu$) – Not As Elementary As It Looks

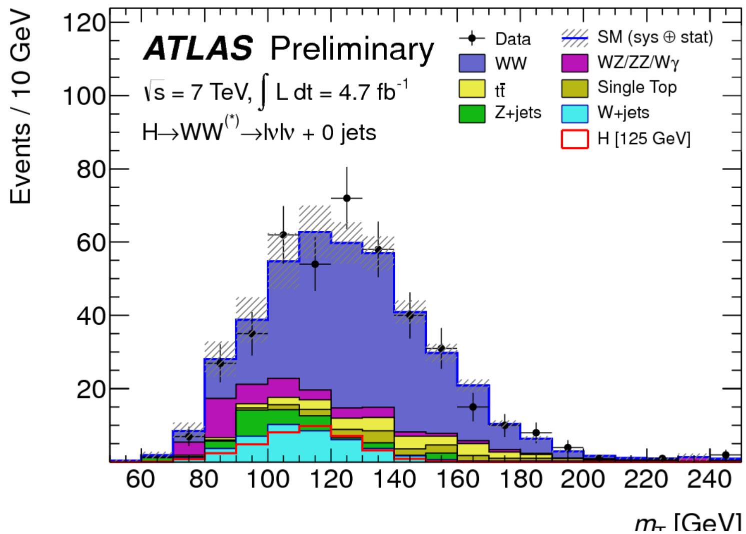


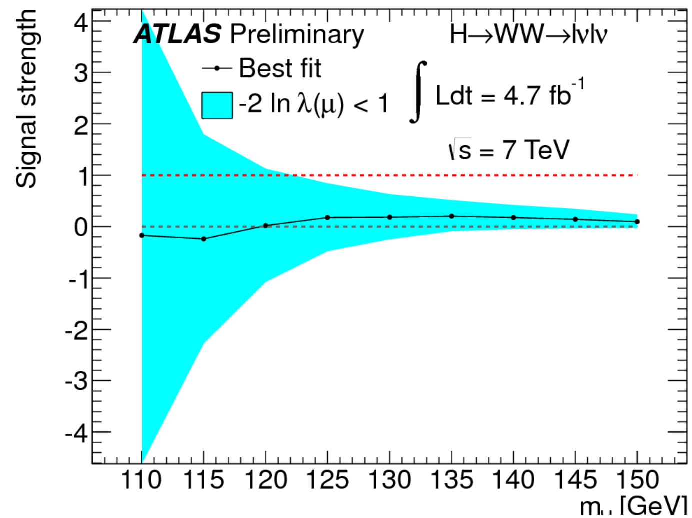
Why Is This So Hard?

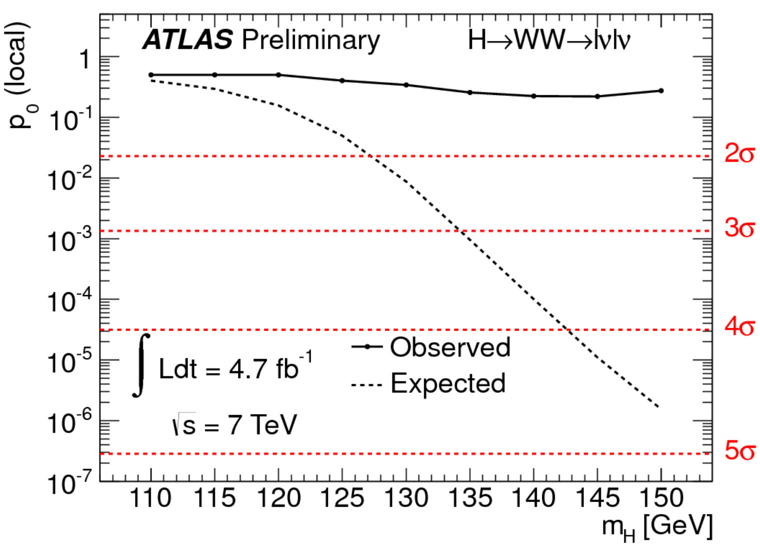


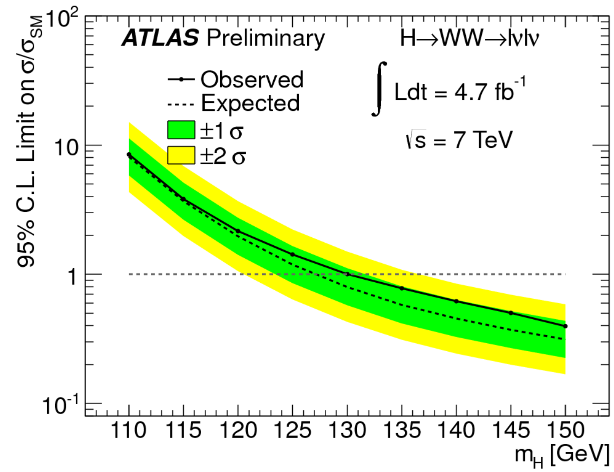
- The two missing neutrinos means you have poor mass resolution: about 30 GeV
  - Too many unknowns for a mass constraint to help you.
- A poor mass resolution means that you have to do this as a very difficult counting experiment.
  - Count events
  - Subtract off everything that you think *isn't* a Higgs – many comparable backgrounds
  - Look for anything left over.
- Cutting on $\Delta\phi$ of the two leptons selects spin-0 WW pairs, reducing background
  - However, once this is done, the remaining backgrounds start to look a lot like signal.
- This analysis works much better at 160 GeV than 125 GeV
  - One W* means soft leptons and missing E_T from the 2^{nd} neutrino
  - At low mass, the mass measurement is driven as much from cross-section as kinematics.

ATLAS 2011 WW Results



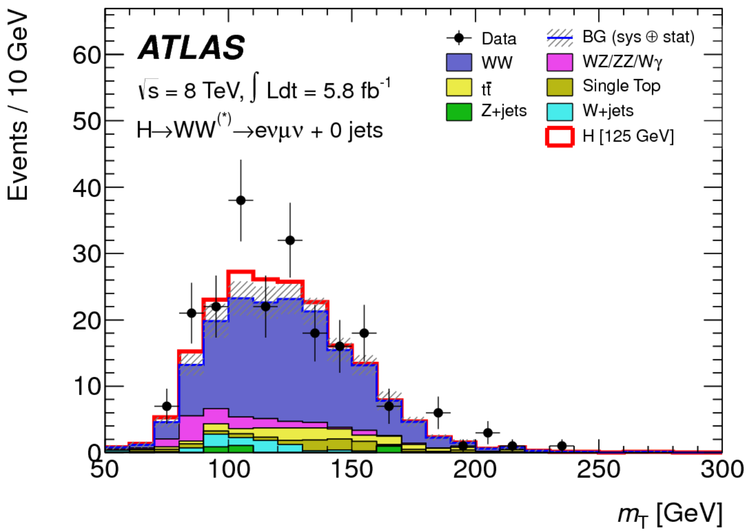


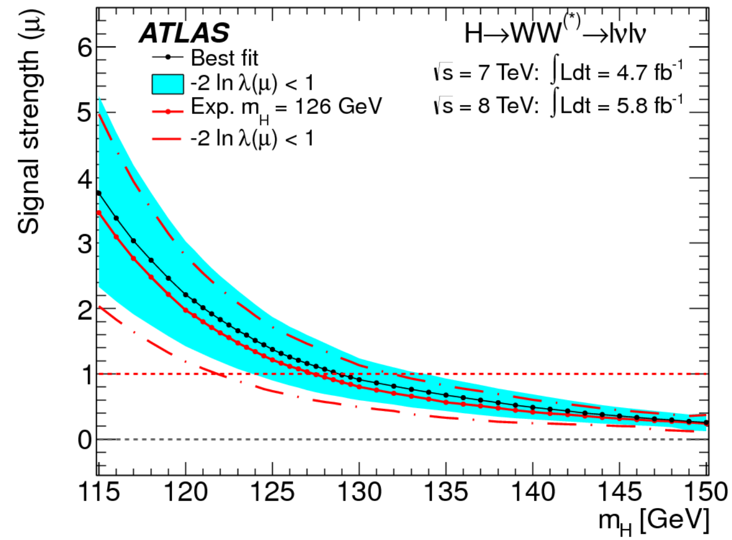


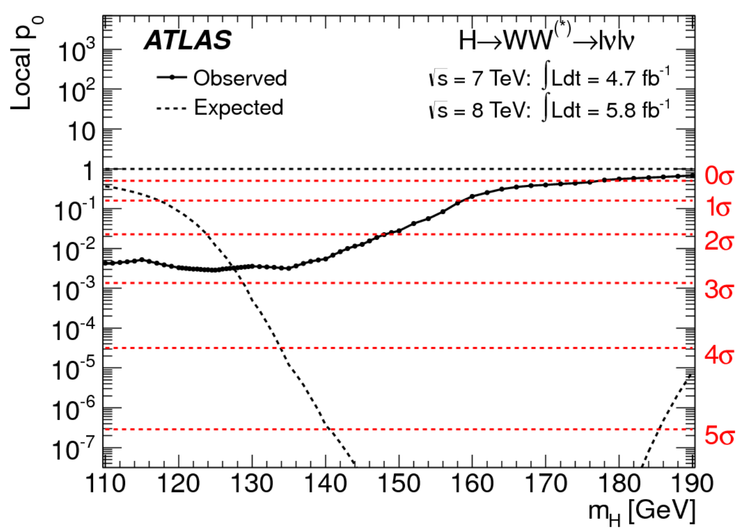


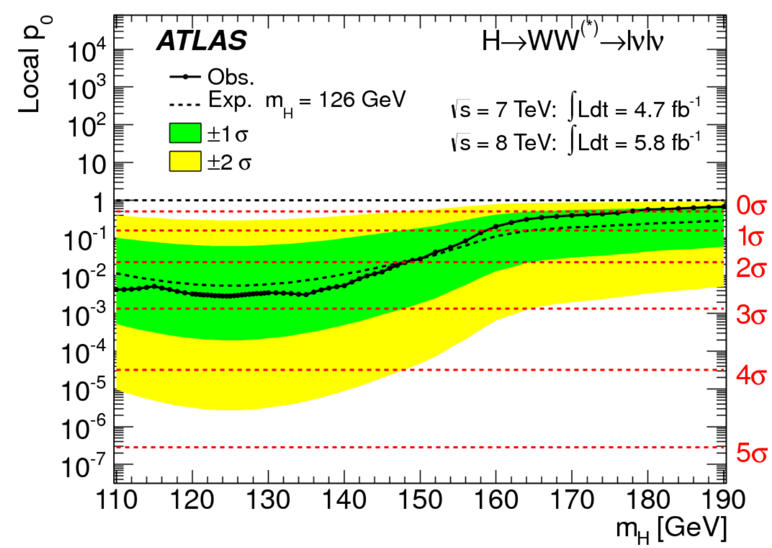
Is μ consistent with 0? With 1?
This time, the answer to both questions is "yes".

Adding the 2012 Data



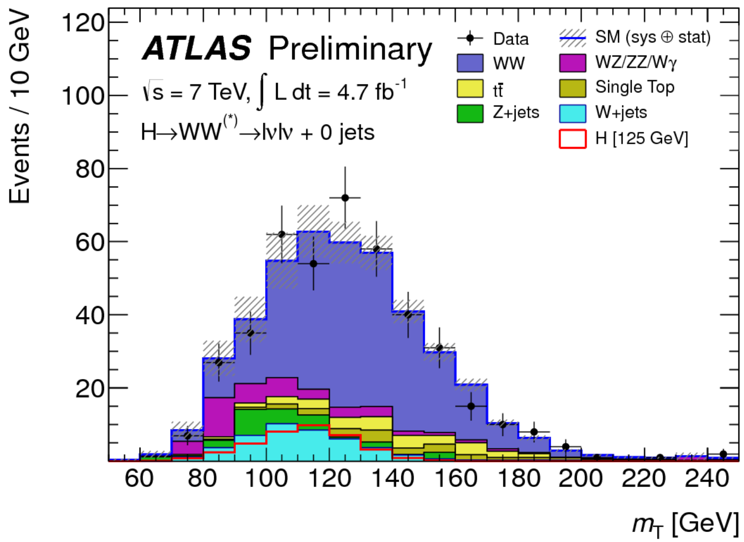


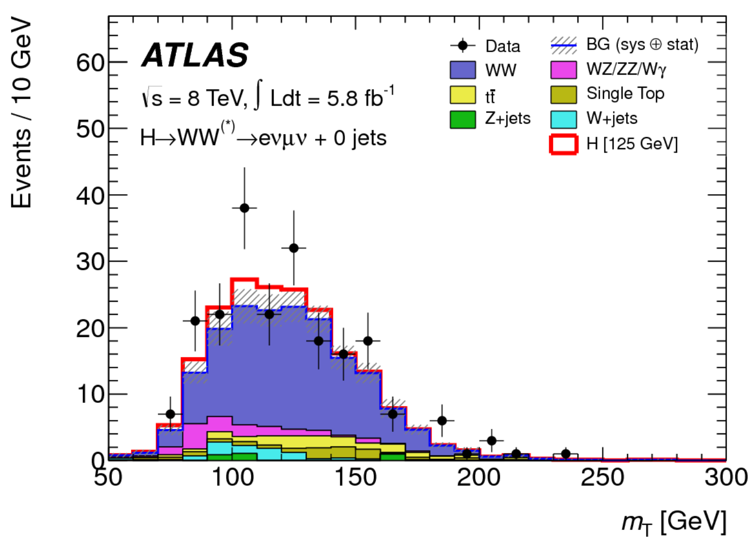




Is μ consistent with 0? With 1?

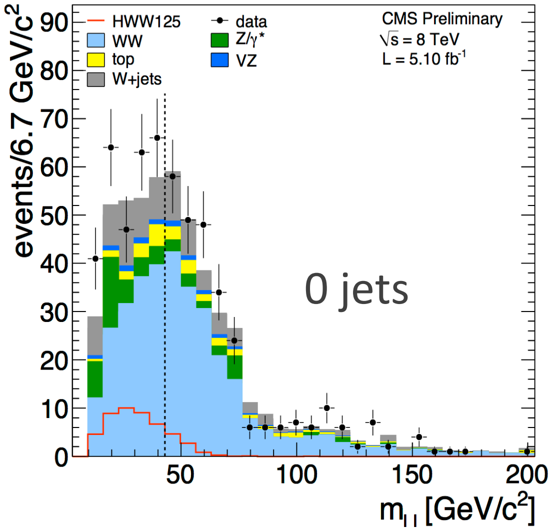
2011 vs. 2012

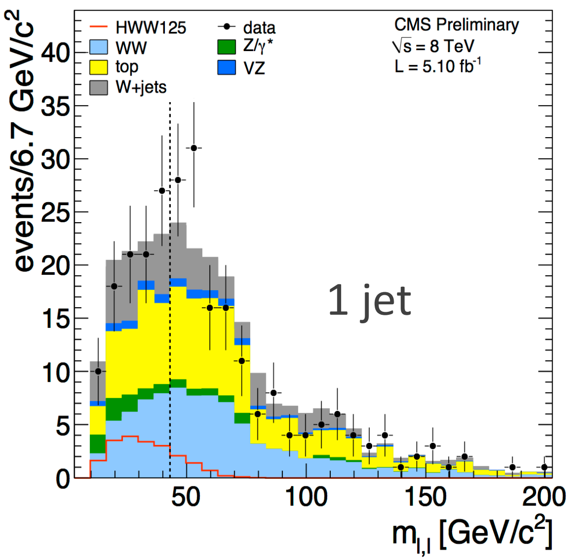


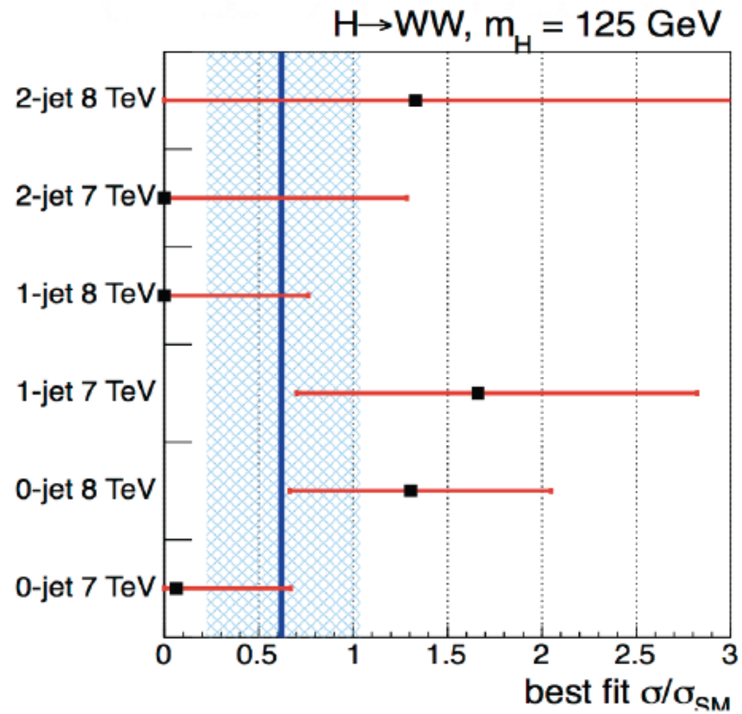


- This is the only channel where things are qualitatively different between 2011 and 2012
  - In 2011 there was no clear excess
  - In 2012 there is.
- Some of this is surely statistics
- Some of this may be due to better background rejection in 2012 due to a more mature analysis
- Why not repeat this for 7 TeV?
  - One of the things there wasn't time for in the build-up to July 4th.
  - A new result every few weeks has its drawbacks.

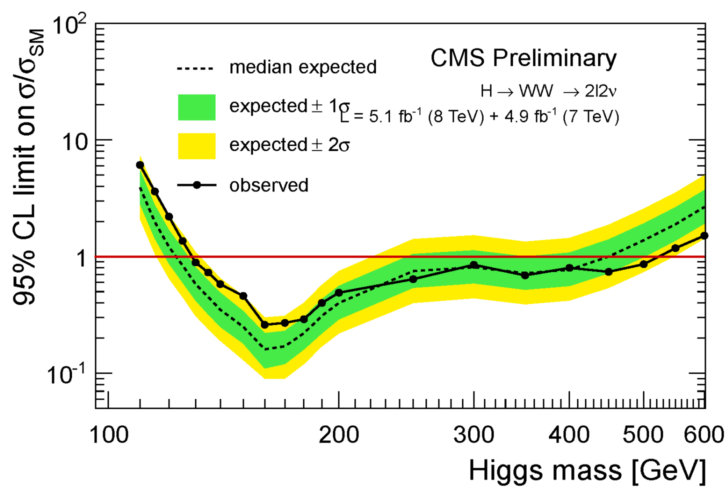
CMS WW Results





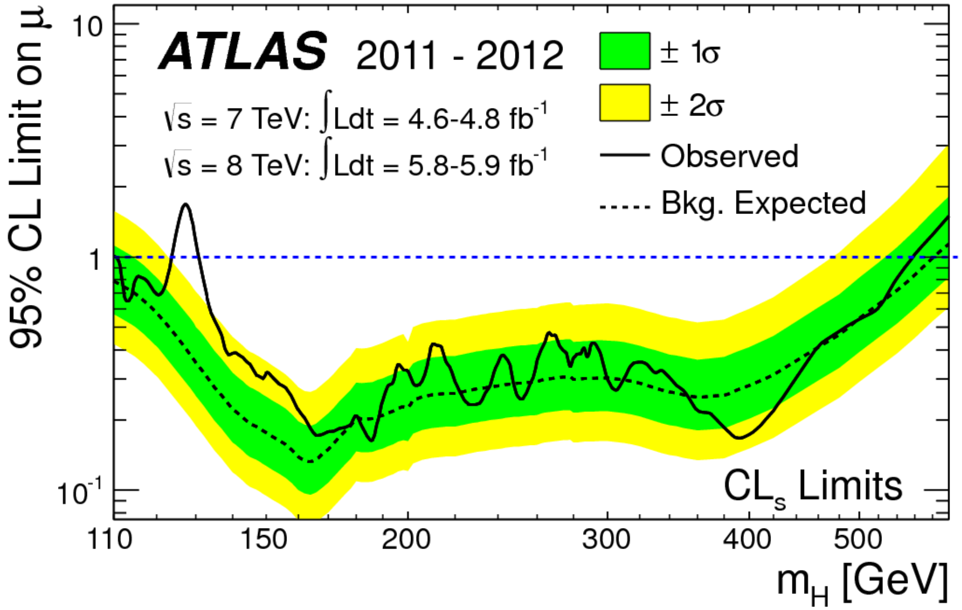


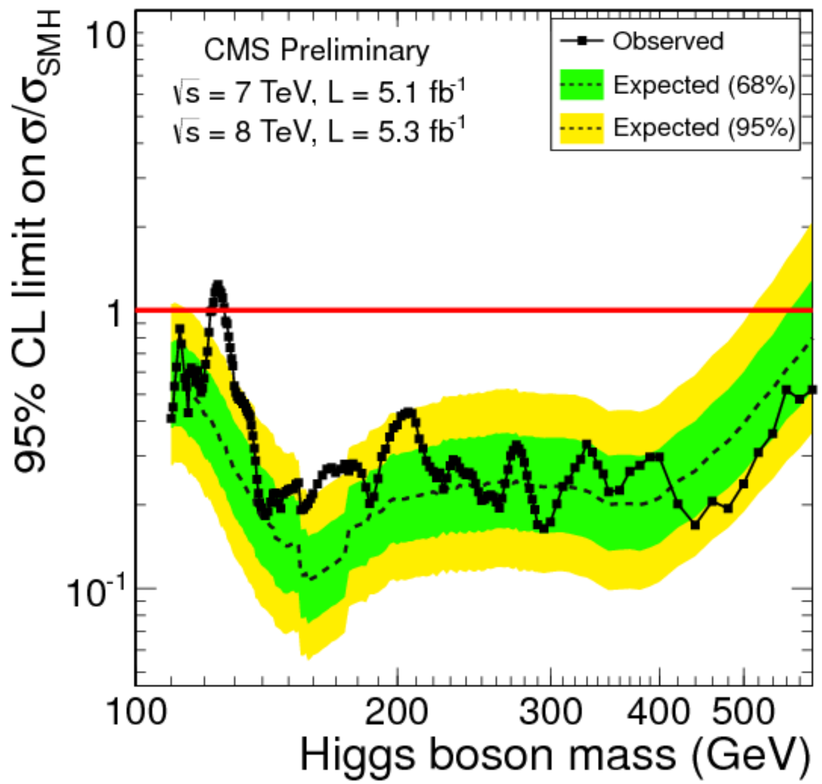
Again we are in a situation where the data is compatible with both the μ=0 and μ =1 hypotheses.



This is 2012 only – the 2011 analysis is based on shapes and isn't easily included.

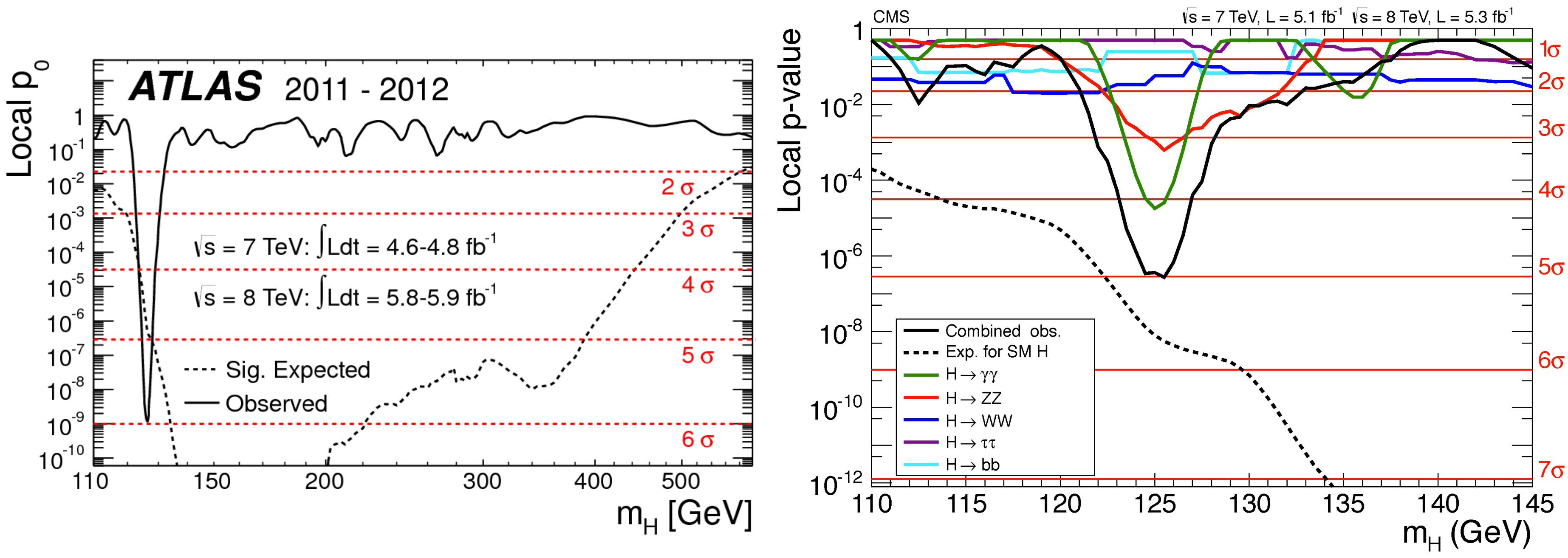
Combination I





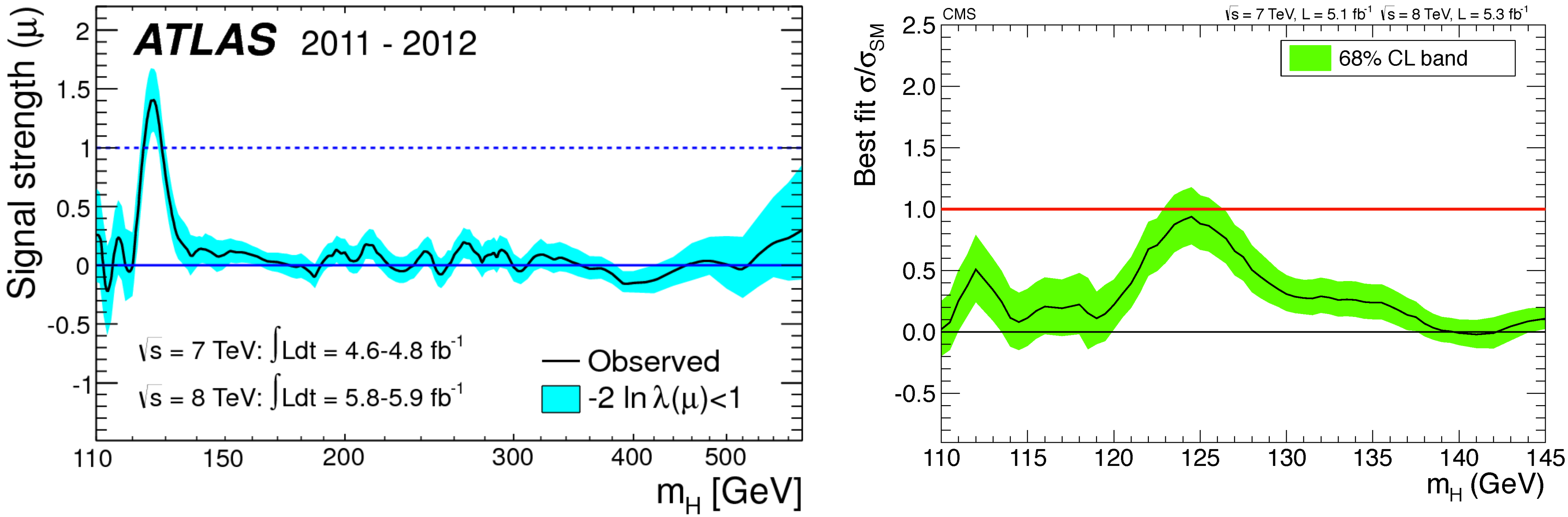
The full range up to 500+ GeV is excluded by ATLAS and CMS, except for the window near 125 GeV.

Combination II



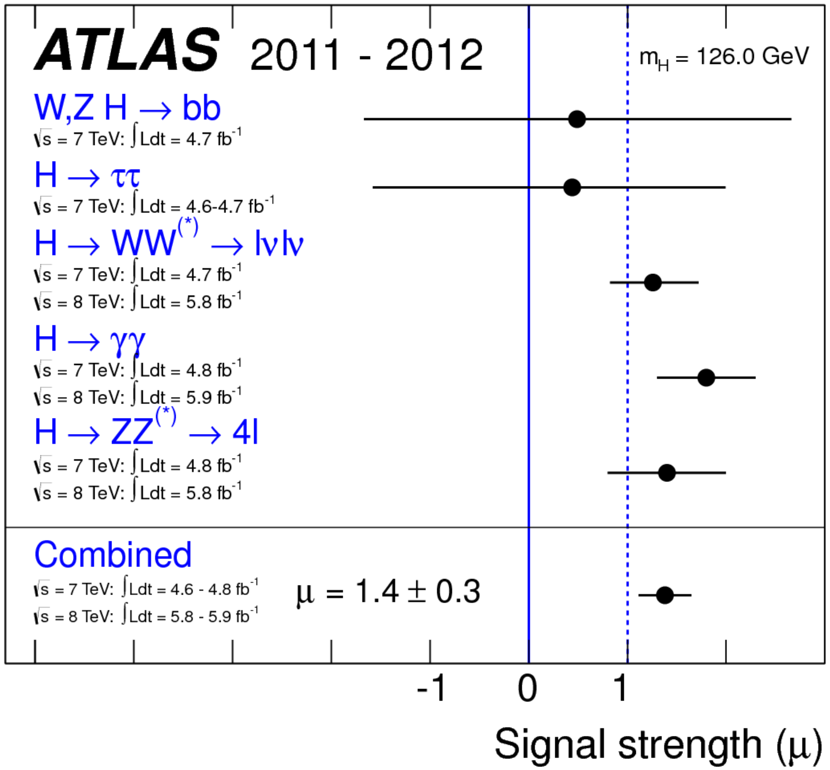
Both experiments show at least a 5σ excess near 125 GeV. In the full mass range reported by ATLAS there are no other statistically significant excesses.

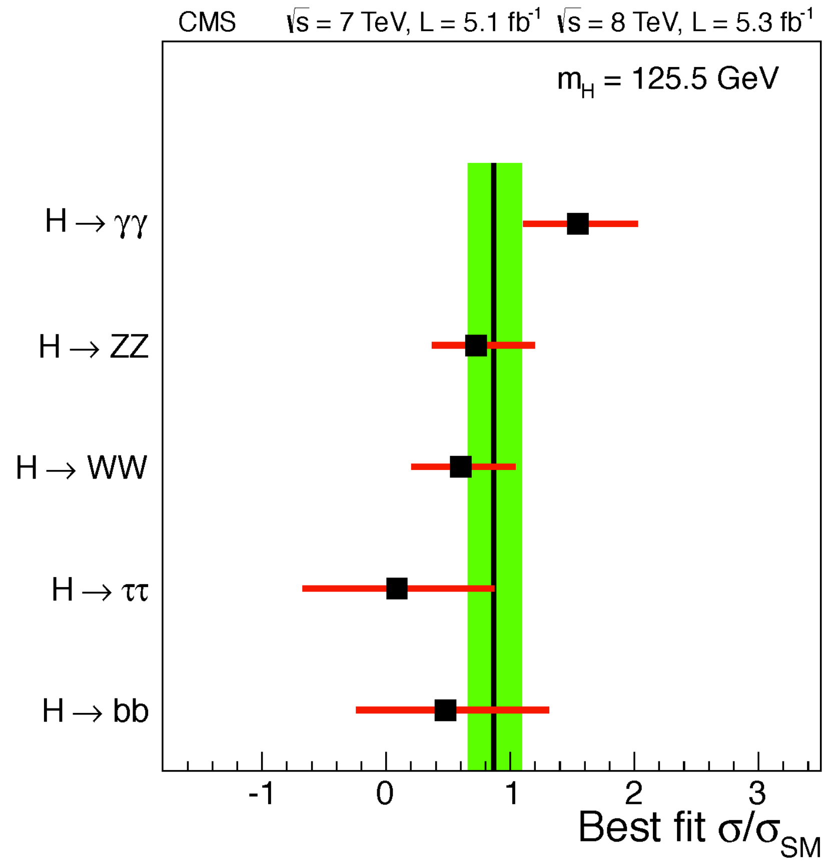
Combination III



Both experiments show a best fit production rate consistent with each other and consistent with a Standard Model Higgs.

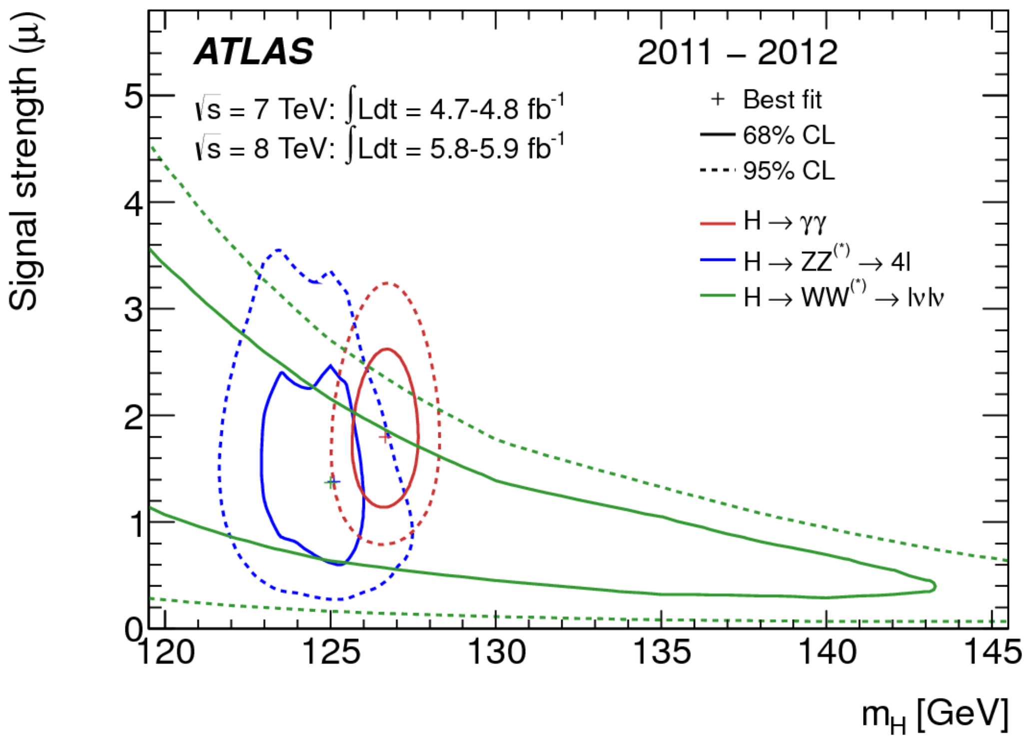
Combination IV

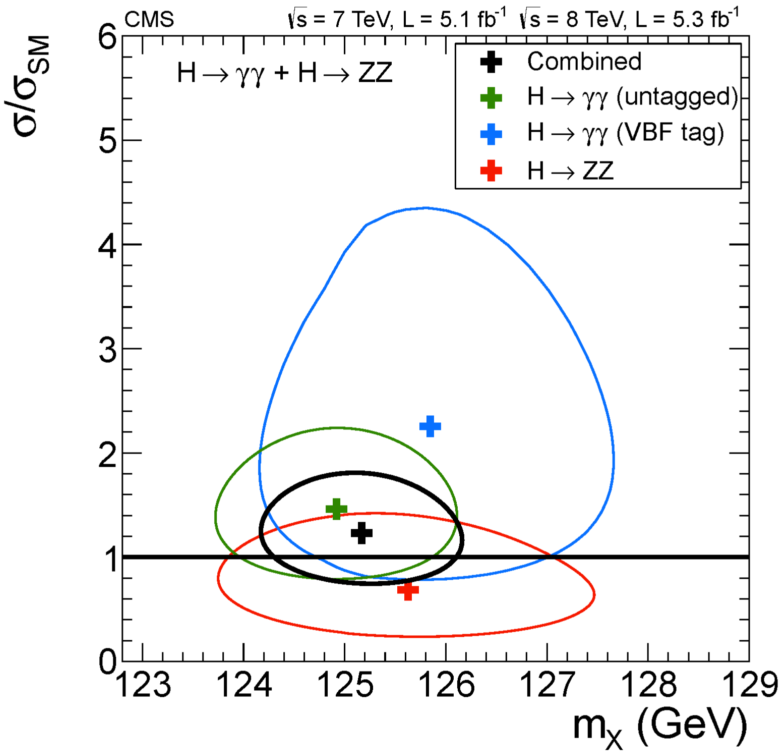




Production rates in every channel are consistent within uncertainties. Where we expect to see a signal, we see it.

Combination V





Production rates and masses in every channel are consistent within uncertainties.

ATLAS quotes a mass of 126.0 ± 0.4 ± 0.4 GeV
CMS quotes a mass of 125.3 ± 0.4 ± 0.5 GeV

Combinations of Combinations

	2011	2012
ATLAS	2.9σ	4.7σ
CMS	3.1σ	3.3σ

These are local significances; the 2012 is calculated (by me) from the 2011+2012 papers and the 2011 papers. This is approximate (but close).

- What is the combined local significance?
  - About 7.5σ (one in a half-quadrillion or so)
- How does this change with the Look Elsewhere Effect?
  - Using the same trials factor (about 80), this becomes about 7.3σ
  - Using three of the four independent data sets (and the fourth to select the search region) this varies between 6.0 and 7.1σ. Six sigma is one in a billion.

This is not a statistical fluctuation. It may turn out to be a mistake (but I doubt it), but it is surely not a fluctuation.

Is It A New Boson?

- It must be a boson – it's undergoing a two-body decay to two spin-1 objects.
  - Making it a fermion requires a three-body decay.
- Ah, but is it the Higgs boson?
  - That's tomorrow's talk.

Summary

- A new boson is observed by both ATLAS and CMS, with independent ~5+ σ significance.
  - It's seen convincingly in 2 channels, and in both the 7 TeV and 8 TeV datasets.
  - Other channels provide weaker support, but do not contradict this.

- Its mass is somewhere between 125 and 126.5 GeV
  - An interesting number: too light to be heavy, and too heavy to be light

- This boson's properties match the SM Higgs Boson to within our ability to measure
  - In particular, it couples strongly to the electroweak boson sector

- More on this tomorrow…