Higgs boson searches at ATLAS

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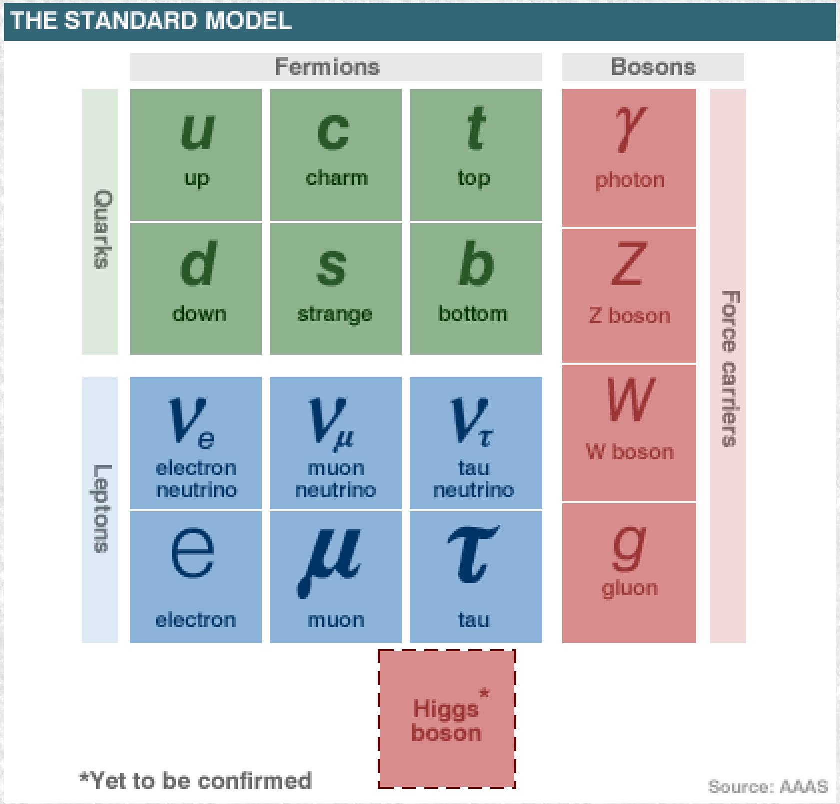
- **The discovery**
- **What do we know so far?**
- **Outlook**

The Standard Model

- The 'Standard Model' has been remarkable successful
  - 3 forces
  - 2→3 families of quarks/leptons
- But the Higgs sector remained unknown...until now
- A Higgs-like boson has been discovered
  - What do we know?
  - What more can we learn?
- Is it alone?



Gauge Symmetries

- This is the symmetry set of the Standard Model
- The symmetries define the structure of the model

$$SU(3) \times SU(2) \times U(1)$$

Forces from Symmetry

Force	Particle	Mass
Electromagnetism	Photon, γ	0
Strong Nuclear force	Gluon, g	0
Weak Nuclear force	W and Z particles	81GeV, 90GeV

The problem is, Gauge symmetry bives massless vector bosons

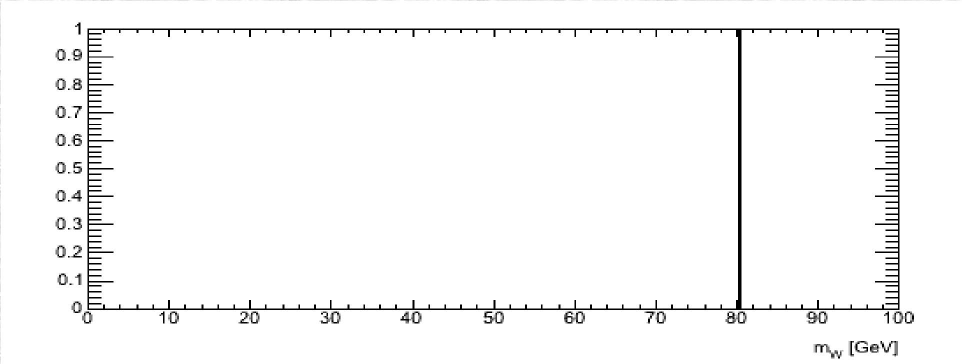
Not true for W, Z!

Are we really on the right lines here at all?

The Higgs model

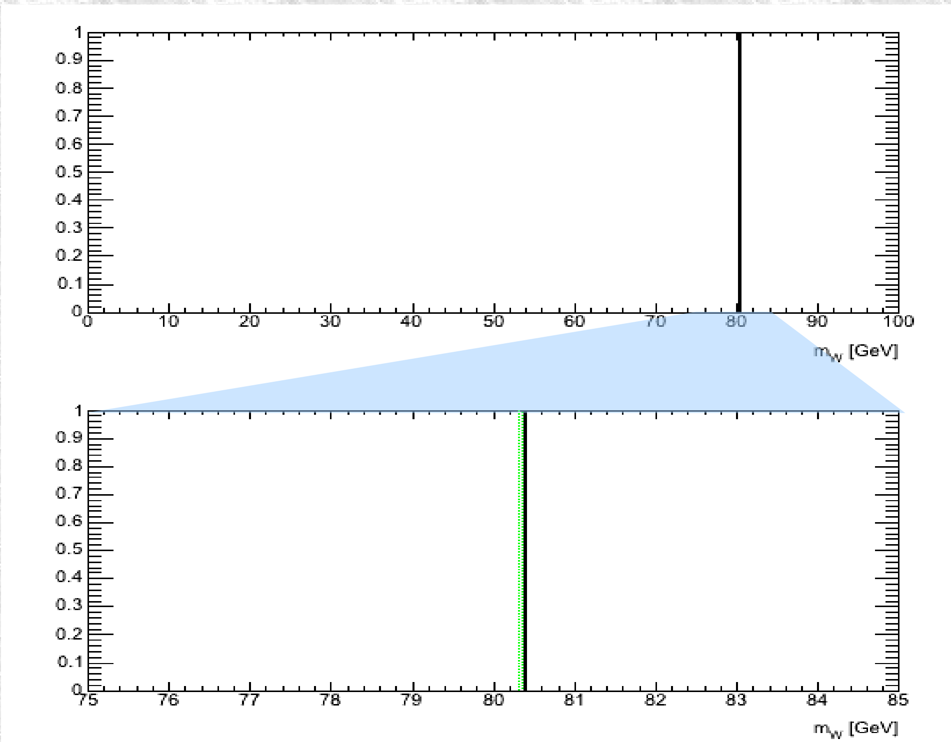
- Mass is an interaction with a field filling the vacuum
  - We cannot escape from it
- The W and Z bosons are intimately linked to it
  - The W mass can be predicted from other forces and masses
  - Allows a test of the model
- The mass for the quarks and leptons can be *described*
  - But each quark or lepton mass is added 'by hand'
  - It makes no predictions here – and is easily changed
- But to make it work there must be a new particle
  - The Higgs boson
  - Everything about this is predicted – except its mass
    - It is spinless
    - It decays almost immediately
    - To things with a probability proportional to m^2
    - Its rate of production is predicted

The W mass



- Green band is SM prediction
  - Its width comes from the (unknown) Higgs mass
  - 115 to 600 GeV shown
- Yellow+black band is the measured mass
- They match incredibly
  - Many theories failed this test

The W mass



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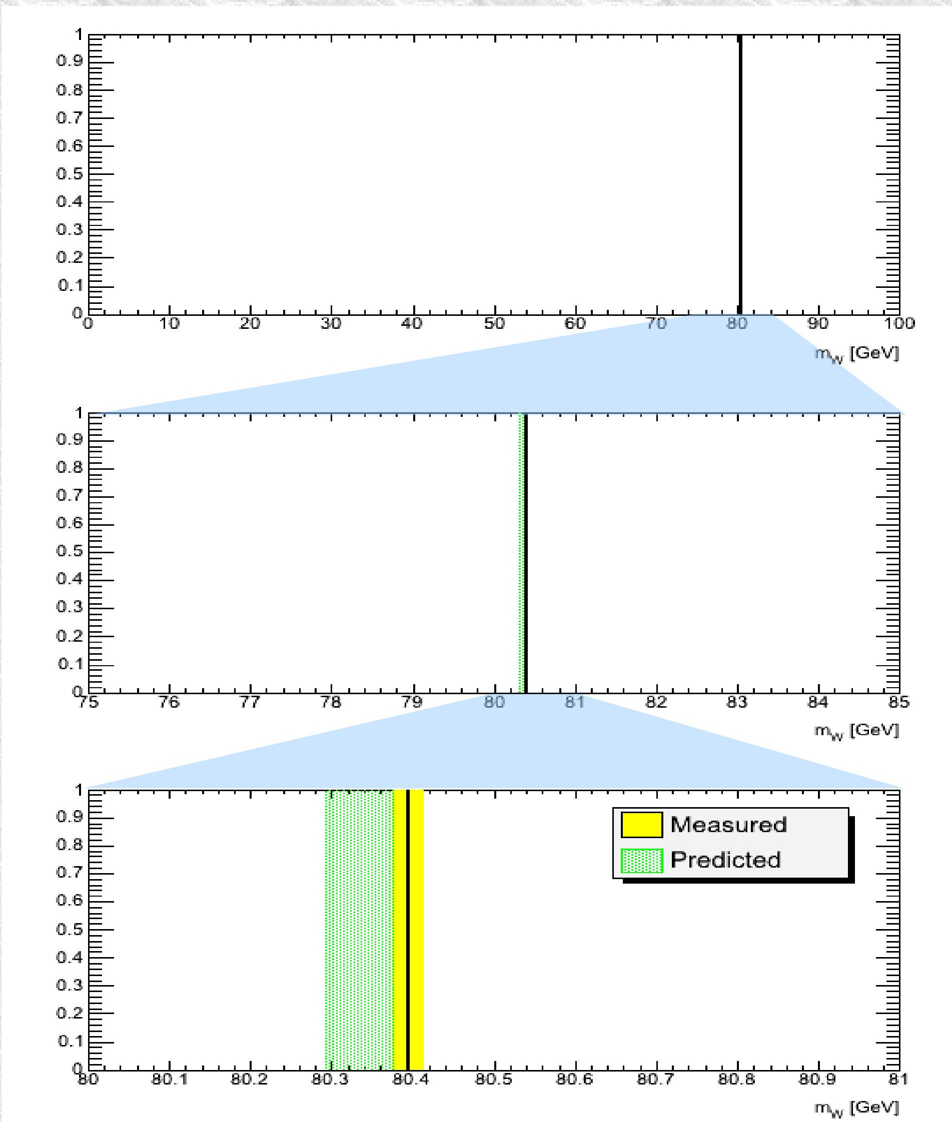
The W mass



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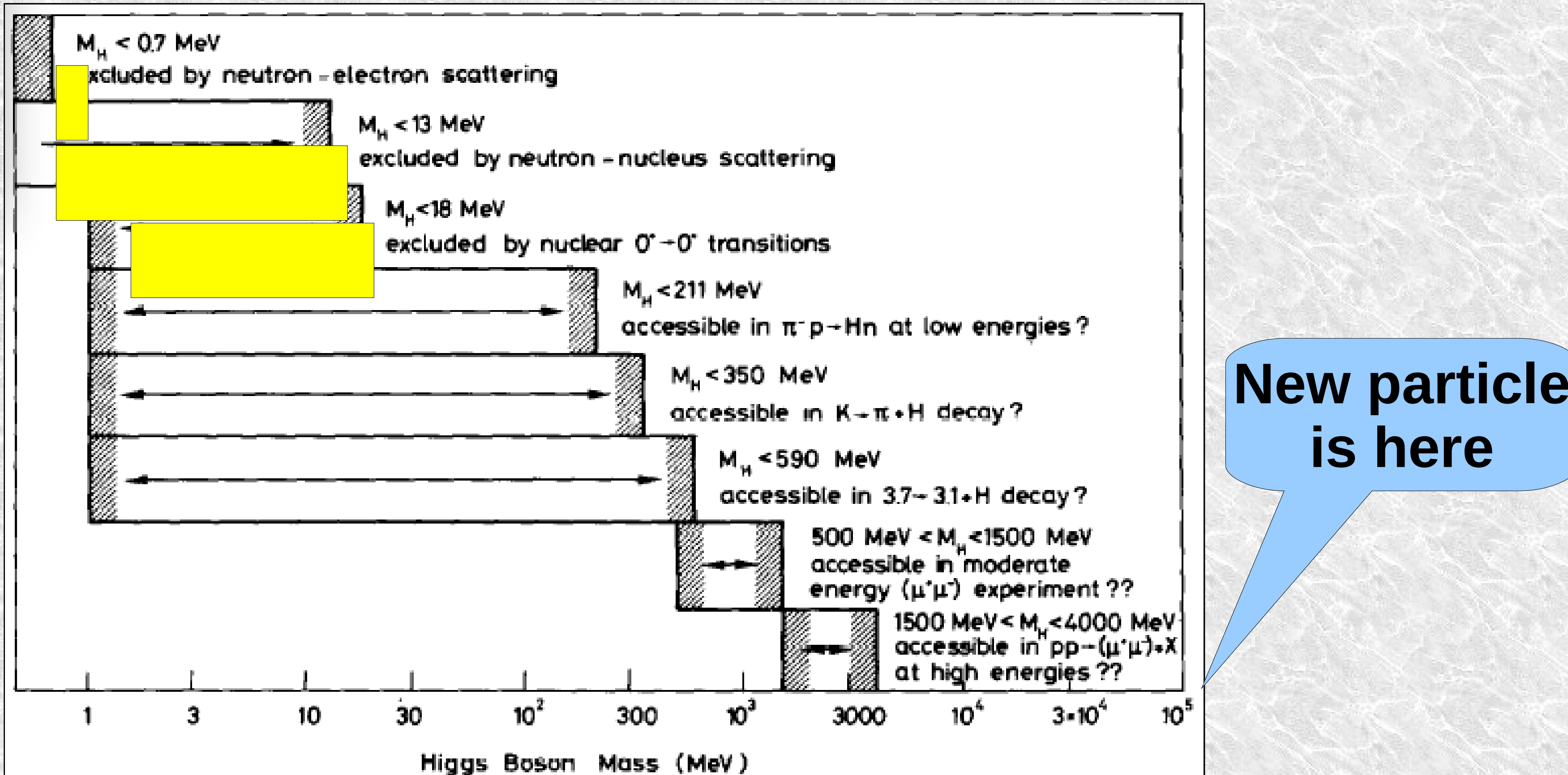
  - Its width comes from the (unknown) Higgs mass
  - 115 to 600 GeV shown
- Yellow+black band is the measured mass
- They match incredibly
  - Many theories failed this test
  - But only works at the right edge of the band
    - A light Higgs, near 115GeV
- Nb. This calculation assumes no unknowns
  - Could be badly wrong

View from 1975

Nucl. Phys. B 106 (1976) 292.

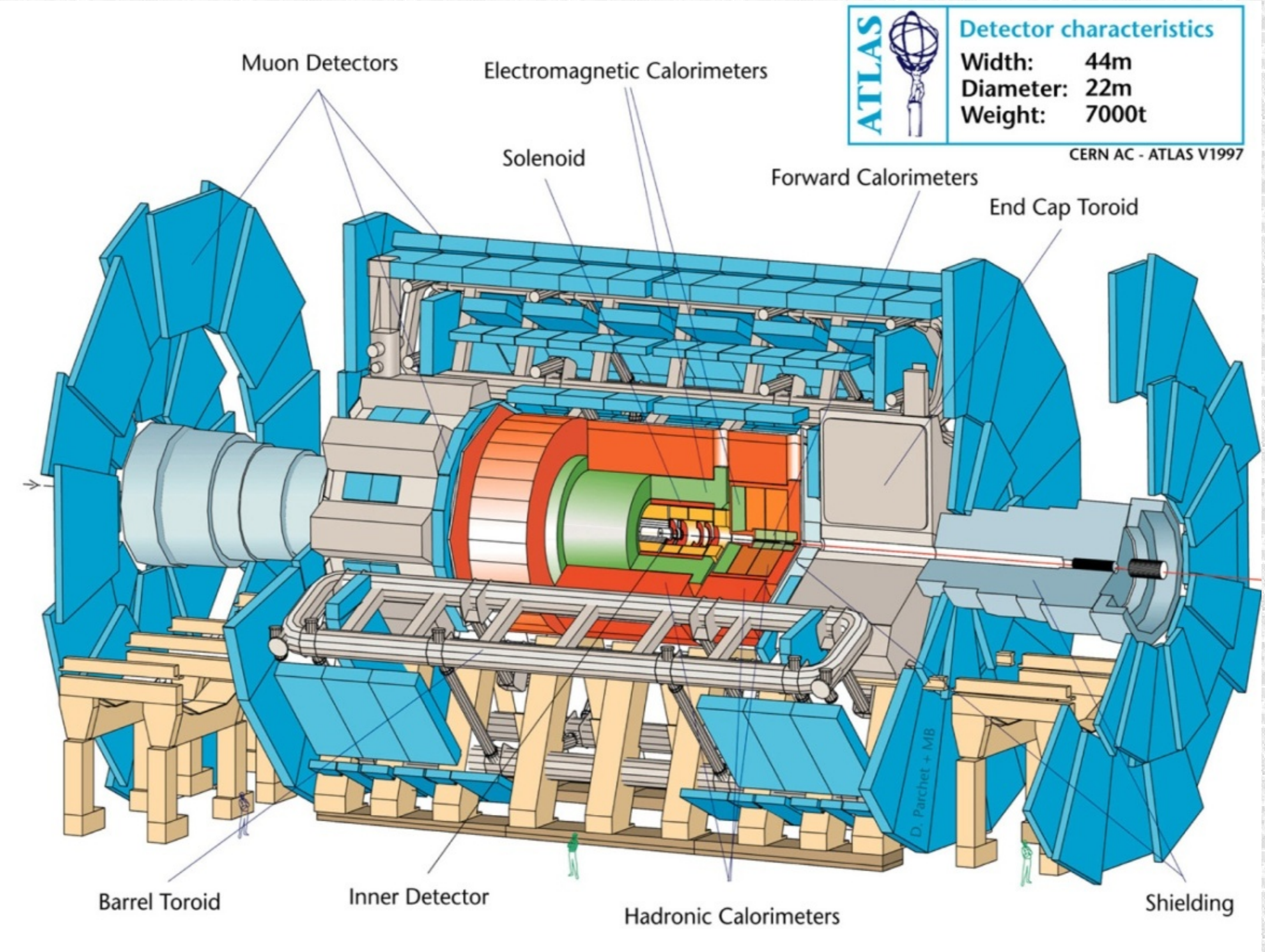


We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

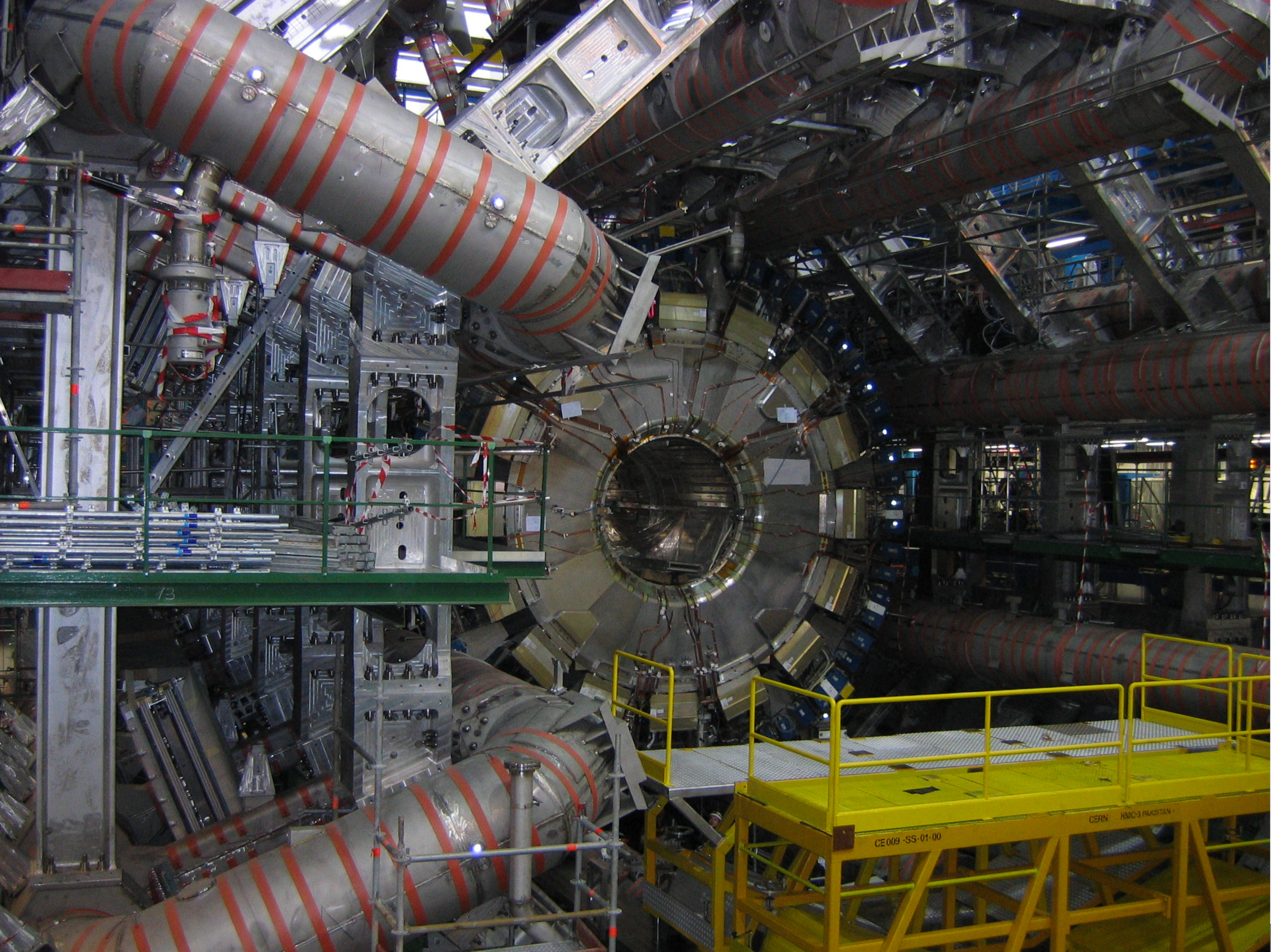
History of the search

- 1964 Brout & Englert, Higgs, Gouralnik, Hagen & Kibble,
  - Not taken too seriously until...
- 1967 Used in the formulation of the 'Standard Model'
  - Proven to be self-consistent in 1971
- 1973 Experimental acceptance of the 'Standard Model'
- 1983 Discovery of W and Z bosons
  - Closely linked to the Higgs boson
- 1993 LEP studies Z's and rules out m_H<53 GeV
  - And indirectly disfavours m_H>300GeV
- 2000 LEP limits reach 114.4 GeV (and EW fit <~170)
  - Hint of production at 115?
- 2011 LHC excludes 130-550GeV, Tevatron 156-175
  - Some indications for a particle at 125?
- 4th July 2012 New particle found at 126GeV
  - Consistent with the Higgs

ATLAS



- Detector emphasis: robust lepton and jet measurement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Hunting the Higgs Boson

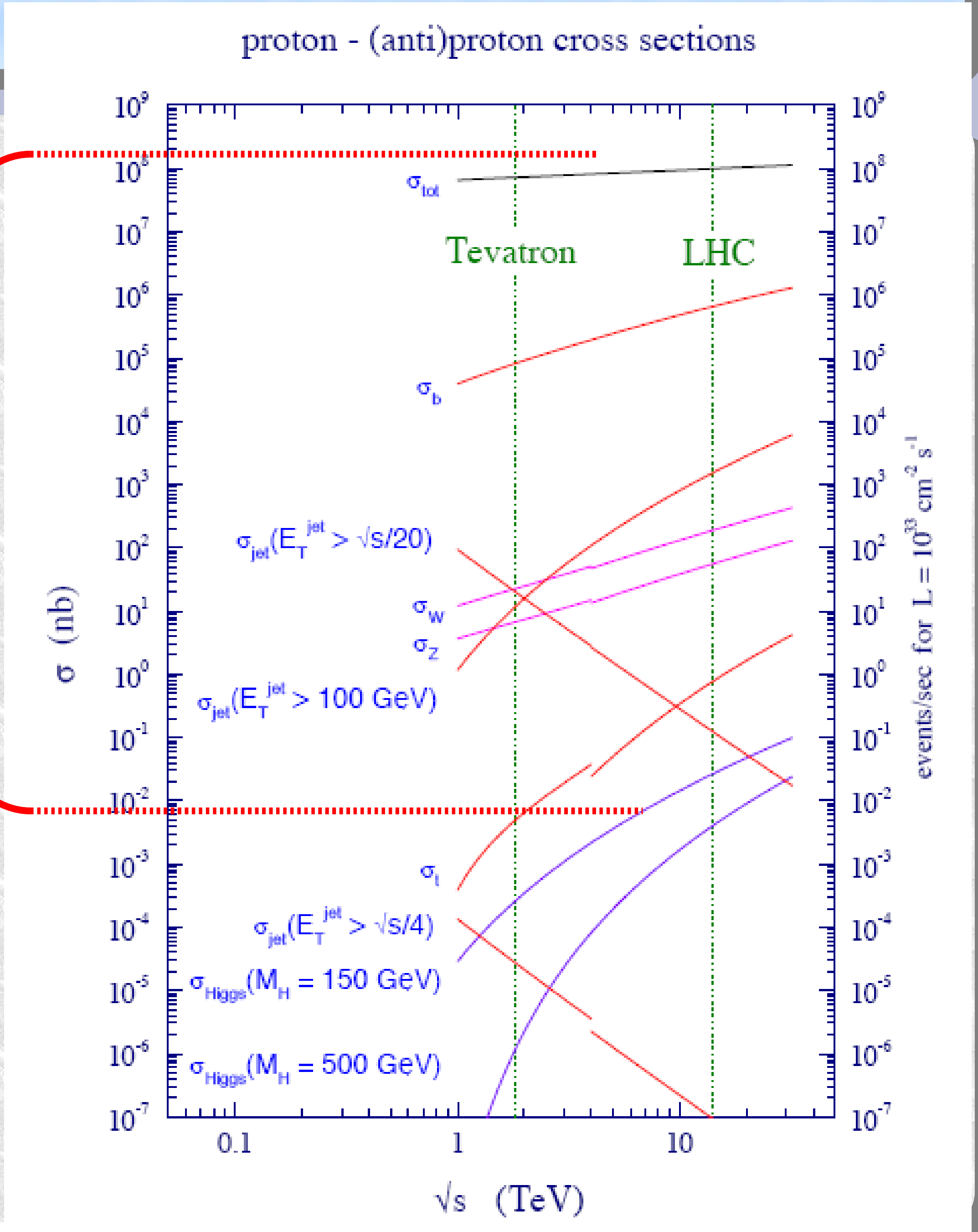
Never forget background

- LHC backgrounds!

10^{10}

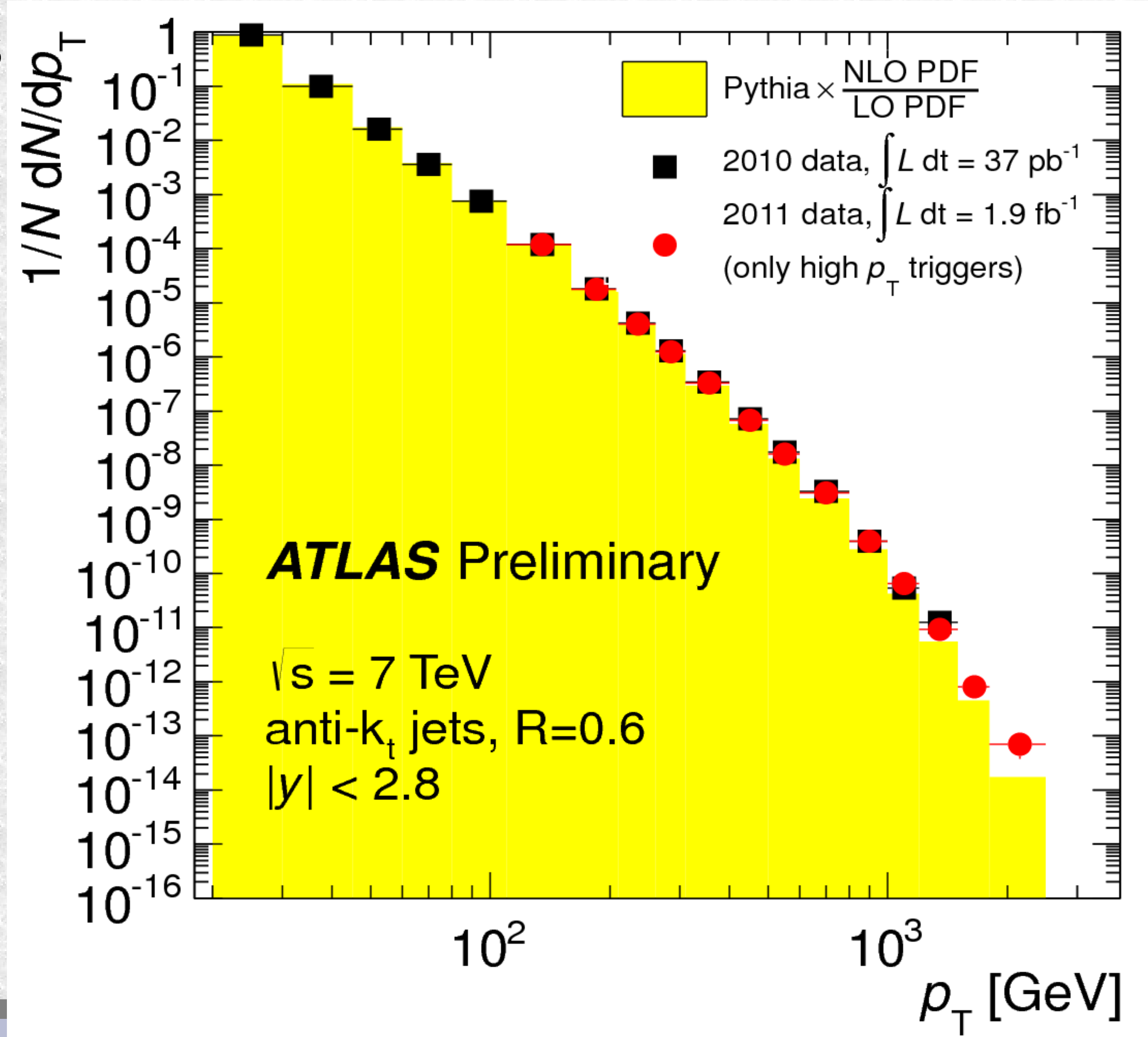
Every event at a lepton collider is physics; every event at a hadron collider is background

Sam Ting

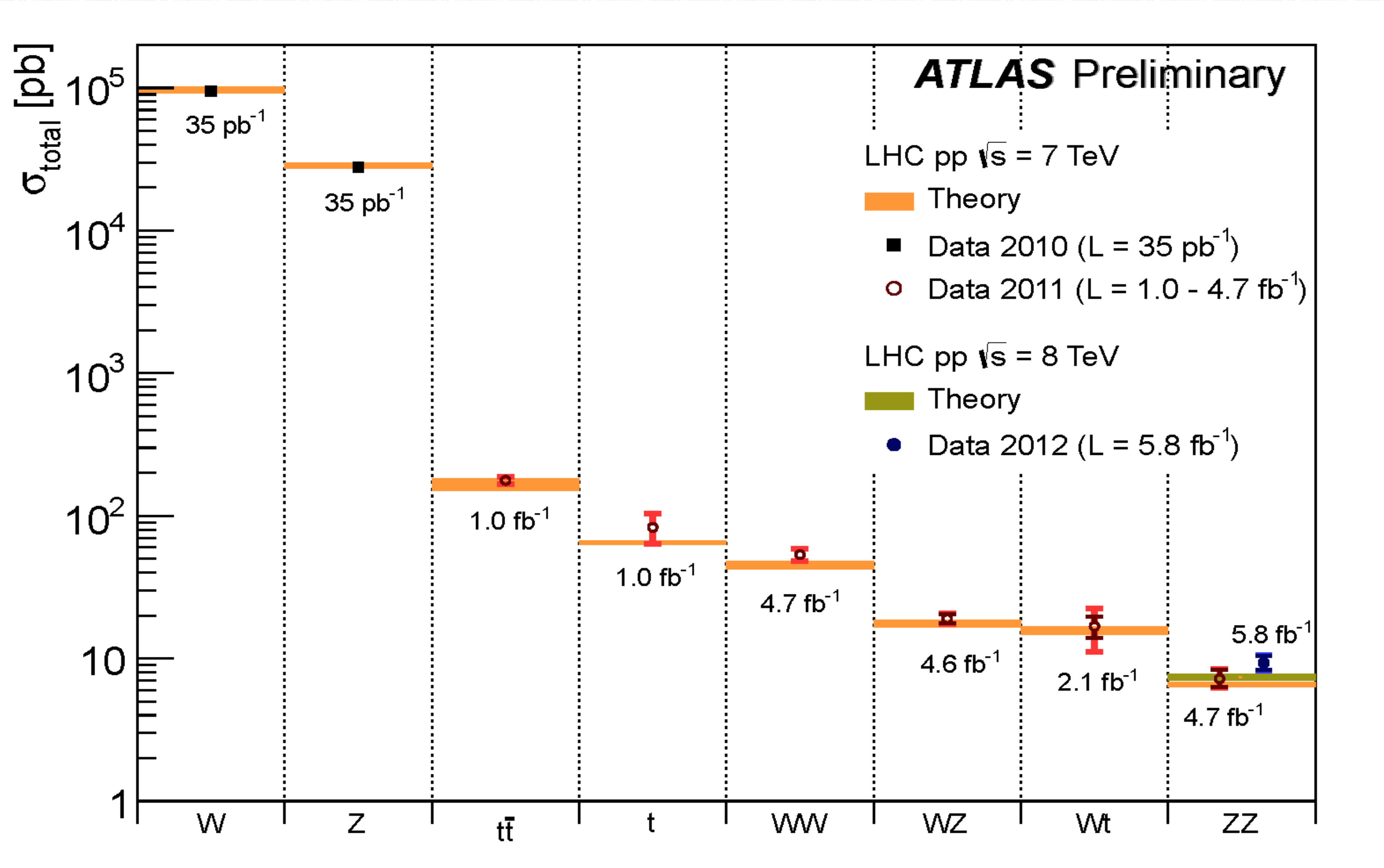


Detailed studies, huge samples

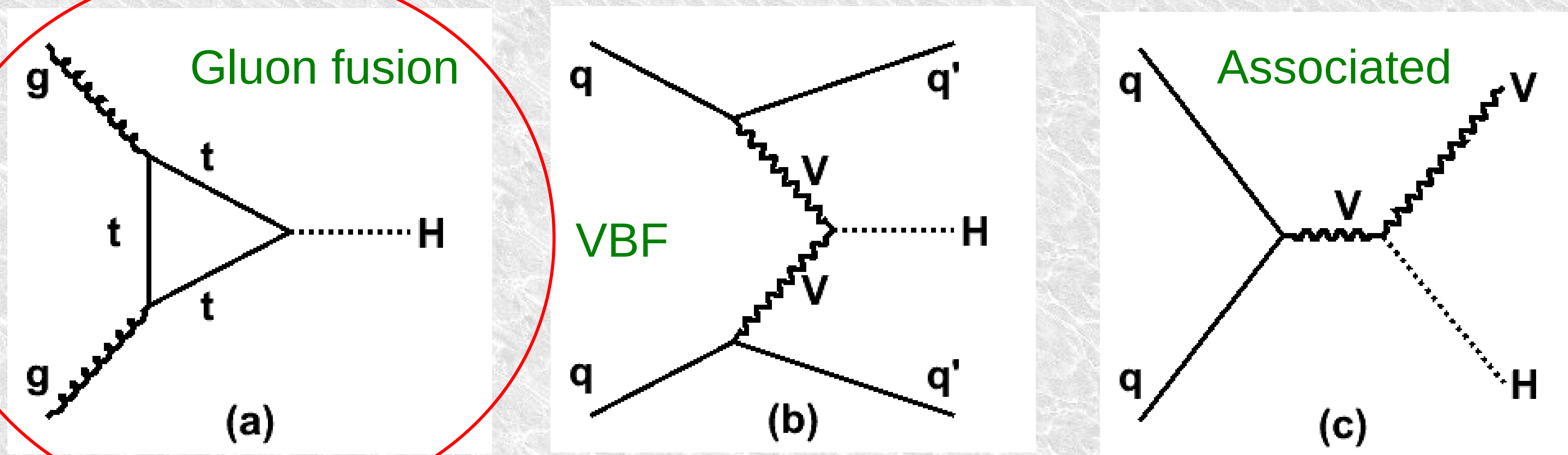
- The rate of jets as a function of p_T
- 20-2000GeV tested
- Rate falls off by thirteen orders of magnitude
- We need to understand the common process extremely well



W/Z/top measurements



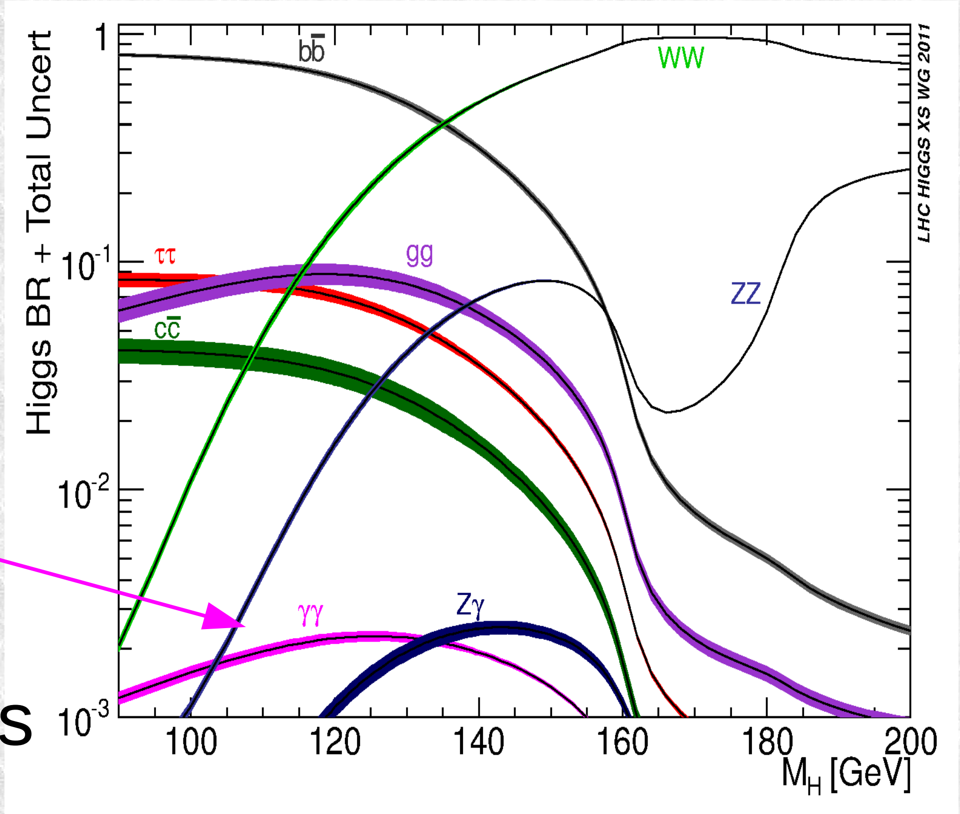
Higgs production



- The three most common modes
  - Others also exist: $t\bar{t}H$, tH , bbH...
- Gluon fusion dominated the discovery
  - The loop allows not only virtual top quarks in principle
- Vector boson fusion and associated also used
  - Can be used to tag process
  - Improves the purity

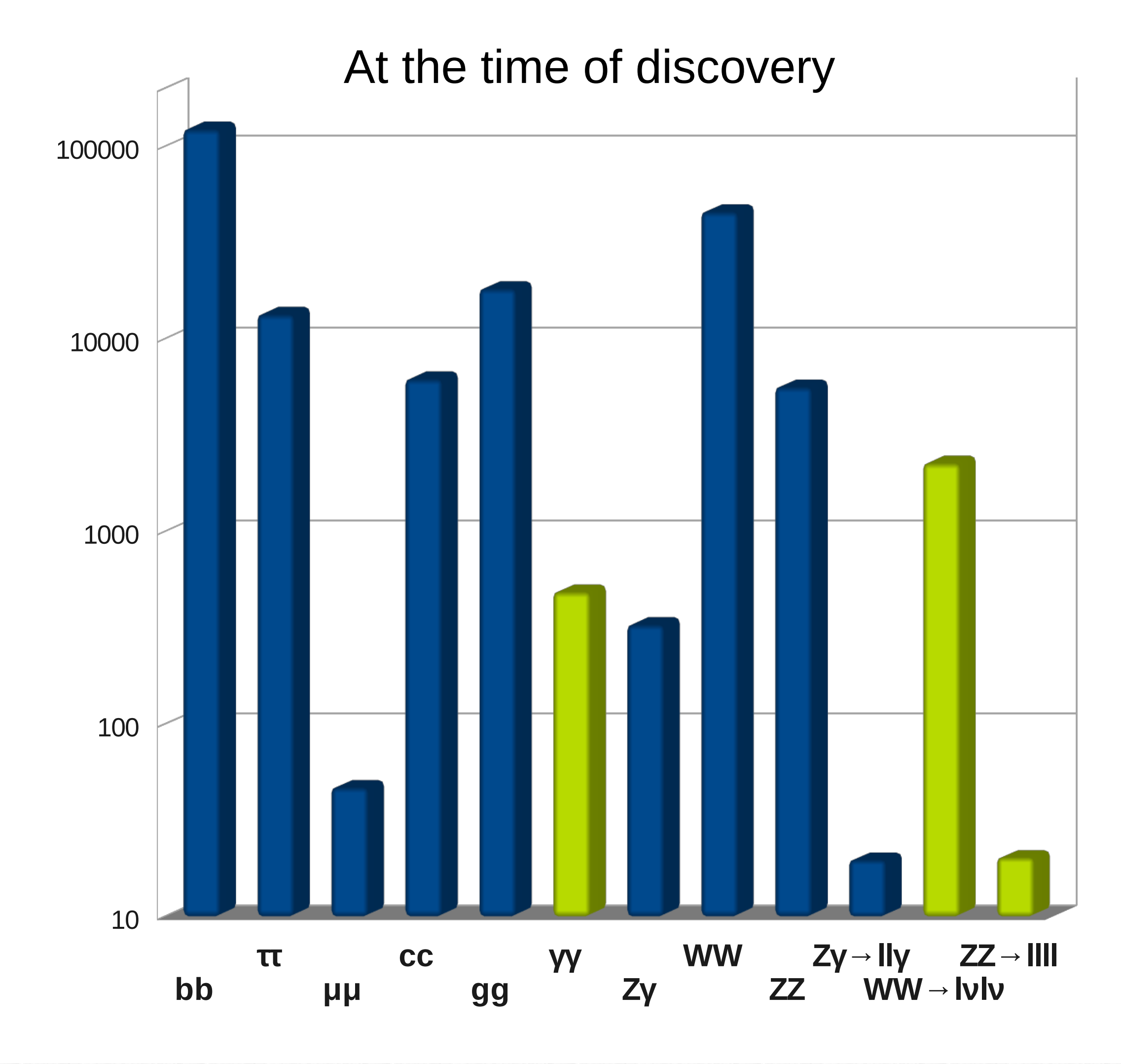
Higgs decay modes used

- H → ZZ
  - ZZ → llll: Golden mode
  - ZZ → llνν: Good High mass
  - ZZ → llbb: Also high-mass
- H → WW
  - WW → lνlν: Most sensitive
  - WW → lνqq: highest rate
- H → γγ
  - Rare, best for low mass
- H → ττ
  - Uses VBF, boost; low mass
- H → bb
  - $t\bar{t}H$, WH, ZH useful but hard



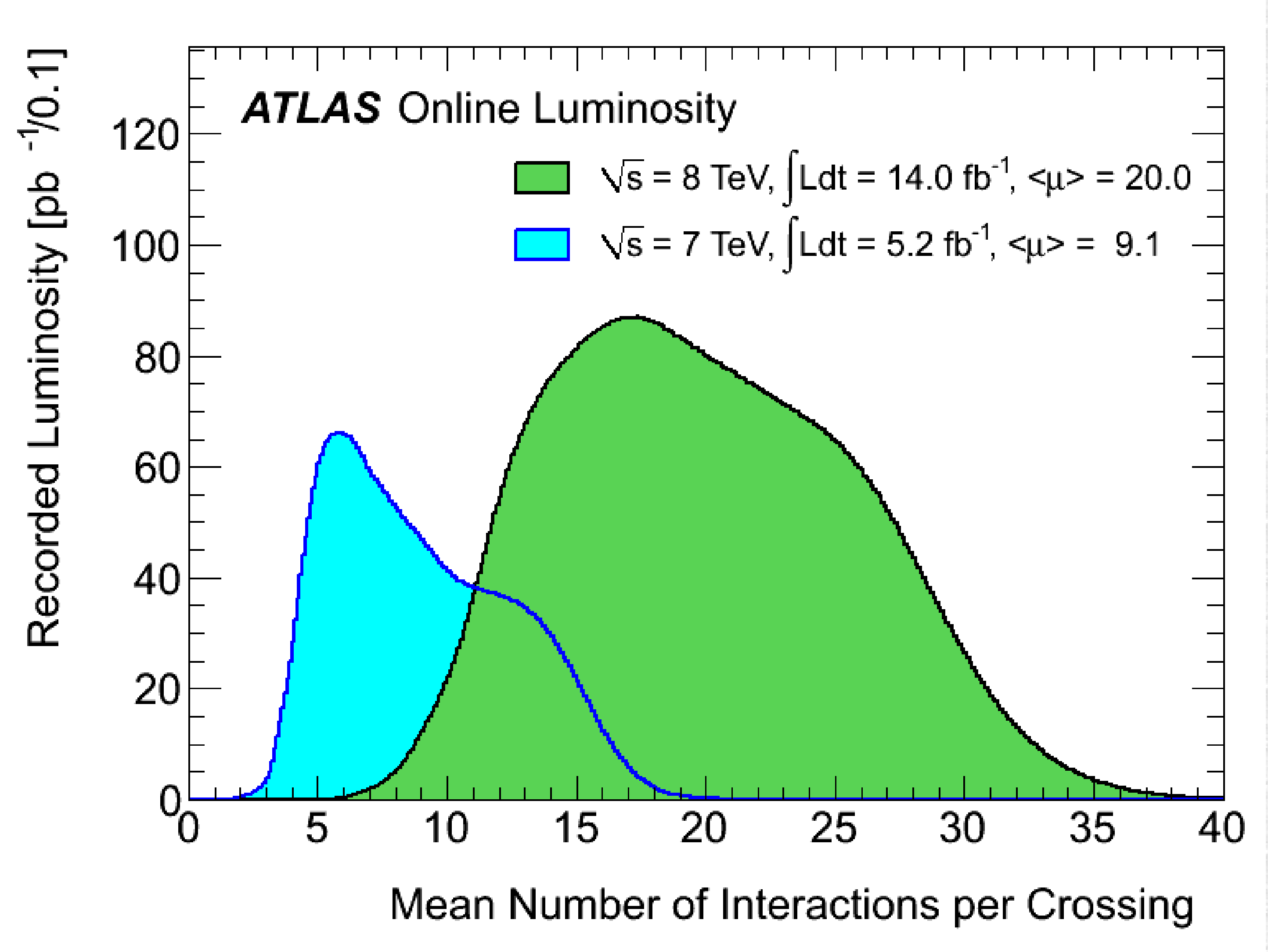
Rates by channel at 125GeV

- Data to June 2012
- From 10s to 100000 events per channel
  - Easy!
- But total pp events: 8×10^{14}
- 20 Higgs to llll events
- Needs incredible background rejection
  - The green channels end up the most sensitive



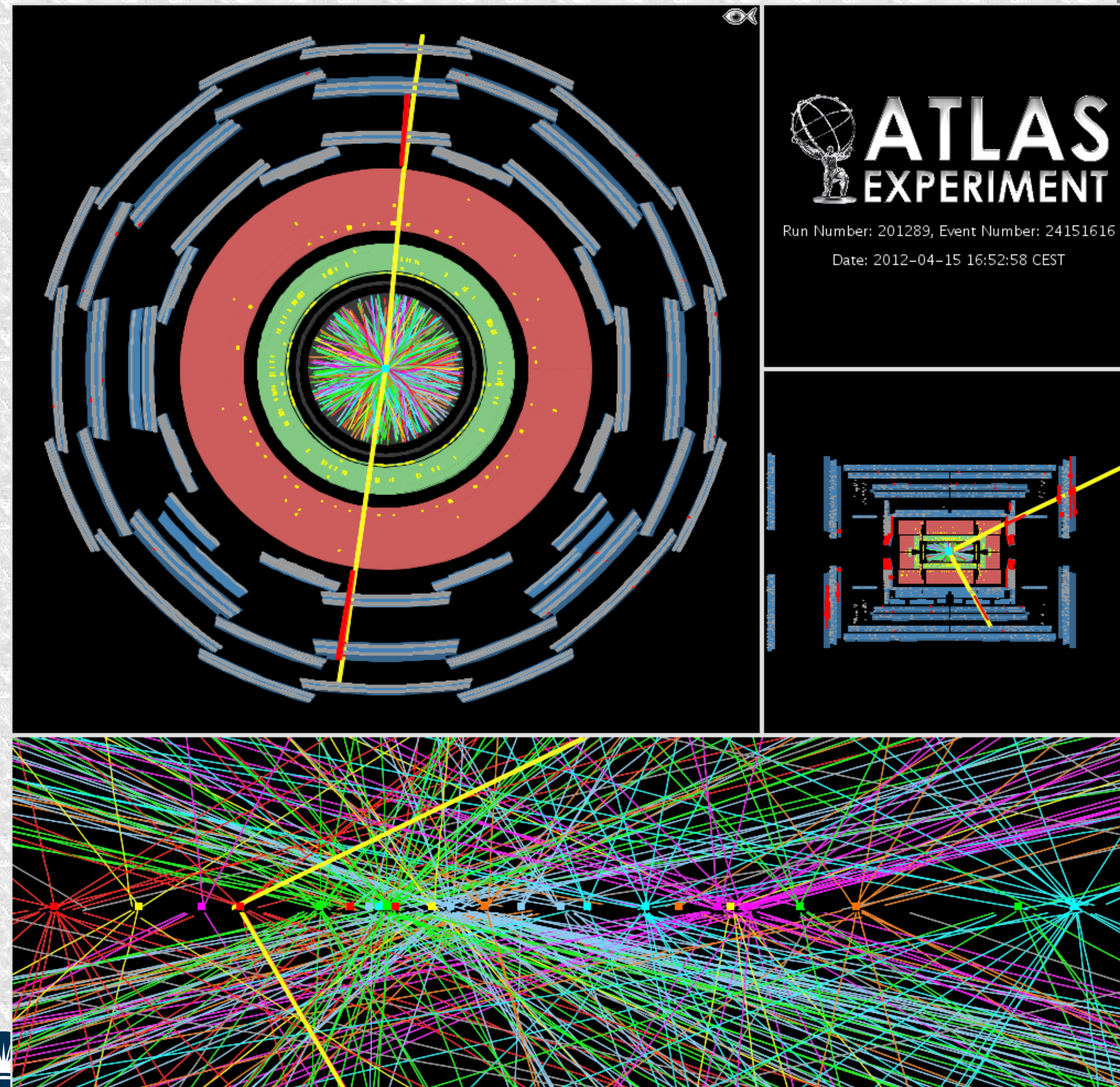
Pileup passing design

- In 2011 9 collisions per bunch crossing
- Changed to 20 in 2012
  - Peak 35+
  - Design: 23
- That is how LHC increased the data rate....
  - So we learn to cope



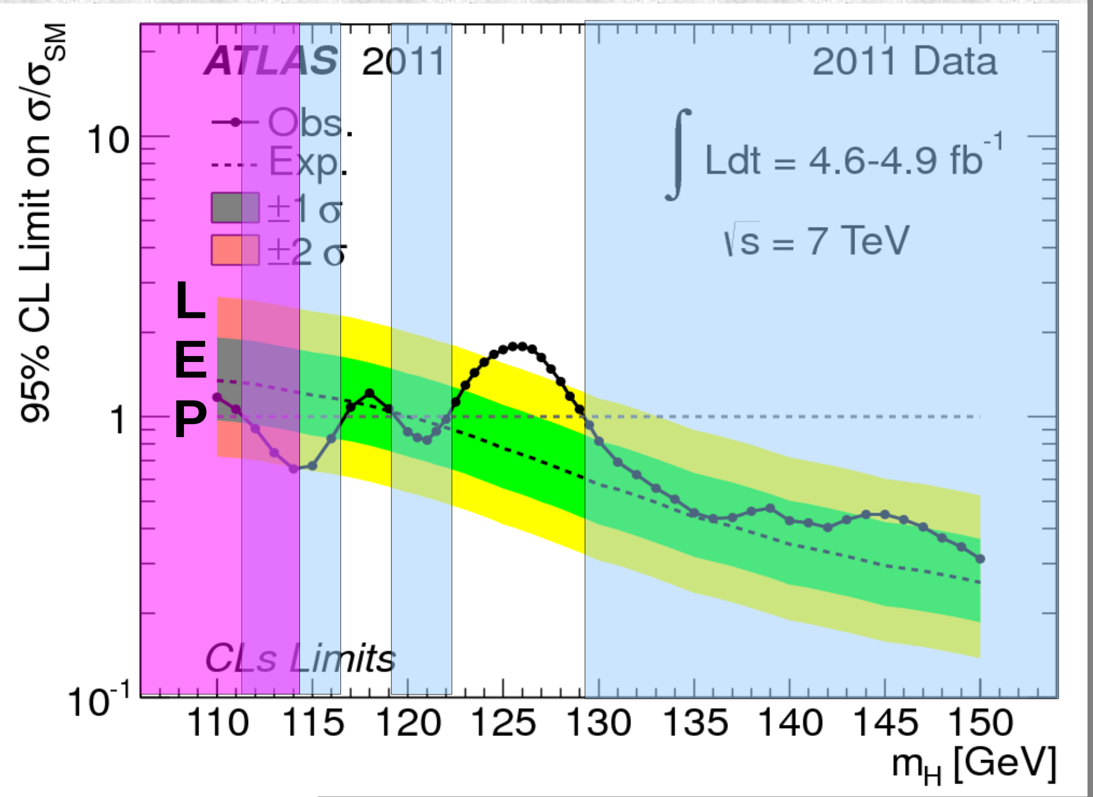
Pileup in 2012

- Example: $Z \rightarrow \mu\mu$
- Has multiple overlayed interactions
  - 25 seen here
- Tracker can distinguish them by position
- Calorimetry suffers
  - Degrades isolation
  - E_t^{Miss}
- We are finding solutions



So what do 2012 data say?

- Papers submitted 31st July by CMS and ATLAS
  - Both claiming observation of a new particle
- Focus on region 117-129GeV left from 2011
- ATLAS paper in July only 3 strongest channels:
  - γγ 4.8@7TeV+5.9@8TeV
  - ZZ 4.8@7TeV+5.8@8TeV
  - WW 4.8@7TeV+5.8@8TeV
- Intermediate
  - ttH, H→bb 4.8@7TeV
- For HCP, November 14th
  - Vbb 4.8@7TeV+13@8TeV
  - ττ 4.8@7TeV+13@8TeV
  - WW 13@8TeV
  - ZZ to llqq 4.8@7TeV



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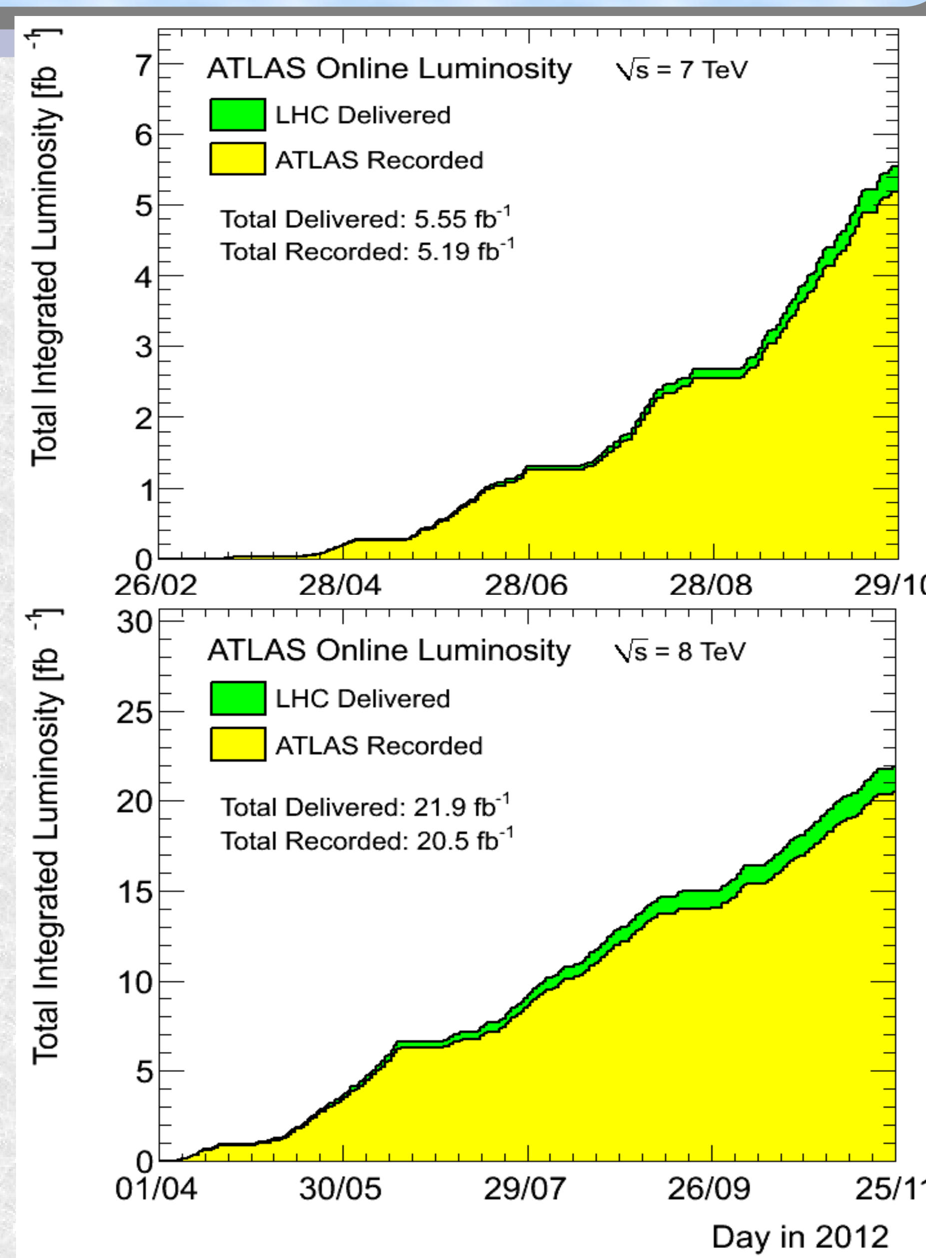
Data collection

- LHC delivered $5fb^{-1}$ in 2011
  - Gave first hints for SM Higgs
- $\sqrt{s}$ raised 7→8TeV in 2012
- $\int Ldt$ 4x 2011
  - 6 fb^{-1} allowed Higgs discovery
- Great effort by LHC team!
- Only a few more days of pp collisions left to Christmas



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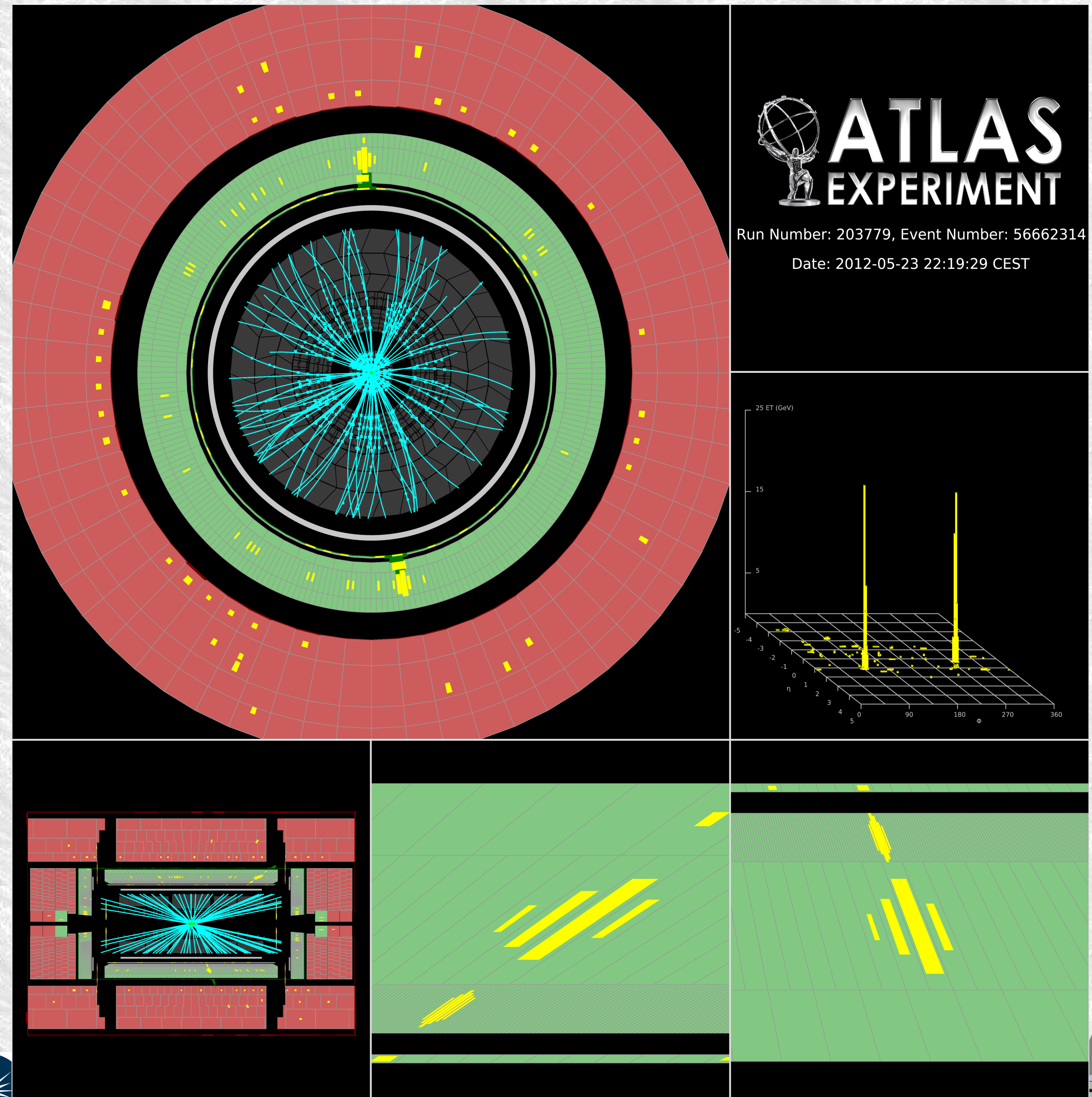
Trigger strategies 2012

Single muon	p_T>24GeV	llll, lνlν
Single electron	p_T>24GeV	llll, lνlν
Muon pair	p_T > (13,13) GeV	llll
Asymmetric Muon pair	p_T > (18,8) GeV	llll
Electron pair	P_t > (12,12) GeV	llll
Photon pair	P_t > (25,35) GeV	γγ

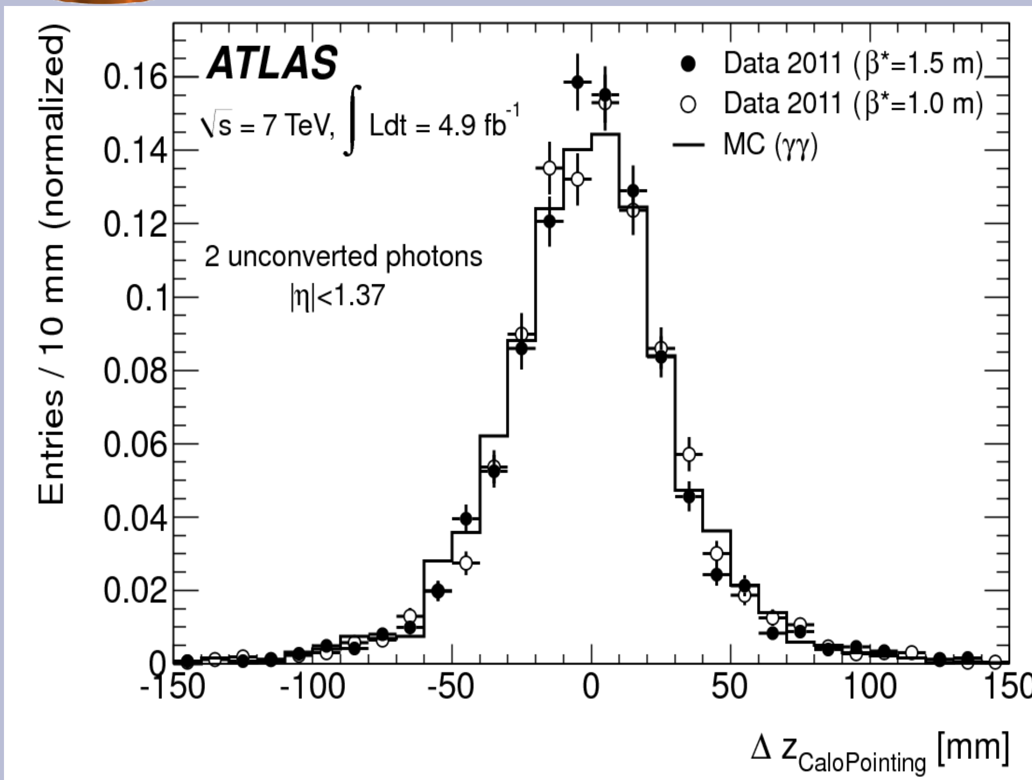
- The llll analysis maximises trigger efficiency
- The WW however emphasizes comprehensibility
- The two-photon efficiency is over 99%
- Triggers for ττ and bb searches more complex

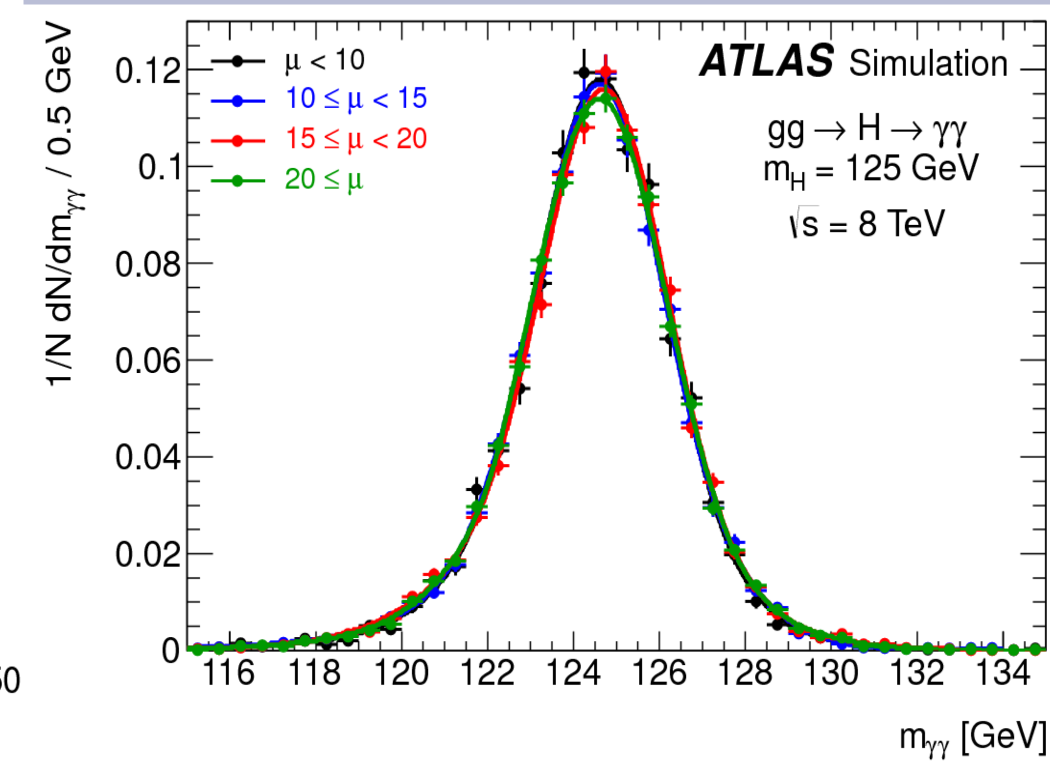
H→γ γ

- Rare decay,
  - 2 per mille
  - $110<m_H<150$
- Drove ECAL design
  - Pointing geometry
- To measure mass need to know vertex position
  - Pileup hurts!
  - But pointing reduces impact
- Good jet rejection also essential



Influence of pileup

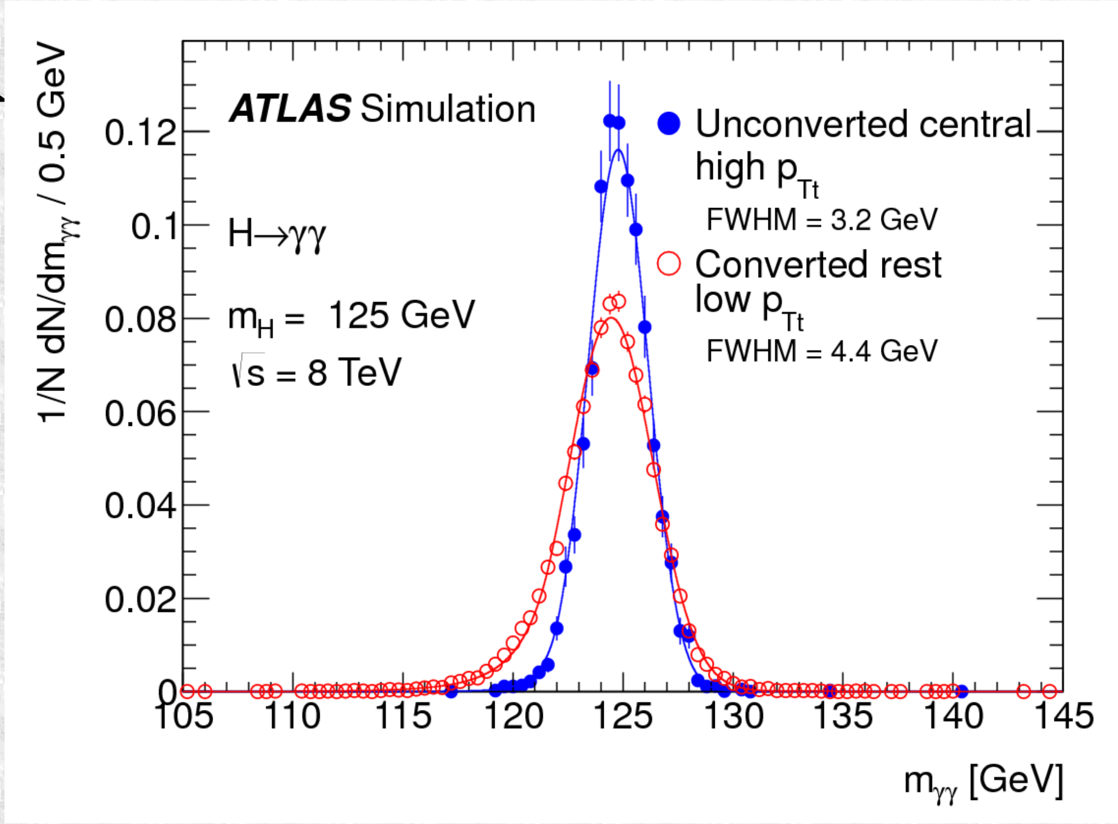




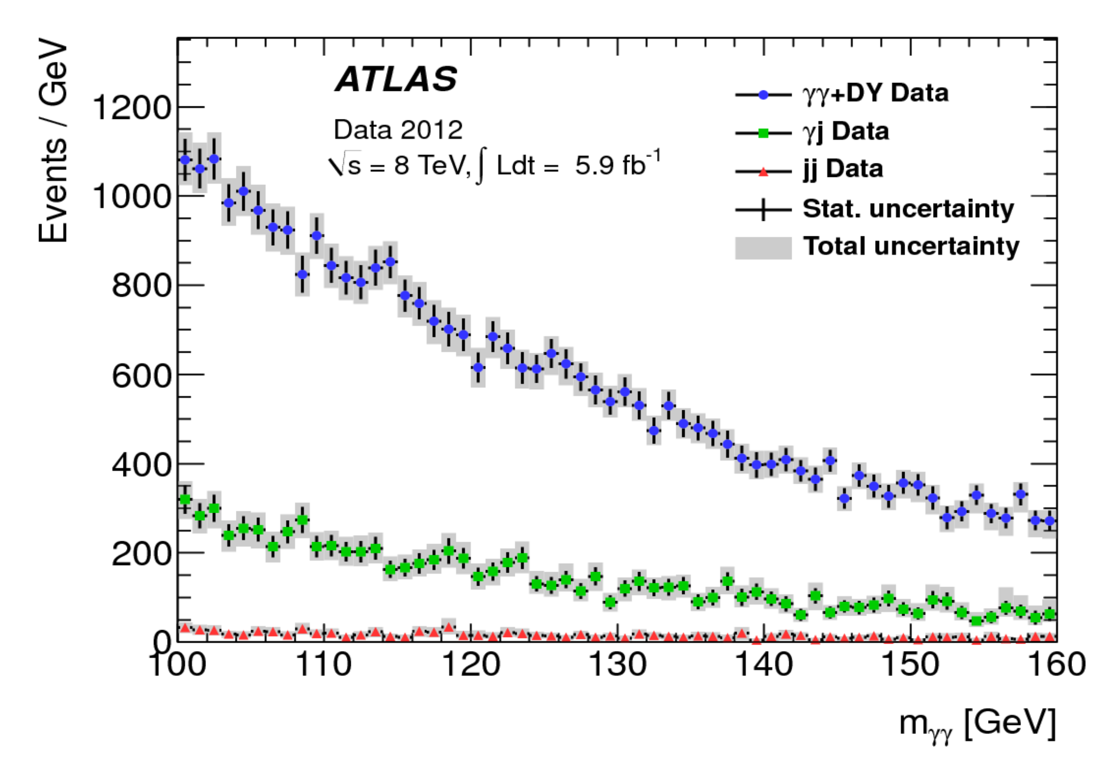
- Extrapolate photon directions to beam position
  - Measure the difference between positions to check resolution
  - Matches simulation, pileup effects small
- Estimated resolution therefore ~μ independent
  - A Likelihood including vertices is used to pick best one
  - But getting it right is normally not crucial

H→γγ mass resolution

- Higgs resolution assesed in classes:
- Understood using Z→ee
  - Z with needs to be unfolded
  - Material effects on e/γ scale taken from MC
- Checked with Z→llγ
  - Statistics limited
  - Will be improved with more data
  - Scale already limits m_H



H → γγ sample makeup

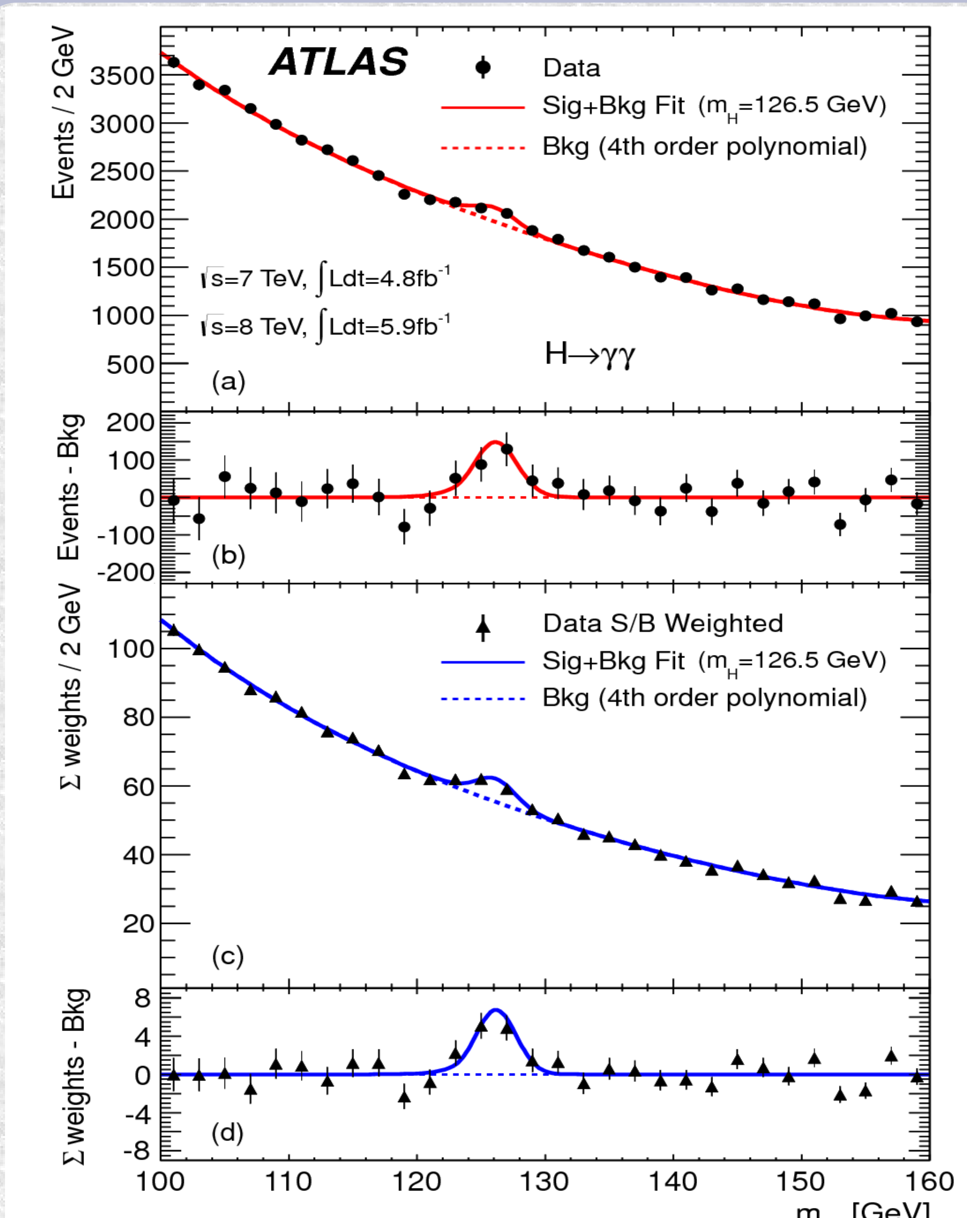


- Measure sample composition in data: γγ, γj or jj?
  - Plus small Drell-Yan
  - Use isolation sidebands
- Samples are dominated by real di-photon.
  - We did reject 99.99% of jets!
  - Little gain from better signal purity

$H \to \gamma\gamma$ analysis method

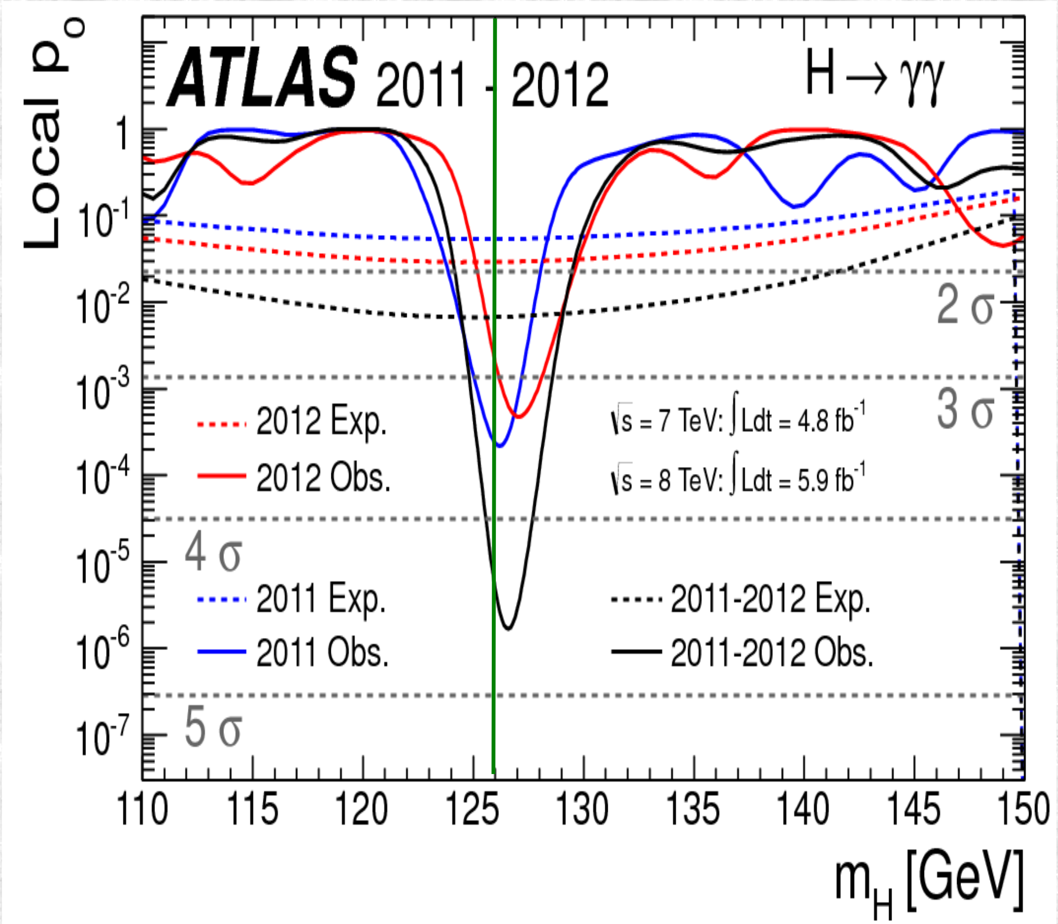
- In principle look at the $m(\gamma\gamma)$ spectrum for a bump
- But signal/background and resolution depend upon other variables
- Split into several categories:
  - p_{Tt},
  - barrel/forward,
  - converted/unconverted
- 2-jet category sensitive to VBF added too
  - 2 jets, p_T>25GeV
    - if $|\eta|$>2.5 require >50% associated track p_T from primary vertex
    - if 2.5<$|\eta|$>4.5 p_T>30GeV
  - $\Delta\eta_{jj}$>2.8
  - m_{jj}>400
- But..20 is too many plots to take in
  - So weight categories and add them up.

H → γγ mass

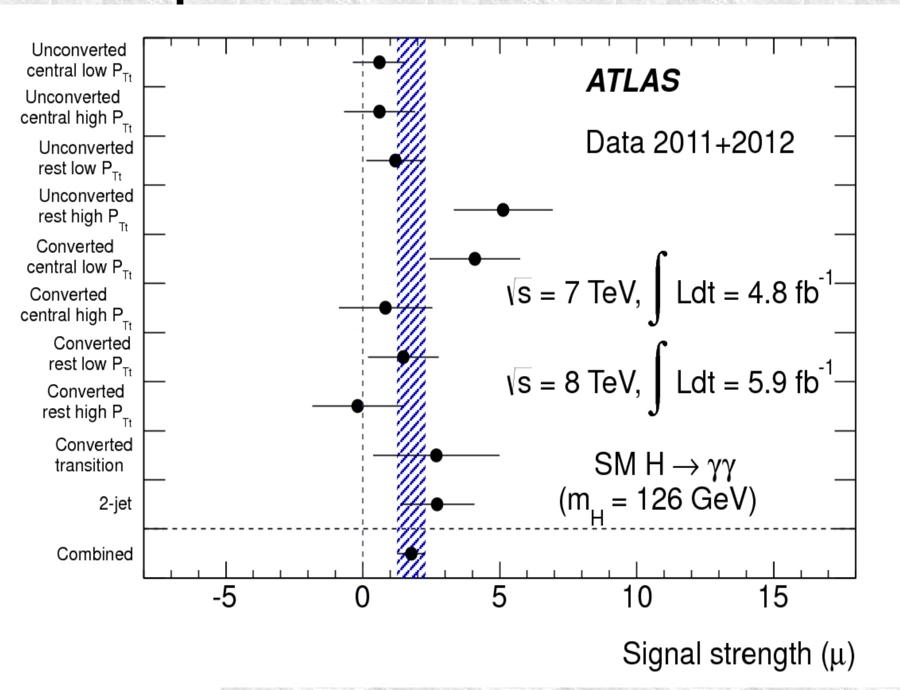


- Simple sum of events (top)
- Weighted by ln(s+b)/b (bottom)
- See significant peaks around 125
  - Weighted sum clearer
  - As it should be if real

Background Compatibility

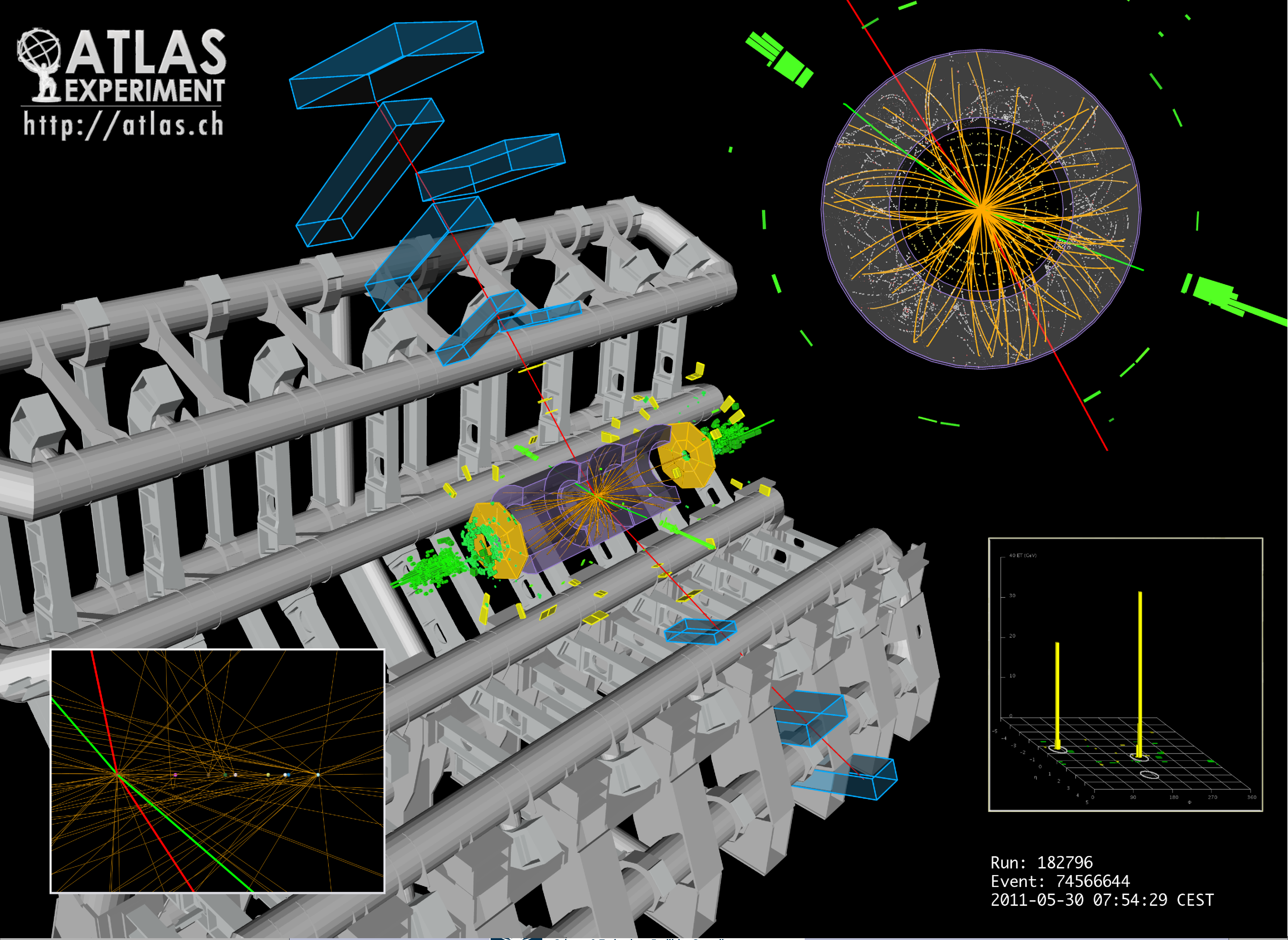


- Peak near 126, both years
- Local excess 4.5σ
  - Best single channel evidence there is....
- Strength exceeds expectation



$H \rightarrow ZZ \rightarrow llll$

- The golden mode
- Good energy measurement like γγ
  - But know production point
- Very low backgrounds
  - Dominated by real $ZZ \rightarrow llll$
- But signal rate low
  - $Z \rightarrow ee$ or μμ Br only 3%
  - Challenge is to maximise efficiency
  - ATLAS improved low-p_T electrons w.r.t 2011
    - New tracking algorithm, allowing for bremsstrahlung


ATLAS EXPERIMENT
http://atlas.ch
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

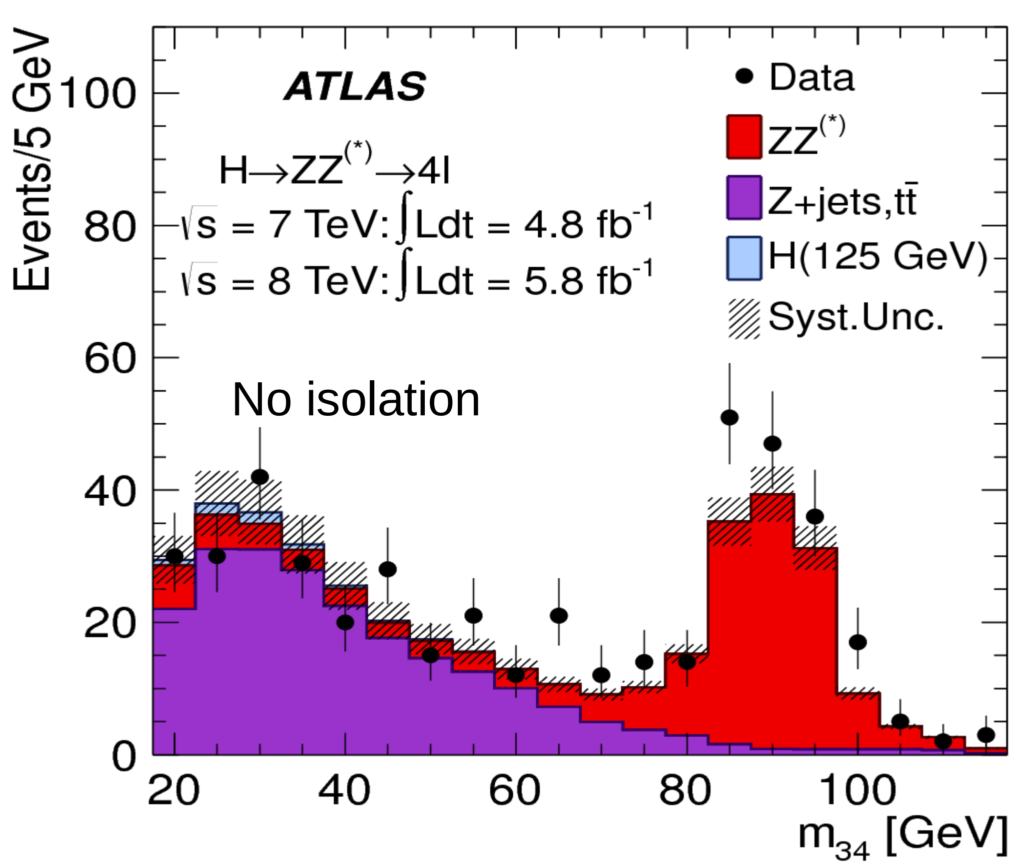
Basic analysis steps

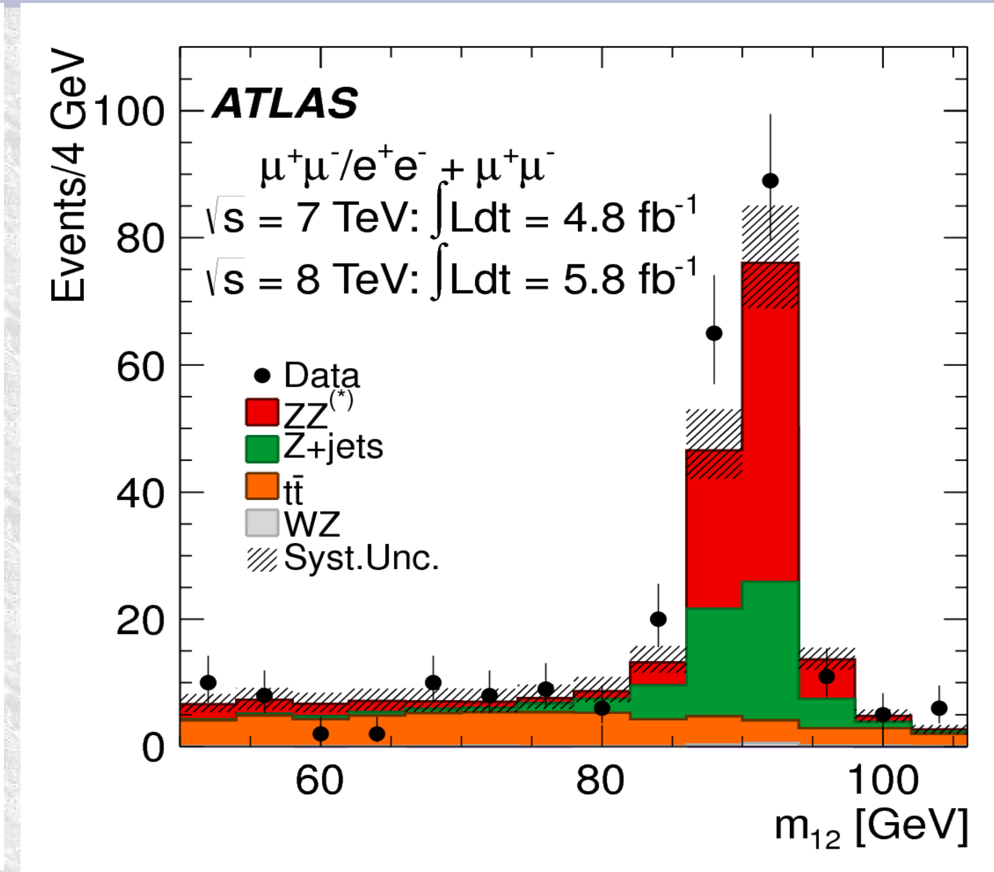
- Find events with 4 leptons (e/μ) in them
- Request a pair is in region of the Z mass
- The second is allowed to be much lower in mass
  - Kinematics requires one Z is forced to be off-shell, lighter

Minimum lepton p_T	7Gev (e) / 6 GeV (μ)
Mass Z_1	50 - 106
Mass, Z_2	17.5 - 115

- Major background:
  - ZZ→llll (where Z's are not to do with the Higgs)
    - 'irreducible'
  - Zqq (Zbb)
  - tt→WbWb→νlbνb
- Two prompt leptons plus b quarks are important, so:
  - Require isolation
  - Require leptons from primary

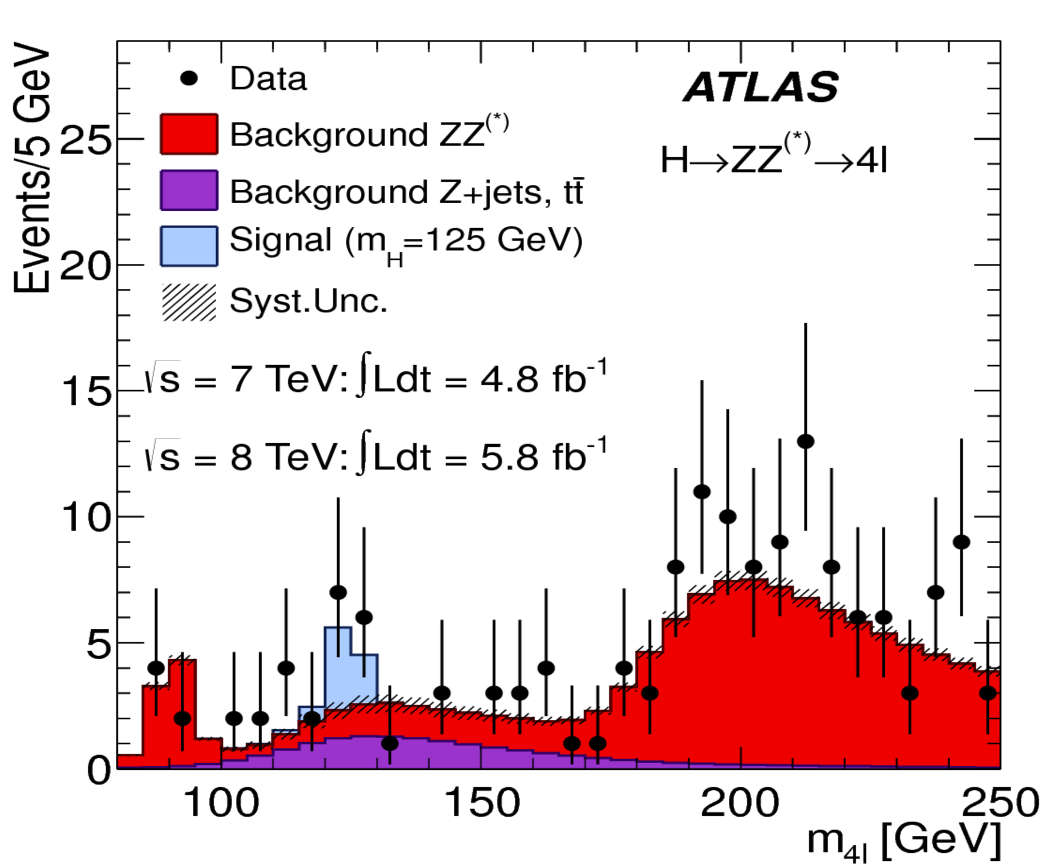
Background Measurement

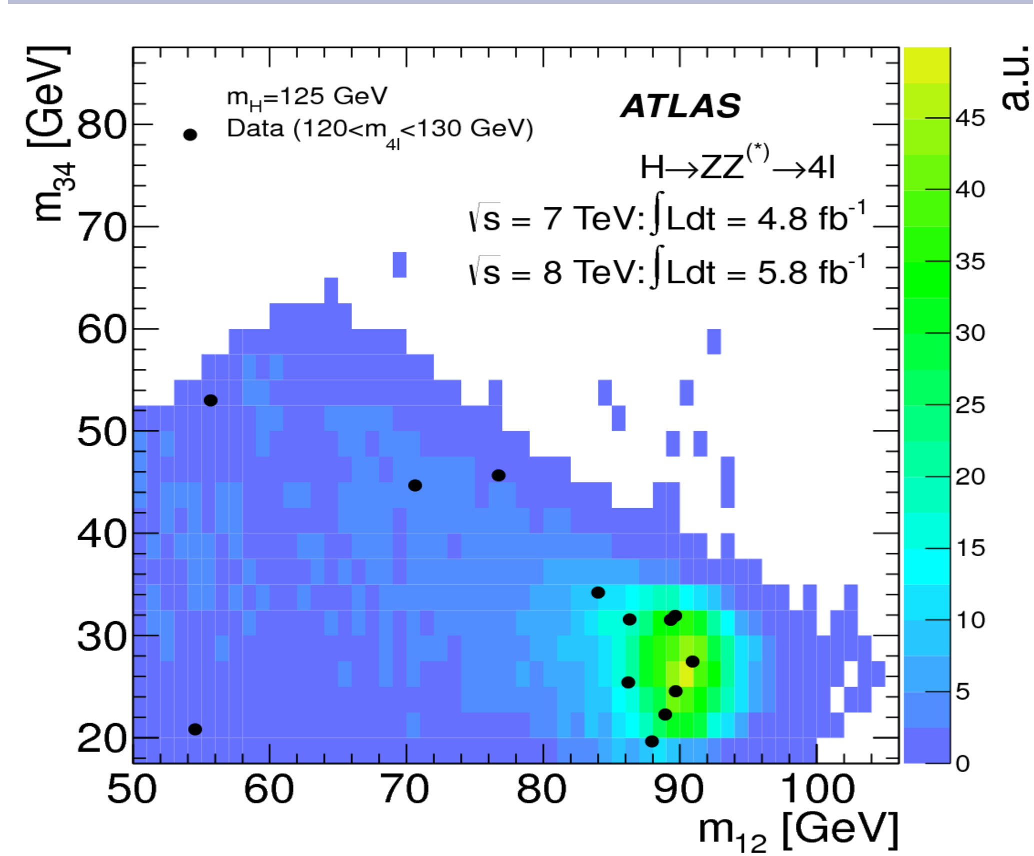




- Remove isolation from 1st or 2nd Z candidate
  - Left is low mass ee candidates
  - Right high mass μμ
- Also detailed studies of electron take rates

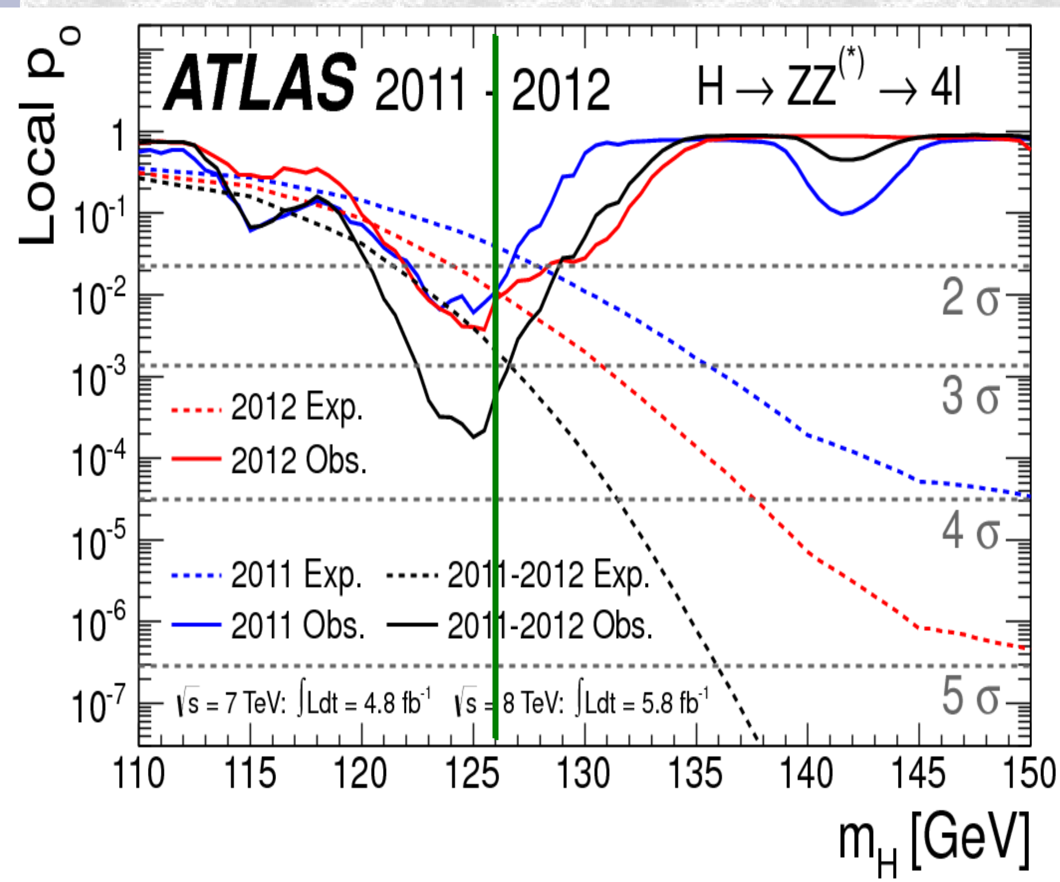
Mass distribution





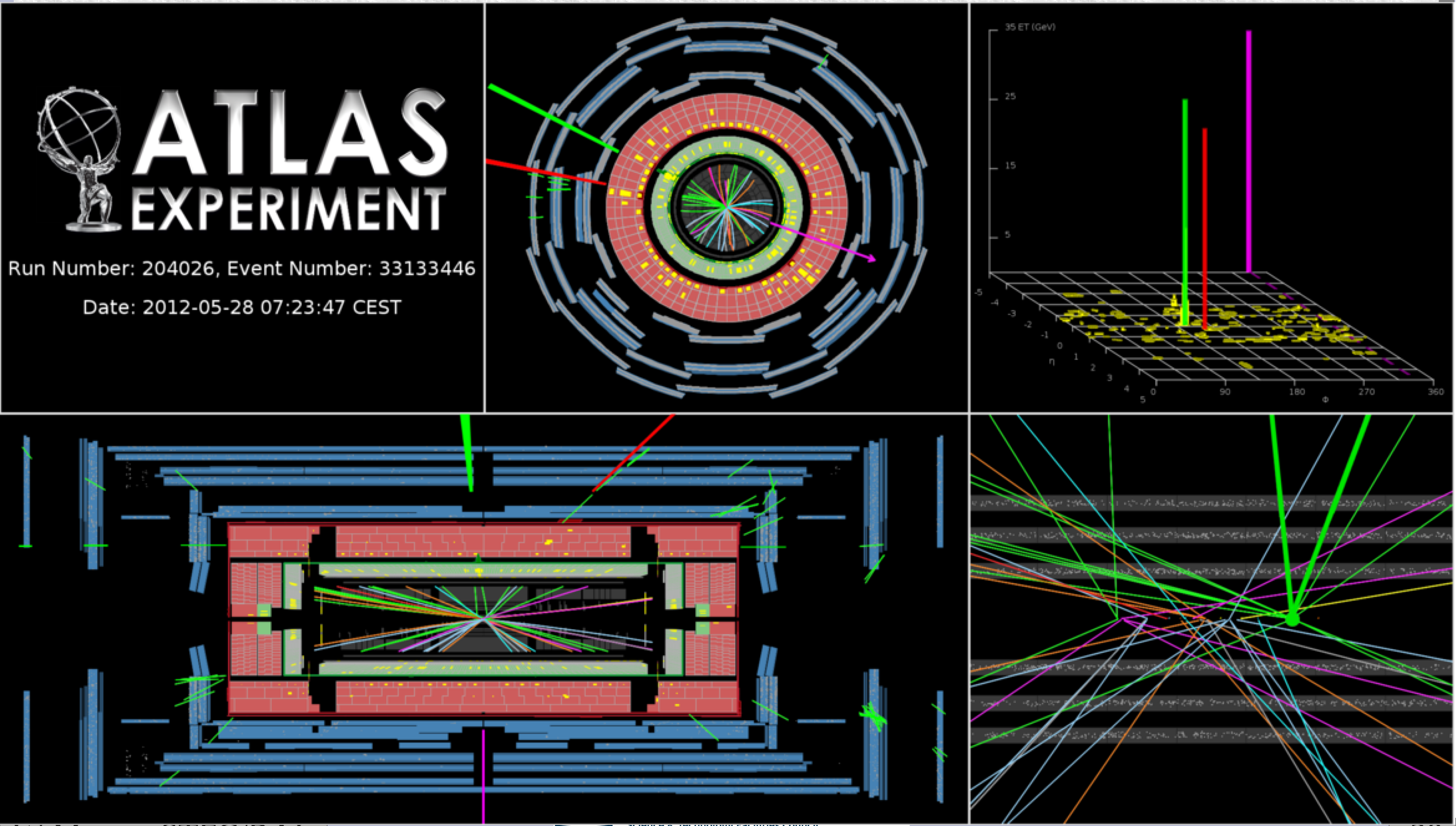
- Background shapes matches expectation
  - Note peaks at 90 and >180 (1 real Z, 2 real Z's)
  - Small peak at 125 GeV seen too...
- Check Z_{12} and Z_{34} masses for candidates

Background compatibility



- ATLAS expects about 2.7sigma at 126GeV
- Observe 3.6σ excess at 125
- Consistent with a Higgs
  - A little high, but not significant

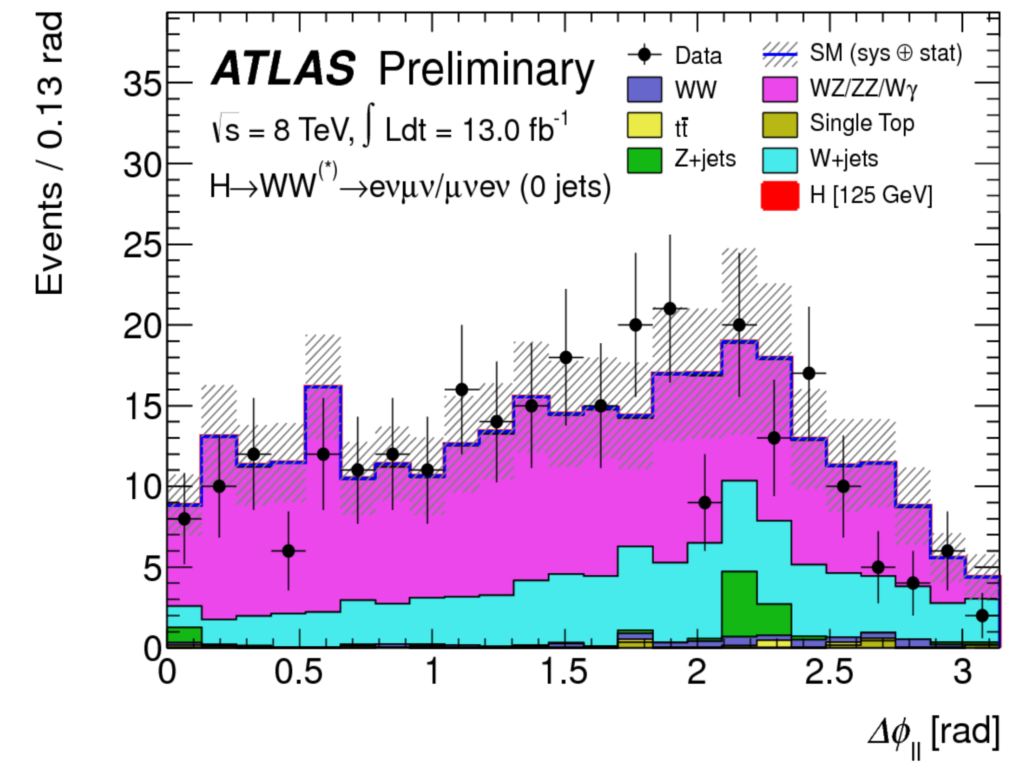
$H \rightarrow WW \rightarrow l\nu l\nu$

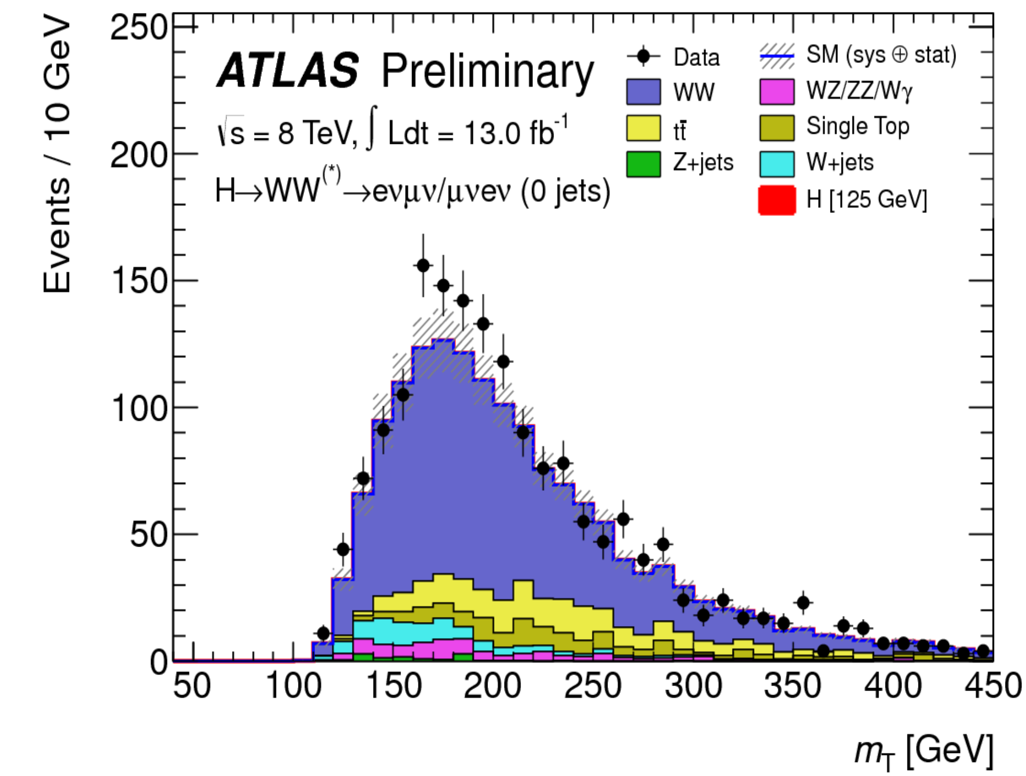


$WW \rightarrow l\nu l\nu$: $13fb^{-1}$@8TeV

- The most sensitive channel for $130<m_H<200$
  - Still one of the 3 most important at 125GeV
  - But poor mass information due to 2 undetected neutrinos
- Good trigger, reasonable rate
  - Largest background is non-resonant WW
    - Also top when looking at WW+1 jet
  - Backgrounds measured from control regions
- Request two leptons
  - 15,25 GeV
  - ATLAS only uses e-μ pairs in 2012 (ee/μμ have more bkgd.)
- Require missing E_T (E_t^{rel}) and $p_T(ll)$ for WW
- Select signal area with $\Delta\varphi$ and m_{ll} selections
  - ATLAS prefers cut-based selections
- Many backgrounds need estimation from data - tricky

WW background extraction





- Backgrounds are (almost) all found in control regions
  - ATLAS same-sign (left) check W+jets
  - ATLAS WW control (right) from high m_T events
    - These plots have W+jets from data, rest simulation
    - WZ/ZZ used as they are; WW measured here

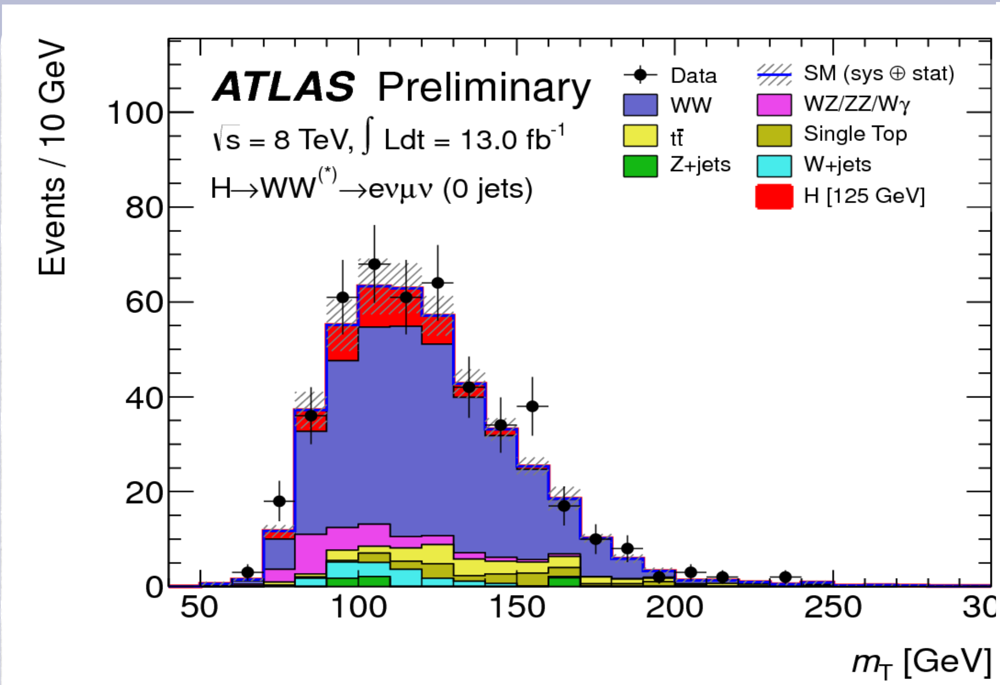
Cutflow in WW

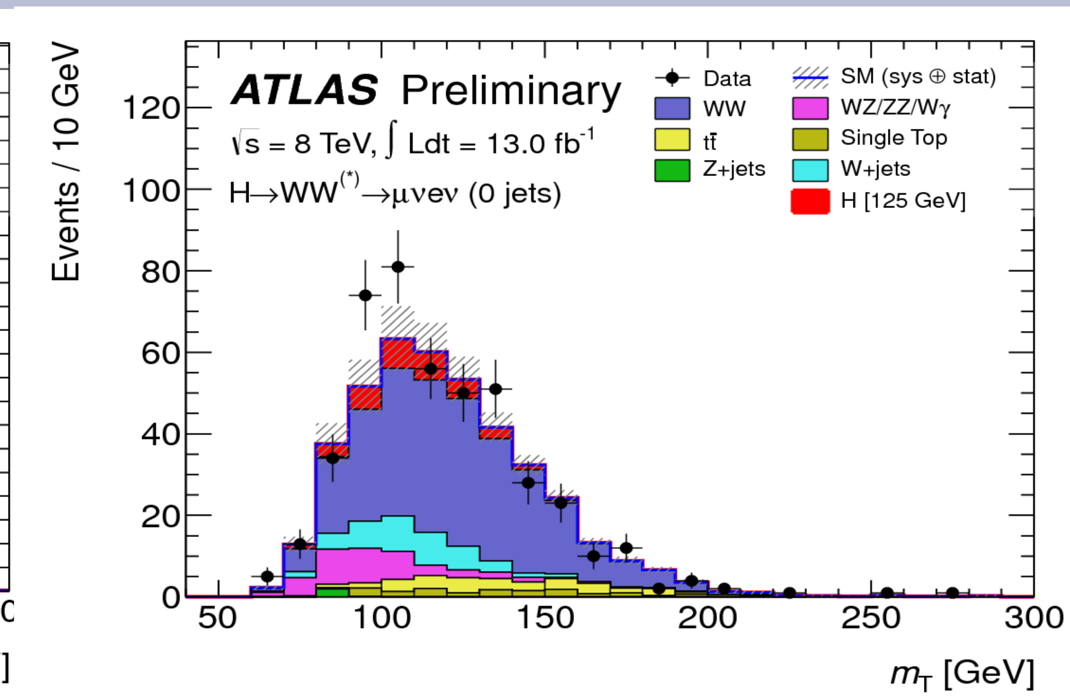
Cutflow evolution in the different signal regions									
$H+0$-jet	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^{*}+$ jets	$W+$ jets	Total Bkg.	Obs.
Jet veto	110 ± 1	3004 ± 12	242 ± 8	387 ± 8	215 ± 8	1575 ± 20	340 ± 5	5762 ± 28	5960
$\Delta\phi_{\ell\ell,E_{\mathrm{T}}^{\mathrm{miss}}} > \pi/2$	108 ± 1	2941 ± 12	232 ± 8	361 ± 8	206 ± 8	1201 ± 21	305 ± 5	5246 ± 28	5230
$p_{\mathrm{T},\ell\ell} > 30$ GeV	99 ± 1	2442 ± 11	188 ± 7	330 ± 7	193 ± 8	57 ± 8	222 ± 3	3433 ± 19	3630
$m_{\ell\ell} < 50$ GeV	78.6 ± 0.8	579 ± 5	69 ± 4	55 ± 3	34 ± 3	11 ± 4	65 ± 2	814 ± 9	947
$\Delta\phi_{\ell\ell} < 1.8$	75.6 ± 0.8	555 ± 5	68 ± 4	54 ± 3	34 ± 3	8 ± 4	56 ± 2	774 ± 9	917
$H+1$-jet	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^{*}+$ jets	$W+$ jets	Total Bkg.	Obs.
One jet	59.5 ± 0.8	850 ± 5	158 ± 7	3451 ± 24	1037 ± 17	505 ± 9	155 ± 5	6155 ± 33	6264
b-jet veto	50.4 ± 0.7	728 ± 5	128 ± 5	862 ± 13	283 ± 10	429 ± 8	126 ± 4	2555 ± 20	2655
$Z \to \tau\tau$ veto	50.1 ± 0.7	708 ± 5	122 ± 5	823 ± 12	268 ± 9	368 ± 8	122 ± 4	2411 ± 19	2511
$m_{\ell\ell} < 50$ GeV	37.7 ± 0.6	130 ± 2	39 ± 2	142 ± 5	55 ± 4	99 ± 3	30 ± 2	495 ± 8	548
$\Delta\phi_{\ell\ell} < 1.8$	34.9 ± 0.6	118 ± 2	35 ± 2	134 ± 5	52 ± 4	22 ± 2	24 ± 1	386 ± 8	433

- Above: statistical errors only
- Below, add 3/4 $m_H < m_T < m_H$ cut, with systemtics

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^{*}+$ jets	$W+$ jets	Total Bkg.	Obs.
$H+0$-jet	45 ± 9	242 ± 32	26 ± 4	16 ± 2	11 ± 2	4 ± 3	34 ± 17	334 ± 28	423
$H+1$-jet	18 ± 6	40 ± 22	10 ± 2	37 ± 13	13 ± 7	2 ± 1	11 ± 6	114 ± 18	141

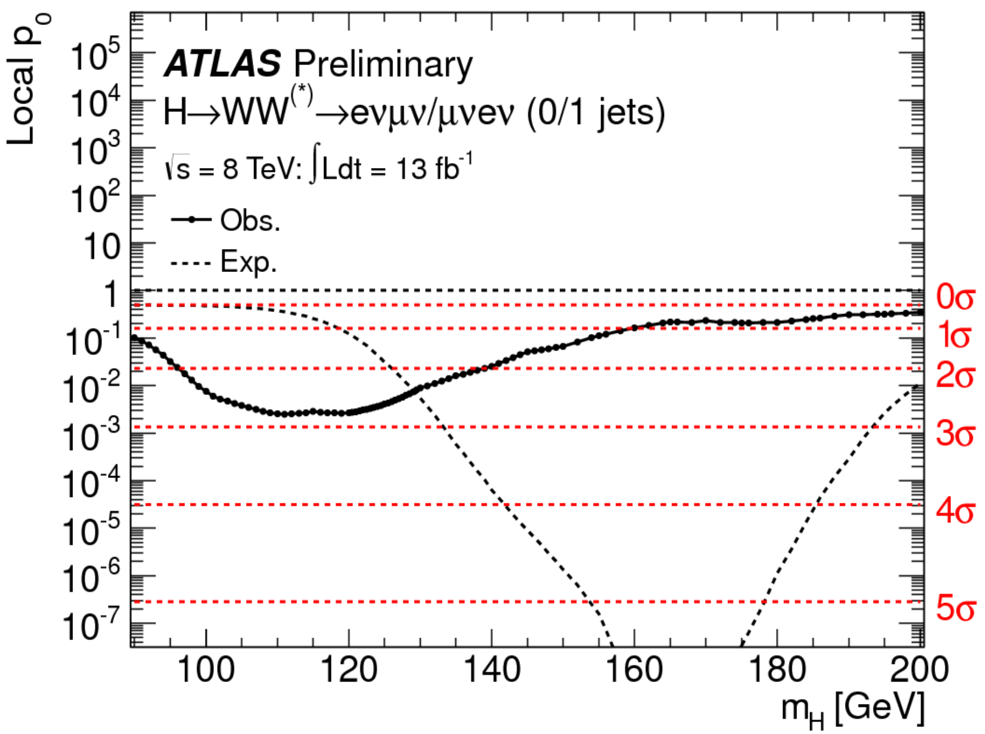
WW signal region

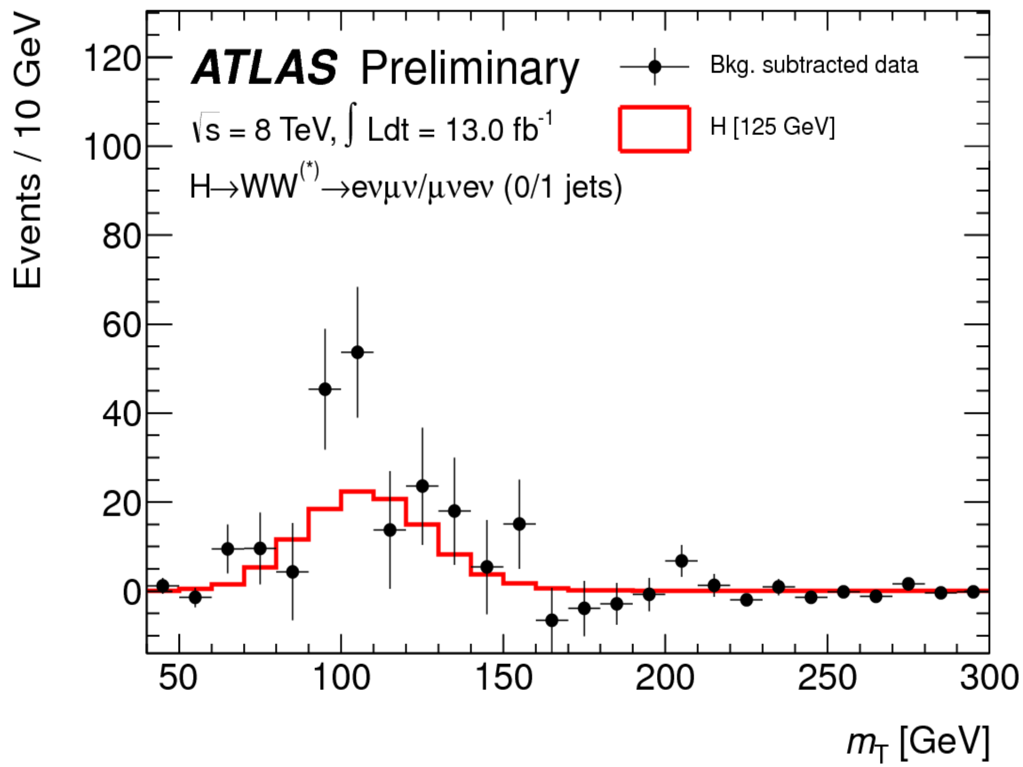




- Treat leading e or μ and 0/1 jets separately
- Delicate analyses, complex data/MC mix
- Distinct excess seen in both 0+1 jets
  - In the region signal is expected
  - But not well localised
  - Excess slightly larger than expected

WW combined





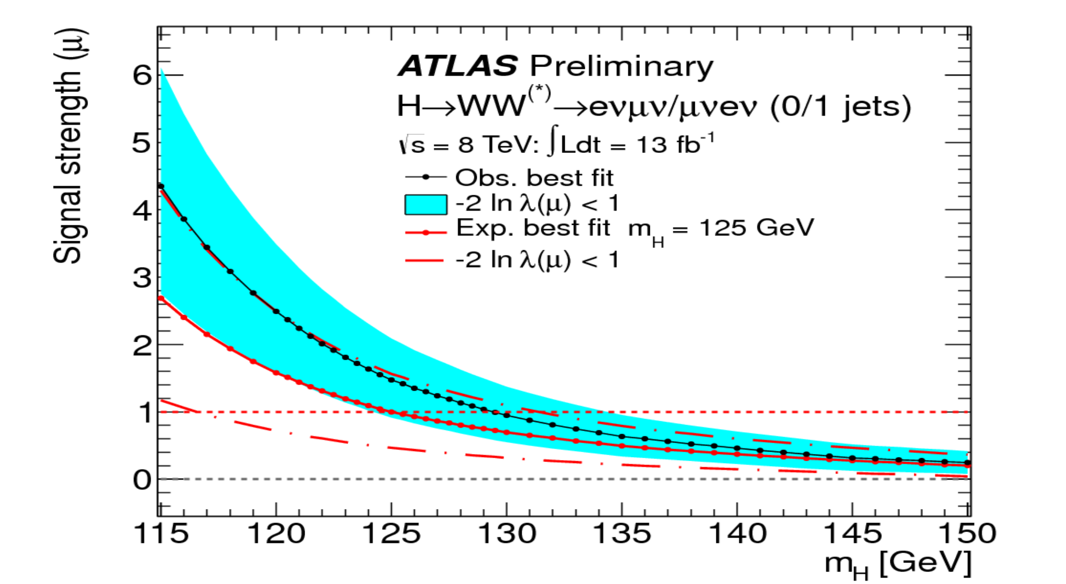
- Fit the m_T spectra as 1D
- 2.8sigma excess around 125GeV
- Two neutrinos means mass not well measured
  - So broad excess seen

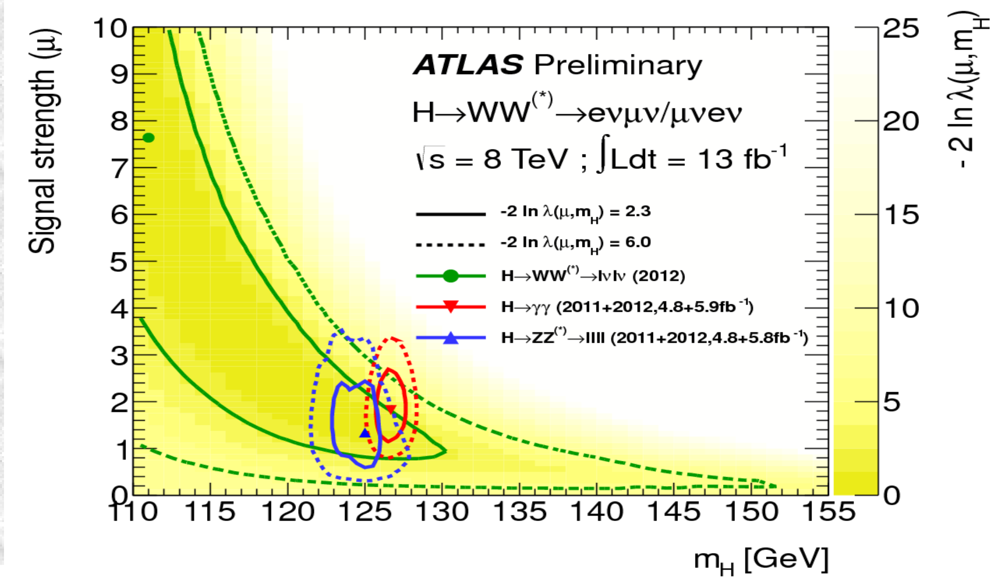
H to WW* results

$$\mu = 1.48^{+0.35}_{-0.33}\,(\text{stat})^{+0.41}_{-0.36}\,(\text{syst theor})\,^{+0.28}_{-0.27}\,(\text{syst exp}) \pm 0.05\,(\text{lumi})$$

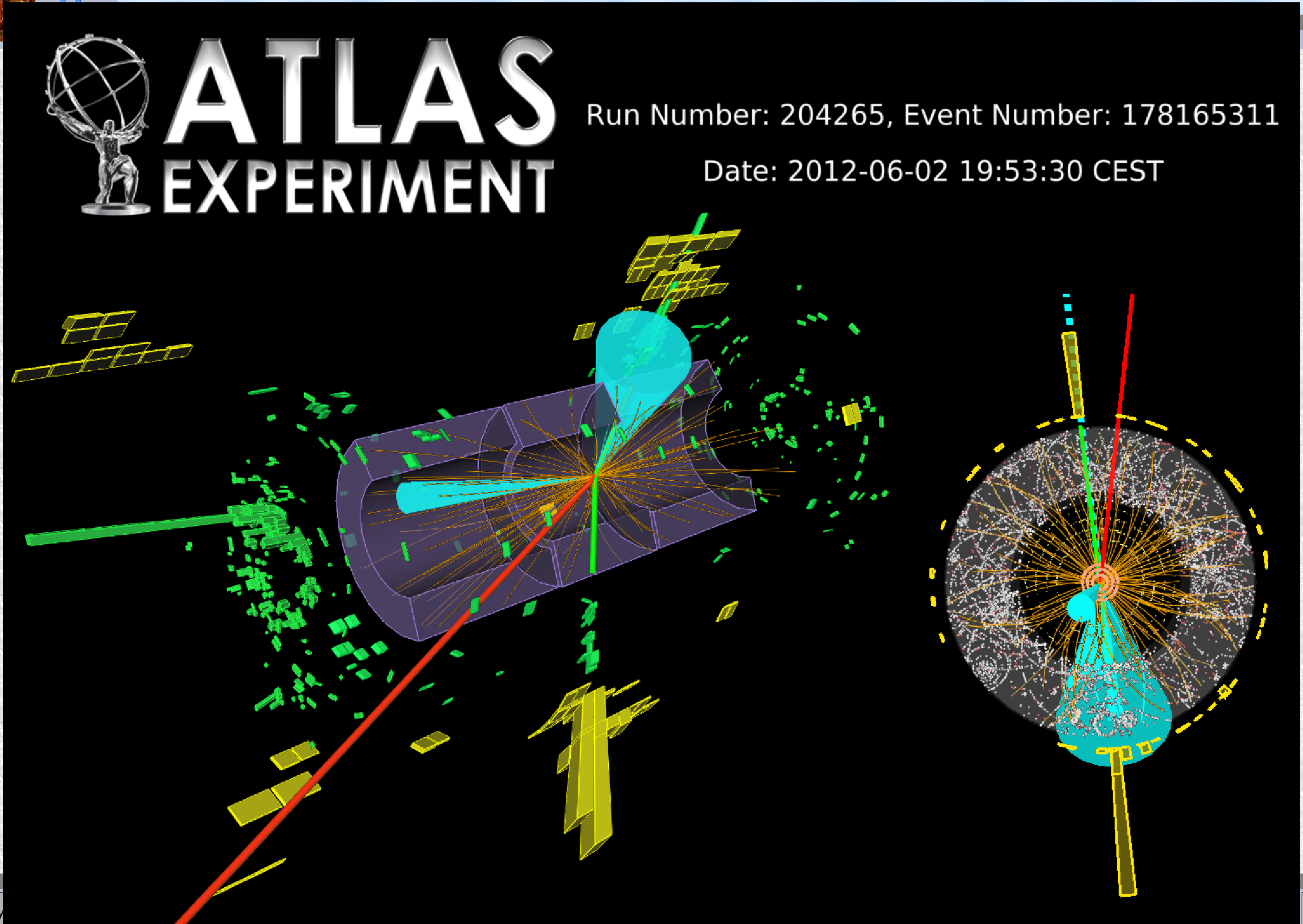
$$\sigma(pp \to H) \cdot \mathcal{B}(H \to WW)_{m_H=125\text{ GeV}} = 7.0\,^{+1.7}_{-1.6}\,(\text{stat})\,^{+1.7}_{-1.6}\,(\text{syst theor})\,^{+1.3}_{-1.3}\,(\text{syst exp}) \pm 0.3\,(\text{lumi})\text{ pb}$$

- μ sensitivity to mass is shown bottom left
- Bottom right is 2D LR contours
  - Best fit at 111GeV, 1-σ extends to 130GeV





Higgs to $\tau\tau$

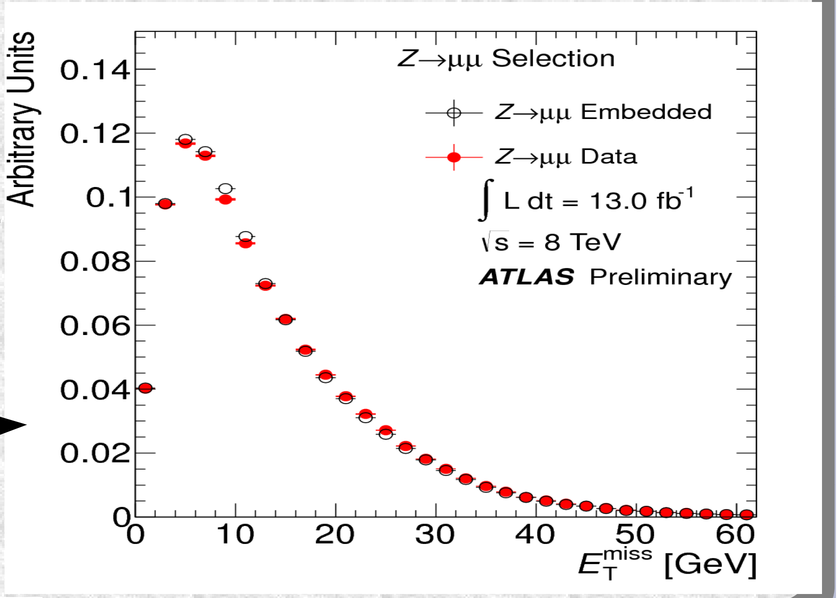


Higgs to ττ

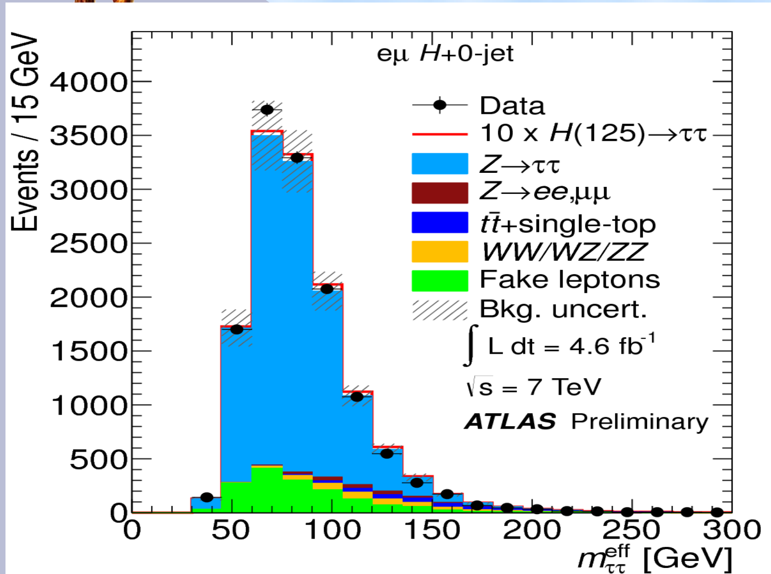
- Analysis is done in many channels
  - 7 and 8 TeV separately
  - ll, lh and hh separately
    - Leptonic modes have more neutrinos so worse mass measure
    - But are easier to trigger
  - Boosted, VH, VBF, inclusive decay modes
    - Inclusive is almost a background measurement
    - Boosted helps the mass estimation (collinear approximation)
    - VBF and VH are boosted and tagged but lower rate
- This is a huge project, not an analysis
  - In the end >50% of sensitivity is from VBF – shown above

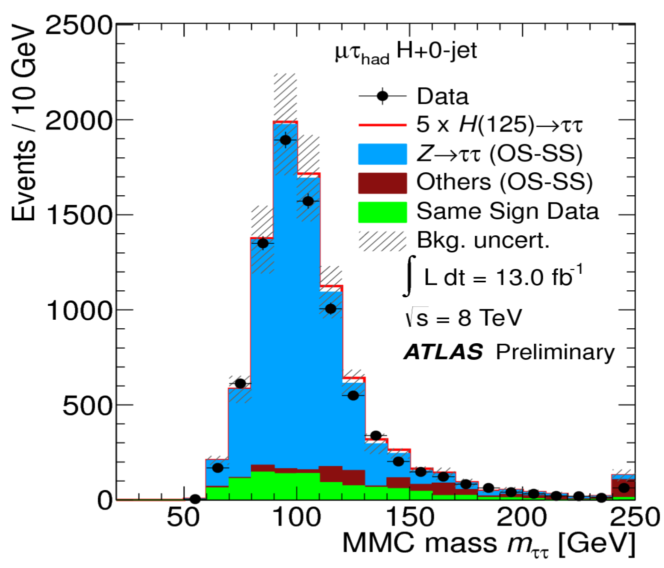
Higgs to ττ background

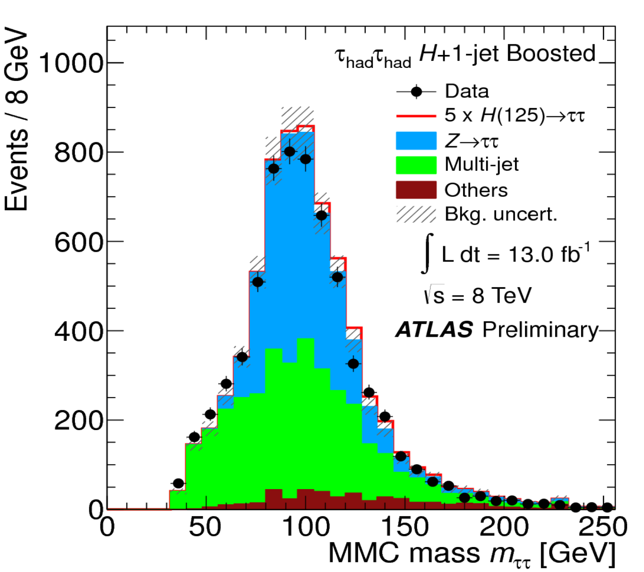
- In all channels, Z to ττ is a very important background
- We do not trust the simulation of underlying event perfectly
- There is no signal-free Z sample
  - Although the inclusive is pretty close
- Embedding is used:
  - Take a data Z to → μμ event
  - Remove the activity associated to the muons
  - Inject taus into simulation with the muon 4-vector scaled
  - Insert the tau into the data event
- This means we only model τ decay
  - Pileup and underlying event from data
- But you need to be careful
  - Which activity in the event is from the μ & should be removed? Test:
  - Biases in the muon pair selection?

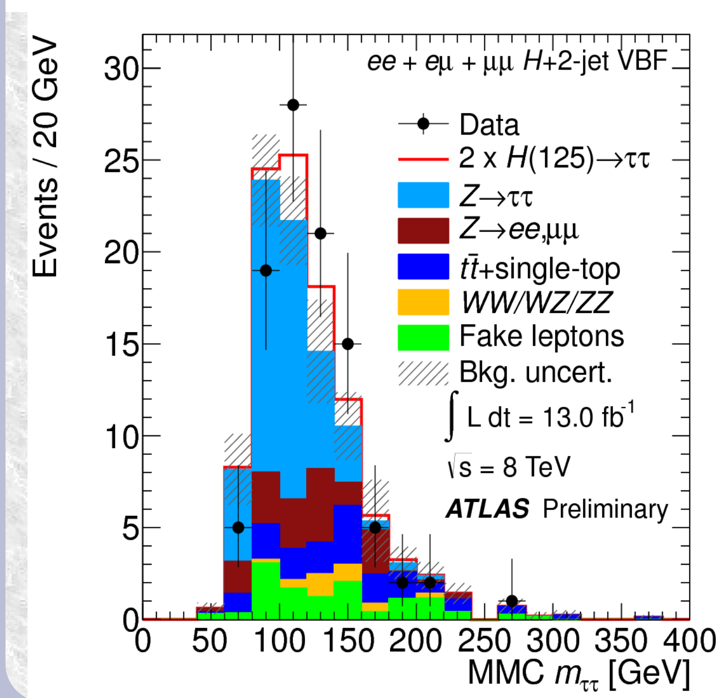


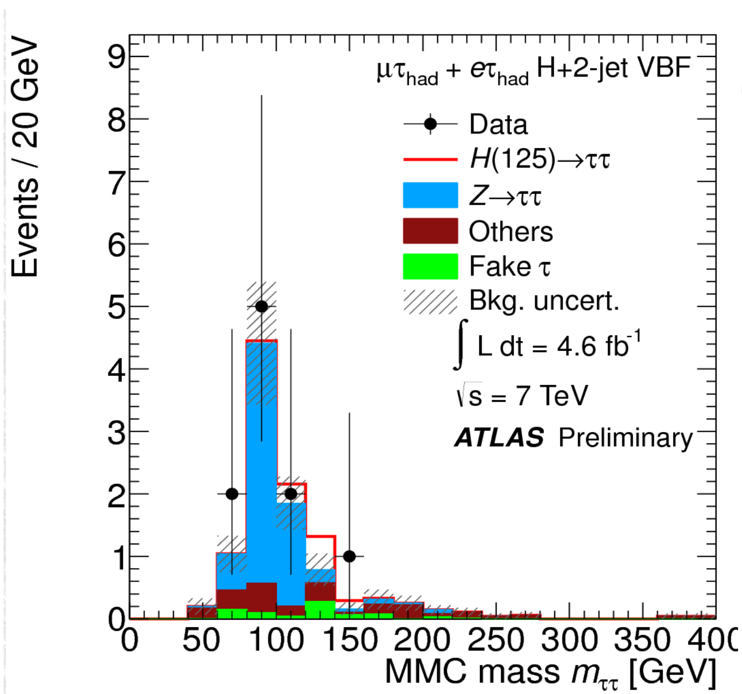
Higgs to ττ: sample mass plots

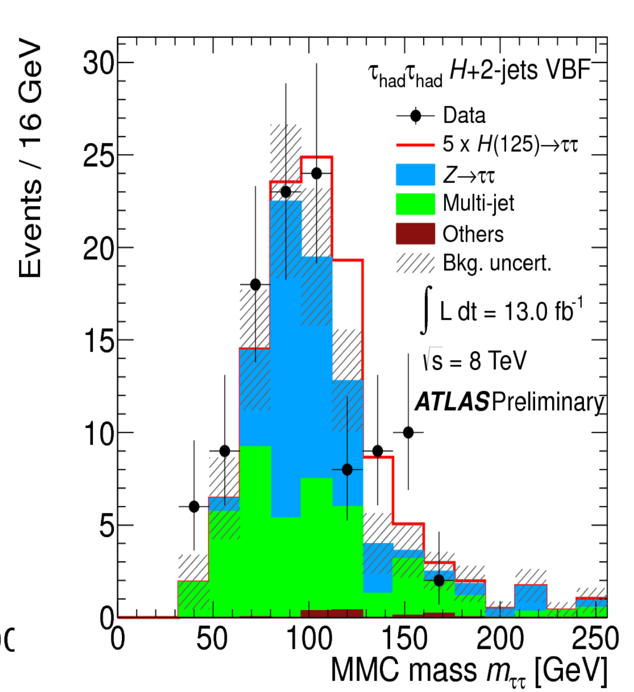




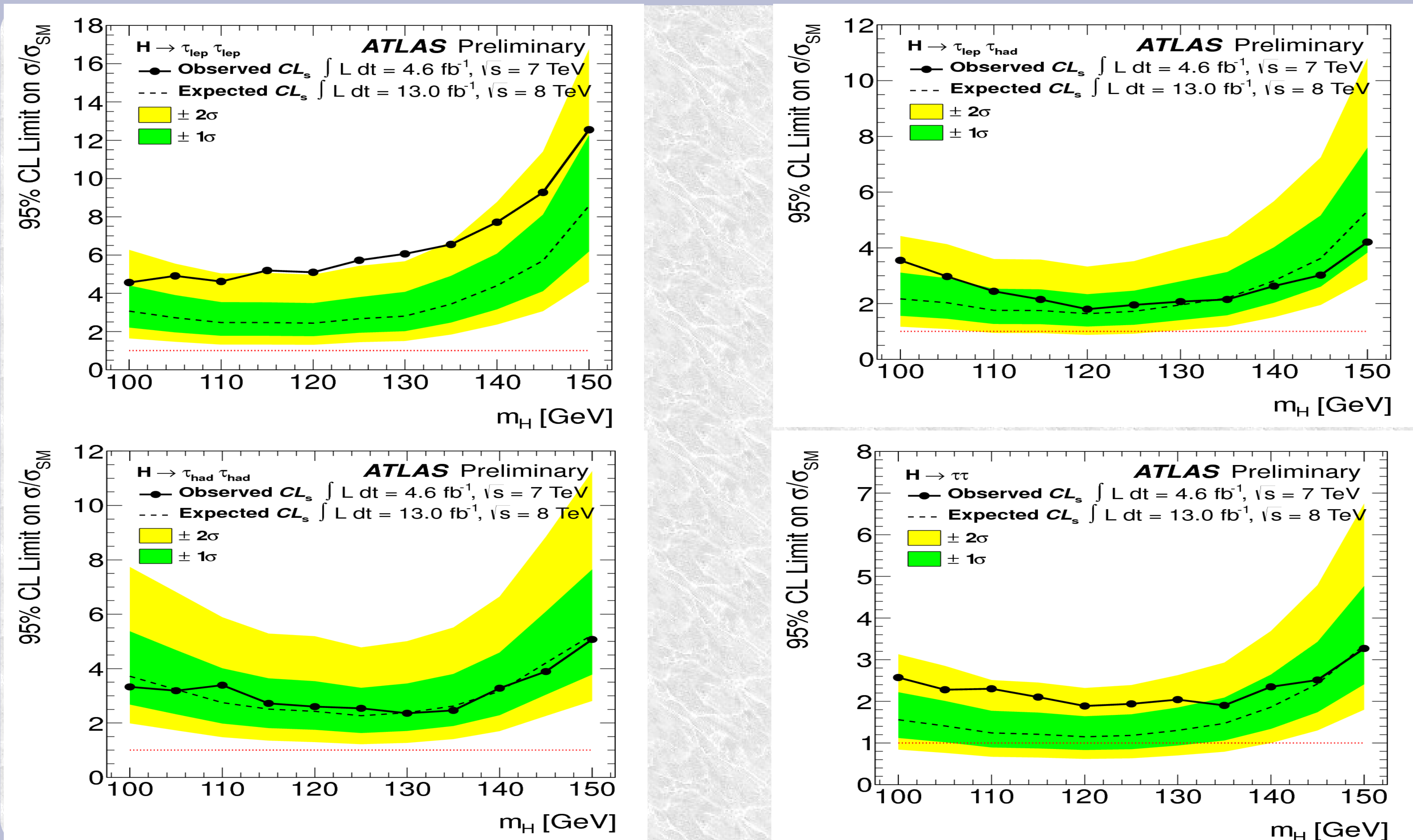






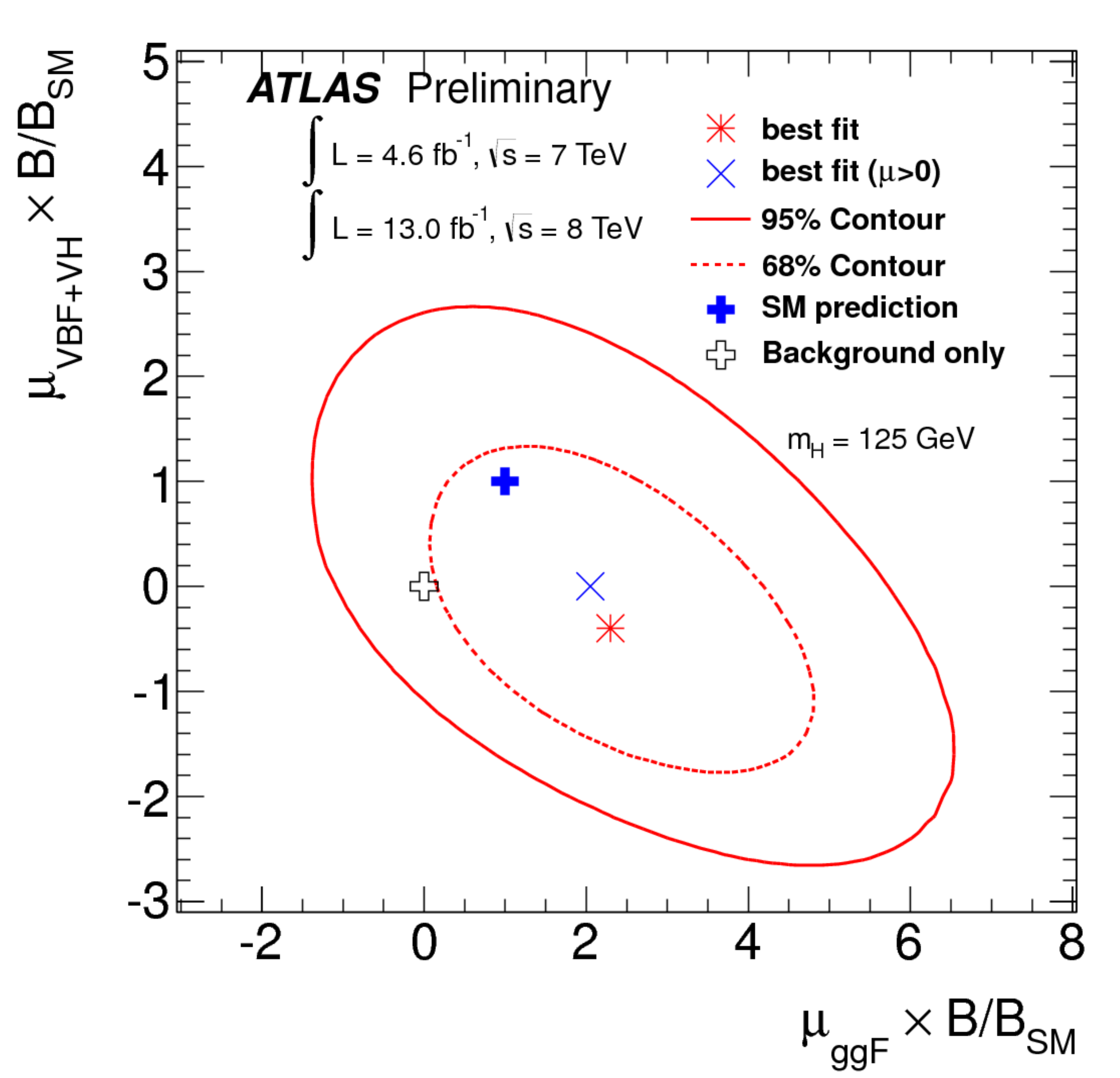


Limits from tau channel



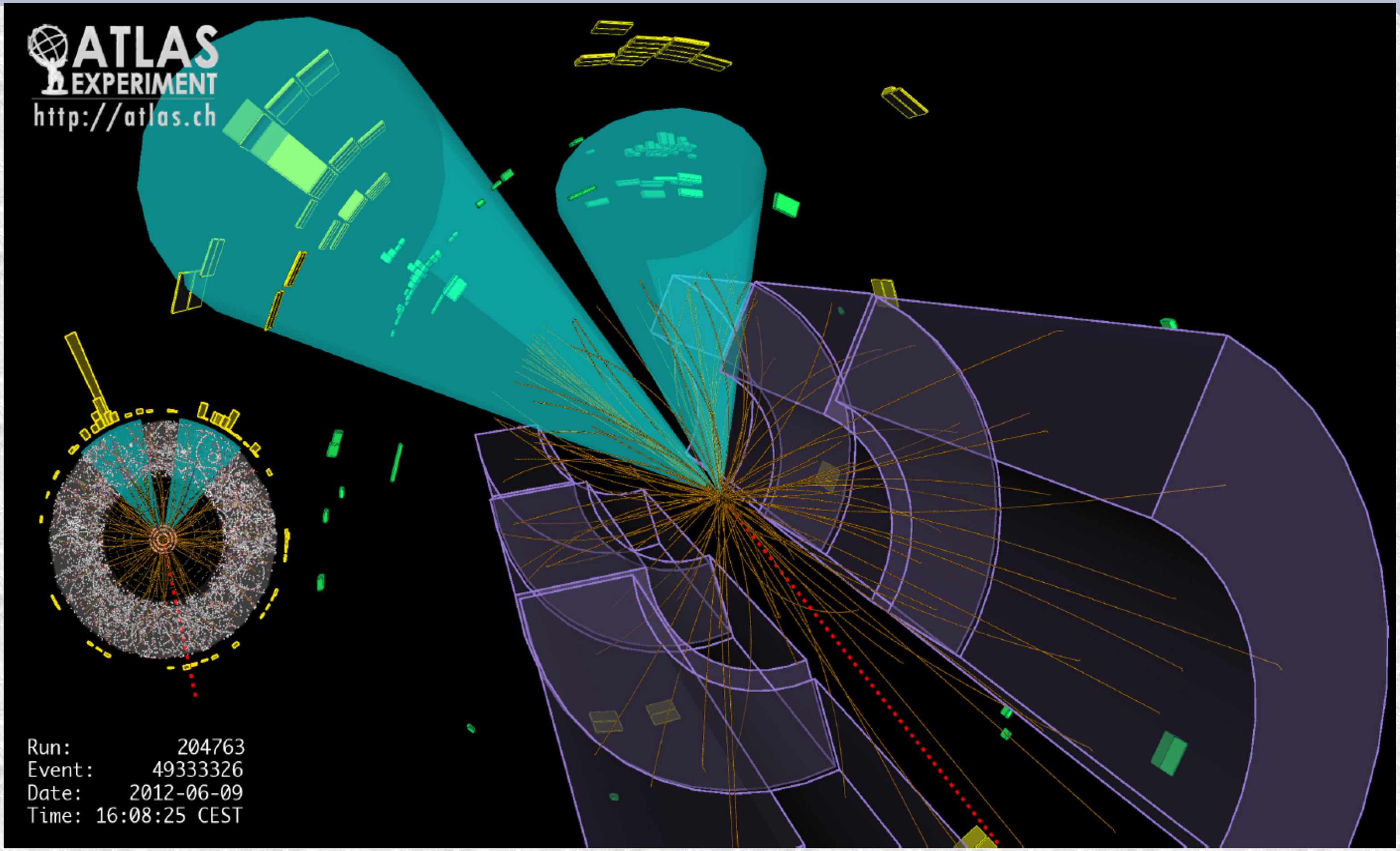
H to ττ production analysis

- The background only is just outside 1sigma band
- There is no evidence from VBF
- But results are currently compatible with almost anything



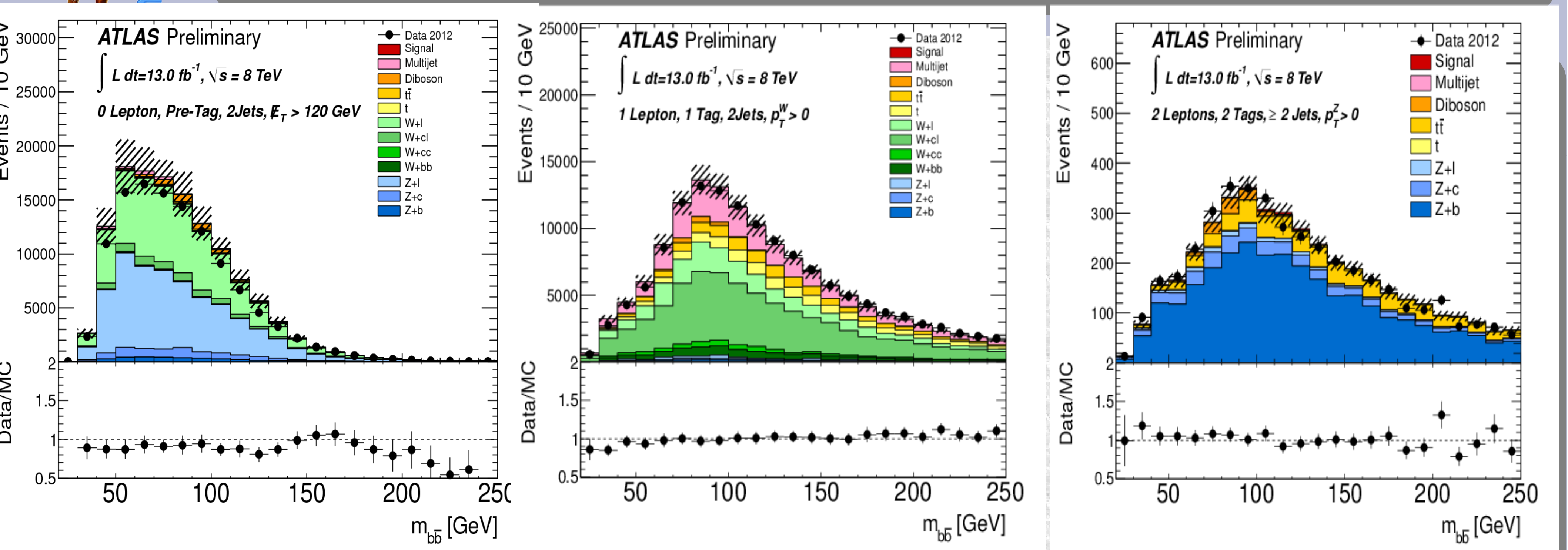
H to bb

- 3 modes:
  - ZH, $Z \to \nu\nu$
  - WH, $W \to l\nu$
  - ZH, $Z \to ll$
- Each done by fit of m_{bb} in p_T bins
- Complex fit to measure background in the data



- We notice boson and top pT spectra are a little too hard in our simulations
  - This is good news

Sample backgrounds

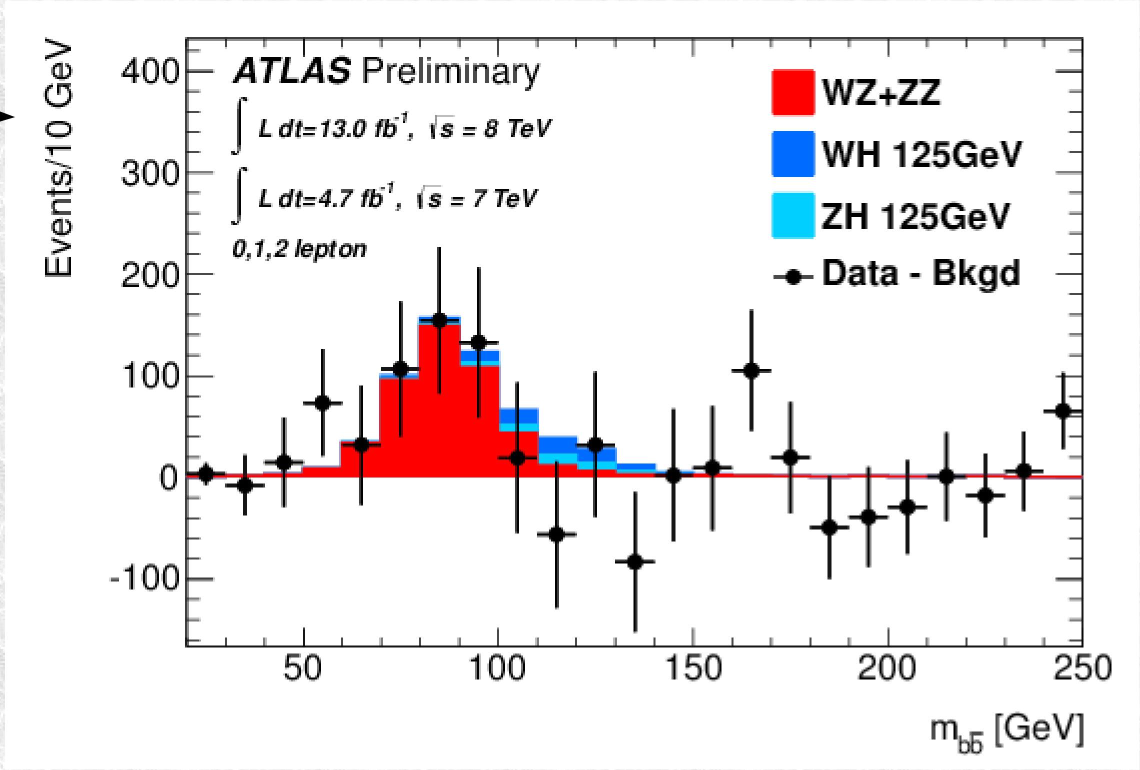


- Events with 0, 1 or 2 leptons analysed
- Divided into 0, 1 or 2 btag
  - Plus 2 jets or 3 jets for 0-lepton, and tt control for 2-lepton
- Fit in p_T bins to rescale Z/W plus light jet & c background
  - All scale compatible with 1
  - except Z+c which had varying MC samples

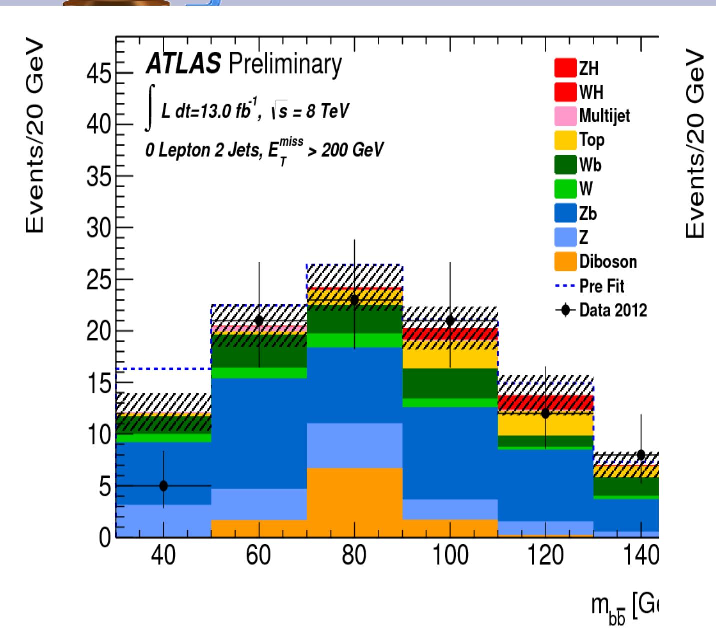
Control check: VZ

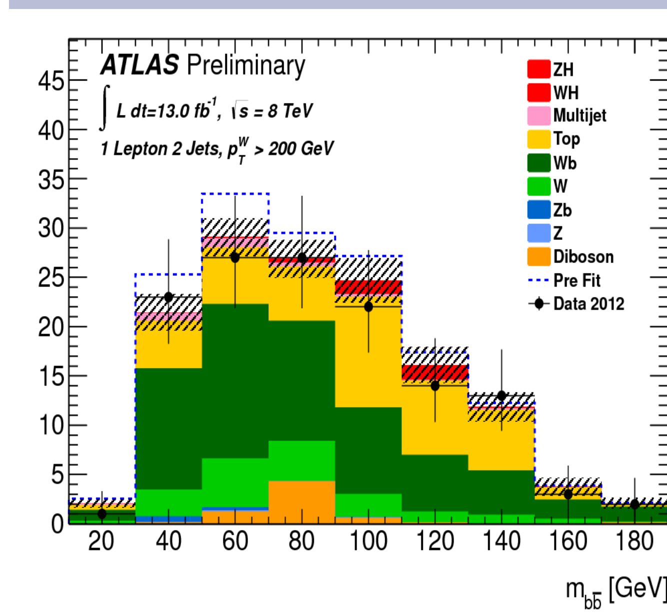
- Treat VZ, Z→bb as a test case for VH, H→bb
- Run fit using this as the signal term
  - But not in pT bins as Z pT is similar to the background
- Sum 3 channels and 3 years
- Background subtracted data

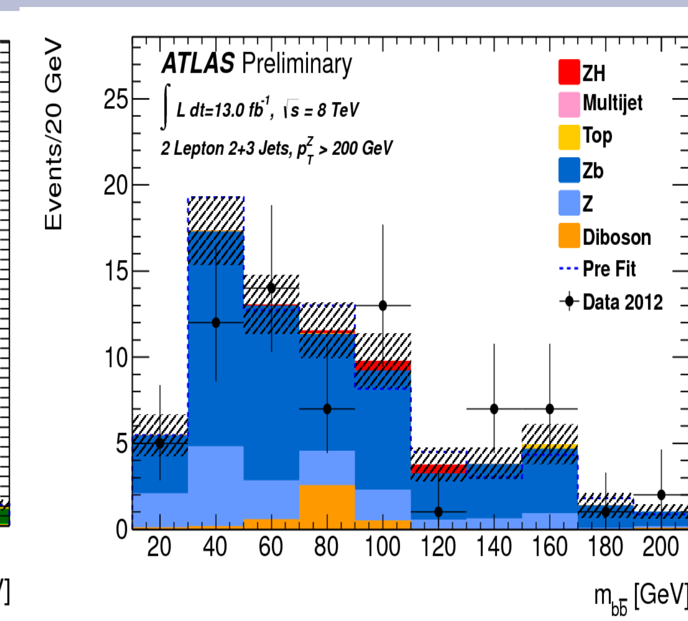
  μ_d=1.09±0.20±0.22
- 4σ evidence for Z to bb
- This peak is an excellent check on the system



Signal Distributions



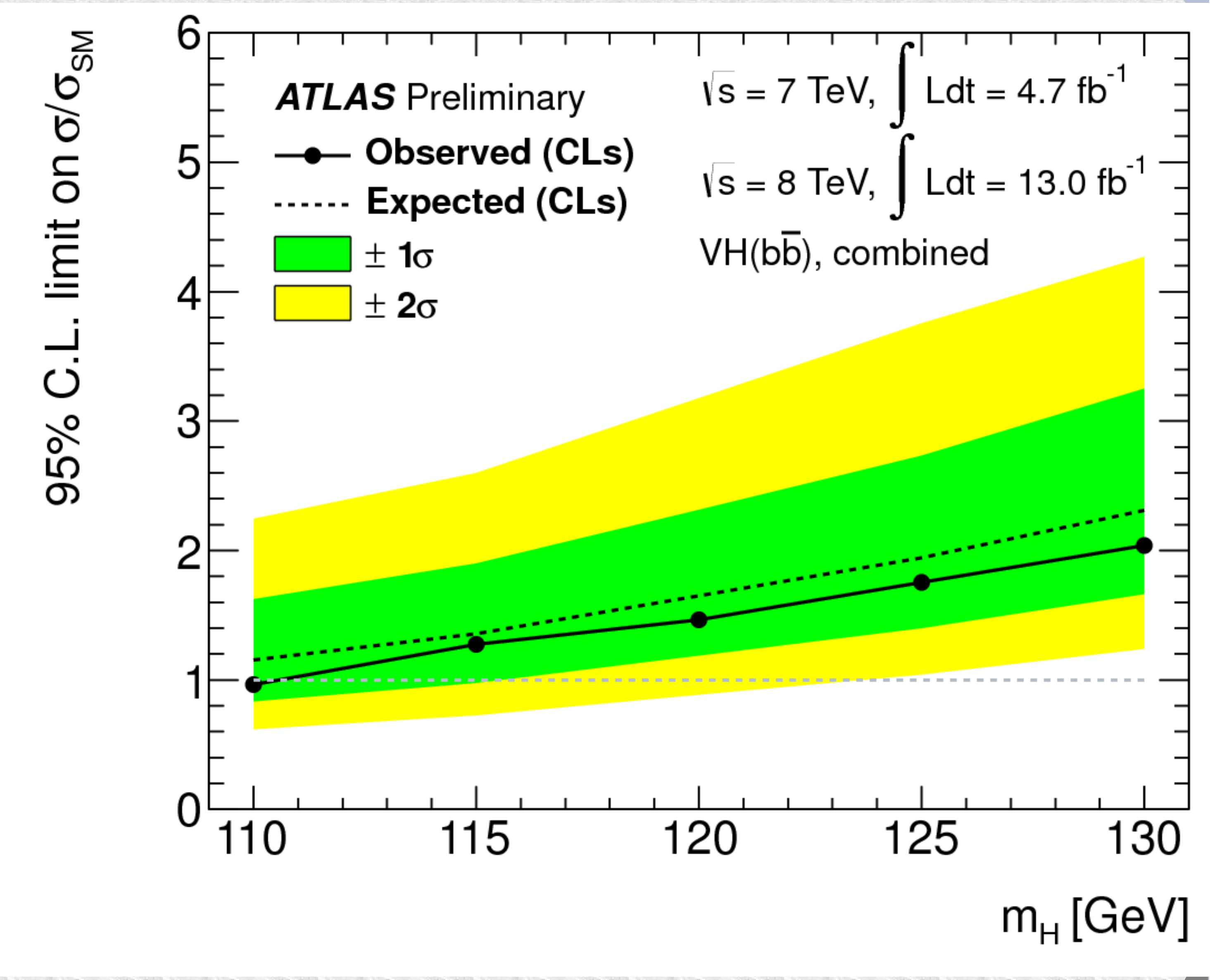




- The highest p_T distributions in the signal region
- s/b can be seen to be poor
- Mix of backgrounds varies considerably
  - Real b's dominant

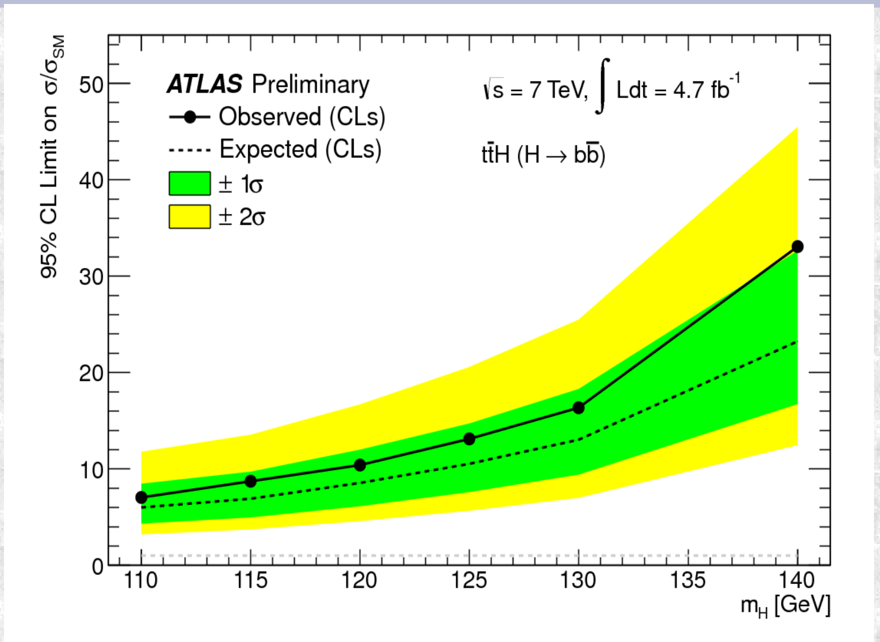
Limits set

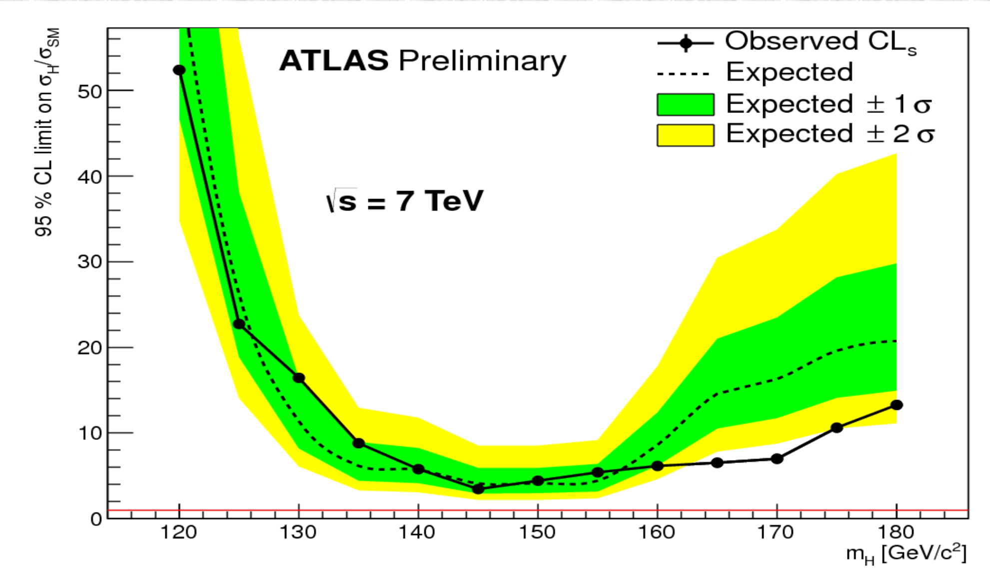
- Sensitivity is 2xSM at 125GeV
- There is a small deficit c/f background
  - μ=-0.4±1.1
  - Compatible with 0 or 1.
- We do exclude 110GeV
  - First LHC exclusion in bb decay mode



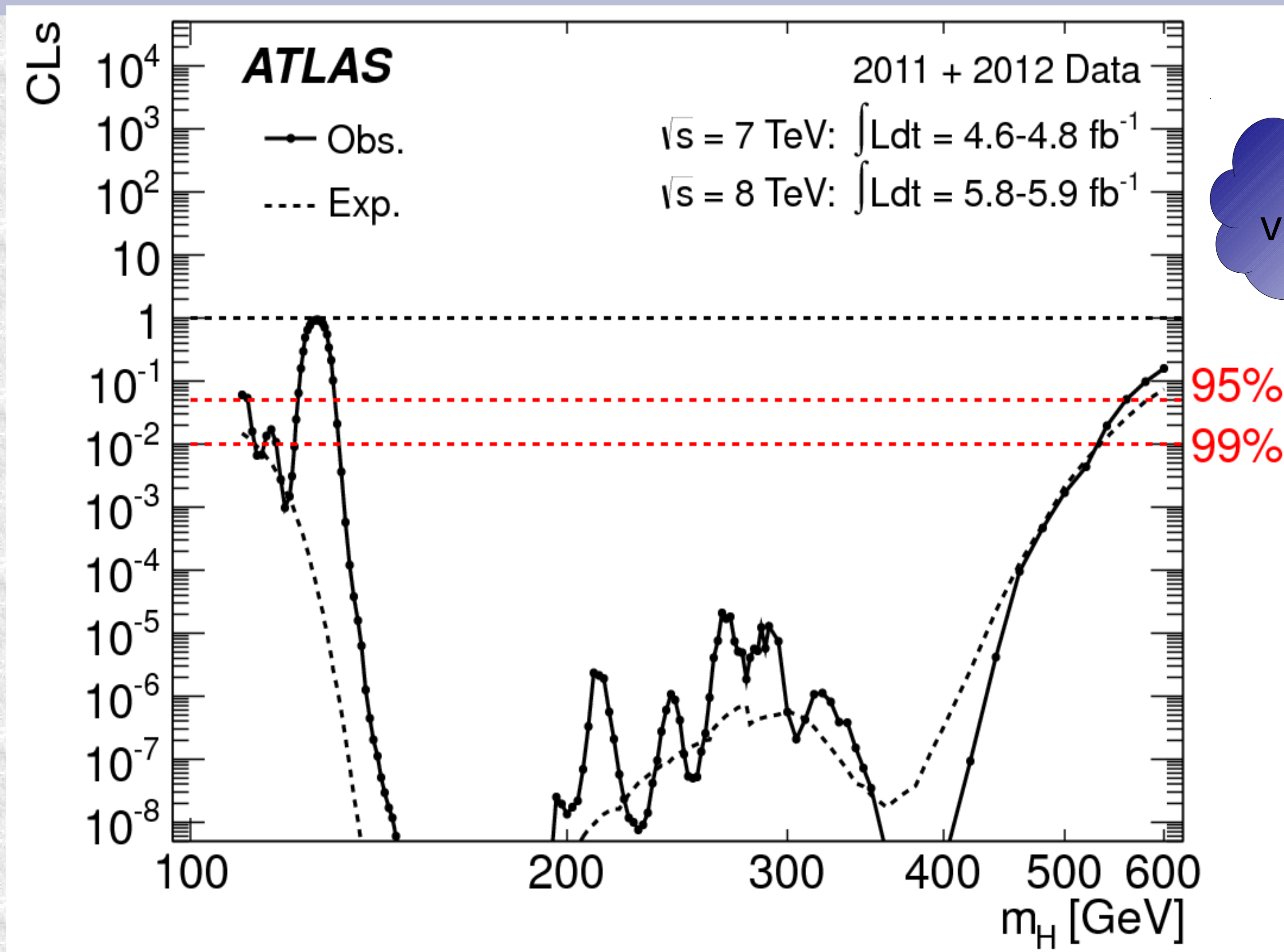
Other modes

- Interesting is ttH, H→bb which is fermionic in both production and decay
  - Recent 2011 results right:
  - ATLAS-CONF-2012-135
  - Will benefit from higher energy
- Also released results on H to ZZ to llqq
  - Not competitive with fully leptonic in this mass range
  - Too much Z plus jets background.





Combined limits



July vintage

- Excludes nearly all mass range at high confidence

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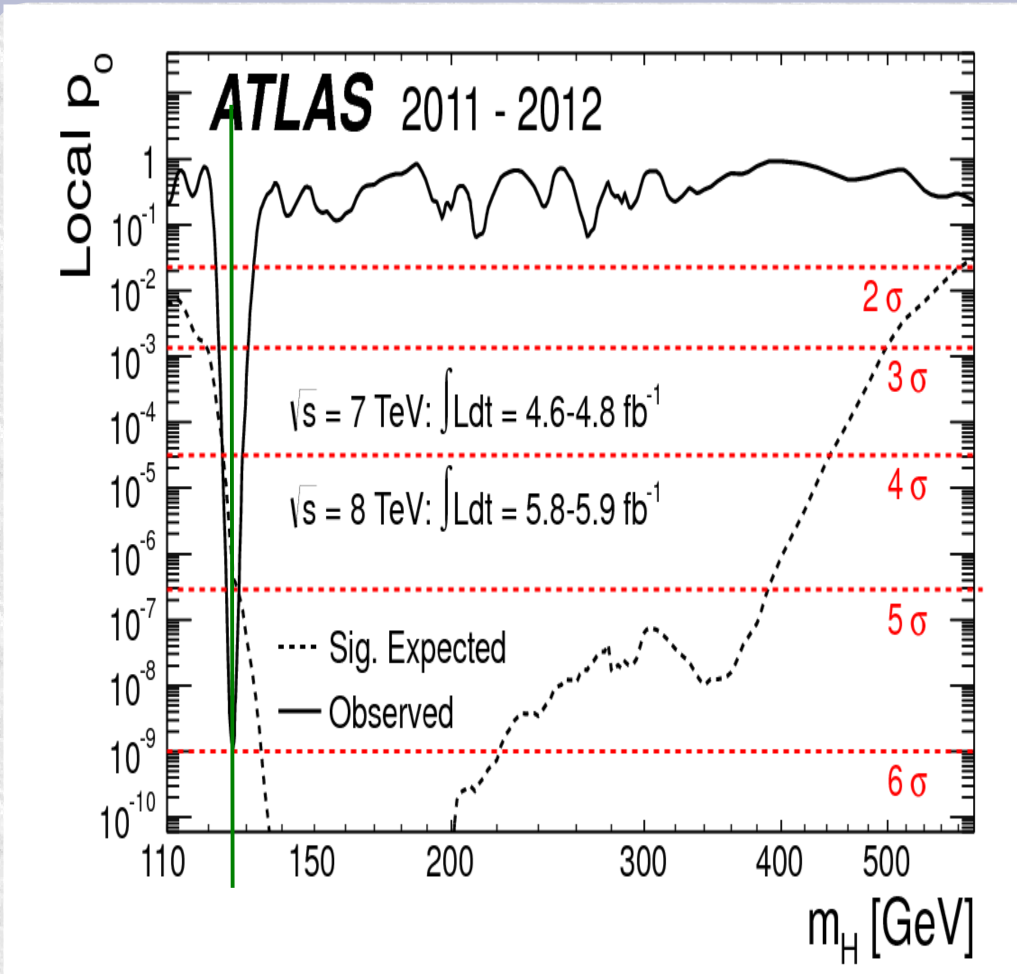
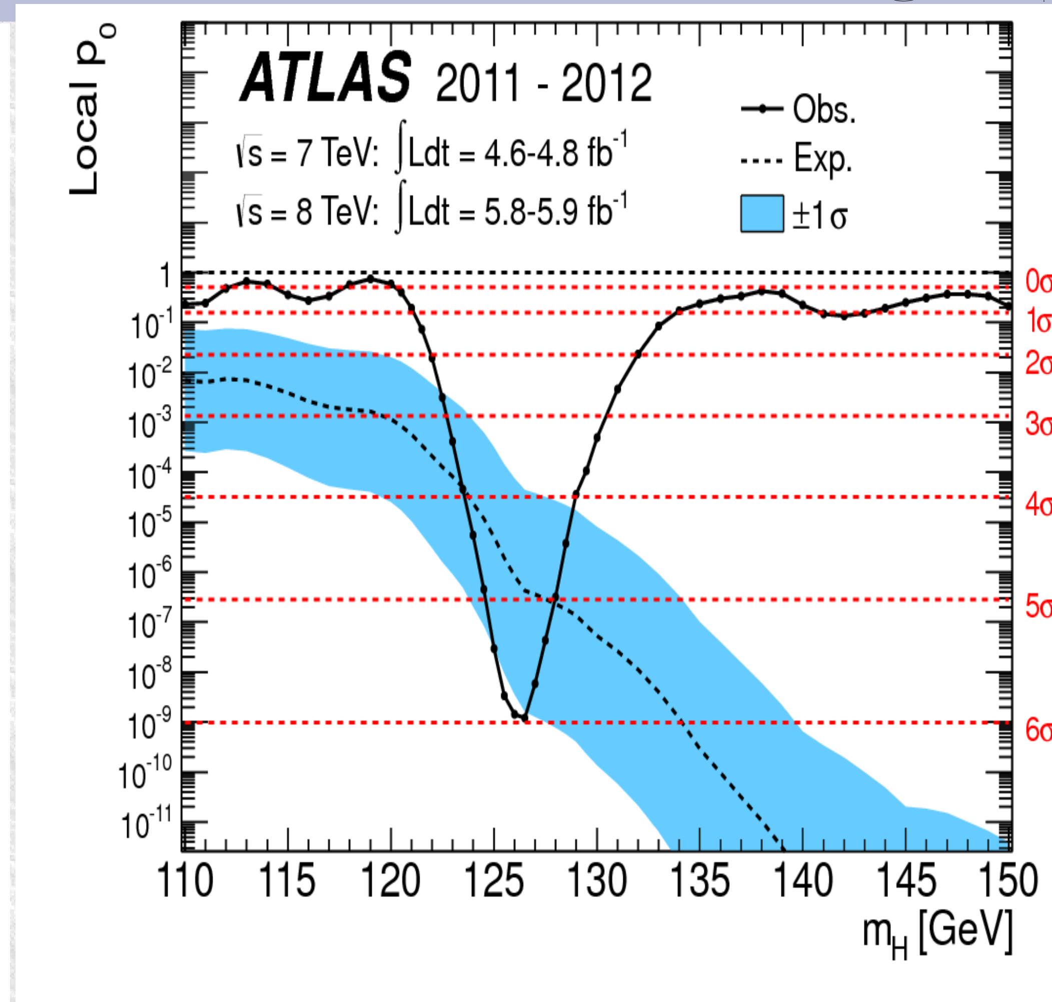
Combined p-value

July vintage





- Probabilities $2x10^{-9}$ or 5.9σ…**we got it**
  - Just outside 1σ band for signal

But what did we get?

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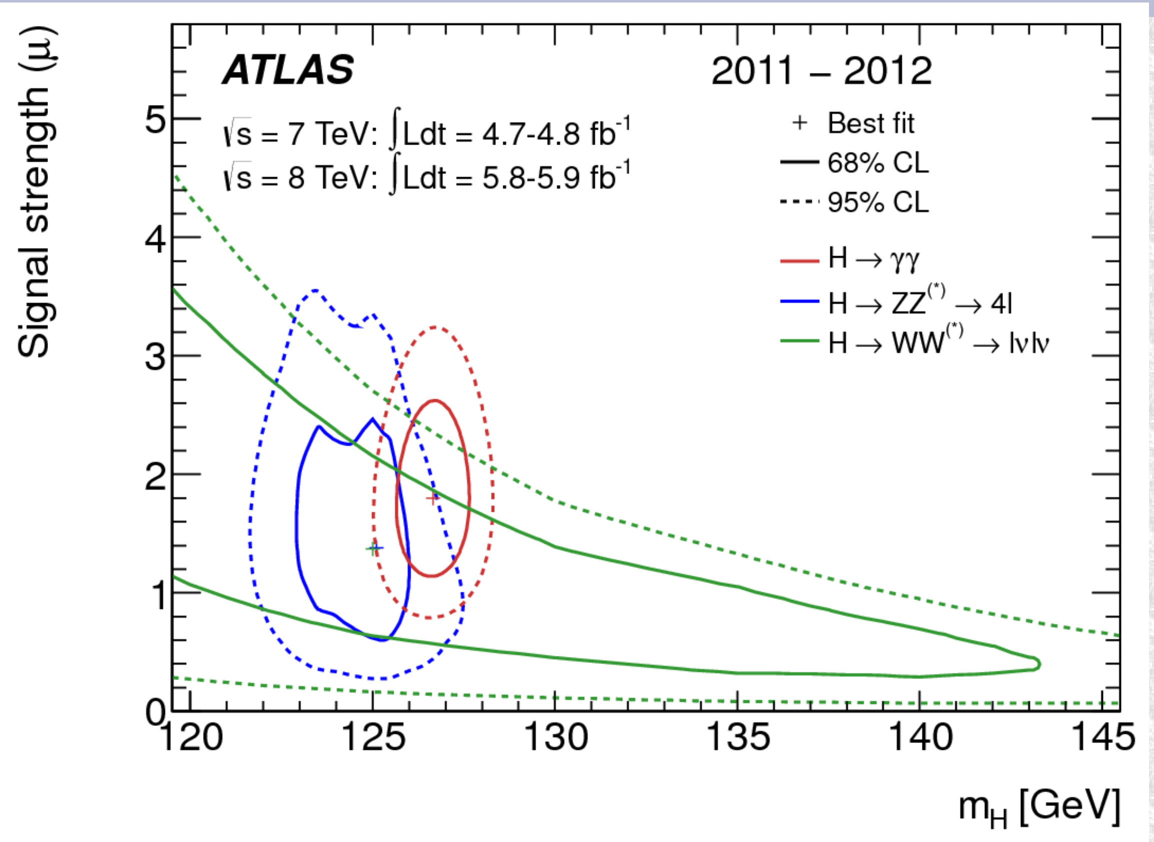
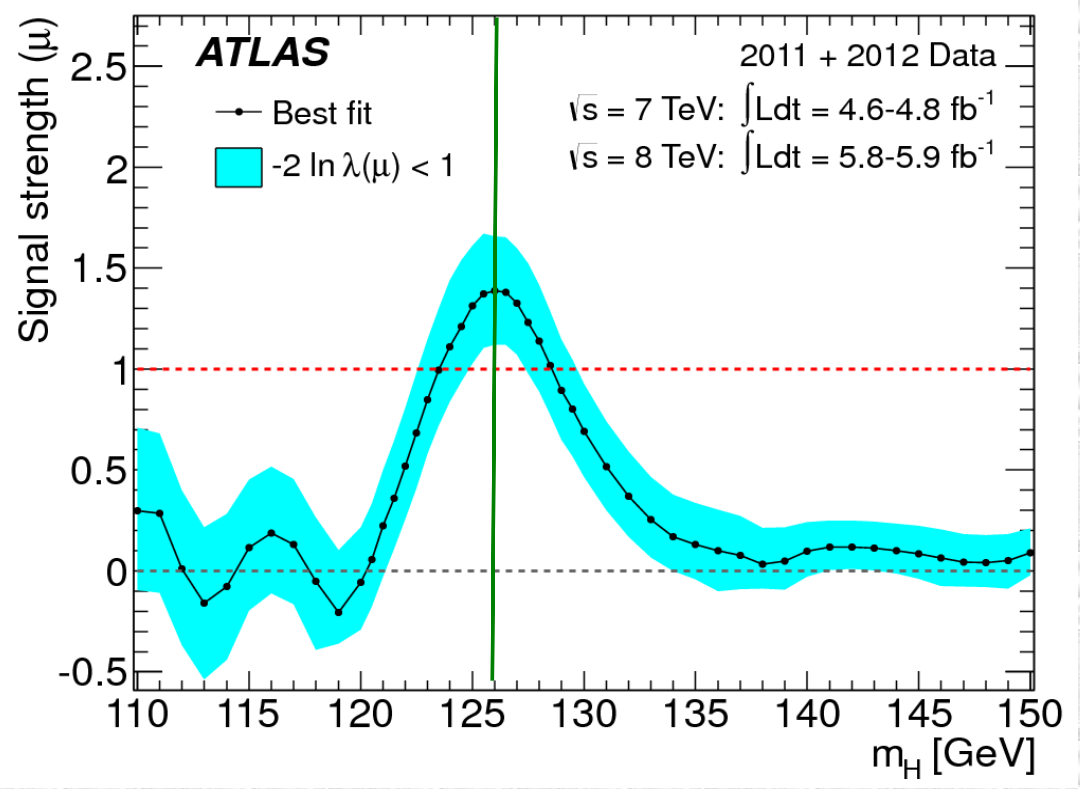
Rate versus Mass



- 2D fits of rate and mass reduce model dependence
  - m_H=126±0.4±0.4
- These channels all have consistent solutions.
  - 1 particle assumed from now on

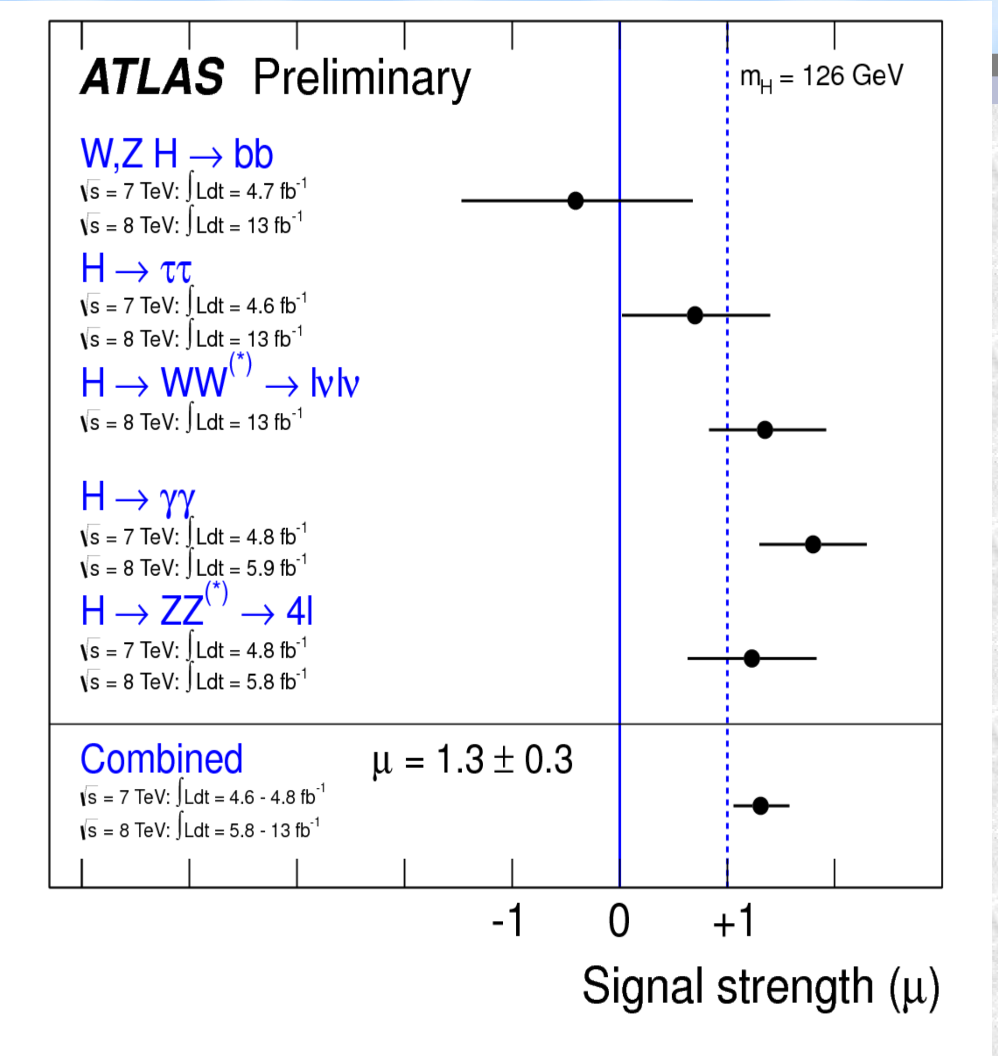
The Combined Results



July vintage

- For a signal at 126 (or 125.3):
  - ATLAS just over a sigma above SM rate, 1.4±0.3 @126
- This is consistent with a SM Higgs

Channel results



- Above zero in 4 out of 5 channel
  - More powerful ones (WW,ZZ,γγ) certainly are.
  - Is there too much γγ? Not really

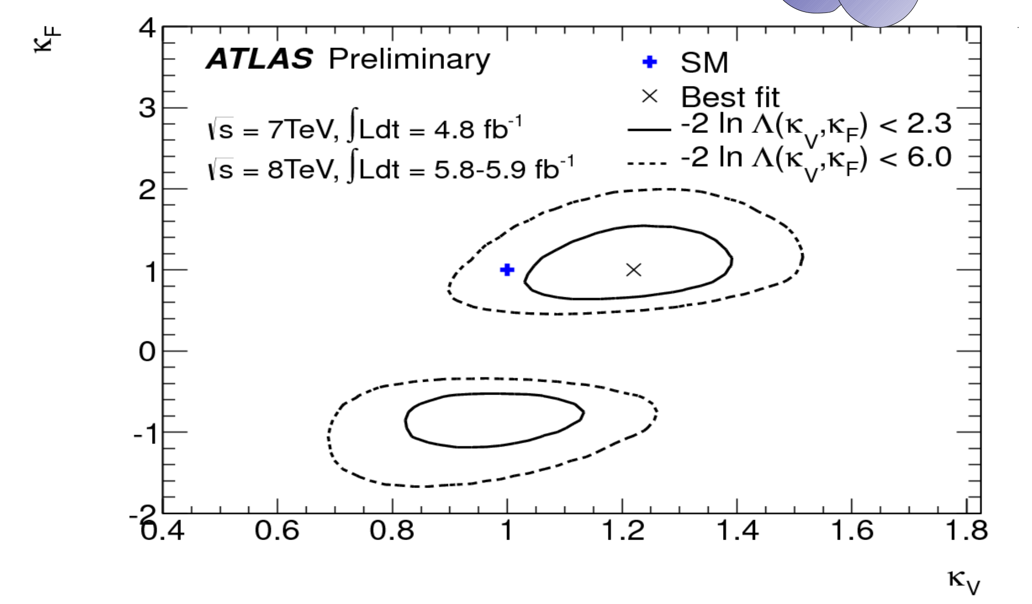
Interpreting couplings

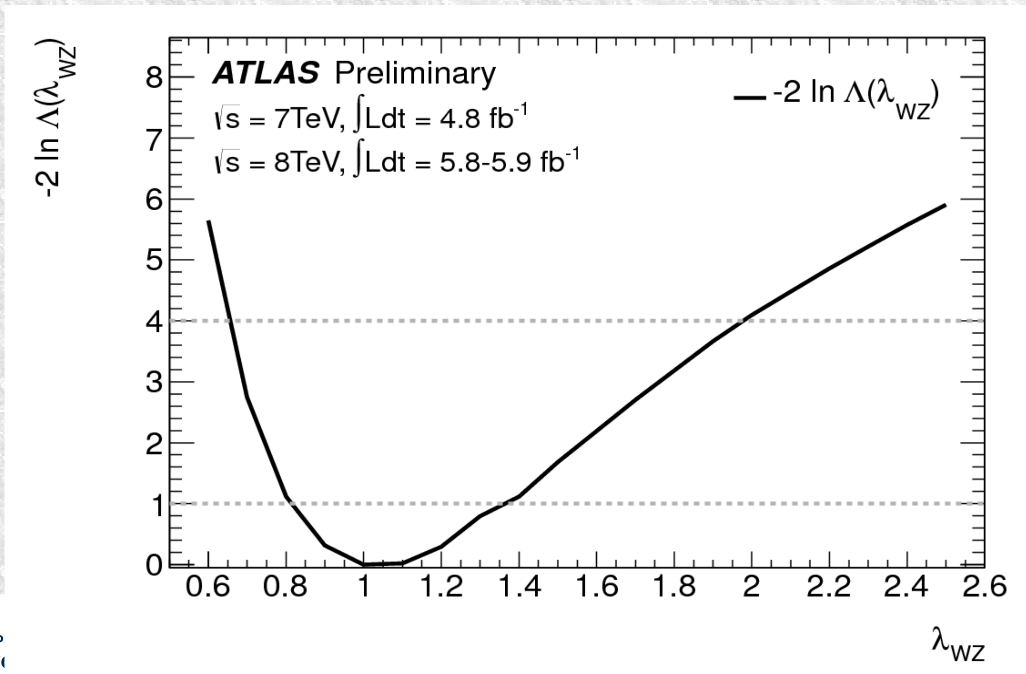
- WE want to test whether what we have is the Higgs boson
  - Like the EW fits done at LEP
- Need 'pseudo observables' that allow fits:
  - http://arxiv.org/abs/arXiv:1209.0040
- The LHC cannot measure the total width
  - There are always impossible decays like $H \rightarrow$ gluons
  - So some assumption is need
- Many couplings accessible eventually:
  - ZZ, WW, γγ, bb, tt, gg, ττ, μμ?, invisible?
  - Note gg/γγ are effective coupling through loops
- Too many to fit all at once
- Simplify by grouping the couplings
  - e.g. Bosons and fermions

$\kappa_V\kappa_F$ couplings

July vintage

- Top right:
  - W/Z scaled via κ_V
  - Fermions by κ_F
  - Assume no invisible decay
- Sign of fermion coupling tested in photon decay loop
  - We will have some sensitivity to sign with more data
- Measuring single top+Higgs would help this
- Bottom right tests W v Z
  - Custodial symmetry
  - $1.07^{+0.35}_{-0.27}$

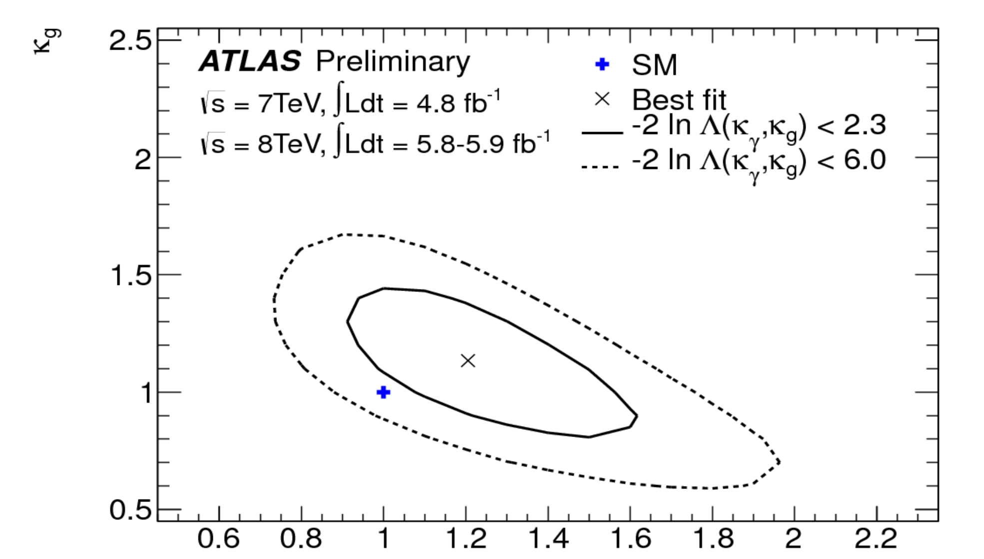


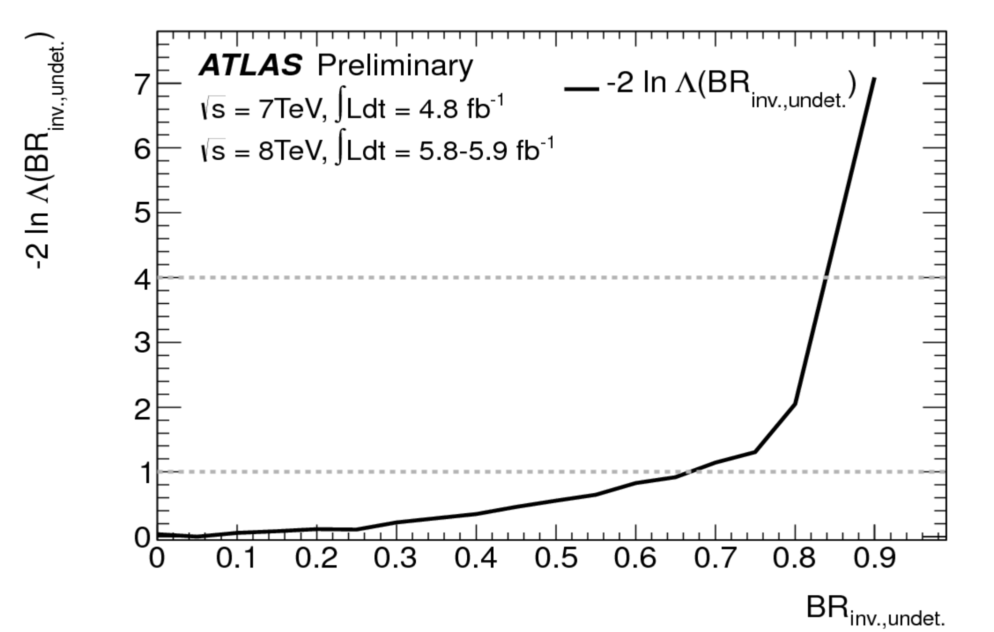


New particle search

July vintage

- Another possibility is to ASSUME a SM Higgs
  - But allow the loops to have unknown particles
  - ggF, H→γγ
- Top assumes no invisible decay
  - (1,1) is the SM strength
  - compatible with this
- Bottom tests for invisible branching ratio
  - Cannot all be invisible as we see it!
- We test many other possibilities ... all look like SM



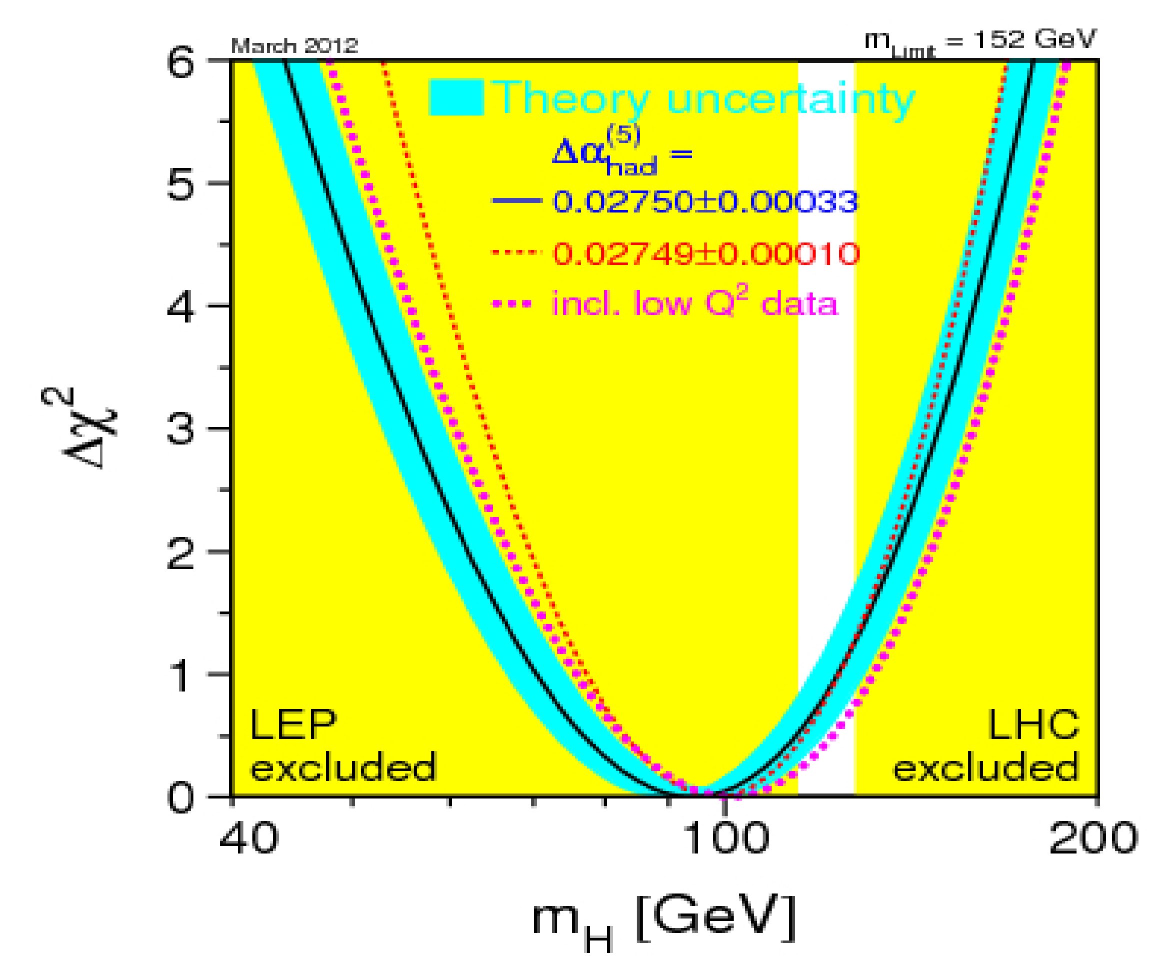


So what do we know?

Higgs Mass	Measured – agrees with SM rough prediction
Spin	Should be 0. We know it is integer, and not 1
Parity (mirror symmetric?)	Should be symmetric. Unknown
Charge	Zero, as it should be
Lifetime	Unknown, but narrow resonance and no obvious flight, OK.
Interaction with W,Z	Rates in WW,ZZ look as expected.
Interaction with matter (quarks/leptons)	ATLAS information weak here (But Tevatron has around 3σ evidence - twice expected)
Interaction with gluons	Total rates suggest this as expected
Interaction with photons	1.8±0.5 (ATLAS) This is less than 2σ high

- It is consistent with the SM Higgs
  - With reasonable statistical fluctuations

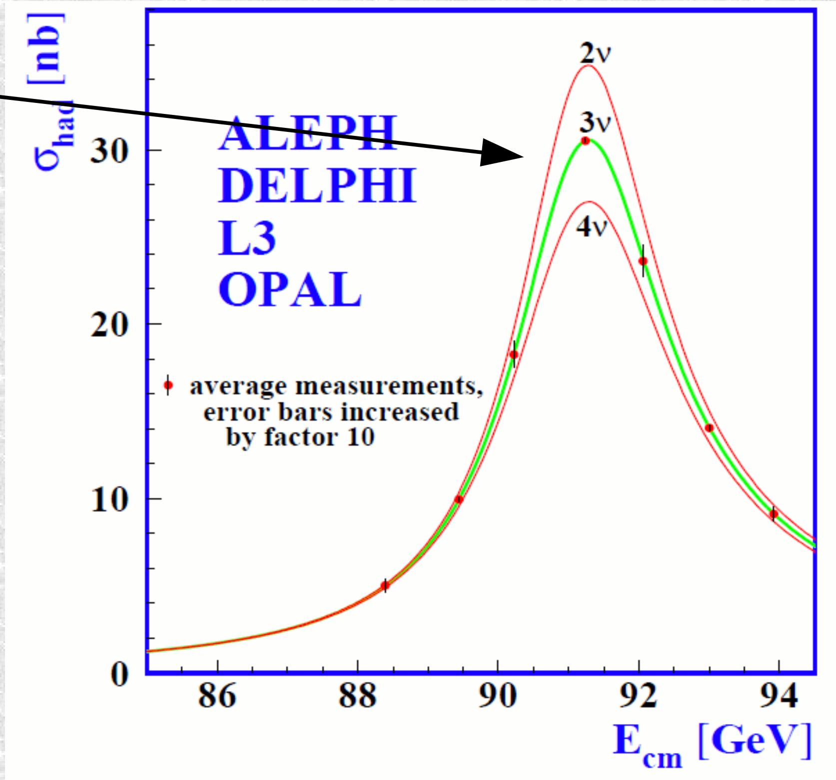
What does 125-126 tell us?

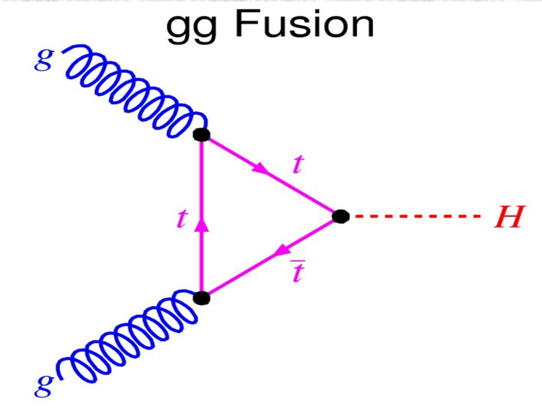


- In SM $m_H=94^{+29}_{-24}$ GeV
  - So observed mass fits SM with no additions

How many neutrinos?

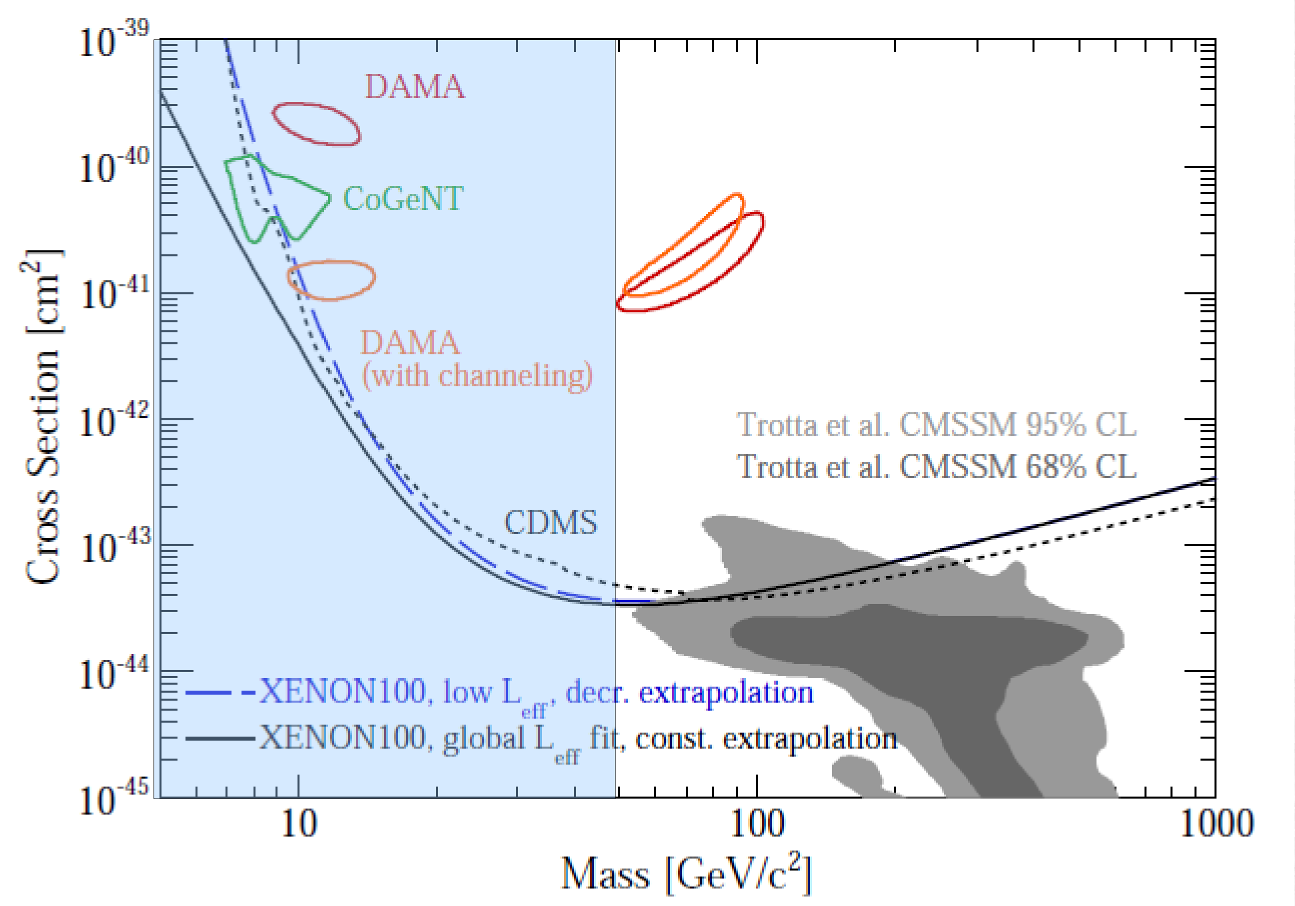
- LEP proved 3 light neutrinos
  - hence 3 generations?
- Now we know neutrinos have mass maybe $2m_\nu > m_Z$?
  - Could be a heavy neutrino
- But Higgs production is mostly through gluon fusion
  - Virtual top in a loop
  - A new heavier quark would increase the rate a lot
  - Whatever mass the quark had
- Much harder to believe in a 4th generation today.





Dark Matter?

- If this is a Higgs, in many models it couples strongly to dark matter
- 5-50GeV dark matter will be tested if Higgs decays as expected
- Not yet, but the blue area will be constrained
  - SUSY prediction OK!



Xenon plot from ArXiv: 1005.0380v3

SUSY prediction from: JHEP 0812:024,2008

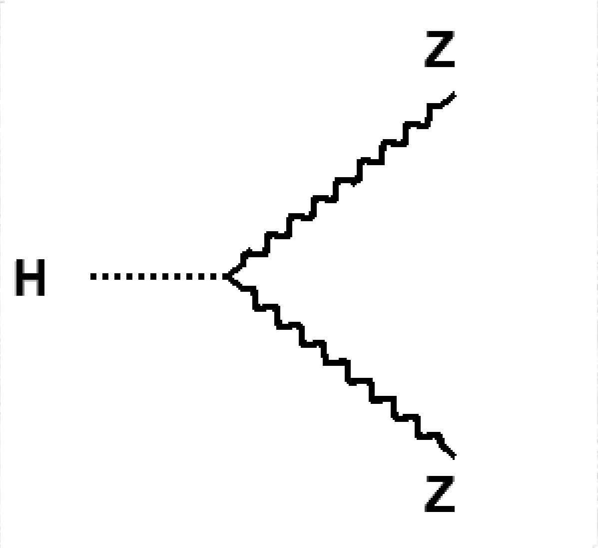
What about the Higgs field?

- A unique prediction of the Higgs mechanism is the vacuum energy density
  - Unlike the forces, it exists without a source
- The energy density of this field conflicts with cosmology
  - It is 120 orders of magnitude larger than dark energy – and the opposite sign
- So how do we persuade people it is there?

- Of course we need a quantum theory of gravity

Evidence: H to ZZ

- The measured HZZ rate is about 10xHγγ
  - After allowing for Br,
  - So HZZ must be singe vertex, not a loop
- The Z interacts with weak charge
  - But Z is neutral (Charge and weak charge)
- ZZH vertex shows the H must be weak charged
  - But in H→ZZ where does the charge go?



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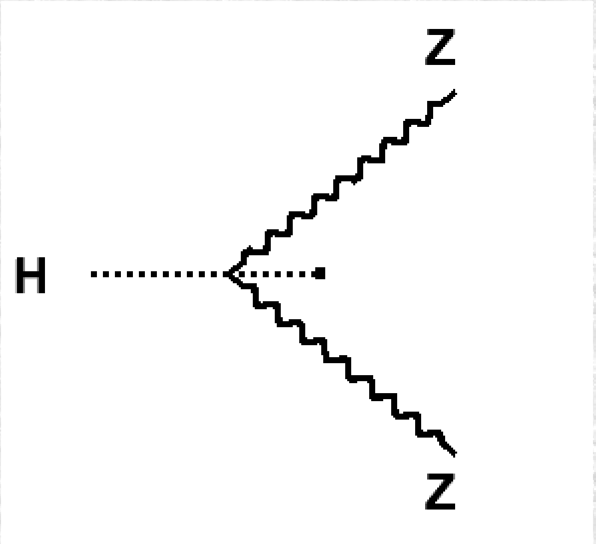
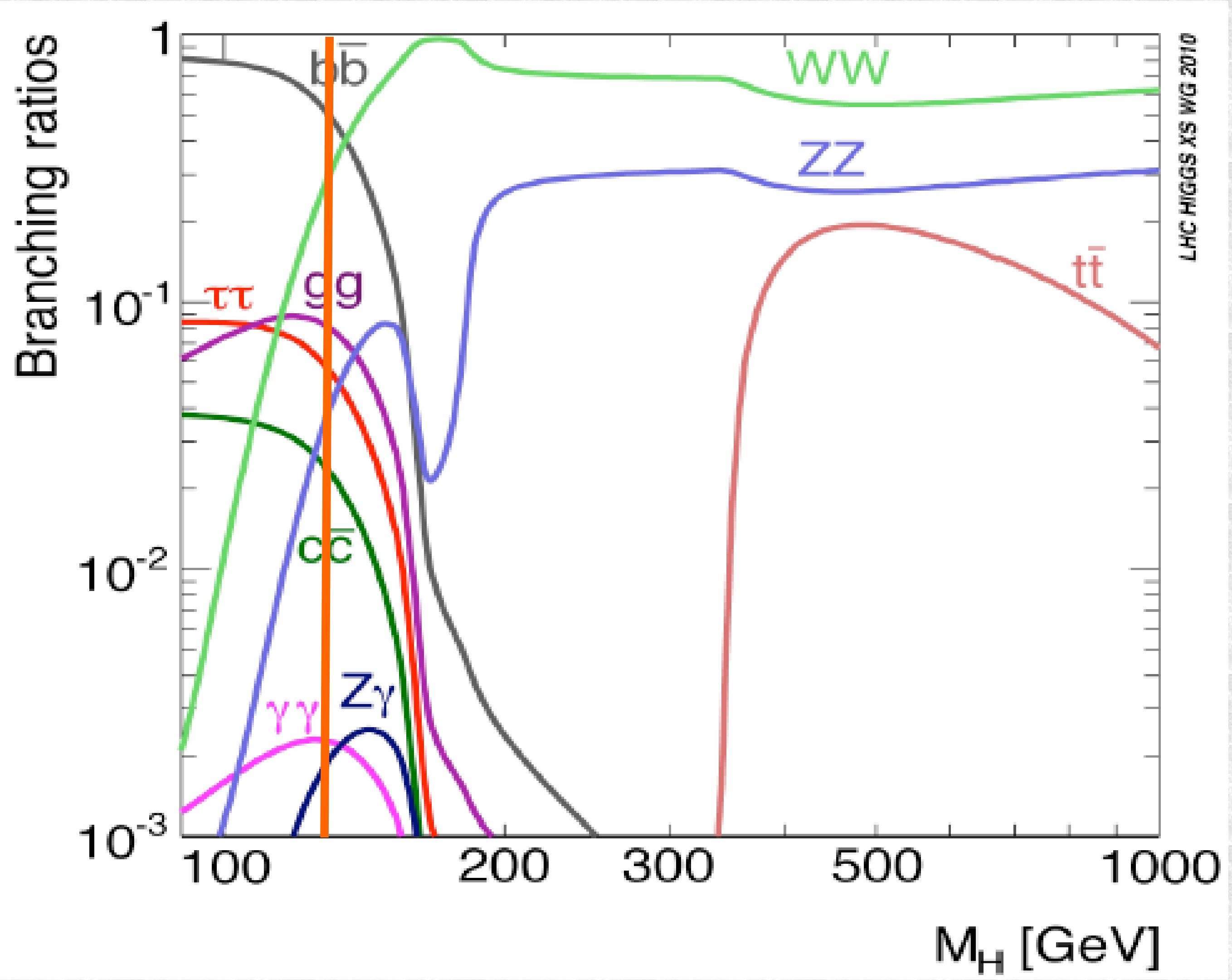
  - So HZZ must be singe vertex, not a loop
- The Z interacts with weak charge
  - But Z is neutral (Charge and weak charge)
- ZZH vertex shows the H must be weak charged
  - But in H→ZZ where does the charge go?
- It is really a 4-point coupling
  - One leg 'grounded' in the vacuum
- The ZZ decay shows vacuum participates
  - With a (weak) charge!
- The apparent 3 point couplings come from $D_\mu \varphi D_\mu \varphi$ expanded about v
- There IS a field



Quid nunc for Higgs?

- The mass is just great
- LHC targets 5 modes
  - ZZ
  - WW
  - γγ
  - bb
  - ττ
- More coming one day?
  - Zγ
  - μμ
  - XX



Full 2012 data

- How will we do?
  - The following GUESSES assume SM rates
  - They also assume a lot of work

	Gluon fusion	VBF	VH	ttH
ZZ	5σ	1σ	0	0
WW	3σ	1σ	0	0
γγ	4σ	2σ	0.5σ	0
bb	0	0	2σ	0.5σ
ττ	0	2.5σ	0.5σ	0

- If true we see 5 decays and 3 production mechanisms
- Pretty good for the discovery year!

Spin/parity

- We know integer spin, not 1
  - To reasonable confidence
- We can establish from ZZ/WW/γγ
  - ~3σ 0^+ v 0^-
  - ~3σ 2^+ v 0^+
- But there are caveats:
  - Spin 2 assumes the production/ helicity structure
    - Why should we assume any such thing?
    - There are some very hard to separate
  - The bosonic decay projects out 0+ from a mixed state
    - We are not sensitive to mixed (CP violating) systems
- So..we WILL learn something
  - But most theorists are not expecting surprises here
  - The rates match too well the 0^+ model...

Whither LHC?

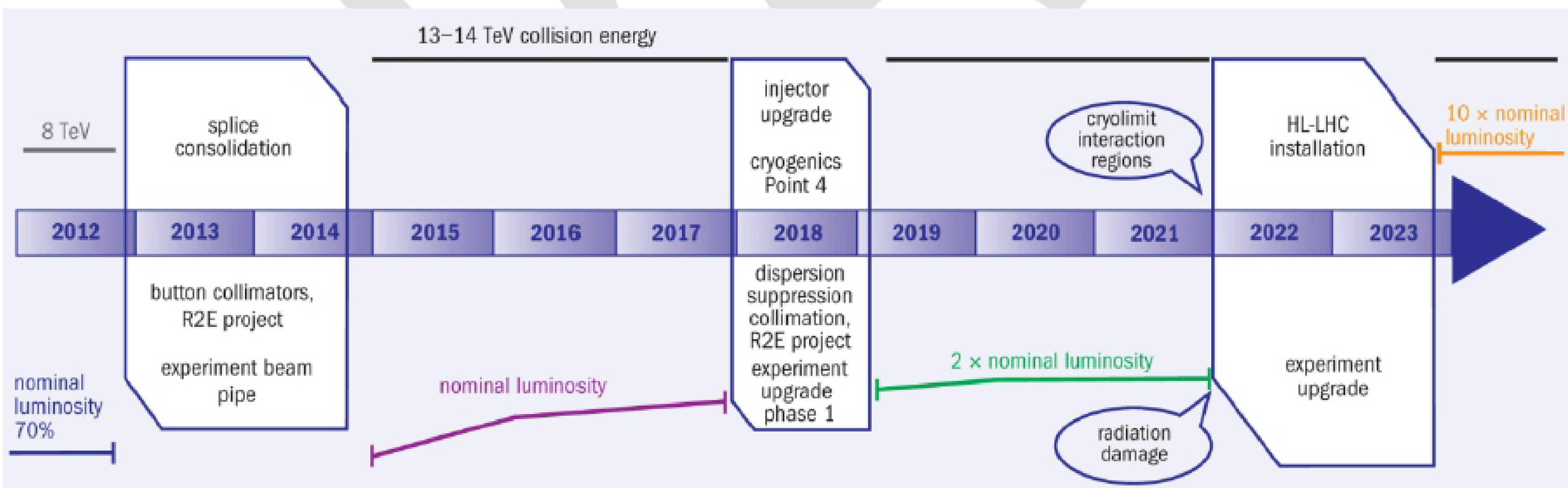
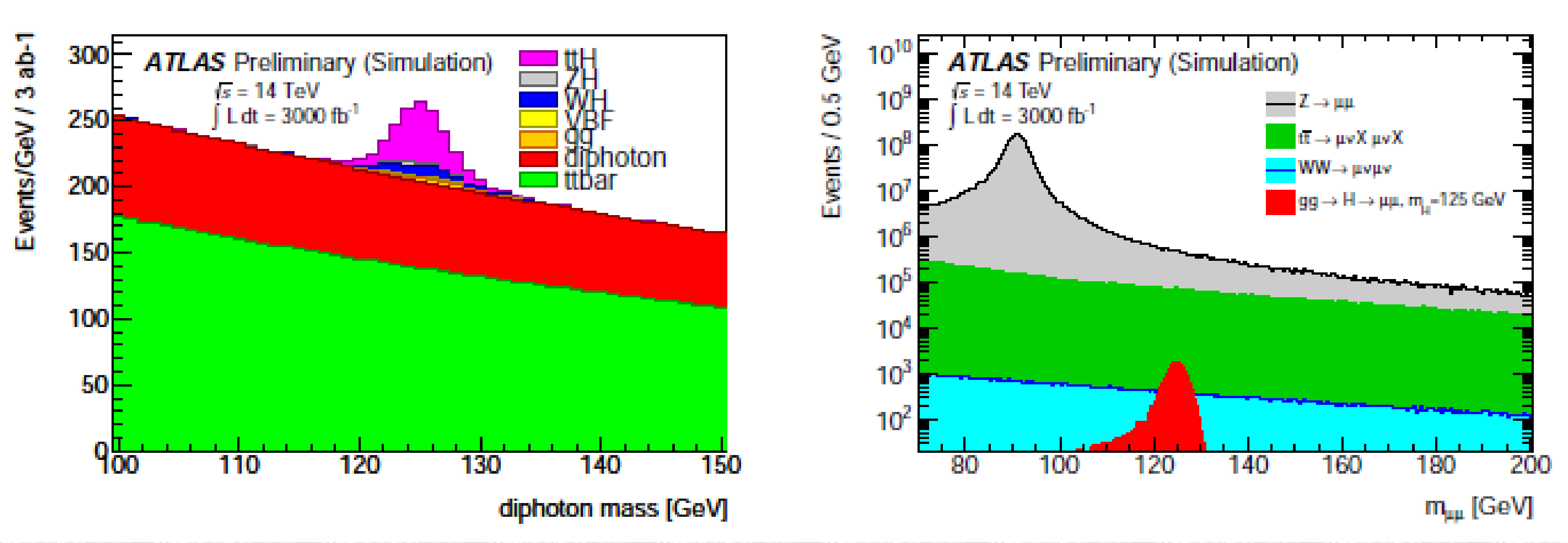


Figure 1: LHC baseline plan for the next ten years. In terms of energy of the collisions (upper line) and of luminosity (lower lines). The first long shutdown 2013-14 is to allow design parameters of beam energy and luminosity. The second one, 2018, is for secure luminosity and reliability as well as to upgrade the LHC Injectors.

- 25fb^{-1} by end of year
- 300fb^{-1} by end of 2021
  - With Energy 13+ TeV
  - ~50 times the Higgs events used for discovery...

HL-LHC and ATLAS

- LHC runs to 2022
- 300fb^{-1} at 14TeV expected
  - SLHC is proposed thereafter - 3000fb^{-1}
- ttH,H→γγ and H→μμ are two interesting studies



- But in general Higgs couplings must gain from factor 10 more data!

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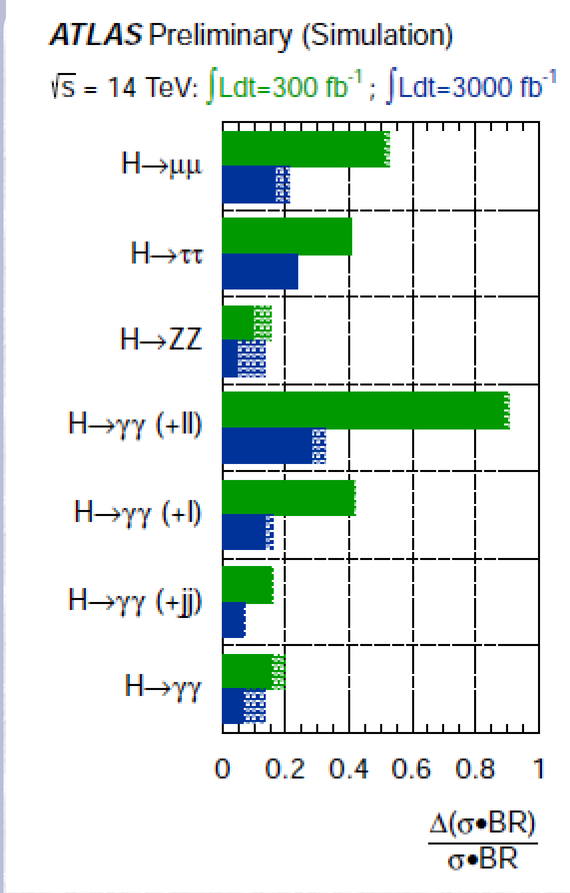
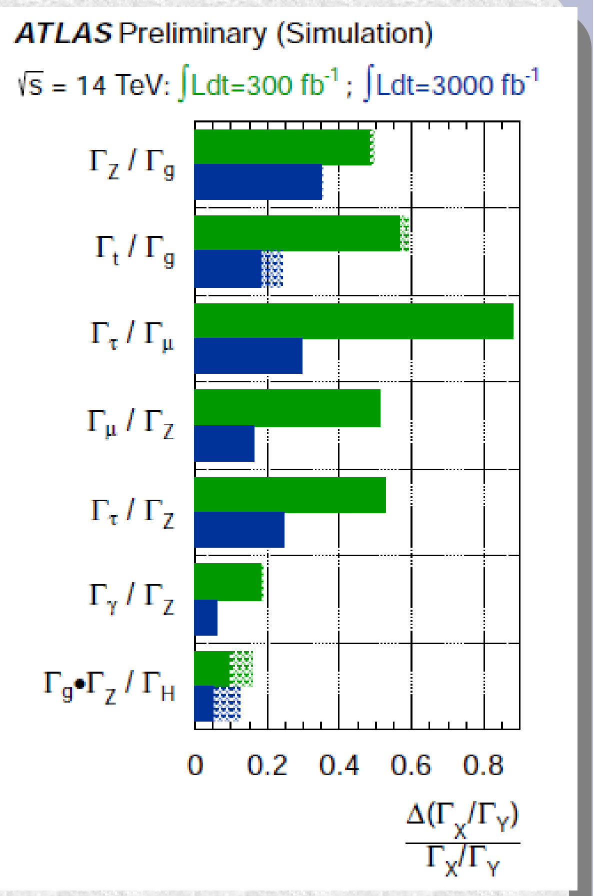
HL-LHC Higgs projections

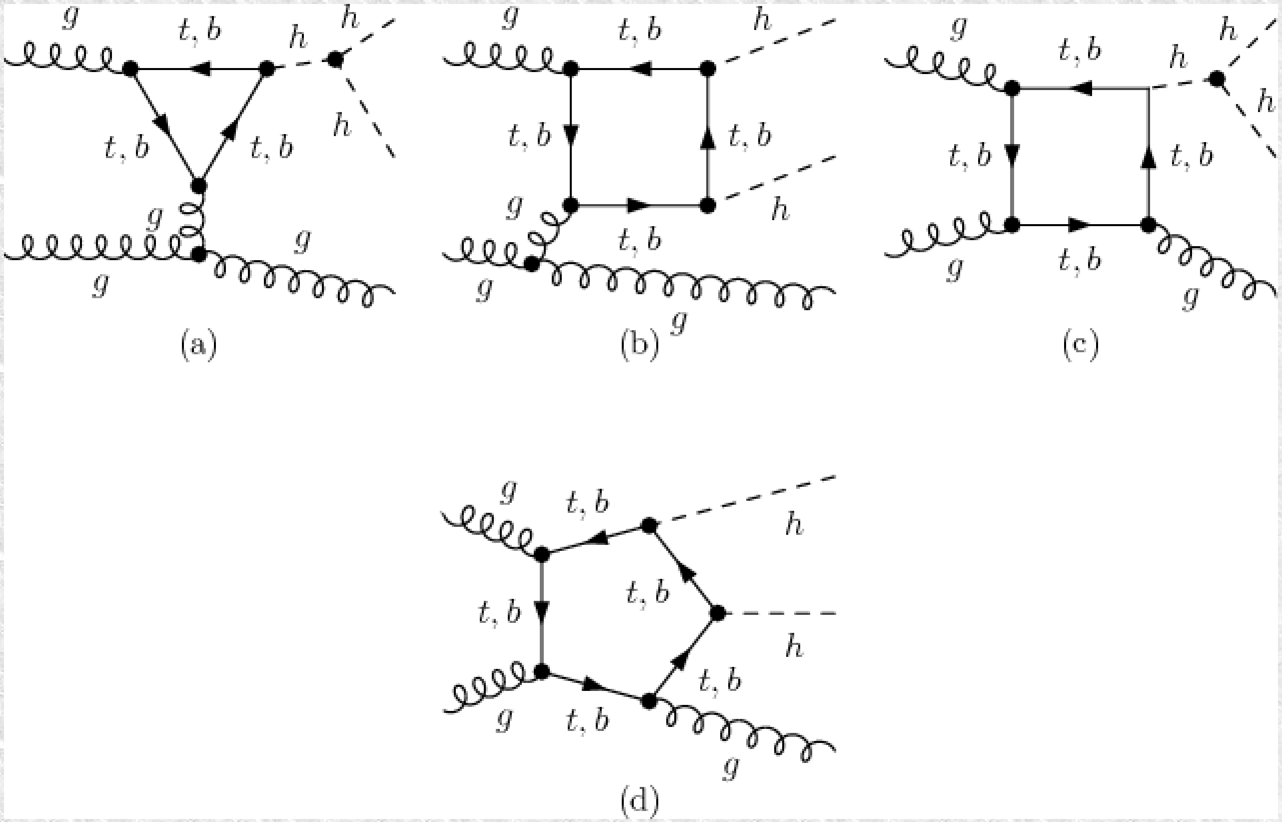


- Only subset of channels studied
  - But impressive performance possible
- LHC can never measure Higgs width
  - But ratios of couplings at O(20%) level
- But systematic errors are approximate in these estimates

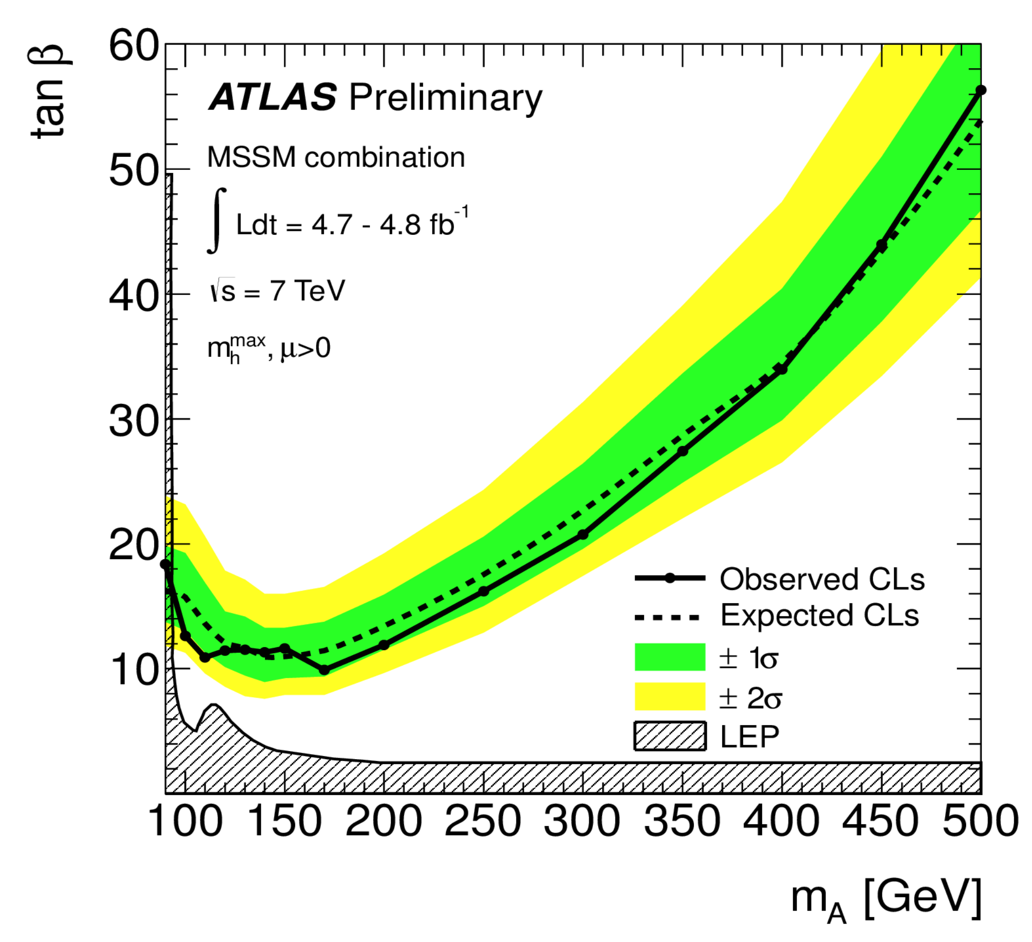


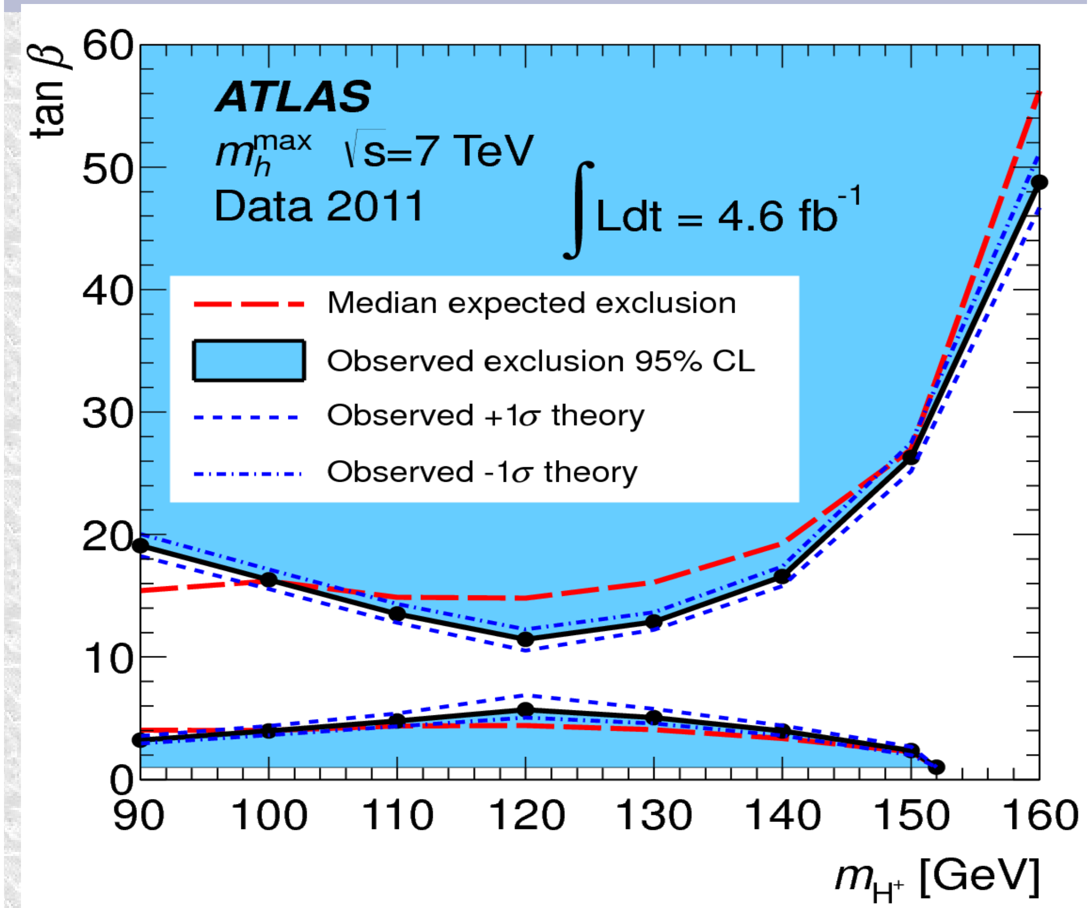
Self coupling

- Needs observation of Higgs pairs
  - Thats a tall order!
- But it is not enough
  - Need to prove triple Higgs involved
  - negative interference :(
- bbγγ allows 3σ HH observation
  - ATLAS+CMS, more channels, may give 3σ *coupling* measurement



MSSM Higgs





- No sign of MSSM Higgs
- If this is heavy Higgs then H+ mass should be below top
  – Maybe a second discovery soon?

Summary

- After 48 years we have found something remarkably like the SM Higgs boson:
  – 'A Higgs boson'; Rolf Heuer
  – Mass 126.0±0.4±0.4
- We need to establish what we have
  - Sensitivity getting to useful level in 5 channels
  - Looking forward to Moriond
- The ATLAS is performing superbly
- In 2012 LHC is working remarkably well
  – ATLAS has recorded over 20fb^{-1} at 8TeV
  – By 2021, 300fb^{-1} at 14TeV will allow first precise studies

SLHC as Higgs factory

- Increasing luminosity, factor 10, to $10^{35}cm^{-2}s^{-1}$
  - New proton linac & focus elements needed
  - Pileup increases by similar factor, 300 events/BX?
  - New trackers, calorimetry readout, TDAQ needed to cope
- Beams are rapidly 'burnt-off'
  - It may be helpful to limit luminosity early on
  - Extends beam lifetime, limits pileup
- Going from $300fb^{-1}$ to $3000fb^{-1}$ at 14 TeV
  - $H\rightarrow ZZ$ go from 300 to 3000
  - Improved measurements clear in ZZ, γγ,
    - $H\rightarrow\mu\mu$ and Zγ can be measured
  - WW, bb, ττ will be improved – but systematics hard to know
  - Self-coupling in HH $\rightarrow$bbγγ and bbττ looks just possible
    - Again, estimates of systematics difficult