Higgs boson searches at ATLAS

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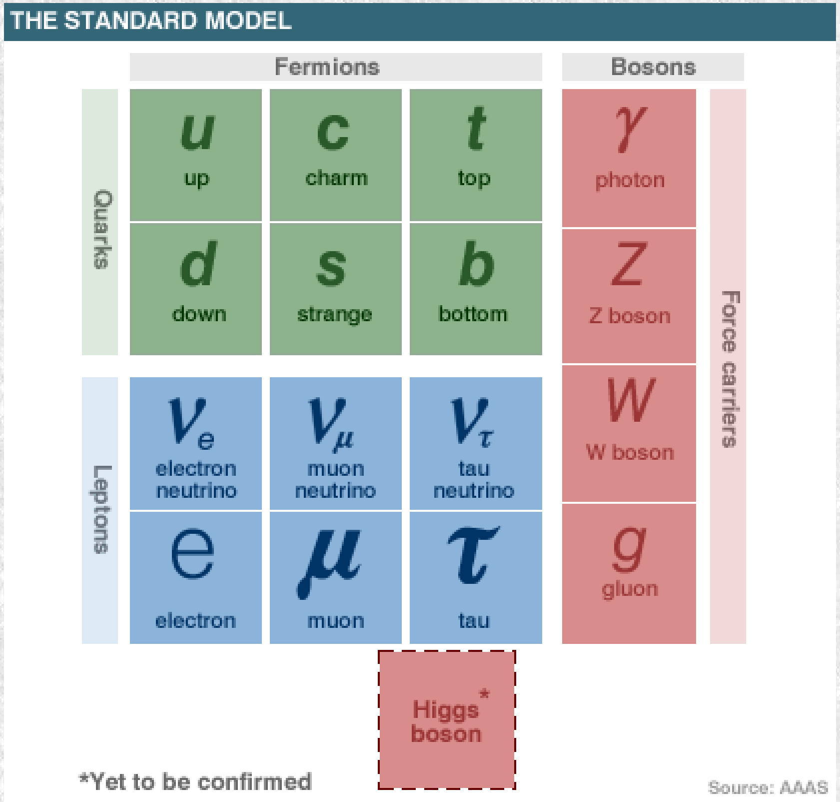
- **The discovery**
- **What do we know so far?**
- **Outlook**

The Standard Model

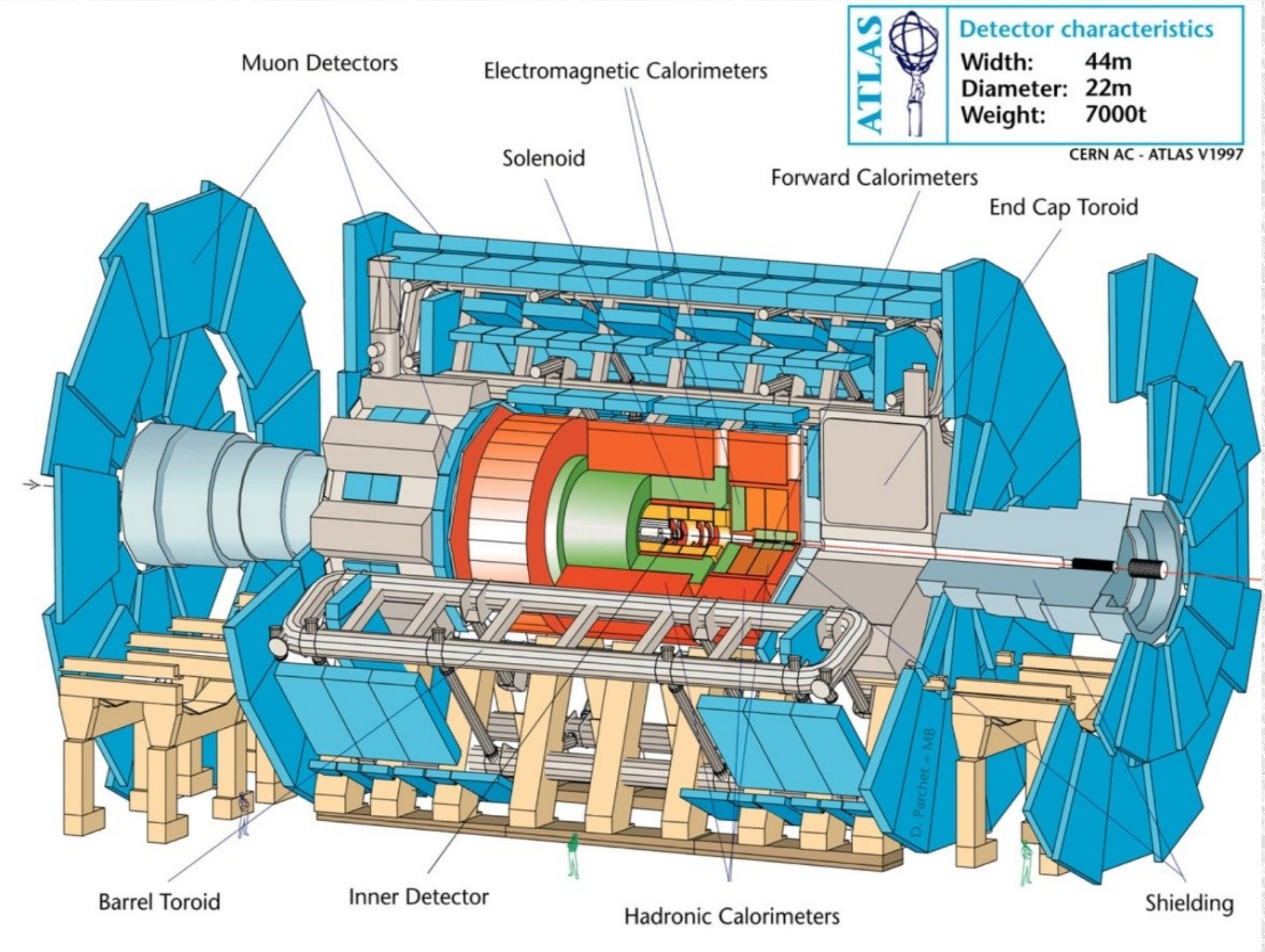
- The 'Standard Model' has been remarkable successful
  - 3 forces
  - 2→3 families of quarks/leptons
- But the Higgs sector remained unknown...until now
- A Higgs-like boson has been discovered
  - What do we know?
  - What more can we learn?
- Is it alone?



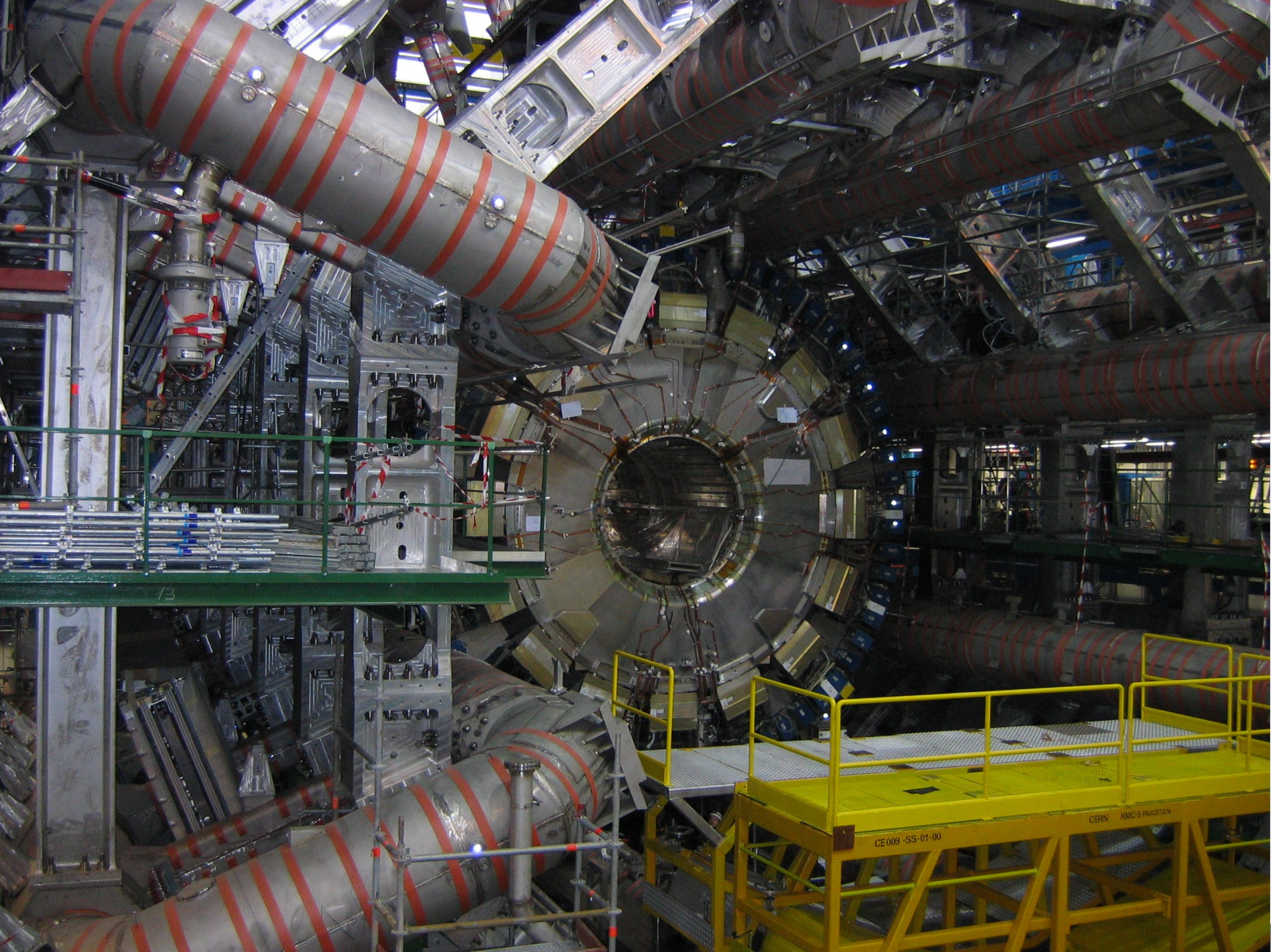
History of the search

- 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 excludes m_H>300GeV
- 2000 LEP limits reach 114.4 GeV
  - 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


CERN HMC-3 PAKISTAN
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Hunting the Higgs Boson

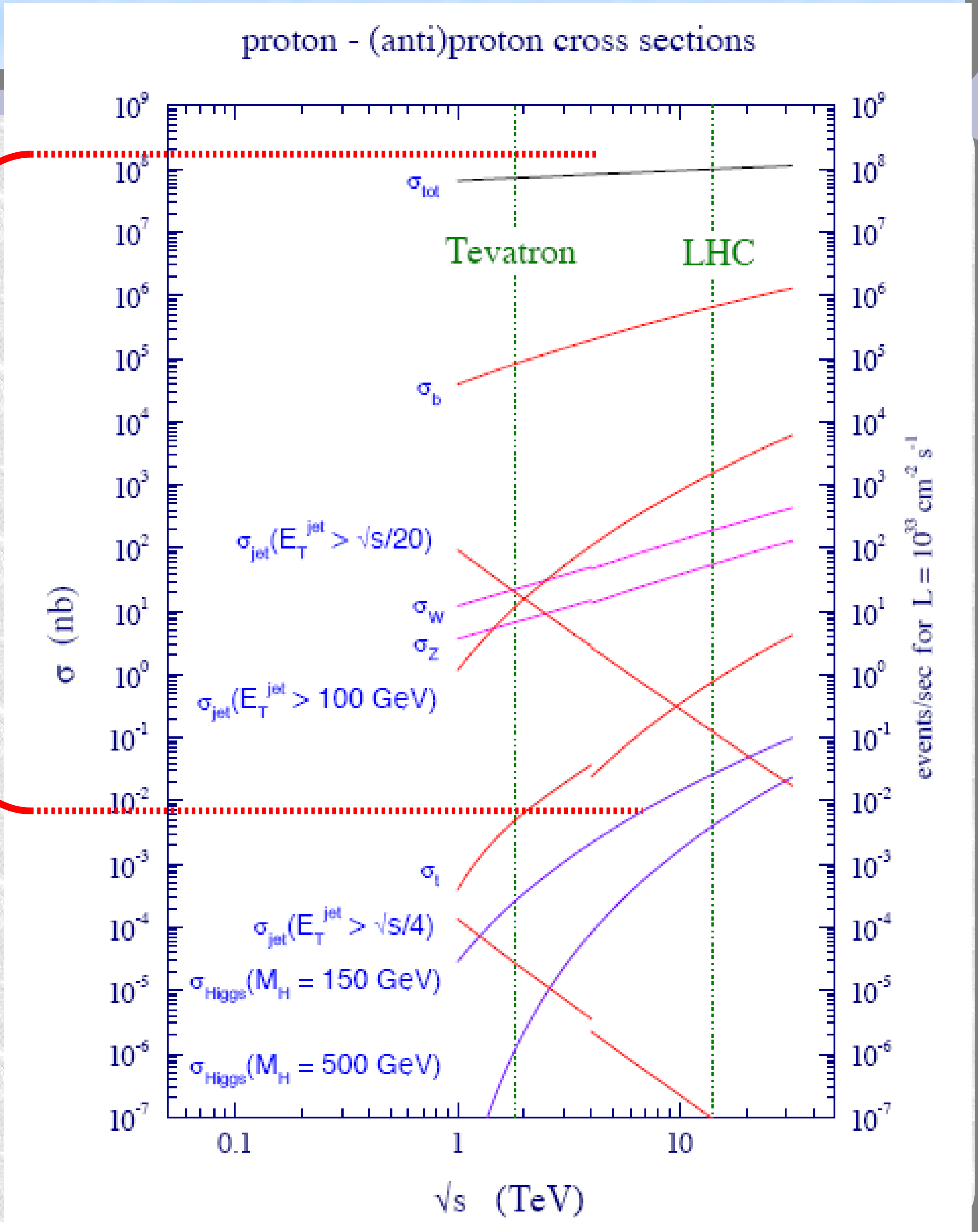
Never forget background

- LHC backgrounds!

10^{10}

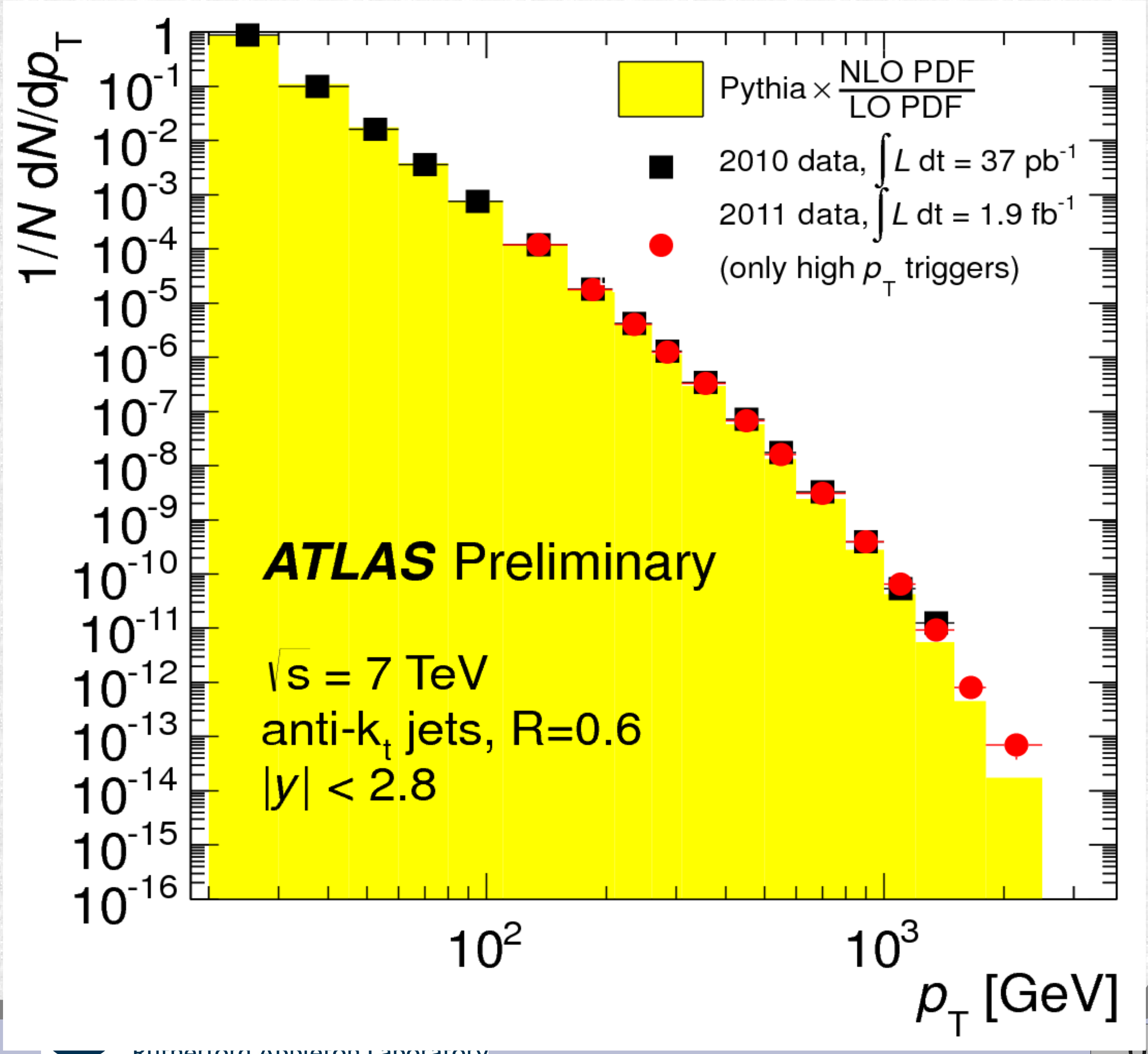
Every event at a lepton collider is physics; every event at a hadron collider is background

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

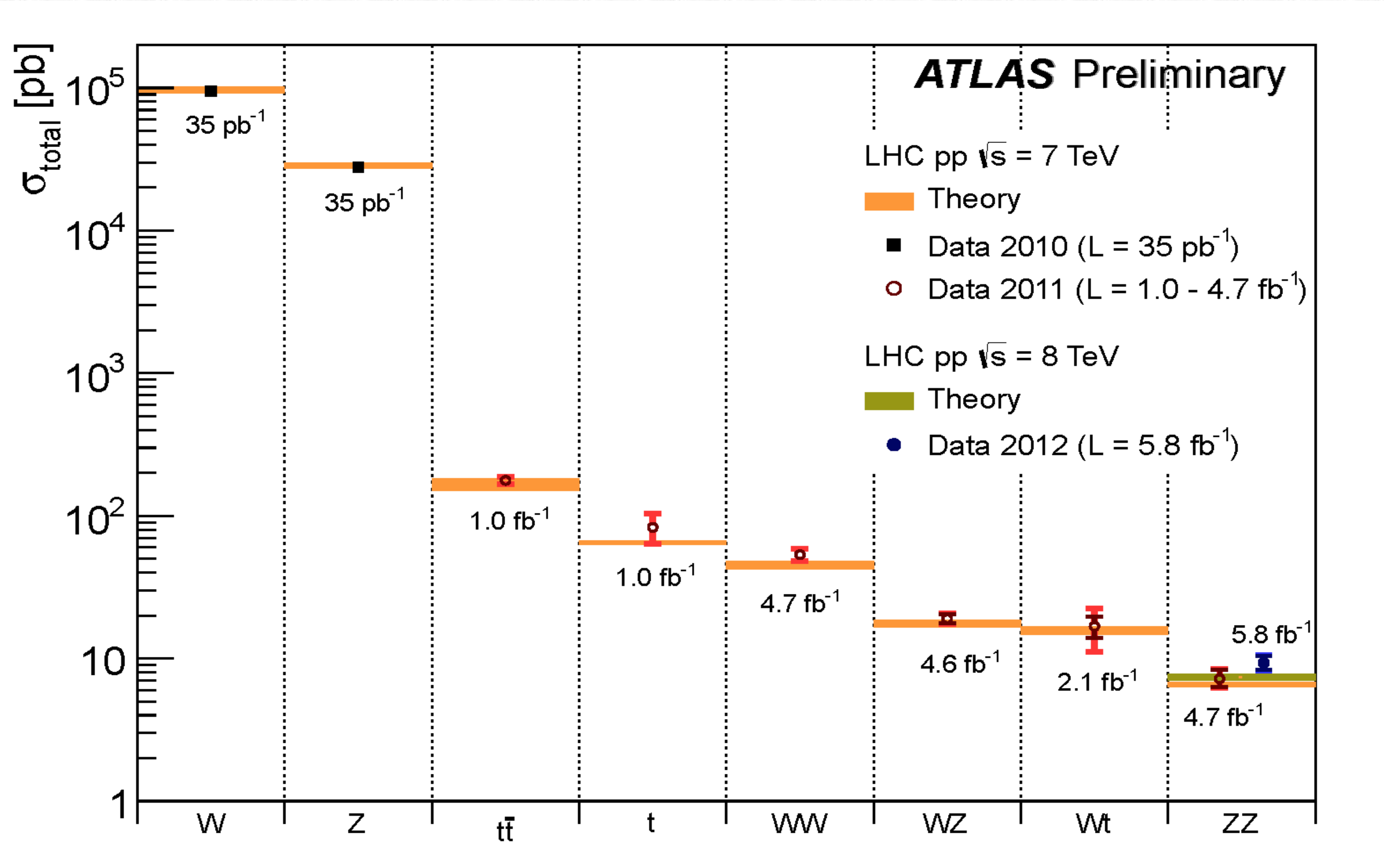


Trigger strategies 2012

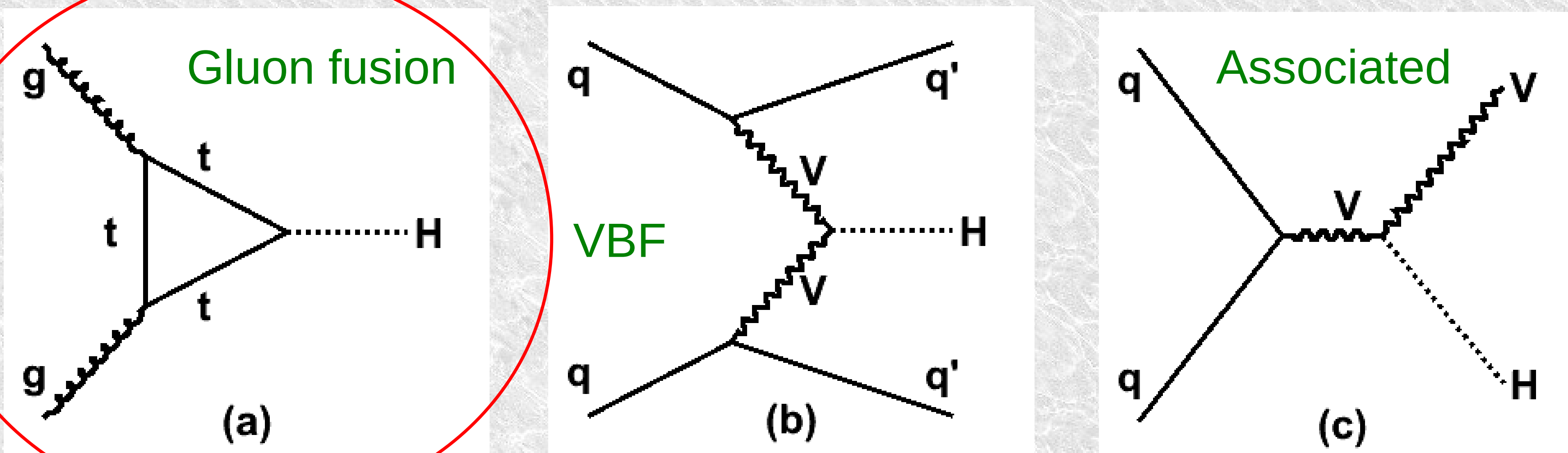
Single muon	p_T>24GeV	llll, lνlν
Single electron	p_T>24GeV	llll, lνlν
Muon pair	p_T > (13,13) GeV	llll
Asymmetric Muon pair	p_T > (18,8) GeV	llll
Electron pair	P_t > (12,12) GeV	llll
Photon pair	P_t > (12,12) GeV	γγ

- The llll analysis maximises trigger efficiency
- The WW however emphasizes comprehensibility
- The two-photon efficiency is over 99%

W/Z/top measurements



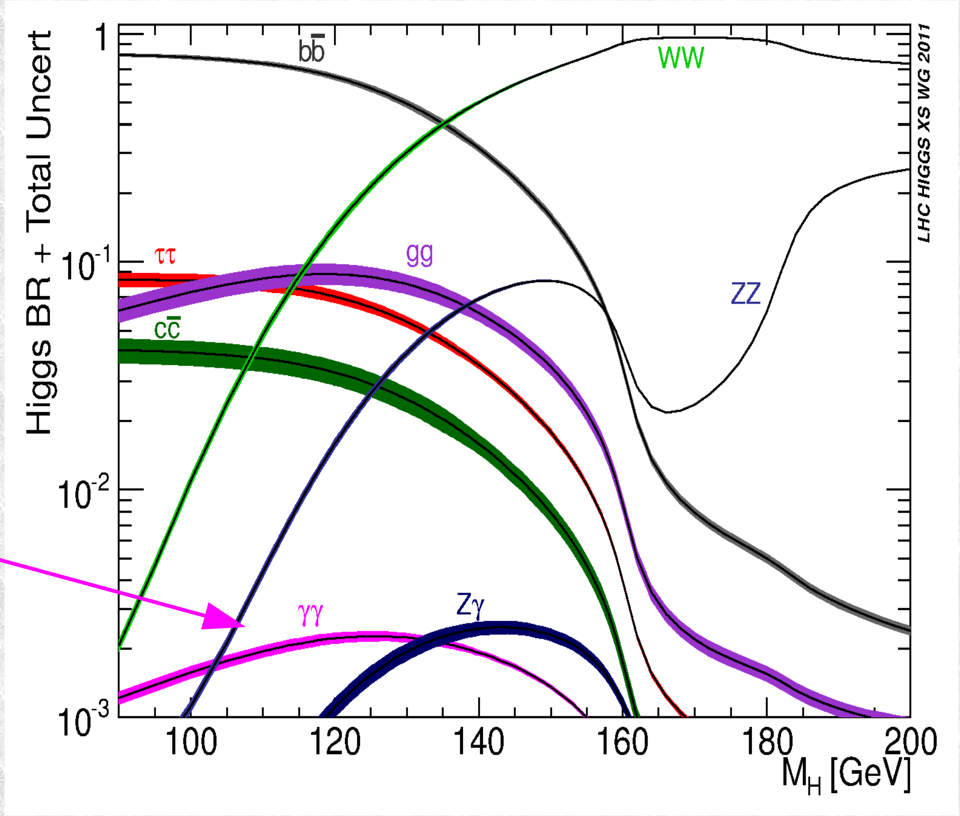
Higgs production



- 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

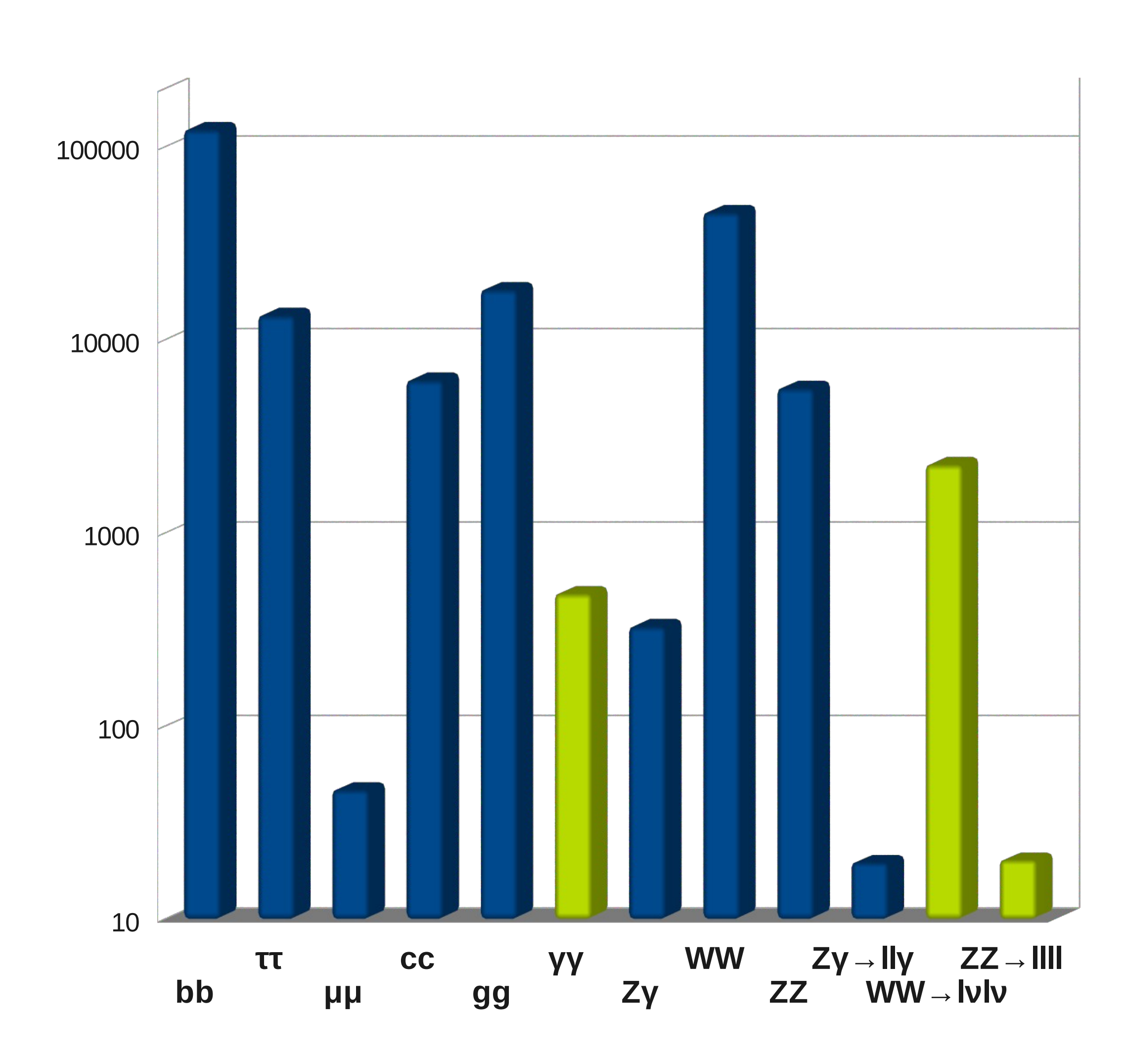
Higgs decay modes used

- 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, low mass
- H → bb
  - $t\bar{t}H$, WH, ZH useful but hard



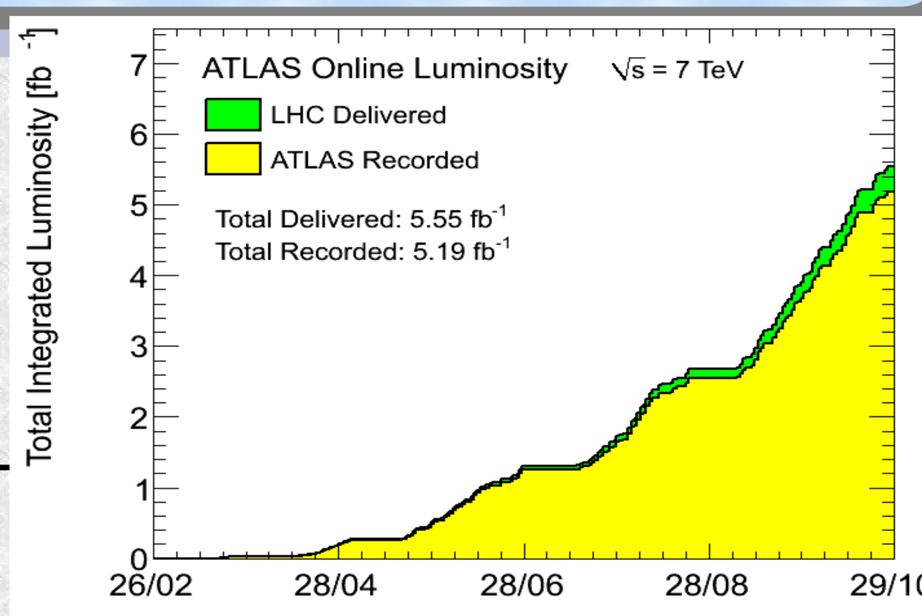
Rates by channel at 125GeV

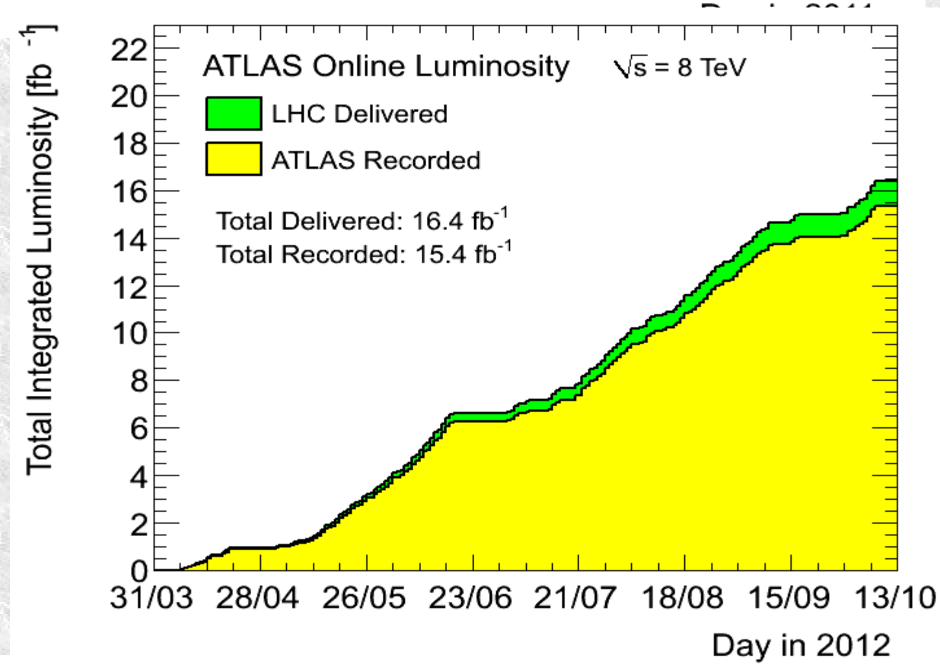
- Data to June 2012
- From 10s to 100000 events per channel
  - Easy!
- But total pp events: 8×10^{14}
- 20 Higgs to llll events
- Needs incredible background rejection
  - The green channels end up the most sensitive



Data collection

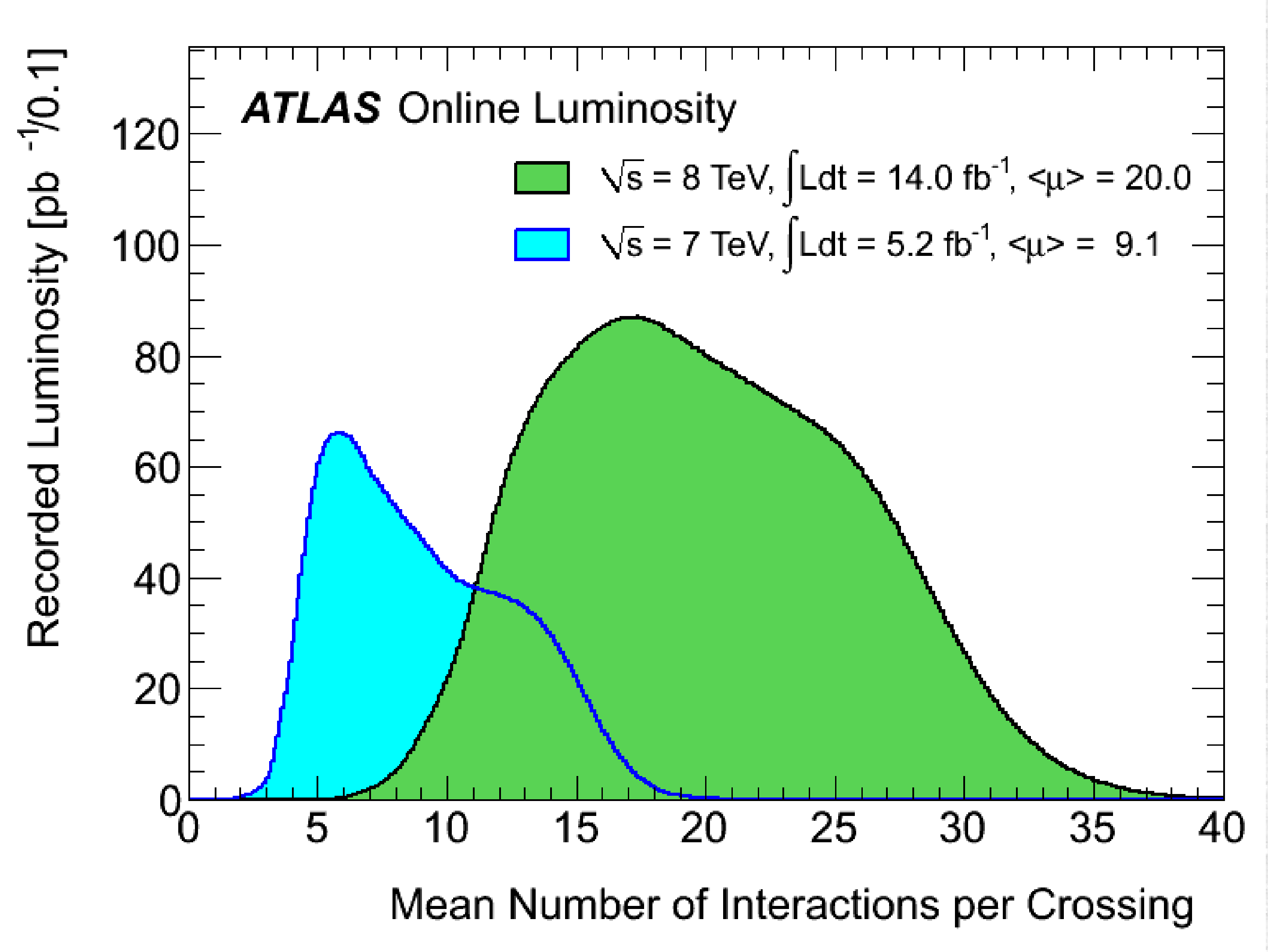
- LHC delivered 5fb^{-1} in 2011
  - Gave first hints for SM Higgs
- √s raised 7 → 8TeV in 2012
- Luminosity already triple 2011
  - 6 fb^{-1} allowed Higgs discovery
- Great effort by LHC team!
- We hope for still more by Christmas





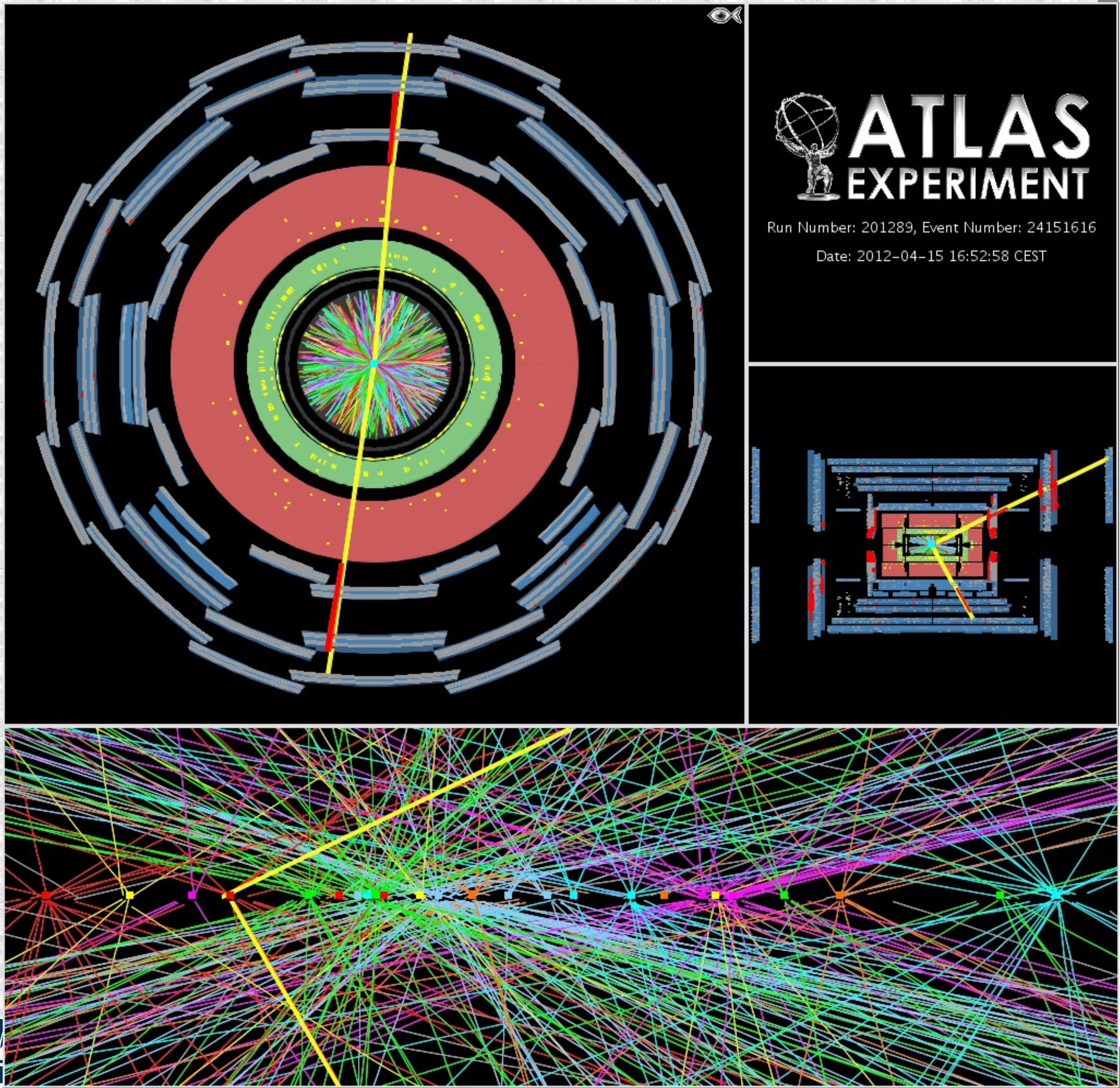
Pileup passing design

- 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



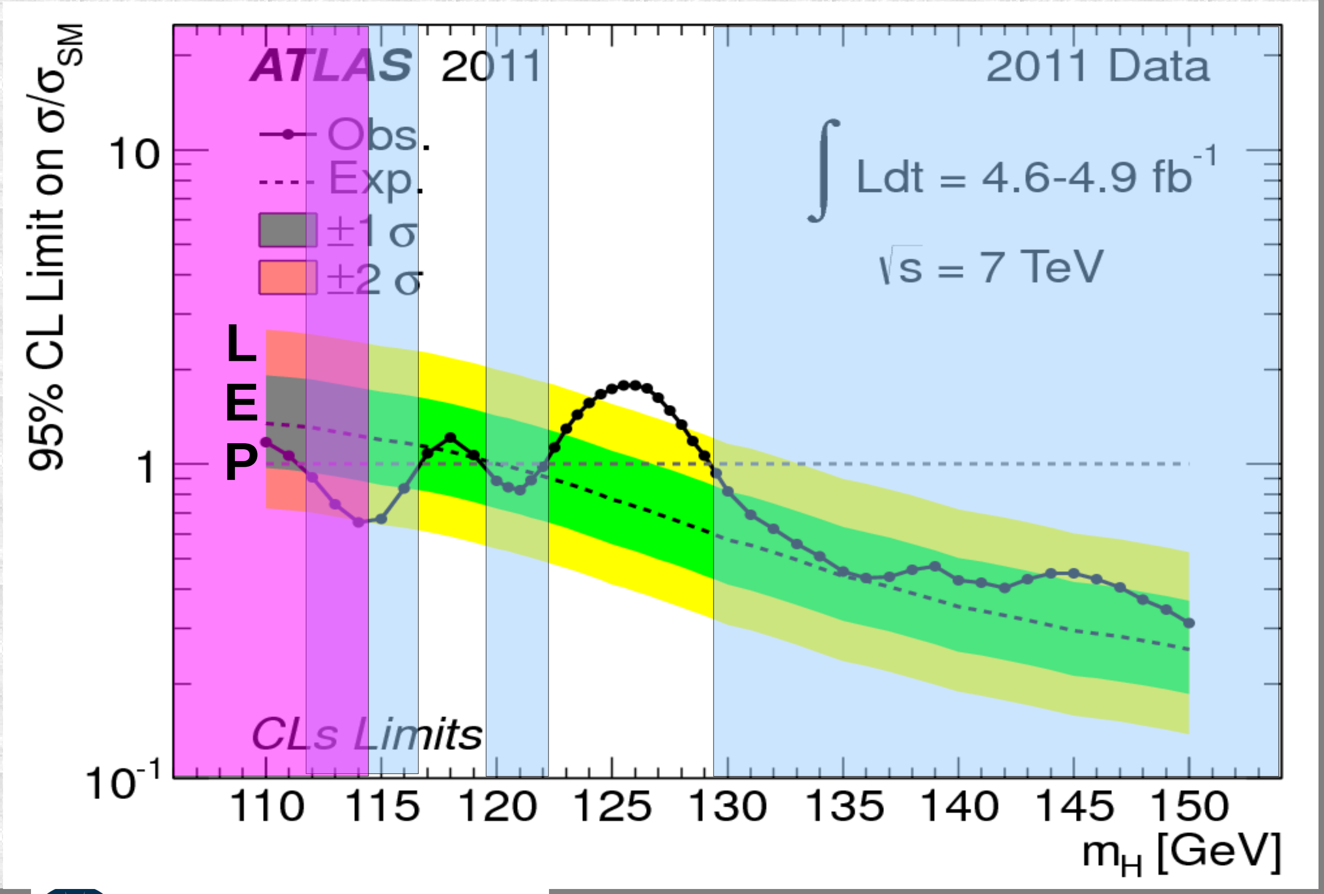
Pileup in 2012

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



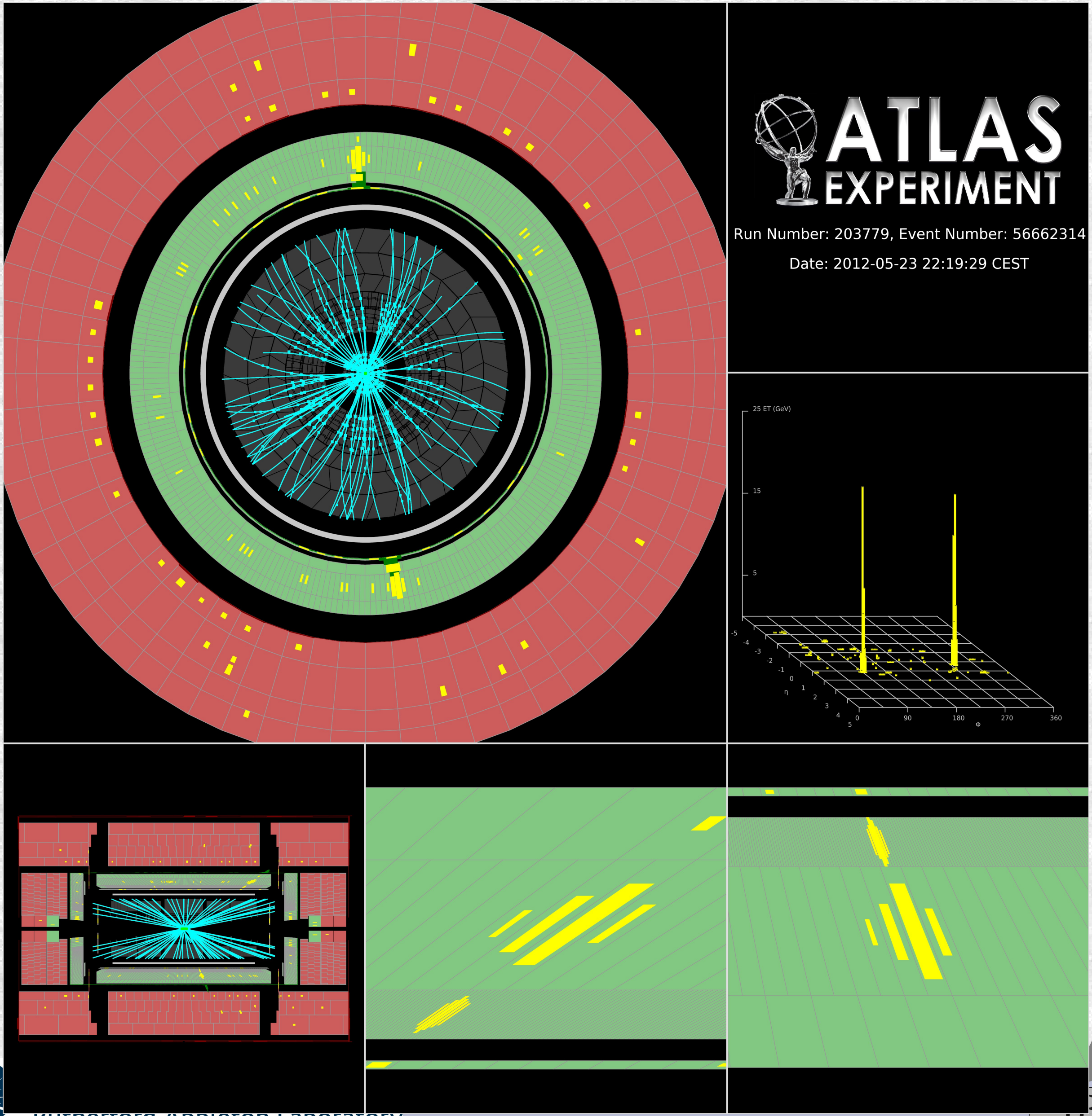
So what do 2012 data say?

- Papers submitted 31st July by CMS and ATLAS
  - Both claiming observation of a new particle
- Focus on region 117-129GeV left from 2011
- ATLAS used only 3 strongest channels:
  - $\gamma\gamma$
  - ZZ
  - WW
- Others will come when they are ready

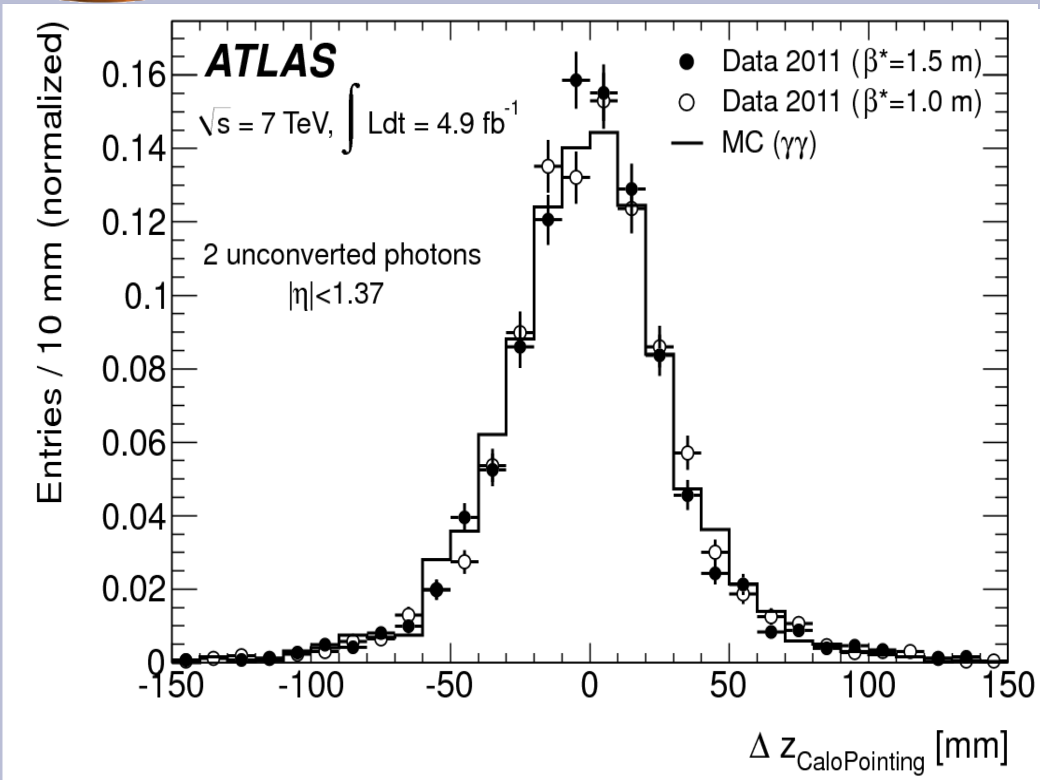


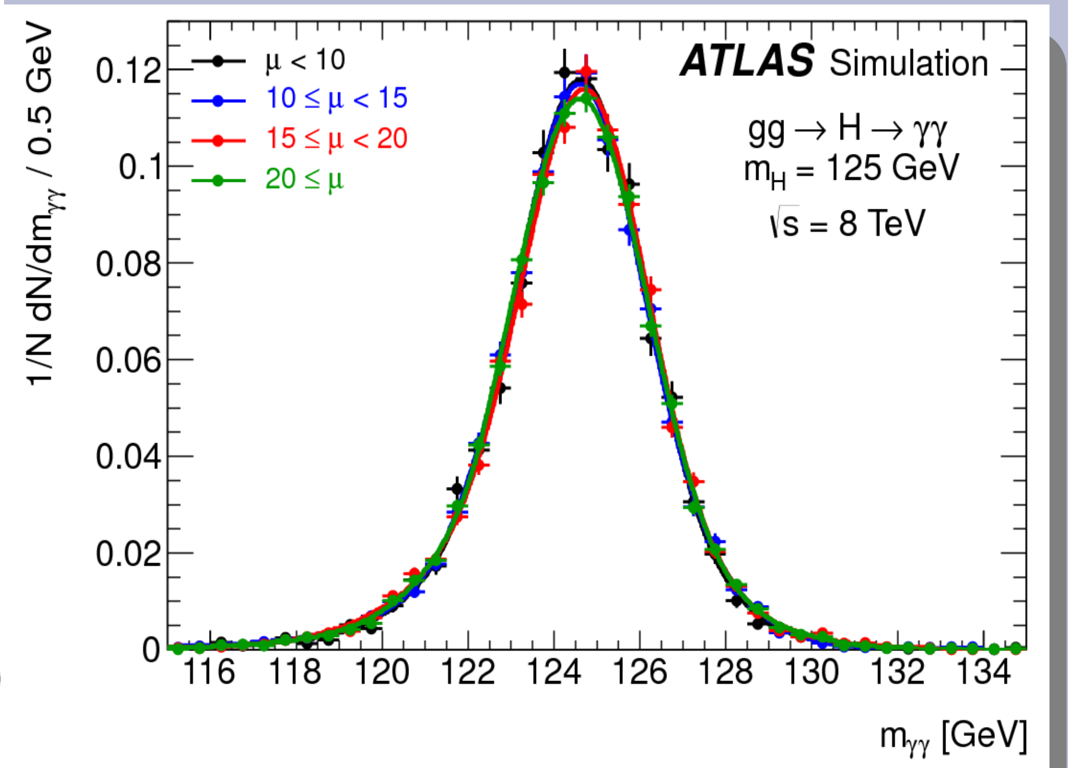
$H \rightarrow \gamma\gamma$

- 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

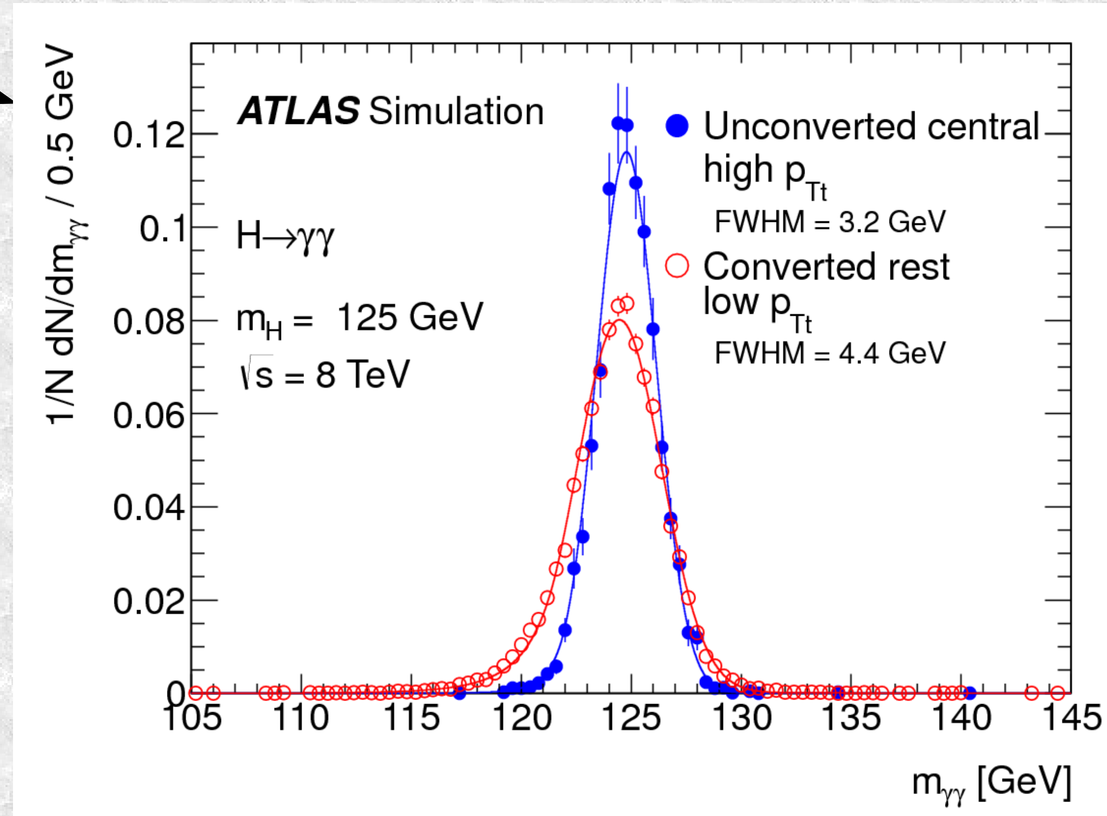




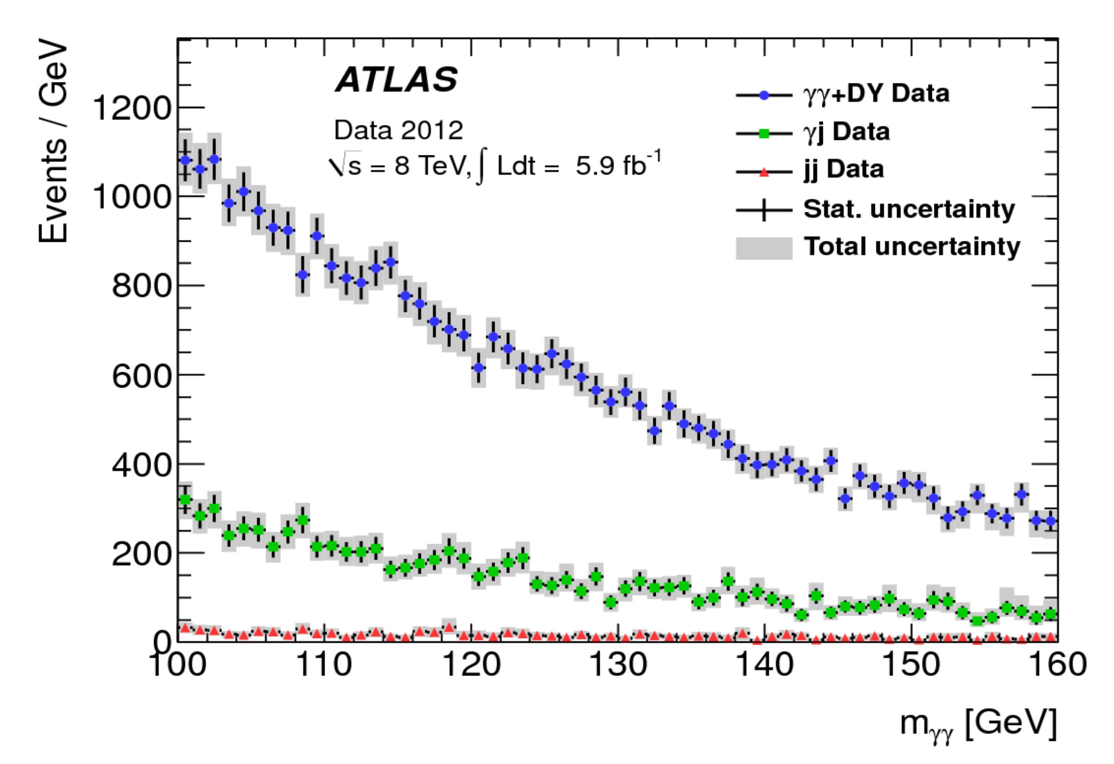
- Extrapolate photon directions to beam position
  - Measure the difference between positions to check resolution
  - Matches simulation, pileup effects small
- Estimated resolution therefore ~μ independent
  - A Likelihood including vertices is used to pick best one
  - But getting it right is normally 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

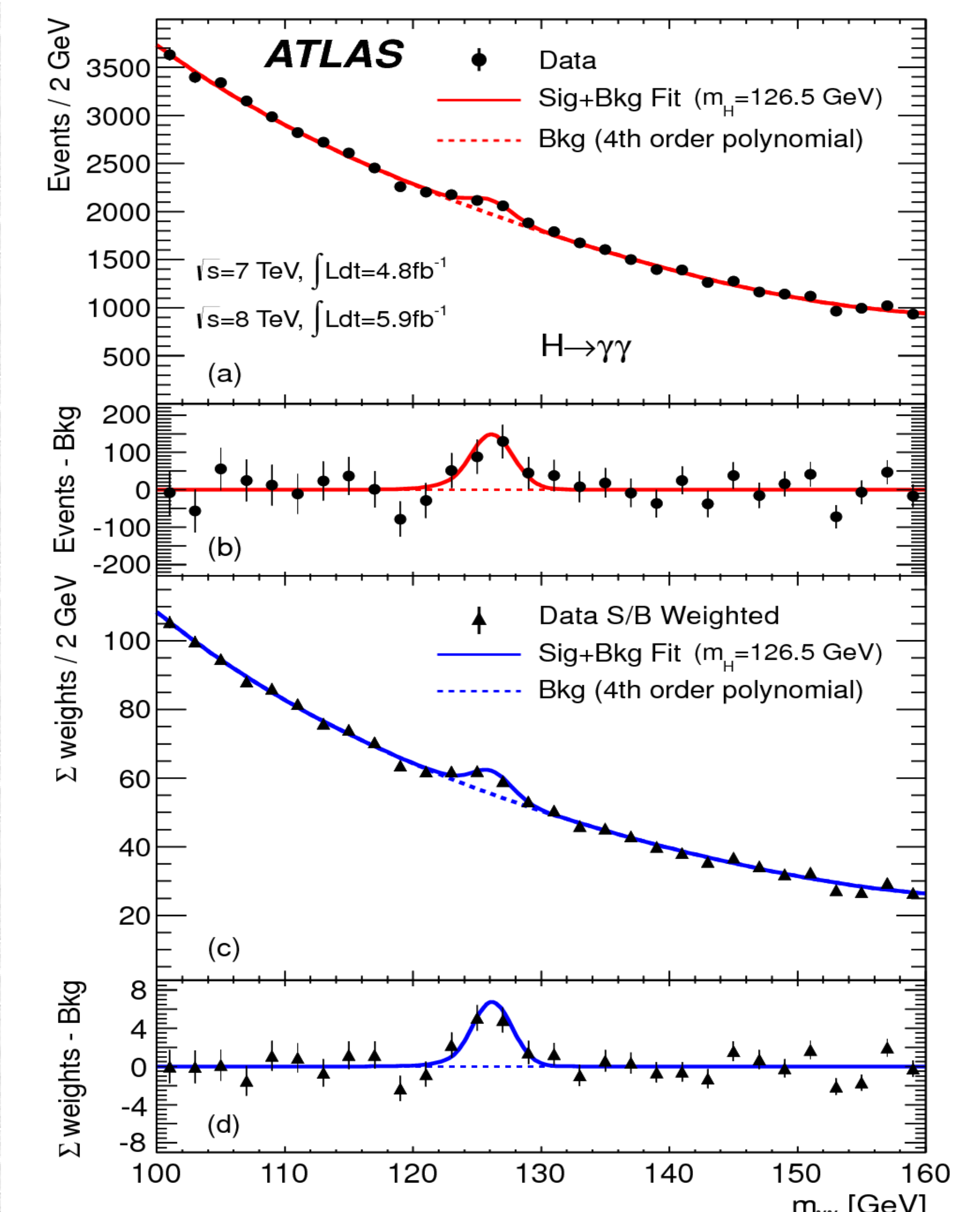


- Measure sample composition in data: γγ, γj or jj?
  - Plus small Drell-Yan
  - Use isolation sidebands
- Samples are dominated by real di-photon.
  - We did reject 99.99% of jets!
  - Little gain from better signal purity

H→γγ analysis method

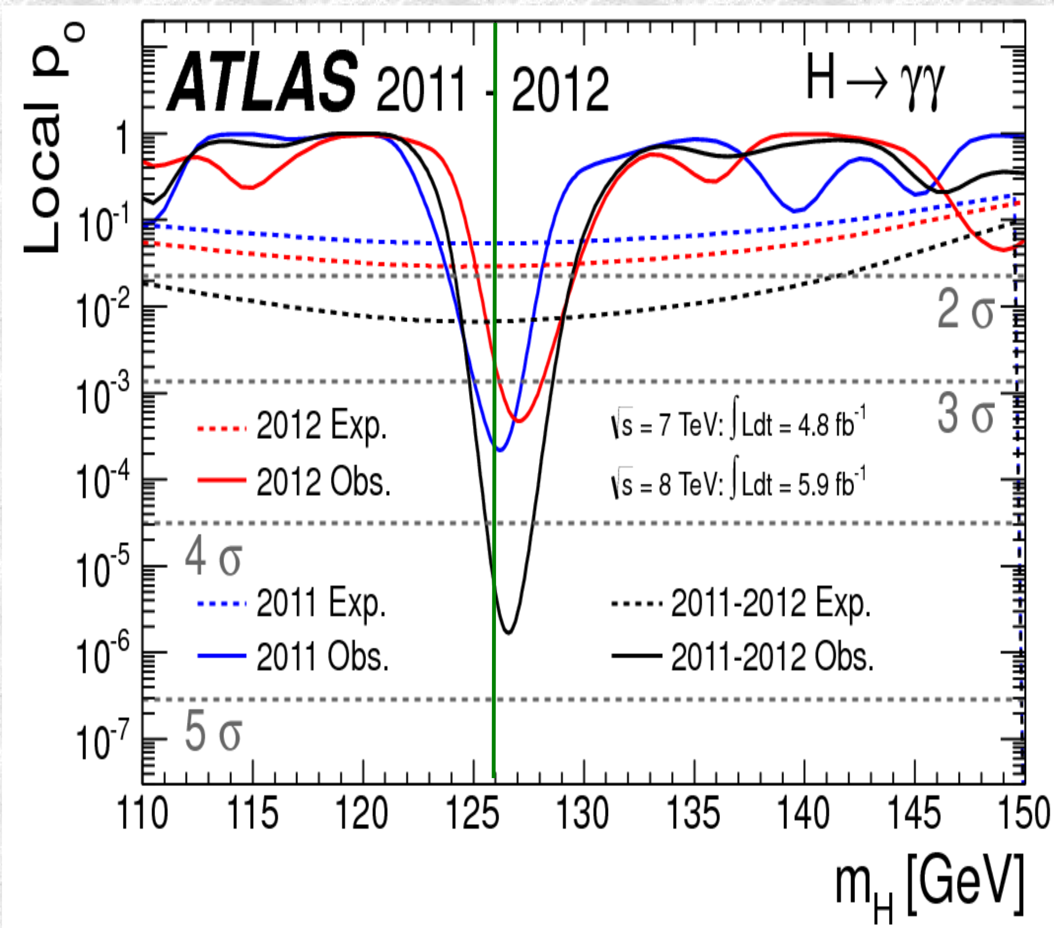
- In principle look at the m(γγ) spectrum for a bump
- But signal/background and resolution depend upon other variables
- Split into several categories:
  - p_{Tt},
  - barrel/forward,
  - converted/unconverted
- 2-jet category sensitive to VBF added too
  - 2 jets, p_T>25GeV
    - if |η|>2.5 require >50% associated track p_T from primary vertex
    - if 2.5<|η|>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

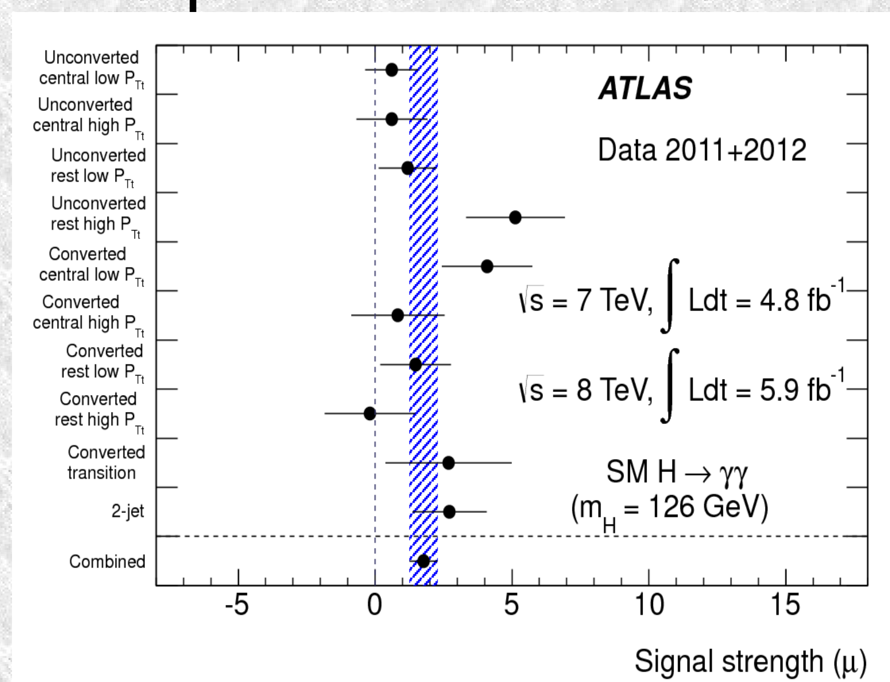


- Simple sum of events (top)
- Weighted by ln(s+b)/b (bottom)
- See significant peaks around 125
  - Weighted sum clearer
  - As it should be if real

Background Compatibility

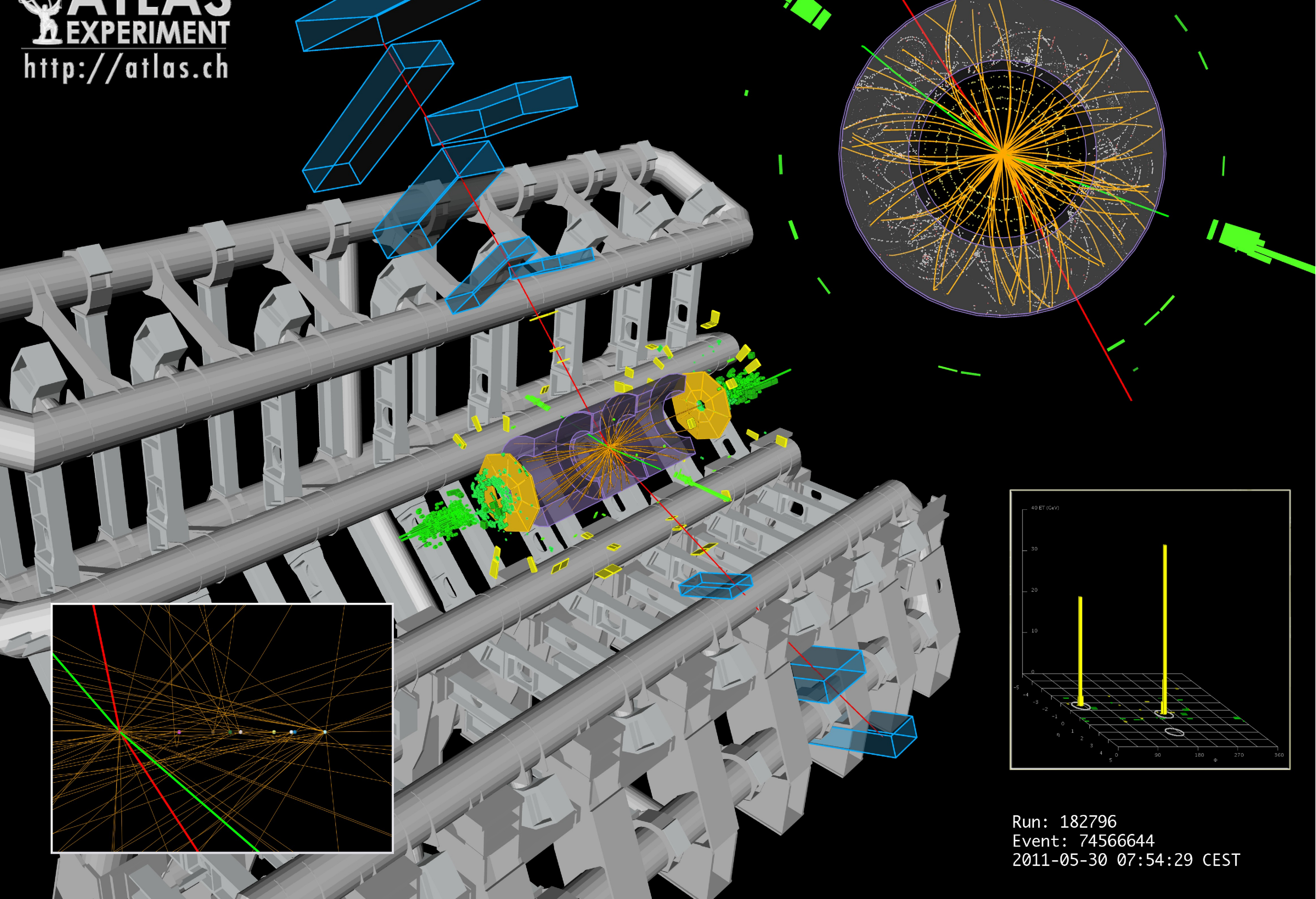


- Peak near 126, both years
- Local excess 4.5σ
  - Best single channel evidence there is....
- Strength exceeds expectation



$H \rightarrow ZZ \rightarrow llll$

- 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


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

efficiency

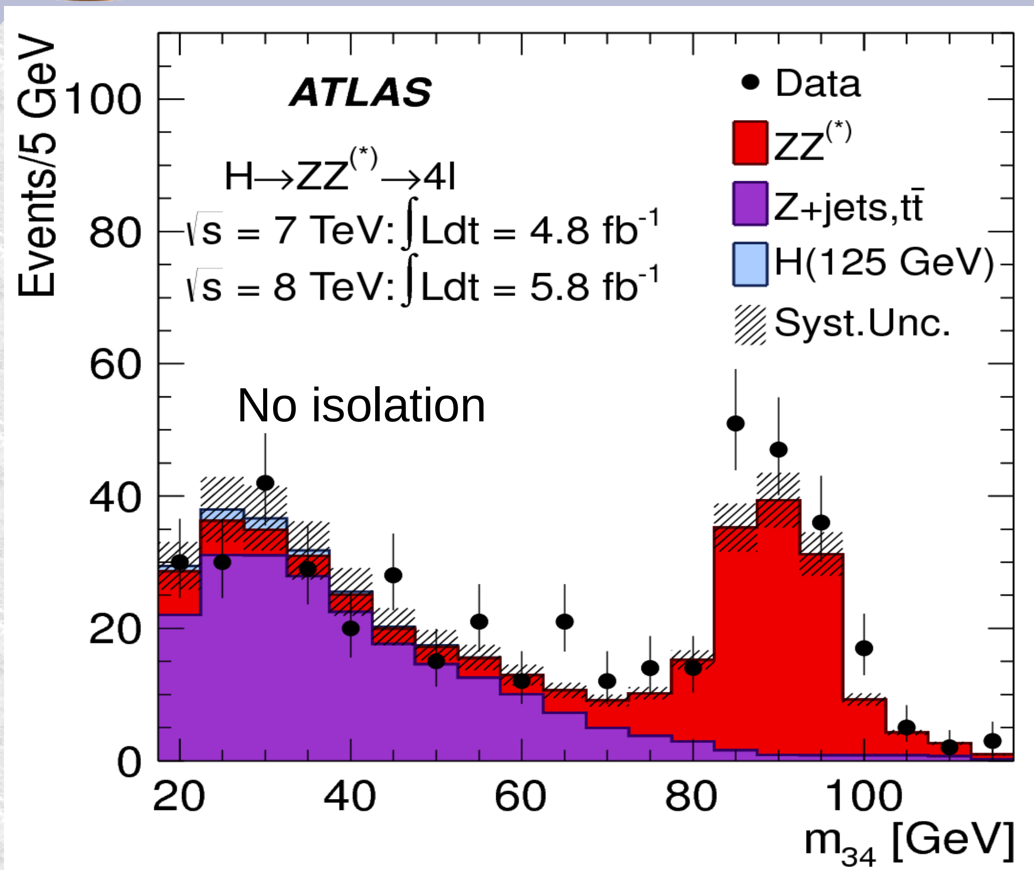
Basic analysis steps

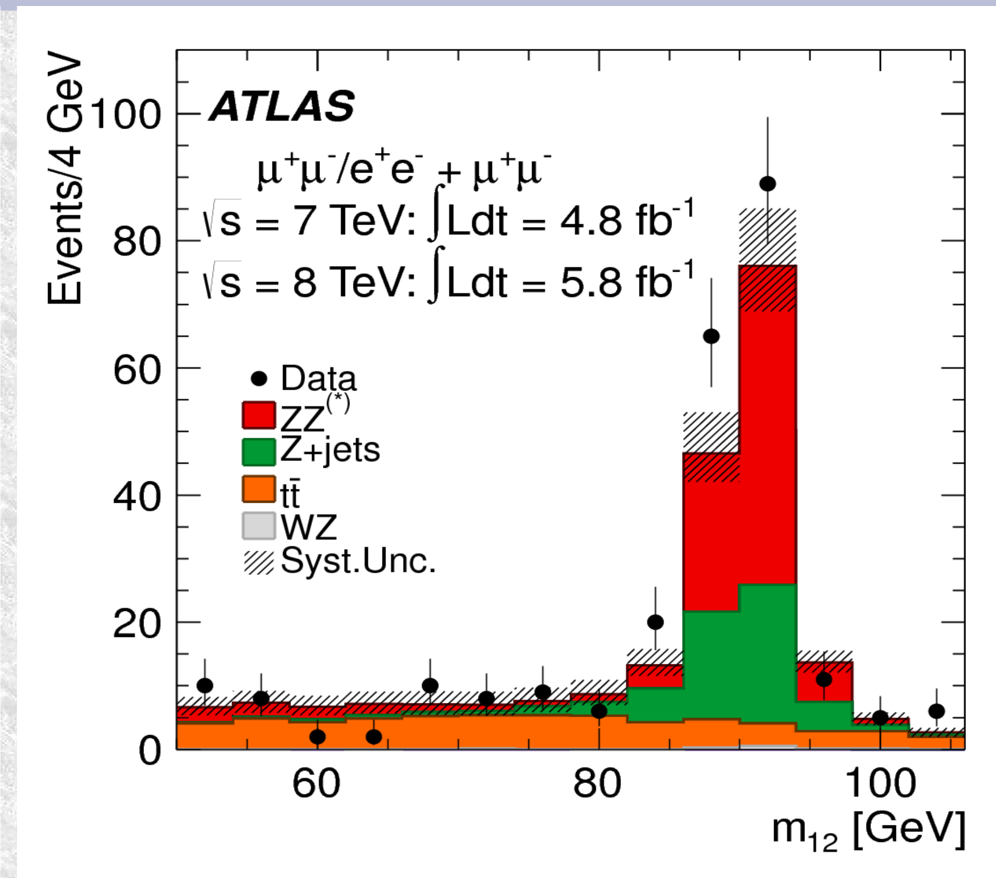
- Find events with 4 leptons (e/μ) in them
- Request a pair is in region of the Z mass
- The second is allowed to be much lower in mass
  - Kinematics requires one Z is forced to be off-shell, lighter

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

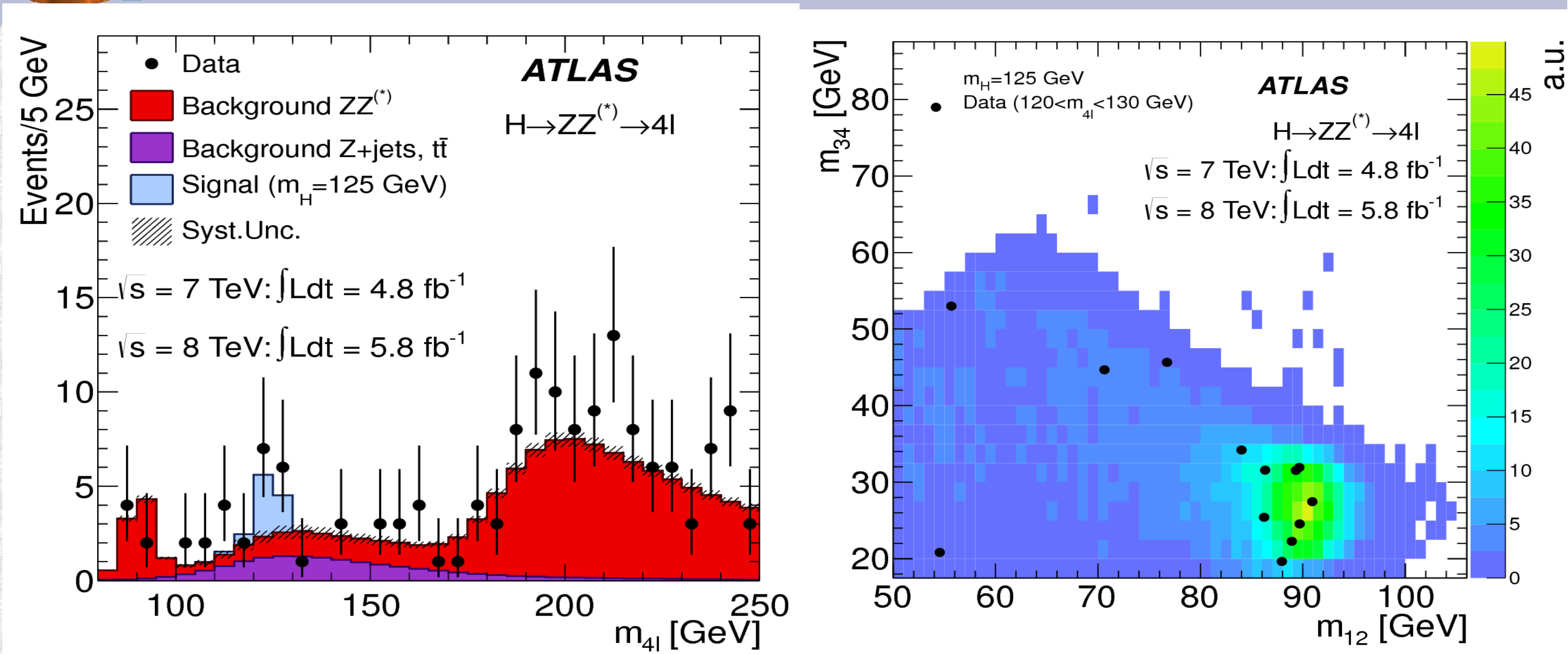
Background Measurement





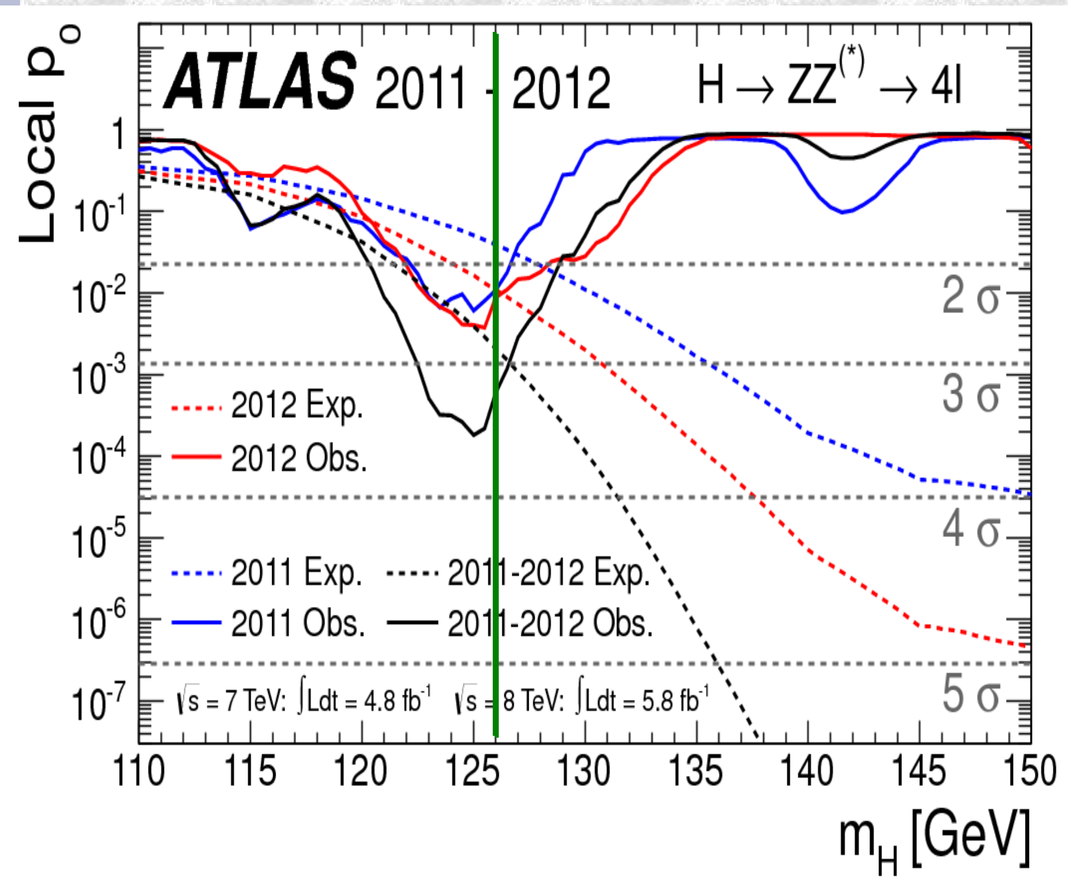
- Remove isolation from 1st or 2nd Z candidate
  - Left is low mass ee candidates
  - Right high mass μμ
- Also detailed studies of electron take rates

Mass distribution



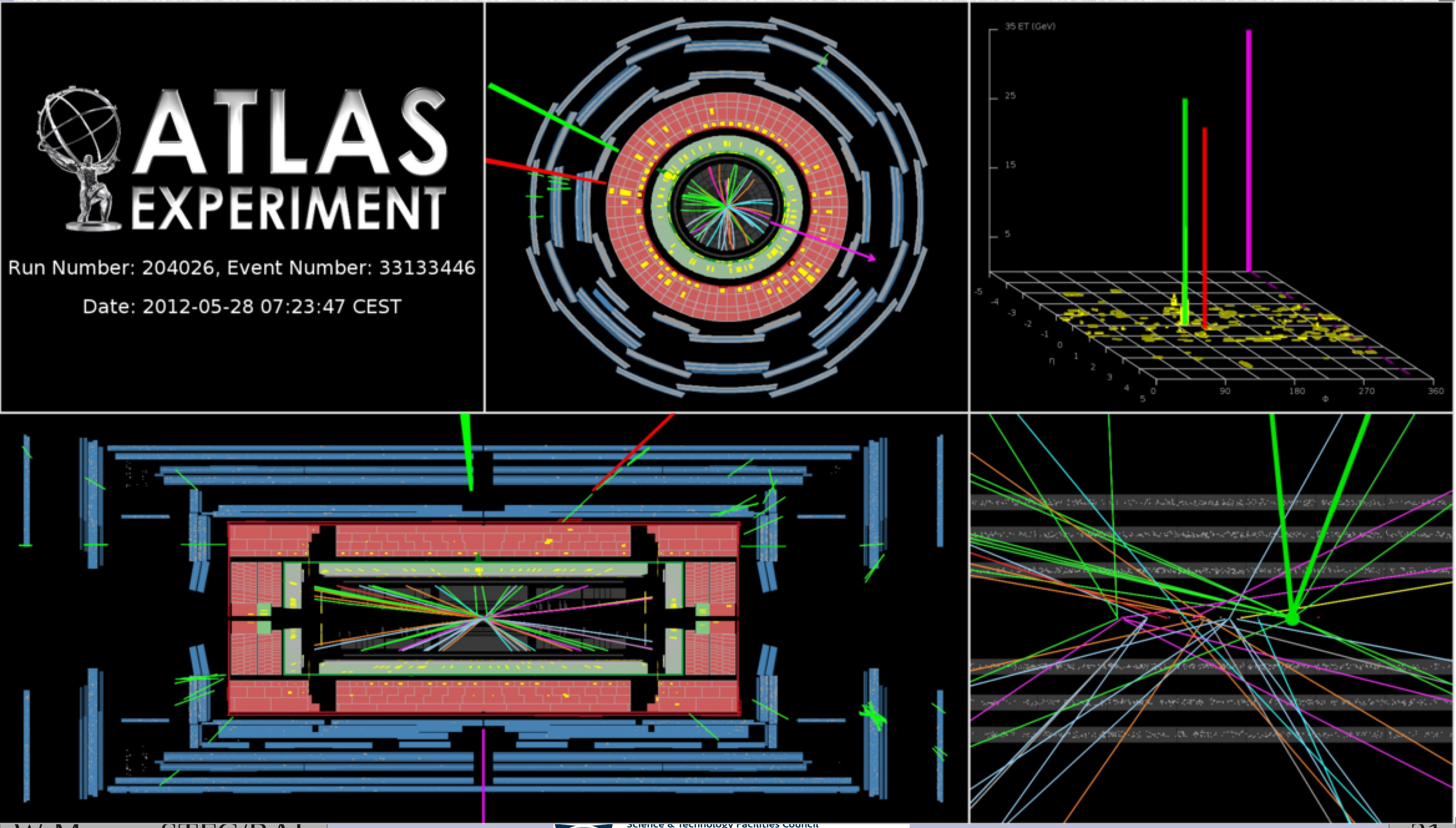
- Background shapes matches expectation
  - Note peaks at 90 and >180 (1 real Z, 2 real Z's)
  - Small peak at 125 GeV seen too...
- Check Z_{12} and Z_{34} masses for candidates

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 → WW → lνlν

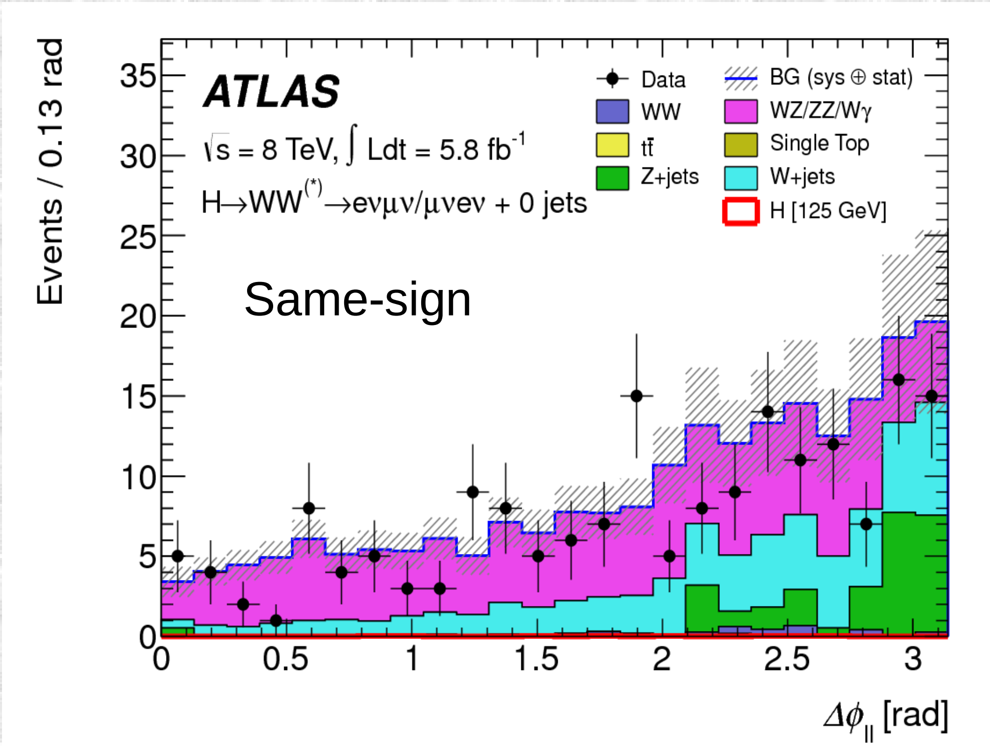


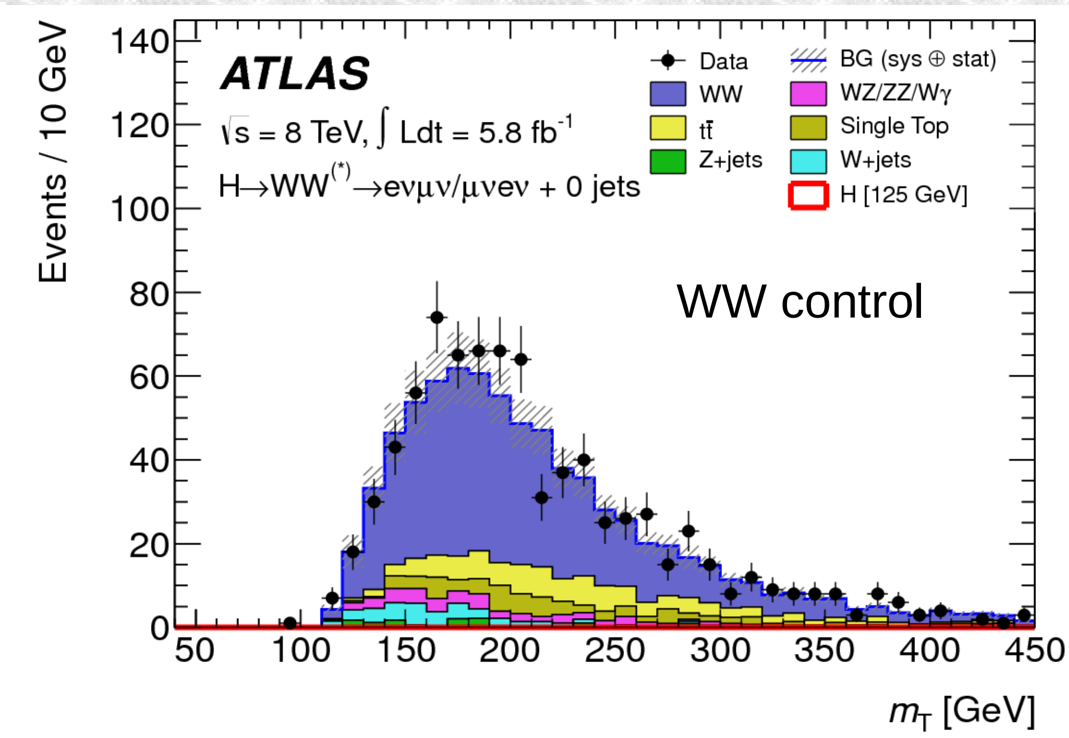
ATLAS EXPERIMENT
Run Number: 204026, Event Number: 33133446
Date: 2012-05-28 07:23:47 CEST

WW → lνlν

- 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 Δφ and m_{ll} selections
  - ATLAS prefers cut-based selections
- Many backgrounds need estimation from data - tricky

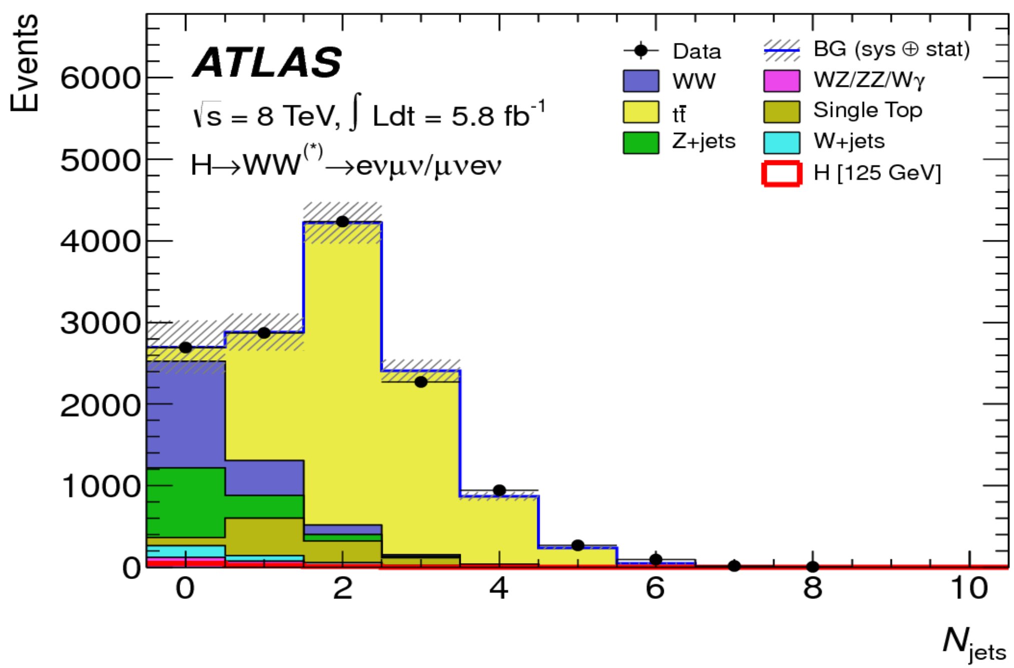
WW background extraction

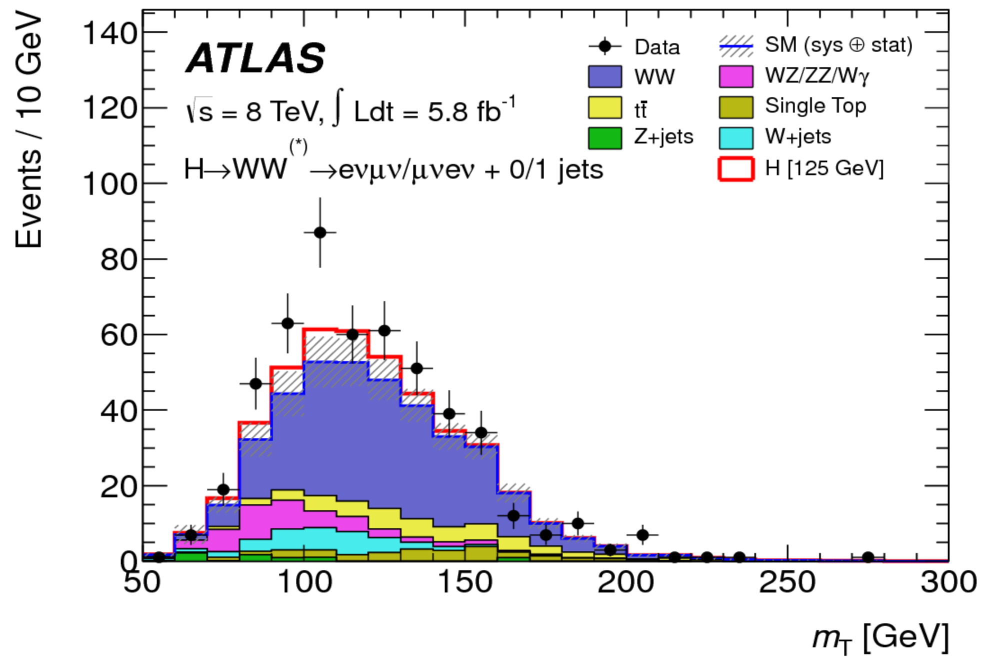




- Backgrounds are (almost) all found in control regions
  - ATLAS same-sign (left) check W+jets
  - ATLAS WW control (right) from high m_T events
    - Integrals must match data/MC by contruction.
    - But scale factors are near 1.

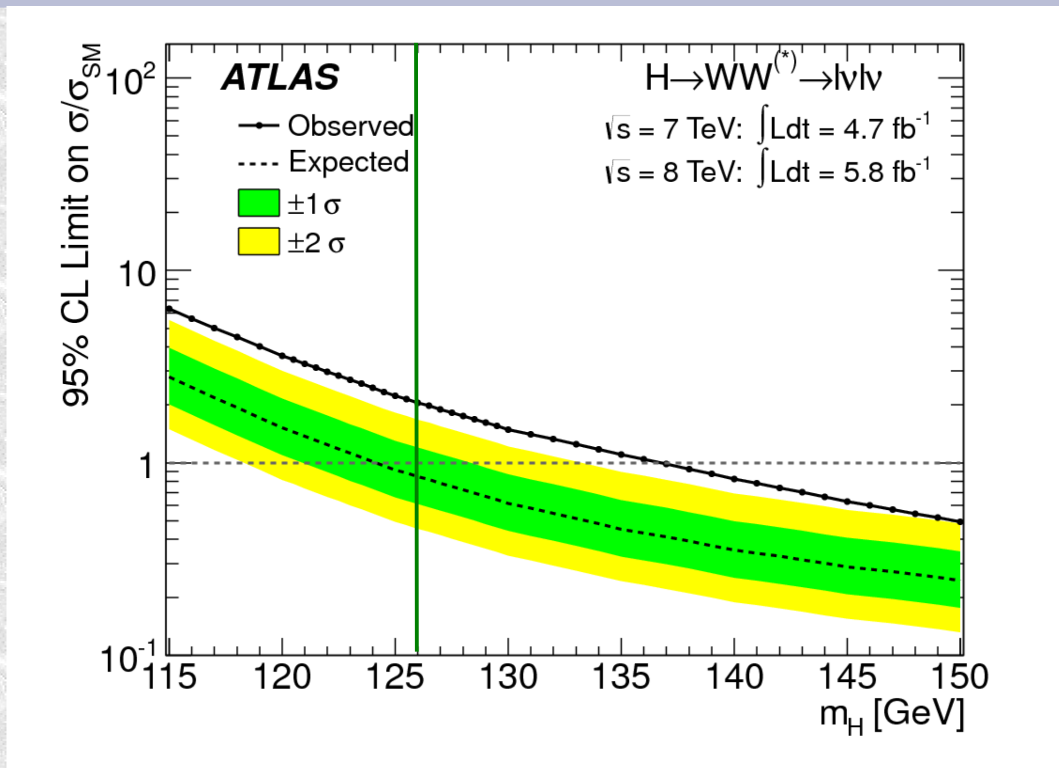
WW signal region





- Treat 0/1/2 jets separately
  - VBF selection has no relevant candidates
- Delicate analyses, complex data/MC mix
- Distinct excess seen in 0+1 jets
  - In the region signal is expected
  - But not well localised
  - 2.8σ in ATLAS

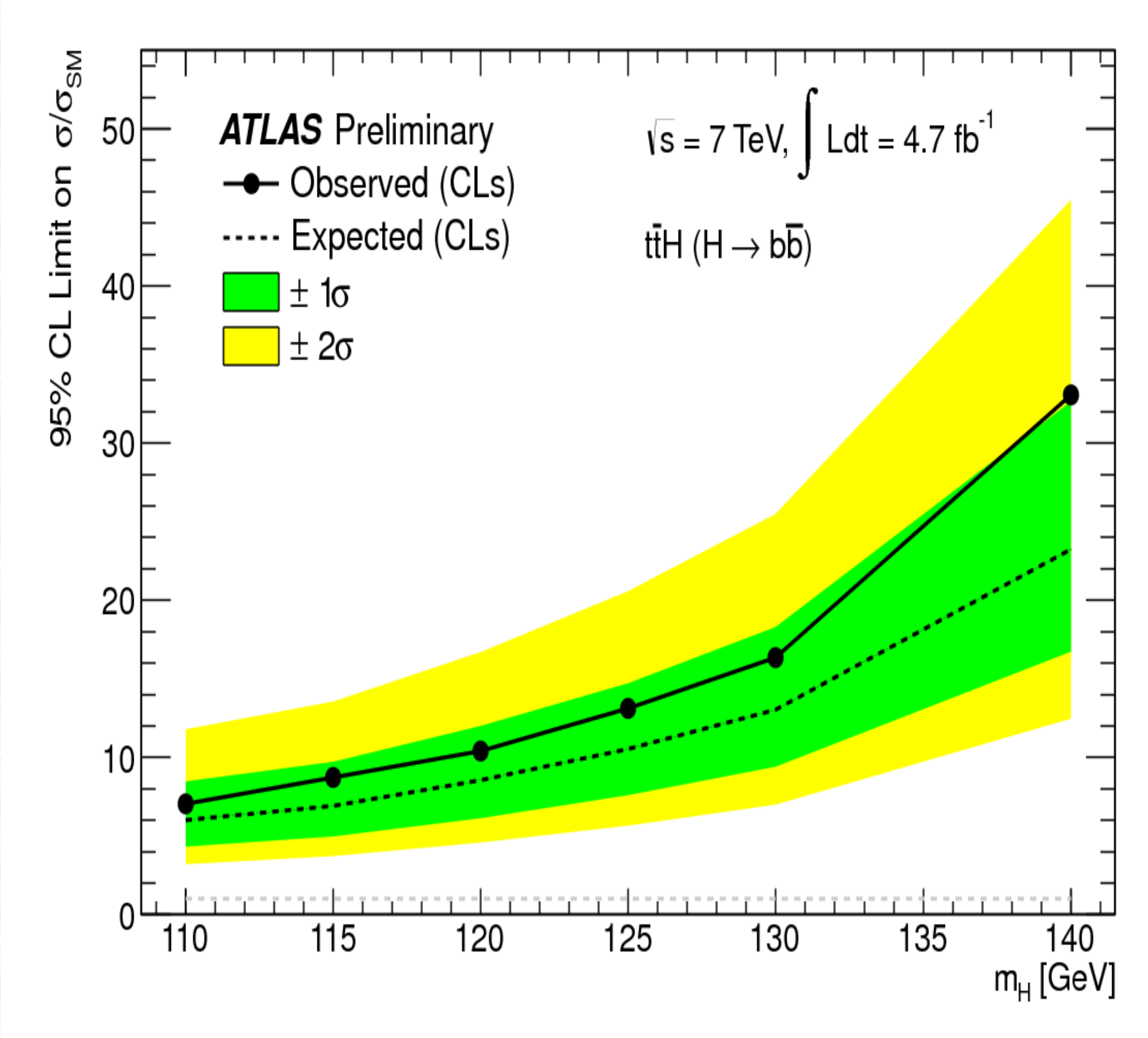
WW limits



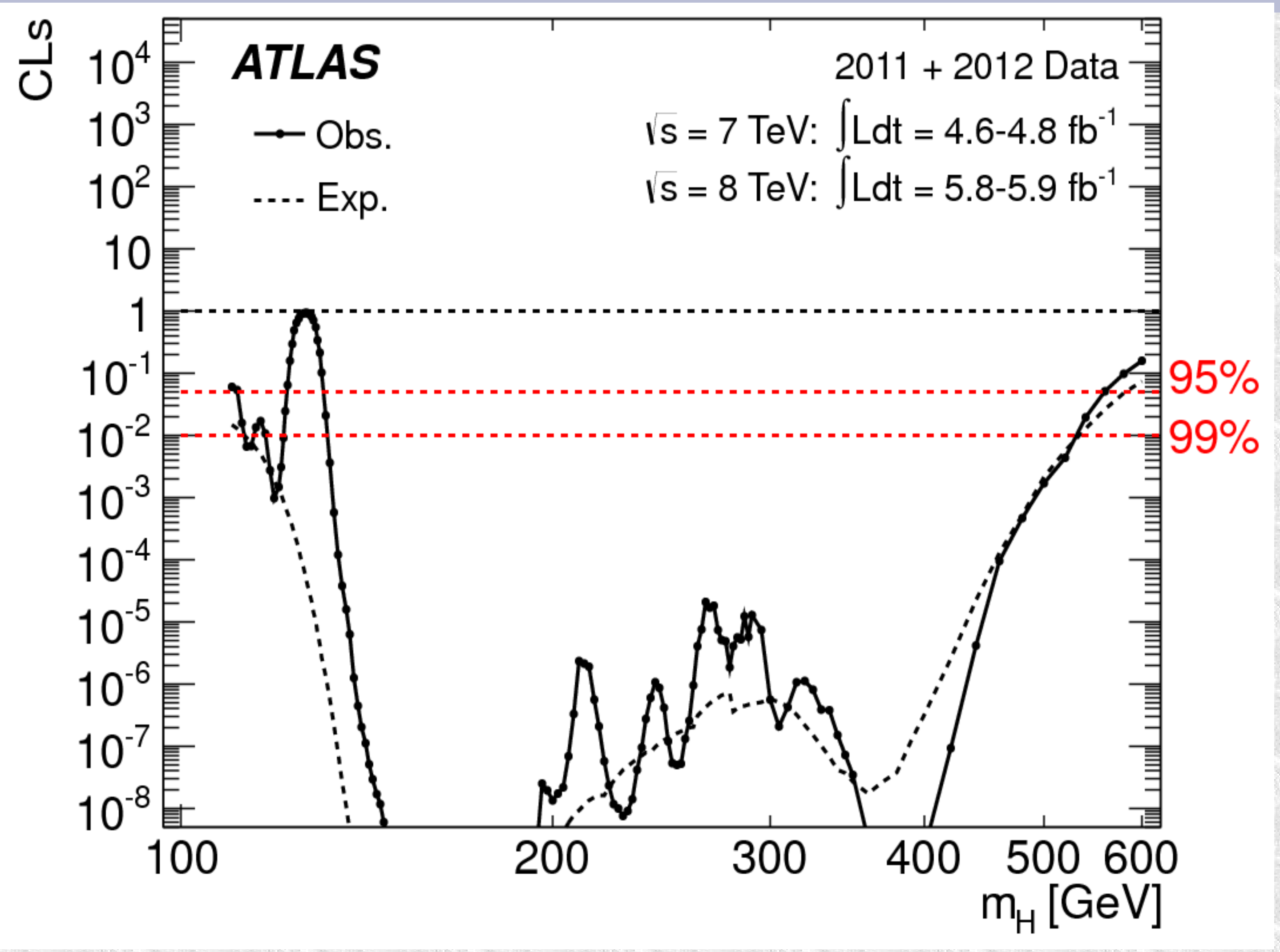
- Set bad limits...
- 2.8sigma excess around 125GeV
- Two neutrinos means mass not well measured
  - So broad excess seen

Fermion couplings?

- ATLAS has released no 2012 fermionic Higgs decay results
  - These are important but delicate
- Unique is ttH, H→bb which is fermions in both production and decay
  - Recent 2011 results right:
  - ATLAS-CONF-2012-135
  - Will benefit from higher energy

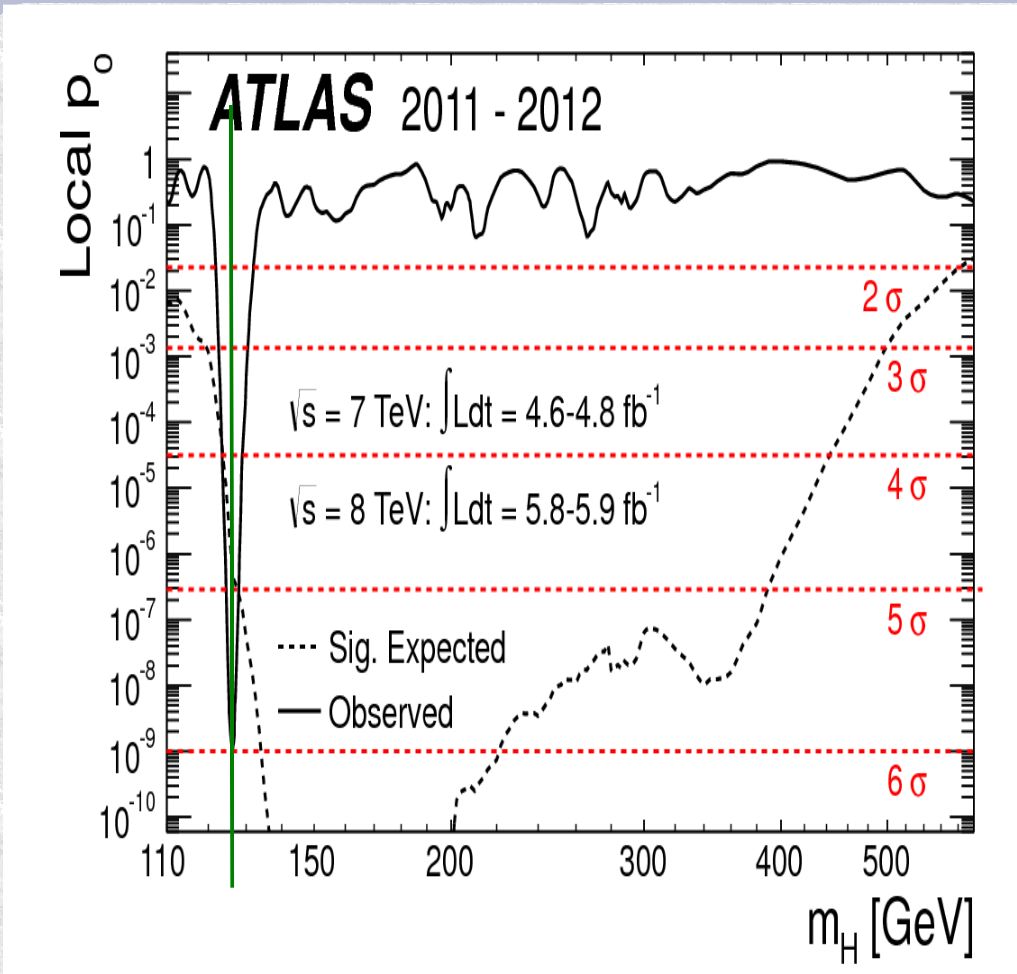


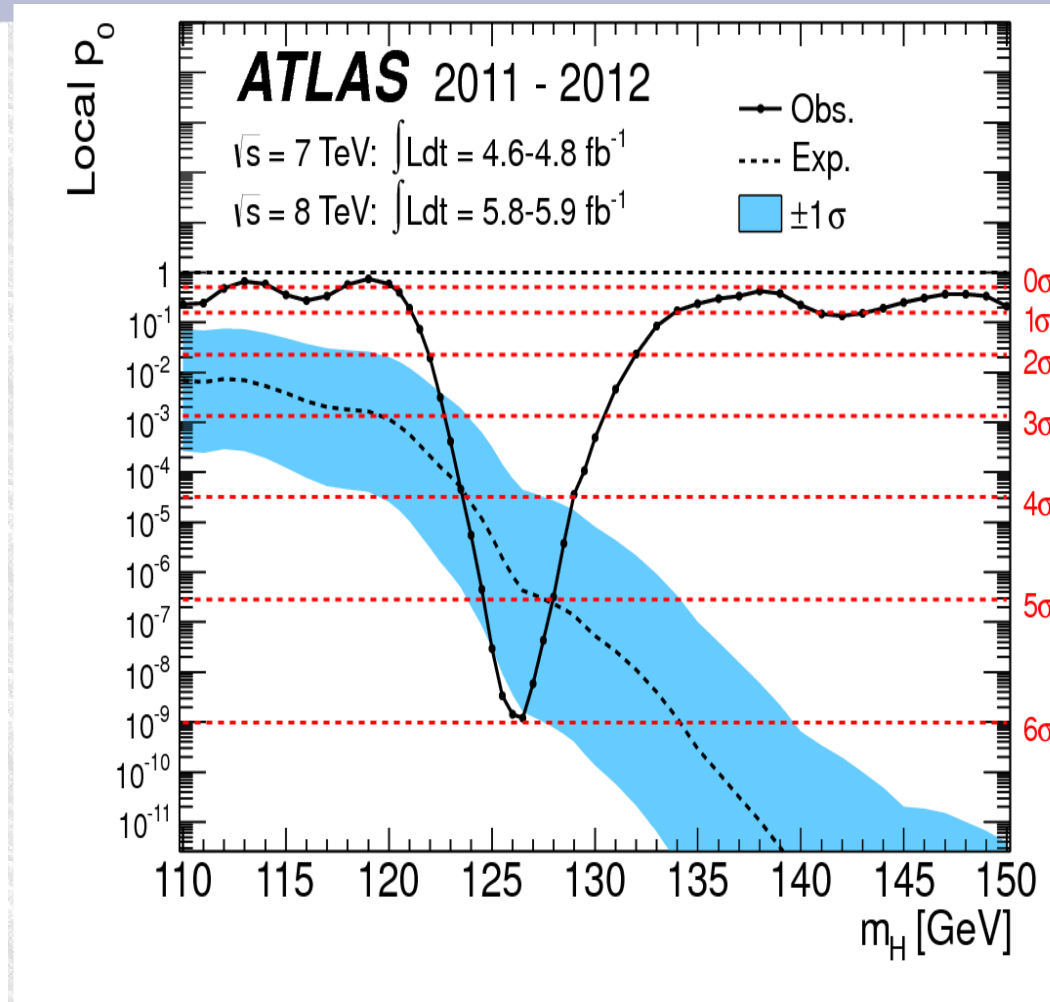
Combined limits



- Excludes nearly all mass range at high confidence

Combined p-value

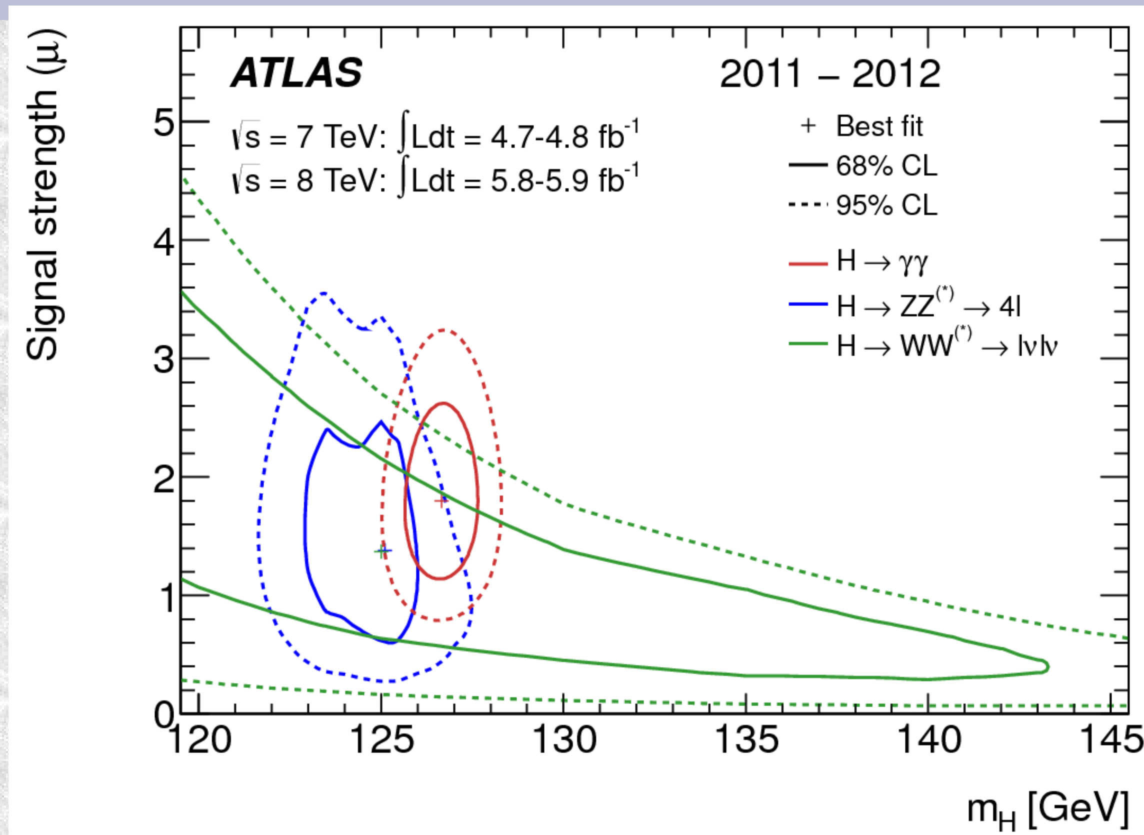




- Probabilities $2x10^{-9}$ or 5.9σ…**we got it**
  - – Just outside 1σ band for signal

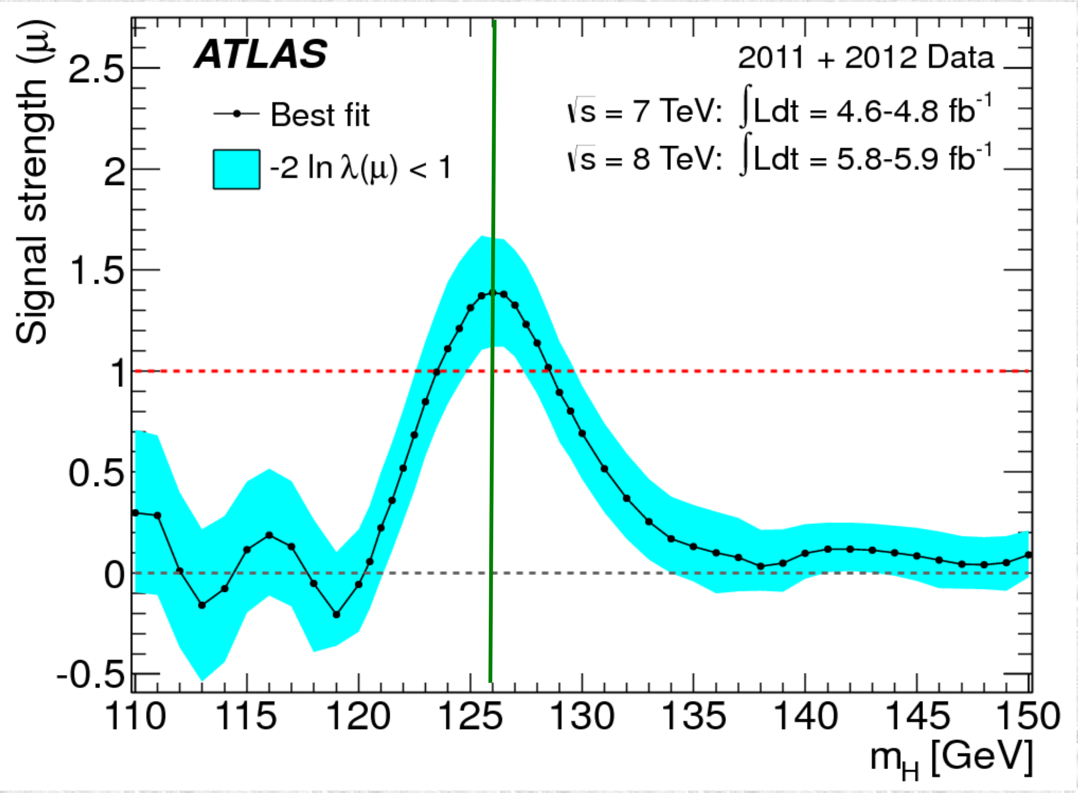
But what did we get?

Rate versus Mass



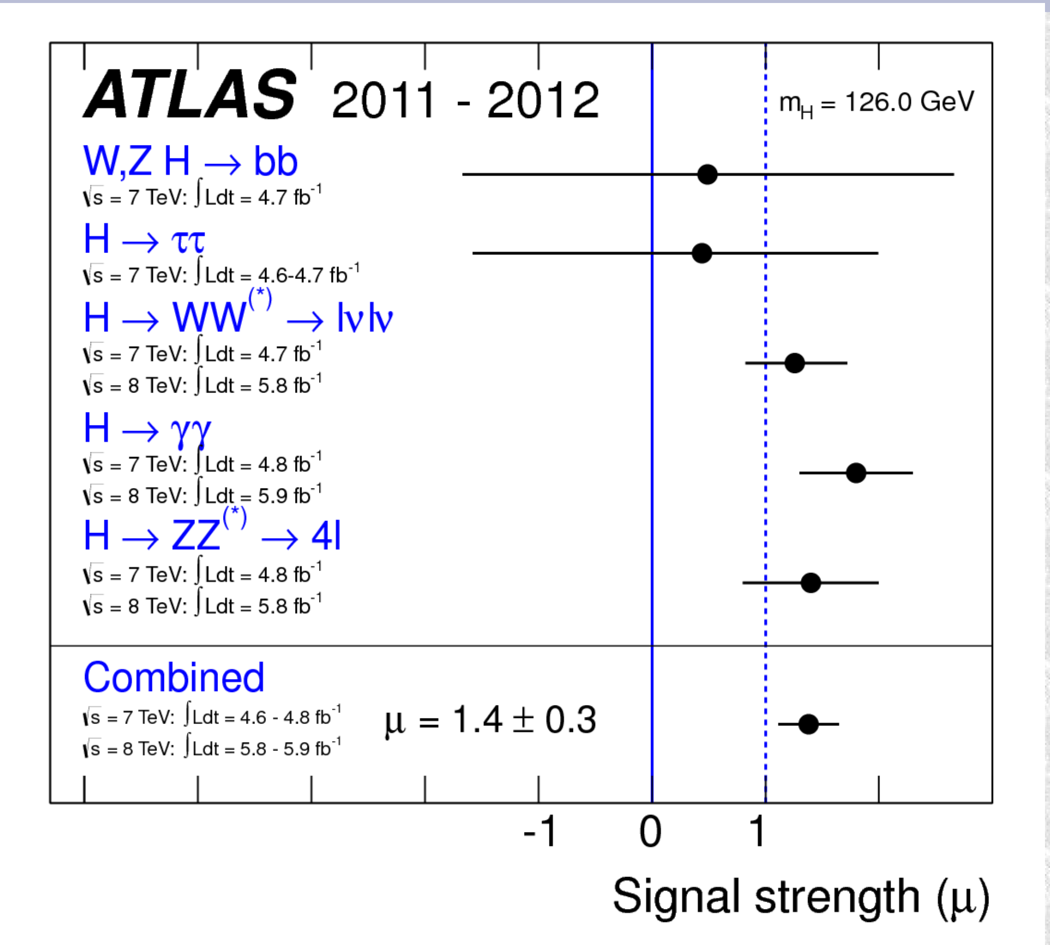
- 2D fits of rate and mass reduce model dependence
  - m_H=126±0.4±0.4
- These channels all have consistent solutions.
  - 1 particle assumed from now on

The Combined Results



- 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 all 5 channels (just)
  - More powerful ones (WW,ZZ,γγ) certainly do.
  - Is there too much γγ? Not really

Open Parenthesis

Limitation of current method

- Pick an m_H hypothesis
- Fit for signal strength at that m_H
  - Compare with expectations for a signal at that mass
- Plot the results as a function of m_H

- So what is wrong?

Limitation of current method

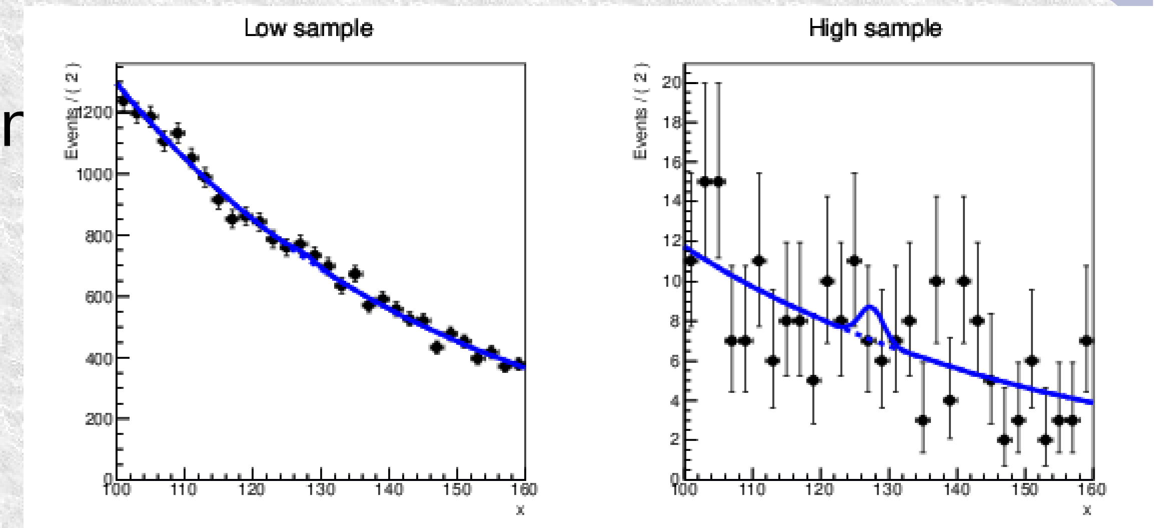
- Pick an m_H hypothesis
- Fit for signal strength at that m_H
  - Compare with expectations for a signal at that mass
- Plot the results as a function of m_H
- So what is wrong?
  - Nothing.
  - Unless you then use the results to select and report one mass
- The above procedure assumes

$$m_H^{tested} \equiv m_H^{true}$$

- So lets start with that....

Dummy experiment

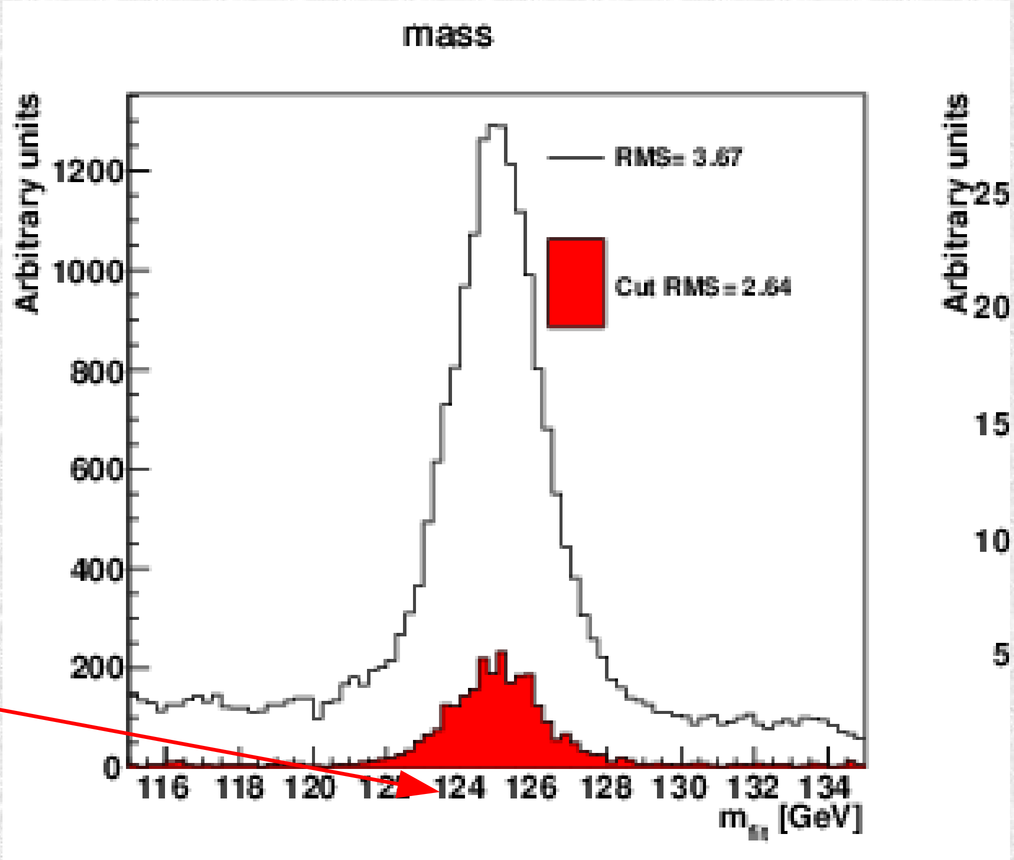
- Like ATLAS search
  - 22K background and 55 sign
  - Two categories
    - 90% signal, 99% bkd.
    - 10% signal, 1% bkd.
  - Mass resolution 1.7GeV



- A bit like the ATLAS 2011 γγ search
  - but just a dummy designed following their papers
  - Parameters designed to have 1.4σ expected sensitivity
- Make toy MC investigations *with a signal*
  - Inject signal
  - Constrain μ to be non-negative
  - Fit with mass fixed or floating to compare results

Fitted Mass distribution

- ML fit in minuit
  - Fit 2 background slopes and rates and 1 signal rate
  - Scan 115-135 first
- Quite often the best fit has NOTHING to do with the signal
  - RMS 3.7 (in this window!)
- RED selects 'lucky' experiments with 2.5-3σ observed excess
  - 2xexpected, as ATLAS/CMS
  - Cluster around the signal
  - But RMS still 2.6GeV
- ATLAS+CMS were compatible!



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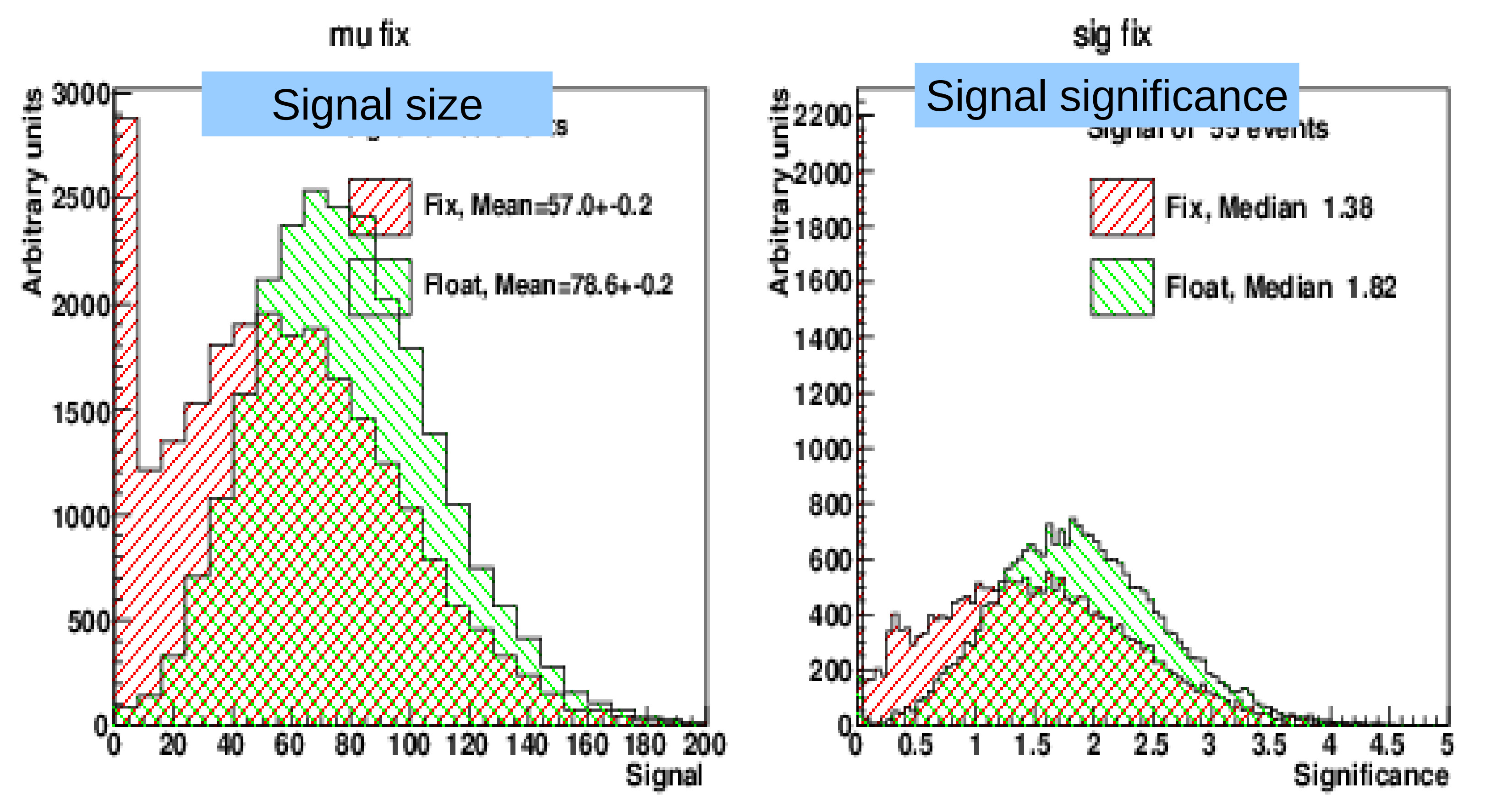
OK, so $m_H^{fitted} \neq m_H^{true}$

- The resolution on m_H is worse than the per-event resolution!
  – The statistics is dominated by background fluctuations

- Imagine a 'perfect' (Asimov) signal
- Add a fluctuating background under it
  – Just above and just below peak gives 2 chances to fluctuate
  – Odds are one of them fluctuates up
  – The signal gets pulled to that point
  – And grows in size!
- This is not included in the ATLAS/CMS 'expected p-values for signal' because they assume $m_H^{fitted} = m_H^{true}$

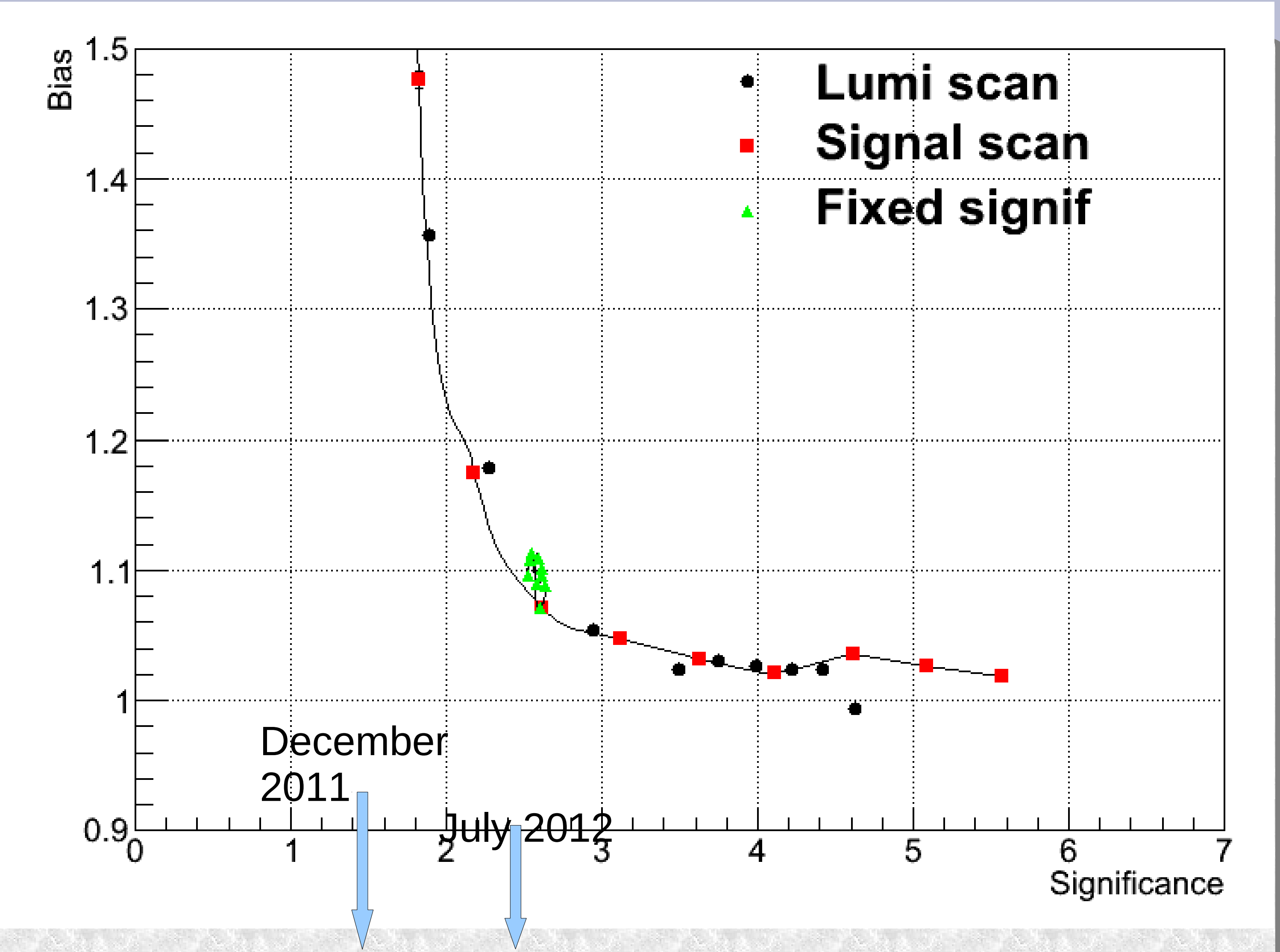
How large is effect on μ?



- Red injects at 125 and tests at 125 – as expts. Do
  - 4% bias, coming from μ≥0
- Green injects at 125 and fits with m_H free
  - **43% bias!**

Bias versus significance

- Vary:
  - Lumi
  - Signal rate
  - both
- Bias seem to be given by expected significance
- Universal curve?
  - Need thought
- <σ> <3 raises alarm bells!



Test of Predictions

- I predicted 6 months ago that the gamma-gamma signals from ATLAS and CMS would converge in mass and reduce in rate

	ATLAS	CMS
January Peak Mass	126.5	123.5
mu	2.0	1.7
ICHEP mass	126.5	125 (124)
mu	1.8	1.5
World Average	125.7	

- Expected about 0.3 drop, see about 0.2
  - Pretty much as expected
- ATLAS' mass remains stubbornly high

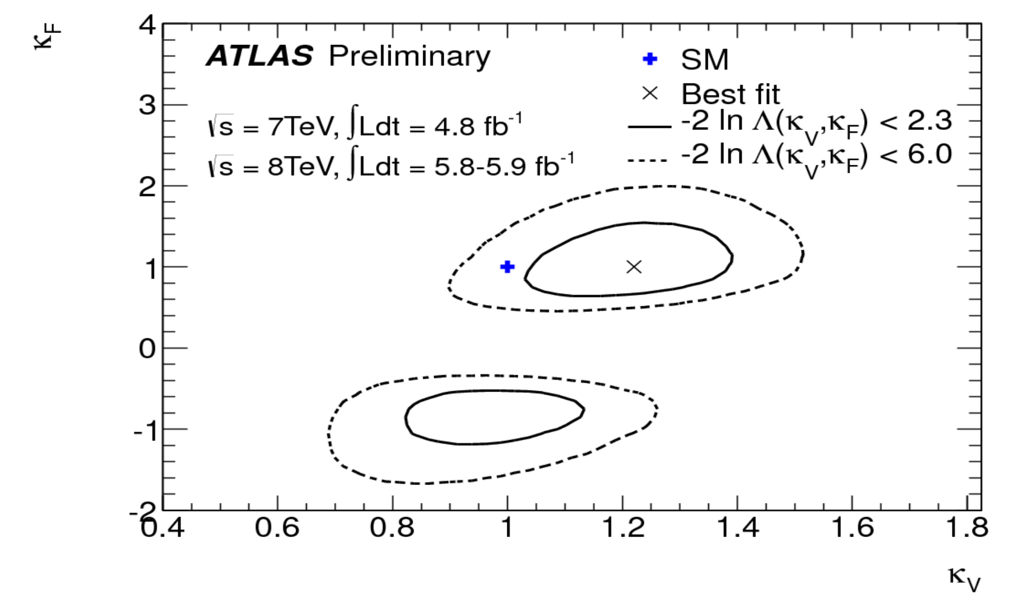
End Parenthesis

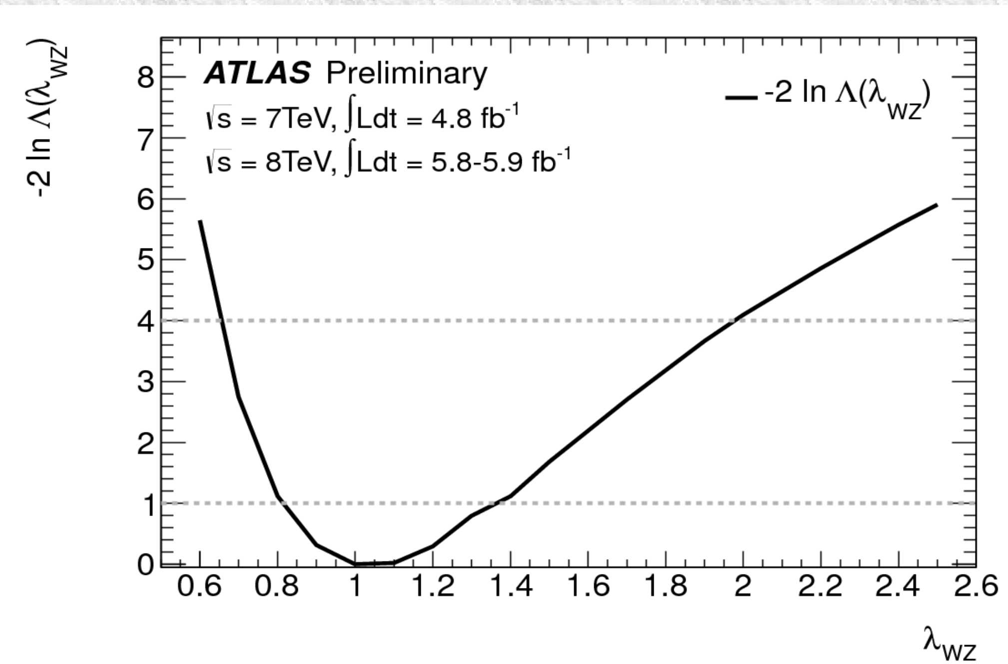
Interpreting couplings

- 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

- 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
  - $1.07^{+0.35}_{-0.27}$

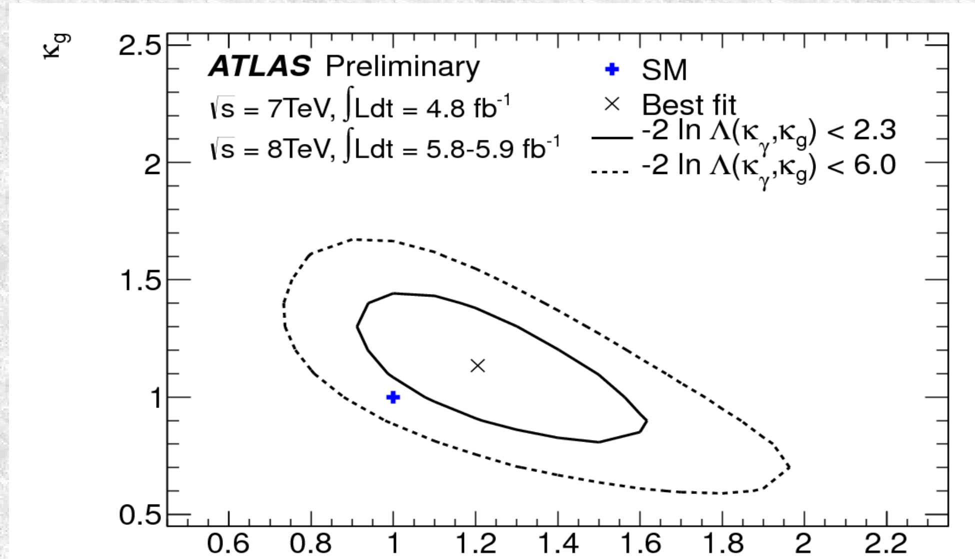


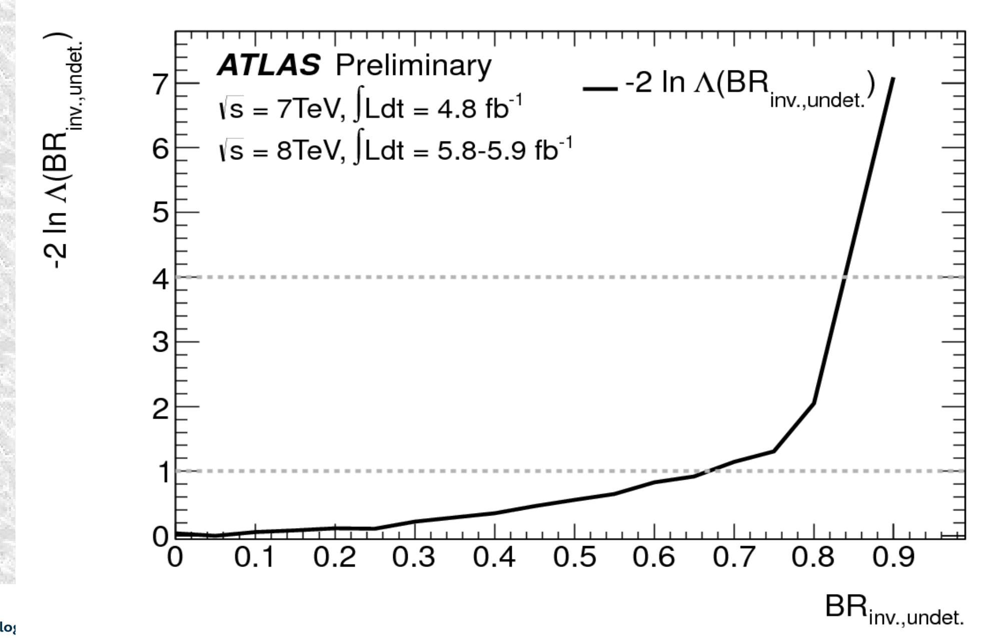


New particle search

- 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



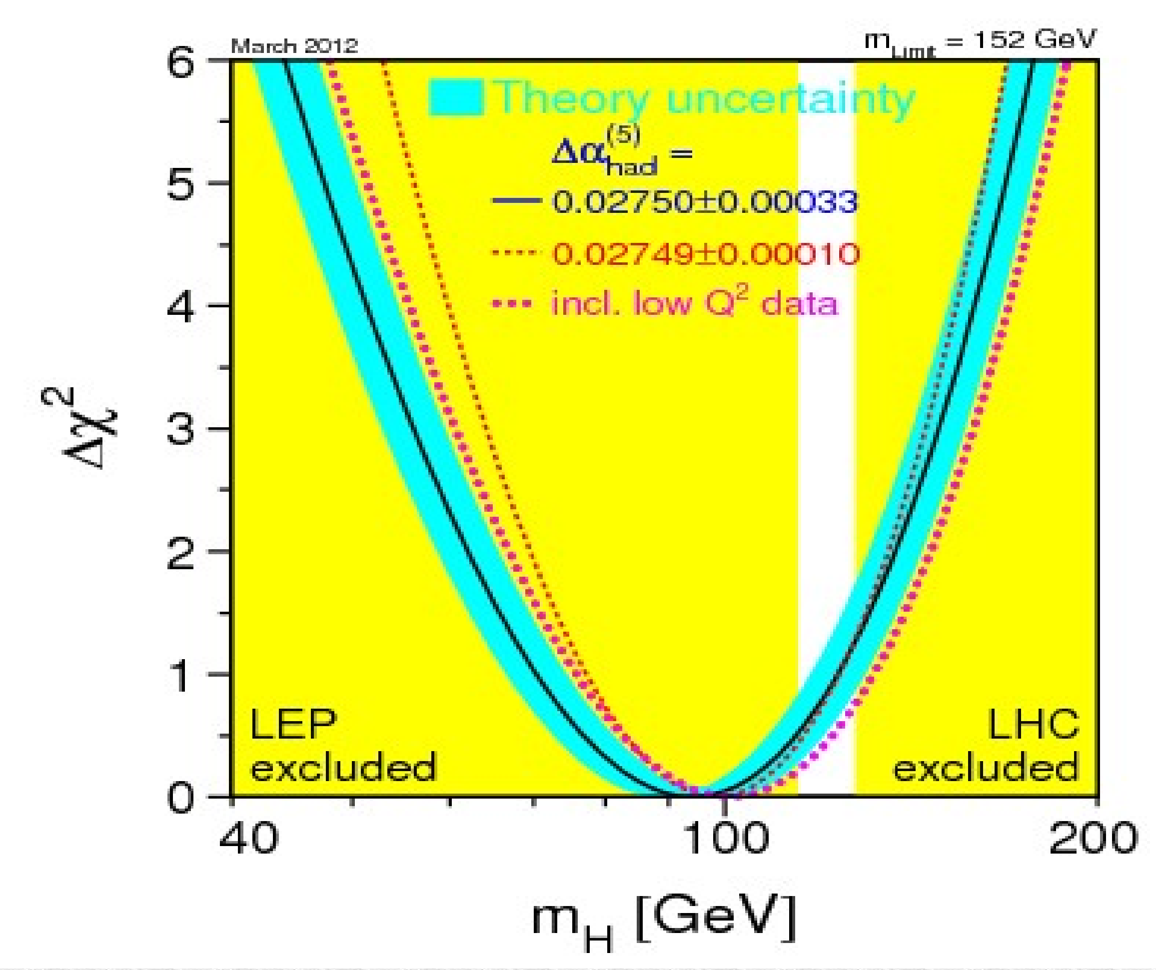


So what do we know?

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

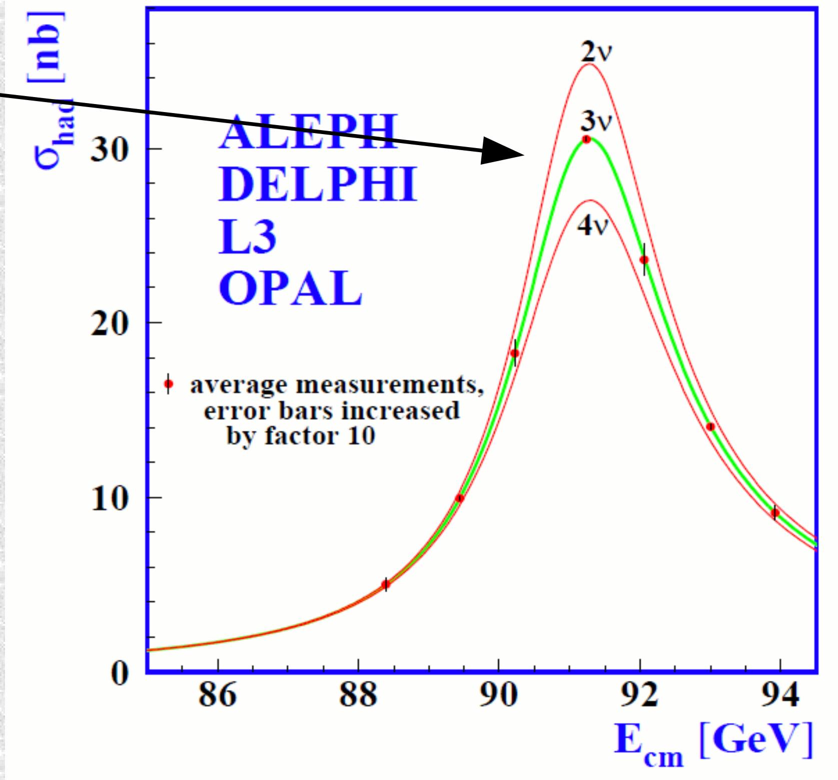
What does 125-126 tell us?

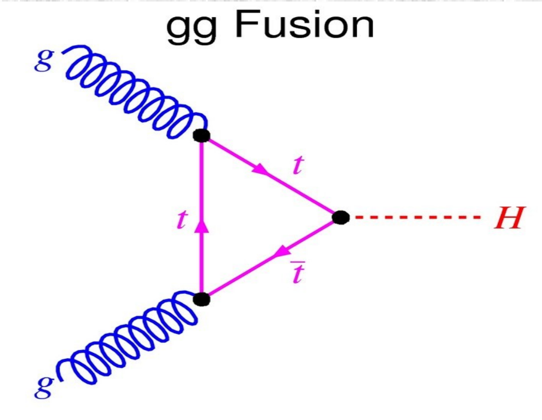


- In SM $m_H = 94^{+29}_{-24}$ GeV
  - So observed mass fits SM with no additions

How many neutrinos?

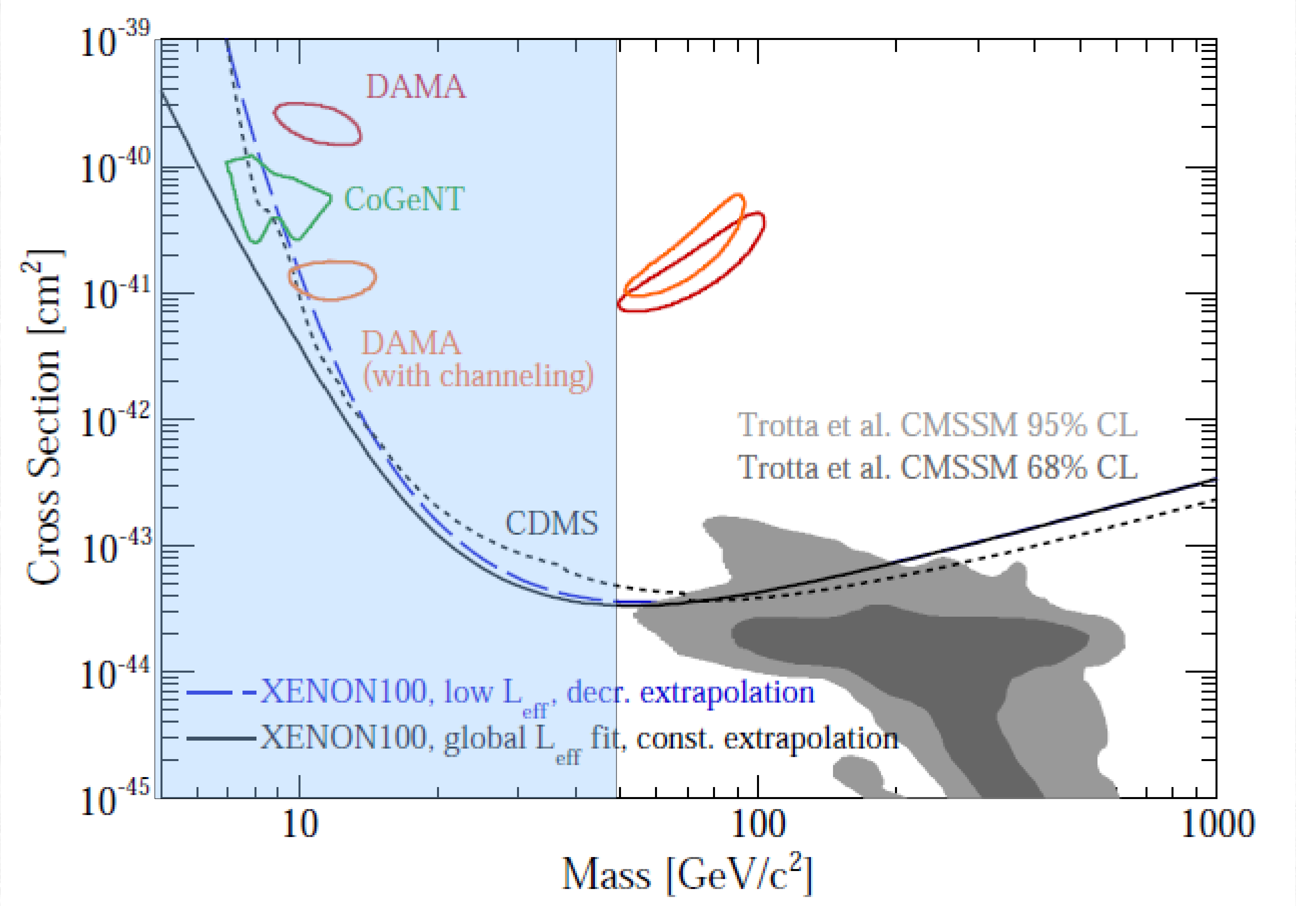
- LEP proved 3 light neutrinos
  - hence 3 generations?
- Now we know neutrinos have mass maybe $2m_\nu > m_Z$?
  - Could be a heavy neutrino
- But Higgs production is mostly through gluon fusion
  - Virtual top in a loop
  - A new heavier quark would increase the rate a lot
  - Whatever mass the quark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

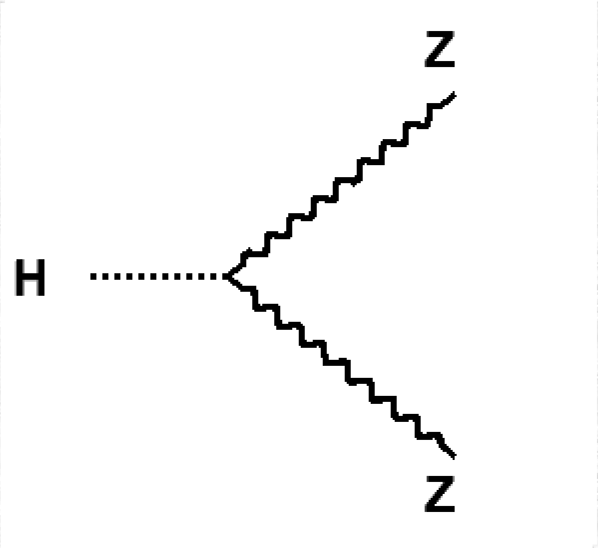
What about the Higgs field?

- 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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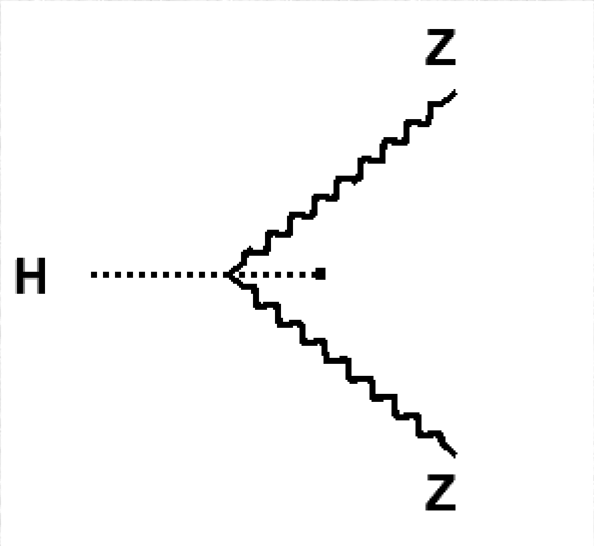
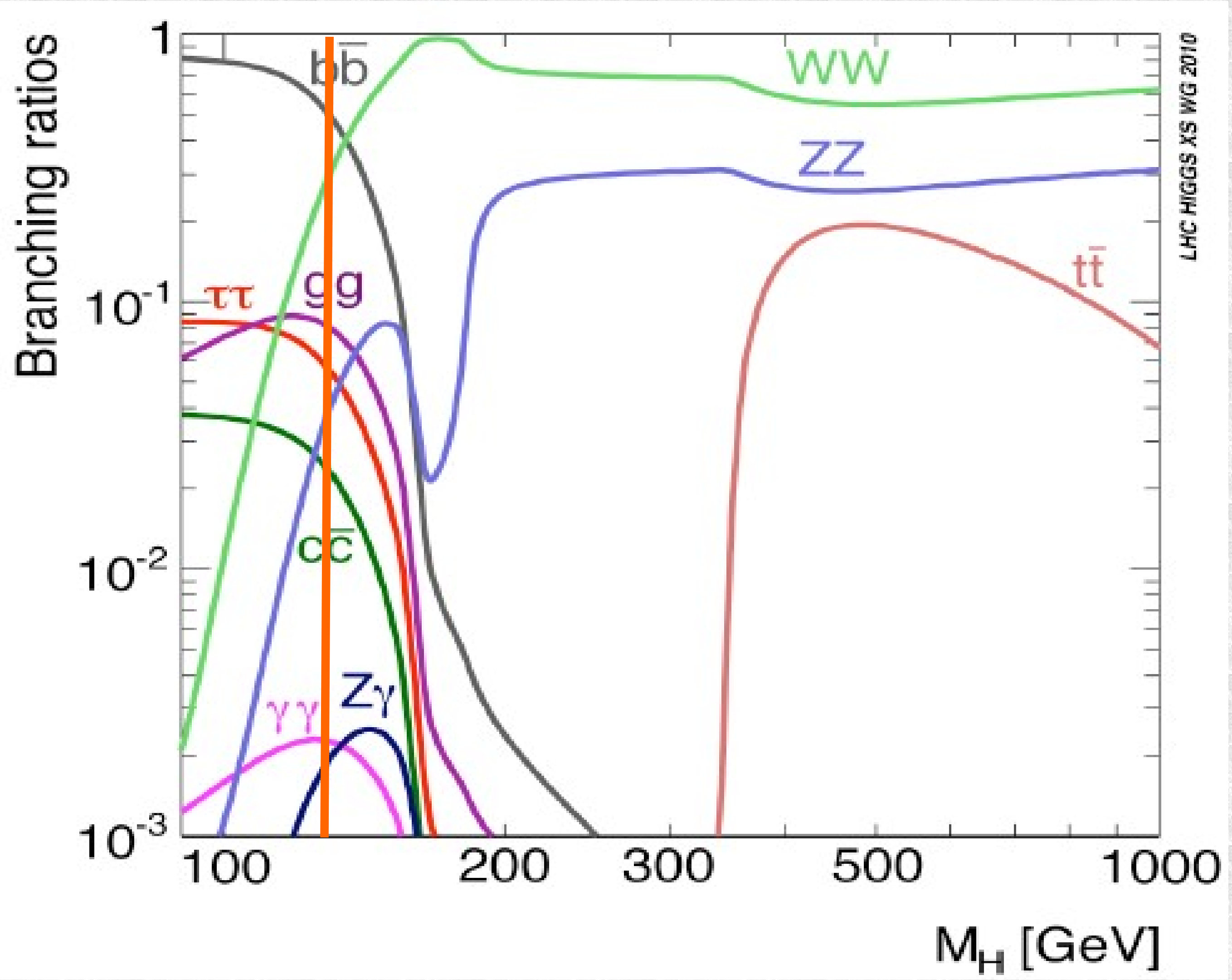
  - But Z is neutral (Charge and weak charge)
- ZZH vertex shows the H must be weak charged
  - But in H→ZZ where does the charge go?
- It is really a 4-point coupling
  - One leg 'grounded' in the vacuum
- The ZZ decay shows vacuum participates
  - With a (weak) charge!
- The apparent 3 point couplings come from $\partial_\mu \phi \partial_\mu \phi$ 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 make those?
    - 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?

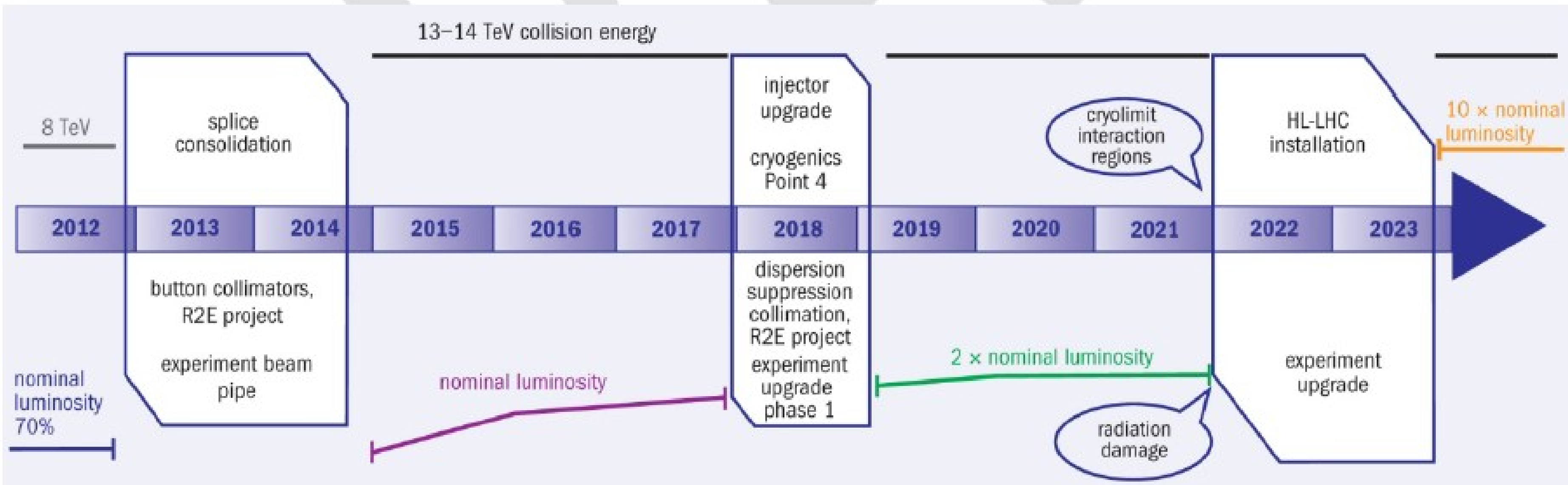
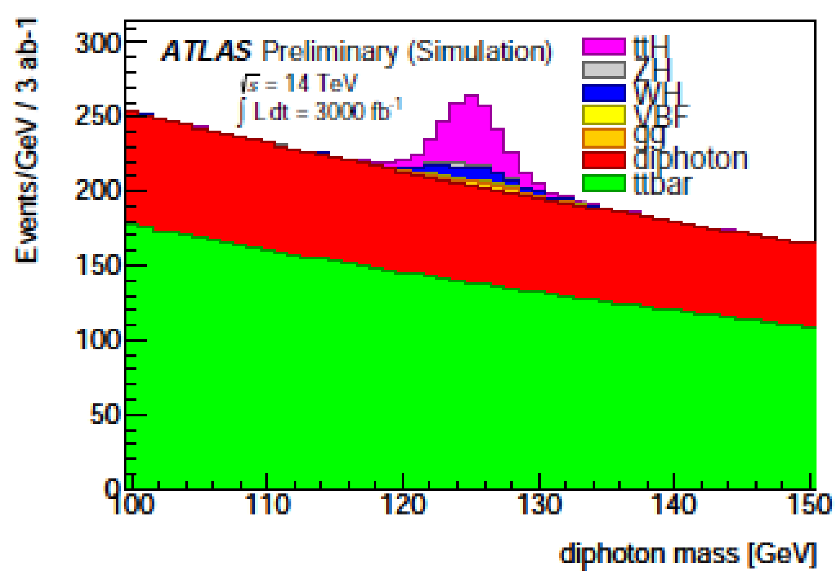


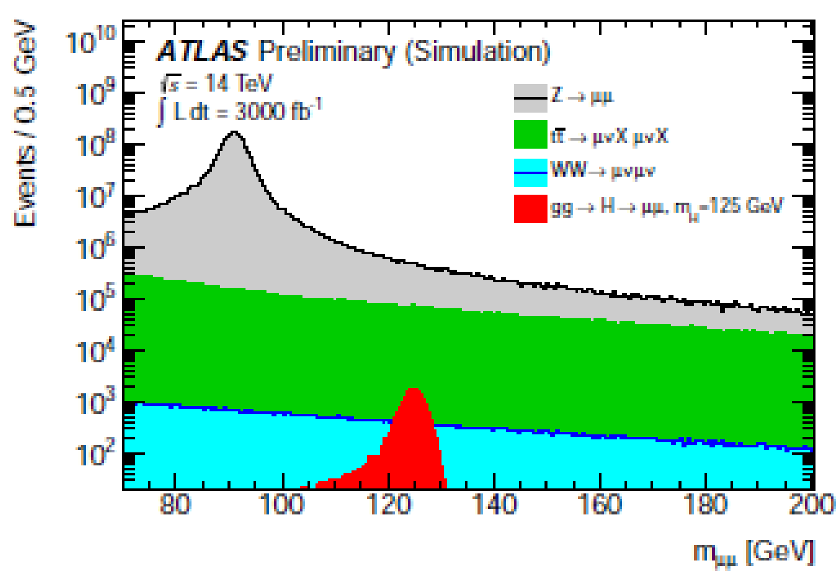
Figure 1: LHC baseline plan for the next ten years. In terms of energy of the collisions (upper line) and of luminosity (lower lines). The first long shutdown 2013-14 is to allow design parameters of beam energy and luminosity. The second one, 2018, is for secure luminosity and reliability as well as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

HL-LHC and ATLAS

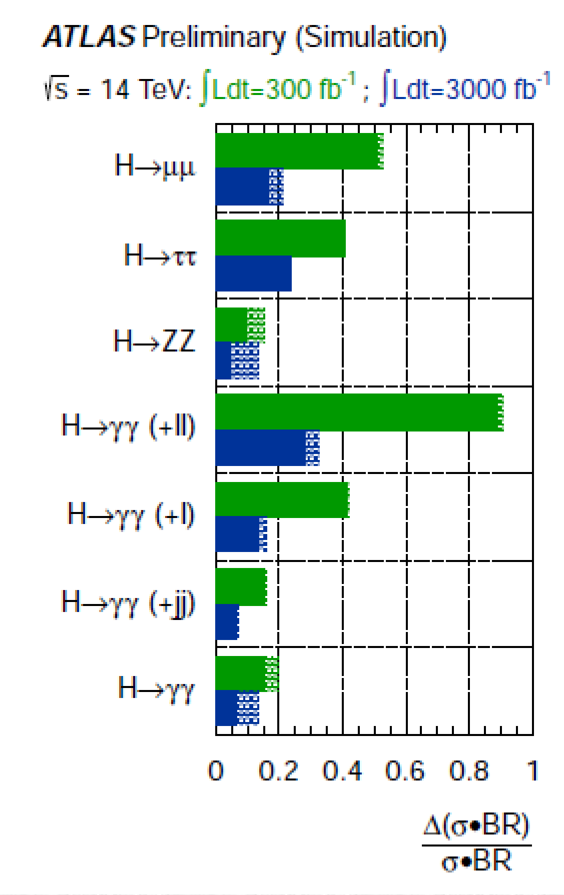
- LHC runs to 2022
- 300fb^{-1} at 14TeV expected
  - SLHC is proposed thereafter - 3000fb^{-1}
- ttH,H→γγ and H→μμ are two interesting studies



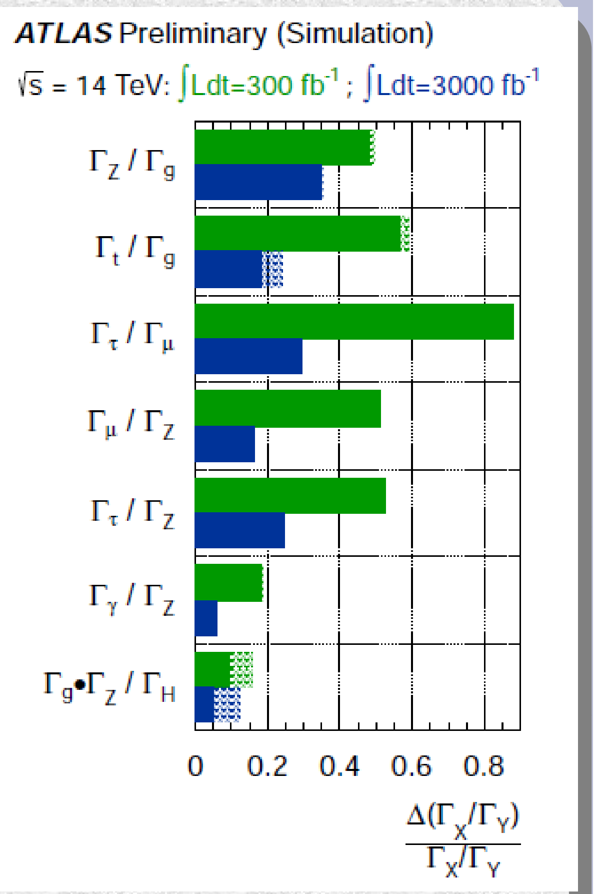


- But in general Higgs couplings must gain from factor 10 more data!

HL-LHC Higgs projections

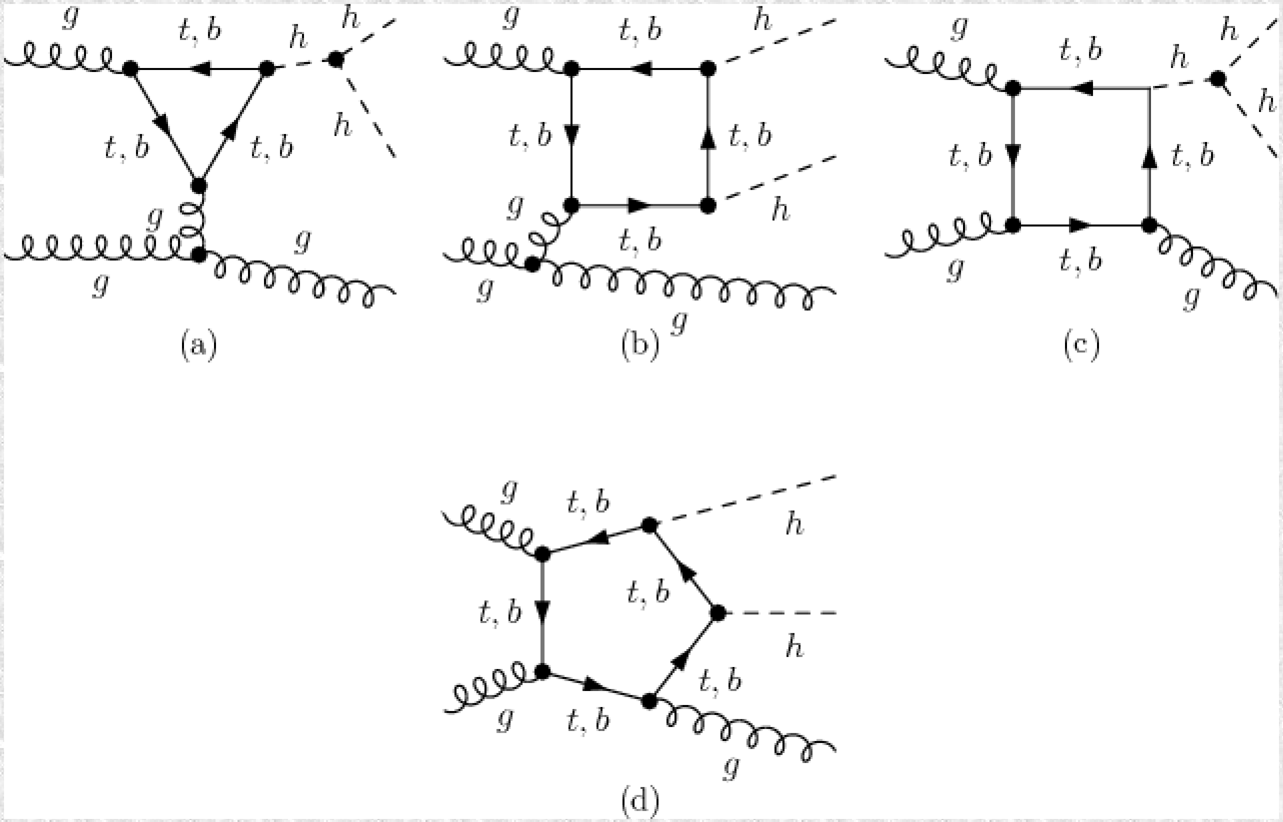


- Only subset of channels studied
  - But impressive performance possible
- LHC can never measure Higgs width
  - But ratios of couplings at O(20%) level
- But systematic errors are approximate in these estimates

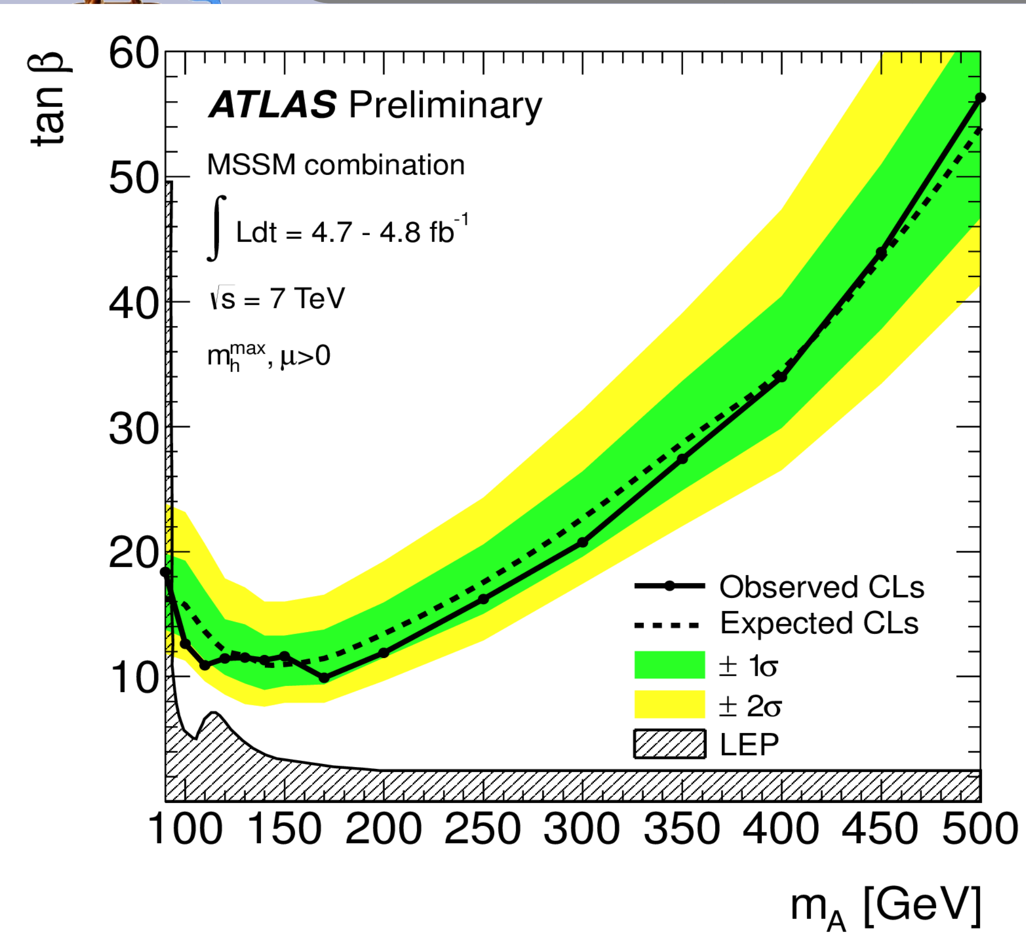


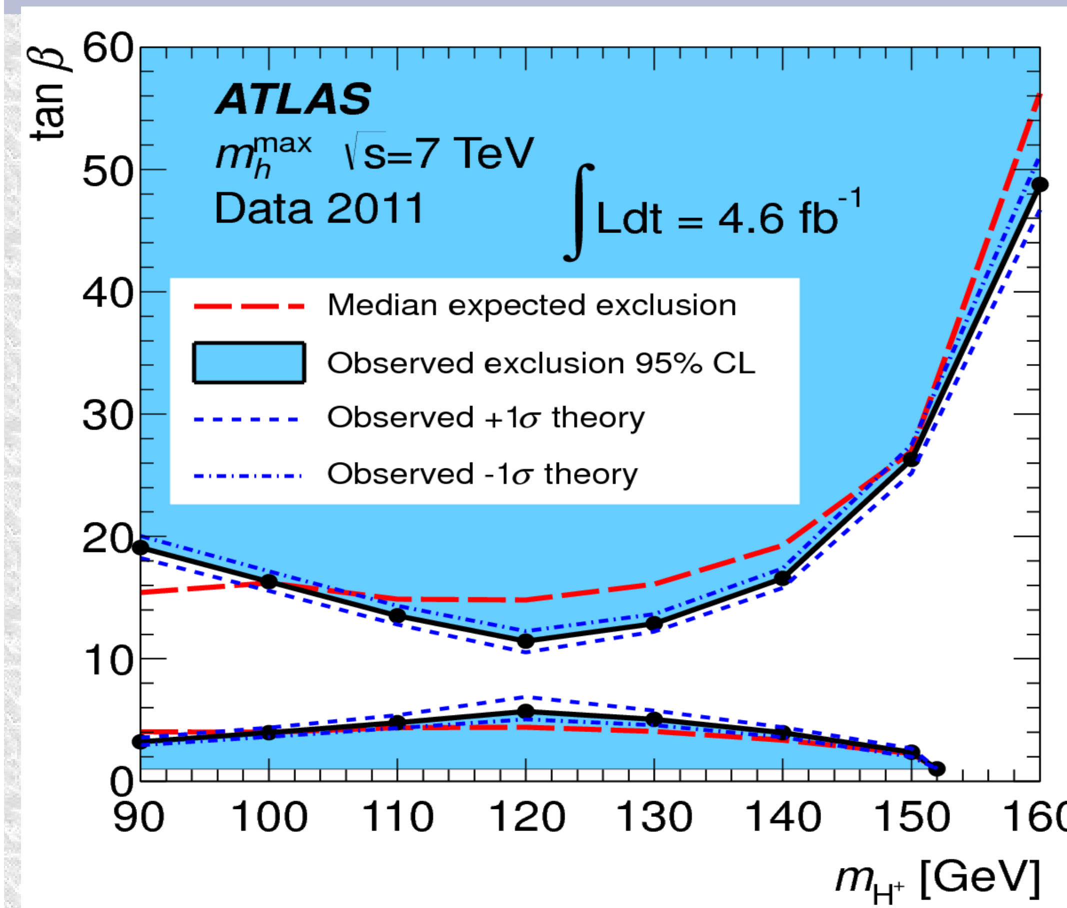
Self coupling

- 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?

Science & Technology Facilities Council
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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
  - We will know more by Christmas for sure
- The ATLAS is performing superbly
- In 2012 LHC is working remarkably well
  - We have twice the discovery data already
  - By 2021, 300fb^{-1} at 14TeV will allow 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