The status of the LHC Higgs programme

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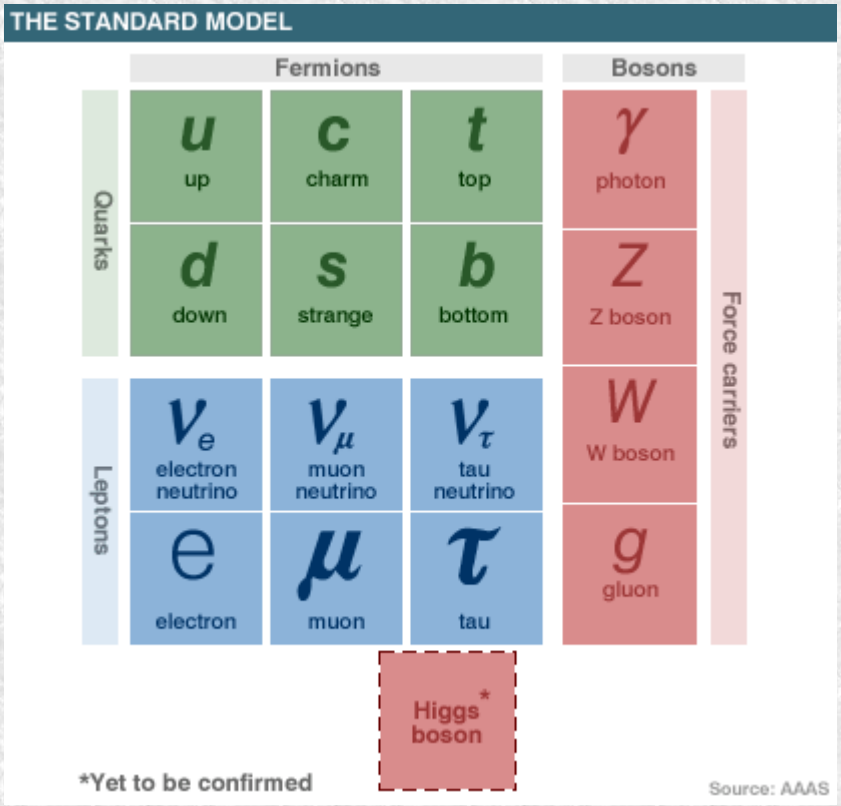
7th April 2014

- The discovery
- What do we know so far?
- Implications

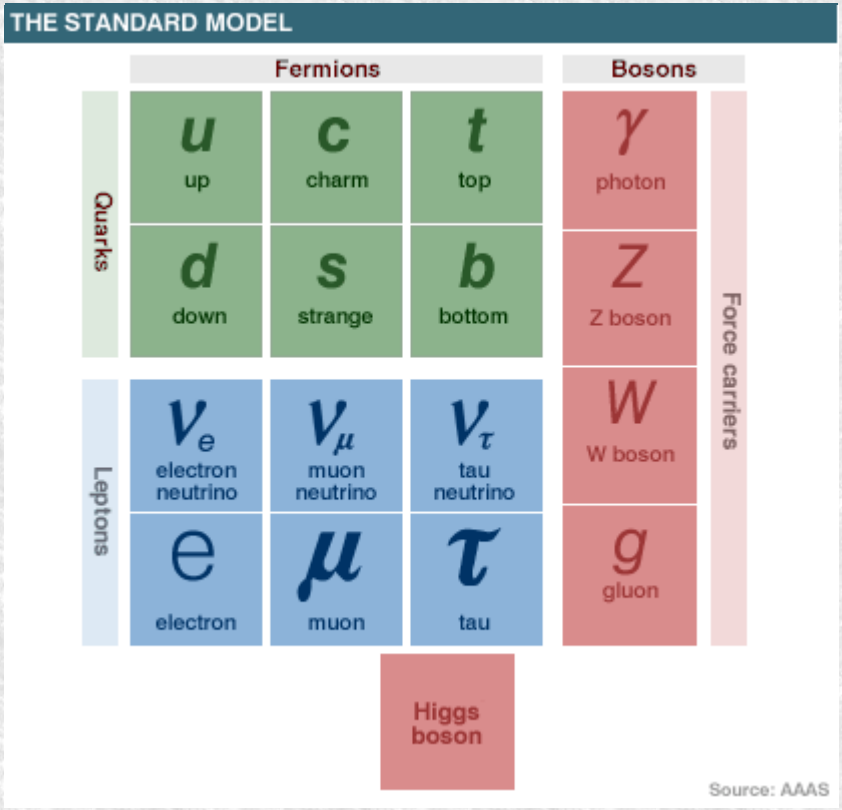
The Standard Model

- The Standard Model has ruled particle physics for 40 years
  - 3 forces
  - 2→3 families of quarks/leptons
- But the Higgs sector remained unknown...



The Standard Model

- The Standard Model has ruled particle physics for 40 years
  - 3 forces
  - 2→3 families of quarks/leptons
- But the Higgs sector remained unknown...until now
- A Higgs boson has been discovered
  - What do we know?
  - What more can LHC tell us?
- Is it alone?

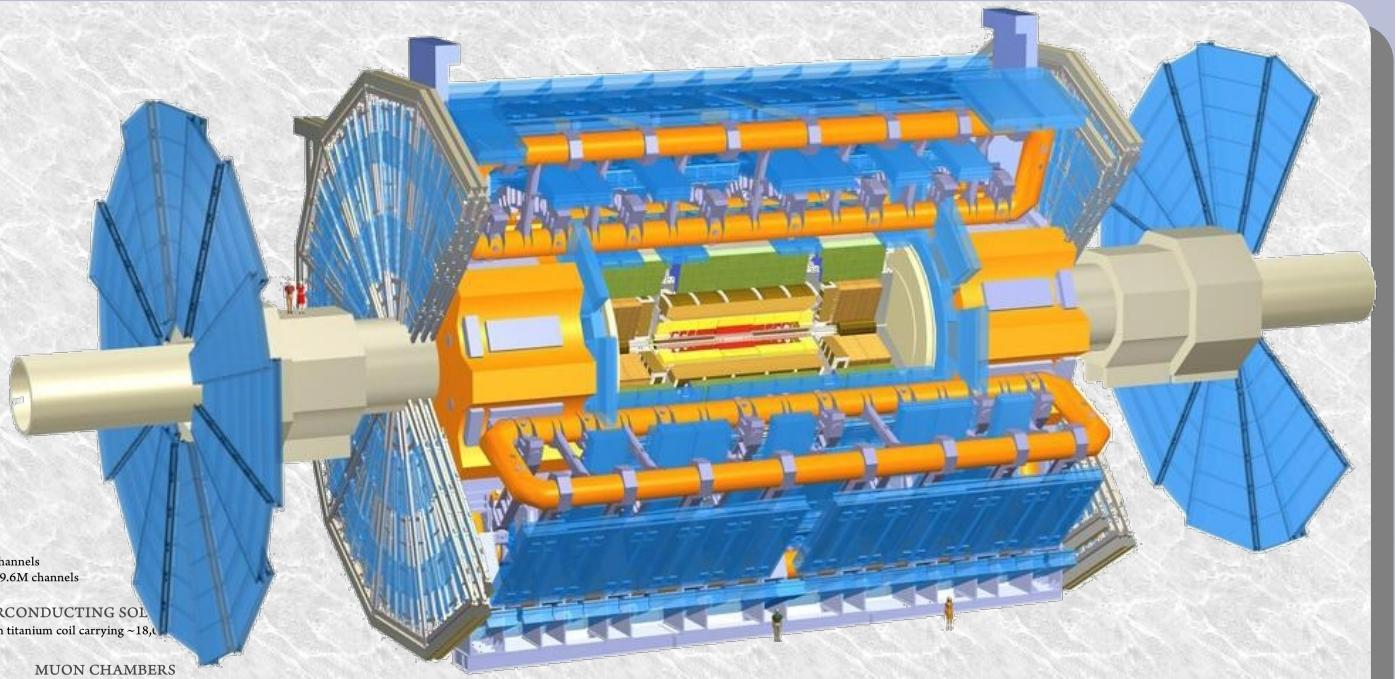


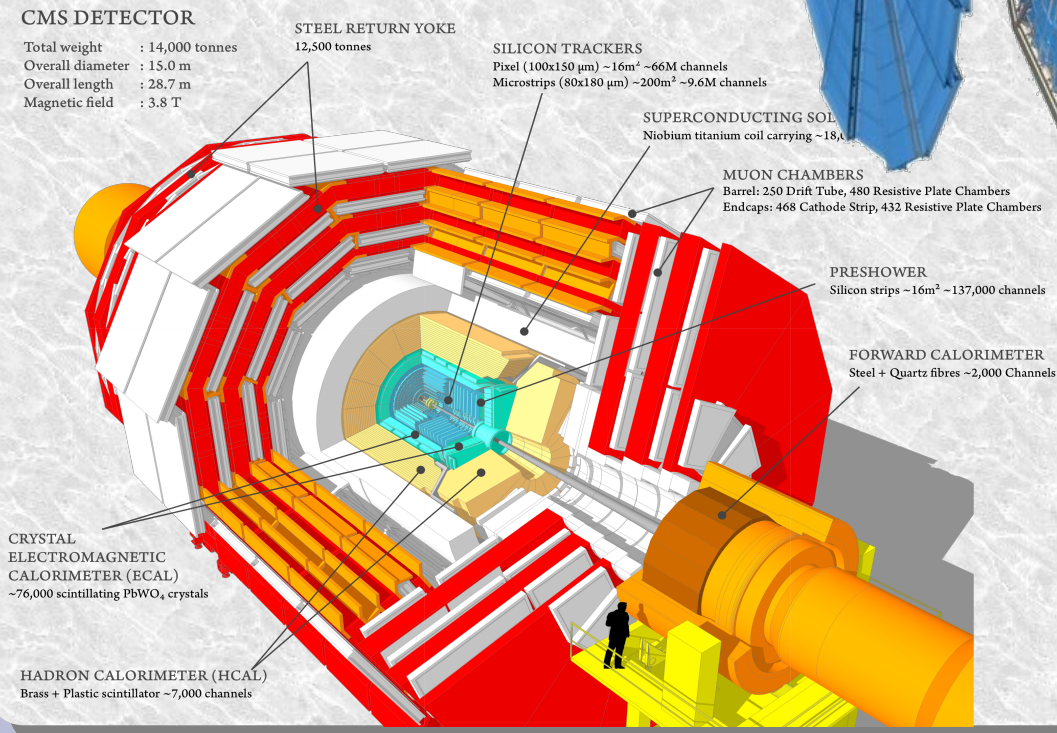
History of the search

- 1964 Brout & Englert, Higgs, Guralnik, 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 lower limit reaches 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 & CMS

- Precisly measure
  - leptons,
  - γ
  - jets
  - E_T^{miss}

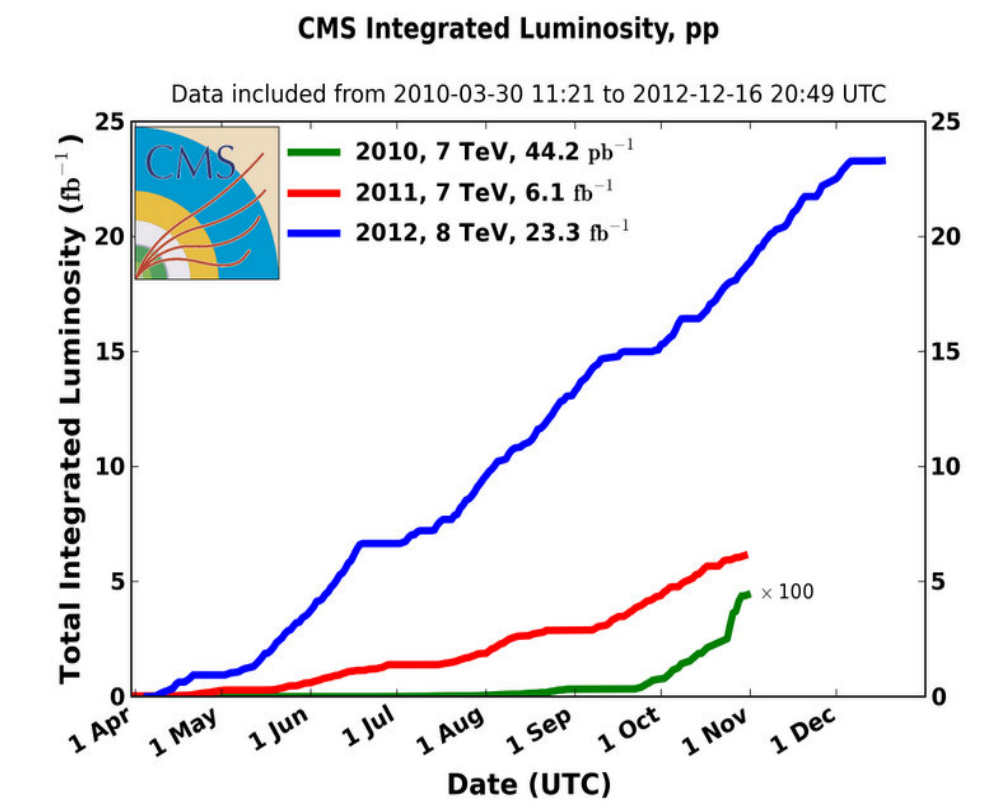




- ATLAS: External magnet provides toroidal muon field
- CMS superb central solenoid

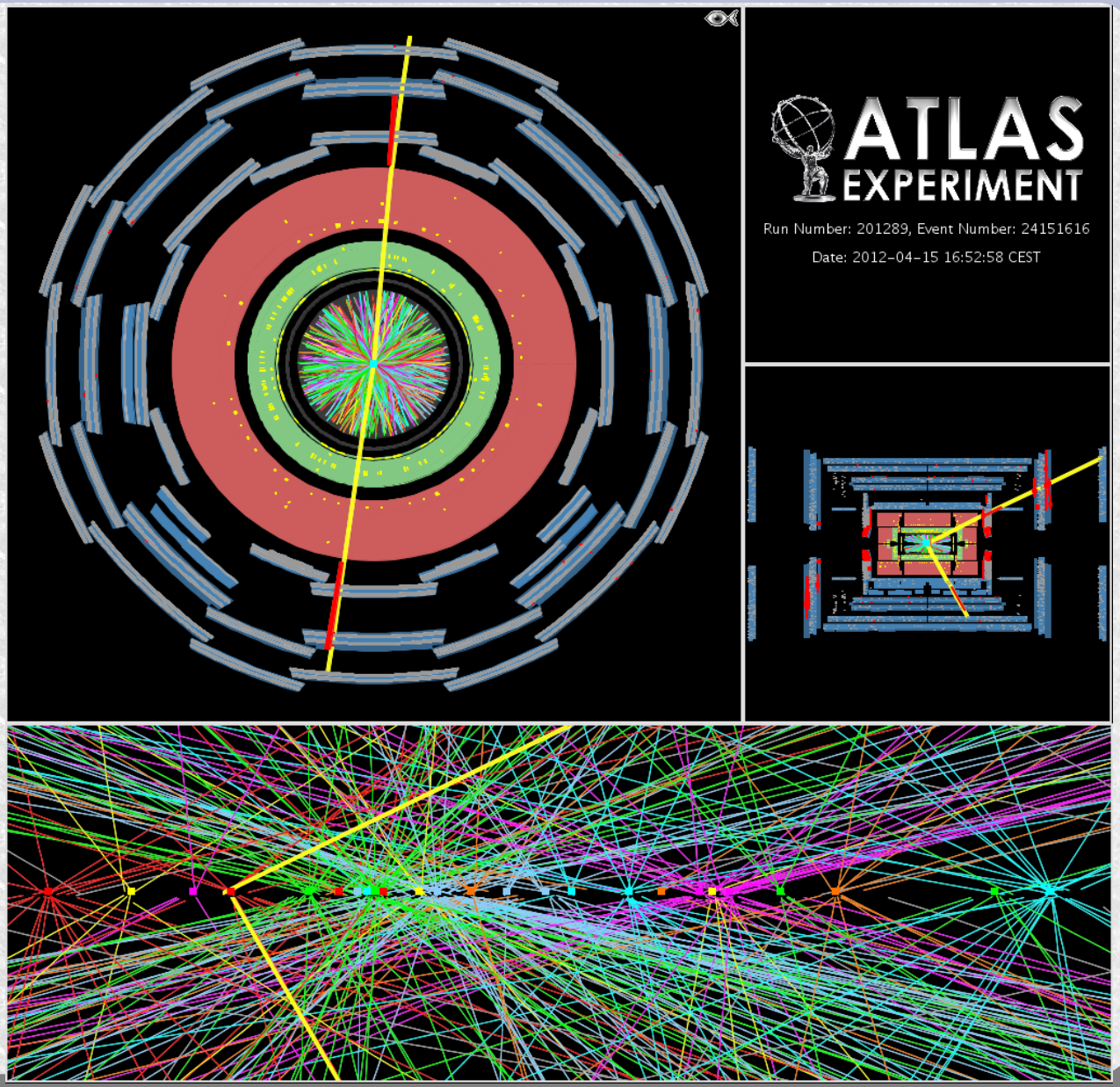
Data collection

- LHC delivered 5fb^{-1} in 2011
  - Gave first hints for SM Higgs
- √s raised 7→8TeV in 2012
- 23.3fb^{-1} delivered
  - 6 fb^{-1} allowed Higgs discovery
  - Now tests of properties
- Great effort by LHC team!
- ~90% of the delivered luminosity is used in analysis
  - Dedication from the systems experts and shift crews.



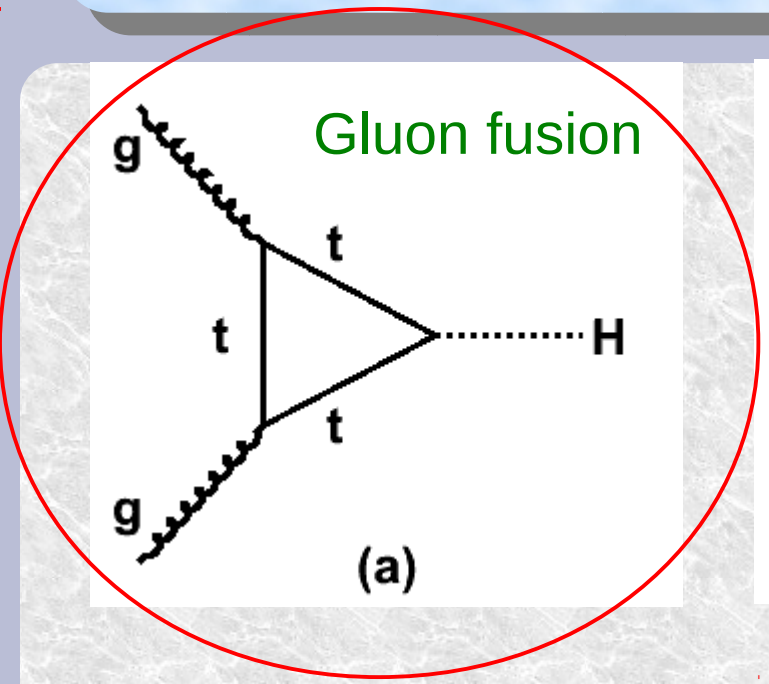
Pileup in 2012

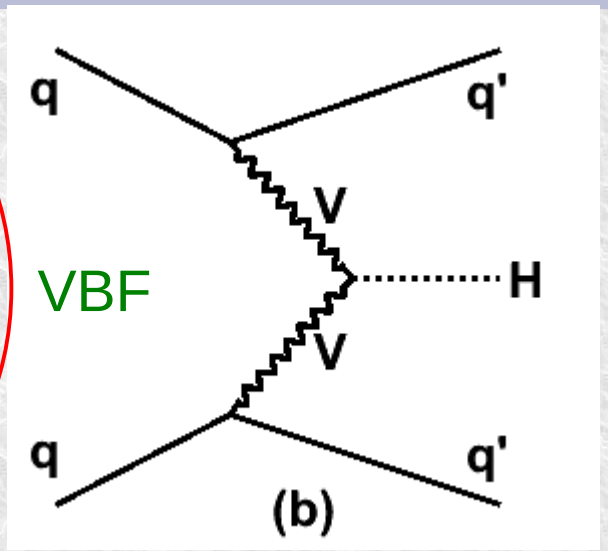
- Example: $Z \rightarrow \mu\mu$
- Has multiple overlayed interactions
  - 25 seen here
- Tracker can distinguish them by position
- Calorimetry suffers
  - Degrades isolation
  - E_t^{Miss}
- We are finding solutions

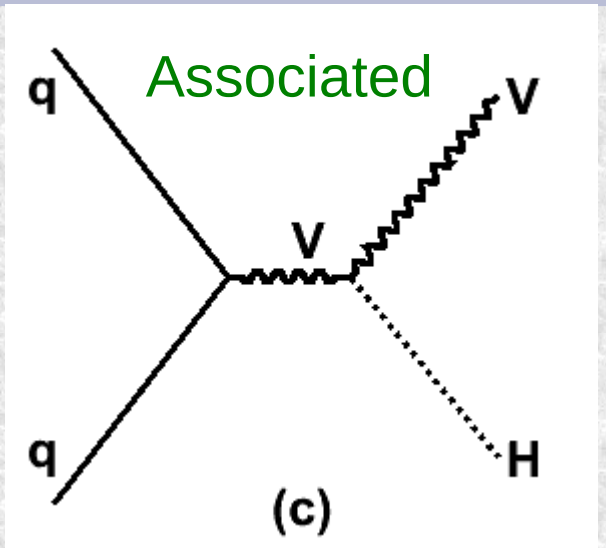


Hunting the Higgs Boson

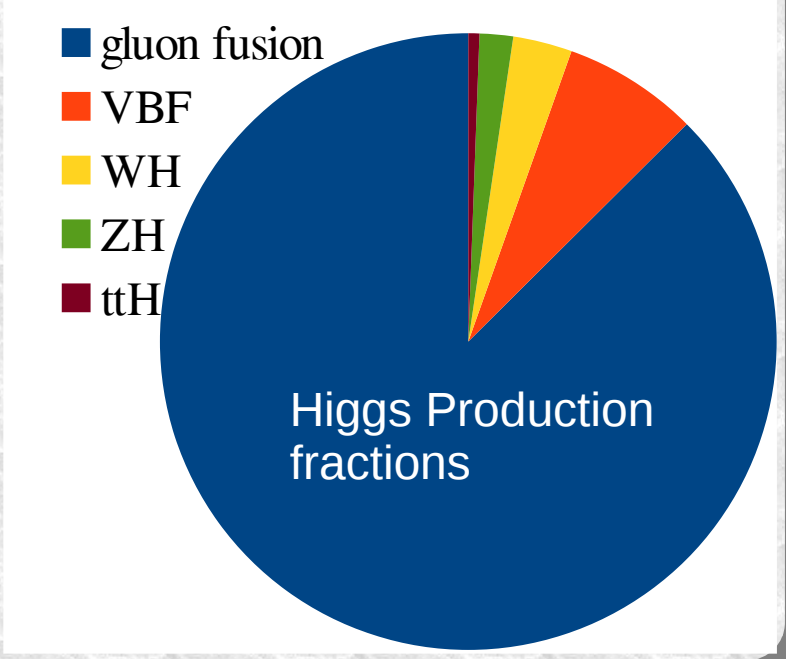
Higgs production



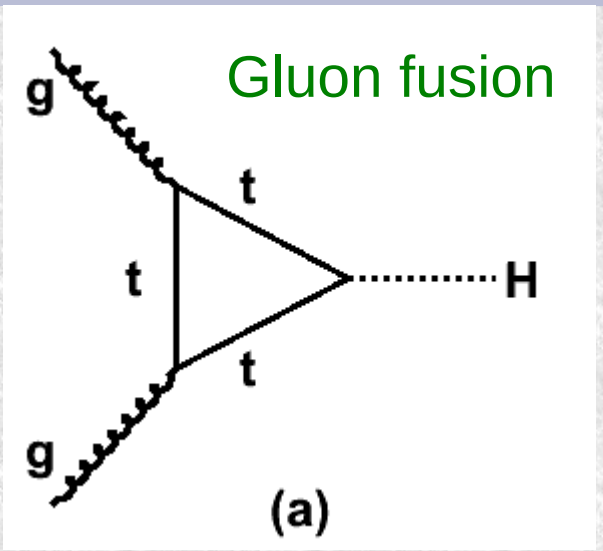


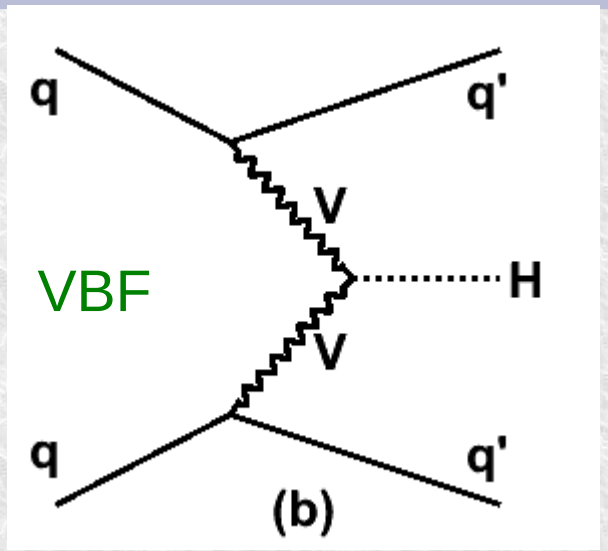


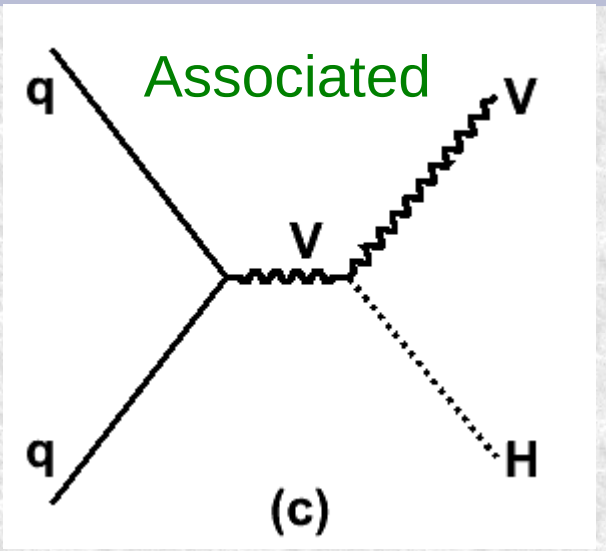
- The three most common modes
  - Others also exist: $t\bar{t}H$, tH , bbH...
- Gluon fusion dominated discovery
  - Top loop (+ BSM?)
- Vector boson fusion/associated
  - Also used to tag signal
  - Improves the purity



Higgs production







$19.7\text{pb}^{+7.2}_{-7.8}\,\%(scale)^{+7.5}_{-6.9}\,\%(PDF)$

$0.69\text{pb}^{+0.2}_{-0.6}\,\%(scale)^{+3.5}_{-3.5}\,\%(PDF)$

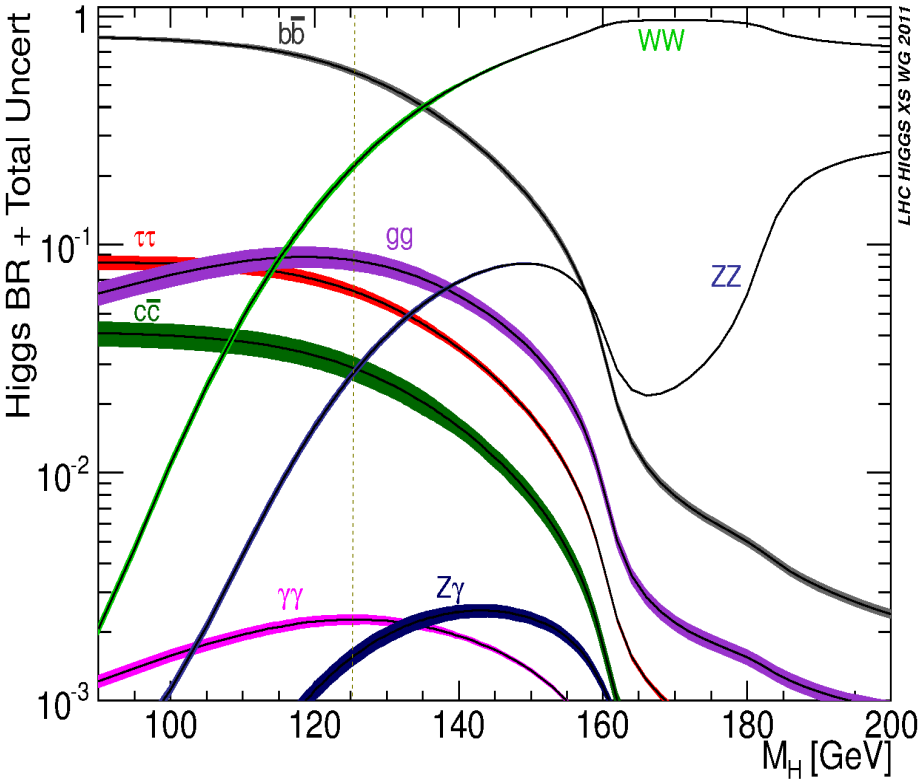
$1.57\,pb^{+0.2}_{-0.2}\,\%(scale)^{+2.6}_{-2.8}\,\%(PDF)$

(WH only)

- Cross-section errors on gluon fusion are the largest systematics in rate measurement
- In the long term the associated or maybe VBF will give stringent test of production rate

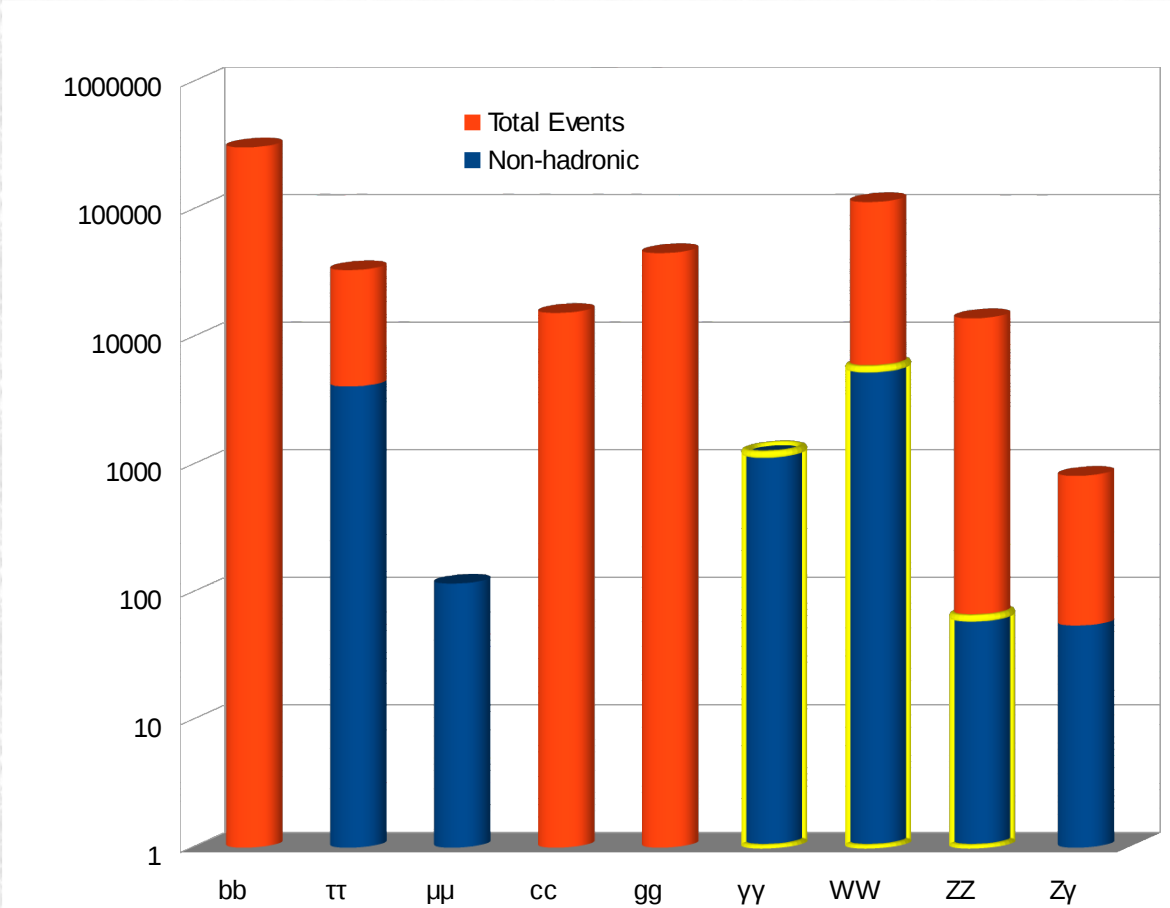
Higgs decay modes used

- H→ZZ
  - ZZ→llll: Golden mode
  - ZZ→llνν: Good High mass
  - ZZ→llbb: Also high-mass
- H→WW
  - WW→lνlν: First 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 decay mode

- Run 1 production in each experiment
- From 100 to 300000 events per channel
  - Easy?
- But total pp events:
  2×10^{15}
- 60 Higgs to llll events
  - *Before* selection
- Needs incredible background rejection
  - The outlined channels are the most sensitive

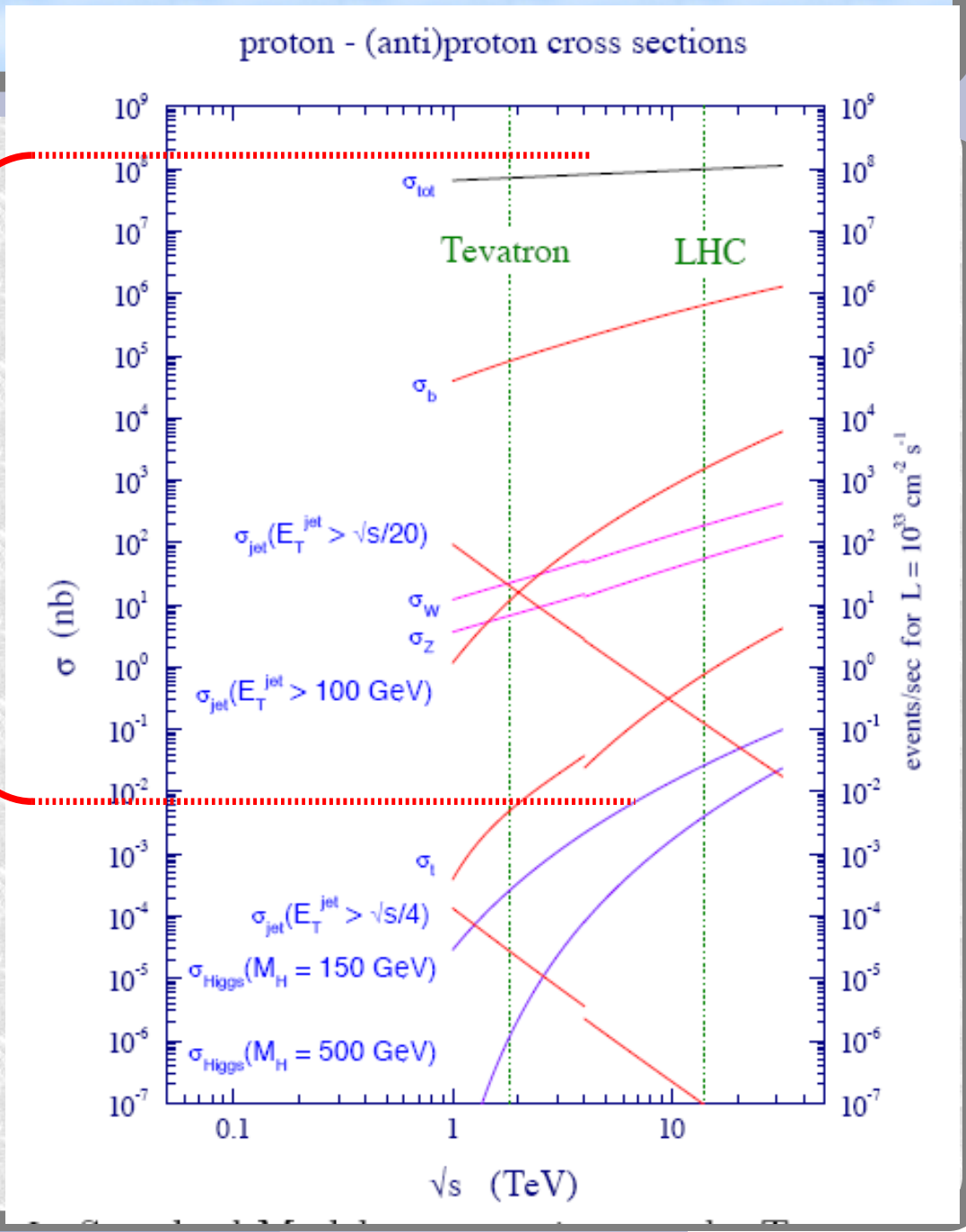


Never forget background

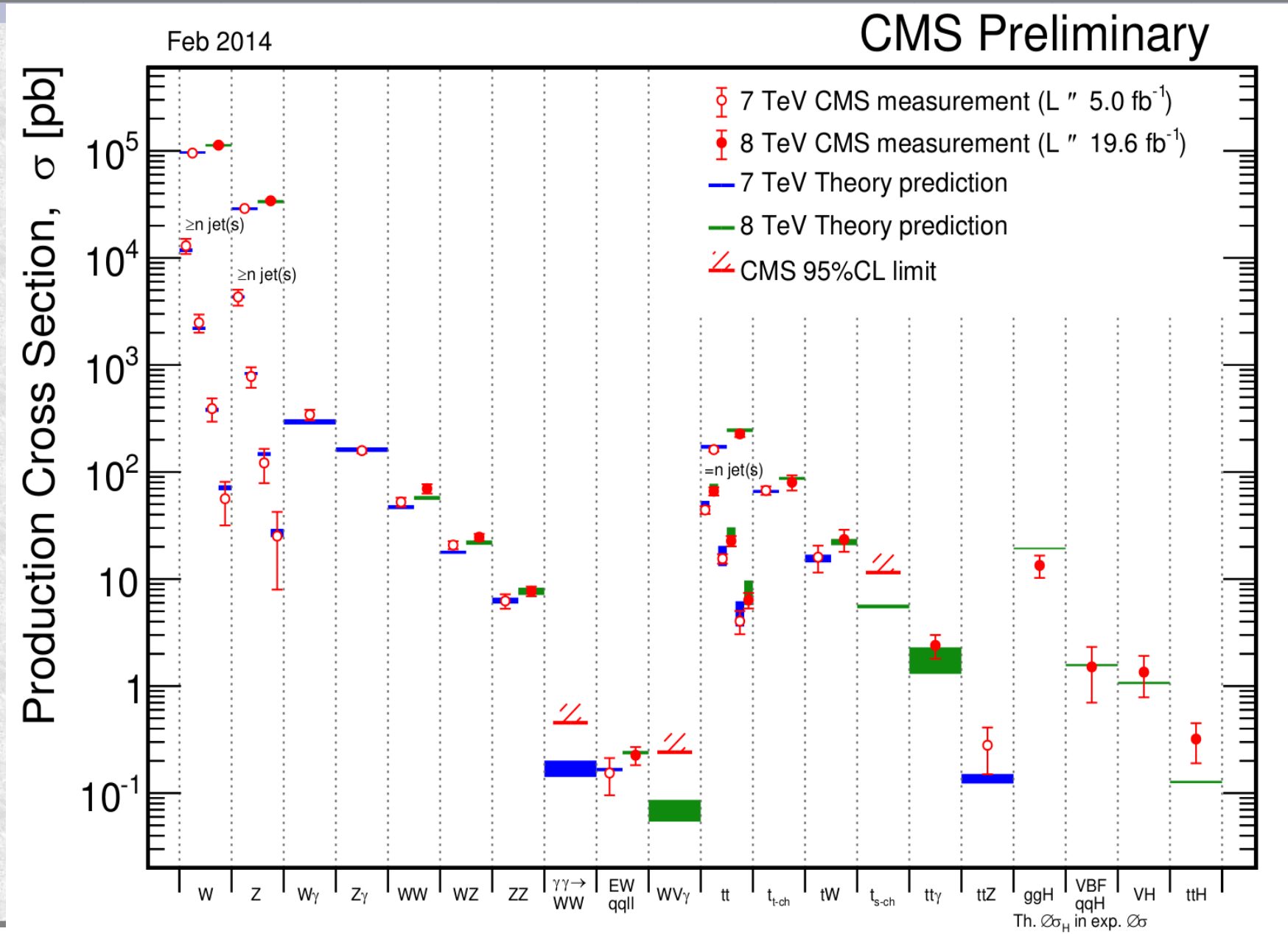
- LHC is all about background rejection 10^{10}

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

Sam Ting

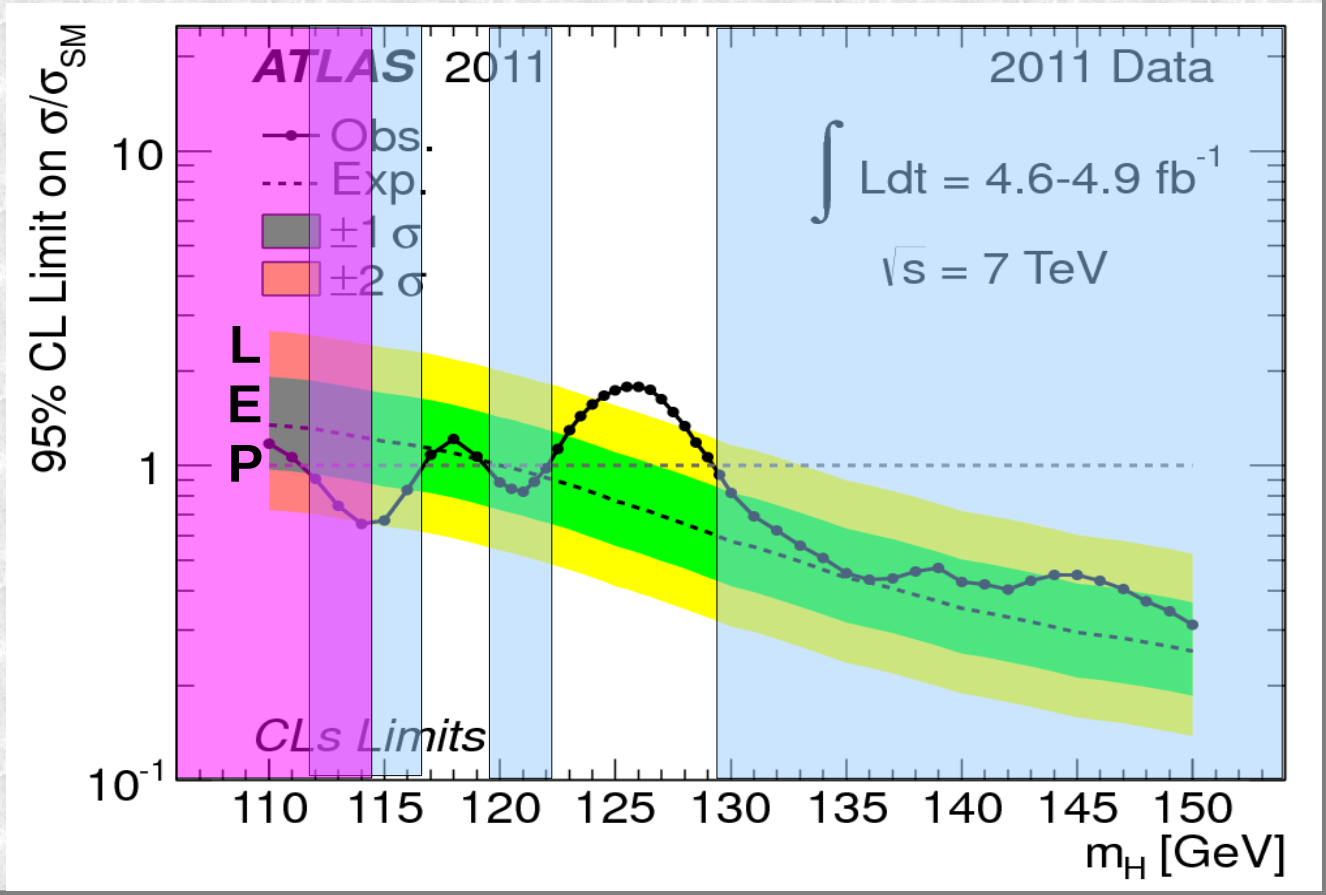


Standard Model measurements



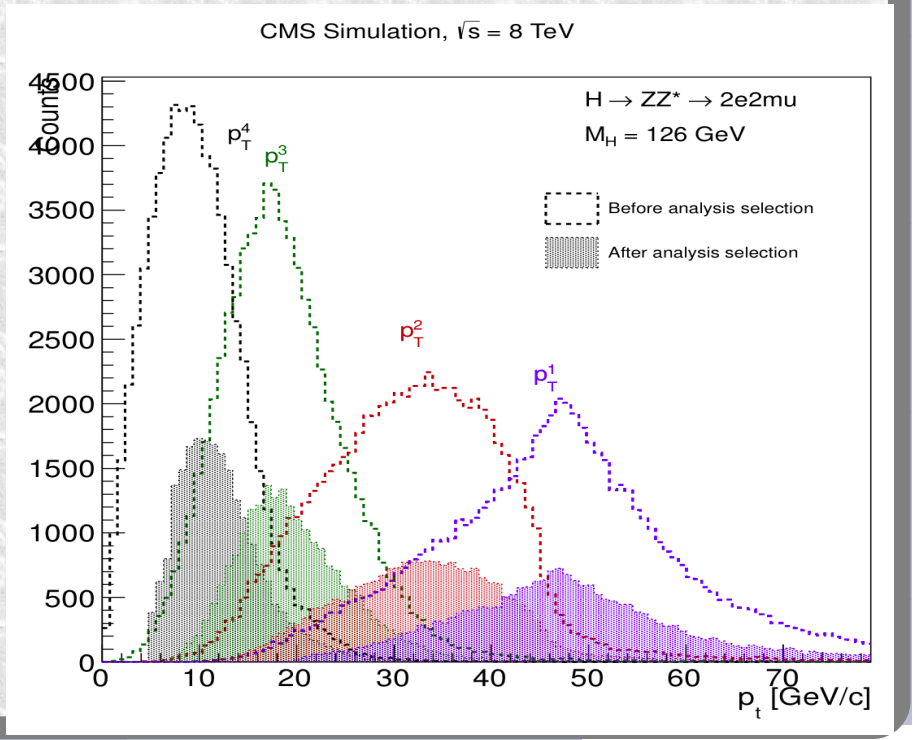
Higgs search in 2012

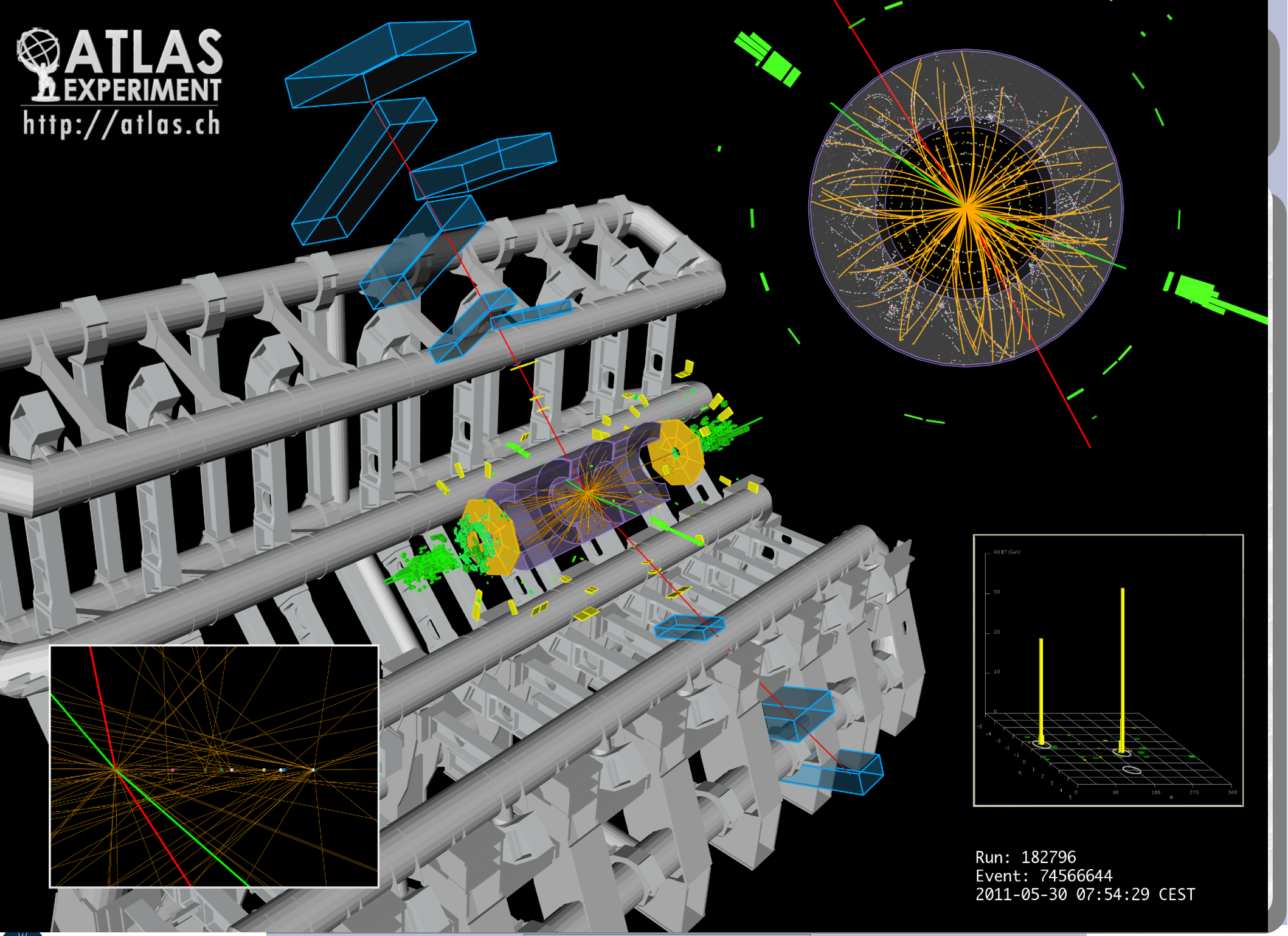
- 2011 had excluded most masses
  - 117 to 129 GeV was focus
- Papers submitted 31st July by CMS and ATLAS
  - Both claiming observation of a new particle
- Three channels are strongest
  - γγ
  - ZZ
  - WW
- But more follow:
  - ττ
  - bb



H →ZZ→llll

- The golden mode
- Good mass/energy measurement
  - Electrons and muons are measured with O(1%) precision
- Very low backgrounds
  - Dominated by real ZZ→llll
  - Plus some Zbb where b decays leptonically
- But signal rate low
  - Higgs couples strongly to ZZ
    - But 2 $m_Z > m_H$ so one Z must be off mass shall
  - Z→ee or μμ Br only 3%
  - Challenge to maximise efficiency
  - Especially for low-p_T electrons
    - Tracking must allowing for bremsstrahlung




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

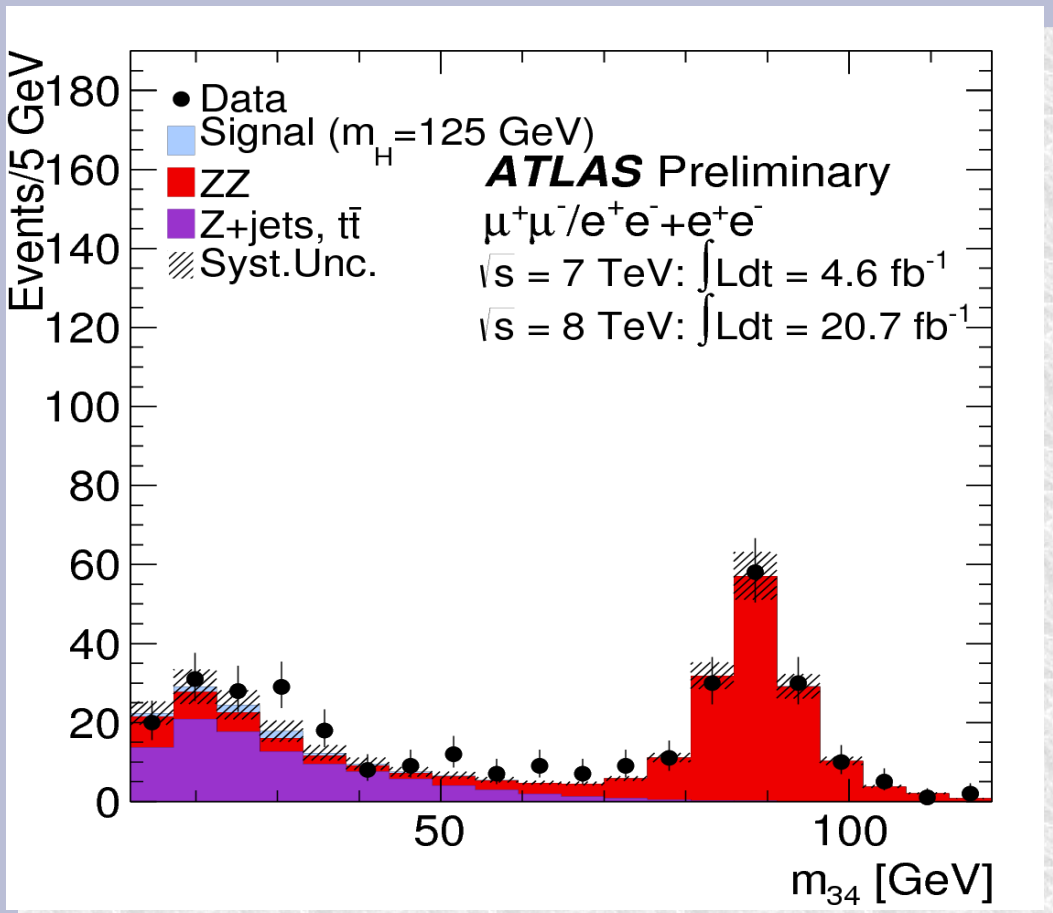
Basic analysis steps

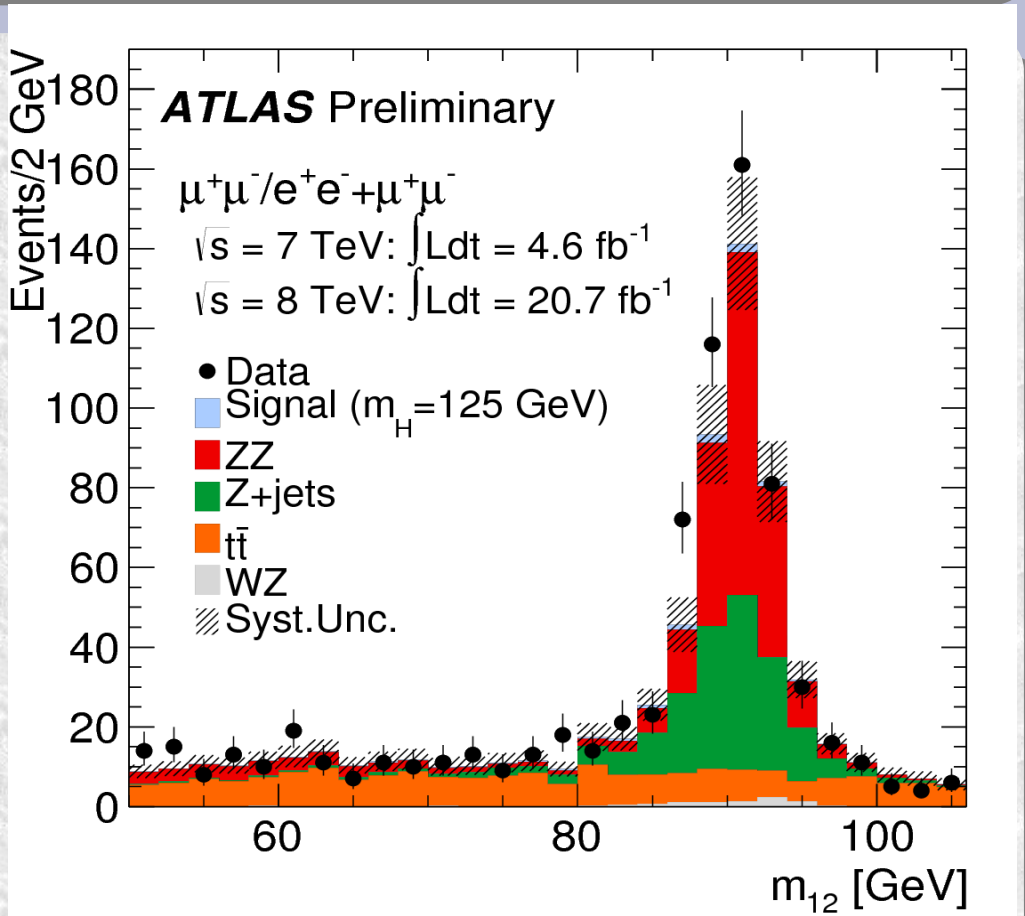
- Find events with 4 leptons (e/μ) in them
- Request a pair is in region of the Z mass
- The second is allowed to be much lower in mass
  - Kinematics requires one Z is forced to be off-shell, lighter

Minimum lepton p_T	7 Gev (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

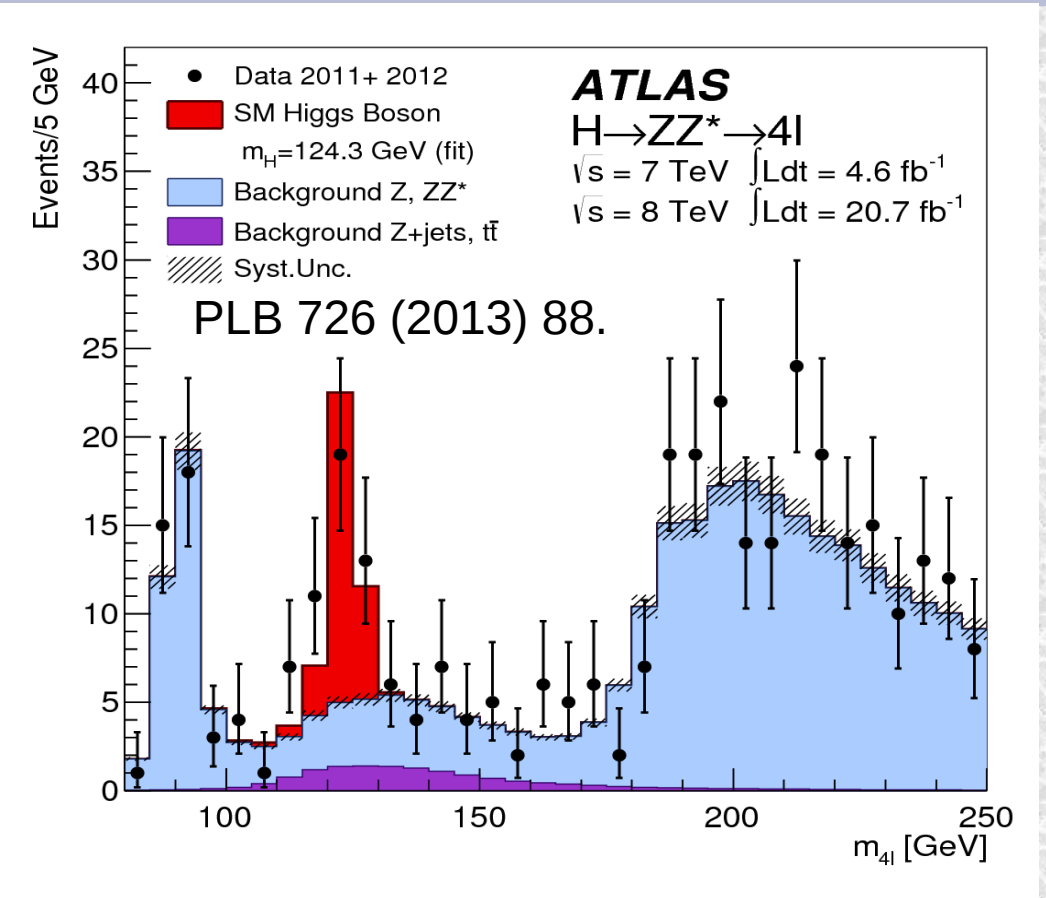
Background Measurement

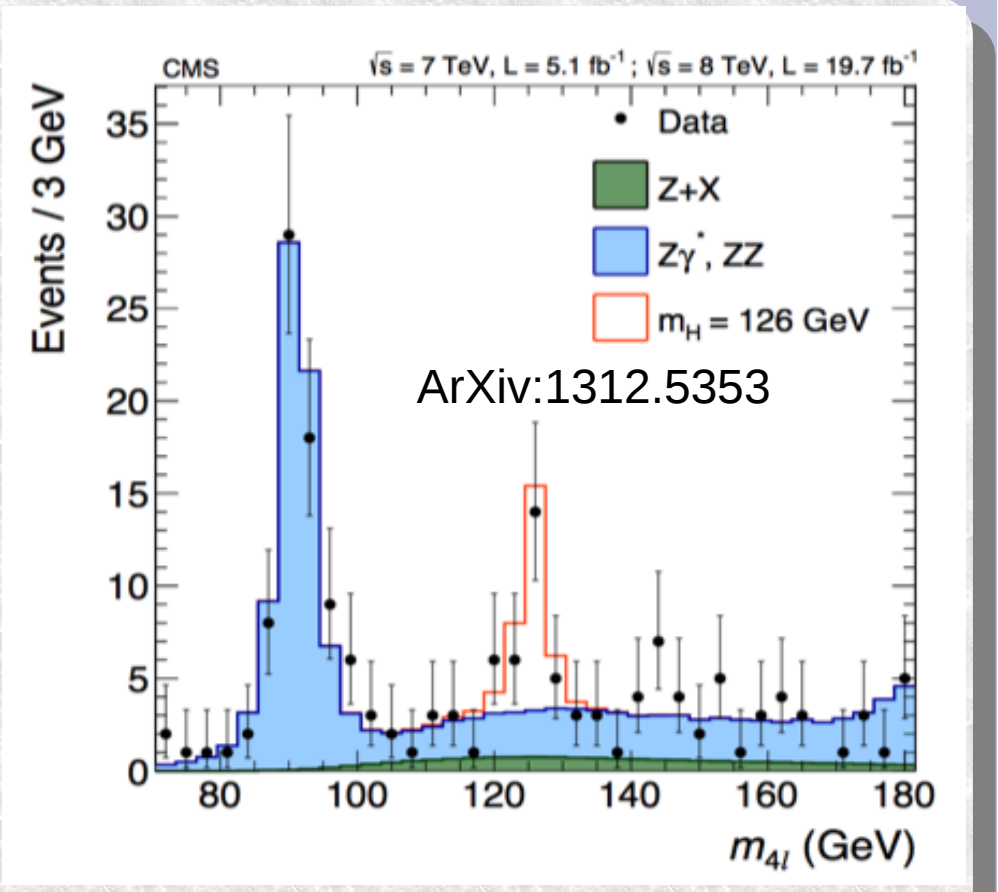




- Remove isolation from 2nd Z candidate
  - Left is low Z mass ee candidates
  - Right high Z mass μμ
- Many detailed studies of e/μ fake rates

Signal Mass distribution

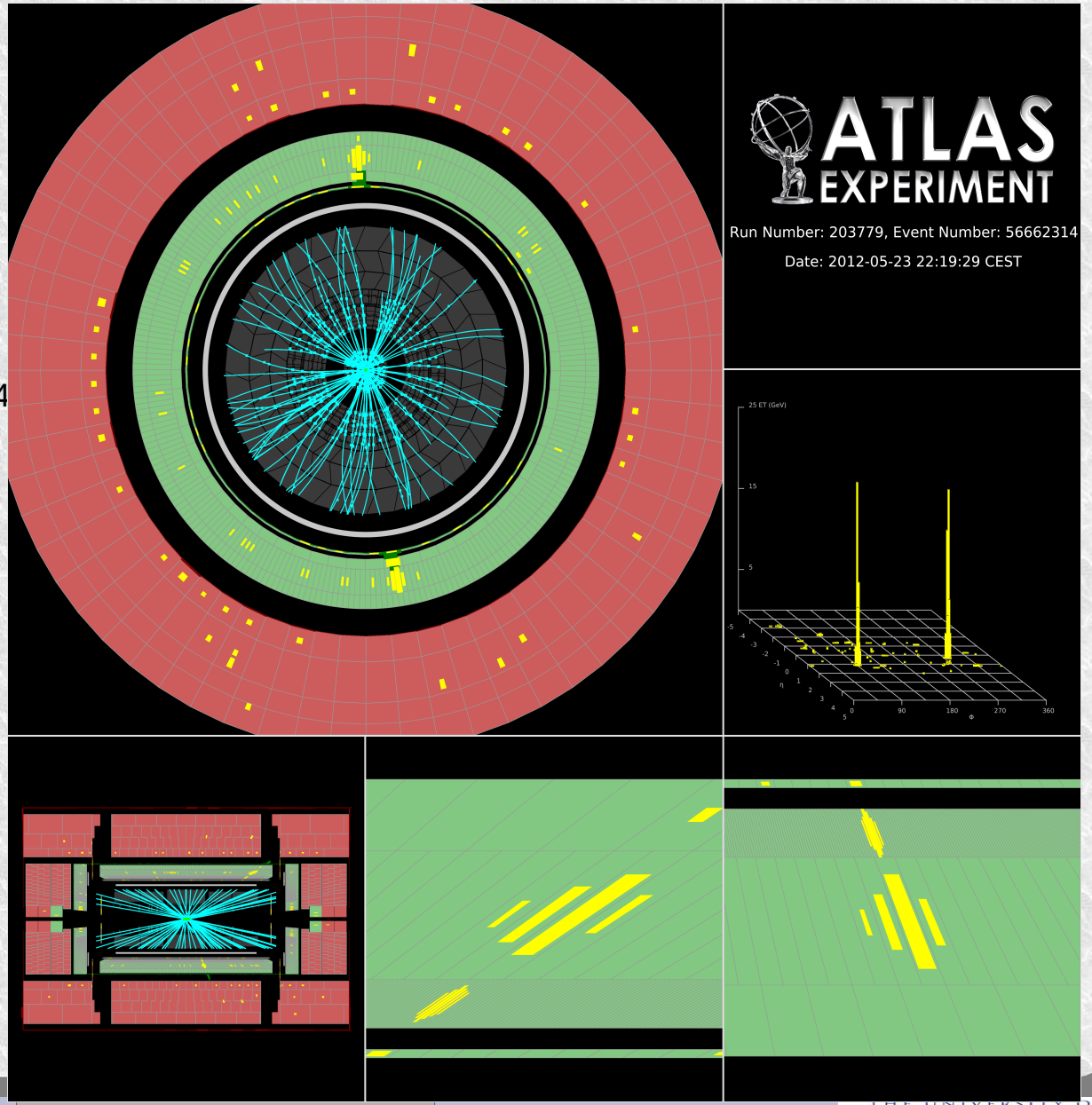




- Clear peak near 125 GeV
  - S/B better than 1
  - The Z→llll peak at 91 GeV is seen too; sanity check
- CMS use matrix element for each event to discriminate

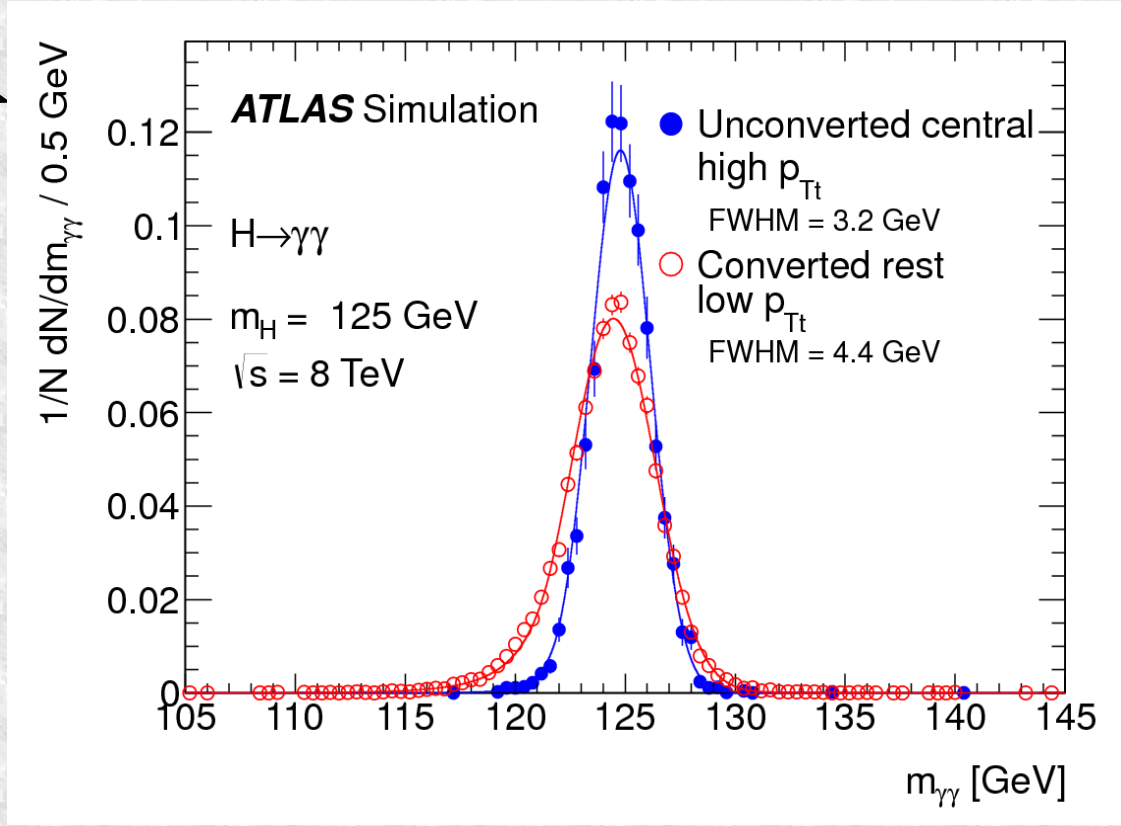
$H \rightarrow \gamma\gamma$

- Rare decay,
  - 2 per mille
  - $110 < m_H < 150$
- Drove ECAL design
  - CMS: Crystal $PbWO_4$
  - ATLAS: LAr accordion
- Give good energy measurement
  - Need vertex position to calculate mass
  - Tracking shows it
- Good jet rejection also essential

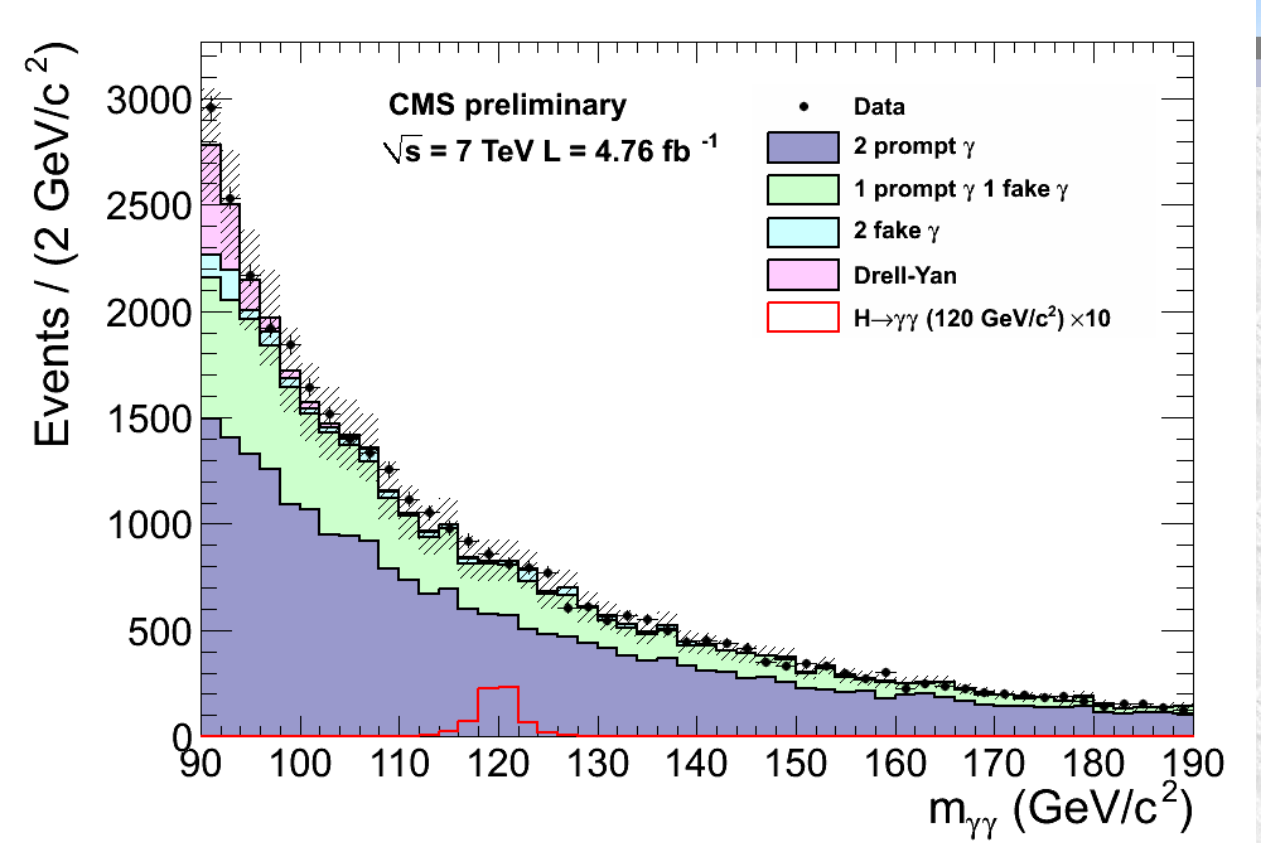


$H \rightarrow \gamma\gamma$ mass resolution

- Higgs resolution assessed in classes:
- Understood using $Z \rightarrow ee$
  - Z natural width needs to be allowed for
  - Material effects on e/γ scale taken from MC
- Checked with $Z \rightarrow ll\gamma$
  - Statistics limited
  - Will be improved with more data
  - Scale already limits m_H accuracy



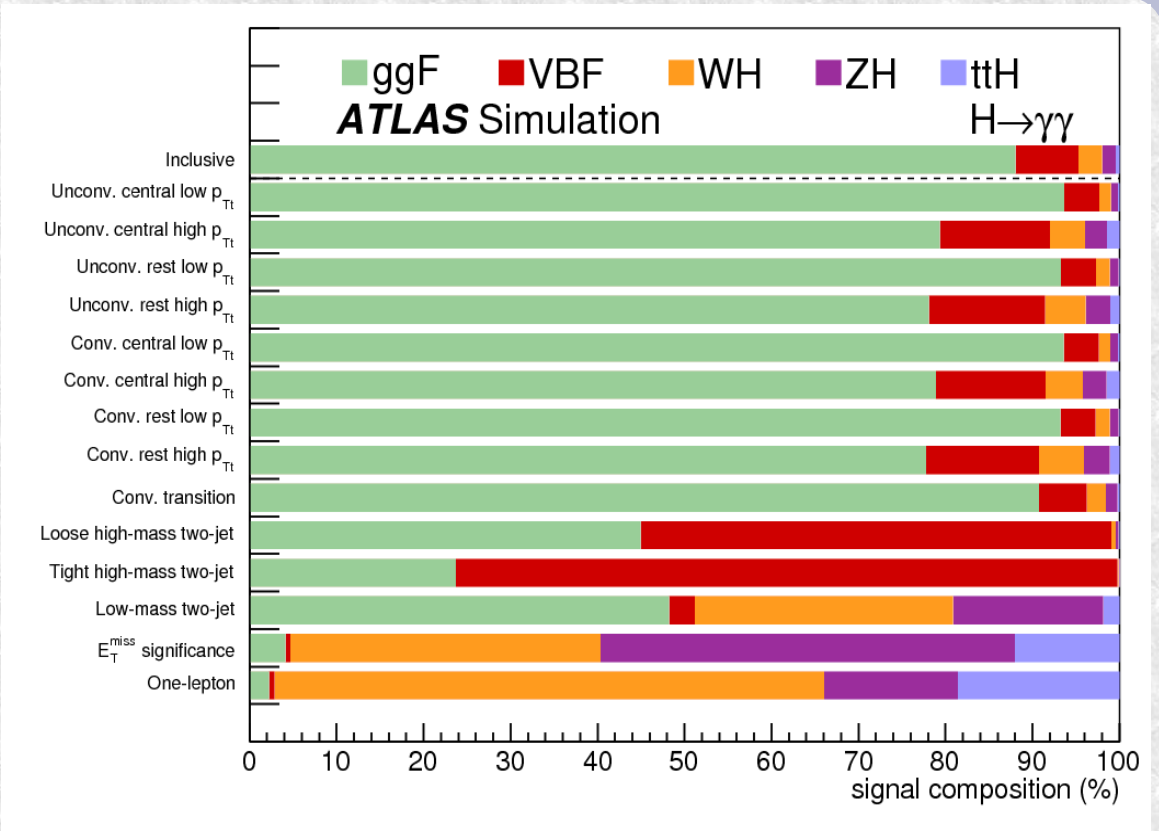
H→γγ sample composition



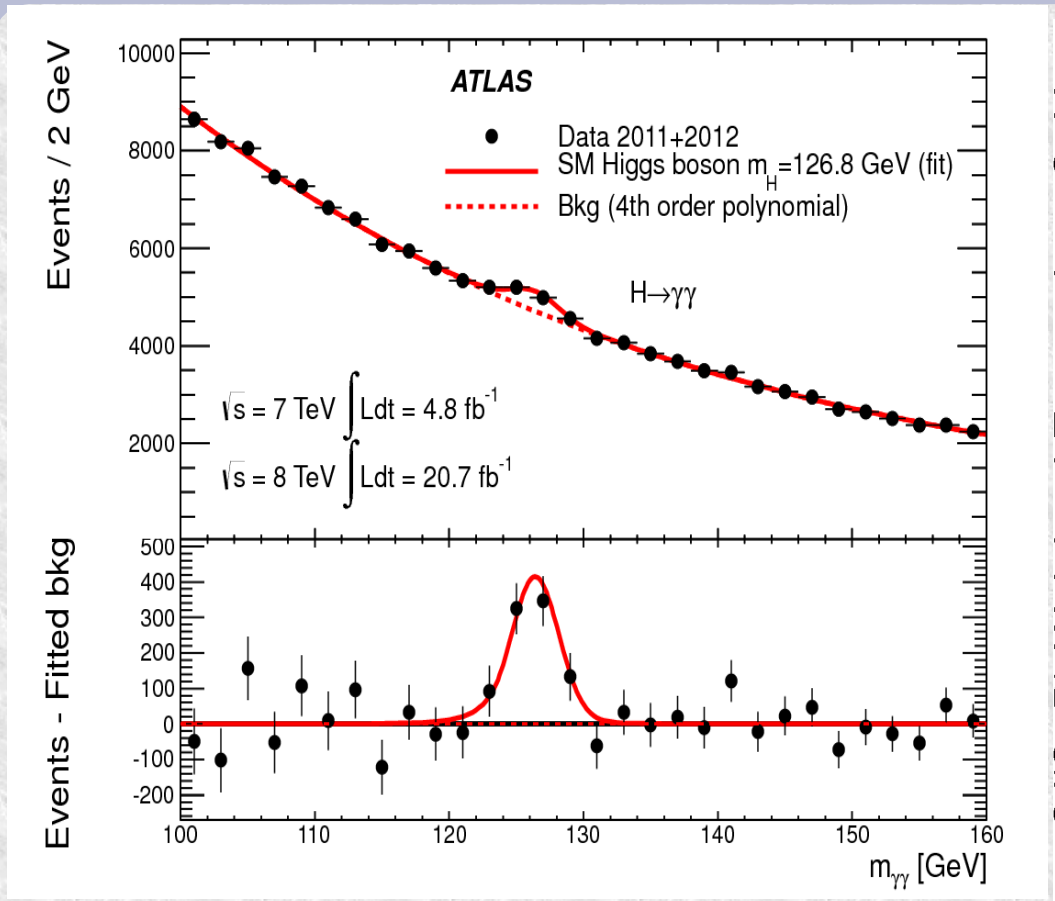
- Measure sample composition in data: γγ, γj or jj?
  - Plus small Drell-Yan
  - Use 2D isolation & photon-ID sidebands
- Samples are dominated by real di-photon.
  - We reject 99.99% of jets!
  - Little gain from better photon purity

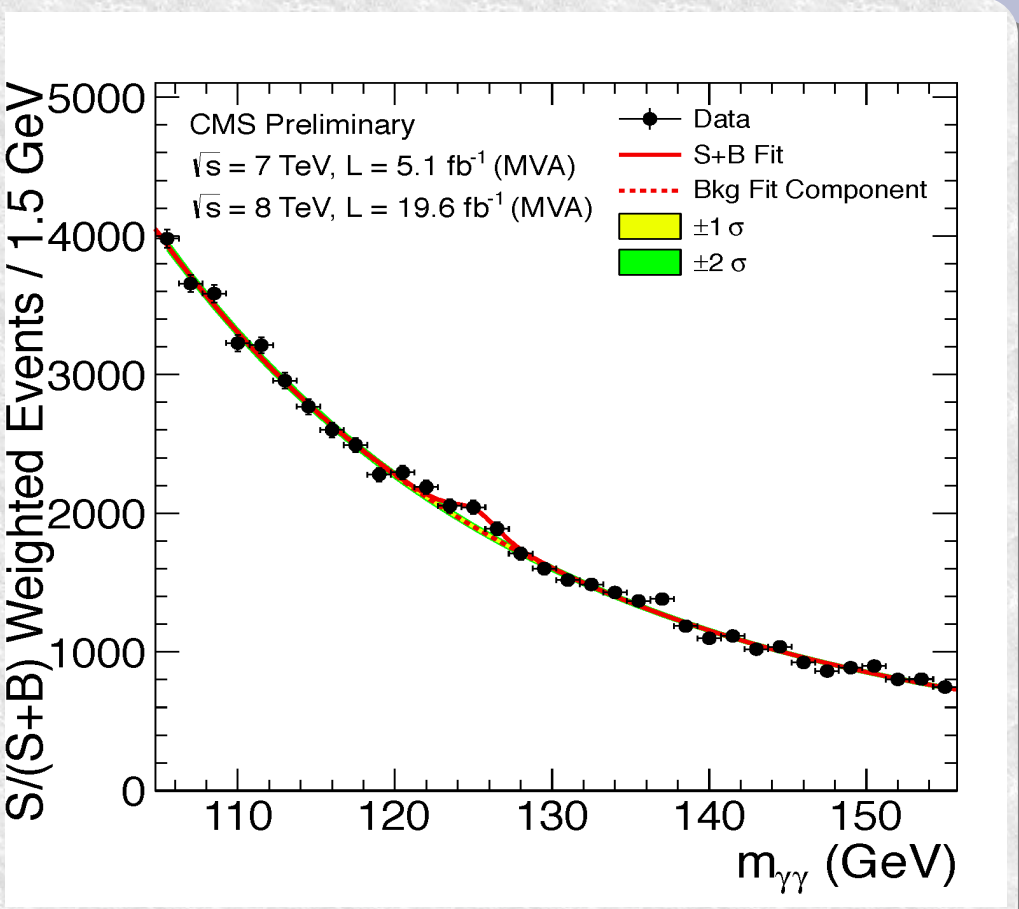
$H \rightarrow \gamma\gamma$ analysis method

- Analyses m($\gamma\gamma$) spectrum for resonance
- Background from smooth functions
- Split into categories:
  - Either with different resolution & s/b
  - Or with evidence for production mode:
    - VBF, ZH, WH, $t\bar{t}H$



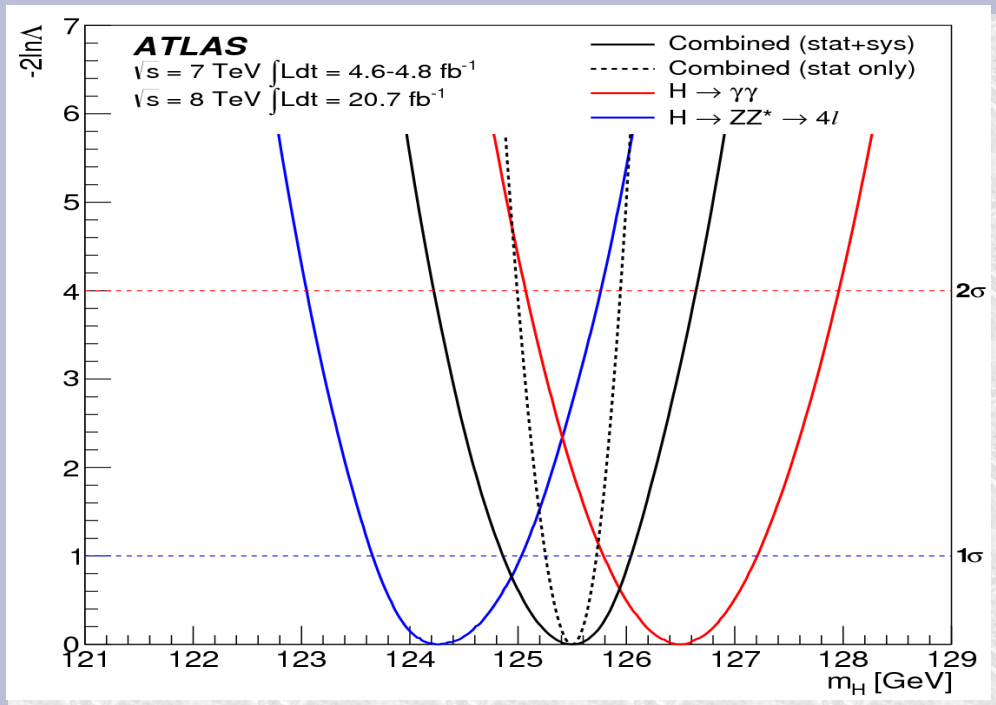
H → γγ mass spectra



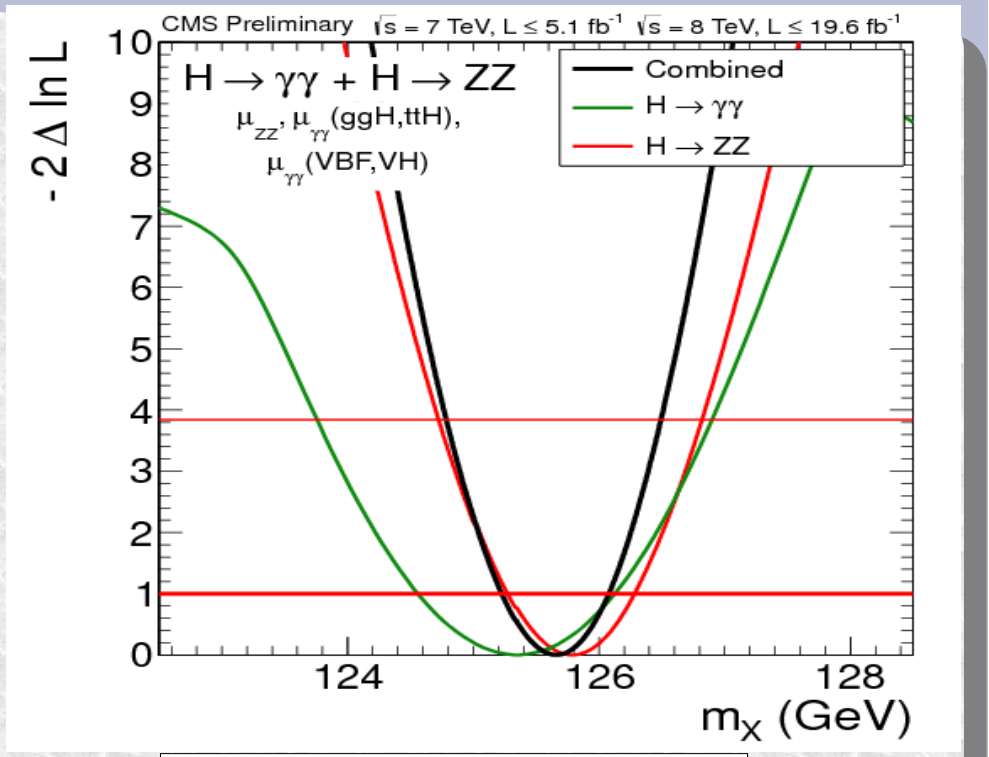


- Background is assumed to be smooth
- Signal is small but clear
  - And grows in significance when analysed in classes

Higgs Mass Estimation



$$m_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(sys)$$



$$m_H = 125.7 \pm 0.3(stat) \pm 0.3(sys)$$

- Two experiments very compatible
  - Some internal tension in ATLAS
- Mass measured to <0.5%
  - Photons hard to calibrate precisely, experiments improving this
- The last parameter of the SM?

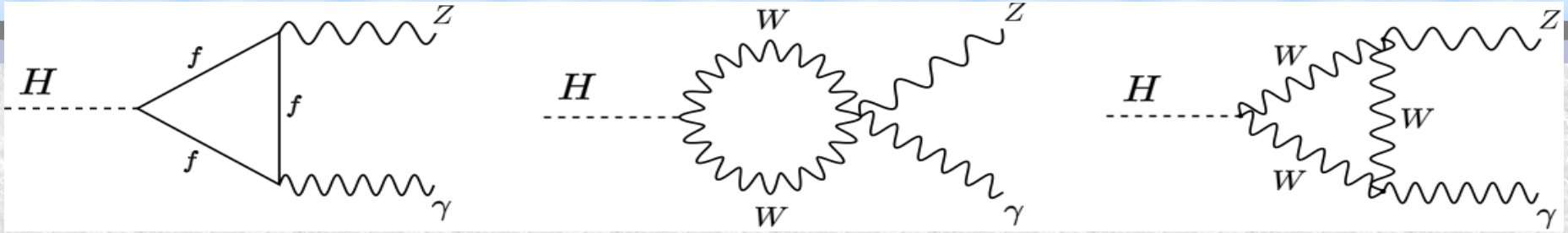
Is that it?

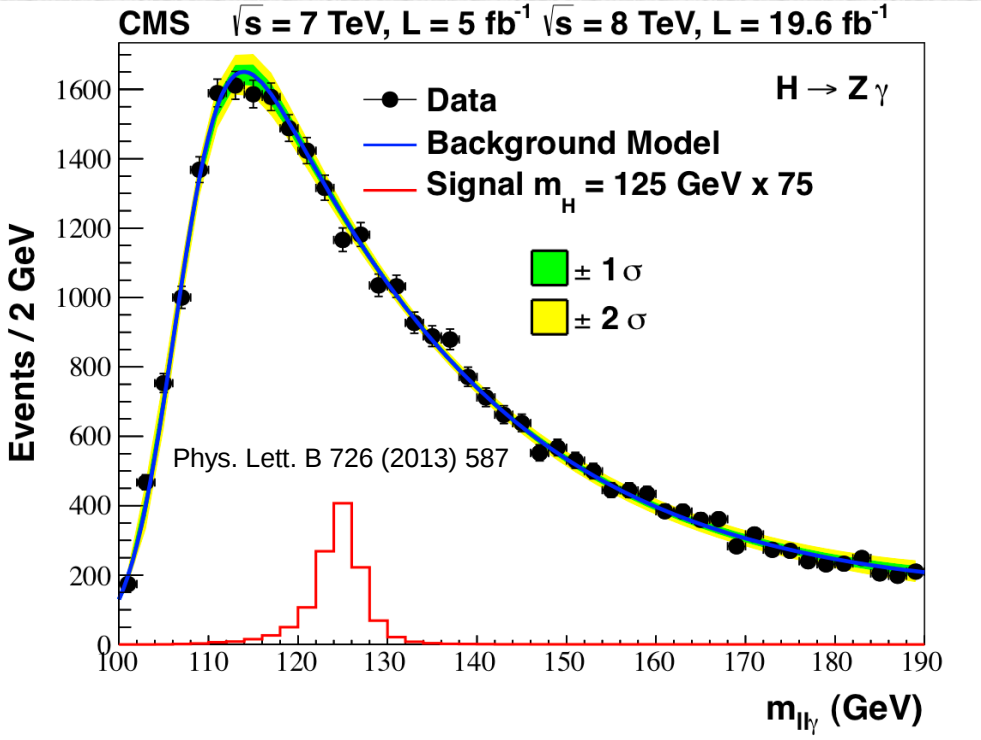
- The SM was missing just one parameter, m_H
  - With that measured are we done?

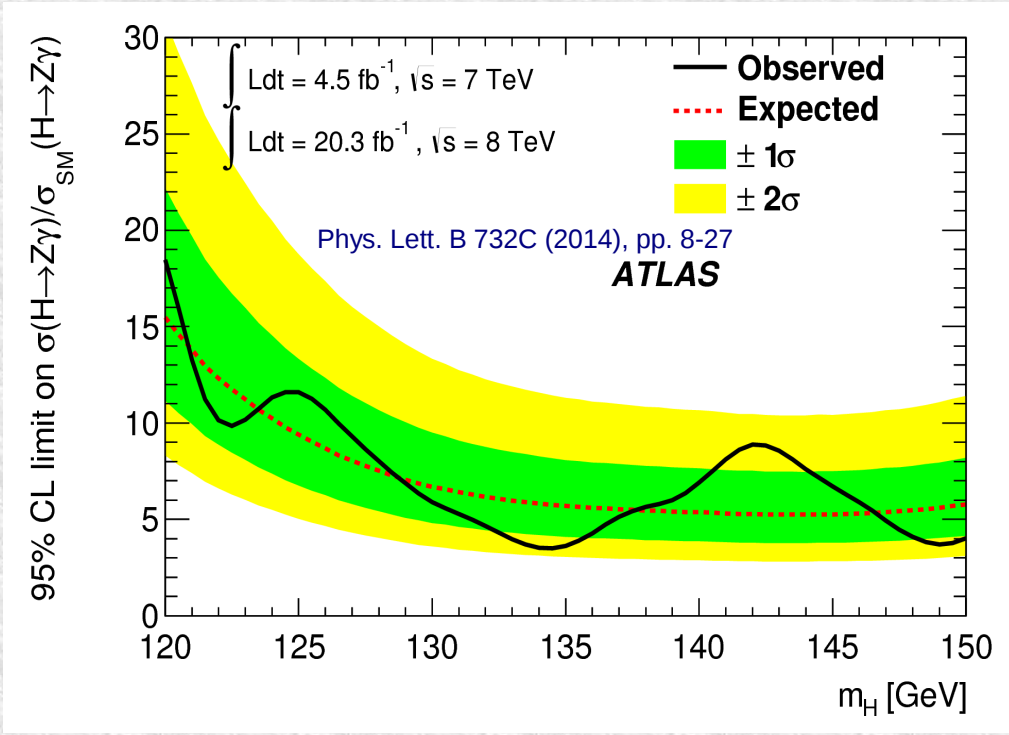
Is that it?

- The SM was missing just one parameter, m_H
  - With that measured are we done?
- Not by a long way!
  - Is this a Higgs boson?
    - Need coupling to Weak vector bosons W and Z
    - Should be Spin 0
    - And Parity plus
  - Does it match the SM Higgs?
    - Does it interact with fermions at all?
    - Does it do it proportional to their mass?
      - Both quarks and leptons?
    - Does it also couple to dark matter?
- We have started to check all of these questions

Higgs to Zγ



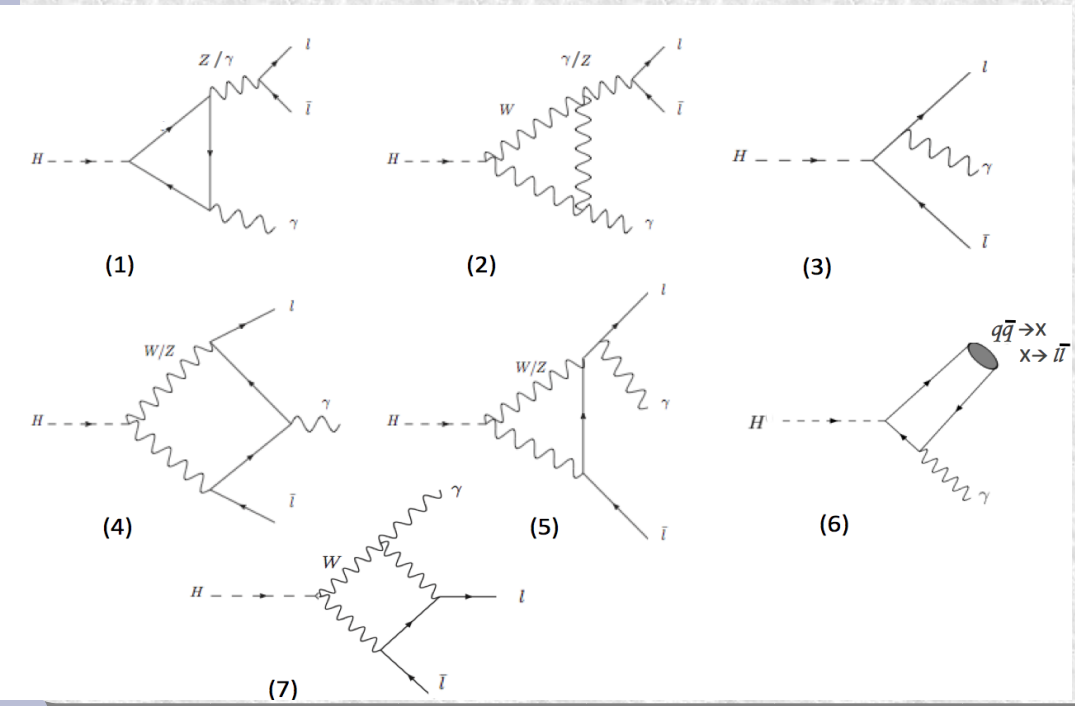


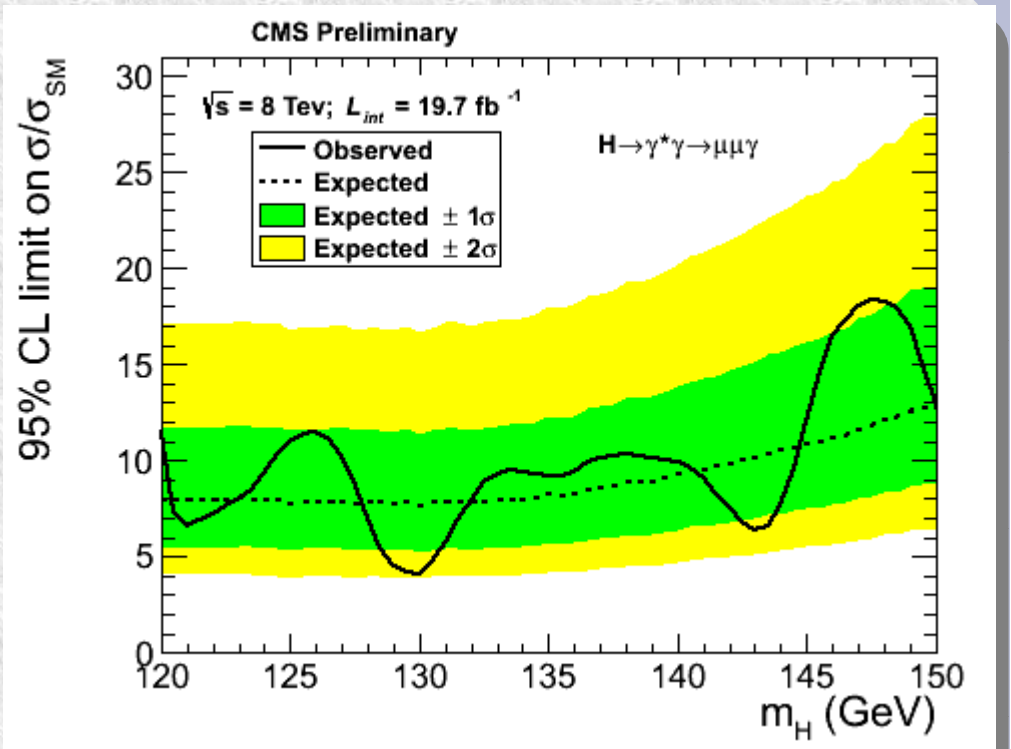


- Loop decay like H → γγ; sensitive to corrections
  - Observed(expected) limit 9-11(9)xSM Higgs
- Nothing unexpected here

Higgs to $\gamma^*\gamma \rightarrow \mu\mu\gamma$

- CMS have searched for the Dalitz decay of the Higgs boson
  - Between $H \rightarrow \gamma\gamma$ & $H \rightarrow Z\gamma$





- Sensitivity about 8xSM at 125 GeV
  - One sigma upward fluctuation in observed

H → WW → lνlν

ATLAS
EXPERIMENT
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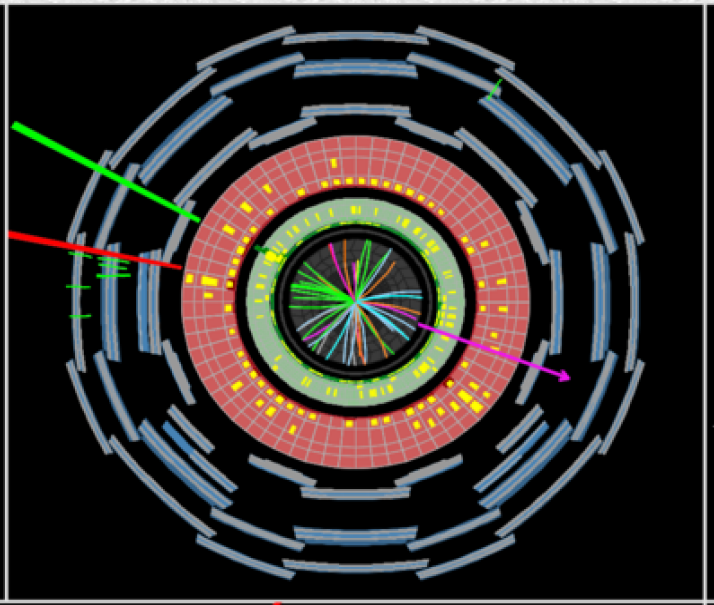
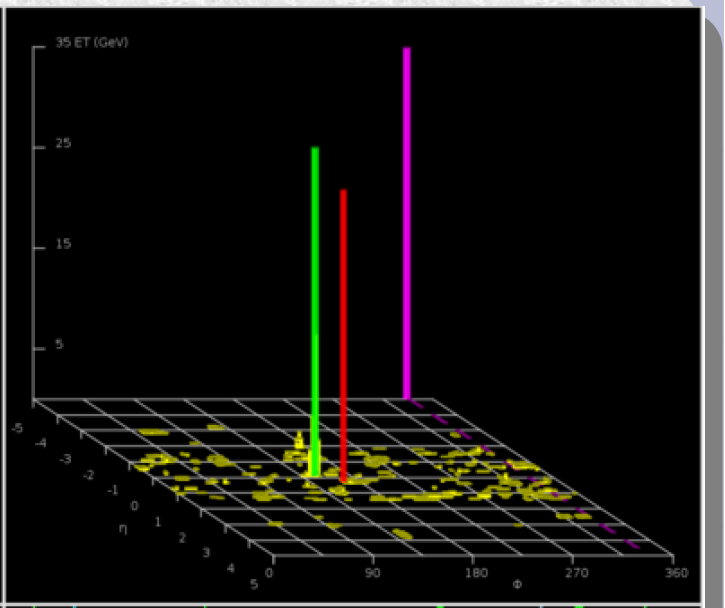
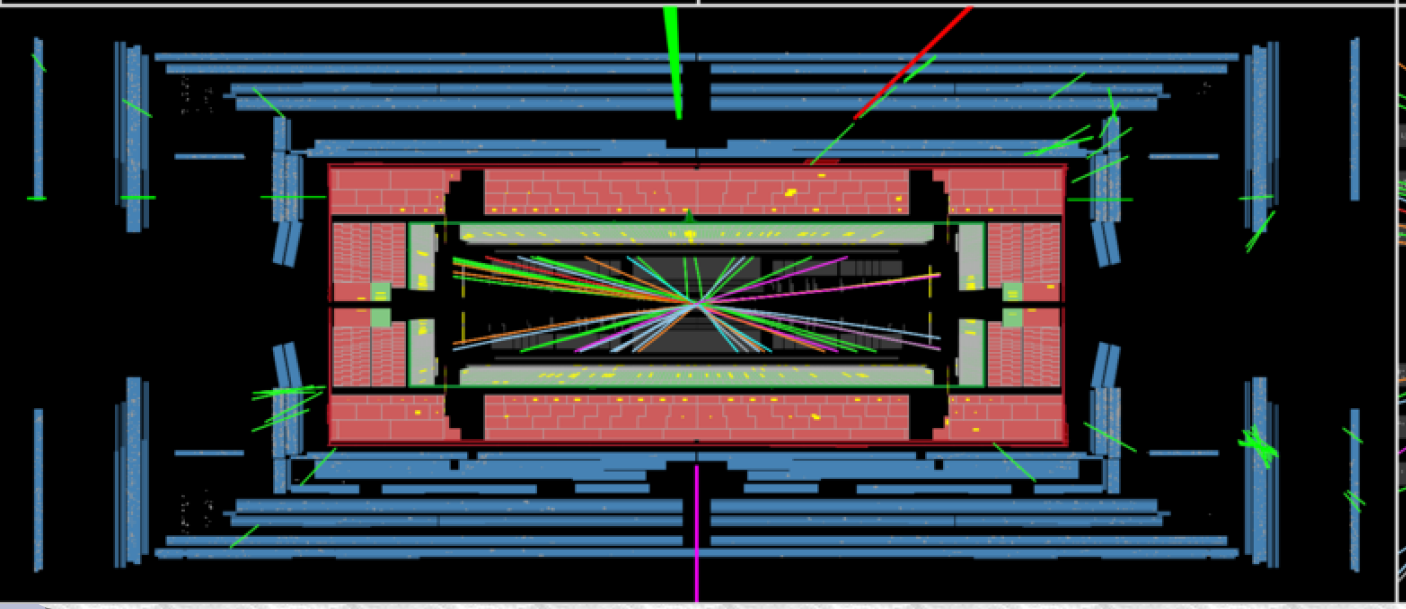
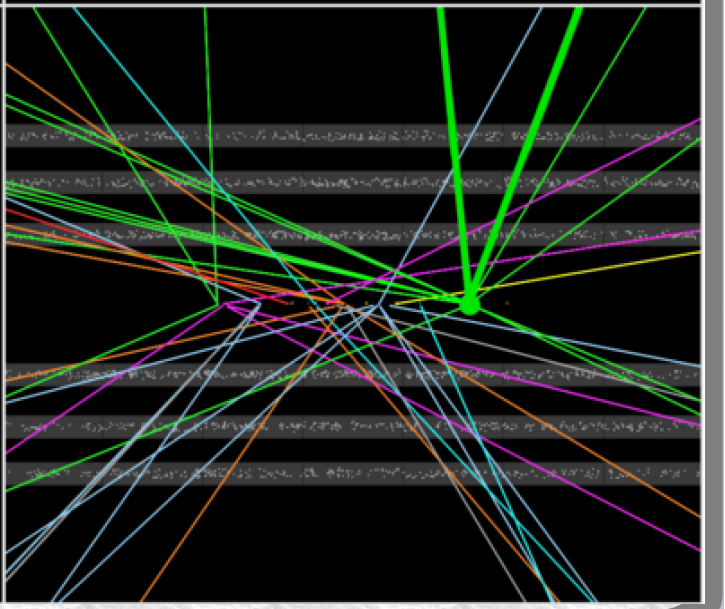



35 ET (GeV)
25
15
5
η
Φ
0
90
180
270
360



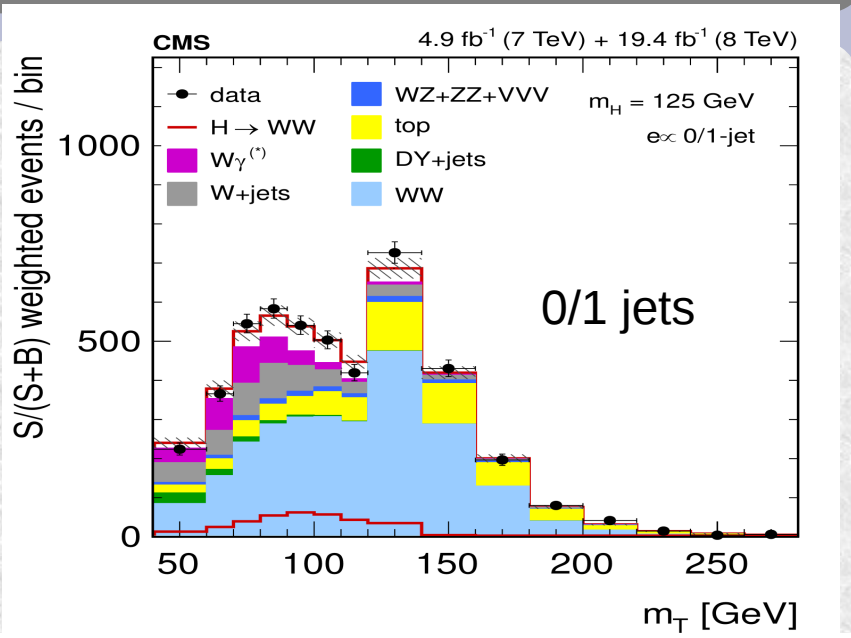


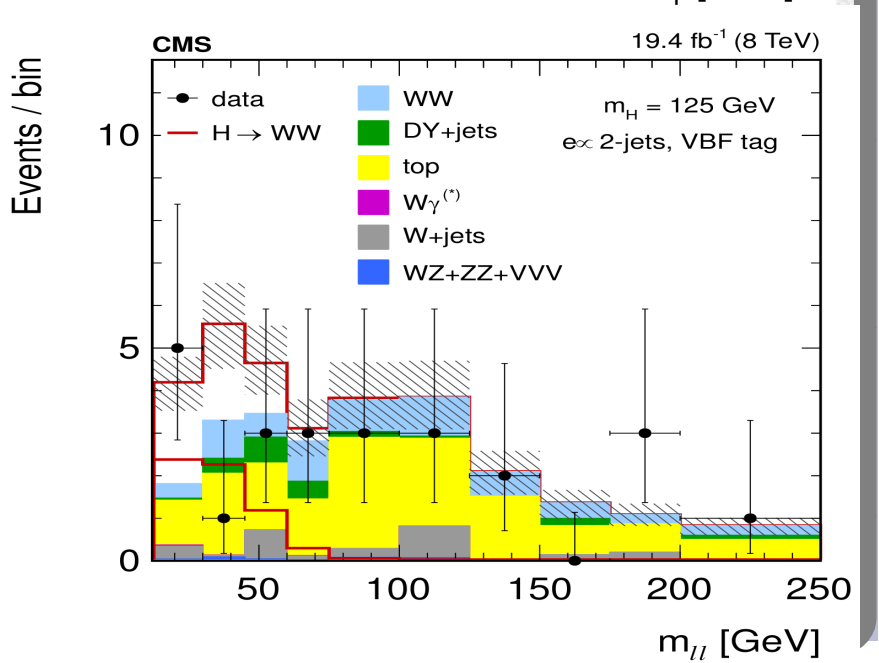
$WW \rightarrow l\nu l\nu$

- The most sensitive channel for $130<m_H<200$ GeV
  - Still one of the 3 most important at 125 GeV
  - 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
  - $p_T>15,25$ GeV in ATLAS
  - All flavour combinations used (e-μ has little D-Y background)
- Require missing E_T (E_t^{rel}) and $p_T(ll)$ for WW
- Select signal using kimenatics : e.g. $\Delta\varphi$ and m_{ll} selections
- Most backgrounds estimated from data

WW signal region

- Treat 0/1/2 jets separately
  - Same flavour/DF both
  - 2-jets (targeting VBF) right
- Complex background mix
  - Signal is extracted with a fit in 2 or 3 dimensions
  - Poorly represented by plots here
- Excess seen in all channels
- The Higgs boson decays to WW



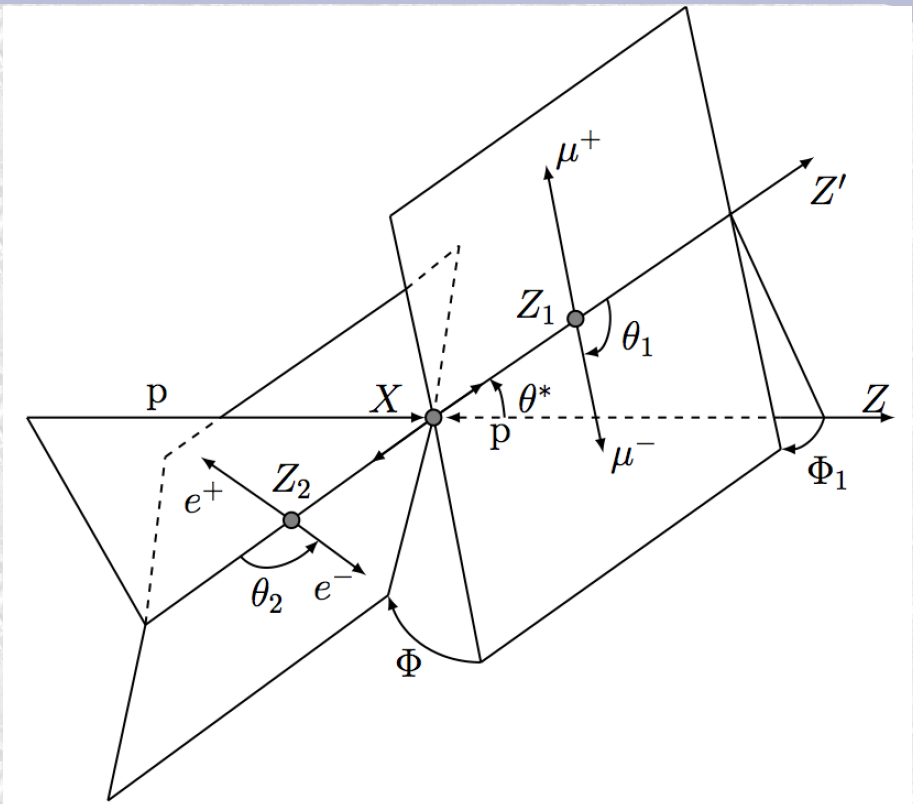


Spin/parity

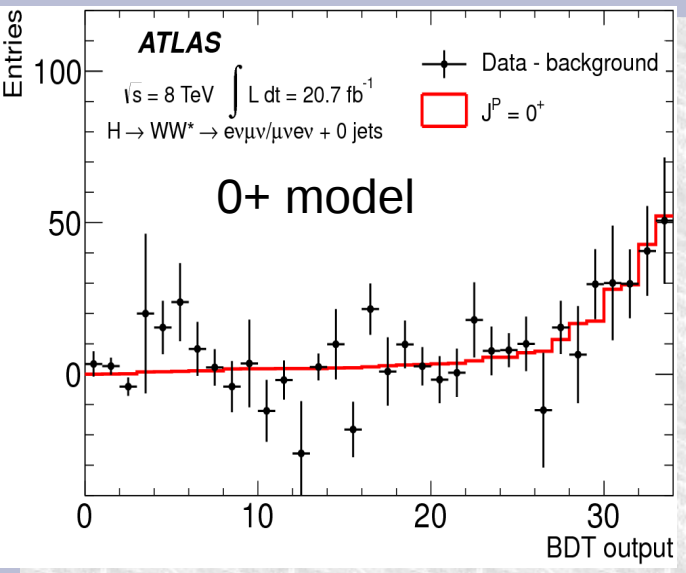
- We know integer spin, not 1 from $\gamma\gamma$ decay observation
  - Unless Yang-Mills is evaded; e.g. Each photon is a pair..
- We can measure in $ZZ/WW/\gamma\gamma$
- But there are caveats:
  - General spin 2 tensor structure too complex to analyse now
    - assume strawman production/helicity structure
    - E.g. gg or $q\bar{q}$ production
  - The bosonic decay projects out 0+ from a mixed state
    - We are not sensitive to mixed CP MSSM for instance
- So..we do learn something
  - But most theorists are not expecting surprises here
  - The rates match too well the 0^+ model...

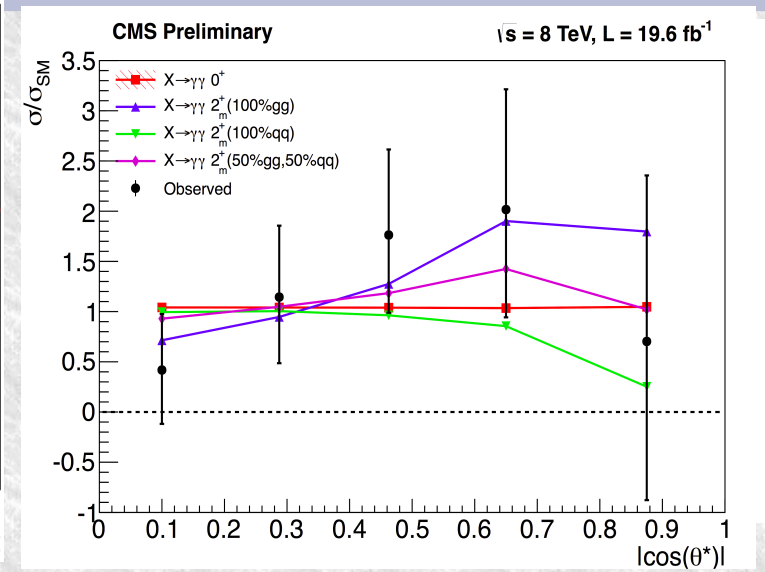
Spin analysis in Higgs decay

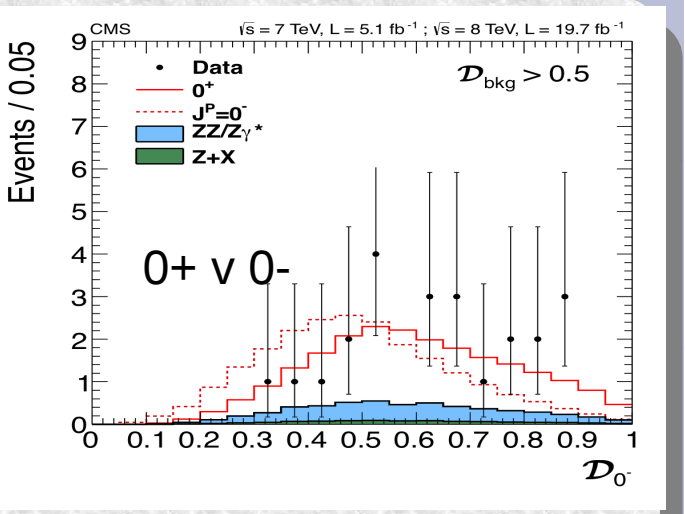
- ZZ decay has 7 observables
  - Mass of the two Z's
  - Overall global phi
  - 4 spin angles
- WW would be better due to large decay asymmetry
  - But the 2 neutrinos rob much sensitivity.
- $\gamma\gamma$ lacks photon mass and their decay angles
  - But production angle sensitive
- All of them bring sensitivity
  - Analysis typically through BDTs
  - Specific spins 0/1/2 models tested
  - Spin 2 structure complex



WW, γγ and ZZ



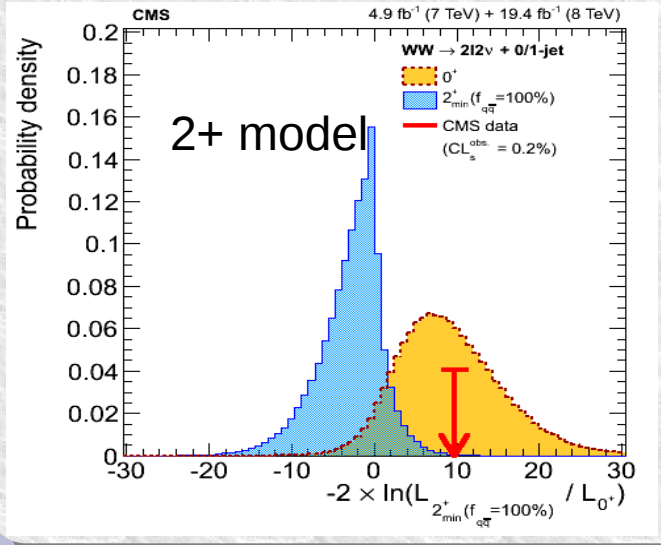


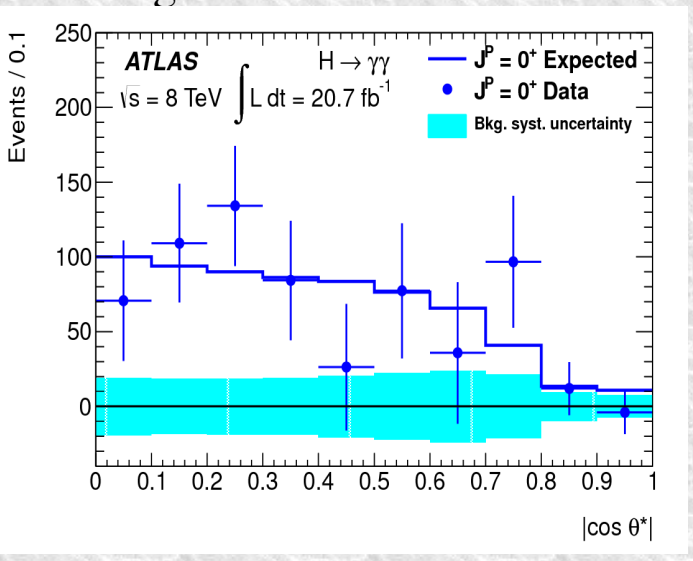


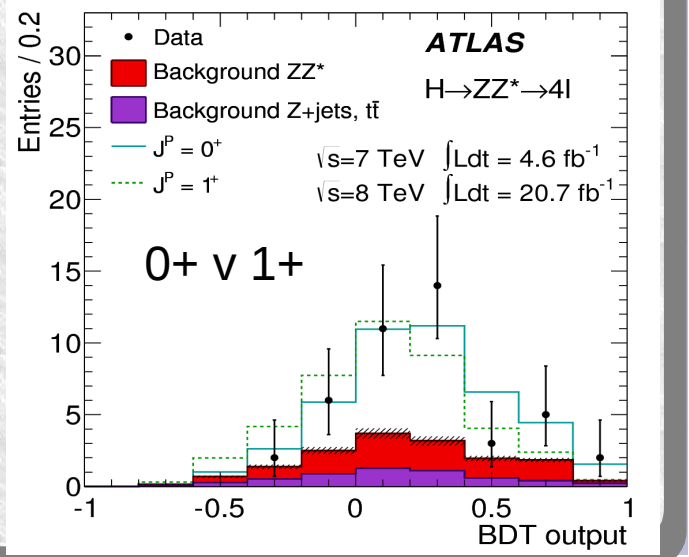
WW for spin 2+

γγ for spin 2. Below is background subtracted

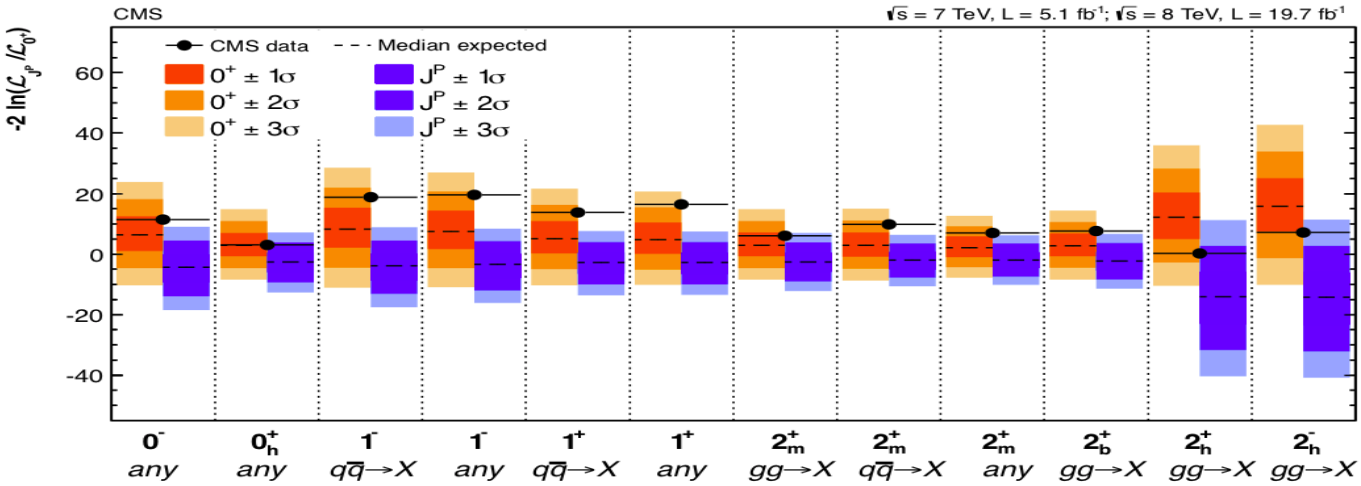
ZZ for 0- above and 1+ below







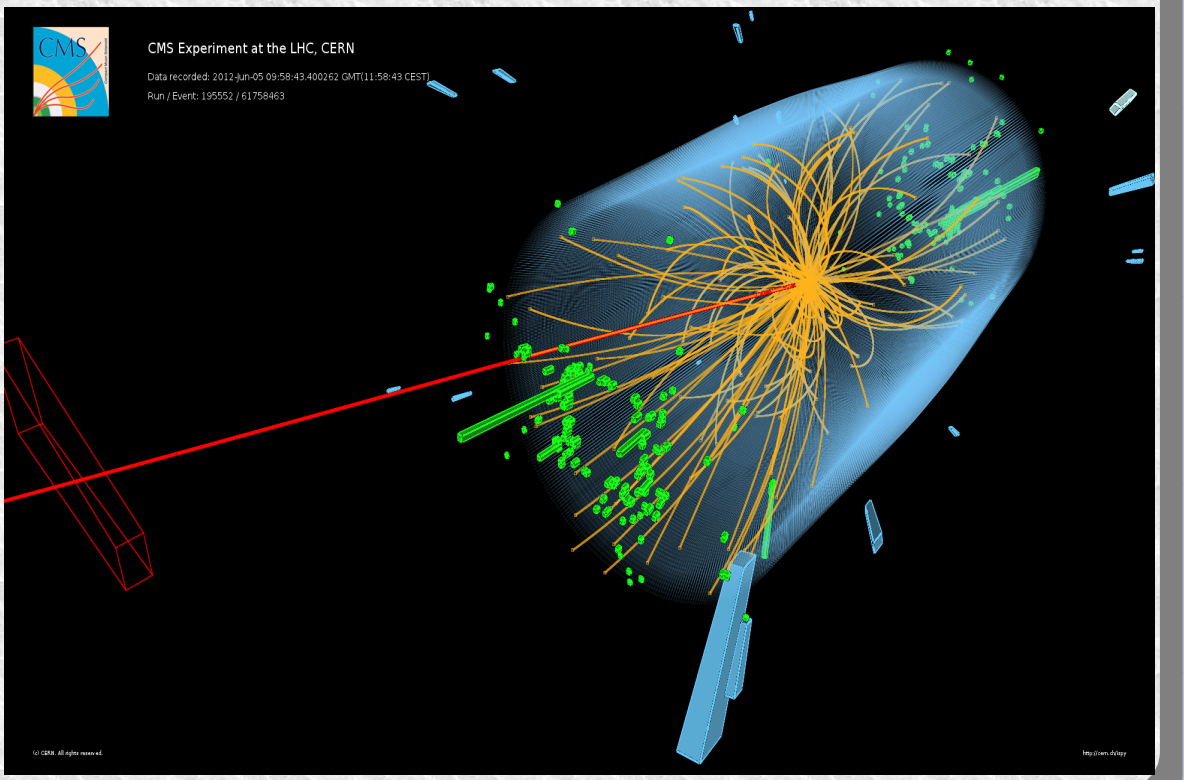
Spin/parity results



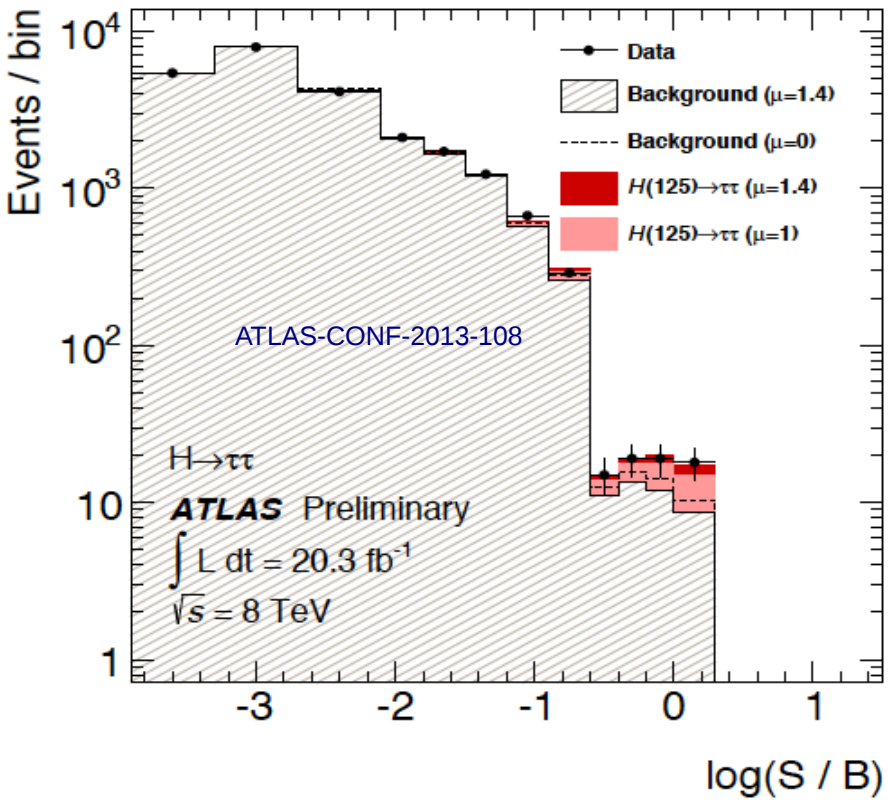
- Most important result is that 0^+ always matches data well
- Spin 1 is strongly disfavoured by $\gamma\gamma$ observation
- Spin 2 model is example model, other could exist
  - For any gg/qq production fractions

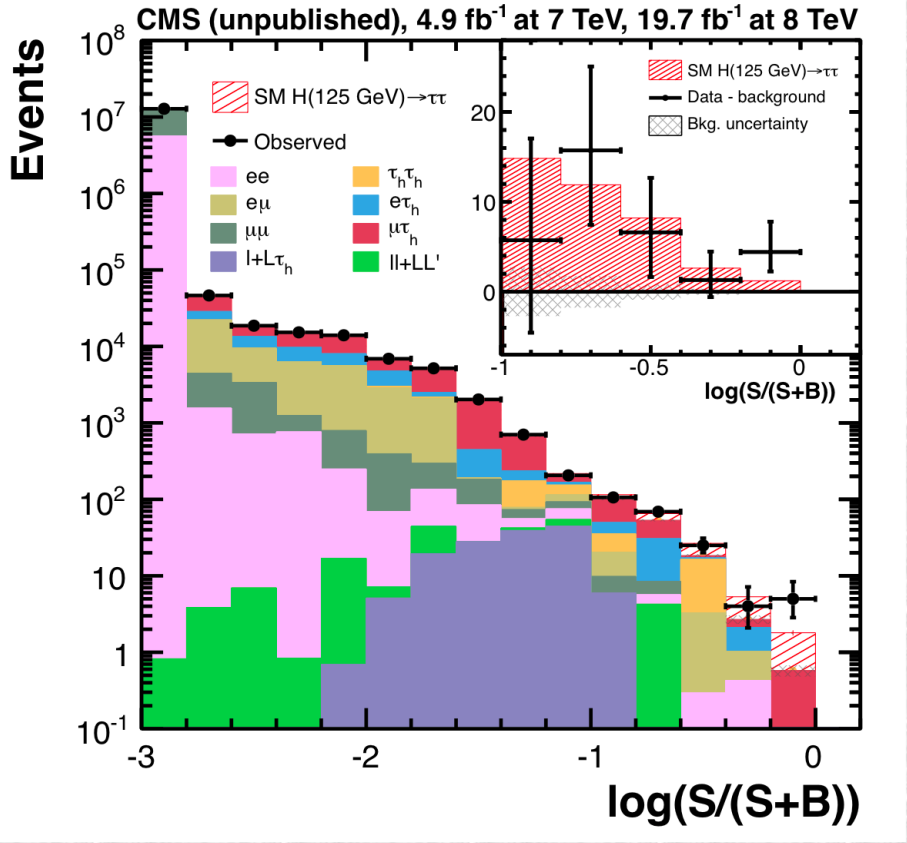
H→ττ status

- H→ττ is a challenging analysis
- Multiple production:
  - Gluon fusion
  - VBF
    - Most sensitive
  - VH
- Multiple decay modes
  - lep-lep
  - lep-had
  - had-had
- Use BDTs to extract signal from background
- Control with Z→ττ
  - Control that via Z→μμ
  - Replace data μ with τ



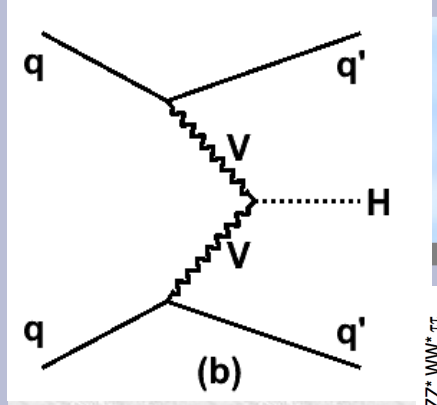
H→ττ status

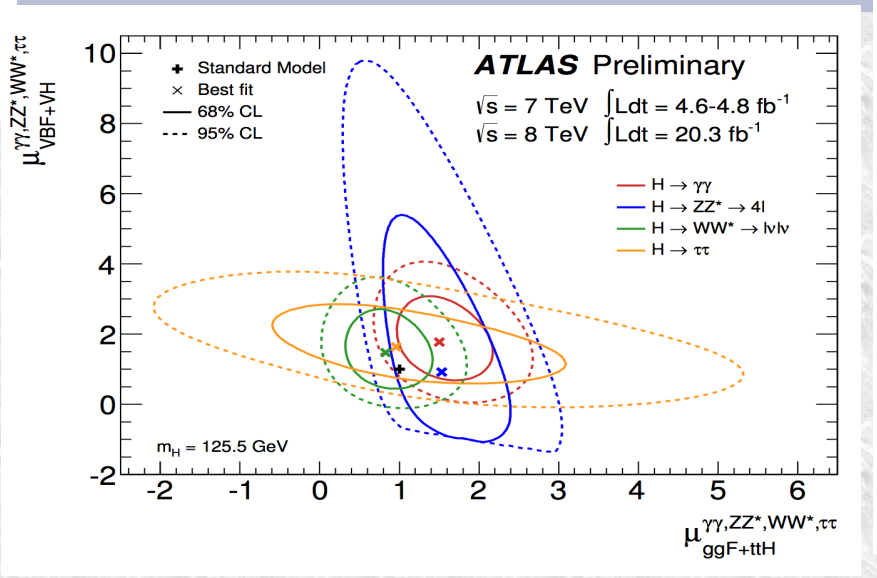


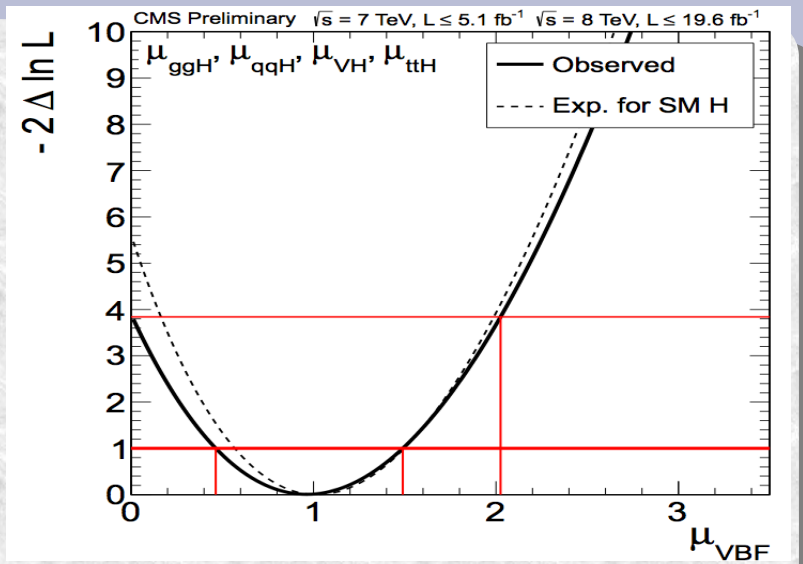


- ATLAS finds 4.1σ evidence (3.2σ expected)
- CMS sees 3.2σ evidence (3.7σ expected)
- Together this looks very solid

Evidence for VBF

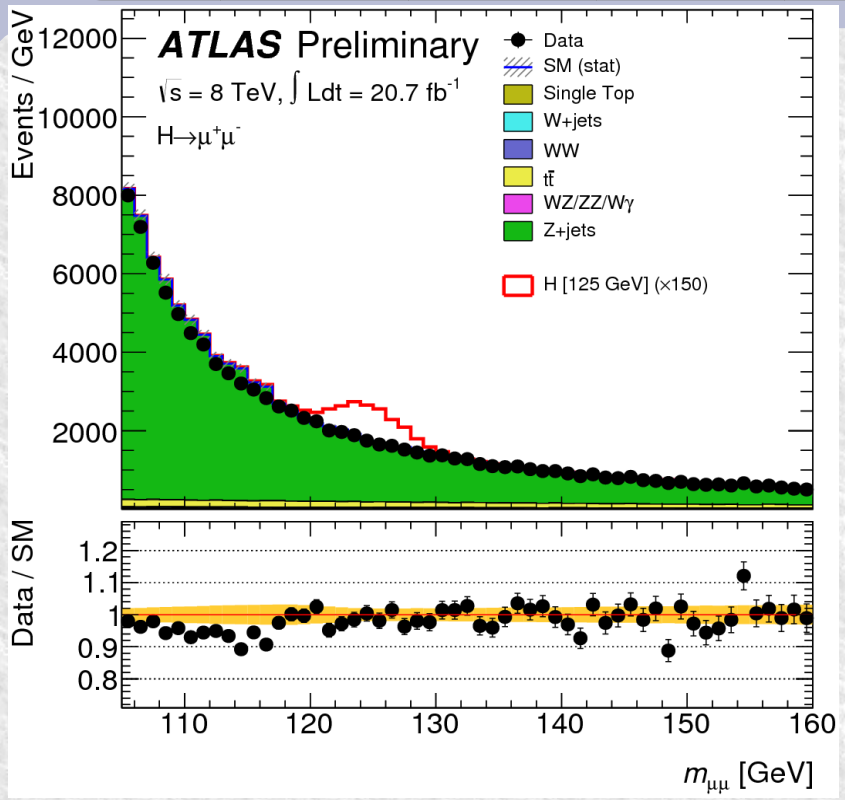


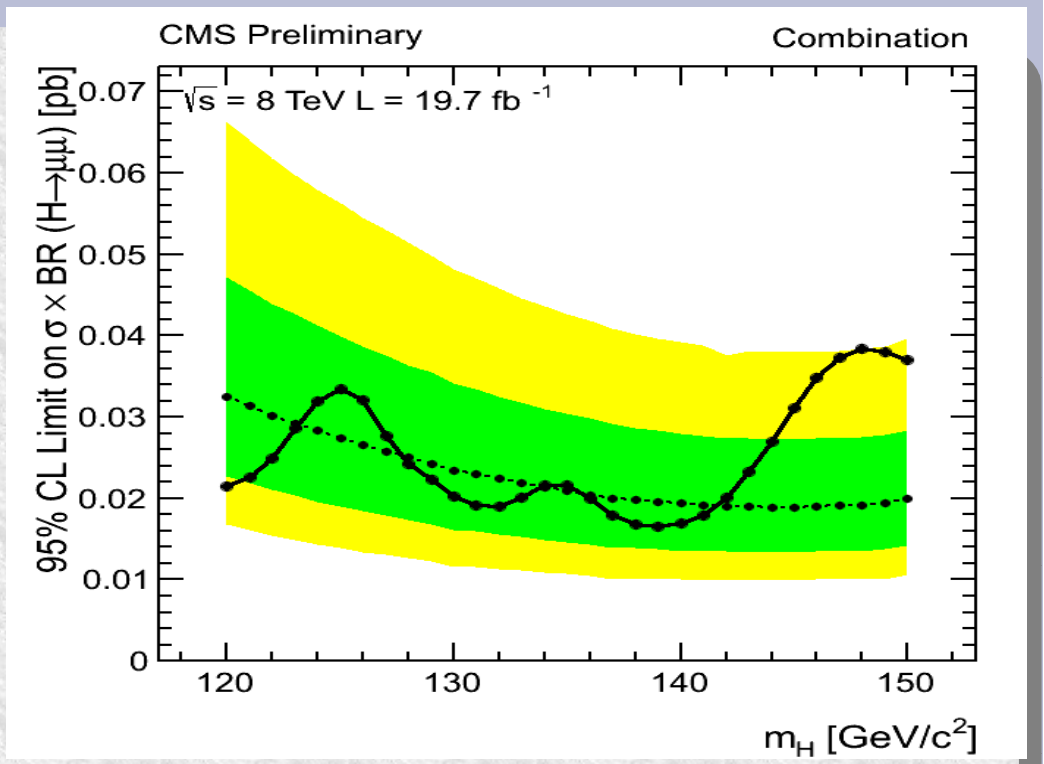




- Use categories where the Higgs boson was seen with forward VBF-tagging jets
  - All 4 channels discussed contribute here
- Both ATLAS (4σ) and CMS (2σ) see something
  - Together make good evidence for VBF
- This means we see vector bosons both in production and decay
  - So the interaction is well established

Higgs to μμ

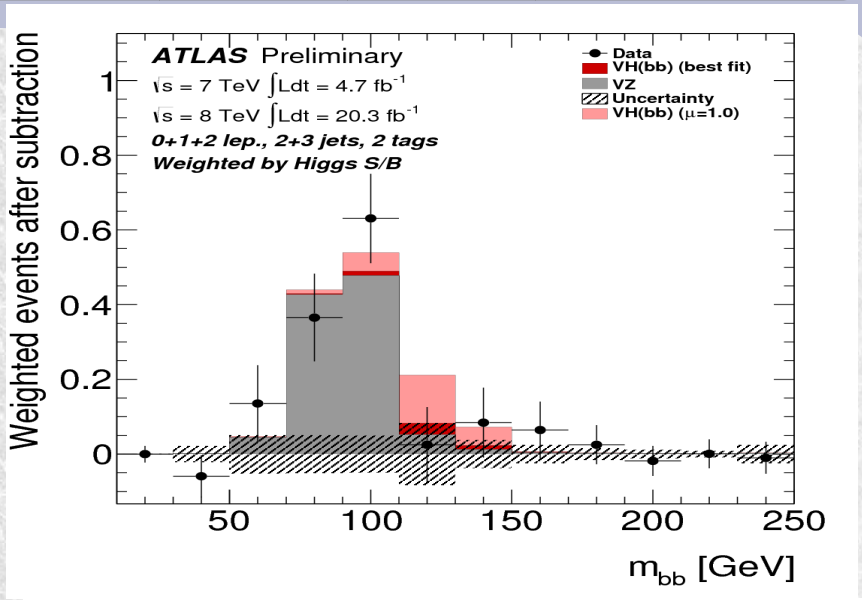


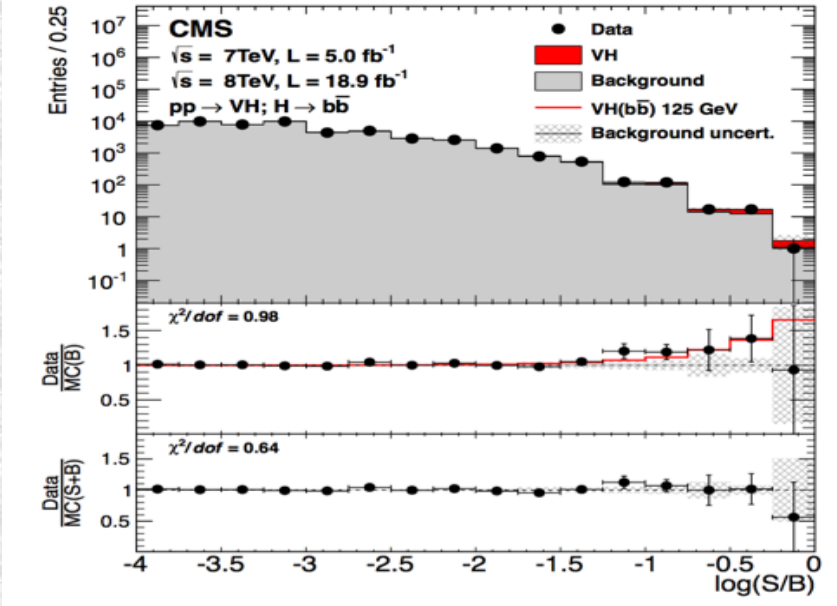


- Expect rate suppressed by $(0.106/1.778)^2 \sim 1/280$ w.r.t. ττ
- Good efficiency & mass resolution improves things
  - Obs(expected) limit 7(5)xSM - CMS
  - Obs(expected) limit 9.8(8.2) xSM - ATLAS
- Clear evidence for lepton non-universality

$H \to b\bar{b}$ status

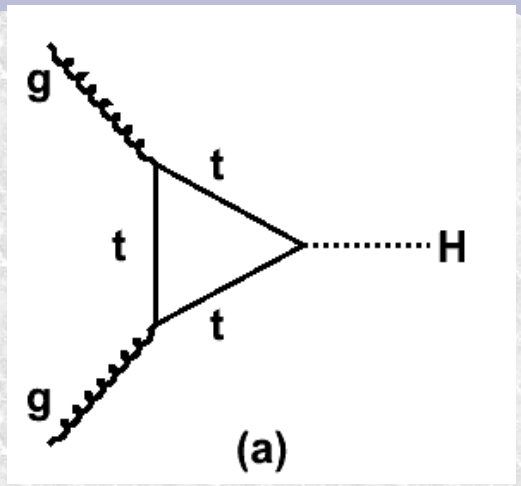
- Dominant decay
  - But lost in $gg \to b\bar{b}$ background
- Use WH and ZH to improve s/b
- Both ATLAS and CMS see something of Higgs decay to bb
  - 2.1σ in CMS
  - 0.4σ in ATLAS
- The Tevatron reported 2.9σ for $H \to b\bar{b}$ Phys. Rev. Lett. 109, 071804 (2012).
- There is some evidence
  - But it is not very solid yet
- In the SM 57% of Higgs bosons decay to b quarks
  - We need this well measured to understand total decay rate

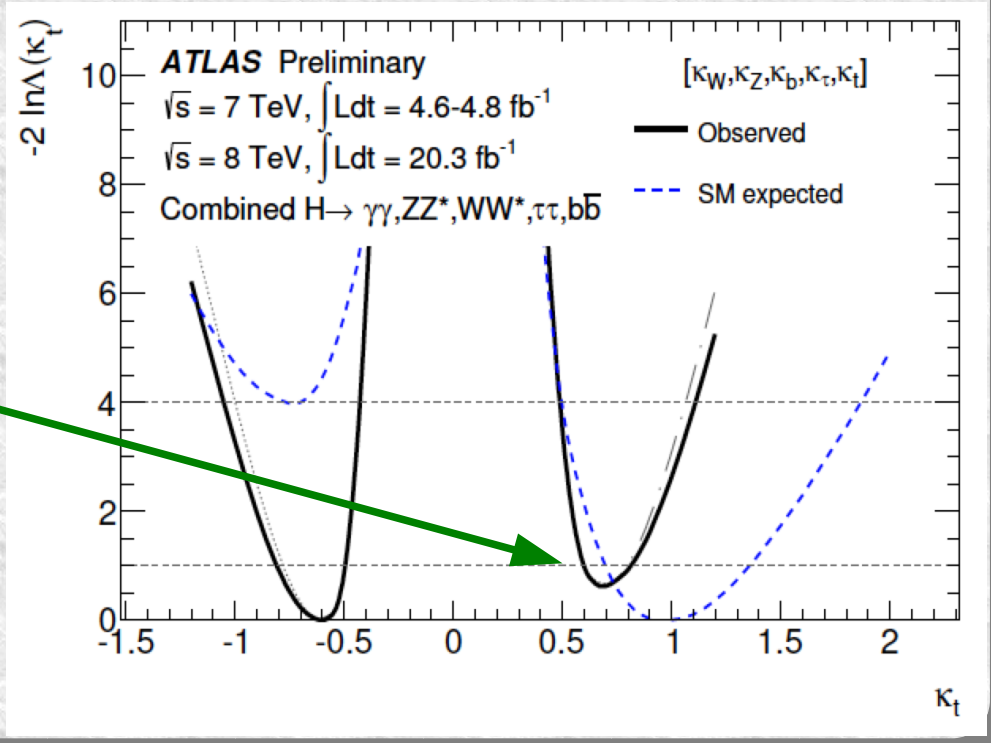




So does H interact with quarks?

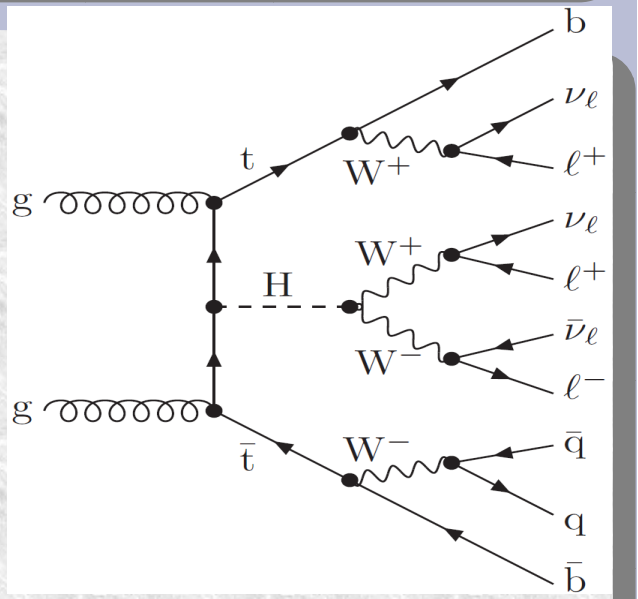
- Yes!
- The gluon-fusion production process is basically a top quark loop
  - Gluons couple to quarks
  - Top quarks are massive and couple to Higgs
- If we do a 5-parameter fit:
  - κ_W, κ_Z, κ_t, κ_b, κ_τ
  - We find the top coupling cannot be zero
  - ATLAS finds it a little low
  - But 14% chance in SM
- But isn't it a bit indirect?

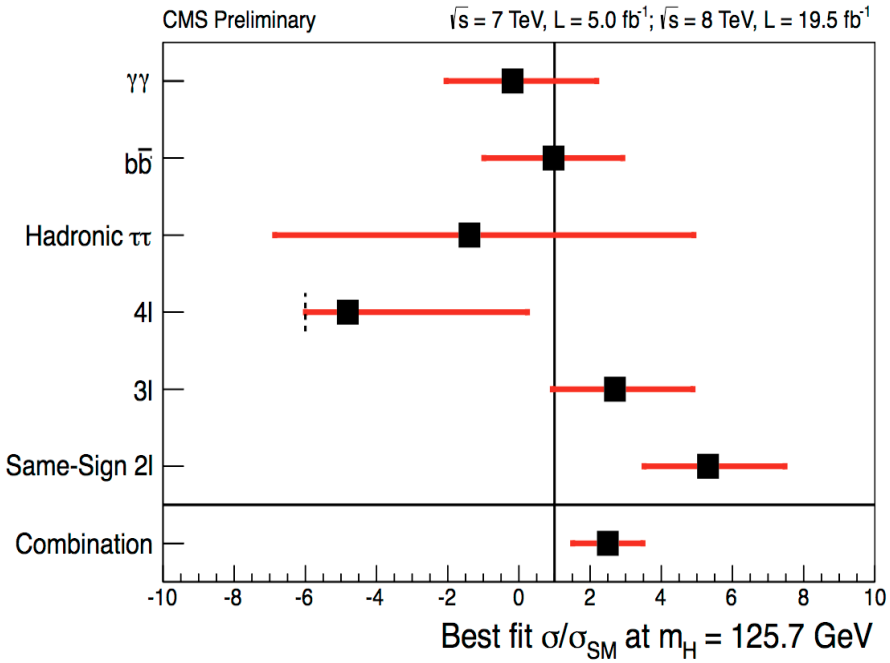




So look for ttH

- $t\bar{t}H$ has low rate but distinctive signature
  - But complicated
- Several Higgs decay modes used:
  - $H \rightarrow \gamma\gamma$, bb, leptons or tau
  - ATLAS only used at $\gamma\gamma$, bb so far

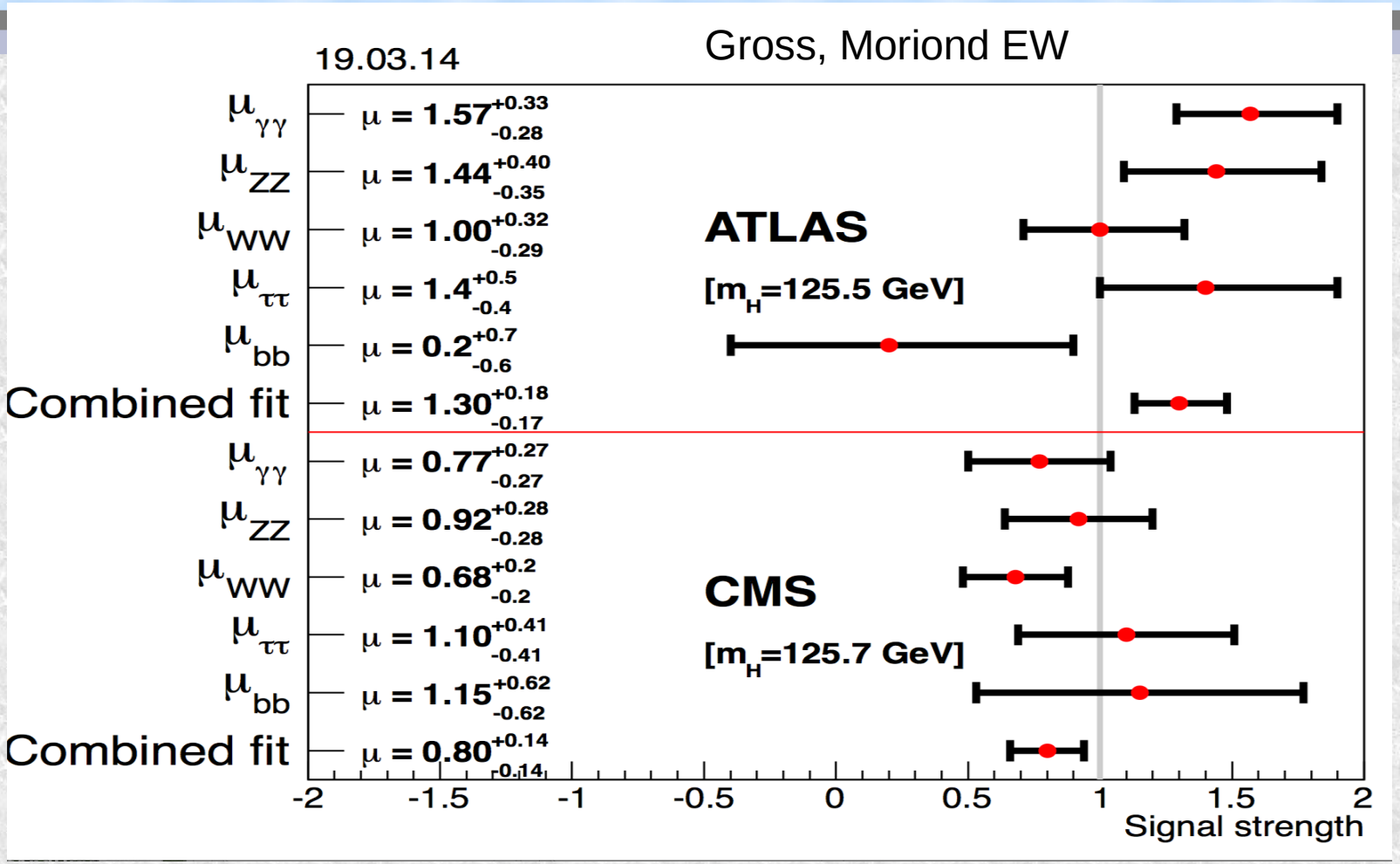




- CMS results (left) give 2.7σ evidence for ttH production
  - 1.2σ expected
- ATLAS found μ =1.7±1.4 in bb mode, no combination yet
- Together there should be 3σ evidence for this modes

So what did we get?

Channel results



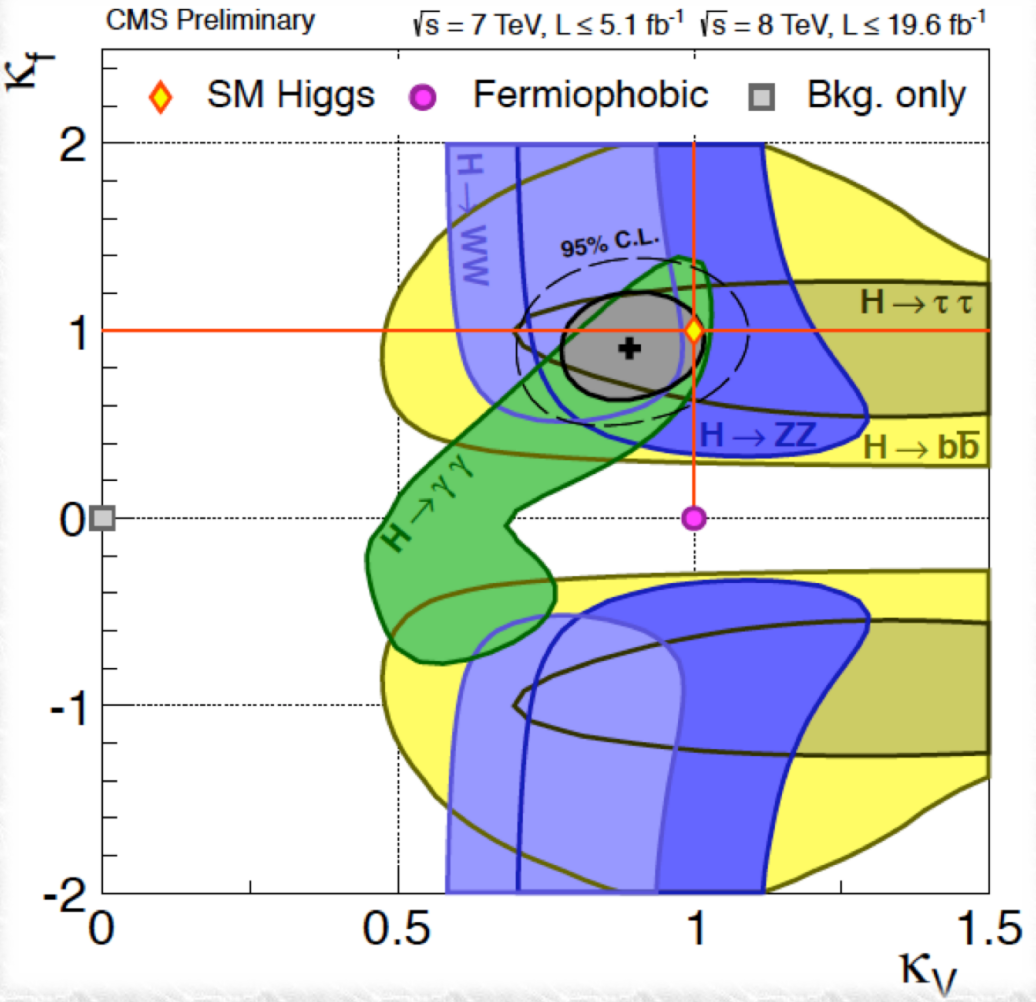
- 5 big channels reasonably consistent
  - ATLAS have opposite fluctuations to CMS!
- Errors includes systematics;
  - PDF and QCD scale are largest

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 unmeasurable decays like H→gluons
  - So some assumption is needed
- Many couplings accessible eventually:
  - ZZ, WW, γγ, bb, tt, gg, ττ, invisible, μμ?
  - Note gg/γγ are effective couplings through loops
- Hard to fit all at once
- Simplify by grouping the couplings
  - e.g. Bosons and fermions

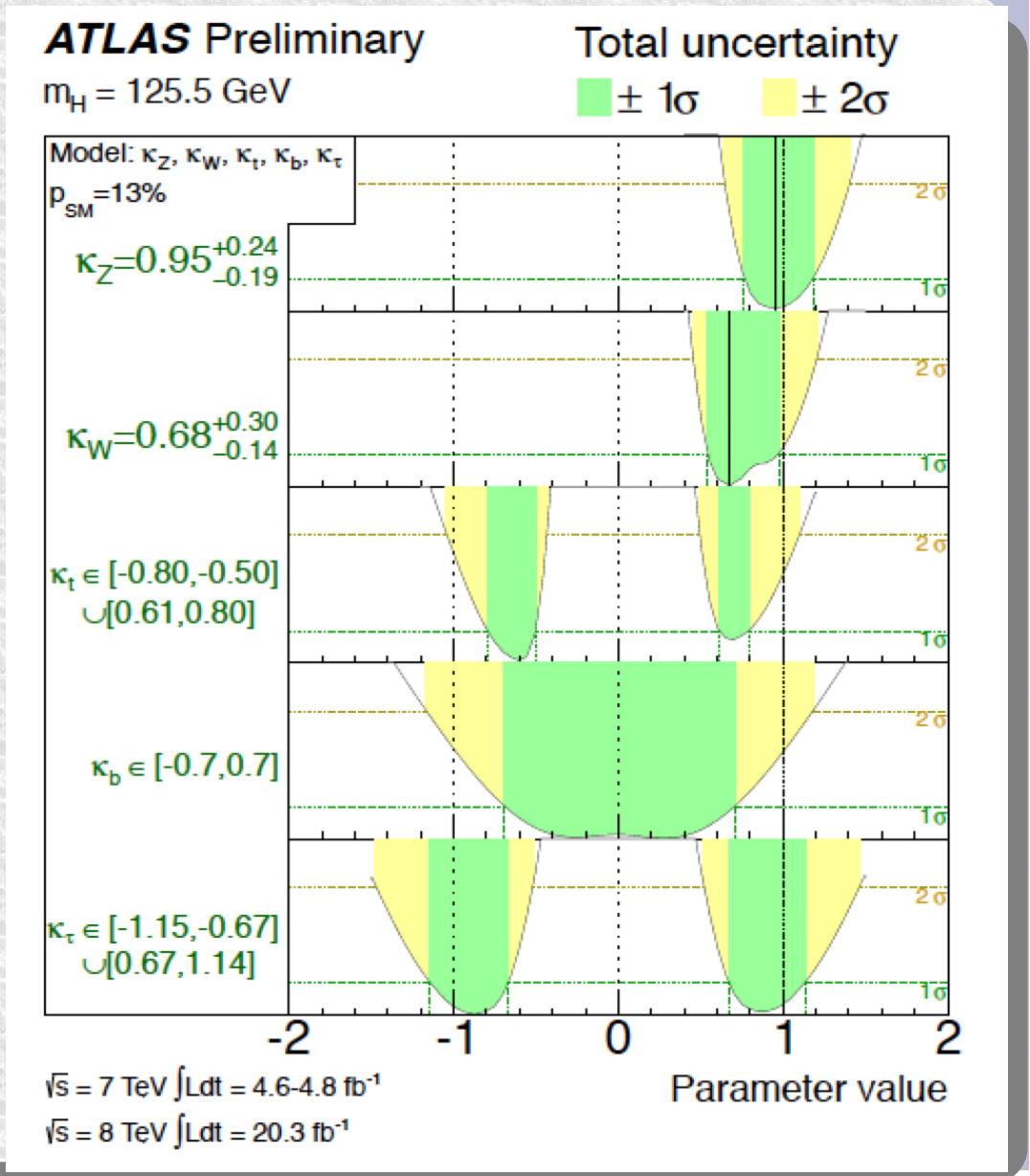
Coupling studies

- Fit with only κ_V and κ_f
- Allows multiple different modes to be compared and contributions assessed
- All channels are compatible with standard model expectations in fermion and vector coupling



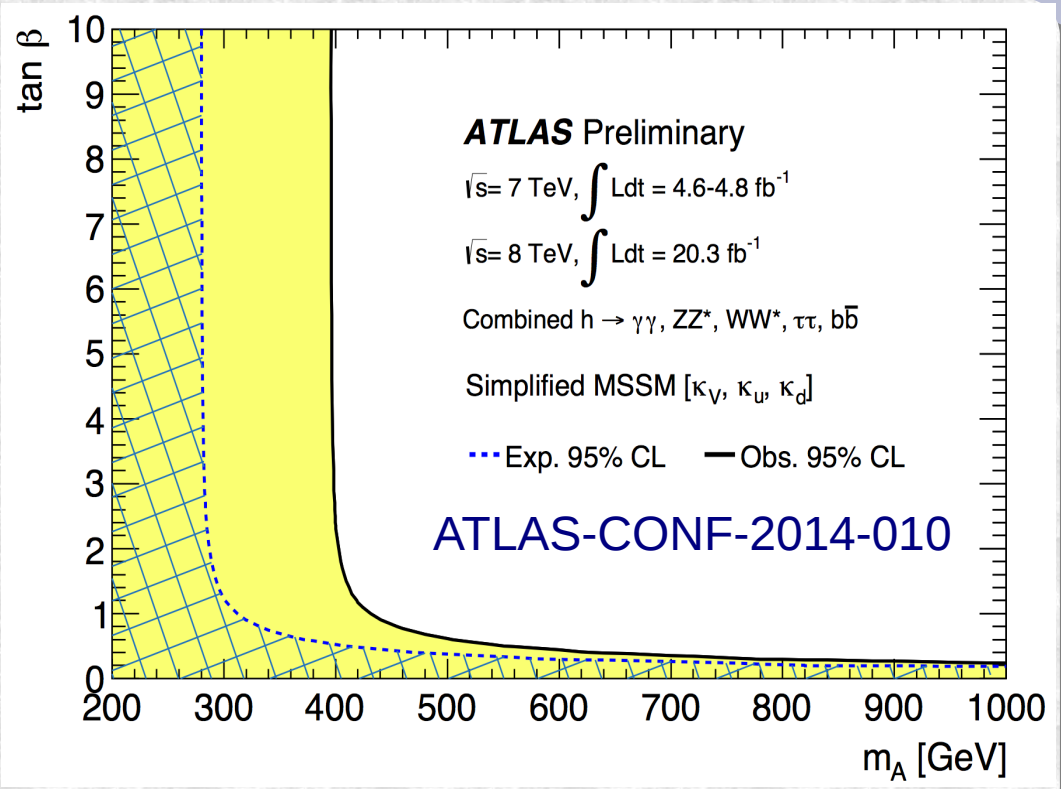
Coupling studies

- This fit was discussed for tt
  - κ_W, κ_Z, κ_t, κ_b, κ_τ
  - Fermionic couplings can be negative
- But all parameters consistent with SM
- Most of them severely constrained.
  - O(20-30%) level typically



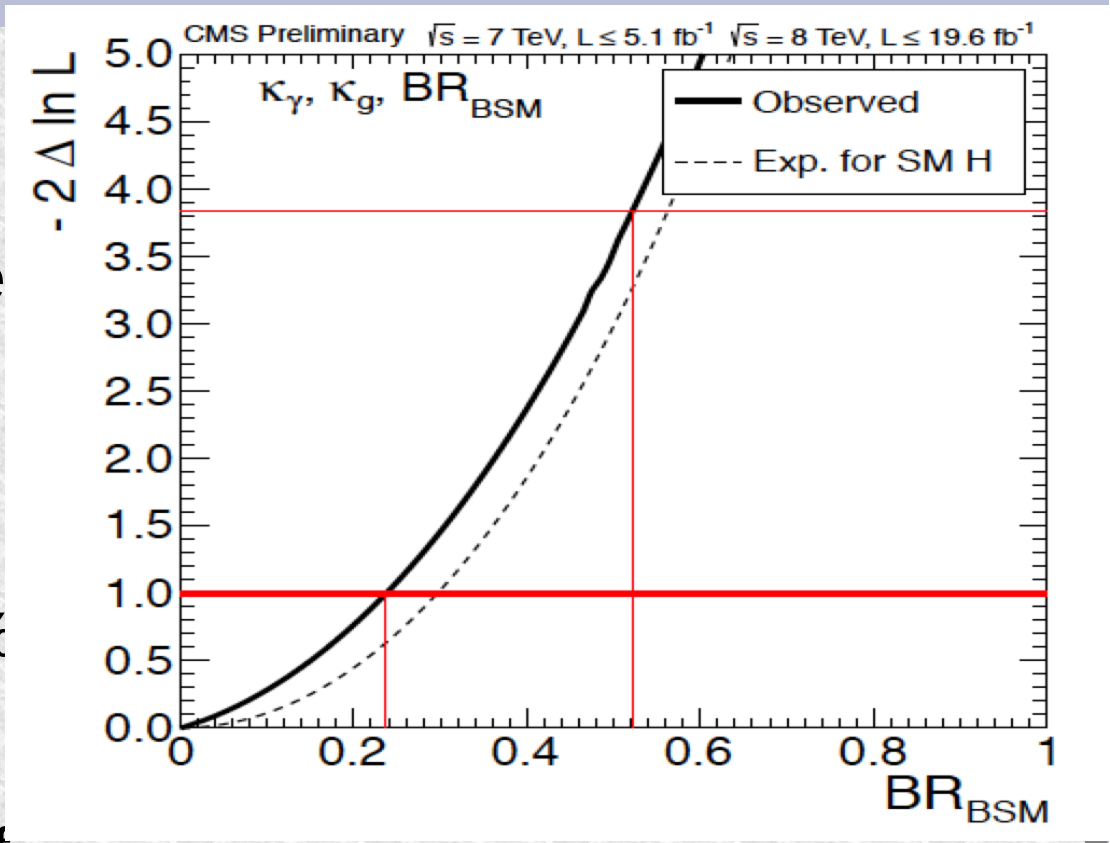
MSSM constraints

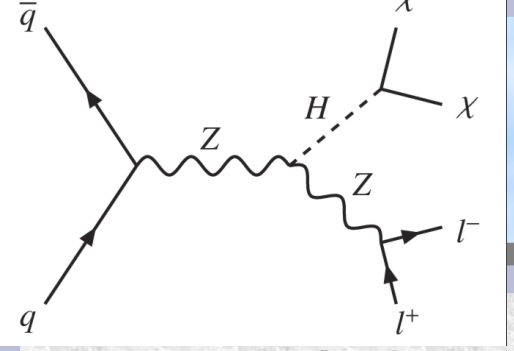
- MSSM Higgs sector is defined by m_A and tanβ at tree level
  - But radiative corrections important
- Old MSSM benchmark scenarios fix all other parameters
  - Do not match m_h=125
- One new approach is to absorb radiative corrections into a single parameter used to fit m_h at each point
  - Only approximately true
- Deduce m_A>400 GeV
  - Within assumptions



New particle search

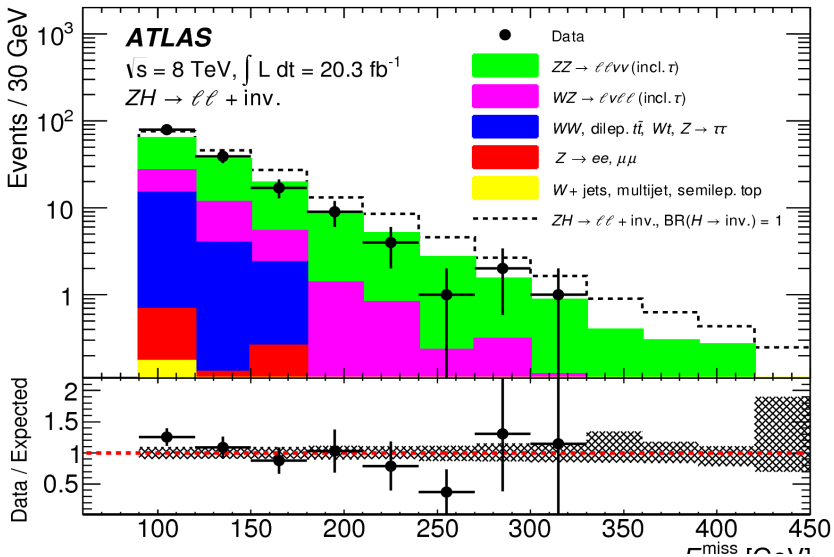
- Another possibility is to ASSUME a SM Higgs
  - But allow the loops to have unknown particles
  - ggF, $H \rightarrow \gamma\gamma$
- Test for invisible/undetectable branching ratio
  - CMS find Br < 52% @ 95%
  - ATLAS Br < 41% (55% expected)
- Loop strengths also with 2σ of SM prediction

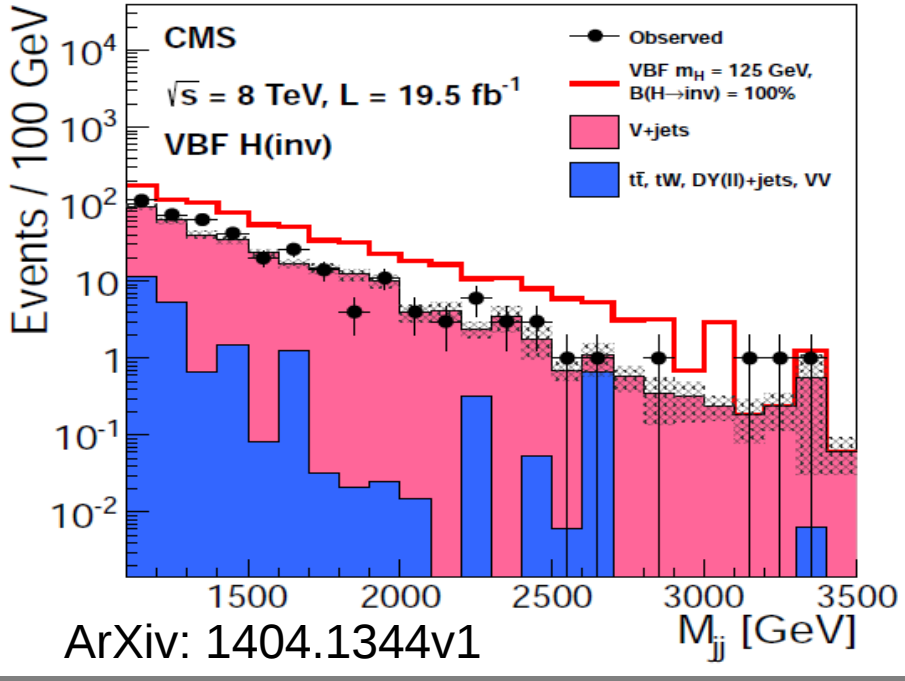




Direct invisible Higgs hunt

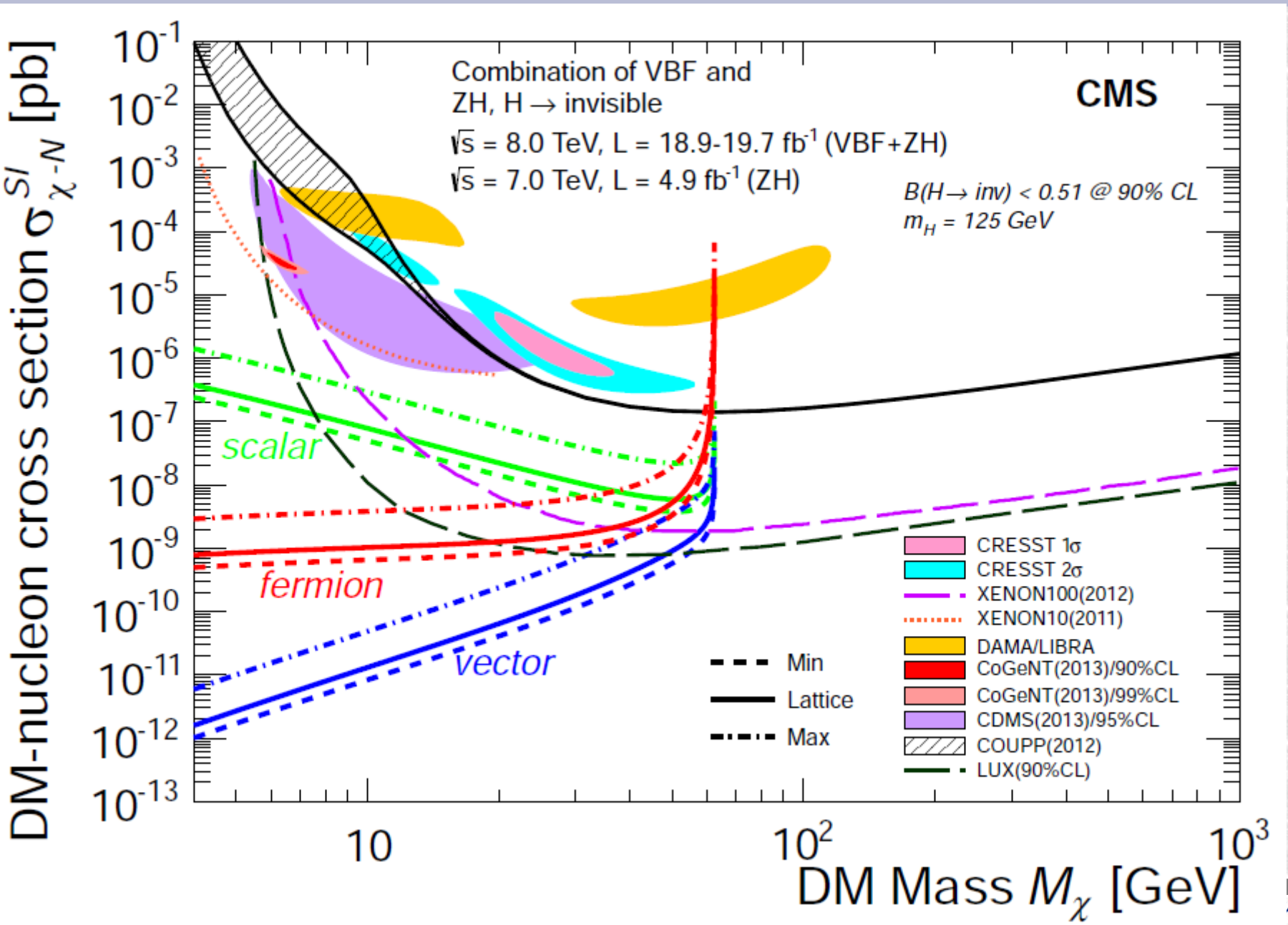
- Search for Higgs decay to invisible particles
- Need to tag production:
  - ZH, Z→ll ATLAS/CMS
    - ZZ background dominates
  - ZH, Z→bb CMS
  - VBF (CMS)
    - Z+jets b
- Control of missing energy essential
- Limits:
  - Br < 75% (62%) - ATLAS
  - Br < 58% (44%) - CMS





ArXiv: 1404.1344v1

DM in Higgs-portal model



Higgs Width methods

- Direct measurement of the peak lineshape
  - Limited by experimental resolution
  - CMS set 3.4 GeV upper limit from llll mode
- Extract from peak position
  - Interference with background moves $\gamma\gamma$ peak c/f llll
    - Or even use high/low p_T difference in $\gamma\gamma$
  - No results yet
- Use high-mass tail of BW in llll (& interference)
  - High-mass cross-section stable; take ratio to peak
  - Assumes line-shape is not distorted by new physics
  - New CMS result next slide
- Extract from invisible, undetected cross-section discussed
  - Assumes relations between couplings
  - 6 MeV upper limit from ATLAS data

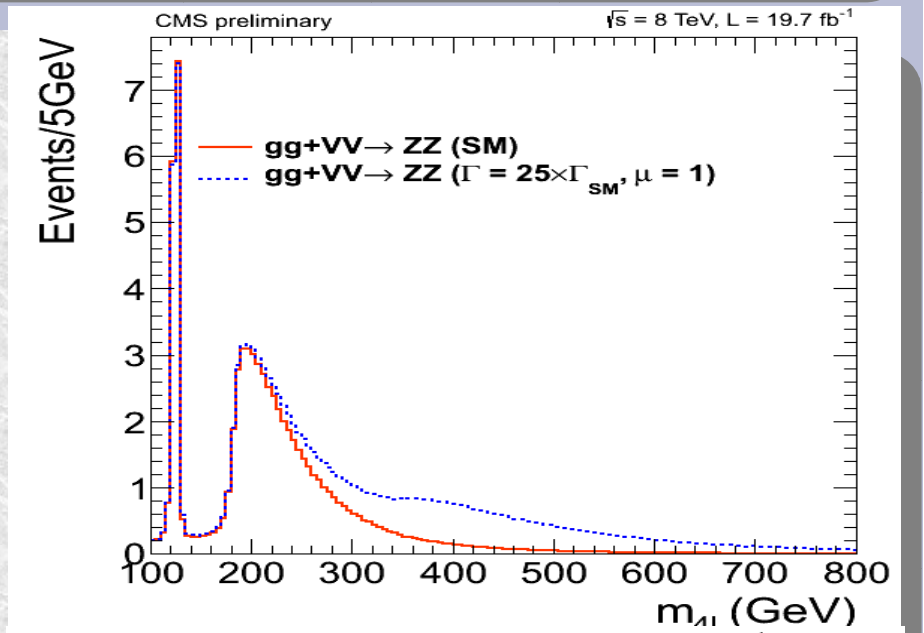
Width via ZZ mass distribution

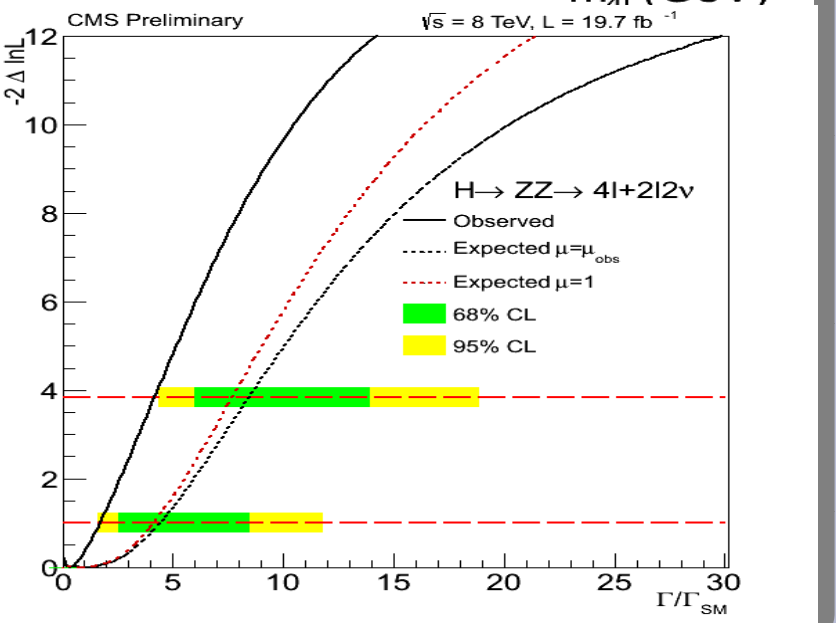
- Use observed lineshape

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa_g^2\kappa_Z^2}{r}(\sigma\cdot \text{BR})_{SM} \equiv \mu(\sigma\cdot \text{BR})_{SM}$$

$$\frac{d\sigma^{\text{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu r \frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

- Need to understand interference with gg→ZZ
  - Assume K-factors same to 10%
- Take measured on-peak σH
- Using ZZ in llll and llνν modes
  - MELA in llll suppresses qq→ZZ
- Γ_H<17MeV (35MeV expected)
  - c/f 4.2MeV in SM
- Could this become measurement?
  - Needs improved calculations





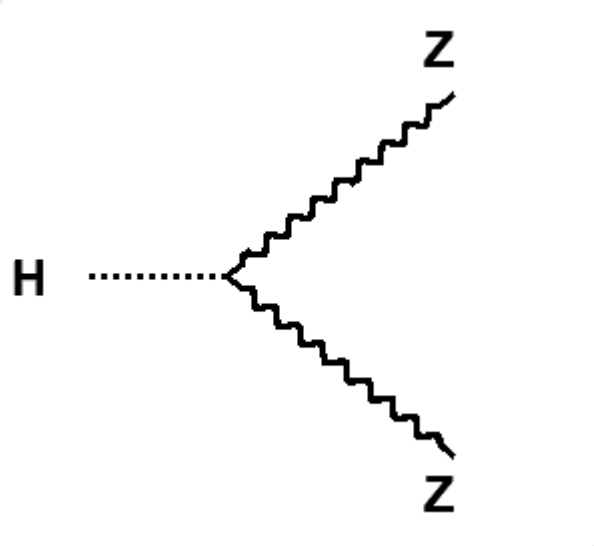
What about the Higgs field?

- 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 many 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 10xH$\gamma\gamma$
  - After allowing for Br,
  - So HZZ must be single 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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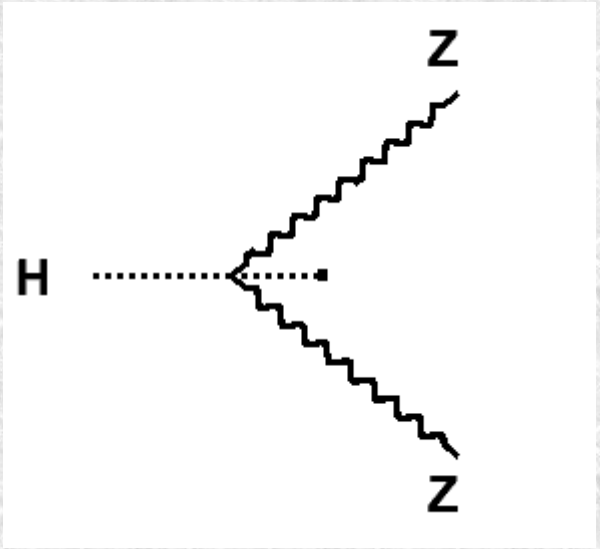
- The Z interacts with weak charge
  - But Z is neutral (Charge and weak charge)
- ZZH vertex shows the H must be weak charged
  - But in H→ZZ where does the charge go?
- It is really a 4-point coupling
  - One leg 'grounded' in the vacuum
- The ZZ decay shows vacuum participates
  - With a (weak) charge!
- The apparent 3 point couplings come from $\partial_\mu\varphi\partial_\mu\varphi$ expanded about v
- There IS a field



Run 2?

- The increased beam energy increases cross-sections by a factor 2+
  - Factor 5 for $t\bar{t}H$
- $100fb^{-1}$ in Run 2 will allow ~10 times the Higgs production
  - Measurements becoming increasingly precise
  - Testing the SM in a new sector
- The BSM Higgs potential is huge
  - New areas in H, A, H^{+} a_1, H^{++}
  - Will naturalness / the Heirarchy problem finally yield?
  - Perhaps we fine SUSY in Higs decays – or vice versa
- Then $300fb^{-1}$, and finally $3000fb^{-1}$ will allow detailed explorations
  - Maybe even access to the self-coupling

Summary

- After 50 years we have found something remarkably like the SM Higgs boson:
  - Mass ~125.6 GeV
  - 0^+ j^p strongly preferred over alternatives
  - Decay to ZZ, WW, γγ, ττ, maybe bb
    - Lack of decay to μμ
  - Evidence for VBF and gluon fusion: ttH next?
  - Γ_H<17 MeV, m_A>400GeV (with assumptions)
- The experiments are preparing for Run2
- In 2012 LHC worked remarkably well
  - We have twice the discovery data already
  - 300fb^{-1} at 14TeV will allow great precision
  - And maybe more discoveries...

Higgs links:

- Full list of all ATLAS & CMS public results

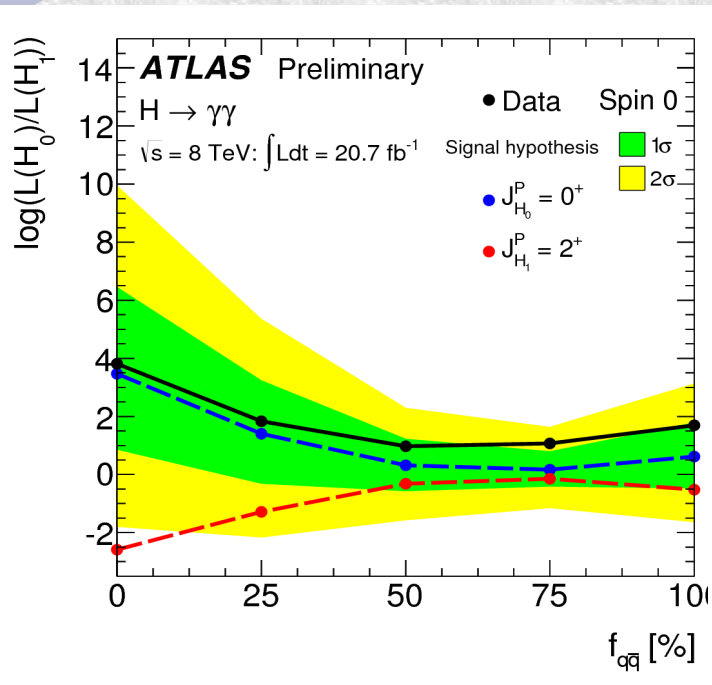
HL-LHC as Higgs factory

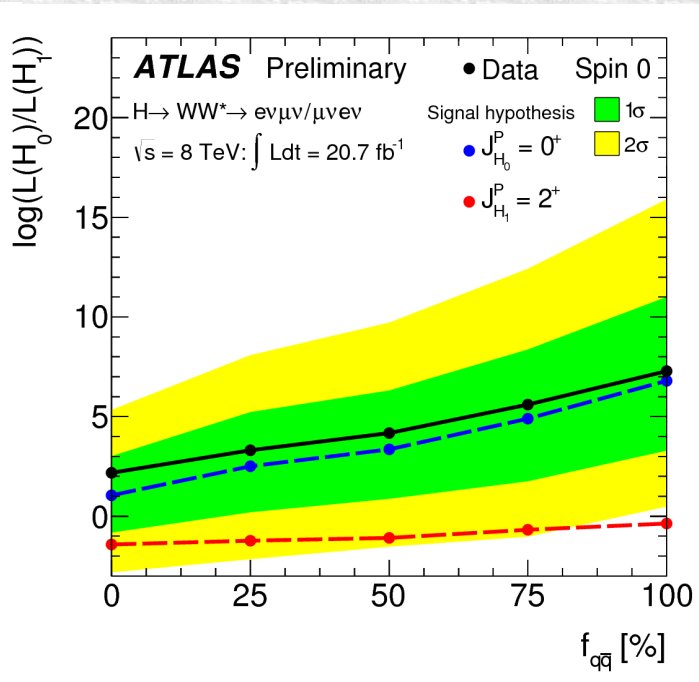
- 2023 for 10 years?
- Increasing luminosity to $5x10^{34}cm^{-2}s^{-1}$
  - New proton linac & focus elements needed
  - Pileup increases by similar factor, 140 events/BX?
  - New trackers, calorimetry readout, TDAQ needed to cope
- Beams are rapidly 'burnt-off'
  - Luminosity levelling is assumed for this upgrade
  - Extends beam lifetime, limits pileup
- Going from $300fb^{-1}$ to $3000fb^{-1}$ at 14 TeV
  - Improved measurements clear in ZZ, $\gamma\gamma$,
    - The ratio of rates is very sensitive test
  - $H \rightarrow \mu\mu$ and $Z\gamma$ can be measured
  - WW, bb, $\tau\tau$ will be improved – but systematics hard to know
  - ttH, $H \rightarrow \gamma\gamma$ measurable
  - Self-coupling in $HH \rightarrow bb\gamma\gamma$ looks maybe possible: other modes?

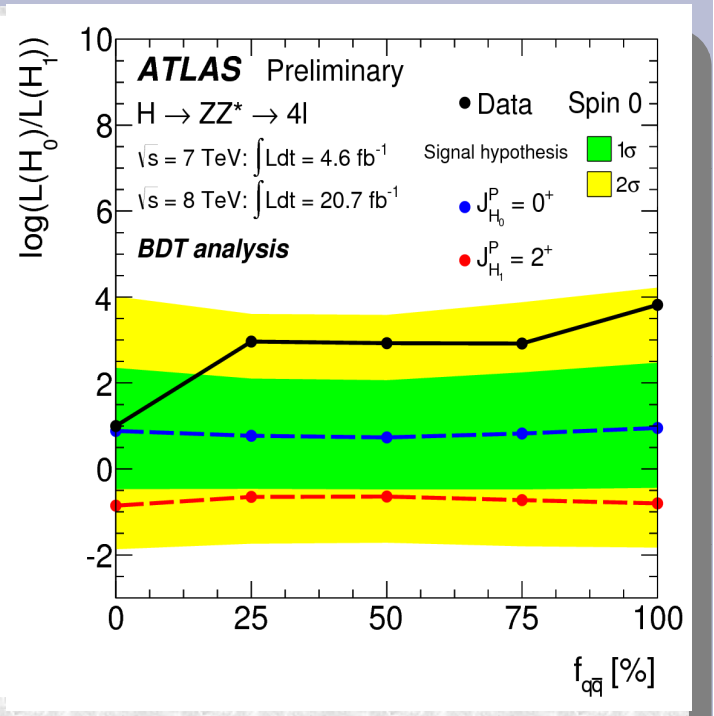
$t \rightarrow qH$

- There could be flavour-changing couplings in the Higgs sector
  - Bounds are much looser than for Z or photon
- CMS: $Br(t \rightarrow cH) < 0.56\%$ (0.65% expected)
- ATLAS: $Br(t \rightarrow cH) < 0.83\%$ (0.53% expected)

Spin Combination

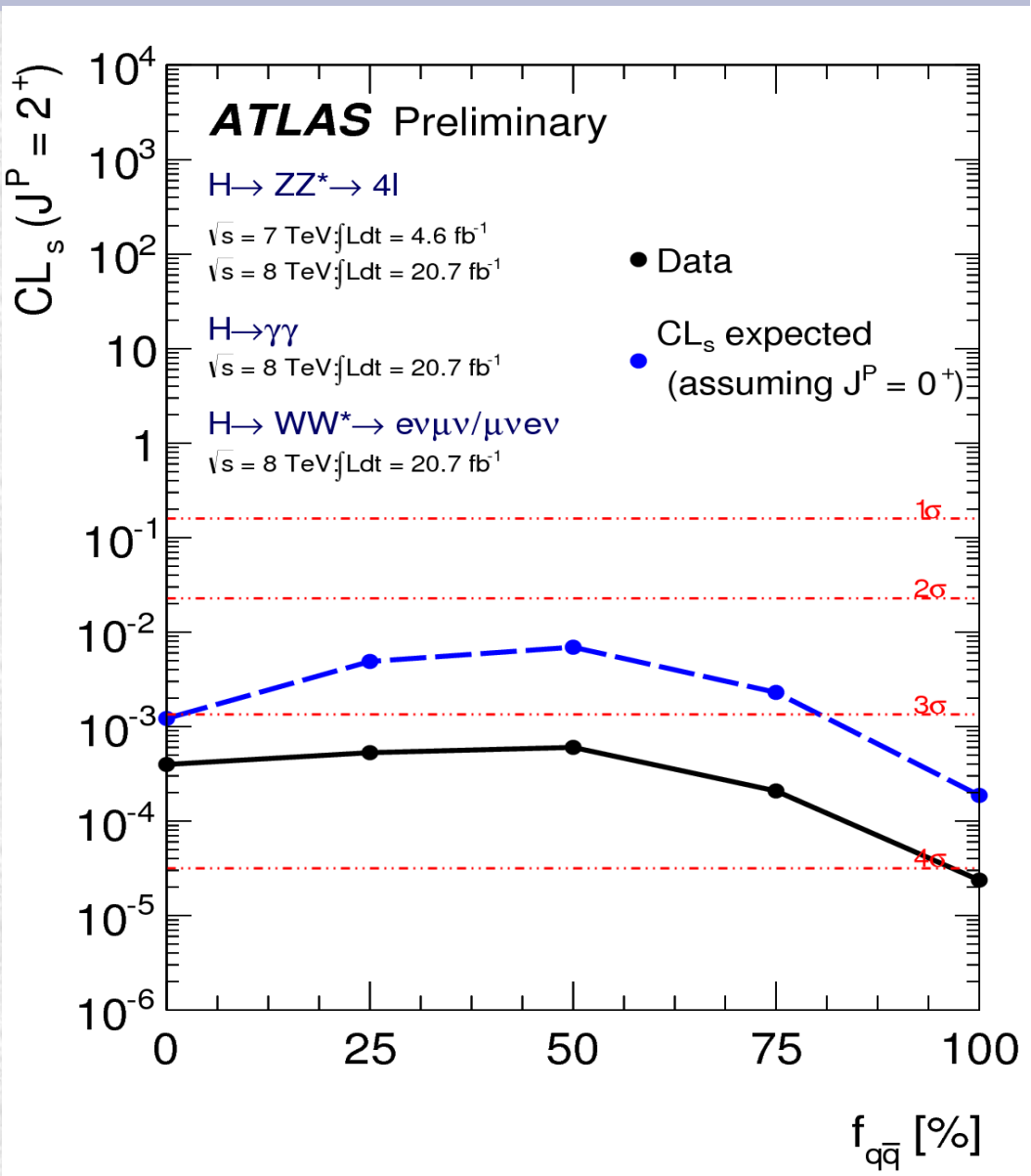




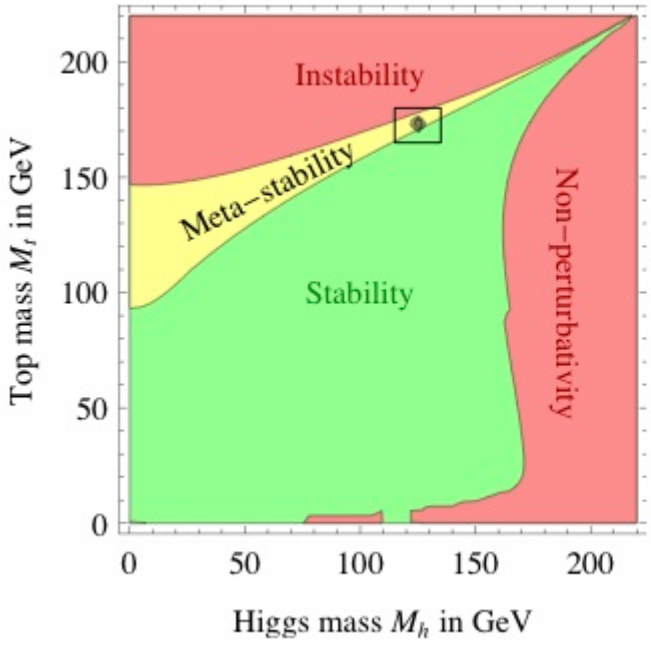


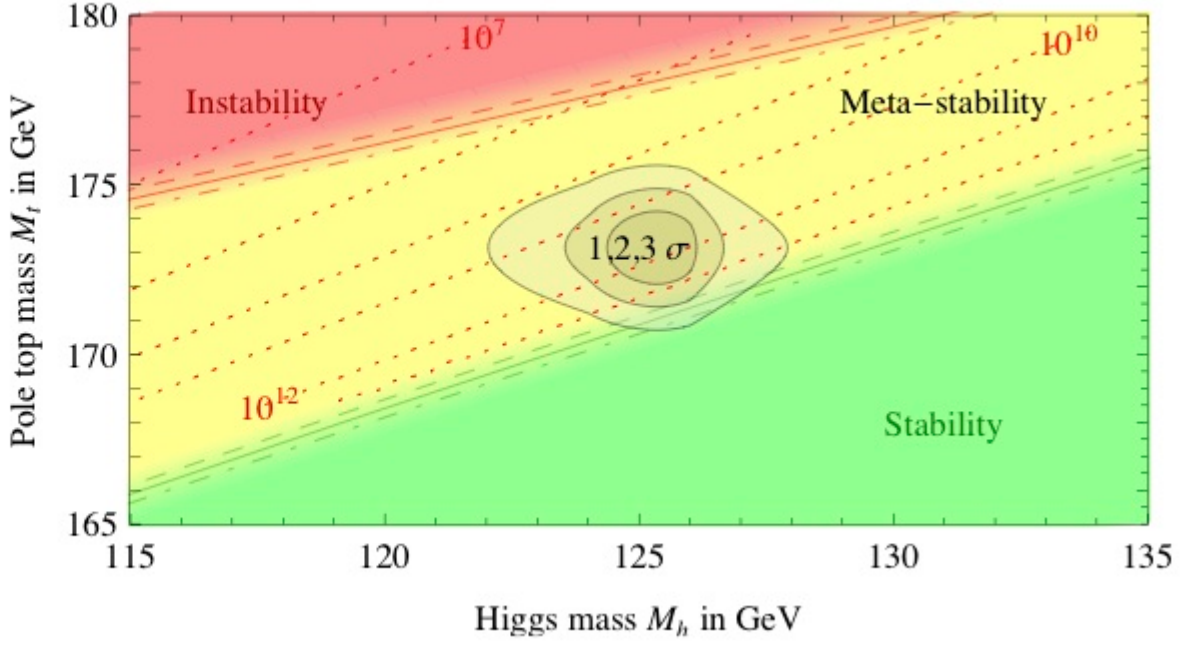
Combined spin-2+ rejection

- All channels contribute
- Overall ~2.5-3.5σ expected for all gg/qq fractions if really spin 0+
- In fact 3.2-4.1σ rejection seen



Vacuum stability





- The running couplings depend on Higgs, top and W mass
- Stability up to plank scale is questioned by m_H
  - But it seems long-lifetime meta-stability possible