The Higgs boson: from discovery to precision measurement

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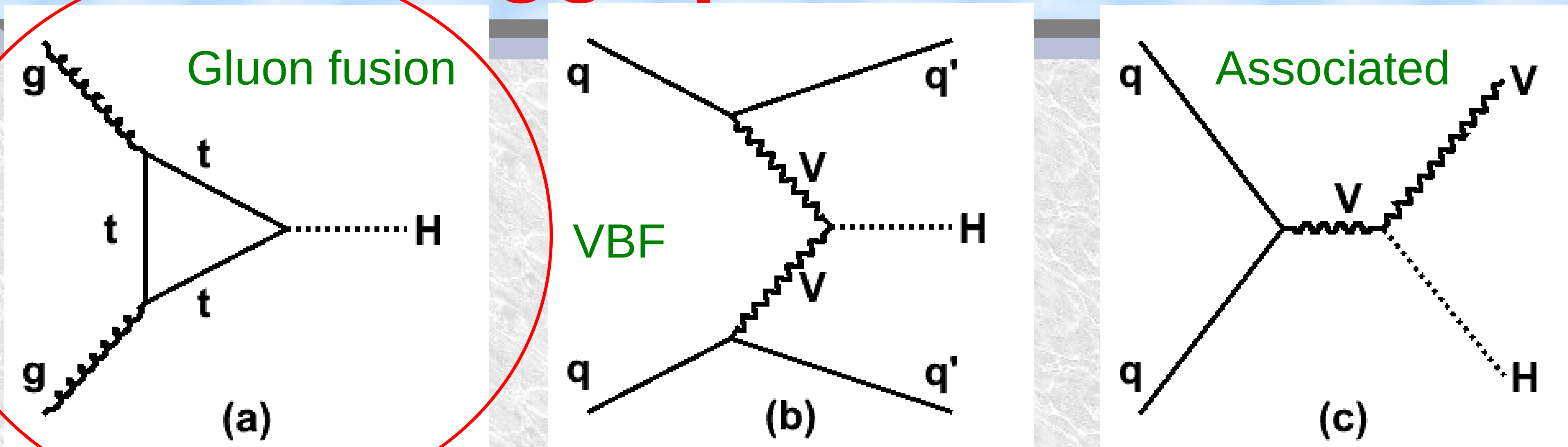
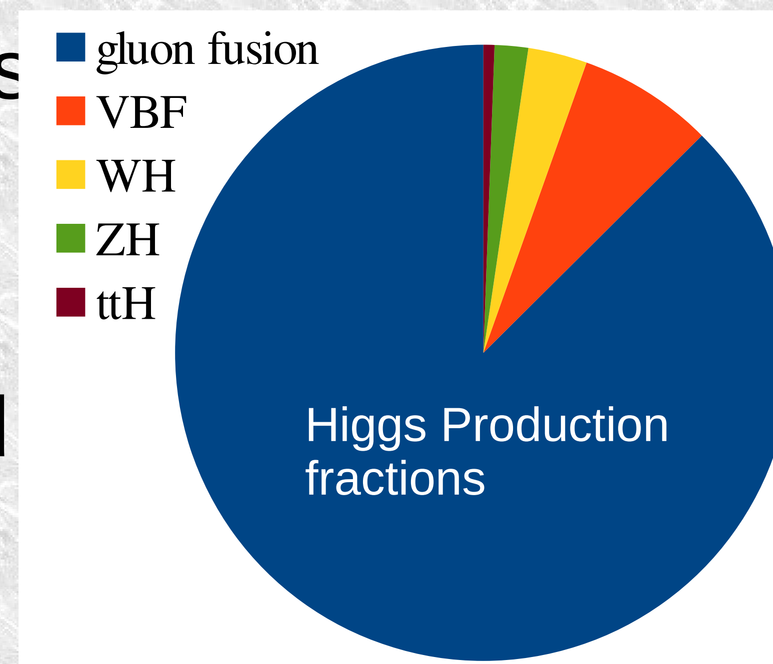
The Higgs discovery
What do we know today?
What might the future hold?

Higgs production

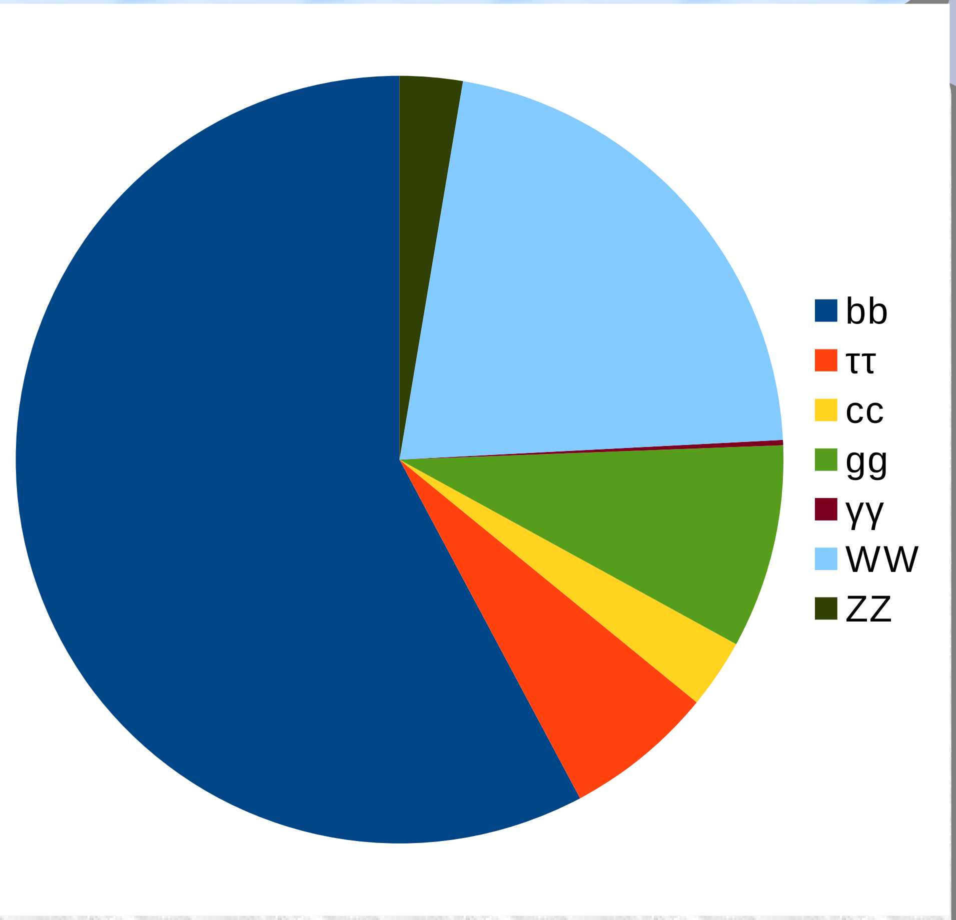


- The three most common modes
  - Others also exist: $t\bar{t}H$, tH , bbH...
- Gluon fusion dominates rate
  - Top loop (+ BSM?)
- Vector boson fusion/associated
  - Also used to tag signal
  - Improves the purity
- ttH: coming soon



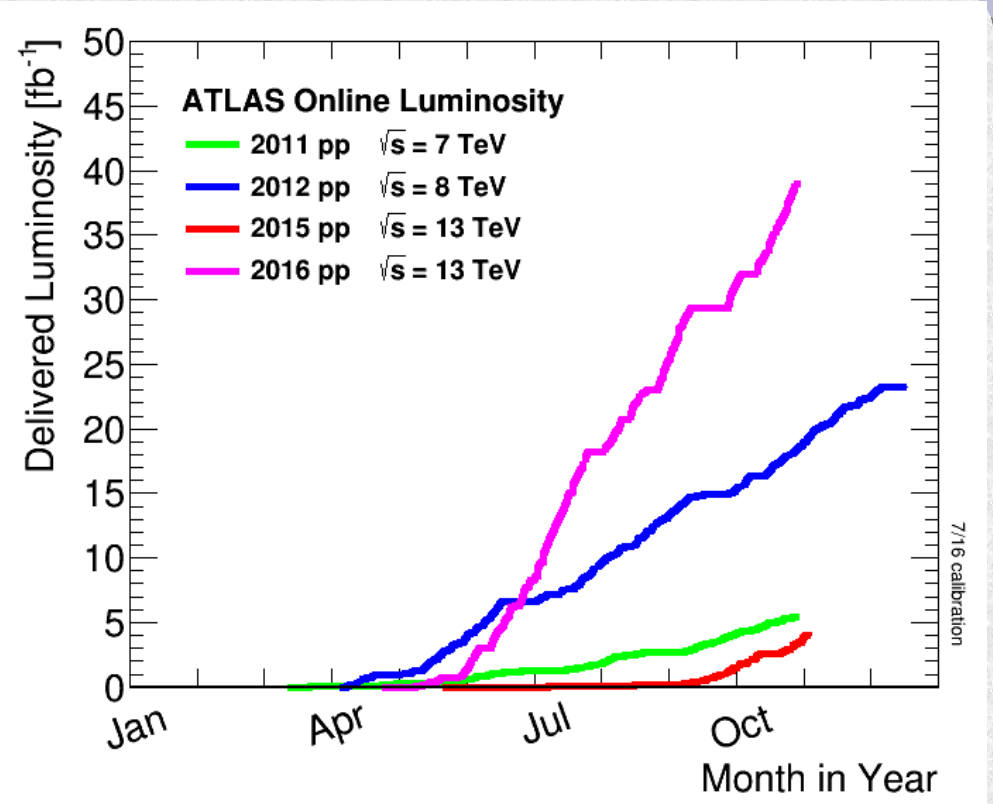
Higgs decay modes used

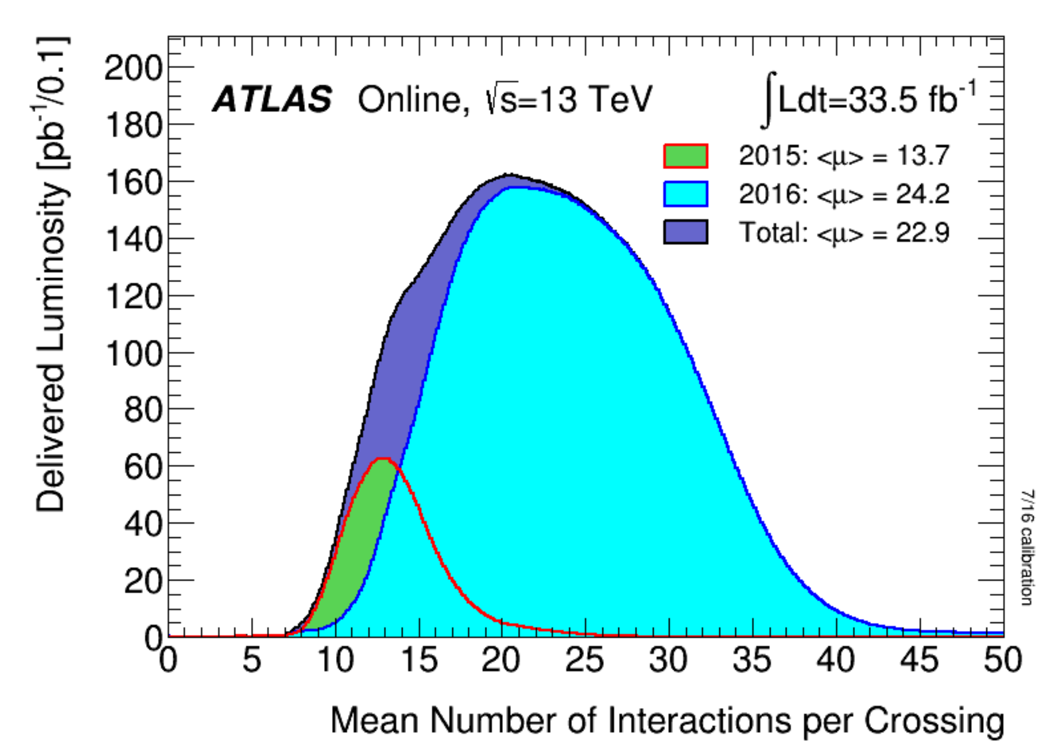
- $H \rightarrow ZZ$
  - $ZZ \rightarrow llll$: Golden mode
  - $ZZ \rightarrow ll\nu\nu$: Good High mass
  - $ZZ \rightarrow llbb$: Also high-mass
- $H \rightarrow WW$
  - $WW \rightarrow l\nu l\nu$: high rate,
  - $WW \rightarrow l\nu qq$: highest rate
- $H \rightarrow \gamma\gamma$
  - Rare, best for low mass
- $H \rightarrow \tau\tau$
  - Uses VBF, low mass
- $H \rightarrow bb$
  - $t\bar{t}H$, WH, ZH: need production tag



2016 LHC ran pp excellently

- 2016 data delivery large
  - $0.6\,fb^{-1}$ in one day!
  - $39\,fb^{-1}$ in year
- $L = 1.4\times10^{34}\,cm^{-2}s^{-1}$
  - Passing design





- Pileup of 35 regularly at start of fill
  - Also passing design

Higgs cross-sections

- ~25fb^{-1} at 7/8TeV allowed the discovery
  - And a suit of measurements
- ~40fb^{-1} at 13 TeV will go much deeper
  - With 100fb^{-1} expected in run 2
- But so far results from ~15fb^{-1}

Cross-sections	8 TeV fb	13 TeV fb	Ratio
ggH	21400	48500	2.3
VBF	1600	3780	2.4
WH	700	1370	2.0
ZH	420	880	2.1
ttH	133	506	3.8

Yields	7/8 TeV	13 TeV	Total
ggH	0.5M	1.9M	2.4M
VBF	40000	150000	190000
WH	17000	55000	70000
ZH	10000	35000	45000
ttH	3300	20000	23000

Higgs measurements in a slide

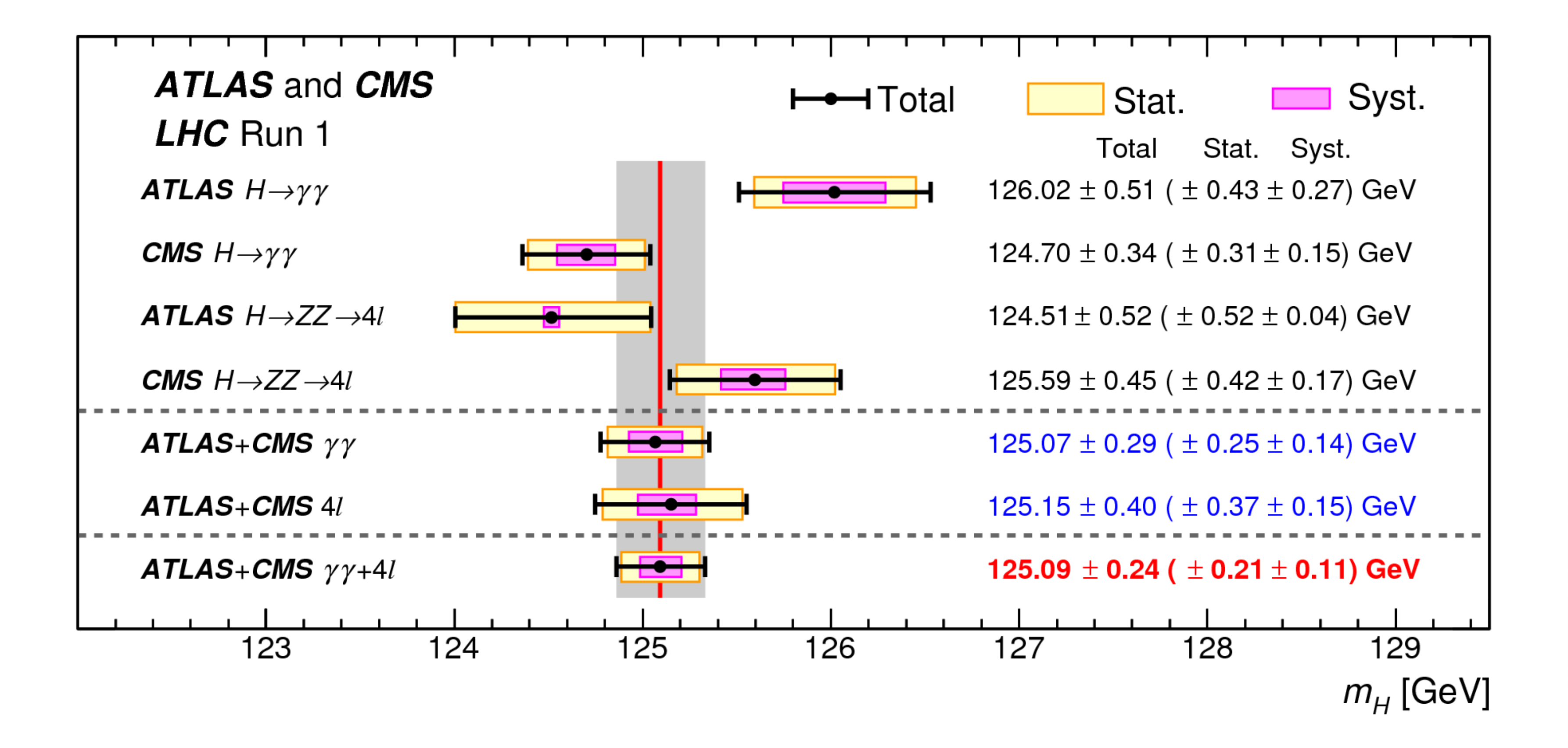
- Discovery in 2012 via γγ and ZZ decays
- WW was soon confirmed
- ττ only via ATLAS+CMS combination
- Other decay modes are not proven.
- Production dominated by gluon fusion
- VBF also seen a 5σ in combination
- Spin/parity assessed in all observed channels
  - Results strongly prefer 0+ over any alternative

Run 1 Higgs

- A lot of our knowledge comes from Run 1 results
- Many of the SM results are seen through the prism of ATLAS+CMS joint papers
  - Mass measurement
  - Coupling measurement
- I think it is significant that there is no combined spin/parity study

The Higgs mass

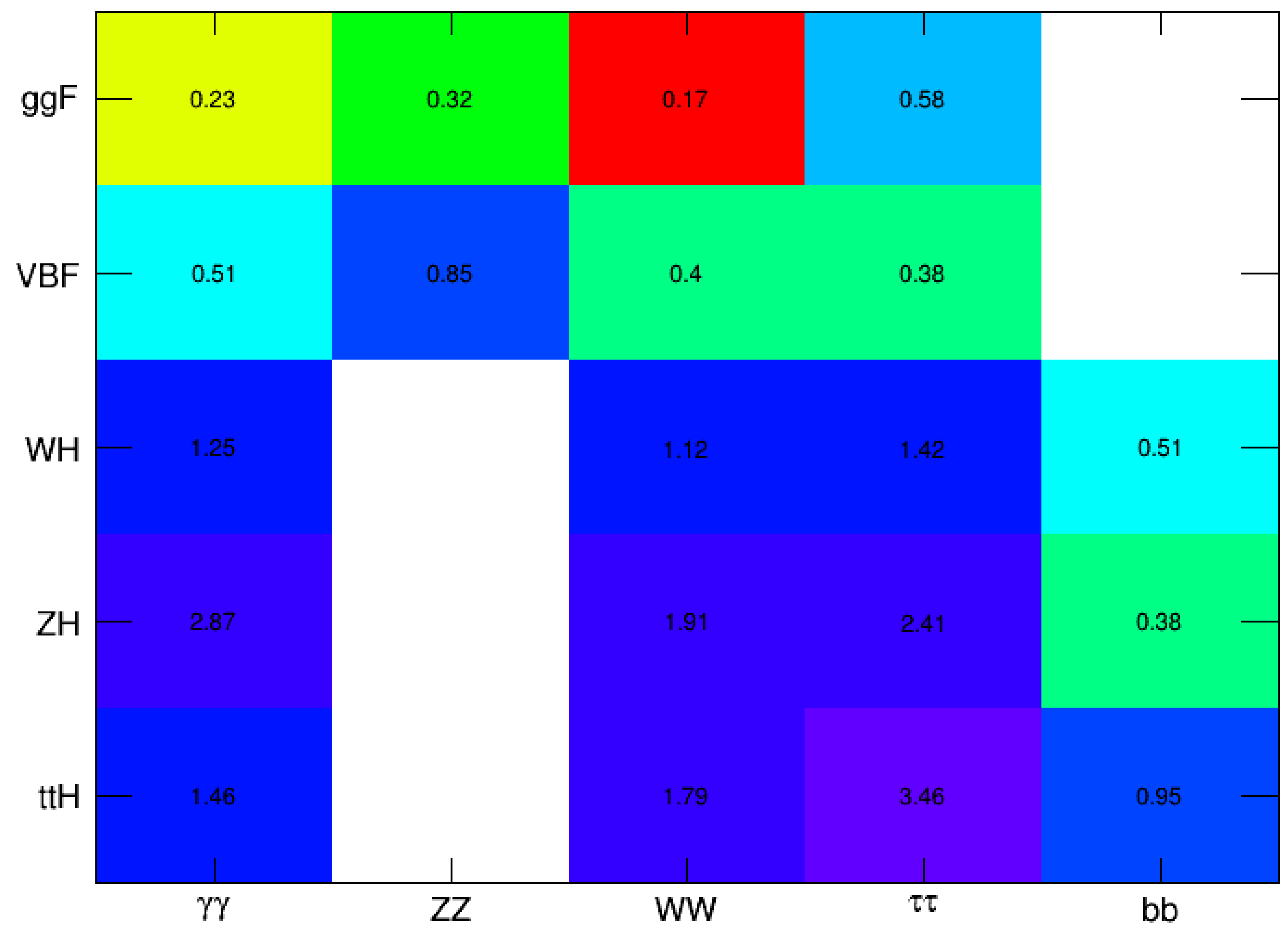
- Measured well in both the discovery modes
  - Results from ATLAS and CMS in ZZ and γγ combined:



- The last unknown of the SM. Now known to 0.2%

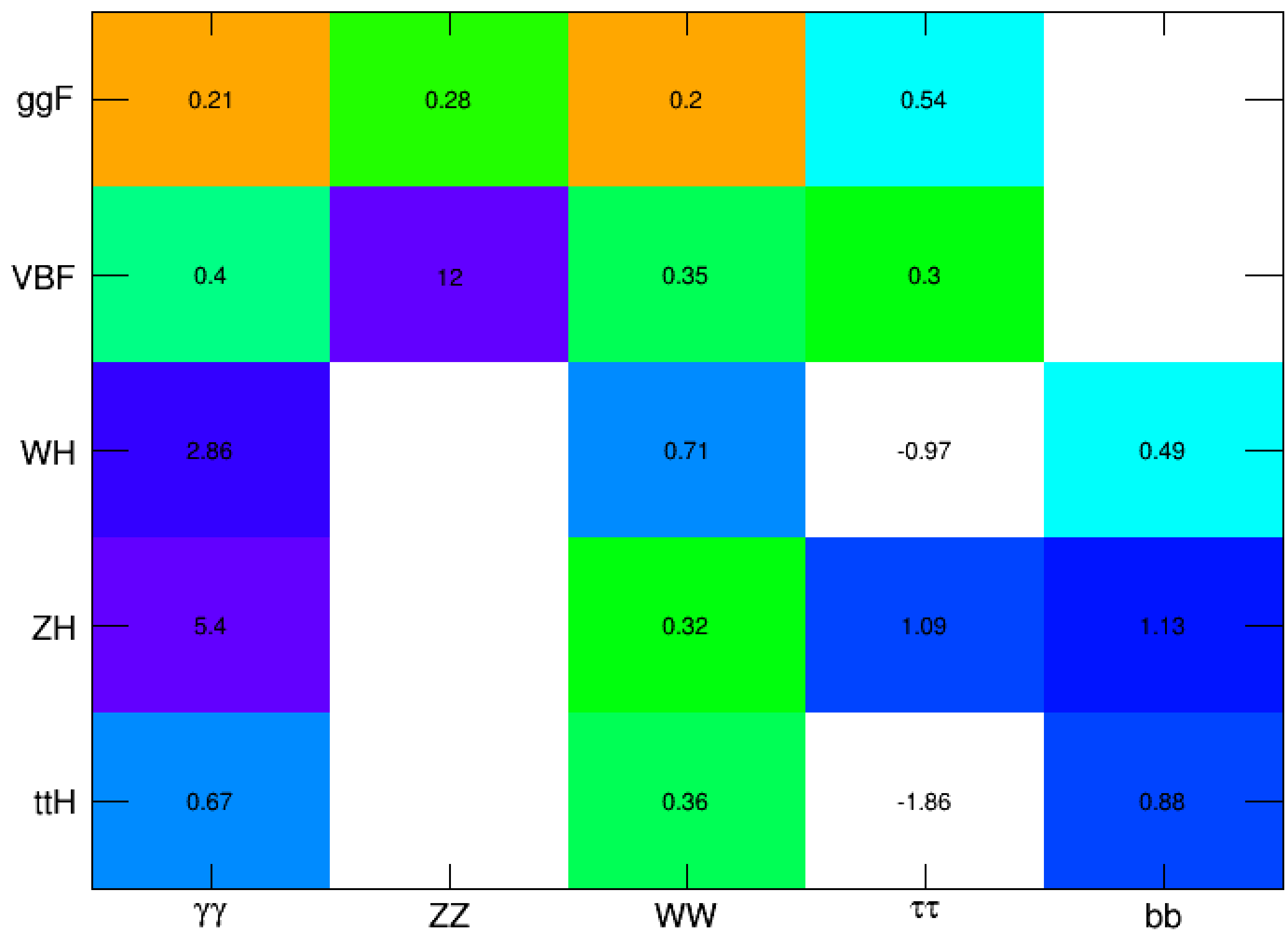
Sensitivity

- Measured error over expected signal rate
- Cyan or brighter has error below 50%



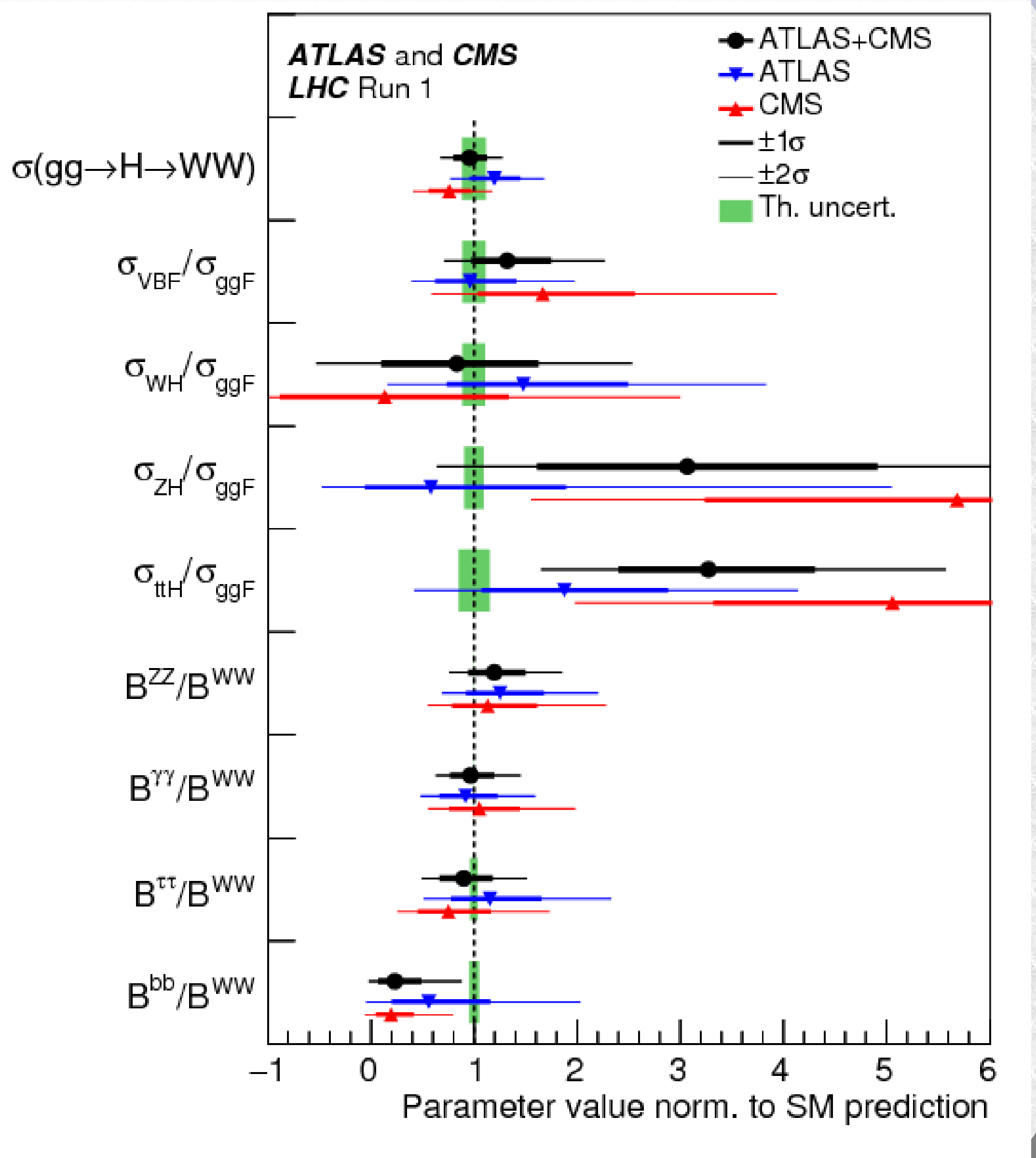
Observed

- Observed pattern matches expected pretty well
- With less bb than anticipated
- and some WW excesses



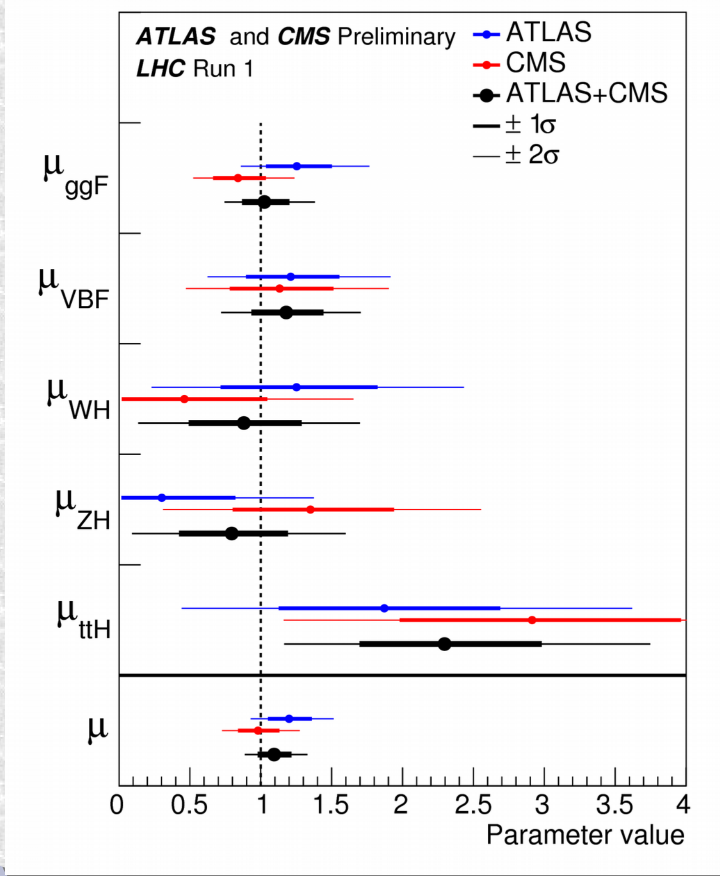
Sigma/br factorization assumed

- Given the table of cross-sections for various process
- Assume one particle then production/decay factorize
- Use ggF→H→WW as a reference
- Good agreement with SM
  - B^{bb}/B^{WW} slight tension

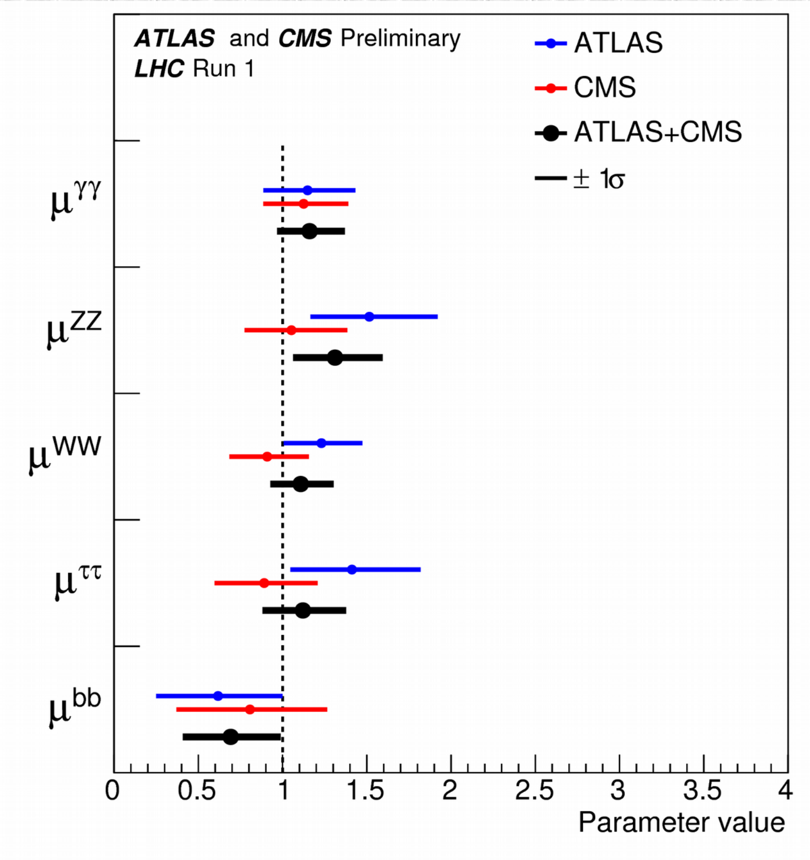


More model-dependent

- LHC run 1 found proof of
  - 4 decay modes (ZZ,γγ,WW and ττ) – prod. assumed
  - 2 production mechanisms (ggH,VBF) – decay assumed

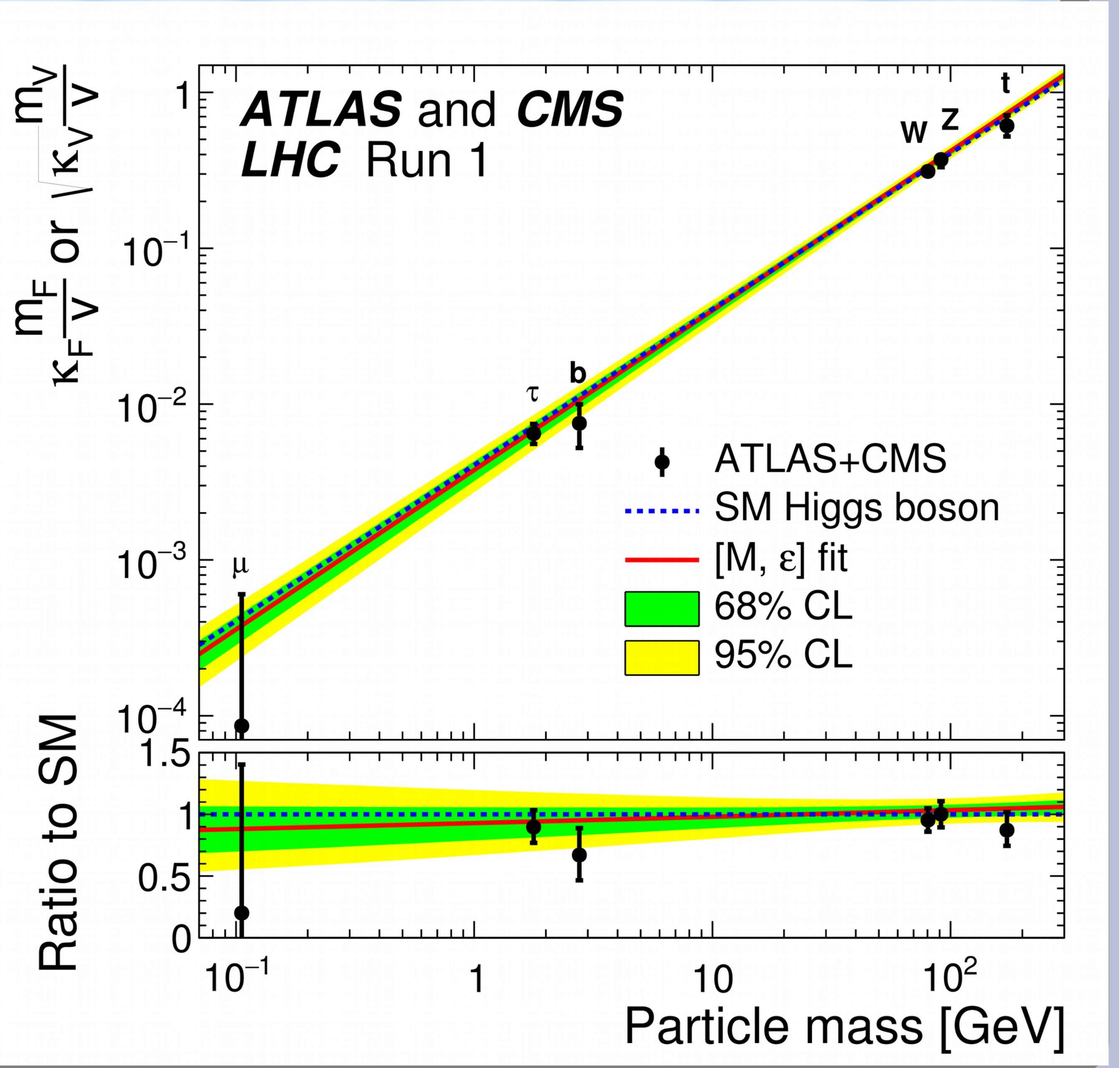


- Rates match SM pred
- Tensions reduced in this approach



Interactions v mass

- Can assume the SM structure
- Fit interactions of t, Z, W, b, τ & μ
- Some are not fully established
- But coupling dependence on mass is clear
- Thats what the Higgs does!



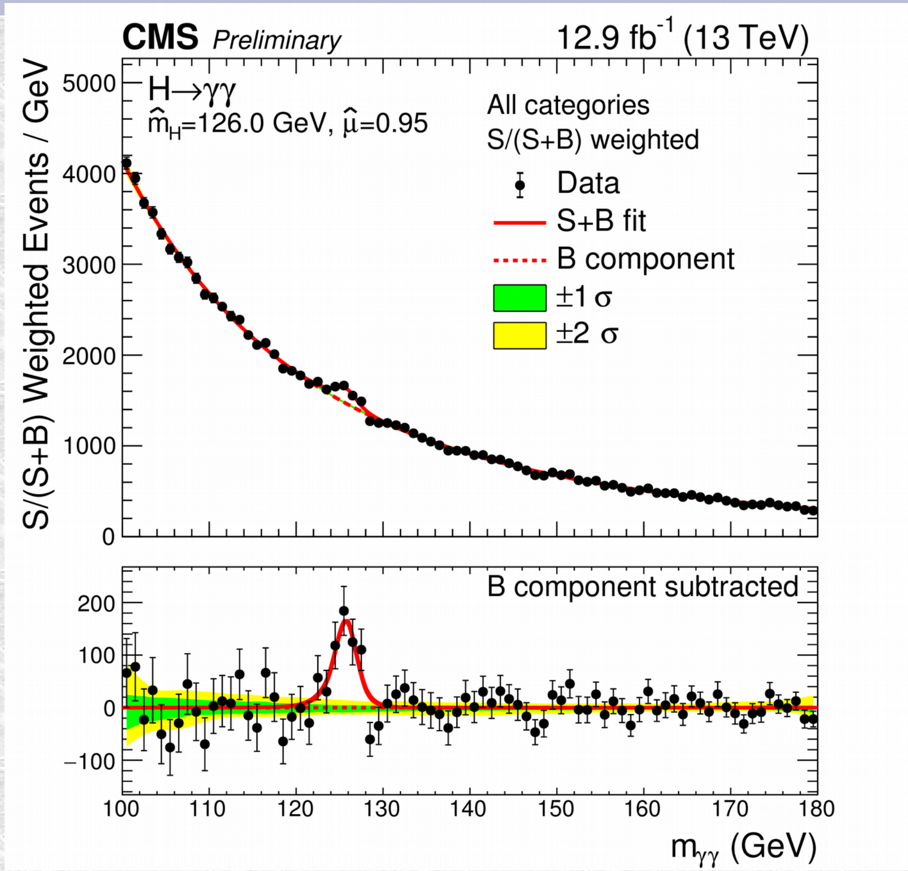
Improved frameworks

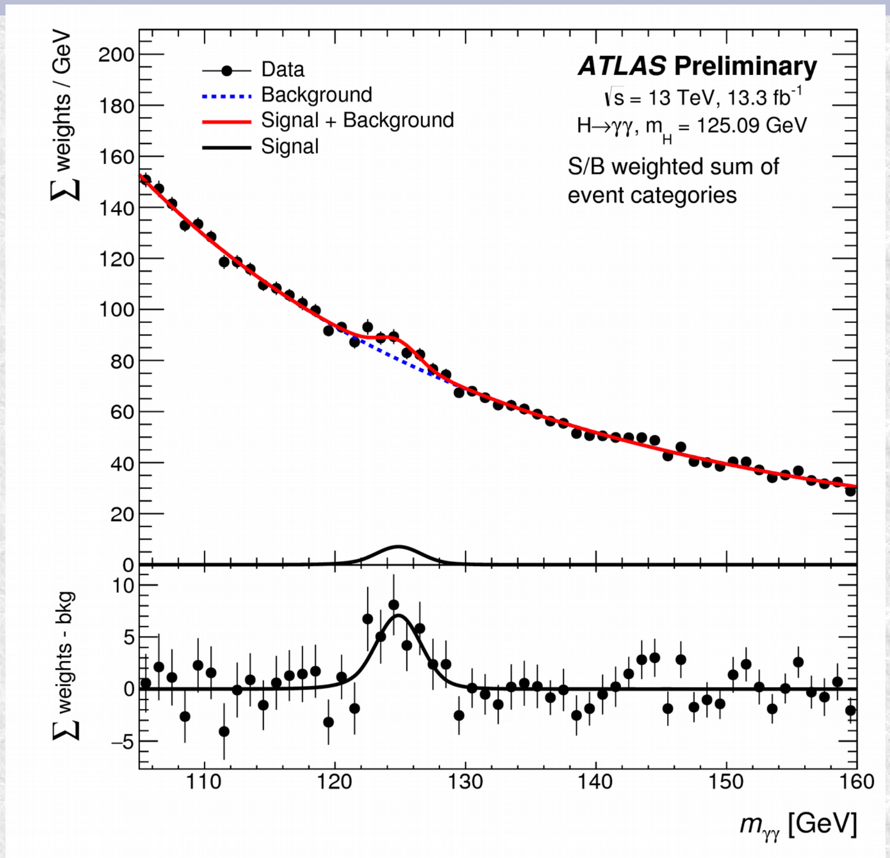
- The previous slides were either rather naively experimental or based on the κ framework – scaling couplings
  - These approaches do not yield consistent theories
  - Plus they do not allow different interaction kinematics.
- A lot of discussion & work is going into EFTs and Pseudo-observables
  - Yellow report 4 from the LHC Higgs XS WG discusses
  - But a consensus has not yet emerged
- Experiments will continue with at least κ for run 2.

Run 2

- Results emerging well
  - But not ‘evenly’ between experiments
  - Different highlights from the 2 groups

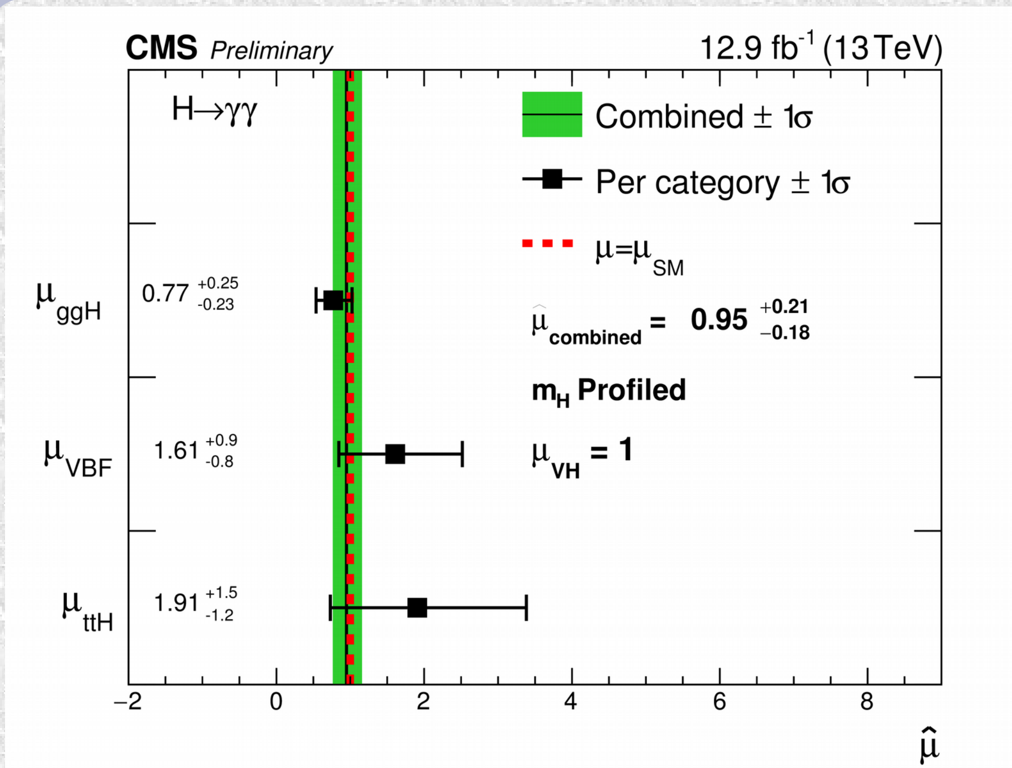
H → γγ

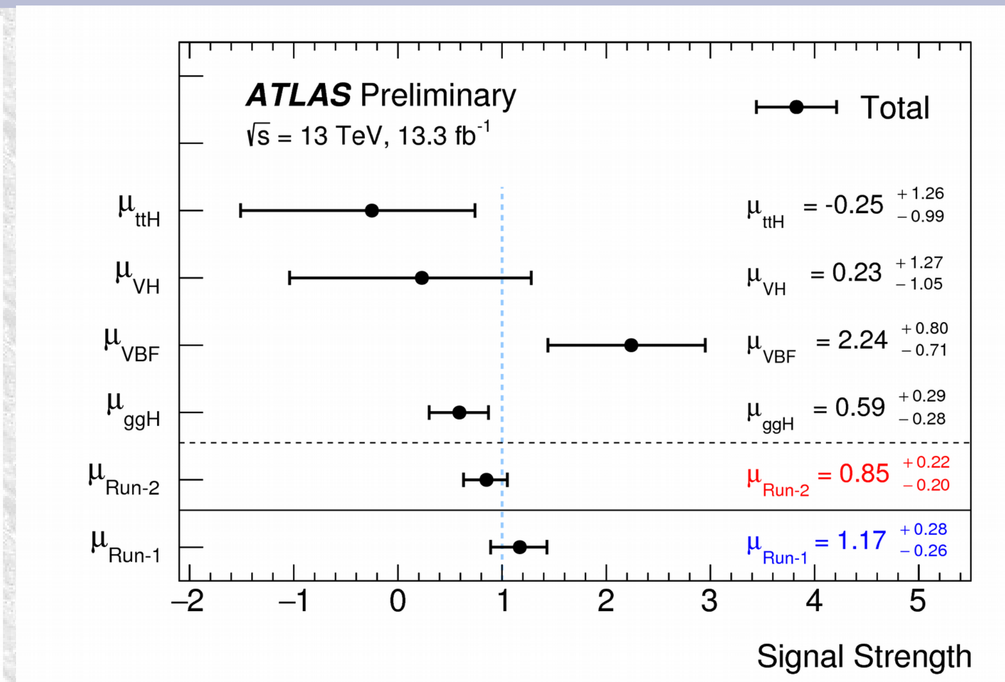




- One of the discovery channels - Its back!
  - 6σ in CMS
- How well can background be ultimately estimated?

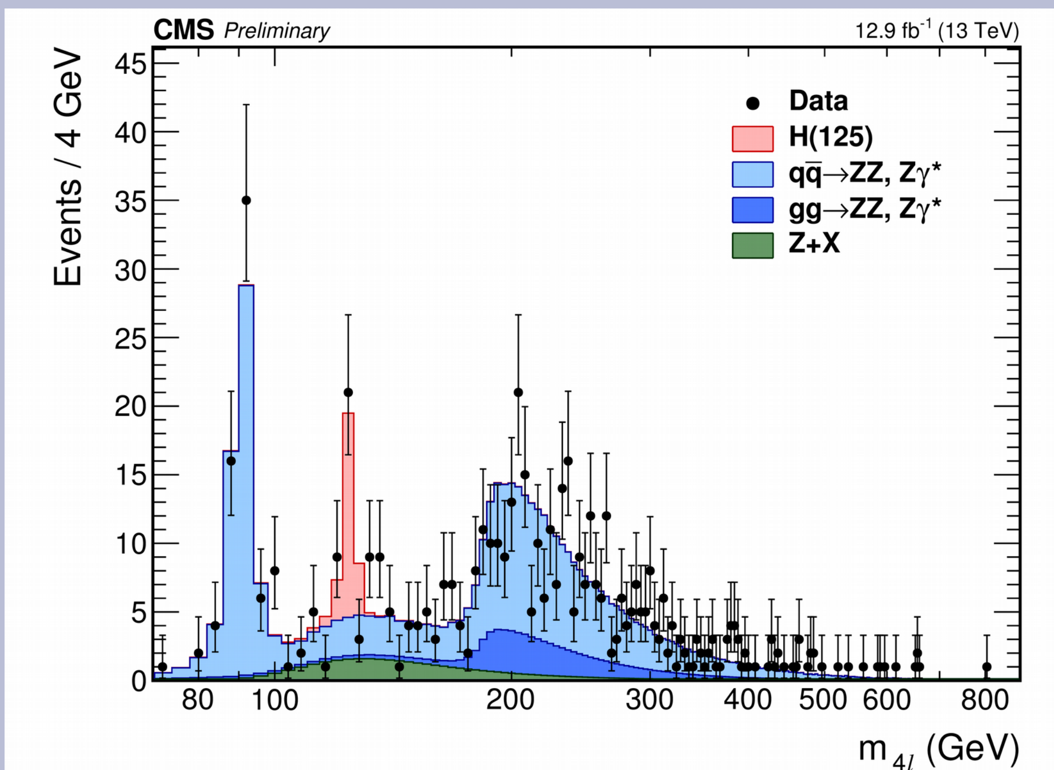
Production of H→ γγ

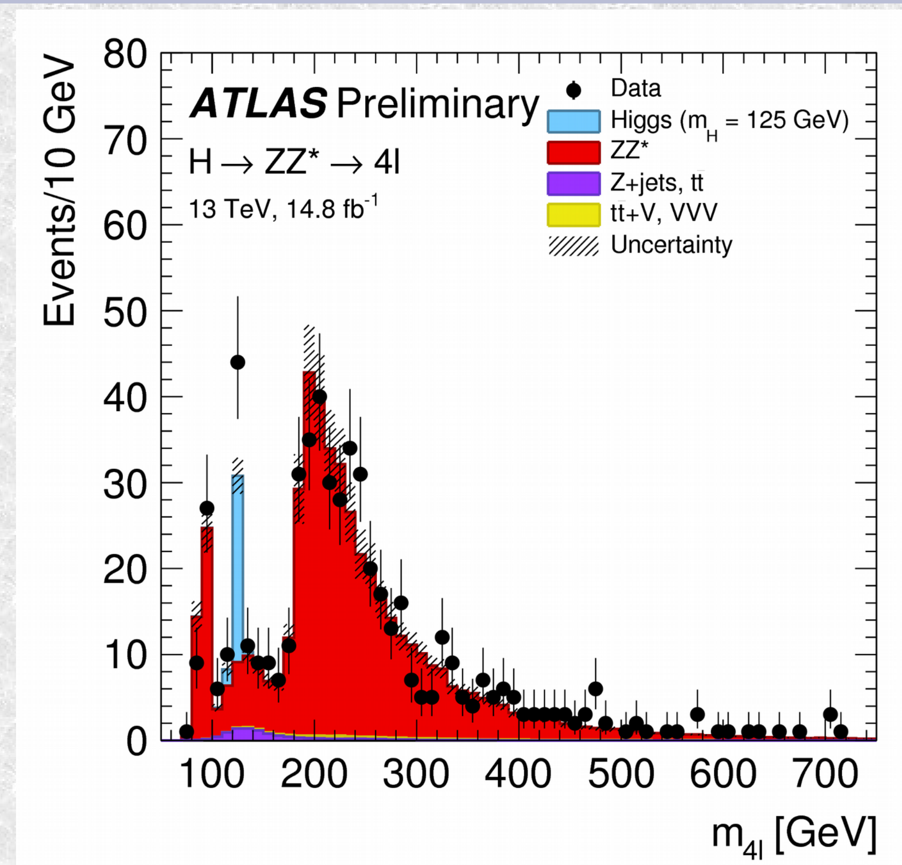




- Some sensitivity to production modes
  - This will just keep getting better with data

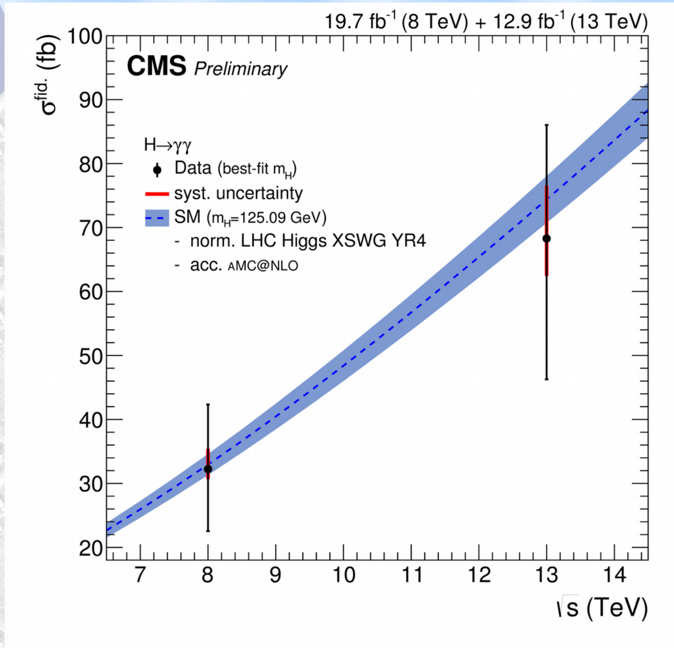
H → llll

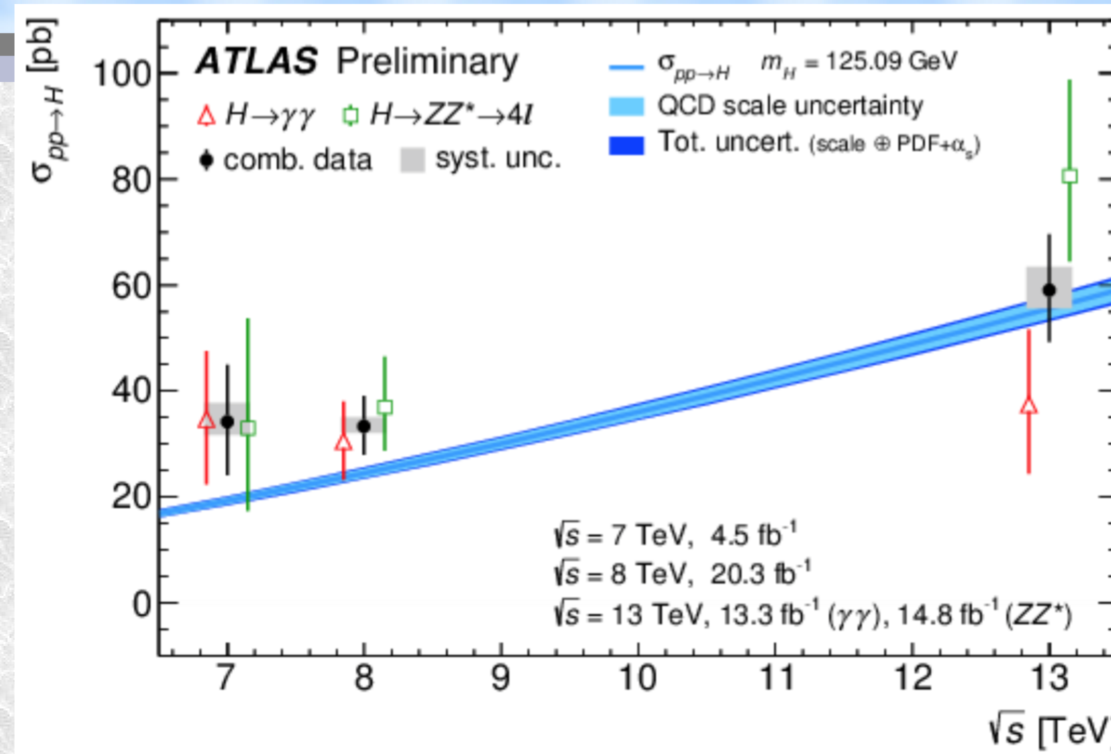


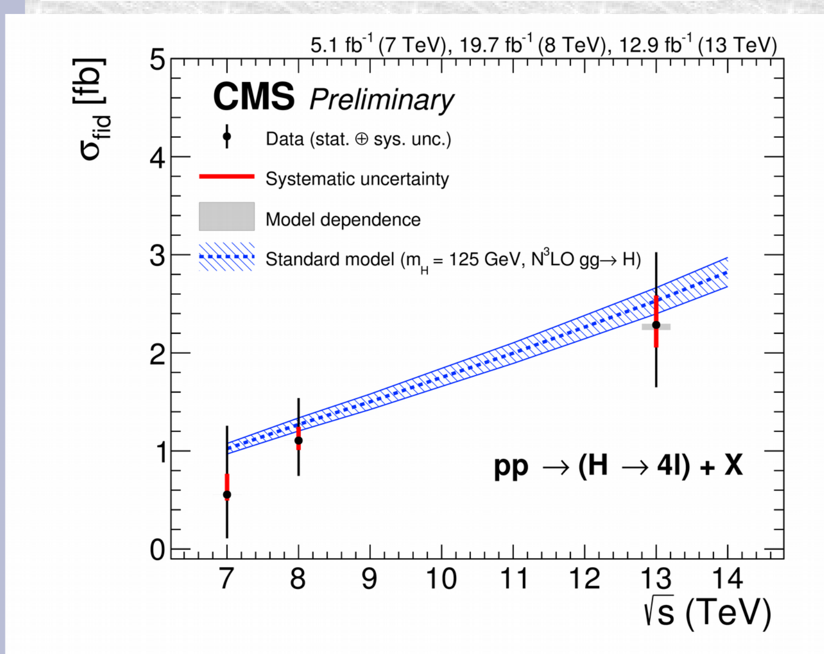


- m_{llll} used for 125 and above
  - Again 6σ in CMS
- Signal rate extracted using also kinematic information

Cross-section evolution



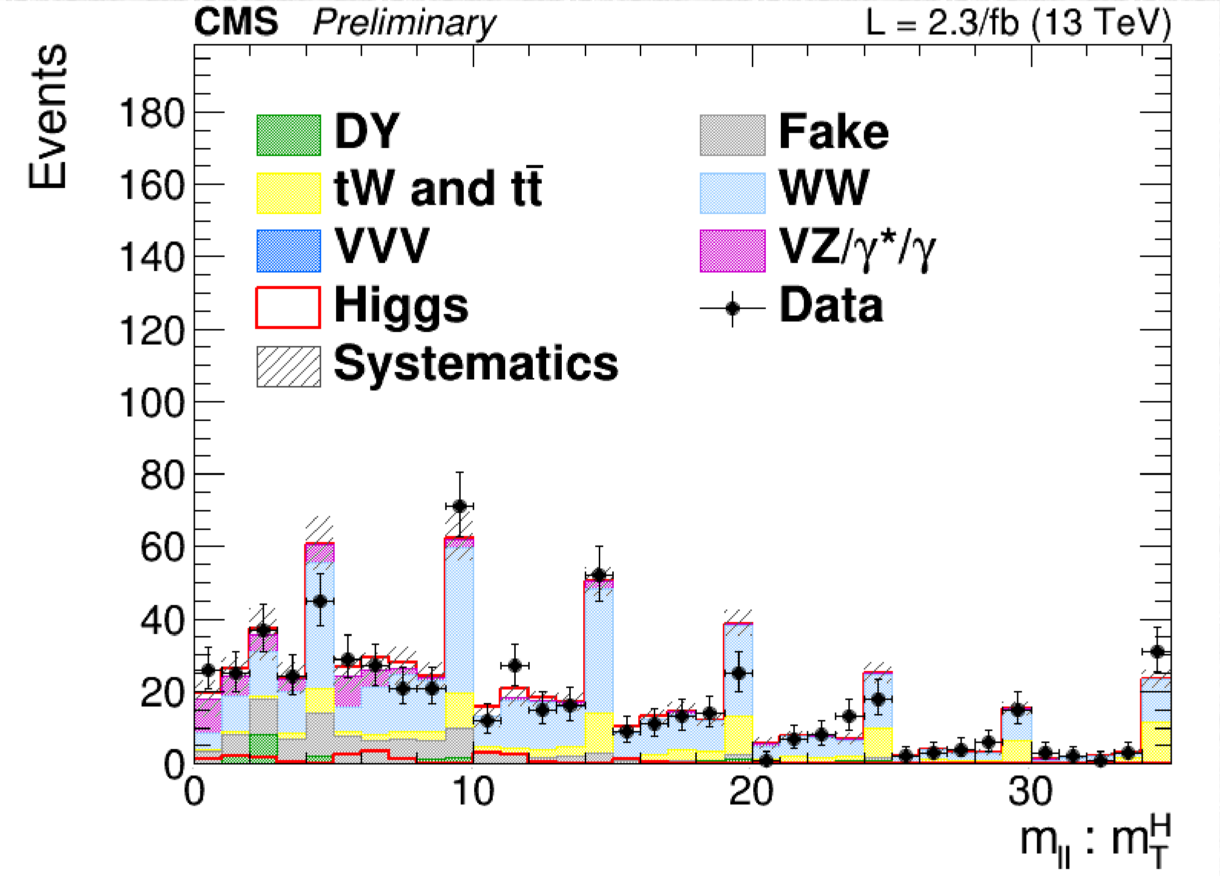




- 2 experiments, both channels see Higgs cross-section increasing with energy
  - 10σ evidence ATLAS combined
- Can we stop ‘discovery’?

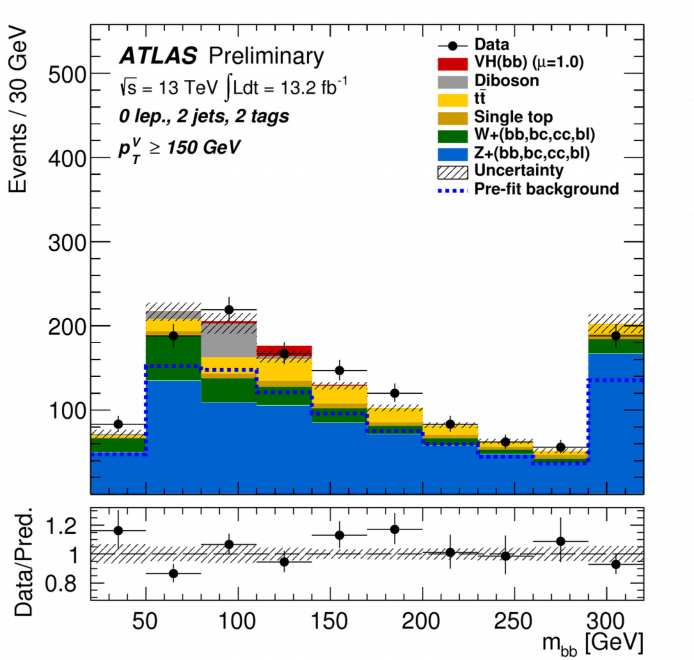
H → WW

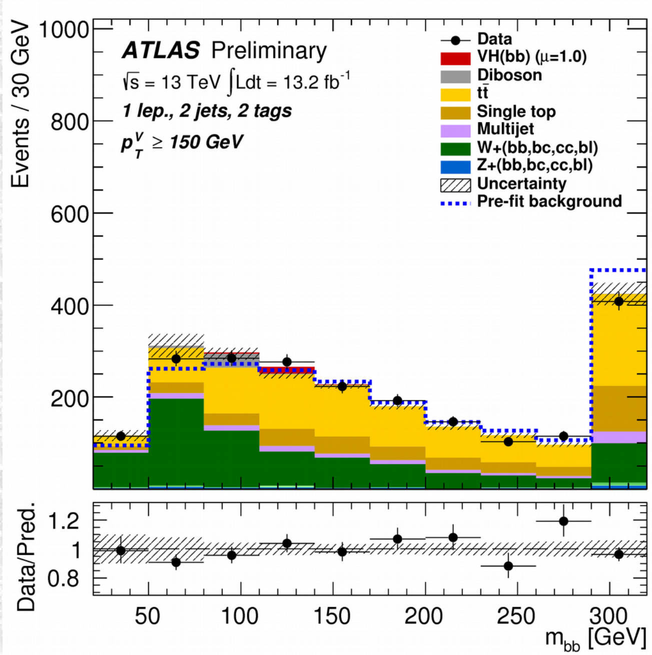
- Final state with dileptons is OK to trigger and has high signal rate
- But large backgrounds & no peak complicate it:
  - WW
  - tt
  - Drell-Yan
  - Fake leptons
- CMS analysis for 2015 is released
- μ=0.3±0.5
- Sensitivity at Run 1 levels needs work

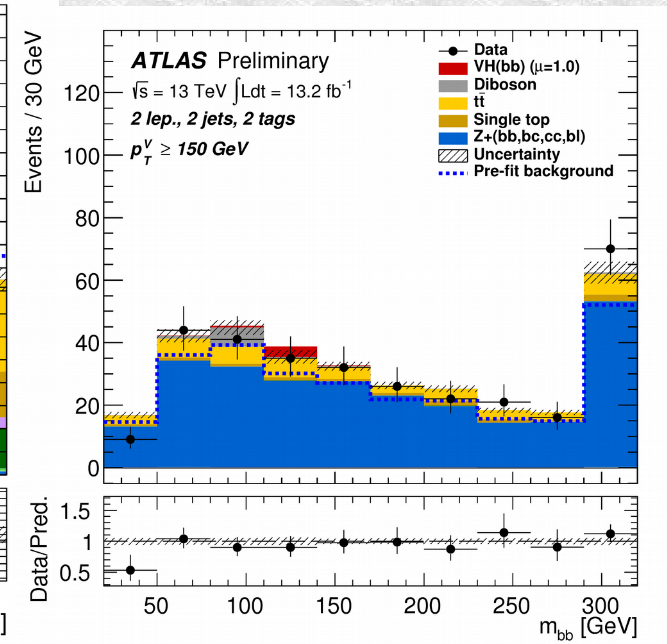


H → bb

- H → bb has not been definitively observed
  - Target for run 2!
- VH is most sensitive channel
  - 0l, Z → νν, 1l, W → lν 2l, Z → ll
  - Most sensitive Highest rate Purest

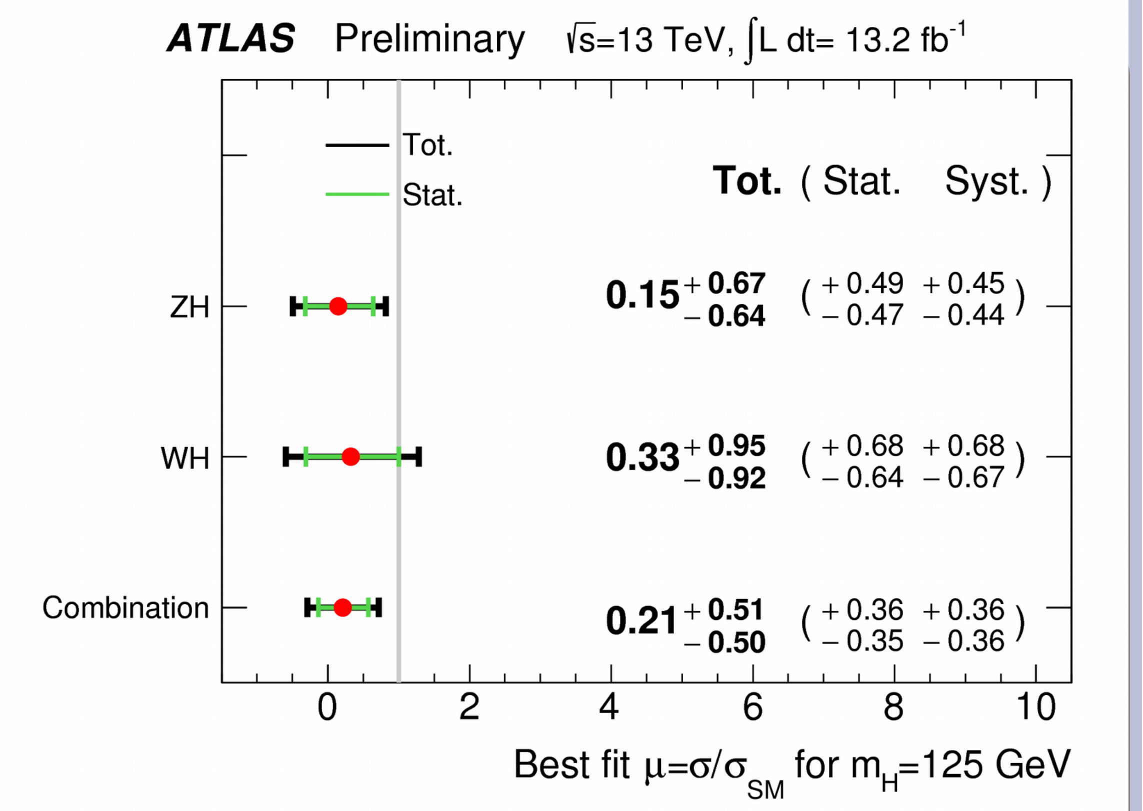






H → bb

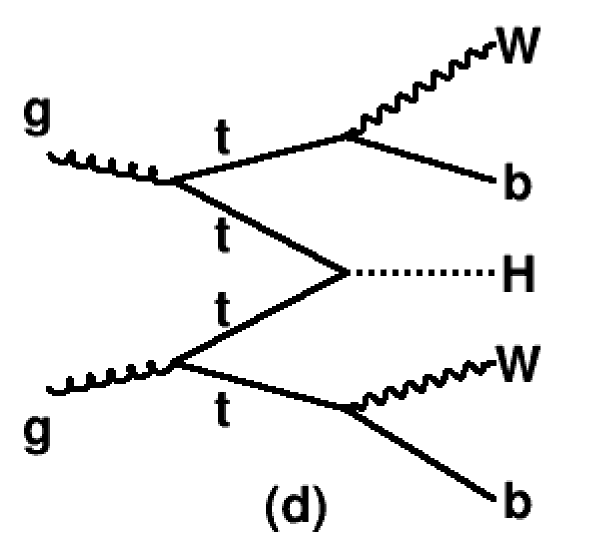
- This was low in 2012
  - 2.6σ seen, 3.7σ expec.
  - C/f Tevatron
    - 3σ obs, 1.9σ exp
- Low again in 2016
  - No CMS VH result yet

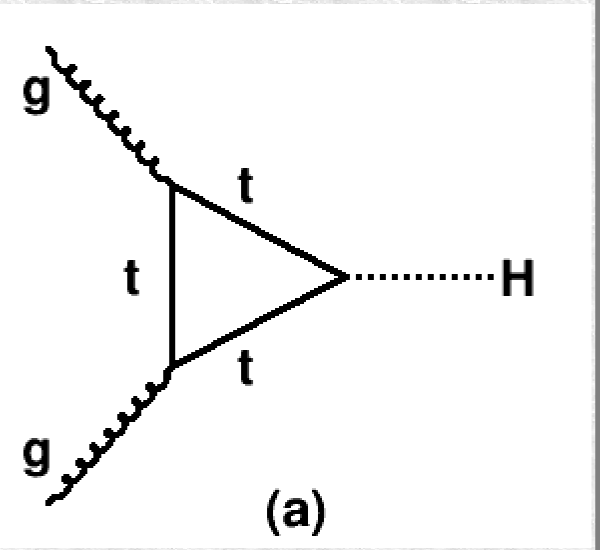


- CMS do have VBF H→bb: μ=1.3±1.1
  - Sensitivity much below VH – but from 2.3fb^{-1} only
  - Much improved c/f run 1 versio

ttH

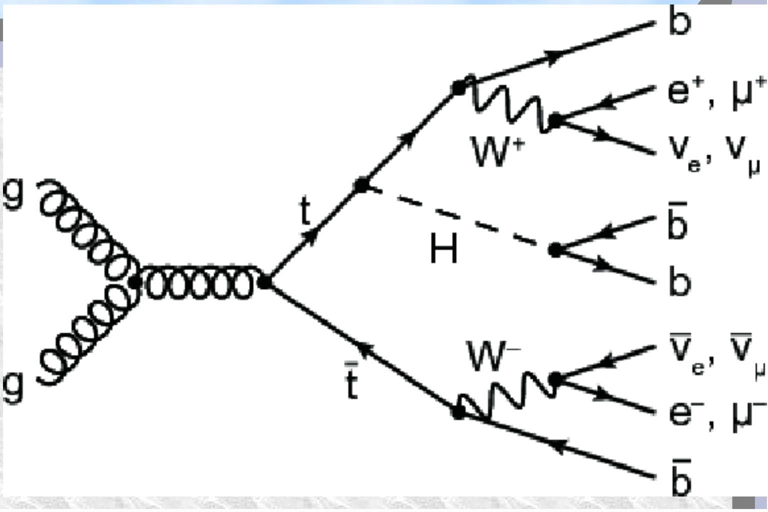
- ttH not directly observed in Run 1
  - Though t presence in ggH loop was inferred
  - But could be affected by BSM particles
- But cross-section grows x3.9 with energy
  - And there was a small excess in rate
- So both experiments chasing it
  - ttH, H→bb
  - ttH ,H→WW, ττ, ZZ
  - ttH, H→γγ (already mentioned)

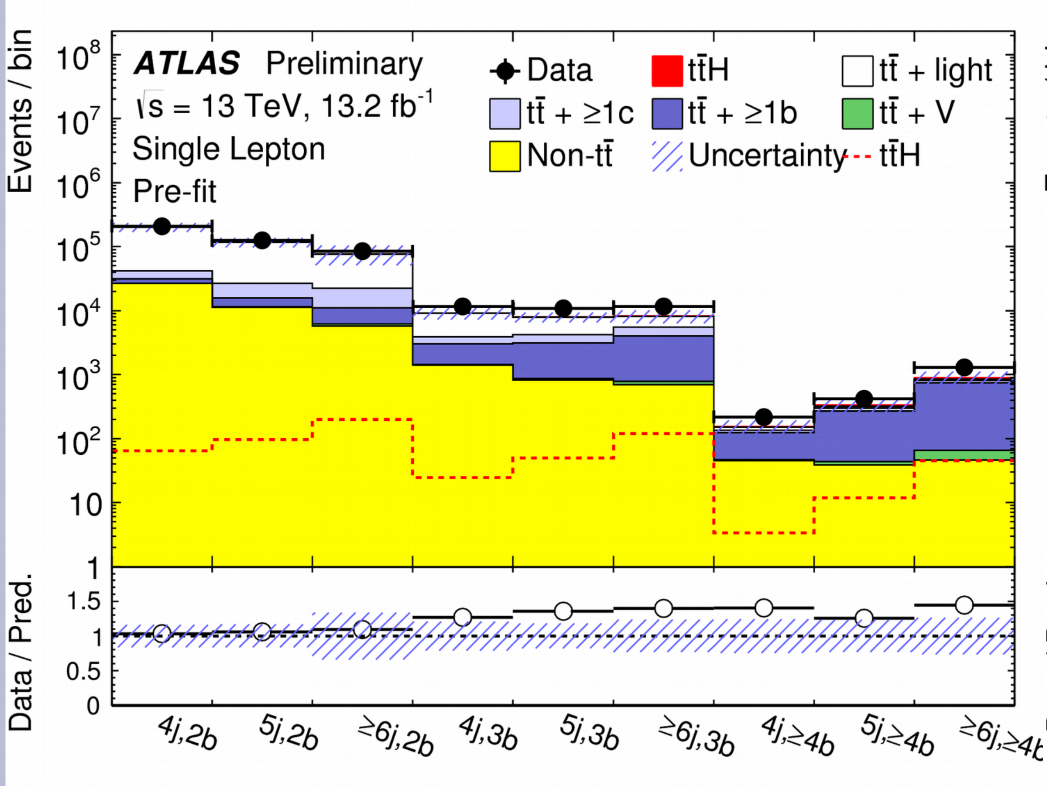


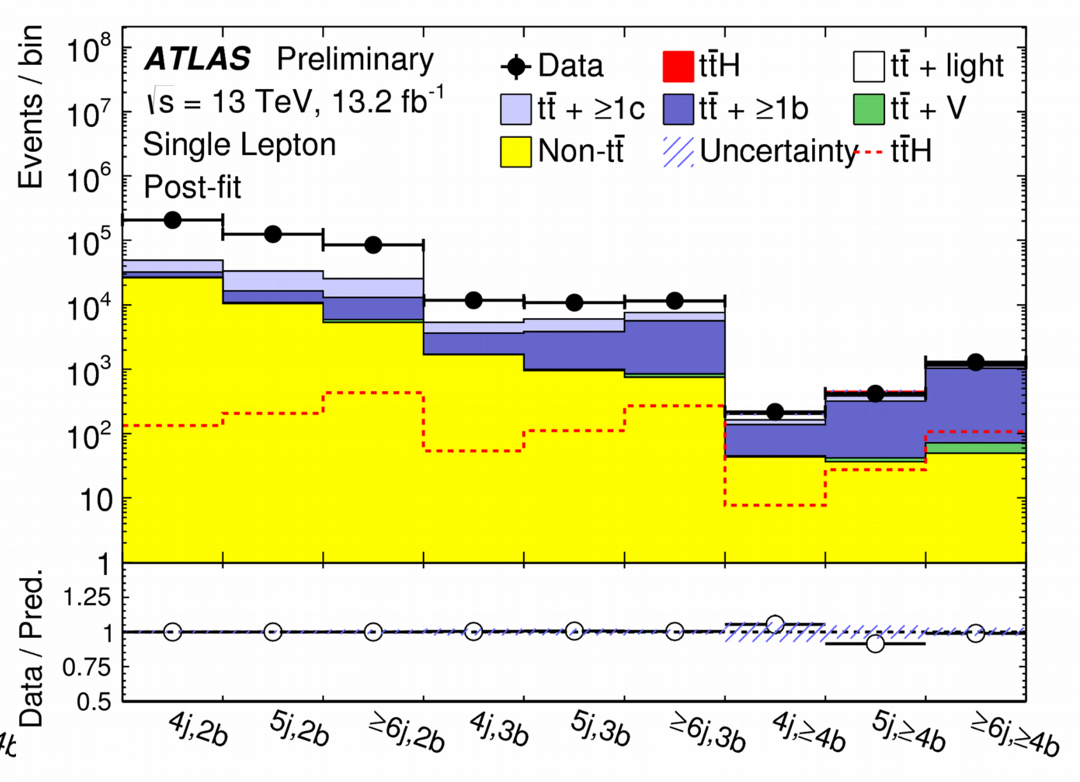


ttH, H → bb

- 8 fermion state with 4 b quarks
- ATLAS rates in bins of nos of jet and b-jets are below
- Model uncertainties fit to data



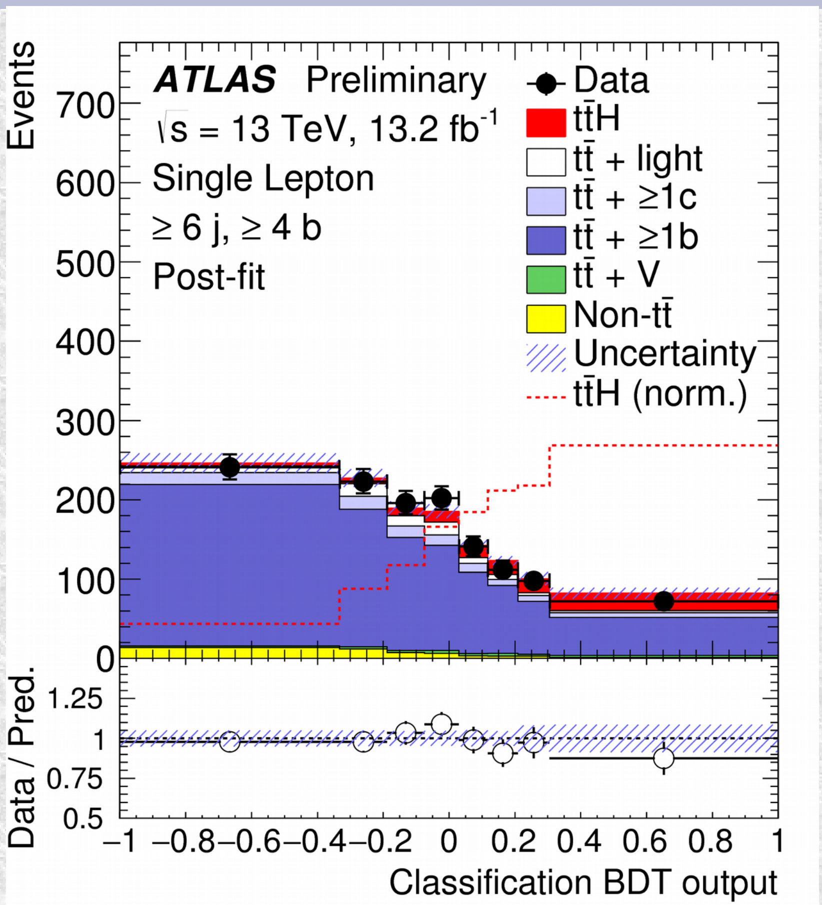


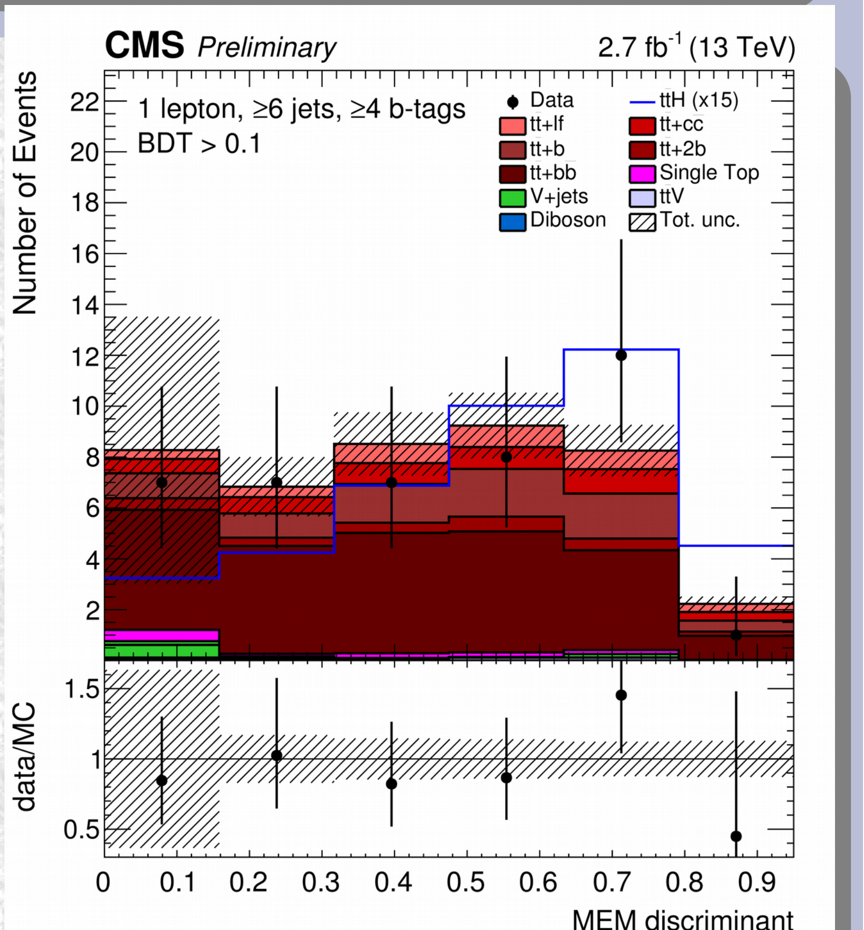


Top modelling

- Lots of work on modeling of top quark behaviour
  - Both theoretically and experimentally
  - Overall we have to be impressed at how good it is
- But with 40M top this year already it is challenging
- ATLAS ttH in 2016 showed about a factor 1.5 mismodelling of event numbers in 6j4b
  - C/f Powheg+Pythia 6 (For CMS MC agreed better)
- 890 expected (80% tt+≥1b), 1285 observed
  - C/f 45 signal expected!
  - Was a factor 2 in 2015 version...
  - ttbb and ttcc cross-section prediction were removed
    - Fitted from data: ttbb 1.33±0.18 (c/f 3% error on bin 6j4b)
    - While trusting NNLO calculations of shapes & uncertainties

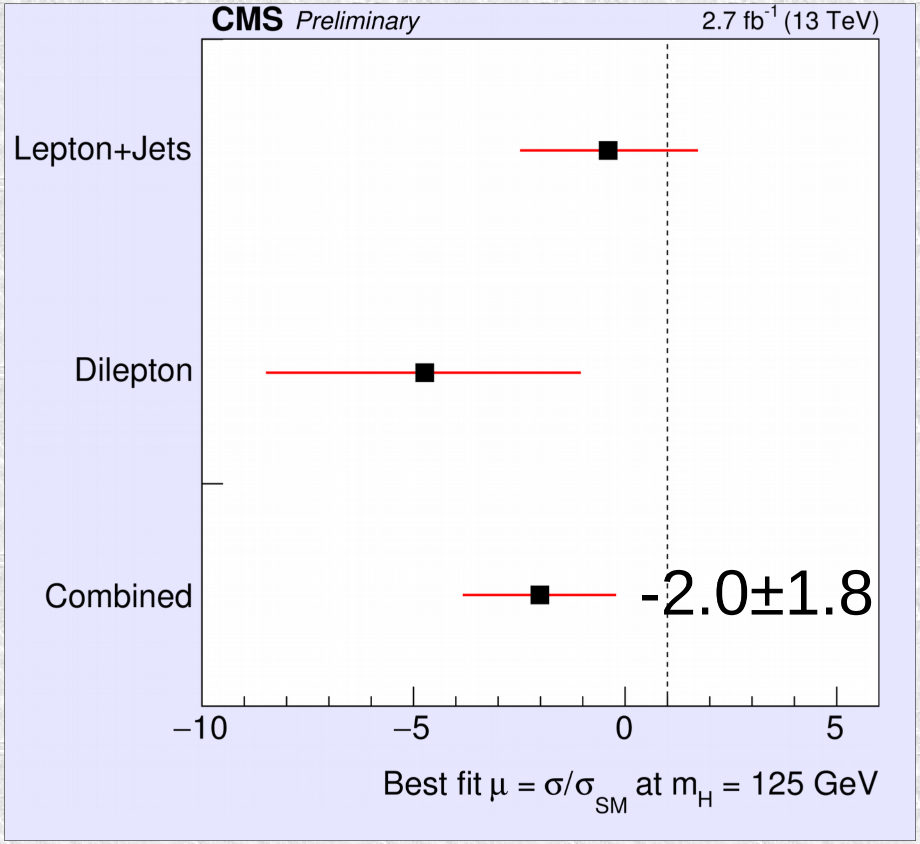
ttH, H → bb

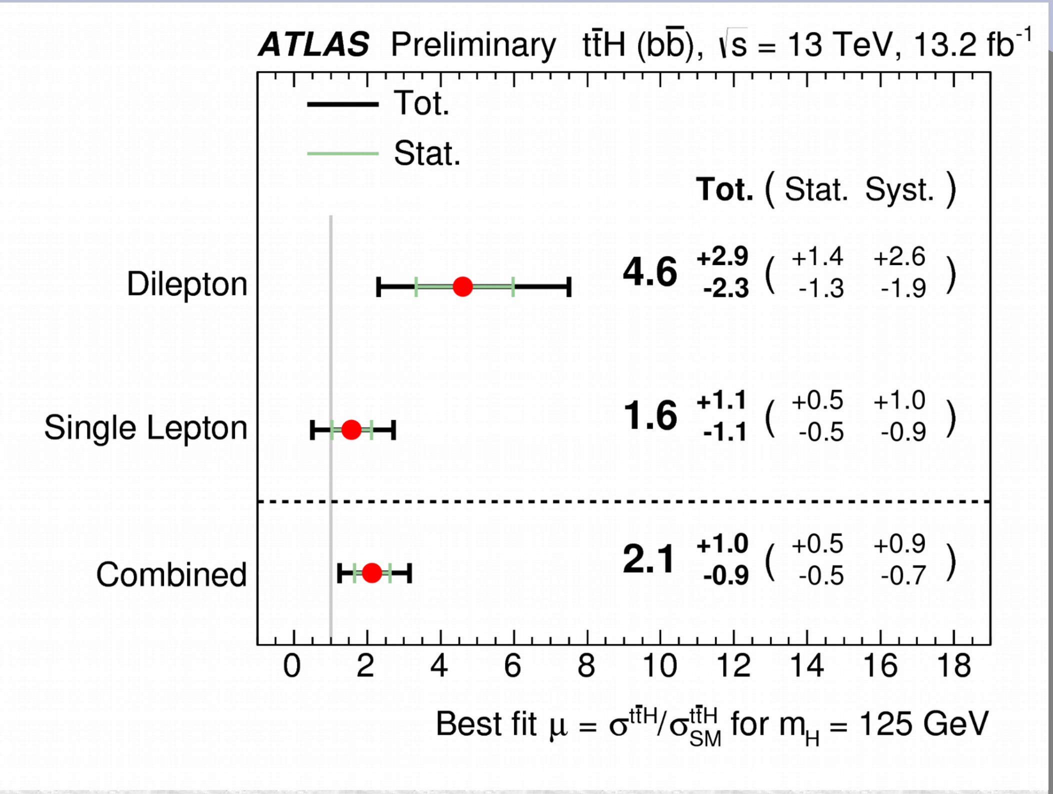




- Single lepton, 6j, 4b is most sensitive channel
- Complex analyses try to separate s from b
- Post fit results look OK, but modelling crucial

ttH, H → bb

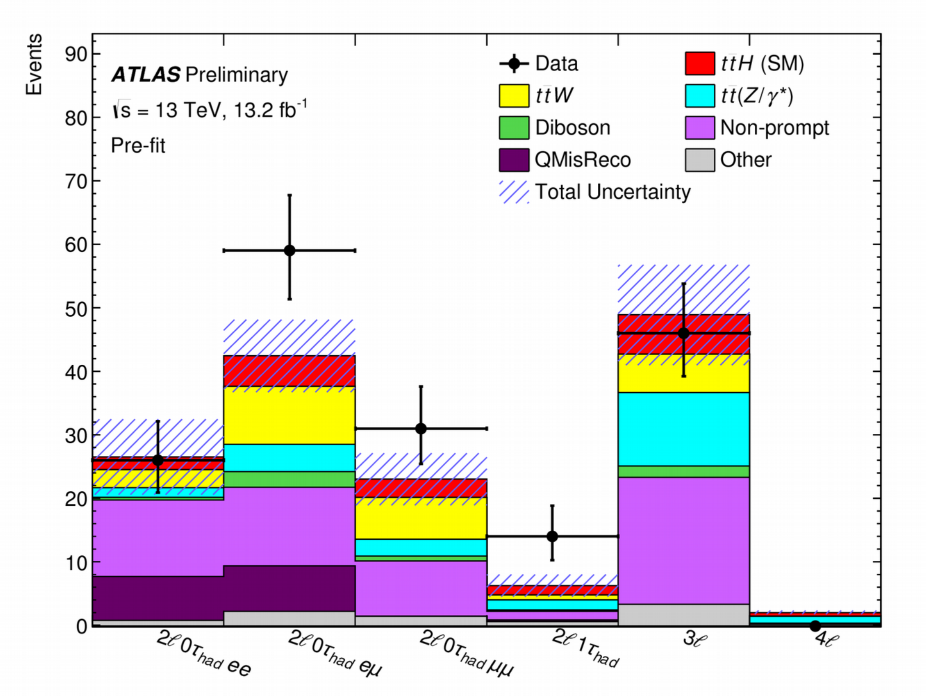


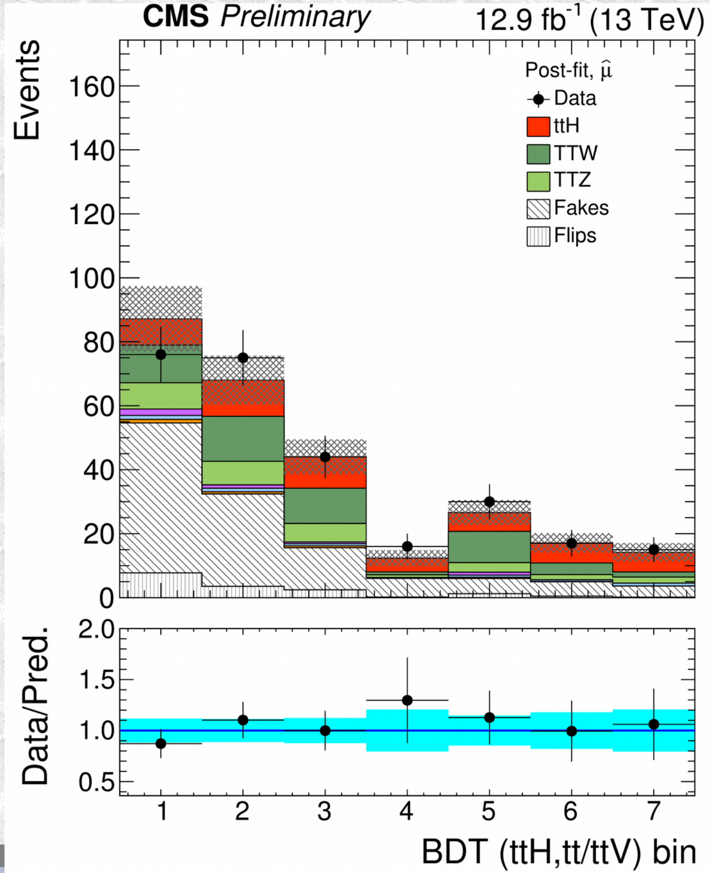


- CMS analysis is 2015 only:
- ATLAS systematic nearly double statistical
  - With 40fb^{-1} this will need great care

ttH, H → leptons

- Various signatures, all including b jets.
  - 3 leptons
  - same-sign leptons – shown below
  - Other (tau+l(l), llll are weaker)
- ATLAS count, CMS fit

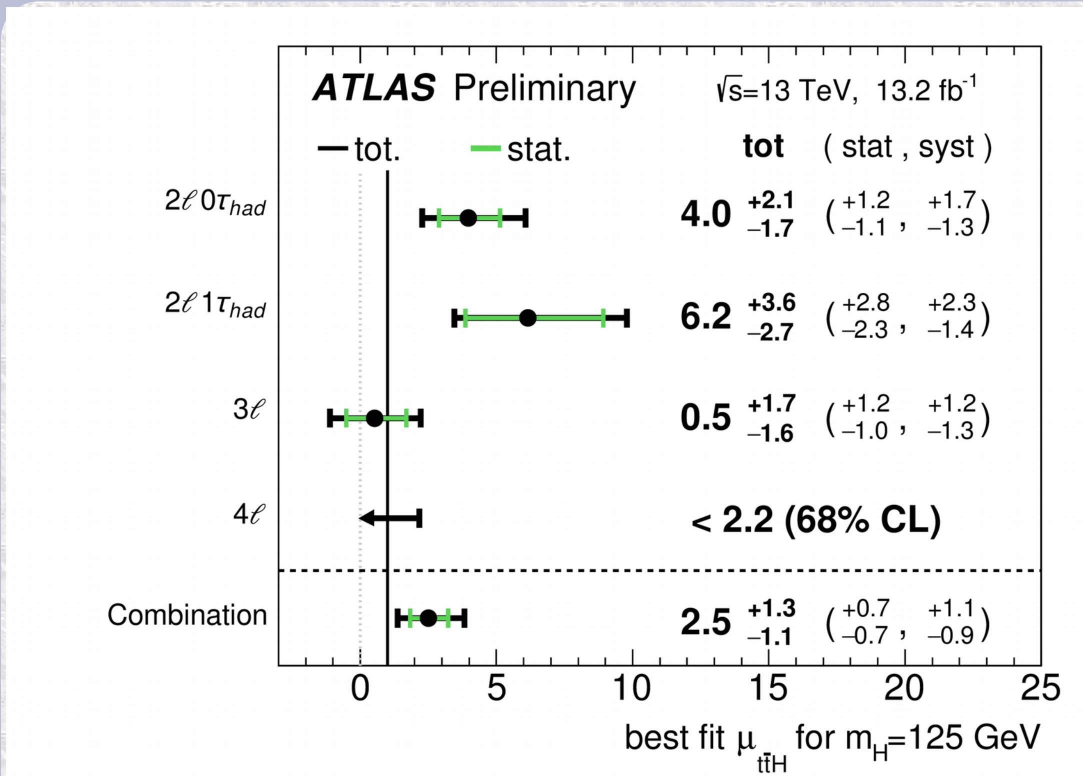


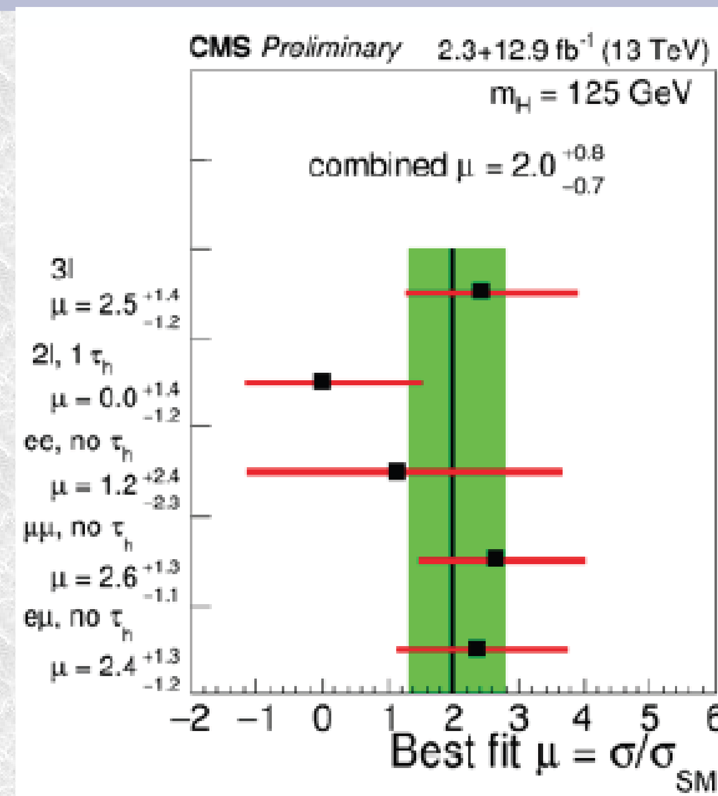


Fake lepton rates

- Compare ATLAS and CMS ttH multilepton search
  - Using SS dilepton as example
  - CMS has lower lepton thresholds (10,25) c/f ATLAS (25,25)
  - CMS has lower jet thresholds 4 c/f ATLAS 5
  - CMS dedicated isolation BDT trained for ttH
- Result is CMS has double sig and background
  - Though s/b slightly better in ATLAS
- Each find fake leptons are 50% of background
  - Double the signal size
  - Predicted to <35 or 30-50%
    - Adjacent regions or inclusive jets
    - Constrained factor 2 in CMS fit

ttH, H → leptons results

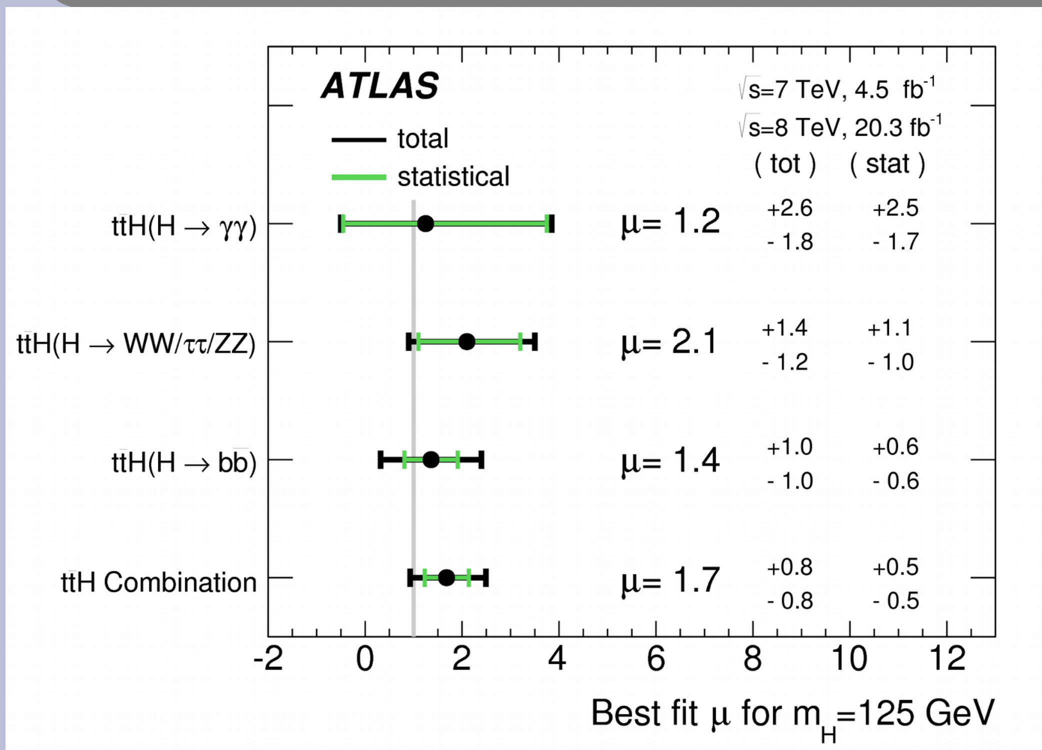


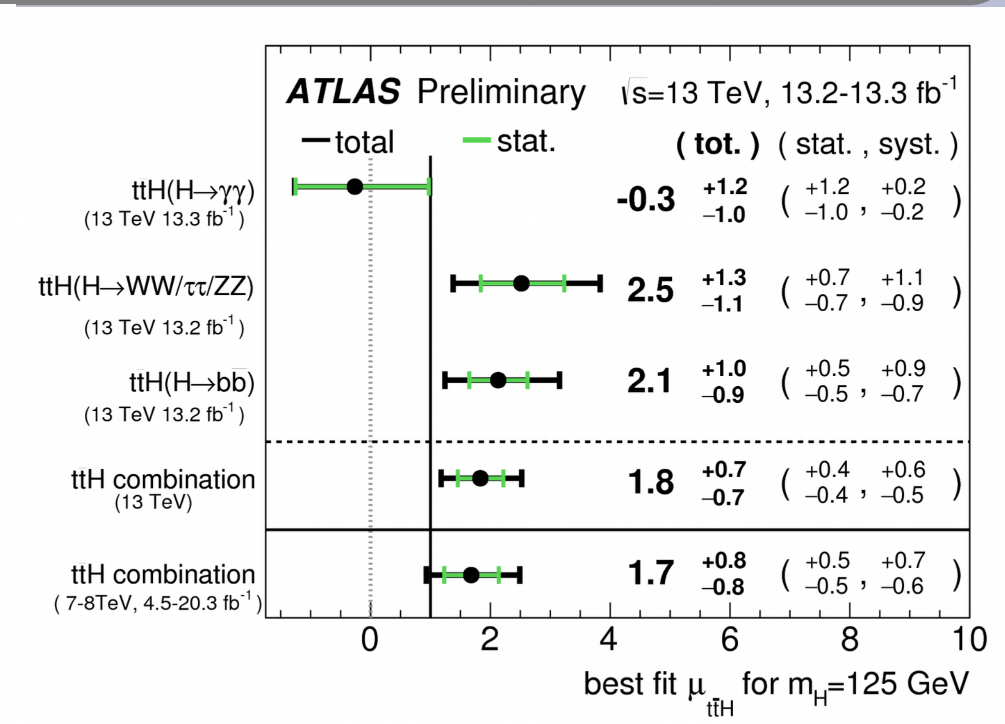


- ATLAS and CMS both see excess
  - Similar to 8 TeV
- Are fake leptons reliable?

ttH → lept	ATLAS	CMS
8 TeV	2.1±1.3	4.1±1.5
13 TeV	2.5±1.2	2.0±0.8

Comparisons of modes: 8 v 13

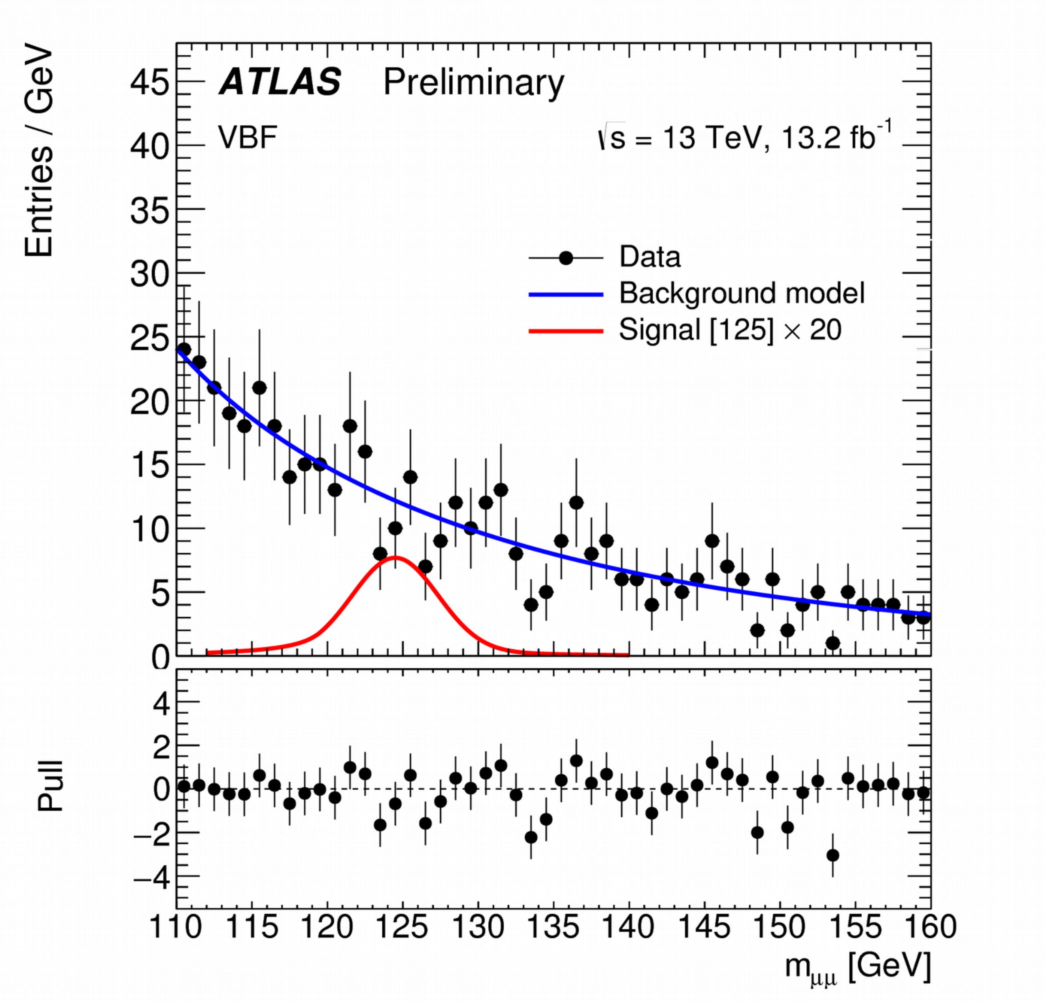




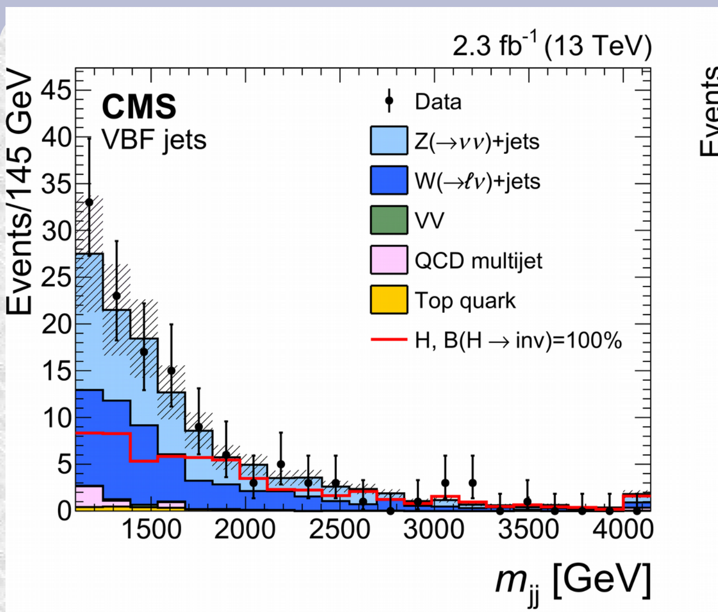
- Th multilepton and bb modes have similar errors
- While γγ improved a factor 2 on a smaller dataset
- The combination is identical!

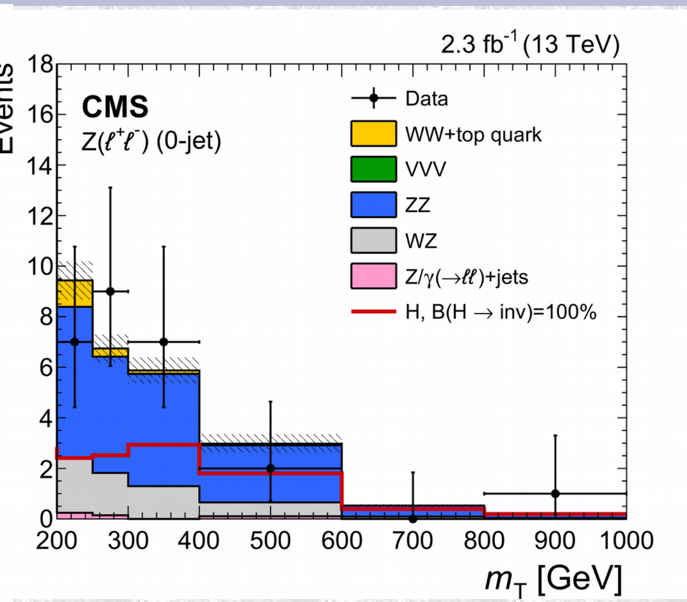
H → μμ

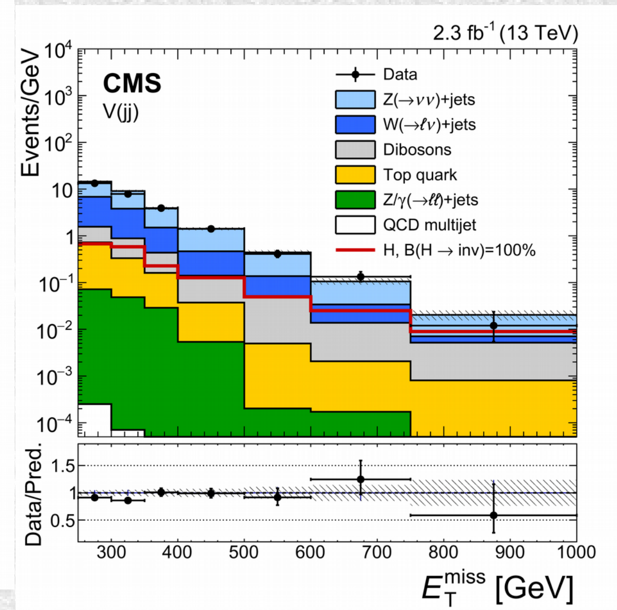
- Most promising second-generation fermion
  - Genuine sensitivity to SM by end of Run 2?
- Rate H → γγ / 10
- Use Higgs production:
  - ggF in high pt/low pt and barrel/central
  - VBF - Plot right
- μ=-2.3±2.7
  - With 2012: μ=-1.5±2.3
- No hint yet...

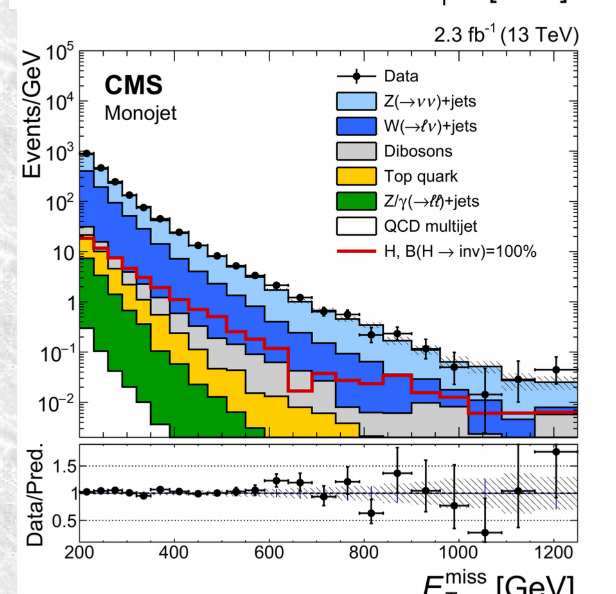


Invisible Higgs decay





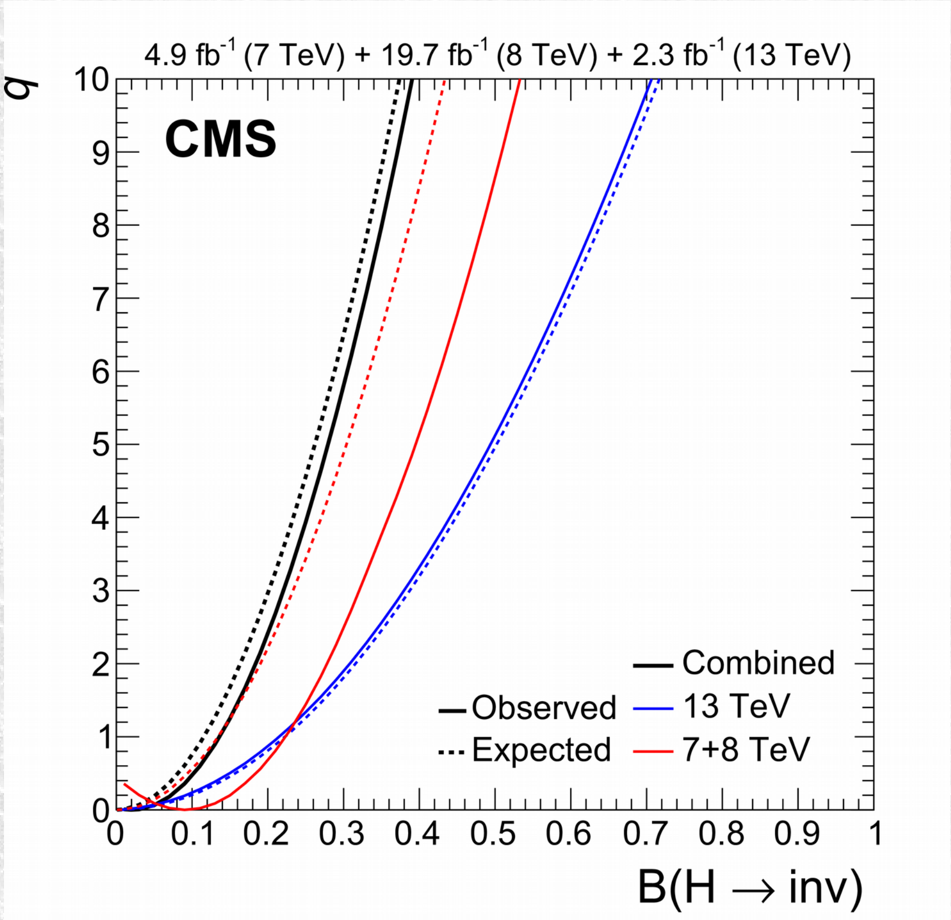




- Nice CMS paper on invisible higgs
- VBF, $Z \rightarrow ll$, $V \rightarrow qq$, ggH
- No sign of signal
- UL on Br of 24% (23% expected)

Invisible Higgs decay

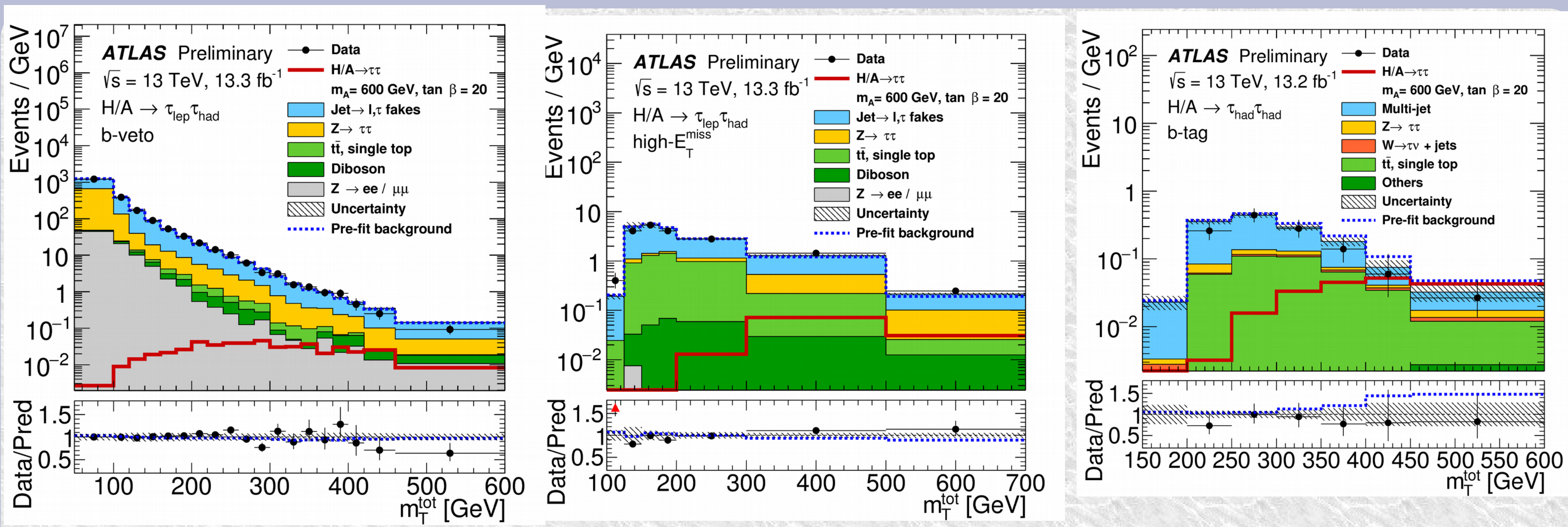
- 8 TeV result still dominates sensitivity
- But 13 TeV somehow shifts observed close to expected
- UL on Br of 24% (23% expected)



More exotic Higgs

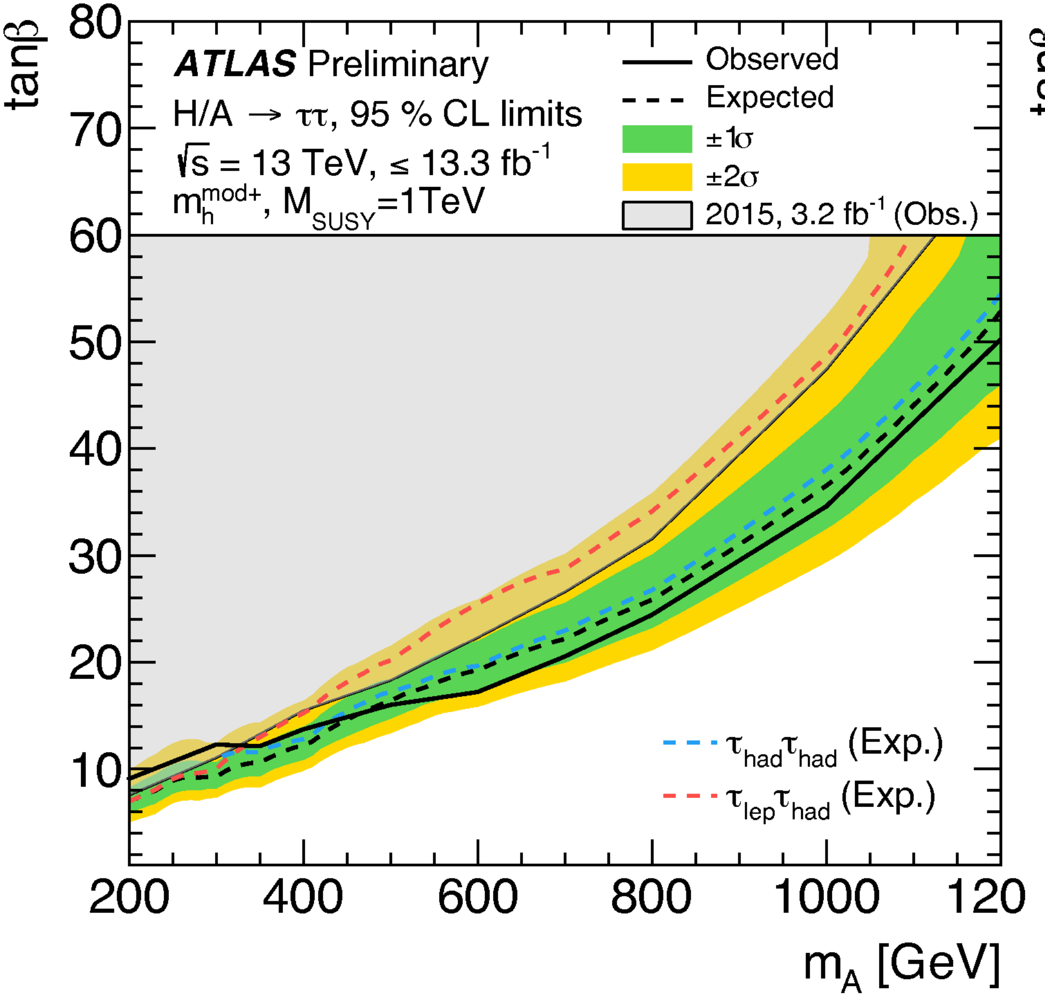
- Rare decays
- Heavy Higgs
  - WW, ZZ, bb, γγ
- Others
  - tH → bb
- Charged Higgs
  - τν, WZ
- H/A → ττ
- Higgs pair production
  - bbττ, bbWW

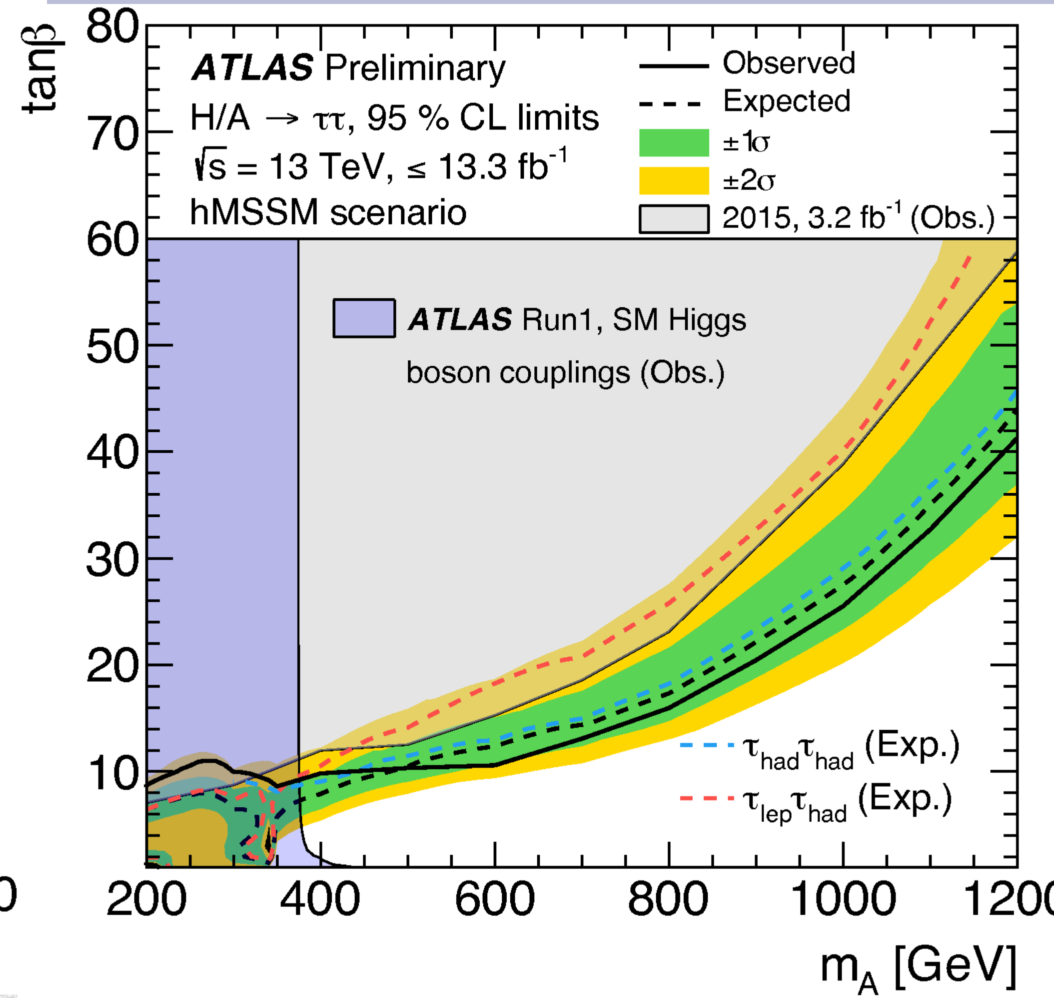
H/A → ττ



- ATLAS analysis focused on high mass
- lh and hh channels only
  - New high-MET channel (centre)
- No serious excess observed

H/A → ττ MSSM exclusions



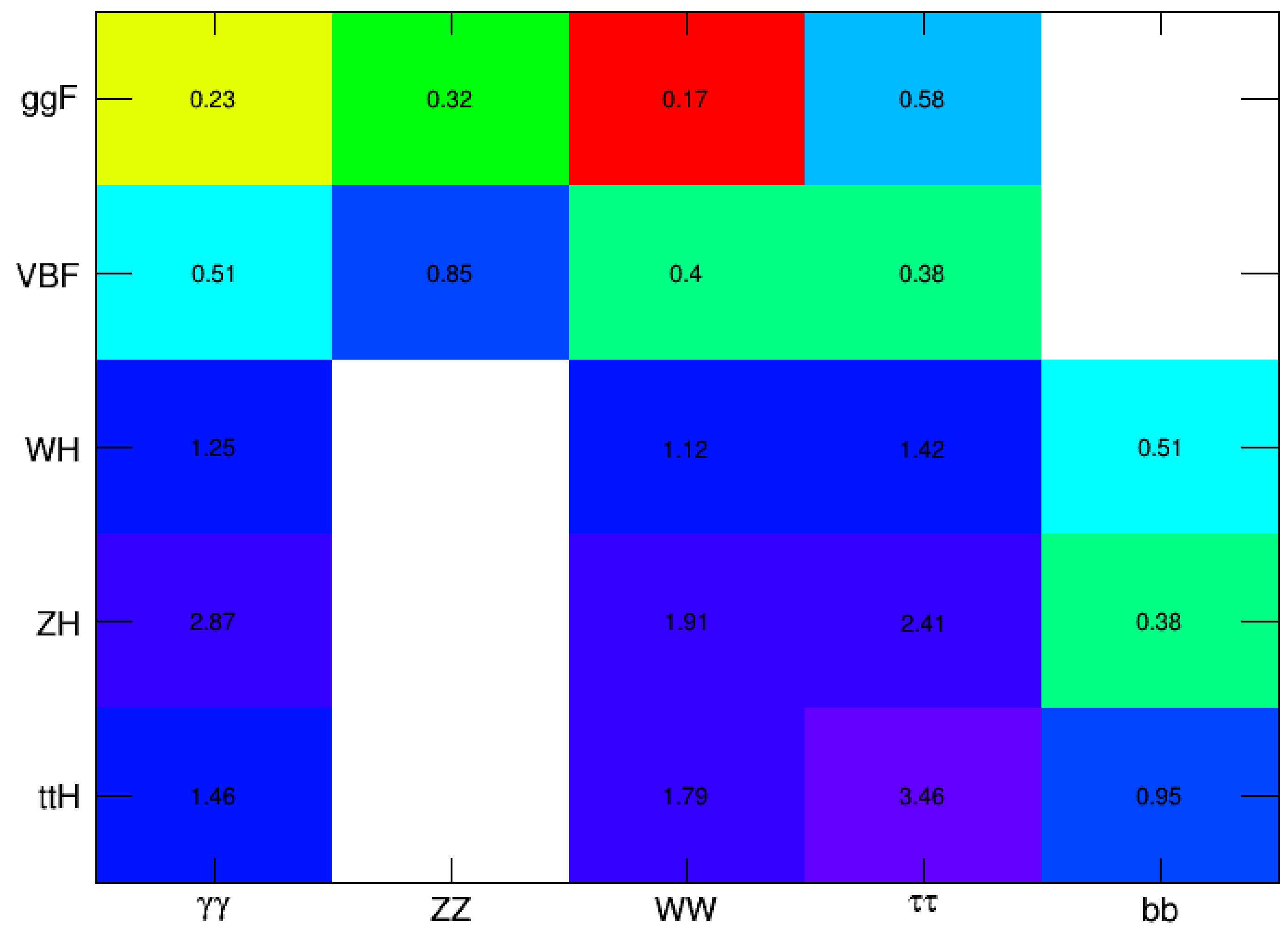


- Benchmark models differ
  - hMSSM stats to show sensitivity up to $2m_t$ for all tanβ

What comes next?

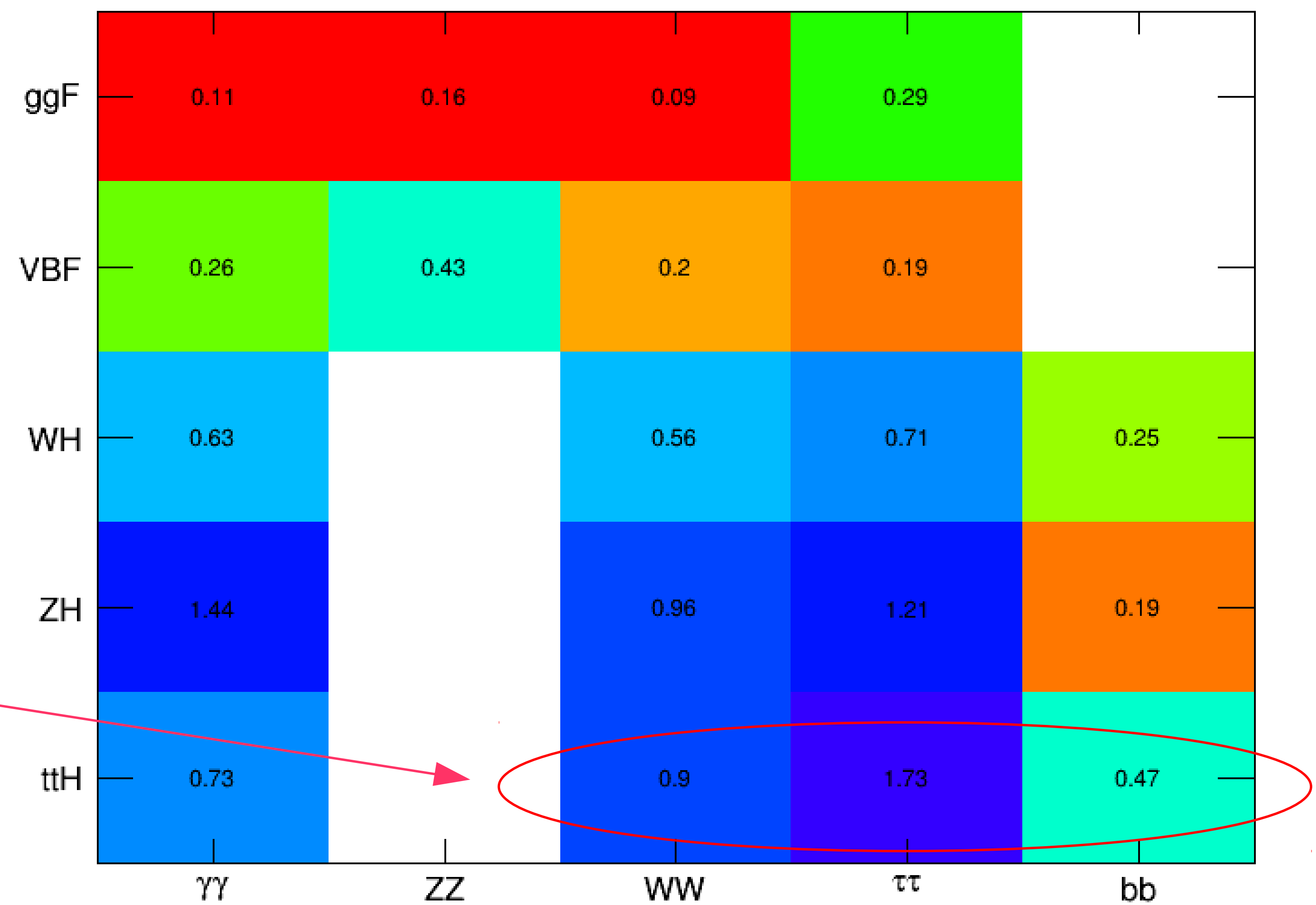
Sensitivity

- Measured error over expected signal rate
- Cyan or brighter has error below 50%



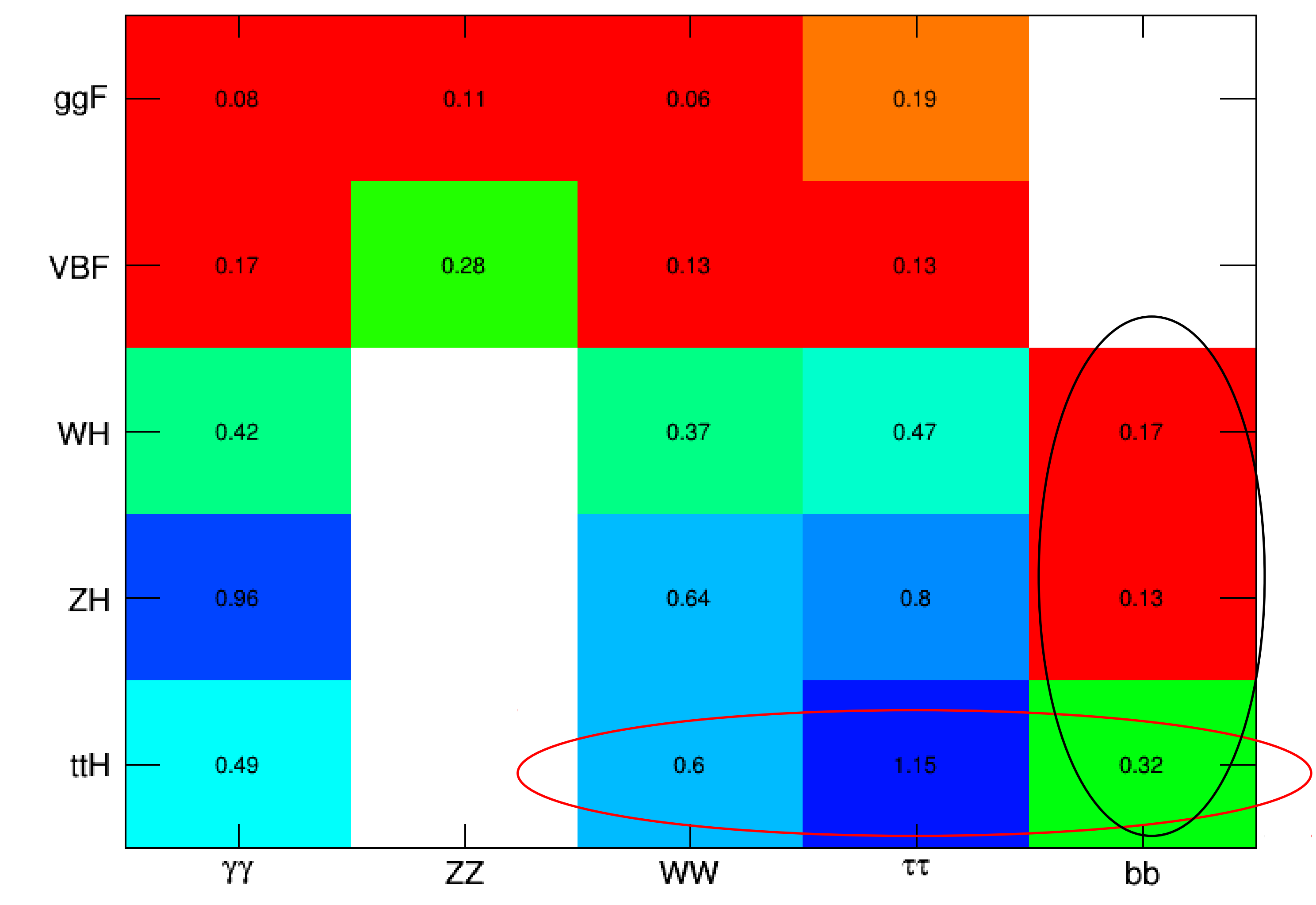
Sensitivity scaled 2

- 25fb-1 8TeV
- Plus 39 fb-1 at 13 TeV
- Quadruple the signal yield
- Assume errors half!
- Improve:
  - bb ??
  - ttH γγ



Sensitivity scaled 3

- Run 2 optimistic hope:
- ggF and VBF well measured
- Real sensitivity in many cross-modes too

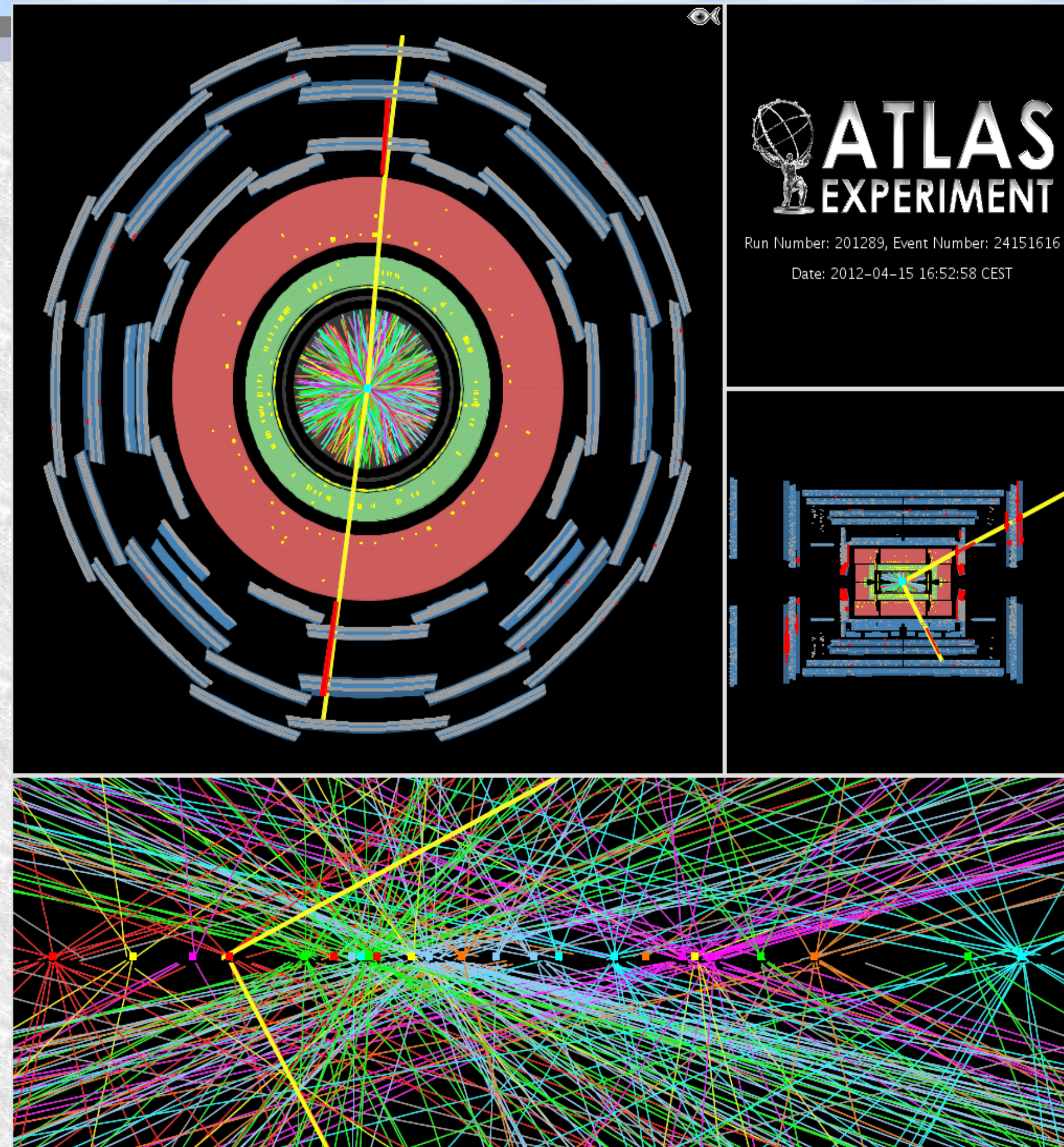


The incomplete theory:

- Mass (pre-LHC problem!)
  - Without Higgs particles are massless
- Gravity
  - There is no gravity in this model
- Neutrino Mass
  - Neutrinos have mass – but how? We do not know
- Dark matter
  - Most matter in the Universe is something unknown
- Dark energy
  - An unknown force accelerates the Universe expansion
- Matter-antimatter asymetry
  - Where did the antimatter go after the big bang?
- The naturalness problem
  - I will explain this later

Here is an event with 2 muons

- Most particles are stopped at the green calorimeter
- The two muons get right to the outside
  - Muons are very penetrating
  - They are heavy copies of electrons
- They both come from the same collision
  - Are they connected?

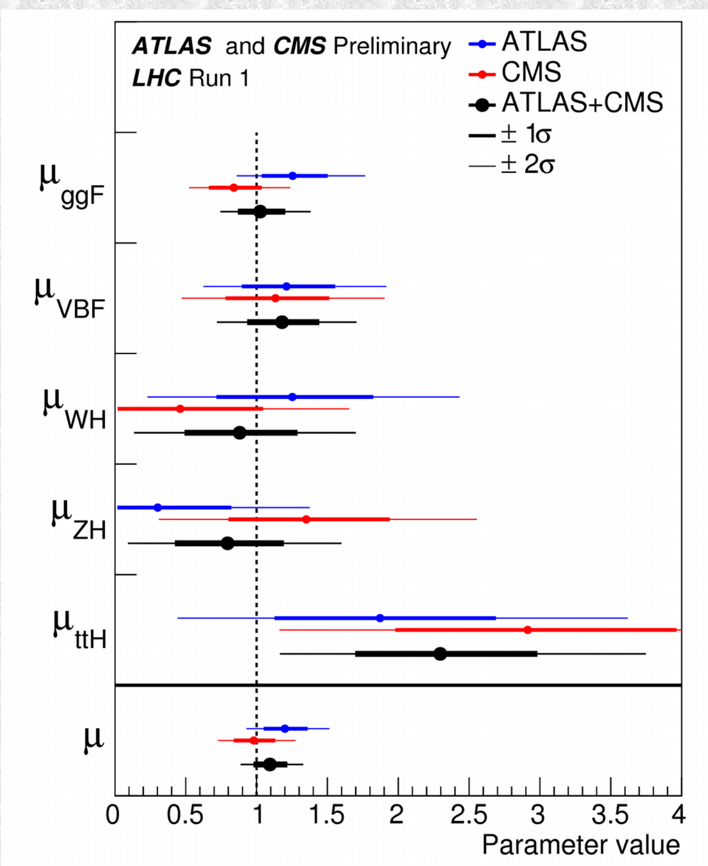


The end?

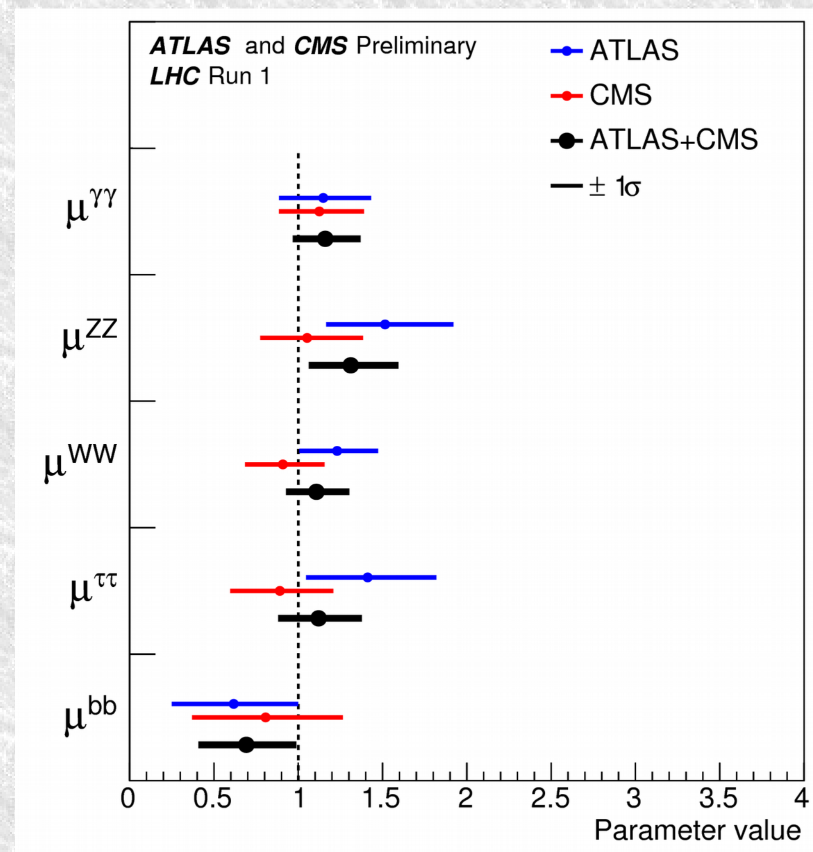
- Yes, we found a new particle…
- But why do we identify it with the Higgs boson?
  - And maybe the SM Higgs?

What have we learnt?

- LHC run 1 found proof of
  - 4 decay modes (ZZ,γγ,WW and ττ)
  - 2 production mechanisms (ggH,VBF)

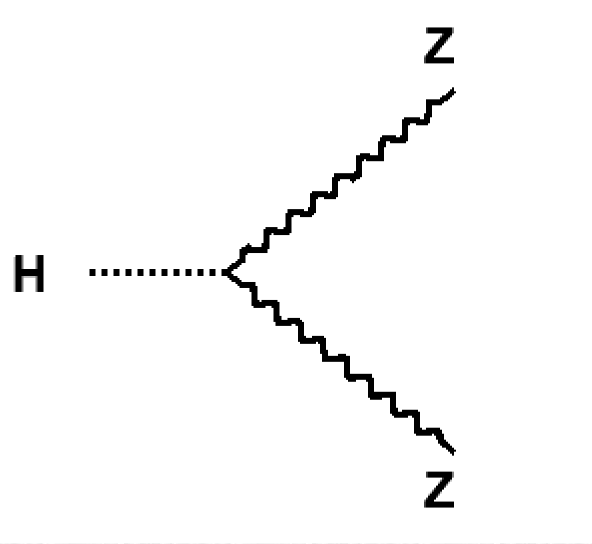


- Rates match SM pred
- All predicted modes seen
- Looks good



H to ZZ and H to γγ

- The measured H→ZZ rate is about 10xH→γγ
  - After allowing for Z→ll Br
  - But the Z is massive, so harder to make
  - So HZZ must be a powerful interaction
- We know the Z interacts with weak charge
  - Just like the photon does with EM charge
- HZZ strength shows the H must be weak charged
  - But Z is neutral (Charge and weak charge)
  - So in H→ZZ where does the charge go?



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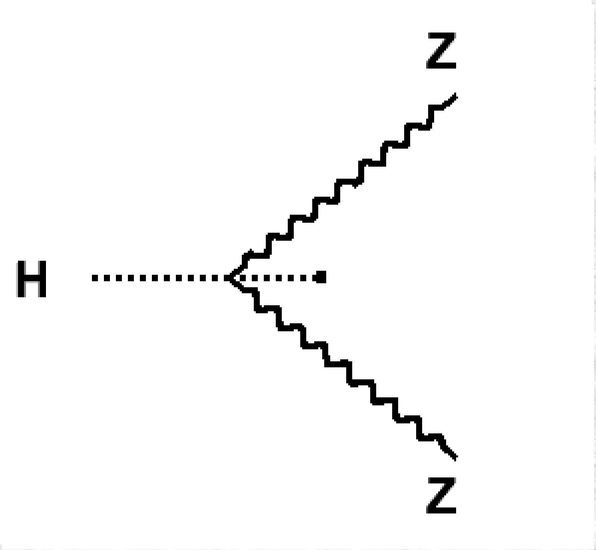
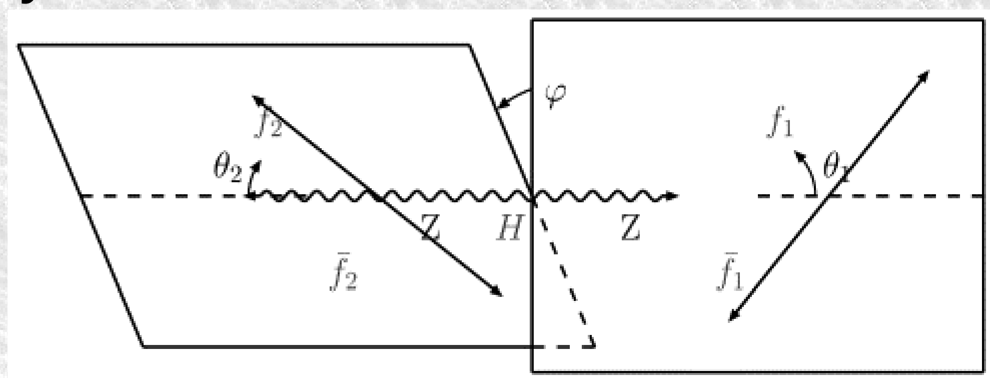
  - So in H→ZZ where does the charge go?
- It is really a 4-point coupling
  - One leg 'grounded' in the vacuum
- The ZZ decay needs vacuum help
  - Absorbing a (weak) charge!
- This is evidence the BEH field exists



H spin

- Higgs is predicted to be scalar boson: zpin 0, parity symmteric
- Study the spin of a particle through angular correlations
  - A spinless particle has no prefered direction
  - A spinning paticle can spin about an axis
- Also conservation of angular momentum means the spins of the daughters add up (vectorially) to the parent
  - So if daughters (WW, ZZ) decay there are correlations in this
- Spin analysis done by comparing models



- See which models fit data best.
- Spin/parity 0^+ always best fit
- 0^- is exclude >99% CL
- 1^+ and 1^- are also strongly excluded
- MANY (~20) spin 2 models tried – all excluded
  - But actually no complete proof it is not spin 2.
- General acceptance that this is a spin 0 object

OK, so what?

- Well...lots
  - Does it interact with matter, or only forces?
  - Is it *a* Higgs
  - Is it *the* Higgs
  - Does it interact with mass?
  - Does it explain the matter/anti-matter asymmetry?
  - Does it interact with Dark Matter?
- But I stick to two questions:
  - The Brout-Englert-Higgs field
  - Naturalness

What about the Higgs field?

- The Higgs mechanism needs the field filling space
- This is neither matter nor particle: something new
- Actually reminiscent of the 'luminoferous ether'
  - But a fully relativistic version
  - Unlike light, you turn it off and it is still there
  - ~2 Higgs bosons / fm^3
- The density of the field is cosmologically ridiculous
  - It is 120 orders of magnitude larger than dark energy
  - Remember: we don't have a quantum theory of gravity
- So do we really expect you to believe its there?
  - Well, there was the $H \rightarrow ZZ$ decay...

Measure Higgs self-interaction?

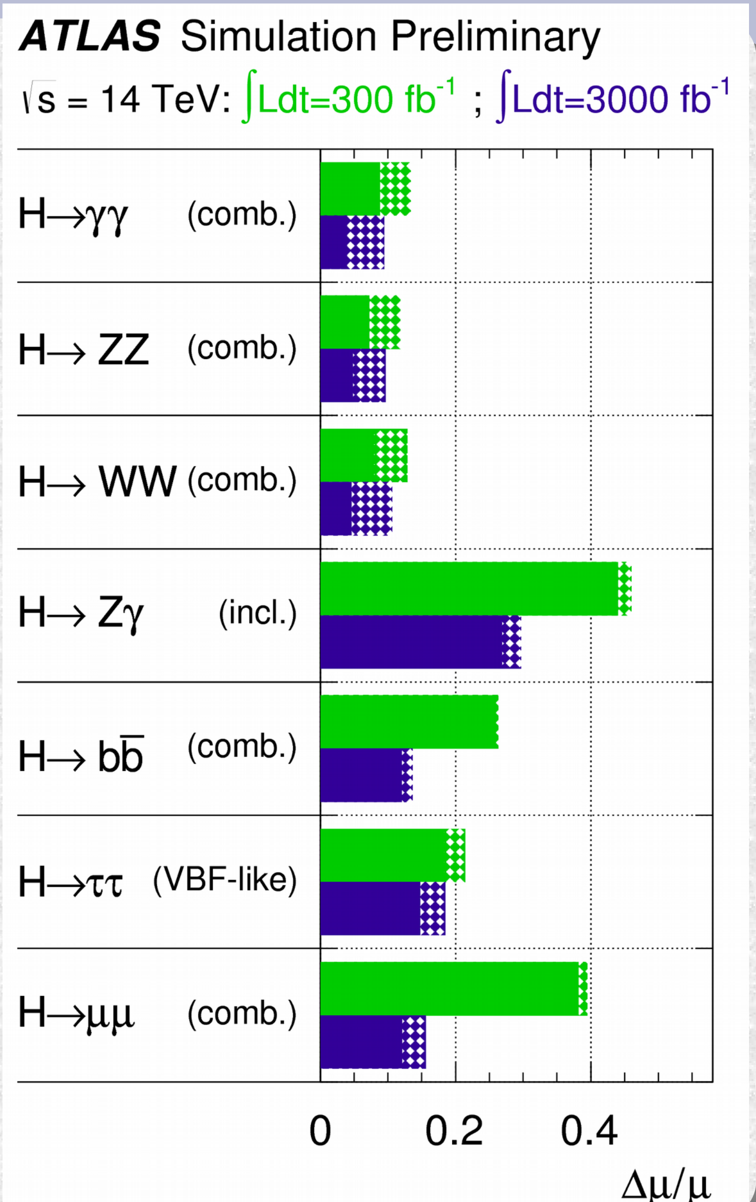
- Need to produce 2 Higgs bosons
  - The LHC is the only machine on earth with a chance
- They are much rarer than making one Higgs
  - And we still need to recognise them
- The best Higgs modes: γγ and ZZ→llll have BR of 0.002 and 0.0002 respectively
  - If we want HH→(γγ)(γγ) we can make one by 2035!!
    - Not enough to measure
  - So we need to try to use more abundant modes
  - e.g. HH→ γγbb has 300 expected events
    - Tough due to backgrounds, but maybe
- This is one of the major goals for the LHC by 2035
  - We do need to study this new aspect of the Universe

HL-LHC

- There are many physics motivations for HL-LHC
- Three seem to dominate to me
  - Extended searches for new particles to higher energies
  - Extended searches for new particles produced more rarely
  - Accurate precision measurements
    - Exemplified by Higgs couplings

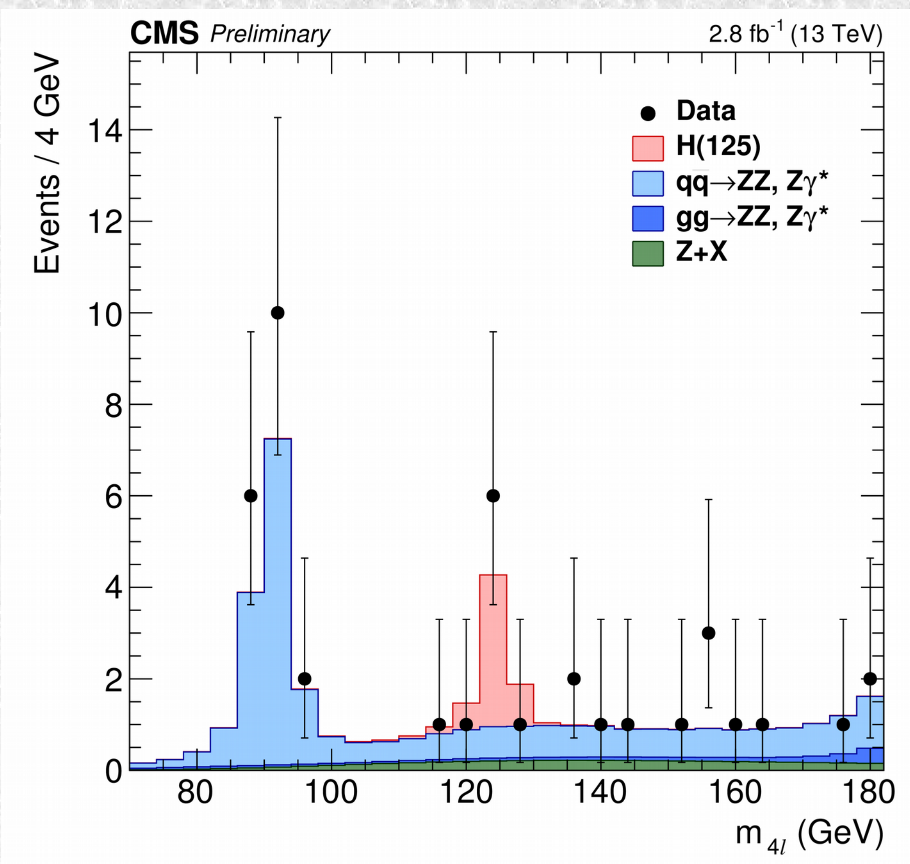
HL-LHC Higgs couplings

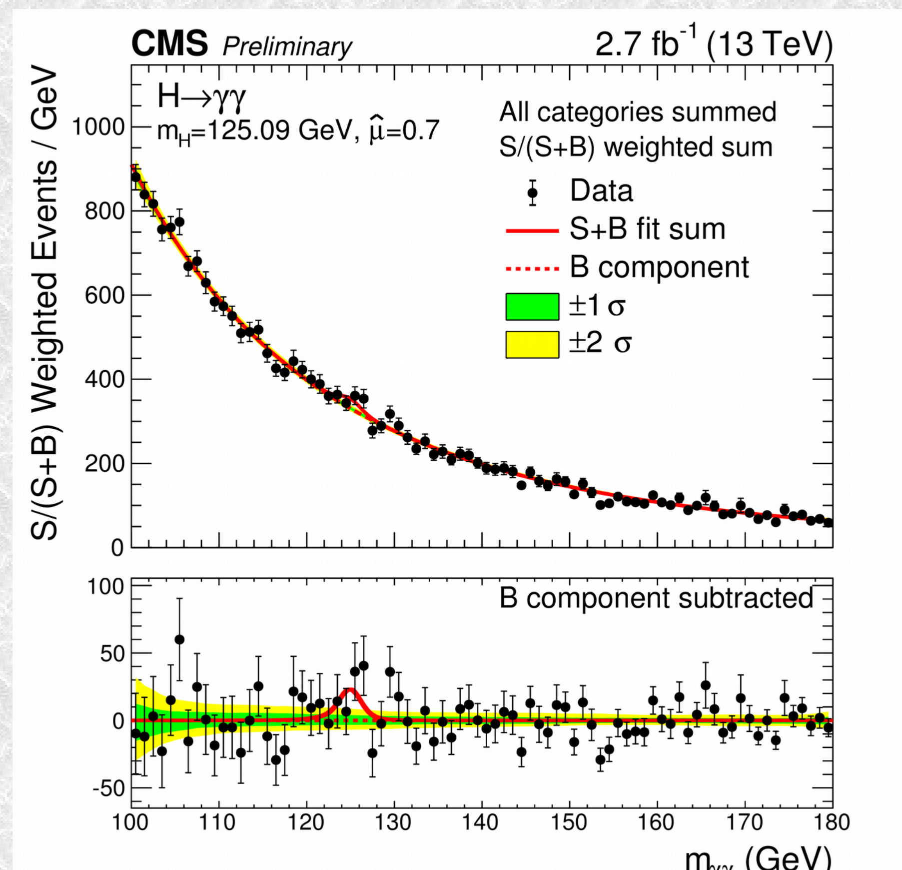
- The projected precision with which Higgs boson couplings can be measured by ATLAS with 300 or 3000 fb^{-1}
- The solid bars excluded theory errors – hashed included them
  - Hard to predict their size
- But 7 decays can be studied to 10-30%, and productions too
  - Sensitive to new physics



What do we see at 13 TeV?

- Public results only from O(3fb^{-1}) from 2015
- Higgs is still there...just
  - Here CMS examples; ATLAS similar





What comes next?

- We have found a Higgs boson
- This confirms a 'Higgs Field' filling spac
  - Unlike light, you turn it off and it persists
  - But it is much denser than lead...
- This is not like matter, not like a force
    - Breaking Newton’s 1730, description
  - It is a Higgs field, something new.
- Now we need to understand it
- LHC is working excellently
  - At 13TeV and higher collision rate
  - We will measure at least 7 decay modes
  - And perhaps di-Higgs production.
  - Great hopes of finding something else too
    - Maybe the γγ is it?

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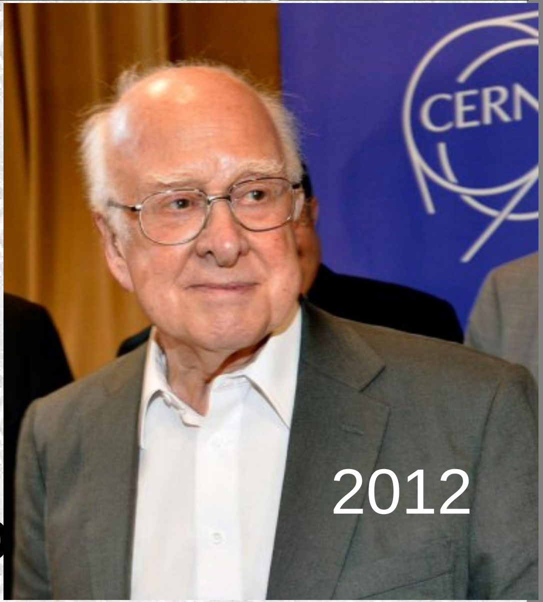
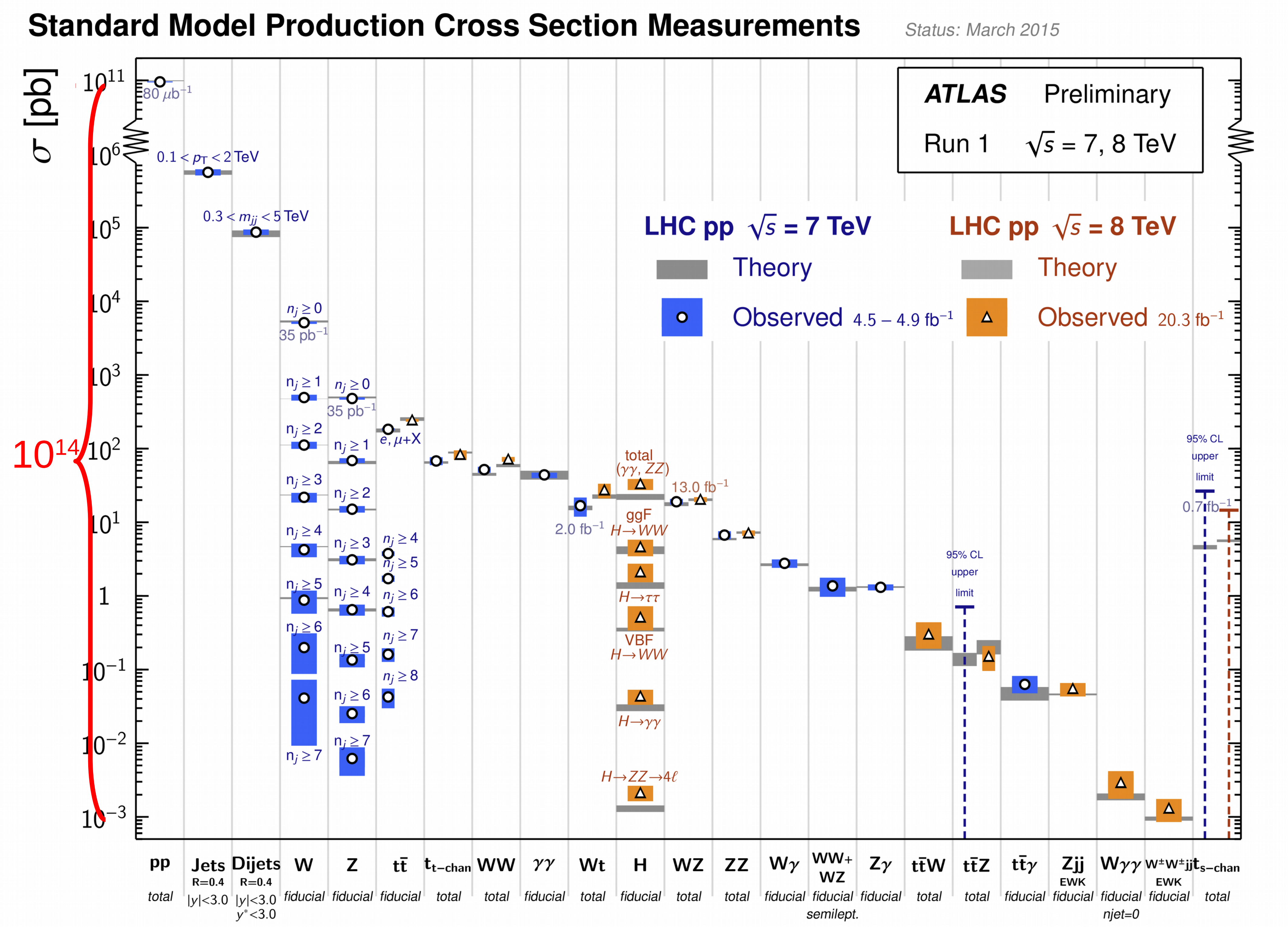


2012


Standard Model Production Cross Section Measurements
Status: March 2015
σ [pb]
10^14
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
Theory
Observed 4.5 – 4.9 fb−1
LHC pp √s = 8 TeV
Theory
Observed 20.3 fb−1
80 μb−1
0.1 < pT < 2 TeV
0.3 < mjj < 5 TeV
35 pb−1
e, μ+X
total (γγ, ZZ)
ggF H→WW
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
13.0 fb−1
2.0 fb−1
95% CL upper limit
0.7 fb−1
pp total
Jets R=0.4 |y|<3.0
Dijets R=0.4 |y|<3.0 y*<3.0
W fiducial
Z fiducial
tt̄ fiducial
tt−chan total
WW total
γγ fiducial
Wt total
H fiducial
WZ total
ZZ total
Wγ fiducial
WW+WZ fiducial semilept.
Zγ fiducial
tt̄W total
tt̄Z total
tt̄γ fiducial
Zjj EWK fiducial
Wγγ fiducial njet=0
W±W±jj EWK fiducial
ts−chan total