
Higgs Boson in the SM and Beyond
Vulcano Workshop 2014
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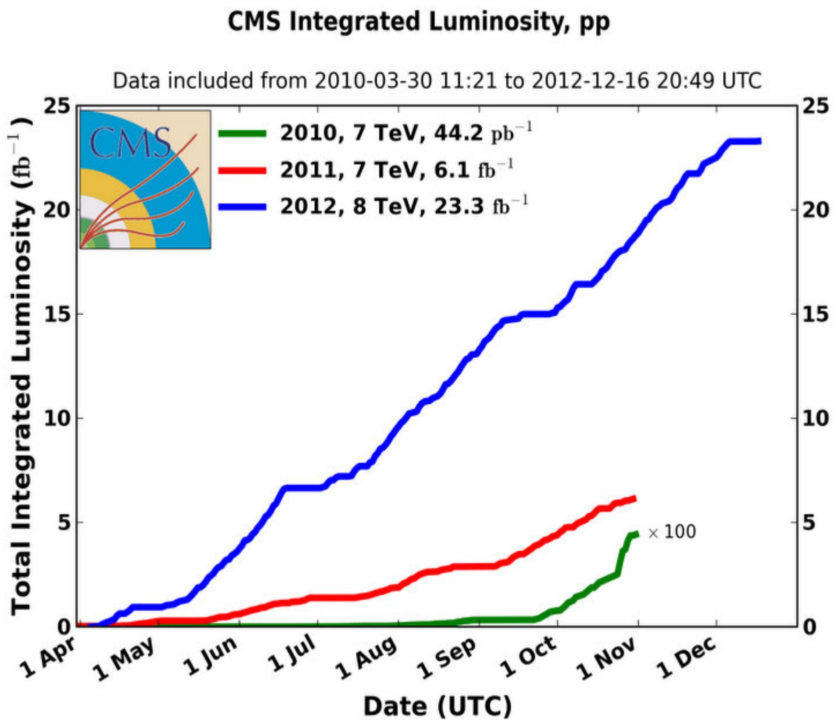
Cern

The LHC so far

An extraordinary combination of three simultaneous fantastic performances!

Data collection

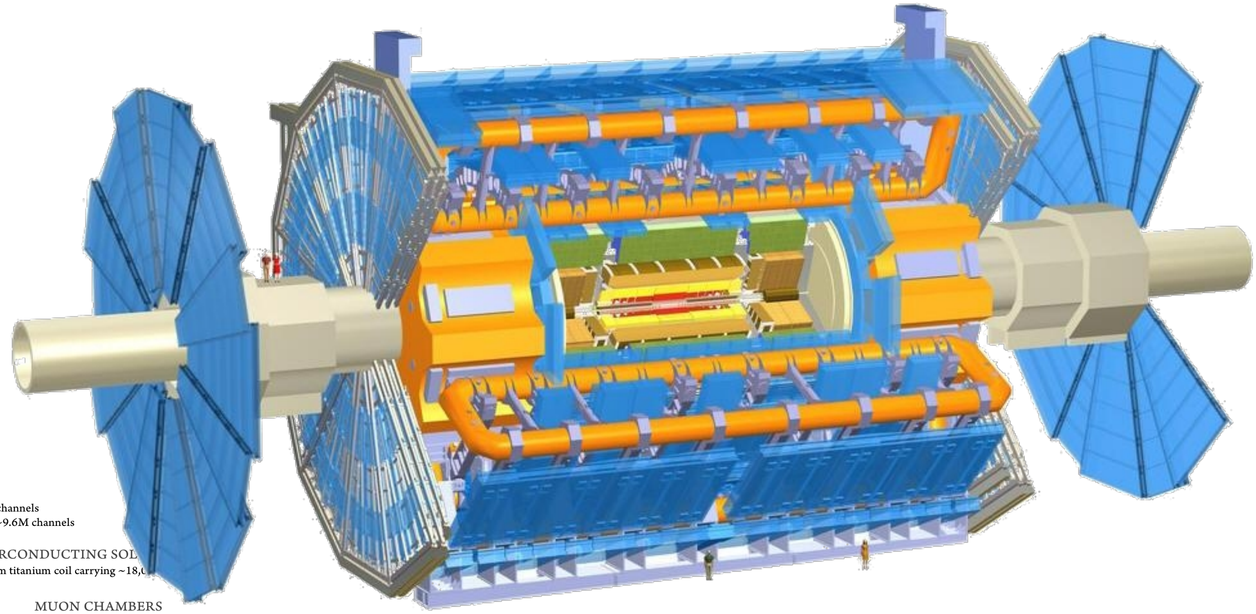
- LHC delivered $5fb^{-1}$ in 2011
  – Gave first hints for SM Higgs
- √s raised 7→8TeV in 2012
- $23.3fb^{-1}$ delivered
  – 6 fb^{-1} allowed Higgs discovery
  – Now tests of properties
- Great effort by LHC team!

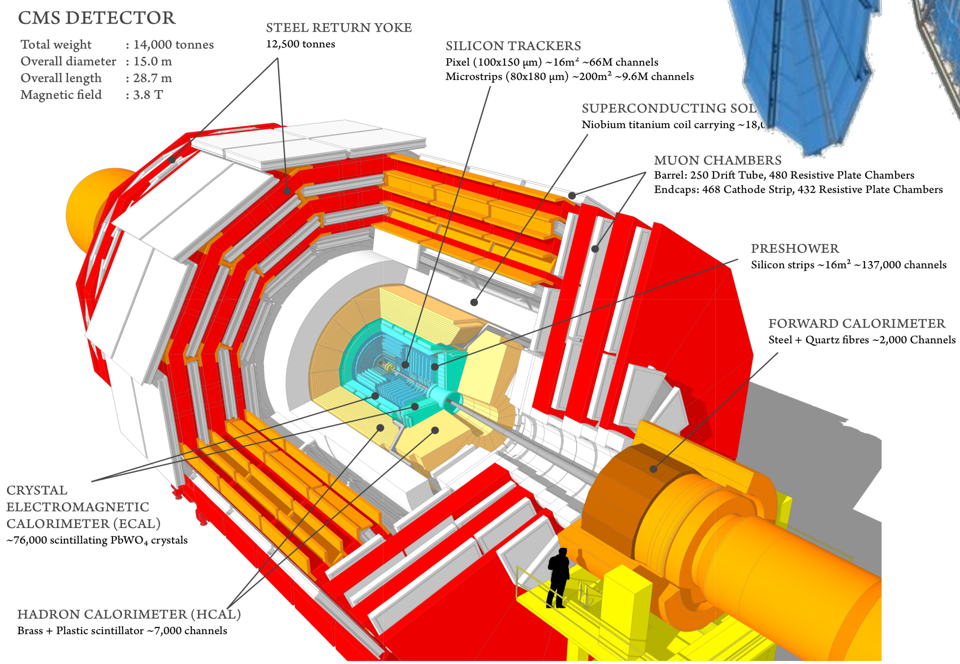


- ~90% of the delivered luminosity is used in analysis
  - Dedication from the systems experts and shift crews.

ATLAS & CMS

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



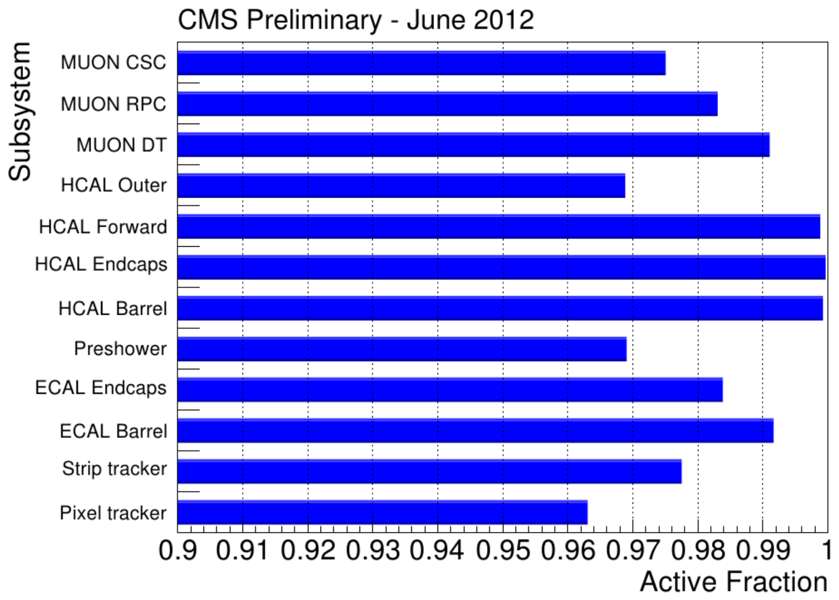


- ATLAS: External magnet provides toroidal muon field
- CMS superb central solenoid

Detectors and LHC operation

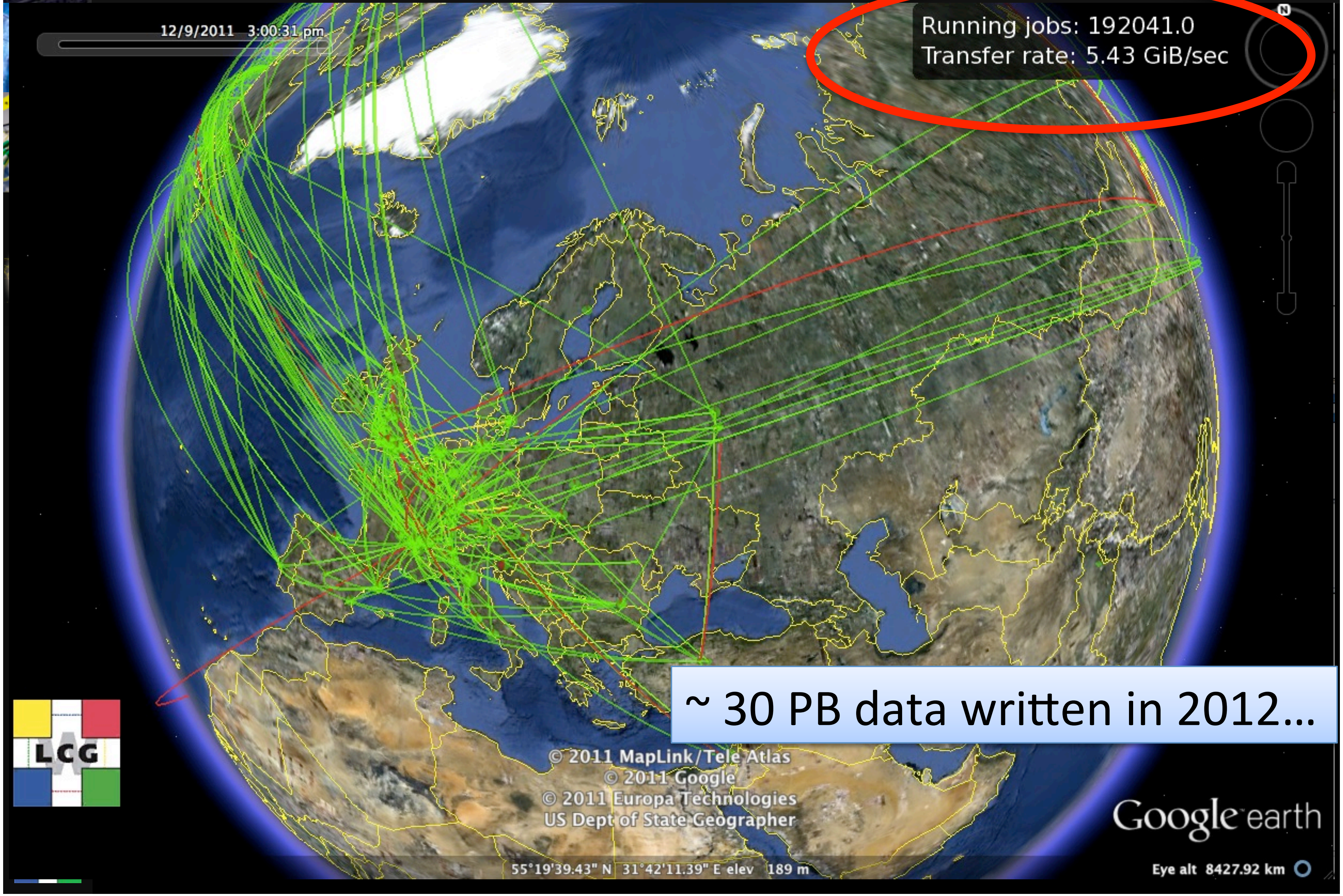
ATLAS - 2012

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.0%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	98.3%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	100%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	96.0%
RPC Barrel Muon Chambers	370 k	97.1%
TGC Endcap Muon Chambers	320 k	98.2%



- ATLAS and CMS in very good shape: Fraction of Active Channels >96%
- 90% of delivered luminosity used in physics analysis

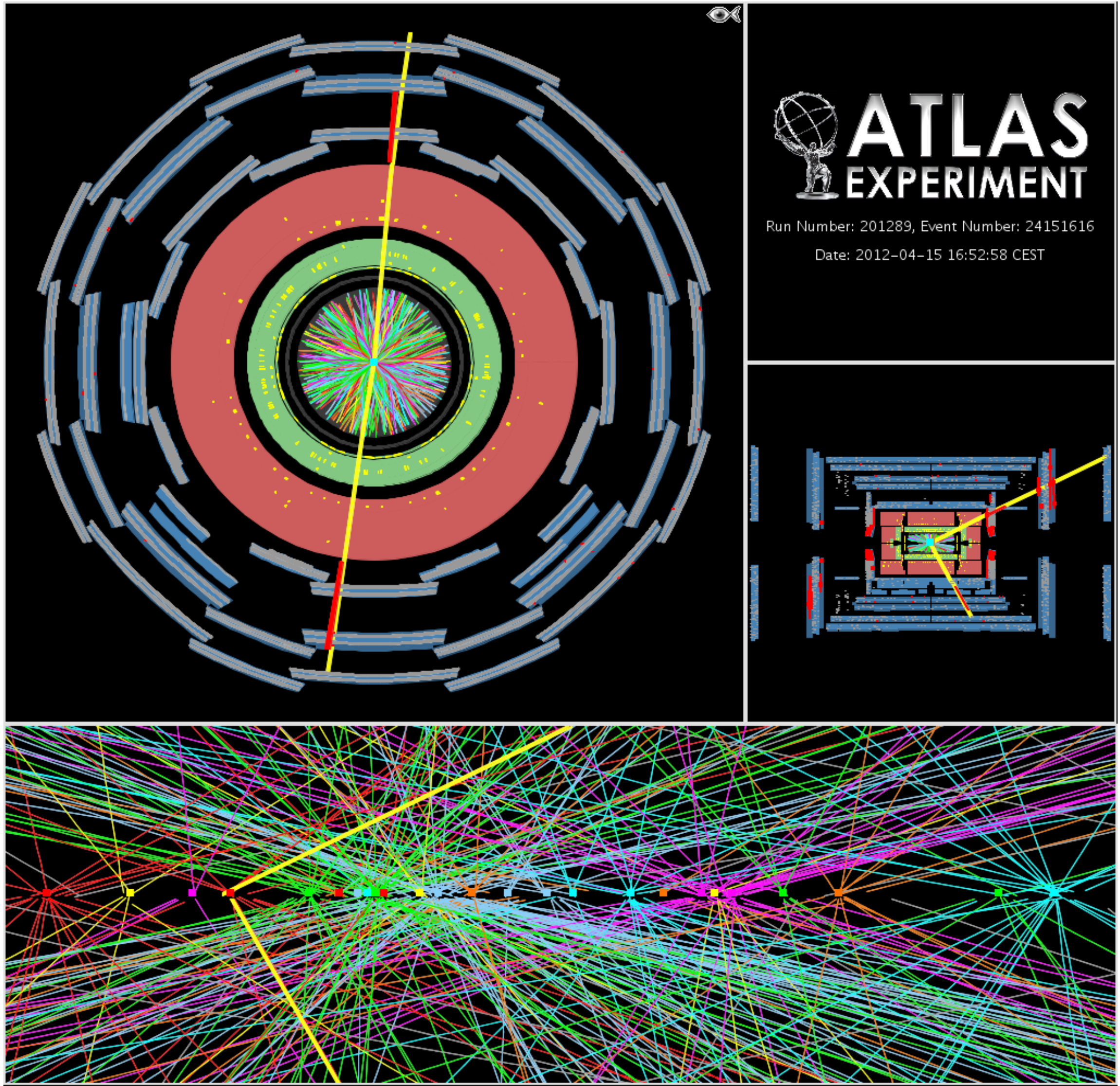
… and the GRID



~ 30 PB data written in 2012…

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}

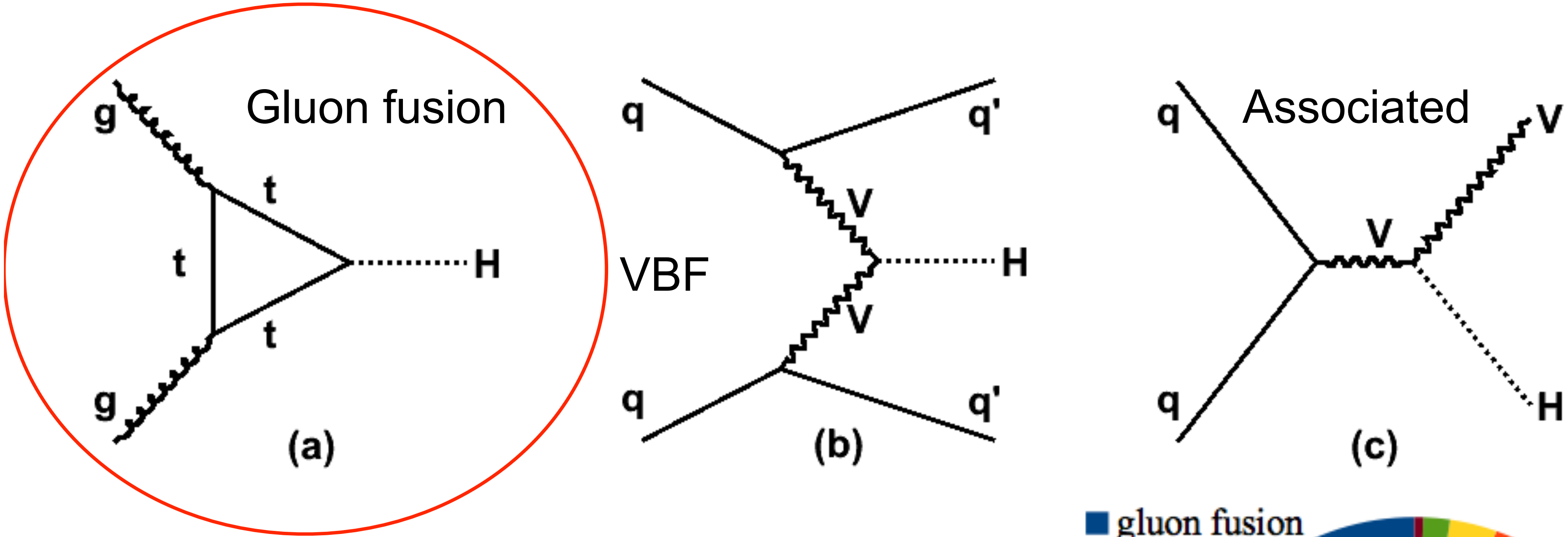


A long history

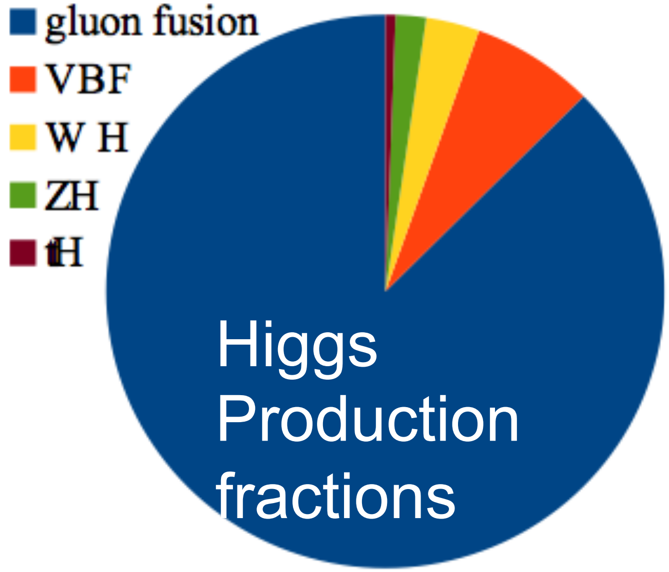
- 1964 Brout & Englert, Higgs, Guralnik, Hagen & Kibble,
  - Not taken too seriously until...
- 1967 Used in the formulation of the Standard Model
  - Proven to be self-consistent in 1971
- 1973 Experimental acceptance of the Standard Model
- 1983 Discovery of W and Z bosons
  - Closely linked to the 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

Hunting the Higgs Boson

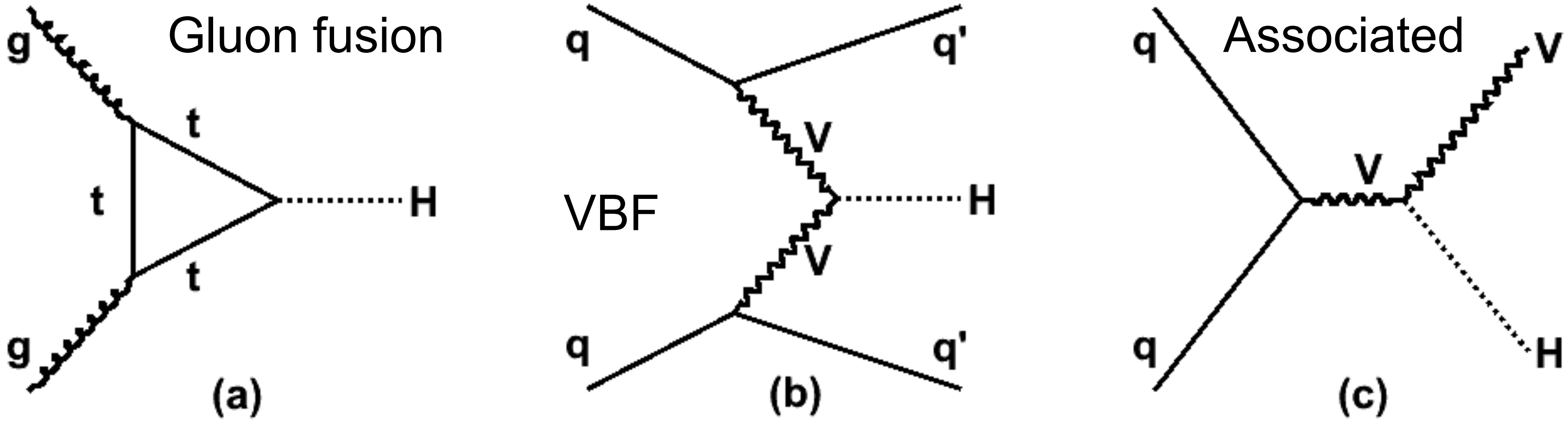
Higgs production



- The three most common modes
- Gluon fusion dominated discovery
  - Top loop (+ BSM?)
- Vector boson fusion/associated
  - Also used to tag signal
  - Improves the purity



Higgs production



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

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

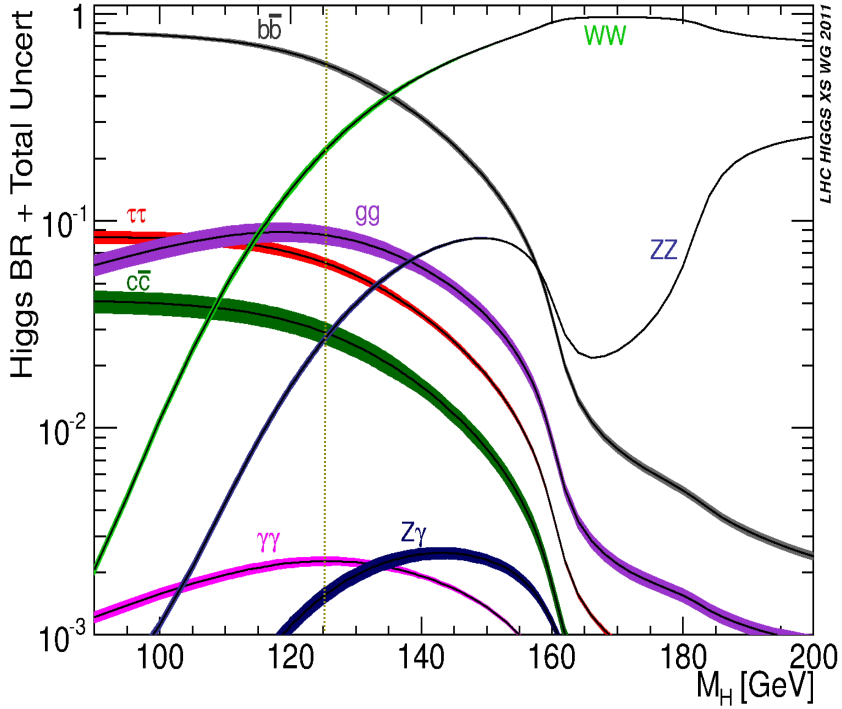
$$0.69\text{pb}\,{}^{+0.2}_{-0.6}\%(\mathit{scale})\,{}^{+3.5}_{-3.5}\%(\mathit{PDF})$$

(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

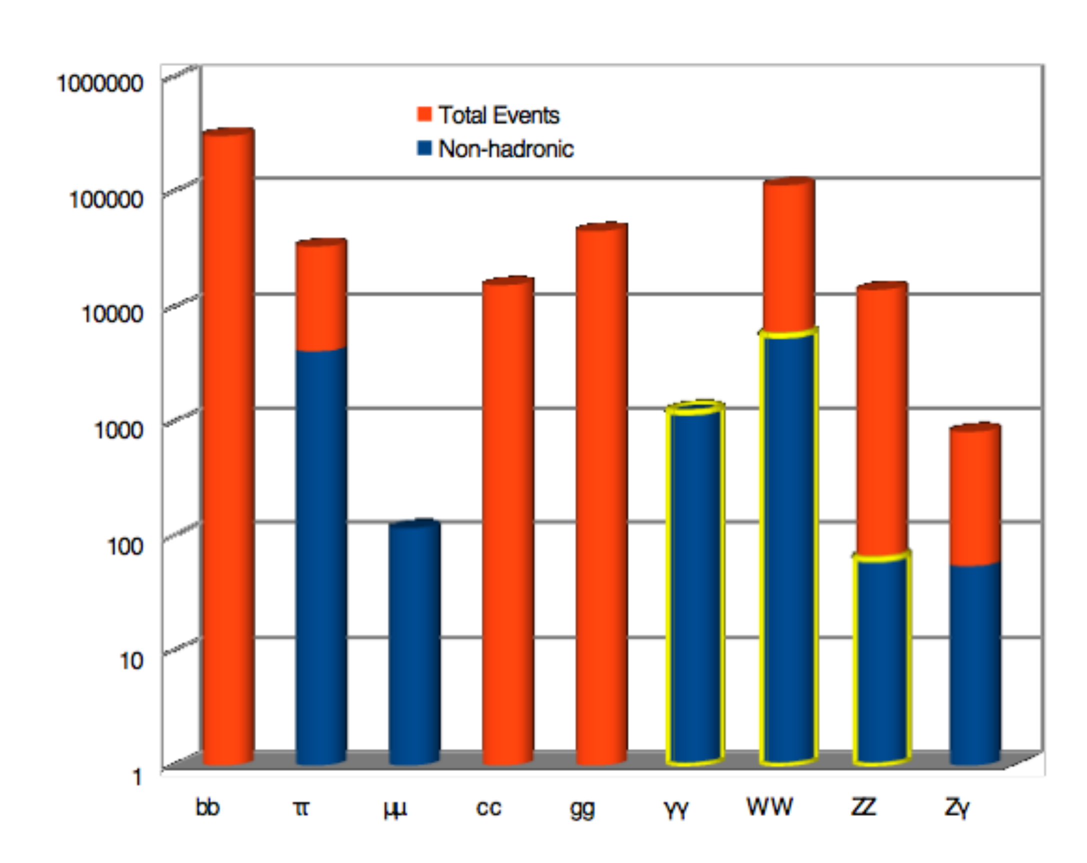
Higgs decay modes used

- $H \rightarrow ZZ$
  - $ZZ \rightarrow llll$: Golden mode
  - $ZZ \rightarrow ll\nu\nu$: Good High mass
  - $ZZ \rightarrow llbb$: Also high-mass
- $H \rightarrow WW$
  - $WW \rightarrow l\nu l\nu$: First sensitive
  - $WW \rightarrow l\nu qq$: highest rate
- $H \rightarrow \gamma\gamma$
  - Rare, best for low mass
- $H \rightarrow \tau\tau$
  - Uses VBF, low mass
- $H \rightarrow bb$
  - ttH, WH, ZH useful but hard

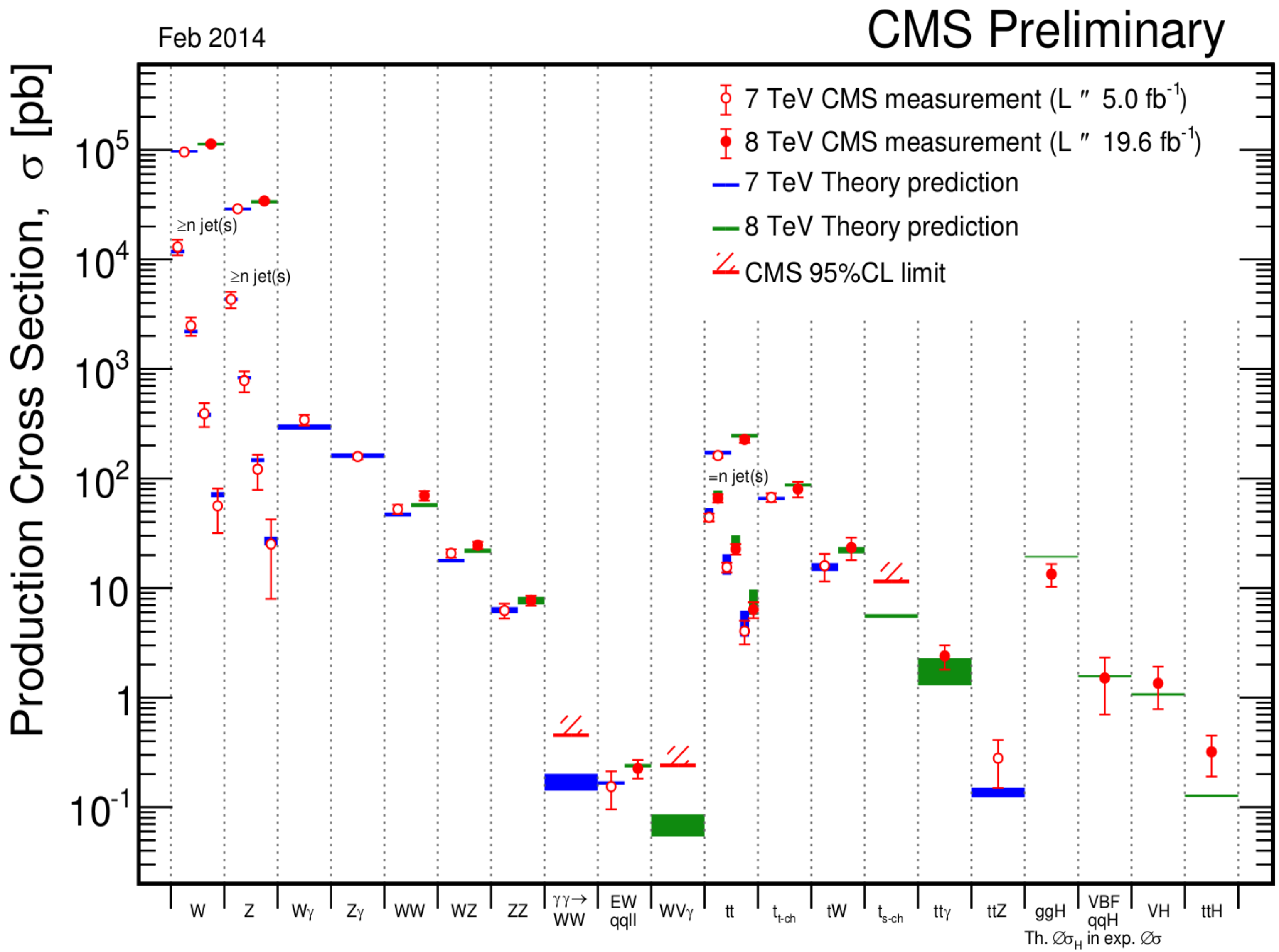


Rates by decay mode

- Run 1 production in each experiment
- From 100 to 300000 events per channel…
- ..but total pp events:
  - $2x10^{15}$
- 60 Higgs to llll events
- Needs incredible background rejection

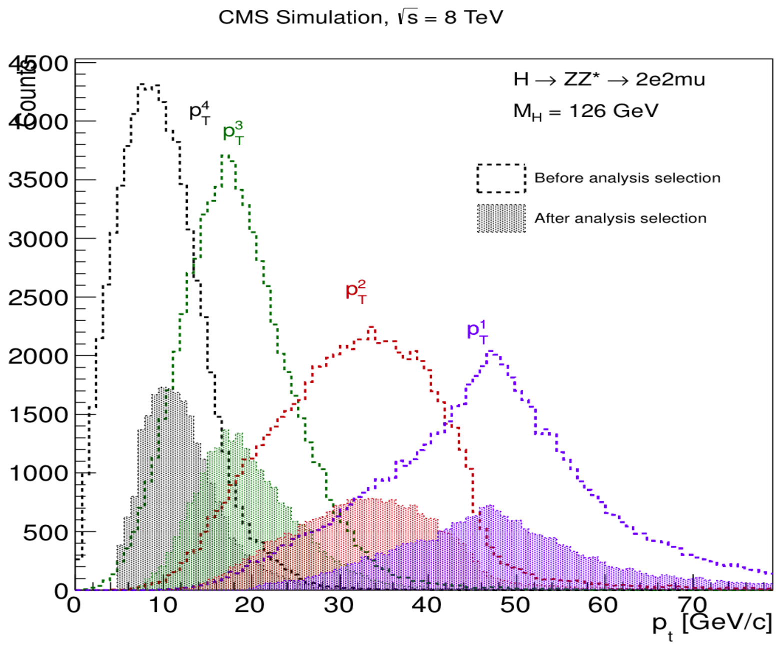


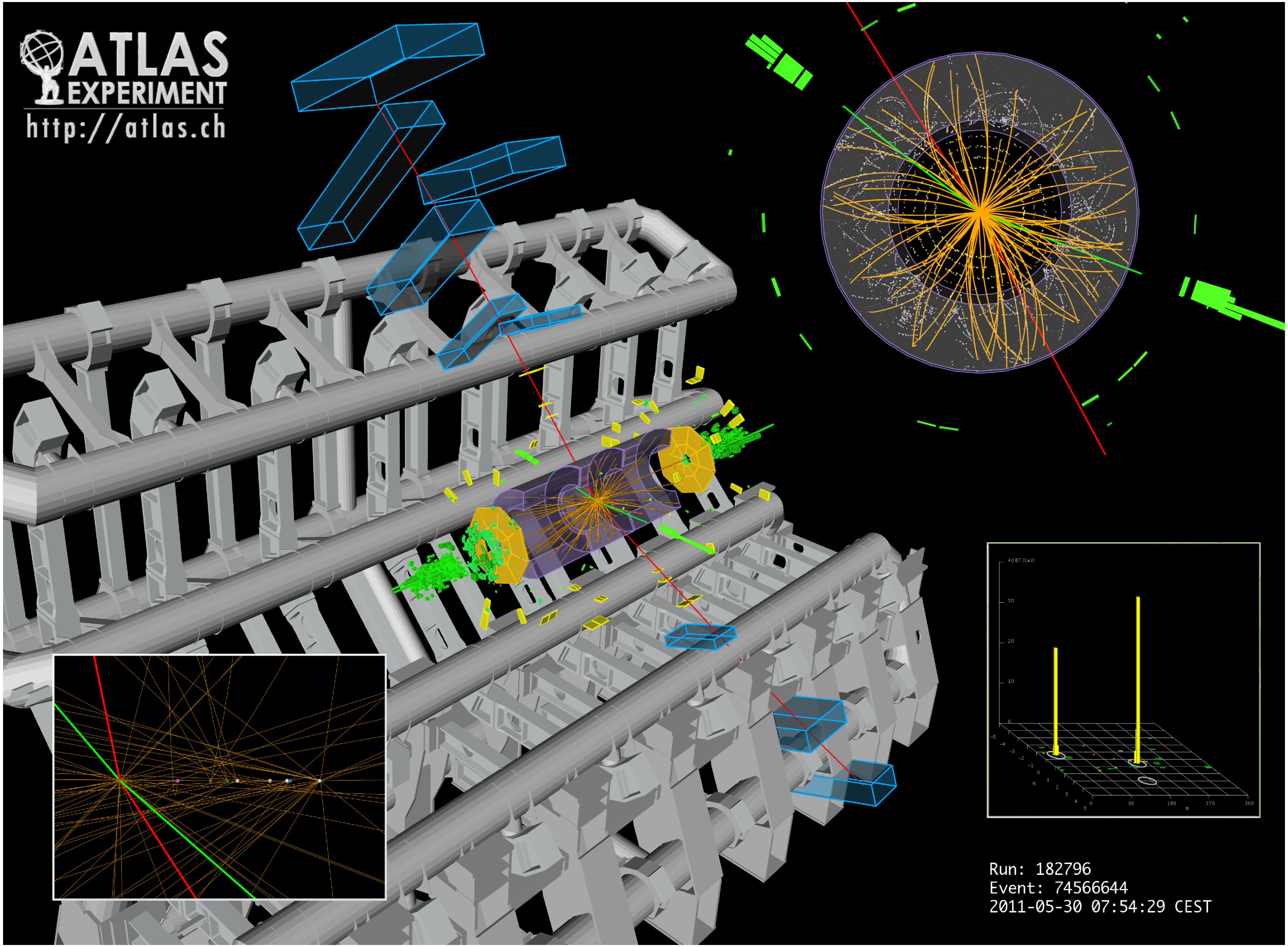
Standard Model measurements



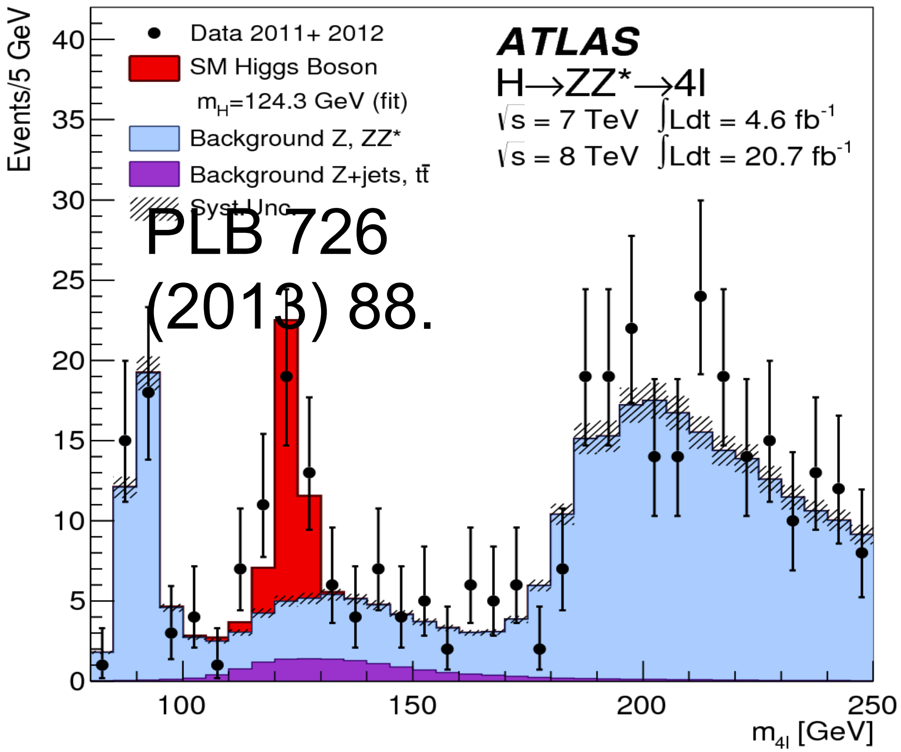
H →ZZ→llll

- 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

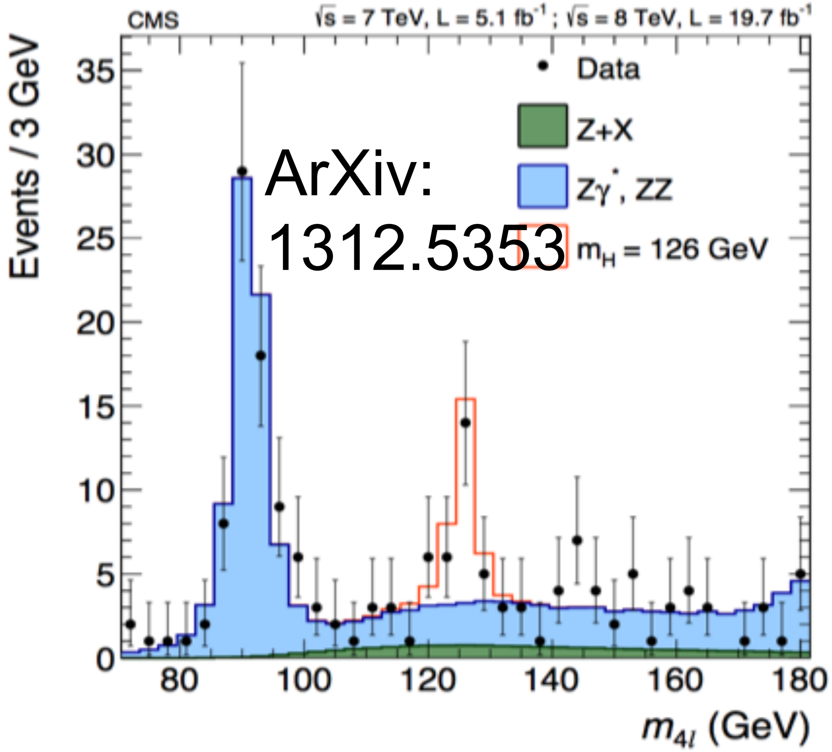



ATLAS
EXPERIMENT
http://atlas.ch
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

Signal Mass distribution



PLB 726 (2013) 88.

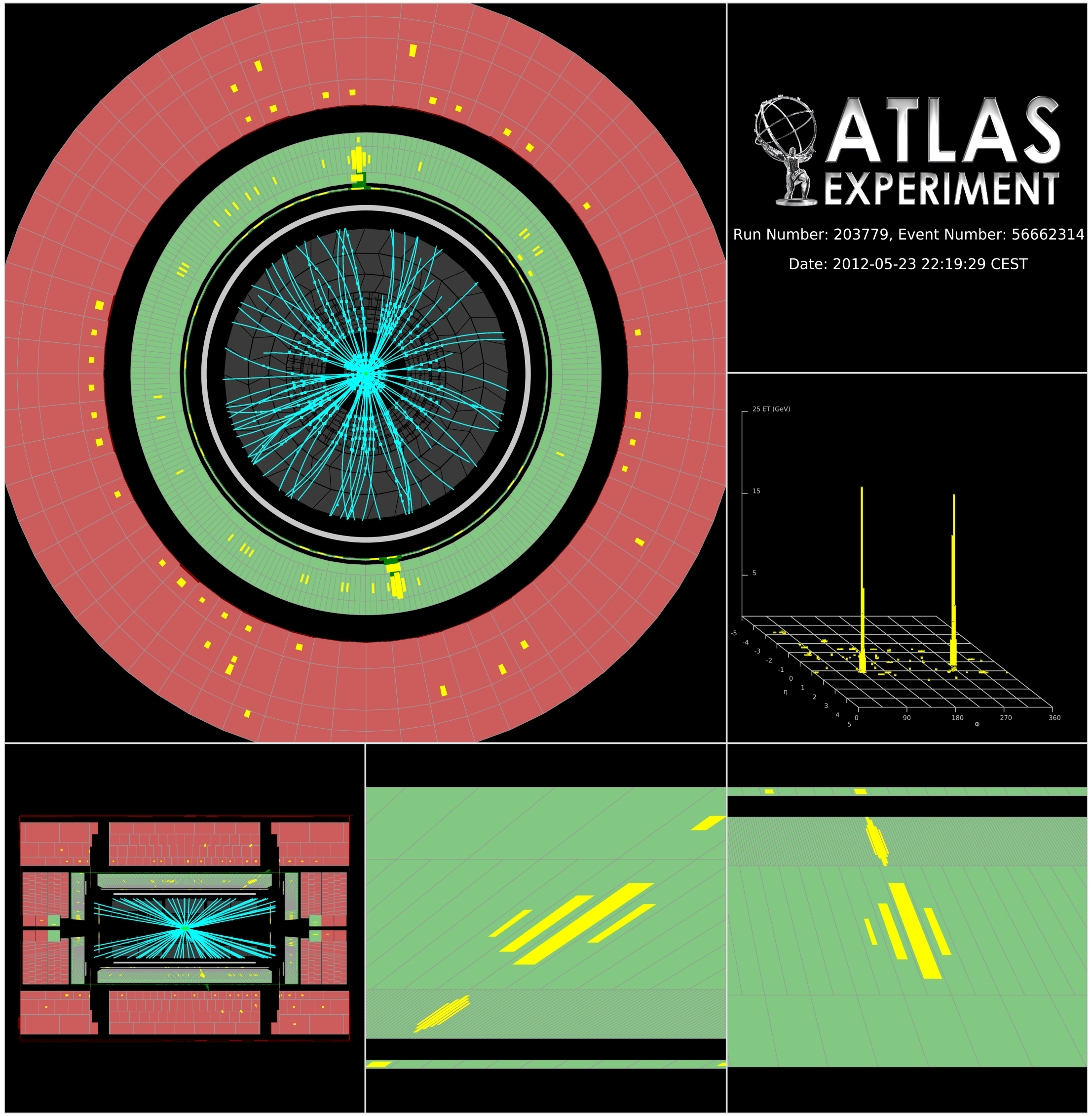


ArXiv: 1312.5353

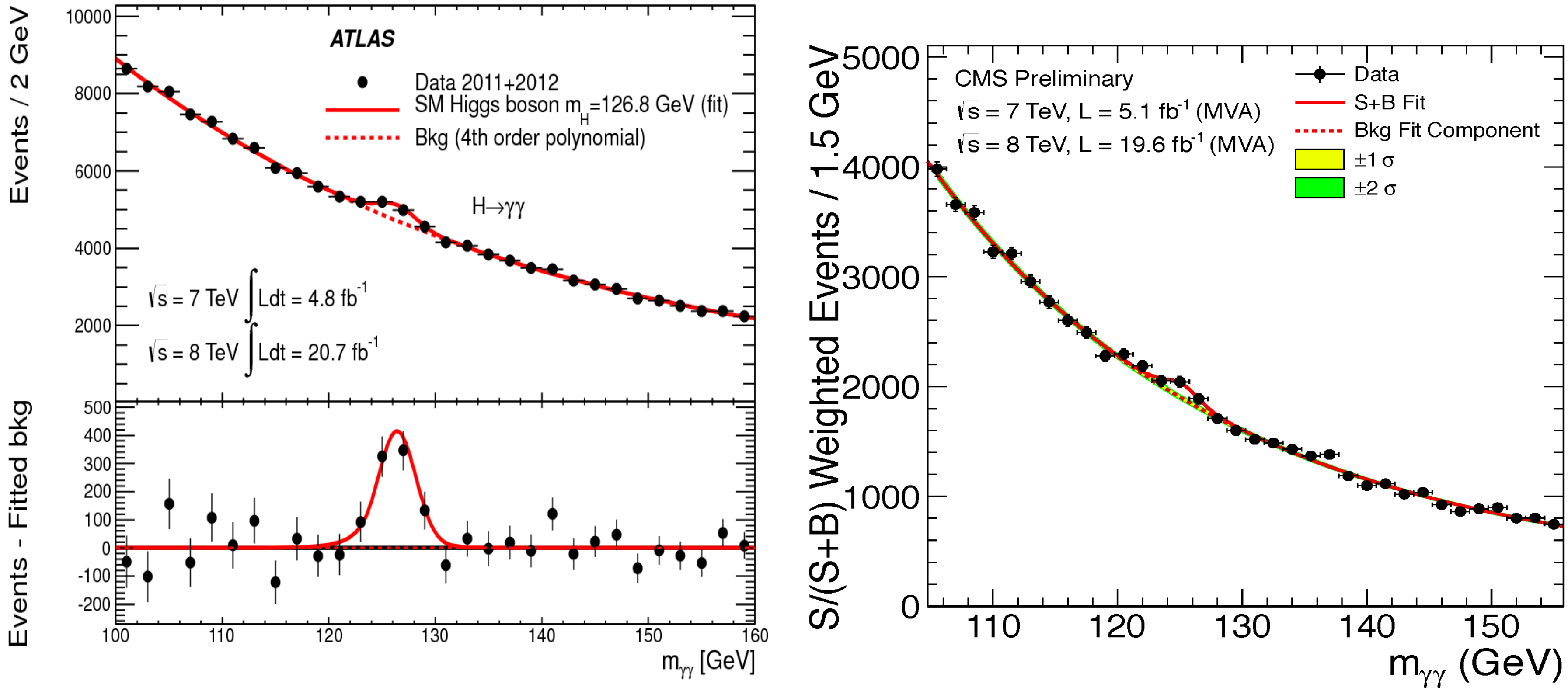
- Clear peak near 125 GeV
  - S/B better than 1
  - The Z→llll peak at 91 GeV is seen too; sanity check
- CMS use matrix element for each event to discriminate

$H \rightarrow \gamma\gamma$

- 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

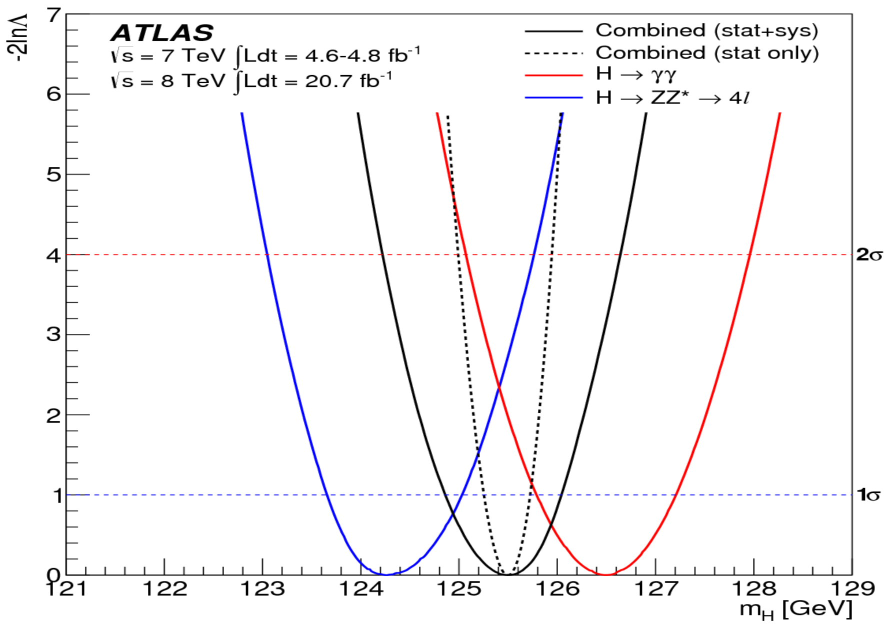


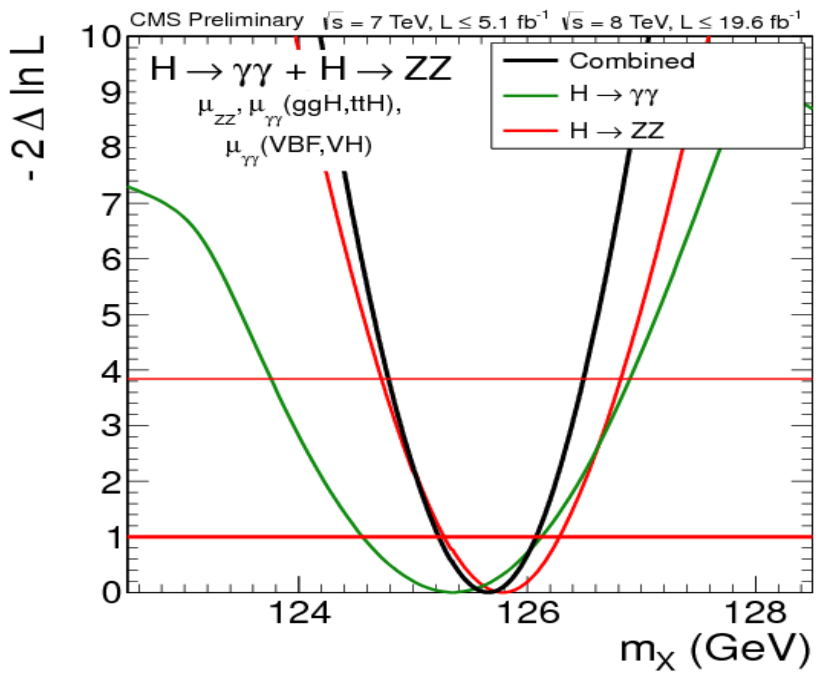
$H \rightarrow \gamma\gamma$ mass spectra



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

Higgs Mass Estimation





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

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

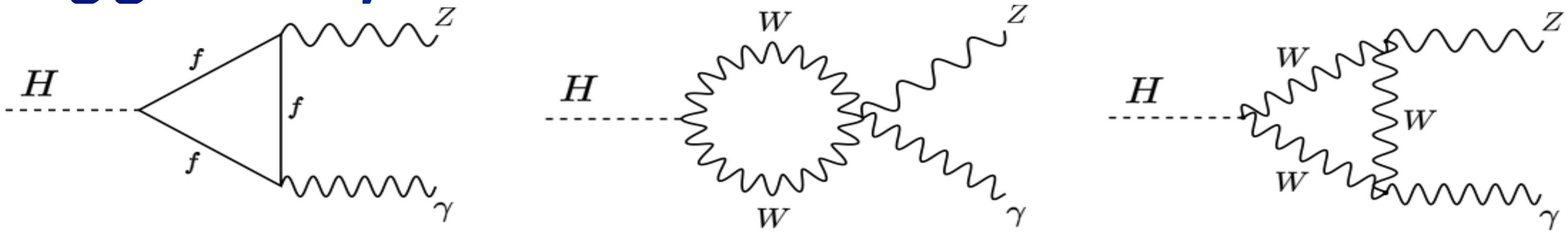
- Two experiments very compatible
  - Some internal tension in ATLAS
- Mass measured to <0.5%
  - Photons hard to calibrate precisely, experiments improving this
- The last parameter of the SM?

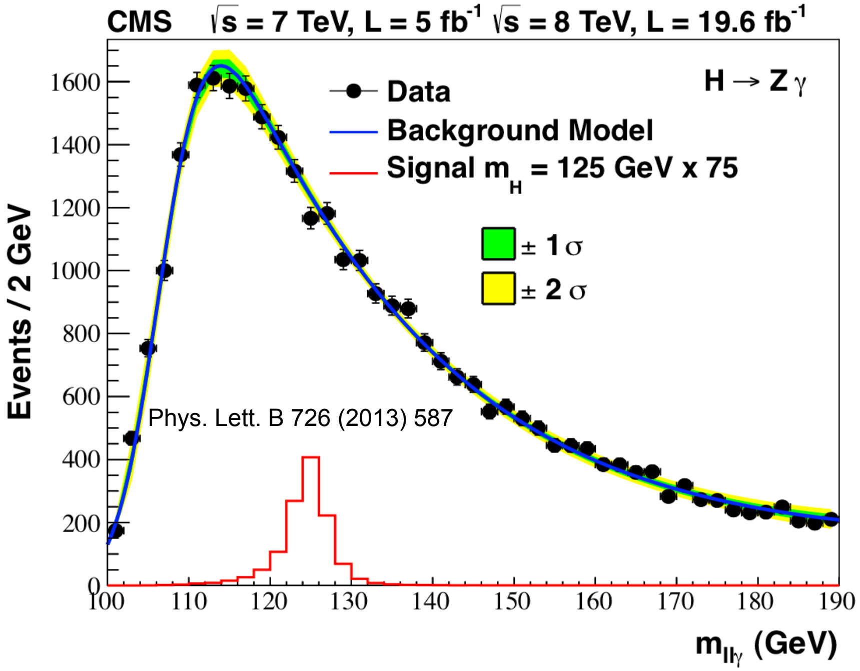
Is that it?

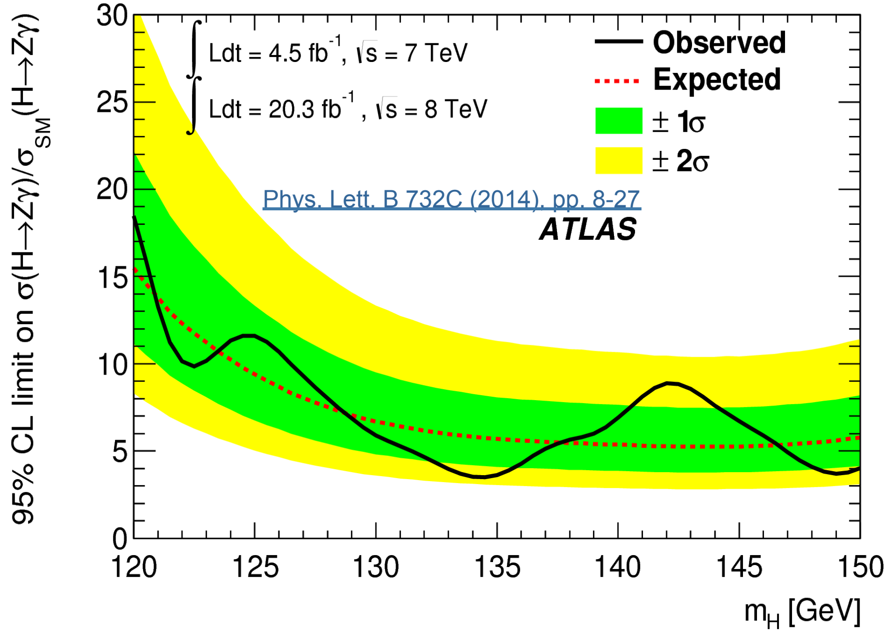
- The SM was missing just one parameter, m_H
  - With that measured are we done?

- 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







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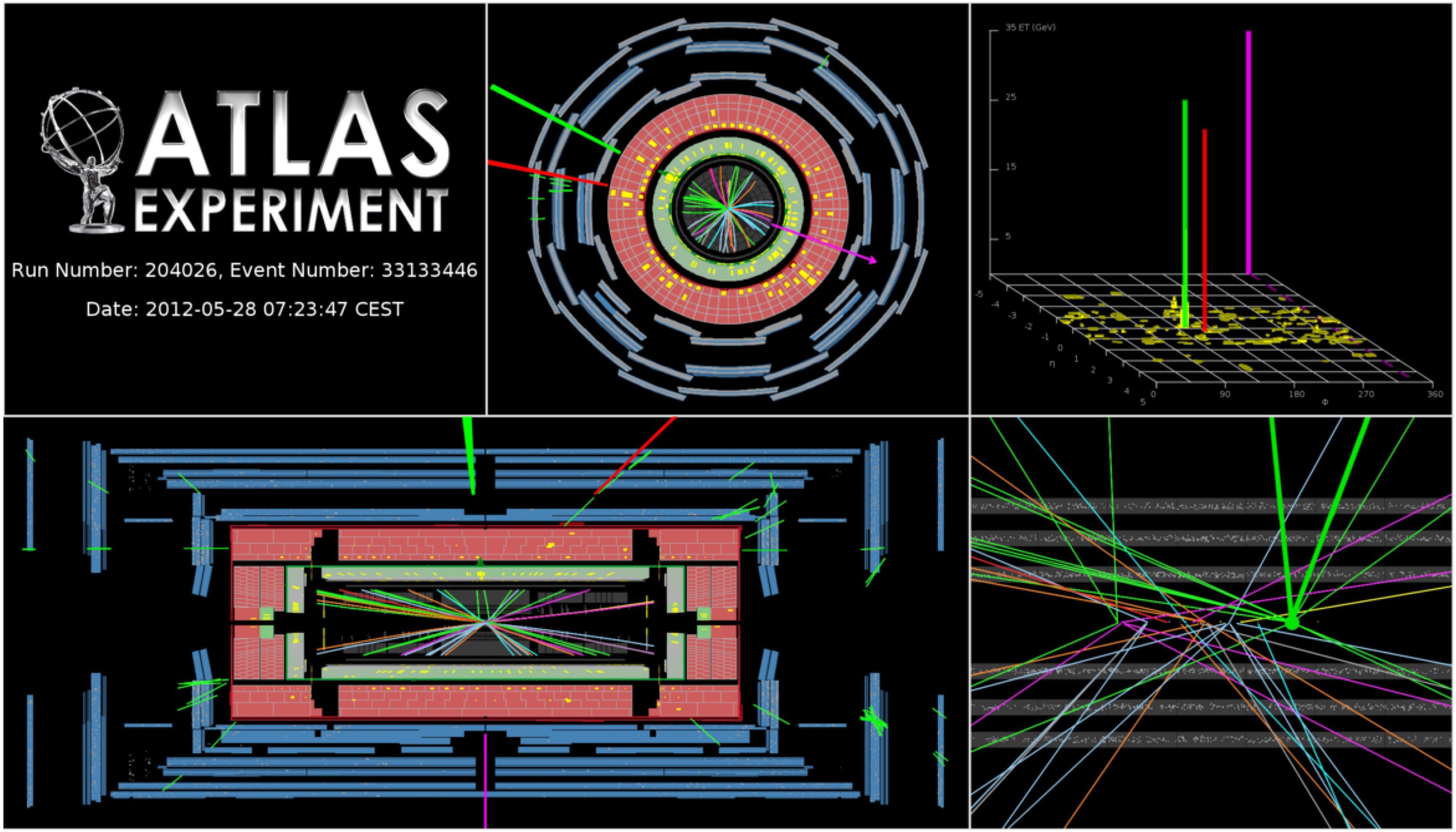
- Loop decay like H→γγ; sensitive to corrections
  - Observed(expected) limit 9-11(9)xSM Higgs
- Nothing unexpected here

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

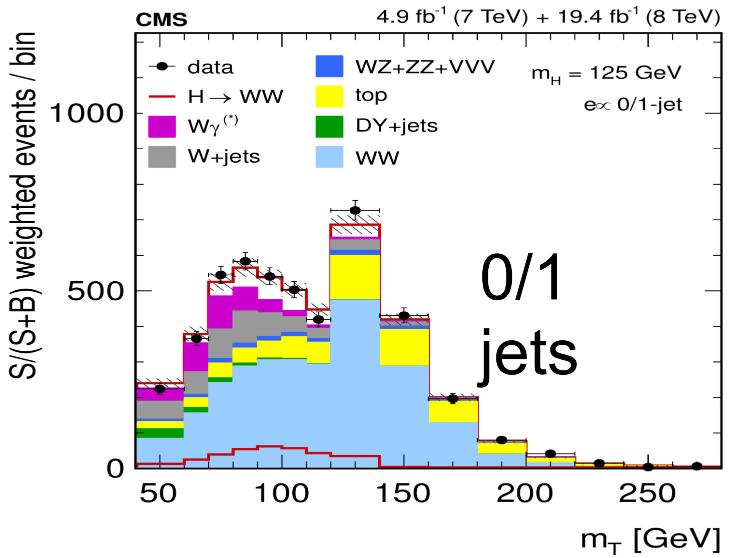


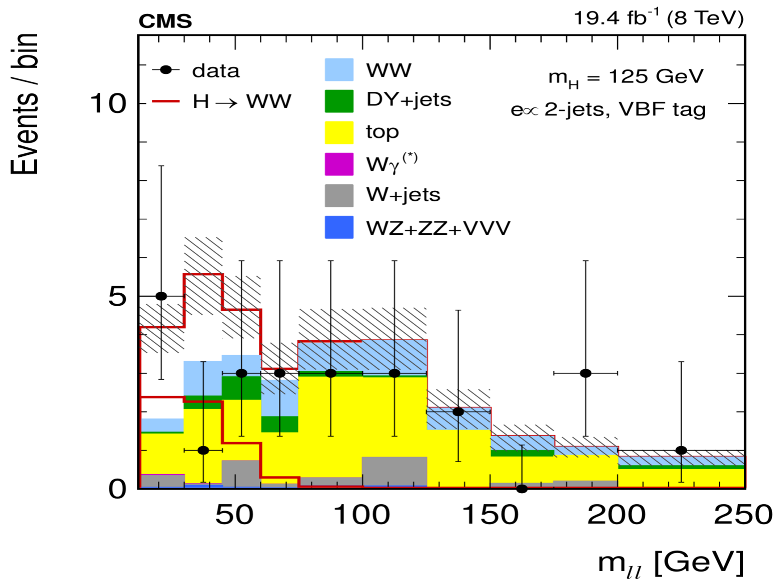
$WW \rightarrow l\nu l\nu$

- 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 kinematics : e.g. $\Delta\phi$ 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



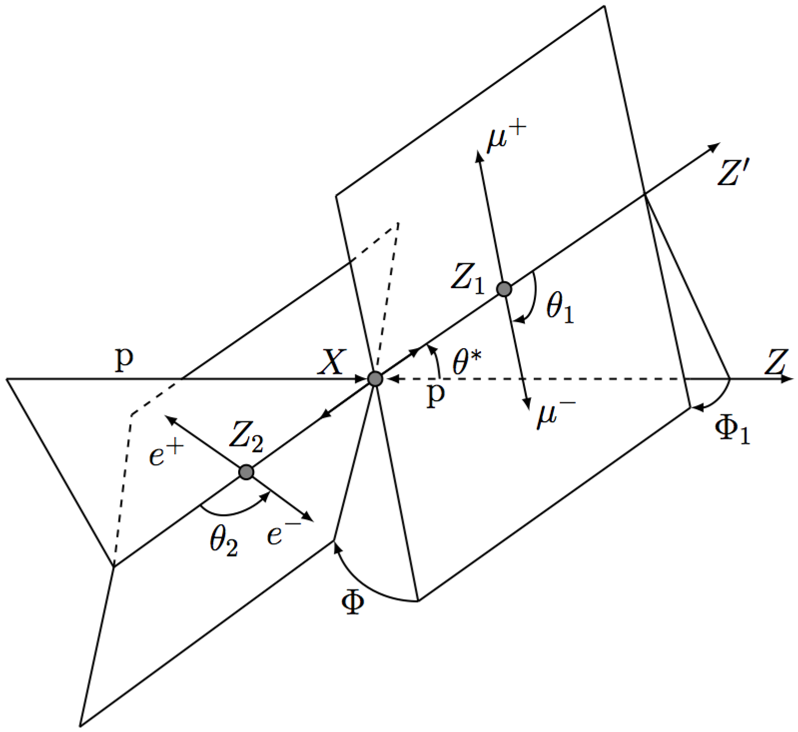


Spin/parity

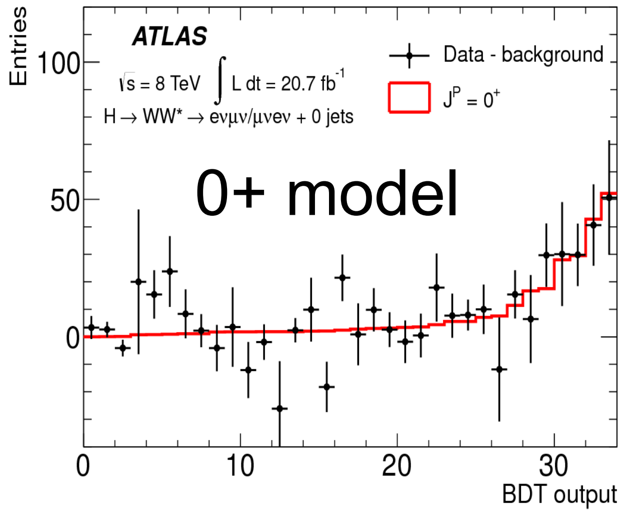
- We know integer spin, not 1 from $\gamma\gamma$ decay observation
  - Unless Yang-Mills is evaded; e.g. Each photon is a pair..
- We can measure in ZZ/WW/$\gamma\gamma$
- But there are caveats:
  - General spin 2 tensor structure too complex to analyse now
    - assume strawman production/helicity structure
    - E.g. gg or qq 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...

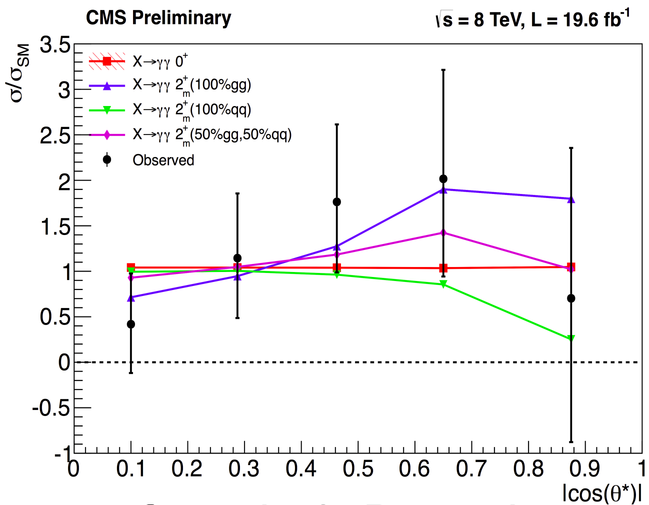
Spin analysis in Higgs decay

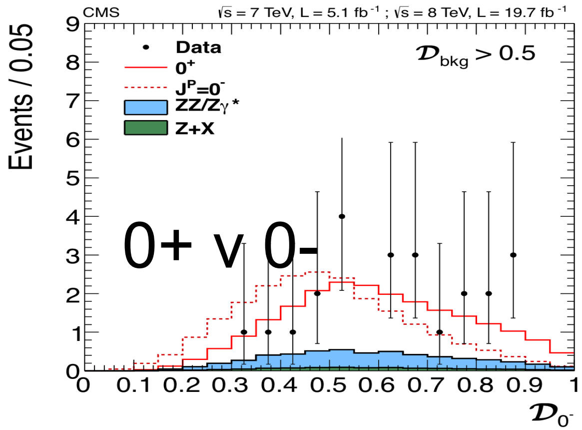
- ZZ decay has 7 observables
  - Mass of the two Z's
  - Overall global phi
  - 4 spin angles
- WW would be better due to large decay asymmetry
  - But the 2 neutrinos rob much sensitivity.
- γγ lacks photon mass and their decay angles
  - But production angle sensitive
- All of them bring sensitivity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



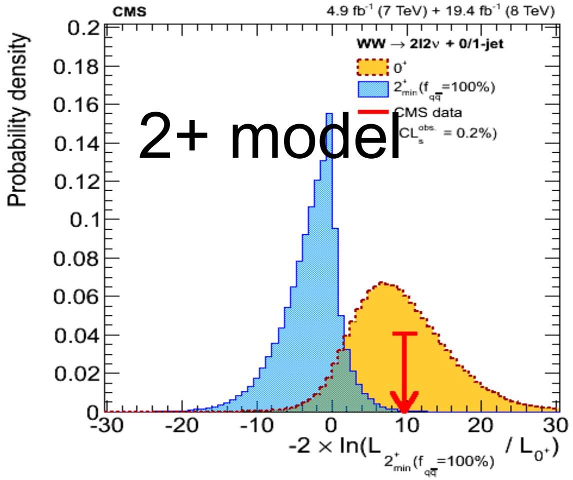
WW, γγ and ZZ



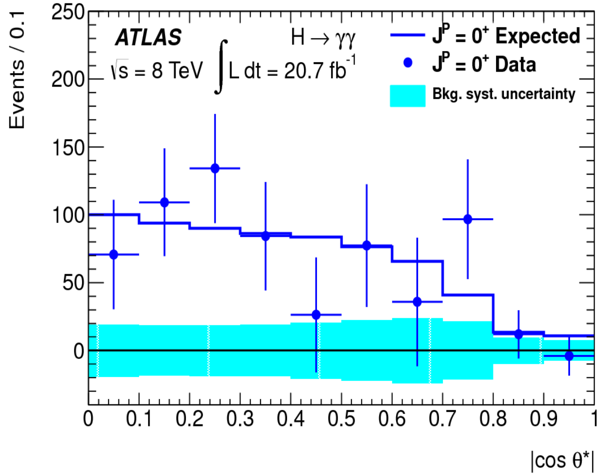




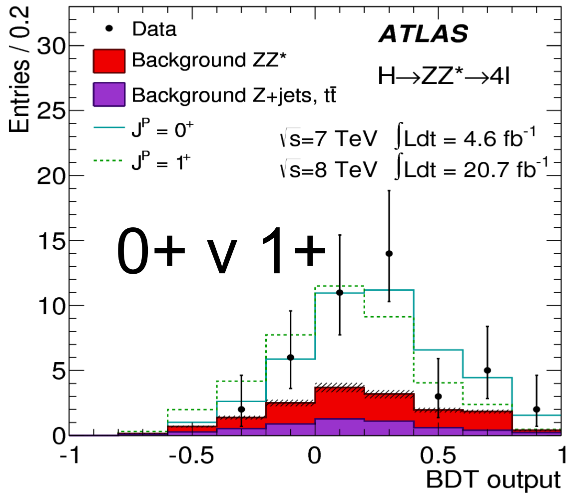
WW for spin 2+



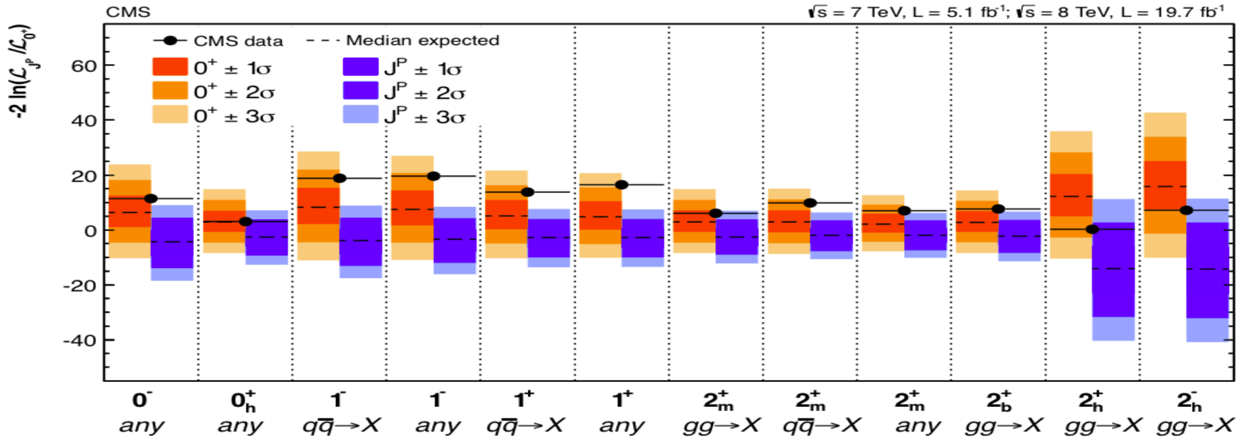
γγ for spin 2. Below is background subtracted



ZZ for 0- above and 1+ below



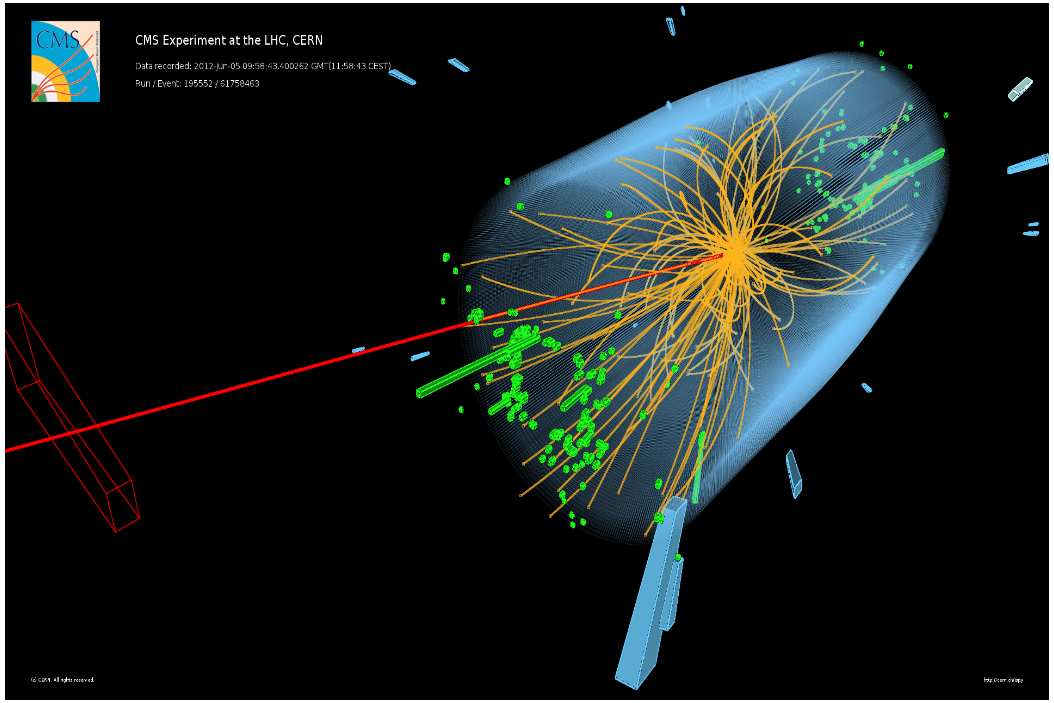
Spin/parity results



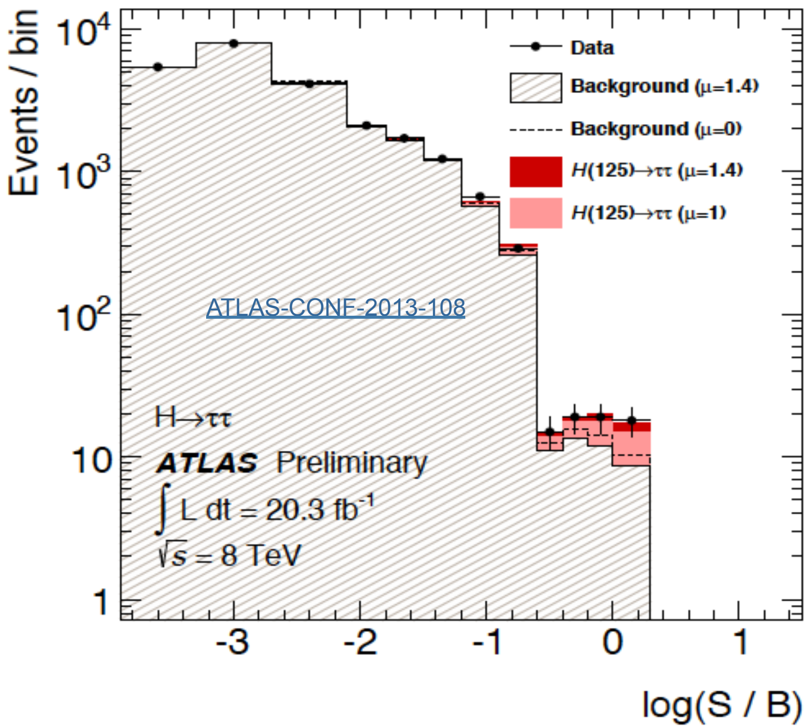
- Most important result is that 0^+ always matches data well
- Spin 1 is strongly disfavoured by $\gamma\gamma$ observation
- Spin 2 model is example model, other could exist
  - For any gg/qq production fractions

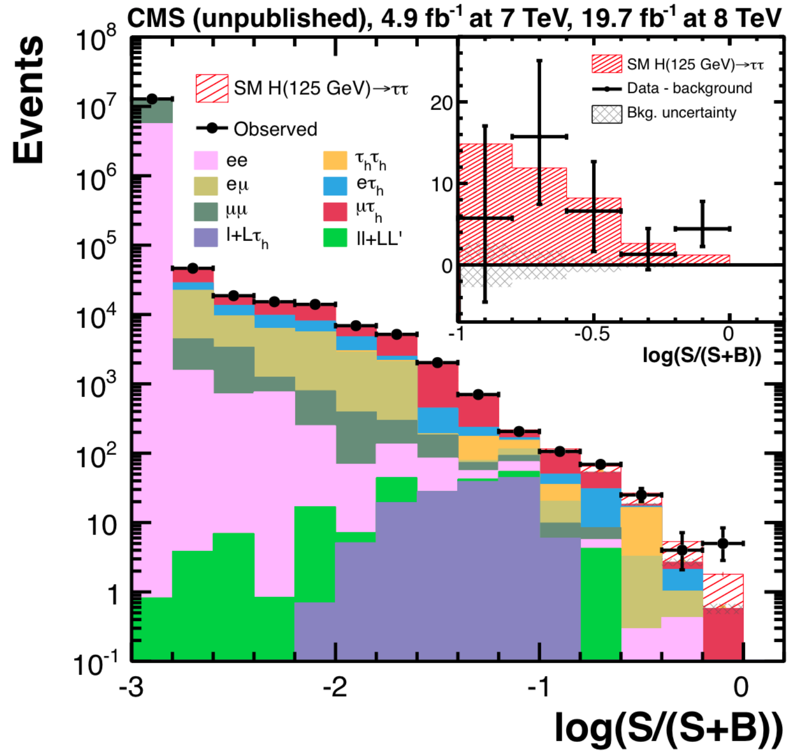
H→ττ status

- 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

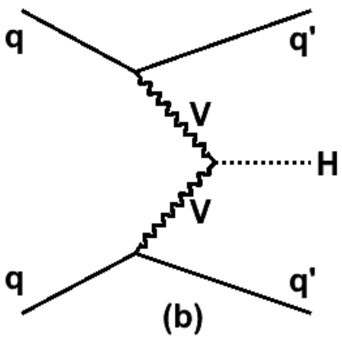


$H \rightarrow \tau\tau$ status

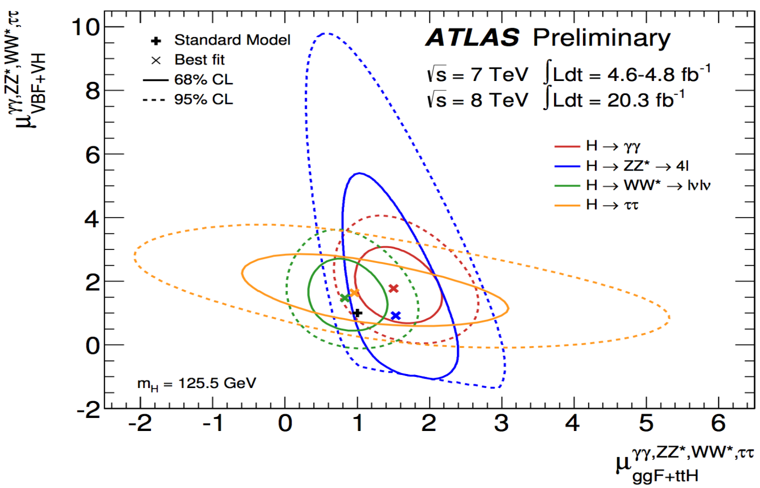


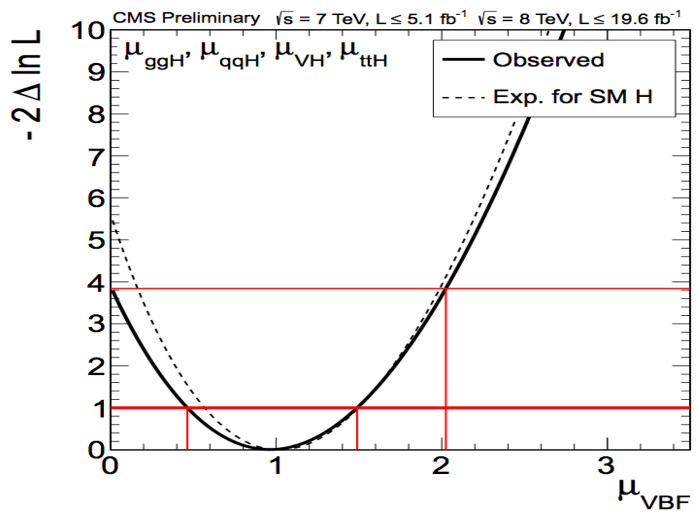


- ATLAS finds 4.1σ evidence (3.2σ expected)
- CMS sees 3.2σ evidence (3.7σ expected)
- Together this looks very solid



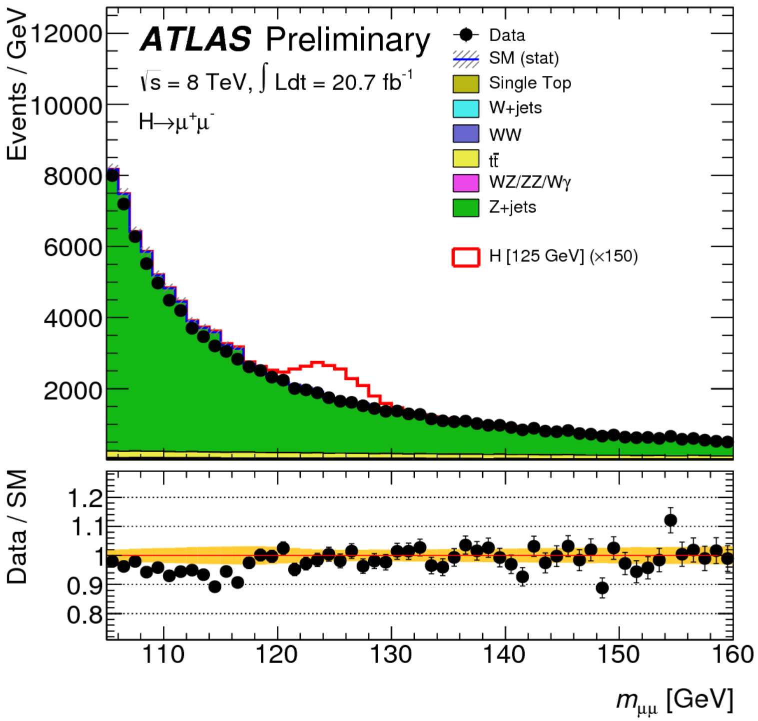
Evidence for VBF

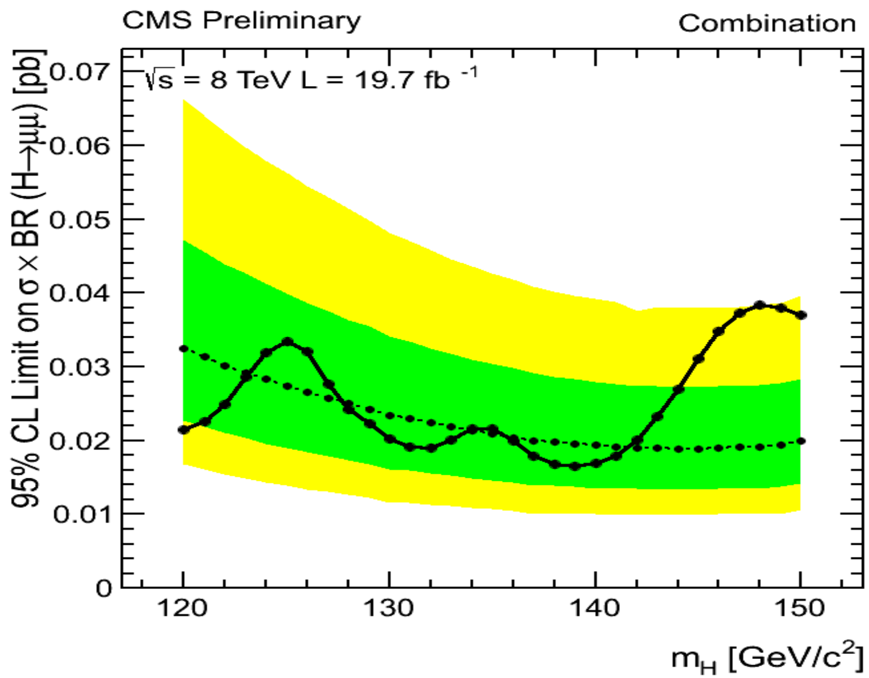




- Use categories where the Higgs boson was seen with forward VBF-tagging jets
  - All 4 channels discussed contribute here
- Both ATLAS (4σ) and CMS (2σ) see something
  - Together make good evidence for VBF
- This means we see vector bosons both in production and decay
  - So the interaction is well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

Higgs to μμ

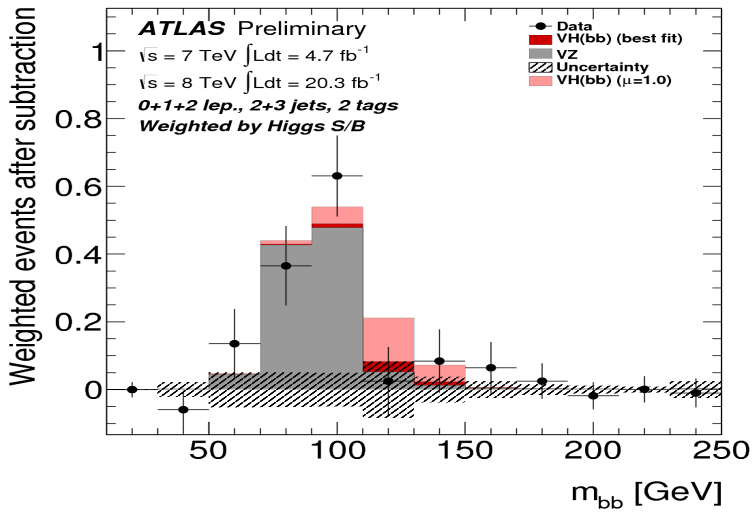


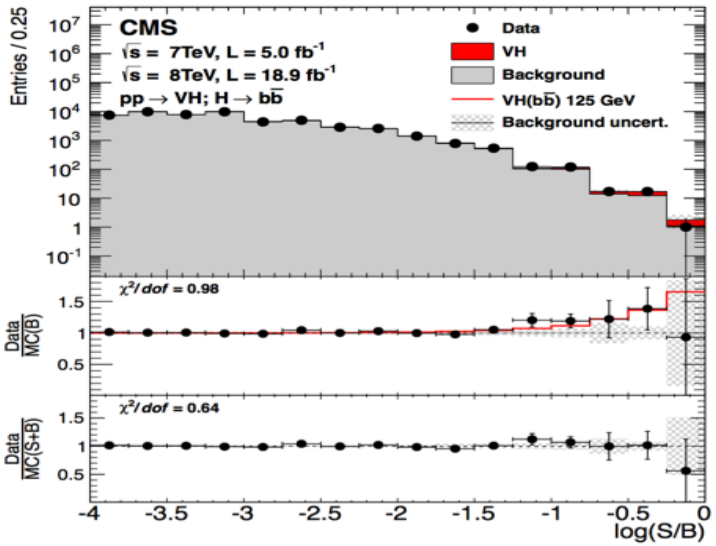


- Expect rate suppressed by $(0.106/1.778)^2$ ~ 1/280 w.r.t. ττ
- Good efficiency & mass resolution improves things
  - Obs(expected) limit 7(5)xSM - CMS
  - Obs(expected) limit 9.8(8.2) xSM - ATLAS
- Clear evidence for lepton non-universality

H→bb status

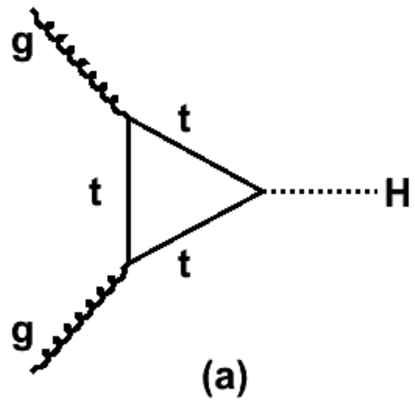
- Dominant decay
  - But lost in gg→bb background
- Use WH and ZH to improve s/b
- Both ATLAS and CMS see something of Higgs decay to bb
  - 2.1σ in CMS
  - 0.4σ in ATLAS
- The Tevatron reported 2.9σ for H→bb [Phys. Rev. Lett. 109, 071804 (2012)](#).
- There is some evidence
  - But it is not very solid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



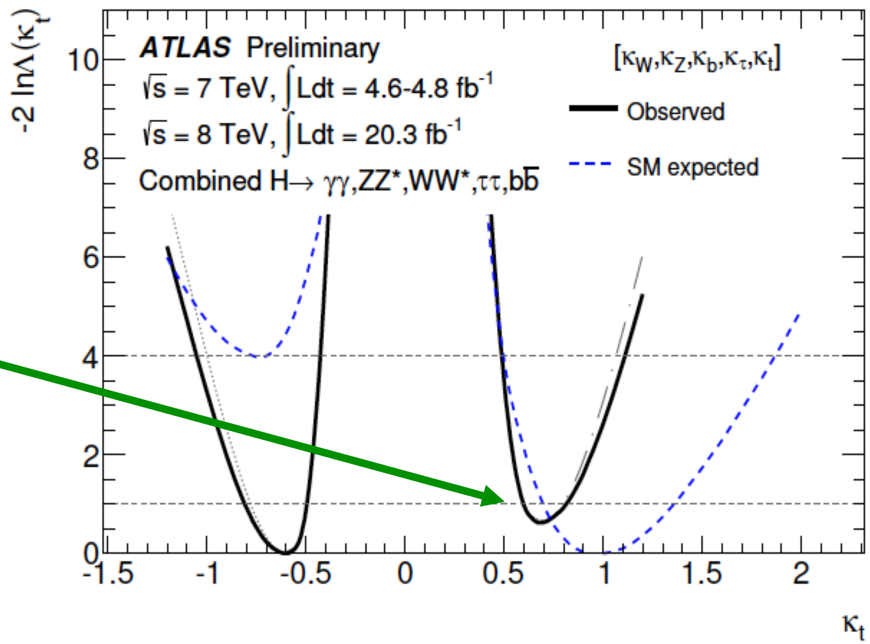


So does H interact with quarks?

- Yes!
- The gluon-fusion production process is basically a top quark loop
  - Gluons couple to quarks
  - Top quarks are massive and couple to Higgs



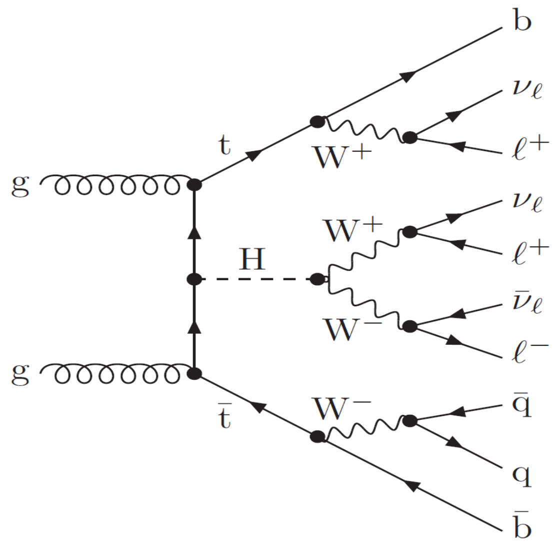
- If we do a 5-parameter fit:
  - κ_W, κ_Z, κ_t, κ_b, κ_τ
  - We find the top coupling cannot be zero
  - ATLAS finds it a little low
  - But 14% chance in SM

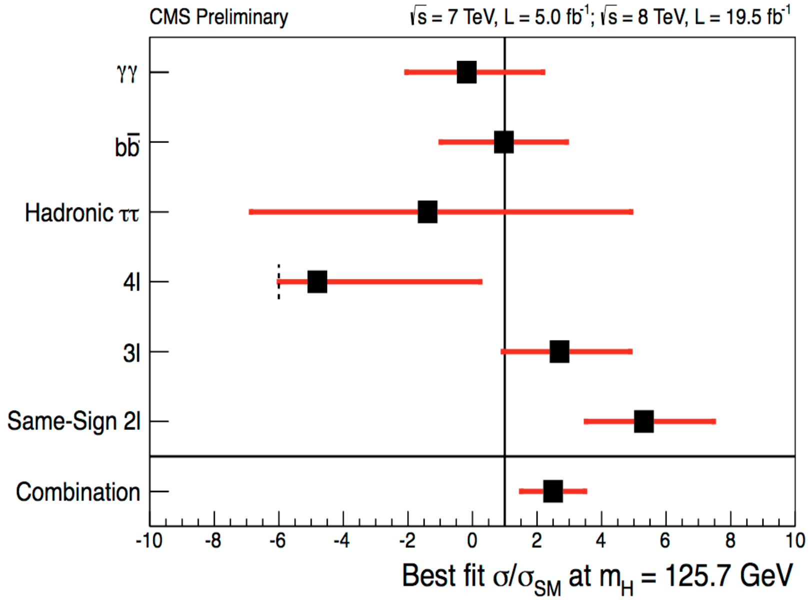


- But isn't it a bit indirect?

So look for ttH

- ttH has low rate but distinctive signature
  - But complicated
- Several Higgs decay modes used:
  - H→γγ, bb, leptons or tau
  - ATLAS only used at γγ, bb so far

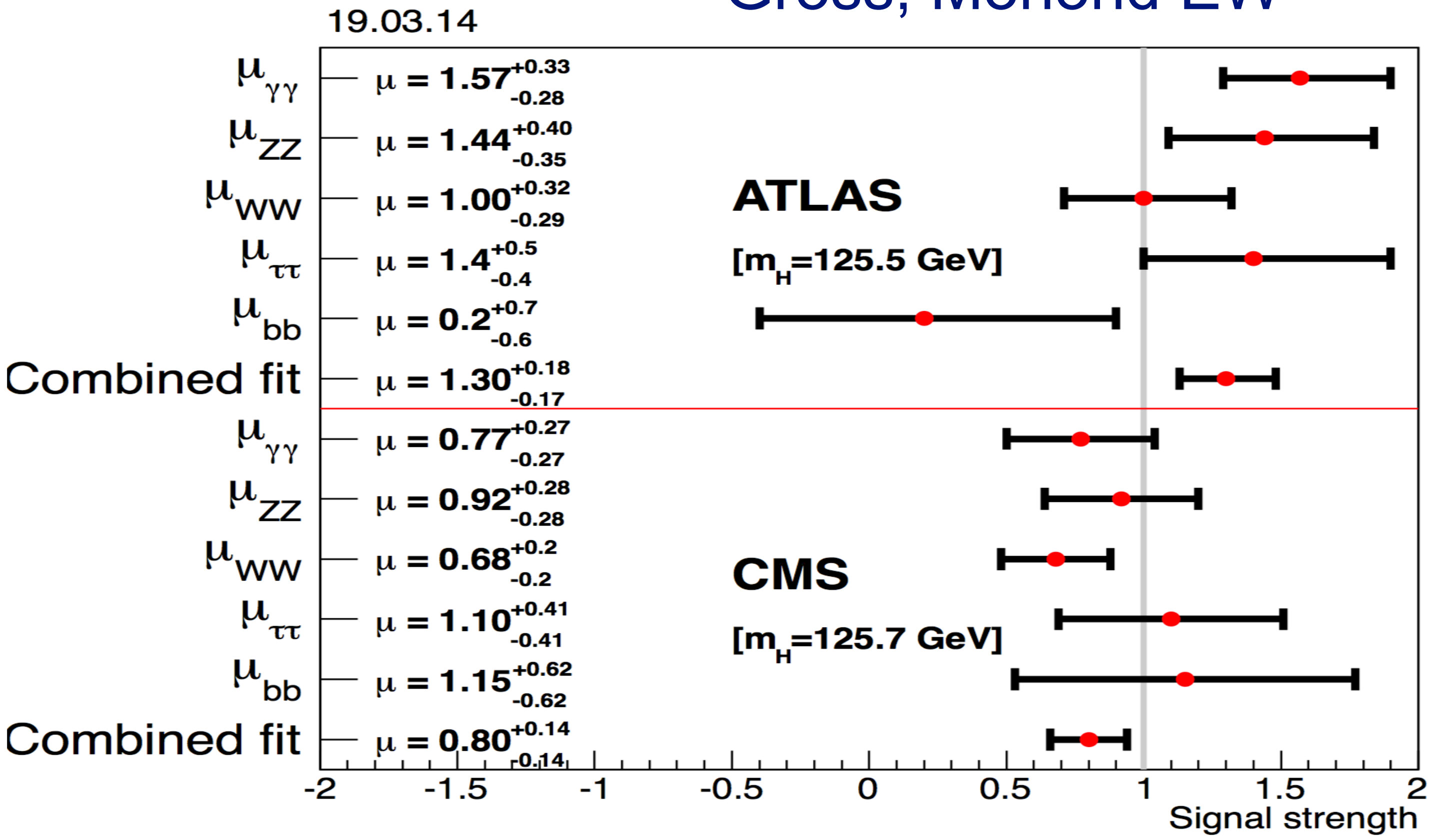




- CMS results (left) give 2.7σ evidence for ttH production
  - 1.2σ expected
- ATLAS found μ =1.7±1.4 in bb mode, no combination yet
- Together there should be 3σ evidence for this modes

In summary

Gross, Moriond EW



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

The couplings fit

- Basic ingredient: yields per category/channel (e.g., VBF 2J tag of H→ $\gamma\gamma$)

Production modes: gg, VBF, W/ZH, ttH + Final states: $\gamma\gamma$, WW, ZZ, bb, $\tau\tau$ $Z\gamma$, $\mu\mu$

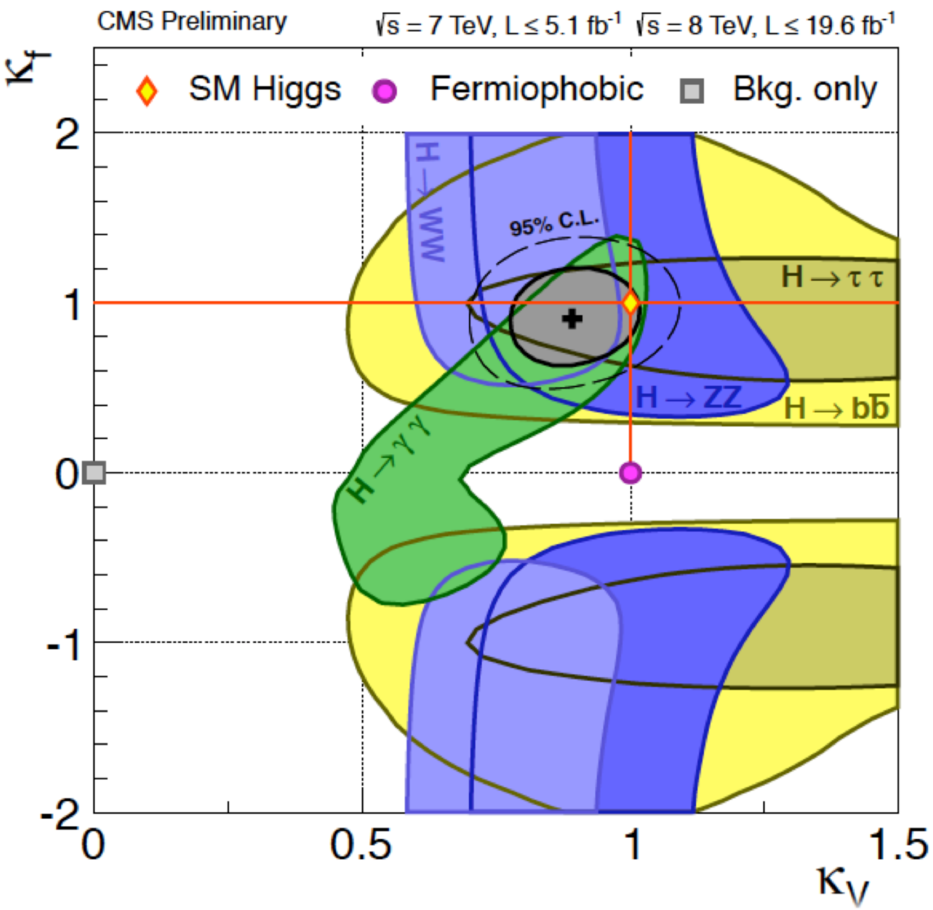
- Follow prescription form LHC-XS working group assuming:
  - Only one resonance + Narrow Width Approx. + SM Lagrangian tensor structure (also implies CP=0^+)
- Observed yields parameterized SM prediction x coupling scaling factors κ^2
  - SM equivalent to all $\kappa=1$
- *This simplified approach is sufficient for today's available statistics*

$$\sigma \times BR(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

$$(\sigma \cdot \mathrm{BR})(gg \to \mathrm{H} \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \boxed{\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}}$$

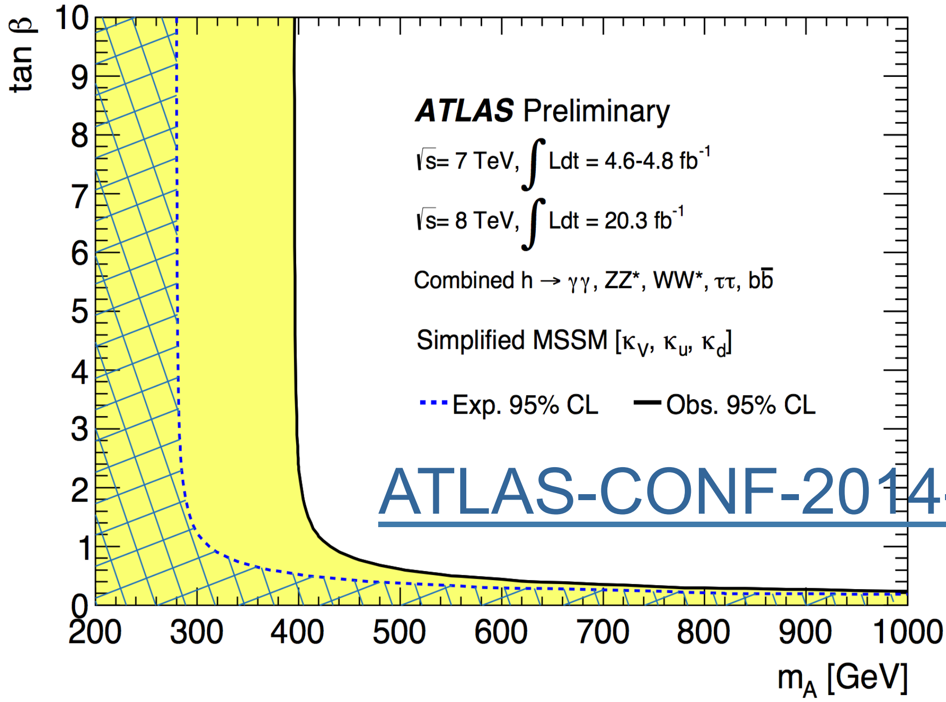
The couplings fit

- 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



MSSM constraints

- MSSM Higgs sector is defined by m_A and $\tan\beta$ 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



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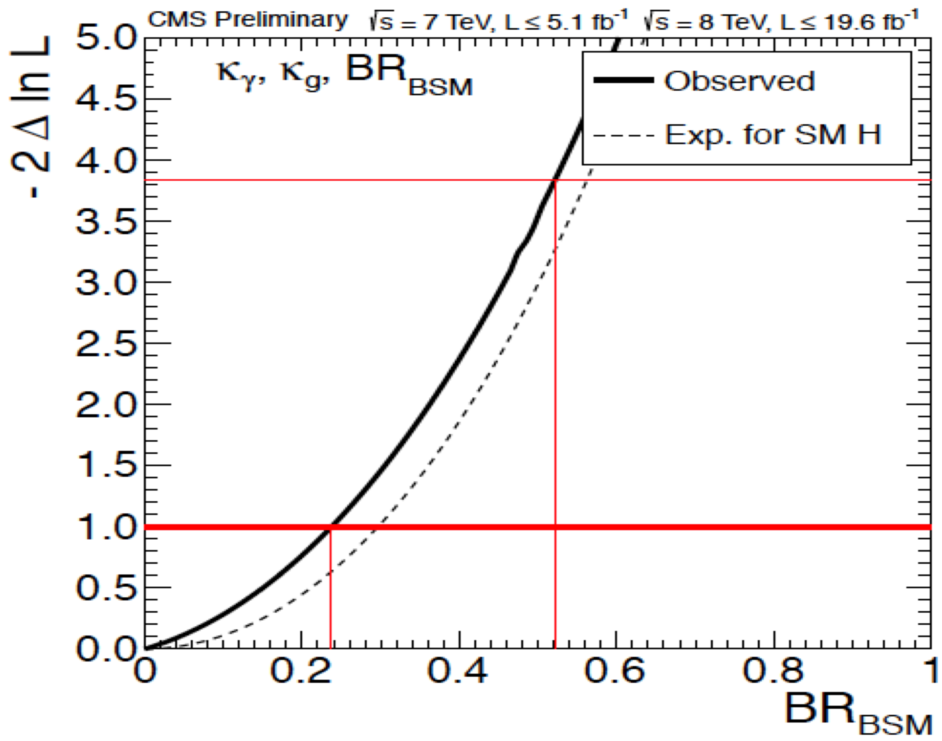
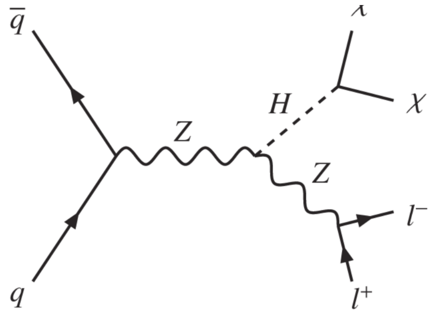
New particle search

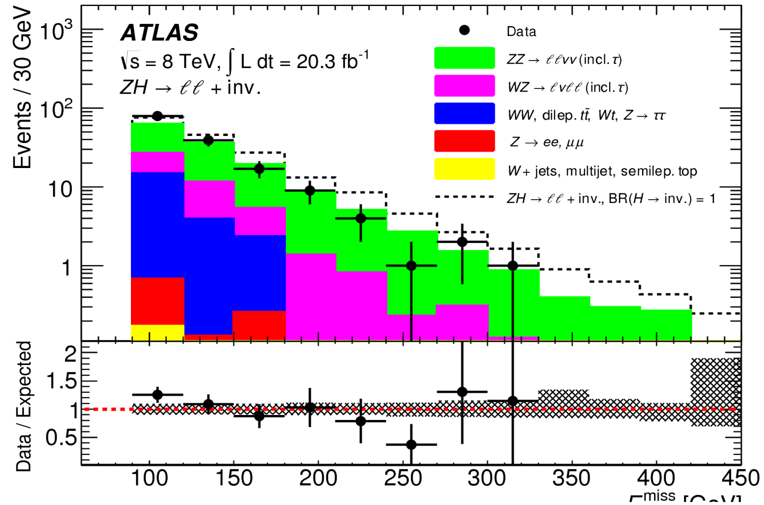
- Another possibility is to ASSUME a SM Higgs
  - But allow the loops to have unknown particles
  - ggF, $H \rightarrow \gamma\gamma$
- Test for invisible/ undetectable branching ratio
  - CMS find Br < 52% @ 95%
  - ATLAS Br < 41% (55% expected)
- Loop strengths also with 2σ of SM prediction

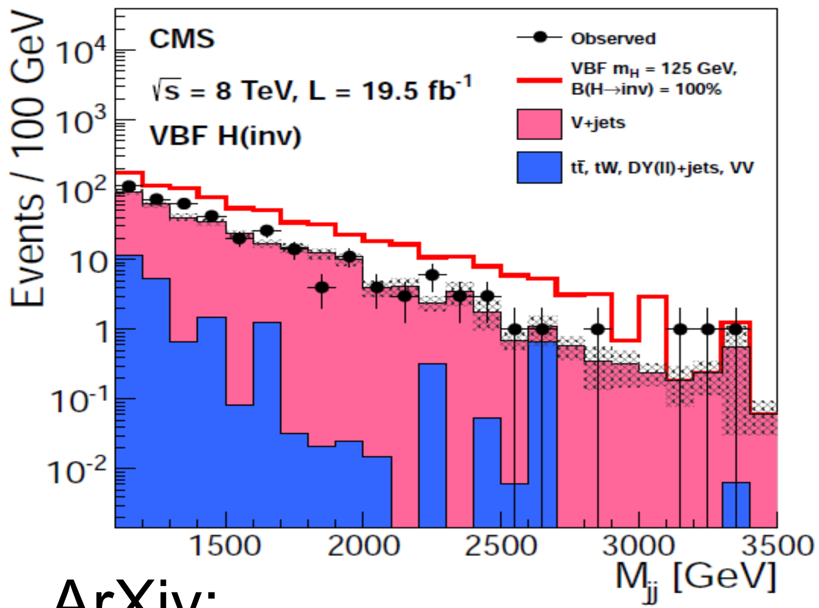




Direct invisible Higgs hunt

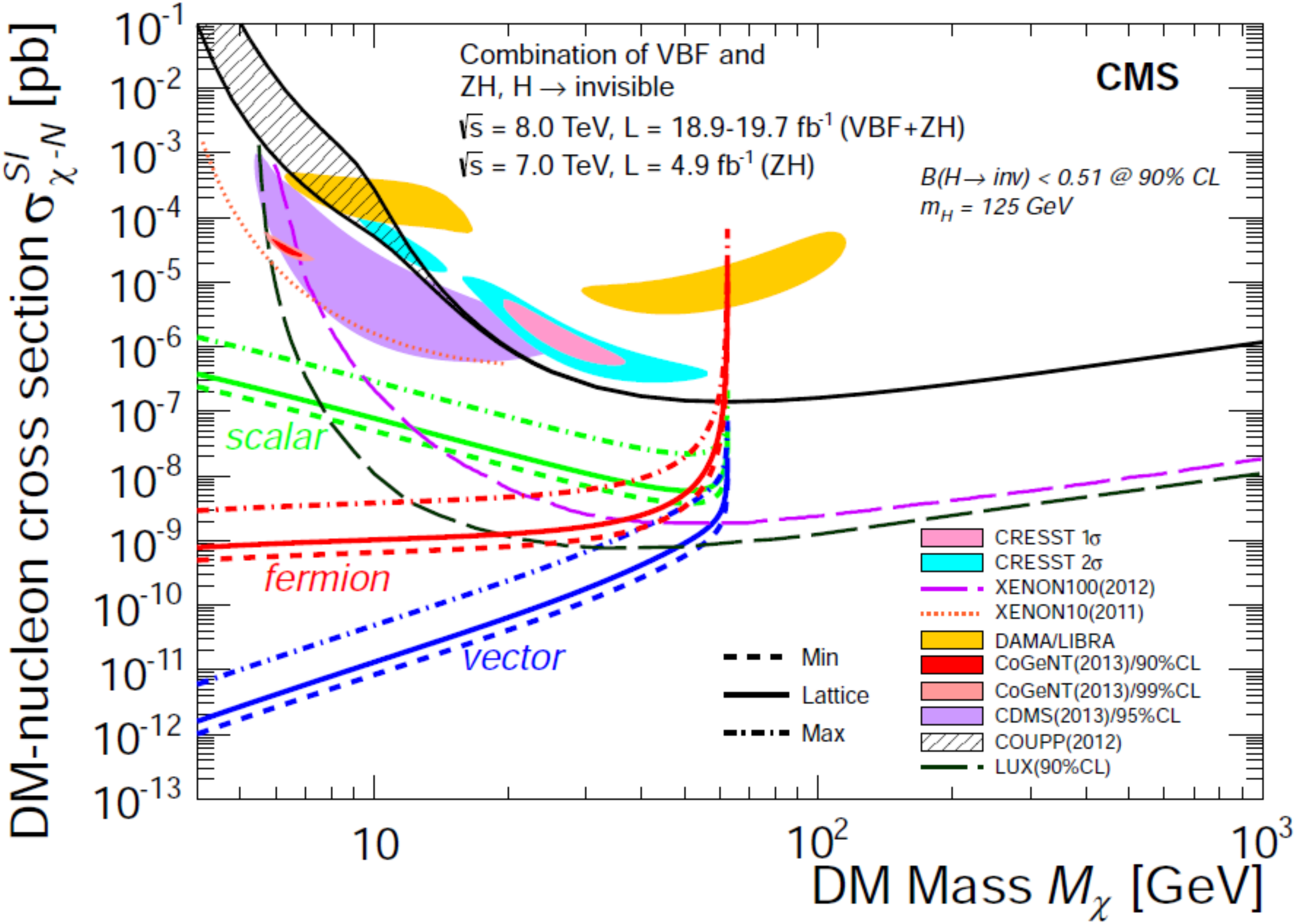
- Search for Higgs decay to invisible particles
- Need to tag production:
  - ZH, Z→ll ATLAS/CMS
    - ZZ background dominates
  - ZH, Z→bb CMS
  - VBF (CMS)
    - Z+jets b
- Control of missing energy essential
- Limits:
  - Br < 75% (62%) - ATLAS
  - Br < 58% (44%) - CMS





ArXiv:

DM in Higgs-portal model



Higgs Width

- 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

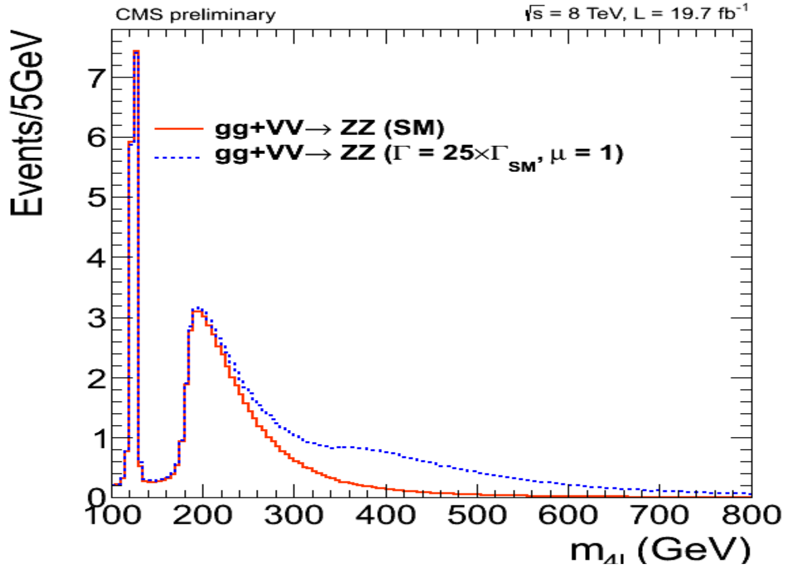
Width via ZZ mass distribution

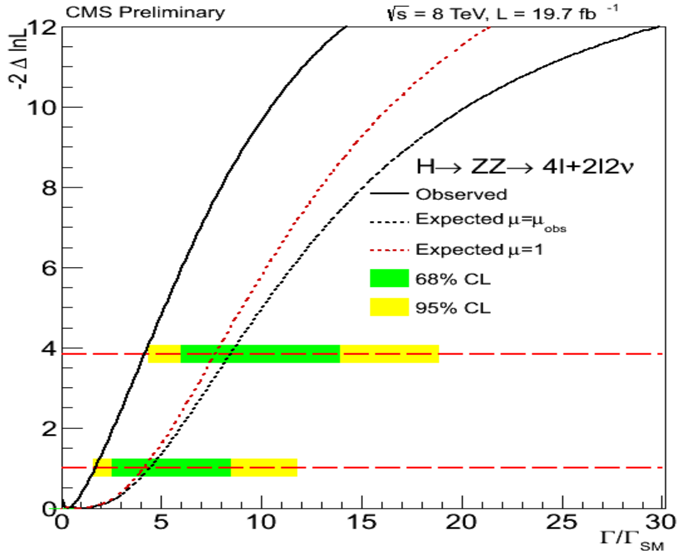
- Use observed lineshape

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

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

- Need to understand interference with gg→ZZ
  - Assume K-factors same to 10%
- Take measured on-peak σH
- Using ZZ in llll and llvv 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 next? Run 2 and beyond

- The increased beam energy increases cross-sections by a factor 2.7
  - ...and a factor 5 for ttH

- $100fb^{-1}$ 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 find SUSY in Higgs decays – or vice versa

- Then $300fb^{-1}$, and finally $3000fb^{-1}$ will allow detailed explorations
  - Maybe even access to the self-coupling

To conclude

- 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...


Thank You!