The Higgs boson from LEP to LHC

Kalmus-Fest
RAL 16th April

Bill Murray
STFC-RAL / University of Warwick
bill.murray@stfc.ac.uk

- **Higgs at LEP**
- **LHC**
- **What do we know?**

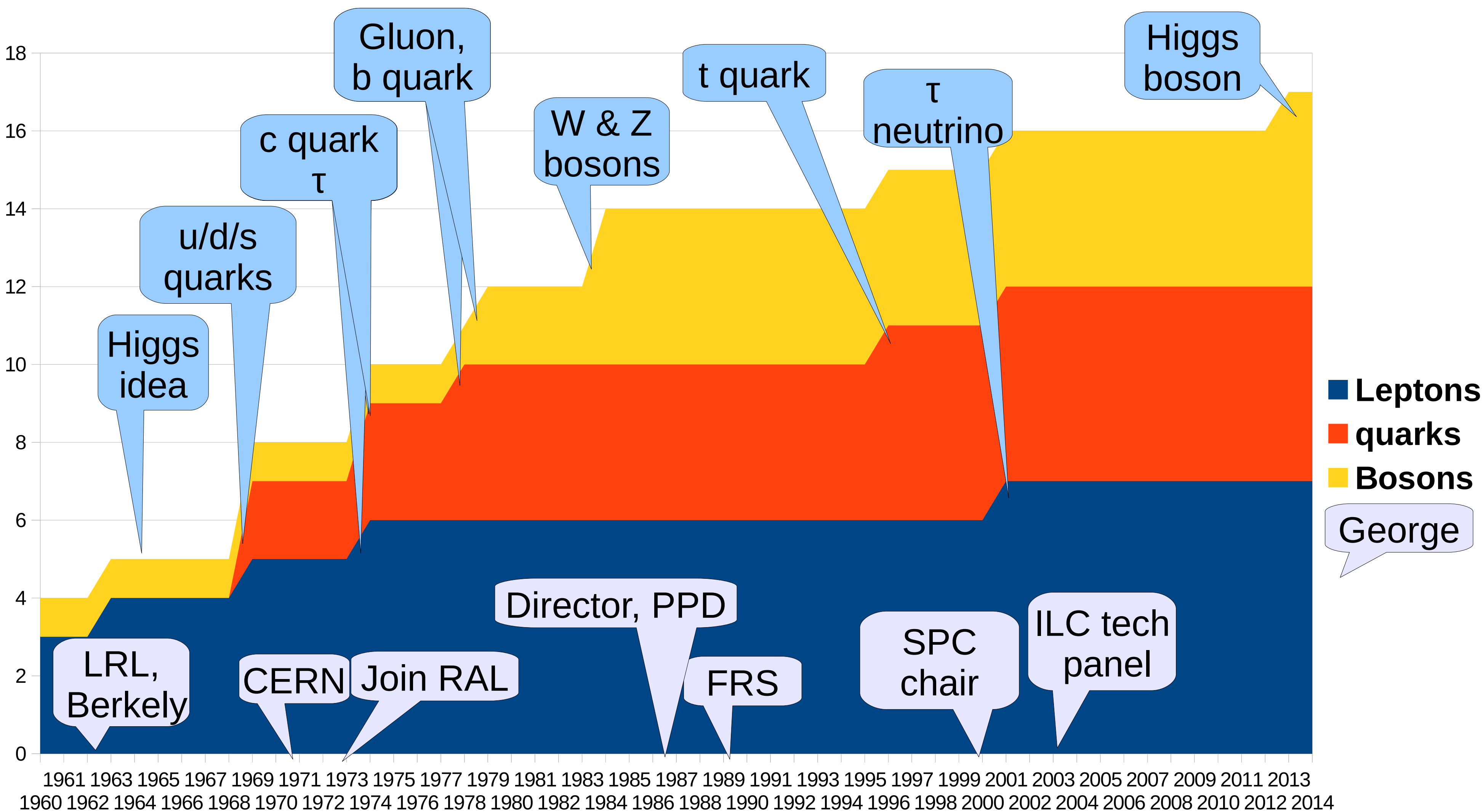
What is Higgs' model?

Full

Empty

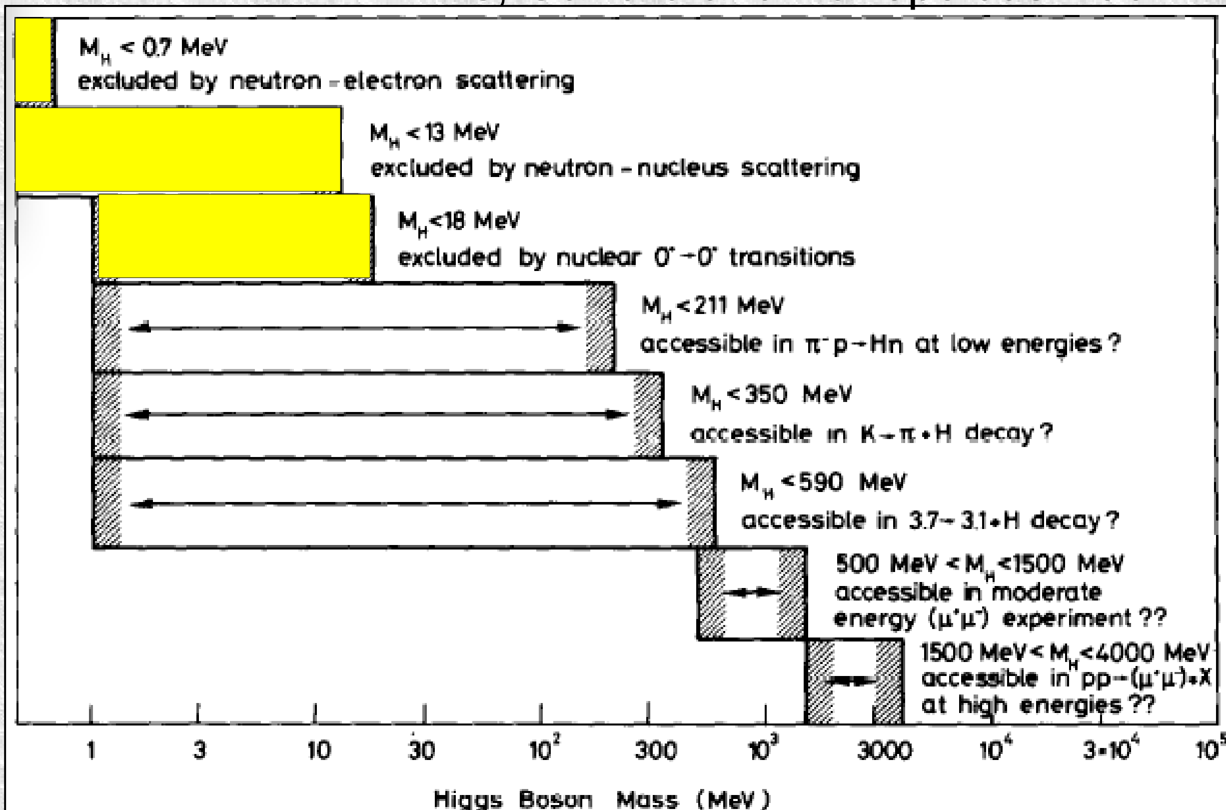
- How to add mass to the SM lagrangian?
- BEH mechanism is a field, with a v.e.v., filling all space
  - Like the fish we don't see it, cannot escape it
- So how do we know it is there?
- The Higgs boson is the quantum of the field
  - Kick the vacuum with a W or Z and one should appear
  - Nb: Z carries 0 weak hypercharge, H is charged....
- The LHC was designed to kick the vacuum hard enough

Timeline for the players



View from 1975

Ellis, Gaillard and Nanopolous Nucl. Phys. B 106 (1976) 292.



Higgs boson is here

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

LEP History

- 1976: CERN discussion of LEP physics case
  - Z mass of 90, W pairs were thhe prime targets
  - Electro-weak symmetry breaking was discussed
  - SUSY merited half a sentence
- 1979: LEP was a 30km machine, up to 130 GeV/beam
  - This would have increased Higgs reach a lot...
- 1983 Work on the 26.67kn machine started
- 1989 First beam
  - 1989-1994 Main Z data (91 GeV)
    - $Z \rightarrow HZ^*$ search
  - 1995-2000 LEP II (130-208 GeV)
    - $Z^* \rightarrow HZ$ search
- 2000 Last beam

COLLEPS/DELPHI plans, 1981

- Ugo Amaldi tried to collect issues:

Turning to more detailed points, the following questions emerged on which some work is needed.

Questions to be answered:

1. Why do we need to identify π^0, η^0, γ? (Higgs?).

   What resolution in m can be obtained realistically?

   How well can e.m. calorimetry separate e/π?

   Can use of Čerenkov counters help?

   What is the cost vs R of various e.m. calorimeters?

   [The ORSAY group will study these questions].

   What is the effect of magnetic field on the proposed projection quantameter?

   [H.-G. FISCHER]

   Offline analysis problems of such a device? [BERGEN + STOCKHOLM*].

Glasgow Herald, sept 12 1989

The elusive Higgs particle could hold secret of weight

PHYSICISTS are using the biggest machine in the world to replicate a theory which an Edinburgh professor worked out on his blackboard more than 20 years ago.

The Higgs particle, whose existence was suggested by Professor Peter Higgs of Edinburgh University in the 1960s, is one of the phenomena scientists are hoping to spot at the £300m Cern Large Electron-Positron Collider (Lep) near Geneva. The particle could hold the secret of weight and gravity, and its existence is thought to be crucial to many of the experiments which a multi-national team of scientists have been carrying out at Lep.

Its importance is such that confirmation of its existence could merit a Nobel Prize for the professor, one of the UK scientists taking part in Lep said in describing their early findings to the annual meeting.

The object of Lep is to replicate the kind of collision between particles of matter and anti-matter which were happening within microseconds of the Big Bang — the point, scientists believe, when the universe began.

Working in a fashion analogous to a television tube, injectors hurl the electrons and positrons at each other round a 27 km diameter tunnel set 150 metres underground in the Franco-Swiss border area. A blunderbuss technique is used, with five million million electrons and positrons fired every 12 minutes and colliding at a rate of about 10 a million.

A battery of instruments is used to detect the collisions and spin-off of fragments, known as Z particles, the first of which occurred towards the end of last month. These Z particles, or bozons, decay into quarks, believed to be the fundamental building blocks of matter.

When the Lep is wound up to full power the scientists hope to detect millions of these Z bozons per year including, they hope, the elusive Higgs bozon, which is thought to give mass to other particles.

The Higgs bozon is envisaged as taking the form of a cloud around the other bozons and transferrable from one to the other on impact. This would explain why the particles under study at Lep appear to have no mass, which if true would mean there was no such thing as weight.

Professor George Kalmus, of the Rutherford Appleston Laboratory, said: "If the Higgs particle were discovered it would be worth a Nobel Prize, and I think Peter Higgs would stand a reasonable chance of getting it, although it might be an institutional award."

The £50m which Britain has already contributed to the project has raised questions about its value, but Professor Kalmus said: "Particle physics is a curiosity-led science which can change the way we look at the universe. Its importance is a cultural one at the moment, but the development of lasers came 40 to 45 years after the development of quantum mechanics on which they are based."

Glasgow Herald, sept 12 1989

The elusive Higgs particle could hold secret of weight

PHYSICISTS are using the biggest machine in the world to replicate a theory which an Edinburgh professor worked out on his blackboard more than 20 years ago.

The Higgs particle, whose existence was suggested by Professor Peter Higgs of Edinburgh University in the 1960s, is one of the phenomena scientists are hoping to spot at the £300m Cern Large Electron-Positron Collider (Lep) near Geneva. The particle could hold the secret of weight and gravity, and its existence is thought to be crucial to many of the experiments which a multi-national team of scientists have been carrying out at Lep.

Its importance is such that confirmation of its existence could merit a Nobel Prize for the professor, one of the UK scientists taking part in Lep said in describing their early findings to the annual meeting.

The object of Lep is to replicate the kind of collision between particles of matter and anti-matter which were happening within microseconds of the Big Bang — the point, scientists believe, when the universe began.

Working in a fashion analogous to a television tube, injectors hurl the electrons and positrons at each other round a 27 km diameter tunnel set 150 metres underground in the Franco-Swiss border area. A blunderbuss technique is used, with five million million electrons and positrons fired every 12 minutes and colliding at a rate of about 10 a million.

A battery of instruments is used to detect the collisions and spin-off of fragments, known as Z particles, the first of which occurred towards the end of last month. These Z particles, or bozons, decay into quarks, believed to be the fundamental building blocks of matter.

When the Lep is wound up to full power the scientists hope to detect millions of these Z bozons per year including, they hope, the elusive Higgs bozon, which is thought to give mass to other particles.

The Higgs bozon is envisaged as taking the form of a cloud around the other bozons and transferrable from one to the other on impact. This would explain why the particles under study at Lep appear to have no mass, which if true would mean there was no such thing as weight.

Professor George Kalmus, of the Rutherford Appleston Laboratory, said: "If the Higgs particle were discovered it would be worth a Nobel Prize, and I think Peter Higgs would stand a reasonable chance of getting it, although it might be an institutional award."

The £50m which Britain has already contributed to the project has raised questions about its value, but Professor Kalmus said: "Particle physics is a curiosity-led science which can change the way we look at the universe. Its importance is a cultural one at the moment, but the development of lasers came 40 to 45 years after the development of quantum mechanics on which they are based."

Glasgow Herald, sept 12 1989

The elusive Higgs particle could hold secret of weight

PHYSICISTS are using the biggest machine in the world to replicate a theory which an Edinburgh professor worked out on his blackboard more than 20 years ago.

The Higgs particle, whose existence was suggested by Professor Peter Higgs of Edinburgh University in the 1960s, is one of the phenomena scientists are hoping to spot at the £300m Cern Large Electron-Positron Collider (Lep) near Geneva. The particle could hold the secret of weight and gravity, and its existence is thought to be crucial to many of the experiments which a multi-national team of scientists have been carrying out at Lep.

Its importance is such that confirmation of its existence could merit a Nobel Prize for the professor, one of the UK scientists taking part in Lep said in describing their early findings to the annual meeting.

The object of Lep is to replicate the kind of collision between particles of matter and anti-matter which were happening within microseconds of the Big Bang — the point, scientists believe, when the universe began.

Working in a fashion analogous to a television tube, injectors hurl the electrons and positrons at each other round a 27 km diameter tunnel set 150 metres underground in the Franco-Swiss border area. A blunderbuss technique is used, with five million million electrons and positrons fired every 12 minutes and colliding at a rate of about 10 a million.

A battery of instruments is used to detect the collisions and spin-off of fragments, known as Z particles, the first of which occurred towards the end of last month. These Z particles, or bozons, decay into quarks, believed to be the fundamental building blocks of matter.

When the Lep is wound up to full power the scientists hope to detect millions of these Z bozons per year including, they hope, the elusive Higgs bozon, which is thought to give mass to other particles.

The Higgs bozon is envisaged as taking the form of a cloud around the other bozons and transferrable from one to the other on impact. This would explain why the particles under study at Lep appear to have no mass, which if true would mean there was no such thing as weight.

Professor George Kalmus, of the Rutherford Appleston Laboratory, said: "If the Higgs particle were discovered it would be worth a Nobel Prize, and I think Peter Higgs would stand a reasonable chance of getting it, although it might be an institutional award."

The £50m which Britain has already contributed to the project has raised questions about its value, but Professor Kalmus said: "Particle physics is a curiosity-led science which can change the way we look at the universe. Its importance is a cultural one at the moment, but the development of lasers came 40 to 45 years after the development of quantum mechanics on which they are based."

Higgs Searches at LEP 1

These were typically two-jet modes

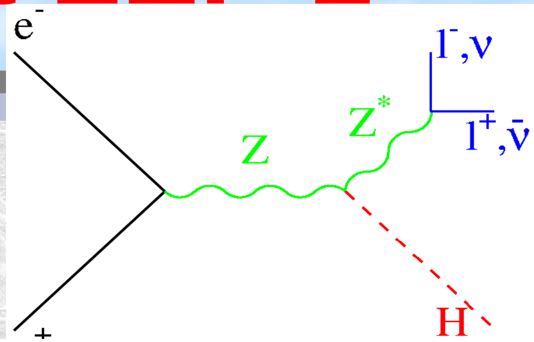
Many modes:

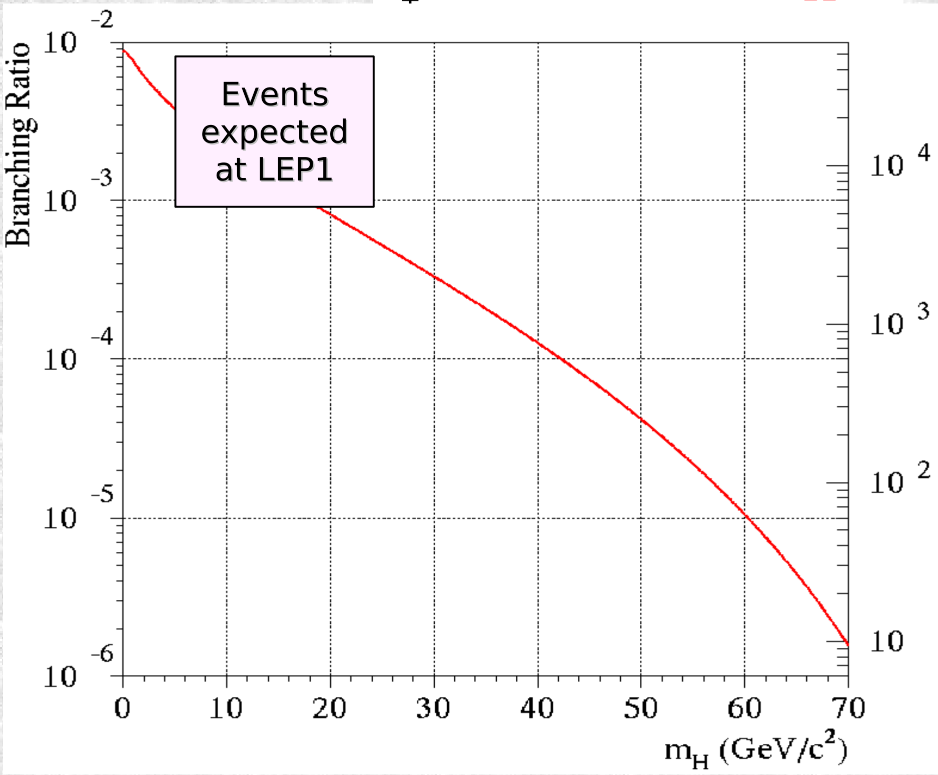
Stable,γγ,ee,μμ,ππ,ρρ, bb

Clean Z decays (ll, νν) used

Prior to LEP only some patchy constraints

The mass range to 0 was excluded, no holes.

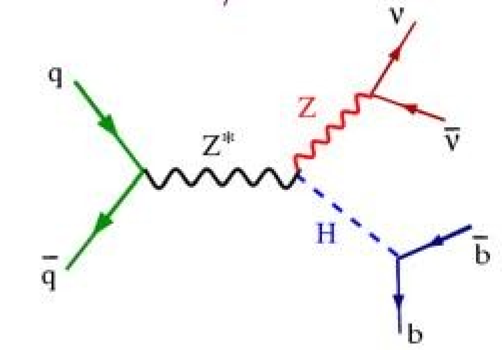




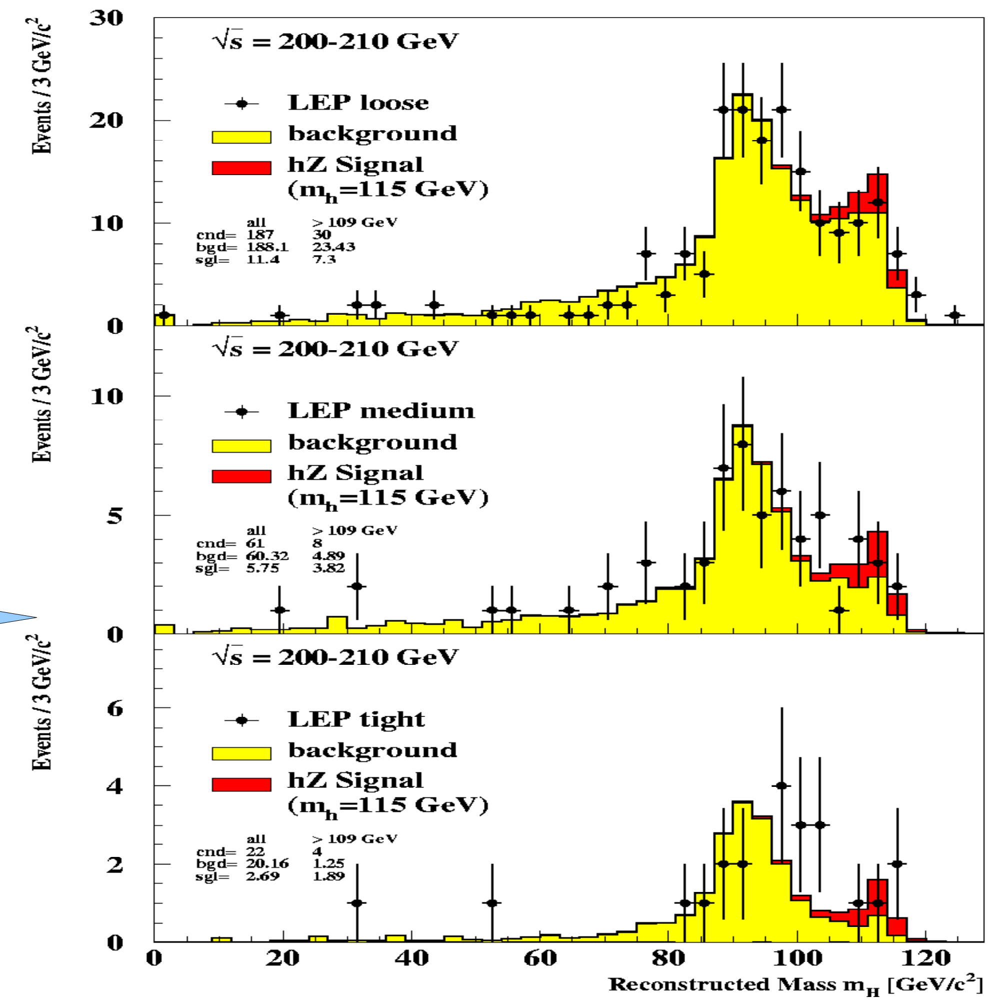
$0.0 < m_H < 65$ GeV/c^2

Excluded at 95% C.L.

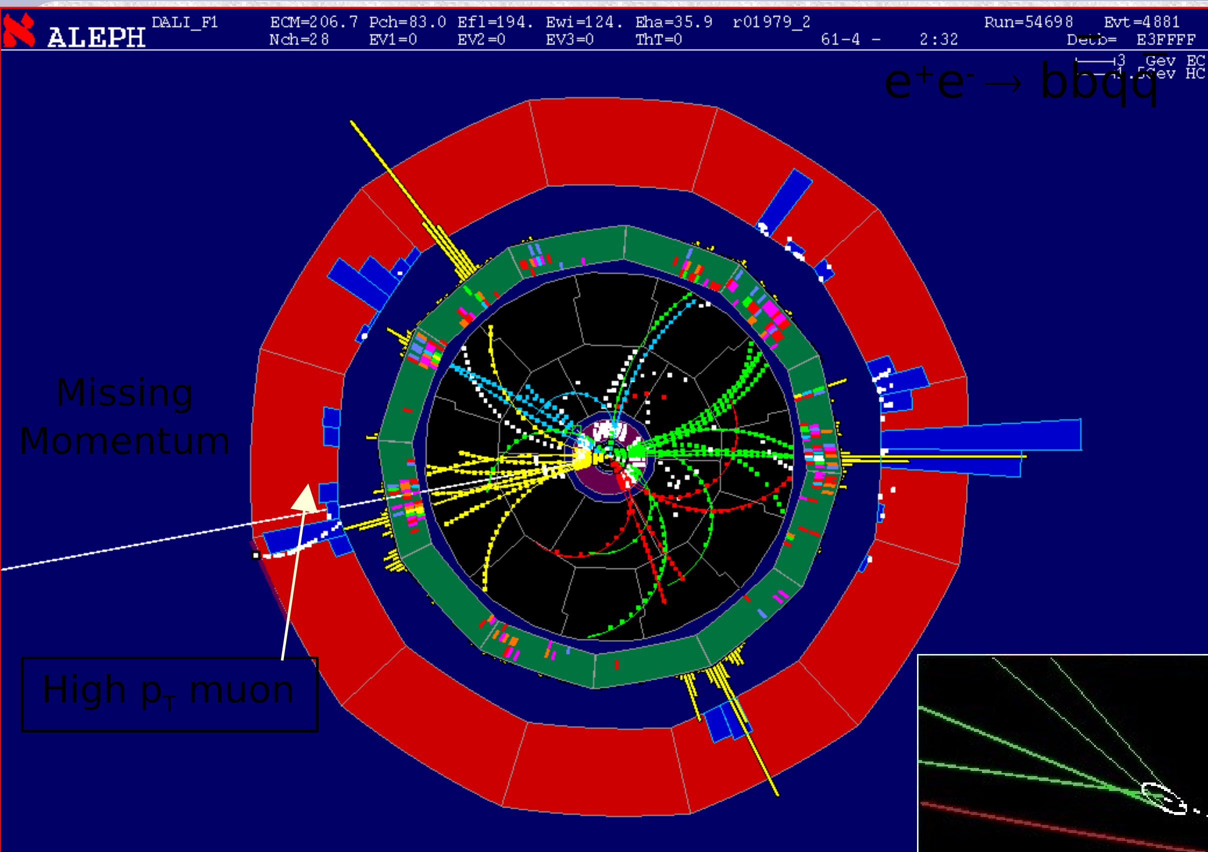
Higgs search at LEP-II



- E_{cm} rose to 208GeV
  - Climbing from 1995 to 2000
- The lead solder dribbled out of the accelerator
- Search using $Z^* \rightarrow ZH$
- Mass reach 208-m_z-2
  - 115 GeV
- In 2000 the combined data looked like this
  - Loose/medium/tight
- The data hinted at a Higgs
  - P-value 0.004 at the time
  - 0.04 when re-done in 2001



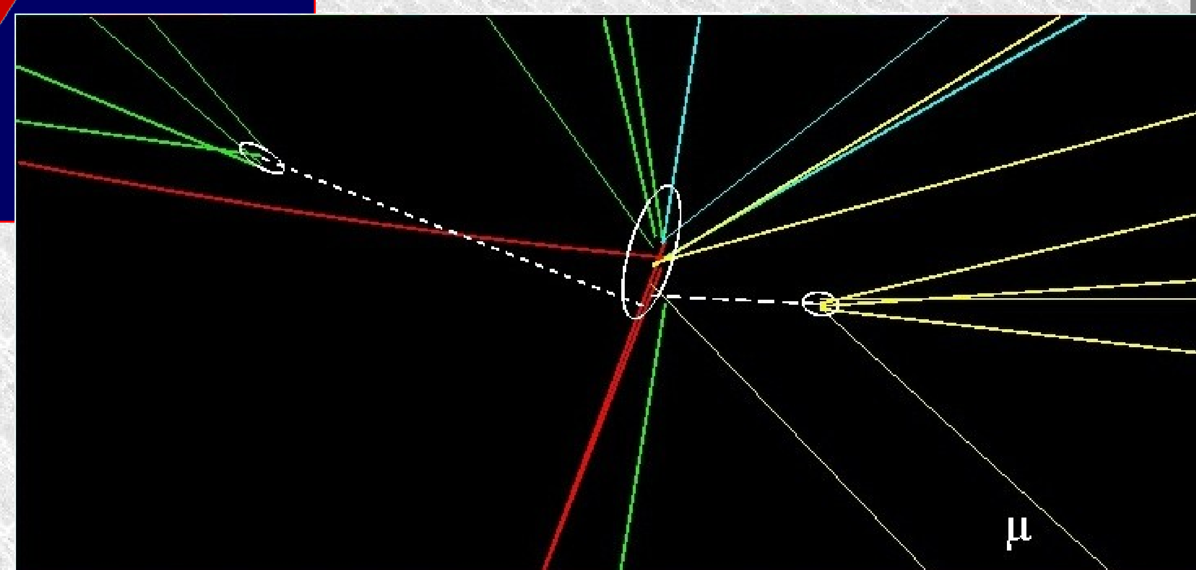
The best candidate: ALEPH



(14-Jun-2000, 206.7 GeV)

Mass 114.3 GeV/c2;
Good HZ fit;
Poor WW and ZZ fits;
P(Background) : 2%
s/b(115) = 4.6

The purest candidate event



b-tagging
(0 = light quarks, 1 = b quarks)

Higgs jets: 0.99 and 0.99;
Z jets: 0.14 and 0.01.

2000: should LEP run in 2001?

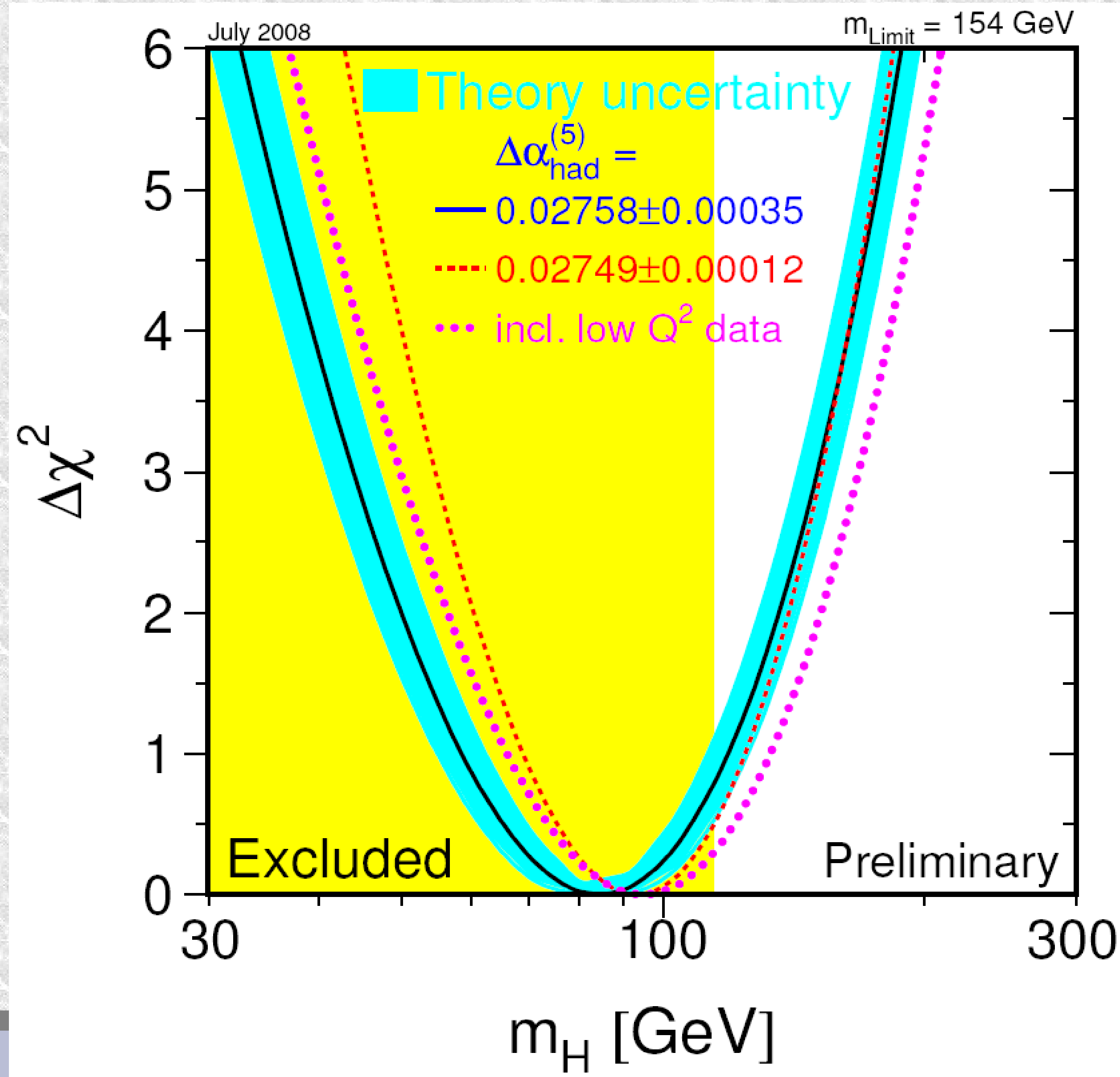
- George was chair of CERN's Scientific Policy Committee and ex-officio a council member
- The Higgs candidates collected that year were a sensation
  - But were not enough to persuade George to lobby for a 2001 run
  - The SPC was ambivalent
- To run LEP in 2001 would have meant cancelling LHC contracts
  - Expensive!
- Finally the committee of council recommended closure
  - With only the UK speaking for continuation

Why expect a light Higgs?

Electroweak fit
(Z properties, W and top mass) give at 95%:

$M_H < 154 GeV/c^2$

$M_H < 185 GeV/c^2$
(including LEP bound)



The Guardian, Aug 21st 2004

- This was an article mostly on ILC, (Ian Halliday was asking for the government for 300M, 10% of the cost)
- George was on the technology recommendation panel

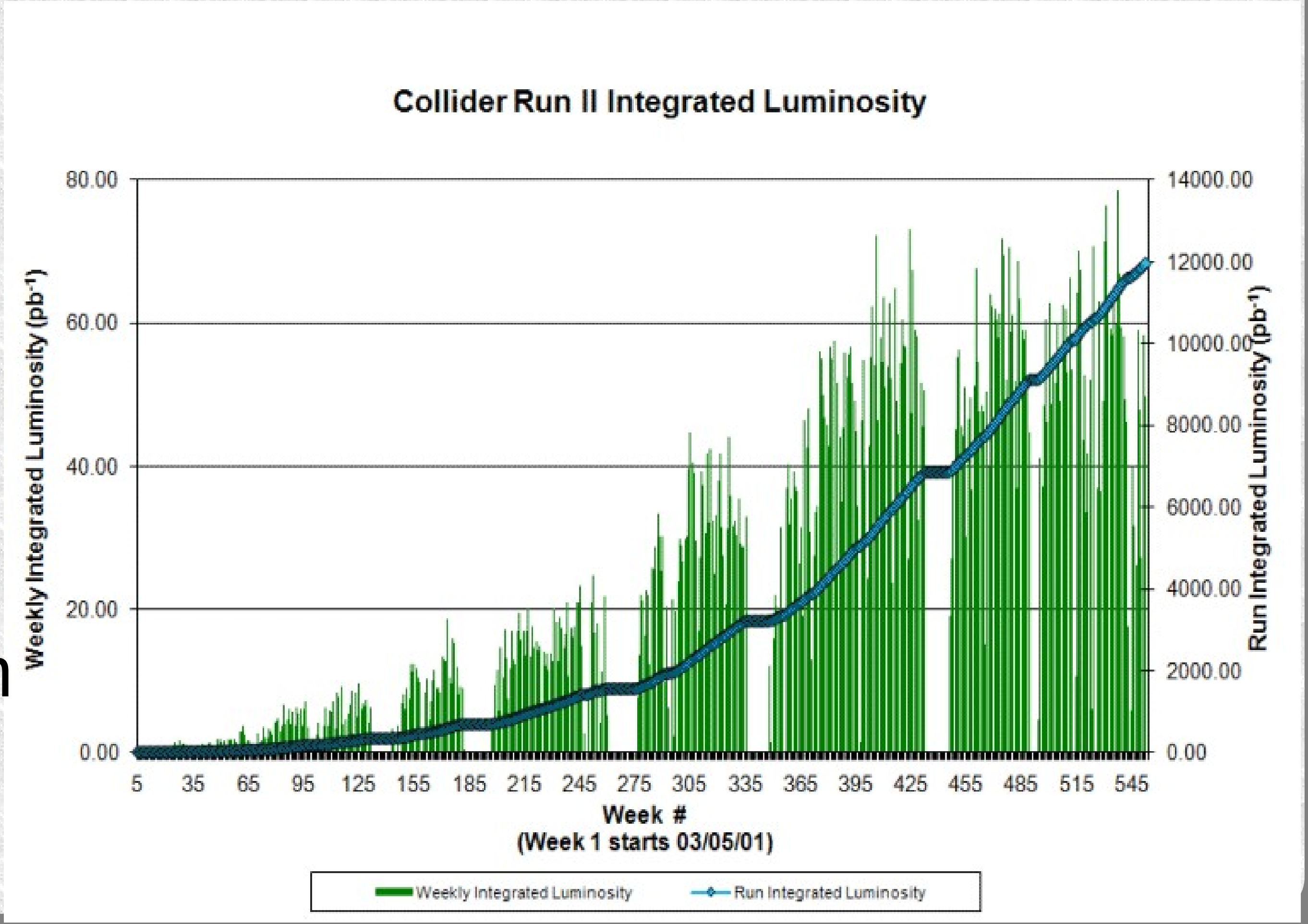
"We keep on looking for the Higgs boson and we keep on not finding it, but we now have an indication of where it is," said Professor Kalmus. He says existing accelerator machines, built in the shape of rings, just cannot get the particles travelling fast enough or to collide with enough force to reach the energy levels where the Higgs particle is believed to exist.

Another accelerator, the large hadron collider, is already under construction at the Cern laboratory under the Swiss Alps and is due to be switched on in 2007. It could have the potential to find the Higgs particle, but will tell physicists little about its interactions.

Prof Kalmus says studying it in more detail is crucial. "The world is running out of easily developed energy sources. If we can learn more about how energy and mass are related in this strange way then who knows what effect that might have."

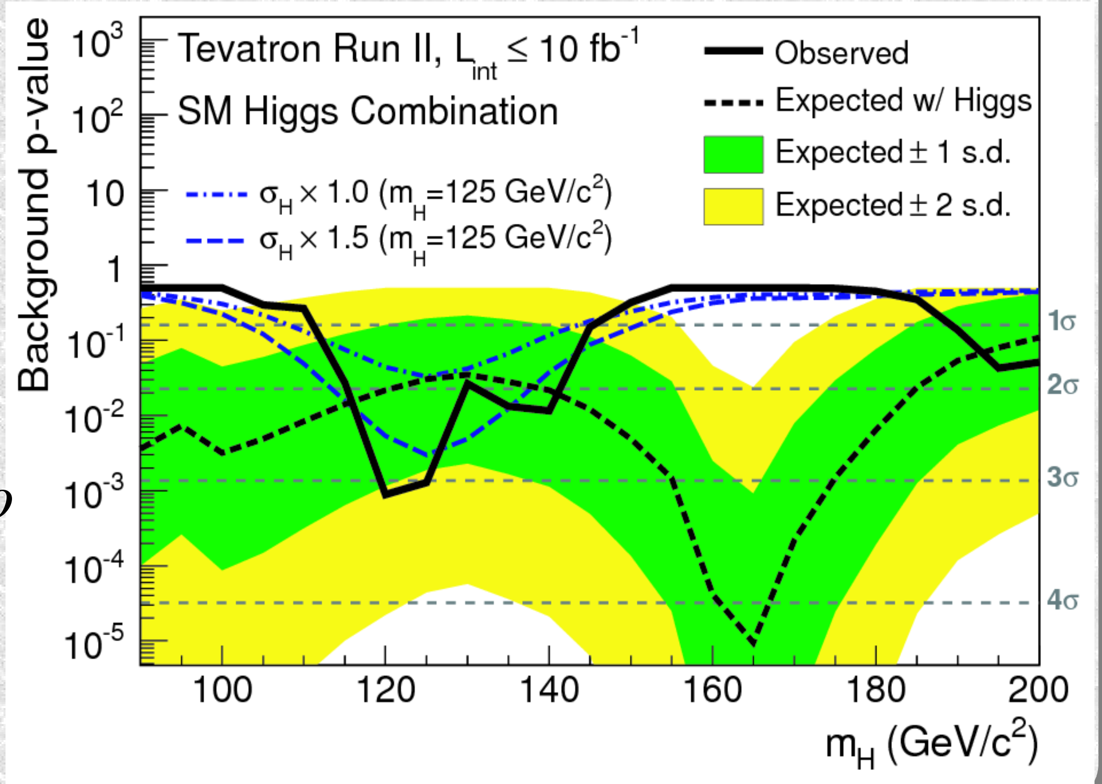
Next up: the Tevatron

- The 6km ring contained a 2TeV $p\bar{p}$ collider which could find the Higgs – given enough luminosity
- After a painful 2001 re-start luminosity did come in well
- But $12fb^{-1}$ delivered took over 10 years
- $p\bar{p} \rightarrow V^* \rightarrow VH$, at low mass, is very much the LEP process
- Lots of enthusiasm

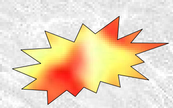


Tevatron Higgs evidence

- In the end, 5σ was not expected anywhere
- But 2-3σ *was* for the most interesting region, 114-150
- And 3σ was indeed observed at around 120-125 GeV.
  - On 2nd July 2012 a press release was issued:
  - *"Tevatron scientists found that the observed Higgs signal in the combined CDF and DZero data in the bottom-quark decay mode has a statistical significance of 2.9 sigma. This means there is only a 1-in-550 chance that the signal is due to a statistical fluctuation."*
  - **Prosecutors fallacy!**

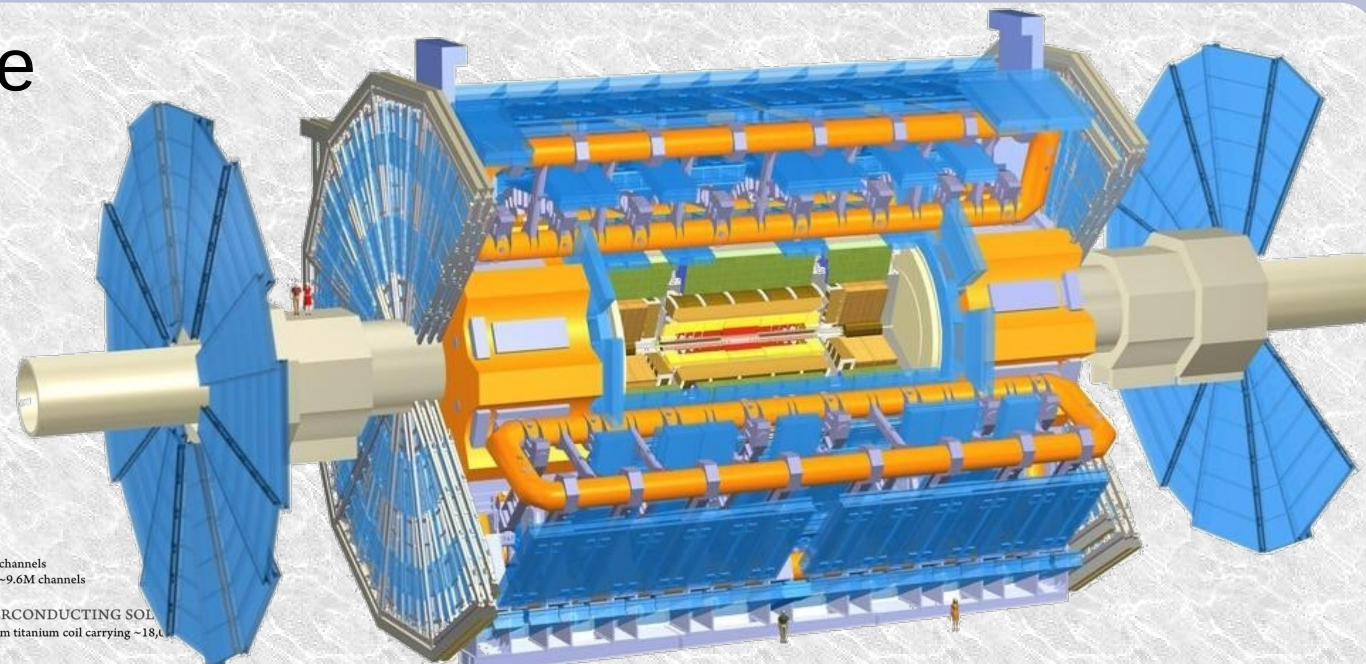


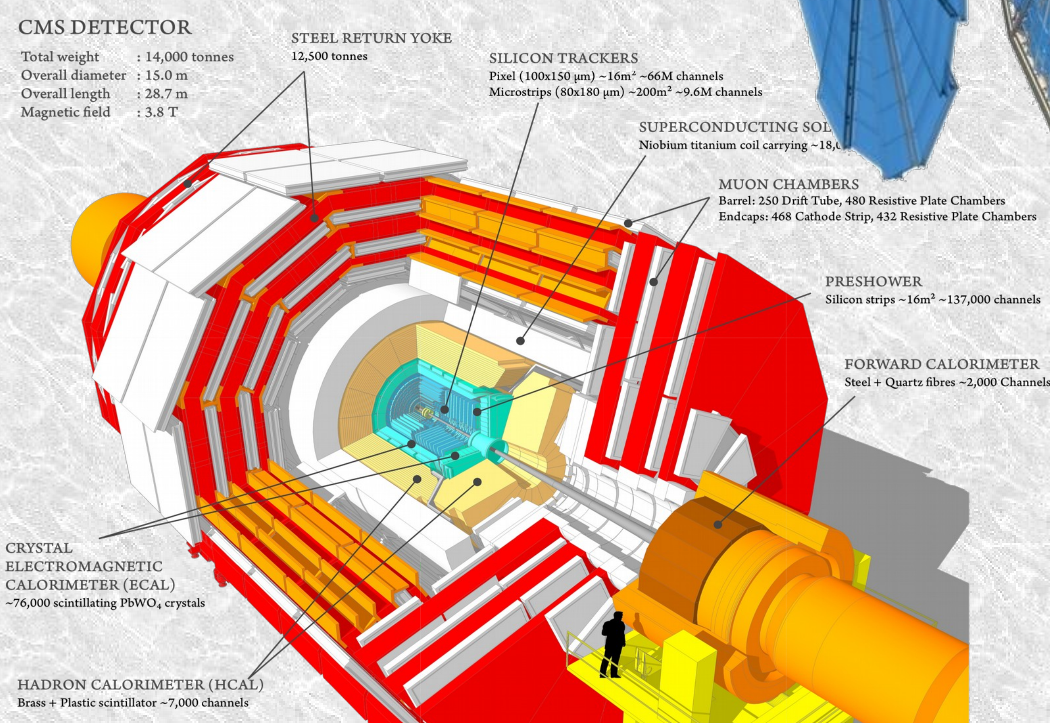
Meanwhile, in Europe

- 21st-27th March 1984: Lausanne workshop "Large Hadron Collider in the LEP tunnel"
- 1st Oct 1992 ATLAS/CMS LOIs published
- 16th Dec 1994 CERN council approves LHC
- 31st May 2002 ATLAS pit digging finished
- 1st February 2005 CMS pit completed
- 26th April 2007 final LHC dipole underground
- 10th September 2008 LHC startup!
- 18th September 2008 Bill arrives in CERN for 1 yr LTA
- 19th September 2009 
- 20 November 2009 beam back in LHC!
- 2010 0.048fb^{-1} at 7 TeV
- 2011 5.1fb^{-1} at 7 TeV
- 2012 23fb^{-1} at 8 TeV: 4th July Higgs discovery announced.

ATLAS & CMS: designed for this

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

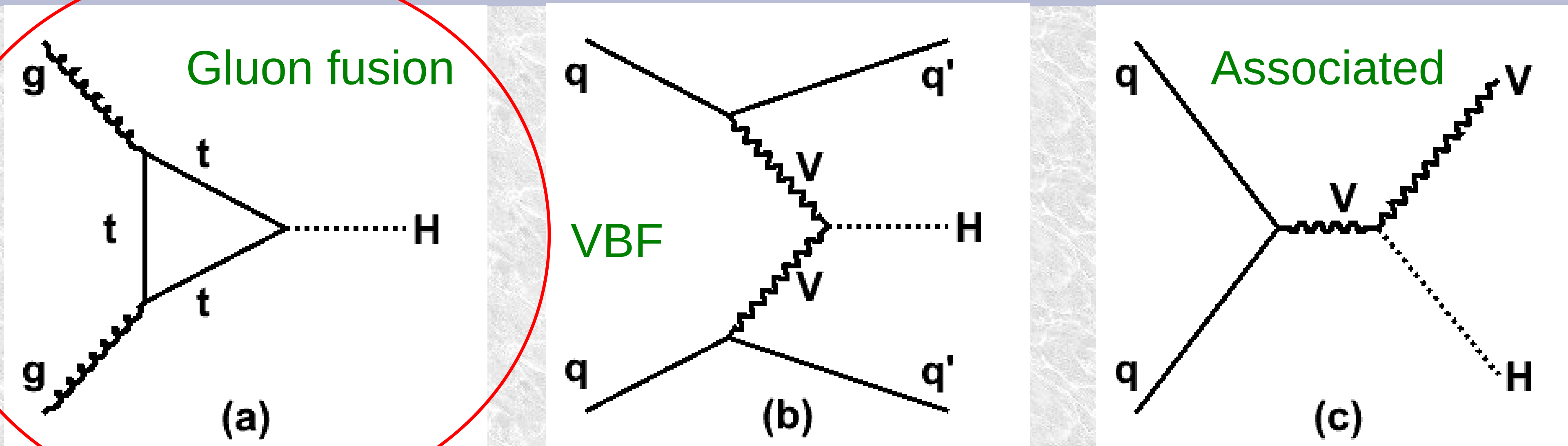




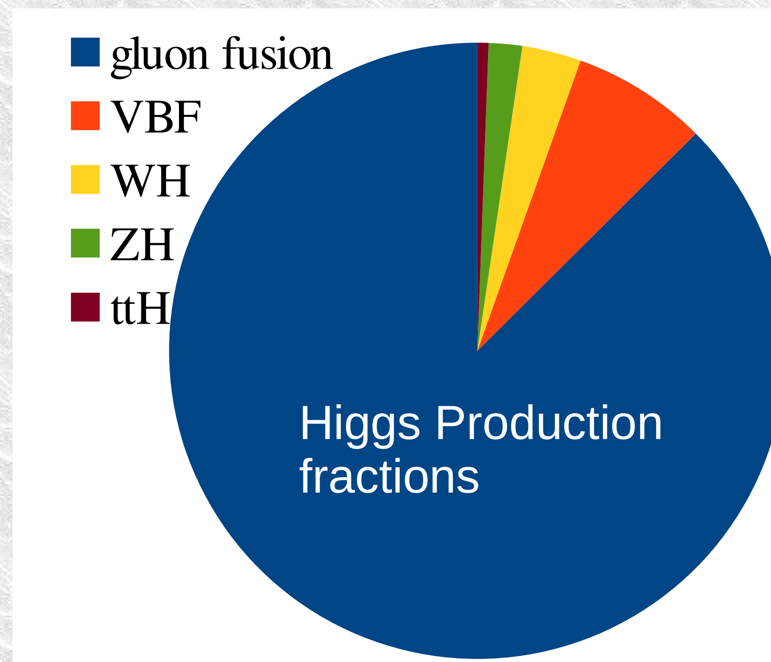
- ATLAS: External magnet provides toroidal muon field
- CMS superb central solenoid

LHC Higgs production

Higgs production

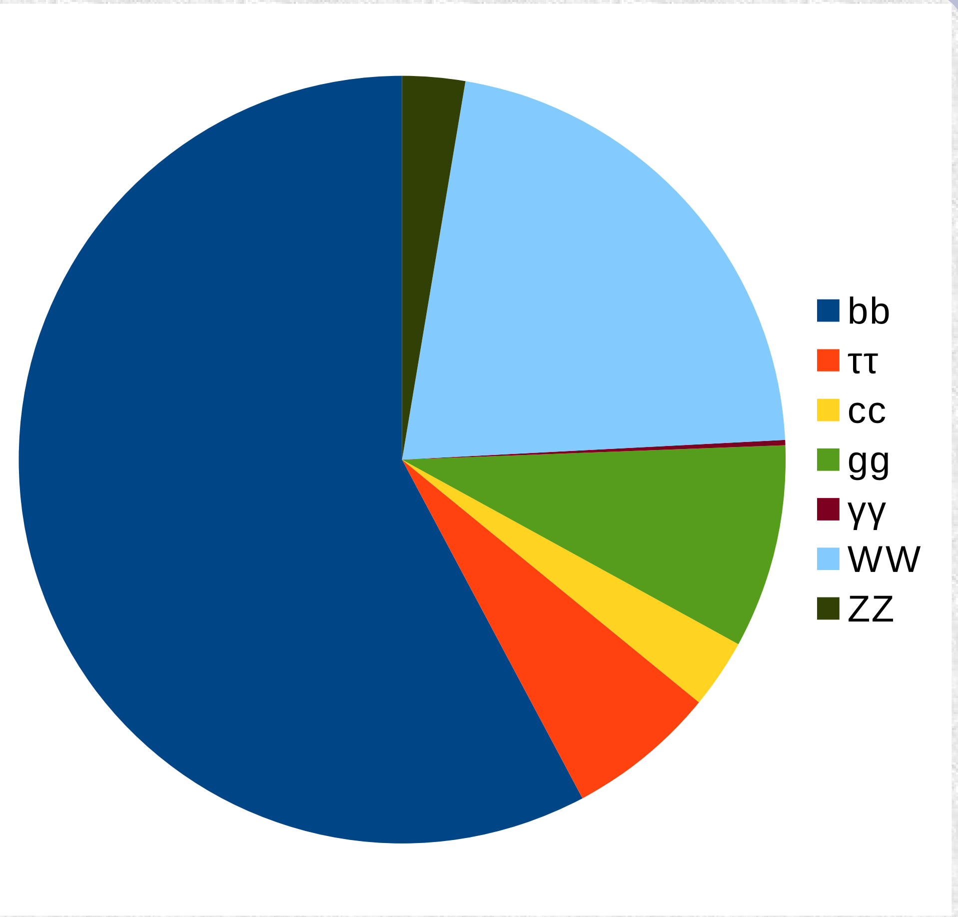


- The three most common modes
  - Others also exist: $t\bar{t}H$, tH , bbH...
- Gluon fusion dominates rate
  - Top loop (+ BSM?)
- Vector boson fusion/associated
  - Also used to tag signal
  - Improves the purity
- ttH: coming soon

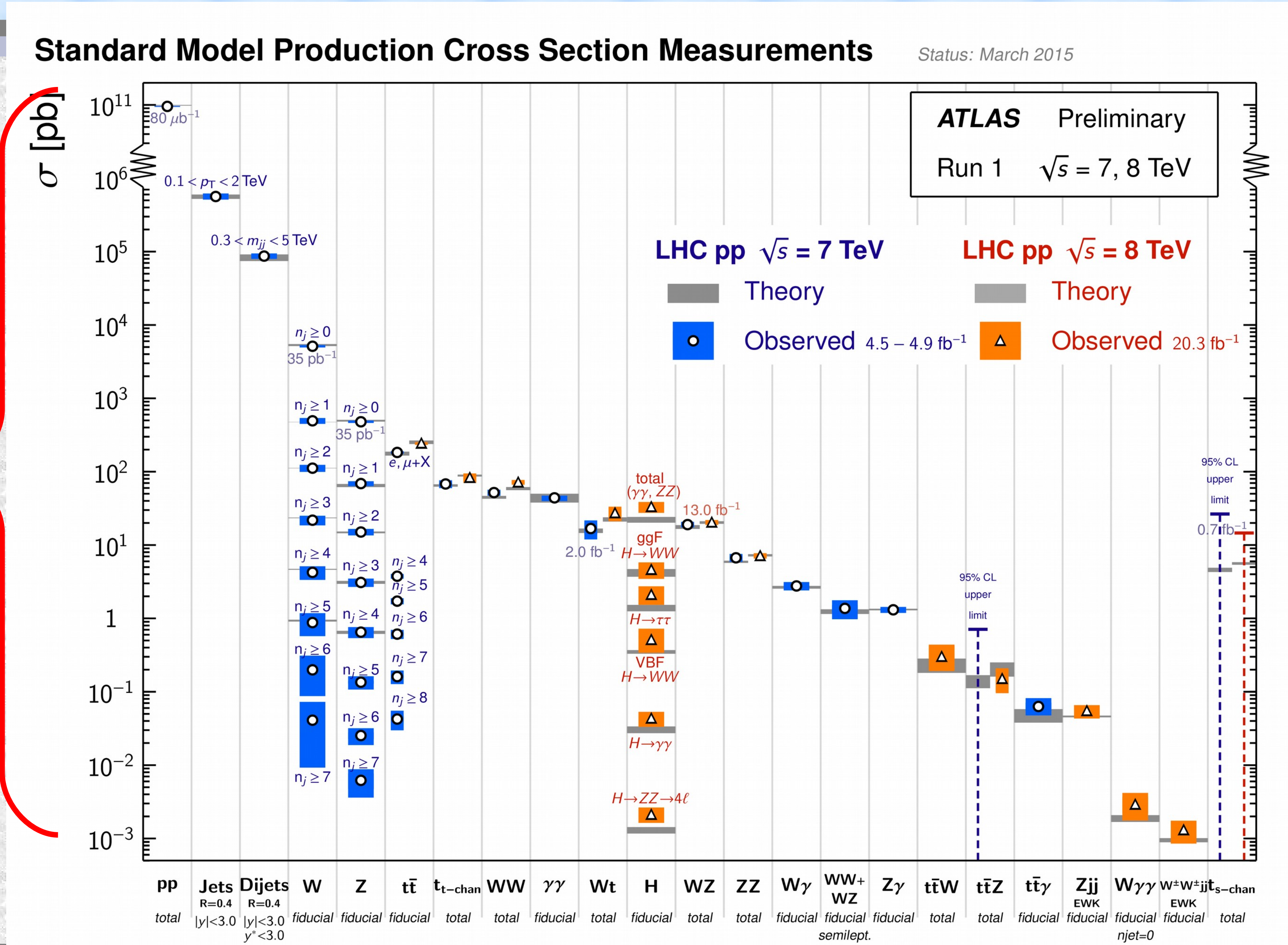


Higgs decay modes used

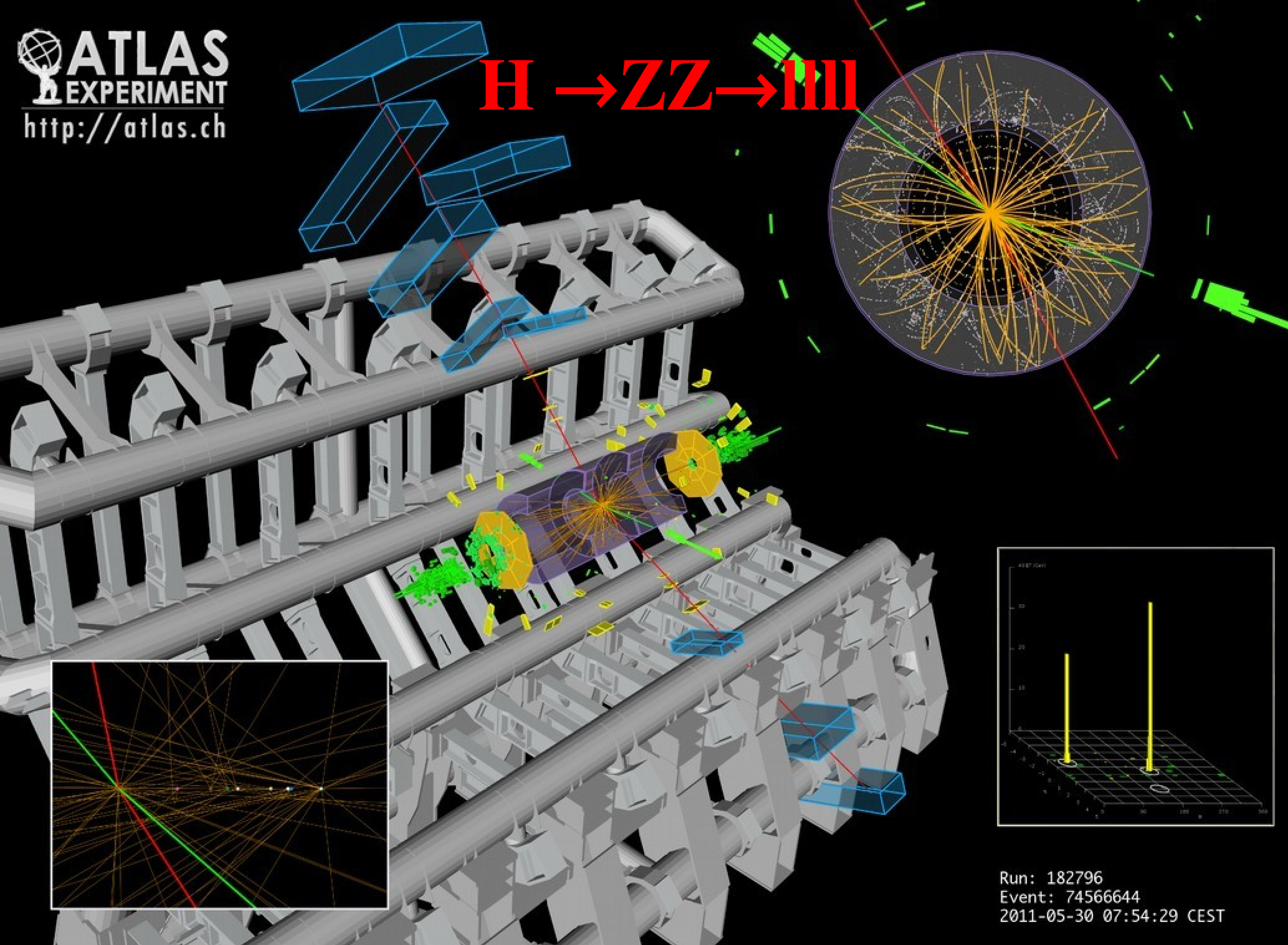
- H → ZZ
  - ZZ → llll: Golden mode
  - ZZ → llνν: Good High mass
  - ZZ → llbb: Also high-mass
- H → WW
  - WW → lνlν: First sensitive
  - WW → lνqq: highest rate
- H → γγ
  - Rare, best for low mass
- H → ττ
  - Uses VBF, low mass
- H → bb
  - $t\bar{t}H$, WH, ZH common but hard



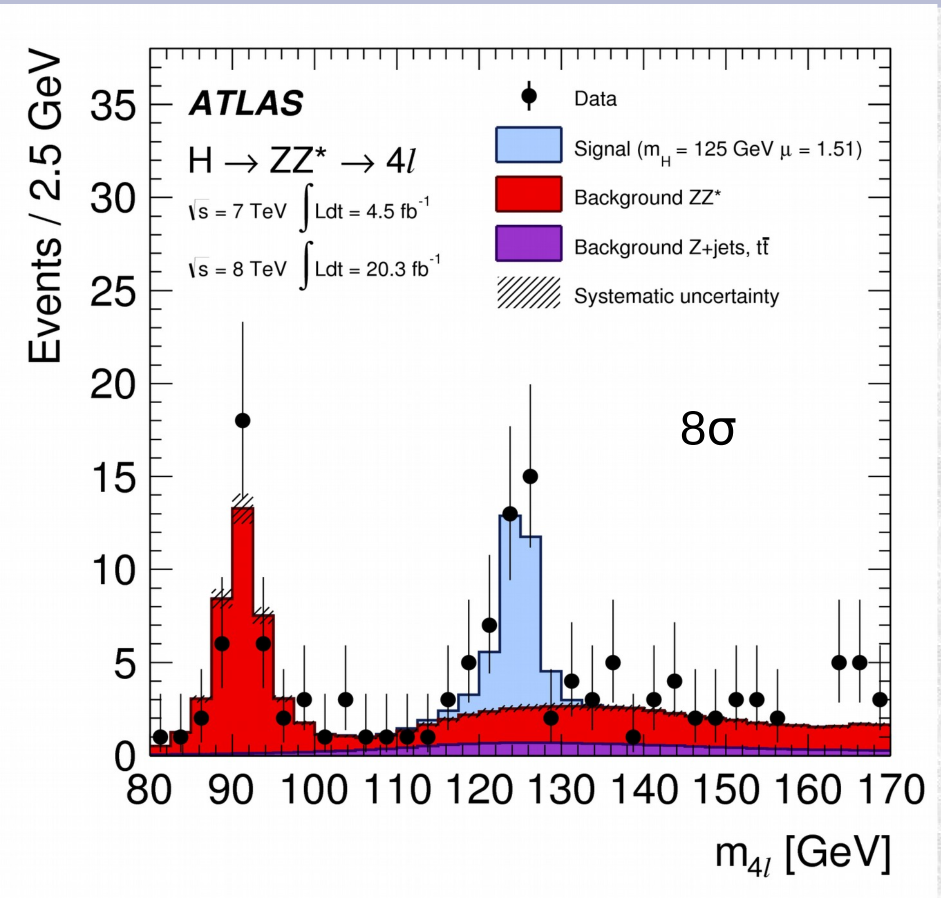
Standard Model measurements

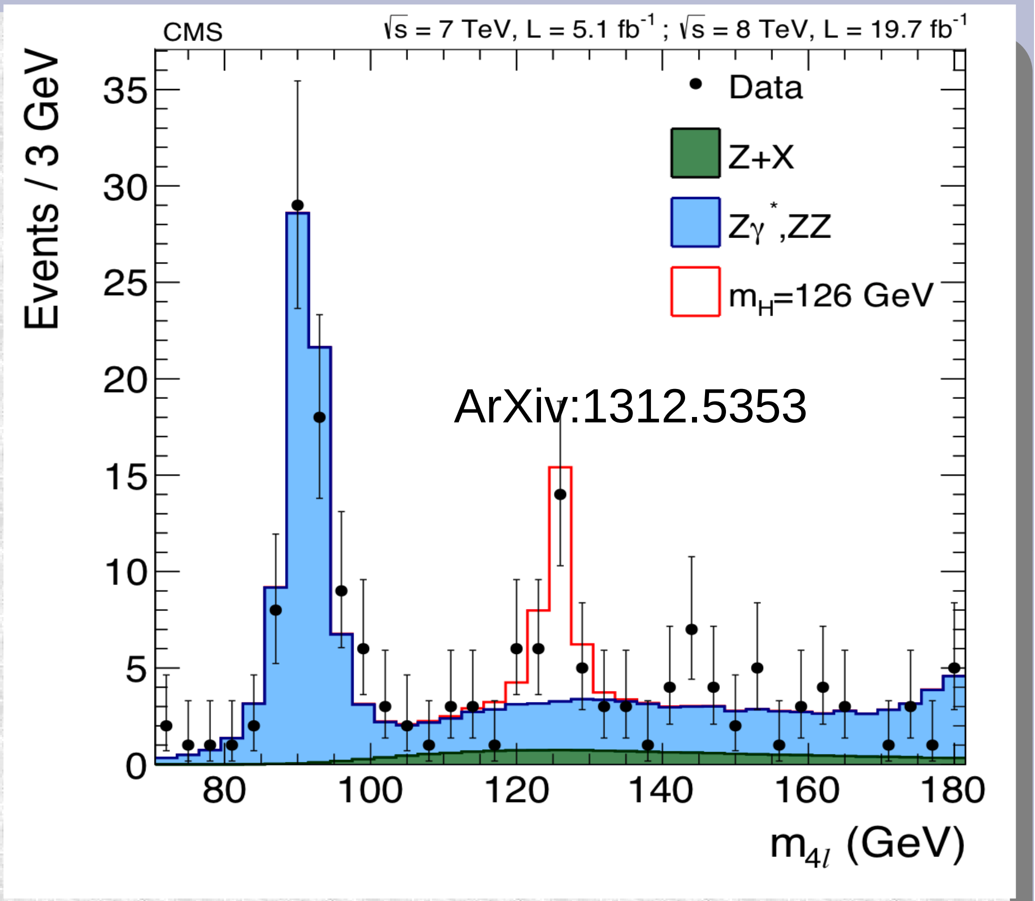


H →ZZ→llll


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

Signal Mass distribution

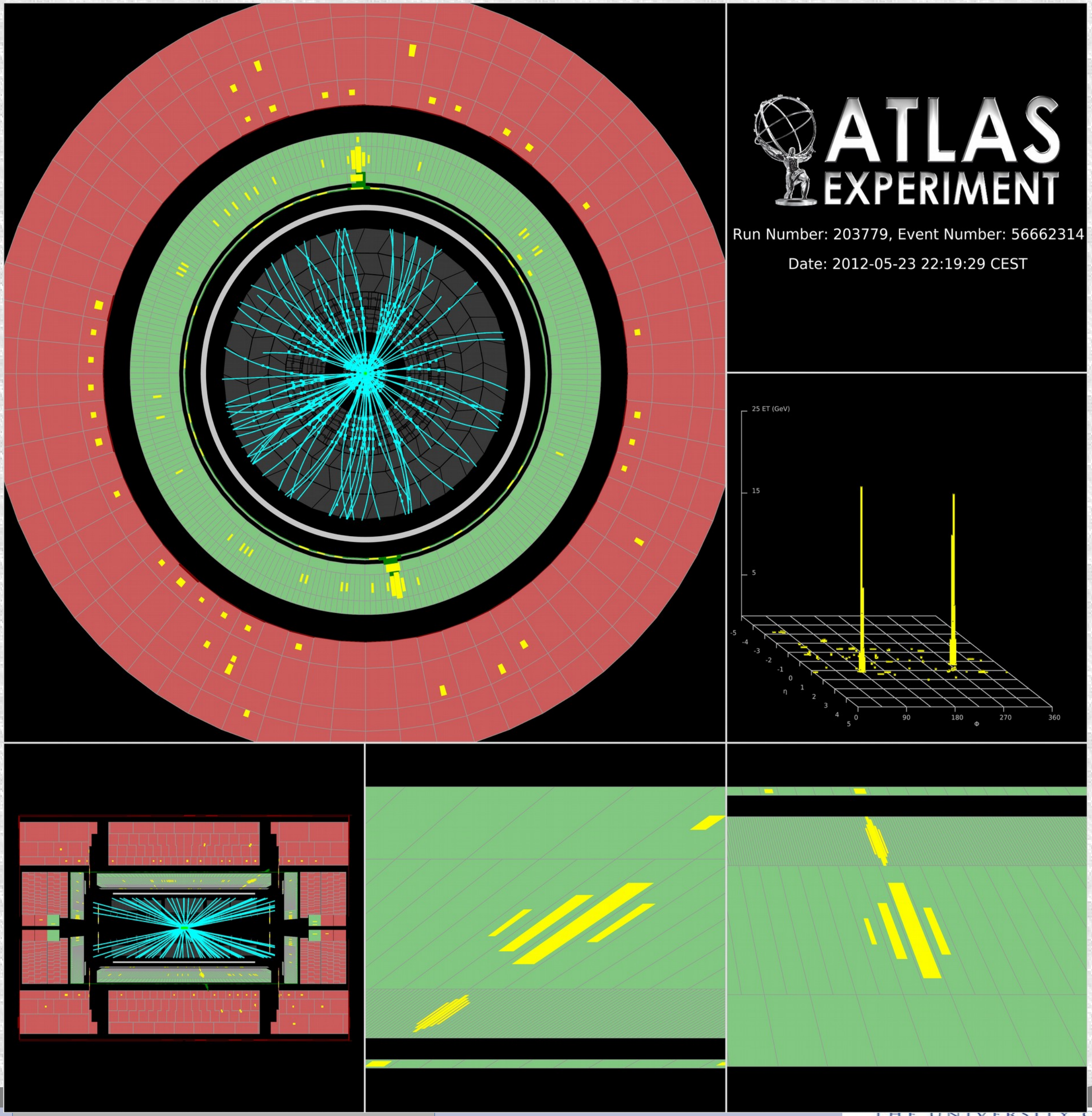




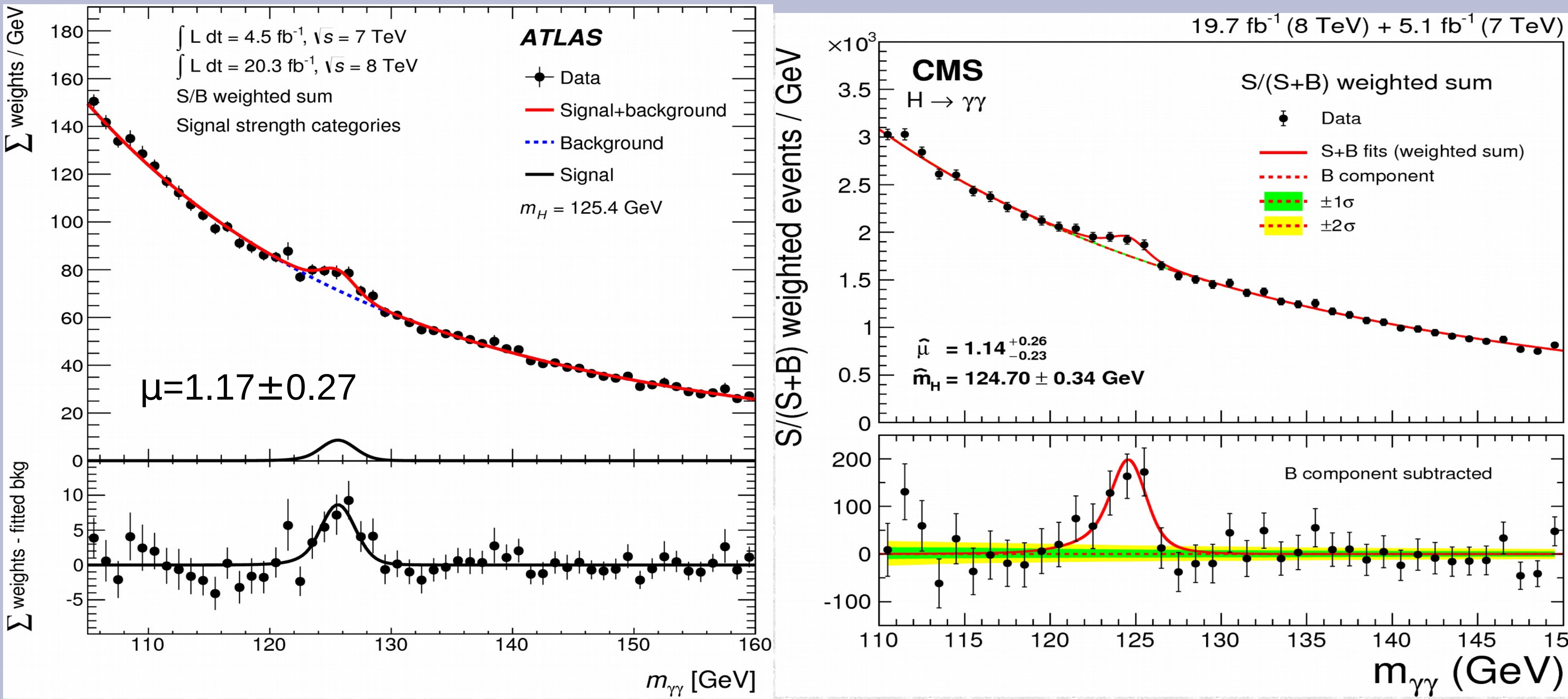
- Clear peak near 125 GeV
  - S/B better than 1
  - The Z→llll peak at 91 GeV is seen too; sanity check
- Matrix element for each event gives better significance

$H \rightarrow \gamma\gamma$

- 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



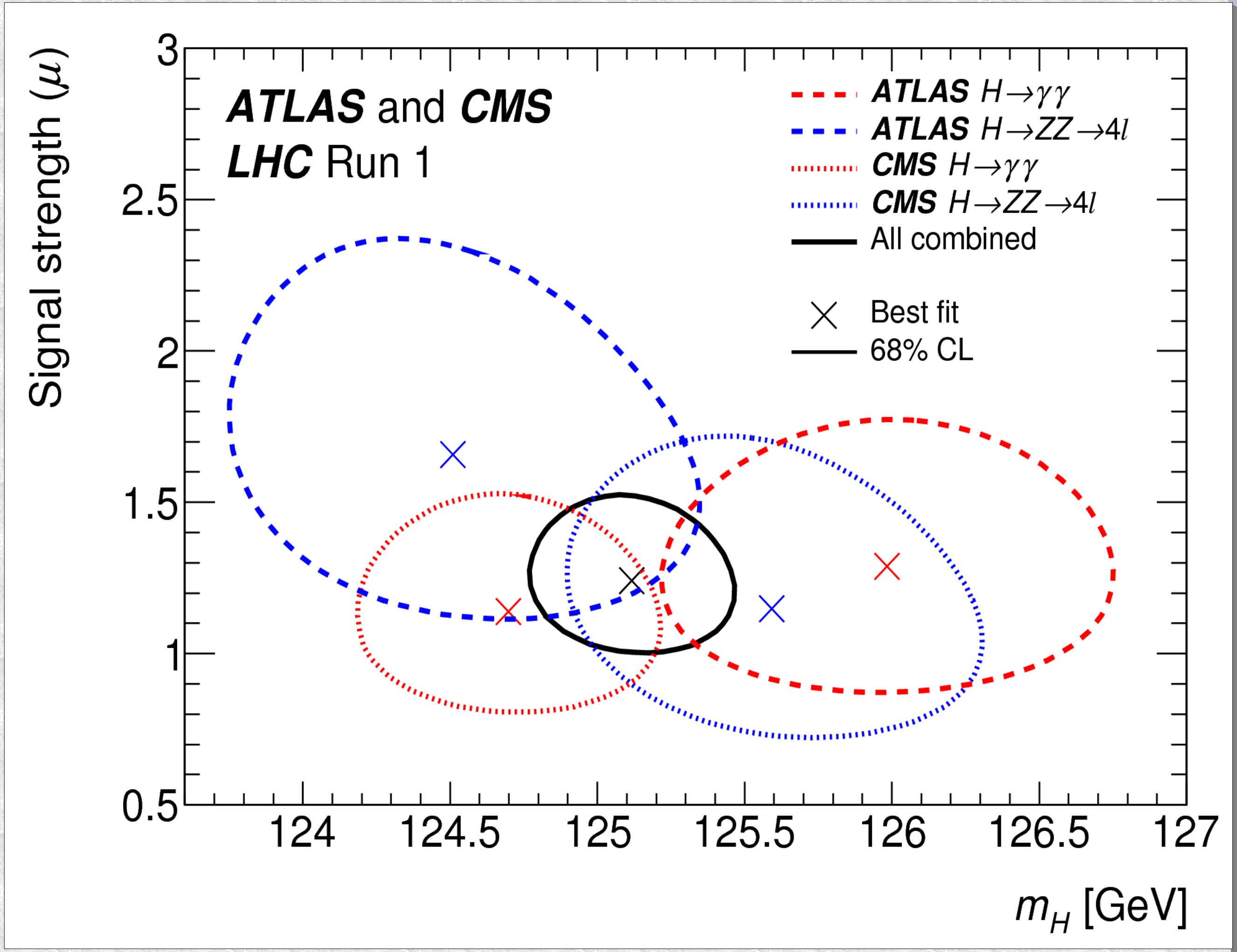
Weighted H →γγ mass spectra



- Finally performance of ATLAS & CMS very similar
- Clearly identified peak, 5.2σ (ATLAS), 5.7σ (CMS)

Higgs Mass Estimation

- Two experiments compatible
  - Combined mass: 125.09±0.21(stat.) ±0.11(syst.)
- Mass measured to ~0.2%
  - Systematics half the size of statistics
- The last parameter of the SM!



Is that it?

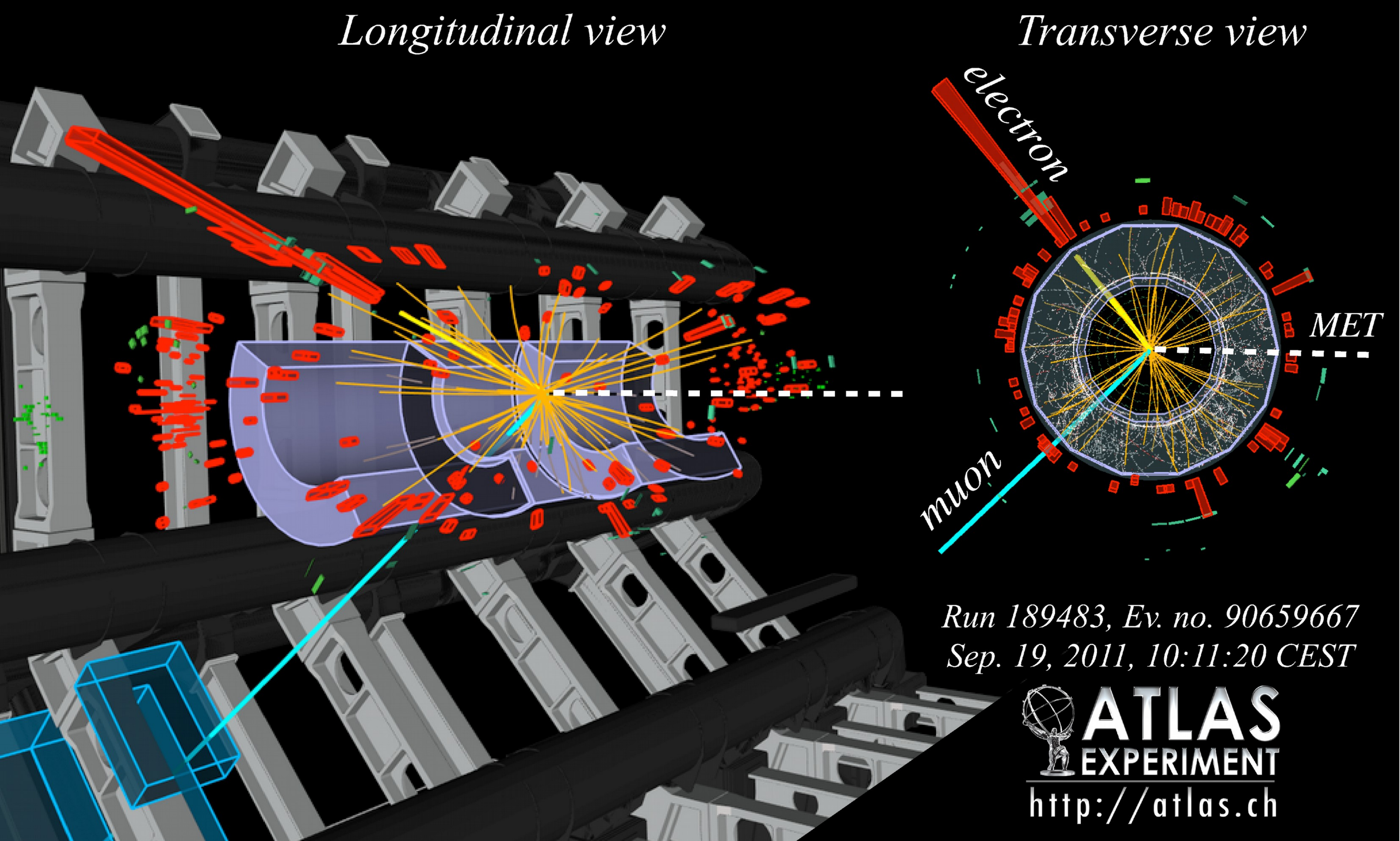
- The SM was missing just one parameter, m_H
  - With that measured are we done?

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
  - If the answers are yes we still need to explore the BEH field.

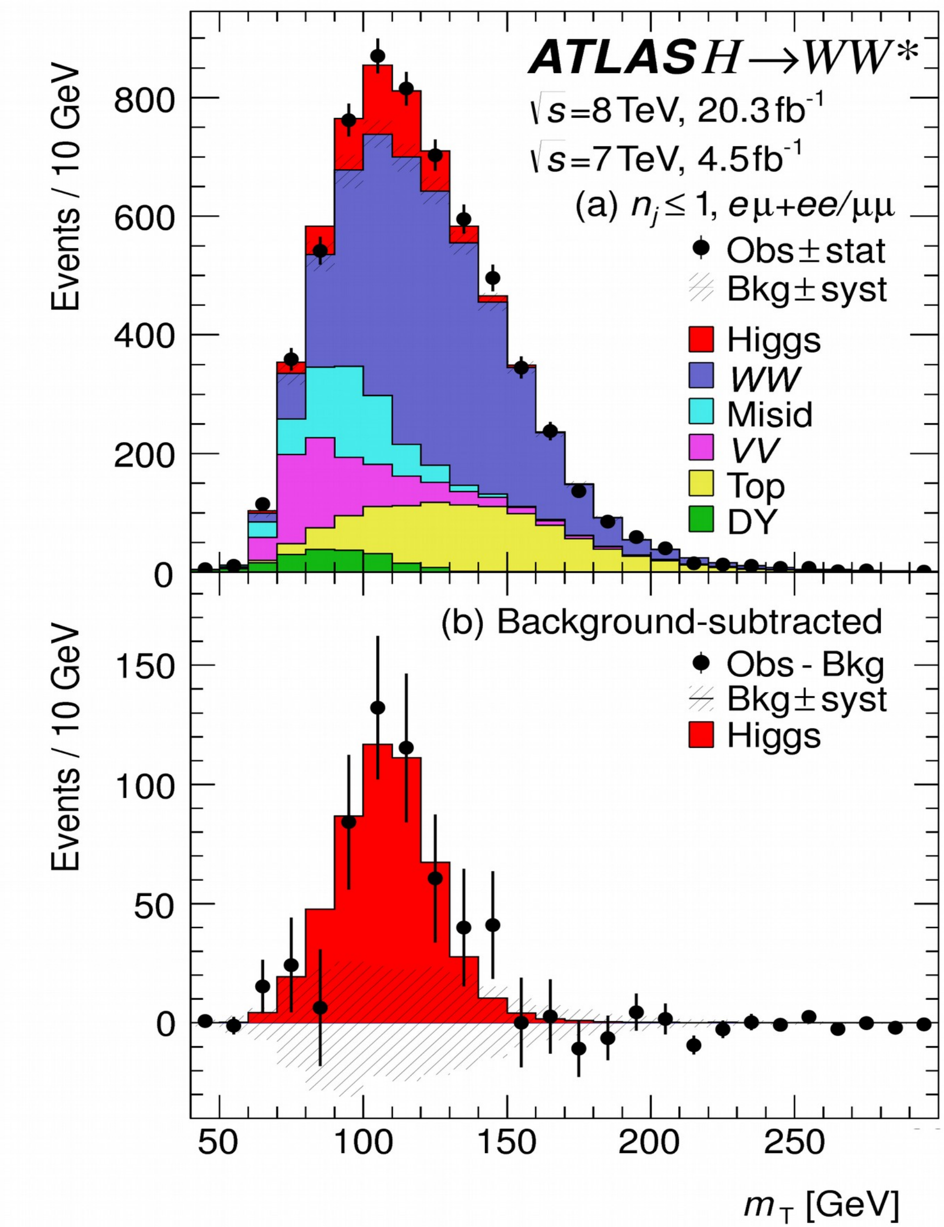
$H \rightarrow WW \rightarrow l\nu l\nu$

(a) $H \rightarrow WW^{*} \rightarrow e\nu\mu\nu$ candidate and no jets



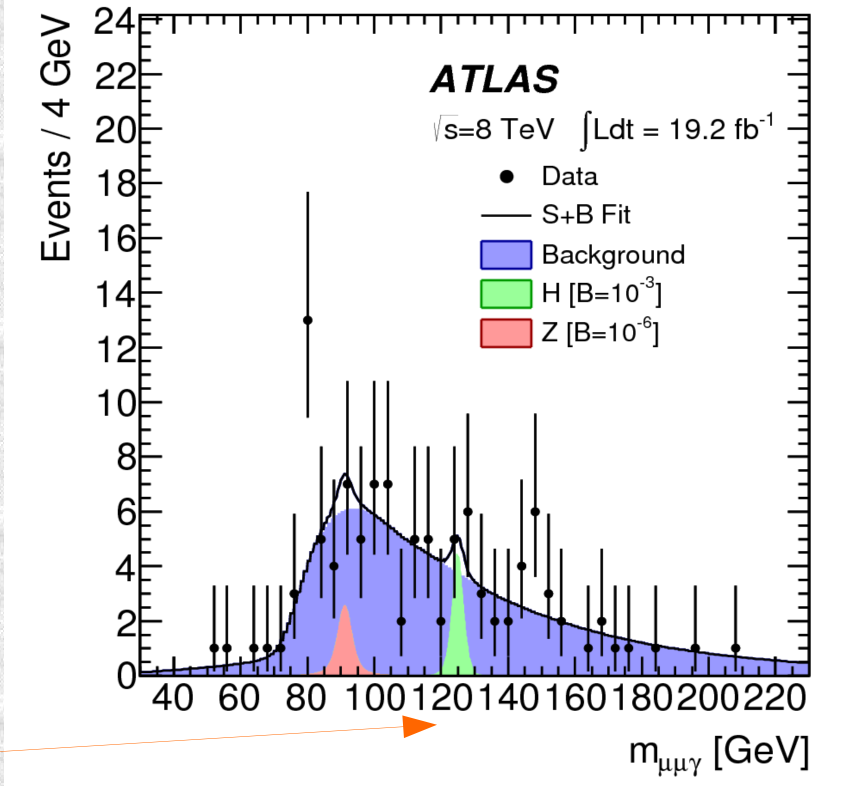
WW in different modes

- Complex analysis
- 2 leptons but also two neutrinos
  - No mass, use m_T
- Spin, as proposed by Dreiner and Dittmar when Herbi here
- Many combinations of lepton flavours, numbers of jets and VBF or VH signatures
- Sum of 0/1 jets shown right
- Many backgrounds, all measured in data control regions
- A lot of work, but clear signal



Rare decays search for:

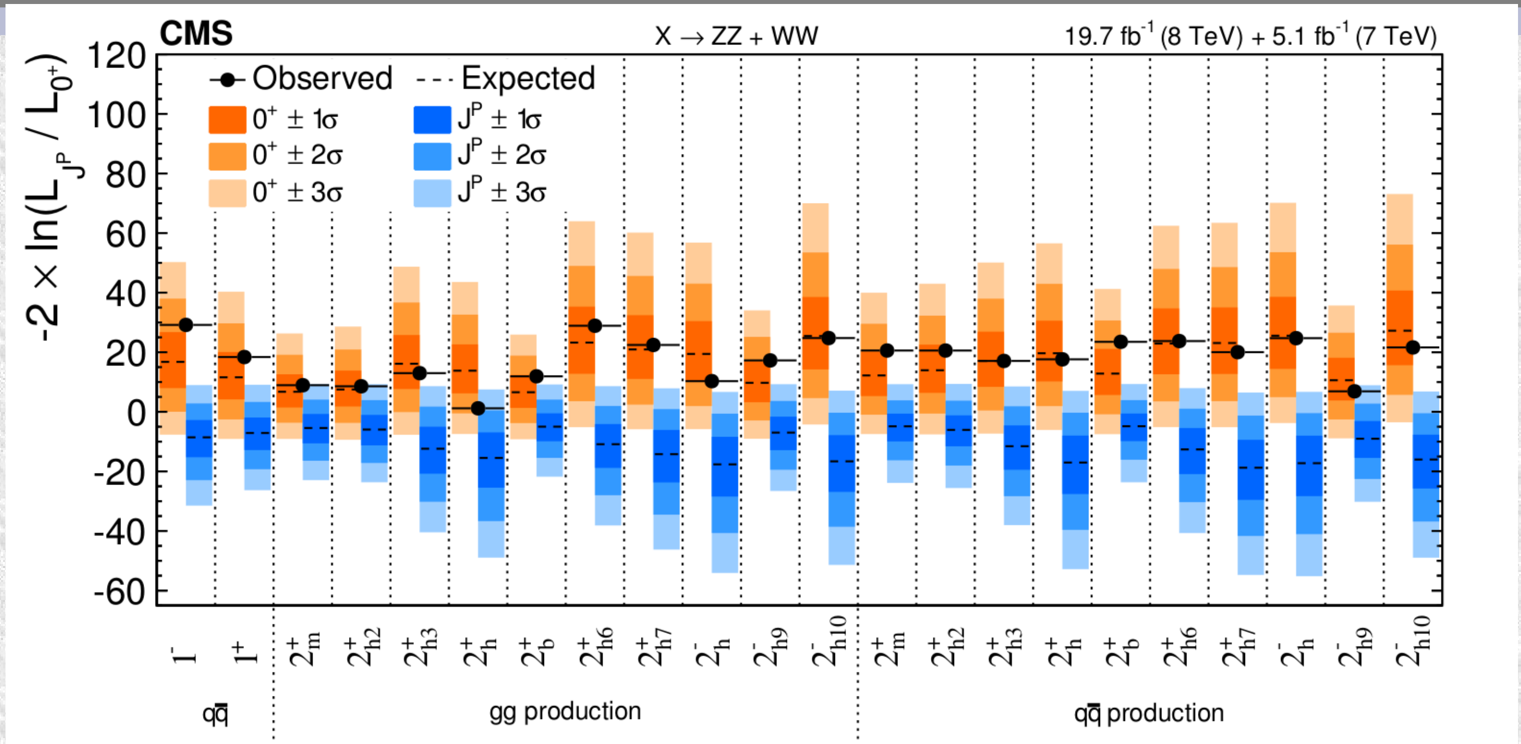
- ATLAS and/or CMS have studied following:
- $H \rightarrow \mu\mu$
  - $\mu<7$
- $H \rightarrow ee$
  - $\mu<3.7x10^5$
- $H \rightarrow \gamma\gamma^*$
  - $\mu<8$
- $H \rightarrow Z\gamma$
  - $\mu<9$
- $H \rightarrow \psi\gamma$
  - $\mu<500$
- $H \rightarrow \tau\mu$
  - BR<1.6% (0.9% favoured??)
- No surprises (yet)



Spin/parity

- We know integer spin, not 1 from $\gamma\gamma$ decay observation
  - Unless Yang-Mills is evaded; e.g. Each photon is really 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 were not expecting surprises here
  - The rates match too well the 0^+ model...

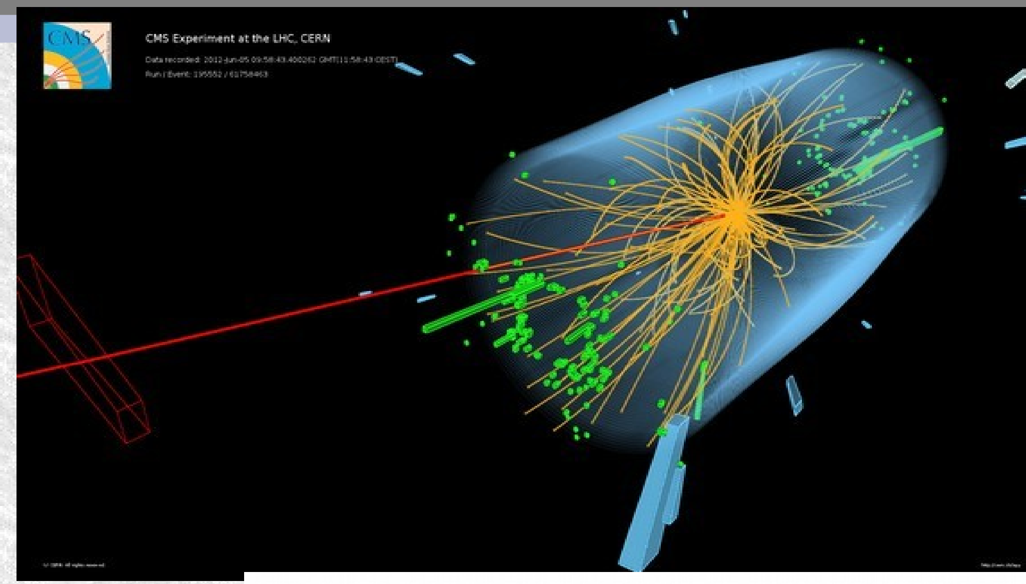
Spin/parity results

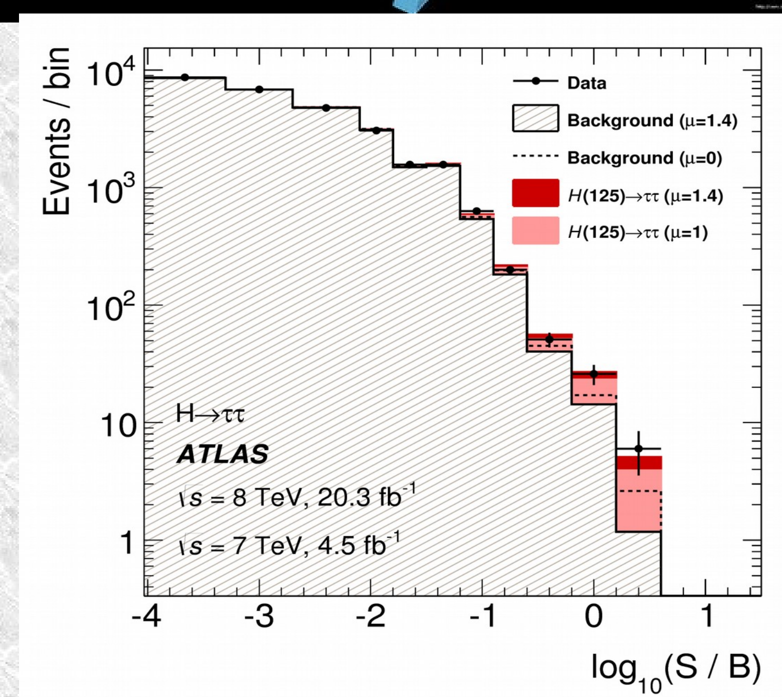


- CMS has made the most extensive survey of modes
- Main result is that 0^+ always matches data well
- ATLAS has studied EFT model – again spin 1,2 are excluded
- How long do we have to keep measuring this?
  - Parity admixtures are very interesting.

H → ττ status

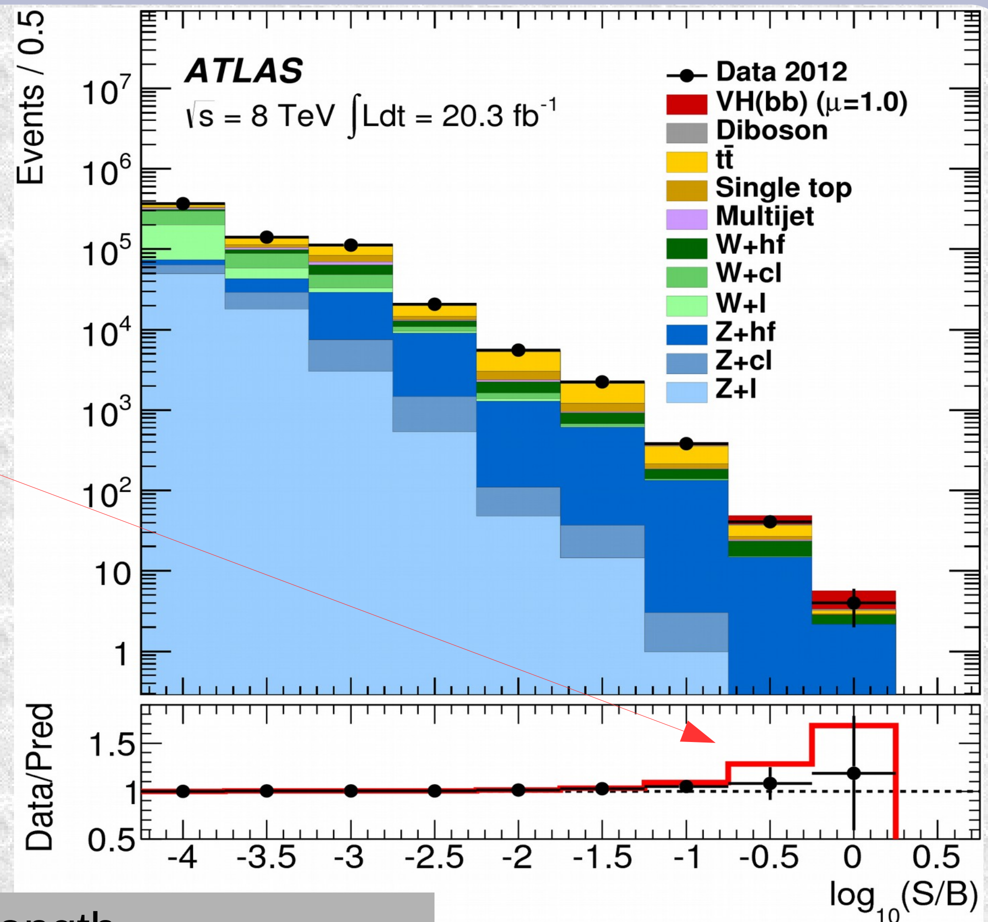
- VBF is most sensitive
  - Boosted gg also important
- Multiple decay modes
  - lep-lep
  - lep-had
  - had-had
- Control with Z→ττ
  - Control that via Z→μμ
  - Replace data μ with τ
- Use BDTs to extract signal from background
- Experiments find & expect 3-4σ
- This seems firmly established
  - 5σ awaits combination





H→bb

- This is tough at LHC
  - But there are a lot of events
- Best analysis is VH
  - With the Higgs high pT
- Again BDTs used
  - But no strong evidence seen
- This is the most sensitive result existing
  - Statistics dominated

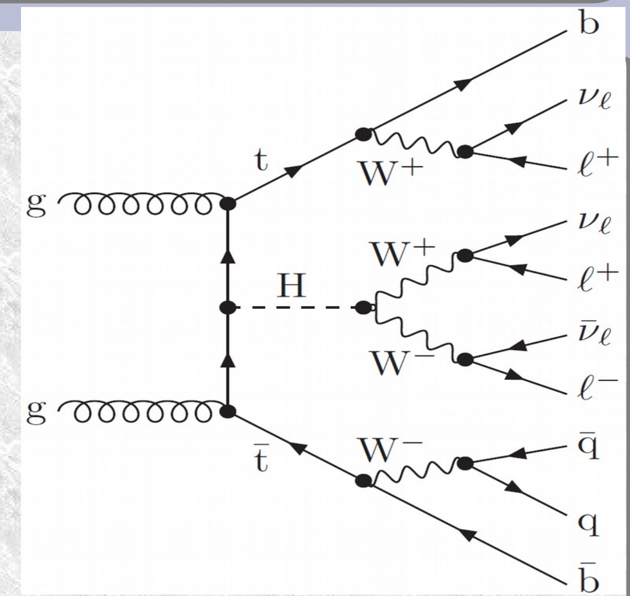


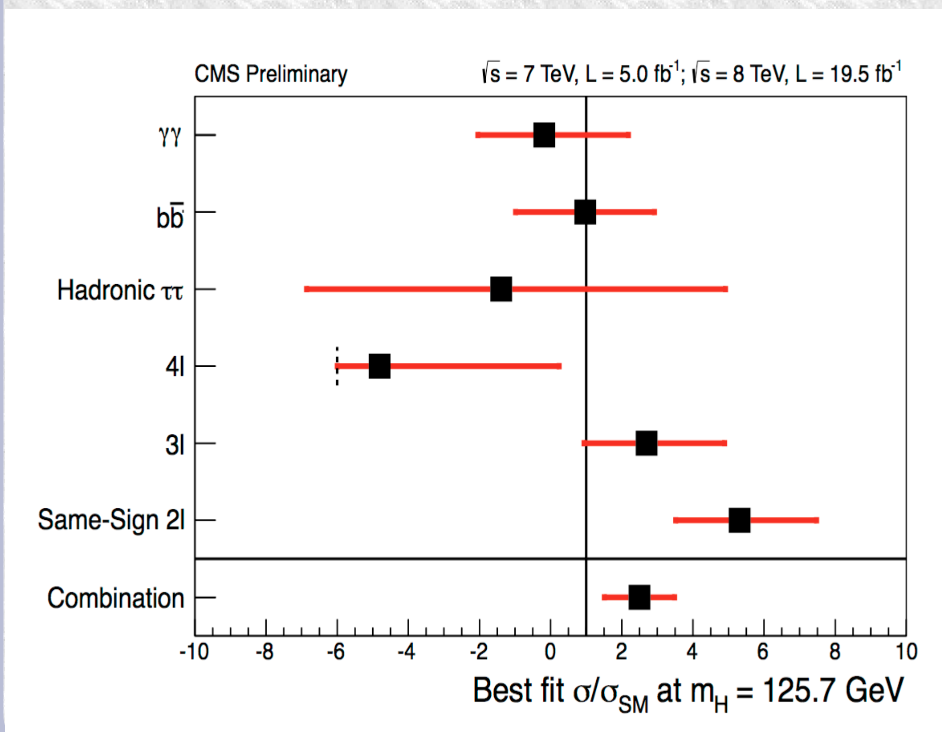
Group	Signal Strength
Tevatron VH	$1.59^{+0.69}_{-0.72}$
ATLAS VH	0.52±0.32(stat.)±0.24(syst.)
CMS	1.0±0.5

Phys. Rev. D 88, 052014

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 γγ, bb so far



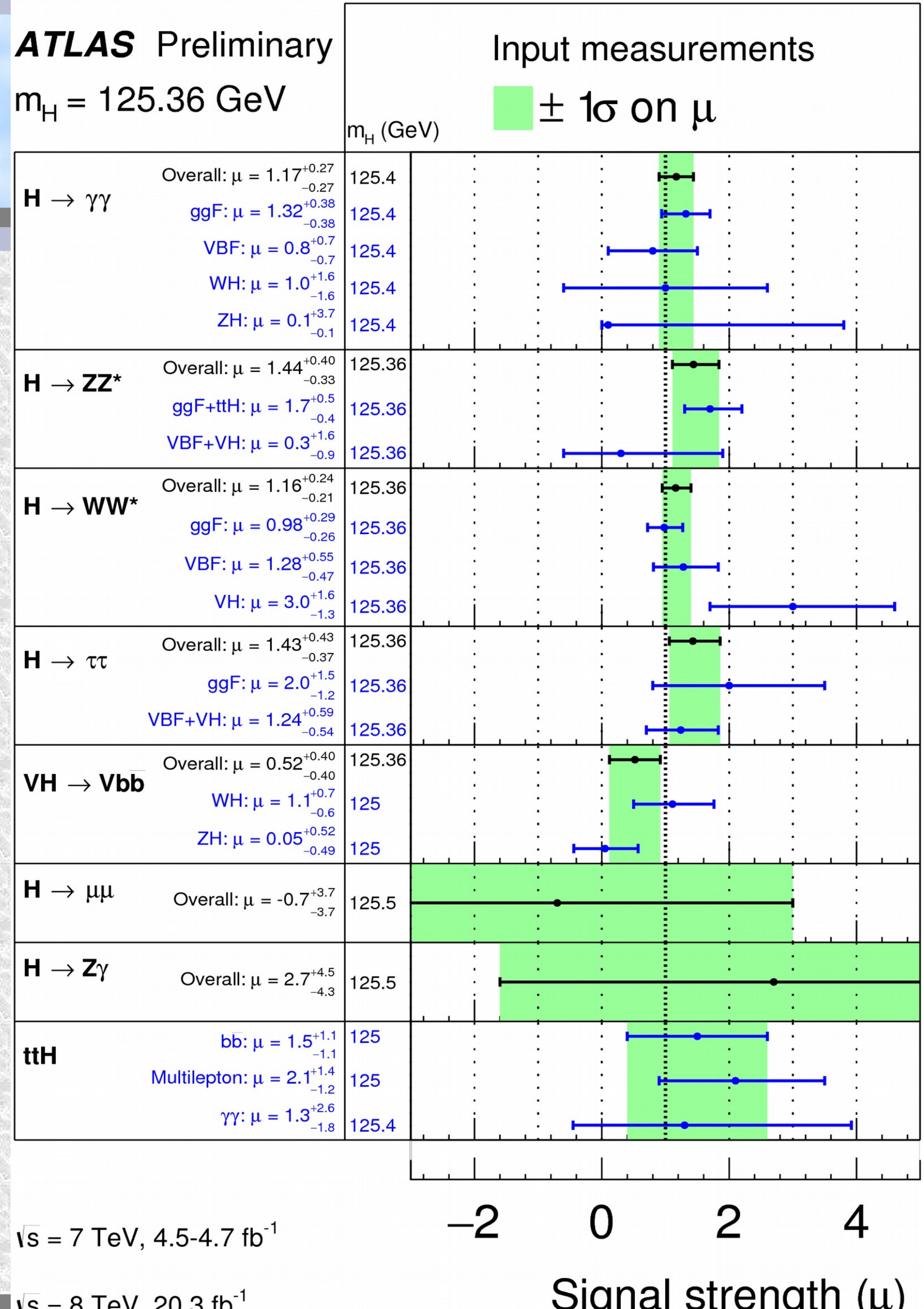


- CMS results (left) give 2.7σ evidence for ttH production
  - 1.2σ expected
- ATLAS find μ=1.81±0.80
- Is there a hint for too much ttH?
  - Not really...< 2σ

So what did we get?

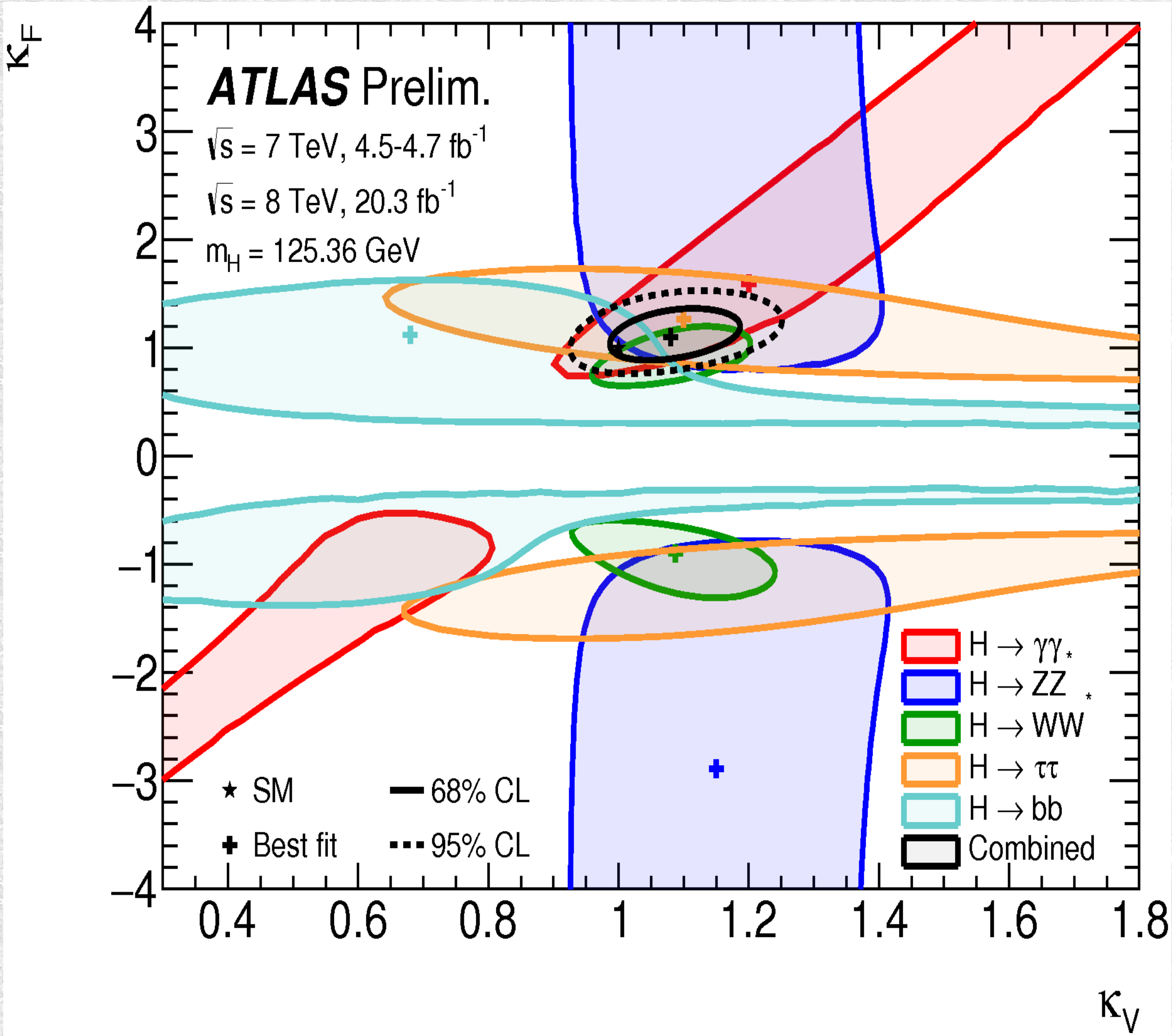
Channel results

- All consistent with SM
- Eighteen different modes studied here
  - All with errors below 5*SM
- Eight of them have errors below 100% for SM strength
- We are learning a great deal very quickly about this particle.
- Run 2 should deliver 10x as many bosons
  - The measurements start to get precise



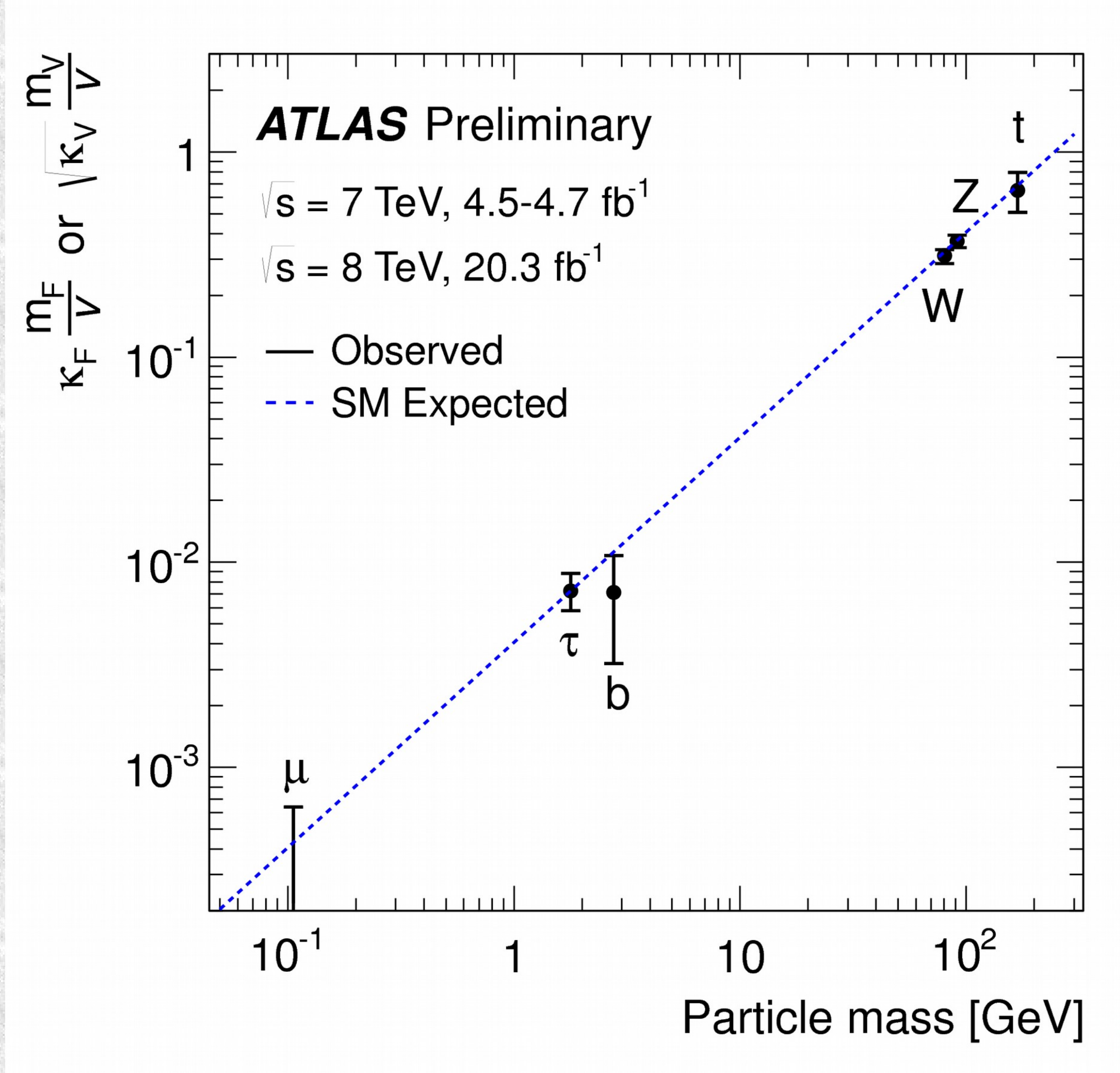
Coupling studies

- Fit with scale factors κ_V and κ_f on the vector boson and fermion couplings
- Allows multiple production/decay modes to be compared
- All channels are compatible
- The relative sign of the fermion and boson couplings determined from interference in the photon decay loop



Coupling studies

- Fit 6 couplings:
  - κ_W, κ_Z, κ_t, κ_b, κ_τ, κ_μ
  - Fermionic couplings can be negative
- Assume no BSM particles
- Result: all parameters consistent with SM
- The lack of μμ signal helps show non-universality.



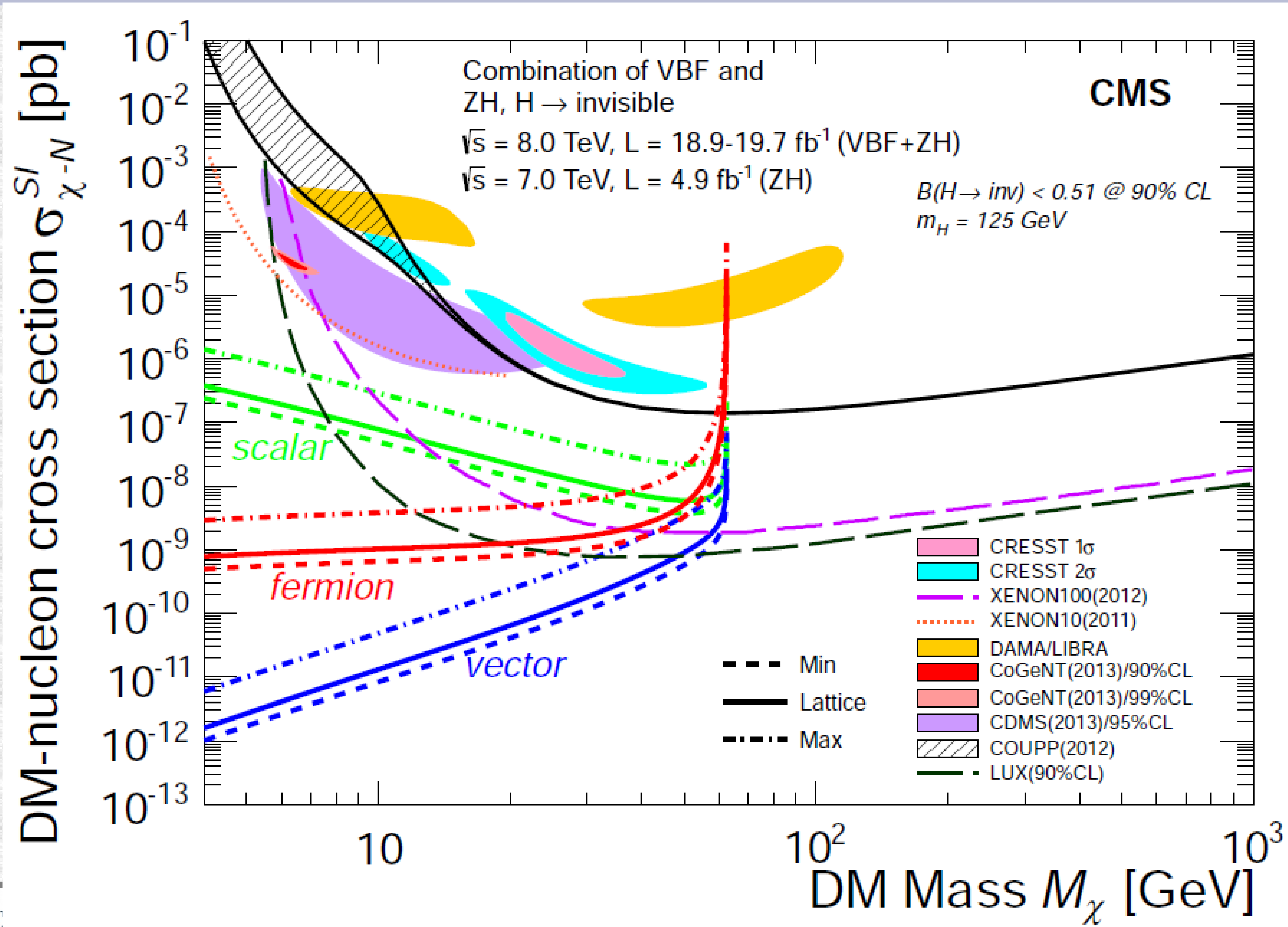
Invisible Higgs decays?

- Repeat Higgs coupling analysis
  - Assume SM particles all couple with SM strengths
  - Allow arbitrary new physics in loops
  - Also allow invisible extra Higgs Br. (== rate reduction)
- ATLAS find possible invisible/undetectable Br < 27%
  - Loop strengths also within 2σ of SM prediction

- Can also look directly for missing energy (i.e. invisible Higgs)
  - ZH was first exploited
  - VBF has more sensitive results
- ATLAS find Br < 29%

- So there is no hint of Higgs decays to DM

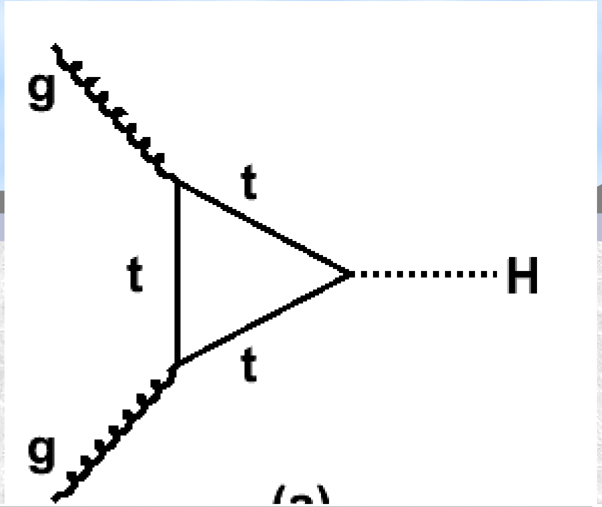
DM in Higgs-portal model



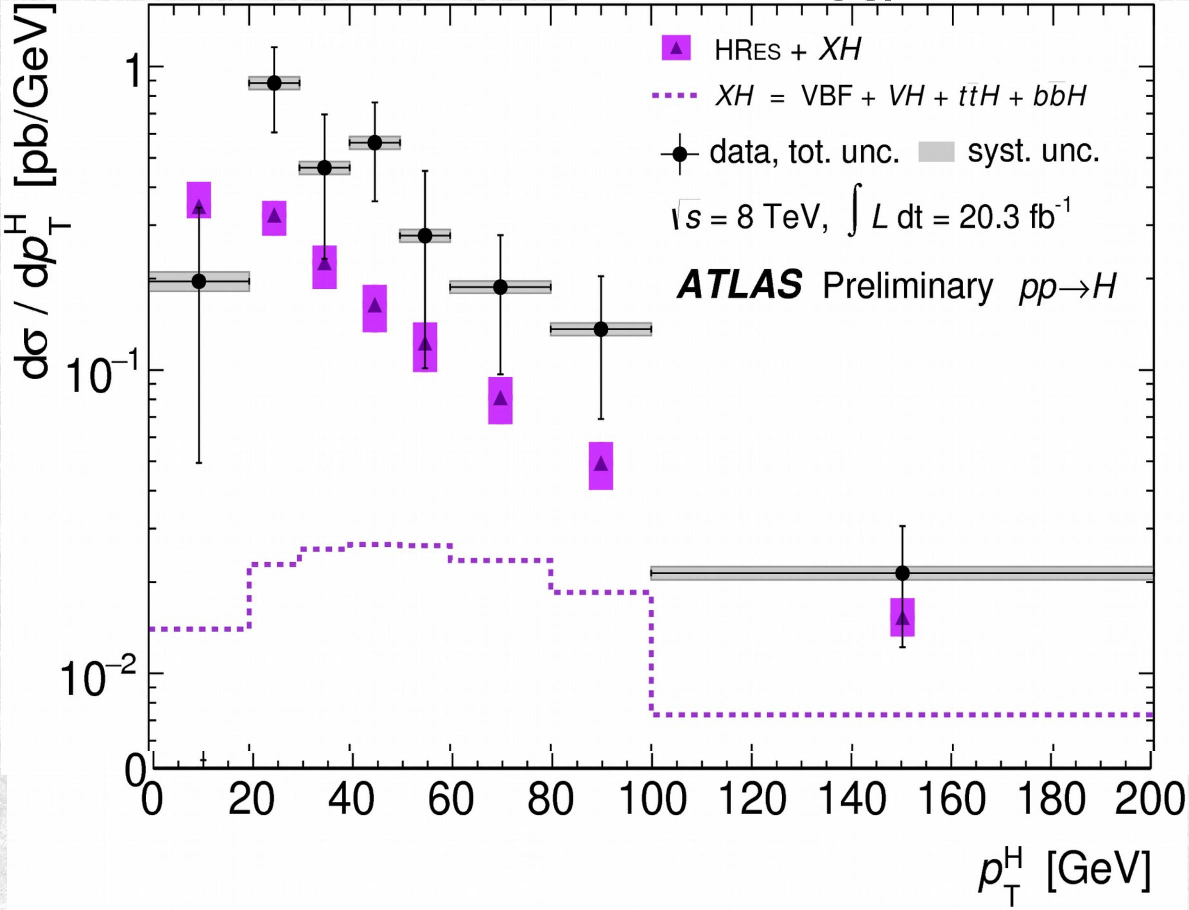
Higgs Width studies

- There is no complete study possible
- 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 γγ peak c/f llll
    - Or even use high/low p_T difference in γγ
  - 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
  - 22 MeV limit
- Extract from invisible, undetected cross-section discussed
  - Assumes relations between couplings
  - 6 MeV upper limit from ATLAS data

Higgs p_T: ZZ+γγ



- Gluon fusion production is supposed to be loop dominated
  - Loop enhances QCD effects
  - define pT spectrum
- Observed spectrum softer than VBF, VH
- But harder than Z production
- Consistent with ggF
- Future measurements test particles in those loops!



The BEH field

- One truly outrageous prediction of the BEH theory is the field of weak charge and a v.e.v.
- The gravitational effects should be enormous
  - 10^{120} times more than Dark Energy and with the opposite sign
- So presumably this is energy which doesn't couple to gravity
  - We really need a theory of Quantum Gravity
- Can we prove it?
  - HL-LHC will have a go at HHH coupling
  - Current di-Higgs limits μ=70
- Evolution of BEH field during inflation seems plausible
- Speculation alert! ArXiv:1410.0722
  - CPT theorem does not hold if background is evolving
  - We may not need CP violation in theory to observe it in matter
  - Higgs field breaks EW & CPT symmetries!

What do we learn from m_H=125?

- Standard Model works well
  - Consistency of top mass, W mass and Higgs is ~ 1 sigma
- The SM is stable up to very high mass
  - But not completely
  - We seem to be in a metastable region where the vacuum is unstable, but with a lifetime >> the Universe.
- The Heirarchy problem is established:
  - Why is EW scale 10^{14} orders of magnitude below blank scale?
  - Laws of nature seem very fine tuned
  - Does new physics relieve the tension
    - Extra dimensions
    - Supersymmetry
    - No-scale arguments
  - Or do we see the mind of God?

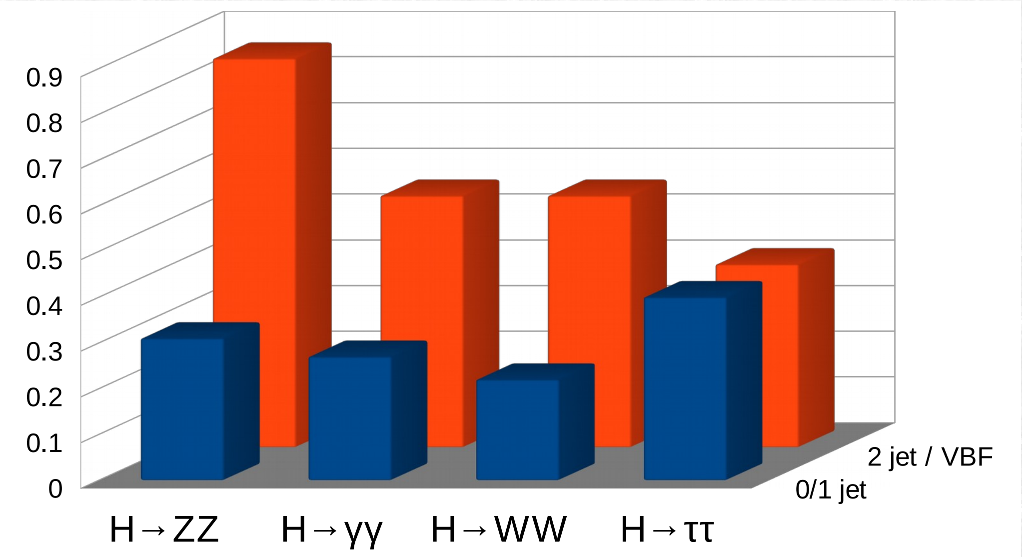
Conclusions

- After 50 years we have found something remarkably like the SM Higgs boson:
  - Mass 125.09 GeV
  - 0^+ j^p strongly preferred over alternatives
  - Decay to ZZ, WW, γγ, ττ, maybe bb
    - Interactions with bosons *and* fermions
    - Lack of decay to μμ – non-universal coupling
  - Evidence for VBF and gluon fusion: ttH next?
- It seems we are living in a fish tank
  - We need to learn more about the water!
- 6.5 TeV beams circulating
  - 3 possible events on Saturday with 2 beams in
  - On the road to more discoveries?

How to extract Higgs couplings

- Here are signal strengths in CMS combination paper

Decay mode	0/1 jet	2 jet / VBF tag
H→ZZ	$0.88^{+0.34}_{-0.27}$	$1.5^{+1.0}_{-0.7}$
H→γγ	$1.01^{+0.29}_{-0.26}$	$1.5^{+0.6}_{-0.5}$
H→WW	$0.77^{+0.23}_{-0.21}$	$0.6^{+0.6}_{-0.5}$
H→ττ	$0.84^{+0.42}_{-0.38}$	$0.9^{+0.4}_{-0.4}$



- The relative uncertainties vary considerably
  - So there is information if we constrain them to each other, in data
- ATLAS effectively do this in their projections

Systematic uncertainty limits

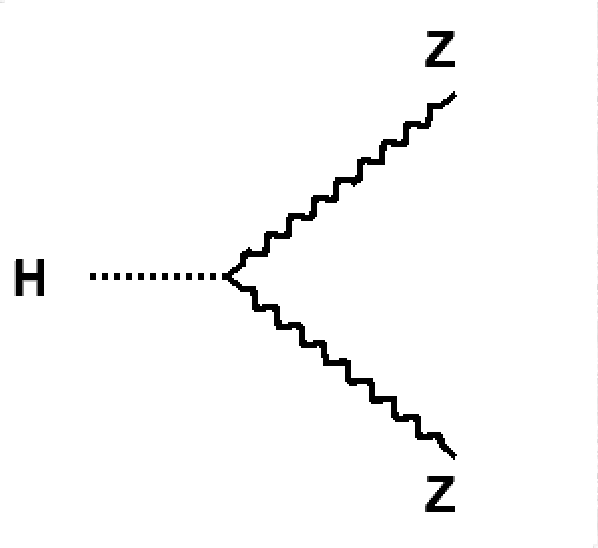
- Hoped for uncertainty reductions:

Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j → 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j → 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j → VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j → VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

- Estimating 100fb^{-1} as √3 worse than 300fb^{-1} then
  - PDF & Scale uncertainties already contribute to κ_{gZ}
  - p_T shape and 0/1/2 jet migration affect λ

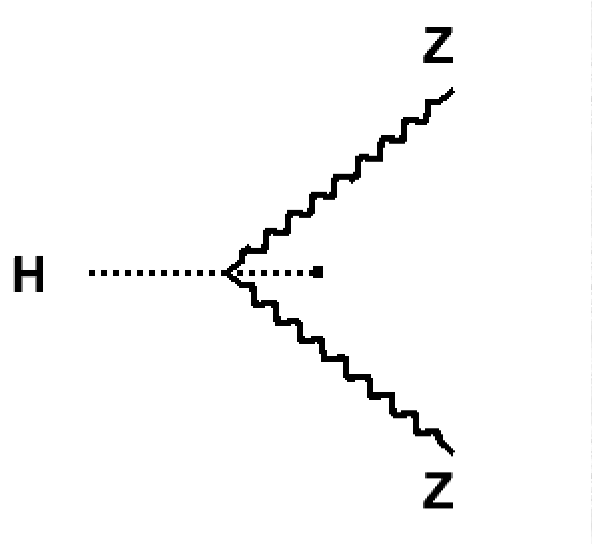
Evidence: H to ZZ

- 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$\rightarrow$ZZ where does the charge go?



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?
- 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



Higgs links:

- Full list of all ATLAS & CMS public results

Composite Higgs

- In nature, massive scalars imply a cutoff to the theory
  - Some new dynamics emerges
- This is one of the strong arguments of the SUSY community http://arxiv.org/abs/1406.5957
  - But might be evidence for a composite Higgs
- Top partners: see e.g.
- A top partner below O(1TeV) is required if it is to explain the light Higgs mass

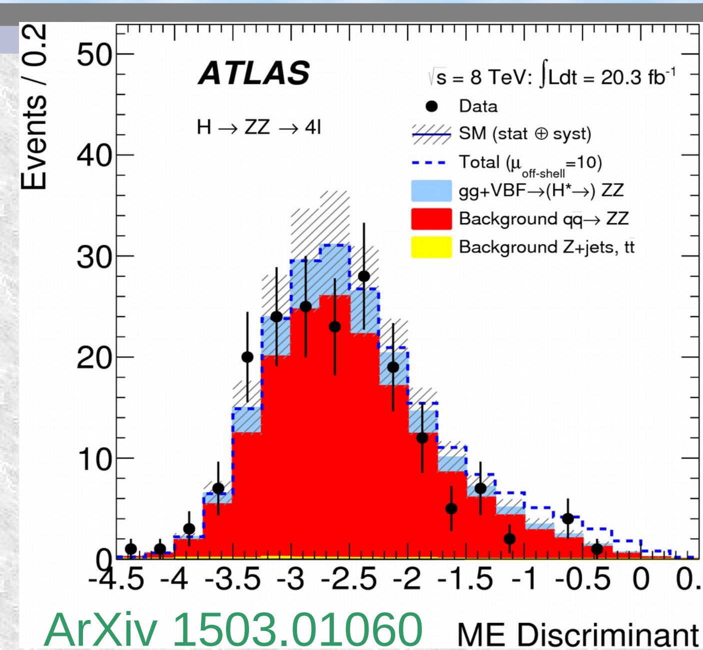
Width via ZZ mass distribution

- Use observed lineshape

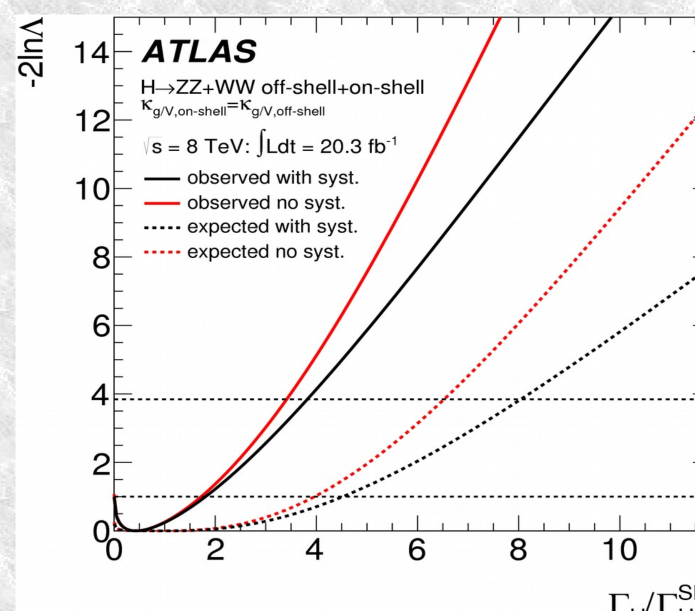
$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa_g^2\kappa_Z^2}{r}(\sigma\cdot \mathrm{BR})_{\mathrm{SM}} \equiv \mu(\sigma\cdot \mathrm{BR})_{\mathrm{SM}}$$

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

- 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
  - ME in llll suppresses qq→ZZ
- Γ_H<22MeV (both ATLAS and CMS)
  - Both experiments 'lucky'
- Could this become measurement?
  - Needs improved calculations

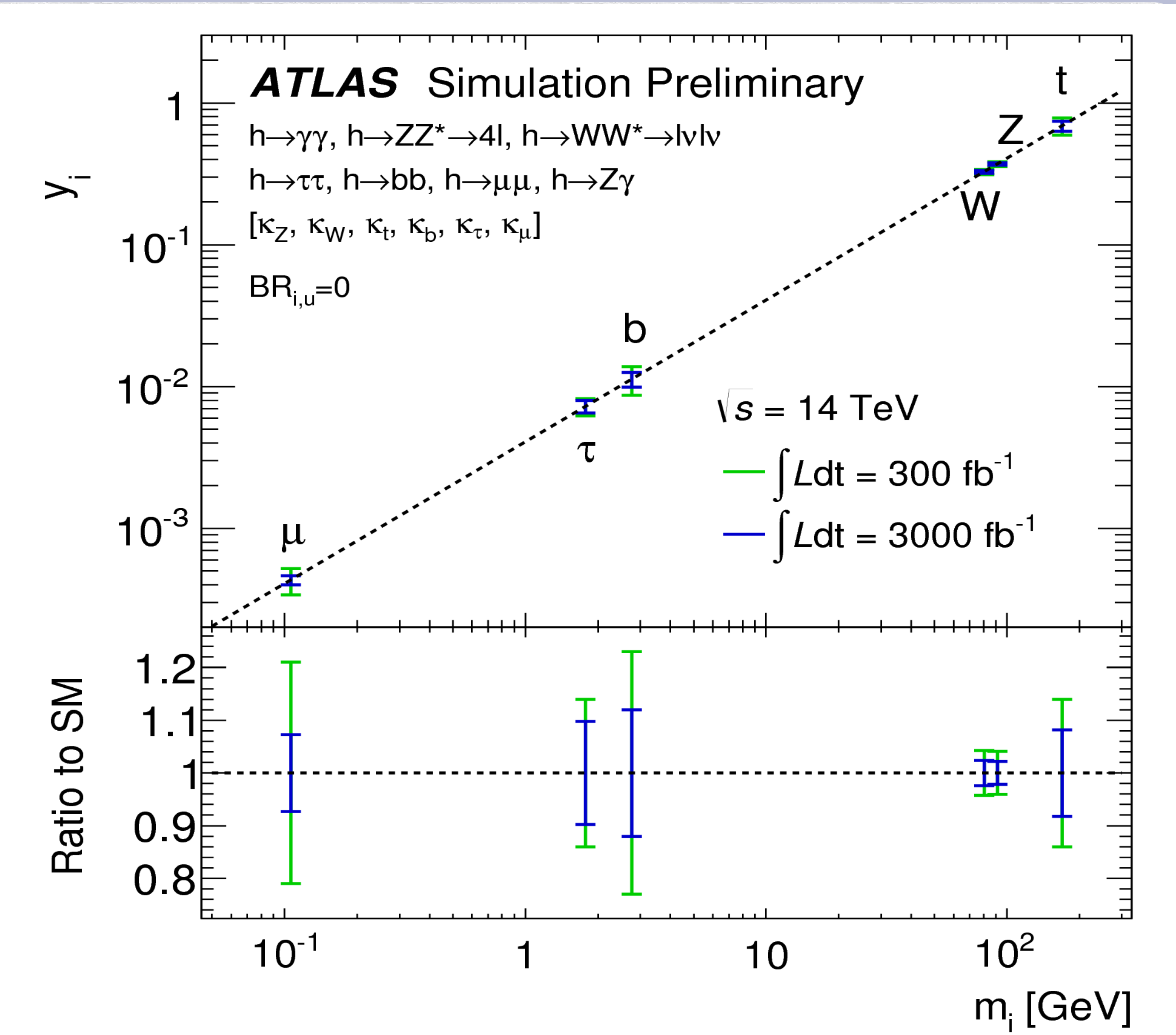


ArXiv 1503.01060



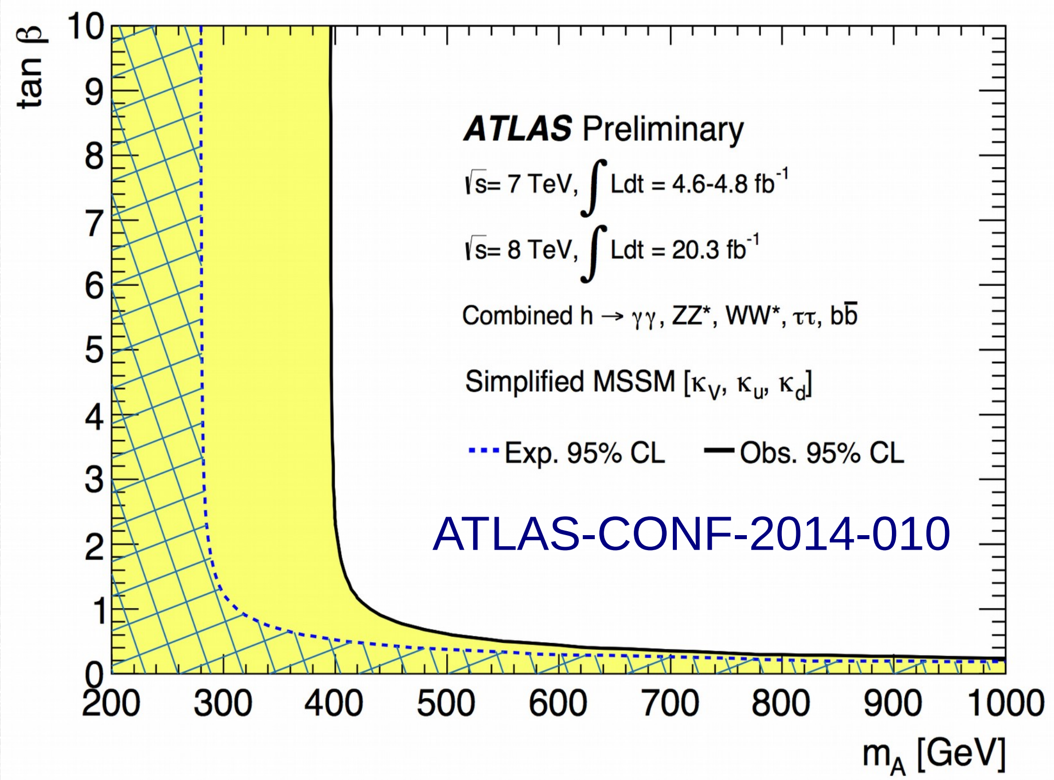
Coupling strengths

- This shows coupling ratios measurable with 300fb^{-1}
- The crude measurements shown already will turn into a precision test of the theory



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



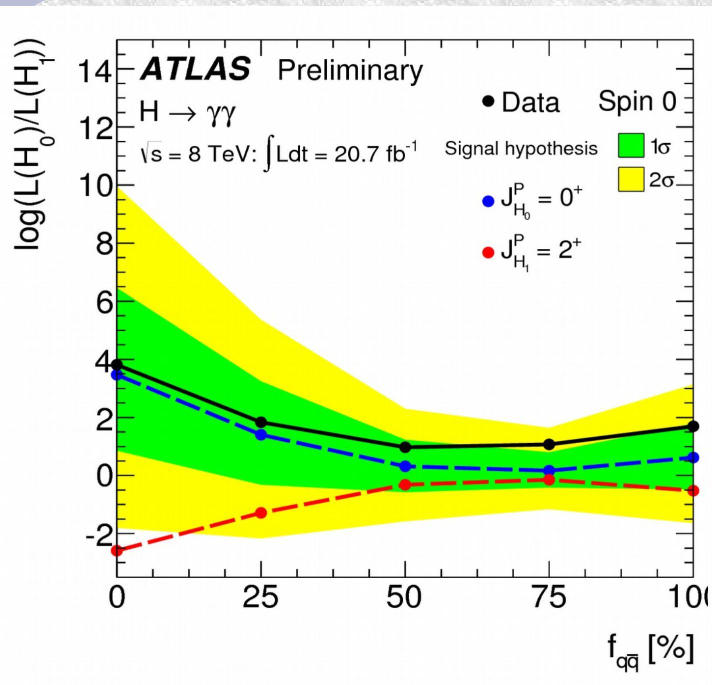
HL-LHC as Higgs factory

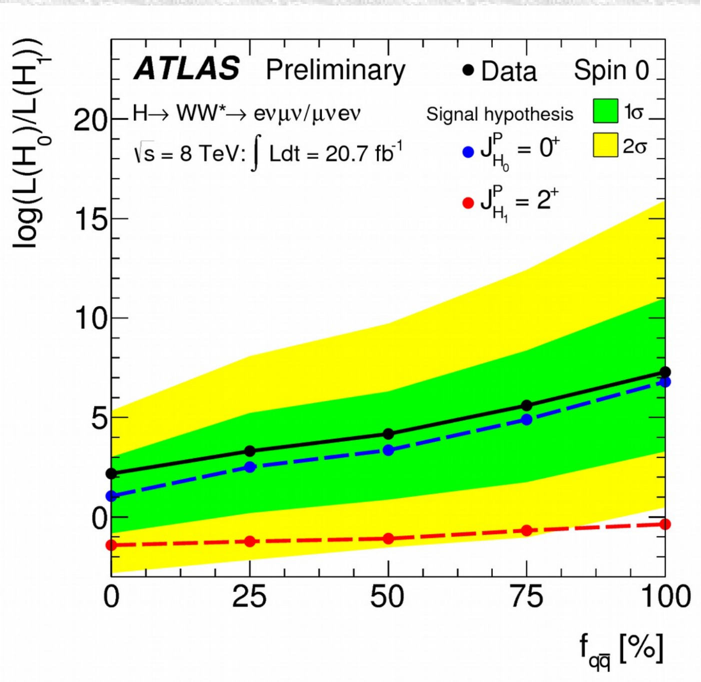
- 2023 for 10 years?
- Increasing luminosity to $5x10^{34}cm^{-2}s^{-1}$
  - New proton linac & focus elements needed
  - Pileup increases by similar factor, 140 events/BX?
  - New trackers, calorimetry readout, TDAQ needed to cope
- Beams are rapidly 'burnt-off'
  - Luminosity levelling is assumed for 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?

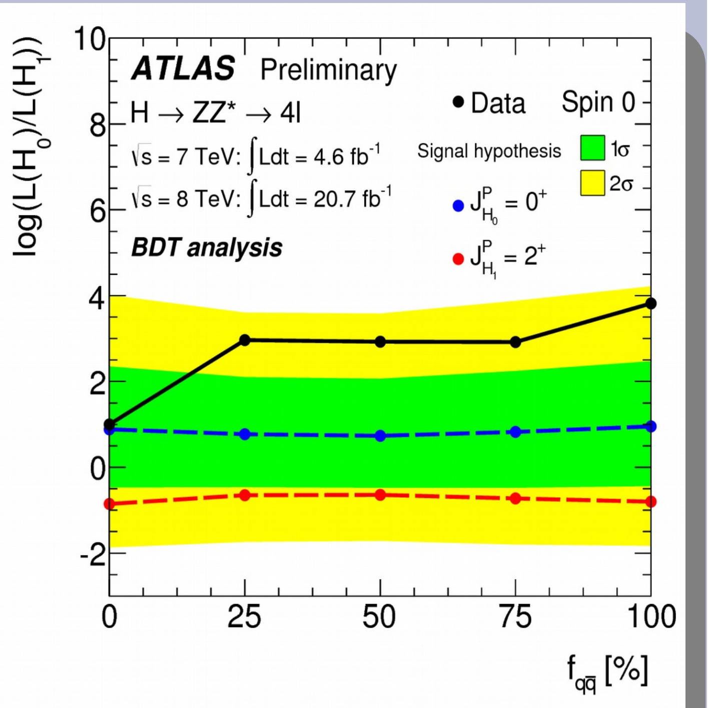
$t \rightarrow qH$

- 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

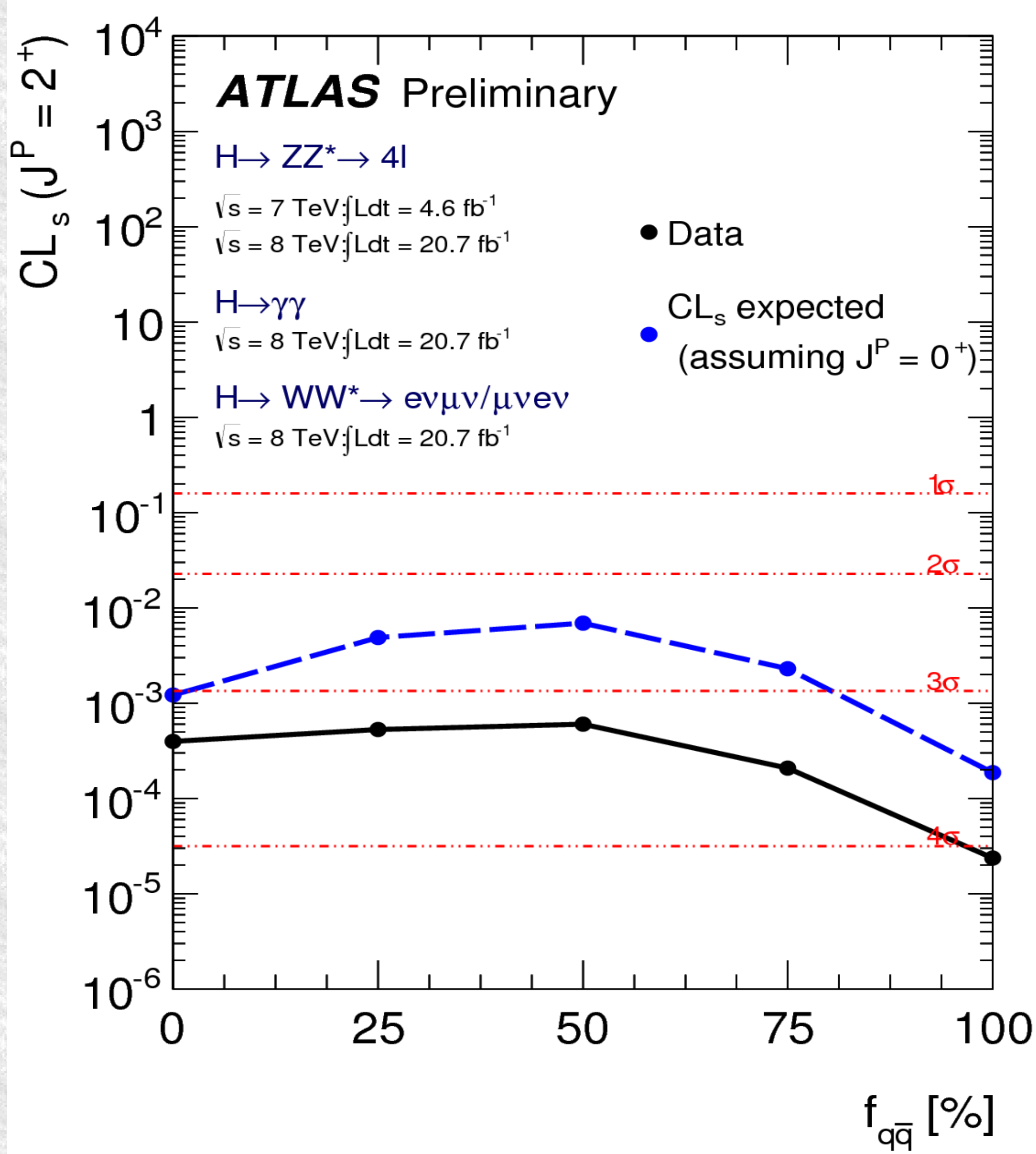




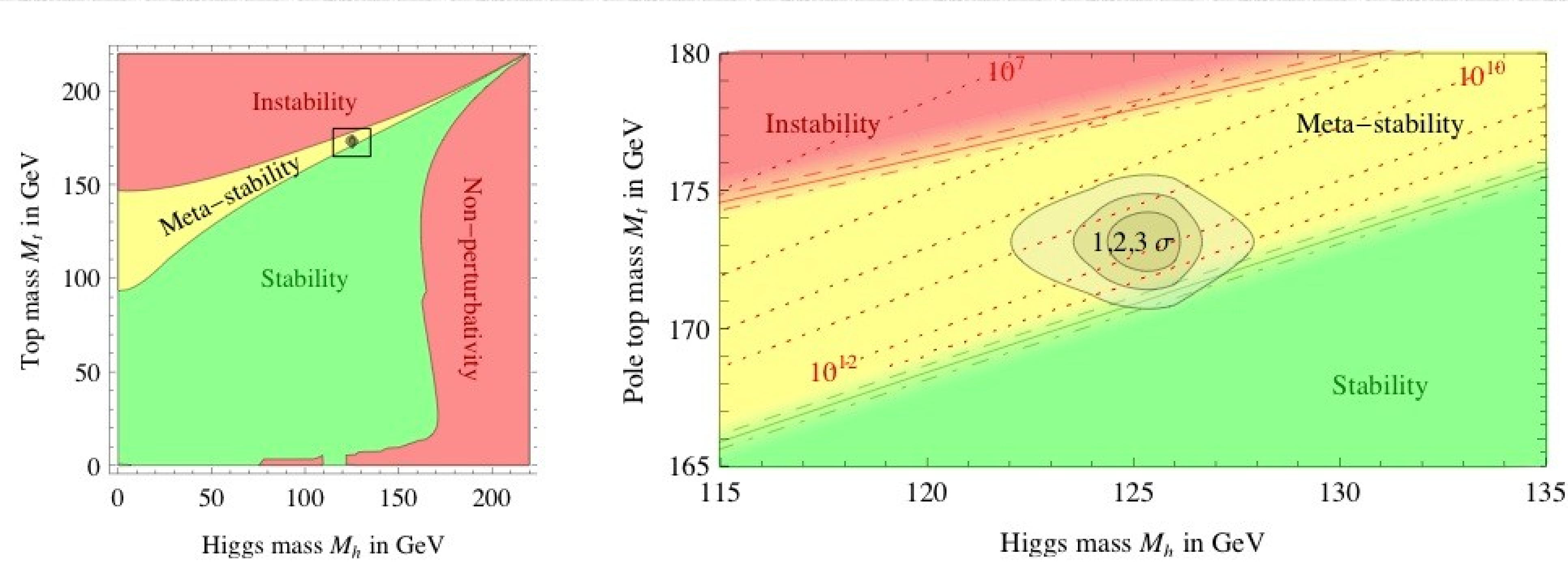


Combined spin-2+ rejection

- 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



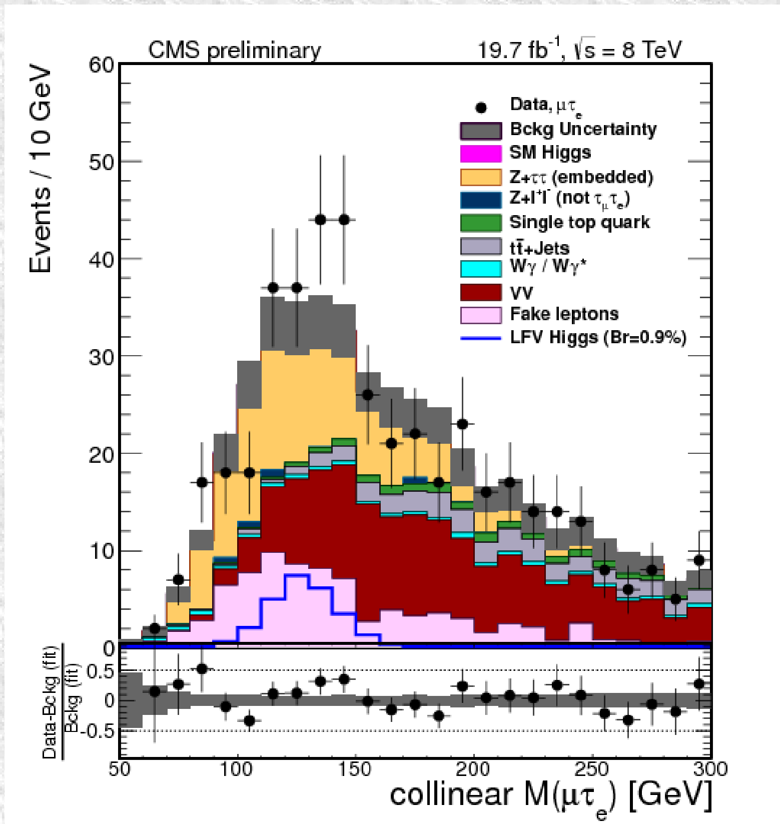
Vacuum stability

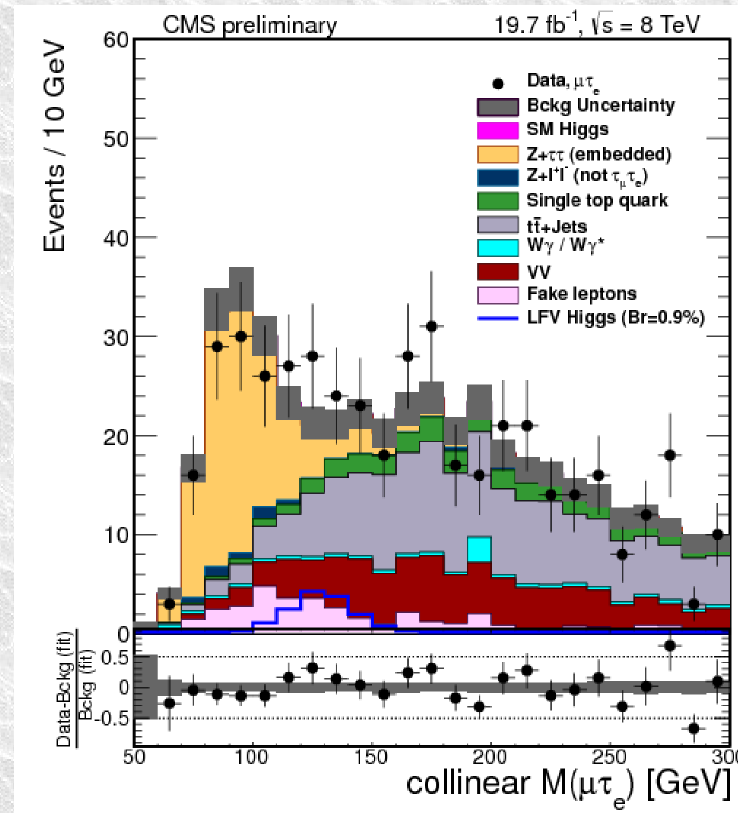


- The running couplings depend on Higgs, top and W mass
- Stability up to plank scale is questioned by m_H
  - But it seems long-lifetime meta-stability possible

CMS H →τμ

- This FCNC Higgs decay is not well constrained
  - No serious constrains from e.g. τ→μγ
- 6 channels searches (3 jet categories, tau to e/had)
  - μe in 0j and 1j are most sensitive
  - Small excess
  - 2.5σ
  - No ATLAS result yet

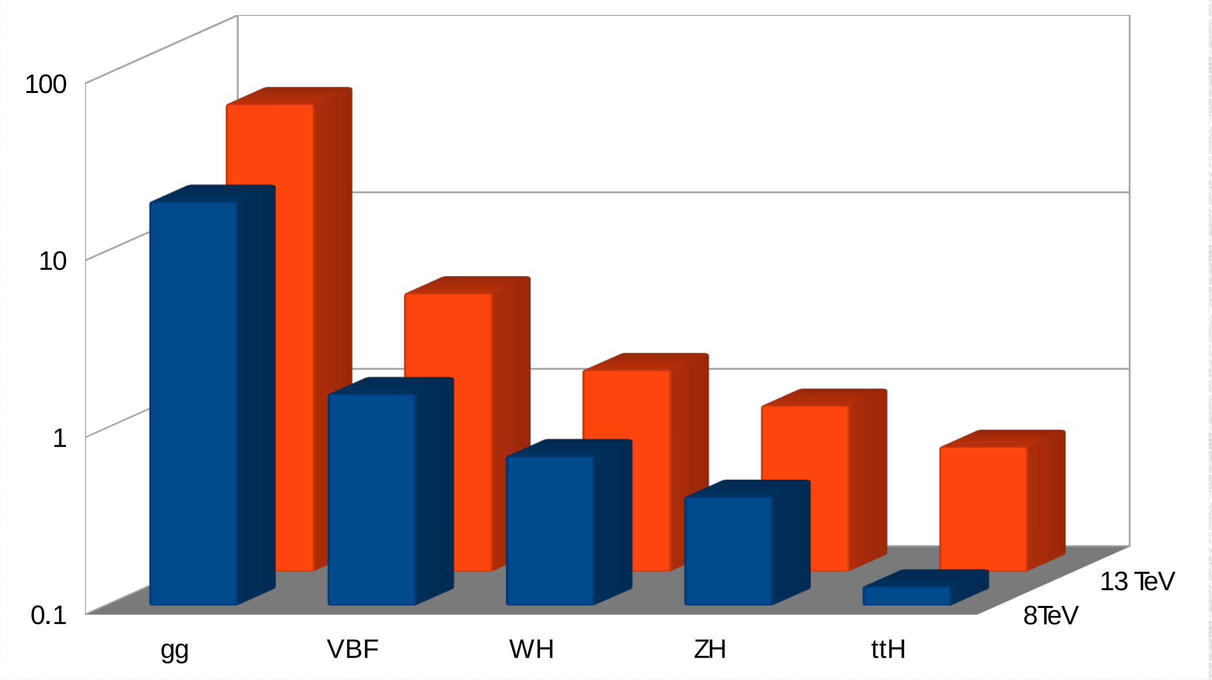




- Worth watching for Run 2.

Run 2??

- The increased beam energy increases cross-sections by a factor 2+
  - Factor 5 for $t\bar{t}H$
- $100fb^{-1}$ in 3 years will give ~10 times the Higgs production
  - Measurements becoming increasingly precise
  - Testing the SM in a new sector
  - With a very different structure from the W, Z bosons



Run 2??

- 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