The Higgs?

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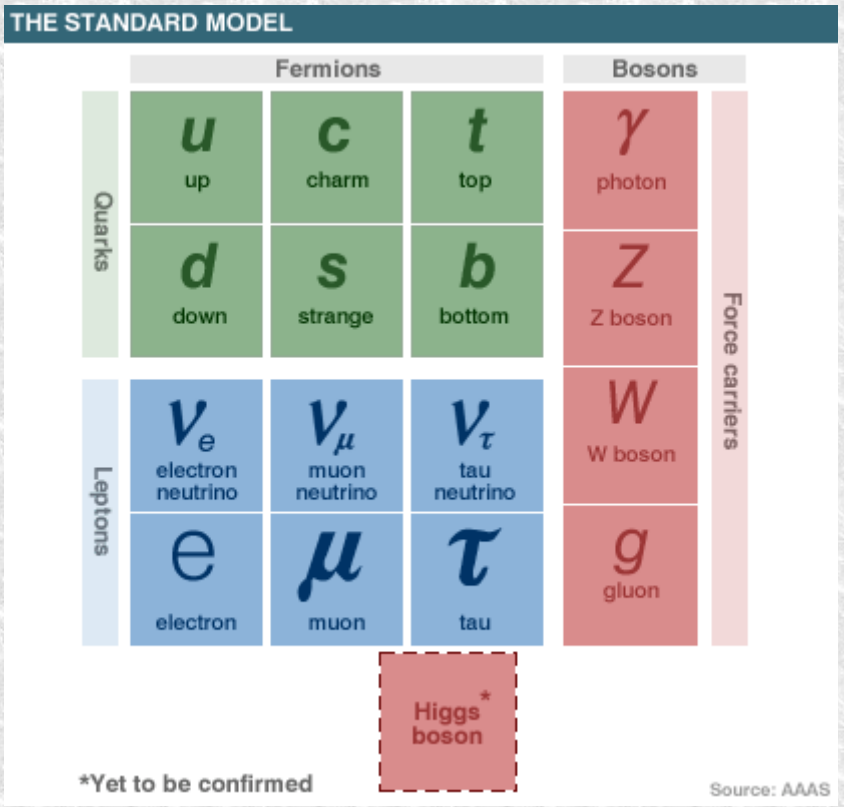
- What is a Higgs boson?
- How do we look for it?
- Did we find it?
- What are the implications?

The Standard Model

- The 'Standard Model' describes the interactions of subatomic particles
- 3 pairs of quarks
  - (u,d),(c,s),(t,b)
- 3 pairs of leptons
  - (e, ν_e), (μ,ν_μ), (τ, ν_τ)
- 3 forces
  - Electromagnetism, (γ)
  - Weak nuclear force, (W,Z)
  - Strong nuclear force (g)



- But what is this dotted Higgs boson for?

- Don't forget: No gravity, dark matter etc....

Unifying principle: symmetry

- Symmetry guided 20th Century physics
- In 1918 E. Noether proved that each symmetry has a conservation law:
  - Mirror reflection → Parity
    - This leads to electron 'exclusion principle' and chemistry
  - Start time → Energy conservation
  - Position→ Momentum conservation
- Internal Symmetries
  - Quantum Mechanics says particles have associated waves
  - The wave height tells you the probability of finding the particle
  - The phase of the wave (crest or trough?) is irrelevant
  - This is a symmetry ⇛ Electric charge conservation

Deeper Symmetries:

- Some symmetries are so complete we don't see them
  - e.g. The phase of quantum mechanical waves
  - Internally important, externally irrelevant
  - A global change of all phase everywhere changes nothing
- 'Gauge' symmetries are one we change locally
  - Change *this* electrons phase but not *that* one over there
  - The implications of this change spread out at the speed of light
  - But more than that....they ARE light
- If the QM phase of an electron is locally changeable
  - You have to add the photon to the theory to keep it consistent.
- Just requiring a symmetry has predicted a particle!

Gauge Symmetries

$$SU(3) \times SU(2) \times U(1)$$

- This is the symmetry set of the Standard Model
- The symmetries define the structure of the model

Forces from Symmetry

Force	Force	Particle
U(1)	Electromagnetism	Photon, γ
SU(3)	Strong Nuclear force	Gluon, g
SU(2)	Weak Nuclear force	W and Z particles

Each force has a symmetry generating it
The symmetry requires force particles

Forces from Symmetry

Force	Particle	Mass
Electromagnetism	Photon, γ	0
Strong Nuclear force	Gluon, g	0
Weak Nuclear force	W and Z particles	81GeV, 90GeV

The problem is, the symmetry also insists the force carriers are massless.....

Not true for W, Z!

Are we really on the right lines here at all?

Spontaneous Symmetry Breaking

??

??

??

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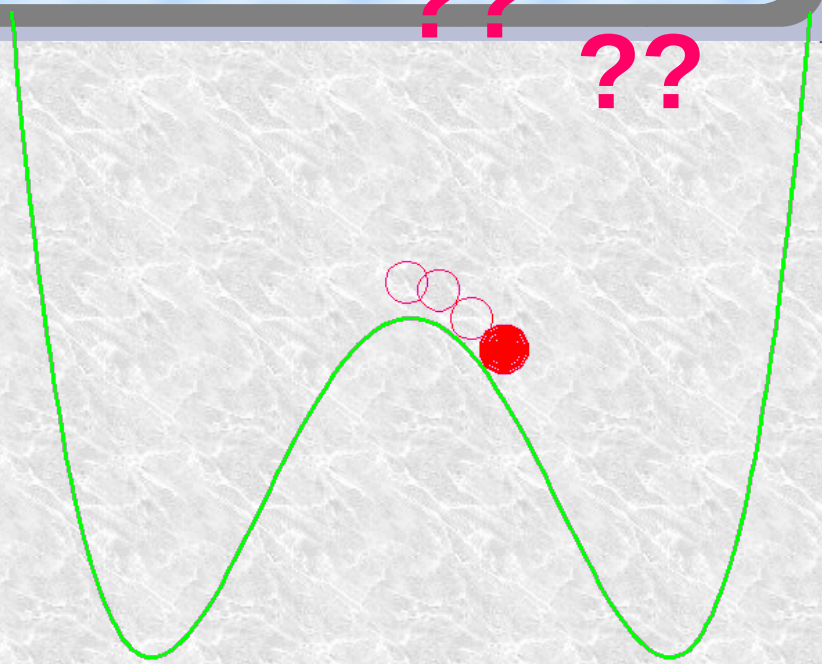
Propose a symmetric potential giving a non-symmetric result. A very neat solution!



Introduce a new field with this property

Matter Particles:

Interact with Higgs field slows them down → generates mass

Force Particles:

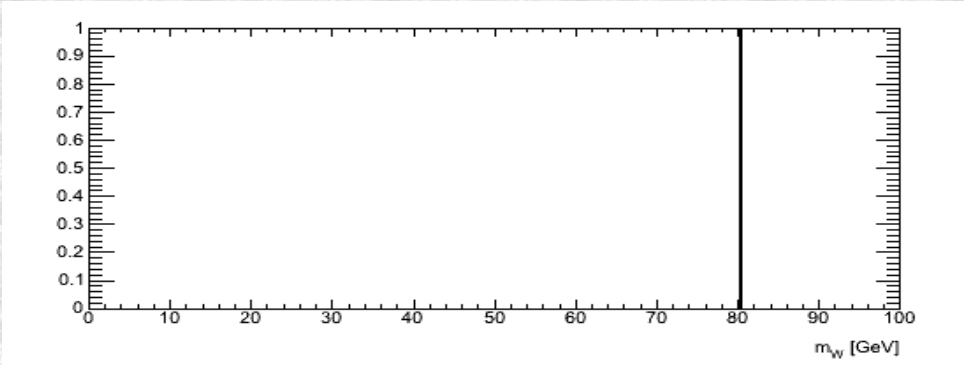
W,Z particles gain mass

Photons/gluons don't notice SU(2); stay massless

The Higgs model

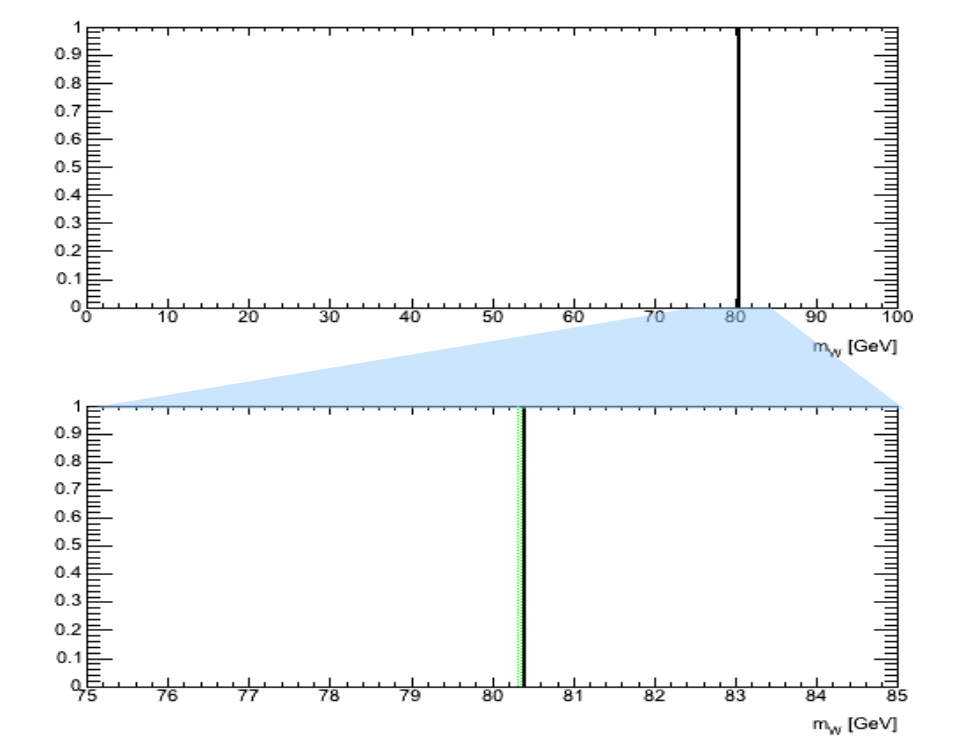
- Mass is an interaction with a field filling the vacuum
  - We cannot escape from it
- The W and Z bosons are intimately linked to it
  - The W mass can be predicted from other forces and masses
  - Allows a test of the model
- The mass for the quarks and leptons can be *described*
  - But each quark or lepton mass is added 'by hand'
  - It makes no predictions here – and is easily changed
- But to make it work there must be a new particle
  - The Higgs boson
  - Everything about this is predicted – except its mass
    - It is spinless
    - It decays almost immediately
    - To things with a probability proportional to m^2
    - Its rate of production is predicted

The W mass



- Green band is SM prediction
  - Its width comes from the (unknown) Higgs mass
  - 115 to 600 GeV shown
- Yellow+black band is the measured mass
- They match incredibly
  - Many theories failed this test

The W mass



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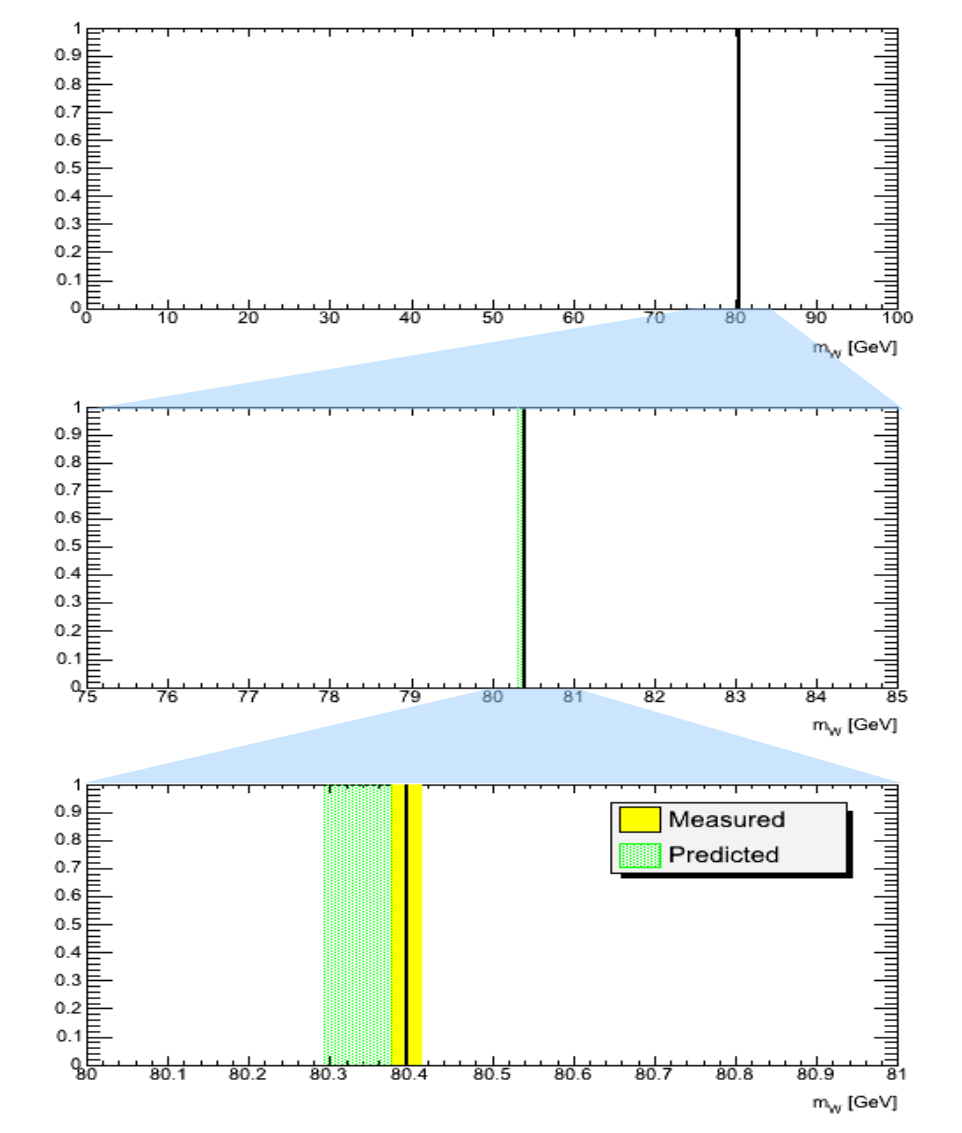
The W mass



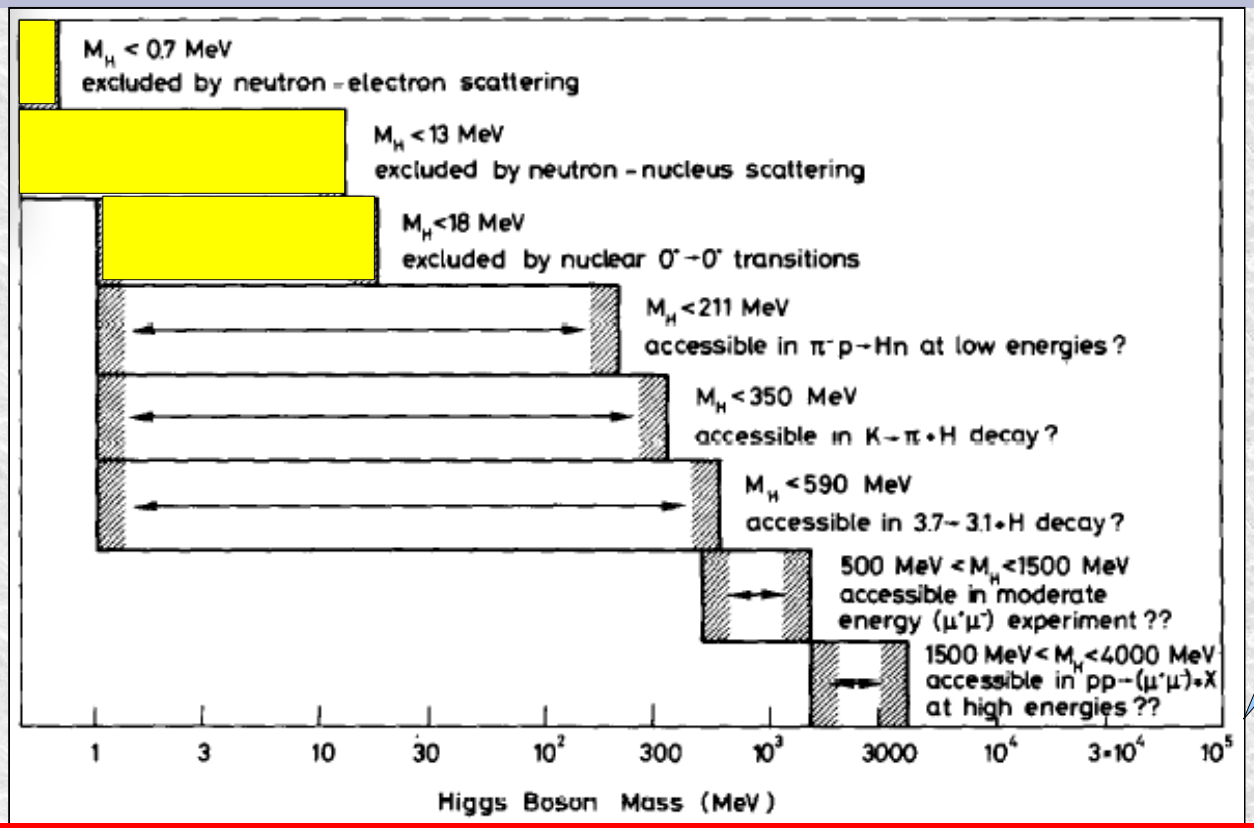
- Green band is SM prediction
  - Its width comes from the (unknown) Higgs mass
  - 115 to 600 GeV shown
- Yellow+black band is the measured mass
- They match incredibly
  - Many theories failed this test
  - But only works at the right edge of the band
    - A light Higgs, near 115GeV
- Nb. This calculation assumes no unknowns
  - Could be badly wrong

History of the search

- 1964 Brout & Englert, Higgs, Gouralnik, Hagen & Kibble,
  - Not taken too seriously until...
- 1967 Used in the formulation of the 'Standard Model'
  - Proven to be self-consistent in 1971
- 1973 Experimental acceptance of the 'Standard Model'
- 1983 Discovery of W and Z bosons
  - Closely linked to the Higgs boson
- 1993 LEP studies Z's and rules out m_H<53 GeV
  - And indirectly excludes m_H>300GeV
- 2000 LEP limits reach 114.4 GeV
  - Hint of production at 115?
- 2011 LHC excludes 130-550GeV, Tevatron 156-175
  - Some indications for a particle at 125?
- 4th July 2012 New particle found at 126GeV
  - Consistent with the Higgs

Nucl. Phys. B 106 (1976) 292.

View from 1975

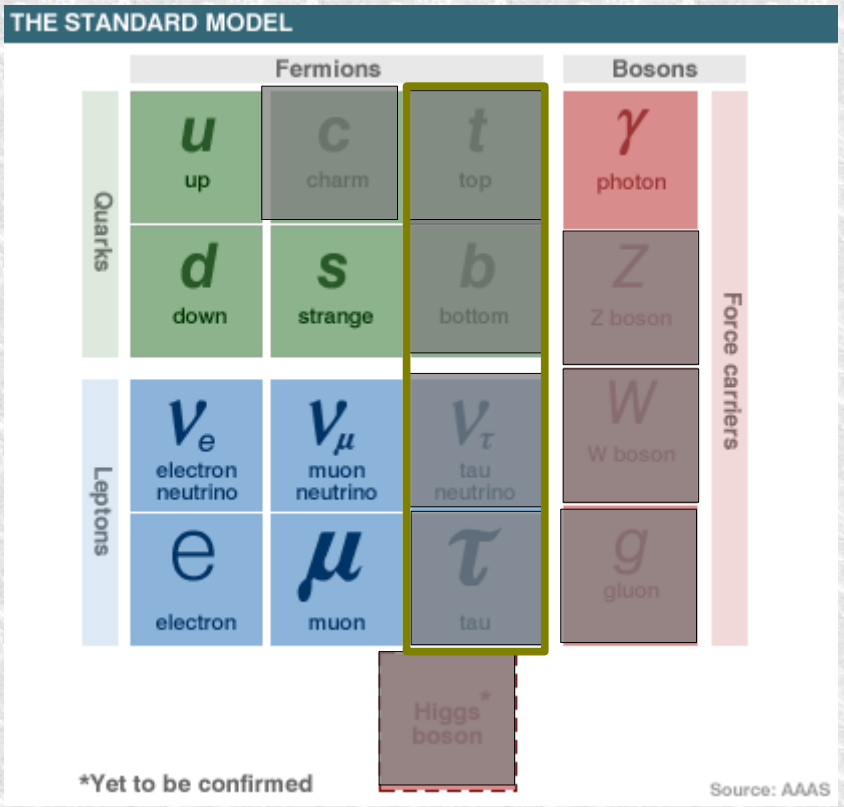


New particle is here

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.

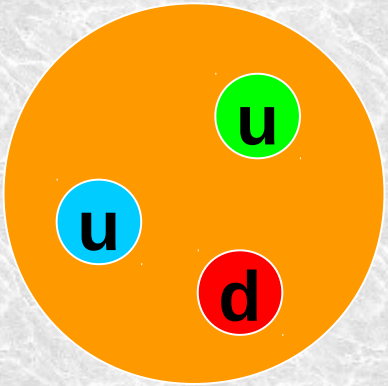
The Standard Model 1970

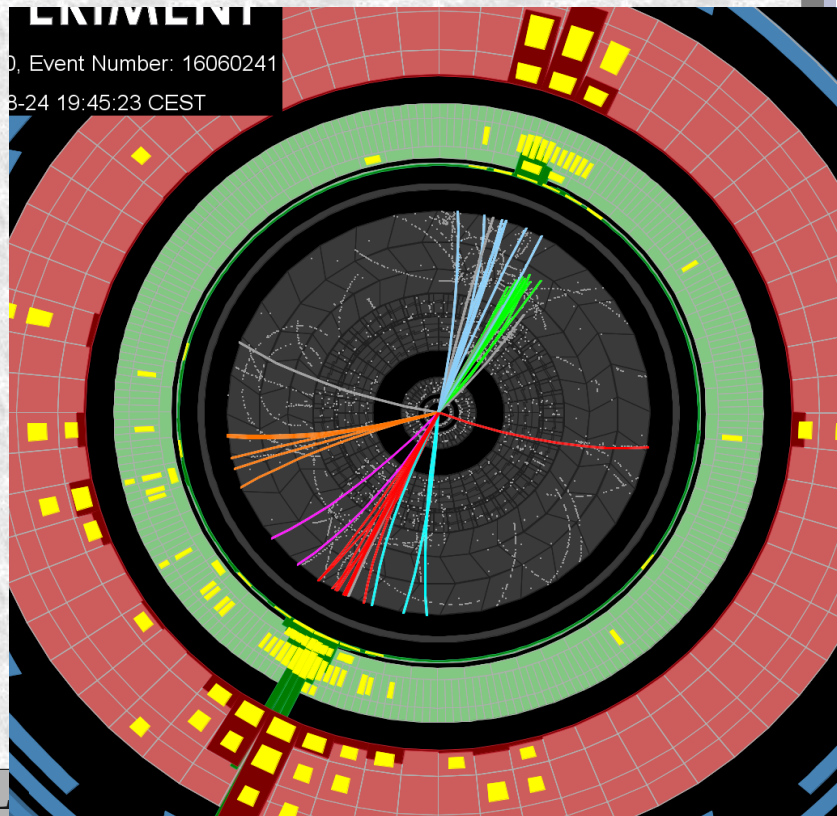
- Only 8 (of 17) particles was known
  - One column was added to the theory in 1973
  - But the forces/Higgs not touched
- The W/Z linked to Higgs sector
  - Not found until 1983/4
- This was really a bold extrapolation
  - But by 1984 14 of the pieces were known
  - The last (ν_τ) arrived in 2003
  - Leaving only the Higgs unseen



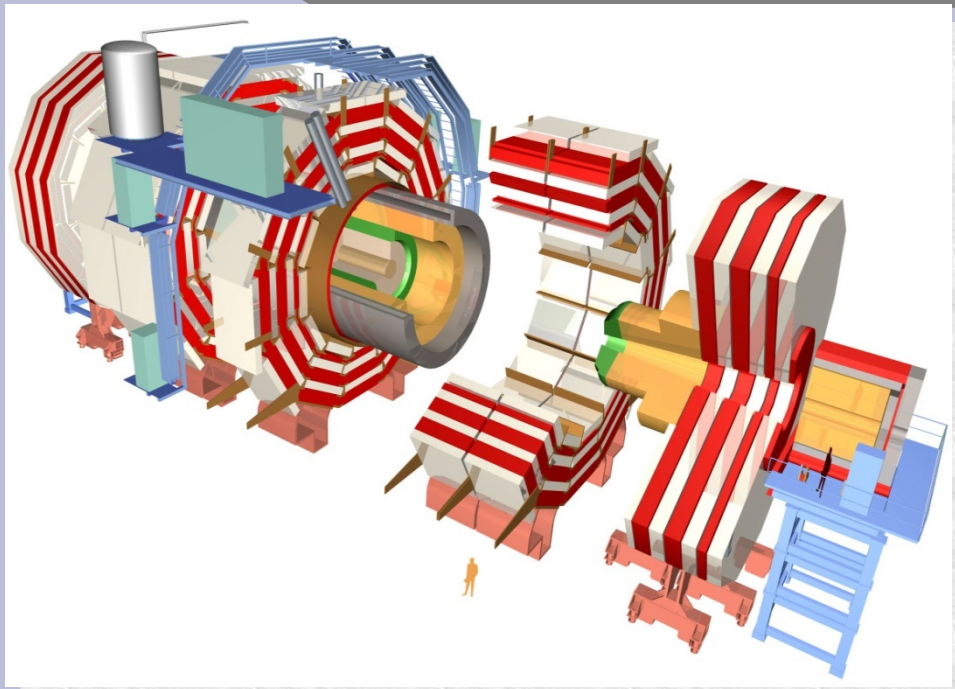
The LHC in a slide

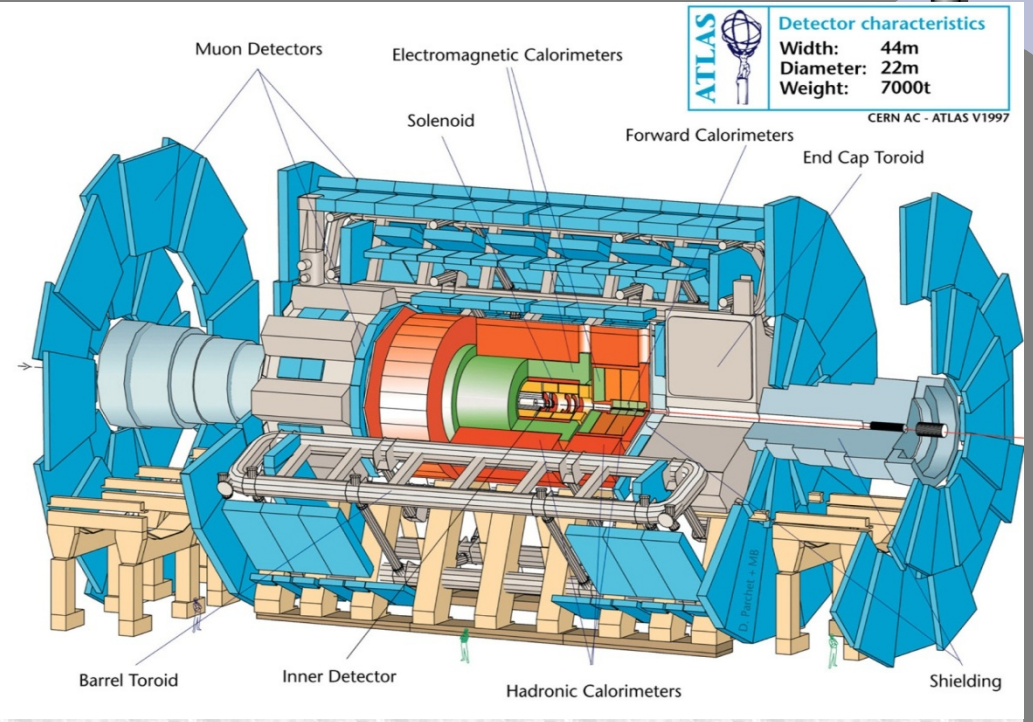
- The LHC collides protons at 4000GeV
  - Two head on makes 8000GeV
  - Will get to 2x7000GeV in 2015
- The energy to make a proton is ~1GeV
  - Many particles can be created in the collision
- A proton is a bag of quarks
  - In most collisions the bag breaks,
  - They 'hadronise' and appear as a jet of known particles
- Occasionally other things appear
  - Maybe one in 10,000,000,000 makes a Higgs
  - But few of those can be recognised
- So bunches collide at 20MHz
  - With 30 protons smashed each time



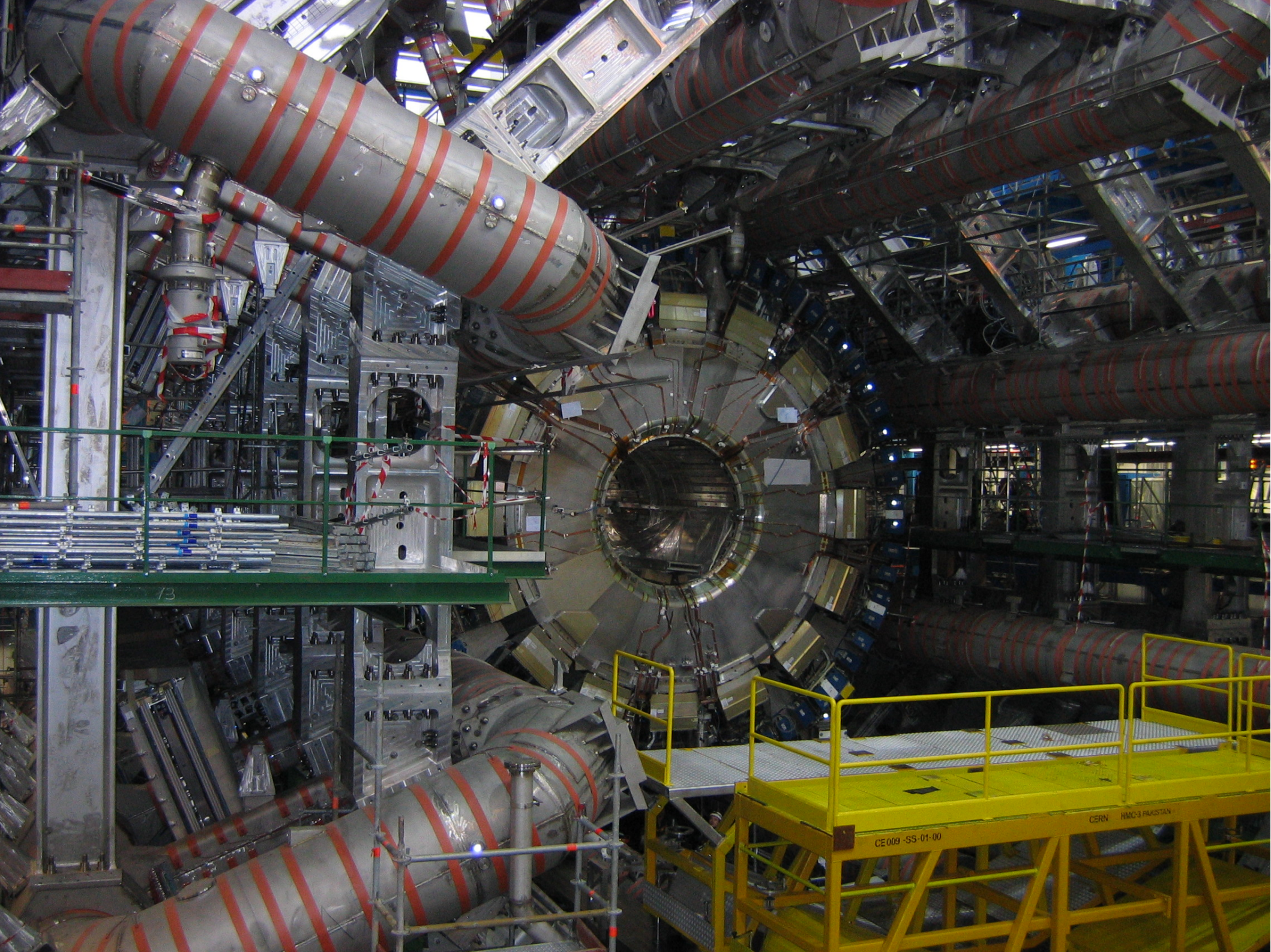


ATLAS and CMS





- Two massive detectors studying highest energies
- 3 stage of identification
  - Tracking charged particle for 1m or so
  - Then massive absorbers stop the particles & measure energy
  - Second set of 'trackers' looks for the penetrating muons
- Note the people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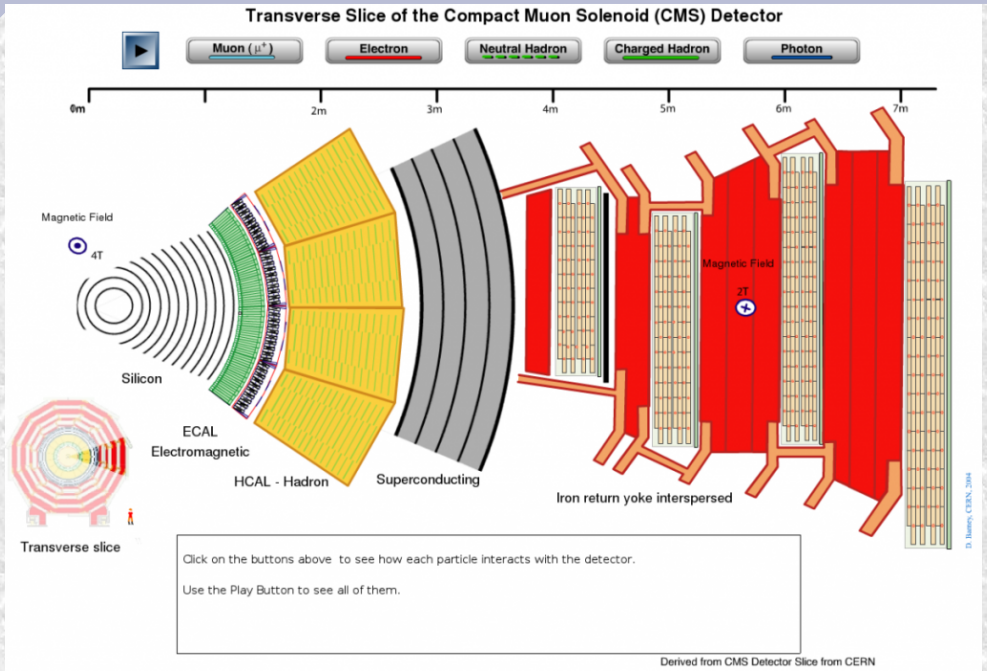
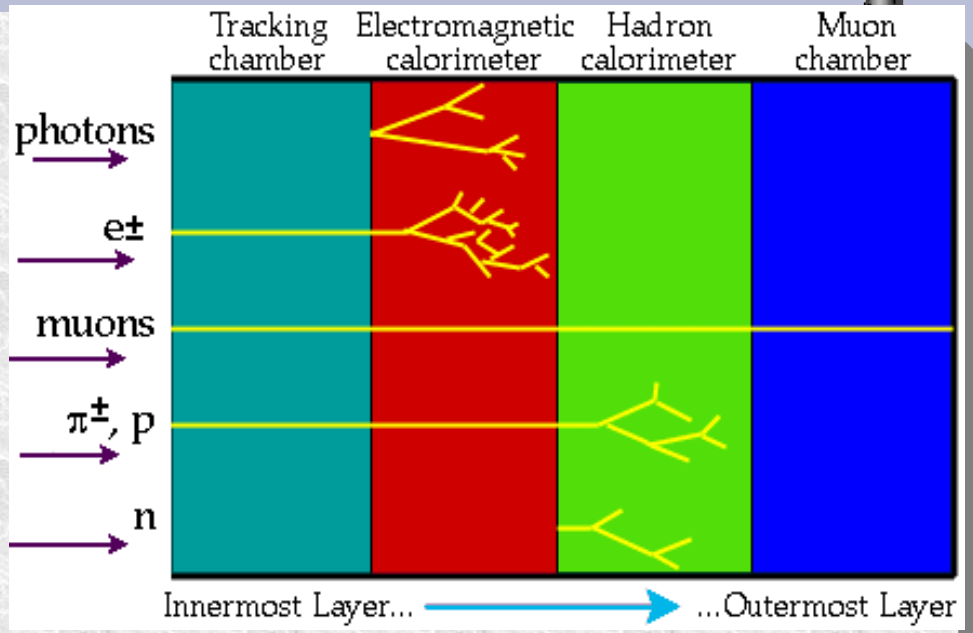
HMC-3 PAKISTAN

Particle identification



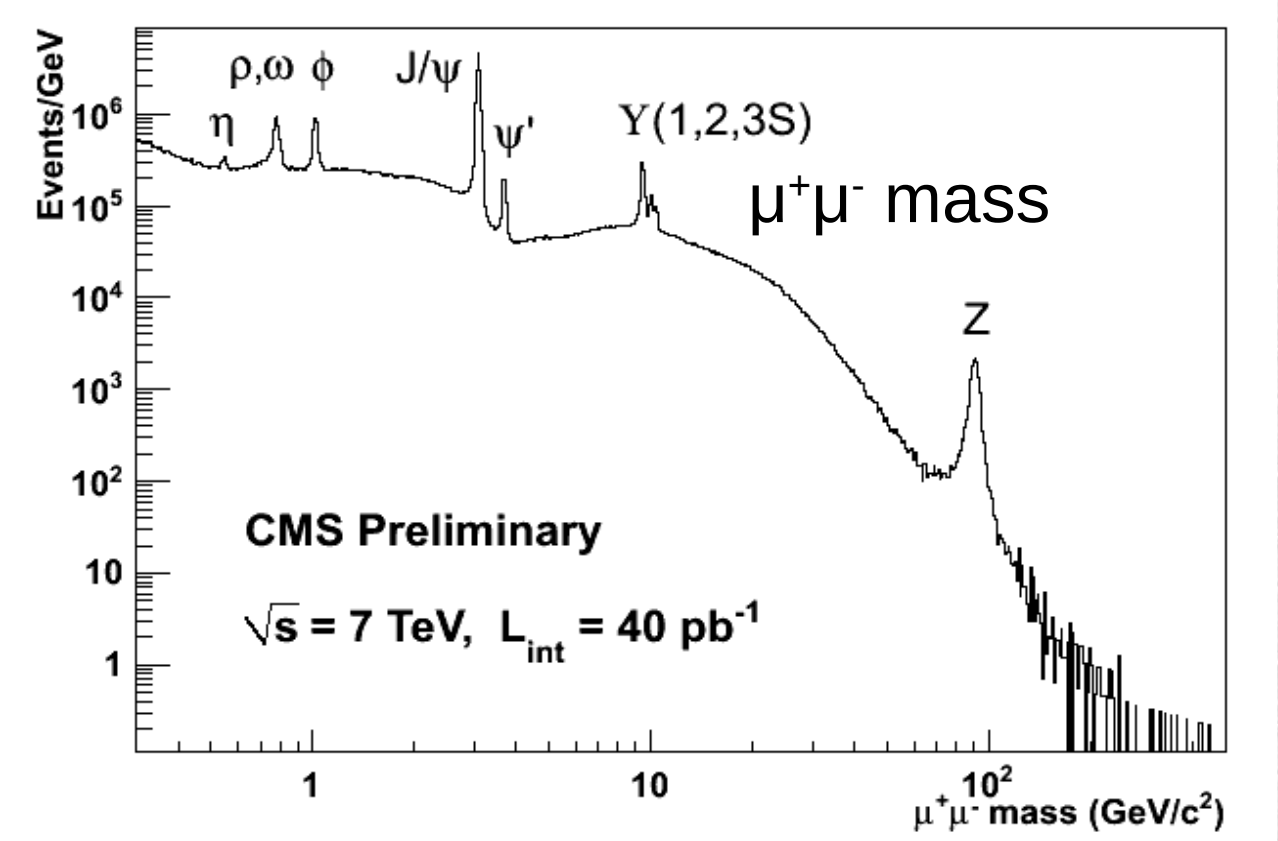


- New particles (e.g. Higgs) decay extremely fast
  - Reconstruct what happened from decay products
  - Can identify type by interaction pattern in the detector
- Electrons, muons and photons are very useful
  - There are none in a proton so their presence in suggestive
  - We can measure their energy very well

How do we look for things?

- Masses of pairs of muons show lots of structure:

Sort through the LHC data
Find events with two muons
Measure their momenta
Assume they come from the breakup of some particle
Calculate its mass
Put entry in the histogram
Repeat for next event



Each peak is a (known) particle decaying to 2 muons

Hunting the Higgs Boson

pre-LHC knowledge

- There was a minimum Higgs mass
  - m_H>114.4GeV
  - Set by LEP, an electron-positron collider at CERN
    - In the same tunnel as LHC but much lower energy
- A region was excluded by the Tevatron
  - Proton-antiproton collider in Fermilab, USA
  - from 155-173GeV ruled out
  - They also have 'evidence for' at 110-140GeV
    - http://arxiv.org/abs/1207.6436 (27th July 2012)
- The W mass suggested below about 160GeV
  - But it assumes there is nothing else to find
  - That cannot really be true

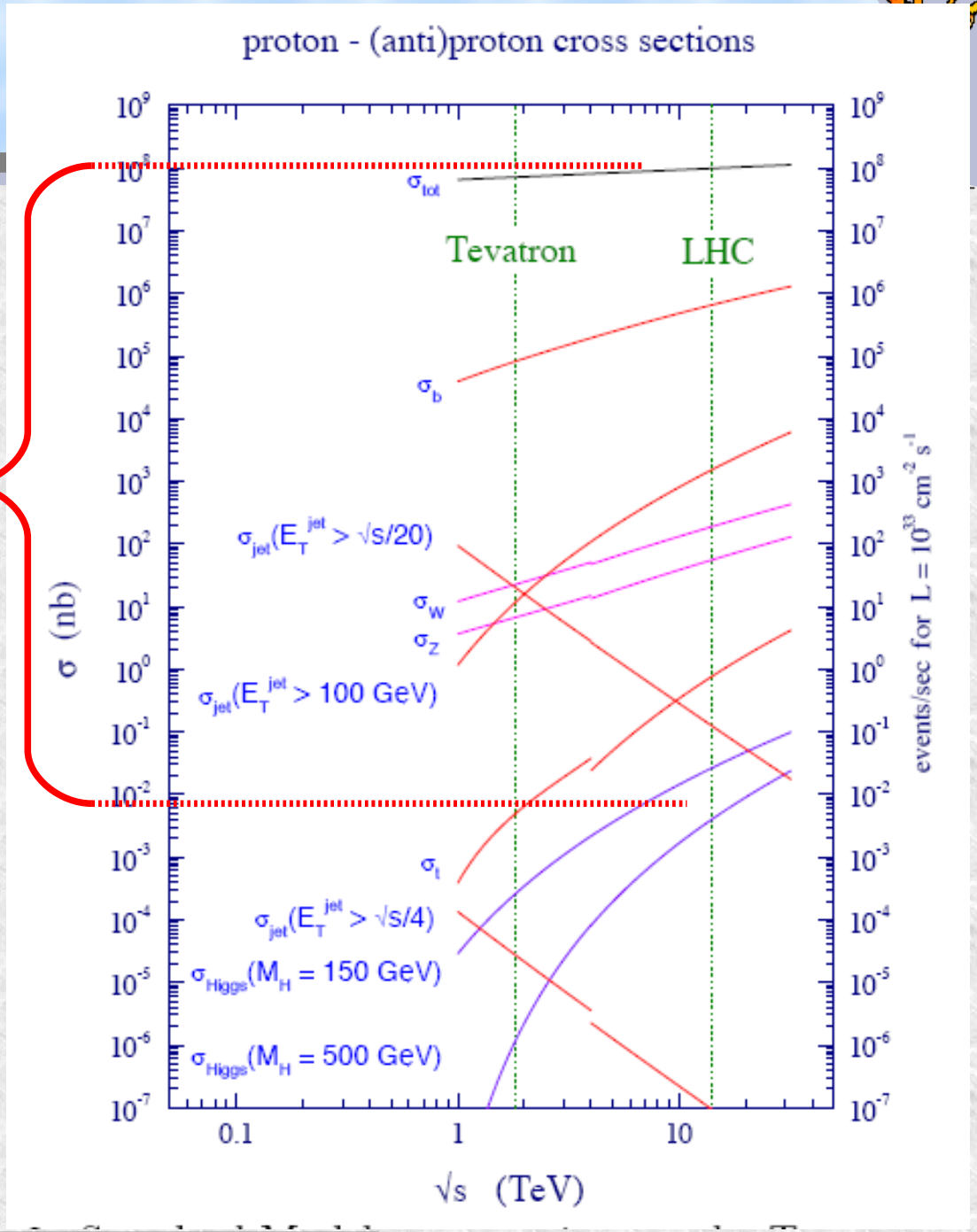
Rates?

- LHC backgrounds!

10^{10}

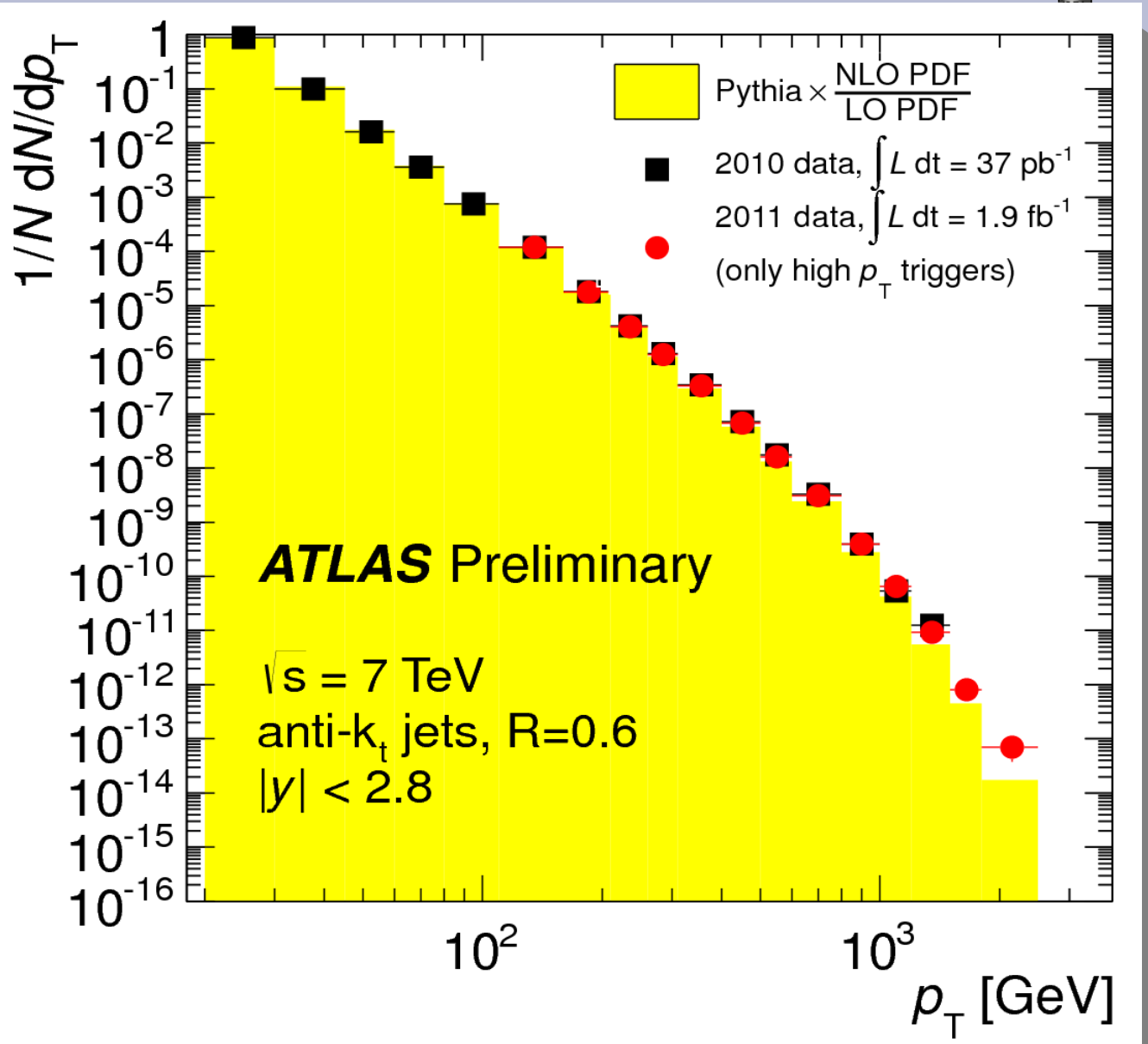
Every event at a lepton collider is physics; every event at a hadron collider is background

Sam Ting

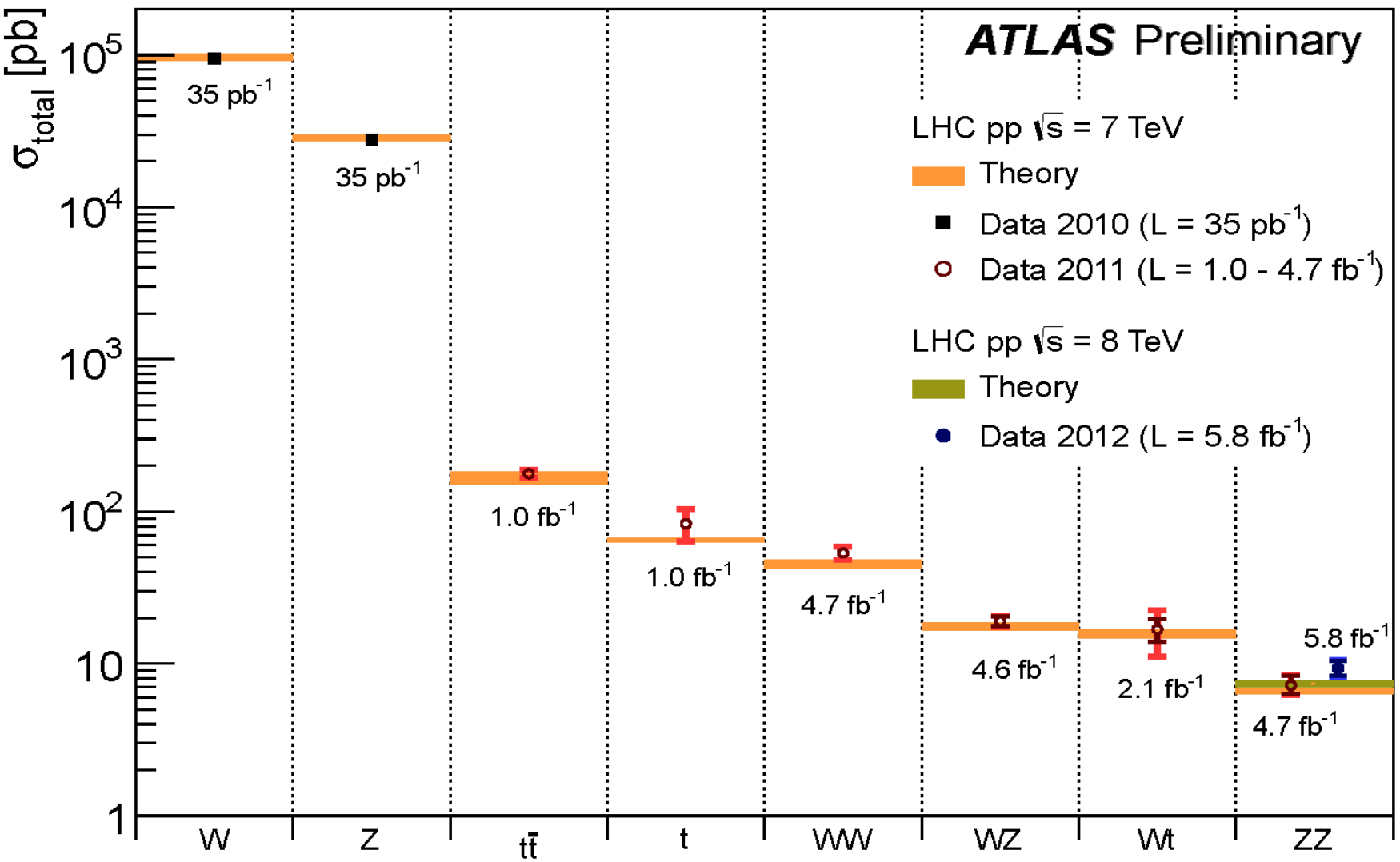


Huge event rates needed

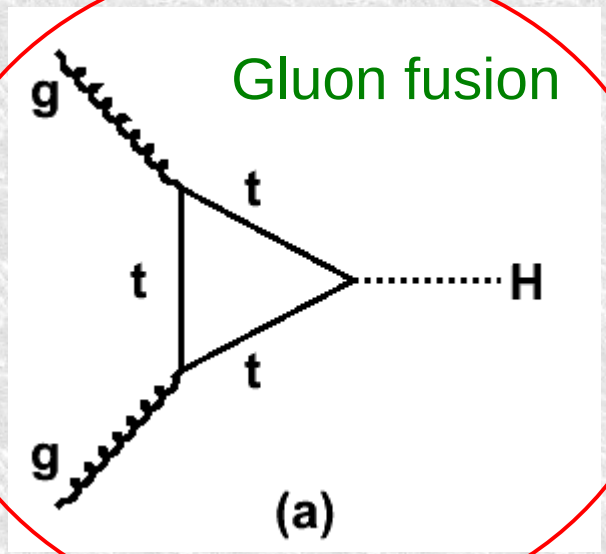
- The rate of jets as a function of their p_T
- 20-2000GeV tested
- Rate falls off by thirteen orders of magnitude
- We need to understand the common process extremely well

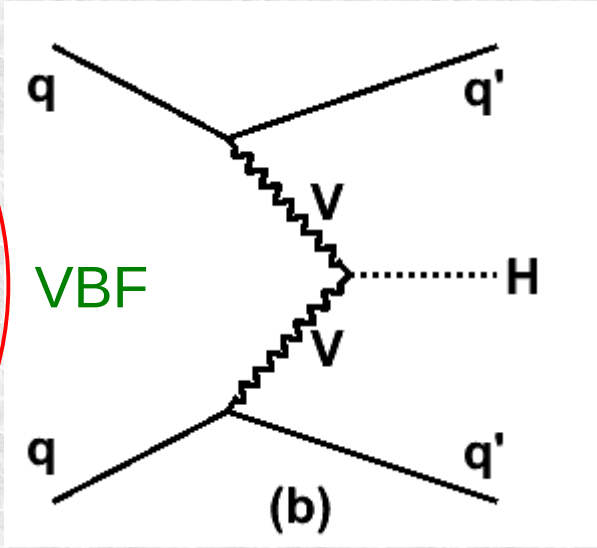


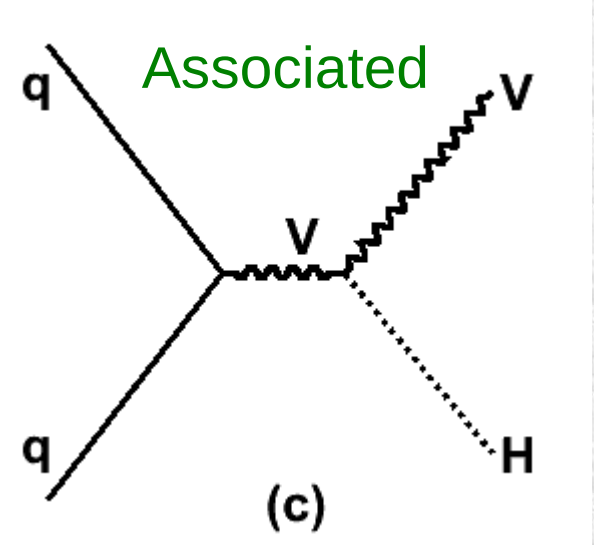
W/Z/top measurements



Higgs production



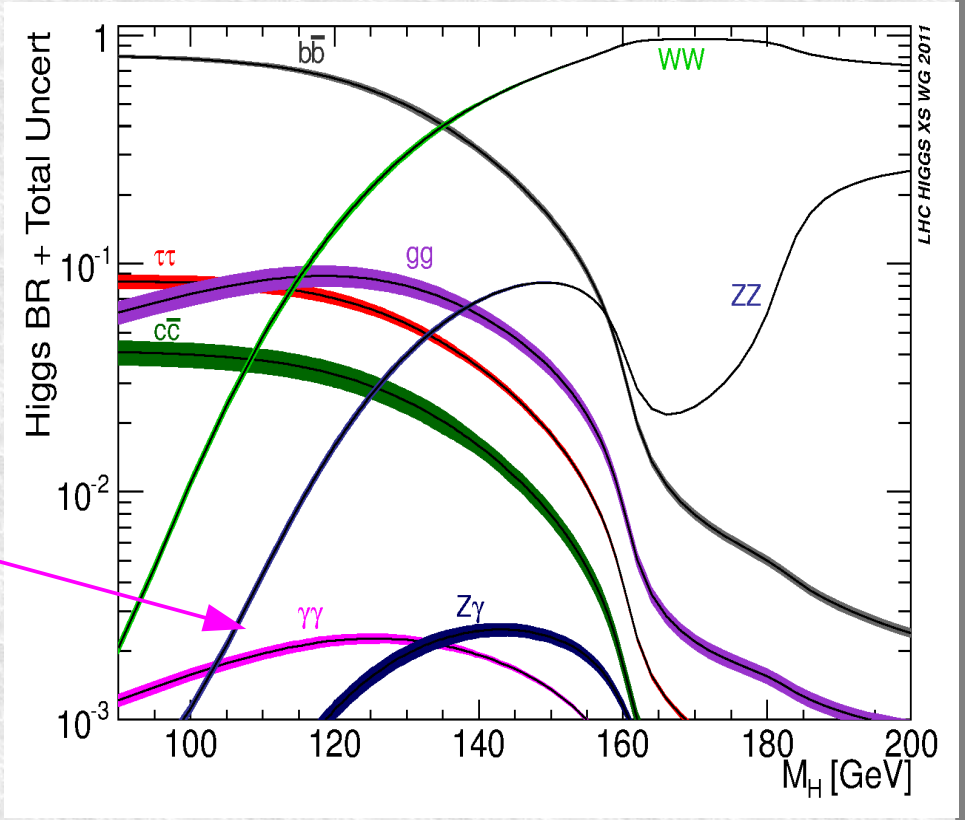




- The three most common modes
  - Others also exits: $t\bar{t}H$, tH ...
- Gluon fusion has highest rate
  - Note: a 'loop' process with a virtual top quark
- Vector boson fusion and associated have extra activity
  - Can be used to tag process
  - Improves the purity

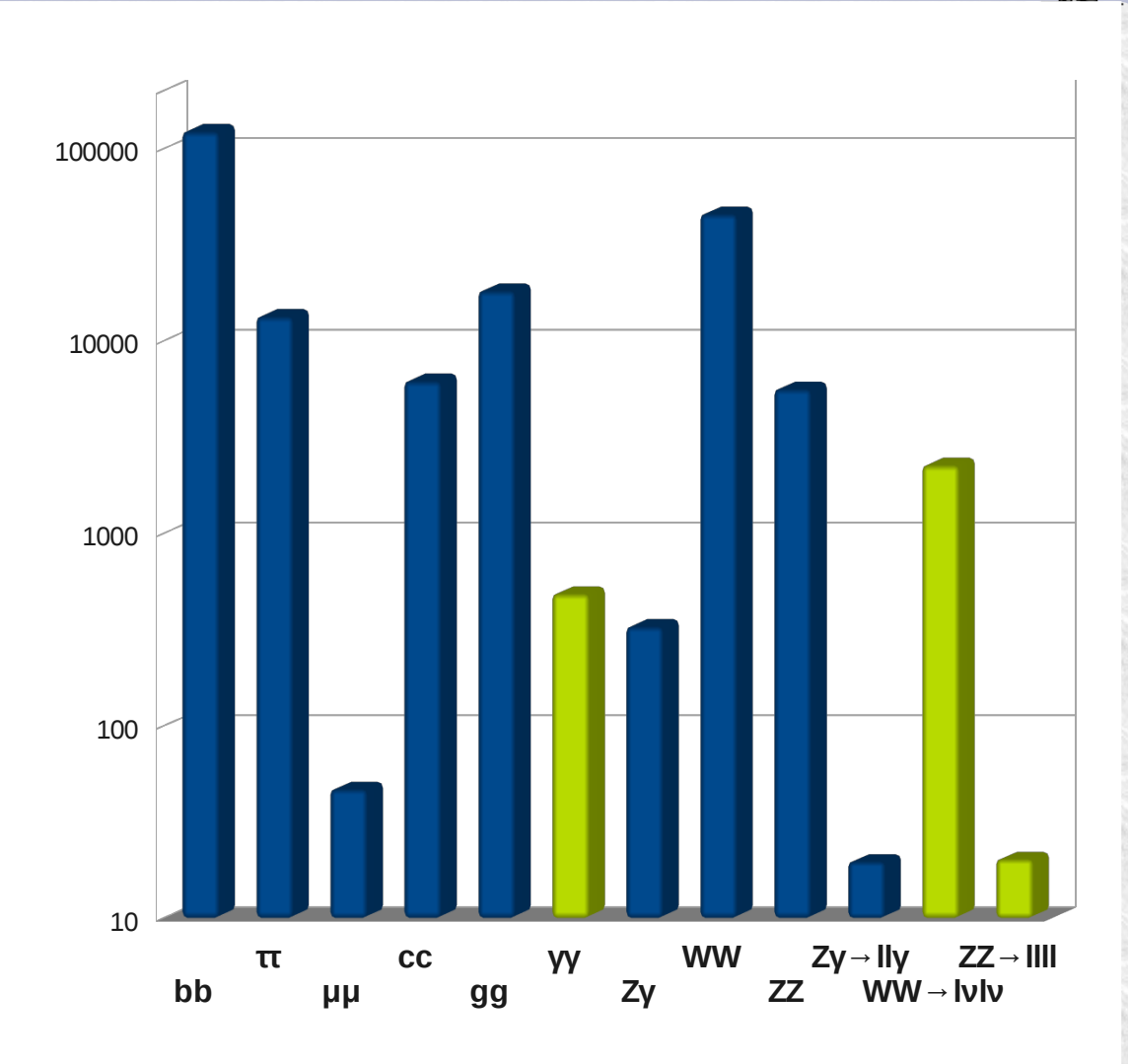
Higgs decay fractions

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



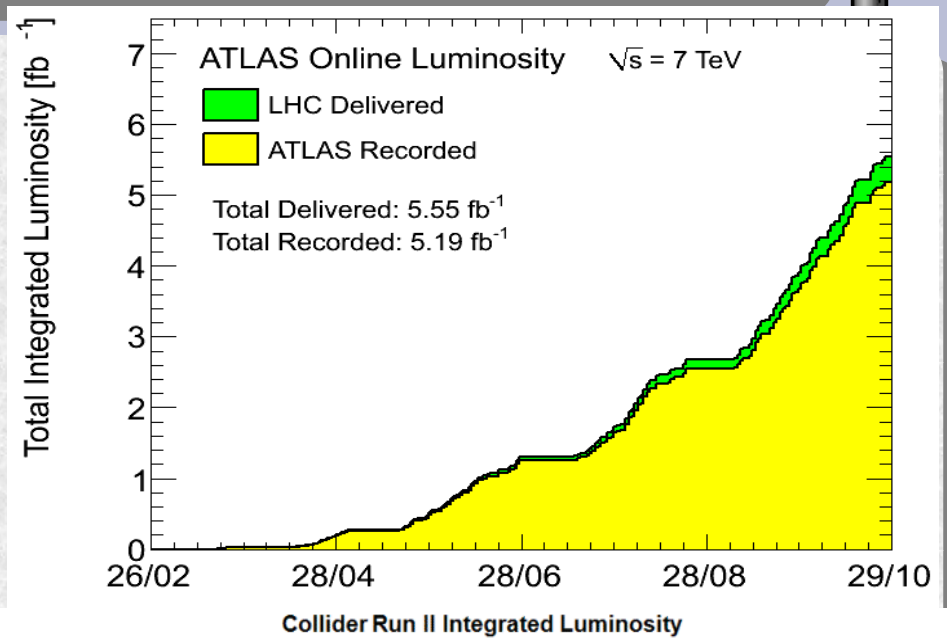
Rates by channel at 125GeV

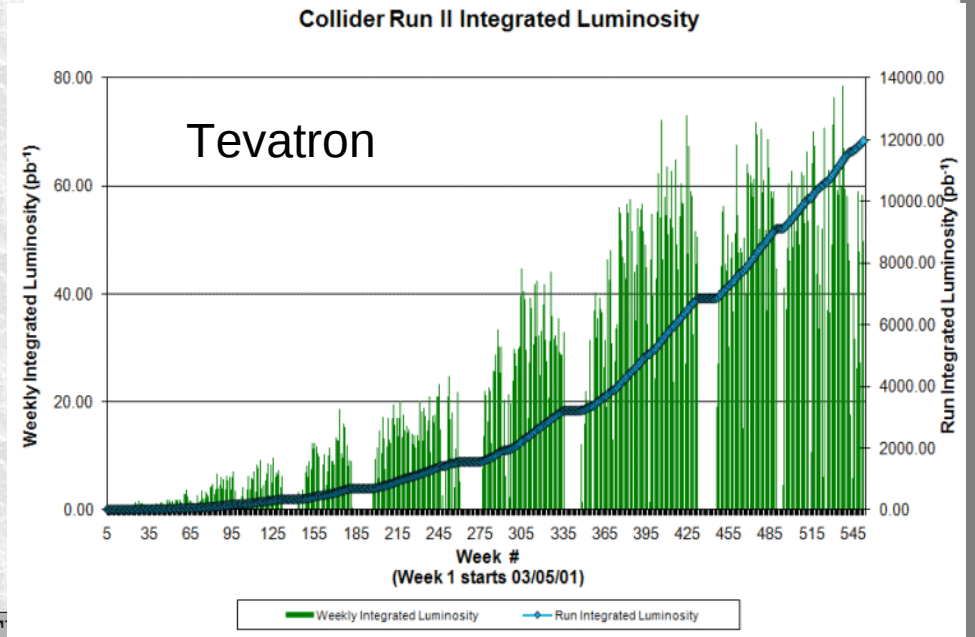
- Data to June 2012
- From 10s to 100000 events per channel
  - Easy!
- But total pp events: 8×10^{14}
- 20 Higgs to llll events
- Needs incredible background rejection
  - The green channels end up the most sensitive



Data collection 2011

- LHC started at 7TeV in 2010
  - But really a development year
- 2011 was first year of large data production
- 5fb^{-1} allowed SM Higgs sensitivity
- Luminosity in 2011 rose smoothly
  - 5.5fb^{-1} delivered
- Compare with Tevatron
  - US $p\bar{p}$ collider. 1TeV+1TeV
  - 12fb^{-1} in 10 years
- Great effort by LHC team!

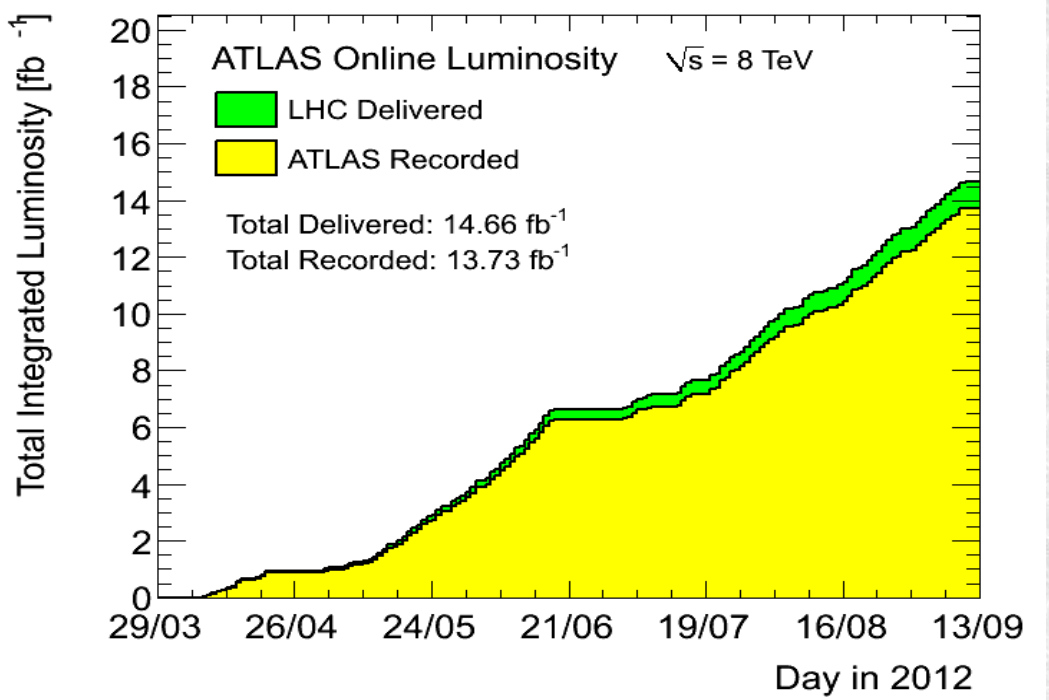




2012

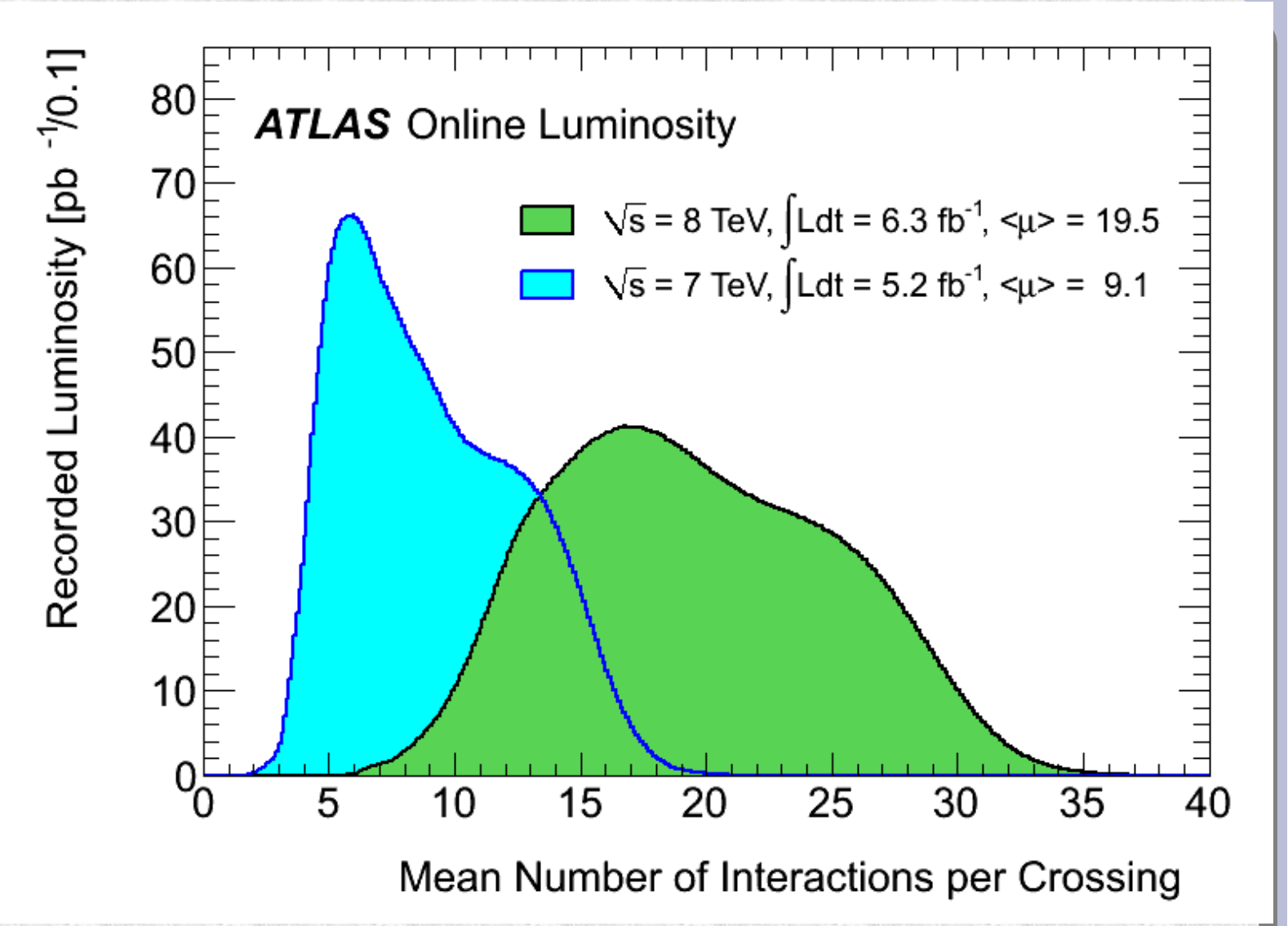
- The LHC energy was increased from 7TeV to 8TeV
  - Brings a 30% increase in Higgs bosons/collision
  - Also increases the collision rate as beams shrink naturally
- The LHC beams were squeezed harder
  - 40% reduction in size – 40% higher chance of colliding
- Overall factor two increase in rate.

- LHC has delivered 14fb^{-1}
  - 6fb^{-1} was used for discovery
- Running until Christmas
  - 20fb^{-1}+ assumed
  - Will allow study



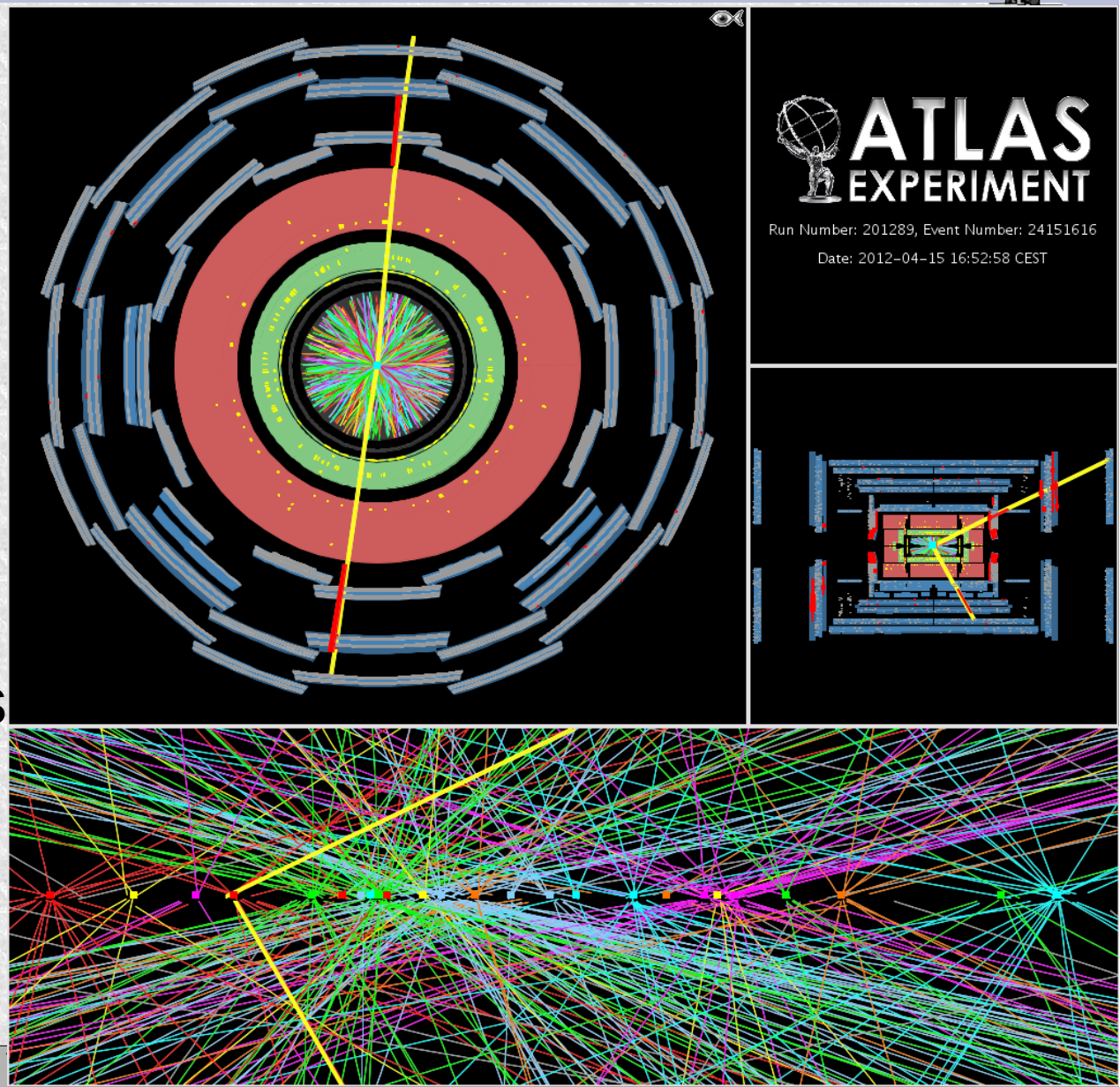
Pileup worse than 2011

- In 2011 9 collisions per bunch crossing
- Changed to 20 in 2012
- That is how LHC increased the data rate....
  - So learn to cope



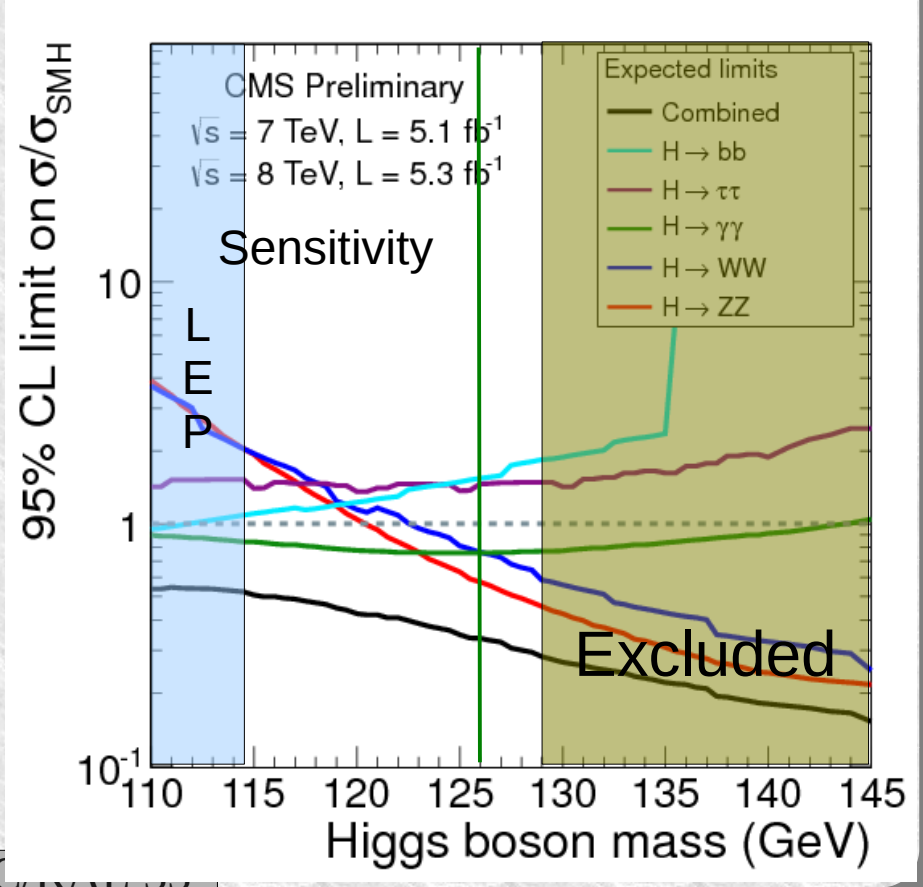
Pileup in 2012

- An interesting event
  - Z→μμ here
- Has multiple overlayed interactions
  - 25 seen here
- The tracker can distinguish them by position
- The calorimeter finds it harder
  - Make checking momentum balance hard



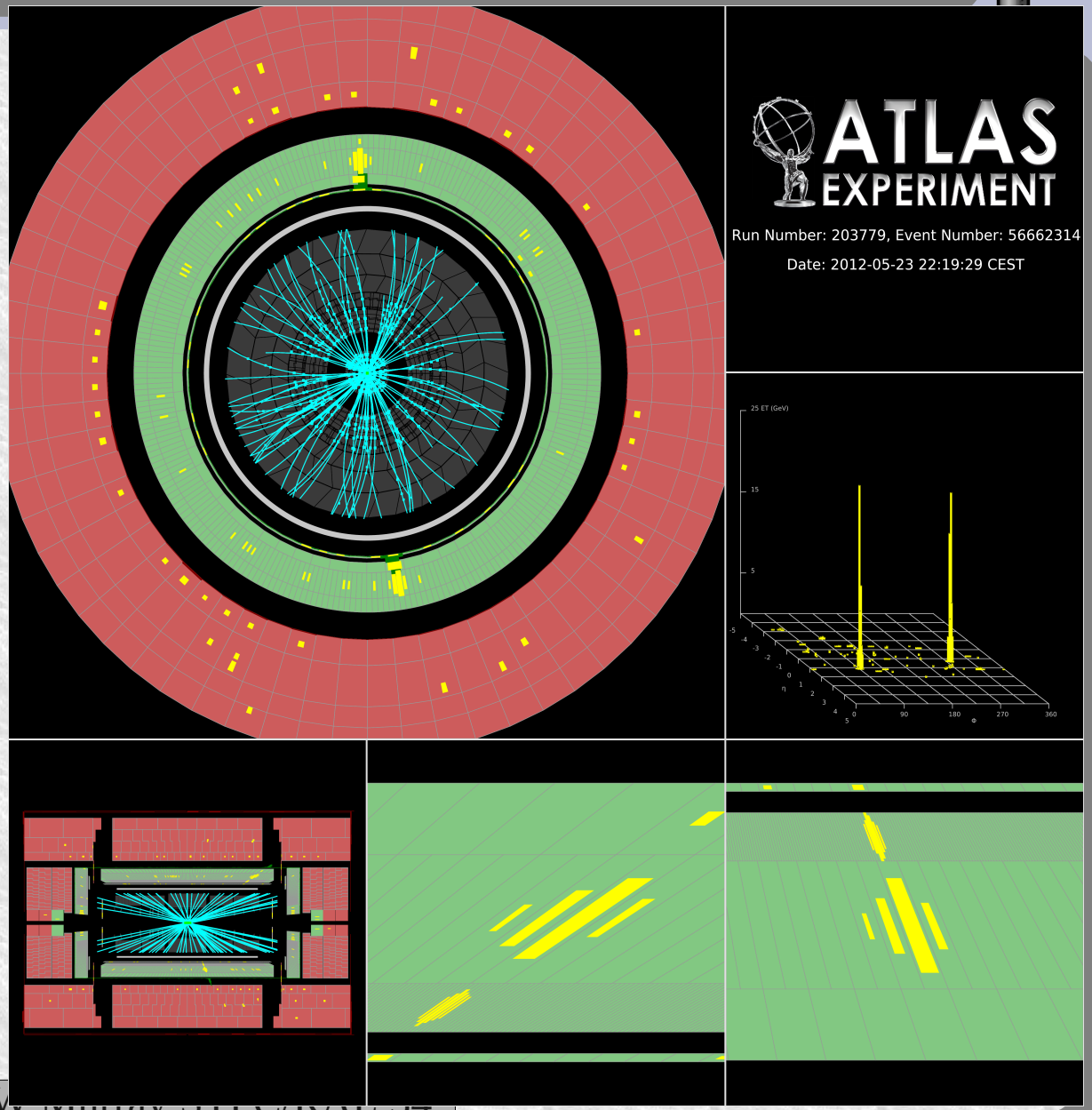
So what do 2012 data say?

- Papers submitted 31st July by CMS and ATLAS
  - Both claiming observation of a new particle
- Focus on region 115-129GeV left from 2011
- ATLAS used only 3 strongest channels:
  - γγ
  - ZZ
  - WW
- CMS used these, but also two more
  - ττ
  - bb



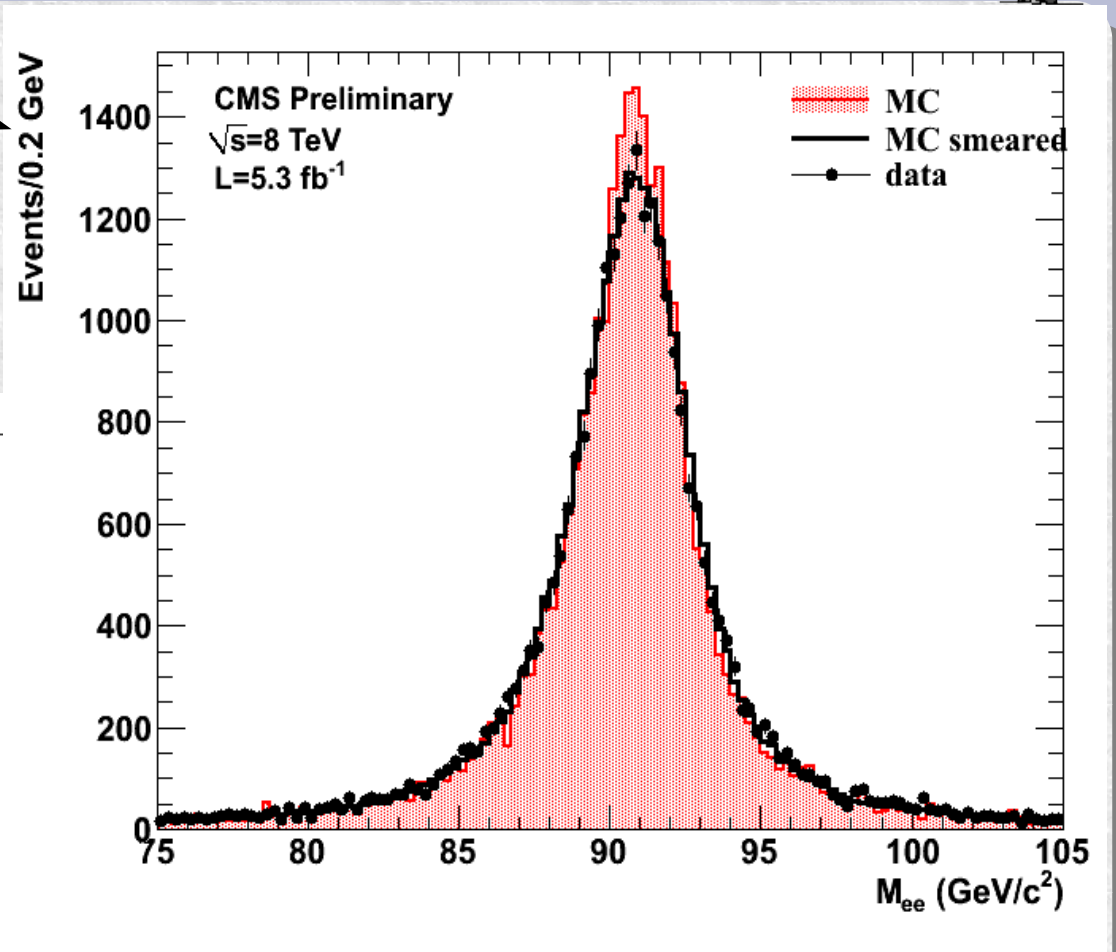
$H \rightarrow \gamma\gamma$

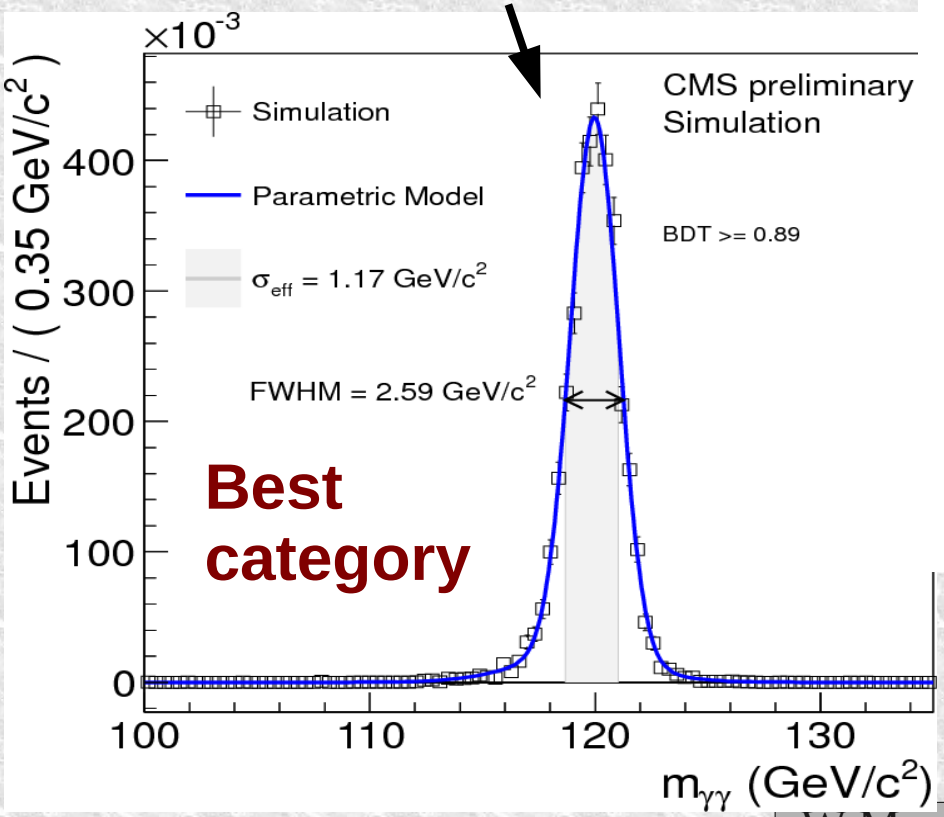
- Rare decay,
  - 2 per mille
  - $110<m_H<150$
- Drove ECAL design
  - Resolution in CMS
  - Pointing in ATLAS
- To measure mass need to know vertex position
  - Pileup hurts!
- Good jet rejection also essential



H→γγ mass resolution

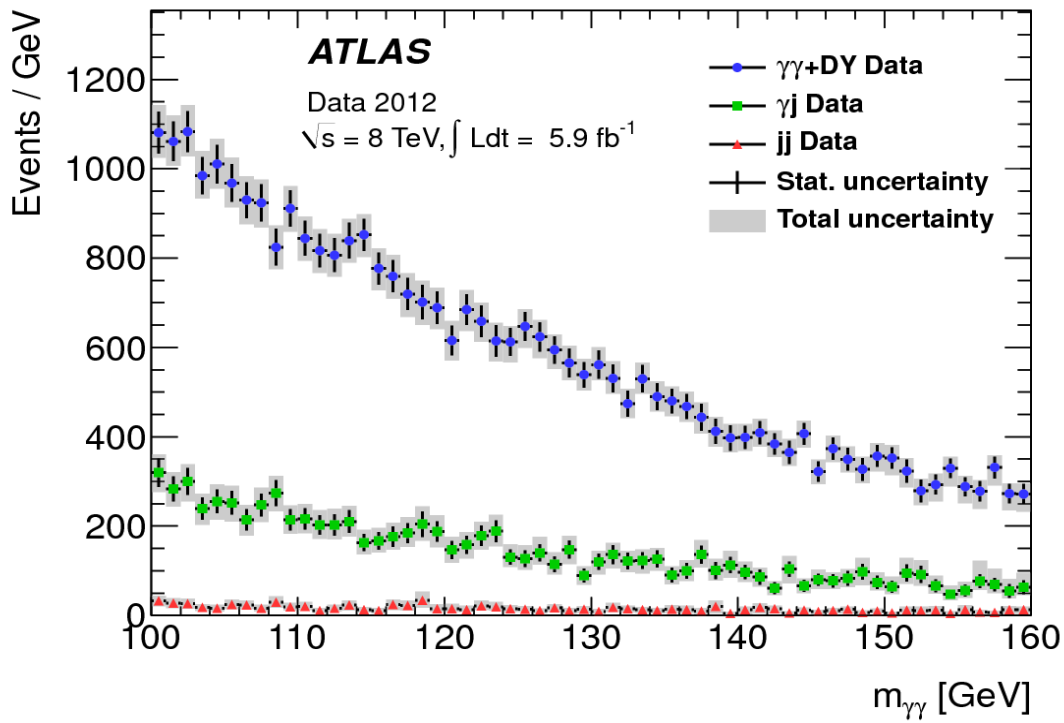
- Best check is Z→ee
  - But Z has a natural width, broadens distn.
- Higgs will be narrower
  - Need to trust MC

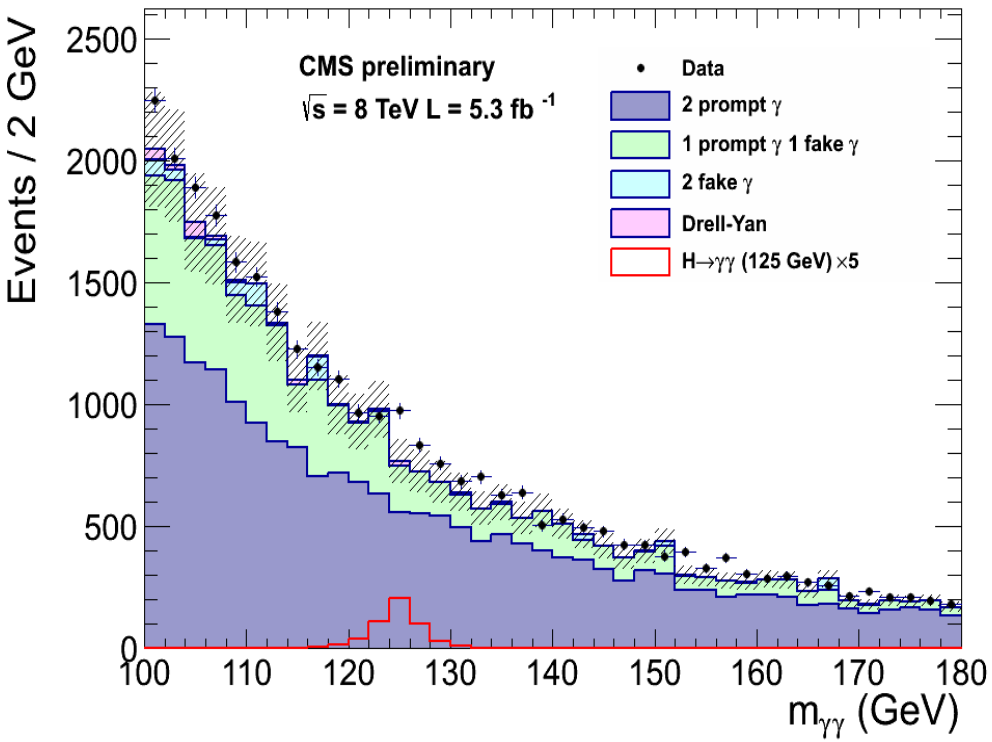




- ATLAS and CMS similar

H→γγ sample makeup



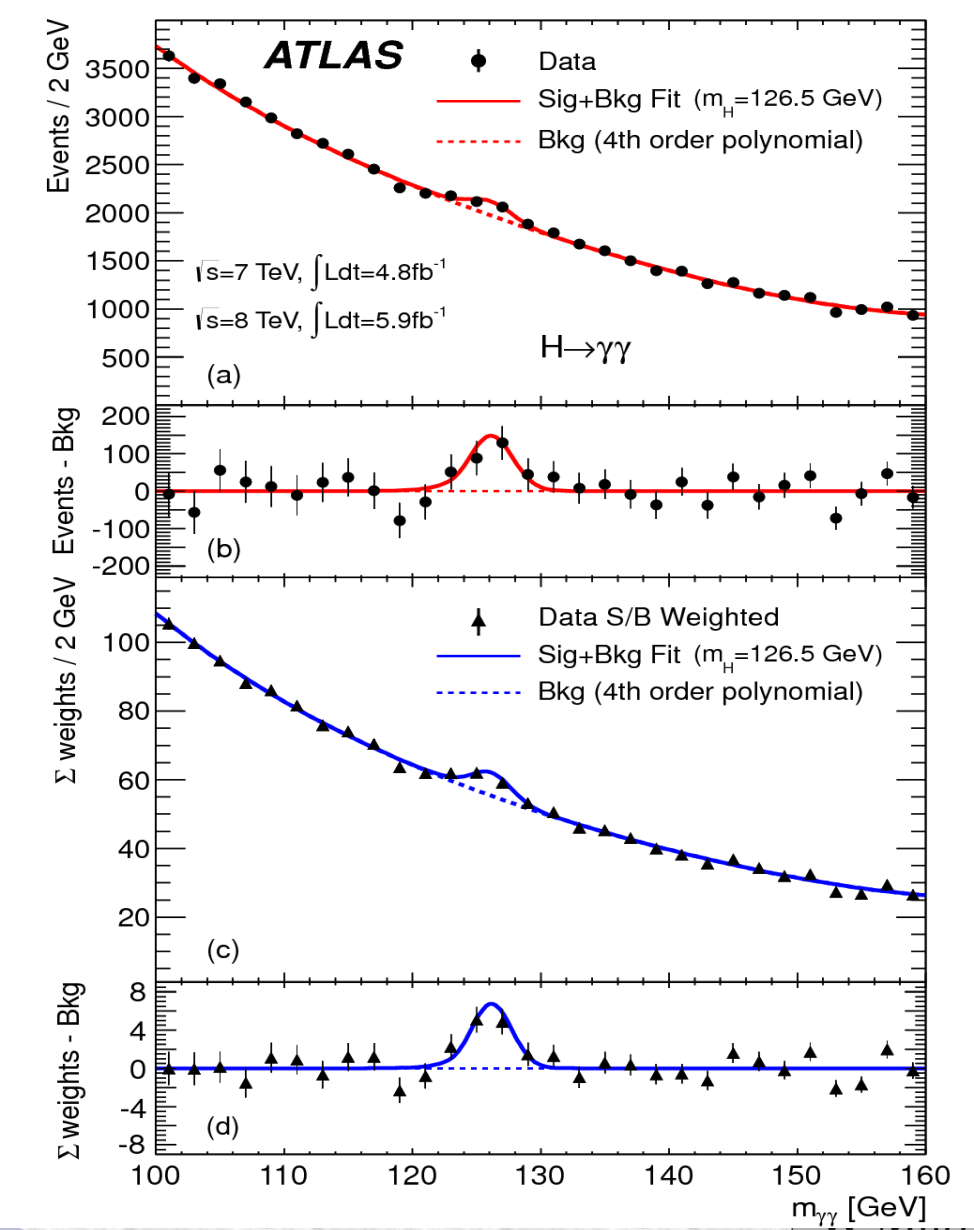


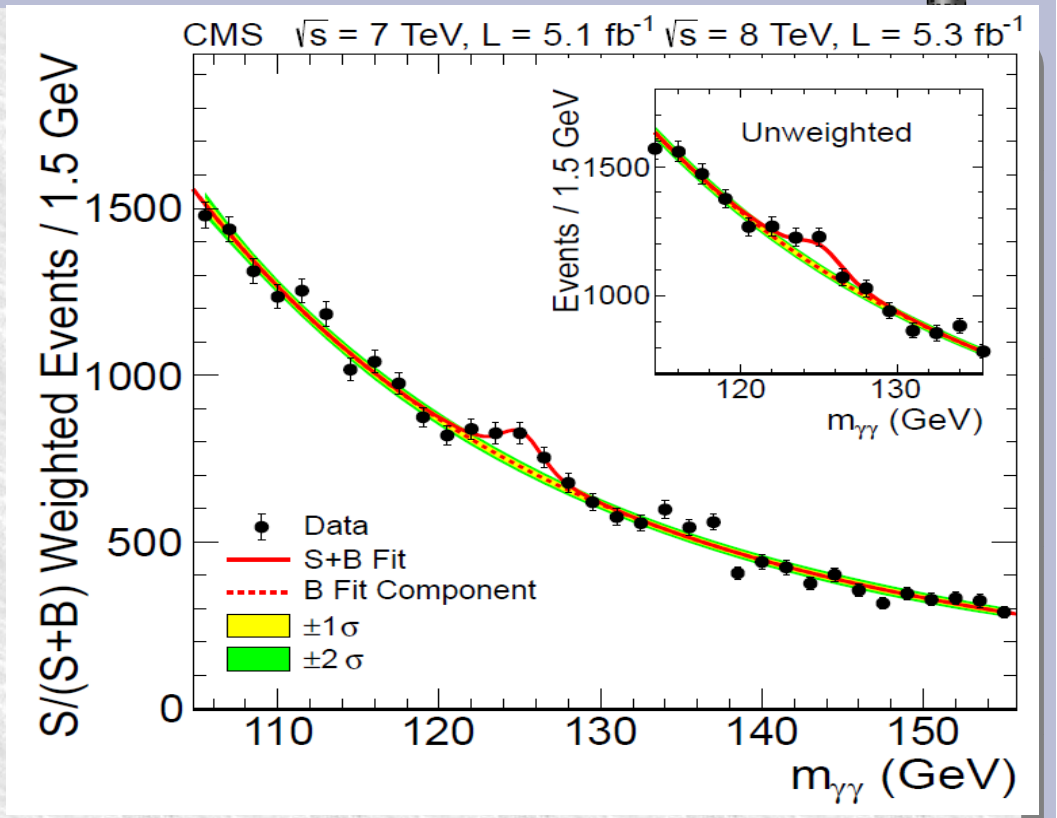
- Both experiments measure sample composition
  - γγ, γj or jj?
  - Use less-well identified data samples to measure it
- Samples are dominated by real di-photon.
  - We did reject 99.99% of jets!

$H \rightarrow \gamma\gamma$ analysis method

- In principle look at the m(γγ) spectrum for a bump
- But signal/background and resolution depend upon other variables
- Both experiments split into several categories, fit at once
  - ATLAS uses p_{Tt}, barrel/forward, converted/unconverted
  - CMS uses MVA to select categories
- One or two 2-jet categories sensitive to VBF added too
  - Gives more power
  - But also useful to understand physics of production
- But..too many plots to take in
  - 20 in ATLAS' case
  - So experiments weight categories and add them up.

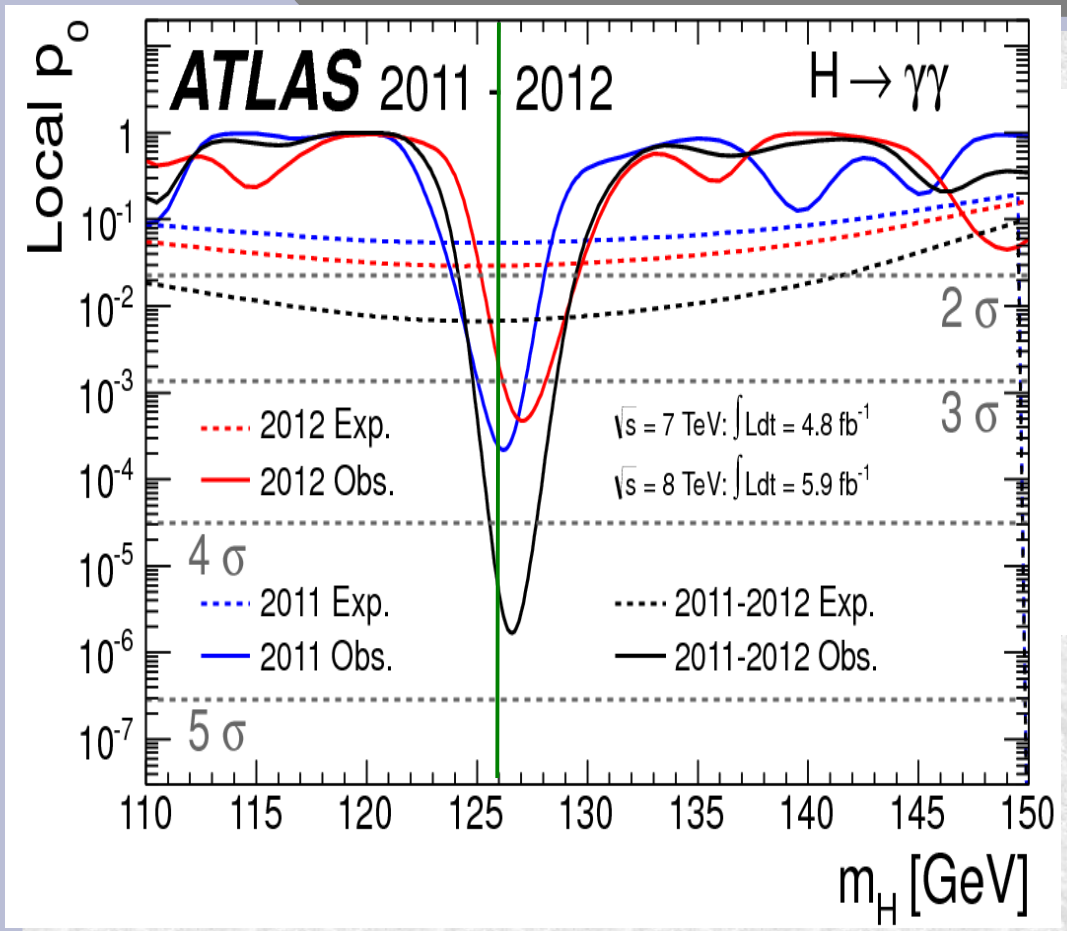
H → γ γ

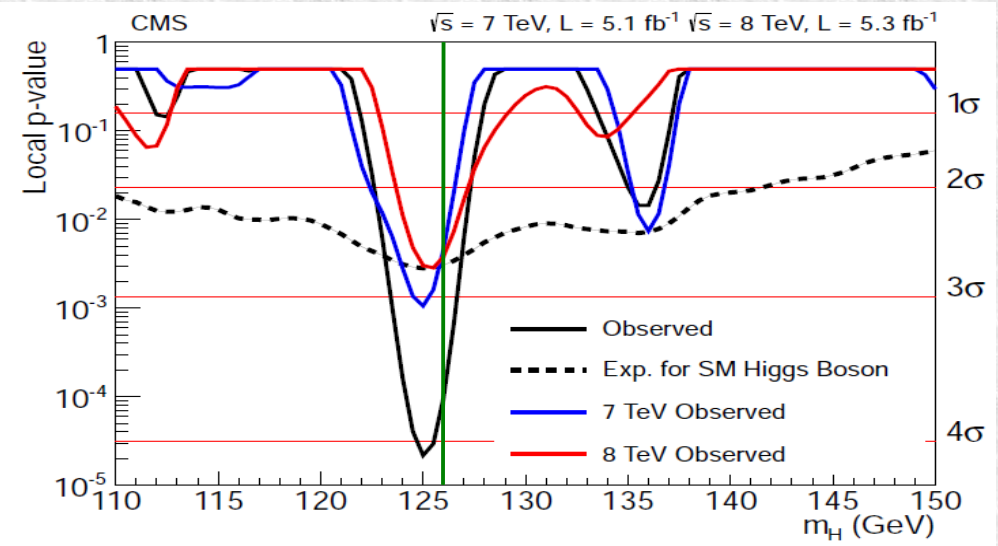




- Both experiments see significant peaks around 125
- Weighted sum clearer

Background Compatibility

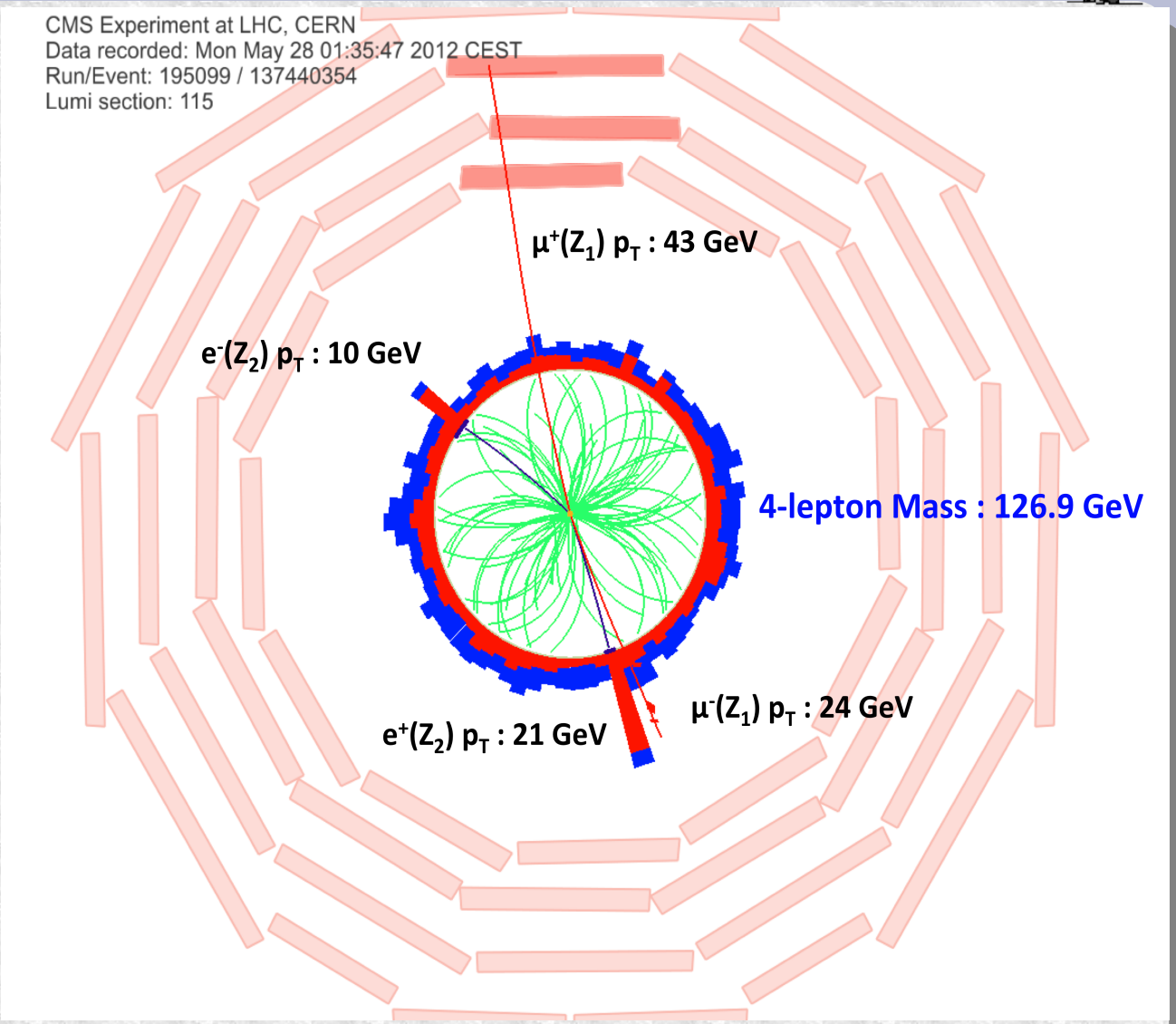




- Peak around 126 in both years, both experiments
- Probability around 10^{-5} in each case
- Definitely looking interesting

H → ZZ → llll

- The golden mode
- Good energy measurement like γγ
  - But know production point
- Very low backgrounds
  - Dominated by ZZ → llll
- But signal rate low
  - Z → ee or μμ br only 3%
  - Need to maximise efficiency



How is analysis done?

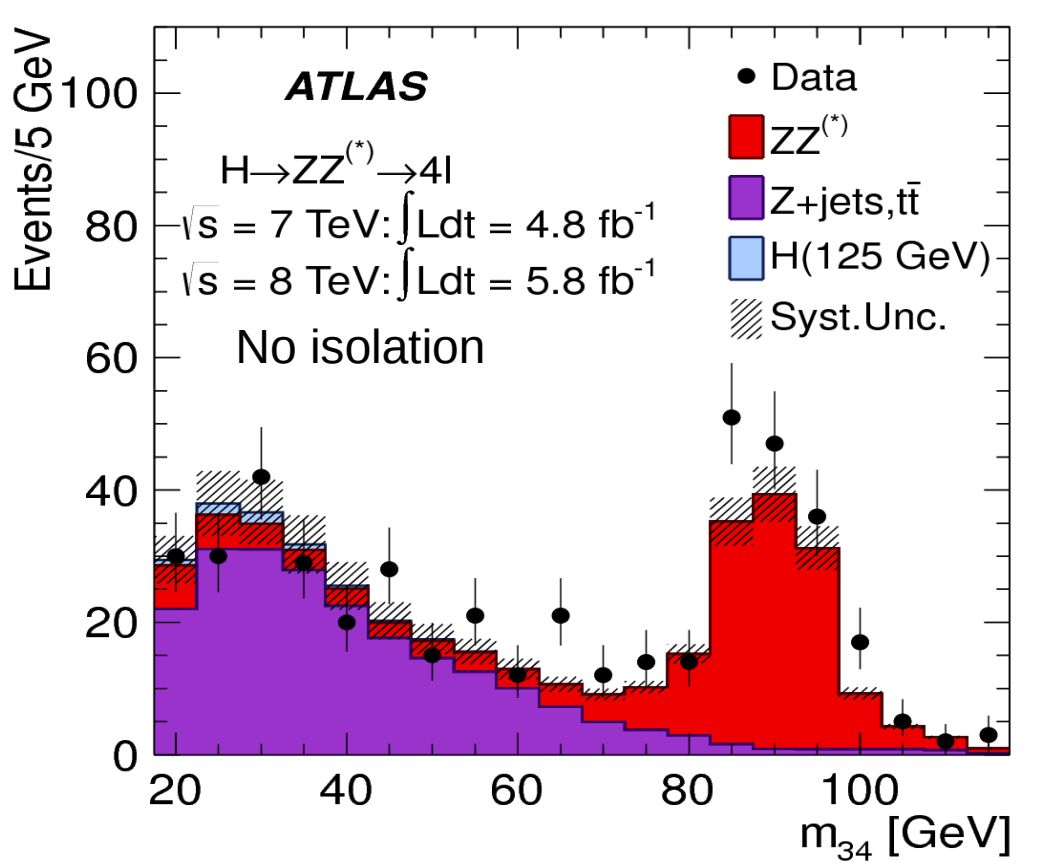
- Find events with 4 leptons (e/μ) in them
- Request a pair is in region of the Z mass
- The second is allowed to be much lower in mass
  - Because two normal Z's weigh more than the Higgs signal
  - One of them is force to be off-shell, lighter
- Major background:
  - $ZZ \rightarrow llll$ (where Z's are not to do with the Higgs)
    - 'irreducible'
  - Zbb
  - $tt \rightarrow WbWb \rightarrow \nu l b \nu b$
- The b quark can decay to a lepton + a charm quark
  - Require isolation – b's decay products should be visible
  - Require leptons from primary – b's travel a mm or so

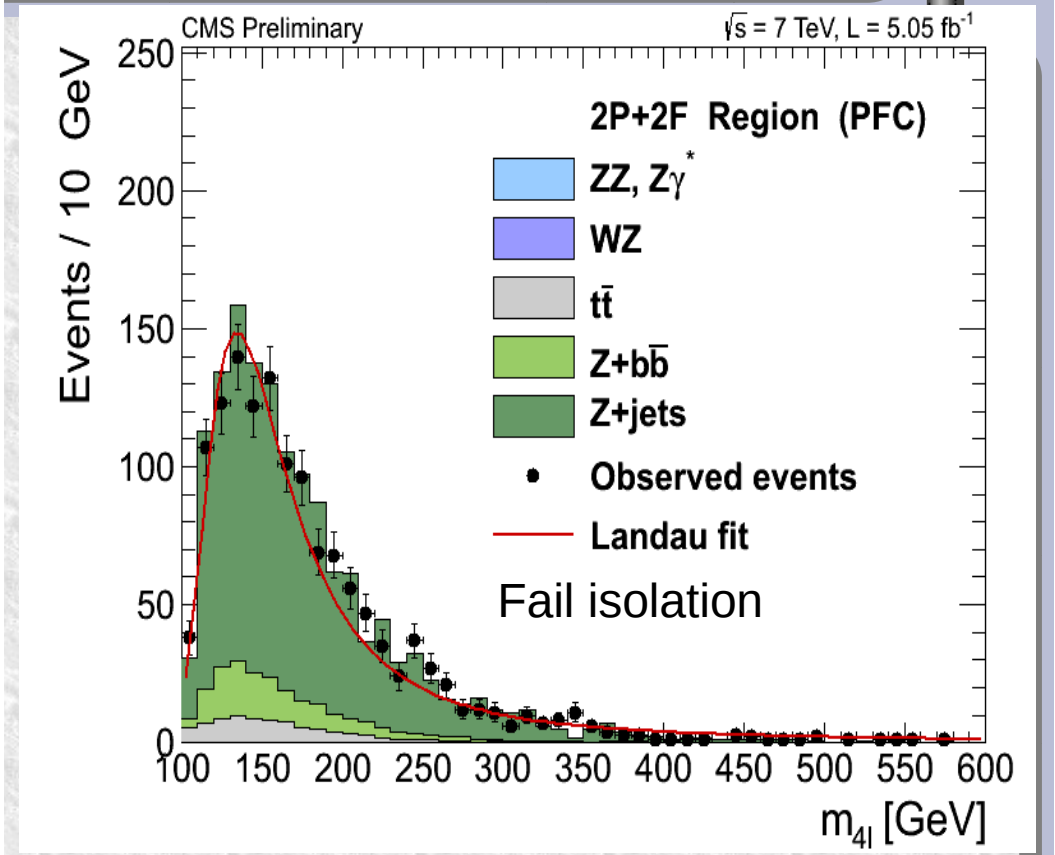
Selection methods

	ATLAS	CMS
Minimum lepton p_T	7Gev (e) / 6 GeV (μ)	7Gev (e) / 5 GeV (μ)
Mass Z_1	50 - 106	40 - 120
Mass, Z_2	17.5 - 115	12 - 120

- CMS cuts always a little looser, more efficient
  - ATLAS efficiency: 36%,21%,18% in μμμμ,eeμμ,eeee
  - CMS efficiency 40%,27%,18% in μμμμ,eeμμ,eeee
  - 10% higher efficiency in CMS
- Backgrounds similar despite different cuts:
  - ATLAS background expected (120-130): 4.9
  - CMS background (121.5 -130.5): 3.8
  - 10% less background in CMS per GeV
- CMS also uses 'matrix element'
  - Uses leptons angles & Z masses to separate sig. from back.

Background control

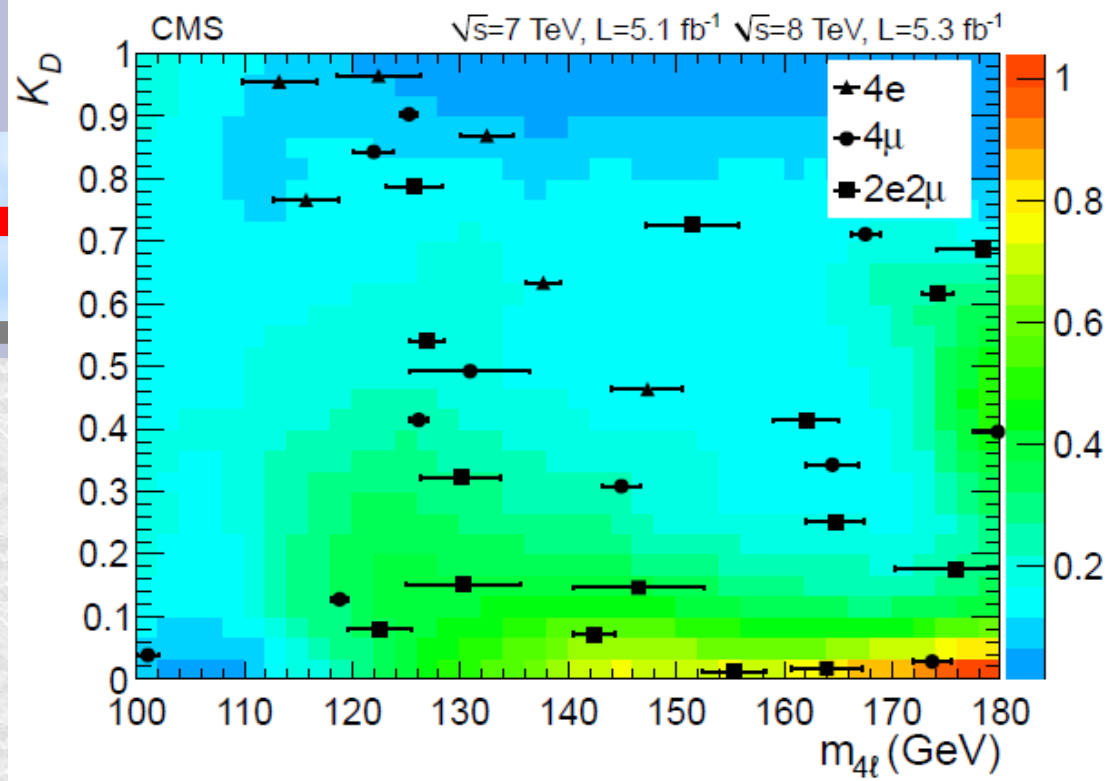


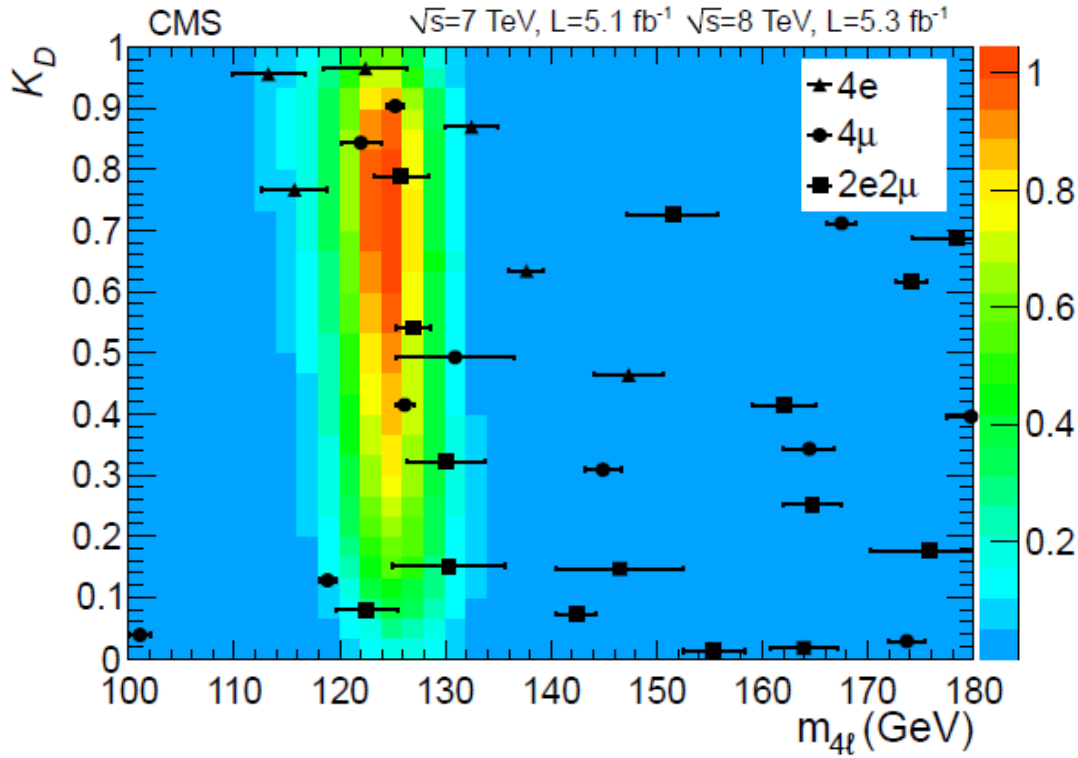


- Request two isolated leptons making Z mass
- Find two more, no isolation or impact parameter cuts
  - ATLAS m_{34} (left) and CMS m_{1234} (right) measure fakes
- Extrapolate fake rate to isolated region

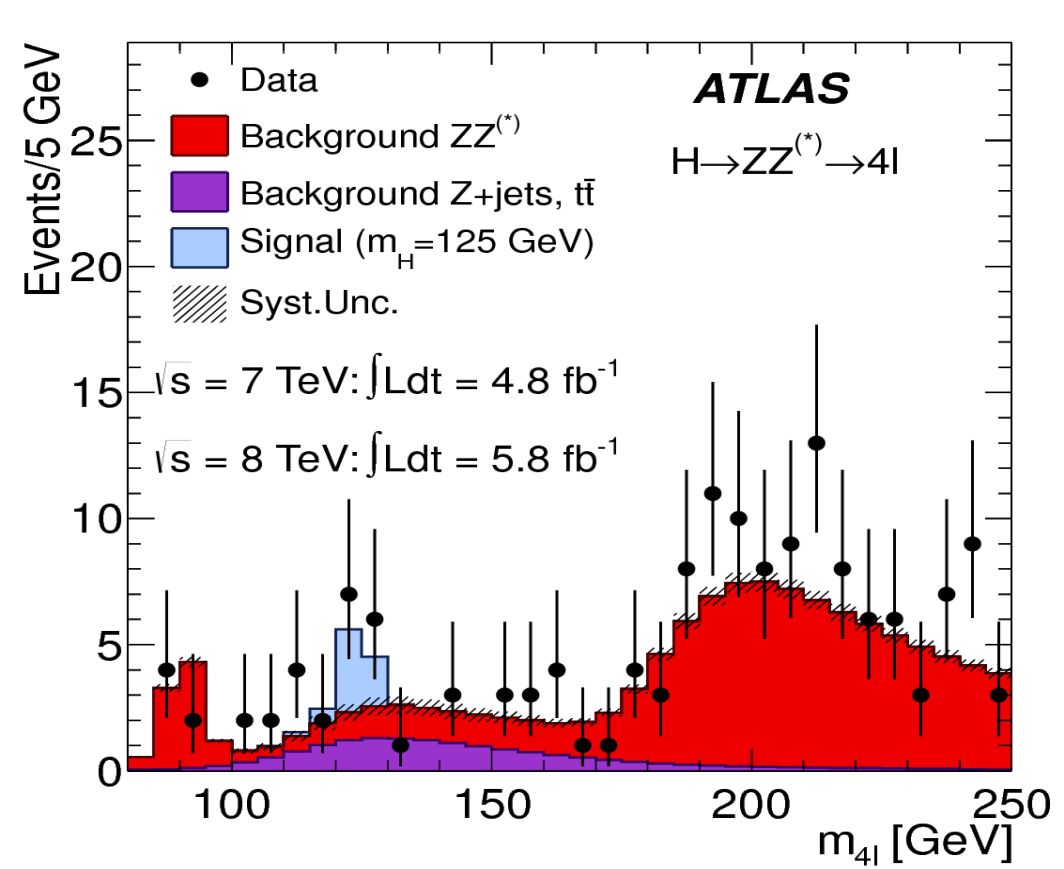
CMS 'MELA'

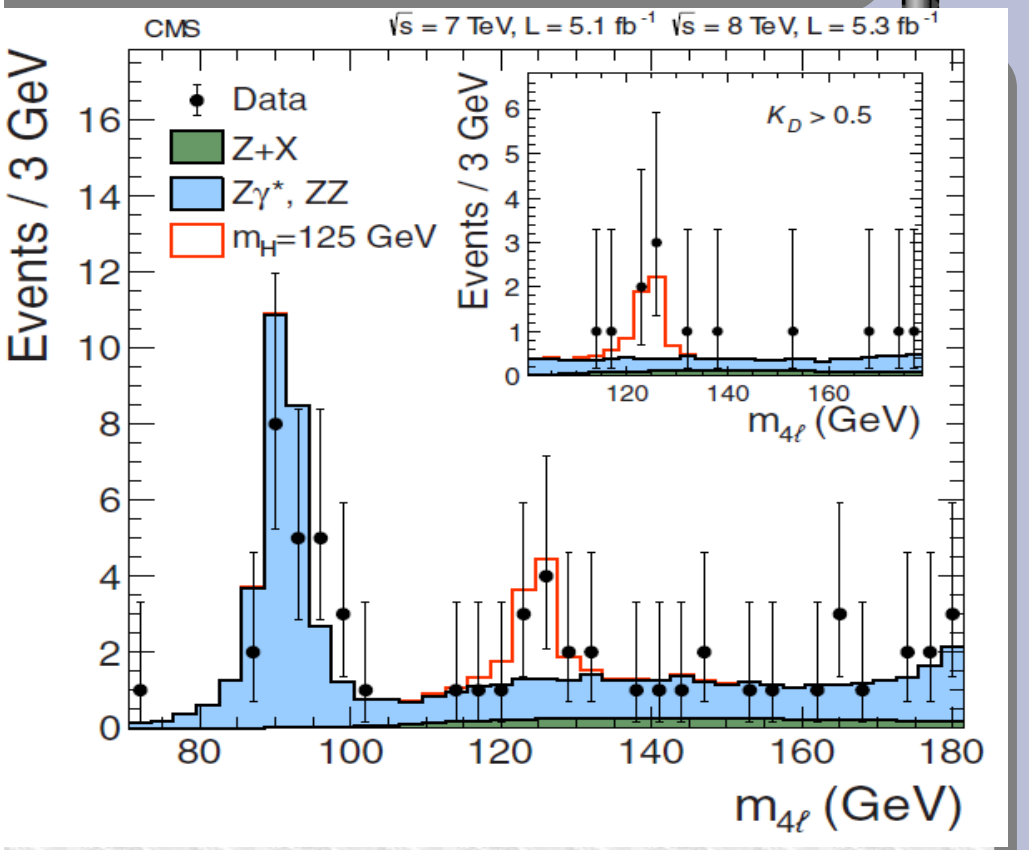
- "Matrix element likelihood analysis"
- Uses predicted distributions of 5 angles and 2 Z masses of the $H \rightarrow ZZ \rightarrow llll$ system to see how like s or b each event is
- Background modelled as $ZZ^*/Z\gamma^*$
- Several events are 125 GeV are seen to have very high 'MELA' values, K_D





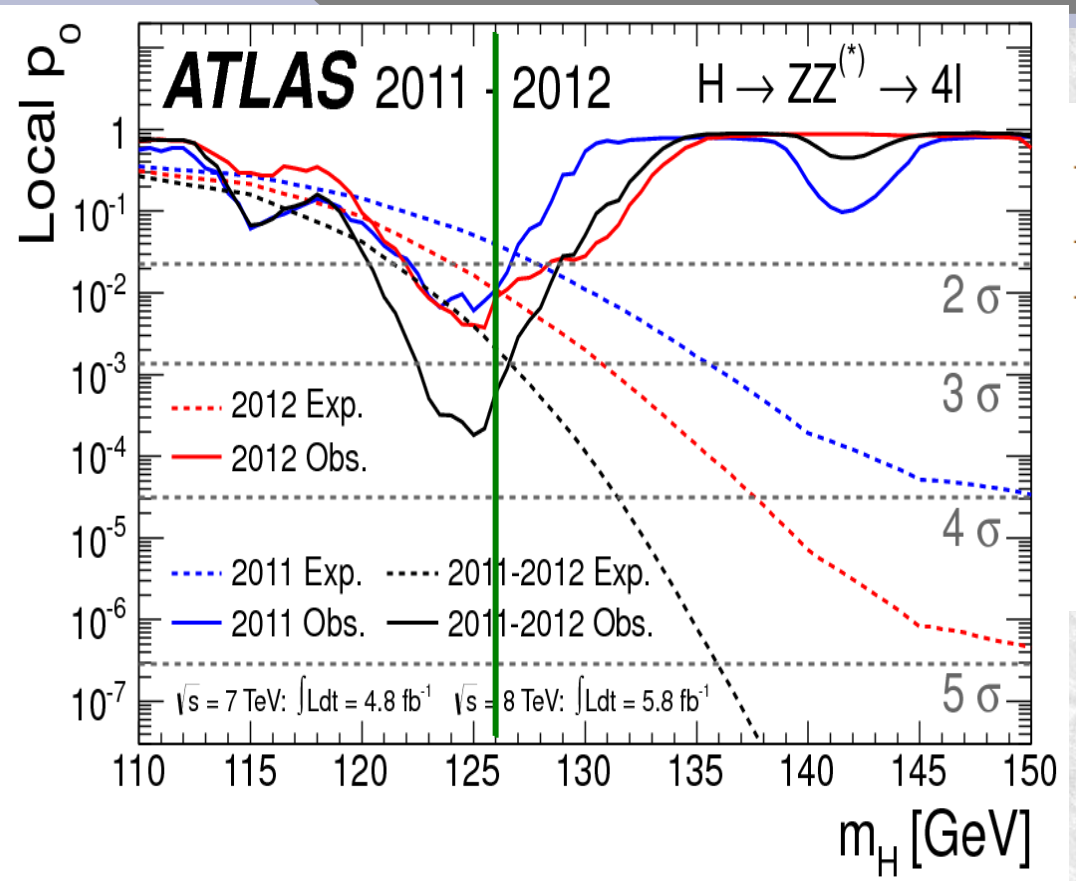
Mass distribution

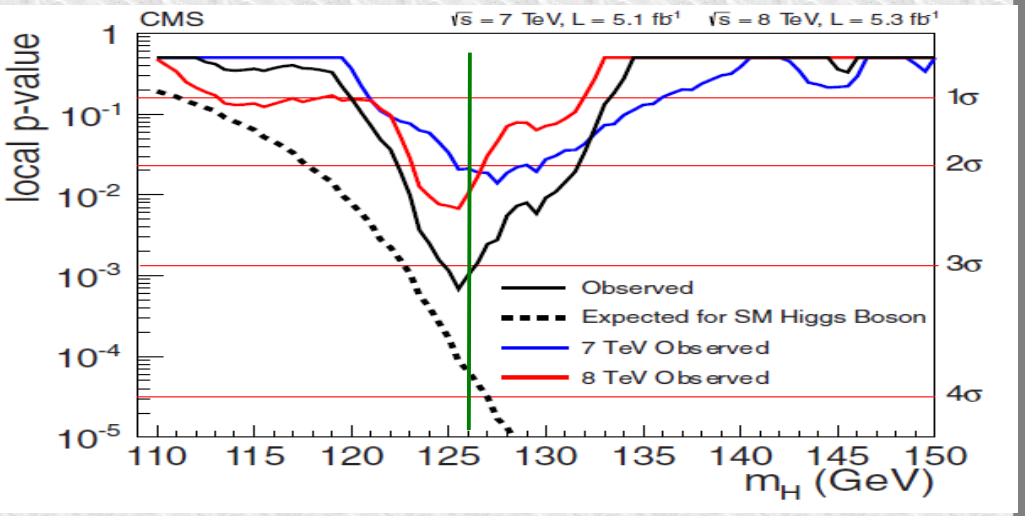




- Background shapes decently seen in both
  - Note peaks at 90 and >180 (1 real Z, 2 real Z's)
- Small peak at 125 GeV seen in both experiments
  - These events are mostly signal!

Background compatibility

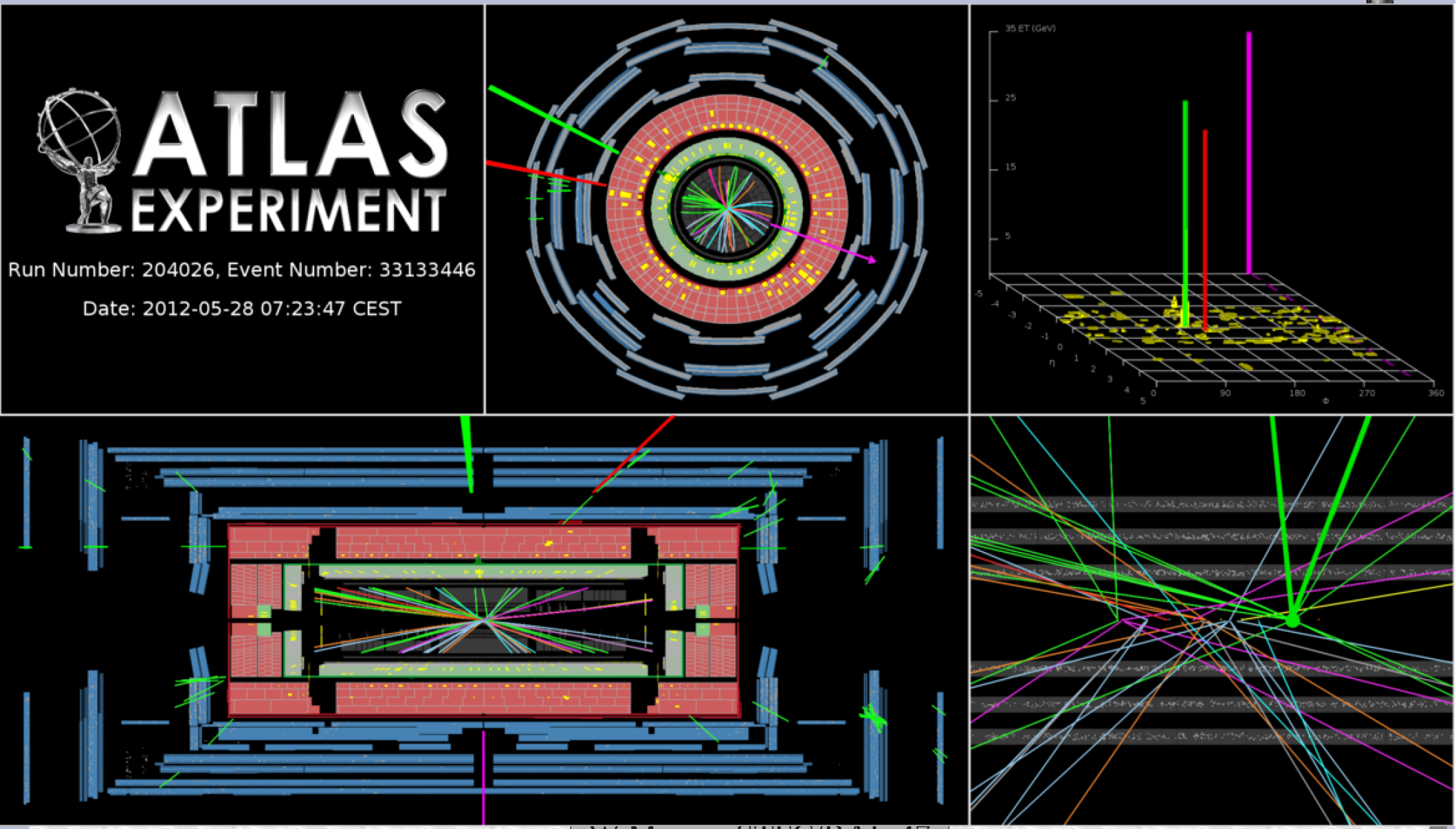




- Both see over 3sigma excess!

- ATLAS expects about 2.8sigma at 126GeV
- CMS sensitivity nearly 4sigma at 126GeV
  - Diference largely from use of 4-lepton matrix-element

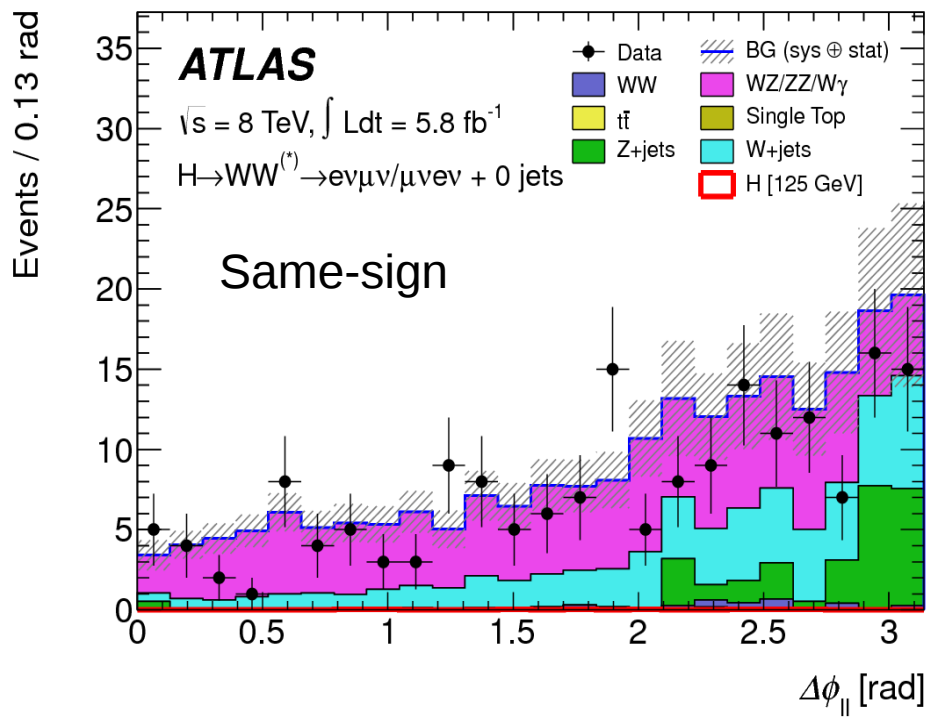
H → WW → lνlν

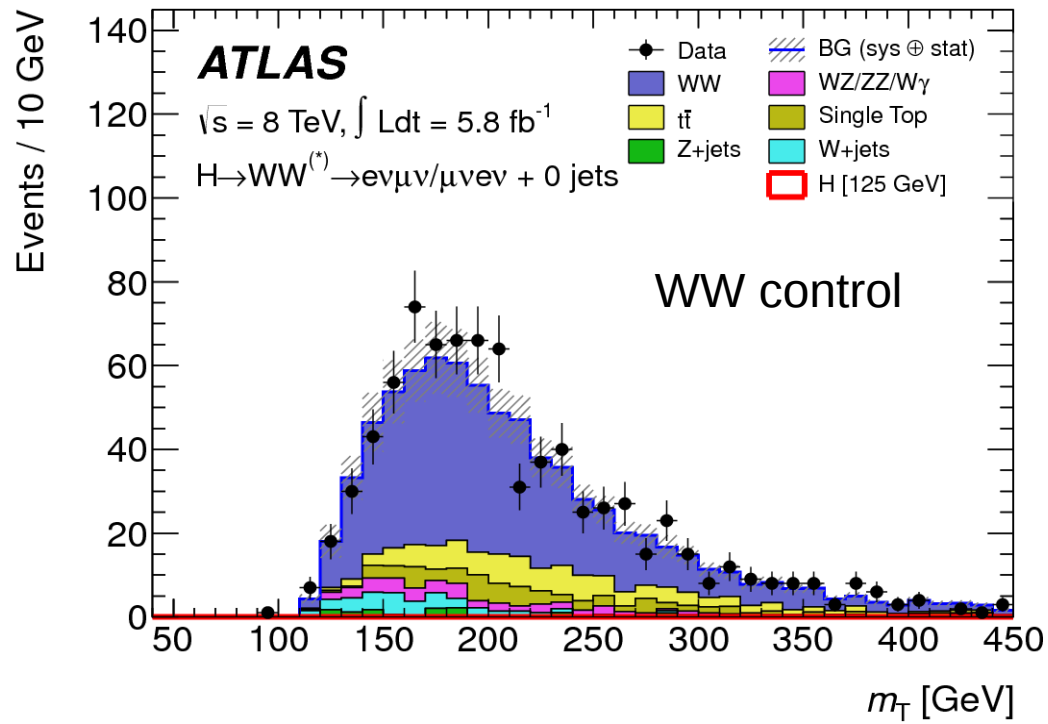

ATLAS
EXPERIMENT
Run Number: 204026, Event Number: 33133446
Date: 2012-05-28 07:23:47 CEST
35 ET (GeV)
25
15
5
η
Φ
0
90
180
270
360

$WW \rightarrow l\nu l\nu$

- The most sensitive channel for $130<m_H<200$
  - Still one of the 3 most important at 125GeV
  - But poor mass information due to 2 undetected neutrinos
- Good trigger, reasonable rate
  - Largest background is non-resonant WW
    - Also top when looking at WW+1 jet
  - Backgrounds measured from control regions
- Request two leptons
  - 15,25 GeV (ATLAS) 10,20GeV (CMS)
  - ATLAS only uses e-μ pairs in 2012 (ee/μμ have more bkgd.)
- Require missing E_T (E_t^{rel}) and $p_T(ll)$ for WW
- Select signal area with $\Delta\varphi$ and m_{ll} selections
  - CMS using cut-based and multivariate
  - ATLAS prefers cut-based.
- Many backgrounds need estimation from data - tricky

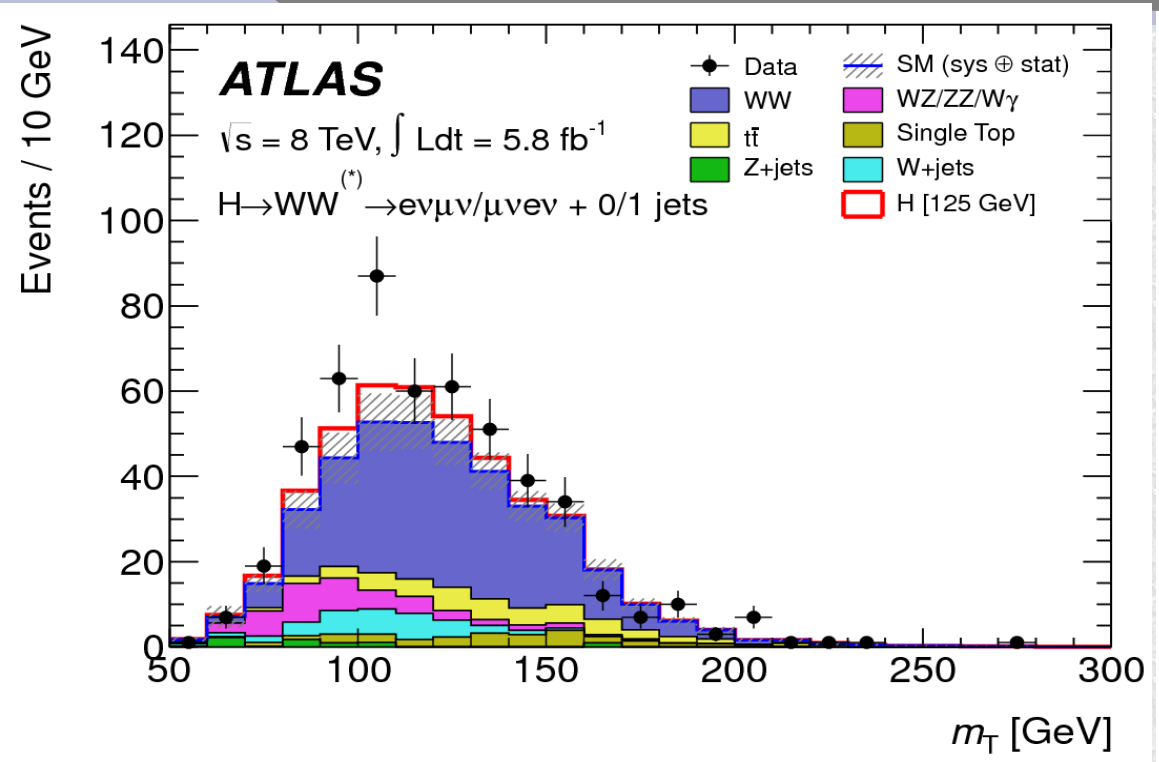
WW background extraction

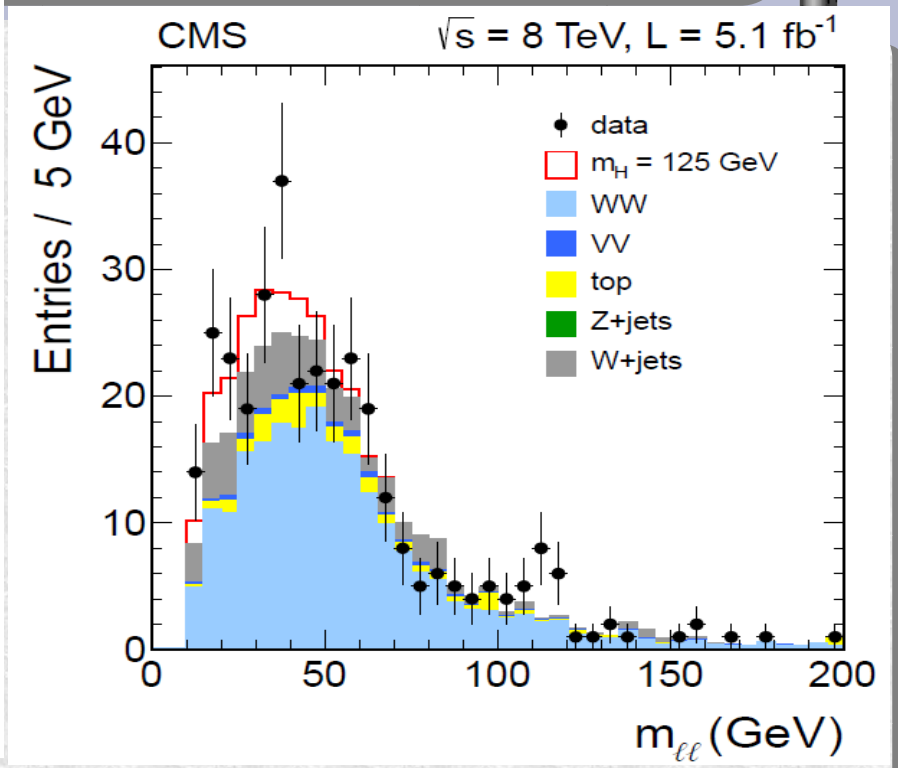




- Backgrounds are (almost) all found in control regions
  - ATLAS same-sign (left) check W+jets
  - ATLAS WW control (right) from high m_T events
    - Integrals must match data/MC by contruction.
    - But scale factors are near 1.

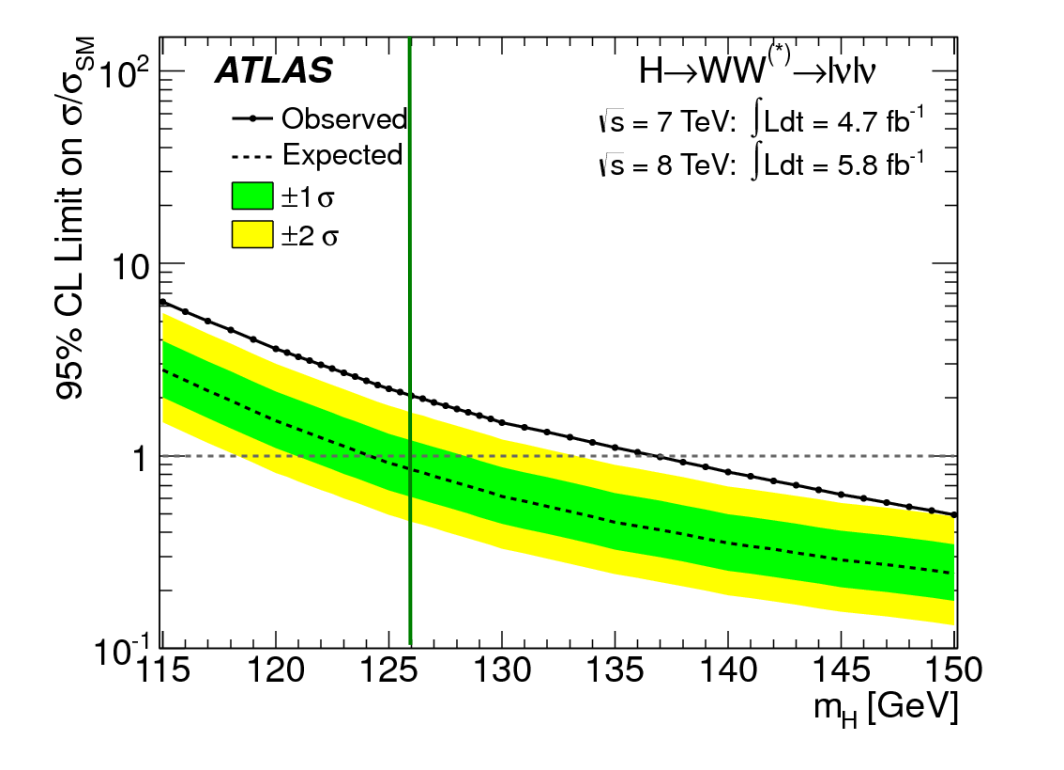
WW signal region

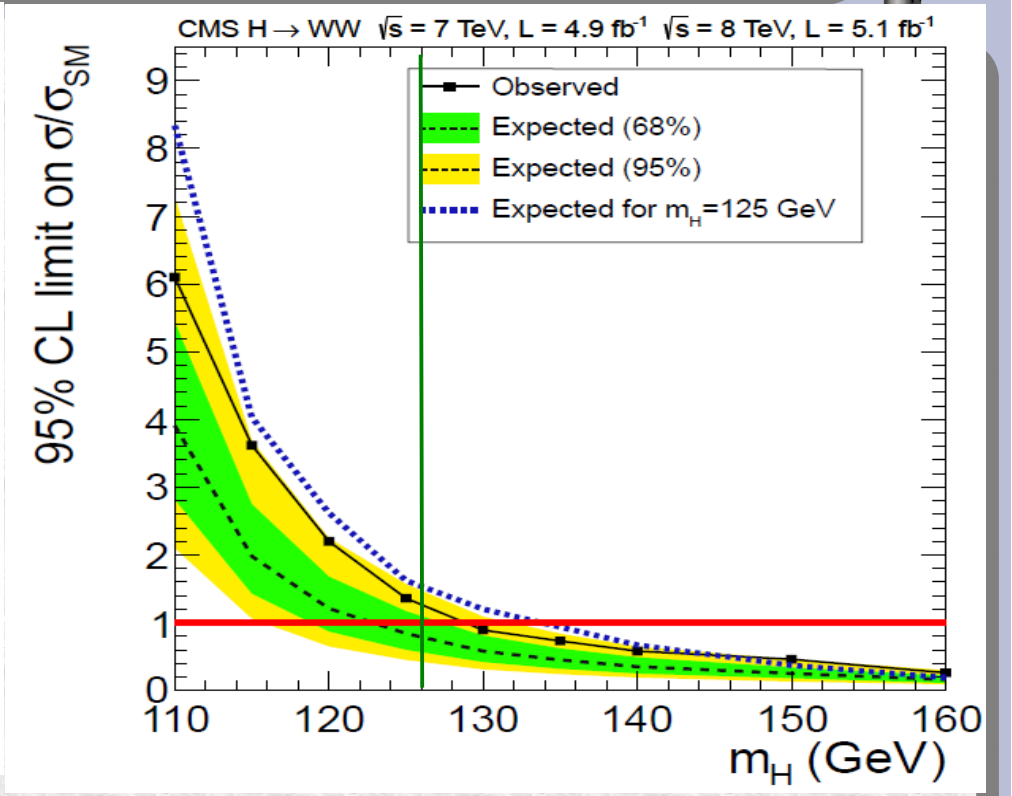




- Modelling of shapes from simulation
  - Tricky business, different simulation programs are compared
- Distinct excess in both experiments
  - In the region signal is expected
  - But not well localised
  - 2.8σ in ATLAS, 1.6σ in CMS

WW limits

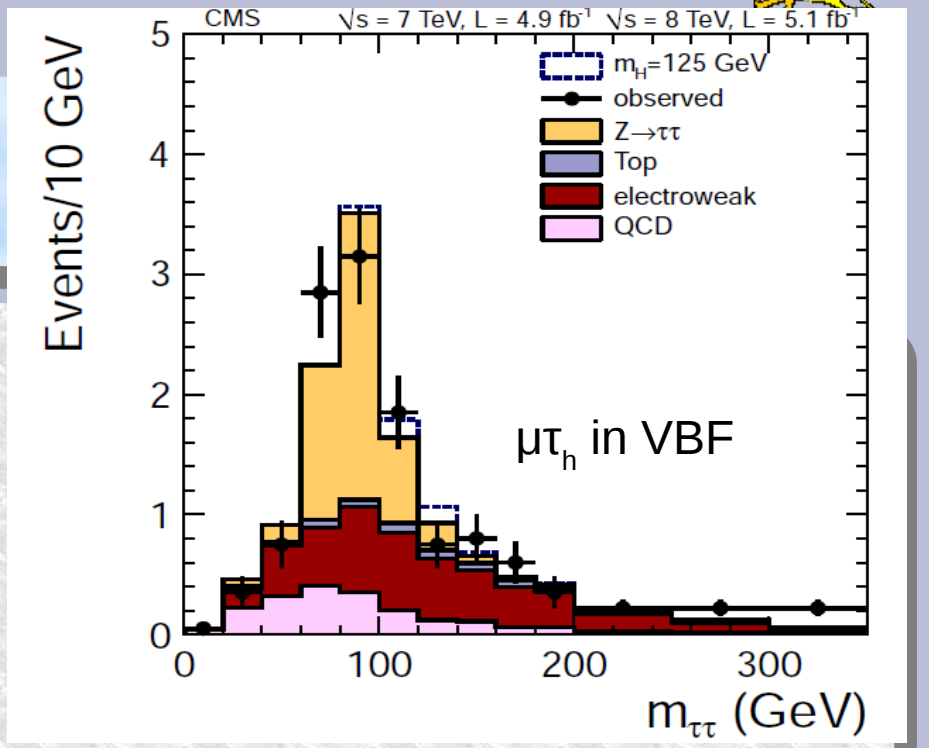


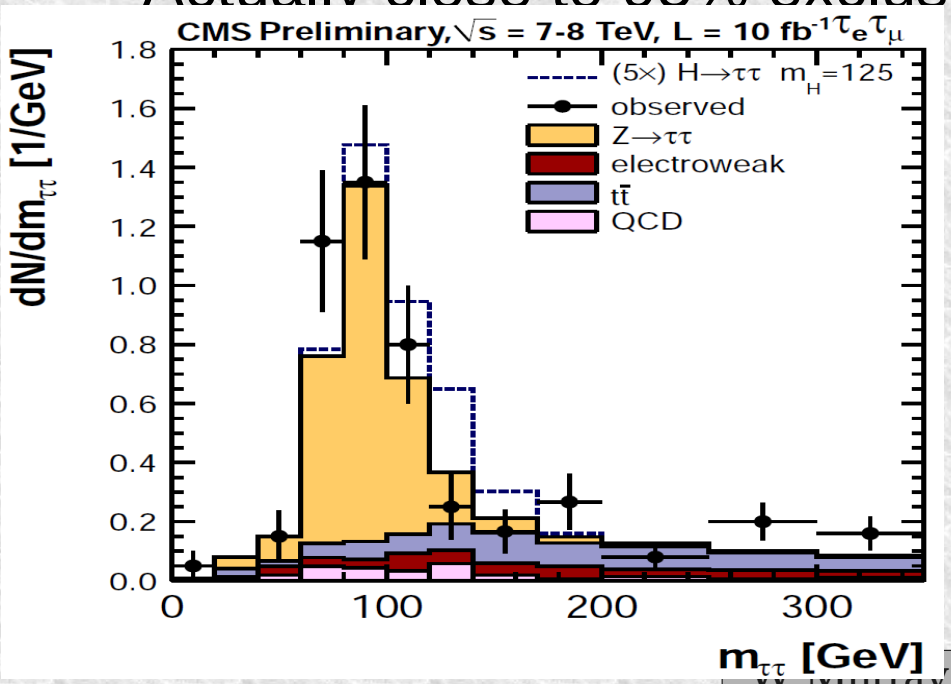


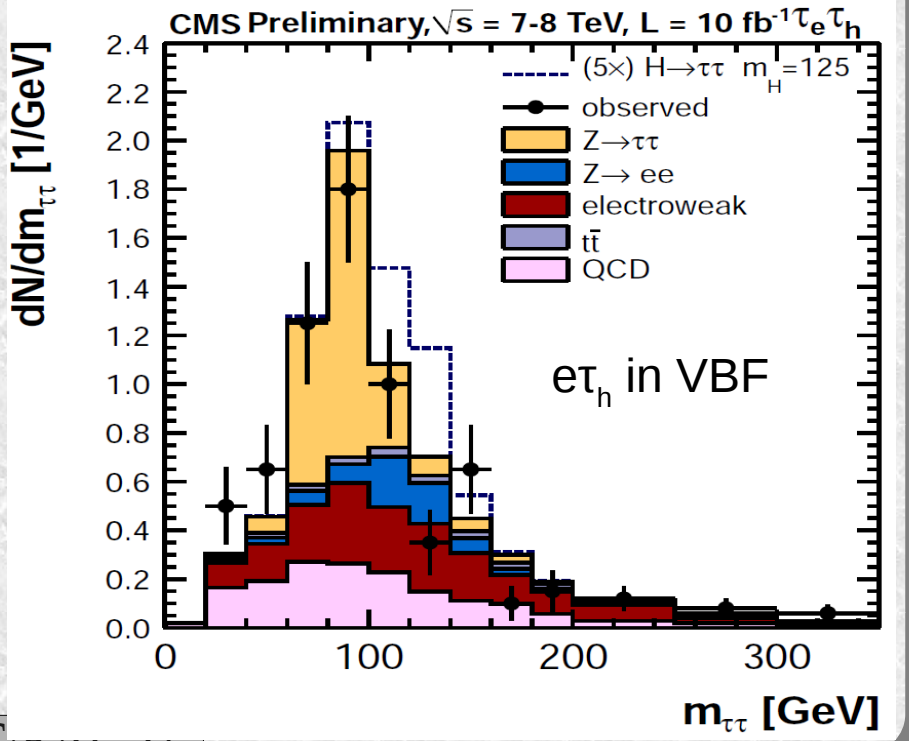
- Both set bad limits
- 2.8sigma excess in ATLAS, 1.6sigma in CMS
- Two neutrinos means mass not well measured
  - So broad excess seen

CMS H → ττ

- Best fermion decay mode
- Using many combinations:
  - eτh, μτh, eμ, μμ decays
  - 0jet/1jet * high/low p_T, + VBF
- VBF is most sensitive
  - No sign of a signal here
  - Actually close to 95% exclusion

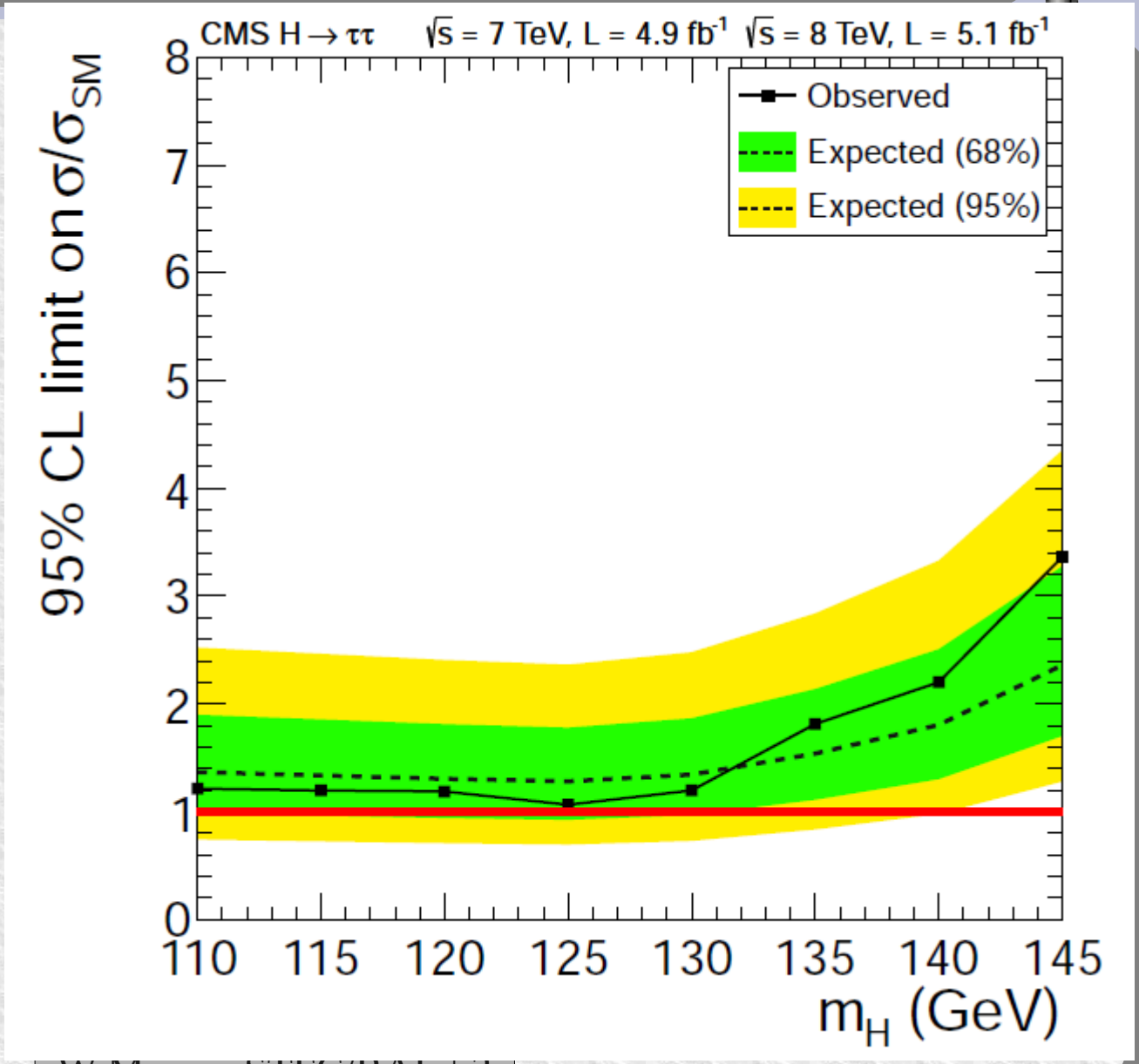






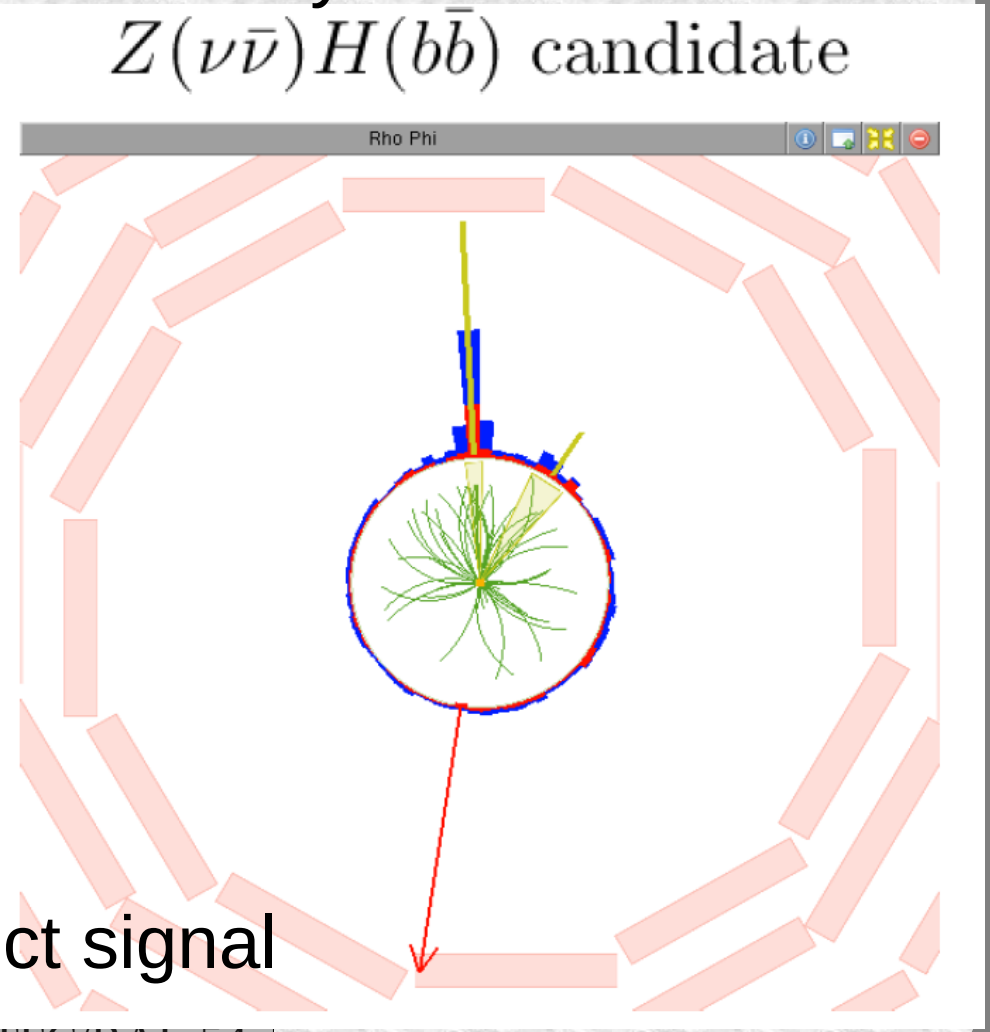
H → ττ limits

- Limits at 1.2xSM at 125GeV
- Almost excludes a signal
  - But doesn't
  - Anyway, break data into enough subsets and one will look odd.
- But it is interesting
  - More data and ATLAS results keenly anticipated



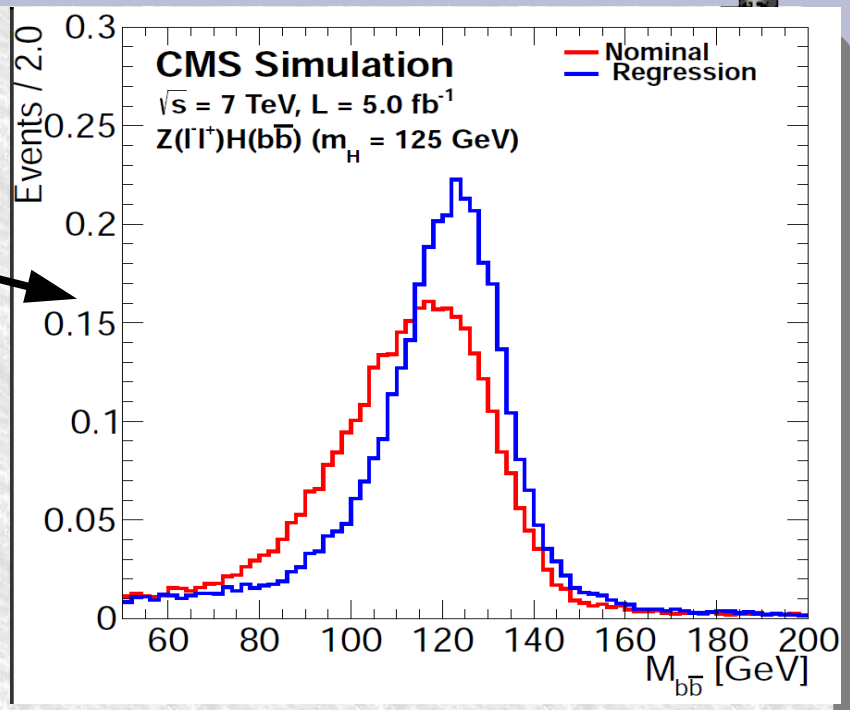
$H \rightarrow bb$

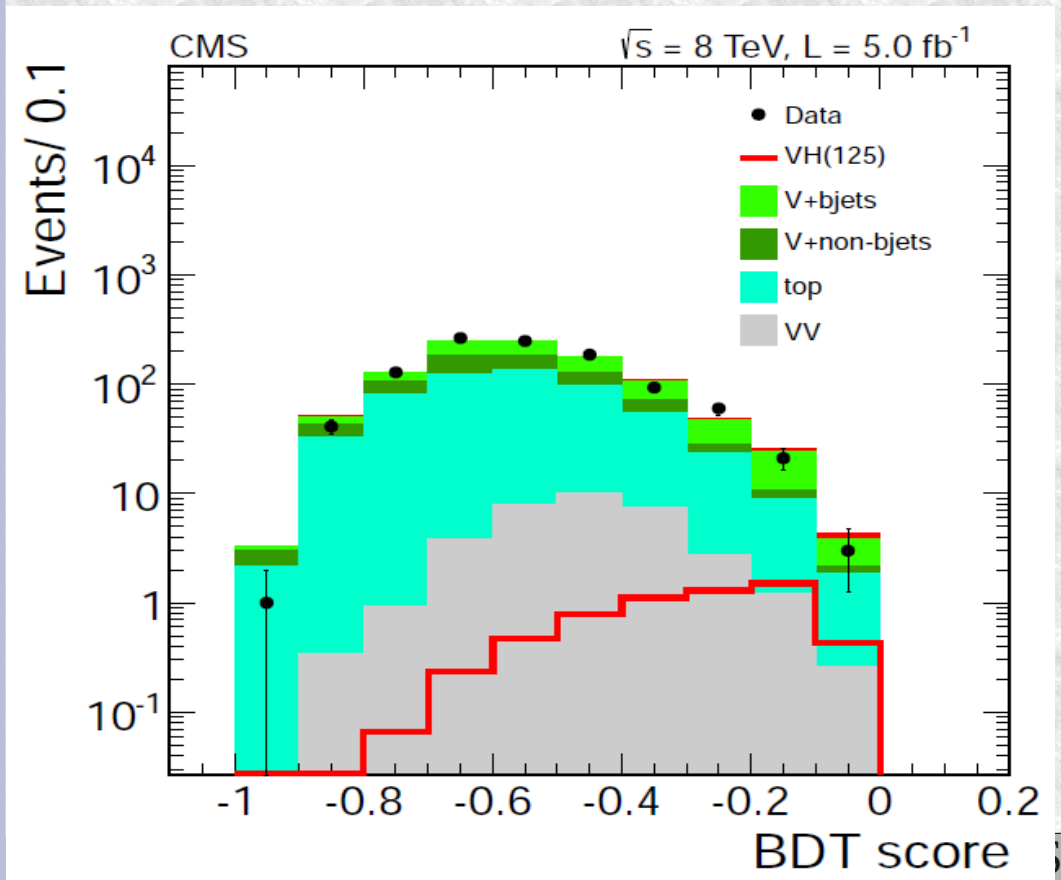
- The most common Higgs decay mode – but hard
- ATLAS has not released 2012 results yet
- CMS uses 6 channels:
  - $WH, W \rightarrow l\nu$ (e,μ)
  - $ZH, Z \rightarrow ll$ (e,μ)
  - $ZH, Z \rightarrow \nu\nu$
  - $t\bar{t}H$ - 2011 only
- Also divided into
  - medium pT
  - high pT (> 100 to >170)
- Backgrounds are from
  - W/Z plus b jets
  - $t\bar{t}$
  - W/Z plus Z
- Boosted Decision Trees select signal



CMS H→bb

- Estimating the mass is difficult
  - B jets break into many pieces
  - But work goes on to improve it

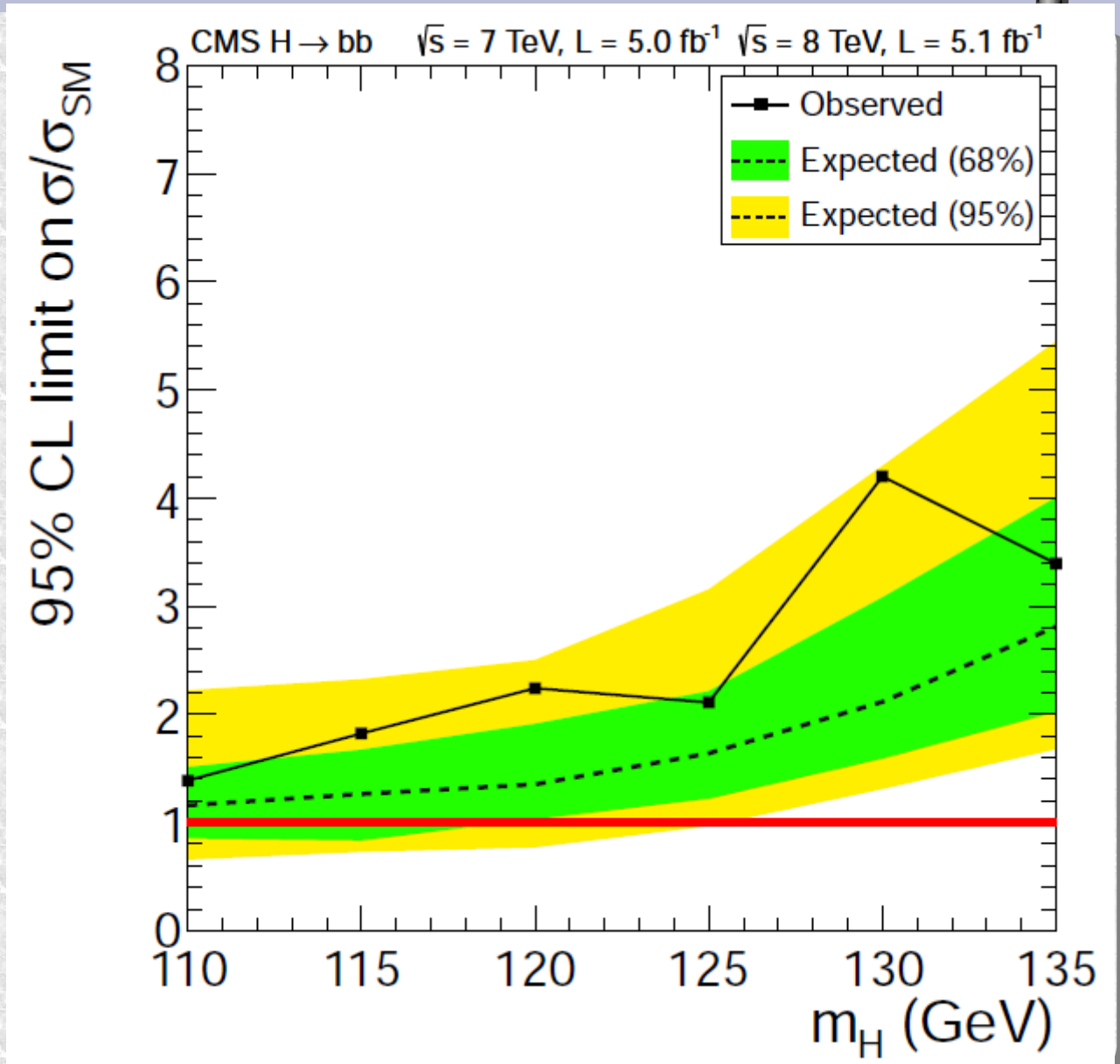




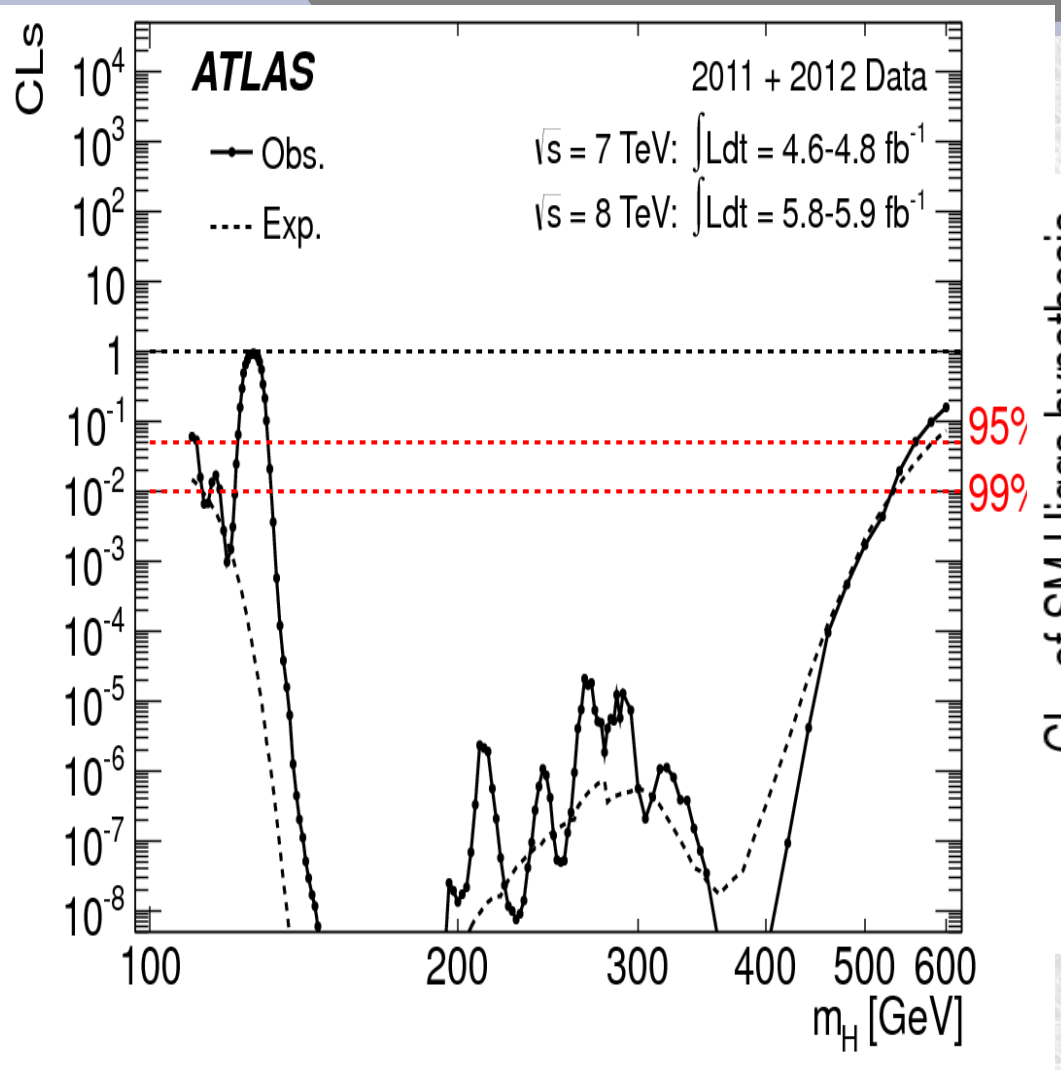
- BDT (pattern recognition algorithm) output for ννbb search is shown to left
- No evidence for a signal

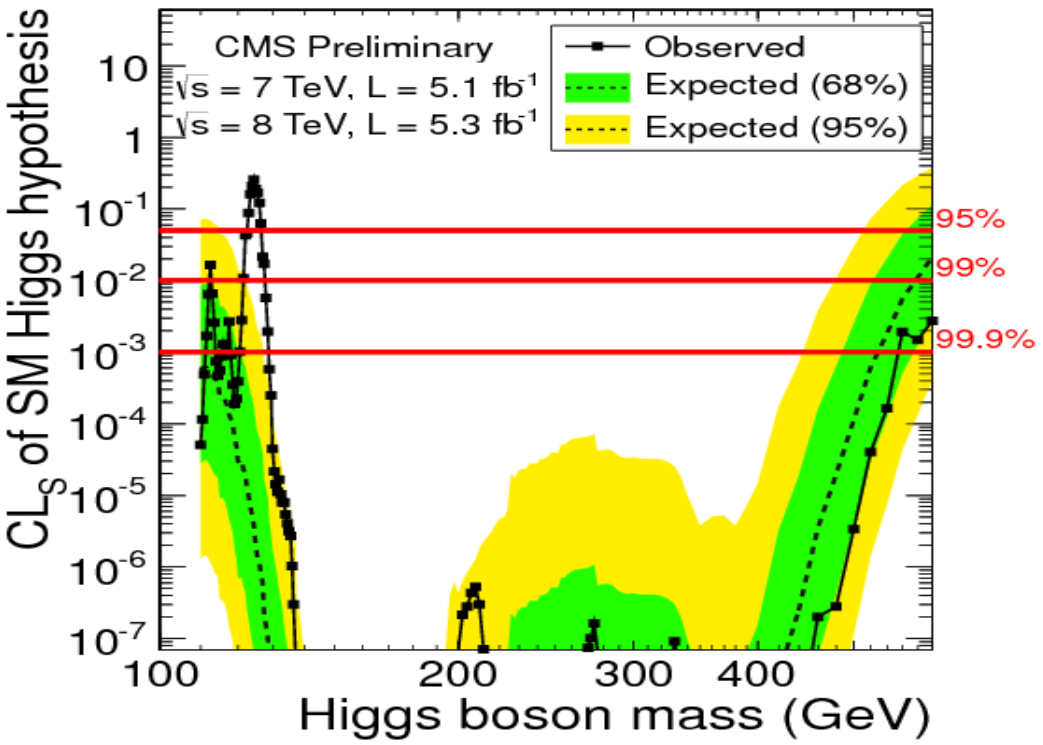
CMS H→bb results

- The expected limit is 1.6xSM strength
  - 2.1x is observed
- Small excess of 0.7σ
  - 1.6σ would have been expected for a Higgs
- So this is not very conclusive today
  - The improvement in sensitivity is remarkable, passing H→γγ at low mass



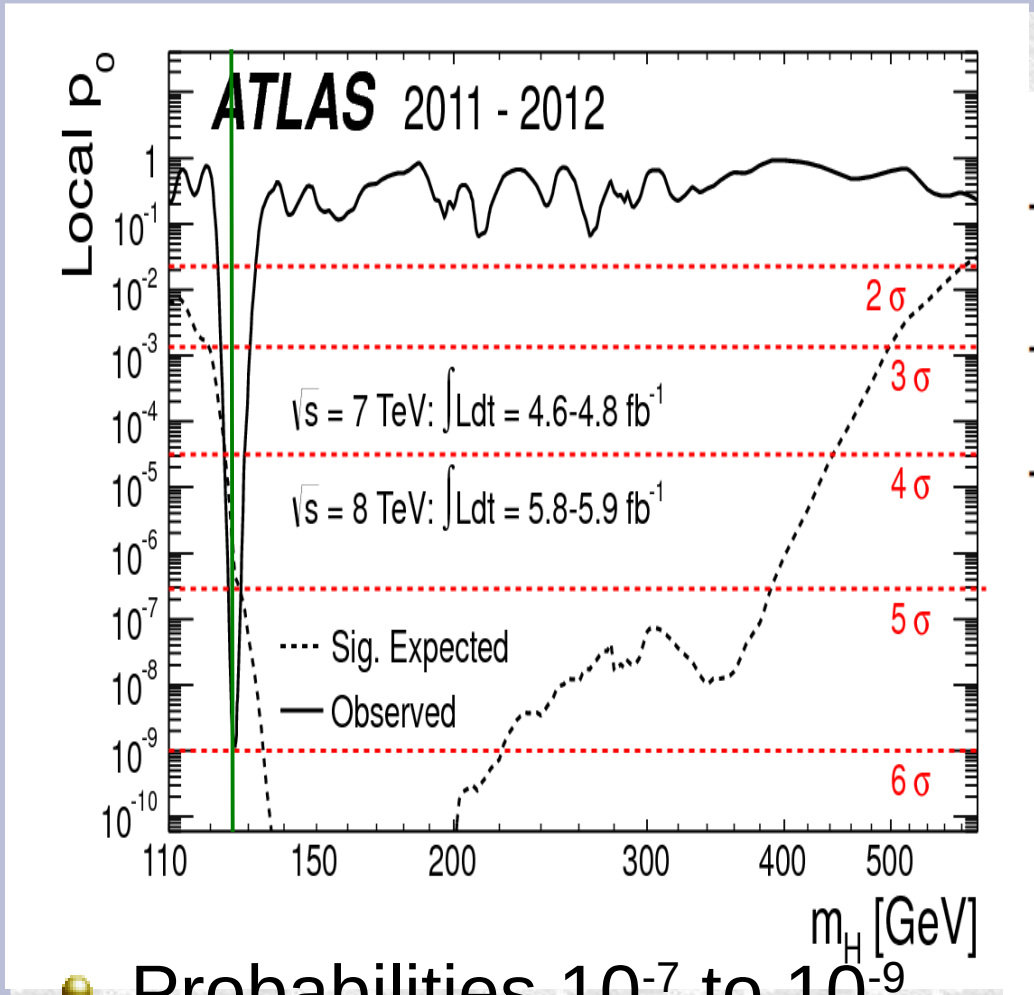
Combined limits

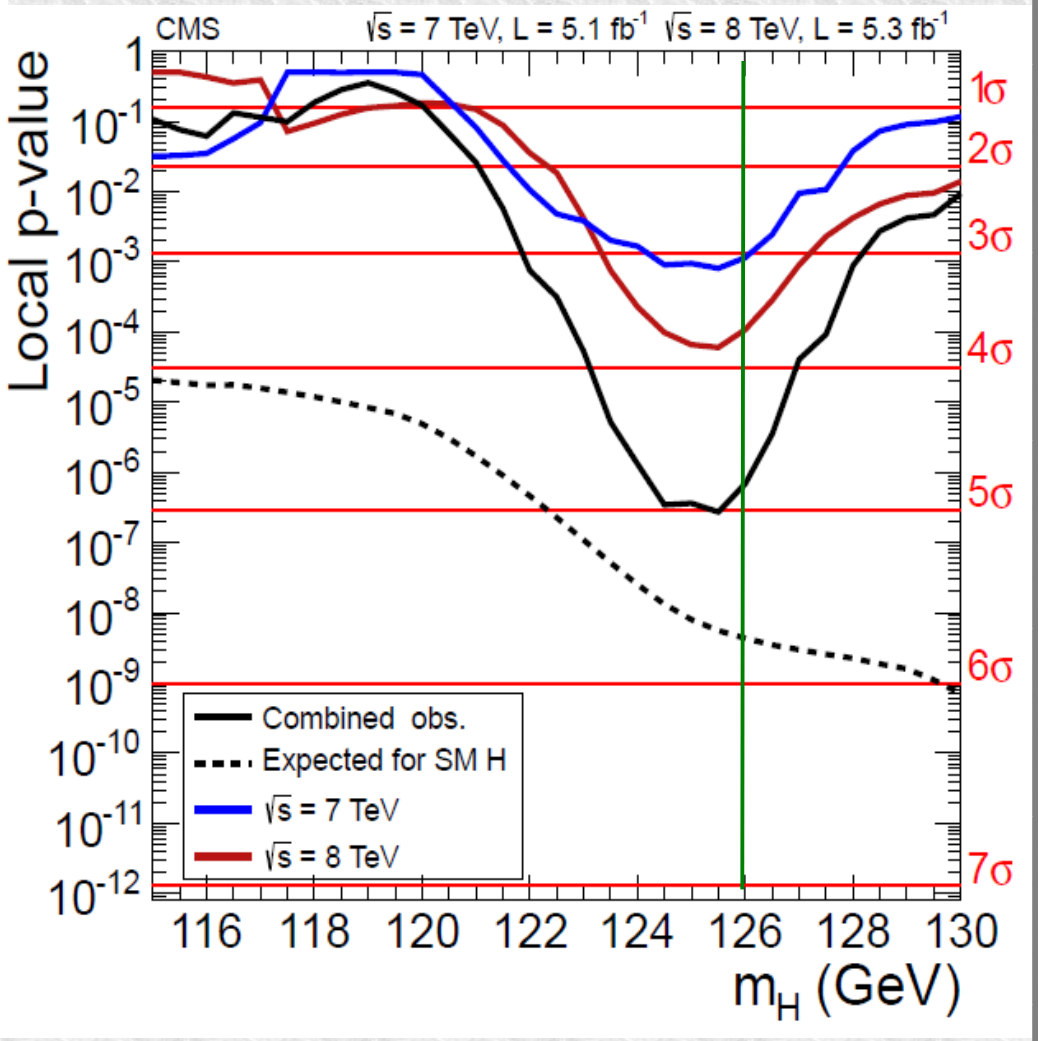




- Both experiments exclude nearly all mass range at high confidence

Combined p-values

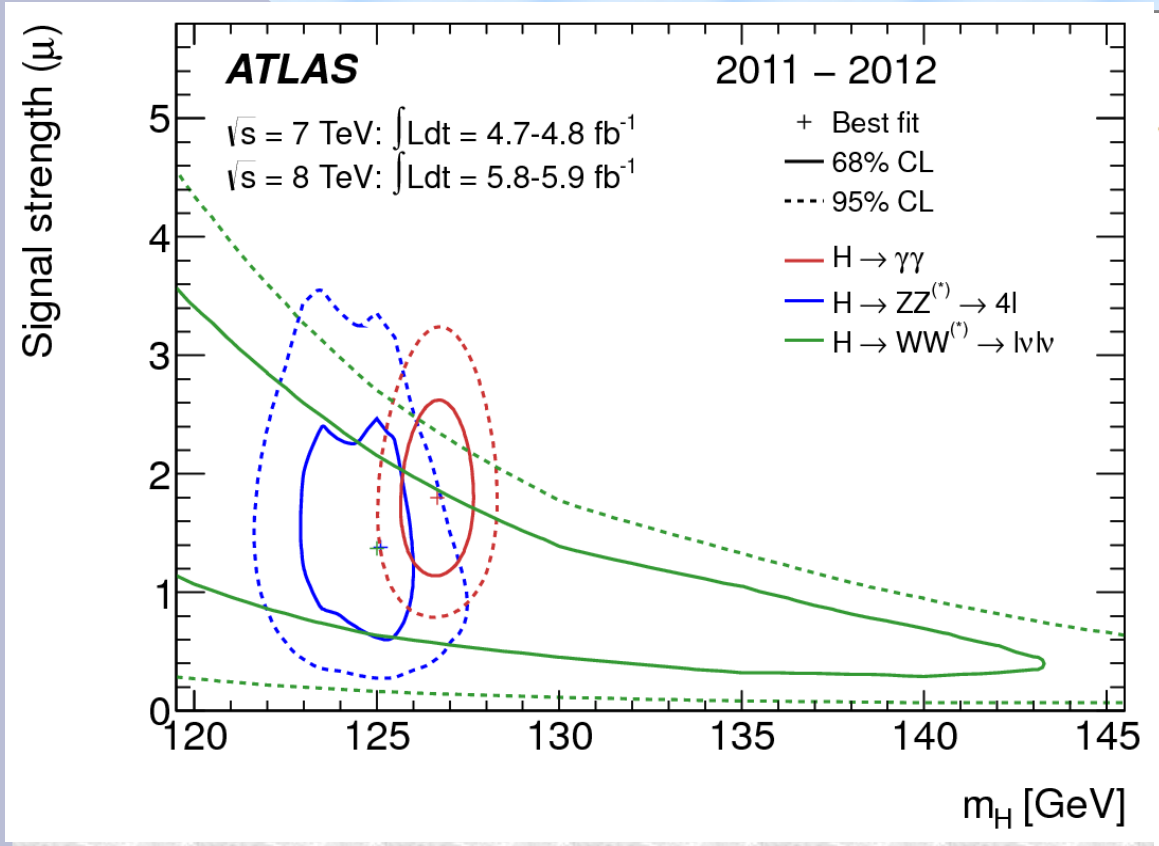


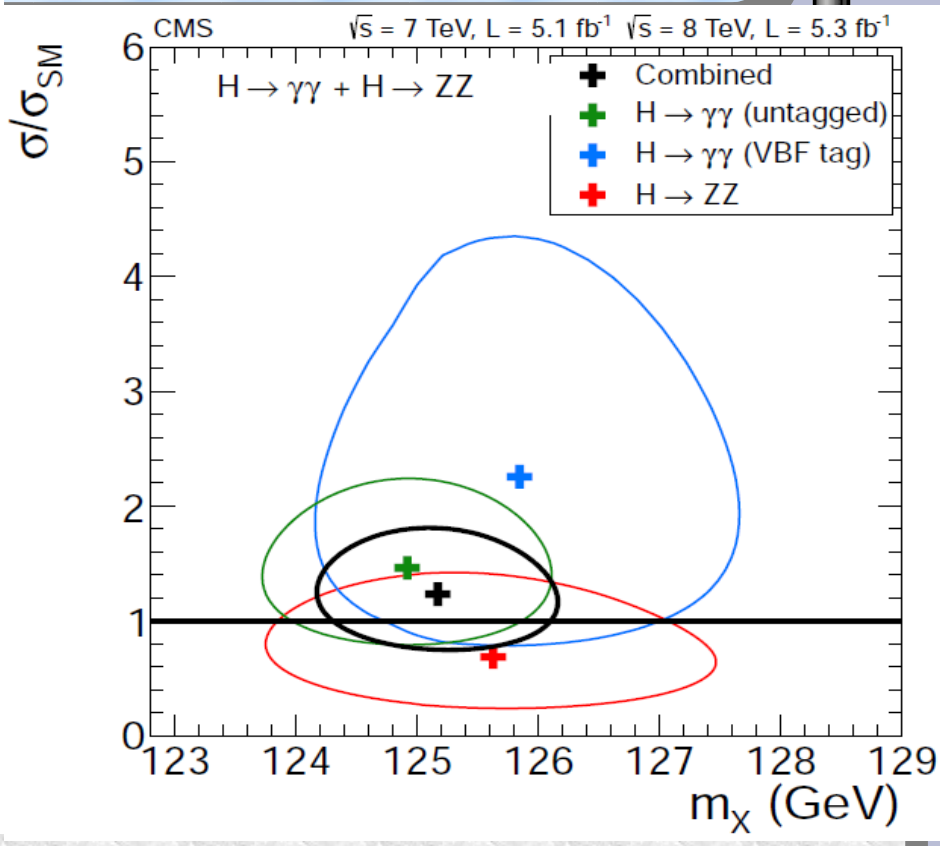


- Probabilities 10^{-7} to 10^{-9}
- 5σ and 5.9σ
- ...we got it

But what did we get?

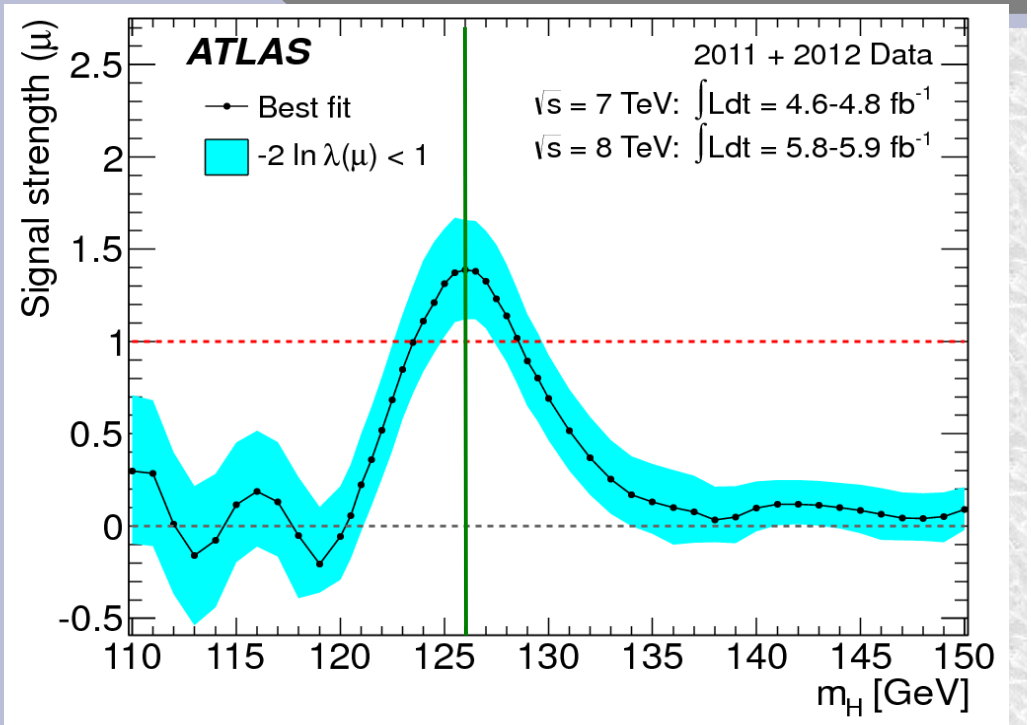
Rate versus Mass

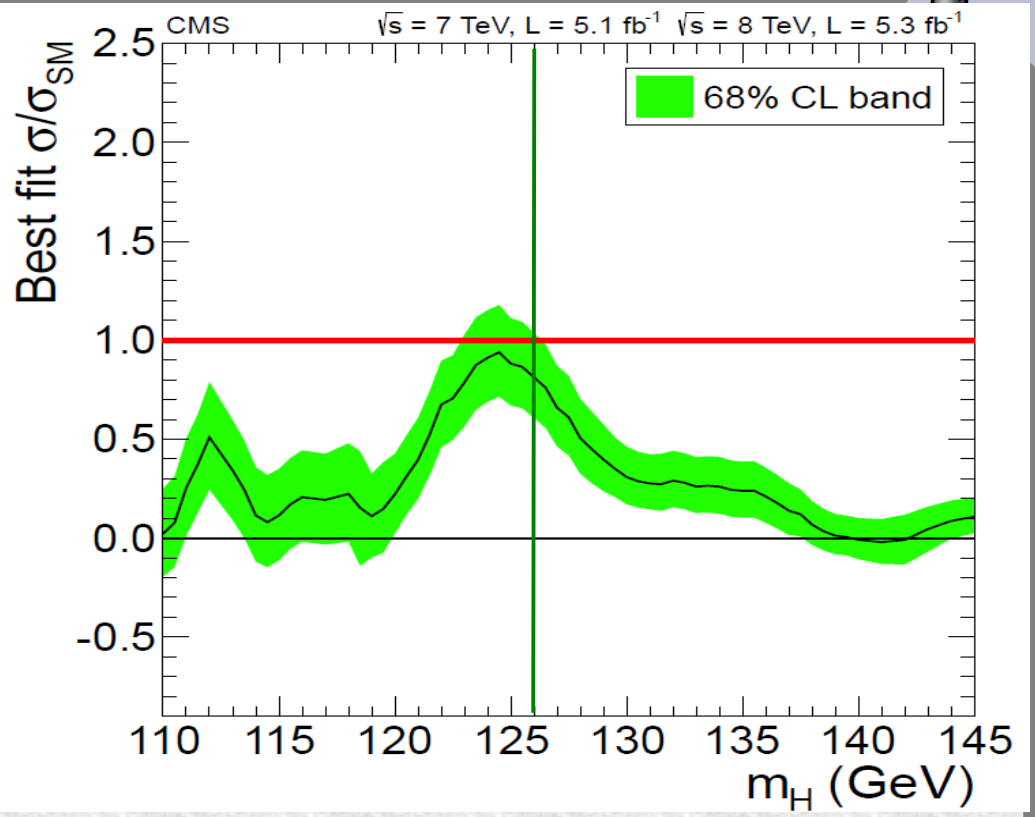




- 2D fits of rate and mass reduce model dependence
  - ATLAS: m_H=126±0.4±0.4
  - CMS m_H=125.3±0.4±0.5
- These channels all have consistent solutions...1 particle

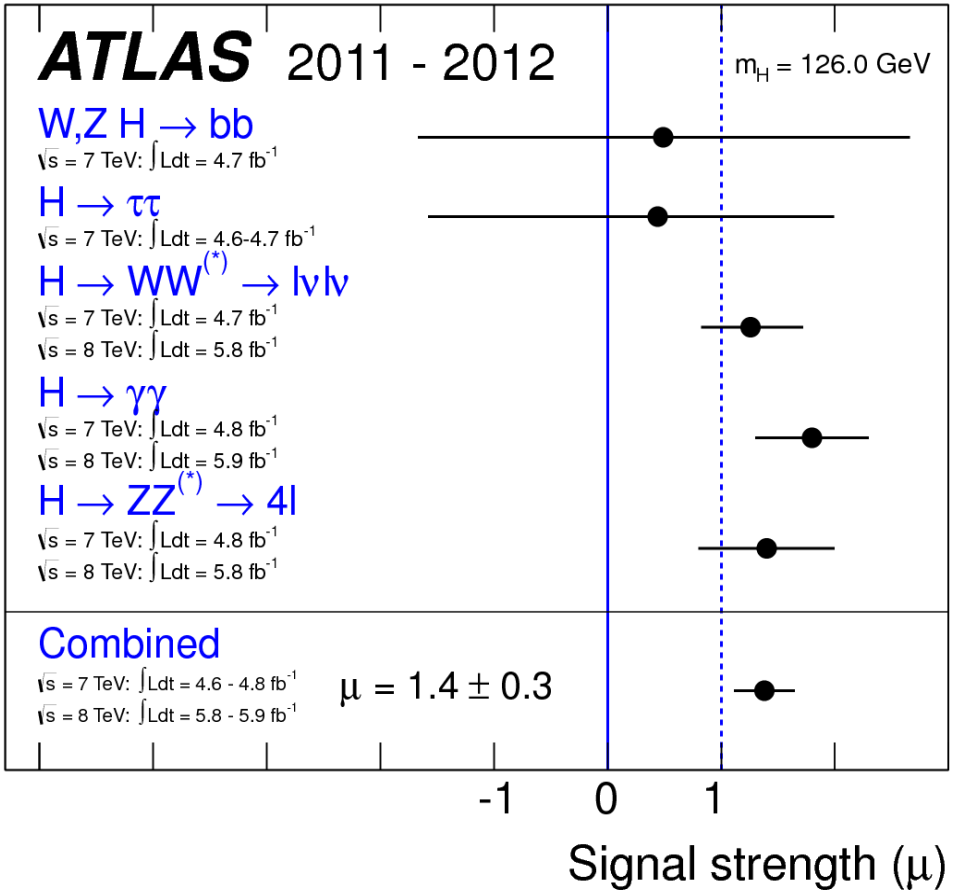
The Combined Results

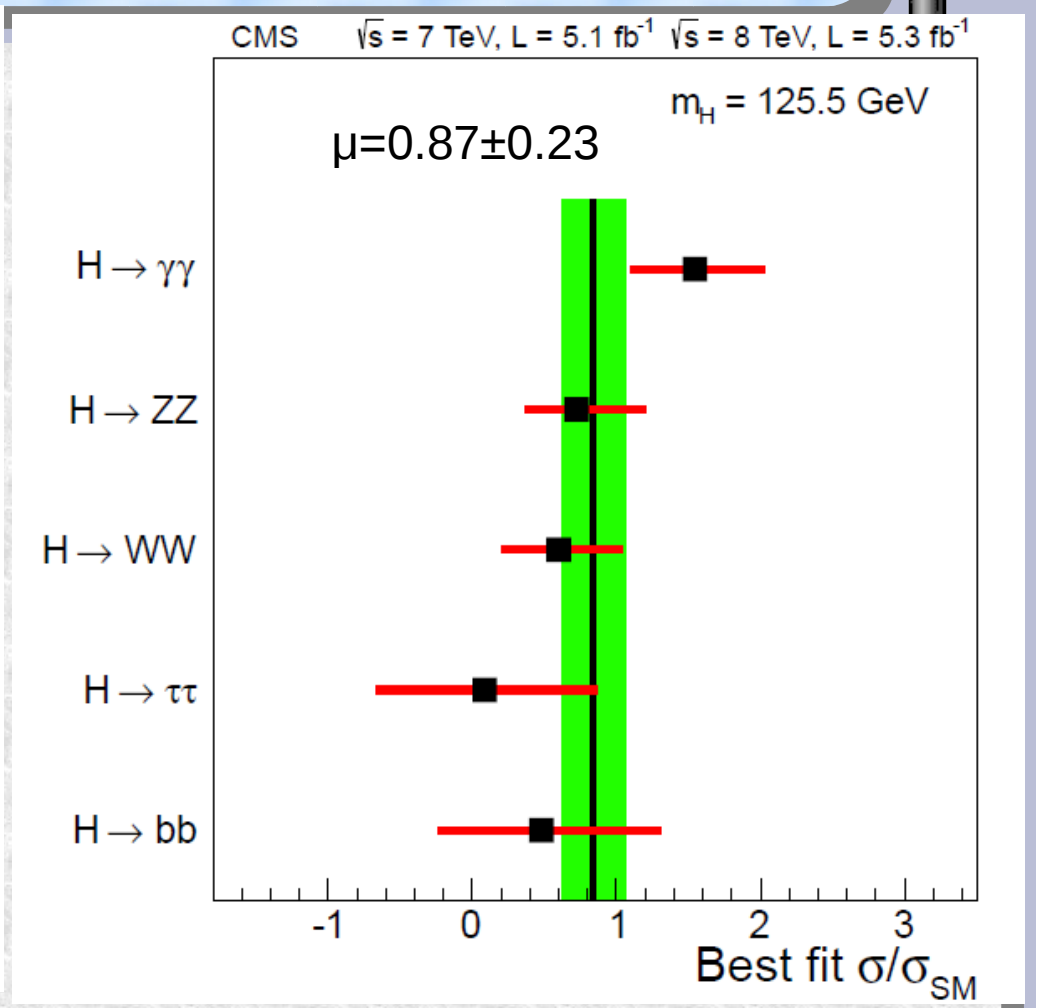




- For a signal at 126 (or 125.3):
  - ATLAS just over a sigma above SM rate, 1.4±0.3 @126
  - CMS just under a sigma below, 0.87±0.23@125.3GeV
- This is consistent with a SM Higgs

Channel results





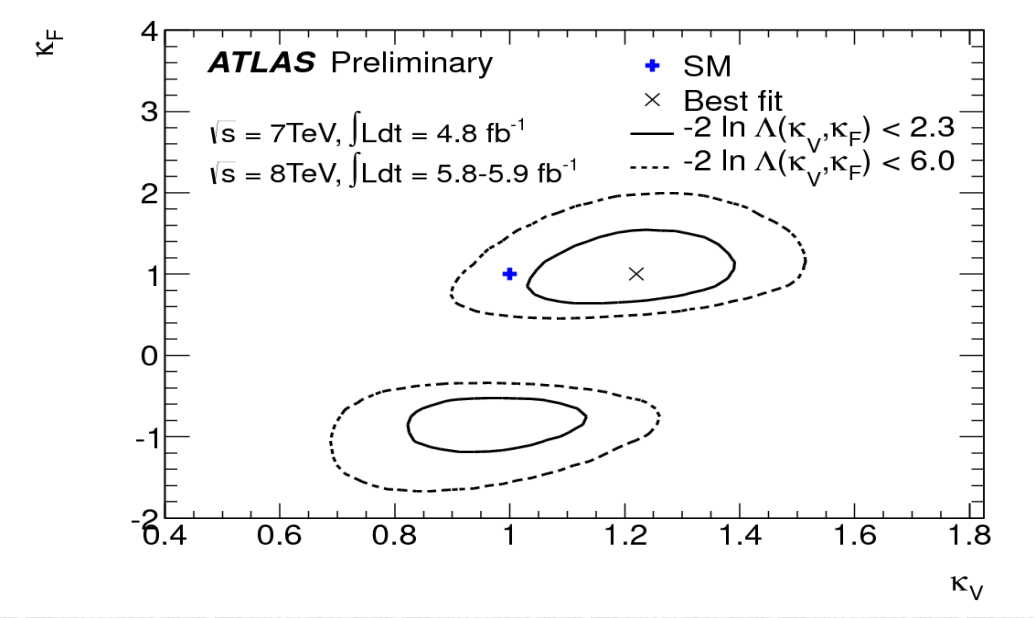
- Allmost all channels favour a signal
  - More powerful ones (WW,ZZ,yy) all do.
  - Is there too much yy? Not really ... so far

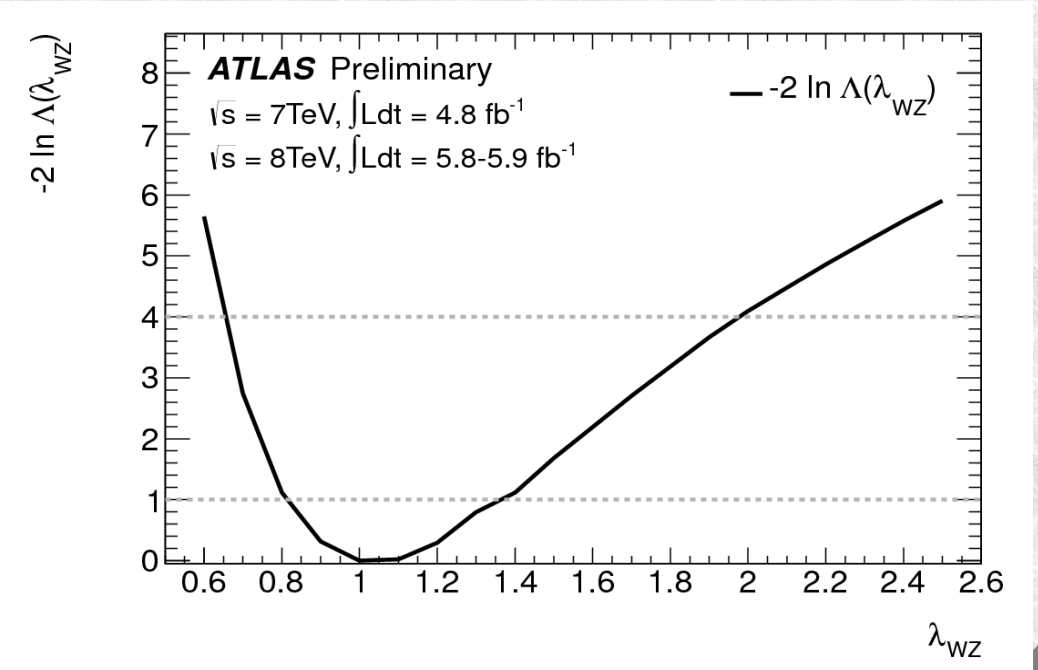
Interpreting couplings

- WE want to test whether what we have is the Higgs boson
  - Like the EW fits done at LEP
- We need 'pseudo observables' that encapsulate results an allow fits:
  - http://arxiv.org/abs/arXiv:1209.0040
- The LHC cannot measure the total width
  - There are always impossible decays like H→gluons
  - So some assumption is need
- Many couplings accessible:
  - ZZ, WW, γγ, bb, tt, gg, ττ, μμ?, invisible?
  - Note gg/γγ are effective coupling through loops
- Too many to fit all at once
- Simplify by grouping the couplings
  - e.g. Bosons and fermions

$\kappa_V\kappa_F$ couplings

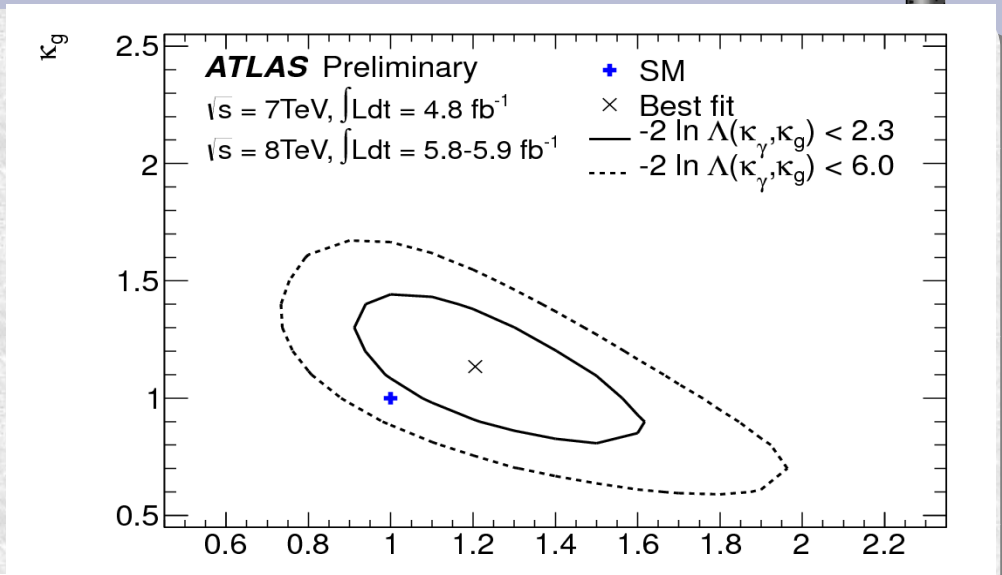
- Top right:
  - W/Z scaled via κ_V
  - Fermions by κ_F
  - Assume no invisible decay
- Sign of fermion coupling tested in photon decay loop
  - We will have some sensitivity to sign with more data
- Measuring single top+Higgs would help this
- Bottom right tests W v Z
  - Custodial symmetry
  - $1.07^{+0.35}_{-0.27}$

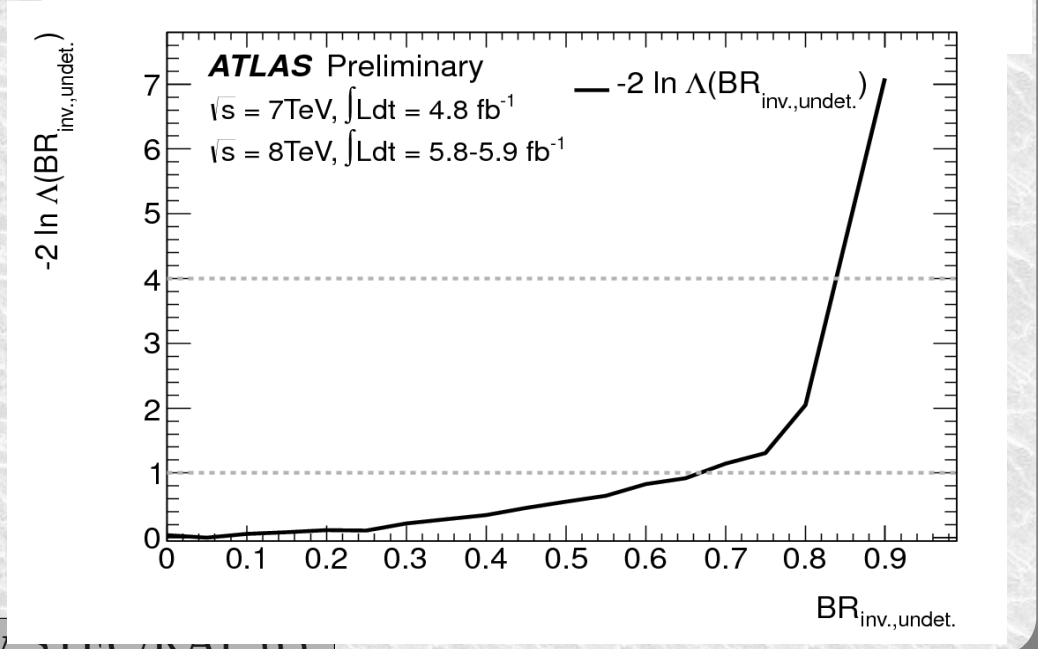




New particle search

- Another possibility is to ASSUME a SM Higgs
  - But allow the loops to have unknown particles
  - ggF, H→γγ
- Top assumes no invisible decay
  - (1,1) is the SM strength
  - compatible with this
- Bottom tests for invisible branching ratio
  - Cannot all be invisible as we see it!
- We test many other possibilities ... all look like SM



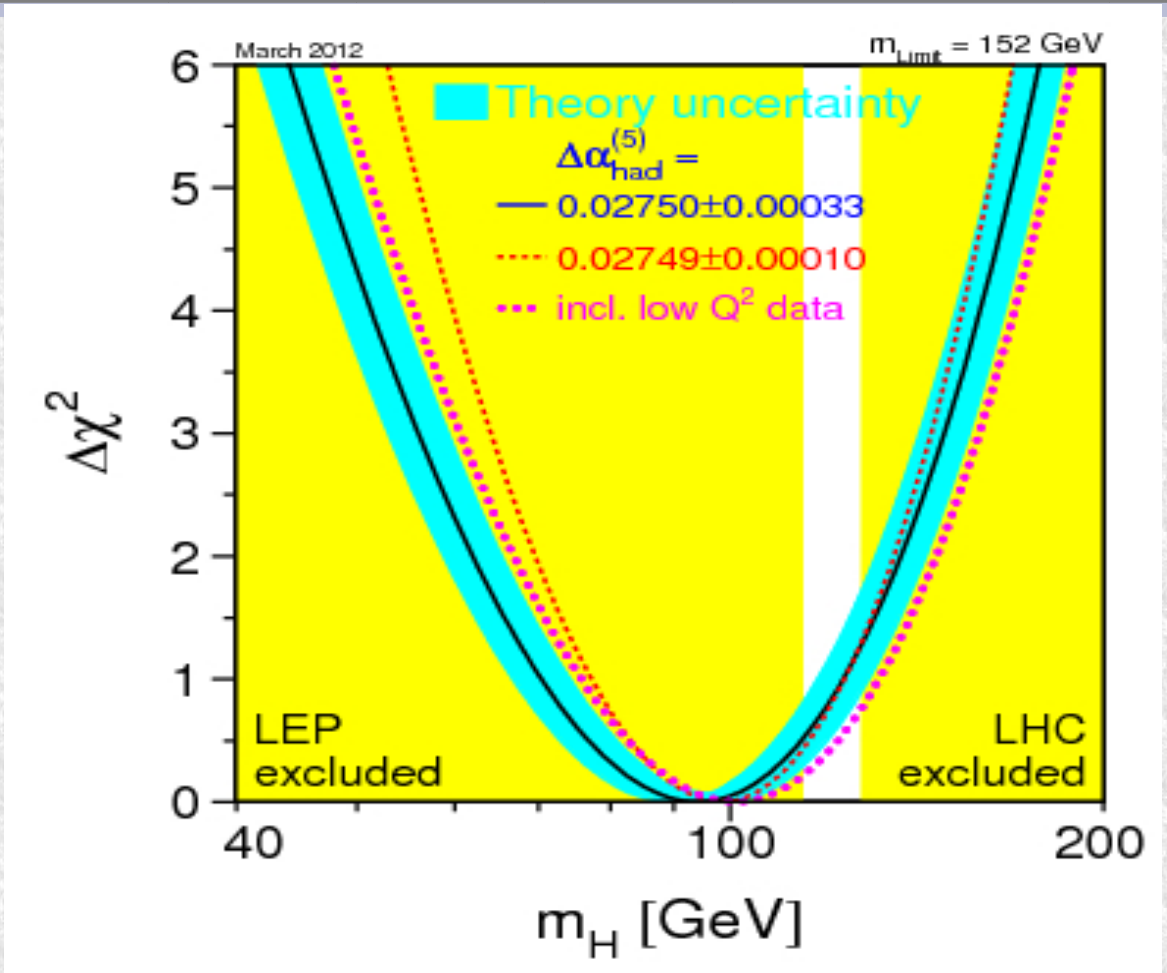


So what do we know?

Higgs Mass	Measured – agrees with SM rough prediction
Spin	Should be 0. We know it is integer, and not 1
Parity (mirror symmetric?)	Should be symmetric. Unknown
Charge	Zero, as it should be
Lifetime	Unknown, but narrow resonance and no obvious flight, OK.
Interaction with W,Z	Rates in WW,ZZ look as expected.
Interaction with matter (quarks/leptons)	ATLAS information weak here CMS bb+ττ combination 2σ low. No LHC proof this exists But Tevatron has around 3σ evidence - twice expected
Interaction with gluons	Total rates suggest this as expected
Interaction with photons	1.6±0.4 (CMS) and 1.8±0.5 (ATLAS) This is ~2σ high

- It is consistent with the SM Higgs
  - With reasonable statistical fluctuations

What does 125-126 tell us?

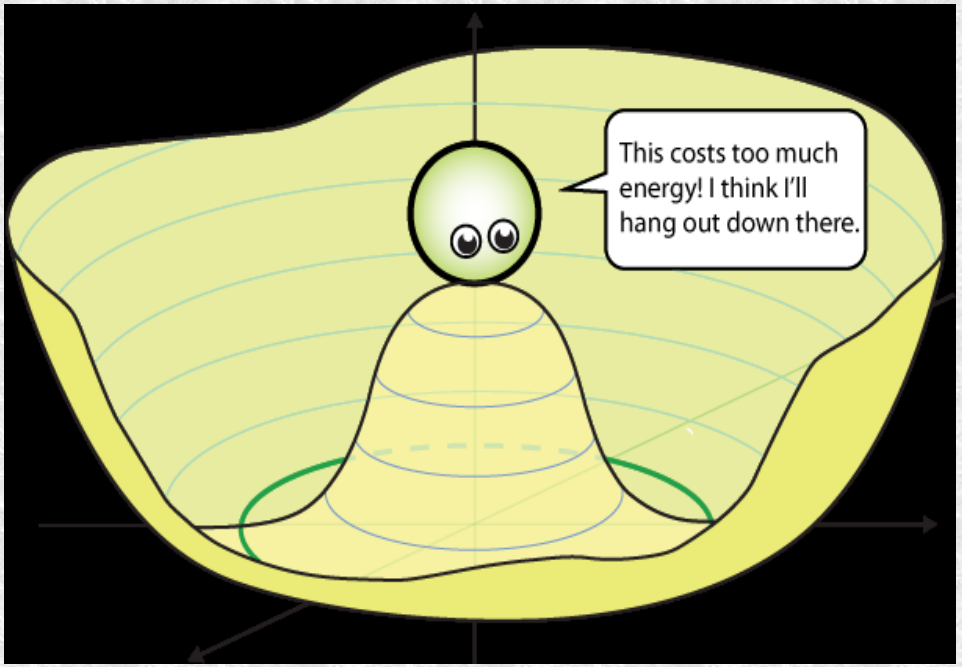


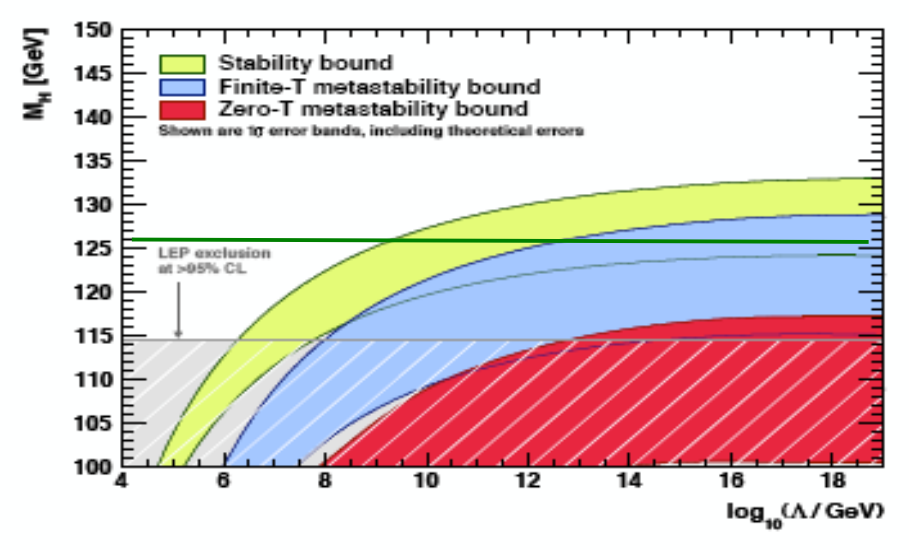
- In SM $m_H = 94^{+29}_{-24}$ GeV
  - So observed mass fits SM with no additions

What does m_H=126 tell us?

- The Higgs self-interaction changes with energy
  - Penalty to make more decreases as E rises
- If m_H is small 'penalty' can become gain
  - Then unlimited are made
  - Vacuum collapses

$$V(\phi)=-\lambda/2|\phi|^2+g/4!|\phi|^4$$



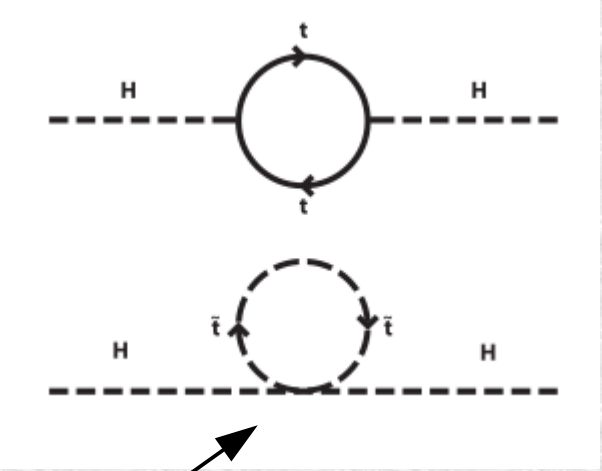


- 125 GeV is at the divide
  - Universe may be meta-stable
  - Suggests unknown 'fix'

What does 125-126 tell us?

- But *why* is m_H so low?
- The Higgs potential:

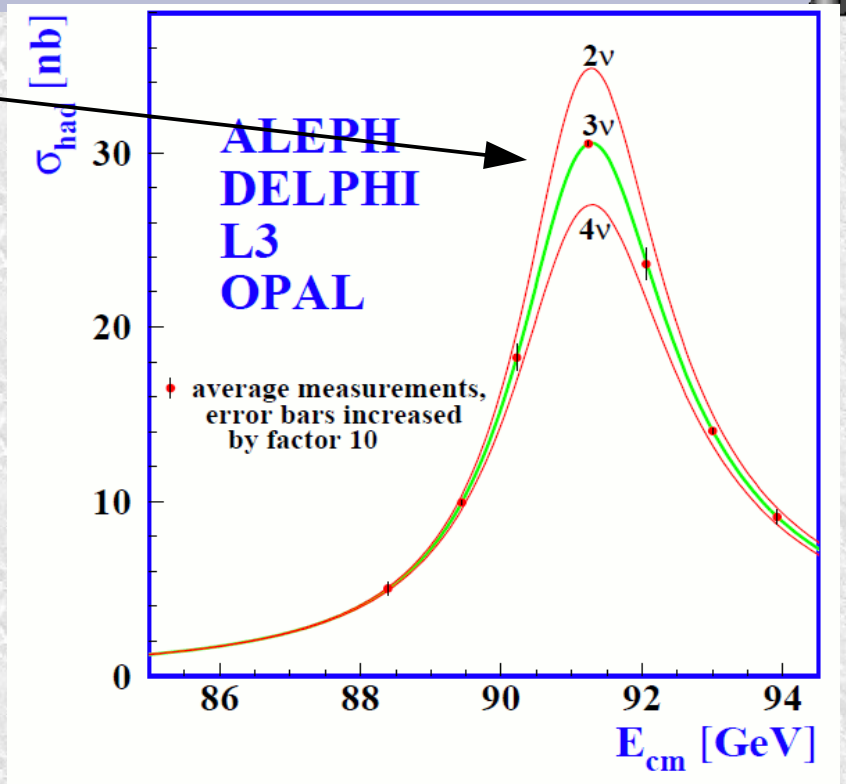
$$V(\phi)=-\lambda/2|\phi|^2+g/4!|\phi|^4$$

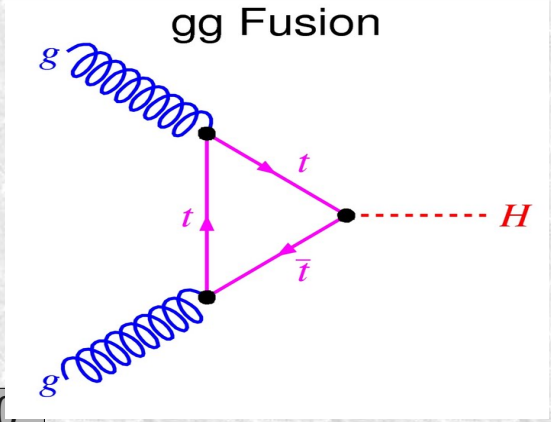


- Suffers from loop correction like the top loop
- The mass gets quantum corrections from the highest scale in the theory
  - Tends to be moved to ~ this scale
  - The only we know is 10^{16}GeV (gravity)
- This 'heirarchy problem' motivates supersymmetry
  - Corrections from superparticles cancel the particles and m_H is allowed (forced!) to be light
- SUSY enthusiasts encouraged!!

How many neutrinos?

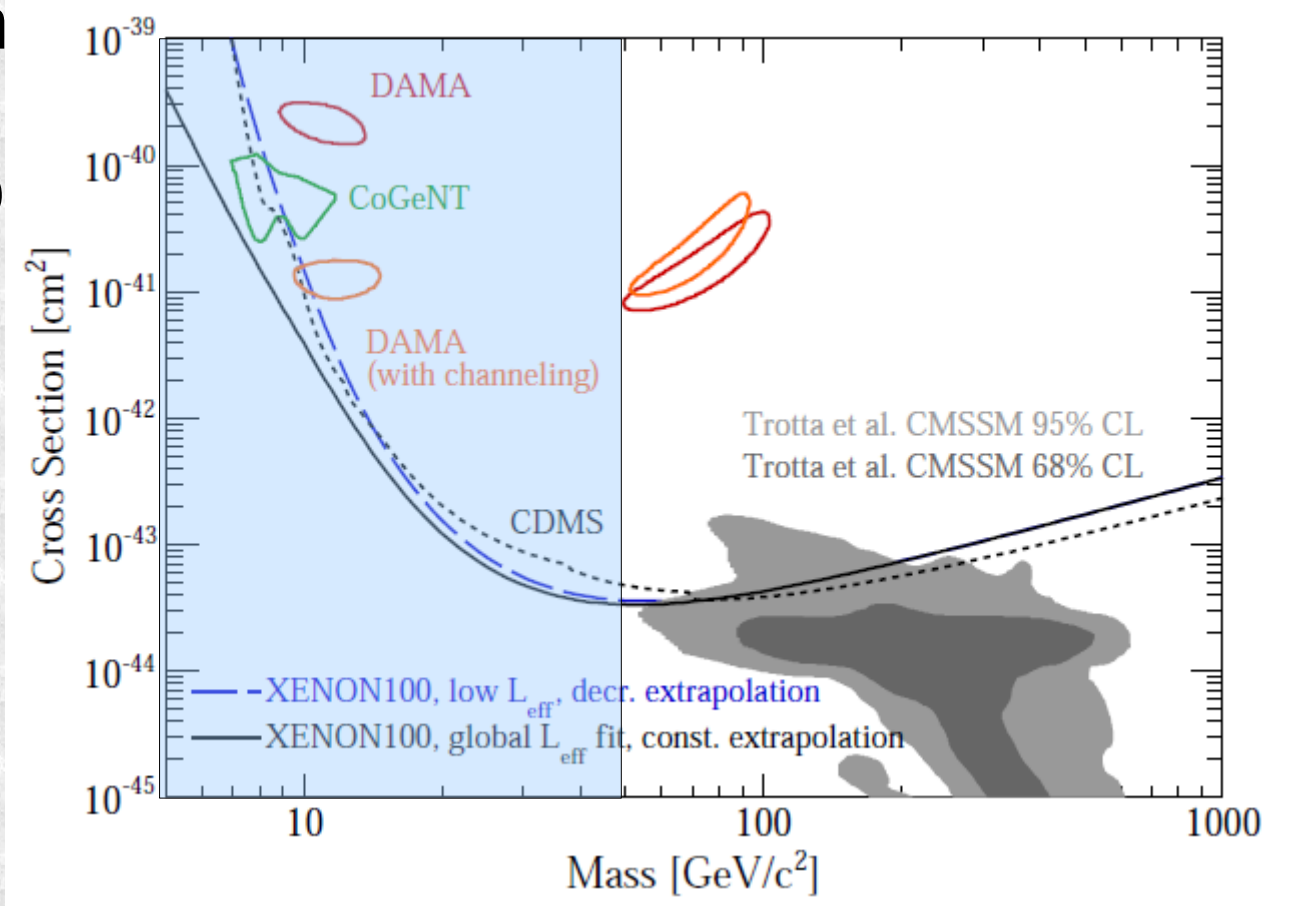
- LEP proved 3 light neutrinos
  - hence 3 generations?
- Now we know neutrinos have mass maybe $2m_\nu > m_Z$?
  - Could be a heavy neutrino
- But Higgs production is mostly through gluon fusion
  - Virtual top in a loop
  - A new heavier quark would increase the rate a lot
  - Whatever mass the quark had
- Much harder to believe in a 4th generation today.





Dark Matter?

- If this is a Higgs, in many models it couples strongly to dark matter
- 5-50GeV dark matter will be severely tested by fact Higgs decays as expected
- Not yet, but the blue area will be constrained
  - SUSY prediction OK!



Xenon plot from ArXiv: 1005.0380v3

SUSY prediction from: JHEP 0812:024,2008

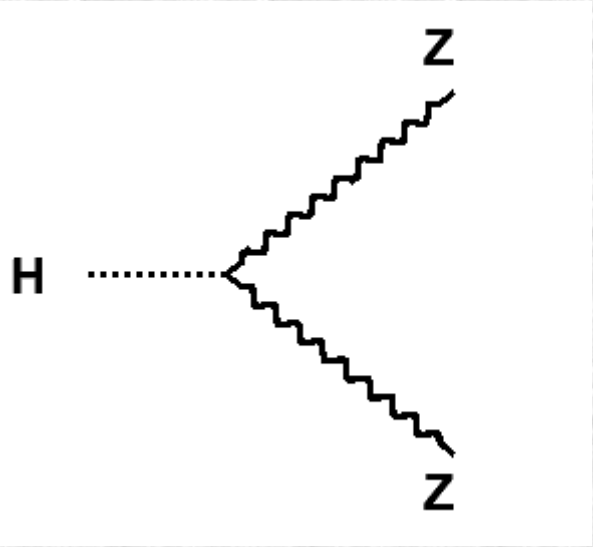
What about the Higgs field?

- A unique prediction of the Higgs mechanism is the field filling space
  - Unlike light, you turn it off and it is still there
  - More like water filling the sea
- The density of this field is ruled out by big-bang cosmology
  - It is 120 orders of magnitude larger than dark energy – and the opposite sign
- So do we really expect you to believe its there?

- This really means we don't have a QM theory of gravity

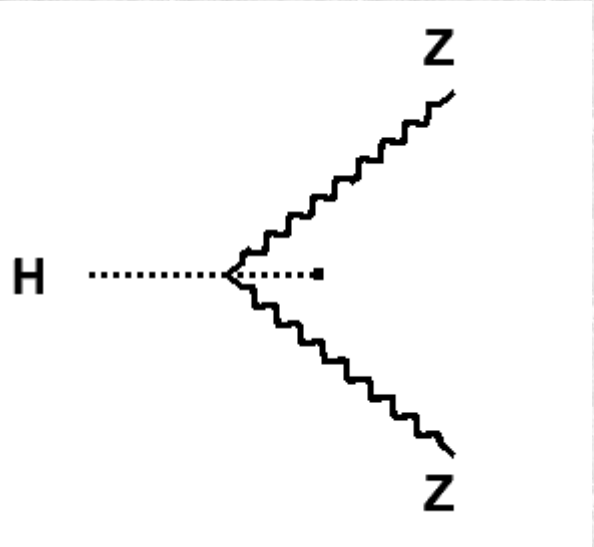
Evidence: H to ZZ

- As a photon only couples to charged particles a Z only interacts with those with weak force charge
- The 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?



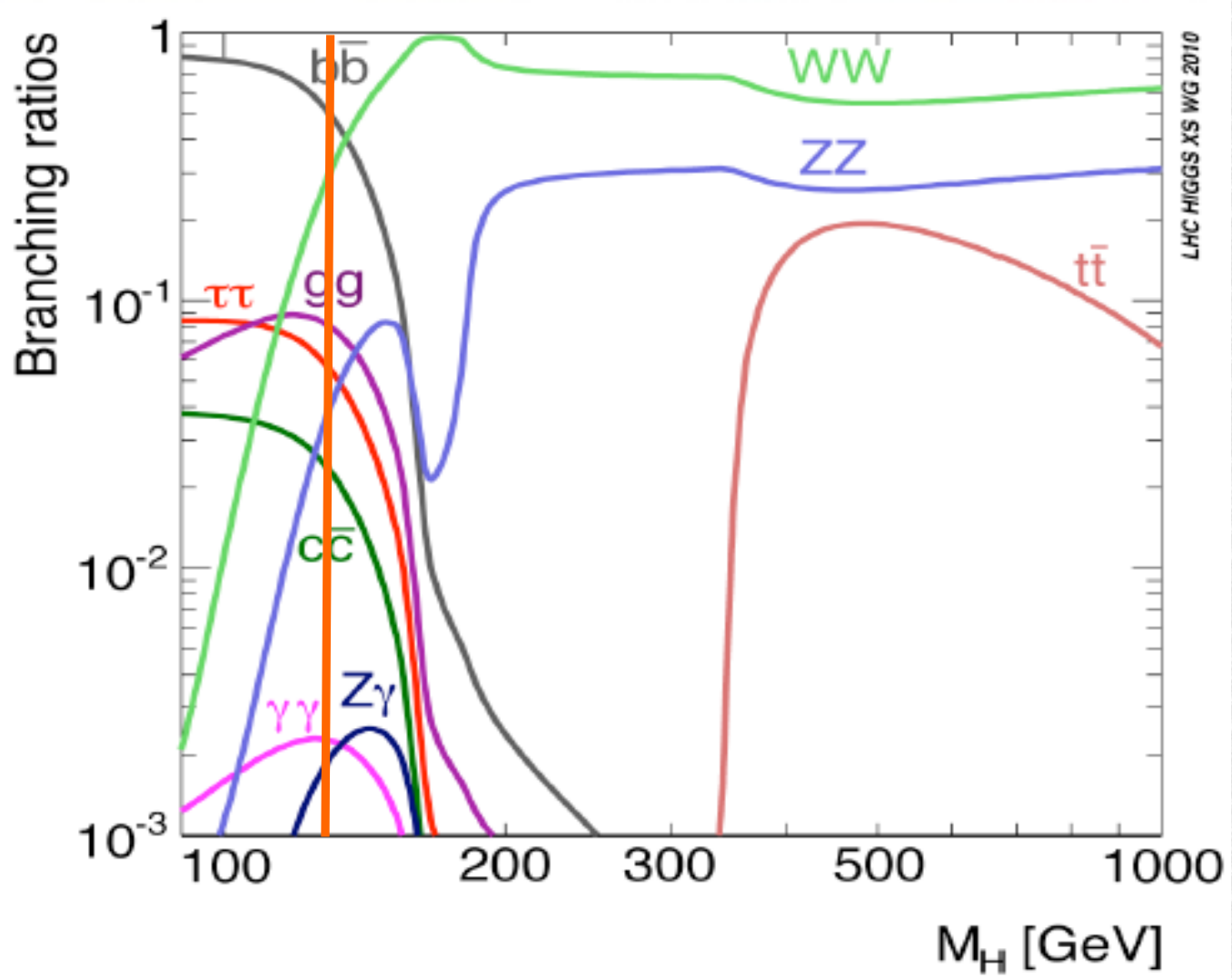
Evidence: H to ZZ

- As a photon only couples to charged particles a Z only interacts with those with weak force charge
- The 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 is telling is the vacuum is really important
  - An active participant in interactions
  - With a (weak) charge!
- The apparent 3 point couplings come from $-\lambda[(v+h)/\sqrt{2}]^4$ – but v is the VeV
- There IS a field



Quid nunc for Higgs?

- The mass is just great
- LHC targets 5 modes
  - ZZ
  - WW
  - γγ
  - bb
  - ττ
- More coming
  - Zγ
  - μμ
  - χχ
- Lepton collider
  - gg
  - cc



Next Steps for Higgs studies

- Proton Colliders
  - LHC: 11fb^{-1} → 25fb^{-1}
  - Run 2021 with 300fb^{-1} at 14TeV delivered
    - 30 times what we have seen so far!
  - HL-LHC calls for 3000fb^{-1} LHC running to 2030
    - Natural extension of LHC, 30% rise in √s sensitivity
  - HE-LHC – 33TeV proton beam with 20T magnets in the LHC tunnel (or even stronger)
  - VLHC – a larger proton ring up to 80 km is considered
- Electron colliders
  - ILC – 250-500GeV, up to 1TeV later, linear collider
  - CLIC – 250-3000GeV linear collider
  - LEP-3 – 240GeV e^+e^- ring in LHC tunnel – (tunnel is in use!)
  - Several ideas for 60-100km ring ee machines
- All this was debated in European Strategy meeting
  - Krakow, 10-12th September

Full 2012 data

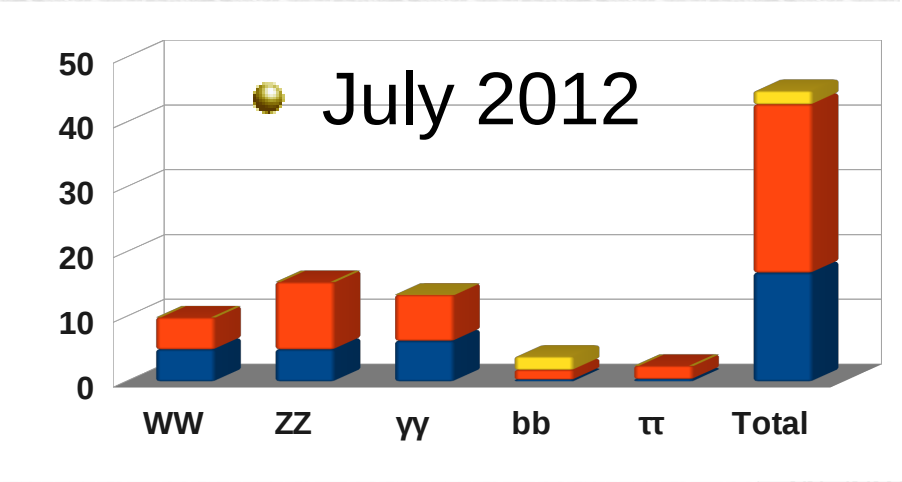
- How will we do?
  - The following GUESSES assume SM rates
  - They also assume a lot of work

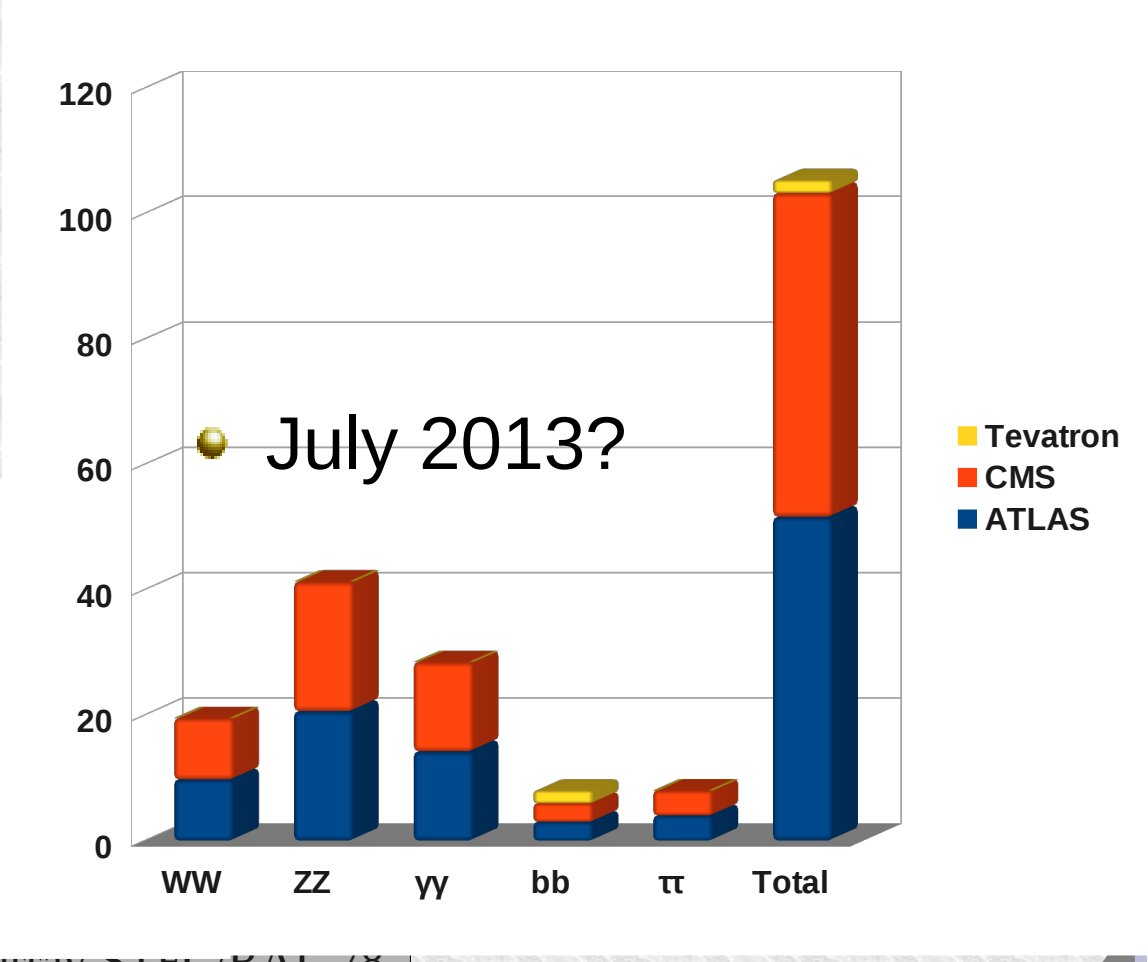
	Gluon fusion	VBF	VH	ttH
ZZ	5σ	1σ	0	0
WW	3σ	1σ	0	0
γγ	4σ	2σ	0.5σ	0
bb	0	0	2σ	0.3σ
ττ	0	2.5σ	0.5σ	0

- If true we see 5 decays and 3 production mechanisms
- Pretty good for the discovery year!

Weights of channels

- Assume results Gaussian – not true
- Plot χ^2 contribution you EXPECT from each channel
  - Tevatron contributes most in bb
  - But (combined) is 3rd by 2013
- But nearly all the evidence is from LHC





Spin/parity

- We know integer spin, not 1
  - To reasonable confidence
- We can establish from ZZ/WW/γγ
  - ~3σ 0^+ v 0^-
  - ~3σ 2^+ v 0^+
- But there are caveats:
  - Spin 2 assumes the production/ helicity structure
    - Why make those?
    - There are some very hard to separate
  - The bosonic decay projects out 0+ from a mixed state
    - We are not sensitive to mixed (CP violating) systems
- So..we WILL learn something
  - But theorists are not expecting surprises here
  - The rates match too well the 0^+ model...

Surprises?

- Today we have two big discrepancies:
- The CMS $\tau\tau$ search almost rules out SM Higgs
  - ATLAS results keenly awaited
  - Fermiophobic already excluded...but some half-way house?
- $H \rightarrow \gamma\gamma$ excess
  - At about 2σ level
  - In an interesting place
- My prejudice:
  - Adding 'new physics' to the SM very likely to affect loops
  - Like $H \rightarrow \gamma\gamma$
- We will know a lot more when 2012 data is fully analysed

Whither LHC?

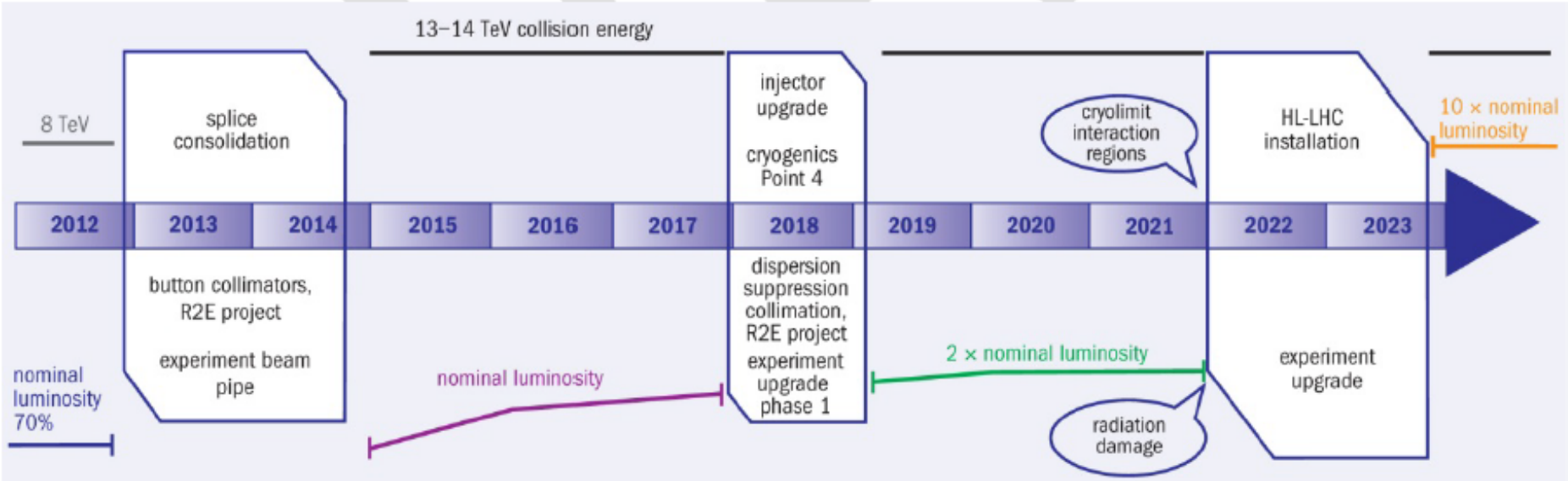
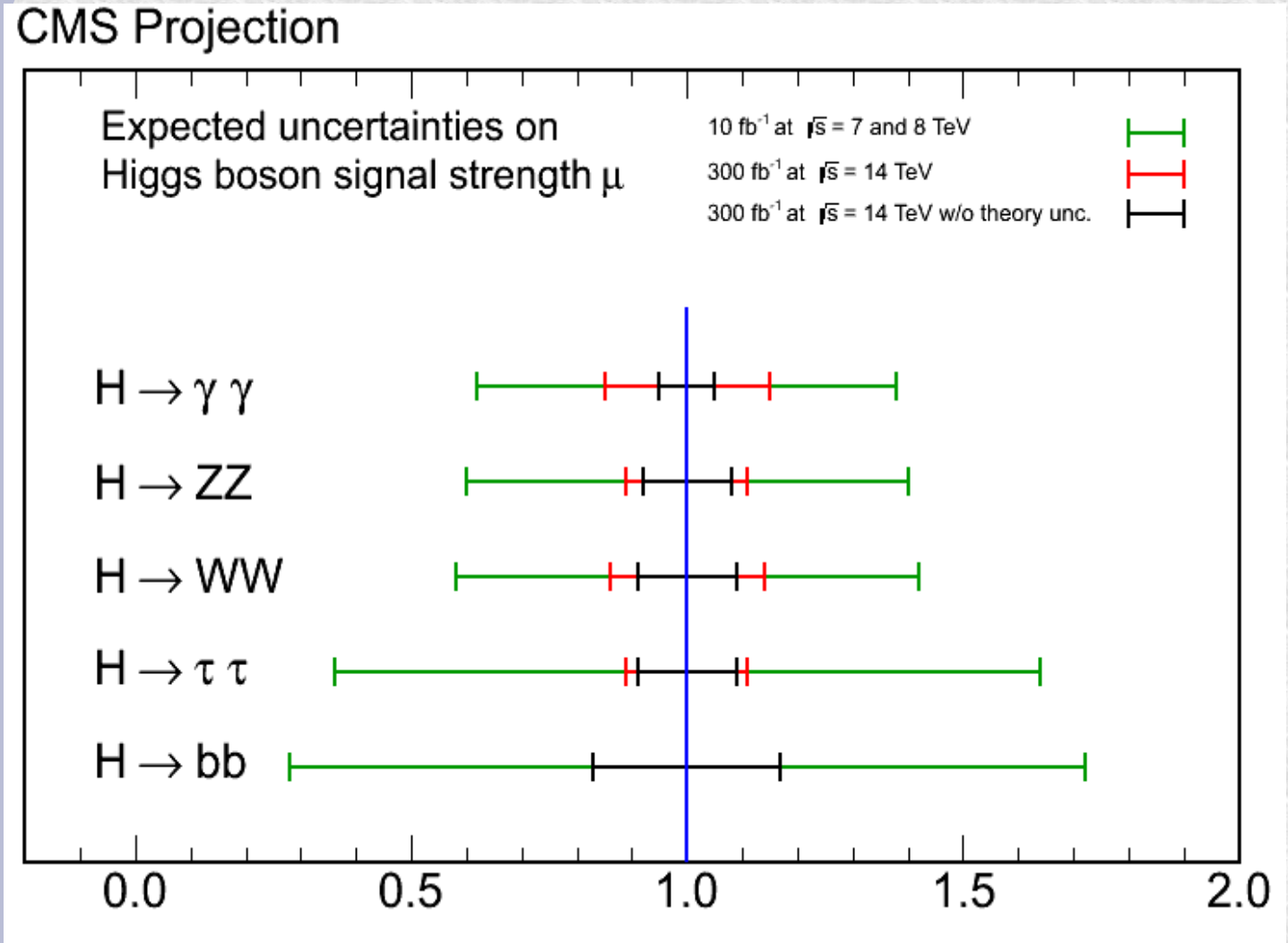


Figure 1: LHC baseline plan for the next ten years. In terms of energy of the collisions (upper line) and of luminosity (lower lines). The first long shutdown 2013-14 is to allow design parameters of beam energy and luminosity. The second one, 2018, is for secure luminosity and reliability as well as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

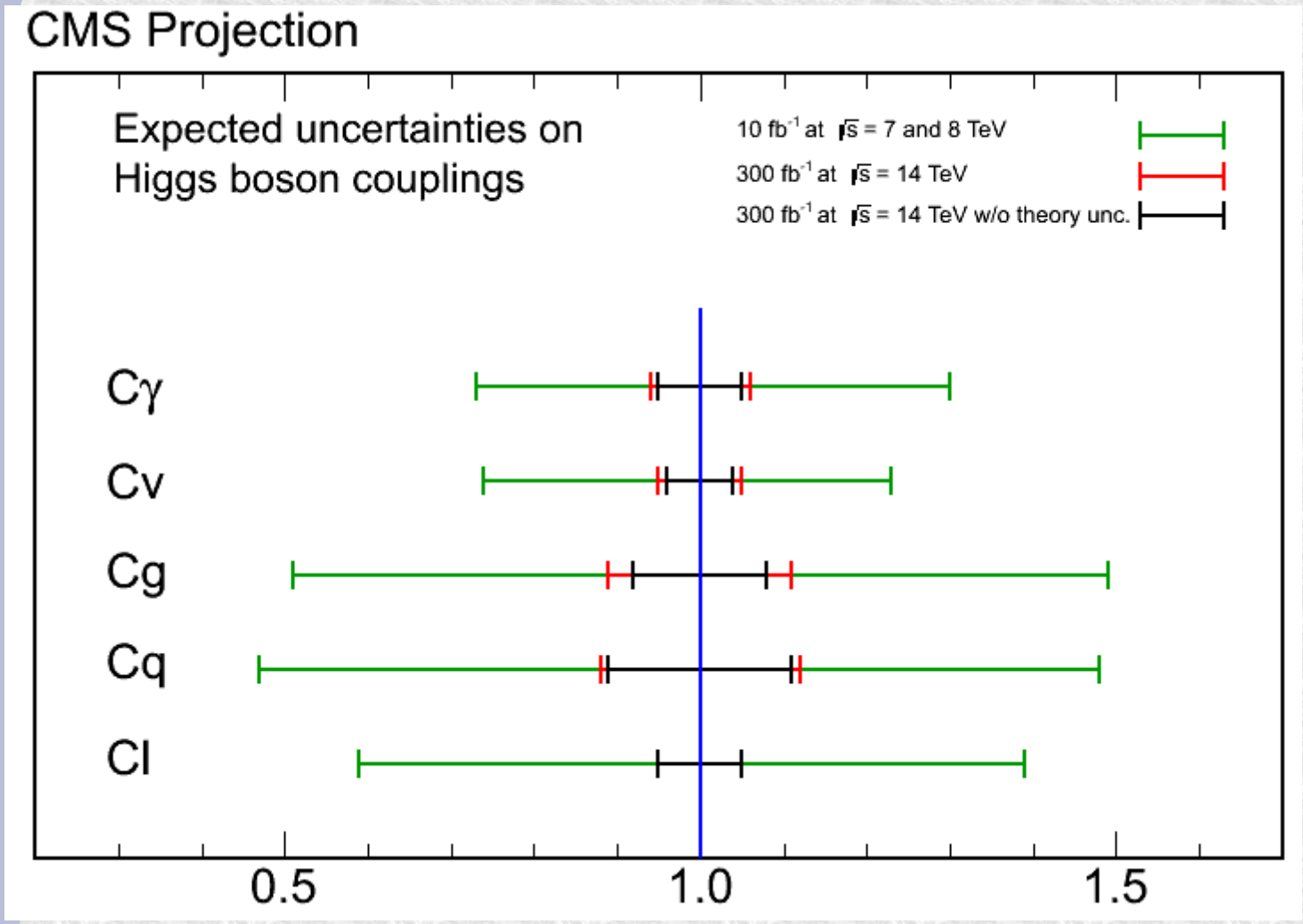
- 25fb^{-1} by end of year
- 300fb^{-1} by end of 2021
  - With Energy 13+ TeV
  - ~50 times the Higgs events reported on so far....

CMS projections



- Comparison of current errors and 300fb^{-1}
- These plot always involve assumptions about systematic errors
- But 10-20% errors expected

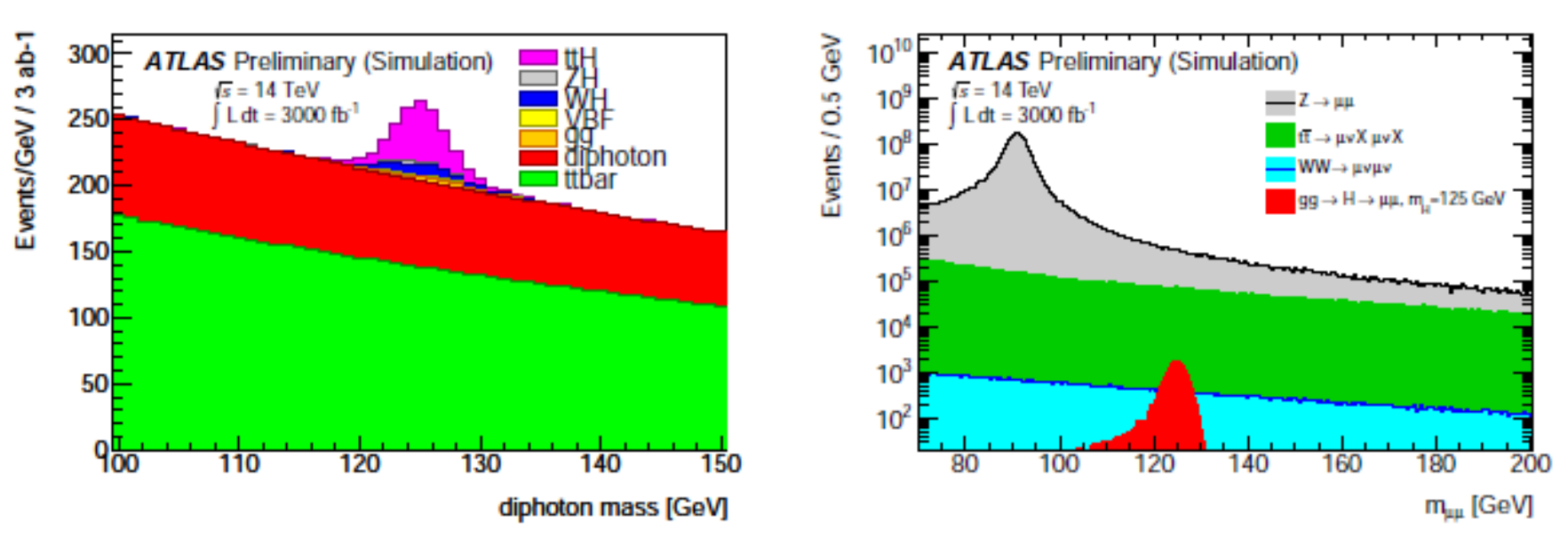
CMS coupling expectations



- 5D fit here
  - Photons (loop)
  - Vector bosons
  - Gluons (loop)
  - Quarks
  - Leptons
- No invisible modes allowed
  - Solves the absolute coupling issues

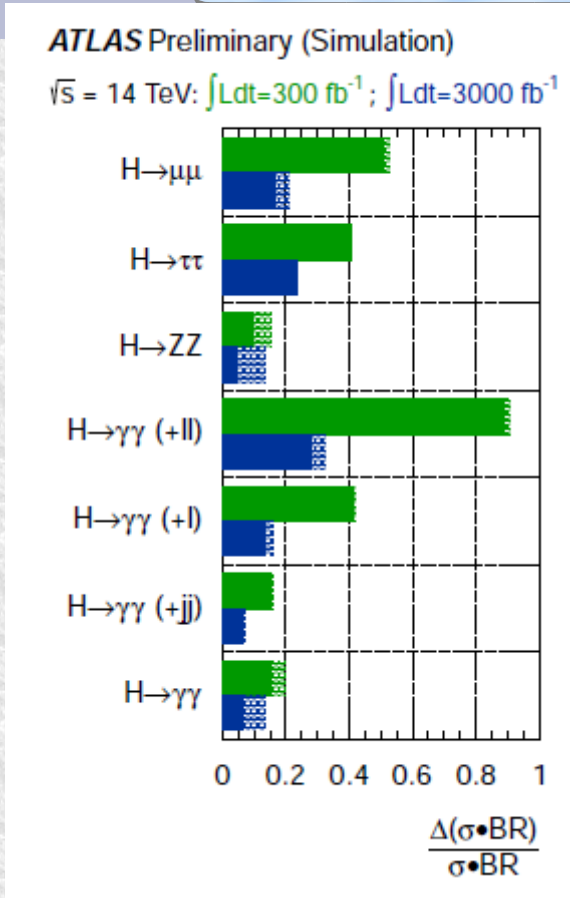
HL-LHC and ATLAS

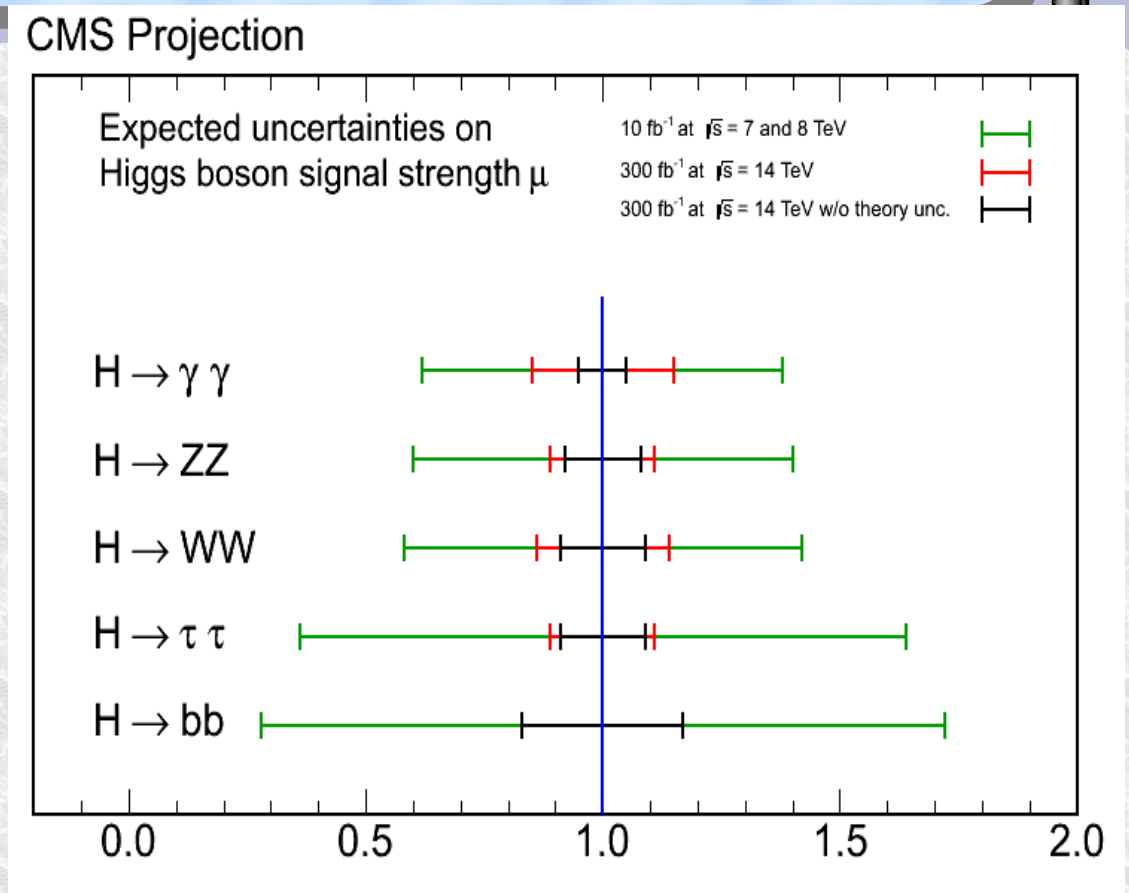
- LHC runs to 2022
- 300fb^{-1} at 14TeV expected
  - SLHC is proposed thereafter - 3000fb^{-1}
- ttH,H→γγ and H→μμ are two interesting studies



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

Krakow: signal rate errors

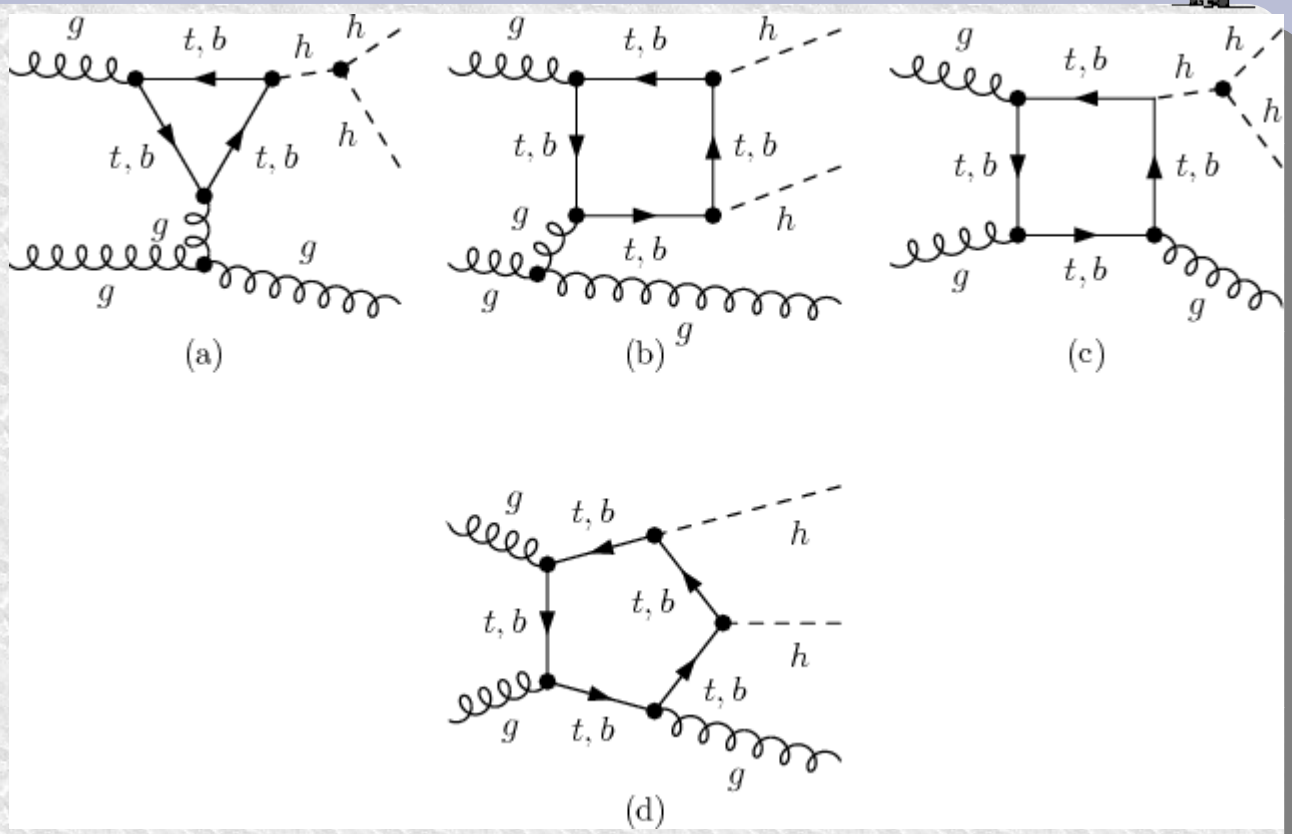




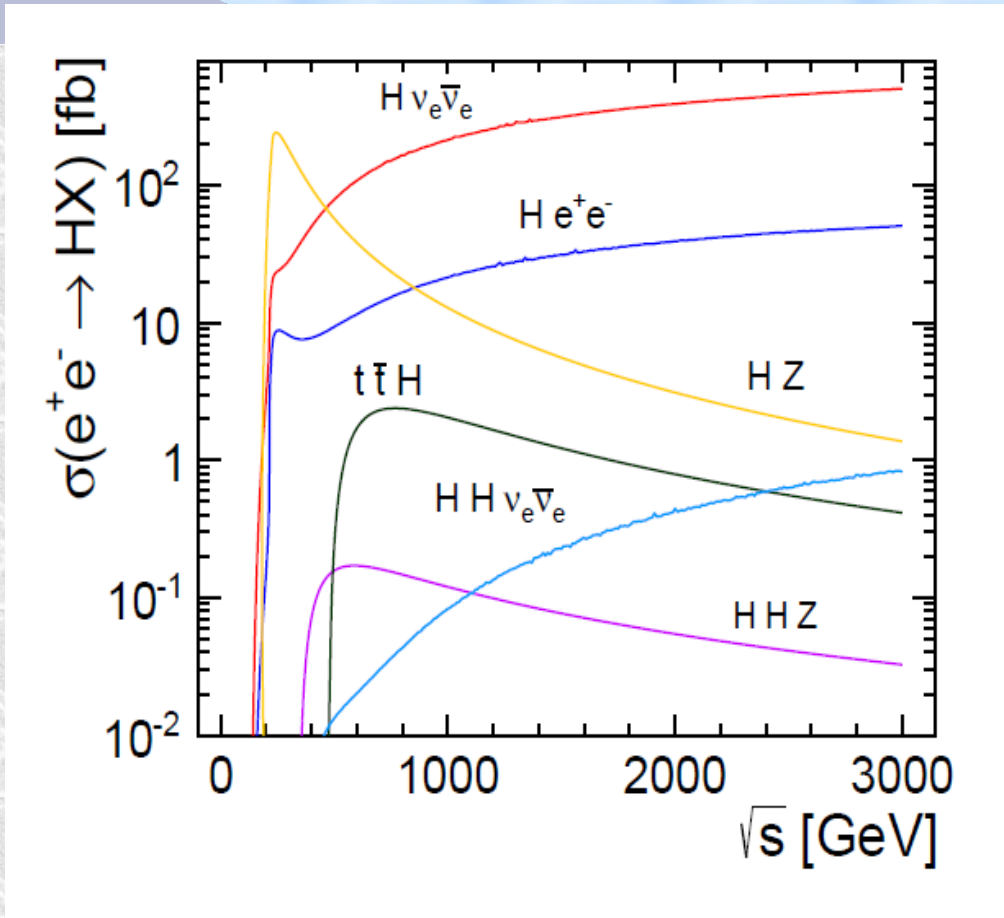
- Interesting to compare ATLAS and CMS expectations
  - Pretty close for ZZ and γγ
  - Factor 3 apart for ττ at 300fb^{-1} (different channels, systematics)
- Being conservative is dangerous too!

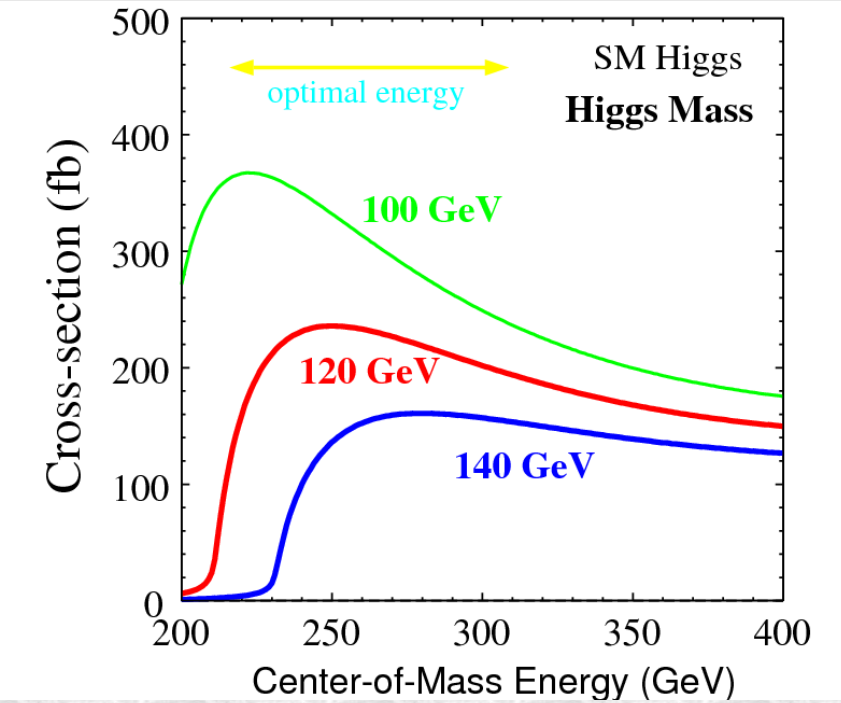
Self coupling

- Needs observation of Higgs pairs
  - Thats a tall order!
- But it is not enough
  - Need to prove triple Higgs involved
  - negative interference :(
- bbyy allows 3σ HH observation
  - ATLAS+CMS, more channels, may give 3σ *coupling* measurement



Higgs beyond LHC





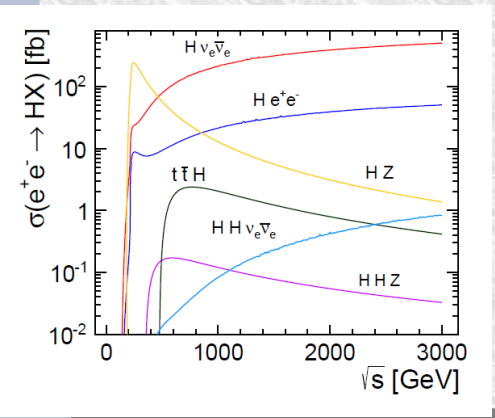
250 GeV gives maximum for ZH

Need a very large energy before the vector boson fusion channels overtake that

HIGGS FACTORIES e^+e^-

e+ e-

- **Linear Colliders**
  - **ILC**
    - 250 GeV
    - 500 GeV
  - **CLIC**
    - 250 GeV + Klystron based
    - 500 GeV
    - > 500 GeV
- **Circular Colliders**
  - **CERN**
    - LEP3 at LHC tunnel
    - DLEP – New tunnel, 53 km
    - TLEP – New tunnel, 80 km
  - **Super TRISTAN**
    - 250 GeV– 40, 60 km tunnel
    - 400
    - 500



HIGGS FACTORIES e+e- R&D & main issues

e+ e-

Linear Colliders

- **ILC** — Almost ready SC rf technology, need of opt for low energy, TDR by end '12, XFEL as test facility
- **CLIC** — Low E : X-band Klystron technology Demonstrated High gradient cavities Sinergy with XFELs
  - ≥ 500, CDR, need >10 years R&D CTF3 test facility

Circular Colliders

- **CERN** — Low E - Tunnel ready (not available) , technology ok , SCrf cavities ok
  - Long tunnel, high costs, environment impact
- **Super TRISTAN** — Technology assessed, tunnel & site ???

e+ e-

Linear Colliders

- **ILC** — **500 GeV: 7B$ (2007), 31 km next costing end '12**
- **240 Klystron based – costing not ready**
- **CLIC** — **500 GeV : 8B$ (2012), 13 km next costing end '12**
- **> 500 GeV staging up to 3 TeV Costing to be defined**

Circular Colliders

- **CERN** — **LEP3: 1.5B$**
- **DLEP, TLEP (40, 80 km), 3-4B$**
- **2.7, 3.5B$ (40, 60 km), 250 GeV**
- **Super TRISTAN** — **4B$ – 60 km 400 GeV**
- **5B$ – 60 km 500GeV**

LEP 3

Use LHC tunnel and detectors

L ~10^{34}

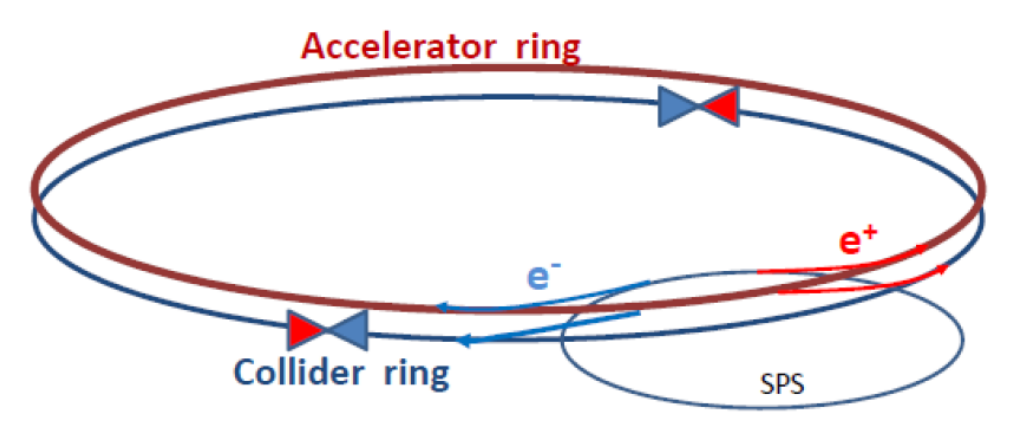
Need of booster + collider ring: two rings in LHC tunnel, lightweight magnets

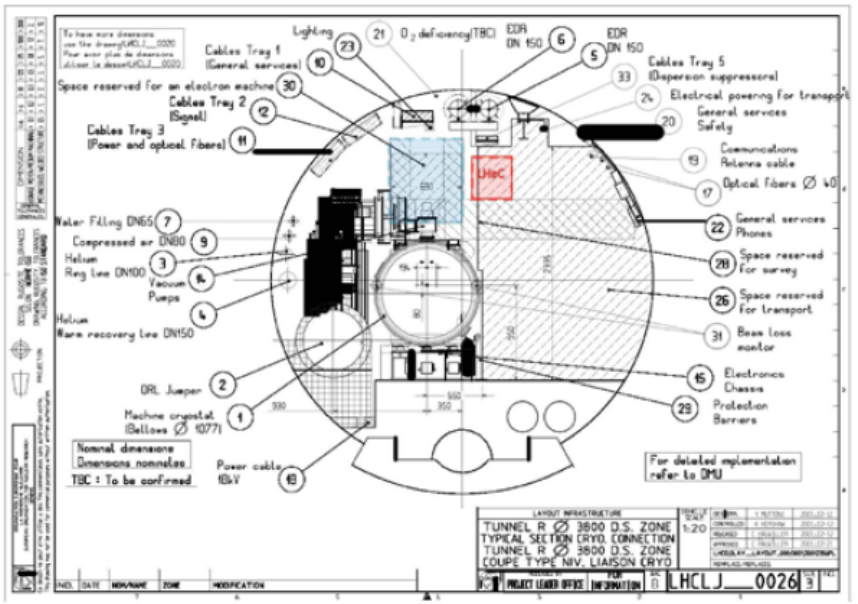
Energy loss per turn : 7 GeV (3.5 @ LEP2)

Rf voltage 12 GV , 1.3GHz (3.6 @ LEP2 , 350 MHz)

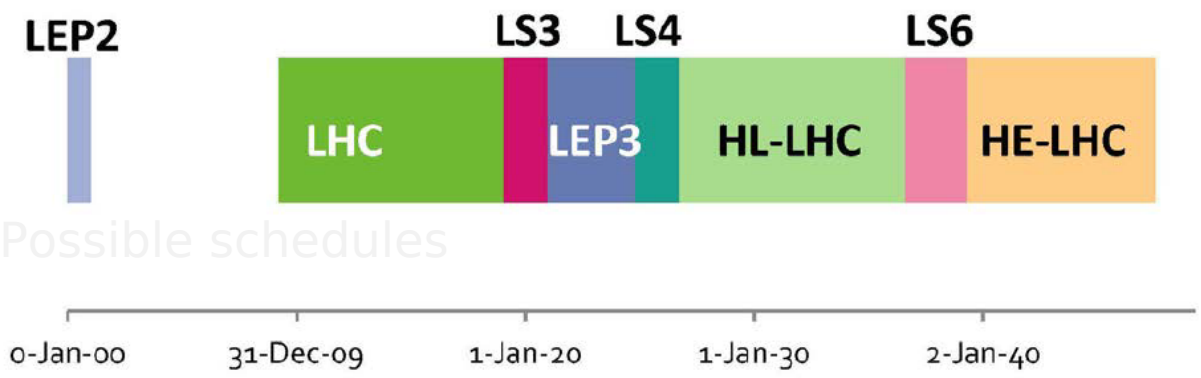
Synchrotron radiation : 100 MW (7.2 mA) total

Integration and cohabitation with LHC, HL-LHC, HE-LHC

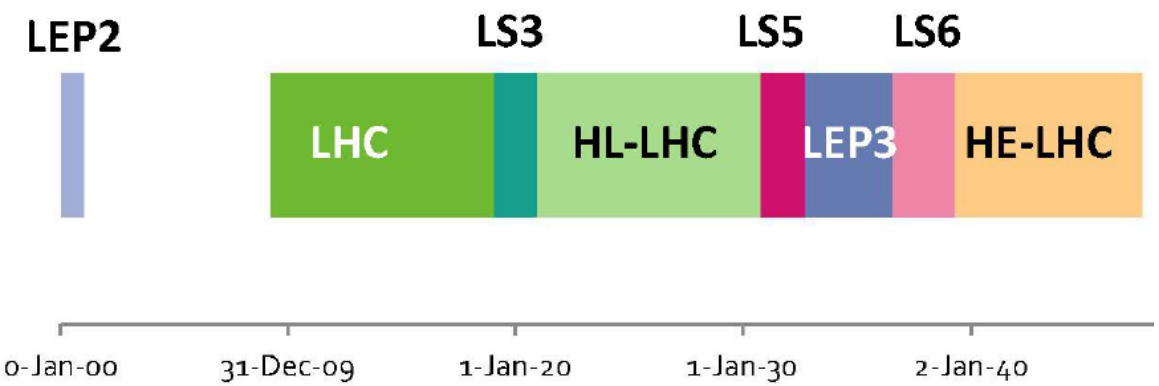




LEP 3 scheduling



Possible schedules



Rough cost estimate

	LEP3
tunnel	-
RF	600
magnets	50
beam pipe	80
accelerator ring	200
injector	100
others	100
total	**1130**

LEP (3)

	LEP2	LHeC	LEP3	DLEP
b. energy E_b [GeV]	104.5	60	120	120
circumf. [km]	26.7	26.7	26.7	53.4
beam current [mA]	4	100	7.2	14.4
#bunches/beam	4	2808	4	60
#e–/beam [10^{12}]	2.3	56	4.0	16.0
horiz. emit. [nm]	48	5	25	10
vert. emit. [nm]	0.25	2.5	0.10	0.05
bending rad. [km]	3.1	2.6	2.6	5.2
part. number J_ε	1.1	1.5	1.5	1.5
mom. c. α_c [10^{-5}]	18.5	8.1	8.1	2.0
SR p./beam [MW]	11	44	50	50
β^*_x [m]	1.5	0.18	0.2	0.2
β^*_y [cm]	5	10	0.1	0.1
σ^*_x [μm]	270	30	71	45
σ^*_y [μm]	3.5	16	0.32	0.22
hourglass F_{hg}	0.98	0.99	0.67	0.75
E^{SR}_{loss}/turn [GeV]	3.41	0.44	6.99	3.5
$V_{RF,tot}$ [GV]	3.64	0.5	12.0	4.6
$\delta_{max,RF}$ [%]	0.77	0.66	4.2	5.0
ξ_x/IP	0.025	N/A	0.09	0.05
ξ_y/IP	0.065	N/A	0.08	0.05
f_s [kHz]	1.6	0.65	3.91	0.91
E_{acc} [MV/m]	7.5	11.9	20	418
eff. RF length [m]	485	42	606	376
f_{RF} [MHz]	352	721	1300	1300
δ^{SR}_{rms} [%]	0.22	0.12	0.23	0.16
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.69	0.23	0.17
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	N/A	107	142
number of IPs	4	1	2	2
beam lifetime [min]	360	N/A	16	22
Υ_{BS} [10^{-4}]	0.2	0.05	10	8
n_γ/collision	0.08	0.16	0.60	0.25
ΔE^{BS}/col. [MeV]	0.1	0.02	33	12
ΔE^{BS}_{rms}/col. [MeV]	0.3	0.07	48	26

This takes into account modifications required to take care of the beamstrahlung effect pointed out by I. Telnov and K. Yokoya

-- energy aperture has been increased to ±4%

-- but energy spread at IP does not increase significantly

NB: This allows multibunch operations at lower than maximum energy

LEP3 offers:

10^{34}/cm2/s Average Luminosity in 2 experiments i.e. 2x500fb-1
2x20'000 ZH events per year.

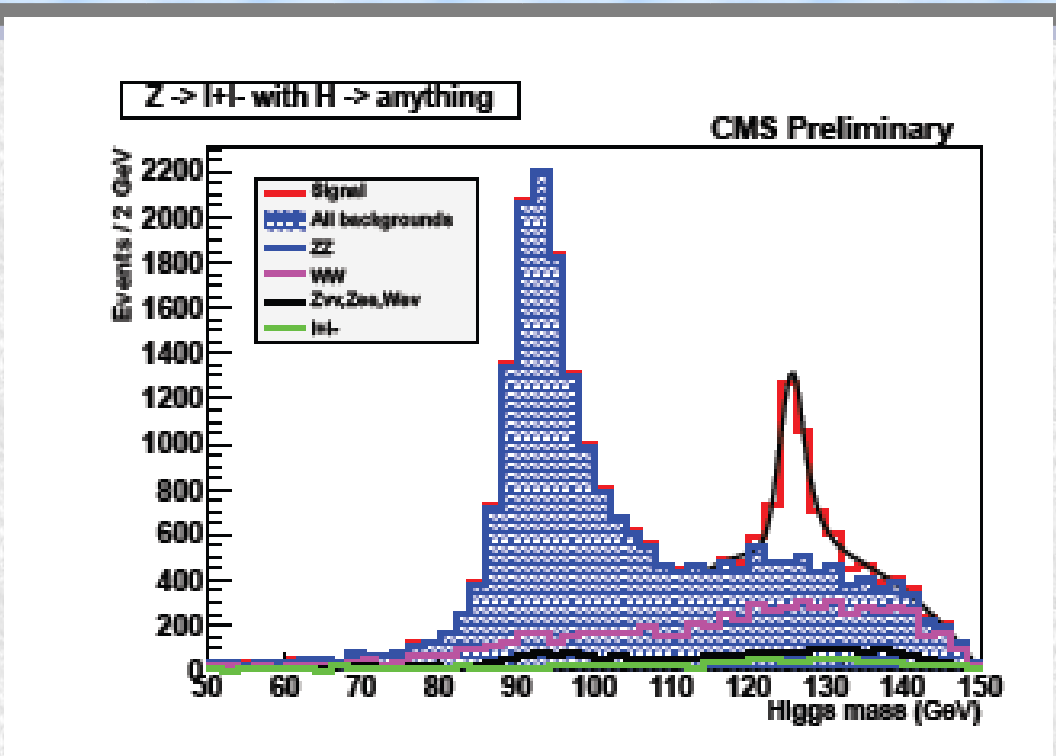
Challenges:

-- low vertical emittance must be maintained while fitting in the existing tunnel
-- beam-beam interaction is somewhat extreme (but nothing like LC!)
-- Most components are 'off-the-shelf'
except RF power source operating in CW mode
-- first use of a large system of ILC cavities (8% of ILC@250 GeV)

By-products

-- By multibunching one would be able to reach luminosities of
O(~5 10^{35})/cm^2/s at the Z pole (Tera-Z)
O(~5 10^{34}) /cm^2/s at the W pair threshold (Mega W)
ΔMW < 1 MeV, ΔMZ ,Γ_Z << 1 MeV, sin2θW_{eff} <<0.0001 (to be studied)
beam transverse polarization easier than LEP
because of low transverse emittance (in collision?)

ZH through Z only



The total cross-section can be seen with very low Higgs decay mode dependence

True of any lepton collider

Janot et al

Table 2: The precision (or 95% C.L. sensitivity for the invisible decay) on the Higgs boson cross sections and couplings obtained from studies of the Higgsstrahlung process, with five years of running at the ILC, at LEP3 with CMS and ATLAS, and at LEP3 with CMS, ATLAS and two additional detectors. The numbers for the ILC were obtained with $m_H = 120\,\mathrm{GeV}/c^2$, $\sqrt{s} = 250\,\mathrm{GeV}$, and leading-order cross sections, while those for LEP3 were conservatively obtained with $m_H = 125\,\mathrm{GeV}/c^2$, $\sqrt{s} = 240\,\mathrm{GeV}$, and next-to-next-to-leading-order cross section. The Hcc and HWW couplings will be added in a forthcoming update of this note.

	ILC	LEP3 (2)	LEP3 (4)
σ_{HZ}	3%	2.7%	1.9%
$\sigma_{HZ} \times BR(H \to b\bar{b})$	1%	1.2%	0.8%
$\sigma_{HZ} \times BR(H \to \tau^+\tau^-)$	6%	3.2%	2.2%
$\sigma_{HZ} \times BR(H \to \text{invisible})$	?	1%	0.7%
g_{HZZ}	1.5%	1.3%	1%
g_{Hbb}	1.6%	1.5%	1%
$g_{H\tau\tau}$	3%	2.1%	1.5%
g_{Hcc}	4%	?	?
g_{HWW}	4%	?	?

ILC aims for 250fb^{-1} in 5 years
LEP 3 offers multiple collision points

TLEP

A possible way to go

80km tunnel around Geneva could be fit avoiding Jura, Vuache and Salève…

Then as a first step a « TLEP » 350 GeV e^+e^- ring
-- still significantly cheaper than the LC of the same energy
-- reaching 175 GeV/beam (top threshold) with $6x10^{33}$ /cm2/s luminosity.

The top threshold is interesting for precision measurements of top mass, (rare) top decays and precise constraint on αS

This machine would have luminosity at ZH threshold of > (2?) 10^{34} /cm2/s

And the tunnel could house a future Hadron collider
(80/27) * (20T/8T) * 14 TeV >≈ 100 TeV ECM

Beyond LHC: new tunnels?

1) 42 TeV c.o.m. with 8.3 T (present LHC dipoles)
2) 80 TeV c.o.m. with 16 T (high field based on Nb3Sn)
3) 100 TeV c.o.m with 20 T (very high field based on HTS)

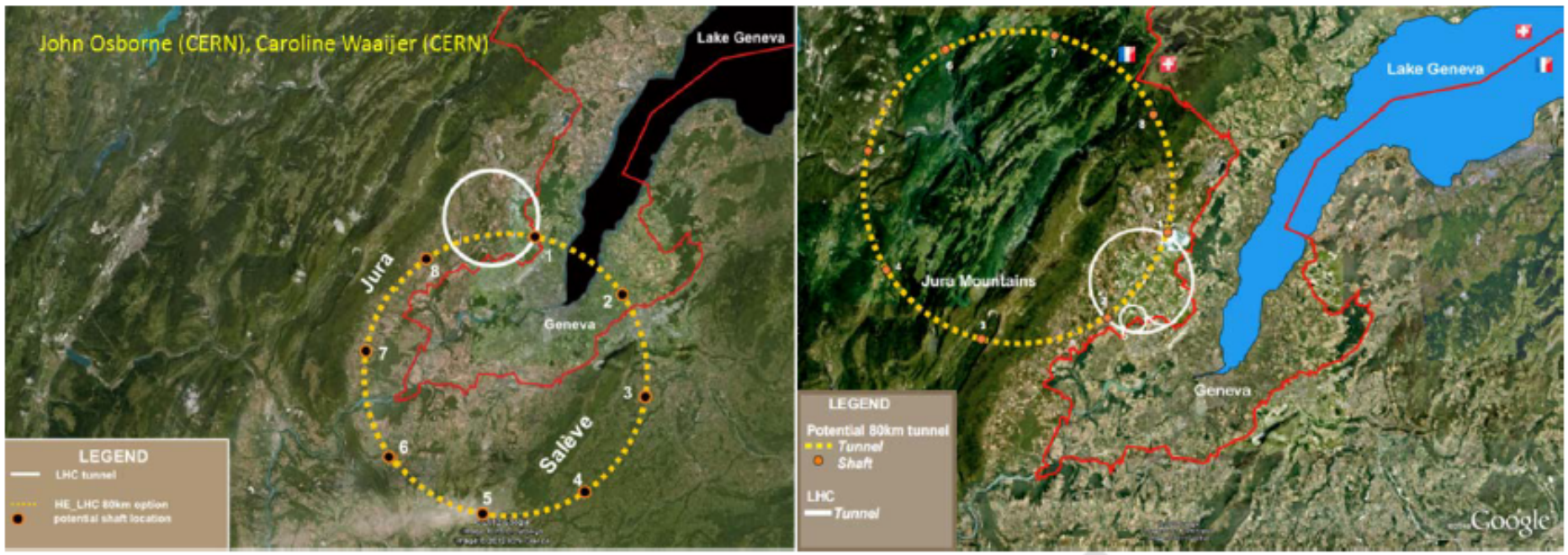


Figure 9. Two possible location, upon geological study, of the 80 km ring for a Super HE-LHC (option at left is strongly preferred)


SuperTRISTAN 40
薬王院
八郷植物センター
12.3 km
KEK
~ 2 B CHF
(only the tunnel)

Higgs self coupling

- LHC will have some chance to impact on this
  - In my opinion we will do better than we can prove
  - But this is guesswork
- LEP 3 can do nothing here

- ILC needs ~1TeV to make a measurement maybe a factor 2 better than LHC
  - ~20% errors?
  - How well do we need to know this?

View from Japan

The Final Report of
the Subcommittee on Future Projects of
High Energy Physics1, 11-02-2012
Toshinori MORI

Recommendations

Should a new particle such as a Higgs boson with a mass below approximately 1 TeV

be confirmed at LHC, **Japan should take the leadership role in an early realization of an e+e- linear collider**

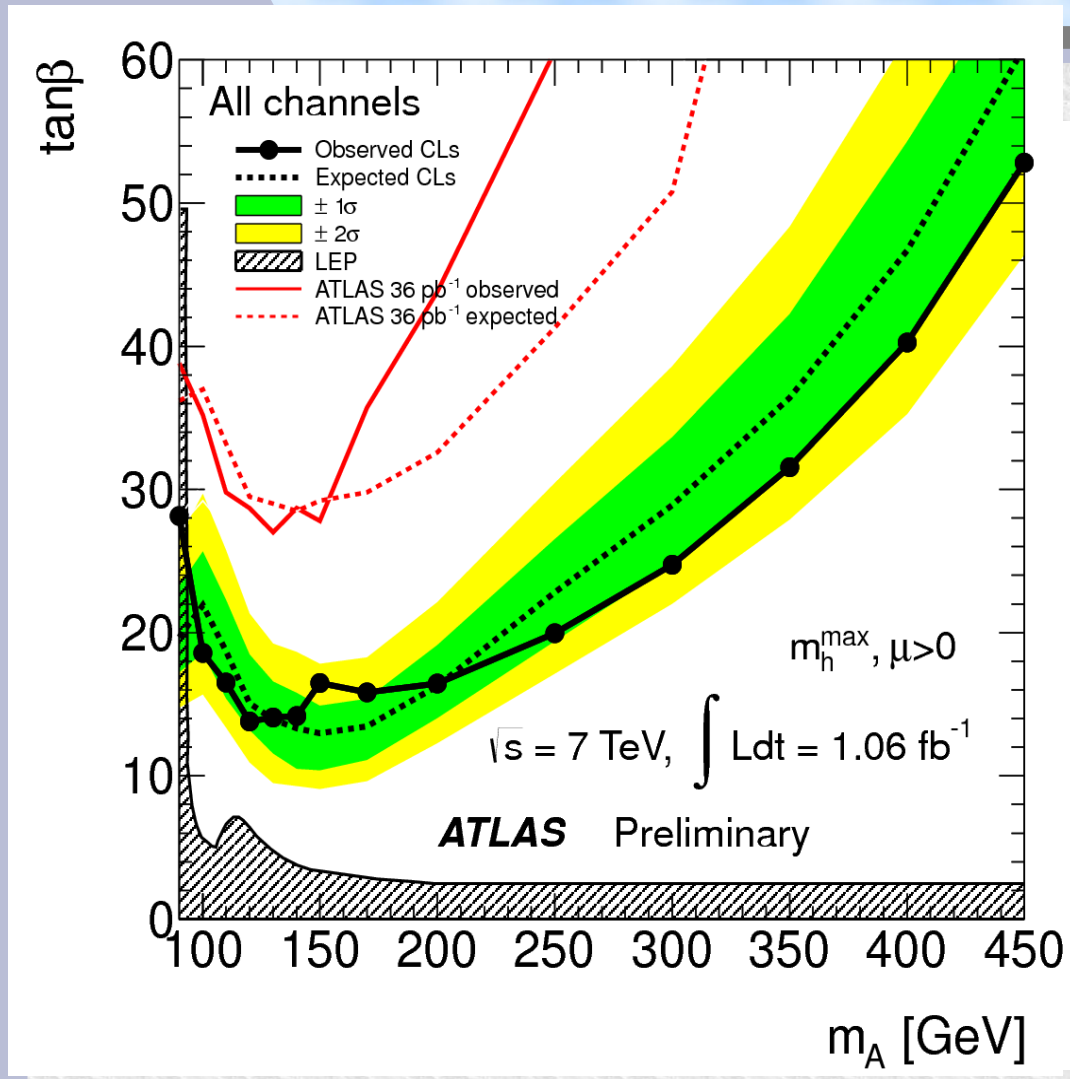
Committee on Future Projects, which includes the High Energy Physics Committee members as its core, should be able to swiftly and flexibly update the strategies for these key, large-scale projects according to newly obtained knowledge from LHC and other sources.

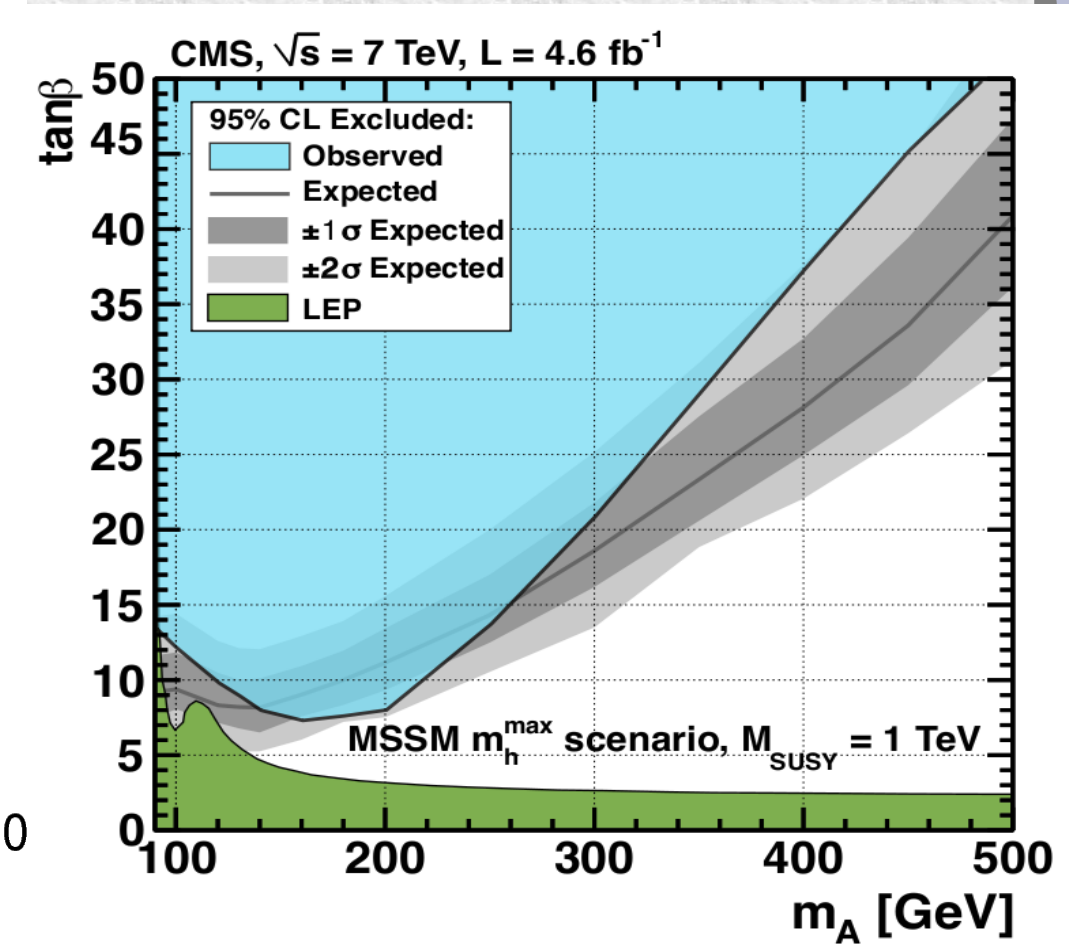
In the light of the 'new boson' a 250GeV 'stage 1' is strongly favoured

Summary

- After 48 years we have found something remarkably like the SM Higgs boson:
  - 'A Higgs boson'; Rolf Heuer, CERN-DG
  - A new form of stuff, not matter or force...
- We need to establish what we have and what clues it has about the next level of understanding
  - We will know more by Christmas for sure
- The detectors ATLAS+CMS perform superbly
- In 2012 LHC is working remarkably well
  - We will have twice the discovery data soon
  - By 2021, 300fb^{-1} at 14TeV will allow precise studies
- Many possible options for closer studies

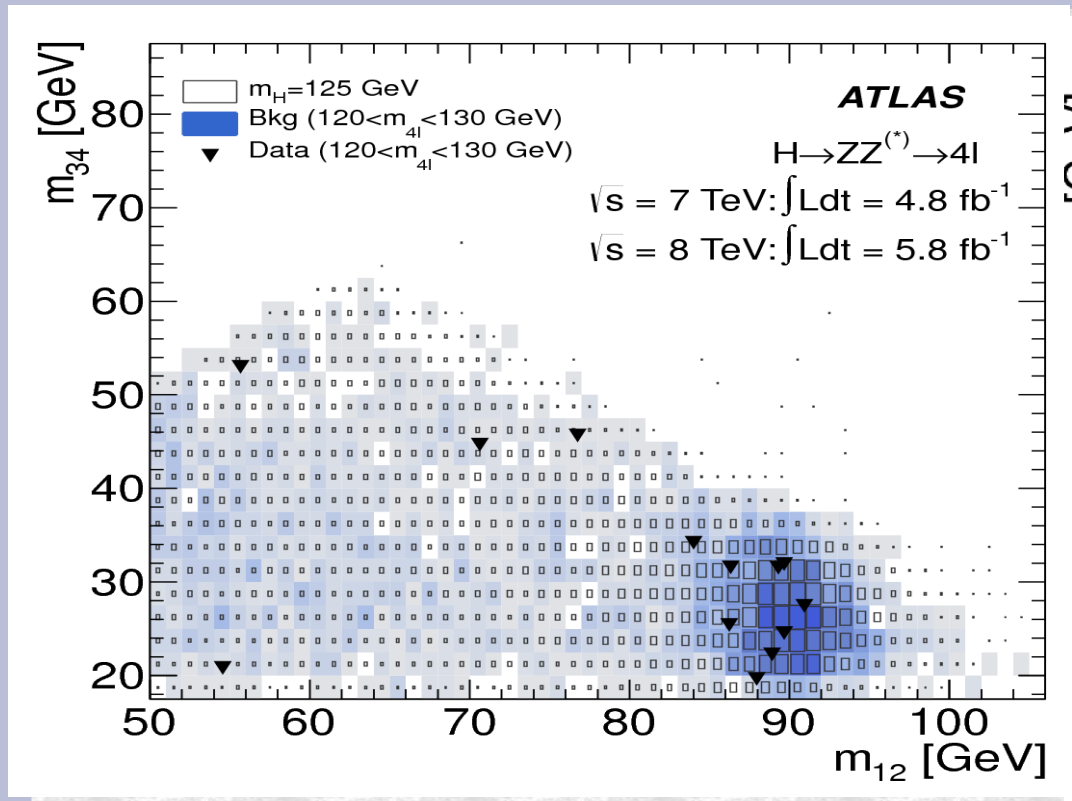
MSSM Higgs

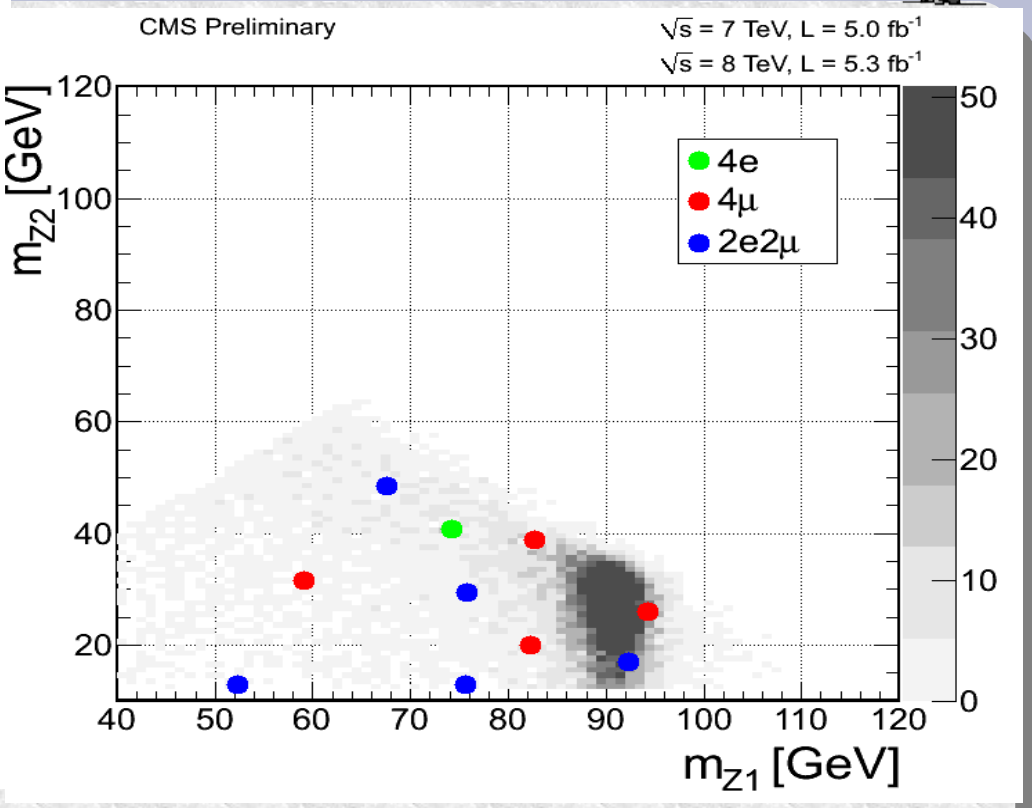




- CMS huge exclusion – close to LEP limit (which?)
- ATLAS only have 1fb^{-1} result public

Candidate masses: m_1 v m_2





- CMS plot showed few events with m_{Z1} >90 GeV
  - Had sparked theoretical papers!
- ATLAS version is reassuring

SUSY Higgs

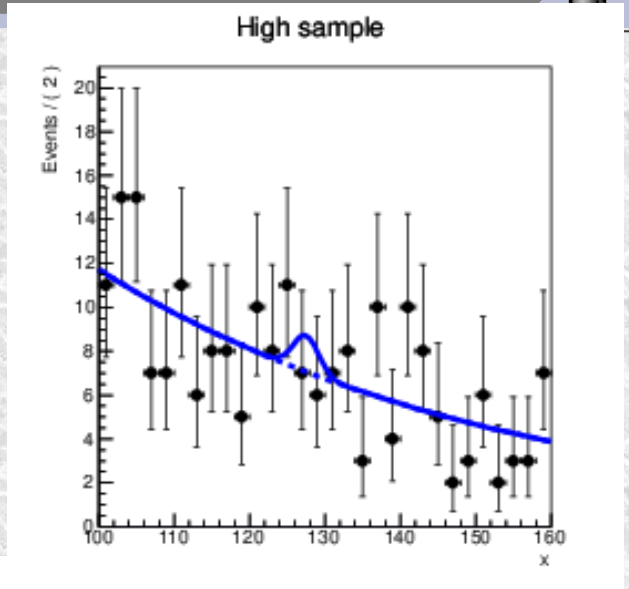
- The new boson might be one of the 5 Higgses of SUSY
  - h,H,A, H^+,H^-
- The most likely in the lightest, h
  - This is bound to be below ~130GeV in most scenarios
  - The others could then be almost any higher mass
    - May or may not ever turn up at LHC
  - The relatively large mass, 126GeV suggests:
    - High SUSY mass scale
    - And/or light stop – near top mass
  - Interestingly, light stau/stop could increase $h \rightarrow \gamma\gamma$ rate
- Alternatively it could be the heaviest, H
  - That would mean the others are all around 100GeV
  - If so H^+/H^- at least should be found this year

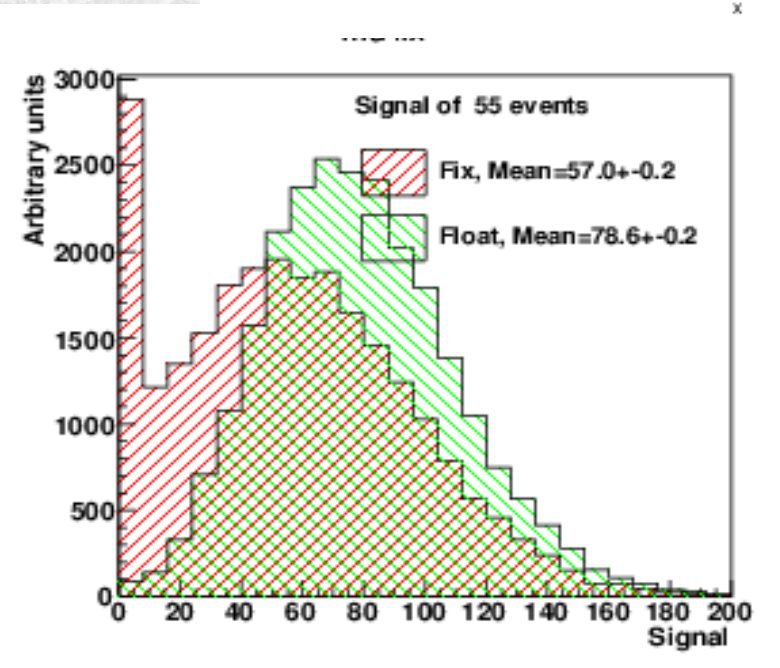
SLHC as Higgs factory

- Increasing luminosity, factor 10, to $10^{35}cm^{-2}s^{-1}$
  - New proton linac & focus elements needed
  - Pileup increases by similar factor, 300 events/BX?
  - New trackers, calorimetry readout, TDAQ needed to cope
- Beams are rapidly 'burnt-off'
  - It may be helpful to limit luminosity early on
  - Extends beam lifetime, limits pileup
- Going from $300fb^{-1}$ to $3000fb^{-1}$ at 14 TeV
  - $H \rightarrow ZZ$ go from 300 to 3000
  - Improved measurements clear in ZZ, γγ,
    - $H \rightarrow \mu\mu$ and Zγ can be measured
  - WW, bb, ττ will be improved – but systematics hard to know
  - Self-coupling in $HH \rightarrow bb\gamma\gamma$ and bbττ looks just possible
    - Again, estimates of systematics difficult

Bias in discovery rates

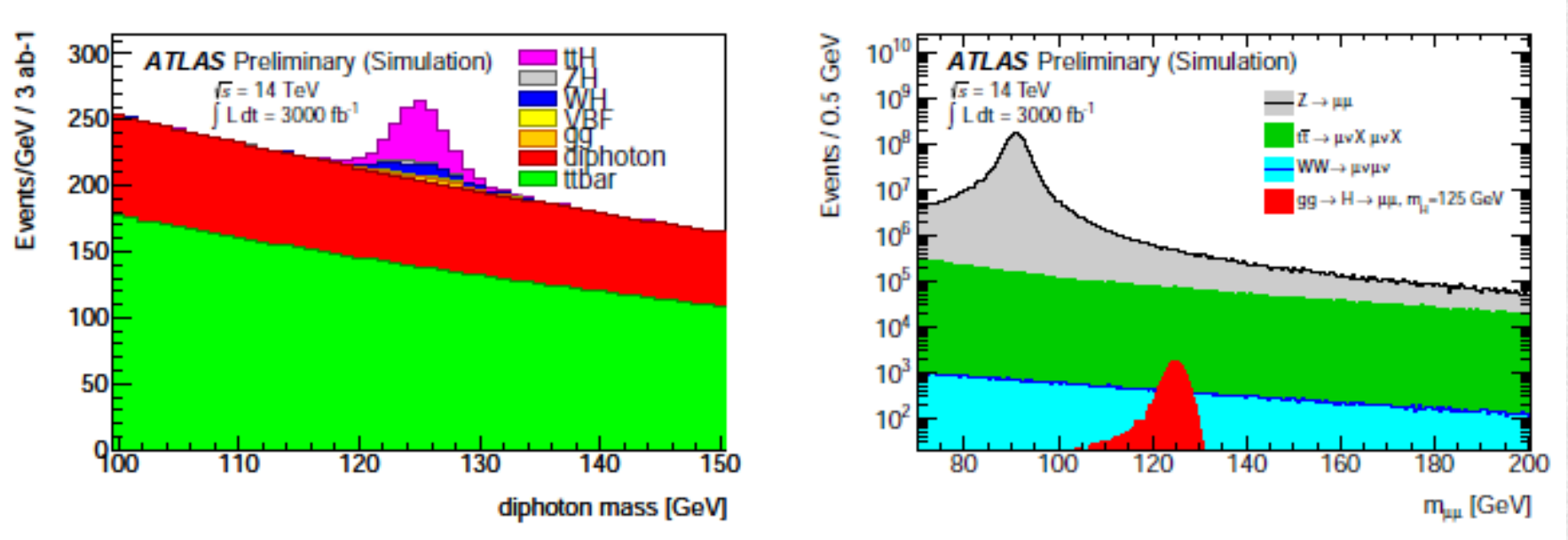
- Mock up experiment like $H \rightarrow \gamma\gamma$
- With a signal present
- Measure the fitted rate
  - At the correct mass
  - At any mass
- If you fit at the true mass you get the correct rate (on average)
- But if you report results at the biggest rate observed you can add a bias
  - Was 40% for LHC in 2011
  - Now down to 8% only
  - Not allowed for ATLAS/CMS





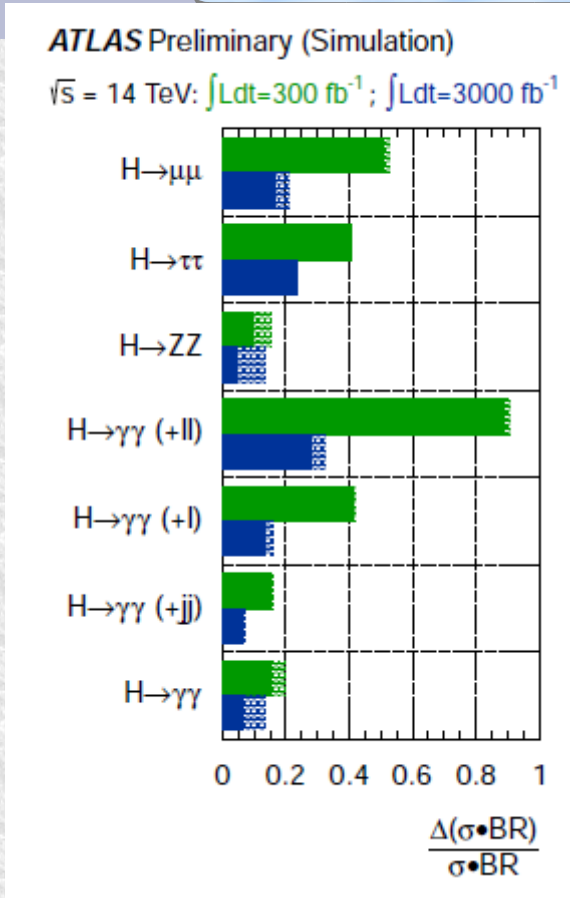
SLHC and ATLAS

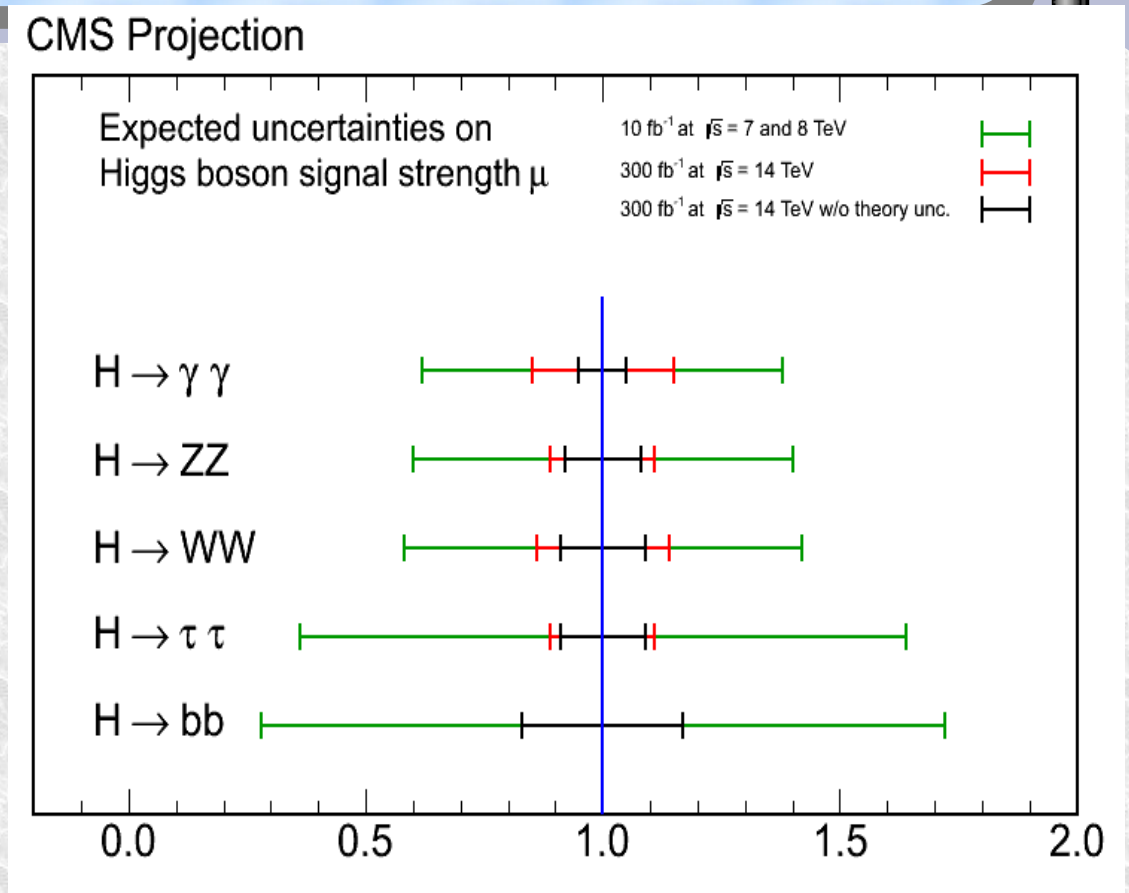
- LHC runs to 2022
- 300fb^{-1} at 14TeV expected
  - SLHC is proposed thereafter - 3000fb^{-1}
- ttH,H→γγ and H→μμ are two interesting studies



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

Krakow: signal rate errors





- Interesting to compare ATLAS and CMS expectations
  - Pretty close for ZZ and γγ
  - Factor 3 apart for ττ at 300fb^{-1}
- We need to understand this!

SLHC as Higgs factory

- Increasing luminosity, factor 10, to $10^{35}cm^{-2}s^{-1}$
  - New proton linac & focus elements needed
  - Pileup increases by similar factor, 300 events/BX?
  - New trackers, calorimetry readout, TDAQ needed to cope
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  - Improved measurements clear in ZZ, γγ,
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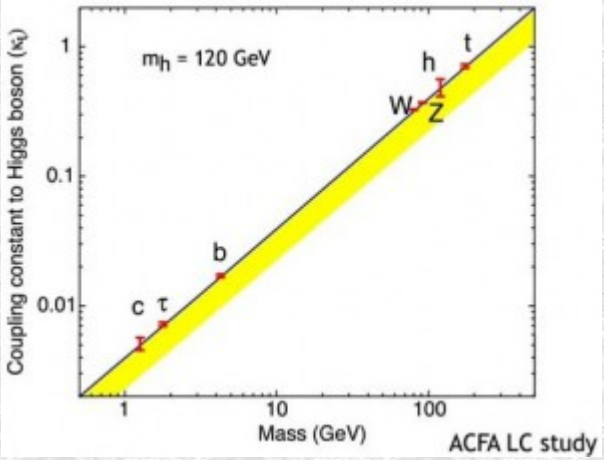
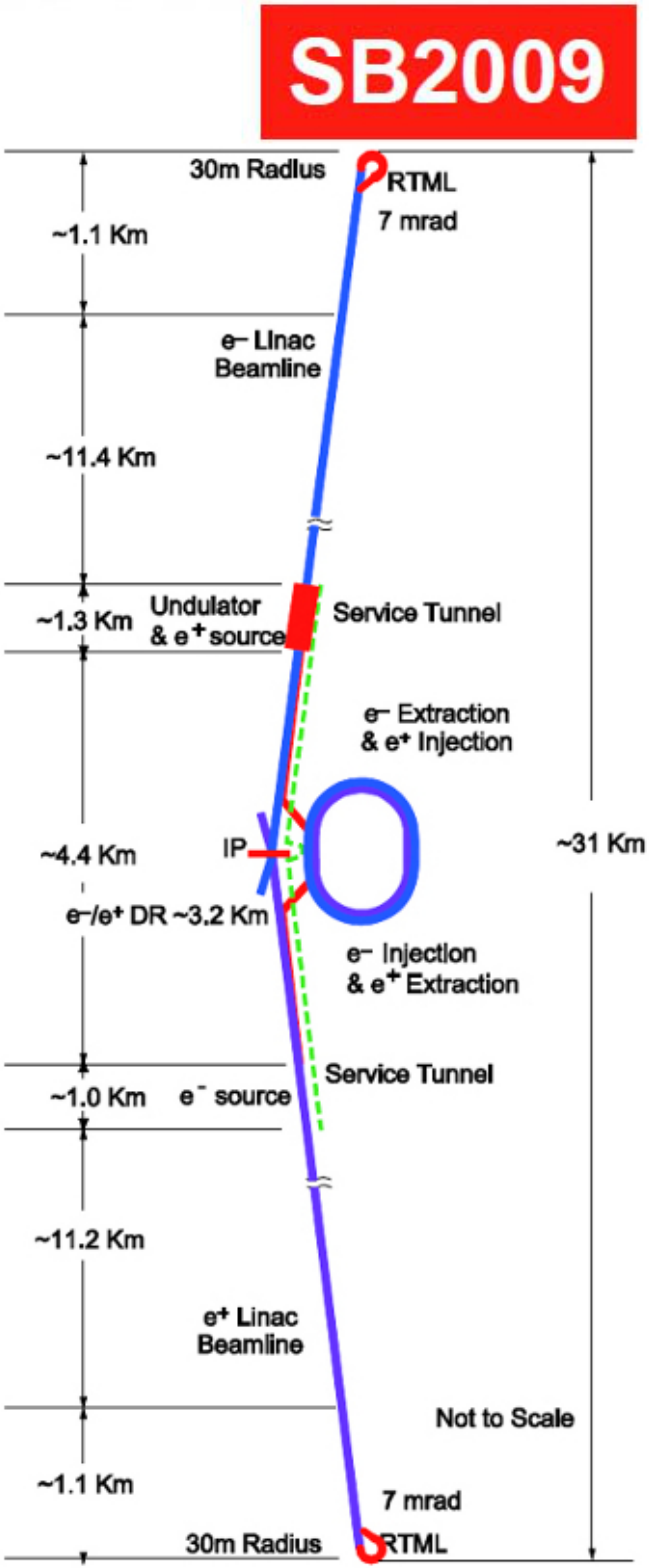
  - WW, bb, ττ will be improved – but systematics hard to know
  - Self-coupling in $HH \rightarrow bb\gamma\gamma$ and bbττ looks just possible
    - Again, estimates of systematics difficult

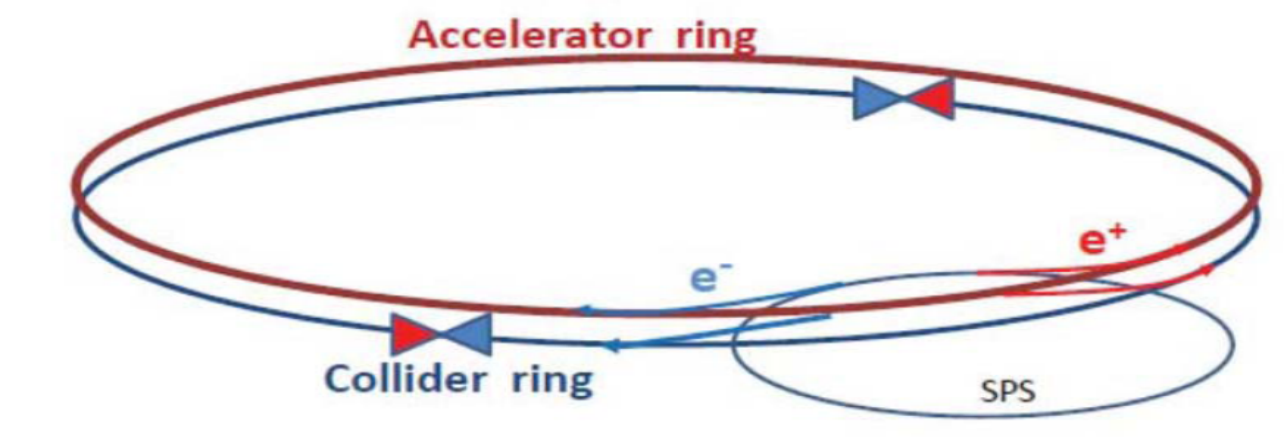
ILC

- Well known proposal for high-energy linear ee collider.
  - Much cleaner collisions than LHC
  - But cost/GeV of RF cavities in high
  - Power bill tends to be large too
- Can make Higgs bosons
  - 10,000 ZH/year
- Sensitive to all, including invisible
  - LHC can never be sure of total rate
- Accurate measure:
  - c, τ, b, W, Z, t
  - hh coupling too
    - Just
- Sensitive to light SUSY





LEP-3?



- LEP3 is an e^+e^- storage ring, maybe in the LHC tunnel
  - $\sqrt{s}$=240GeV
  - 4 bunch mode gives $10^{34}cm^2s^{-1}$.
  - Dual-ring allows 'top-up mode' to maintain average luminosity.
  - $100fb^{-1}$ per year
  - 20,000 ZH events per year/experiment
  - 50MW/beam synchrotron loss
- Physics programme:
  - 1 'year' at 91GeV – 10^{11} Z^0
  - 1 'year' at 160 GeV – sub -MeV statistical precision on m_W
  - 5 'years' at 240 GeV – 100,000 HZ/experiment

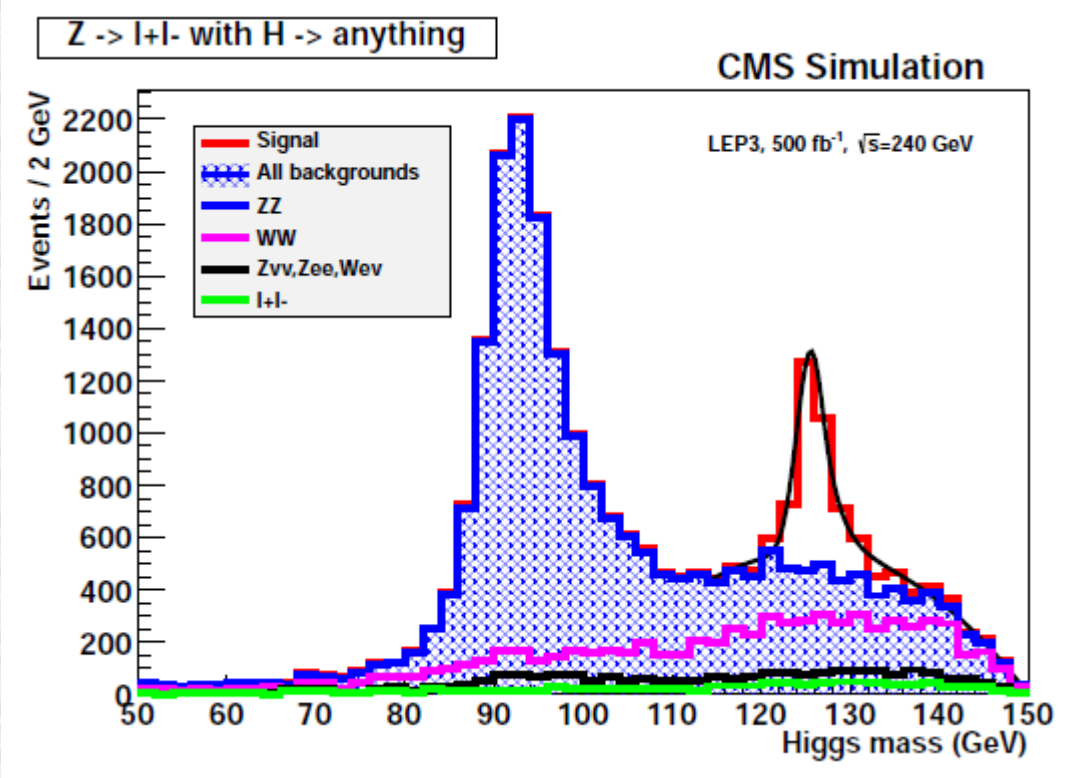
Higgs studies potential

	ILC	LEP3 (2)	LEP3 (4)	LHC
σ_{HZ}	3%	2.7%	1.9%	–
$\sigma_{HZ} \times BR(H \to b\bar{b})$	1%	1.2%	0.8%	–
$\sigma_{HZ} \times BR(H \to \tau^+\tau^-)$	6%	3.1%	2.2%	–
$\sigma_{HZ} \times BR(H \to \text{invisible})$	?	1%	0.7%	–
g_{HZZ}	1.5%	1.3%	1%	13%
g_{Hbb}	1.6%	1.5%	1%	21%
$g_{H\tau\tau}$	3%	2.0%	1.5%	13%
g_{Hcc}	4%	?	?	?
g_{HWW}	4%	?	?	11%

- The electron machine beats LHC for Higgs coupling
  - But ttH is not doable at LEP-3
  - Higgs self-coupling is tough anywhere – but impossible LEP-3

LEP 3 schedule

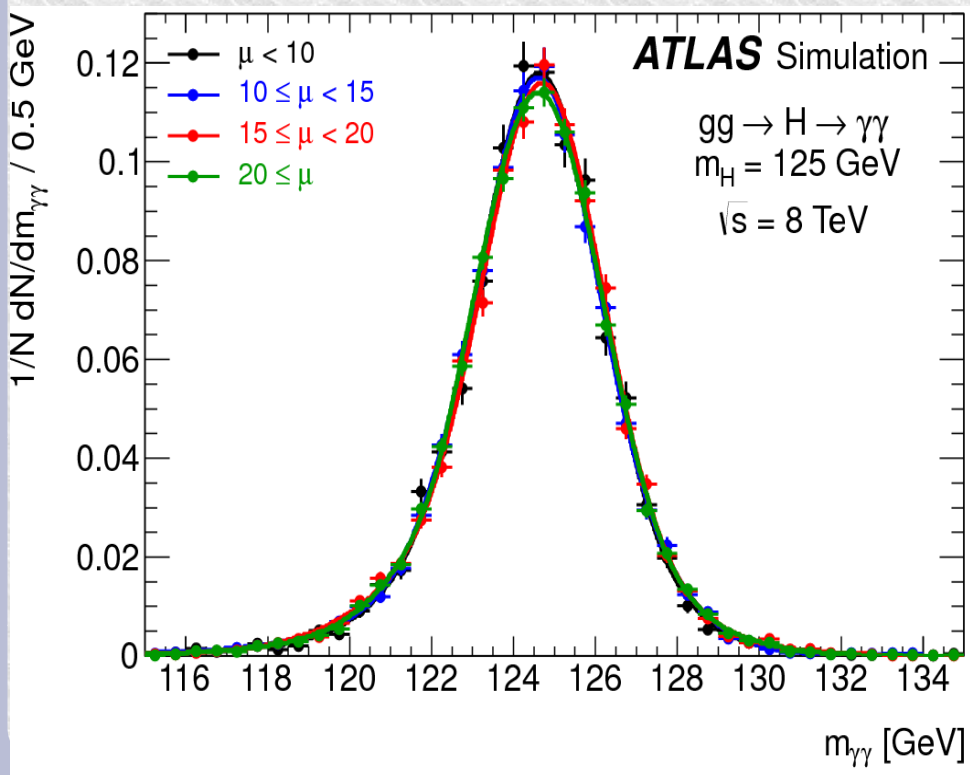
- The ideal schedule from LEP-3 side is to run in 2022
  - LHC has delivered 300fb^{-1}
  - ATLAS and CMS might be available
  - CMS simulations indicate it can do the physics:
  - $Z \rightarrow ll$, $H \rightarrow X$ shown

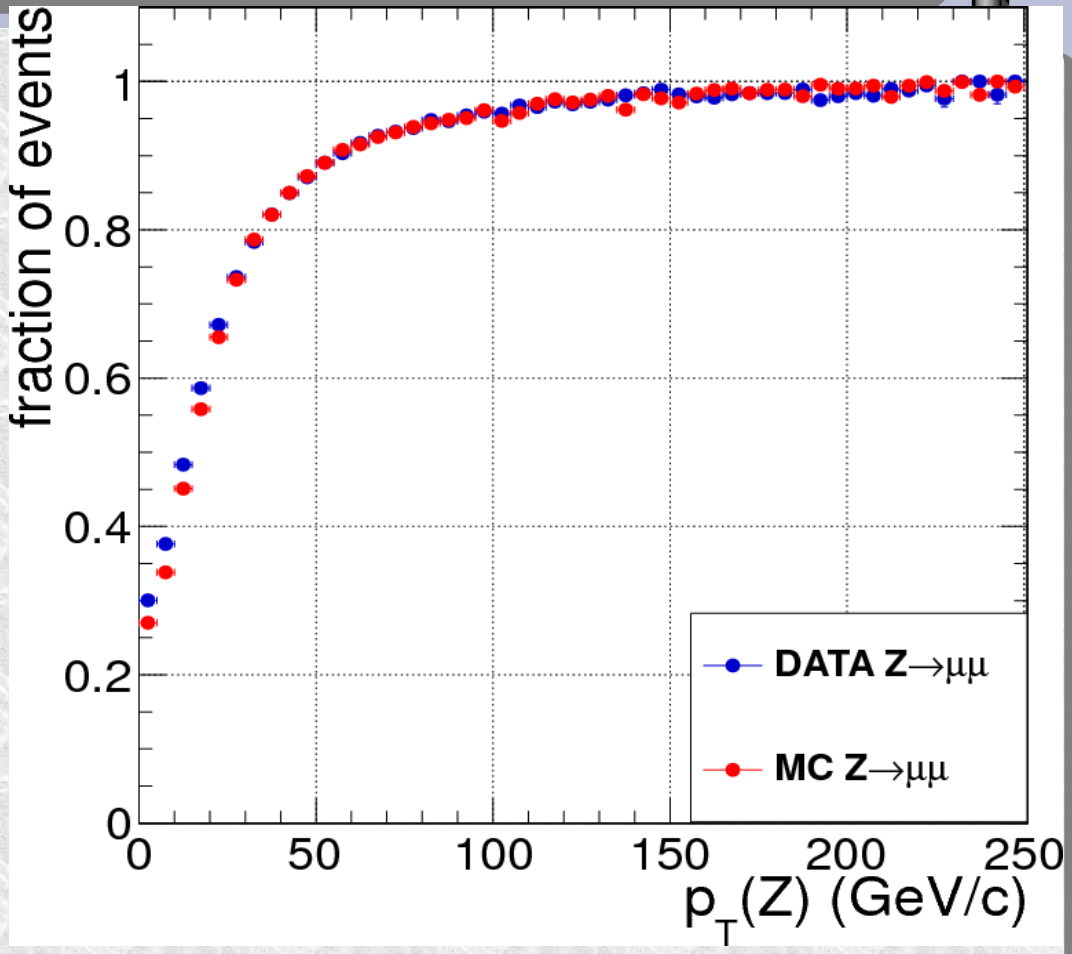


- The problem is: SLHC would be cancelled!
- This is an interesting choice
- One which I believe deserves to be studied
- I THINK the LHC case would win. But we should look

Calculating H→γγ mass

- Need H decay position
  - CMS compare tracking vertices; match p_T etc
  - ATLAS use pointing from calorimetry – vertex not needed

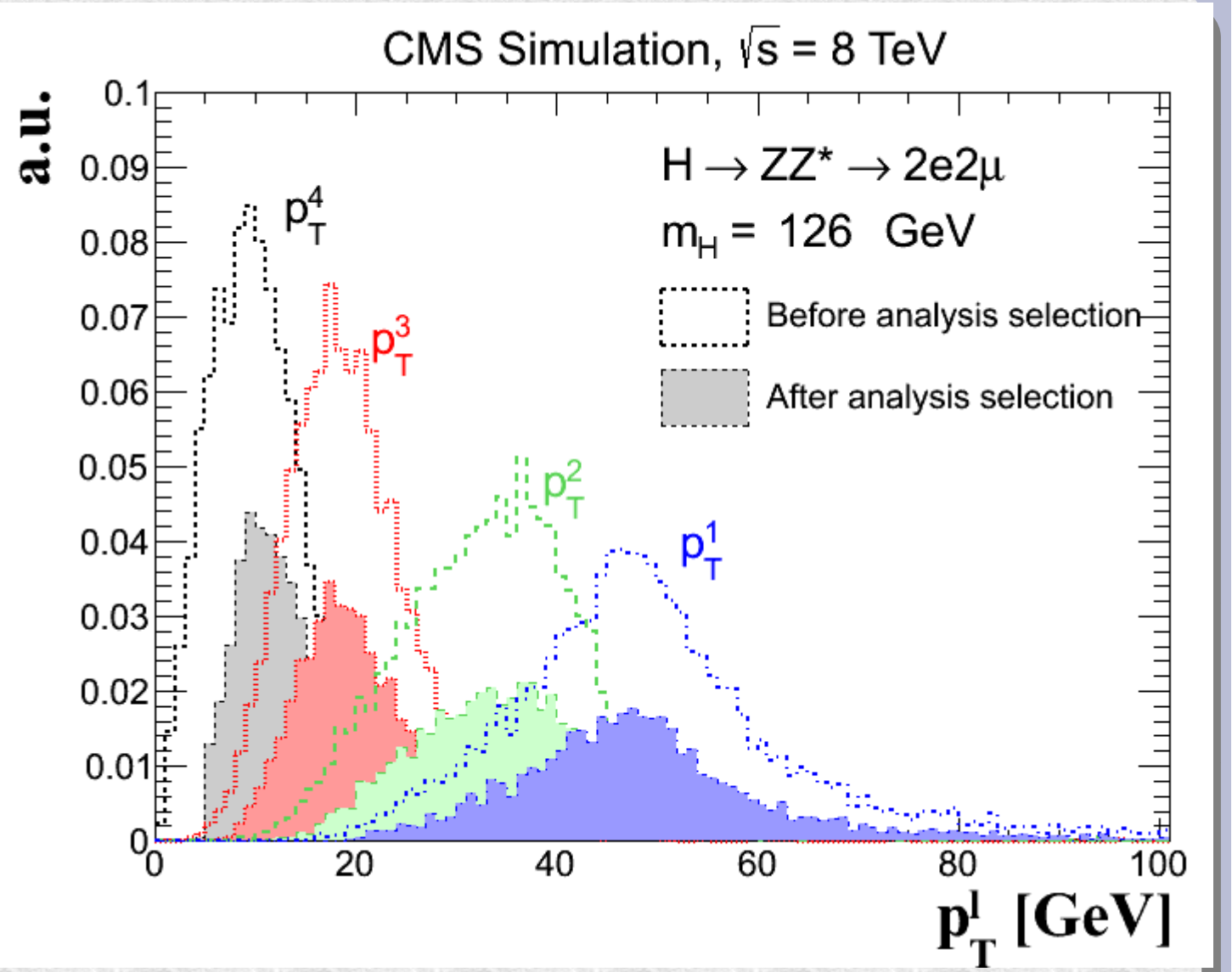




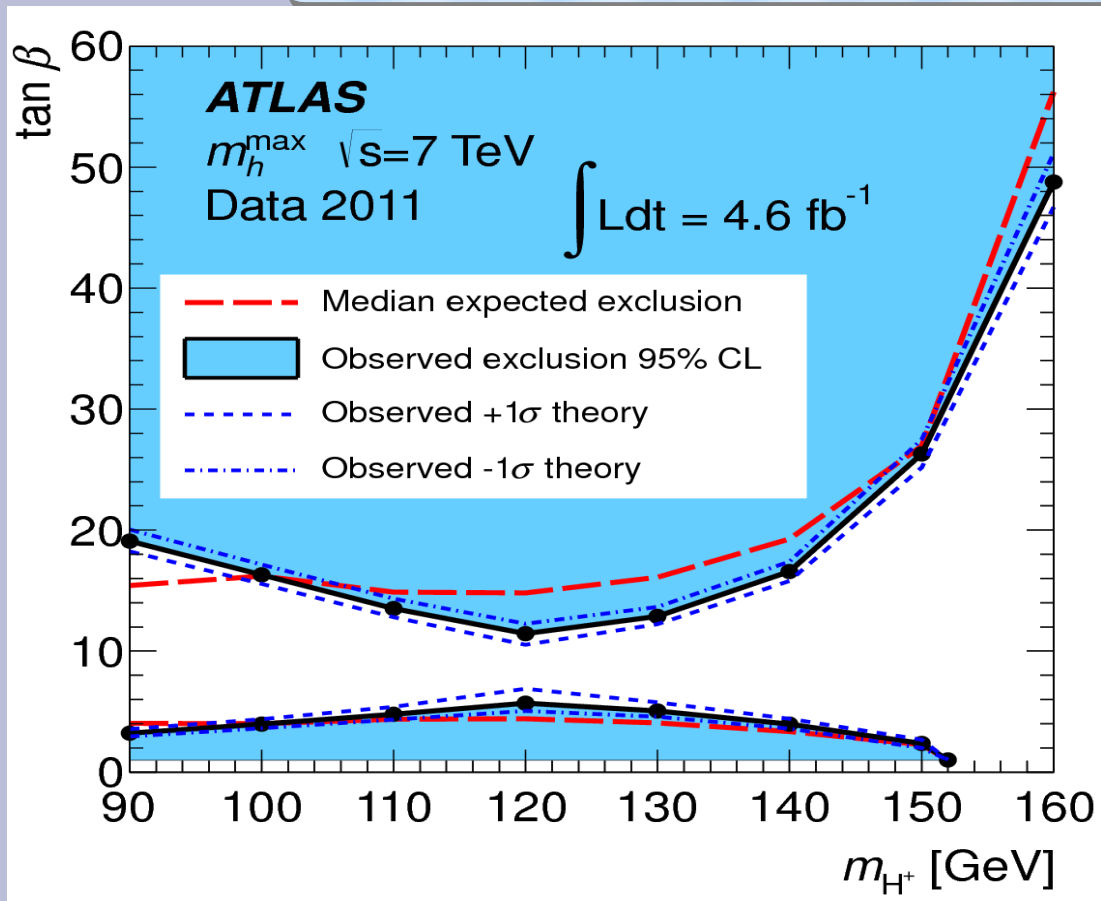
- ATLAS somewhat more pileup robust

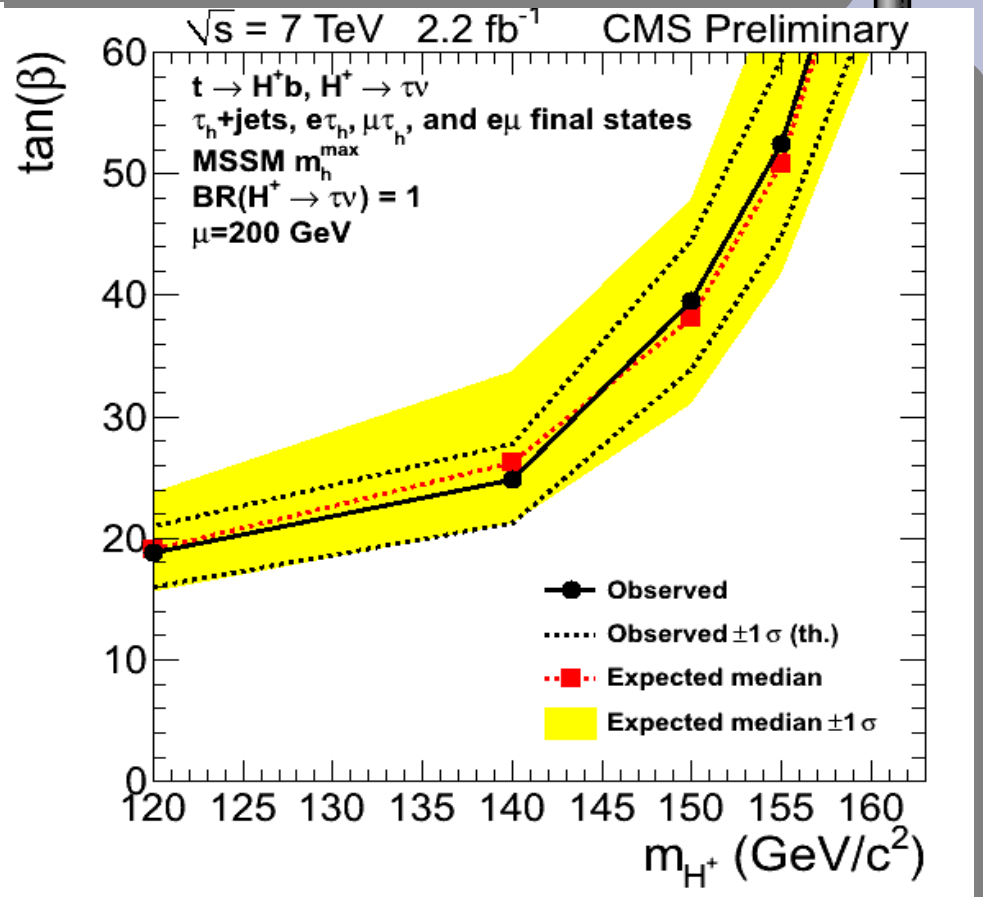
Lepton p_T distribution

- $m_H << 2m_Z$
- The decay involves one Z being far from 'mass-shell'
- The softest lepton is typically below 10GeV p_T
- Need to push lepton momentum range



Charged Higgs at LHC





- Space for charged Higgs below m_t getting squeezed
  - Next round will aim for m_t exclusion tanβ independent
- m_{H+}>m_t still largely unexplored