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Standard Model @ Hadron Colliders
IV. Higgs Boson

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Bergische Universität Wuppertal

Combining all searches

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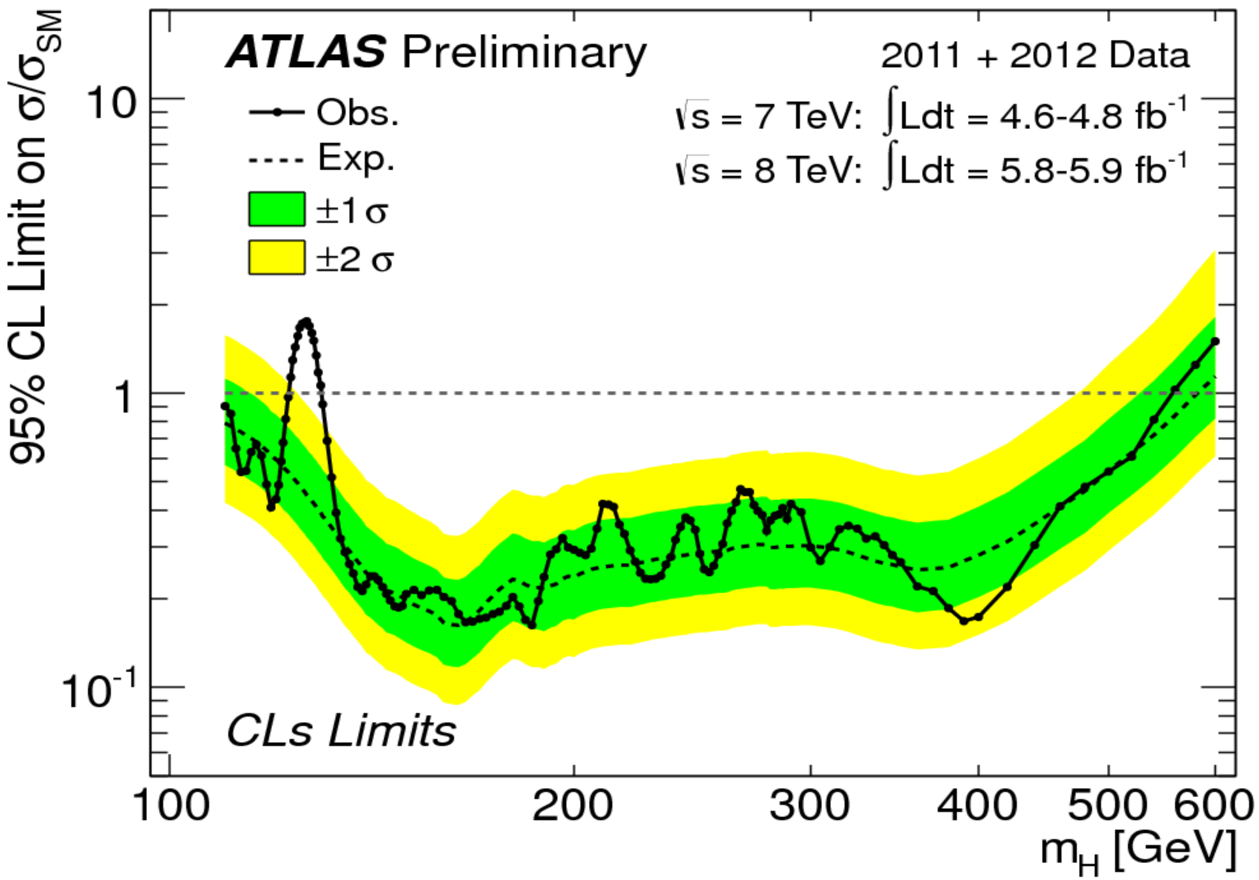

High mass range:

- $ZZ \rightarrow l^+l^-l^+l^-$
- $ZZ \rightarrow l^+l^-\nu\nu$
- $ZZ \rightarrow l^+l^-qq$
- $WW \rightarrow l^+\nu l^-\nu$

Higgs EXCLUDED $2 \cdot M_W < M_H < 558$ GeV (CMS: 600GeV)

High mass Standard Model Higgs boson (almost) excluded

The final assault on Standard Model

Higgs searches at Hadron Colliders

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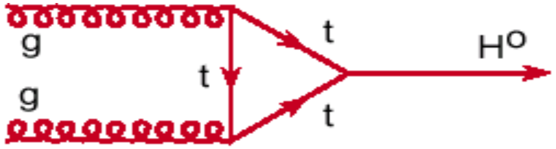
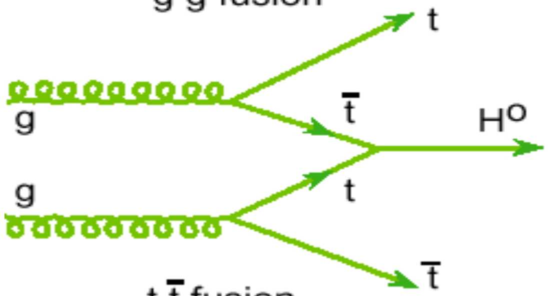
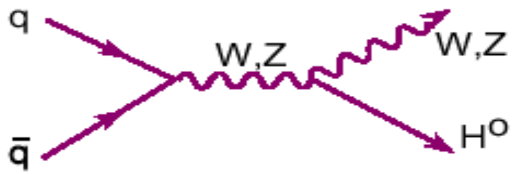


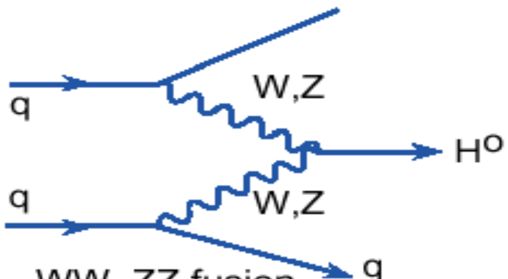
g g fusion



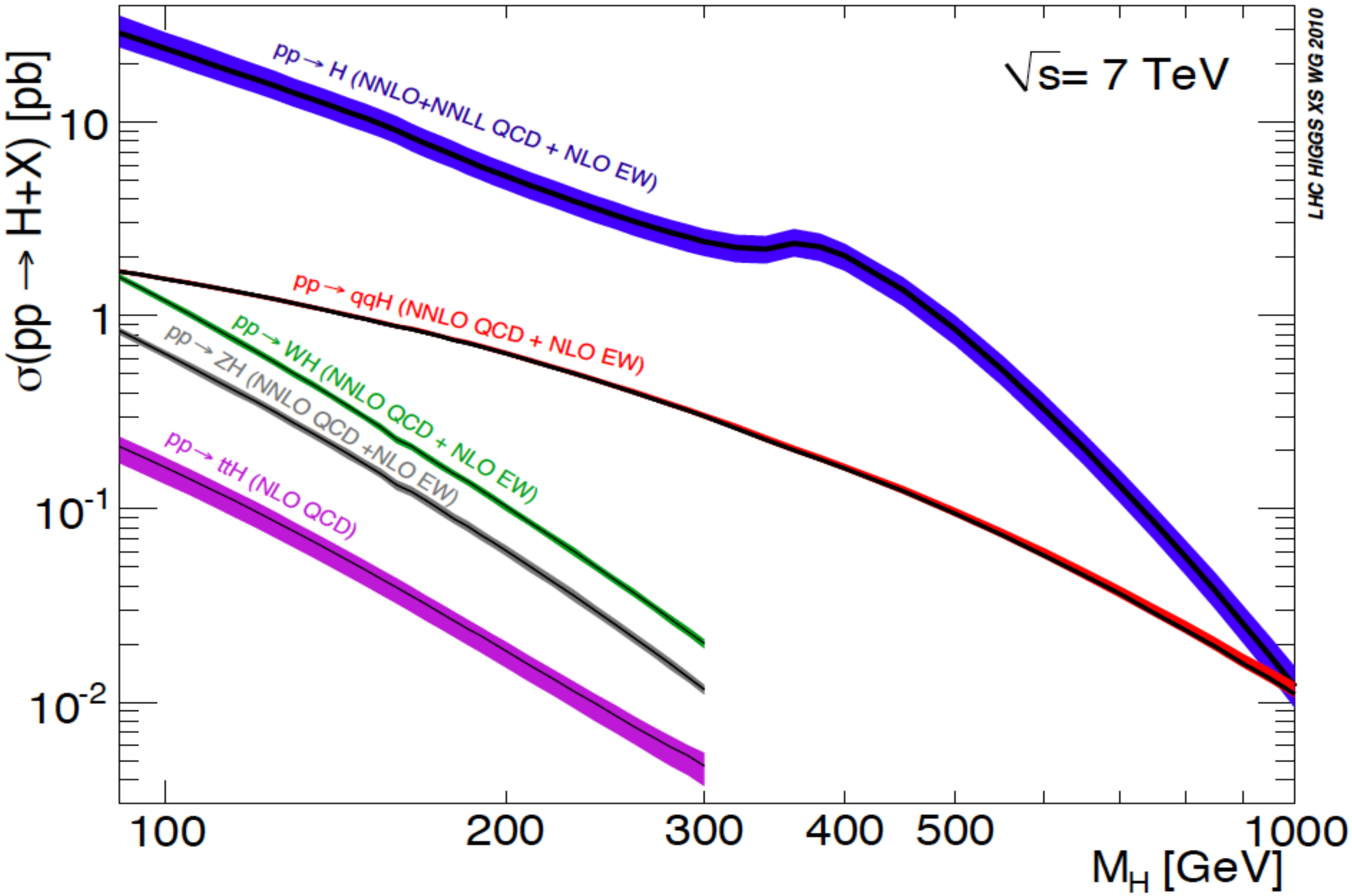
t t̄ fusion



W, Z bremsstrahlung



WW, ZZ fusion



Branching ratio: 100 – 200 GeV

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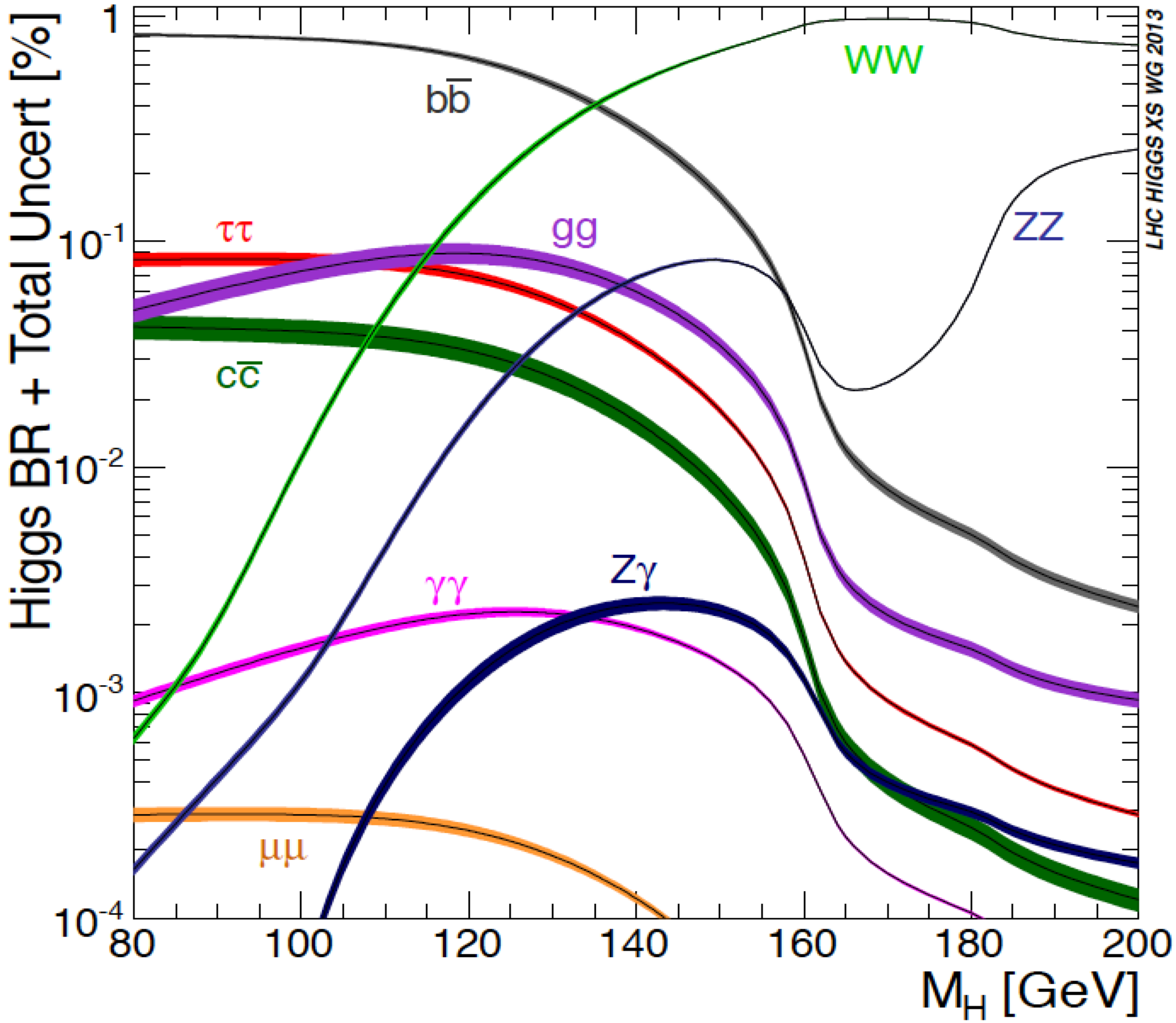

How to find the Higgs @ 125 GeV?

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→ How many Higgs bosons (should be) produced?

cross section	≈ 20 pb
collected luminosity	≈ 25 fb^{-1}
	→ 500 000 events

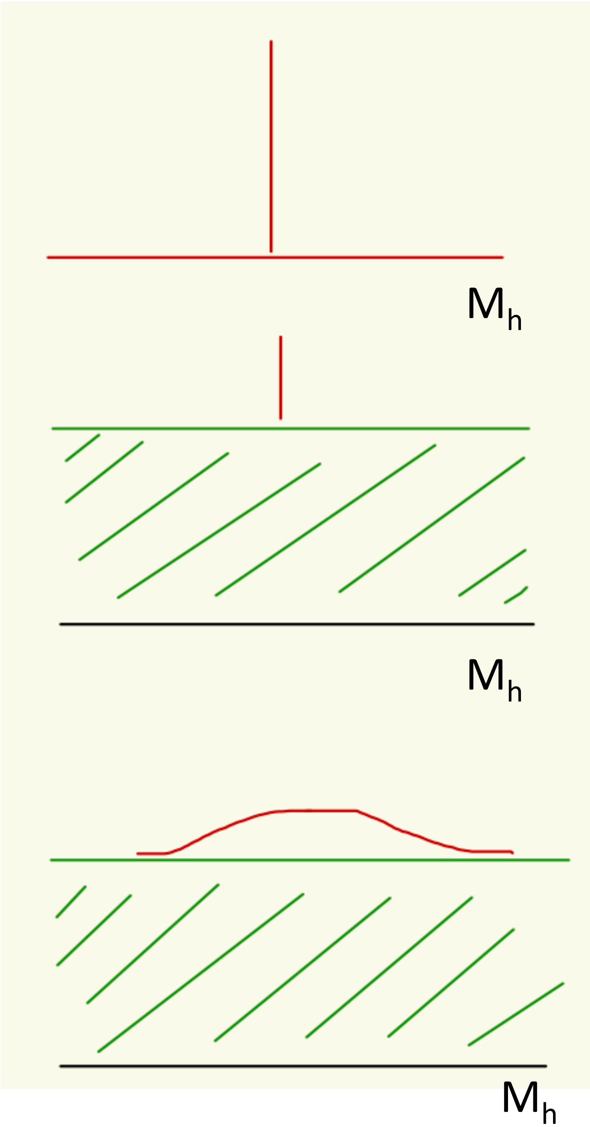
→ Decays:

H→ bb	:	285 000
H→ WW	:	105 000
H→ ZZ	:	13 000
H→γγ	:	750

Sheer numbers: seems an easy task ……

BUT …..

How the Higgs would show up



The ideal world: a narrow excess at M_h
…. nothing else
➔ A handful (one) of events sufficient

Closer to reality:
Other processes similar signatur, but smoothly distributed

reality:
Other processes similar signatur, but smoothly distributed +
Exptl resolution broadens signal

How to find the Higgs @ 125 GeV?

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Comments:

- Large background: hard selection cuts
- in addition: how well is background known?
- sometimes use subdominant production channel

channel	selection	reduction	width	background
bb	identify bottom	0.5	15 GeV	huge
WW	electrons, muons	0.05	25 GeV	large
ZZ	electrons, muons	0.001	2.5 GeV	small
$\gamma\gamma$		1	1.7 GeV	large

Clearest signals in ZZ and $\gamma\gamma$ channel expected !

Harvesting the Higgs - some nbs

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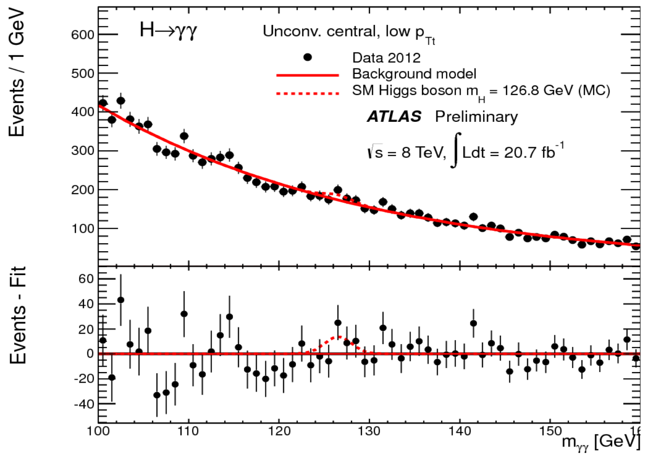
In 2010 -2012:

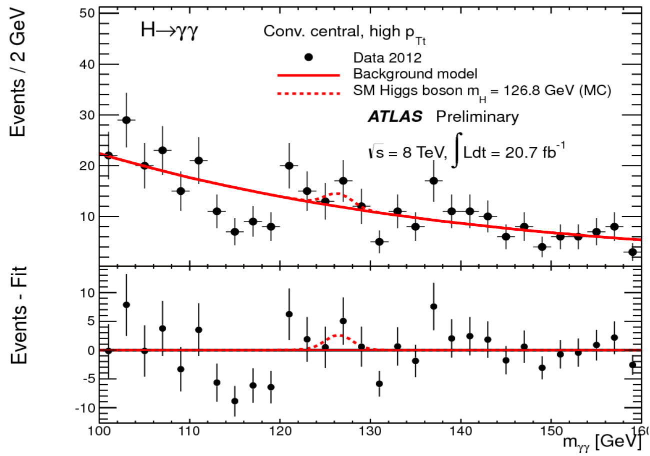
Bunch Xings :	**200 000 000 000 000**
Triggered events:	**6 000 000 000**
Higgs produced:	**500 000**
Higgs selected:	**500**

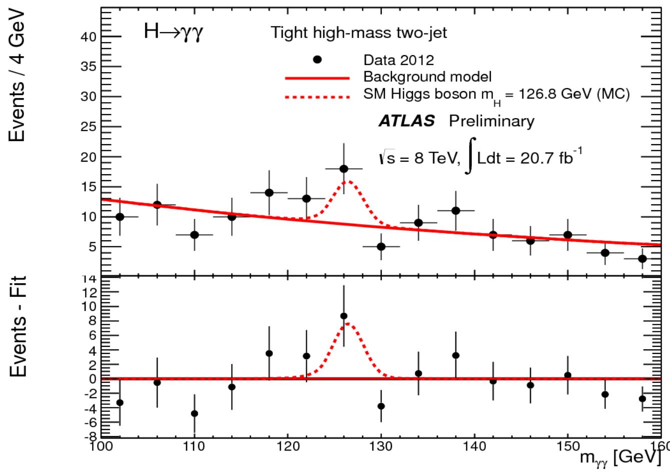
This is equivalent to selecting
5×10^7 Bytes out of 5×10^{20}!!

BIG DATA for science ....
facebook, google, ... nsa, ...

Higgs → γγ different samples



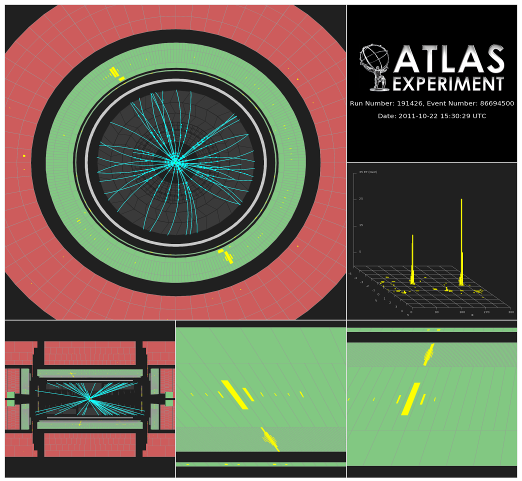


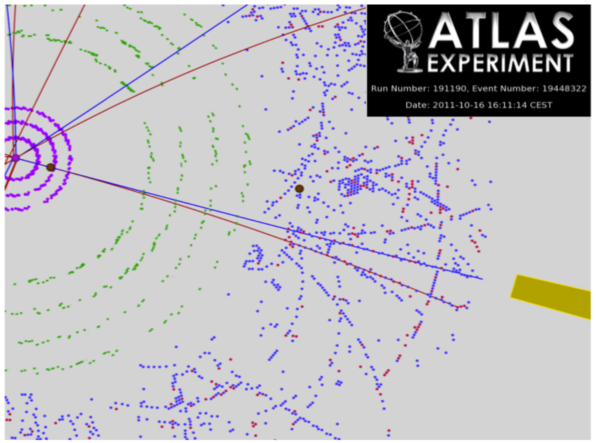


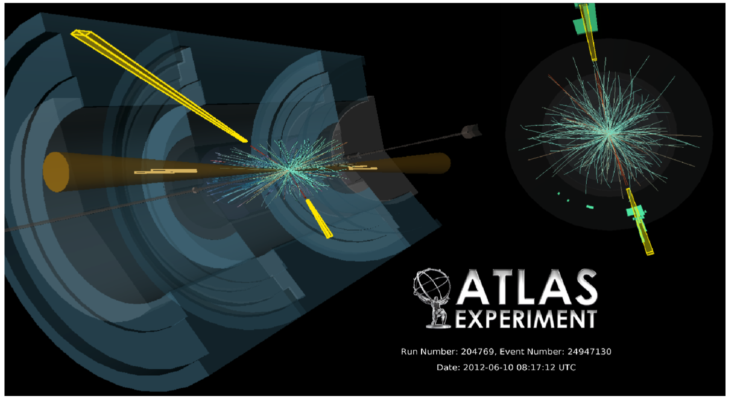
Direct photons
Direction from calo

Conversion γ→e^+e^-
Electrons in track-det.

Vector Boson Fusion
Two jets very fwd







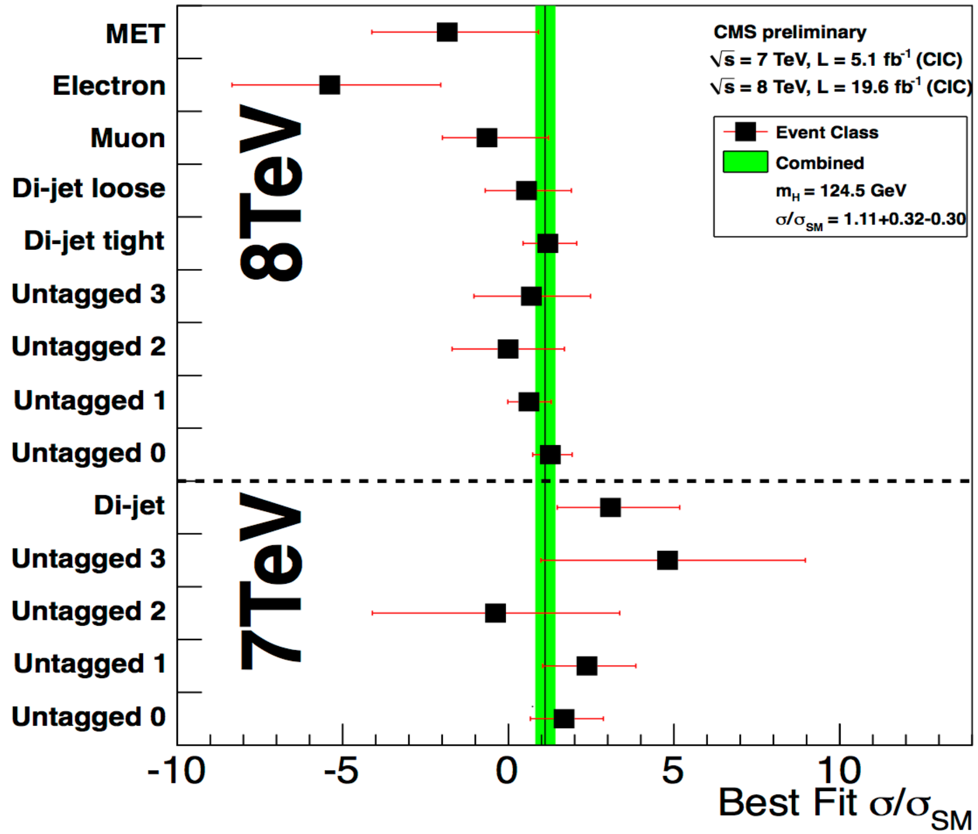
Higgs ➔ γγ combination

Sum over 9/11 individual contributions
converted/non – converted photons, regions of detector .....
Individually not significant

Each has

- **different background,**
- **resolution**

➔ **optimal use of info**
➔ **Channels fluctuate around SM Higgs expect.**



Combining the categories

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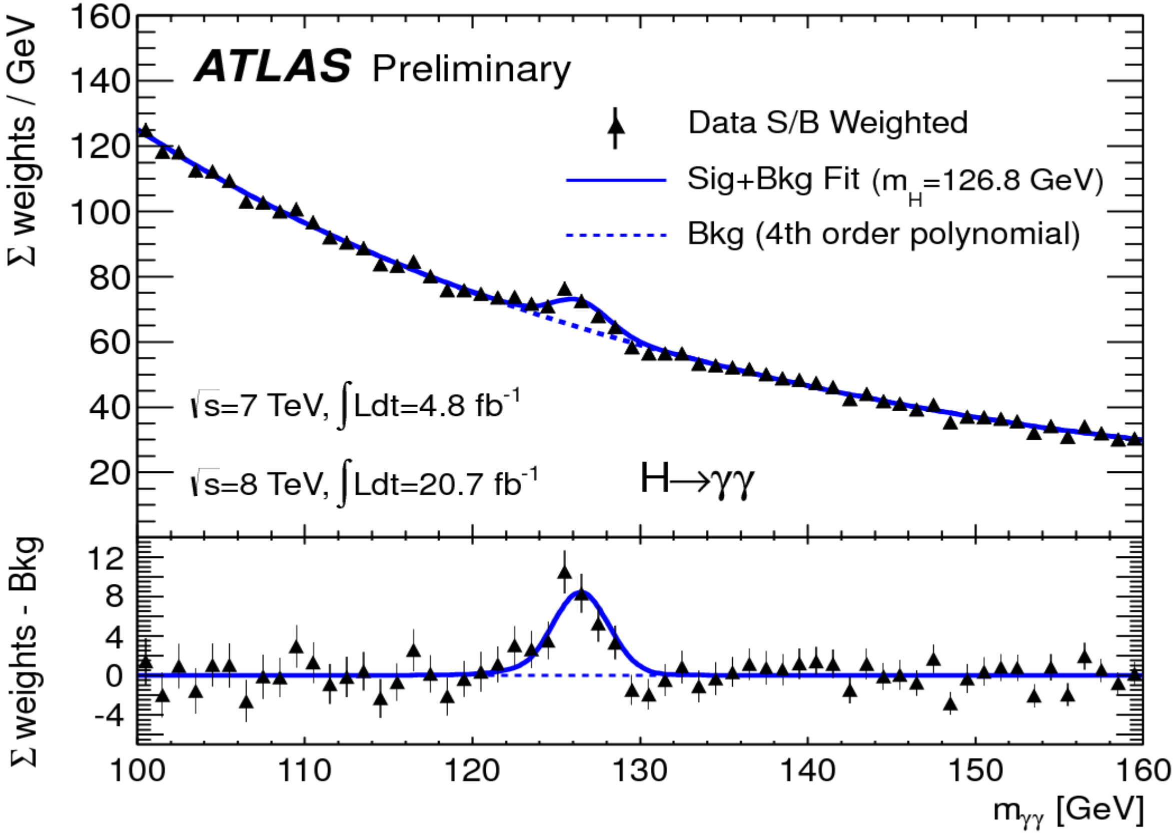

Background smooth ➔ shape ‚fixed'

No smooth background can produce excess around 126 GeV

➔ Observation of a Boson decaying into two photons

Significance of observation

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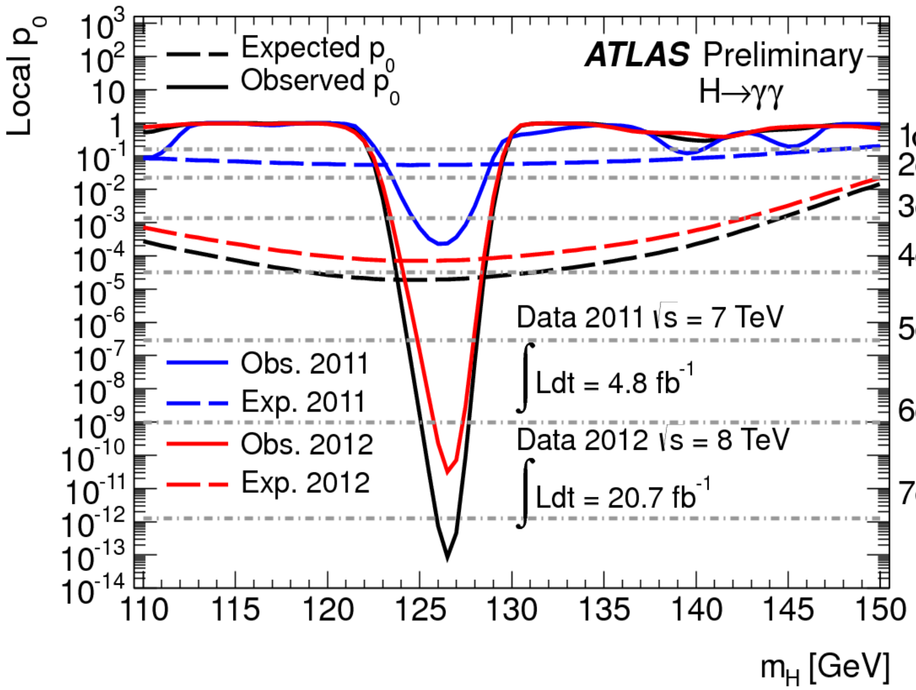
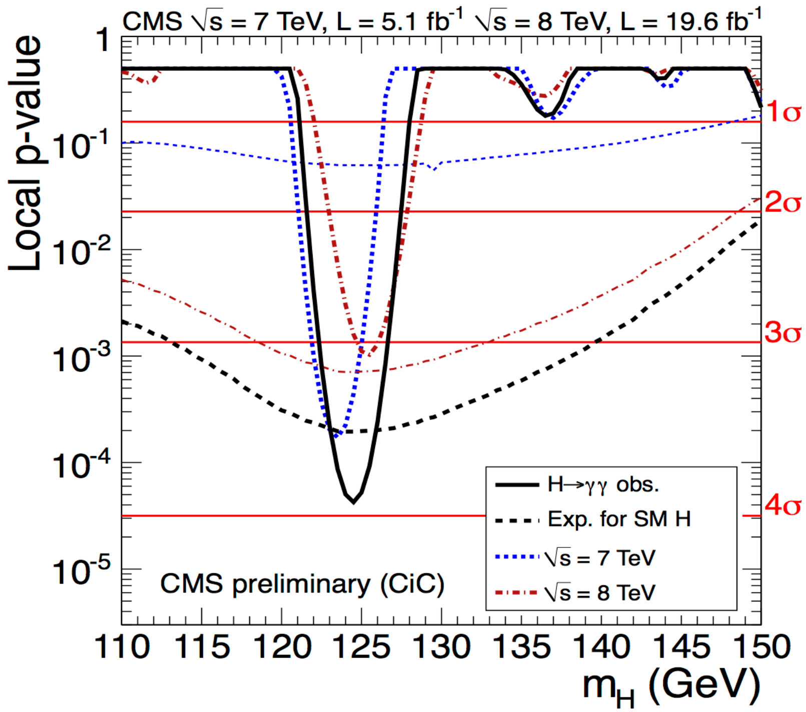
p-value: probability for the background to fluctate to observation



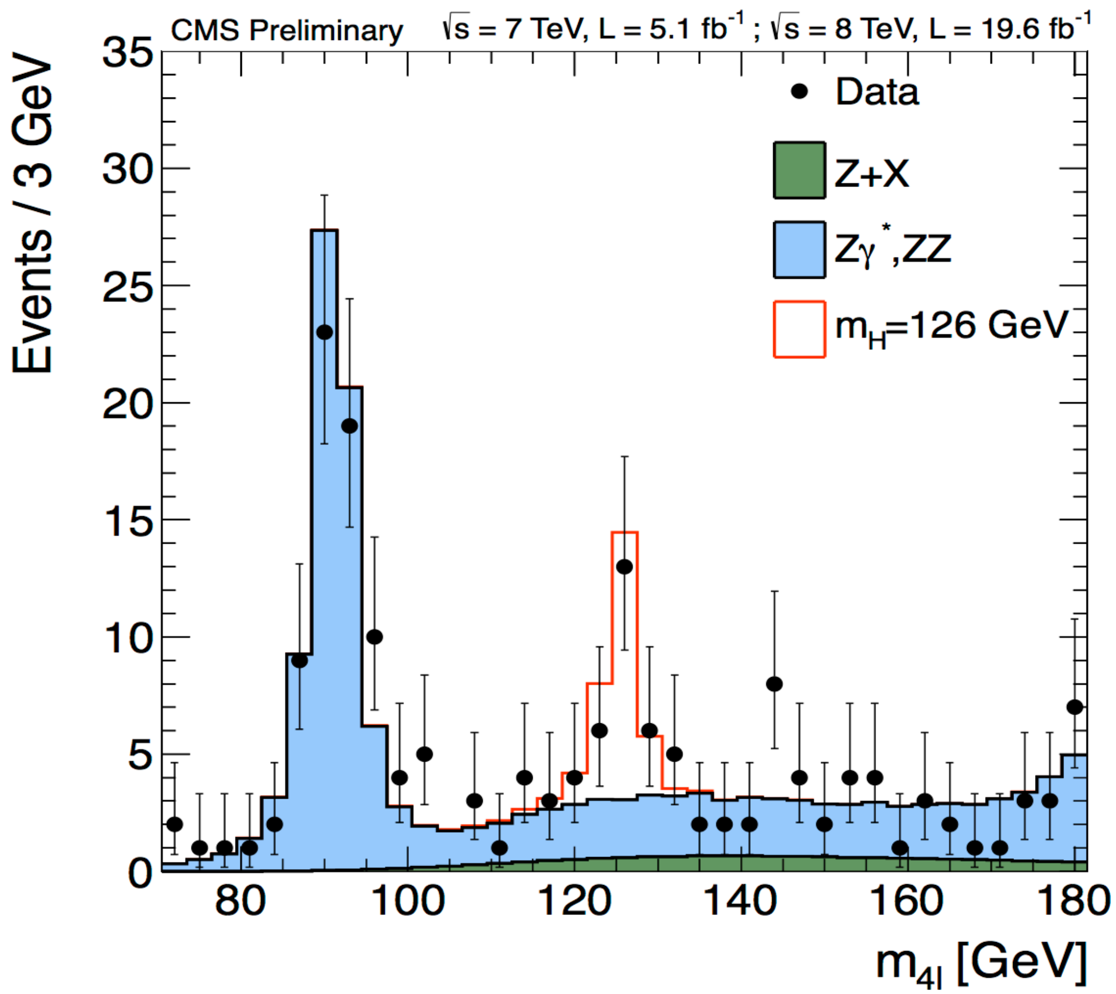


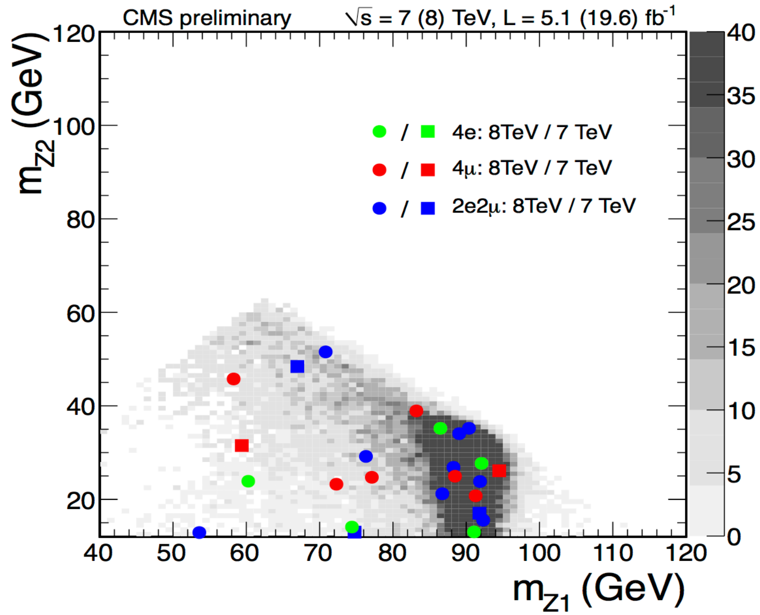
Both experiments observe strong excess at about 125 GeV!

ATLAS: 7 standard deviations excess – more than expected

CMS : 4 standard deviations excess - agrees with expectation

Mass of ZZ→ $(e^+e^-)(\mu^+\mu^-)$

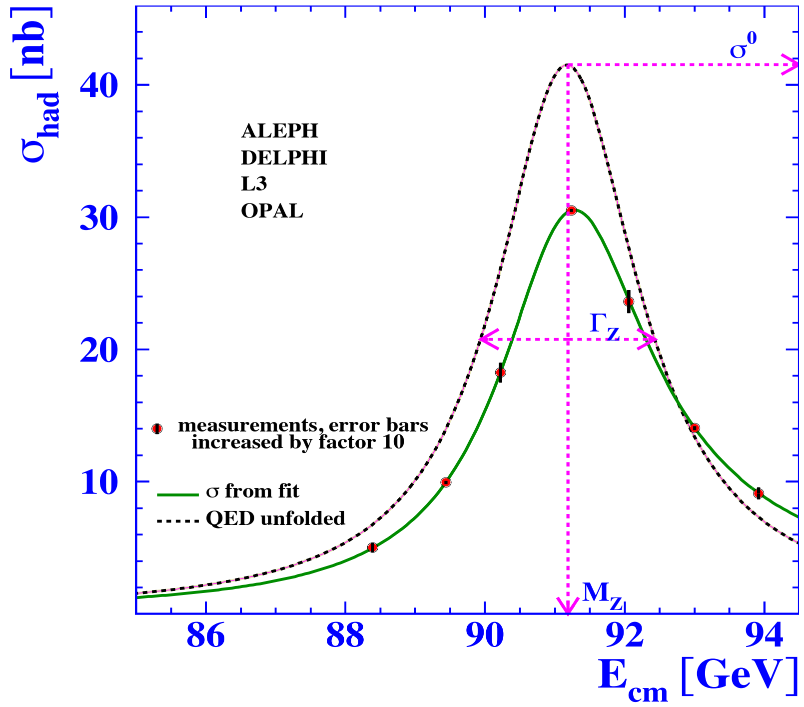




One of Z's: 'on-shell'
Other mass < M_Z

➔ Clear excess at about 125 GeV

H➔ZZ below 2* M_Z



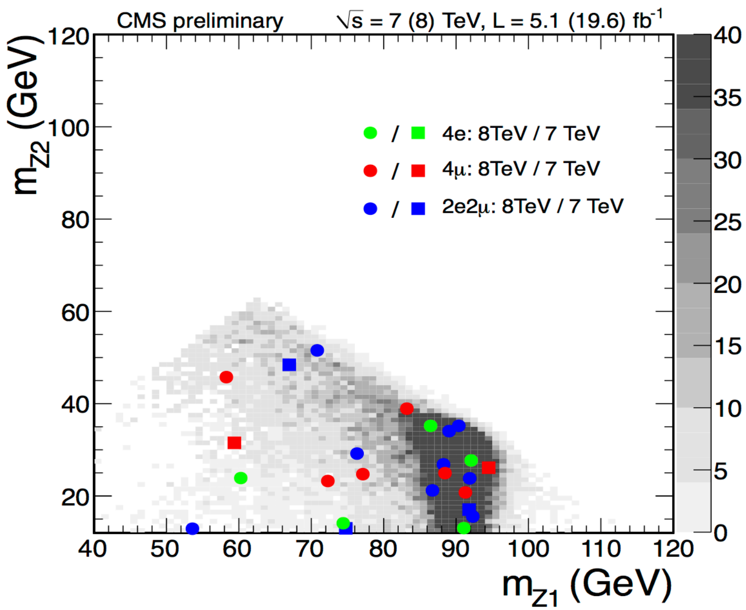
At 126 GeV:

how can a Higgs decay into 2 * M_Z?

Answer:

it does NOT!

Breit – Wigner shape of Z^0 ➔ reduced chance to produce Z at 30 GeV



CMS Simulation: mostly

-one l^+l^- combination M = 91.16 GeV

- second combination 10 – 40 GeV

Significance of observation

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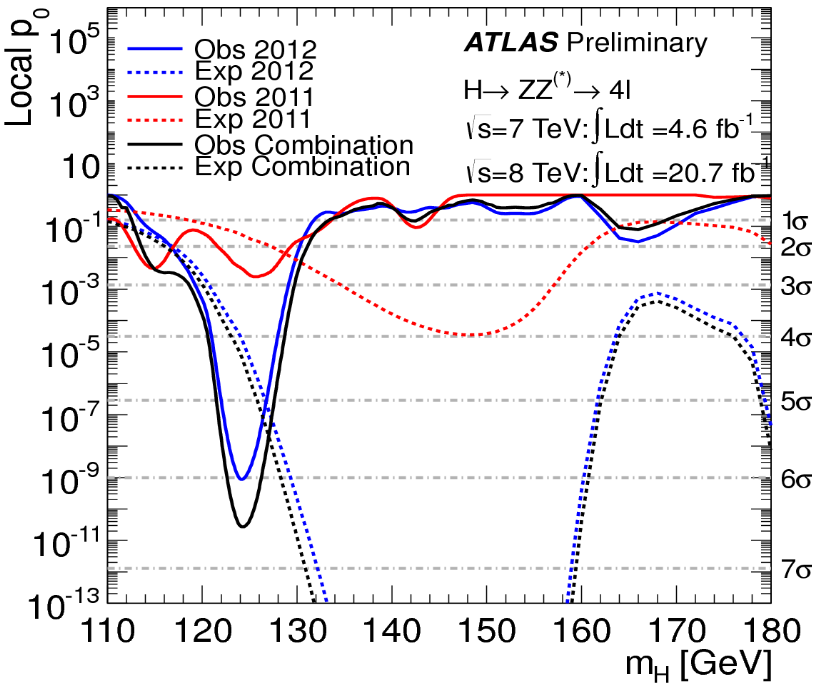
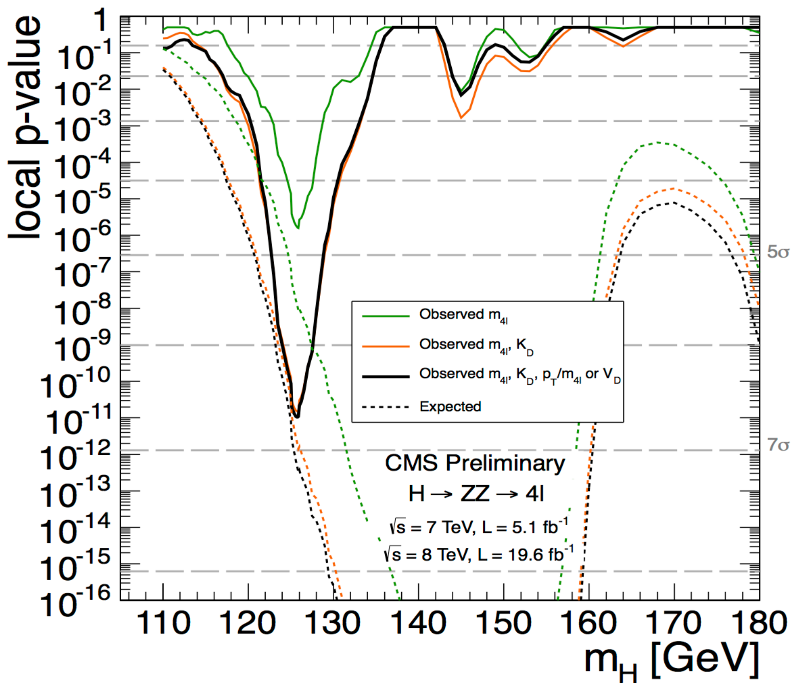
p-value: probability for the background to fluctate to observation





Both experiments observe strong excess at about 125 GeV!

ATLAS: 6.6 standard deviations excess – more than expected

CMS : 6.7 standard deviations excess - agrees with expectation

July 4, 2012: Announcement!

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Historical precedents: better wait and see .....

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Examining “its” properties

Is ‚it‘ the Higgs boson?

Given mass: all Higgs properties predicted

- **Production mechanisms**
- **Branching ratios into bosons and fermions**
- **Width of Higgs boson**
- **Spin and parity**
- **Higgs self coupling (Higgs potential)**

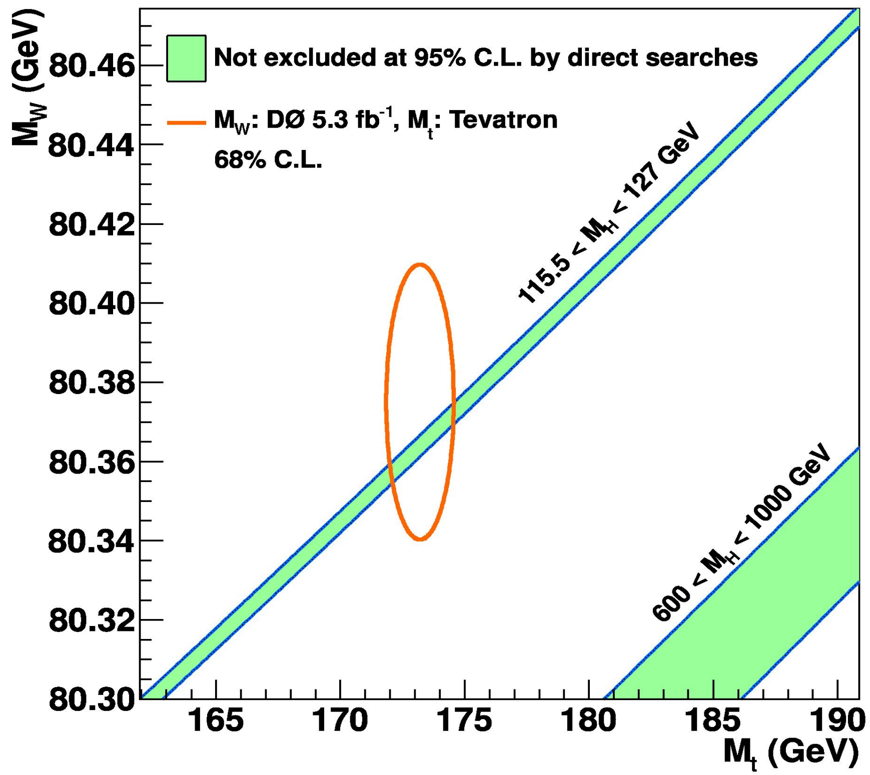
Last year significant progress!

A new particle

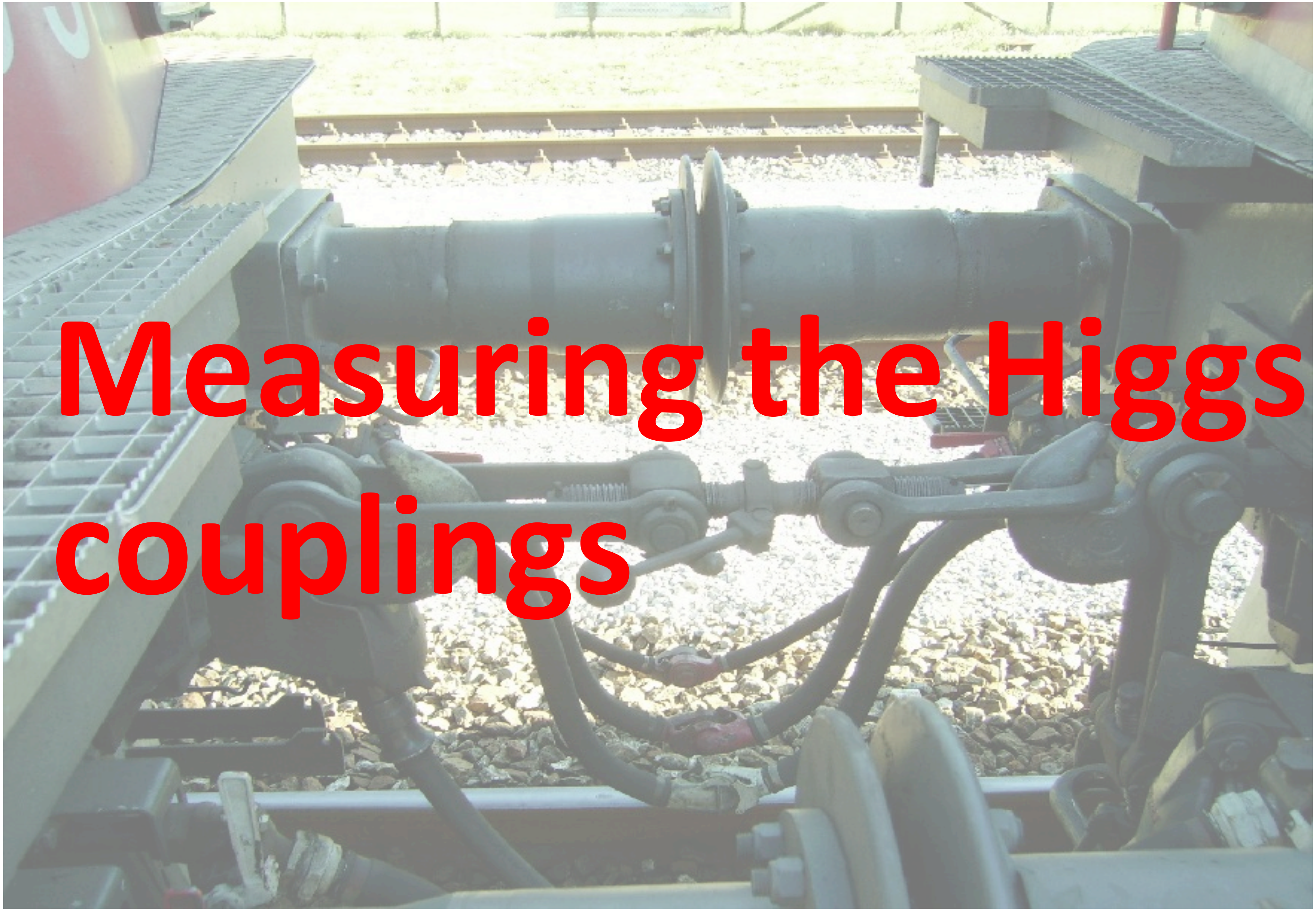
Mass:

CMS	**125.7 ± 0.5 GeV**
ATLAS	**125.5 ± 0.6 GeV**

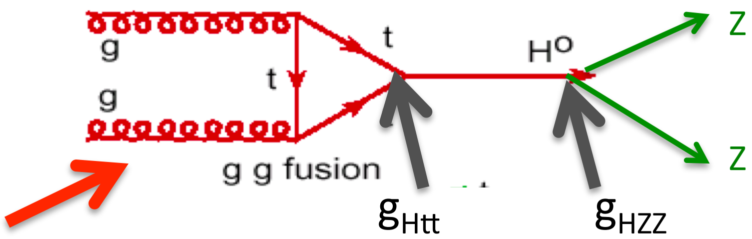
Exactly where precision physics expects the Higgs boson



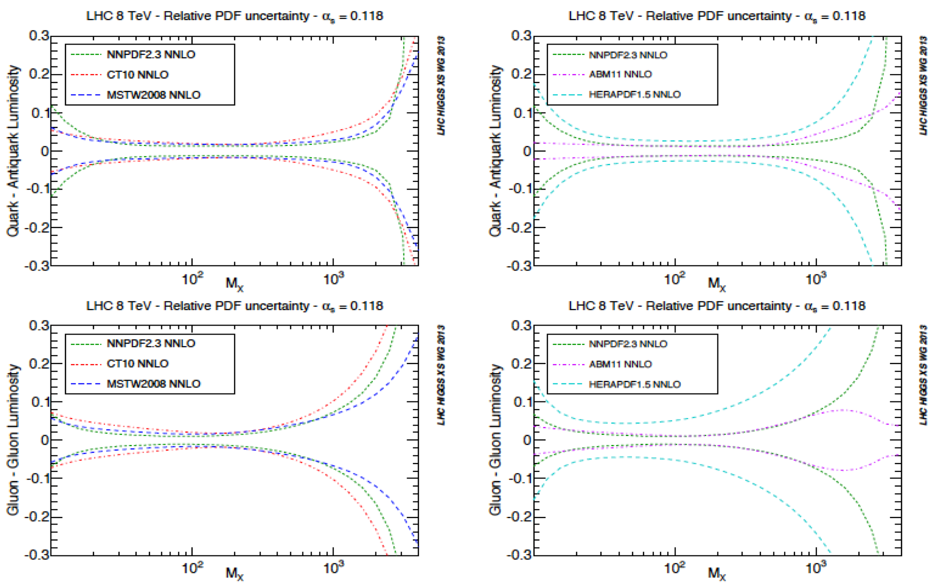
Measuring the Higgs couplings



How to measure the couplings



Gluon fusion cross section 'known'



Compare observed cross section to predicted one
➔ Products of couplings

Theoretical prediction known to 10%

Comparing data and theory

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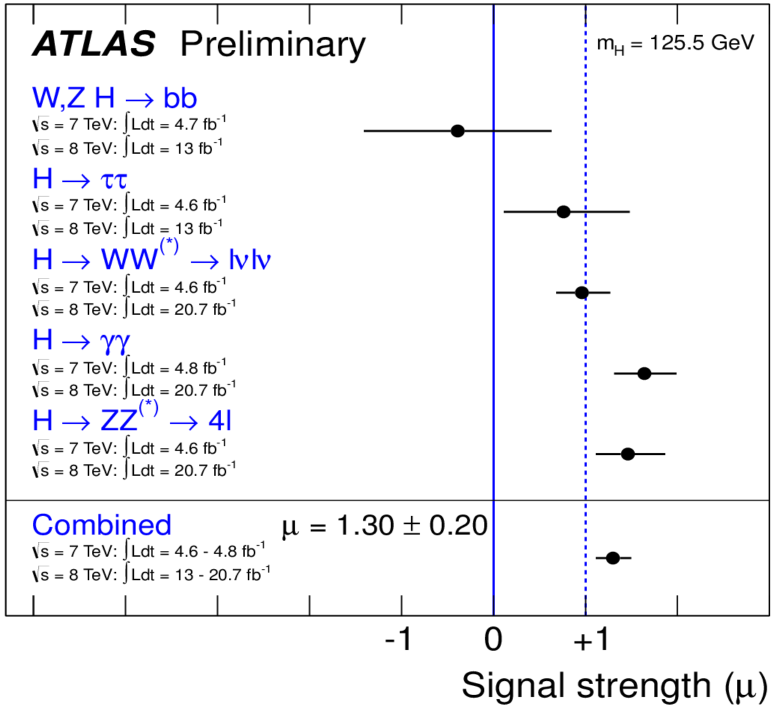
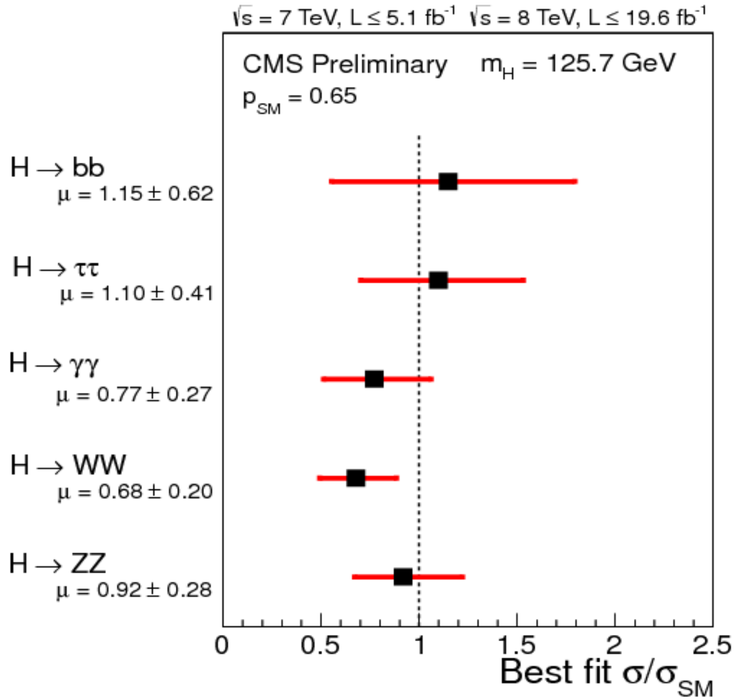
Measure $\mu = \sigma(\text{measured})/\sigma(\text{predicted})$ for different decays





All results agree with expectation for Standard Model Higgs!

Uncertainties on couplings to fermions substantial!

Examples hbb and htt

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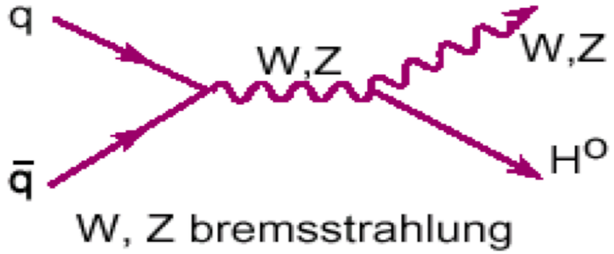
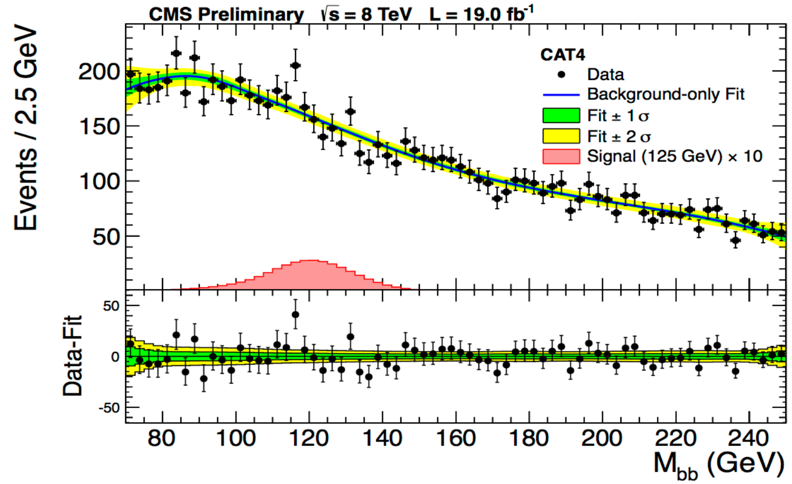
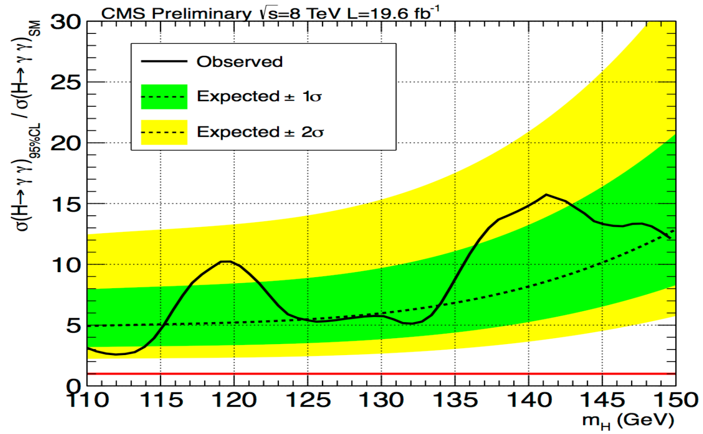


Select associated production
➔ much reduced background



hbb

No significant signal observable



htt

Note also:
search for top coupling in process tth
No signal observable

Does the Higgs couple to fermions?

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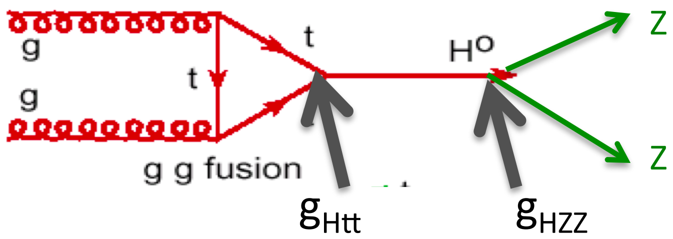
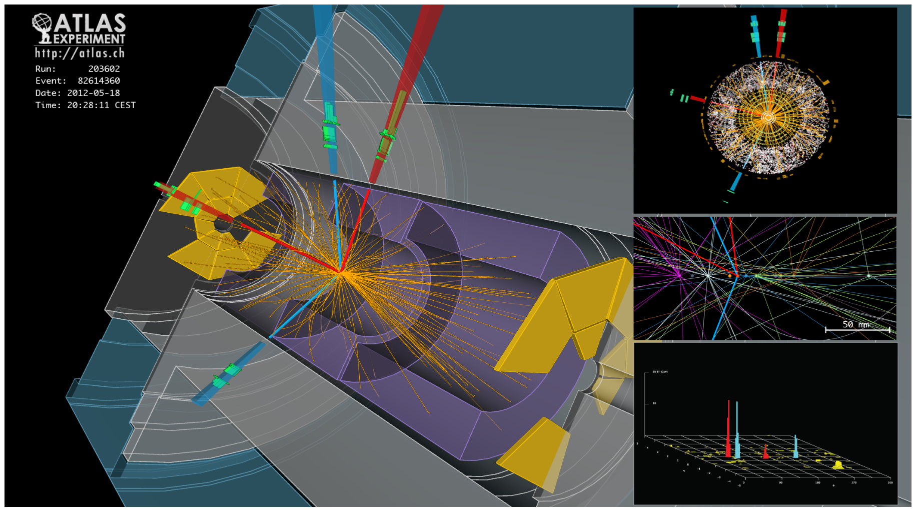
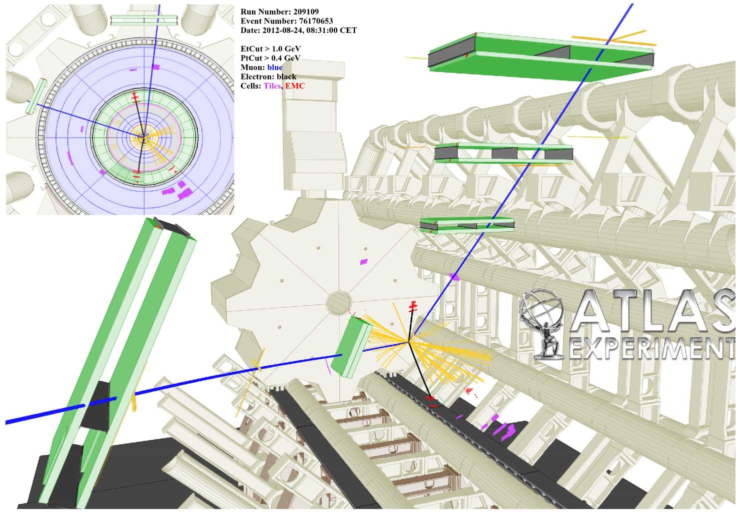


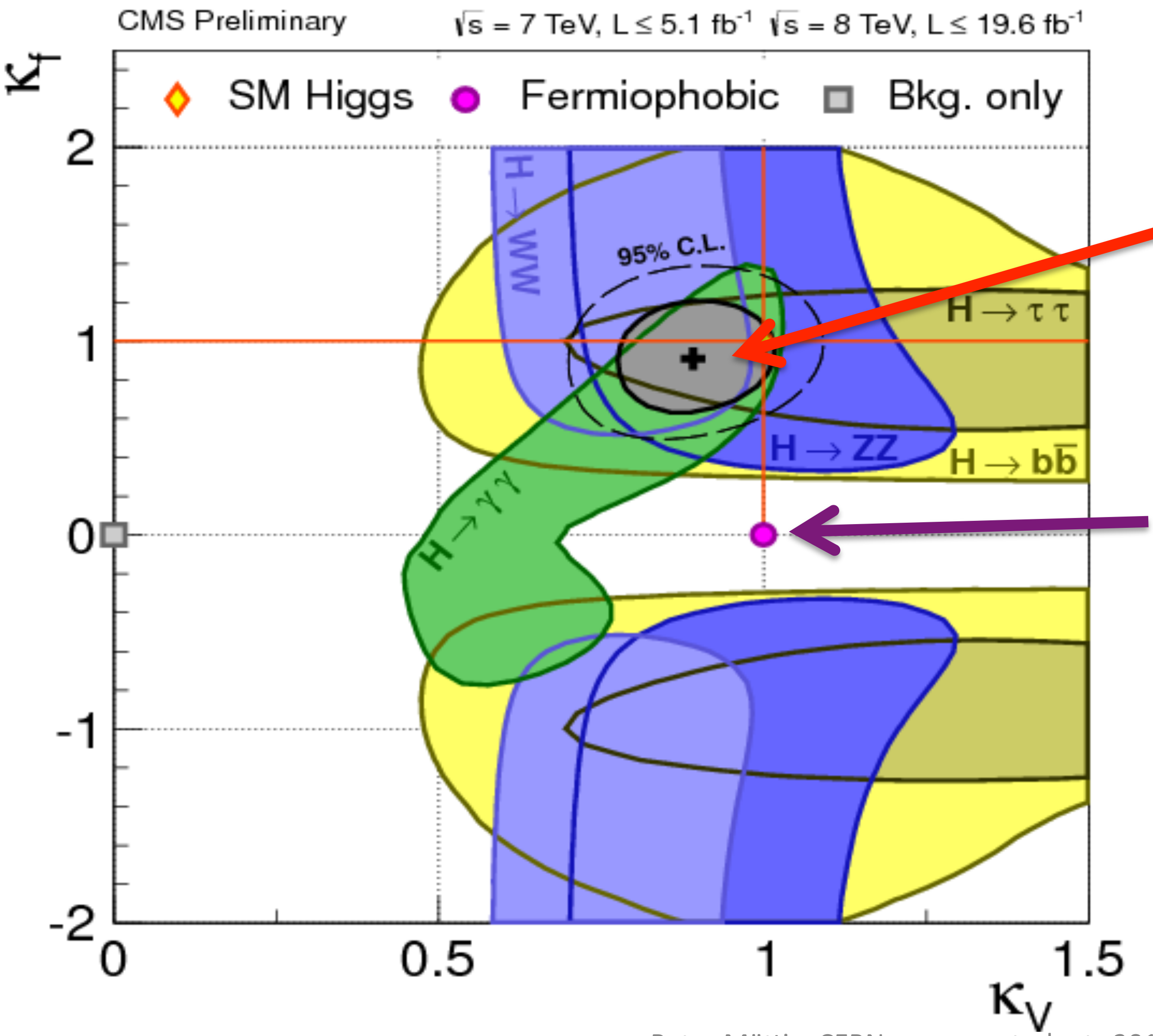
Existence of gluon fusion → indirect evidence for htt – cplg.





Discrimate gg→h from WW→ h by jets in fwd direction

Gluon fusion vs. Boson fusion



In very good agreement with expected tth cplg.

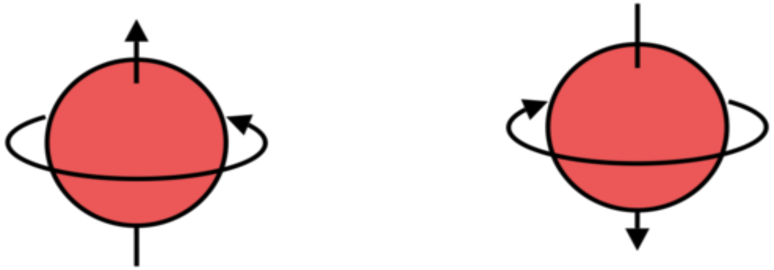
'no' coupling to fermions excluded

Spin + parity measurements

Higgs Spin/Parity: 0^+

Spin: angular momentum 'of a point'

Measured from angular distribution of Higgs decay products

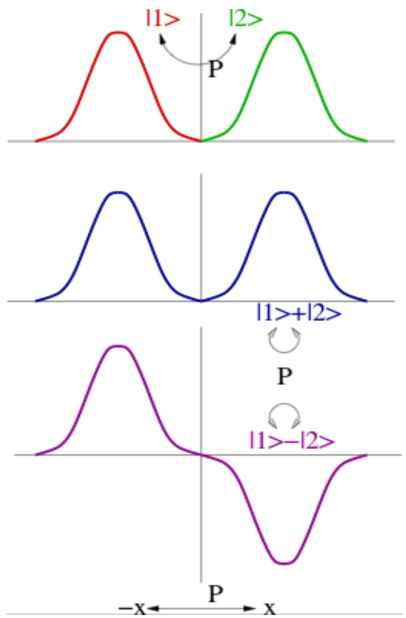


Parity: how does a particle look in the mirror?

parity transformation (x, y, z, t) → (-x, -y, -z, t)

wave function either symmetric (+) or antisymmetric (-)

Measured by sequential decay



Spin of the Higgs

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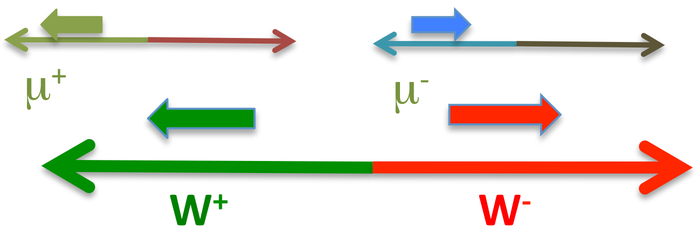
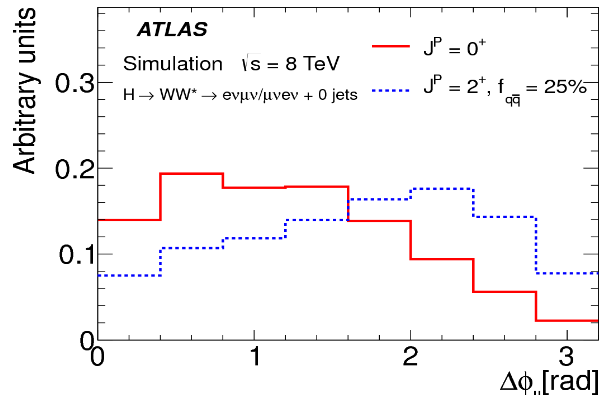
Example: h → W^+W^-

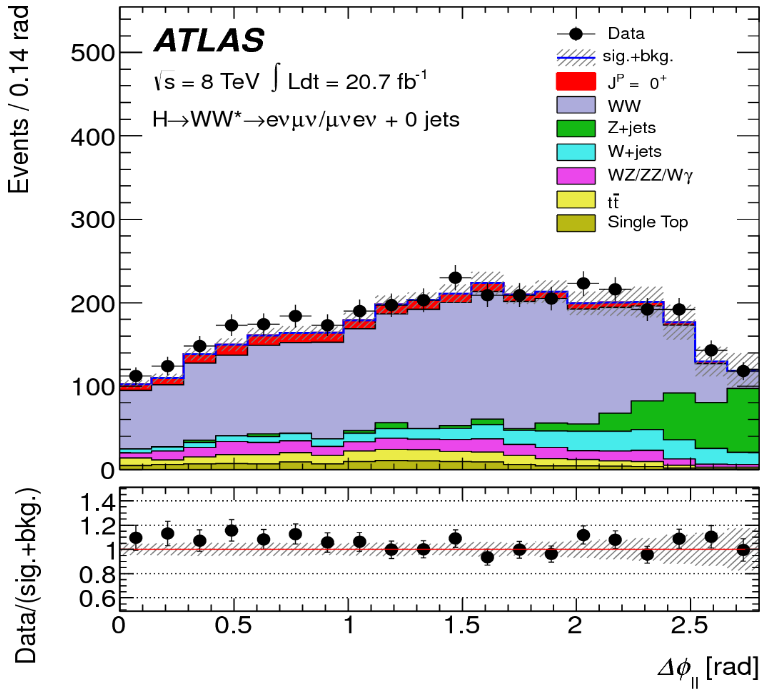
Spin 0 → Spins of W's opposite
μ's aligned



Spin 2: no such correlation

(After subtracting background) data agree better with spin 0





Parity of the Higgs

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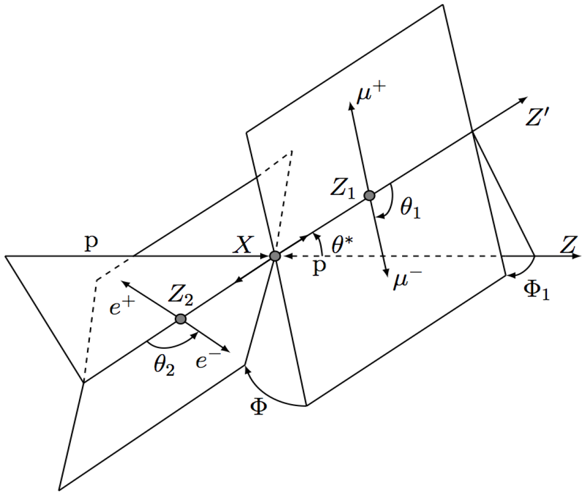
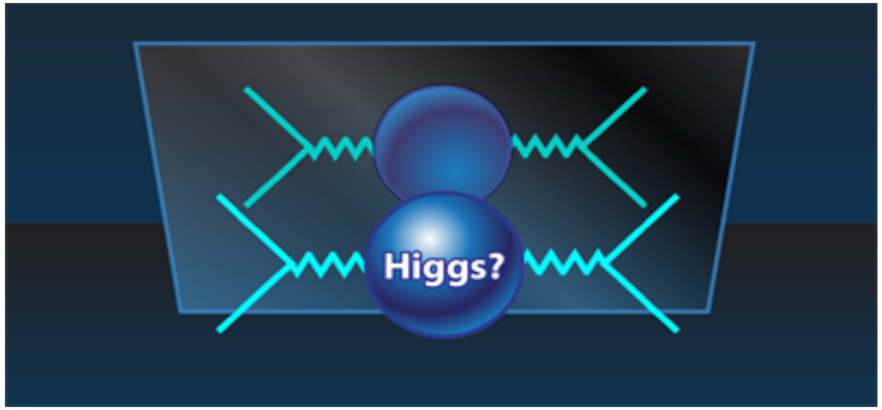
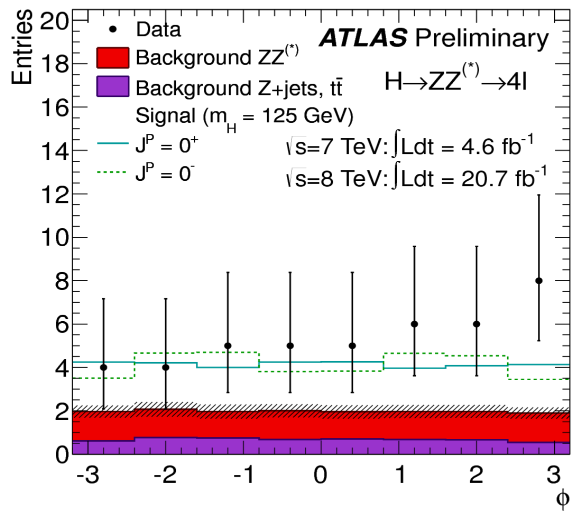
Example: h→ ZZ
compare 0^+ versus 0^-





E.g. angle between decay planes
Use several observables to find optimal discrimination



Spin – Parity summary

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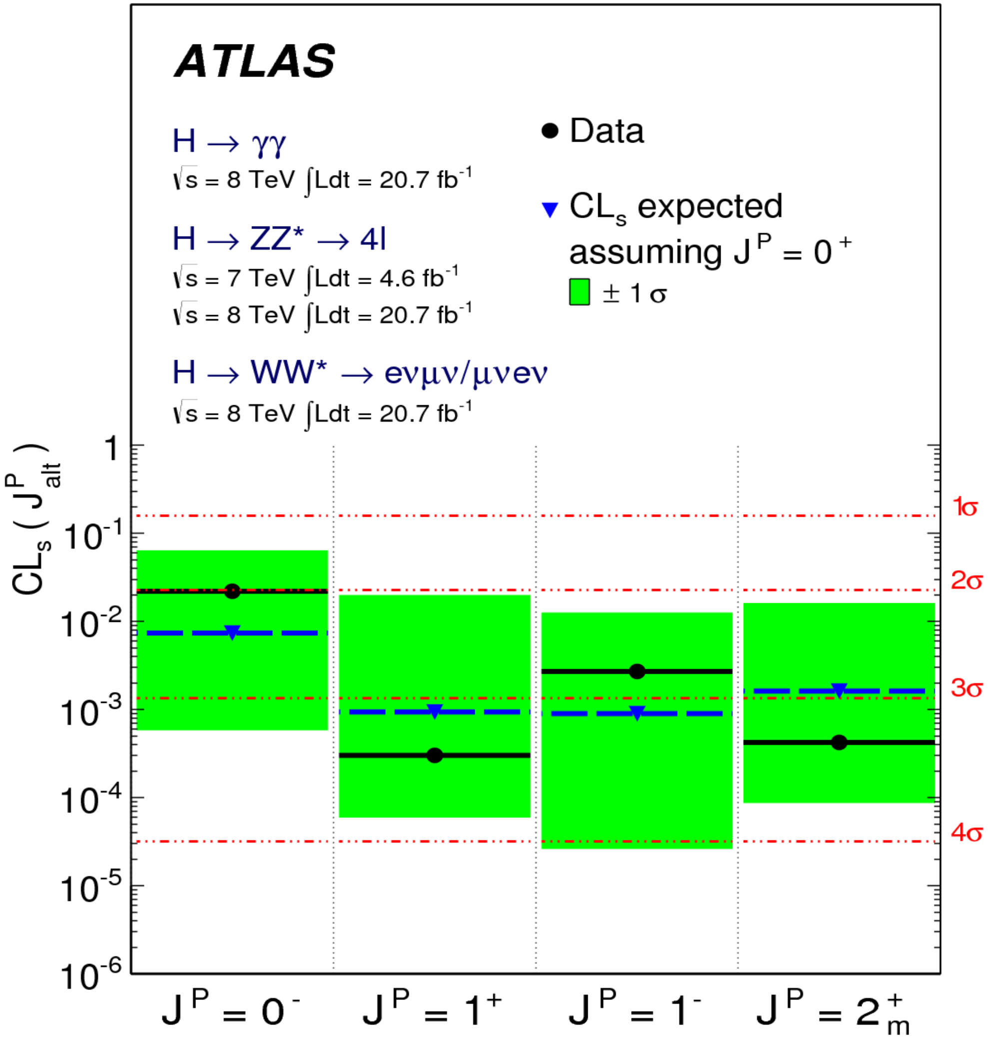
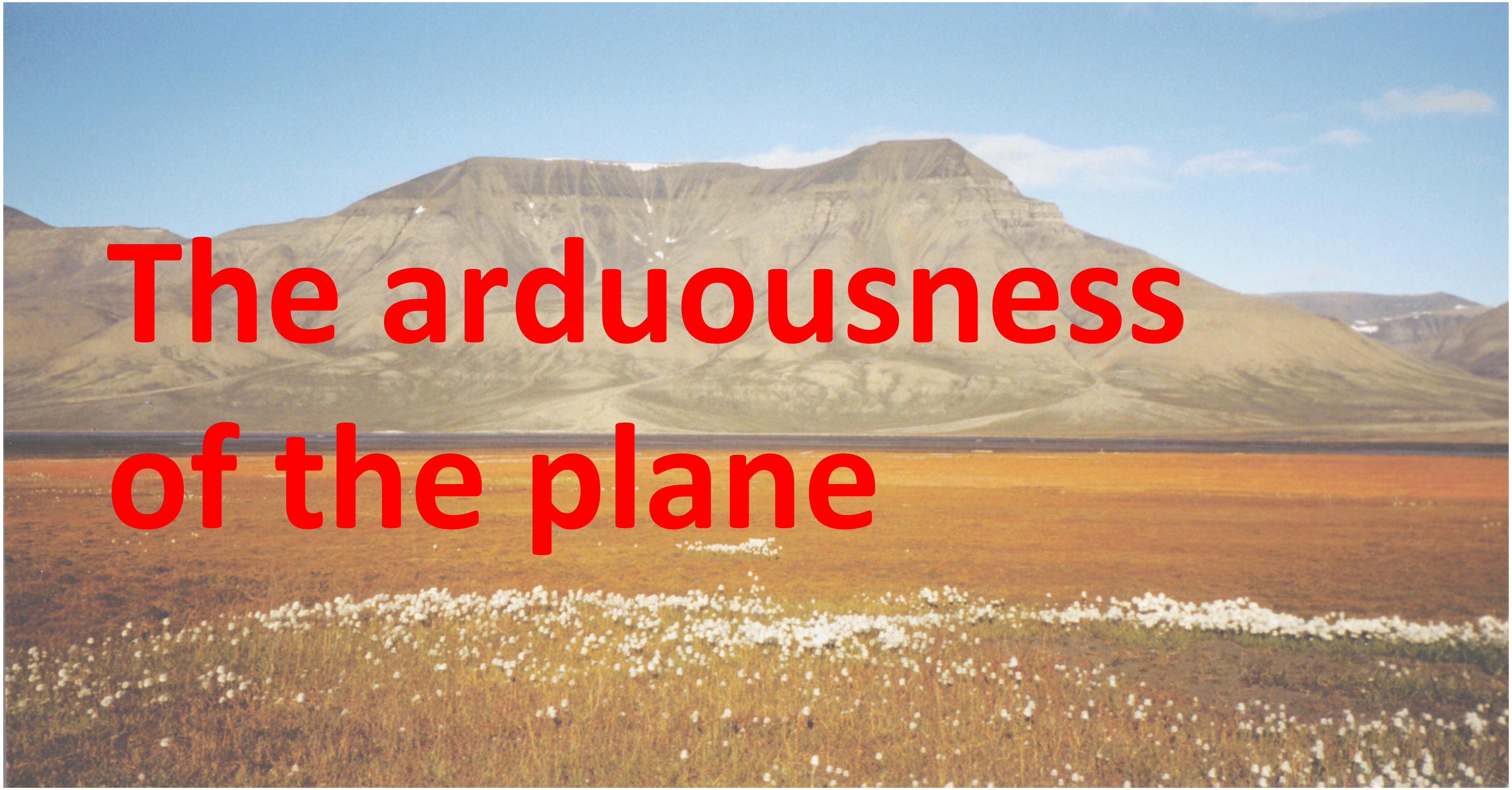


Compare SM 0^+ with other possibilities

Other possibilities disfavoured with 10^{-2} – 10^{-4} probability


The arduousness
of the plane

The remaining questions

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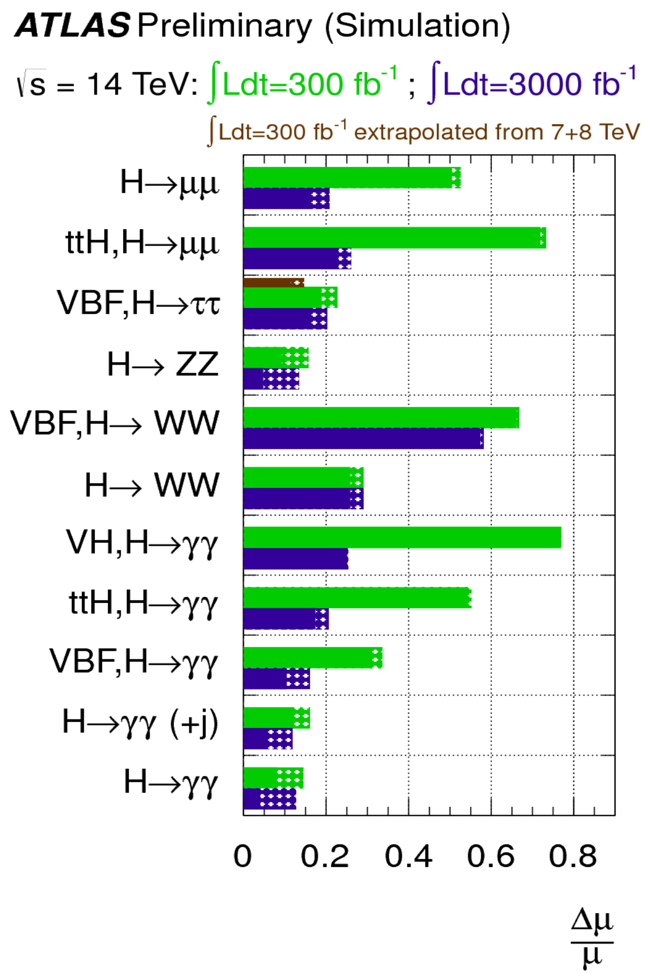
- Higher precision for couplings to W, Z, ….. spin/parity
- Direct measurements of coupling to fermions
- Higgs potential: h → hh

Requires a lot of detailed work and statistics
A program for the next 20 years

It will be a much slower progress now …
Next 10 years: couplings 10 – 20%
Next 20 years: new decay modes in reach
Higgs self coupling to be measured with about 3 standard deviations



Is it the Higgs?

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Pro:

- **mass agrees with precision physics**
- **production rates as expected**
- **spin – parity favours 0^+**

precision to be improved
But as yet: no disagreement

‚it tastes like a Higgs, it smells like a Higgs, it looks like a Higgs'

➔ general feeling: indeed 'we have found it'

It took 116 years to establish the SM

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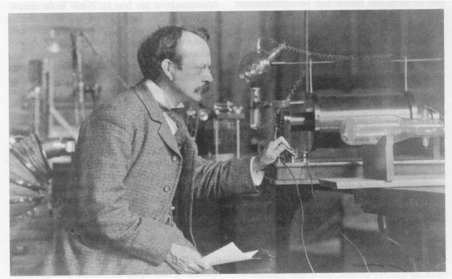
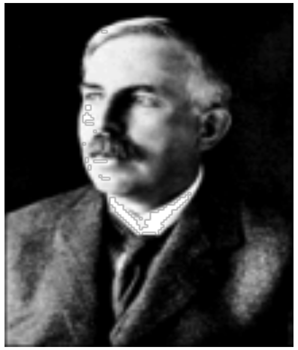


1896: First elementary particle found



New forces discovered
➔ Diverse description of matter and forces

Coherent description based on few principles
➔
Final element found (?)

.....

Problem solved → New questions

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For the first time in history: an elementary scalar

→ Hierarchy/Naturalness problem emphasised
(or is it no problem at all???)

Higgs provides a mechanism to generate mass

→ no predictive power on mass values

Mass of Higgs boson known

→ is there a message associated?

A huge step forward
But still a lot to understand!
We need a more encompassing theory!

.... and need tools to probe deeper

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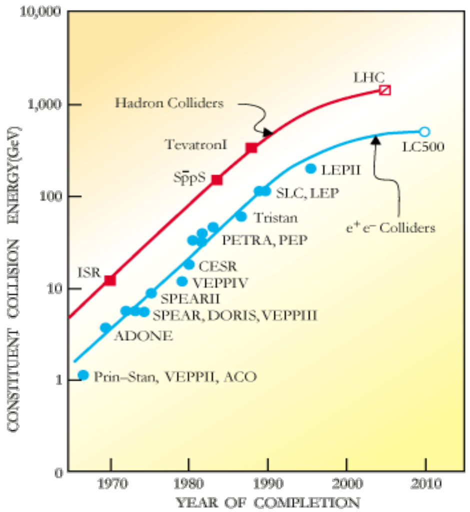
LHC will run for the next 20 years

➔ able to probe masses up to some 10 TeV

Will we find something beyond the Standard Model?
Whatever it will be: homework of SM analyses has to be done!



But we also have to look beyond:
R&D on more powerfull accelerators
should proceed with vigour!

Both for theory and experiment: an exciting time ahead!

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BACK - UP

Consistency of masses

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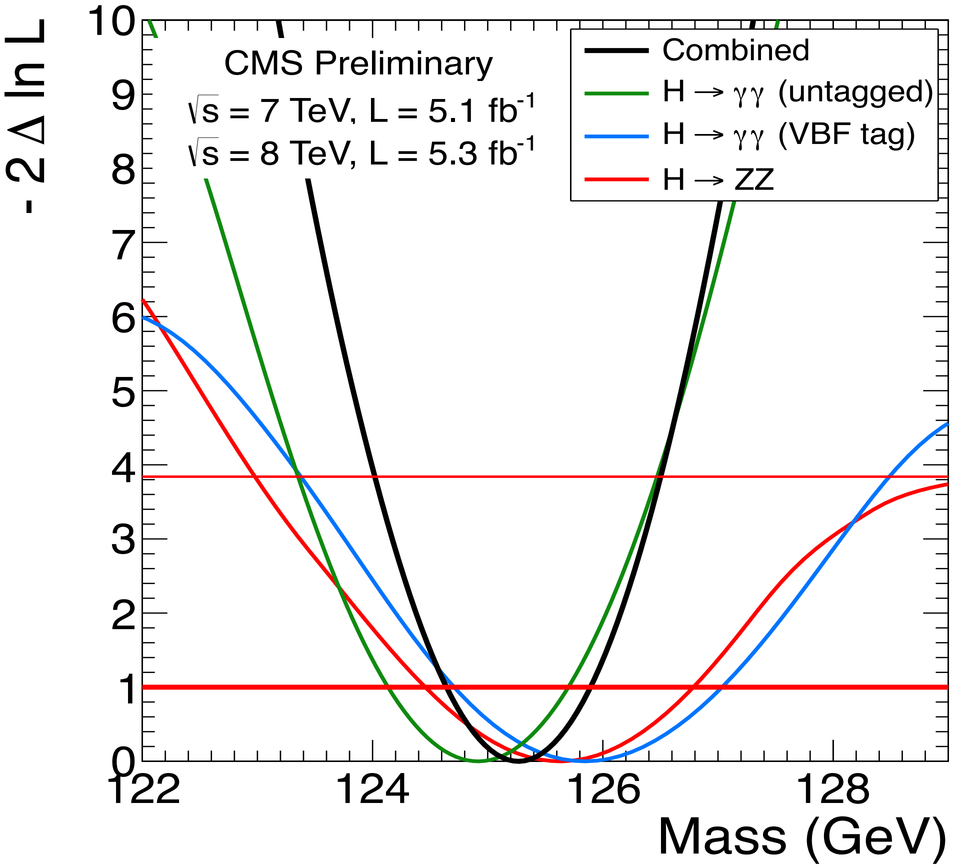

Disadvantage: broad signal

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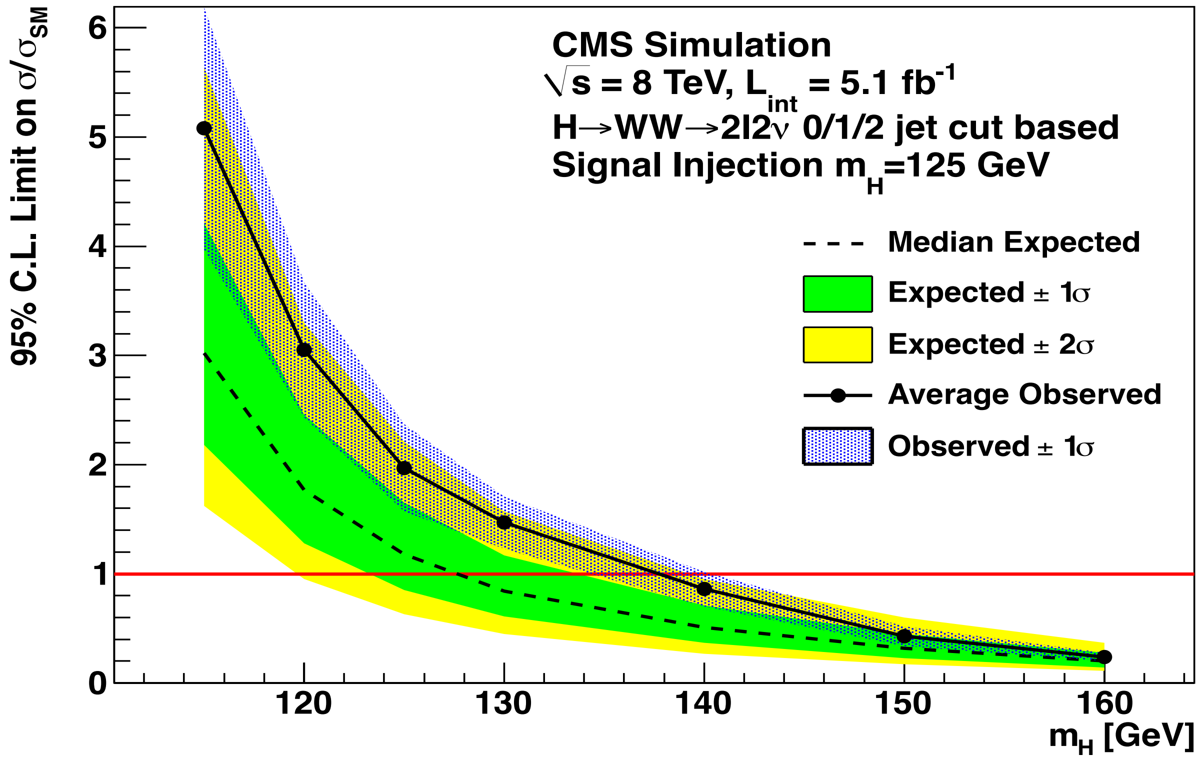
Simulation: assume Higgs @ 125 GeV



Note: 2 ν's
i.e. half of the mass not measurable
➔ to be inferred from charged leptons alone

Larger than expected limit over 40 GeV
➔ very good control of normalisation & background needed