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Standard Model @ Hadron Colliders
IV. Higgs Boson

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Why are masses a problem?

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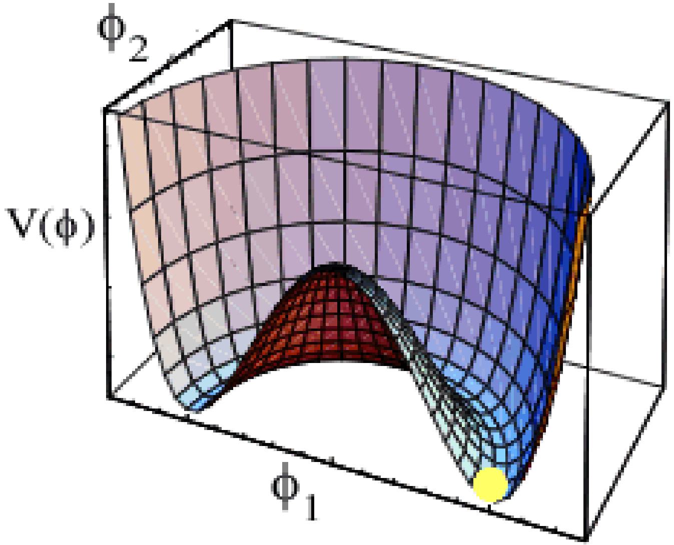
„Standard Model" without masses:
built on local gauge invariance & self - consistent

But:
masses of bosons and fermions break gauge symmetry
massive gauge – bosons:
cross sections $W_L W_L \rightarrow W_L W_L$ outside theoretical bound at ~ 1.2 TeV
Note: guaranteed discovery at LHC!

Way out: introduce new scalar (spin 0) particle 'Higgs boson'
Theory devised in 1964 by Brout & Englert; Higgs

The ‚Higgs mechanism'



$$V = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$\frac{\partial V}{\partial\phi} = 0 \Longrightarrow \phi_0 = v^2 = \frac{\mu^2}{\lambda}$$

Introduce potential (by hand)

Two unknowns: λ, μ

Higgs fields

- gives mass to bosons
- provides means for fermion mass
- implies elementary physical particle
- gives mass to Higgs Boson
- NOTE: no prediction of masses!

Mass of W $\qquad M_W = \frac{1}{2} v \cdot g$

Mass of Higgs $\qquad M_h = \sqrt{2\cdot\lambda}\cdot v$

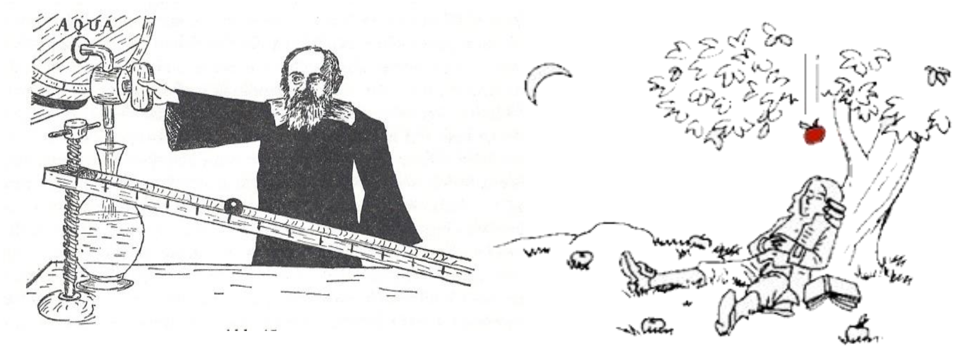
Mass of fermions $\qquad M_f = \frac{1}{\sqrt{2}} G_f \cdot v$

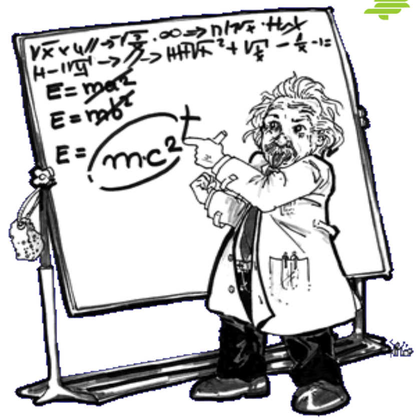
v: ‚vacuum expectation value'

M_W ➔ v = 246 GeV

Left over λ – from Higgs mass

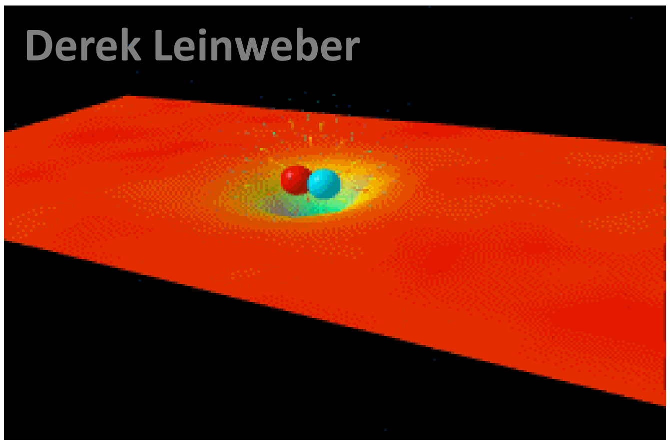
A few notes on mass



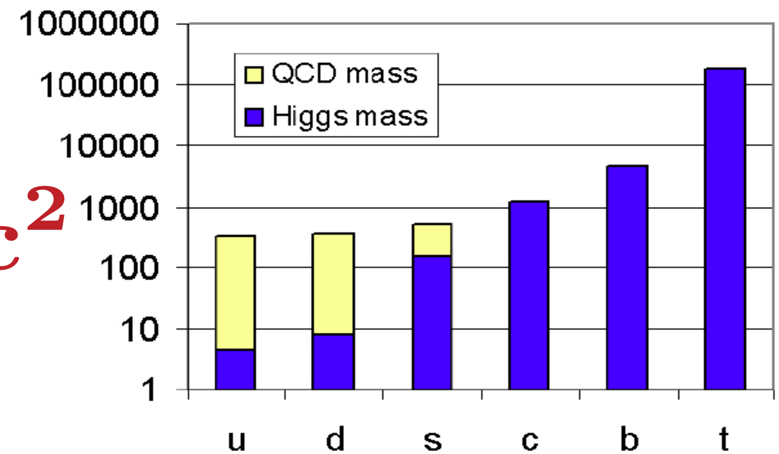


Mass always of basic importance

B.Müller



$$\mathbf{E = m \cdot c^2}$$



A dynamical generation of hadron masses ➔
99% of visible matter due to strong interaction
This principle does not work if particles are elementary!

Strategy to find the Higgs Boson

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Unambiguous predictions of Higgs boson properties

What is to be known to search for the Higgs boson:

- **how is it produced?**
- **how strongly is it produced?**
- **how does it decay?**

Devise search strategy along this line

J.Ellis, M.K.Gaillard, D.V.Nanopoulos (1975)
"We should perhaps finish our paper with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, ..., 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 doing experiments vulnerable to the Higgs boson should know how it may turn up."

Higgs physics in 2009: pre - LHC

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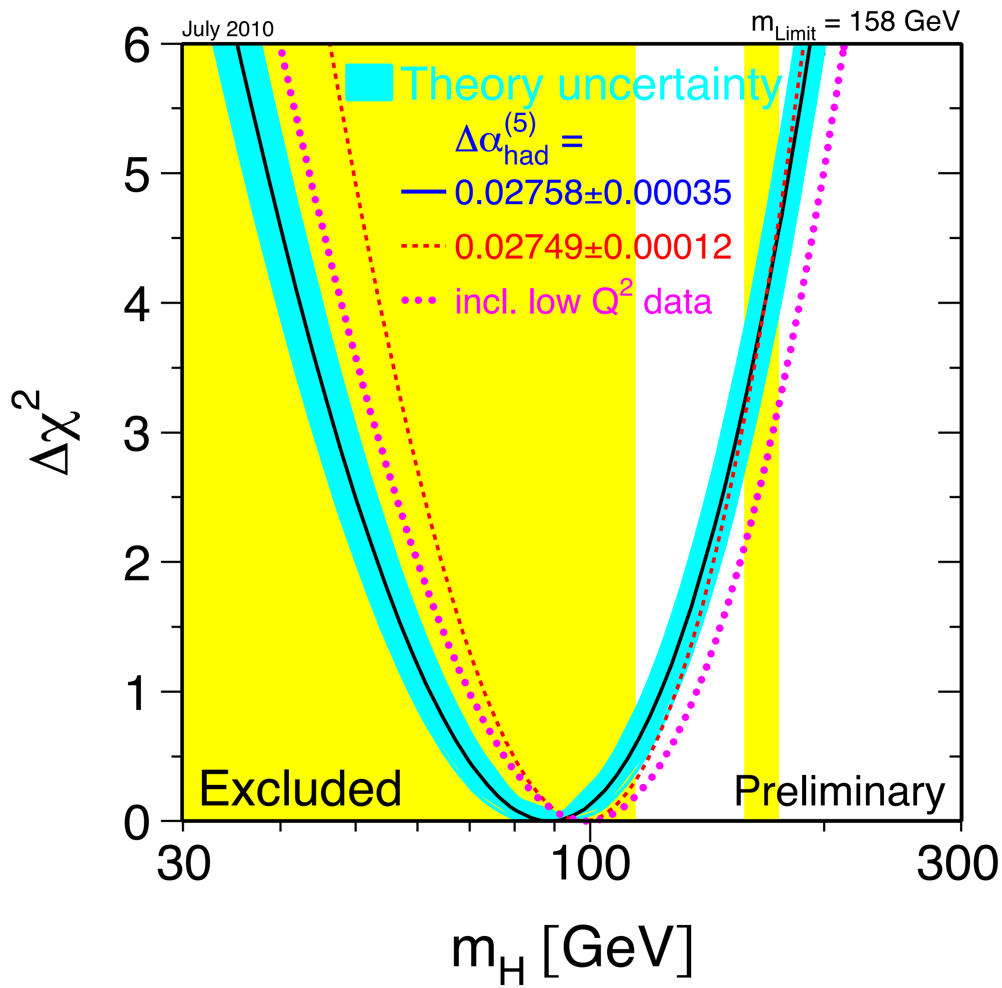
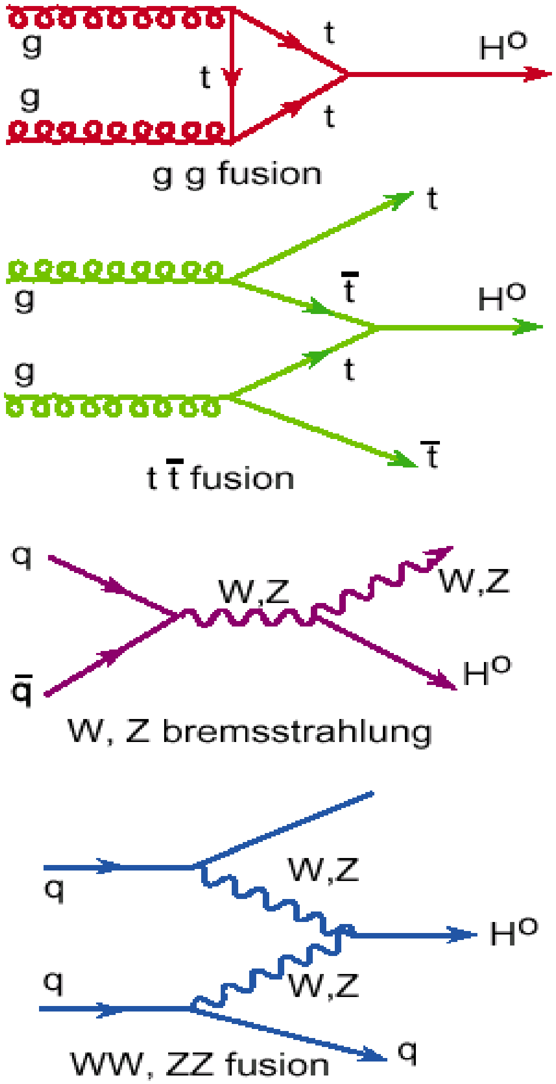


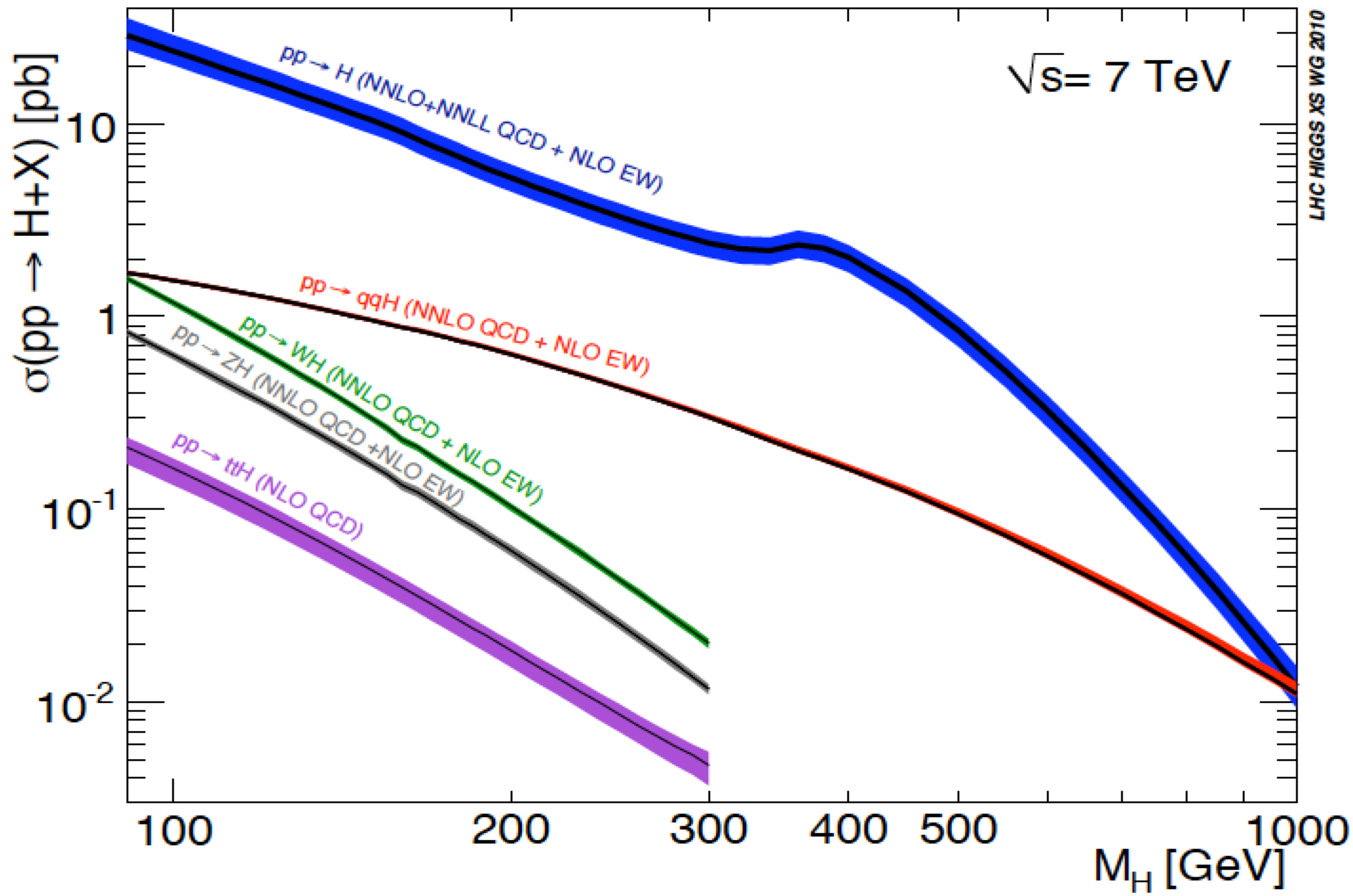
Direct Searches at LEP&Tevatron
M_h > 114.4 GeV &
not around 160 GeV

Indirect limits from electroweak precison experiments & theory
M_h < 158 GeV (@ 95% confidence)

The final assault on Standard Model

Higgs searches at Hadron Colliders





How do Higgs Bosons decay?

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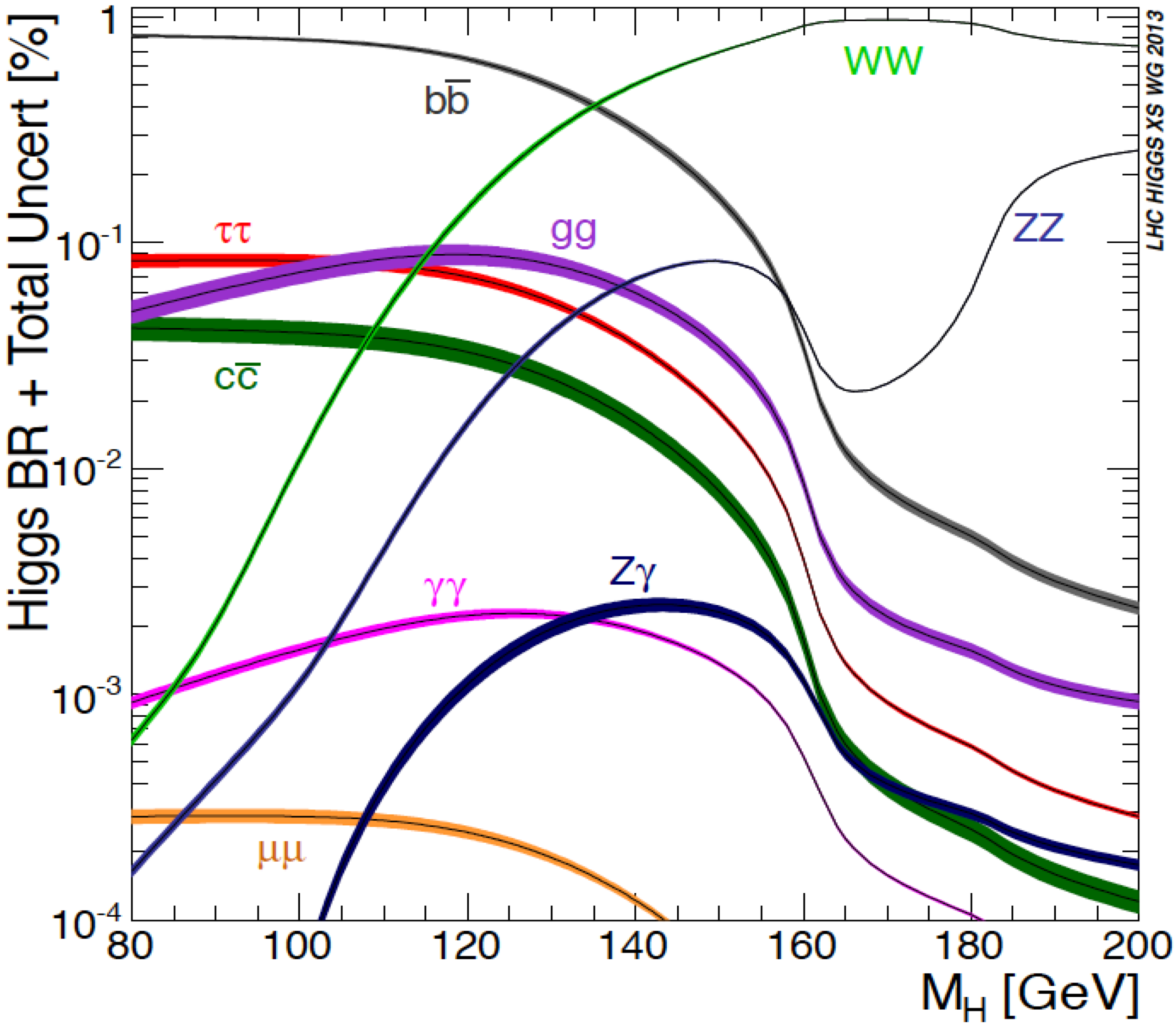

How strong is the coupling?

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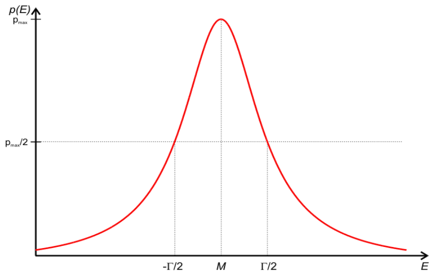
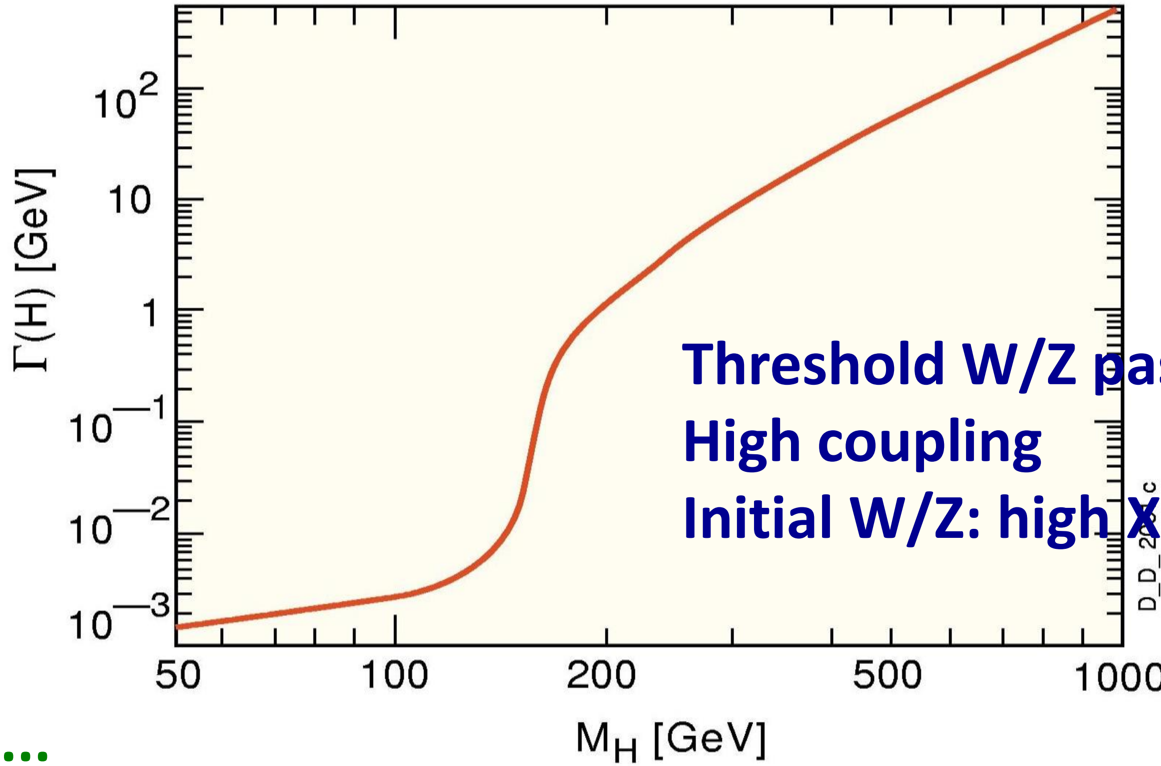
Width of higgs boson proportional to coupling

$\Gamma(H) \sim M(H)$





Threshold W/Z passed:
High coupling
Initial W/Z: high X-section

Very small width ...
Very small coupling!

How many Higgs Bosons @ 125 GeV?

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- ➔ cross section ≈ 20 pb
- collected luminosity ≈ 25 fb^{-1}

} 500 000 events

➔ Dominant Decays:

$H \rightarrow bb$:	285 000
$H \rightarrow WW$:	105 000
$H \rightarrow ZZ$:	13 000
$H \rightarrow \gamma\gamma$:	750

Large numbers:

But: experimental challenge to separate these from formidable background

How the Higgs would show up

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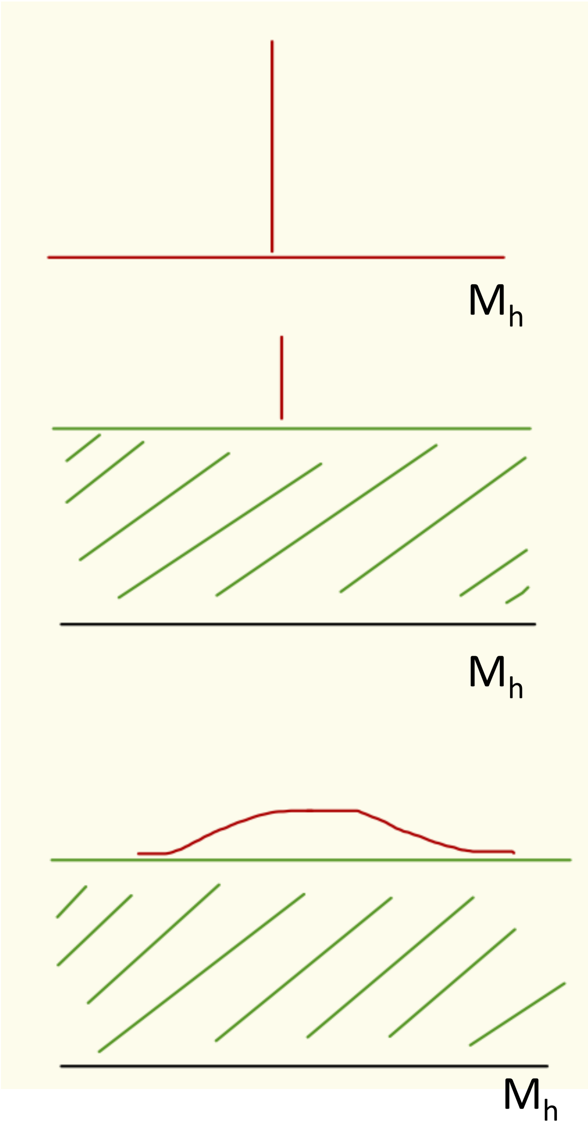


The ideal world: a narrow excess at M_h

…. 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?

Comments:

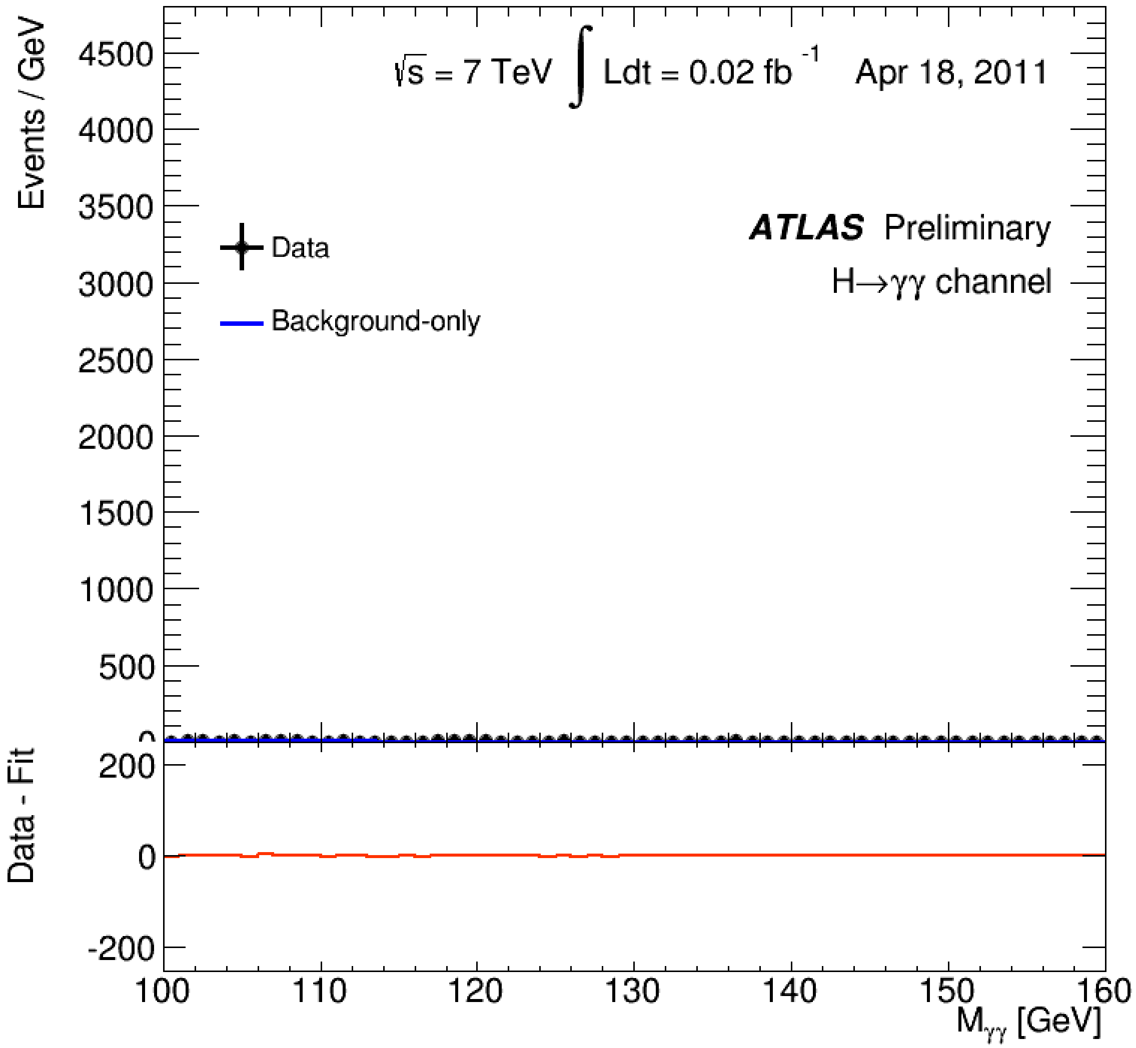
- suppress large background: hard selection cuts ➔ low efficiency
- systematic uncertainties: how well is background known?

➔ Sometimes subdominant production/decay channel

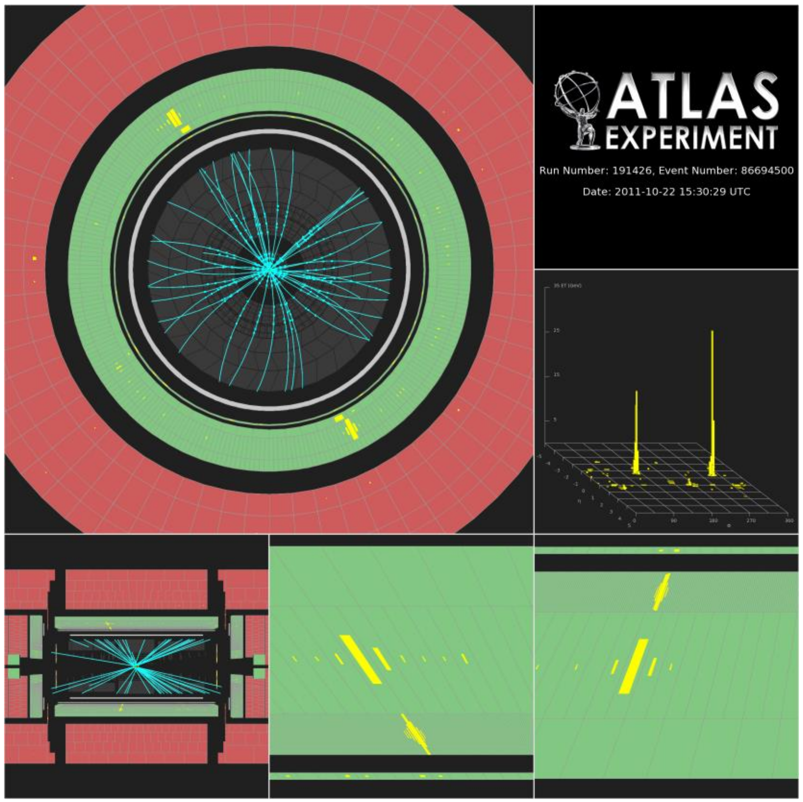
channel	selection	reduction	width	background
bb	identify bottom	0.5	15 GeV	huge
WW	electrons, muons	0.05	25 GeV	large
ZZ	electrons, muons	0.001	2.5 GeV	small
gg		1	1.7 GeV	large

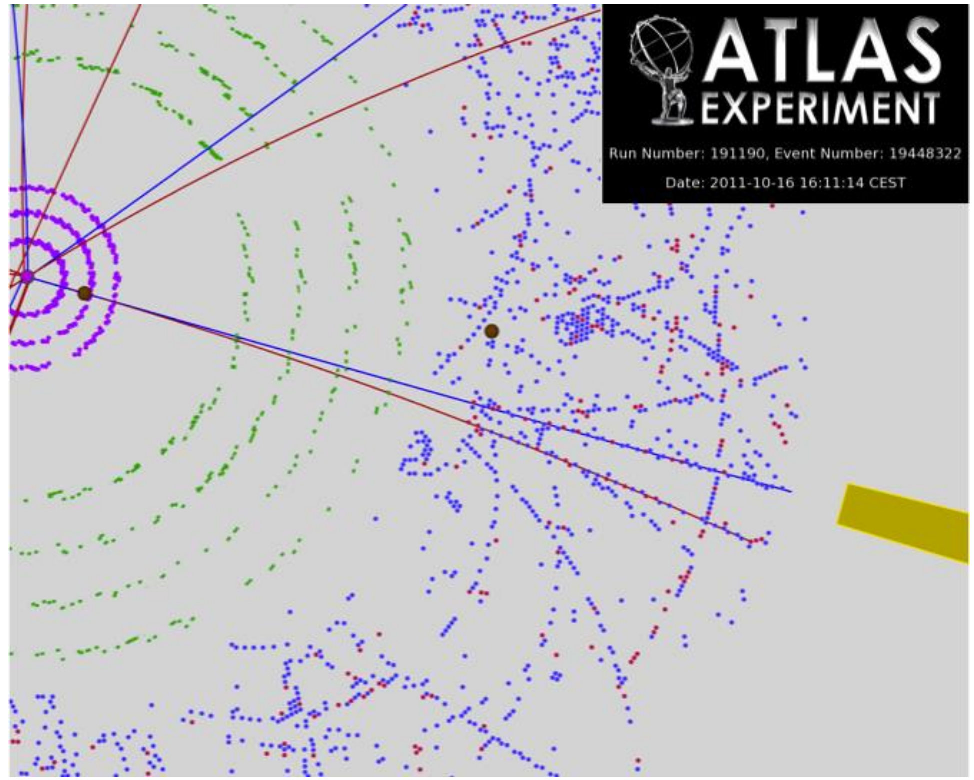
Clearest signals in ZZ and $\gamma\gamma$ channel expected !

Higgs discovery I: H→γγ



Photon Identification





‚Isolated‘ photons not in jets
Information about direction

Converted photon $\gamma \rightarrow e^+e^-$
In tracking chamber + deposition

Higgs Discovery II: $ZZ \rightarrow (e^+e^-)(\mu^+\mu^-)$

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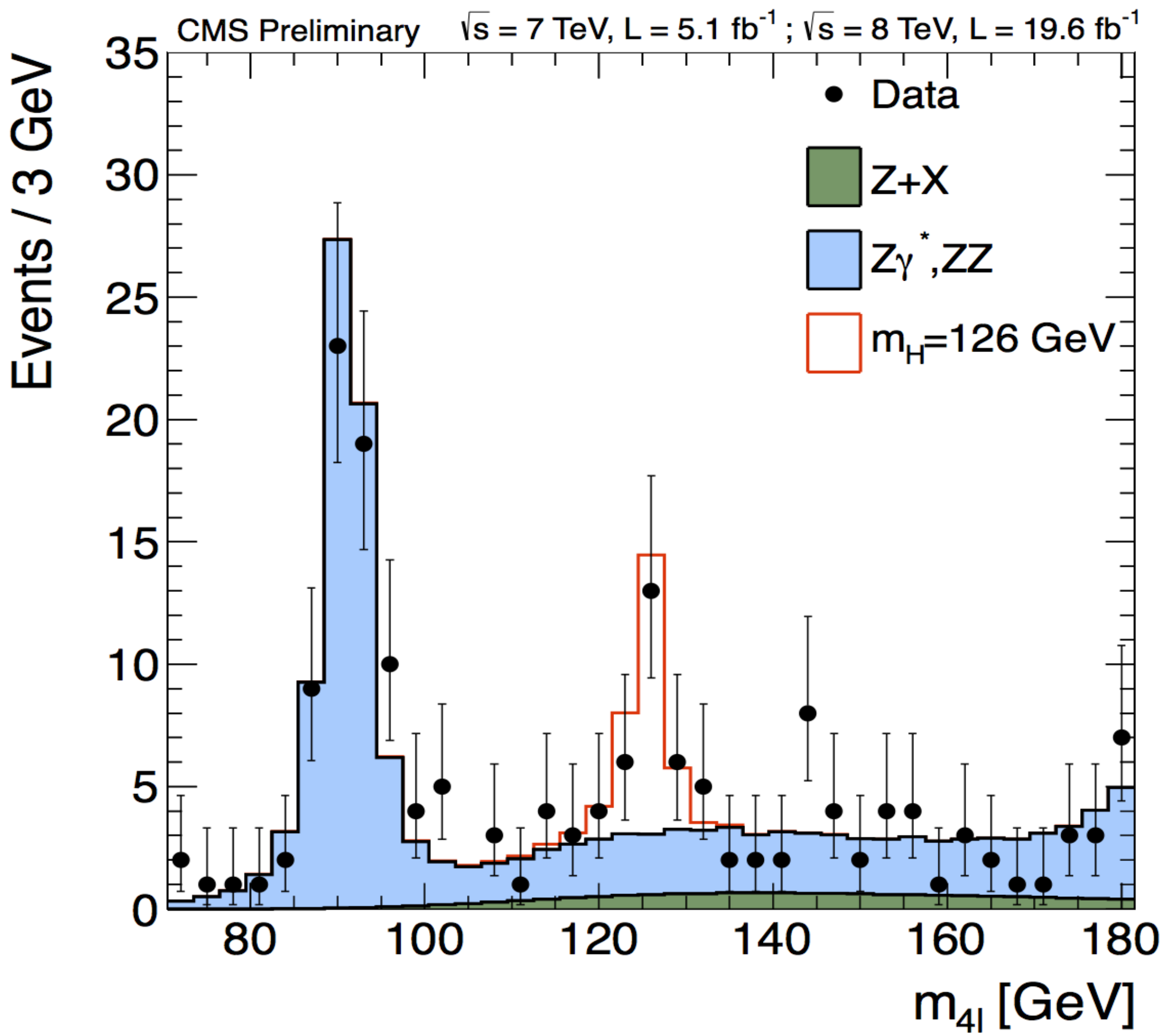

H➔ZZ below 2* M_Z

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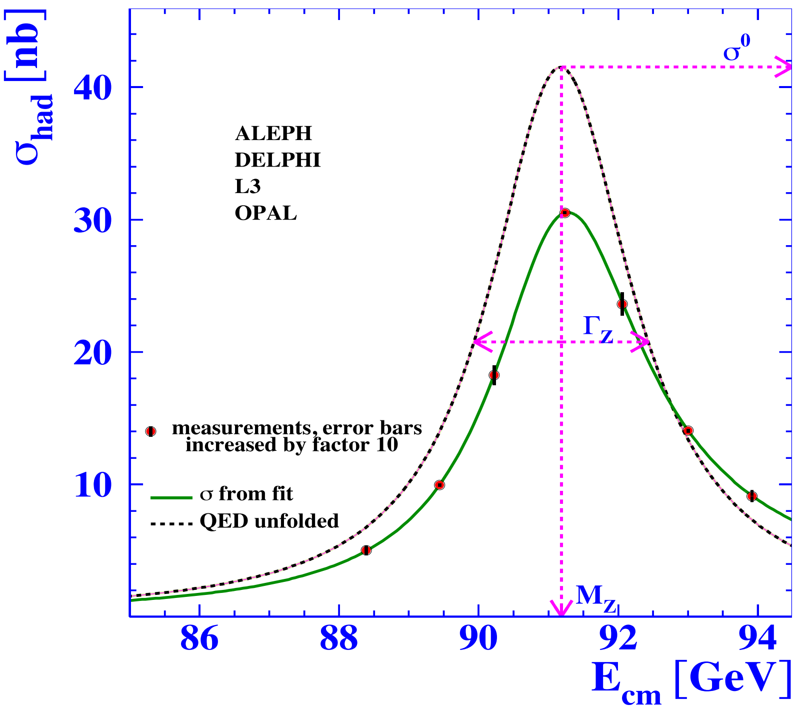
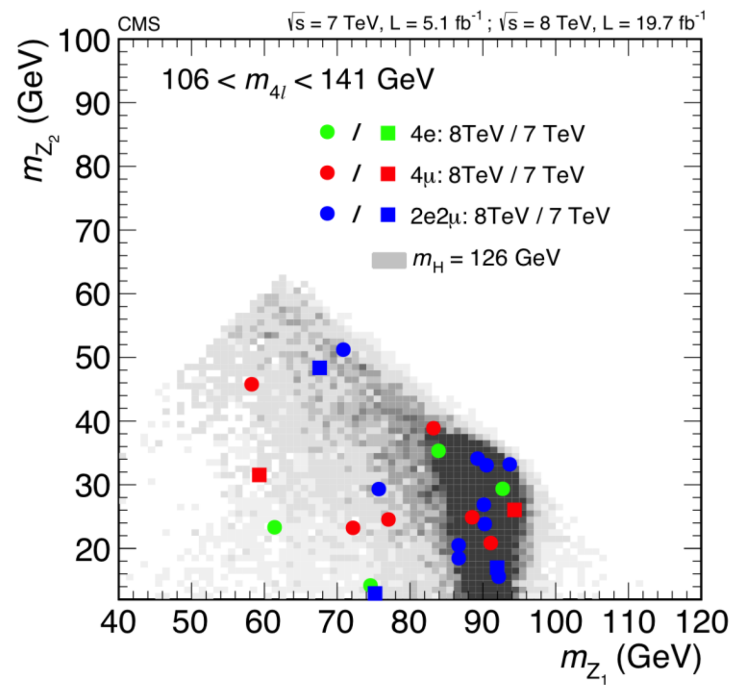


Remember: M_Z = 91.16 GeV

➔ $M_h << 2*M_Z$

Breit – Wigner shape of Z^0 ➔

Some chance to produce Z at 30 GeV



CMS Simulation: mostly

- one l^+l^- combination M = 91.16 GeV
- second combination 10 – 40 GeV

A new particle!
A new boson!

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Mass:

ATLAS:	**125.36 ± 0.37 ± 0.18 GeV**
CMS:	**125.03 ± 0.26 ±0.14 GeV**

Higgs: needle in hay stick

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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**

Selecting $5x10^7$ Bytes out of $5x10^{20}$!!

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

July 4, 2012: Announcement!

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Historical precedents:
Don‘t jump to early on conclusions

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The arduousness of the plane

Die Mühen der Berge haben wir hinter uns, vor uns liegen die Mühen der Ebenen
(Berthold Brecht)

A new particle! A Higgs boson?

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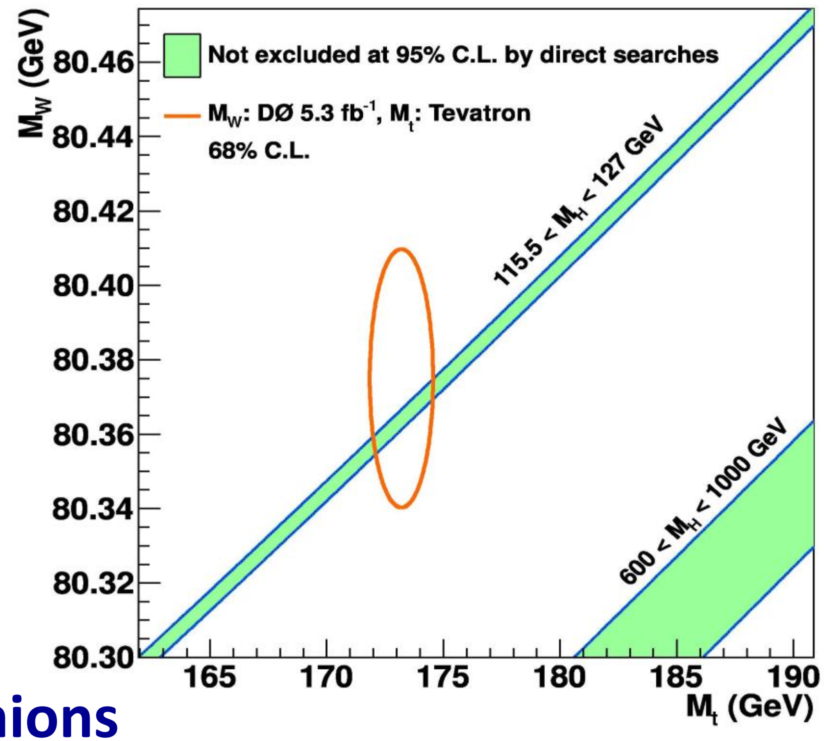
Qualitative: 'Higgs' suggestive!

- Mass accords with expectation
- It is a boson (NOT spin 1!)
- Found in expected decay channel



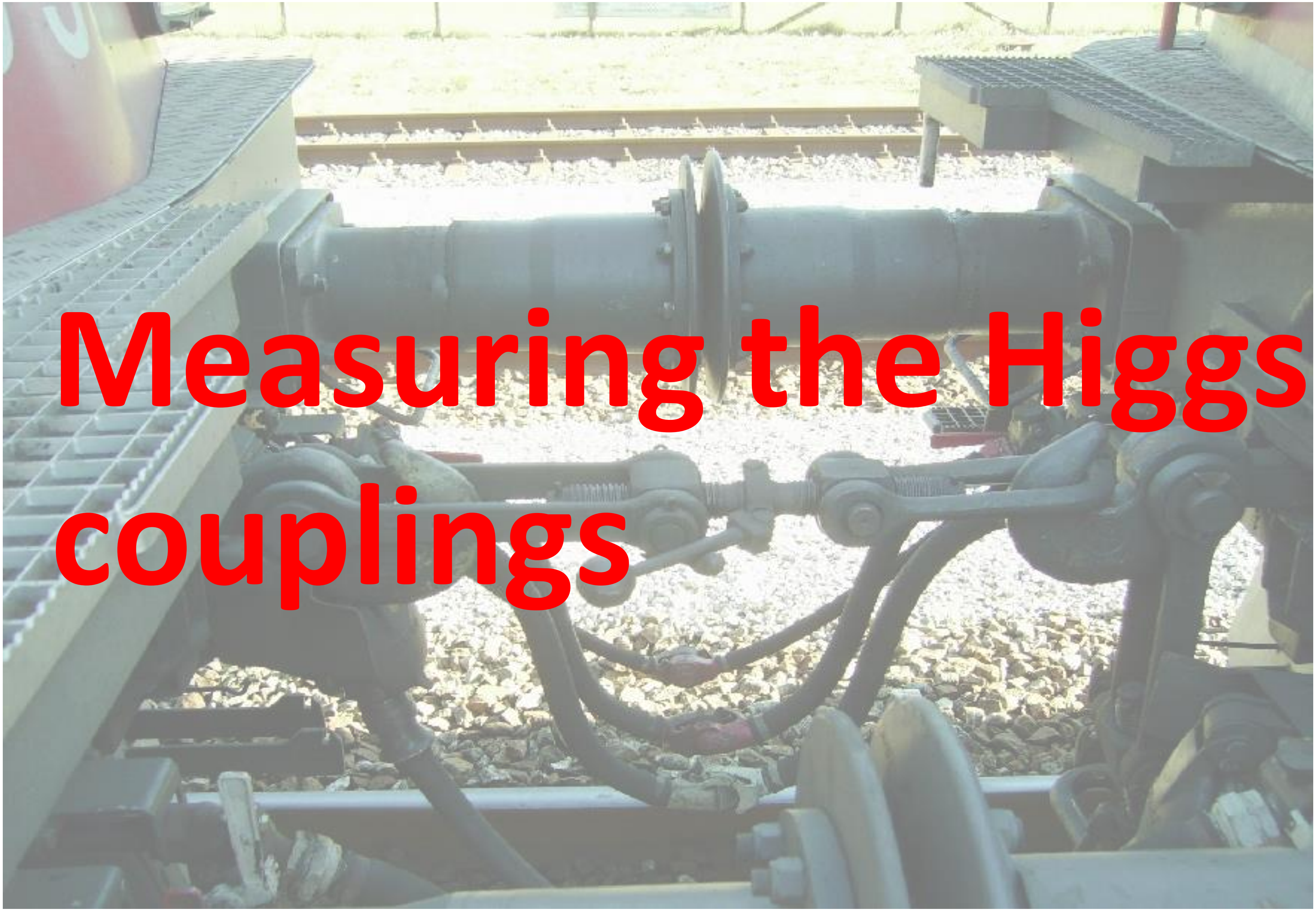
Move to quantify agreement

Higgs properties exactly predicted

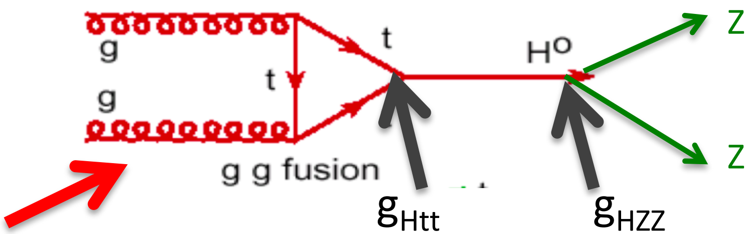
- Production mechanisms
- Branching ratios into bosons and fermions
- Width of Higgs boson
- Spin and parity
- Higgs self coupling (Higgs potential)

Significant progress since discovery

Measuring the Higgs couplings

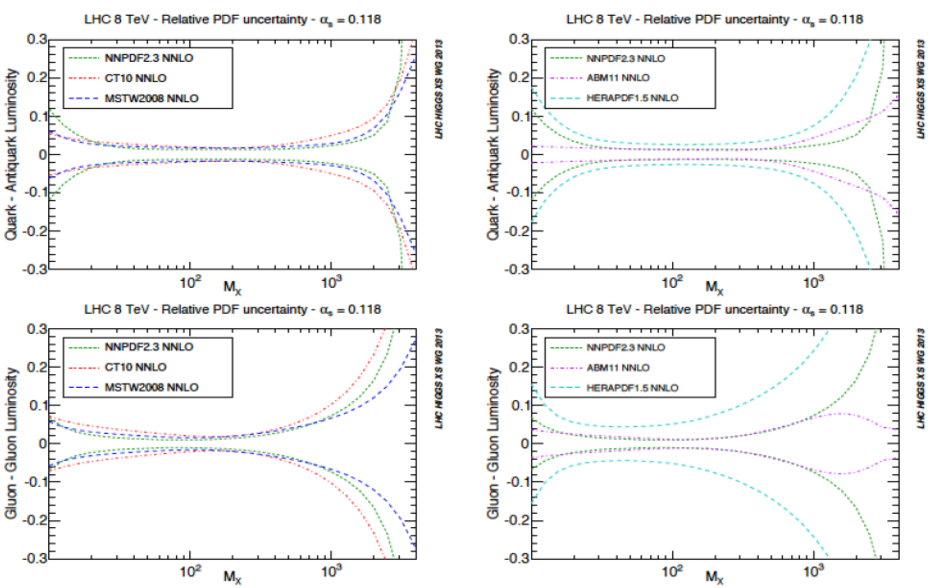


How to measure the couplings



$$\sigma \sim |g_{Htt} * g_{HZZ}|^2$$

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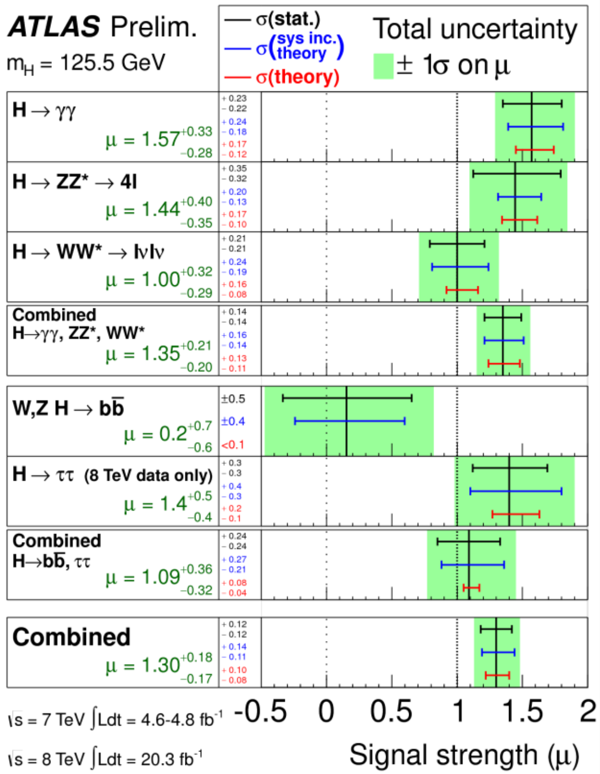
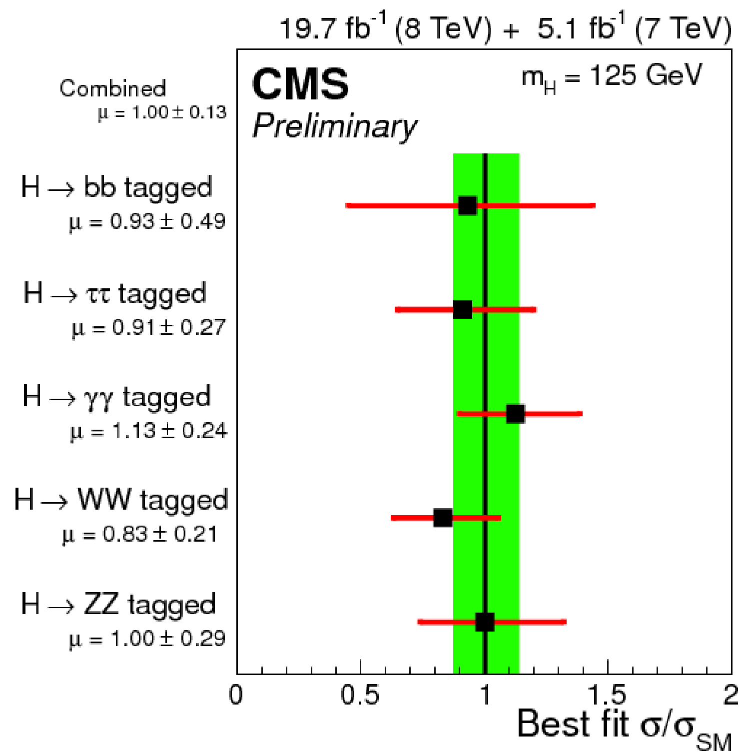
Measure $\mu = \sigma(\text{measured})/\sigma(\text{predicted})$ for different decays

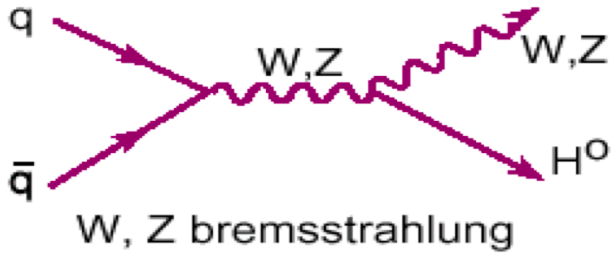




All results agree with expectation for Standard Model Higgs!

Uncertainties on couplings to fermions substantial!

Example hbb



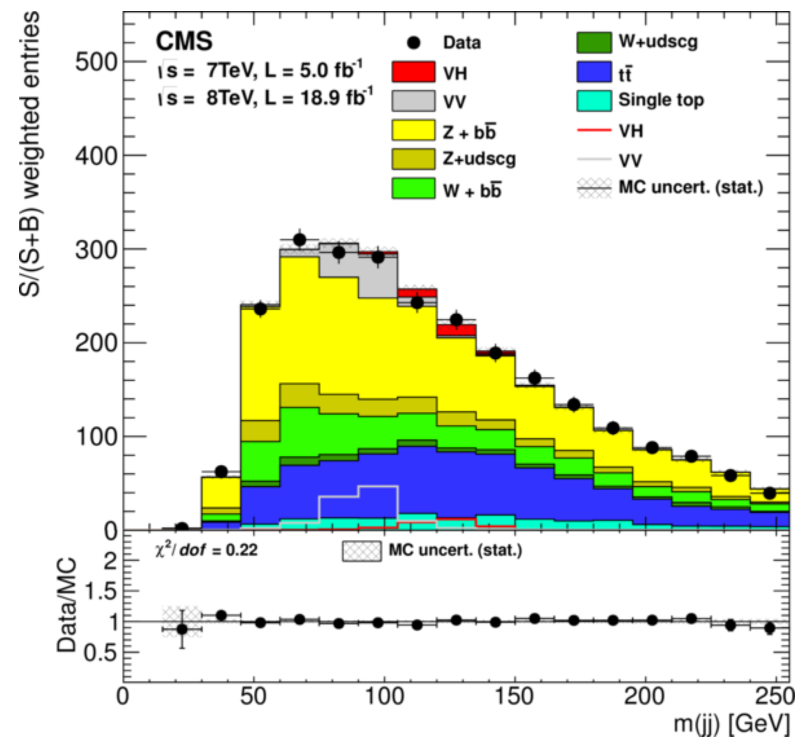
H→ bb largest decay fraction
in gluon fusion: enormous background
Associated production: tag W/Z→leptons
→ much better S/B

…. but still formidable!

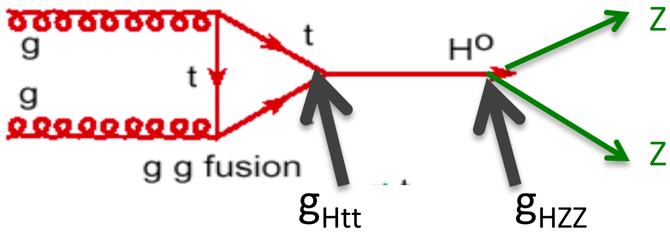
Various contributions
Zbb, Wbb, tt, ……

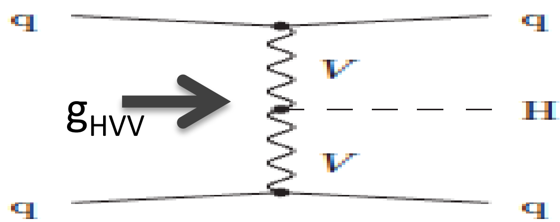
and: broad reconstructed signal

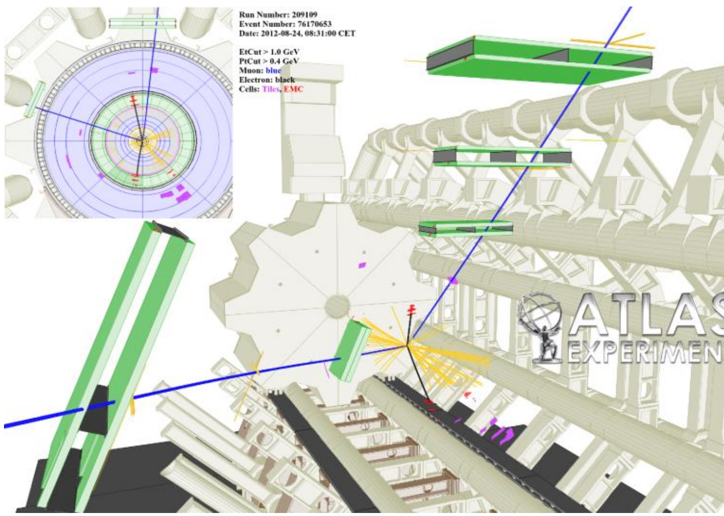
As yet, no significant signal observed

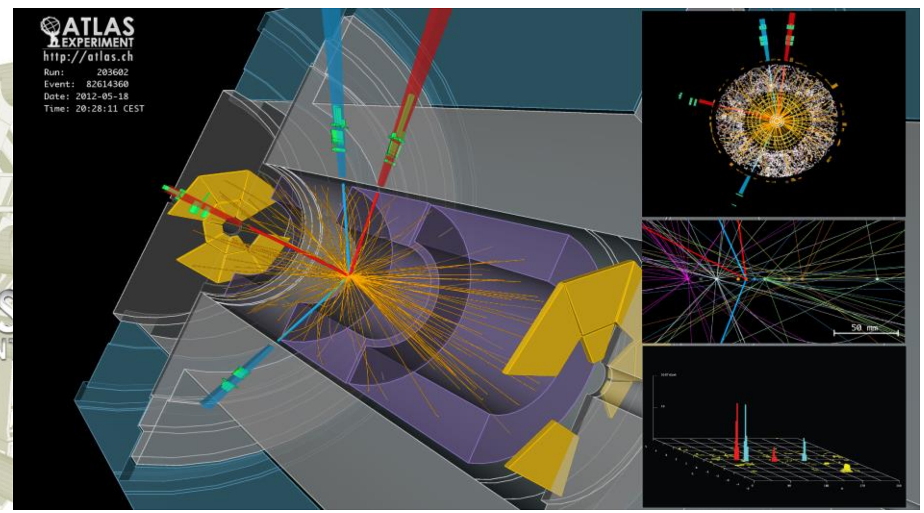


Fermion vs. Boson Couplings









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

Couplings fermions vs. couplings W/Z

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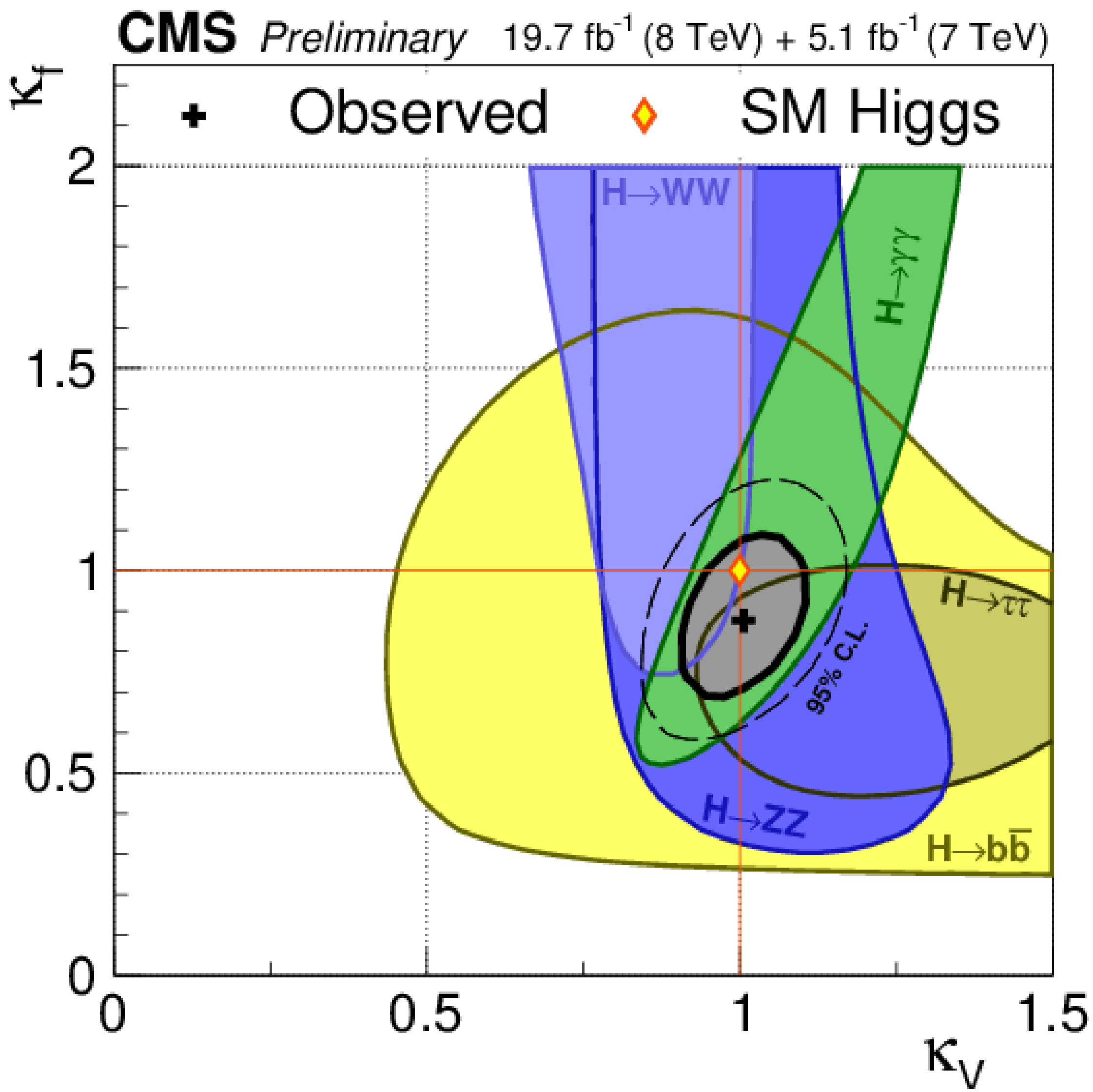


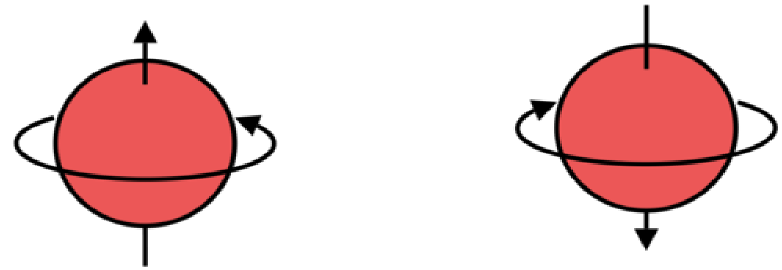
For each channel separate gg/VBF production

Data agree with the Standard Model expectation

Measuring the Higgs spin

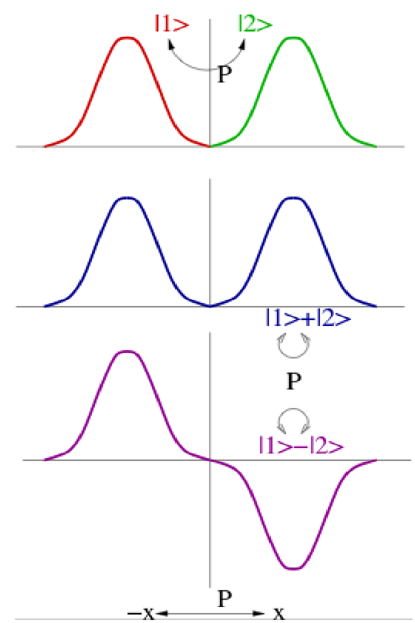
Spin + parity measurements

Predicted 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 $(x, y, z, t) \rightarrow (-x, -y, -z, t)$

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

Measured by sequential decay

Spin of the Higgs

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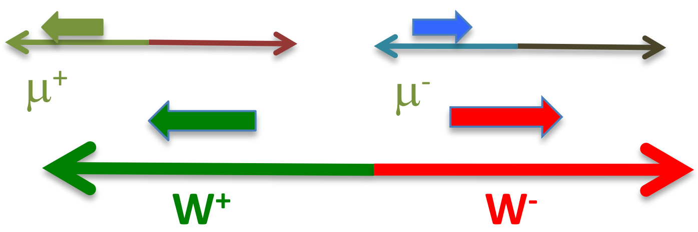
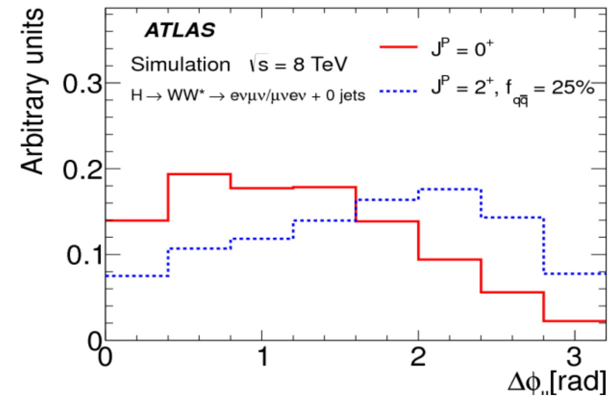
Example: $h \rightarrow W^+W^-$

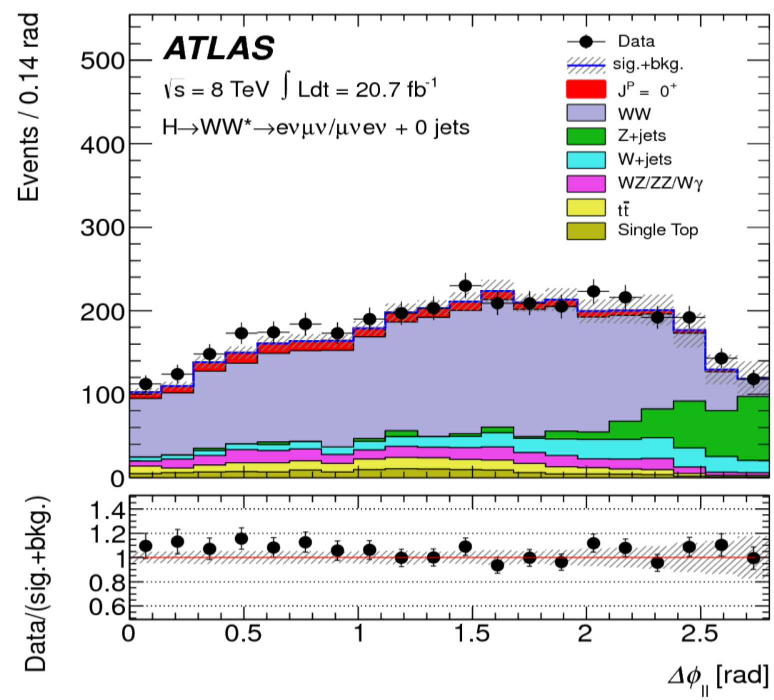
Spin 0 ➔ Spins of W's opposite
μ's aligned



Spin 2: no such correlation

(After subtracting background)
data agree better with spin 0





Parity of the Higgs

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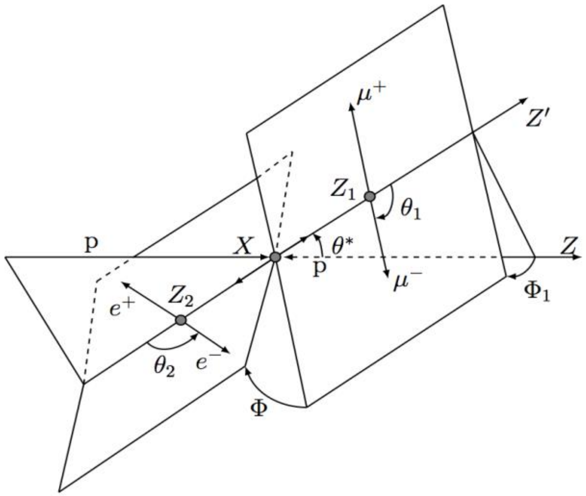
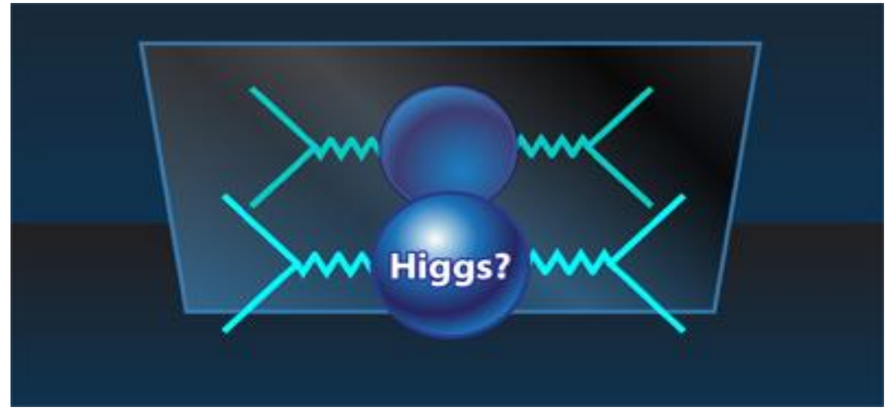
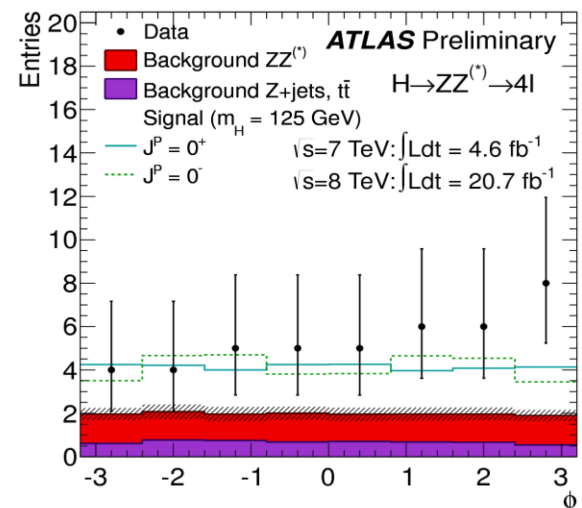
Example: h→ ZZ
compare 0^+ versus 0^-

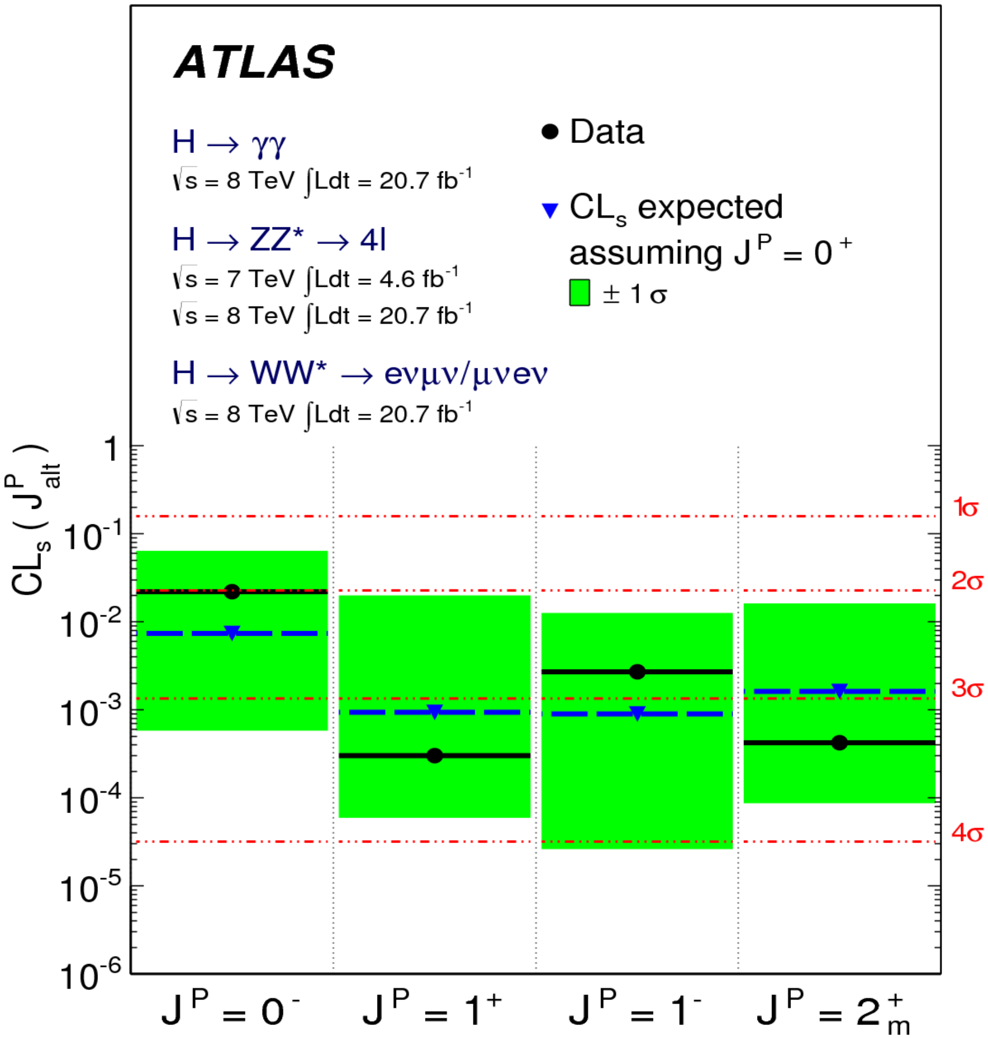




E.g. angle between decay planes
Use several observables to find optimal discrimination



Spin – Parity summary



Compare SM 0^+ with other possibilities

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

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 feels like a Higgs‘

➔ indeed ‘we have found it’ = ‘a Higgs boson’

The next tasks

The remaining questions

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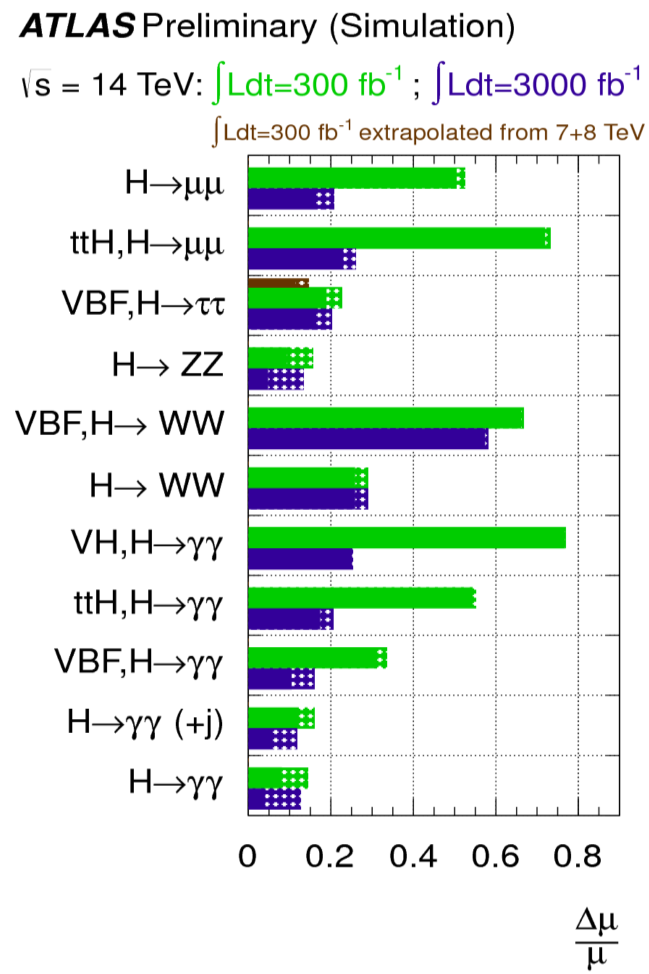
- Higher precision for couplings to W, Z, ….. spin/parity
- Direct measurements of coupling to fermions
- Higgs potential: h → hh

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



It took 116 years to establish the SM

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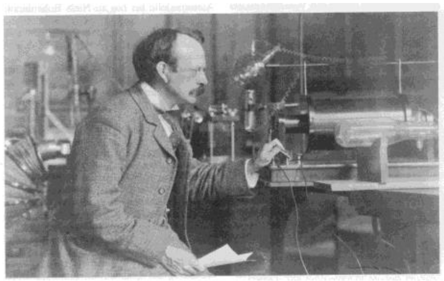
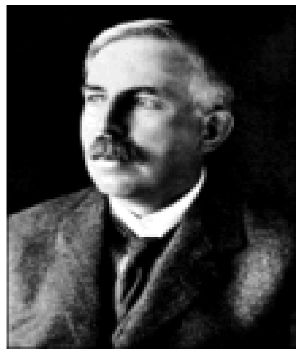


1896: First elementary particle found



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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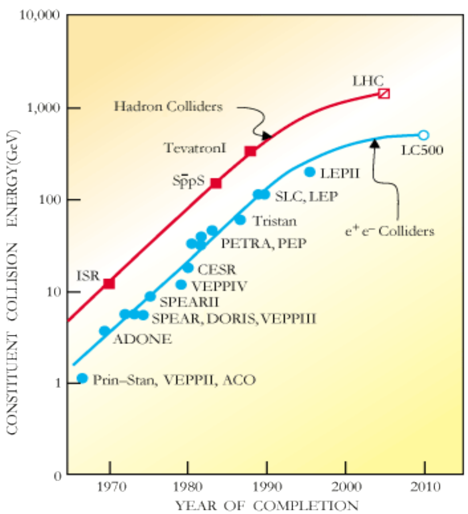
LHC will run for the next 20 years

➔ 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!

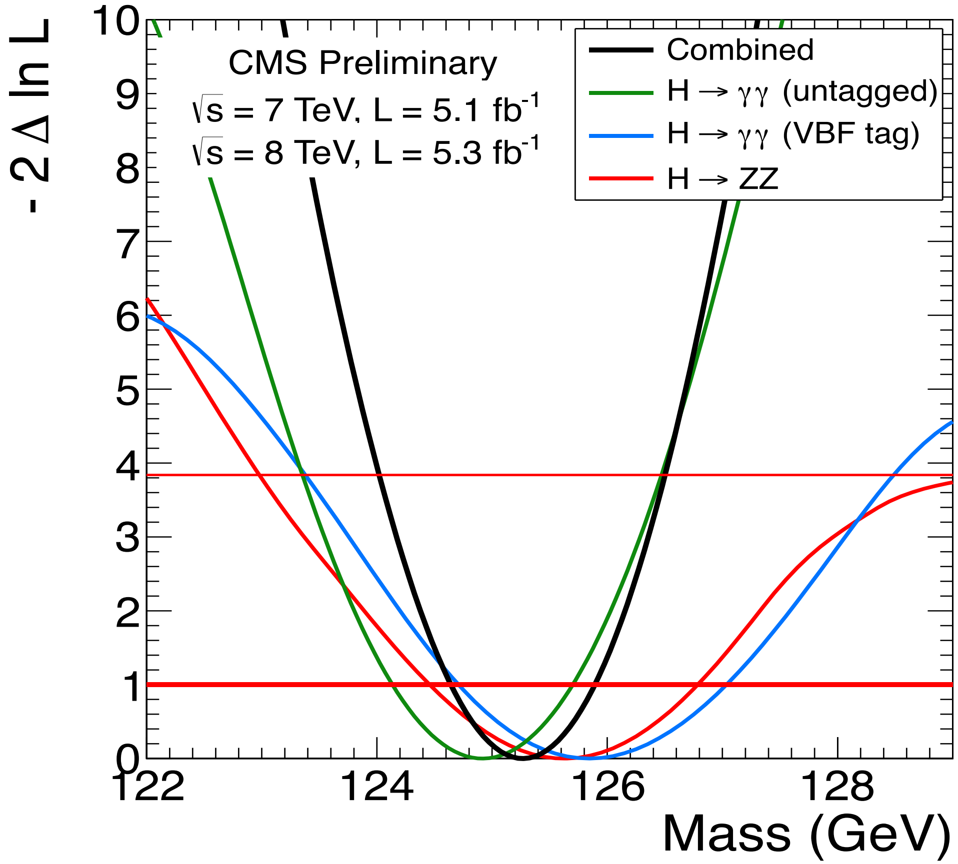


But we also have to look beyond:
R&D on more powerfull accelerators should proceed with vigour!

Both for theory and experiment: an exciting time ahead!

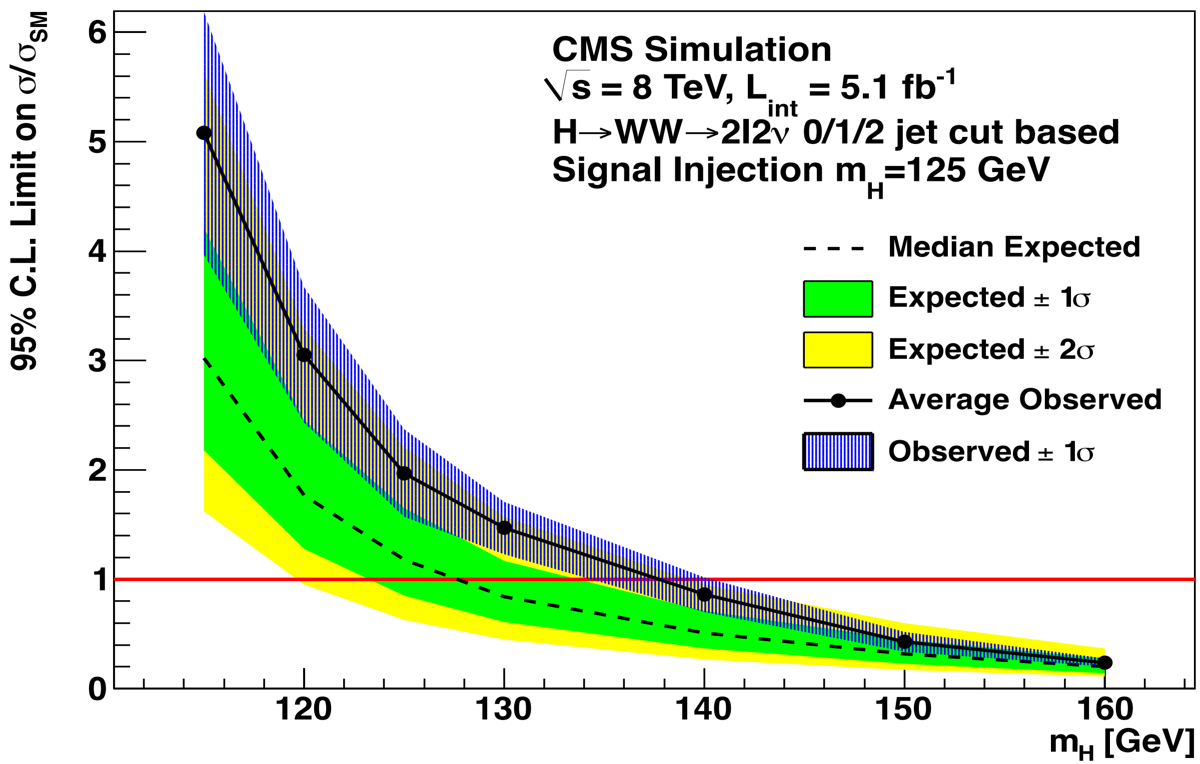
BACK - UP

Consistency of masses



Disadvantage: broad signal

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

Significance of observation

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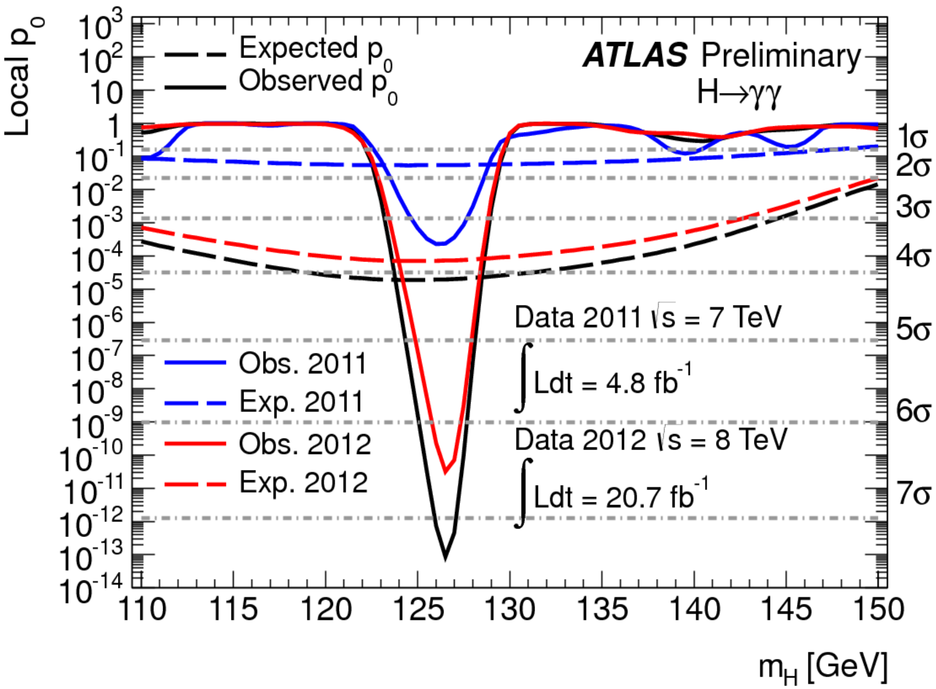
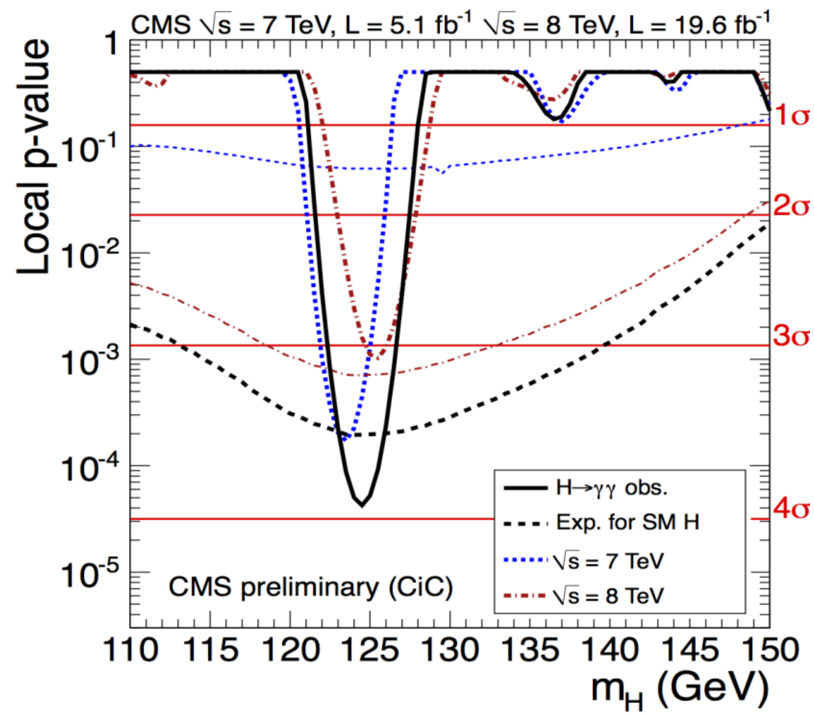
p-value: probability for the background to fluctate to observation





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

Significance of observation

BERGISCHE
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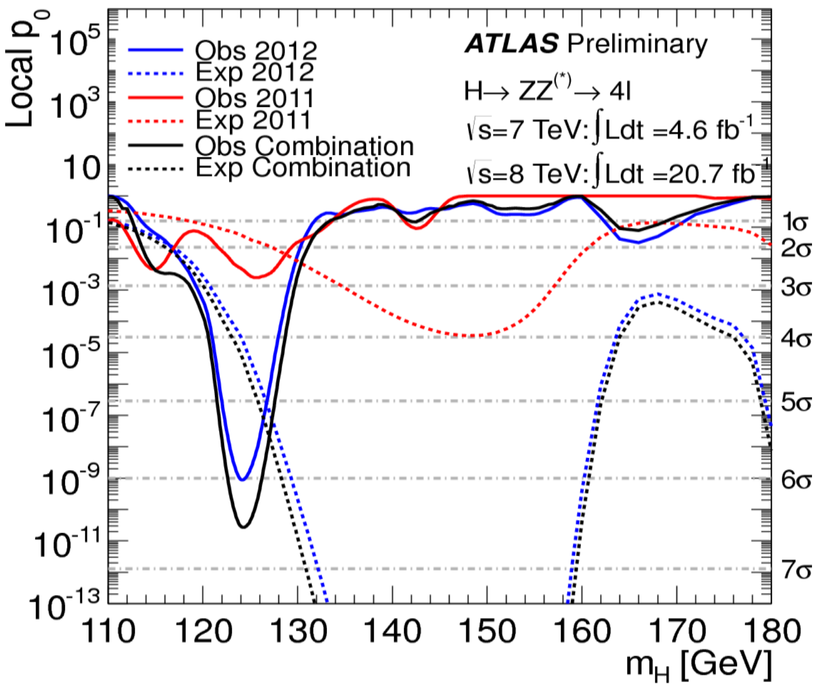
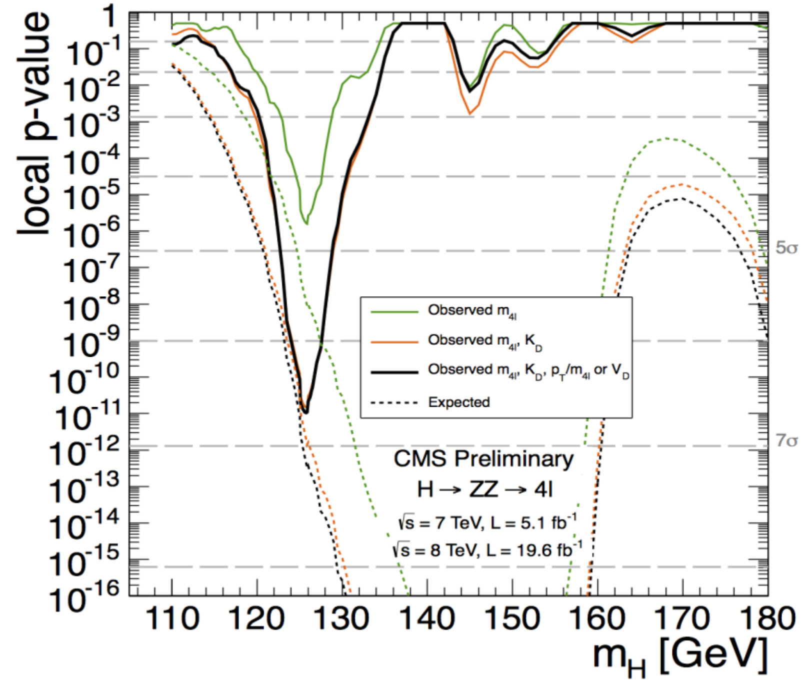
WUPPERTAL

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