Higgs searches

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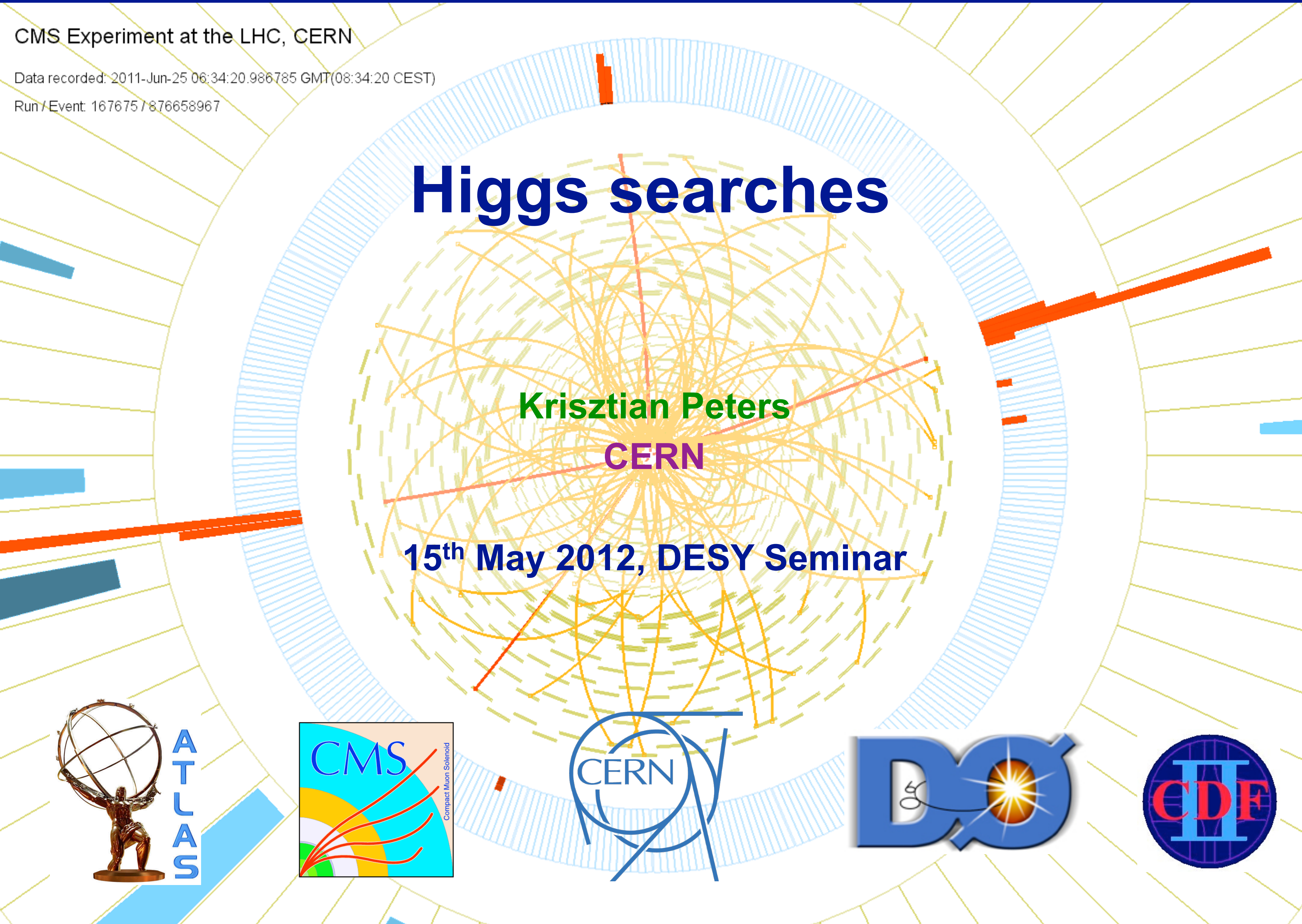
CERN

15th May 2012, DESY Seminar

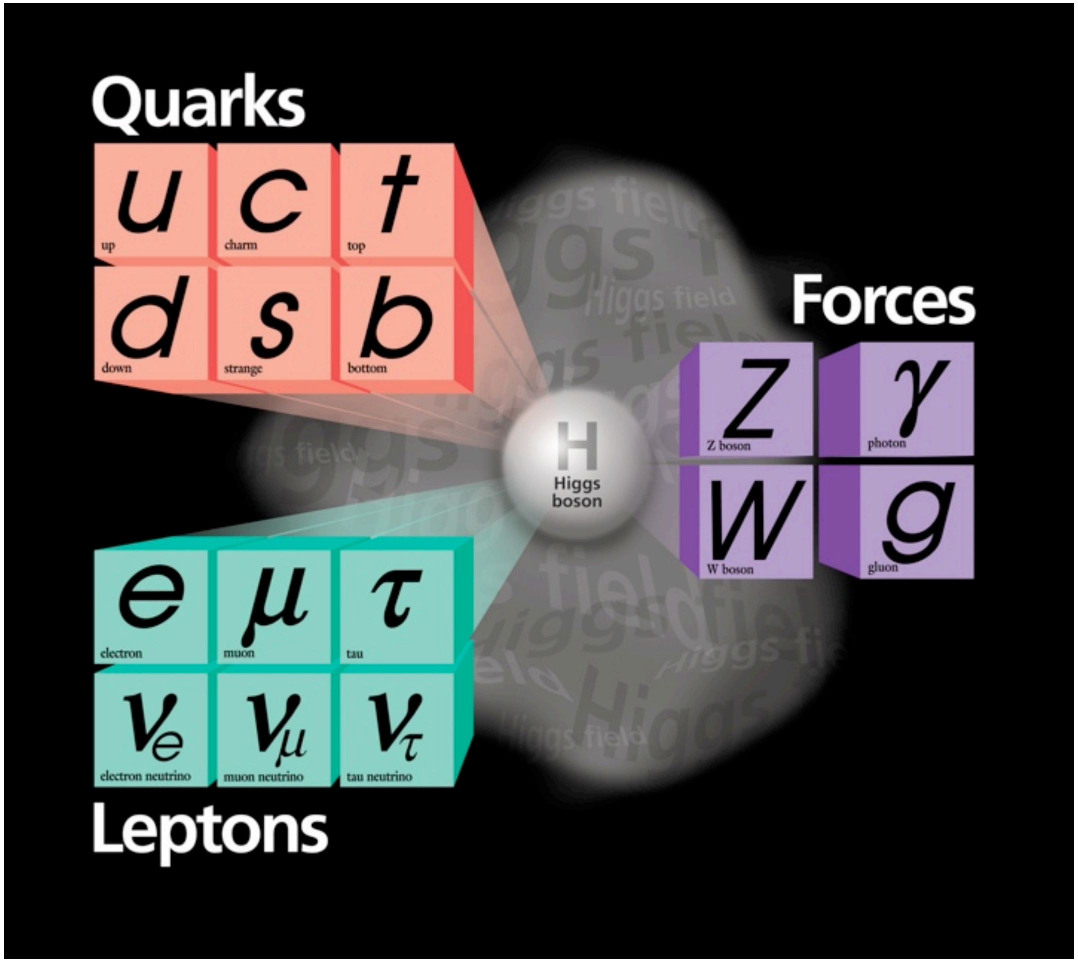


Outline

CMS Experiment at the LHC, CERN
Data recorded: 2011-Jun-25 06:34:20.986785 GMT(08:34:20 CEST)
Run / Event: 167675 / 876658967

- Introduction
- Challenges and analysis strategies
- Main discovery channels at the LHC
- Combined LHC results
- Tevatron results
- Conclusions

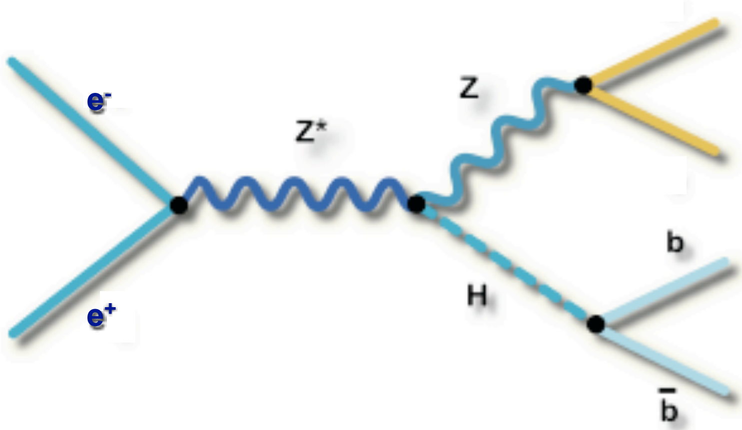
The Standard Model of Particle Physics



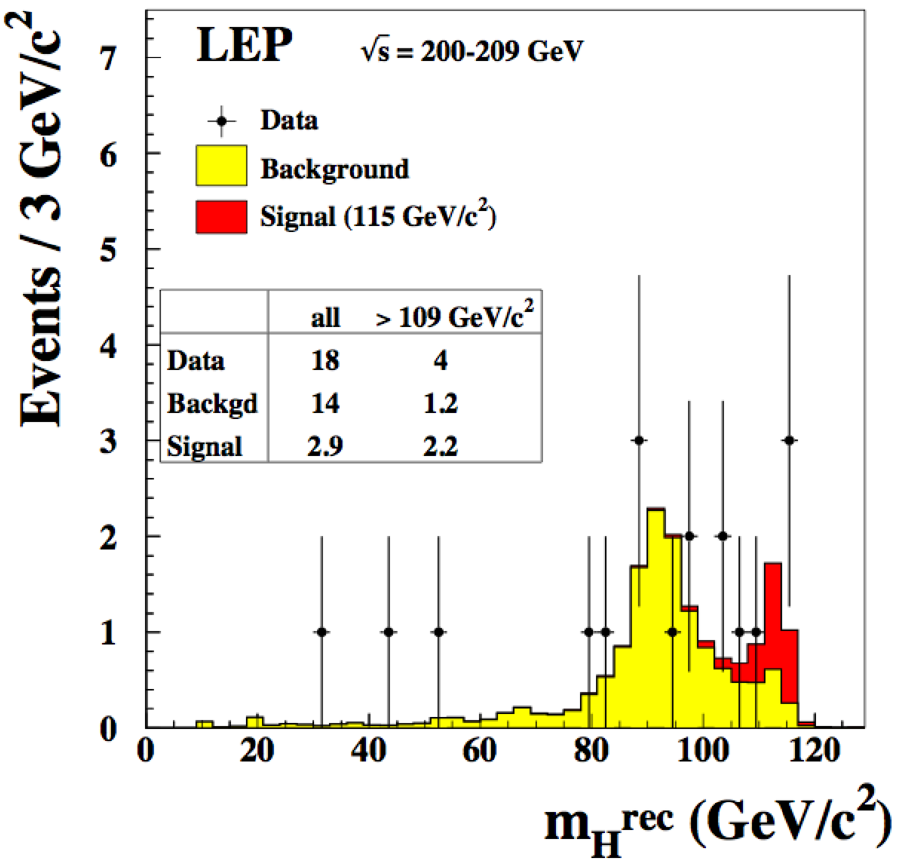
The origin of mass is one of the key questions of particle physics

The Higgs particle is the only missing piece of the Standard Model

Higgs searches at LEP



$\sqrt{s} - m_Z = 206.6 - 91.2 = 115.4$ GeV

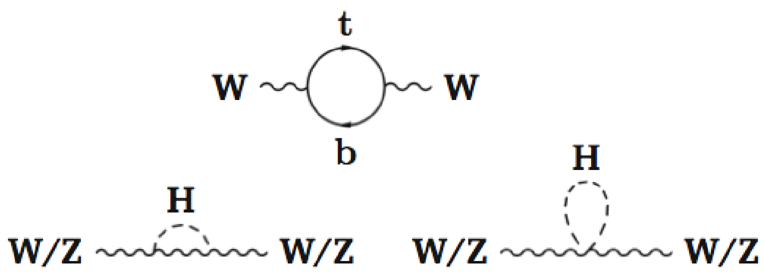


Excess around 115 GeV not significant

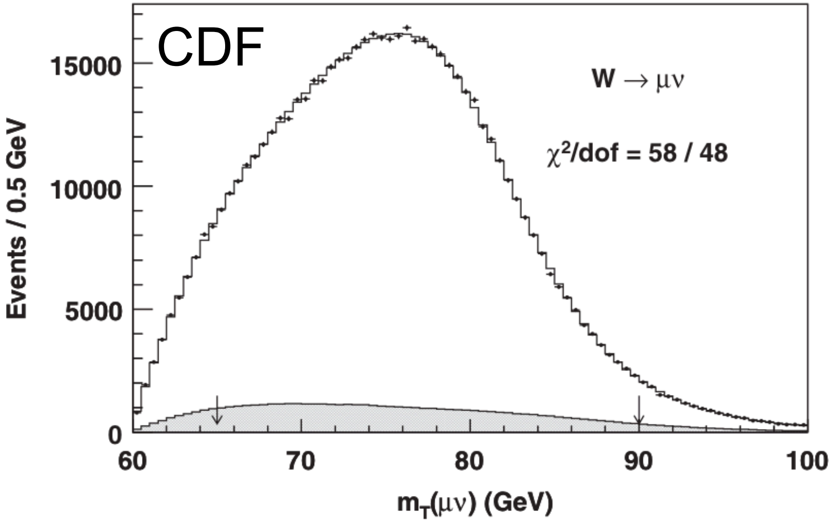
$m_H \geq 114.4$ GeV @ 95% CL

Stalking the Higgs

The SM relates m_H, m_t, m_W via radiative corrections:



PRL **108**, 151803 (2012)

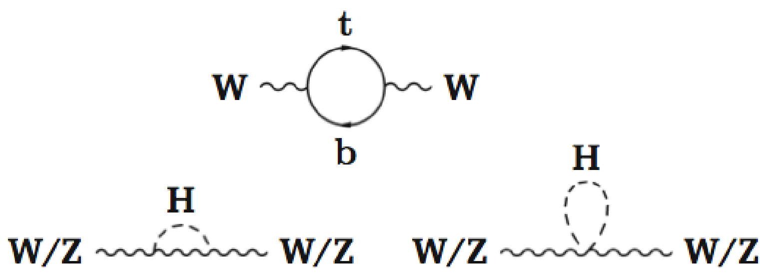


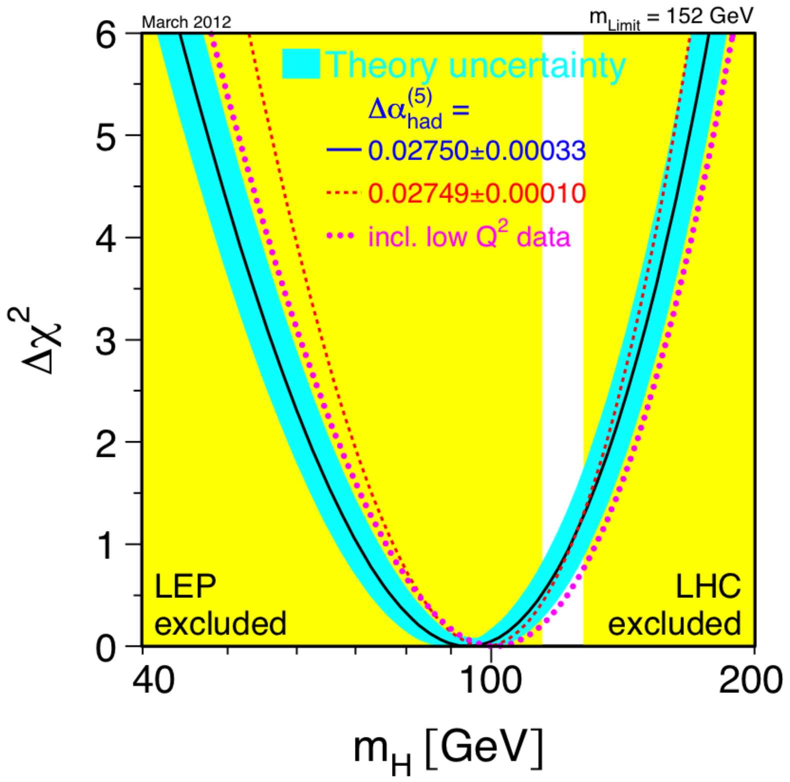
Combined top mass from CDF+DØ:
173.2 ± 0.9 GeV

Combined *W* mass from CDF+DØ:
80387 ± 16 MeV

Stalking the Higgs

The SM relates m_H, m_t, m_W via radiative corrections:





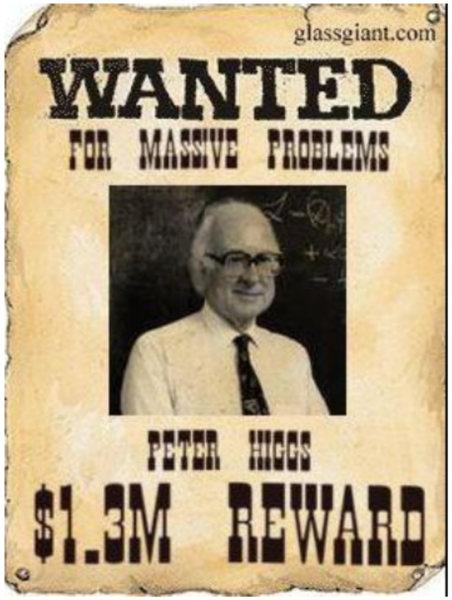
Indirect constraints on the Higgs boson mass from global EW fits:

$m_H < 152$ GeV @95%CL

Today's Higgs hunt

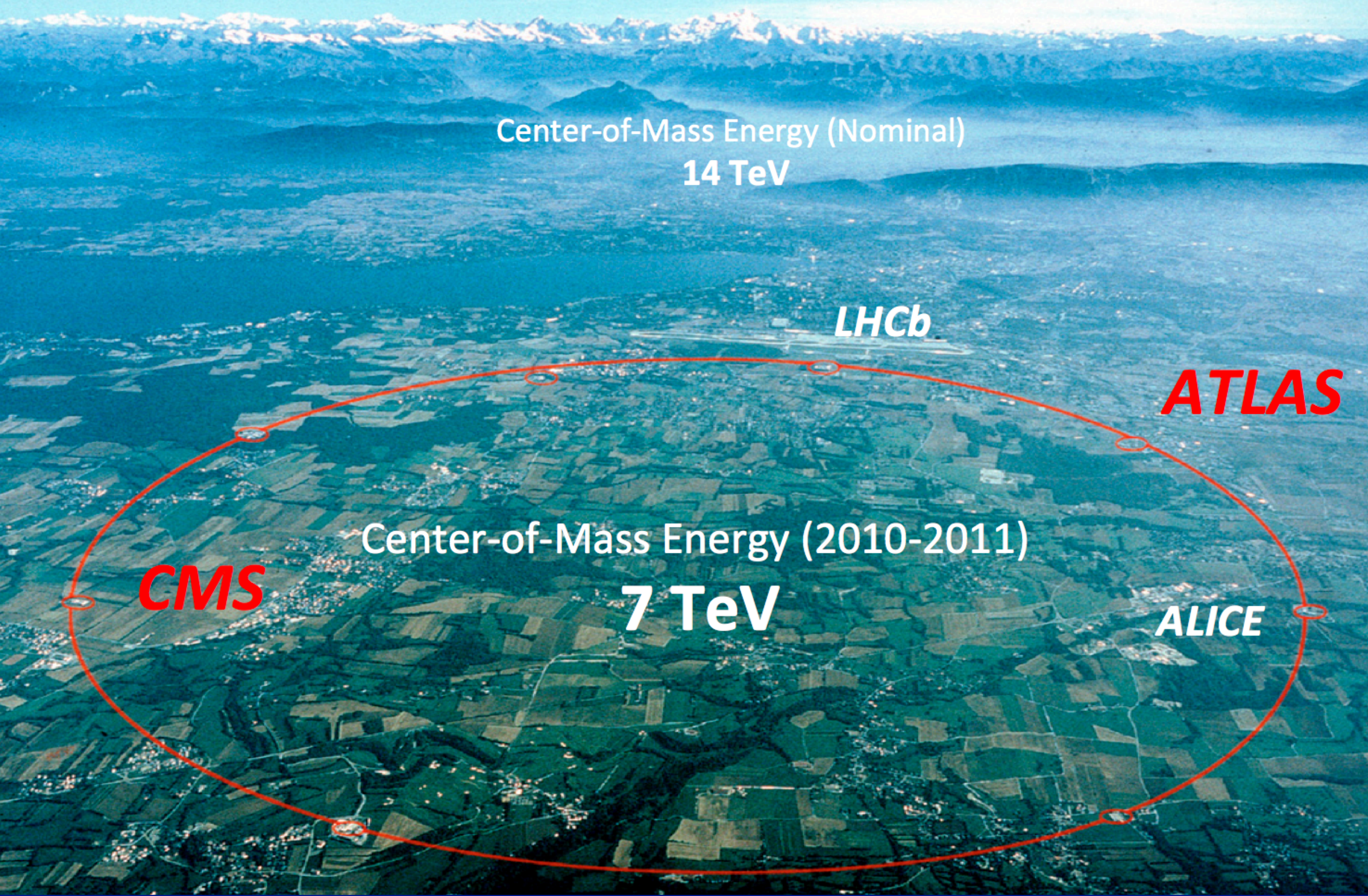
LHC

Tevatron

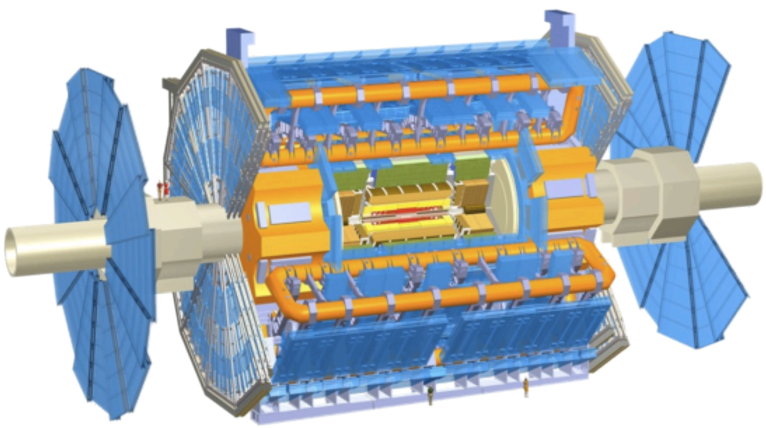


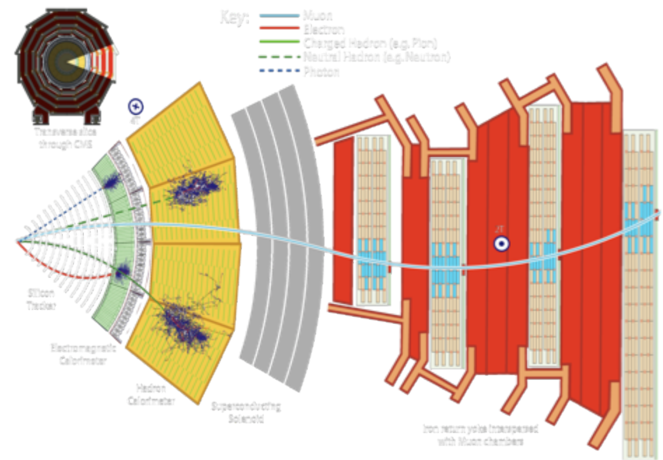
Searching for the Higgs is highest priority in LHC's and Tevatron's physics programme

LHC collider



ATLAS and *CMS* experiments





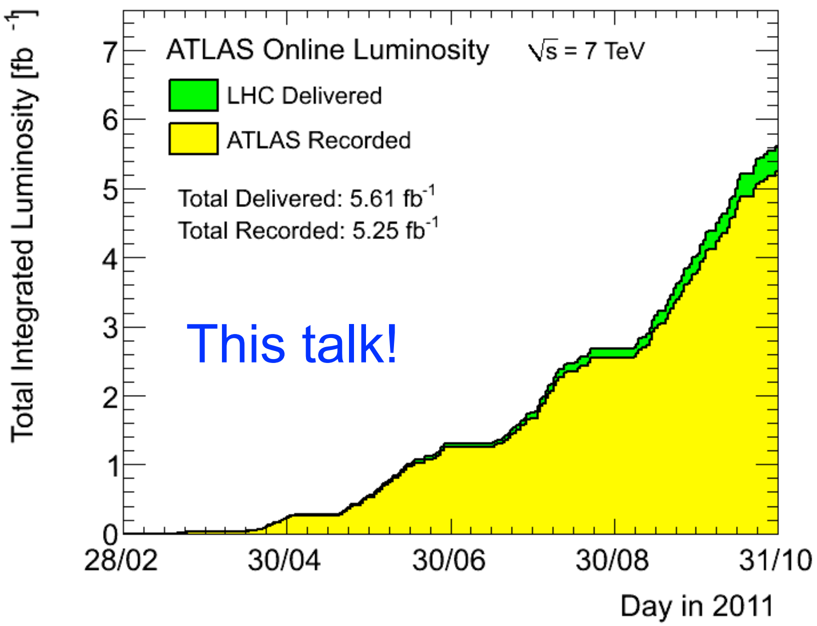
ATLAS: emphasis on excellent jet and missing E_T resolution, particle identification, and standalone muon measurement

CMS: emphasis on excellent electron/photon and tracking (muon) resolution

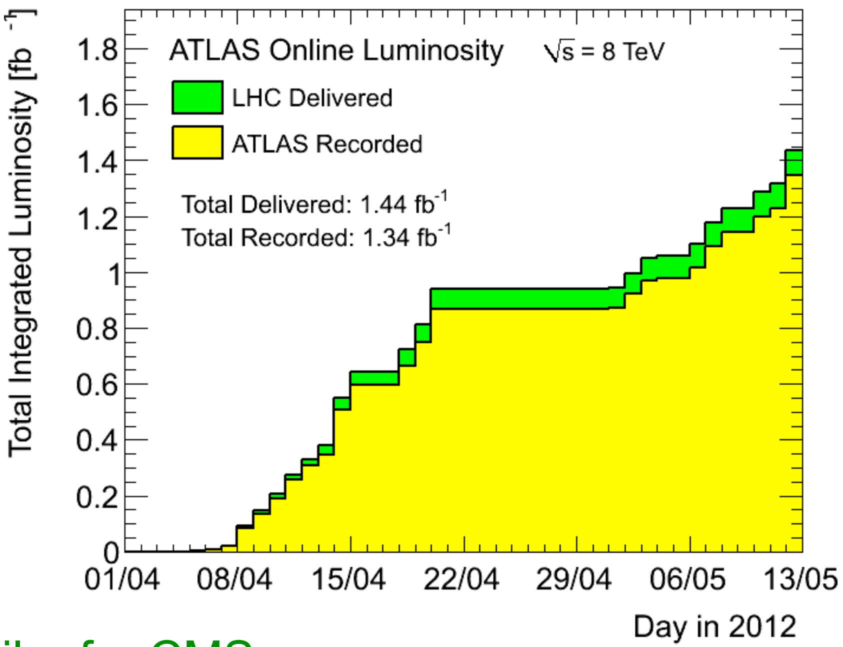
Detectors well understood, stable operation and data taking efficiencies above 90%

Dataset

2011



2012

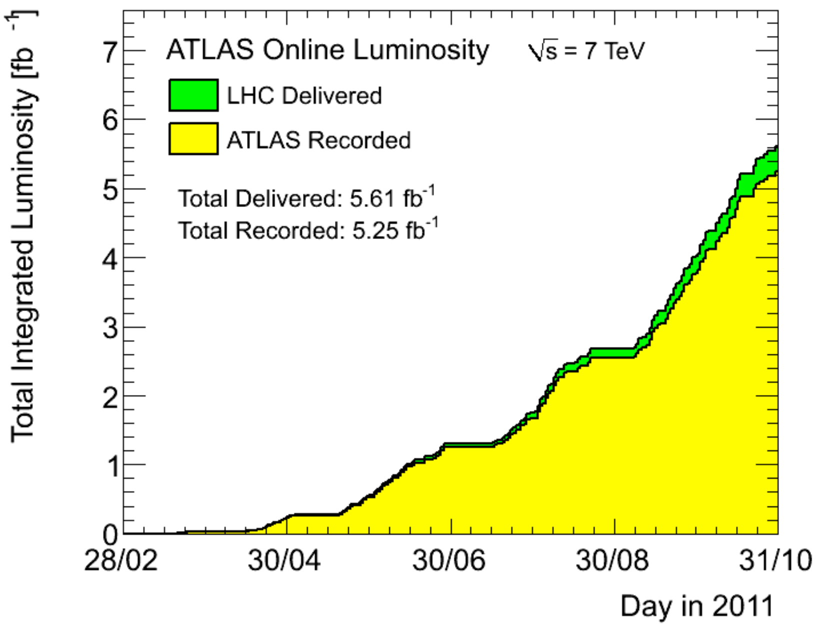


Similar for CMS

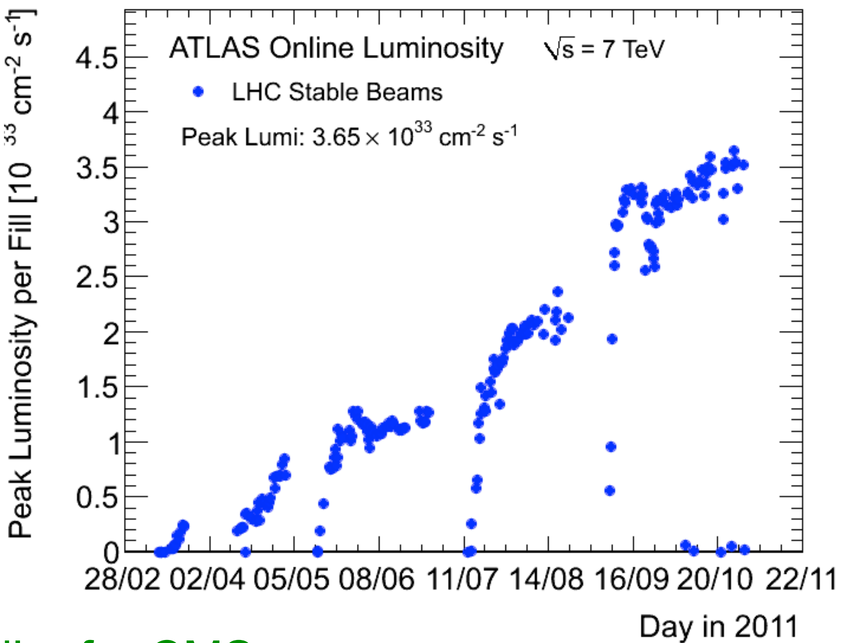
Total recorded luminosity in 2011 ~5 fb^{-1}

Dataset

2011



2011



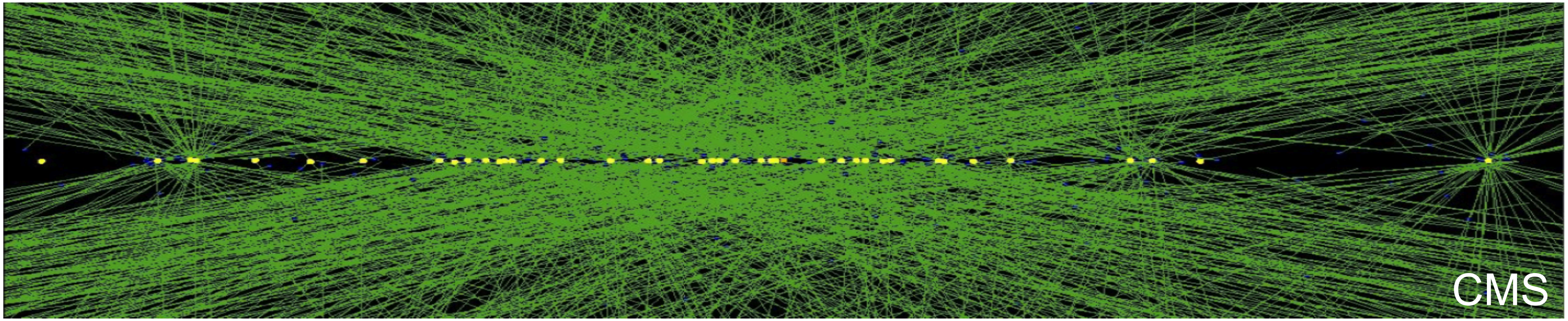
Similar for CMS

Total recorded luminosity in 2011 ~5 fb^{-1}

More data with higher instantaneous luminosities

Challenges with high luminosity

Event with 40 reconstructed vertices from a high pile-up fill (LHC)

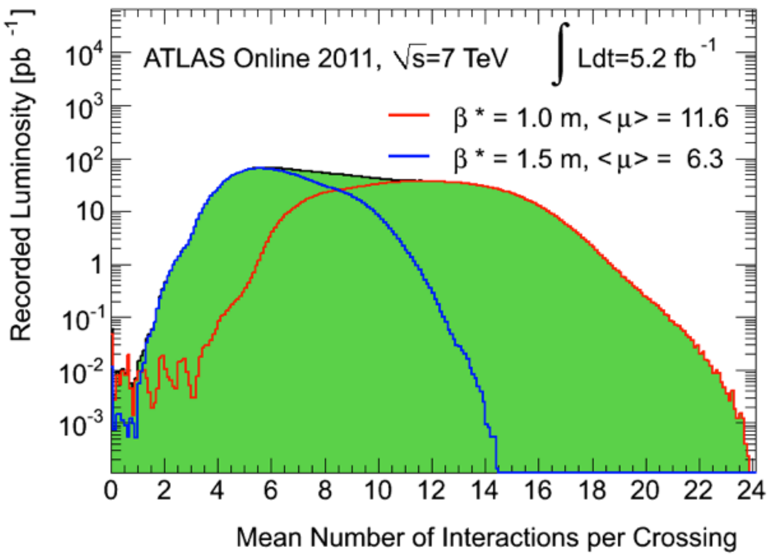


Average number of interactions:

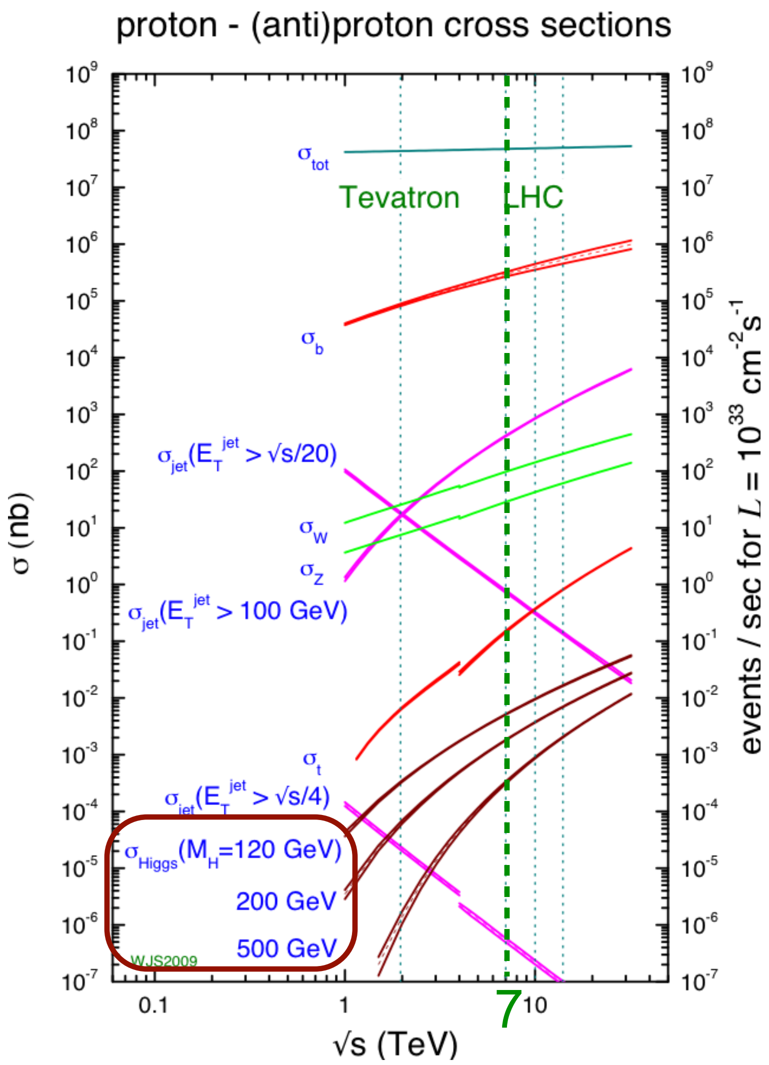
2010: <N>=2

2011: <N>=6 − 12

2012: <N>=~30

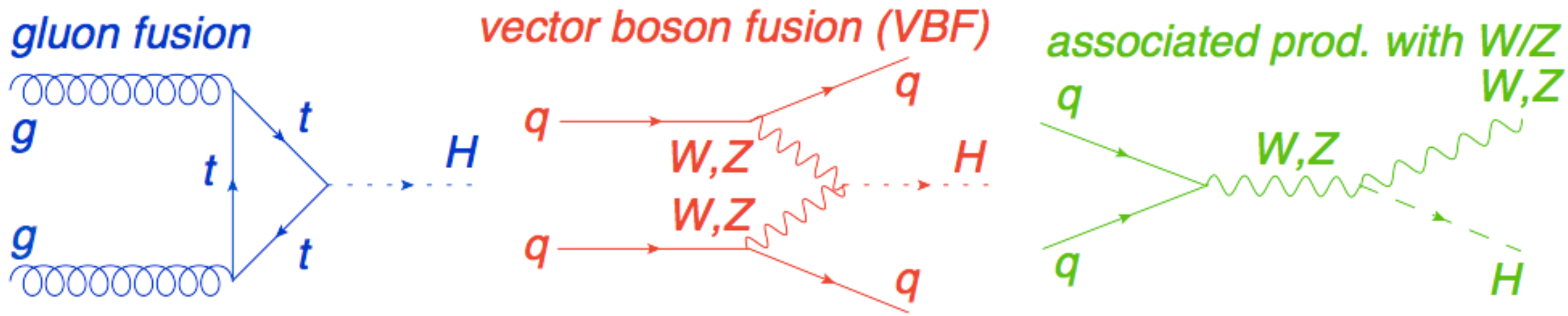


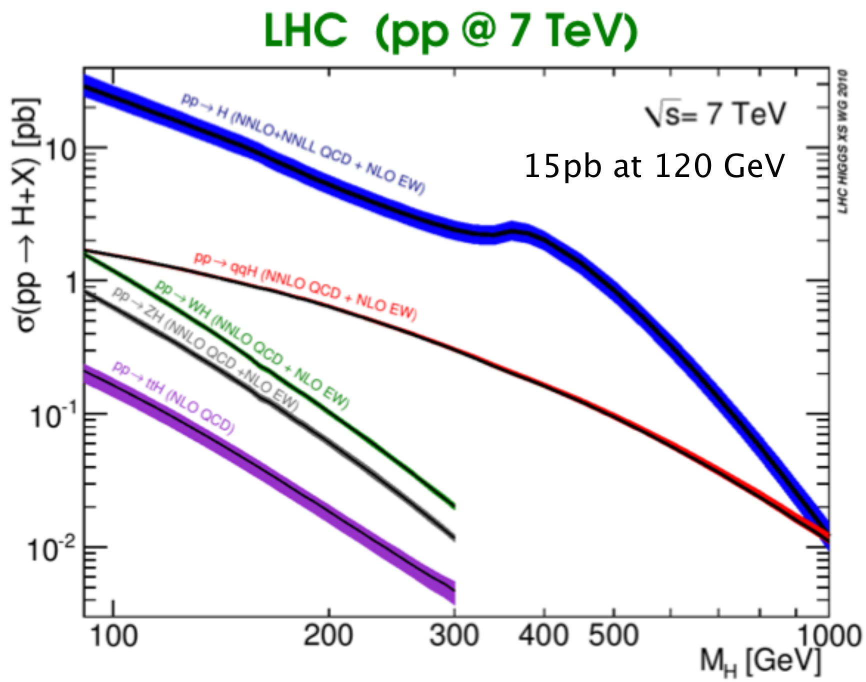
Higgs production



Only one in 10^{10} events will be a Higgs boson (m_H=120 GeV) at the LHC

Higgs production

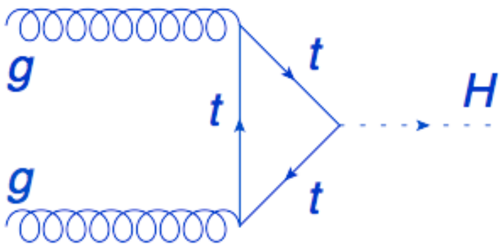




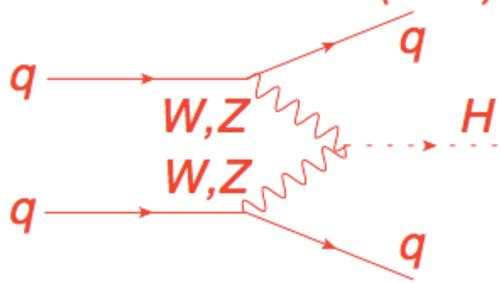
Leptonic decay modes of the Higgs provide main handle against overwhelming QCD backgrounds

Higgs production

gluon fusion

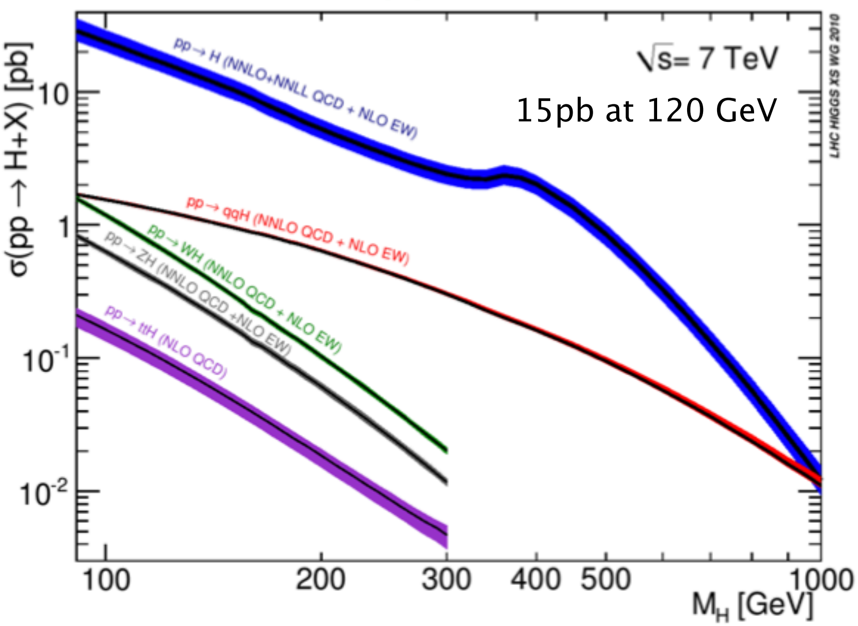


vector boson fusion (VBF)

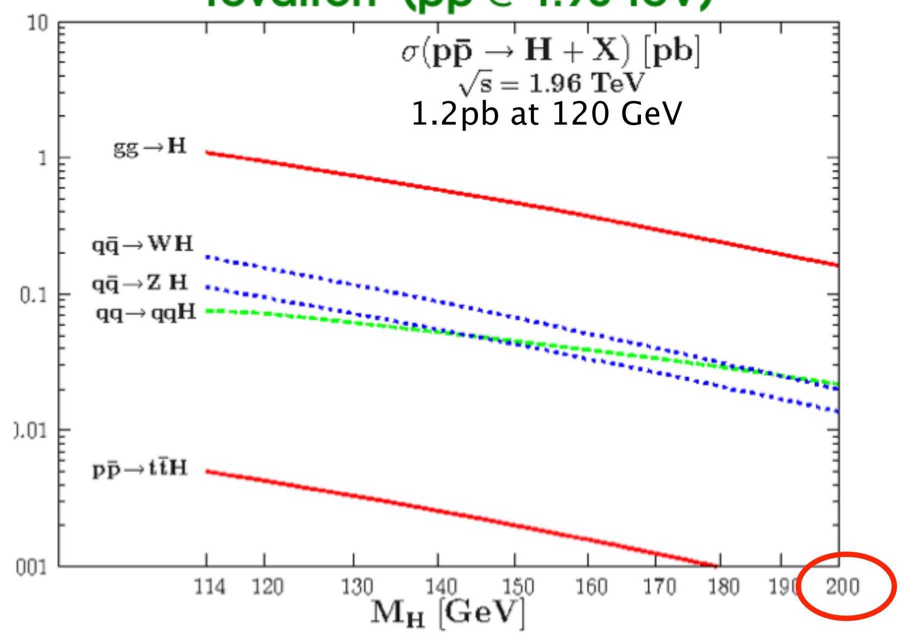


associated prod. with W/Z

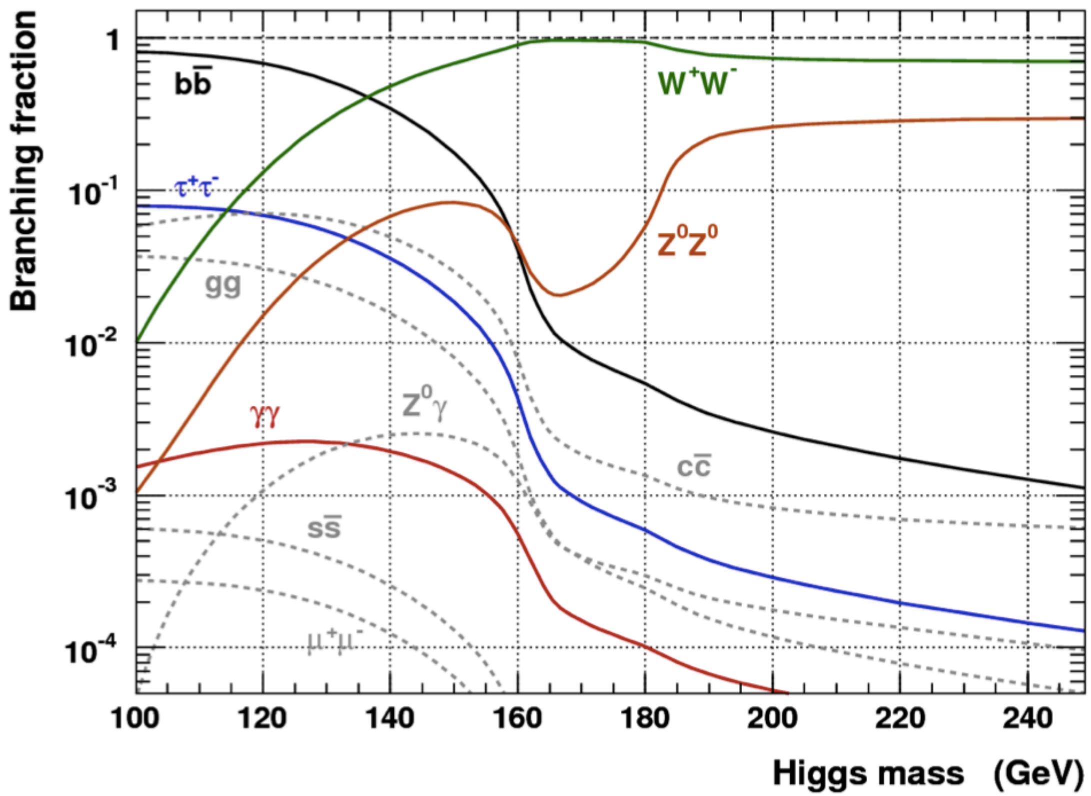
LHC (pp @ 7 TeV)



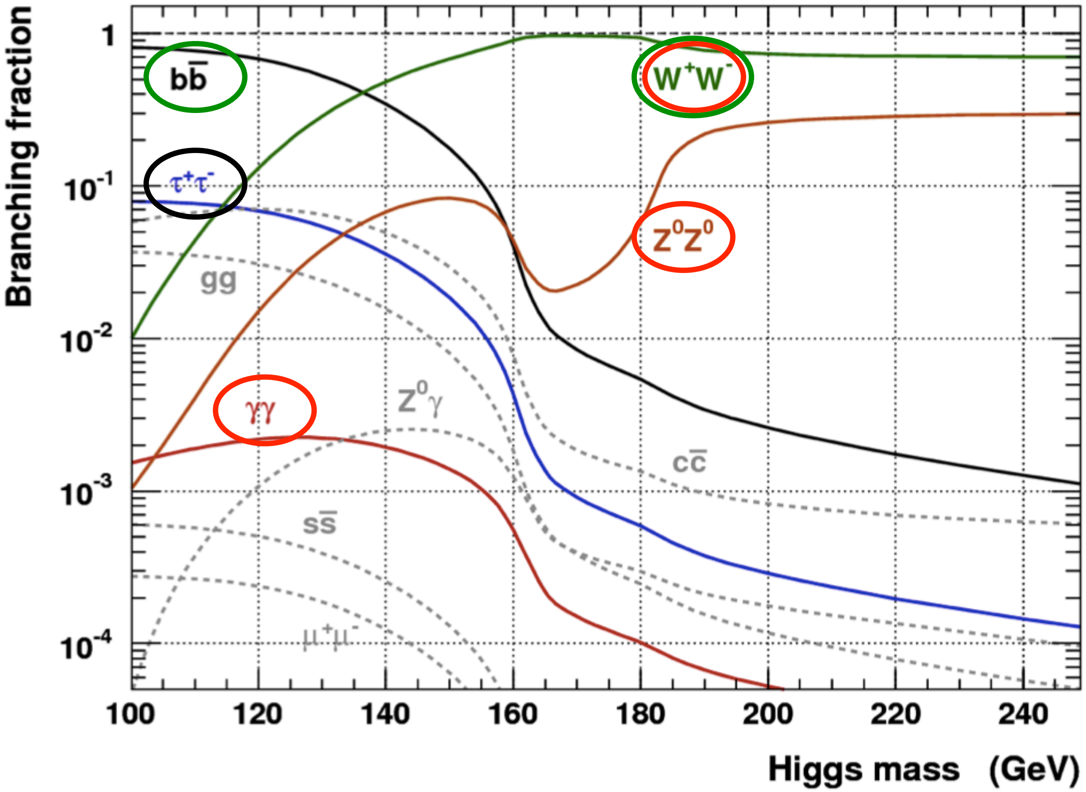
Tevatron ($p\bar{p}$ @ 1.96 TeV)



Higgs decays



Search strategy



Main discovery channels at:

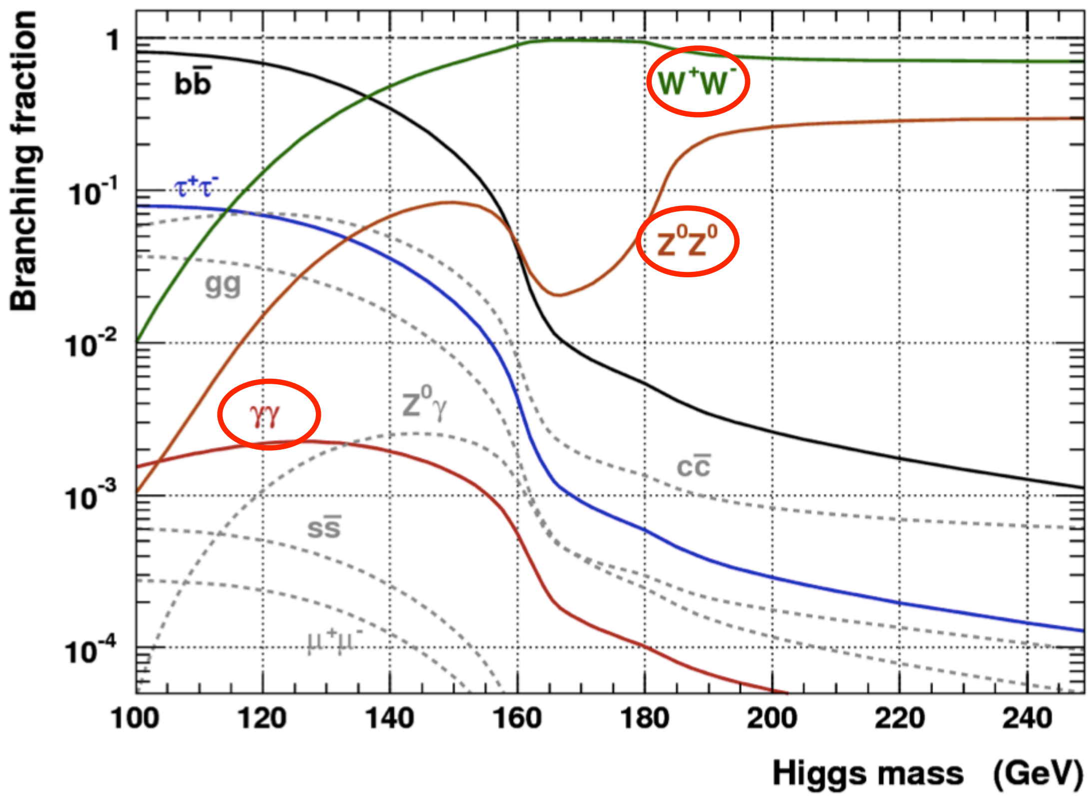
LHC

Tevatron

Investigate different production mechanisms and a large number of final states

→ Focus on the main search channels in this talk

Main LHC discovery channels

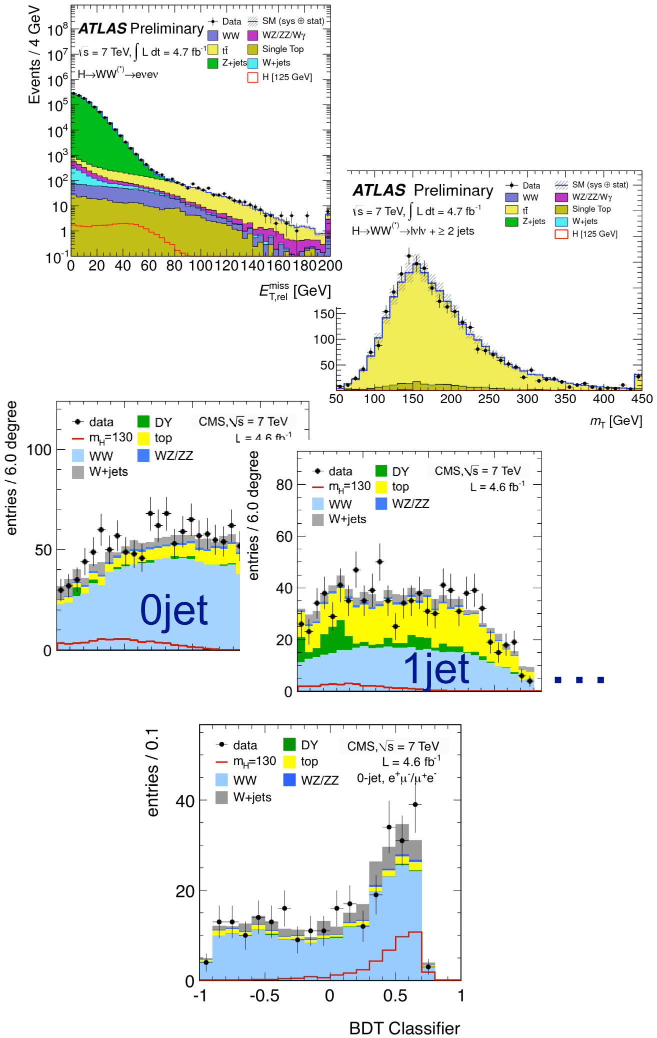


Complemented with: exclusive searches (low mass)

- Vector boson fusion (decay to $\tau\tau$, $\gamma\gamma$, WW)
- Boosted Higgs (decay to bb)

semi-leptonic WW/ZZ decays (high mass)

Basic analysis strategies

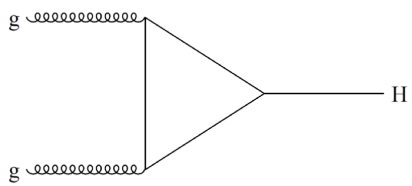


1. Select event with isolated leptons or photons to remove the bulk of the backgrounds
2. Estimate or cross check backgrounds (with data driven methods) in control regions (depleted signal contributions)
3. Increase sensitivity by splitting analysis into sub-channels with different S/B
4. Tighten selection and/or use MVA techniques
5. Searches complemented with measurements of SM backgrounds

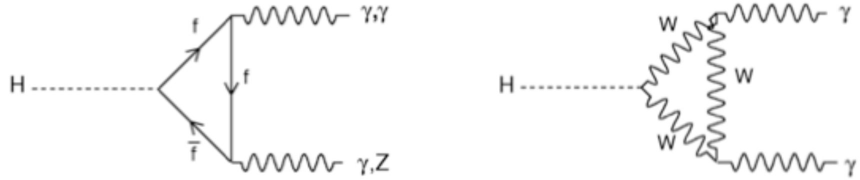
Higgs boson with diphoton decay

Most sensitive in the mass region above LEP limit (high resolution 1-2%)

Main production and decay through loops



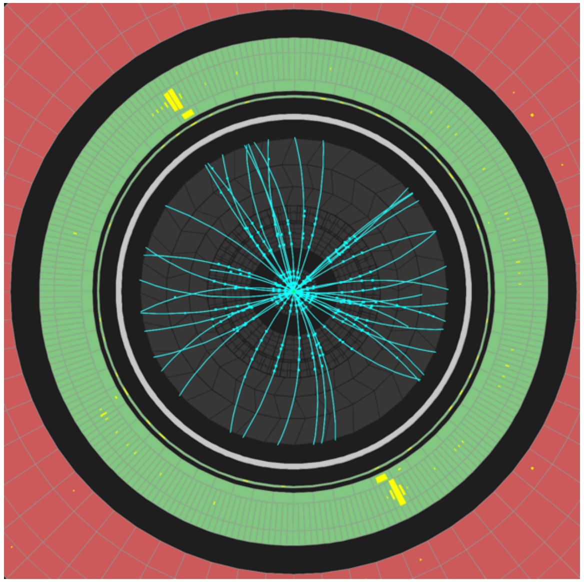
gluon-fusion production



BR ~ 0.2%

decay to $\gamma\gamma$

Clean discovery channel: Select events with two isolated high p_T photons. Look for bump in deeply falling diphoton mass spectrum



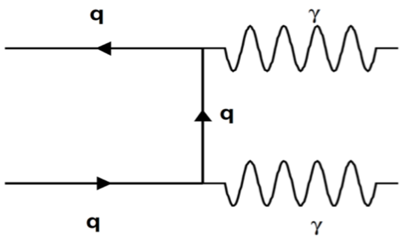
Relevant aspects:

- Photon identification / background rejection
- Good diphoton mass resolution
- Signal extraction

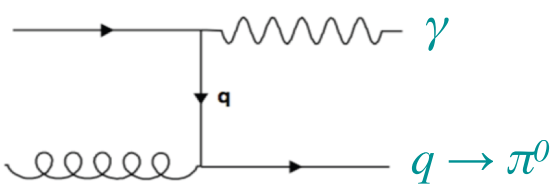
Photon purity

Main backgrounds (estimated from data)

- Irreducible: SM $\gamma\gamma$ production
- Reducible: γj production with $q/g \rightarrow \pi^0$



Irreducible



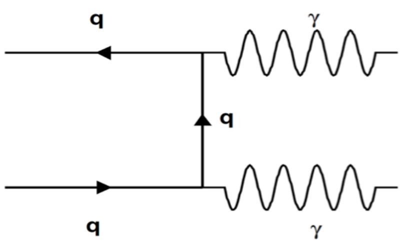
Reducible

Critical to reach rejections $O(10^4)$

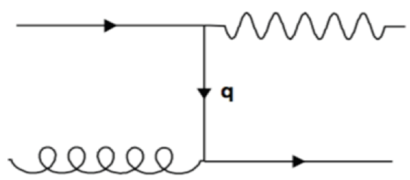
Photon purity

Main backgrounds (estimated from data)

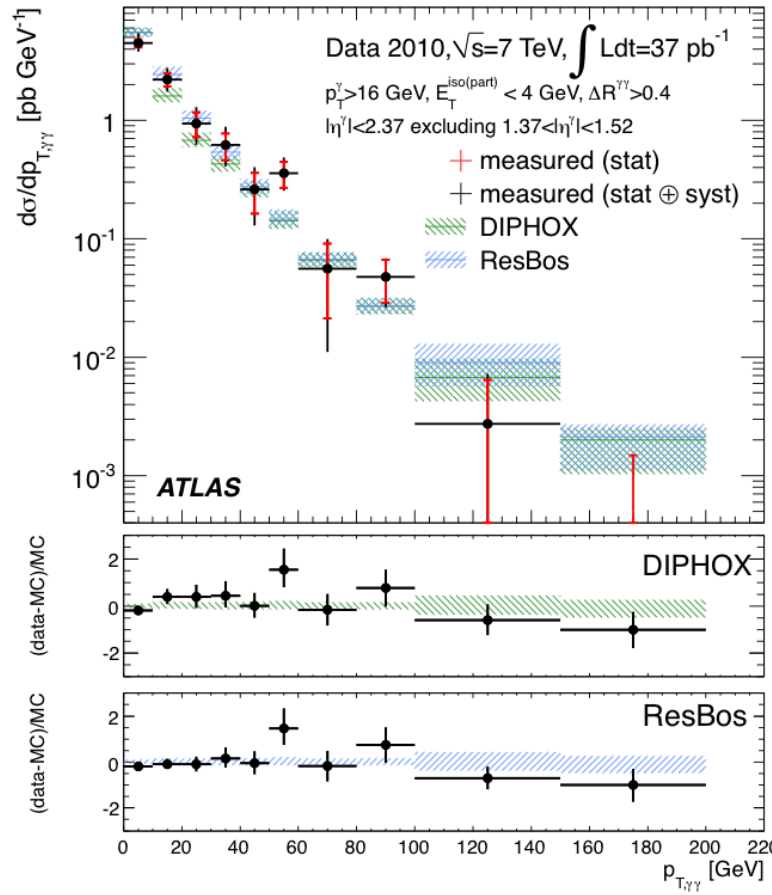
- Irreducible: SM $\gamma\gamma$ production
- Reducible: γj production with $q/g \rightarrow \pi^0$



Irreducible



Reducible



Measure SM diphoton production cross section

- Cross check of diphoton selection procedure
- Good understanding of dominant background

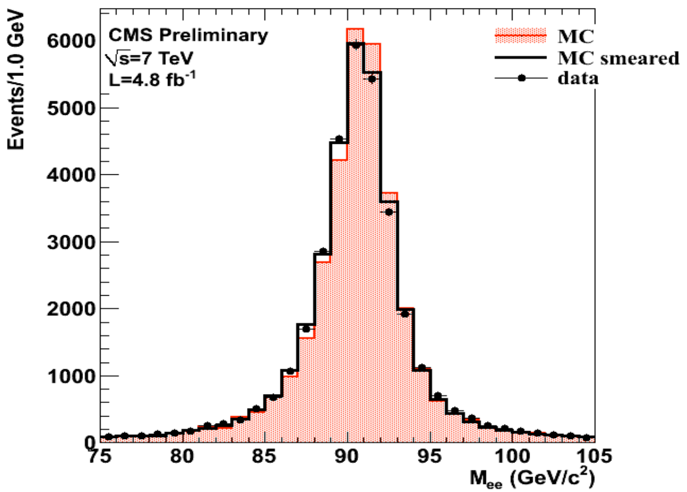
Diphoton mass

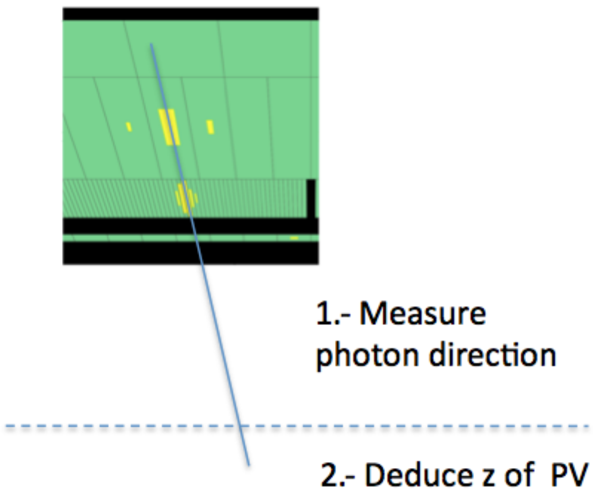
Photon energy calibration

- Energy scale and resolution corrections from *Z* decay to electrons
- Need accurate material description for $e \rightarrow \gamma$ extrapolation

Photon polar angle measurement

- Use photon pointing (*ATLAS*), MVA technique (*CMS*)
- Improvement on mass resolution ~5−20% with 2011 pile-up range





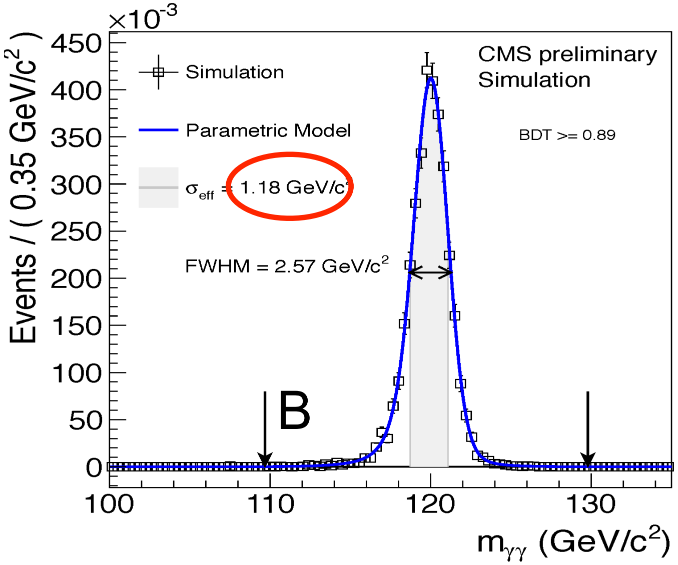
$H \to \gamma\gamma$ event categorisation

Separate events into categories with different S/B and resolutions, based on:

- Photon conversions, γ impact point on CAL, diphoton p_T related variable (*ATLAS*)
- VBF signature category & MVA analysis to define further categories (*CMS*)

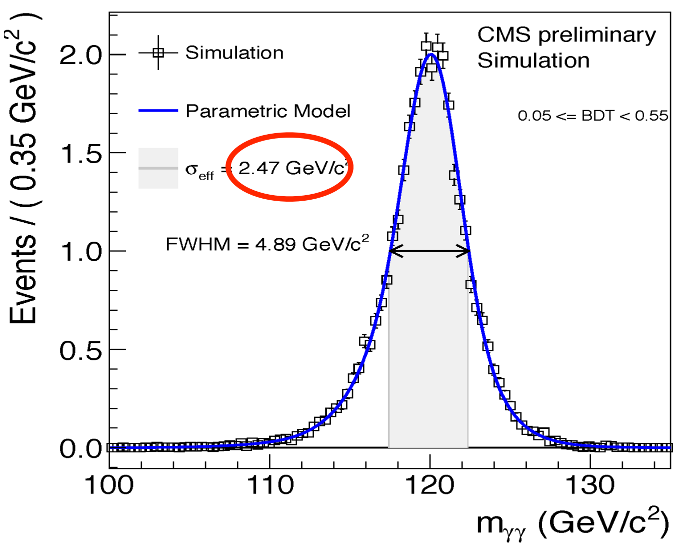
→ Considerable increase in sensitivity

Best class by MVA output



S/B = 3.8%

4th class by MVA output

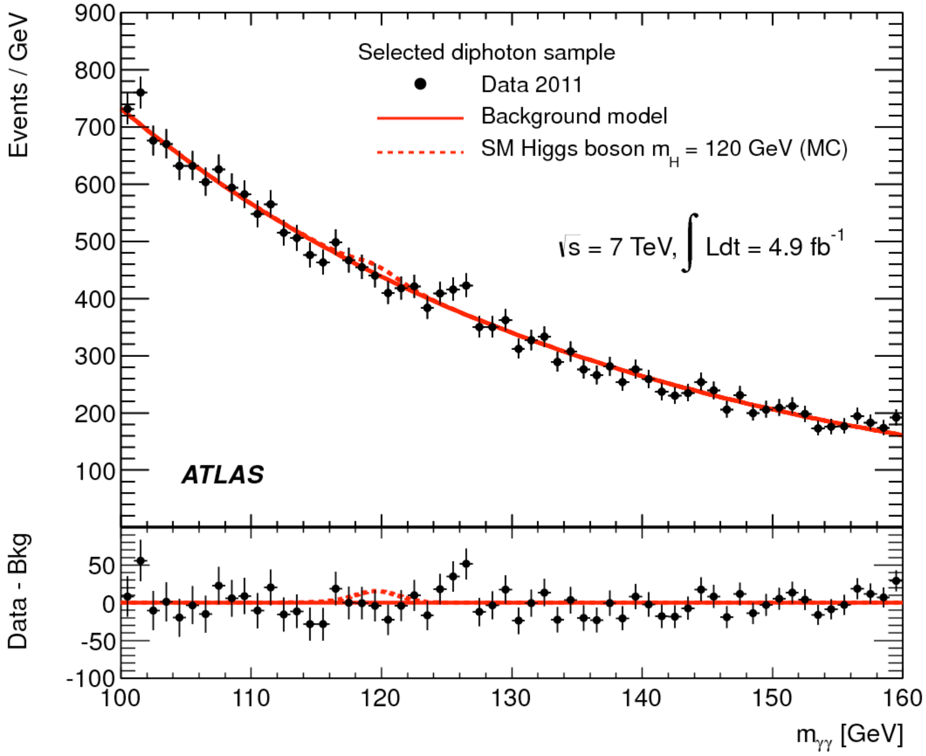


S/B = 0.7%

1-2% m_H resolution

$H \rightarrow \gamma\gamma$ signal extraction

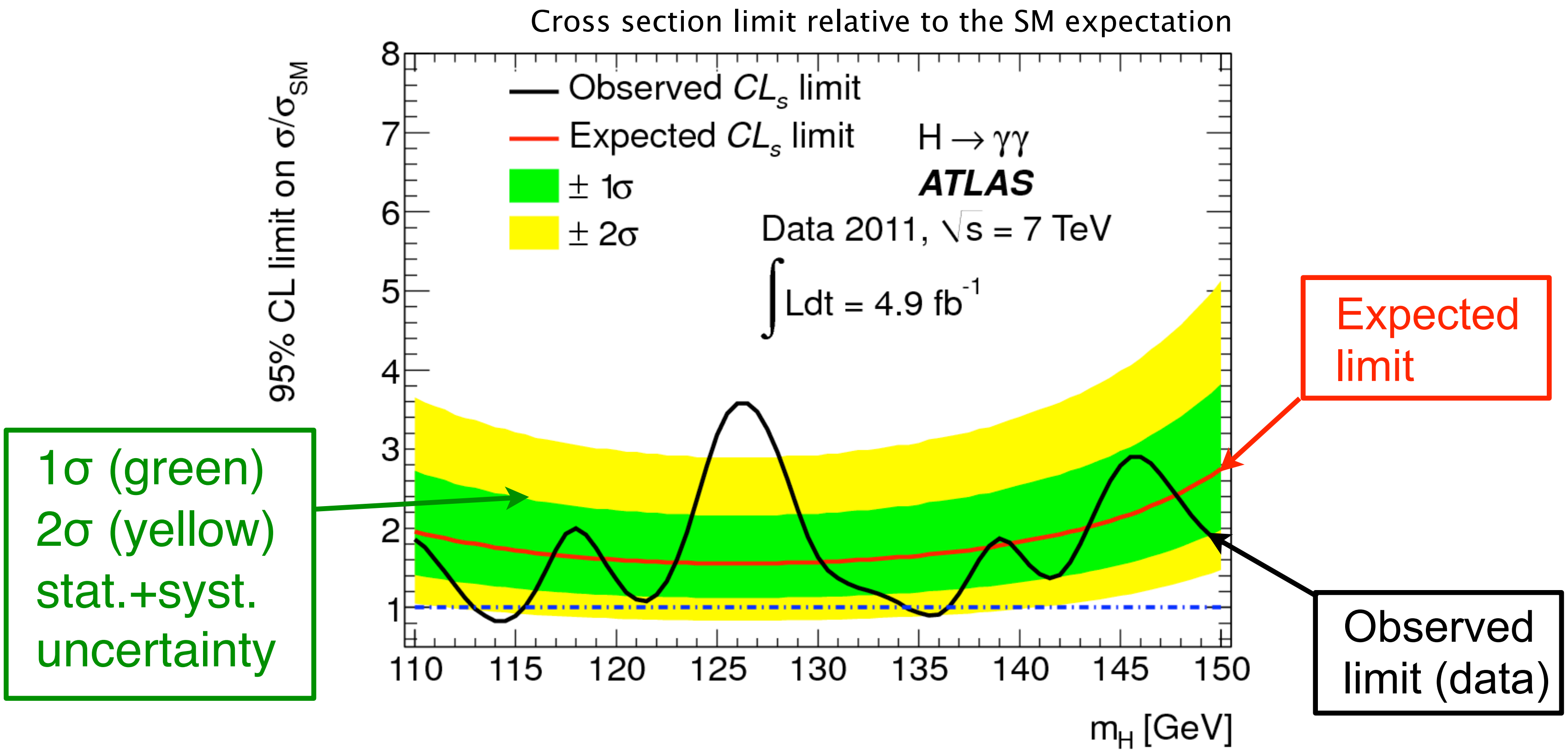
Estimate background contribution with fit to diphoton mass spectrum in data



Sum of all categories for illustration

Use as discriminating variable to distinguish signal and background

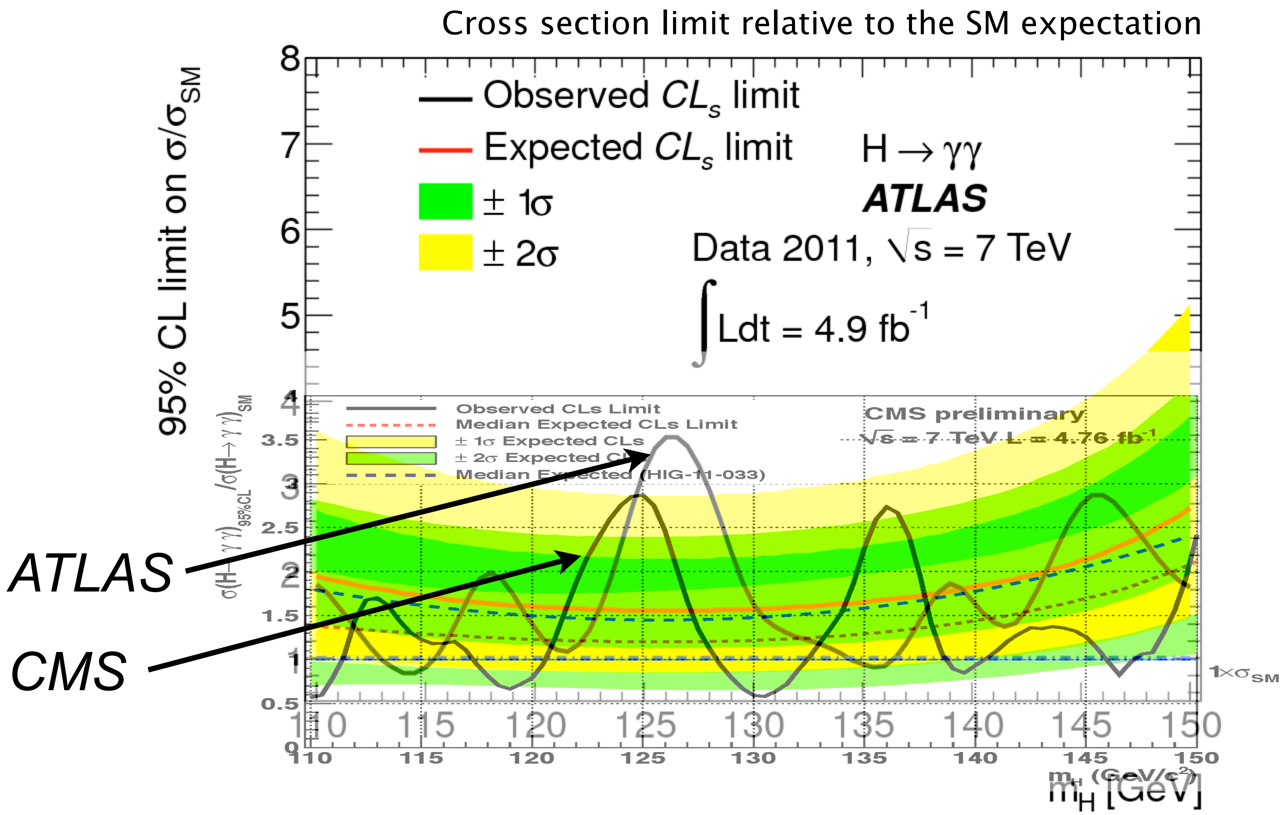
$H \to \gamma\gamma$ results



Expected sensitivity close to 1 x σ_{SM}

1.6 x σ_{SM} *ATLAS*, 1.2 x σ_{SM} *CMS* at m_H = 125 GeV

$H \to \gamma\gamma$ results

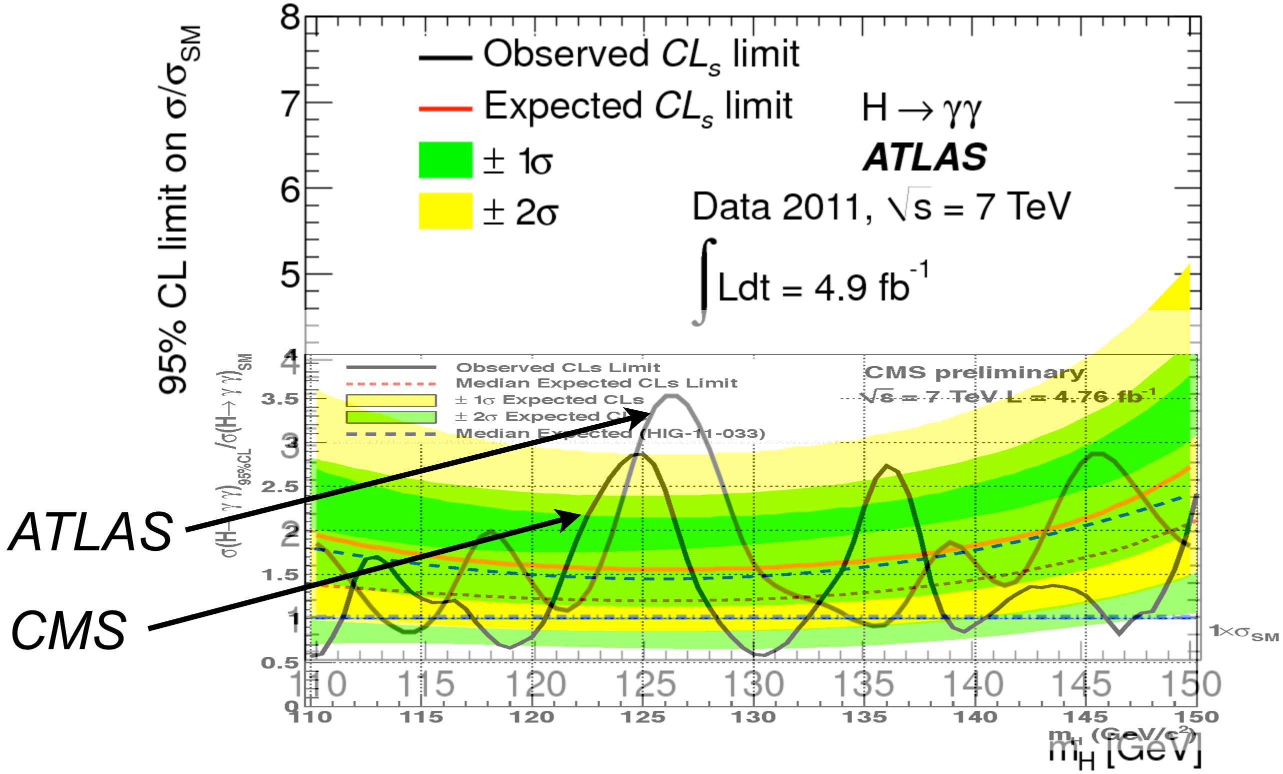


Expected sensitivity close to 1 x σ_{SM}

1.6 x σ_{SM} *ATLAS*, 1.2 x σ_{SM} *CMS* at m_H = 125 GeV

$H \rightarrow \gamma\gamma$ results

Cross section limit relative to the SM expectation



Expected sensitivity close to 1 x σ_{SM}

1.6 x σ_{SM} *ATLAS*, 1.2 x σ_{SM} *CMS* at m_H = 125 GeV

Sub-leading channel at the Tevatron due to the worse signal to background yields and ~2 times weaker resolution and jet/π^0 rejection

$H \rightarrow \gamma\gamma$ results

p0 probability that a background only experiment be more signal like than observed

Both experiments observe an excess around m_H = 125 GeV (compatible within energy scale and statistical uncertainties)

→ *Local* significance of excess

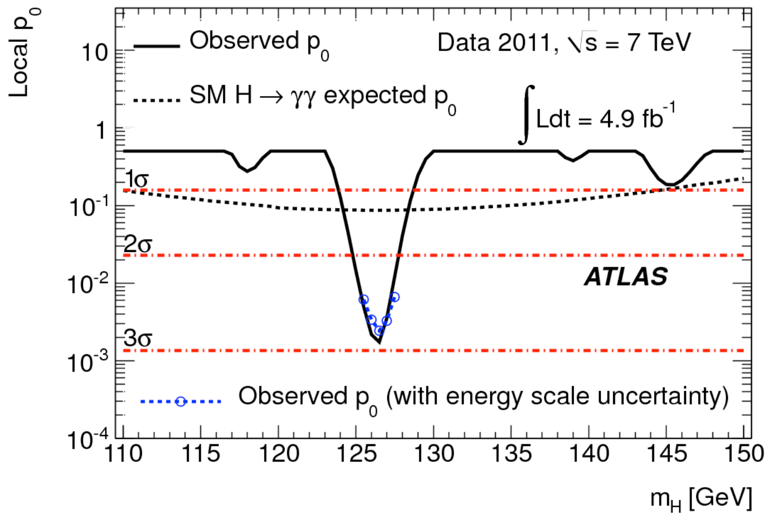
ATLAS 2.8σ *CMS* 2.9σ

Correct for higher probability to observe an excess *anywhere* in the mass range (trial factor a.k.a. look-elsewhere effect)

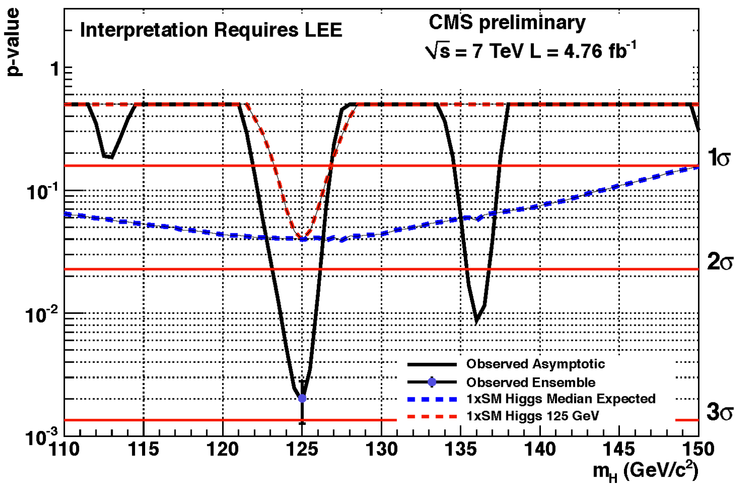
→ *Global* significance of excess

ATLAS 1.5σ *CMS* 1.6σ

ATLAS

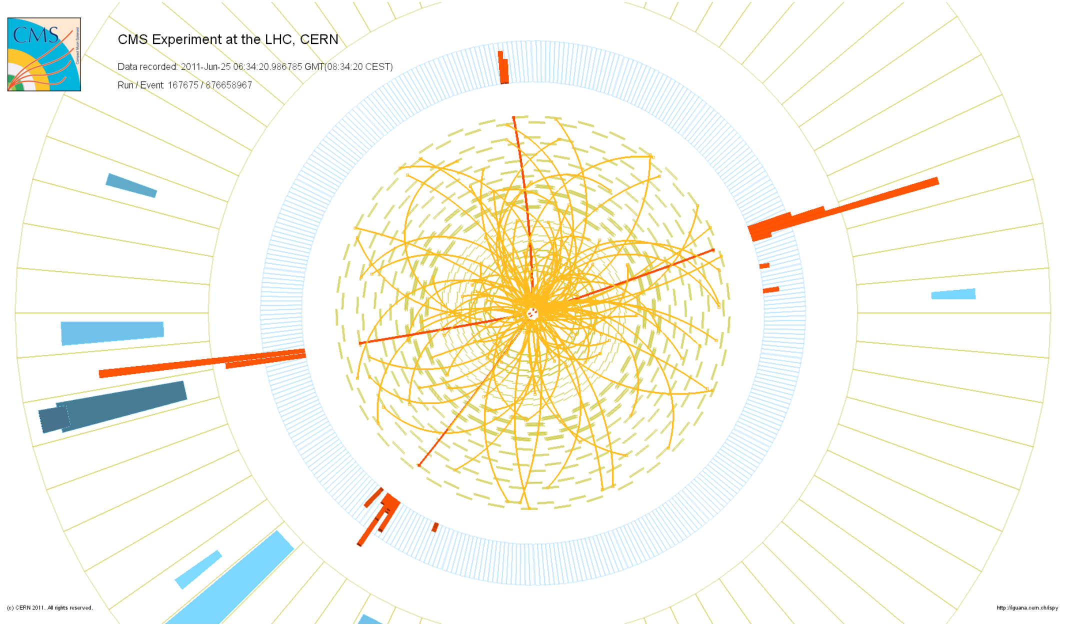


CMS



$H \rightarrow ZZ \rightarrow 4l$: the golden mode

Good mass resolution (1−2%) and low background yields

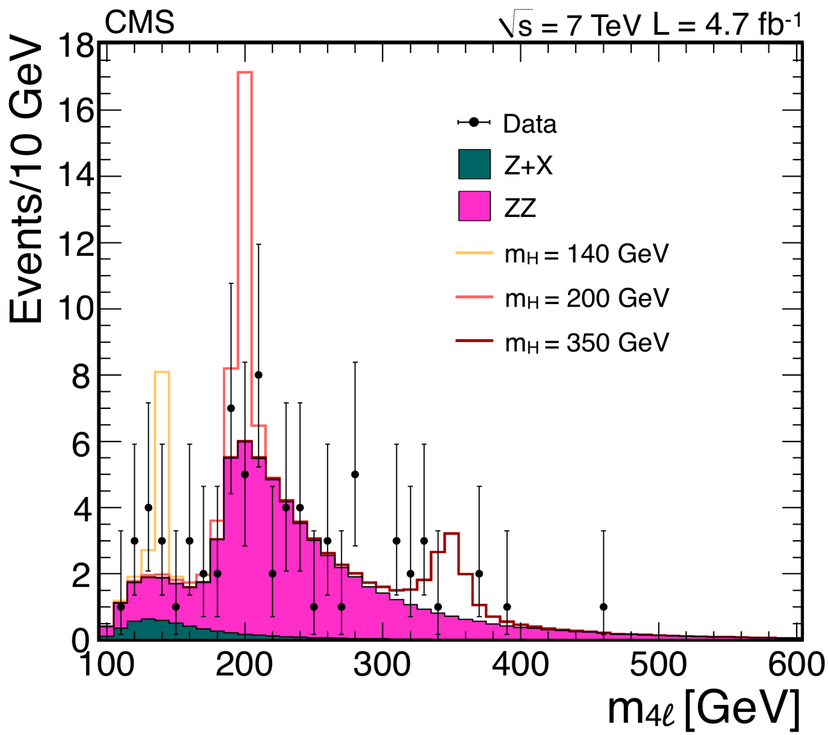


2 same flavour, opposite charge lepton pairs

consistent with *Z* mass

Crucial: high lepton reconstruction efficiency down to low pT (5 GeV)

$H \rightarrow ZZ \rightarrow 4l$: the golden mode



Candidate selection:

- 2 leptons pairs (opposite sign, same flavour)
- one dilepton mass consistent with *Z* mass (other can be off-mass shell)
- all leptons must originate from same primary vertex
- require isolation and small impact parameter (to suppress background from *b* decays)

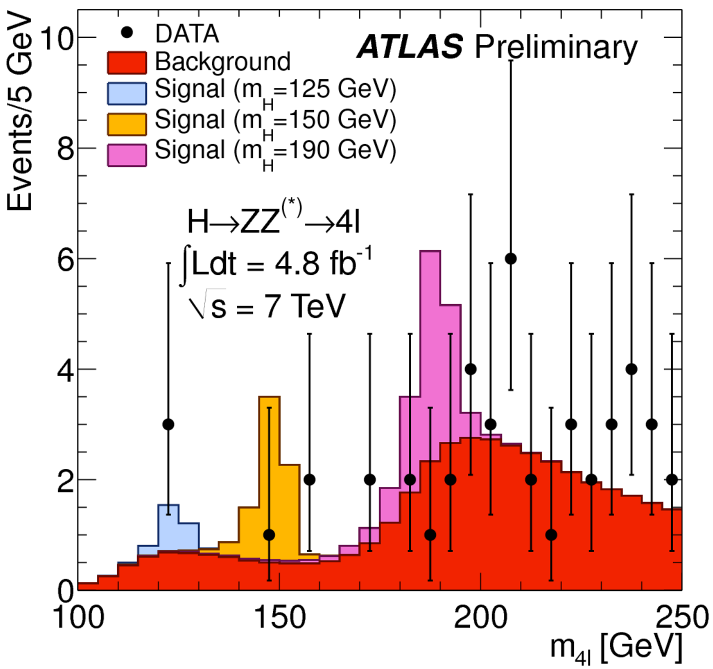
Main backgrounds:

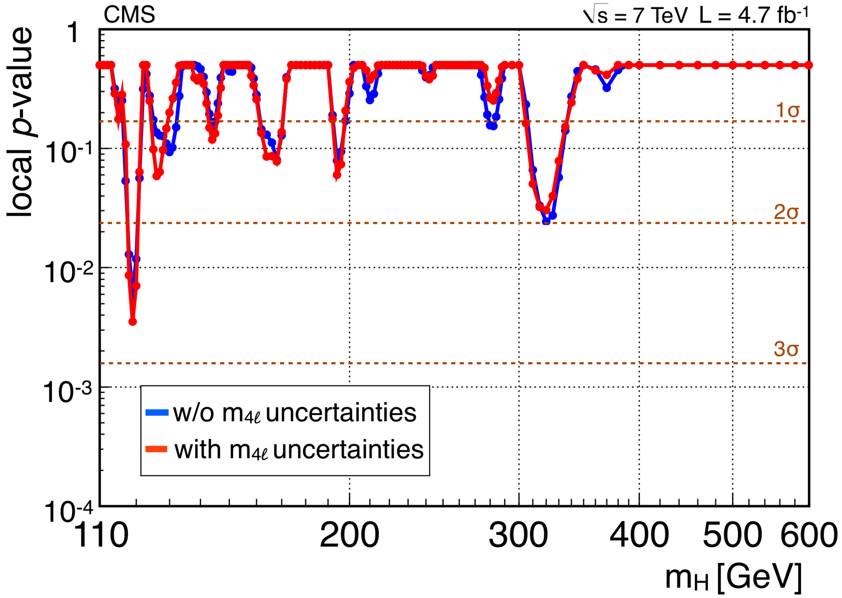
- SM *ZZ** production, irreducible (estimated from MC)
- Top, *Z*+bb, *Z*+jj (data driven estimation)

$H \to ZZ \to 4l$: results

Look for a clustering of events in the 4-lepton invariant mass distribution

lower mass range





$H \rightarrow ZZ \rightarrow 4l$: results

Look for a clustering of events in the 4-lepton invariant mass distribution

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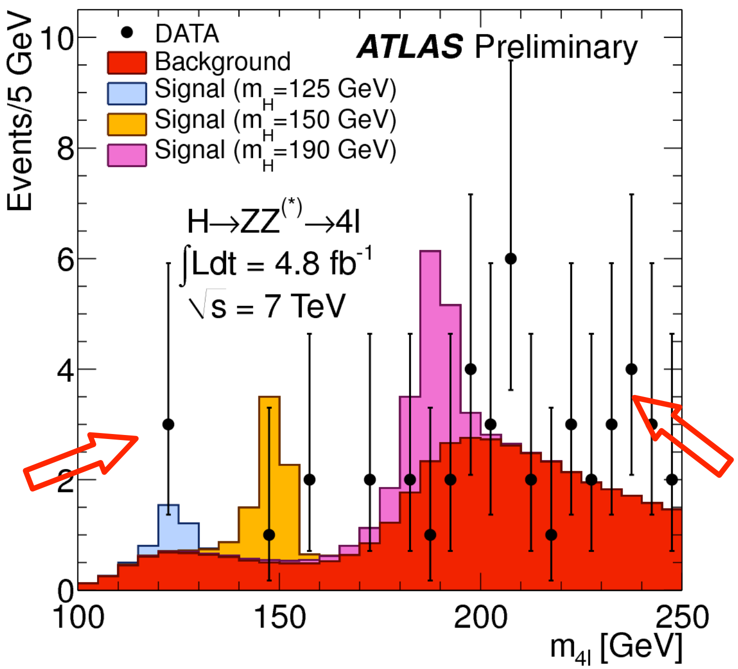
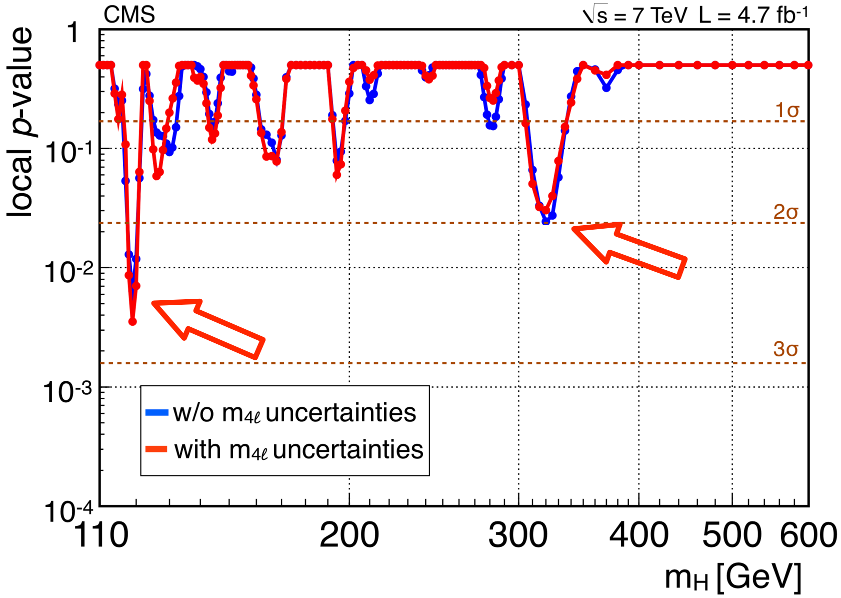




Small excesses observed at m_{4l} values of:

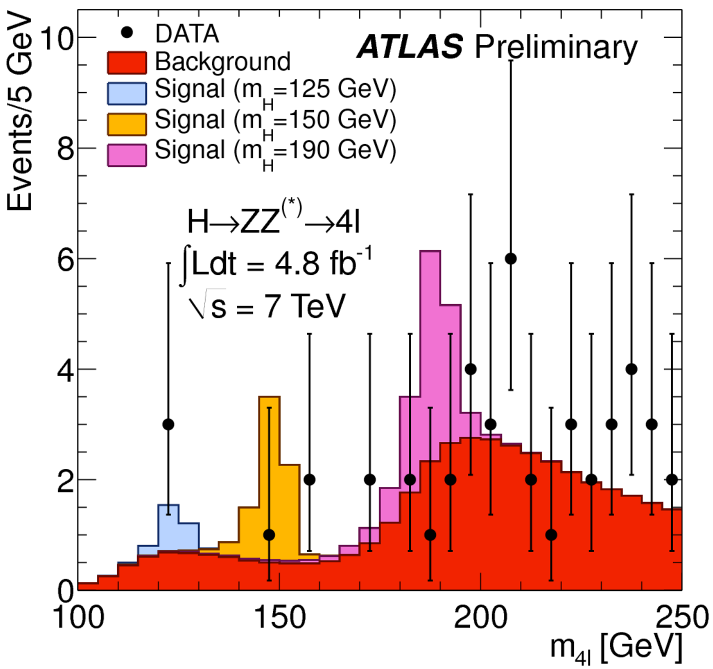
- ATLAS: 125, 244 and 500 GeV
- CMS: 119 and 320 GeV

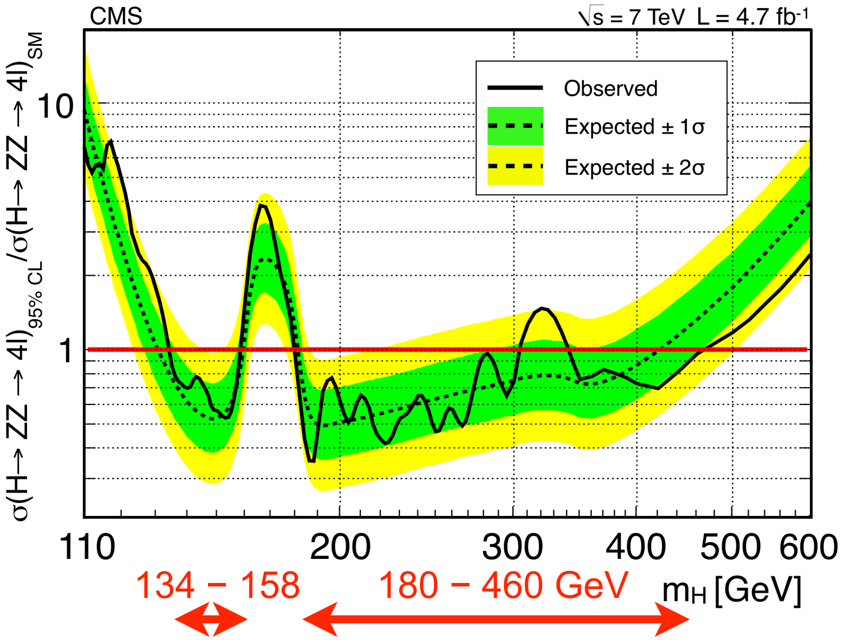
Non of them significant (with look-elsewhere effect <1.3σ)

$H \to ZZ \to 4l$: results

Look for a clustering of events in the 4-lepton invariant mass distribution

lower mass range

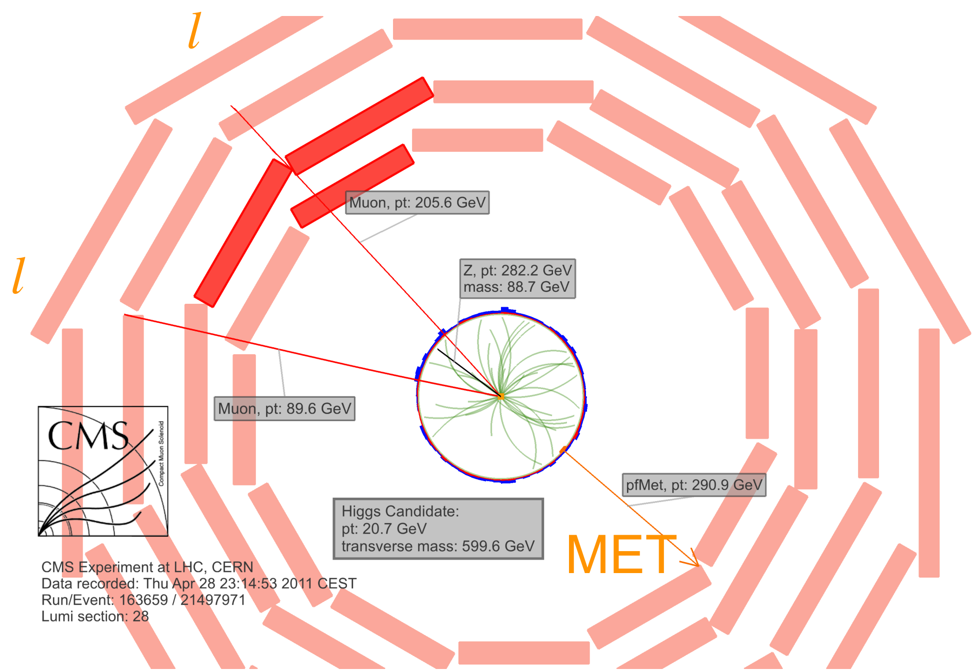




Due to very low background yields increasing relevance with more data (significance scales with $\mathcal{L}$ instead of $\sqrt{\mathcal{L}}$)

$H \to ZZ \to ll\nu\nu$

Most sensitive channel above m_H 300 GeV



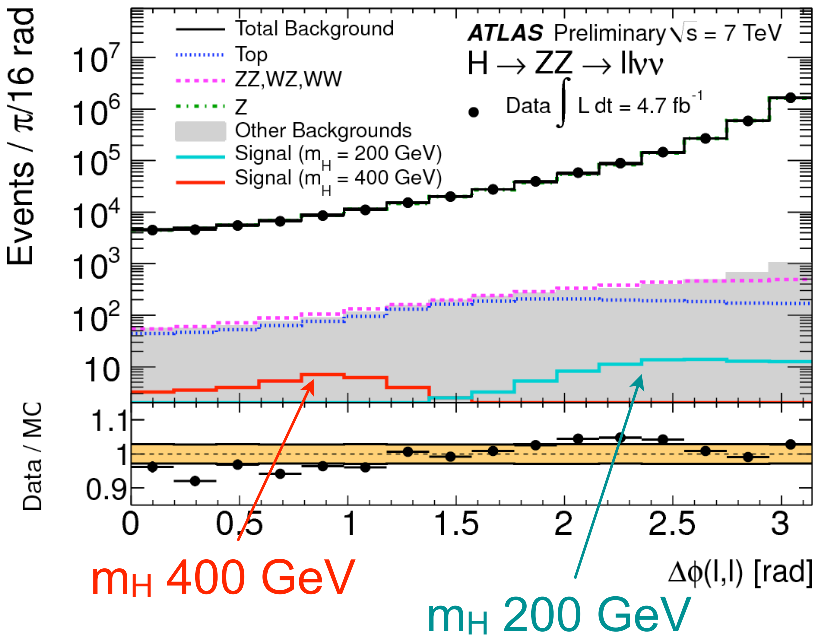
2 opposite charge high p_T leptons, consistent with *Z*

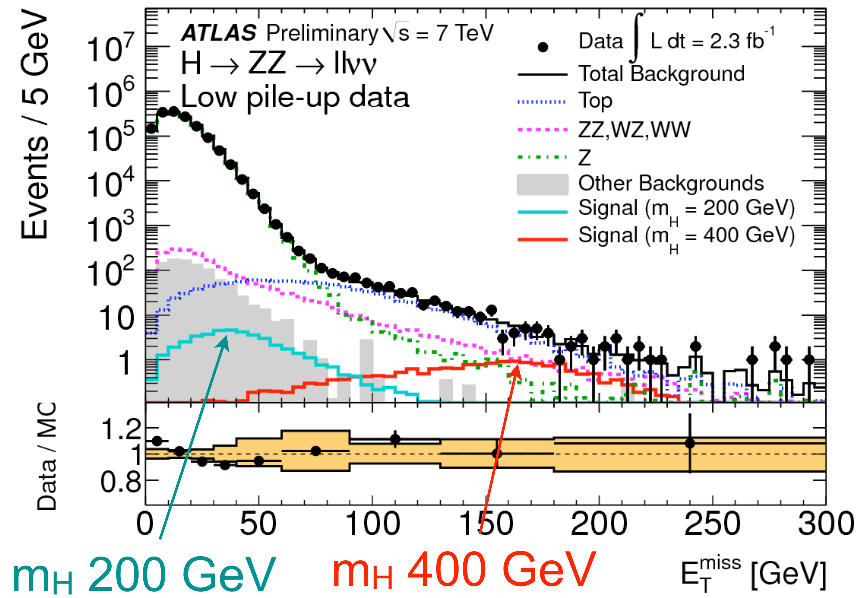
large missing E_T

Search range:
m_H 200 − 600 GeV

Large signal yields and efficient background subtraction if *Z* bosons boosted (requires large m_H)

$H \to ZZ \to ll\nu\nu$





Main backgrounds (after *Z* mass requirement):

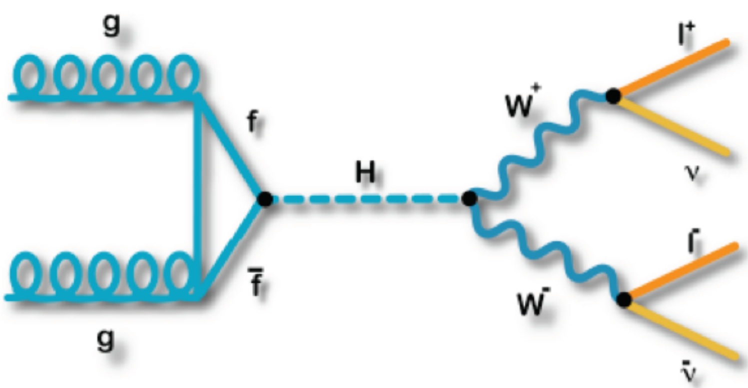
- *Z*+jets (suppressed with missing E_T cut)
- Top (suppressed with *b*-jet veto)

ATLAS+CMS exclude SM Higgs in the range m_H 270 − 560 GeV in this channel

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

Dominant decay for m_H>135 GeV: $H \rightarrow W^*W$

Mass resolution ~20%, but takes advantage from large signal yield



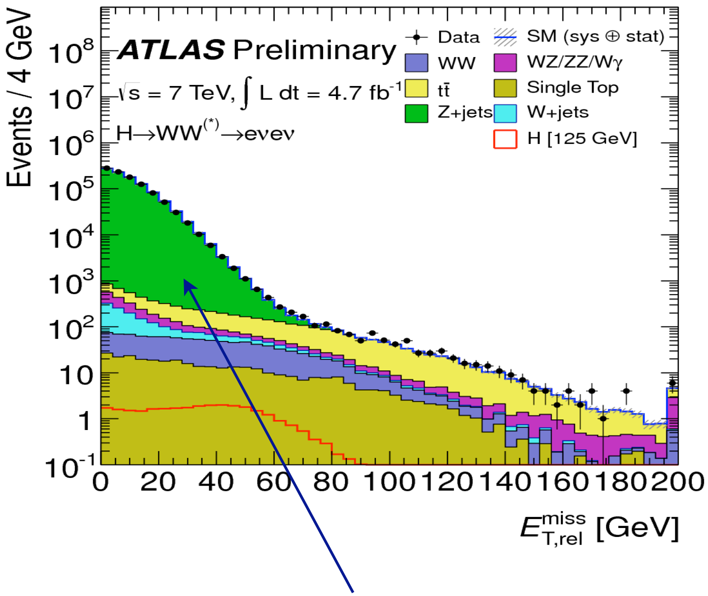
2 opposite charge high pT leptons

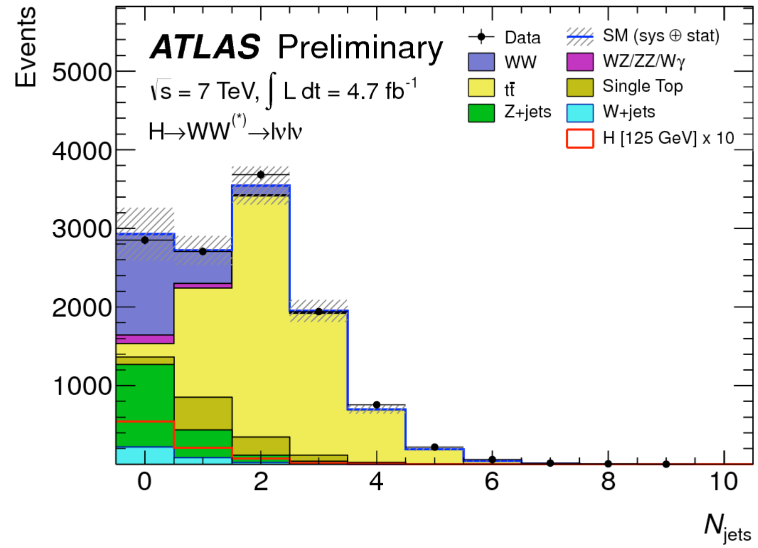
missing ET

Main challenge: need good understanding of all the high-energy SM processes occurring at a hadron collider (no background be neglected)

$H \rightarrow WW$ preselection and backgrounds

Preselection: two isolated, opposite charge, high p_T leptons





Backgrounds: Drell-Yan production (dominant background), diboson, top production, W+jets/γ, multijet

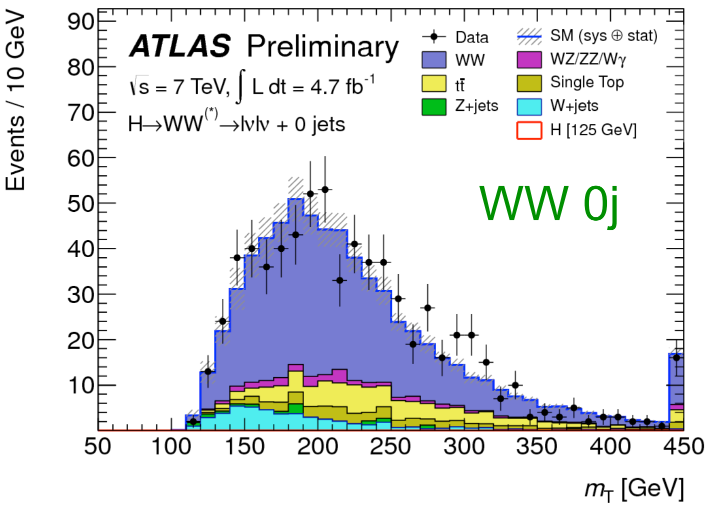
Reject Drell-Yan background by requiring large missing E_T

Signal topology & background composition depend strongly on jet multiplicity
→ Optimise analysis in bins of jet multiplicities

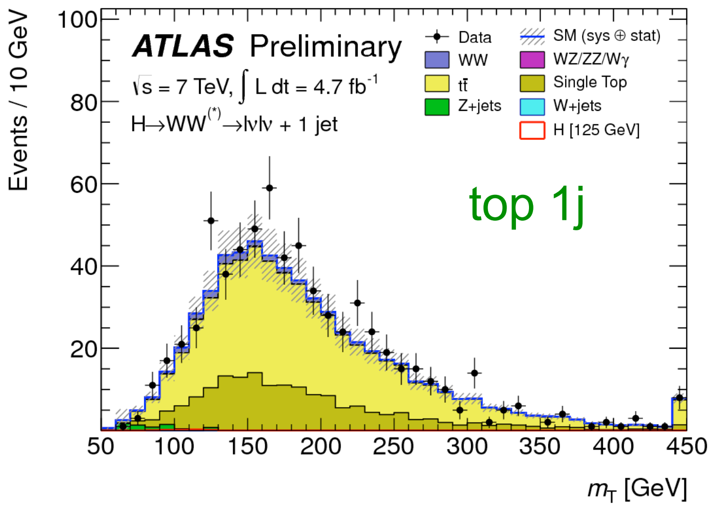
$H \rightarrow WW$ backgrounds estimation

Top and SM *WW* production normalised to data in control samples, extrapolate to signal region with simulation

Require large dilepton mass



Require b-jets

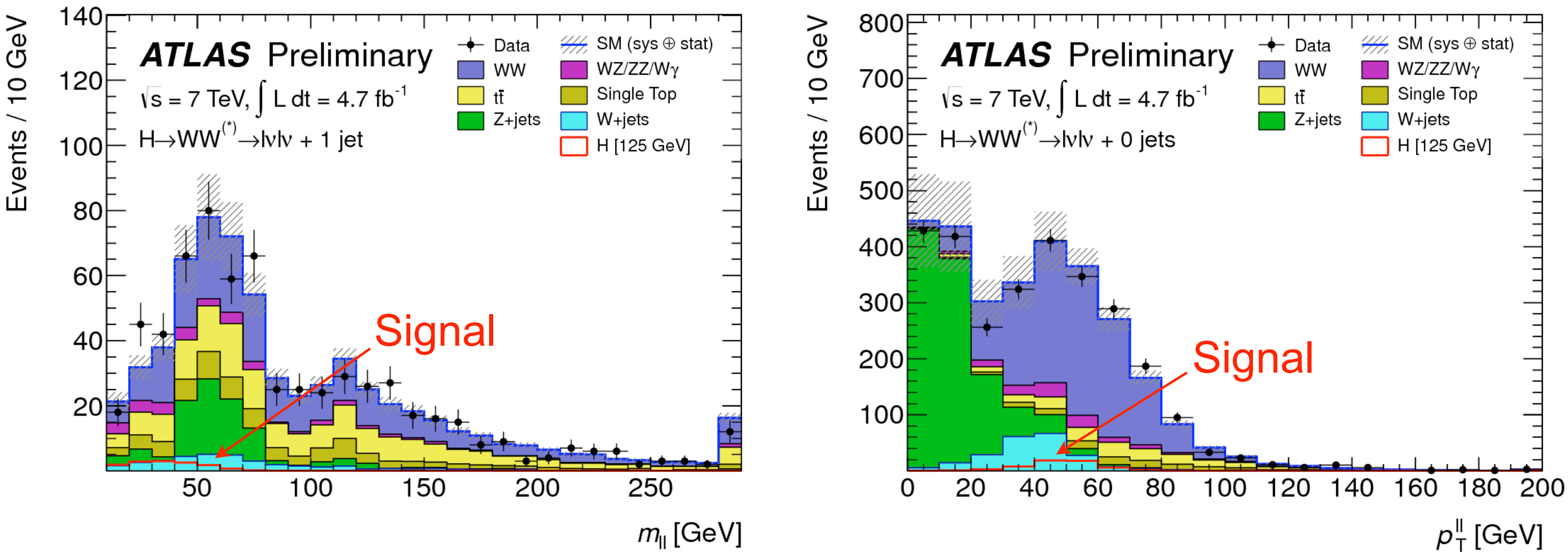


W/Z+jets estimated directly from data

$H \to WW$ topological cuts

Suppress backgrounds further with topological selection

- Dilepton mass and angular separation, p_T variables, b-jet veto, etc.



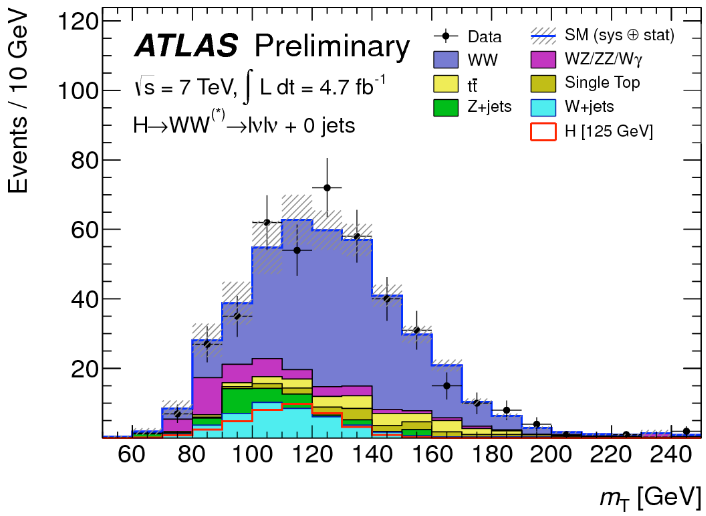
Search over a wide mass region: m_H = 110 - 600 GeV

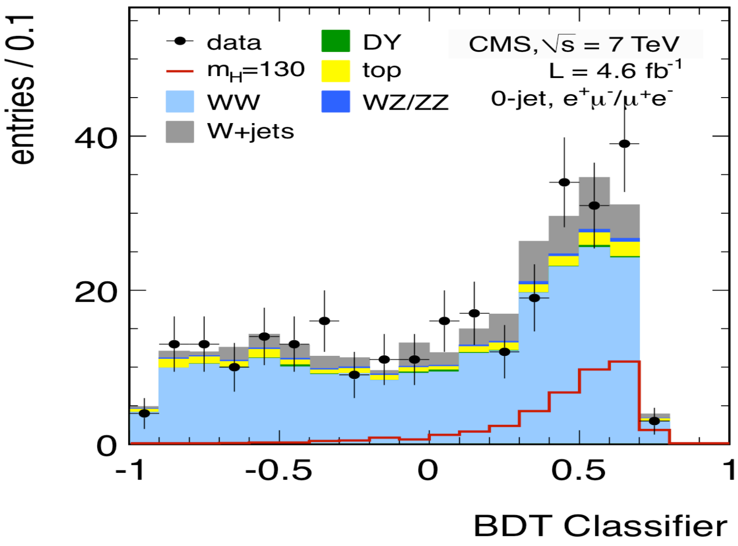
Kinematics of signal events depends strongly on m_H

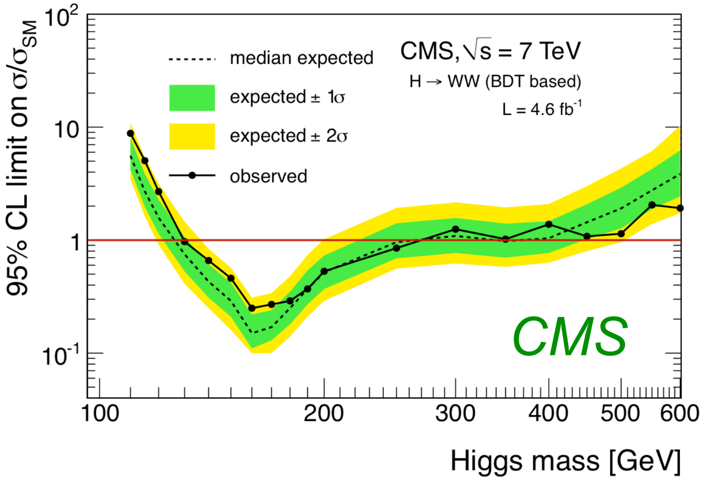
→ Mass dependent selection optimisation

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

Use transverse mass distribution or MVA output to test presence of signal





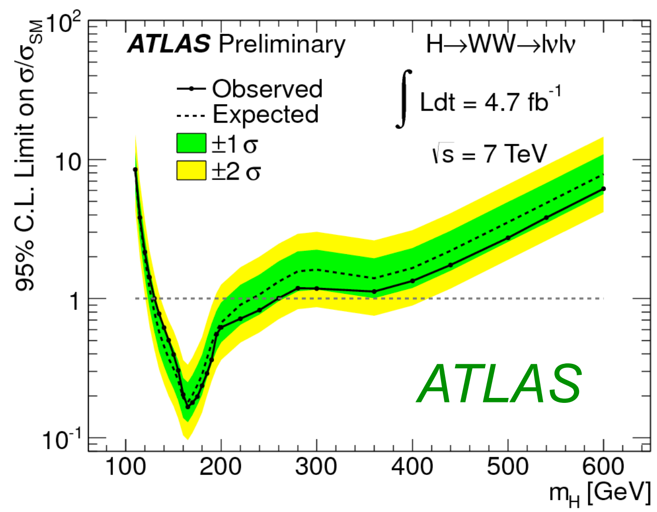


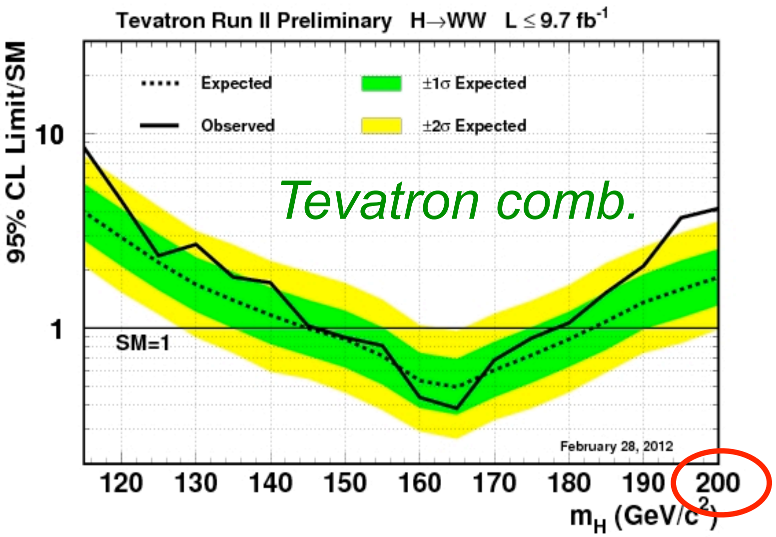
No significant excess over the entire mass range

Similar exclusion range for both experiments:

130 - 270 GeV at 95%CL

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





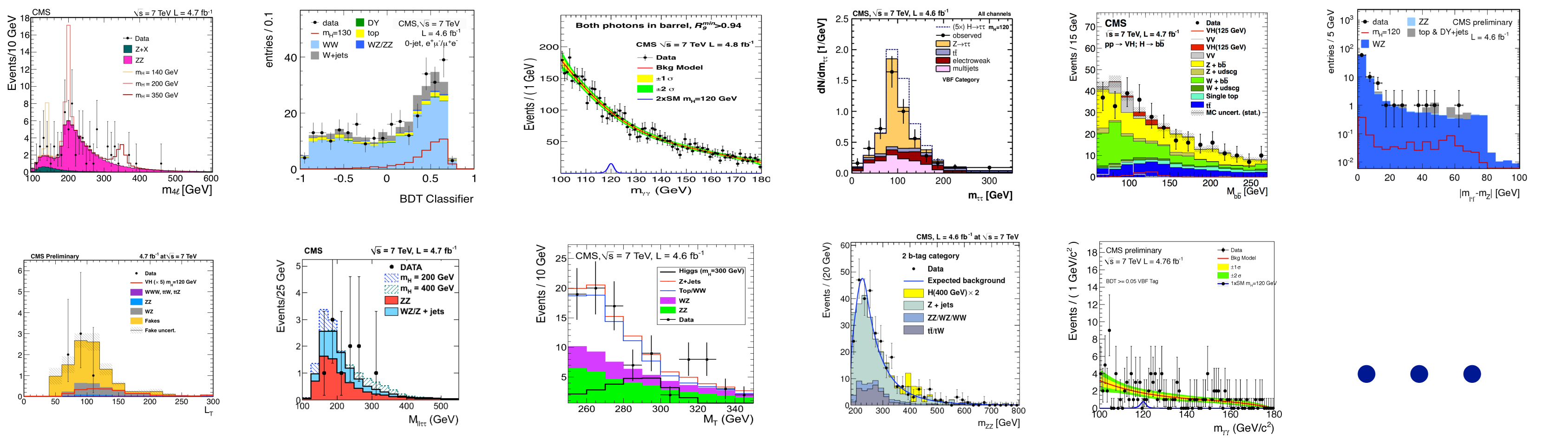
H → WW searches at the Tevatron very similar, but only up to m_H 200 GeV

First direct exclusion since LEP in 2009! Today larger exclusion range from LHC experiments due to the higher S/B yields

Combining the individual searches

Full combination of all channels for best sensitivity

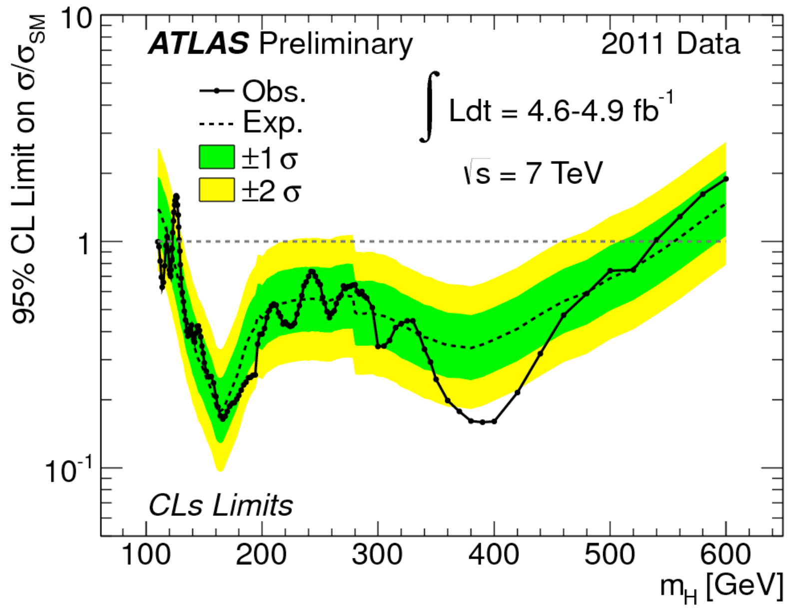
- Combining more than 50 different search categories per experiment

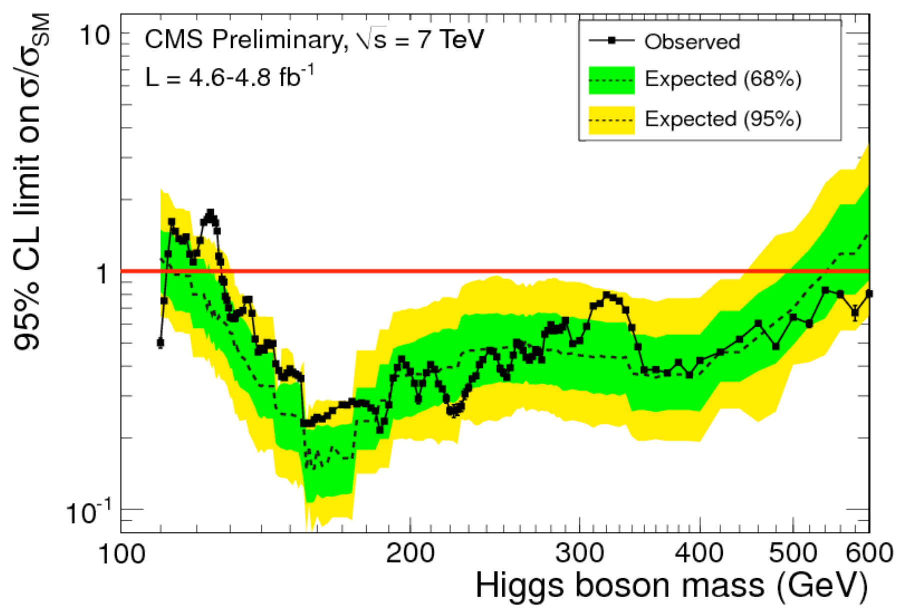


Large number of different sources of systematic uncertainties considered (and constrained in sidebands)

Use different techniques to cross check calculations (Bayesian, modified frequentist) → Results agree within few %

ATLAS and *CMS* exclusion limits





ATLAS exclusion region:

- 110 − 122 GeV (except 118 GeV)
- 129 − 540 GeV at 95% CL

(Expected: 120 − 555 GeV)

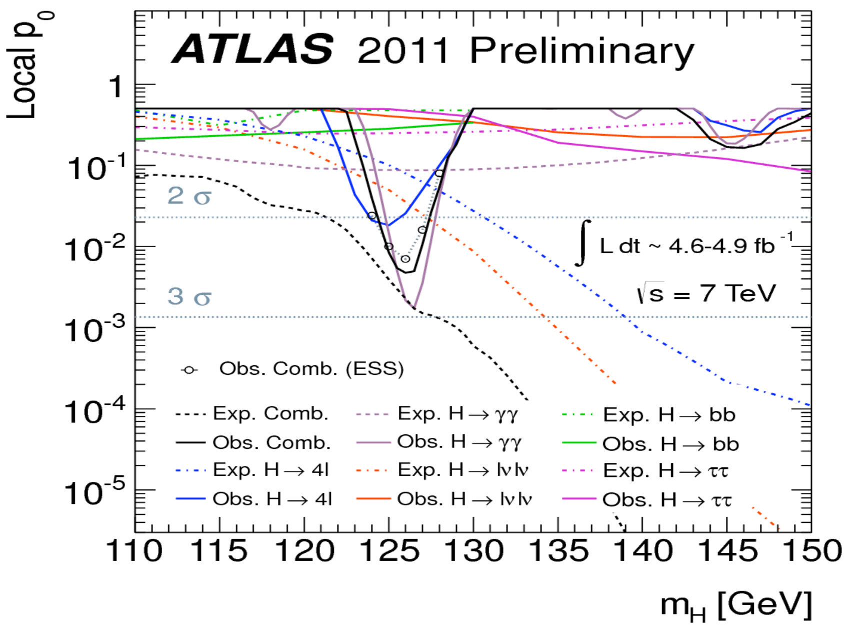
CMS exclusion region:

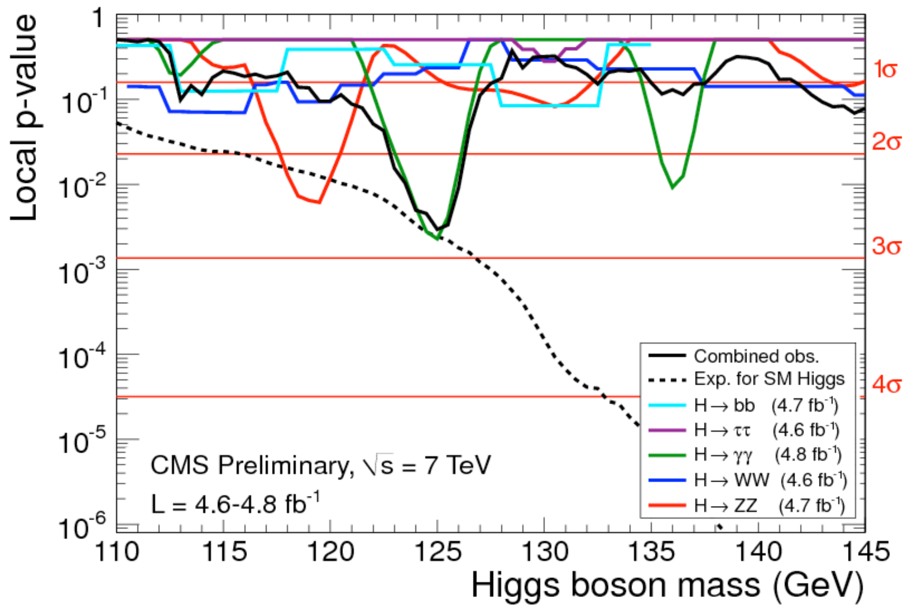
- 128 − 600 GeV at 95% CL

(Expected: 114 − 540 GeV)

Only mass range not excluded at the 99% CL is 115 − 130 GeV!

ATLAS and *CMS* excesses





Most significant excess for both experiments around same mass range

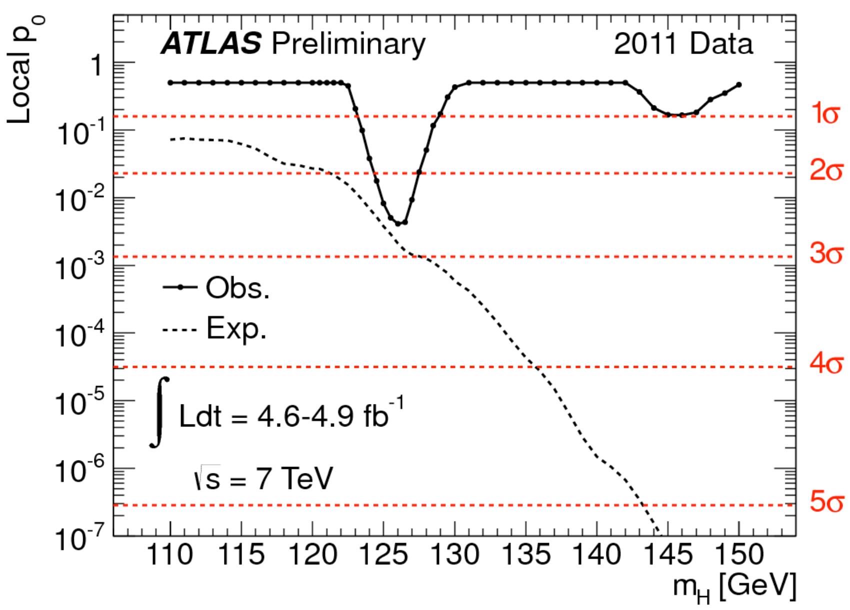
ATLAS at 126 GeV

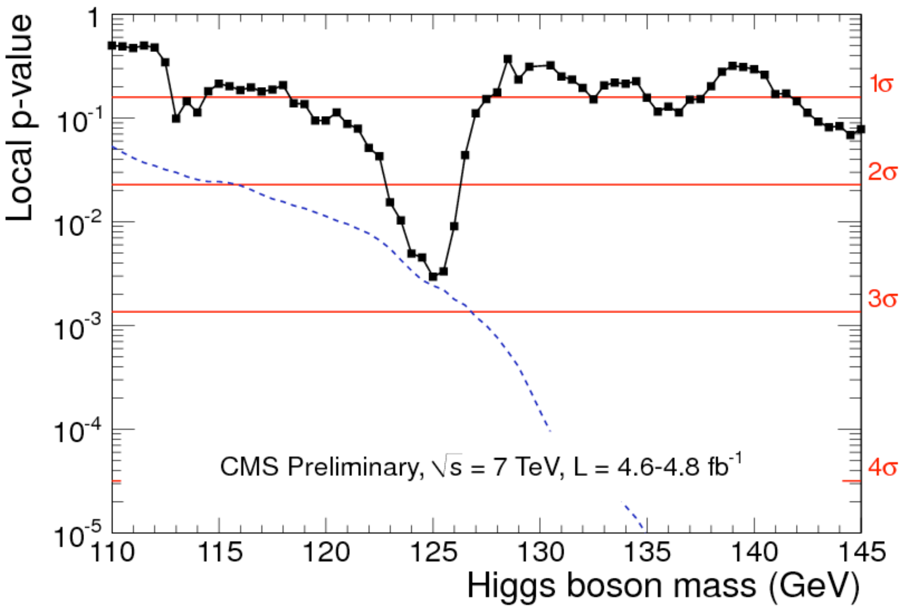
Excess mostly in $\gamma\gamma$
Small excess in 4l
Very little in lvlv, bb, …

CMS at 125 GeV

Excess mostly in $\gamma\gamma$
Slight excess in 4l, lvlv, ...

ATLAS and *CMS* excesses





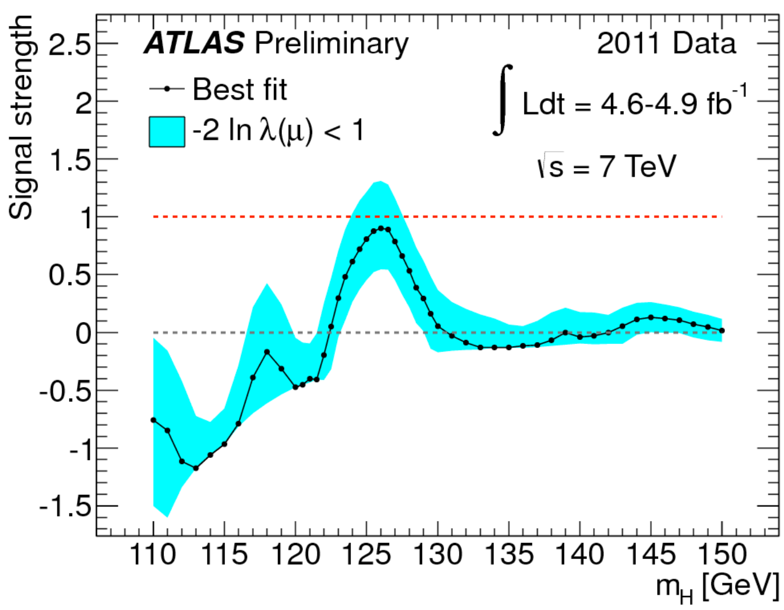
Most significant excess for both experiments around same mass range

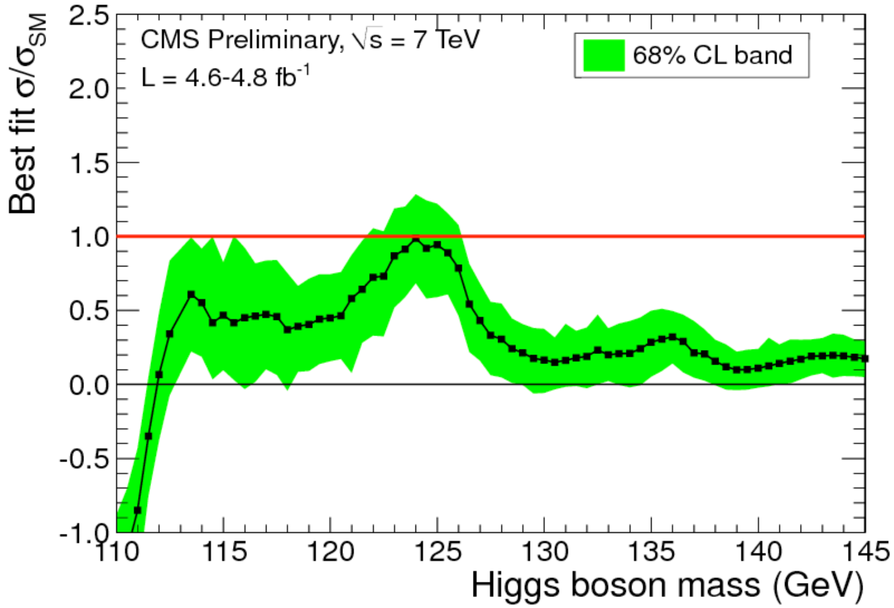
ATLAS:
Local 2.5σ

CMS:
Local 2.8σ

ATLAS example: 30% probability for such an excess to occur anywhere in the full search range (m_H 110 − 600 GeV)

Best fit



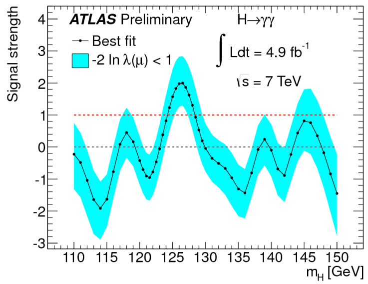


Fit S+B hypothesis to observed data, allow signal strength to vary

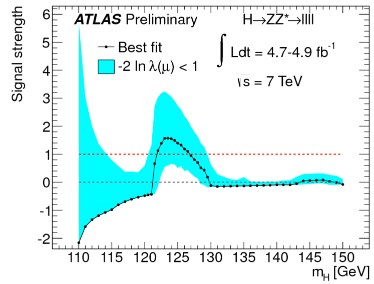
→ obtain best-fit signal strength

Channel by channel (low mass region)

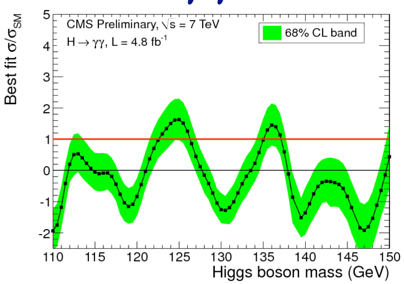
γγ



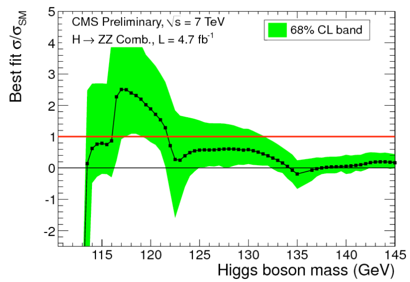
4l



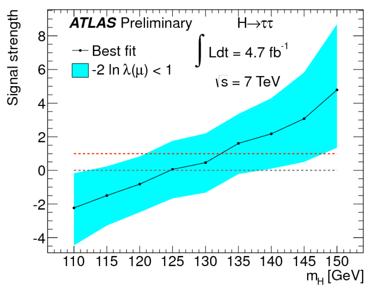
γγ



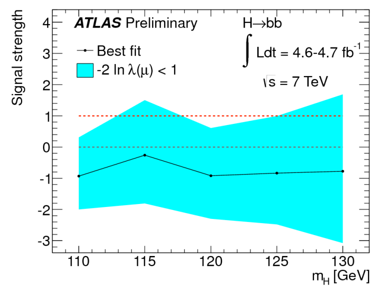
4l



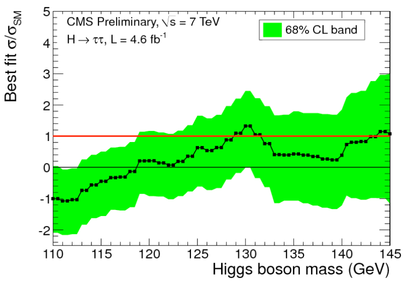
ττ



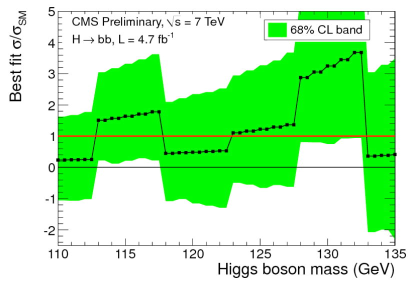
bb



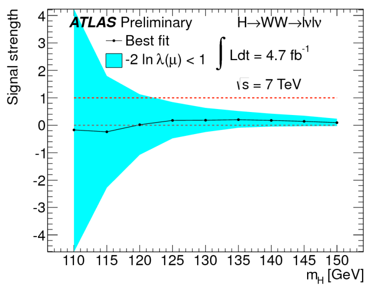
ττ



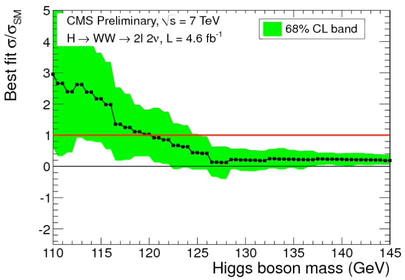
bb



lνlν



lνlν

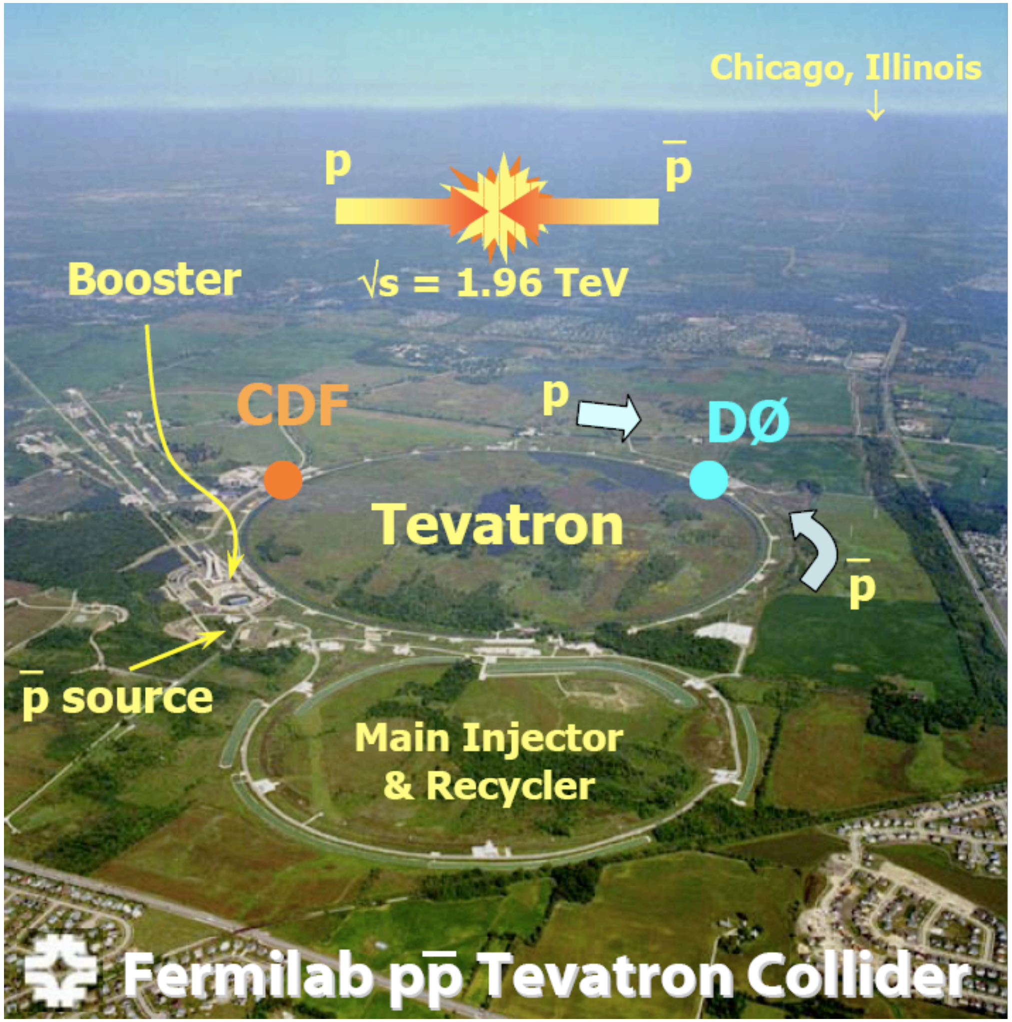


ATLAS

CMS

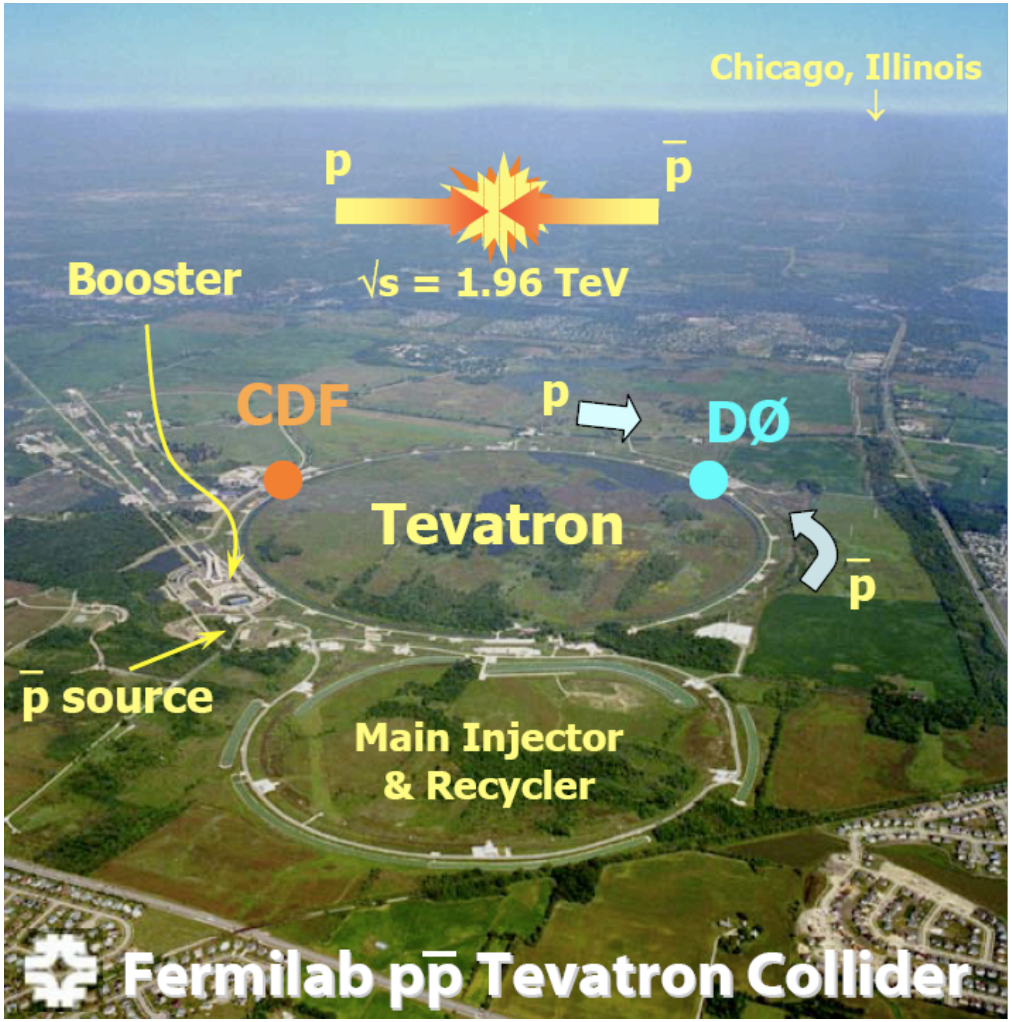
Everything consistent with SM expectation at ~125 GeV (*lνlν* slightly low)

Tevatron collider in Run II

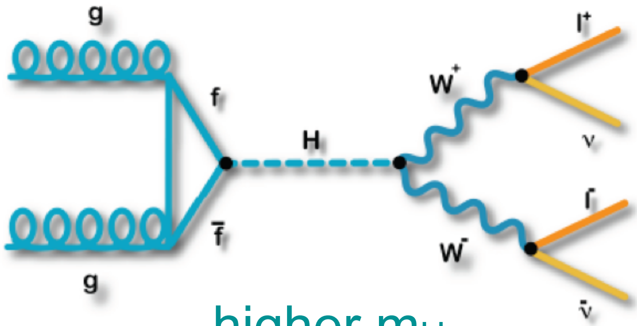


Run II dataset 10 fb^{-1}

Tevatron collider in Run II

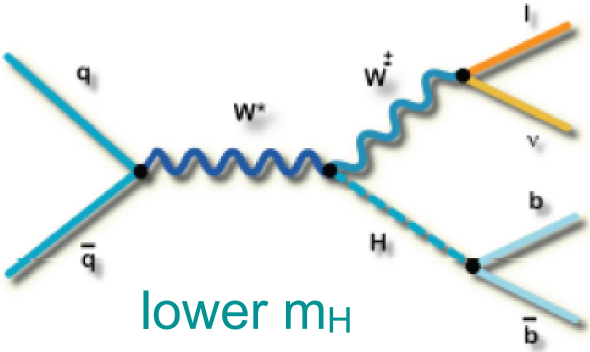


Main channels:



higher m_H

At $m_H \sim 130$ GeV similar sensitivity

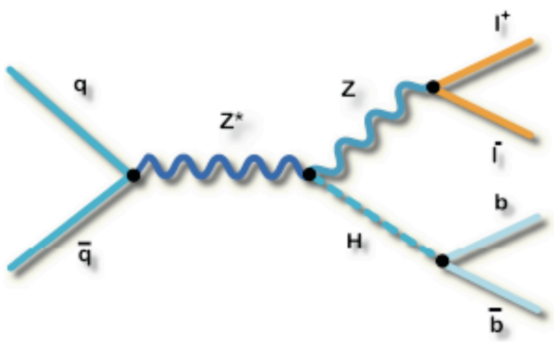


lower m_H

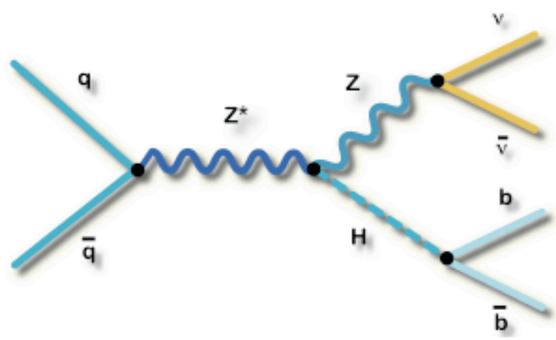
Searches for low mass Higgs

Main channels:

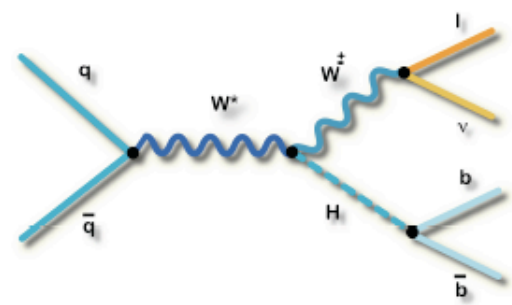
$ZH \to llbb$



$ZH \to \nu\nu bb$



$WH \to \ell\nu bb$



Experimental signature:

- Two jets with high transverse momentum, b-tagged (from the Higgs decay)
- Isolated leptons and/or missing transverse energy (from the W/Z decay)

Backgrounds:

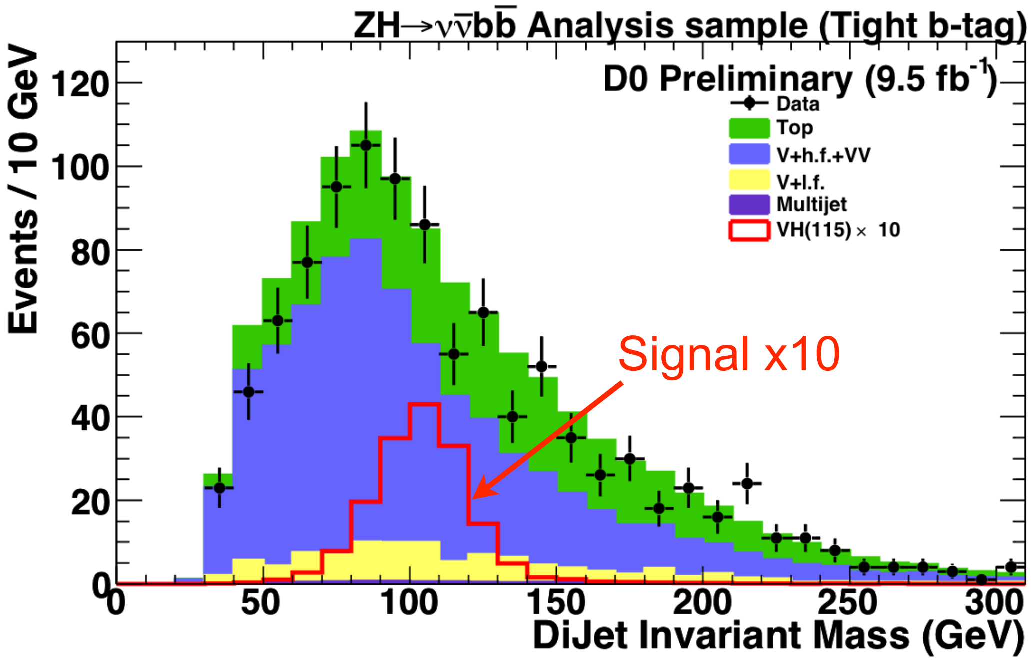
- SM Physics (from MCs): W/Z+jets, diboson, $t\bar{t}$, single top
- Instrumental (from Data)

Searches for low mass Higgs

Select events with *W/Z* and 2 jets

Separate b from light-quark jets

Optimise separation using multivariate discriminant



Main discriminating variable: dijet invariant mass

Recent largest improvement: optimised b-tagging

Challenge: need a very good understanding of *W/Z+bb* background

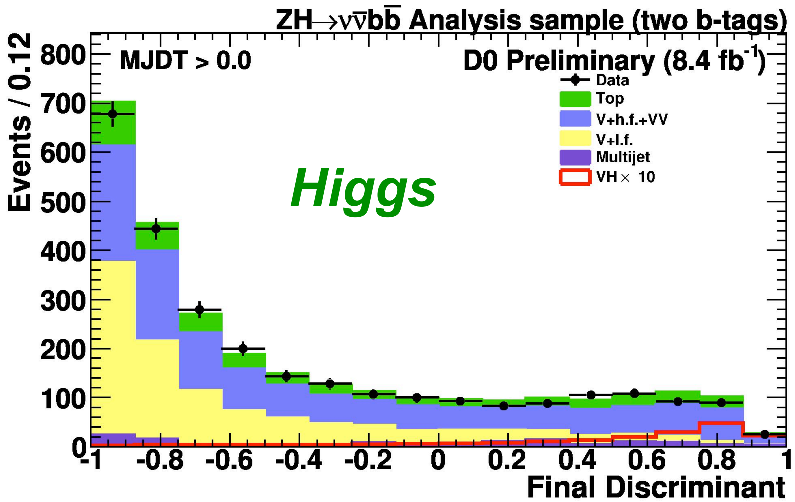
The main test: *VZ(bb)* observation

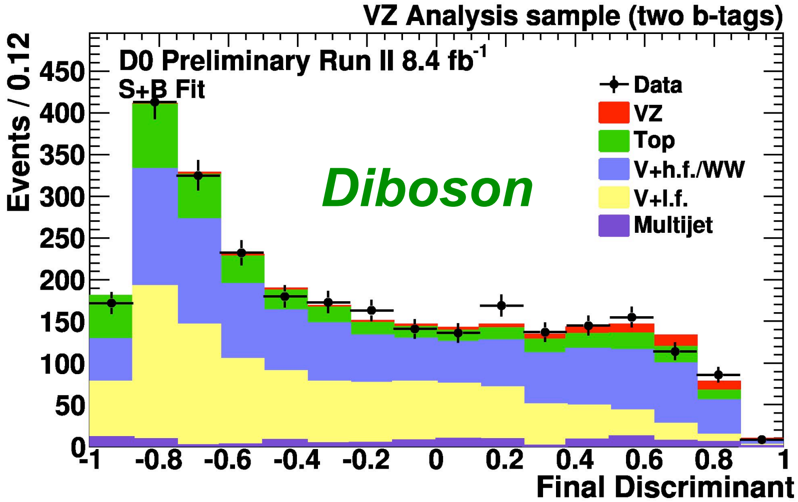
Main benchmark for Tevatron low mass Higgs searches

→ Observation of *WZ(bb)/ZZ(bb)*

Analysis identical to the scalar boson searches

VZ(bb) = ~4 x *VH(115)*, but more backgrounds

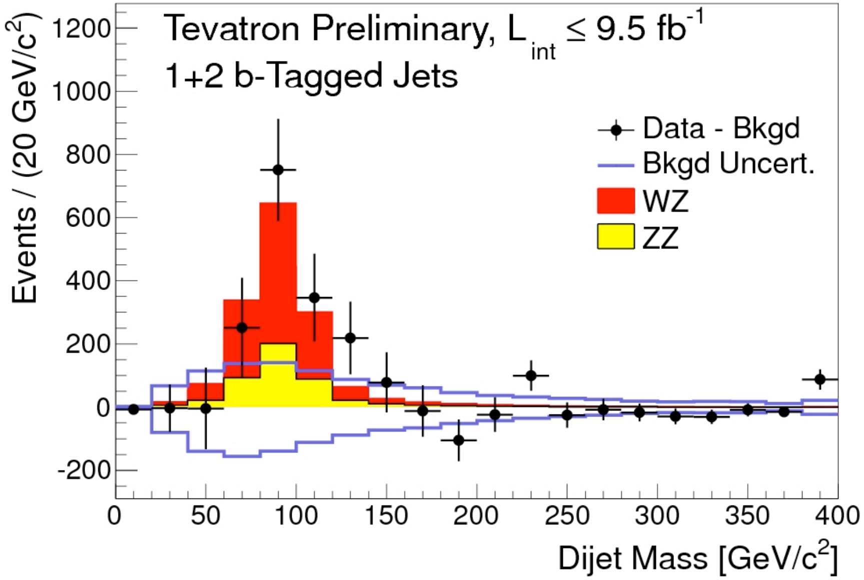




Both experiments >3σ evidence for *VZ* production with heavy flavour jets

The main test: *VZ(bb)* observation

Tevatron *VZ(bb)* combination

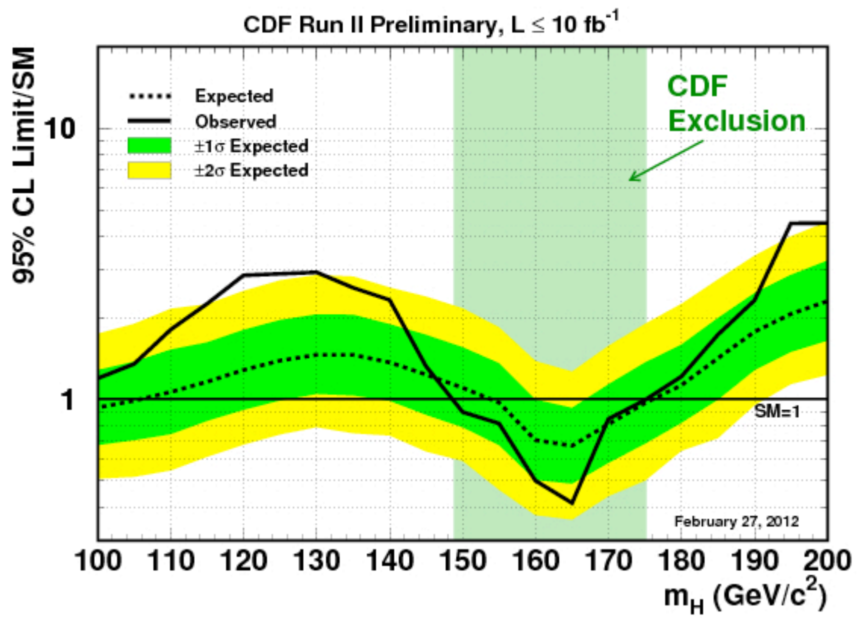


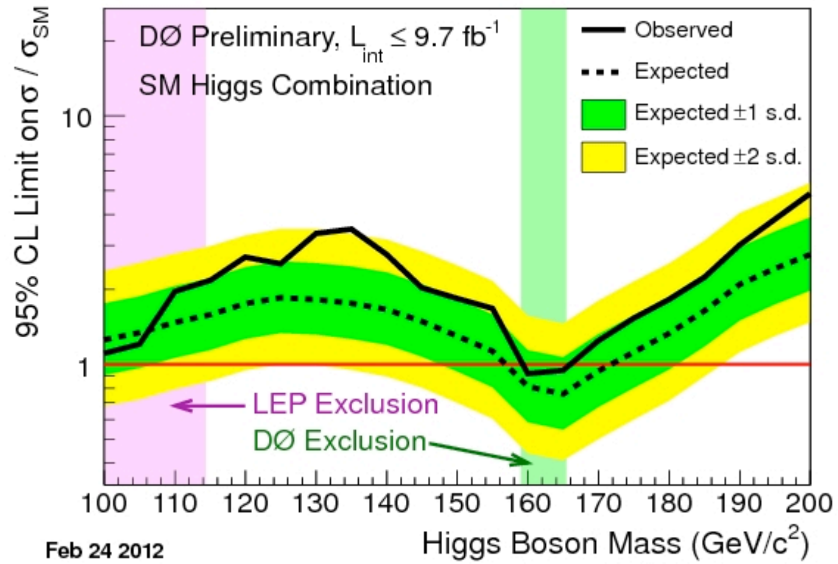
Data background subtracted

$\sigma_{obs} = (1.01 \pm 0.21) \times \sigma_{SM}$

4.6σ evidence for *WW*+*WZ* production with heavy flavour jets

CDF and DØ Higgs combinations





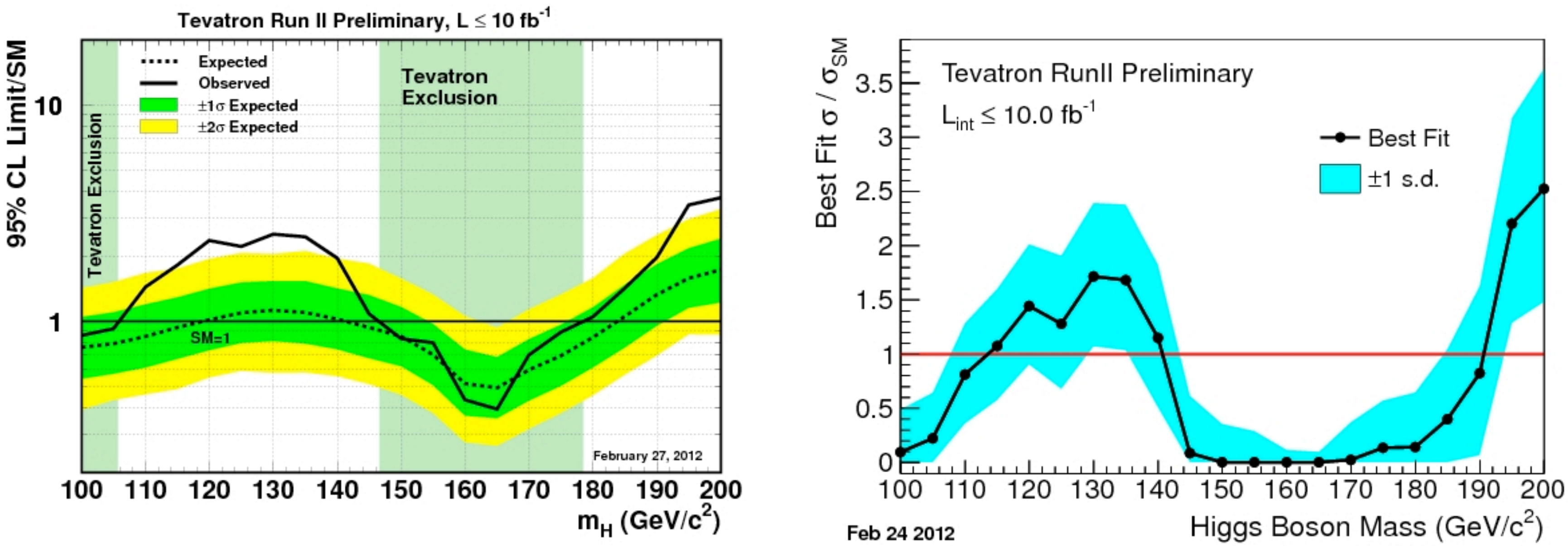
Excluded regions around m_H 160 GeV

Both experiments observe an excess around m_H 120 − 130 GeV

CDF: mainly *bb*, DØ *bb*+*WW*

Low mass resolution from *bb* and *WW* decays

Tevatron Higgs combination

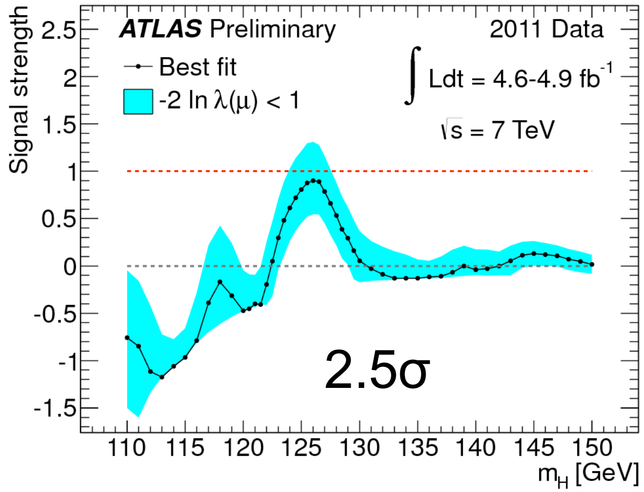


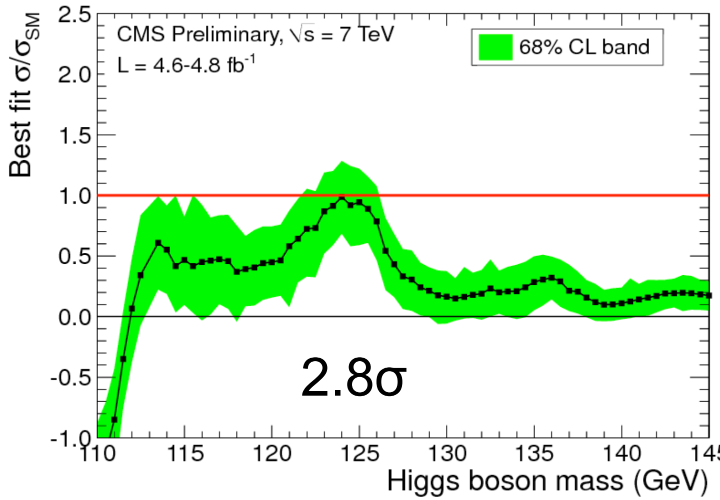
95% CL exclusion sensitivity close to or below the SM prediction through the whole mass range up to 180 GeV

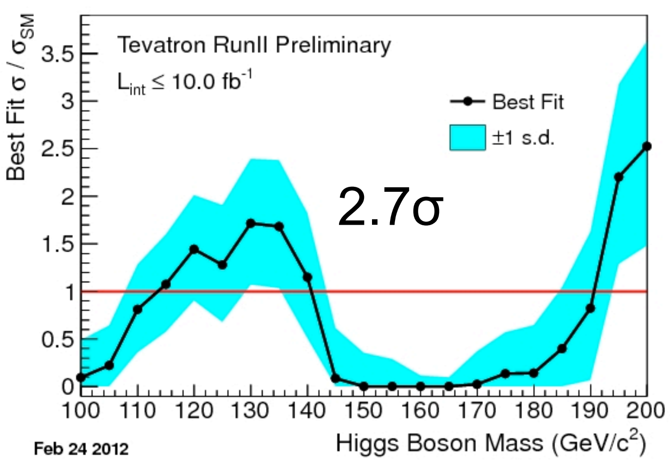
Broad data excess from 115 to 140 GeV, consistent with signal

Significance: 2.7σ (local) / 2.2σ (global) at 120 GeV

The global picture





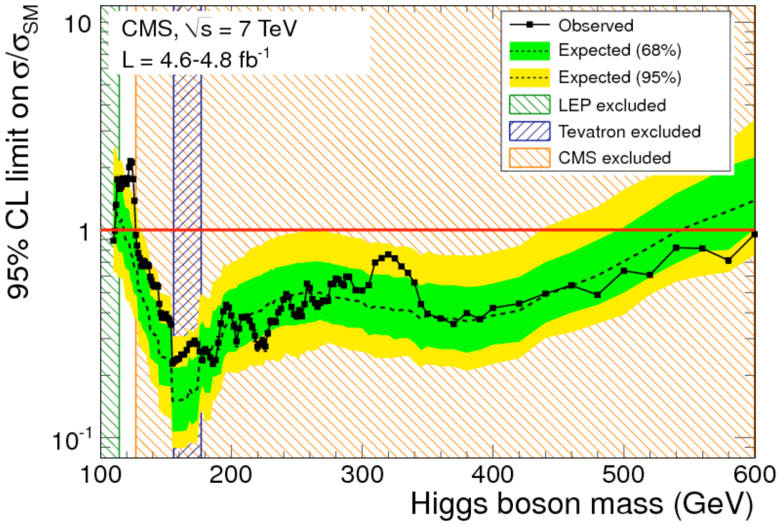


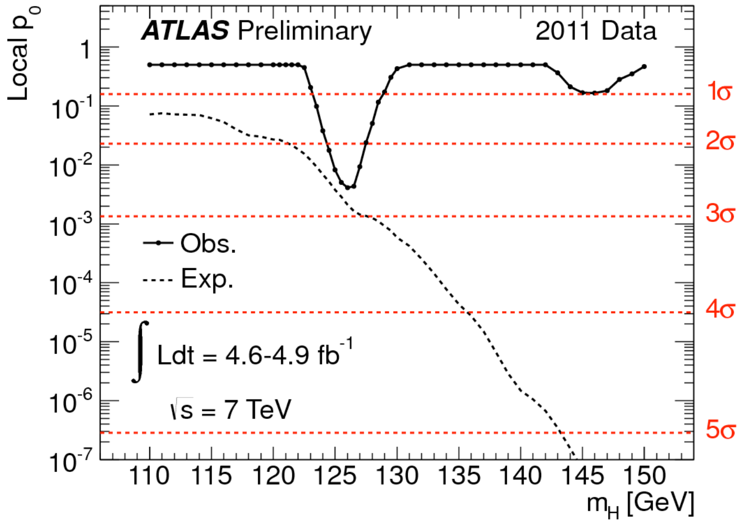
ATLAS, CMS and *Tevatron* results give a consistent picture

ALTAS/CMS excess mostly in $\gamma\gamma$ but consistent with the observation of other channels

Conclusions

The SM Higgs search landscape has completely changed in one year





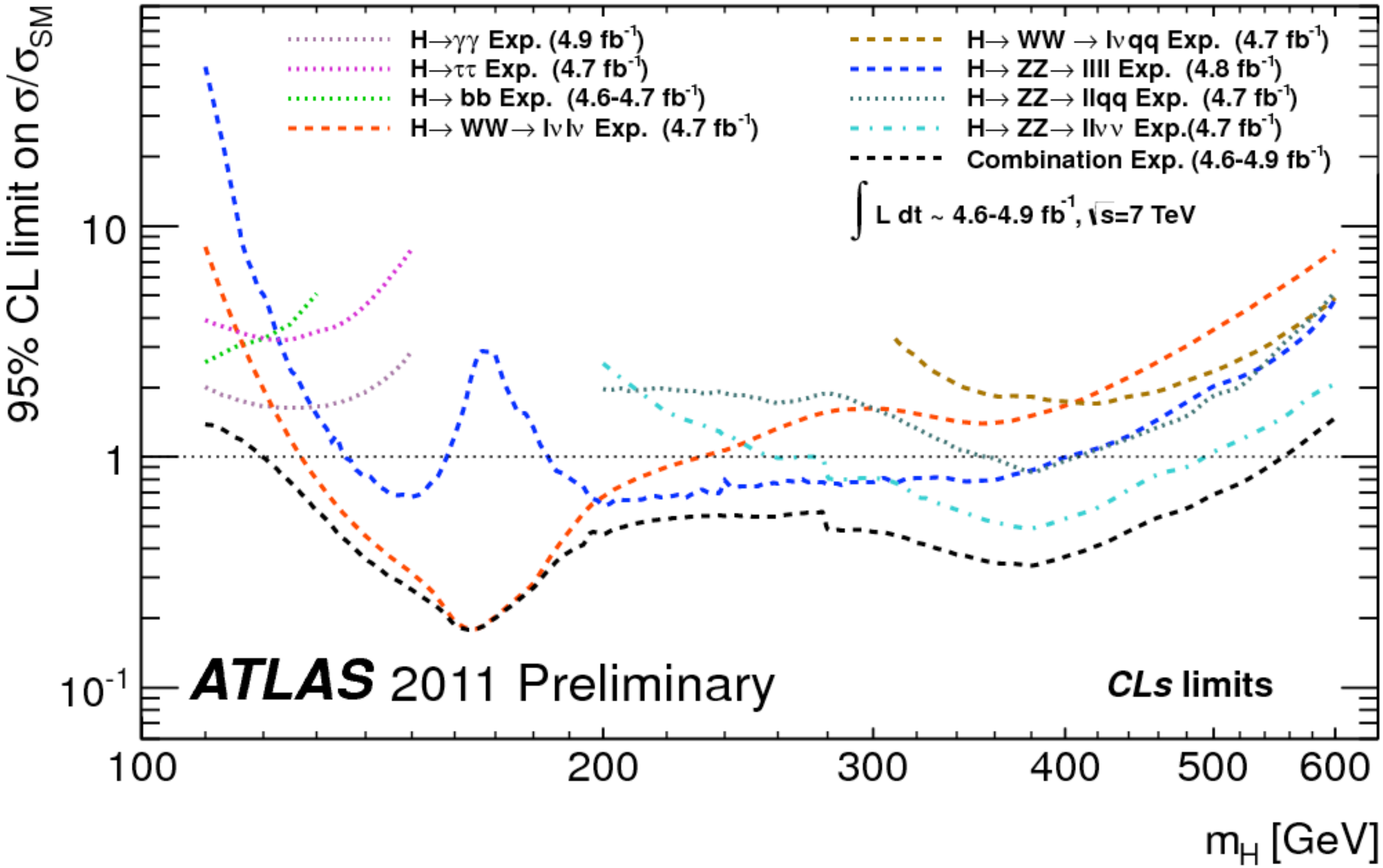
Tantalising hints around 125 GeV. Taken individually, non of these observations are globally very significant

Need more data for a definitive answer!

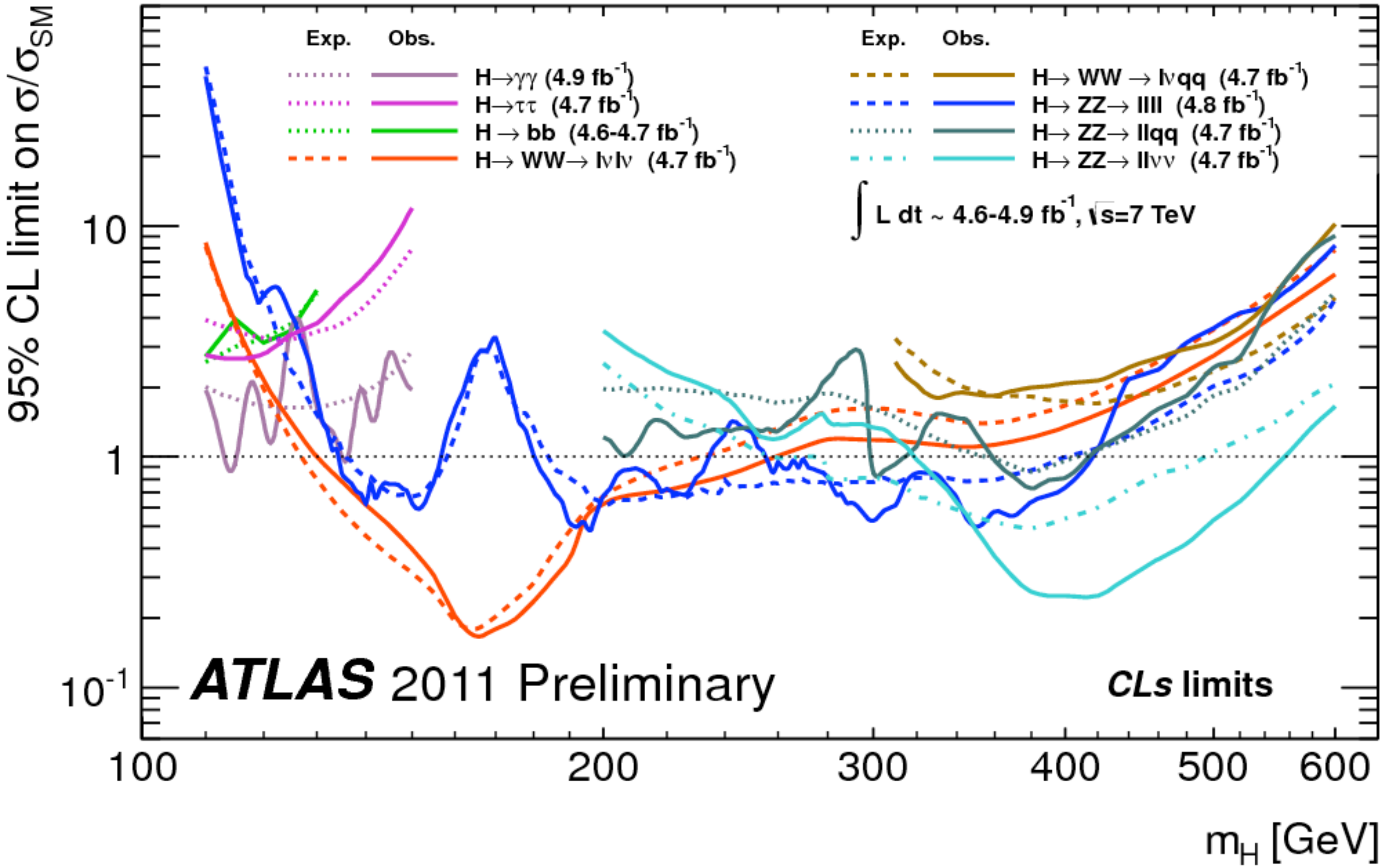
Within a year the LHC will likely to answer one of the key questions of particle physics and considerably shape the future of our field

Backup

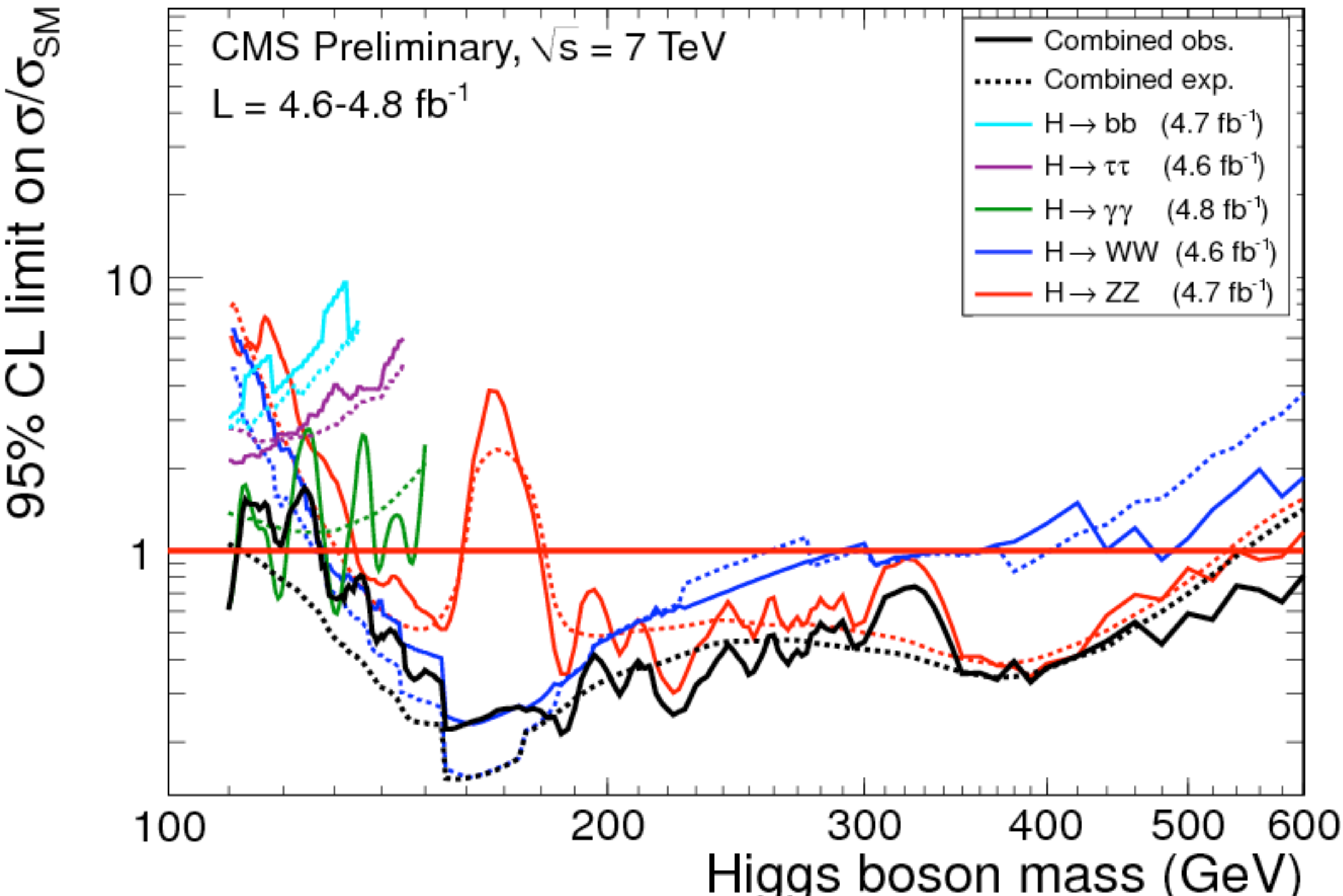
Expected sensitivity channel by channel



ATLAS combination



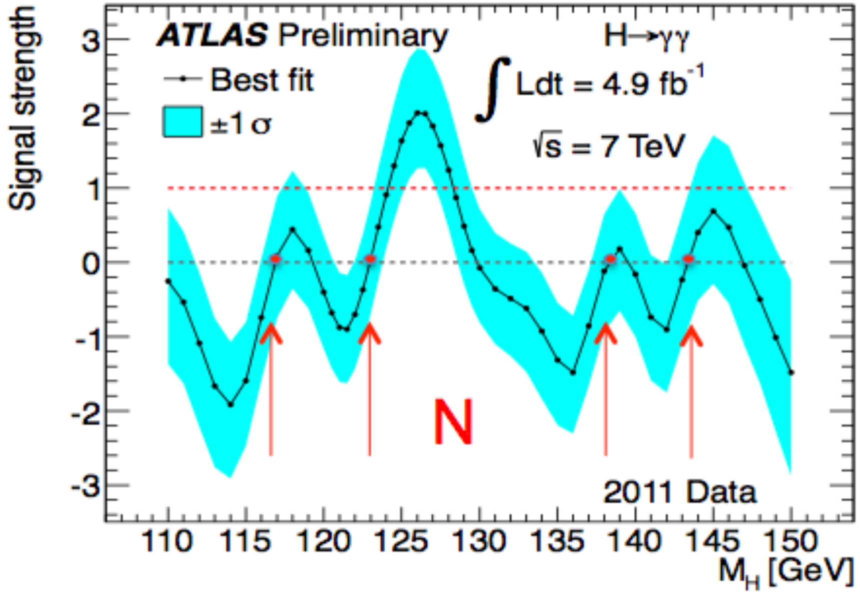
CMS combination



Local vs. Global Probability

Look Elswhere Effect

Approximate Formula



Based on counting the numbers of up-crossings

Then applying the very simple following formula (Z is the local significance)

$$p_{global} = p_{local} + N \times e^{-\frac{Z^2}{2}}$$

Trial factor ~ Here the dependence is explicit…

E. Gross and O. Vitells, *Trial factors for the look elsewhere effect in high energy physics*, Eur. Phys. J. **C70** (2010) 525–530.