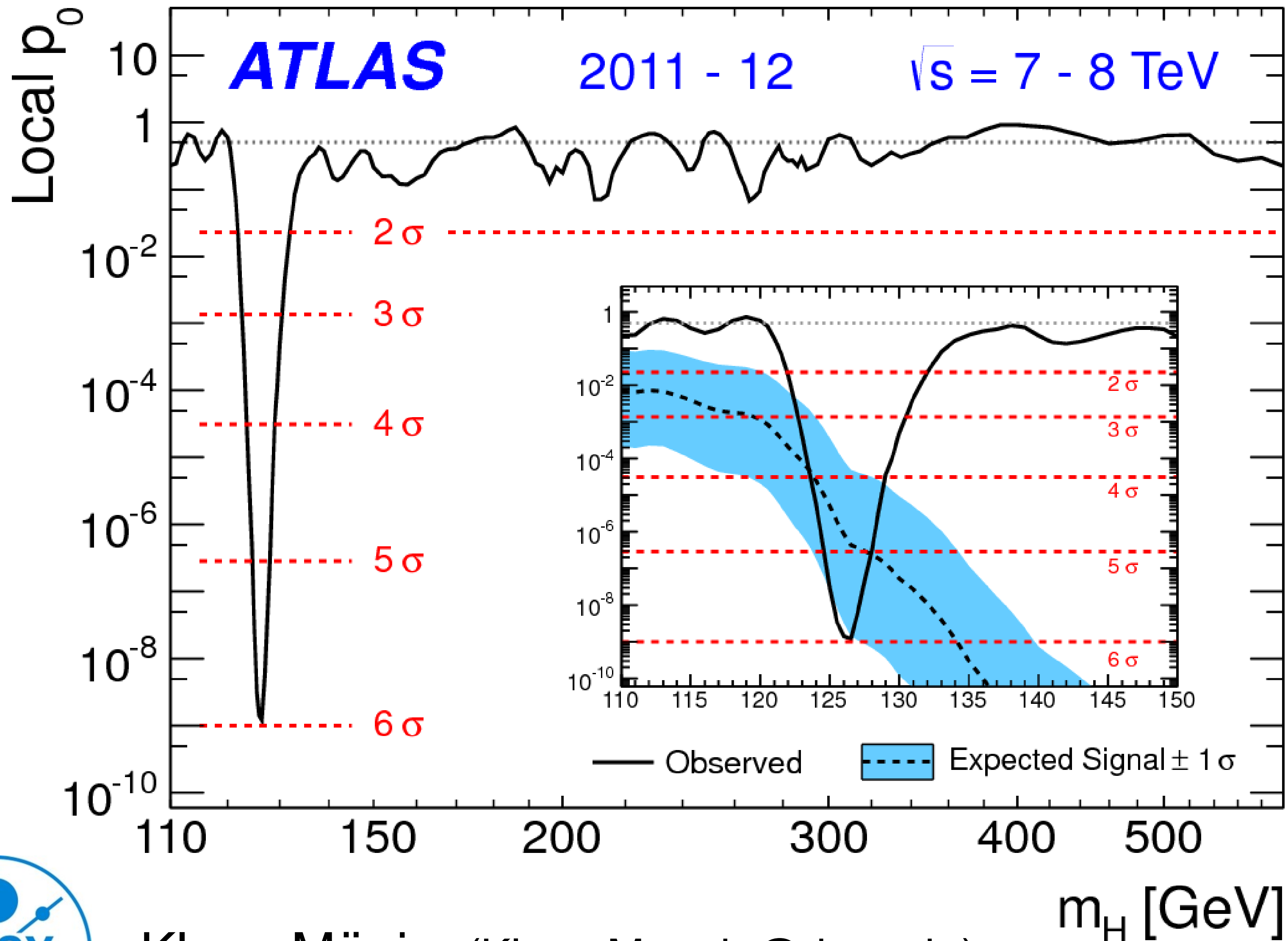
Electroweak Measurements



Klaus Mönig (Klaus.Moenig@desy.de)

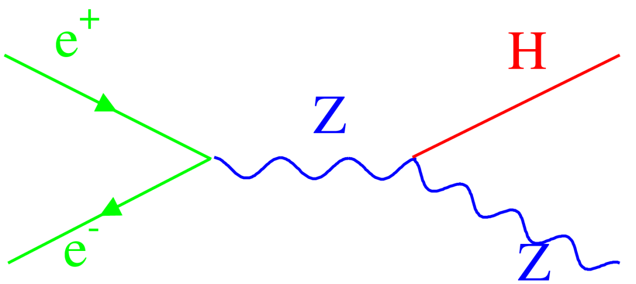
Outline

- Introduction
- Accelerators for electroweak physics
- Electroweak measurements at LEP and SLD
- Electroweak measurements at hadron colliders
- Electroweak measurements at HERA
- Electroweak fits
- Higgs boson production
- Gauge boson production and couplings

Higgs boson production

Higgs searches at LEP1

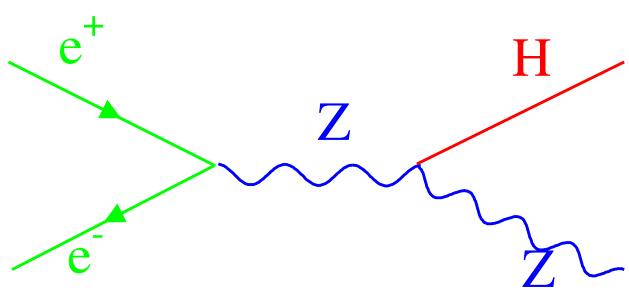
- The Higgs mass in the SM is a free parameter
  $\rightarrow \approx 0 < m_H < 1$ TeV (upper limit from unitarity)
- Before LEP, limits from K and B decays existed, but untrustworthy due to QCD uncertainties
- Higgs production at LEP

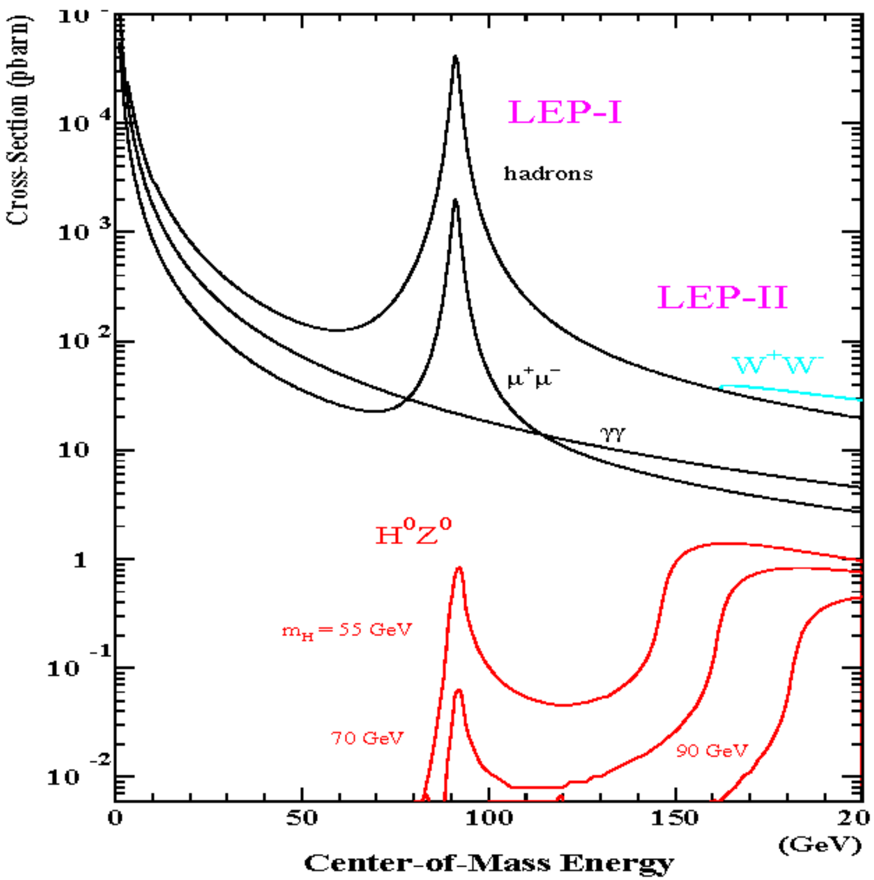


- Production cross section can be calculated reliably

Higgs production

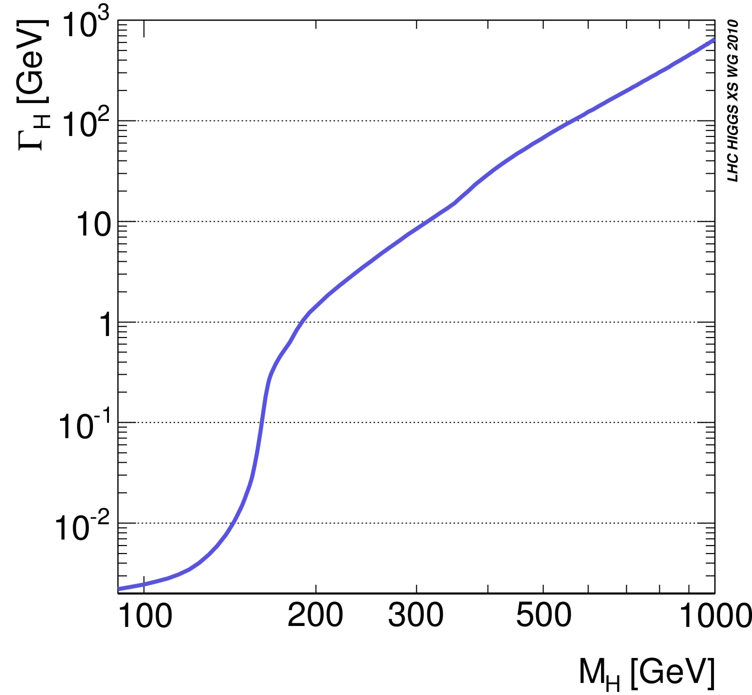
- For a light Higgs the cross section has two maxima:
  - when the 1st Z is on-shell
  - when the 2nd Z is on-shell
- When m_H approaches m_Z the 1st maximum vanishes

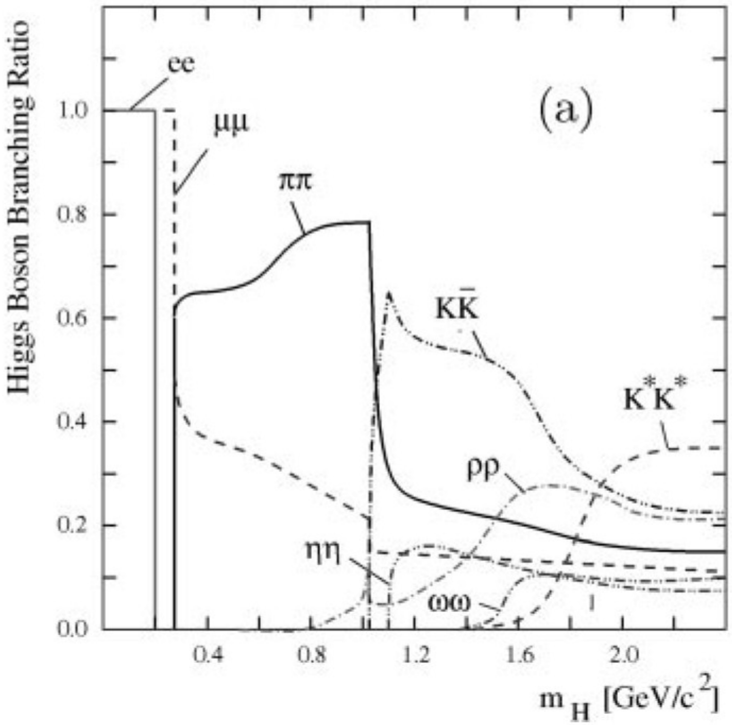


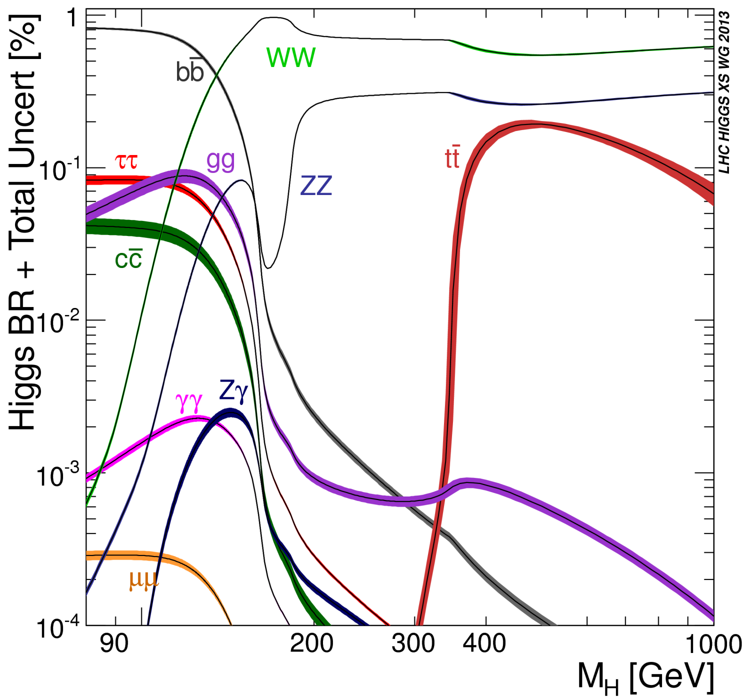


Higgs branching ratios

- At low mass the decays are non perturbative
- At higher mass one has the usual decays proportional to the mass







LEP1 searches

- All searches looked for a Higgs opposite to a Z decay to leptons and neutrinos
  - For $m_H<2m_e$ the Higgs is ~stable and the search was for missing energy opposite to a leptonic Z decay
  - For m_H<few GeV the search is for two particles recoiling against the Z
  - For $m_H<20$ GeV one looks for monojets
  - Above ~20 GeV b-tagging can be used on the recoil
- With this set of searches the full range $m_H<60$ GeV could be excluded

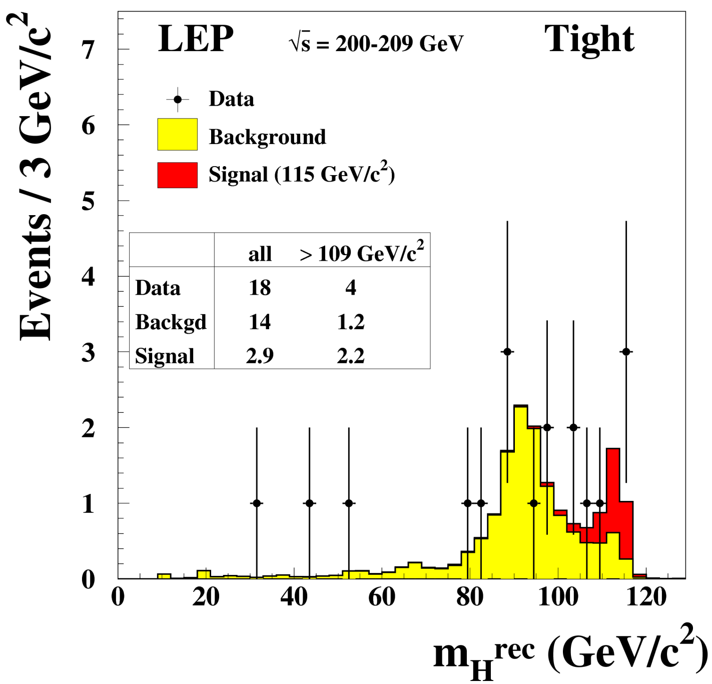
Higgs searches at LEP2

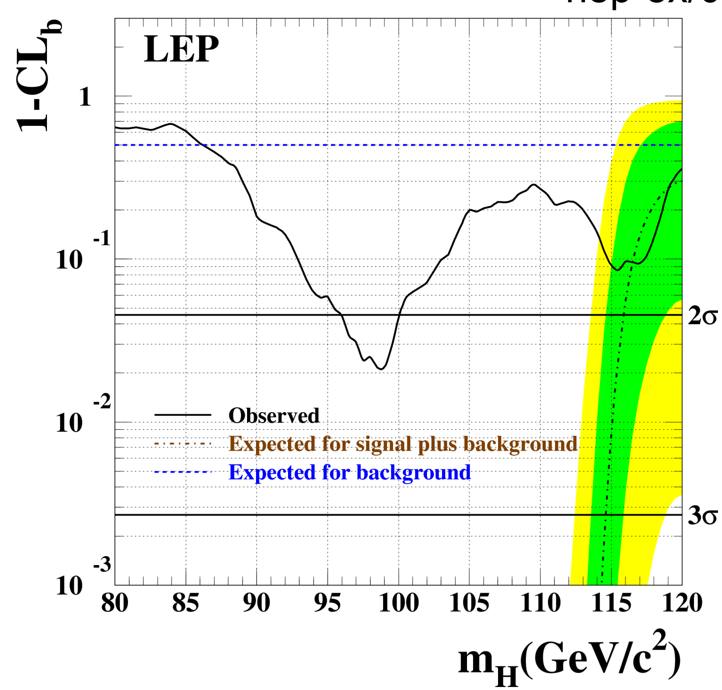
- At LEP2 the relevant production mode is a Higgs together with an on-shell Z
- This results in a best possible mass limit around $\sqrt{s}-m_Z$ which means around 115 GeV
- In this mass region only $H \rightarrow b\bar{b}$ is relevant
- With b-tagging for the Higgs and the Z-mass constraint for the recoil all Z decays can be used
- There is an irreducible background from ZZ events around m_H=91 GeV

Results at LEP2

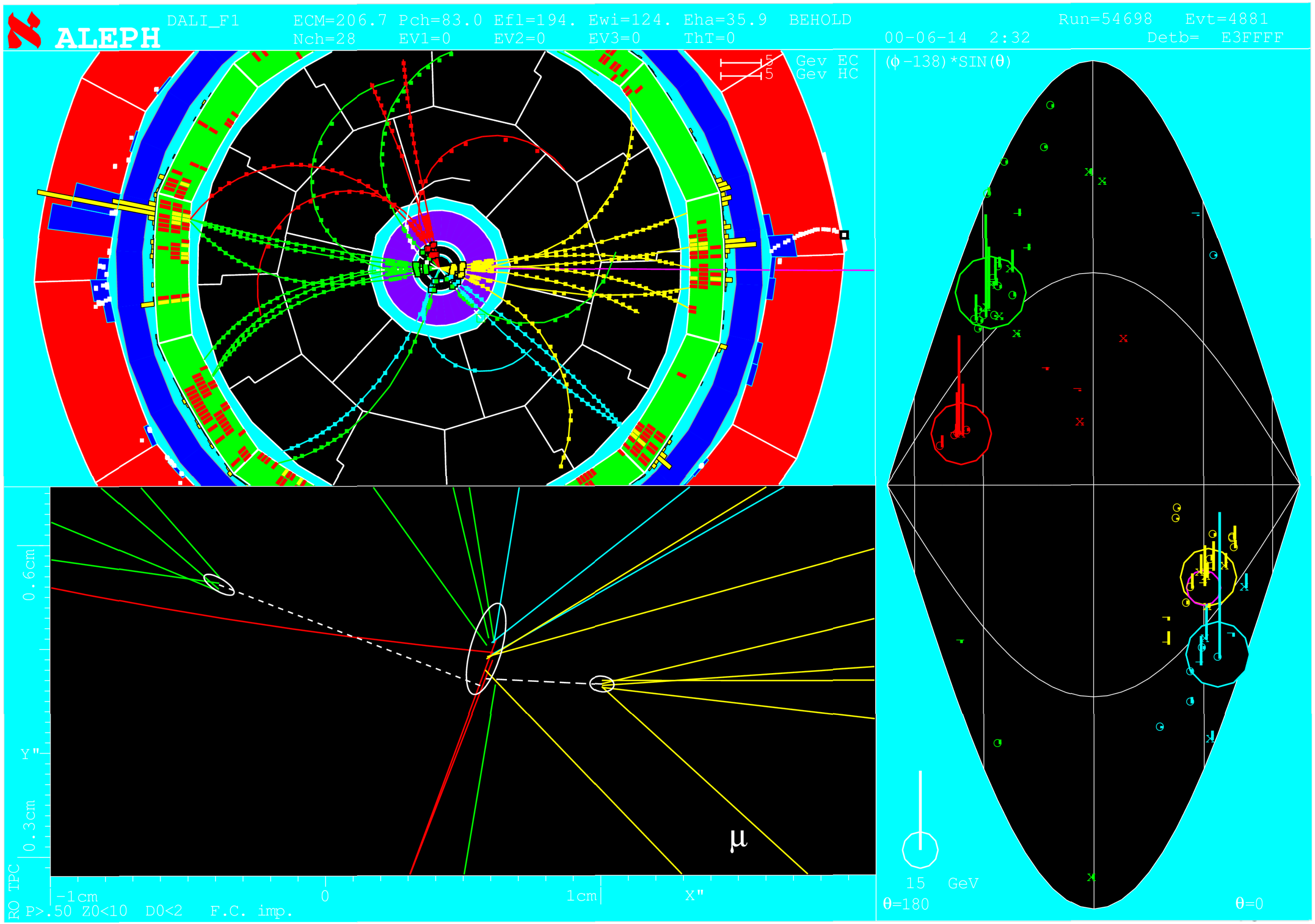
- There is a slight excess (1.5σ) around 115 GeV, mainly seen by ALEPH (3σ), which weakens the final limit
- There is a 2σ excess around 100 GeV seen by all experiments which cannot be a SM Higgs

hep-ex/0306033





ALEPH Higgs candidate at 115 GeV



Results at LEP2 (ii)

- A limit m_H<114.4 GeV has been obtained
- The limit on the signal strength falls quickly below 30% and below 10% for masses < m_Z

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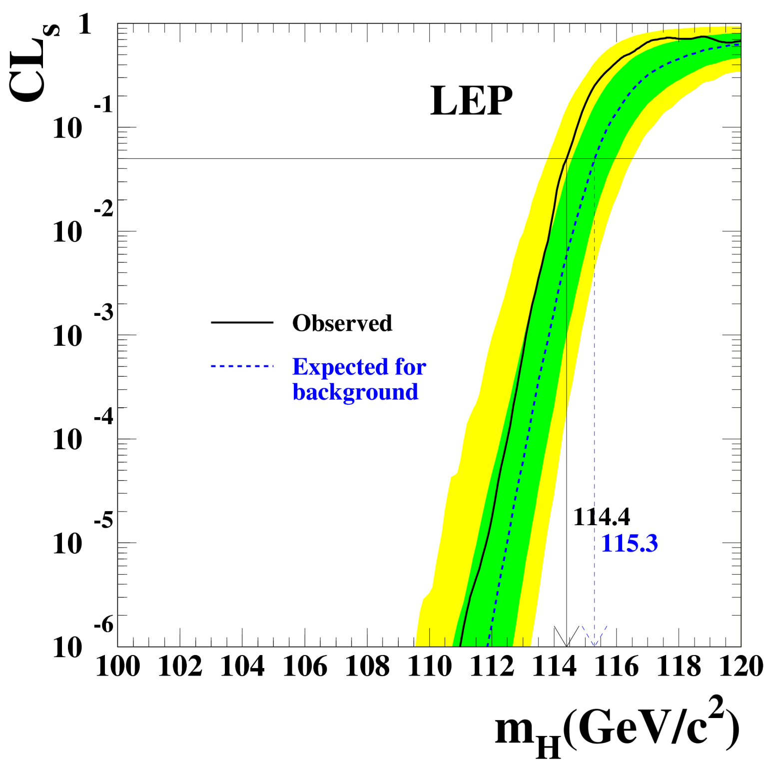
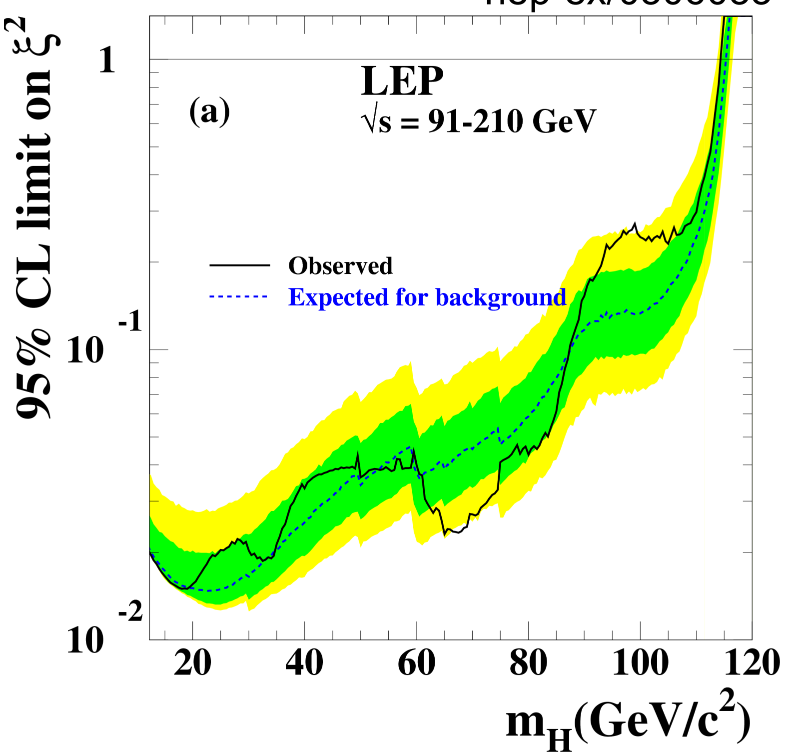
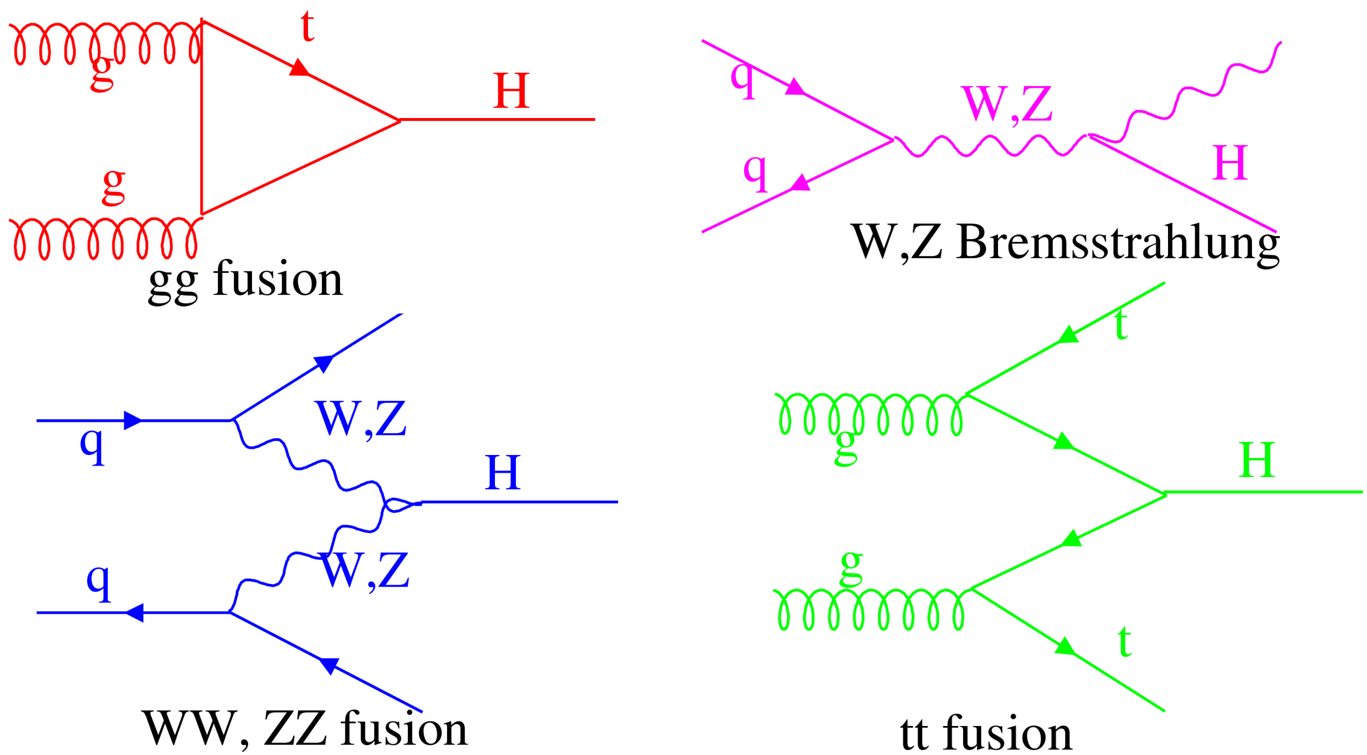




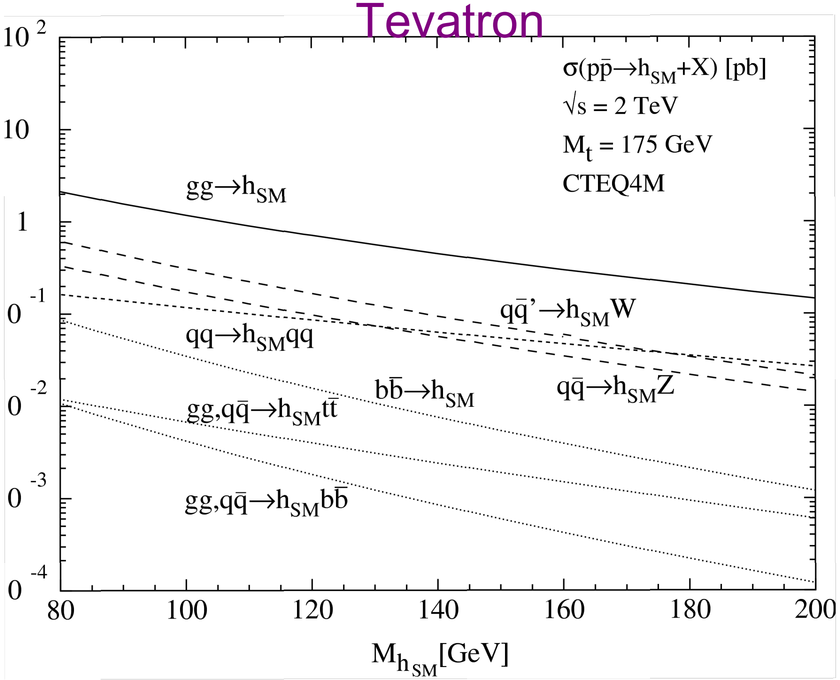
Higgs production at hadron colliders



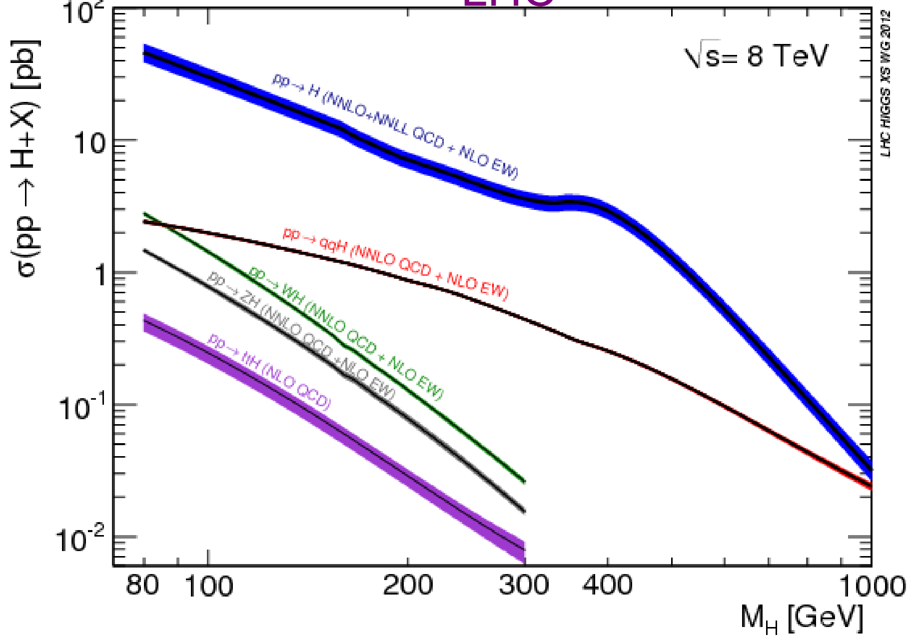
- gg-fusion produces Higgs and nothing else in the detector
- All other graphs have associated particles that help in the tagging

Higgs cross sections

Tevatron



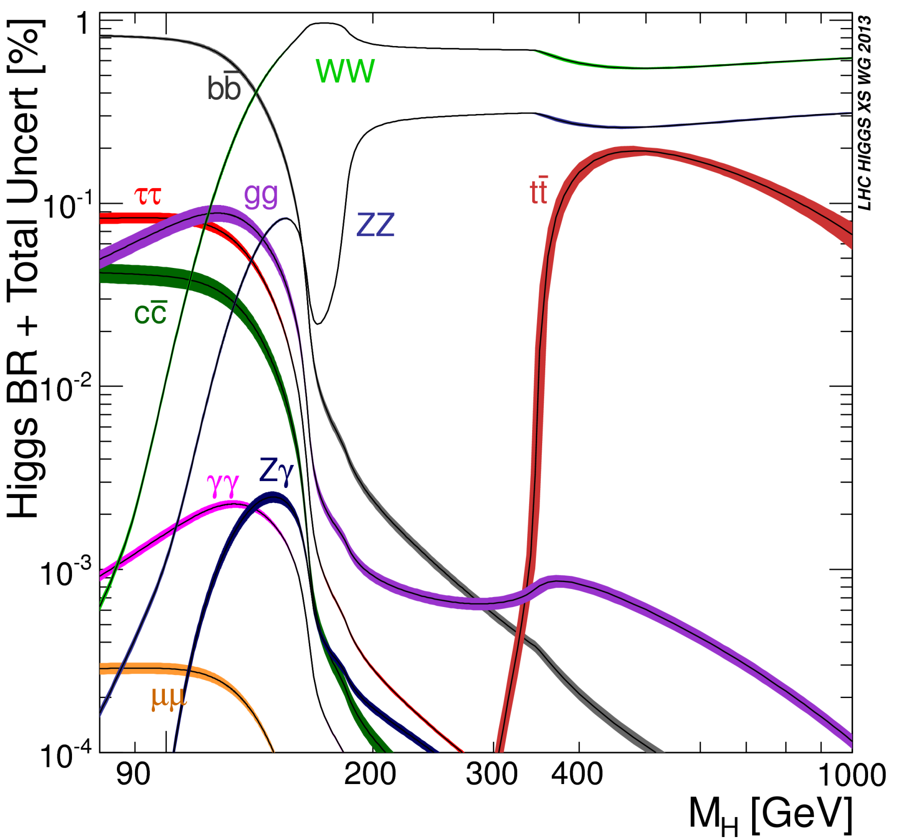
LHC



- gg-fusion dominates
- At LHC WW-fusion significant, rest small
- At Tevatron WW-fusion and W,Z bremsstrahlung relevant
- Total cross section large at LHC, factor 10 smaller at Tevatron
- At 14 TeV cross section is a factor 2 larger than at 8 TeV

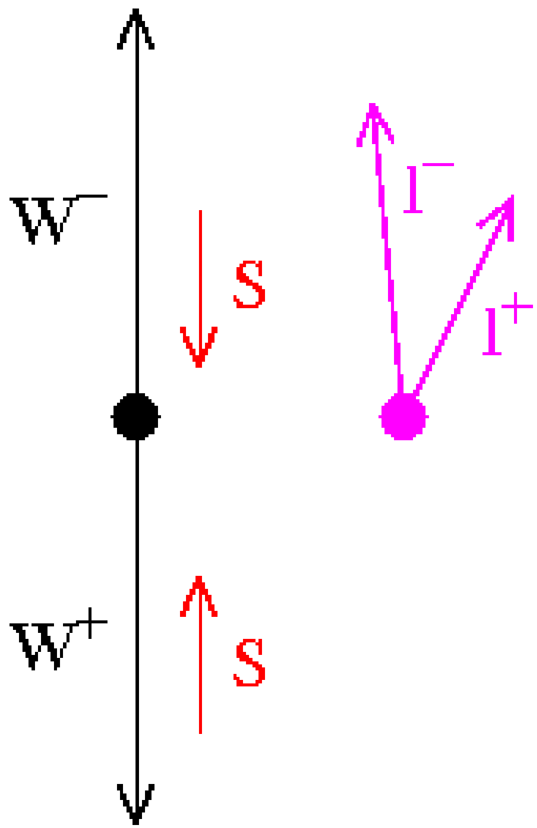
Higgs searches at the LHC

- At low mass H→γγ has best sensitivity (low BR, but clean)
- H→ZZ→4l quickly becomes competitive apart from a window around $2m_W$
- H→WW→lνlν is sensitive between 120 GeV and 250 GeV
- For high masses the hadronic Z and W decays and especially H→ZZ→llνν become important
- With these modes the region up to ~530GeV is excluded with 10 fb^{-1} apart from a window around 125 GeV

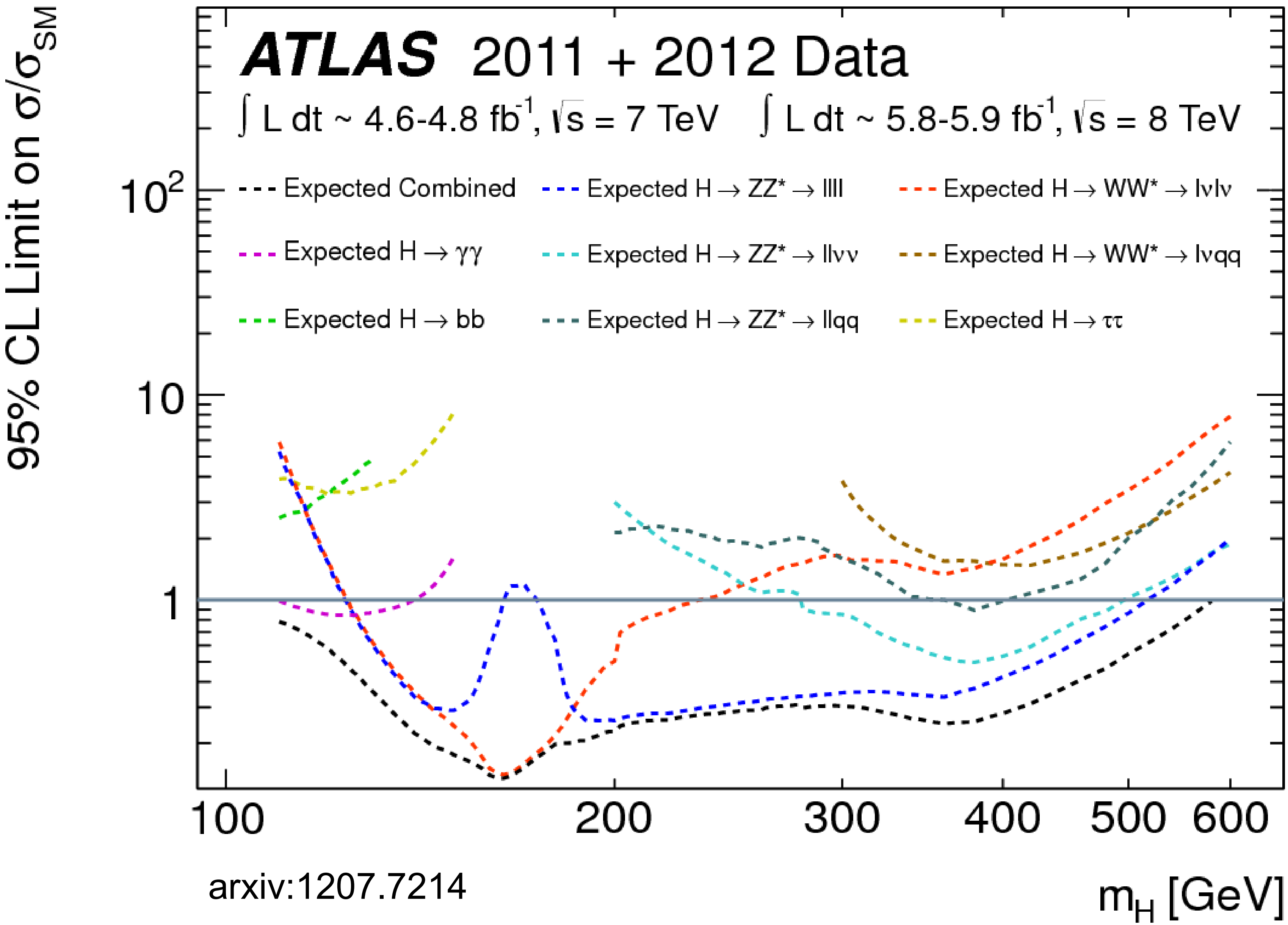


The mode $H\to WW\to l\nu l\nu$

- The mode $H\to WW\to l\nu l\nu$ has a large rate, however a large background from SM WW and a bad mass resolution
- If the WW come from a Higgs they have same helicity
- WW from SM predominantly have opposite helicity
- Because of the left- (right-) handed coupling of the W^- (W^+) the leptons tend to be close in phase space for H and far for WW

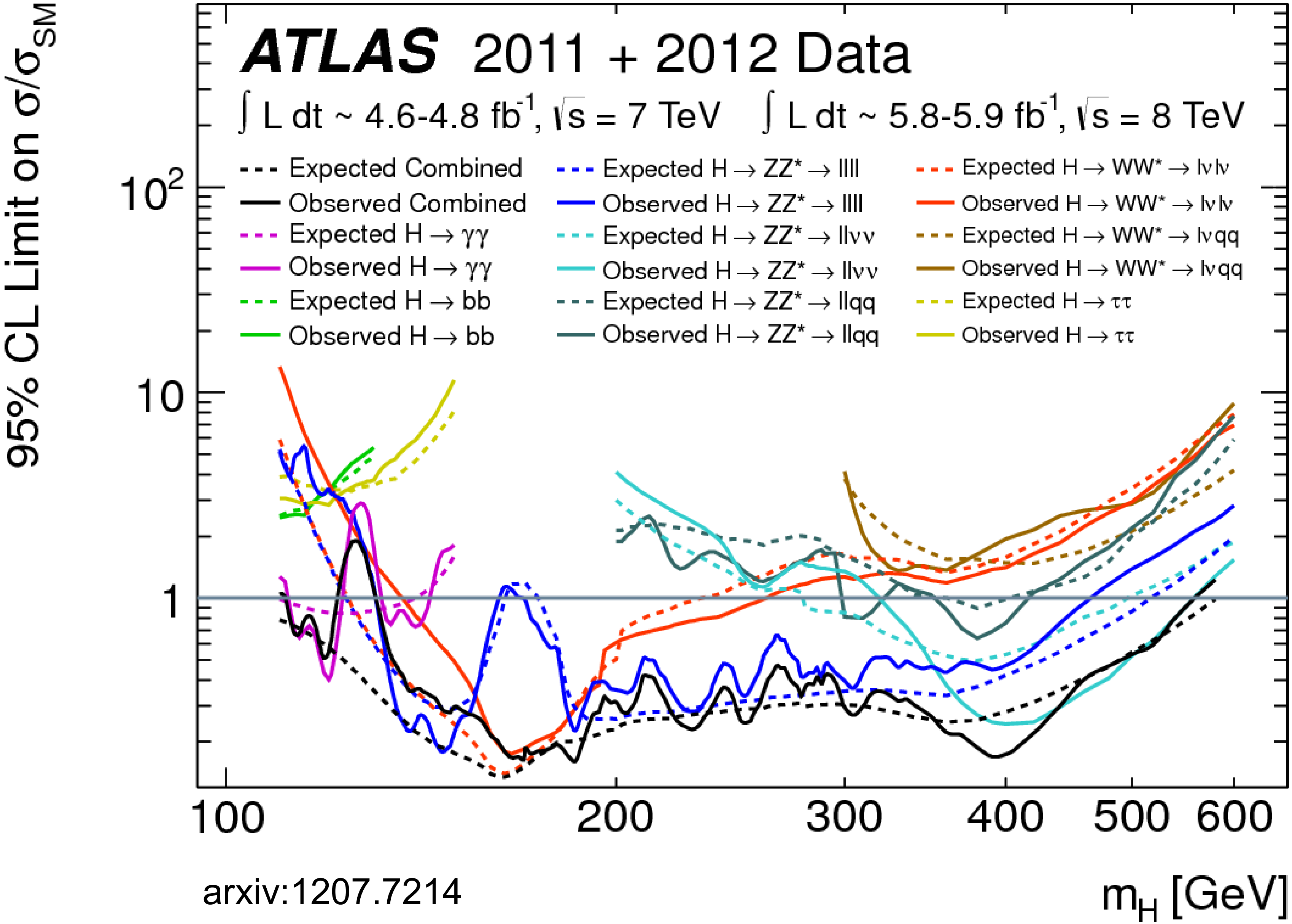


Expected search limits at the LHC



arxiv:1207.7214

Observed search limits at the LHC



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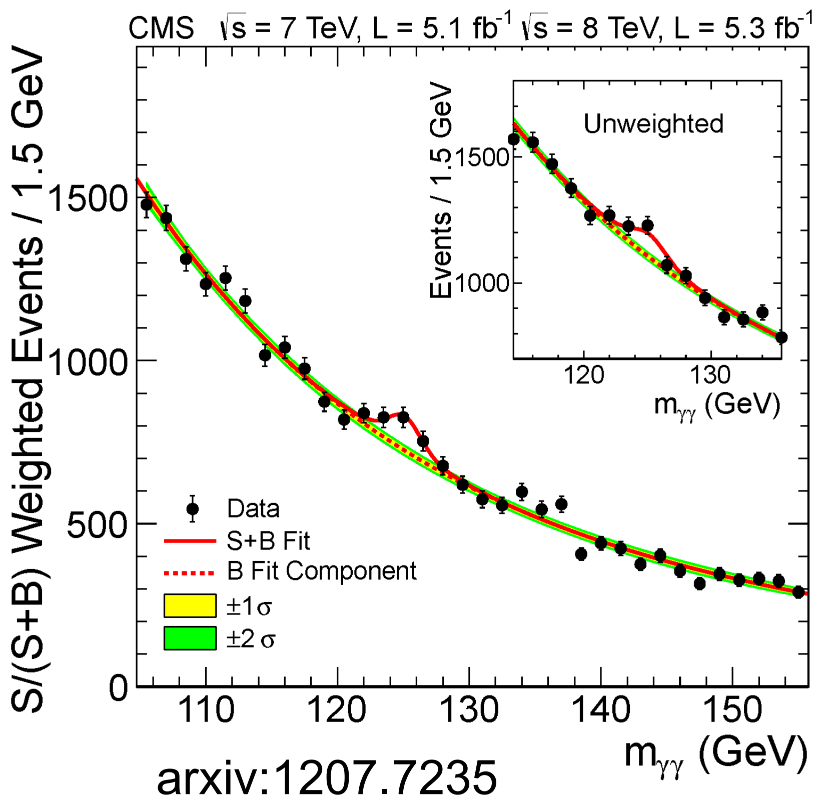
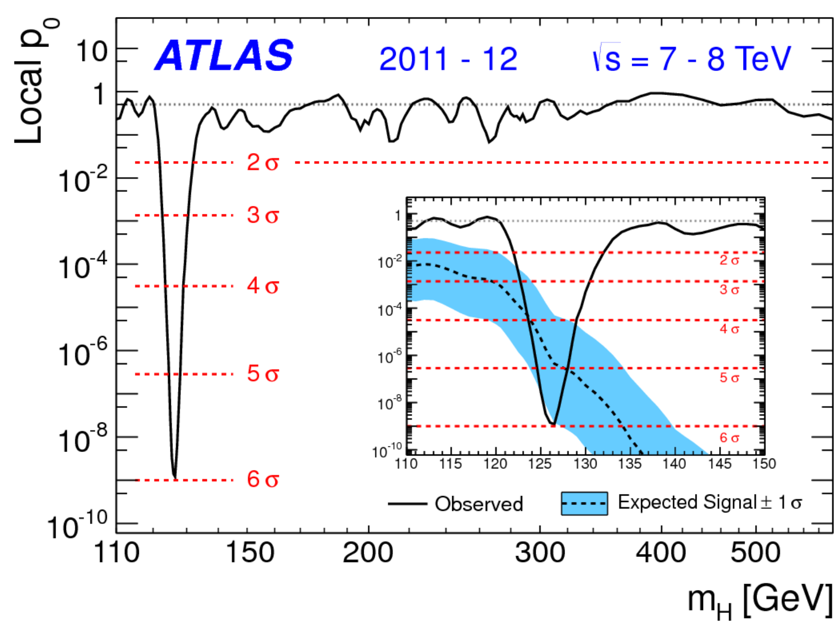
Higgs discovery at the LHC

- You all know that the Higgs was discovered on July 4 2012
- In the following I will go through the Higgs measurements using the best available statistics



arxiv:1207.7235

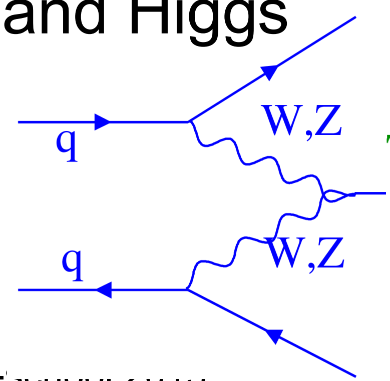


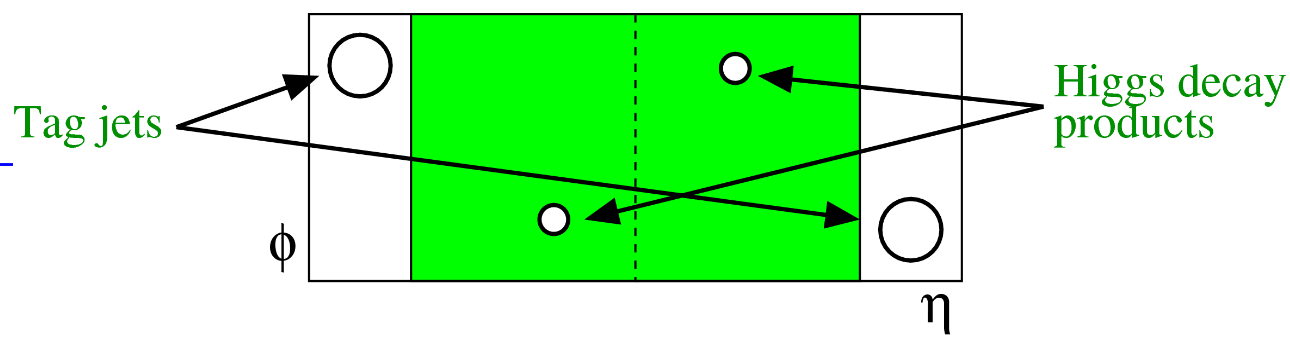
arxiv:1207.7214

How to separate production modes?

- gg-fusion results in a Higgs in the detector and nothing else (apart from ISR)
- ZH, WH, $t\bar{t}$H has reconstructible W,H,t
- VV fusion:
  - Propagator: $$\frac{1}{t - m_W^2} \qquad t = (p - p')^2 \approx 4pp' \sin^2 \frac{\theta}{2} \sim m_W^2$$

    $\rightarrow$tag jets visible in the detector
  - Higgs is colour singlet $\rightarrow$ no activity between tag-jets and Higgs

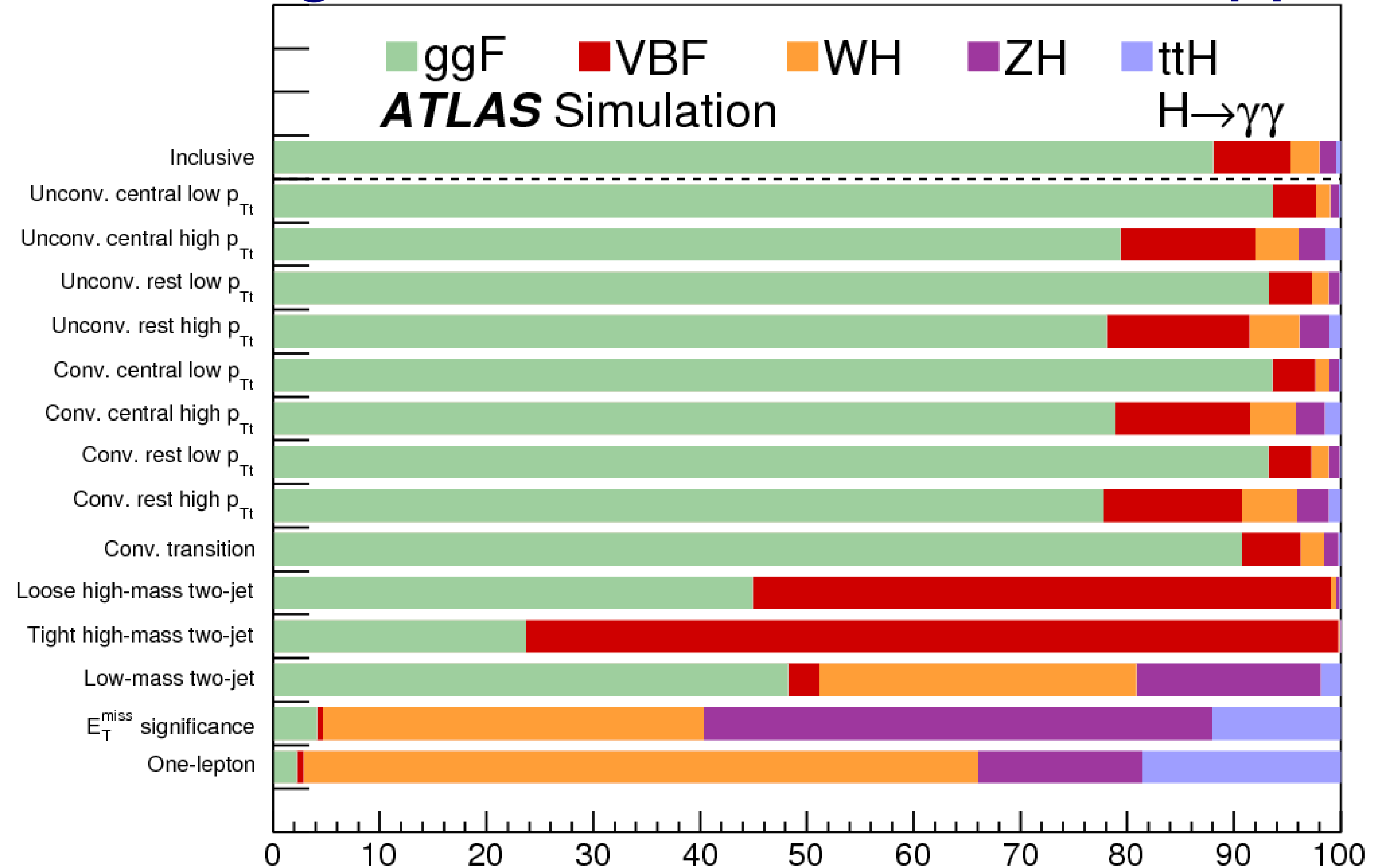




Event categorisation

- In a typical analysis the events are put into different categories
- This has two reasons:
  - the signal to background ratio depends on detector dependencies like conversion status, angle..., this increases the statistical power of the analysis
  - special features like extra jets or leptons give different ratios of different production modes allowing to disentangle them

Categorisation of ATLAS H→γγ



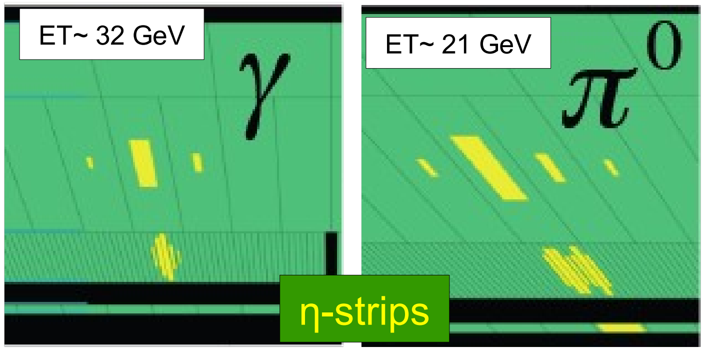
arxiv:1307.1427

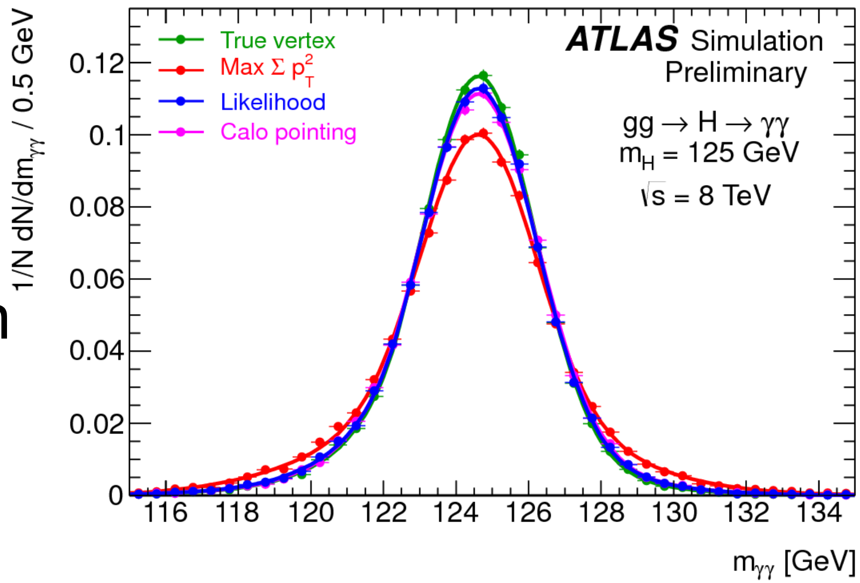
Results in the different channels

- The experiments provide results in the different decay channels:
  - $\gamma\gamma$, ZZ, WW, $b\bar{b}$, $\tau\tau$
- Limits exist in some rare decay modes
  - $Z\gamma$, $\mu\mu$, invisible
- From the categorisation the different bosonic production modes can be disentangled
- Special searches exist to look for associated production with $t\bar{t}$

$H \to \gamma\gamma$

- Large background from QCD $q\bar{q} \to \gamma\gamma$
- Huge bg. from $q\bar{q} \to \gamma j$ and $q\bar{q} \to jj$
  $\to$ need excellent γ-j separation
- Signal fitted on top of smooth bg.
- Need good mass resolution to get good signal/bg
- ATLAS: very good spacial resolution for γ-j separation and photon direction
- CMS: excellent energy resolution in crystal calorimeter, however need vertex for direction



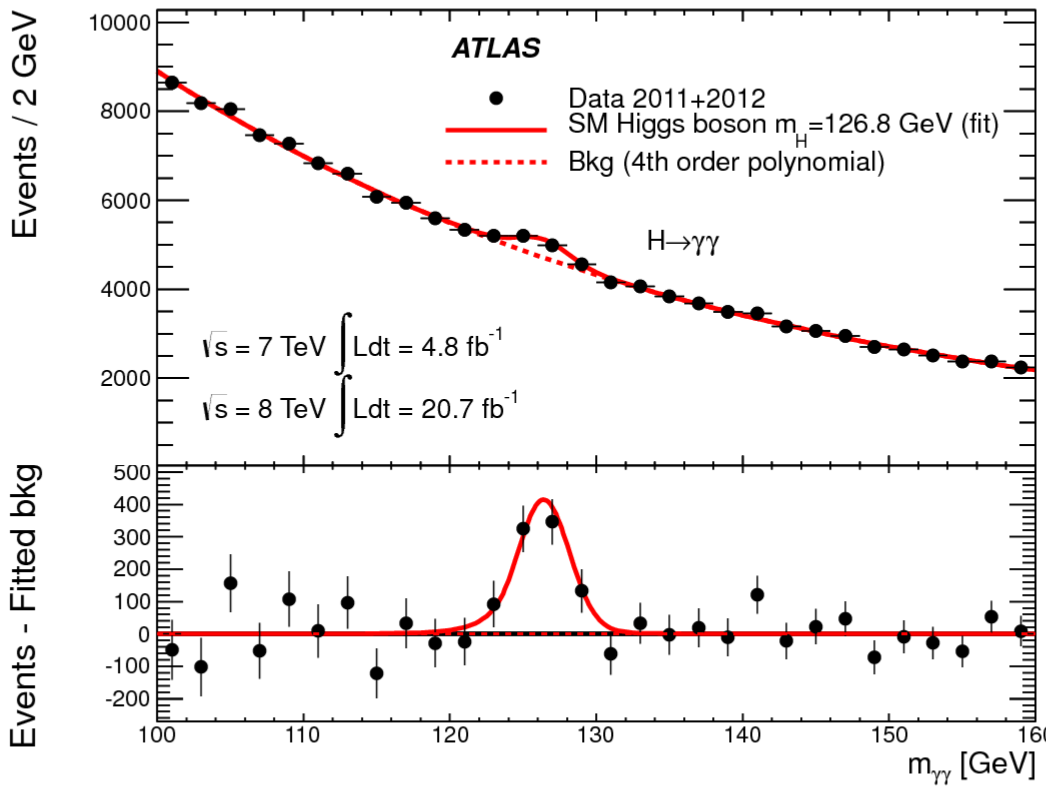


H→γγ (ii)

- ATLAS:
  - strong signal with 7.4σ evidence (4.3σ expected)
  - correspondingly slightly high signal strength:

    $\mu = 1.55^{+0.33}_{-0.28}$

arxiv:1307.1427



  - allows for differential cross section measurement ans spin analysis

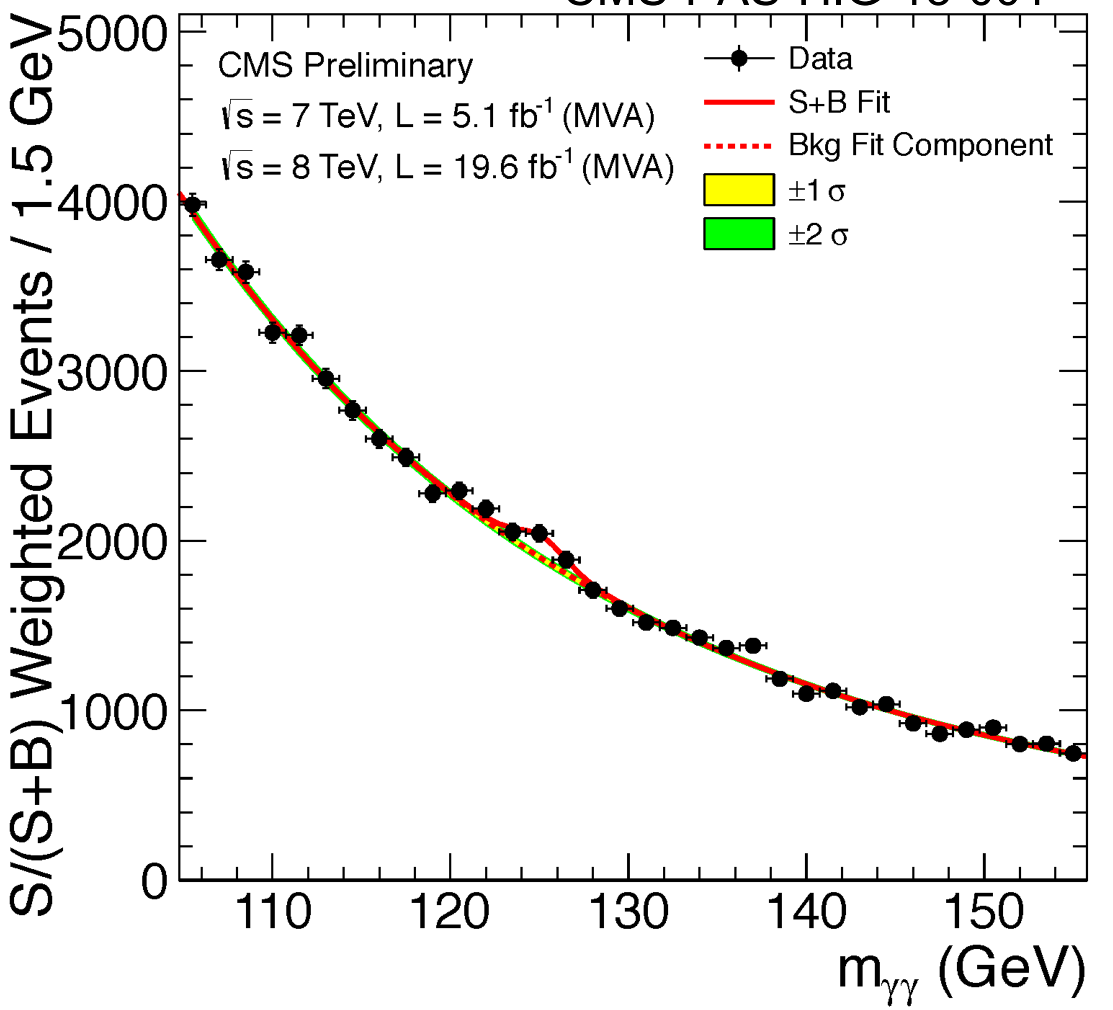
$H\rightarrow\gamma\gamma$ (iii)

- CMS
  - downward fluctuation signal 3.2σ evidence (4.2σ expected)
  - correspondingly low signal strength

$$\mu = 0.78^{+0.28}_{-0.26}$$

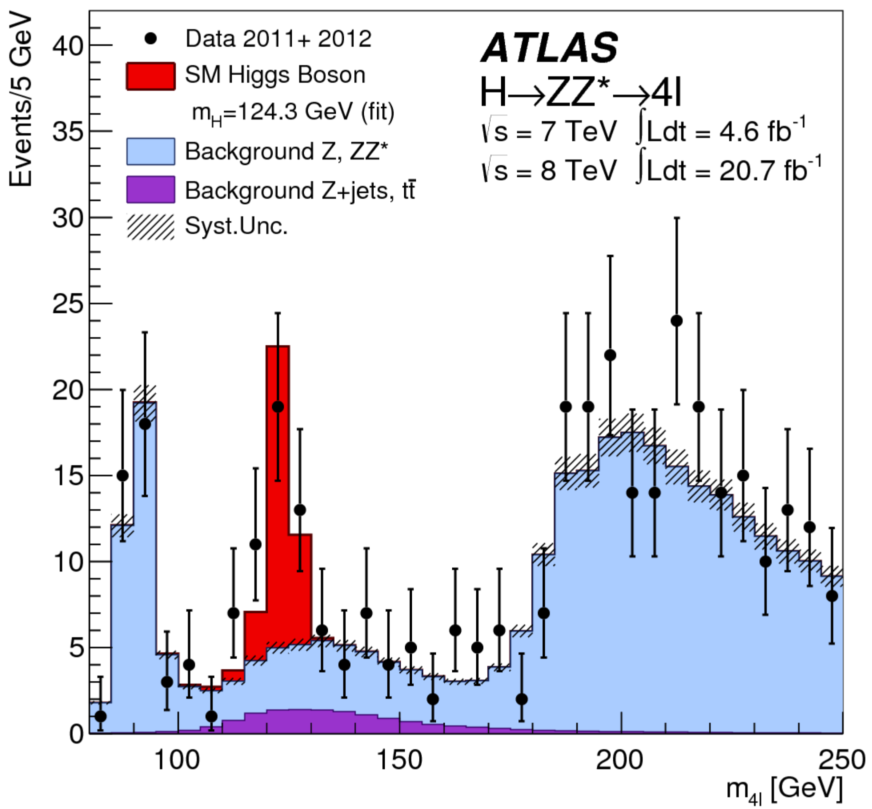
  - cross check cut analysis gives μ=1.1 with slightly larger error

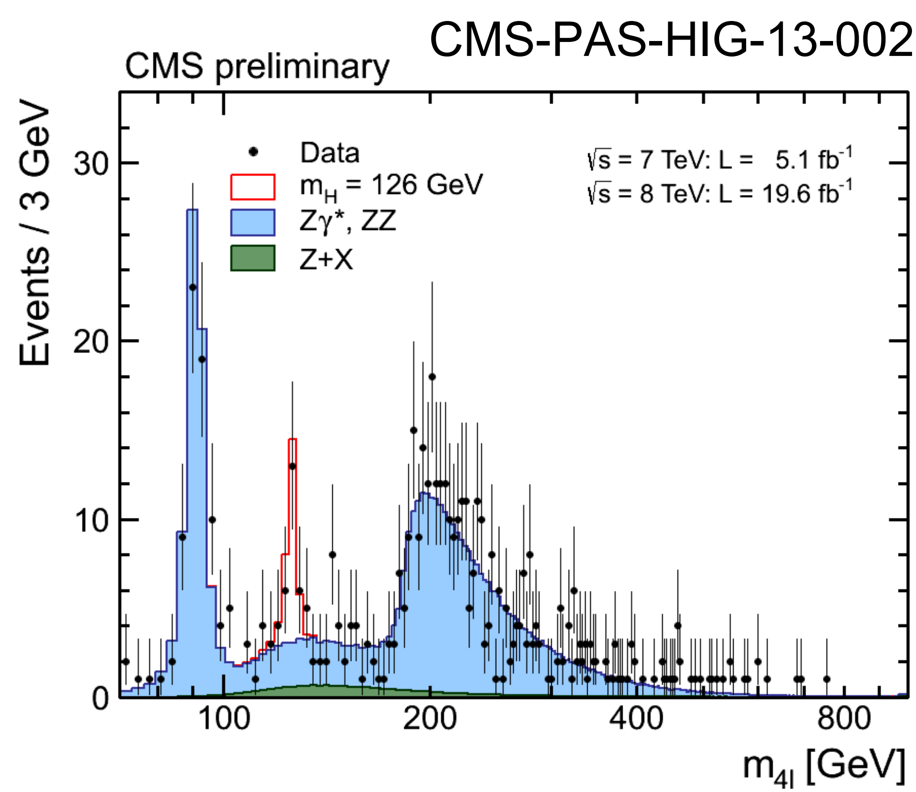
CMS-PAS-HIG-13-001



H→ZZ→4l

- Very clean channel
- Almost only irreducible background ZZ→4l
- Strong signal from both experiments

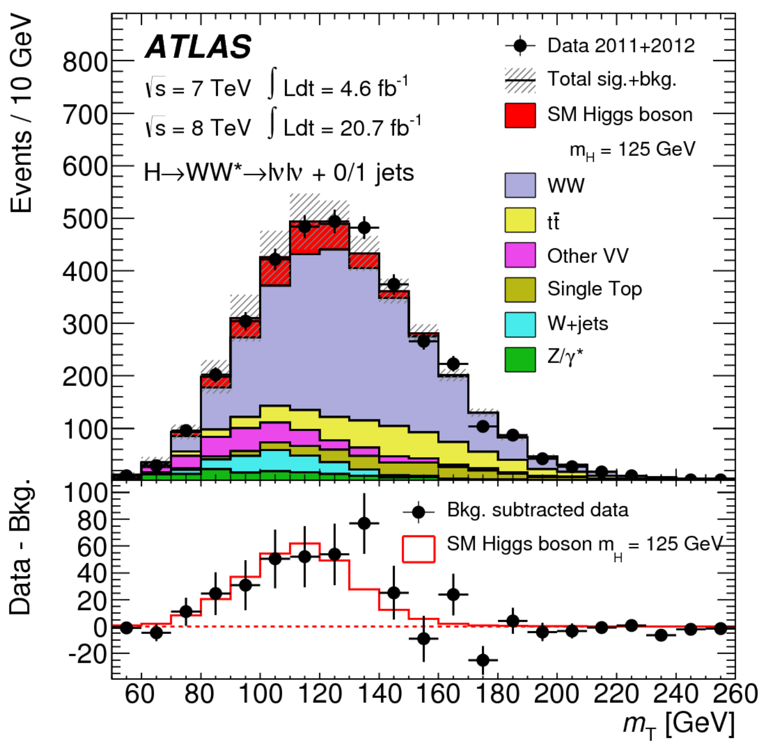


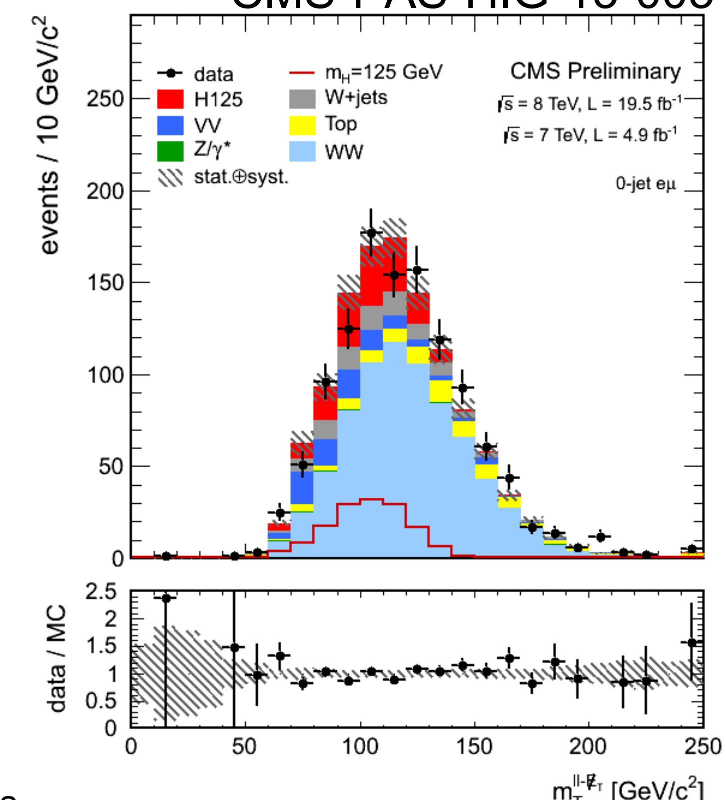


H→WW→lνlν

- No mass peak, need to understand background very well
- Categorisation in number of jets to separate production modes
- ~4σ signal by both experiments

CMS-PAS-HIG-13-003





leasurements-

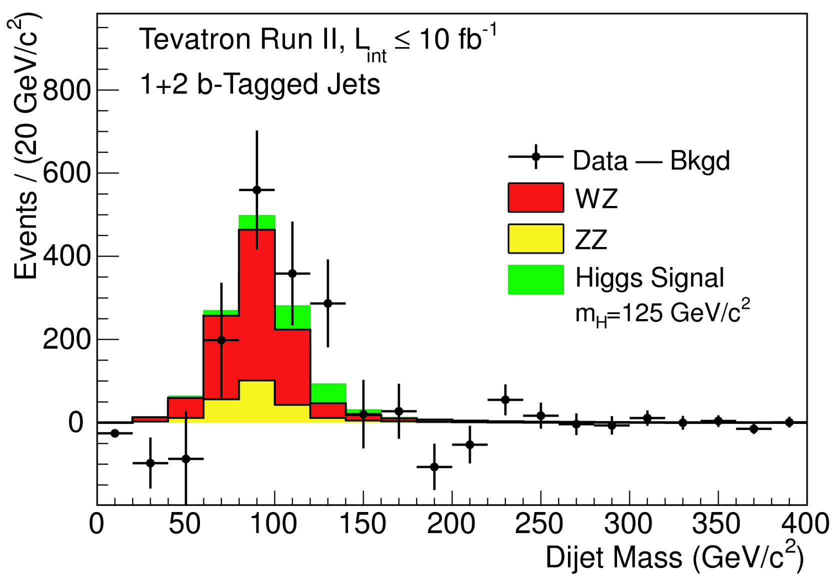
$H \to b\bar{b}$

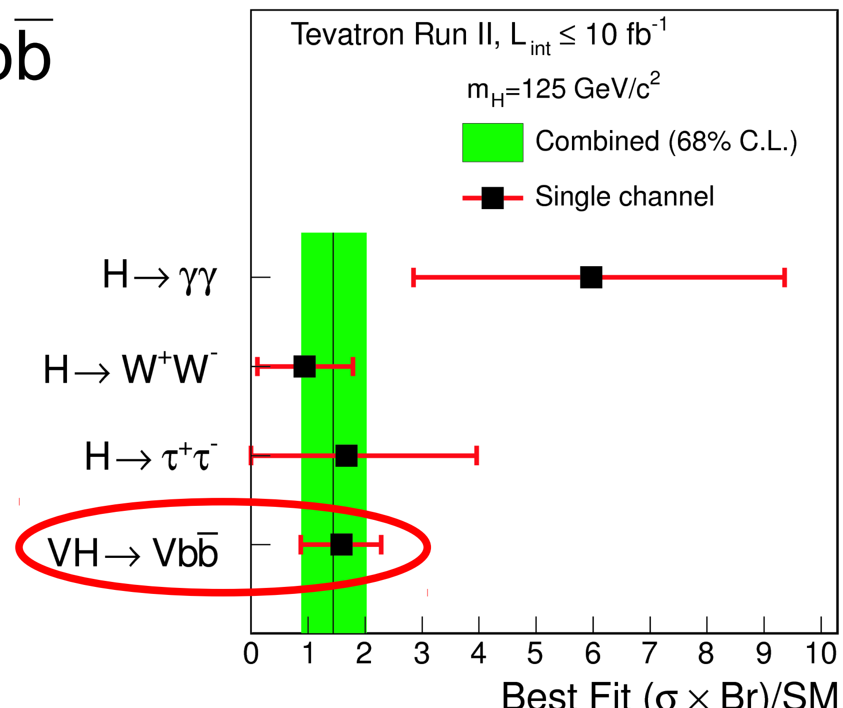
- $H \to b\bar{b}$ is the largest decay mode (57%)
- $gg \to H \to b\bar{b}$ is completely hopeless due to QCD background
- $VH \to Vb\bar{b}$ has some chance due to the additional vector boson
- Signal/background is better at lower energy so that the Tevatron is competitive in this channel
- At the LHC one can improve signal/bg by going to boosted topologies (large $V, b\bar{b}$ energies $\to$ merging jets)

$H \rightarrow b\bar{b}$ at the Tevatron

arxiv:13036346

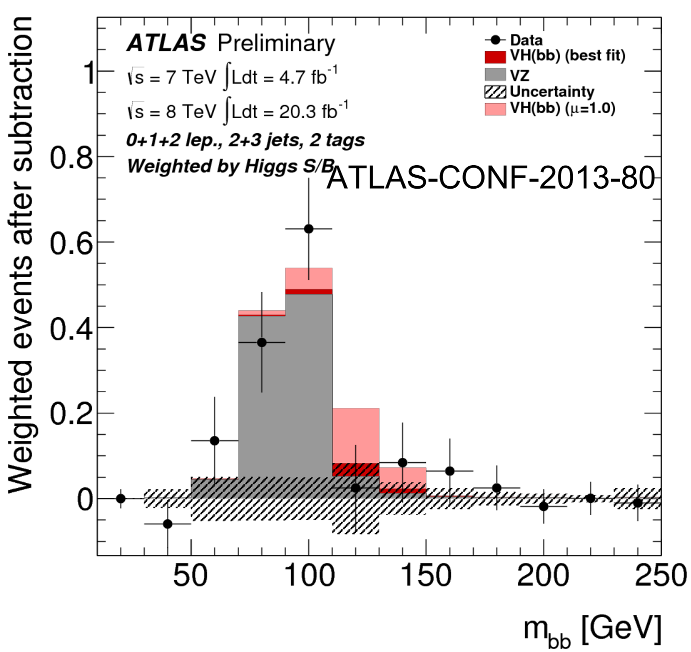
- The Tevatron has searched for the Higgs with their full luminosity of ~10 fb^{-1}
- In the 115-140 GeV region $VH \rightarrow Vb\bar{b}$ is the most sensitive channel
- With some upward fluctuation the Tevatron sees about 3σ evidence for $H \rightarrow b\bar{b}$

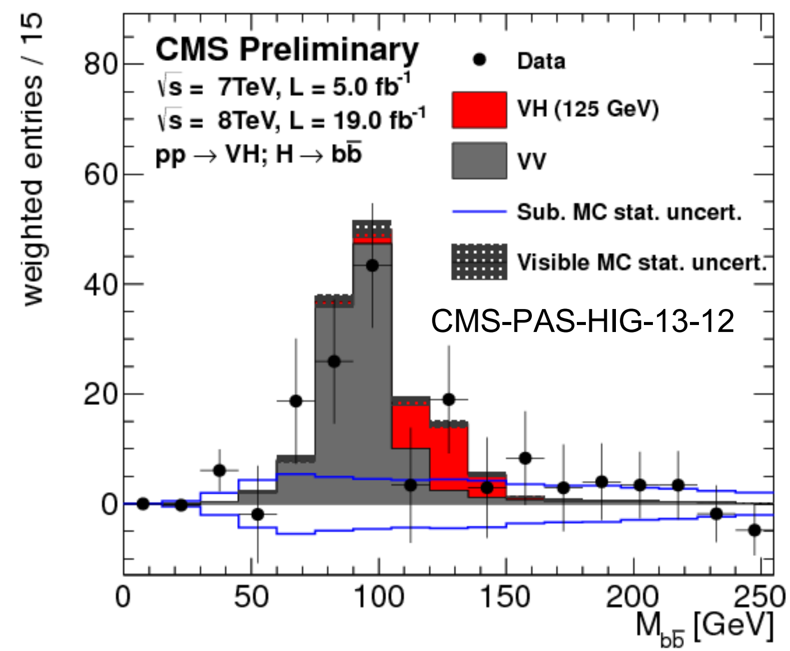




H→b$\bar{b}$ at the LHC

- Both experiments search for VH→Vb$\bar{b}$ in the 0/1/2-jet mode and in bins of $p_{T,H}$
- Both experiments see clear signal of VZ production
- CMS has 2σ evidence for H→b$\bar{b}$ ($\mu = 1.0 \pm 0.5$) while ATLAS has a downward fluctuation with similar sensitivity ($\mu = 0.2^{+0.7}_{-0.6}$)





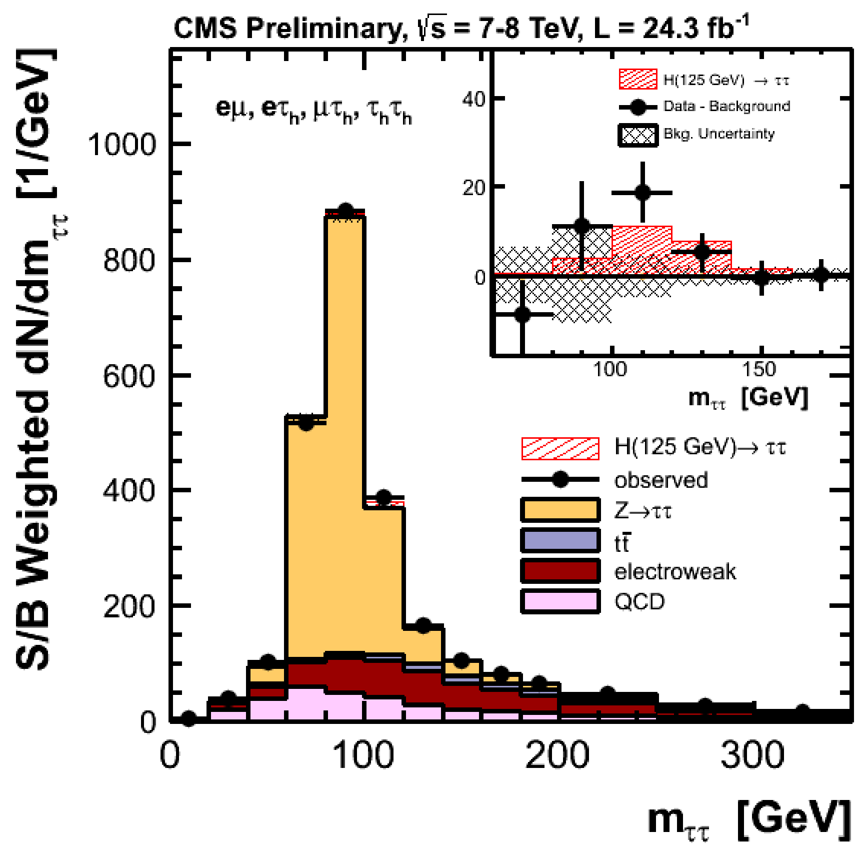
$H \rightarrow \tau\tau$

- In $H \rightarrow \tau\tau$ events always (at least) 2 neutrinos are missing
- The τ-momenta can be reconstructed under the assumption that the ν is collinear with the τ and if the 2 τs are not collinear in the transverse plane
- This makes the $H \rightarrow \tau\tau$ analysis more sensitive in VBF, VH and gg with significant ISR
- The analyses are split according to the τ-decay mode (leptonic or hadronic) and the jet multiplicity

H→ττ (ii)

- CMS sees 2.9σ evidence (2.6σ expected)
- Together with $H \to b\bar{b}$ this gives 3.4σ evidence for the Higgs coupling to down-type fermions
- ATLAS doesn't use the full 2012 statistics yet

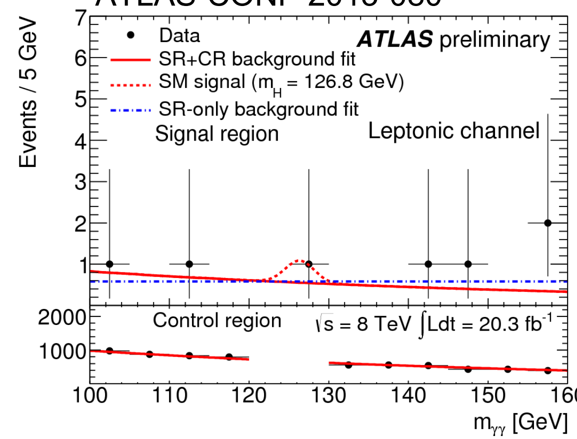
CMS-PAS-HIG-13-04



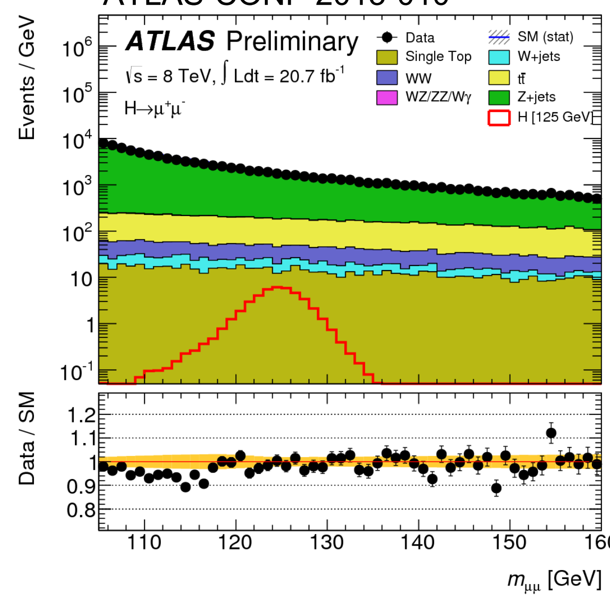
Searches for rare modes

- ATLAS searched for several rare modes
- Limits (95% C.L. meas(exp. no Higgs)):
  - ttH (H→γγ): μ<5.3(6.4)
  - H→μμ: μ<9.8(8.2)
  - H→Zγ: μ<18.2(13.5) ATLAS-CONF-2013-009
  - H→inv.: BR(H→inv)<65%(84%)
  - t→cH: BR(t→cH)<0.83%(0.53%)
- CMS has similar results

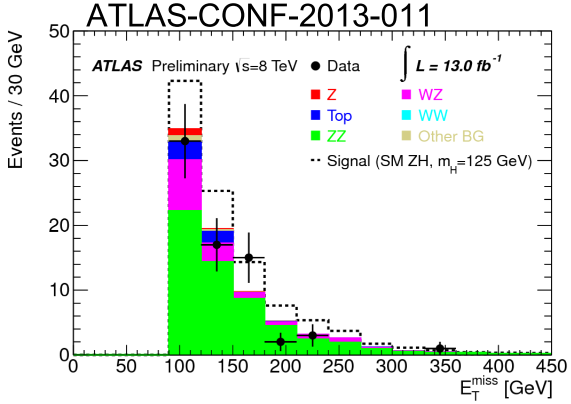
ATLAS-CONF-2013-080



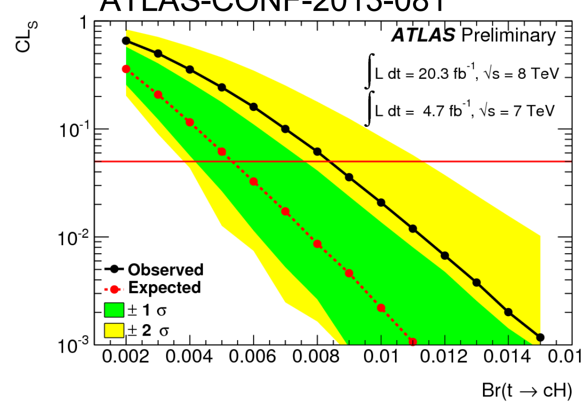
ATLAS-CONF-2013-010



ATLAS-CONF-2013-011

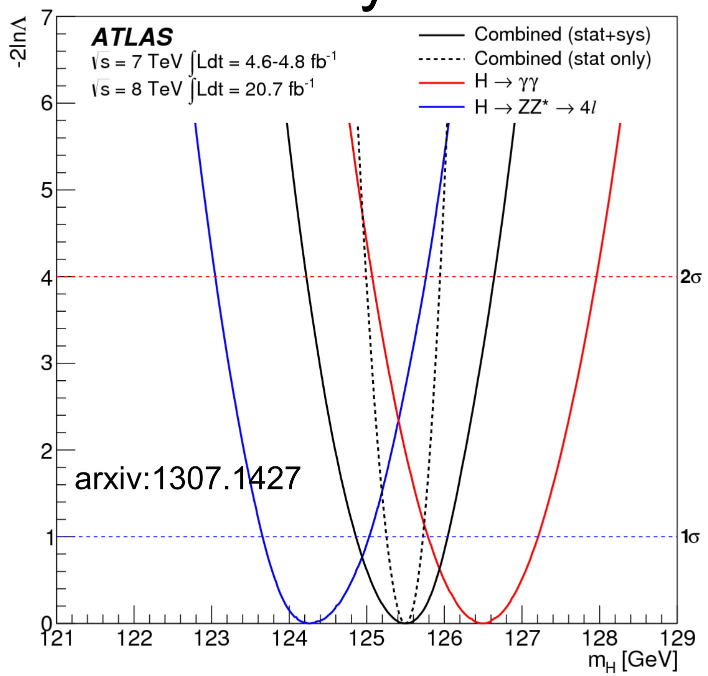


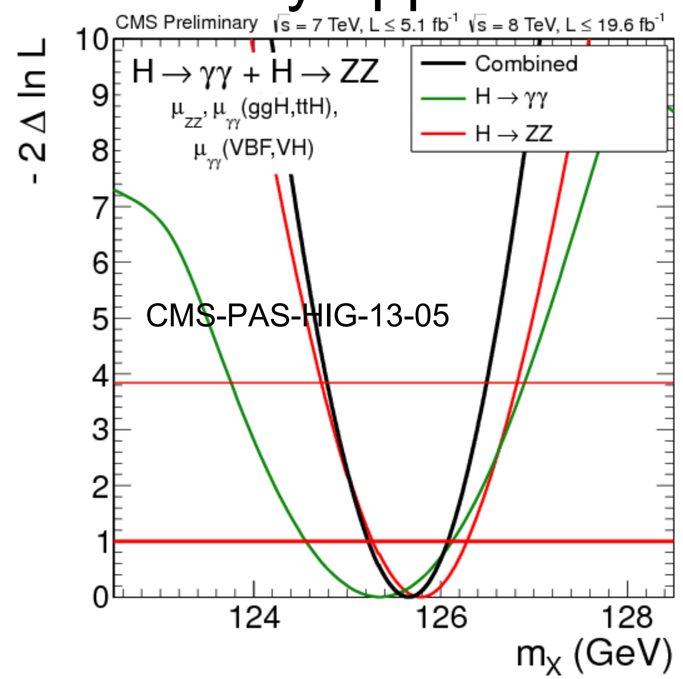
ATLAS-CONF-2013-081



The mass of the Higgs boson

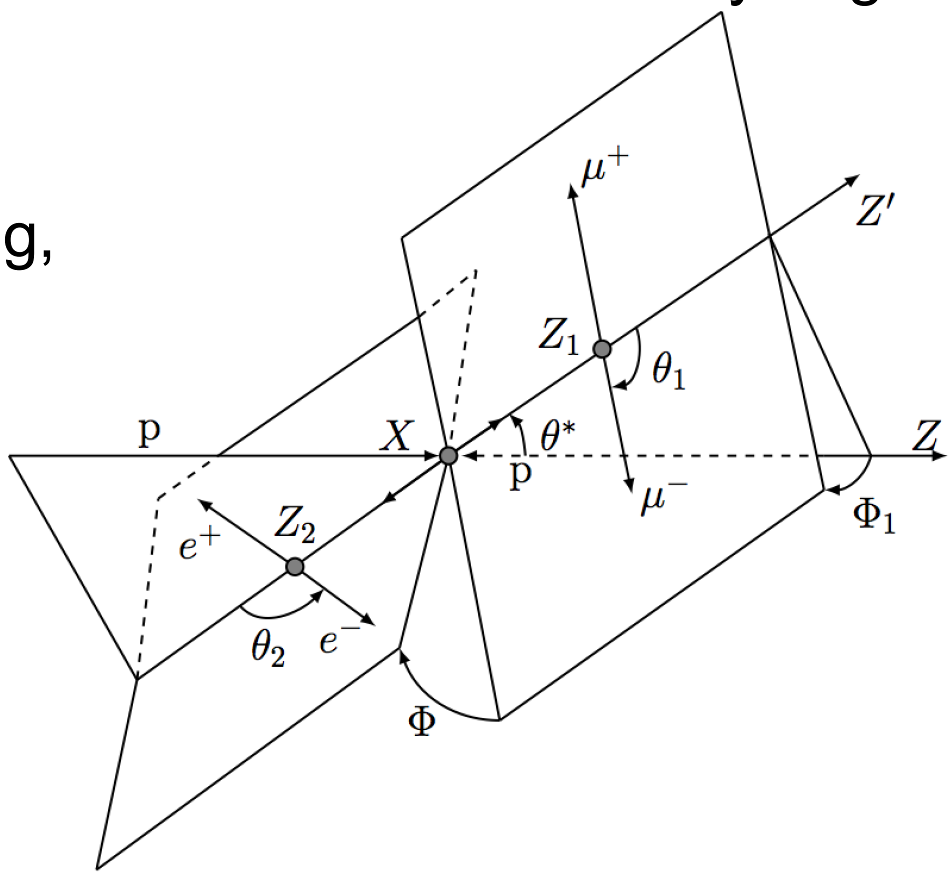
- The mass can be obtained in an (almost) model independent way from the two high resolution channels H→γγ and H→ZZ
  - ATLAS: $m_H = 125.5 \pm 0.2 \pm 0.6\text{GeV}$
  - CMS: $m_H = 125.7 \pm 0.3 \pm 0.3\text{GeV}$
- This is already better than needed for any application





Spin and CP of the new boson

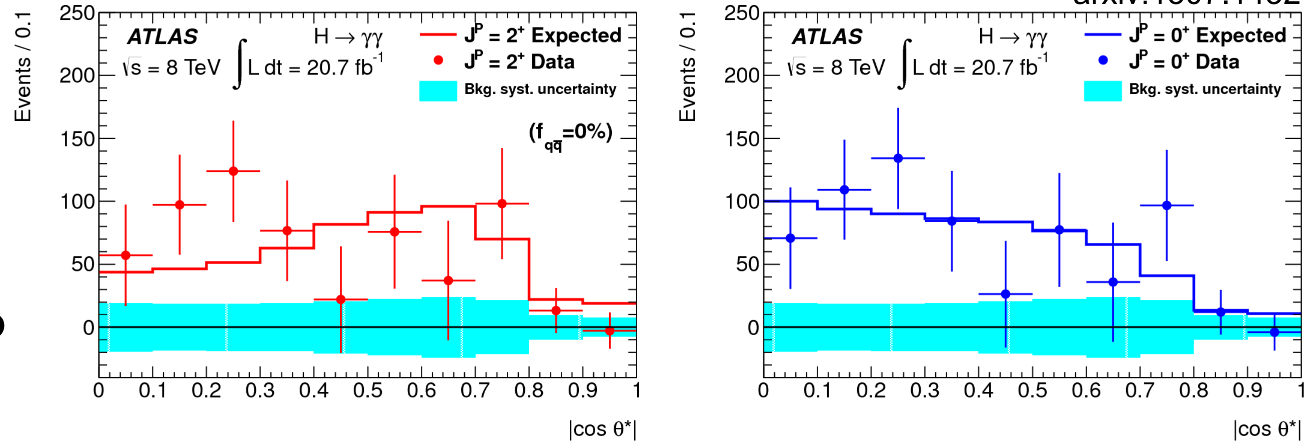
- From the observation of $H \rightarrow \gamma\gamma$ one knows that the new particle cannot have J=1 (Landau Yang theorem)
- In general J^P can be measured from the decay angles of the Higgs
- For J≠0 also the production mode (gg, qq) influences the decay angles



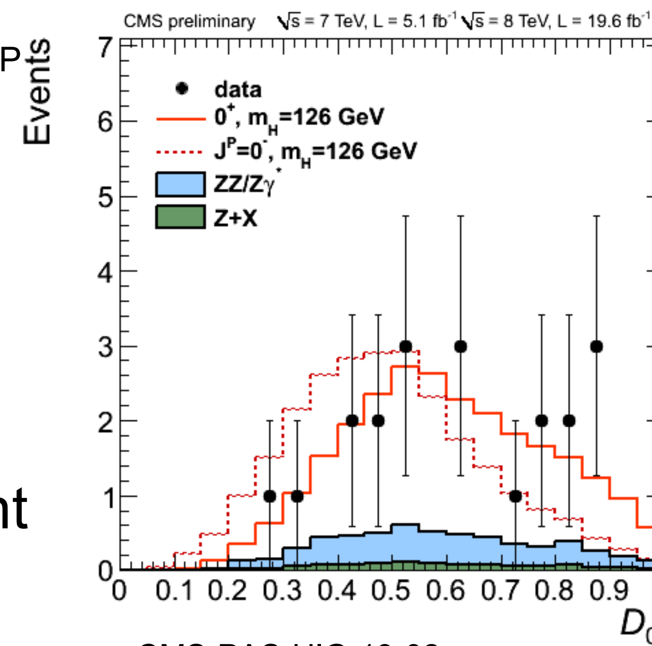
Spin and CP (ii)

- $H \to \gamma\gamma$:
  - $\cos(\theta^*)$ is sensitive to J
  - if J=0 no sensitivity to P

arxiv:1307.1432



- $H \to WW \to l\nu l\nu$:
  - several variables (Φ_{ll}, m_{ll}) sensitive to J^P
  - can be combined with BDT
- $H \to ZZ \to 4l$:
  - full final state sensitive to J^P can be reconstructed
  - combined in BDT or with matrix element method



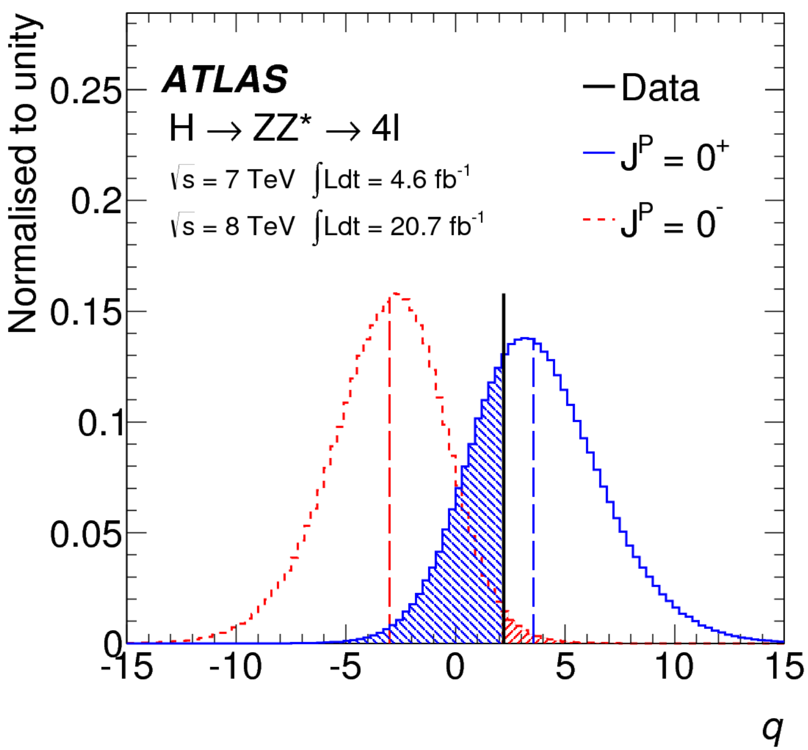
CMS-PAS-HIG-13-02

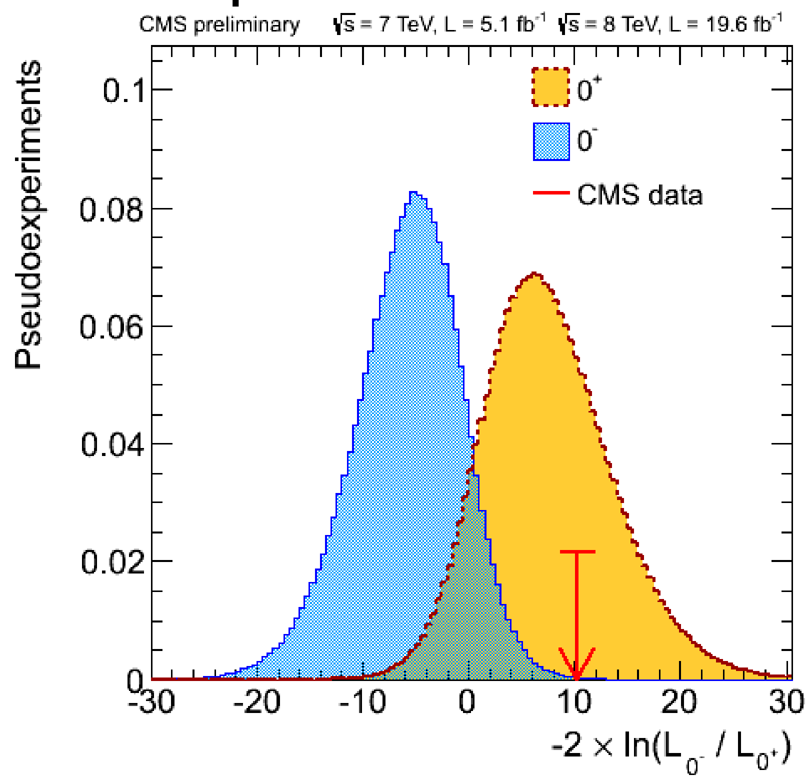
Spin and CP (ii)

- Hypotheses tested pair-wise with log likelihood ratio

$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0+}, \hat{\hat{\theta}}_{0+})}{\mathcal{L}(J^P_{alt}, \hat{\hat{\mu}}_{alt}, \hat{\hat{\theta}}_{alt})}$$

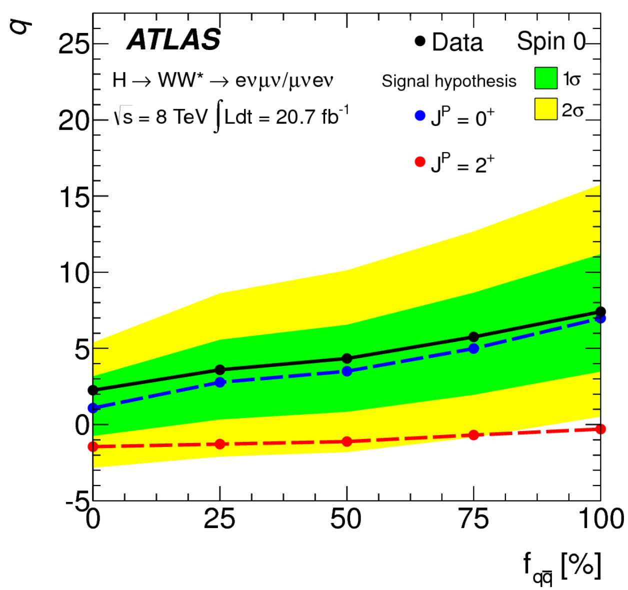
- 0^- excluded with ~99% C.L. compared to 0^+

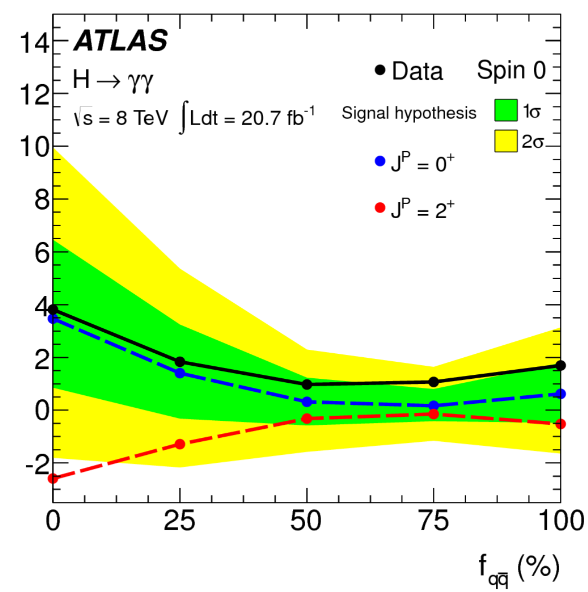


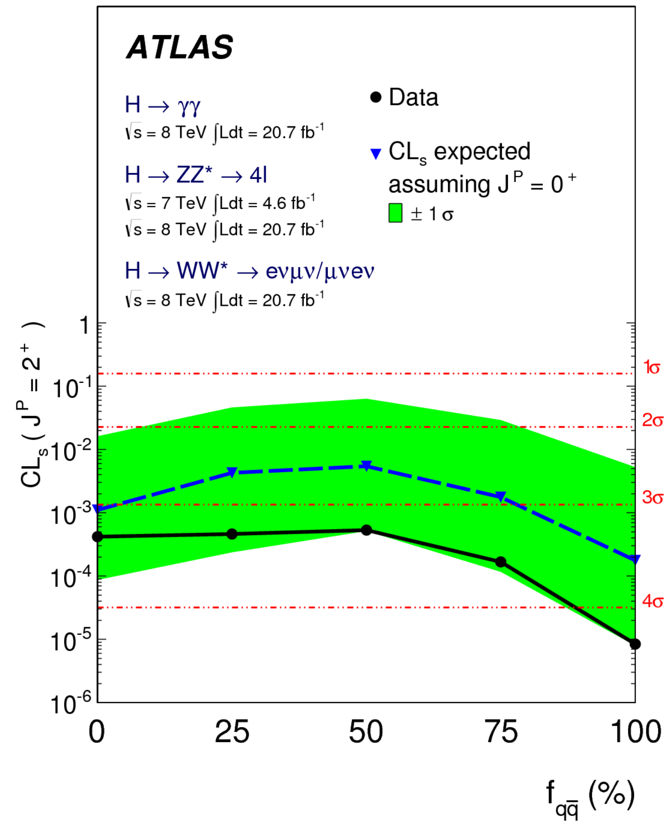


Test of scalar vs tensor

- Use minimal coupling graviton inspired model
- Still qq/gg production fraction free parameter
- WW(ZZ) and γγ complementary
- Spin 2 model excluded with >99.9% C.L. over full range!







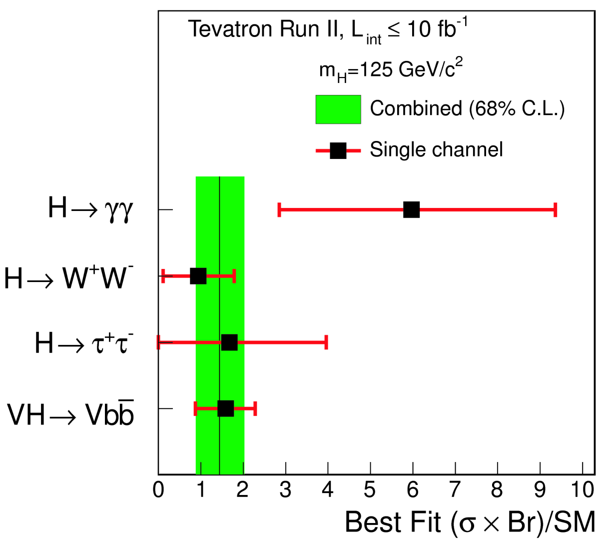
Higgs couplings

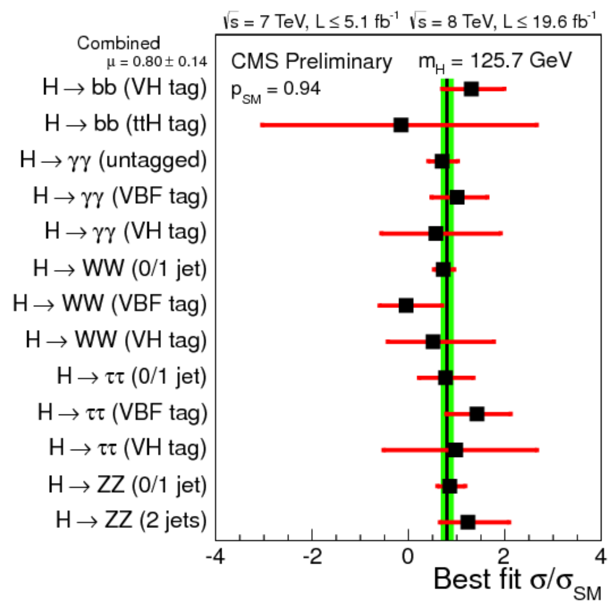
- A single Higgs cross section is proportional to $\Gamma_i\Gamma_f/\Gamma_H$
- There is no model independent way to measure the Higgs width and consequently the partial widths
- Model independent measurements:
  - measure cross sections and express results as $\mu=\sigma_{meas}/\sigma_{SM}$
  - from fits to different categories can get ratio of partial widths of initial state
  - from ratio of different analyses can get ratio of partial widths of final state
- Any further interpretation needs model assumptions!

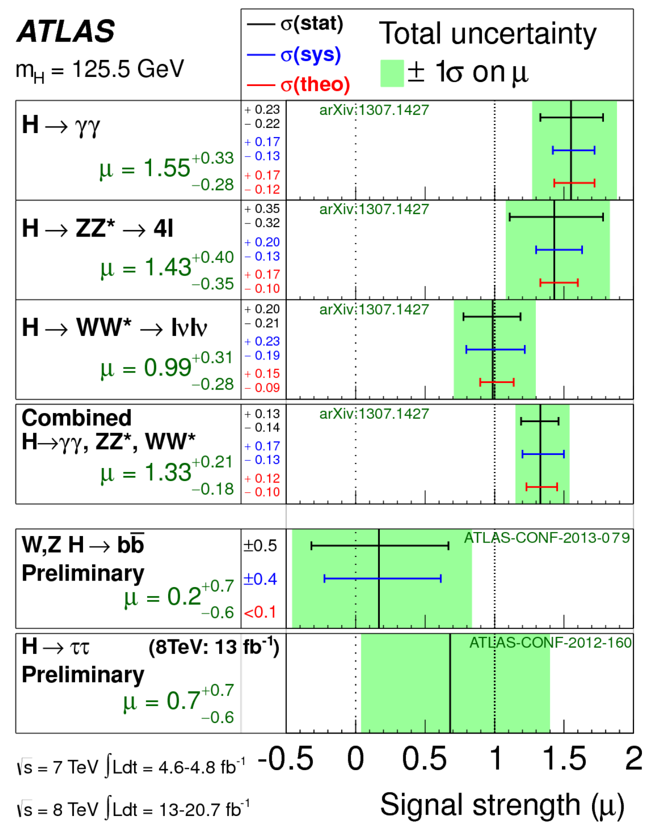
Total signal strength

- Experiments measure μ for all analysis and combine
- All results are consistent with μ=1
- Accuracy ~15%

- ATLAS: μ=1.23±0.18
- CMS: μ=0.80±0.14
- TEV: μ=1.44±0.60



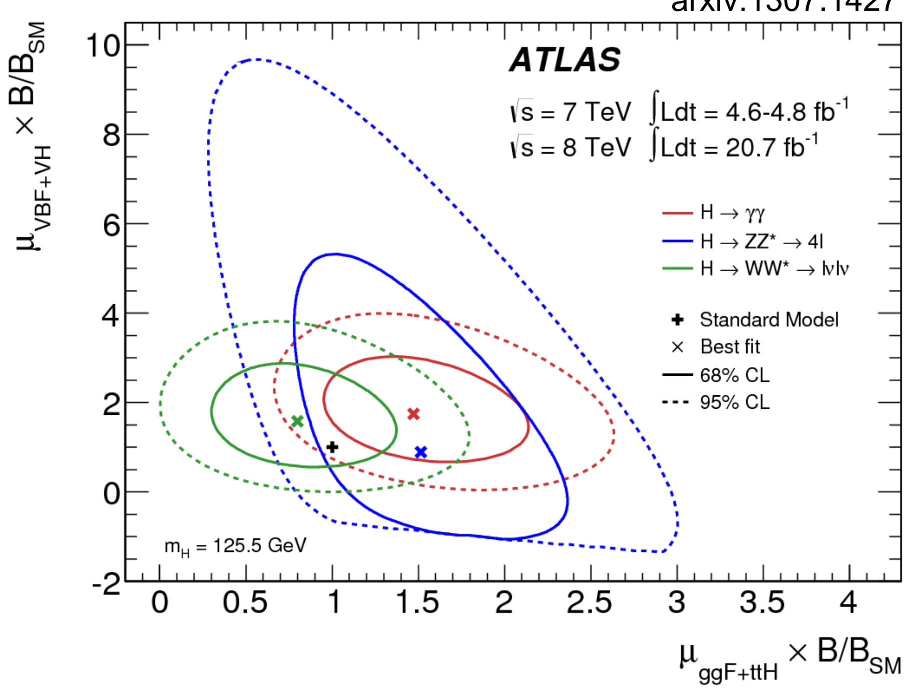


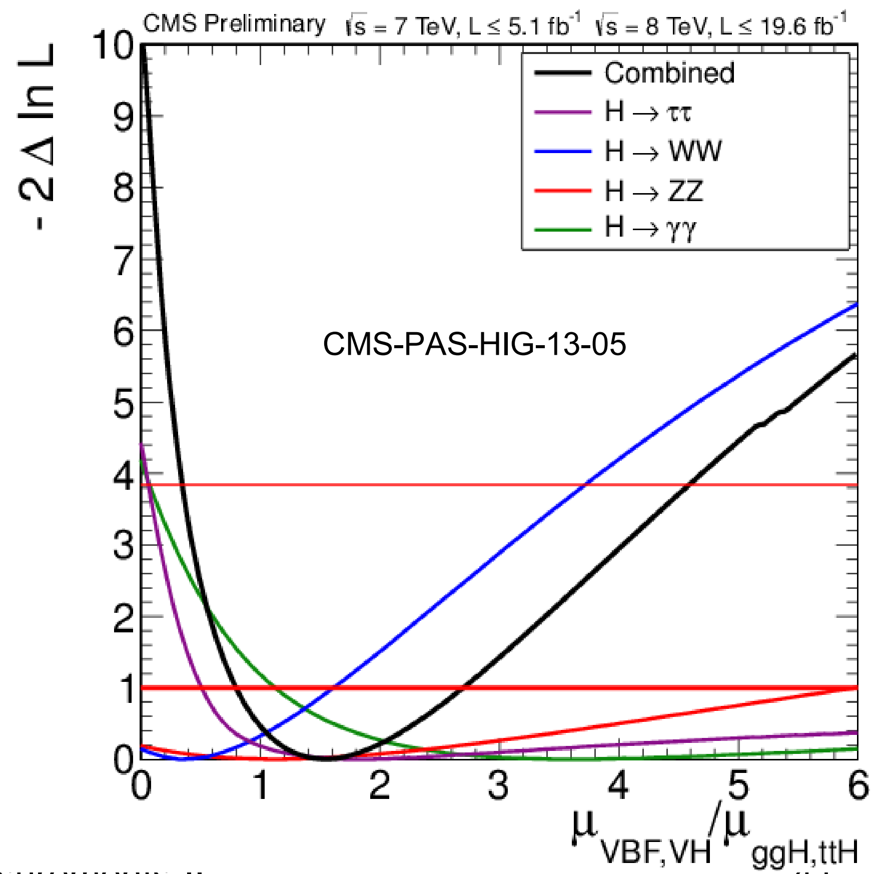


Higgs production modes

- 2D fits are only possible in μ_{prod}•BR
- The ratio can be obtained in a model independent way
- gg production is established without any doubt and vector boson production with >3σ

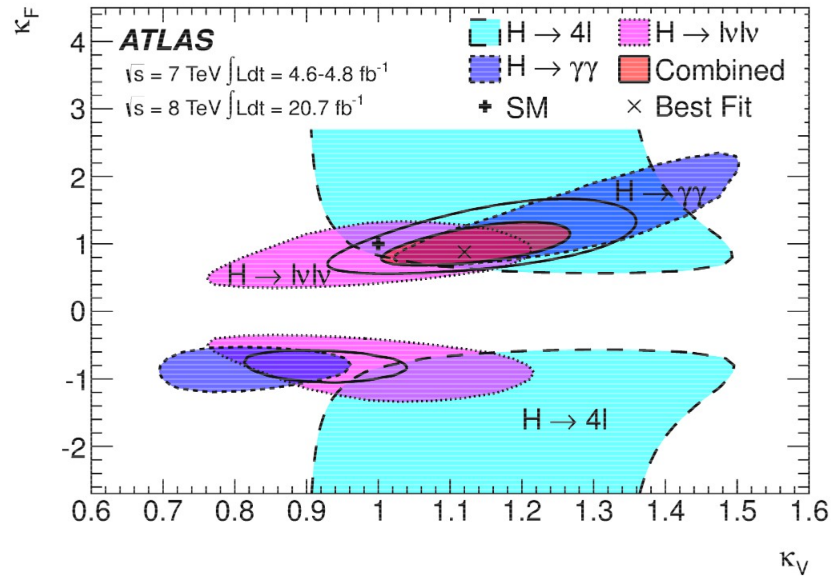
arxiv:1307.1427

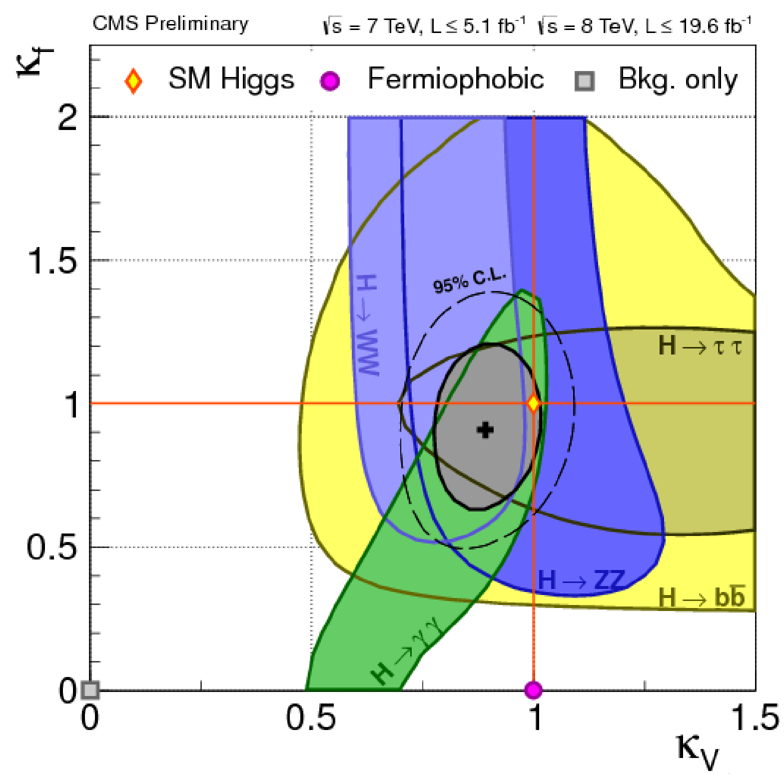




Fermion vs boson couplings

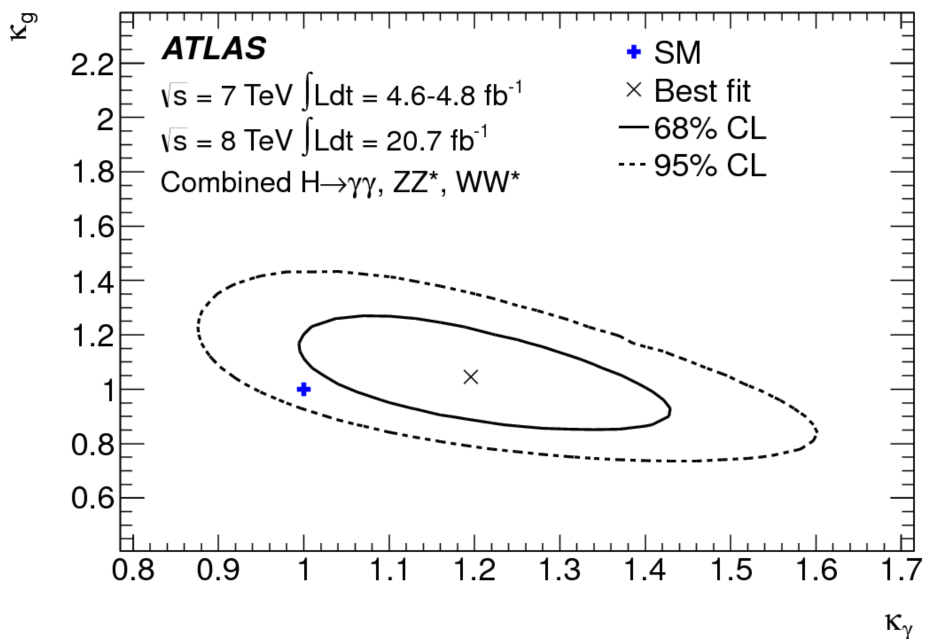
- Assume:
  - all fermion couplings scale with $\kappa_F(=\kappa_b=\kappa_t=\kappa_\tau...)$
  - all boson couplings scale with $\kappa_V(=\kappa_W\kappa_Z)$
  - no BSM contributions to Γ_H and γ,g loops
- $\kappa_F,\kappa_V\neq 0$ established at >5σ
- (κ_F mainly from gg-loop, direct evidence from CMS ~3σ)

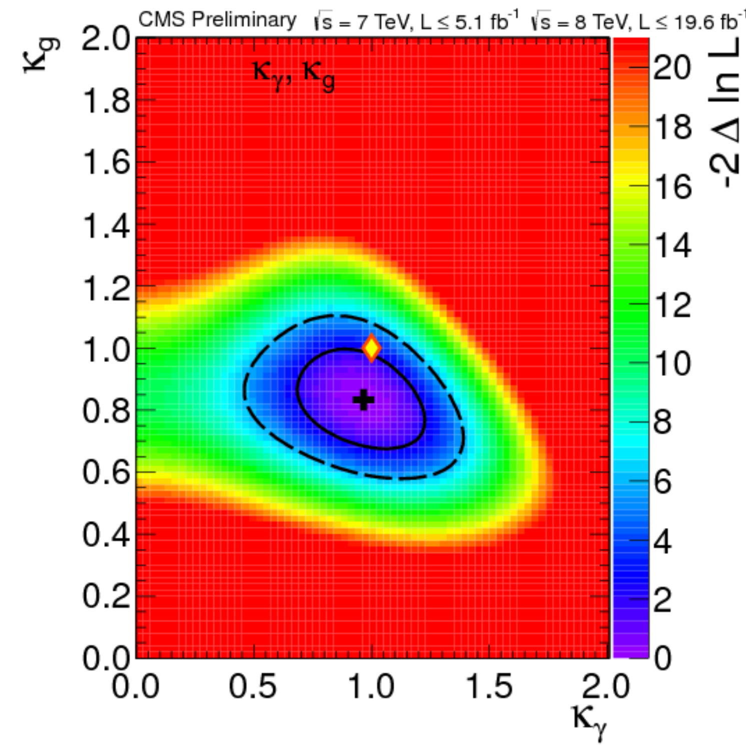




Loop induced couplings

- Assume:
  - all tree-level couplings to SM particles as in SM
  - no direct BSM contributions to Γ_H

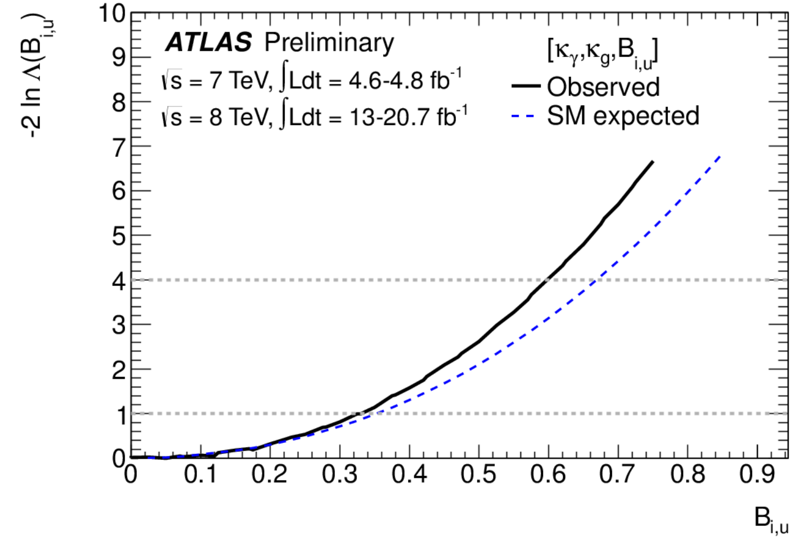


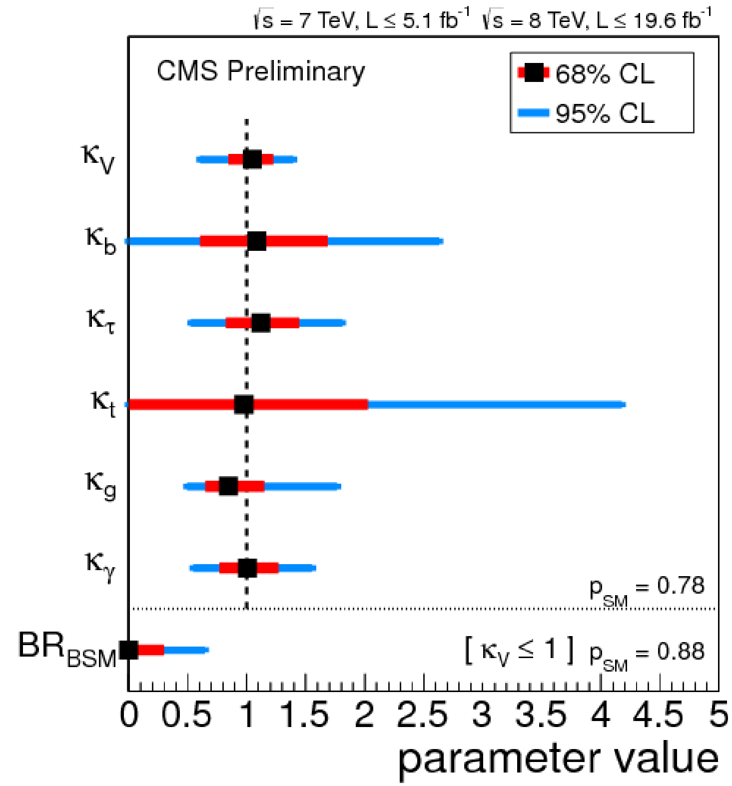


- κ_γ and κ_g compatible with 1 with ~15% uncertainty
- puts limits on heavy (colour-)charged particles coupling to the Higgs

BSM couplings

- Direct searches ZH→ll+inv. gives BR(H→inv)<0.6 (95%C.L.)
- Parametrise $\Gamma_H=\Gamma_{SM}+\Gamma_{BSM}$ (sensitiv to undetectable modes)
- ATLAS:
  - assume κ=1 for all tree level SM modes
  - fit for κ_γ, κ_g, BR_{BSM}
  - BR_{BSM}<0.60 (95%C.L.)
- CMS:
  - assume $\kappa_V \leq 1$
  - fit for $\kappa_V, \kappa_b, \kappa_\tau, \kappa_t, \kappa_\gamma, \kappa_g$, BR_{BSM}
  - BR_{BSM}<0.64 (95%C.L.)





Conclusions on Higgs measurements

- The new particle found at the LHC is most probably a scalar
- Its mass is 125.6GeV with an error <0.5%
- All coupling measurements agree with the SM prediction with errors down to 15%
- By now we can be reasonable sure that the new particle is a Higgs
- E.g. SUSY predicts a Higgs doublet where the light Higgs can agree with the SM prediction to an arbitrary level
- This means we will never know if we found the Higgs unless we find that we didn't