Higgs Physics with ATLAS

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on behalf of the ATLAS collaboration

Outline

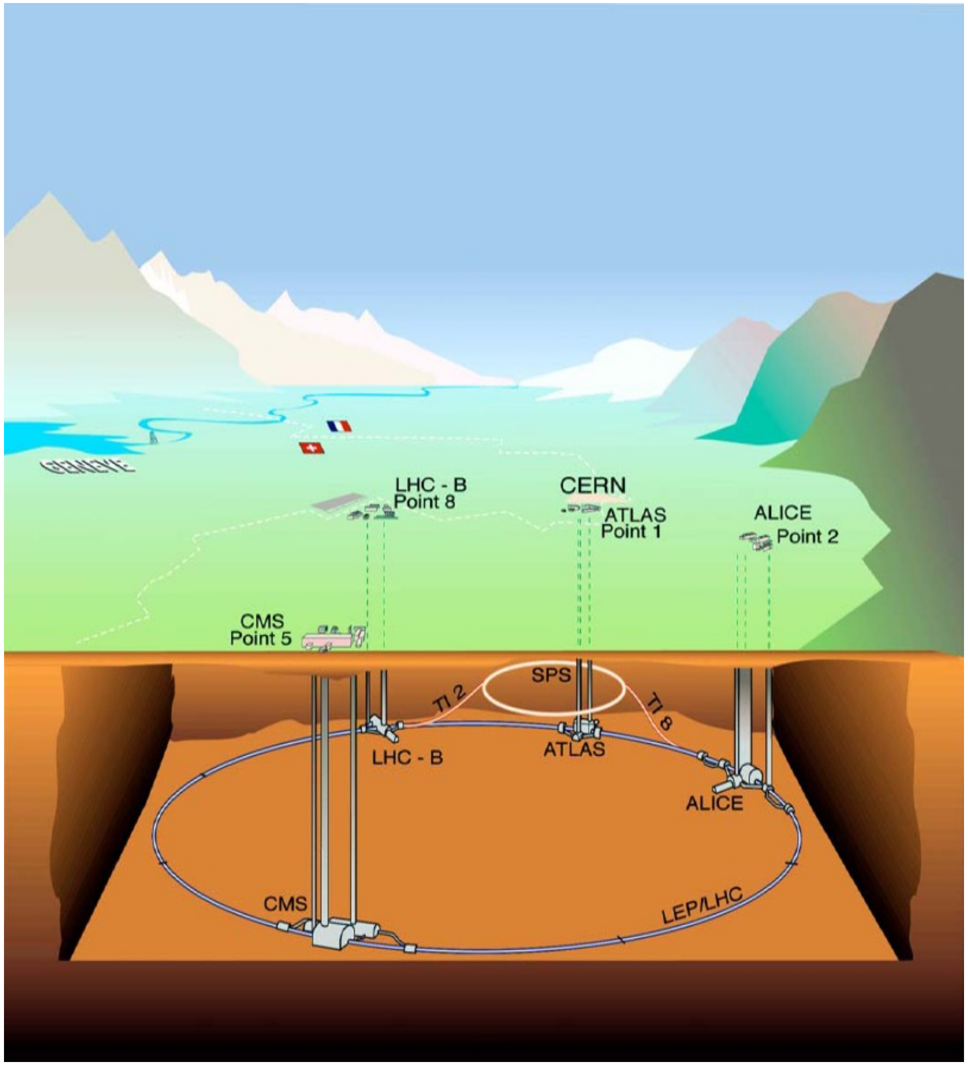
- Higgs boson
- LHC and ATLAS experiment
- Current experimental limits
- Higgs boson cross-sections and branching ratios
- (Selected) Standard Model Higgs searches @ ATLAS
  - $H \rightarrow \gamma+\gamma$, $H \rightarrow \tau+\tau$, $H \rightarrow Z+Z^{(*)} \rightarrow 4l$, $H \rightarrow W+W^{(*)} \rightarrow 2l+2\nu$
- MSSM Higgs bosons
  - $h/H/A \rightarrow \tau+\tau$, $h/H/A \rightarrow \mu+\mu$, charged Higgs boson searches
- Higgs properties measurements
  - spin & CP, couplings
- Conclusions

Higgs boson

- The goal is to understand the mechanism by which particles acquire mass
- Concept of the electroweak symmetry breaking in Standard Model via Higgs mechanism:
  - Introduce a doublet of complex scalar fields
  - One real scalar field is not absorbed in that mechanism (Higgs field) and corresponds to real particle (Higgs boson)
  - Its interaction with particles generates the particles' mass

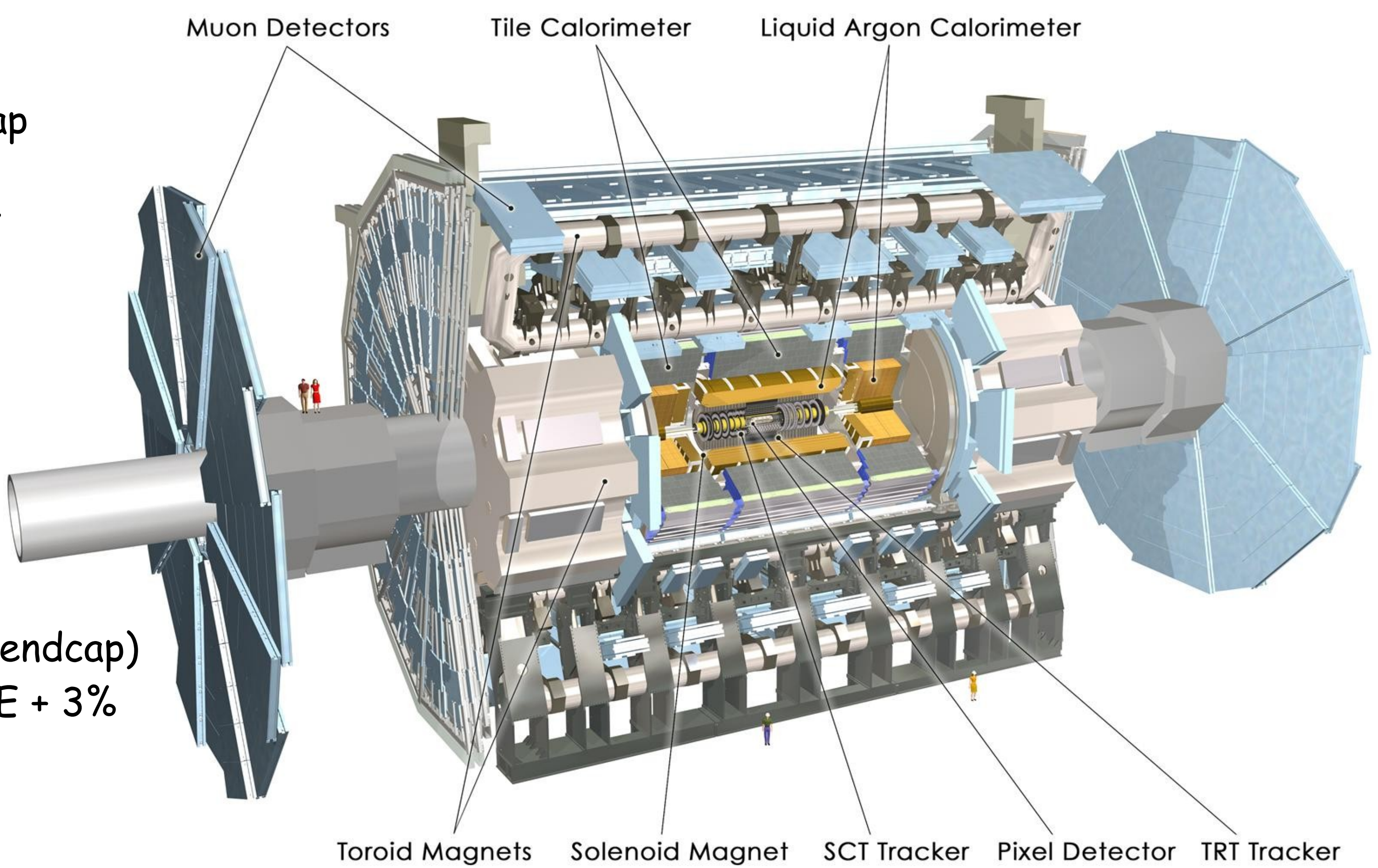
Large Hadron Collider

design parameter	value
CM energy	14 TeV
Luminosity	10^{34} cm^{-2}s^{-1}
Bunch crossing spacing	24.95 ns
Protons per bunch	1.15×10^{11}
Beam radius	16.7 μm
Main dipoles	1232
Dipole field	8.33 T
Smaller magnets	7000
Stored energy	360 MJ/beam



ATLAS detector

Muon spectrometer:
- air-core toroids:
  0.5 T in barrel, 1 T in endcap
- momentum resolution:
  2% @ 50 GeV, 10% @ 1 TeV
  (combined ID+MS)



HCAL:
- Fe+scint (barrel), Cu+LAr (endcap)
- resolution $\sigma(E)/E \approx 50\%/\sqrt{E} + 3\%$
  (ECAL+HCAL, barrel part)

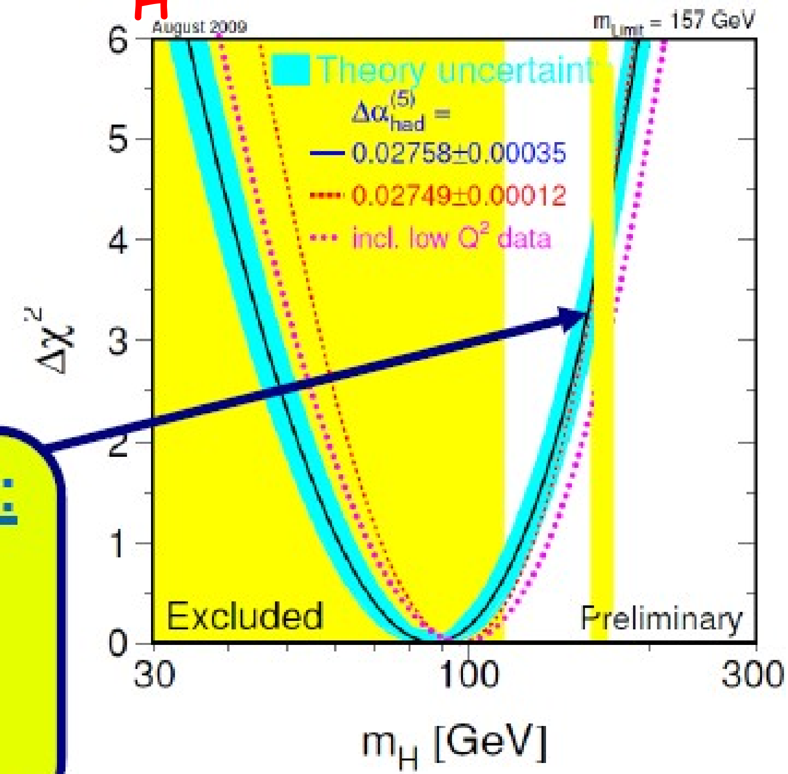
ECAL:
- Pb+LAr technology
- resolution $\sigma(E)/E \approx 10\%/\sqrt{E} + 0.7\%$

Tracker:
- Si pixels, Si strips, TRT inside 2 T solenoid
- resolution: $\sigma(p_T^{-1}) \approx 0.36 + 13/(p_T \cdot \sqrt{\sin\theta})$ [TeV^{-1}]

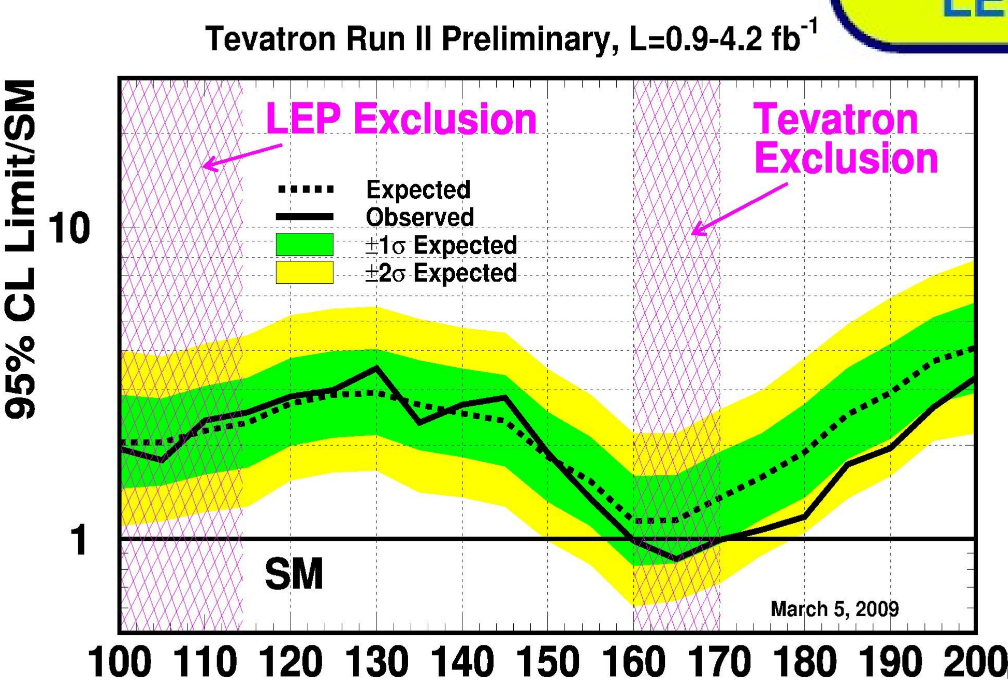
Further details in Ref:
G. Aad et al., JINST 3 (2008) S08003

Current limits on M_H

- Latest results from Tevatron presented at Lepton-Photon '09 conference (August 2009)



Precision EW fit:
m_H < 157 GeV
@95%CL
(<186 GeV with LEPII Limit)



- Updated results available for CDF and D0, but no new combined results yet....

About results

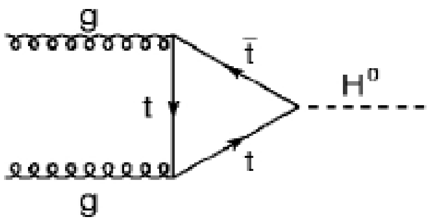
- Studies presented in this talk were performed assuming
  - $\sqrt{s}$ = 14 TeV pp center-of-mass energy
  - lower luminosity $L = 10^{33}$ $cm^{-2}s^{-1}$
    - average number of pp collisions per bunch ~2.3
  - bunch spacing 25 ns

  Most of the results are published in CERN-OPEN-2008-020, also available in arXiv:0910.0512

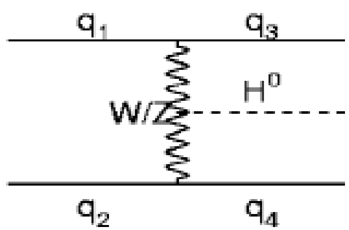
- However, the scenario for LHC running in 2009/2010 should be
  - start with $\sqrt{s}$ =7 TeV, hopefully go up to 10 TeV
  - luminosity from $L = 5 \cdot 10^{31}$ $cm^{-2}s^{-1}$ to L = few times 10^{32} $cm^{-2}s^{-1}$
  - bunch spacing 450 ns to 75/50 ns

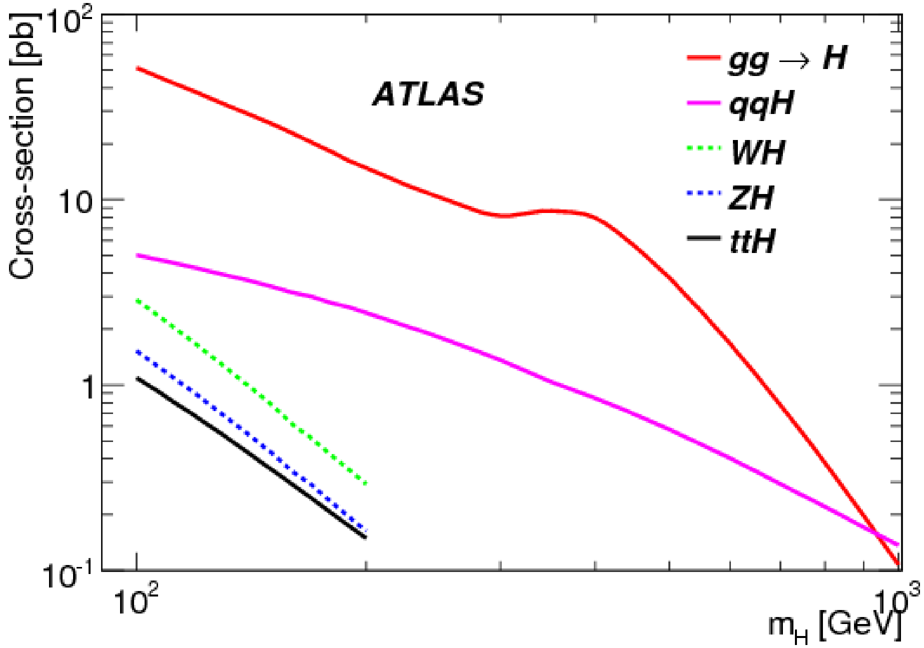
SM Higgs boson production and decay

Gluon-Gluon Fusion



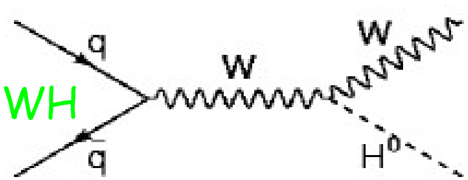
Vector Boson Fusion



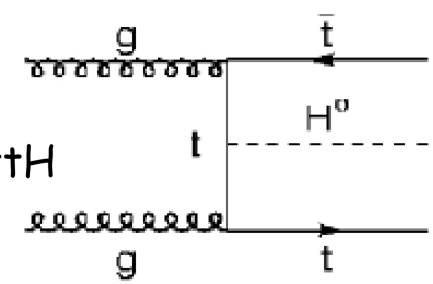


Associated production:

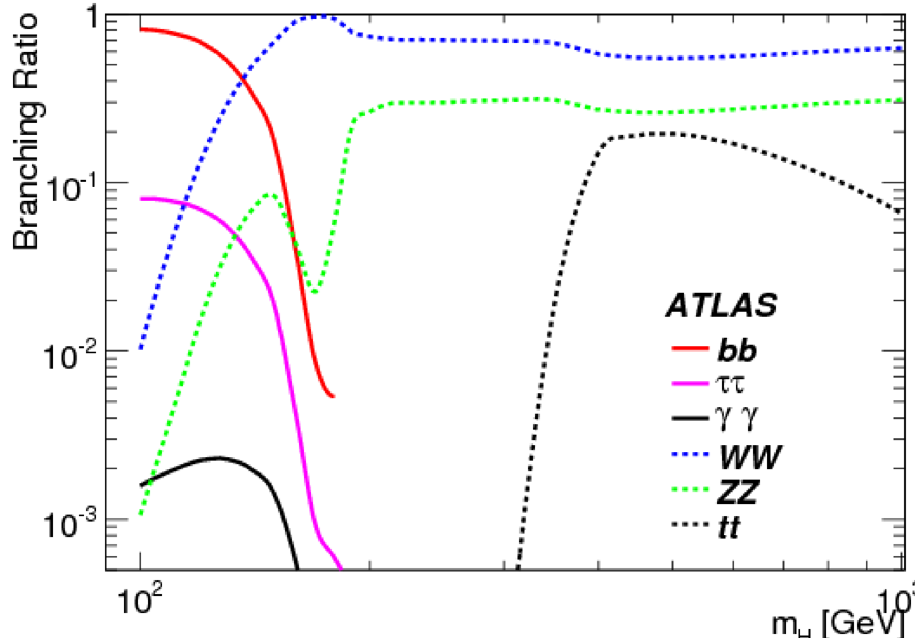
WH



ttH



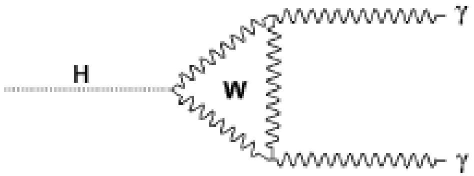
Decay modes considered for analysis:



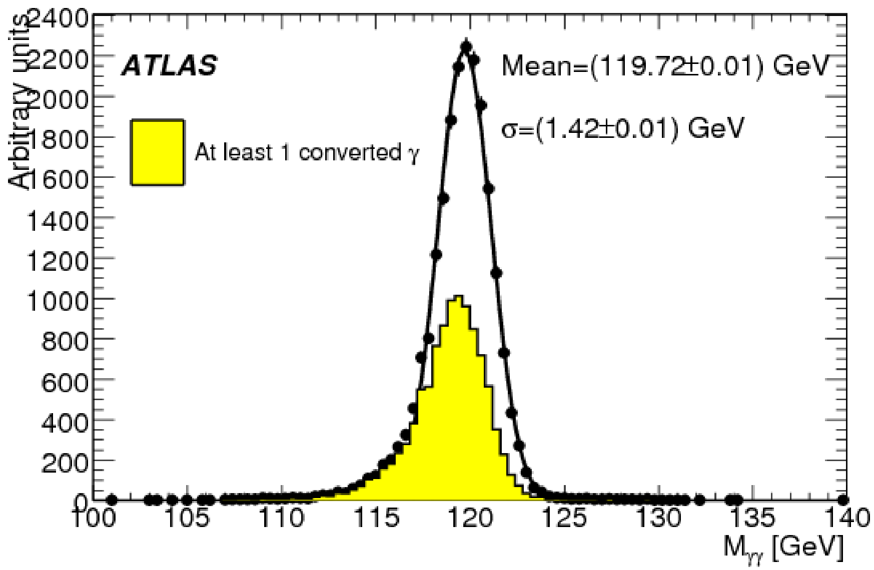
Importance of individual decay modes depends on Higgs boson mass M_H

- $H \rightarrow b+b$: $M_H < 130$ GeV
- $H \rightarrow \gamma+\gamma$: $M_H < 140$ GeV
- $H \rightarrow \tau+\tau$: $M_H < 150$ GeV
- $H \rightarrow Z+Z$: $M_H > 130$ GeV
- $H \rightarrow W+W$: $130 < M_H < 190$ GeV, $M_H > \sim 250$ GeV

$H \rightarrow \gamma+\gamma$ (1)

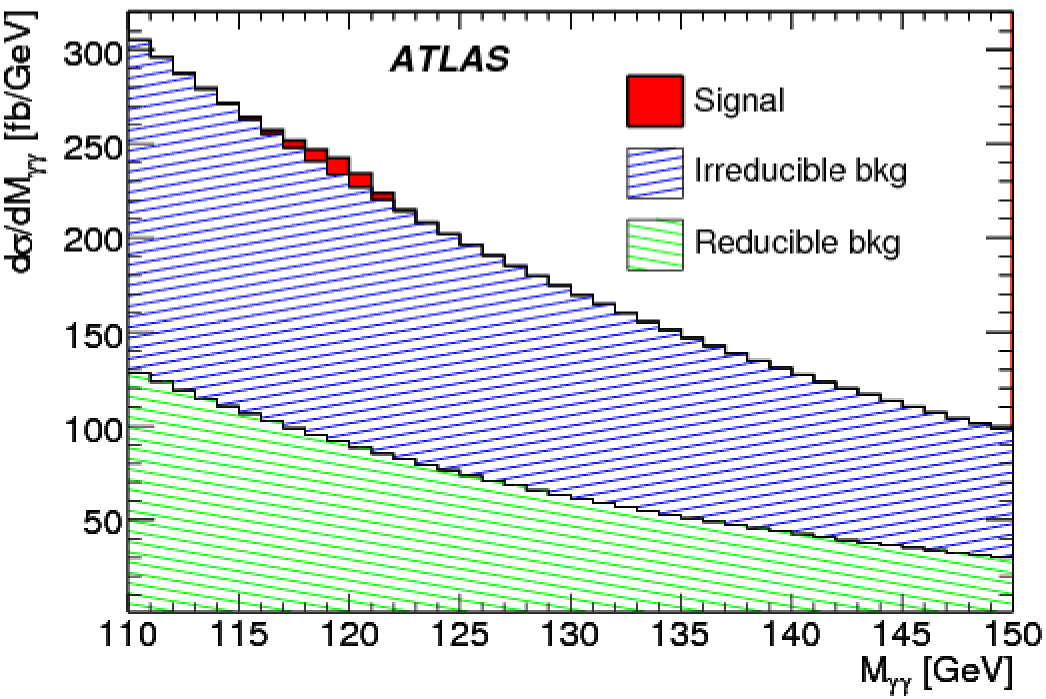


- Decay via W/top-loop, very small cross-section (σ=0.08 pb)
- Full kinematics reconstruction $M_{\gamma\gamma}^2 = 2*E_1*E_2*(1-\cos\theta)$
- Trigger: at least 2 photons with p_T>17 GeV
- Selection criteria
  - $0<|\eta|<1.37$ or $1.52<|\eta|<2.37$ to avoid calorimeter crack region
  - isolation cut in a cone of R=0.3 around the EM cluster
  - momentum cut $p_T^{\gamma1} > 40$ GeV, $p_T^{\gamma2} > 25$ GeV
- Photon conversion in front of calorimeter (60% of events)
  - affects photon ID and energy resolution
  - need to recover high fraction
- Gaussian fit in asymetric range (mean-2σ,mean+3σ)



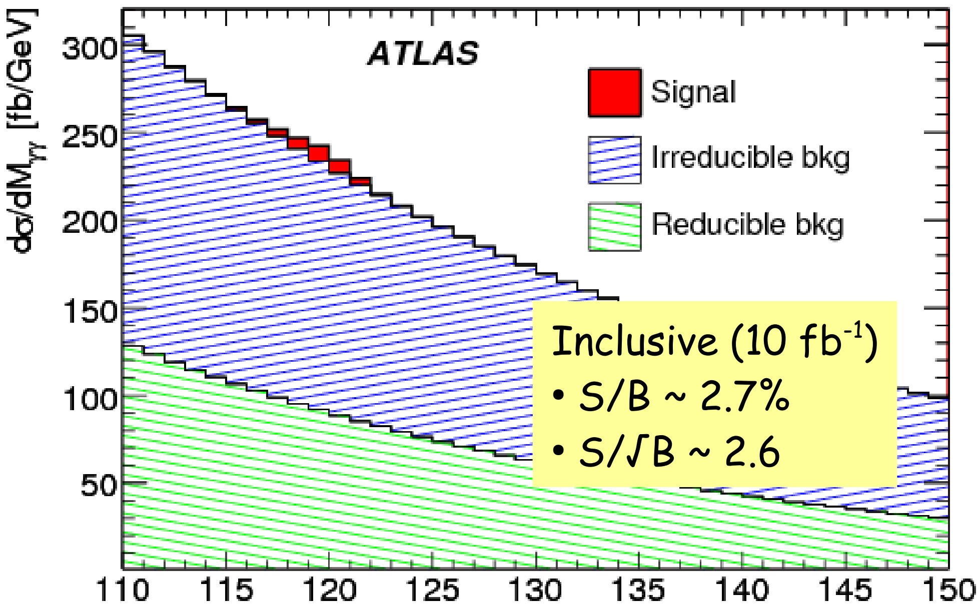
$H \rightarrow \gamma+\gamma$ (2)

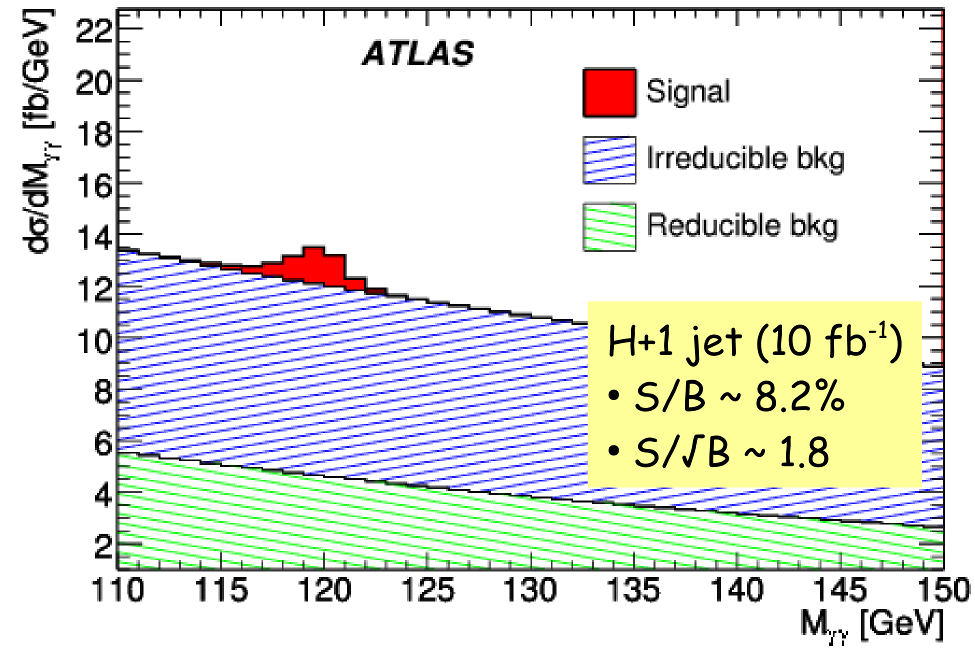
- Signal cross-section very small, huge background
  - irreducible background from $p+p \rightarrow \gamma+\gamma + X$ (σ~30 pb)
  - reducible background from $p+p \rightarrow \gamma$+jet/jet+jet + X (σ~1.8×10^5 pb/σ~4.8×10^8 pb), photons come from leading π^0

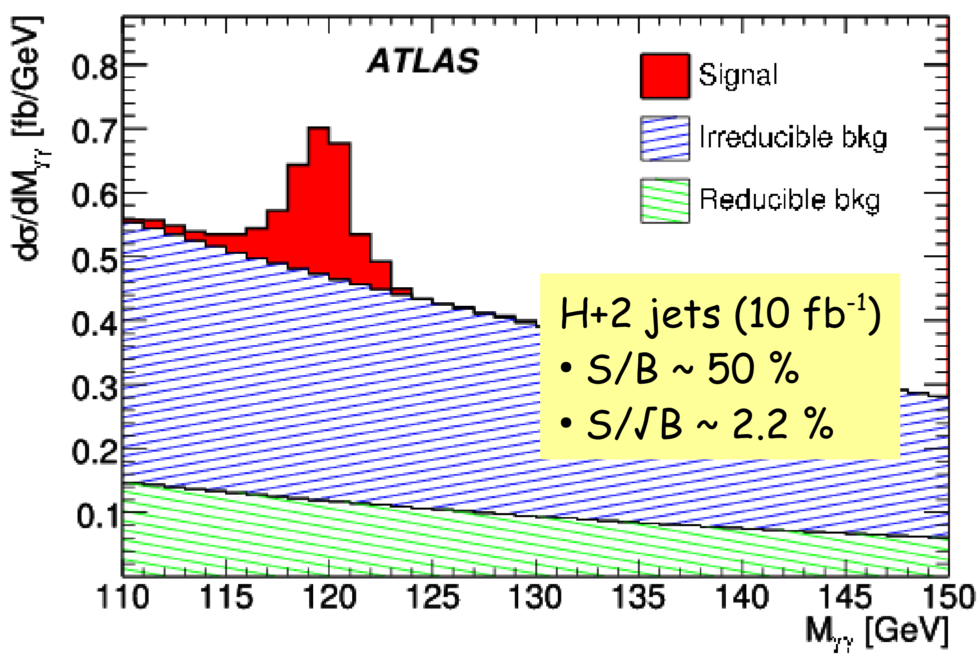


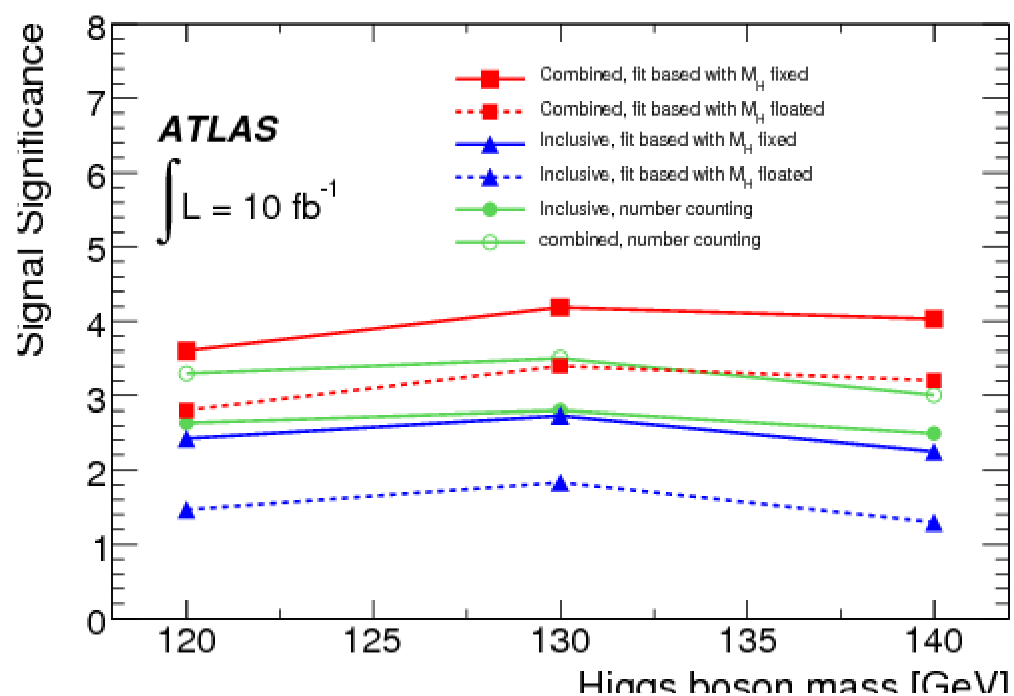
- Further improvement possible e.g. with H+jet(s) final states
  - require 1 or 2 high-p_T jet(s) produced in addition to Higgs boson
  - gluon radiation patterns in GF or VBF strongly differ from that of background

H → γ+γ (3)


ATLAS
Signal
Irreducible bkg
Reducible bkg
Inclusive (10 fb-1)
• S/B ~ 2.7%
• S/√B ~ 2.6
dσ/dMγγ [fb/GeV]


ATLAS
Signal
Irreducible bkg
Reducible bkg
H+1 jet (10 fb-1)
• S/B ~ 8.2%
• S/√B ~ 1.8
dσ/dMγγ [fb/GeV]
Mγγ [GeV]


ATLAS
Signal
Irreducible bkg
Reducible bkg
H+2 jets (10 fb-1)
• S/B ~ 50 %
• S/√B ~ 2.2 %
dσ/dMγγ [fb/GeV]
Mγγ [GeV]

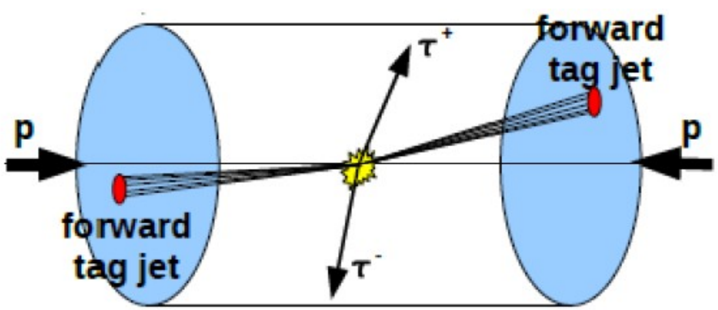

ATLAS
∫L = 10 fb-1
Combined, fit based with MH fixed
Combined, fit based with MH floated
Inclusive, fit based with MH fixed
Inclusive, fit based with MH floated
Inclusive, number counting
combined, number counting
Signal Significance
Higgs boson mass [GeV]

$H \rightarrow \tau+\tau$ (1)

- Biggest BR (after H→bbbar) in the low Higgs mass region
- Final state signatures depend on the τ-decay
  - $H \rightarrow \tau+\tau \rightarrow l+2\nu+l+2\nu$ (ll-mode), BR = 12%
  - $H \rightarrow \tau+\tau \rightarrow l+2\nu+h+\nu$ (lh-mode), BR = 46%
  - $H \rightarrow \tau+\tau \rightarrow h+\nu+h+\nu$ (hh-mode), BR = 42%
- Dominant background from Z→ττ+jets, W→lν+jets, ttbar+jets and QCD di-jets (especially for hh-mode)

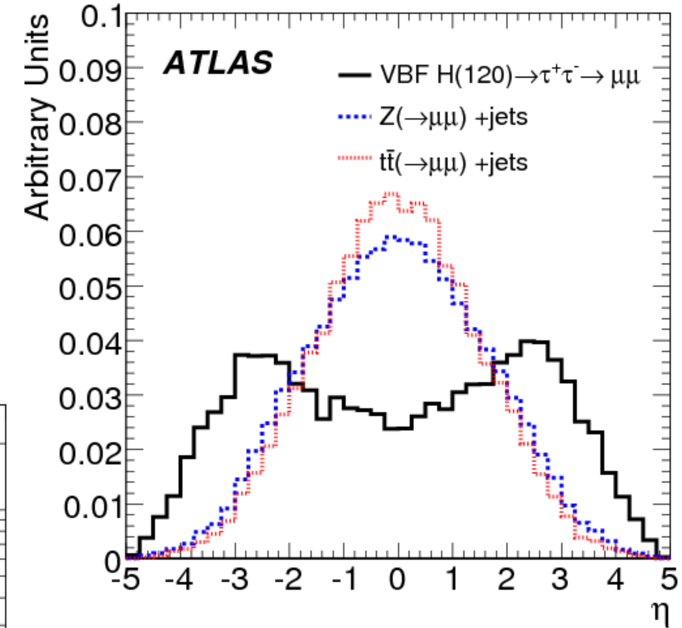
- Difficult to select signal events, therefore exploit VBF signatures:
  - 2 forward tagged jets
  - no central color activity

    → rapidity gap

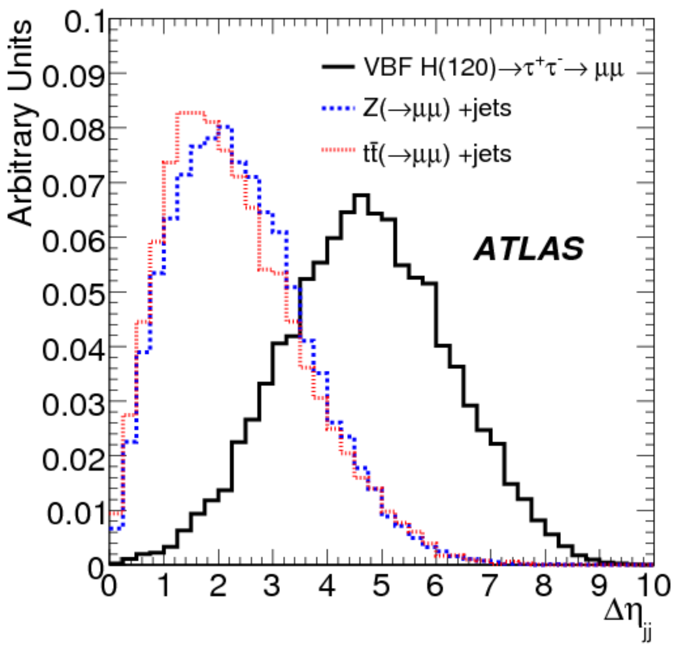


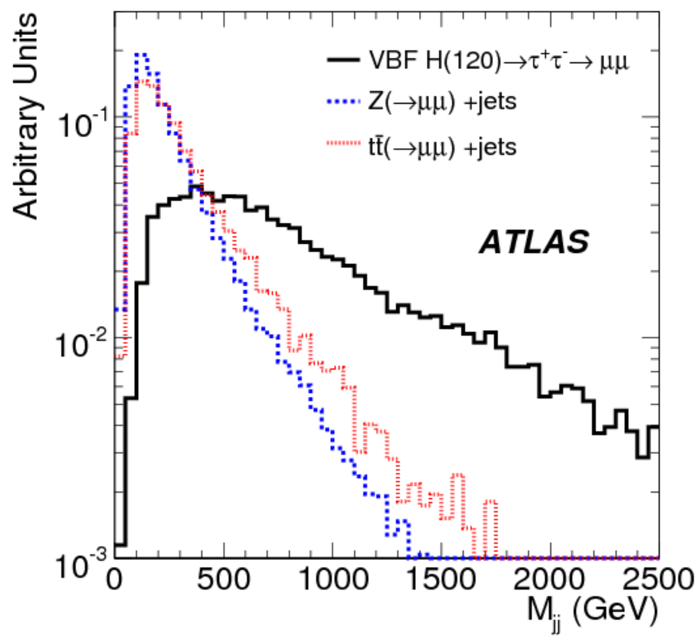
$H \rightarrow \tau+\tau$ (2)

- VBF $H \rightarrow \tau+\tau$ event selection:
  - rapidity gap in signal distribution



  - use cuts on $\Delta\eta_{jj}$ and M_{jj} in the analysis

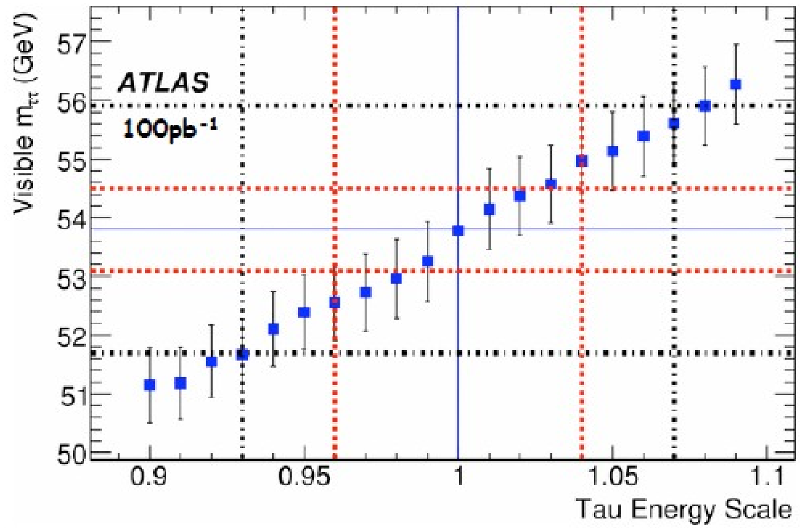




  - missing E_T > 40 GeV (ll, hh modes), missing E_T > 30 GeV (lh mode)
  - central jet veto
  - b-jet veto on forward jets (important especially for ll-mode where the largest background comes from ttbar+jets→lνblνb+jets)

$H \to \tau+\tau$ (3)

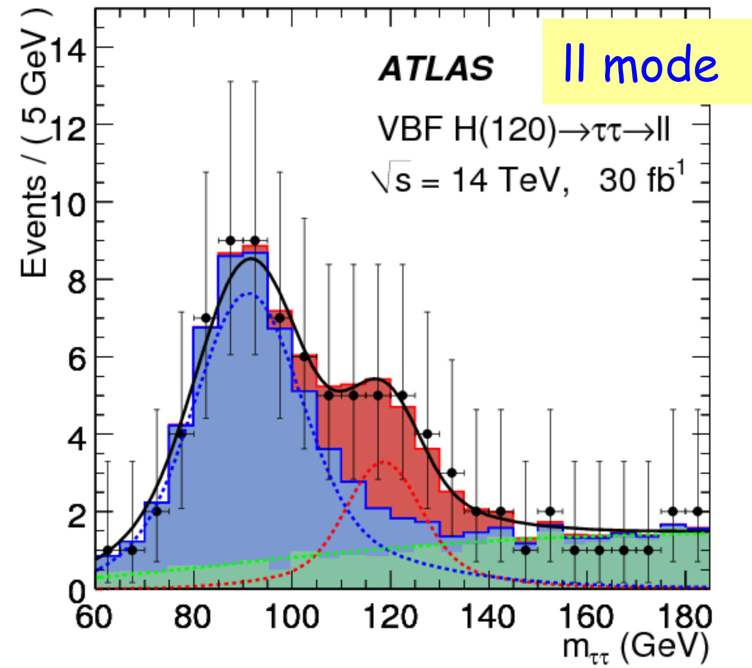
- Cannot fully reconstruct the final state (≥ 2ν), exploit collinear approximation:
  - assume neutrinos are almost collinear with original taus that are highly boosted in LAB
  - additional cut on visible τ-products ($\cos\Delta\varphi > -0.9$) to avoid back-to-back taus
- Energy calibration of tau hadronic decays:
  - select $Z \to \tau+\tau \to l+2\nu+h+\nu$
  - visible $M_{\tau\tau}$ is used to calibrate hadronic tau energy scale (and hence E_T^{miss} scale)

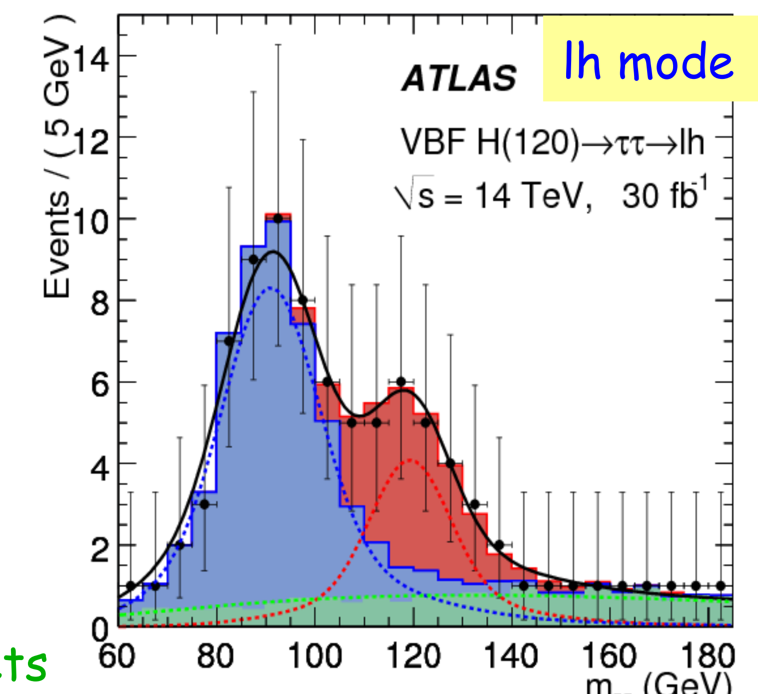


- $Z \to \tau+\tau$ will be also used to commission tau-trigger and for cross-section measurements

$H \rightarrow \tau+\tau$ (4)

- Two methods of evaluating the signal significance
  - event counting in the Higgs mass window
  - fitting $M_{\tau\tau}$ spectrum
- Background obtained from data driven analysis
  - shape of $Z\rightarrow\tau\tau$+jets estimated using clean $Z\rightarrow\mu\mu$+jets sample, then replace μ (data) $\rightarrow$ τ(MC)
  - normalization of $Z\rightarrow\tau\tau$ from Z-peak in $M_{\tau\tau}$ spectrum

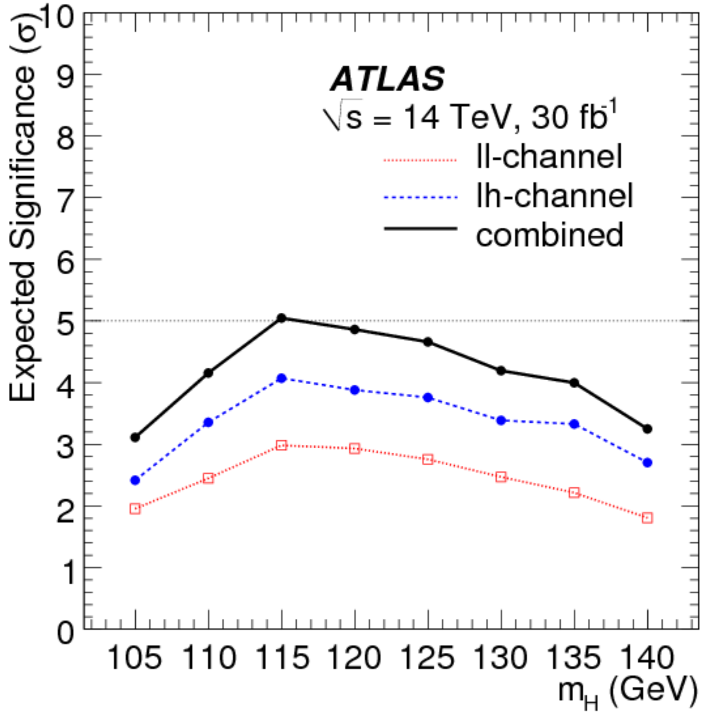


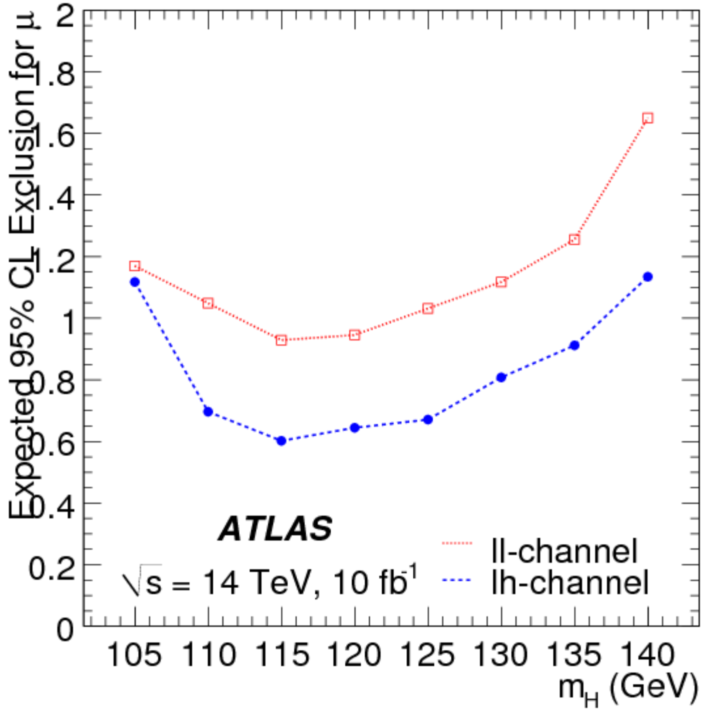


signal: VBF $H\rightarrow\tau\tau$
irreducible background: $Z \rightarrow \tau\tau$+jets
reducible background: W+jets, t+tbar+jets

$H \rightarrow \tau+\tau$ (5)

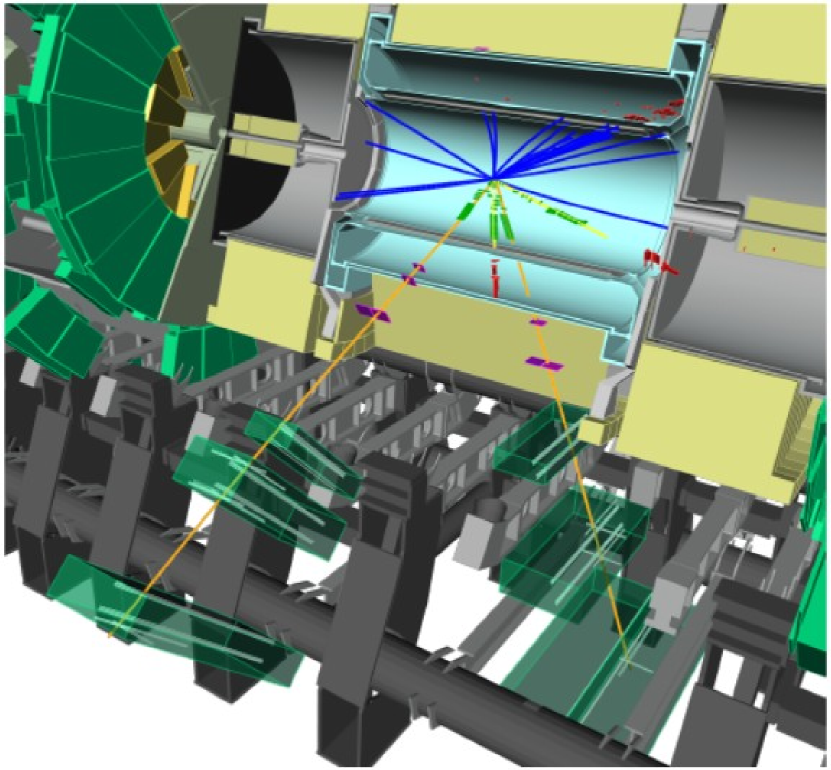
- Signal significance and exclusion limits
  - ll and lh-modes only, hh-mode under study





$H \rightarrow Z+Z^{(*)} \rightarrow 4l$ (1)

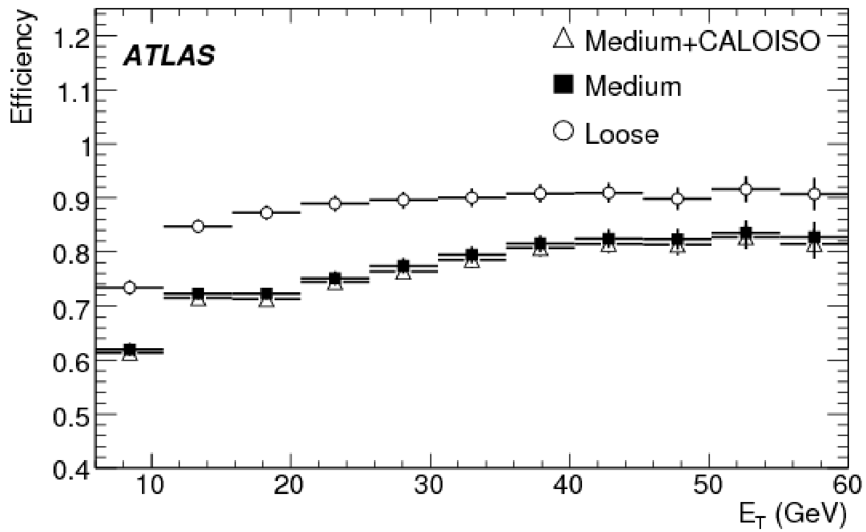
- So-called gold-plated channel
  - very clean signature ($l=e$ or μ), but efficiency $\varepsilon_H \sim \varepsilon_l^4$
  - full kinematics reconstruction possible
- Issues:
  - single lepton efficiency & rejection against jets
  - lepton energy resolution

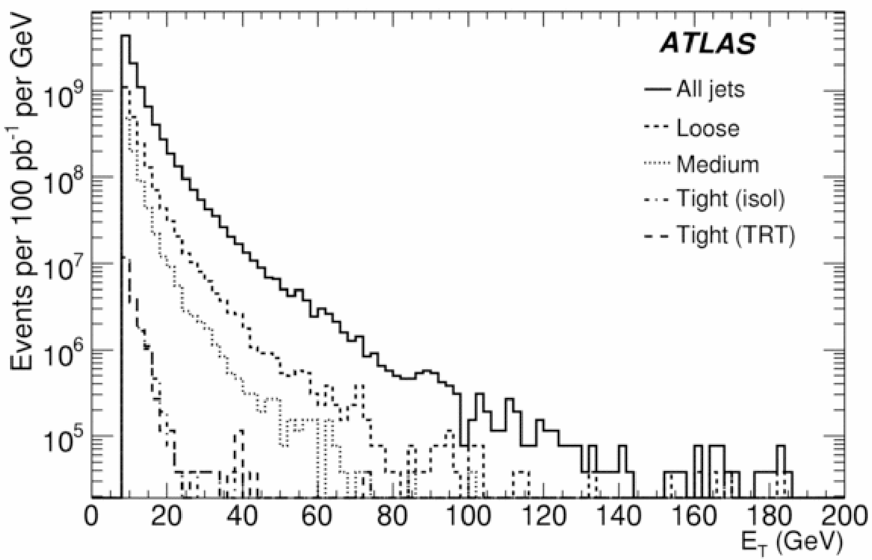


- Event display of a high-p_T $H \rightarrow ZZ \rightarrow ee\mu\mu$ decay after full ATLAS simulatiuon & reconstruction (M_H=130 GeV). Four leptons and recoiling jet (E_T=135 GeV) are displayed

$H \to Z+Z^{(*)} \to 4l$ (2)

- Electron identification criteria
  - loose
    - small hadronic leakage (low ratio E_T^{had}/E_T^{em})
    - EM shower shape measured in 2nd radial EM calo compartment
  - medium
    - EM shower shape measured in 1st radial EM calo compartment
    - loose associated track quality
  - tight
    - isolation (high E_T fraction in cone $\Delta R=0.2$)
    - tight associated track quality, tight cluster-track position, ratio E/p



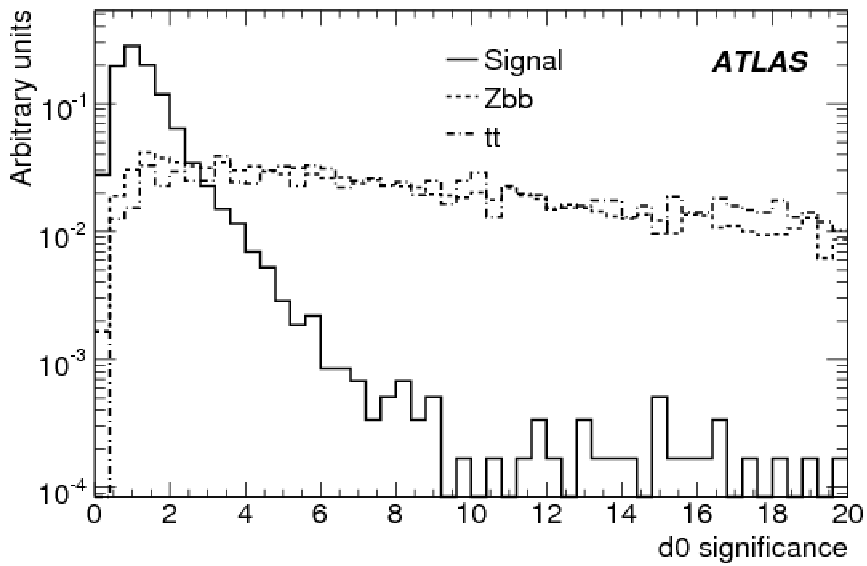


Differential inclusive jet cross-section after applying various selection criteria

$H \rightarrow Z+Z^{(*)} \rightarrow 4l$ (3)

- Analysis cuts:
  - two opposite-charged leptons p_T > 20 GeV, $|\eta|<2.5$
  - other two opposite-charged leptons p_T > 7 GeV, $|\eta|<2.5$
    - electrons of "medium" (M_H<200 GeV) or "loose" (M_H>200 GeV) quality
    - combined reconstructed muons (ID+MS)
  - at least one reconstructed Z (M_Z constraint)
  - mass window around the Higgs peak

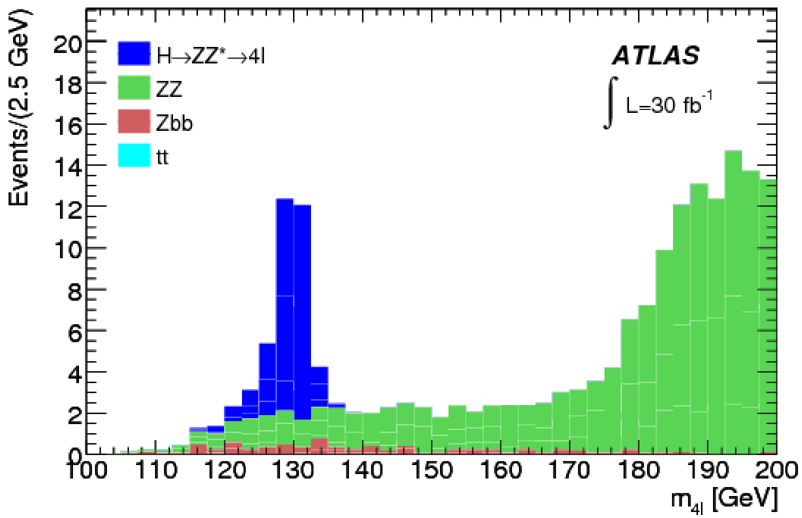
- Main background from ZZ, Zbb, tt; also Z+jet
- Extra cuts needed to further reduce the background:
  - lepton isolation (ID and calo)
  - impact parameter significance



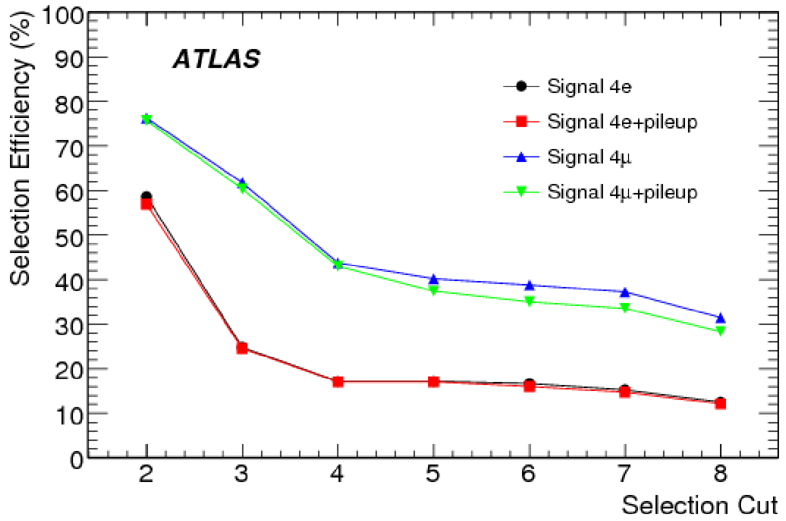
(leptons from Zbb, tt originate most likely from displaced vertices, example shown for muons)

$H \rightarrow Z+Z^{(*)} \rightarrow 4l$ (4)

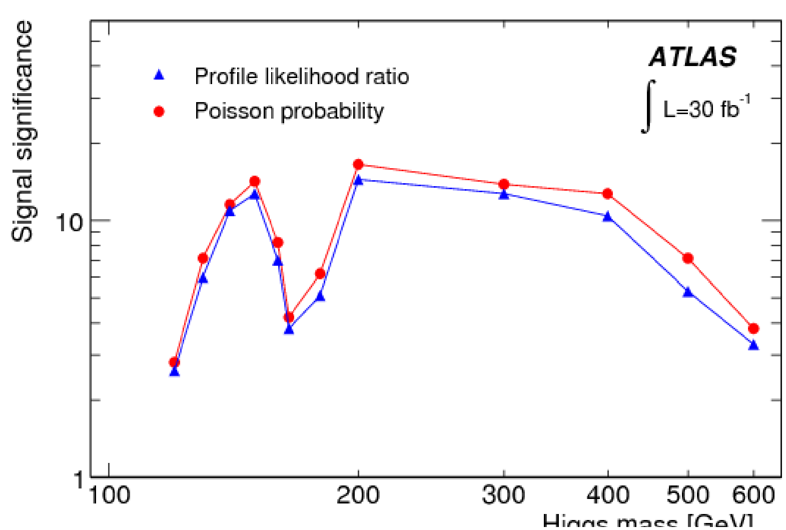
- Signal and background (M_H = 130 GeV)

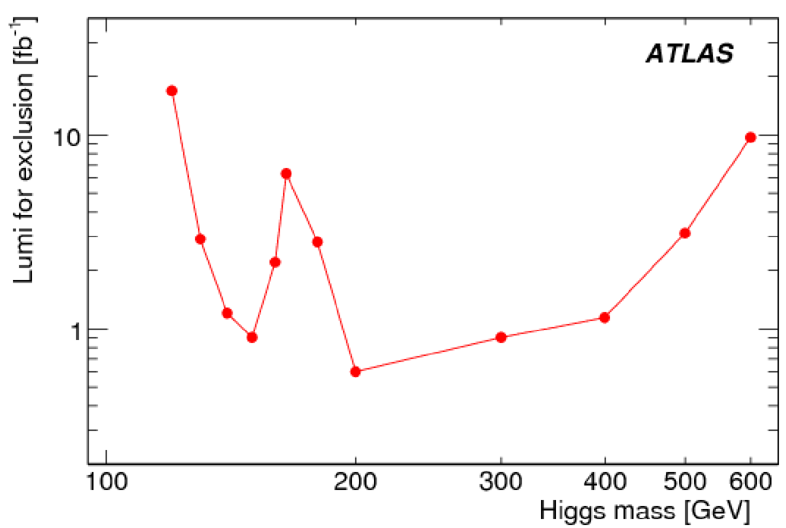


- Pile-up and cavern background lower the signal efficiency by ~10% (M_H= 130 GeV)



Total expected $H \rightarrow Z+Z^{(*)} \rightarrow 4l$ signal significance and exclusion limits



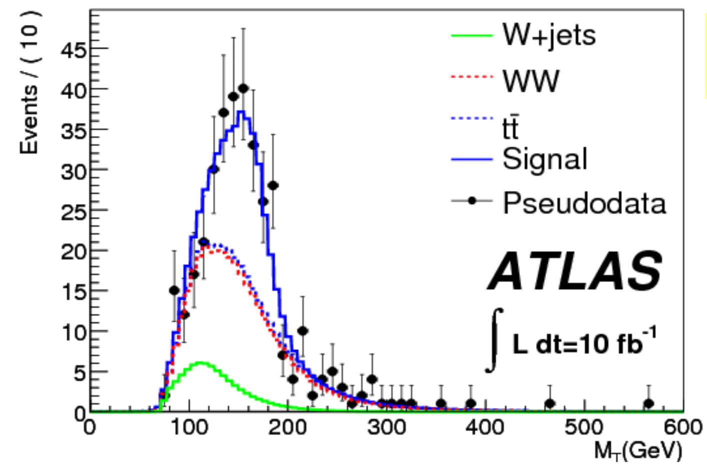


$H \to W^+W^{(*)} \to 2l+2\nu$ (1)

- Main background from WW,tt, W+jets, $Z \to \tau\tau$
- Event preselection:
  - 2 isolated high-p_T leptons and E_T^{miss} > 30 GeV
  - no jet (a) or 2 forward jets (b)
  - jet veto in central region, b-jet veto
- Higgs mass cannot be reco'ed, use transverse mass instead

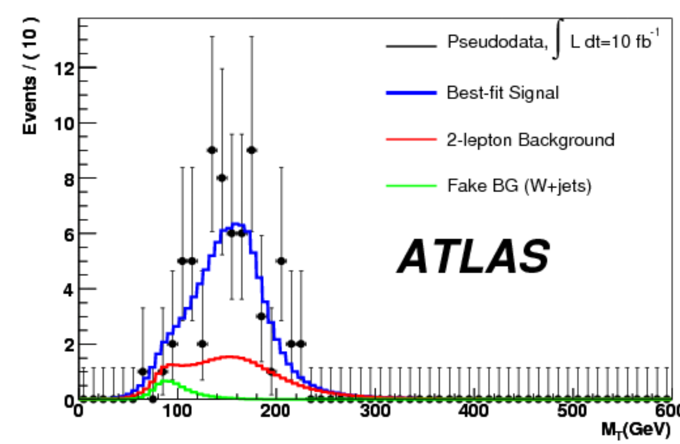
$$M_T^2 = (E_T^{ll} + E_T^{miss})^2 - (\vec{p}_T^{\,ll} + \vec{p}_T^{\,miss})^2$$

- (a) H+0jet (gg fusion)
  - cuts on angular correlations (l-l) and p_T^{WW} to reduce QCD WW



H+0jet

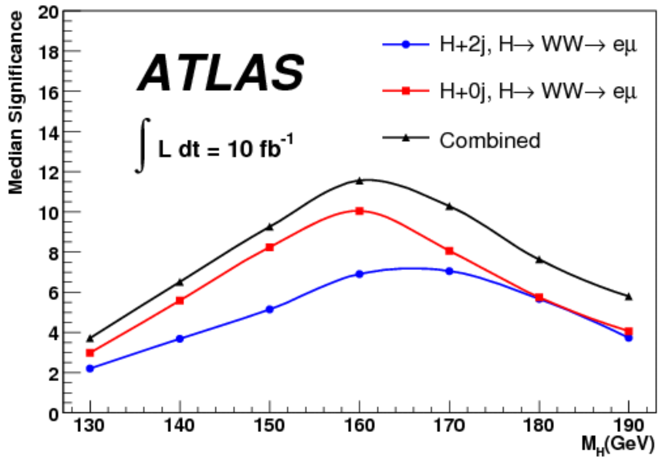
- (b) H+2jets (VBF)
  - neural net used for further event selection



H+2jets

$H \to W{+}W^{(*)} \to 2l{+}2\nu$ (2)

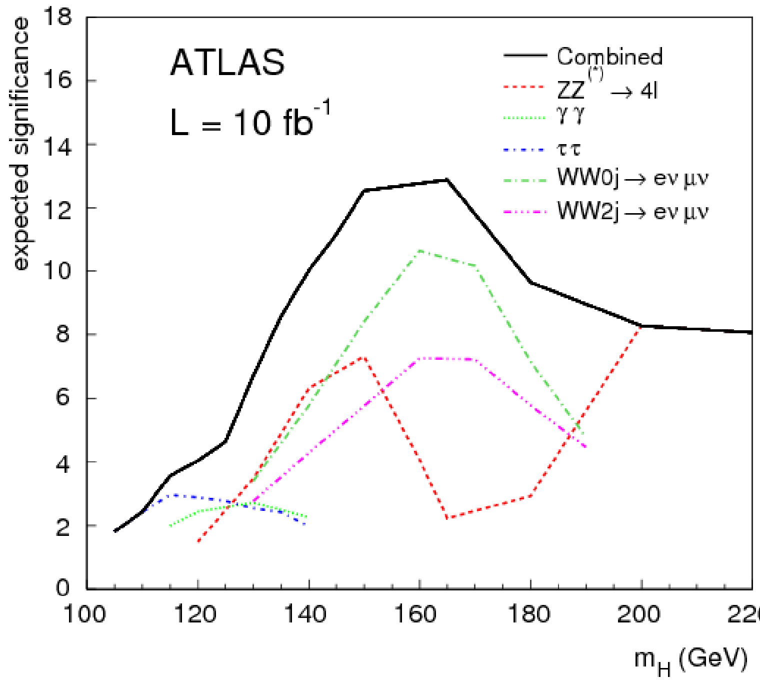
- This decay mode important especially for $2M_W < M_H < 2M_Z$ (where other modes are suppressed), but high significance for broader range

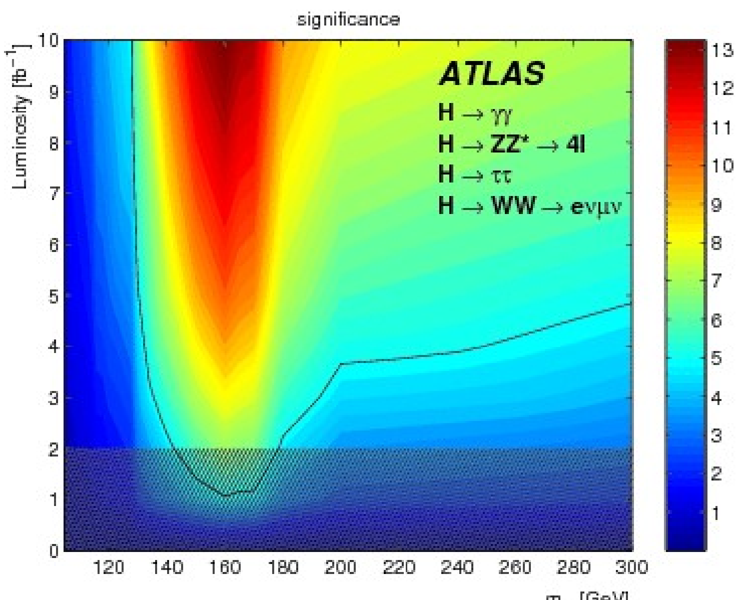


- So far consider only $e\mu\nu\nu$ in the final state, $ee\nu\nu$ and $\mu\mu\nu\nu$ still being studied

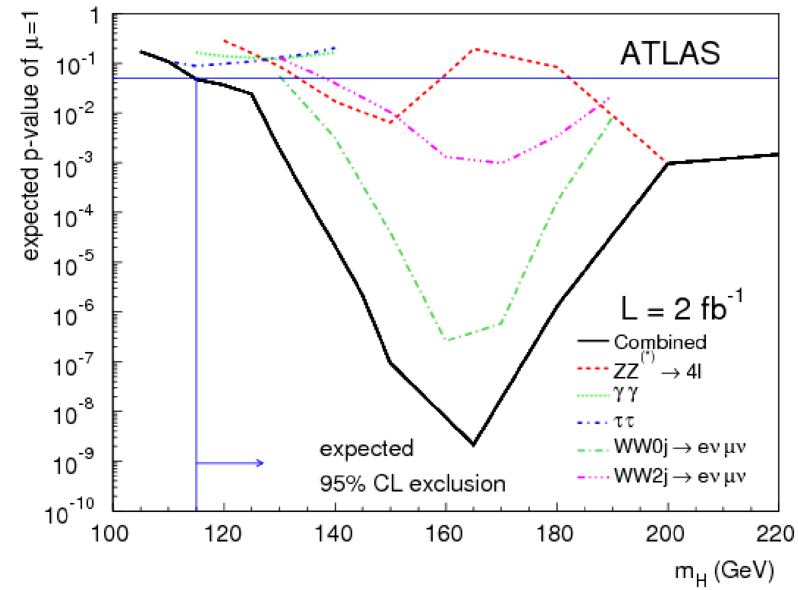
Summary on SM Higgs boson searches

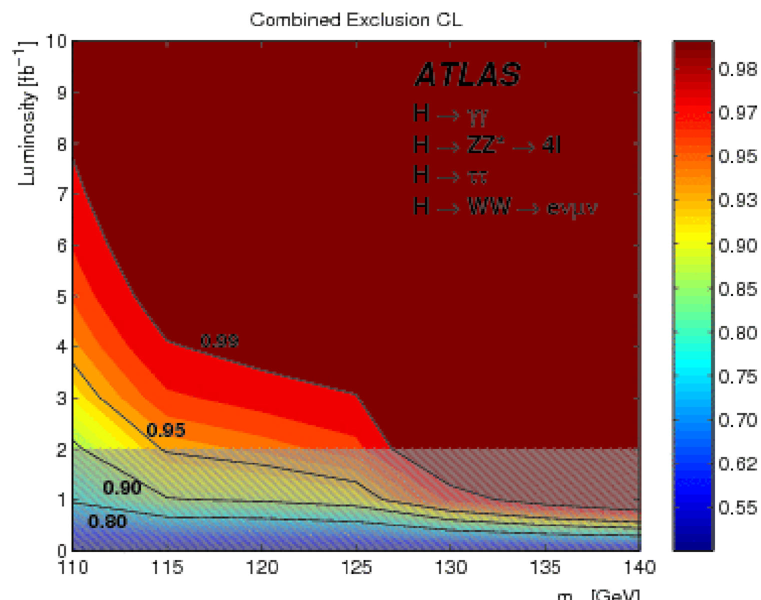
- Discovery:





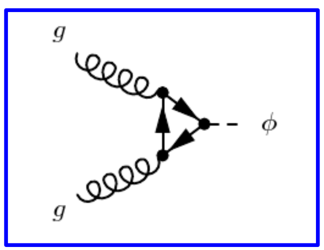
- Exclusion limits:
  - With 2 fb^{-1}: 115 < M_H < 460 GeV

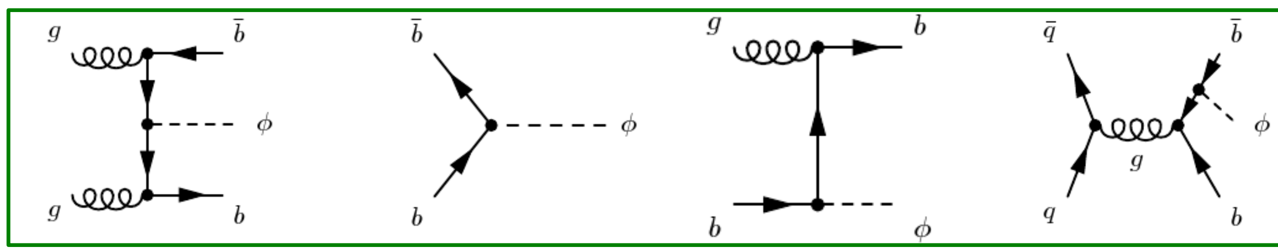




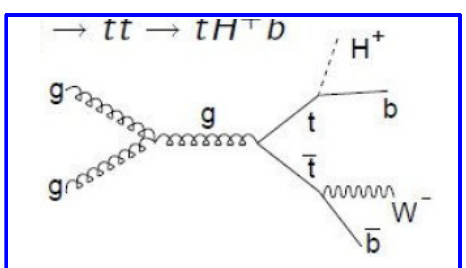
MSSM Higgs bosons

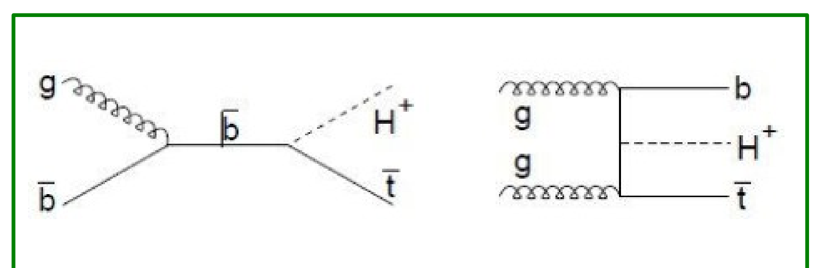
- Minimal Supersymmetric Standard Model contains 2 Higgs doublets → 3 neutral Higgs bosons (CP-even h/H, CP-odd A), 2 charged ($H^{\pm}$)
- Several MSSM scenarios explored (non-mixing, M_h-max, gluophobic, small-α), Higgs sector usually described with 2 parameters: M_A, tanβ
- Higgs production modes:
  - neutral (φ=h/H/A) – direct vs. associated b-quark production





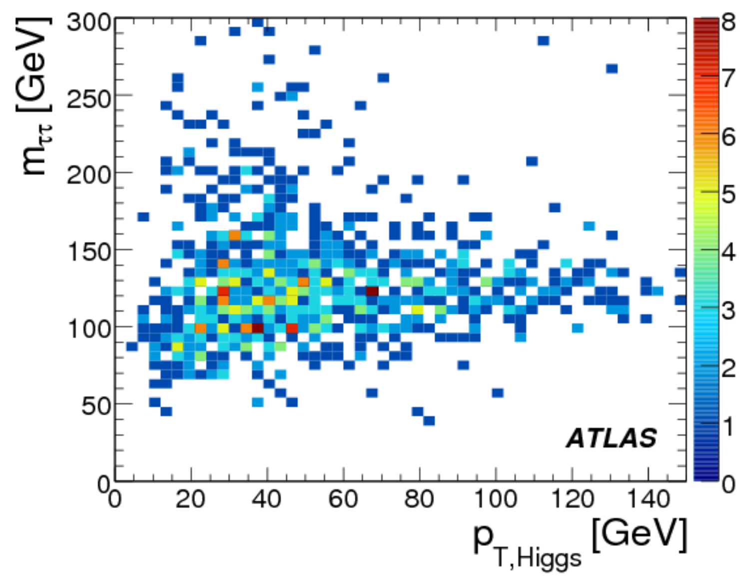
  - charged – light (M_H<M_t) vs. heavy (M_H>M_t)





$h/H/A \to \tau+\tau \to 2l + 4\nu$ (1)

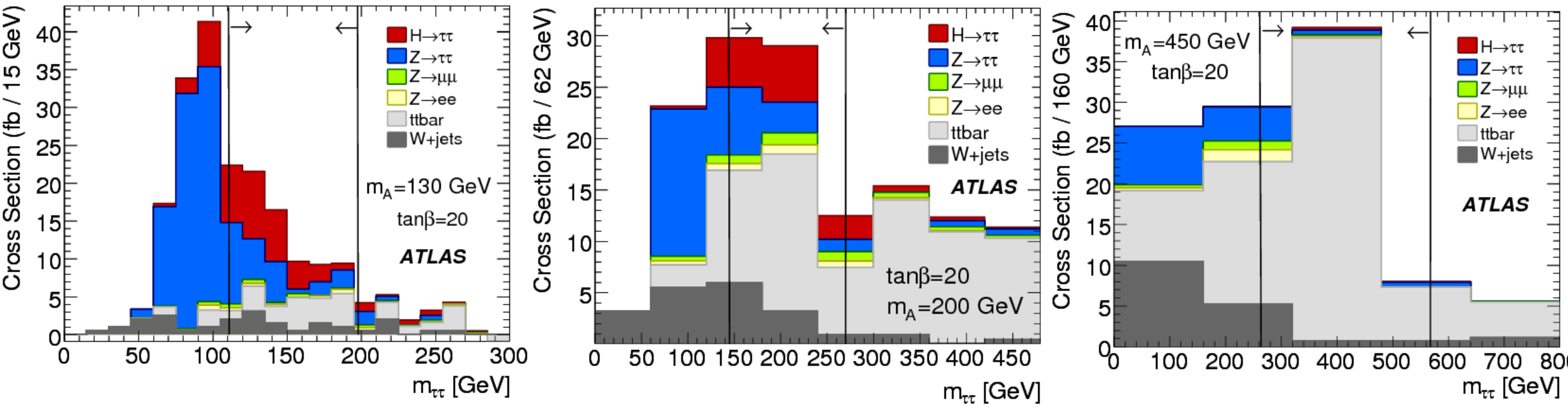
- Note: couplings to 3[rd] family fermions enhanced in MSSM
- Mode investigated for Higgs mass between 110 and 450 GeV, shown for M_h-max scenario
- Event selection:
  - two opposite-charged leptons, isolation around μ-track
  - p_T^{miss} > 20 GeV (ee/μμ), 15 GeV (eμ)
  - at least 1 b-tagged jet (b-quark associated production), <3 jets and $M_{ll} < M_Z$ to suppress bckg
- Higgs mass reco'ed with collinear approximation ($\Delta\varphi_{ll} < 3$)
  - resolution improves with $p_T^{h/H/A}$



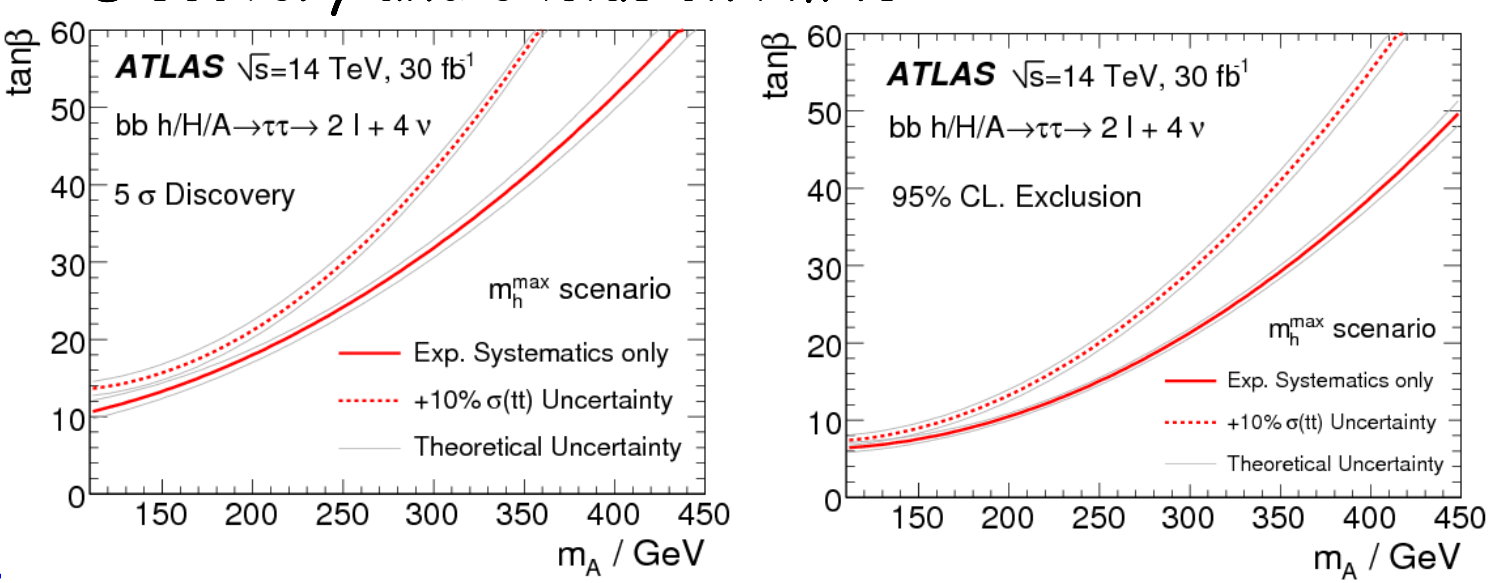
- Background sources
  - $Z \to \tau+\tau$, normalization & shape obtained from data
  - W+jets, t+tbar+jets

h/H/A → τ+τ → 2l + 4ν (2)

- Systematics uncertainties (energy & momentum resolutions for e/μ/γ/jet) are conservative, for non-optimal detector peformance

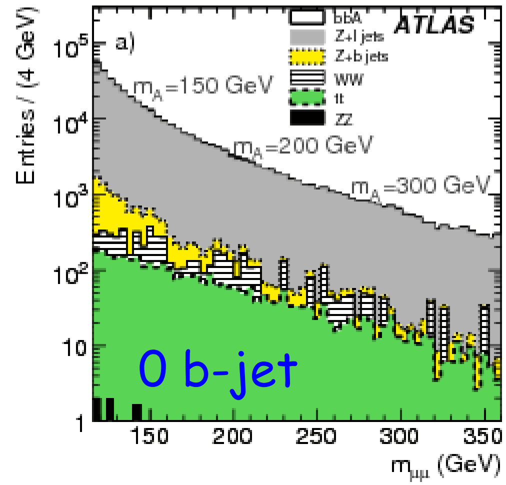


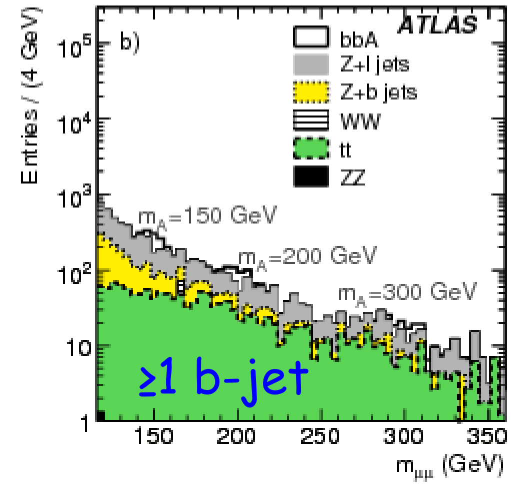
- Discovery and exclusion limits



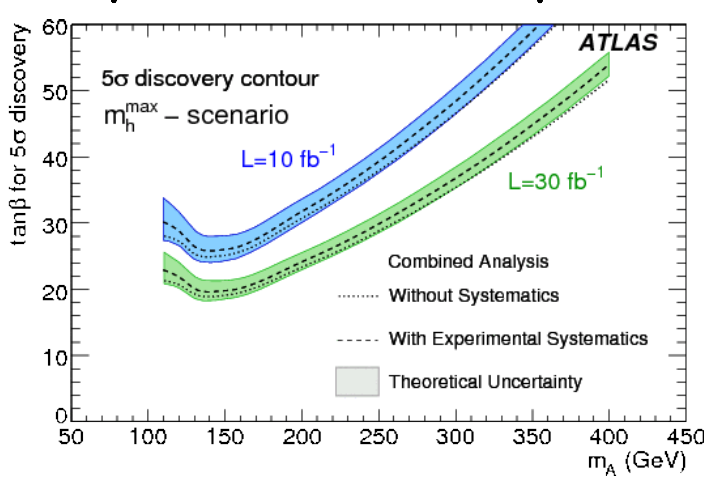
h/H/A → μ+μ

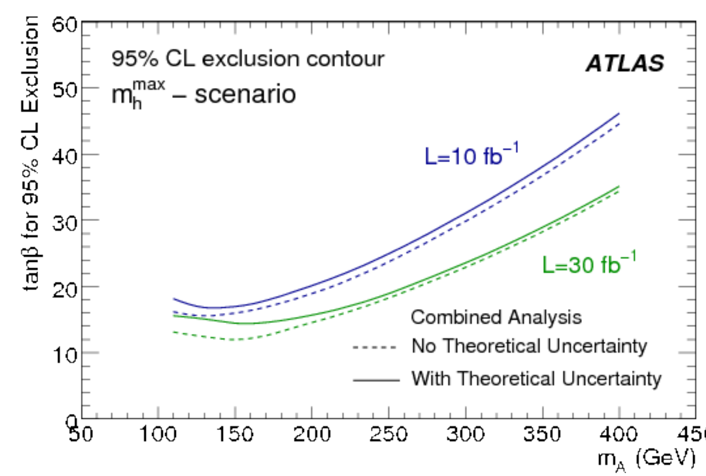
- Coupling suppressed wrt τ+τ mode
- Clean signature and full M_H reco allows for better mass determination





- The two samples are uncorrelated, they are combined for the discovery and exclusion plots



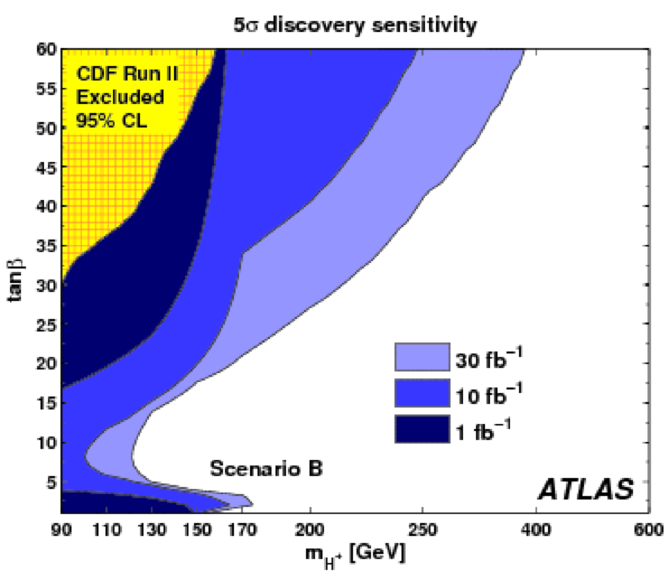


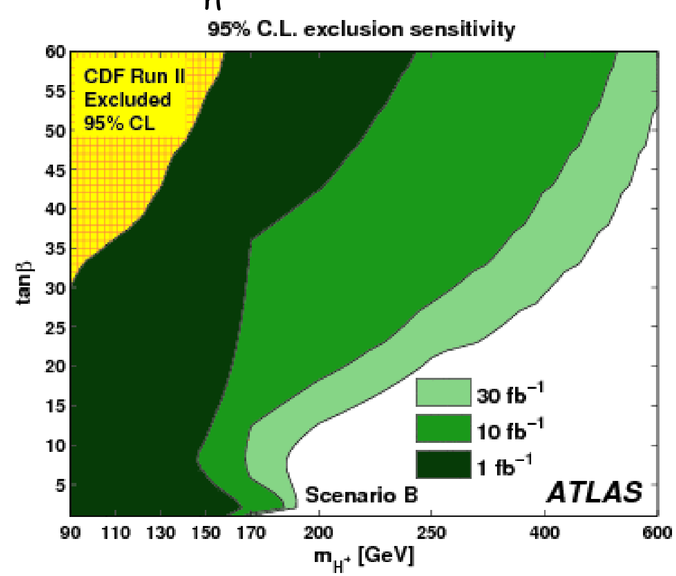
Charged MSSM Higgs boson searches

- Light $H^{\pm}$ ($M_H < M_t$)
  - $H^{\pm} \rightarrow \tau^{\pm}+\nu$, final states explored:
    - $tt \rightarrow bH^{\pm}bW \rightarrow b\tau^{\pm}(had)\nu bqq$
    - $tt \rightarrow bH^{\pm}bW \rightarrow b\tau^{\pm}(had)\nu bl\nu$
    - $tt \rightarrow bH^{\pm}bW \rightarrow b\tau^{\pm}(lep)\nu bqq$
    - $tt \rightarrow bH^{\pm}bW \rightarrow b\tau^{\pm}(lep)\nu bl\nu$ (under study)
  - $H^{\pm} \rightarrow c+s$ (under study)

- Heavy $H^{\pm}$ ($M_H > M_t$)
  - $H^{\pm} \rightarrow \tau^{\pm}+\nu$
    - $t[b]H^{\pm} \rightarrow bqq[b]\tau^{\pm}(had)\nu$
  - $H^{\pm} \rightarrow t+b$
    - $t[b]H^{\pm} \rightarrow bW[b]bWb \rightarrow bl\nu[b]bqqb$

- Discovery and exclusion limits (M_h-max scenario)





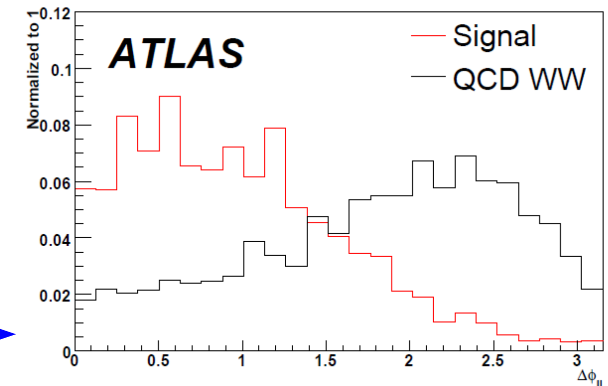
Uncovered region for medium tanβ - exclusion possible at least for light $H^{\pm}$

Higgs boson properties

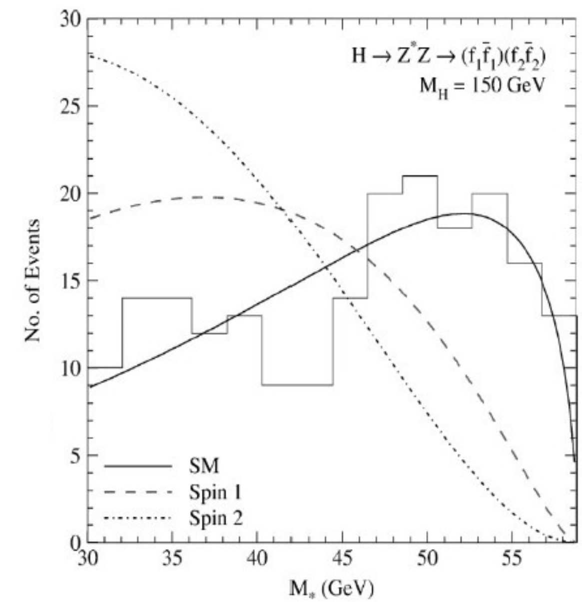
- Suppose Higgs-like particle was discovered → focus turns to its properties
- Briefly look at some of them:
    - spin, CP
    - couplings
- If only 1 Higgs boson is discovered, is it SM Higgs or MSSM one?

Spin & CP (1)

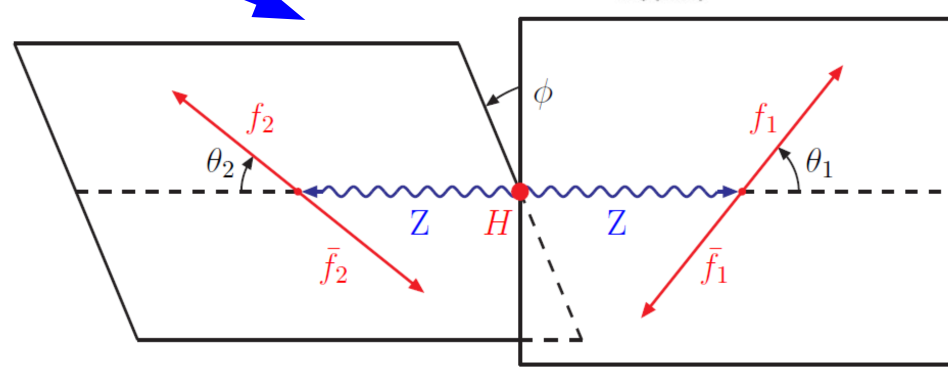
- Observation of $H \rightarrow \gamma+\gamma$ rules out $S(H)=1$
- Spin assumptions used e.g. in SM Higgs search $H \rightarrow W+W^{(*)} \rightarrow 2l+2\nu$



- $H \rightarrow Z+Z^{(*)} \rightarrow 4l$
  - lower Higgs mass – spin sensitive to M_* (invariant mass of leptons from Z*)

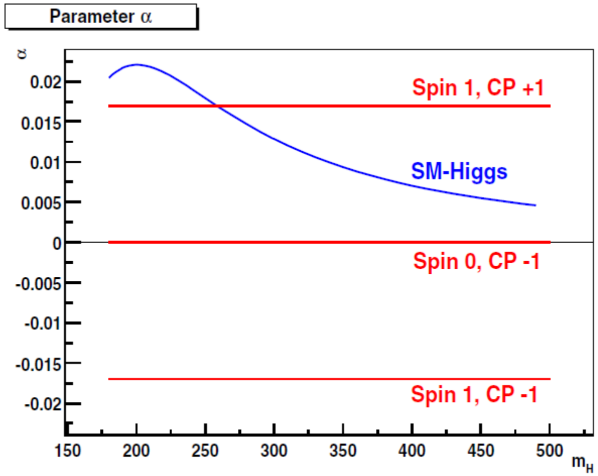


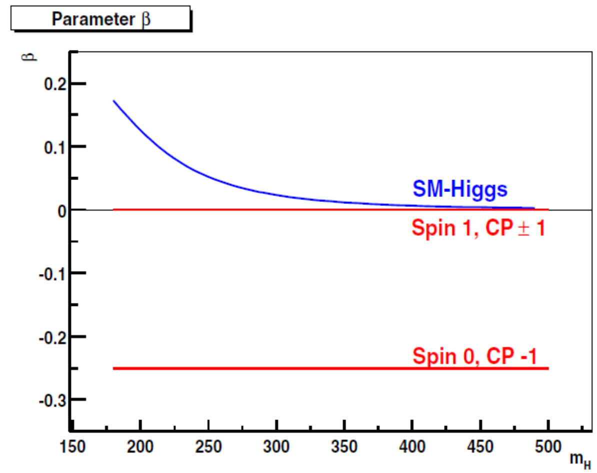
  - $M_H > 2M_Z$ – look at distributions in φ (angle between decay planes) and θ (polar angle in Z rest frame)
    - $F(\varphi) = 1+\alpha\cdot\cos(\varphi)+\beta\cdot\cos(2\varphi)$
    - $G(\Theta) = T\cdot(1+\cos^2(\Theta))+L\cdot\sin^2(\Theta)$
      - L, T stand for longitudinal and transverse Z polarization

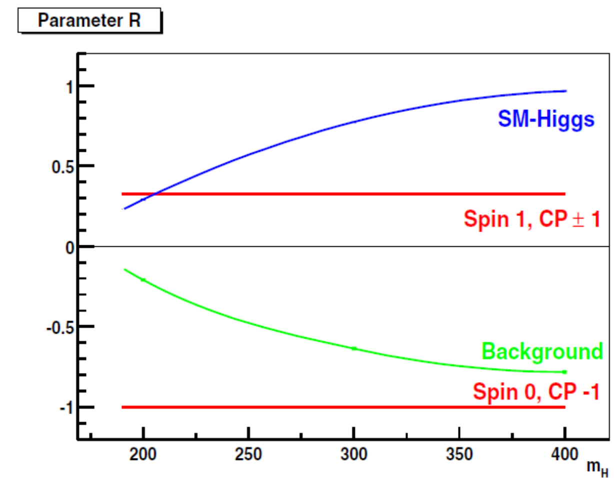


Spin & CP (2)

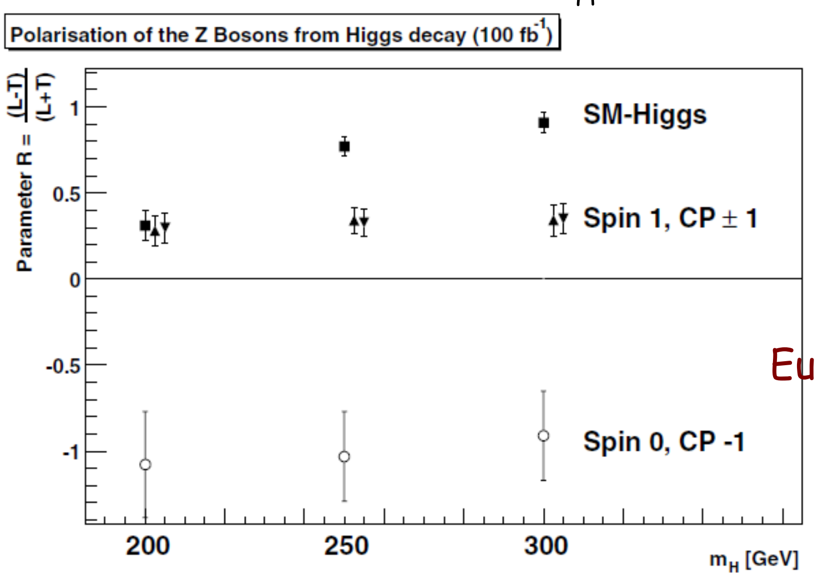
– parameters α, β, R≡ (L-T)/(L+T) distinguish between several spin & CP

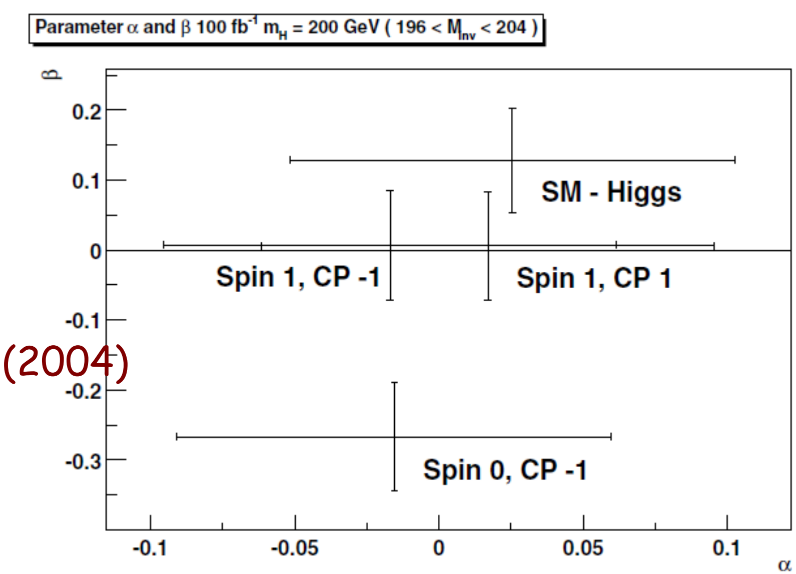






- R provides good separation for M_H > 230 GeV
- α, β help for M_H ≈ 200 GeV; sensitivity can be enhanced with sign(cos(Θ))





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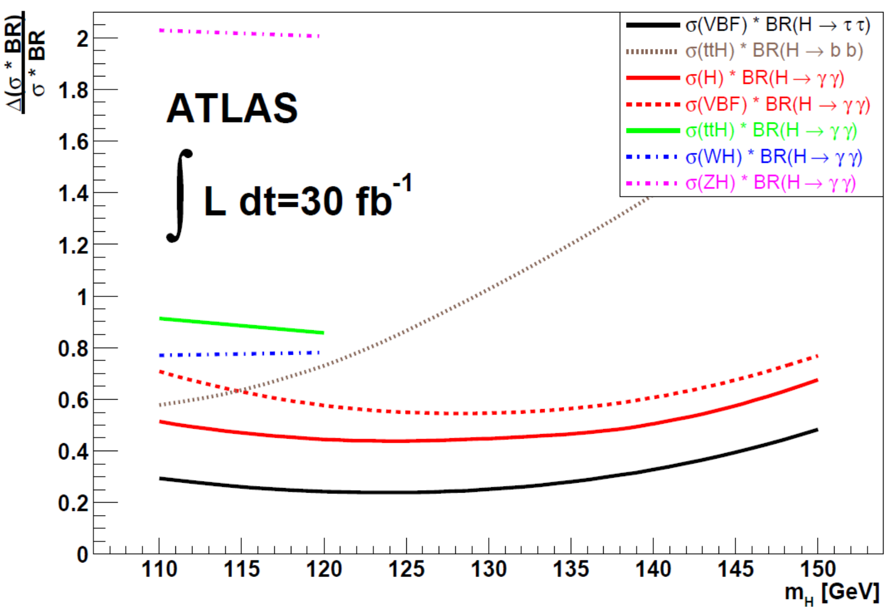
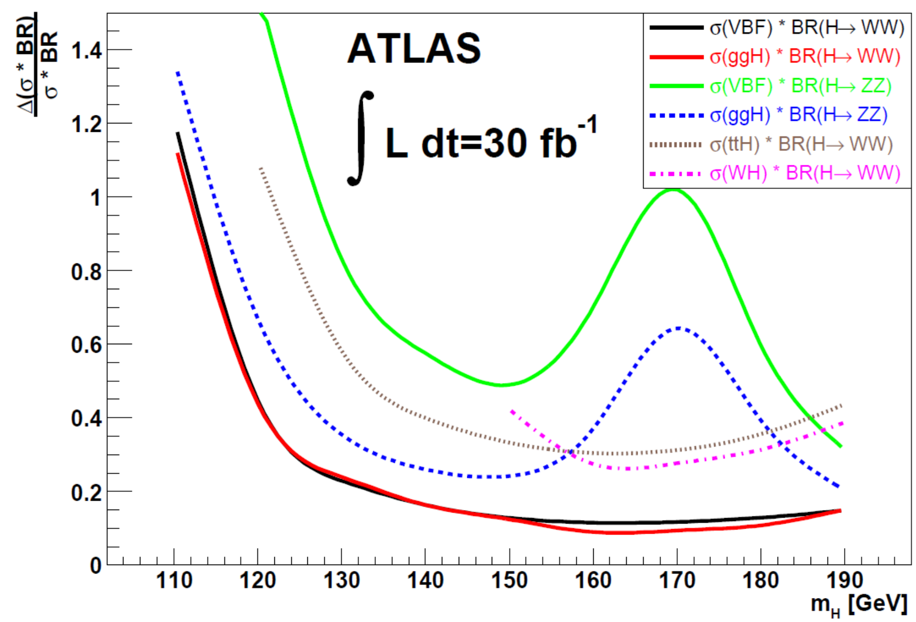
Couplings (1)

- Measure the rates in various search channels and then try to extract widths and couplings
  - some Higgs decay modes undetectable, others difficult (H → bb)
  - relative uncertainties 10 – 100% depending on the channel
  - example for SM Higgs:





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Couplings (2)

- Evaluate ratios of partial widths:
  - uncertainties reduce in the ratio
  - use Γ_W for normalization (measured most accurately)
- Extract the absolute couplings:
  - need few more theoretical assumptions
    - fix ratio Γ_b/Γ_τ, or
    - assume $\Gamma_{W,Z} \leq \Gamma_{W,Z}^{SM}$
  - allow for undetectable decays (free parameter $\Gamma_{invisible}$), make global fit

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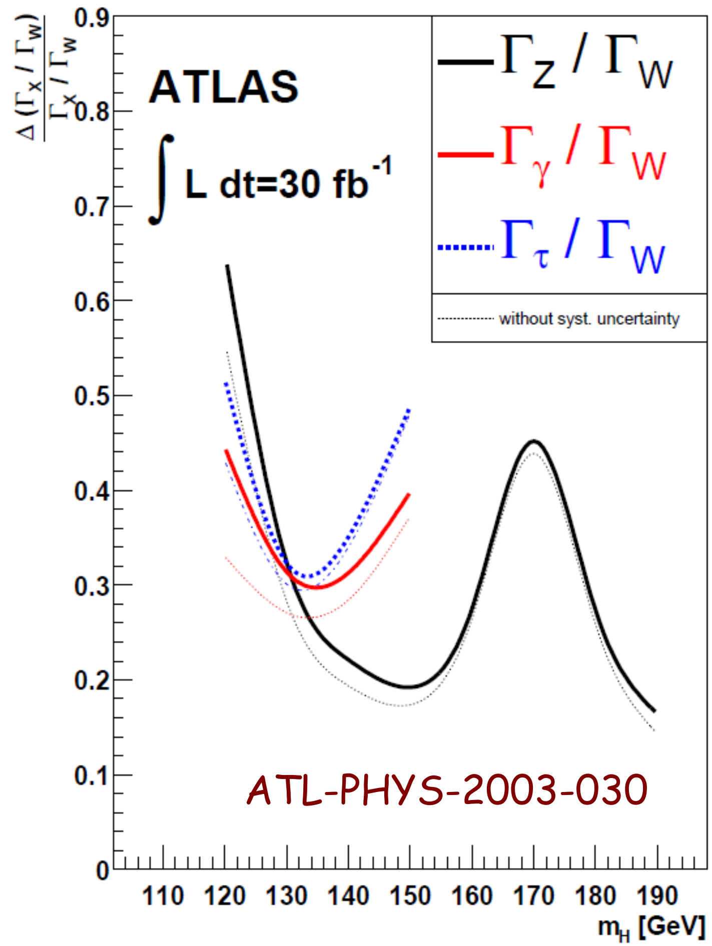
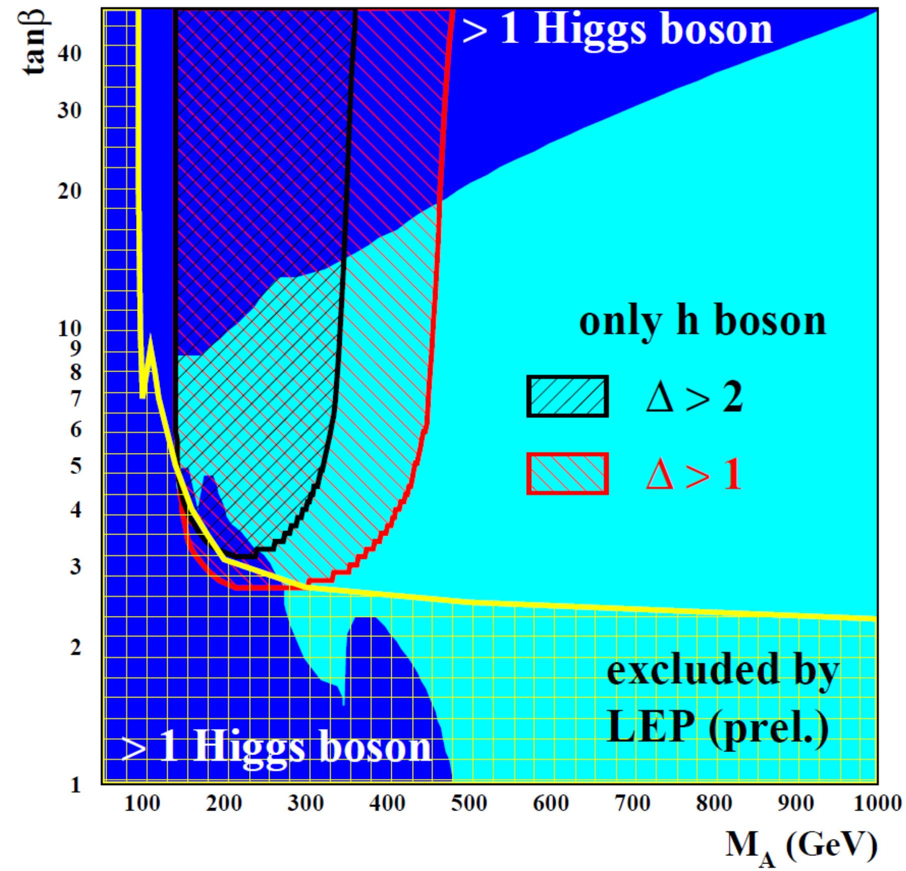


SM vs non SM Higgs boson

- SM and MSSM predict different couplings for the Higgs boson(s), exploit BR to fermions and vector bosons
  - $R \equiv BR(H \to \tau+\tau)/BR(H \to WW)$
  - $\Delta \equiv (R(MSSM)-R(SM))/\sigma(R)_{exp}$
- example for M_h-max scenario:
  - using VBF production only
  - integrated luminosity 300 fb^{-1}



hep-ph/0410112

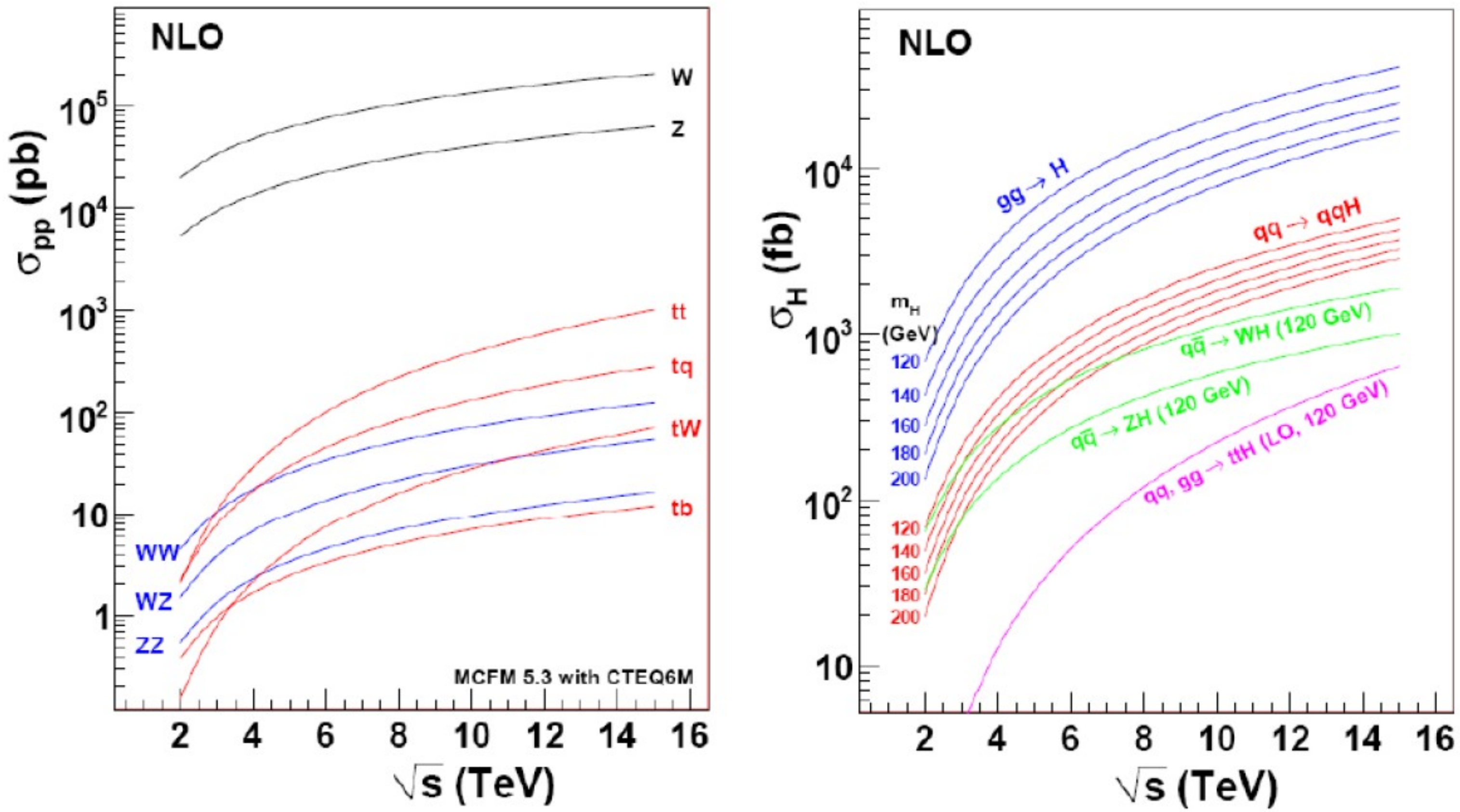
Conclusions

- Search for Higgs@ATLAS was investigated in many channels for $\sqrt{s}$ = 14 TeV, for Standard Model scenario and beyond
  - studies still ongoing in some cases, especially dealing with background estimation from data
- Measurements of the final states requires good undestanding of the detector physics performance and reconstruction of photons, leptons, jets and missing E_T
- Combining all investigated SM Higgs decay modes
  - 5σ discovery possible with 10 fb^{-1} for $M_H \geq 125$ GeV
  - expect 95% CL exclusion for $M_H \geq 115$ GeV already with 2 fb^{-1} (remember LEP limit 114.4 GeV)

Thanks to K. Assamagan, J. Qian, C. Potter, W. Murray and others for help.

Backup slides

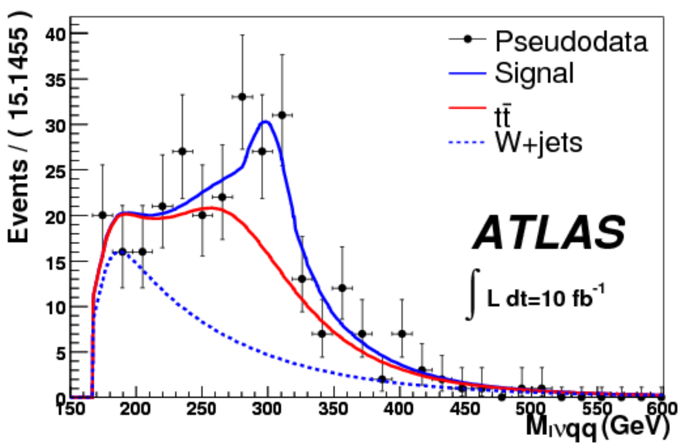
Comparison 14 TeV vs. 10 TeV



- Higgs cross-section is reduced by a factor of ~2 @ 10 TeV
- Significance decreases by ~1.5
  - need ~2x higher integrated luminosity to reach the same significance as at 14 TeV

Other SM Higgs boson searches

- $H \rightarrow W+W^{(*)} \rightarrow l\nu qq$
  - important for $M_H \geq 250$ GeV
  - studied for VBF (H+2jets)
  - full invariant mass reconstruction possible



  - W+4jets background needs to be measured with first data

- Associated production channels:
  - $t\bar{t}H$, $H \rightarrow b+b$
  - $t\bar{t}H$, $H \rightarrow W+W^{(*)}$
  - WH, $H \rightarrow W+W^{(*)}$
  - WH, $H \rightarrow b+b$
  - ZH, $H \rightarrow b+b$