A few selected topics on Higgs Boson searches in Atlas

- Introduction
- Standard model Higgs boson
- Some exotica
- Summary

first beam event seen in ATLAS

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on behalf of the Atlas collaboration

Open issues/requests are marked with

Introduction

What questions the LHC experiments should try to answer :

Does a Higgs boson exist ?

→ definite answer within the standard model (SM) foreseen in 2012 (?)

If yes :

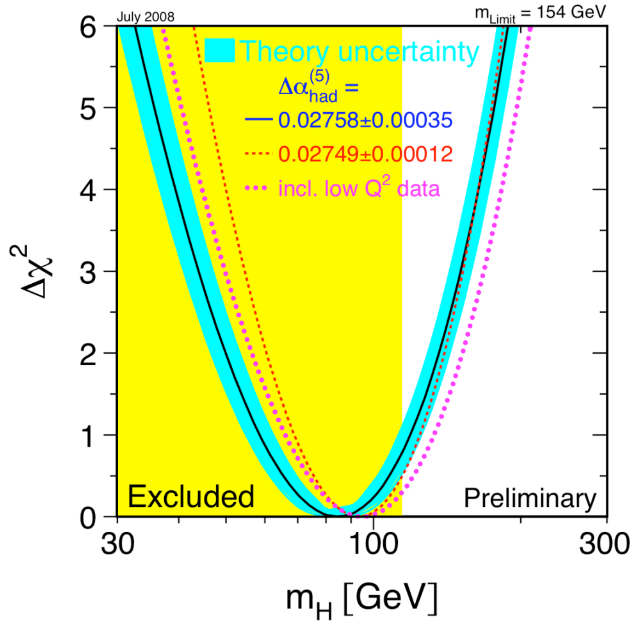
✓ is there only one ?
✓ what are its mass, width, quantum numbers ?
✓ does it generate electroweak symmetry breaking *and* give mass to fermions too as in the SM or is something else needed ?
✓ what are its couplings to itself and other particles

If no :

be ready for

- very tough searches at the (S)LHC ($V_L V_L$ scattering, …) or
- more spectacular phenomena such as W', Z' (KK) resonances, technicolor, etc…

Where to look for :



LEP direct :

$$m_H > 114.4 \text{ GeV/c}^2 \text{ @ 95\% C.L.}$$

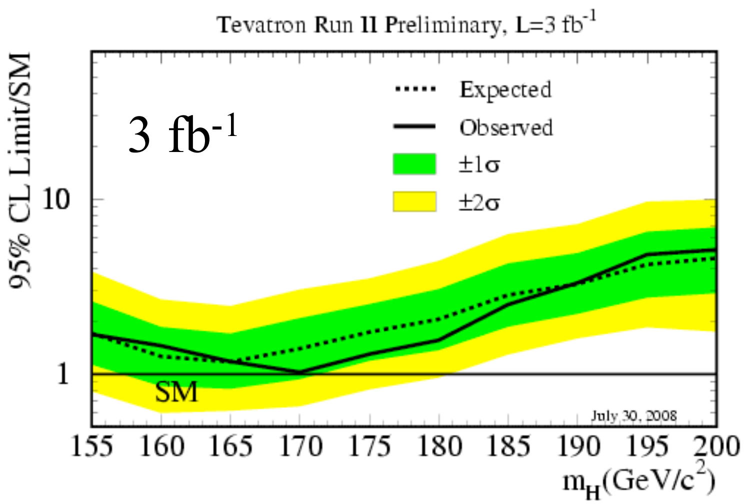
LEP/SLD/Tevatron EW fit (within the SM) :

$$m_H = 84^{+34}_{-26} \text{ GeV/c}^2$$

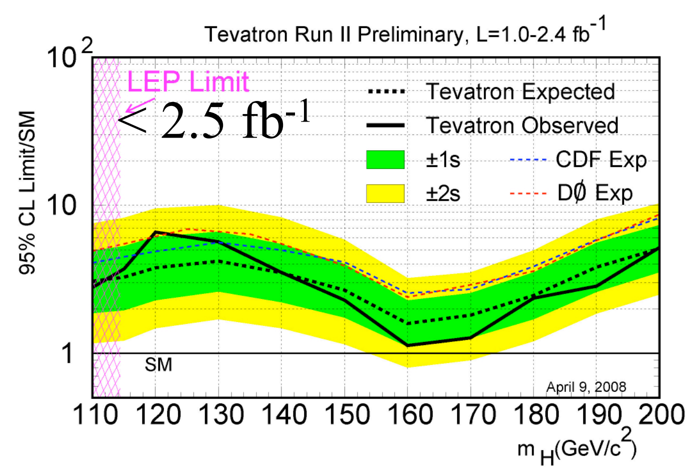
$$m_H < 154 \text{ GeV/c}^2 \text{ @ 95\% C.L.}$$

And do not forget the Tevatron :

m_H = 170 GeV/c^2 excluded @ 95% C.L.



But still a long way to go before reaching sensitivity to lower masses SM Higgs boson…



What is new in the Atlas Higgs boson searches since the "Physics TDR" (1999) and its update for vector boson fusion studies (2003) :

- ✓ Better generators : N(N)LO, Parton Shower-Matrix Element matching, …
- ✓ Better detector description and simulation :
  geometry, material budget, Geant4 ⇒ much more realistic
- ✓ Improved trigger simulation, event reconstruction (*a priori*) and analysis tools
  also towards more realism
- ✓ Strategies to estimate backgrounds from data
- ✓ Improved statistical treatment
  (also including treatment of systematic uncertainties)

One of the most important improvements : sensitivities given at NLO

The most frequent reproach done to Atlas before :
no use of K factors, supposed to be conservative as soon as $K_S \times K_S > K_B$ (Gaussian statistical significance ~ $S/\sqrt{B}$)
was OK since not all backgrounds were known at NLO in the old (TDR) time, but no excuse anymore…

Although a major effort was done to re-assess the Atlas sensitivity to Higgs bosons with improved tools in the past three years, resulting in robust baseline analyses for further studies, many aspects still need to be revisited :

- ✓ Spin determination
- ✓ CP properties
- ✓ Couplings
- ✓ Heavy Higgs boson

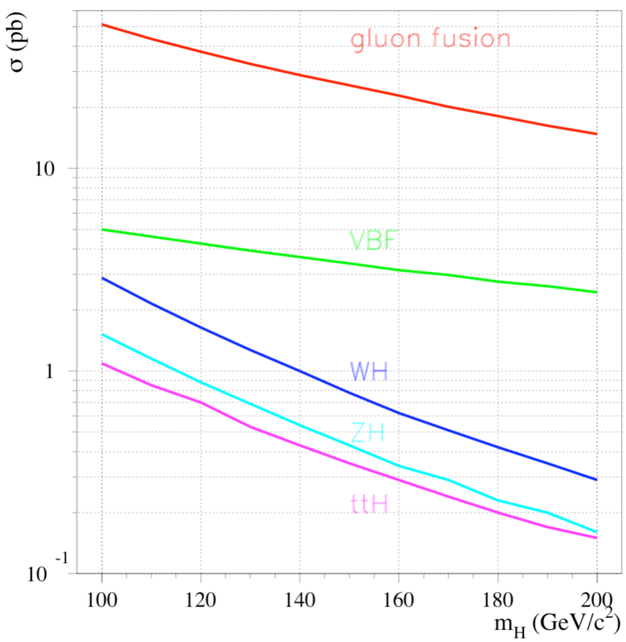
$\Rightarrow$ require a large integrated luminosity

(The SM Higgs boson mass measurement is less sensitive to the latest improvements)

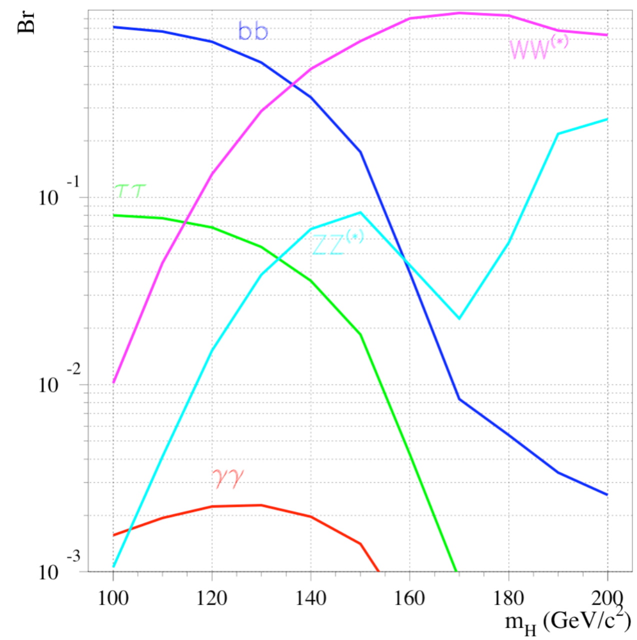
$\Rightarrow$ In this presentation,
only results on low mass SM and some MSSM Higgs bosons are shown
with emphasis on discovery at (relatively) low luminosity and $\sqrt{s} = 14$ TeV

Standard model Higgs boson

Production cross-sections



Branching ratios



Due to the overwhelming QCD background :
forced to use rare (but clean) decay modes and/or sub-dominant production processes :

- $m_H < 130$ GeV/c^2 : γγ combined with all production processes or ττ from VBF
- $m_H > 130$ GeV/c^2 : decay to WW$^{(*)}$/ZZ$^{(*)}$ (followed by at least one gauge boson leptonic decay)
- the bb decay revealed itself to be even harder than previously thought :
  ttH very hard, VH currently being revisited, maybe hope from VBF + photon

The *good old* two photon final state : $H \rightarrow \gamma\gamma$

Very few events expected (~1200 *produced* events @ 10 fb^{-1} for m_H = 120 GeV/c^2) on top of a huge background, but narrow mass peak ($\sigma(m_{\gamma\gamma})$ ~ 1.5 GeV/c^2)

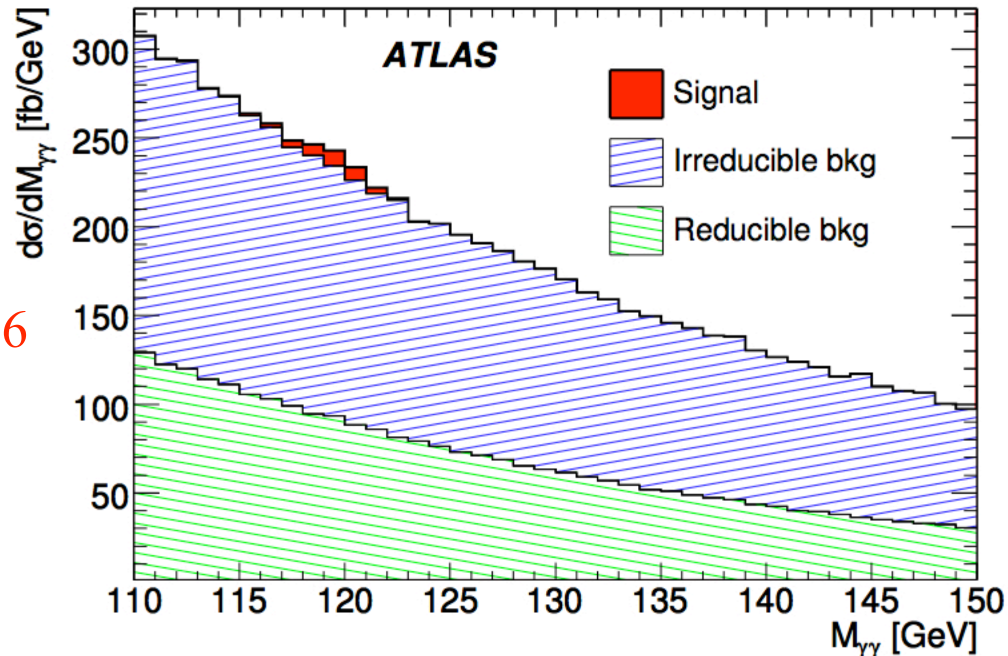
→ in the end, a very robust channel for discovery

⇒ Inclusive analysis (~ look only at the di-photon system) result (cross-sections in a mass window):

Signal (120 GeV/c^2) = 21 (gg) + 2.7 (VBF) + 1.3 (VH) + 0.4 (ttH) fb
Background = 562 ($\gamma\gamma$) + 318 (γj) + 49 (jj) + 18 (Drell-Yan) fb

S/B ~ 2.6%

standard significance @ 10 fb^{-1} : σ ~ 2.6



Comment :
the fraction of reducible background is ~ 40%, much higher than in the Atlas TDR (~ 26%)
⇒ Will need a careful monitoring of the photon/jet separation

(but can still expect improvements (improved jet rejection) and the Atlas γj estimation might be over-conservative)

Background estimation :

Control samples should be easily available in the data, from the sidebands of the $m_{\gamma\gamma}$ distribution
However, good MC generators needed to assess the search strategy and
be more confident when data arrive

- Irreducible background :
  Uses Alpgen to generate $\gamma\gamma$+n(<4) jets and reweight events according to the $p_T^{\gamma\gamma}$ spectrum from ResBos

→ For robustness, would need an implementation of the $\gamma\gamma$ process (with 2 prompt or 1 prompt-1frag. photons) in a MC@NLO-like generator

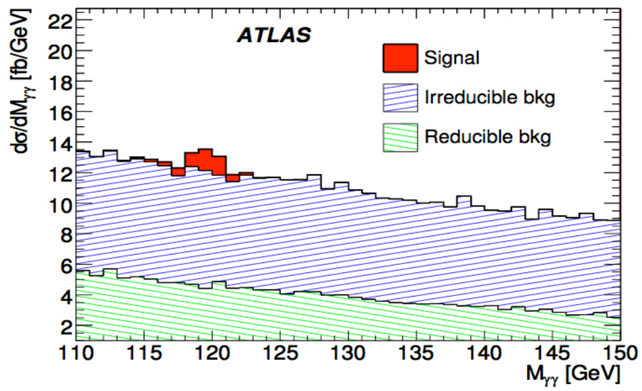
→ Events at a given $p_T^{\gamma\gamma}$ but with different jet multiplicities are given the same weight. Is this OK ? What is the less wrong reweighting procedure ?

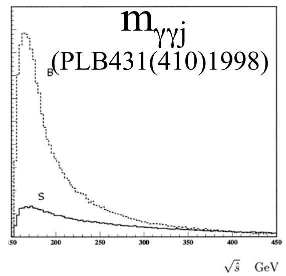
- Parton-to-photon fragmentation : can a state-of-the-art fragmentation procedure *à la* Diphox be implemented in a parton shower Monte Carlo ?

- The reducible backgrounds γj (from Jetphox) and jj (from NLOjet) are still quite uncertain (e.g. $K_{\gamma j} \sim 2.1$, not easy to estimate)

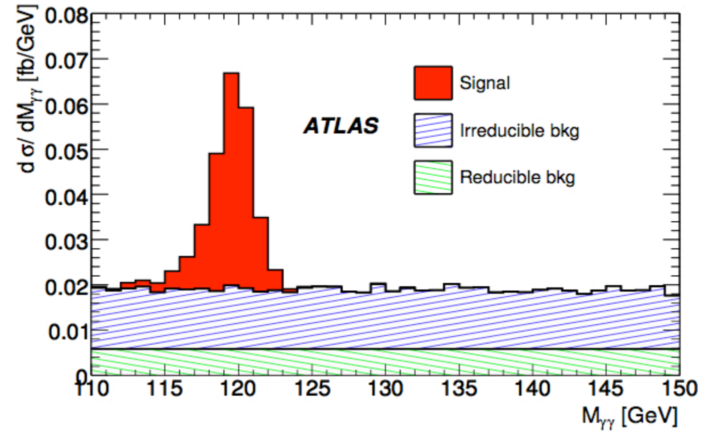
Beyond the inclusive analysis : Use distinctive features of different production mechanisms

$\gamma\gamma$ + 1 jet, S/B ~ 8%, VBF ~ 0.6×gg





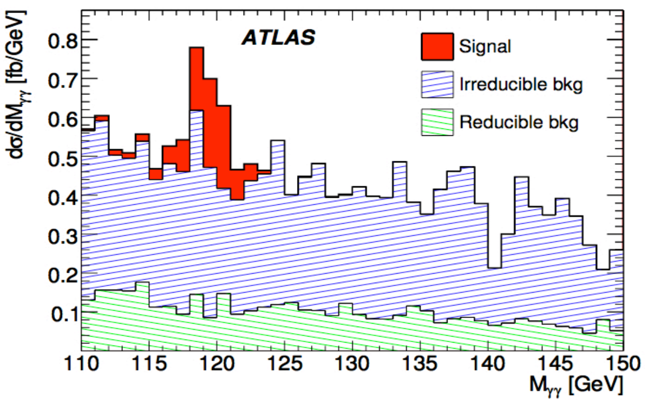
$\gamma\gamma$ + 1 μ/e + E_T^{mis}, S/B ~ 1.7, WH, ttH



Spectacular but…

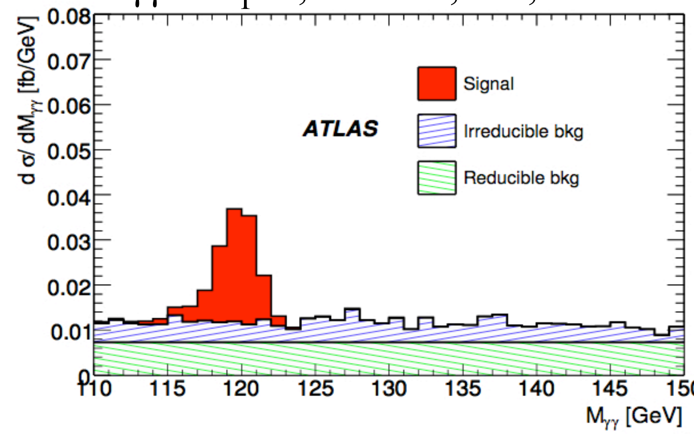
behold the vertical scale

$\gamma\gamma$ + 2 jets, S/B ~ 0.5, VBF ~ 4.4×gg



Improved purity but worse statistics

$\gamma\gamma$ + E_T^{mis}, S/B ~ 2, ZH, WH



→ Drawback : less inclusive may be more sensitive to systematic uncertainties

needs precise background generators :

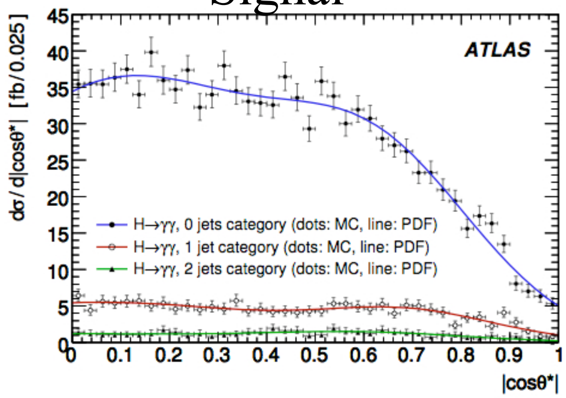
e.g. • what is the best way to simulate the tt$\gamma\gamma$ or rather blνbqq$\gamma\gamma$ process ?

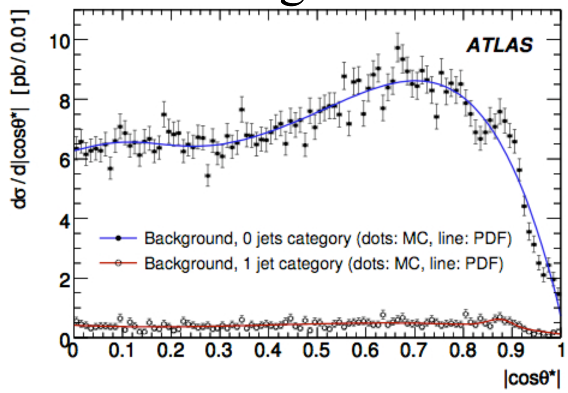
• does a NLO QCD estimation of γjj exist (to complete the H + 1 jet analysis @ NLO) ?

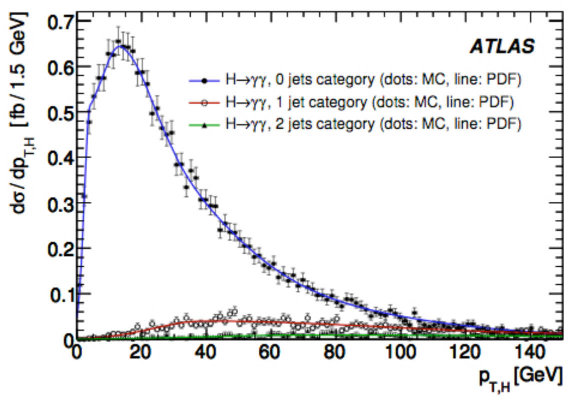
On the experimental side, event categorisation could also help, e.g. unconverted/converted photons or η_γ

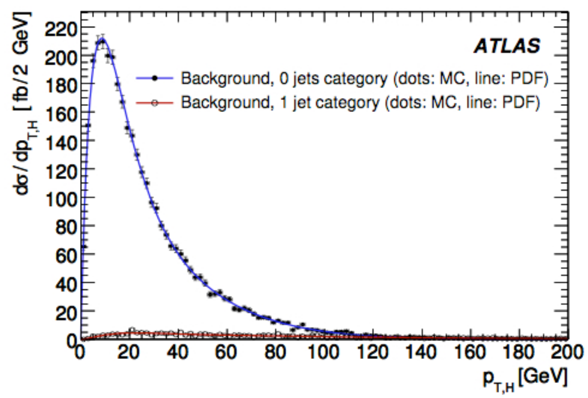
Using more discriminating variables : e.g. $\cos\theta^*$, p_T^H

Signal | Background









Requires precise shape estimation

e.g. for the signal

- ideally a MC@NNLO, or
- FEHIP/HNNLO + resummation
- meanwhile, try NNLO reweighting of MC@NLO (Davatz *et al*)

and use sideband for background shapes

Combining the 0, 1 and 2 jets analyses,

the significance is ~ 2.8 @ 10 fb^{-1} and for $m_H = 120\ GeV/c^2$

(taking into account the *look-elsewhere* effect, *i.e.* we look for an excess anywhere between 100 and 150 GeV/c^2)

~ 30 fb^{-1} is needed for a 5σ (@ 120 GeV/c^2) discovery with this channel alone

The *still golden 4 lepton* final state : H → ZZ$^{(*)}$ → 4 leptons

Very few events (~ 63 (205) produced for m_H = 130 (200) GeV/c^2 @ 10 fb^{-1})

but narrow mass peak ($\sigma(m_{4l})$ ~ 2 GeV/c^2 @ m_H = 130 GeV/c^2) on top of a smooth background

Important over the whole mass range (but around the WW threshold)

However, the low mass region (< 180 GeV/c^2) remains difficult : off-shell Z ⇒low p_T leptons,

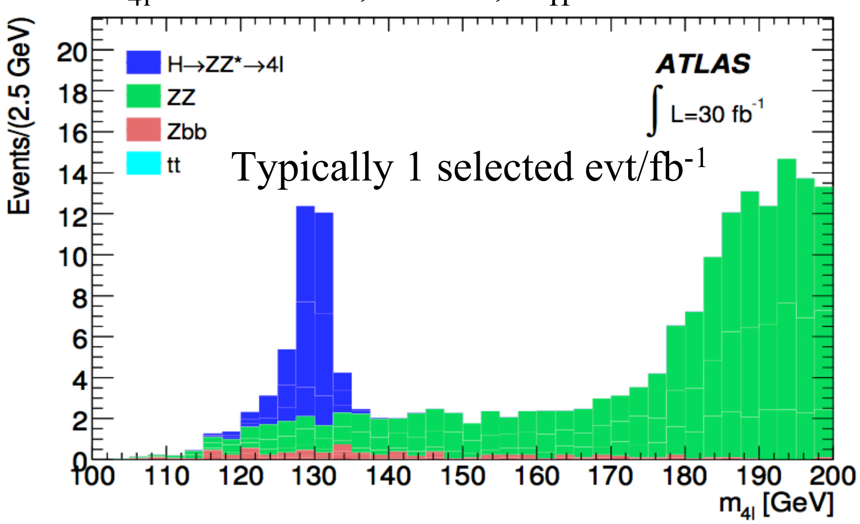
→ smaller efficiencies or larger fake rate (Z+jets difficult to estimate but should be negligible)

→ reducible background Zbb and tt with leptons from semileptonic B/D hadron decays

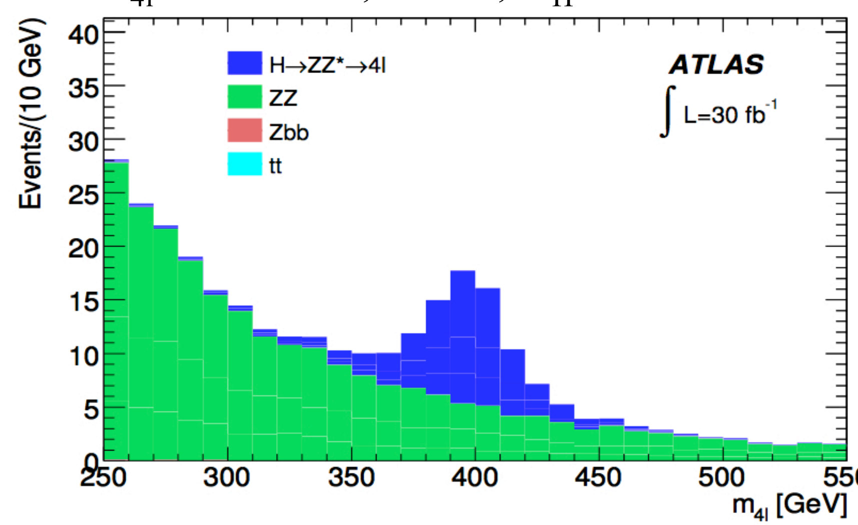
(tight cuts (lepton isolation) select events in the tail of the b fragmentation function

⇒ very uncertain, but hopefully much below the irreducible ZZ$^{(*)}$ background level)

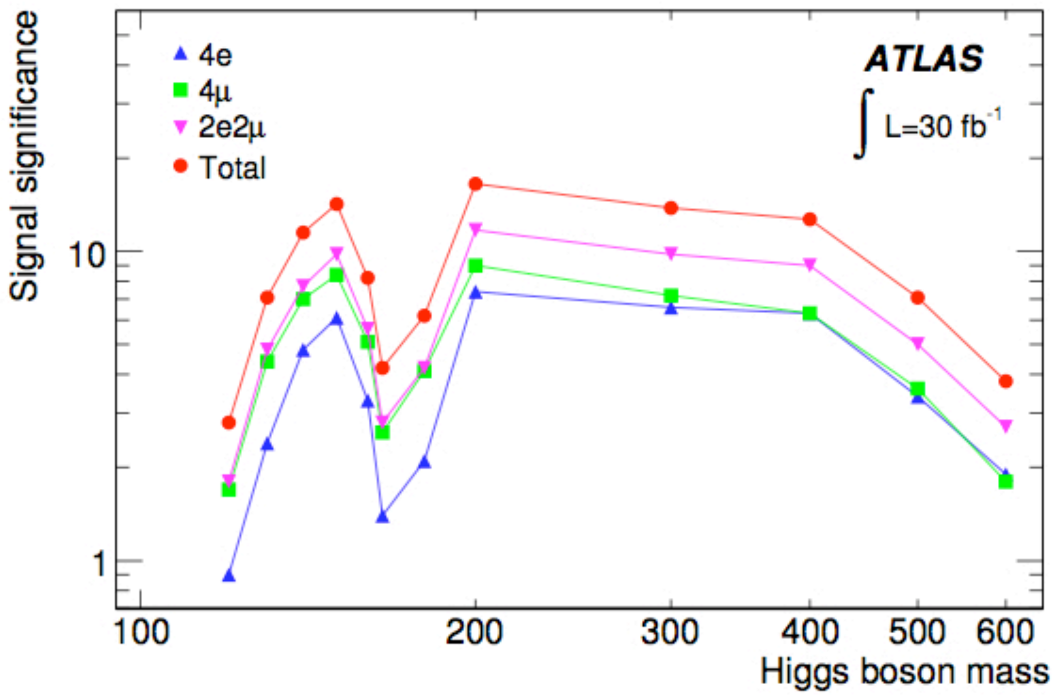
m_{4l} distribution, 30 fb^{-1}, m_H = 130 GeV/c^2



m_{4l} distribution, 30 fb^{-1}, m_H = 400 GeV/c^2



⇒ With 10 fb^{-1}, 5σ discovery for $m_H \in$ [~135, ~155] and [~190, ~400] GeV/c^2



⇒ From the MC side,

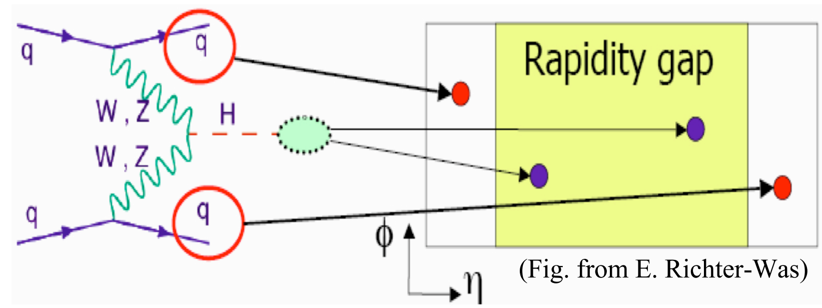
- need to include the gg → ZZ in the event generation

  (only a rescaling of the cross-section for the time being, should not alter too much the qq → ZZ shapes)
- For spin and CP measurements, need to look at refined MC

  (e.g. PROPHECY4f; a similar MC for background would also help for the normalisation of the ZZ background at low mass from the high mass region)
- Interferences between resonant and non resonant ZZ production @ high mass ?

VBF $H \rightarrow \tau\tau$: more intricate but more fun

~ 1600 events produced @ 10 fb^{-1}, for m_H = 120 GeV/c^2 in the lepton-hadron (lh) and di-lepton (ll) final states, but large and difficult backgrounds, small efficiencies



(Fig. from E. Richter-Was)

All detector capabilities needed :

- soft leptons, hadronic taus
- E_T^{mis} (mass reconstruction)
- b-tagging (veto against tt)
- forward jets and soft central jets (central jet veto CJV)

→ Large impact of the underlying event (UE) and pile-up events (E_T^{mis} resolution, CJV)

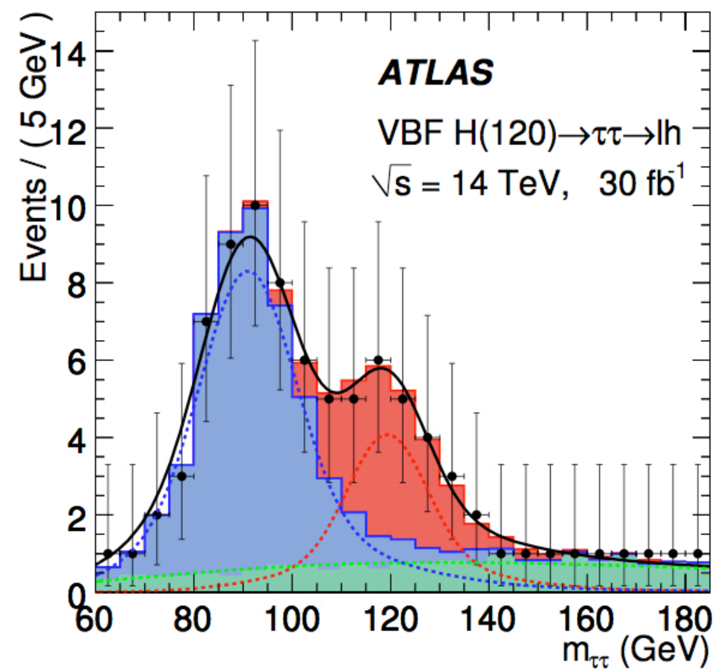
⇒Very difficult experimentally, but also very promising

Example of mass spectrum for m_H = 120 GeV/c^2 and 30 fb^{-1} in the lh final state

B ~ 2.5 fb / S = 0.72 fb

Within $m_H \pm$ 15 GeV/c^2 : S/B ~ 3

$\sigma(m_{\tau\tau}) \sim 10$ GeV/c^2

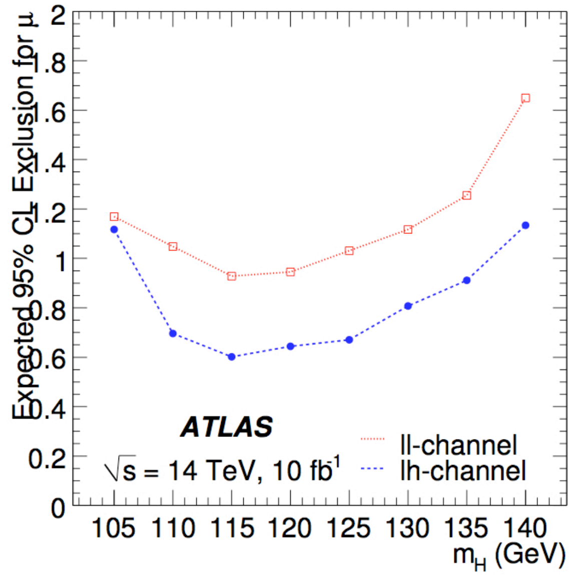


$\Rightarrow$ Combining the lh and ll channels,

5σ discovery with 30 fb^{-1} for m_H = 115 GeV/c^2, and above ~ 4σ for $m_H \in$ [110,135] GeV/c^2

The hadron-hadron channel is considered as well but needs further studies (QCD background)

With 10 fb^{-1}, can exclude the SM Higgs boson @ 95% C.L. with the lh channel only, over most of the interesting ττ range



Open issues:

- From the theory side, parton level theoretical uncertainties are under very good control
- The estimation of background normalisations and shapes from data control samples makes the analyses less MC-dependent

What could be improved (among others) :

- an implementation of the VBF signal in MC@NLO would be very valuable 
- deleterious influence of the UE and QCD radiation on CJV

  PS generators Pythia, Herwig+Jimmy or Sherpa show large discrepancies in this respect

  → could hinder couplings and spin/CP measurements 

  → more work needed to understand the differences between generators

  → hopefully, the UE will be one of the first measurements at LHC experiments

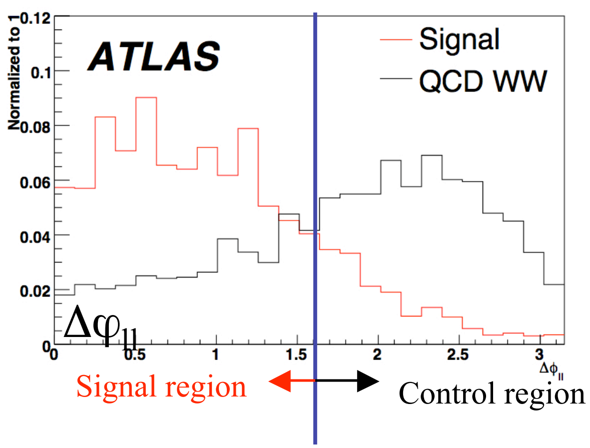
The most abundant channel : H → WW → eνμν

• needed for $m_H \sim 2\ m_W$, and complementary to other channels elsewhere
two dedicated analyses : H + 0 jet / 2 jets selecting mainly gluon fusion / VBF events

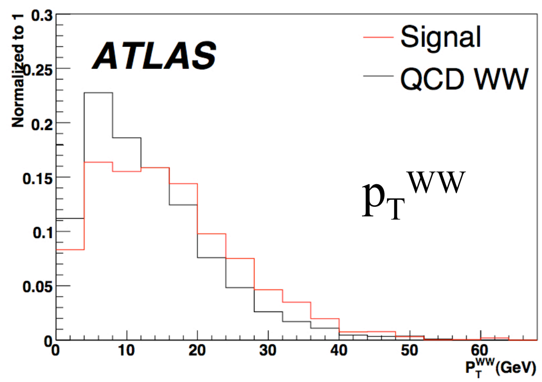
• many events produced (~ 6K at 10 fb^{-1} for m_H = 170 GeV/c^2) BUT no mass peak

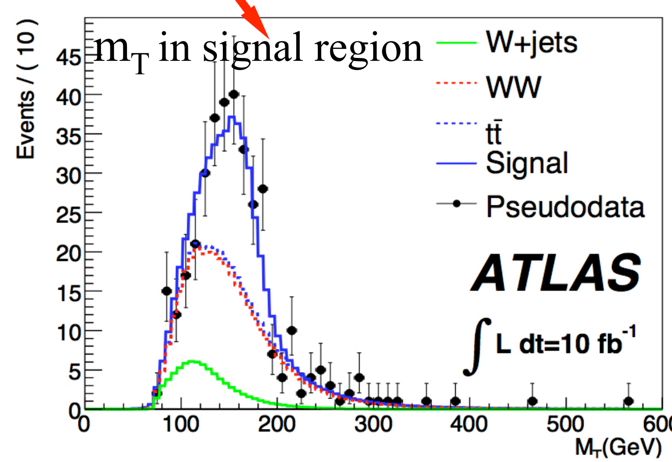
→ use *transverse* mass m_T (small sensitivity to mass measurement), p_T^{WW} and lepton angular correlation $\Delta\varphi_{ll}$
→ use a jet veto (mainly against tt) in the 0 jet analysis
→ a very precise determination of the backgrounds (WW, tt, single top, ..) is mandatory but no obvious control sample

Example of results for the 0 jet analysis :



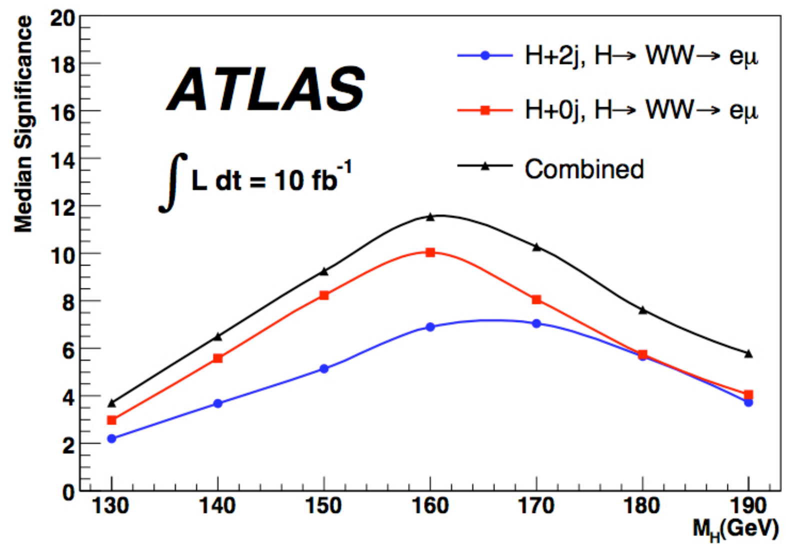
Fit signal and backgrounds in the (p_T^{WW}, m_T) plane in two bins of $\Delta\varphi_{ll}$





Combining the 0, 2 jets analyses,

the significance is > 5 @ 10 fb^{-1} for $m_H \in [135,190]$ GeV/c^2



Potential improvements :

✓ add same flavor leptons ? Needs a strategy for *in situ* Z → ll background extraction

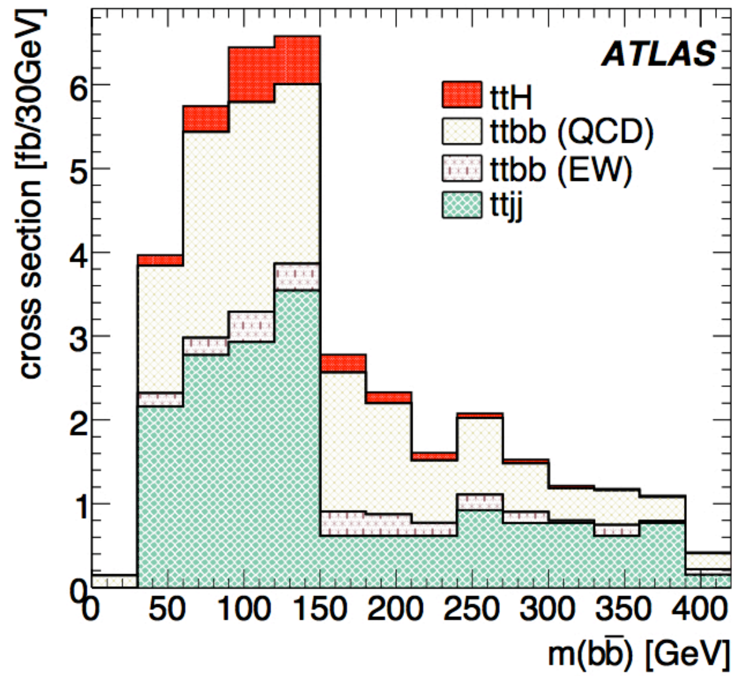
✓ gg →WW is large (~ 35% of the qq initiated process) and similar in shape to the signal : a NLO computation would be very valuable

✓ implementation of more processes in MC@NLO-like generator, especially tt + 1 jet, Z/W + 2 jets (also very important for VBF H → ττ analyses)

✓ what is the status of W+3 jets and tt + 2 jets at NLO ?

Why has the ttH, H$\rightarrow$ bb channel disappeared from sensitivity plots ?

Why has the ttH, H→ bb channel disappeared from sensitivity plots ?



Why has the ttH, H→ bb channel disappeared from sensitivity plots ?

(one of) The only possibility to observe H→ bb at LHC
- was contributing to ~ 50% of a low mass SM Higgs boson discovery in the old days (~ 2000), before the revival of VBF
- very intricate final state : ≥ 6 jets (4 b), lepton, E_T^{mis}
  - → large combinatorial background
  - → background prediction very uncertain : tt + 2jets, ttbb (and control samples not easy to select)

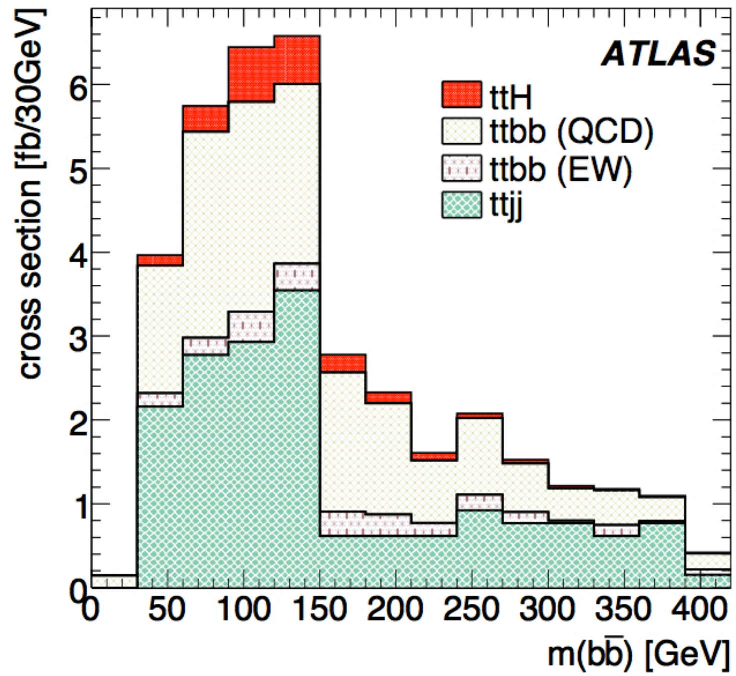
S/B ~ 0.1

Significance @ 30 fb^{-1}, for m_H = 120 GeV/c^2

without systematic uncertainties :

$\sigma \sim 2.0$

No sensitivity anymore with systematics included



- On the experimental side : need more sophisticated techniques (e.g. improved b-tagging, BDT, …)

- On the theory side :
  - can spin correlation in top decays help ?
  - best way to simulate the ttjj and ttbb backgrounds with no overlap ? (MC@NLO, ME ?)
  - what can we trust from current Monte Carlo generators : m_{bb} shape, fraction of ttbb in ttjj, … ?

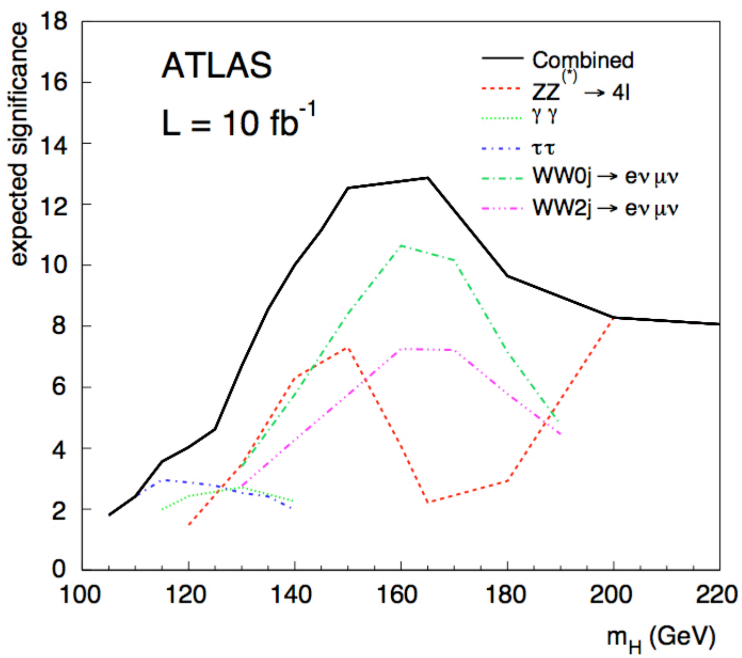
⇒ requires the most from experiment and theory, still a long term task…

Combined sensitivity

With 10 fb^{-1}

(*normally* considered as one LHC year at low luminosity),

5σ discovery for $m_H \in [127, 440]$ GeV/c^2



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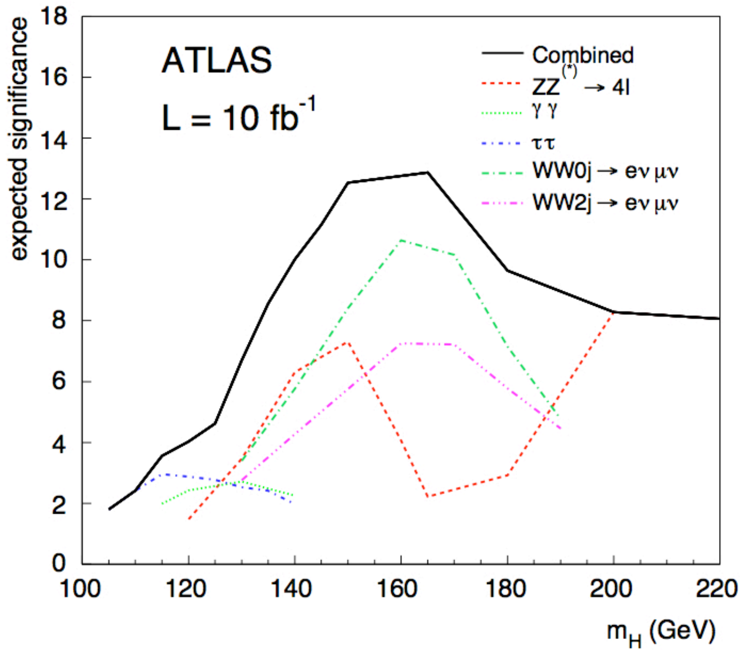
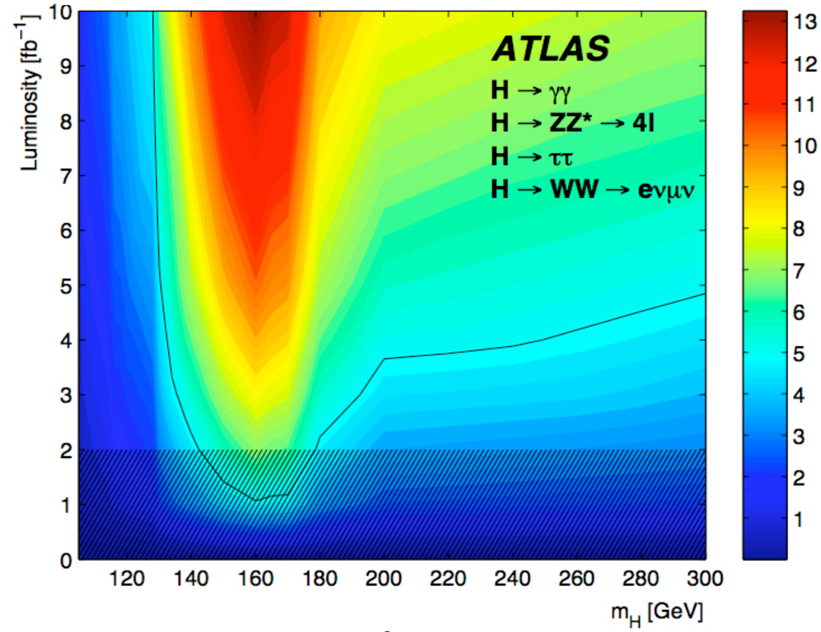


Significance vs (m_H, integrated luminosity)



Discovery @ 115 GeV/c^2 is still not around the corner…

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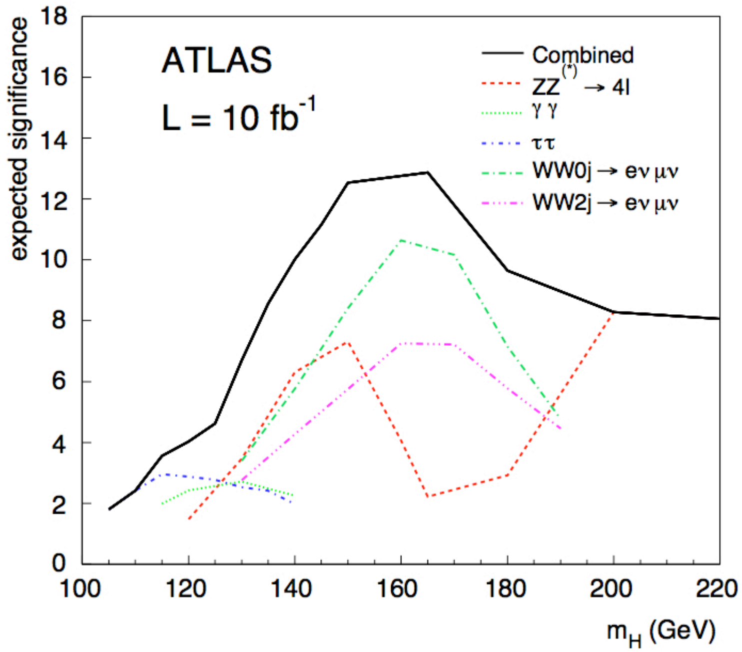

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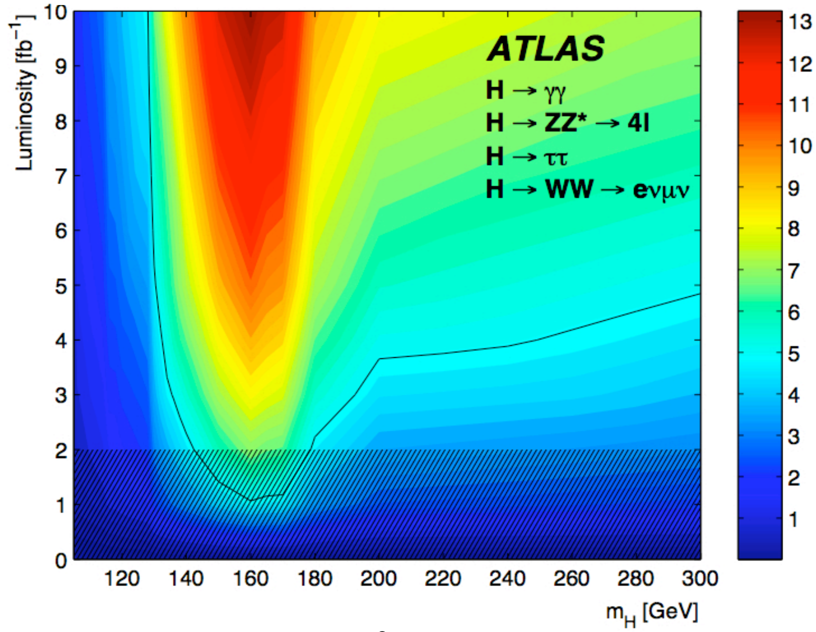
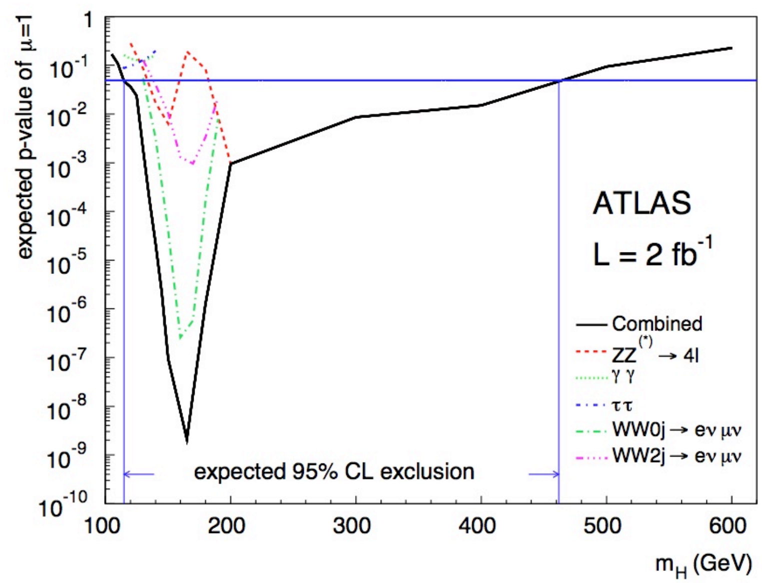


Discovery @ 115 GeV/c^2 is still not around the corner…

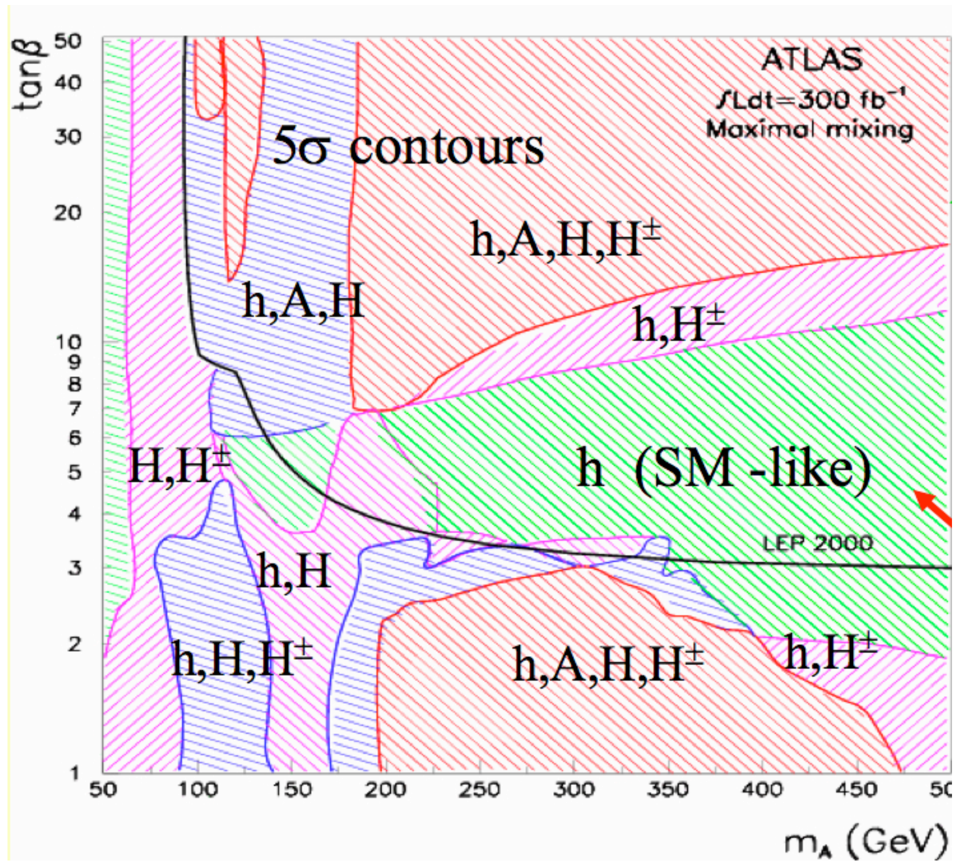
… 95 % C.L. exclusion not so far ahead : with 2 fb^{-1}, m_H is restricted to be less than 115 GeV/c^2 or above 460 GeV/c^2



Some Exotica : Higgs bosons in the MSSM

Higgs sector intricate, but no loose theorem :
LHC should be able to observe ≥ 1Higgs boson
whatever the chosen point by Nature in the CP-conserving MSSM

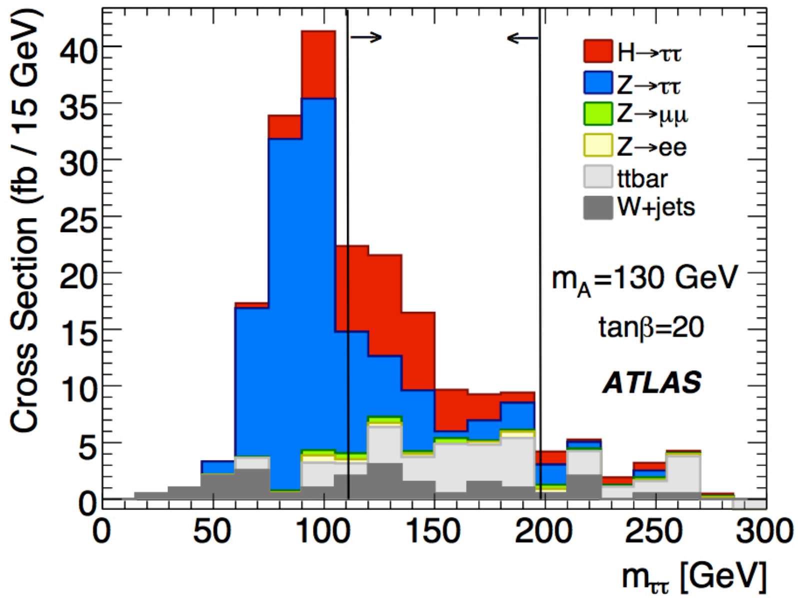
(very old) Example of
$(m_A, \tan\beta)$ plane coverage :
(300 fb^{-1}, maximal mixing scenario)



Holes might still exist in CP-violating MSSM and NMSSM
⇒ analyses on their way, no finalized results yet

Associated production (b)bϕ, $\phi \rightarrow \tau\tau \rightarrow$ 2l 4ν

Requires all detector capabilities (especially E_T^{mis} for mass reconstruction and b-tagging)
Drell-Yan $Z \rightarrow \tau\tau$ difficult at low mass but robust strategy to determine it from data
At high mass, tt dominates



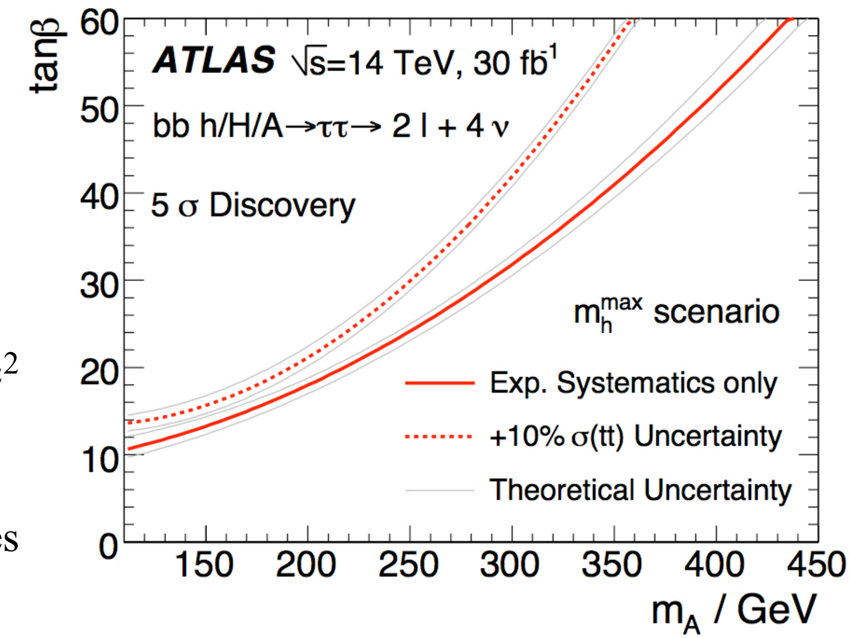
At m_A = 130 GeV/c^2, tanβ = 20

S = 43.3 fb
B = 32.8 (tt) + 114.9 (Z) + 21 (W) fb

(before mass window cut)

5σ discovery contour in the (m_A,tanβ) plane :

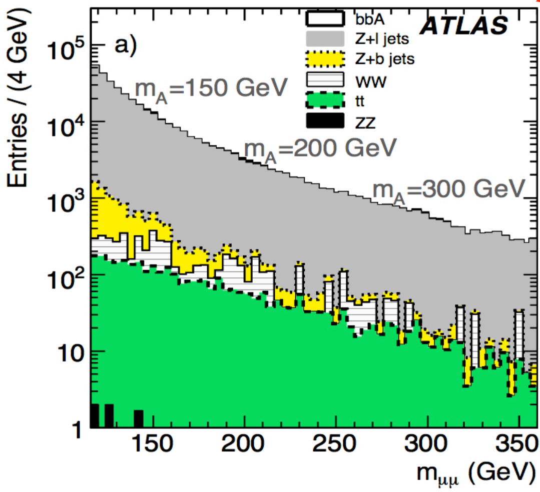
with 30 fb^{-1}, tanβ = 50 :
can observe A up to m_A = 350 GeV/c^2



Sensitivity expected to increase after inclusion of final states with tau hadronic decays

The very rare di-muon decay : $\phi \rightarrow \mu\mu$

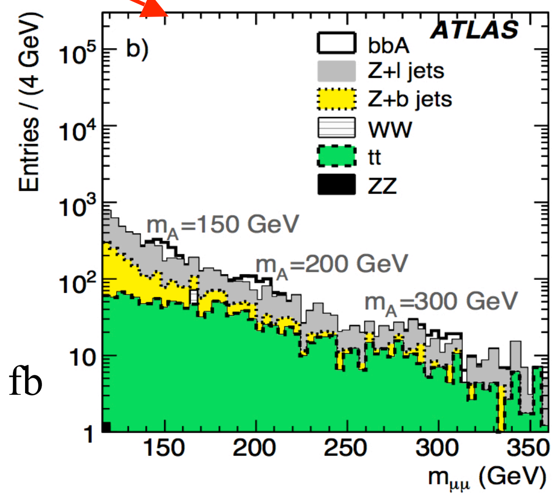
- Very small branching (0.2-0.3 ‰ for $\tan\beta$ = 20 and 100 < m_ϕ < 450 GeV/c²) but excellent mass resolution
- Huge background from Z and tt but large control samples available in the ee and eμ final states
- Two analyses dedicated to the direct production (0 jet) and associated (≥ 1 b-tagged jet) production

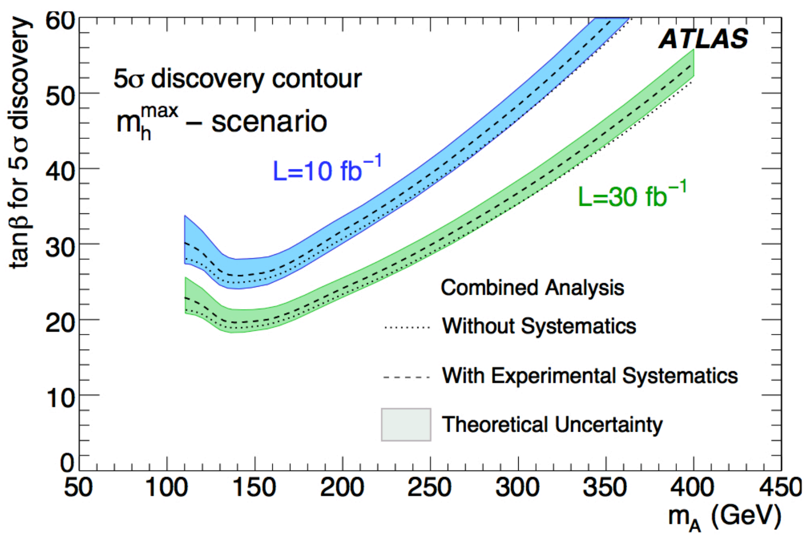


For $\tan\beta$ = 30, m_A = 200 GeV/c²

0 jet : S = 12.8 (bbA) + 2.0 (direct) fb
B = 625 fb (96% Z)

≥ 1 b jet : S = 2.4 fb
B = 6.7 (Z+l) + 5.8 (tt) + 2 (Z+b) fb





(b)(b)ϕ cross-section now quite well understood,
but MC generation and normalisation still not trivial

Two methods to estimate uncertainties :
- Pythia (bbϕ)
- Sherpa (consistent combination of
  bb → ϕ, bg → ϕb and gg → ϕbb)

Charged Higgs bosons decaying to fermions

- $m_{H^+} < m_t$: main production from top decays, decay : $H \rightarrow \tau\nu$, 3 different final states considered
- $m_{H^+} > m_t$: production through $gg/gb \rightarrow t(b)H^-$, decay $H \rightarrow \tau\nu/tb$: 2 final states considered

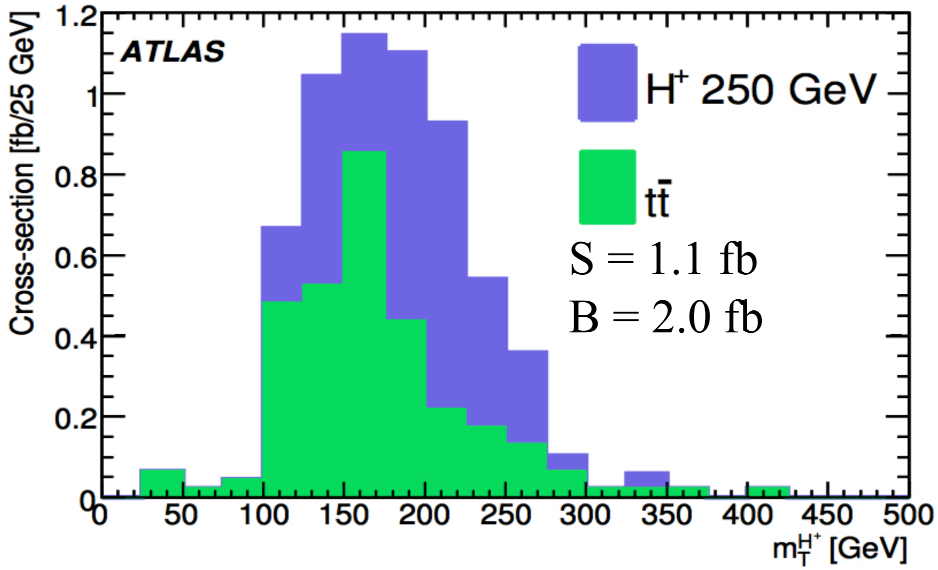
 $\Rightarrow$ Complex final states relying on all detector components

 Main background : tt

Example at high mass : $bbq\tau\nu$, $\tau \rightarrow \nu$ hadrons transverse mass distribution

($m_{H^+} = 250$ GeV/c^2, $\tan\beta = 35$)

The $H^+ \rightarrow tb$ analysis is much more difficult, similar to the ttH, $H \rightarrow bb$ SM analysis



From the MC side :

- would benefit from consistent implementation (without overlap) of the two processes

 $gg \rightarrow tbH$ and $gb \rightarrow tH$

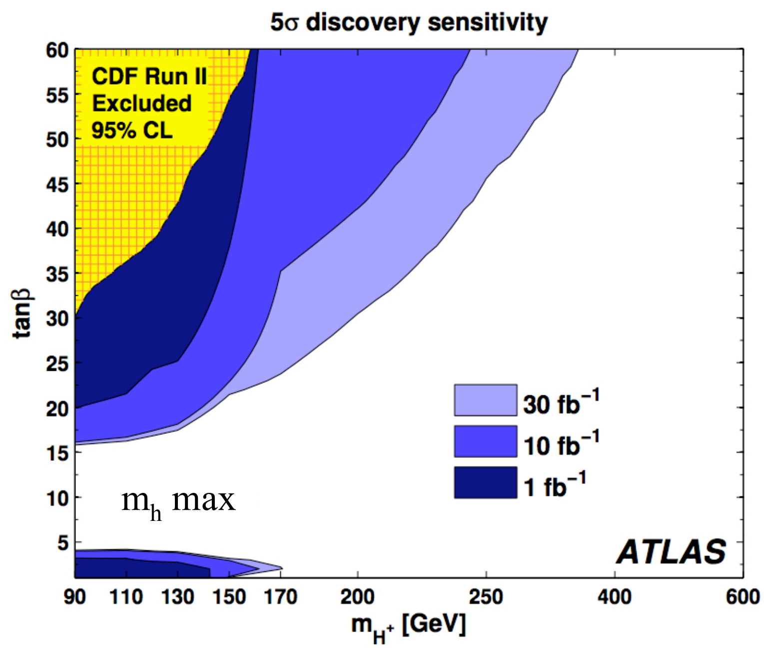
 (done in Atlas, with Matchig (J. Atwall) which must use the *old Pythia Parton Shower model* whereas Atlas adopted the new one)

- in general, flexible generators treating consistently such overlaps are very appreciated, but not many of them available on the market

At $\tan\beta = 50$, masses up to ~ 300 GeV/c^2 can be reached with 30 fb^{-1}

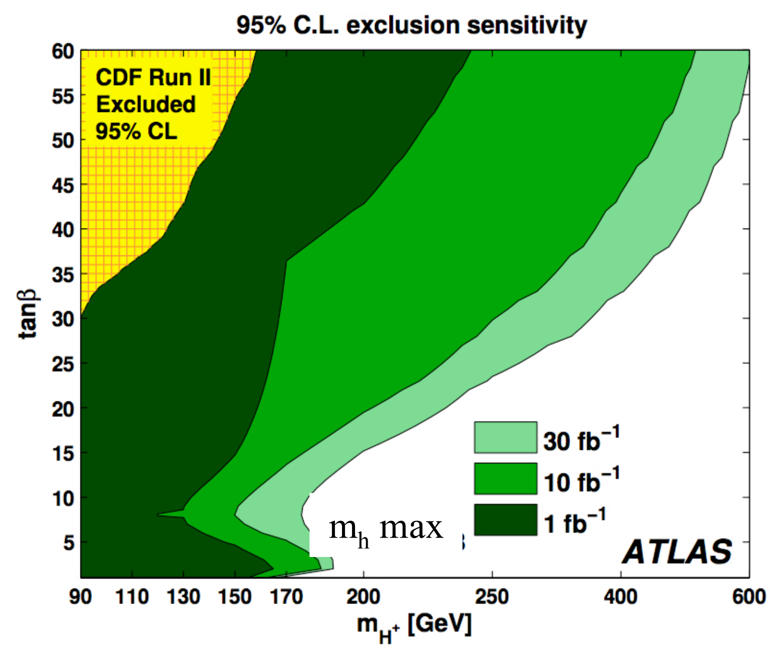
Intermediate $\tan\beta$ regime difficult, but could be greatly improved

(Absence of sensitivity is quite misleading since the main problem here is the lack of MC statistics)



Exclusion :

e.g. $m_{H+} < m_t$ is covered with 10 fb^{-1} except in the intermediate $\tan\beta$ regime



Summary

- In the past three years, Atlas has re-assessed its sensitivity to Higgs bosons
  many channels were studied, with greatly improved realism and robustness

good sensitivity already with a few fb^{-1}

in both the SM and MSSM

All channels studied form also a good basis for analyses within more exotic models

- Many studies still on their way :
  add other channels to improve coverage
  try to generalize the use of *state-of-the-art* Monte Carlo (NNLO, …)

- Analyses are going on to estimate sensitivities also at $\sqrt{s}$ = 10 TeV
  with new issues (e.g. pdf reweighting and the underlying event)

The next few years should be thrilling for experiments and theory…