Searches for Higgs and physics beyond the Standard Model in ATLAS

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on behalf of the ATLAS collaboration

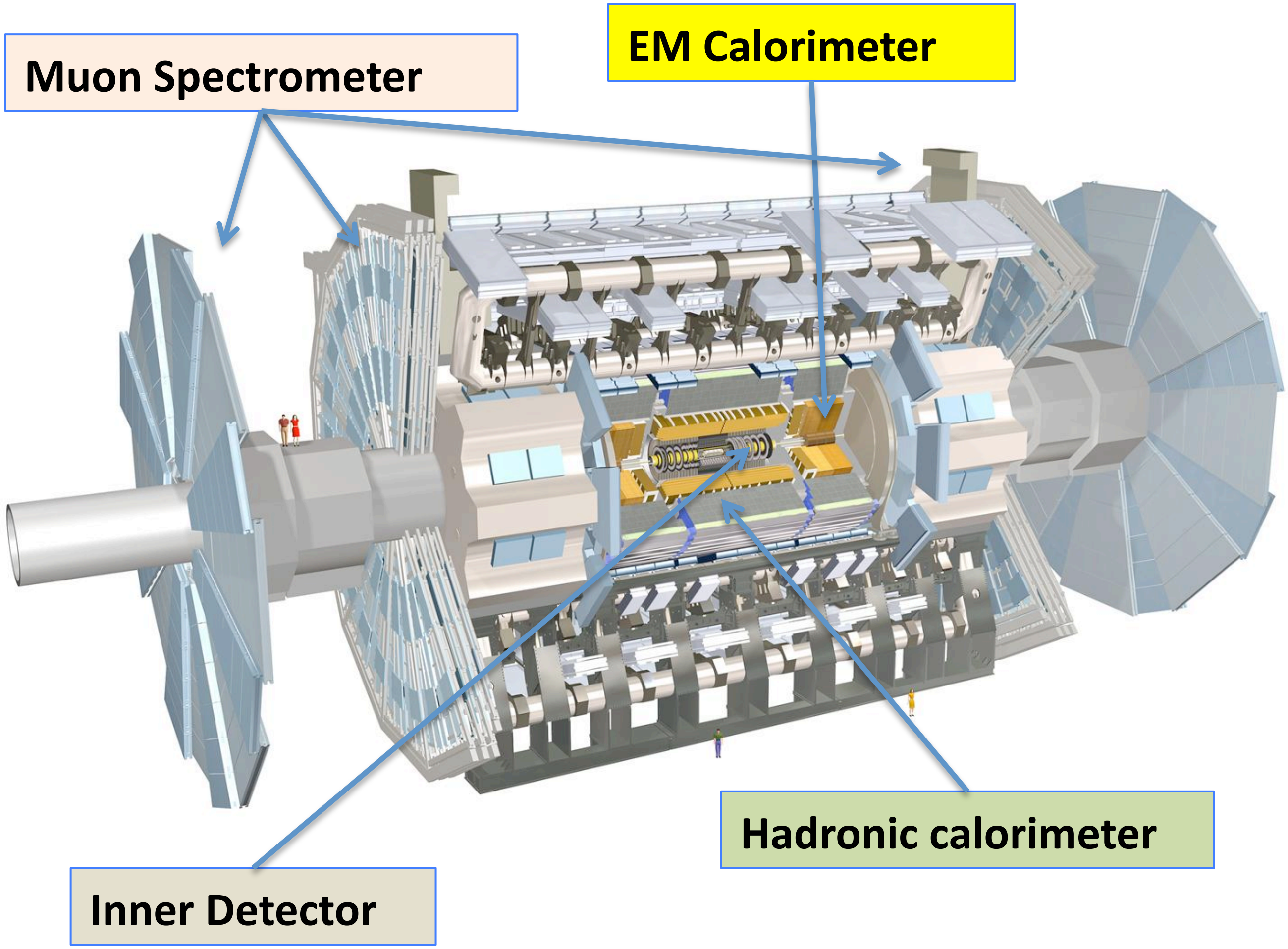
Outline:

(1) The ATLAS experiment at LHC
(2) Searches for a Standard Model Higgs Boson
  - → Analysis strategy
  - → A selection of channels
  - → Combined results
(3) Searches for physics beyond the Standard Model
  - → Measurement of Standard Model processes
  - → Searches for new particles
  - → Supersymmetry
(4) Conclusions

The ATLAS Experiment at LHC - I

Multi-purpose, high resolution and highly hermetic detector

- Magnets ➔ 1 Central Solenoid + 3 air-core toroids
- Tracking ➔ Silicon+Transition radiation tracker
- EM calo ➔ Sampling LAr calo
- HAD calo ➔ Plastic scintillator (barrel) + LAr technology (endcap)
- Muon ➔ Trigger chambers (RPC and TGC) + Precision chambers (MDT and CSC)



Reconstructed Objects:

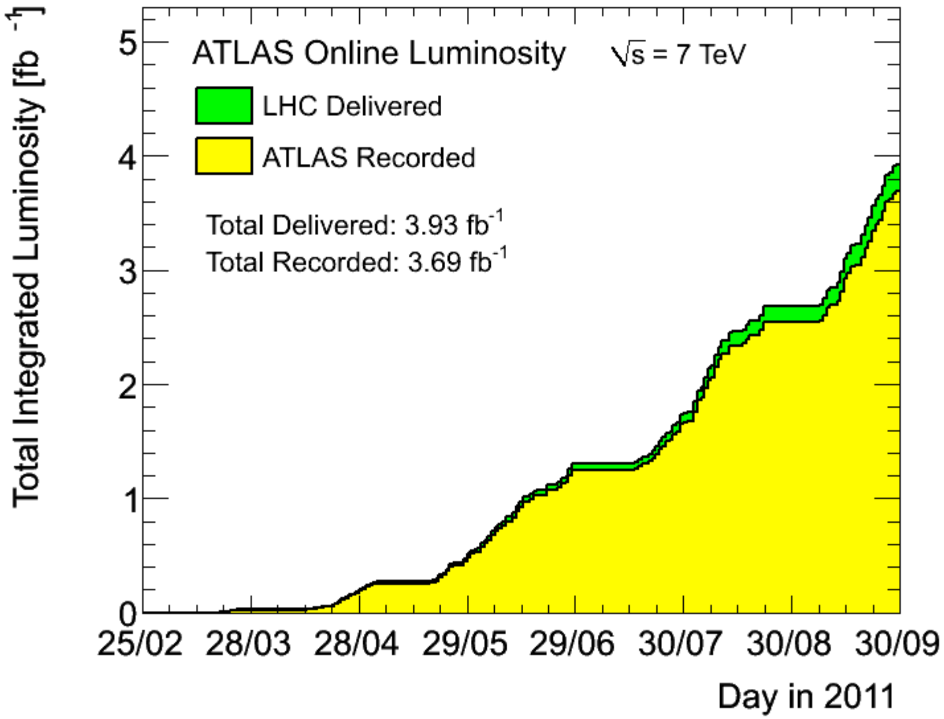
- **leptons**
  - *electrons*
  - *muons*
  - *taus*
- **photons**
- **jets**
- **missing energy**
- **b-jets**

Kinematic variables:

- $p_T = |p| \sin\theta$
- $\eta = -\log\tan(\theta/2)$

The ATLAS Experiment at LHC - II

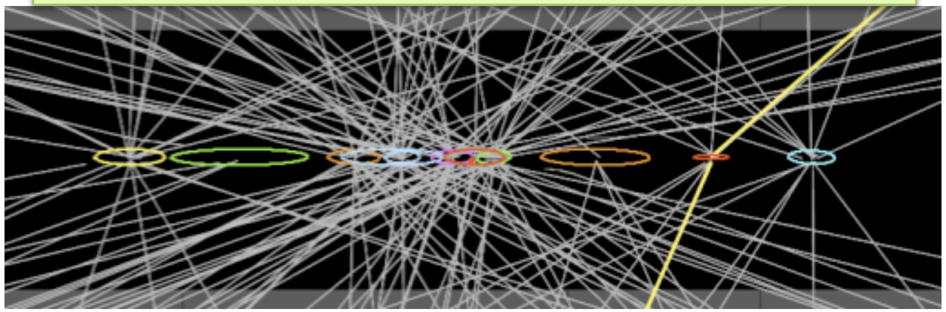
→ LHC reached a peak luminosity of **~ 3.3 ×10^{33} cm^{-2} s^{-1}** with 50 ns bunch trains
→ Data taking started in March with √s = 7 TeV and going on up to the end of 2012;
→ 95% of LHC delivered luminosity (3.9 fb^{-1} up to date) is recorder by ATLAS;
→All subsystems are highly efficient (between 90% and 100%), performance are continuosly monitored



Results presented here: up to August 2011
L_{int} < 2.2 fb^{-1}

The Pile-Up effect is a “challenge” for extracting physics !
<#evts/bunch crossing> ~ 6
and depending on LHC conditions.
Much progress understanding impact on performance, with data & simulation

Example of collision with 11 events: in yellow Z→$\mu^+\mu^-$



Ongoing runs (Sept.2011)with high luminosity:
<#evts/bunch crossing> **~ 15**

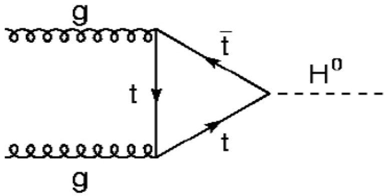
Searches for a Standard Model Higgs Boson

First item of the ATLAS physics program in 2011-2012 run:

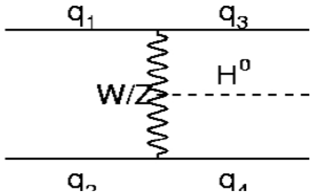
Discovery or exclusion of the Standard Model Higgs Boson in the full allowed mass range

Higgs production in pp collisions at √s = 7 TeV

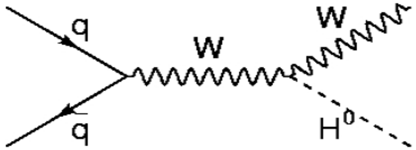
Gluon Fusion
pp→H

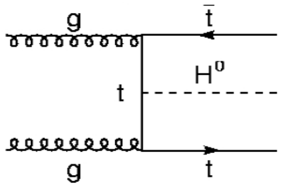


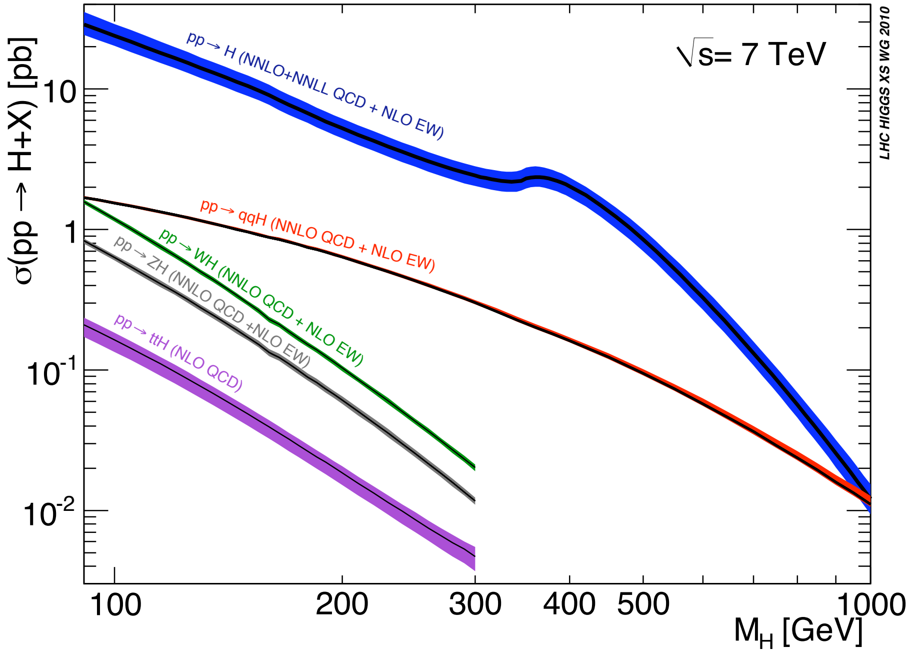
Vector Boson Fusion:
pp→qqH



Associated Production:
pp→ WH, ZH, ttH



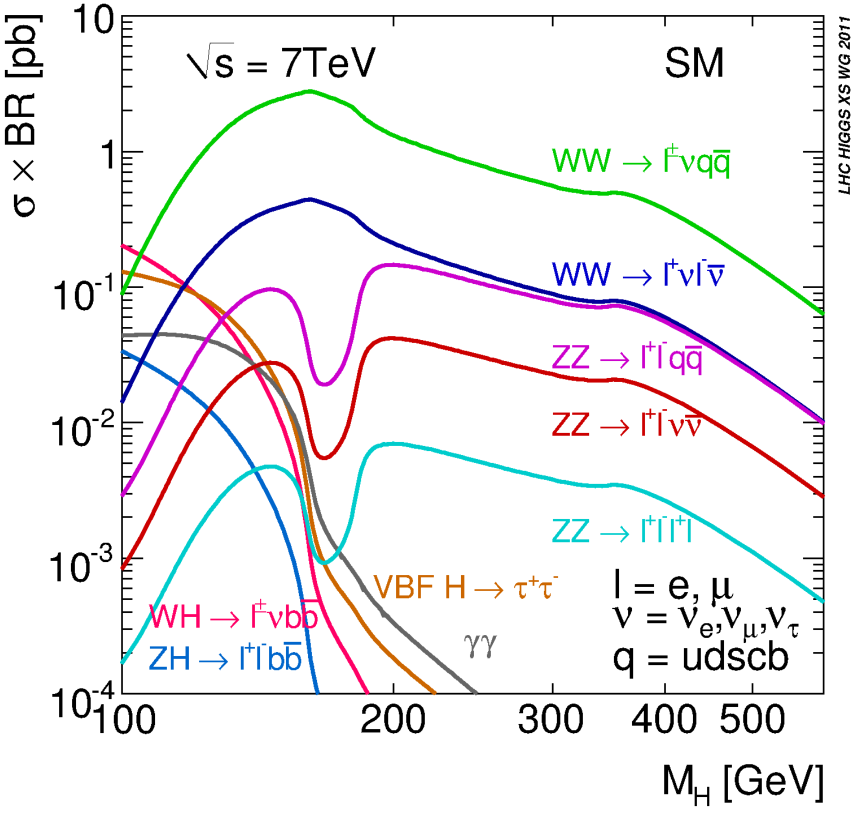




gluon-gluon fusion is the most abundant production channel, but **VBF** and **associate production** can be experimentally more favourable in specific cases.

Higgs decay channels: BRs depend on Higgs mass

Depending on Higgs mass different channels become relevant
A "multi – channel" combined analysis is required
In any case the expected cross-sections are below the *"few pb"* level
➔ integrated luminosity and background rejections are the two important issues



channel	Mass range (GeV)	Lumi (fb^{-1})	
$H \to \gamma\gamma$	110 ÷ 150	1.08	(*)
Z(W)H→Z(W)bb	110 ÷ 150	1.04	A.P.
$H \to \tau\tau$	110 ÷ 150	1.06	V.B.F.
$H \to WW^{(*)} \to l\nu l\nu$	110 ÷ 300	1.70	(*)
$H \to ZZ^{(*)} \to llll$	110 ÷ 600	2.20	(*)
H→ZZ→lljj	200 ÷ 600	1.04	
$H \to ZZ \to ll\nu\nu$	200 ÷ 600	1.04	

Additional channels are possible and will be added with larger luminosities

Higgs boson searches: analysis strategy

"*Cut & Count*" based analyses

- Trigger (changing along data taking)

- Event Selection
  Object definition (lepton, jets, missing ET,…);
  Collision event selection (common to all channels);
  Specific event selection and acceptance definition

- Background evaluation
  Mostly, *data-driven methods*:
  (1) count events in background enhanced control regions
  (2) extrapolation to signal region based on MC or data

- For each value of M_H *likelihood fit* of data in one or more variables

- *Confidence interval* based on CL_s method on $\mu = \frac{\sigma_{meas}}{\sigma_{SM}}$

Then: channel "combination" ➔ Confidence intervals for μ vs. M_H

H → γγ: the low mass "golden channel"

Low cross-section (< 0.1 pb) BUT very clean signature with limited background.

Trigger:

2 photons with E_T>20 GeV (≈99% efficient)

Selection:

Object "photon": measure energy and direction

2 isolated "photons" (E_T^1>40 GeV, E_T^2>25 GeV)

Di-"photon" Invariant Mass range 100 ÷160 GeV

Backgrounds:

Di-photon (irreducible) (72%)

photon + jet (rej. needed ≈10^4)

Di-jet (rej. needed ≈10^7)

Discriminant variable

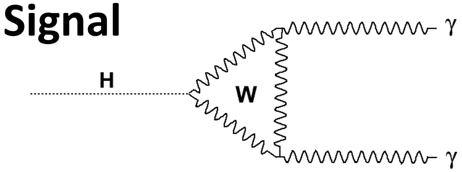
$m_{\gamma\gamma}$, resolution ≈ 1.7 GeV

Fit

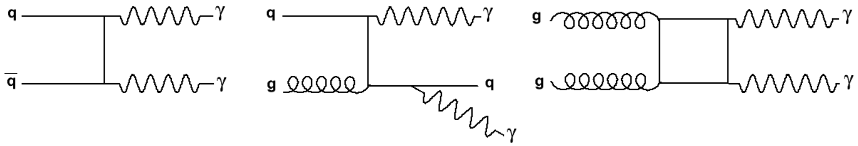
exponential (background)

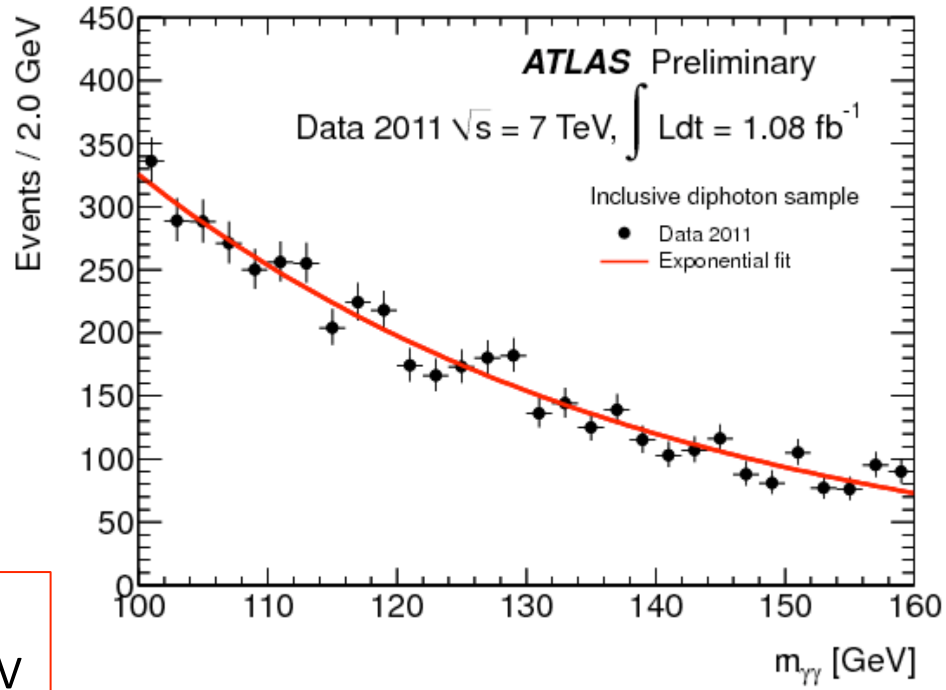
CrystalBall resol. function(signal)

Signal



Irreducible background: pp→γγ + X





No signal found

→ Set upper limits on μ for 110<M_H<150 GeV

$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$: the best channel at intermediate masses - I

Highest sensitivity for $130<M_H<200$ GeV and good sensitivity for $110<M_H<300$ GeV
Signature: two leptons, Missing energy and limited "jet activity"
No possibility to reconstruct Higgs mass.

Trigger:

Single lepton: p_T(electron)>20÷22 GeV OR p_T(muon)>18 GeV

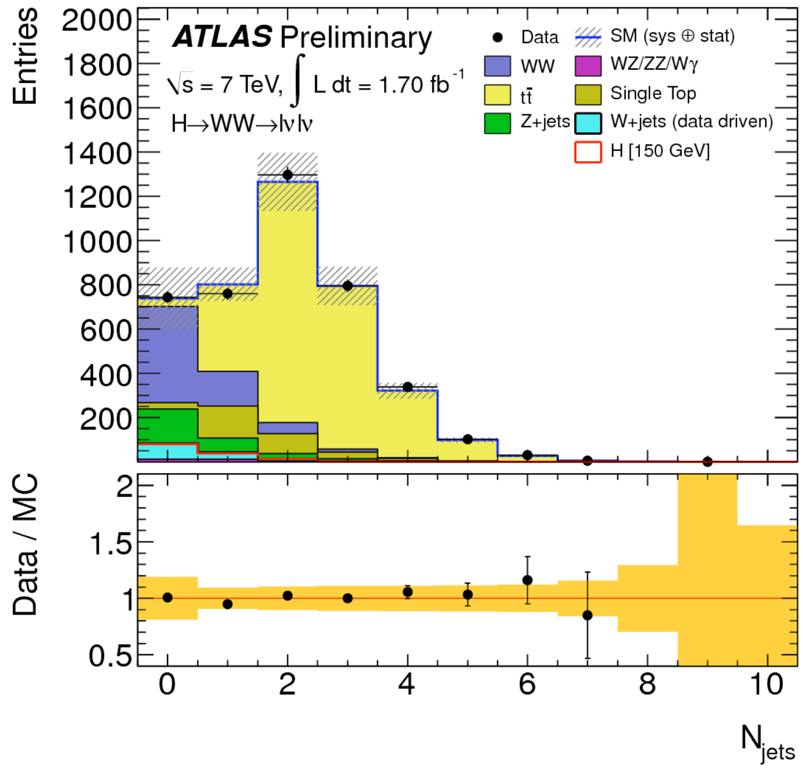
Selection:

2 opposite sign isolted high-p_T(*) leptons
Large E_T^{miss} > 40 (25) GeV
Topological cuts on two-lepton system (m^{ll}, p_T^{ll}, $\Delta\phi^{ll}$)
Transverse mass m_T (**) cut (M_H); $0.75\times M_H<m_T<M_H$

Backgrounds:

WW production (irreducible)
top-antitop
single top
Z+jets

Count events in signal region, estimate backgrounds



(*) cuts depend on leptons being ee, μμ or eμ

(**) $$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$

H → WW$^{(*)}$→lνlν: the best channel at intermediate masses - II

After selection the events are divided in two categories:

0-jet

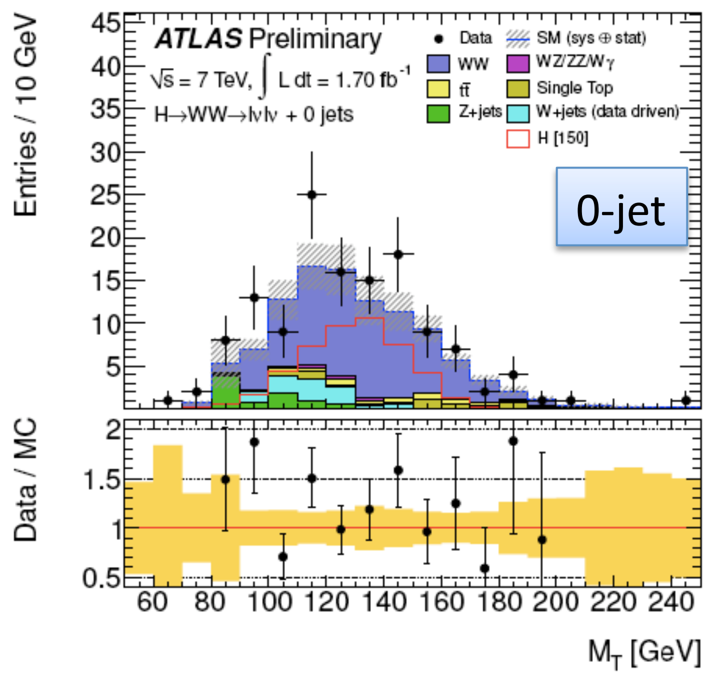
1-jet (p_T(jet)> 25 GeV, |η|(jet)<4.5, b-tag veto)

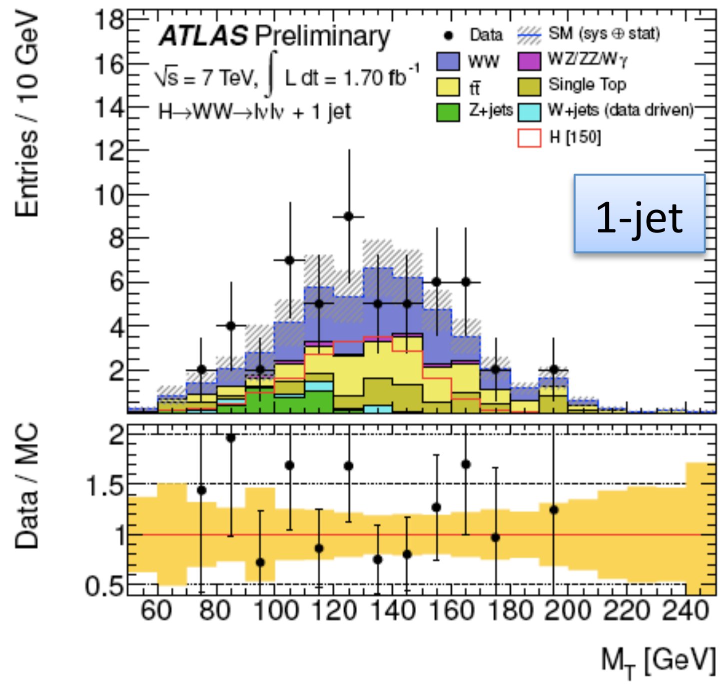
to exploit the different background composition in the two bins.

	WW	ttbar	Total back.	Data	Higgs M_H=150
0-jet	**43±6**	**2.2±1.4**	**53±9**	**70**	34±7
1-jet	**10±2**	**6.9±1.9**	**23±4**	**23**	12±3

No signal found

➔Set upper limits on μ for 110<M_H<300 GeV





$H \rightarrow ZZ^{(*)} \rightarrow llll$: the "golden" channel

Very clean signature (4μ, 4e ,$2\mu 2e$) with good sensitivity in the full mass range

Trigger:

Single lepton: p_T(electron)>20÷22 GeV OR p_T(muon)>18 GeV

Selection:

Four isolated leptons: 2 with p_T>20 GeV, 2 with p_T>7 GeV

Two pairs of same flavour opposite sign leptons

M_{12} within $M_Z \pm 15$ GeV; M_{34}> 15 ÷ 60 GeV(depending on M_H)

Backgrounds:

ZZ (irreducible but dominant)

Z+jets (for electron channel)

Zbb (for muon channel)

top-antitop

Discriminant variable:

4l invariant mass m_{4l}.

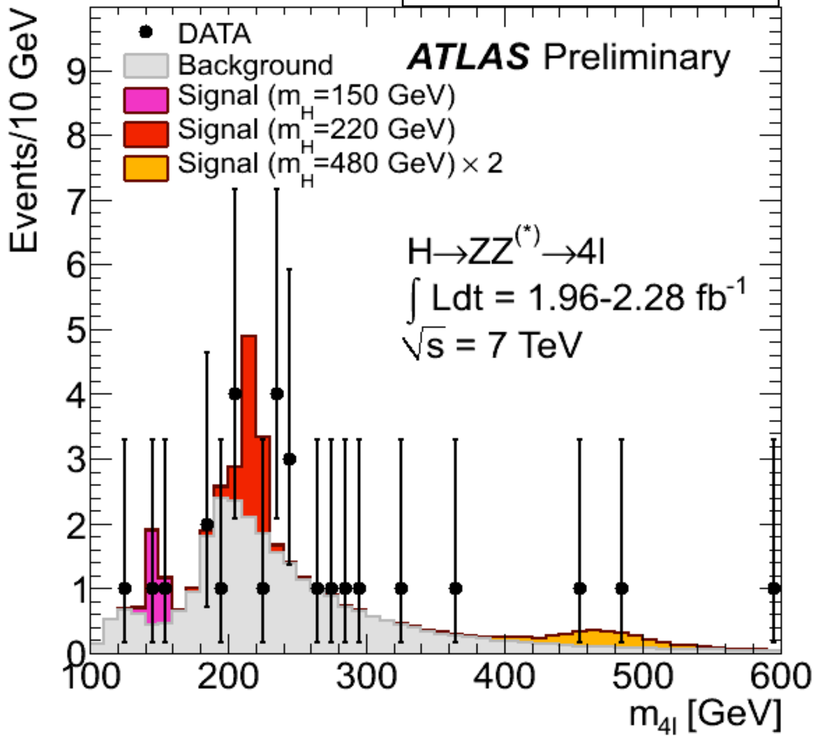
$\sigma(m_{4l})$ = 4.5 ÷ 6.5 GeV (low M_H) 15 GeV (high M_H)

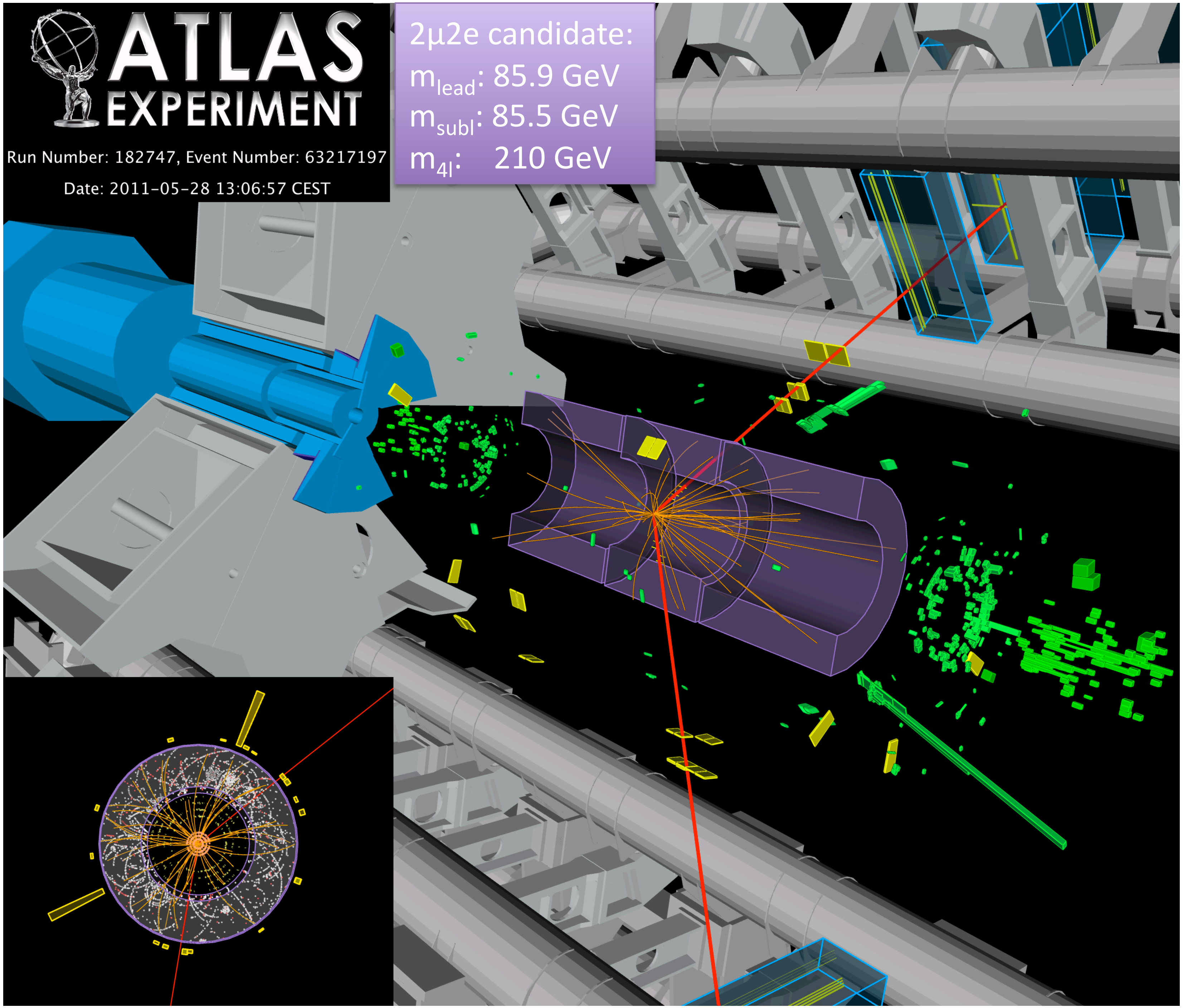
	4μ	$2e2\mu$	4e	total
Data	12	9	6	27
Background	10.4	12.9	5.0	28 ± 4

No signal found

➔Set upper limits on μ for 110<M_H<600 GeV

error bars = 68.3%
central confidence intervals




ATLAS EXPERIMENT
Run Number: 182747, Event Number: 63217197
Date: 2011-05-28 13:06:57 CEST
2μ2e candidate:
m_{lead}: 85.9 GeV
m_{subl}: 85.5 GeV
m_{4l}: 210 GeV

Higgs boson searches: summary of single limits

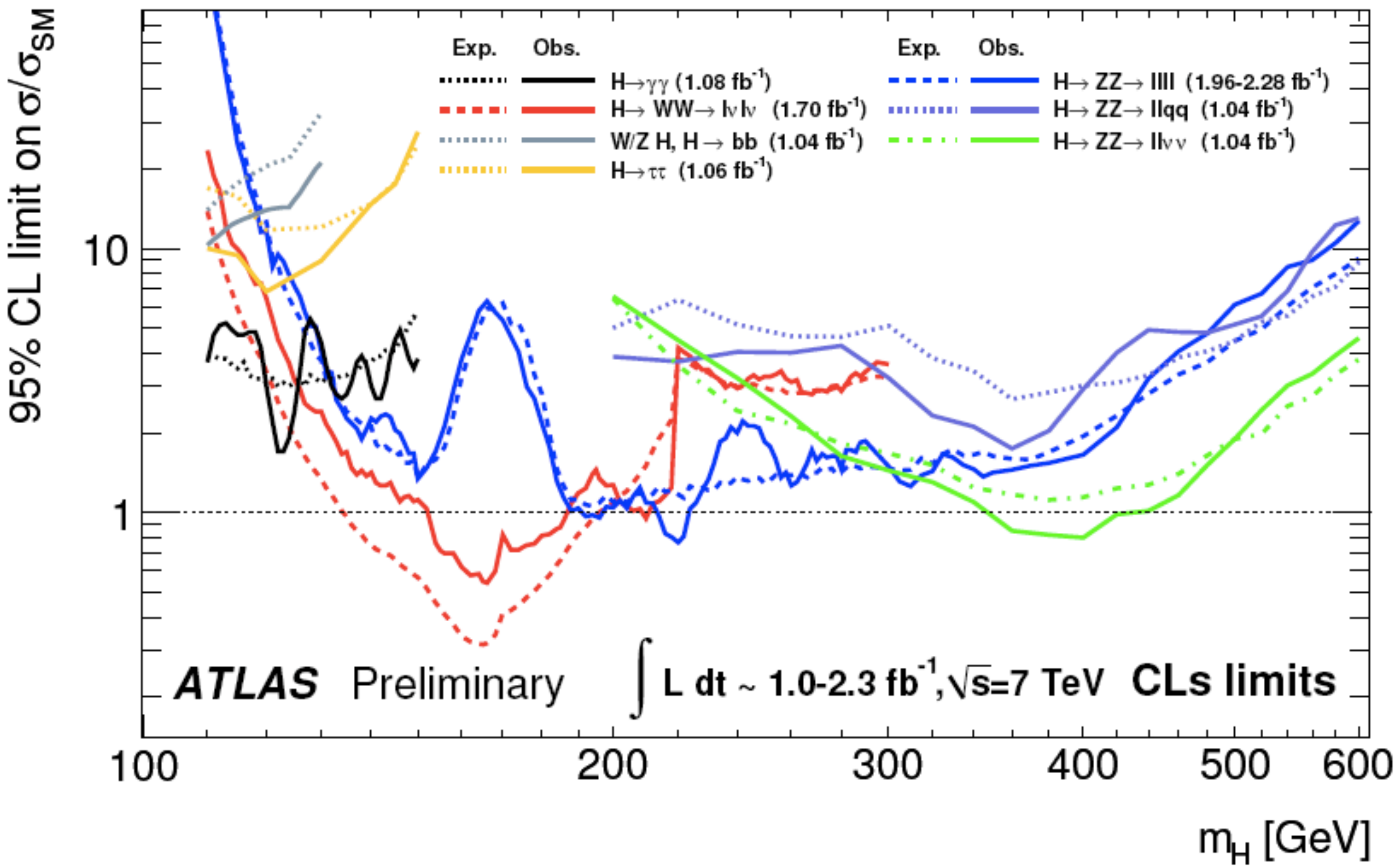
95% C.L. limit (frequentist CL_s method) on μ for all channels:

→ solid colored lines: observed limit

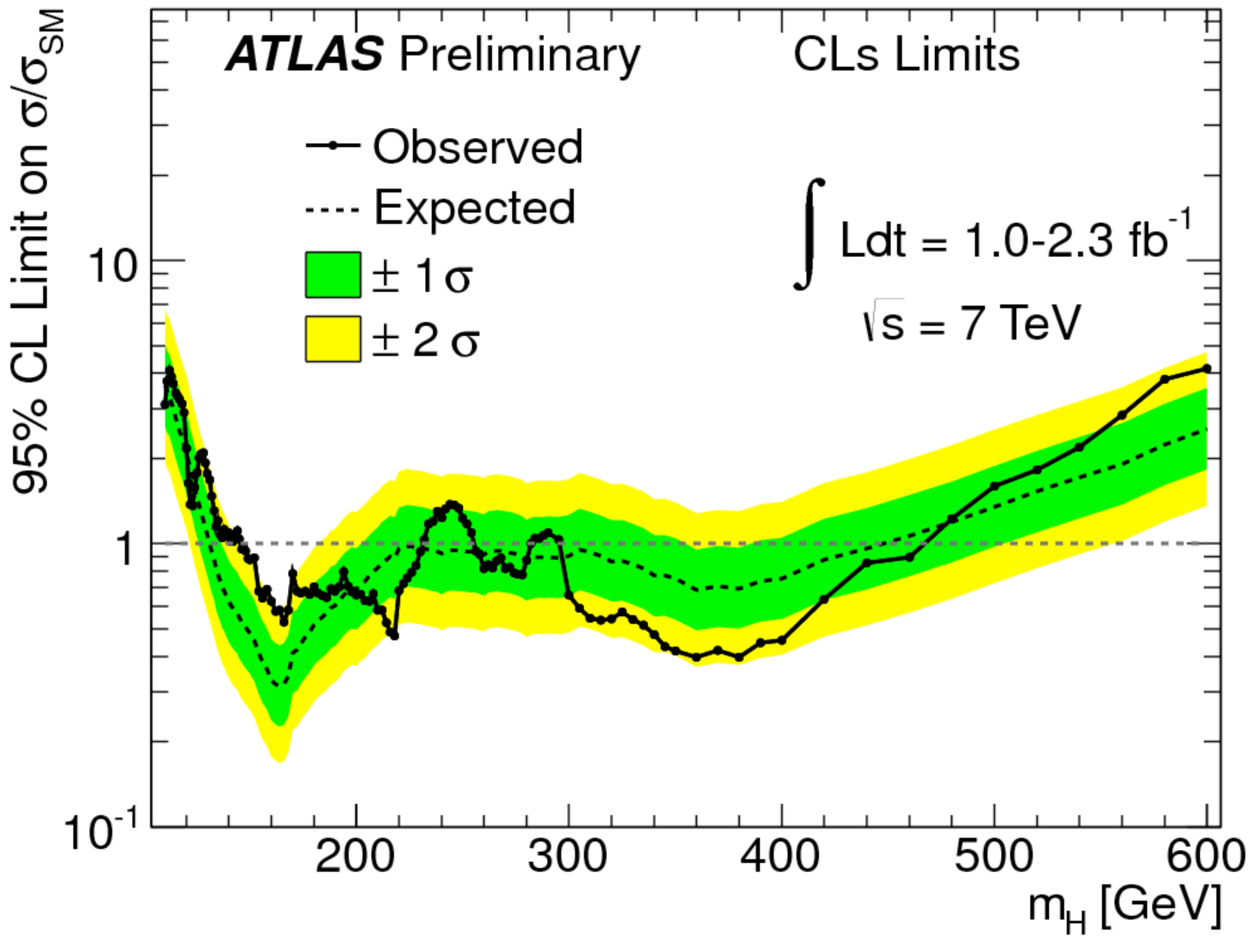
→ dashed/dotted colored lines: expected limit based on MC pseudo-experiments

Observed > Expected ➔ data “over-fluctuate”

Observed < Expected ➔ data “under-fluctuate”



Higgs boson searches: combined limits



ATLAS excludes @ 95% C.L. a SM Higgs Boson with masses in three ranges:

$146<M_H<232$ GeV, $256<M_H<282$ GeV, $296<M_H<466$ (expected exclusion $131<M_H<447$ GeV)

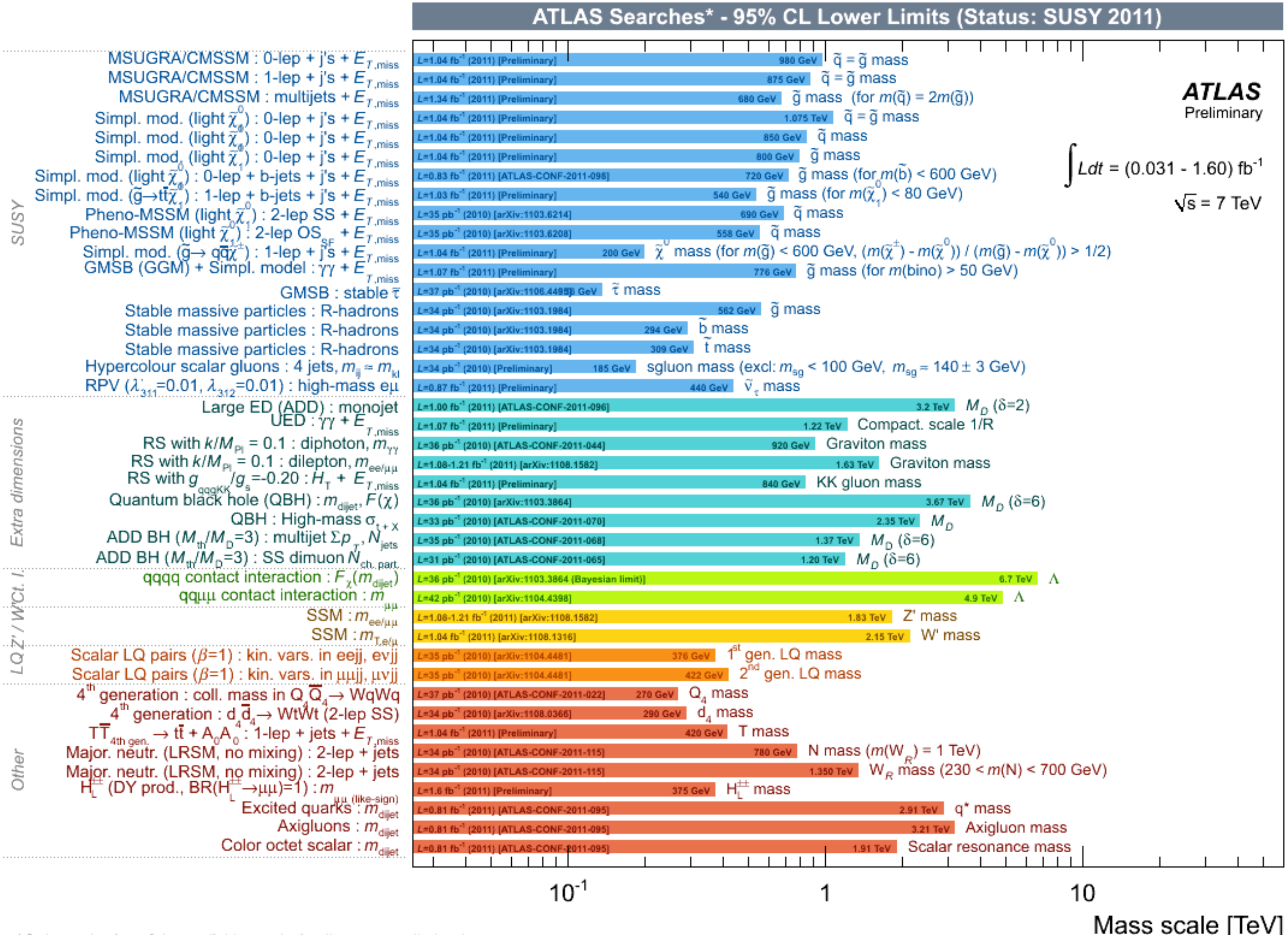
Poor consistency with "background only hypothesys" in the region $130<M_H<170$ GeV

Higgs boson searches: conclusions

- ATLAS has performed a Higgs boson search on pp data corresponding to an integrated luminosity between 1 and more than 2 fb^{-1} using several channels
- No significant excess is found in the mass range 110-600 GeV.
- Exclusion limits at 95% C.L. are set in the mass regions:
  - $146 < m_H < 232$ GeV
  - $256 < m_H < 282$ GeV
  - $296 < m_H < 466$ GeV
- These are exclusions of SM HIGGS BOSON, so that searches in the excluded regions are going on (a Higgs with different properties could emerge)
- By end of 2012 with O(10 fb^{-1}) a conclusive answer on the Standard Model Higgs should be obtained.

Searches for physics beyond the Standard Model

A huge amount of searches in a wide range of physics



It is not possible to describe all searches. Move in three steps:

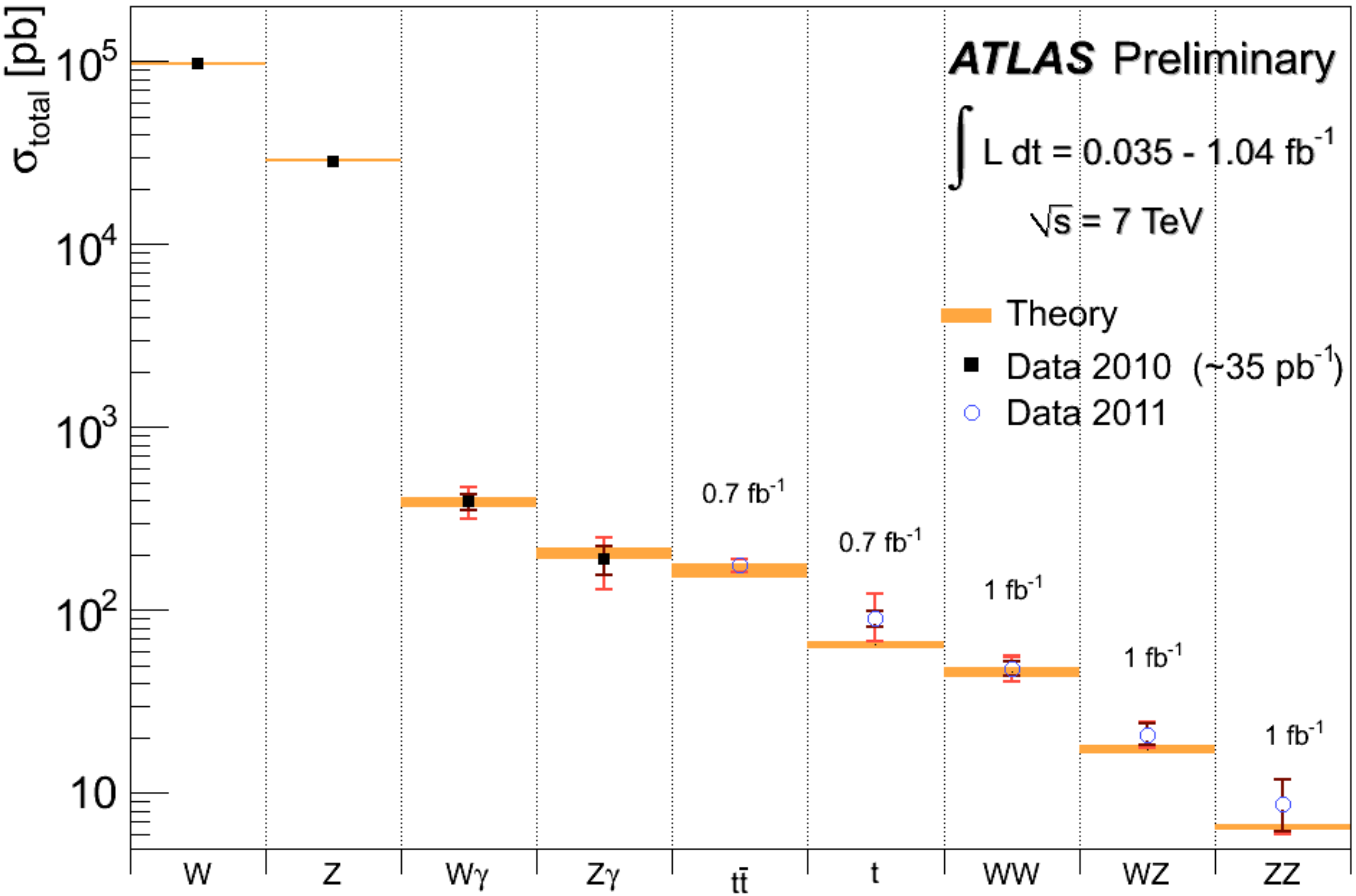
(1) Cross-section (and other observable) measurements of ***Standard Model processes*** at $\sqrt{s} = 7$ TeV are compared to theory predictions and extrapolations;

(2) Search for ***new particles*** appearing as "peaks" in mass distributions: the new energy frontier opens new "horizons";

(3) Search for specific signatures corresponding to well defined models of BSM physics:
My choice: main results of the searches for ***Supersymmetry***.

Step-(1) Cross-section measurements compared to SM predictions

→ Predictions are evaluated at NLO and more;
→ PDF extrapolation uncertainty is included
→ Good agreement over 4 orders of magnitude
  ➔ SM is able to predict cross-sections once we increase energy

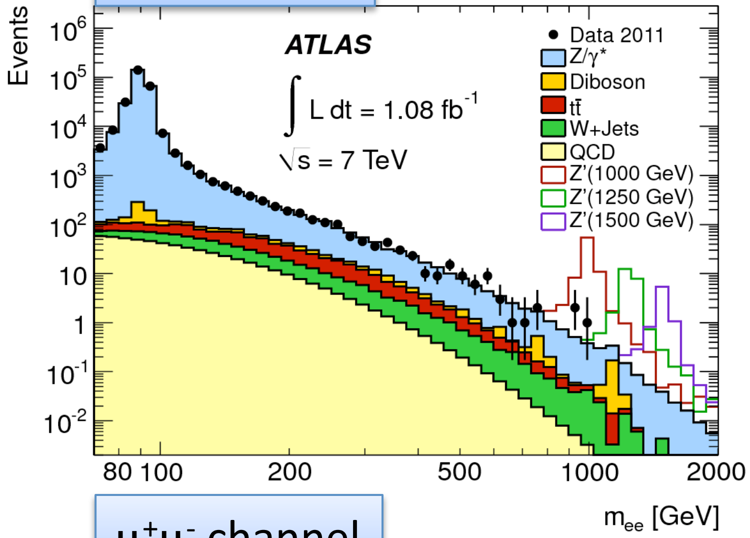


Step-(2) Increase of energy opens new horizons.

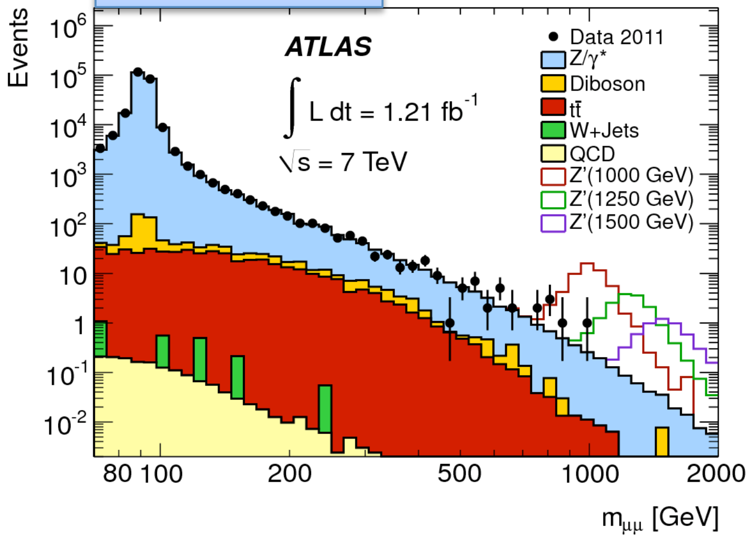
→ Search for a Z′ boson in dileptons (μμ or ee)

"conceptually" simple analysis: search for a peak in a mass spectrum.

e^+e^- channel



$\mu^+\mu^-$ channel

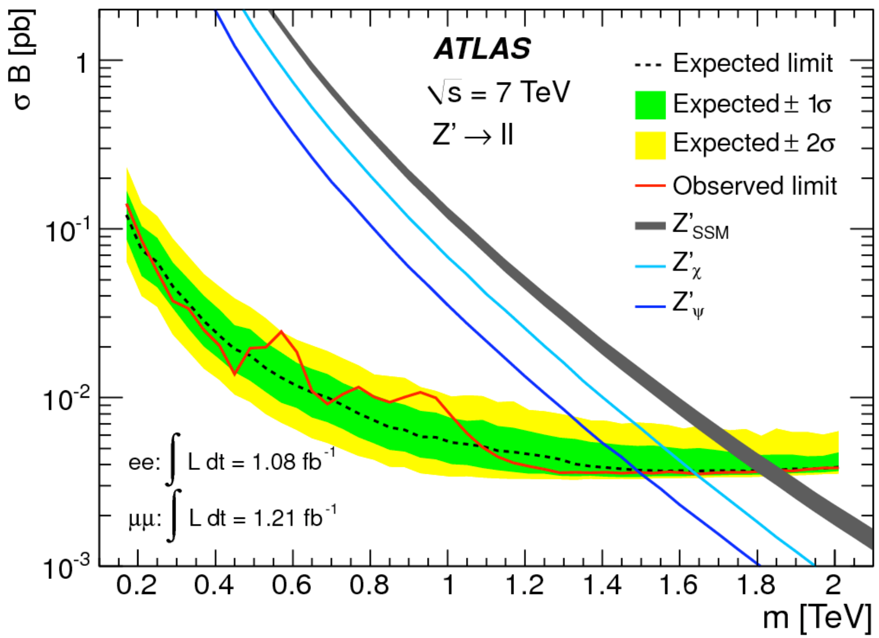


Model independent upper limits on σ × B.R.
as a function of the mass of the new vector boson;

→Model dependent lower limits on the Z′ mass:

SSM: m(Z′) >1.83 TeV @ 95% C.L.

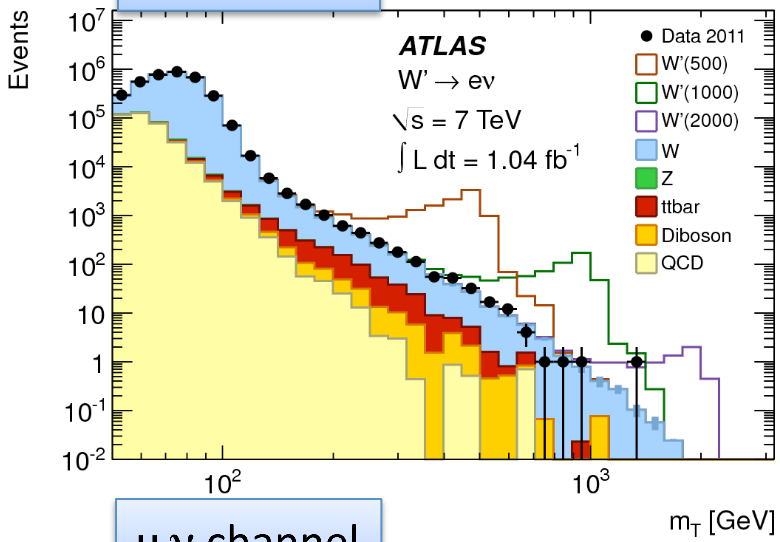
RS graviton: m(G*)>1.64 TeV @ 95% C.L.



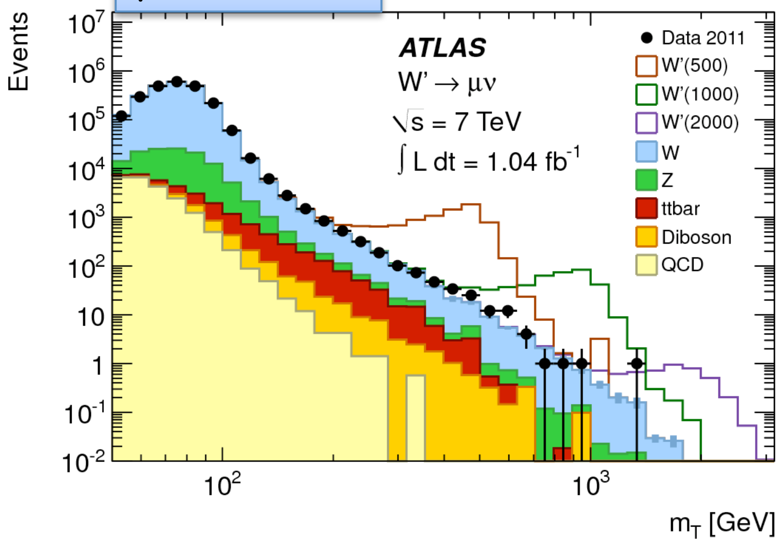
Step-(2) Increase of energy opens new horizons.

→ Search for a W′ boson decaying in lepton+neutrino search for a “jacobian” peak in a transverse mass spectrum.

e ν channel

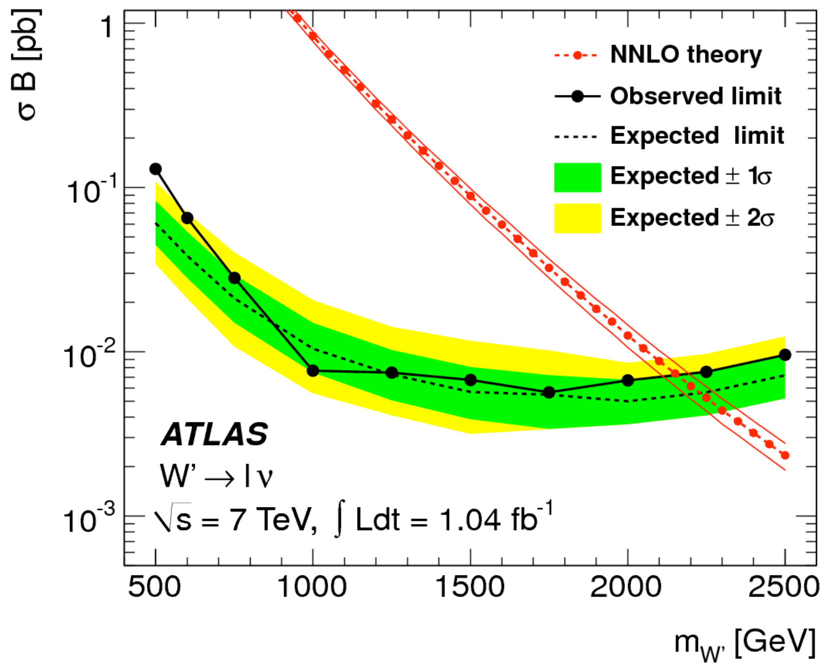


μ ν channel



Model independent upper limits on $\sigma \times$ B.R. as a function of the mass of the new vector boson;

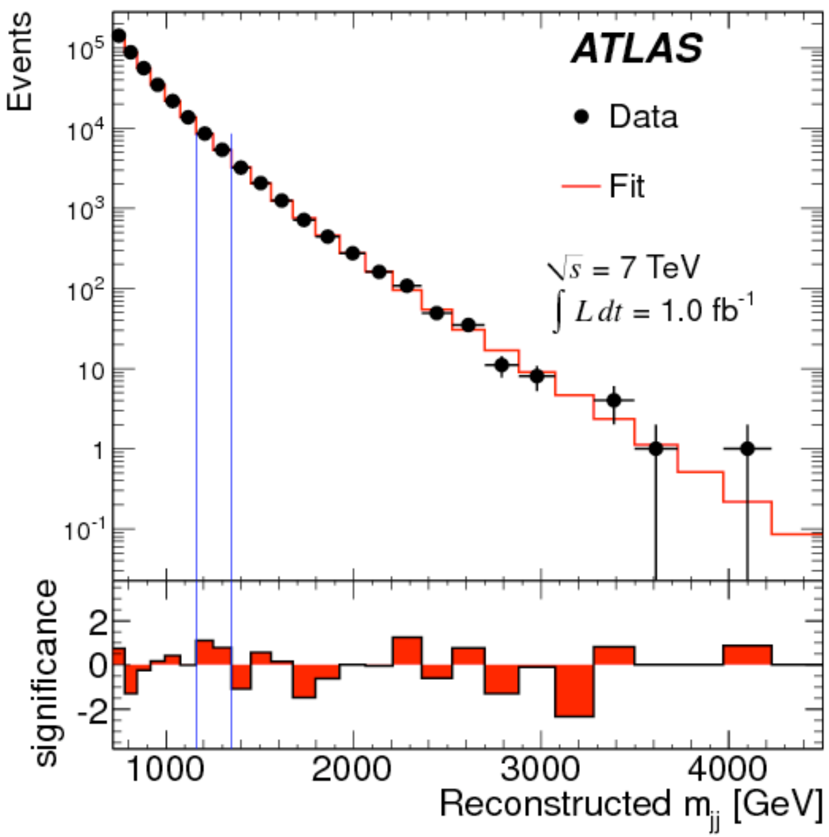
→Model dependent lower limits on the Z’ mass:
SSM: m(W’) >2.15 TeV @ 95% C.L.



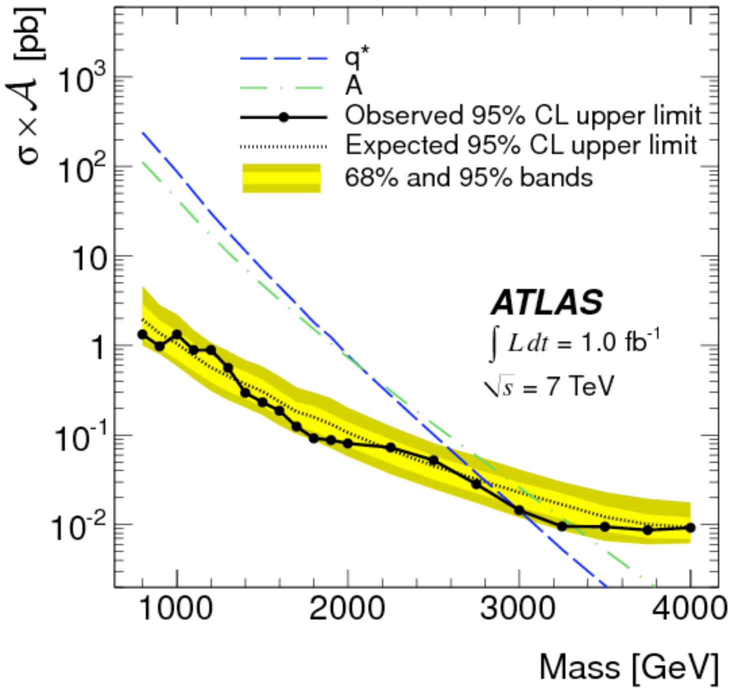
Step-(2) Increase of energy opens new horizons.

→ Search for jet-jet resonances in Dijet events
search for a peak in a dijet mass spectrum.

Reconstructed dijet mass distribution fitted with a smooth functional form describing the QCD background.
Vertical lines show the most significant excess found by the “BumpHunter” algorithm.

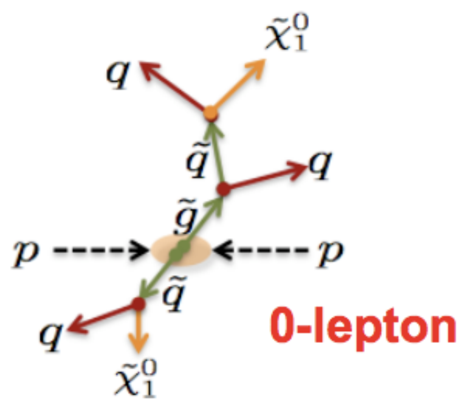


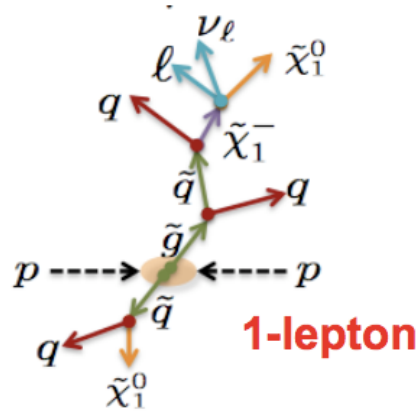
Model dependent Mass lower limit:
→Excited Quark q*: M(q*)>2.99 TeV
→Axigluon: M(A) > 3.32 TeV
→Colour Octet Scalar: M(S) > 1.92 TeV



Step-(3) SUSY

select event topologies with large $\mathbf{E_T^{miss}}$ and multi-jet/leptons activity



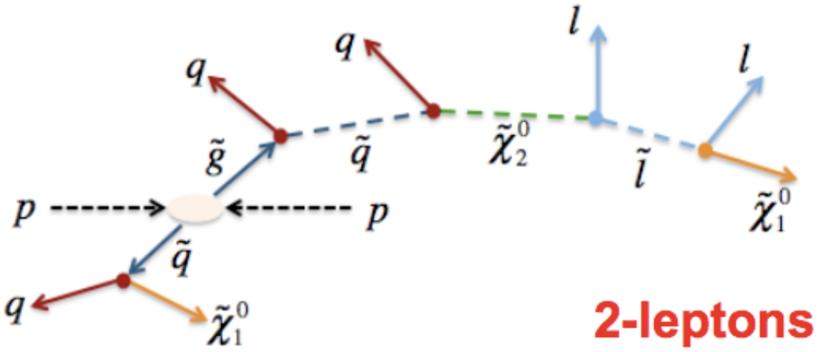


SUSY particles production in pp collisions: cascade toward a LSP

$$pp \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$$

$$\tilde{q} \rightarrow q\tilde{\chi}_1^0$$

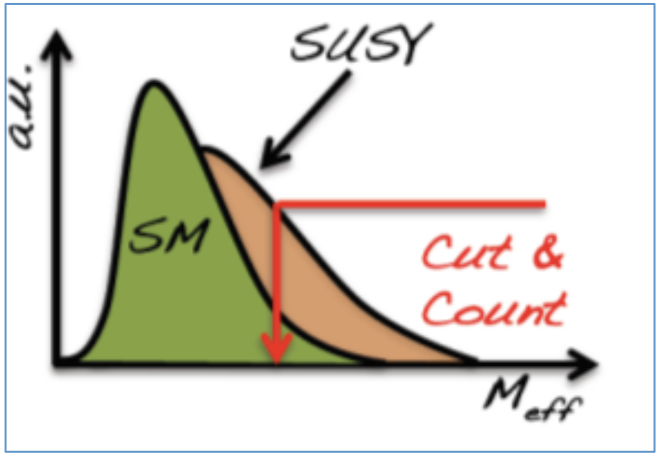
$$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$$



channel	L (fb^{-1})
0leptons + jets + E_T^{miss}	1.04
0leptons + mult. jets + E_T^{miss}	1.34
1lepton + jets + E_T^{miss}	1
2leptons + jets + E_T^{miss}	1
0leptons + b-jets + E_T^{miss}	0.83
1lepton + b-jets + E_T^{miss}	0.83
$\gamma\gamma$ + E_T^{miss}	1

General analysis strategy:

- cut-based selection
- background estimate through control regions
- count events at end of selection and compare to background predictions
- upper limit on cross-sections
- exclusion areas in SUSY planes (many possible choises, mainly mSUGRA/MSSM)



Examples:

0leptons + jets + E_T^{miss} analyses:

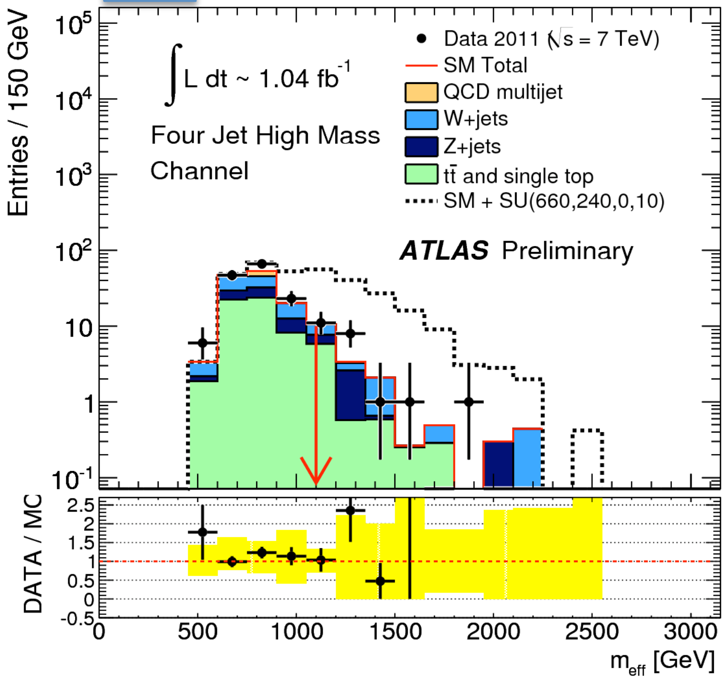
(a) 2 ÷ 4 jet analysis

(b) > 6 jet analysis

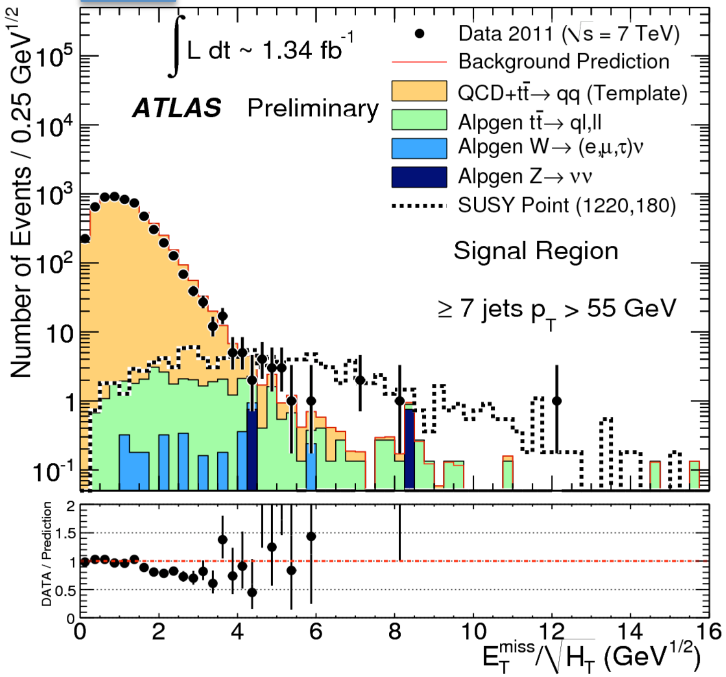
Discriminant variables are m_{eff} (a) or E_T^{miss}/H_T (b)

$$m_{eff} = \sum_{i=1}^{N_{jet}} \left| p_T^i \right| + \sum_{j=1}^{N_{lept}} \left| p_T^j \right| + E_T^{miss}$$

(a)



(b)

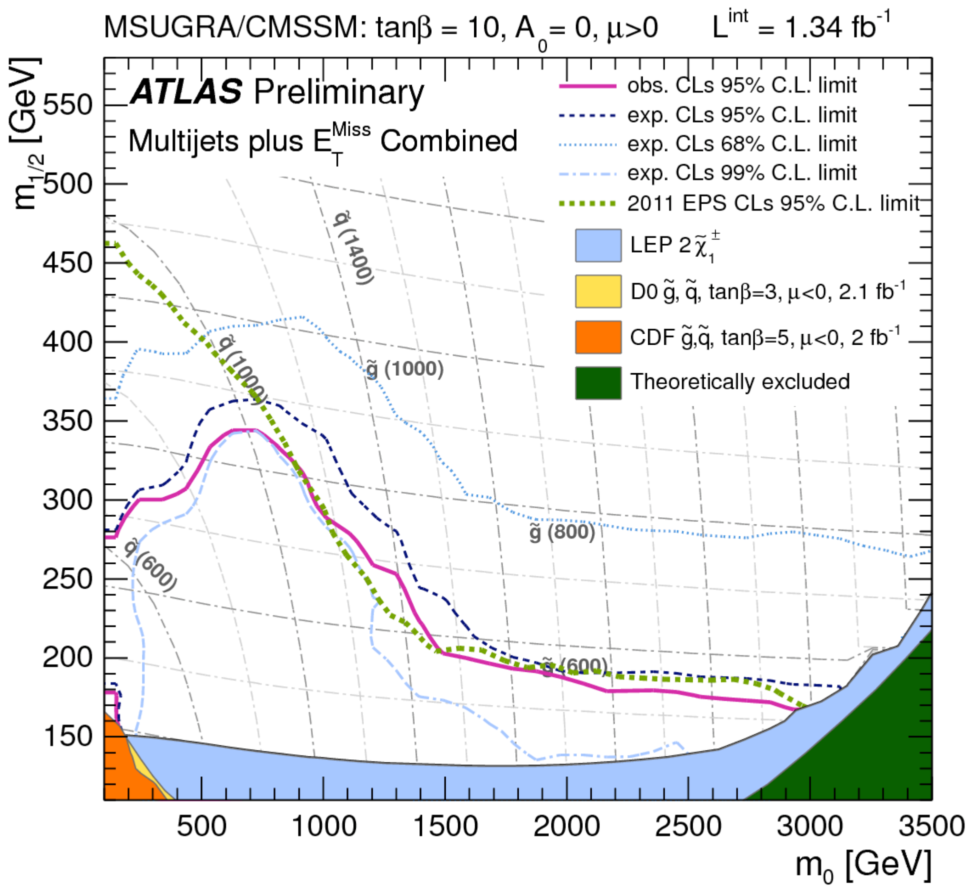


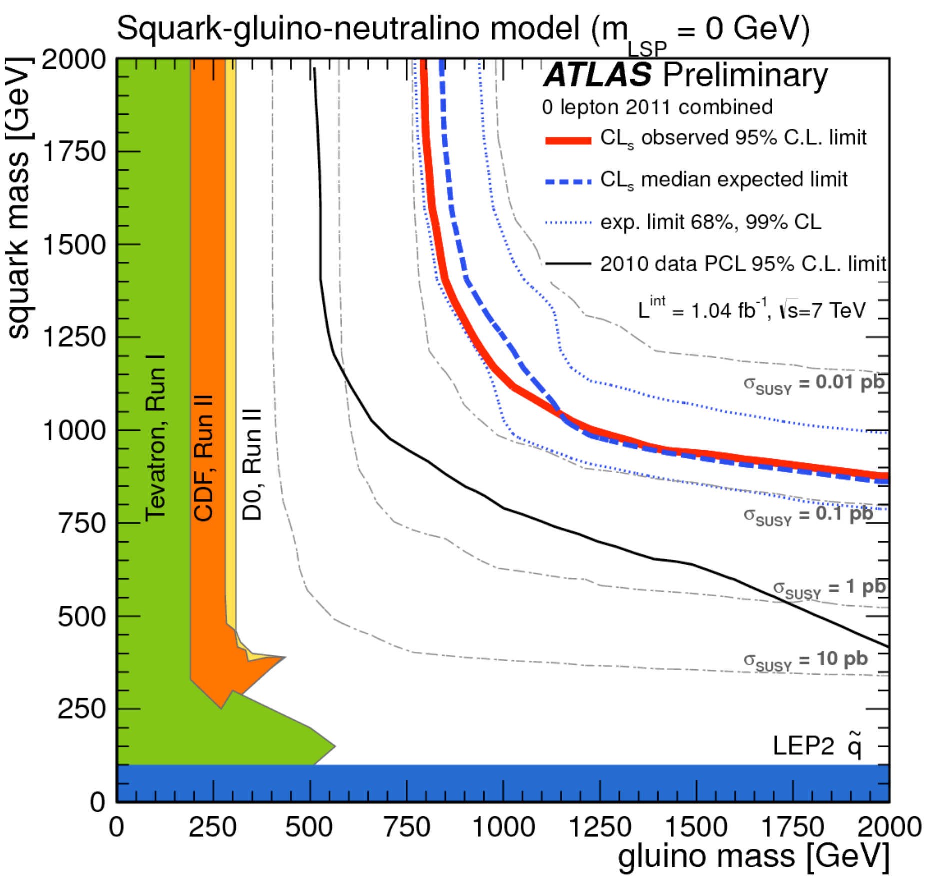
Data agree well with background estimates (SM processes) and exclude SUSY points

SU(660,240,0,10) means (m_0,$m_{1/2}$,A,tgβ)

ATLAS SUSY exclusion plots from 0leptons + jets + Etmiss analysis:

If M(squark)=M(gluino)=M ➔ M> 980 (1075) GeV





Still large space for SUSY, but constraints start to be significant

(see "Implications of LHC results for TeV-scale physics" CERN workshop 29/8-2/9)

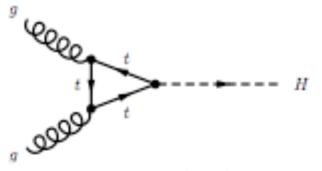
Higgs mass > 130 GeV ➔ SUSY experimentally unaccessible

Conclusions

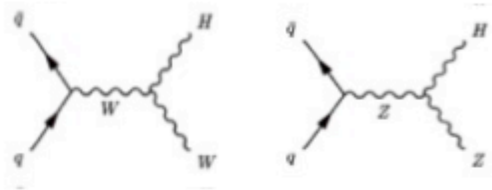
- The **LHC** and **ATLAS** are working well: continuous monitor and improvement of performance;
- **Standard Model** also well at work: all predictions are up to now well matched by data, remarkably accurate description of "background processes" for new physics searches is available;
- Searches for the **Higgs boson** are in a very exciting status, the answer to the quest for SM Higgs is behind the corner, 2011-2012 run is crucial;
- Many **BSM searches** are in progress with a wide and open range of possibilities: no signal found yet, however still large space for discoveries.

Backup

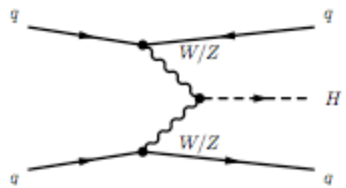
Higgs cross-sections



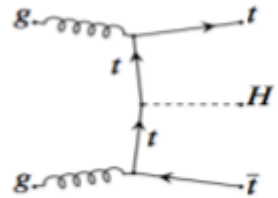
Gluon fusion: known at NNLO
with large uncertainty ~15-20%
on gluon processes



Associated production
with W / Z:
Known at NNLO
uncertainty ~5%



Vector Boson Fusion:
Known at NNLO QCD+NLO EW,
uncertainty ~ 5%

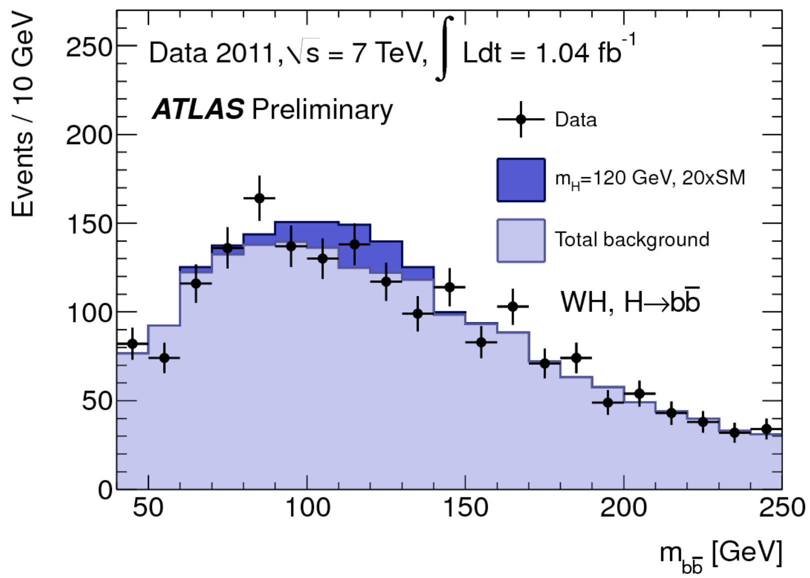


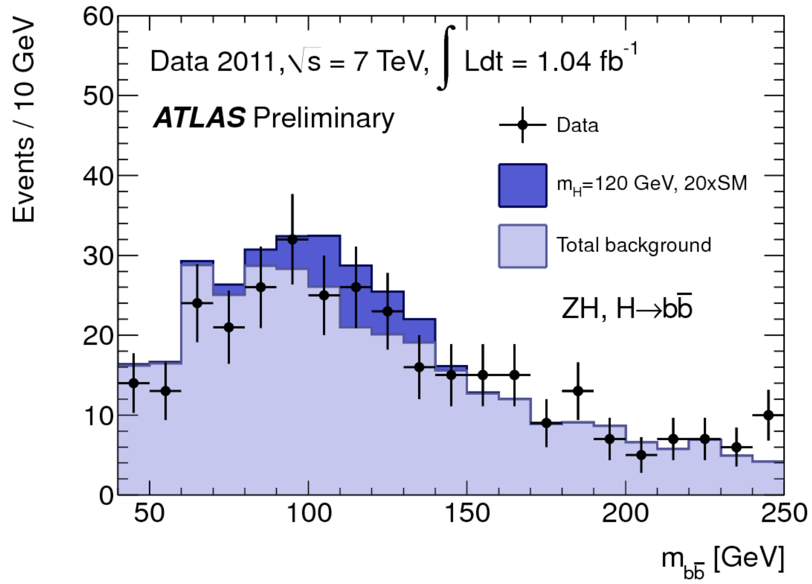
Associated production
with ttbar:
Known at NLO
uncertainty ~15%

- Common effort (ATLAS, CMS, Theorists)
for cross sections determinations
(Yellow Report CERN-2011-002)

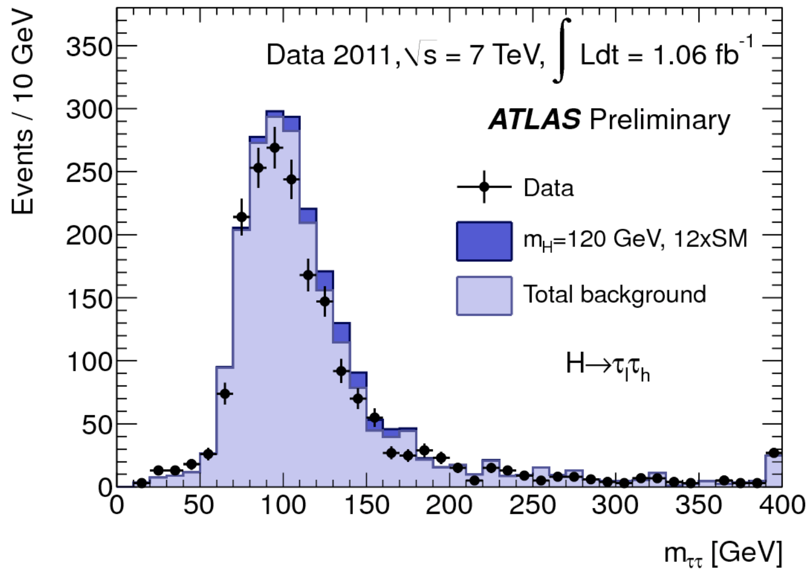
- Backgrounds are in general determined
from data
→ use N(N)LO signal cross sections for
exclusion

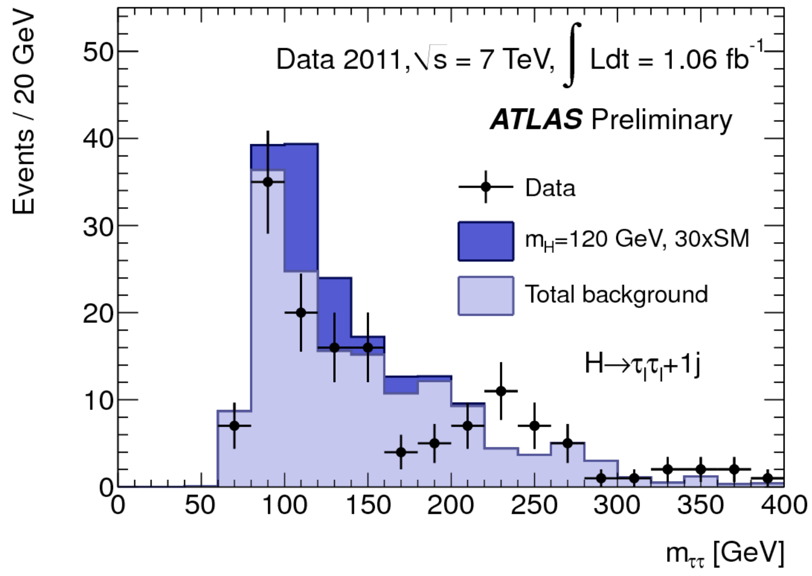
Search for low mass Higgs in WH, H→bb and in ZH, H→bb



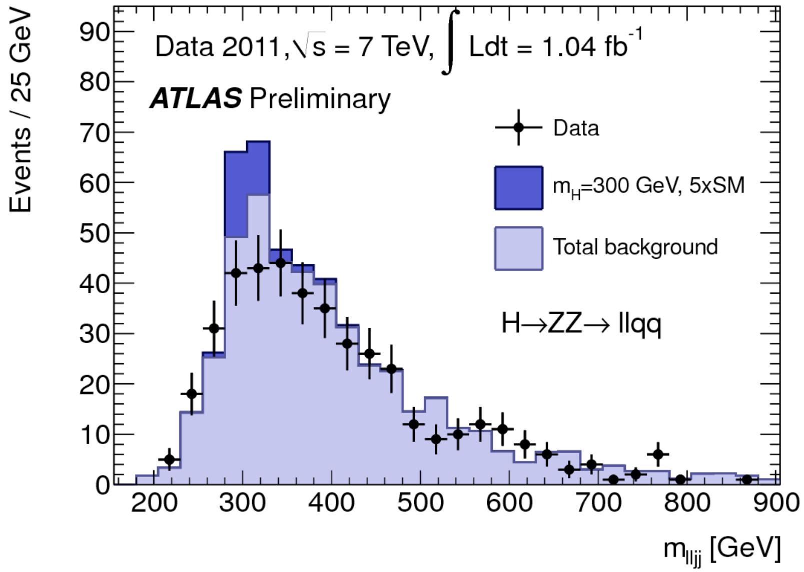


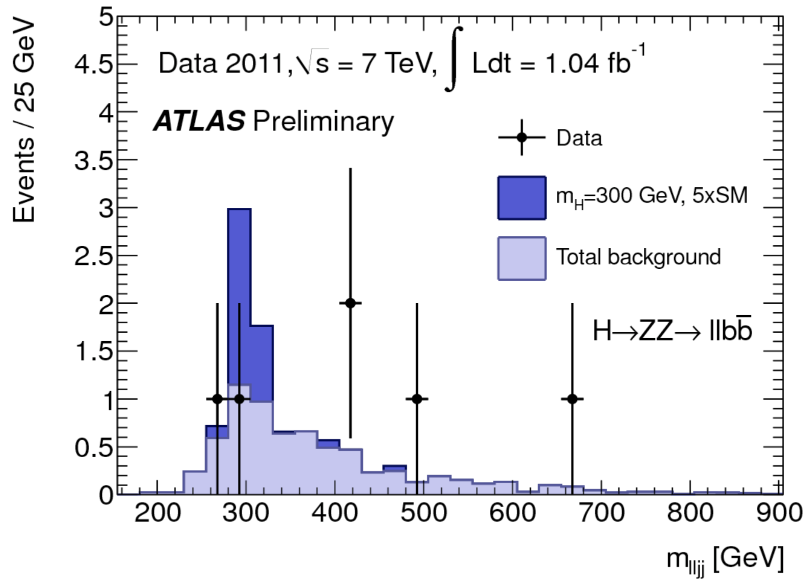
Search for low mass Higgs in H→ττ→lτ_{had}3ν (left) and H→ ττ→ll4ν (right)



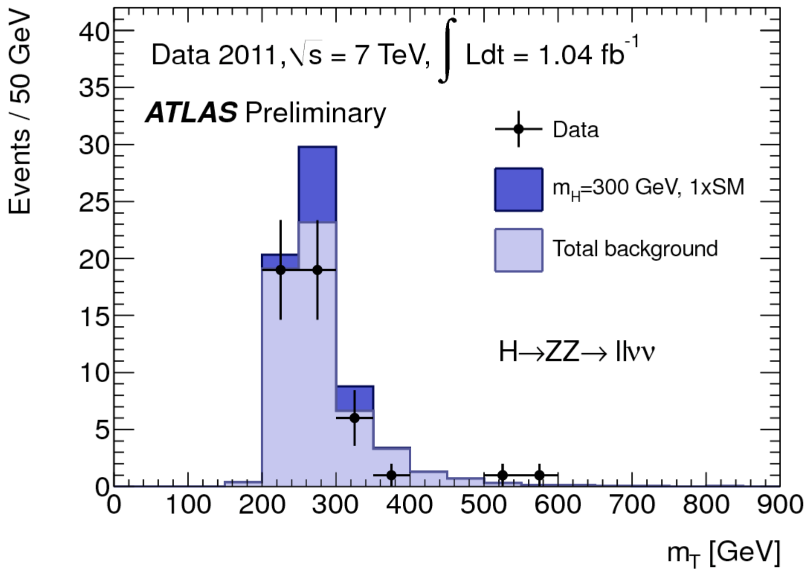


Search for high mass Higgs in H→ZZ→lljj: untagged jets (left) and b-tagged jets (right)





Search for high mass Higgs in H→ZZ→llνν



The most sensitive high mass Higgs boson channel.
With 1 fb-1, the llνν analysis alone excludes
the Standard Model Higgs mass range
$350<M_H<450$ GeV

Limit setting: a frequentist procedure based on the CLs concept (A.Read, J.Phys.G28 (2002) 2693)

→ First write down the expected number of events for a given channel *i*

$$N_i^{\exp} = \mu s_i(\underline{\theta}) + b_i(\underline{\theta})$$

μ= signal strength

$s_i(\underline{\theta})$ = expected signal for channel *i* at the end of the selection
(includes cross-section, luminosity, efficiency…)

$b_i(\underline{\theta})$ = sum of the expected backgrounds at the end of the selection
(depends on control region, MC, cross-sections,…)

$\underline{\theta}$ = set of "nuisance parameters"

→ From the profile likelihood ratio get the observed value q_μ^{obs} of the test statistic

$$q_\mu = -2\ln\frac{L(N_i^{obs}/\mu,\hat{\hat{\theta}})}{L(N_i^{obs}/\hat{\mu},\hat{\theta})}$$

that depends on observed and expected number of events for any given μ.

→ Then find that value of μ for which the probability ratio satisfies

$$CL_s = \frac{P(q_\mu \geq q_\mu^{obs}/\mu,\hat{\theta}_\mu)}{P(q_\mu \geq q_\mu^{obs}/0,\hat{\theta}_0)} = 0.05$$

For the combined result use the same technique with a profile likelihood based on the product of the single channels likelihoods

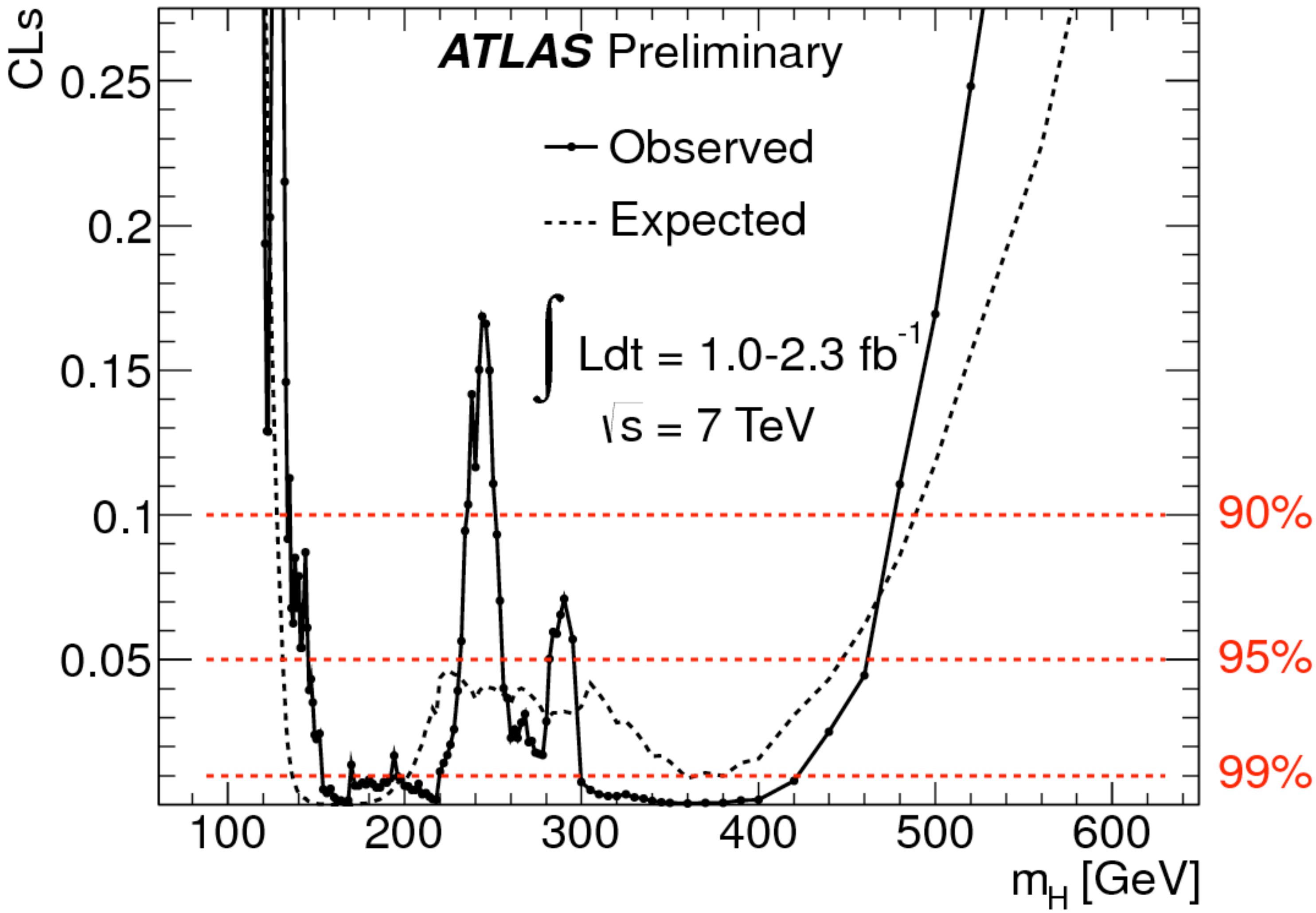
The combination method naturally takes into account all uncertainties.

- Correlated uncertainties are due to experimental common conditions (see table below)
- Uncorrelated uncertainties are due to channel specific problems
  - (control regions, background extrapolation,..)
- Theoretical uncertainties are either correlated (PDFs, cross-sections) and uncorrelated

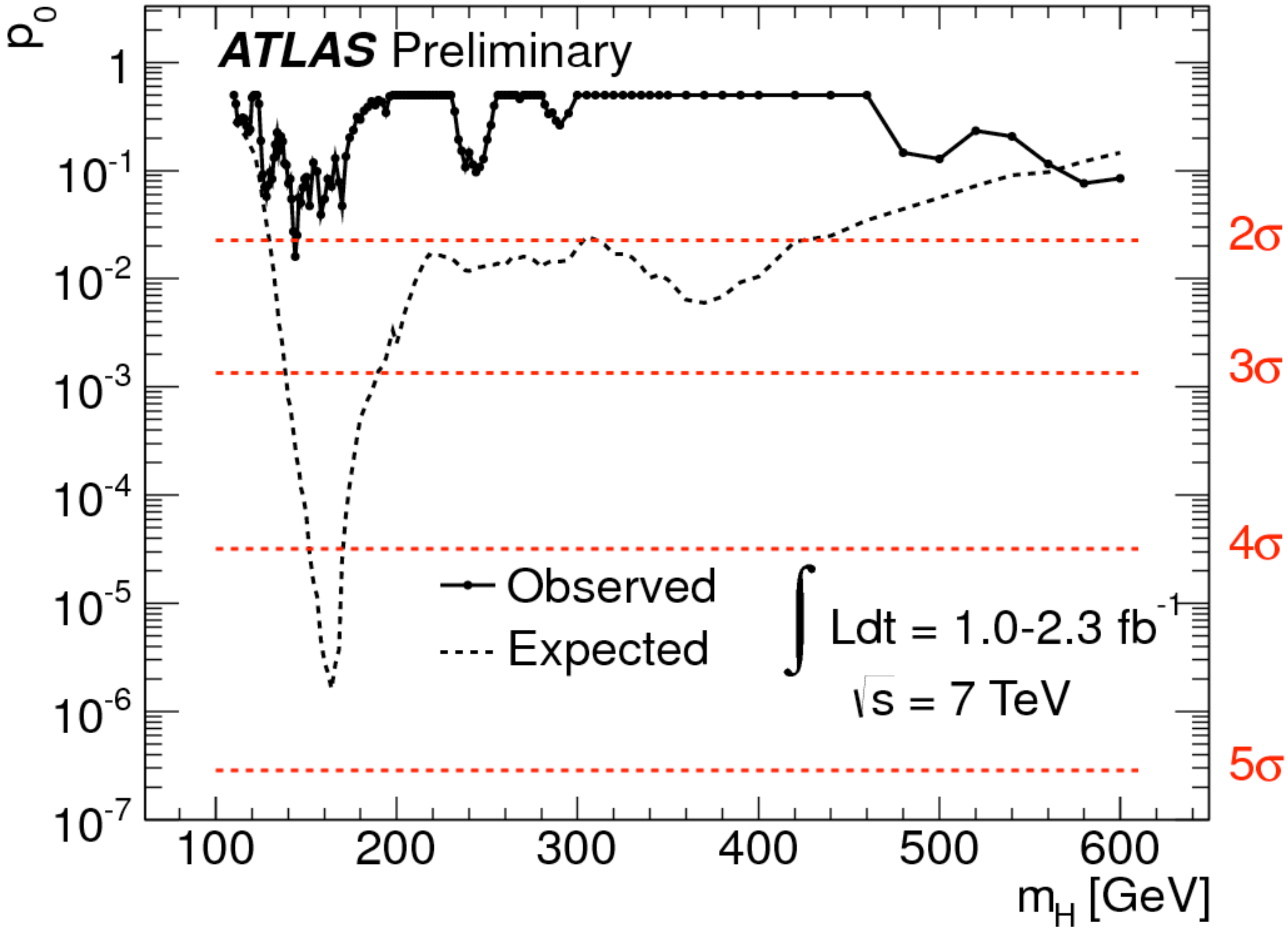
Table 3: Main correlated systematic uncertainties used in the analysis. These relative uncertainties (%) correspond to the overall effect on the per-event signal efficiency of the $\pm 1\sigma$ variation of the source of systematic uncertainty. Some of them, such as the energy scale in the $H \to \gamma\gamma$ search, are included but are not apparent in this table as they do not affect event rates.

	$H \to \tau^+\tau^-$		$H \to \gamma\gamma$	$H \to b\bar{b}$	$H \to WW^{(*)}$	$H \to ZZ^{(*)}$		
	$\tau_\ell \tau_{had}$	$\tau_\ell \tau_\ell + jet$			$\ell\nu\ell\nu$	$\ell\ell\ell\ell$	$\ell\ell\nu\nu$	$\ell\ell qq$
Luminosity	± 3.7	± 3.7	± 3.7	± 3.7	± 3.7	± 3.7	± 3.7	± 3.7
e/γ eff.	± 3.5	$^{+2.0}_{-2.1}$	$^{+11.6}_{-10.4}$	± 2.3	± 2.2	± 3.3	± 1.2	± 1.1
e/γ E. scale	$^{+1.3}_{-0.1}$	$^{+0.2}_{-0.5}$	-	$^{+1.5}_{-1.6}$	± 0.1	-	$^{+0.8}_{-1.1}$	-
e/γ res.	-	± 3.7	-	$^{+2.1}_{-1.5}$	± 0.1	-	-	-
μ eff.	± 1.0	$^{+2.0}_{-2.1}$	-	$^{+1.1}_{-2.0}$	± 0.6	± 1.2	$^{+0.8}_{-0.7}$	± 0.6
μ res.	-	$^{+0.4}_{-0.6}$	-	± 5.8	± 1.6	-	-	-
Jet/τ/MET E. scale	$^{+19}_{-16}$	$^{+3.3}_{-10.0}$	-	$^{+21}_{-17}$	± 6.1	-	$^{+5.9}_{-4.0}$	$^{+3.7}_{-10.4}$
JER	-	± 2.0	-	± 2.5	$^{+2.2}_{-1.8}$	-	-	$^{+2.1}_{-0.0}$
MET	-	$^{+4.4}_{-5.3}$	-	$^{+5.5}_{-6.1}$	-	± 0.6	$^{+6.6}_{-4.2}$	-
b-tag eff.	-	-	-	$^{+37}_{-33}$	± 0.1	-	$^{+4.3}_{-4.4}$	-

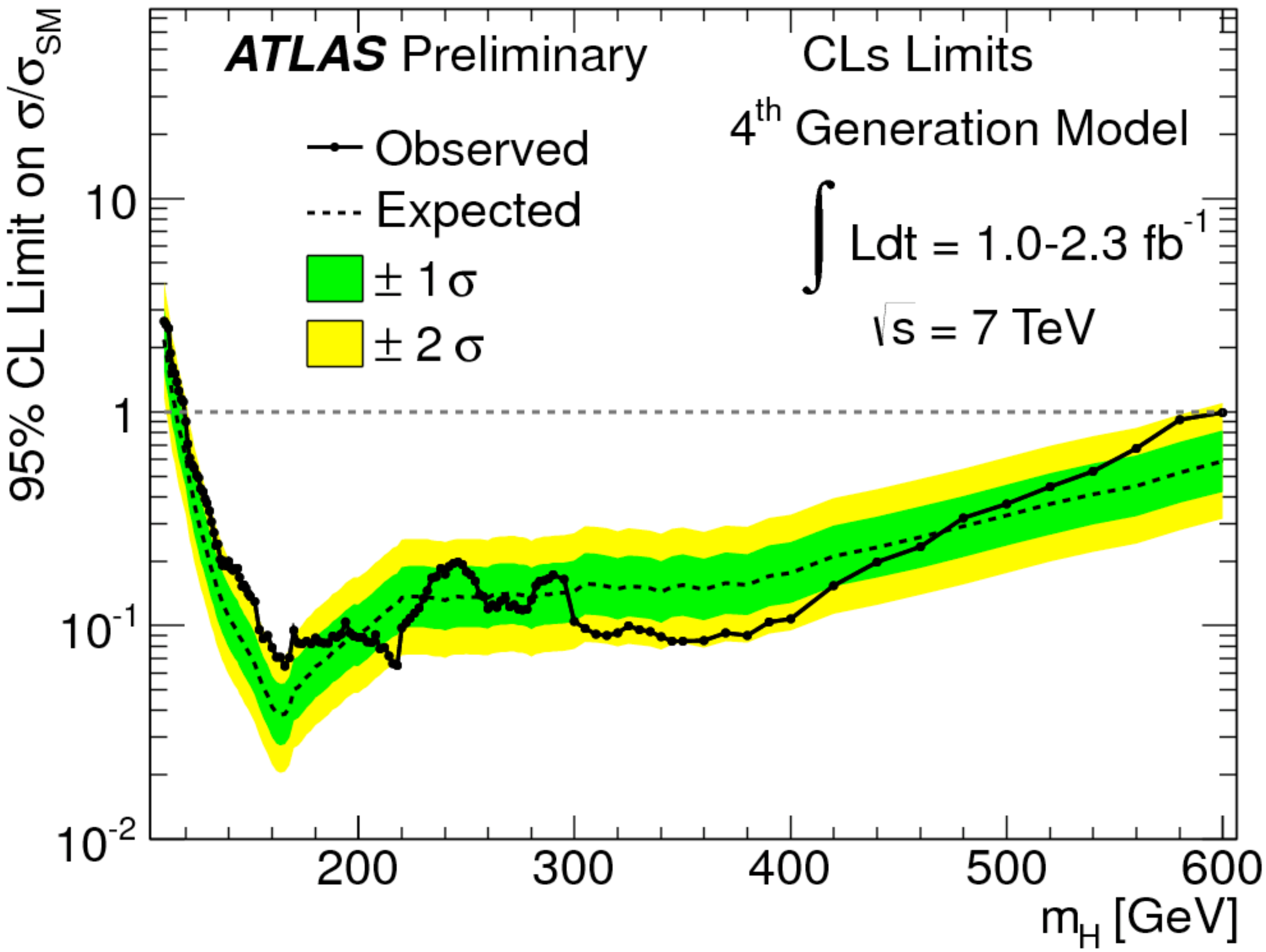
Another "view" of the exclusion plot.
The value of the combined CLs for $\mu = 1$ (testing the Standard Model Higgs boson hypothesis) as a function of M_H in the full mass range.
By definition, the regions with CLs < α are considered excluded at the $(1 - \alpha)$ CL or stronger.



Another view of the exclusion plot:
The consistency of the observed results with the background-only hypothesis is shown in the full mass range. The dashed line shows the median expected significance in the hypothesis of a Standard Model Higgs boson production signal.



The combined 95% CL limit on the Higgs boson production cross section in the framework of a Standard Model with the addition of a heavy fourth generation of fermions as a function of M_H. All the range is clearly excluded.



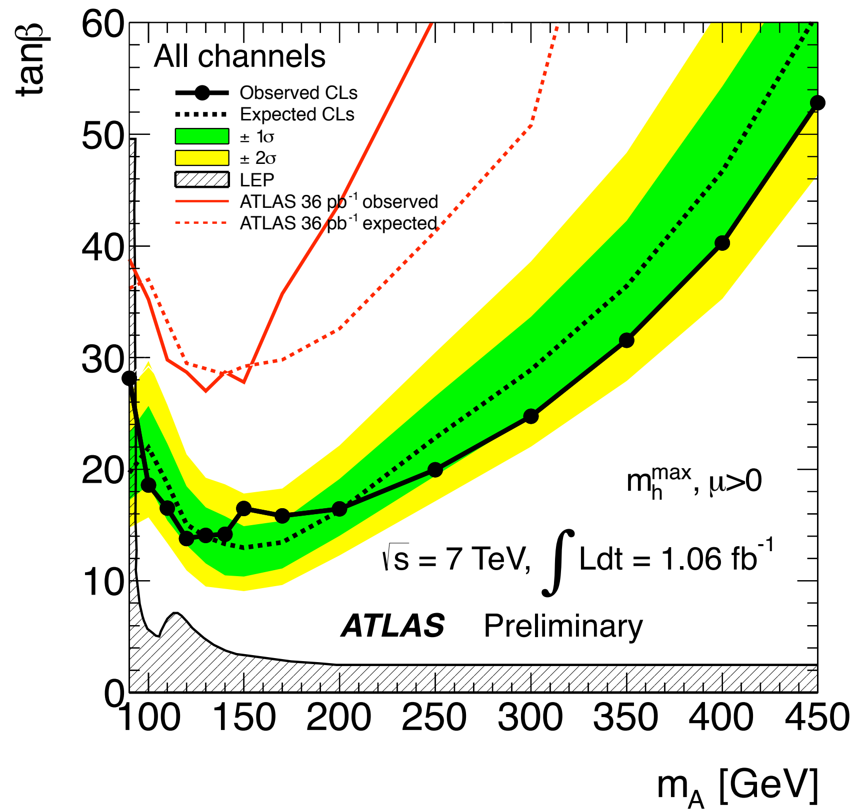
Search for the Higgs Bosons in the context of MSSM

Higgs sector in MSSM → 5 physical states:
 h/H/A (neutrals scalar/pseudoscalars)
 $H^{\pm}$ (charged scalar)
Masses and properties depending on two parameters only : m_A and $\tan\beta$

Production mechanism in pp collisions:
 gg→h/H/A (gluon-gluon fusion)
 bbh/H/A (associate production)
 t→H^{+}b (from top decay, light H)

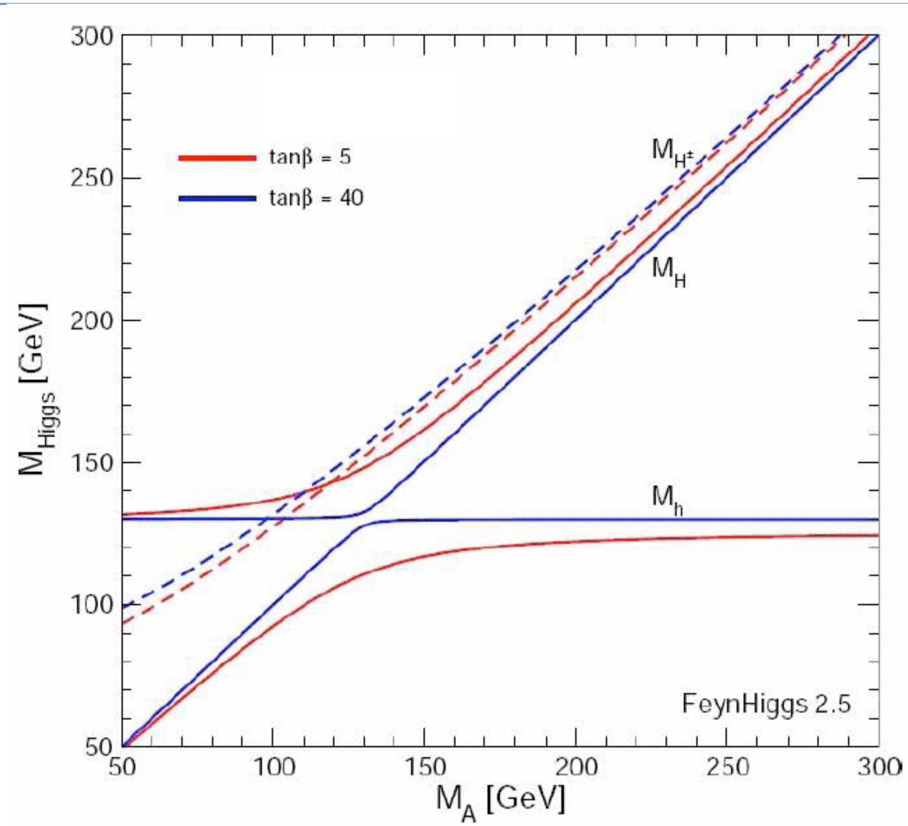
Main decay channels (in large regions of parameter space):
 h/H/A→$\tau^{+}\tau^{-}$
 $H^{\pm}$ →$\tau\nu$, cs

ATLAS analyses:
 h/H/A→$\tau^{+}\tau^{-}$ (see limit)
 t→H^{+}b→csbar b
 H^{+} → $\tau\nu$

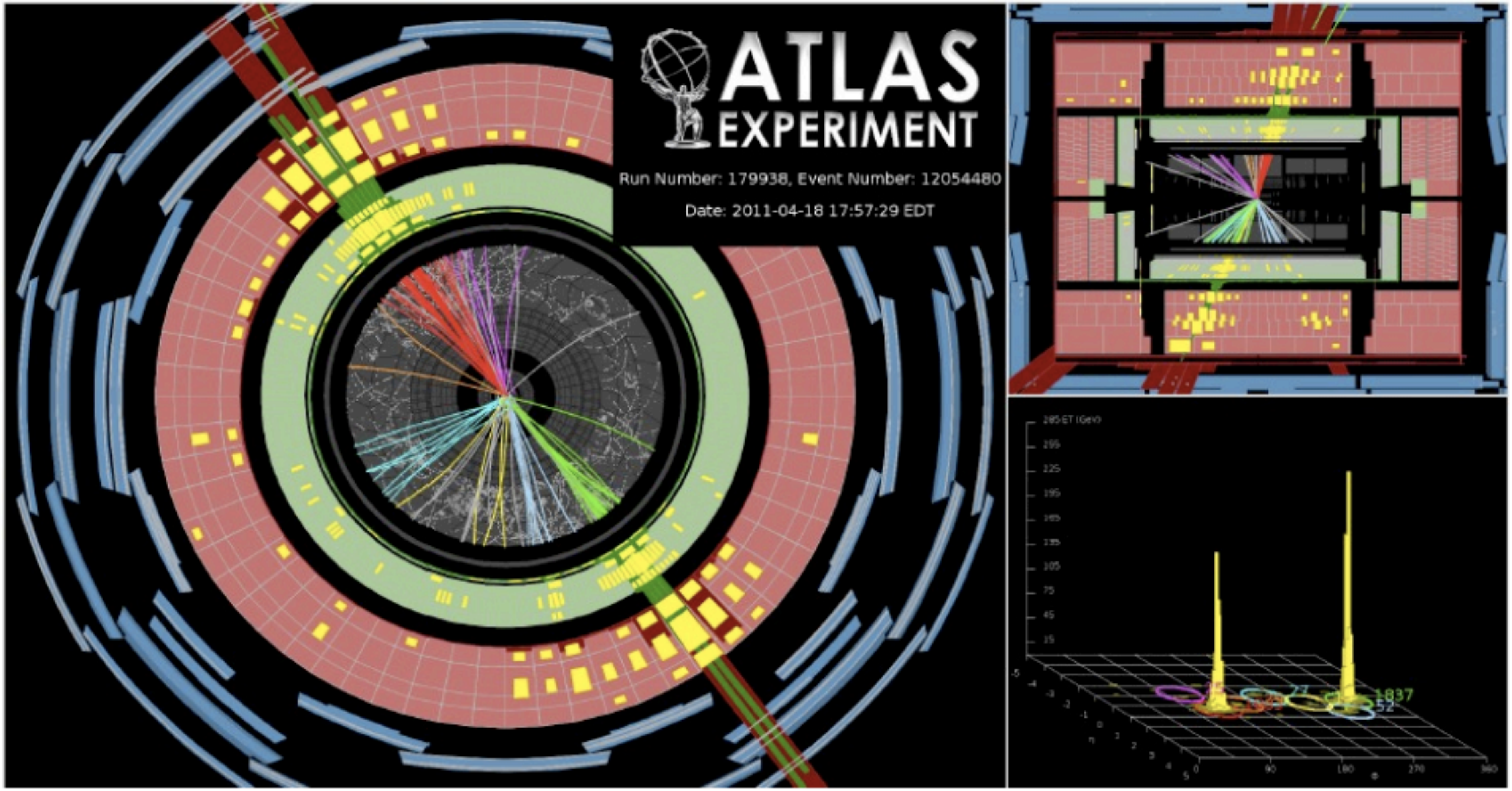


Expected and observed exclusion limits based on CLs in the m_A – tan β plane of the MSSM derived from the combination of the analyses for the eμ, $l\tau_{had}$ and $\tau_{had}\tau_{had}$ final states. The dark green and yellow) bands correspond to the ±1σ and ±2σ error bands, respectively.

MSSM Higgs bosons



- **Five Higgs bosons: h, H, A, $H^{+/-}$**
- **Higgs sector is defined at tree level by M_A, tanβ**
  - *rad. corrections introduce dependence on other model parameters*
- **Upper limit on m_h ~ 135 GeV**



m(jet-jet) = 4.0 TeV **Missing E_T = 100 GeV**