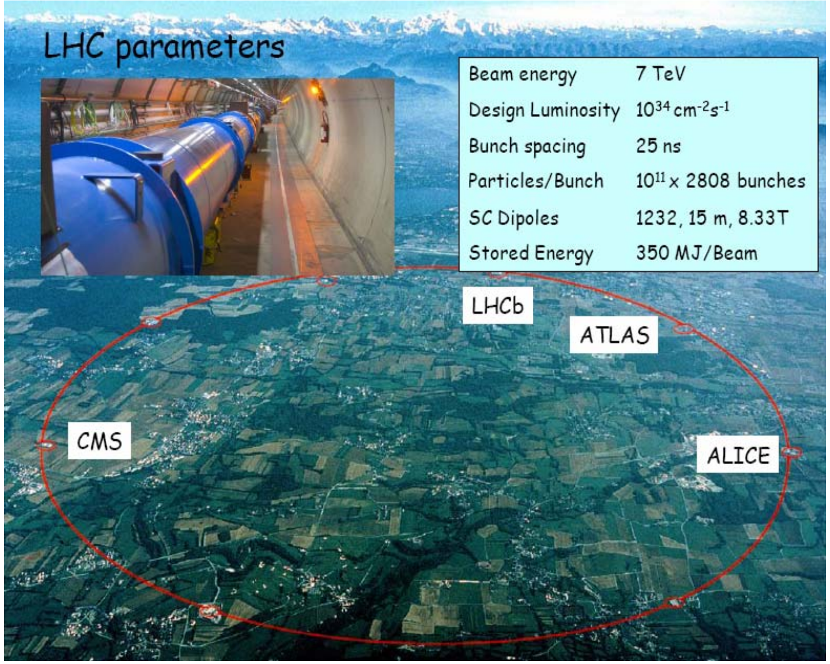
Prospects for Higgs boson searches at the LHC(*)

E. Richter-Was (UJ/IFJ-PAN)
on behalf of the ATLAS Collaboration

- The Higgs boson(s)… still a dream….
- Overal discovery potential and some details on selected channels
  - SM Higgs sector
  - MSSM Higgs sector
- Summary



(*)Disclaimer: this is personal selection , most results from ATLAS, recent news on CMS in talk by Albert De Roeck.

Large Hadron Collider: from dream to reality

The most ambitious project in high-energy physics ever, and one of the most ambitious in science.

1983 : First W±/Z *observation* at the SPS proton-antiproton collider
Tevatron becomes operational

1984 : First studies for a high-energy pp collider in the LEP tunnel

1989 : Start of SLC and LEP e+e- colliders

1994 : LHC approved by the CERN Council

1995 : Top-quark discovery at the Tevatron

1996 : Construction of LHC machine and experiments start

2000 : End of LEP2

2003 : Start of the experiments installation

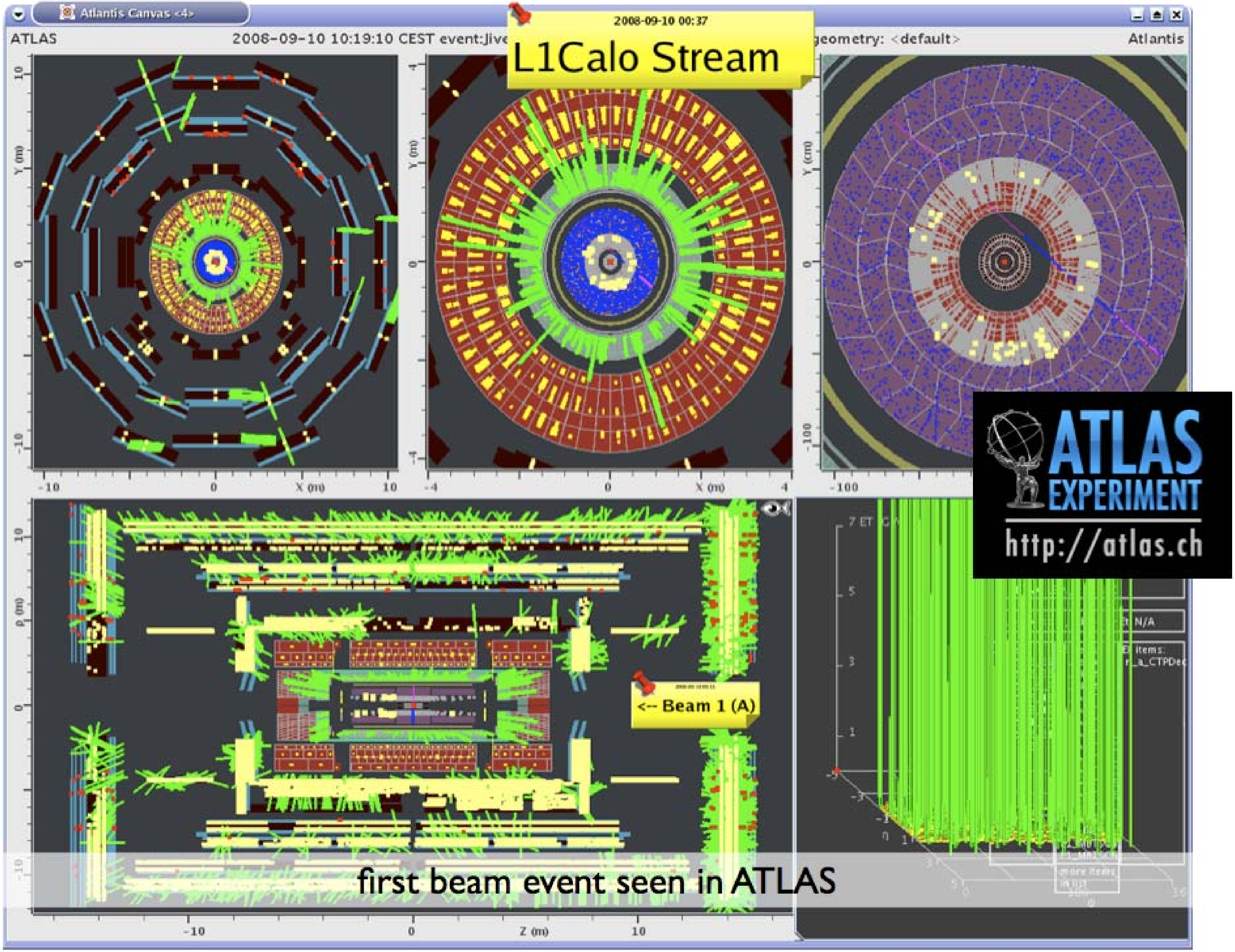
September 2008

Detectors ready and first single beam passing LHC line

Summer 2009

Will start several years long physics program…..

in parallel ongoing intensive R&D activity for super-LHC



first beam event seen in ATLAS

Higgs boson(s): still a dream …..

What is the origin of the particle mass ?

The mass mystery could be solved by the "Higgs mechanism", which predicts the existence of a new elementary scalar particle : **The Higgs Boson** **(P.W. Higgs, Phys. Lett. 12 (1964)).**

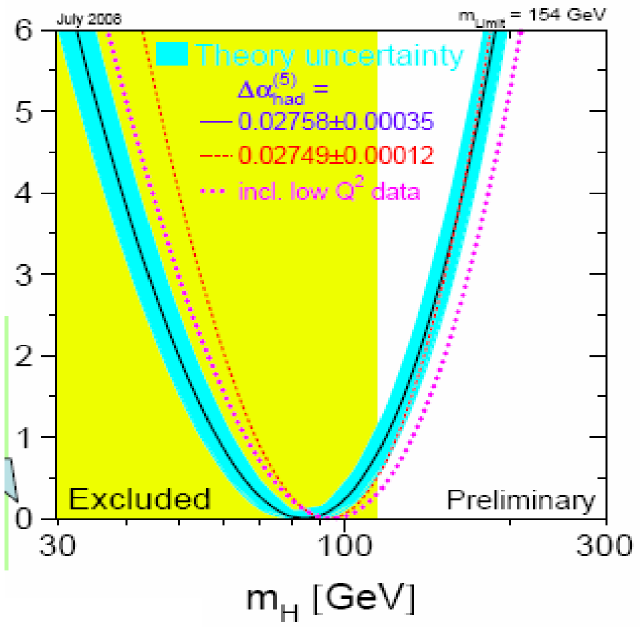
- This particle has been searched for 20 years at collider experiments and has not been observed yet… by now more and more constrained by direct and indirect limits (LEP).
- Original Standard Model mechanism extended to other scenarios: H2DM, MSSM, NMSSM, Higgs in exotic models, ….

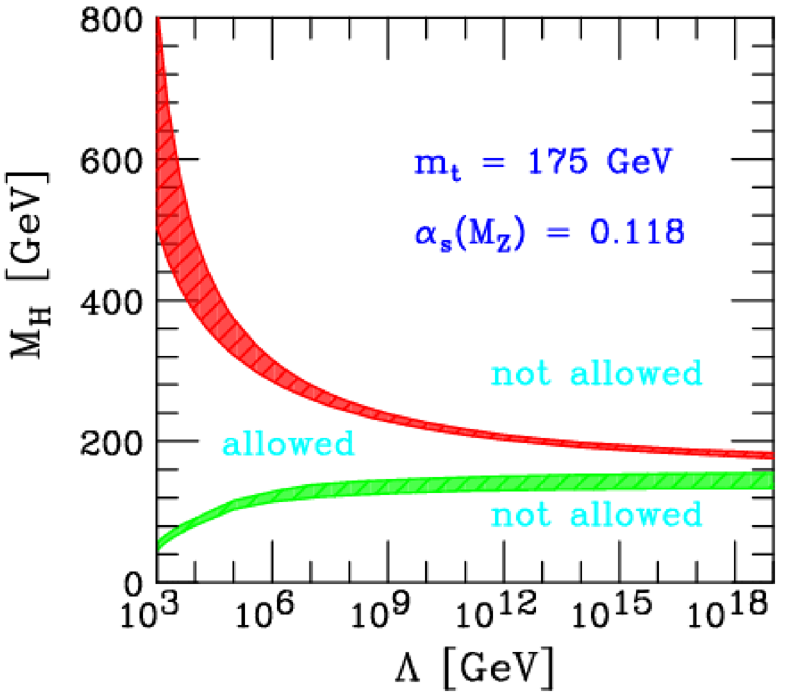
From the very beginning the "goal " of building LHC was to find Higgs boson.

"Millestones" for preparing searches scenarios for the Higgs Boson(s)

- **1992 : ATLAS Letter of Intent, CMS Letter of Intent** **(mostly SM channels)**
- **1994 : ATLAS Technical Proposal, CMS Technical Proposal** **(SM + few MSSM channels)**
- **1999 : ATLAS Physics and Detector TDR** **(large variety of SM and MSSM channels)**
- → **Direct limits from LEP**
- → **Tevatron enters the game with very ambitious search program**
- **2006 : CMS Physics and Detector TDR**
- **Series of collaboration notes with more exotic scenarios, including benchmark MSSM scenarios, CP violation in MSSM, Little Higgs models, etc.**
- **2008 : ATLAS CSC Book**

SM Higgs mass constraints





Indirect constraints from precision EW data

M_H < 154 GeV at 95 %CL (July 2008)

Direct limit from LEP:

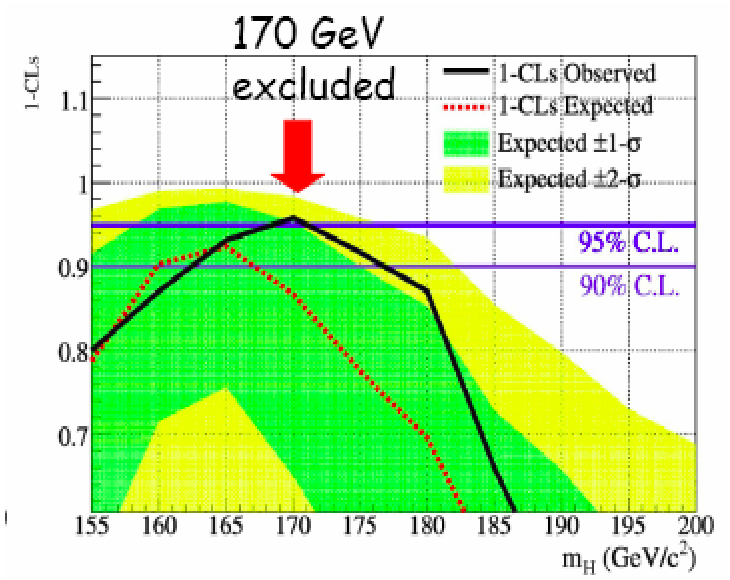
M_H > 114.4 GeV @ 95% CL

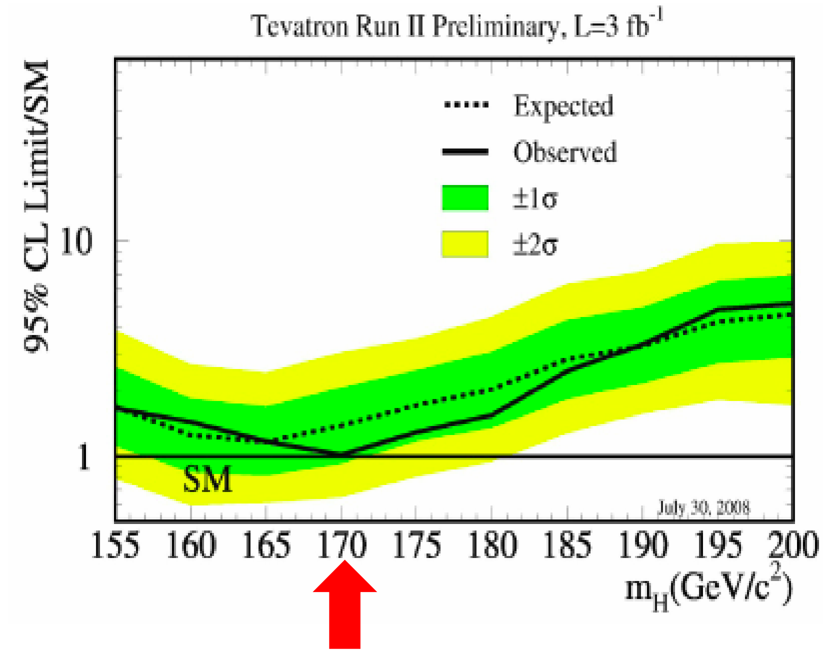
Indirect + direct constraints from LEP

M_H < 185 GeV @ 95% CL

The triviality (upper) bound and vacuum stability (lower) bound as function of the cut-off scale L

SM Higgs mass constraints: Summer08 results from Tevatron





Tevatron high mass combination

Excludes at 95% C.L. the production of the SM Higgs boson at 170 GeV

First direct exclusion since LEP!

Recent progress on LHC Higgs studies (theory)

- Since original paper on the Higgs mechanism several extentions of the model : MSSM, NMSSM, 2HDM, Little Higgs, etc. In all cases well defined predictions (calculable it perturbative framework) for the width, couplings, decay modes, production mechanisms, …..
- Impressive progress on higher order calculations for signal and background processes.
  - Signal cross-section calculated to NLO or NNLO, **remaining theoretical uncertainties of 5-15%**. However, not always available at the same precision level in form of the Monte Carlo generators.
  - Backgrounds only in few cases can be simulated with NLO precision for the QCD part. In most cases ME & PS (improved LO) shower approach can be used. **Real break-through complete NLO parton shower** implementation **not available yet**.

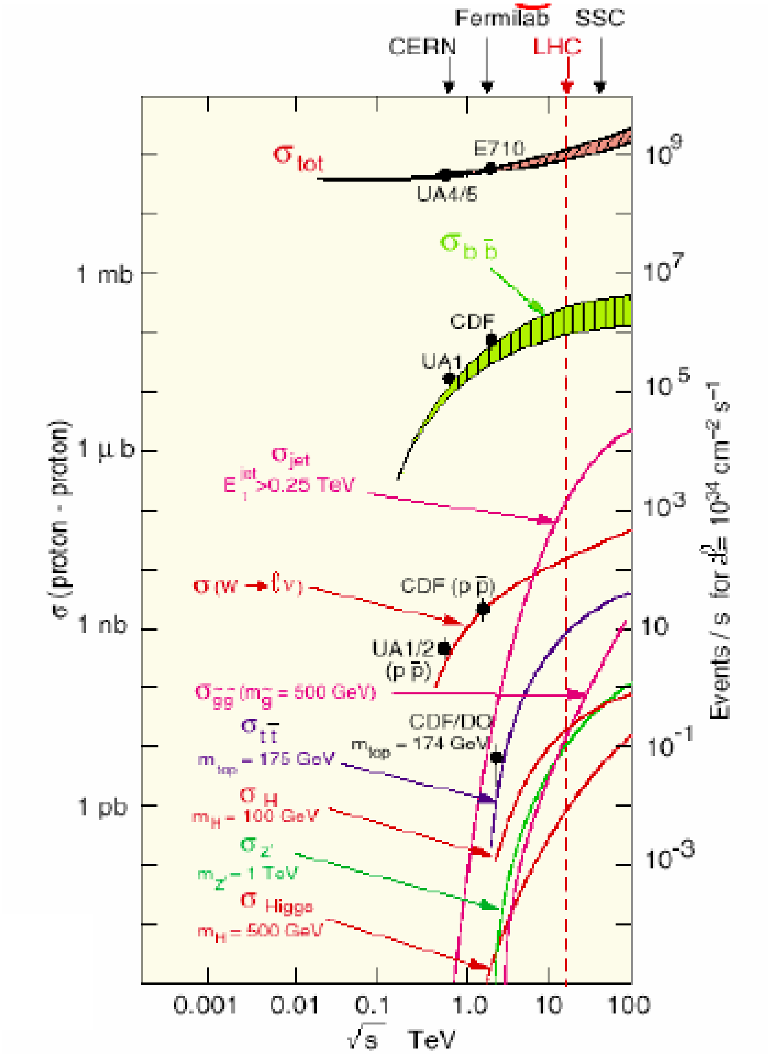
Recent progress on LHC Higgs studies (experiments)

- Detailed GEANT simulations of the detector and more detailed, ready for data-taking reconstruction (partially based on test beams results)
- New (N)NLO Monte Carlos (also for backgrounds), new approaches to match parton showers and matrix elements in use, if available.
- Focus on evaluation of theoretical and experimental systematics, trigger simulation, data-driven control on backgrounds, multi-variate discriminating techniques, advanced statistical methods for sensitivity limits
- Further studies of new Higgs boson scenarios (various MSSM benchmark scenarios, CP-violating scenarios, …)

Physics Performance Technical Design Report CMS Collaboration,
CERN/LHCC 2006-021, J. Phys. G: Nucl. Part. Phys. 34 (2007) 995–1579

ATLAS CSC (Computing System Challenge) notes
CERN-OPEN-2008-020 (released on 20th December 2008)

Higgs searches at LHC: the challenge

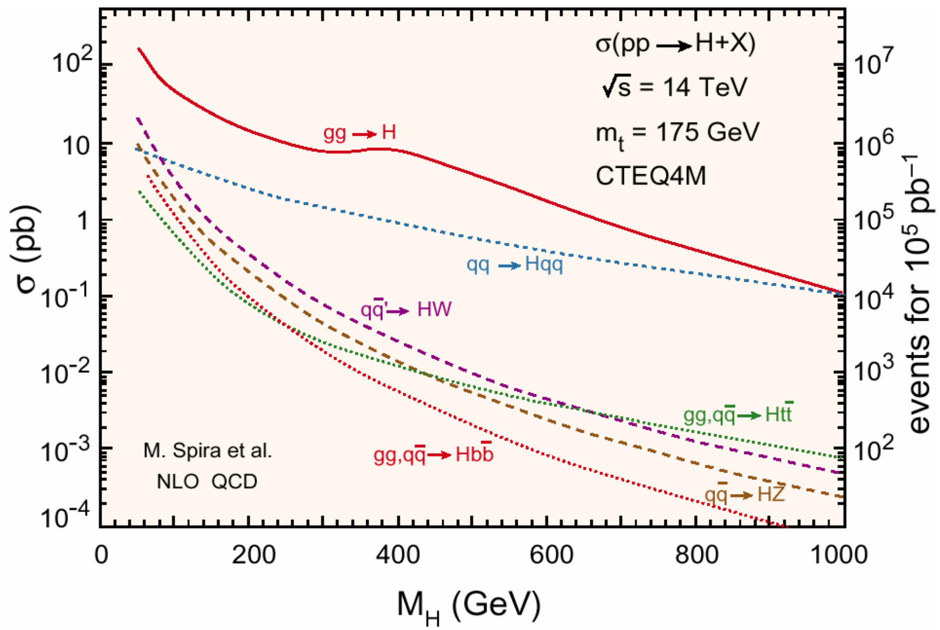


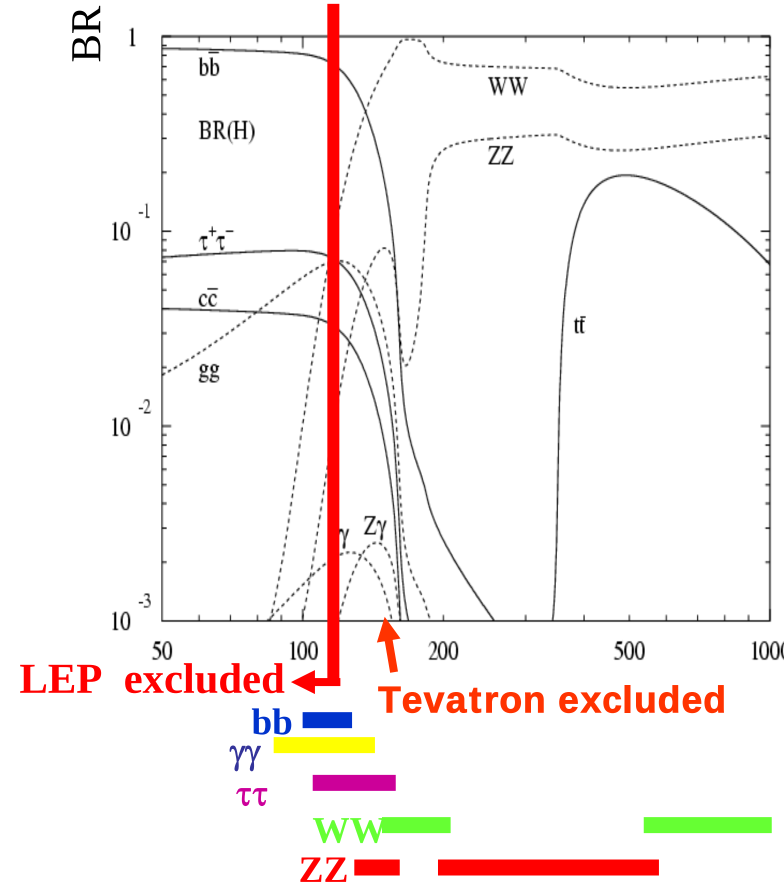
Orders of magnitude of event rates for different physics channels (L~ 10^{34}):

Inelastic	100 mb
bb production	100 μb
$W \rightarrow l\,\nu$	10 nb
tt production	100 pb
Higgs (m=150 GeV)	10 pb
Higgs (m=600 GeV)	10^{-1} pb

Selection power needed for Higgs boson discovery : $10^{14\text{-}15}$

SM Higgs signal





m_H < 130 GeV : H → bb, ττ dominate

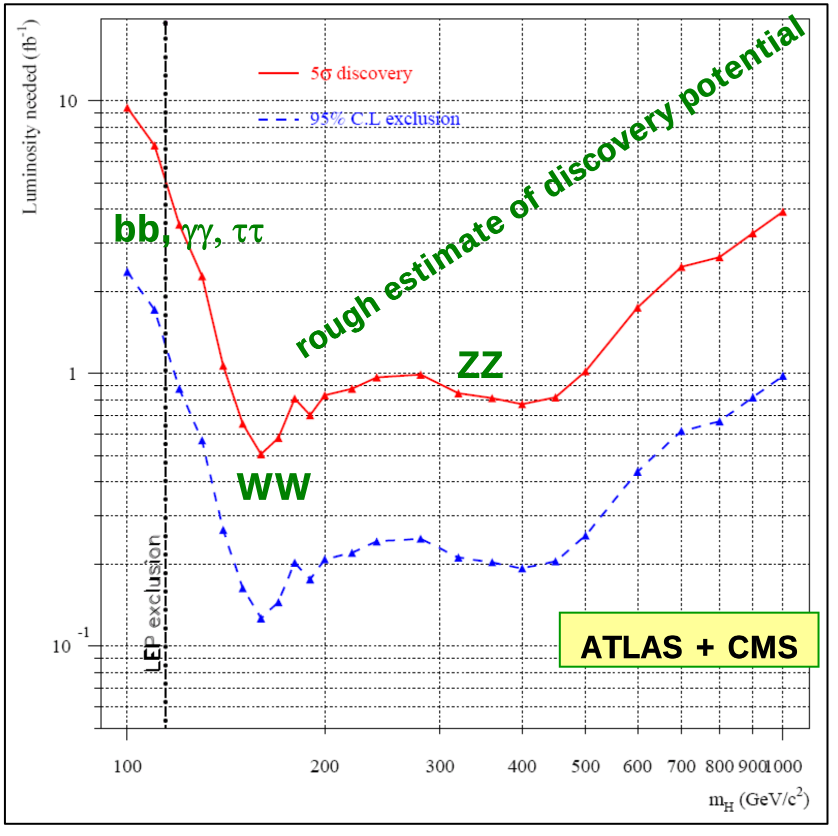
→ best search channels at the LHC : qqH→qq ττ, H → γγ, ttH → lbbX

m_H > 130 GeV : H → $WW^{(*)}$, $ZZ^{(*)}$ dominate

→ best search channels at the LHC : H → $ZZ^{(*)}$ → 4l (gold-plated)

H → $WW^{(*)}$ → lν lν

Prospects for the discovery of the Higgs



Luminosity required for a 5σ discovery or for a 95% CL limit – (< 2006 estimates)

~ < 1 fb^{-1} needed to set a 95% CL limit in most of the mass range

(low mass ~ 115 GeV/c^2 more difficult)

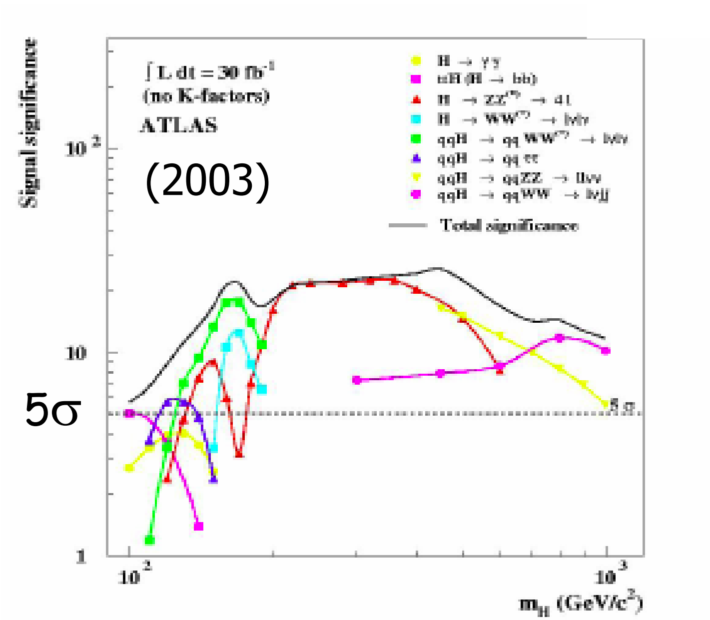
comments:

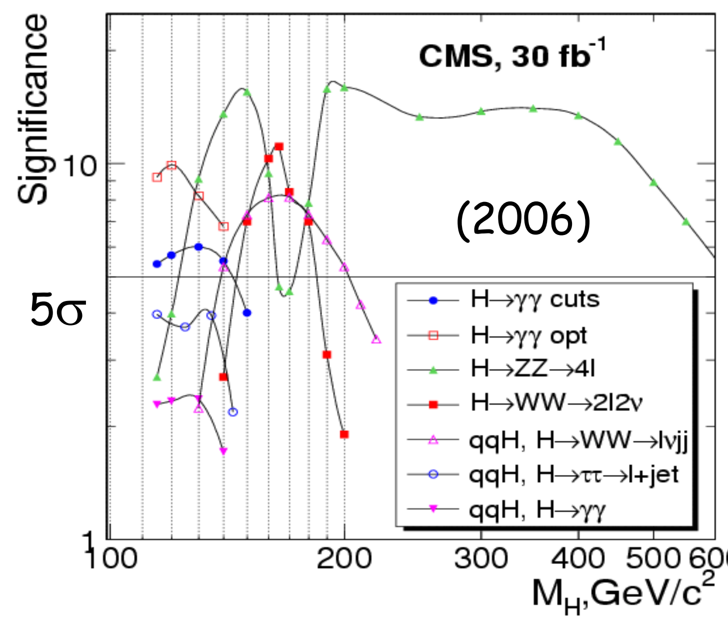
- these curves were optimistic on the ttH, H→ bb performance
- systematic uncertainties assumed to be luminosity dependent (no simple scaling, s ~ √L, possible)

J.J. Blaising, A. De Roeck, J. Ellis, F. Gianotti, P. Janot, G. Rolandi and D. Schlatter, **Eur. Strategy workshop (2006)**

Final word about Higgs mechanism about 2011 (?)

Discovery potential for individual experiments (at the time of **Eur. Strategy workshop (2006)**)





Several overlapping channels. Most difficult remains low mass range.

During last few years big effort to re-establish analyses with strategies for systematics evaluation, background extraction from data, advanced statistical treatment for combinations.

New combination plots from ATLAS: expected exclusion limits

General combination method, based shapes as well as taking systematics into account by use of the profile likelihood ratio, has been prepared.
Four important search channels used in the combination. It is planned to include other channels in the future, in particular for higher Higgs boson masses

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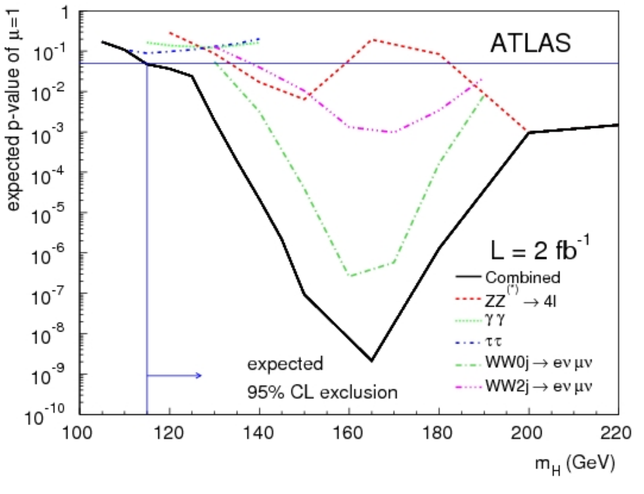

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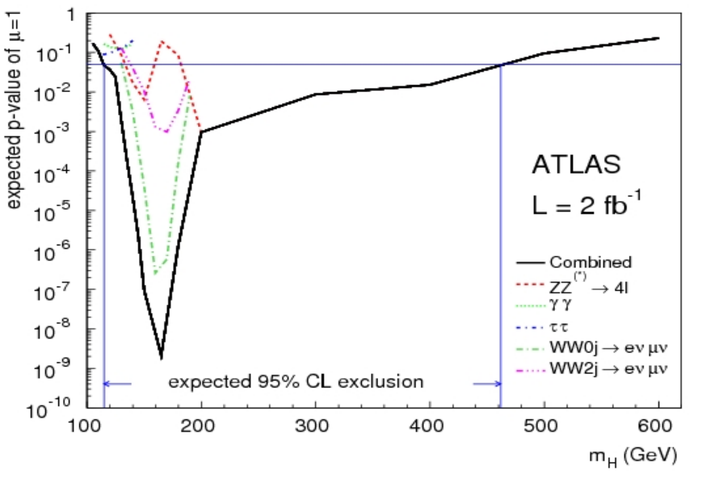

The median p-value obtained for excluding SM Higgs boson for various channels as well as combinations. Value below p=0.05 indicates an exclusion.

With a luminosity of 2 fb^{-1} sensitivity to exclude Higgs boson with mass above 115 GeV at 95% Confidence Level.

New combination plots from ATLAS: expected significances

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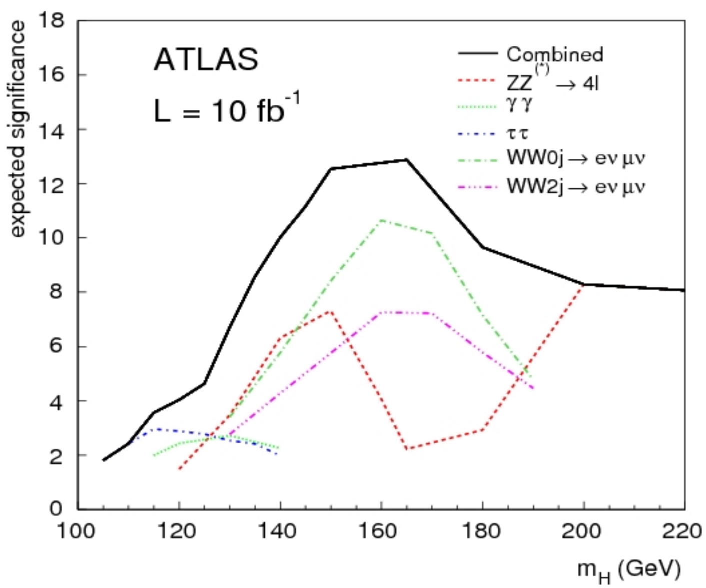

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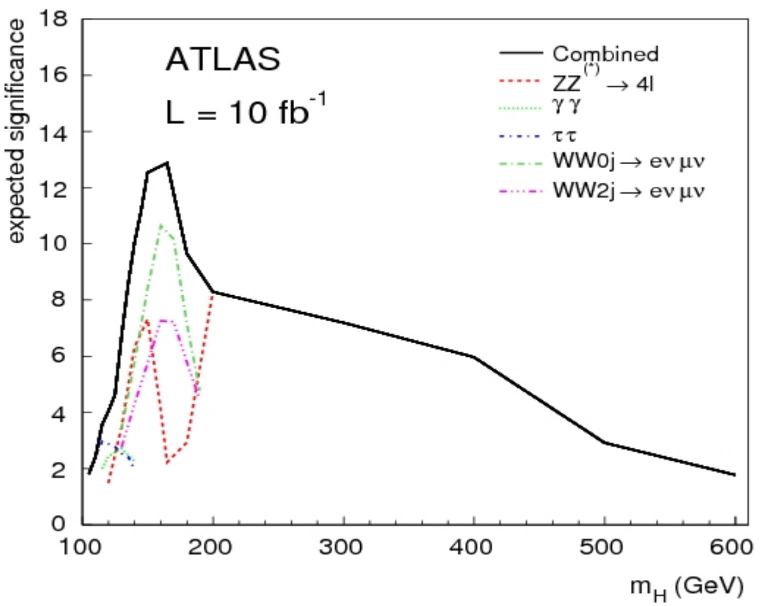

The median discovery significance for the various channels and the combination with an integrated luminosity of 10 fb^{-1}.

With a luminosity of 2 fb^{-1} the expected (median) sensitivity is at 5σ level or greater for discovery of Higgs boson in the mass range between 143 – 179 GeV.

$H \rightarrow \gamma\gamma$

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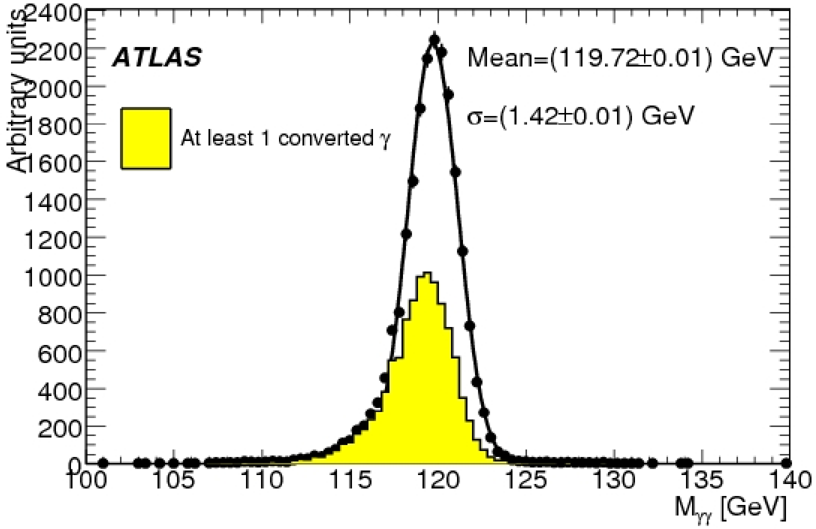
- Excellent energy and angular resolution to achieve ~1.2% resolution in Higgs mass reconstruction, degrading slightly when pileup added.
    - Photon calibration energy scale and resolution, separation of converted and unconverted photons.
    - Photon angle correction from calorimeter pointing and tracking-based vertices.
- Excellent photon identification to reject the large QCD background. Rejection larger than 8 10^3 per single jet with photon efficiency larger than 80%.



Signal	σxBR	Background		σxBR
gg -> H	21 fb	γγ		562 fb
VBF H	2.7 fb	reducible	γ j jj	318 fb 49 fb

Inclusive analysis, after selection in mass window.

$H \to \gamma\gamma$

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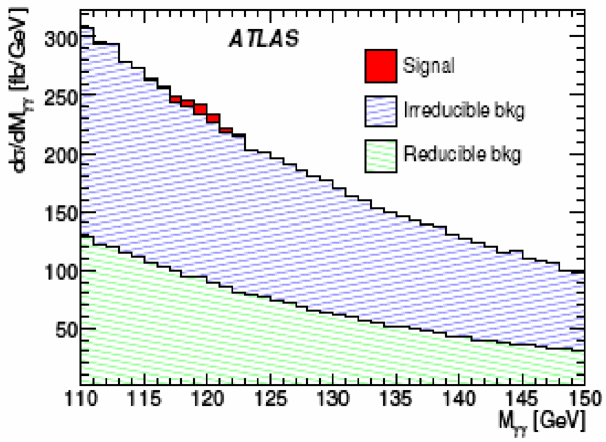
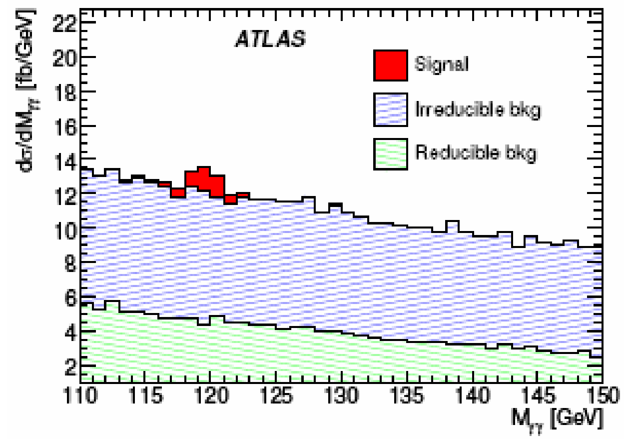
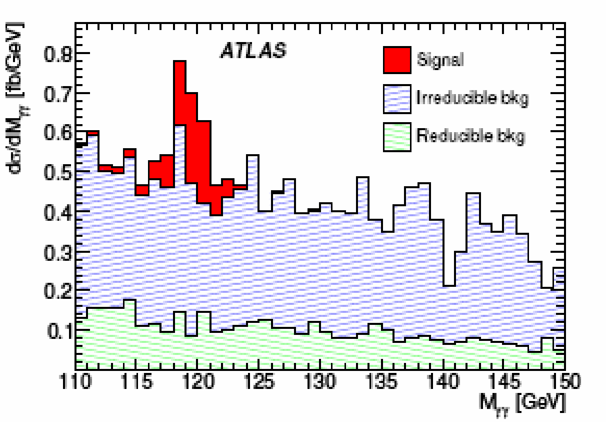


inclusive
S/B ~ .03



H+1j
S/B ~ .08
VBF + more jets with gg→ H



H+2j
S/B ~ .4
VBF mainly

For 10 fb^{-1} and $\pm$ 1.4σ mass window

m_H (GeV)	Inclusive	H+1 jet	H + 2 jets	Combined
120	2.6	1.8	1.9	3.3
130	2.8	2.0	2.1	3.5
140	2.5	1.8	1.7	3.0

Significance based on event counting.
The combined significance is ~25% higher than the significance of the inclusive analysis.

H→4 leptons

- **The experimentally cleanest signature** of high quality reconstructed trajectories.
- **Dominant backgrounds** :

ZZ$^{(*)}$ (PYTHIA + MCFM), Zbb (AcerMC + MCFM), ttbar (MC@NLO).

Reject with p_t threshold; Z mass cuts; calorimetric and tracker isolation of leptons; impact parameter cut.

- **Mass resolution** at 130 GeV:

2.2 GeV (4e), 1.8 GeV (4 μ), 1.9 GeV (2e 2μ).

Sensitivity in channels with different lepton flavours calculated with Poisson statistics and without systematic errors.

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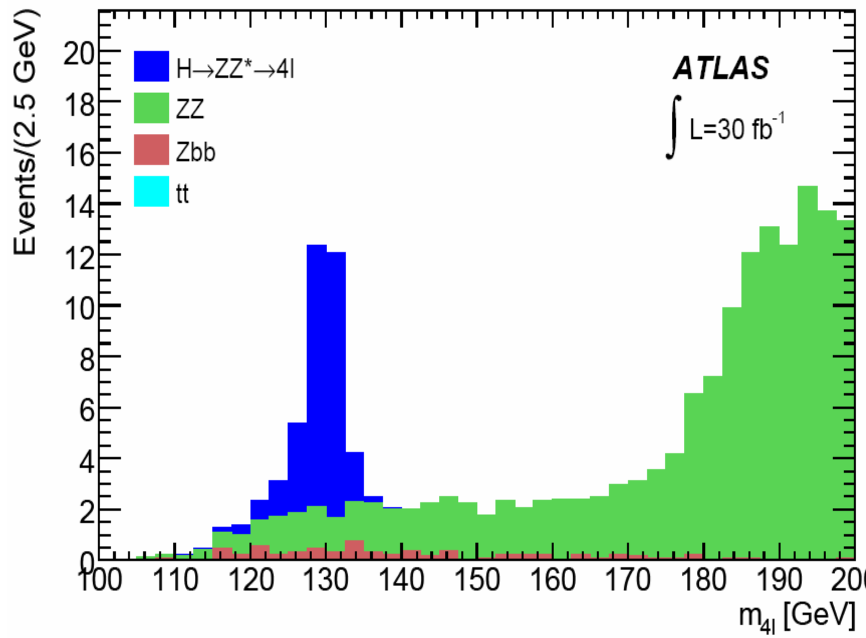

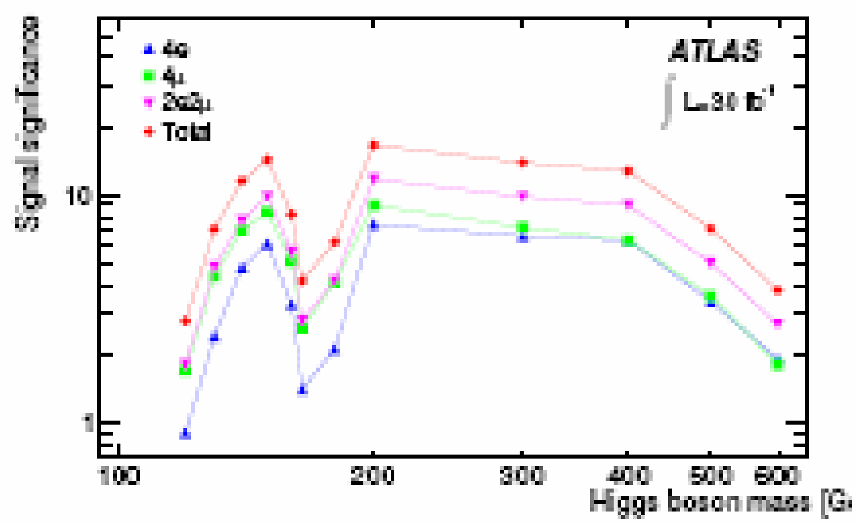

H→ 4 leptons

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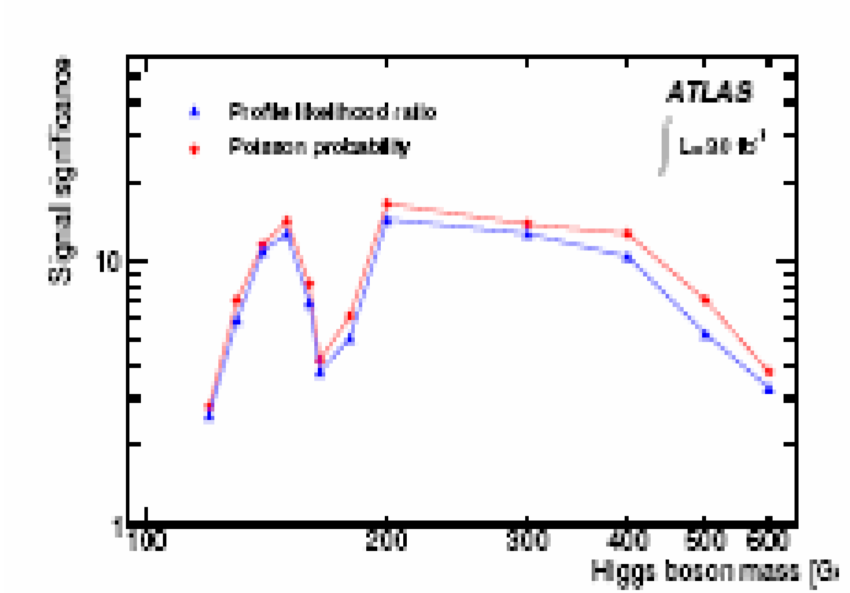

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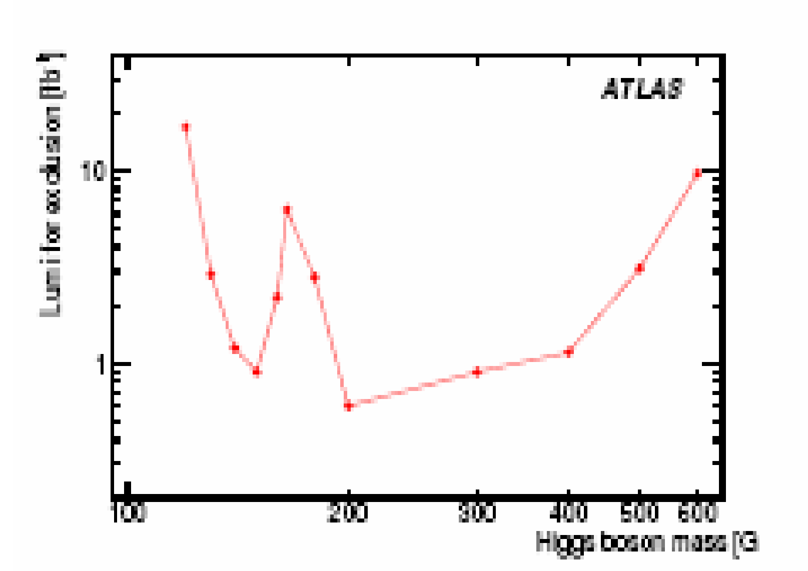


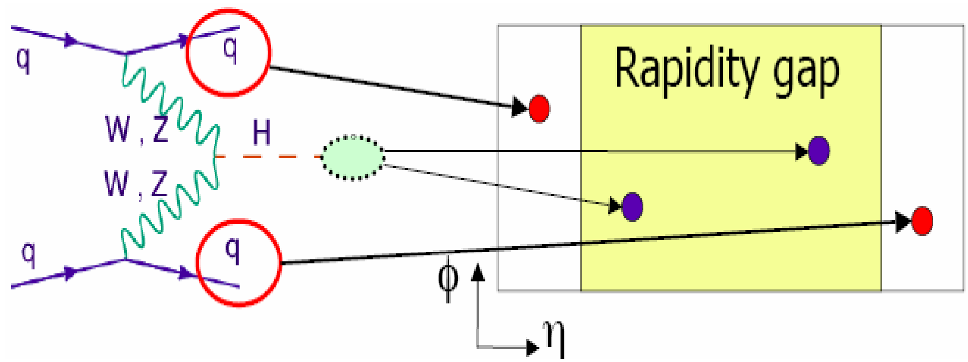
Combined sensitivity (red) from the profile likelihood ratio.

Inclusion of systematics effects have a total effect less than 4%.

Compared to the one (blue) calculated from Poisson statistics and without systematic errors.

Less than 1 fb^{-1} with H → ZZ→ 4l channel alone needed for exclusion at 150 GeV.

VBF H → ττ



- Lep-lep, lep-had, had-had final states
- **Selection flow:**
  - identify had-taus and/or leptons
  - tag forward jets
  - require evidence for rapidity gap
  - reconstruct invariant mass of ττ system
- **Backgrounds:**

large, need to achieve rejection factors (challenging to simulated adequate in size MC samples).

Rejection needed: 10^5 (Z, W), 10^{11} (QCD)

- **Data-driven methods to control bgds:**
  - QCD bgd from track multiplicity tail of hadronic taus.
  - Z+jets bgd from emulated taus using Z→μμ events, with μ replaced by simulated tau

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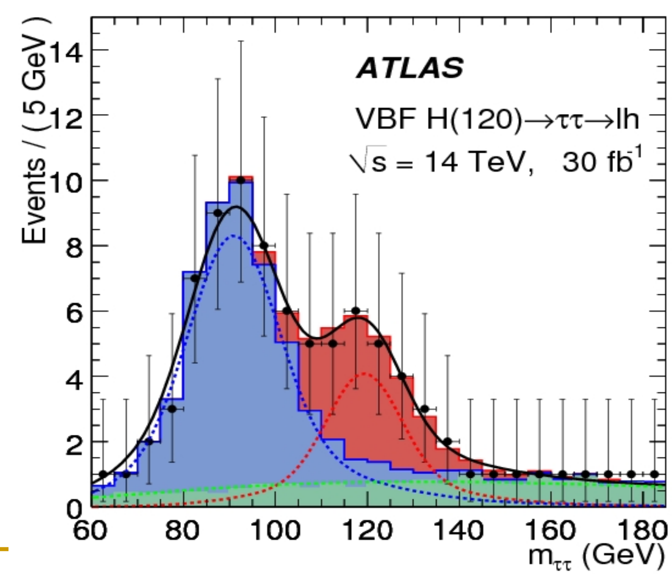

VBF $H \rightarrow \tau\tau$

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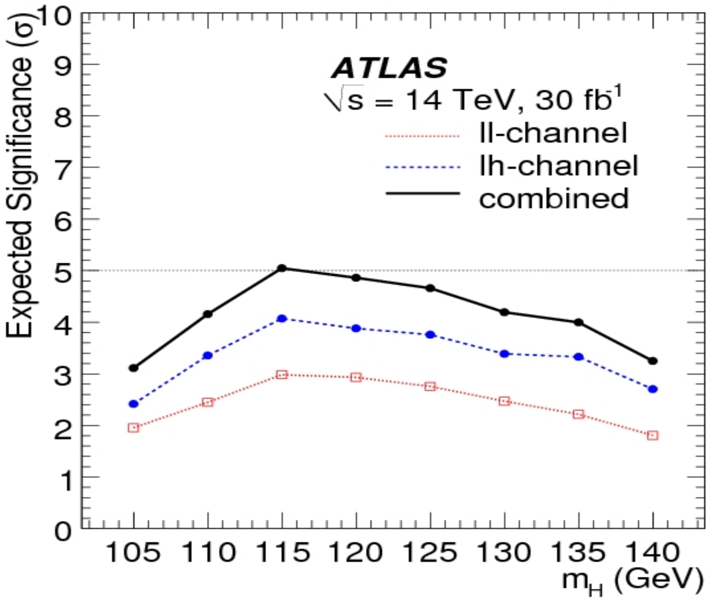
Only lep-had and lep-lep channels used for combination due to challenge in predicting QCD bgd for had-had final state.



Expected signal significance based on fitting $m_{\tau\tau}$ spectrum, background uncertainties incorporated by using profile likelihood ratio. Pile-up not included.

m_H (GeV)	ll - channel	lh-channel	combined
115	2.98	3.35	5.04
125	2.75	3.75	4.65
135	2.21	3.32	3.99

Results without pile-up indicates sensitivity up to 5σ for 30fb^{-1}, m_H=115 - 125 GeV and combining lep-lep and lep-had channels.

The mass resolution is approximately 10 GeV, leading to 3.5% precision on mass measurement.

gg and VBF production

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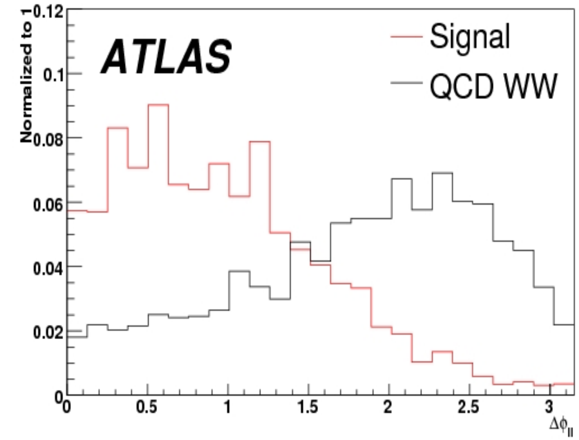
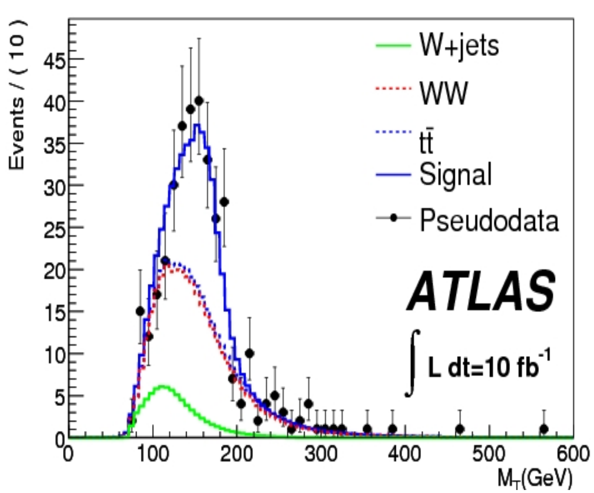
$H \rightarrow WW^{(*)} \rightarrow e\nu\ \mu\nu$

- **Final state:** two leptons and significant missing energy in second case also forward jets with large rapidity gap.
- **Higgs mass is not reconstructed directly**, so less sensitive to E_T^{miss} resolution. Use transverse mass only.
- **Proper modeling of bgd kinematics crucial**: spin correlations, forward jets, rapidity gap.
- **Established data-driven methods** to control bgd.



Transverse opening angle Δϕ(ll)



Transverse mass for events after selection.

Cross-section (in fb) after all cuts for a number-counting analysis H+0jets.

Region	Signal (mH=170GeV)	ttbar	WW	$Z\rightarrow\tau\tau$	W+jets
Signal-like	28.65 ± 0.80	1.13 ± 1.14	29.3 ± 1.59	< 1.74	38±38
Control	1.47 ± 0.27	5.71 ± 2.55	61.13± 2.33	4.06 ± 0.82	<114
b-tagged	0	6.85 ± 2.80	0.11±0.09	1.16±0.82	<114

gg and VBF production $H \rightarrow WW^{(*)} \rightarrow e\nu\ \mu\nu$

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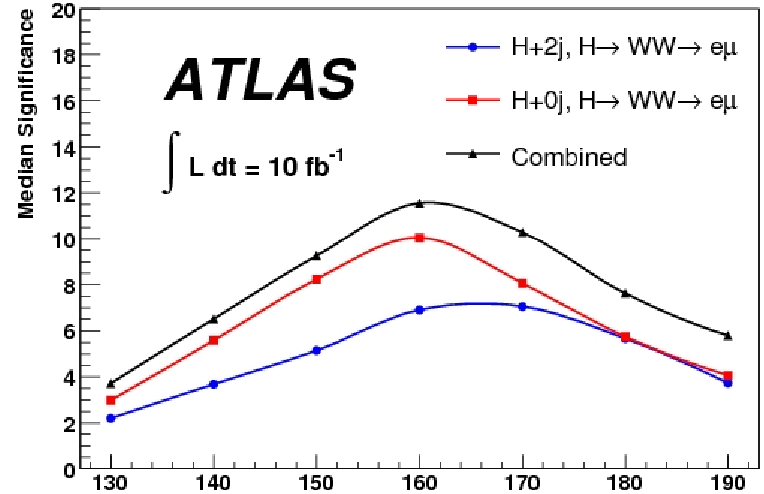
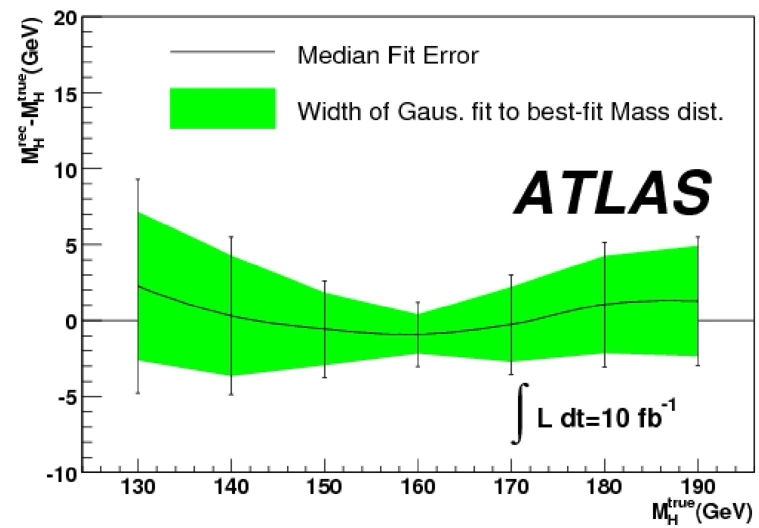
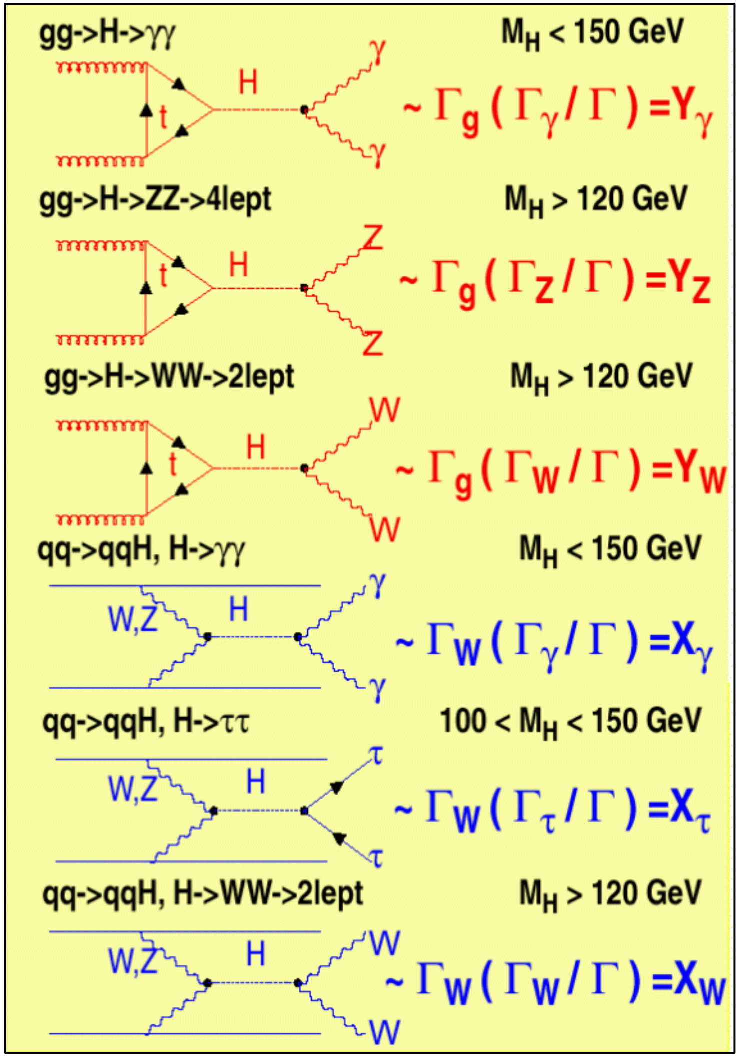
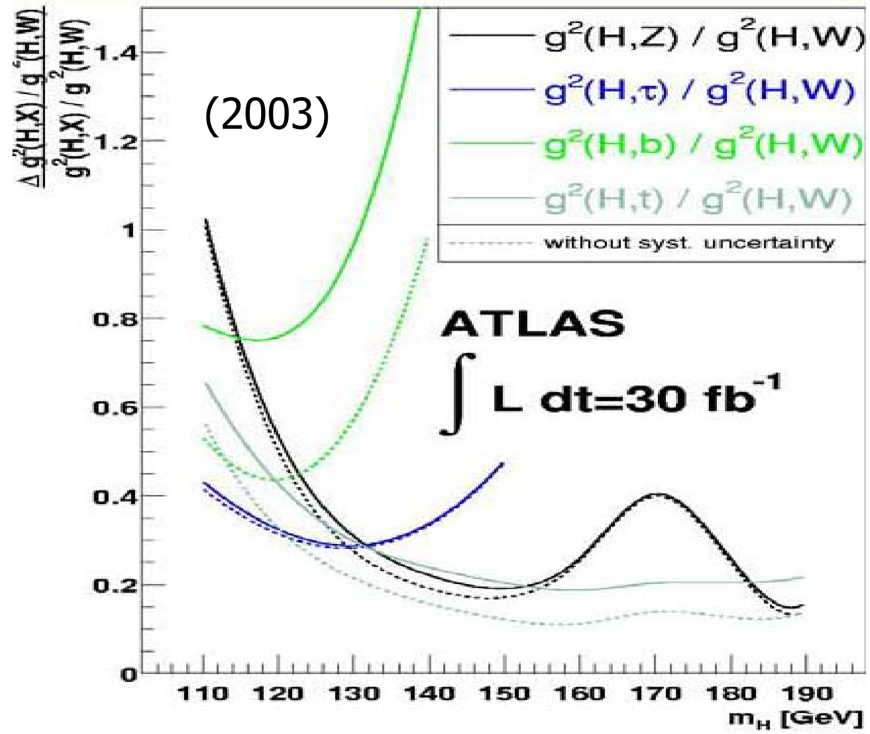
- For **inclusive production (H+0j)** above 5σ sensitivity for masses 140-185 GeV for $10fb^{-1}$. Background control with two dimensional fit to transverse mass and momenta of the WW system.
- Spectrum sensitivity to the mass of 2 GeV (about 160 GeV) , 4 GeV (about 140 GeV).
- For **VBF H** sensitivity above 5σ in range 150-180 GeV. Spectrum sensitivity to the mass of 4 GeV (about 160 GeV) and 8 GeV (about 140 GeV).
- For **combined channels** sensitivity 5σ for m_H larger than 140 GeV.





Measurements of the SM Higgs boson properties





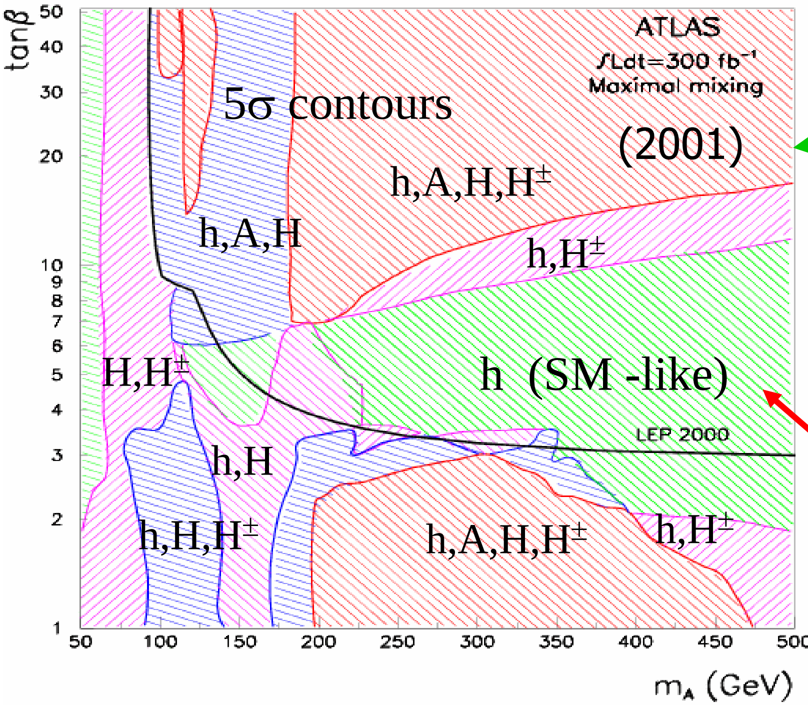
Mass will be measured with precision of 0.1% in mass range 130-450 GeV (gg, H->4l).

Angular distributions in in H->4l sensitive to **spin and CP** eigenvalue.

Relative couplings will be measured with precision of 20% at 300fb^{-1}.

The Higgs self-coupling would require the super-LHC.

LHC discovery potential for SUSY Higgs bosons



A, H, H± cross-sections ~ $\tan^2\beta$

-best sensitivity from
$A/H \rightarrow \tau\tau$, $H^\pm \rightarrow \tau\nu$
(not easy the first year ....)

- $A/H \rightarrow \mu\mu$ experimentally easier
(esp. at the beginning)

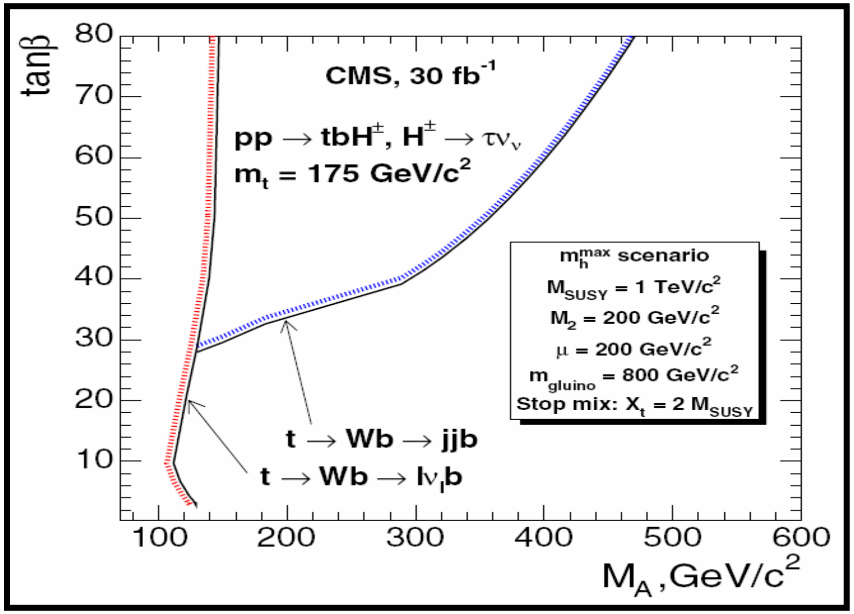
Here only SM-like h observable if SUSY particles neglected.

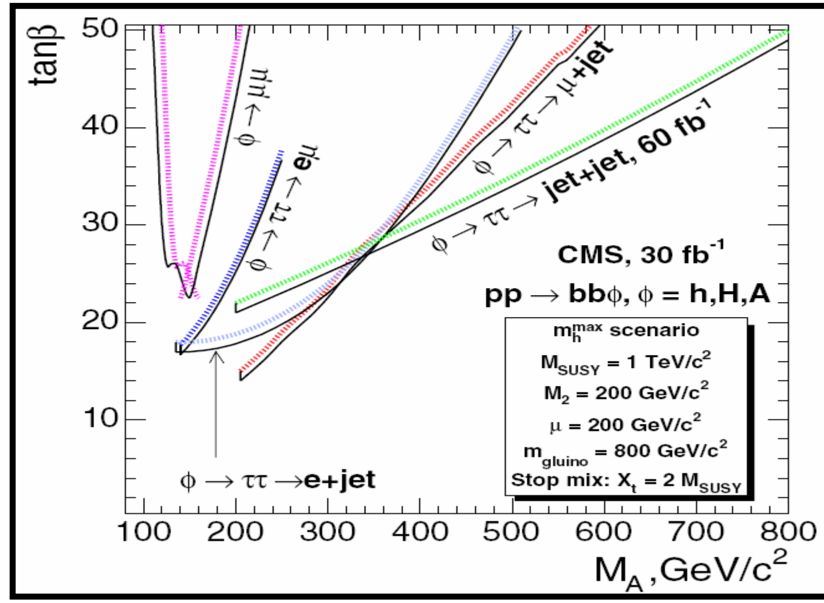
- 4 Higgs observable
- 3 Higgs observable
- 2 Higgs observable
- 1 Higgs observable

Coverage in the large m_A edge region can be improved (slightly) by:

- Higher luminosity: sLHC
- Additional SUSY decay modes (however, model dependent)

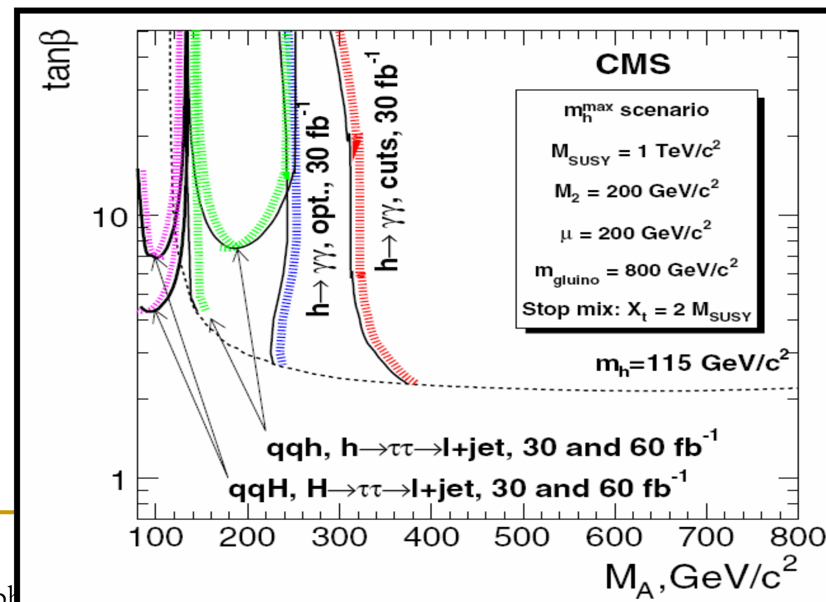
General 5 σ discovery regions in MSSM (m_h^{max} scenario)





Everything is covered

CMS TDR



The MSSM neutral Higgses: di-muon channel

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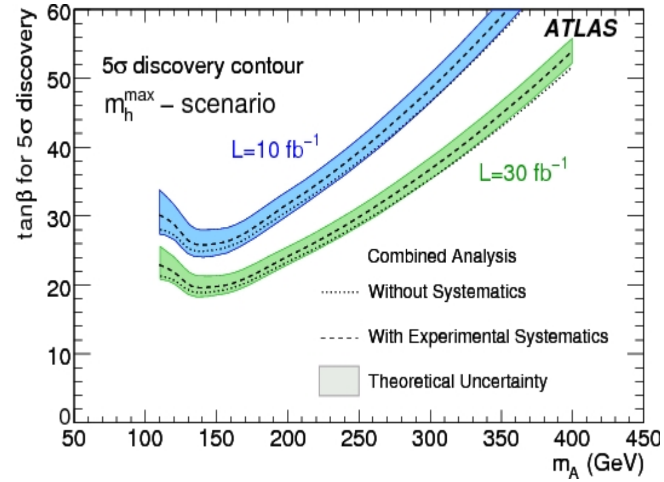
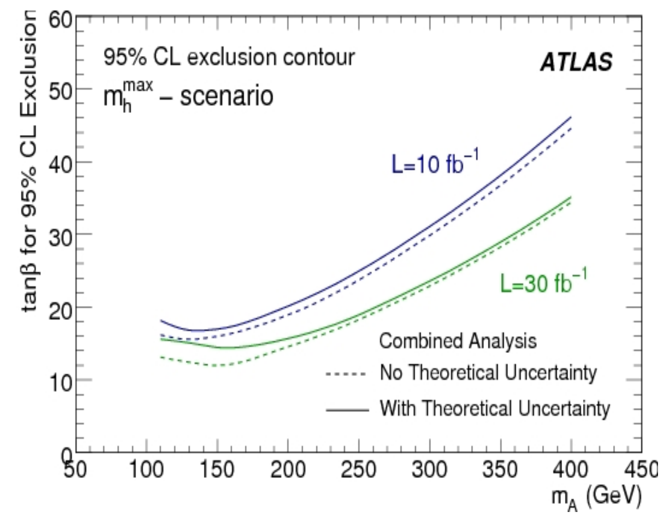
- **Not visible in SM , enhanced in MSSM**
- **Combine analyses**: 0-bjet and at least 1 b-jet
- Z+jets bgd dominates at low masses, tt becomes at important at higher.
- Average muon p_T resolution better than 3%, allows for **excellent di-muon mass resolution**.
- Theoretical uncertainty on the signal is up to 20% while the detector-related systematic uncertainties degradate signal significance by 5-10%.





Sensitivity not as good as in ττ channel but may be easier at the beginning.

The MSSM charged Higgs

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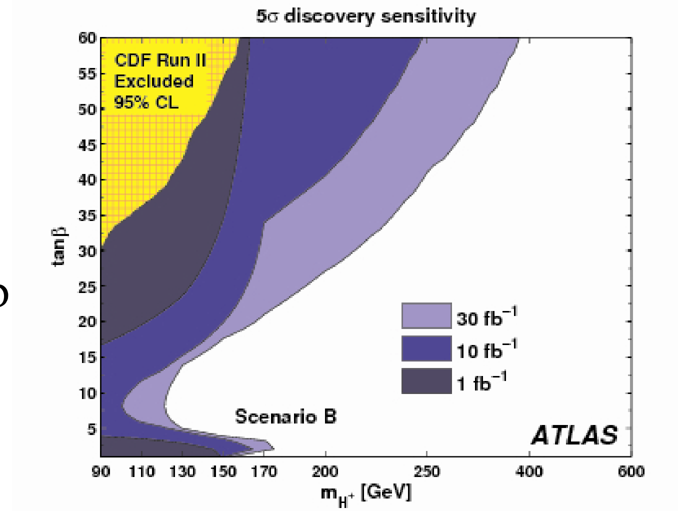
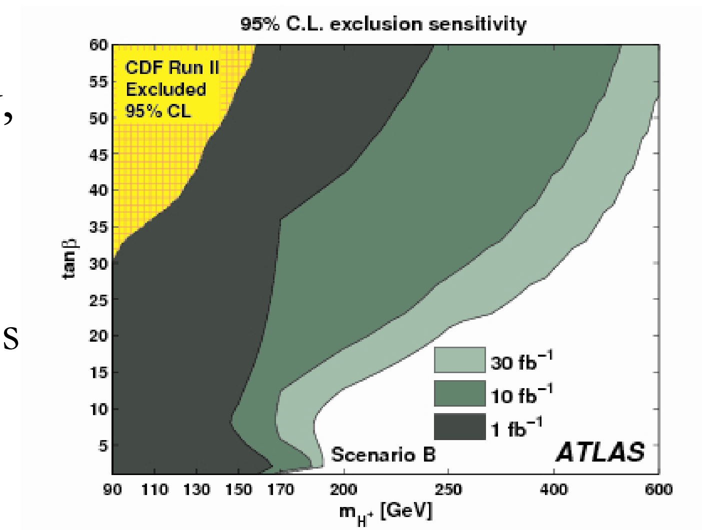
- Naturally **predicted in many non-minimal Higgs** scenarios, here presented typeII-2HDM, mh-max.
- **Light charged Higgs** (below top mass)
  - dominant production is tt, with $t \rightarrow H^{\pm}b$
  - dominant decay mode $H^{\pm} \rightarrow \tau\nu$
- **Heavy charged Higgs** (above top mass)
  - dominant production $gg/gb \rightarrow t(b)H^{\pm}$
  - dominant decay $H^{\pm} \rightarrow \tau\nu$ or $H^{\pm} \rightarrow tb$
- **Final states:** 2-4 b-jets, light jets from W decay, neutrinos, most channels with tau-lepton.
- **Several topologies** (i.e. five) studied.
- **Profile Likelihood** used for discovery or exclusion including 10% systematic uncertainties on bgd (data-driven control on tt background shape and normalisation).





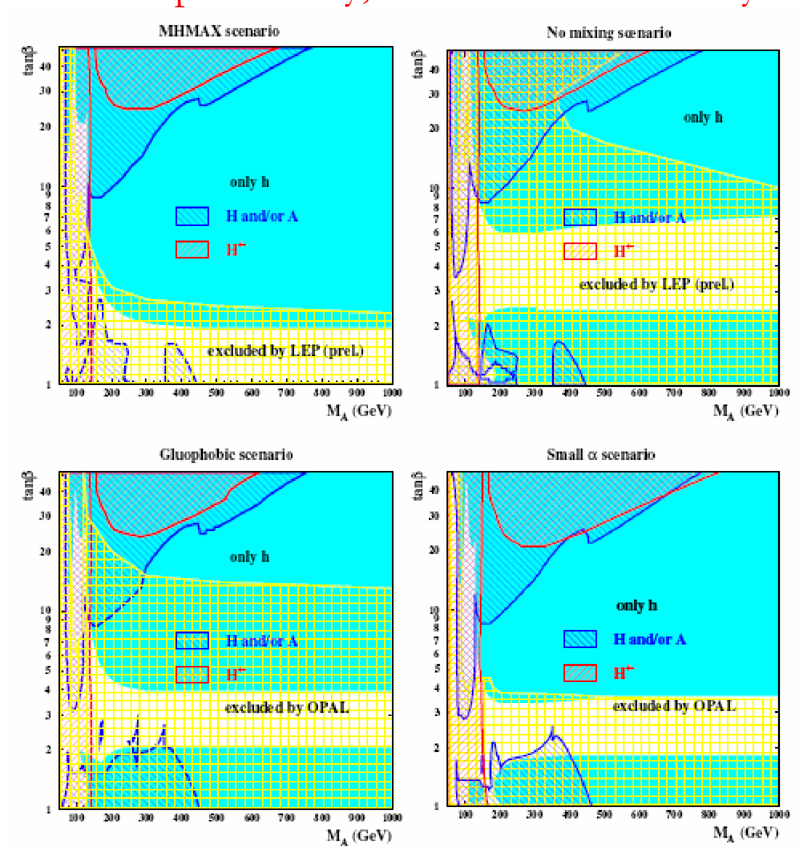
Expect significant improvement of present day constraints already with $1fb^{-1}$.

assuming infMC

Different benchmark scenarios

Benchmark scenarios as defined by M.Carena et al. (h mainly affected)

ATLAS preliminary, 30 fb^{-1}, 5σ discovery (2004)



MHMAX scenario (M_{SUSY} = 1 TeV/c^2)

maximal theoretically allowed region for m_h

Nomixing scenario (M_{SUSY} = 2 TeV/c^2)

(1TeV almost excl. by LEP)

small m_h → difficult for LHC

Gluophobic scenario (M_{SUSY} = 350 GeV/c^2)

coupling to gluons suppressed

(cancellation of top + stop loops)

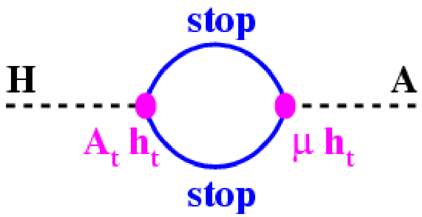
small rate for g g → H, H→ **gg** and Z→4 ℓ

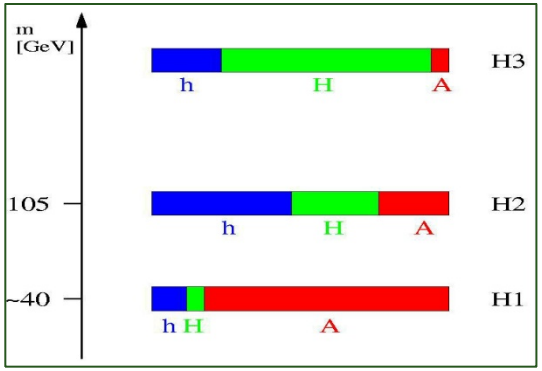
Small a scenario (M_{SUSY} = 800 GeV/c^2)

coupling to b (and **t**) suppressed (cancellation of sbottom, gluino loops) for large tan b and M_A =100 to 500 GeV/c^2

Higgs search in CP-violating scenarios

- CP conservation at Born level, but CP violation via complex **A_t, A_b, M….**

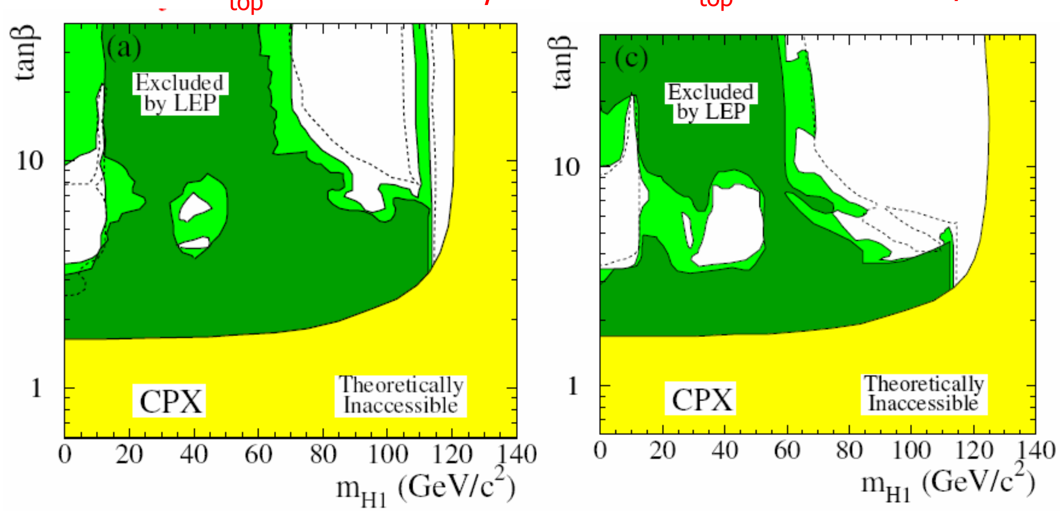




-CP eigenstates h, A, H mix to mass eigenstates H_1, H_2, H_3

Effect maximized in a defined benchmark scenario (CPX)

m_{top} = 169.3 GeV/c² m_{top} = 174.3 GeV/c²



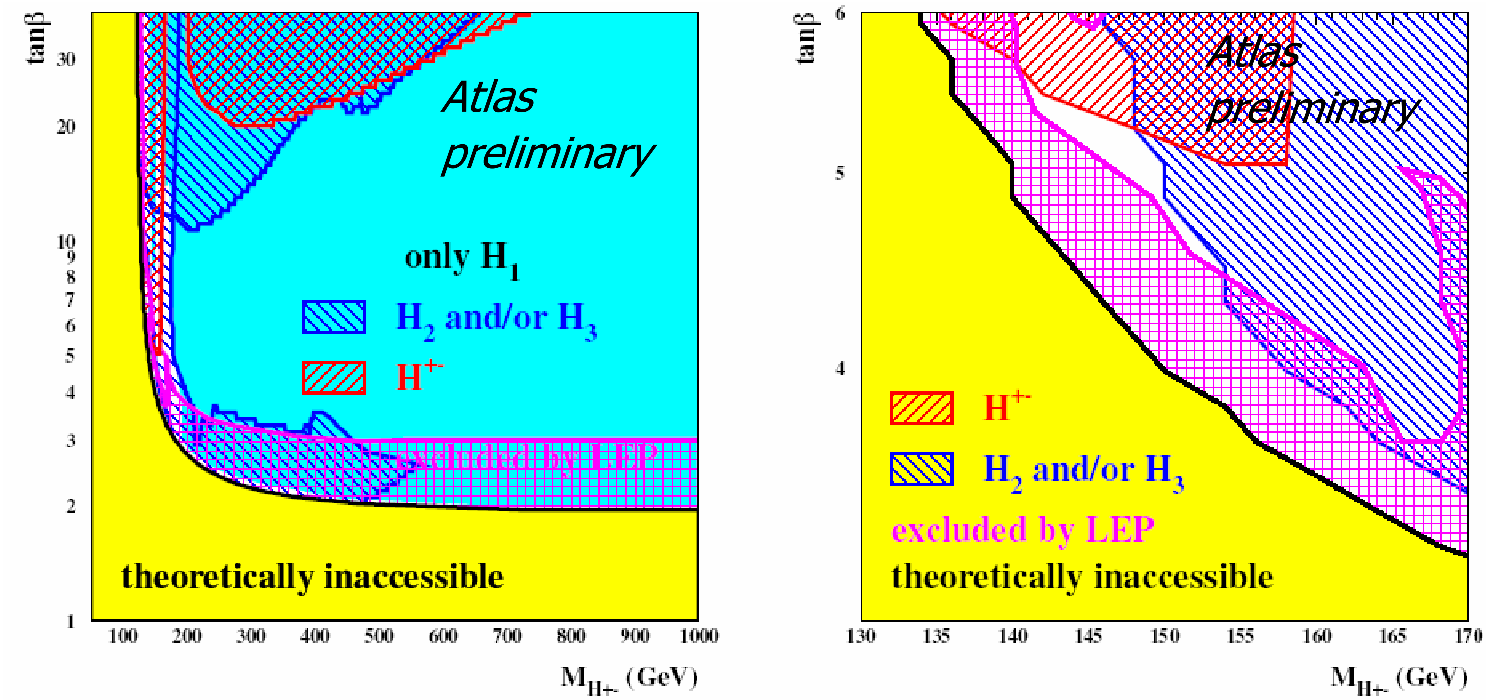
(M. Carena et al., Phys.Lett. B 495 155 (2000))

$\arg(A_t) = \arg(A_b) = \arg(M_{gluino}) = 90^o$

No lower mass limit for H_1 from LEP !
(decoupling from the Z)
details depend on m_{top} and on theory model
(FeynHiggs vs. CPsuperH)

MSSM discovery potential for the CPX scenario

(2006)



- Large fraction of the parameter range can be covered, however, small hole at (intermediate tanβ , low m_{H+}) corresponding to low m_{H_1}
- More studies needed, e.g. investigate lower H_1 masses, additional decay channels: $tt \rightarrow Wb\, H^{+}b \rightarrow \ell\nu b\, WH_1 b$, $H_1 \rightarrow bb$

Summary

- The LHC experiments are well set up to explore the existence of a Standard Model or MSSM Higgs bosons and are well prepared for unexpected scenarios.
- The full Standard Model mass range and the full MSSM parameter space can be covered (CP conserving case).
- In addition important parameter measurements (mass, spin, ratio of couplings) can be performed (VBF processes important).
- More difficult invisible Higgs boson decays or NMSSM models.

LHC data will hopefully soon give guidance to the theory and to future experiments.

The first Higgs in ATLAS … (4th April 2008)

Toolbox for Higgs studies in ATLAS

- Event generators
  - Full MC generators (LO ME + PS, hard process, ISR/FSR)
    - PYTHIA, HERWIG, SHERPA
  - ME MC generators (hard process only)
    - AcerMC, ALPGEN, COMPHEP, MADGRAPH
  - NLO MC generators
    - MC@NLO, GRACE, NLOJET, JETPHOX
- For comparison studies
  - Semi-inclusive MC generators
    - ResBos, Diphox
- For evaluation of cross-sections or BR
  - Integrators (only total xsection or BR, some cuts possible)
    - HIGLU, QQH, VVH, HDECAY, FEYNHIGGS
    - MCFM (also 4-vectors possible)

Application of N(N)LO corrections in MC's crucial for proper understanding of backgrounds and increase power of inclusive analyses