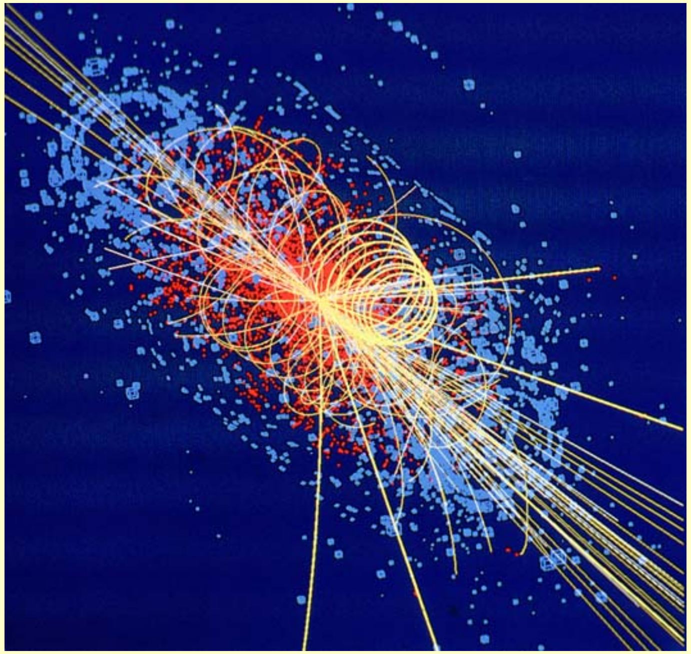
Prospects for Higgs Boson Searches at the LHC



- Introduction, Status of the ATLAS experiment
- Updated results on SM Higgs Searches
- Measurement of Higgs Boson parameters
- MSSM Higgs bosons and more exotic scenarios

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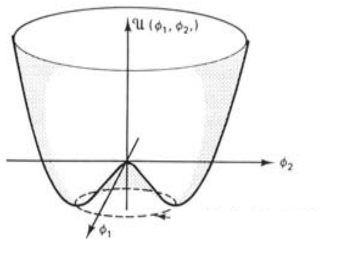
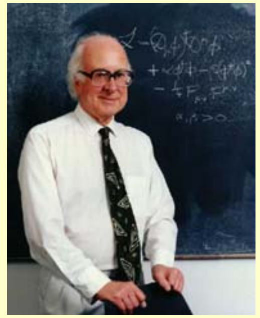
Universität Freiburg / Germany



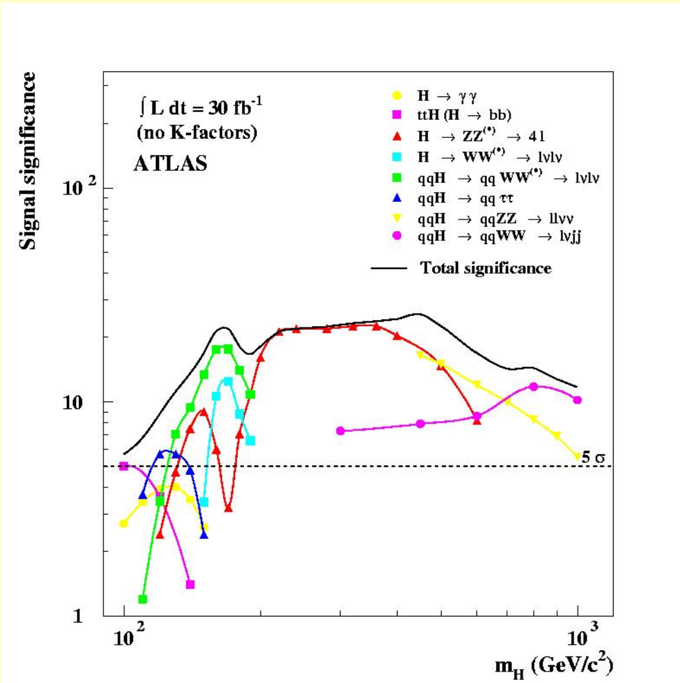
The Higgs Boson

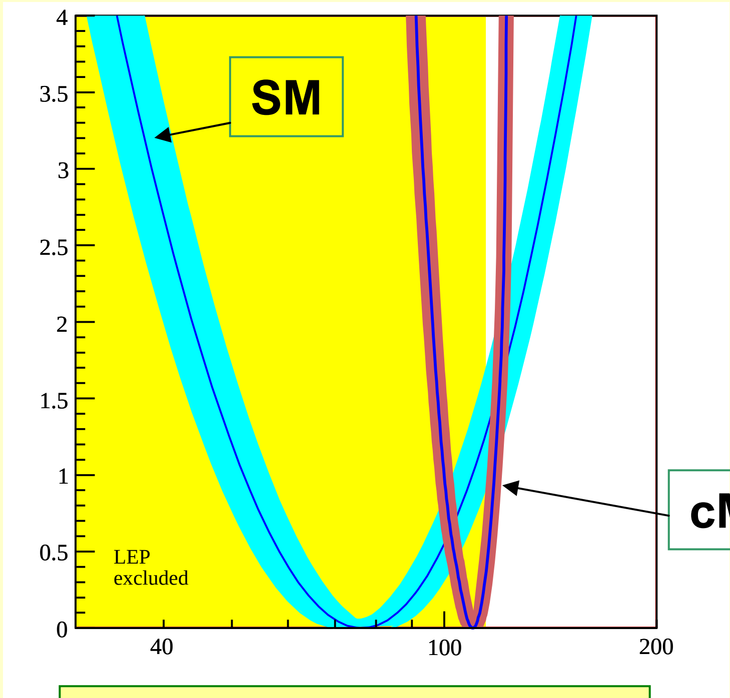


- "Revealing the physical mechanism that is responsible for the breaking of electroweak symmetry is one of the key problems in particle physics"

- "A new collider, such as the LHC must have the potential to detect this particle, should it exist."

O. Buchmüller et al., arXiv:0707.3447





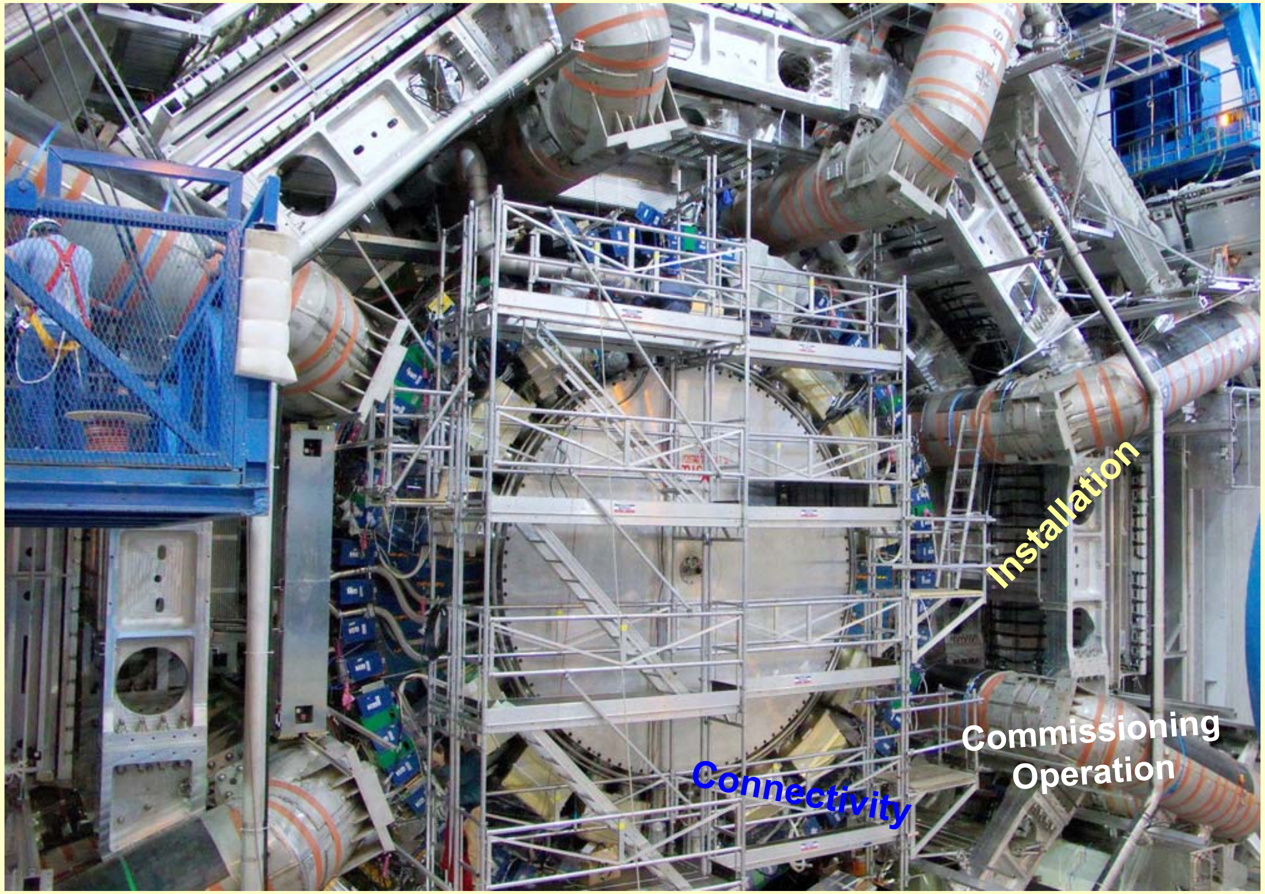
Includes:
- WMAP
- $b \rightarrow s\gamma$
- a_μ

…expected to be achieved (ATLAS & CMS studies)

m_h = 110 (+8) (-10) ± 3 (theo) GeV/c^2

….watch the low mass region !

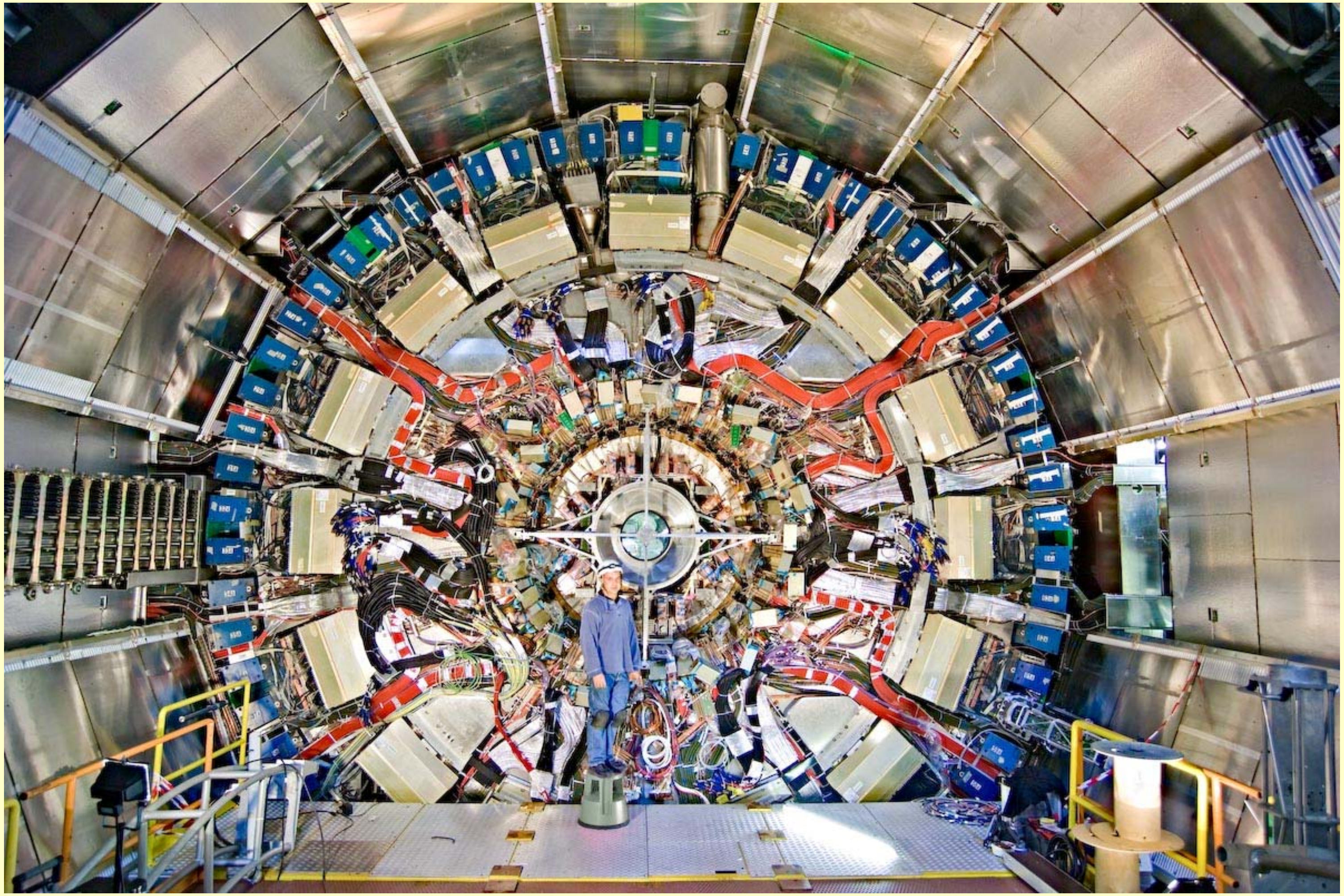
Status of the ATLAS Installation



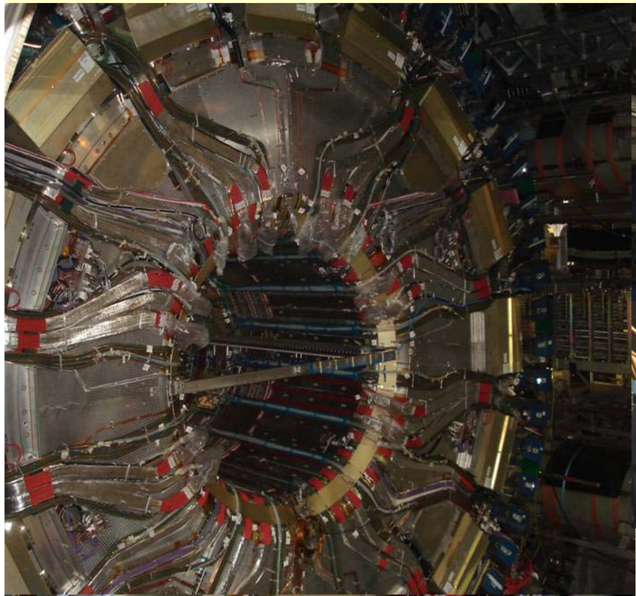
Calorimeters in place, since Sept. 2006

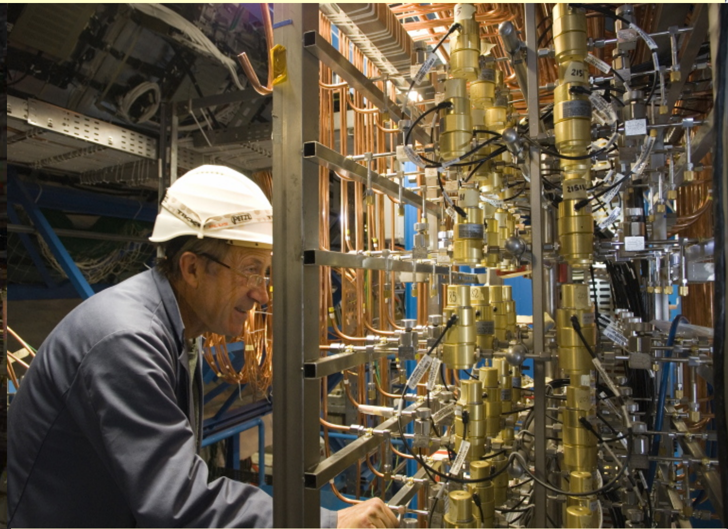
- Installation and Commissioning of the detector in full swing
- ATLAS will be ready for first pp collisions in Summer 2008

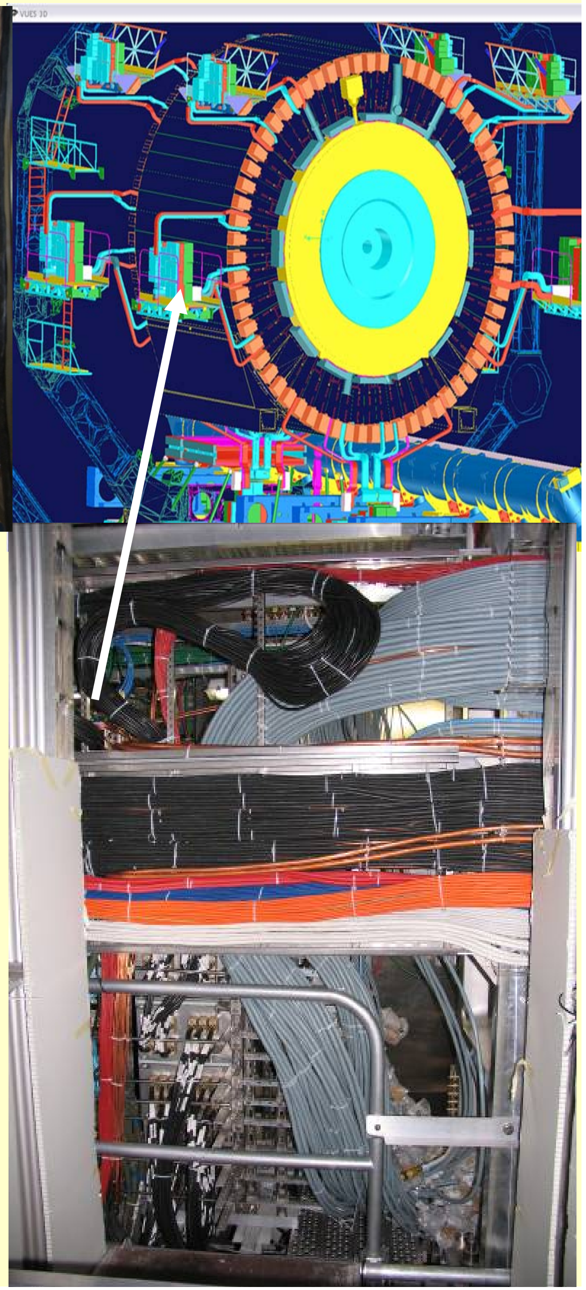
Installation of one of the ATLAS Endcap Tracking Detectors (completed on 29. May 2007)



Installation of Inner Detector Services







~ 800 man-months of installation work over

~18 months, ~ 45 people involved/day

- ✓ ~ 9300 SCT cable-bundles
- ✓ ~ 3600 pixel cable-bundles
- ✓ ~ 30100 TRT cables
- ✓ ~ 2800 cooling & gas pipes

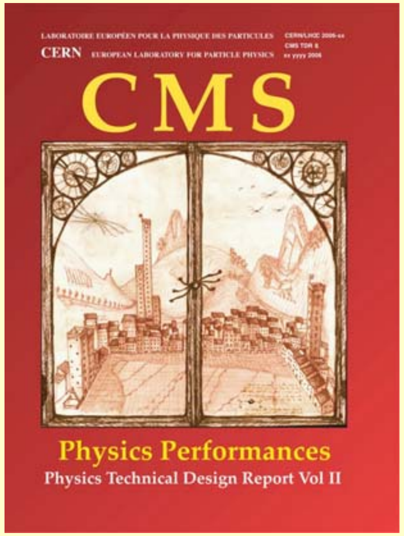
All tested and qualified

Muon detectors and endcap toroid magnets

Installation of the second (last) endcap toroid: 12. July 07

What is new on LHC Higgs studies ?

- Many studies have meanwhile been performed using detailed GEANT simulations of the detectors
  - Physics Performance Technical Design Report from the CMS collaboration
  - ATLAS CSC (Computing System Challenge) notes in preparation, to be released towards the end of 2007



CERN / LHCC 2006-021

- New (N)NLO Monte Carlos (also for backgrounds)
  - MCFM Monte Carlo, J. Campbell and K. Ellis, http://mcfm.fnal.gov
  - MC@NLO Monte Carlo, S.Frixione and B. Webber, wwwweb.phy.cam.ar.uk/theory/
  - T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D68, 073005 (2003)
  - E.L.Berger and J. Campbell, Phys. Rev. D70, 073011 (2004)
  - C. Anastasiou, K. Melnikov and F. Petriello, hep-ph/0409088 and hep-ph/0501130
  - …..

- New approaches to match parton showers and matrix elements
  - ALPGEN Monte Carlo + MLM matching, M. Mangano et al.
  - SHERPA Monte Carlo, F. Krauss et al.
  - …

  Tevatron data are extremely valuable for validation, work has started

- More detailed, better understood reconstruction methods

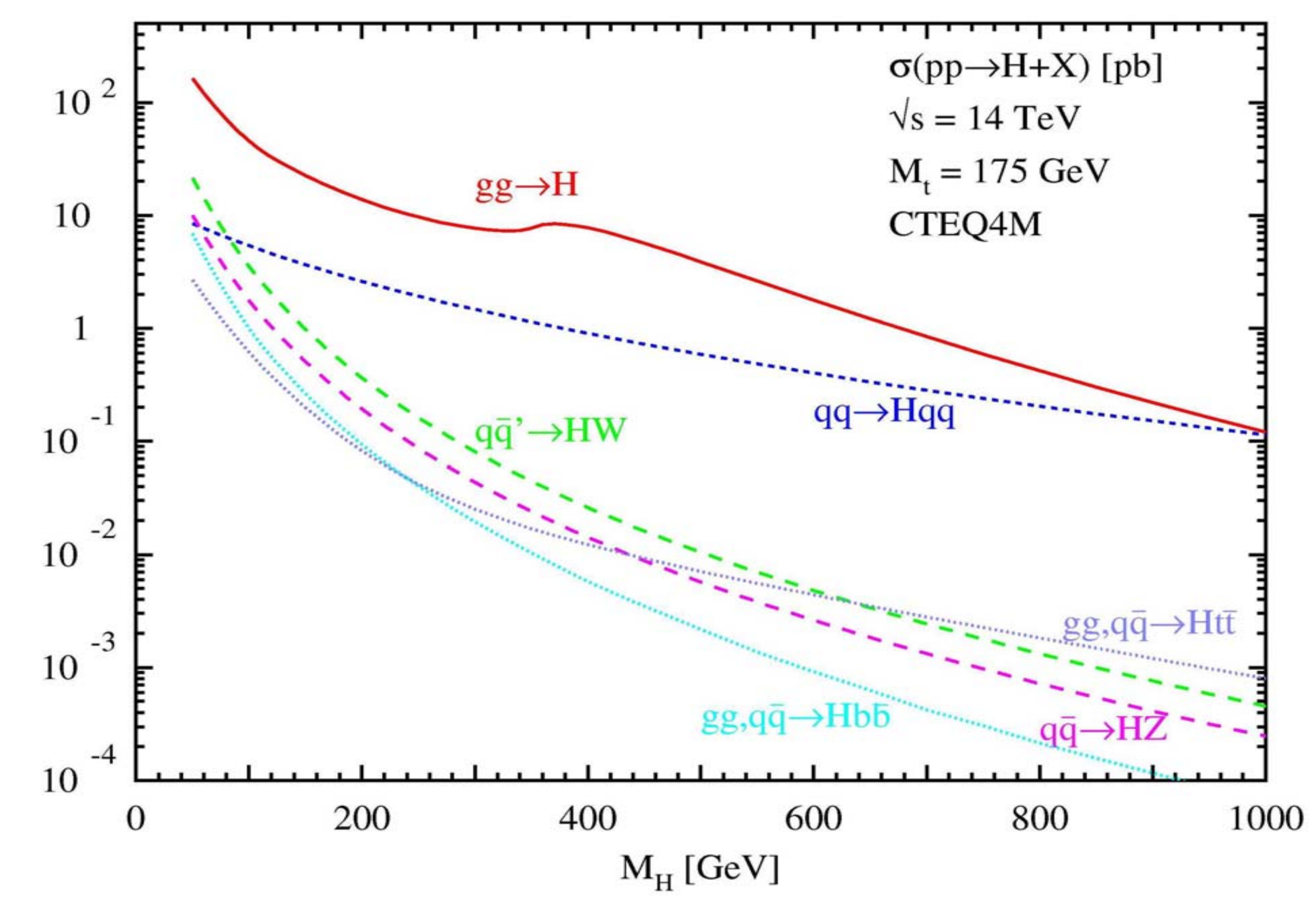
  (partially based on test beam results,…)

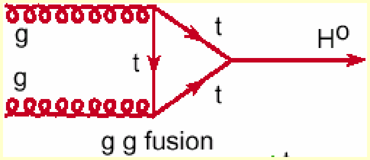
- Further studies of new Higgs boson scenarios

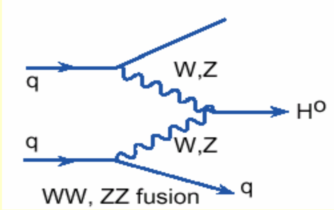
  (Various MSSM benchmark scenarios, CP-violating scenarios, Invisible Higgs boson decays,…..)

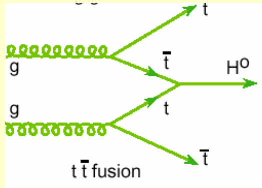
Standard Model
Higgs Boson Searches

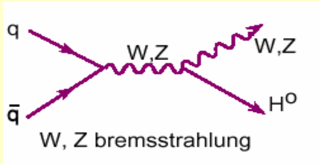
NLO cross sections, M.Spira et al.











H → ZZ* → ℓℓ ℓℓ

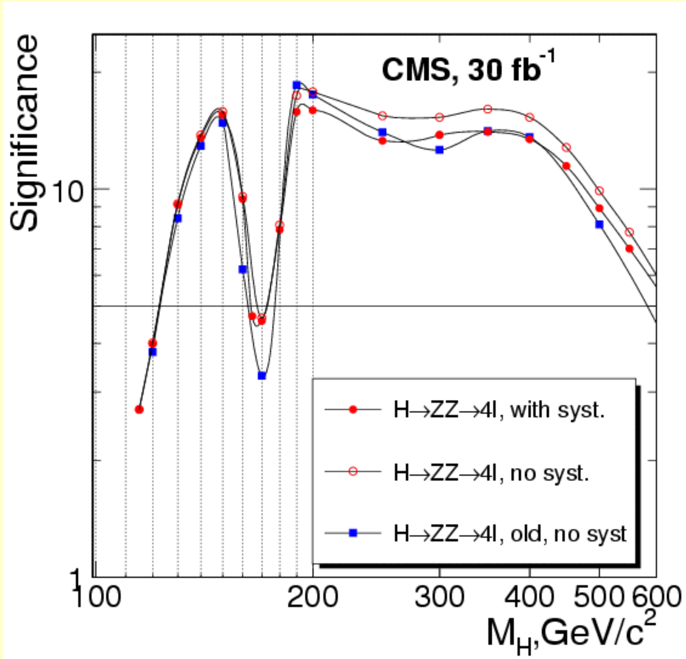
- Main backgrounds: ZZ (irreducible), tt, Zbb (reducible)

- Main experimental tools for background suppression:
  - lepton isolation in the tracker and in the calorimeter
  - impact parameter

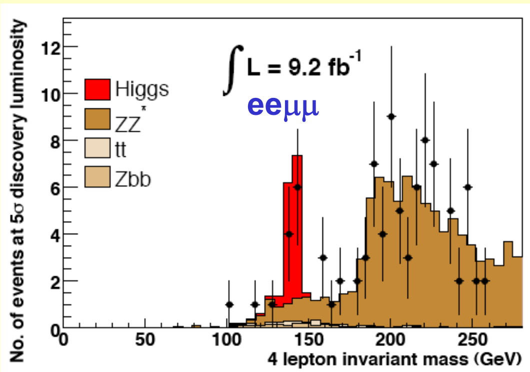
Updated CMS study:

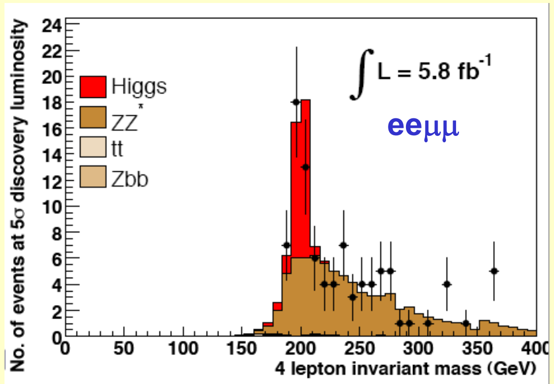
- ZZ background: NLO K factor used
- background from side bands

(gg->ZZ is added as 20% of the LO qq->ZZ)



Signal and background at 5 σ discovery

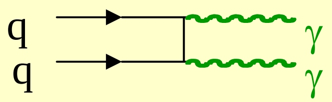




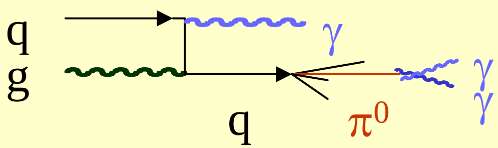
$H \rightarrow \gamma\gamma$

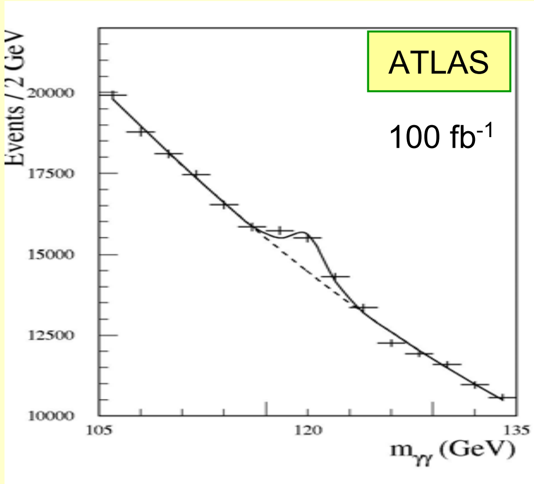
Main backgrounds:

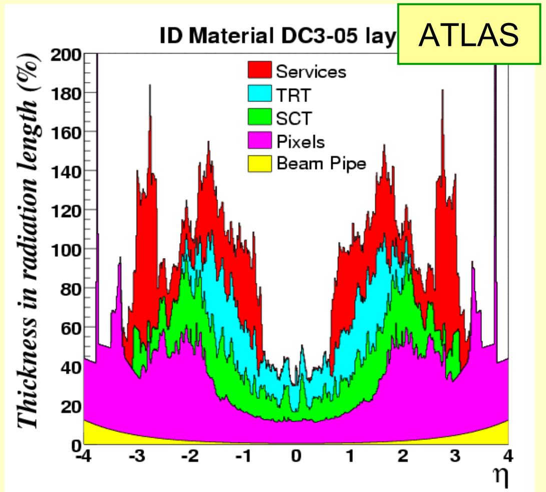
$\gamma\gamma$ irreducible background



γ-jet and jet-jet (reducible)



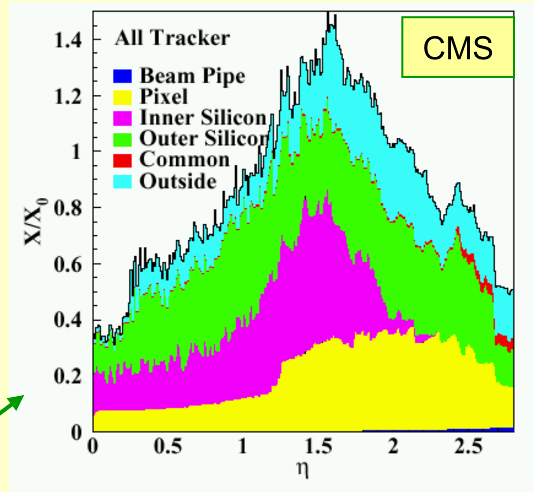




$\sigma_{\gamma j+jj} \sim 10^6\ \sigma_{\gamma\gamma}$ with large uncertainties

$\rightarrow$ need $R_j > 10^3$ for $\varepsilon_\gamma \approx 80\%$ to get

$\sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}$



- Main exp. tools for background suppression:
  - photon identification
  - γ / jet separation (calorimeter + tracker)

  - note: also converted photons need to be reconstructed (large material in LHC silicon trackers)

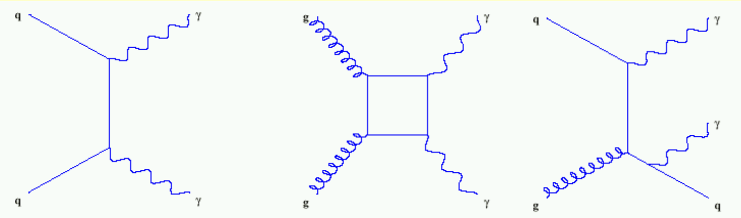
CMS: fraction of converted γs

Barrel region:	42.0 %
Endcap region:	59.5 %

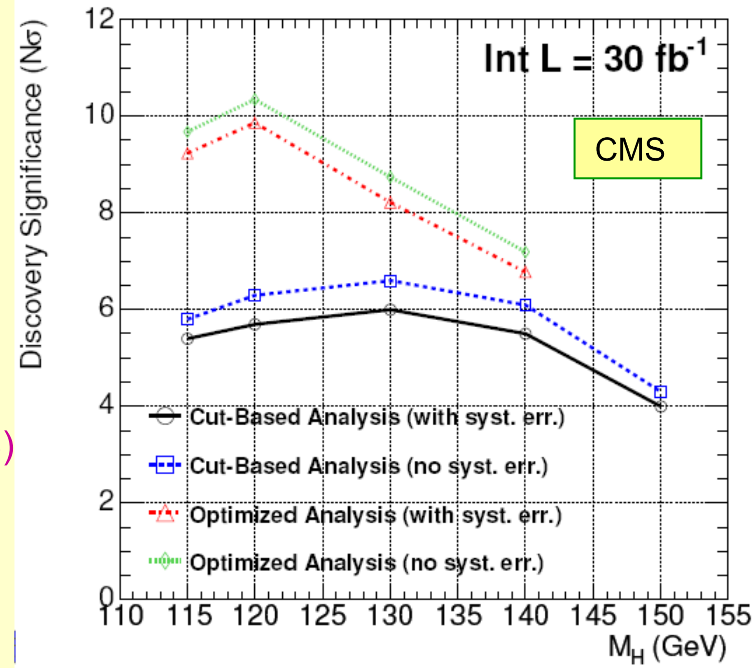
CMS Study: TDR (updated)

New elements of the analysis:

- more contributions to the γγ background



- NLO calculations available (Binoth et al., DIPHOX, RESBOS)
- Realistic detector material
- More realistic K factors (for signal and background)
- Split signal sample acc. to resolution functions
- Improvements possible by using more exclusive γγ + jet topologies



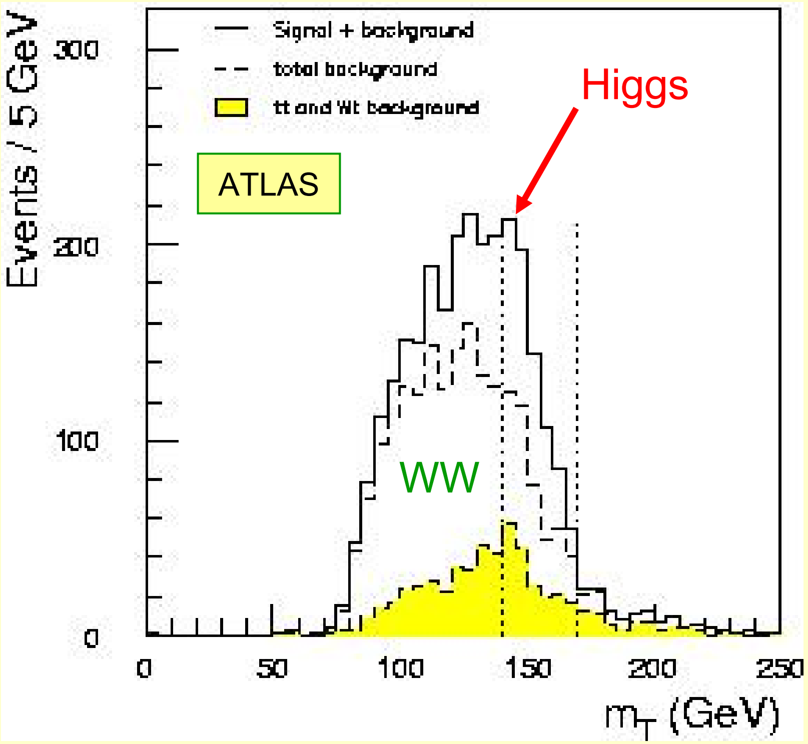
Signal significance for m_H = 130 GeV/c^2 and 30 fb^{-1}

ATLAS	LO (TDR, 1999)	3.9 σ
	NLO (update, cut based)	6.3 σ
	NLO (likelihood methods)	8.7 σ
CMS	NLO (cut based, TDR-2006)	6.0 σ
	NLO (neural net optimization, TDR-2006)	8.2 σ

Comparable results for ATLAS and CMS

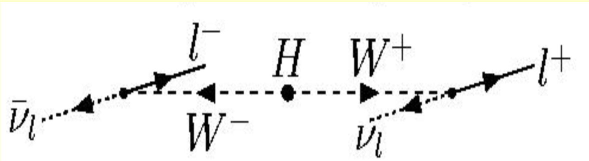
H → WW → ℓν ℓν

- Large H → WW BR for m_H ~ 160 GeV/c^2
- Neutrinos → no mass peak,
  → use transverse mass
- Large backgrounds: WW, Wt, tt



- Two main discriminants:

  (i) Lepton angular correlation



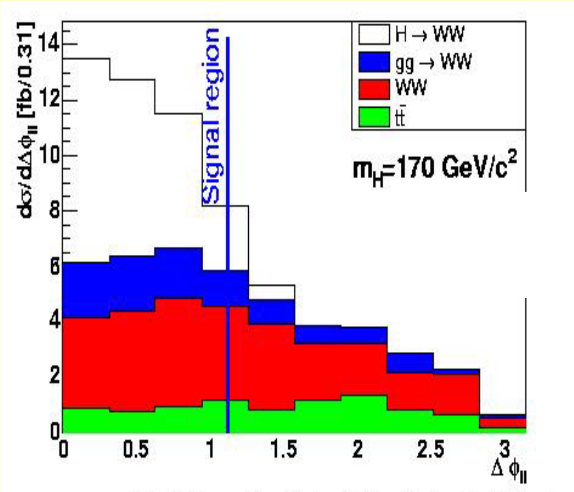
  (ii) Jet veto: no jet activity in central detector region

Difficulties:
(i) need precise knowledge of the backgrounds
Strategy: use control region(s) in data, extrapolation in signal region
(ii) jet veto efficiencies need to be understood for signal and background events
→ reliable Monte Carlo generators

Discovery reach in H → WW →ℓν ℓν

New developments:

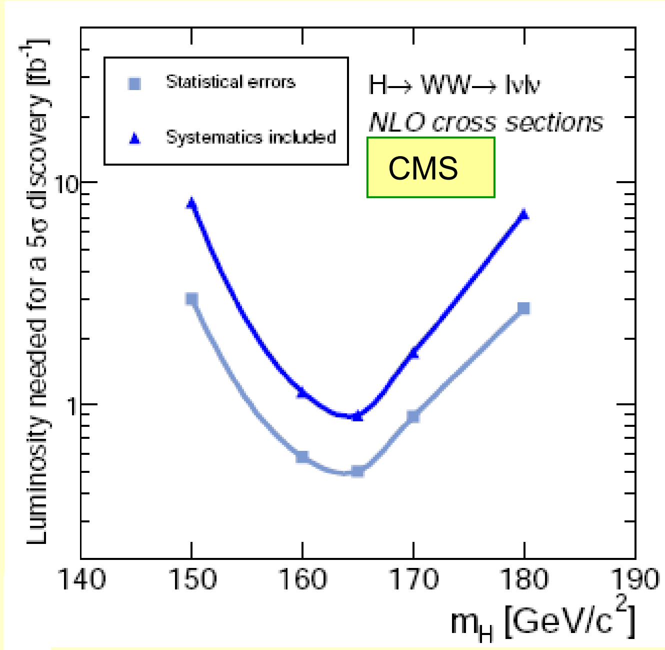
- gg → WW box contribution found to be important
  Small cross section (5% of WW backgr.) before cuts, but Δϕ shape similar to signal (30% contribution after cuts)



M. Dührssen et al., hep-ph/0504006

- Include both tt and single t background at NLO (Les Houches 2005)

CMS Phys. TDR 2006

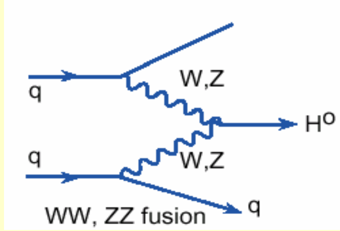


LHC:
luminosity needed for a 5σ discovery

Estimated background uncertainties:

- tt from data:	±16% at 5 fb^{-1}
- WW from data:	±17% at 5 fb^{-1}
- Wt from theory:	± 22%
- gg → WW from theory:	± 30%

Vector Boson Fusion qq H



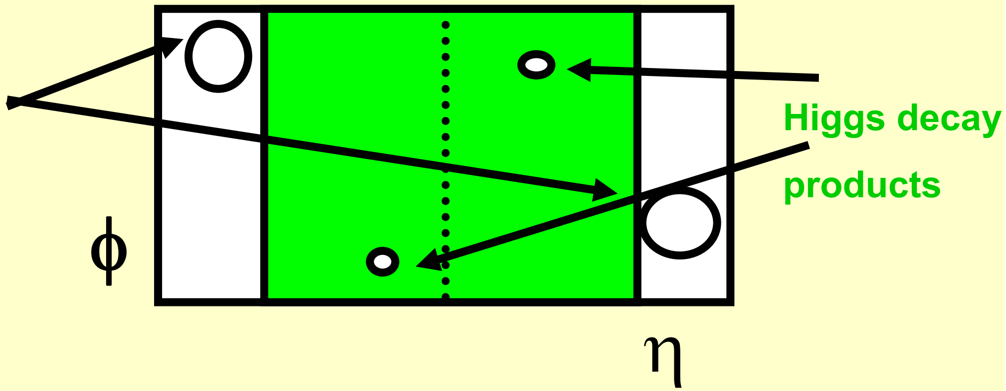
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions)

Established (low mass region) by D. Zeppenfeld et al. (1997/98)
Earlier studies: Kleiss & Stirling (1988);
Dokshitzer, Khoze, Troyan, Sov.J. Nucl. Phys. 46 (1987) 712;
Dokshitzer, Khoze, Sjöstrand, Phys.Lett., B274 (1992) 116.

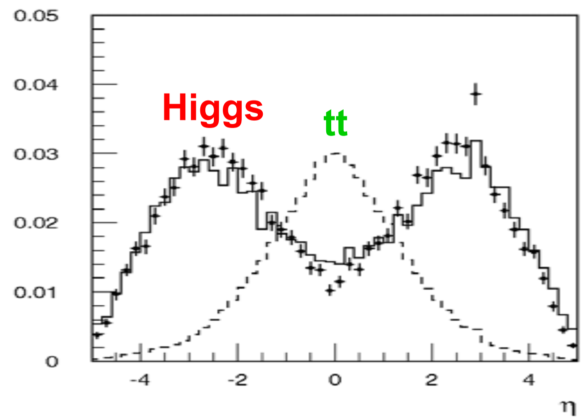
Distinctive Signature of:

- two high P_T forward tag jets
- little jet activity in the central region

  $\Rightarrow$ central jet Veto



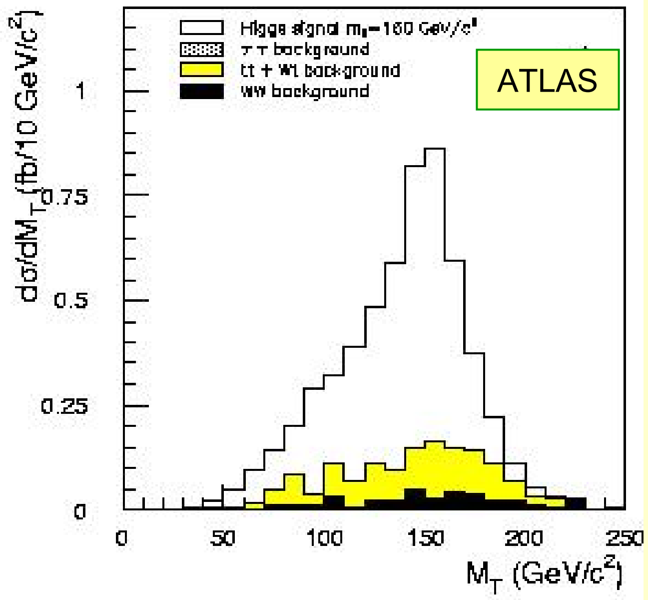
Rapidity distribution of jets in tt and Higgs signal events:



Two search channels at the LHC:

(i) qq H → qq W W*
→ qq ℓν ℓν

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



Selection criteria:

- Lepton P_T cuts and tag jet requirements ($\Delta\eta$, P_T)
- Require large mass of tag jet system
- Jet veto (important)
- Lepton angular and mass cuts

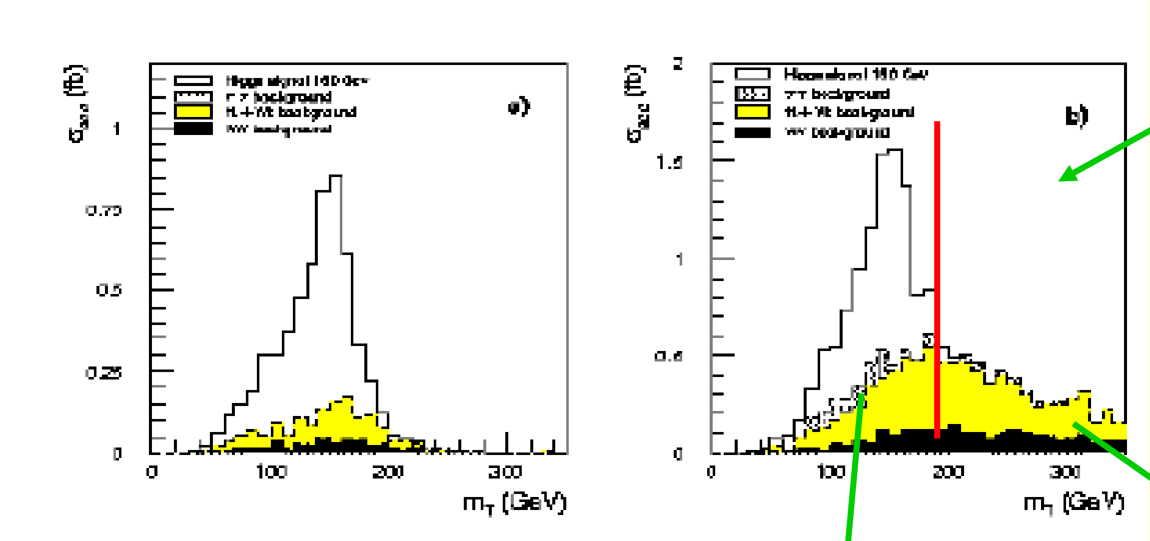
Provides > 5σ discovery potential for 30 fb^{-1} in mass range
125 < m_H < 200 GeV/c^2 (ATLAS)
140 < m_H < 190 GeV/c^2 (CMS, new study)

(differences need to be understood)

How reliable is this signal ?

background shape (the experimental approach)

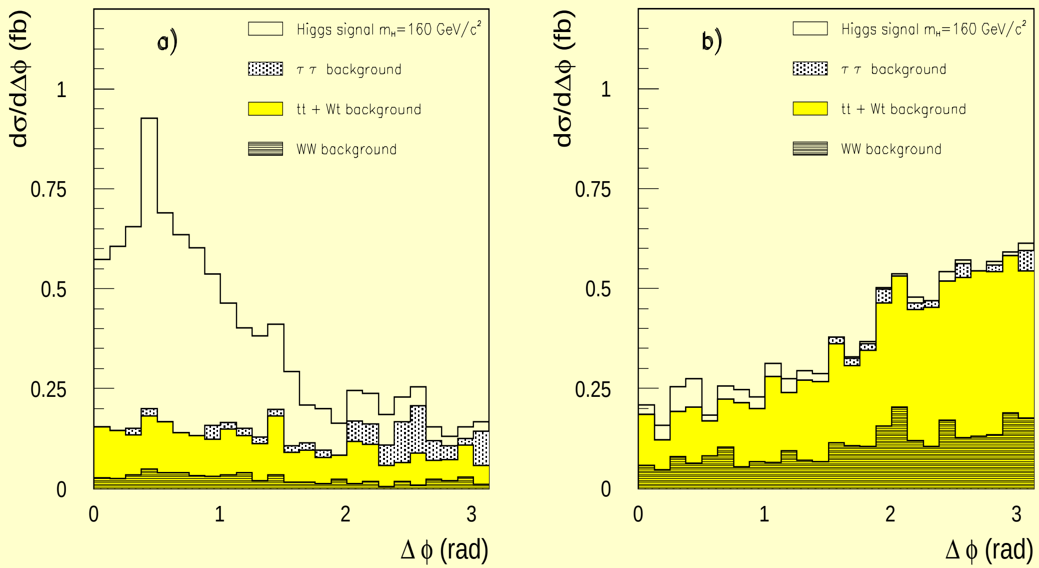
- Cuts can be relaxed, to get background shape from the data + Monte Carlo:



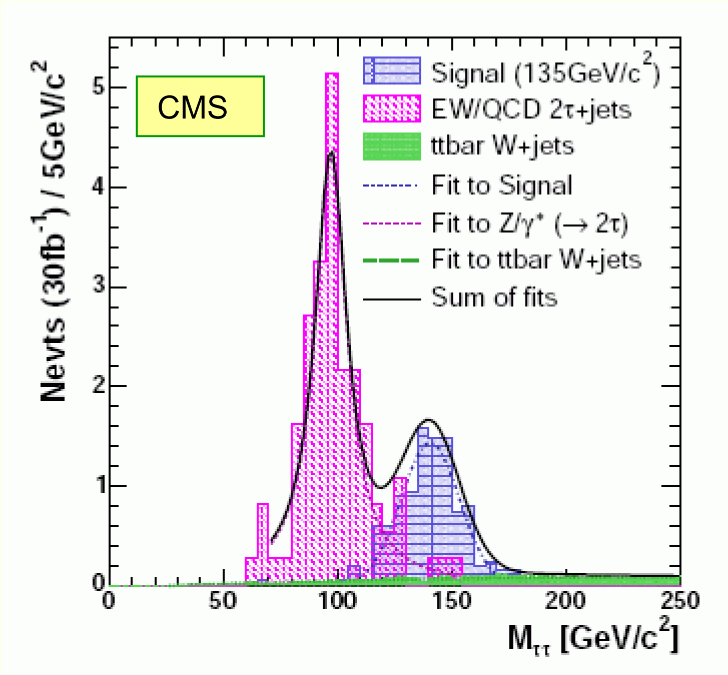
No kinematical cuts on leptons applied: (ATLAS study)

Evidence for spin-0 of the Higgs boson, Δφ distribution

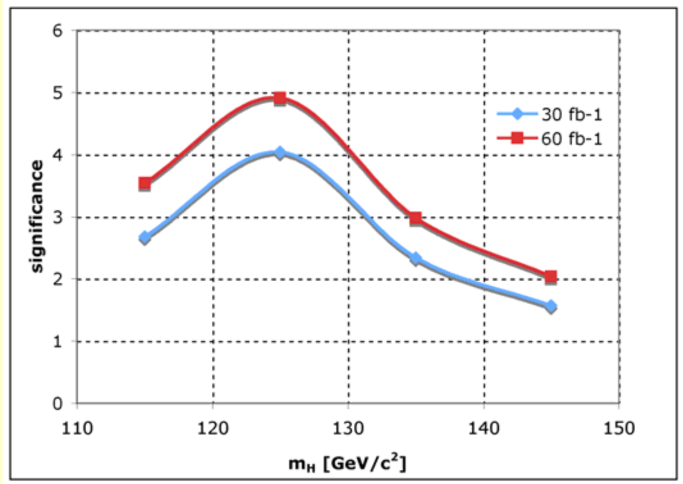
Spin-0 → WW → ℓνℓν expect leptons to be close by in space

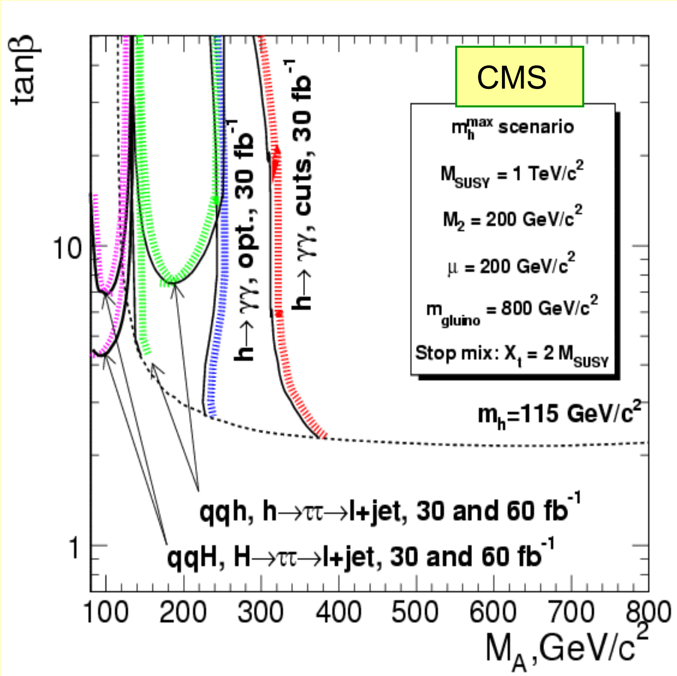


(ii) Results from the first full simulation analysis of $qqH \rightarrow qq\,\tau\tau \rightarrow qq\,\ell\nu\nu\,\text{had}\,\nu$



Signal significance, SM Higgs, eμ channel:





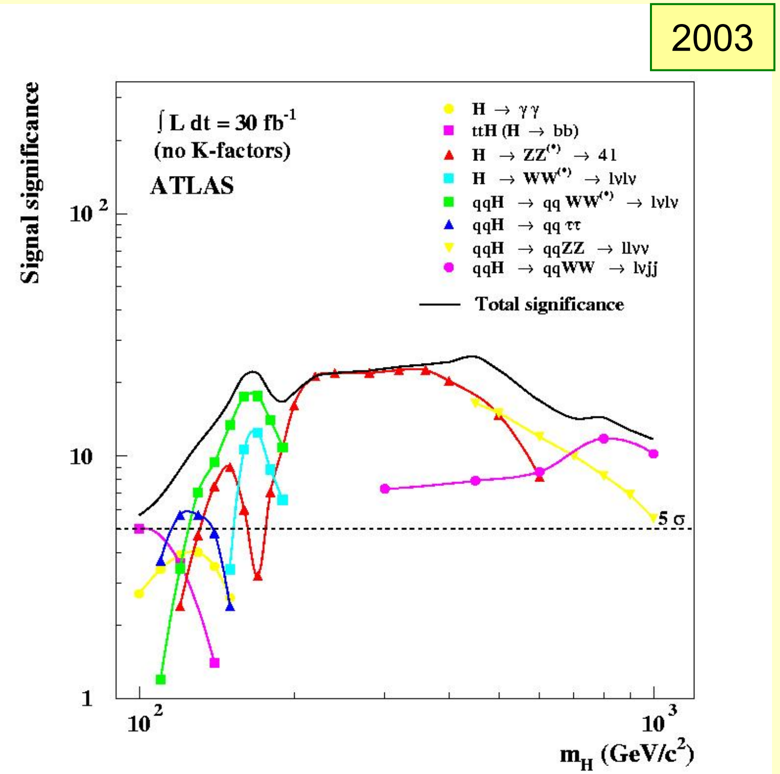
discovery region in the MSSM

Experimental challenge:

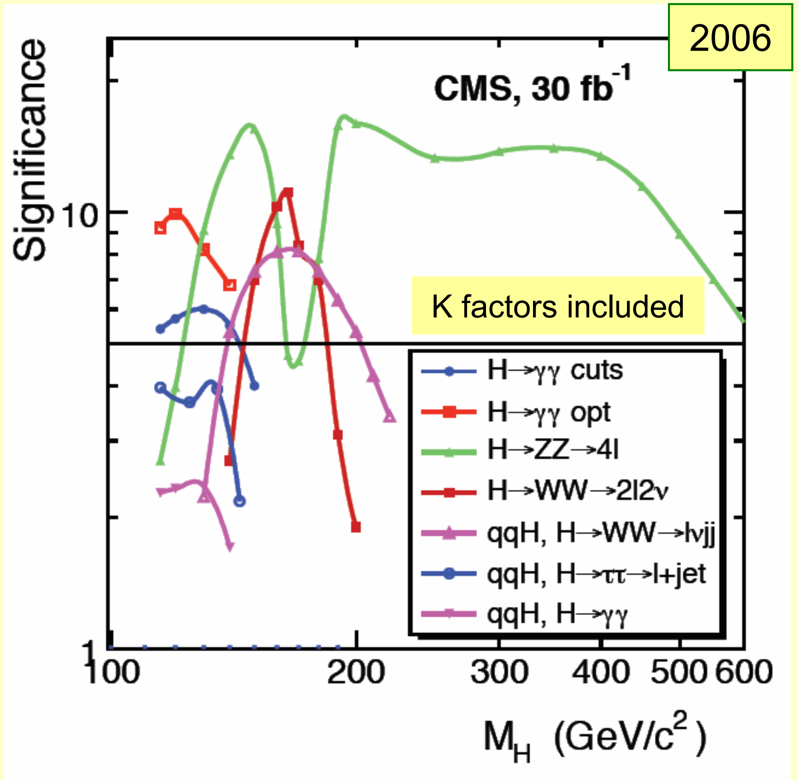
- Identification of hadronic taus
- good P_T^{miss} resolution
  ($\tau\tau$ mass reconstruction in collinear approximation)
- control of the $Z \rightarrow \tau\tau$ background shape in the high mass region
  → use data to constrain the background

LHC discovery potential for 30 fb^{-1}

2003



2006



- Full mass range can already be covered after a few years at low luminosity
- Several channels available over a large range of masses

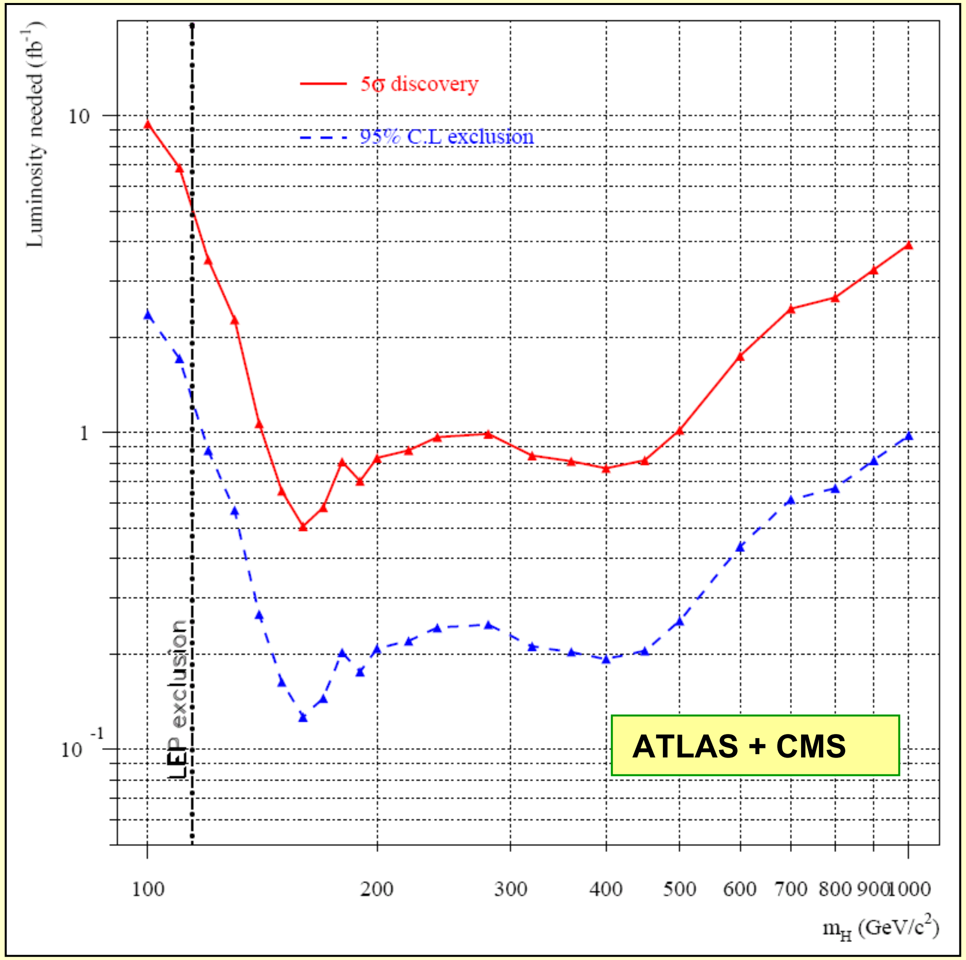
  Vector boson fusion channels play an important role at low mass !

Important changes w.r.t. previous studies:

- **$H \rightarrow \gamma\gamma$** sensitivity of ATLAS and CMS comparable
- **$ttH \rightarrow tt\,bb$** disappeared in CMS study (updated (ME) background estimates, under study in ATLAS)

Combined ATLAS + CMS discovery potential

- Luminosity required for a 5σ discovery or a 95% CL exclusion -



J.J. Blaising et al, Eur. Strategy workshop

~ 5 fb^{-1} needed to achieve a 5σ discovery

(well understood and calibrated detector)

~ < 1 fb^{-1} needed to set a 95% CL limit

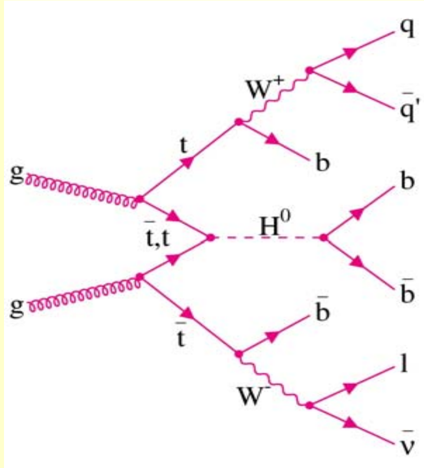
(low mass ~ 115 GeV/c^2 more difficult)

comments:

- present curves assume the old ttH, H→ bb performance
- systematic uncertainties assumed to be luminosity dependent
  (no simple scaling, σ ~ √L, possible)

$t\bar{t}\,H \to t\bar{t}\,b\bar{b}$

Complex final states: H→ bb, t → bjj, t → bℓν
t → bℓν, t → bℓν
t → bjj, t → bjj

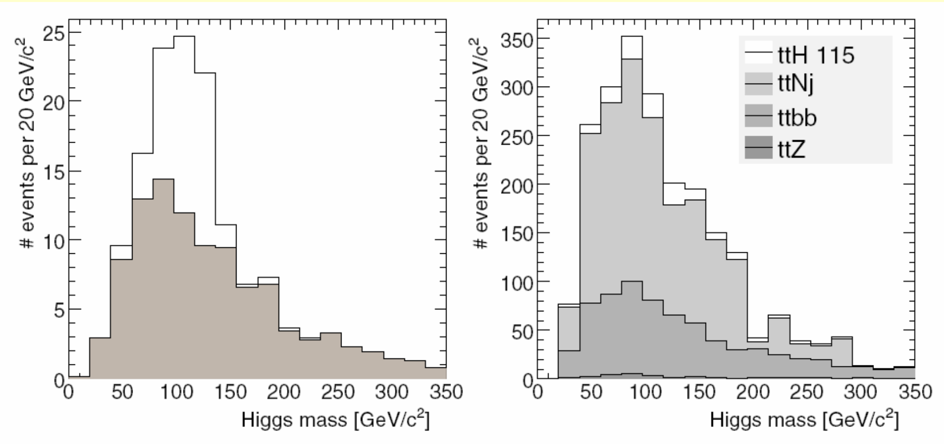


Main backgrounds:

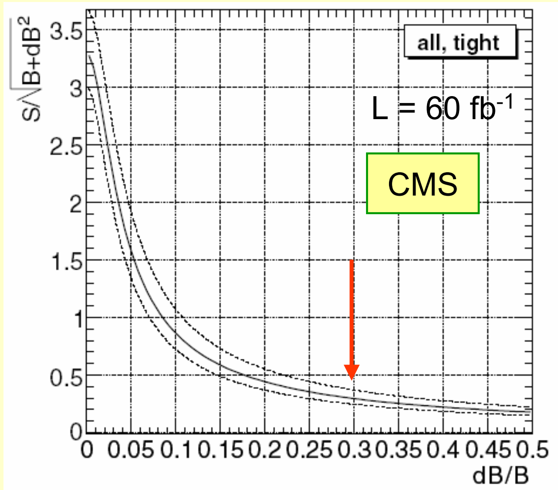
- combinatorial background from signal (4b in final state)
- ttjj, ttbb, ttZ,…
- Wjjjjj, WWbbjj, etc. (excellent b-tag performance required)

• Updated CMS study (2006): ALPGEN matrix element calculations for backgrounds
→ larger backgrounds (ttjj dominant), experimental + theoretical uncertainties, e.g. ttbb, exp. norm. difficult…..

M (bb) after final cuts, 60 fb^{-1}

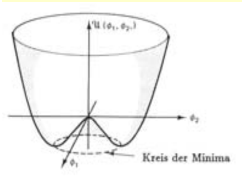


Signal events only …. backgrounds added



Signal significance as function of background uncertainty

ATLAS study ongoing, results expected by end of the year



Is it a Higgs Boson ?

-can the LHC measure its parameters ?-

1. Mass

Higgs boson mass can be measured with a precision of 0.1%
over a large mass range (130 - ~450 GeV/c^2)
($\gamma\gamma$ and ZZ→ 4ℓ resonances, el.magn. calo. scale uncertainty assumed to be ± 0.1%)

2. Couplings to bosons and fermions

3. Spin and CP

Angular distributions in the decay channel H → ZZ(*) → 4 ℓ are sensitive to spin and CP eigenvalue

C.P. Buszello et al. Eur. Phys. J. C32 (2003) 209;
S. Y. Choi et al., Phys. Lett. B553 (2003) 61.
→ ATLAS and CMS studies on H → ZZ → 4ℓ
\+ new studies using VBF (CP from tagging jets) in ATLAS **(→ Talks in parallel sessions)**

4. Higgs self coupling

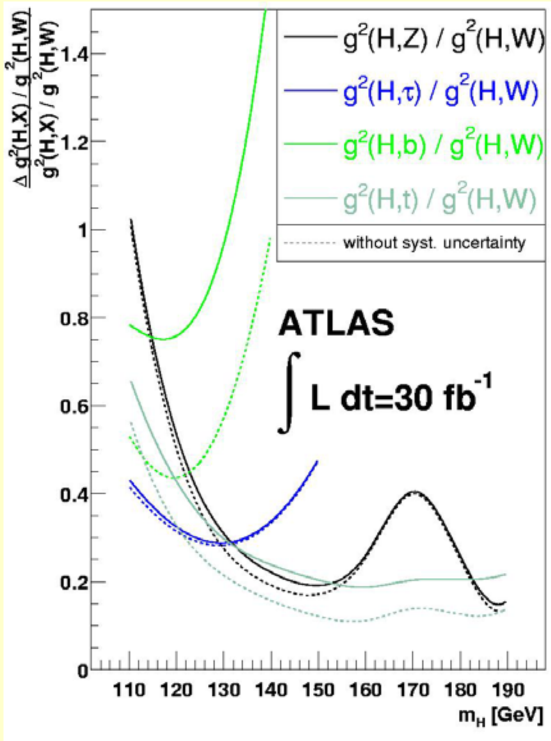
Possible channel: **gg → HH → WW WW → ℓν jj ℓν jj** (like sign leptons)
Small signal cross sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

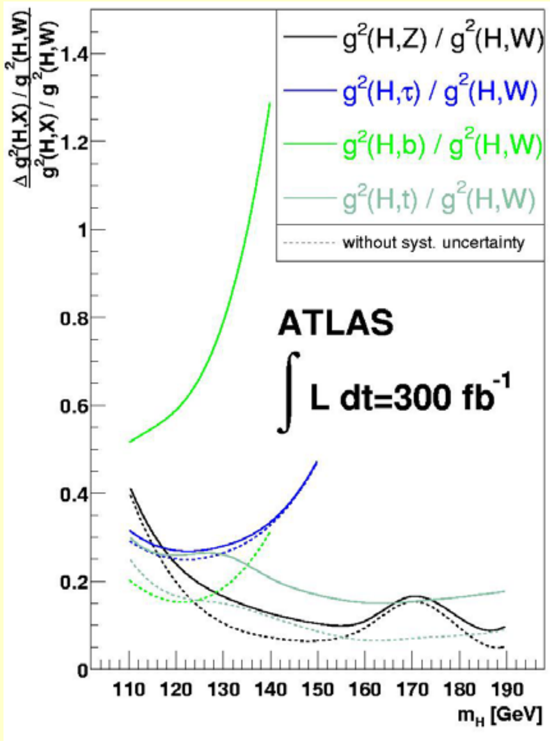
⇒ no significant measurement possible at the LHC
very difficult at a possible SLHC (6000 fb^{-1})
limited to mass region around 160 GeV/c^2 (update will appear soon)

Measurement of Higgs Boson Couplings

Global likelihood-fit (at each possible Higgs boson mass)
Input: measured rates, separated for the various production modes

Output: Higgs boson couplings, normalized to the WW-coupling

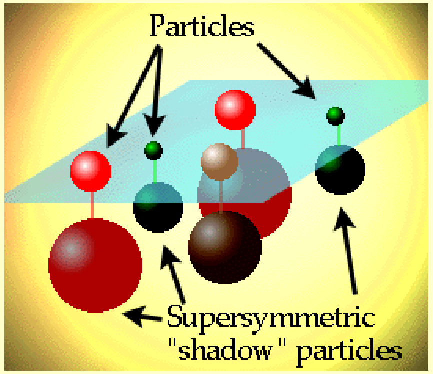




Relative couplings can be measured with a precision of ~20% (for 300 fb^{-1})

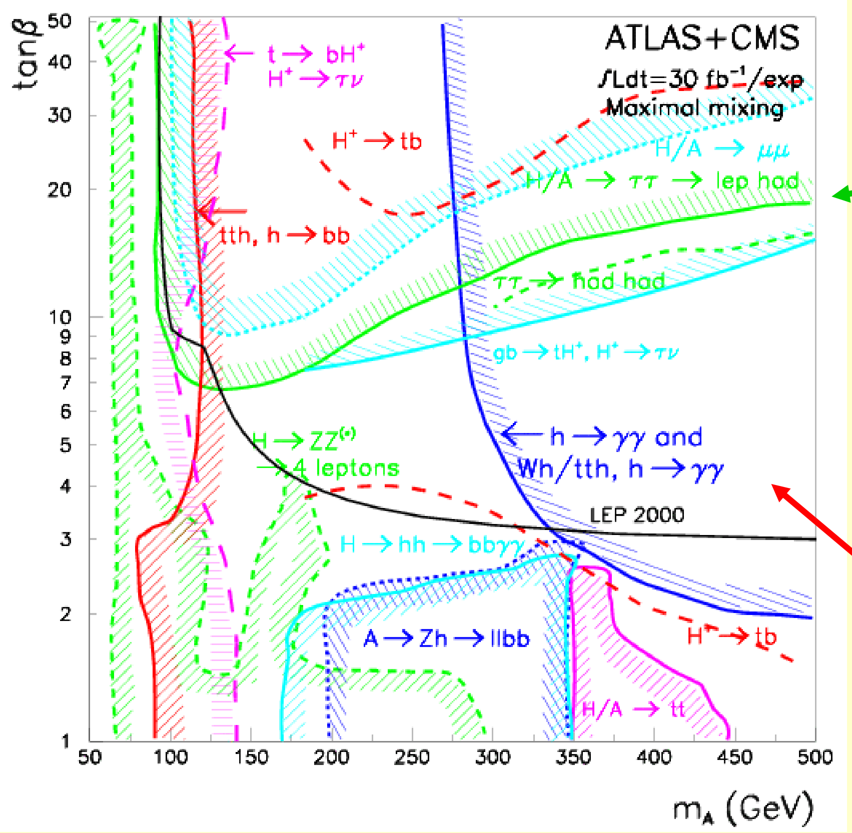
The Higgs Sector

in the MSSM



MSSM Higgs bosons h, H, A, $H^{\pm}$

$m_h < 135$ GeV/c^2
$m_A \approx m_H \approx m_{H\pm}$ at large m_A



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

- best sensitivity from A/H → ττ, H± → τν
  (not easy the first year ....)

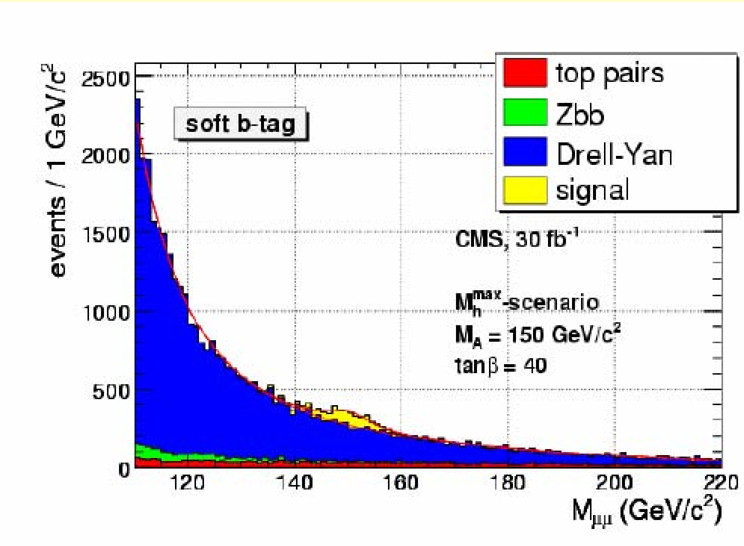
- A/H → μμ experimentally easier
  (esp. at the beginning)

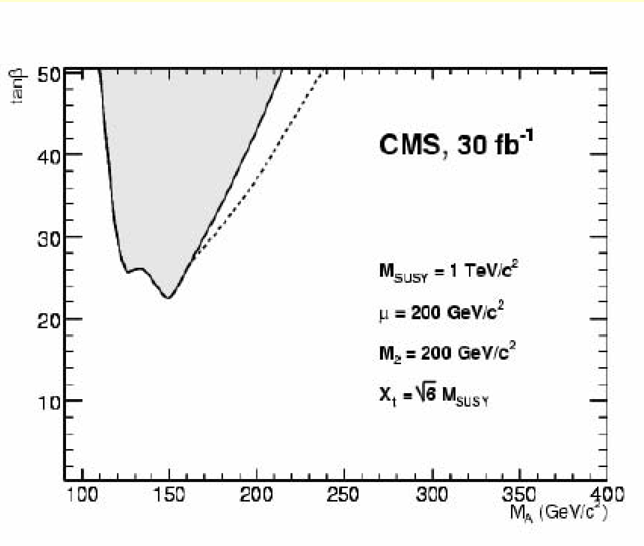
Here only SM-like h observable if SUSY particles neglected.

* Validated by CMS TDR full simulation studies *

Some examples of updated MSSM studies

CMS: A/H → μμ





ATLAS: Charged Higgs boson searches
$H^+ \to \tau\nu$ decay mode

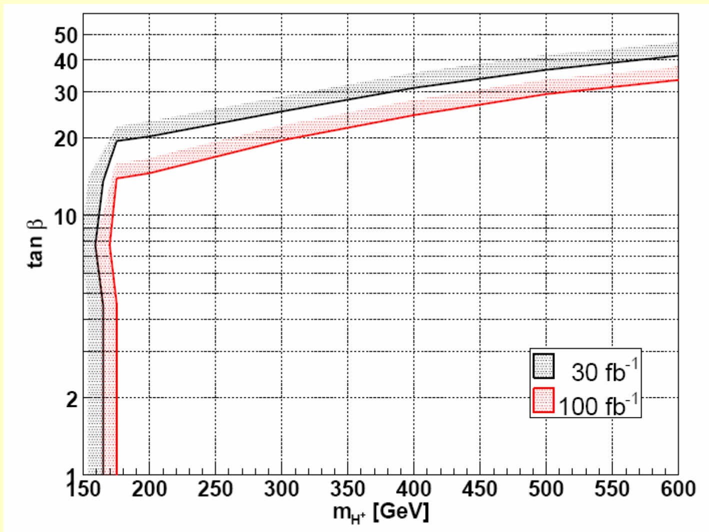
Production modes:

$t \to H^+b$ $gg \to tbH^+$ $gb \to tH^+$

Consistent treatment of the transition region $m_{H^+} \sim m_t$

Event generator MATCHIG
(→ talk in parallel session)

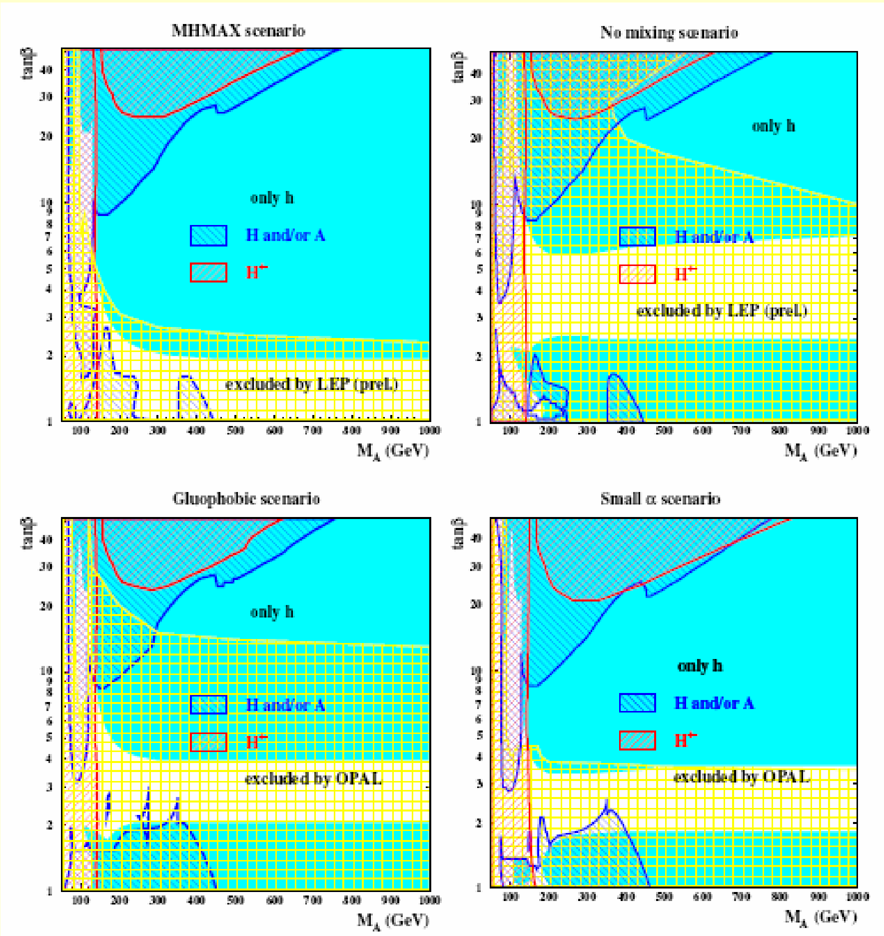
5σ discovery contours for 30 and 100 fb^{-1}



Updated MSSM scan for different benchmark scenarios

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

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



MHMAX scenario   (M_{SUSY} = 1 TeV/c^2)
maximal theoretically allowed region for m_h

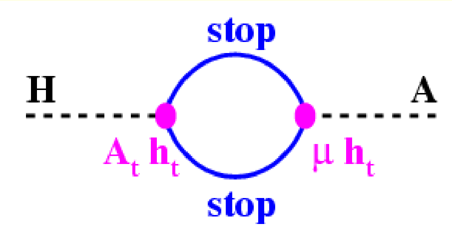
Nomixing scenario   (M_{SUSY} = 2 TeV/c^2)
(1TeV almost excl. by LEP)
small m_h → difficult for LHC

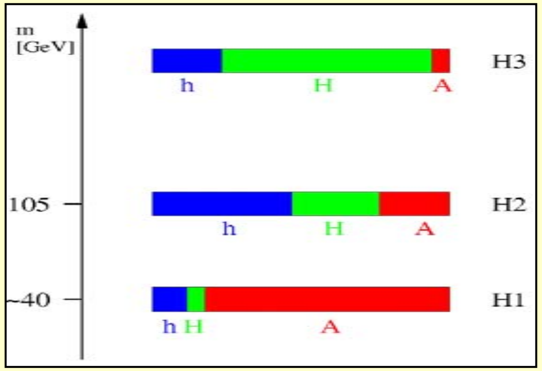
Gluophobic scenario (M_{SUSY} = 350 GeV/c^2)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for g g → H, H→ γγ and Z→4 ℓ

Small α scenario   (M_{SUSY} = 800 GeV/c^2)
coupling to b (and **t**) suppressed
(cancellation of sbottom, gluino loops) for
large tan β and M_A 100 to 500 GeV/c^2

Higgs search at the LHC 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)

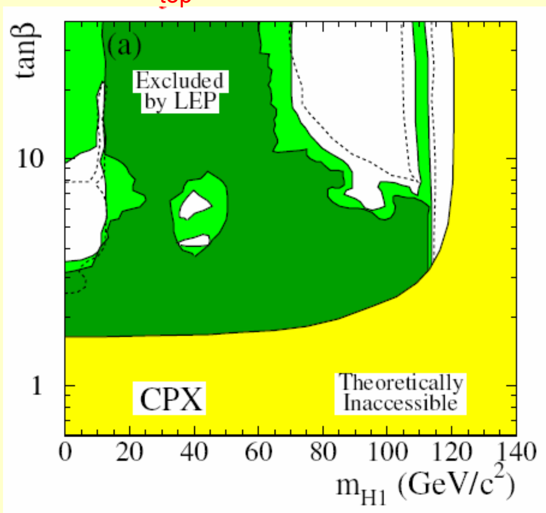
  (M. Carena et al., Phys.Lett. B 495 155 (2000))

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

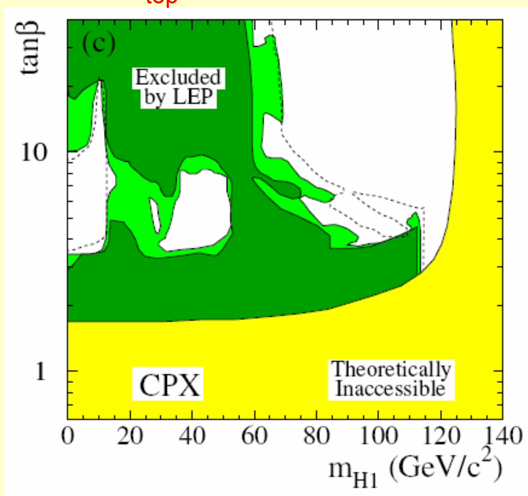
- No lower mass limit for H_1 from LEP !
  (decoupling from the Z)

  details depend on m_{top} and on theory model
  (FeynHiggs vs. CPsuperH)

m_{top} = 169.3 GeV/c²

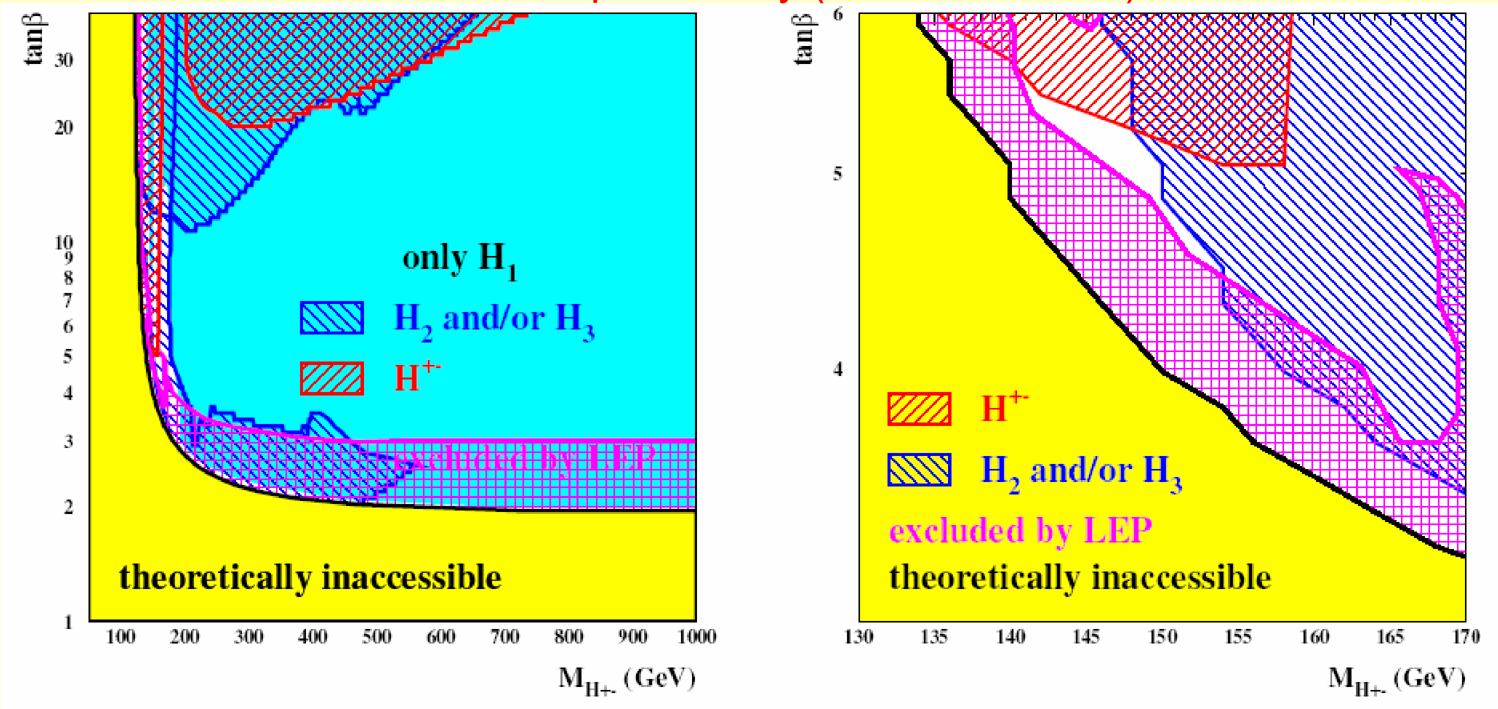


m_{top} = 174.3 GeV/c²



MSSM discovery potential for the CPX scenario

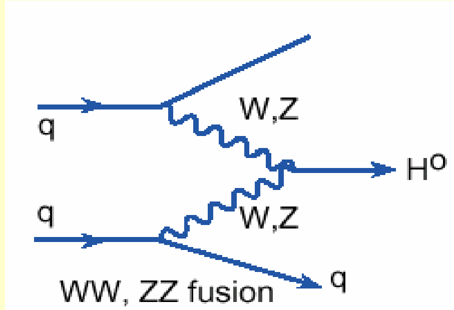
ATLAS preliminary (M. Schumacher)



- 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:
  $tt \rightarrow Wb\ H^{+}b \rightarrow \ell\nu b\ WH_1 b$, $H_1 \rightarrow bb$

Invisible Higgs decays ?



P_T^{miss}

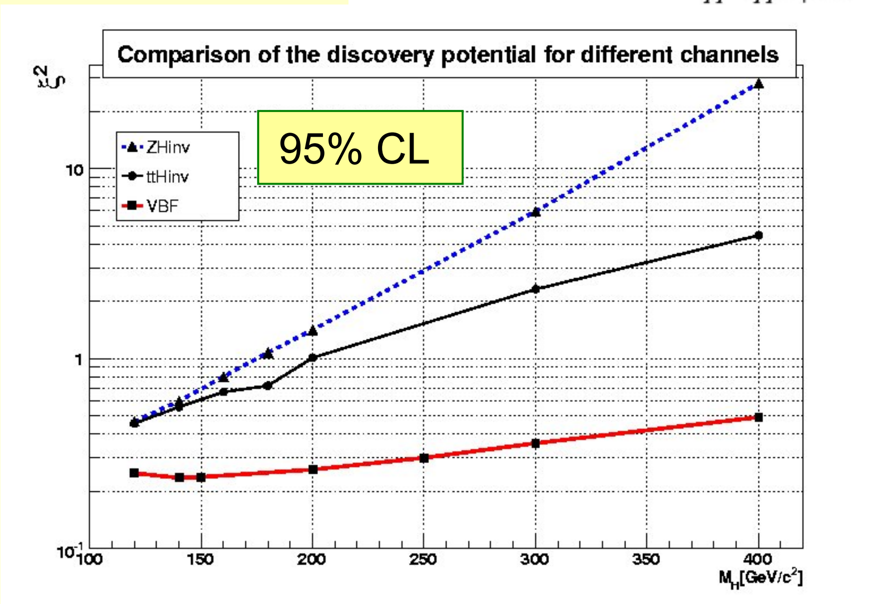
Possible searches: tt H $\rightarrow$ $\ell\nu$b qqb + P_T^{miss}
Z H $\rightarrow$ $\ell\ell$ + P_T^{miss}
qq H $\rightarrow$ qq + P_T^{miss}

- J.F. Gunion, Phys. Rev. Lett. 72 (1994)
- D. Choudhury and D.P. Roy, Phys. Lett. B322 (1994)
- O. Eboli and D. Zeppenfeld, Phys. Lett. B495 (2000)

All three channels have been studied:

key signature: excess of events above SM backgrounds with large P_T^{miss} (> 100 GeV/c)

Sensitivity: $$\xi^2 = Br(H \rightarrow Inv.)\frac{\sigma_{qq\rightarrow qqH}}{\sigma_{qq\rightarrow qqH}|_{SM}}$$



ATLAS preliminary

Problems / ongoing work:

- ttH and ZH channels have low rates
- More difficult trigger situation for qqH
- backgrounds need to be precisely known (partially normalization using ref. channels possible)
- non SM scenarios are being studied at present first example: SUSY scenario

Conclusions

- 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 models)

  in addition: important parameter measurements (mass, spin, ratio of couplings) can be performed, vector boson fusion channels are important

  more difficult: - invisible Higgs boson decays or NMSSM models
  - measurement of Higgs boson self coupling

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