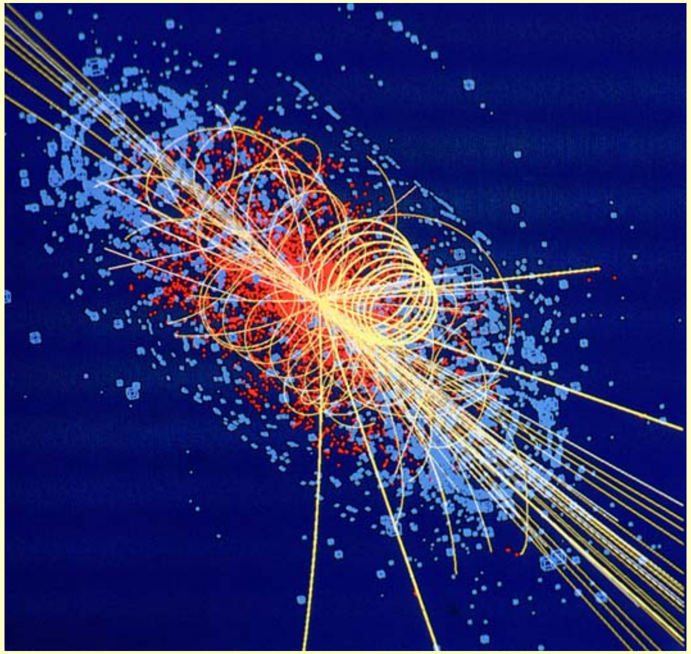
# Higgs and SUSY at the LHC

## - prospects for luminosities above 1 $fb^{-1}$ -



- **Introduction**

- **Higgs**
  - **Updated results on Higgs boson searches**
  - **Measurement of Higgs boson parameters**

- **SUSY**
  - **Discovery prospects**
  - **Parameters of the SUSY model**

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# Key Questions of Particle Physics

*Answers to some of these questions are expected at the TeV mass scale, i.e. at the LHC*

## 1. Mass: What is the origin of mass?

- How is the electroweak symmetry broken ?
- Does the **Higgs boson** exist ?

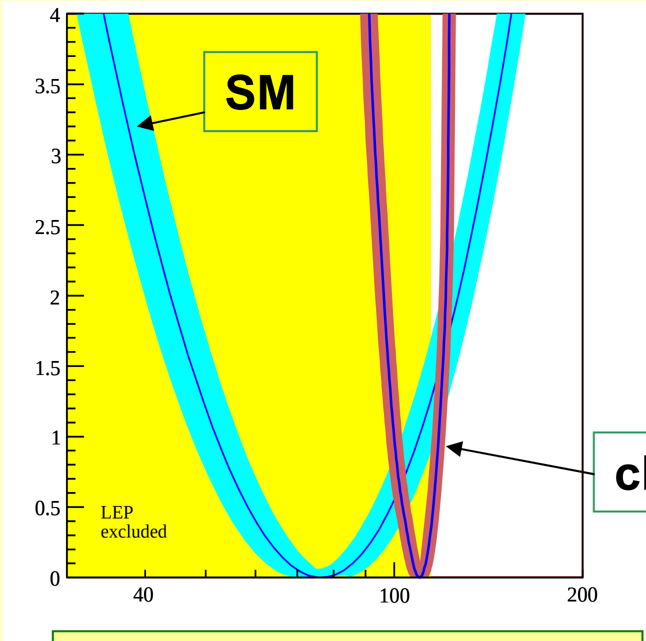
## 2. Unification: What is the underlying theory ?

- Can the interactions be unified at larger energy?
- How can gravity be incorporated ?
- Is our world **supersymmetric** ?
- What is the nature of Dark Matter / Dark Energy

## 3. Flavour: or the generation problem

- Why are there three families of matter?
- Neutrino masses and mixing?
- What is the origin of CP violation?

O. Buchmüller et al., arXiv:0707.3447




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

Includes
- WMAP
- $b \rightarrow s\gamma$
- $a_\mu$

….watch the low mass region !

… but don‘t focus too much on it, be open for surprises !!

# The Search for

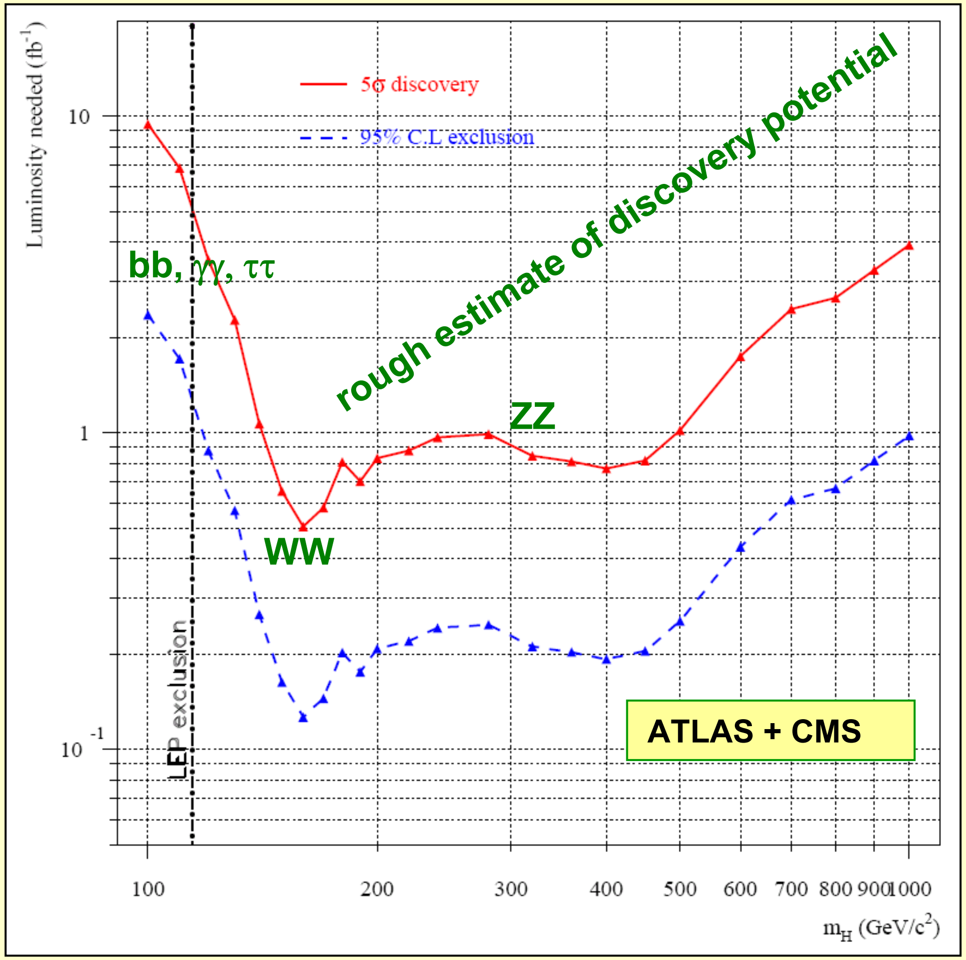
## The Higgs boson

In contrast to the TeVatron:

the first Higgs has already been seen at ATLAS

# …. also the prospects for the discovery of the Higgs particle are good

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




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

~ < 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 are optimistic on the ttH, H→ bb performance
- systematic uncertainties assumed to be luminosity dependent (no simple scaling, σ ~ √L, possible)

*This talk: "grand LHC picture"*
- *discovery potential (large L)*
- *parameter measurements*
- *MSSM scenarios*

*Y. Sirois:*
- *low luminosity discovery channels, e.g. WW;*
- *how to start up;*
- *data driven background determinations*

# 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 2008

- 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.
  - …

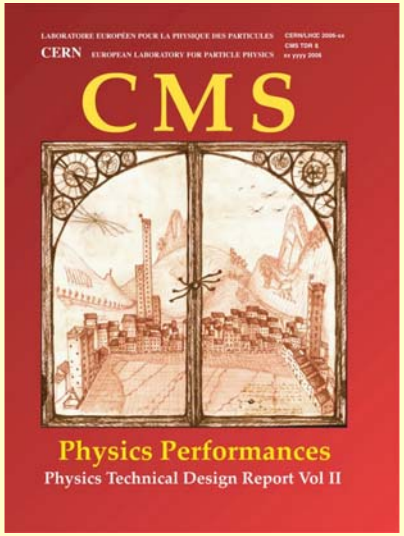
  Tevatron data are extremely valuable for validation, work has started

- 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,…..)

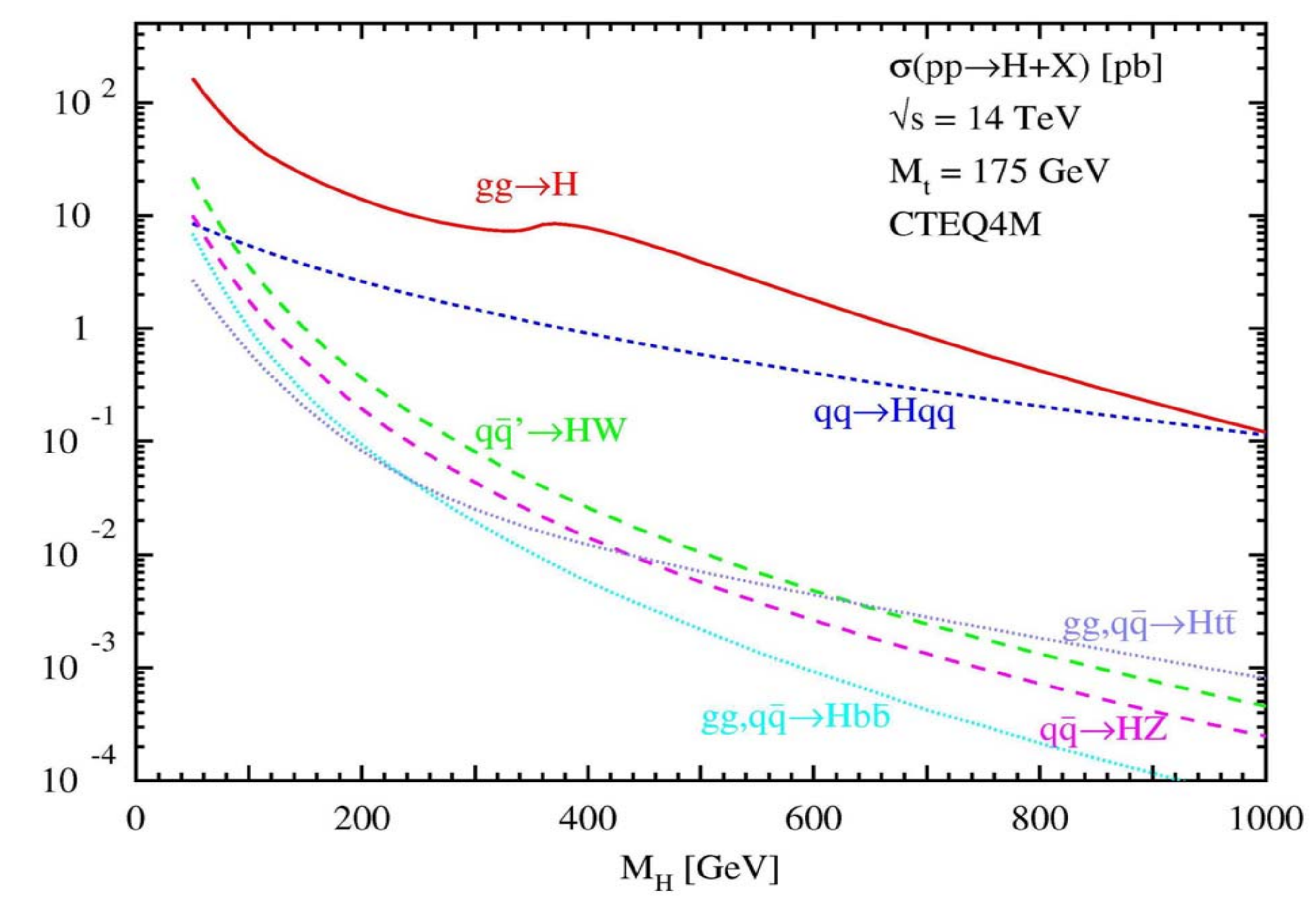


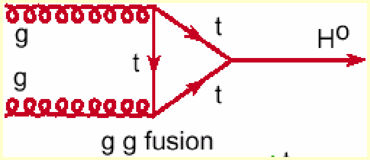

**CMS: CERN / LHCC 2006-021**

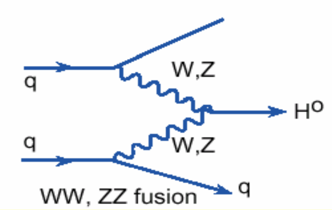
**ATLAS: CERN-OPEN 2008-020 (to appear)**

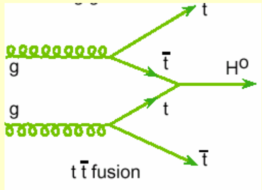
# Standard Model
# Higgs Boson Searches

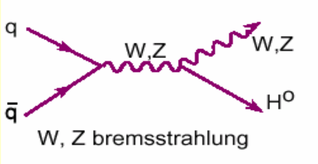
NLO cross sections, M.Spira et al.



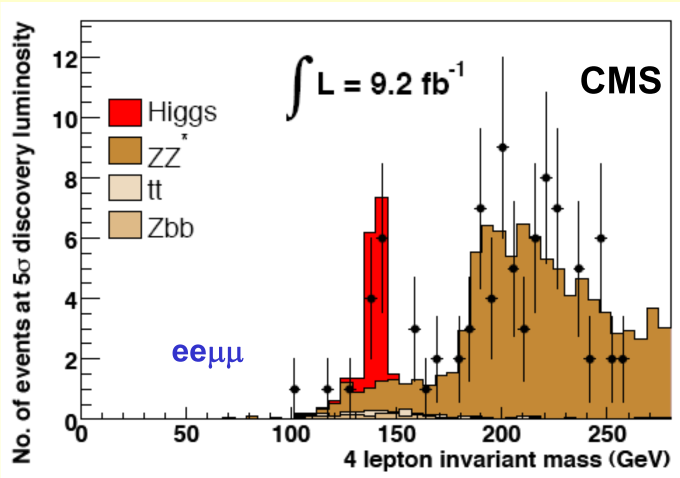



# $H \rightarrow ZZ^* \rightarrow \ell\ell\ \ell\ell$



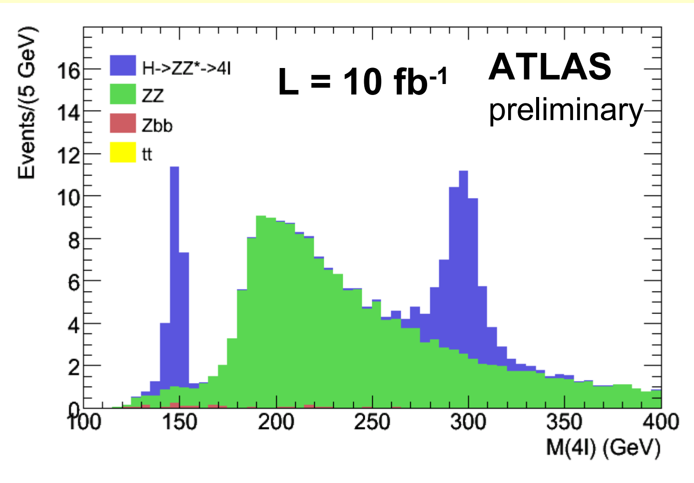

- Main backgrounds: ZZ (irreducible), tt, Zbb (reducible)

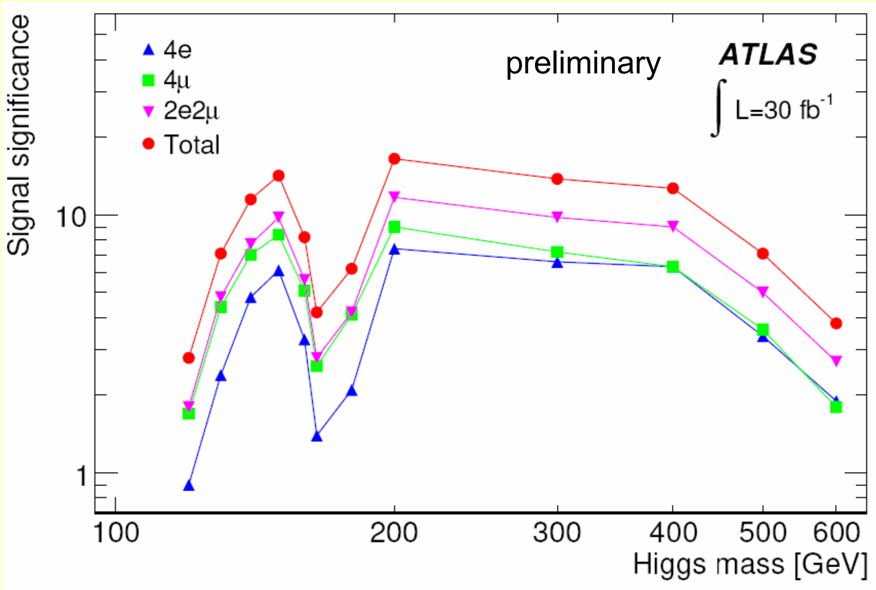
- Main experimental tools for background suppression:
  - lepton isolation in the tracker and in the calorimeter
  - impact parameter

Updated ATLAS and CMS studies:

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

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

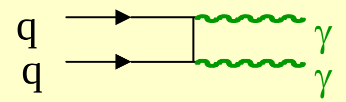


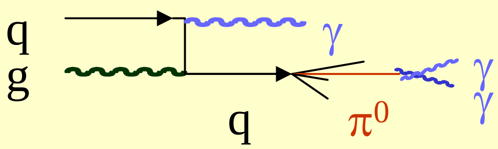
# $H \rightarrow \gamma\gamma$

## Main backgrounds:

$\gamma\gamma$ irreducible background




$\gamma$-jet and jet-jet (reducible)

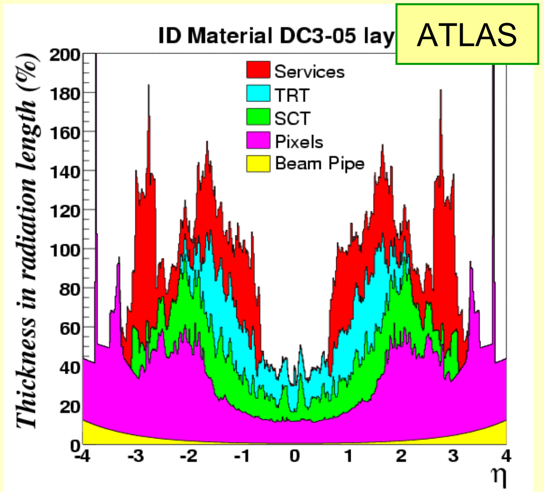


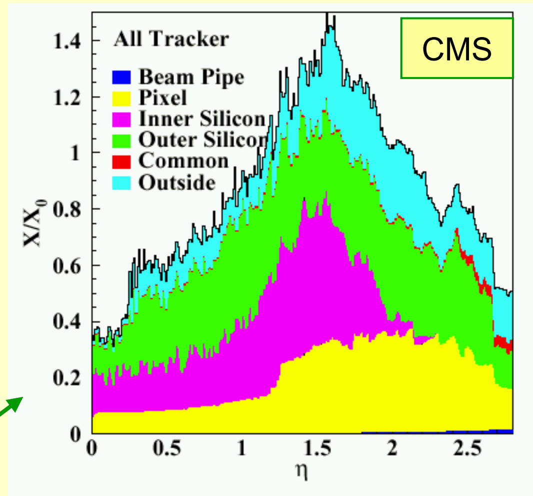

$\sigma_{\gamma j+jj} \sim 10^6 \, \sigma_{\gamma\gamma}$ with large uncertainties

$\rightarrow$ 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
  - $\gamma$ / jet separation (calorimeter + tracker)
  - note: also converted photons need to be reconstructed (large material in LHC silicon trackers)



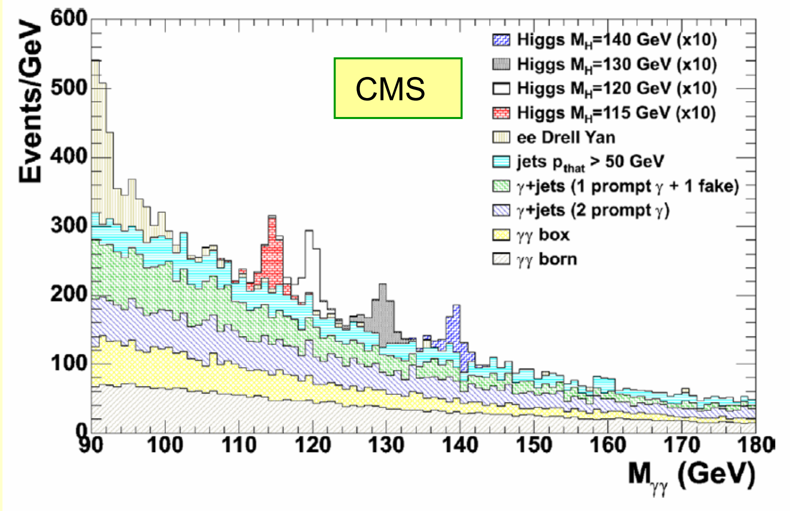



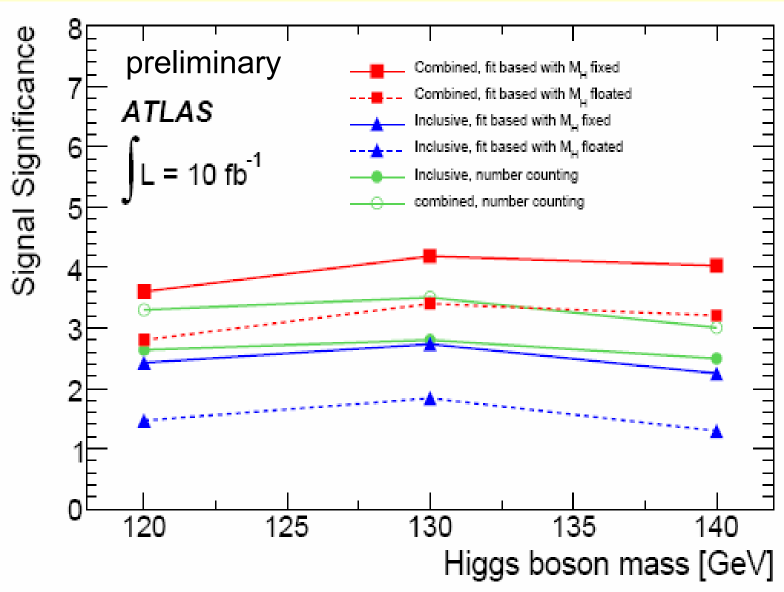

CMS: fraction of converted $\gamma$s

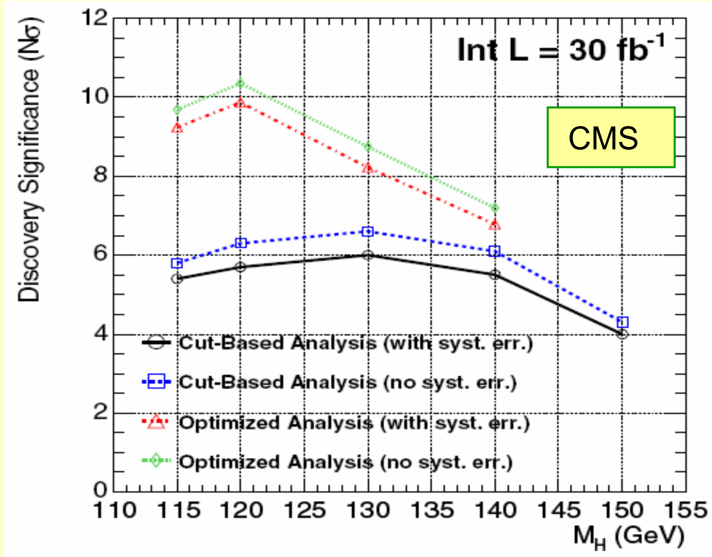
| | |
|---|---|
| Barrel region: | 42.0 % |
| Endcap region: | 59.5 % |

New elements of the analyses:

- 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



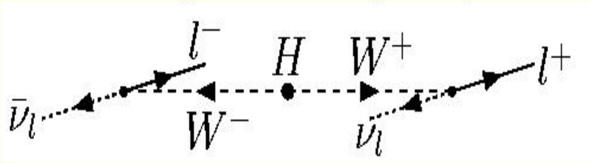

- Comparable results for ATLAS and CMS
- Improvements possible by using more exclusive γγ + jet topologies

# $H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$

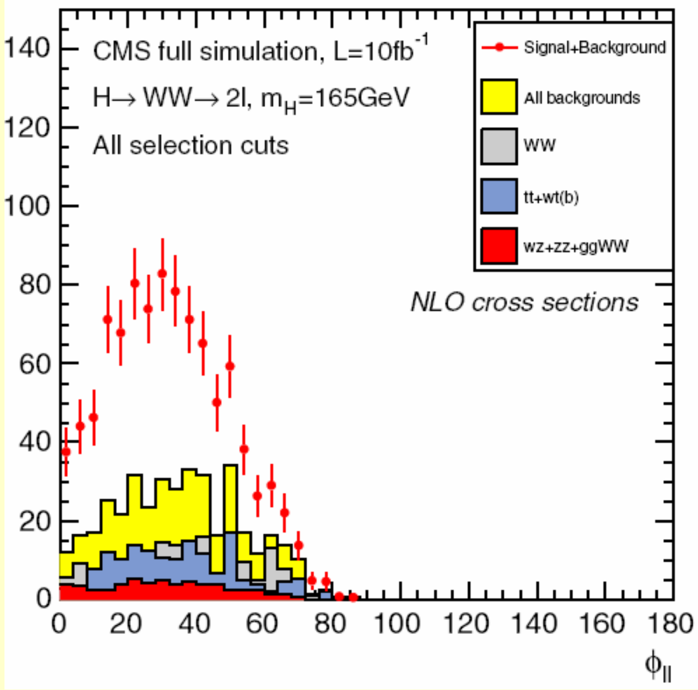
- Large $H \rightarrow WW$ BR for $m_H \sim 160$ GeV/$c^2$
- Neutrinos → no mass peak,
  → use transverse mass
- Large backgrounds: WW, Wt, tt

- Two main discriminants:

  (i) Lepton angular correlation



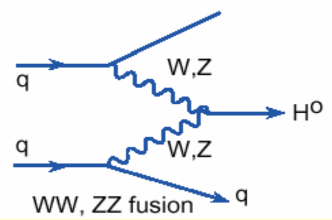

  (ii) Jet veto: no jet activity in central detector region




Discovery channel at low L
→ see talk by Y. Sirois

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, data driven-background normalizations

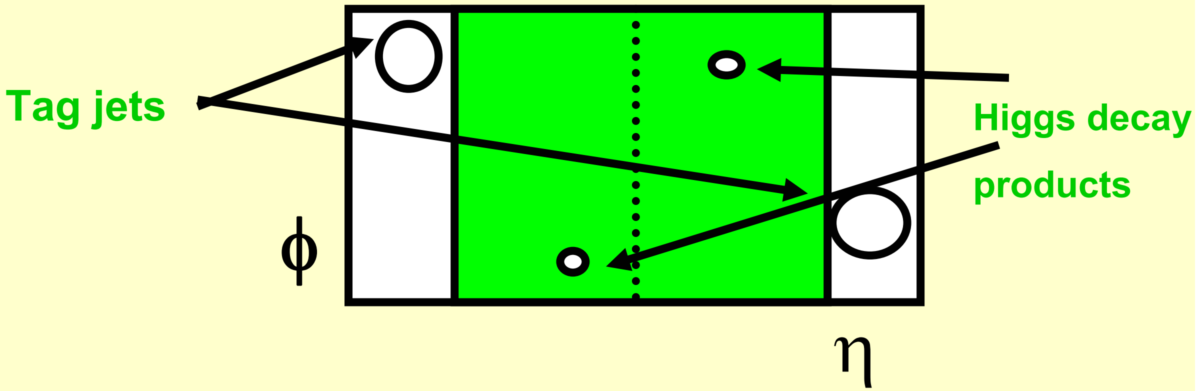
# Vector Boson Fusion qq H



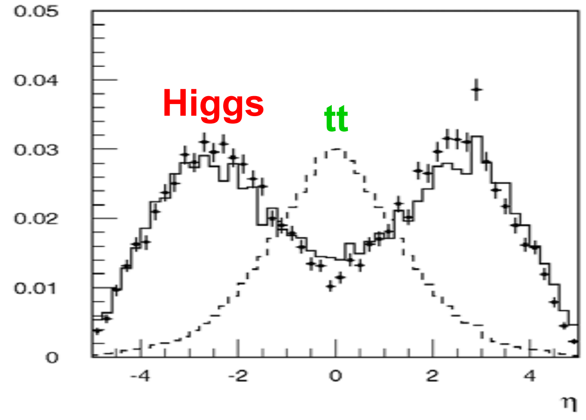

**Motivation**: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions)

Established (low mass region) by D. Zeppenfeld et al. (1997/98)
Earlier studies: R.Kleiss W.J.Stirling, Phys. Lett. 200 (1988) 193;
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



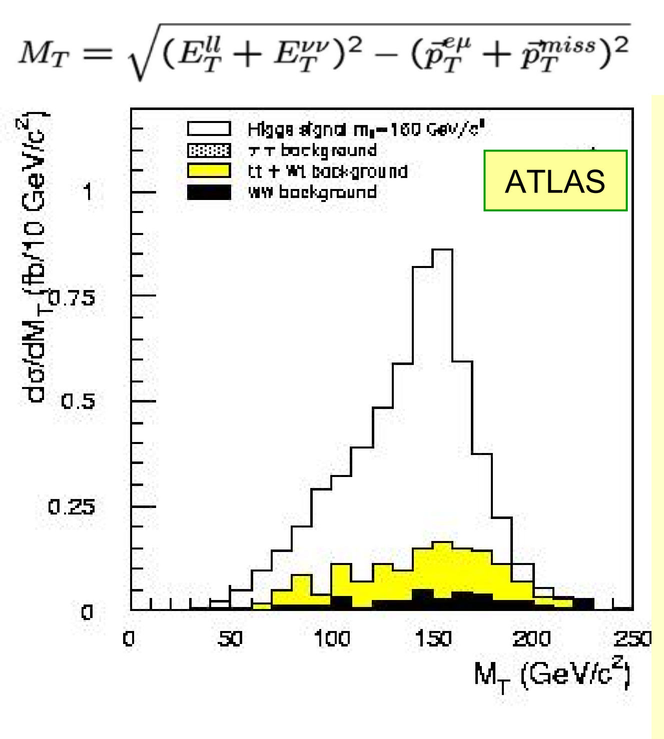

Rapidity distribution of jets in tt and Higgs signal events:

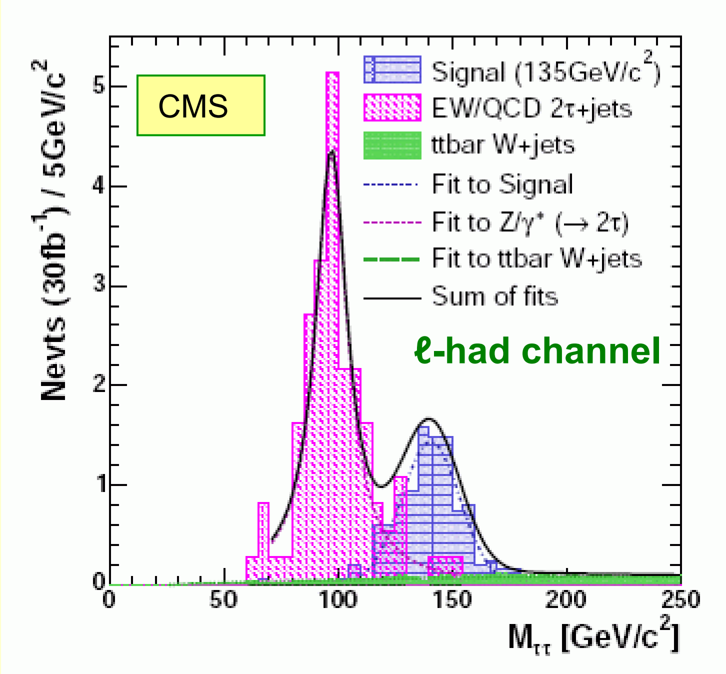


# Two search channels at the LHC:

**qq H → qq W W***
**→ qq ℓν ℓν**

**qq H → qq τ τ**
**→ qq ℓνν ℓνν**
**→ qq ℓνν had ν**




Selection criteria:

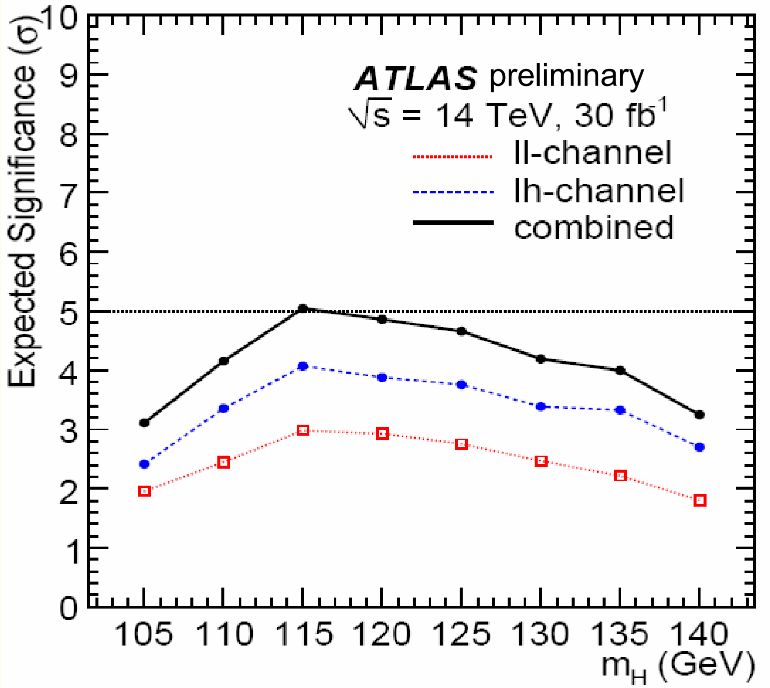
- Lepton $P_T$ cuts and
- Tag jet requirements (Δη, $P_T$, Large mass)
- Jet veto (important)
- Lepton angular and mass cuts

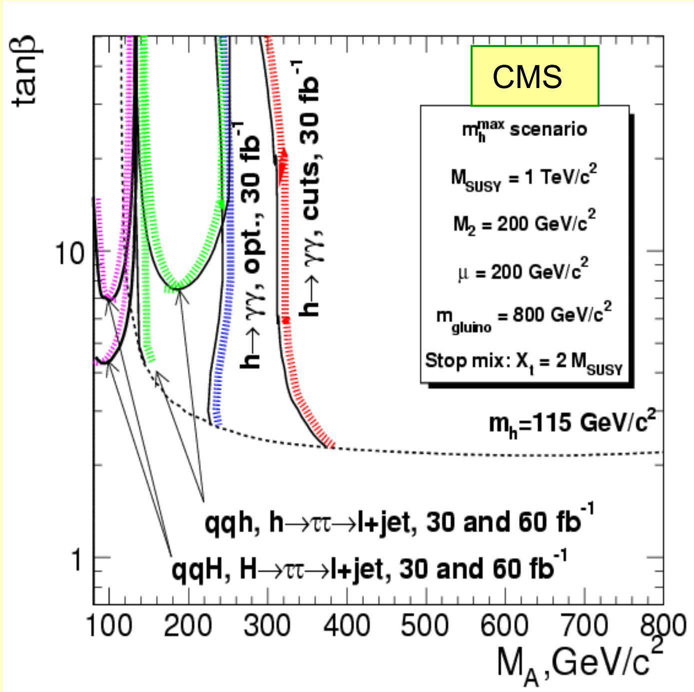
Experimental challenge:

- Identification of hadronic taus
- good $E_T^{miss}$ resolution (ττ mass reconstruction in collinear approximation)
- control of the Z → ττ background shape in the high mass region
  → use data to constrain the background (Z → μμ), see talk by Y. Sirois

# (ii) Results from the first full simulation analysis of $qqH \to qq\,\tau\tau \to qq\,\ell\nu\nu$ had $\nu$

Signal significance, SM Higgs



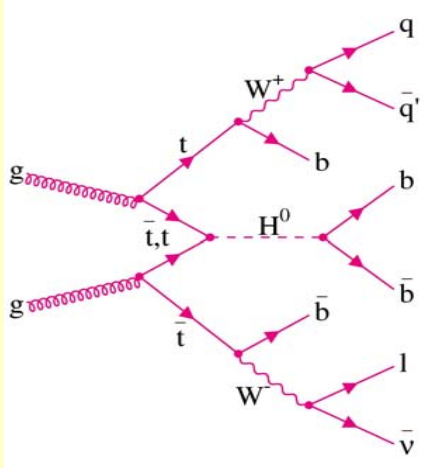




discovery region in the MSSM

- This channel plays an important rôle for the Higgs search at low mass at the LHC both in the Standard Model as well as in the MSSM

- Two key issues: efficient tau identification
  control of $Z \to \tau\tau$ background from data !

# $t\bar{t}\,H \rightarrow t\bar{t}\,b\bar{b}$

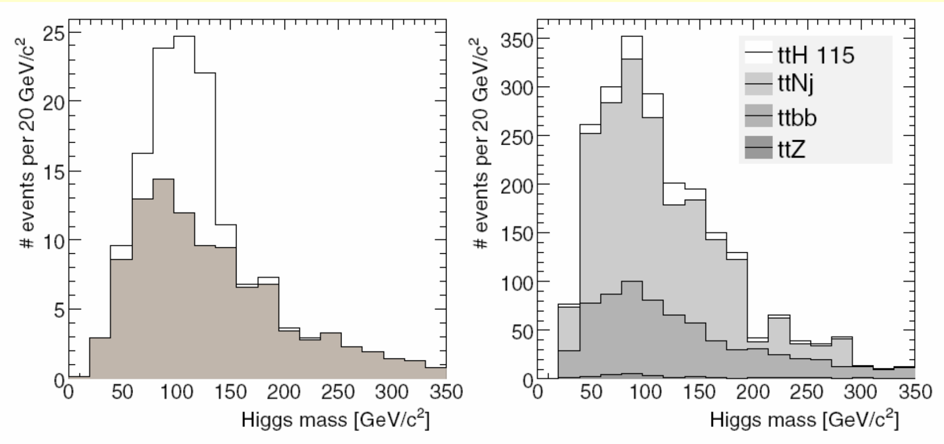



Complex final states: H→ bb, t → bjj, t → bℓν
t → bℓν, t → bℓν
t → bjj, t → bjj

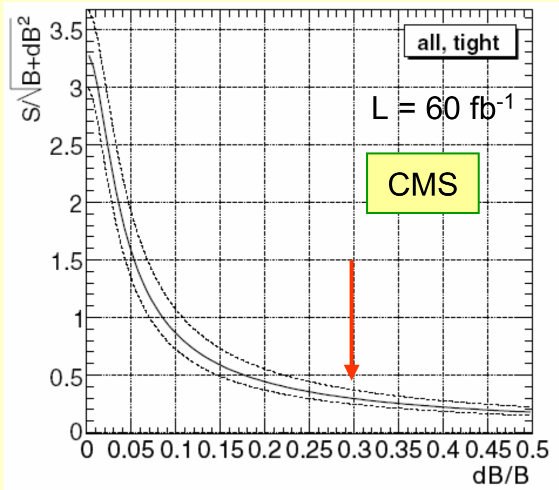
Main backgrounds:
- combinatorial background from signal (4b in final state)
- ttjj, ttbb, ttZ,…
- Wjjjjj, WWbbjj, etc. (excellent b-tag performance required)

• 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

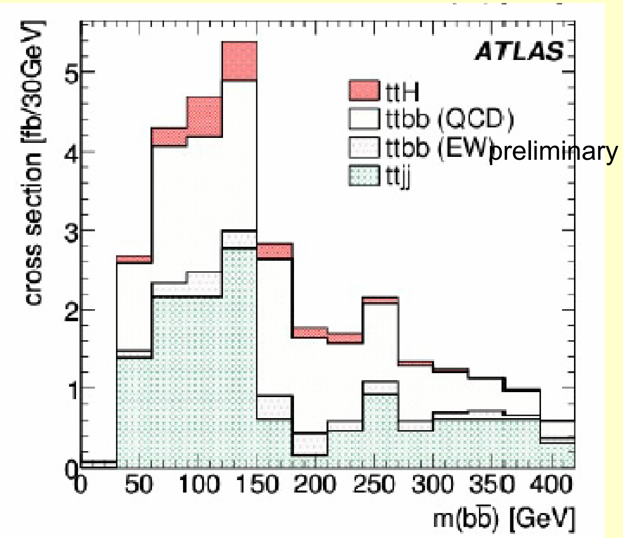


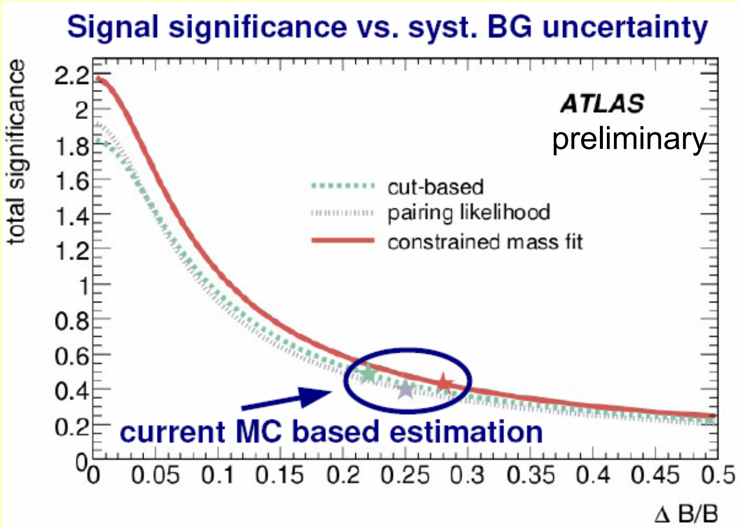

Signal significance as function of background uncertainty

## .....comparable situation in ATLAS (ttH cont.)

preliminary

| Preselection cut | $t\bar{t}H$(fb) | $t\bar{t}b\bar{b}$(EW) (fb) | $t\bar{t}b\bar{b}$(QCD) (fb) | $t\bar{t}X$ (fb) |
|---|---|---|---|---|
| lepton cuts (ID + $p_T$) | 57. ± 0.2 | 141 ± 1.0 | 1356 ± 6 | 63710 ± 99 |
| + ≥ 6 jets | 36 ± 0.2 | 77 ± 0.9 | 665 ± 4 | 26214 ± 64 |
| + ≥ 4 loose $b$-tags | 16.2 ± 0.2 | 23 ± 0.7 | 198 ± 3 | 2589 ± 25 |
| + ≥ 4 tight $b$-tags | 3.8 ± 0.06 | 4.2 ± 0.2 | 30 ± 0.8 | 51 ± 2 |
| | LO | LO | LO | NLO |

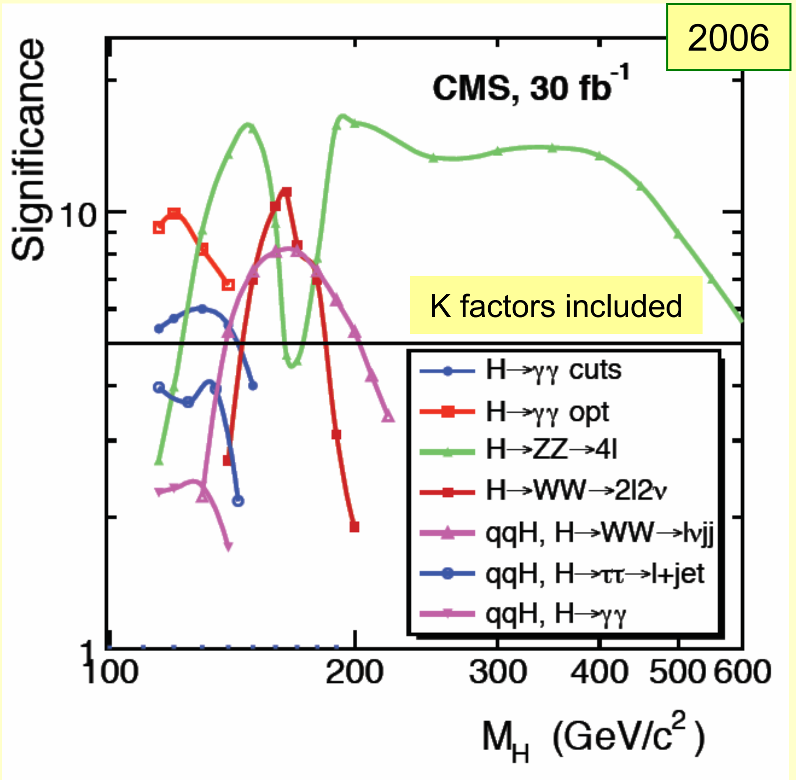


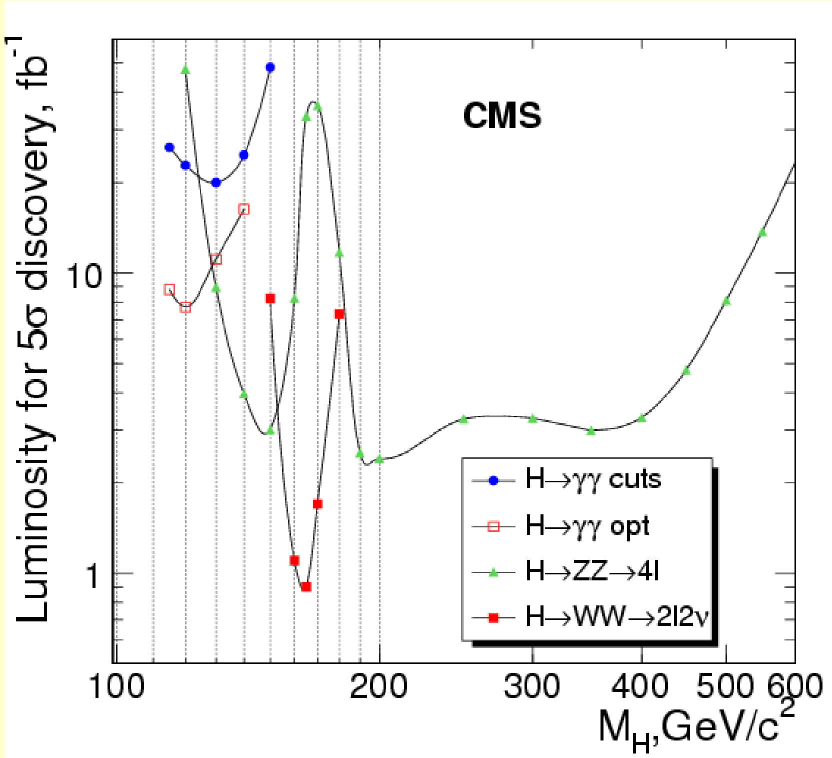




estimated uncertainty on the background: ± 25% (theory, + exp (b-tagging))
⇒ Normalization from data needed to reduce this (non trivial,…)

W/Z H associated production appears difficult as well;
re-assessed at present for highly boosted Higgs (see paper by J. Butterworth et al.)

# LHC discovery potential for 30 $fb^{-1}$

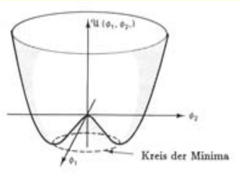



- Full mass range ( up to ~ 1TeV/$c^2$) can be covered after a few years at low luminosity
  [at high mass: more channels (in WW and ZZ decay modes) available than shown here]
- Comparable performance in the two experiments
- Several channels available over a large range of masses

Important changes w.r.t. previous studies:

- **H → γγ** sensitivity of ATLAS and CMS comparable
- **ttH → tt bb** disappeared in both ATLAS and CMS studies




# *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

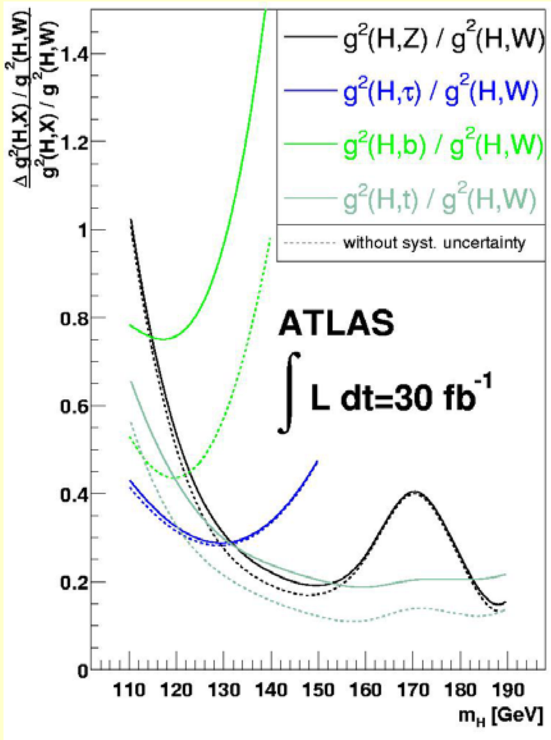
4. **Higgs self coupling**

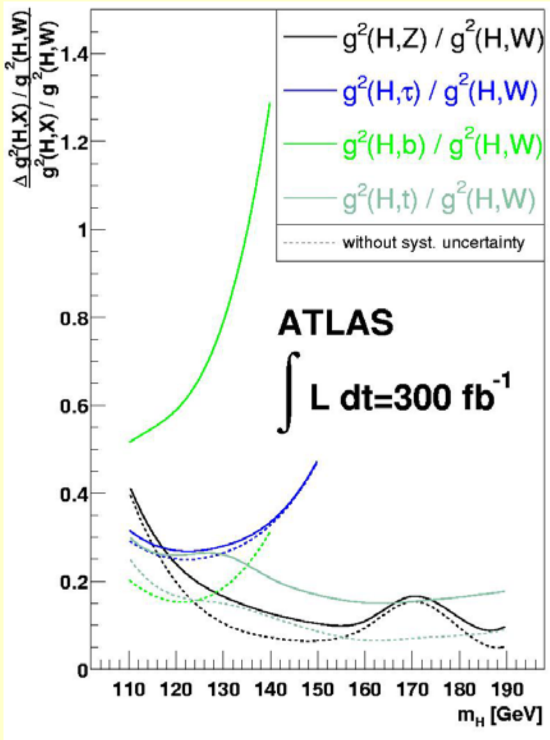
   Possible channel: **gg → HH → WW WW → ℓν jj ℓν jj** (like sign leptons)

# 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

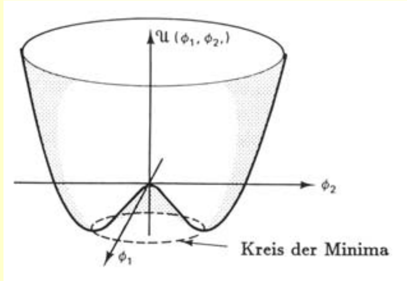


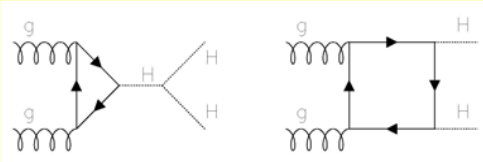

Relative couplings (Z/W, $\tau$/W, t/W) can be measured with a precision of ~20% (for 300 $fb^{-1}$)

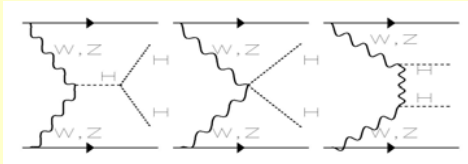
# Higgs Bosons Self-coupling ? (prel., update 2007)

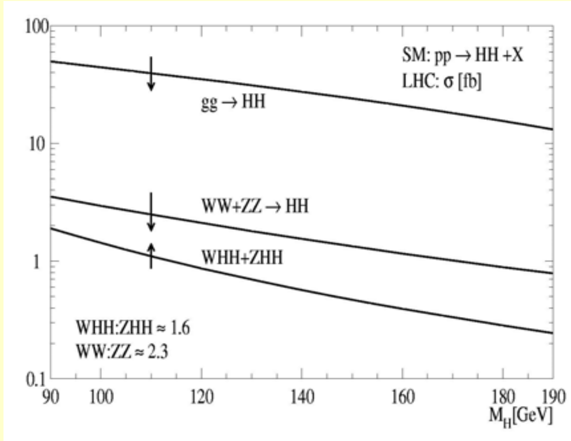
To establish the Higgs mechanism the Higgs boson self-coupling has to be measured:




## Cross sections for HH production:




small signal cross sections,
large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

⇒ no significant measurement possible at the LHC
need Super LHC $L = 10^{35}$ cm$^{-2}$ sec$^{-1}$, 6000 fb$^{-1}$

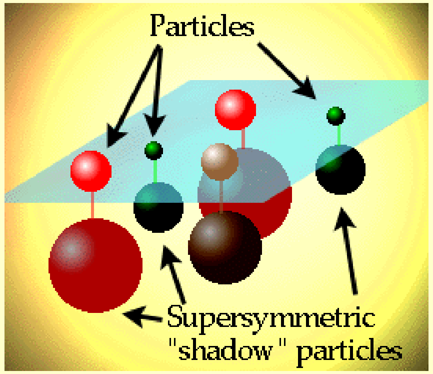
Most sensitive channel: **gg → HH → WW WW → $\ell\nu$ jj $\ell\nu$ jj**

6000 fb$^{-1}$ ⇒ $\Delta \lambda_{HHH} / \lambda_{HHH}$ = 19 % (stat.) (for $m_H$ = 170 GeV)

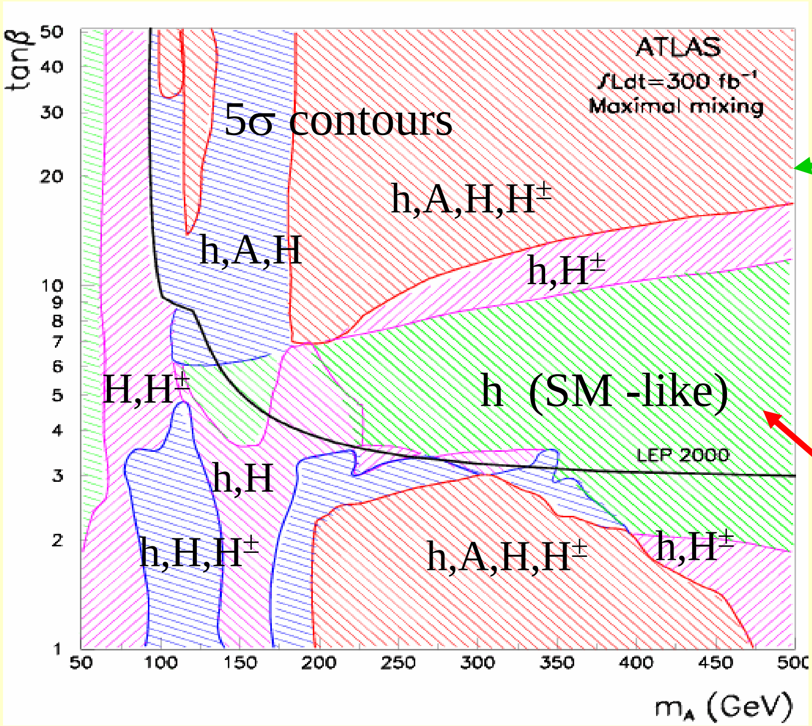
Sensitivity is restricted to a limited mass region around 165 GeV

# The Higgs Sector

# in the MSSM



# LHC discovery potential for SUSY Higgs bosons




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

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)

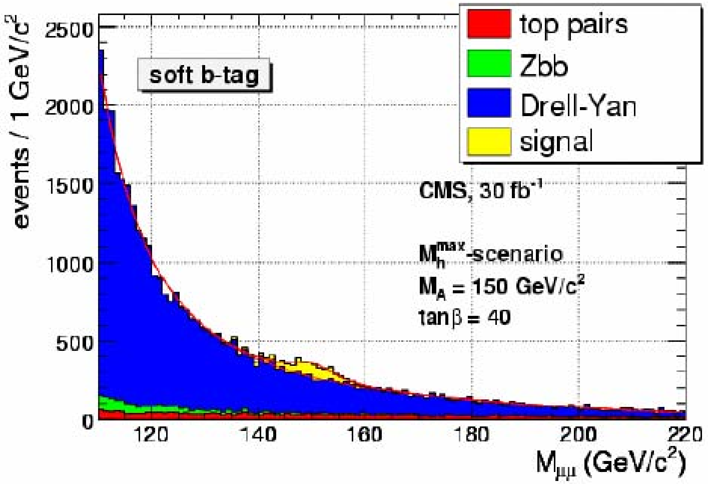
Here only SM-like h observable if SUSY particles neglected.

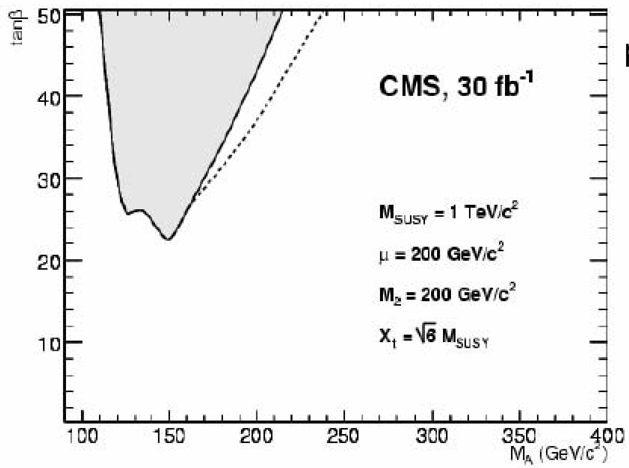
* Validated by recent ATLAS and CMS full simulation studies *

Coverage in the large $m_A$ wedge region can be improved (slightly) by:
- Higher luminosity: sLHC
- Additional SUSY decay modes (however, model dependent)

# Some examples of updated MSSM studies

CMS: A/H → μμ

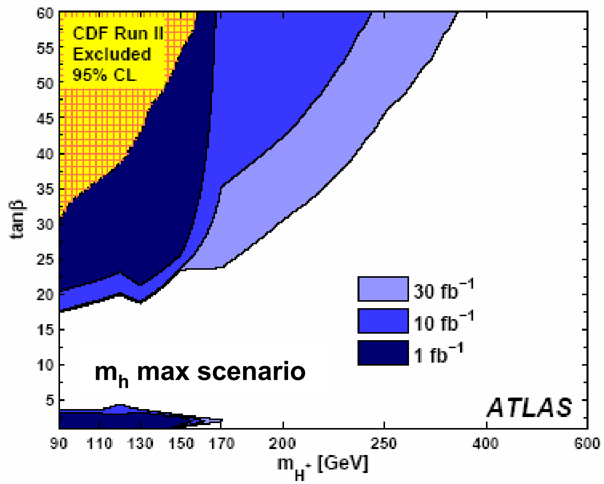


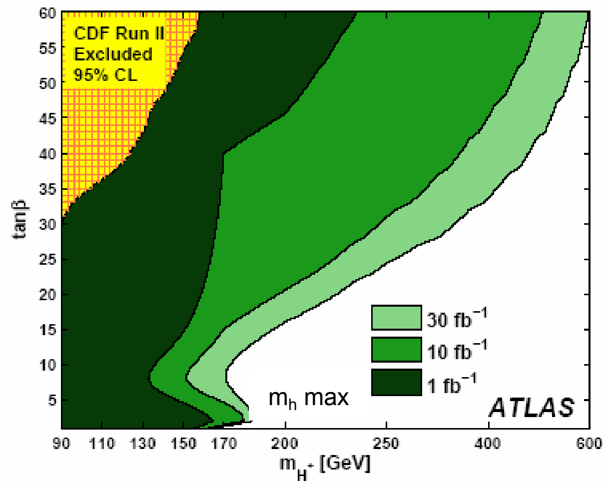

preliminary

ATLAS: Charged Higgs boson searches $H^+ \to \tau\nu$ and tb decay modes

5σ discovery contours for 1 to 30 $fb^{-1}$



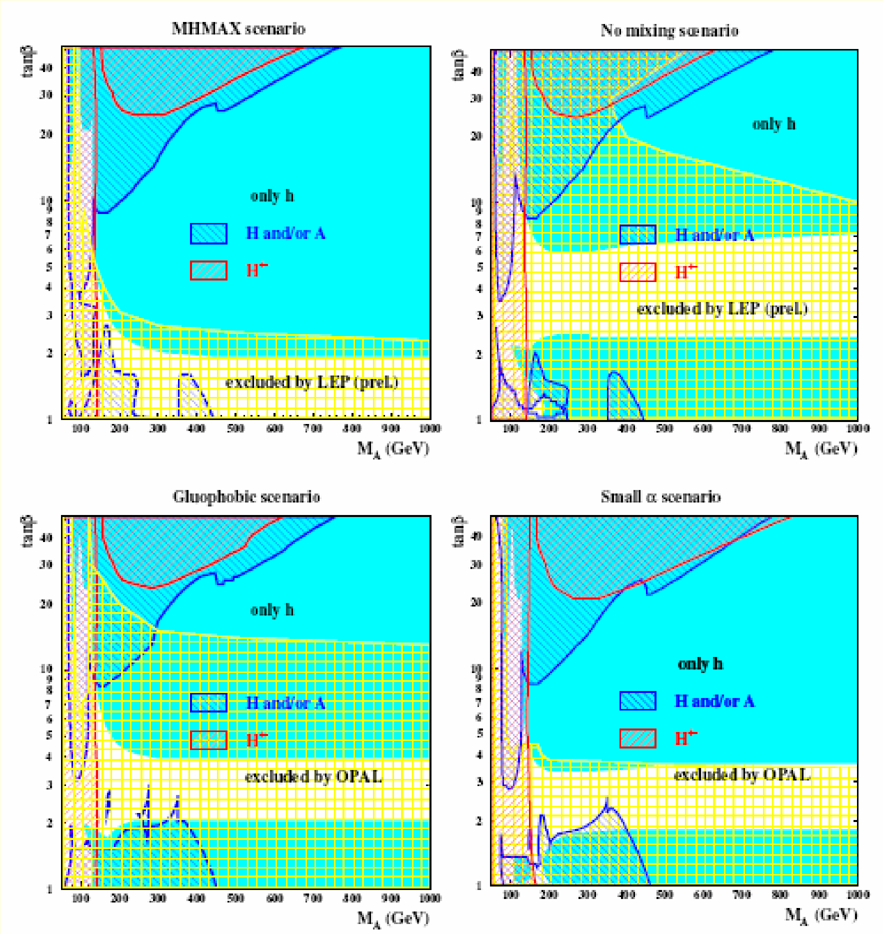

95% CL exclusions for 1 to 30 $fb^{-1}$



# 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 $m_h$

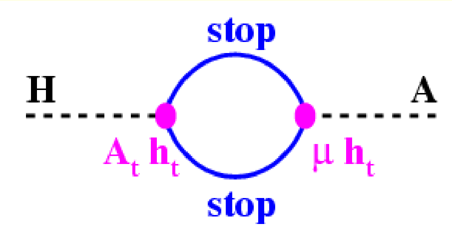
**Nomixing scenario** ($M_{SUSY}$ = 2 TeV/$c^2$)
(1TeV almost excl. by LEP )
small $m_h$ → difficult for LHC

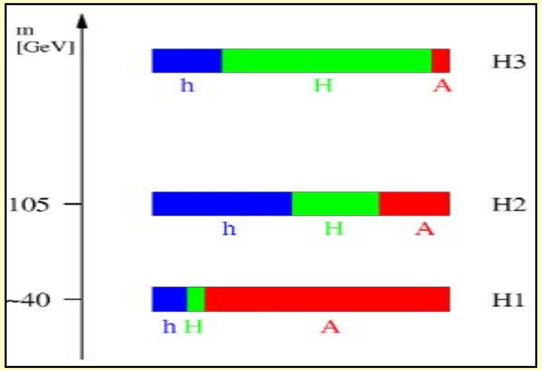
**Gluophobic scenario** ($M_{SUSY}$ = 350 GeV/$c^2$)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for g g → H, H→ γγ and Z→4 ℓ

**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))

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

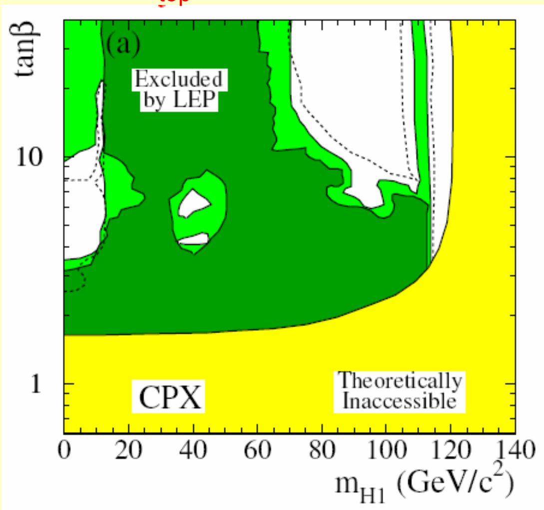
- No lower mass limit for $H_1$ from LEP !

  (decoupling from the Z)

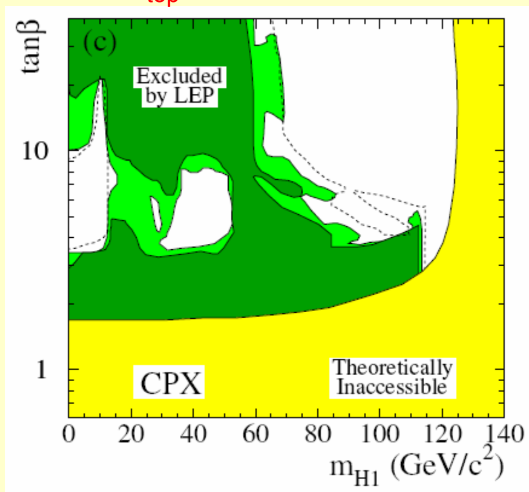
  details depend on $m_{top}$ and on theory model

  (FeynHiggs vs. CPsuperH)

$m_{top}$ = 169.3 GeV/$c^2$

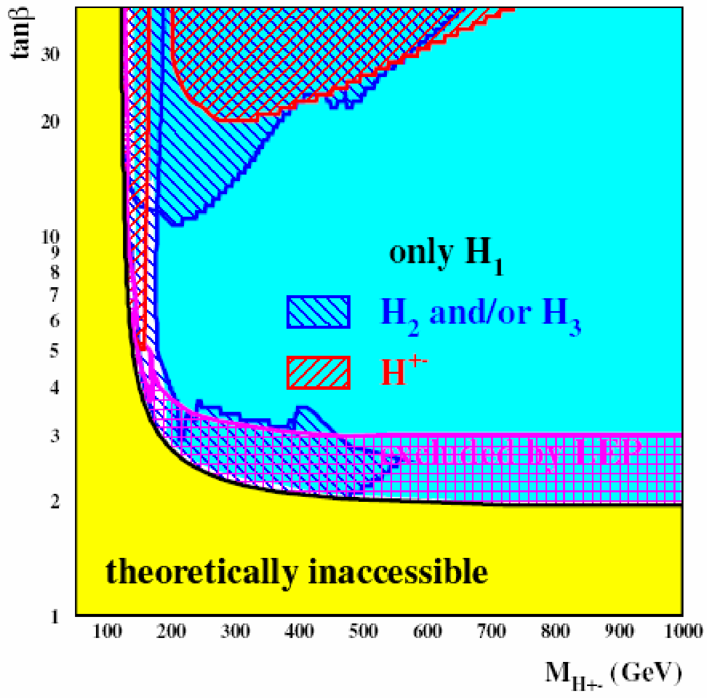


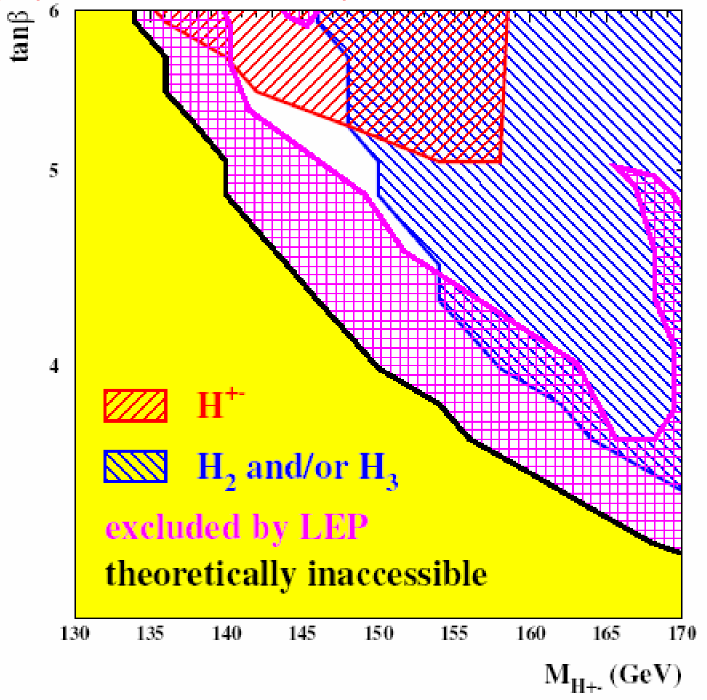

$m_{top}$ = 174.3 GeV/$c^2$



# 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 tan$\beta$ , low $m_{H+}$) corresponding to low $m_{H_1}$

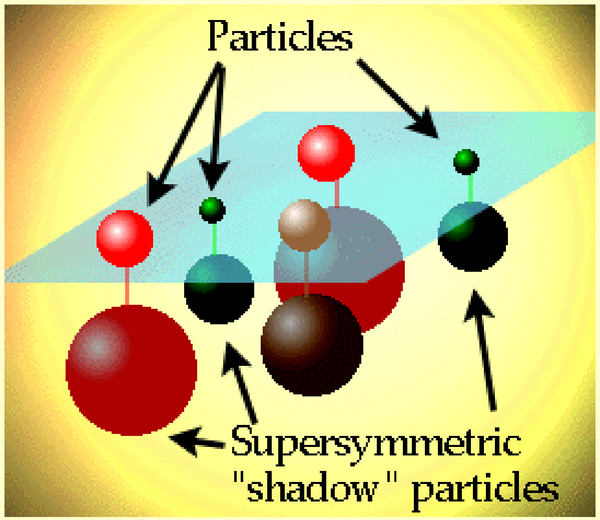
- More studies needed, e.g. investigate lower $H_1$ masses,
  additional decay channels:
  $tt \rightarrow Wb\ H^{+}b \rightarrow \ell\nu b\ WH_1 b,\ \ H_1 \rightarrow bb$

# Search for

# Supersymmetry

*First hints of supersymmetry might show up already in early data……*

*e.g. deviations from the Standard Model expectation in the $E_T^{miss}$ spectrum*



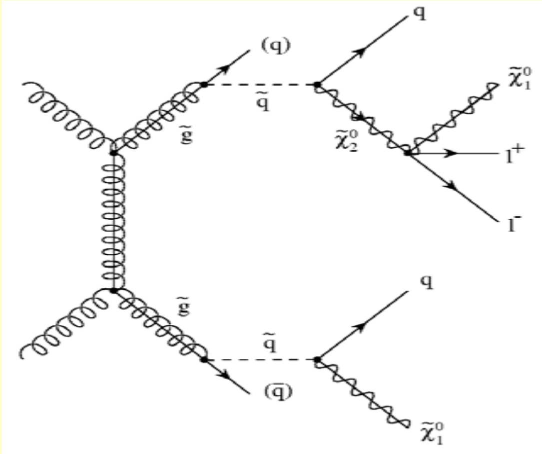

*Here: overview*

*More details on individual analyses and data-driven background normalizations will be given in the talk of Beate Heinemann*

# Search for Supersymmetry

- Squarks and Gluinos are strongly produced

  They decay through cascades to the lightest SUSY particle (LSP)




$\Rightarrow$ combination of
Jets, Leptons, $E_T^{miss}$

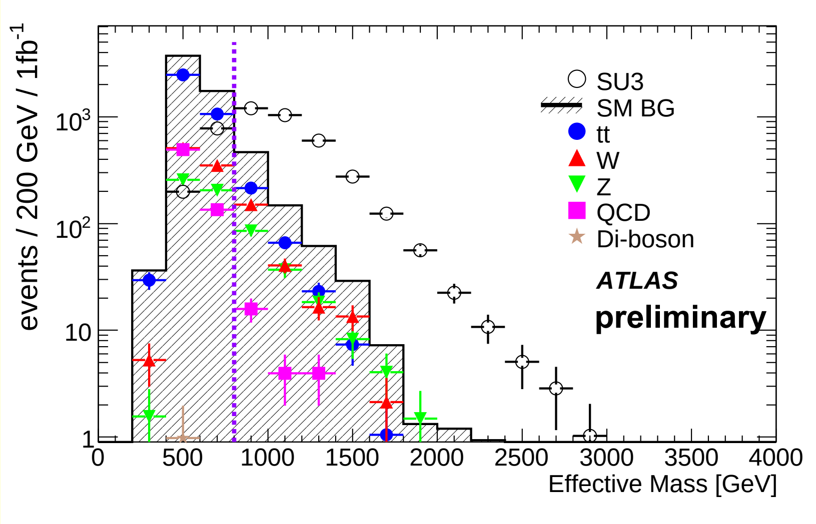
1. Step: Look for deviations from the Standard Model
   Example: Multijet + $E_T^{miss}$ signature

2. Step: Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution

3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to determine mass combinations

# Squarks and Gluinos

- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and $E_T^{miss}$
- Typical selection: $N_{jet} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{miss} > 100$ GeV
- Define: $M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)



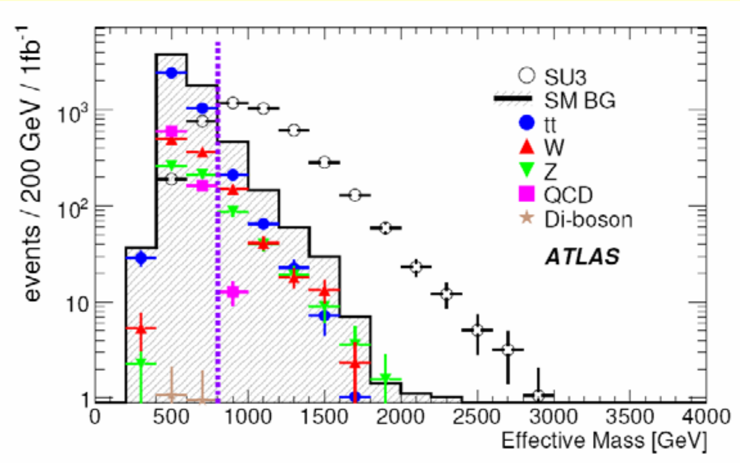

example: mSUGRA, point SU3 (bulk region)
$m_0$ = 100 GeV, $m_{1/2}$ = 300 GeV
tan $\beta$ = 6, $A_0$ = -300 GeV, $\mu > 0$

LHC reach for Squark- and Gluino masses:

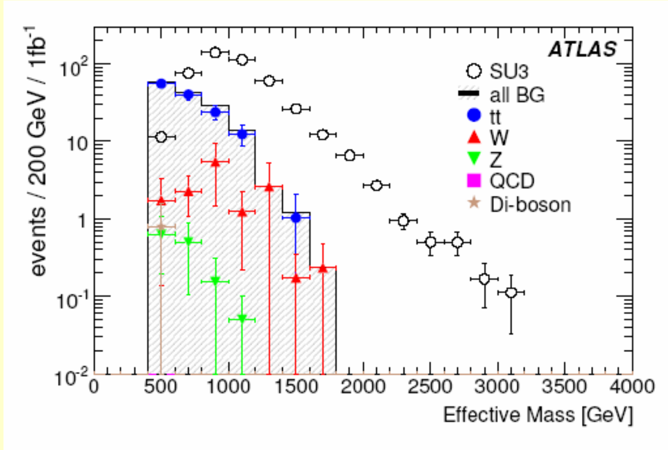
0.1 fb$^{-1}$ $\Rightarrow$ M ~ 750 GeV
1 fb$^{-1}$ $\Rightarrow$ M ~ 1350 GeV
10 fb$^{-1}$ $\Rightarrow$ M ~ 1800 GeV

Deviations from the Standard Model due to SUSY at the TeV scale can be detected fast !

# …additional potential: inclusive searches with leptons

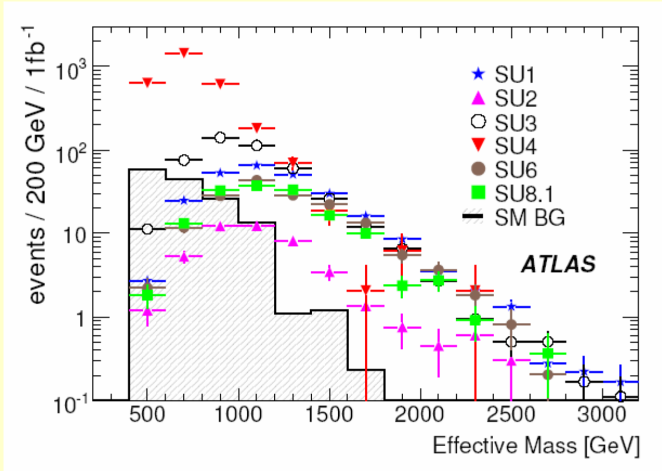



SU3, 4 jets + 0 lepton final states




SU3, 4 jets + 1 lepton final states

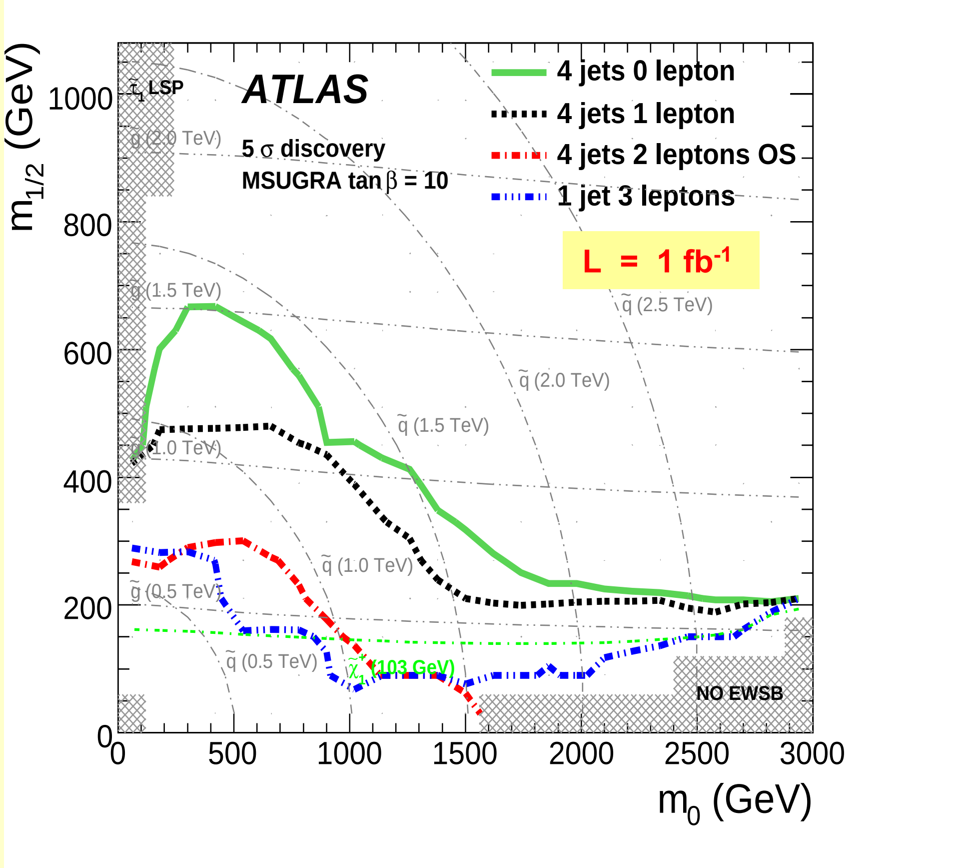
- smaller signal rates, but better S:B conditions
- Discovery potential is more robust, in particular at the beginning, when systematic uncertainties on the backgrounds are large
- Similar analyses with $\tau$ lepton and b quark final states



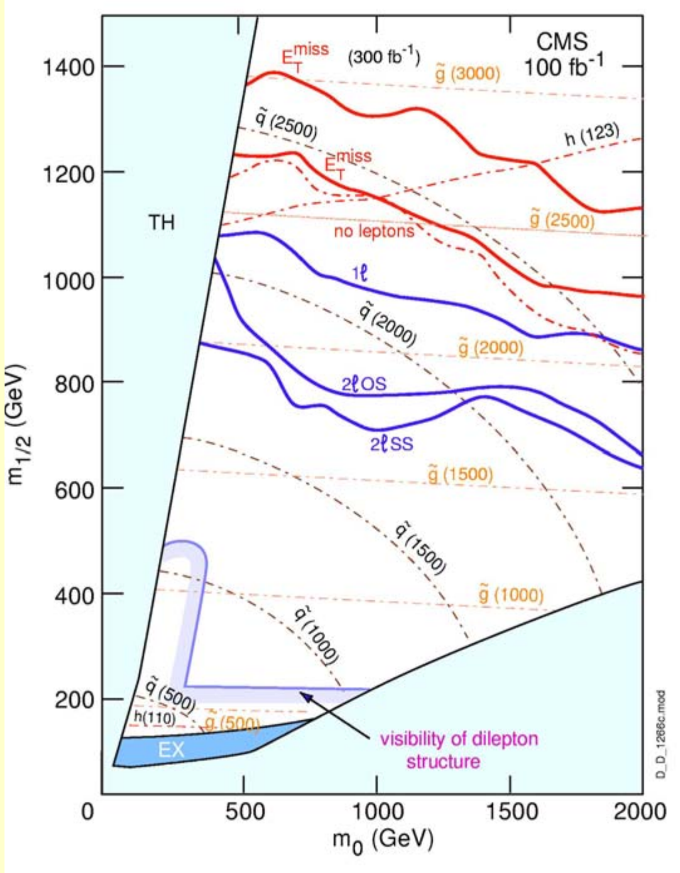

4 jets + 1 lepton final states for other benchmark points

# LHC reach in the $m_0$ - $m_{1/2}$ mSUGRA plane:

Multijet + $E_T^{miss}$ signature




SUSY cascade decays give also rise to many other inclusive signatures: **leptons, b-jets, τ's**



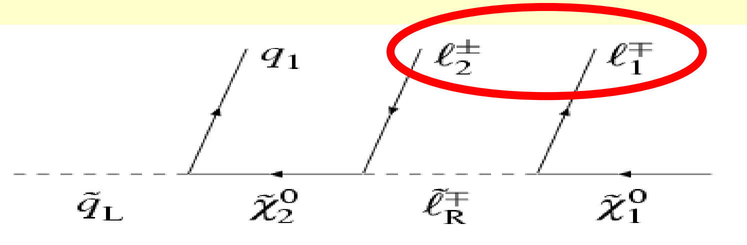

- Tevatron reach can be extended with early data
- Expect multiple signatures for TeV-scale SUSY

  Long term mass reach (300 $fb^{-1}$): 2.5 – 3 TeV

# LHC Strategy for determination of model parameters:

## End point spectra of cascade decays

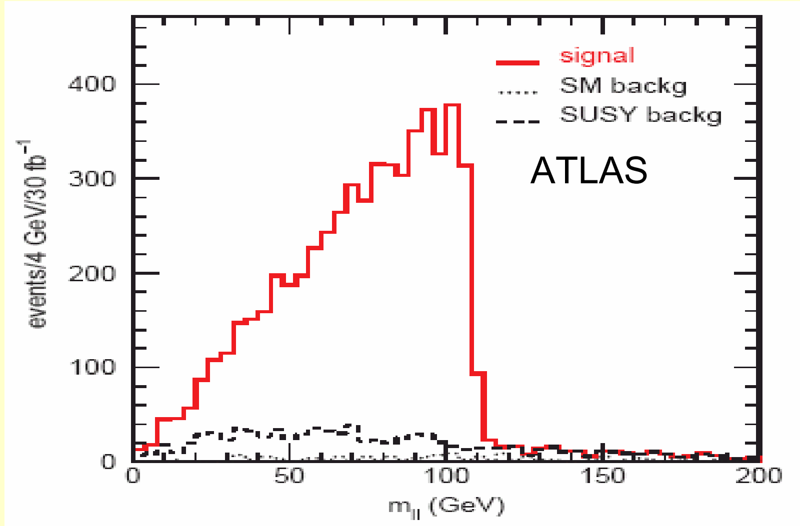
Example: $\tilde{q} \rightarrow q\tilde{\chi}^0_2 \rightarrow q\tilde{\ell}^{\pm}\ell^{\mp} \rightarrow q\ell^{\pm}\ell^{\mp}\tilde{\chi}^0_1$




$$M^{max}_{\ell^+\ell^-} = \frac{\sqrt{(m^2_{\chi^0_2} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\chi^0_1})}}{m_{\tilde{\ell}}}$$

$$M^{max}_{\ell_1 q} = \frac{\sqrt{(m^2_{\chi^0_2} - m^2_{\tilde{\ell}})(m^2_{\tilde{q}} - m^2_{\chi^0_2})}}{m_{\chi^0_2}}$$

- Due to LSPs in the final state the SUSY particle masses cannot be reconstructed
- Measure shapes of kinematic distributions of final state particles;
  endpoints depend on sparticle masses involved
- $\Rightarrow$ global fit



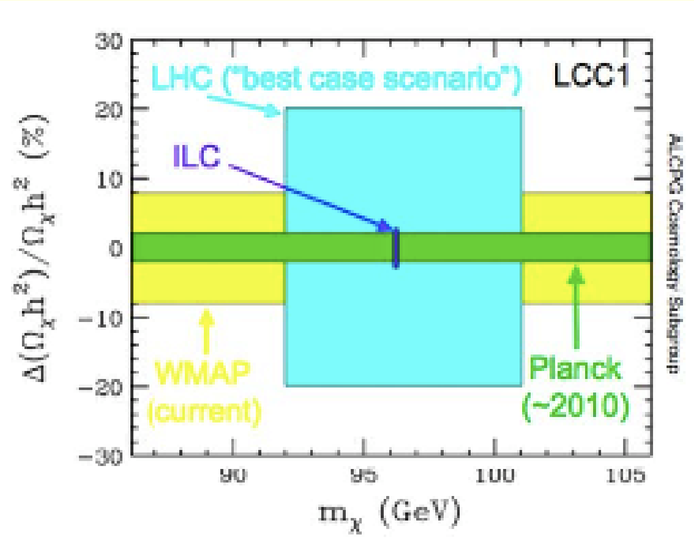
Strategy in SUSY Searches at the LHC:

- Search for multijet + $E_T^{miss}$ excess
- Look for special features ($\gamma$'s , long lived sleptons)
- Look for $\ell^\pm$, $\ell^+ \ell^-$, $\ell^\pm \ell^\pm$, b-jets, $\tau$'s
- End point analyses, global fit

$\Rightarrow$ Parameters of the SUSY model

Complex: requires close cooperation between experimentalists and theorists !

$\Rightarrow$ Predict dark matter relic density, check consistency with other measurements



# Models other than SUGRA

GMSB:

- LSP is light gravitino
- Phenomenology depends on nature and lifetime of the NLSP
- Generally longer decay chains, e.g. $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \tilde{\chi}_1^0 \ell^+\ell^- \rightarrow \tilde{G}\gamma\ell^+\ell^-$

$\Rightarrow$ models with prompt NLSP decays give additional handles and hence are easier than SUGRA

- NLSP lifetime can be measured:
  - For $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$, use Dalitz decays (short lifetime) or search for non-pointing photons
  - Quasi stable sleptons: muon system provides excellent „Time of Flight“ system

RPV :

- R-violation via $\chi^0_1 \rightarrow \ell\ell\nu$ or $qq\ell$, $qq\nu$ gives additional leptons and/or $E_T^{miss}$
- R-violation via $\chi^0_1 \rightarrow cds$ is probably the hardest case; (c-tagging, uncertainties on QCD multijet background)

# Conclusions

- The LHC experiments are well set up to explore the existence of Higgs Bosons and Supersymmetry
  ….... and are well prepared for unexpected scenarios

- Higgs: 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

- SUSY: discovery of deviations from the Standard Model due to SUSY should be easy and fast, the determination of model parameters is more difficult

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