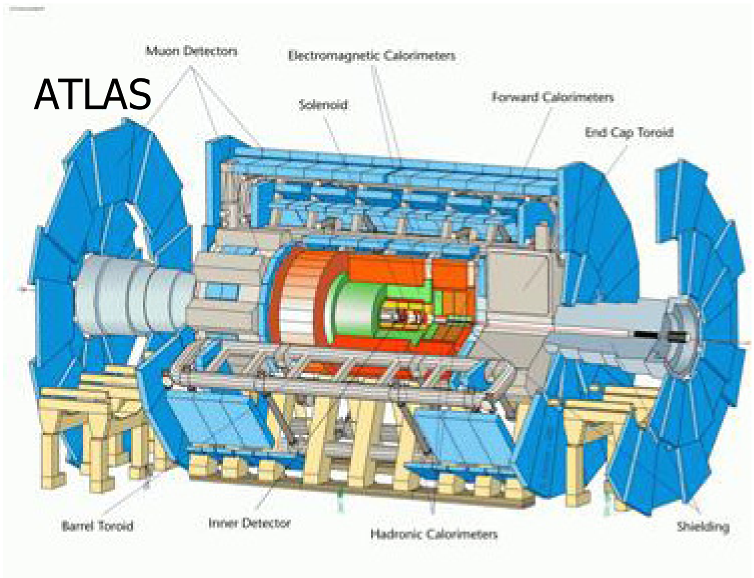
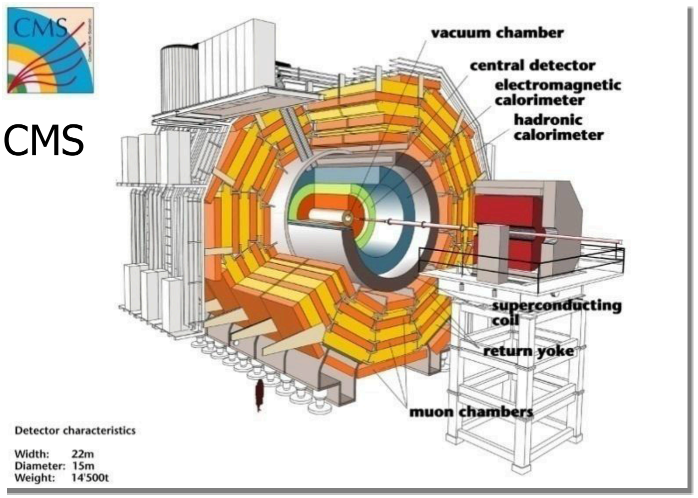
Higgs boson searches at LHC

- ✓ LHC physics goals
- ✓ Standard Model and a Higgs boson
- ✓ Experimental challenges
- ✓ Prospects for SM Higgs
- ✓ Prospects for MSSM Higgs
- ✓ Summary on the road path





LHC a brief history

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

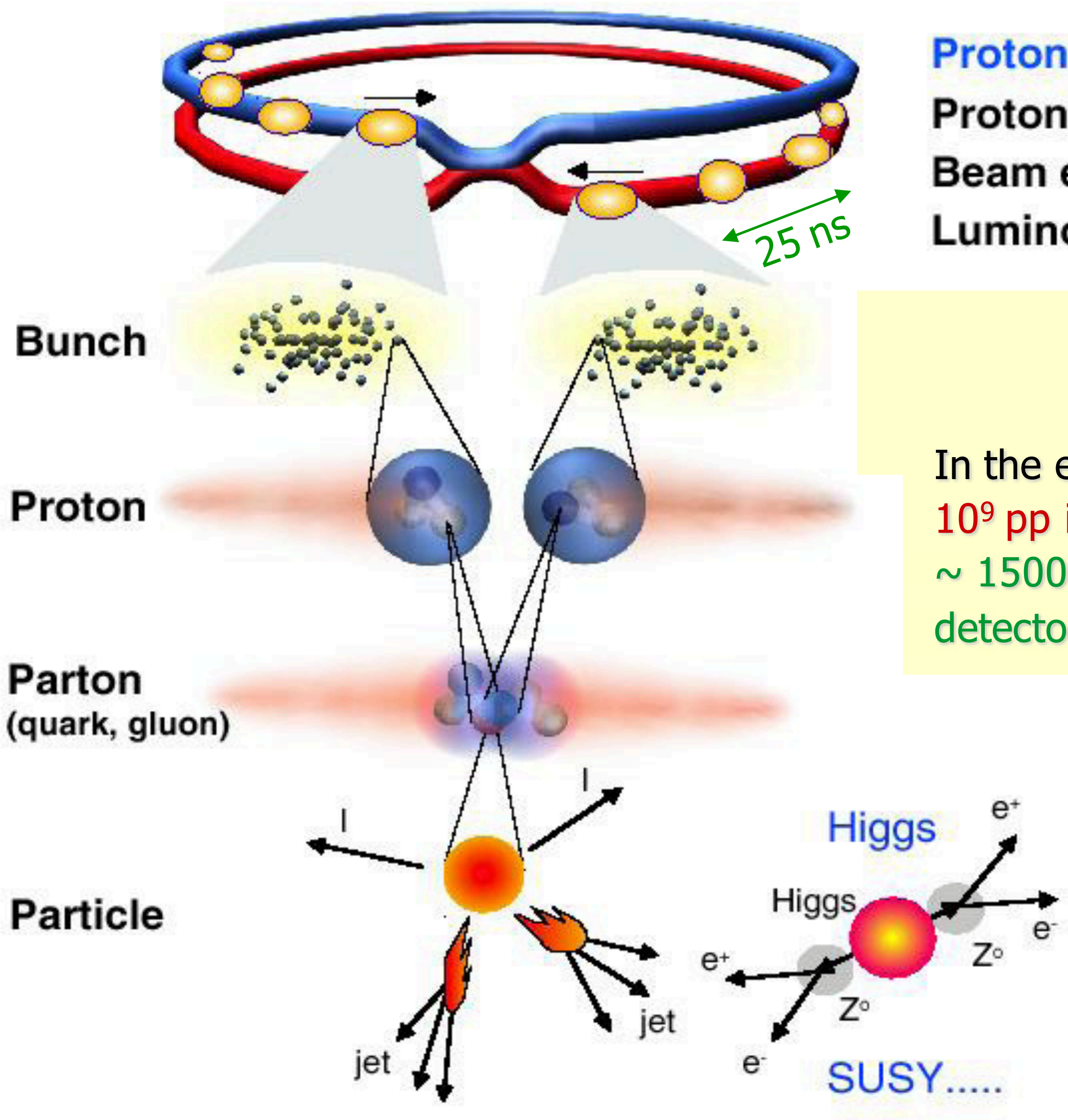
1983 : W±/Z detected at SPS proton-antiproton collider
Tevatron becomes operational
1984 : First studies for a high-energy pp collider in the LEP tunnel
1989 : Start of SLC and LEP e+e- colliders
1993 : SSC is cancelled
1994 : LHC approved by the CERN Council
1995 : Top-quark discovery at the Tevatron
1996 : Construction of LHC machine and experiments start
2000 : End of LEP2
2003 : Start of the accelerator and experiments installation

A 40-year project !!

Summer 2008

Expect First collisions at $\sqrt{s}$ = 10TeV (14 TeV)
Start a ~15-year long physics program

Collisions at LHC



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

In the experiments:
10^9 pp interactions per second
~ 1500 particles (p,n, π) produced in the detectors at each bunch-crossing

Selection of 1 in 10,000,000,000,000

LHC physics goals (pp collision)

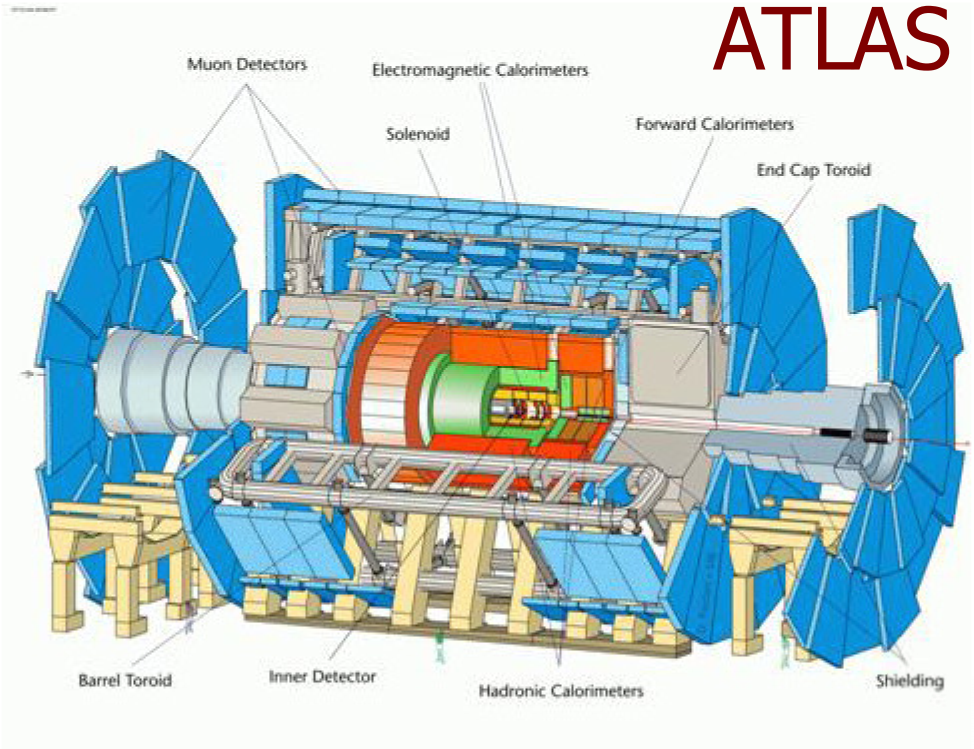
Higgs boson is a keystone of Standard Model construction. Elusive itself though interations is expected to define properties of all known particles. That is why search for the Standard Model Higgs boson over mas range $\sim 115 < m_H < 1000$ GeV is focusing point of LHC experiments.

Explore the highly-motivated TeV-scale, search for physics beyond the SM (Supersymmetry (more than one Higgs boson), Extra-dimensions, q/l compositness, leptoquarks, W'/Z', heavy q/l, etc.)

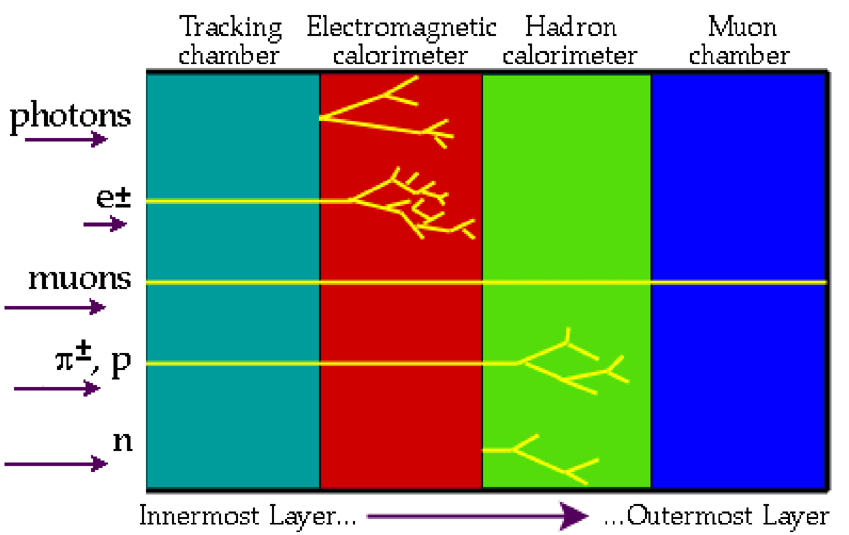
Precise measurements

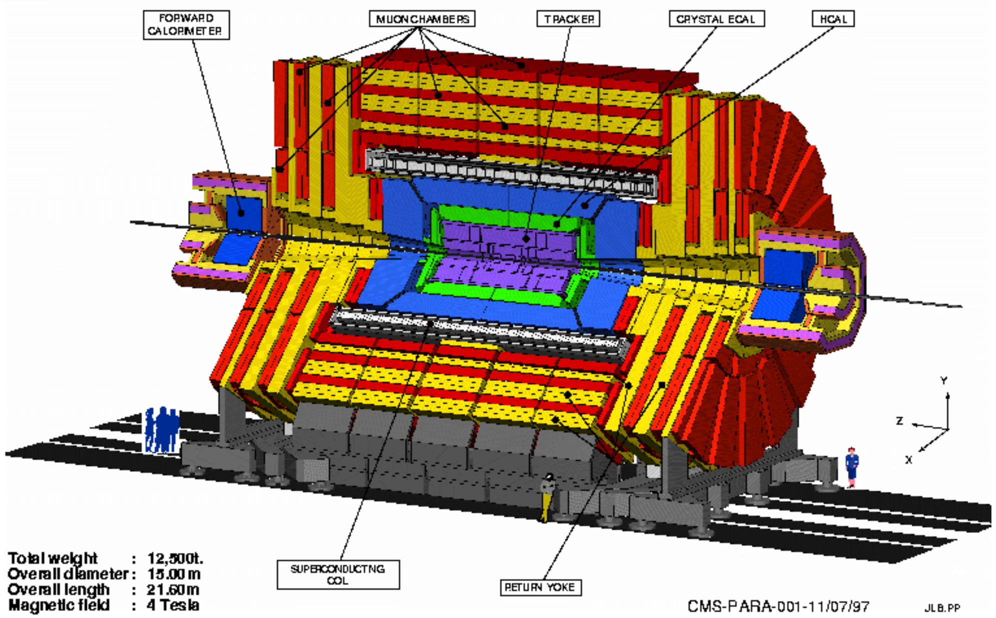
- -- W mass
- -- Top mass, couplings and decay properties
- -- Higgs mass, spin, couplings (if Higgs found)
- -- B-physics (mainly LHCb): CP violation, rare decays,…..
- -- QCD jet cross-section and α_s
- -- etc.…

ATLAS and CMS detectors



- Multi-purpose : able to detect all know particles
- Fast response : ~50 ns
- 10^8 electronic channels
- Radiation hard (up to 10^6 Gy in the hottest regions after 10 years of operation)

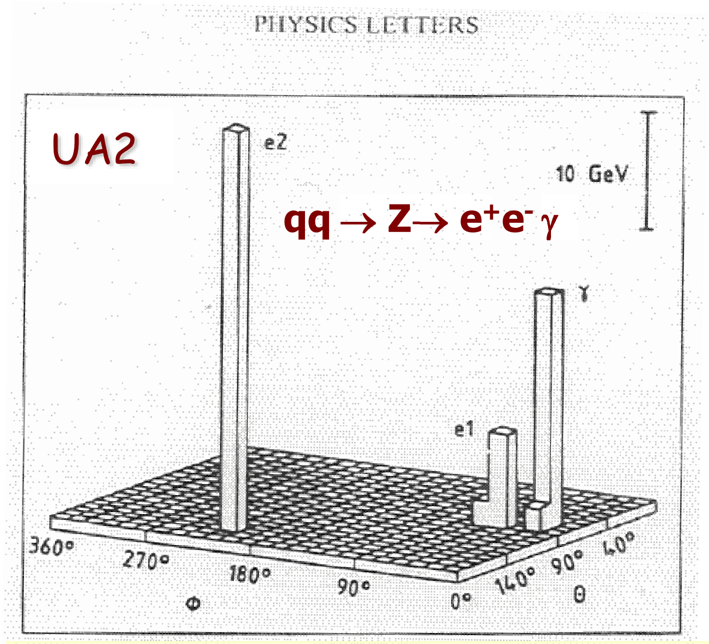




Why do we like the Standard Model ?

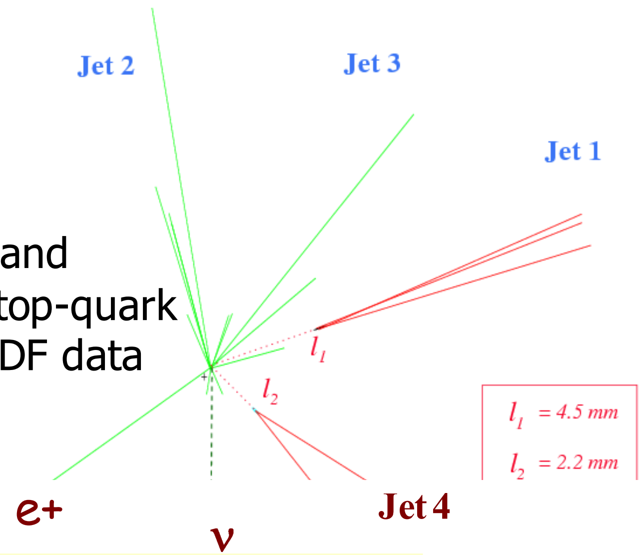
All the SM predictions (but one ...), in terms of particles and features of their interactions, have been verified by many experiments at many machines

1983 : **W, Z** discovered at CERN $p\bar{p}$ Collider
m ~ 100 GeV as predicted by theory



1994 : **top quark** discovered at Fermilab $p\bar{p}$ Collider: m ~ 175 GeV
Heaviest elementary particle !

Production and decay of a top-quark pair from CDF data



1989-2000: LEP e^+e^- collider at CERN

several precise measurements of Z particle
→ agreement theory-data at the permil level !

But still many open questions… first of all
What is the origin of the particle masses?

Mass of quark top (heaviest elementary particle observed)
$\approx$ mass of Gold atom.
Electron mass = 1 000 000 times smaller than top-quark mass
Photon mass = 0

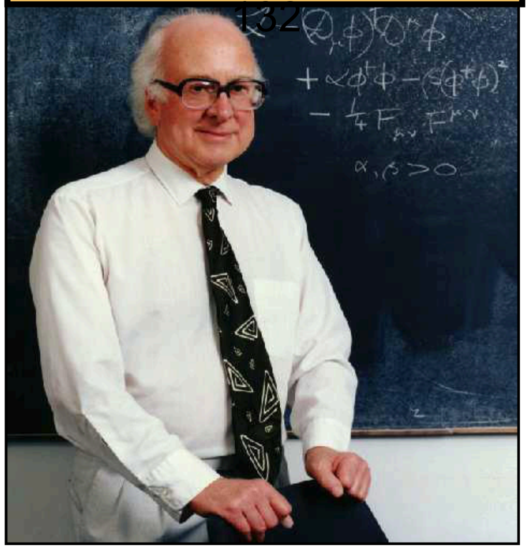
The mass mystery could be solved by the "Higgs mechanism", which predicts the existence of a new elementary scalar particle : **the Higgs boson**

This particle has been searched for 20 years at accelerators all over the world and has not been observed yet.

The Higgs particle has a mass between 2 times the mass of an Iron atom and 4 times the mass of an Uranium atom.
The LHC has sufficient energy to produce it.

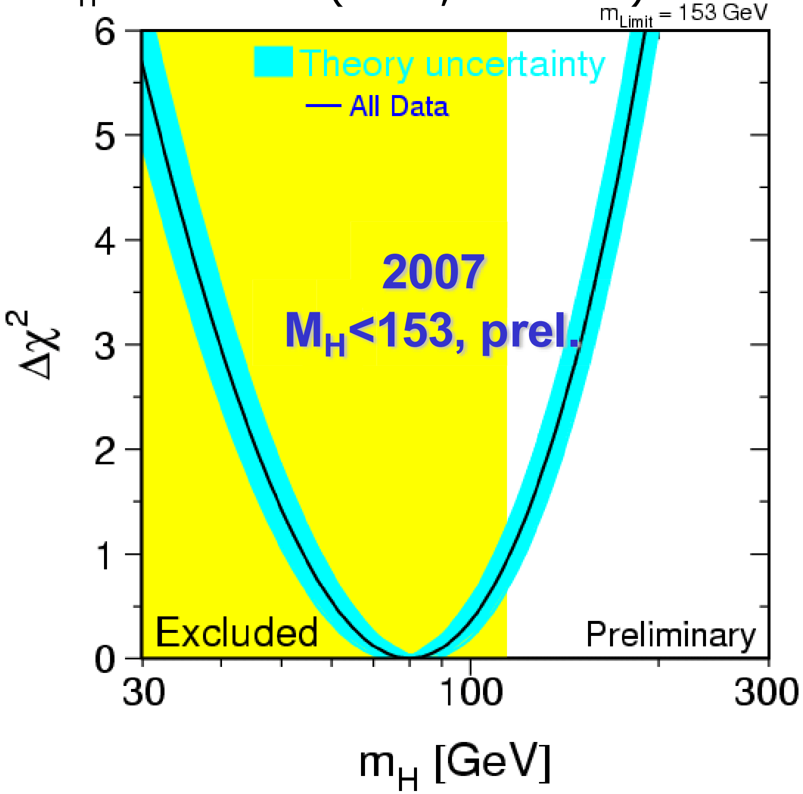
If the Higgs particle is not found at the LHC, the Higgs mechanism is wrong and we will have to find another solution to the mass problem.

P.W. Higgs,
Phys. Lett. 12 (1964) 132

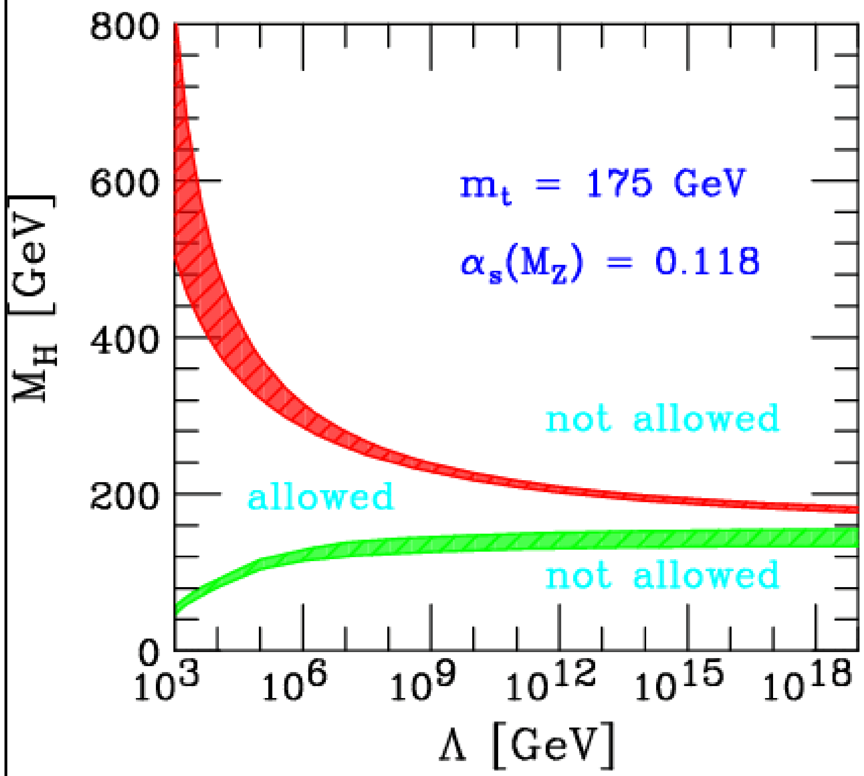


SM Higgs mass constraints

Experiment	SM theory
Indirect constraints from precision EW data M_H < 260 GeV at 95 %CL (2004) M_H < 186 GeV with Run-I/II prelim. (2005) M_H < 166 GeV (2006, ICHEP06)	The triviality (upper) bound and vacuum stability (lower) bound as function of the cut-off scale Λ



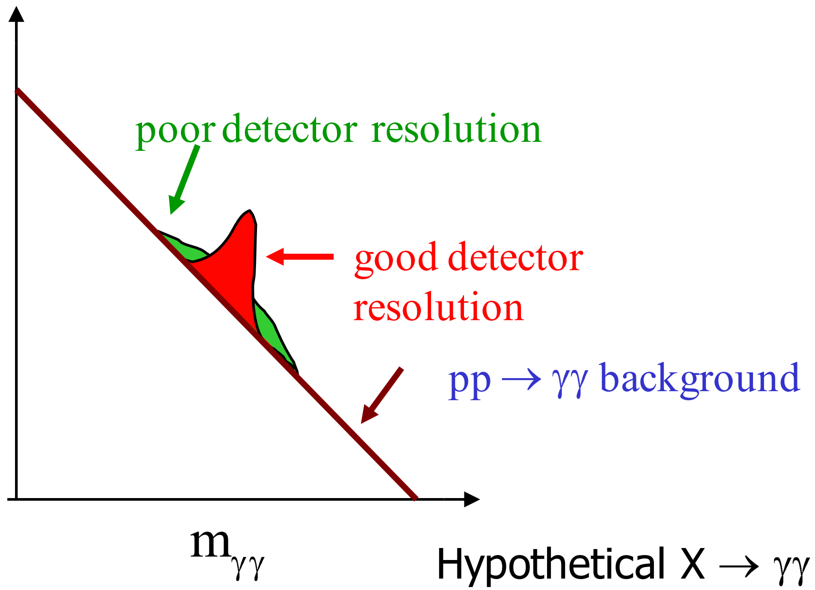
Direct limit from LEP: M_H > 114.4 GeV



The experimental challenges

❶ Don't know how New Physics will manifest

- detectors must be able to detect as many particles and signatures as possible: **e, μ, τ, ν, γ, jets, b-quarks ....**
- ATLAS and CMS are general-purpose experiments.



Hypothetical X → γγ signal on top of background

Lepton measurement:
$p_T \approx$ GeV → 5 TeV (b → l+X, W'/Z',...)

Mass resolutions:
$\approx$ 1% decays into leptons or photons (Higgs, new resonances)
$\approx$ 10% W → jj, H → bb (top physics, Higgs, ...)

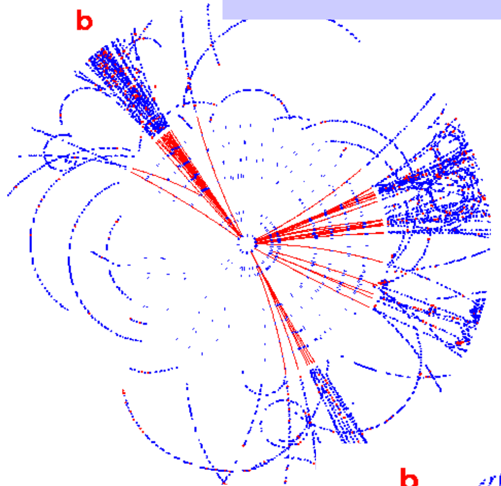
Particle identification:

- b/jet separation : ε (b) ≈ 50% R (jet) ≈ 100 (H → bb, SUSY, 3rd generation !!)
- τ/jet separation : ε (τ) ≈ 50% R(jet) ≈ 100 (A/H → $\tau\tau$, SUSY, 3rd generation !!)
- γ/jet separation : ε (γ) ≈ 80% R(jet) > 103 (H → $\gamma\gamma$)
- e/jet separation : ε (e) > 70% R(jet) > 105 (inclusive electron sample)

The experimental challenges

❷ Event rate and pile-up (high luminosity…)

$H \rightarrow bb$ event



ATLAS tracking

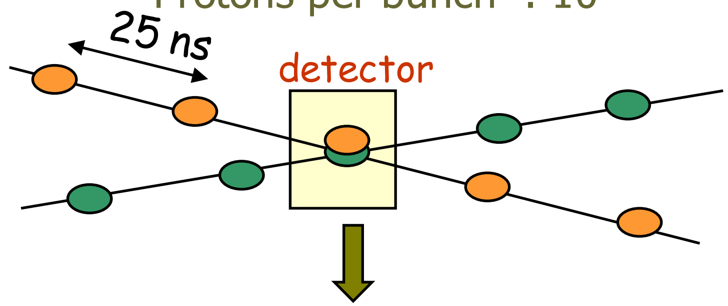
Event rate in ATLAS, CMS :

$N = L \times \sigma_{inelastic}(pp) \approx 10^{34}\ cm^{-2}\ s^{-1} \times 70$ mb

$\approx 10^{9}$ interactions/s

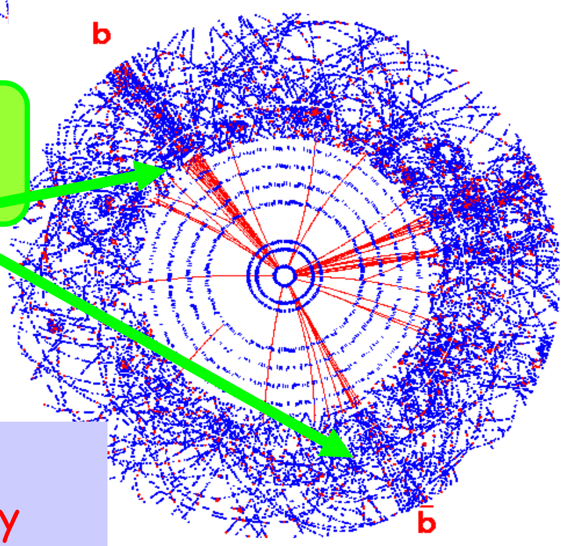
Proton bunch spacing : 25 ns

Protons per bunch : 10^{11}



~ 20 inelastic (low-p_T) events ("minimum bias") produced simultaneously in the detectors at each bunch crossing → **<u>pile-up</u>**

Track density in jet >>pile-up



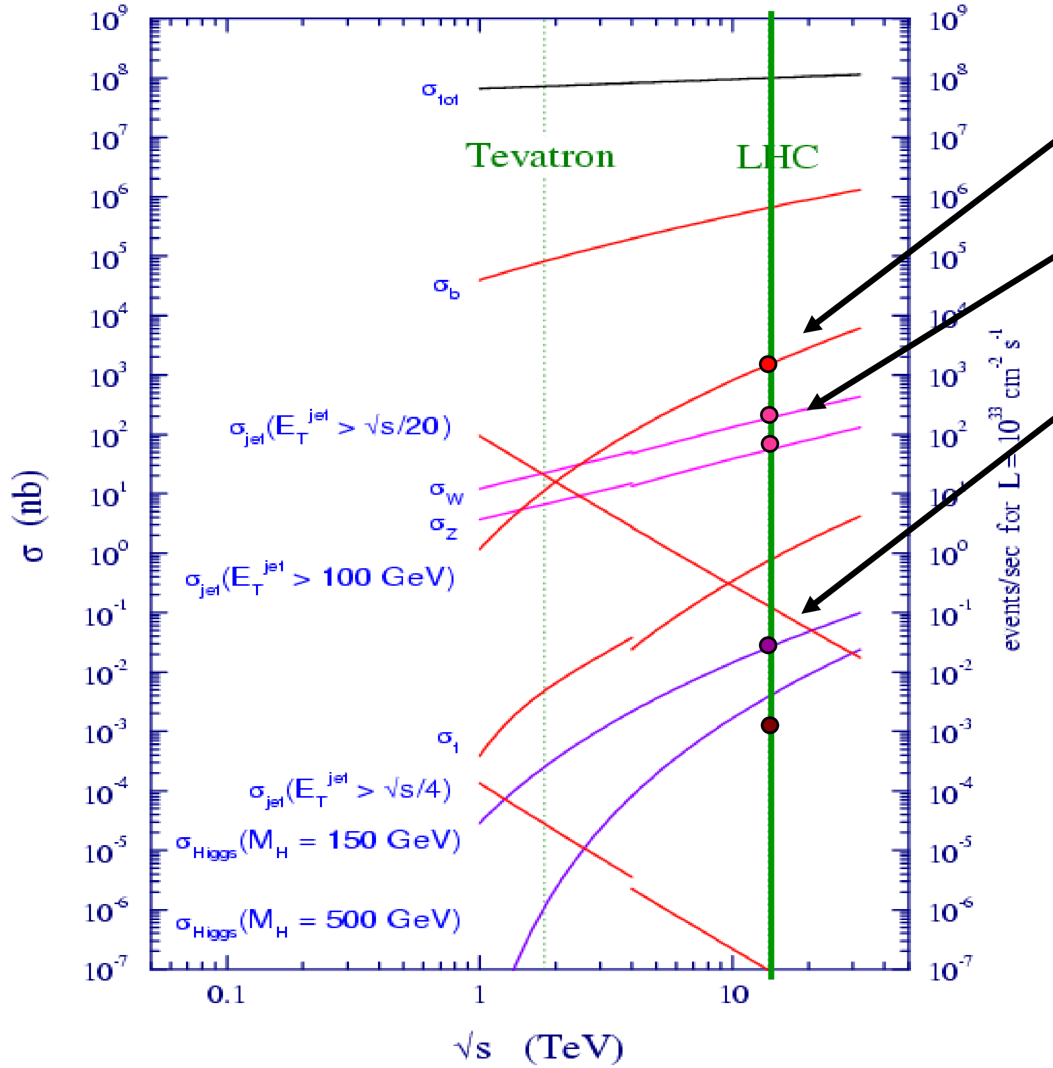
$H \rightarrow bb$ event
@ high luminosity

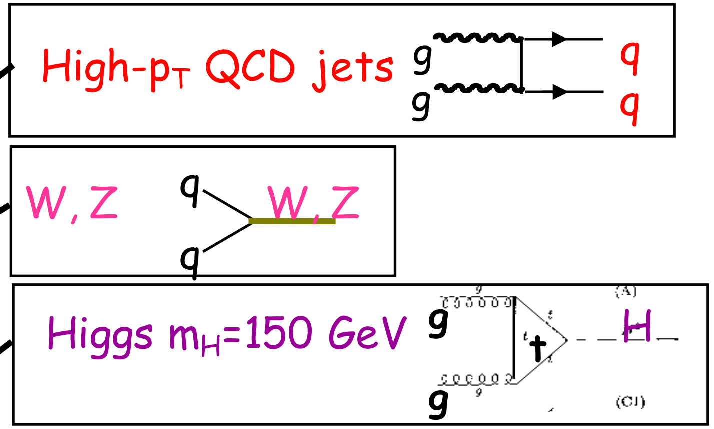
<u>Impact of pile-up on detector requirements and performance</u>:

-- fast response : ~ 50 ns
-- granularity : > 10^{8} channels
-- radiation resistance
(up to 10^{16} n/cm^2/year in forward calorimeters)
-- event reconstruction much more challenging than at previous colliders

The experimental challenges

❸ Huge (QCD) backgrounds (high energy …)





No hope to observe light objects (W, Z, H ?) in fully-hadronic final states → rely on l, γ

Fully-hadronic final states (e.g. $q^* \to qg$) can be extracted from backgrounds only with hard O(100 GeV) p_T cuts → works only for heavy objects

Mass resolutions of ~ 1% (10%) needed for l, γ (jets) to extract tiny signals from backgrounds

Excellent particle identification: e.g. e/jet separation

Expected data samples (examples) with 100 pb^{-1}

Channels (examples …)	Events to tape for 100 pb^{-1} (ATLAS)	Total statistics from LEP and Tevatron
$W \to \mu \nu$	$\sim 10^6$	$\sim 10^4$ LEP, $\sim 10^{6-7}$ Tevatron
$Z \to \mu \mu$	$\sim 10^5$	$\sim 10^6$ LEP, $\sim 10^{5-6}$ Tevatron
$tt \to W\,b\,W\,b \to \mu\,\nu + X$	$\sim 10^4$	$\sim 10^{3-4}$ Tevatron
QCD jets $p_T > 1$ TeV	$> 10^3$	---
$\tilde{g}\tilde{g}$ m = 1 TeV	~ 50	---

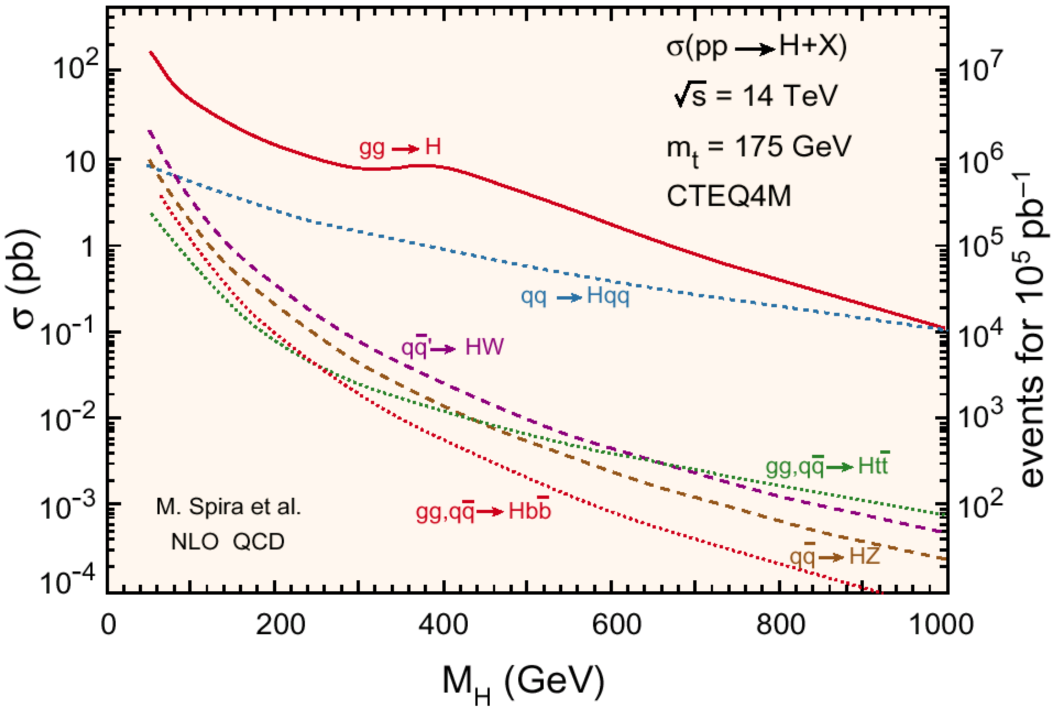
Goals in 2008-2009:

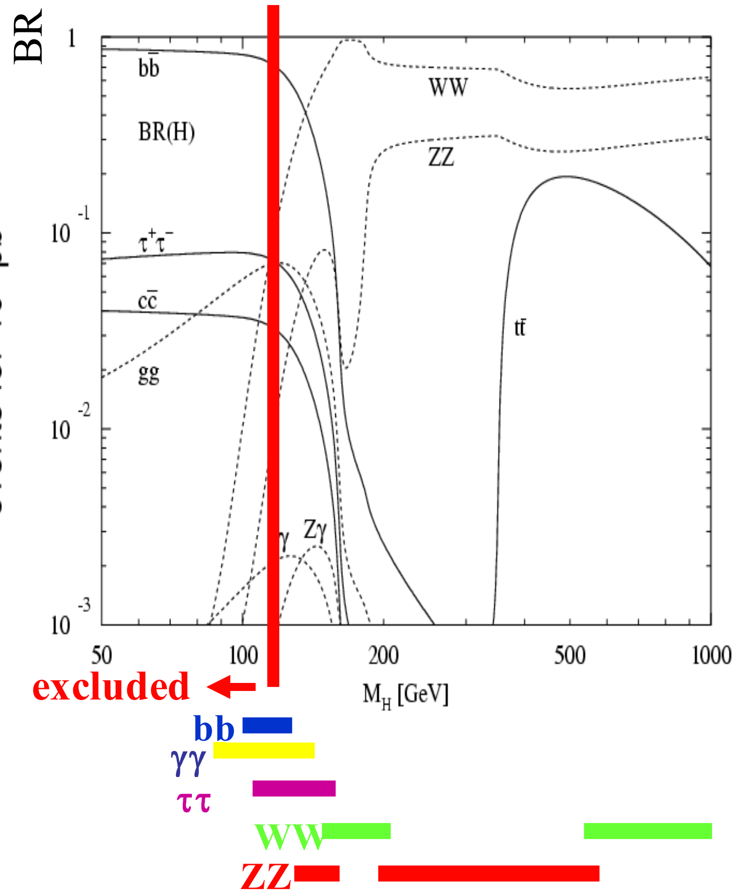
1. Commission and calibrate the detector **in situ using physics samples**
   e.g. - $Z \to ee, \mu\mu$ tracker, ECAL, Muon chamber calibration and alignment, etc.
   - $tt \to bl\nu\, bjj$ jet scale from $W \to jj$, b-tag performance, etc.

2. "Rediscover" and measure SM physics at $\sqrt{s}$ = 14 TeV (10TeV?)
   W, Z, tt, QCD jets … (also backgrounds to New Physics)

3. Early discoveries ?
   Potentially accessible: Z′, SUSY, …. surprises ?

SM Higgs signal



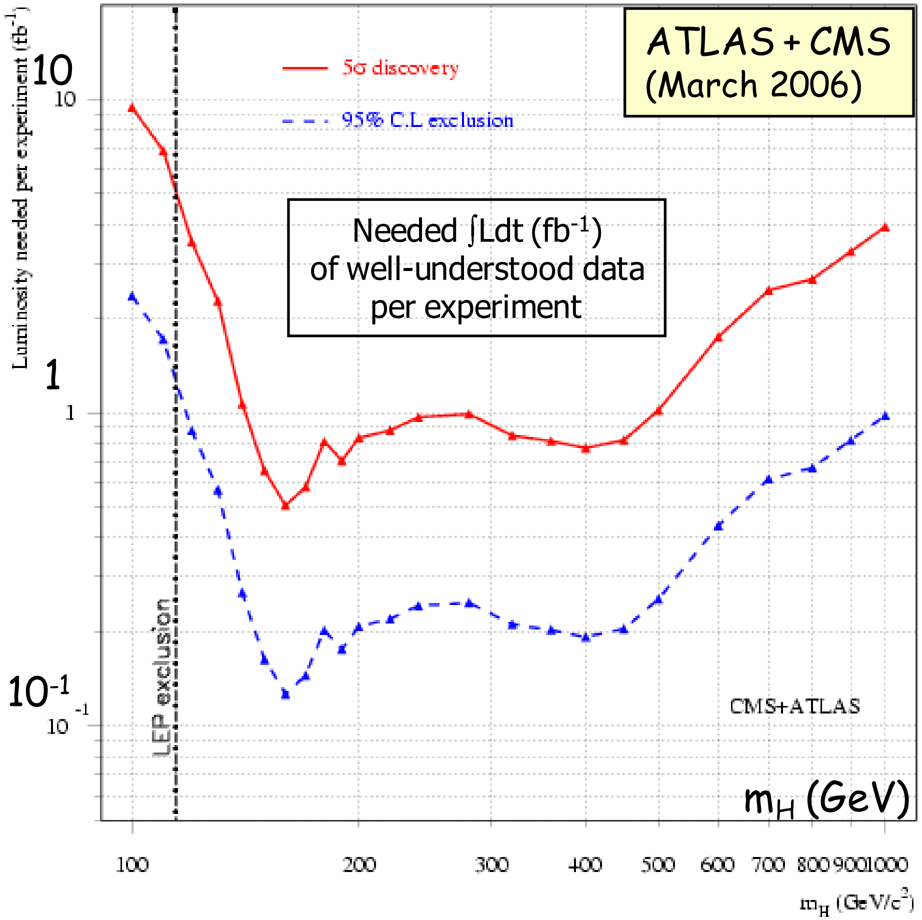


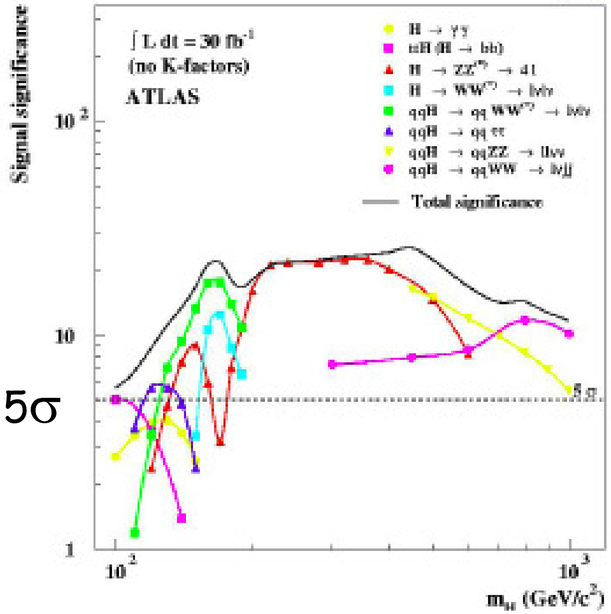
m_H < 130 GeV : H → bb, ττ dominate
→ best search channels at the LHC : qqH→qq ττ, H → γγ, ttH → lbbX

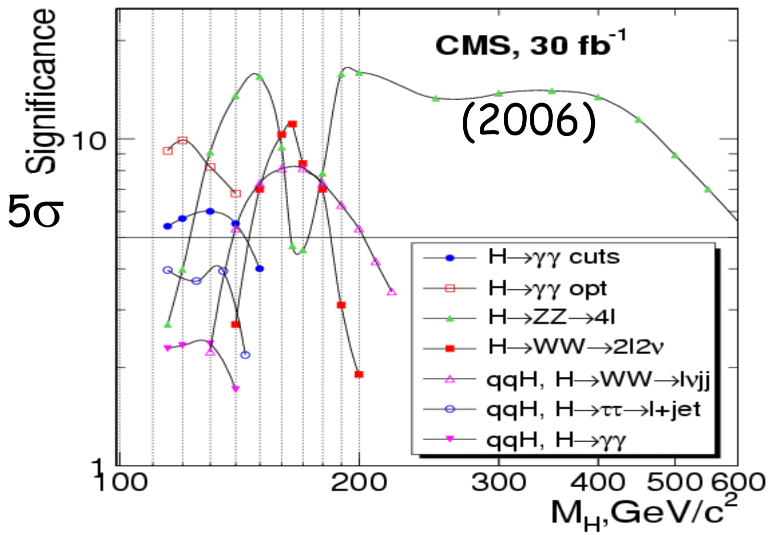
m_H > 130 GeV : H → $WW^{(*)}$, $ZZ^{(*)}$ dominate
→ best search channels at the LHC : H → $ZZ^{(*)}$ → 4l (gold-plated)
H → $WW^{(*)}$ → lν lν

Discovery potential in a complete mass range

2003







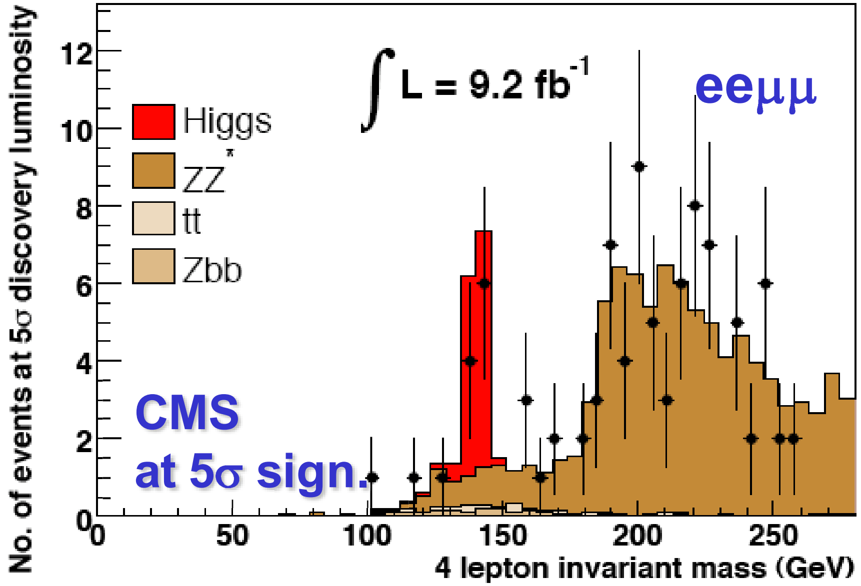
≤ 1 fb^{-1} for 95% C.L. exclusion

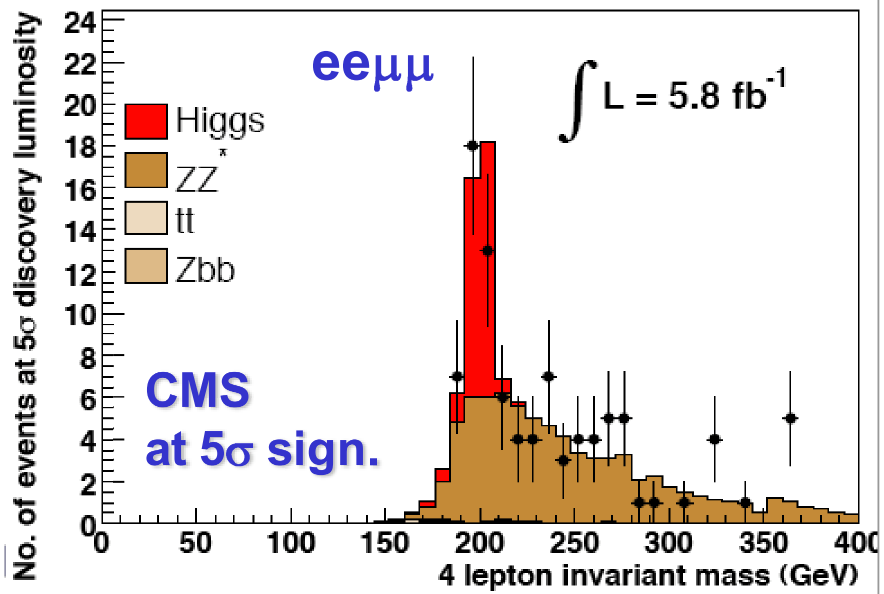
≤ 5 fb^{-1} for 5σ discovery

over full allowed mass range

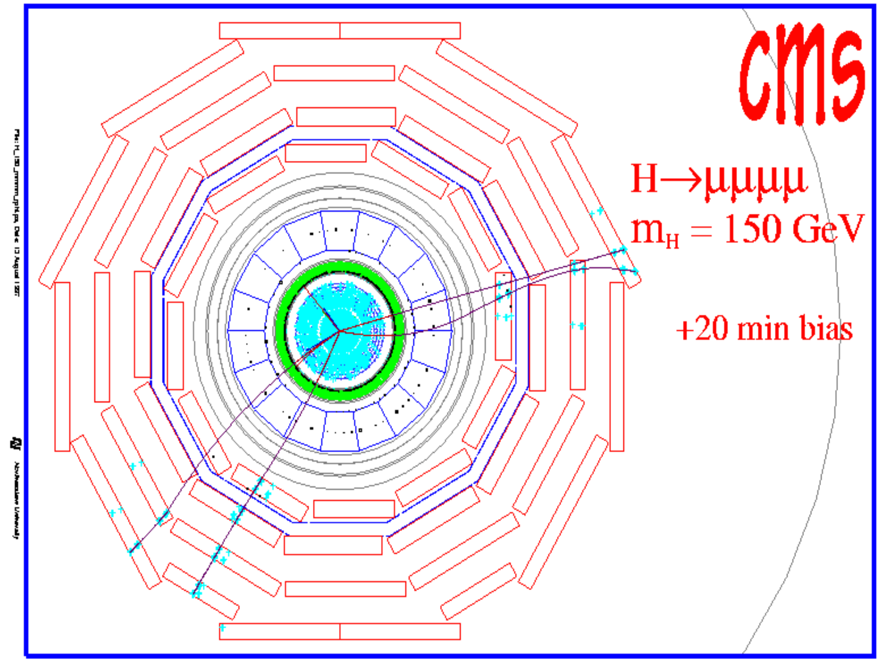
Final word about Higgs mechanism by 2010?

The „gold plated" channel: H->ZZ(*)->llll





Signal and background
at 5σ discovery

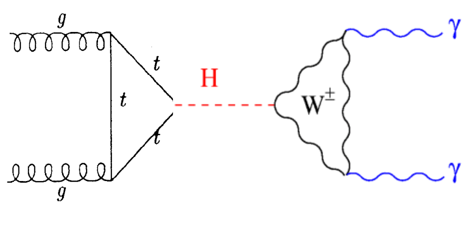


The most difficult low-mass region: $m_H \sim$ 115-150 GeV…

ATLAS : $m_H \sim 115$ GeV 10 fb^{-1} : $S/\sqrt{B} \approx$ 4-5.5 ← range comes from $H \to \gamma\gamma$: LO vs NLO cross-section, cuts vs likelihood analysis

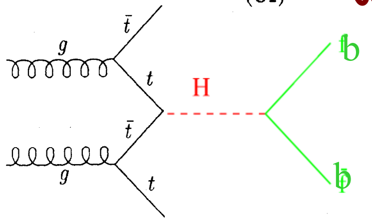
3 (complementary) channels with (similar) small significances:

$H \to \gamma\gamma$



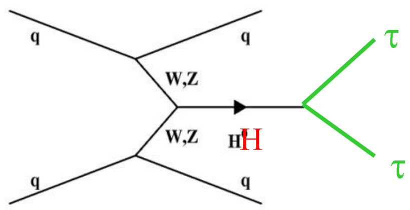
S=130, B=4300, $S/\sqrt{B}$= 2 - 4.4

$ttH \to ttbb \to bl\nu bjjbb$



$S/\sqrt{B}$~2, being re-evaluated

$qqH \to qq\tau\tau$



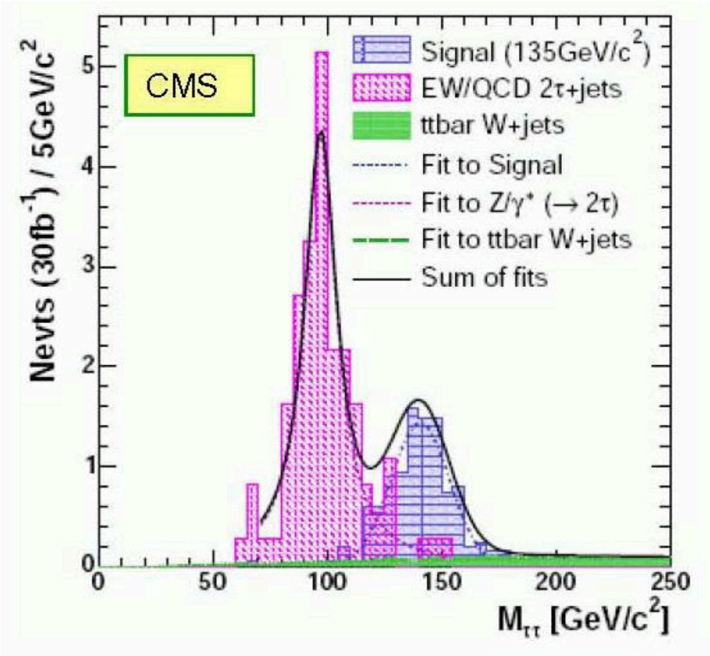
S=10, B=10, $S/\sqrt{B}$=2.7

- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  - -- ECAL crucial for $H \to \gamma\gamma$ (in particular response uniformity) : $\sigma/m \sim$ 1% needed
  - -- b-tagging crucial for ttH : 4 b-tagged jets needed to reduce combinatorics (background being re-evaluated)
  - -- efficient jet reconstruction over $|\eta| < 5$ crucial for $qqH \to qq\tau\tau$: forward jet tag and central jet veto needed against background

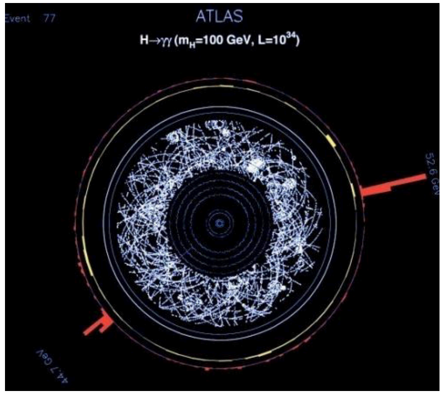
All three channels require very good understanding of detector performance and background control to 1-10% → convincing evidence likely to come mid-end 2009 …

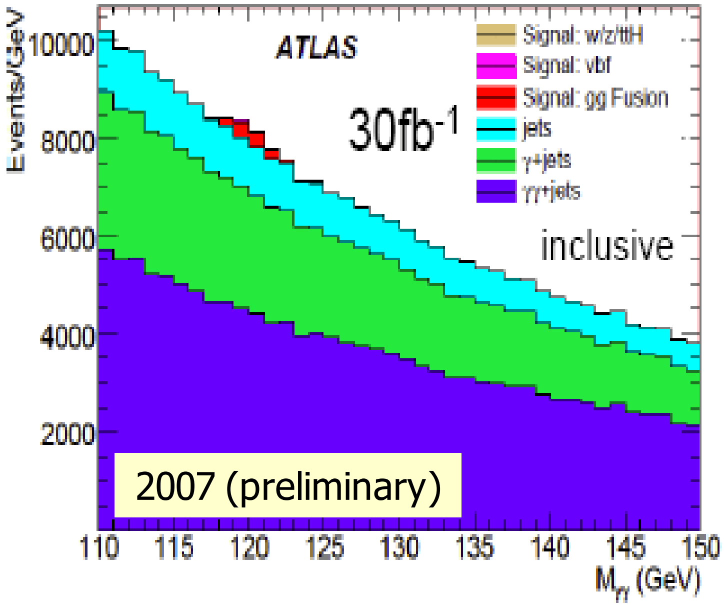
More difficult channels

<u>$qqH \to qq\tau\tau \to qq\, l\nu\ \tau\text{-had}\ \nu$</u>



<u>$H \to \gamma\gamma$</u>





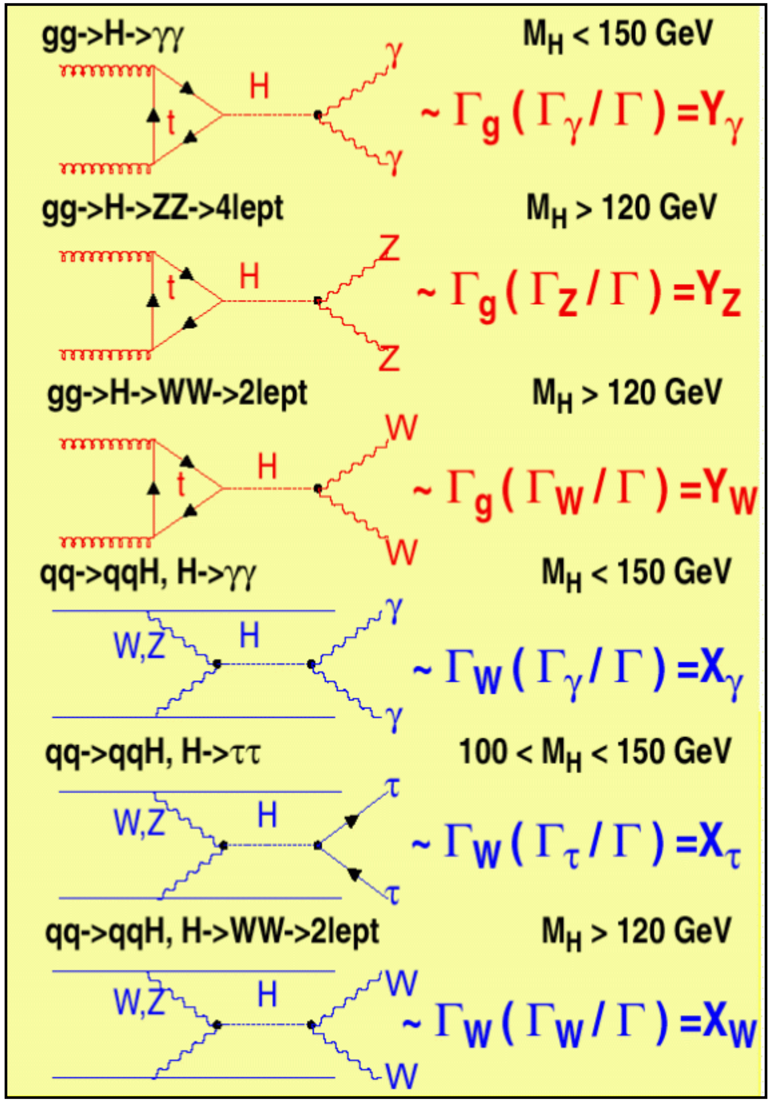
Experimental challenges:

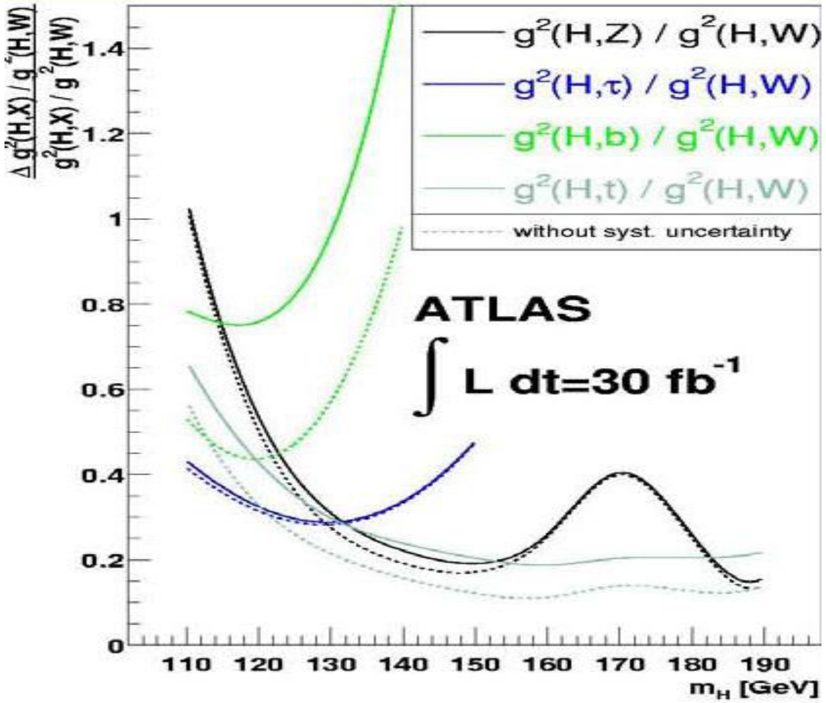
- identification of hadronic taus
- good p_T^{miss} resolution (tau mass reconstruction in collinear approximation
- control of the $Z \to \tau\tau$ background shape in the high mass region

Experimental challenges:

- photon identification and γ/jet separation (calorimeter + tracker)
- mass resolution of the photon system
- low signal-to-background ratio

Measurements of the SM Higgs boson couplings





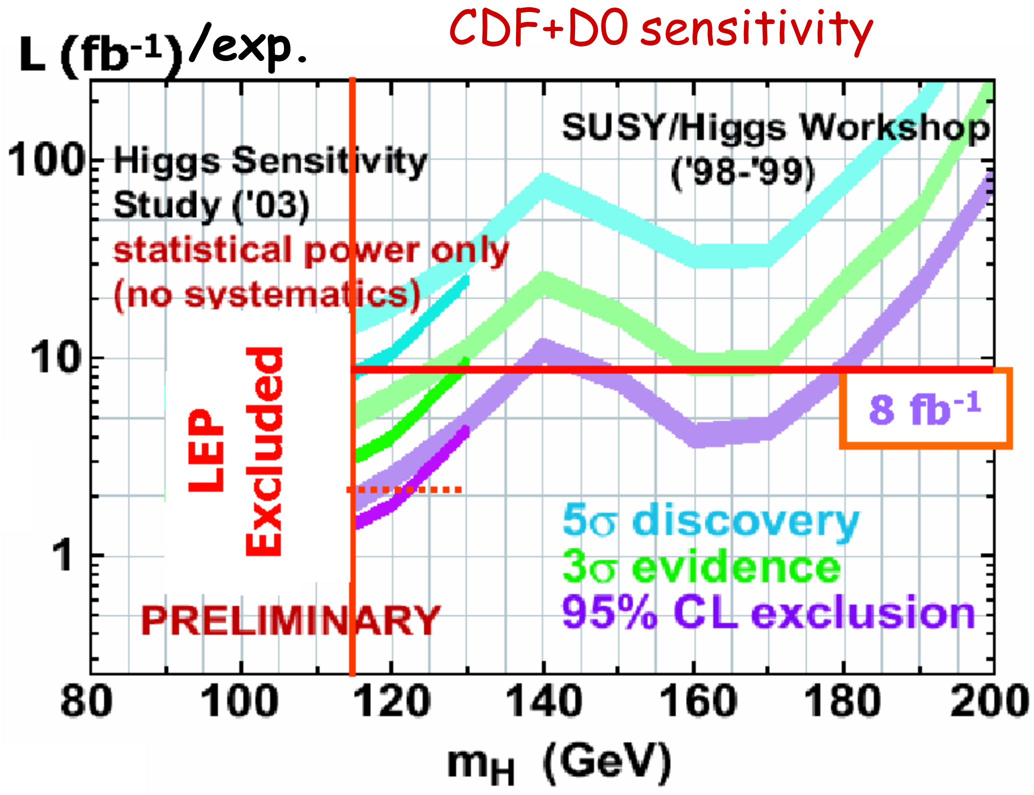
Mass will be measured with precision of 0.1% in mass range 130-450 GeV (gg, H->4l).

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

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

What about the Tevatron experiments?

Today ~ 3 fb^{-1} /experiment	→	2009 expect 6-7 fb^{-1} /experiment



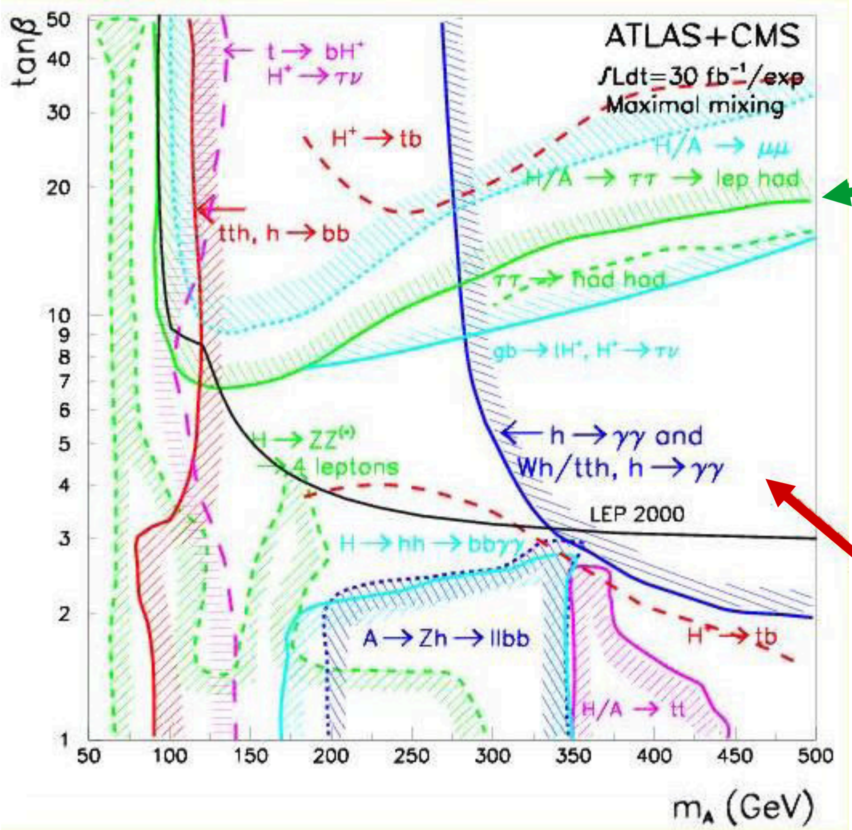
With **4** (**8**) **fb^{-1}:**

~no 5σ sensitivity **3σ evidence** up to 120 (130) GeV

95% C.L. exclusion up to ~ 130 (180) GeV

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

(2001)



m_h < 135 GeV , $m_A \approx m_H \approx m_{H\pm}$

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

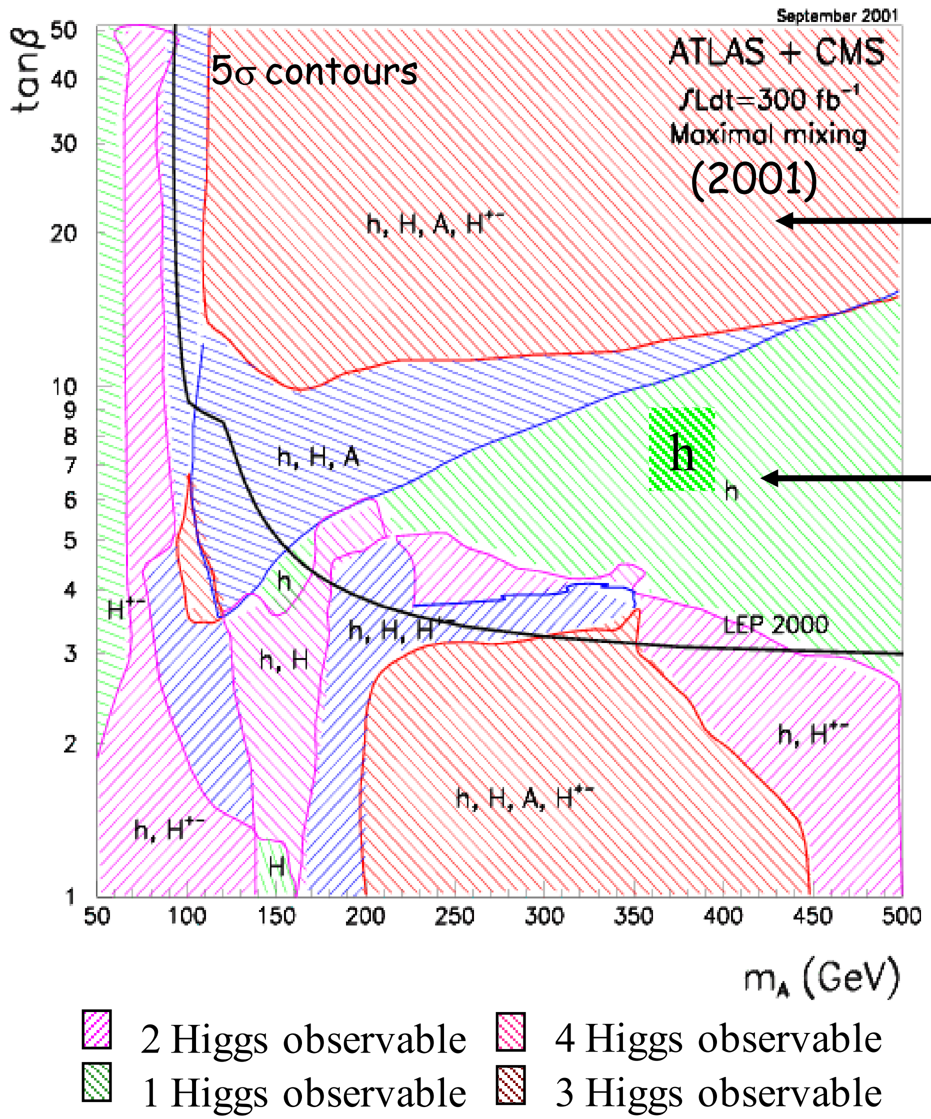
Best sentitivity from A/H->ττ, H^+->τν
not easy the first year

A/H->μμ experimentally easier specially for the beginning

Here only SM-like observable
If SUSY particles neglected

Also reevaluated with different SUSY „benchmark scenarios", CPX scenario, etc.

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



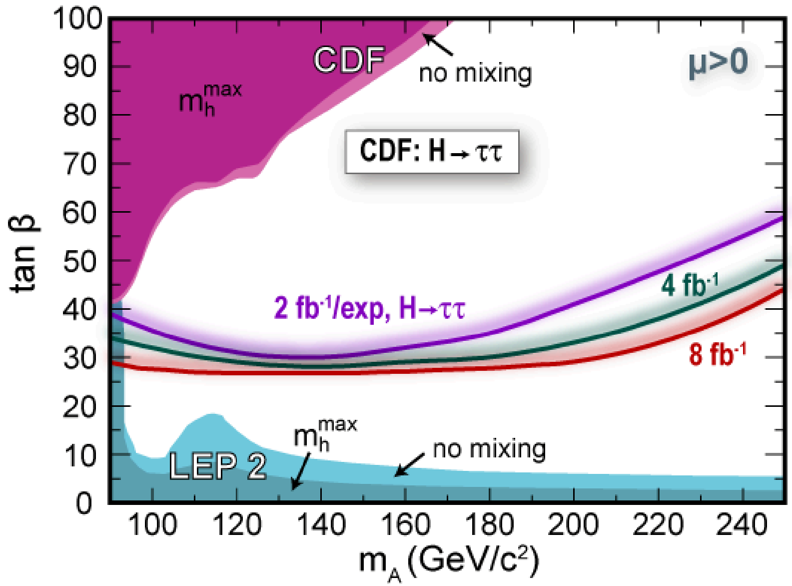
$m_h < 135$ GeV , $m_A \approx m_H \approx m_{H\pm}$

H, A $\rightarrow \mu\mu, \tau\tau$
$H^{\pm} \rightarrow \tau\nu$, tb

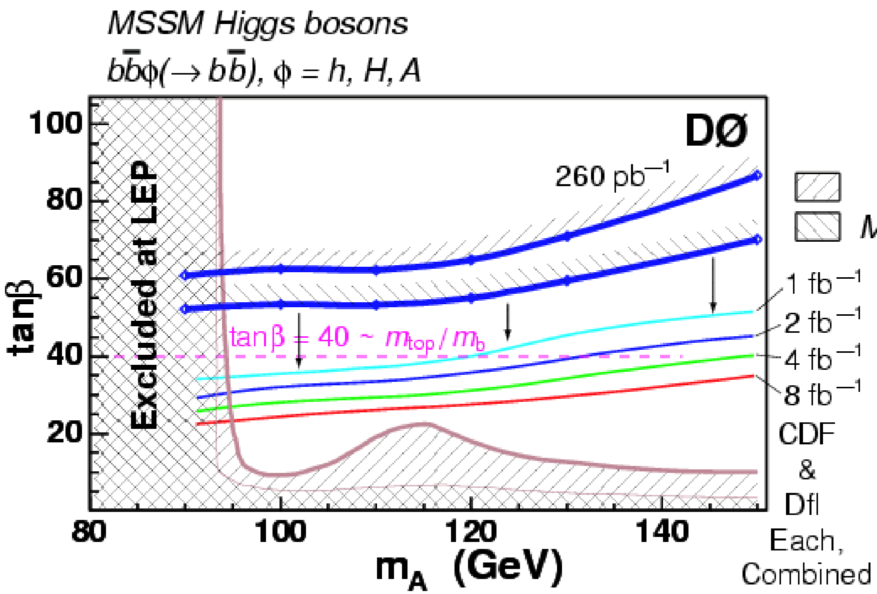
Here only h (SM - like) observable at LHC, unless A, H, $H^{\pm} \rightarrow$ SUSY
$\rightarrow$ LHC may miss part of the MSSM Higgs spectrum
Observation of full spectrum may require high-E ($\sqrt{s} \approx 2$ TeV) Lepton Collider

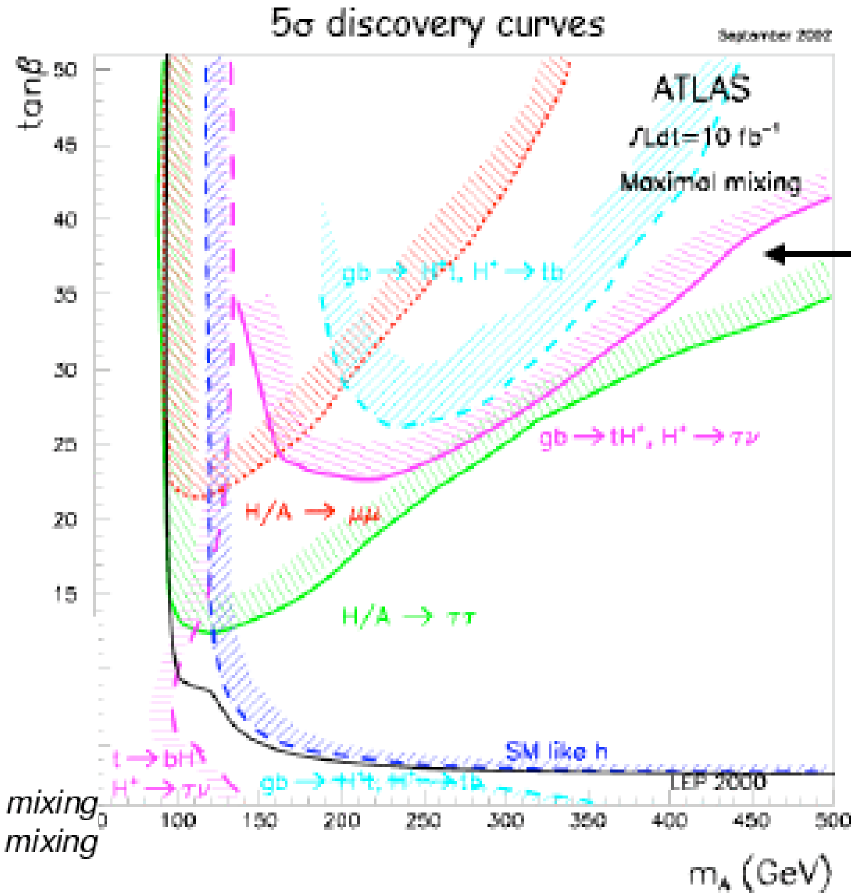
Assuming decays to SM particles only

What about the Tevatron experiments?



CDF+D0 prospects





LHC prospects (10fb-1)

The road path for Higgs boson discovery

The large number of channels and scenarios studied demonstrate the detector sensitivity to many signatures $\rightarrow$ robustness, ability to cope with unexpected scenarios

With the very first collision data ($\leq$ 100 pb^{-1})

Commission/calibrate the detectors in situ in the LHC environment, tune the software tools (simulation, reconstruction, etc.)

Perform first physics measurements of Standard Model processes:
e.g. cross-sections for W, Z, top, QCD jets with 10-30% precision;

Much more luminosity (at least 1 fb-1) will be needed to:

Discover a SM Higgs boson (<10 fb-1) [watch the Tevatron ...]
Completely cover parameter space of the MSSM Higgs bosons

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 concerving case).

→ In addition

Important parameter measurements (mass, spin, ratio of couplings) can be performed (vector boson fusion processes important).

→ More difficult

invisible Higgs boson decays or NMSSM models

measurement of the Higgs boson self – coupling

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

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