Higgs at the LHC

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The ATLAS and CMS experiments are getting ready for the start of the LHC later this year. According to the current schedule:

Beam commissioning starts May 08

First 14 TeV collisions expected for July 08

Current schedule foresees to reach $L=2x10^{32}$ cm^{-2} s^{-1} by the end of the year with an integrated luminosity less than ~100 pb^{-1}.

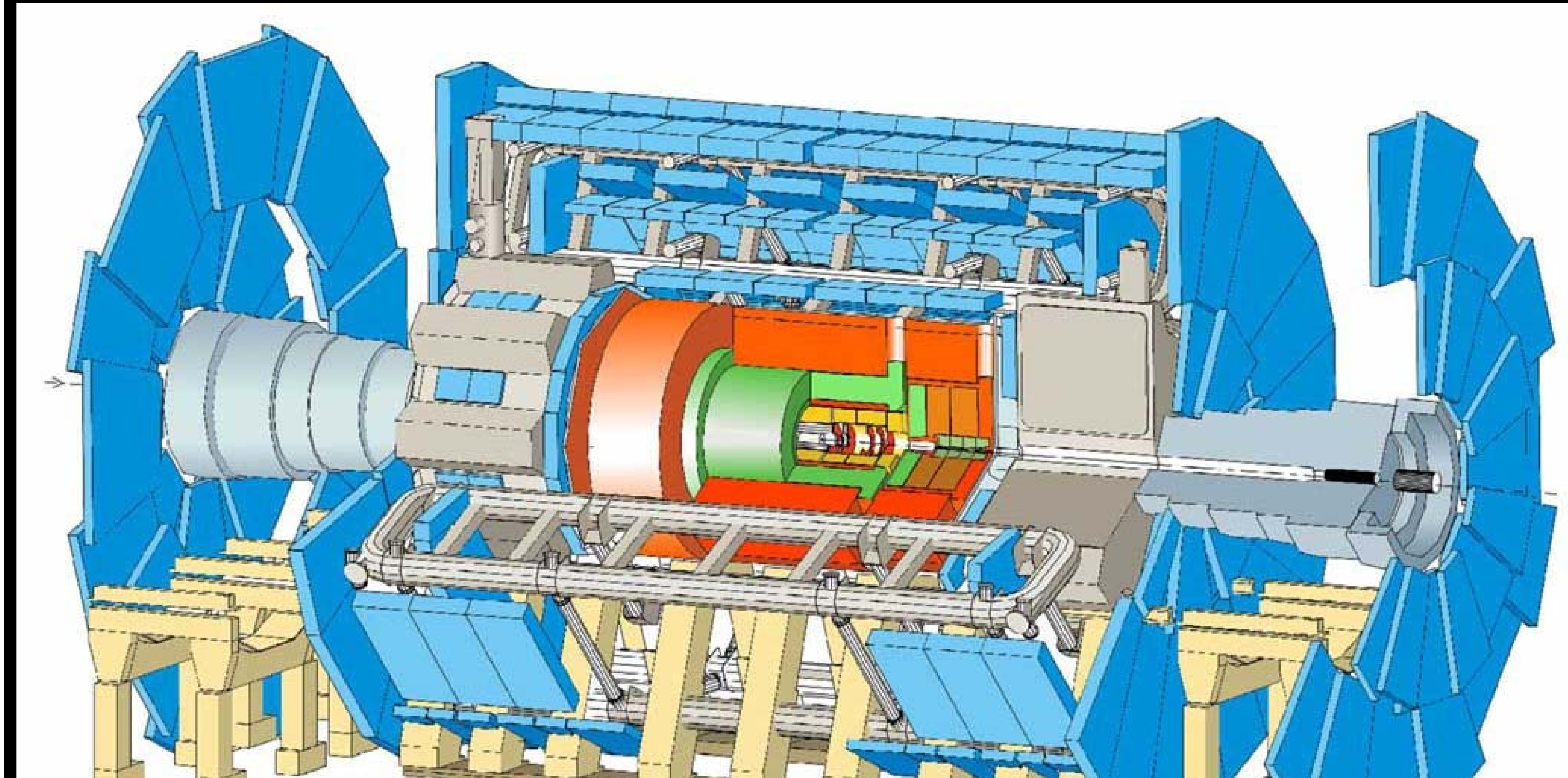
About 4 pile-up (minimum bias) events expected at 10^{32} $cm^{-2}s^{-1}$ (because of larger bunch spacing and no. part./bunch)

Then the luminosity should reach $2x10^{33}$, the so-called "low luminosity"

Pile-up of ~4 events per bunch crossing (at nominal 25 ns bunch spacing)

Finally (probably >2010) the luminosity should reach the design luminosity of 10^{34} cm^{-2} s^{-1}, "high luminosity"

Pile-up of ~20 events per bunch crossing



Sub-detector	N. of channels
Pixels	80x10^{6}
Silicon strip detector (SCT)	6x10^{6}
Transition Radiation Tracker (TRT)	3.5x10^{5}
Electromagnetic calorimeter	1.7x10^{5}
Fe/scintillator (Tilecal) calorimeter	9800
Hadronic end-cap LAr calorimeter	5600
Forward LAr calorimeter	3500
Barrel Muon Spectrometer	7x10^{5}
End-cap Muon Spectrometer (TGC)	3.2x10^{5}
Forward detectors	1.2x10^{4}
total	~ 87.6 x 10^{6}

Parameter	ATLAS
Total weight (tons)	7,000
Overall diameter (m)	22
Overall length (m)	46
Magnetic field for tracking (T)	2
Solid angle for lepton ID or tracking $(\Delta\phi \times \Delta\eta)$	$2\pi \times 5.0$
Solid angle for energy measurements $(\Delta\phi \times \Delta\eta)$	$2\pi \times 9.6$

ATLAS status

The installation of the ATLAS detector (and all related services) is nearly completed:

Only part of the forward muons and forward shielding still to be installed

Still a lot of work to be done during next months to be ready for collisions

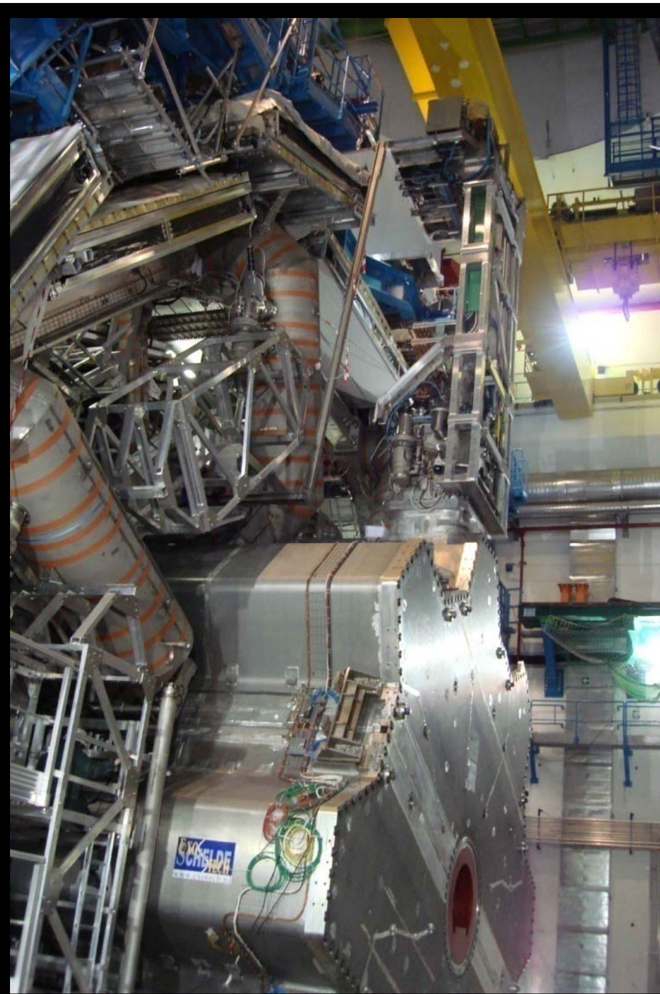
Hardware commissioning of all electronics components, controls and safety systems on going

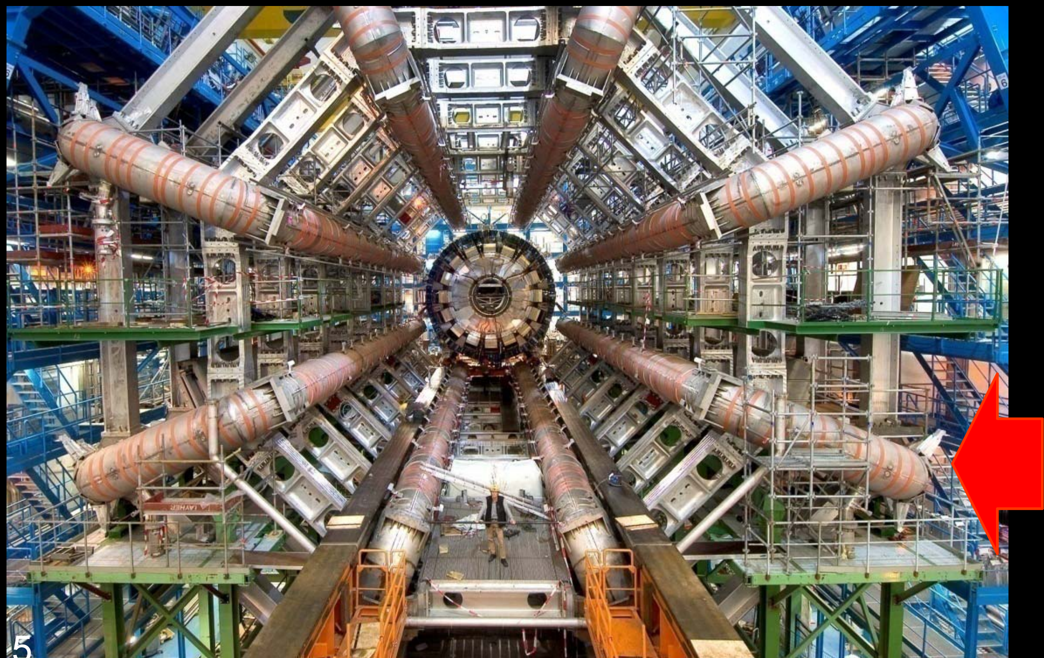
Magnet system:

Barrel solenoid + barrel toroid + 2 end-cap toroids: all installed, cold tested one by one.

In spring 2008 there will be a full magnet test (when ATLAS is closed and fully integrated) and then continuous operation.

Barrel solenoid mapped during fall ’06. Field in muon system to be defined during full magnet test



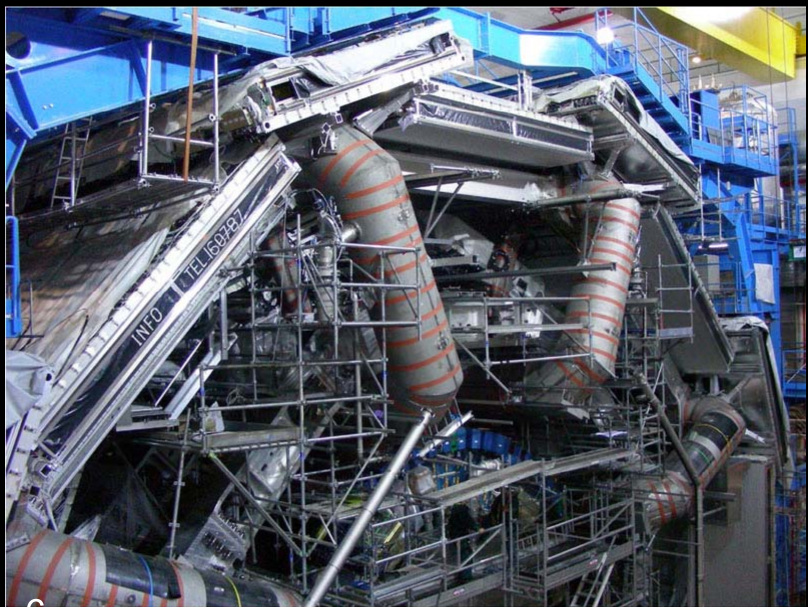


- 20.1 m diameter x 25.3 m length
- ~12000 m^3 volume
- 118 t superconductor
- 370 t cold mass
- 830 t total weight
- 56 km superconductor
- 20.5 kA at 4.6 T
- 1.05 GJ stored Energy

Muon system:

Most muon chambers are installed and are being tested and read out through the final data flow/trigger chain.

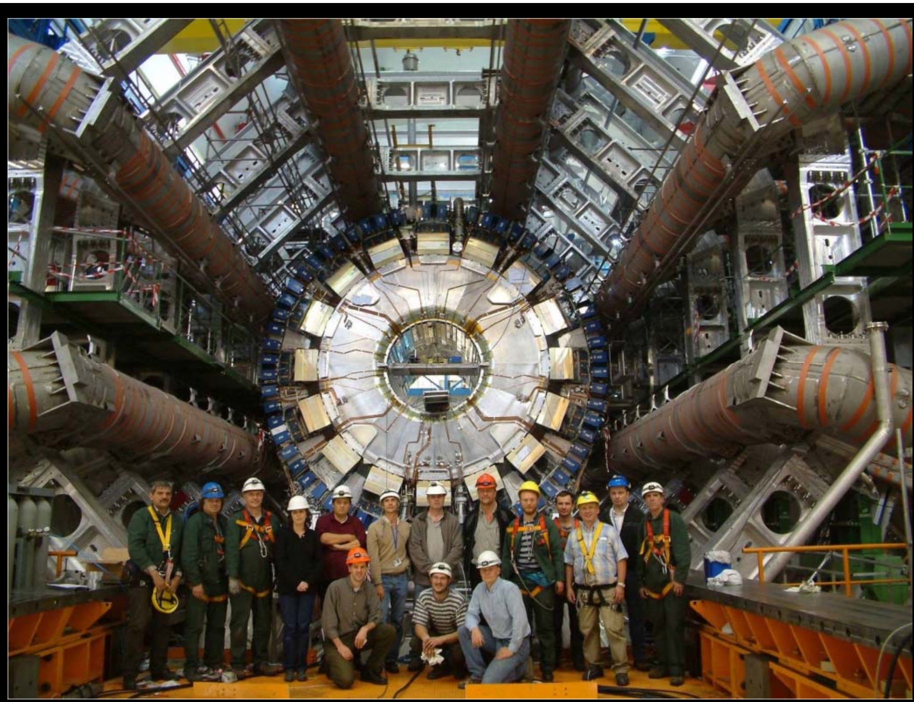
Total : ~12’000 m^2, ~ 1.1 M channels

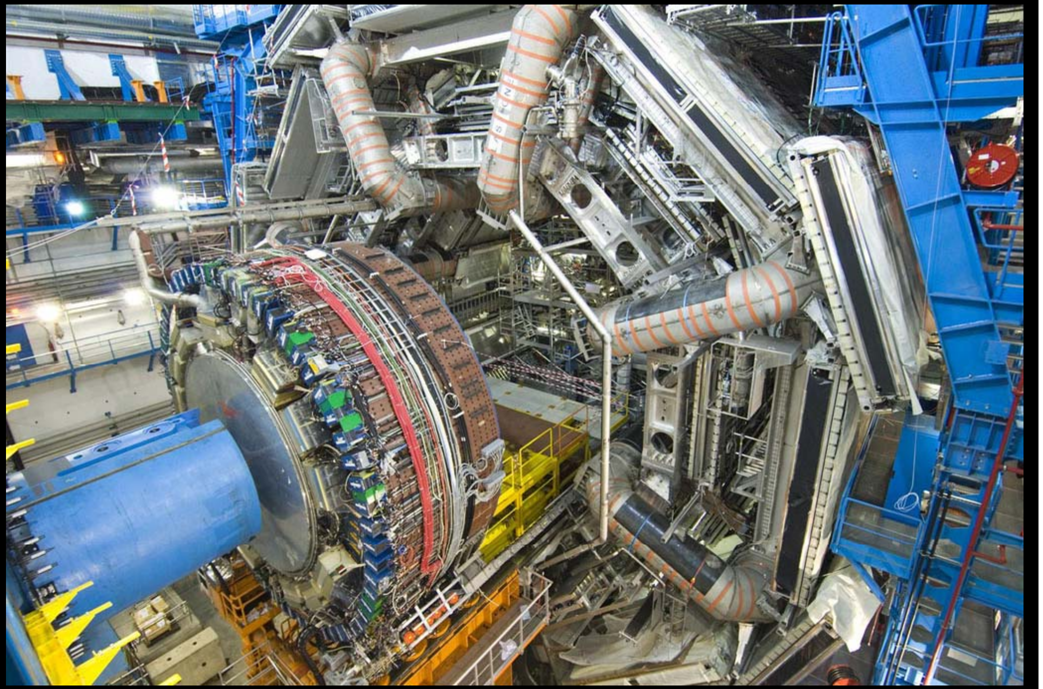


Calorimeters:

Hadronic barrel (tile calorimeter) was the first detector to be integrated.

Three (barrel + 2 endcaps) cryostats installed and filled with LAr. Detectors operated for long time last year.





Inner detector:

All ID subdetectors (pixels, SCT, TRT) have been installed.

Cooling to be ready soon: then it will be possible to operate the detector.

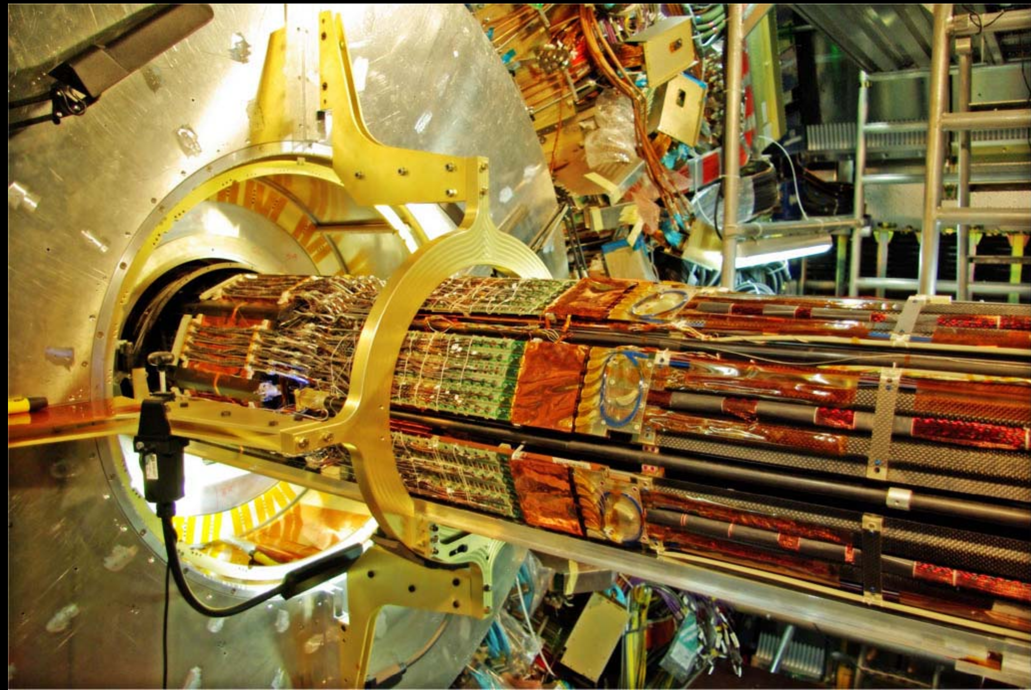
Successful installation and testing of the 3 pieces of the beam pipe inside the detector.

Pixels:

1744 modules, *50x400* μm^2

Strips:

4088 modules, 80 μm *micro-strips*



Still a lot of work to do: service connections to be finalized, components to be commissioned, some back-end electronics to be installed,...

No show-stoppers: full ATLAS will be ready on time for first collisions

Detector commissioning started already in 2006 with cosmics:

Installation work during day and running with cosmics during week-ends and dedicated “Milestone” weeks (every 6-8 weeks)

One detector after the other integrated in central DAQ, trigger and DCS:

First barrel calo, then barrel muons, end-caps, TRT. Next month pixels and Si-strips will complete the integration.

Several useful studies on-going are increasing our knowledge of the detector:

- Timing studies
- Alignment of muon chambers (and of pixels/strips)
- Study of calorimeter response

What do we need to discover the Higgs boson?

Good understanding of the detector and trigger. Several (all!) ingredients are needed to cover all the foreseen channels: electrons and photons, muons, b-tagging, jets, E_T^{miss}, τ's

Prove that we can do SM physics (top, W, Z)

Control of the backgrounds

High production cross sections for SM processes: bb, W, Z, tt,...

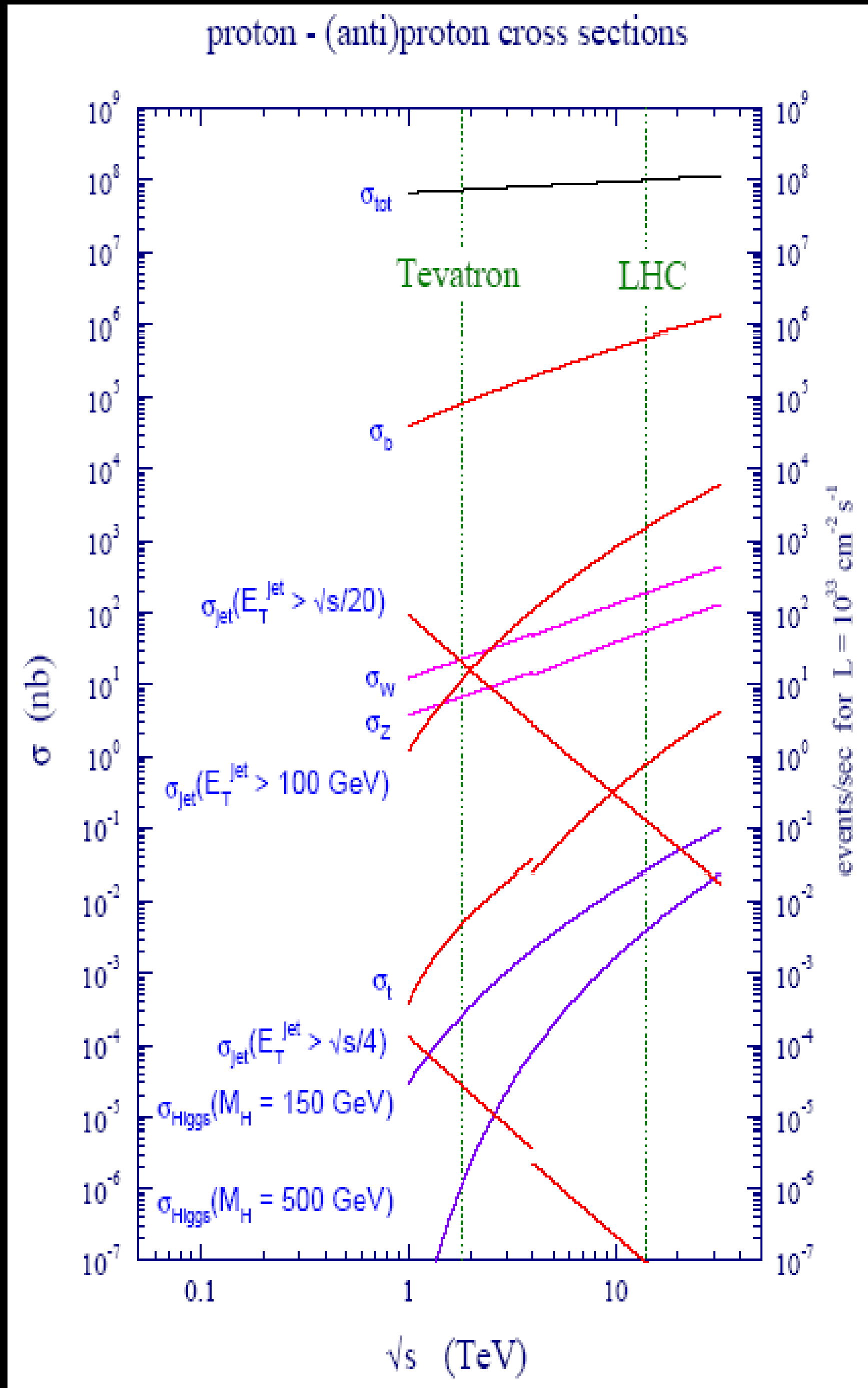
- pp inelastic: ≈70 mb
- b inclusive (p_T>6 GeV): ≈6 μb
- tt: ≈800 pb

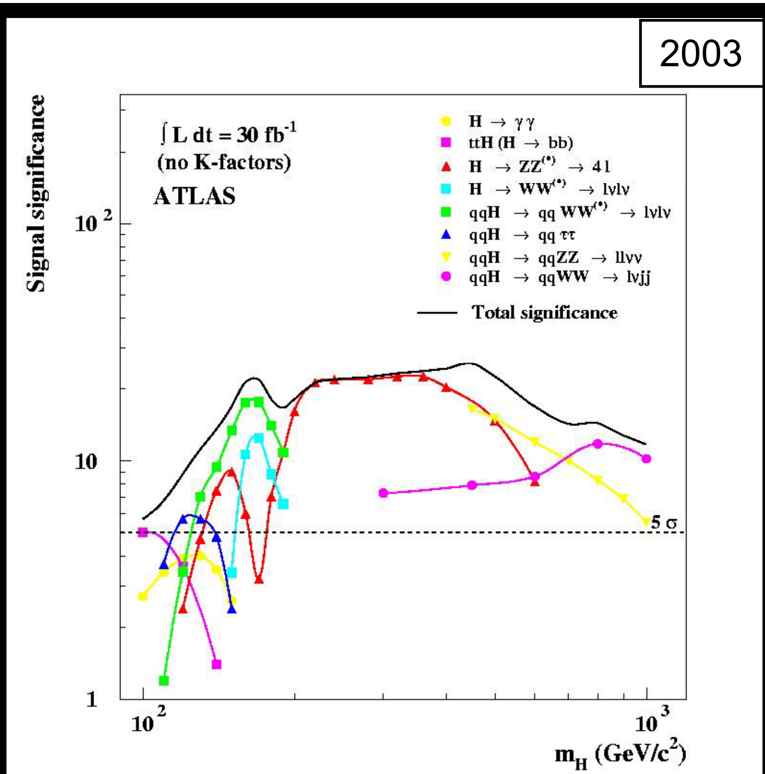
[cfr: H(125 GeV): ≈40 pb]

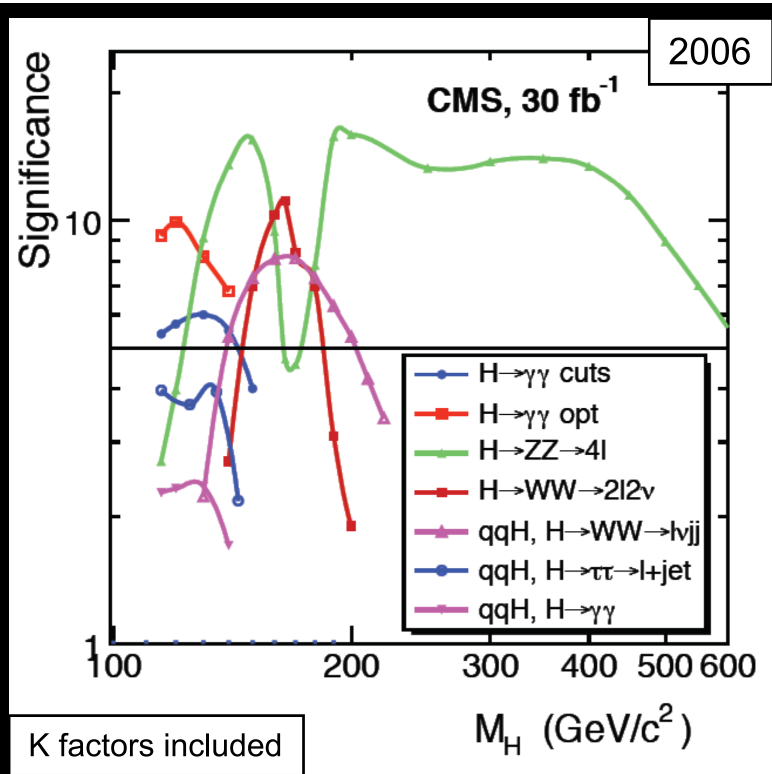
These processes are interesting per se and will be used for early physics studies and for various calibration issues.

However they represent a large background to several new physics searches including Higgs and SUSY:

- e.g., tt and W/Z+jets are background to several discovery channels





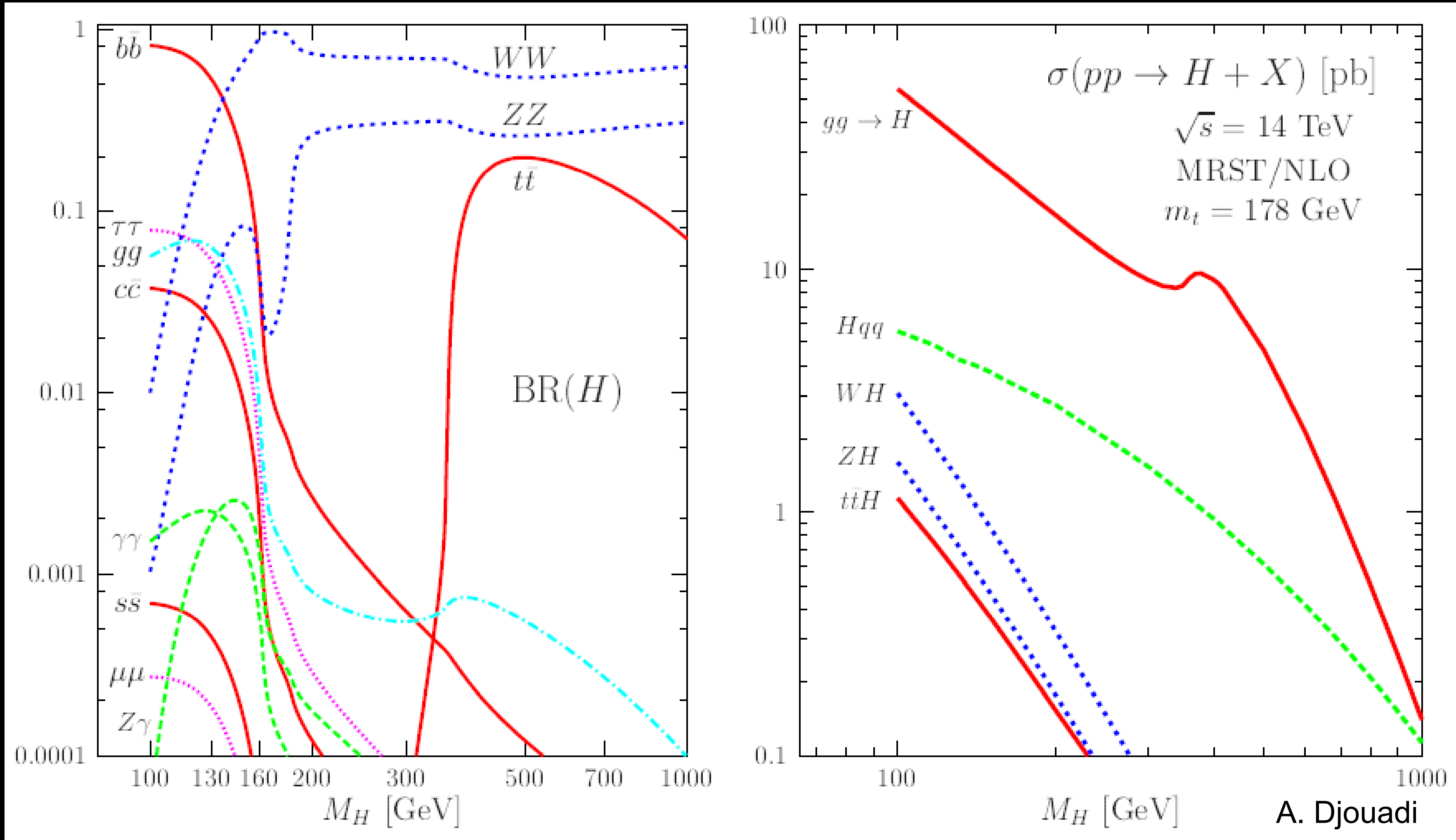


Both LHC experiments have been designed to discover a SM Higgs on all the expected mass range. Goal achievable after a few years of running at low L.

More than one channel available over most of the mass range.

Recently, most of the studies have been focused on the discovery of a light Higgs (M_H<200 GeV) during the initial lower luminosity period ($L=10^{33}$ cm^{-2} s^{-1}). This is not the easiest region at LHC: for higher masses, the $H \rightarrow ZZ \rightarrow 4l$ represents the golden channel (at least up to 500-600 GeV)

Which channels?



"Compromise" between various factors: production mechanism, decay mode, trigger, background levels. In general final states with leptons or photons in the final state are easier to handle at the LHC.

Inclusive analyses:

Do not use any feature of the production mechanism.

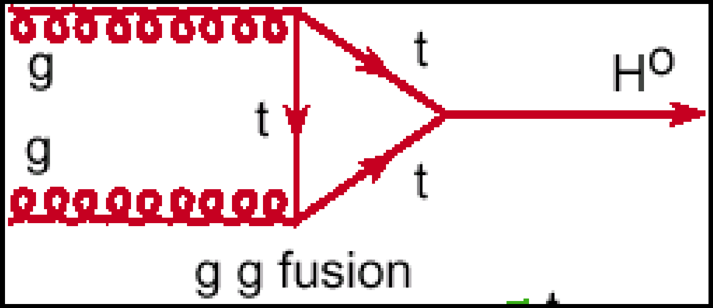
One makes less assumptions than in other search strategies. However to reduce the backgrounds need to have a clean final state with leptons or photons.

The gluon-gluon fusion channel has the highest rate.

The gluon-gluon fusion process is dominated by top and bottom quark loops. The large size of the top Yukawa coupling and of the gluon density functions explains the high production rate for this process.

In this talk:

$H \to \gamma\gamma$, $H \to ZZ^{(*)}$, $H \to WW^{(*)}$



$H \to \gamma\gamma$

Features: Low mass range: <140 GeV; small BR (~2×10^{-3}) but can see signal over a smooth background; estimate background from data (side bands)

Trigger: High P_T di-photon trigger, single photon trigger

Backgrounds: Irreducible: 2γ production
Reducible: γ+jet , di-jet

Analysis: Need good mass resolution (intrinsic light H width is negligible) of about 1%:

1. EM energy resolution
2. Primary vertex determination: contributes to mass resolution. Can use stand-alone calorimeter photon direction reconstruction (ATLAS) or tracks in the event (ATLAS, CMS), including tracks from conversions.

H→γγ

Need good photon ID to reduce γ+jet and jet+jet backgrounds well below the irreducible one: $R \sim 10^3$ for $\varepsilon_\gamma \approx 80\%$. The background of isolated high P_T π^0 is particularly dangerous. Make use of:

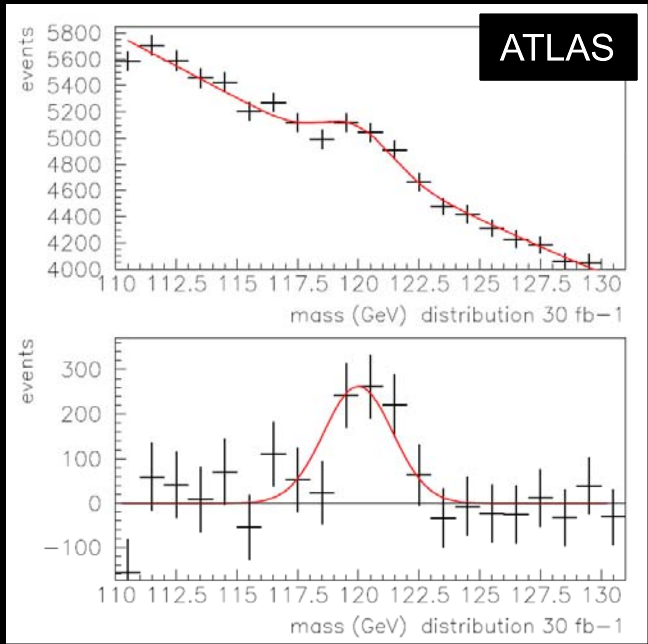
1. Photon isolation (with tracker and calorimeter)
2. Study of shower shapes in calorimeter

Photon conversion recovery: about 50% γ convert before the calorimeter in the tracker material (on average 1 X_0). Need to be reconstructed using tracking information

Signal:

Simplest analysis: count events in mass windows. This gives a $S \approx 6$ for 30 fb^{-1} at M_H=130 GeV

Level of background will be known from data. A 10-15% sys error from the fit to the background has been estimated.



$H \rightarrow \gamma\gamma$

The significance can be increased (~30-40%) including additional handles:

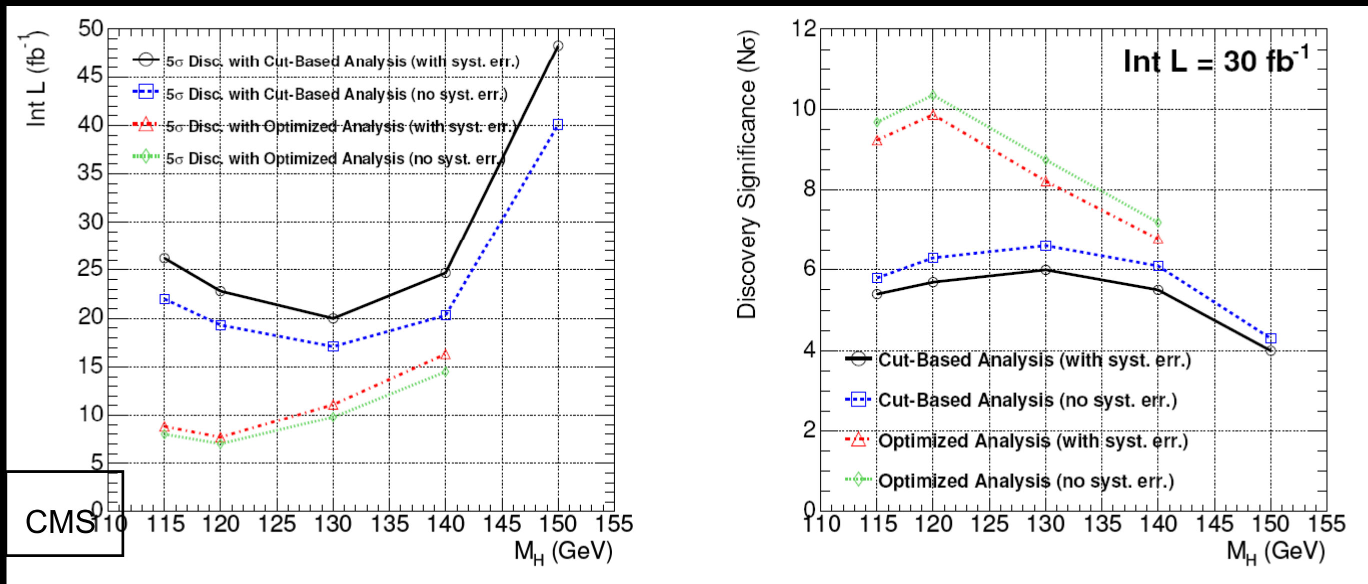
ATLAS:

Builds a likelihood including also

1. $\gamma\gamma$ P_T (background has softer spectrum and less pronounced rise at low P_T)
2. $\cos\theta^*$, the photon decay angle in the H rest frame with respect to the H flight direction in the lab rest frame (the background distribution is somewhat enhanced for collinear photons)

CMS:

Uses 6 variables: isolation of each photon, $E_{Ti}/M_{\gamma\gamma}$, $|\eta_1-\eta_2|$, $P_{L\gamma\gamma}$ (E_{Ti} and η_i are the transverse energy and pseudorapidity of i-th γ)



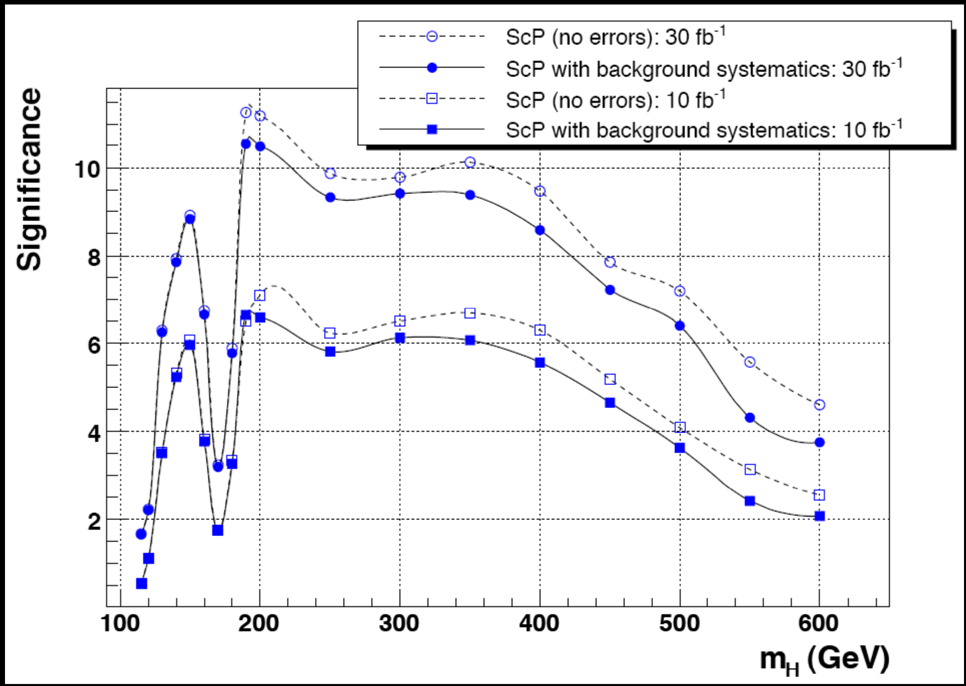
$H \rightarrow ZZ^* \rightarrow 4l$

Features: Clean channel: can see peak over background; low statistic for M_H<130 GeV and M_H~170 GeV. Can use 4e, 4μ, 2e2μ.

Trigger: High P_T single and dilepton triggers

Backgrounds: Irreducible: $qq,gg \rightarrow ZZ^*/\gamma^* \rightarrow 4l$
Reducible: $Zbb \rightarrow 4l$, $tt \rightarrow 4l$

Analysis: Need reconstruction of relatively low P_T electrons and muons
Need good electron and muon energy resolution (1-2%); recover brems effects for electrons
Reducible background is handled via lepton isolation (tracking and calorimeter) and impact parameter cuts
Background level can be estimated from sidebands

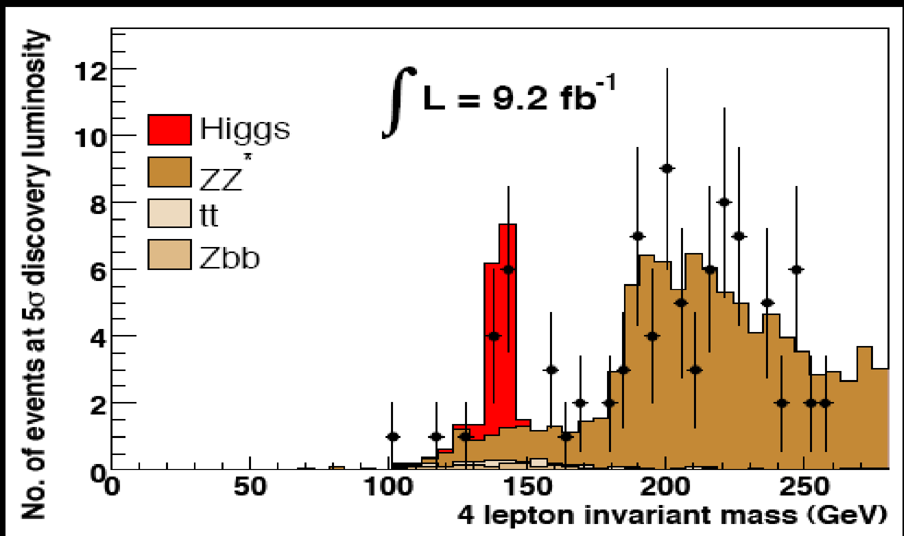


CMS study

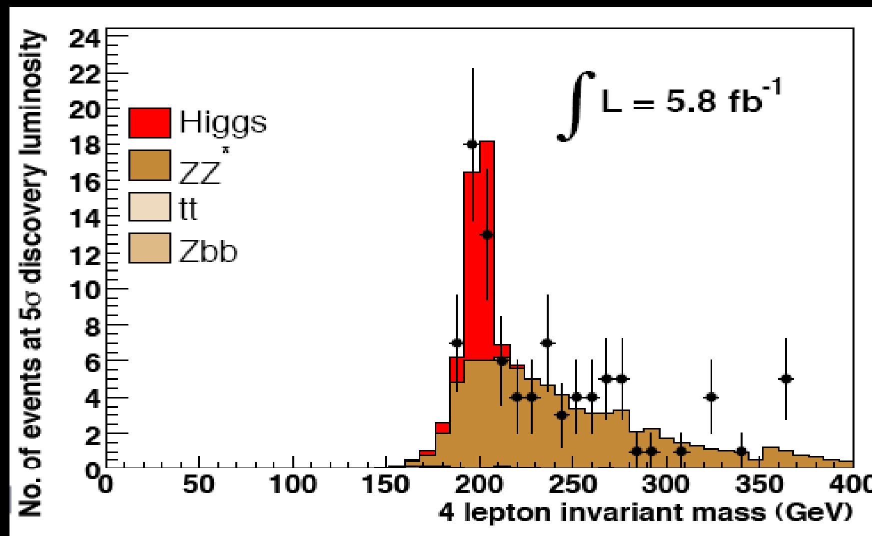
Uncertainty includes:

Stat error on the estimation of the background from side bands (from 2 % to 13% for M_H<200 GeV/c)

Theory uncertainty on the bkg shape (0.5% to 4.5%)



M_H=140 GeV



M_H=200 GeV

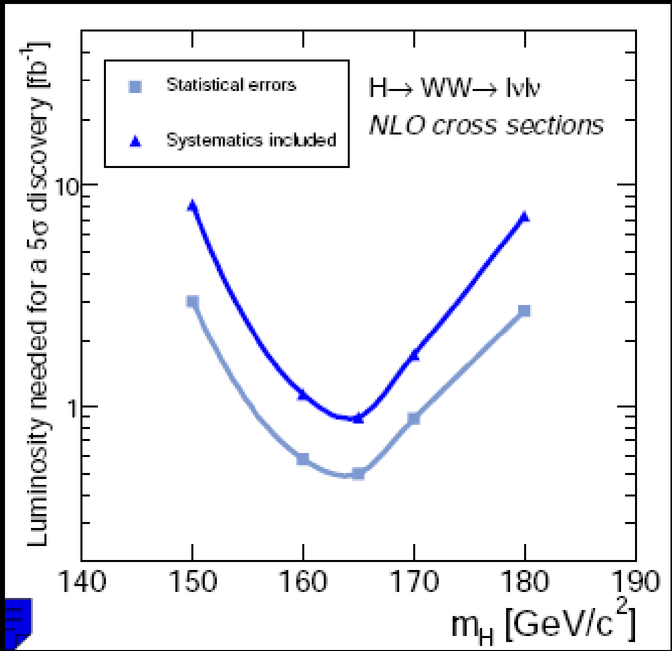
$H \rightarrow WW^* \rightarrow 2l2\nu$

Features: Particularly interesting for $2M_W < M_H < 2M_Z$ (but its sensitivity extends also to lower masses) where all other decay modes are suppressed. Signature is 2μ, $2e$, $e\mu + E_T^{miss}$.
However no mass peak and high background that needs to be well understood.

Trigger: High P_T dilepton and single lepton triggers

Backgrounds: Continuum WW, WZ, ZZ (including $gg \rightarrow WW$)
tt production and single top production tWb
also: Z, bb, W+jets

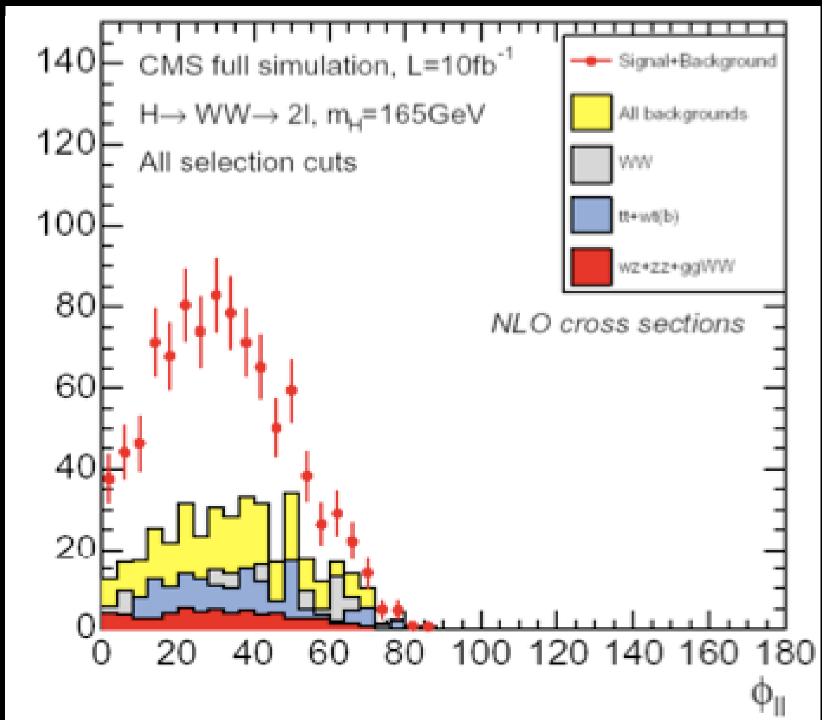
Analysis: Select events with exactly two isolated (tracking and calorimeter) opposite sign primary leptons and E_T^{miss}.
Apply a jet veto in the event.
Cut also on small dilepton mass and opening angle.



CMS study

Estimated background uncertainties:

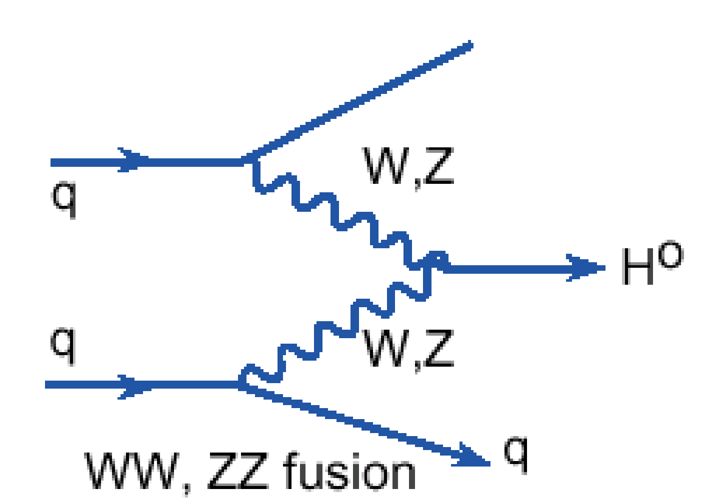
tt	±16%	(from control samples)
WW	±17%	
Wt	± 22%	(from theory)
gg → WW	± 30%	



Vector Boson Fusion

Features:

Originally studied for the medium-high mass range (M_H>300 GeV), this process has been found useful also in the low mass range. Lower rate than gluon-gluon fusion but clear signature.



Signature:

Two distinct signatures:

1. Two forward "tag" jets (large η separation with high-p_T) with large M_{jj}
2. No jet activity in the central region (between the two tag jets): jet veto

Typical cuts require:

- Tag jets are assumed to be the highest E_T jets in opposite hemispheres, with E_T>~40 GeV, $\Delta\eta_{jj}$>~4, M_{jj}>500-1000 GeV.
- Higgs decay products between tag jets in η
- No additional jet activity in the event

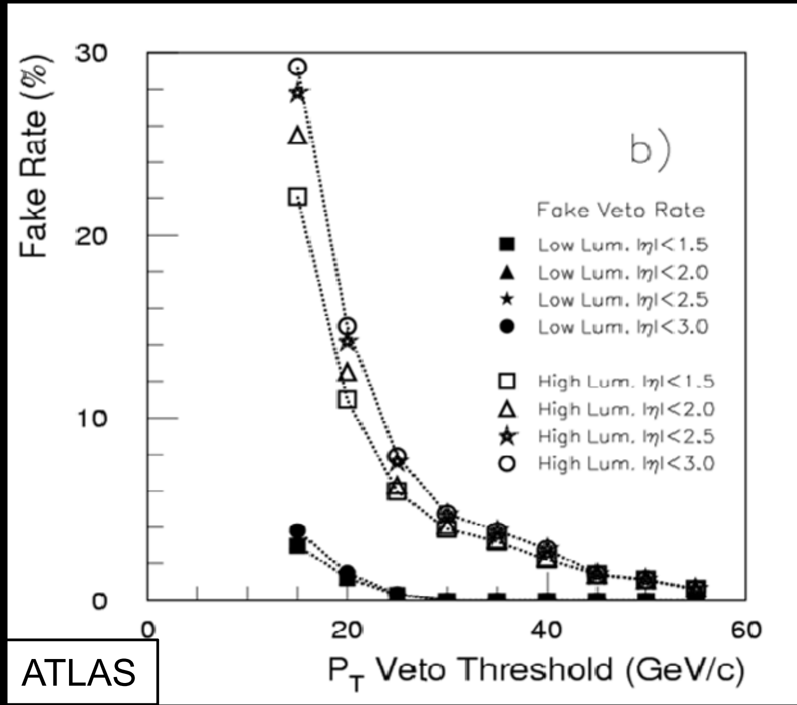
Vector Boson Fusion

Experimental issues:

Good efficiency for the reconstruction of forward jet is required.

There are also uncertainties on the robustness of the jet veto with respect to radiation in the underlying event and to the presence of pile-up.

So far VBF channels have been studied at low luminosity only.



Channels:

$qqH \rightarrow qq\gamma\gamma$

$qqH \rightarrow qqWW^{(*)}$ where can use $WW^{(*)} \rightarrow l\nu\ l\nu$ and $l\nu\ jj$

$qqH \rightarrow qq\tau\tau$ where can use $\tau\tau \rightarrow l\nu\nu\ l\nu\nu$, $l\nu\nu$ had ν and had had

$qqH \rightarrow qq\tau\tau \rightarrow qq\ l\nu\nu\ had\ \nu$

Features: Interesting channel for M_H<150 GeV: increases sensistivity to low mass H

Trigger: High P_T single lepton triggers

Backgrounds: EW/QCD 2τ+2/3 jets
tt production
W+jets

Analysis: Besides the VBF cuts, one has to apply cuts to select the primary isolated electron, together with a $M_T(l\text{-}E_T^{miss})$ cut to reduce the W background.

τ jet identification important: use tracking and calorimeter information.

The H mass can be reconstructed using the collinear approximation: the τ mass is neglected and it is assumed that the ν direction coincides with the visible decay products of the τ's

qqH→qqττ→qq lνν had ν

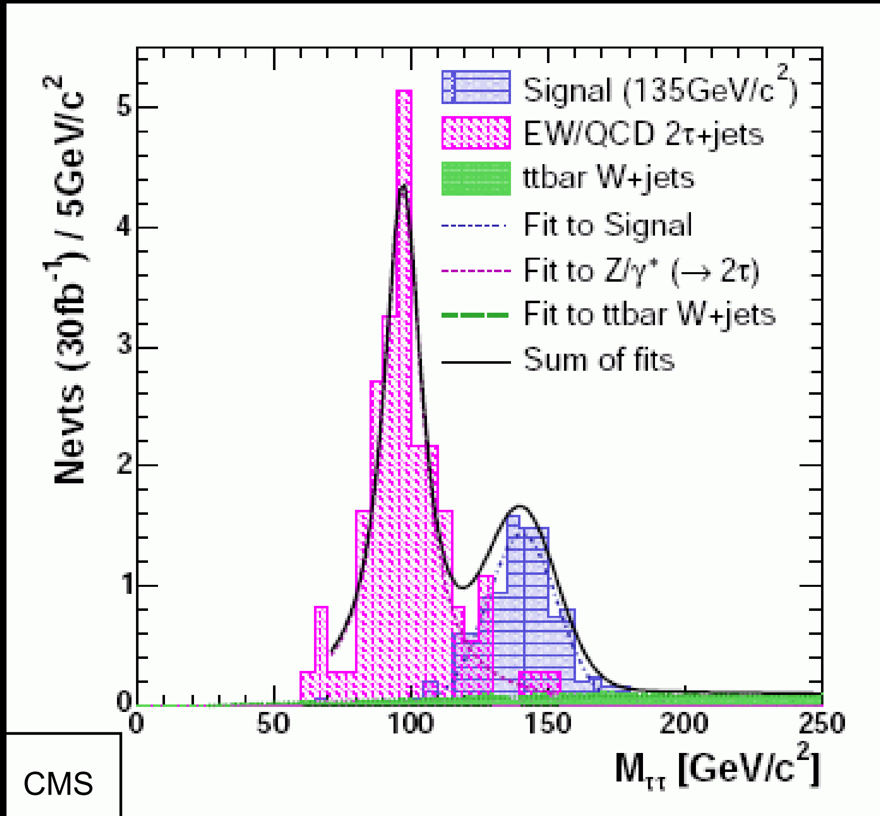
Experimental issues:

Need good E_T^{miss} resolution
Need identification of hadronic τ's

In the end H mass resolution ≈9%.

Dominant background:
Z+jets with Z→ττ
(dangerous for low Higgs masses)

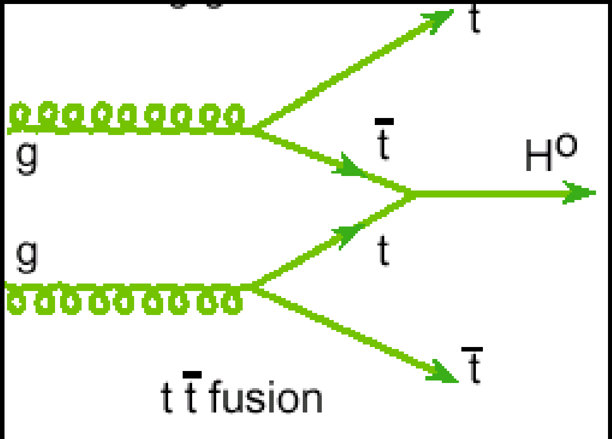
Control samples for the background:
Z+jets with Z→ee, Z→μμ

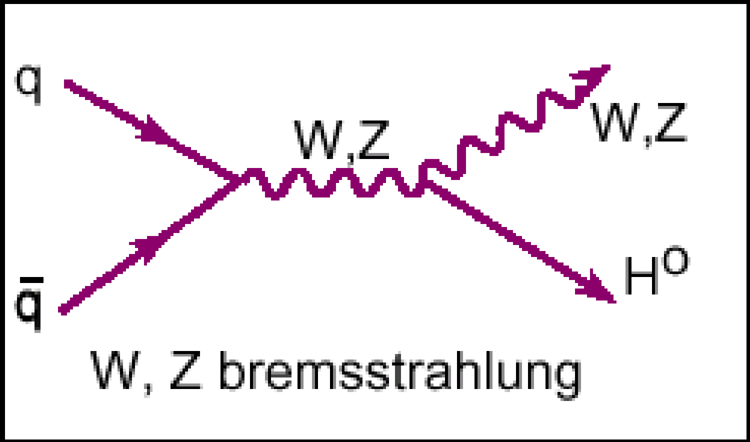


For 30 fb^{-1}, at M_H=135 GeV, expect about 8 signal events with a significance of about 4 (CMS)

Other search channels

Associated productions





pp → WH, ZH, ttH with W → lν, Z → ll or Z → νν

Low rates.

Leptons from W, Z and t→Wb→lνb can provide trigger and discrimination from background. Provide useful channels with higher integrated luminosity (~100 fb^{-1}).

A few examples:

Other search channels

$pp \rightarrow WH, ZH, ttH$ with $H \rightarrow \gamma\gamma$

It has been shown that the combination of these channels with the ones already discussed can increase the discovery potential. When fitting for the signal another possibility is to divide the event sample in various categories: H+0j, H+1j, H+2j

$WH \rightarrow WWW(*)$

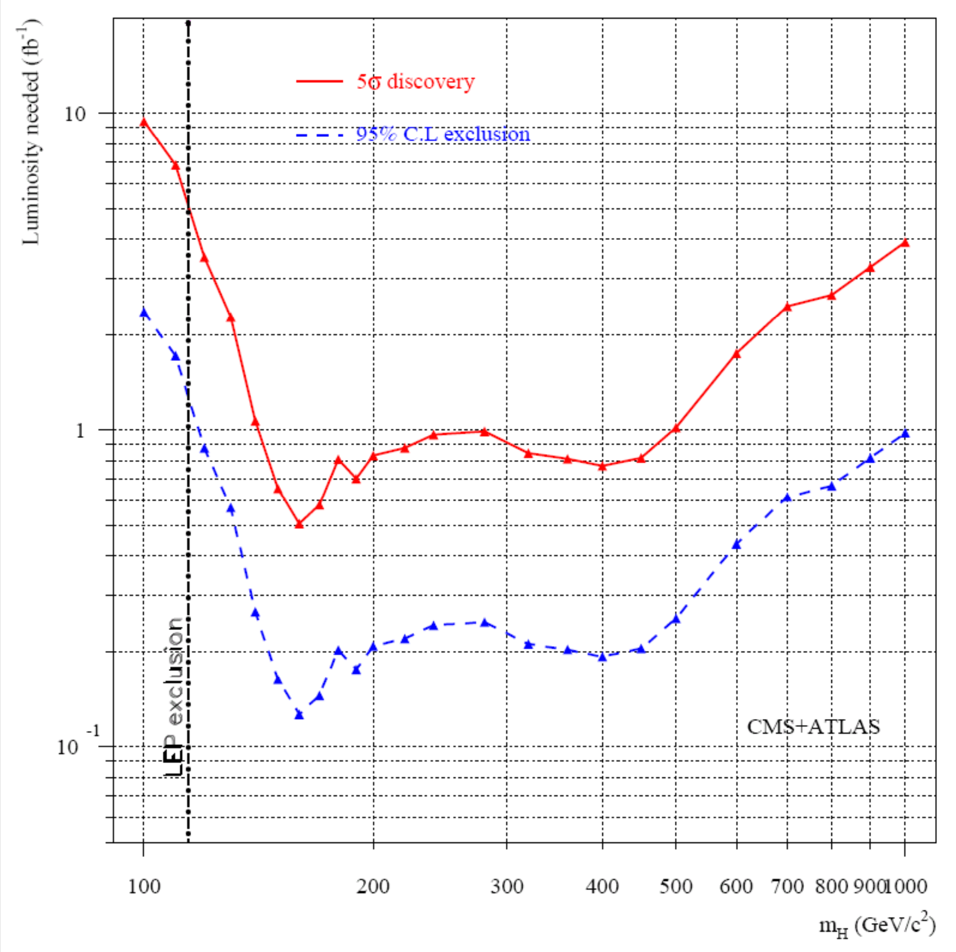
Three lepton final state.

$ttH \rightarrow ttbb$ (with one t decaying semileptonically)

Complex final states: 4 b's + 2 (or more) light jets. b-tagging is crucial. High combinatorics. High ttbb and ttjj backgrounds. Significance ~3σ for 30 fb^{-1} (CMS; ATLAS results in progress)

$ZH \rightarrow ll$ + invisible H decay products

Higgs bosons decaying to stable neutral weakly interacting particles (neutralinos, gravitinos,...) in some SM extensions. Trigger on Z leptons and require large E_T^{miss} in the event



(old ATLAS ttH result has been assumed)

For m_H>140 GeV an accumulated statistics of order ~1 fb^{-1} might be sufficient

For low mass higgs (< 140 GeV) the situation is more complex: around 5 fb^{-1} are needed and several channels need to be combined

In both cases it is assumed that the detectors and the data are well understood.

Measurement of Higgs properties

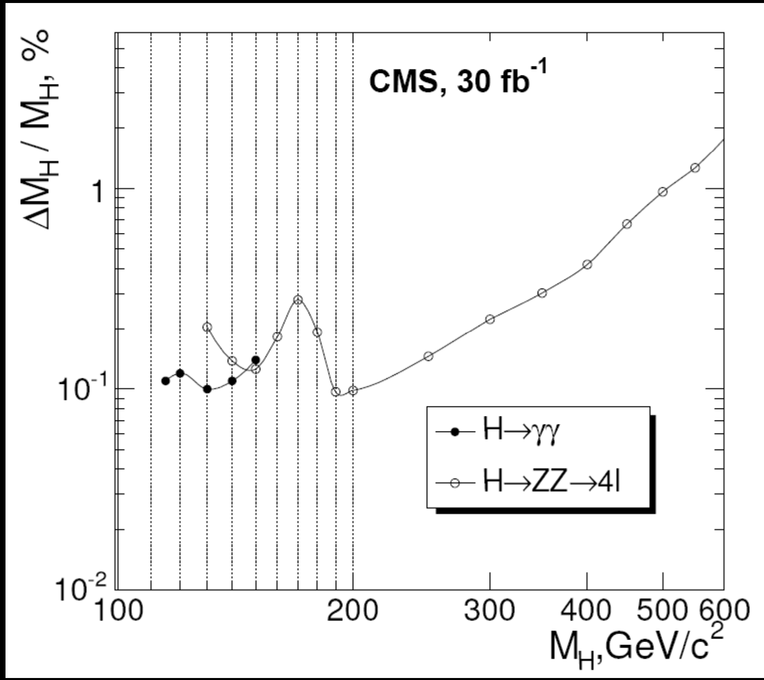
Mass measurement

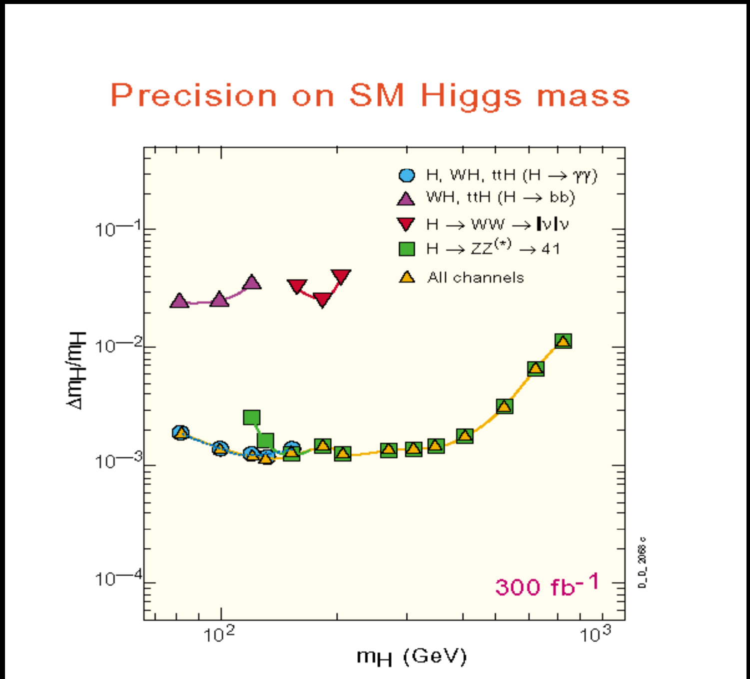
Best channels for this measurement are $H \rightarrow \gamma\gamma$ and at higher masses $H \rightarrow 4l$.

CMS estimates a precision <0.3 % up to 350 GeV (stat error only) with 30 fb^{-1}

ATLAS estimated about 0.1 % up to 400 GeV with 300 fb^{-1} including sys errors.

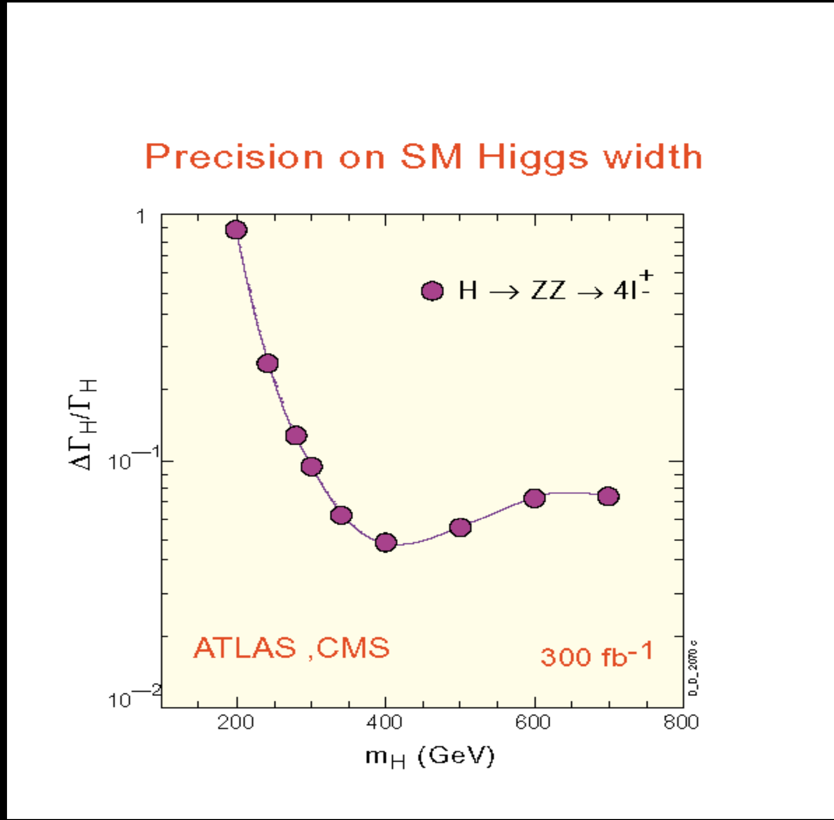
The precision will be limited by the uncertainty on the lepton and photon energy scale, which is expected to be at the level of 0.1%





Width measurement

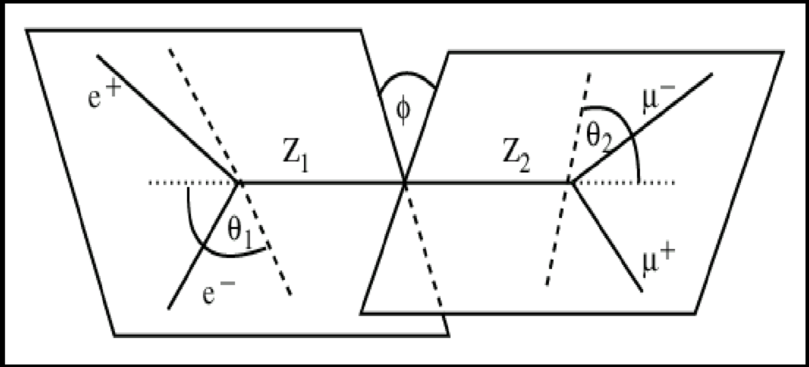
For small H masses, the intrinsic H with is negligible with respect to the experimental resolution. Direct measurement with reasonable accuracy can be performed only above ~200 GeV (better than 10% for M_H>300 GeV with 300 fb^{-1})



Spin and CP

In the SM, H has $J^{PC}=0^{++}$

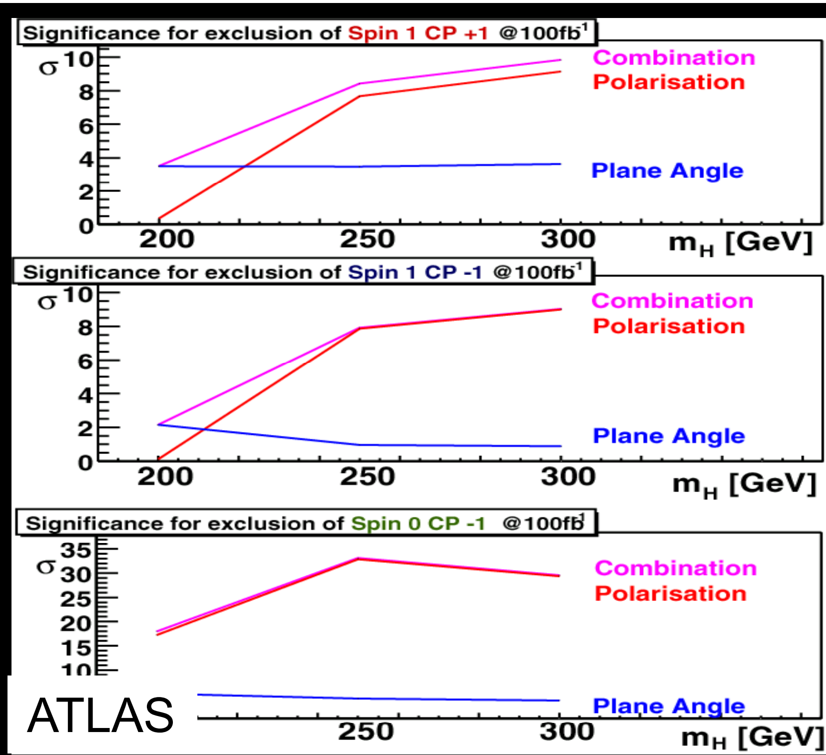
If H→γγ or gg→H are established, J=1 can be excluded. This and other J^{PC} combinations can be also excluded studying angular correlations in H→4l decays.



$\theta \rightarrow$ polar angle l^- wrt Z momentum

$\varphi \rightarrow$ angle between decay planes

With 100 fb^{-1} can provide discrimination from J=1 and J=0/CP=-1 hypothesis for masses greater than ~200 GeV



Structure of HVV (V=W,Z) coupling

The presence of an additional CP even or CP odd term in the HVV coupling can be excluded using a similar method for M_H>200 GeV.

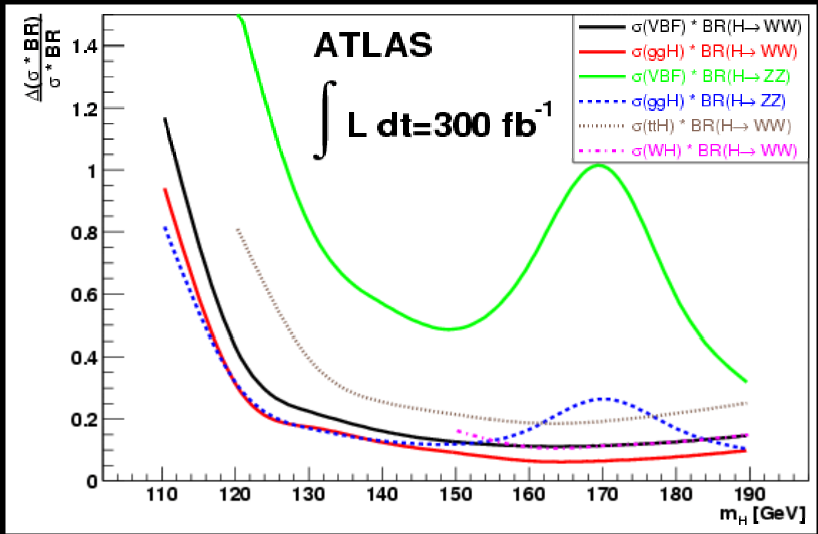
For smaller masses the study of the $\Delta\phi_{jj}$ separation between tag jets in VBF events can be used. The VBF $H\rightarrow\tau\tau$ process has been studied down to 120 GeV and the VBF $H\rightarrow WW$ process around 160 GeV.

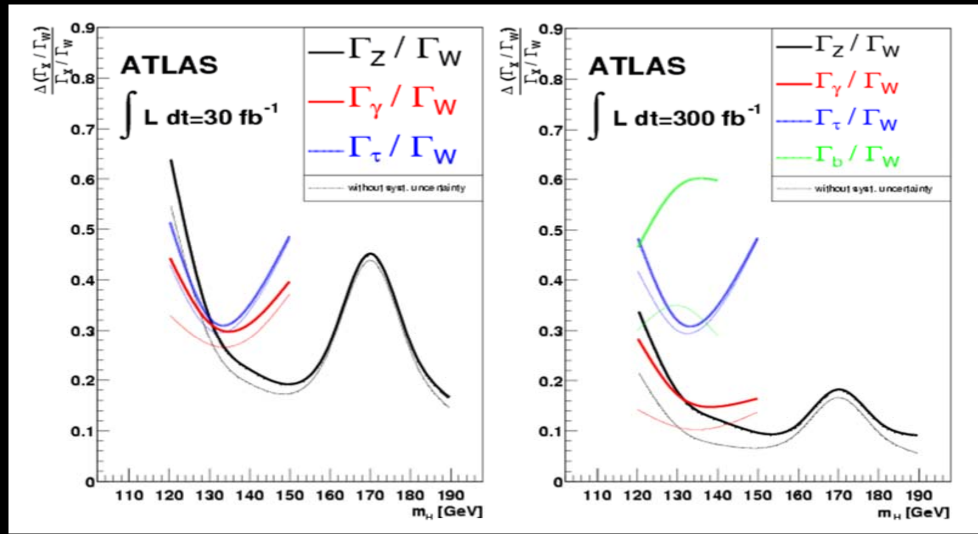
Measurement of couplings

Likelihood fit to expected number of events in all observable channels. Include sys errors from detector effects, luminosity, background normalization, cross sections.

Concentrating on low Higgs masses (<200 GeV), several measurements are possible, depending on how many assumptions are done:

1. Assuming Higgs have spin 0, $\sigma \cdot BR$ can be measured
2. Assuming there is only one H boson, can fit ratio of widths Γ_i/Γ_W, in this case normalized to the Γ of $H \rightarrow WW$
3. Assuming there are no new particles in loop and no strong couplings to light fermions, can obtain ratio of (5) couplings
4. Assuming that $\Gamma_V < \Gamma_V^{SM}$, can "measure" absolute couplings


ATLAS
∫ L dt=300 fb-1
σ(VBF) * BR(H→ WW)
σ(ggH) * BR(H→ WW)
σ(VBF) * BR(H→ ZZ)
σ(ggH) * BR(H→ ZZ)
σ(ttH) * BR(H→ WW)
σ(WH) * BR(H→ WW)
Δ(σ * BR) / σ * BR
mH [GeV]


ATLAS
∫ L dt=30 fb-1
Γz / Γw
Γγ / Γw
Γτ / Γw
without syst. uncertainty
ATLAS
∫ L dt=300 fb-1
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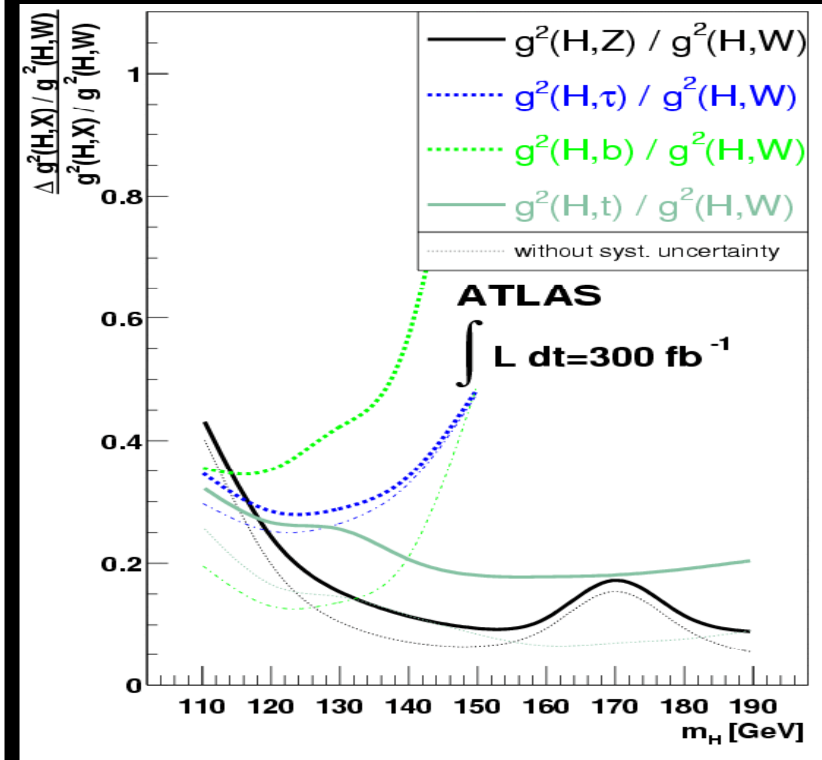
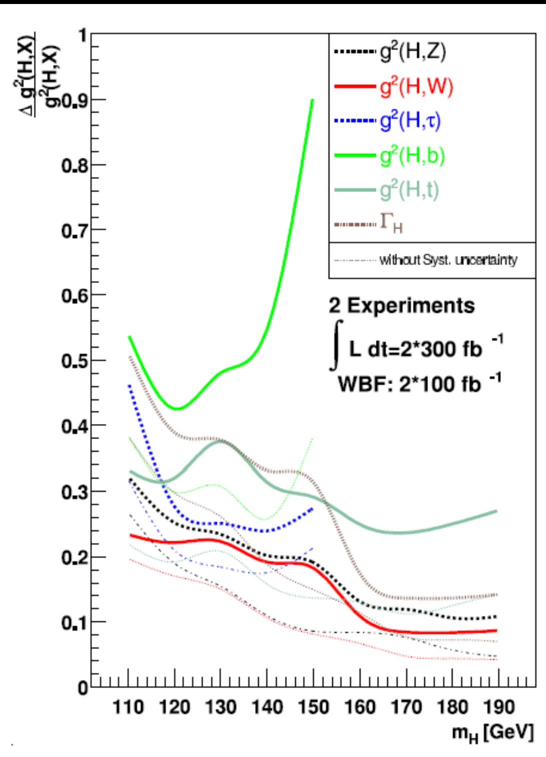
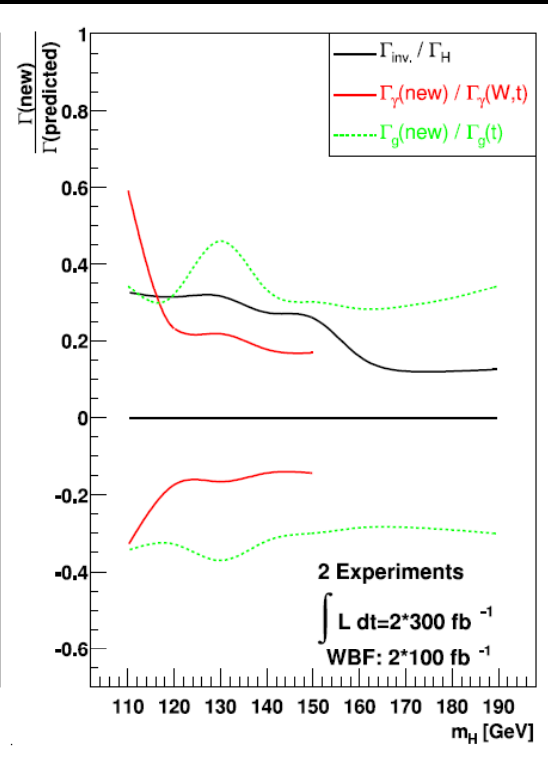
without syst. uncertainty
mH [GeV]


g2(H,Z) / g2(H,W)
g2(H,τ) / g2(H,W)
g2(H,b) / g2(H,W)
g2(H,t) / g2(H,W)
without syst. uncertainty
ATLAS
∫ L dt=300 fb -1
Δ g2(H,X) / g2(H,W) / g2(H,X) / g2(H,W)
mH [GeV]


g2(H,Z)
g2(H,W)
g2(H,τ)
g2(H,b)
g2(H,t)
ΓH
without Syst. uncertainty
2 Experiments
∫ L dt=2*300 fb -1
WBF: 2*100 fb -1
Δ g2(H,X) / g2(H,X)
mH [GeV]


Γinv. / ΓH
Γγ(new) / Γγ(W,t)
Γg(new) / Γg(t)
2 Experiments
∫ L dt=2*300 fb -1
WBF: 2*100 fb -1
Γ(new) / Γ(predicted)
mH [GeV]

SUSY Higgs

Because of the large parameter space, searches are performed for specific choice of parameters: benchmark scenarios.
In the MSSM (but there are also NMSSM preliminary studies):

- M_h^{max}: maximum allowed mass for h. Replaces the "maximal mixing" scenario used in the past.
- No-mixing: as above but no mixing in stop sector. Smaller M_h
- Gluophobic H: large mixing suppresses gluon fusion production $gg \rightarrow h$ and $h \rightarrow \gamma\gamma$, $h \rightarrow 4l$
- Small α_{eff}: small mixing angle of the neutral CP-even Higgs boson can suppress $h \rightarrow bb$, $\tau\tau$
- CPX: CP eigenstates h, A, H mix to mass eigenstates H_1, H_2, H_3. Maximal mixing.

Channels

Several channels have been studied in different mass ranges. In addition to channels similar to the SM ones (SM-like h at large M_A, H at “low“ M_A) rescaled for the corresponding MSSM cross sections and BRs, examples of relevant channels are:

A/H

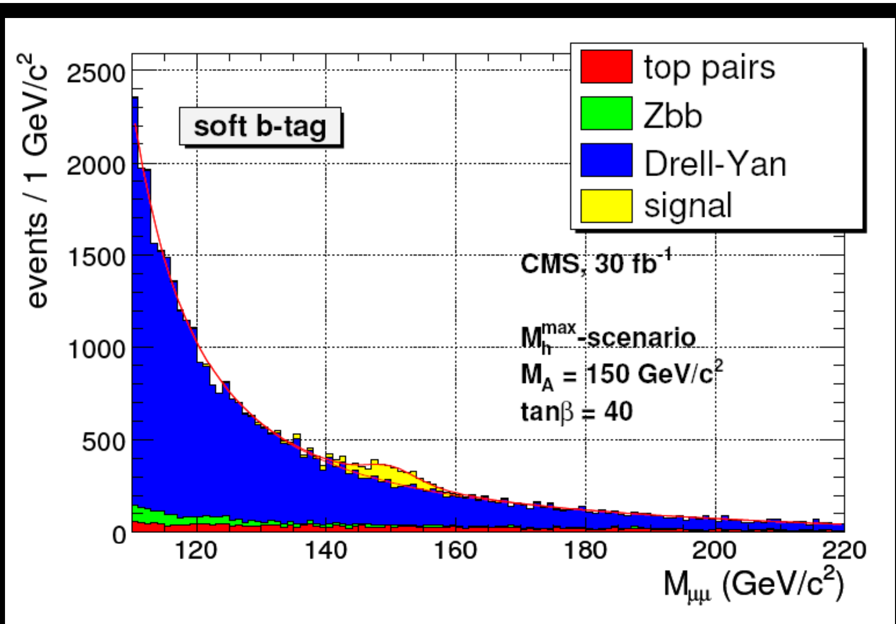
Degenerate in mass in most of the parameter space.

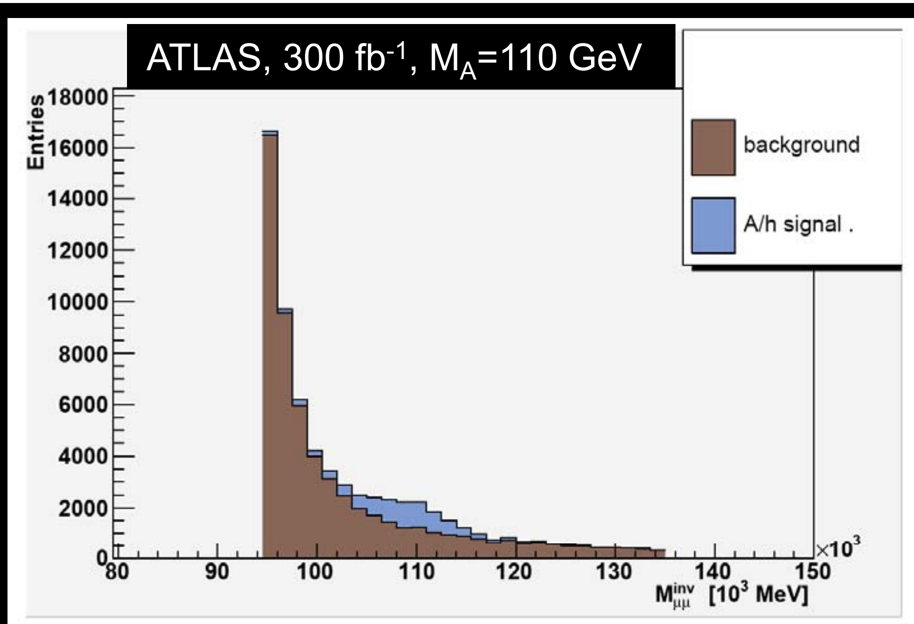
gg→bbH, A with A/H→$\tau\tau$ or A/H→$\mu\mu$

Usually at least one of the b is tagged to reduce the background

The $\tau\tau$ decay has a higher BR, 10% (bb, 90% has trigger problems) and exploits all possible $\tau\tau$ decays: lep-lep, lep-had, had-had

The $\mu\mu$ decay has a much lower BR, but clean signature (thanks to the high muon resolution of the experiments) and full mass reconstruction. However it is not possible to separate A/H (and h).





$H^{\pm}$

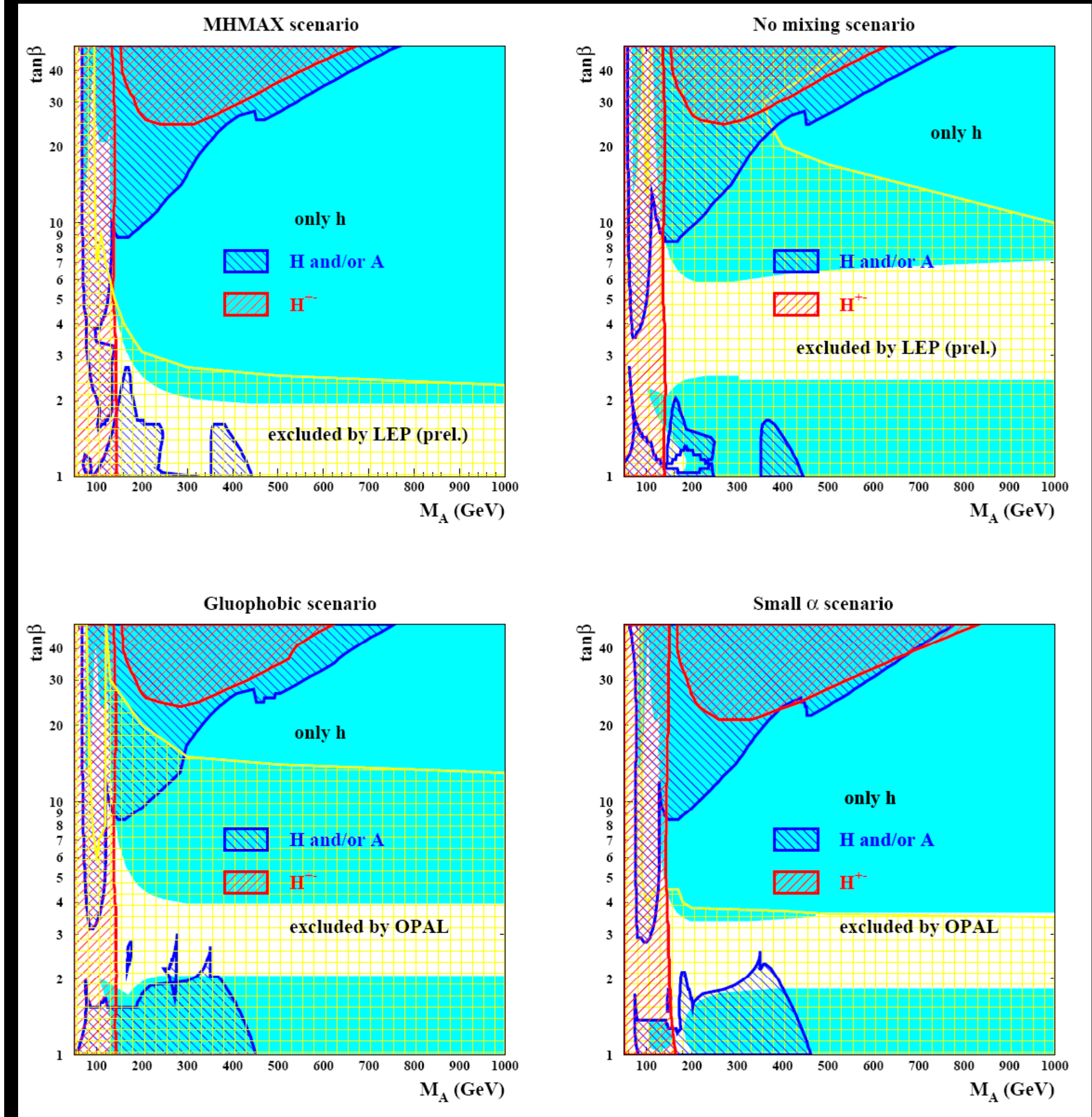
Production modes: $t \to H^+ b$, $gg \to tbH^+$, $gb \to tH^+$

Decays: most promising $H^+ \to \tau\nu$ which leads to τ+3 jets+E_t^{miss}

Fully hadronic final state: uses a τ trigger.

Backgrounds are: tt, Wt, W+3 jets

Handles: τ-ID, top mass reconstruction, lepton veto, b-tag, τ helicity



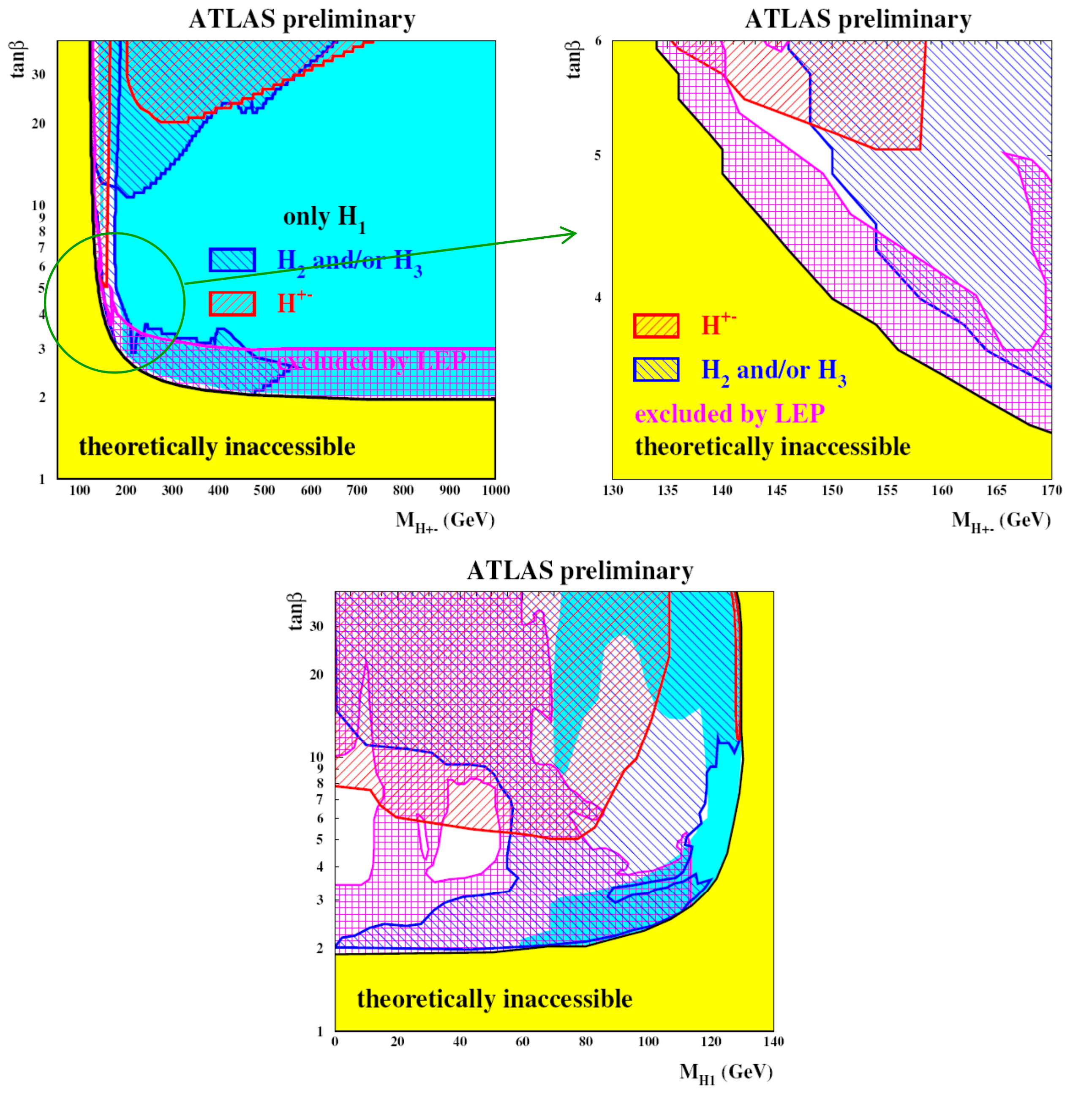
ATLAS preliminary

ATLAS, 30 fb^{-1}, 5σ discovery potential in 4 benchmark scenarios

At least one Higgs boson is expected to be found in the allowed parameter space.

However, in some regions of the parameter space only one Higgs boson (SM like), h, can be observed.

At higher luminosity (300 fb^{-1}) the h boson can be seen in more than one channel in most of the parameter space.



ATLAS, 300 fb^{-1}, 5σ discovery potential in CPX scenario.

Almost all of the parameter space is covered by the observation of at least one Higgs boson (mainly the lightest H_1)

Small region of phase space not covered: corresponds to M_{H1}<50 GeV.

Conclusions

I have presented a partial review of Higgs studies in ATLAS and CMS:

Several results have been taken from the CMS Physics Performance Technical Design Report (CERN/LHCC 2006-021)

The ATLAS Physics TDR which dates back to '99 (CERN/LHCC 99-14/15) is being updated with a series of notes that will be published soon.

Several SM H channels have been studied with detailed detector simulation and latest theoretical developments:

There is already good sensitivity with ~10 fb^{-1}, although more detailed studies (including measurement of H properties) will require more data

Data will tell if the detector behave as expected and if we can control the background levels

More than one channel along the expected mass range give robustness to the results

MSSM well covered

The two detectors are also powerful enough to face unexpected scenarios.

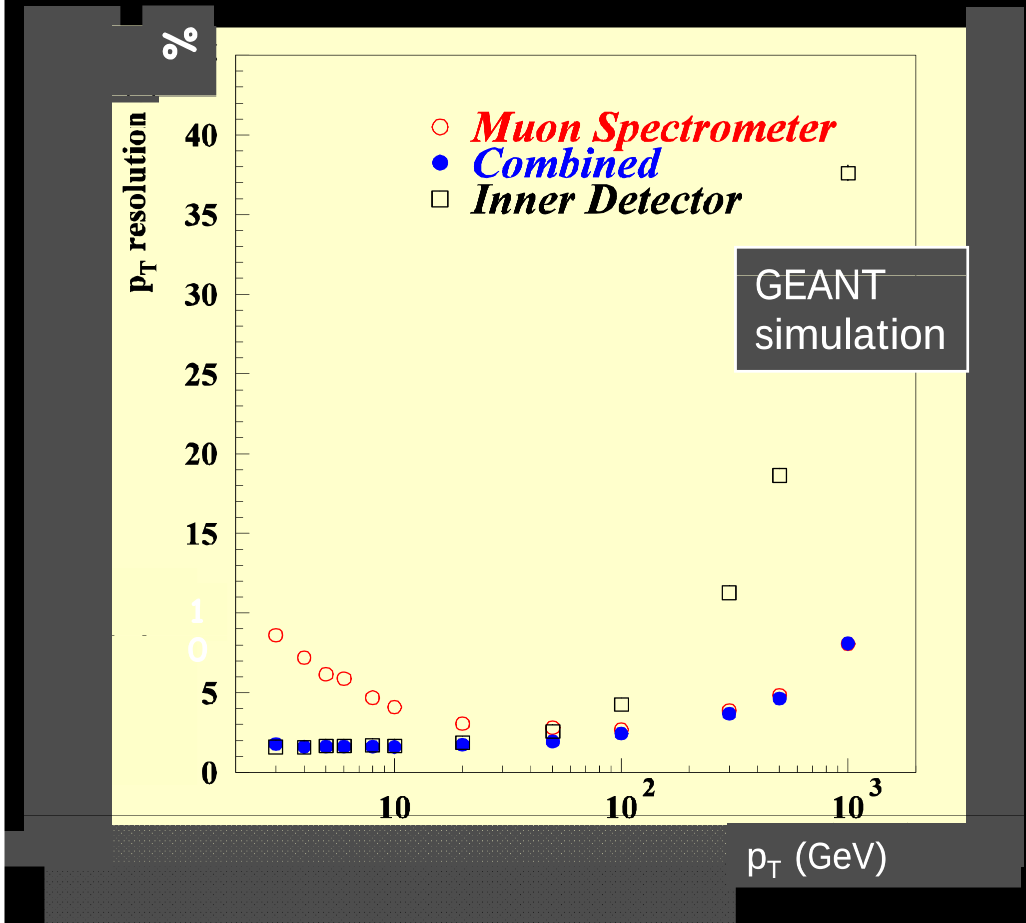
First LHC collisions are expected later this year

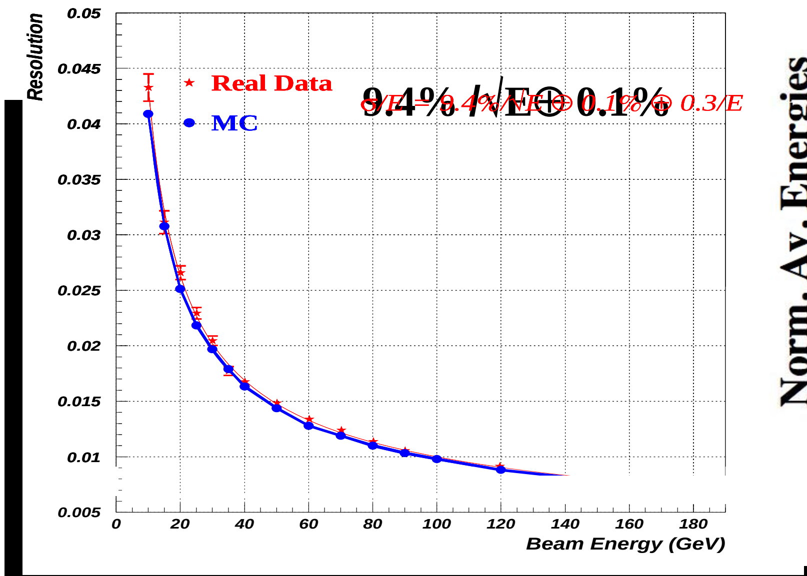
Big activities on-going in commissioning the detectors, the offline computing, preparing alignment and calibration strategies,…

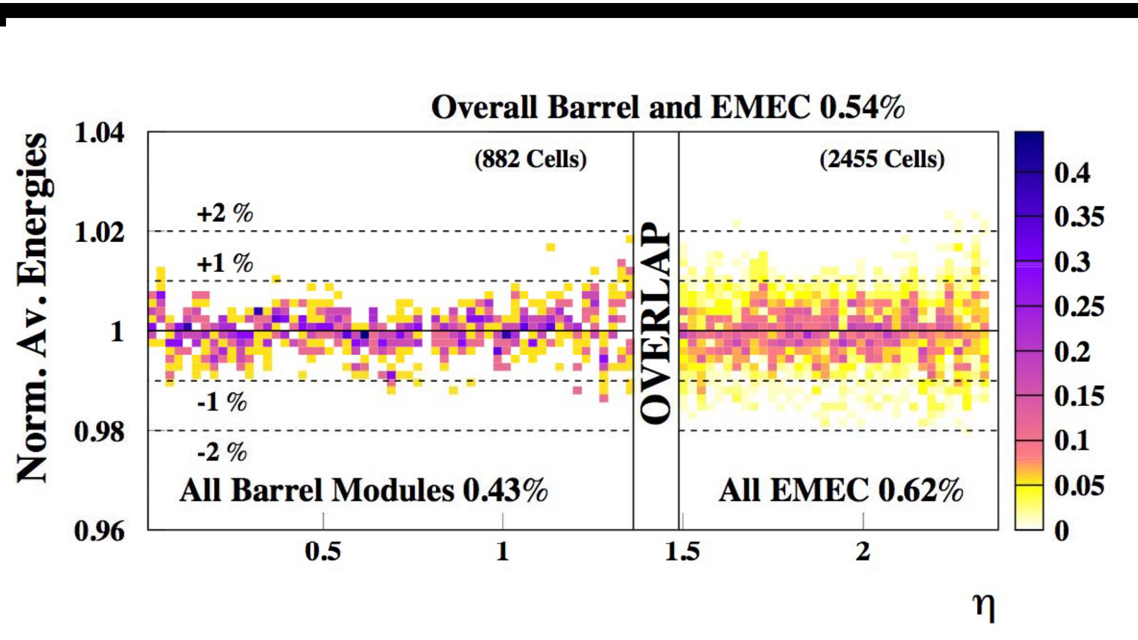
We face a long period of development and understanding of the two detectors

Work has already started using cosmics data and will continue with first collisions.

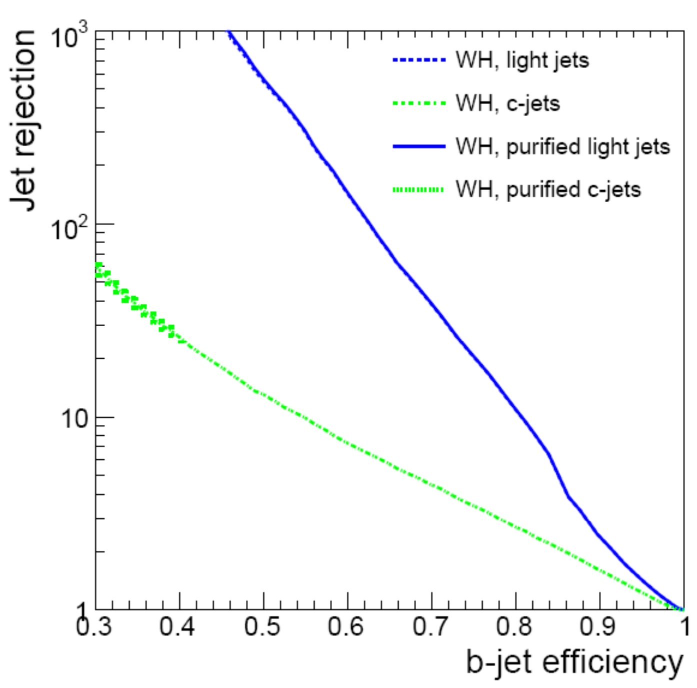
Backup Material

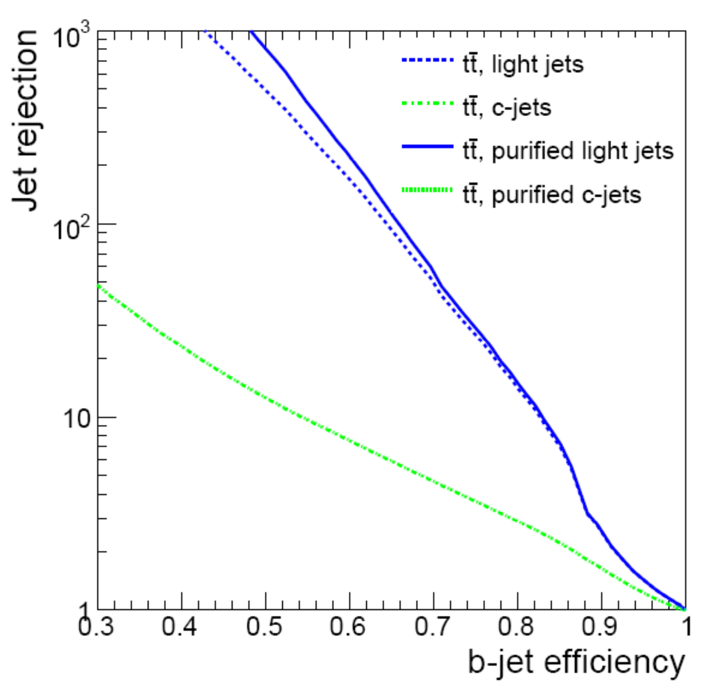

%
p_T resolution
Muon Spectrometer
Combined
Inner Detector
GEANT simulation
0
5
10
15
20
25
30
35
40
10
10^2
10^3
p_T (GeV)

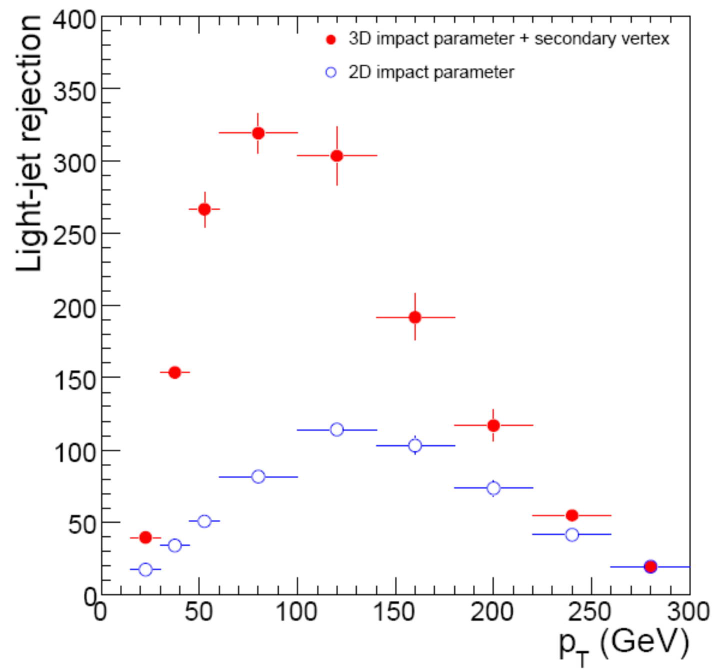


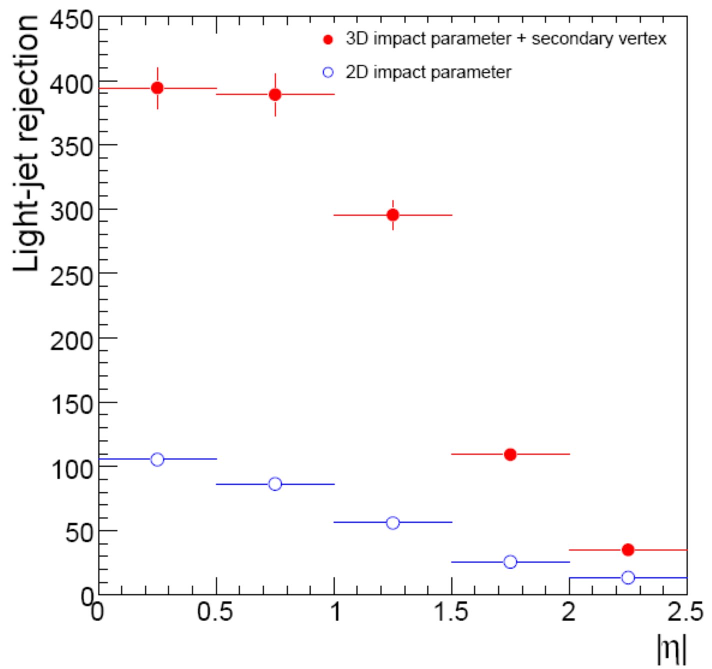


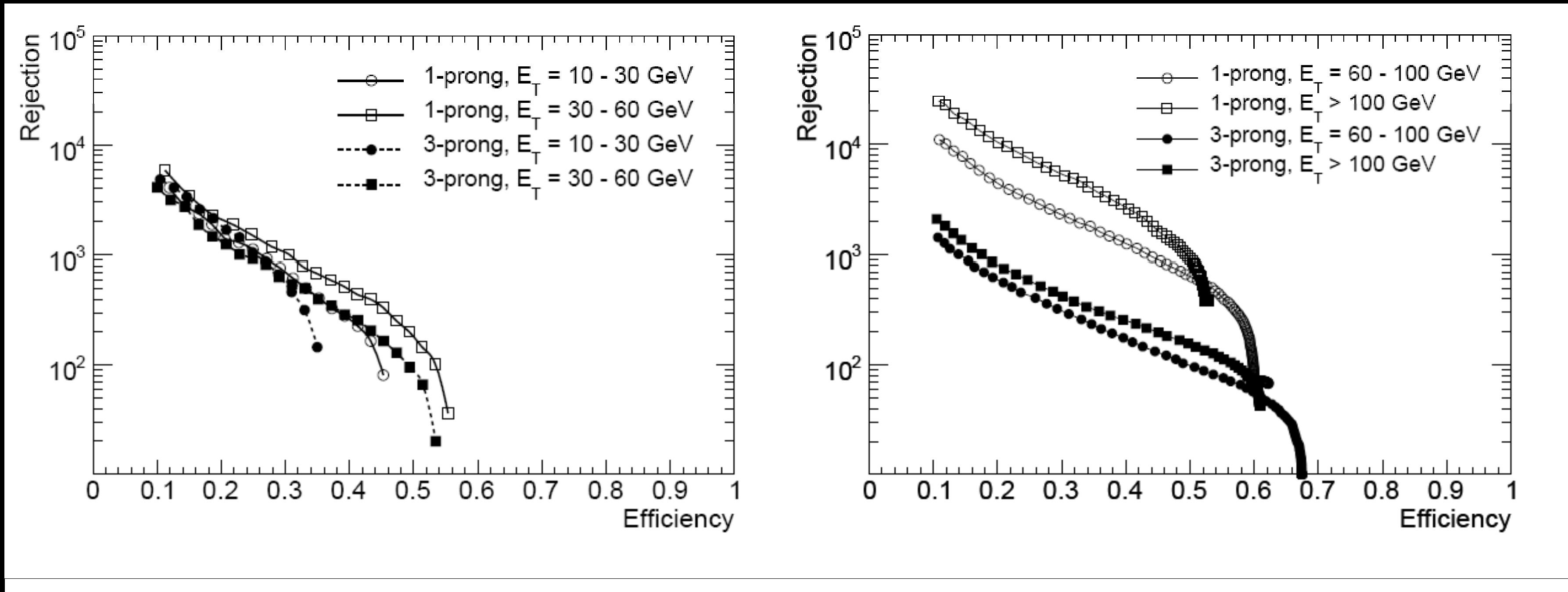
	Expected performance day-0	Physics samples for improvement (examples)
ECAL uniformity	1-2% (~0.5% locally)	Isolated electrons, Z→ ee
e/γ E-scale	~ 2 %	Z → ee
HCAL uniformity	~ 3 %	Single pions, QCD jets
Jet E-scale	< 10%	γ/Z + 1j, W → jj in tt events


Jet rejection
b-jet efficiency
WH, light jets
WH, c-jets
WH, purified light jets
WH, purified c-jets


Jet rejection
b-jet efficiency
tt̄, light jets
tt̄, c-jets
tt̄, purified light jets
tt̄, purified c-jets

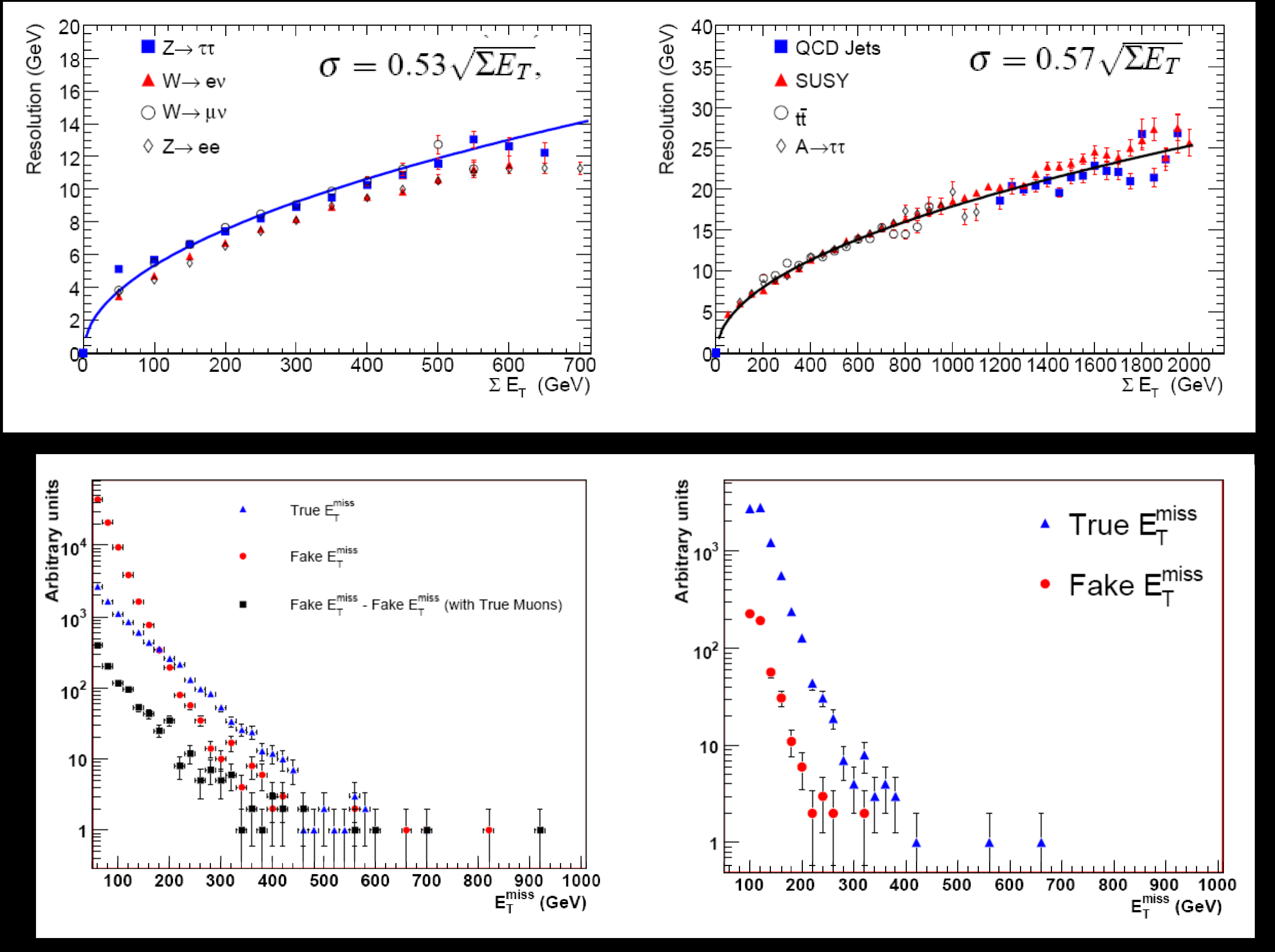

Light-jet rejection
p_T (GeV)
3D impact parameter + secondary vertex
2D impact parameter


Light-jet rejection
|η|
3D impact parameter + secondary vertex
2D impact parameter



Algorithm		E_T = 10-30 GeV	E_T = 30-60 GeV	E_T = 60-100 GeV	$E_T > 100$ GeV
Track-based	1-prong	740±70	1030±160		
(neural network)	3-prong	590±50	590±70		
Calorimeter-based	1-prong		1130±50	2240±140	4370±280
(likelihood)	3-prong		187±3	310±7	423±8

ε=30%



Resolution (GeV)
$\sigma = 0.53\sqrt{\Sigma E_T}$
Z→ ττ
W→ eν
W→ μν
Z→ ee
Σ E_T (GeV)
$\sigma = 0.57\sqrt{\Sigma E_T}$
QCD Jets
SUSY
tt̄
A→ττ
Arbitrary units
True E_T^miss
Fake E_T^miss
Fake E_T^miss - Fake E_T^miss (with True Muons)
E_T^miss (GeV)

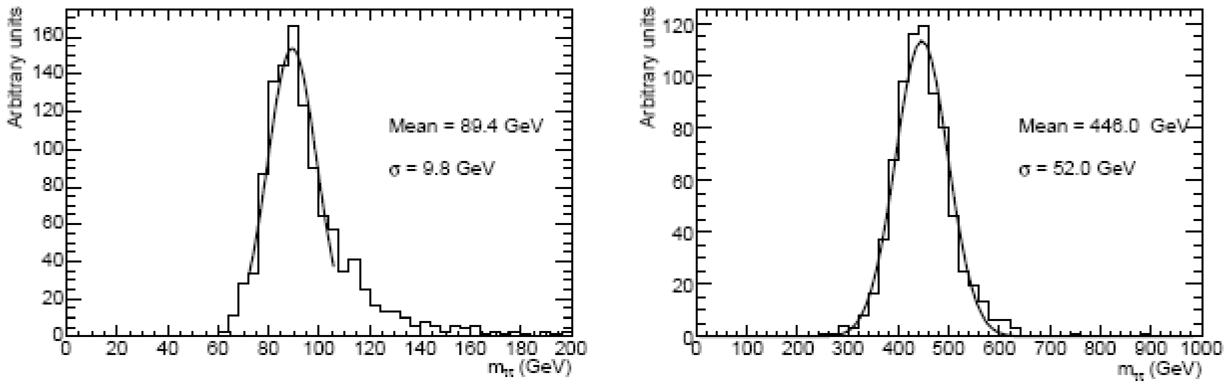


Figure 276. Expected distributions for the reconstructed invariant mass of τ-lepton pairs, with one τ-lepton decaying to a lepton and the other one decaying to hadrons. The results are shown for $Z \rightarrow \tau\tau$ decays (left) and for $A \rightarrow \tau\tau$ decays with $m_A = 450$ GeV (right).

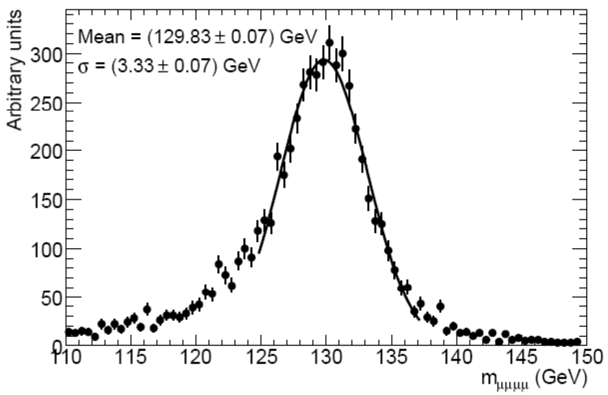


Figure 230. For $H \rightarrow \mu\mu\mu\mu$ decays with $m_H = 130$ GeV, reconstructed mass of the four muons using stand-alone reconstruction. The results do not include a Z-mass constraint.

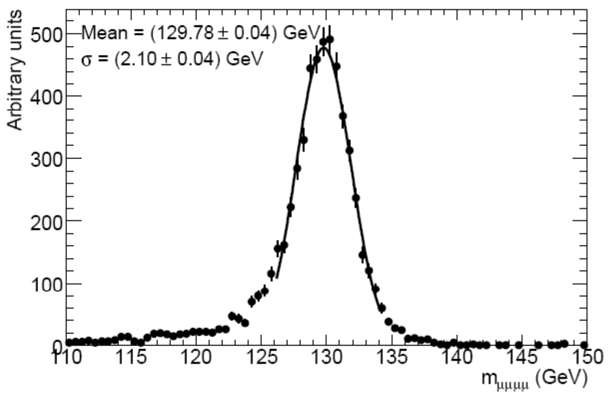
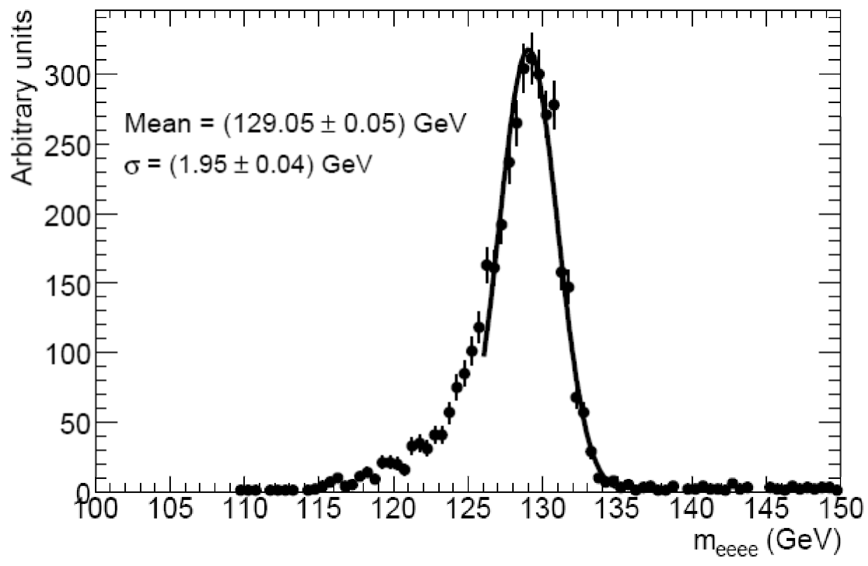
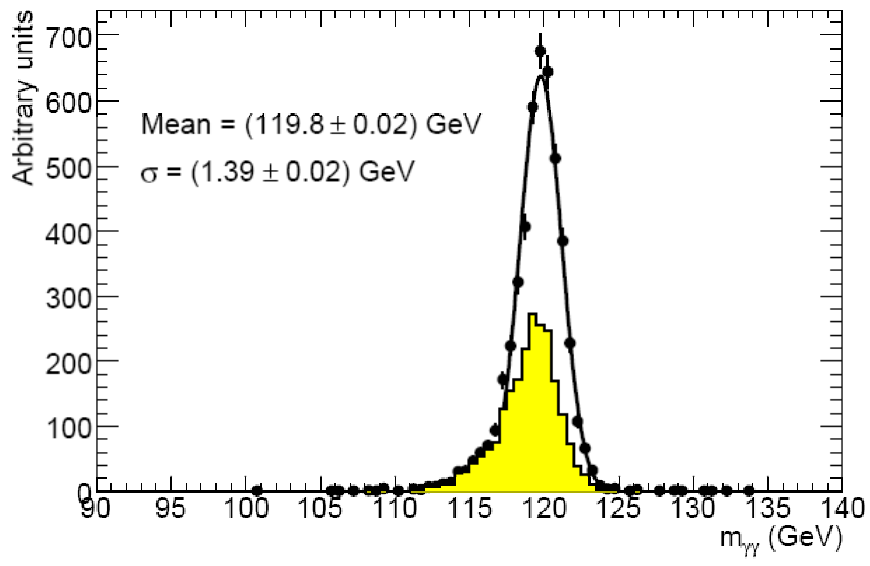
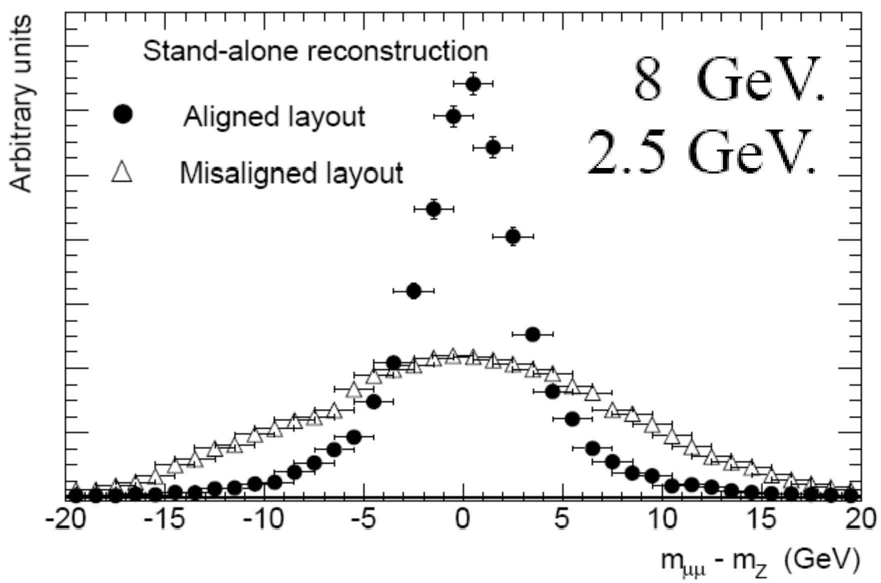


Figure 231. For $H \rightarrow \mu\mu\mu\mu$ decays with $m_H = 130$ GeV, reconstructed mass of the four muons using combined reconstruction. The results do not include a Z-mass constraint.


Arbitrary units
Mean = (129.05 ± 0.05) GeV
σ = (1.95 ± 0.04) GeV
m_eeee (GeV)


Arbitrary units
Mean = (119.8 ± 0.02) GeV
σ = (1.39 ± 0.02) GeV
m_γγ (GeV)


Arbitrary units
Stand-alone reconstruction
Aligned layout
Misaligned layout
8 GeV.
2.5 GeV.
m_μμ - m_Z (GeV)