Higgs Searches at the Large Hadron Collider

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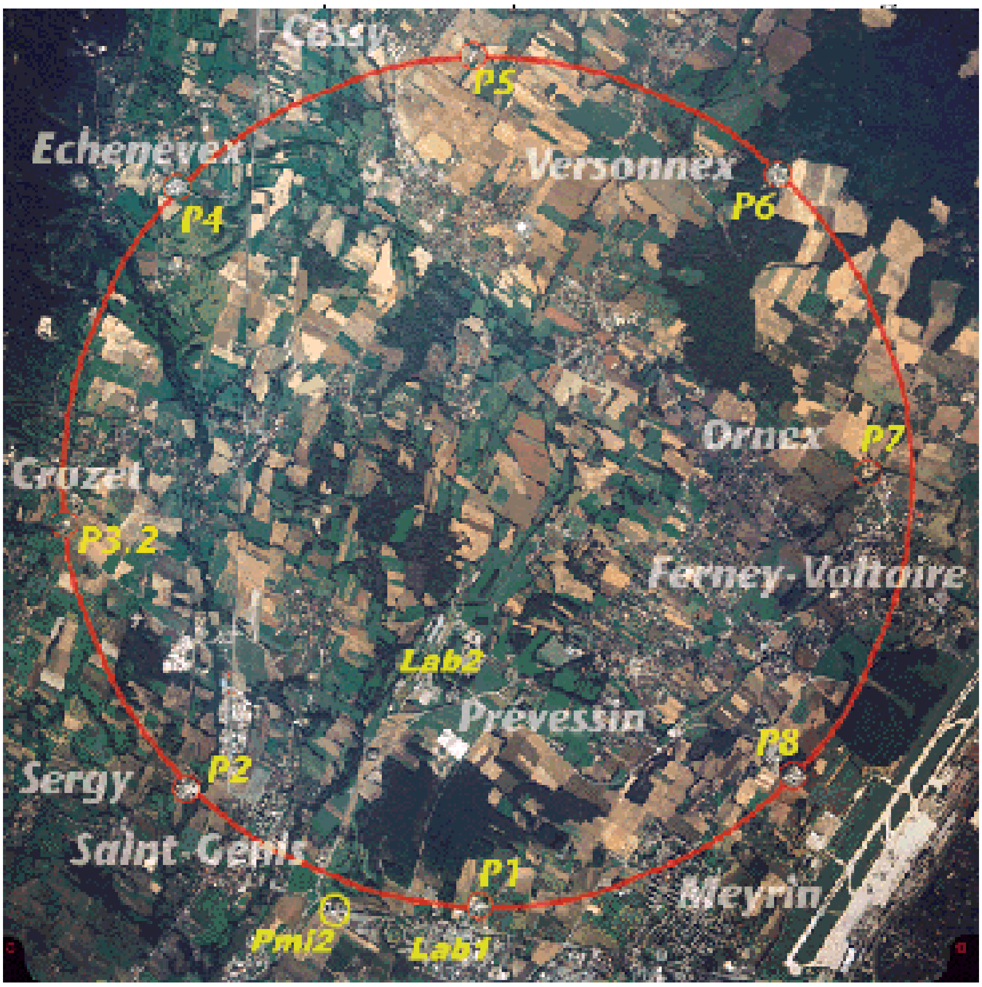
outline

- the LHC project
- the search of the Higgs boson(s) at the LHC: detector requirements
- the physics environment
- the ATLAS detector and its physics performance
- the search of the Standard Model Higgs boson
- the search of the MSSM Higgs bosons
- summary

the LHC project

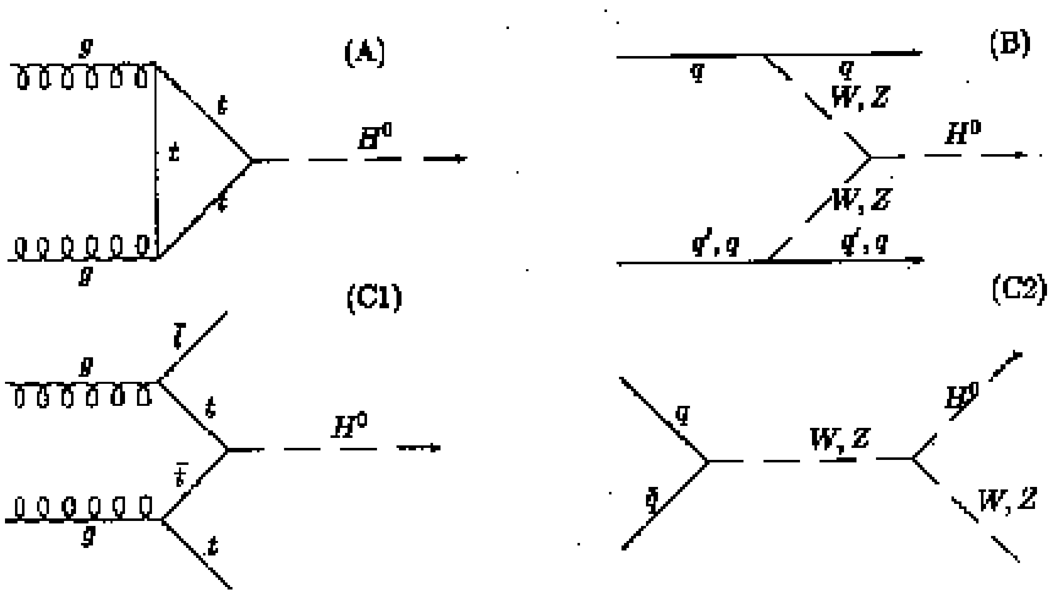


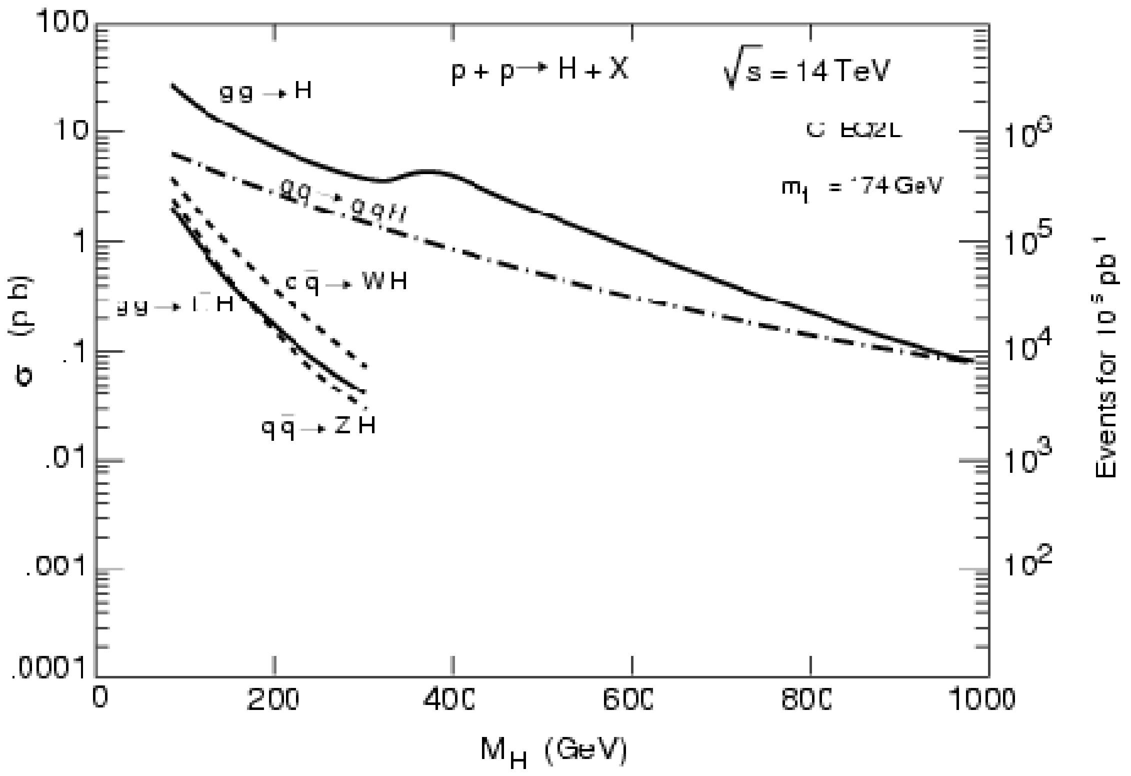
Large Hadron Collider: proton-proton collider in the LEP tunnel.

Main parameters:

- Circumference: : ~ 27 km
- Beam energy at collision point: 7 TeV
- Luminosity: 1 x $10^{34} cm^{-2} s^{-1}$
- Bunch separation: 24.95 ns
- Bunch spacing: 7.48 m

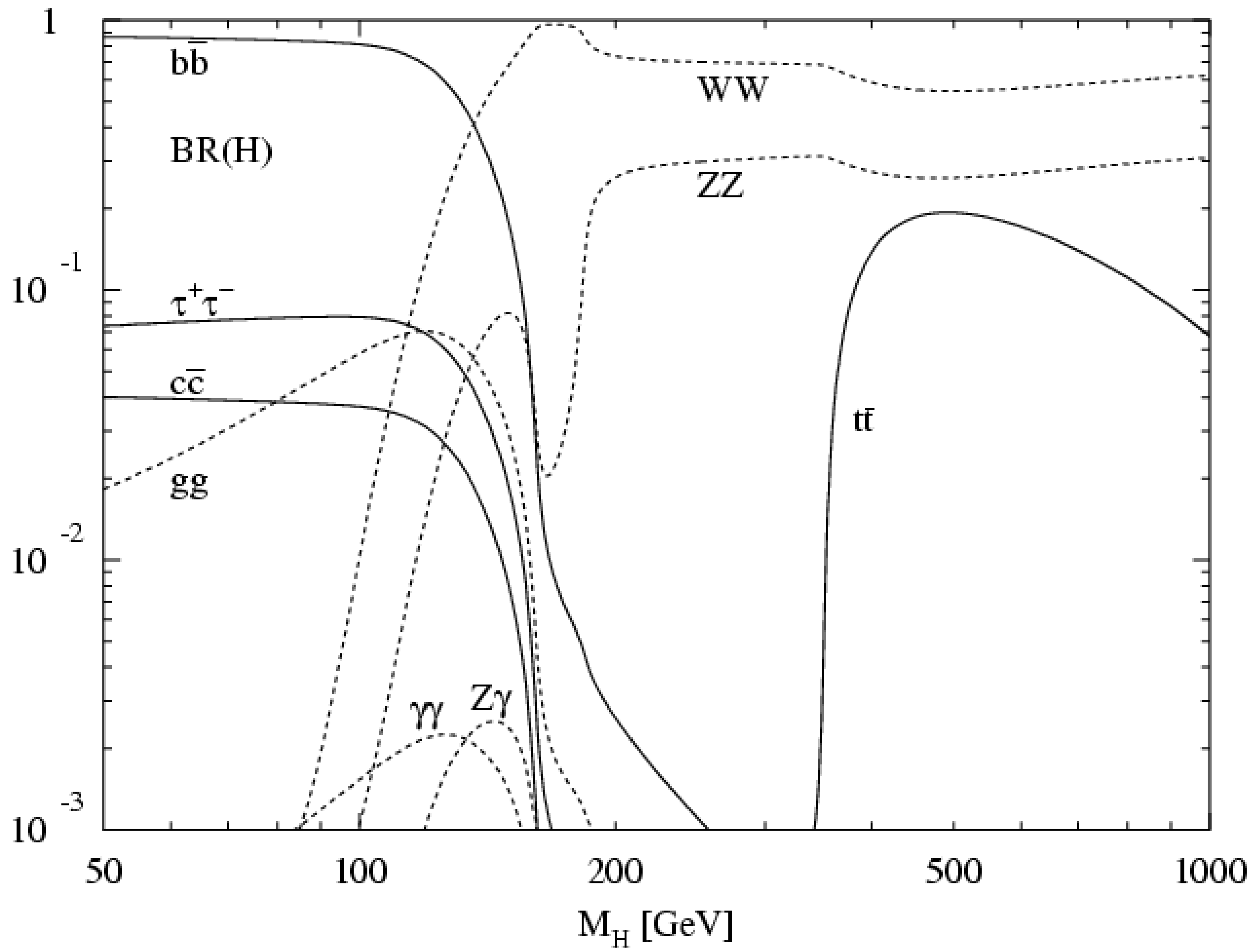
Higgs production at LHC





the Standard Model Higgs ...

The Standard Model Higgs boson branching ratios



the Higgs boson is ‘’strongly’’ coupled with high-mass fermions, W- and Z-pair.

the Standard Model Higgs -2-

The Standard Model Higgs boson is searched for at the LHC in various decay channels, each channel being viable only in a specific mass range:

- $H \rightarrow \gamma\gamma$ direct production; $100 < m_H < 150$ GeV;
- $H \rightarrow \gamma\gamma$ from the associated production WH, ZH and $t\bar{t}H$; $100 < m_H < 120$ GeV;
- $H \rightarrow b\bar{b}$ from the associated production WH, ZH and $t\bar{t}H$; $80 < m_H < 120$ GeV;
- $H \rightarrow ZZ^* \rightarrow 4l$; $130\ \text{GeV} < m_H < 2m_Z$;
- $H \rightarrow ZZ \rightarrow 4l$; $2m_Z < m_H < 0.7$ TeV;
- $H \rightarrow WW \rightarrow l\nu jj$, $H \rightarrow ZZ \rightarrow lljj$ and $H \rightarrow ZZ \rightarrow ll\nu\nu$; $0.4\ \text{TeV} < m_H < 1$ TeV;

...and the MSSM Higgs

In addition to the above signatures, the Minimal Supersymmetric Standard Model Higgs searches also require sensitivity to:

- $H/A \rightarrow \tau^+\tau^- \rightarrow e\mu + \nu$'s or $H/A \rightarrow \tau^+\tau^- \rightarrow l$ + hadrons+ ν's;
- $H^\pm \rightarrow \tau^\pm \nu$;
- $H/A \rightarrow t\bar{t}$;

detector requirements

The basic detector requirements are:

- very good electromagnetic calorimetry for electron and photon reconstruction:
  - **e.m. energy measurement ($H \to \gamma\gamma$; $H \to ZZ^* \to 2e2l$)**
  - **photon direction (in η) to estimate the $H \to \gamma\gamma$ vertex;**
- jet and missing E_T from calorimetry;
  - **energy and missing transverse energy measurement ($H \to b\bar{b}$, $A \to \tau\tau$, $H \to ZZ \to ll\nu\bar{\nu}$,...);**
- efficient and accurate tracking at nominal luminosity for:
  - **precise track momentum measurement (all channels);**
  - **b-quark tagging ($H \to b\bar{b}$, $H \to ZZ^* \to 4l$,...);**
  - **vertexing;**
  - **enhanced electron identification;**
- stand-alone, accurate muon momentum measurement; robust and flexible level-1 muon trigger (many channels of direct and associated production rely on high p_T muon tags);

physics environment

- **small bunch crossing period: T=25ns** $\rightarrow$ fast, finely segmented detectors; fast FE electronics.

- **High radiation level;** sources of radiation at LHC: particle showers induced by particle production at the interaction point interacting with the machine elements and the detector. Local beam losses and beam-gas interactions.

$\rightarrow$ need of a performant shielding system.

Two important consequences:

a. radiation damage of the detectors and of the FE electronics $\rightarrow$ Detectors and Electronics radiation hard;

b. high occupancy of the tracking systems $\rightarrow$ fast, finely segmented tracking detectors;

Detectors at LHC

Two complementary experimental approaches to exploit the LHC p-p physics potential:

ATLAS (A Toroidal LHC Apparatus)

- Central Tracker: High-granularity radiation-hard semiconductor detectors at small radii complemented by highly redundant system of small-diameter drift tubes at large radii(*)
  $\rightarrow$ *Pixel detectors + Silicon strip detectors + Straw Tubes (the "TRT detector");*
- EM Calorimeter: fast, radiation-hard system
  $\rightarrow$ *Liquid Argon with an "Accordion" geometry;*
- HAD Calorimeter $\rightarrow$ Iron + scintillating tiles;
- Muon System: Standalone spectrometer with high precision momentum measurement down to $|\eta| = 2.7$ $\rightarrow$ *large air toroid spectrometer instrumented with pressurized drif tubes; independent Level-1 Muon Trigger system based on RPCs and coincidence logic;*
- Magnets: a central solendoid (B=2T) + 3 external air core toroids (B ~ 0.5 – 1.0 T);

(*) with transition radiation detector function

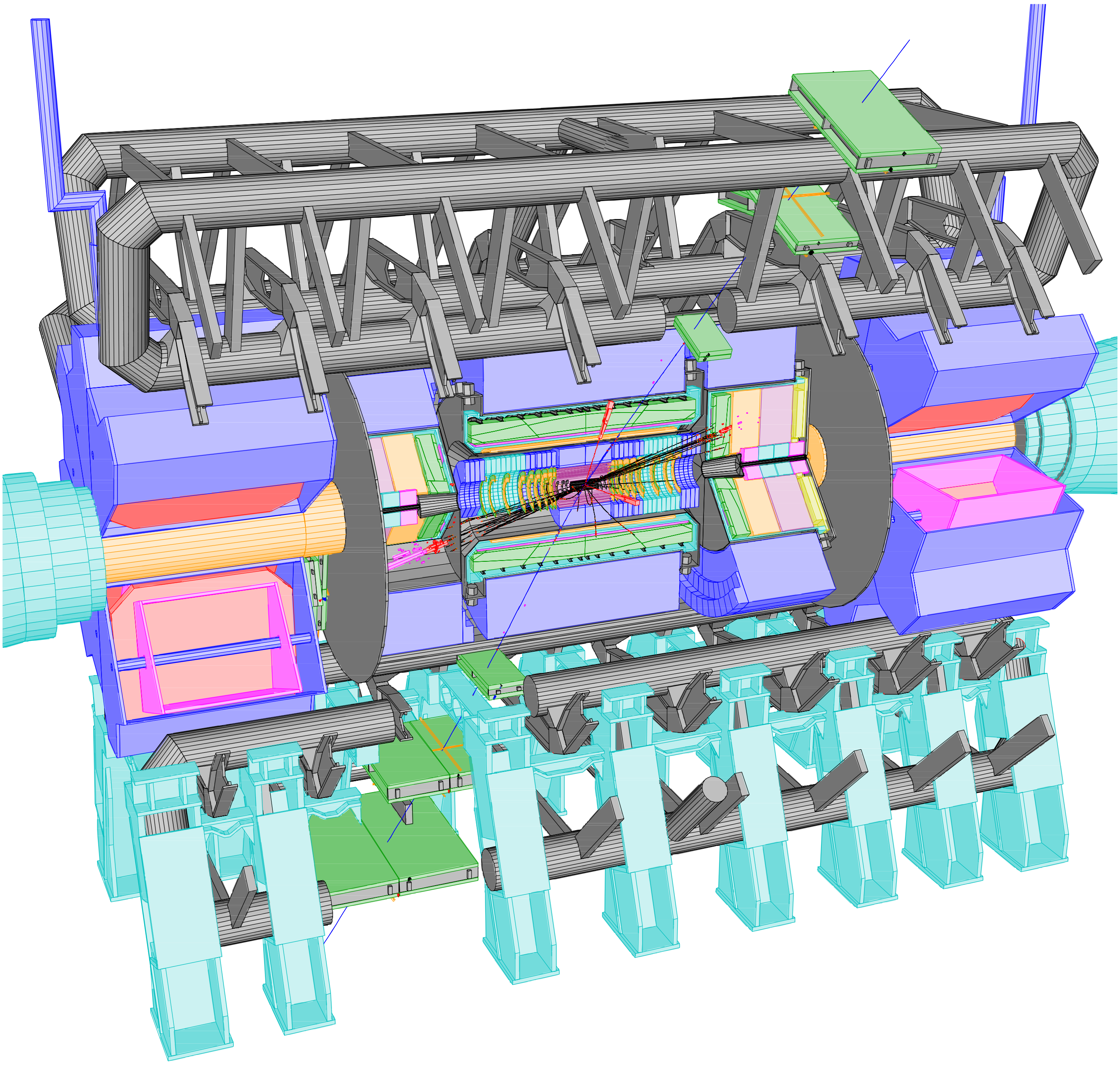
Detectors at LHC -2-

CMS (Compact Muon Solenoid)

The driving idea: a compact, simple apparatus based on a strong central solenoid (the only magnet of the spectrometer) surrounded by a high density calorimeter and an instrumented return yoke for muon detection.

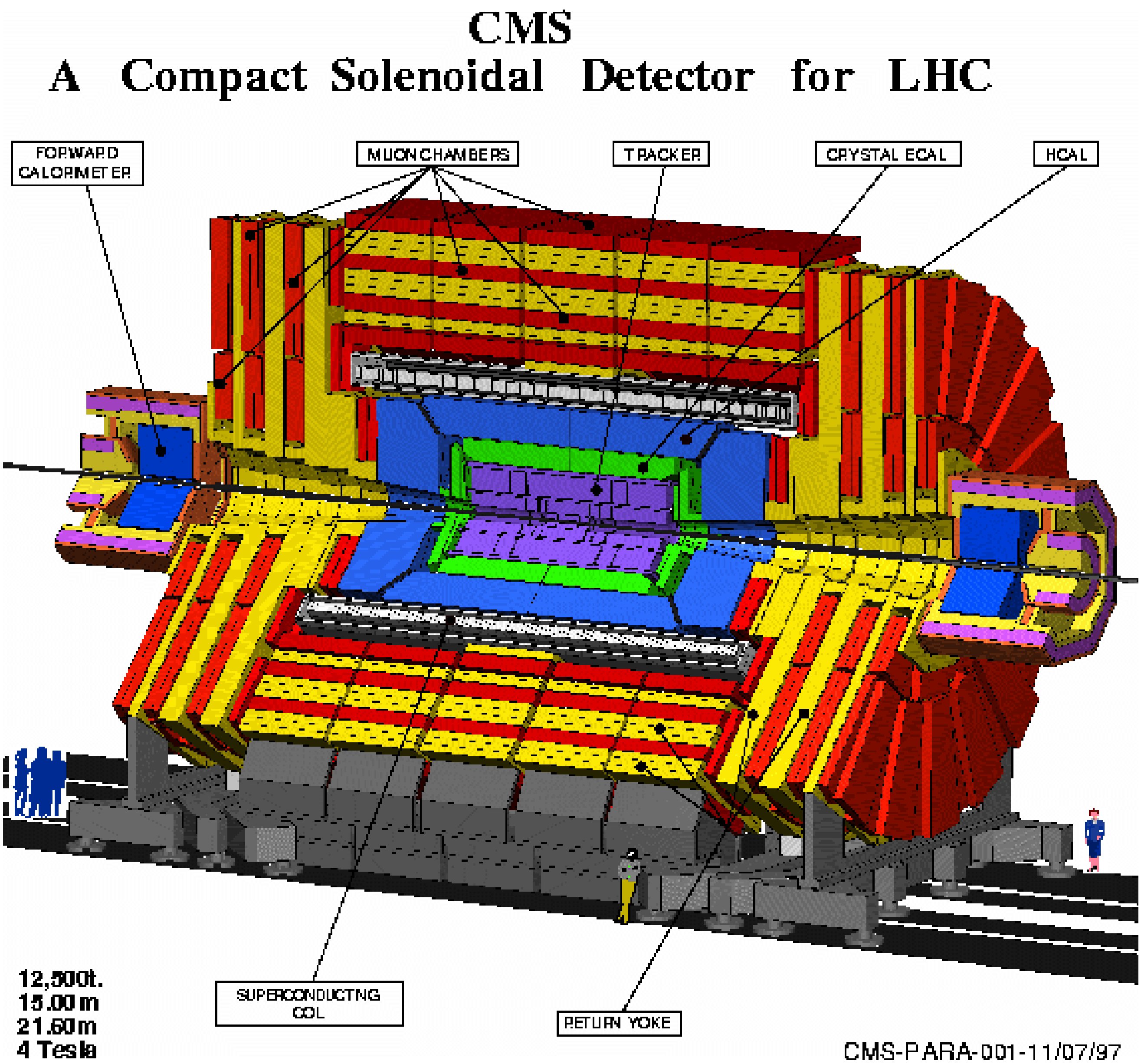
- Central Tracker: $\rightarrow$ *Silicon Strip detector*;
- EM Calorimeter: $\rightarrow$ *rad-hard Crystals (Lead Tungestanate, $PbWO_4$)*;
- HAD Calorimeter: $\rightarrow$ *Copper + Scintillating Tiles*;
- Muon System: $\rightarrow$ *an iron spectrometer based on the central solenoid return yoke instrumented with drift tubes (barrel) and Cathode Strip Chambers (endcap)*;
- Magnet: one large central solendoid (B=4T);

the ATLAS detector



artistic view of the Atlas apparatus

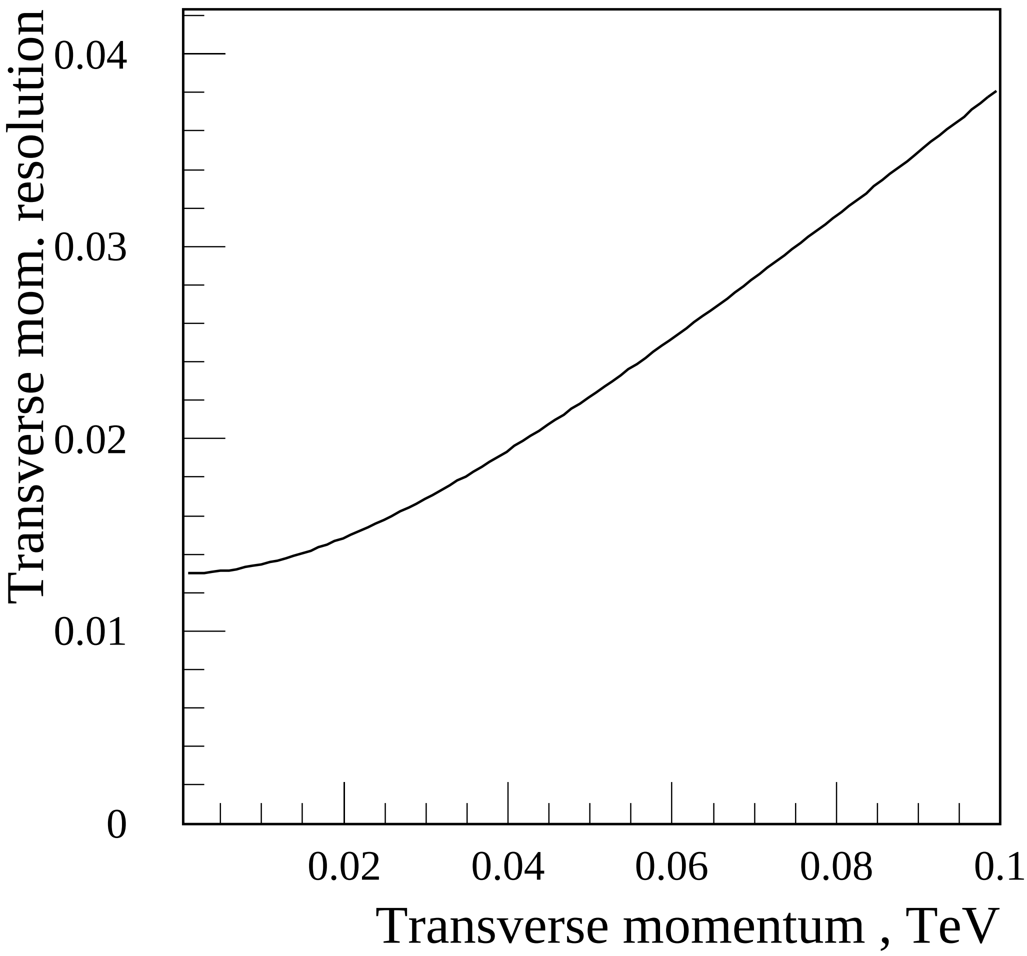
the CMS detector



the ATLAS detector physics performance: the Inner Detector

Transverse momentum resolution (muons):

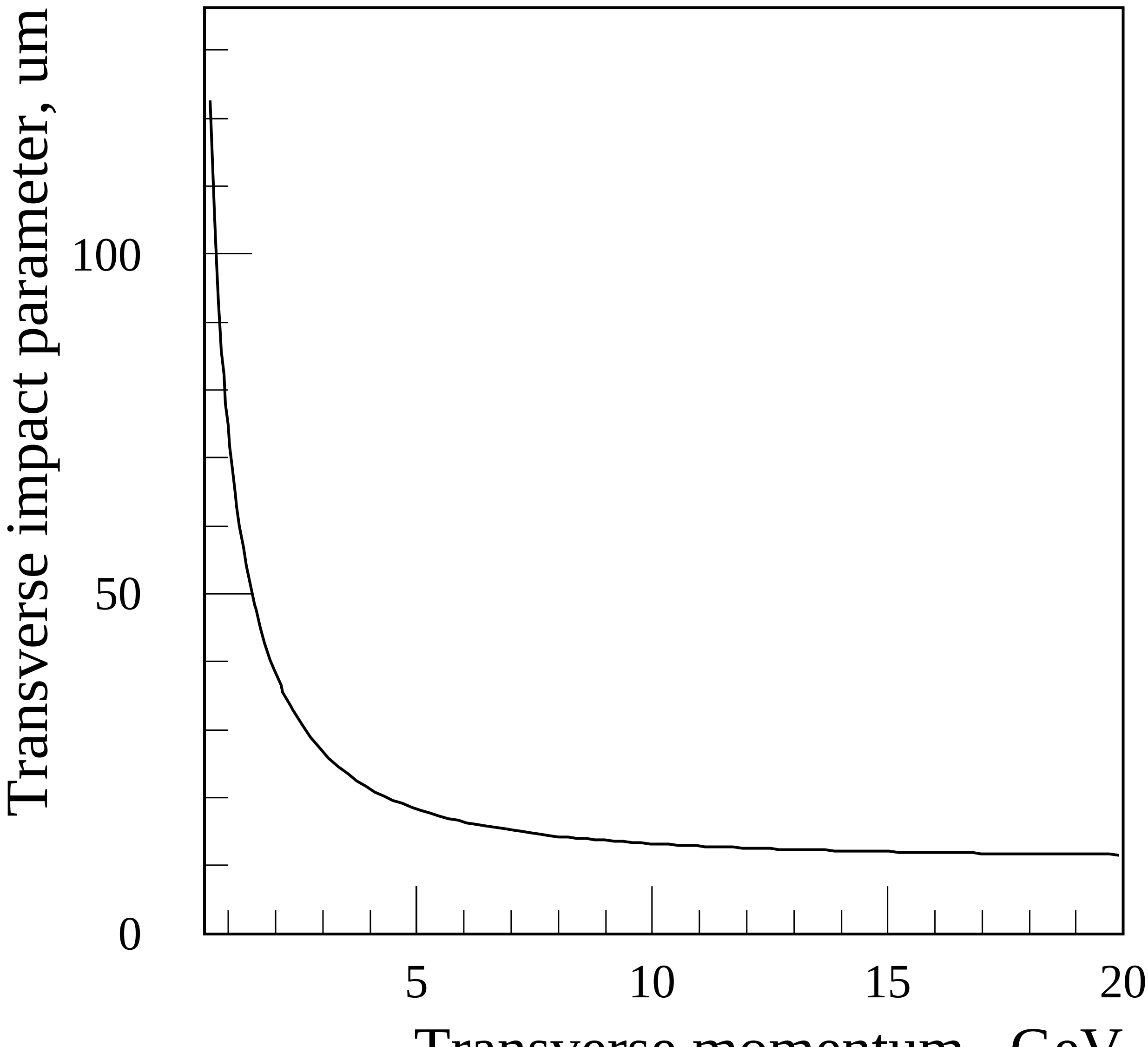
$$\frac{\sigma(p_T)}{p_T} \approx \frac{0.013}{\sqrt{\sin\vartheta}} \oplus 0.36 \bullet p_T \qquad (p_T \mathrm{in TeV})$$



the ATLAS detector...-2-

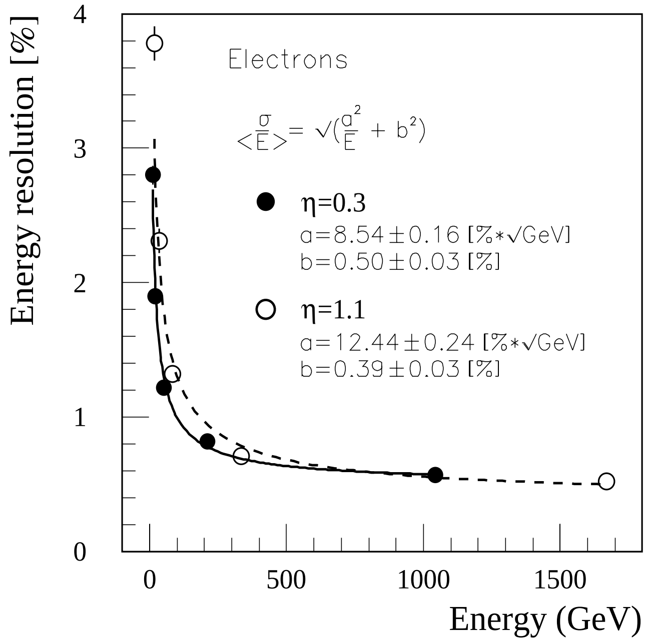
transverse impact parameter accuracy:

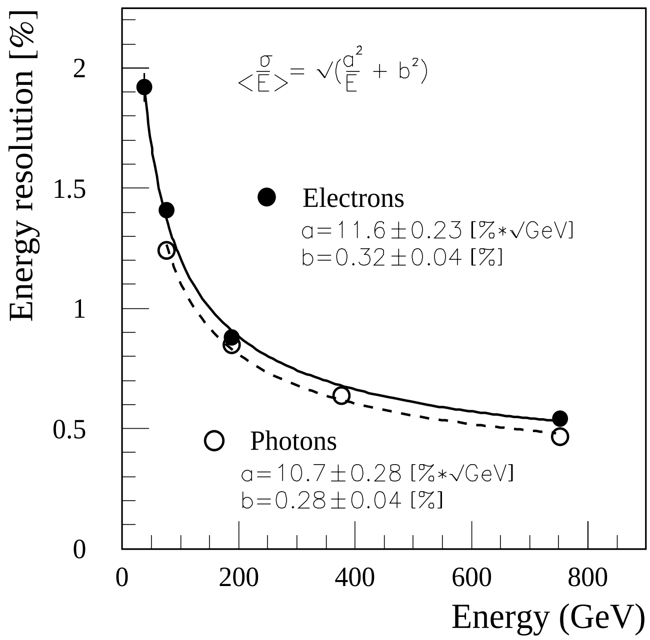
$$\sigma(d_0) \approx 11 \oplus \frac{73}{p_T\sqrt{\sin\vartheta}} \qquad (\mu m)$$



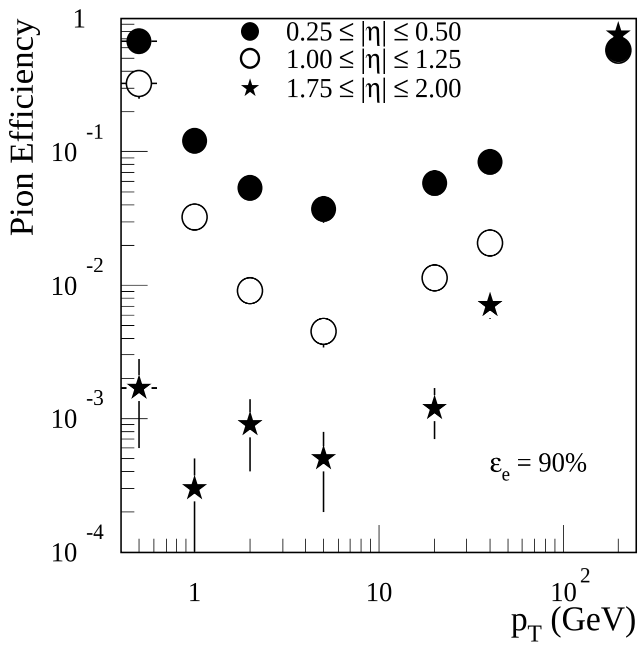
electron reconstruction

EM calorimeter granularity: three samplings: 1) $\Delta\eta$ x $\Delta\phi$=0.003x0.1 2) 0.025x0.025 3) 0.05x0.025.





top plots: EM Calorimeter energy resolution for electrons and photons at |η|=0.3, 1.1 (left) and |η|=2.0 (right), as a function of the incident energy

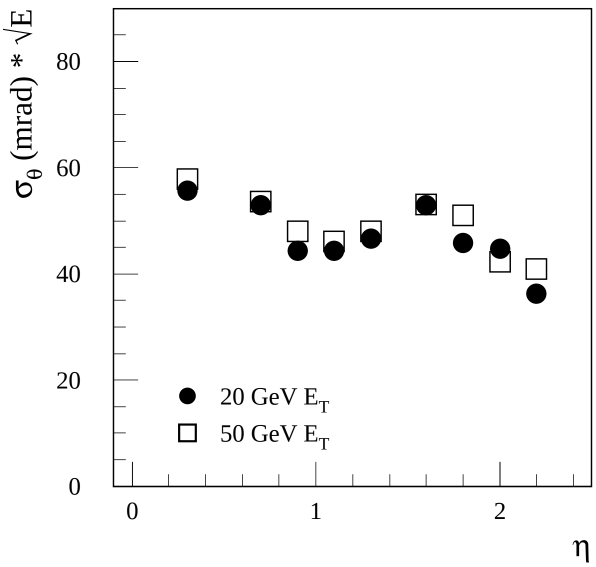


right plot: TRT performance: pion efficiency as a function of p_T in various pseudorapidity intervals for 90% electron identification efficiency.

photon reconstruction

photon energy resolution: see electron energy resolution;

photon direction measurement crucial for $H \rightarrow \gamma\gamma$ reconstruction



$$m^2 = 2E_1E_2(1 - \cos\theta)$$

approximated formula for $E\gamma \approx 80$ GeV and $\theta \approx \pi/2$:

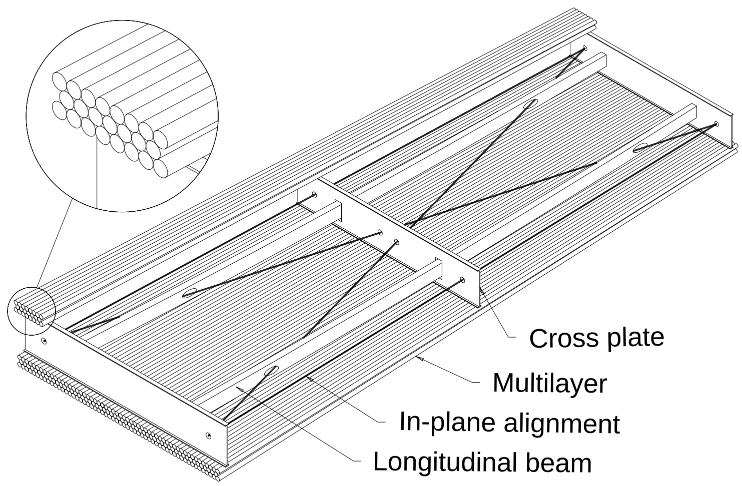
$$\frac{(\Delta m)}{m} \cong \frac{1}{\sqrt{2}} \bullet \left(\frac{\Delta E}{E} \oplus \Delta\theta\right) \cong \frac{1}{\sqrt{2}} \bullet \left(\frac{0.1}{\sqrt{E}} \oplus \frac{0.05}{\sqrt{E}}\right)$$

the Muon System

muon identification:

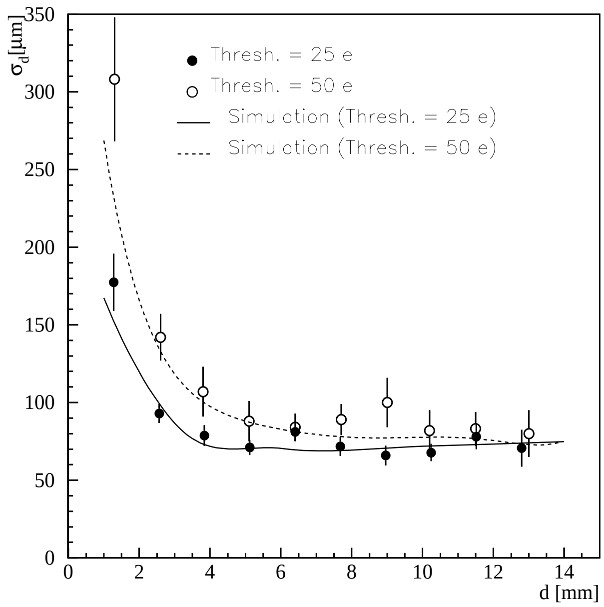
in ATLAS the muon can be identified and measured:

- **by the external muon system**
- **by the combined central tracker and calorimeter systems (m.i.p. signatures for isolated muons).**

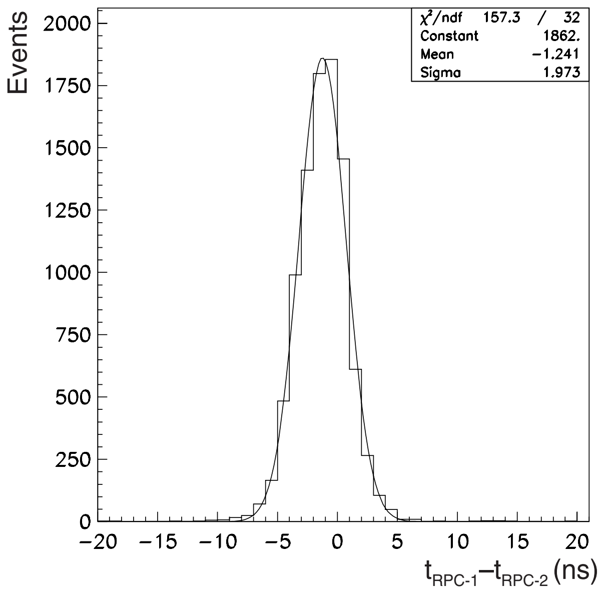


The Monitored Drift Tube chamber instruments the high precision ATLAS muon spectrometer.

The single tube single-hit space resolution as a function of the drift distance, as measured in test-beam experiments; a typical space resolution of about 80 μm is achieved.

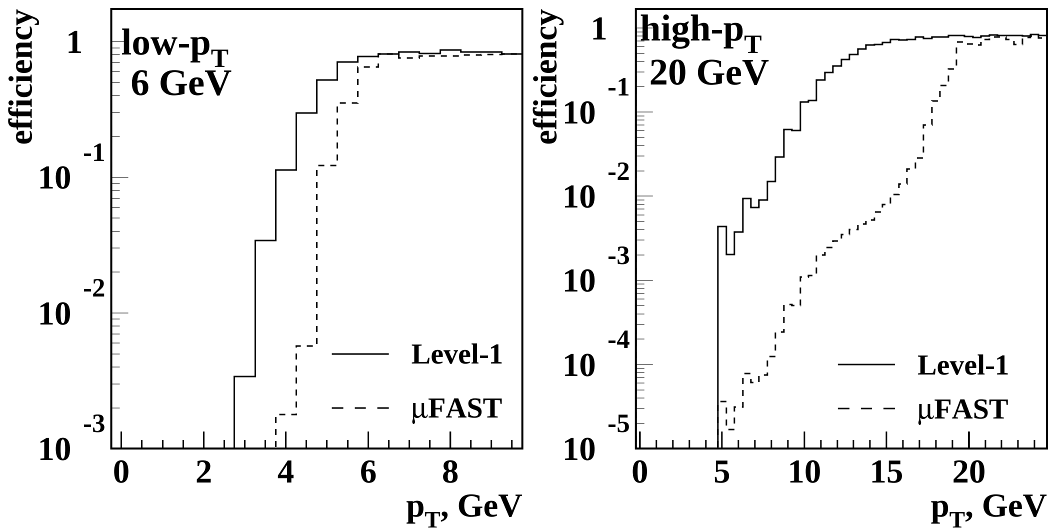


the muon trigger



Distinct feature of ATLAS: Level-1 Muon Trigger based on a *dedicated fast system*.

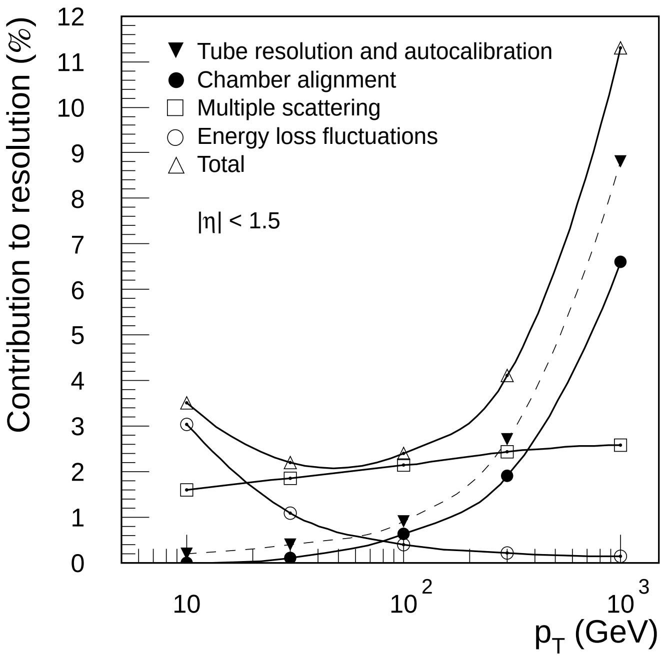
Instrumentation: Resistive Plate Chambers (RPC) in the barrel region and Thin Gap Chambers (TGC) in the endcap region.

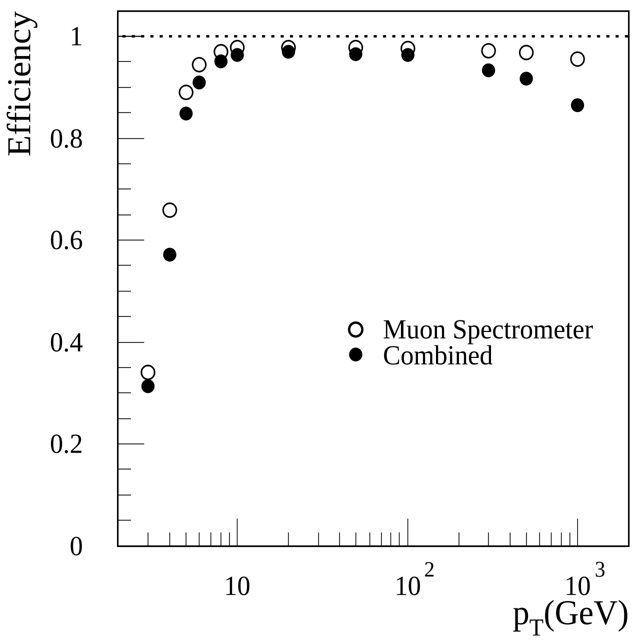


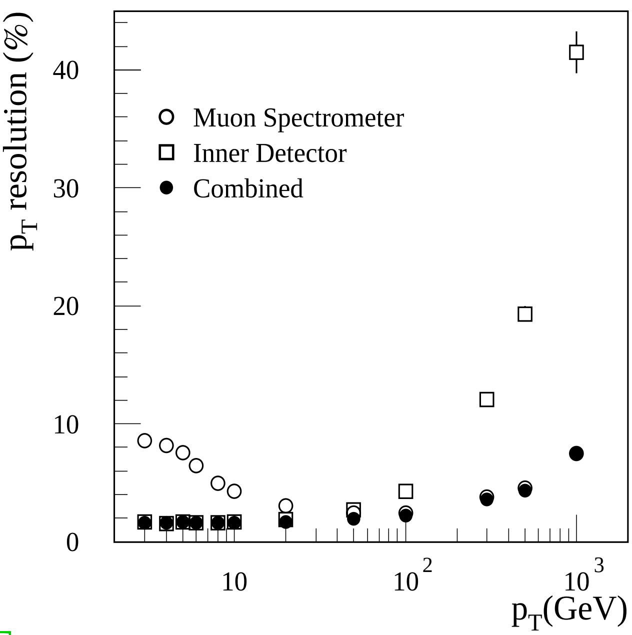
Selection efficiencies for prompt muons at Level-1 and Level-2 (μFAST). The Level-2 efficiency accounts for the efficiency from Level-1.

muon reconstruction

Standalone muon momentum resolution; the main contributions to the measurement accuracy are shown individually as well as the global performance.







E

reconstruction fficiency (left) and p_T resolution (right) of track reconstruction in Muon system, in Inner Detector and of combined tracks, as a function of p_T.

tau reconstruction

the tau identification is based on the low particle multiplicity produced in the decay and on the small size of the jet radius:

1. R_{em}: the jet radius

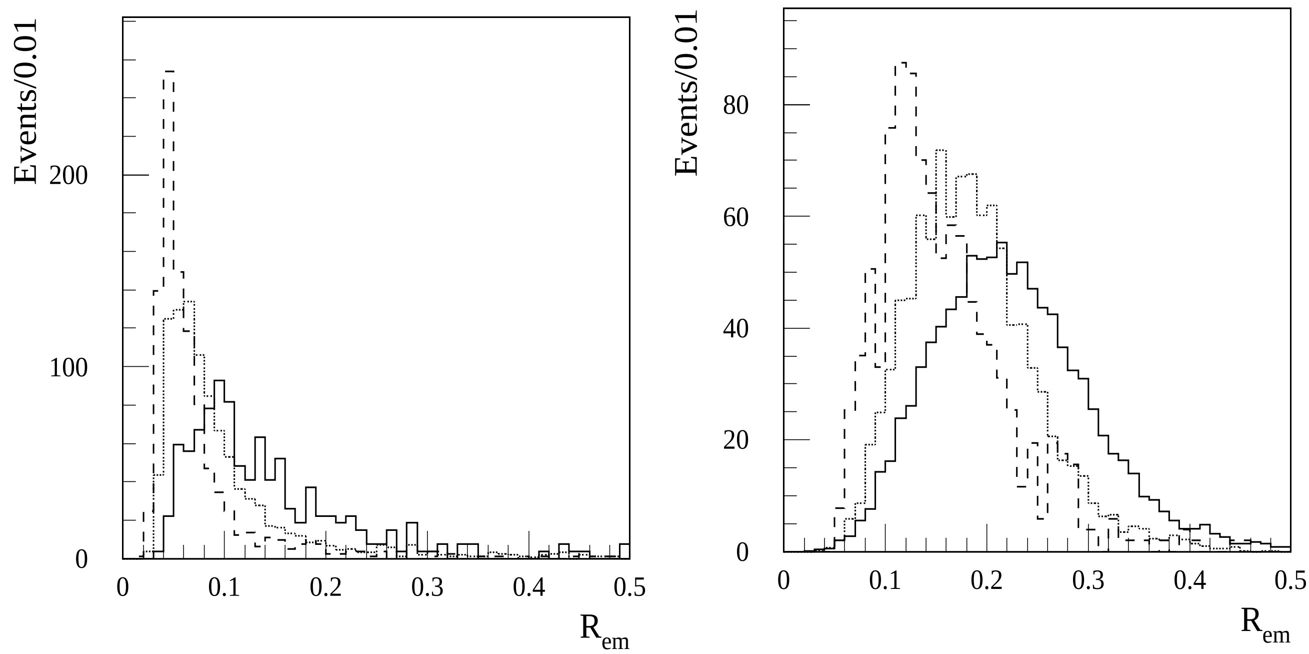
$$\mathrm{Rem} = \frac{\sum_{i=1}^{n} E_{t_i}\sqrt{(\eta_i - \eta_{clus})^2 + (\varphi_i - \varphi_{clus})^2}}{\sum_{i=1}^{n} E_{t_i}}$$

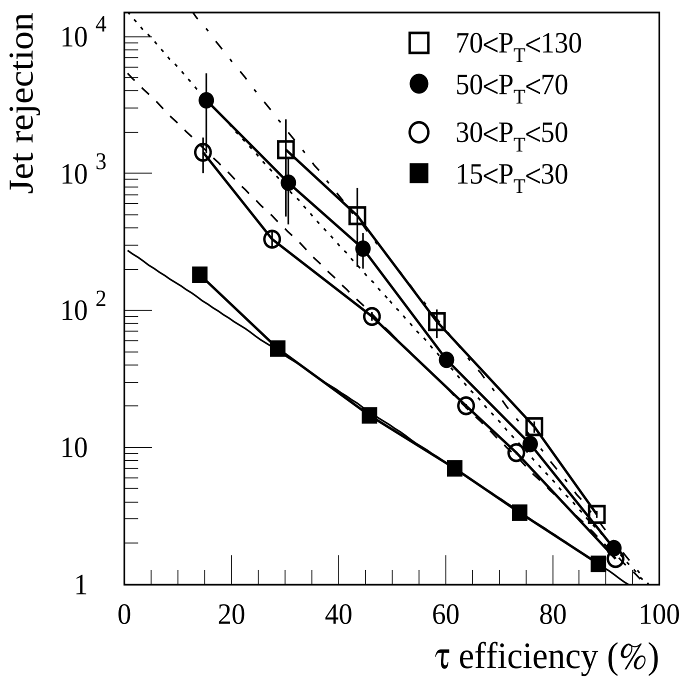
2. ΔE_T^{12}: the fraction of transverse energy in the EM and HAD calorimeters present in a region $0.1 < \Delta R < 0.2$ around the centre-of-gravity of the cluster;

3. N_{tr}: the number of high-p_T tracks pointing to the calorimeter cluster within $\Delta R=0.3$.

tau reconstruction -2-

Rem distribution for τ-jets (left) with different p_T (15-30; 30-70; 70-130 GeV) and for QCD jets (right).





Jet rejection as a function of the τ efficiency, as obtained over the region |η|<2.5 and in various p_T ranges. Straight-line fits are superimposed.

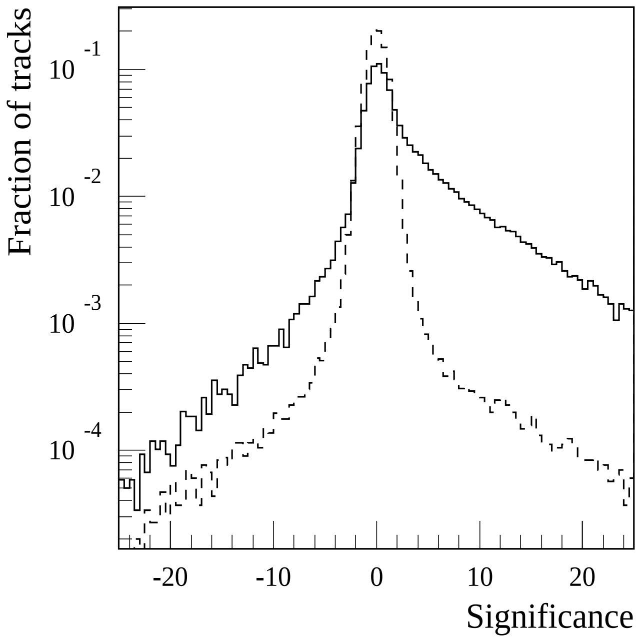
b-jet tagging

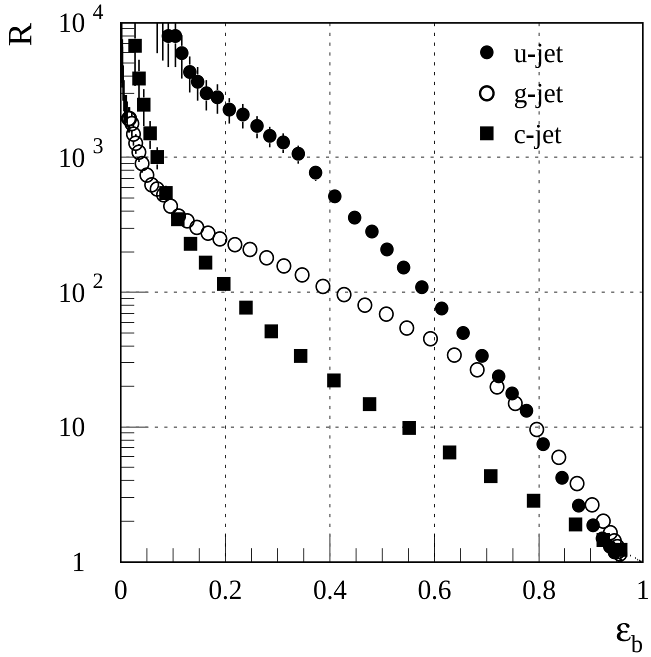
The flavour tagging of b-jets is important because allows the reconstruction of signal events such as $H \to b\bar{b}$ and the rejection of background events such as $Zb\bar{b} \to 4l$.

strategy:

1. look for tracks with significant impact parameter to the pp vertex;

2. look for (soft) electrons and muons.





Left: Signed impact parameter, normalized to its error, for b-jets (solid) and u-jets(dashed).

Right: Background rejection as a function of b-jet efficiency.

H $\rightarrow \gamma\gamma$

- rare decay mode; appropriate for $m_Z < m_H < 150$ GeV;

- physics background:
  - irreducible:
    - Born qq$\rightarrow$ $\gamma\gamma$
    - box gg $\rightarrow \gamma\gamma$
    - quark bremsstrahlung
  - reducible:
    - pp $\rightarrow$ jet-jet and pp $\rightarrow$ γ-jet in which one or both jets are misidentifed as photons;
    - Z $\rightarrow$ ee decays where both electrons are mistaken as photons;

- $\rightarrow$ severe requirements on EM calorimeter: excellent energy and angular resolutions needed;

However, at present $m_H > 107$ GeV from LEP2

Higgs search at Large Hadron Collider

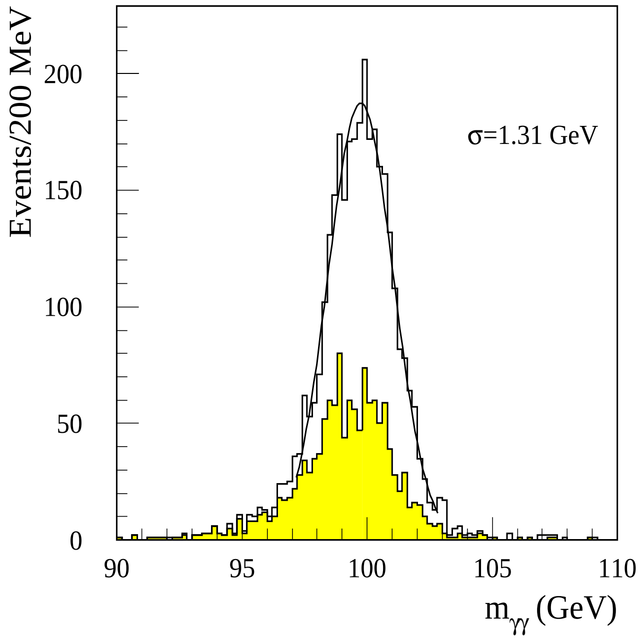
$H \rightarrow \gamma\gamma$ (2)

- Irreducible background - σ=1 pb/GeV for m_H=100 GeV;
- Reducible background - jet-jet $\sigma = 2 \times 10^6$ pb/GeV; full dector simulation of large jet-jet event samples showed that this background can be reduced to ~ 2/5 of the irreducible one (ATLAS).
- Observability of the $H \rightarrow \gamma\gamma$ signal (direct and associated production) for 120 < m_H < 140 GeV. The expected number of events in the mass window, chosen to be $m_H \pm 1.4\sigma$, are given for L=100 fb^{-1}. The signal significances are given for L=100 fb^{-1} (at nominal lumin.) and L=30 fb^{-1} (at low lumin.).

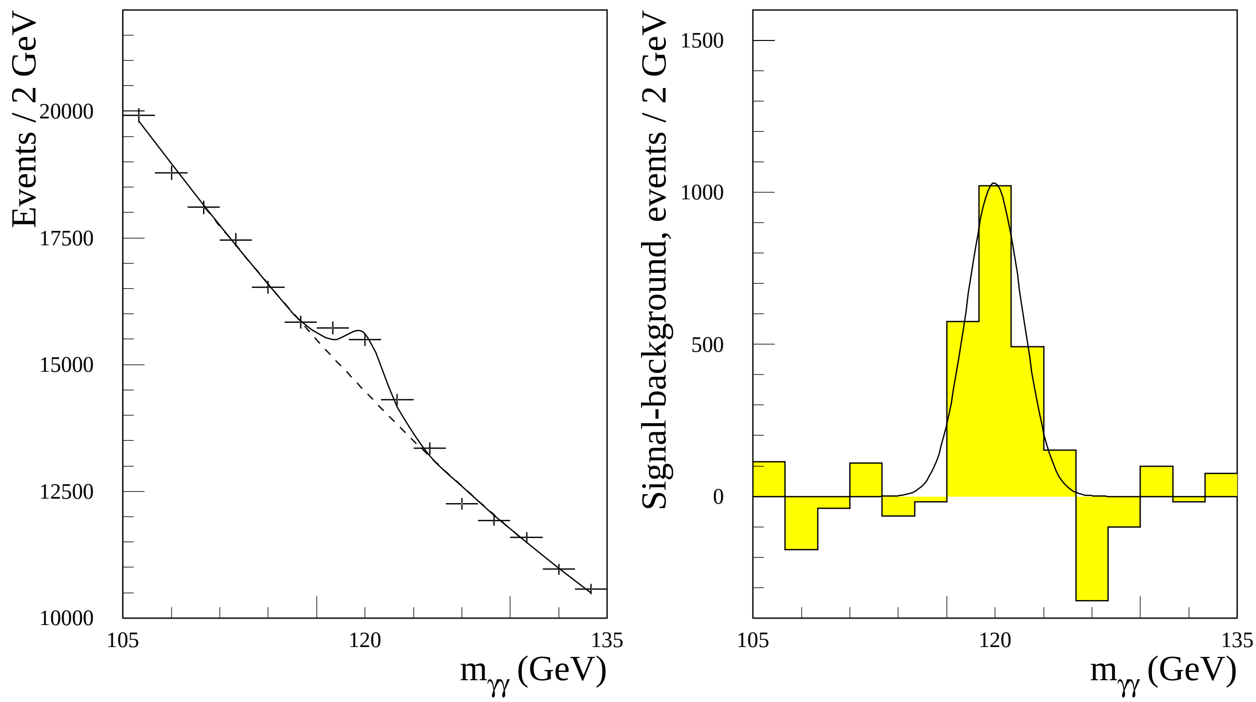
m_H, GeV	120	130	140
signal, direct	1190	1110	915
signal (WH, ZH, $t\bar{t}H$)	93	76	58
$\gamma\gamma$ back.	29000	24700	20600
jet-jet back.	4600	4100	3550
γ-jet back.	5800	4900	4100
$Z \rightarrow e^+e^-$	-	-	-
Stat. sign. for 100 fb^{-1}	6.5	6.5	5.8
Stat. sign. for 30 fb^{-1}	3.9	4.0	3.5

Higgs search at Large Hadron Collider

$H \rightarrow \gamma\gamma$ (3)



Reconstructed two-photon invariant mass for $H \rightarrow \gamma\gamma$ decays with m_H=100 GeV at high luminosity. The shaded histogram represents events containing at least one converted photon.



Expected $H \rightarrow \gamma\gamma$ signal for m_H = 120 GeV and for L=100 fb^{-1} on top of the irreducible background (left) and after background subtraction (right).

Higgs search at Large Hadron Collider

$H \rightarrow b\bar{b}$

If $m_H < 2m_W$ --> $H \rightarrow b\bar{b}$ dominat decay mode (B.R. ~ 90%).

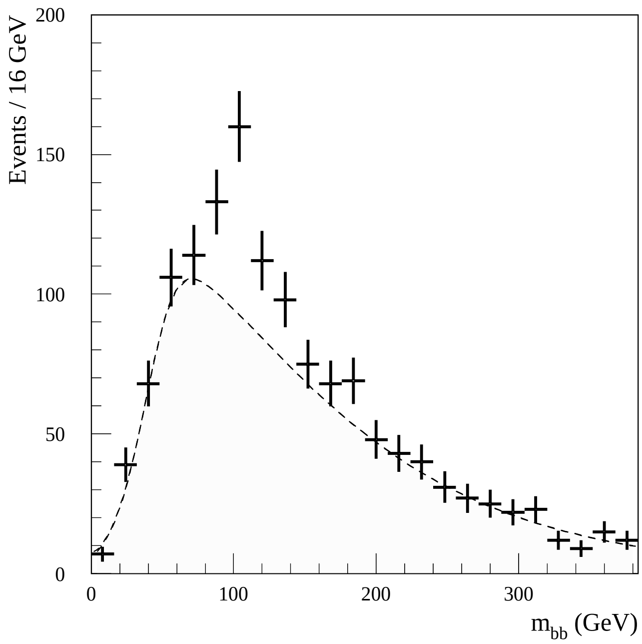
Direct production: QCD two-jet background too large: search not possible.

The search in the associated channels (W,Z,$t\bar{t}$) is possible, but rather difficult.

Main physics background, for example, to the ttH channel:

- **ttjj**
- **ttZ**
- **W+jets**

Invariant mass distribution of tagged b-jet pairs in fully reconstructed $t\bar{t}H$ events (m_H=100 GeV) above the background, for L = 100 pb^{-1}. The points with the error bars represent the result of a single experiment and the dashed line shows the background distribution.



The extraction of a Higgs signal from the ttH process, with $H \rightarrow b\bar{b}$, appears feasable as long as the two top decays are fully reconstructed with high efficiency:
$\rightarrow$ excellent b-tagging capability is demanded.

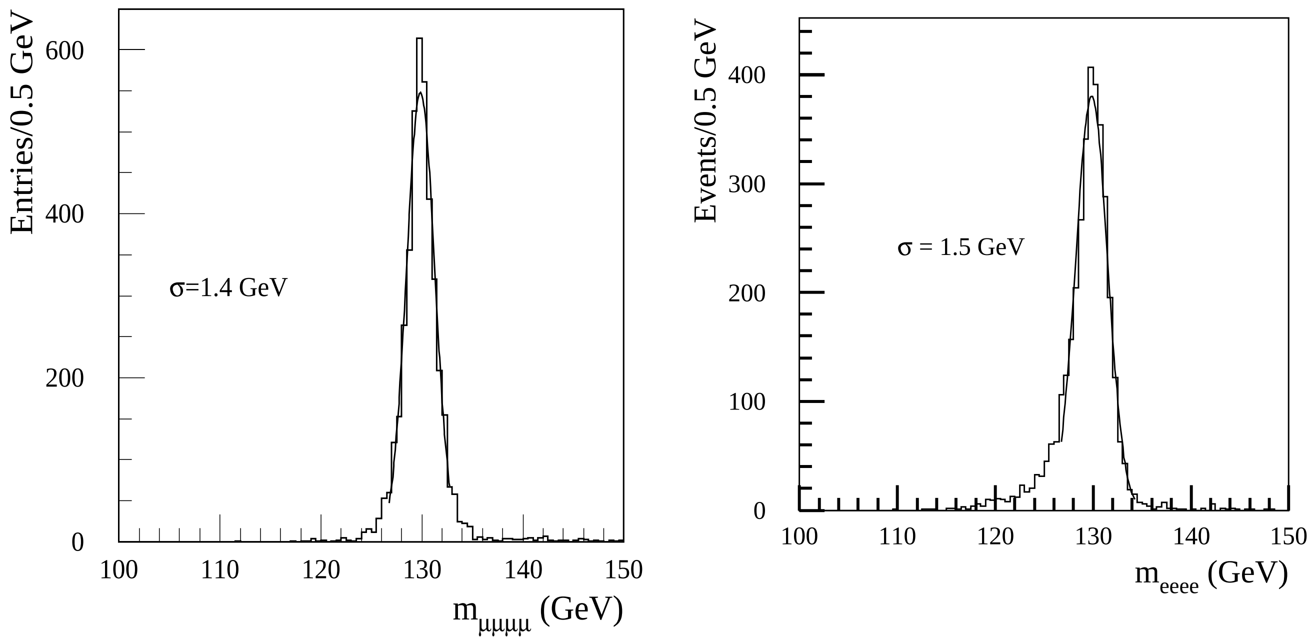
$H \rightarrow ZZ^{*} \rightarrow 4l$

- The best channel to search for the SM Higgs in the mass range ~130 < m_H < $2m_Z$;
- The B.R. is larger than B.R. ($H \rightarrow \gamma\gamma$) and increases with m_H up to $2m_W$;
- Background:
  - Irreducible -
    - $pp \rightarrow ZZ^*$; $pp \rightarrow Z\gamma^*$;
  - Reducible -
    - $pp \rightarrow tt$; $Zb\bar{b}$

- **Trigger:** two leptons with p_T>20 GeV and $|\eta|$<2.5;

- **Offline selection:**
  - two additional leptons with $\mathbf{p_T>7}$ GeV and $|\eta|$**<2.5**;
  - invariant mass of one pair of leptons (appropriate charge and flavour) compatible with the Z mass; invariant mass of the other pair larger than 15 GeV.

$H \to ZZ^* \to 4l$ (2)



Higgs mass reconstruction at low luminosity of $H \to \mu^+\mu^-\mu^+\mu^-$(left plot) and $H \to e^+e^-e^+e^-$ decays (right plot); m_H=130 GeV.

Signal and background rates after all selection cuts and signal significances as a function of m_H. L=100 fb^{-1}.

m_H, GeV	**120**	**130**	**150**	**170**	**180**
Signal	10.3	28.7	67.6	19.1	49.7
tt	0.05	0.10	0.13	0.12	0.12
Zbb	0.53	0.79	1.14	1.01	1.02
ZZ*	3.53	6.36	7.03	7.54	7.61
ZZ>ττll	0.33	0.51	0.62	0.20	0.06
Signifi-cance	3.8	10.3	22.6	5.3	16.7

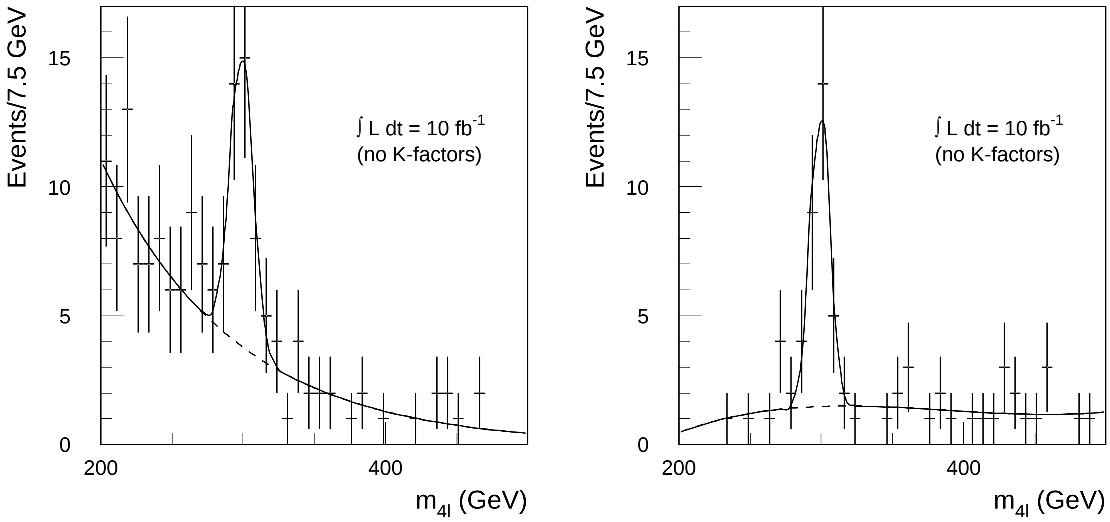
$H \rightarrow ZZ \rightarrow 4l$

- The best channel to search for the SM Higgs in the mass range $2m_Z < m_H < 700$ GeV ("Gold Plated Channel"): **Easy detection/discovery up to ~ m_H = 700 GeV**
- Background:
  - Irreducible -
    - $pp \rightarrow ZZ$; $pp \rightarrow Z\gamma^*$;
  - Reducible -
    - $t\bar{t}$, ...

- **Trigger:** two leptons with p_T>20 GeV and $|\eta|<2.5$;
- **Offline selection:**
- two additional leptons with **p_T>7** GeV and $|\eta|<$**2.5**;
- invariant mass of both pair of leptons (appropriate charge and flavour) compatible with the Z mass;

Higgs search at Large Hadron Collider

$H \rightarrow ZZ \rightarrow 4l$



Expected $H \rightarrow ZZ \rightarrow ll$ signal for m_H = 300 GeV and for an integrated luminosity of 10 fb^{-1}. The signal is shown on top of the ZZ continuum before (left) and after (right) the $p_T max(Z_1,Z_2)$ cut is applied.

Higgs discovery can be made with 10 fb^{-1}, equivalent to 1 year data taking at low luminosity.

$H \to WW \to l\nu jj$

For Higgs masses of the order of 1 TeV the signal rate of the channel $H \to ZZ \to 4l$ is too small;

the Higgs decay in the channel $H \to WW \to l\nu jj$ increases the rate by a factor ~ 150 and makes possible the Higgs observation; additional channel is $H \to ZZ \to lljj$.

production mechanism: WW/ZZ fusion:
$qq \to qqH \to qqW^+W^- \to qq + l\nu jj$

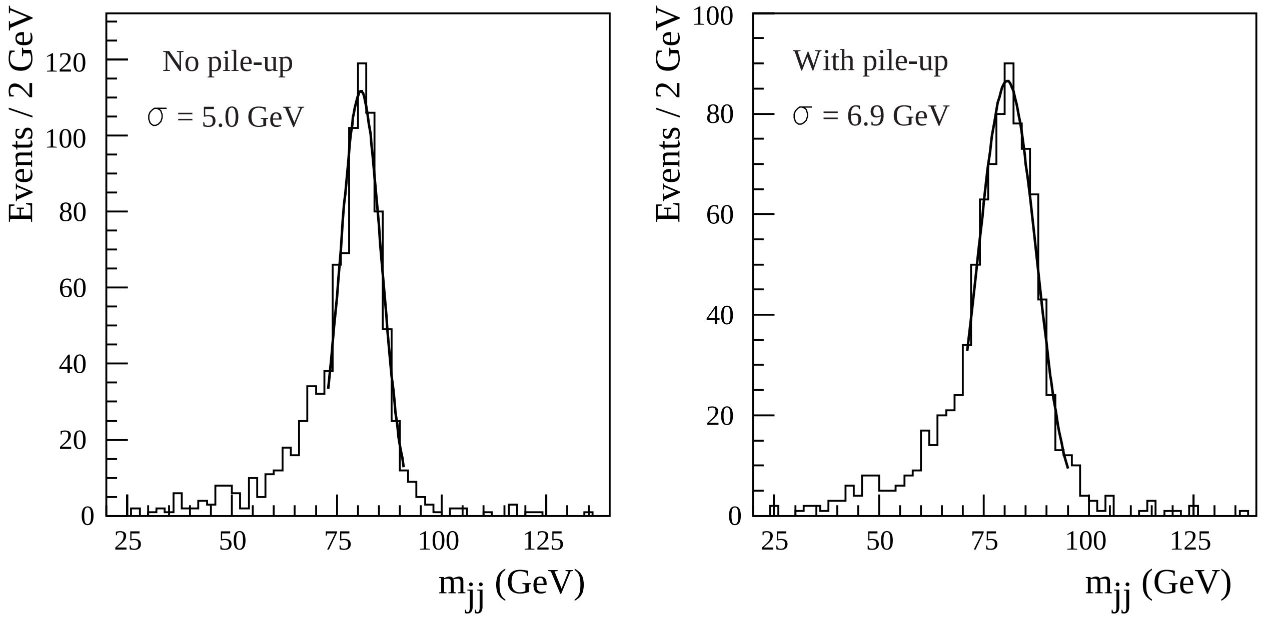
background:

- **$pp \to W$ + jets $\to l\nu$ + jets; potentially is the largest source; suffers from theoretical uncertainties (higher-order corrections);**
- **$pp \to t\bar{t} \to l\nu jjb\bar{b}$;**
- **$pp \to WW \to l\nu jj$ (continuum); low rate but irreducible background.**

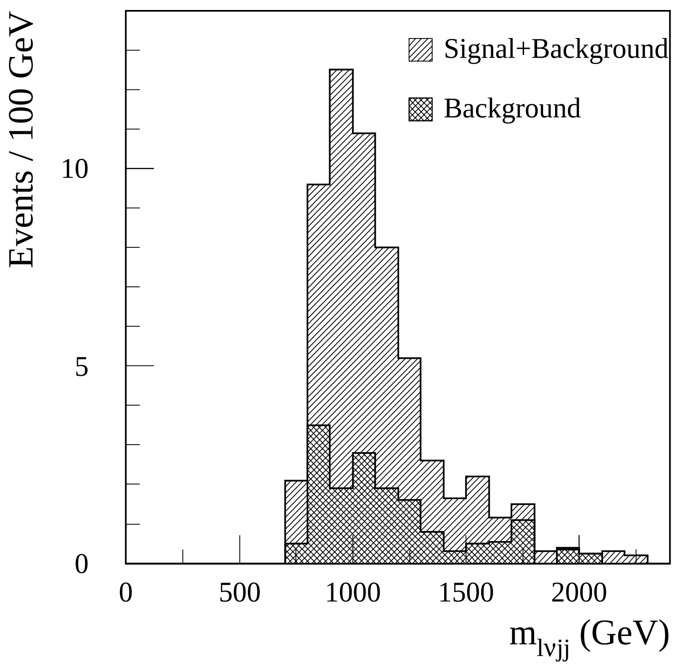
Signal reconstruction:

- **a high-p_T central lepton ($|\eta|<2$);**
- **large missing transverse energy from escaping neutrino;**
- **two central high-p_T jets from the second W decay in hadrons;**
- **two low-p_T tag jets in the forward region;**
- **low hadronic activity in the central region except $W \to jj$.**

$H \rightarrow WW \rightarrow l\nu jj$ -2-

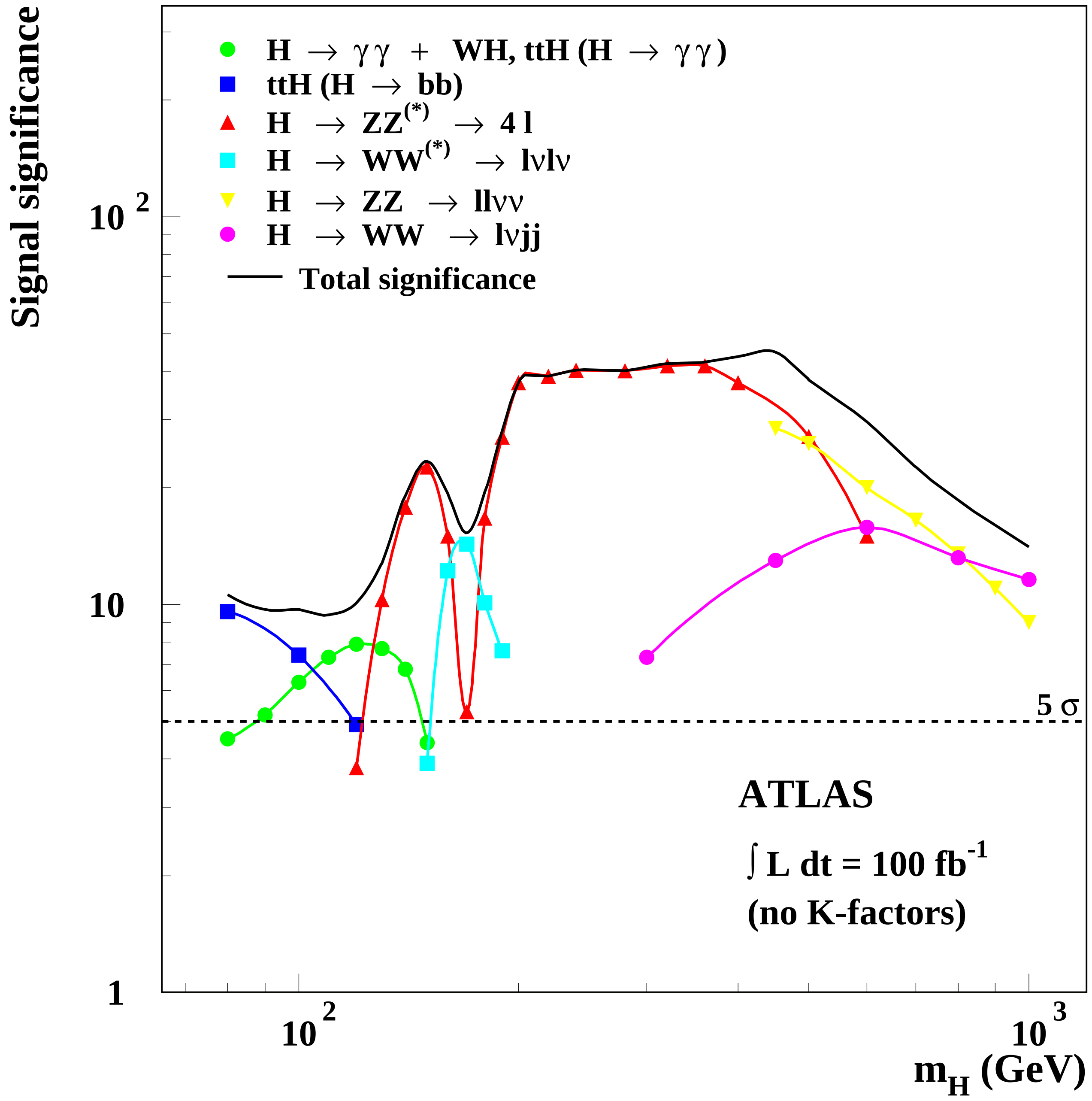


$H \rightarrow WW \rightarrow l\nu jj$ with m_H=1 TeV; distributions of the jet-jet invariant mass (the hadronic W) for low (nominal) luminosity operation shown in the left (right) plot.



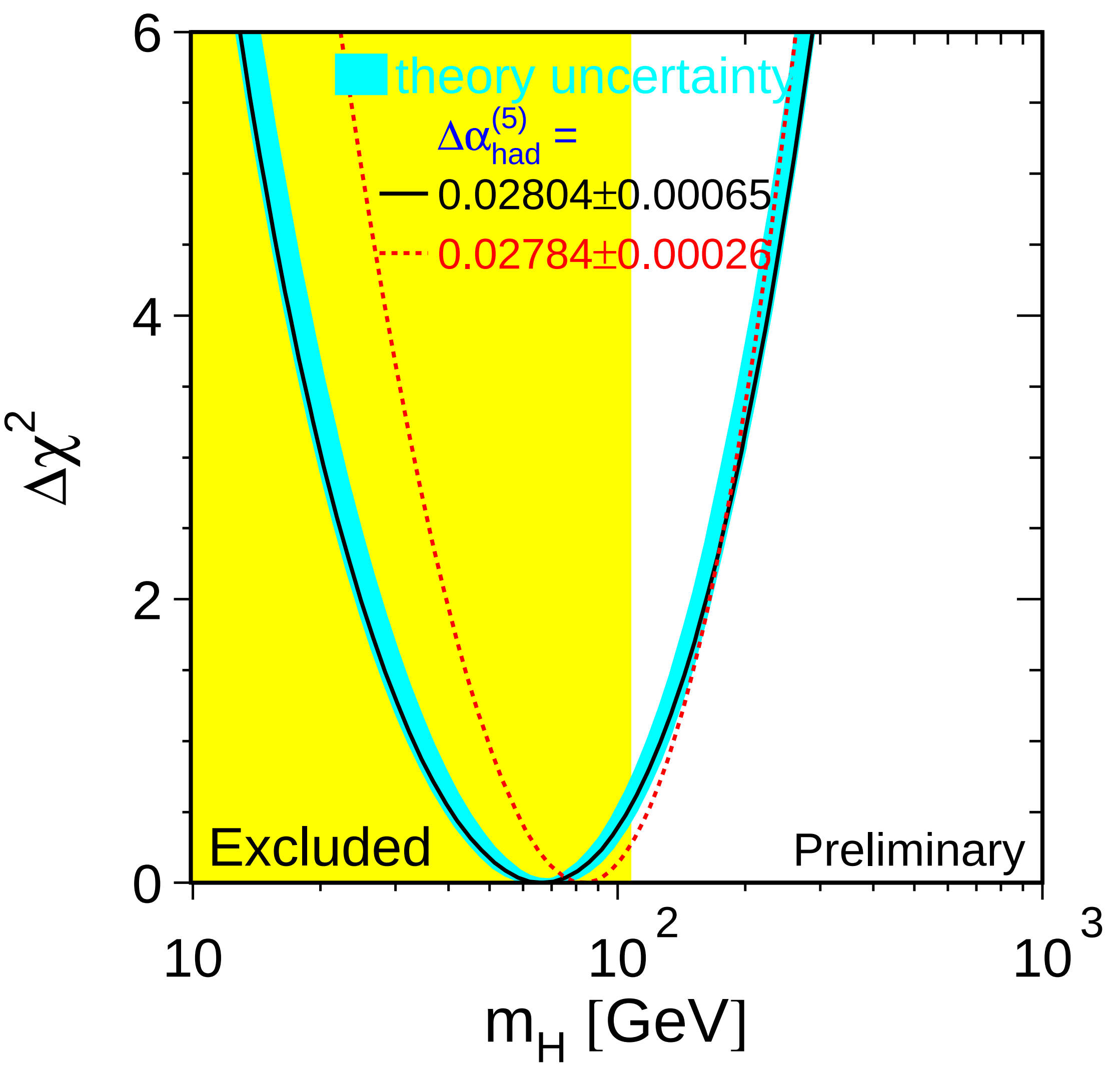
events $H \rightarrow WW \rightarrow l\nu jj$ with m_H=1 TeV; distribution of the invariant mass of the system $l\nu jj$ for the background and the and the summed background + signal.

overall sensitivity to the SM Higgs searches



ATLAS sensitivity for the discovery of a Standard Model Higgs boson. The statistical signficances are plotted for individual channels as well as for the combination of all the channel assuming integrated luminosity L=100 fb^{-1}.

LEP and SM limits (preliminary)



Expected ultimate LEP limit on the Higgs mass:

$m_H > 115$ GeV

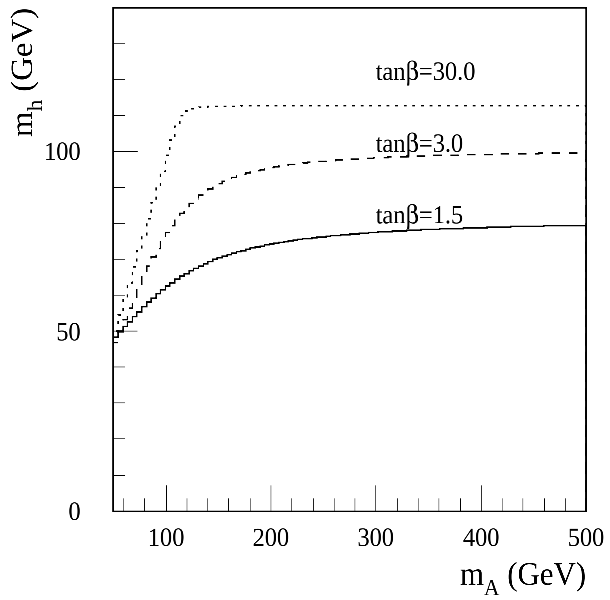
Minimal Supersymmetric Standard Model Higgs

Complex investigation: two charged ($H^{\pm}$) and three neutral (h, H, A) physical states. At tree level all Higgs-boson masses and couplings can be expressed in terms of two parameters only; usually: m_A and $\tan\beta$.

Two different scenarios:

- if Susy particle masses are large, Higgs-boson decays kinematically allowed only in SM particles:
  - $h \rightarrow \gamma\gamma$; $h \rightarrow bb$; $H \rightarrow ZZ \rightarrow 4l$;
  - $H/A \rightarrow \tau\tau, \mu\mu$; $A \rightarrow Zh$; $H \rightarrow hh$;
- in case of light Susy particles the SM decay modes can be suppressed in favour of decays to charginos and neutralinos.

the MSSM Higgs



Two loop prediction for m_h as a function of m_A and for $\tan\beta = 1.5$, 3, 30 in the minimal mixing scenarios

channels useful for MSSM Higgs detection:

- $h, H, A \rightarrow \gamma\gamma$
- $t\bar{t}h,\ h \rightarrow b\bar{b}$
- $H \rightarrow ZZ^* \rightarrow 4l$
- $H/A \rightarrow \tau\tau,\quad \mu\mu,\quad t\bar{t}$
- $H/A \rightarrow b\bar{b}$
- $H \rightarrow hh$
- $A \rightarrow Zh$
- $H^\pm \rightarrow cs,\ \ H^\pm \rightarrow \tau\nu.$

H/A$\rightarrow \tau\tau$

In the MSSM H/A$\rightarrow \tau\tau$ rates are strongly enhanced over a large region of the parameter space. For example, at large tanβ values the production is dominated by the associated production of bbH and bbA with B.R.(H/A$\rightarrow \tau\tau$)≈10%.

Standard Model H$\rightarrow \tau\tau$ not expected to be observable at the LHC because unfavourable signal/background.

Background:

- **irreducible pp$\rightarrow$ Z+X $\rightarrow \tau\tau$+...;**
- **QCD processes: $t\bar{t}$, $b\bar{b}$, and W+jets.**

Trigger; based on the leptonic decay of one of the tau leptons: one isolated e/μ with p_T>24 GeV, $|\eta|$<2.5

offline selection:

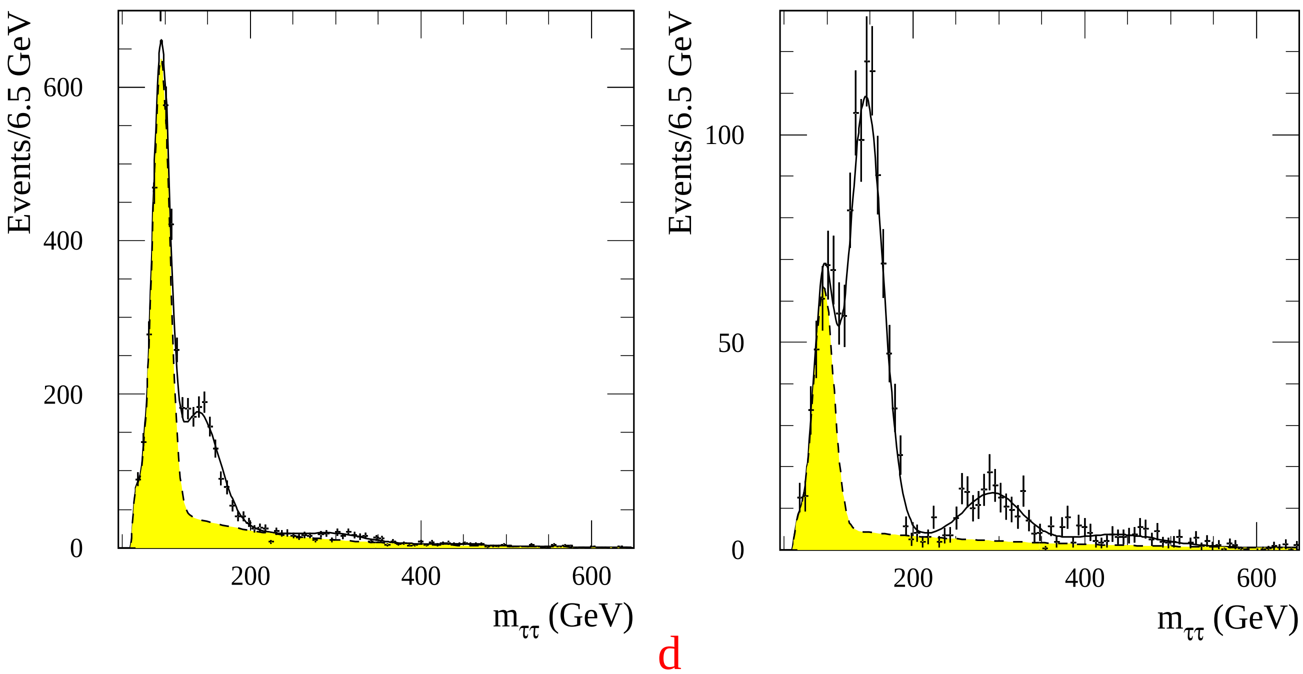
- **focus the analysis on lepton-jet events (rate from lepton-lepton is small)**
- **τ-jet E_T>40 GeV, $|\eta|$<2.5;**
- **E_T^{miss} > 18 GeV;**
- **transverse mass m_T(lepton-E_T^{miss}) < 25 GeV;**
- **1.8 < $\Delta\phi$(τ-jet - lepton) < 4.5 (excluding the region $\pi \pm 0.25$)**

H/A$\rightarrow \tau\tau$ –2–

The mass reconstruction of τ-jet pairs requires the estimate of the tau lepton energy: potential problem because the neutrinos in the event are undetected. This difficulty can be overcome with the measurement of E_T^{miss} and with a few reasonable assumptions:

1. assume that there are only three neutrinos in the event (two with same direction of flight from the leptonic decay and one from the hadronic decay);
2. assume that the direction of the neutrino system in each of the two taus coincides with the detected products;
3. assume that m_τ=0.

The mass resolution that can be achieved is $\Delta m/m \approx 10\%$.



d

direct (left) and associated (right) H+A signal shown on top of the total background (yellow area) for three m_H/A values: 150, 300 and 450 GeV; L=30 fb^{-1}.

$A \rightarrow Zh$

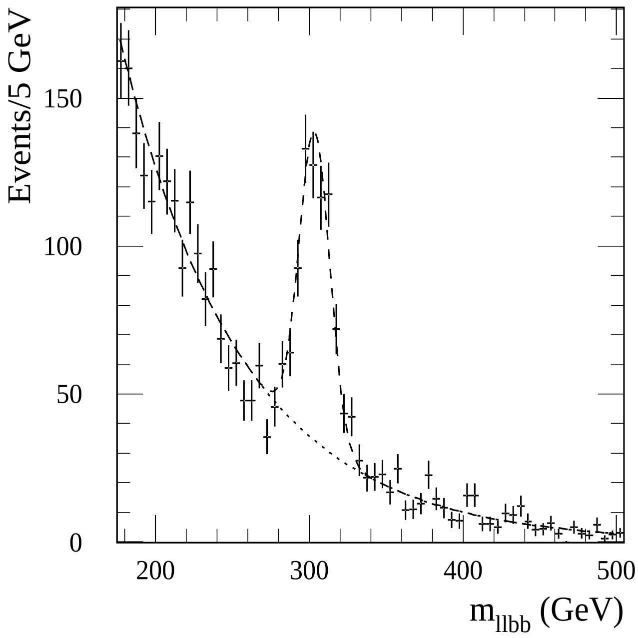
* Particularly interesting because it correspond to the simultaneous observation of two Higgs bosons.

* Dominant A-boson decay mode for low tanβ values and for $m_Z + m_h < m_A < 2m_t$.

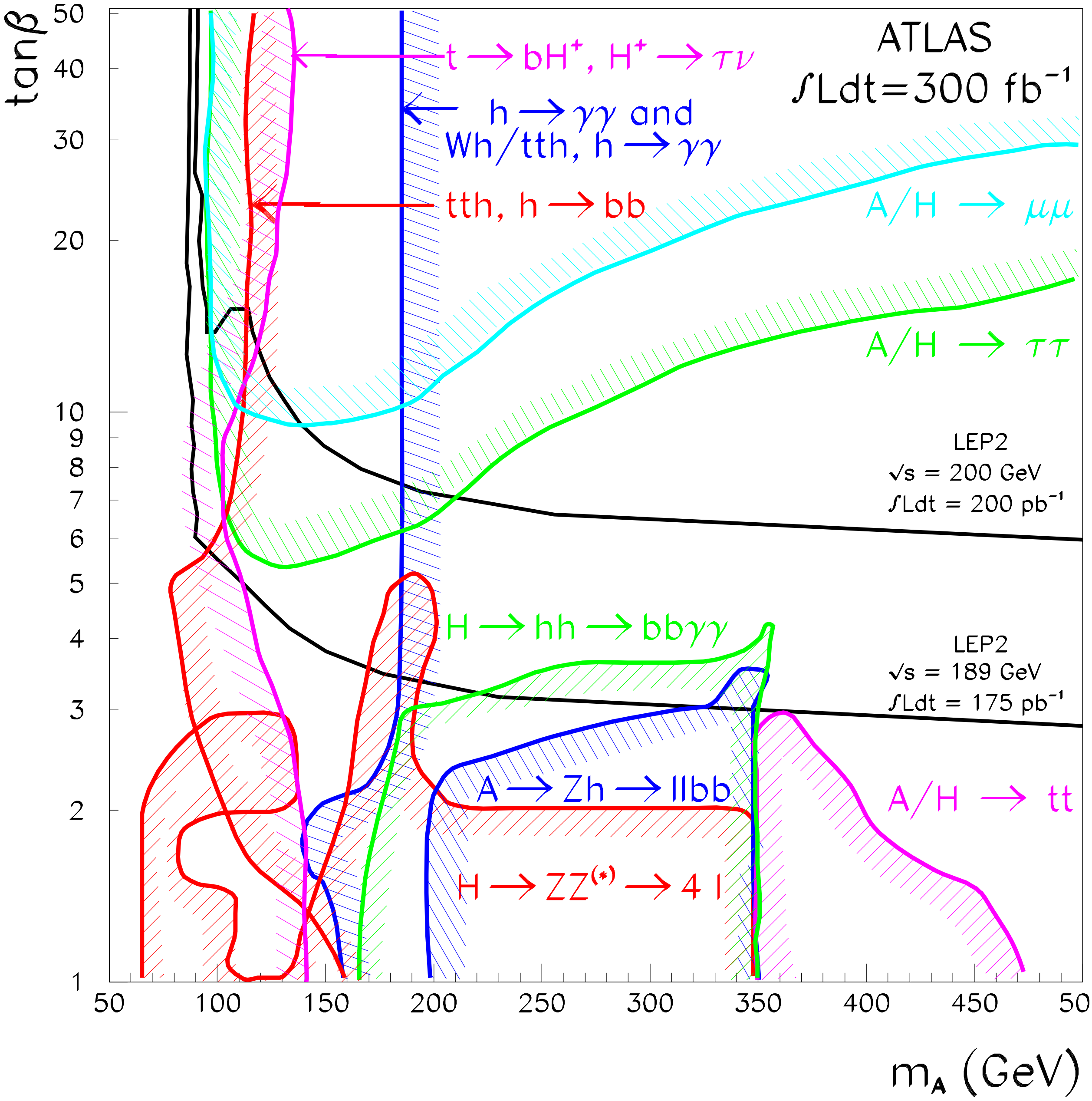
* Possible final states useful for signal detection:

- **$A \rightarrow Zh \rightarrow b\bar{b}b\bar{b}$; offers the largest signal rate but it does require a four-jet trigger with ETthresh. = 40 GeV.**
- **$A \rightarrow Zh \rightarrow llbb$; can be easily triggered; good signal rate.**
- **$A \rightarrow Zh \rightarrow ll\gamma\gamma$; better kinematic constraints in the final state but expected rates too low.**

The expected signal+background distribution for llbb invariant mass for m_A=300 GeV and tanβ=1 (m_h=71 GeV) and for L= 30 fb^{-1}.



overall sensitivity to the MSSM Higgs searches



ATLAS sensitivity for the discovery of a MSSM Higgs boson (in the case of the minimal mixing). The 5σ discovery contours are shown in the (mA, tanβ) plane for individual channels and for an integrated luminosity L=300 fb^{-1}. Also included is the expected ultimate LEP2 limit (for L=200 pb^{-1} per experiment).

Summary

- the LHC machine and the ATLAS and CMS detectors have a large potential in the investigation of one of the key questions of physics: the origin of electroweak symmetry-breaking.

- If a Standard Model Higgs boson exists, discovery over the full mass range, from the LEP2 limit to the TeV mass scale, will be possible after <2 years running at low luminosity.

- In case of the MSSM Higgs bosons the full parameter space in the conventional (m_A, $\tan\beta$) space can be covered with an integrated luminosity of about 100 fb^{-1}.