Searches for the Standard Model Higgs boson in the $H \rightarrow ZZ^* \rightarrow 4l$ decay channel with the ATLAS detector at LHC

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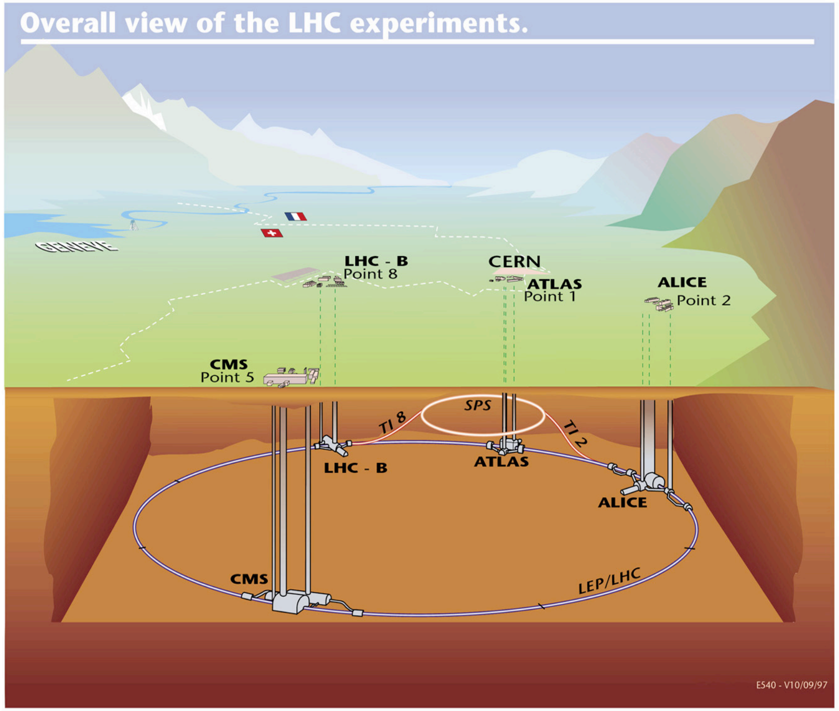
Outline

- The Large Hadron Collider at CERN.
- Standard Model Higgs boson.
- The ATLAS detector at LHC.
- The Monte Carlo data.
- Event trigger.
- Offline reconstruction.
- Event selection.
- Higgs mass reconstruction.
- Conclusion.

Introduction

- The Large Hadron Collider (LHC) is designed to collide the protons with the center-of-mass energy of $\sqrt{S}$=14 TeV.

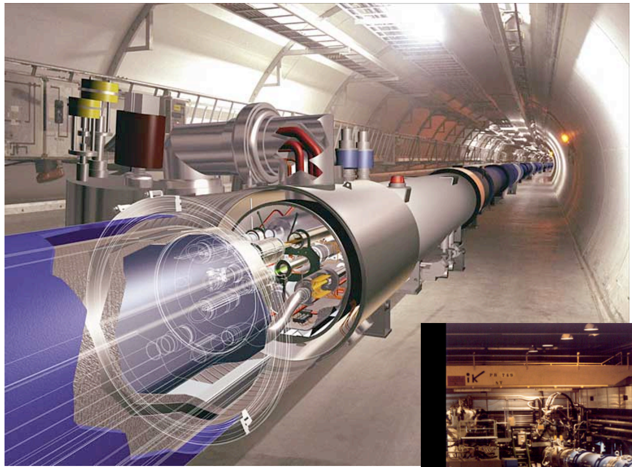


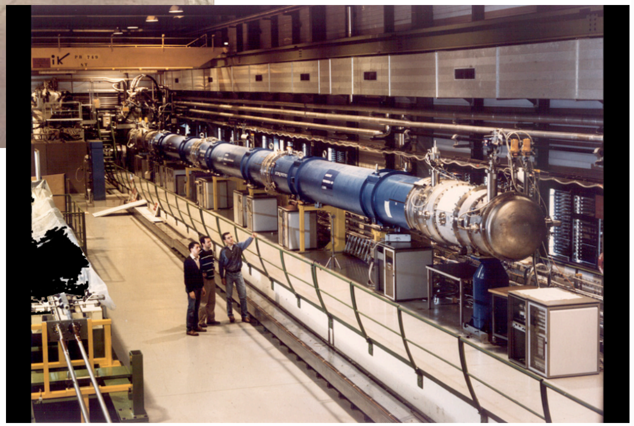
- Design luminosities:
  - Initial phase: $2 \cdot 10^{33}$ $cm^{-2}s^{-1}$ average of 4.6 pp collisions per bunch crossing
  - Nominal luminosity run: 10^{34} $cm^{-2}s^{-1}$ average of 24 collisions per bunch crossing.

- The first collisions at the energy of $\sqrt{S}$=10 TeV and reduced luminosity will take place at the end of summer 2008.

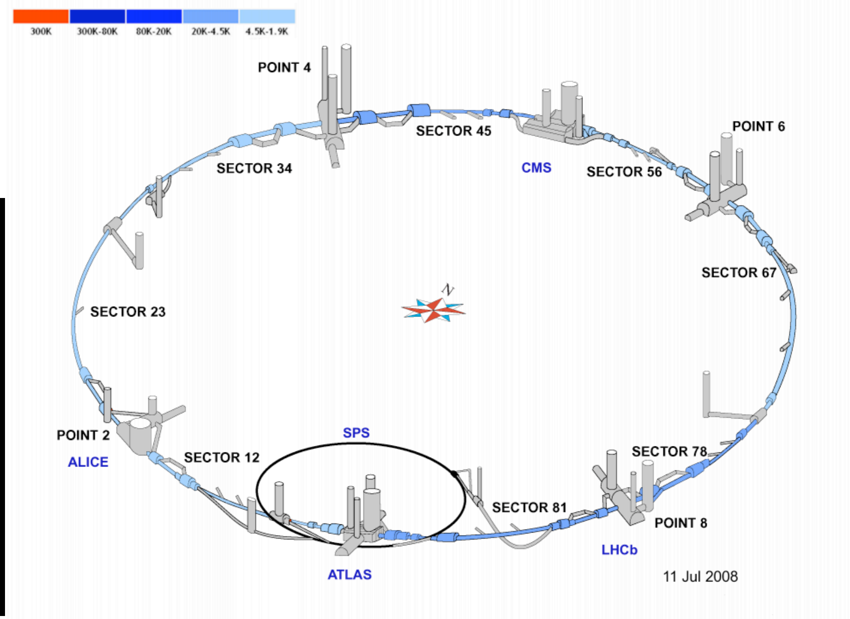
- The $\sqrt{S}$=14 TeV collisions are planned for the spring 2009.

The Large Hadron Collider





The LHC Hardware commissioning and cooling status can be followed on the WEB: *http://hcc.web.cern.ch/hcc/*



Present LHC Schedule
(ATLAS Overview week, BERN July the 7th 2008)

Year	√S (TEV)	Peak Lumi. ($cm^{-2}s^{-1}$)	Integrated (fb^{-1})	Total (fb^{-1})
2009	14	10^{33}	6	6
2010	14	$2x10^{33}$	12	18
2011	14	$5x10^{33}$	30	48
2012	14	10^{34}	60	108

More than 30 fb^{-1}: discovery of SM Higgs in $H \rightarrow ZZ^* \rightarrow 4l$ for most of masses.

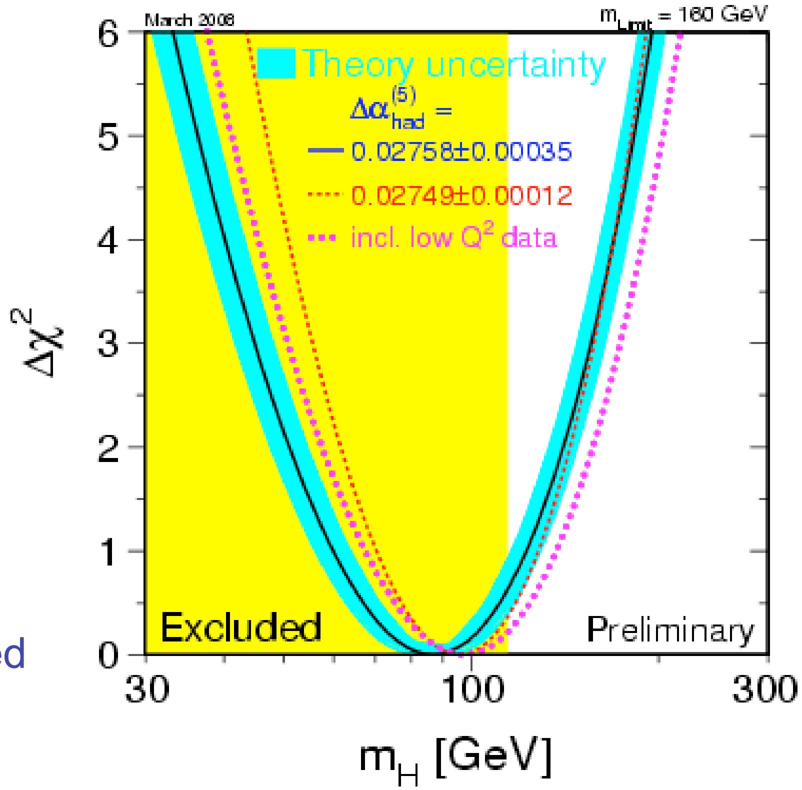
The Standard Model Higgs boson

- A major missing component of the Standard Model.
  - Does the Electroweak Symmetry breaking happens through the Higgs mechanism?
  - Is there some new physics beyond?

- The mass of the Higgs boson is a free parameter of the Standard Model.
  - Limits come however from the direct searches (LEP, CDF, D0) and fits to the electroweak data:

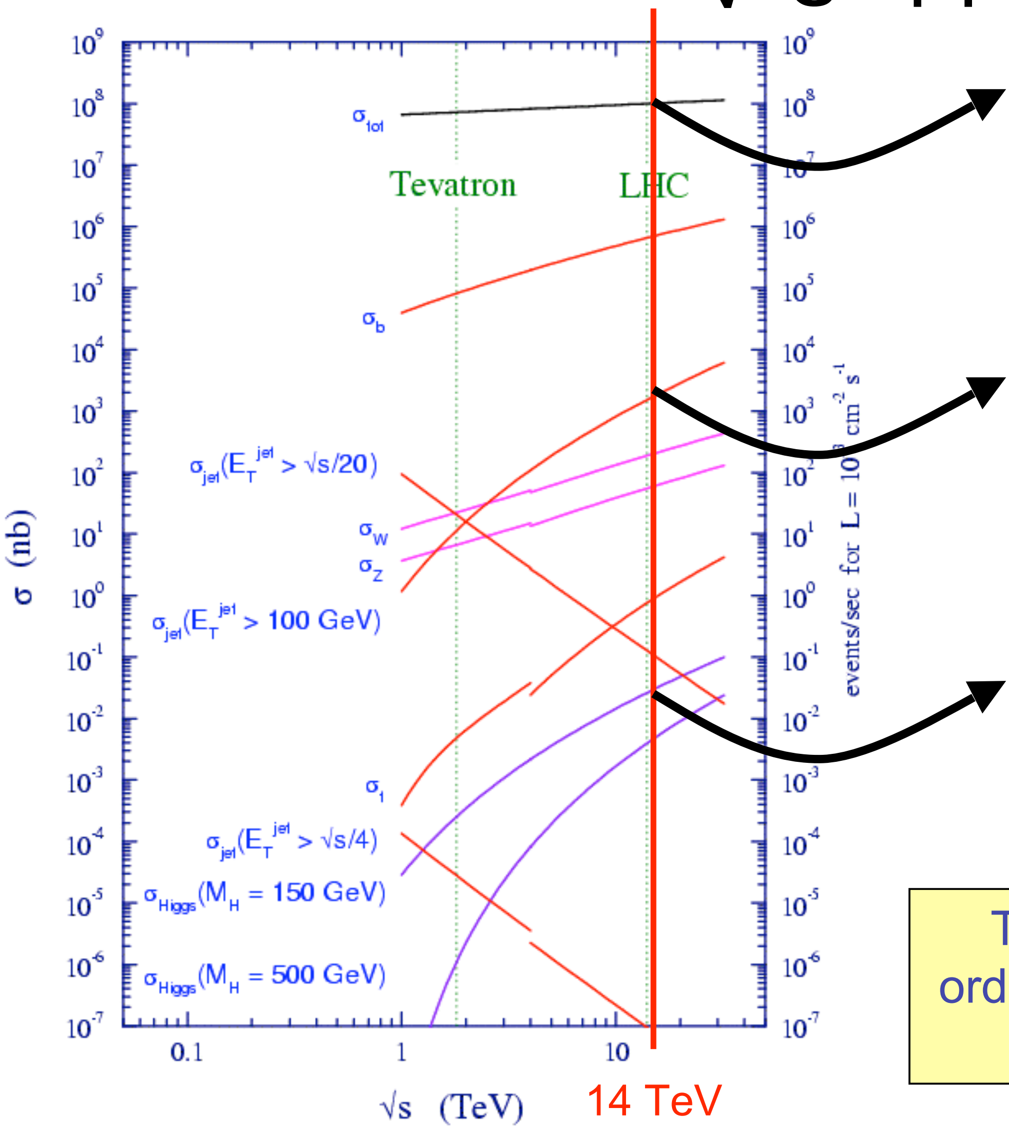
    M_H > 114.4 GeV (LEP)

    M_H < 182 GeV @ 95% CL (electroweak fits)



- At the LHC the searches for the low mass Higgs boson are focused in the region of 120-200 GeV
  - The higher masses SM Higgs will be excluded (or discovered) with early data.

Cross sections and event rates at $\sqrt{S}$=14 TeV



Total inelastic cross-section

$\sigma \sim$ 80mb

Inclusive jet production E_t>100GeV

$\sigma \sim$ few μb

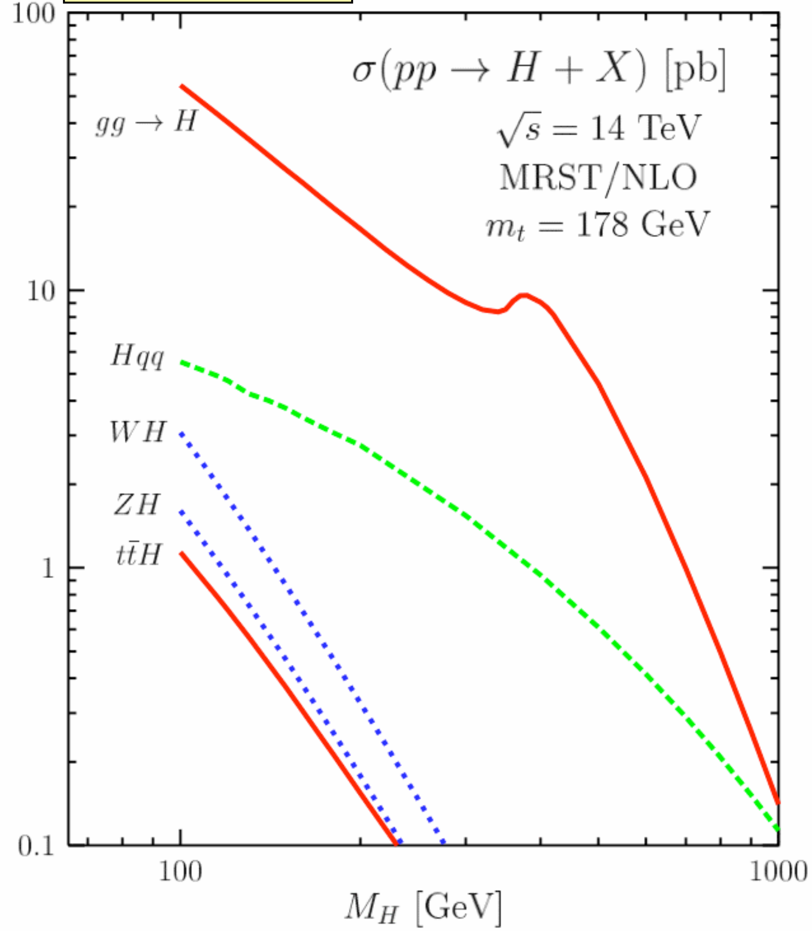
Higgs (150 GeV) production

$\sigma \sim$ 30 pb

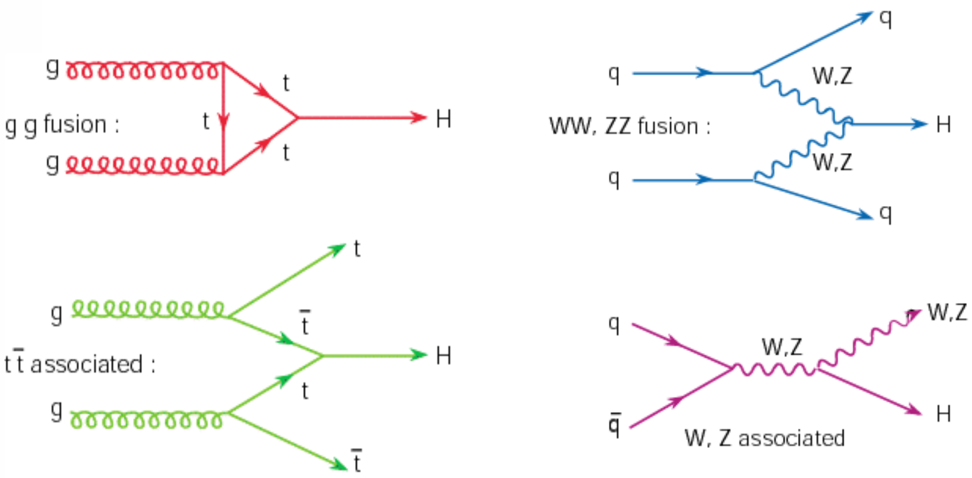
The Higgs production cross section is orders of magnitude smaller than those for the main processes.

Higgs Production at the LHC

hep-ph/0503172v2



Dominant processes: gluon-gluon fusion and vector boson fusion.



Higgs Decay

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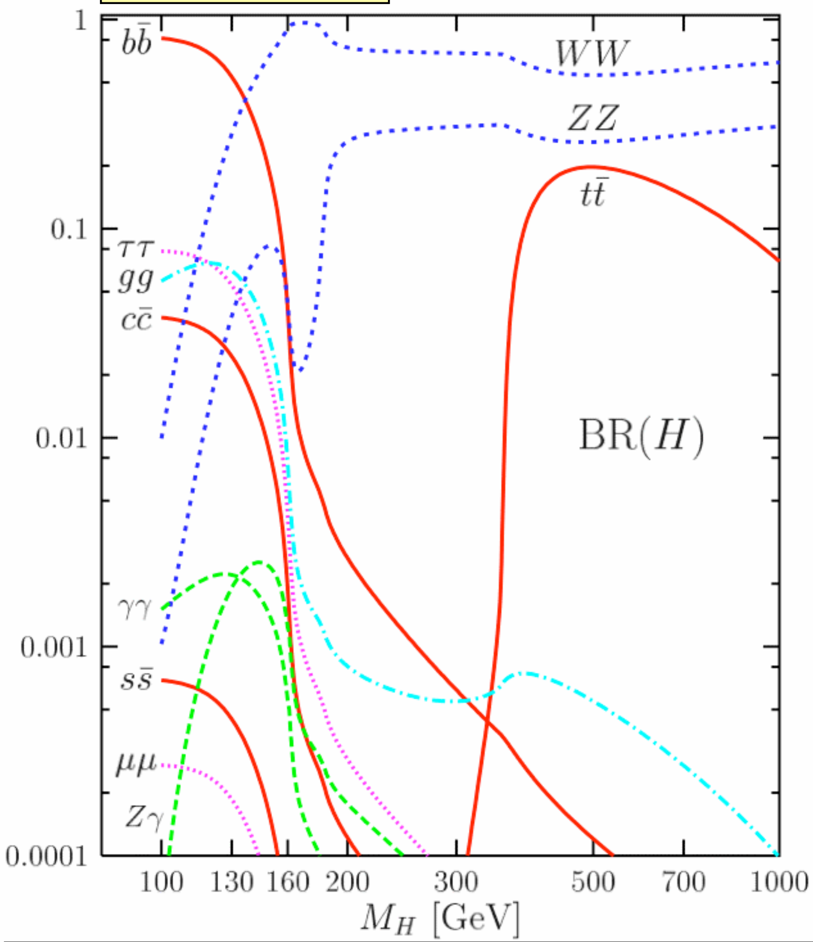


- m_H < 120 GeV:
  $H \to b\bar{b}$ dominates
- 130 GeV < m_H < 2 m_Z:
  $H \to WW^{(*)}, ZZ^{(*)}$ dominate
  (virtual *Z*'s or W's)
- m_H > 2 m_Z :
  1/3 $H \to ZZ$ (real *Z*'s)
  2/3 $H \to WW$ (real *W*'s)

The hadronic final states dominate the branching fraction, but can be hardly extracted from the large QCD background. The final states containing photons and leptons have an advantage. In the interesting mass region, the $H \to ZZ^* \to 4l$ is the cleanest "golden" signature.

The "Golden" Channel

- The Higgs boson should manifest itself as a narrow invariant mass peak over a 4-lepton background.
  - The S/B ratio after all the selection cuts depends on the mass of the Higgs.

- Relatively simple reconstruction:
  - Only electrons and muons are involved.
  - Simple trigger setup: high p_t single and di-leptons.
  - First objects to be understood by ATLAS.

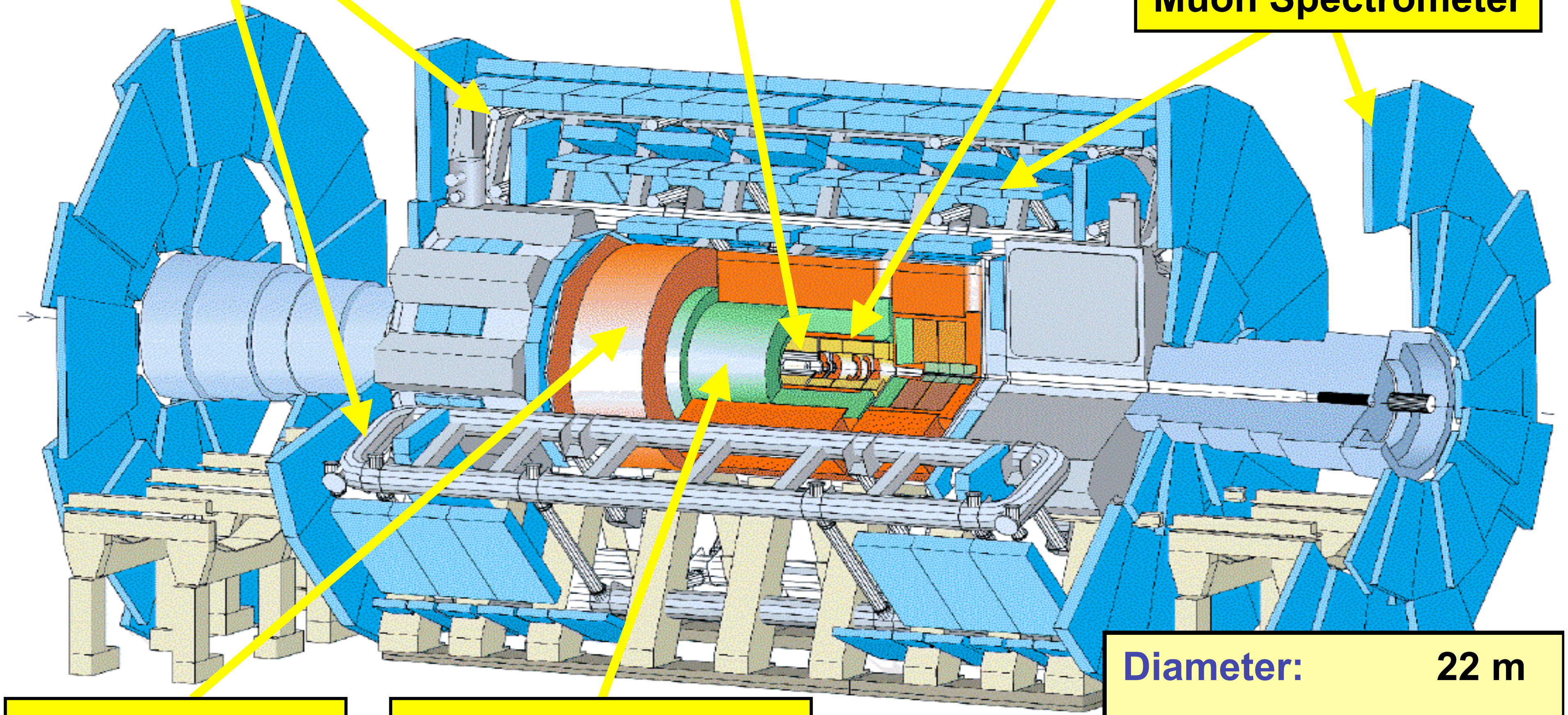
- Challenges:
  - Relatively low statistics: $BR(Z \rightarrow ee)$, $BR(Z \rightarrow \mu\mu) \approx 3.37\%$
  - Efficient identification and reconstruction of low-p_t leptons (5 to 15 GeV/c), good rejection of fakes is mandatory.
  - Only one (or sometimes no) on-shell Z at low Higgs masses.

Signal and Background

•**Process**	**σ x BR [fb] (NLO)**
•Signal	
•*H→ZZ*→4l* for m_H=120-200 GeV.	2.8 - 20.5
•Irreducible backgrounds:	
• *qq→ZZ*→4l*	2×10^2
• *gg→ZZ*→4l*	6×10^1
•Reducible backgrounds:	
•*qq,gg→Zbb→2lbb*	8×10^4
•*qq,gg→tt*	8×10^5

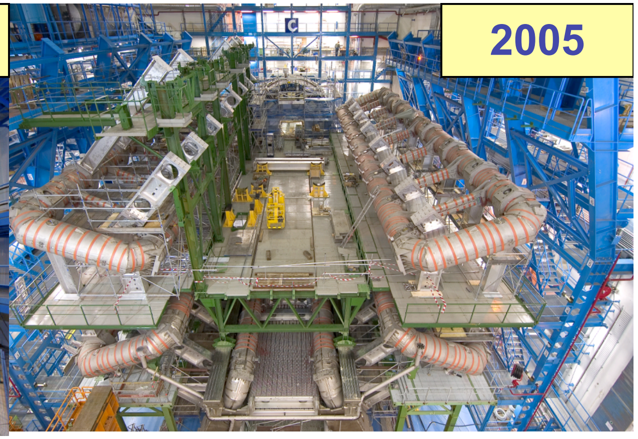
- The cross sections of reducible Zbb and tt backgrounds are large compared to the H→4l.
  - Reduction of these processes below the level of irreducible ZZ* is a safeguard against the uncertainties on their cross sections.
  - A robust method of lepton identification is required.

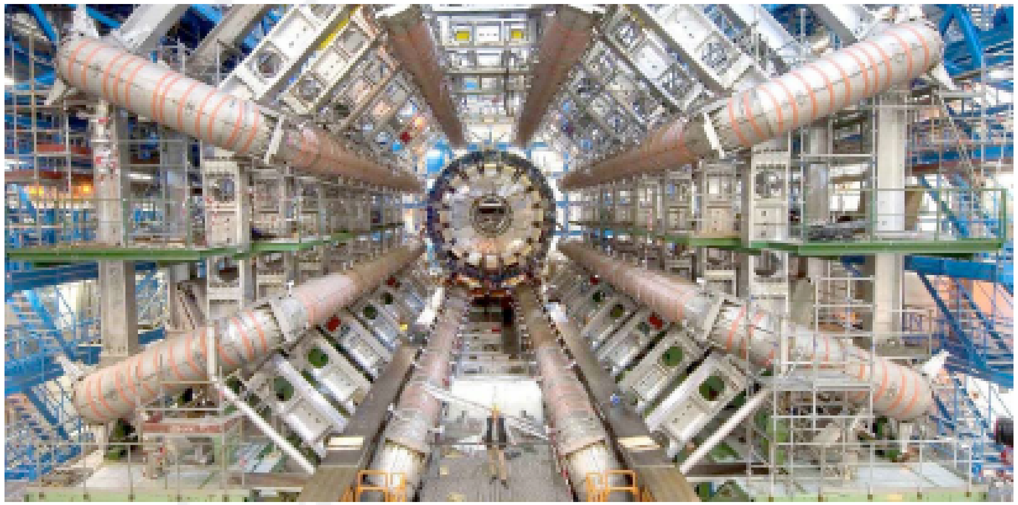
The ATLAS Detector at LHC

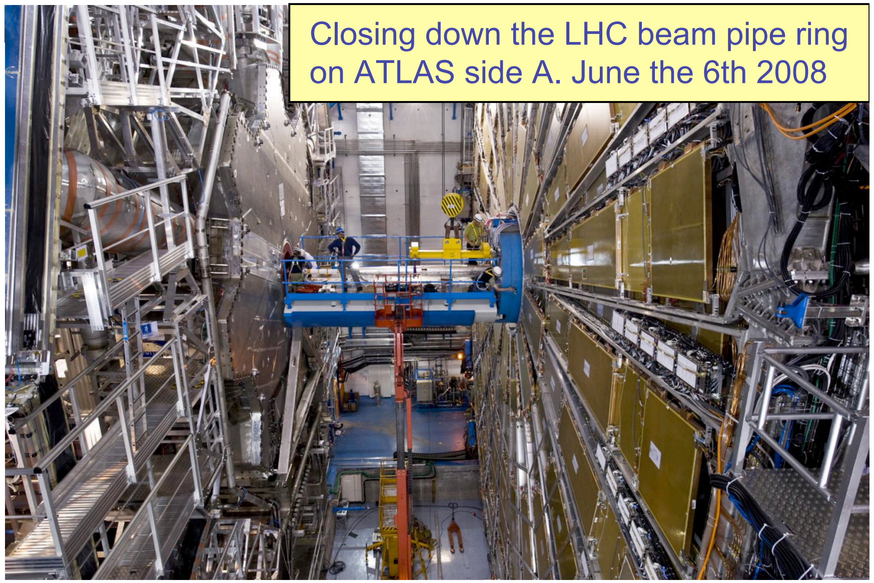


Diameter:	**22 m**
Length:	**46 m**
Total weight:	**7'000 t**

The ATLAS Detector at LHC







Closing down the LHC beam pipe ring on ATLAS side A. June the 6th 2008

Monte Carlo Samples

- Signal Monte Carlo Data.
  - A set of H→4l samples for masses of 120 GeV to 600 GeV (Pythia 6.3 and 6.4).
  - Gluon-gluon fusion and Weak Boson Fusion. LO effects are taken into account by Pythia, NLO effects are considered by scaling cross sections.

- Background Monte Carlo Data
  - A set of reducible *pp→tt→4l* (MC@NLO), *pp→Zbb→4l* (AcerMC3) and irreducible *pp→ZZ*→4l* (Pythia 6.3) background samples.
  - The NLO effects are taken into account at by scaling the generator's cross section.
  - The K-factors are calculated using the MCFM program (*Phys.Rev. D73:054007*).
  - In the case of *pp→tt→4l* the NLO is taken into account at generator level.

- The constant luminosity of 10^{33} $cm^{-2}s^{-1}$ is assumed for all the samples.

- The pile-up and cavern backgrounds are simulated by superimposing the Higgs signal and background events at digitization level.
  - Cavern background: permanent bath of thermalized neutrons and low energy photons resulting in Compton electrons and spallation protons.

Analysis Strategy

- Signal Selection.
  - Aim: selecting signal events with maximum efficiency.
  - Selection of leptons: cuts on the p_t, quality of trajectory reconstruction.
  - Cuts on the mass of two leptons.

- Rejection of the Background.
  - Aim: reducing the level of reducible background to be no larger than 50% of the irreducible one.
  - Isolation of leptons.
  - Study of impact parameter of leptons, χ^2 of the 4-lepton vertex.

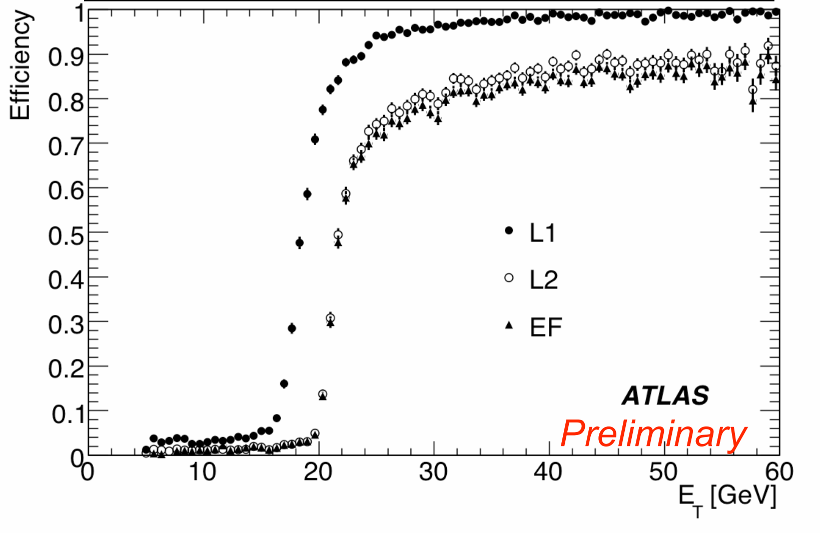
- Reconstruction of the Higgs mass.
  - Aim: to improve the resolution on the reconstructed Higgs mass.
  - Combined lepton reconstruction: Calo + ID, Muon Spectrometer + ID
  - Z mass constraint where possible (Breit-Wigner + Gaussian)

Trigger Selection

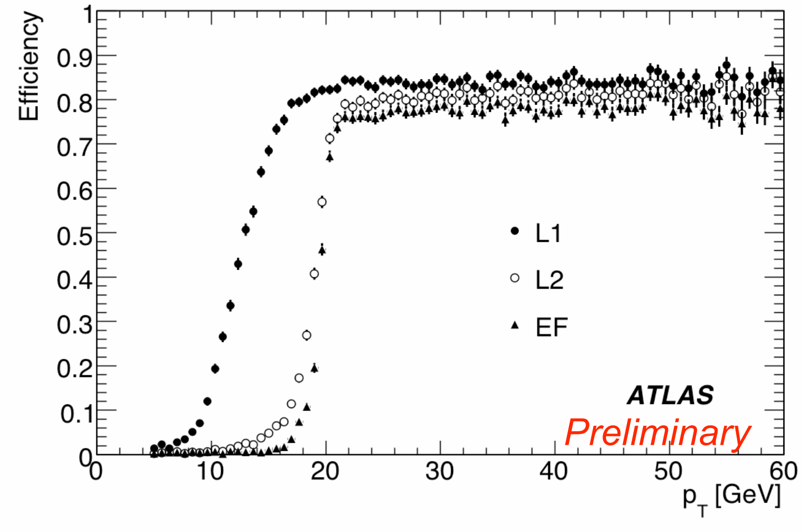
- Level-1: Selects $\Delta\eta\times\Delta\varphi$ regions of interest where a lepton satisfying the given criteria is found.
  - Muons: p_t^{Thresh} range 4 GeV/c to 40 GeV/c, Electrons: E_t^{Thresh} = 15, 22 GeV
- High Level Trigger (Level-2): Validation of selected leptons using fast reconstruction algorithms.
  - Leptons passing the quality cuts and fixed energy thresholds are retained.
- High Level Trigger (Event Filter): Reconstruction of pre-selected leptons with the same algorithms used for offline reconstruction.

Trigger efficiency

Electrons E_t^{thres} = 22 GeV



Muons p_t^{thres} = 20 GeV/c

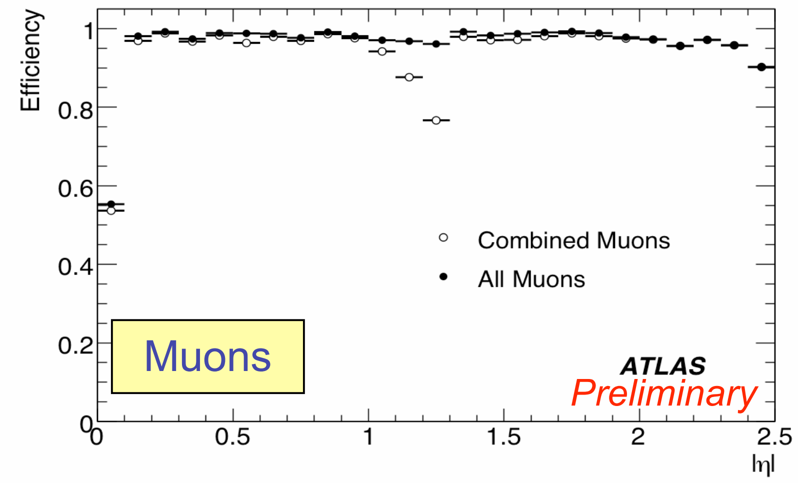


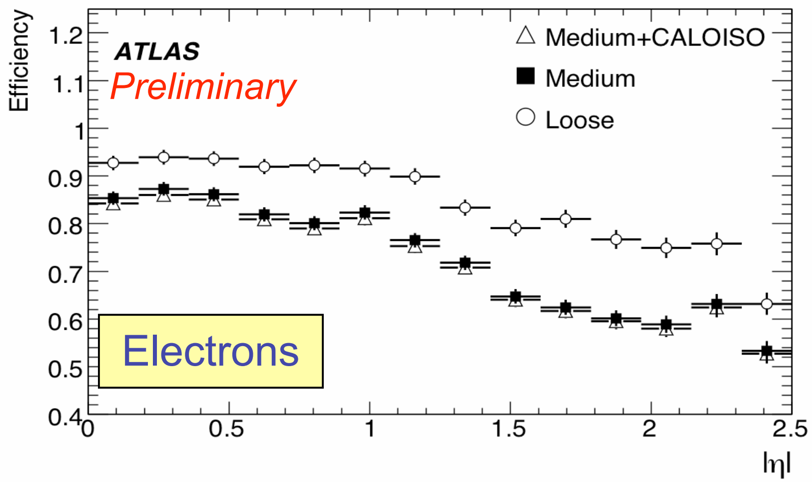
Reconstruction of Leptons

- Electrons
  - A cluster in the LAr EM Calorimeter associated with a track in the Inner Detector.
  - Consistency of the shower shape with an electron.
  - Inconsistency of the shower shape with $\pi^0 \to \gamma\gamma$ decay.
  - Track quality requirements: number of hits in the Pixel and SCT detectors and small transverse impact parameter: $d_0 < 0.1$mm.

- Muons
  - Muon tracks are reconstructed separately in the Muon Spectrometer and Inner Detector.
  - The Inner Detector tracks are combined with nearest MS tracks in a certain cone $\Delta R = \sqrt{(\Delta\eta^2 + \Delta\varphi^2)}$. Combinations with best χ^2 are kept.

Reconstruction efficiency

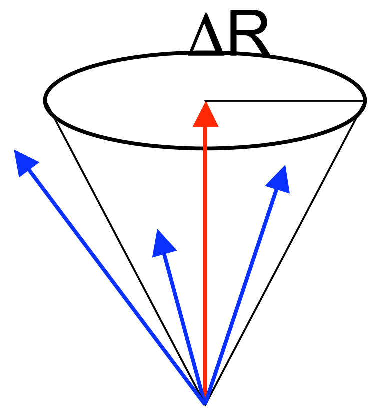




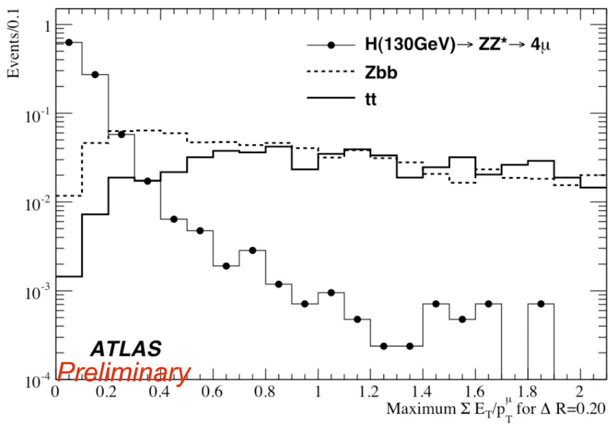
Isolation of Leptons

- The semi-leptonic b-decays compared to the leptonic Z decays:
  - Less isolated leptons with more significant transverse impact parameter.

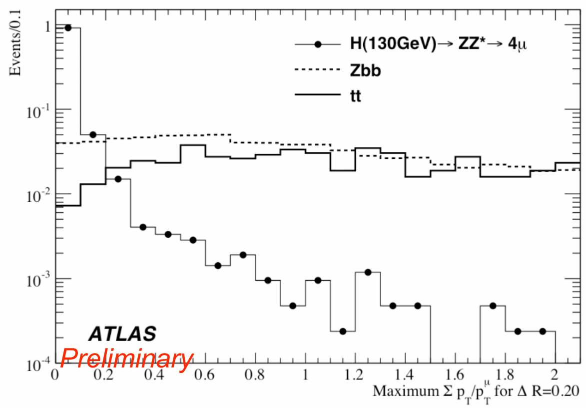
- Definitions of the isolation:
  - Calorimeter: $\Sigma E_t/p_t^l$ in a cone $\Delta R = \sqrt{(\Delta\eta^2 + \Delta\varphi^2)}$
    - $\Delta R=0.2$ for muons; $\Delta R=0.4$ for electrons
  - Inner Detector: $\Sigma p_t/p_t^l$ in a cone $\Delta R = 0.2$



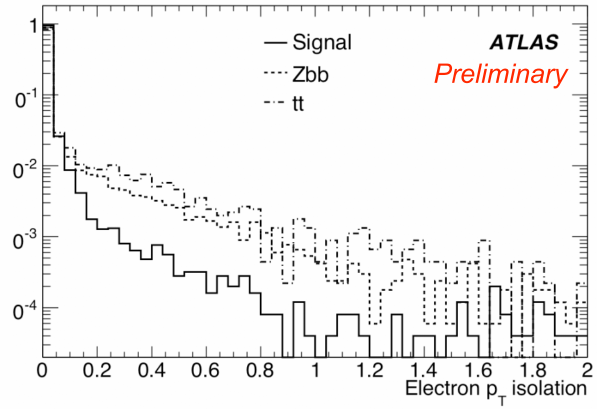
Calorimeter (Muons)



Inner Detector (Muons)

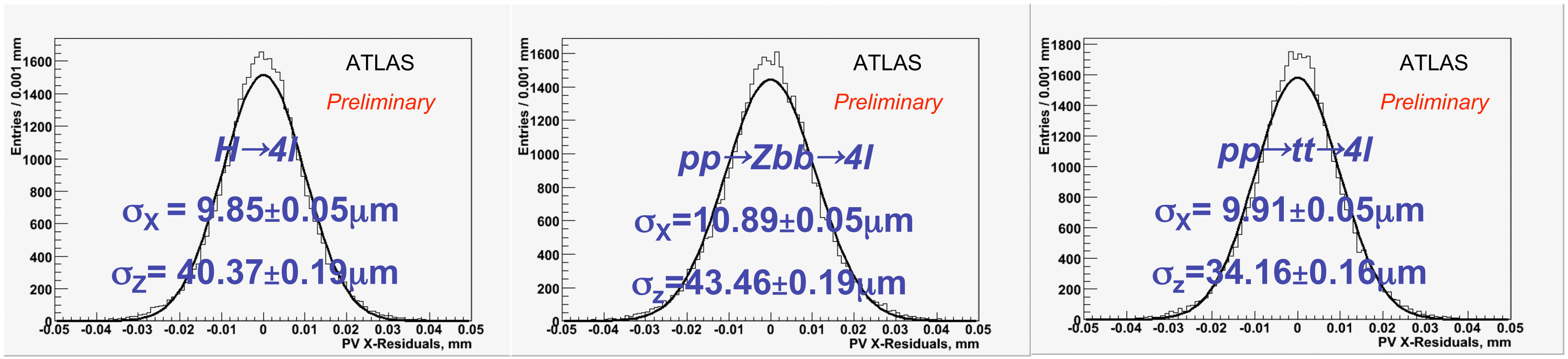


Inner Detector (Electrons)



Reconstruction of Primary Vertices

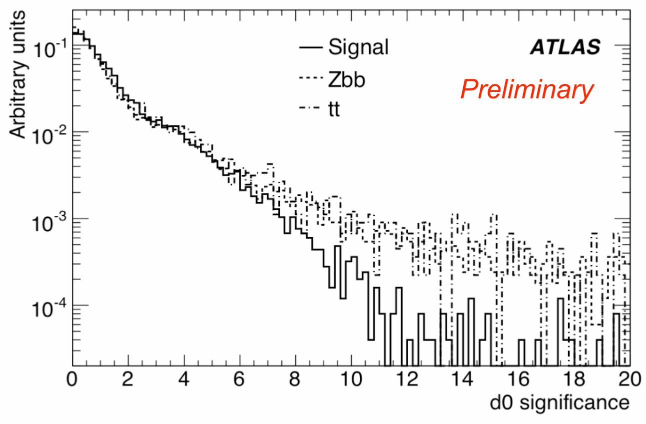
- The pp interaction region is distributed according to a Gaussian with sigma:
  - σ_X ~15μm, σ_Z~5.6cm
- Each signal collision is superimposed with several minimum bias events.
  - Average of 4.6 and 24 at low and high luminosity luminosity modes respectively.
  - Knowledge of position of the signal collision is important for the analysis: impact parameter etc.
- MultiAdaptivePrimaryVertexFinder: iterative re-weighted χ^2 fitter.
  - Tracks are down-weighted w.r.t several vertex candidates at the time.
  - During the fit, the vertex candidates compete to attract more tracks.
  - Signal vertex is selected according to the highest Σp_t^2 of tracks.



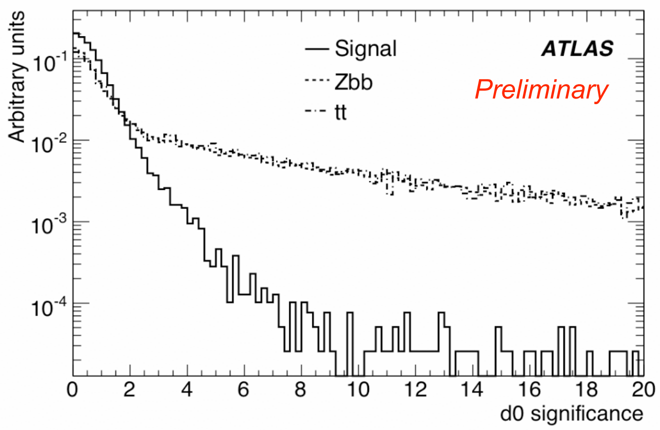
Impact Parameter Analysis

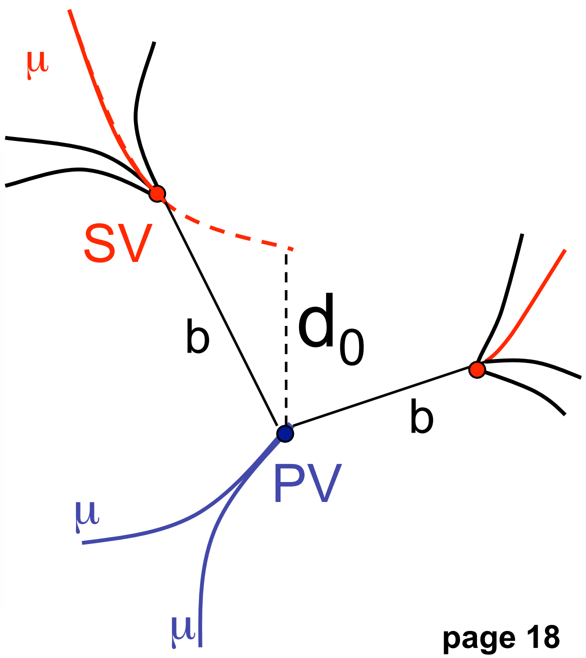
- The leptons from the *b*-flavored decays in the *tt* and *Zbb* backgrounds are likely to originate from displaced vertices.
  - The significance of the transverse impact parameters $d_0/\sigma(d_0)$ of final state leptons can be used as discriminating variable.
  - The $d_0/\sigma(d_0)$ can be calculated with respect to the origin of coordinates.
    - Distribution is smeared with the beam spot distribution, $\sigma(d_0)$ includes only contributions from the reconstructed parameters of track.
  - or with respect to the reconstructed primary vertex.
    - No smearing, $\sigma(d_0)$ includes also contributions from the reconstructed primary vertex.

Electrons



Muons

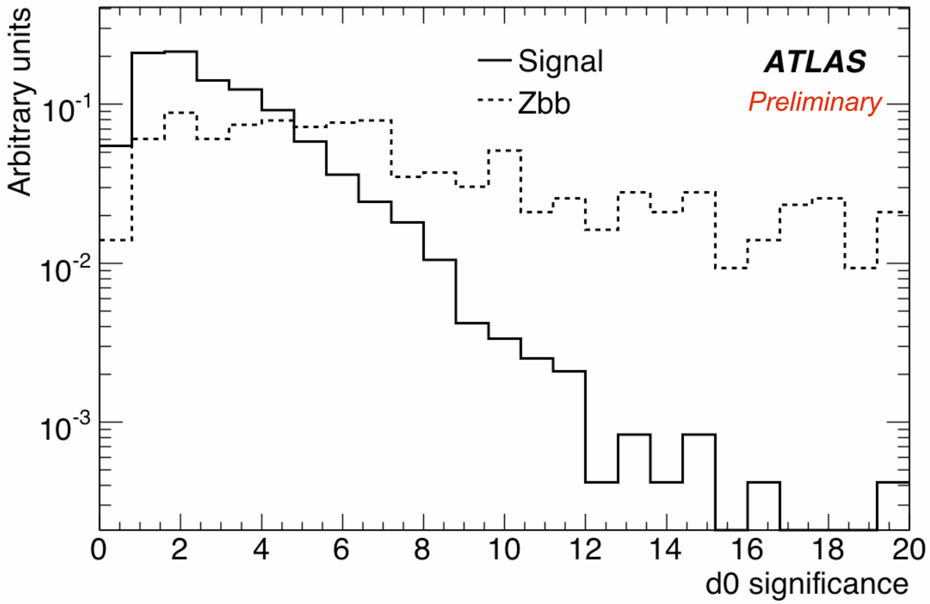




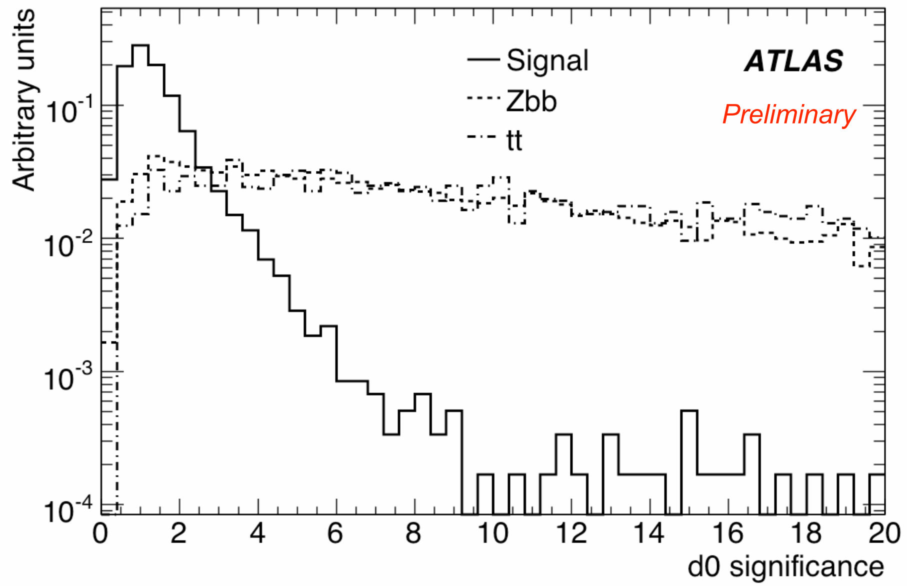
Impact Parameter Analysis

- In the analysis, the $d_0/\sigma(d_0)$ of a track with maximum d_0 out of 4 is used as discriminating variable.

electrons



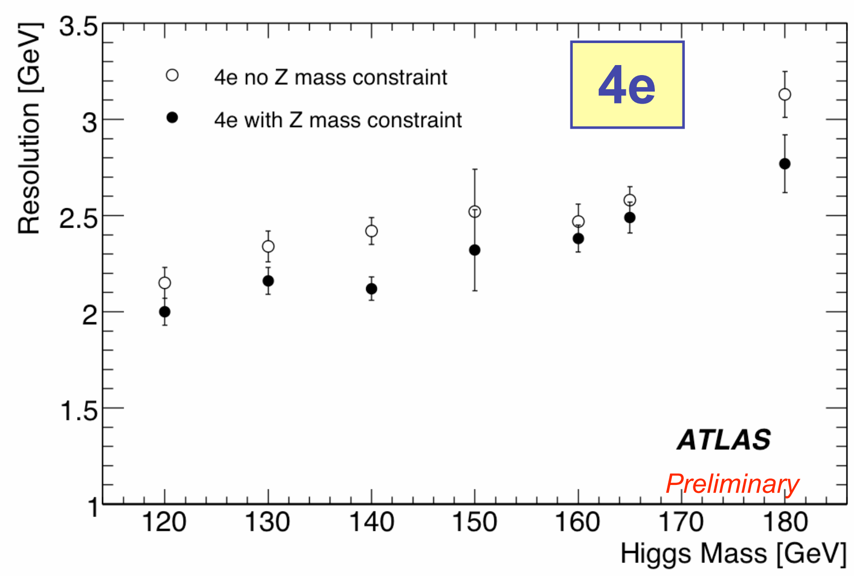
muons

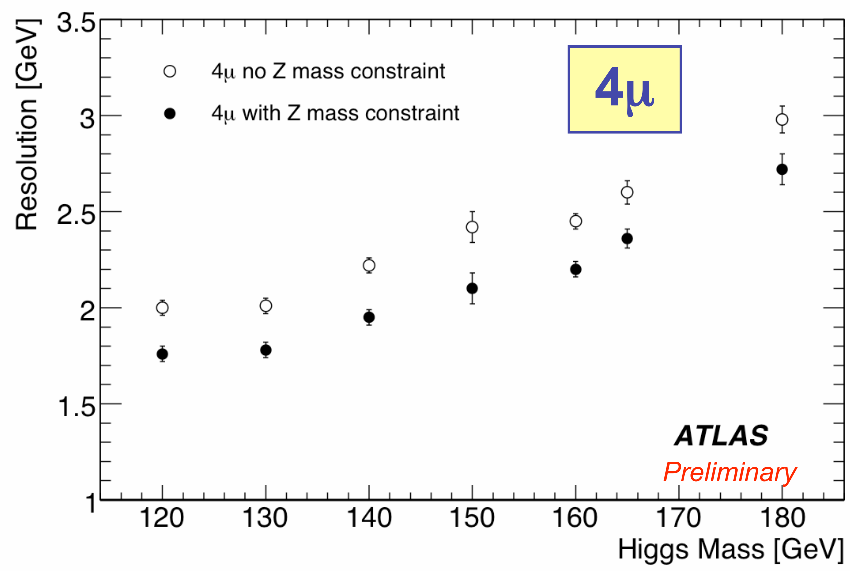


Reconstruction of the Higgs Mass

- Events with at least 4 leptons in pairs of opposite charge and same flavor.
  - If several quadruplets are found, one with pair closest to the Z mass is selected.
  - The Z mass constraint is applied to the pair with mass closest to the mass of the Z.
  - In the case of 2 on-shell Z's, mass constraint can be applied to both of them.
  - Constraint: convolution between the Breit-Wigner and a Gaussian centered in the measured value and σ equal to the experimental resolution.

Experimental resolution on the Higgs mass reconstructed with and without Z mass constraint as a function of the Higgs mass

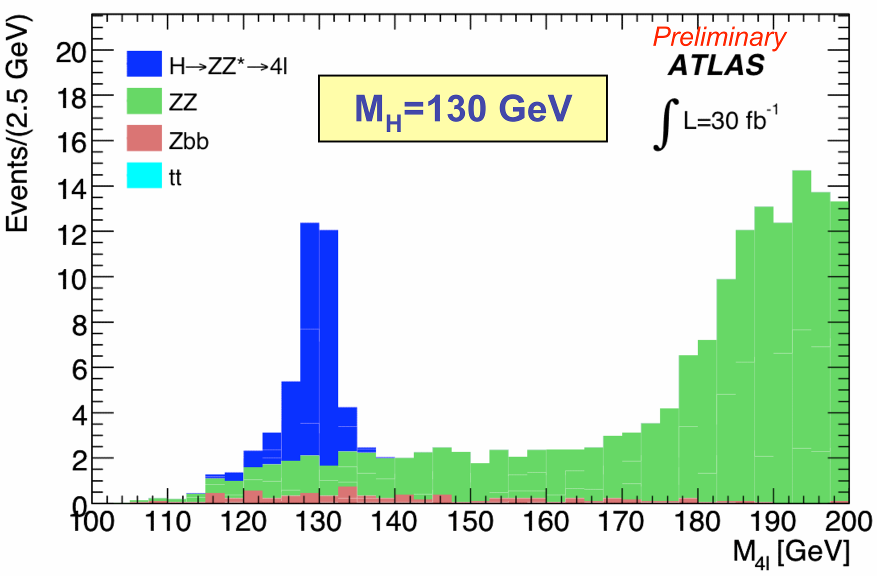


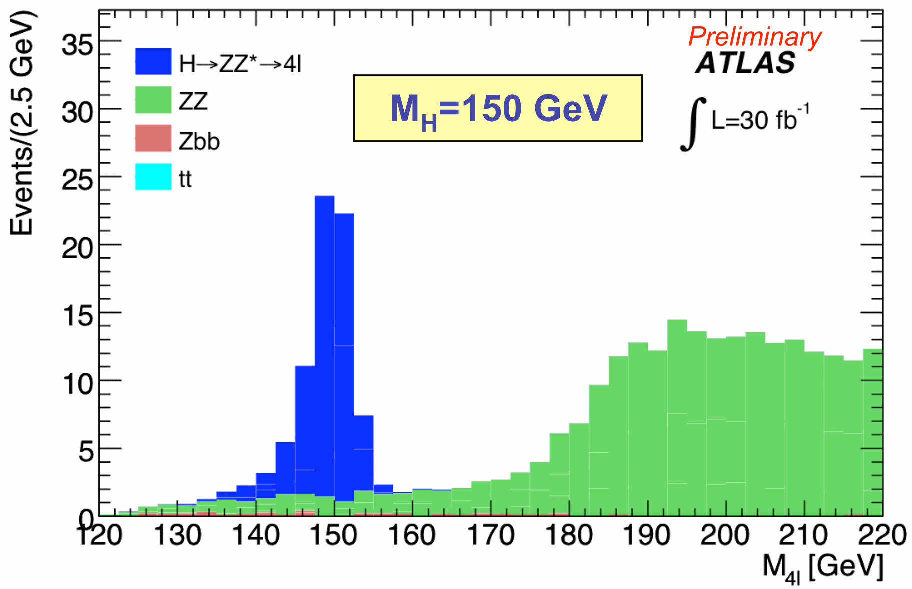


Event Selection

- Event selection flow
  - Trigger selection.
  - Selection of leptons: high quality reconstructed trajectories, p_t threshold.
  - Z mass cuts.
  - Calorimetric and tracker isolation of leptons.
  - Impact parameter cut.
  - Higgs mass cut: $M_H \pm 2\sigma_H$

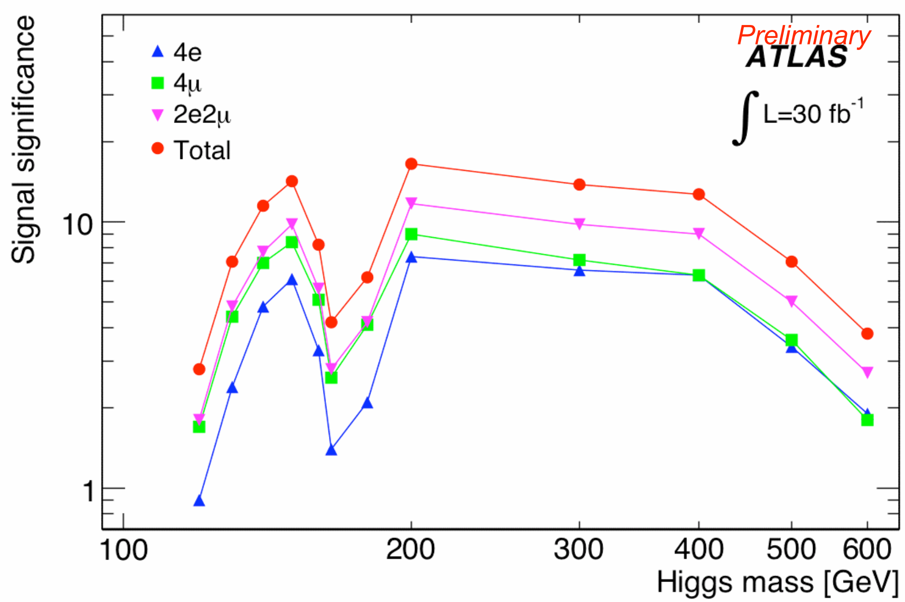
Reconstructed 4 lepton mass for signal and background processes





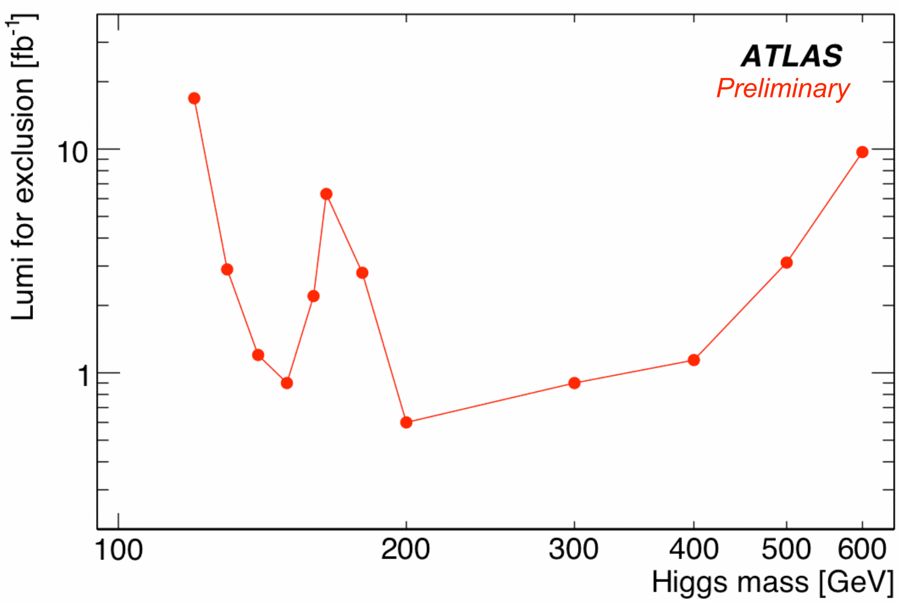
Signal Significance

Signal significance as a function of the Higgs mass for 30 fb^{-1}. Calculation performed assuming the background is known with negligible uncertainty.



Luminosity required for exclusion of the SM Higgs (95% C.L.) with the $H \rightarrow ZZ^* \rightarrow 4l$ as a function of the Higgs mass.

Profile Likelihood ratio under "no signal" hypothesis is used. The likelihood function is calculated on the basis of signal and background pdf's determined from the Monte Carlo.



Conclusion

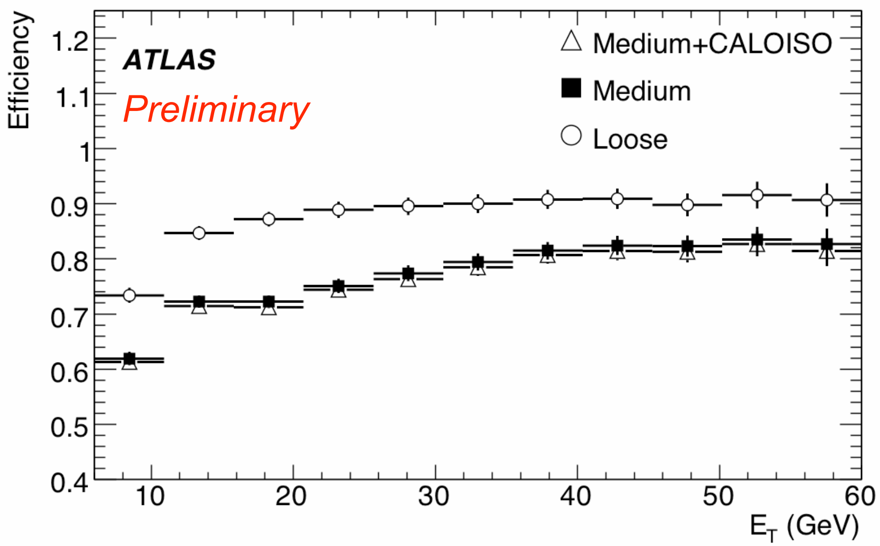
- The ATLAS experiment at the Large Hadron Collider is now ready to take the first data.
- According to the schedule, the integrated luminosity will exceed the 30 fb^{-1} in the year 2011.
- For an integrated luminosity of 30 fb^{-1} ATLAS will discover the Standard Model Higgs boson in the $H \to ZZ^* \to 4l$ channel for Higgs masses 130-500GeV.
  - Exception: region around 160 GeV, the significance of 4σ is expected. The WW channel turns on.
  - Can be combined with $H \to WW$ to increase sensitivity.
  - Exception: very low mass limit around LEP exclusion limit (~120 GeV): 3σ expected.
  - Can be combined with $H \to \tau\tau$ and $H \to \gamma\gamma$ to increase sensitivity.
- The top sensitivity is obtained in the region $200 < M_{4l} < 400$ GeV
  - Higgs discovery with 5 fb^{-1}.
- The work on further optimization of selection cuts and signal extraction is on-going.

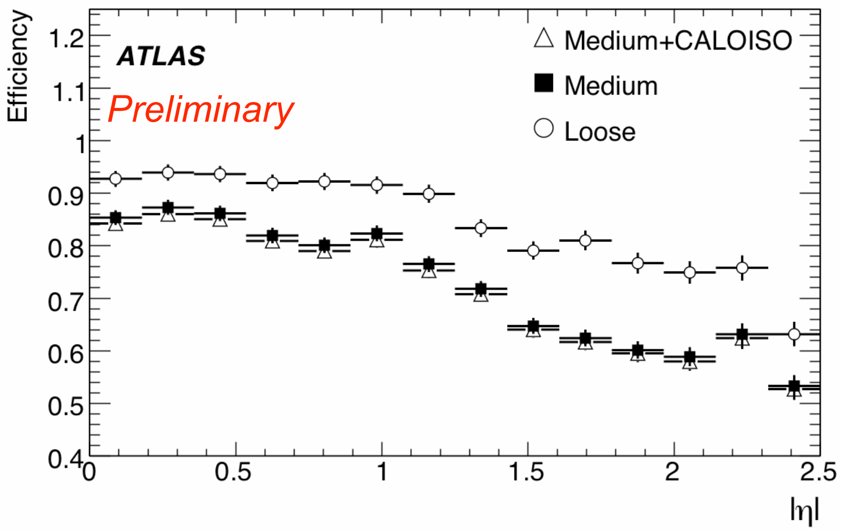
Backup Slides

Reconstruction of Electrons

- A cluster in the LAr EM Calorimeter reconstructed by the offline software associated with a track in the Inner Detector.
- The cluster is contained within the LAr EMC.
- The lateral shower shape is consistent with an electron isolated from hadronic activity and inconsistent with a $\pi^0 \rightarrow \gamma\gamma$ decay.
- Track quality requirements: number of hits in the Pixel and SCT detectors and small impact parameters.

Reconstruction efficiency

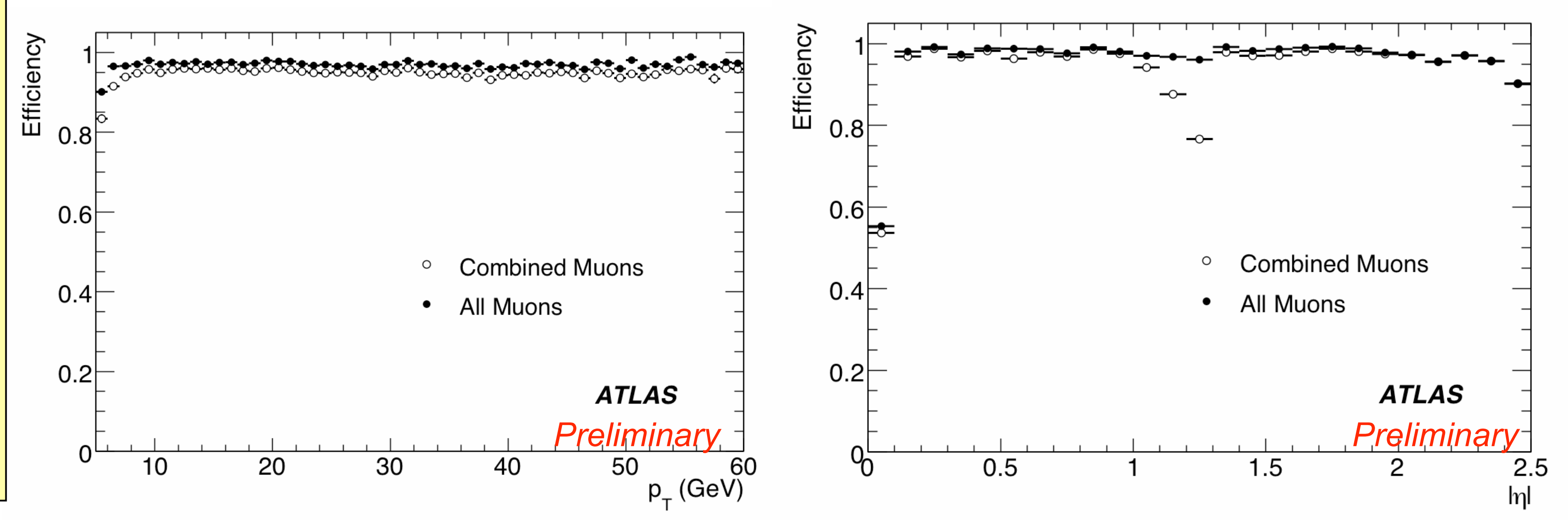




Reconstruction of Muons

- Standalone track segments are reconstructed using the Muon Spectrometer.
- The track reconstruction in the Inner Detector is also performed.
- The Inner Detector tracks are combined with nearest MS tracks in a certain cone $\Delta\eta = \sqrt{(\Delta\eta^2 + \Delta\varphi^2)}$. Combinations with best χ^2 are kept.

Reconstruction efficiency



Early Data

Detector performance calibration and alignment

- Common strategy to all sub-systems
- Use of Z, W, top for most of the studies

- For calorimeter calibration
  - $J/\psi \rightarrow e^+e^-$ and $Z \rightarrow e^+e^-$ for electromagnetic calorimeter
  - $Z \rightarrow l^+l^-\gamma$ mass constraint to set γ energy scale
  - $W \rightarrow jj$ from Top and Z/γ + 1 jet events Jet Energy Scale
  - $Z \rightarrow \nu\nu$, $W \rightarrow l\nu$ Missing ET calibration

- For momentum calibration
  - $J/\psi \rightarrow \mu^+\mu^-$ and $Z \rightarrow \mu^+\mu^-$ for muon momentum

- b-tagging efficiency
  - tt events

Precision we expect to have in the beginning
Inner tracking alignment 20-200 μm
e/m calo Uniformity ~1% e/γ scale ~1-2 %
Jet Energy Scale ~10%

→

Desired precision
10 μm
7‰(unif) 1‰ (scale)
1 %

Early Data

Verify that the detector works

- Verify lepton identification

– use well known processes like $Z \rightarrow ll$

– at $10pb^{-1}$ with $\sqrt{s}$=14TeV about 5k $Z \rightarrow ll$ expected (after cuts)

- Prove that we understand the detector

– verify Standard Model properties

- Prove that we have the background under control

– Estimate the background from data

- Significances depend on m_H and knowledge of background

– for $1fb^{-1}$: between 0.5 and 2.5

– for $5fb^{-1}$: between 1.0 and 5.9

ATLAS Inner Detector

Transient Radiation Tracker

Based on the use of straw detectors separated layers of a plastic radiator. Straws are 4 mm in diameter and up to 150 cm in length. 50’000 straws in barrell and 320’000 radial straws in the endcaps. About 36 measurements per trajectory. 420’000 readout channels.

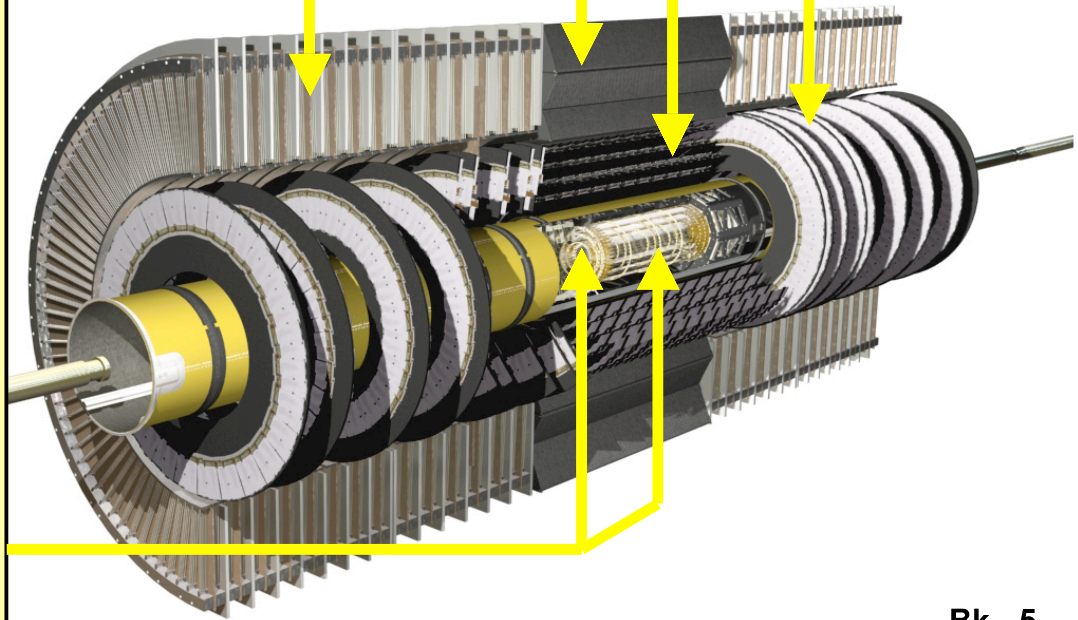
Semiconductor Tracker

4 barrel layers of the silicon microstrip detectors. 9 endcap wheels (each side). Provide measurements in both Rφ and z. 6.2 M readout channels.

Pixel Detector

High precision and granularity measurements close to the interaction point, early separation of particle trajectories.

3 barrel layers at radii of 5, 8.8 and 12.2 cm and 4 endcap disks (each side). Rφ resolution ~12μm. 140 M readout channels.



ATLAS Calorimeters

Hadronic Tile Calorimeter

Plastic scintillator tiles embedded in the iron absorber plates. Provides a precise energy measurements of hadronic jets.

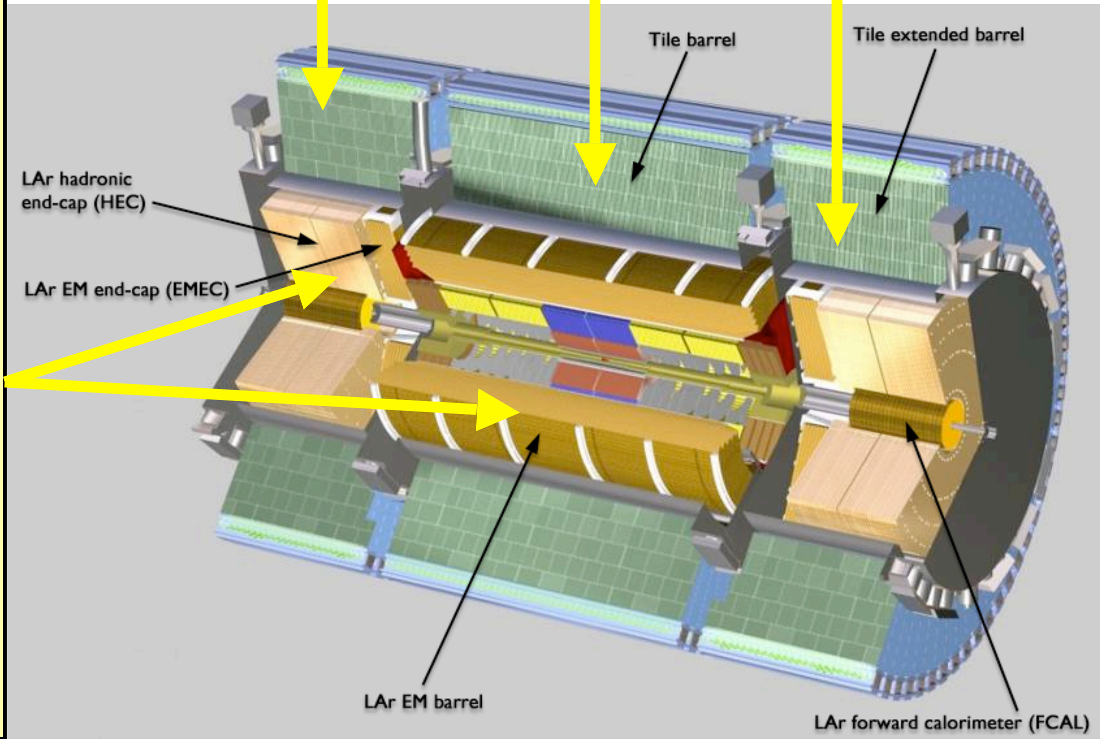
$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Electromagnetic Calorimeter

The modules are made of accordion-shaped lead absorbers alternating with liquid argon gaps and readout electrodes. Provides a precise measurement of electrons and photons with energies from MeV to TeV scale.

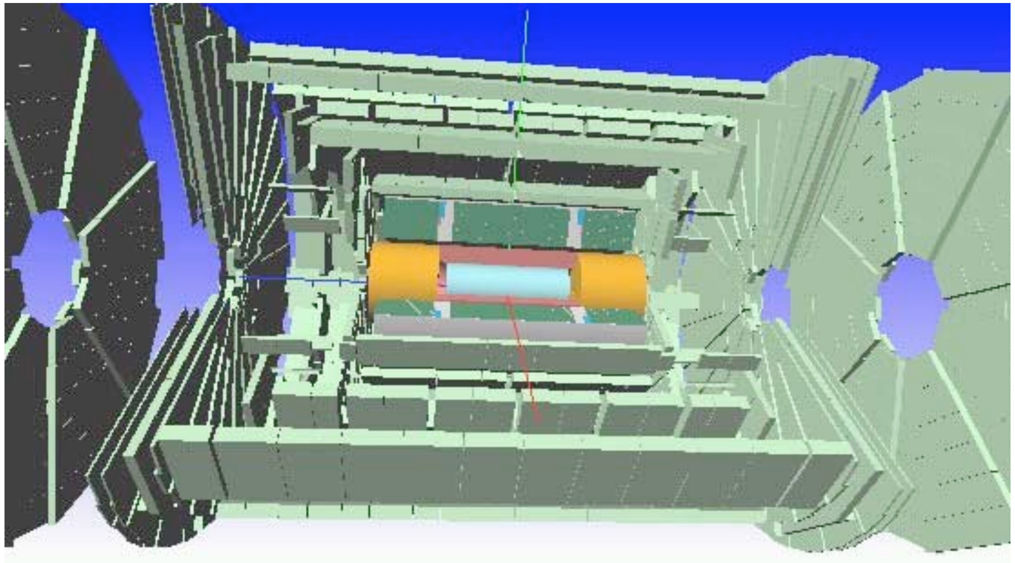
$\sigma/E \sim 10\%/\sqrt{E}$

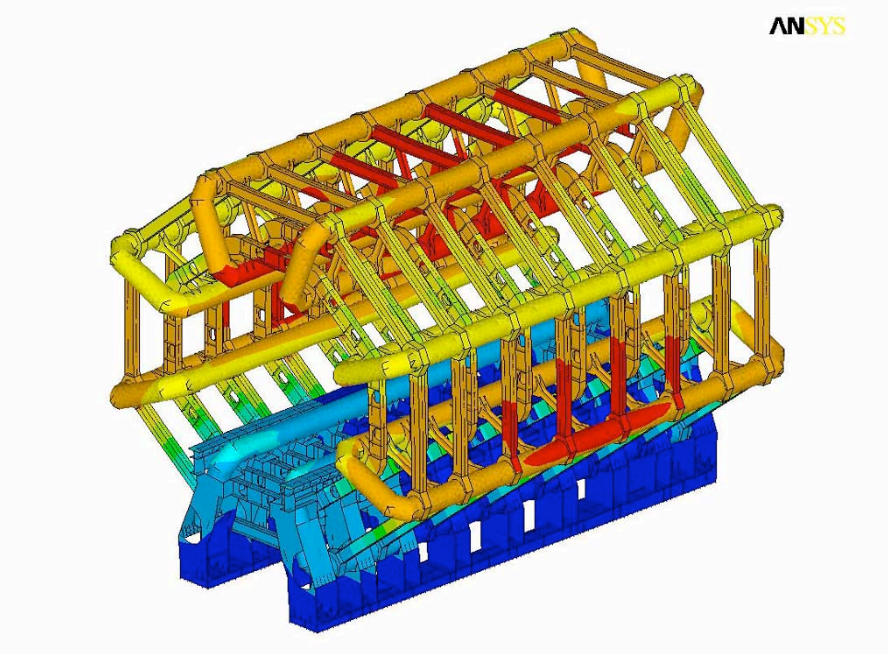
Provides e/γ identification γ/jet, γ/π^0 separation.

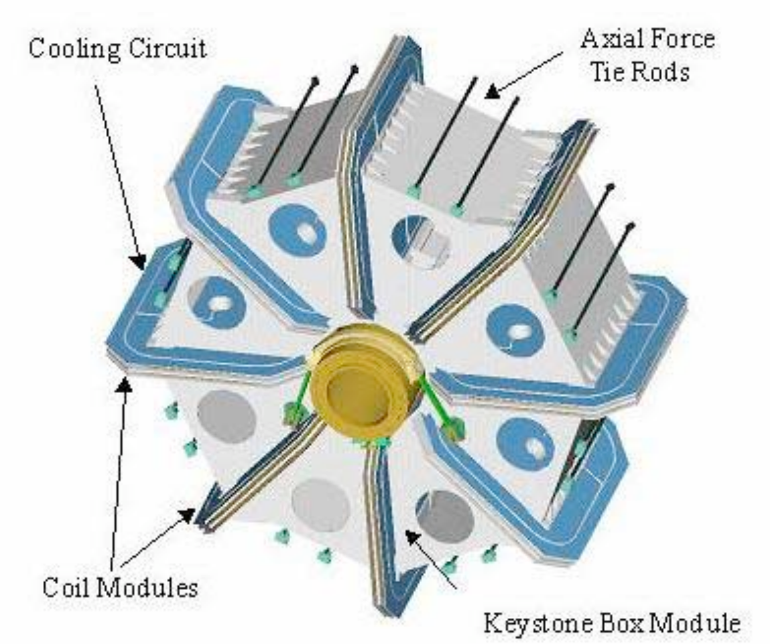


ATLAS Muon Spectrometer

Superconducting toroid magnets instrumented with separate trigger and high-precision tracking chambers. Provides a precise measurement of muon trajectories. High transverse momentum resolution for muons in the p_t range of 5 to 1000 GeV is expected.
σ/p_t~7% at 1TeV





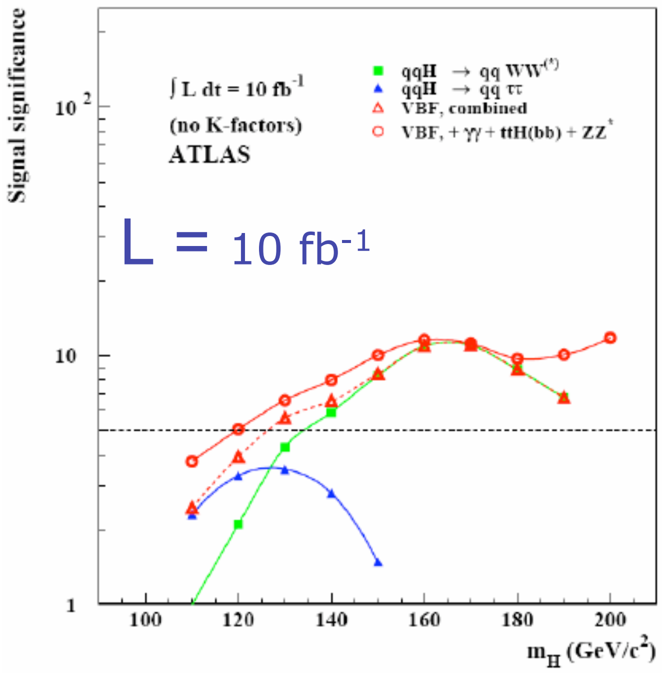


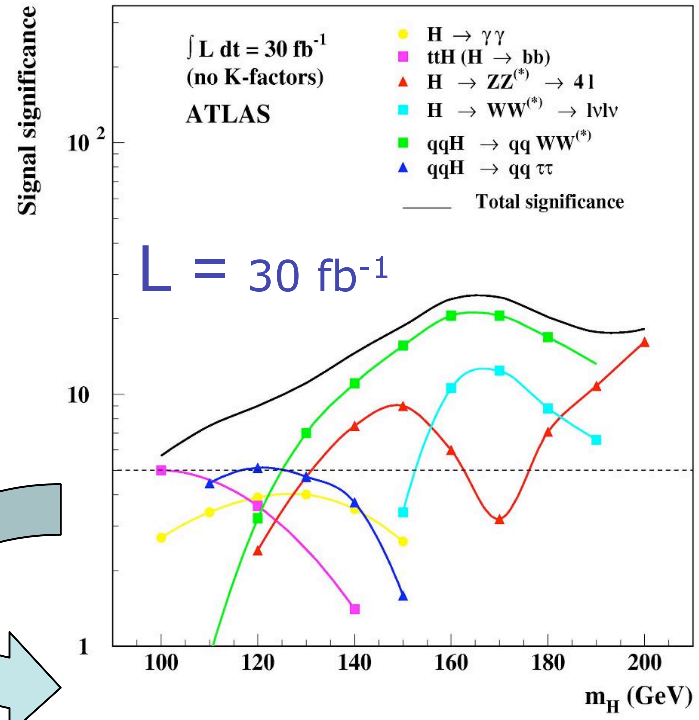
Total ATLAS Sensitvity

General remarks: 1. Absence of NLO cross sections in the following plots
2. Studies in some channels ongoing
- New sensitivity
- Full simulation with new MC generators

- Both VBF channels H→WW, ττ sensitive to low mass Higgs
- By combining all the channels: gg→H with H→γγ, 4l , qqH with H→ ττ, WW(*), ttH, with H→bb, ττ

A 5σ discovery could be reached for mH>120 GeV

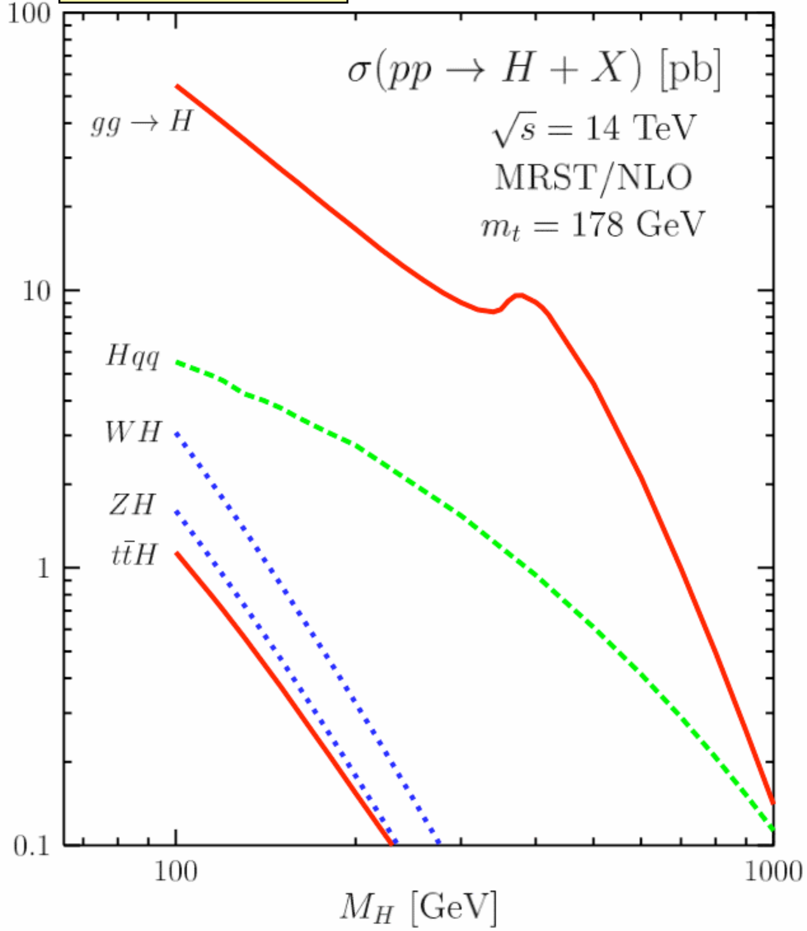




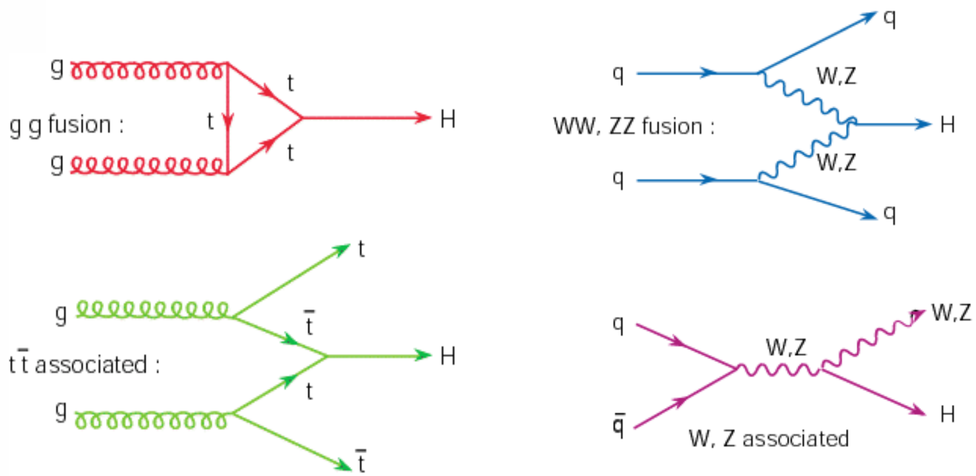
Atlas potential for a light SM Higgs with L=30 fb -1
Several channels can be combined at mH~115 GeV

Higgs Production at the LHC

hep-ph/0503172v2



Dominant processes: gluon-gluon fusion and vector boson fusion.

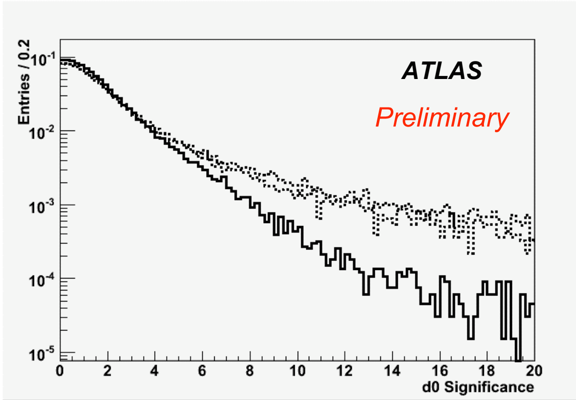


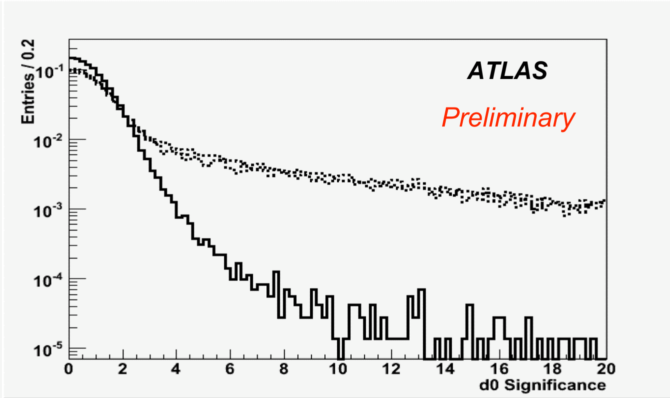
Typical uncertainties on the cross sections

gg fusion	:	~ 10-20 %	NNLO
VBF	:	~ 5%	NLO
ttH	:	~ 10 %	NLO
WH,ZH	:	~ 5%	NNLO

Impact Parameter Analysis

electrons	muons





- Removing the track from primary vertex before $d_0/\sigma(d_0)$ estimate.
  - Allows to estimate the compatibility of a track to vertex in unbiased way.

- In the analysis, the $d_0/\sigma(d_0)$ of a track with maximum d_0 out of 4 is used as discriminating variable.