ATLAS in Run 2: from the isolation of the muons to the measurement of the cross section of the Higgs boson decaying into four leptons.

Arthur LESAGE

IRFU days 2016

The thesis project

- 2011-2014: **École d'Ingénieur Supélec**.

- 2012: Degree in **Fundamental Physics** at the Université Paris Sud XI.

- 2013-2014: **MPhil in Physics** (Semiconductor physics) at the Cavendish Laboratory, Cambridge (UK).

2014-2017: **PhD thesis** with the CEA (Saclay) / DSM / IRFU / SPP (ATLAS group). Based at CERN.

Under the supervision of **Mrs. Rosy Nikolaidou**.

- Study of the muon isolation for Run 2 (qualification task).

- Study of the cross section of the Higgs boson decaying into 2 Z bosons decaying into four leptons (analysis). $H \rightarrow ZZ^* \rightarrow 4\ell, \ell \in \{e, \mu\}$

The ATLAS experiment Overview

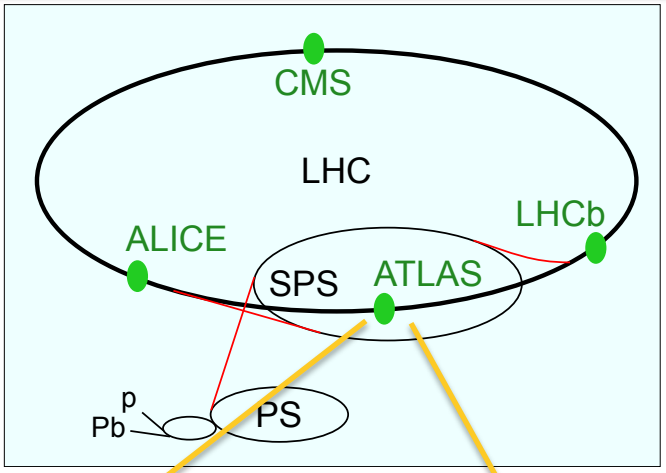
LHC, proton-proton collisions:

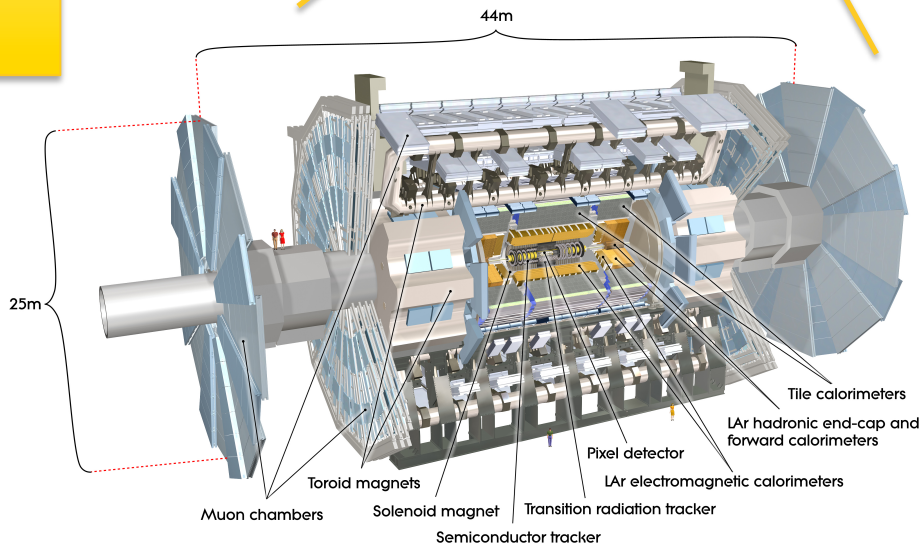
- Run 1 from 2010 to 2013:
  - 5.1 fb^{-1} recorded by ATLAS at 7 TeV.
  - 21.3 fb^{-1} recorded by ATLAS at 8 TeV.

- Run 2 from 2015 to 2018:
  - 3.2 fb^{-1} recorded by ATLAS at 13 TeV (2015).
  - About 10 fb^{-1} recorded by ATLAS at 13 TeV so far (2016).

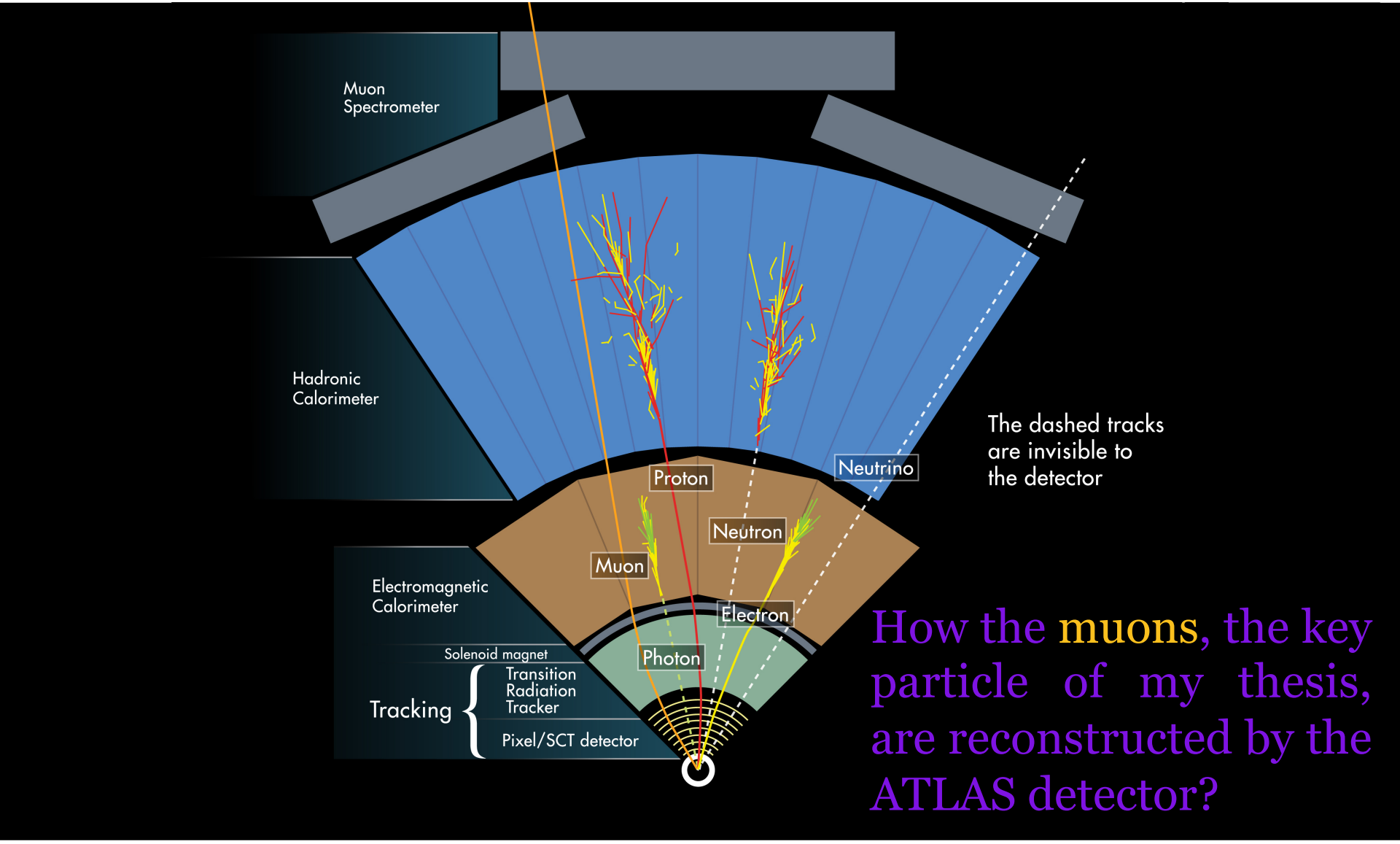
ATLAS is a **general purpose experiment**.

A large part of the physics programme is dedicated to the **Higgs physics**.



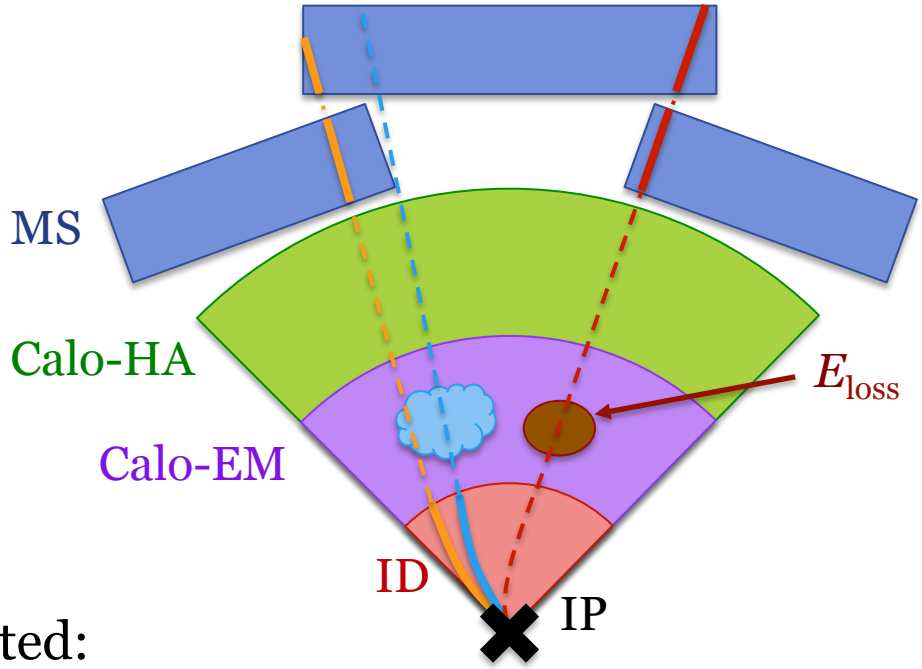


The ATLAS experiment The sub-detectors



How the muons, the key particle of my thesis, are reconstructed by the ATLAS detector?

- The three sub-detectors are used:
  - Mainly Muon Spectrometer (MS) and Inner Detector (ID).
  - At a lesser extent, the Calorimeters (Calo).



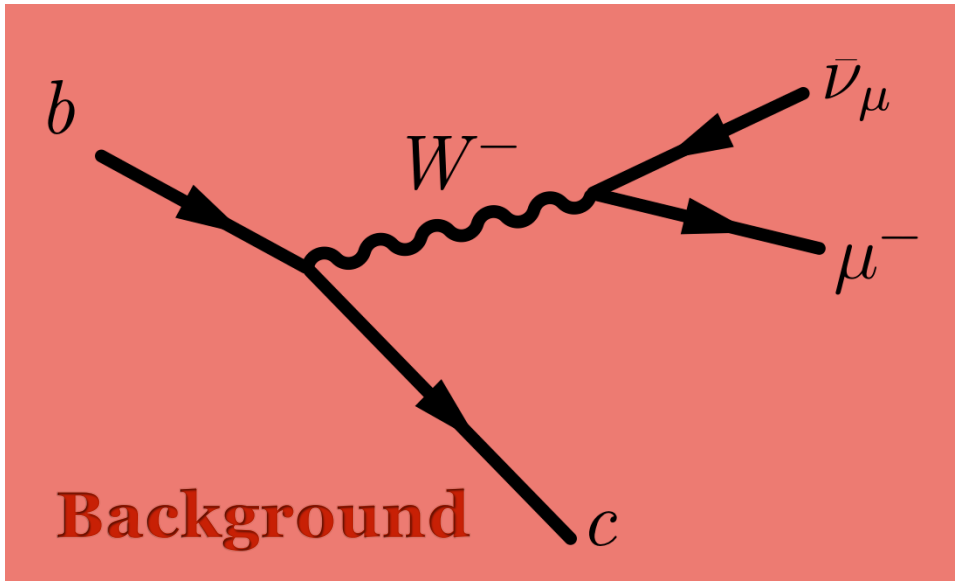
- Several types of muon are reconstructed:
  - **Combined:** a track in the MS matches one in the ID.
  - **Calorimeter-Tagged:** tracks in the ID match clusters in the Calo.
  - **Extrapolated:** tracks in the MS are extrapolated to the interaction point (IP) taking into account the energy loss in the Calo.

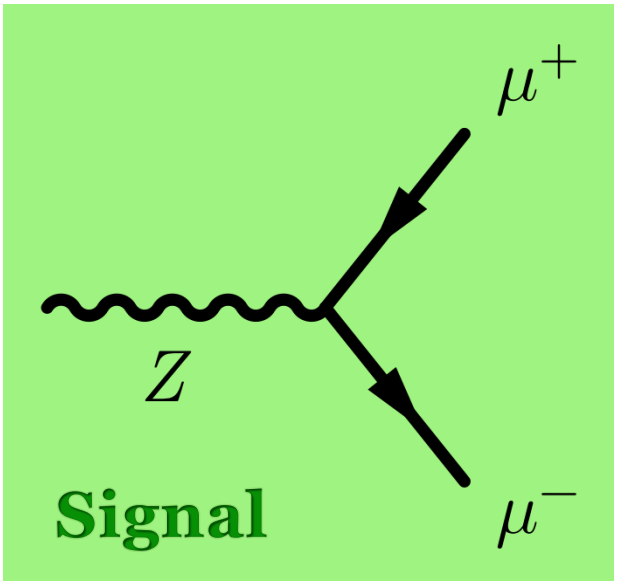
The muon isolation

Discriminating signal / background

- The isolation aims at measuring the **activity surrounding the trajectory** of a particle in the detectors.

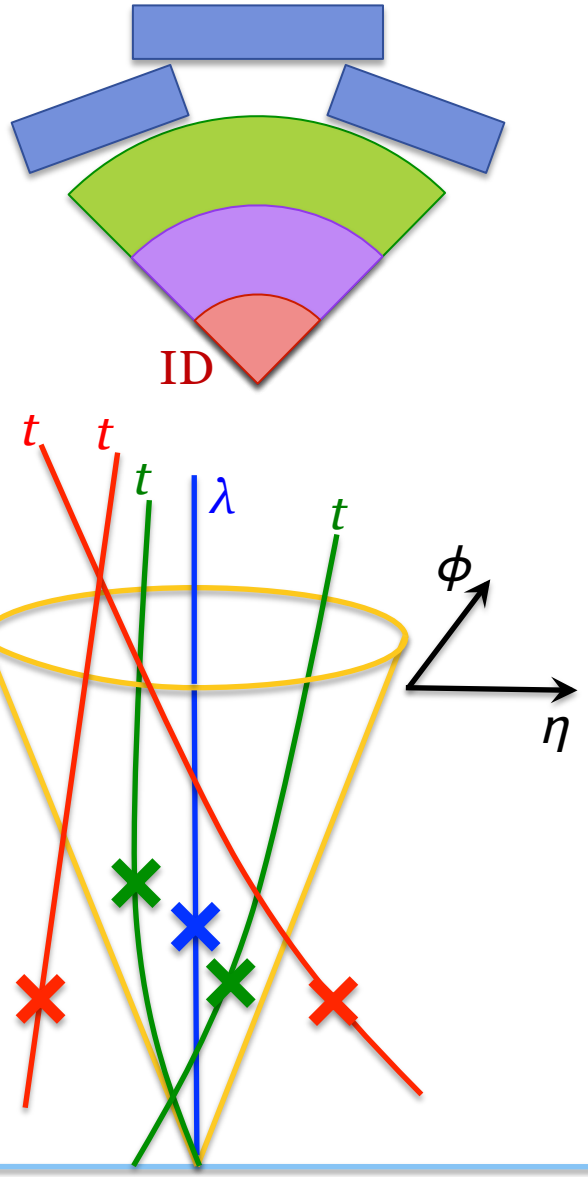
- **Signal**: well **isolated** objects.





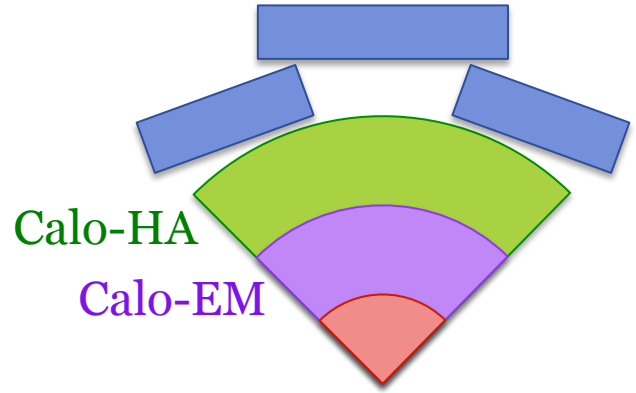
The muon isolation Calculation (tracking)

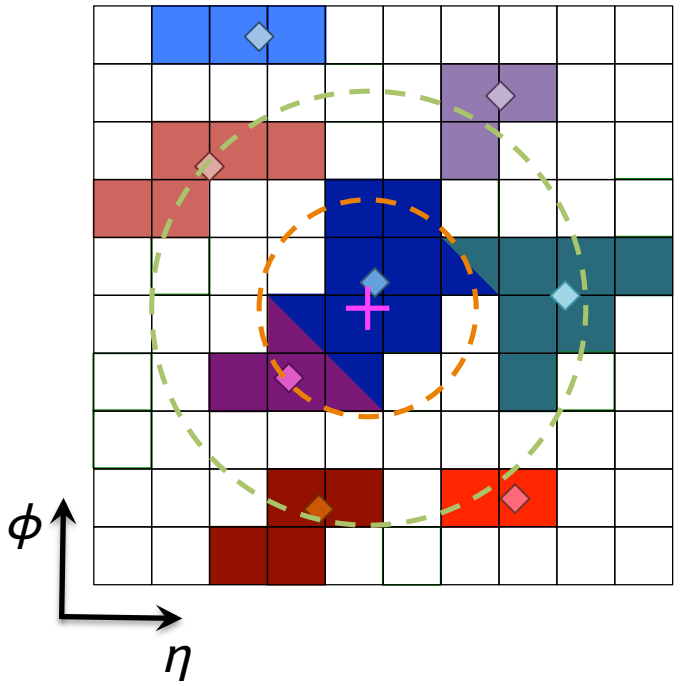
- Two kinds of isolation:
  - **Track isolation**: summing up the transverse momentum of the tracks surrounding the track of the particle in the ID.



The muon isolation Calculation (calorimetry)

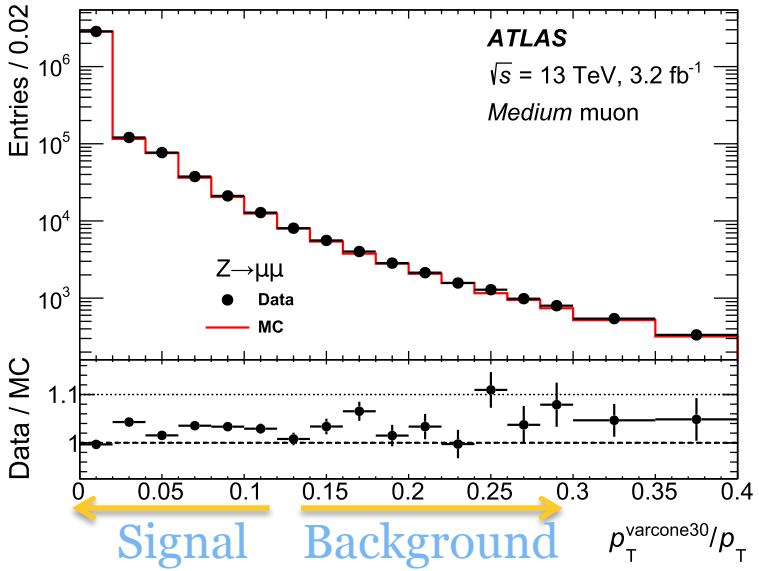
- Two kinds of isolation:
  - **Calorimetric isolation**: summing up the energy deposits surrounding the trajectory of the particle in the Calo, removing the energy deposited by the particle itself.



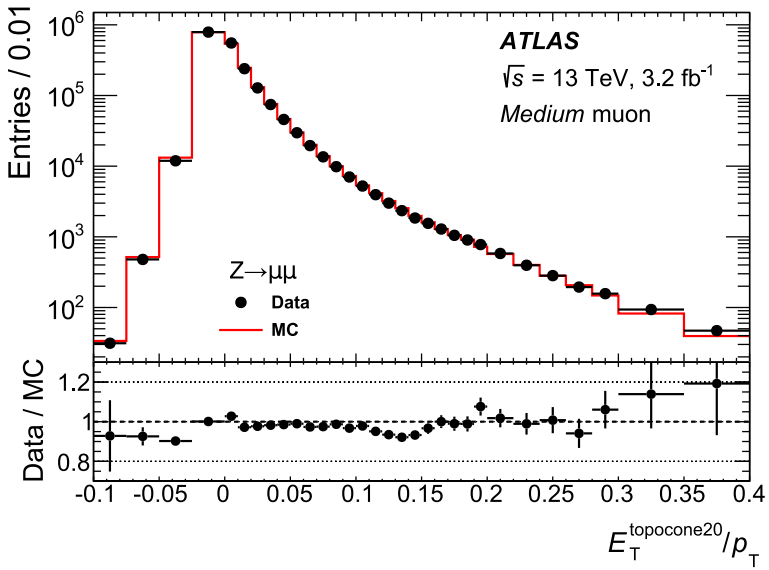


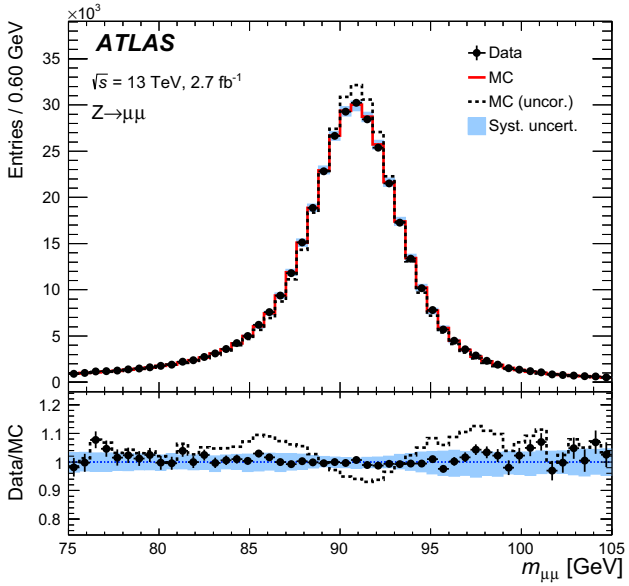
The muon isolation The distributions

Track



Calo





Z peak

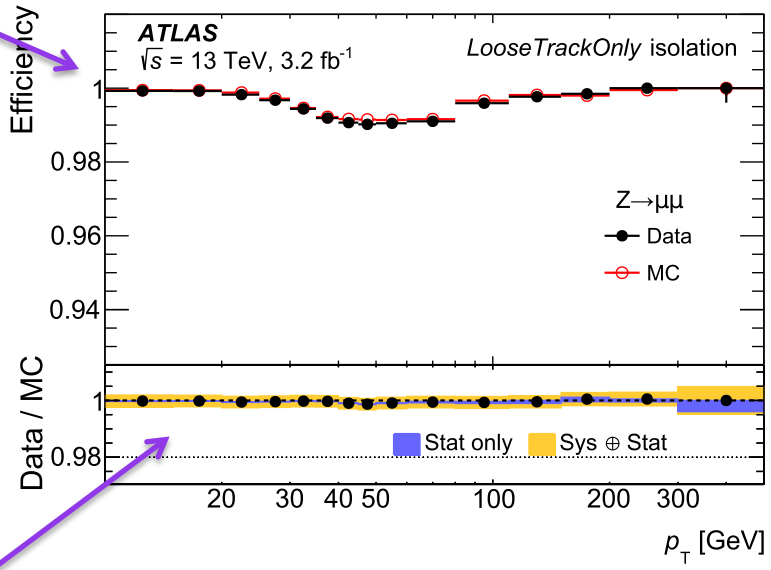
$$Z \rightarrow \mu\mu$$

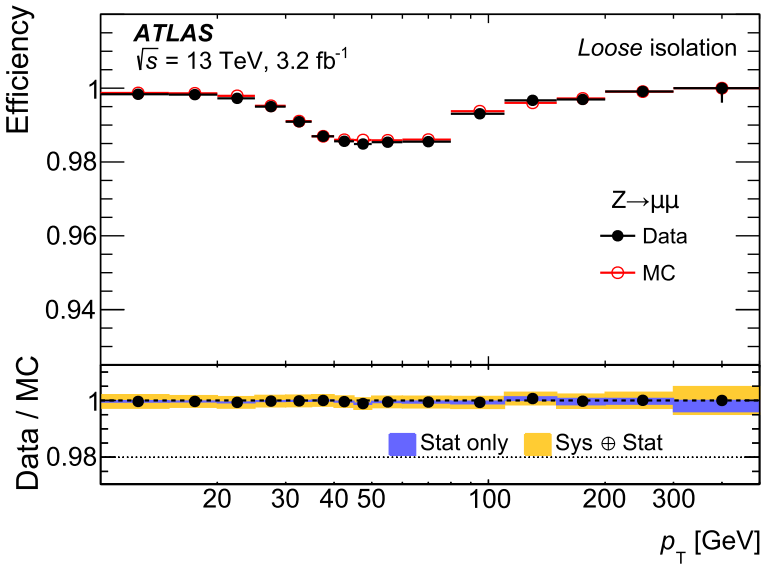
In order to study the isolation variables, **muon pairs from Z decays** are selected.

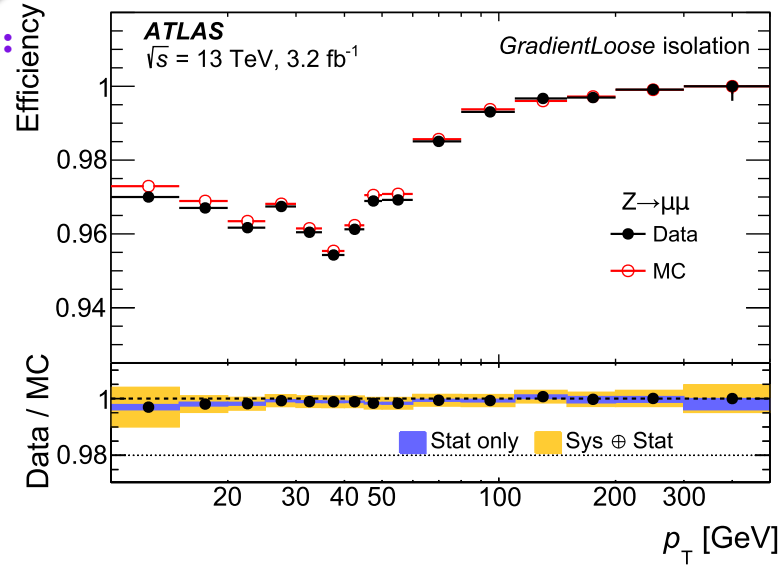
The muon isolation The working points

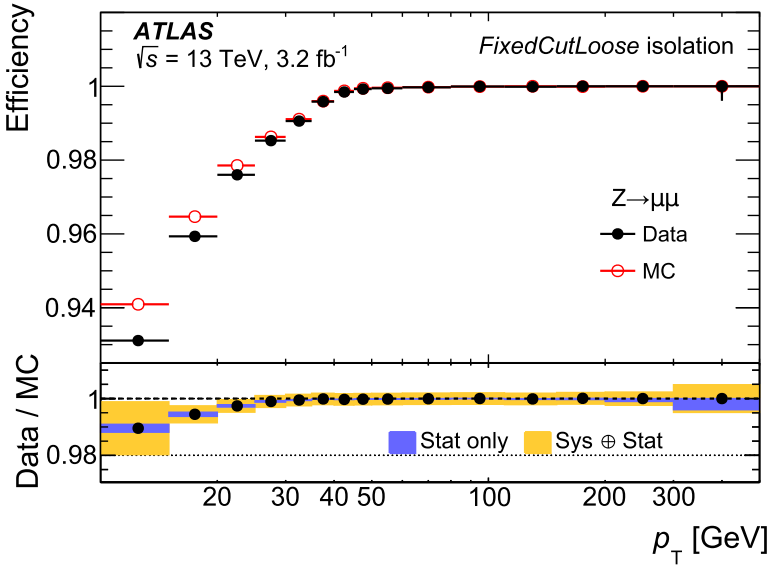
Efficiency: number of muons passing the isolation cuts divided by the total number of reconstructed muons.

Scale factors: ratio of efficiencies in data and MC.





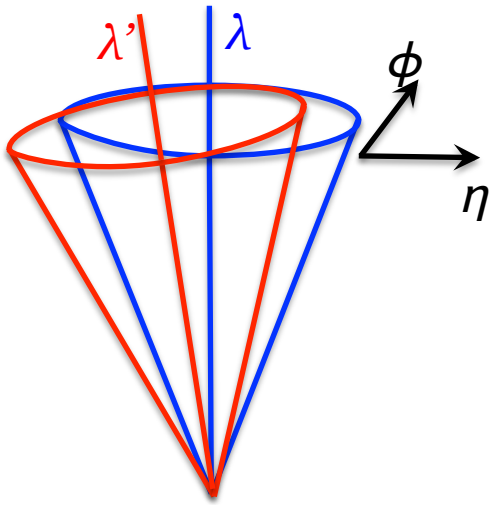




The muon isolation

Correction for close-by objects

- When two **objects are too close** (boosted decays), the activity of one object is counted in the isolation of the other and vice-versa.
- This increase of activity causes a higher rejection, even for signal events.
- Therefore, a **tool** has been implemented, which calculates the correction to remove to the isolation variables to **account for close-by objects**: the rejected signal should be recovered.



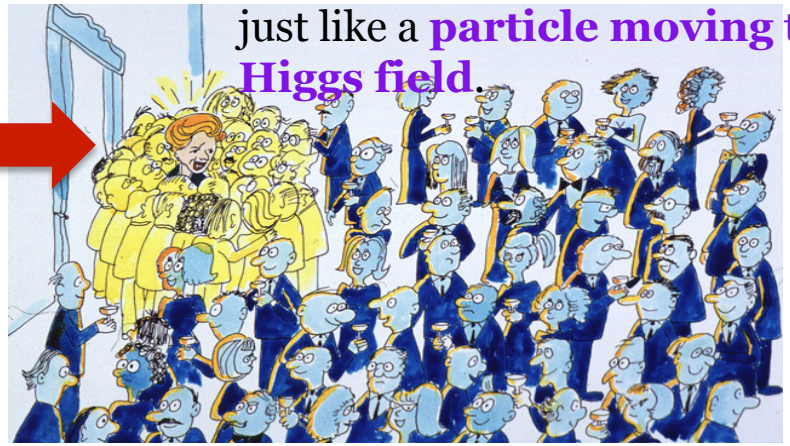
The muon isolation Summary

- Initially intended for my **qualification task**.
- Each time more data is available (**used by the whole ATLAS collaboration**):
  - We check the comparison data / MC.
  - We calculate the efficiencies of the working points.
  - We derive the scale factors.
- In parallel, I have **developed the tool** for the correction for close-by objects.
  - Growing interest in the collaboration!
- Working on optimising the isolation variables.

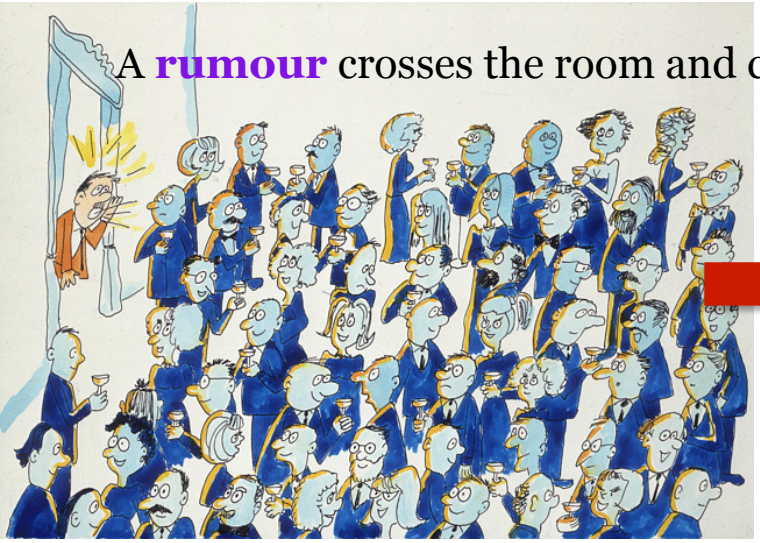
The Higgs in Run 2 The Higgs mechanism

Imagine a room full of physicists, quietly chattering. This is the space filled with the **Higgs field only**.

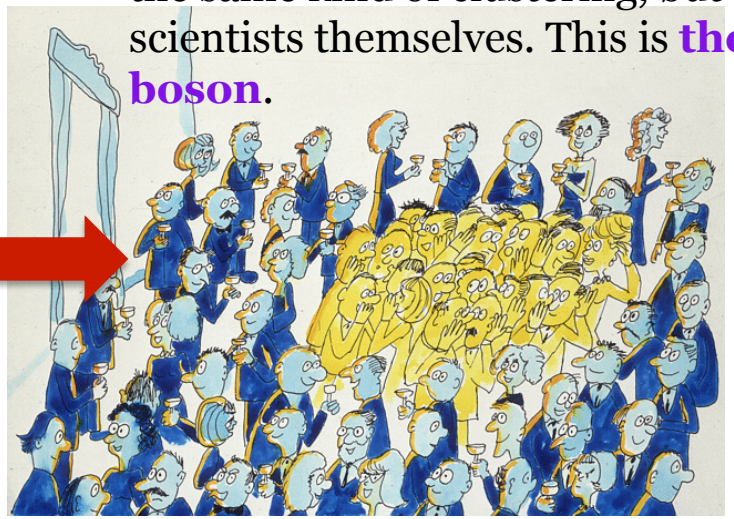
A well-known lady walks in, creating a disturbance as she moves across the room: admirers cluster around. She acquires mass, just like a **particle moving through the Higgs field**.



A **rumour** crosses the room and creates

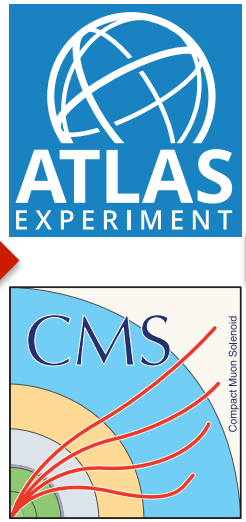


the same kind of clustering, but among the scientists themselves. This is **the Higgs boson**.



The Higgs in Run 2 From Run 1 to Run 2

Run 1 data taking



Discovery

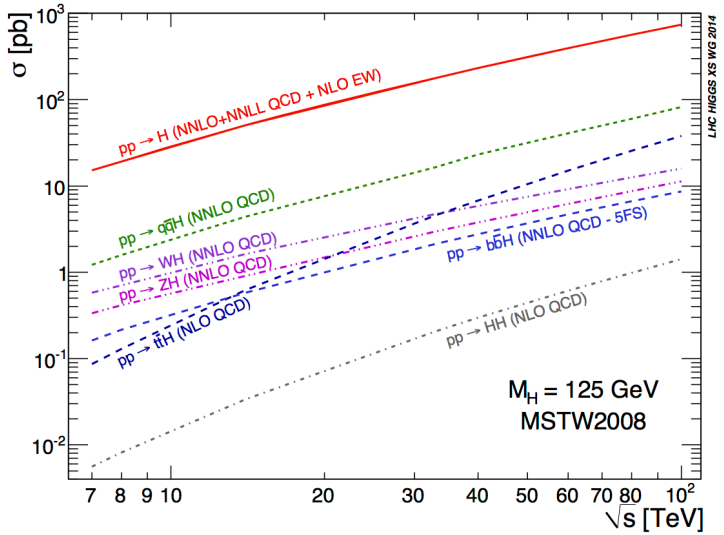
During **Run 2**, it is expected:

- to test the **validity of the Standard Model** Higgs mechanism.
  - ➢ Beyond Standard Model physics?

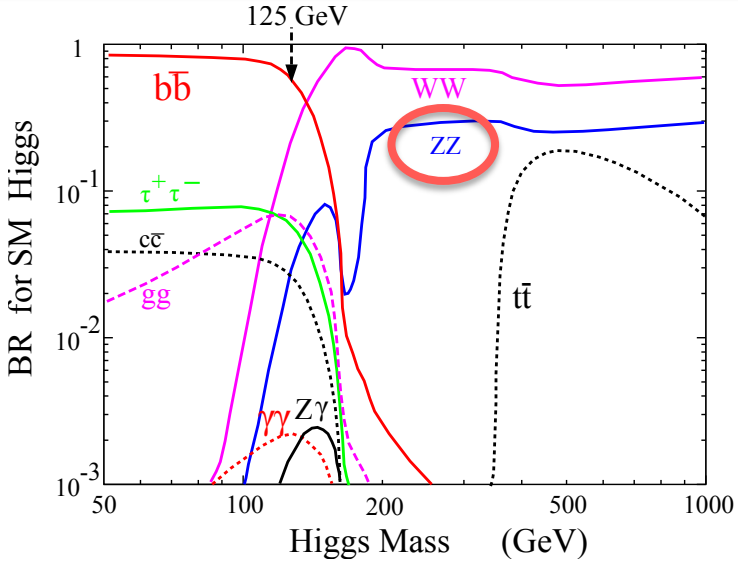
- to **precisely measure** the properties of the Higgs.

Run 2
+
PhD thesis

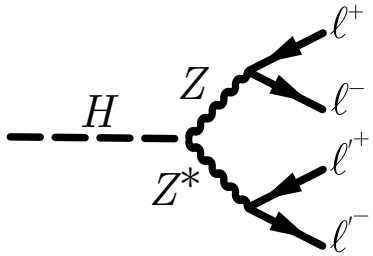
The Higgs in Run 2 My group of analysis



Production of the Higgs with centre of mass energy.



Branching ratios of the Higgs.

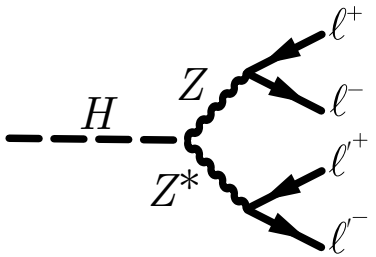


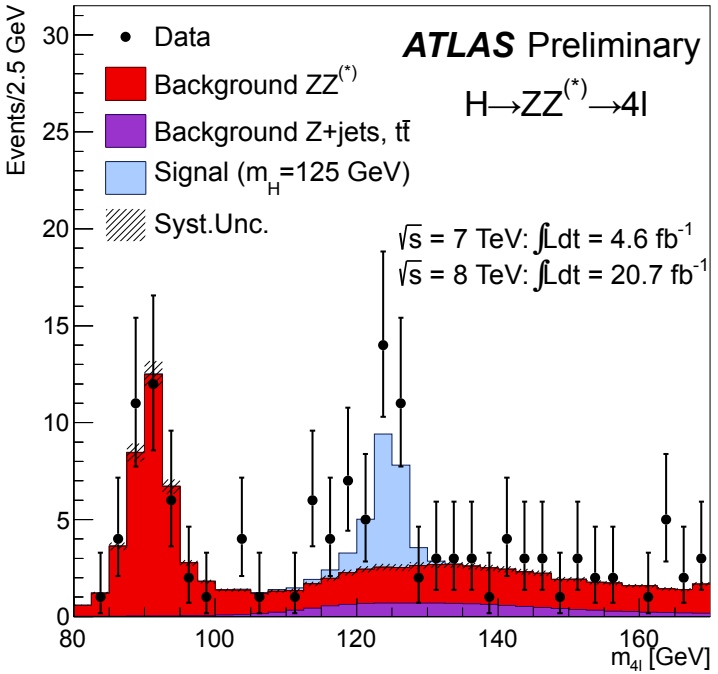
$$H \to ZZ^* \to \ell\bar{\ell}\ell'\bar{\ell}', (\ell, \ell') \in \{e, \mu\}^2$$

Possible final states: 4μ, $2\mu 2e$, $2e2\mu$, $4e$

Study of the cross-section The fiducial selection

Lepton defintion	
Muons: $p_{\mathrm{T}}^{\mu} > 5\,\mathrm{GeV}$, $\lvert\eta^{\mu}\rvert < 2.7$	Electrons: $p_{\mathrm{T}}^{e} > 7\,\mathrm{GeV}$, $\lvert\eta^{e}\rvert < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection	
Lepton kinematics:	Leading lepton $p_{\mathrm{T}} > 20, 15, 10\,\mathrm{GeV}$
Mass requirements:	$50 < m_{1,2} < 106\,\mathrm{GeV}$; $12 < m_{3,4} < 115\,\mathrm{GeV}$
Lepton separation:	$\Delta R_{\ell_i,\ell_j} > 0.1(0.2)$ for same (opposite) flavor leptons
J/ψ veto:	$m_{\ell_i,\ell_j} > 5\,\mathrm{GeV}$ for all SFOS lepton pairs
Mass window:	$115 < m_{4\ell} < 130\,\mathrm{GeV}$





- This selection aims at **imitating the selection performed on real reconstructed events**.
- The selection of reconstructed events include the ***FixedCutLoose* isolation working point for muons** and cuts on the impact parameter.

Study of the cross-section Definitions

- I work on the measurement of the **total and fiducial cross-section (XS)** of the Higgs into 4 leptons.
- The total cross-section is given by:

Branching ratio

Number of observed signal events

$$\sigma^{\text{tot}} = \frac{N_s}{\mathcal{A} \times C \times \mathcal{R} \times \mathcal{L}_{\text{int}}}$$

Integrated luminosity

- The fiducial XS (corresponding to the volume associated to the selection):

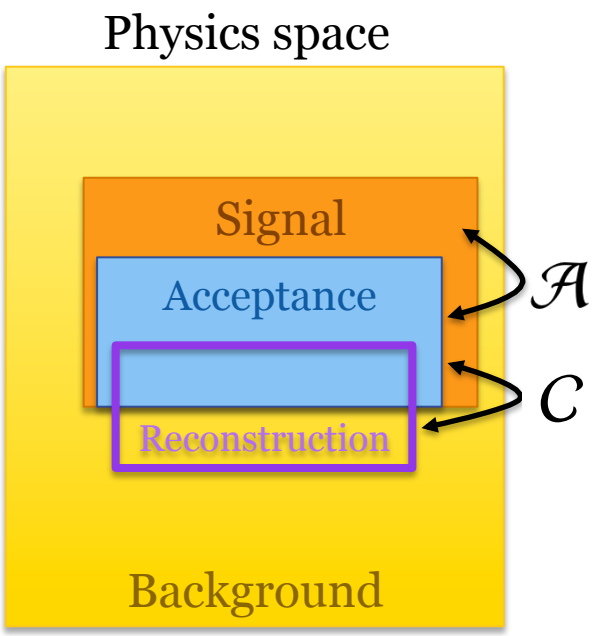
$$\sigma^{\text{fid}}_{4\ell} = \frac{N_s}{C \times \mathcal{L}_{\text{int}}}$$

- **The total and fiducial XS are linked**:

$$\sigma^{\text{tot}} = \frac{1}{\mathcal{A} \times \mathcal{R}} \sigma^{\text{fid}}_{4\ell}$$

The factors

- Two factors (introduced in the previous equations) are used:



– **The acceptance factor**: assesses the acceptance of the detector.

$$\mathcal{A} = \frac{N_{\text{Fid}}}{N_{\text{Tot}}}$$

N_{Fid}: Number of selected events (from generator particles).

N_{Tot}: Number of generated events.

– **The correction factor**: assesses the performance of the reconstruction.

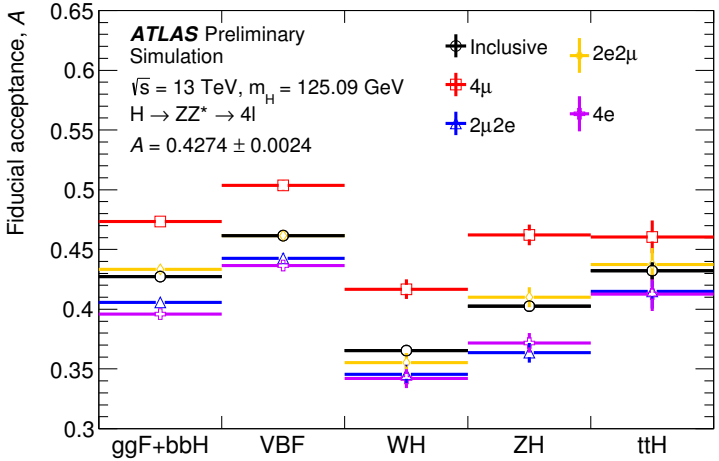
$$\mathcal{C} = \frac{N_{\text{Reco.}}}{N_{\text{Fid.}}}$$

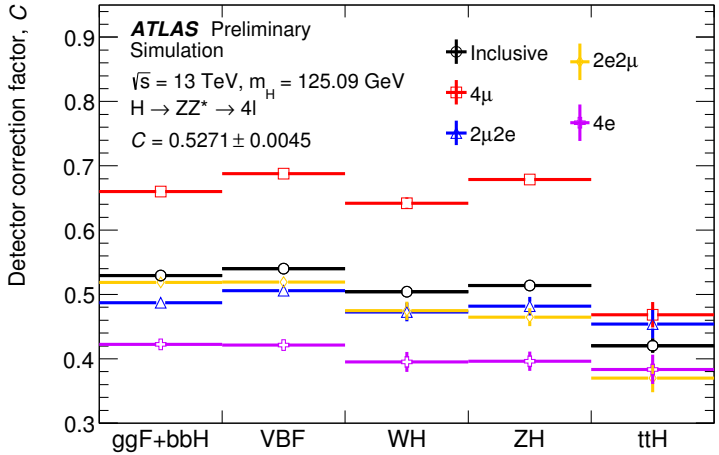
$N_{\text{Reco.}}$: Number of selected events (from reconstructed particles).

$N_{\text{Fid.}}$: Number of selected events (from generator particles).

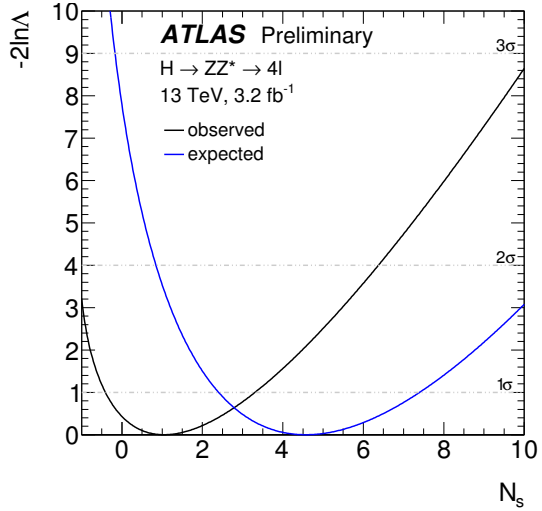
Study of the cross-section The results (EOY 2015)

- In 2015, the *A* and *C* factors have been calculated at **13 TeV**.





- This allows to infer the **fiducial and total cross-sections**.



Theoretical predictions:

	$\sqrt{s}$		
	7 TeV	8 TeV	13 TeV
$\sigma^{tot}_{theor.}$	17.5 ± 1.6 pb	22.3 ± 2.0 pb	$50.9\ ^{+4.5}_{-4.4}$ pb

Measurements at 8 TeV:

$$\sigma^{fid}_{4\ell} = 2.14\ ^{+0.53}_{-0.47}\ (stat.)\ ^{+0.10}_{-0.07}\ (syst.)\ lumi.\ fb$$

$$\sigma^{tot} = 37.0\ ^{9.5}_{-8.3}\ (stat. \oplus syst. \oplus lumi)\ pb$$

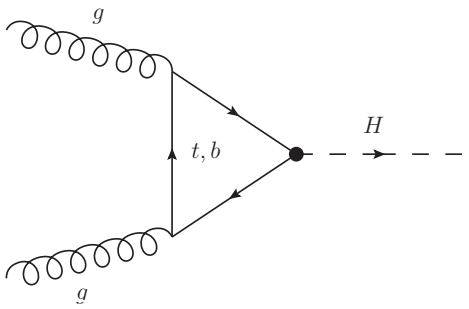
Conclusion A lot to do!

- **Continuing the study of the muon isolation with new data coming.**
  - The scale factors are used and will be used by the entire ATLAS collaboration.
  - Already one paper published: http://link.springer.com/article/10.1140%2Fepjc%2Fs10052-016-4120-y
  - The tool for the correction of isolation is growing in interest.
- **Measuring the cross section of the Higgs boson decaying into four leptons.**
  - I am responsible for a note which is being prepared for ICHEP (Summer conference).
  - For the end of the thesis, aiming at presenting the cross-section measurements with full 2015 and 2016 data at the Winter conferences.

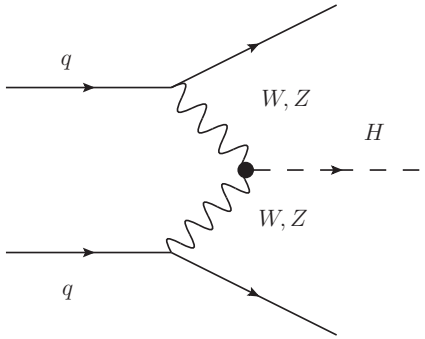
Back-up slides

For the more curious

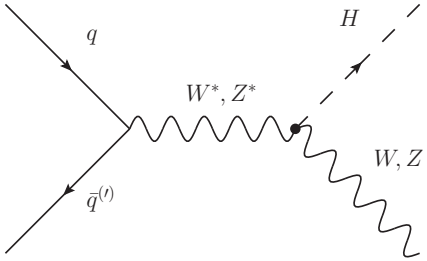
The Higgs mechanism The production modes



Gluon-gluon fusion: dominant process at LHC.



Vector boson fusion: sub-dominant process at LHC.



Associated production with *W* or *Z* bosons: was the dominant one at Tevatron.

Associated production with top quarks: lower yields.