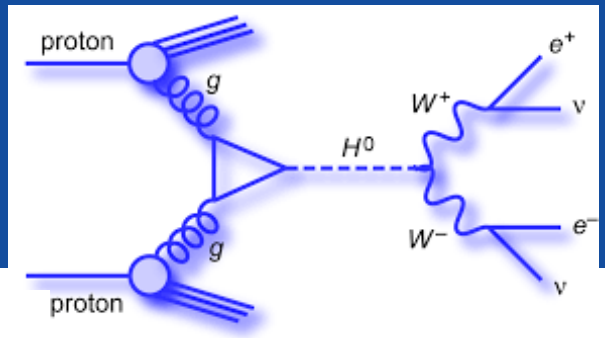
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

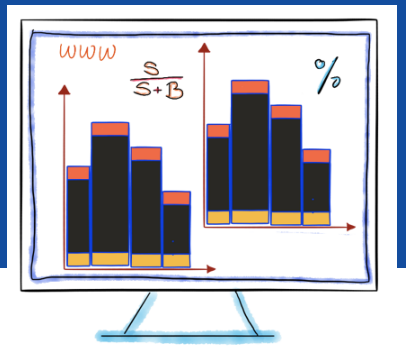
[HANDS *on* HIGGS]

Rute Pedro | 6 Feb2020

5th Lisbon mini-school on Particle and Astroparticle Physics

Rediscovering the Higgs with H→WW*→lνlν



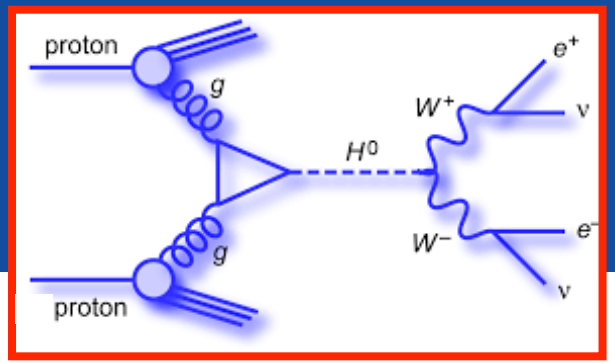


1. Set the Stage

2. Web Analysis

3. Do It Yourself

Rediscovering the Higgs with H→WW*→lνlν



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The LHC: colliding proton beams

Protons are made of 3 **valence** quarks, exchanging gluons, and a **sea** of **virtual** quark pairs

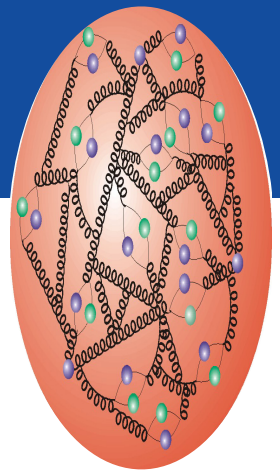
The LHC: colliding proton beams

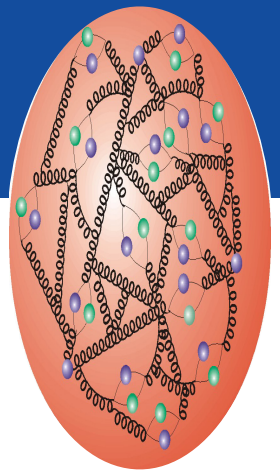
Protons are made of 3 **valence** quarks, exchanging gluons, and a **sea** of **virtual** quark pairs

The deeper we look (**more energy**, smaller distances) the more we see gluons and quarks from the sea

Only a part ***x*** of the proton's momentum intervenes in a collision. Generally $x_{proton\ 1} \neq x_{proton\ 2}$

=> The collision reference frame is boosted

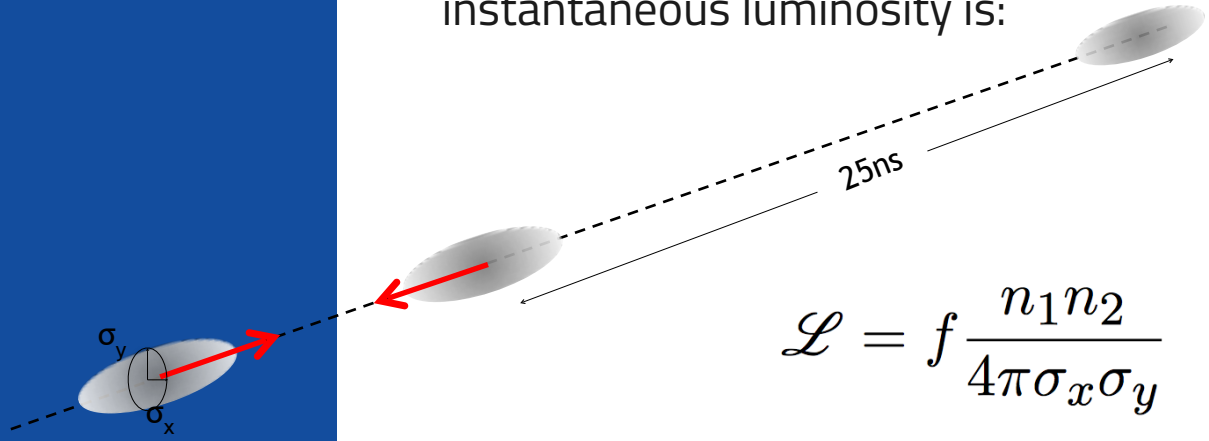




The LHC: Instantaneous Luminosity

The instantaneous luminosity measures the rate of collisions

If we collide, with a frequency f, two "bunches" with width σ_x and σ_y (rms) containing n_1 and n_2 protons, the instantaneous luminosity is:



$$\mathscr{L} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

inverse area and time units
usually: [cm^{-2} s^{-1}], [b^{-1} s^{-1}]

The LHC: Integrated Luminosity

The expected number of events N_{exp} for a certain process is given by the product of the integrated luminosity and the cross section σ_{exp}

We needed around 10.6 fb^{-1} to discover the Higgs boson!
(4.8 fb^{-1} at 7 C.o.M. energy and 5.8 fb^{-1} at 8 TeV)

$$N_{exp} = \sigma_{exp} \times \int \mathscr{L}(t)dt$$

area units
usually: [cm^2,b]

inverse area units
usually: [cm^{-2}], [b^{-1}]

Q: Luminosity

At the LHC, proton bunches collide every 25ns

Each bunch has 10^{11} protons and a radius of 11.1μm (rms)

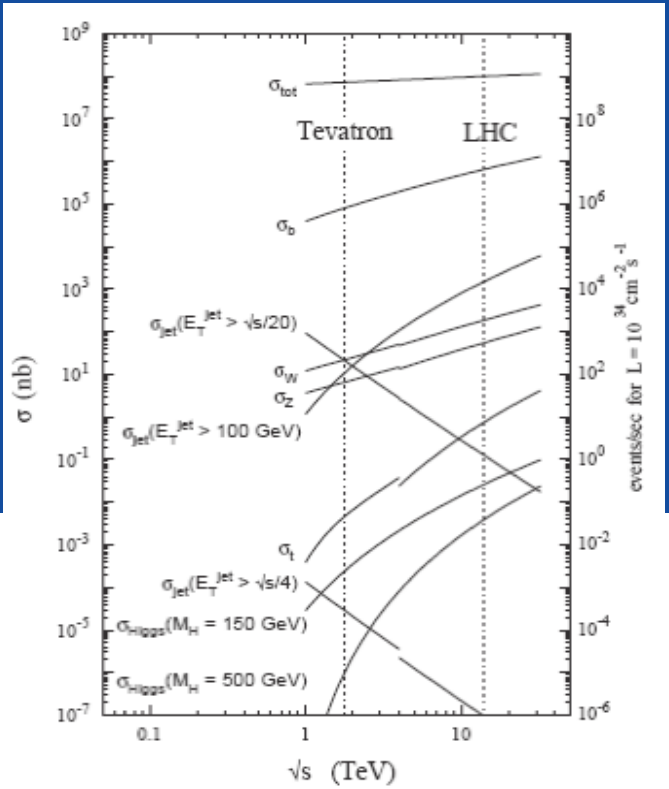
The LHC is a 27km ring

- What is the instantaneous luminosity measured by the CMS experiment?
- If the inclusive cross section for Z boson production is 28nb, how many are produced per second in ATLAS?
- In 20fb^{-1}, how many Higgs bosons were produced during LHC run 1 if the inclusive cross section is 20pb?
- How many proton bunches fit in the LHC?

The LHC: experiments and trigger

25 ns bunch crossing
- Means 40 million crossings per second
- Each collision ≈1.5MBytes
- Means > 60TB per second

Impossible to keep all these data
- And unnecessary!
- Most collisions are boring (99%)

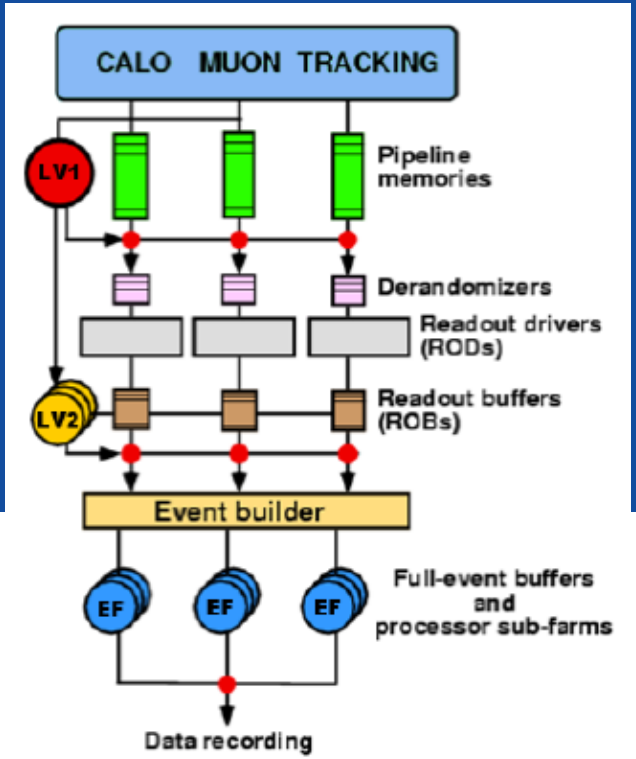


The LHC: experiments and trigger

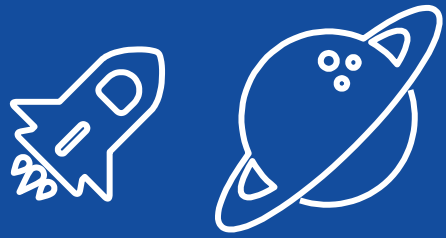
25 ns bunch crossing
- Means 40 million crossings per second
- Each collision ≈1.5MBytes
- Means > 60TB per second

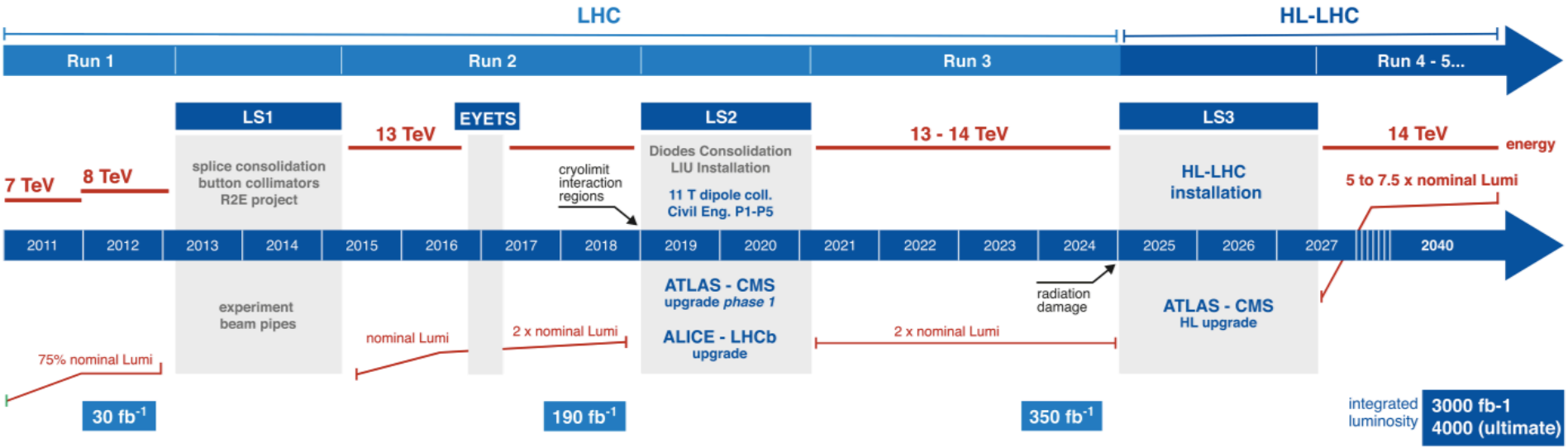
Use the trigger system to keep only 1 collision for every 40 000

But need to decide in 2.5μs for the first trigger level!!



BIG DATA




LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
13 - 14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
11 T dipole coll.
Civil Eng. P1-P5
HL-LHC
installation
5 to 7.5 x nominal Lumi
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2040
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
radiation
damage
ATLAS - CMS
HL upgrade
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
30 fb-1
190 fb-1
350 fb-1
integrated
luminosity
3000 fb-1
4000 (ultimate)

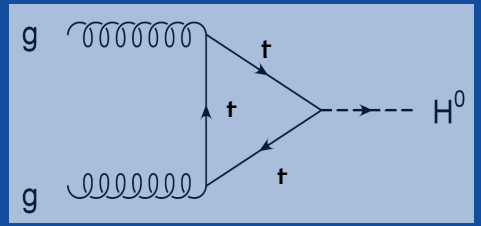
Higgs production at the LHC

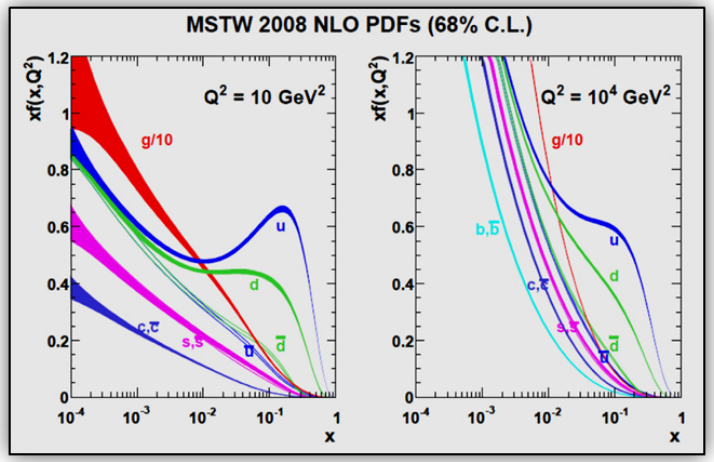
The Higgs couples to particles with mass:

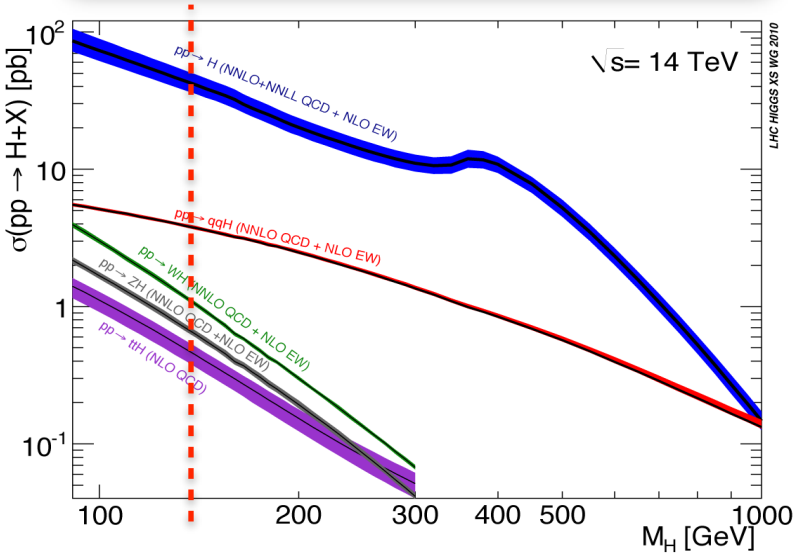
- Fermions or weak bosons, but not (directly) gluons or photons
- But there are many gluons in our beams …

Largest cross section is “gluon fusion”

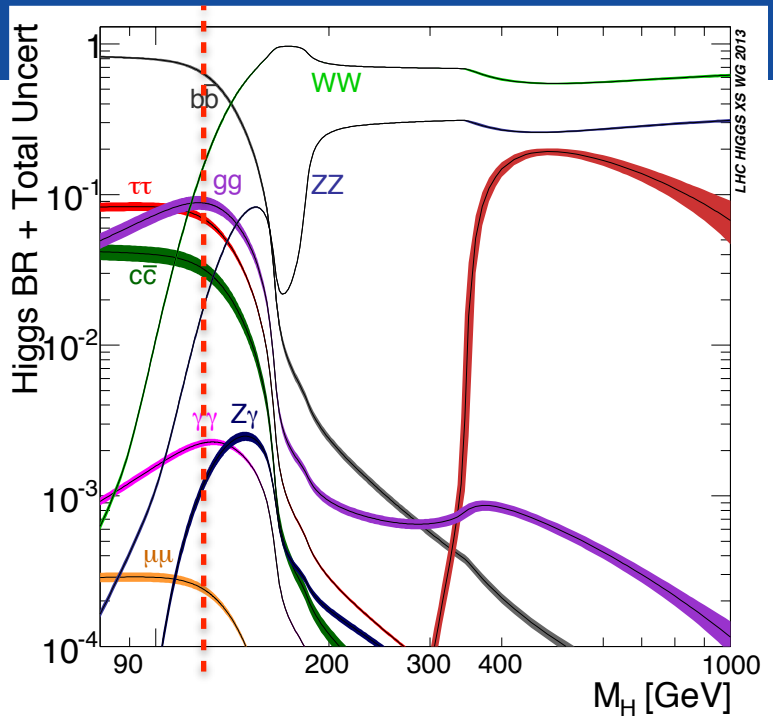
- Loop is dominated by virtual top quarks







Higgs decay

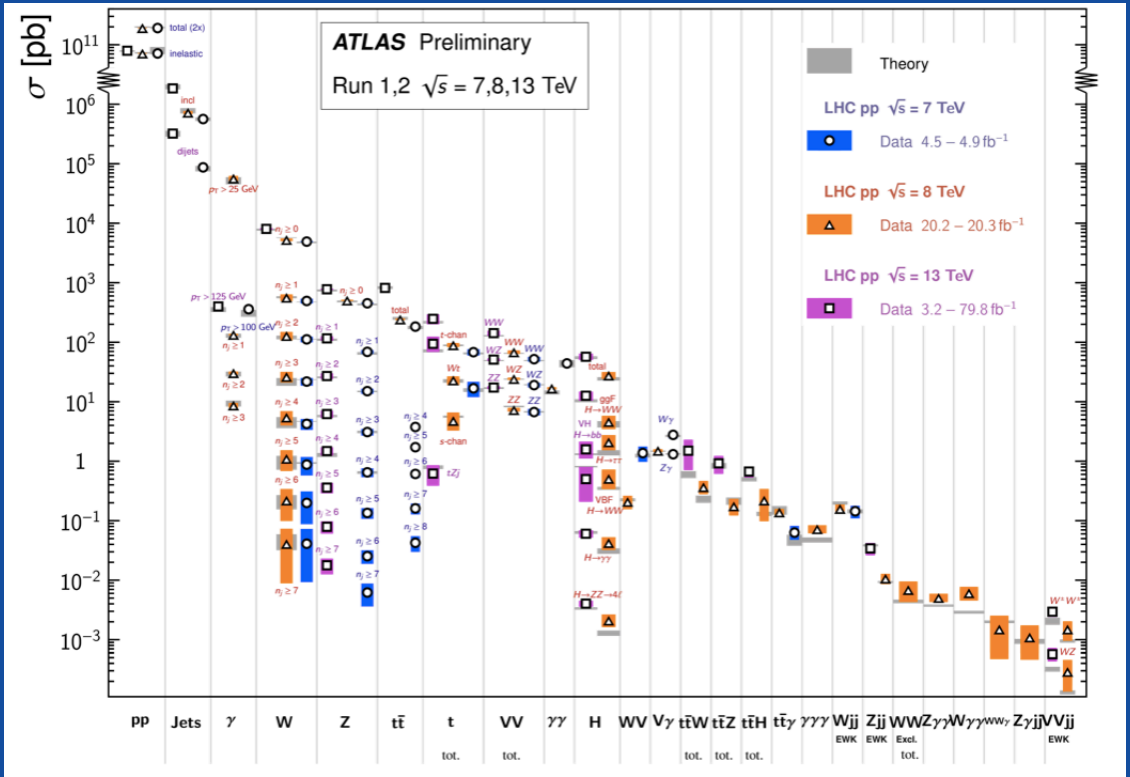


With the mass of m_H=125GeV, the Higgs boson decays mostly to b quarks

But it is basically impossible to separate this signal from the b-quark production background (10^6 times more frequent!...)

H⟶γγ decays through W & top dominated loop

Finding a needle in a haystack



Q: The Higgs at the LHC

The centre of mass energy during the LHC run 1 was 7 and 8 TeV

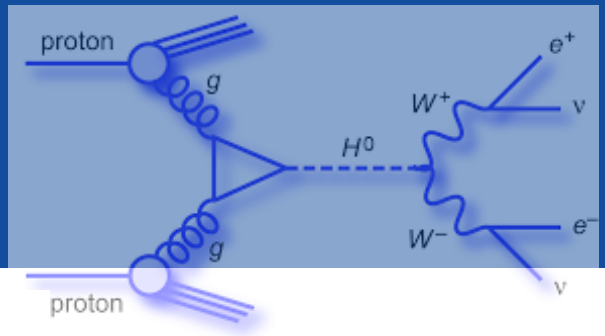
The integrated luminosity needed for the Higgs discovery was 4.8 fb^{-1} at c.o.m. 7 TeV and 5.8 fb^{-1} at 8 TeV

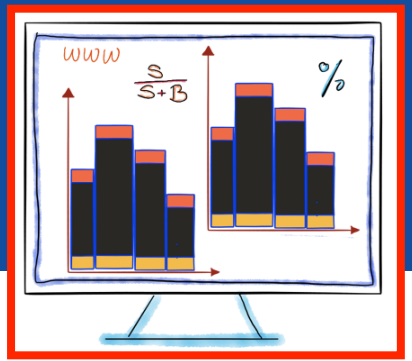
The calculated Higgs production cross section is 17.4 pb at 7 TeV and 22.3 pb at 8 TeV

The Branching Ratio BR of $H \rightarrow WW^*$ is 0.214 and the BR of $W \rightarrow l\nu$ is 0.327

- How many Higgs bosons were expected at the LHC discovery data set?
- How many of those decayed into 2 W bosons?
- And how many went through the full decay chain of $H \rightarrow WW^* \rightarrow l\nu l\nu$?
- If the Higgs coupling is proportional to the particle's mass, why is BR($H \rightarrow bb$) larger than BR($H \rightarrow WW^*$)?

Rediscovering the Higgs with H→WW*→lνlν





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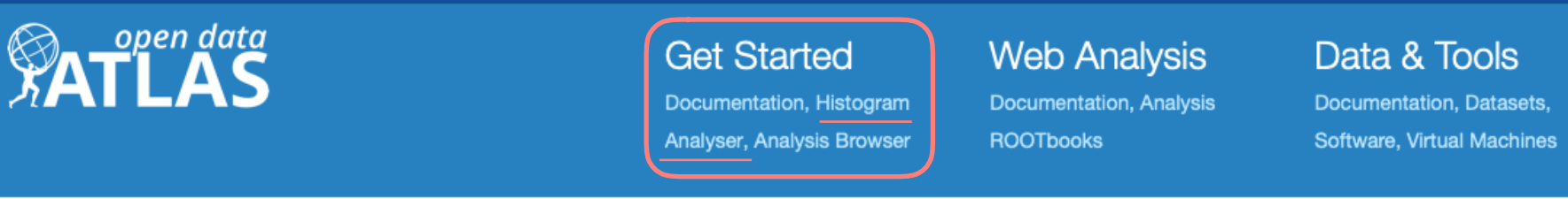
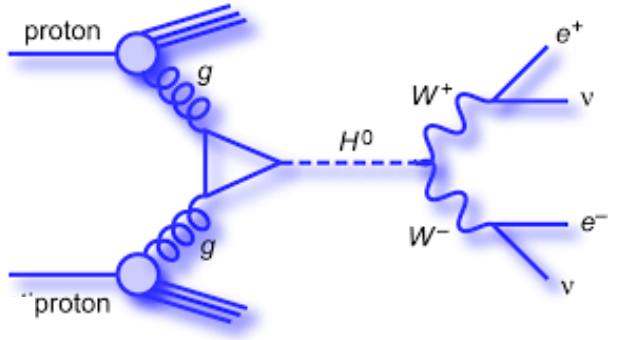
Searching for H→WW*→lνlν in the ATLAS Open Data

http://opendata.atlas.cern/visualisations/analyser-js.php



The ATLAS data from 100 trillion proton collisions is now public!

H→WW*→lνlν
in the history of the Higgs discovery



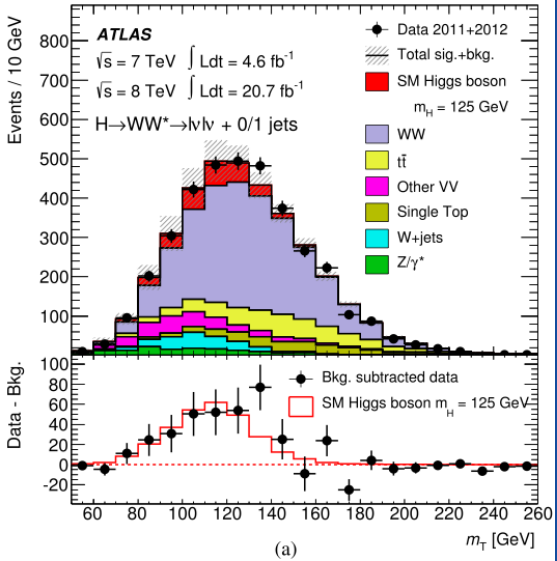
H→WW*→lνlν was one of the golden channels of the Higgs discovery in 2012

Two other processes contributed:

- H→γγ
- H→ZZ*→llll

They provide clean signals in the detector:

- photons
- electrons, muons
- large missing energy (neutrinos)



https://arxiv.org/pdf/1207.7235.pdf

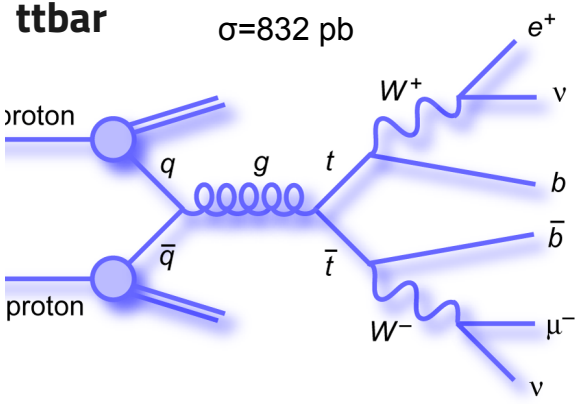
https://arxiv.org/pdf/1207.7214.pdf

Background processes

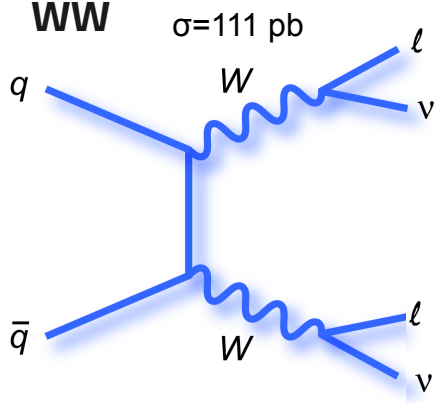
Many other processes have similar final states
And they have much larger cross sections

The task of particle physics experimentalists is to find ways to select signal an discard background events

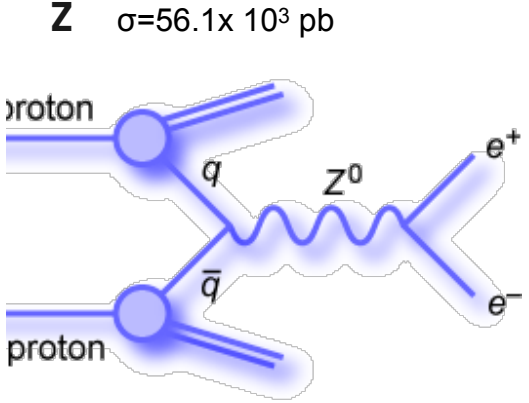
ttbar σ=832 pb



WW σ=111 pb



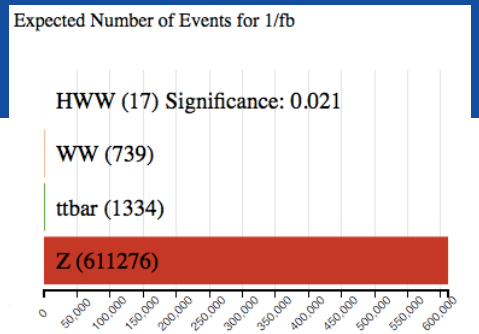
Z σ=56.1x 10^3 pb

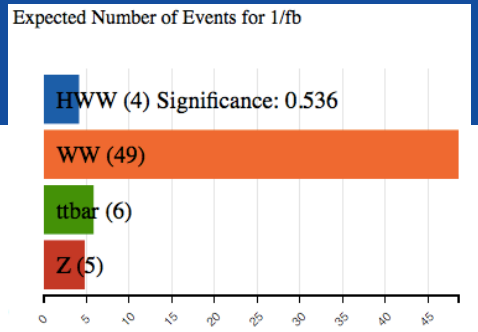


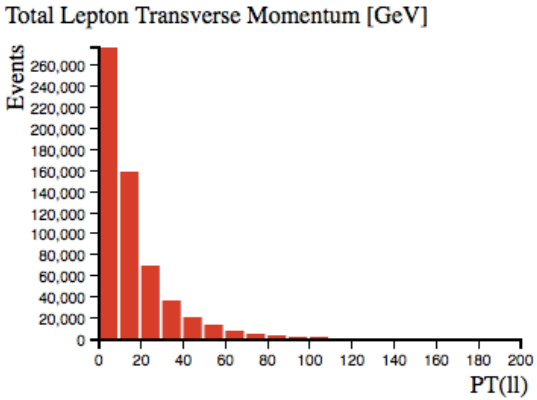
Signal significance

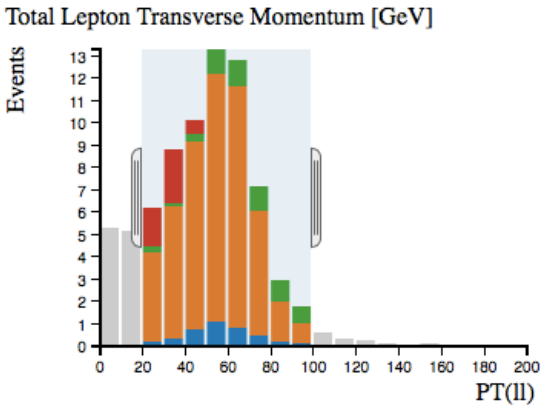
Physicists study how to select events of interest and discard background events => increase sensitivity

If S is the number of signal events and B the number of background events, the signal significance is: $\frac{S}{\sqrt{S+B}}$







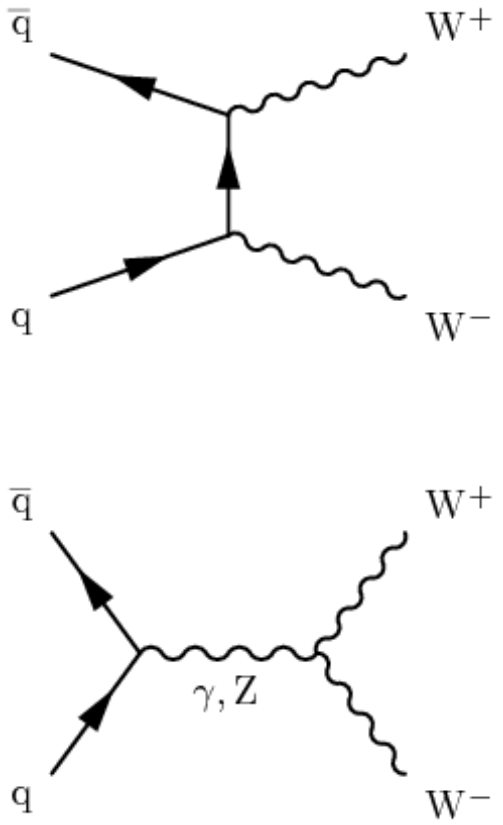


WW background

More than one production mechanism:

- $q\bar{q} \rightarrow W^+W^-$ (dominant)
- $\gamma\gamma \rightarrow W^+W^-$
- $gg \rightarrow W^+W^-$

Ws have opposite electric charge (same sign production is also possible but at much lower rate)



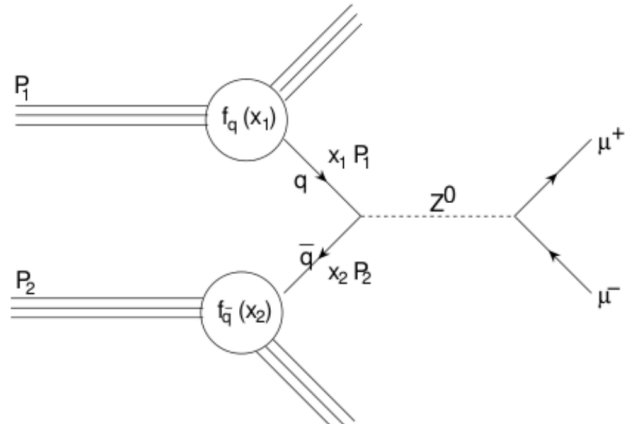
Z background

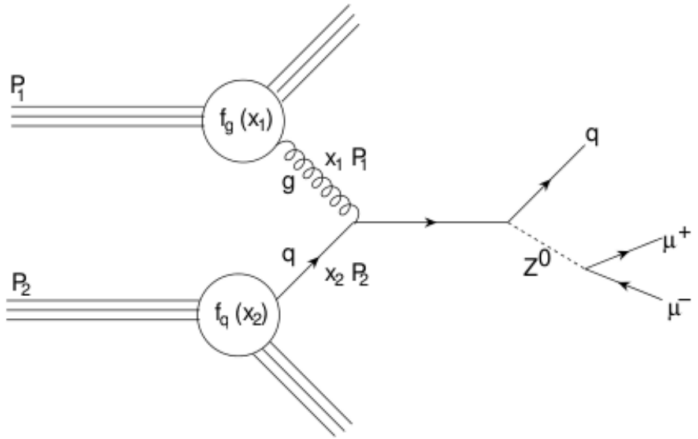
Production:

- Drell-Yan q\q→Z (65%)
- qg→Zq (35%)

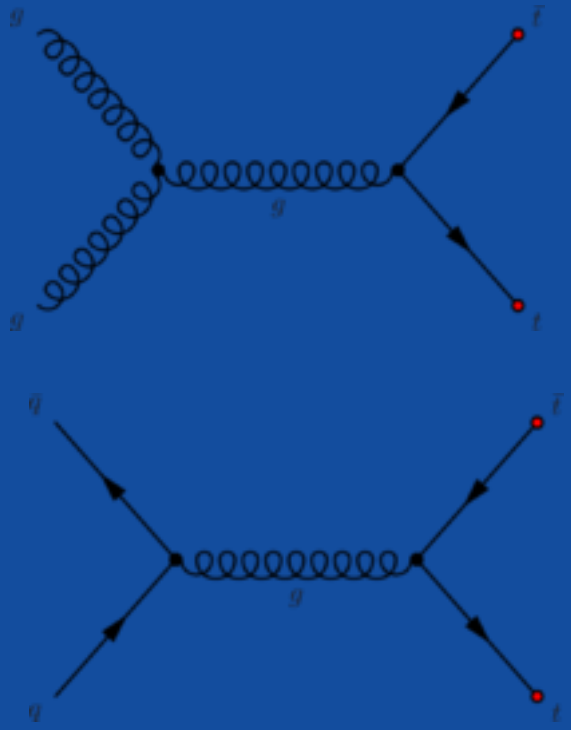
The Z boson has 0 electric charge an decays to:

- quark-antiquark pairs (~70%)
- neutrino-antineutrino (~20%)
- charged lepton pairs (10%)



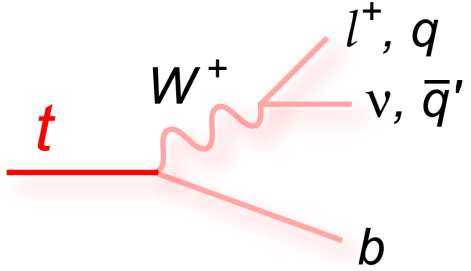


Top pairs background



Other quarks hadronise when produced freely

But the top decays decays basically imediately into a W and a b-quark (>99%) via weak interaction



Top pairs have multiple possible final states

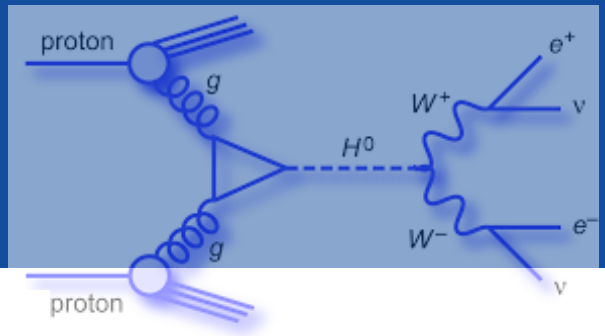
Q: Web Analysis

What variables and cuts did you use to select the signal and improve it’s significance?

Which cut helped you more removing the Z background?

What signal significance did you reach?

Rediscovering the Higgs with H→WW*→lνlν



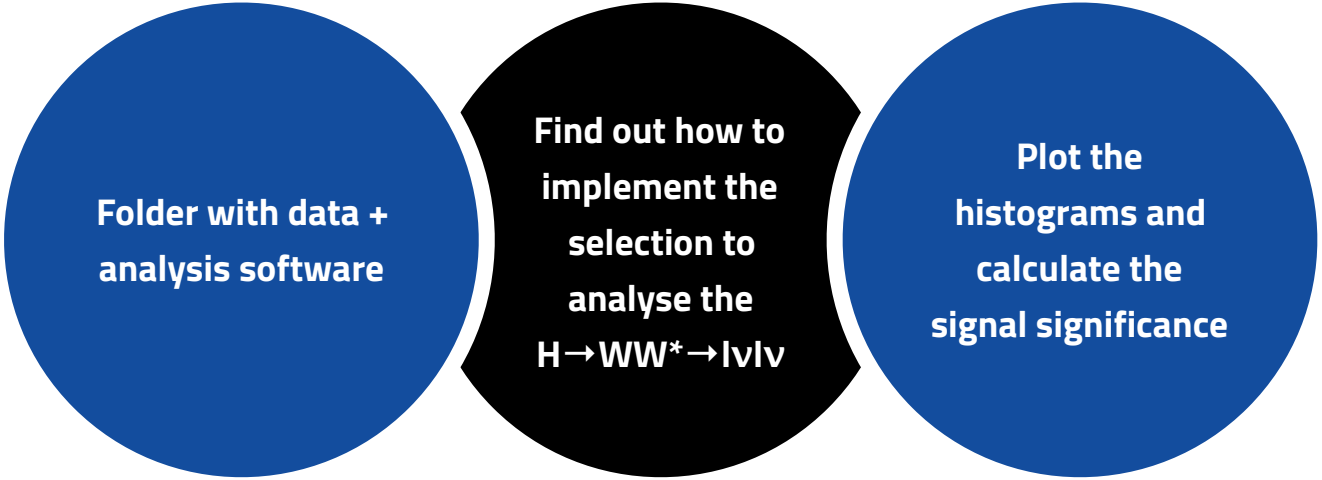
1. Set the Stage

2. Web Analysis

3. Do It Yourself

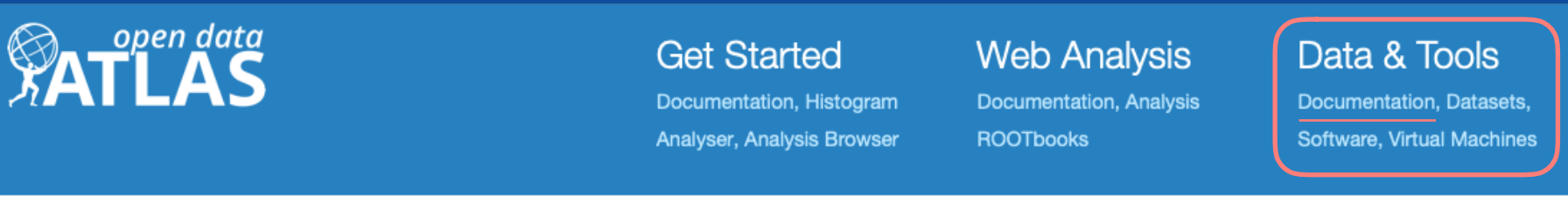
Coding up

your own Higgs discovery



Searching for H→WW*→lνlν in the ATLAS Open Data

http://opendata.atlas.cern/extendedanalysis/documentation.php



Online Software Documentation

Data and Analysis Software

```
[rute@fermi02 ~/lstore/tutorial_Caparica/ATLAS-OpenDataAndTools 14:37 > ls -1
Analysis ..... Definition of the Analyses Classes
Configurations ..... Configuration of the Analyses and Plotting
Input ..... Simulation and Real Data
Output ..... Default Output Plots Directory
PlotResults.py ... Script to plot the analysis histograms
Plotting ..... Configuration of the Plotting Style, etc...
README.md
RunScript.py ..... Script to run the analysis
```

How To: Run the analysis

```
rute@fermi02 ~/lstore/tutorial_Caparica/ATLAS-OpenDataAndTools 14:40 > python RunScript.py -a HWWAnalysis

--------------------DISCLAIMER--------------------
This Software is intended for educational use only!
Under no circumstances does it qualify to reproduce
actual ATLAS analysis results or produce publishable
results!
--------------------------------------------------

Wed Feb  5 14:40:22 2020 Job WtaunuWithB: Intialization phase

Basic .rootlogon.C script
 .rootlogon.C script finished.
Wed Feb  5 14:40:23 2020 Job WtaunuWithB: Adding file: Input/MC/mc_167746.WtaunuWithB.root
Error in <TTree::SetBranchStatus>: unknown branch -> jet_flag
Error in <TChain::SetBranchAddress>: unknown branch -> jet_flag
Wed Feb  5 14:40:23 2020 Job WtaunuWithB: Now looping over 10000 events
Wed Feb  5 14:40:24 2020 EventStatistics WtaunuWithB.HWWAnalysis: +-------------------------------------------------------------+
Wed Feb  5 14:40:24 2020 EventStatistics WtaunuWithB.HWWAnalysis: |                 all :                10000 :          2515.21 |
Wed Feb  5 14:40:24 2020 EventStatistics WtaunuWithB.HWWAnalysis: |              no cut :                10000 :          2515.21 |
Wed Feb  5 14:40:24 2020 EventStatistics WtaunuWithB.HWWAnalysis: |           EventCuts :                 9937 :          2498.12 |
Wed Feb  5 14:40:24 2020 EventStatistics WtaunuWithB.HWWAnalysis: |                Jets :                    1 :             0.07 |
Wed Feb  5 14:40:24 2020 EventStatistics WtaunuWithB.HWWAnalysis: |   2 high pt Leptons :                    1 :             0.07 |
Wed Feb  5 14:40:24 2020 EventStatistics WtaunuWithB.HWWAnalysis: +-------------------------------------------------------------+
Wed Feb  5 14:40:24 2020 Job WtaunuWithB: finished successfully. Total time:    2s
```

How To: Implement the Event Selection

Edit the **Analysis/HWWAnalysis.py** file:

```
# Definition of variables for the selection (Energy/Momentum quantities given in GeV)
combTLV = leadLepton.tlv() + trailLepton.tlv()  # This is the system composed of the two leptons
mll     = combTLV.M()                           # Mass of the 2 lepton system
ptll    = combTLV.Pt()                          # Transverse momentum of the 2 lepton system
leadLepCharge  = leadLepton.charge()            # Electrical charge of the leading lepton
trailLepCharge = trailLepton.charge()           # Electrical charge of the sub-leading lepton
leadLepID  = abs(leadLepton.pdgId())            # PDG ID of the leading lepton (11 for electrons, 13 for muons)
trailLepID = abs(trailLepton.pdgId())           # PDG ID of the sub-leading lepton (11 for electrons, 13 for muons)
met = etmiss.et()                               # Missing Transverse Momentum
deltaPhiMETll = combTLV.DeltaPhi(etmiss.tlv())  # Azymuthal angular separation between the MET and 2 lepton system in radians
#deltaPhill    =  ???????                       # Azymuthal angular separation between the 2 leptons


## EXERCISE BLOCK: IMPLEMENT EVENT SELECTION FOR SIGNAL DETECTION AND BACKGROUND REJECTION

# EX: select events with oposite charged leptons
if leadLepCharge*trailLepCharge > 0: return False
self.countEvent("Oposite charged leptons", weight)  # To count events that pass this cut









## END EXERCISE BLOCK
```

Useful Tips

While prototyping your solution:

- Configure the analysis to run over a fraction of events (ex. 10%)
- Adjust "**Fraction**" in the **Configurations/Configuration.py** file:

```
Job = {
    "Batch"           : True,
    "Analysis"        : "HWWAnalysis",
    "Fraction"        : 0.1,
    "MaxEvents"       : 1234567890,
    "OutputDirectory" : "results/"
}
```

- Run over **selected samples**:

```
ATLAS-OpenDataAndTools 15:27 > python RunScript.py -a HWWAnalysis -s ggH125_WW2lep,Zee
```

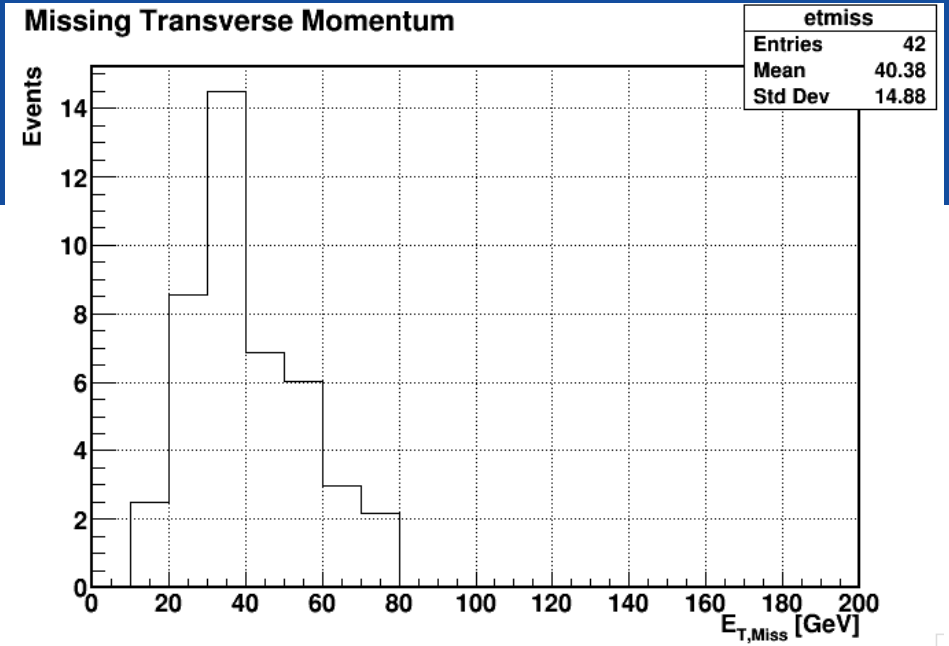
How To: Explore your results

```
rute@fermi02 ~/lstore/tutorial_Caparica/ATLAS-OpenDataAndTools 15:55 > root -l results/ggH125_WW2lep.root

Basic .rootlogon.C script
 .rootlogon.C script finished.
root [0]
Attaching file results/ggH125_WW2lep.root as _file0...
(TFile *) 0x38093e0
root [1] .ls
TFile**         results/ggH125_WW2lep.root
 TFile*         results/ggH125_WW2lep.root
  KEY: TH1D     pvxp_n;1        Number of Vertices
  KEY: TH1D     deltaphill;1    Azimuthal Opening Angle between Leptons
  KEY: TH1D     leadlep_ptconerel30;1   Leading Lepton Relative Transverse Momentum Isolation
  KEY: TH1D     traillep_etconerel20;1  Trailing Lepton Relative Transverse Energy Isolation
  KEY: TH1D     etmiss;1        Missing Transverse Momentum
  KEY: TH1D     leadlep_type;1  Leading Lepton Absolute PDG ID
  KEY: TH1D     traillep_E;1    Trailing Lepton Energy
  KEY: TH1D     traillep_type;1 Trailing Lepton Absolute PDG ID
  KEY: TH1D     vismass;1       Visible Mass
  KEY: TH1D     leadlep_eta;1   Leading Lepton Pseudorapidity
  KEY: TH1D     leadlep_etconerel20;1   Leading Lepton Relative Transverse Energy Isolation
  KEY: TH1D     traillep_phi;1  Trailing Lepton Azimuthal Angle
  KEY: TH1D     traillep_d0;1   Trailing Lepton d0 impact parameter
```

How To: Explore your results

```
root [3] etmiss->Draw("hist")
Info in <TCanvas::MakeDefCanvas>:  created default TCanvas with name c1
```



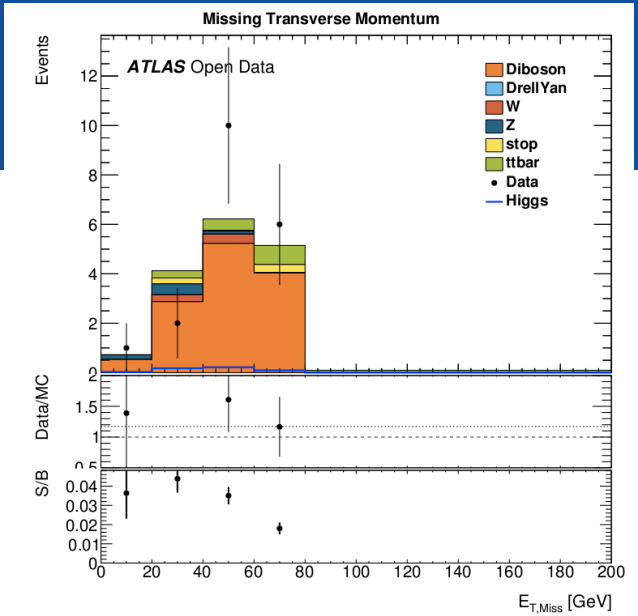
How To: Plot your histograms

```
rute@fermi02 ~/lstore/tutorial_Caparica/ATLAS-OpenDataAndTools 16:18 > python PlotResults.py Configurations/PlotConf_HWWAnalysis.py

Basic .rootlogon.C script
 .rootlogon.C script finished.
Drawing plot: traillep_pt
Info in <TCanvas::Print>: pdf file Output/traillep_pt.pdf has been created
Drawing plot: leadlep_ptconerel30
Info in <TCanvas::Print>: pdf file Output/leadlep_ptconerel30.pdf has been created
Drawing plot: traillep_etconerel20
Info in <TCanvas::Print>: pdf file Output/traillep_etconerel20.pdf has been created
Drawing plot: pvxp_n
Info in <TCanvas::Print>: pdf file Output/pvxp_n.pdf has been created
Drawing plot: leadlep_type
Info in <TCanvas::Print>: pdf file Output/leadlep_type.pdf has been created
Drawing plot: traillep_E
Info in <TCanvas::Print>: pdf file Output/traillep_E.pdf has been created
Drawing plot: vismass
Info in <TCanvas::Print>: pdf file Output/vismass.pdf has been created
Drawing plot: leadlep_eta
```

How To: Display your plots

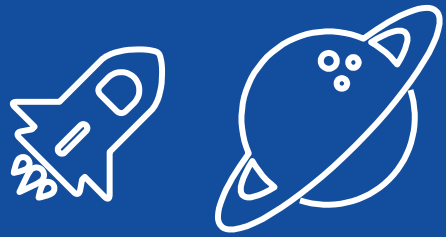
```
[rute@fermi02 ~/lstore/tutorial_Caparica/ATLAS-OpenDataAndTools 16:26 > evince Output/etmiss.pdf
```



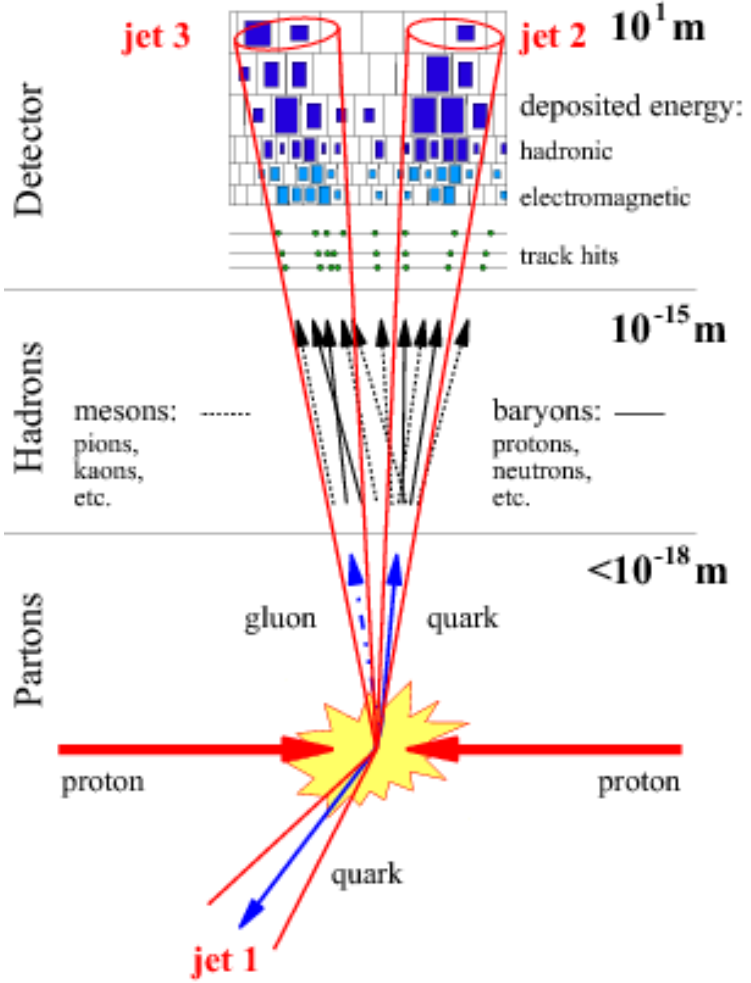
Acknowledgements

POCI/01-0145-FEDER-029147 PTDC/FIS-PAR/29147/2017

EXTRA SLIDES

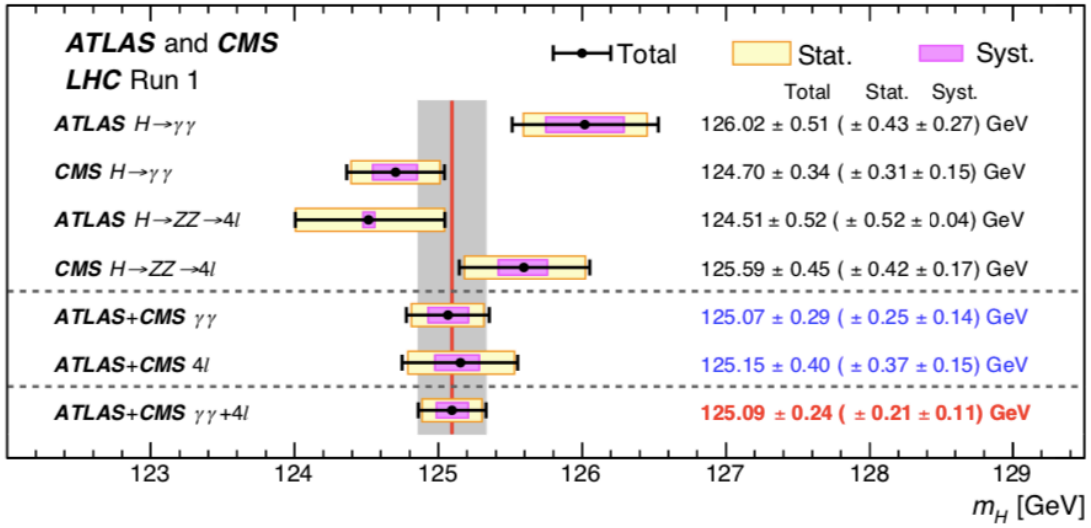


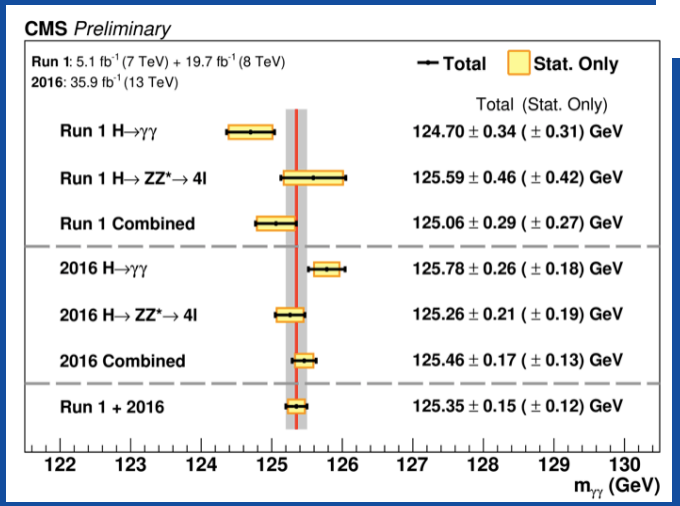
A word about jets



Higgs mass

https://arxiv.org/pdf/1503.07589.pdf

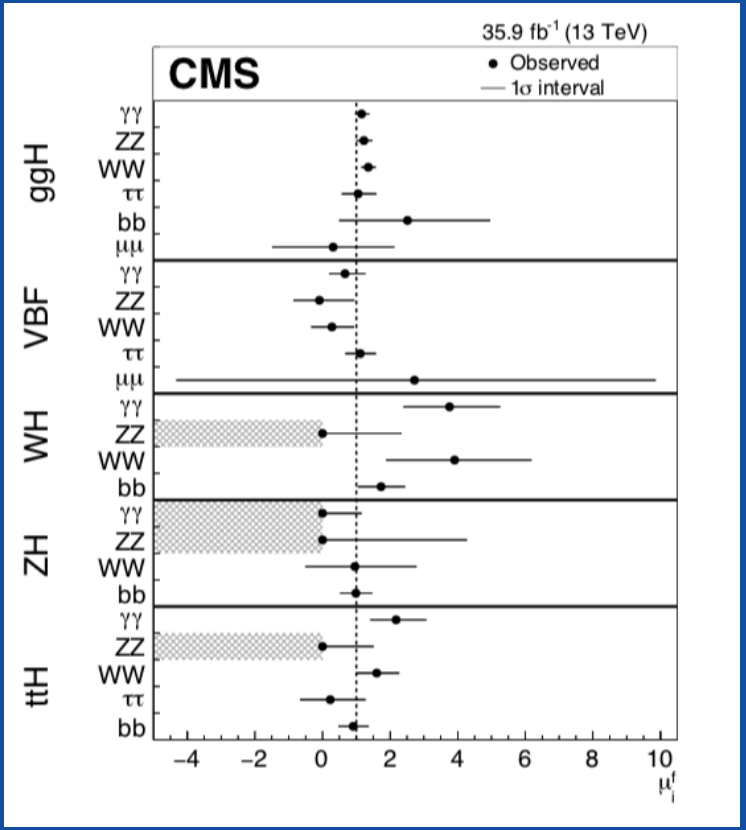


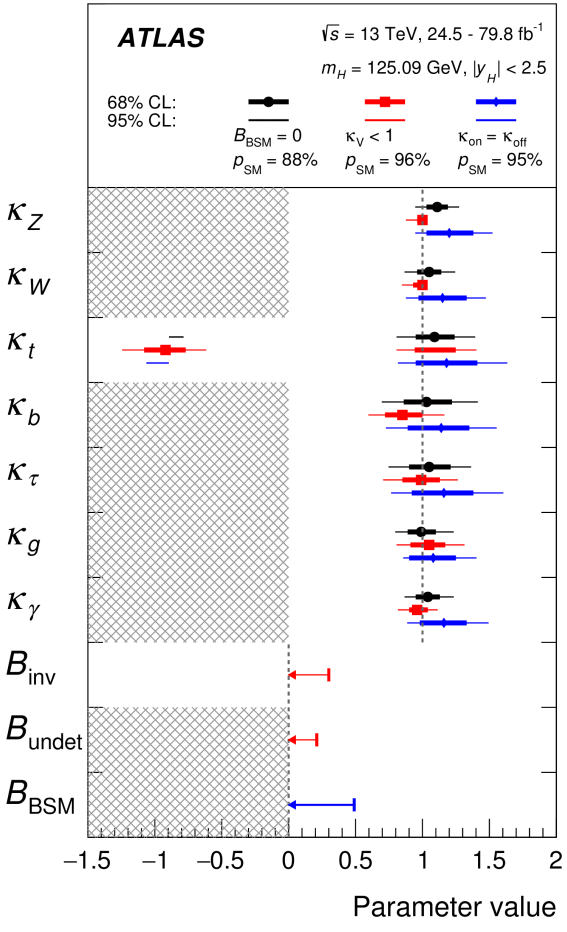


New mass measurement at unprecedented precision from the CMS experiment

https://cms.cern/news/cms-precisely-measures-mass-higgs-boson

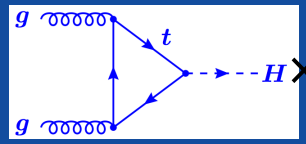
Higgs couplings



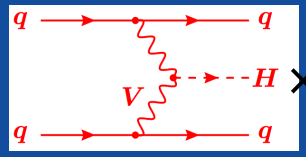


Combining Higgs analyses

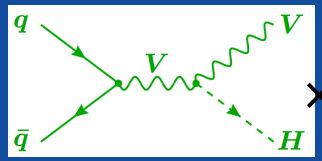
Production



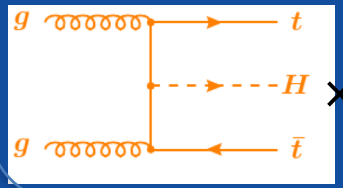
$\times\kappa_g^2$



$\times\kappa_{W/Z}^2$



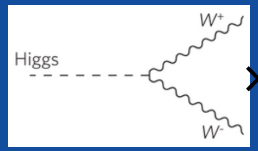
$\times\kappa_{W/Z}^2$



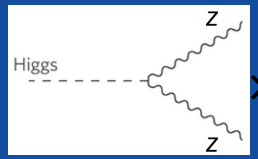
$\times\kappa_t^2$

$\times$

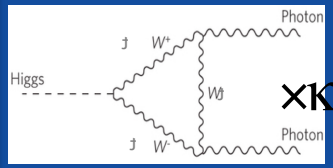
Decay



$\times\kappa_W^2$



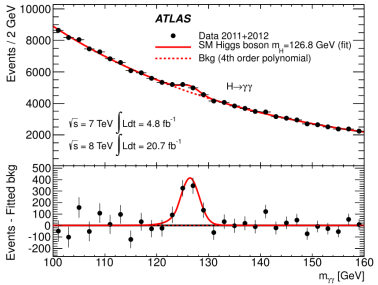
$\times\kappa_Z^2$



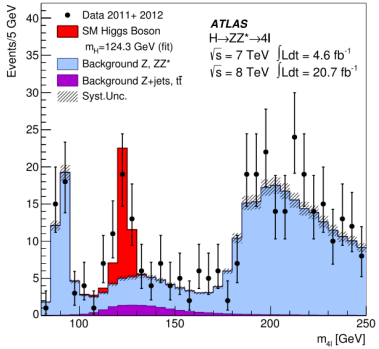
$\times\kappa_\gamma^2$

FIT

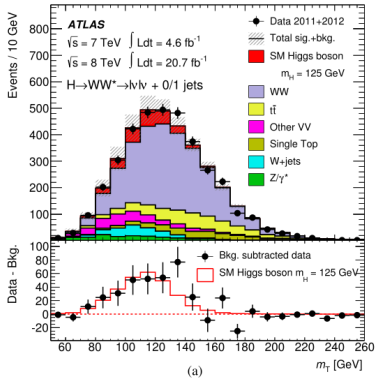
Backgrounds +



H->γγ



H->ZZ



H->WW