LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

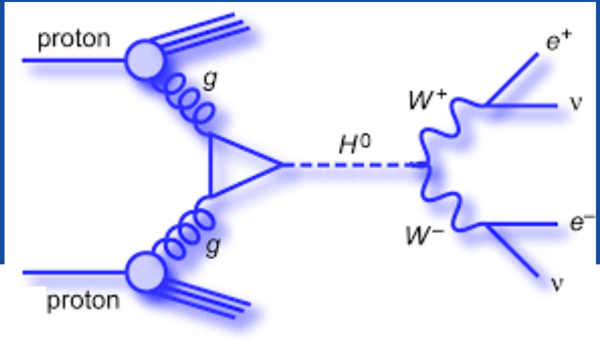
[HANDS *on* HIGGS]

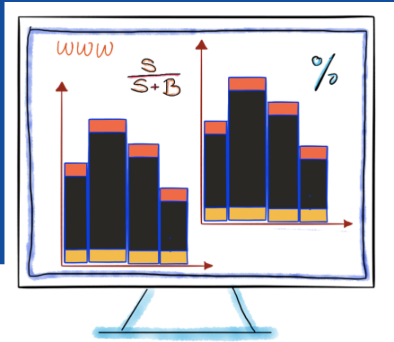
Rute Pedro | 14th May 2022

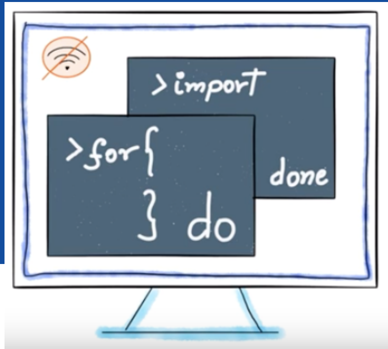
7th Mini-school on Particle and Astroparticle Physics

Rediscovering the Higgs

with H→WW*→lvlv and H→ZZ*→llll







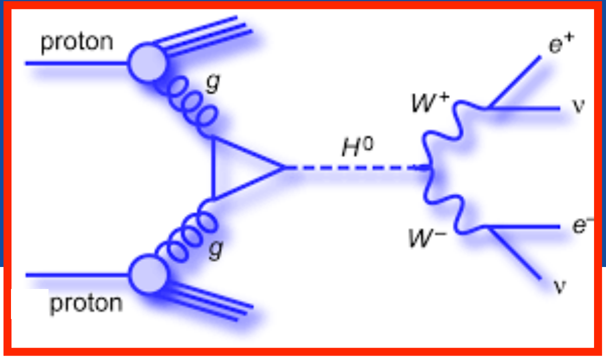
1. Set the Stage

2. Web Analysis

3. Code It Yourself

Rediscovering the Higgs

with H→WW*→lvlv and H→ZZ*→llll



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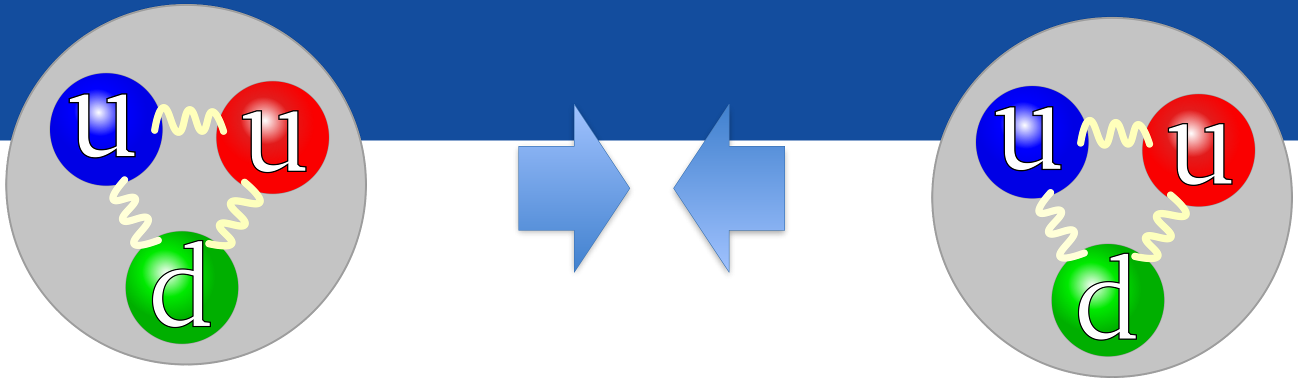
The LHC: colliding proton beams

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



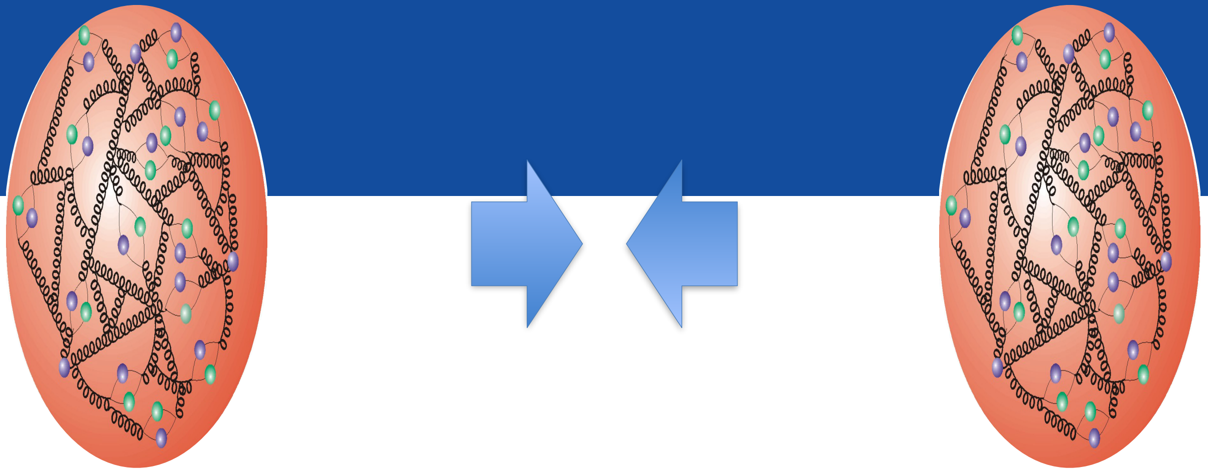
The LHC: colliding proton beams

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 $x_{\text{proton 1}} \neq x_{\text{proton 2}}$

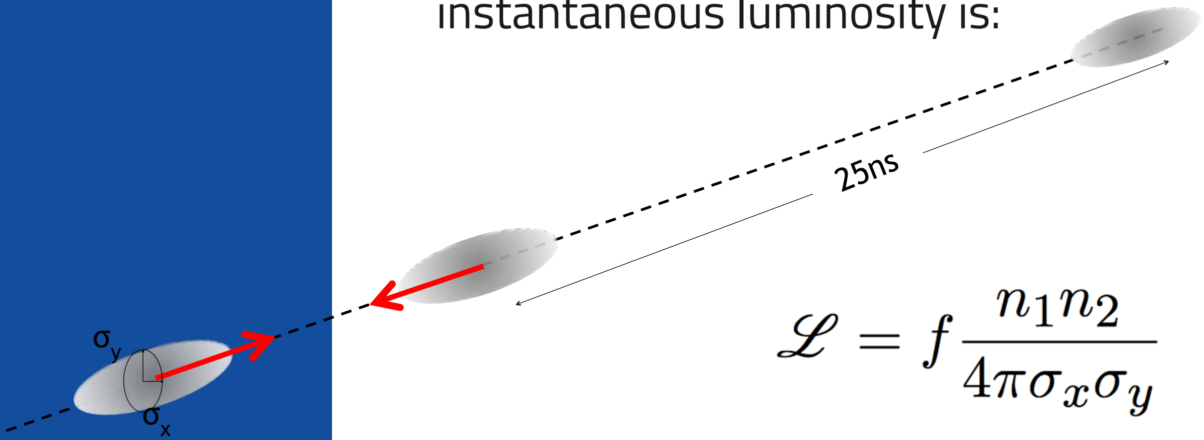
=> The collision reference frame is boosted



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?

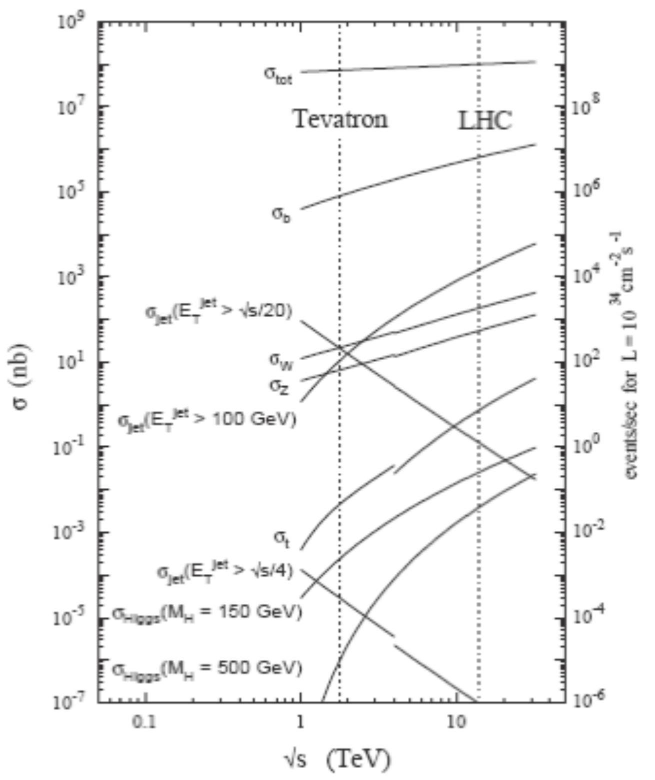
The LHC: experiments and trigger

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%)

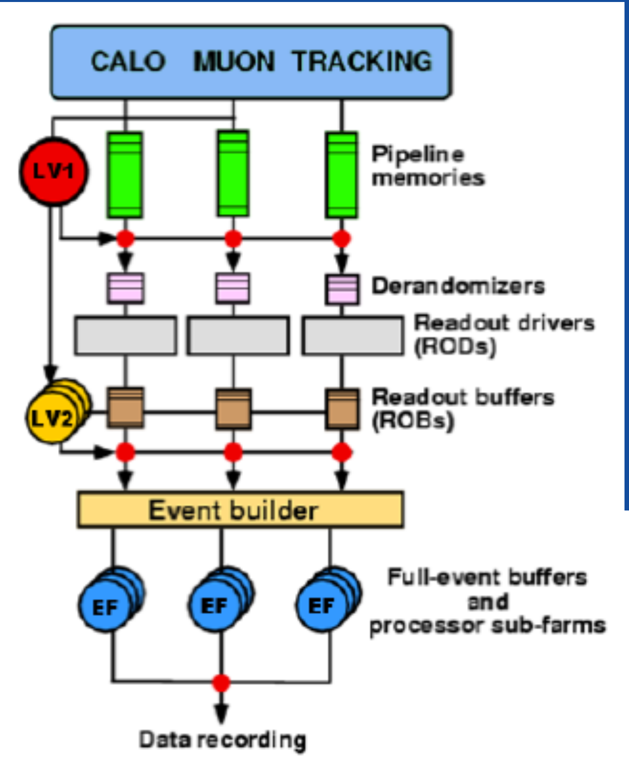


The LHC: experiments and trigger

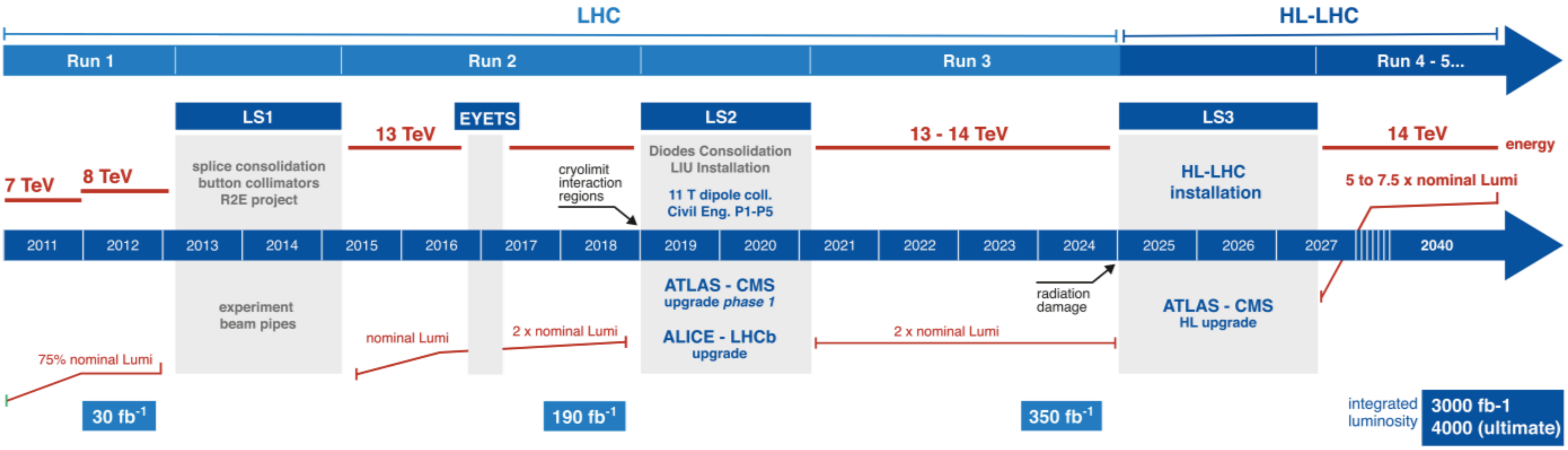
25 ns bunch crossing
- Means 40 million crossings per second
- Each collision ≈1.5MBytes
- Means > 60TB per second

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)

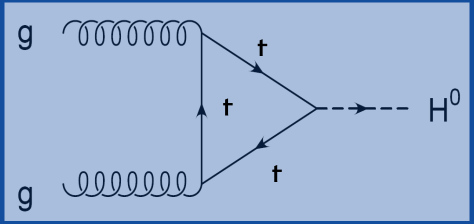
Higgs production at the LHC

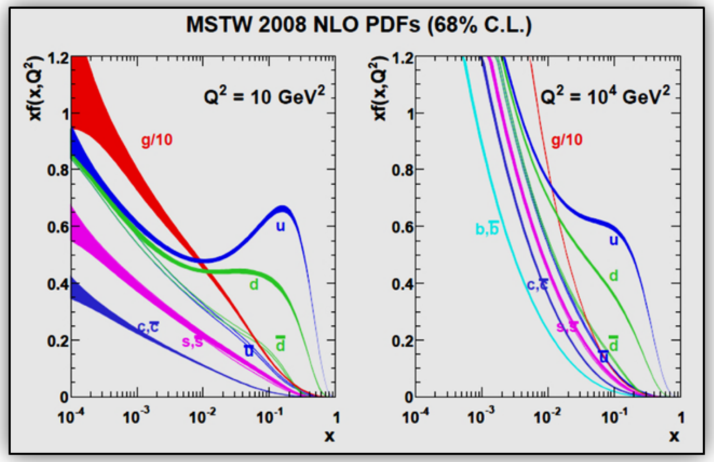
The Higgs couples to particles with mass:

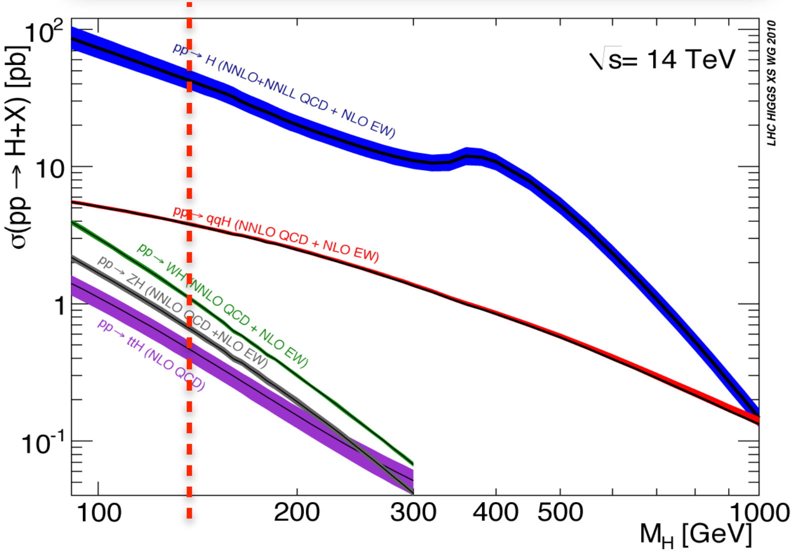
- Fermions or weak bosons, but not (directly) gluons or photons
- But there are many gluons in our beams …

Largest cross section is "gluon fusion"

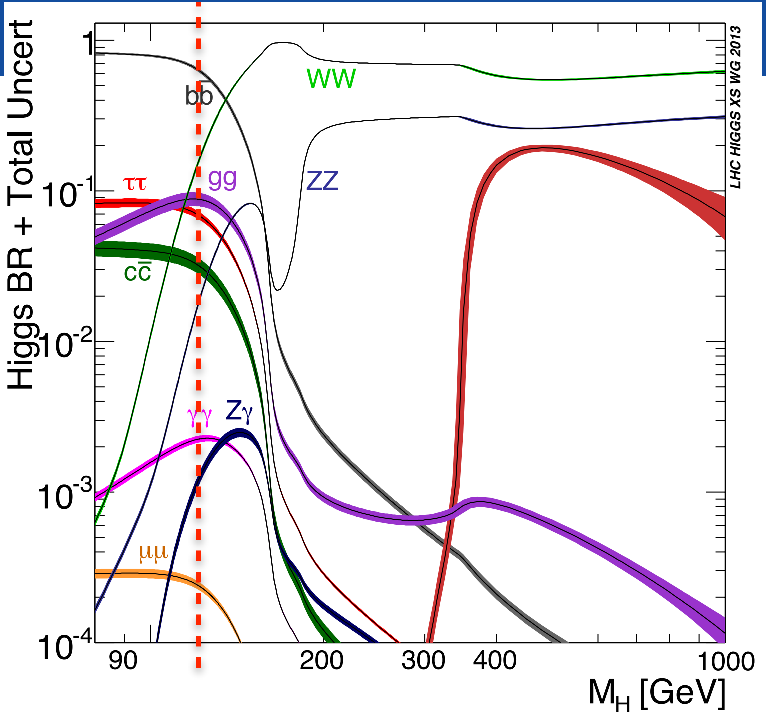
- Loop is dominated by virtual top quarks







Higgs decay

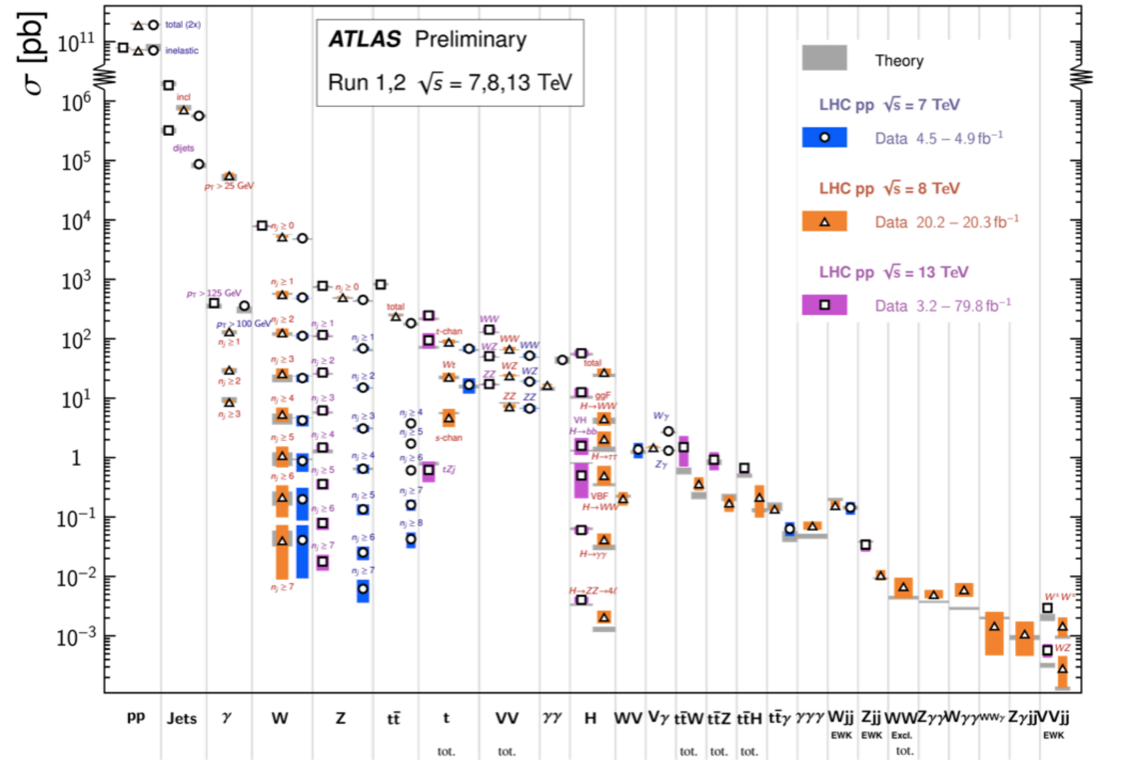


With the mass of m_H=125GeV, the Higgs boson decays mostly to b quarks

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

$H \rightarrow \gamma\gamma$ 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

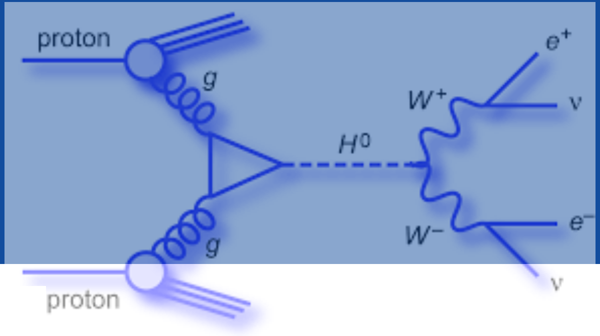
The calculated Higgs production cross section is 17.4 pb at 7 TeV and 22.3 pb at 8 TeV

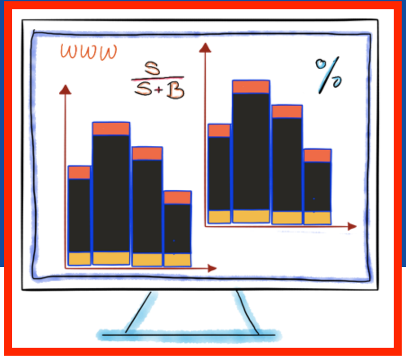
The Branching Ratio BR of $H \rightarrow WW^*$ is 0.214 and the BR of $W \rightarrow l\nu$ is 0.327

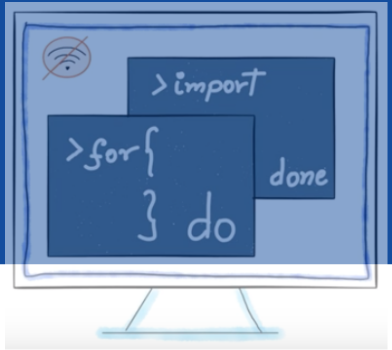
- How many Higgs bosons were expected at the LHC discovery data set?
- How many of those decayed into 2 W bosons?
- And how many went through the full decay chain of $H \rightarrow WW^* \rightarrow l\nu l\nu$?

Rediscovering the Higgs

with H→WW*→lvlv and H→ZZ*→llll







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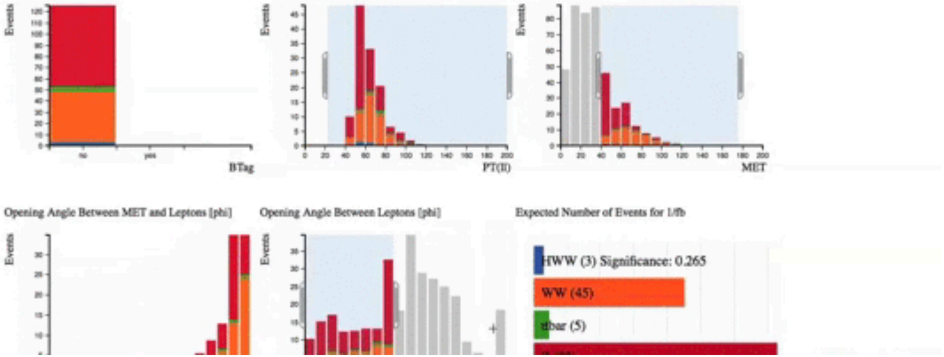
Searching for H→WW*→lvlv in the ATLAS Open Data

ATLAS
EXPERIMENT

8 TeV Open Data resources

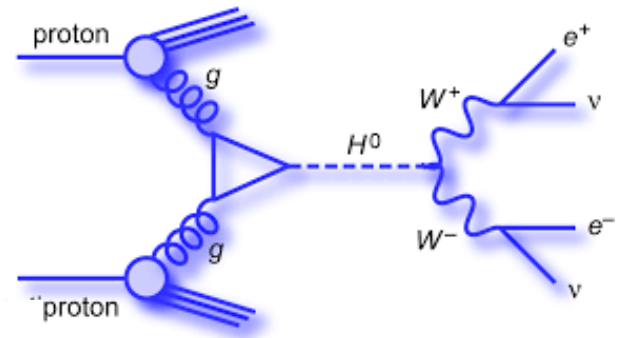


ATLAS released its first open data in 2016, making public 1 fb^{-1} of 8 TeV data that is still in use for many individuals and institutions. One of the best tools to study ATLAS 8 TeV Open Data is the "Histogram Analyser", which allow users to explore physics concepts in a graphical way.

http://opendata.atlas.cern/histogram-analyser-02/

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:

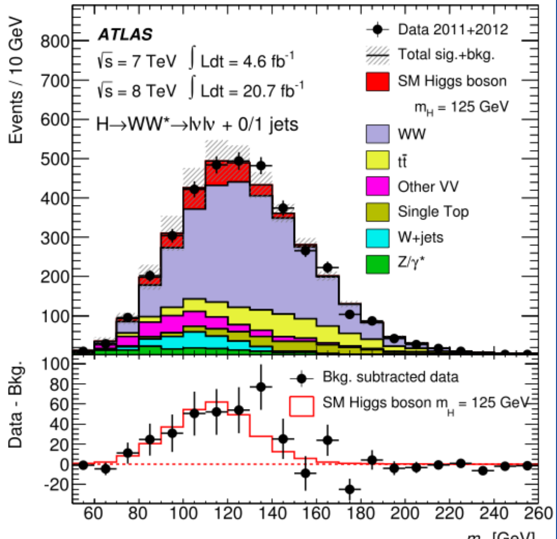
- H→γγ
- H→ZZ*→llll

They provide clean signals in the detector:

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

CMS H discovery paper https://arxiv.org/pdf/1207.7235.pdf

CMS H discovery paper https://arxiv.org/pdf/1207.7214.pdf



(a)

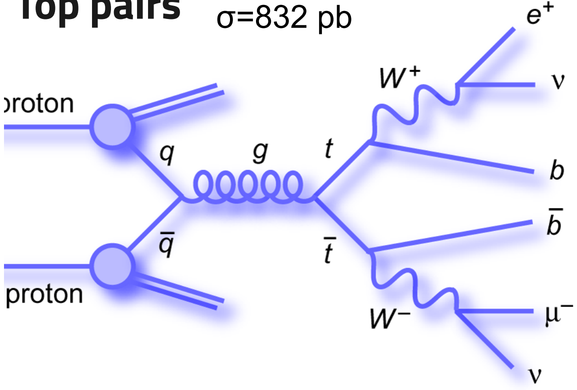
Background processes

Many other processes have similar final states

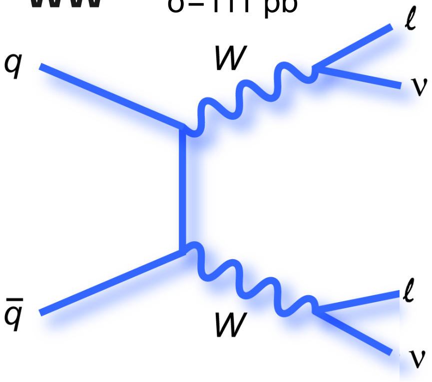
And they have much larger cross sections

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

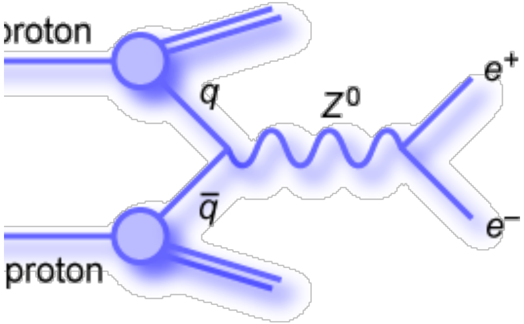
Top pairs σ=832 pb



WW σ=111 pb



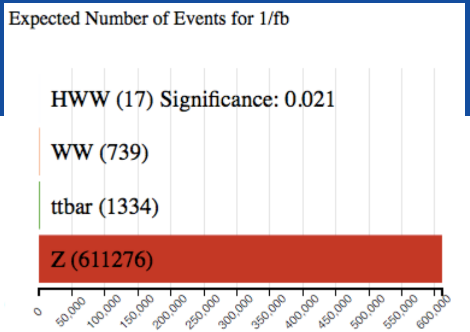
Z σ=56.1x 10^3 pb

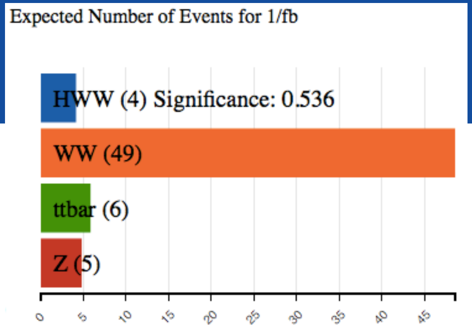


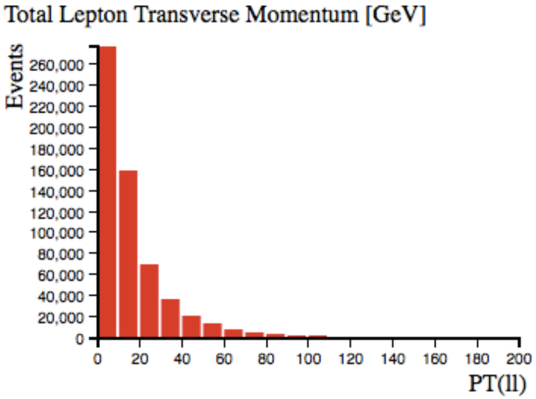
Signal significance

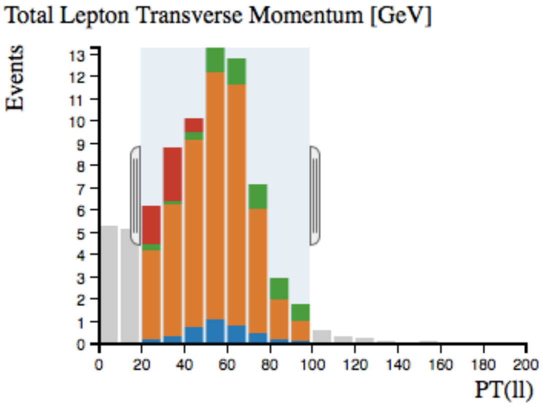
Physicists study how to select events of interest and discard background events => increase sensitivity

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







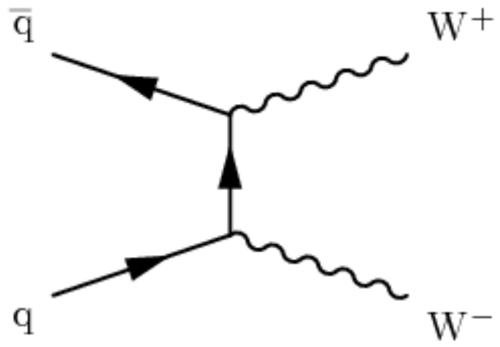


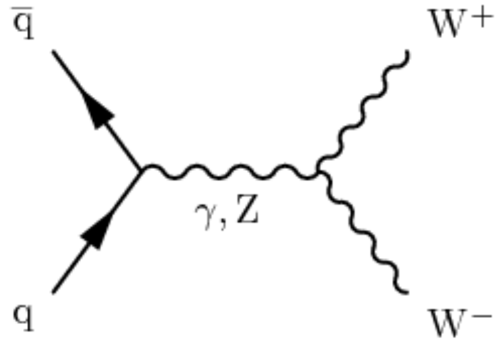
WW background

More than one production mechanism:

- q\q→W^+W^- (dominant)
- γγ→W^+W^-
- gg→W^+W^-

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





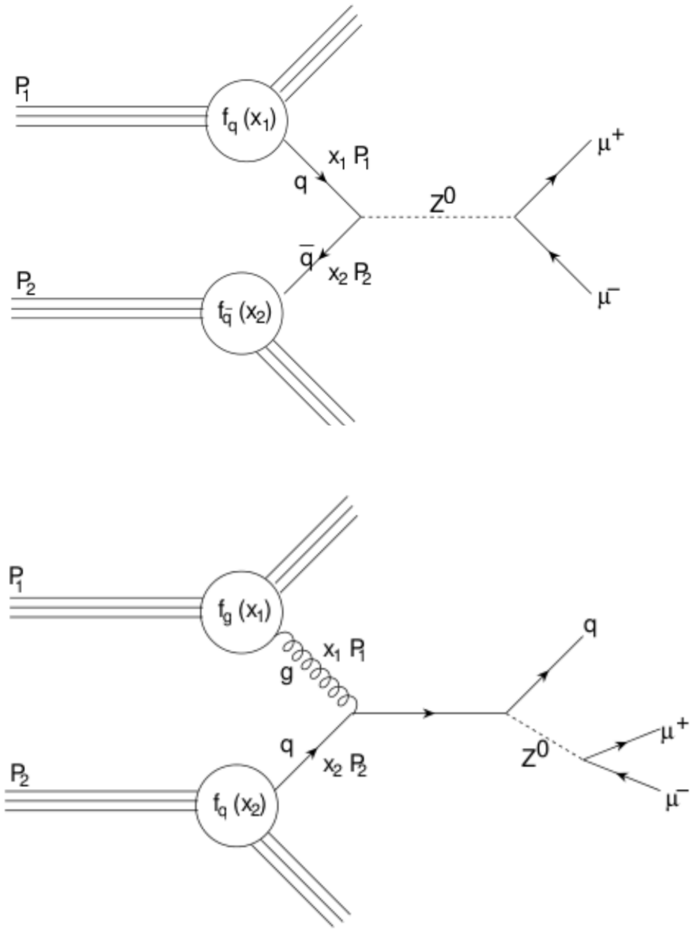
Z background

Production:

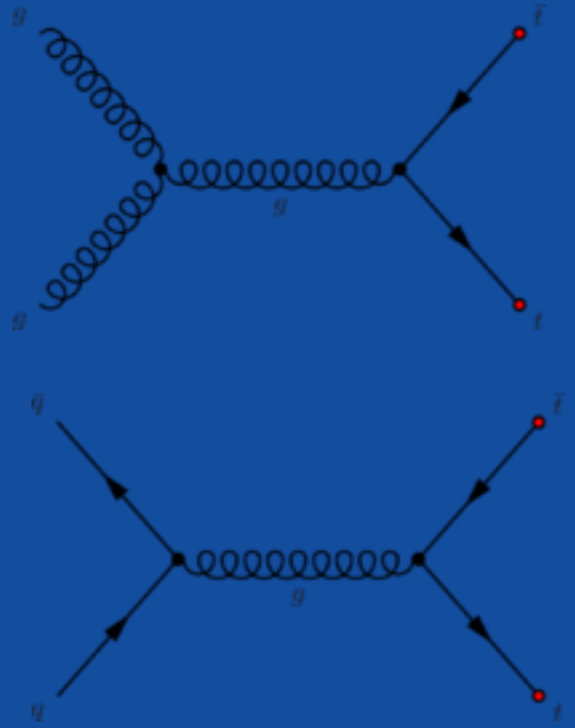
- Drell-Yan q\q→Z (65%)
- qg→Zq (35%)

The Z boson has 0 electric charge an decays to:

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

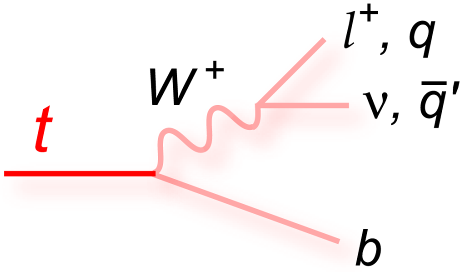


Top pairs background



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

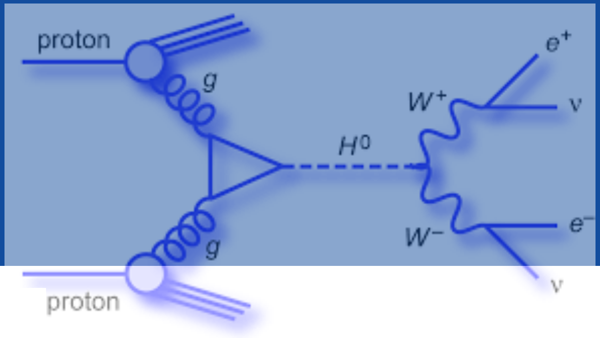
What variables and cuts did you use to select the signal and improve it's significance?

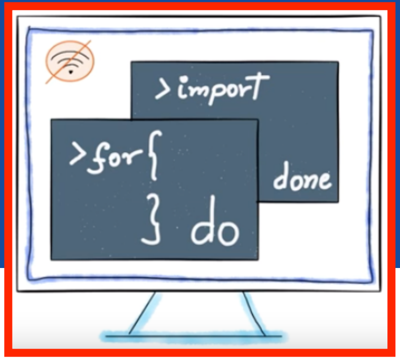
Which cut helped you more removing the Z background?

What signal significance did you reach?

Is you event selection similar to the one used for the discovery paper?

Rediscovering the Higgs with H→ZZ*→llll





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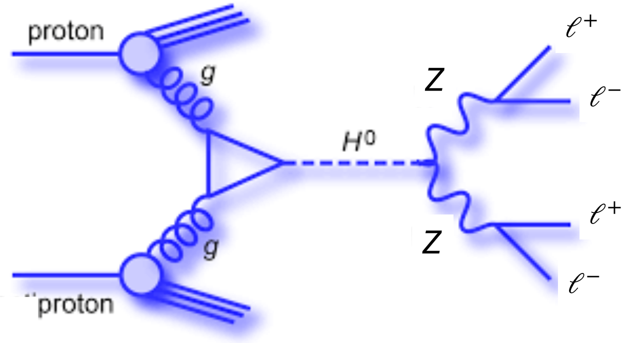
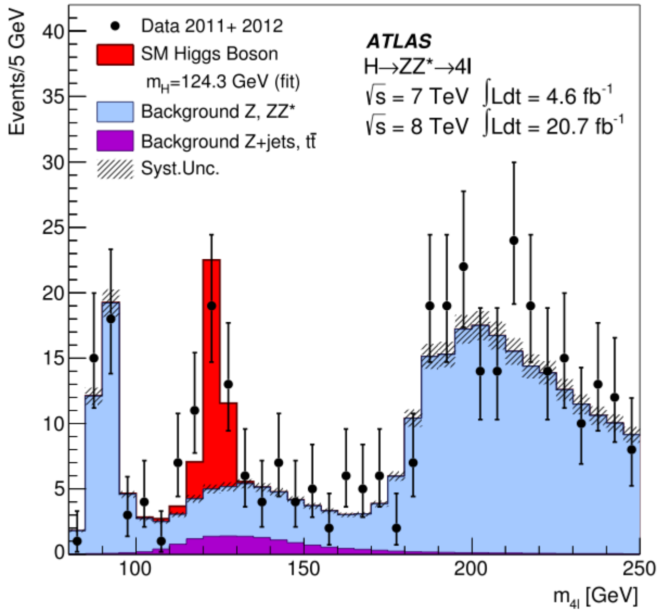
H→ZZ*→llll

H→ZZ*→llll, possible final state particles:

- $e^+e^-e^+e^-$
- $e^+e^-\mu^+\mu^-$
- $\mu^+\mu^-\mu^+\mu^-$

Full reconstruction of the Higgs candidate from the 4-momentum of the final state particles



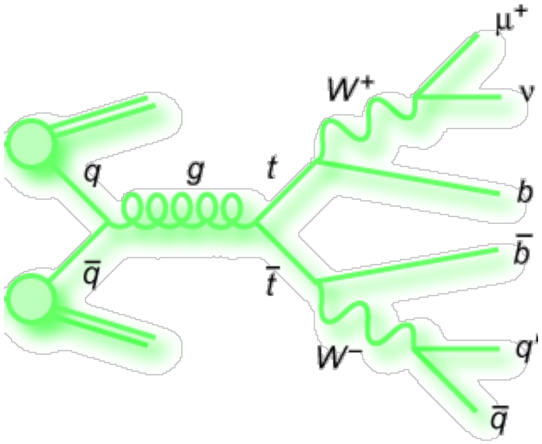


CMS H discovery paper https://arxiv.org/pdf/1207.7235.pdf

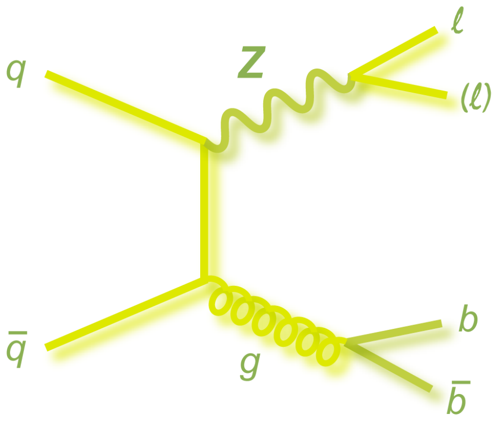
ATLAS H discovery paper https://arxiv.org/pdf/1207.7214.pdf

Background processes

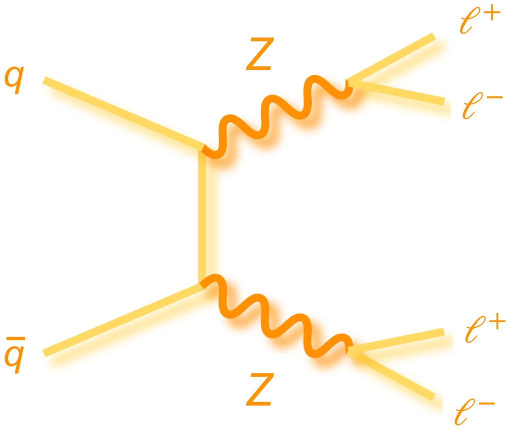
Top pairs



Z



ZZ



Coding up
your own Higgs discovery

[discovery paper](#)

Python notebook to access access and analyse data online

Find out how to implement the selection to analyse the $H \rightarrow ZZ^* \rightarrow llll$

Plot the histograms and calculate the signal significance

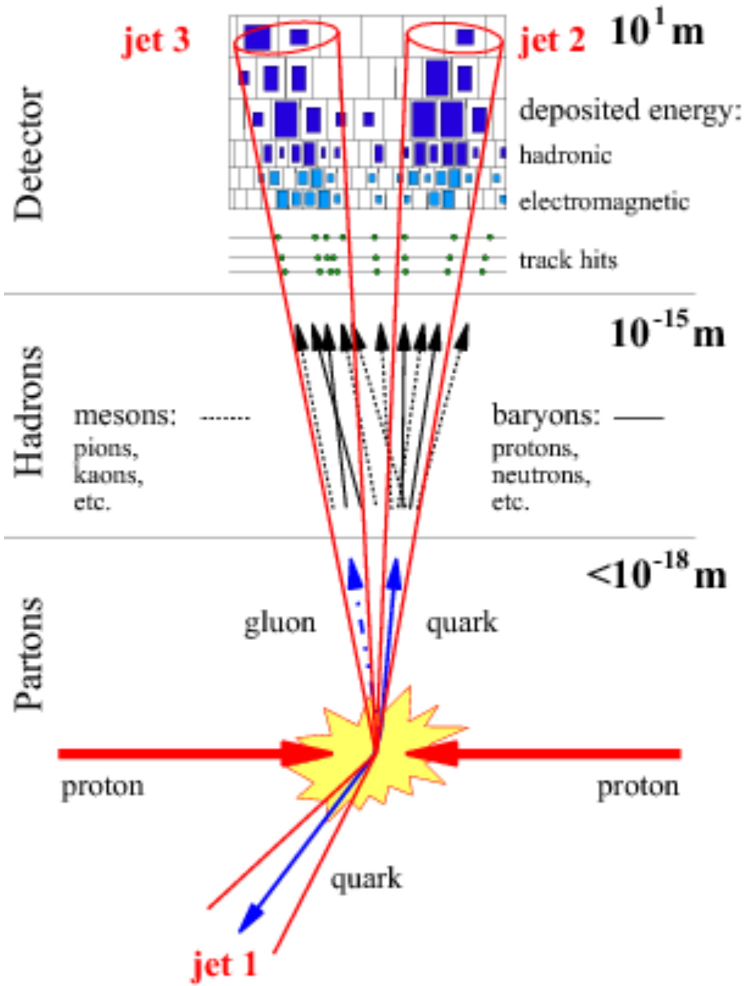
[GoogleColab HZZAnalysis Notebook](#)

Acknowledgements

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

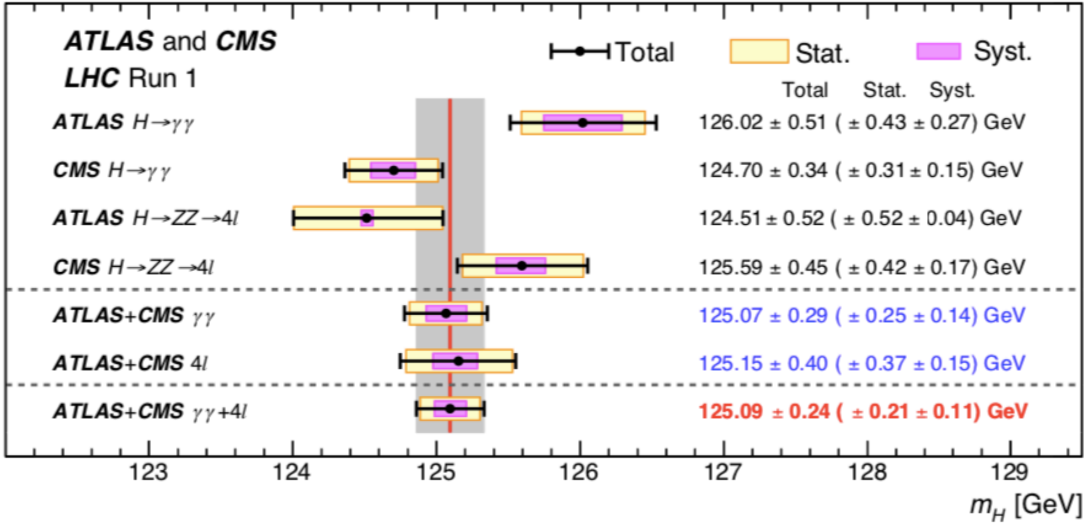
EXTRA SLIDES

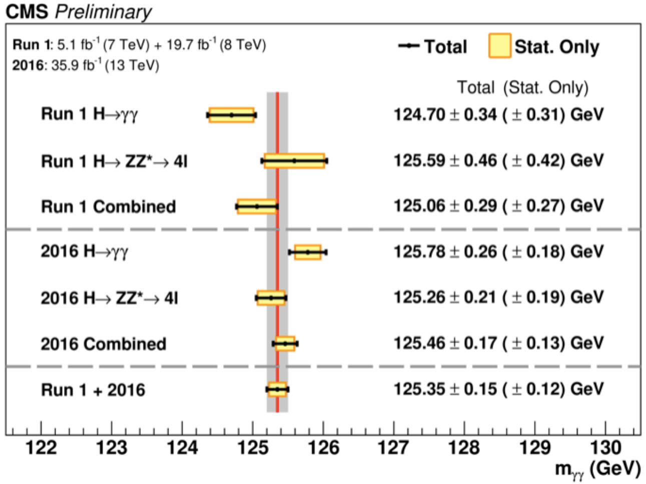
A word about jets



Higgs mass

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

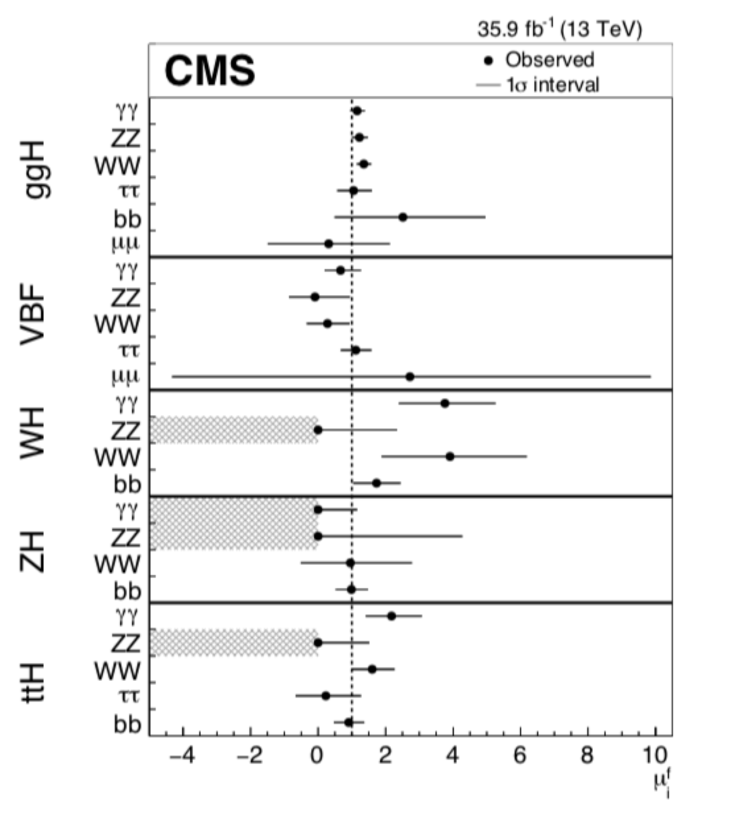


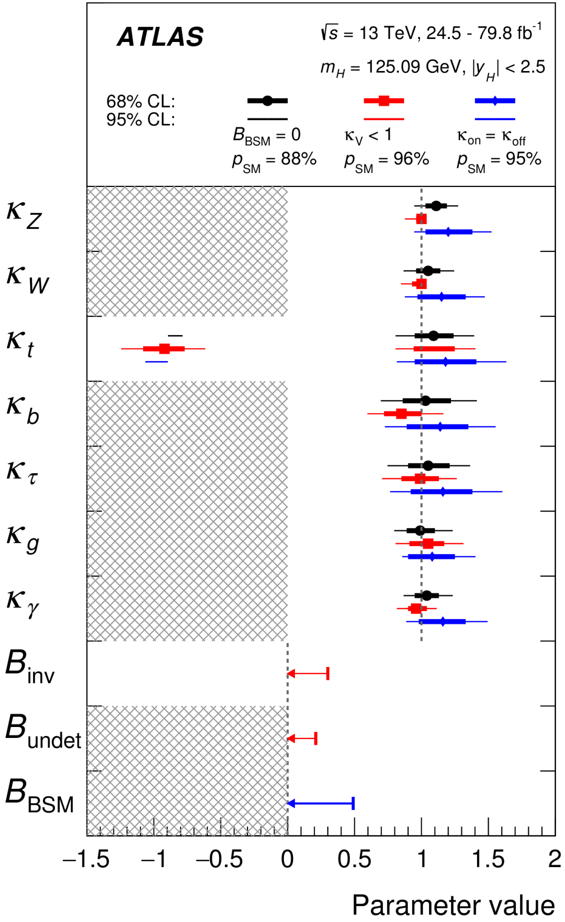


New mass measurement at unprecedented precision from the CMS experiment

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

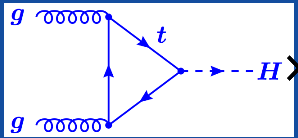
Higgs couplings



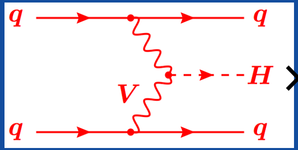


Combining Higgs analyses

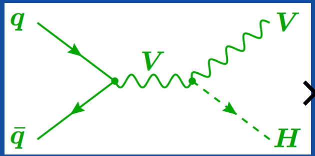
Production



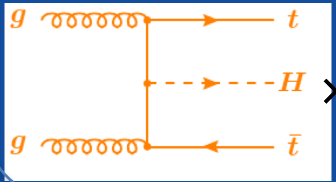
$\times\kappa_g^2$



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



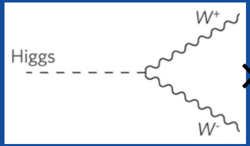
$\times\kappa_{W/Z}^2$



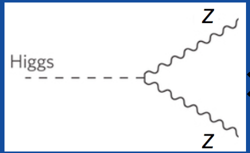
$\times\kappa_t^2$

$\times$

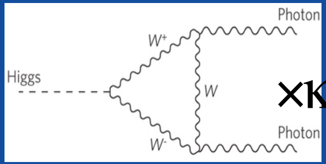
Decay



$\times\kappa_W^2$



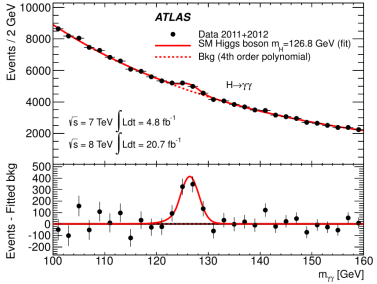
$\times\kappa_Z^2$



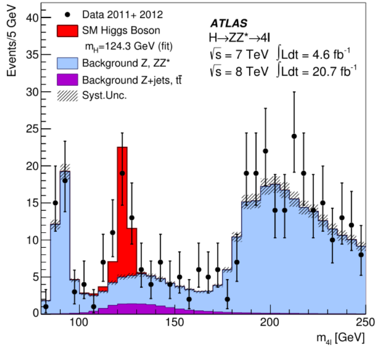
$\times\kappa_\gamma^2$

FIT

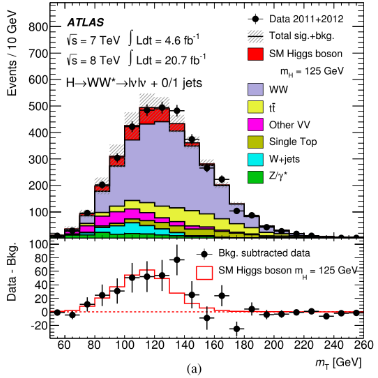
Backgrounds +



H->γγ



H->ZZ



H->WW