



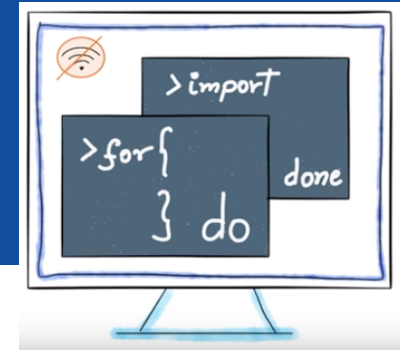
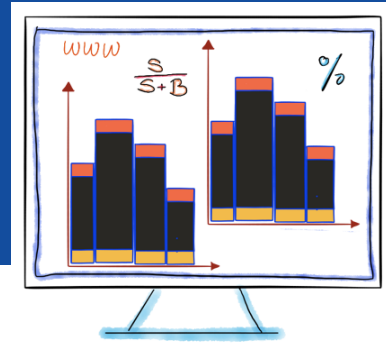
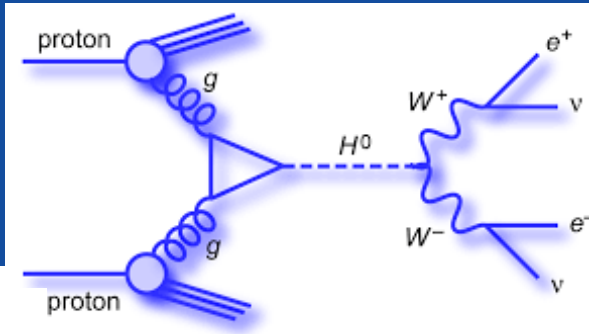
LABORATÓRIO DE INSTRUMENTAÇÃO  
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

# [ **HANDS** *on* **HIGGS** ]

Rute Pedro and Prof. Jorge Romão | [rute@lip.pt](mailto:rute@lip.pt) | 5th February 2024  
9th Mini-school on Particle and Astroparticle Physics

# Rediscovering the Higgs

with  $H \rightarrow WW^* \rightarrow l\nu l\nu$  and  $H \rightarrow ZZ^* \rightarrow llll$



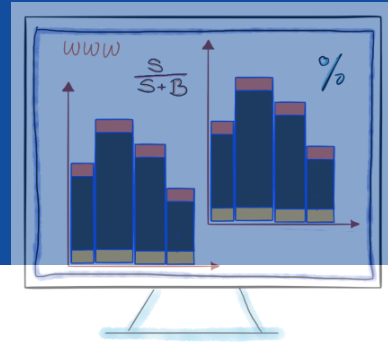
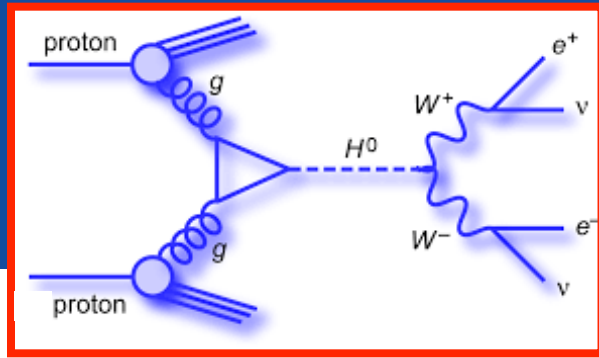
1. Set the  
Stage

2. Web  
Analysis

3. Code It  
Yourself

# Rediscovering the Higgs

with  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  and  $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$



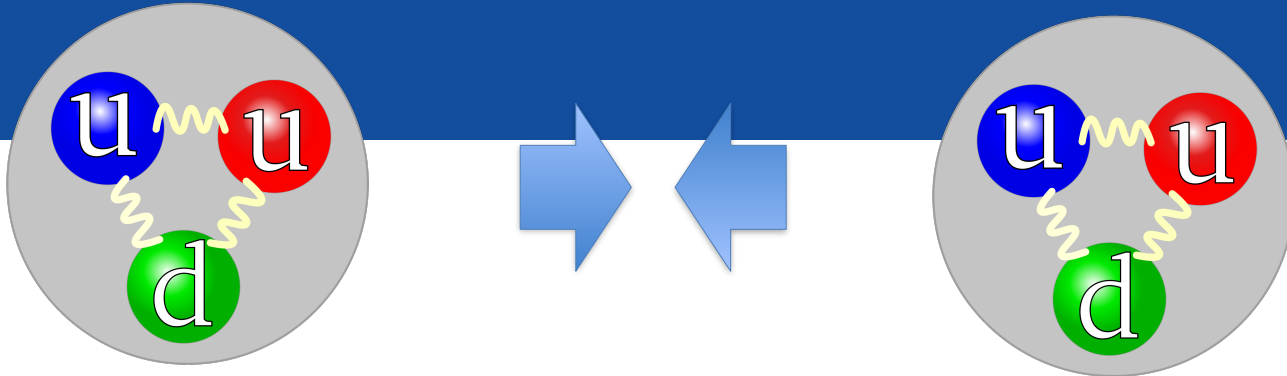
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# The LHC: colliding proton beams

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

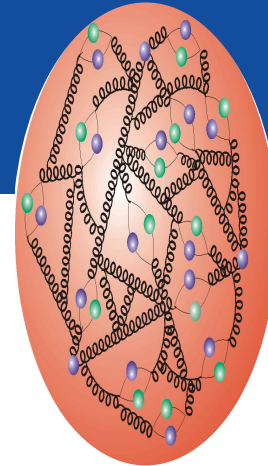
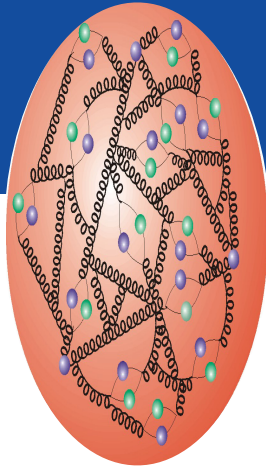


# The LHC: colliding proton beams

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

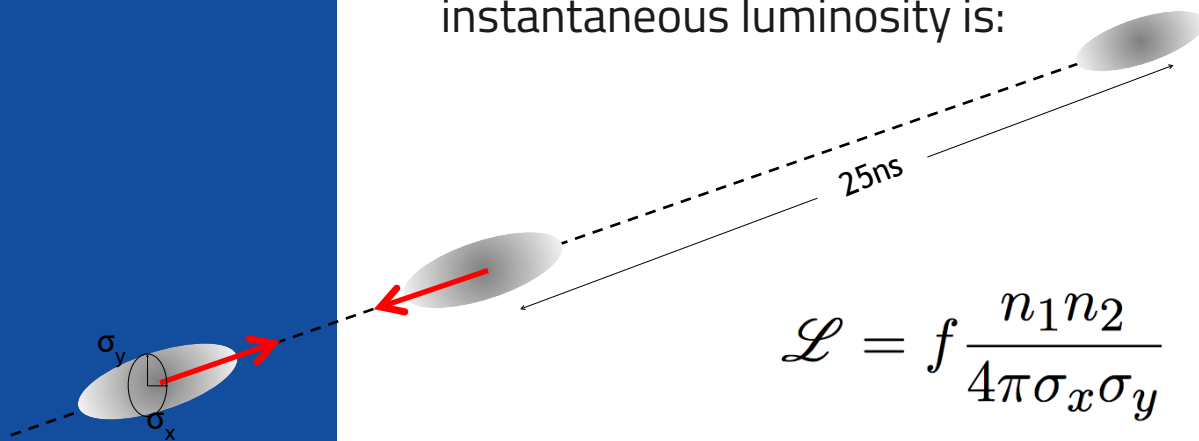
The deeper we look (**more energy**, smaller distances) the more we see gluons and quarks from the sea

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  $\sigma_x$  and  $\sigma_y$  (rms) containing  $n_1$  and  $n_2$  protons, the instantaneous luminosity is:

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

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

# 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  $\sigma_{exp}$

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

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

area units  
usually:  $[\text{cm}^2]$ ,  $[\text{b}]$

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

## Q: Luminosity

At the LHC, proton bunches collide every 25ns

Each bunch has  $10^{11}$  protons and a radius of  $11.1\mu\text{m}$  (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  $20\text{fb}^{-1}$ , 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?



## Q: Luminosity

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The LHC is a 27km ring

- What is the instantaneous luminosity measured by the CMS experiment

$$\mathcal{L} = 2.58 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

- If the inclusive cross section for Z boson production is 28nb, how many are produced per second in ATLAS?  $f_Z = 722.4 \text{ s}^{-1}$

- In  $20\text{fb}^{-1}$ , how many Higgs bosons were produced during LHC run 1 if the inclusive cross section is 20pb?  $N_Z = 400000$

- How many proton bunches fit in the LHC?  $N_b = 3600$

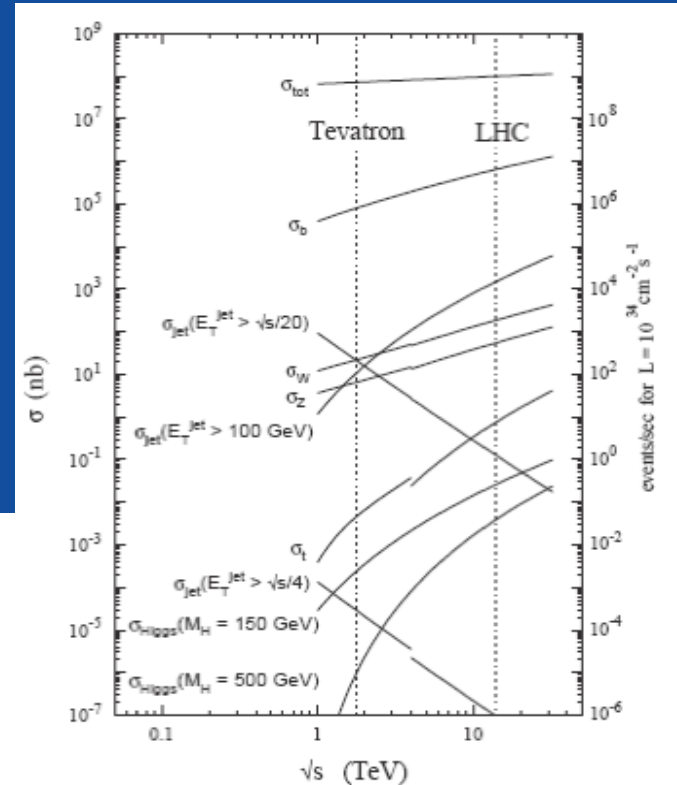
# The LHC: experiments and trigger

25 ns bunch crossing

- Means 40 million crossings per second
- Each collision  $\approx 1.5$  MBytes
- Means  $> 60$  TB per second

Impossible to keep all these data

- And unnecessary!
- Most collisions are boring (99%)



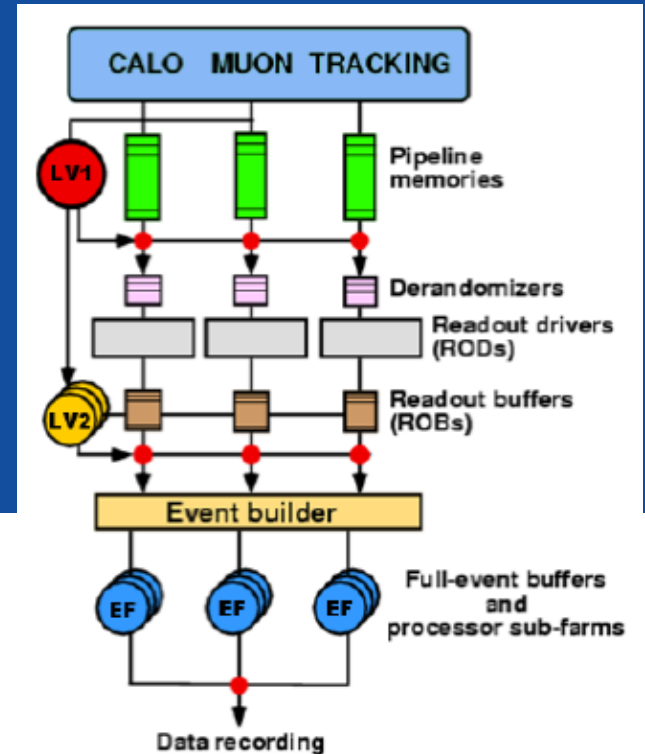
# The LHC: experiments and trigger

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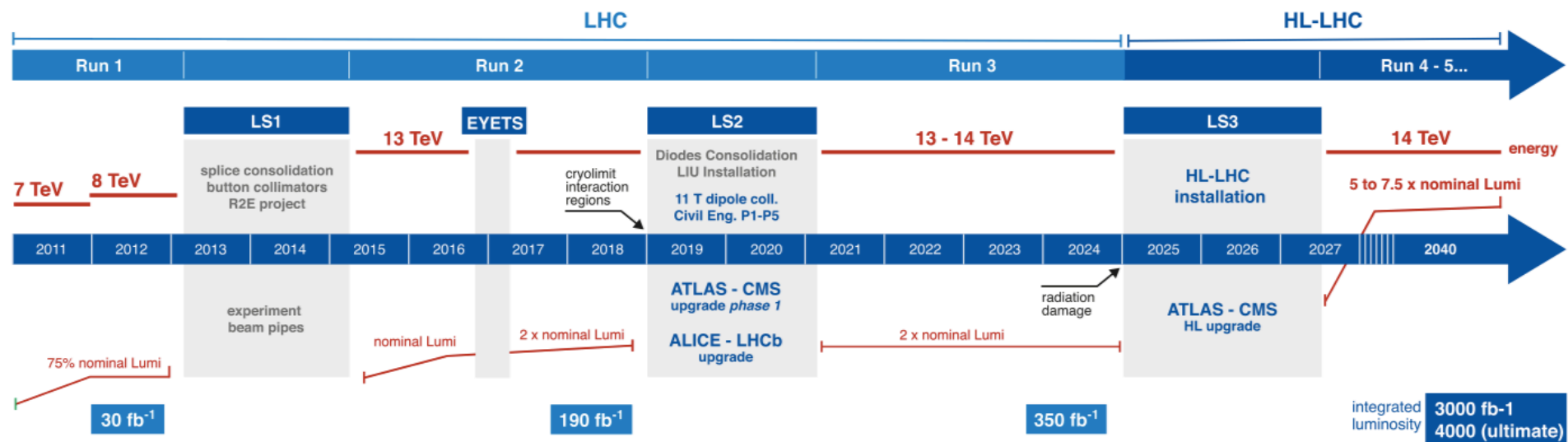
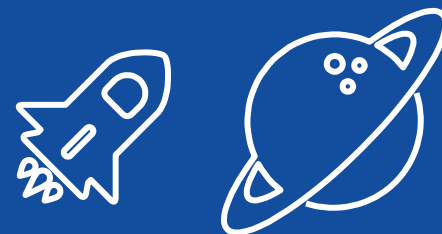
- Means 40 million crossings per second
- Each collision  $\approx 1.5\text{MB}$ Bytes
- Means  $> 60\text{TB}$  per second

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

But need to decide in  $2.5\mu\text{s}$  for the first trigger level!!



# BIG DATA



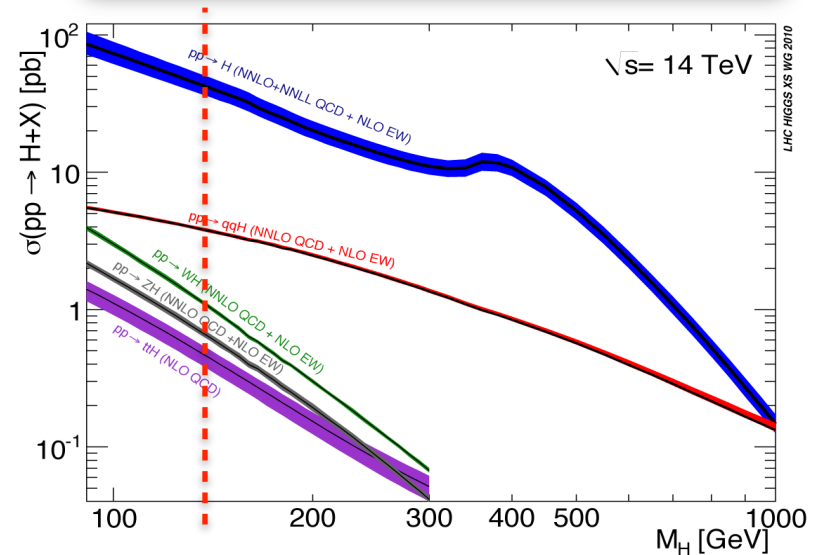
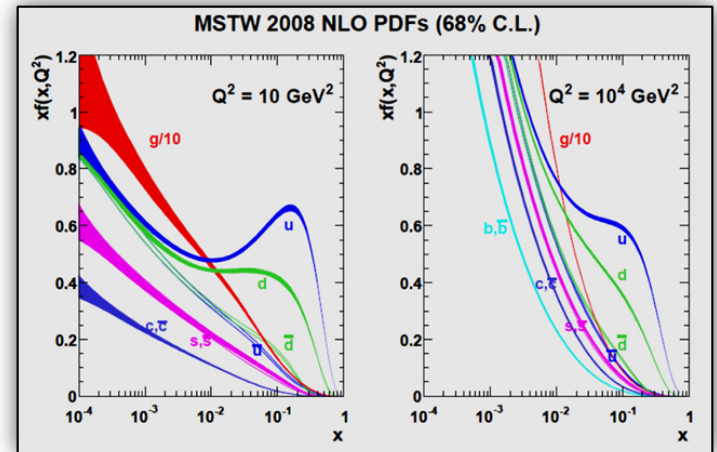
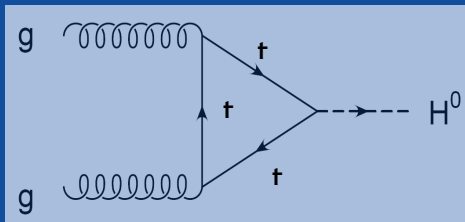
# Higgs production at the LHC

The Higgs couples to particles with mass:

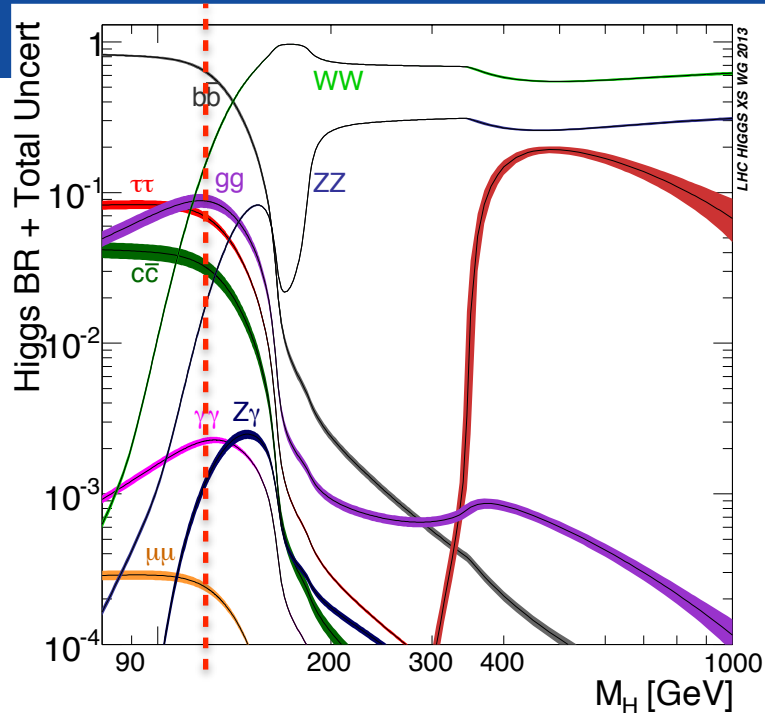
- Fermions or weak bosons, but not (directly) gluons or photons
- But there are many gluons in our beams ...

Largest cross section is "gluon fusion"

- Loop is dominated by virtual top quarks



# Higgs decay

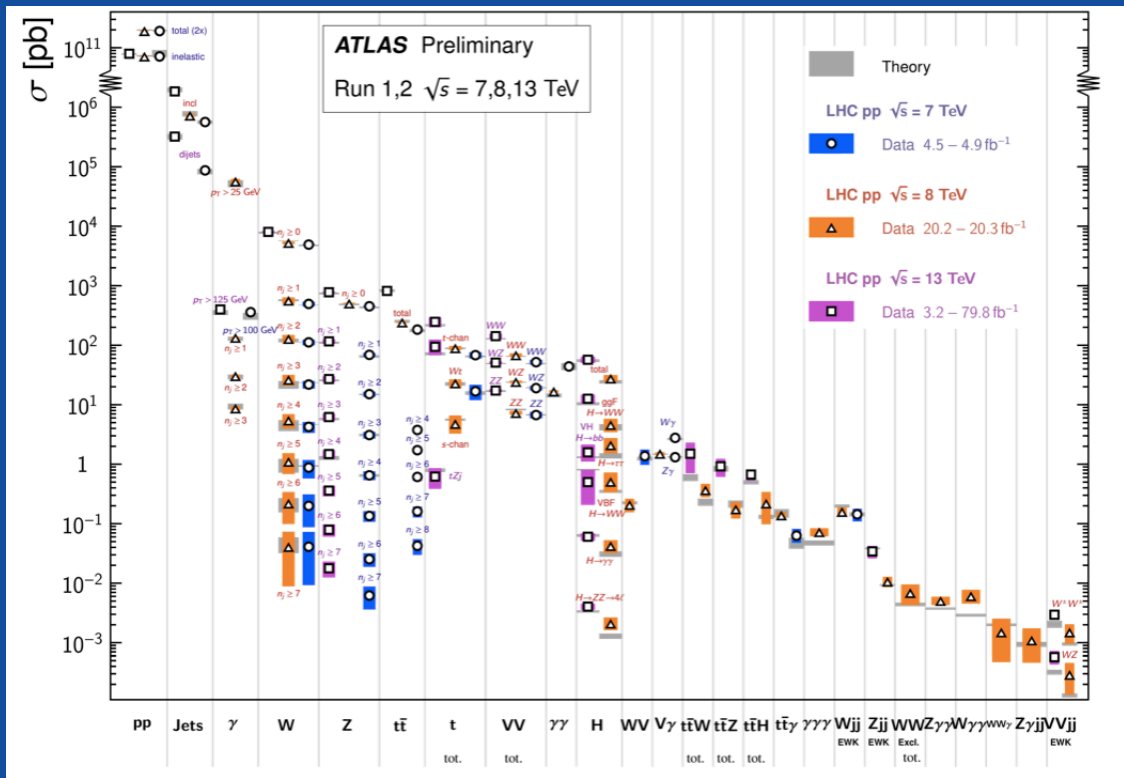


With the mass of  $m_H=125\text{GeV}$ , the Higgs boson decays mostly to b quarks

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  $4.8 \text{ fb}^{-1}$  at c.o.m. 7 TeV and  $5.8 \text{ fb}^{-1}$  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  $H \rightarrow WW^* \rightarrow l\nu l\nu$ ?



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- How many Higgs bosons were expected at the LHC discovery data set?  $N_H = 212860$

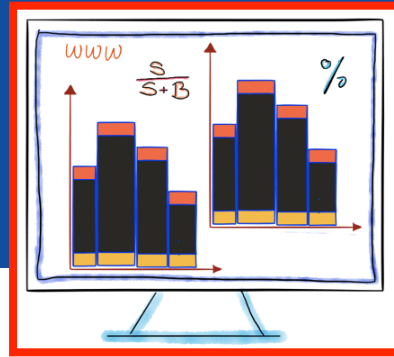
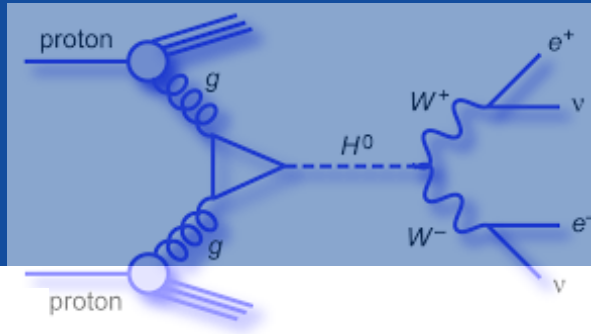
- How many of those decayed into 2 W bosons?  $N_{H \rightarrow WW} = 45552$

- And how many went through the full decay chain of  $H \rightarrow WW^* \rightarrow \ell \nu \ell \nu$ ?

$$N_{H \rightarrow WW \rightarrow \ell \nu \ell \nu} = 4870.8$$

# Rediscovering the Higgs

with  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  and  $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$



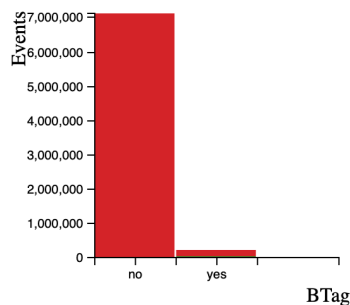
1. Set the  
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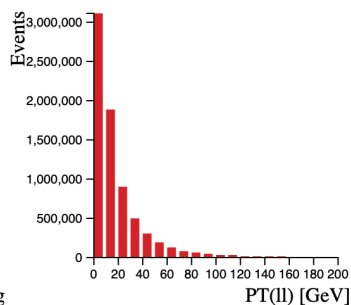
3. Code It  
Yourself

# Searching for $H \rightarrow WW^* \rightarrow l\nu l\nu$ in the ATLAS Open Data

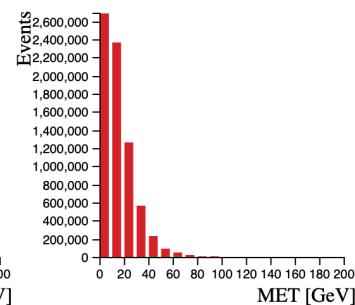
Are Jets b-tagged?



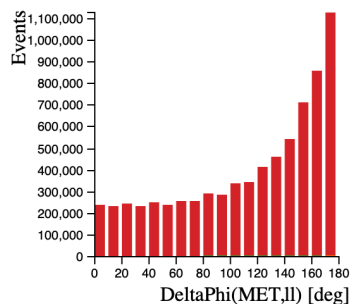
Total Lepton Transverse Momentum



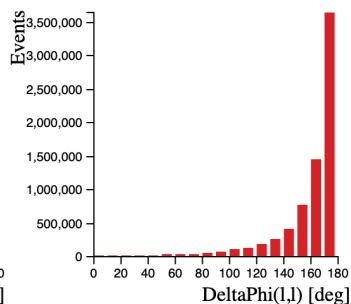
Missing Transverse Momentum (MET)



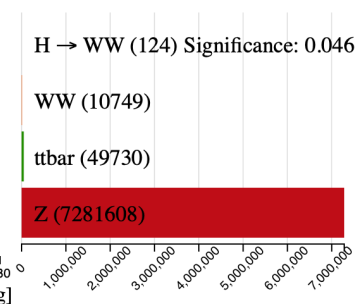
Opening Angle Between MET and Leptons



Opening Angle Between Leptons

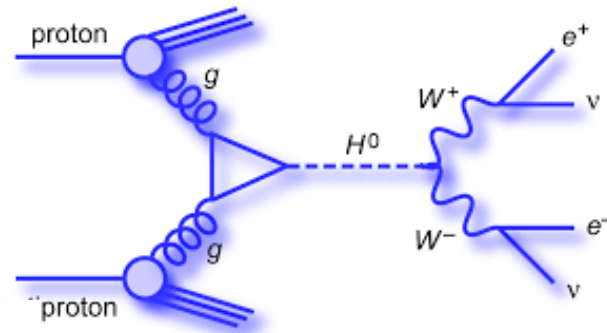


Expected Number of Events for 10/fb



$$H \rightarrow WW^* \rightarrow l\nu l\nu$$

## in the history of the Higgs discovery



$H \rightarrow WW^* \rightarrow l\nu l\nu$  was one of the golden channels of the Higgs discovery in 2012

Two other processes contributed:

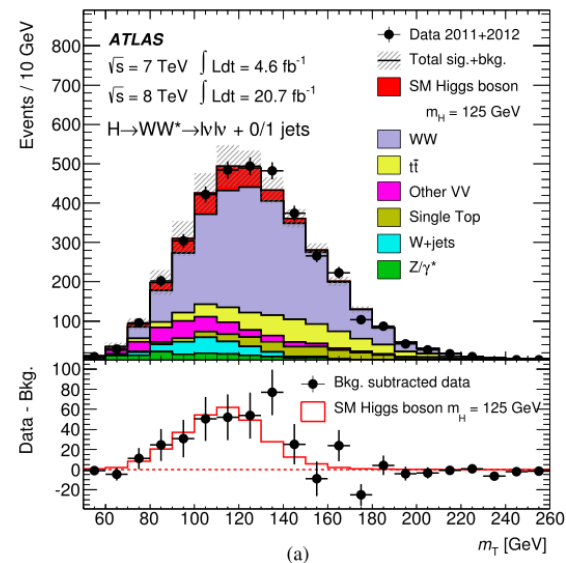
- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^* \rightarrow llll$

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>



# Background processes

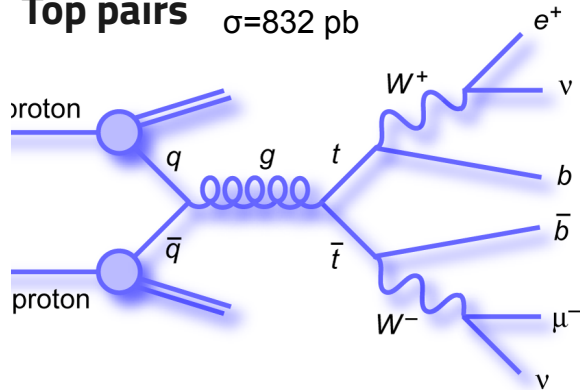
Many other processes have similar final states

And they have much larger cross sections

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

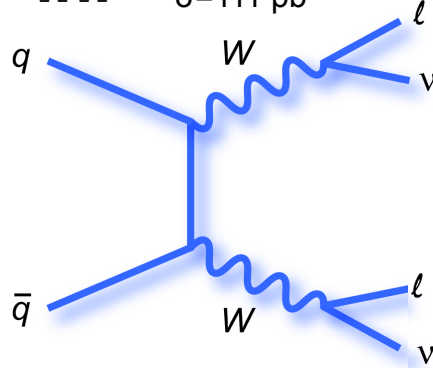
## Top pairs

$$\sigma = 832 \text{ pb}$$



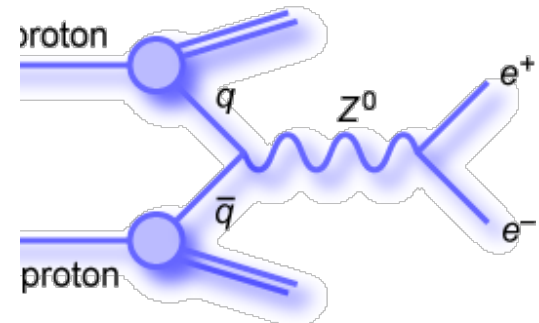
## WW

$$\sigma = 111 \text{ pb}$$



## Z

$$\sigma = 56.1 \times 10^3 \text{ pb}$$

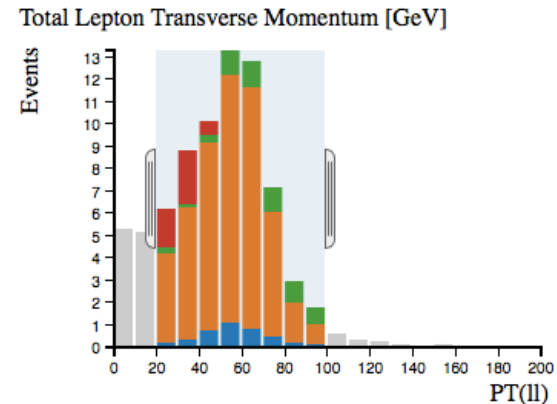
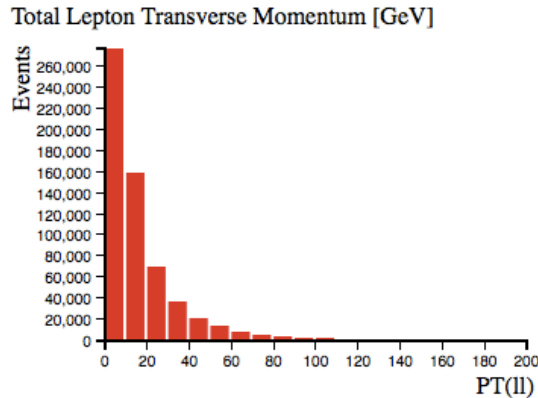
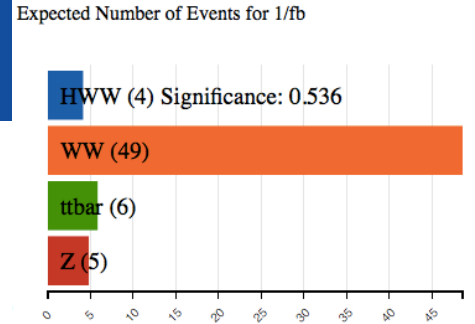
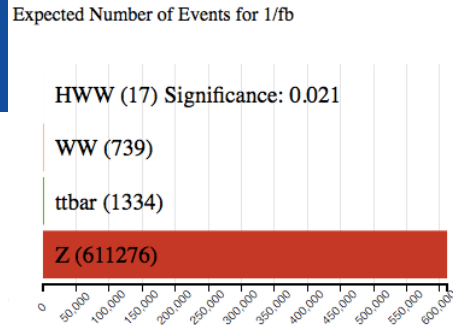


# Signal significance

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:

$$\frac{S}{\sqrt{S + B}}$$

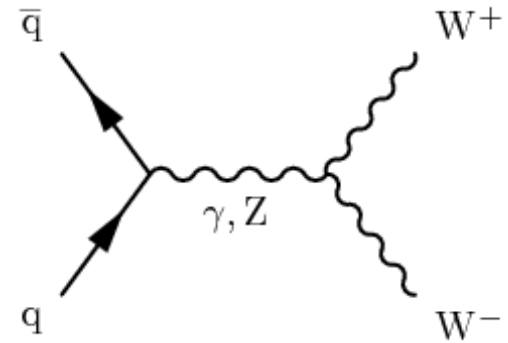
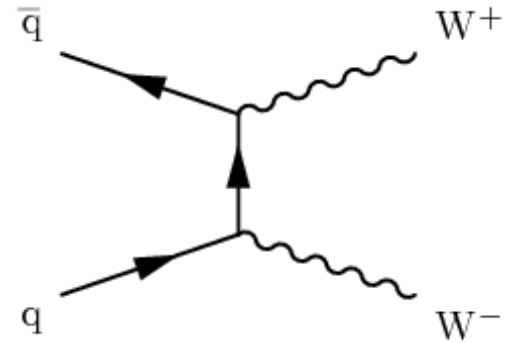


# WW background

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)



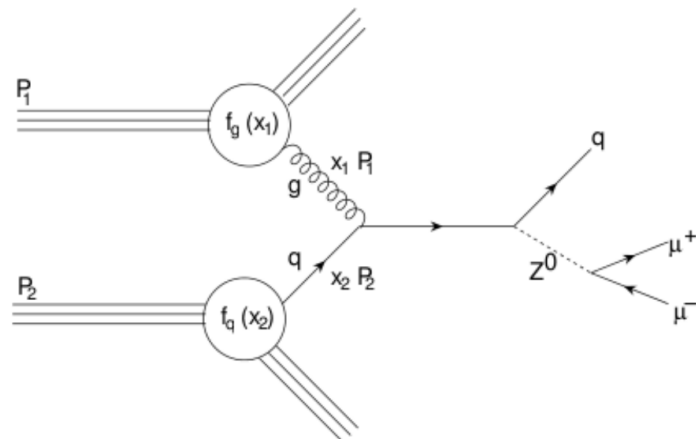
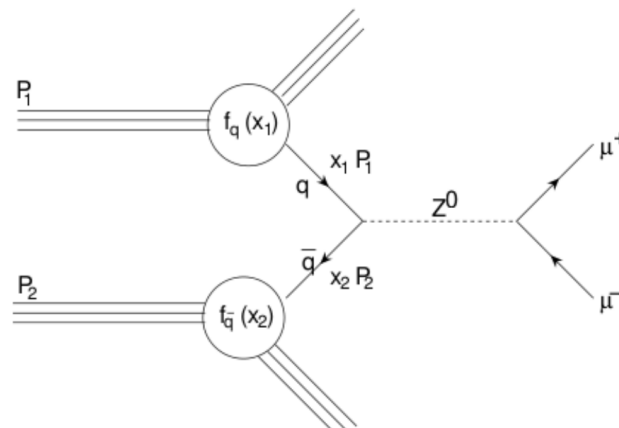
# Z background

Production:

- Drell-Yan  $q\bar{q} \rightarrow Z$  (65%)
- $qg \rightarrow Zq$  (35%)

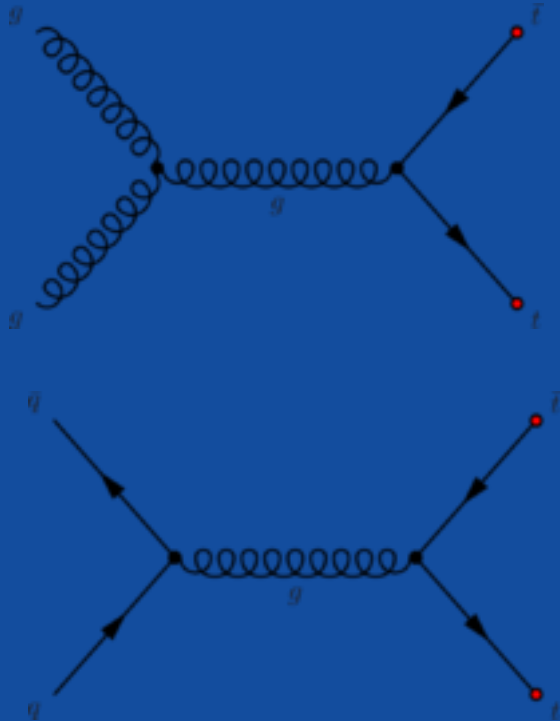
The Z boson has 0 electric charge and decays to:

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



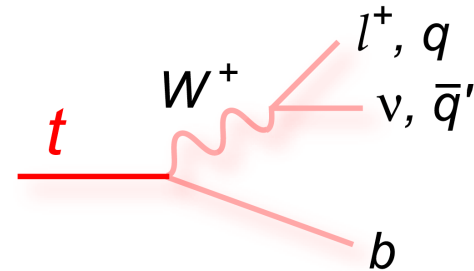


# Top pairs background



Other quarks hadronise when produced freely

But the top decays basically immediately 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?

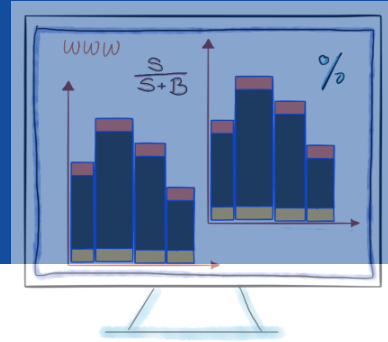
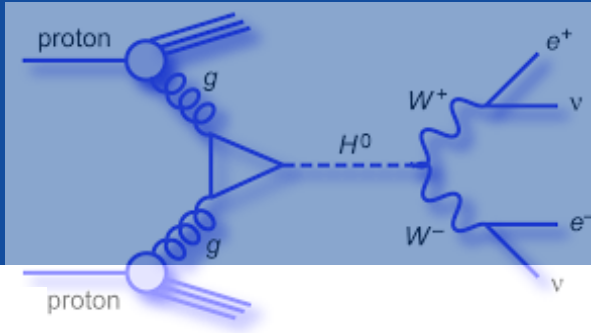
Which cut helped you more removing the Z background?

What signal significance did you reach?

Is you event selection similar to the one used for the discovery [paper](#)?

# Rediscovering the Higgs

## with $H \rightarrow ZZ^* \rightarrow llll$



1. Set the  
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# $$H \rightarrow ZZ^* \rightarrow llll$$

$H \rightarrow ZZ^* \rightarrow llll$ , possible final state particles:

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

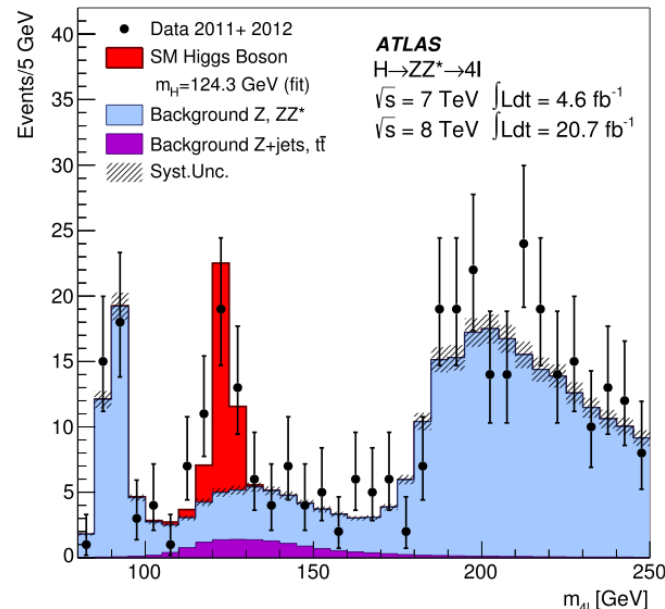
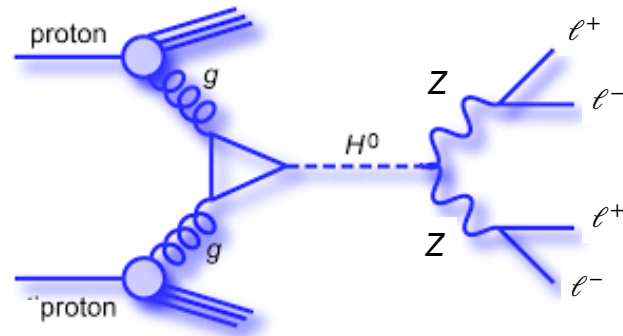
Full reconstruction of the Higgs candidate from the 4-momentum of the final state particles

CMS H discovery paper

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

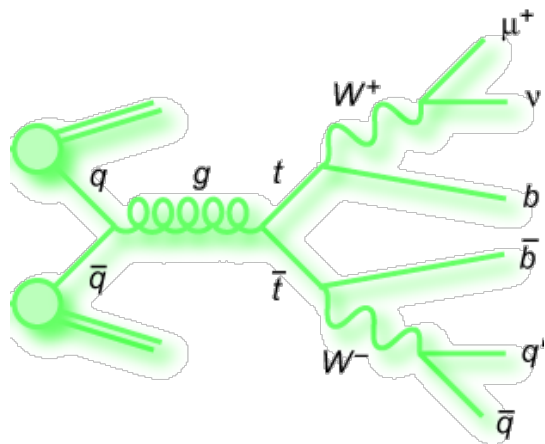
ATLAS H discovery paper

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

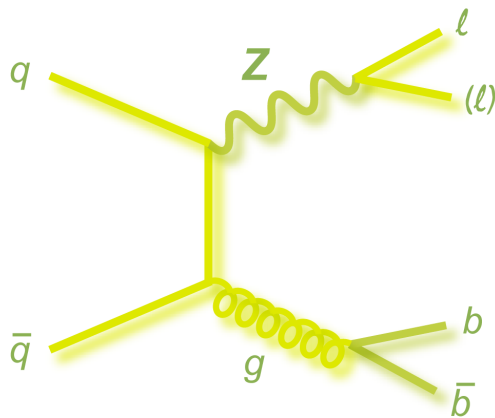


# Background processes

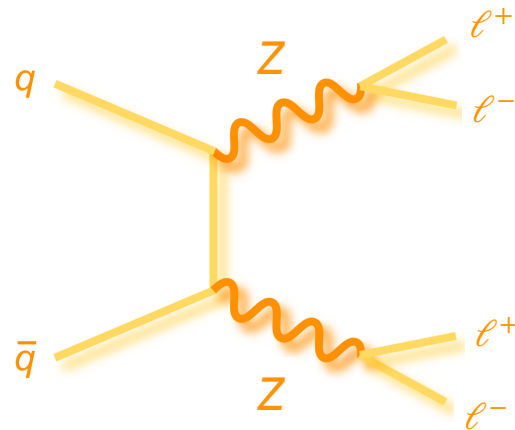
Top pairs



Z



ZZ



# Coding up your own Higgs discovery

Python notebook  
to access access  
and analyse data  
online

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

Plot the  
histograms and  
calculate the  
signal significance

[discovery paper](#)

[GoogleColab HZZAnalysis Notebook](#)

# Acknowledgements

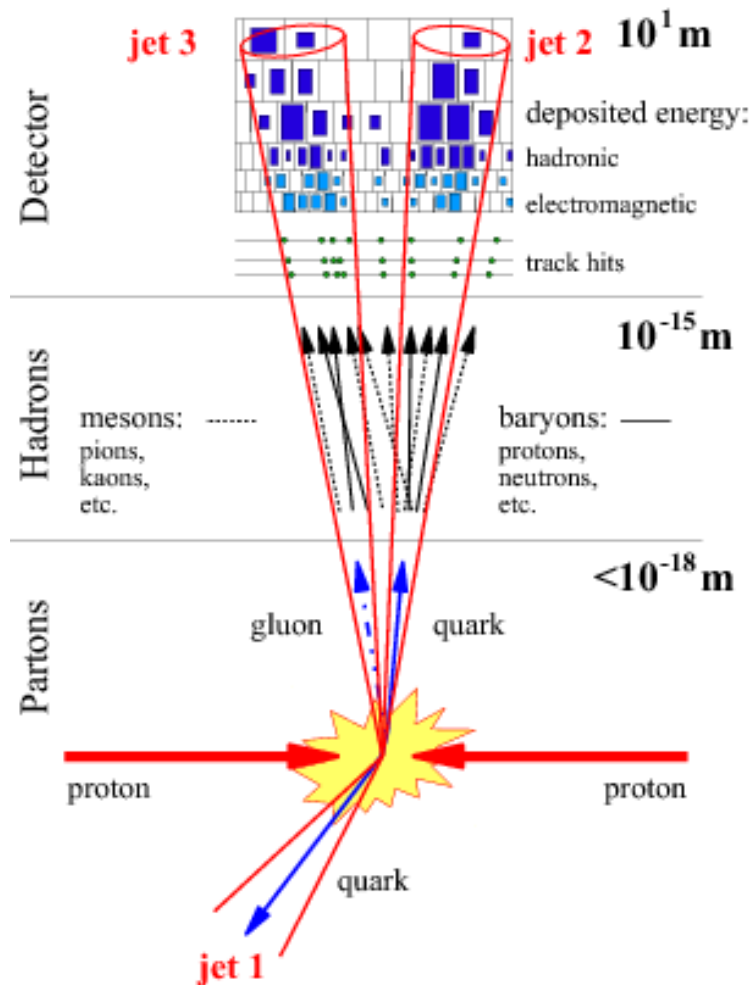


# EXTRA SLIDES



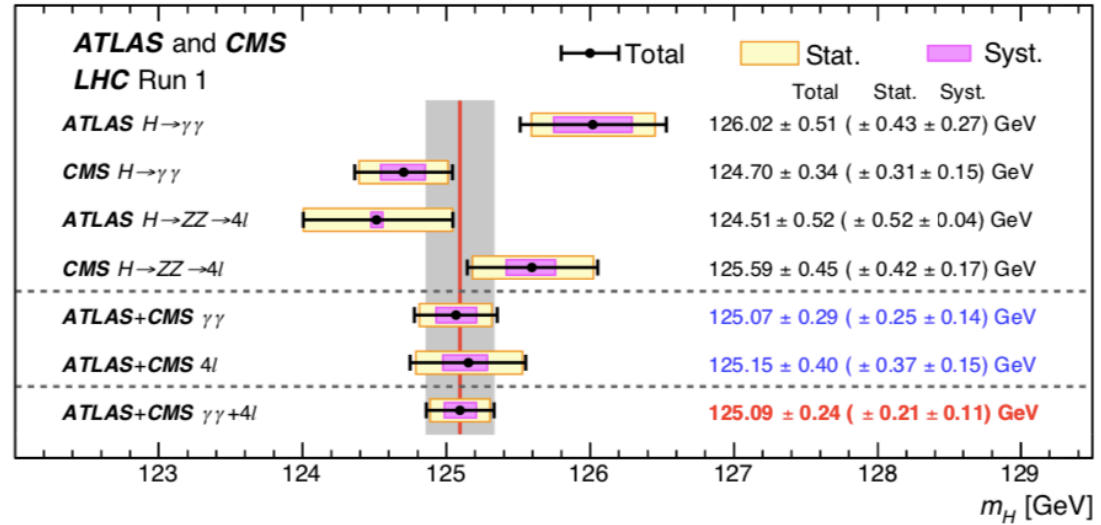


# A word about jets

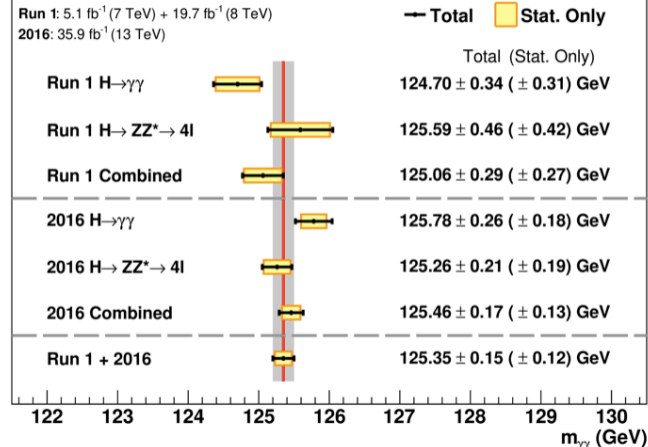


# Higgs mass

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



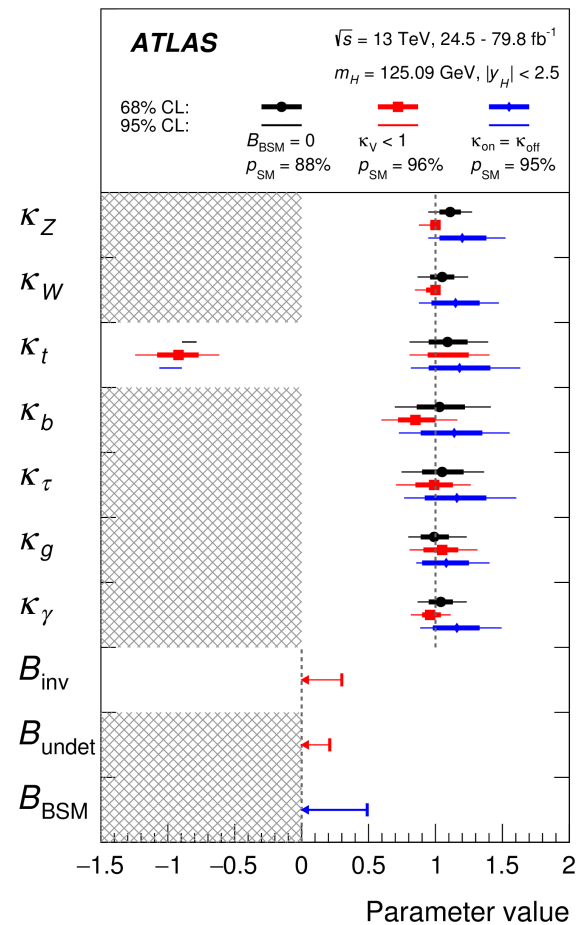
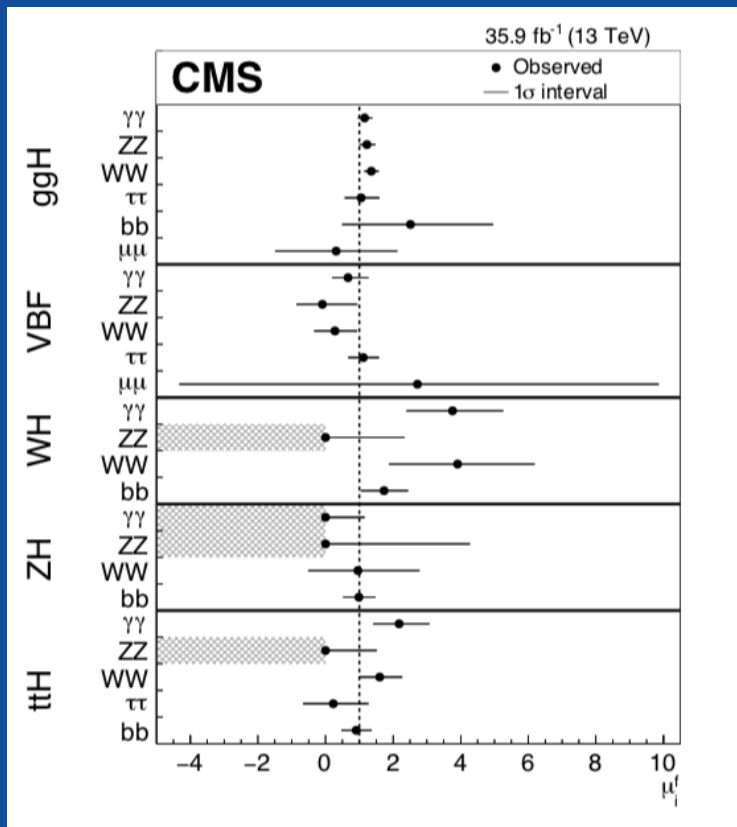
## CMS Preliminary



New mass measurement at  
unprecedented precision from the  
CMS experiment

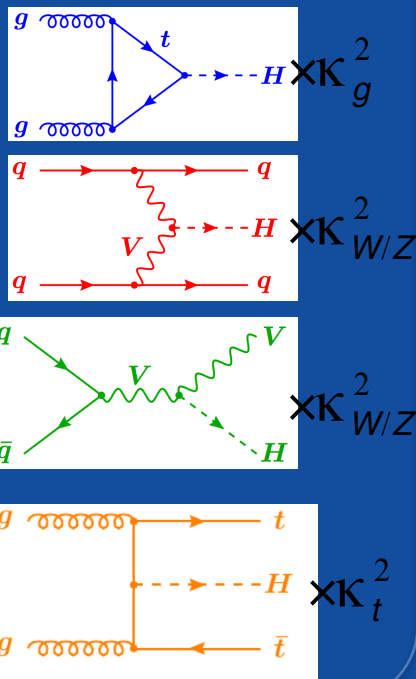
<https://cms.cern/news/cms-precisely-measures-mass-higgs-boson>

# Higgs couplings

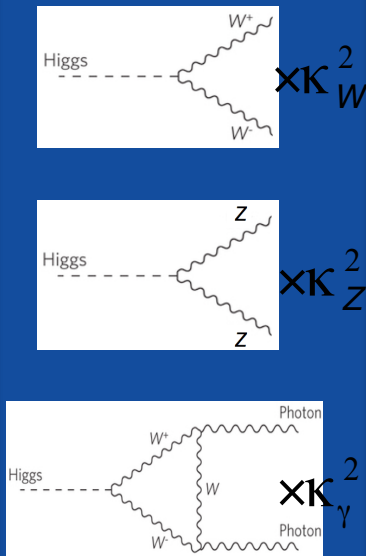


# Combining Higgs analyses

## Production

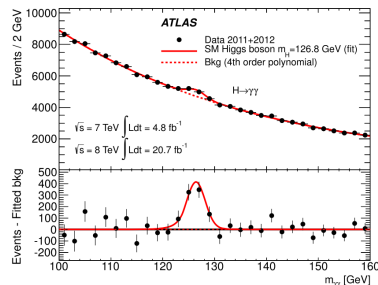


## Decay

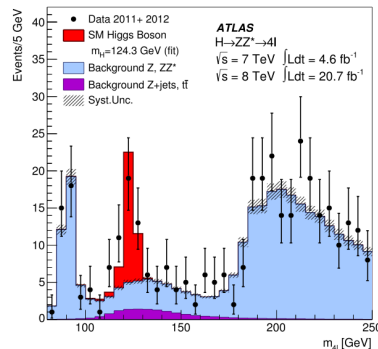


FIT

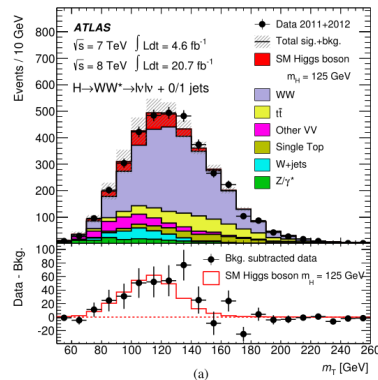
Backgrounds +



$H \rightarrow \gamma\gamma$



$H \rightarrow ZZ$



$H \rightarrow WW$