Universidade do Minho
Escola de Ciências

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

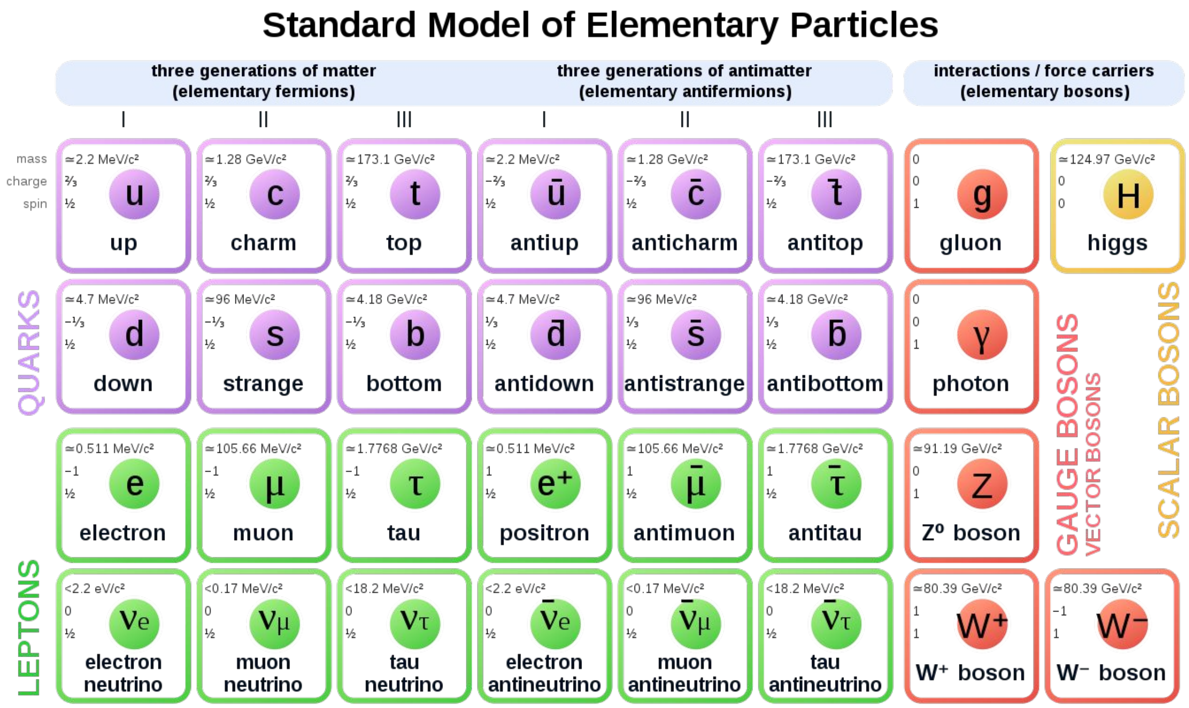
Probing the Standard Model and Beyond at the LHC

Nuno Castro
nfcastro@lip.pt

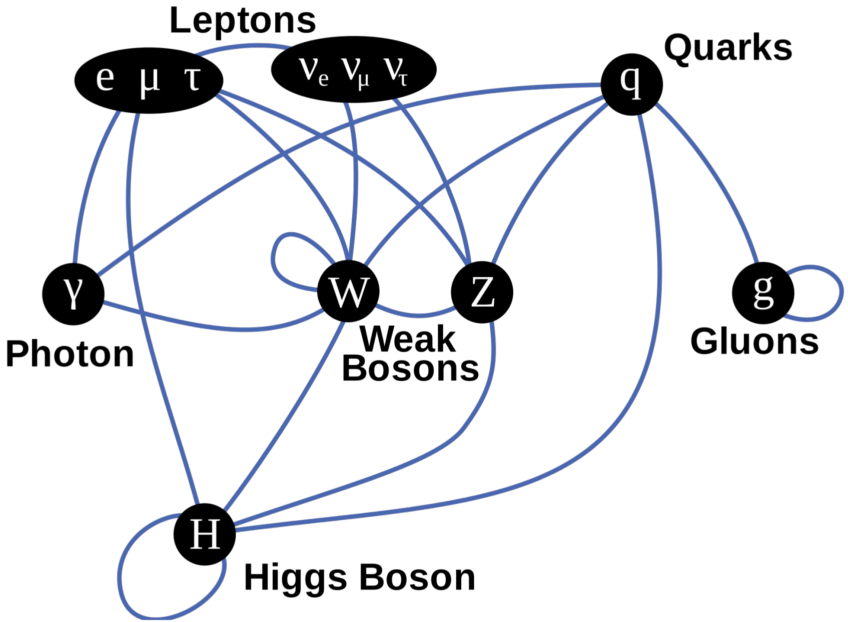
LIP Internship 2022

Fundação para a Ciência e a Tecnologia
UIDP/50007/2020
LA/P/0016/2020
CERN/FIS-PAR/0010/2021

The Standard Model of Particle Physics
particles & interactions

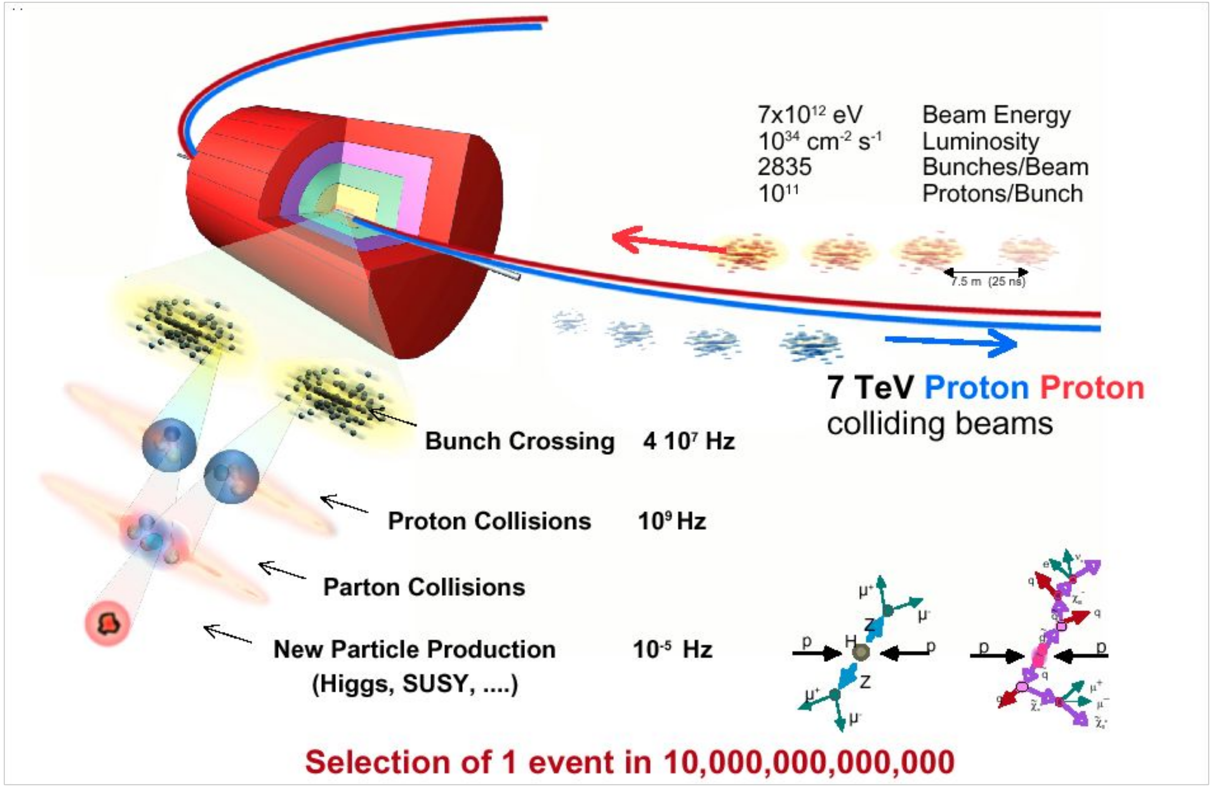


The Standard Model of Particle Physics
particles & interactions



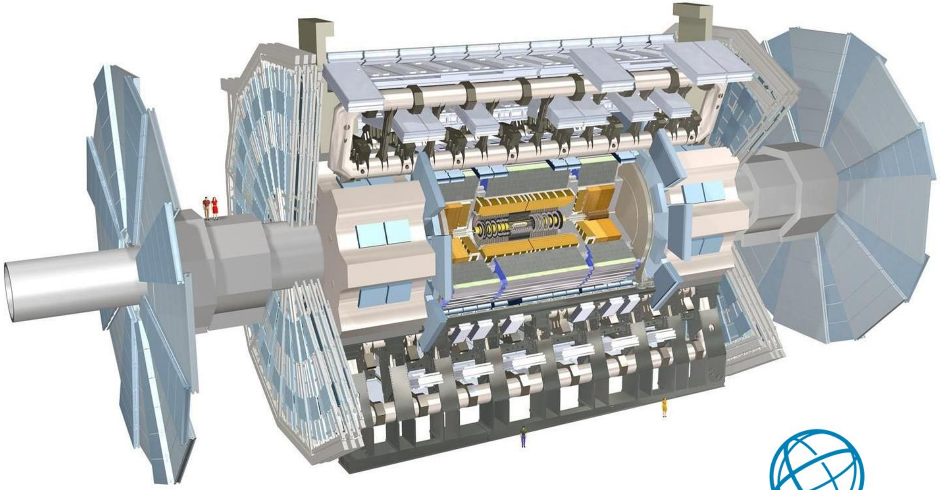
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

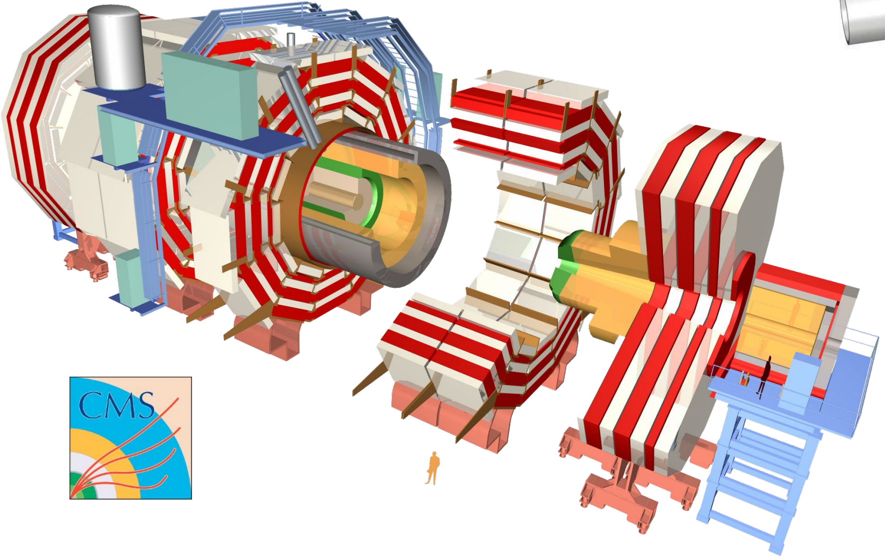
The Standard Model of Particle Physics
probing it at colliders



The Large Hadron Collider
and its detectors

The Large Hadron Collider
and its detectors





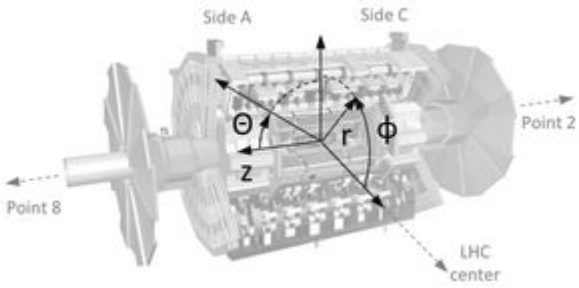
ATLAS
EXPERIMENT

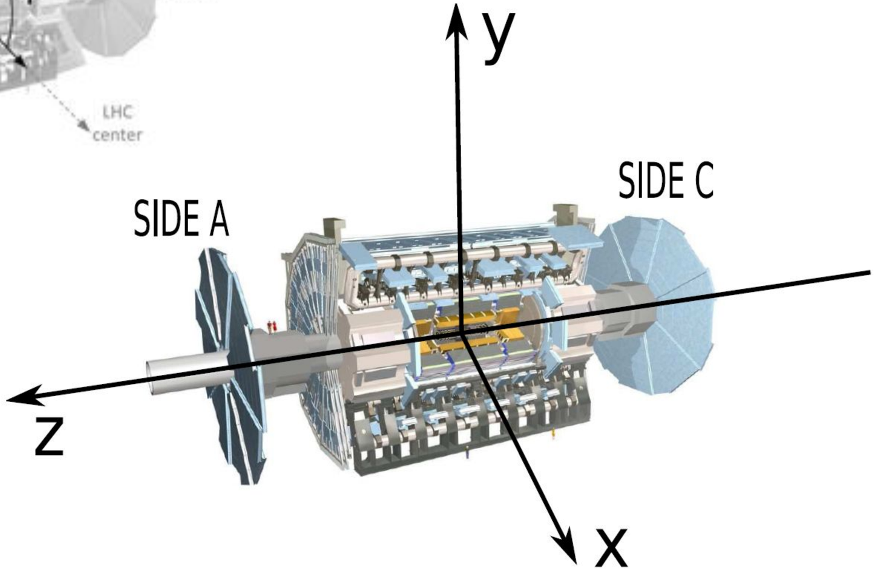
CMS

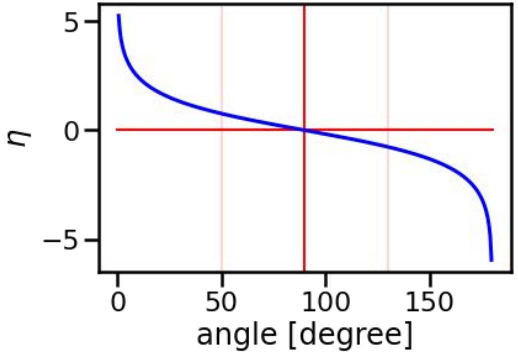
Hadron colliders
kinematic variables

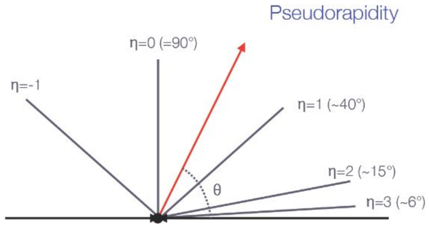
Relevant kinematic variables:

- Transverse momentum: p_T
- Rapidity: $y = ½ \cdot \ln (E-p_z)/(E+p_z)$
- Pseudorapidity: $\eta = -\ln \tan ½\theta$
- Azimuthal angle: φ

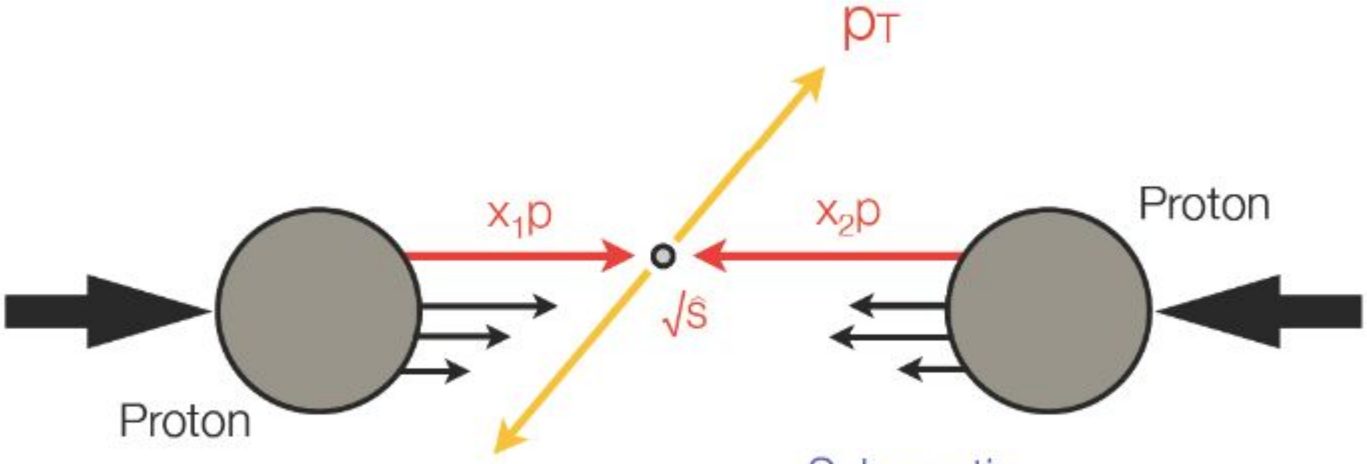






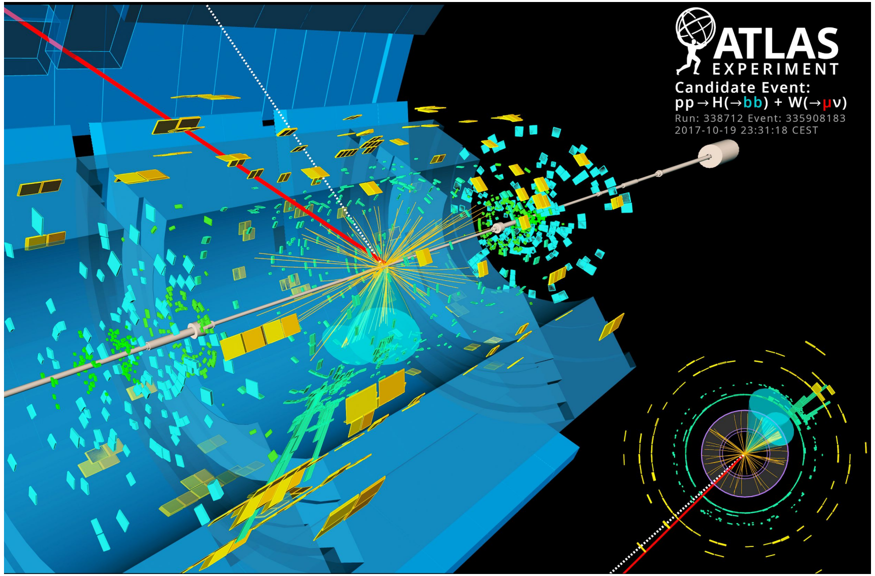


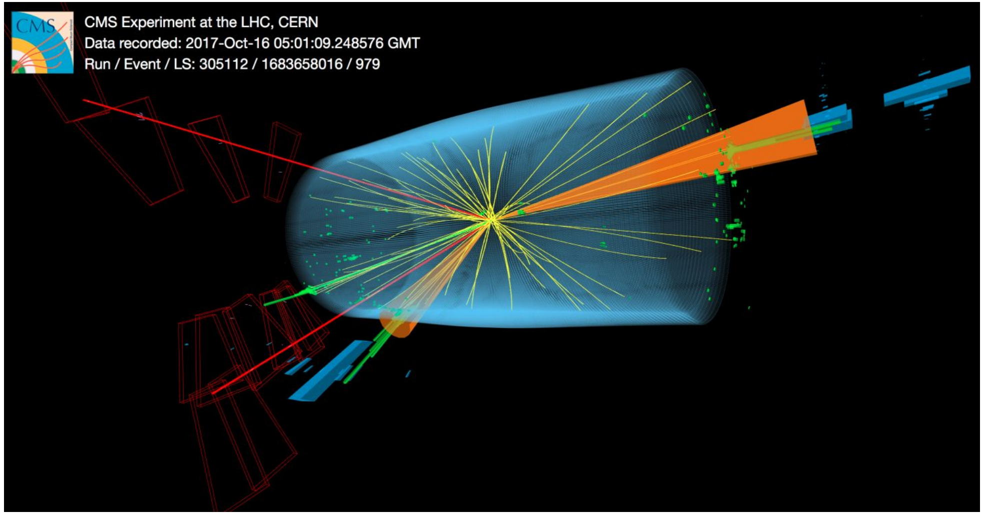
Hadron colliders
protons are not fundamental!



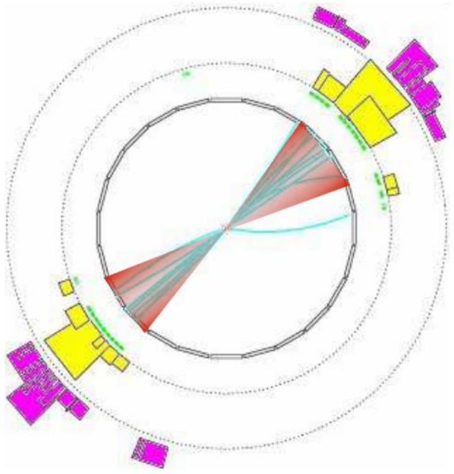
Schematic
proton-proton scattering

The Large Hadron Collider experiments
what is the outcome of a collision?

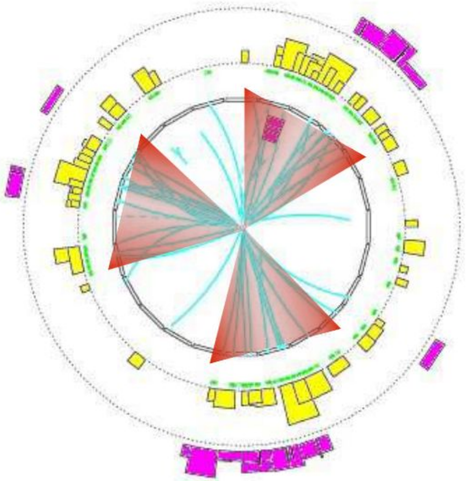




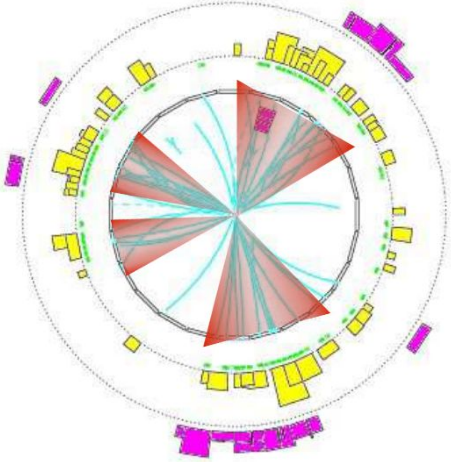
Hadron colliders
jets, jets and more jets



2 clear jets



3 jets?

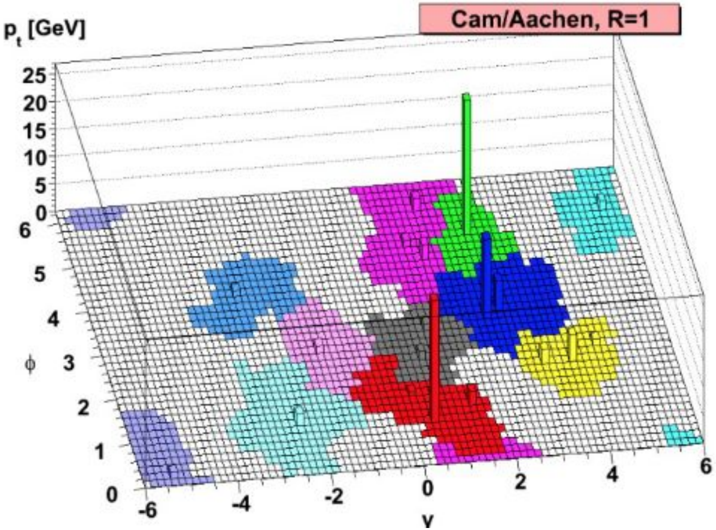


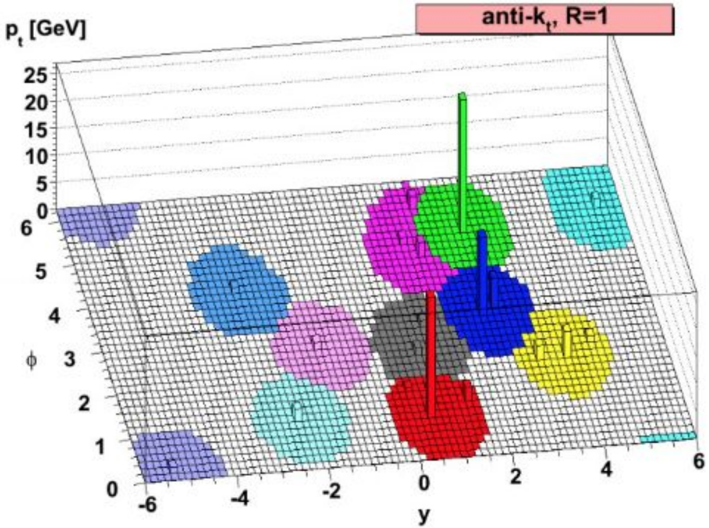
3 jets?
or 4 jets?

Reconstructing jets is an ambiguous task!

Hadron colliders

jets, jets and more jets





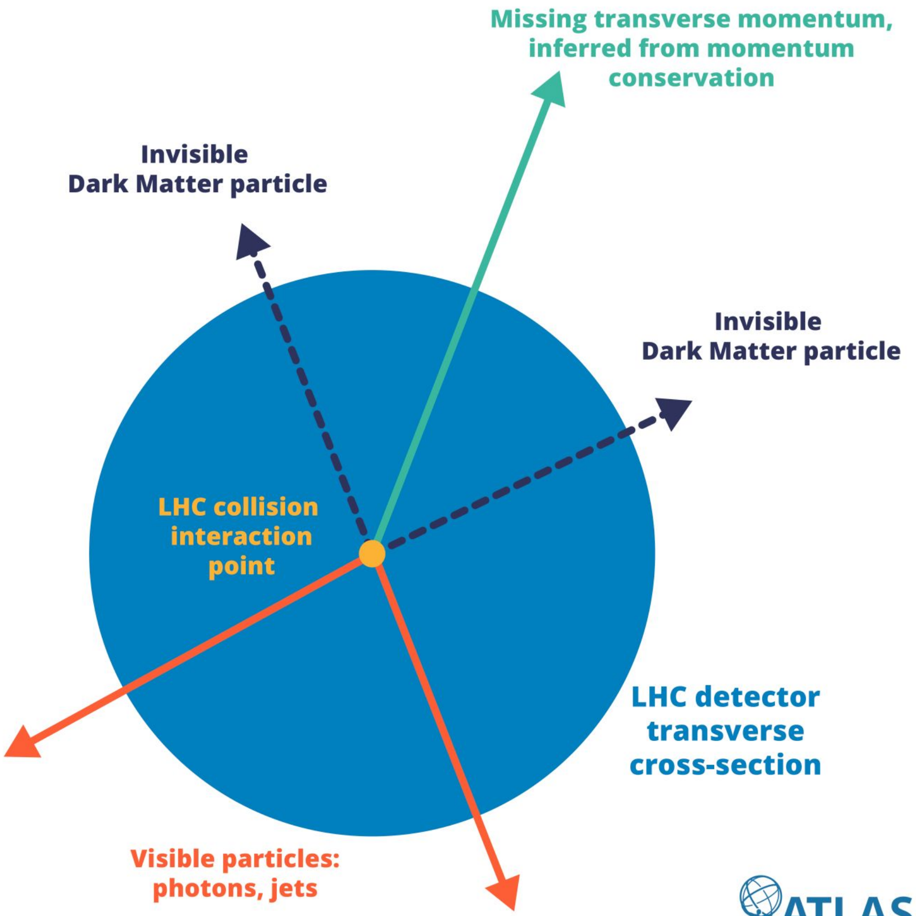
Reconstructing jets is an ambiguous task!

Energy balance

missing transverse energy (MET)

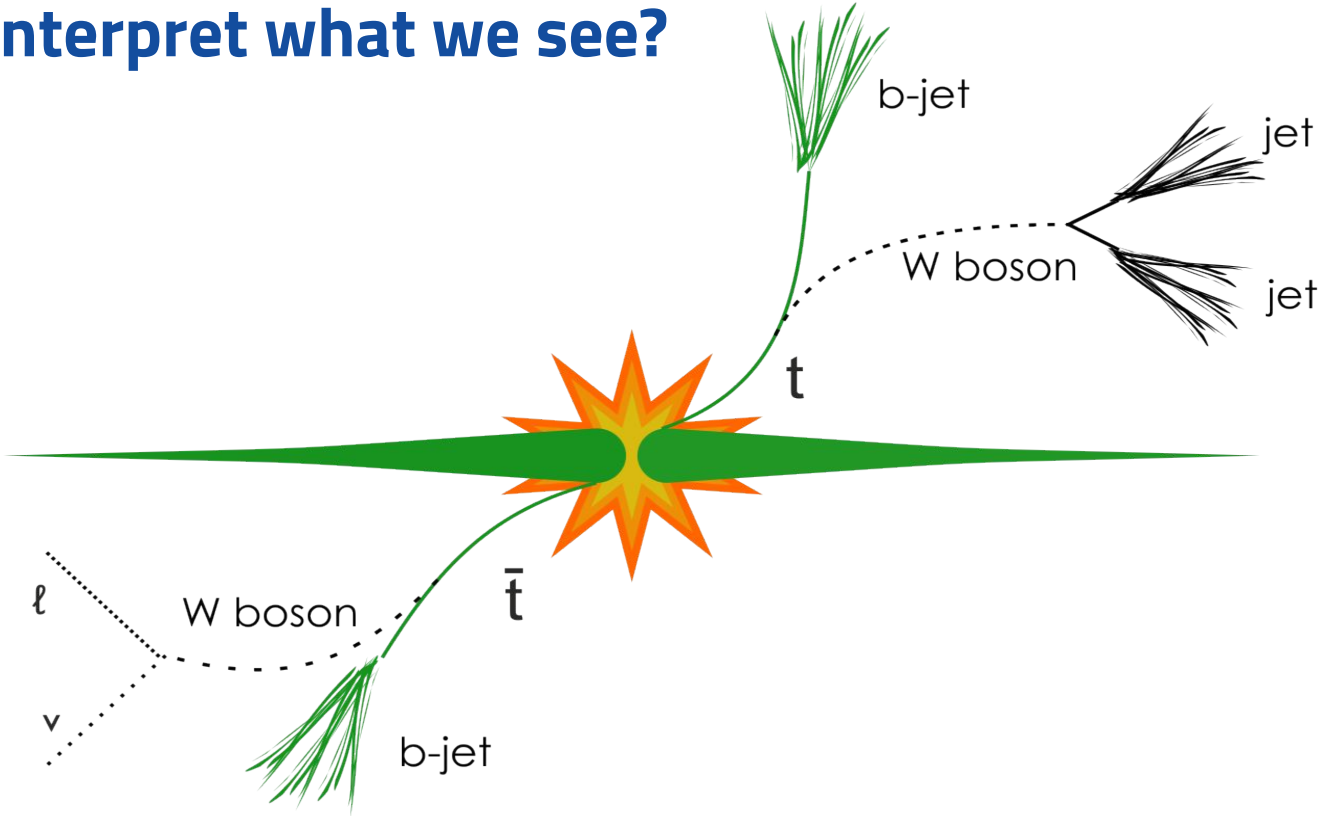
$$\overrightarrow{p_T^{\text{miss}}} = -\sum_i \overrightarrow{p_T^{i}}$$

transverse momentum
of each visible particle

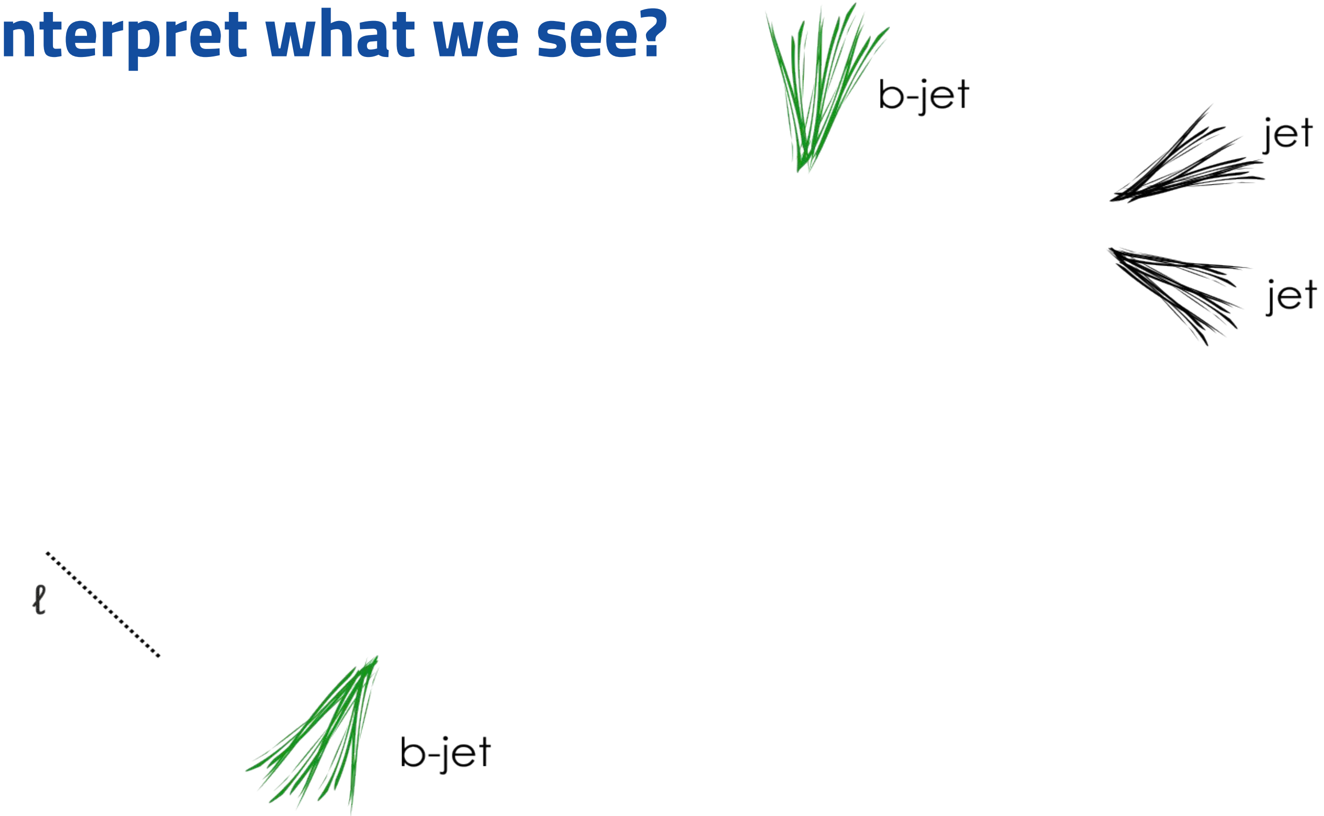


ATLAS EXPERIMENT

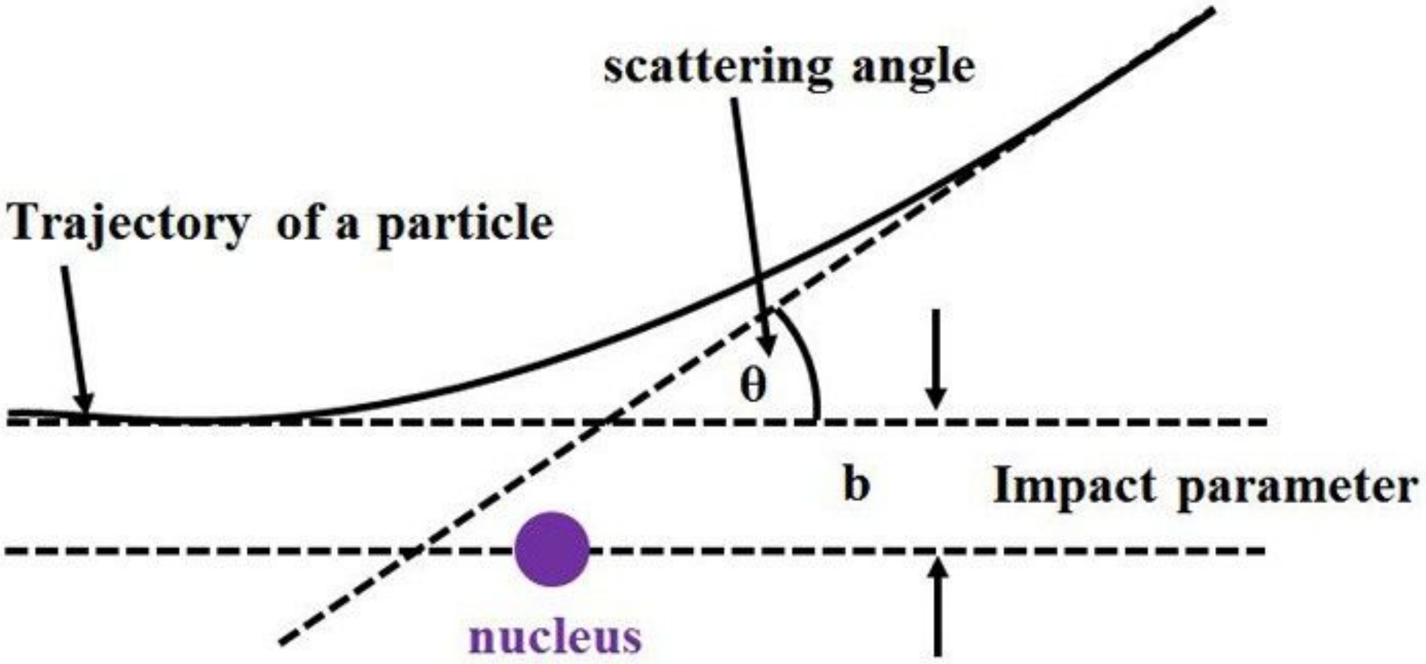
The Large Hadron Collider experiments
how to interpret what we see?



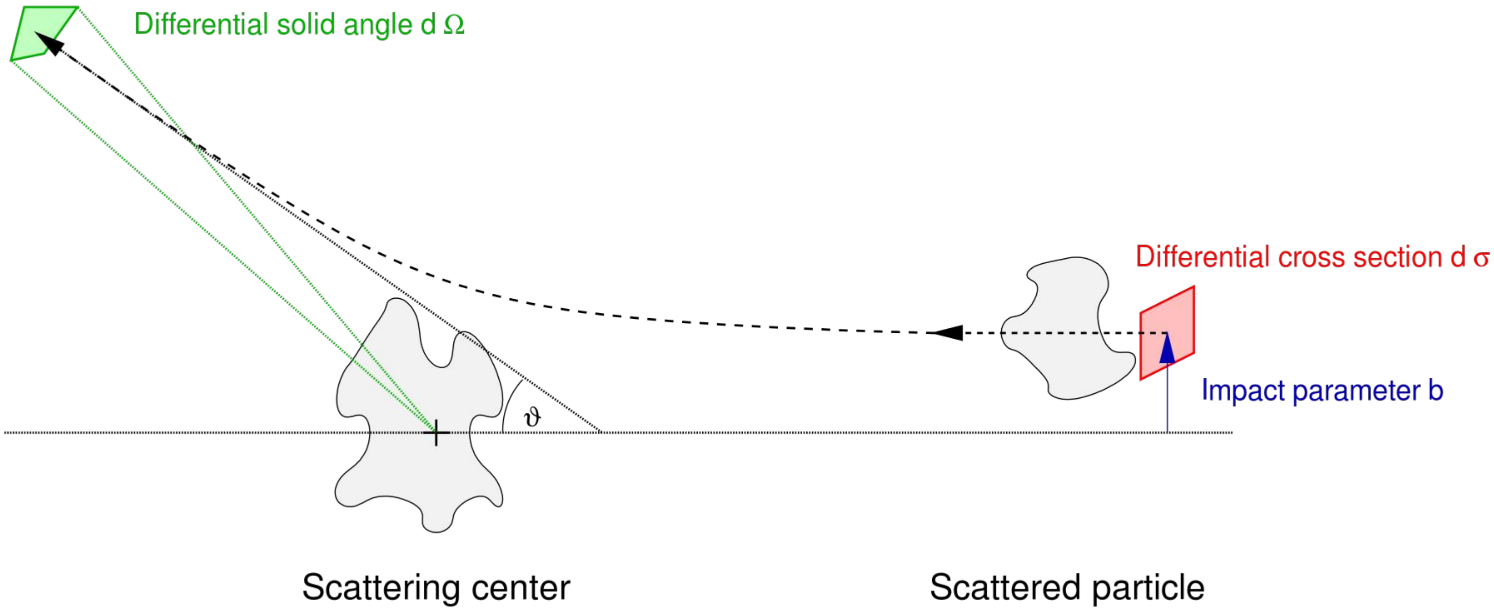
The Large Hadron Collider experiments
how to interpret what we see?



“Probability” for a collision to happen
cross-section



"Probability" for a collision to happen
differential cross-section



The Large Hadron Collider experiments
counting events

Number of observed events
just count …

Background
measured from data or calculated from theory

$$\sigma = \frac{N^{obs} - N^{bkg}}{\int \mathcal{L}\,dt \cdot \varepsilon}$$

Luminosity
determined by accelerator, triggers, …

Efficiency
many factors, optimized by experimentalist

slide from J. Varela: https://indico.cern.ch/event/862001/?view=standard#8-standard-model-at-the-lhc

The Large Hadron Collider experiments
counting events

$$L = f\frac{nN_aN_b}{A} = f\frac{nN_aN_b}{4\pi\sigma_x\sigma_y}$$

LHC:

N_x	~ 10^{11}
A	~ .0005 mm^2
n	~ 2800
f	~ 11 kHz
L	~ 10^{34} cm^{-2} s^{-1}

- N_a : number of particles per bunch (beam A)
- N_b : number of particles per bunch (beam B)
- U : circumference of ring
- n : number of bunches per beam
- v : velocity of beam particles
- f : revolution frequency
- A : beam cross-section
- σ_x : standard deviation of beam profile in x
- σ_y : standard deviation of beam profile in y

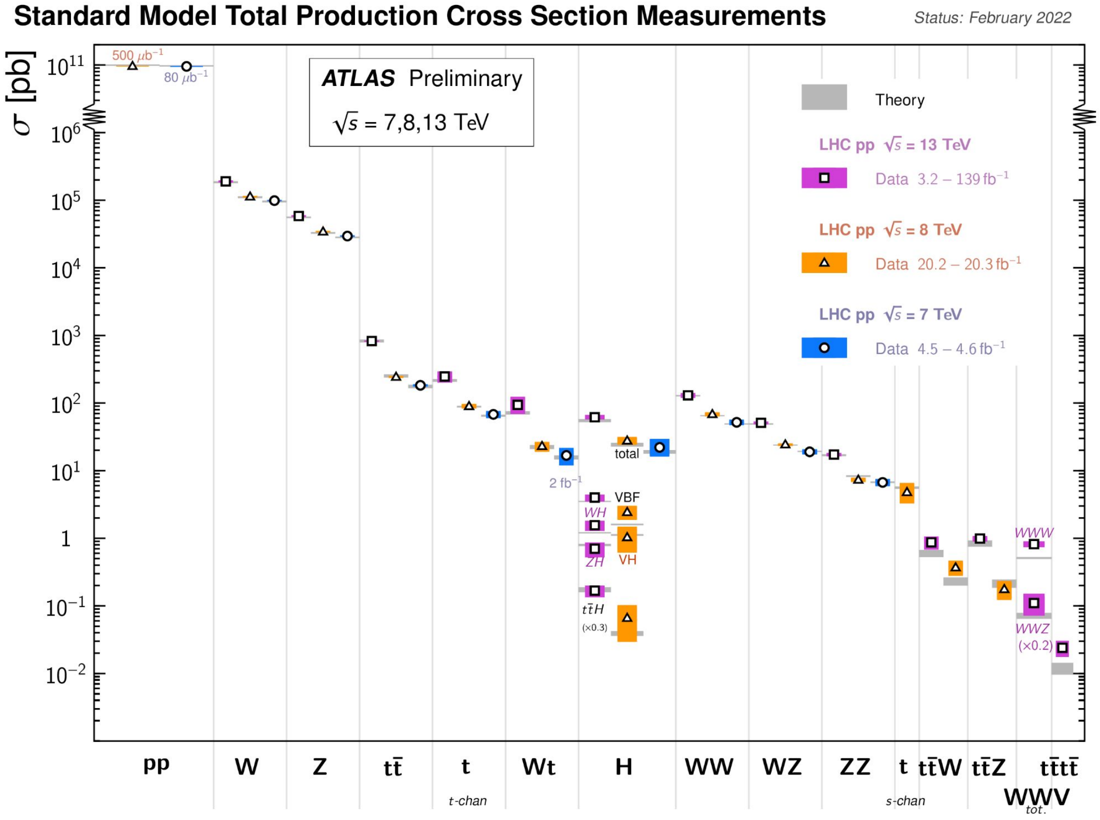
slide from J. Varela: https://indico.cern.ch/event/862001/?view=standard#8-standard-model-at-the-lhc

What can we do with the LHC data?

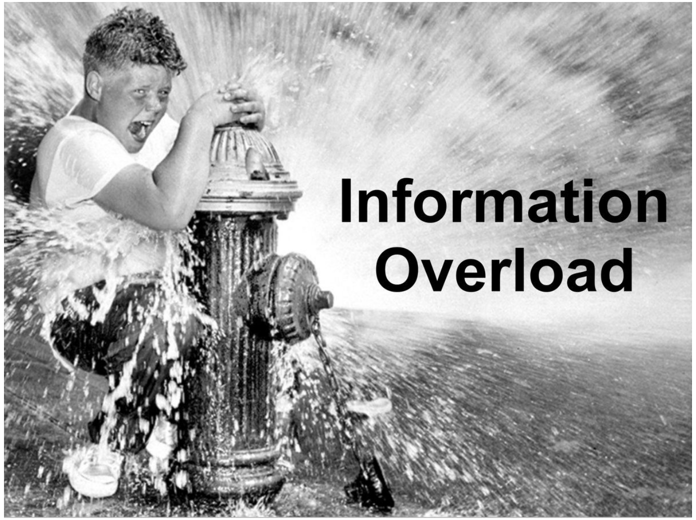
probe the Standard Model !

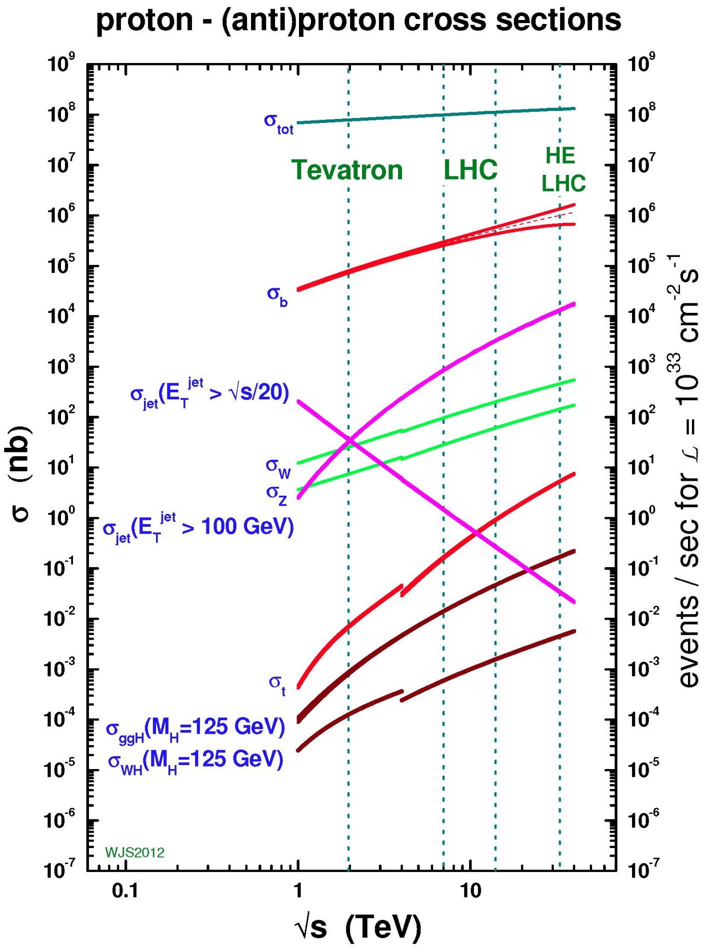
Comparing with theory predictions

excellent agreement

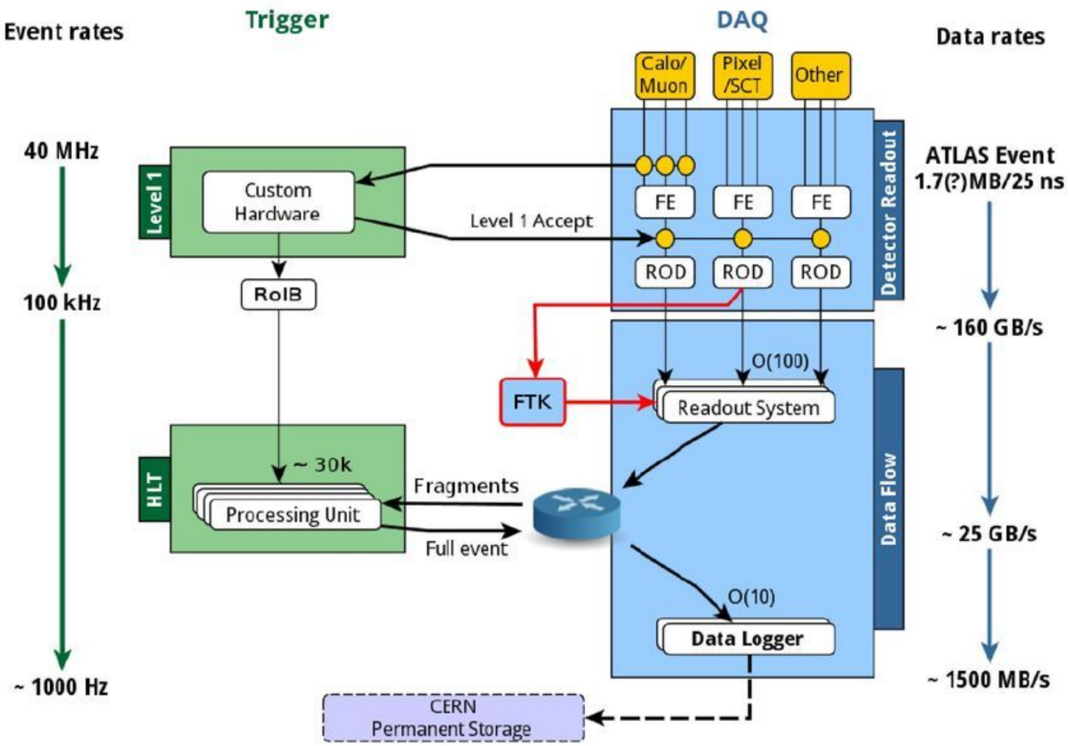


The LHC experiments
the need to select events





The LHC experiments
the need to select events: triggers

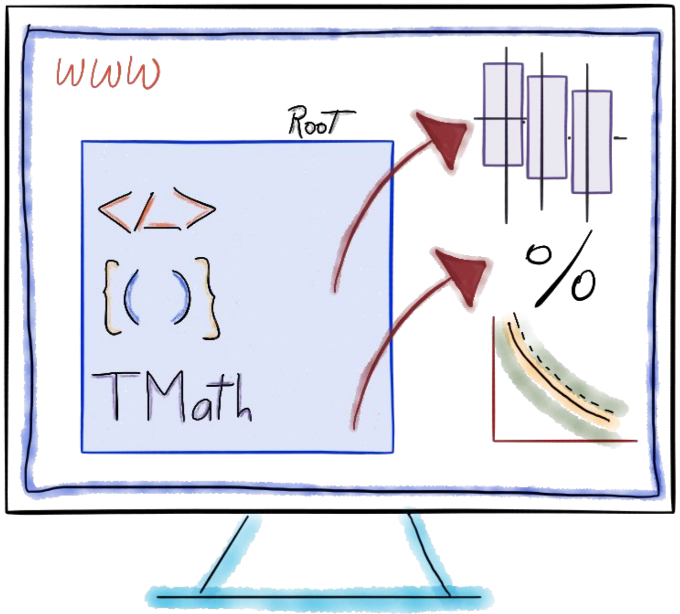


doing a data analysis!
the need to select events

open data ATLAS

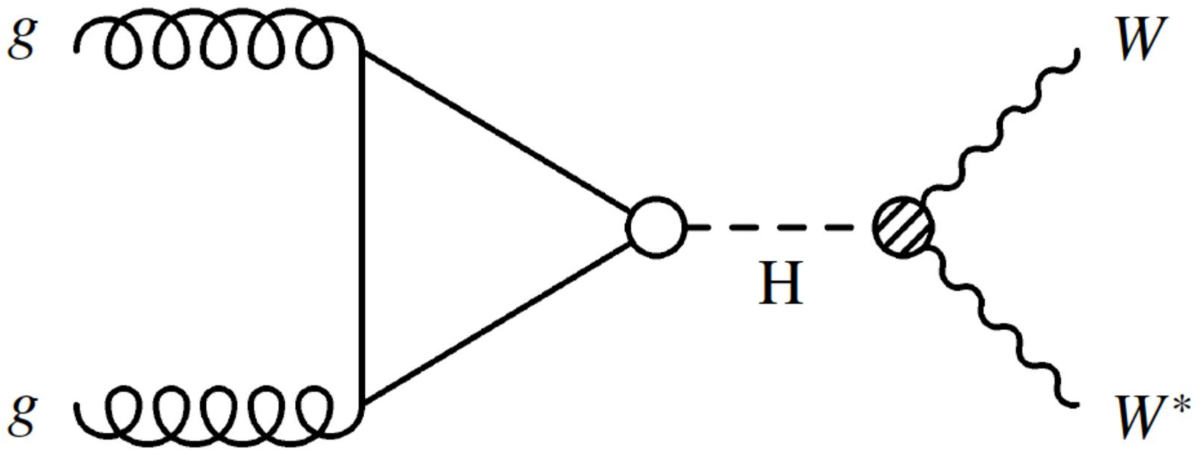
http://opendata.atlas.cern

- triggers
- define the physics objects
    - jets
    - electrons
    - muons
    - taus
    - photons
    - MET
    - …
- define the good set of cuts to increase the signal to background ratio



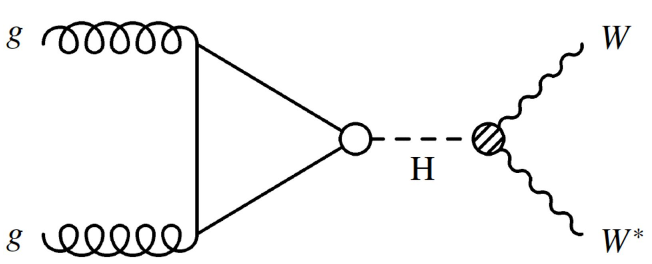
http://opendata.atlas.cern

Higgs boson production in the H → WW decay channel in the two-lepton final state



http://opendata.atlas.cern

Higgs boson production in the H → WW decay channel in the two-lepton final state



looking for events with two charged isolated leptons (electrons or muons) and (almost) no jets

open data ATLAS

http://opendata.atlas.cern

Higgs boson production in the H → WW decay channel in the two-lepton final state

$$p_\mu = \left(\frac{E}{c}, p_x, p_y, p_z\right)$$

$$p_\mu p^\mu = -\frac{E^2}{c^2} + p_x^2 + p_y^2 + p_z^2 = -\frac{E^2}{c^2} + p^2 = m^2 c^4$$

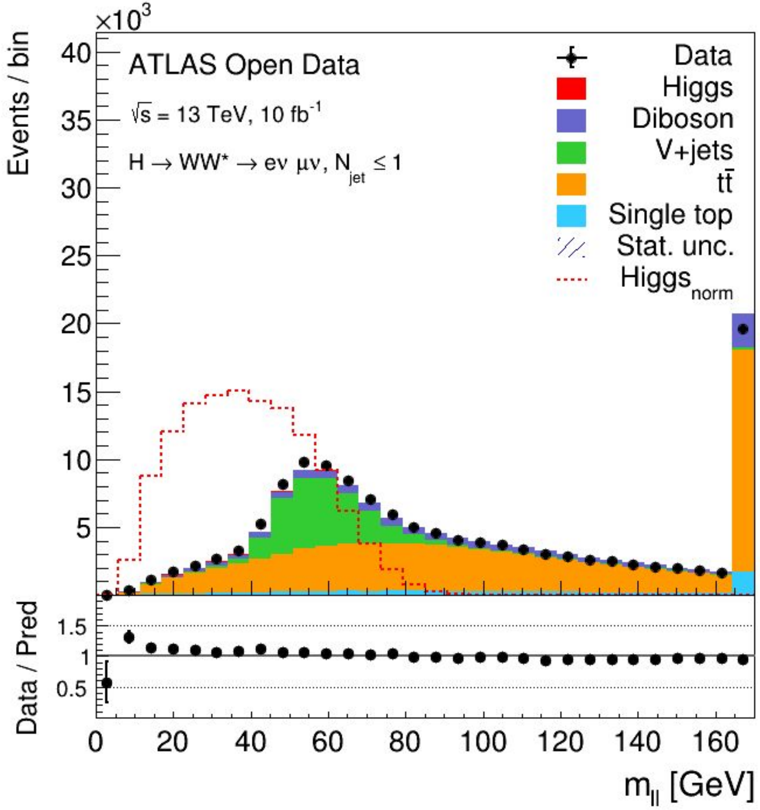
$$E^2 = p^2 c^2 + m^2 c^4$$

$$\hbar = c = 1$$

open data ATLAS

http://opendata.atlas.cern

So, let’s look at the dilepton invariant mass!

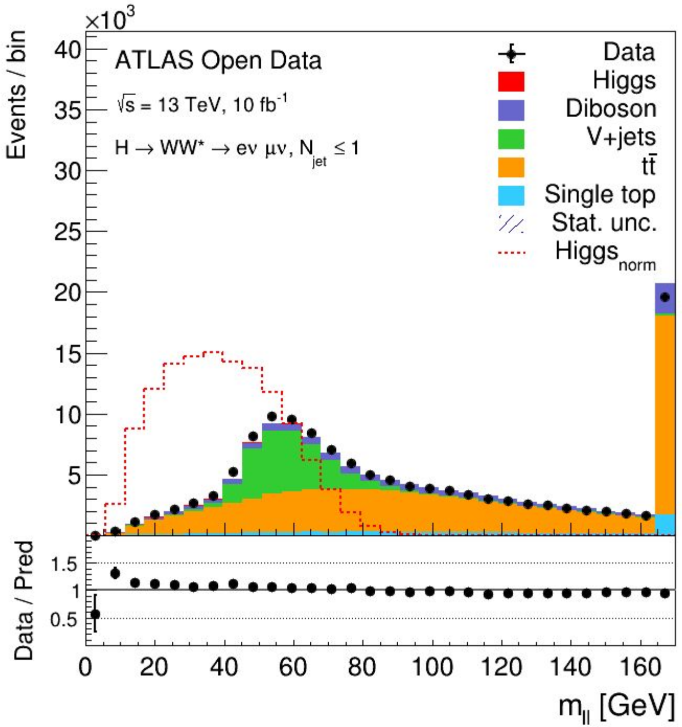


(still no hint for a signal)

http://opendata.atlas.cern

be clever and select "good" events!

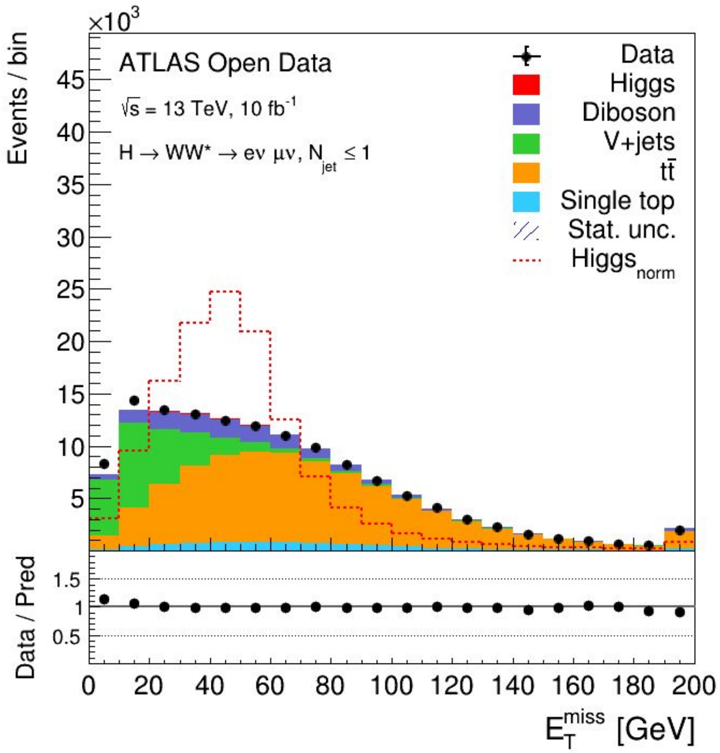
- Single-electron or single-muon trigger satisfied;
- Exactly two isolated, different-flavour opposite-sign leptons (electrons or muons) with $p_T > 22$ and 15 GeV, respectively;
- Missing transverse momentum E_T^{miss} larger than 30 GeV;
- Exactly zero or at most one jet with $p_T > 30$ GeV, and exactly zero b-tagged jets (MV2c10 @ 85% WP) with $p_T > 20$ GeV;
- Azimuthal angle between E_T^{miss} and the dilepton system $\Delta\phi(\ell\ell, E_T^{miss}) > \pi/2$;
- Transverse momentum of the dilepton system $p_T^{\ell\ell} > 30$ GeV;
- The invariant mass of the two leptons $m_{\ell\ell}$ must satisfy: 10 GeV < $m_{\ell\ell}$ < 55 GeV;
- Azimuthal angle between the two leptons $\Delta\phi(\ell, \ell) < 1.8$.



be clever and select “good” events!

http://opendata.atlas.cern

- Single-electron or single-muon trigger satisfied;
- Exactly two isolated, different-flavour opposite-sign leptons (electrons or muons) with $p_T > 22$ and 15 GeV, respectively;
- Missing transverse momentum E_T^{miss} larger than 30 GeV;
- Exactly zero or at most one jet with $p_T > 30$ GeV, and exactly zero b-tagged jets (MV2c10 @ 85% WP) with $p_T > 20$ GeV;
- Azimuthal angle between E_T^{miss} and the dilepton system $\Delta\phi(\ell\ell, E_T^{miss}) > \pi/2$;
- Transverse momentum of the dilepton system $p_T^{\ell\ell} > 30$ GeV;
- The invariant mass of the two leptons $m_{\ell\ell}$ must satisfy: 10 GeV < $m_{\ell\ell}$ < 55 GeV;
- Azimuthal angle between the two leptons $\Delta\phi(\ell, \ell) < 1.8$.

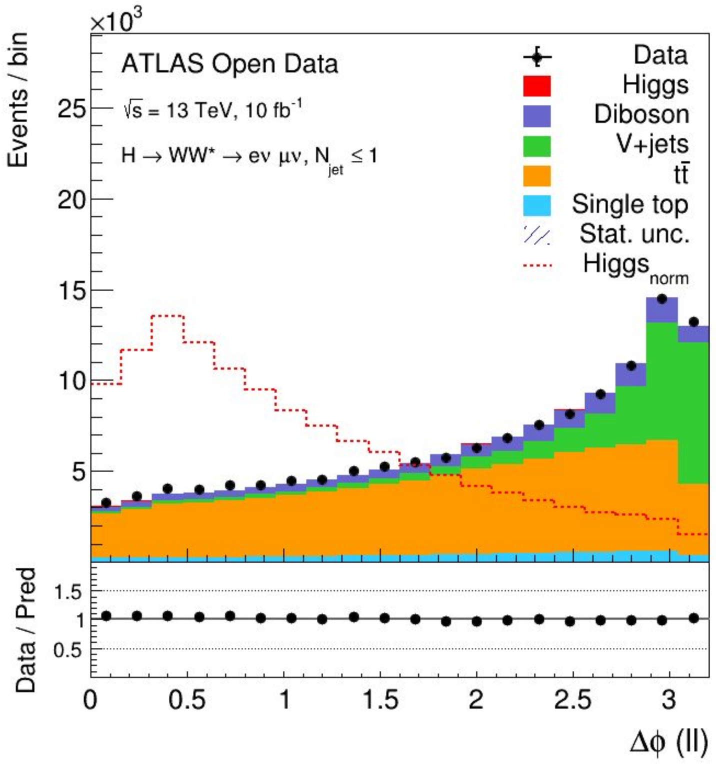


ATLAS open data

http://opendata.atlas.cern

be clever and select “good” events!

- Single-electron or single-muon trigger satisfied;
- Exactly two isolated, different-flavour opposite-sign leptons (electrons or muons) with $p_T > 22$ and 15 GeV, respectively;
- Missing transverse momentum E_T^{miss} larger than 30 GeV;
- Exactly zero or at most one jet with $p_T > 30$ GeV, and exactly zero b-tagged jets (MV2c10 @ 85% WP) with $p_T > 20$ GeV;
- Azimuthal angle between E_T^{miss} and the dilepton system $\Delta\phi(\ell\ell, E_T^{miss}) > \pi/2$;
- Transverse momentum of the dilepton system $p_T^{\ell\ell} > 30$ GeV;
- The invariant mass of the two leptons $m_{\ell\ell}$ must satisfy: 10 GeV < $m_{\ell\ell}$ < 55 GeV;
- Azimuthal angle between the two leptons $\Delta\phi(\ell, \ell) < 1.8$.

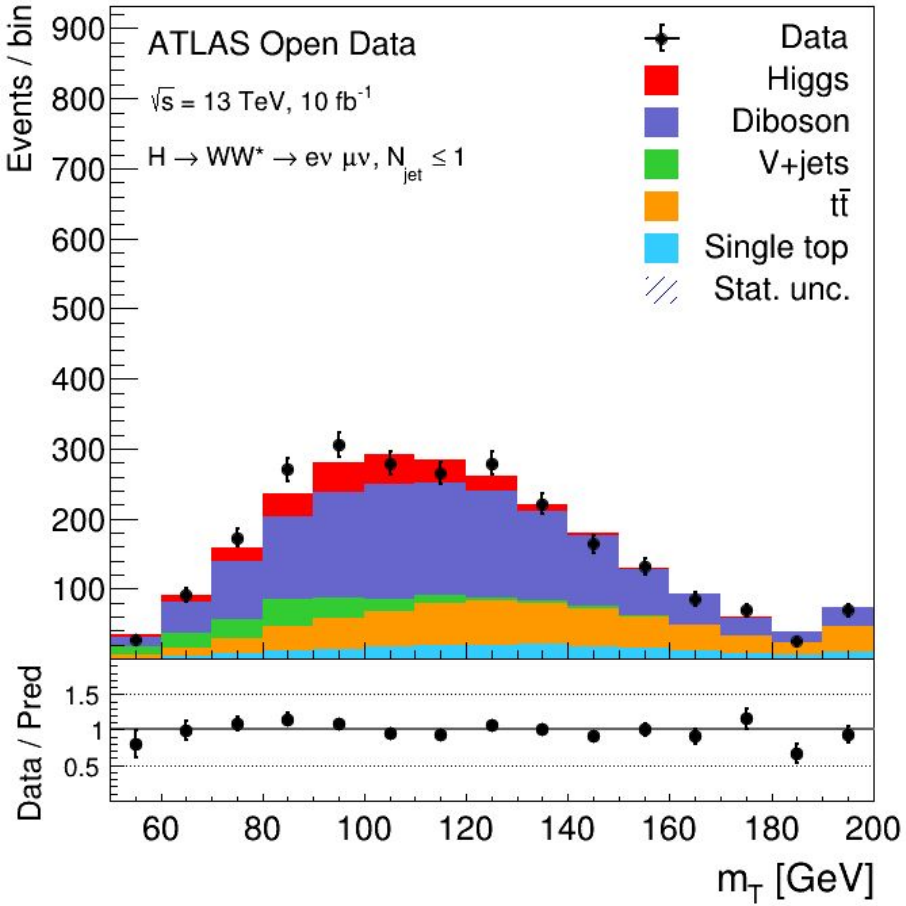


open data ATLAS

http://opendata.atlas.cern

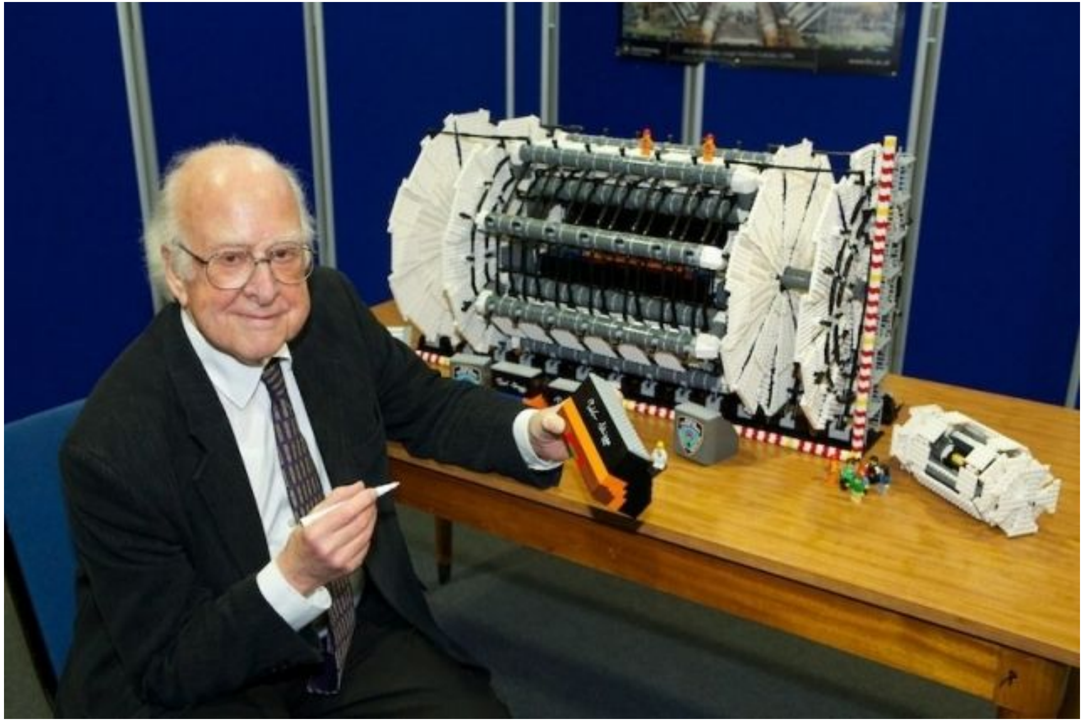
after all cuts…

...voila our signal!



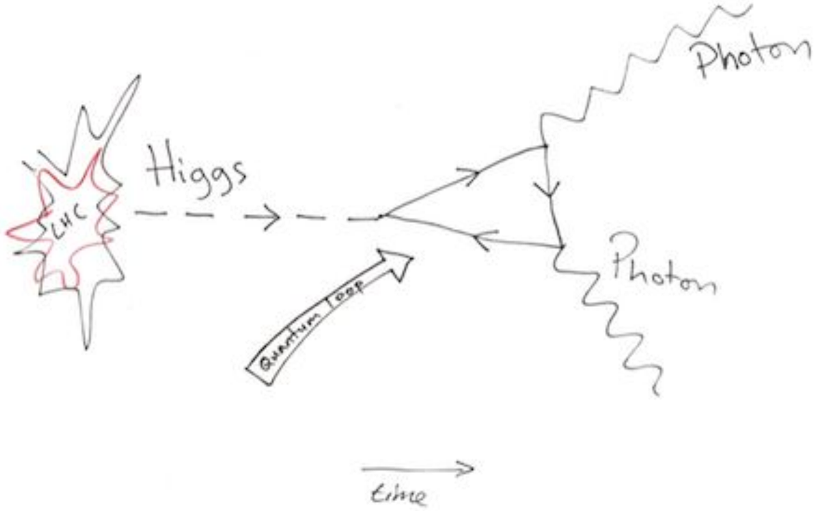
What can we do with the LHC data?

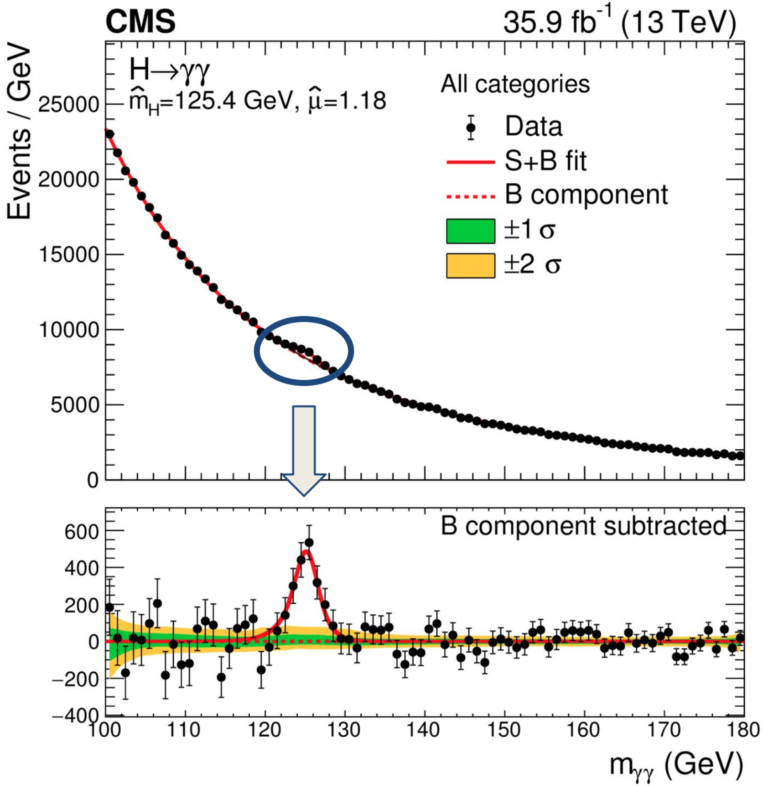
probe the Standard Model - the Higgs boson and its properties



What can we do with the LHC data?

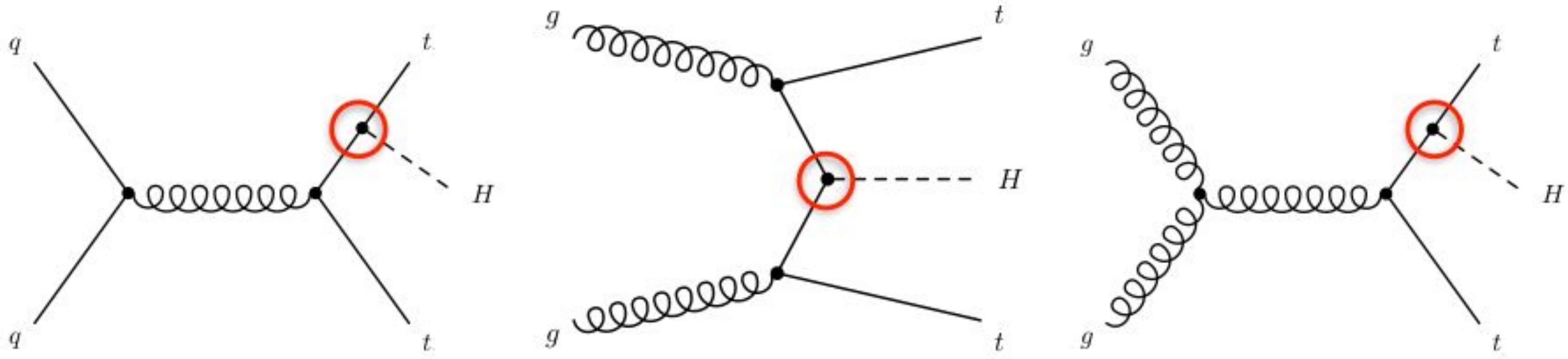
probe the Standard Model - the Higgs boson and its properties





What can we do with the LHC data?

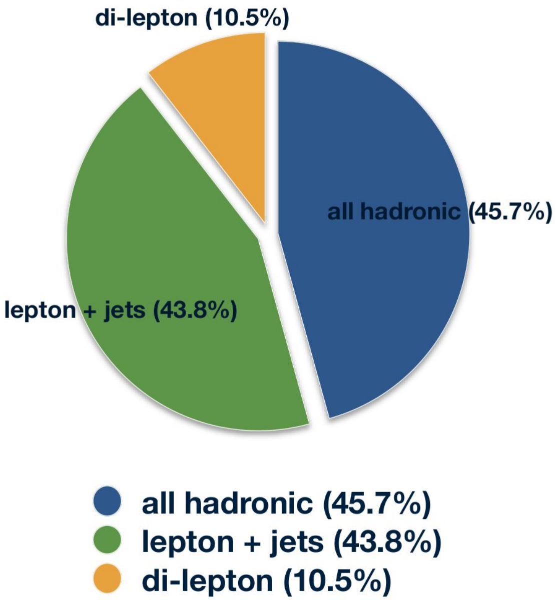
probe the Standard Model - the Higgs boson and its properties



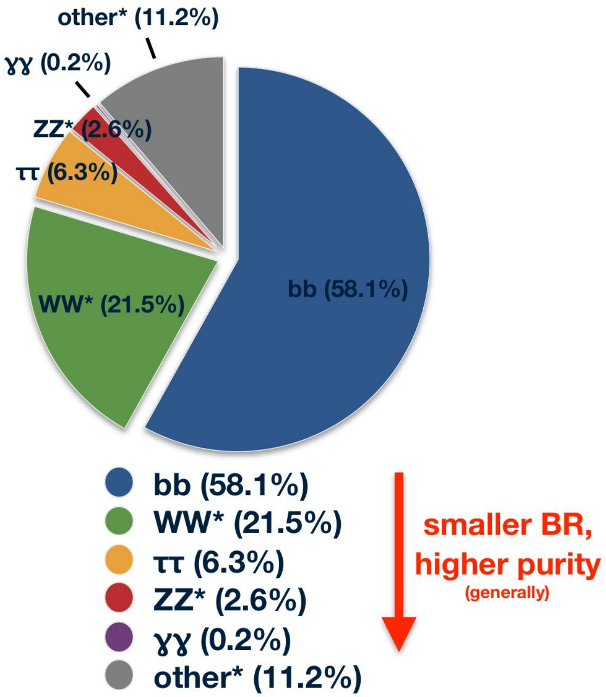
What can we do with the LHC data?

probe the Standard Model - the Higgs boson and its properties

ttbar decay BRs

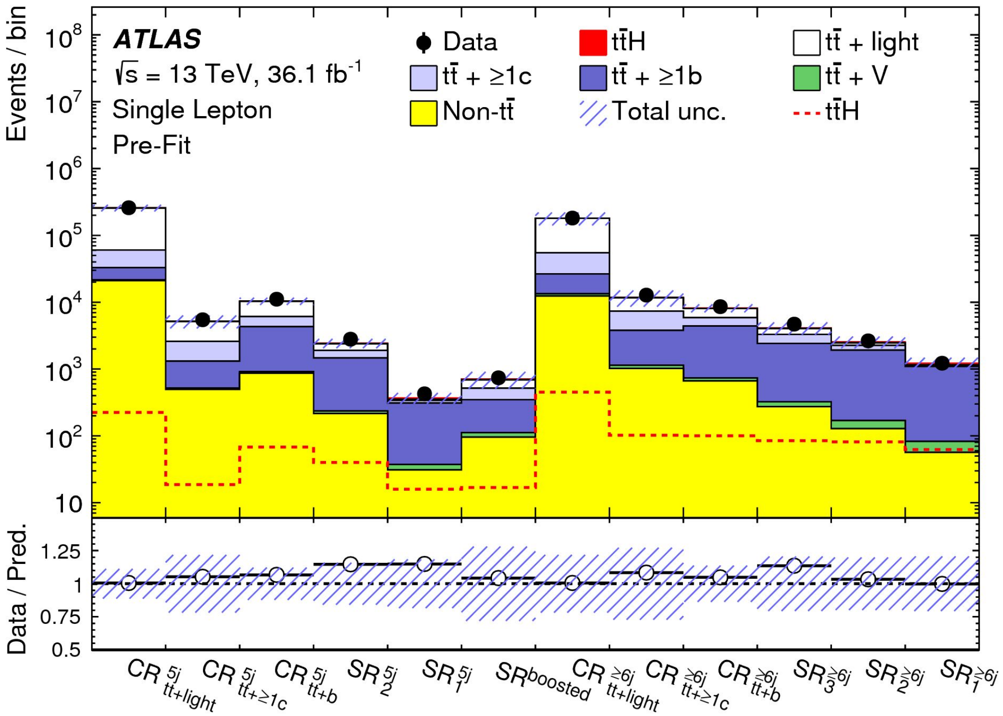


Higgs decay BRs



What can we do with the LHC data?

probe the Standard Model - the Higgs boson and its properties

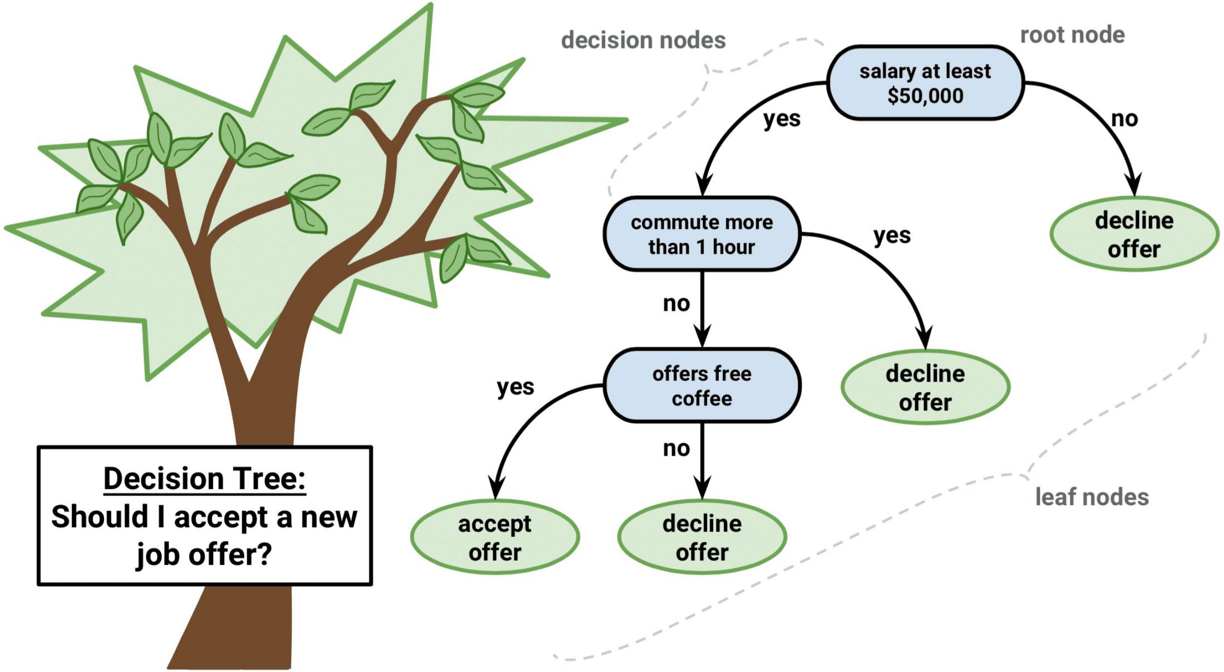


What can we do with the LHC data?

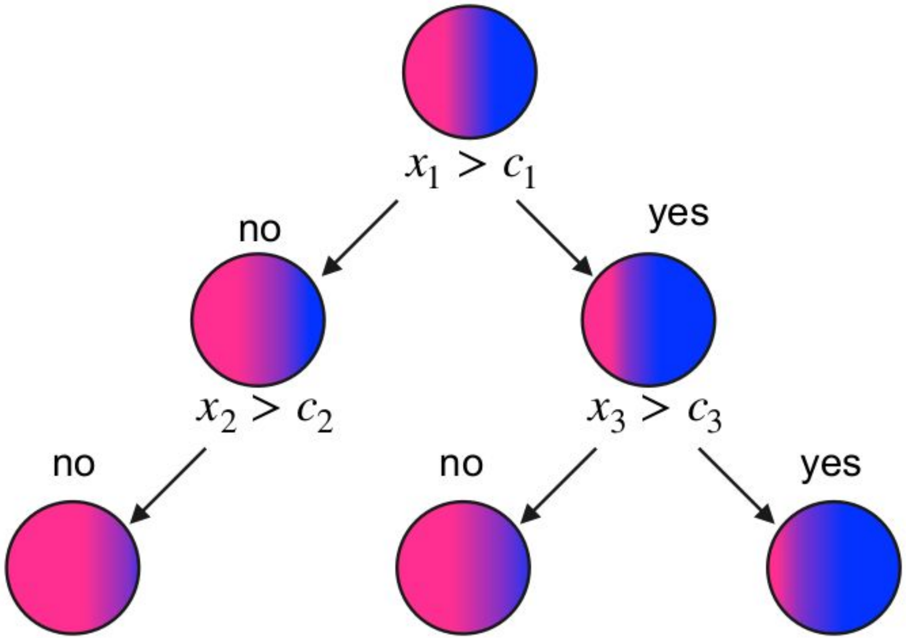
probe the Standard Model - the Higgs boson and its properties

machine learning:

decision trees



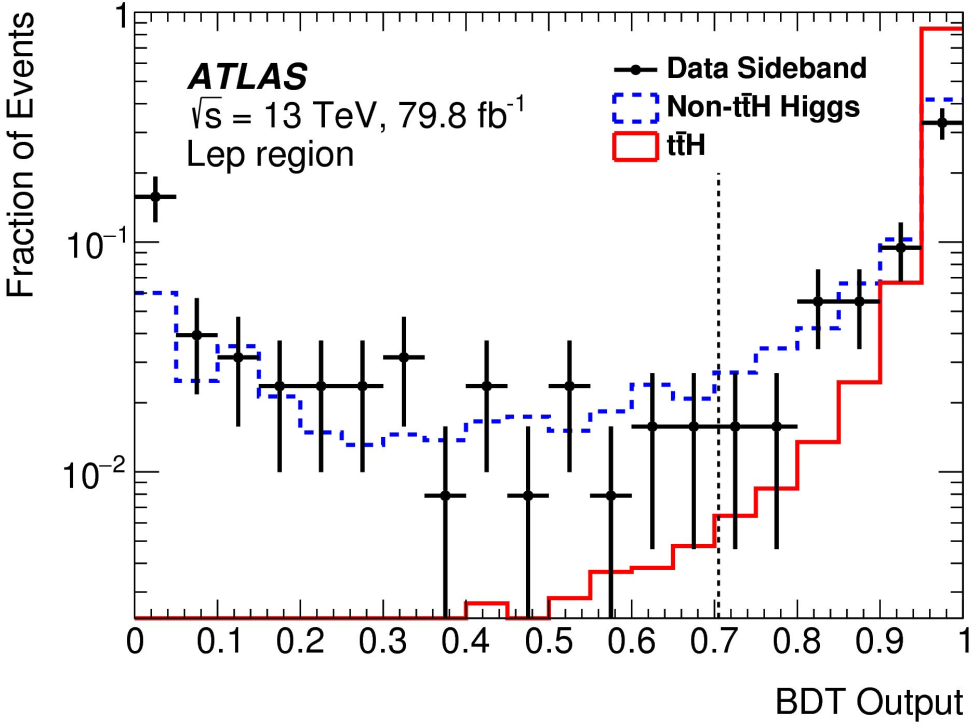
Shallow Learning
Decision Tree



- $\vec{x}$ input features
- Labeled samples of data: **blue**/pink
- Partitions the data to increase sample purity
- Finds optimal criteria $x_i > c_i$ to separate data categories
- Category prediction based on the label of the majority samples of the end leaf
- Core of the most popular algorithms used in LHC event classification (Boosted Decision Trees)

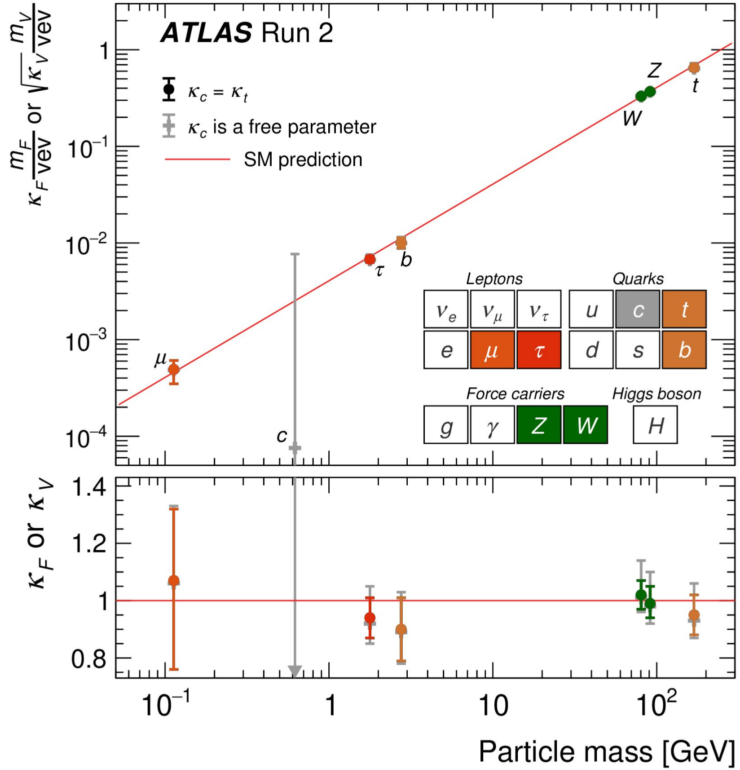
What can we do with the LHC data?

probe the Standard Model - the Higgs boson and its properties



What can we do with the LHC data?

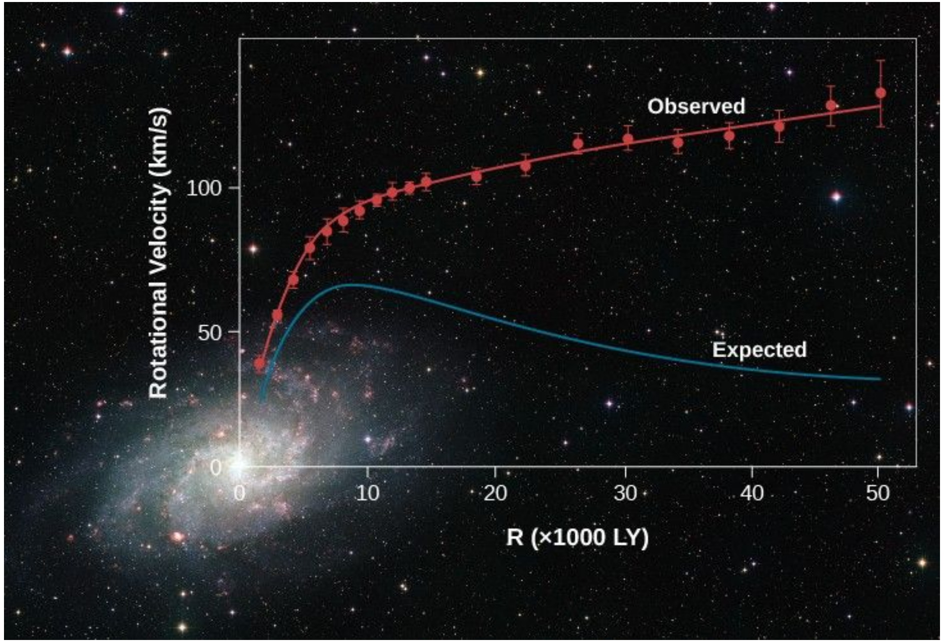
probe the Standard Model - the Higgs boson and its properties

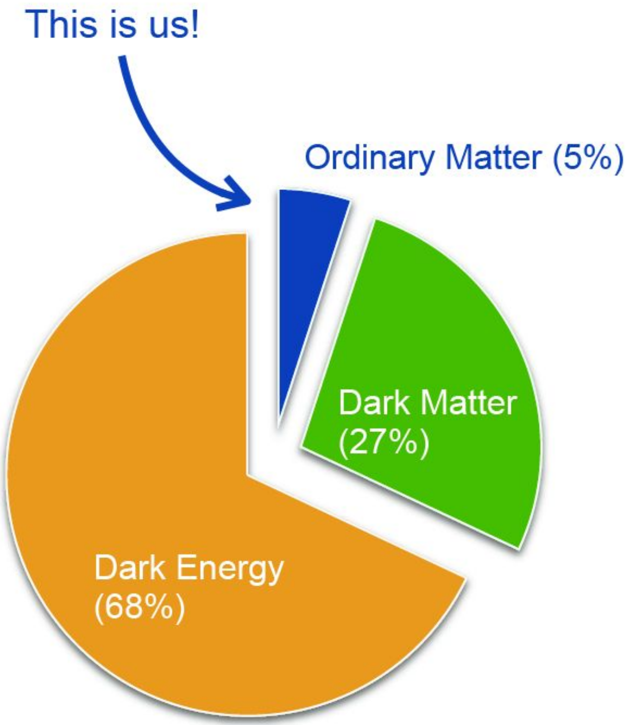


[Nature (2022)](#)

Why going beyond the Standard Model?

there must be new physics!





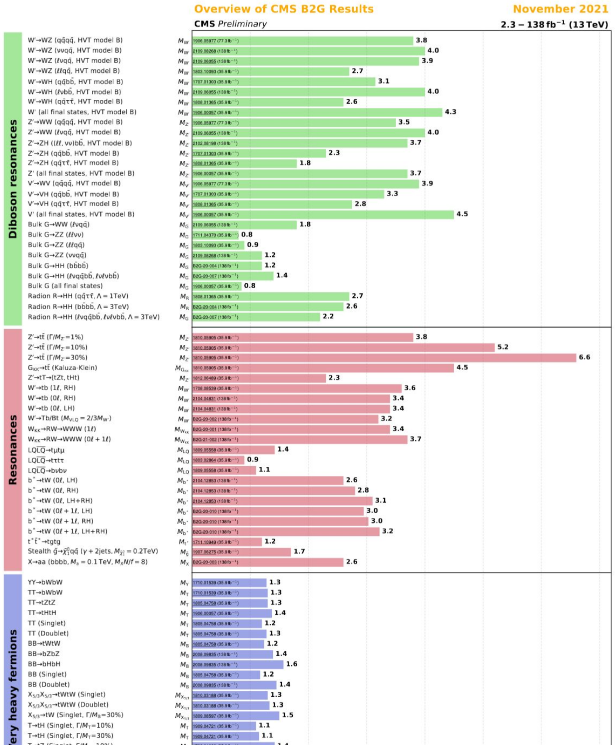
What can we do with the LHC data?

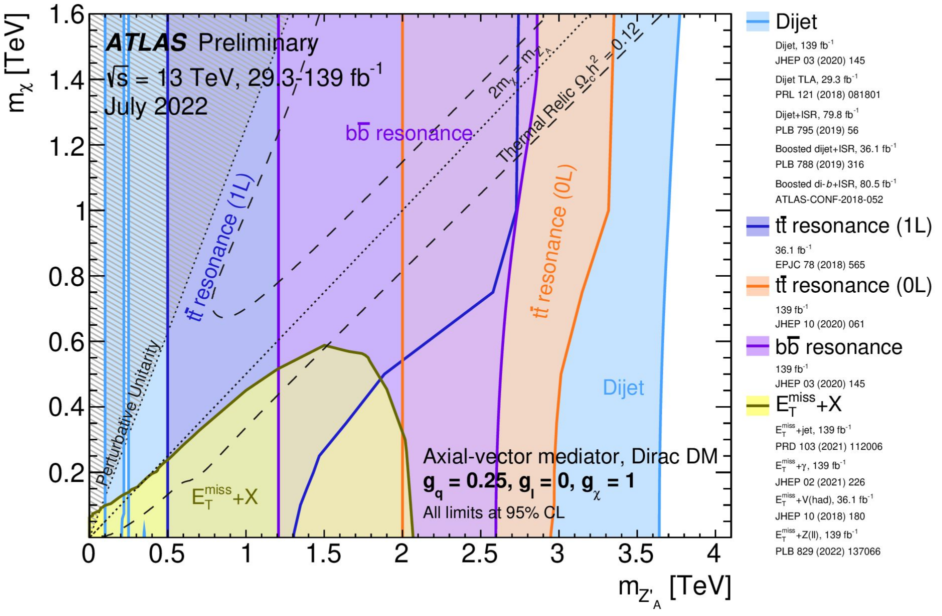
probe the Standard Model - and search for new phenomena beyond it!

- Why should we search for new physics beyond the Standard Model?
  - we *must* leave no stone unturned in data
  - … and we have good motivations to think that new physics exists
    - mass hierarchy of the fermions
    - matter/anti-matter asymmetry
    - dark matter
    - …

What can we do with the LHC data?

probe the Standard Model - and search for new phenomena beyond it!

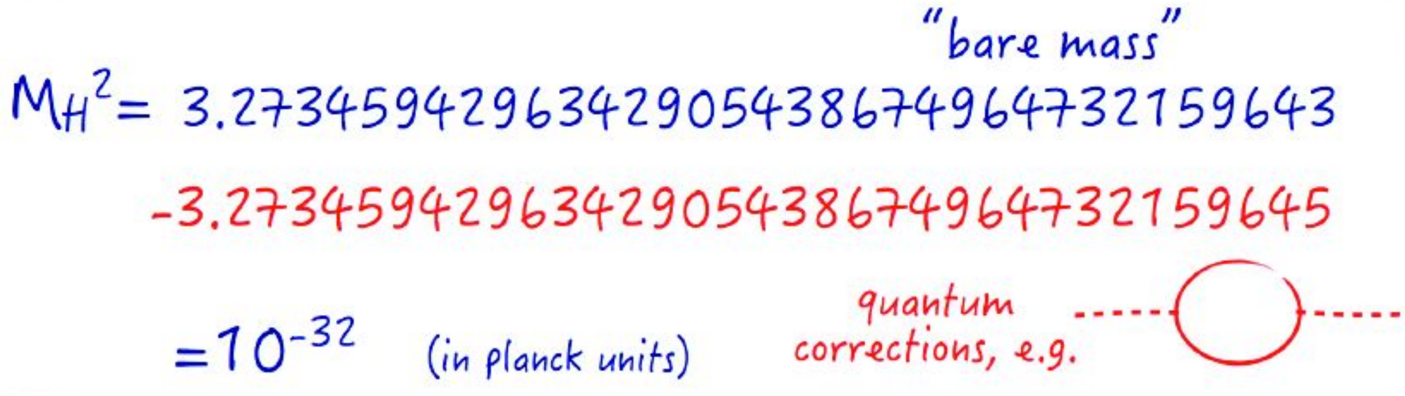




What can we do with the LHC data?

probe the Standard Model - and search for new phenomena beyond it!

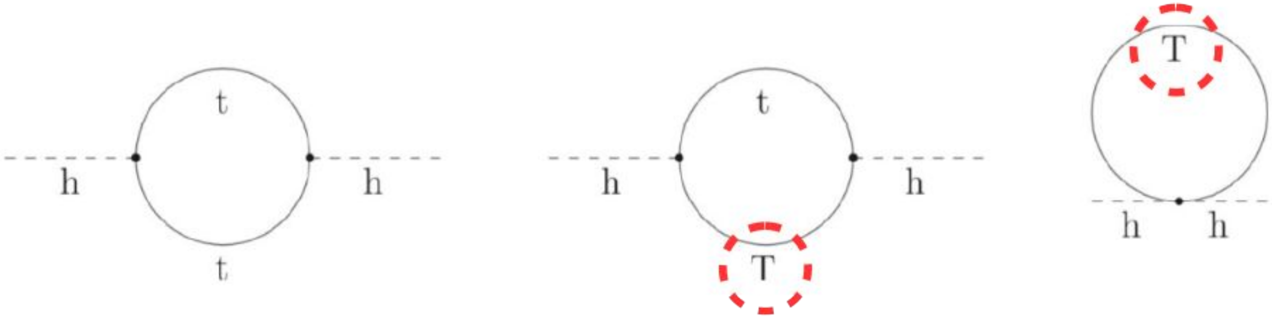
- If we assume that the Standard Model is the low energy limit of a more general theory at higher energy
  - the Higgs boson mass can be calculable (and not a free parameter):



searching for the unknown

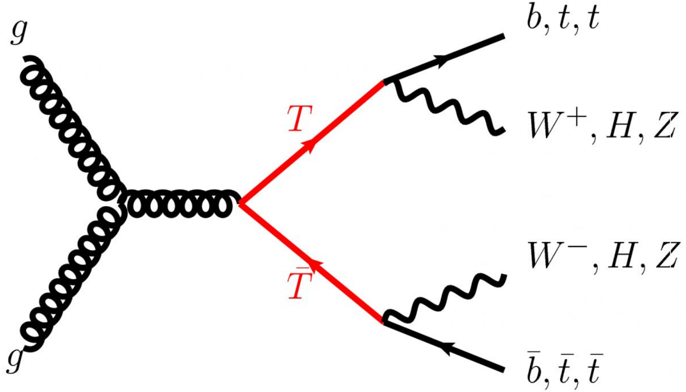
an example: the hierarchy problem

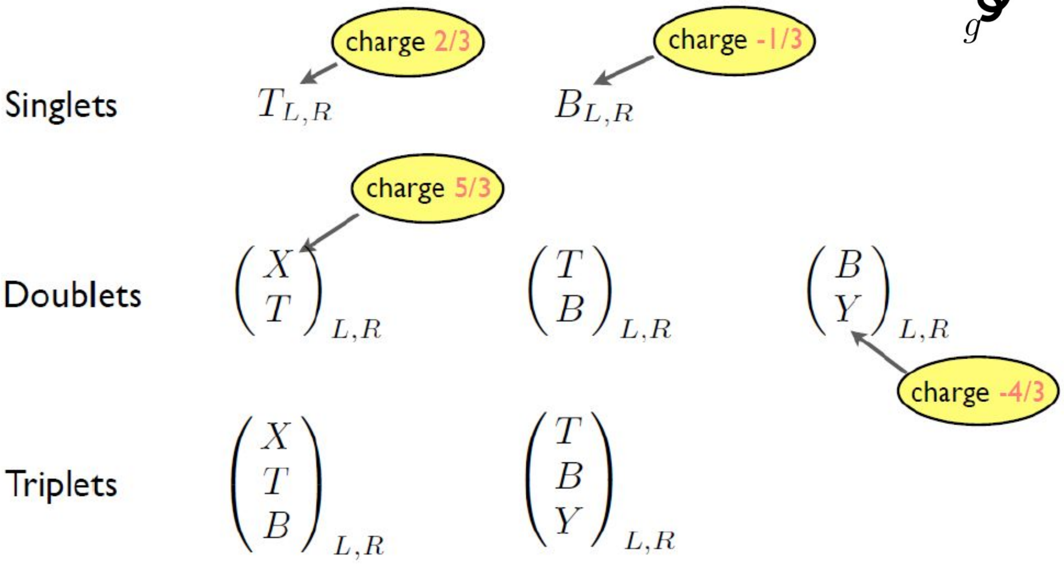
- The *natural* solution for this balancing in mass without fine-tuning is to have counter terms originating from new heavy particles (top partners)



searching for the unknown

an example: vector-like quarks



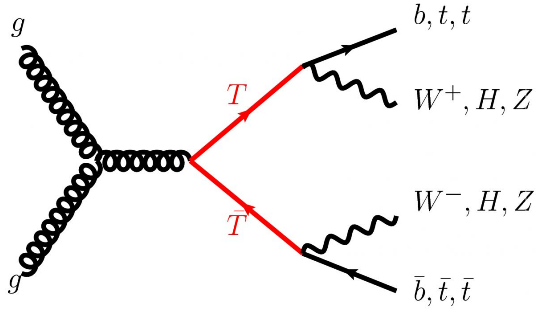


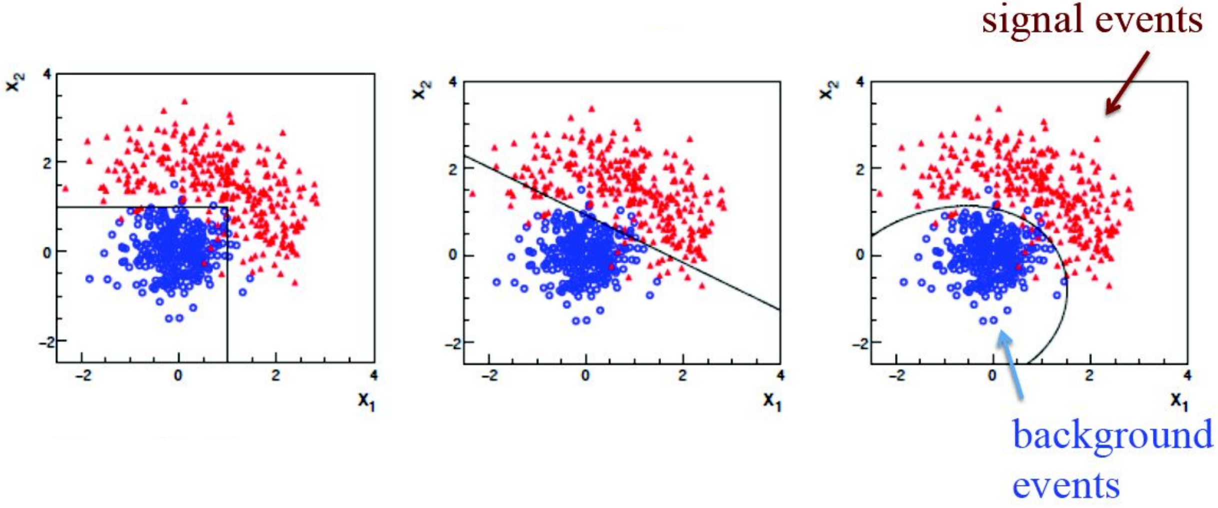
searching for the unknown

an example: vector-like quarks

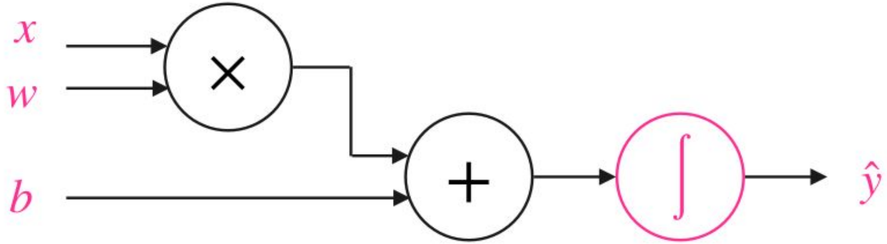
- Many different topologies
- Looking for extremely small signals

- *Advanced analysis methods are mandatory!*





Artificial Neuron

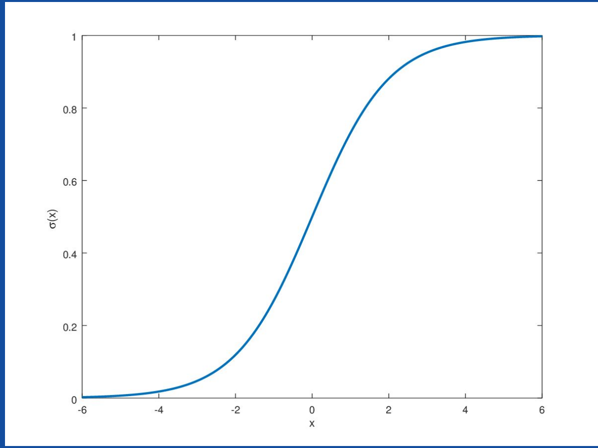


- x is the input feature
- y is the target feature (or "label")
- w, b are the model trainable parameters
- $\hat{y}$ is the output (model prediction)

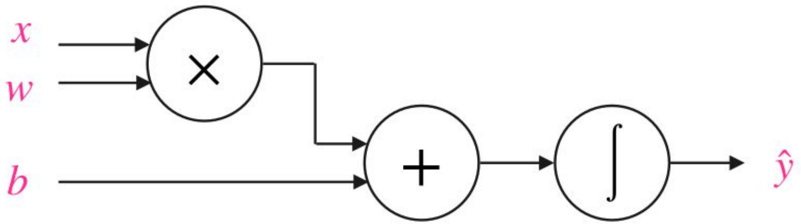
Activation function

- e.g. linear for regression
- e.g. sigmoid for classification

$$f(x) = \frac{1}{1+e^{-x}} \rightarrow \hat{y}$$



Loss function and Training Objective



Loss function L: measure of how good is $\hat{y}$ in predicting y

- e.g. Mean squared error: $L = \frac{1}{N}\sum_{i}^{N}(y_i - \hat{y}_i)^2$
- e.g. Binary cross-entropy: $L = \frac{1}{N}\sum_{i}^{N} y_i \cdot log(\hat{y}_i) + (1 - y_i) \cdot log(1 - \hat{y}_i)$

Training objective: find w, b that minimise the Loss function

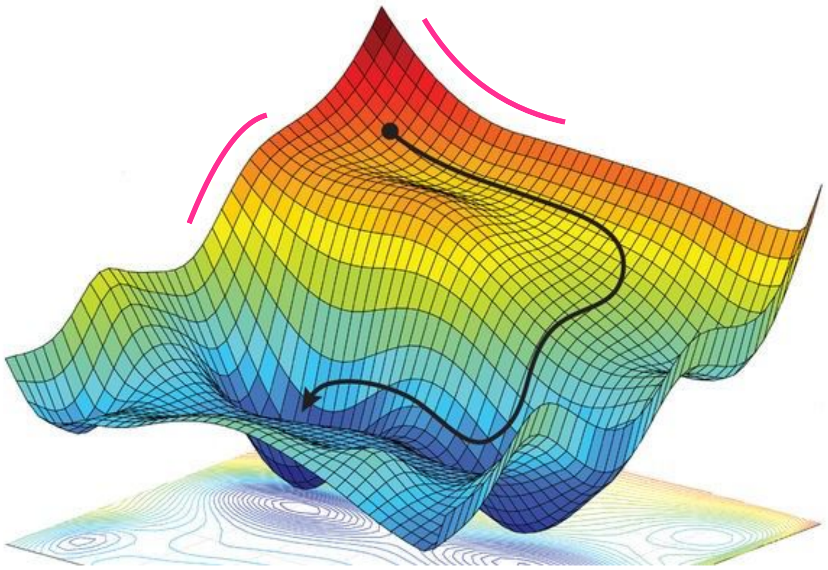
Gradient Descent and Back-propagation

Loss minimisation: **descend the Loss surface**

- Loss gradient

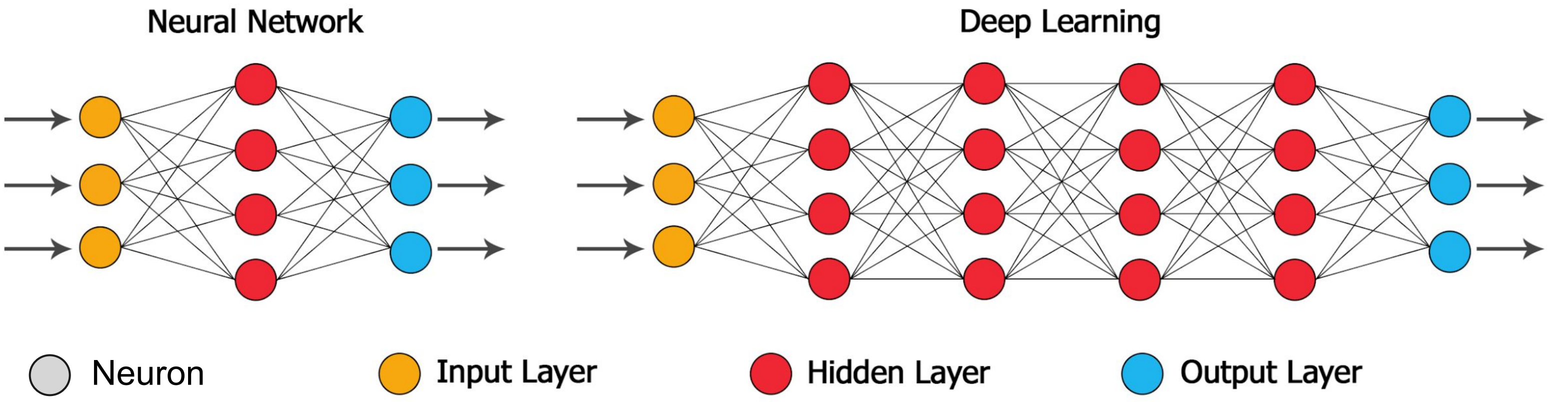
Back-propagate the Loss gradient (iteratively)

- and update
- and update
- is an hyper-parameter that adjusts the learning rate



Loss surface

Deep Learning



- Neural networks with many hidden layers, each with a given number of artificial neurons
- Capable of highly non-linear representations of the data
- In principle, can model any function
- Architecture -> hyper-parameters: number of layers, number of neurons/layer, …

Practicable Deep Neural Networks

Many layers + many units

- **Vanishing gradient**: new activation functions made training possible (ReLU) (~2010)
- Advances in hardware: **GPU** increased speed of computation by 100 (~2010)
- APIs: **Keras**, **Tensorflow** (2015)

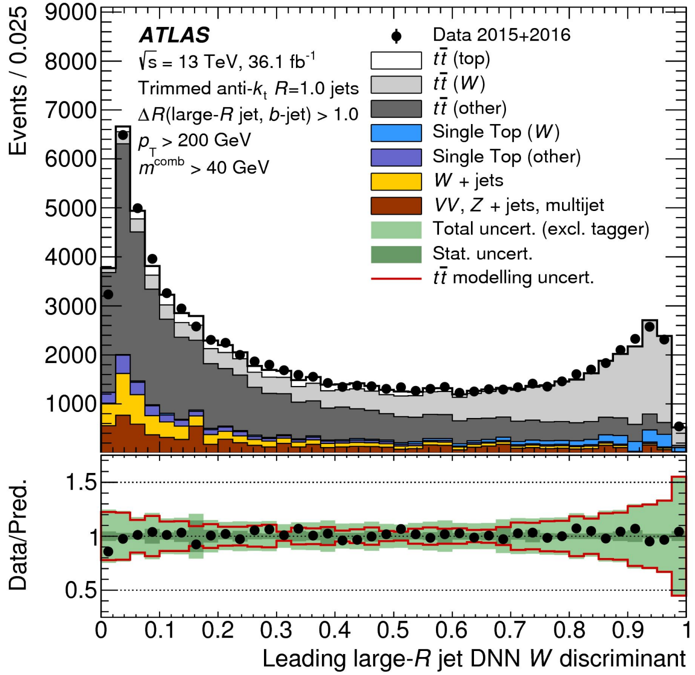
Deep learning

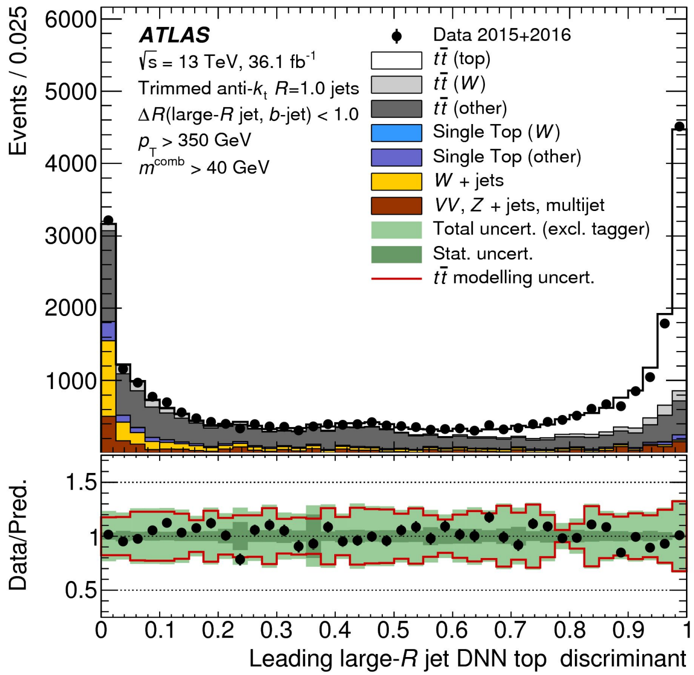
- Many parameters to estimate:
- **Data** thirst

```
_________________________________________________________________
Layer (type)                 Output Shape              Param #
=================================================================
flatten_10 (Flatten)         (None, 784)               0
_________________________________________________________________
dense_22 (Dense)             (None, 128)               100480
_________________________________________________________________
activation_19 (Activation)   (None, 128)               0
_________________________________________________________________
dense_23 (Dense)             (None, 128)               16512
_________________________________________________________________
activation_20 (Activation)   (None, 128)               0
_________________________________________________________________
dense_24 (Dense)             (None, 10)                1290
_________________________________________________________________
activation_21 (Activation)   (None, 10)                0
=================================================================
Total params: 118,282
Trainable params: 118,282
Non-trainable params: 0
_________________________________________________________________
```

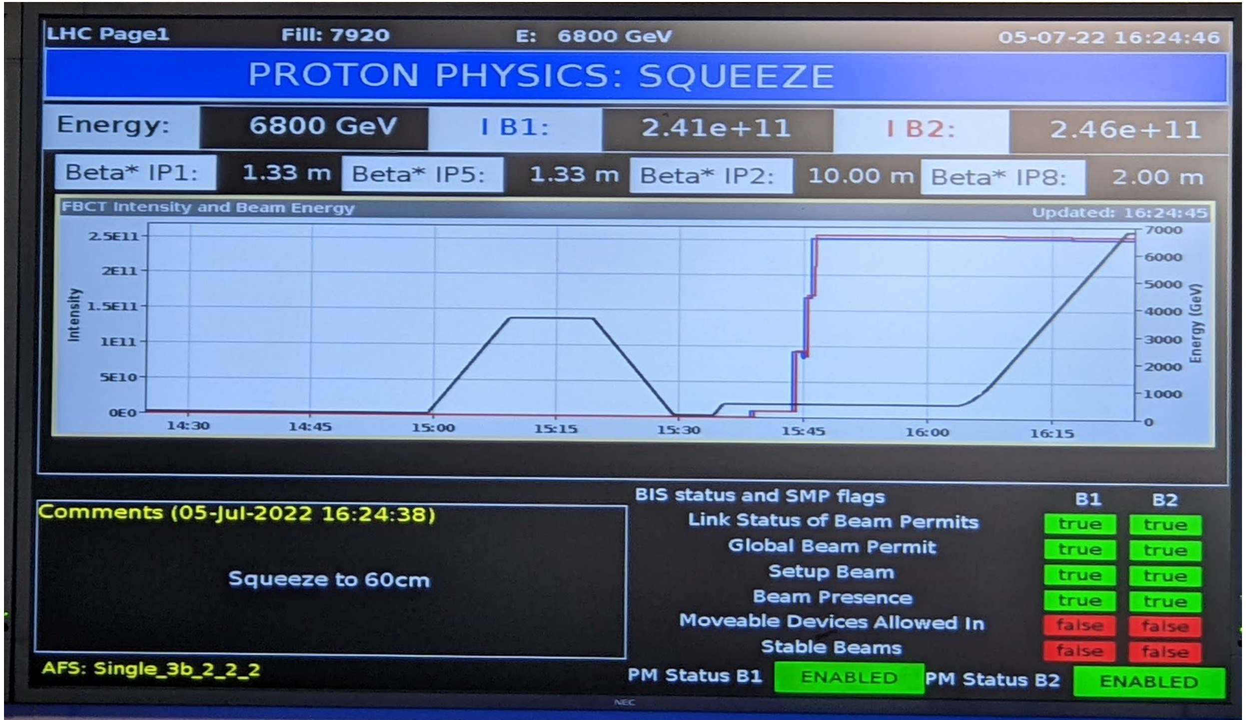
searching for the unknown

an example: use of neural networks in searches





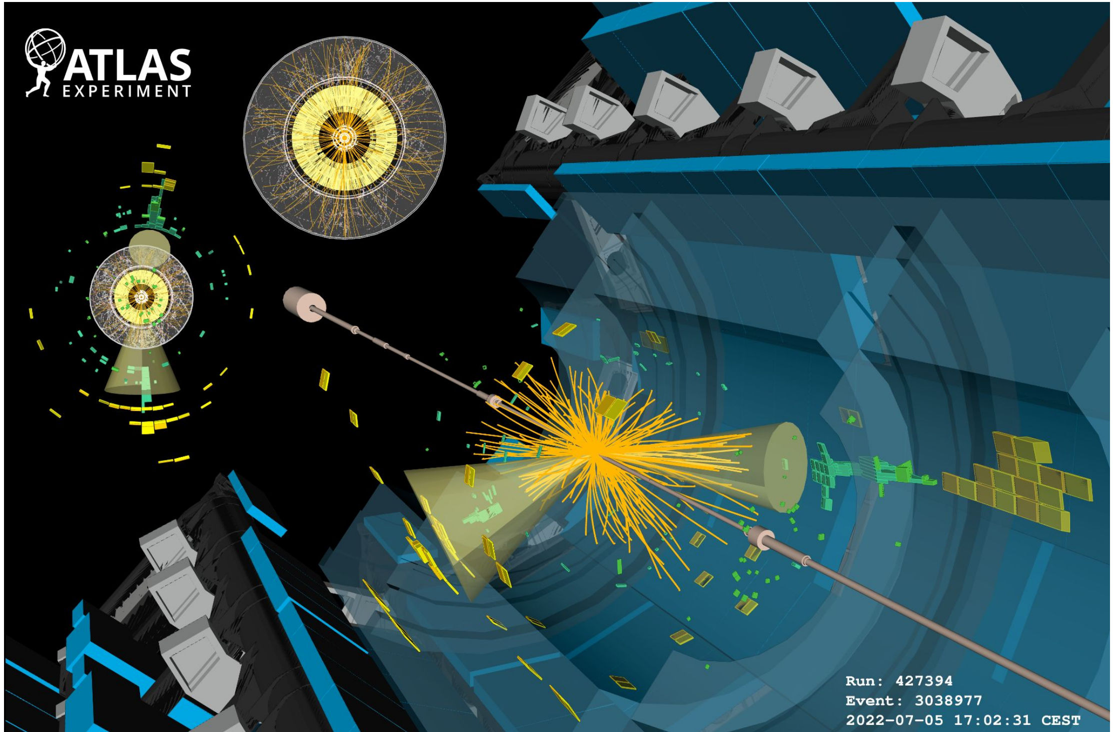
What’s next?
LHC run-3: the future has arrived!



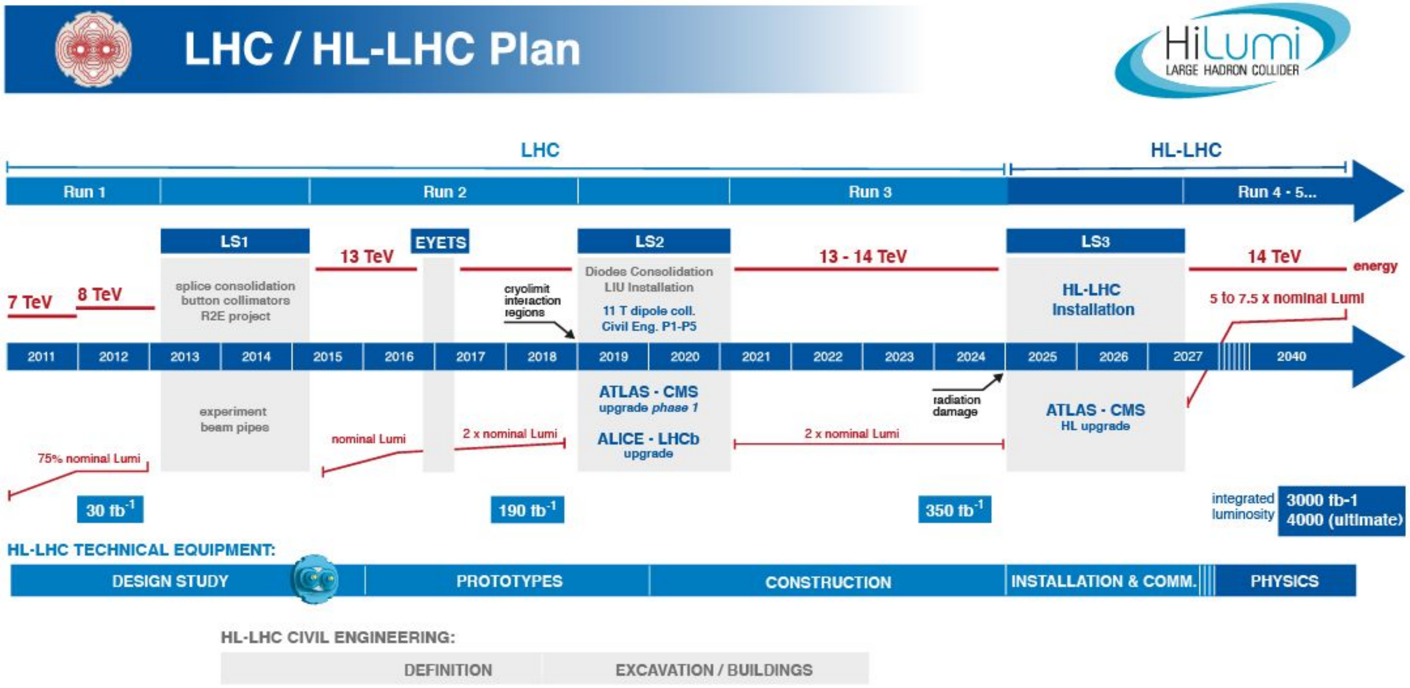
What's next?
LHC run-3: the future has arrived!

What's next?

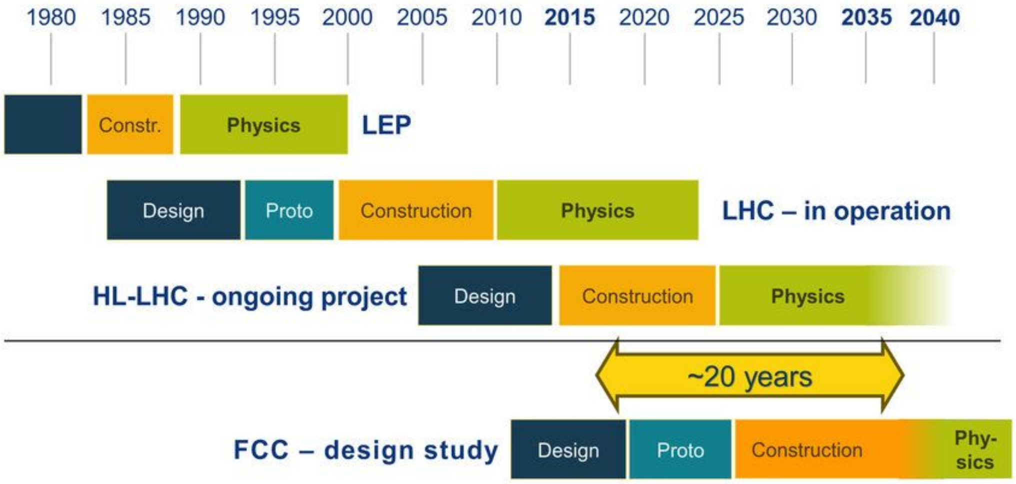
LHC run-3: the future has arrived!

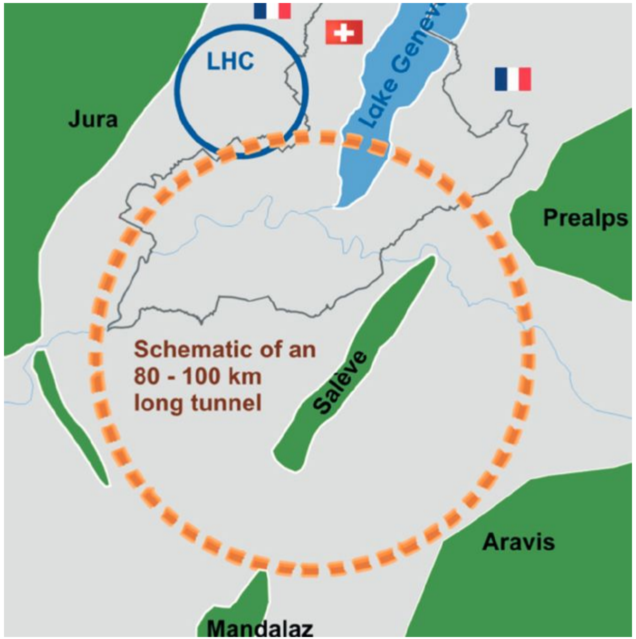


What's next?
LHC and beyond

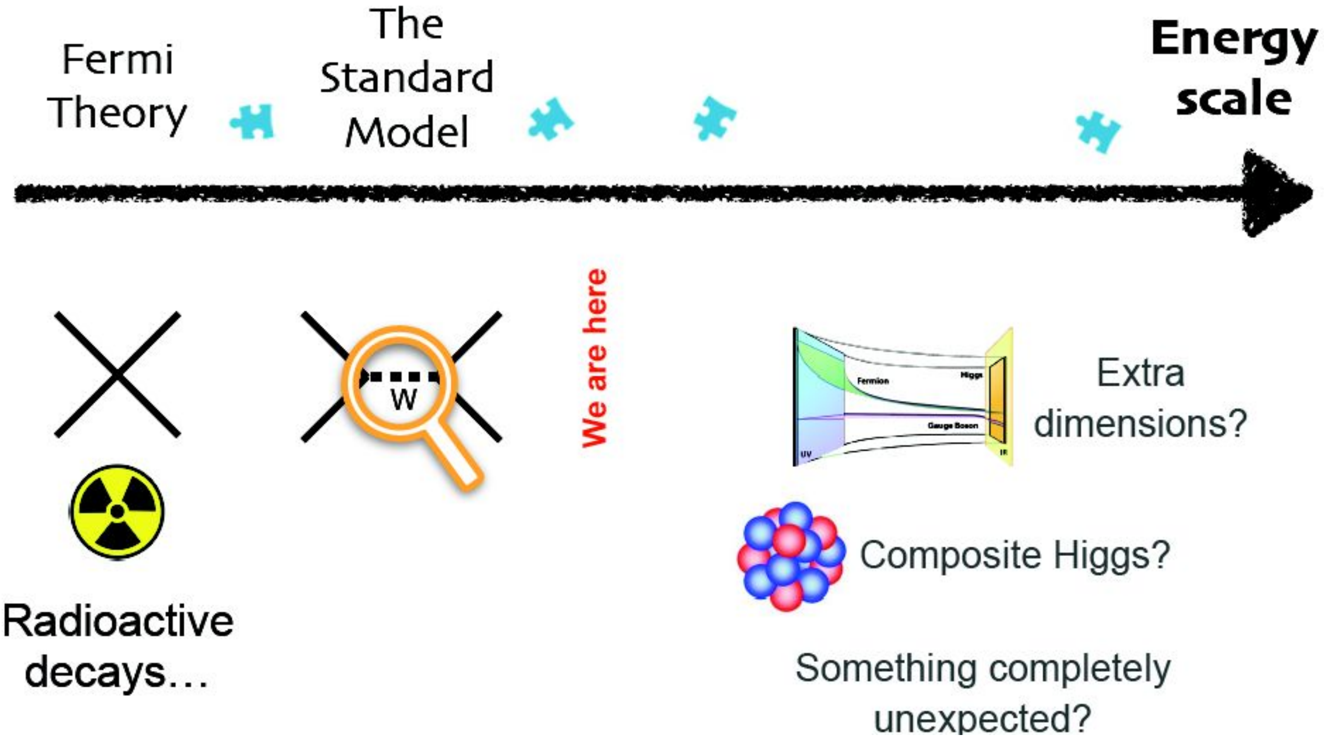


What's next?
LHC and beyond





What's next?
The energy frontier



slide from I. Ochôa:
https://indico.lip.pt/event/738/contributions/2409/attachments/2074/2817/ChallengesPP_Jun2020_v2.pdf

Thanks for your attention

Questions?

you can always reach me at nfcastro@lip.pt

What can we do with the LHC data?

probe the Standard Model - and search for new phenomena beyond it!