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

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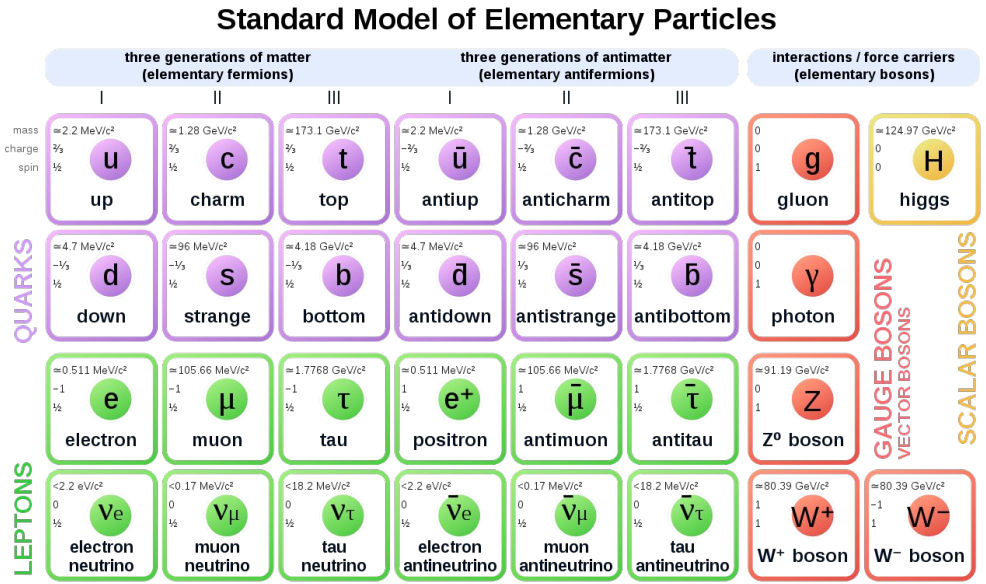
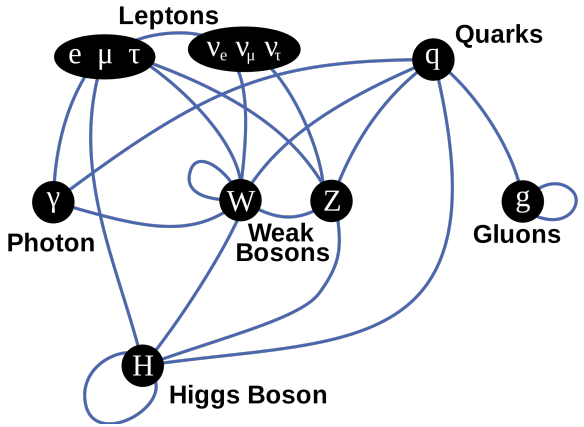
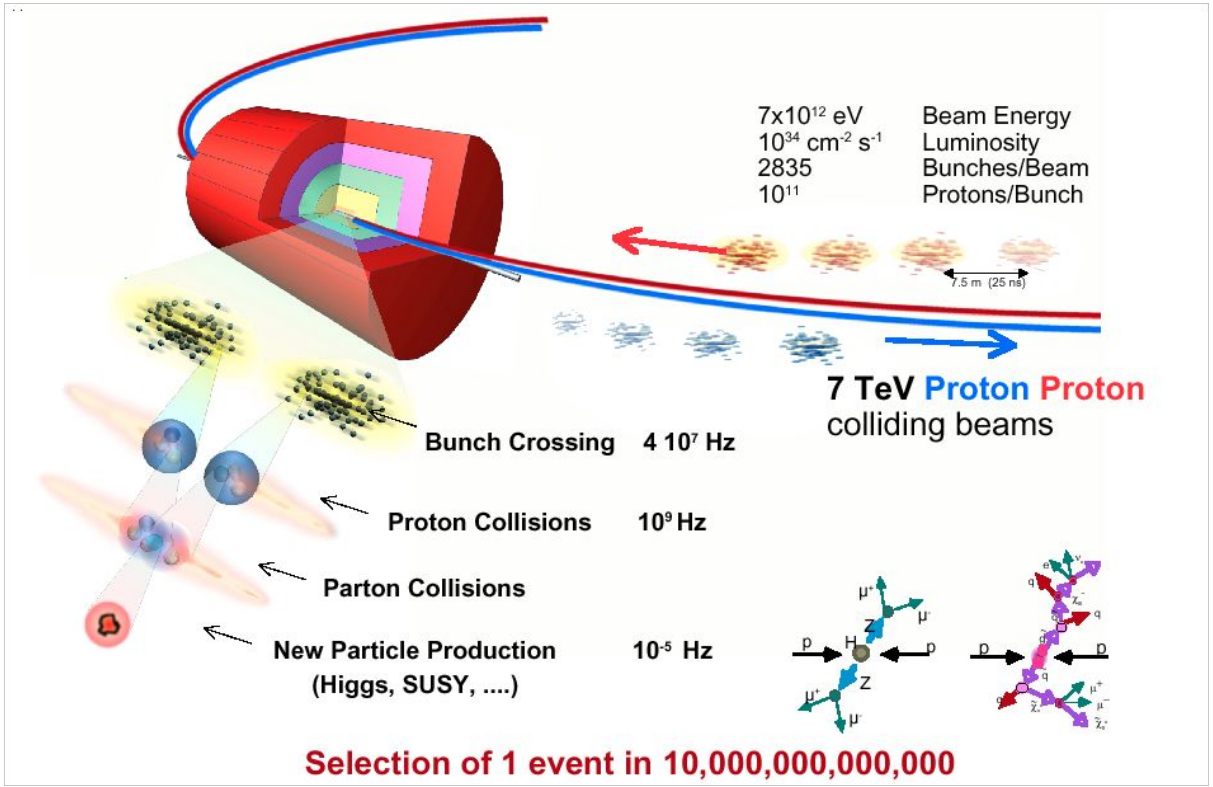
The Standard Model of Particle Physics
particles & interactions





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

The Standard Model of Particle Physics
probing it at colliders



The Large Hadron Collider
and its detectors

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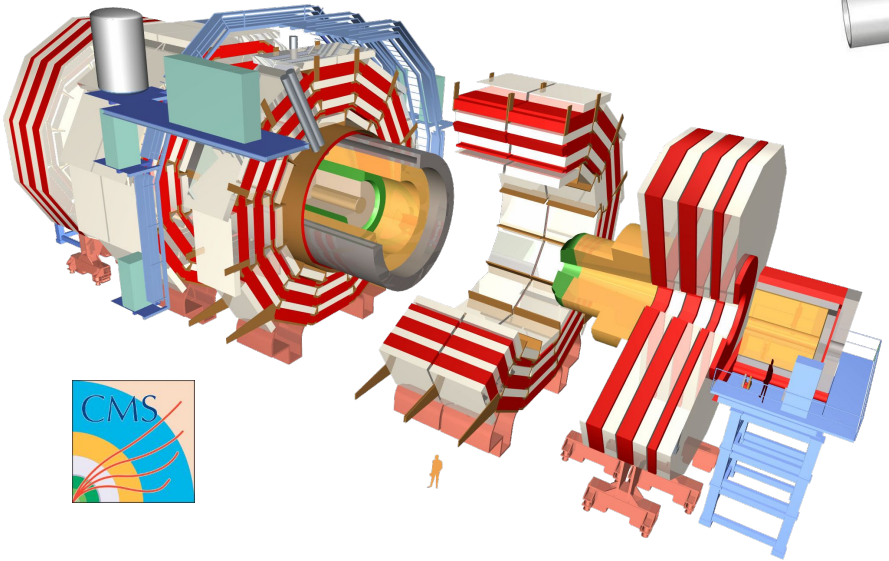
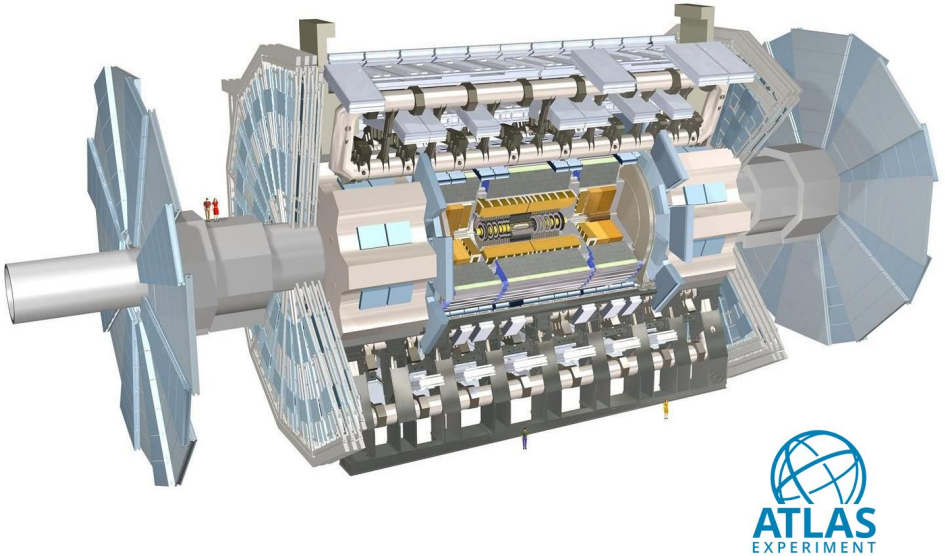
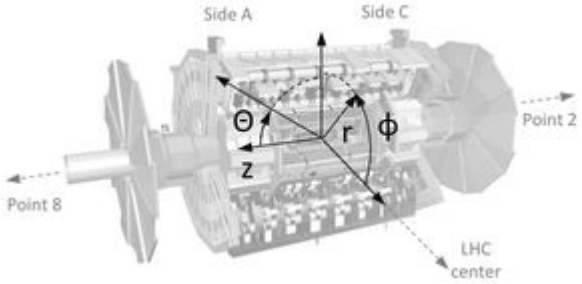


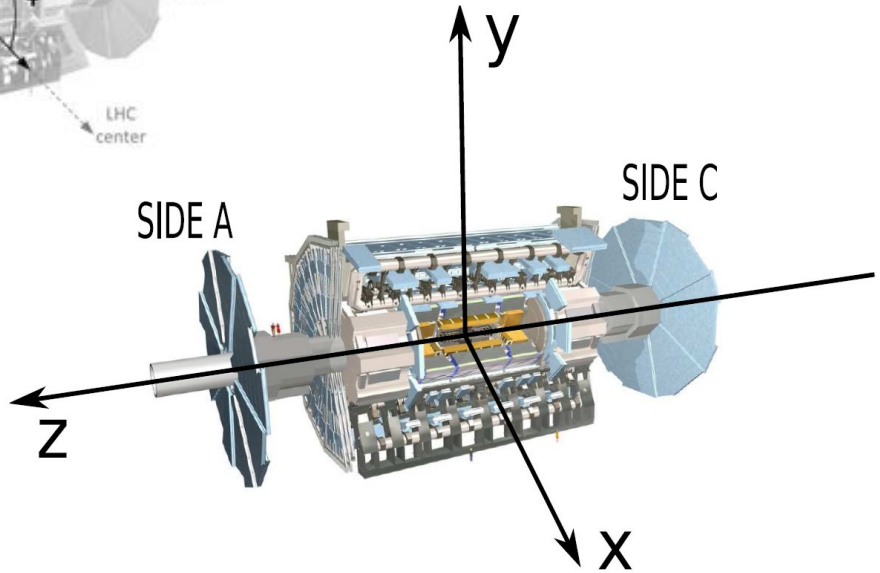


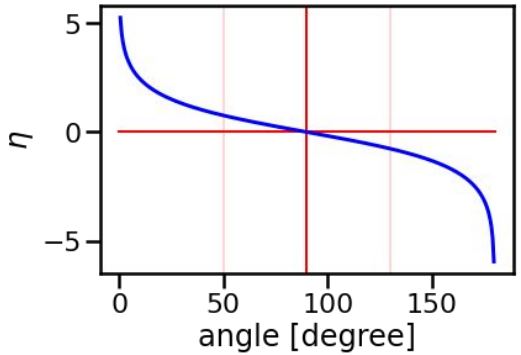
Hadron colliders
kinematic variables

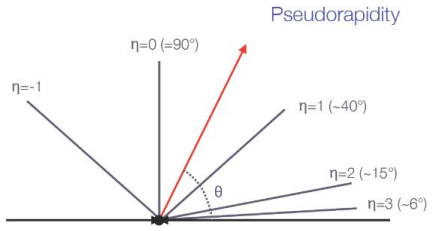
Relevant kinematic variables:

- Transverse momentum: p_T
- Rapidity: $y = \frac{1}{2} \cdot \ln (E-p_z)/(E+p_z)$
- Pseudorapidity: $\eta = -\ln \tan \frac{1}{2}\theta$
- Azimuthal angle: φ



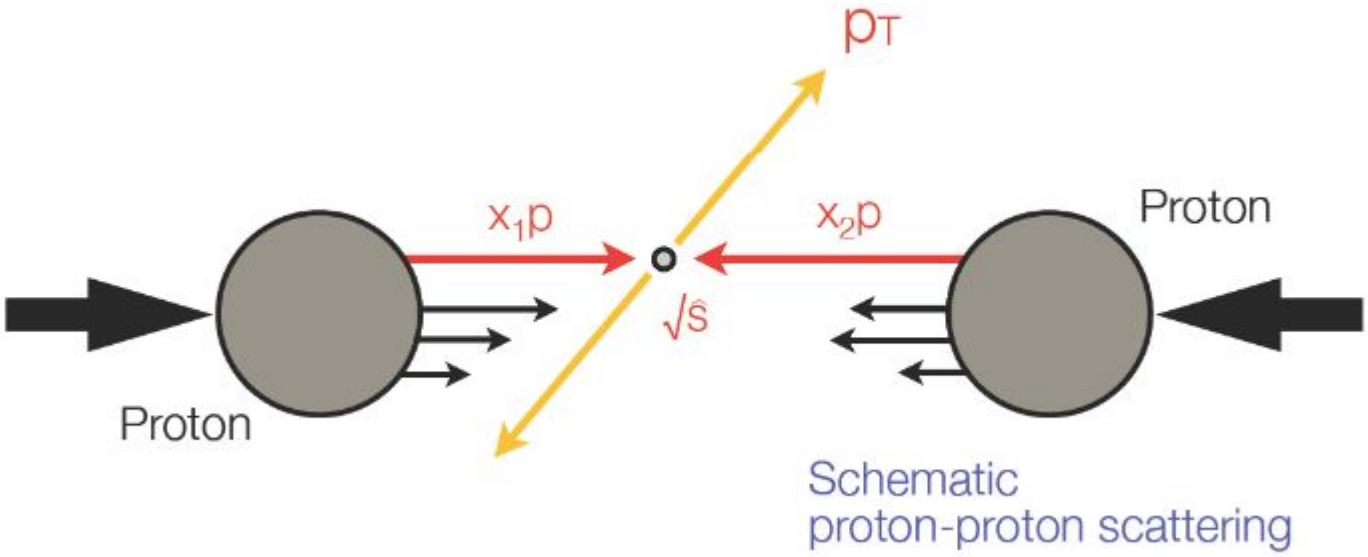




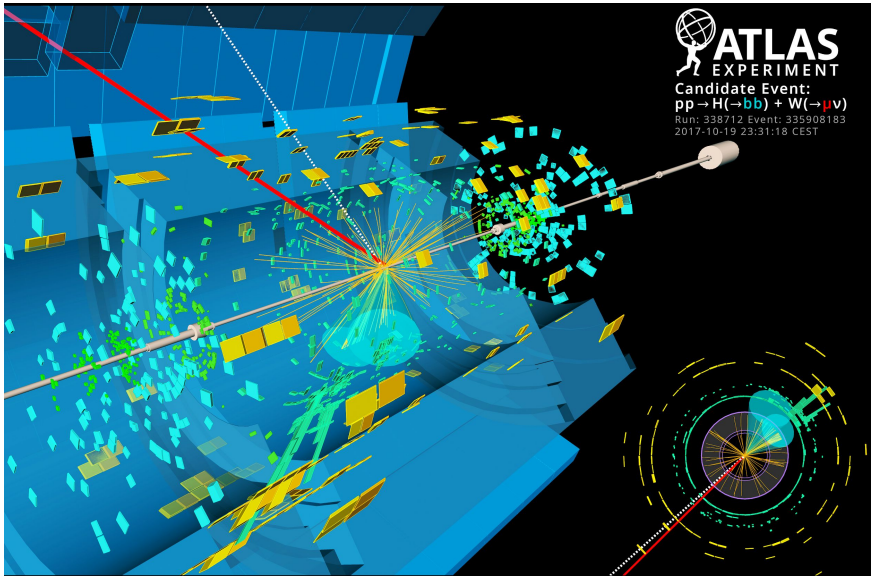


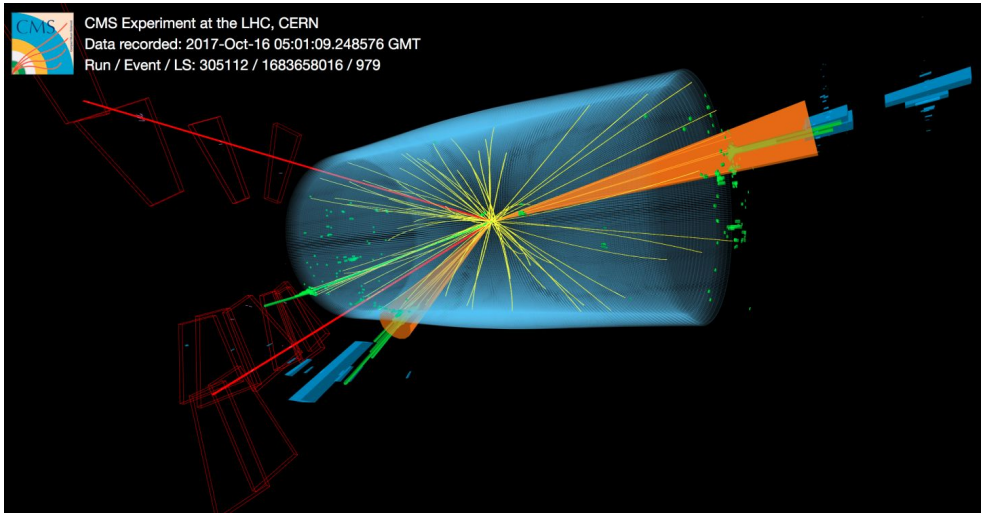
Hadron colliders

protons are not fundamental!

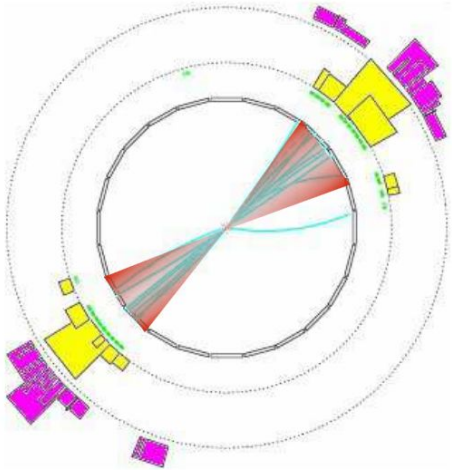


The Large Hadron Collider experiments
what is the outcome of a collision?

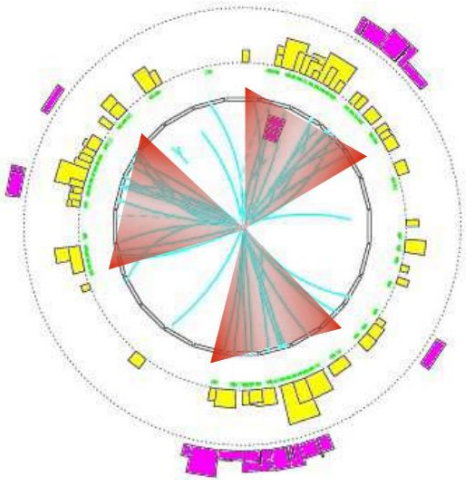




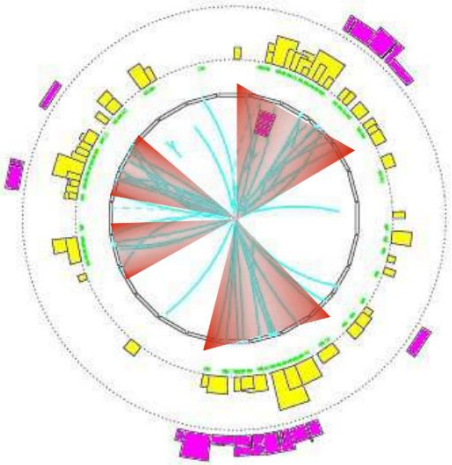
Hadron colliders
jets, jets and more jets



2 clear jets



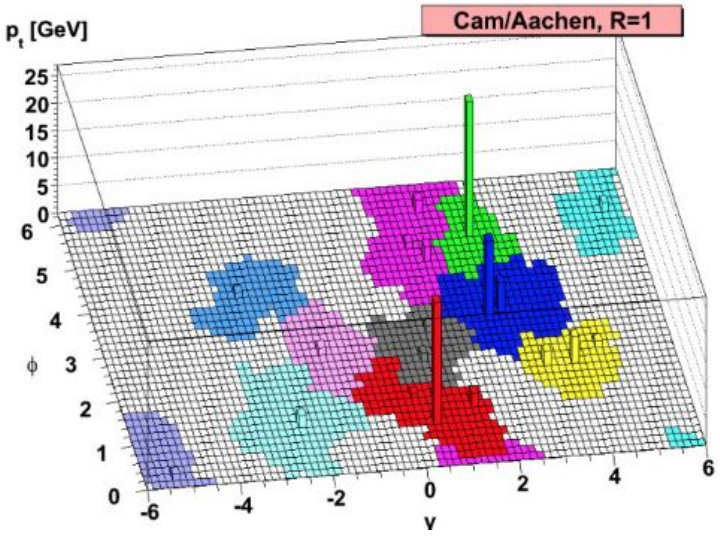
3 jets?

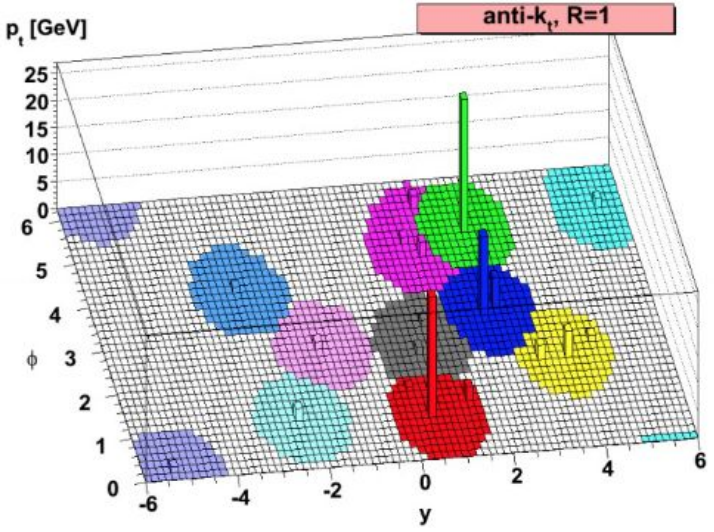


3 jets?
or 4 jets?

Reconstructing jets is an ambiguous task!

Hadron colliders
jets, jets and more jets





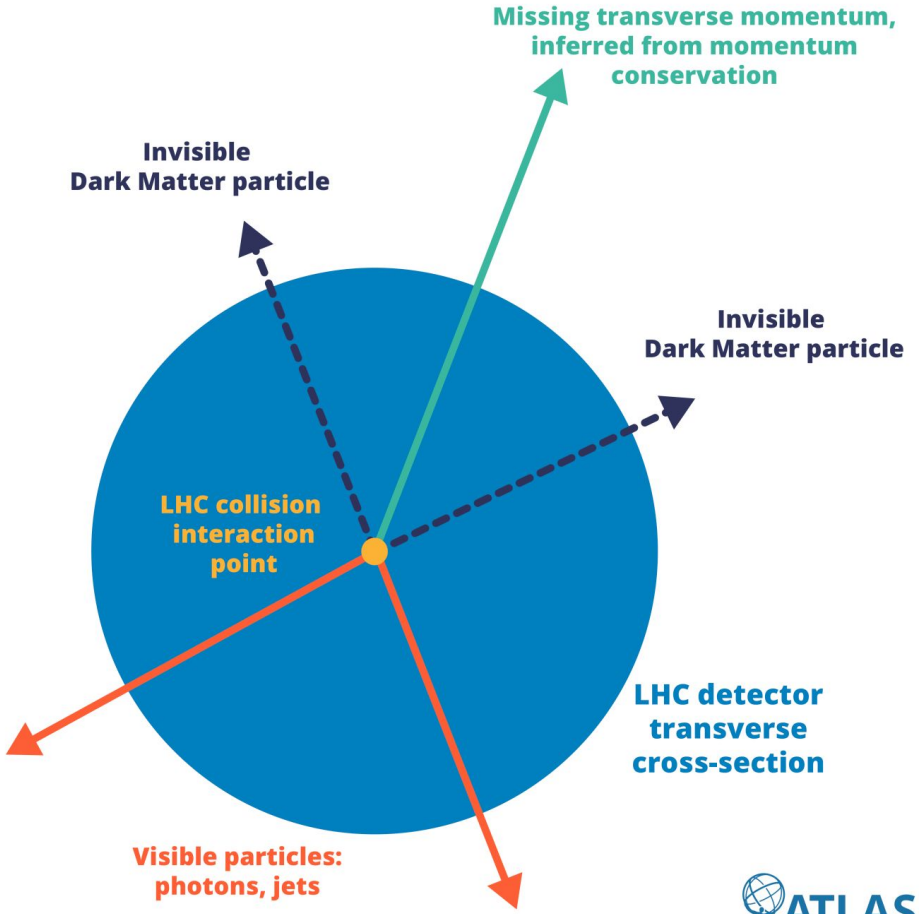
Reconstructing jets is an ambiguous task!

Energy balance

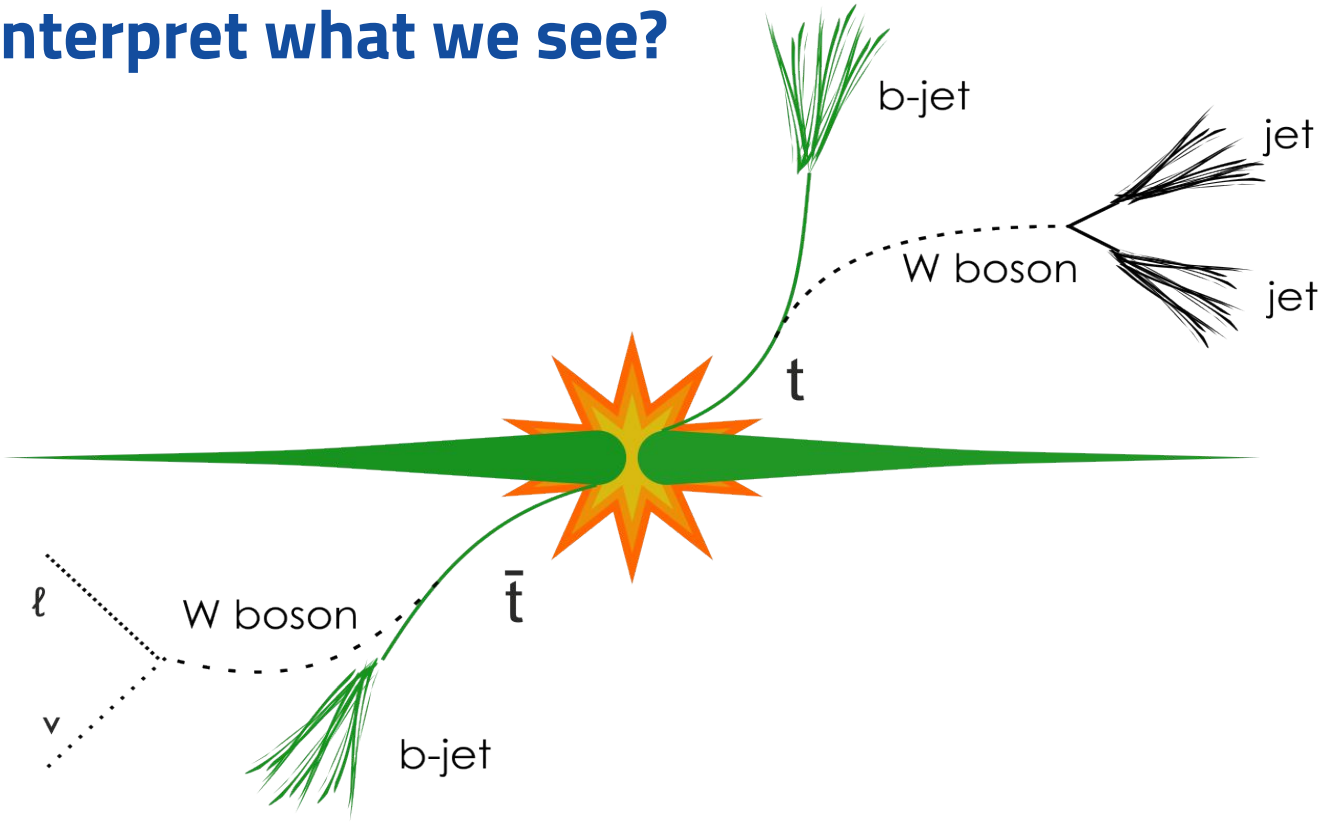
missing transverse energy (MET)

$$\vec{p}_T^{\,\text{miss}} = -\sum_i \vec{p}_T^{\,i}$$

transverse momentum
of each visible particle



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



The Large Hadron Collider experiments
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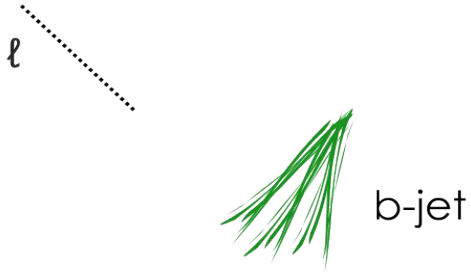
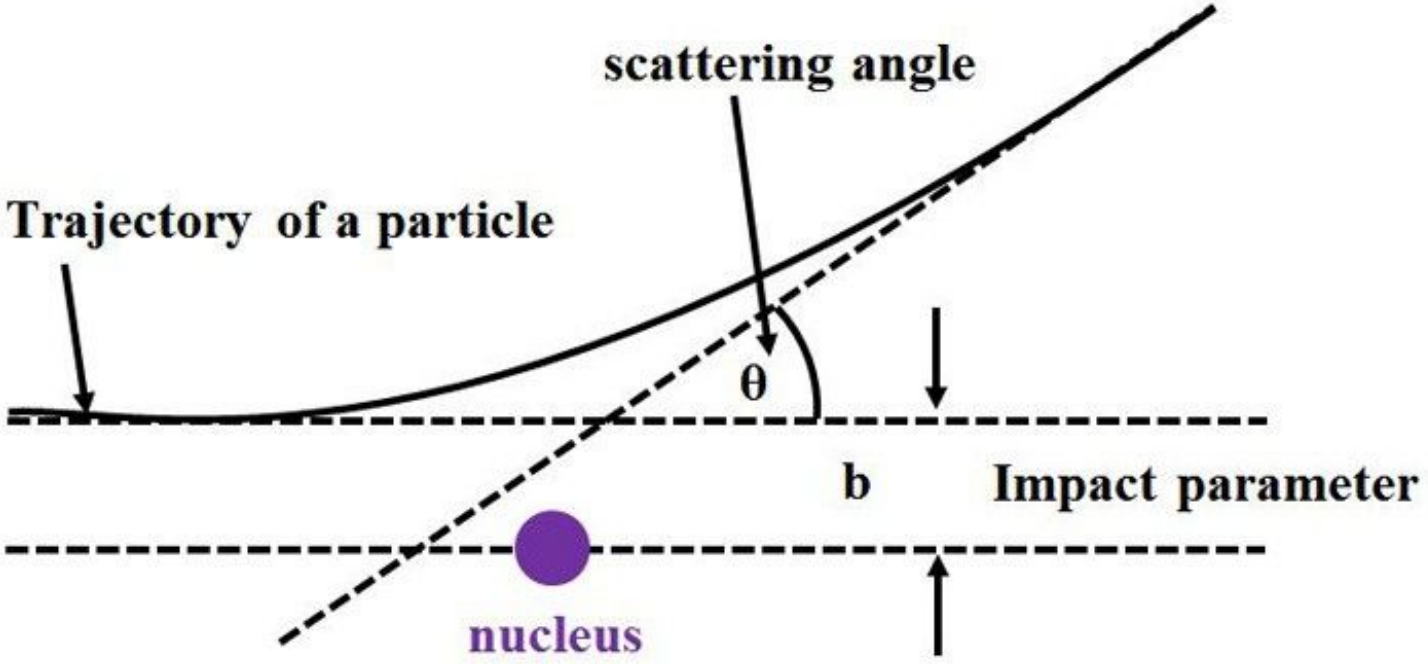
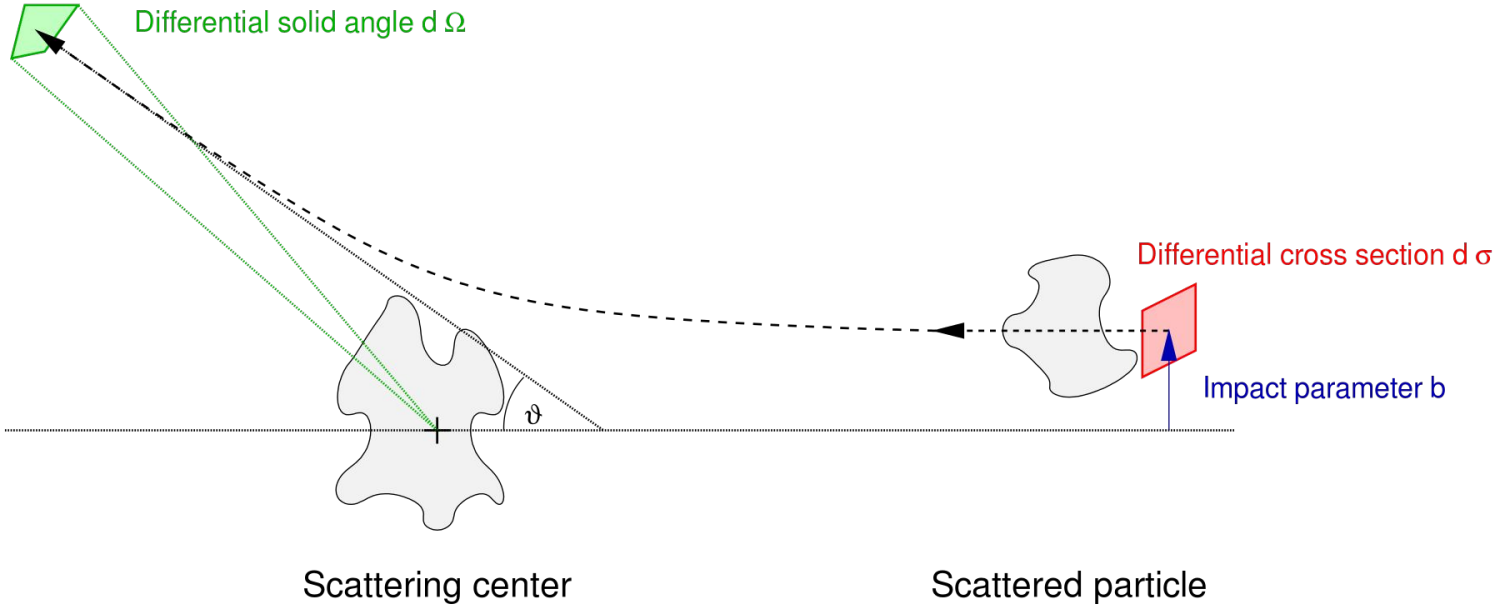


“Probability” for a collision to happen

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

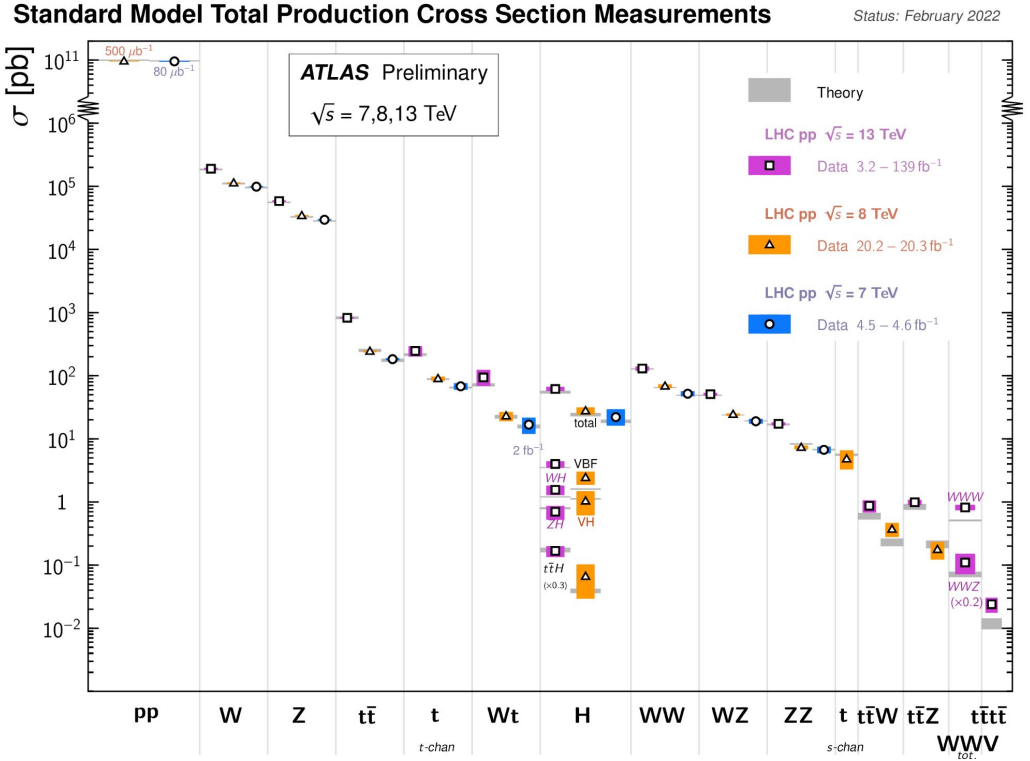
slide from J. Varela: https://indico.cern.ch/event/862001/?view=standard#8-standard-model-at-the-lhc

What can we do with the LHC data?

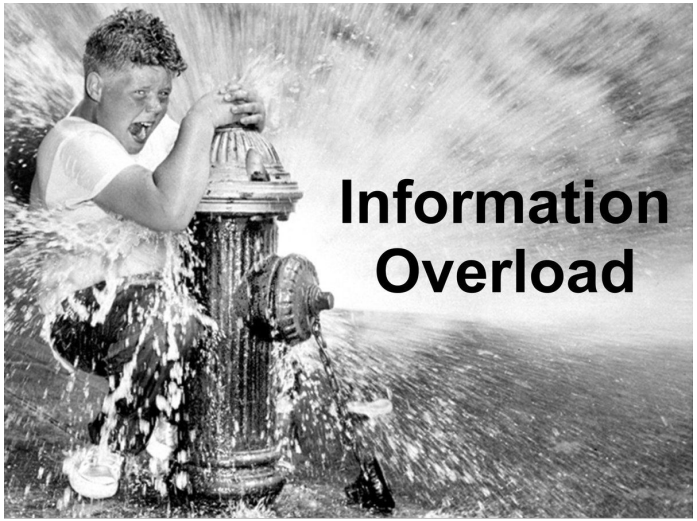
probe the Standard Model !

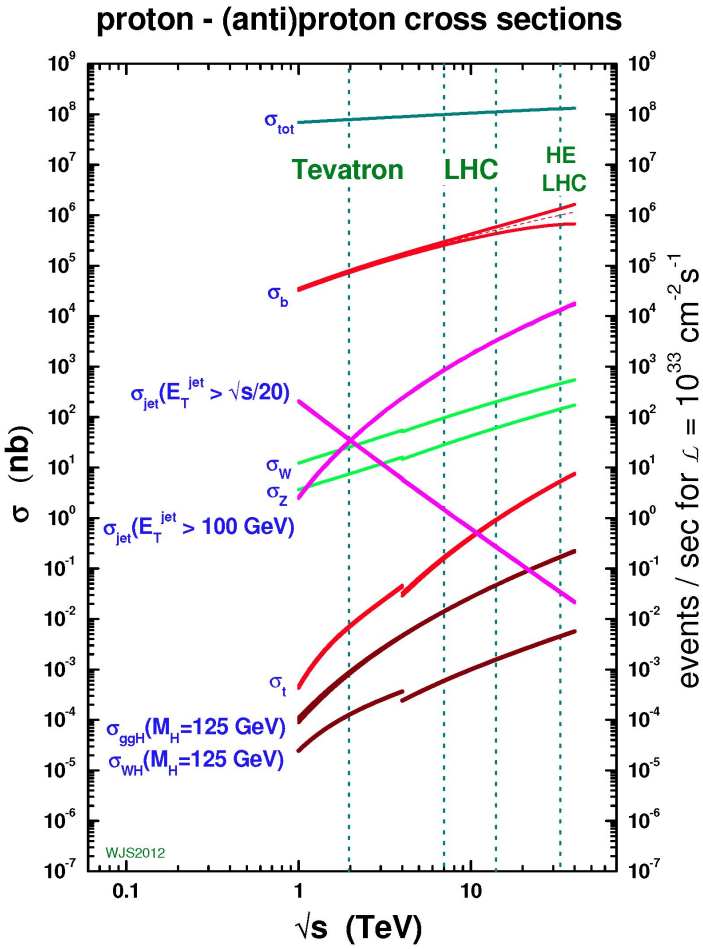
Comparing with theory predictions

excellent agreement

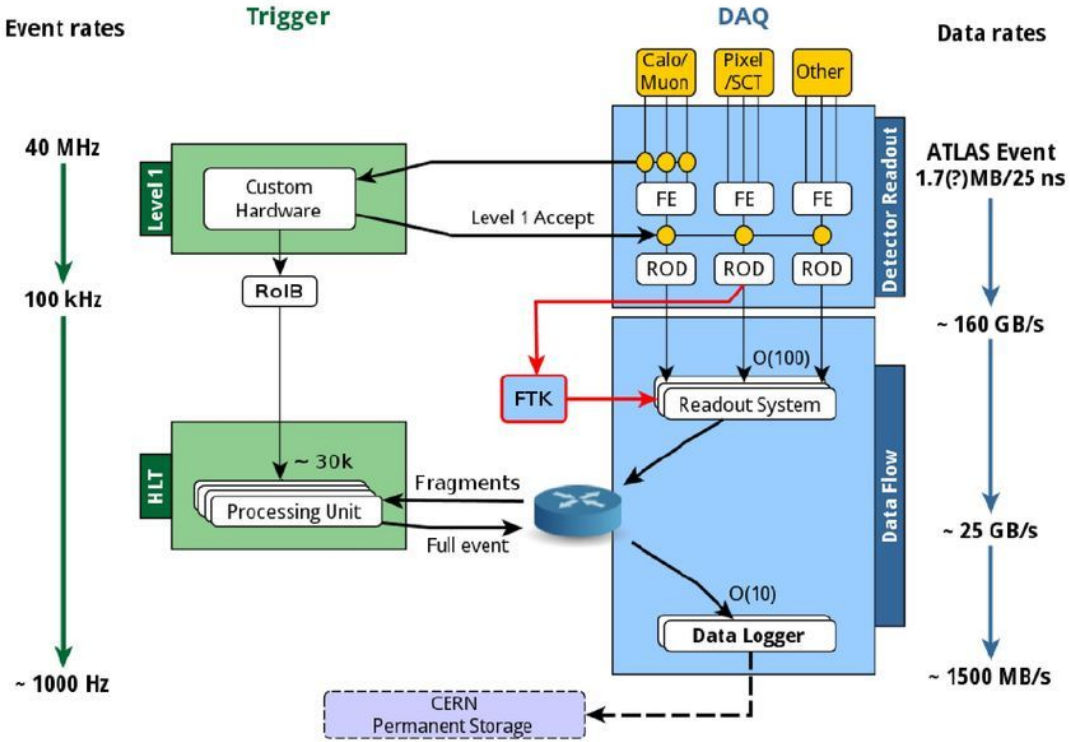


The LHC experiments
the need to select events





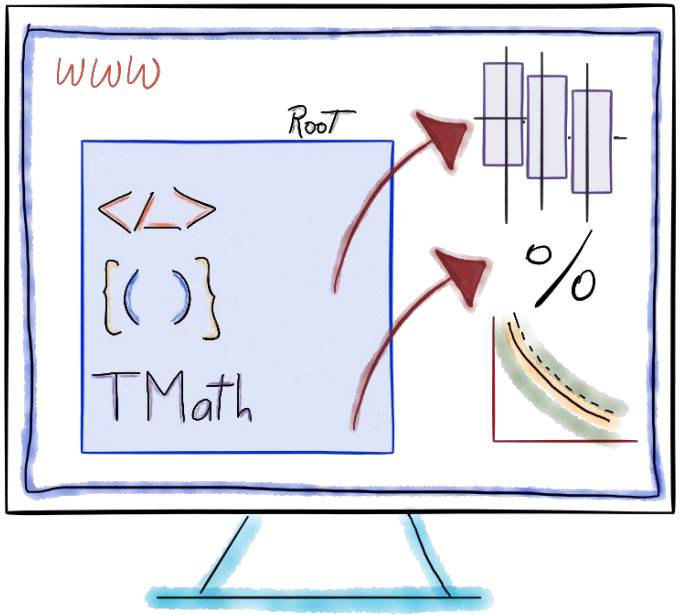
The LHC experiments
the need to select events: triggers



doing a data analysis!
the need to select events

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



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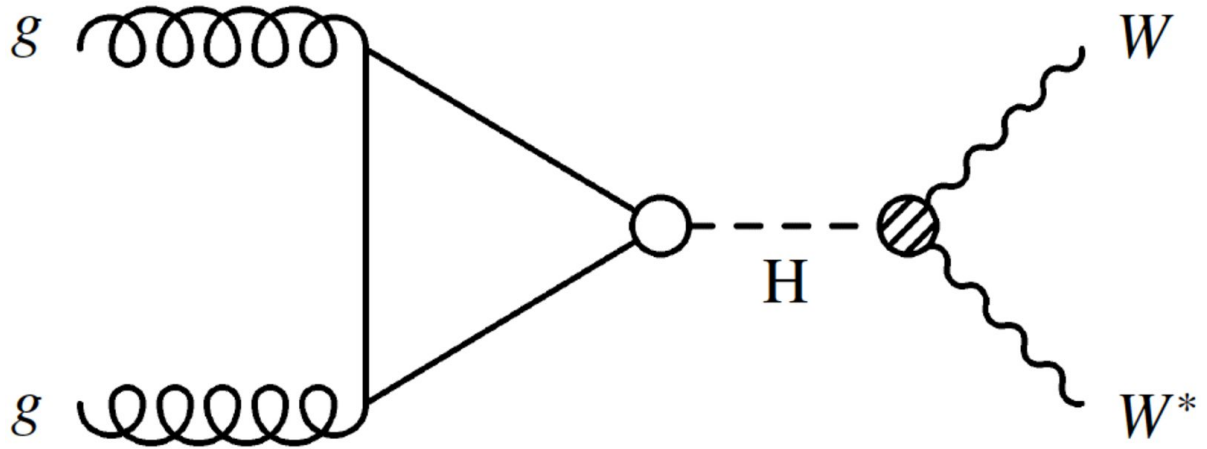
Higgs boson production in the H → WW decay channel in the two-lepton final state



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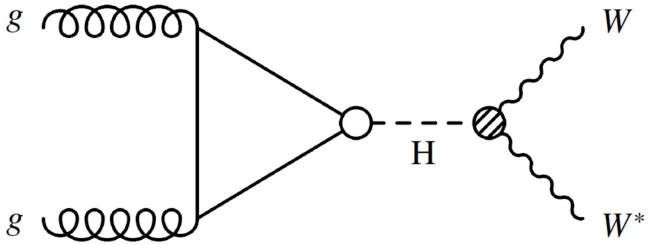


looking for events with two charged isolated leptons (electrons or muons) and (almost) no jets

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

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

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

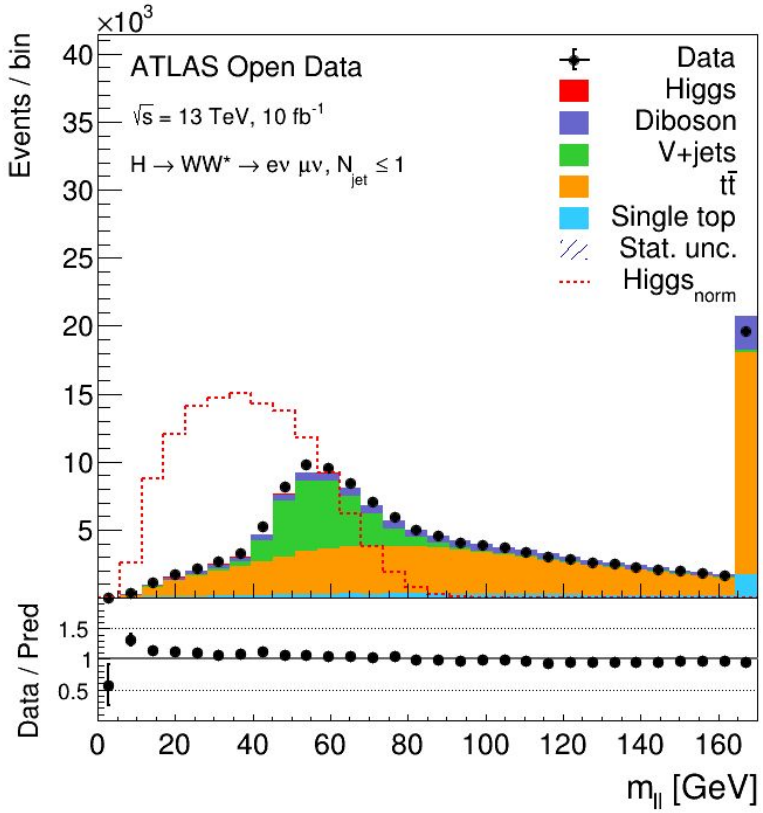
$$E^2 = p^2 c^2 + m^2 c^4$$

$$\hbar = c = 1$$

http://opendata.atlas.cern

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

(still no hint for a signal)



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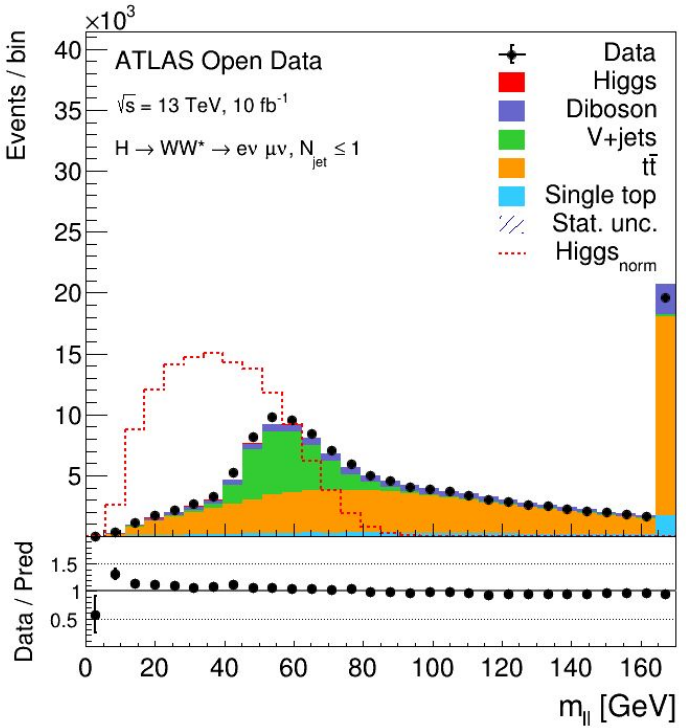
be clever and select “good” events!

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



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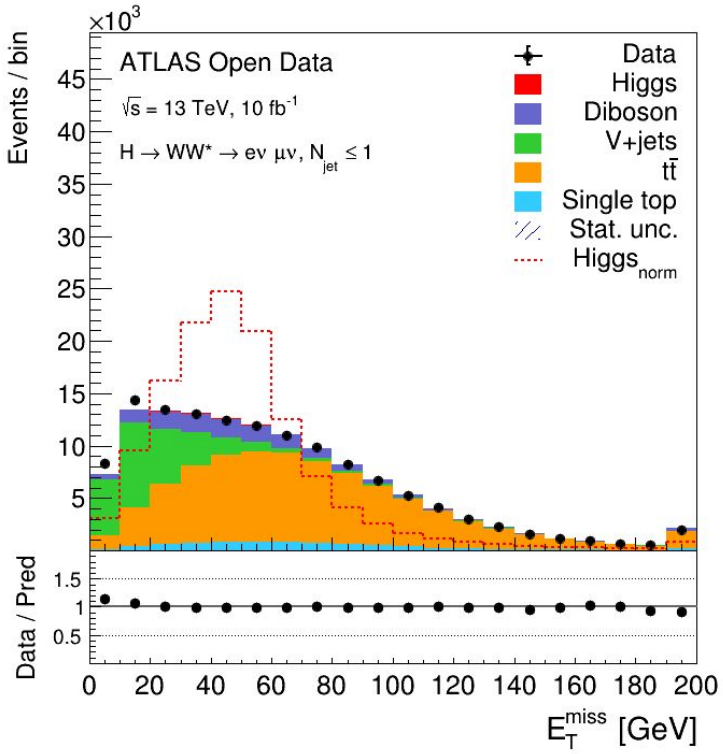

open data ATLAS

http://opendata.atlas.cern

be clever and select “good” events!

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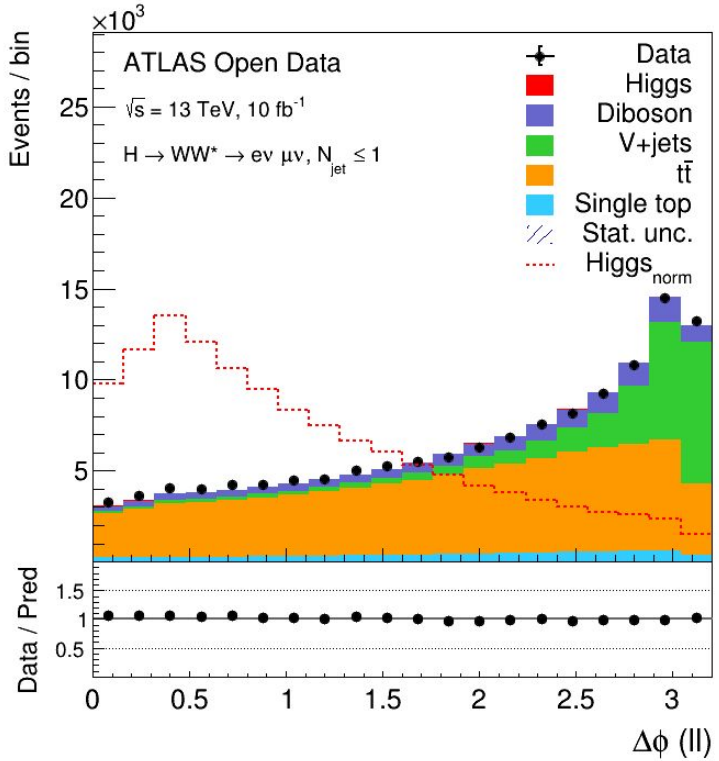
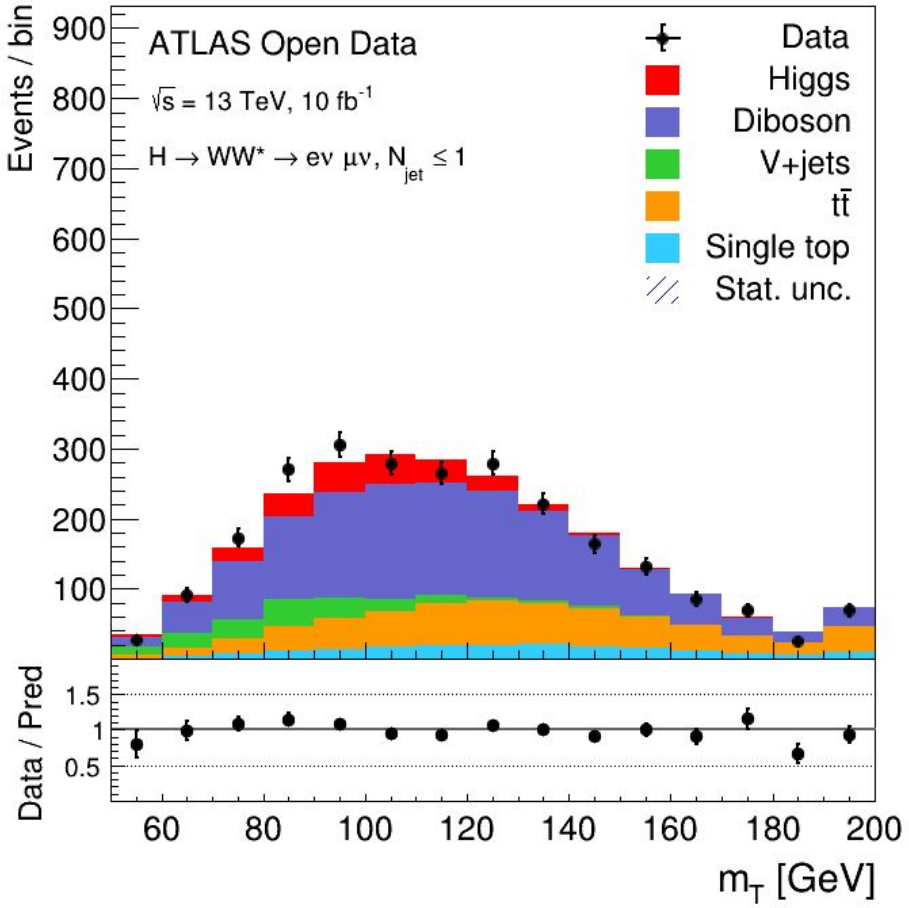


http://opendata.atlas.cern

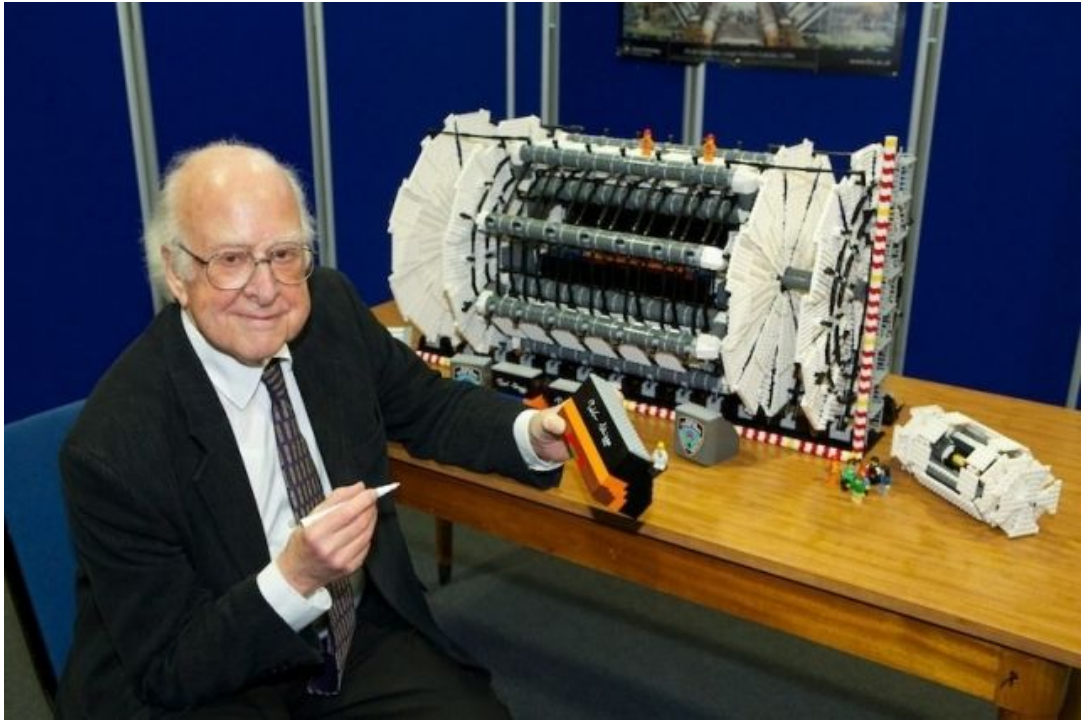
after all cuts…

...voila our signal!



What can we do with the LHC data?

probe the Standard Model - the Higgs boson and its properties



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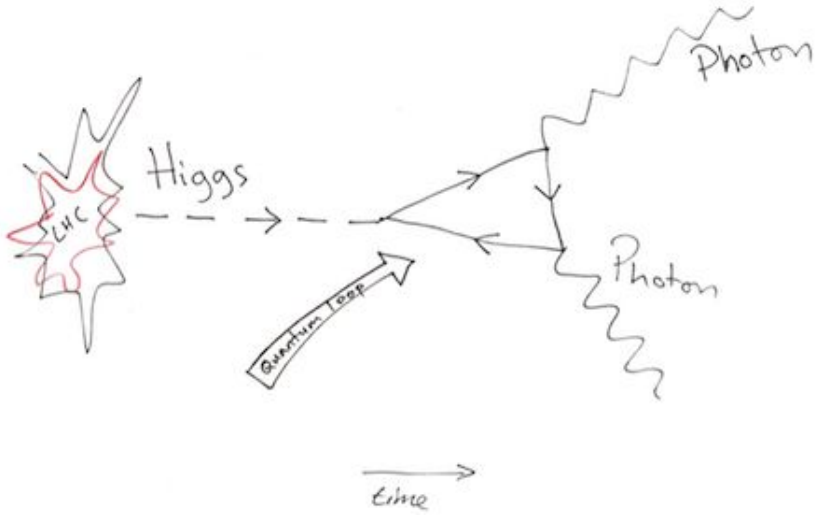

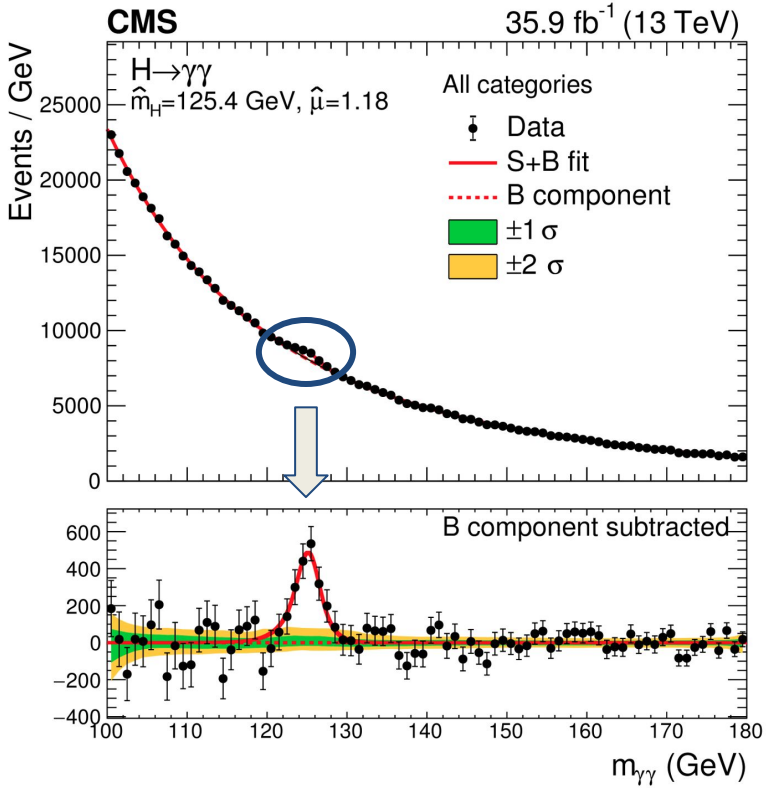

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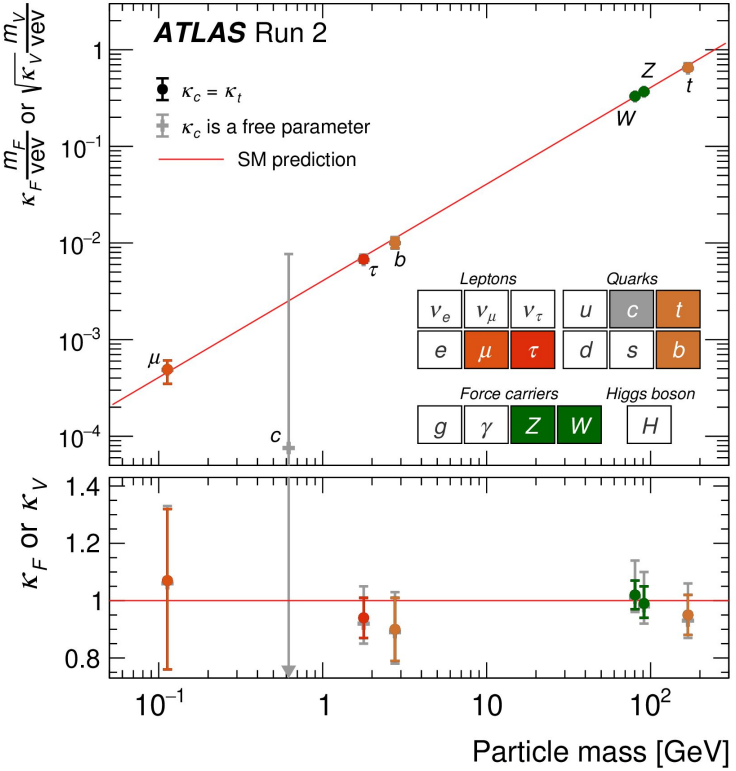
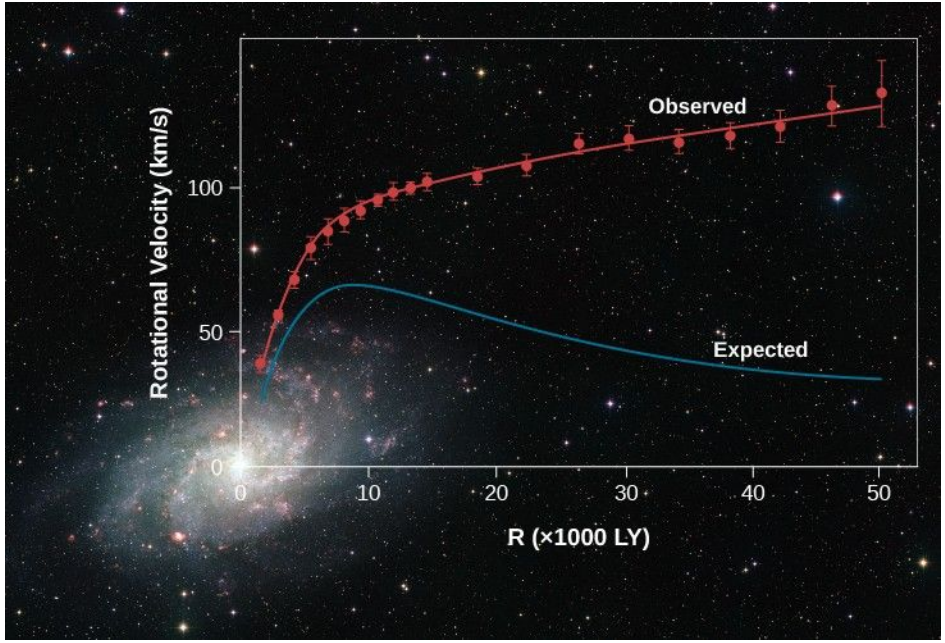
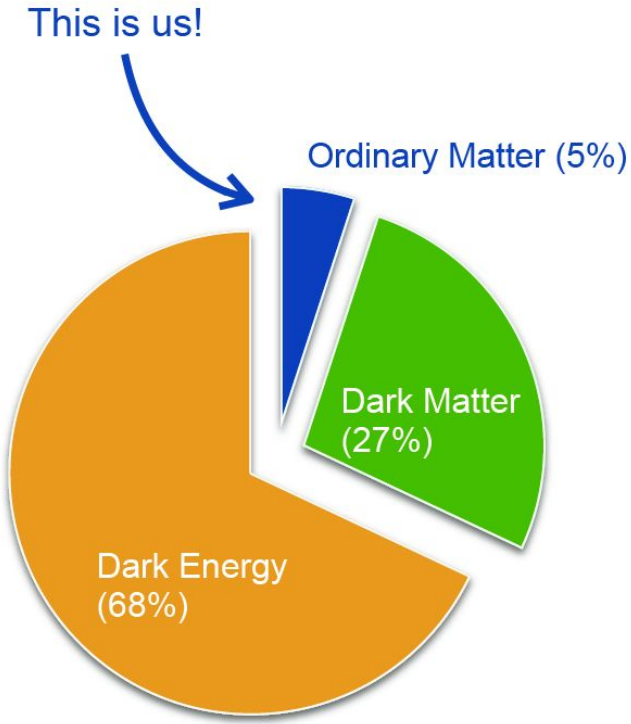


[Nature (2022)]

Why going beyond the Standard Model?

there must be new physics!





What can we do with the LHC data?

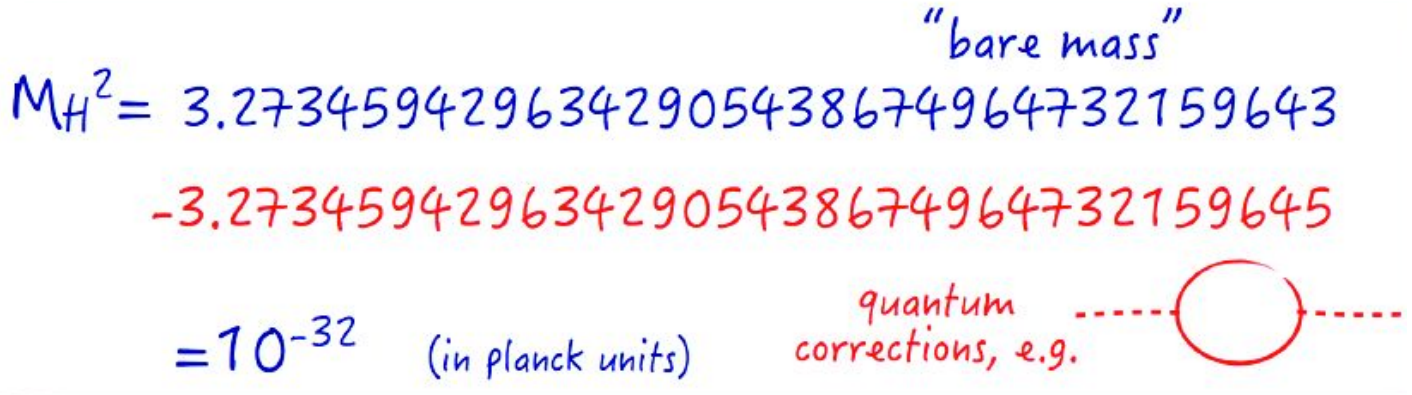
probe the Standard Model - and search for new phenomena beyond it!

- 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!

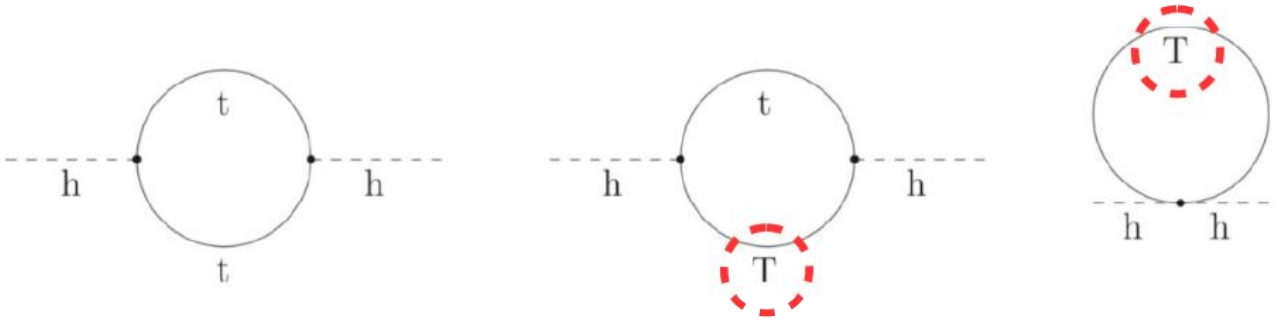
- If we assume that the Standard Model is the low energy limit of a more general theory at higher energy
    - the Higgs boson mass can be calculable (and not a free parameter):



searching for the unknown

an example: the hierarchy problem

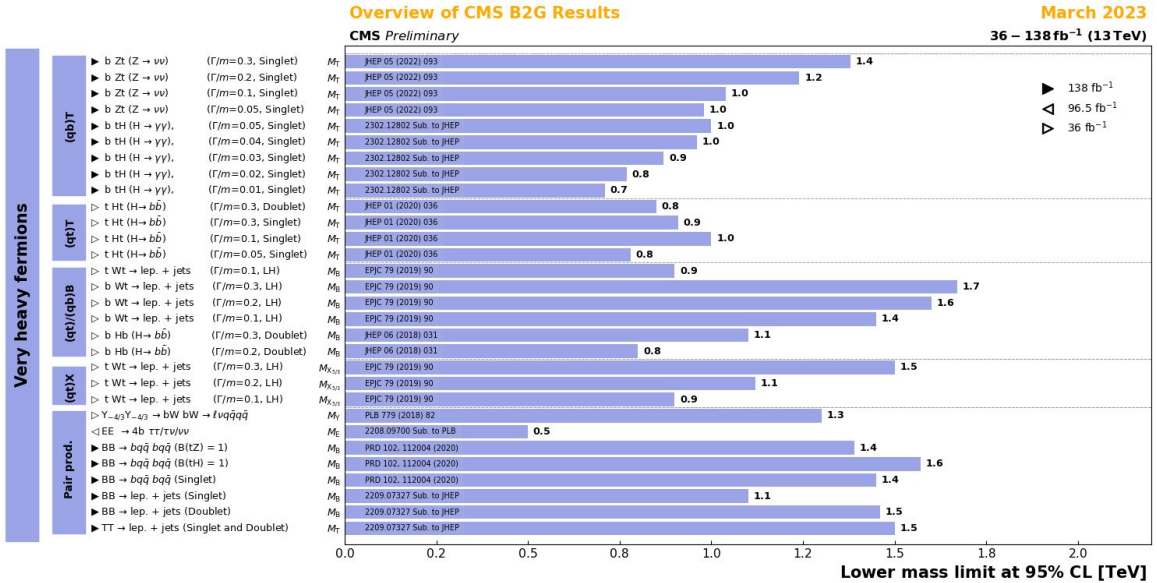
- The *natural* solution for this balancing in mass without fine-tuning is to have counter terms originating from new heavy particles (top partners)

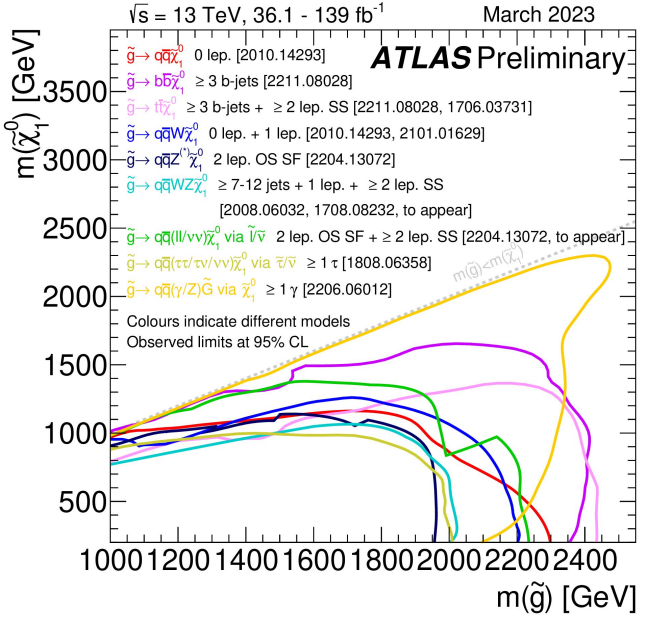


$M_H^2 \sim 10 - 9 = 1$ (in units of ~100 GeV squared)

What can we do with the LHC data?

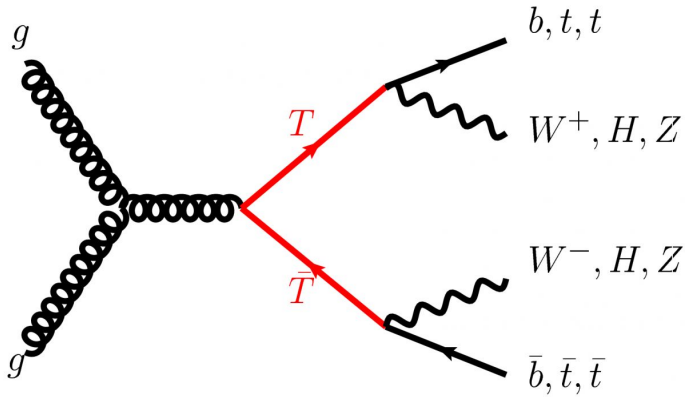
probe the Standard Model - and search for new phenomena beyond it!





searching for the unknown

an example: vector-like quarks



Singlets

charge 2/3 → $T_{L,R}$

charge -1/3 → $B_{L,R}$

Doublets

charge 5/3 → $\begin{pmatrix} X \\ T \end{pmatrix}_{L,R}$

$\begin{pmatrix} T \\ B \end{pmatrix}_{L,R}$

$\begin{pmatrix} B \\ Y \end{pmatrix}_{L,R}$ ← charge -4/3

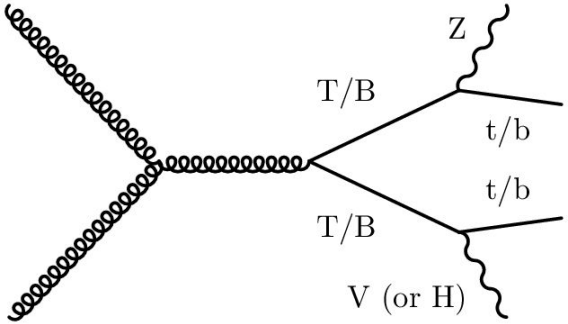
Triplets

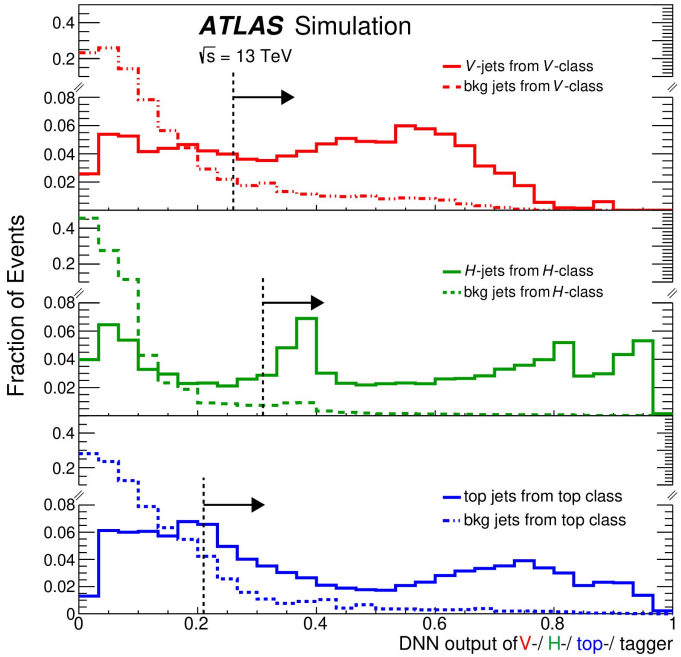
$\begin{pmatrix} X \\ T \\ B \end{pmatrix}_{L,R}$

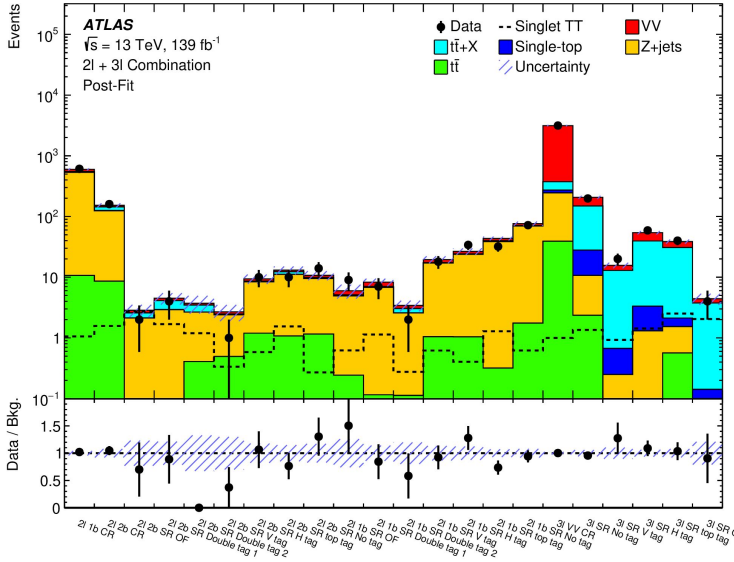
$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}_{L,R}$

searching for the unknown

an example: vector-like quarks







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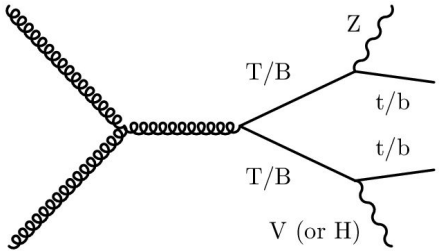
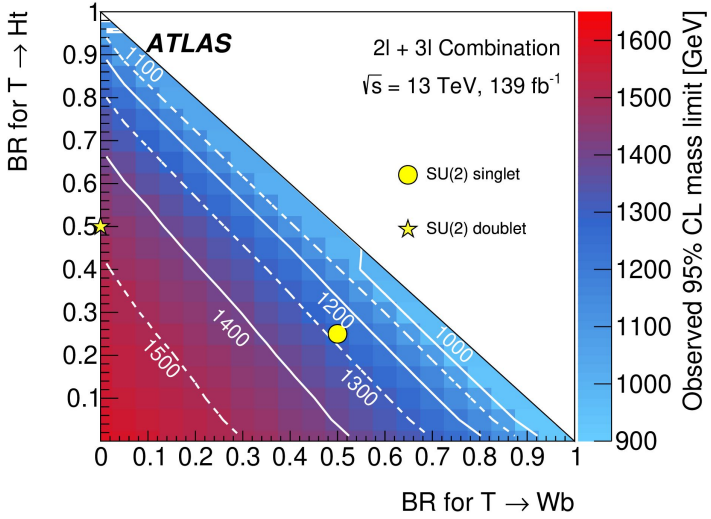
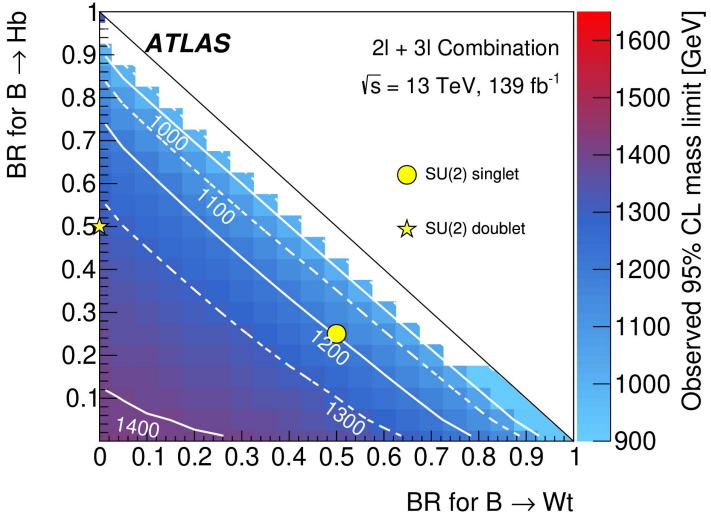
searching for the unknown

an example: vector-like quarks







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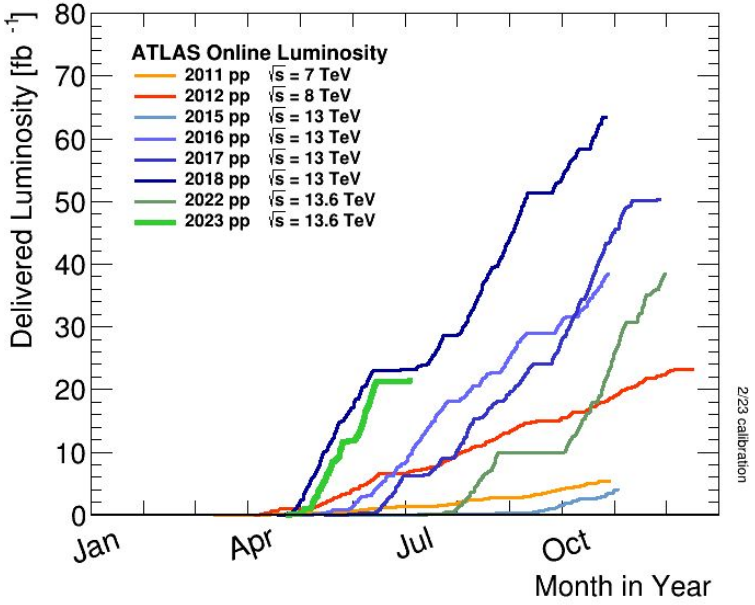
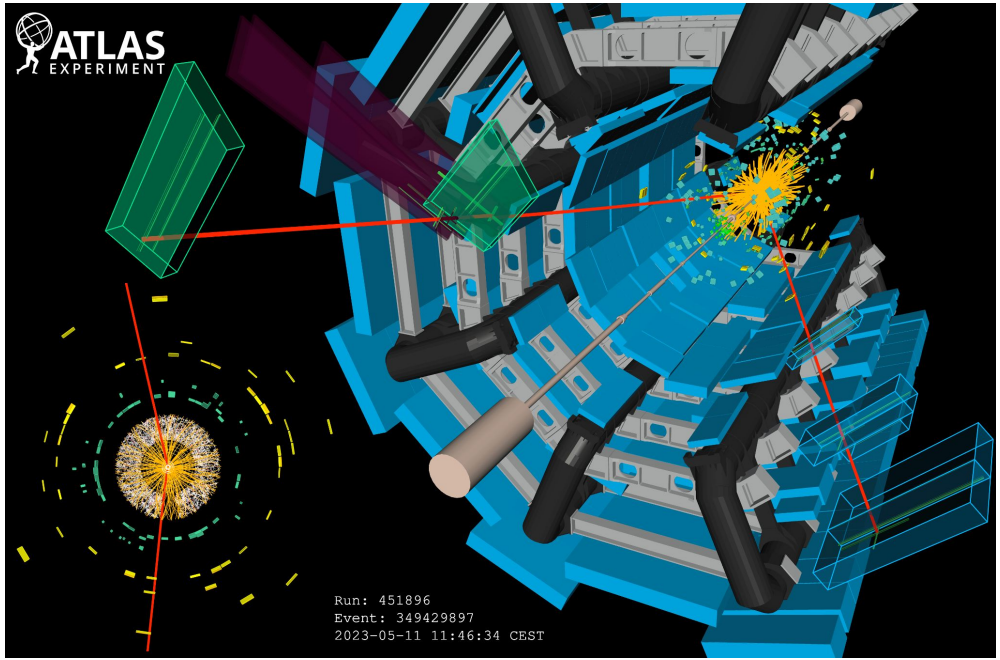
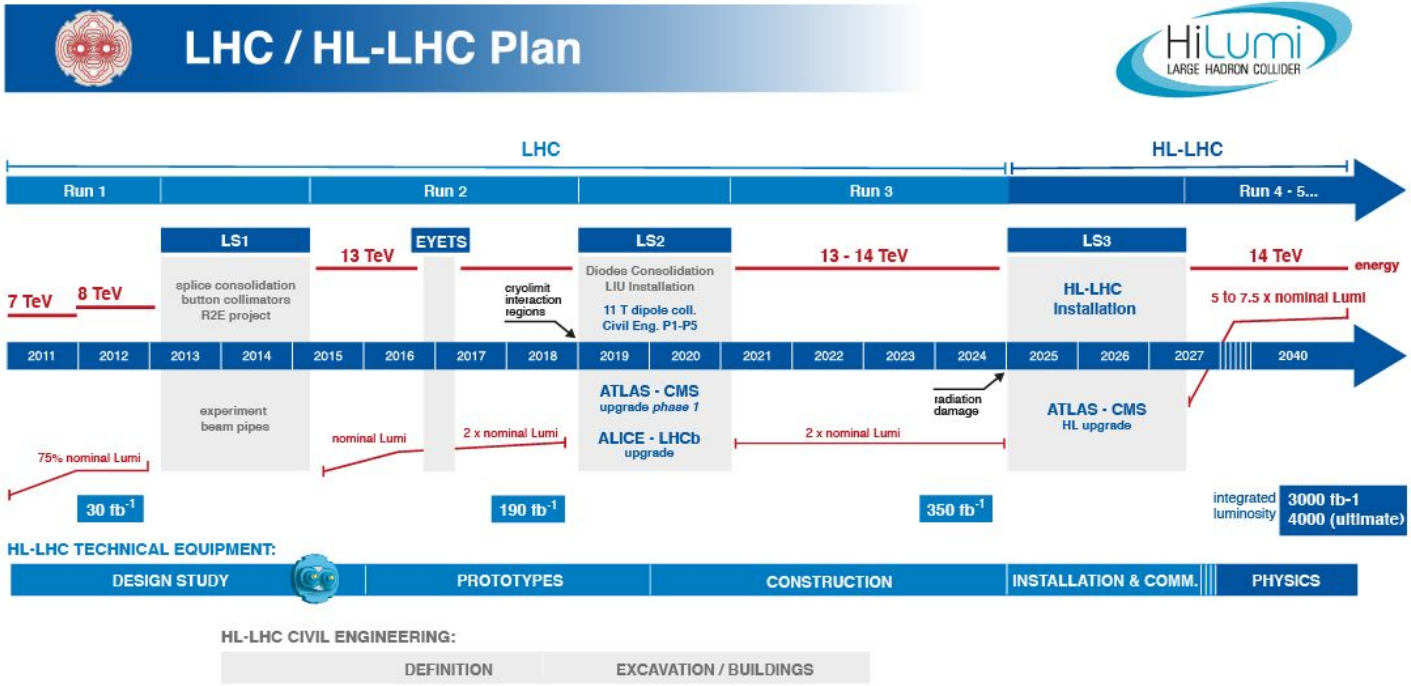
What's next?
LHC run-3: the future has arrived!

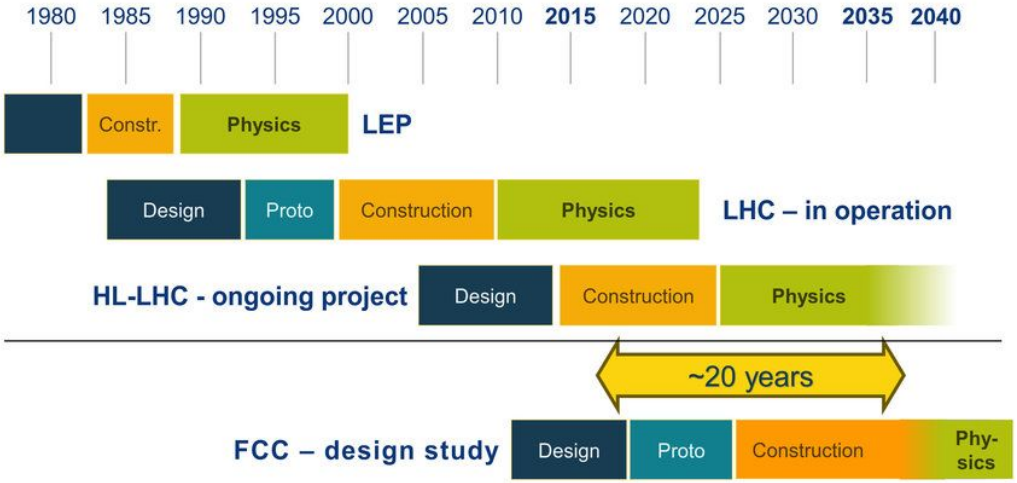


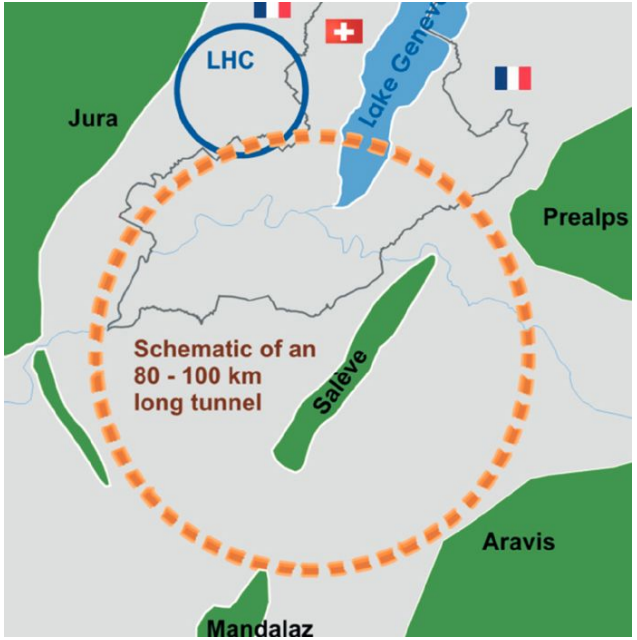


What's next?
LHC and beyond

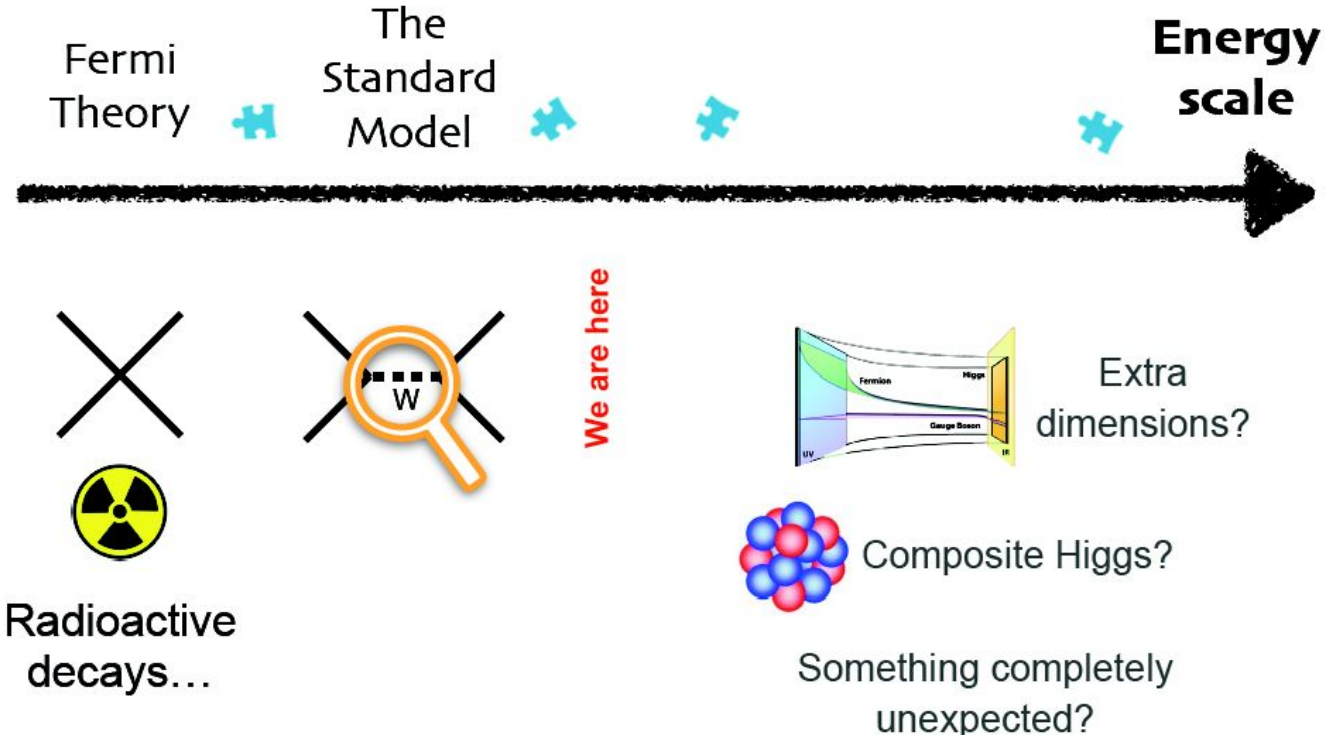


What's next?
LHC and beyond





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