August 4th 2020

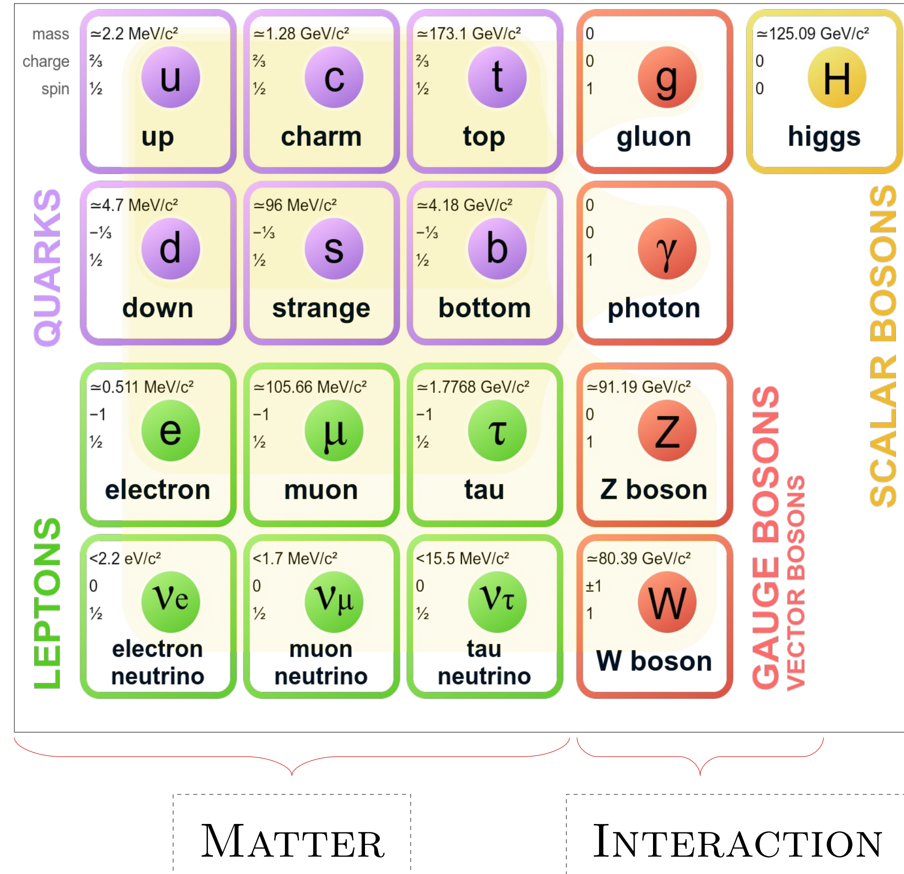
CMS Top group presentation

Top quark physics at CMS-DESY

Nicolas Tonon for the CMS DESY group

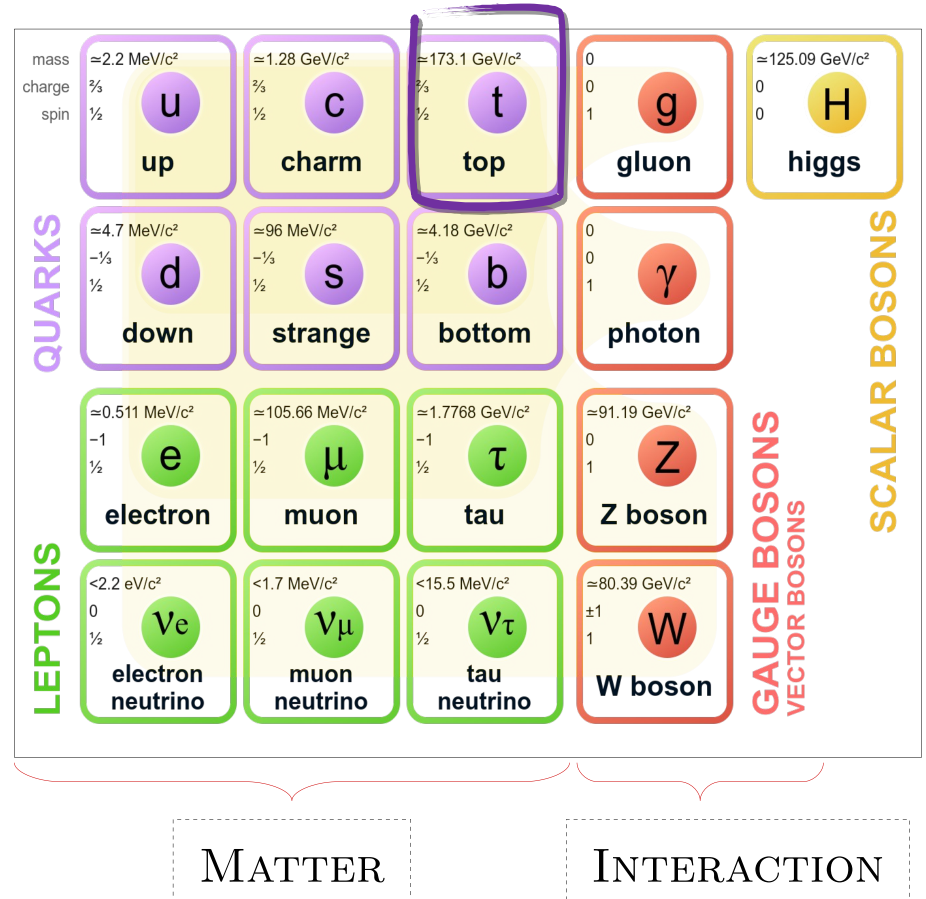
STANDARD MODEL (SM)

- Describes elementary particles & interactions
  - Excellent data/theory agreement
  - *2012* : Higgs Boson discovery (predicted in 1964 !)

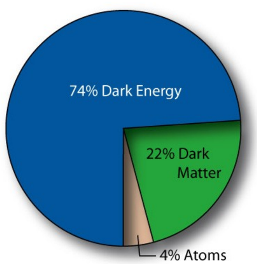


STANDARD MODEL (SM)

- Describes elementary particles & interactions
  - ✔ Excellent data/theory agreement
  - ✔ *2012* : Higgs Boson discovery (predicted in 1964 !)



? Several missing pieces :



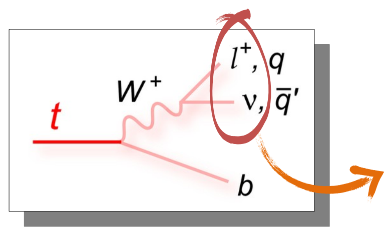
- ✗ Dark matter, neutrino masses, …
- ✗ Gravity not included, …

- Many « Beyond Standard Model» (BSM) scenarios postulate explanations (new particles, mechanisms, etc.)

- New physics accessible through
  - Direct observation
  - Deviation in precision measurement

THE TOP QUARK IS SPECIAL

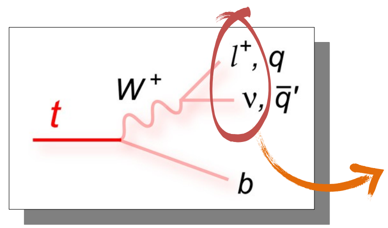
- Top quark (1995, Tevatron) has several unique features :
  - Heaviest known fundamental particle
  - Only quark decaying before forming bound state (hadrons)
  - Signature decay : $\mathrm{t} \to \mathrm{W\ b}$



Leptonic decay to **e** or **μ** (~ 20 %) offers **best signal/background** ratio

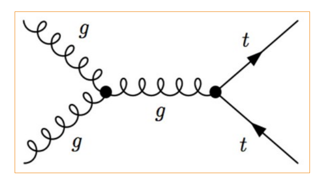
THE TOP QUARK IS SPECIAL

- Top quark (1995, Tevatron) has several unique features :
  - Heaviest known fundamental particle
  - Only quark decaying before forming bound state (hadrons)
  - Signature decay : $\mathbf{t} \rightarrow \mathbf{W\ b}$



Leptonic decay to **e** or **μ** (~ 20 %) offers **best signal/background** ratio

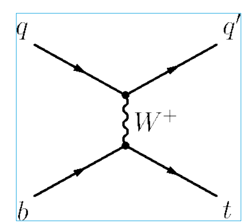
<u>$t\bar{t}$ pair production</u> (QCD) : dominant at LHC, σ ~ 800 pb



~130M $t\bar{t}$ pairs

Run 2 (2015-2018)

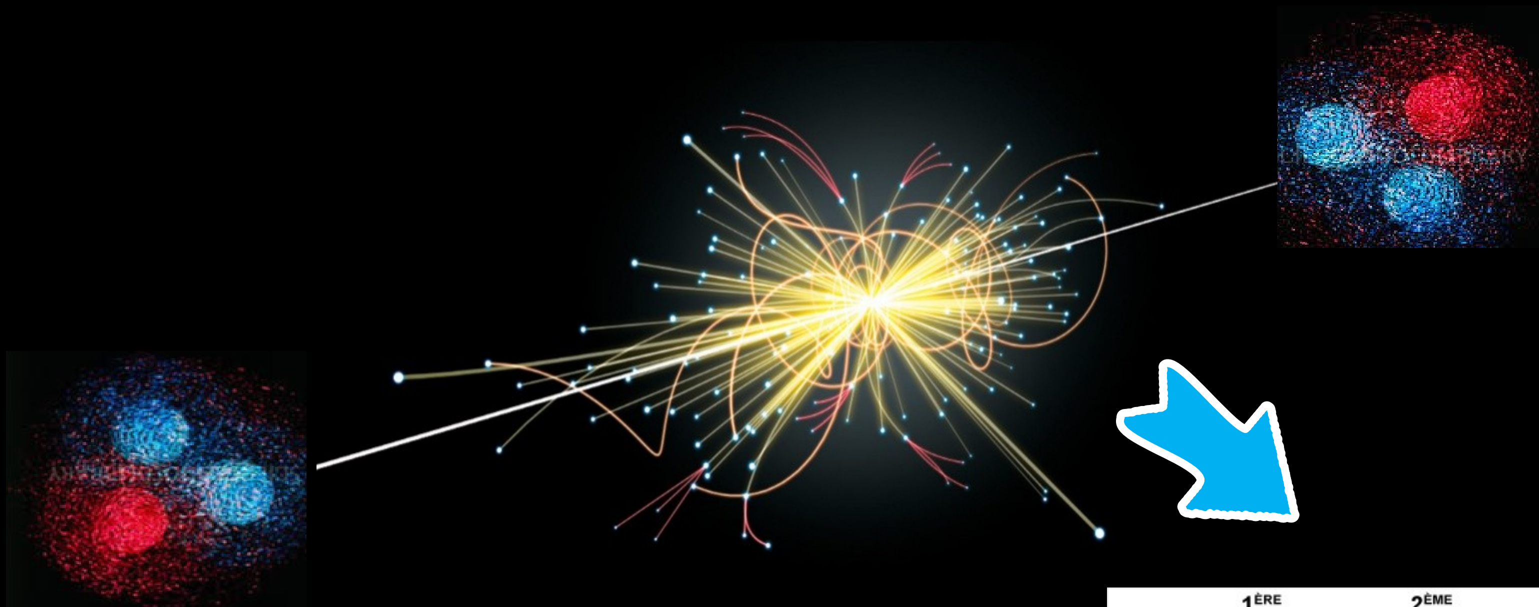
<u>Single top</u> (electroweak) : observed in 2009, σ ~ 280 pb

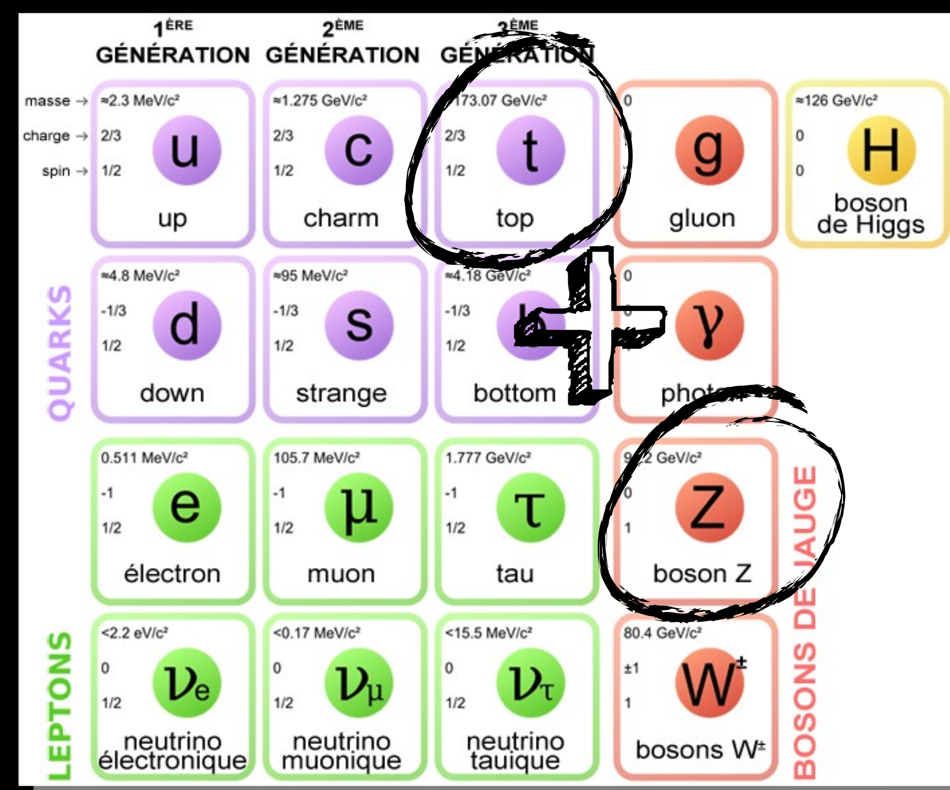


~50M single top quarks

Extremely rich phenomenology, probes profoundly self-consistency of Standard Model

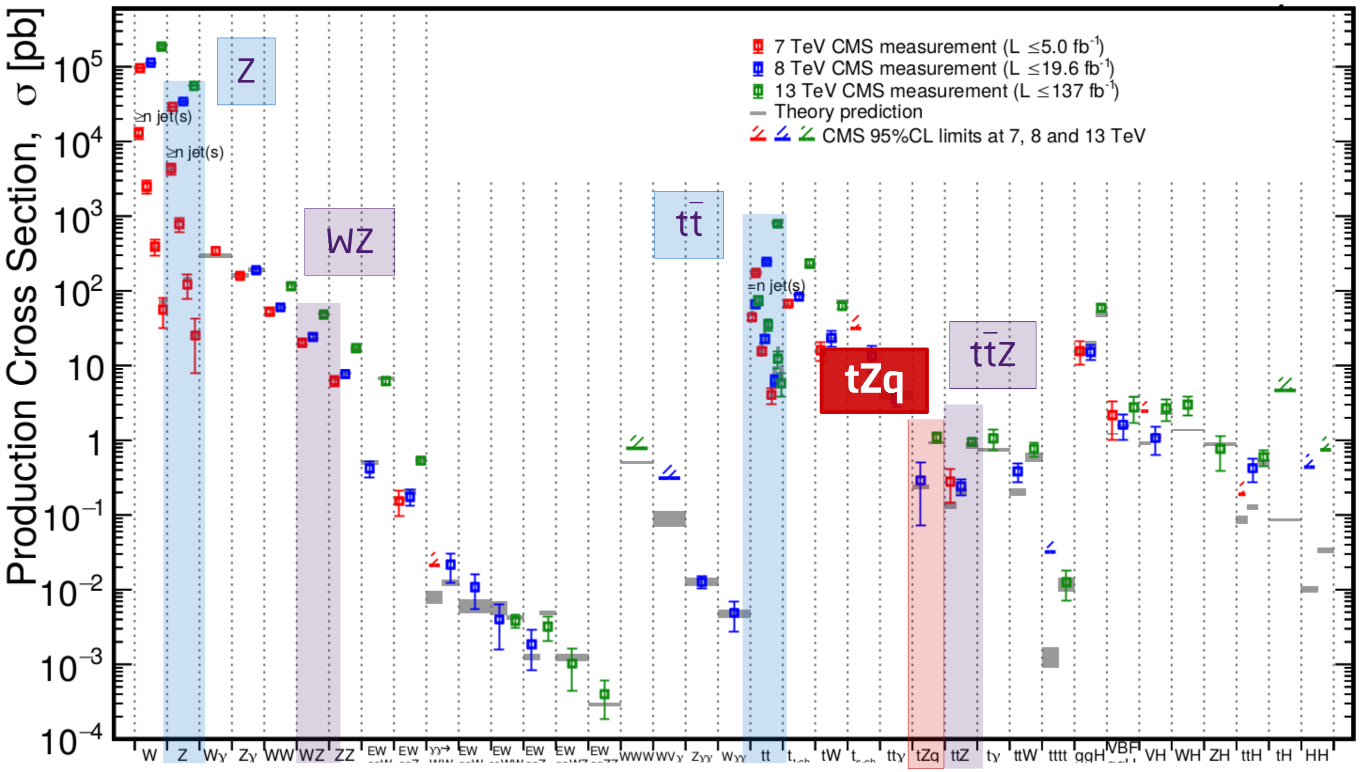
PHYSICS EXAMPLE Search for top-Z associated production (tZq)

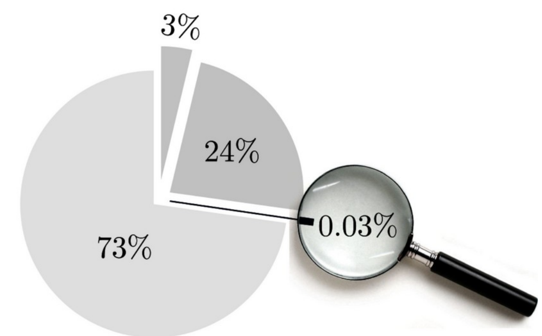




- Single top quark process, recently observed at LHC for the first time
- **Directly** sensitive to top-Z coupling
- Many BSM scenarios predict deviations in cross section & kinematics

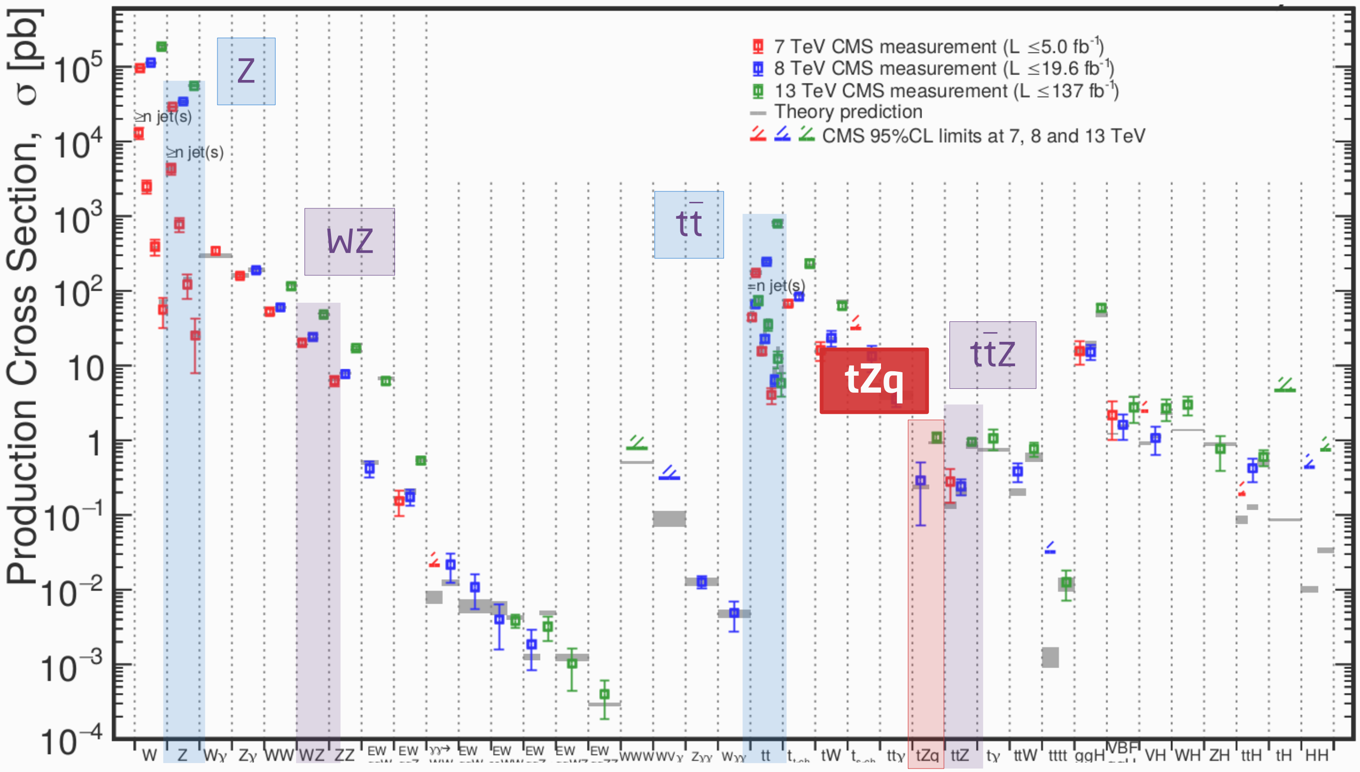
A VERY TINY SIGNAL...

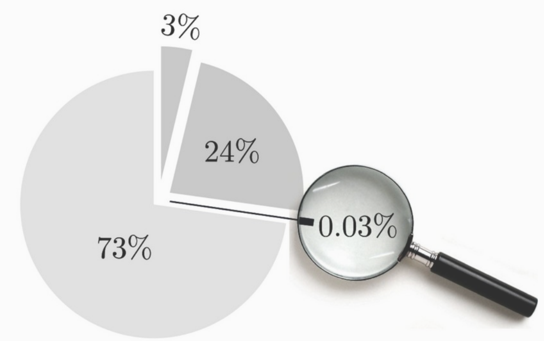




(Of total single-top cross-section)

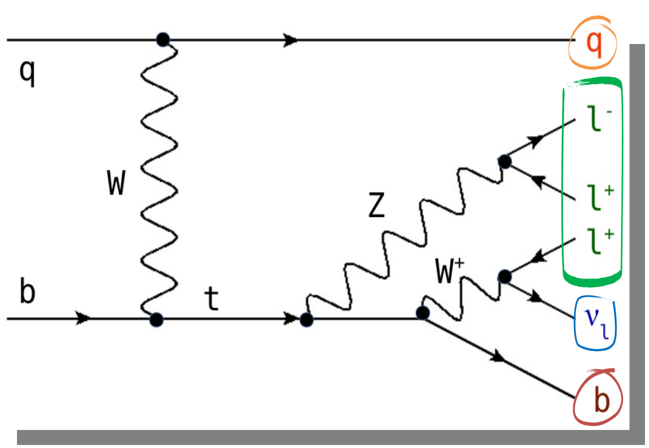
A VERY TINY SIGNAL…





(Of total single-top cross-section)

- Target events with 3 leptons in final state (clear signature, best signal/bkg ratio)



Light jet emitted in forward region (parallel to beams)

Neutrino not detected (missing energy)

b-jet *tagged* using dedicated algorithm

ANALYSIS WORKFLOW

- Main steps of a typical search at the LHC :

Simulation

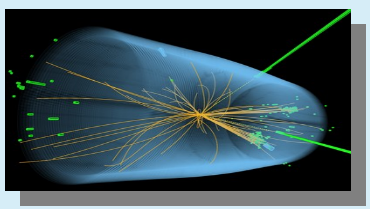
DATA

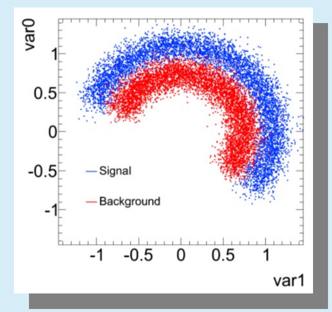
Object selection
(reconstruct particles)

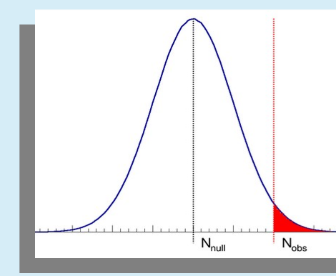
Event selection

Optimize
signal separation

Statistical
analysis







Most of the analyst's work
(understand simulation,
estimate backgrounds, etc.)

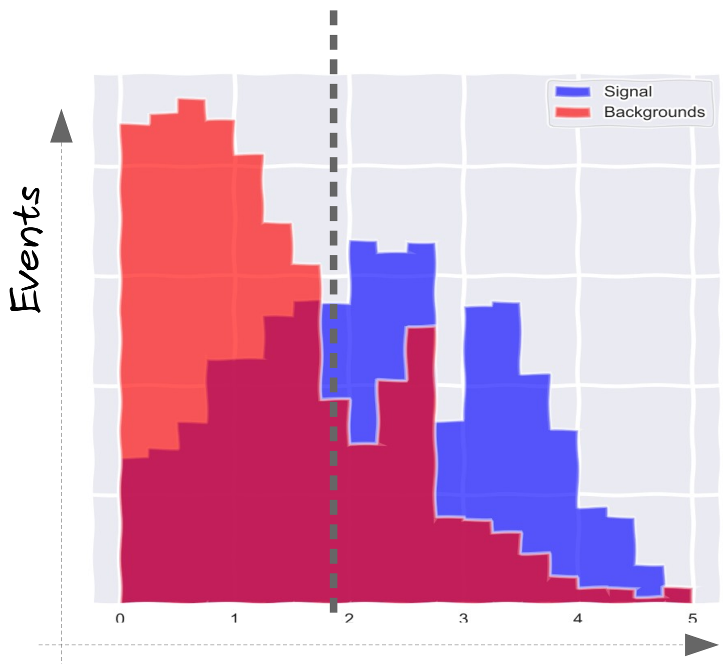
My favourite part !

HOW TO ISOLATE MY SIGNAL ?

- Rare signal can’t be separated efficiently from immense backgrounds using just few observables

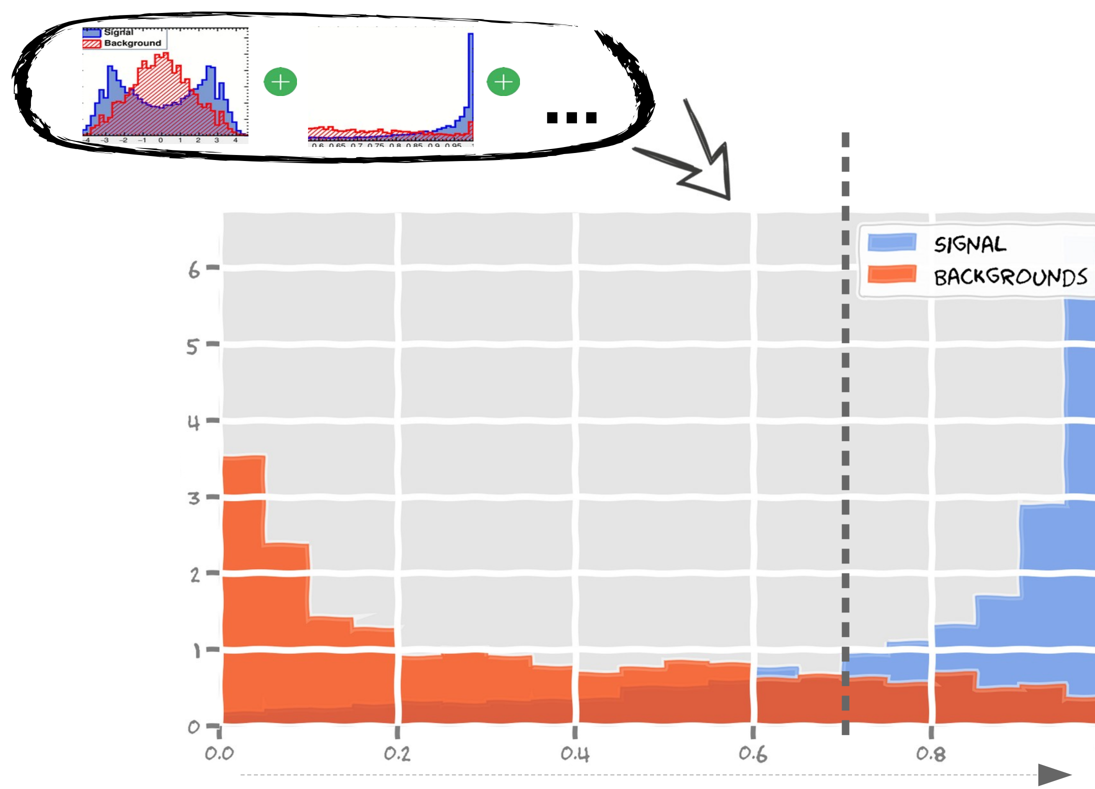
Multi-variate analysis → Check **many observables** to decide whether event is more signal- or background-like

- This process must be automated → Machine-Learning techniques (e.g. neural networks)
  - Easy to implement but… requires lots of optimization (simul.) and validation (simul. + data) !



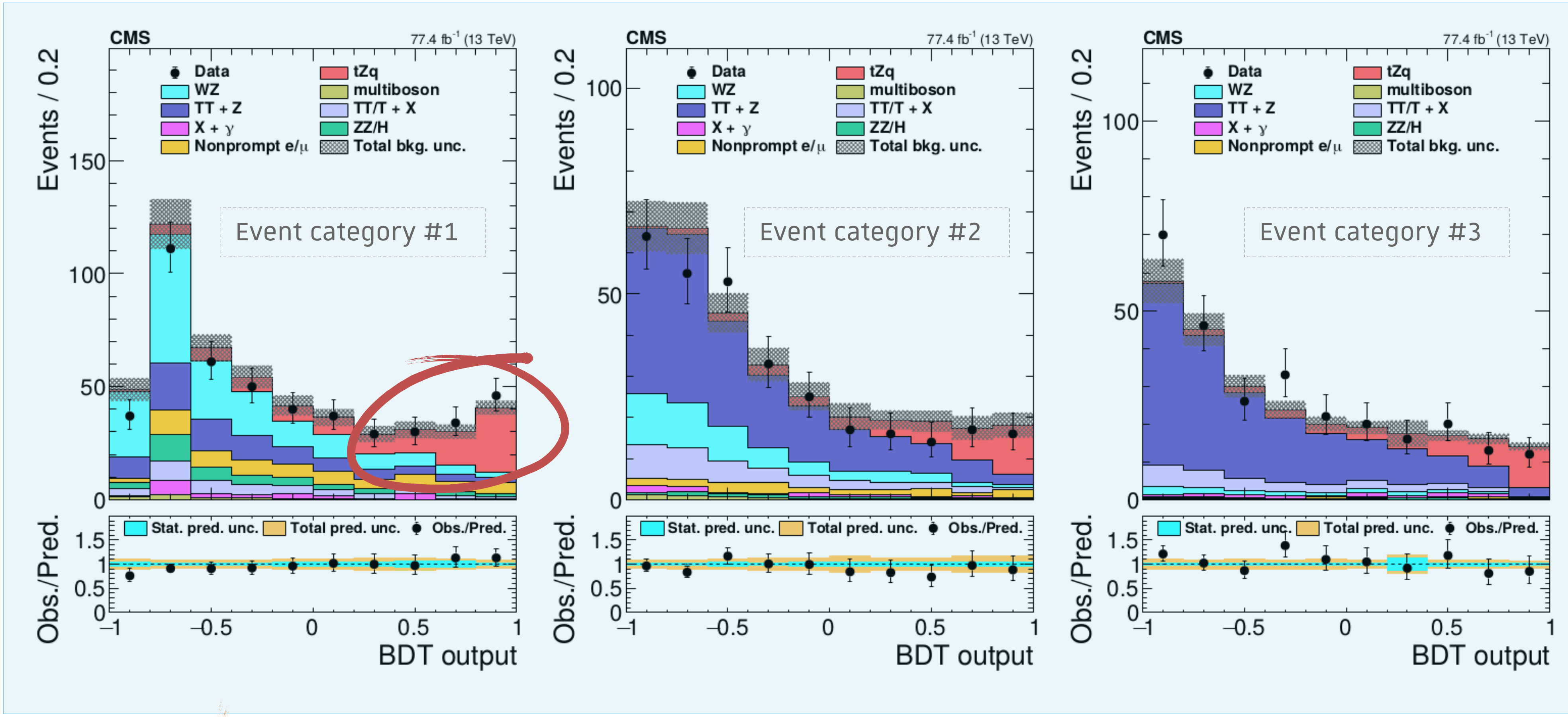
Single variable

(good separation, but sub-optimal)



Optimal variable from Machine-Learning

- Estimate the ‘signal’ contribution by fitting the simulation to the data



First observation of this rare process

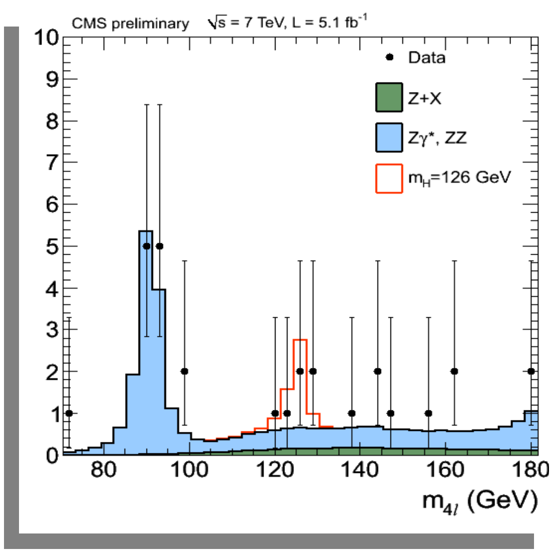
Observed significance : 8.2 σ (7.7 σ expected)

« STATISTICAL DISCOVERY » ?

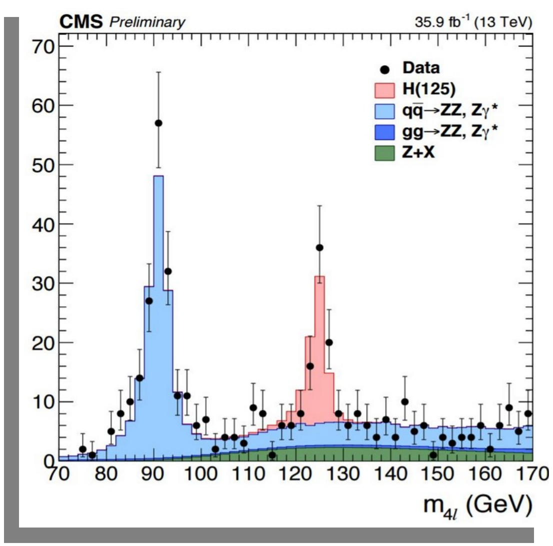
Example : search for the Higgs boson

Number of collisions

5 fb^{-1} of data, 7 TeV



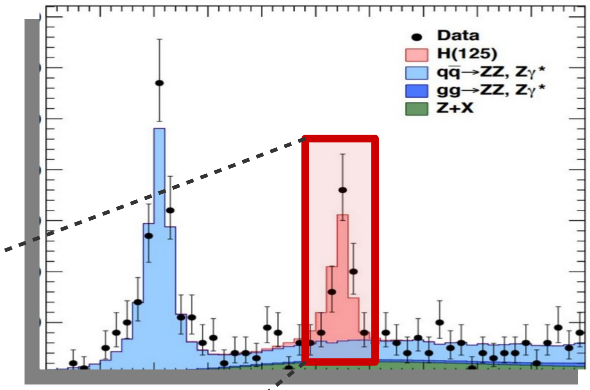
36 fb^{-1} of data, 13 TeV



Mass (4-leptons)

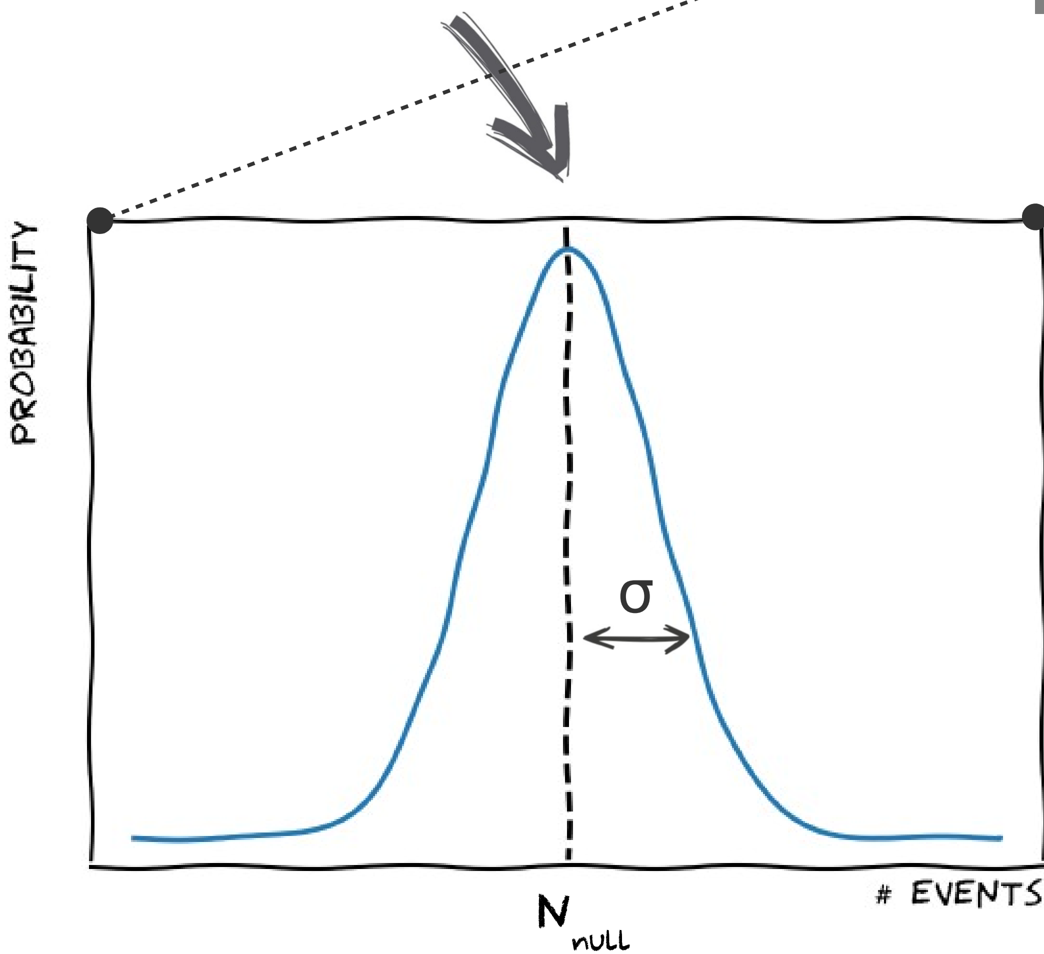
Is the excess of data « statistically significant »… ?

HYPOTHESIS TESTING – SIMPLIFIED



Prediction of null hypothesis

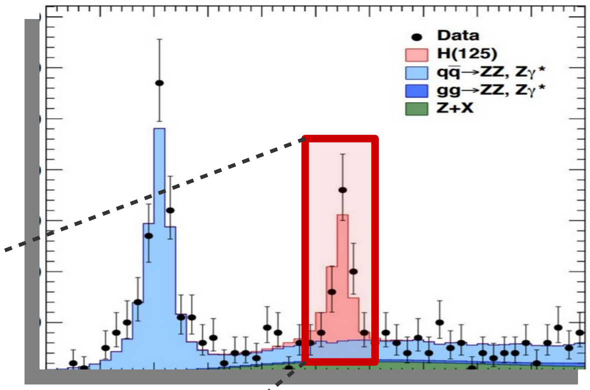
= SM without Higgs

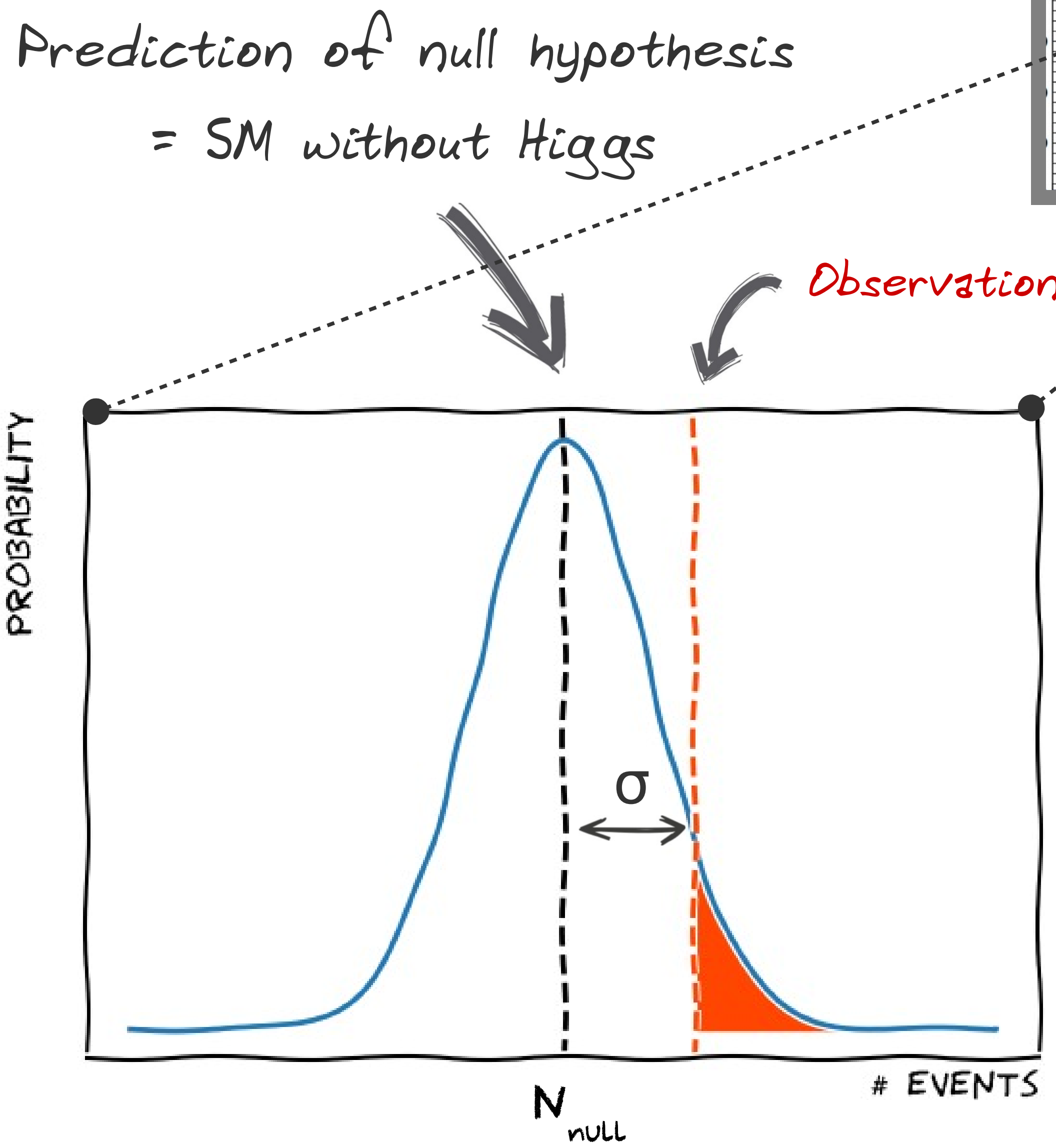


For a given mass range (bin) :

- If dataset is large enough, # of observed events N_{null} predicted by null hypothesis H_0 approximately follows a normal distribution

HYPOTHESIS TESTING – SIMPLIFIED



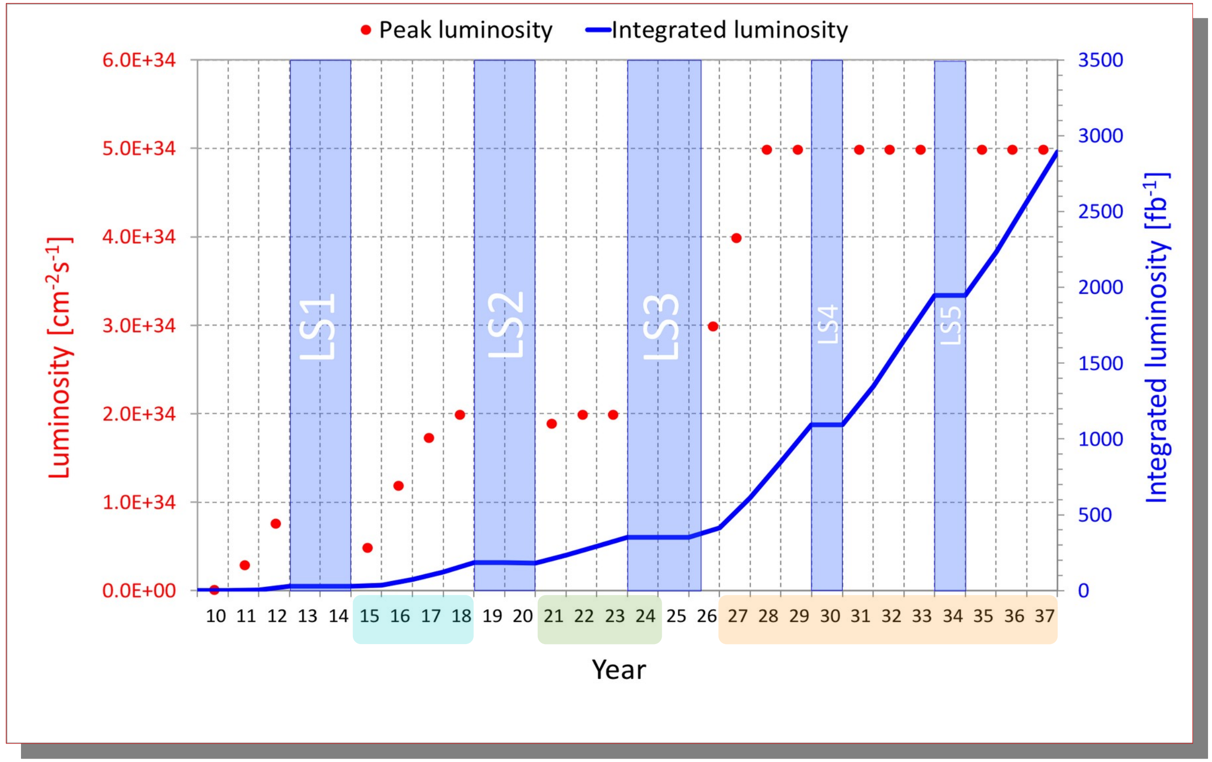


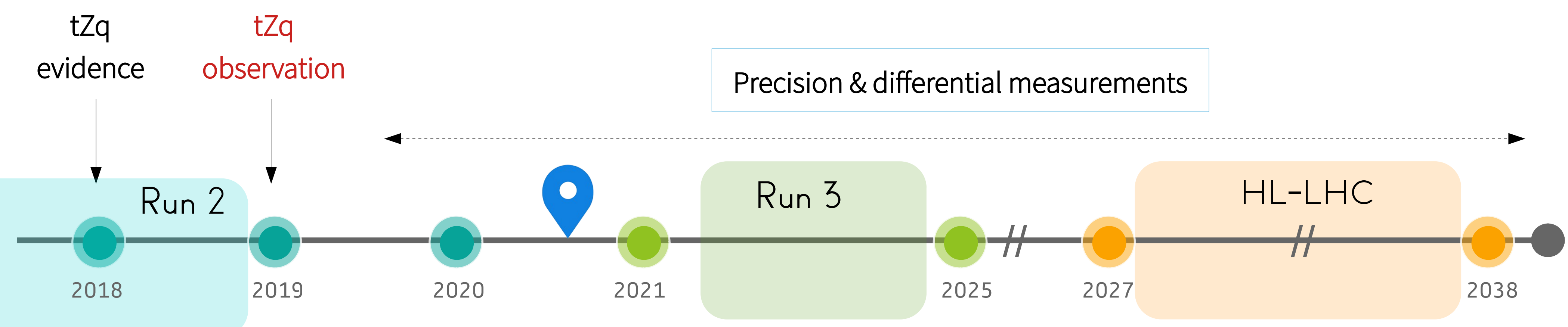
For a given mass range (bin) :

- If dataset is large enough, # of observed events N_{null} predicted by null hypothesis H_0 approximately follows a normal distribution
- Significance : $\mathcal{S} = (N_{obs} - N_{null})/\sigma$
- P-value : $p = \int_{N_{obs}}^{+\infty} H_0 \cdot dx$

S = 3 σ → « Evidence »
S = 5 σ → « Observation »

FROM DISCOVERY TO PRECISION





WHAT'S NEXT ?

- Several top quark couplings (to Z, γ, H) are still quite poorly known
  - Many BSM extensions predict sizeable deviations

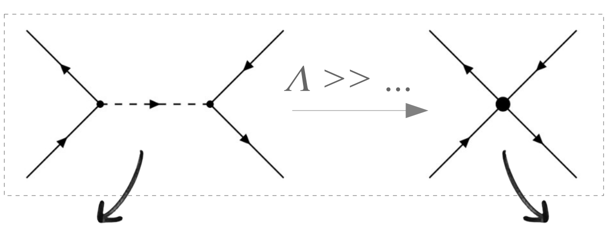
- Effective Field Theory (EFT) provides framework to interpret potential deviations from SM predictions
  - Assume new physics is characterized by energy scale $\Lambda >> E_{LHC}$
  - Expand SM Lagrangian with higher-order operators
  - Model-independent → Can re-interpret results within different models

Strength

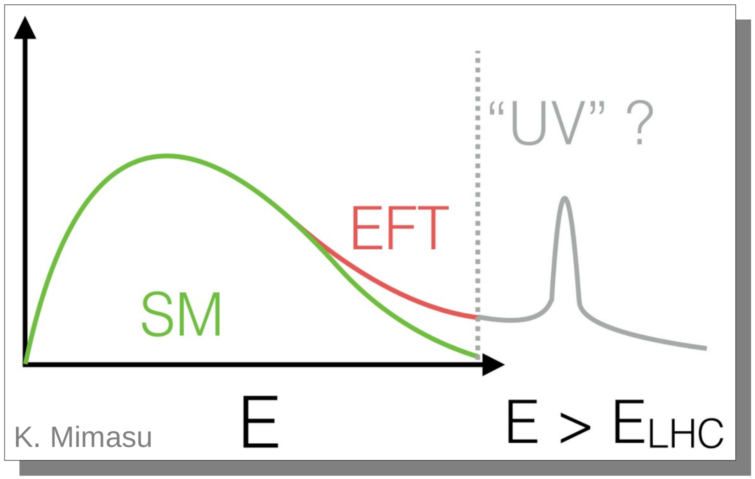
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \sum_{d>4} \frac{C_i^d}{\Lambda^{d-4}} O_i^d$$

Higher-order operators

- Example : Fermi theory of weak interaction ($E << m_Z, m_W$)

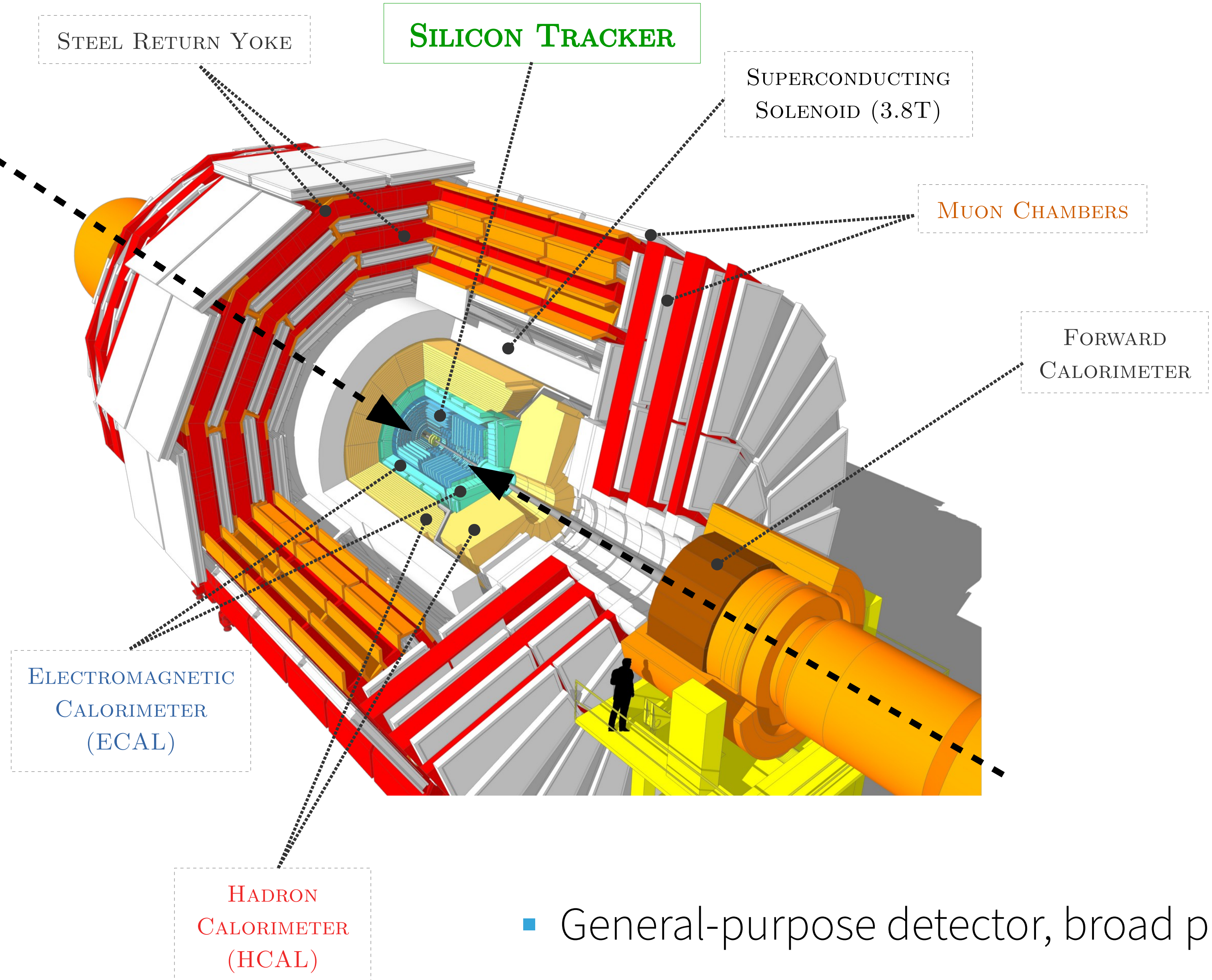


The actual W boson ... approximated as ... an effective interaction



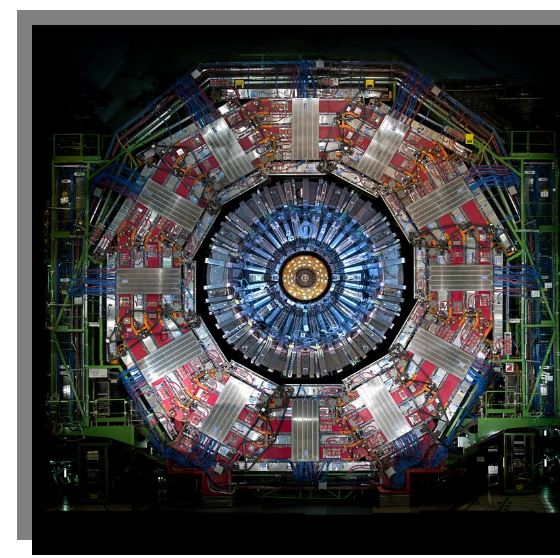
BACKUP

CMS (COMPACT MUON SOLENOID)



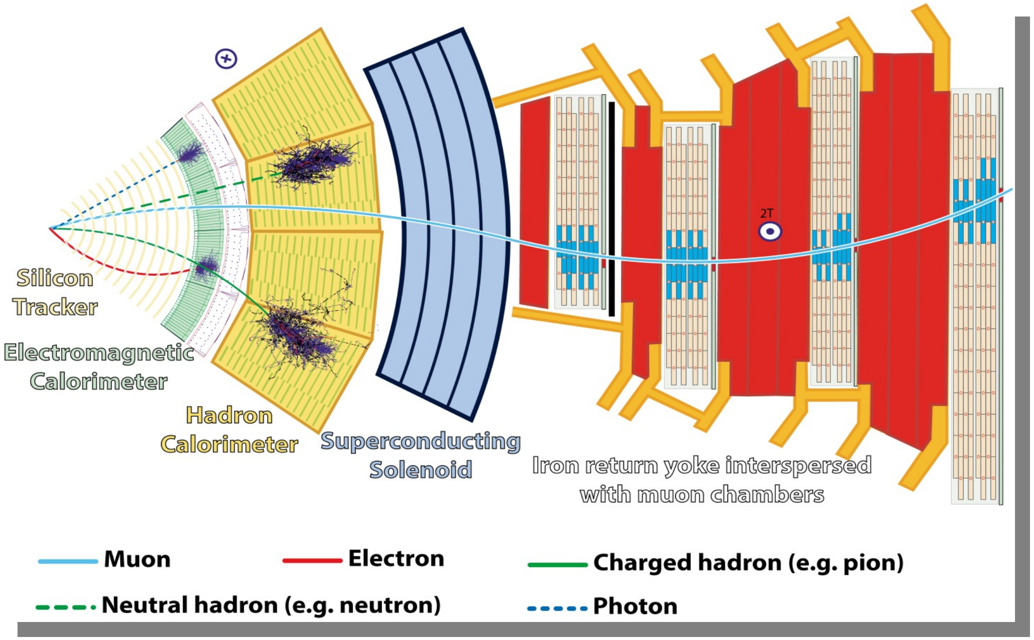
22m long

15m diameter



- General-purpose detector, broad physics programme
- Many specialized sub-detectors

CMS (COMPACT MUON SOLENOID)

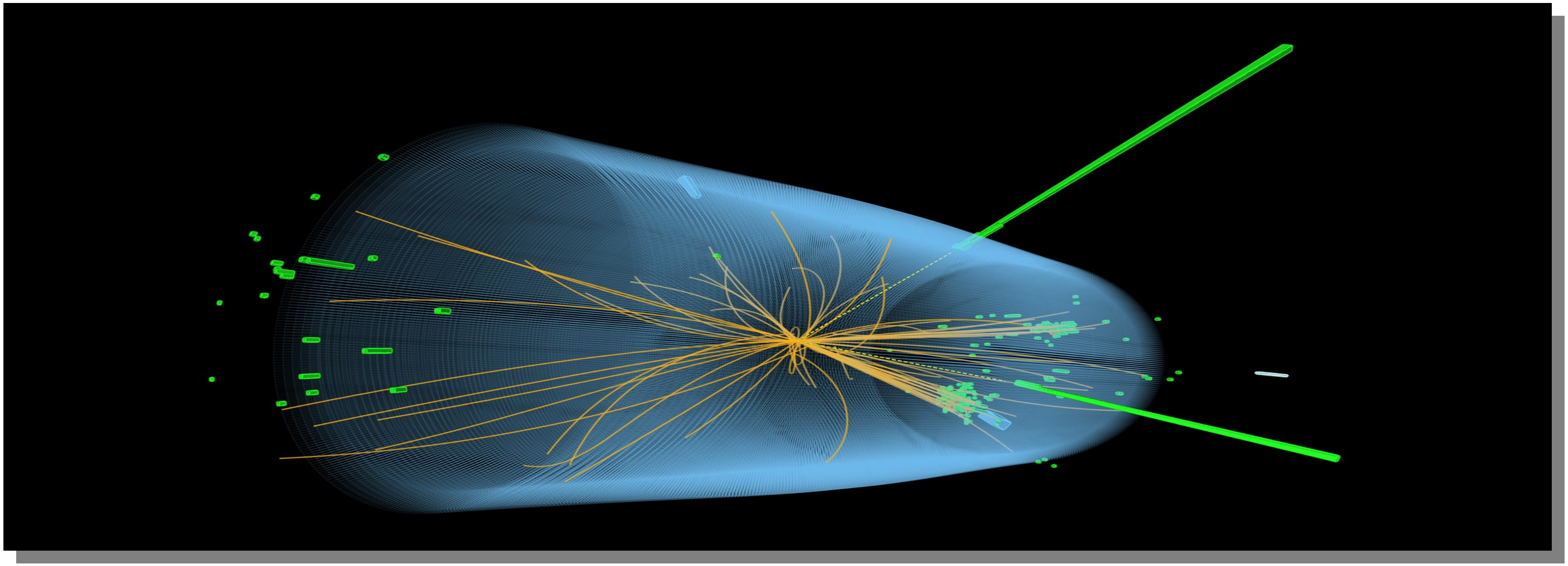


- Combine informations from all sub-detectors

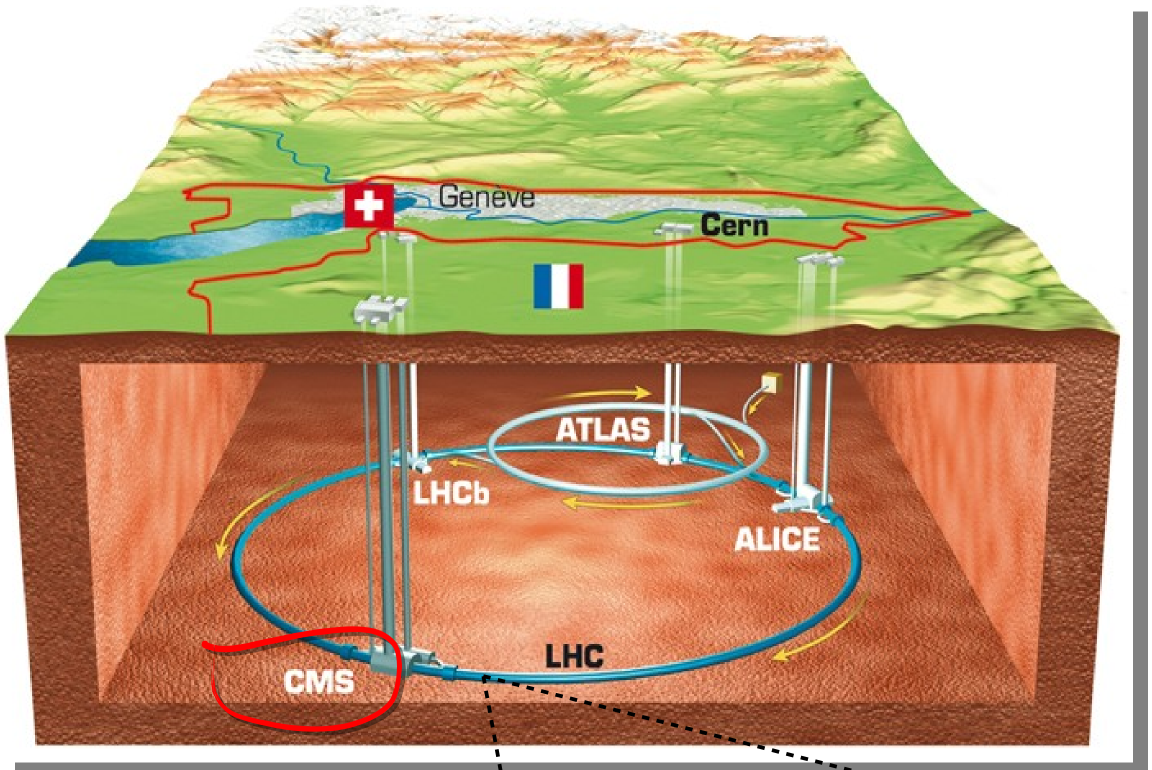
  → Identify nature of created particles

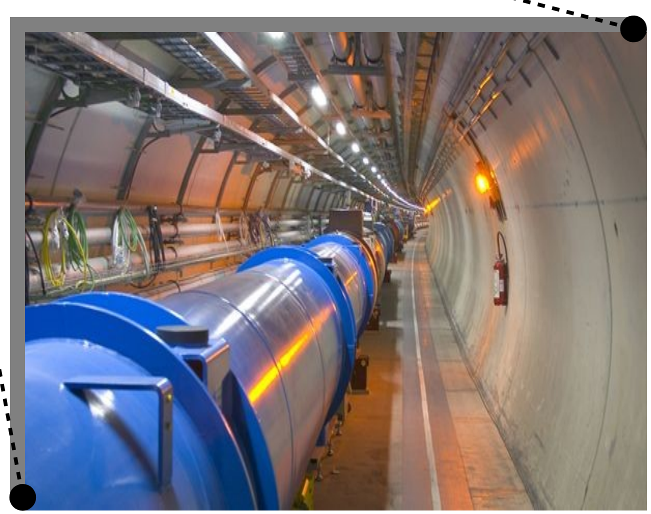
  → Reconstruct full picture of the event

$H \to \gamma\gamma$



LHC (LARGE HADRON COLLIDER)





- 27 km circonference
- 10^9 proton collisions/second
  → Can study rare particles
- Highest energy ever achieved
  - 13 Tera-electronvolts (TeV)
  - $E = M.c^2$