Introduction to The Standard Model*

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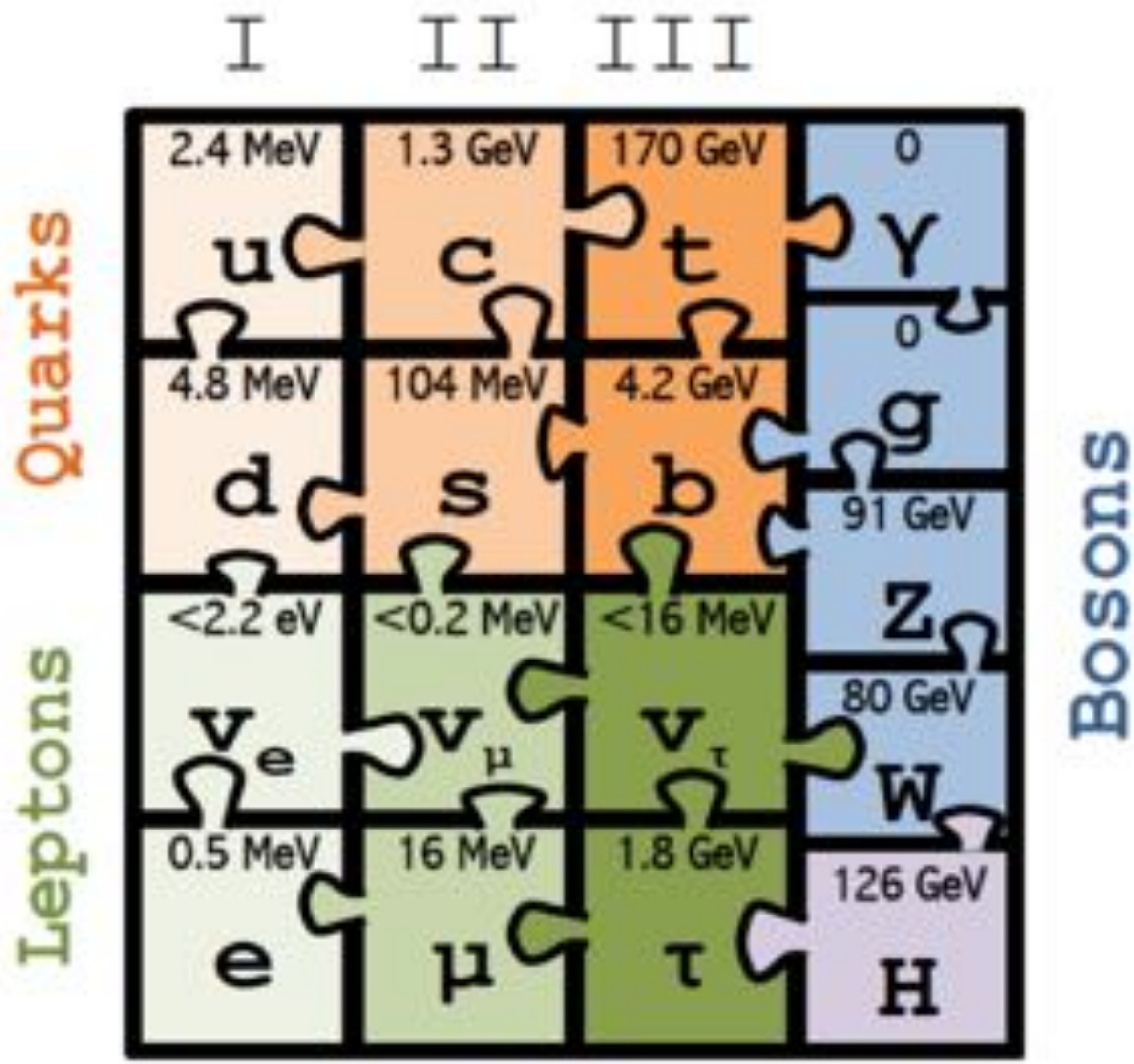
* *A very biased introduction from an experimentalist!*

The Standard Model (SM)
Reminder

- A successful model (from the experimental point of view) that describes the interactions between known fundamental particles of matter



The Standard Model (SM)

Reminder

- The particle physics world in 1975

- The **local gauge symmetry** that defines the SM is

QCD → SU(3) x SU(2) x U(1) ← Electro weak

- The group representation determines the interaction form
  - Leptons: SU(3) singlets → do not interact strongly
  - Quarks: SU(3) triplets → interact with gluons

- Parity violation → Separation of the left and right SU(2) representations:
  - Left fermions: SU(2) doublets → interact weakly
  - Right fermions: SU(2) singlets → do not interact weakly
  - **No mass terms for fermions**

- Also, **no mass terms for bosons W and Z**

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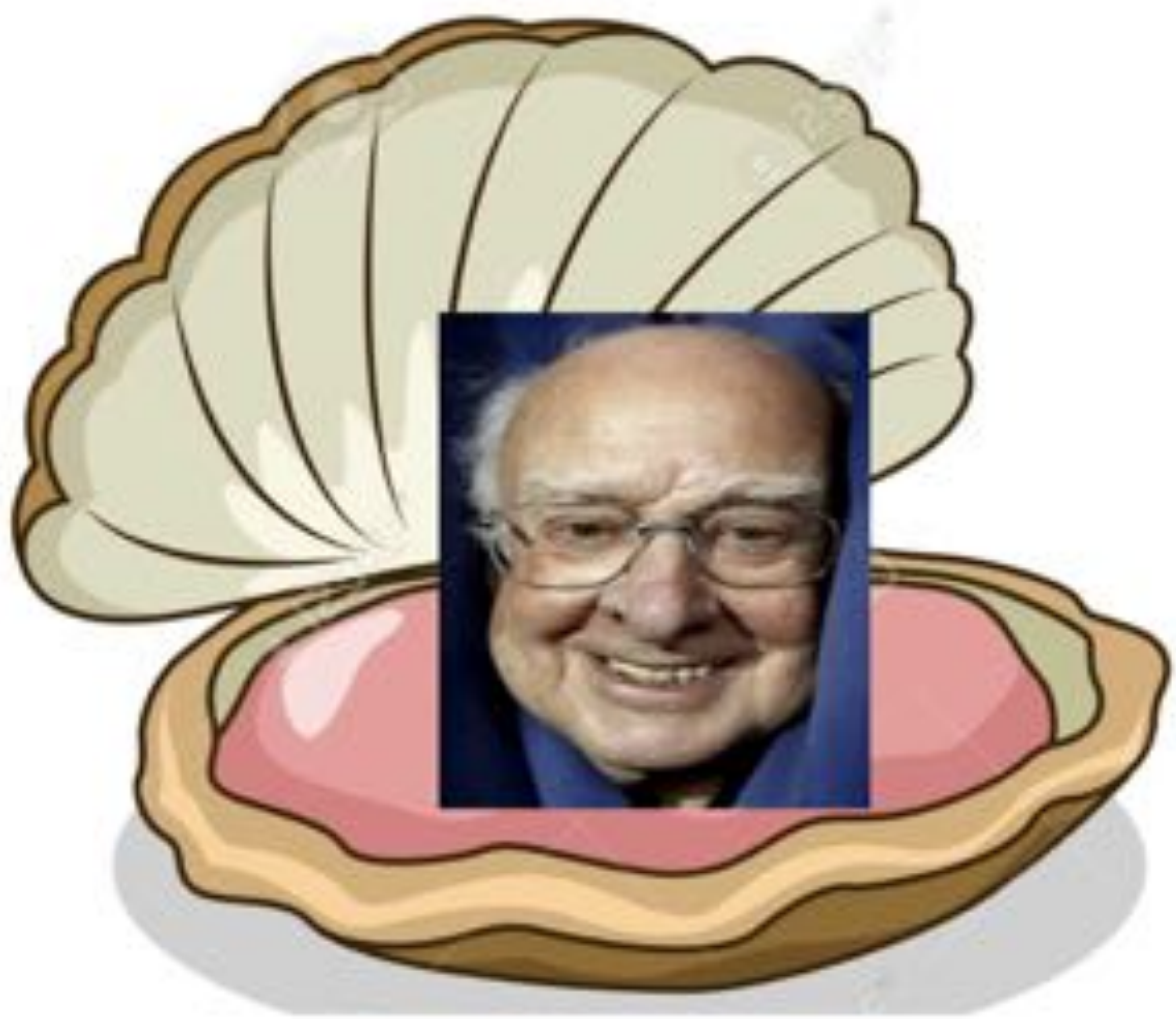
  - Right fermions: SU(2) singlets → do not interact weakly
  - **No mass terms for fermions**
- Also, **no mass terms for bosons W and Z**
- In 1983 UA1 and UA2 announced the discovery of a massive W boson

The Standard Model (SM)

And the Higgs physics field was born...



The Standard Model (SM)

And the Higgs physics was born...

SM solution to the mass problem

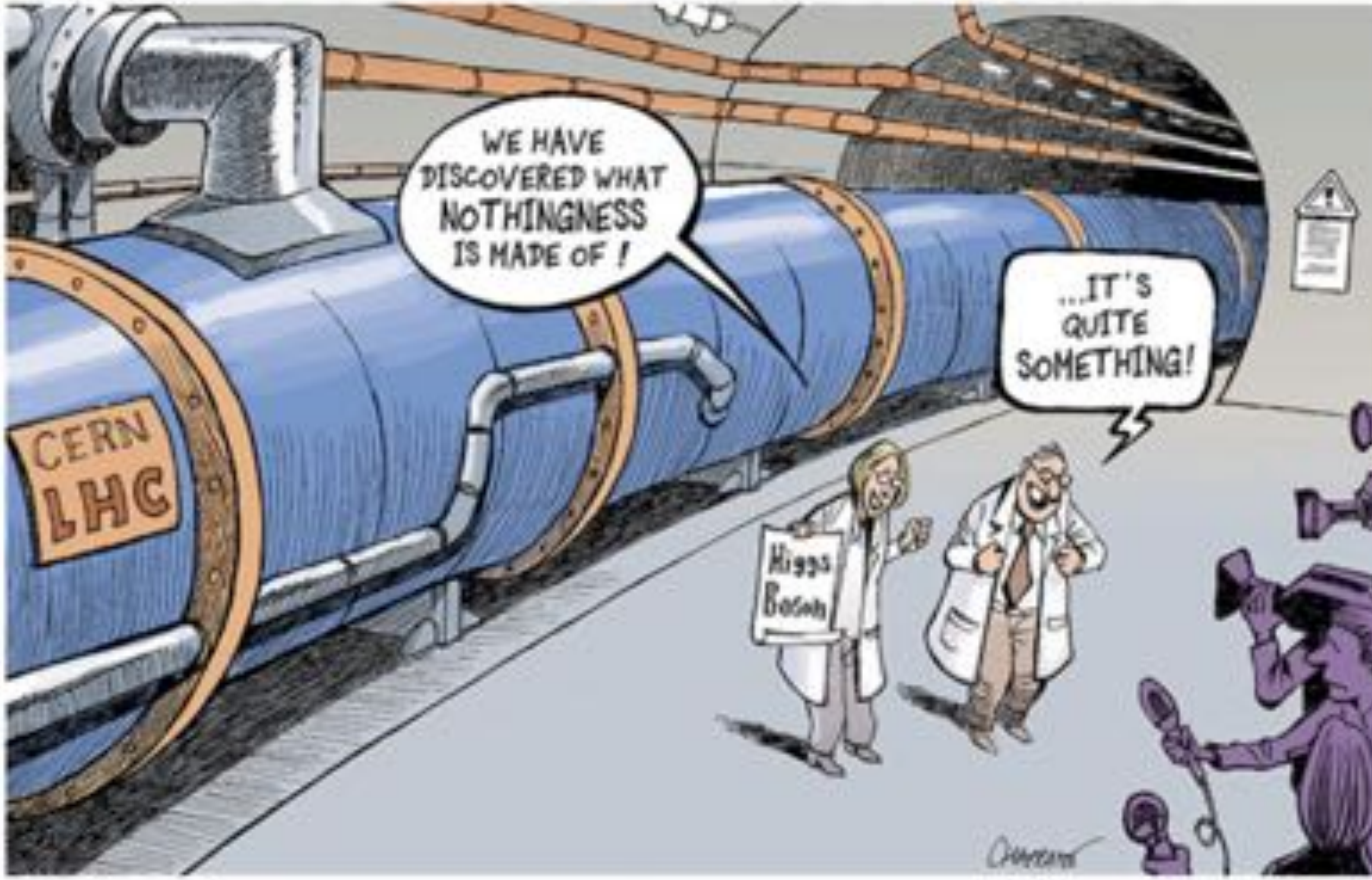
Add scalar field with spontaneous symmetry breaking → W, Z boson masses

Add Yukawa couplings → Fermion masses

- *ABEGHHK'tH mechanism (known commonly as Higgs mechanism) proposed by three independent groups in 1964*
- *Yukawa interaction, was not formalized in first seminal papers (introduced by S. Weinberg)*

The Standard Model (SM)

And the Higgs physics was born...



- Mass is not an intrinsic property of particles, but results from an interaction with the Higgs field that fills the space

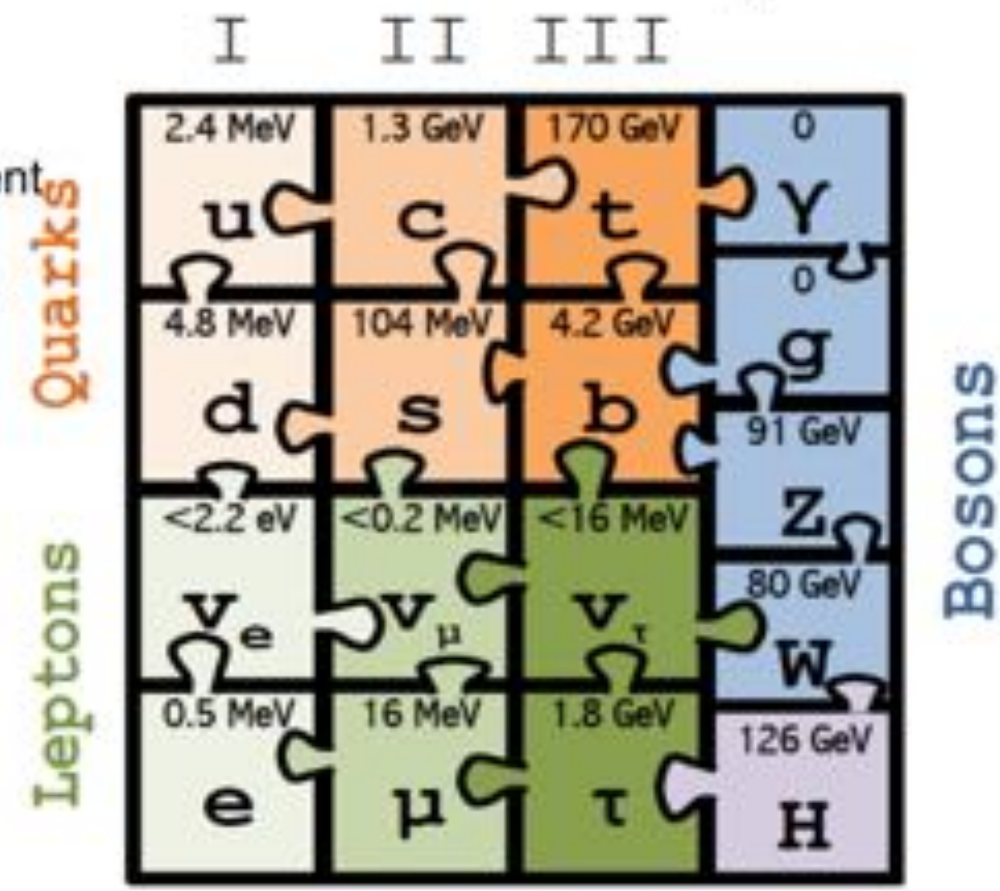
- The Higgs boson is the particle corresponding to the Higgs field

The Standard Model (SM)

Global overview

Top physics:
- A special kind of quark
- Decays before hadronizing $t \rightarrow Wb$

QCD physics:
- Strong interaction
- 8 gluons, 6 quarks
- Asymptotic freedom weakly interaction at high E) and confinement (strong at low E)
- In experiment → jets



Electroweak physics:
- Mostly related with boson measurements: W,Z,photons
- Precise tool to probe the gauge structure of EWK sector in the SM

Neutrino physics:
- Weak interaction
- Tiny mass
- Sources: solar, nuclear reactors and accelerators

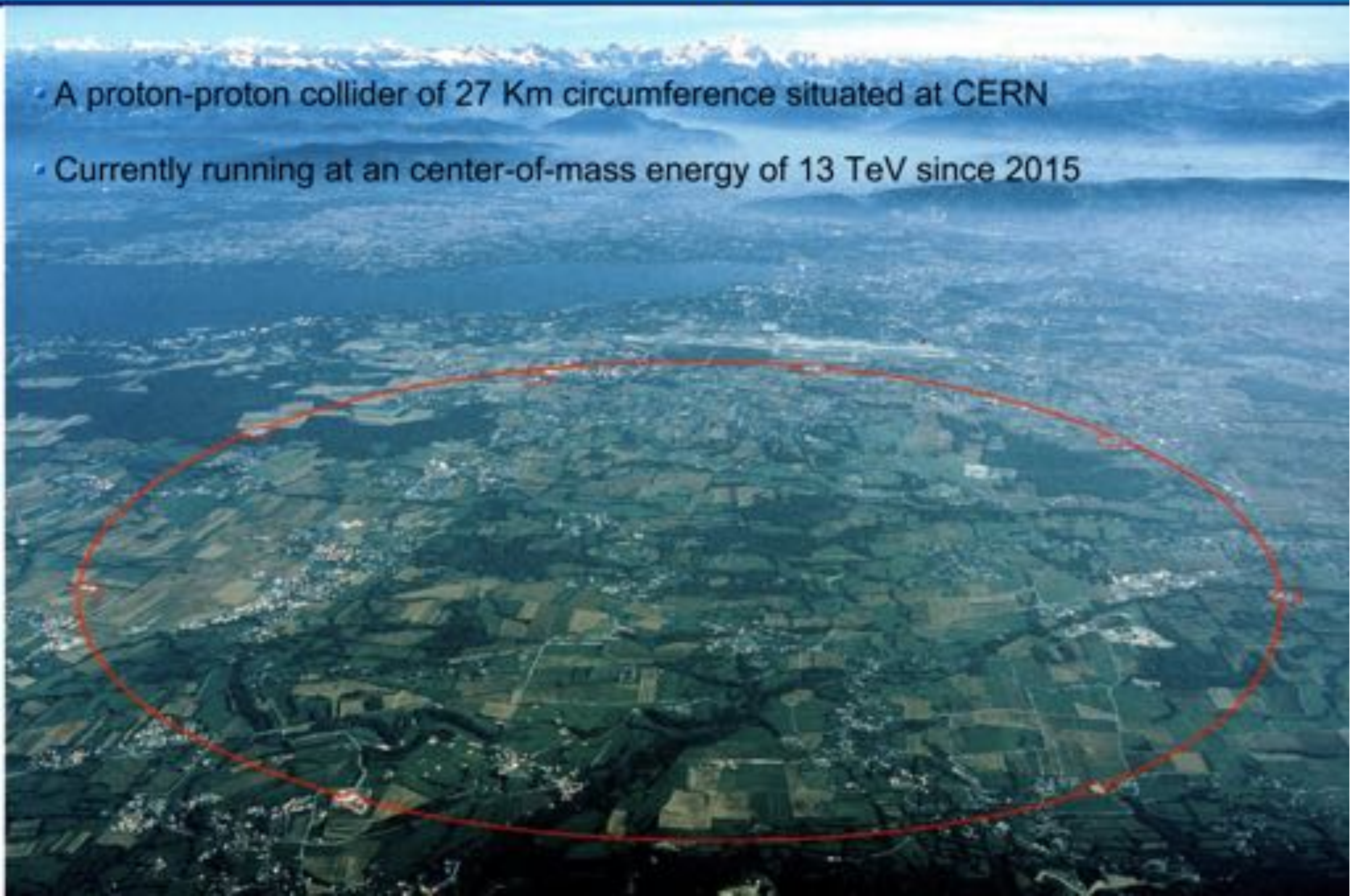
Higgs physics:
- Will know a lot more after this session!

- *A lot of interconnections but we need some organization so...*

So how do we study all these particles?

The current tools: The Large Hadron Collider (LHC)

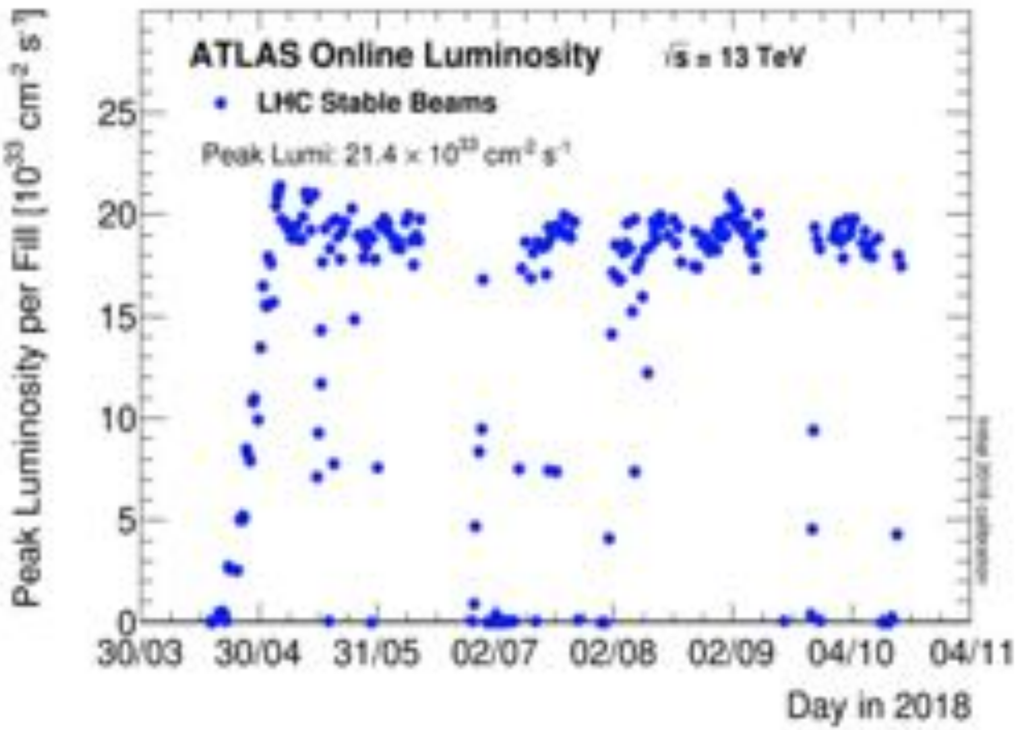
- A proton-proton collider of 27 Km circumference situated at CERN
- Currently running at an center-of-mass energy of 13 TeV since 2015

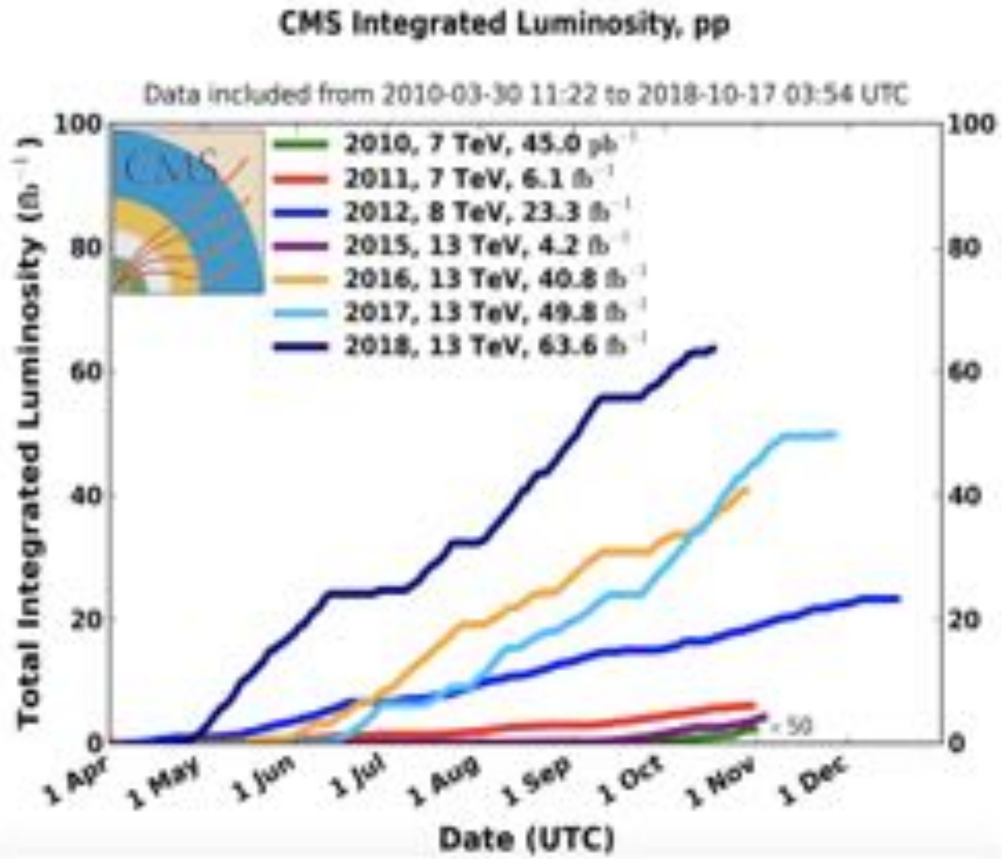


So how do we study all these particles?

LHC performance

$$N_{events} = \sigma \times L$$





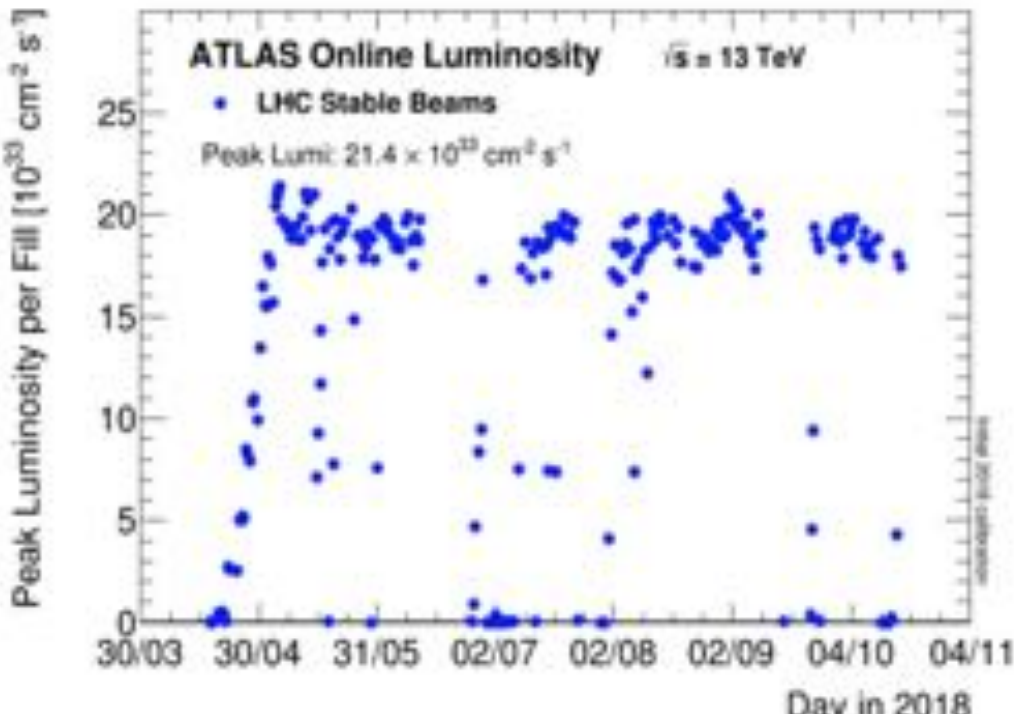
Peak luminosity twice larger than LHC design luminosity!

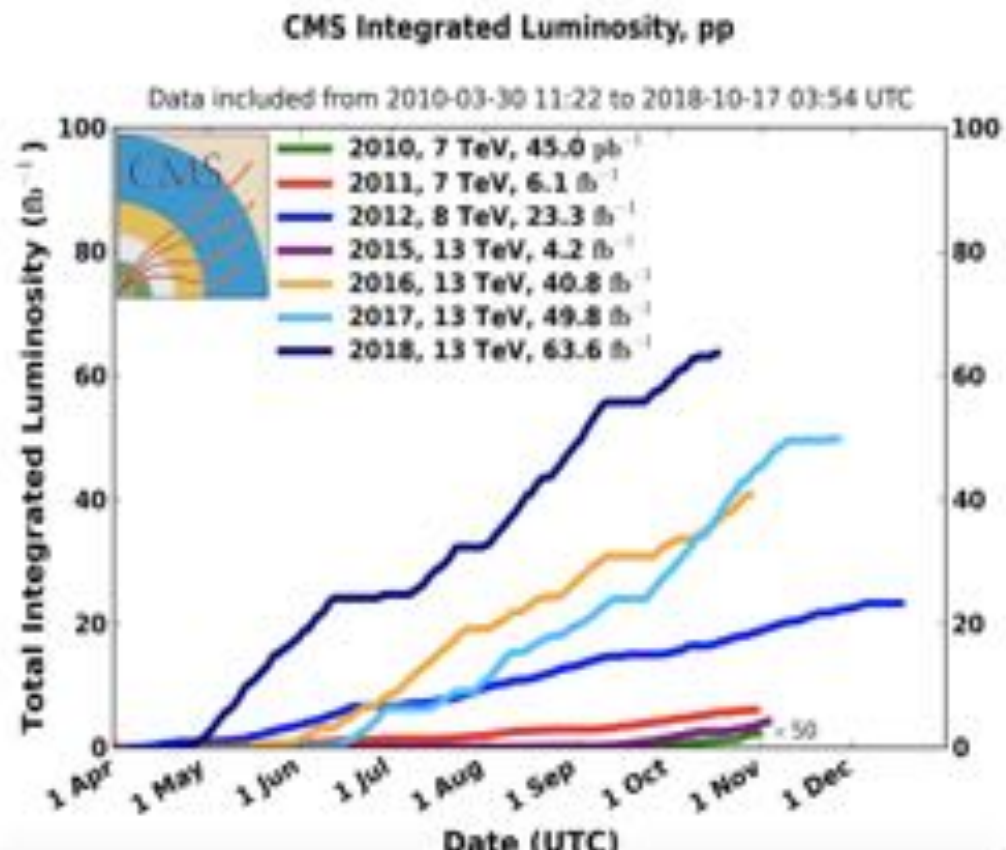
fb^{-1} is a measure of the amount of data collected $=\sim 10^{12}$ proton-proton collisions. Used to translate σ into a total number of events. For the SM Vh with $h \rightarrow bb$ process, $\sigma \sim 1305$ fb → in 100/fb of collected data, we expect a total of 130500 events

So how do we study all these particles?

(Outstanding) LHC performance

$$N_{events} = \sigma \times L$$





Future integrated luminosity goals:

- 300 /fb until 2023
- >3000 /fb at the end or the HL-LHC to start in 2026

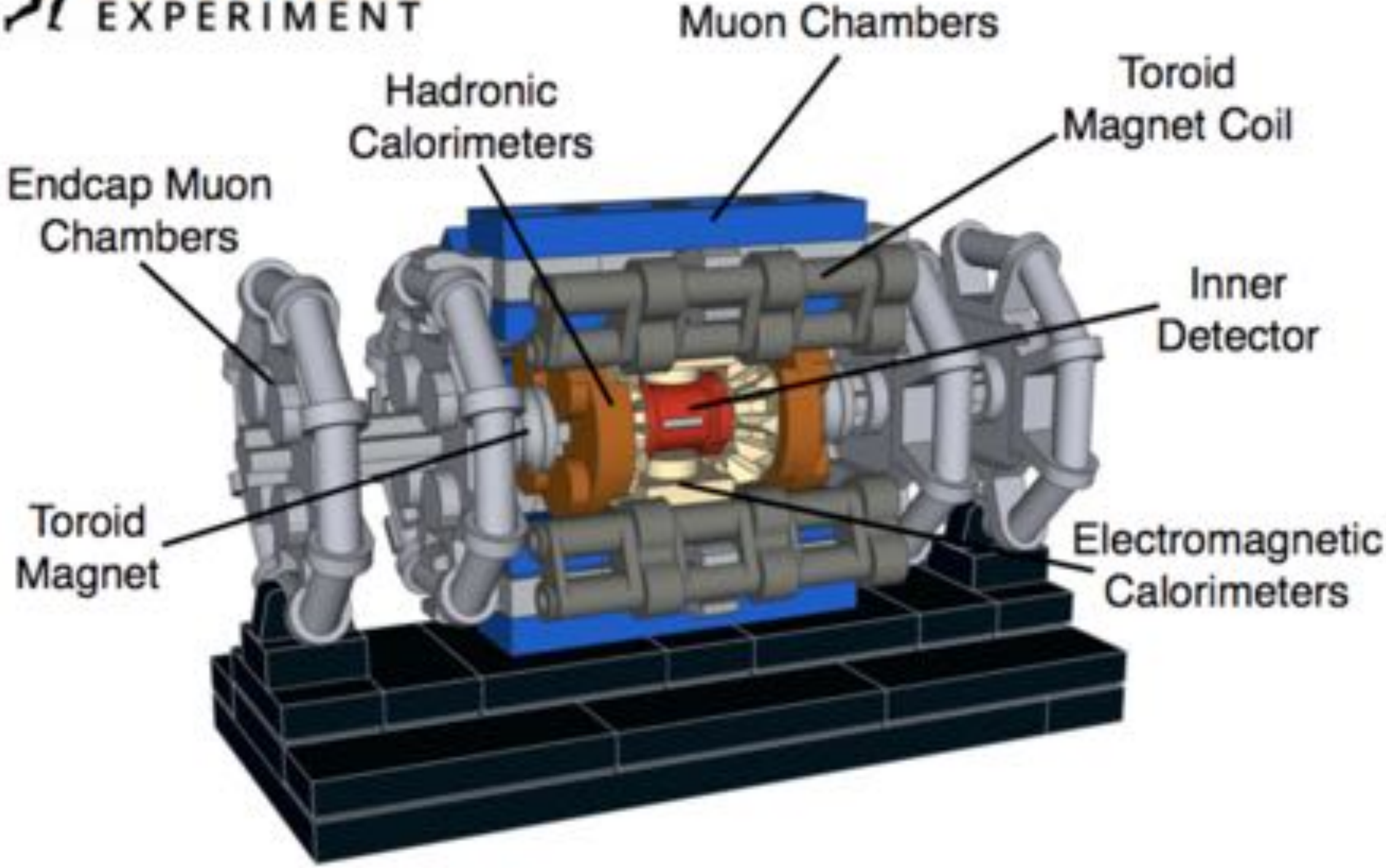
So how do we study all these particles?

The particle detectors

- I know there are more than two but will mainly hear in this section about these two
- Non-specialized detectors: broad range of physics, same concept, different technologies
  - Excellent vertex and tracking systems
  - Large coverage for muon detection
  - Excellent calorimetry with extended coverage

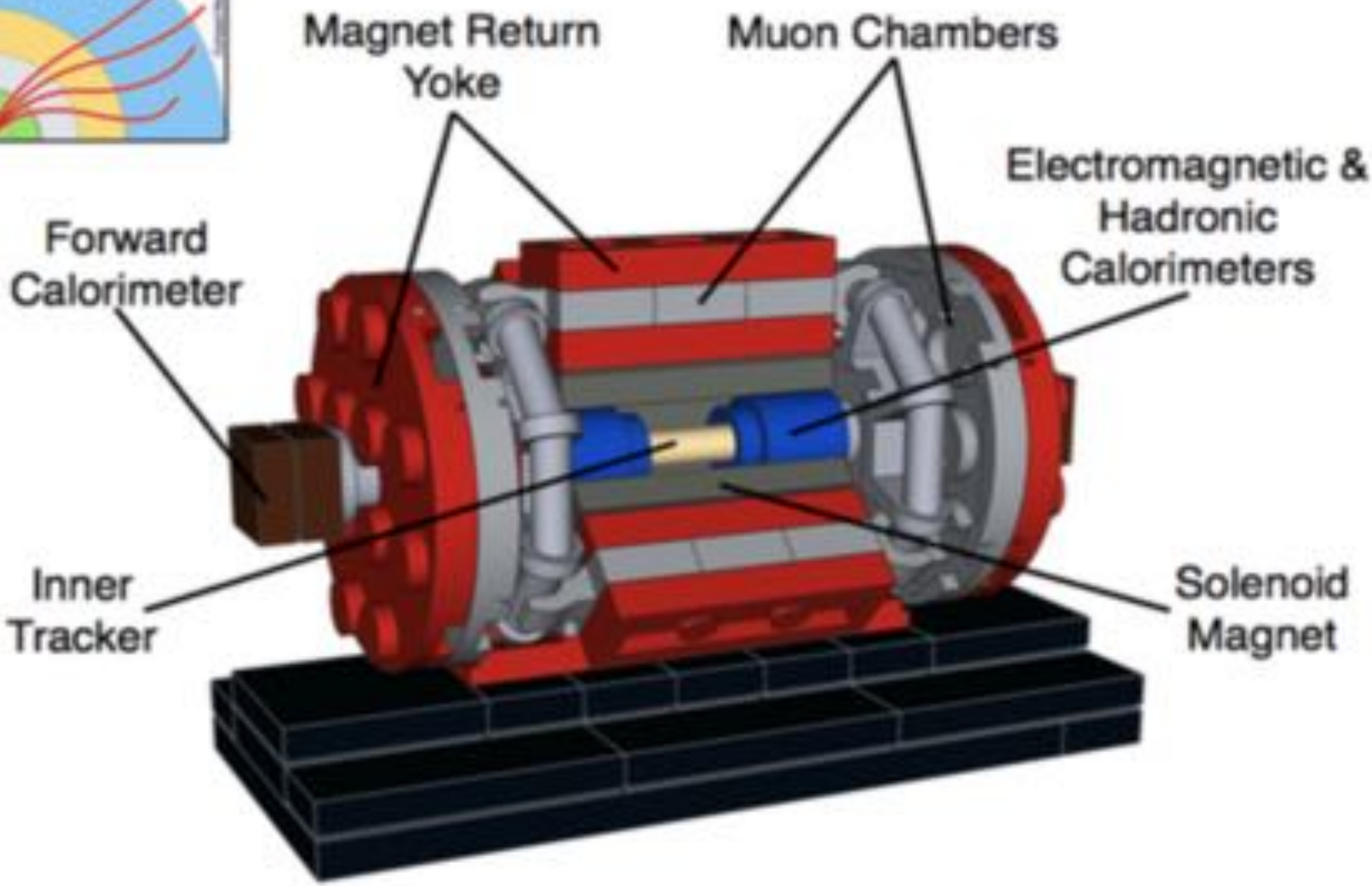
So how do we study all these particles?

The ATLAS detector



So how do we study all these particles?

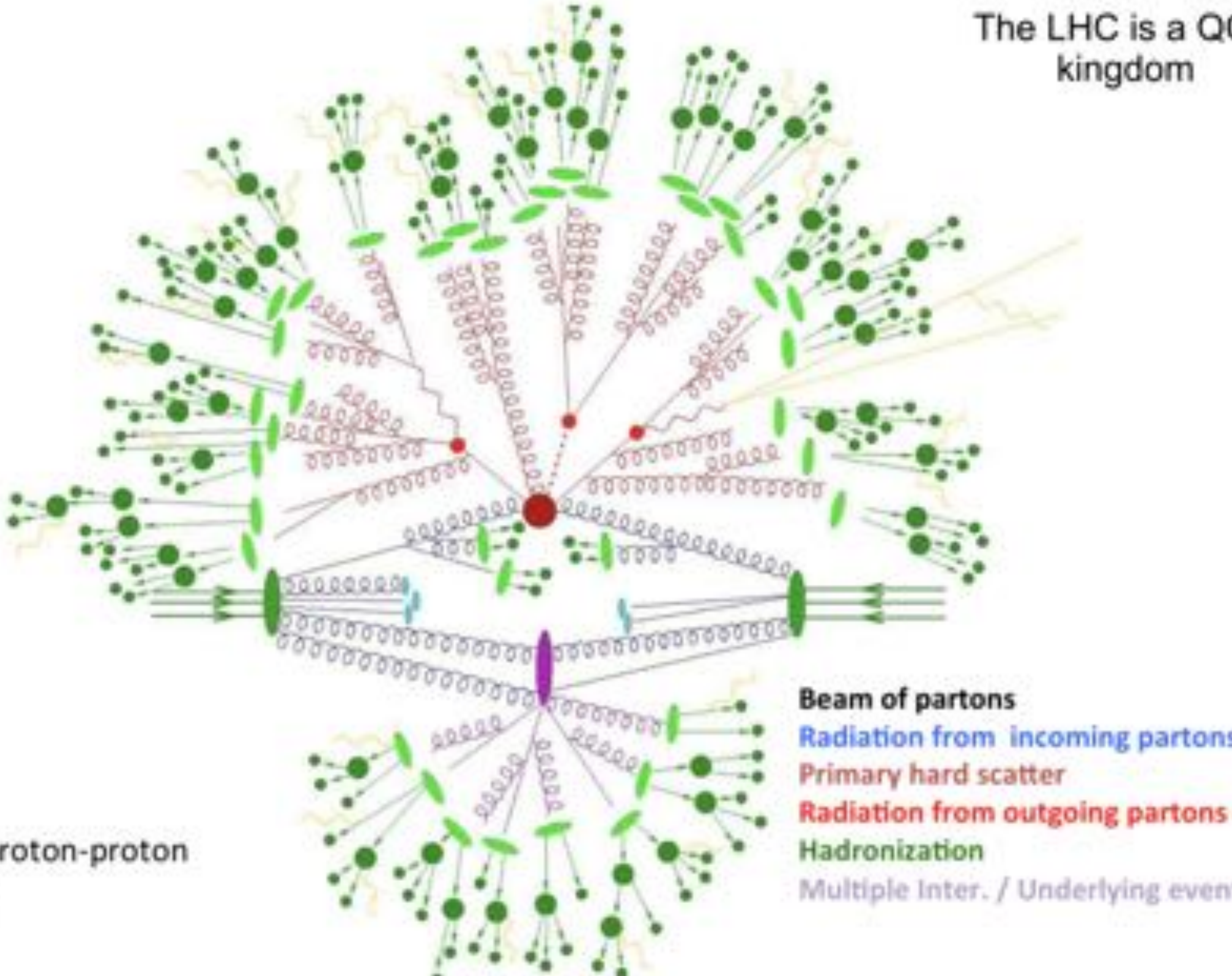
The CMS detector



So how do we study all these particles?

The collisions

The LHC is a QCD kingdom

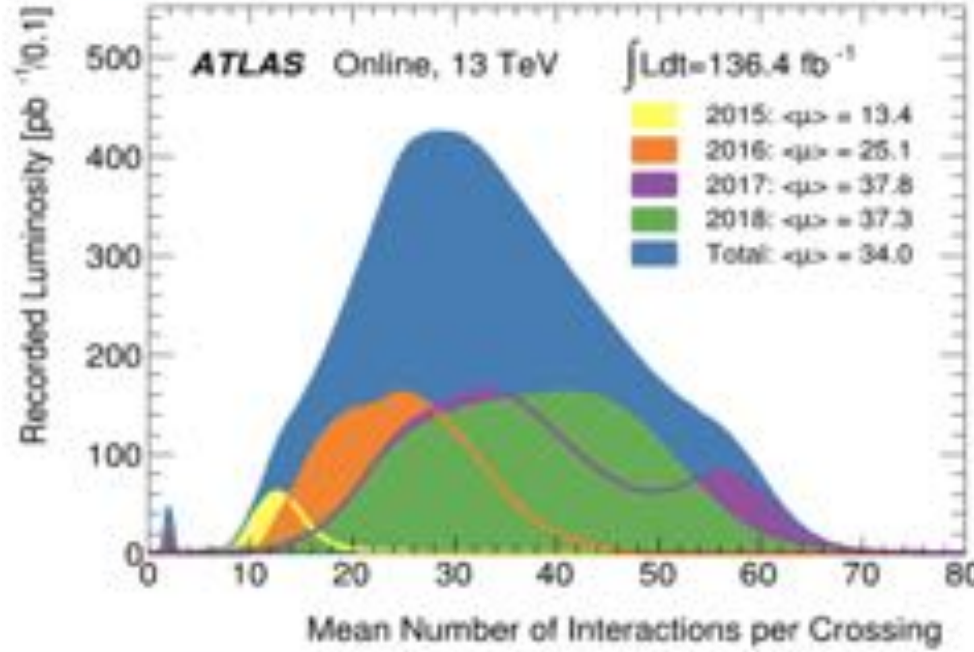


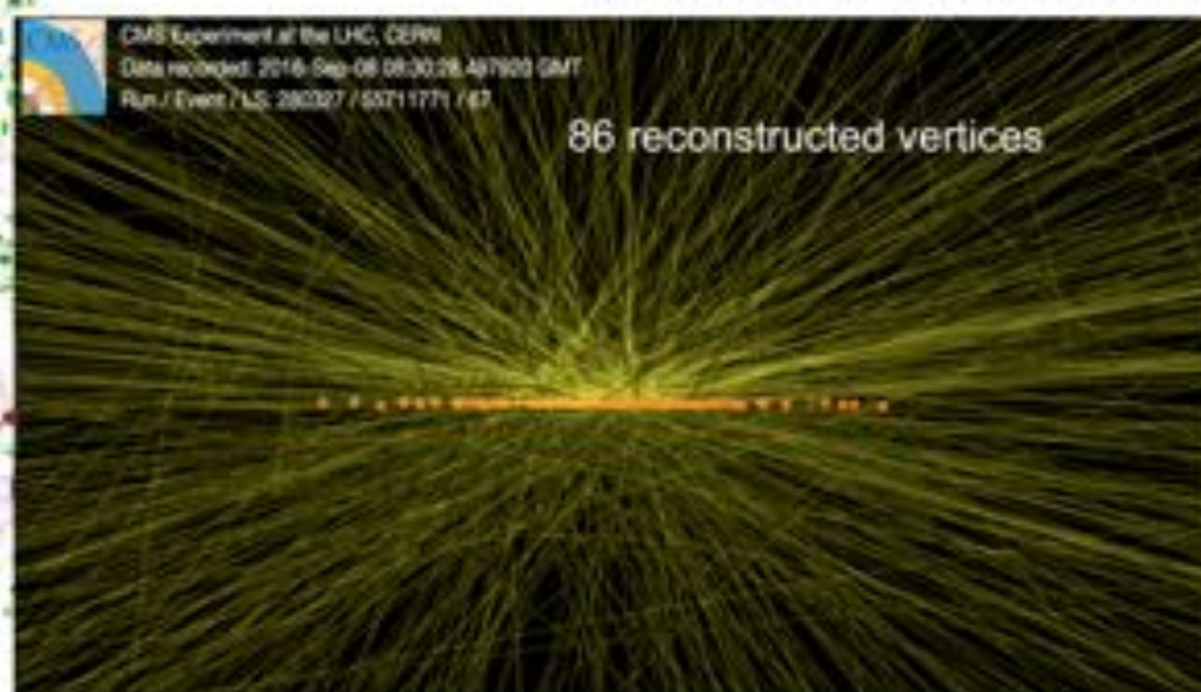
Typical proton-proton collision

So how do we study all these particles?

The collisions

High Lumi
=
high pileup

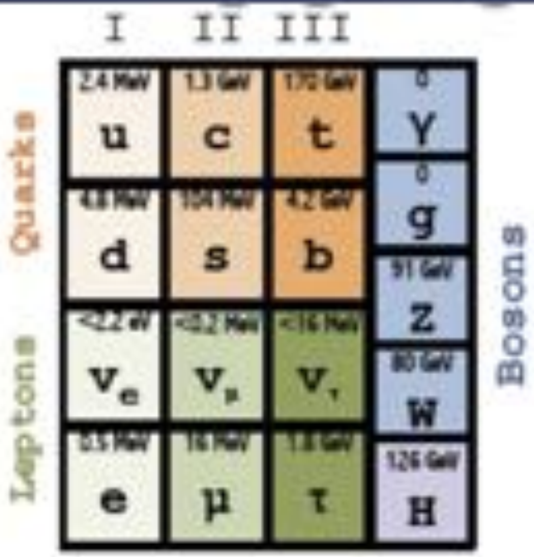


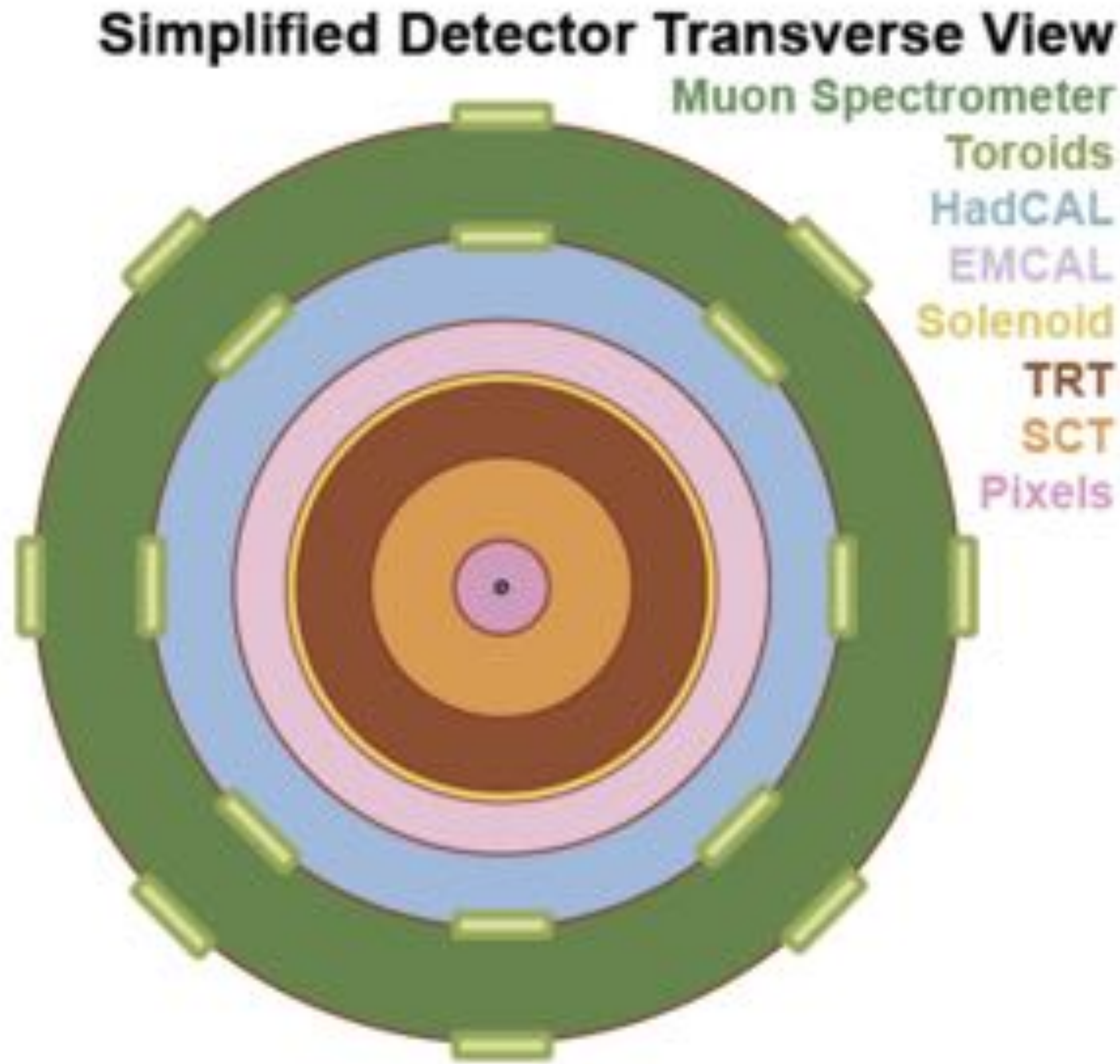


Impressive
detectors

So how do we study all these particles?

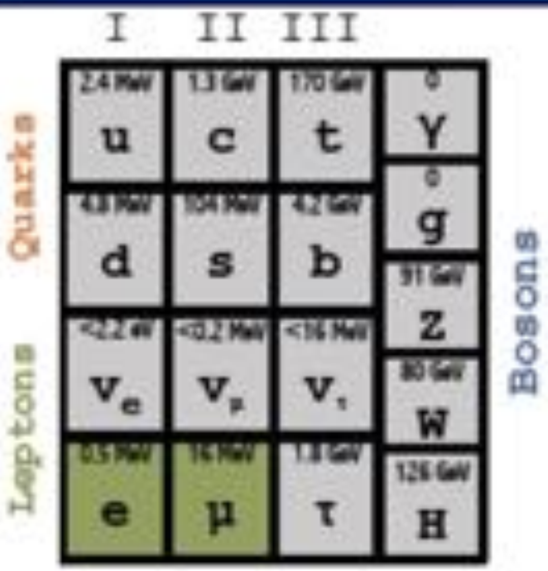
How do we detect the particles?

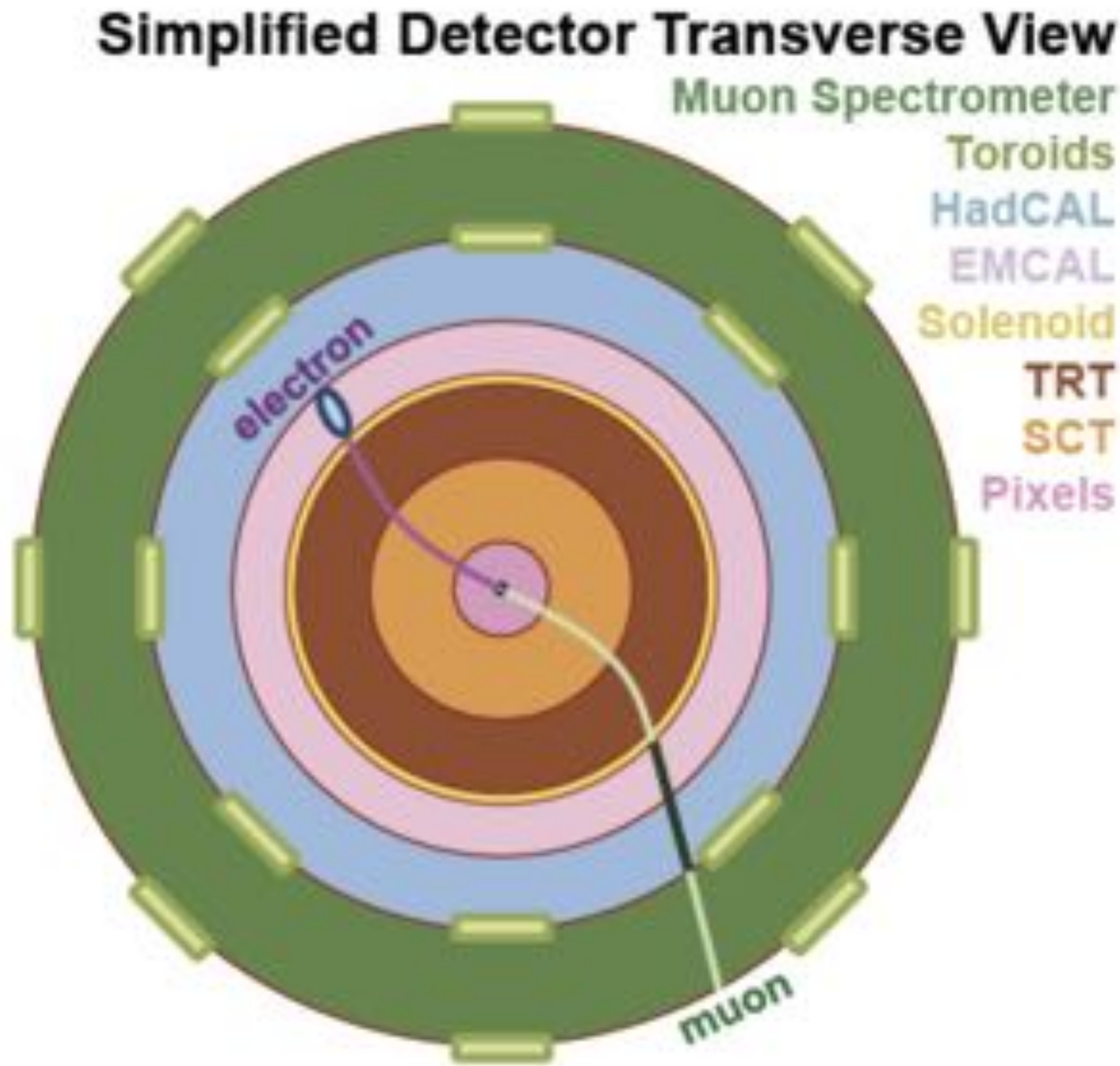




So how do we study all these particles?

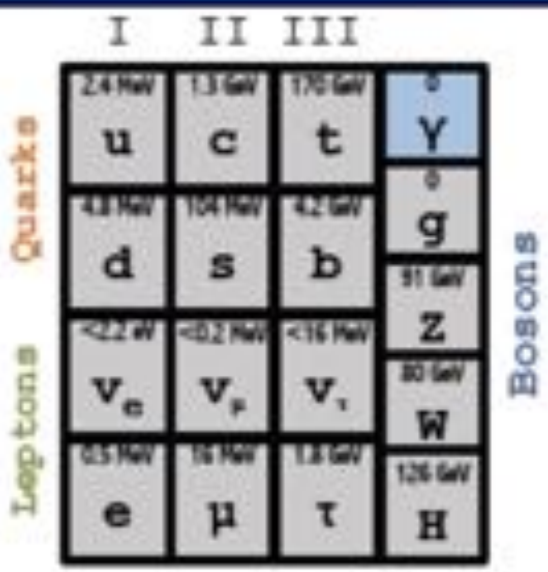
How do we detect the particles?

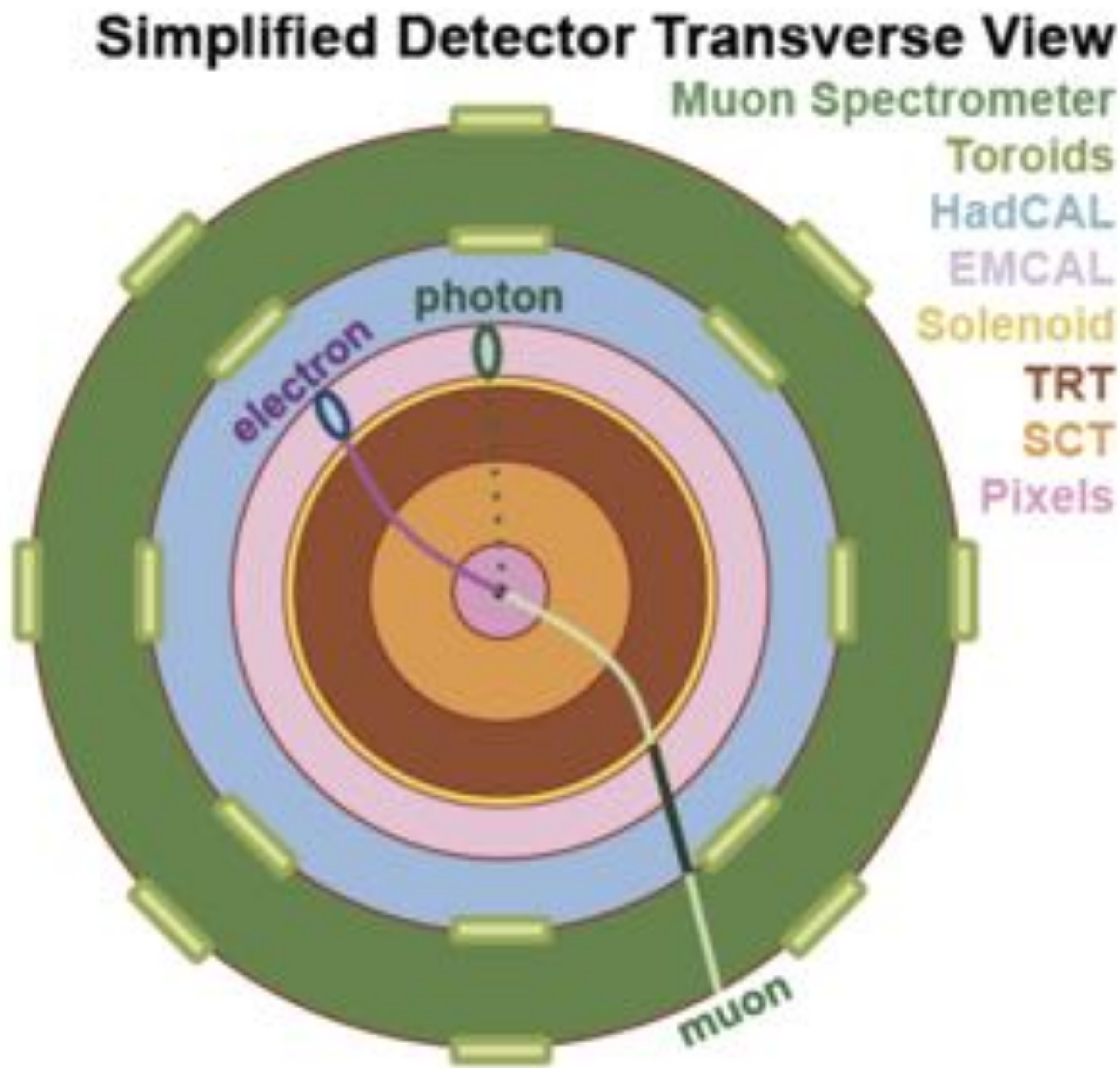




So how do we study all these particles?

How do we detect the particles?





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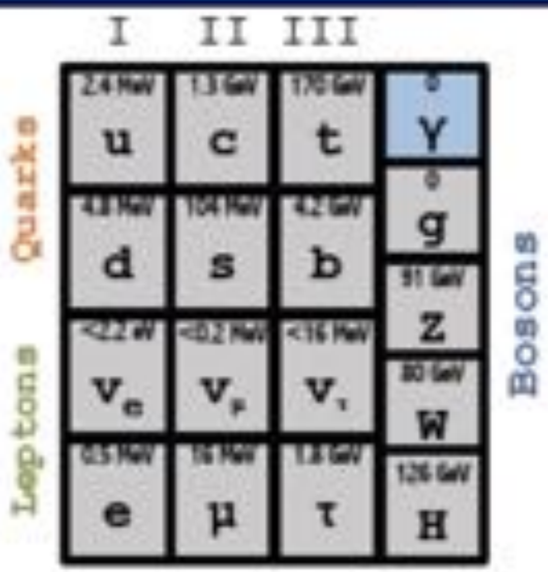
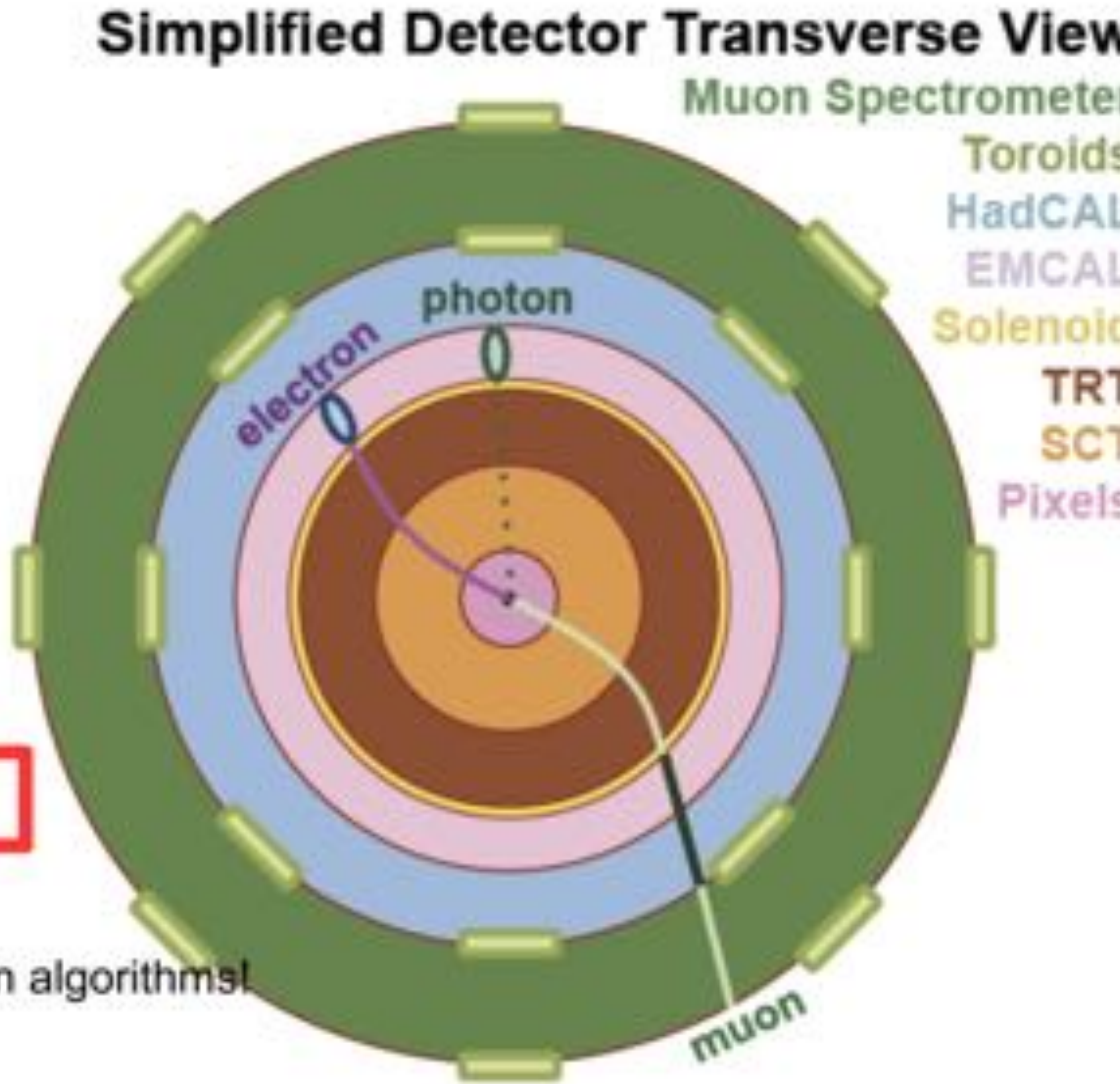




See Hicham A. and Mykola K.'s talks

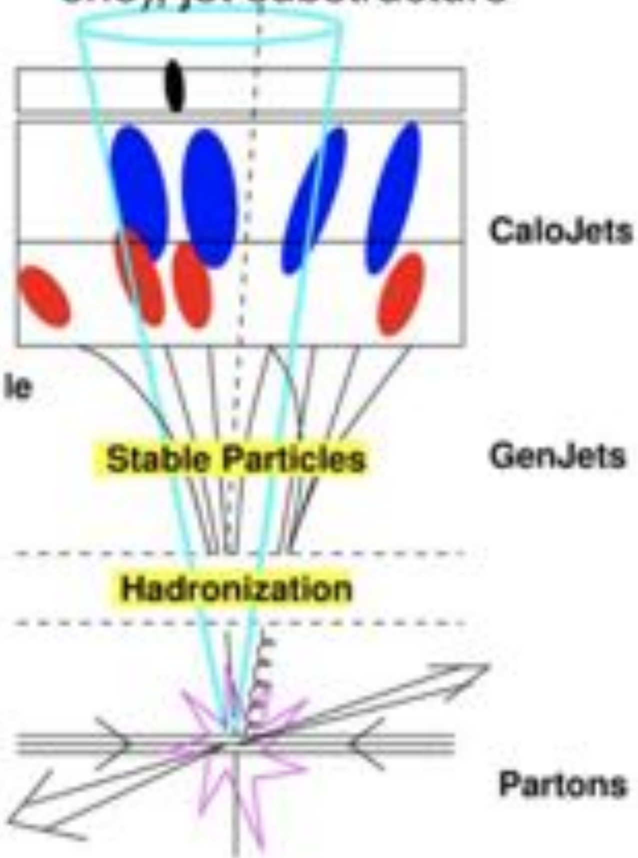
From the experimental point of view

- Dedicated reconstruction/identification algorithms!
- Calibrating them is essential

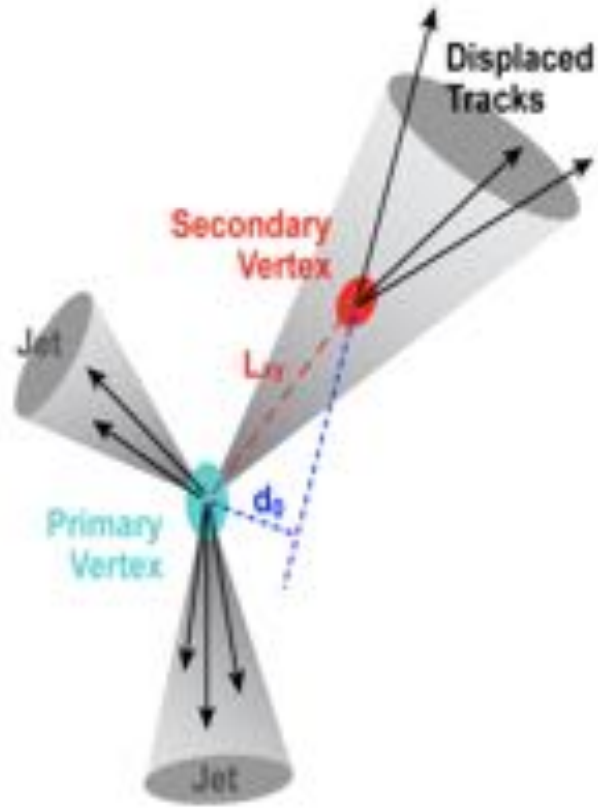
Important to model all these well in simulation

So how do we study all these particles?
Some of them are harder to identify/measure

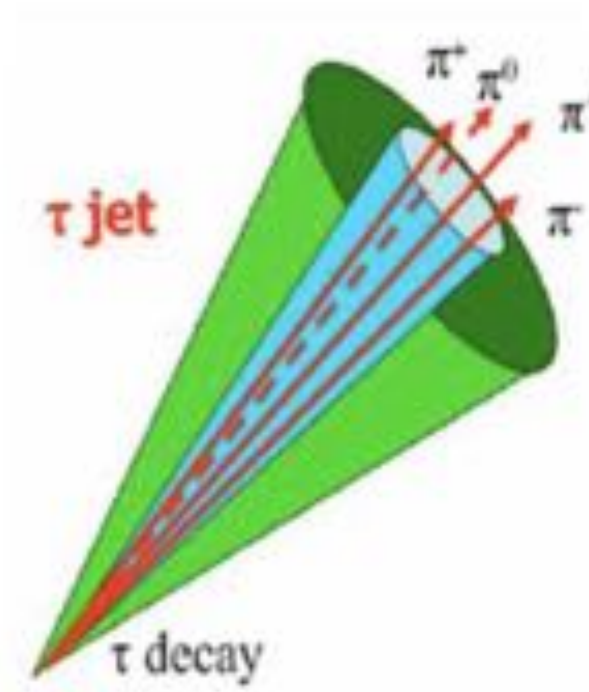
We do not detect **quarks and gluons but jets:** different jet algorithms (anti-kT is the common one), jet substructure



Jets from b-quarks: b-hadrons fly before decaying this allow us to define advanced identification algorithms

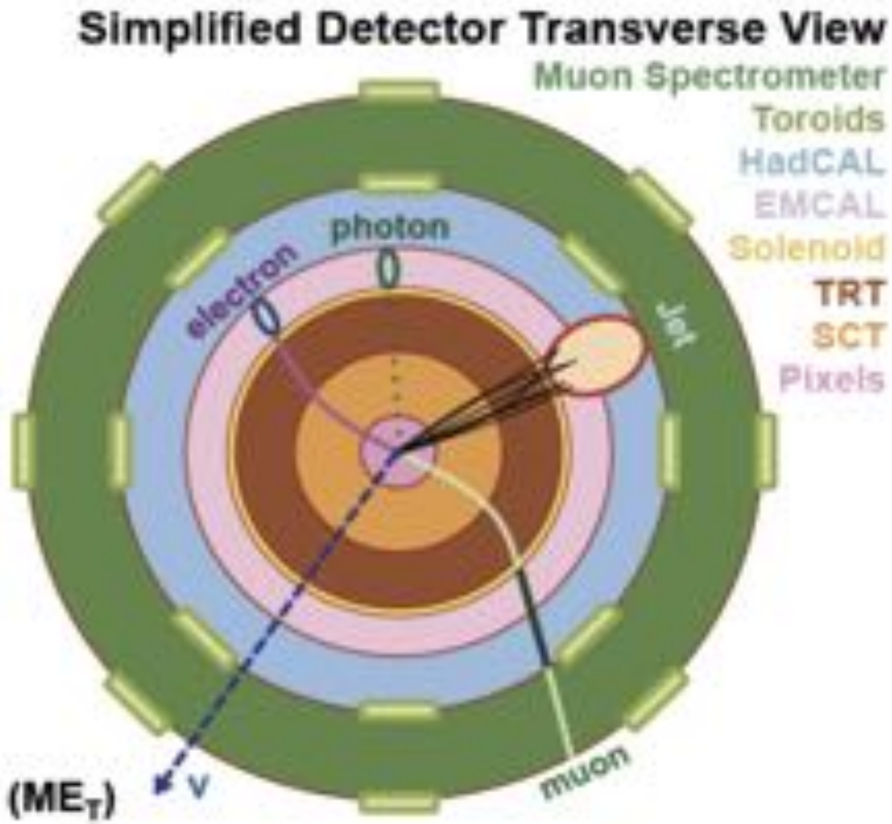


Tau leptons decay to hadrons and form jets: usually narrower jets with less tracks



So how do we study all these particles?

How do we detect the particles?



In the transverse plane:

$$\sum \vec{p}_T = 0$$

Missing Transverse Momentum (ME_T)

In reality things are much more complicated, but in a simple manner, and for each event

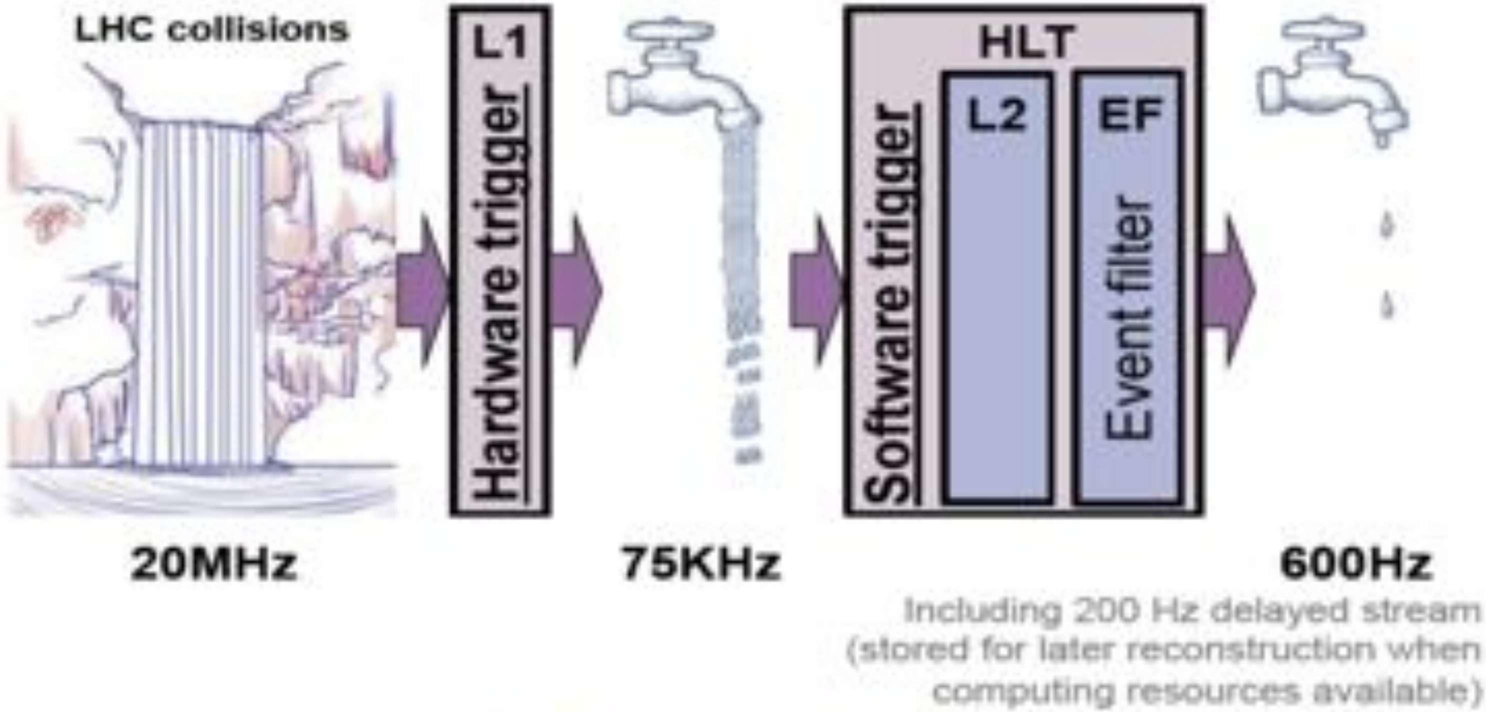
- $E_T^{miss} = -(E_T^{electrons} + E_T^{photons} + E_T^{muons} + E_T^{jets} + E_T^{soft\ energy\ not\ related\ to\ an\ object})$

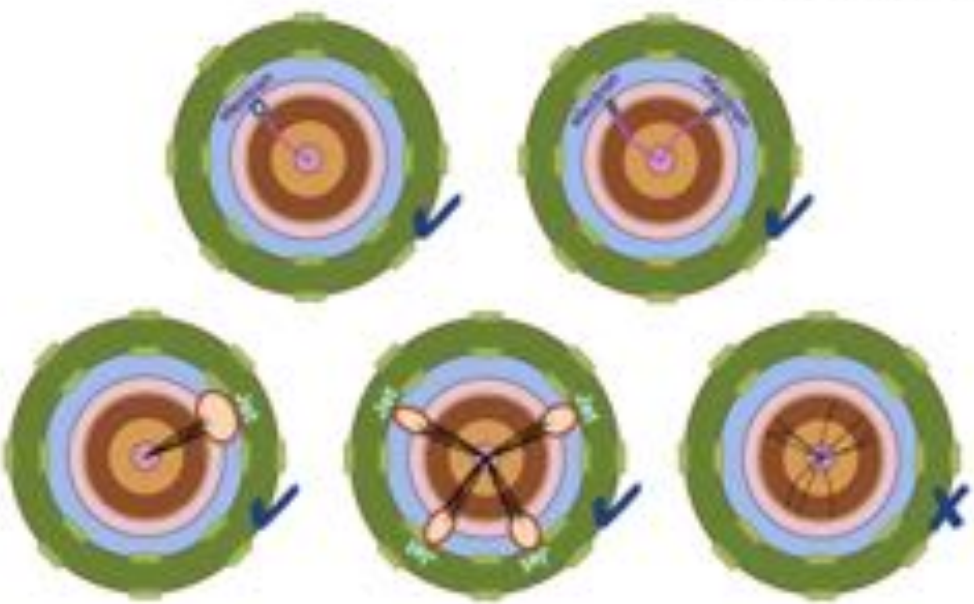
- *Don't get fooled next time you hear "missing energy". It is actually all the visible (non-missed) energy with a "-" sign in front..* 😊

· *Slide shamelessly stolen from Dimitris Varouchas's JRJC 2017 talk*

So how do we study all these particles?

Trigger





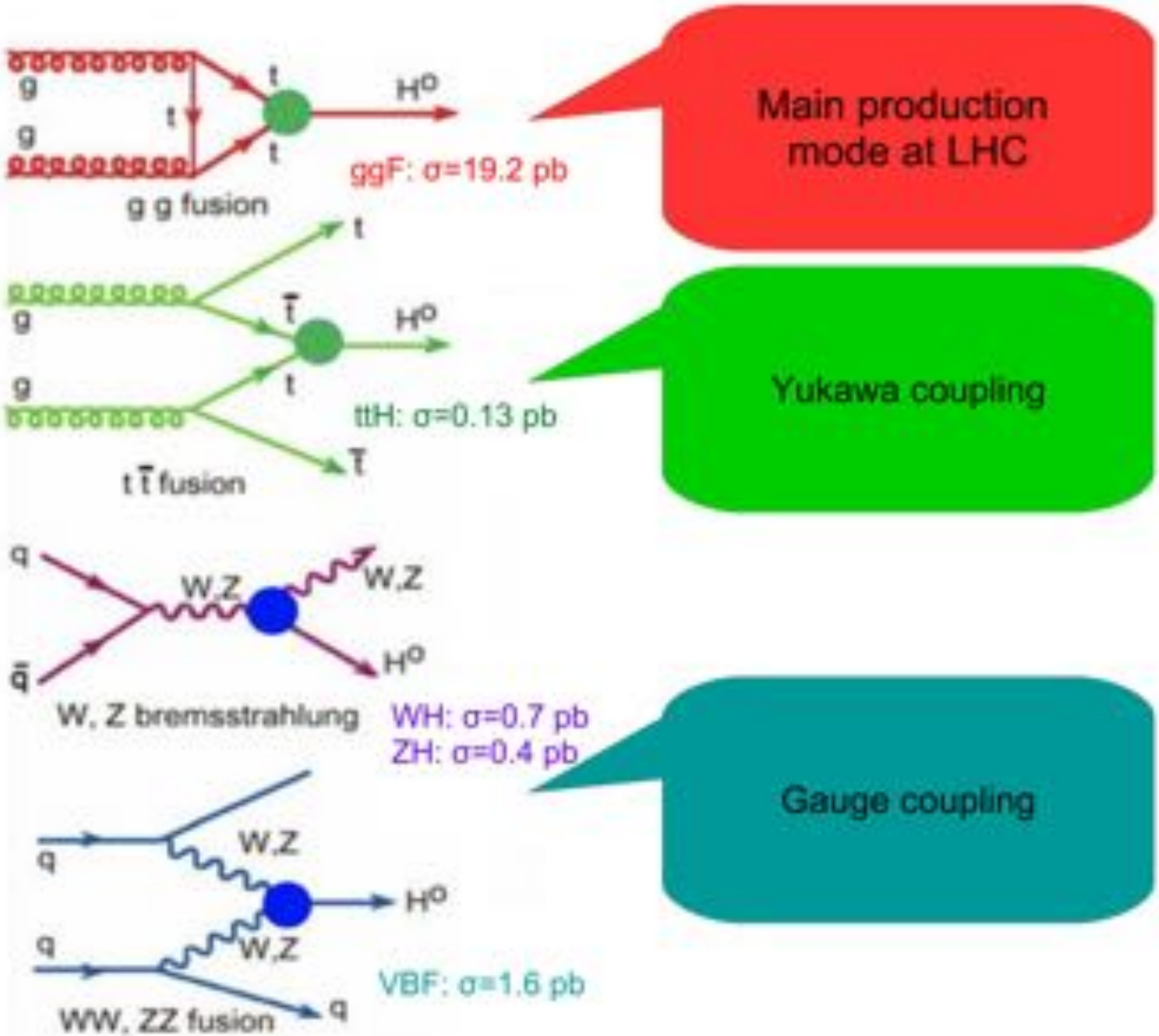
We trigger on the physics!

See Giovanni B. and Cristina M.'s talks

A Higgs boson was discovered in 2012

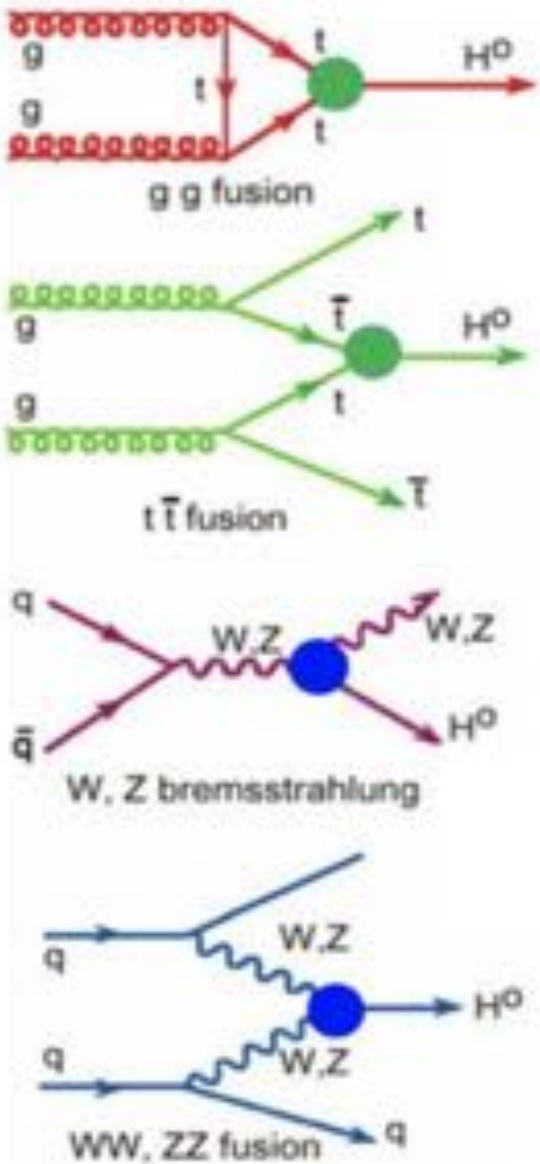
Higgs is a hot topic in this session

Higgs production

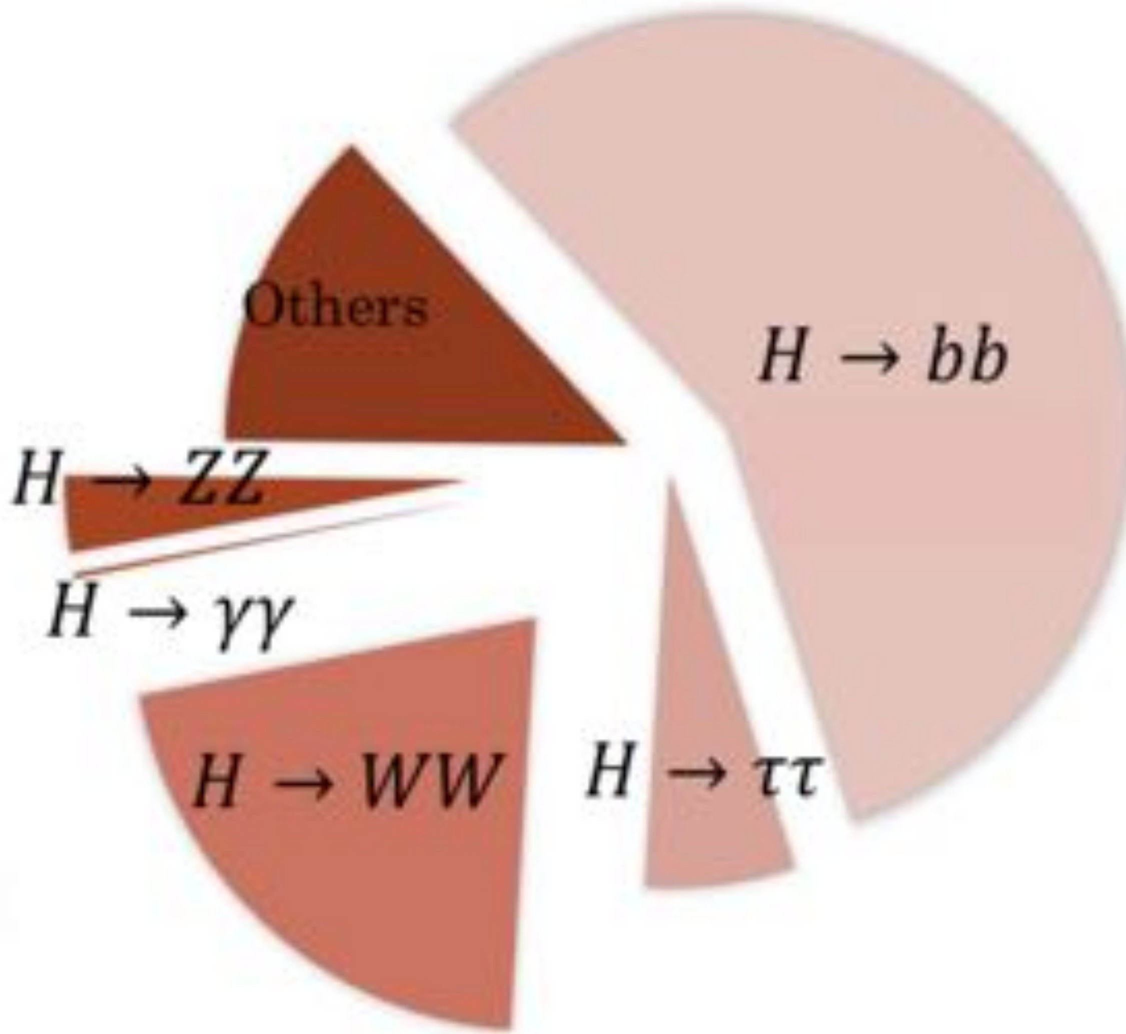


Higgs is a hot topic in this session

Higgs production and decay



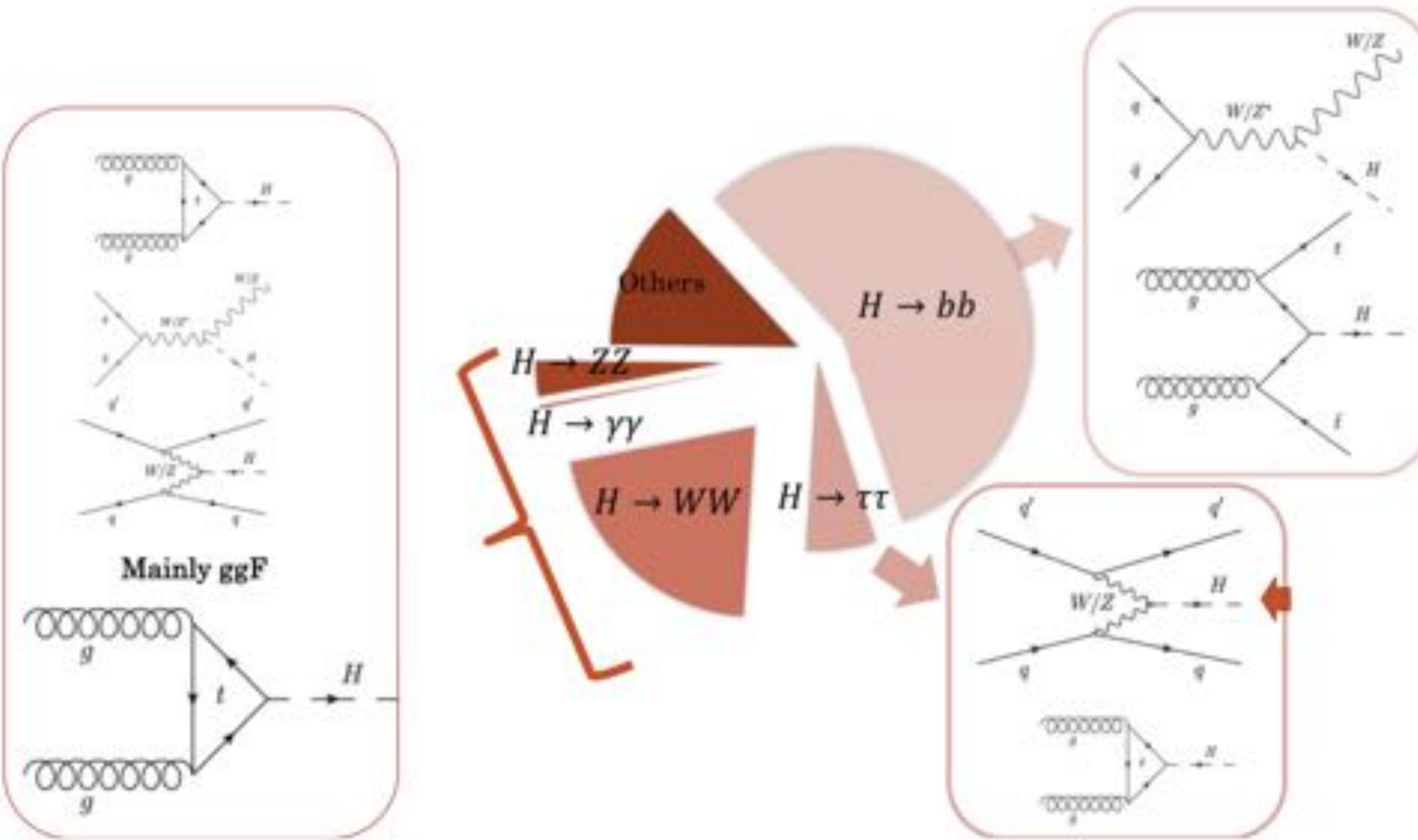
Which production mode or/and decay is the best?



There is an interplay between production and decay based on the backgrounds

Higgs is a hot topic in this session

Higgs production and decay



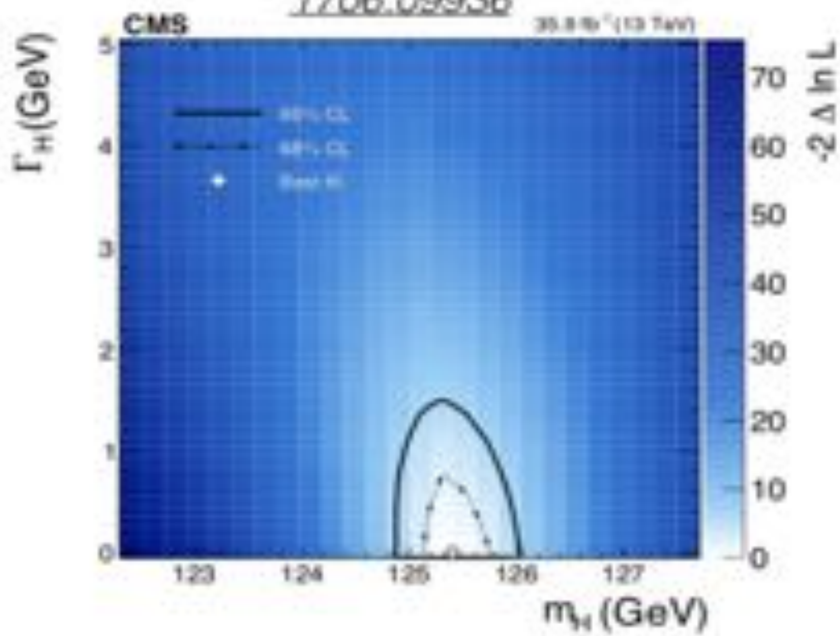
- *Slide shamelessly stolen from George Aad's JRJC 2014 talk*

Higgs is a hot topic in this session

Higgs production and decay

ZZ, WW and γγ were the first ones to be observed!
Now we are doing precision measurements with them

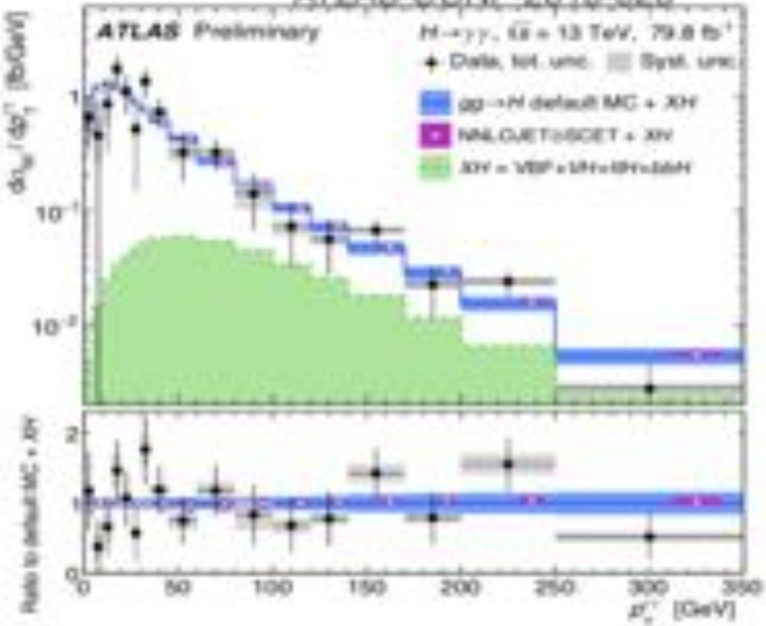
1706.09936

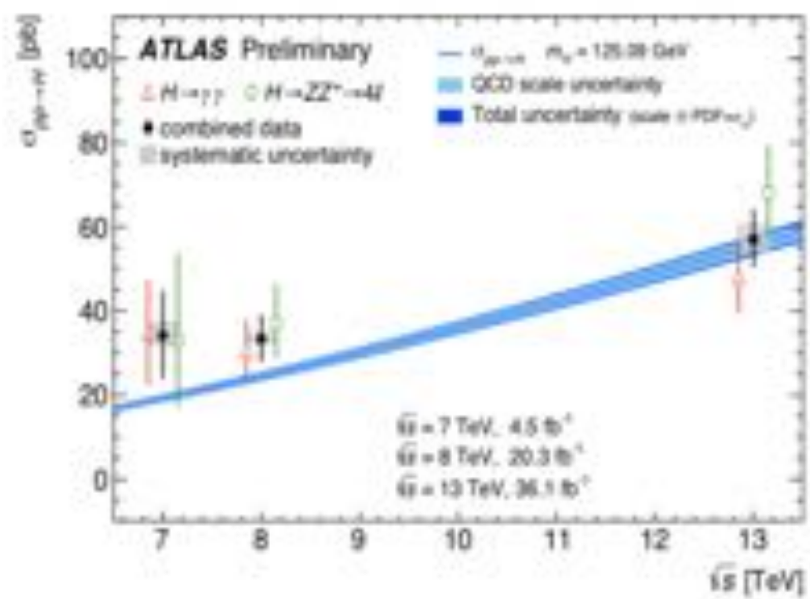


CMS 4l channel
event-by event resolution
+S/B discriminant
(3D fit)

125.26 ± 0.21 GeV
Γ_H<1.1 GeV (95%CL)

ATLAS-CONF-2018-028

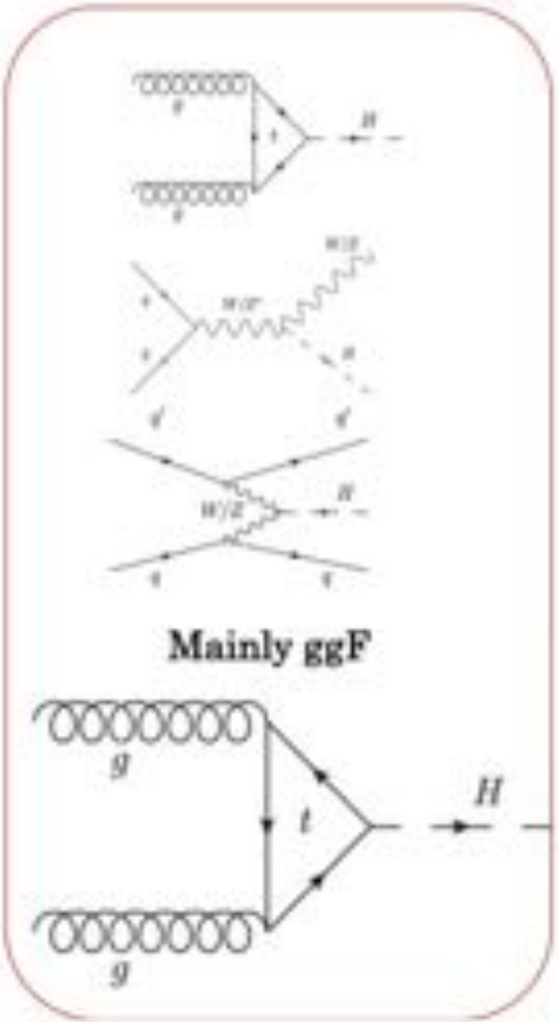


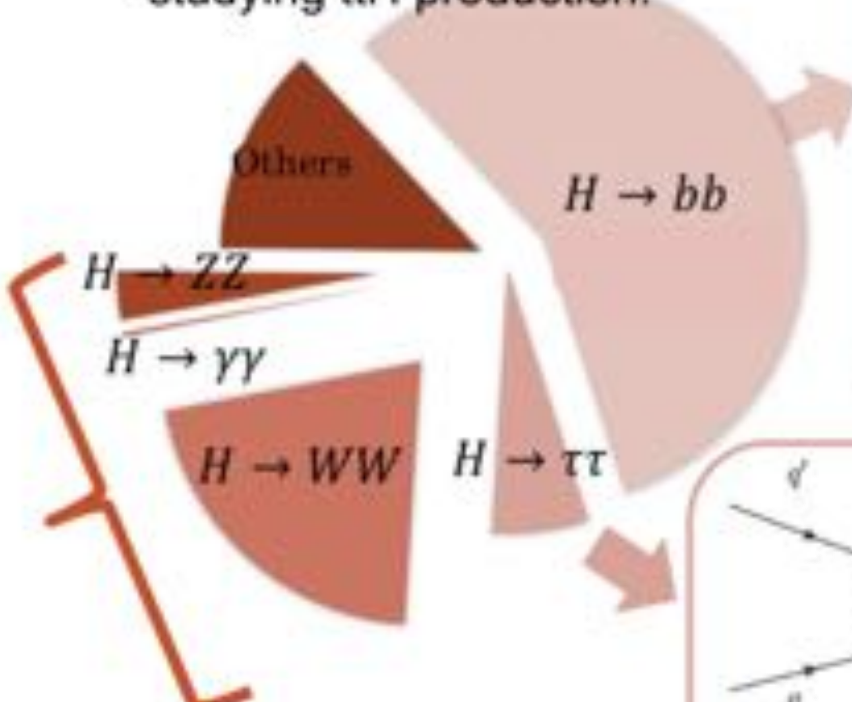


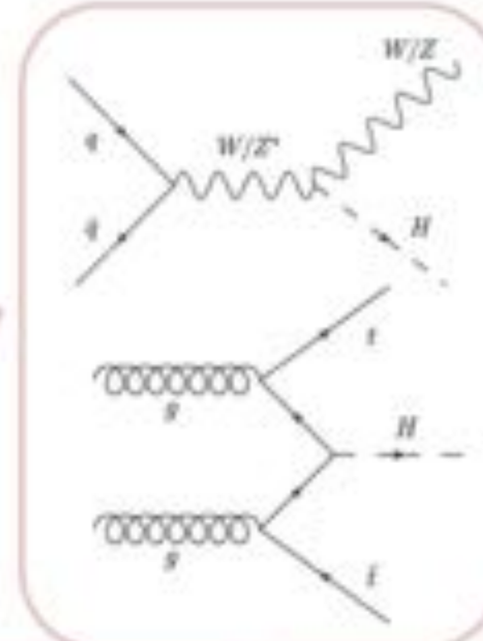
Higgs is a hot topic in this session

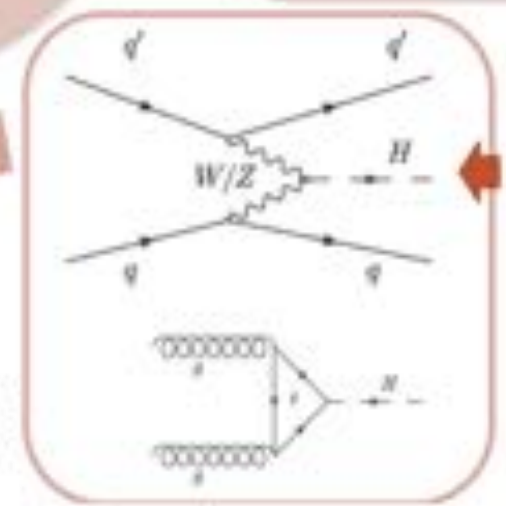
Higgs production and decay

Decays to b-quarks observed this summer in VH production! We will hear more about how to improve the uncertainties in Konie's talk!
And we also have Giovanni, a brave studying ttH production!









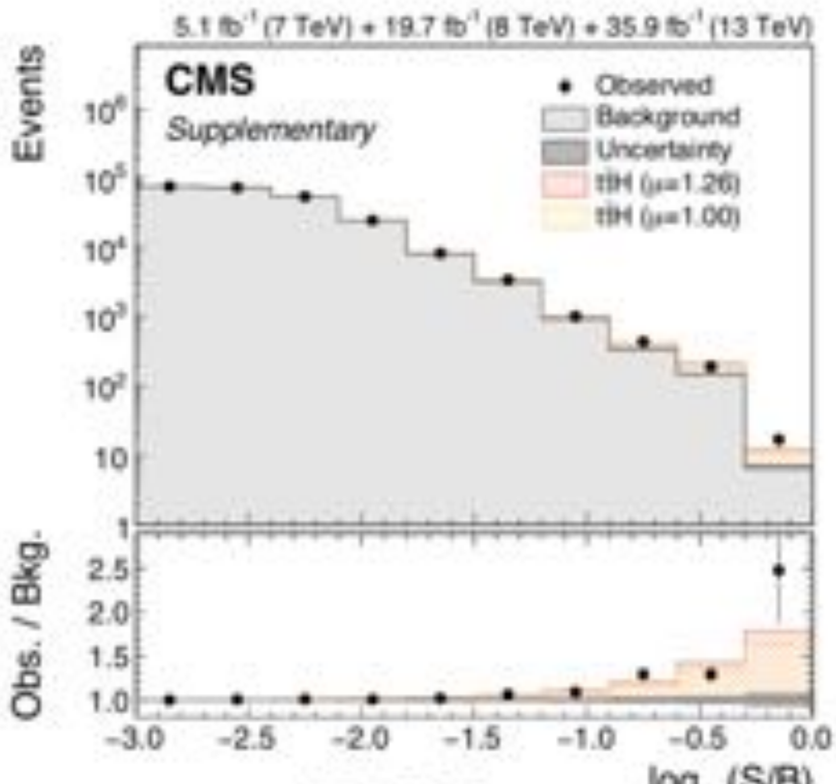
Tau decays observed by each experiment independently using 2016 data. See Cristina's talk to know more about ttH ($H \to \tau\tau$)!

ttH observation

Combine different decay modes assuming SM for the decay BR
Combine also with run 1 data (lower sensitivity, 20 (5) fb^{-1} @ 8(7) TeV)

Expected significance 4.2 (CMS), 5.1 (ATLAS)
Observed significance 5.2 (CMS), 6.3 (ATLAS)
(note that ATLAS uses 2017 data for ttH,H->gamma gamma and 4l)

Giovanni B. for ttH(bb)
Merve N. for ttH(WW,ZZ,ττ)
Cristina M for ttH(ττ)



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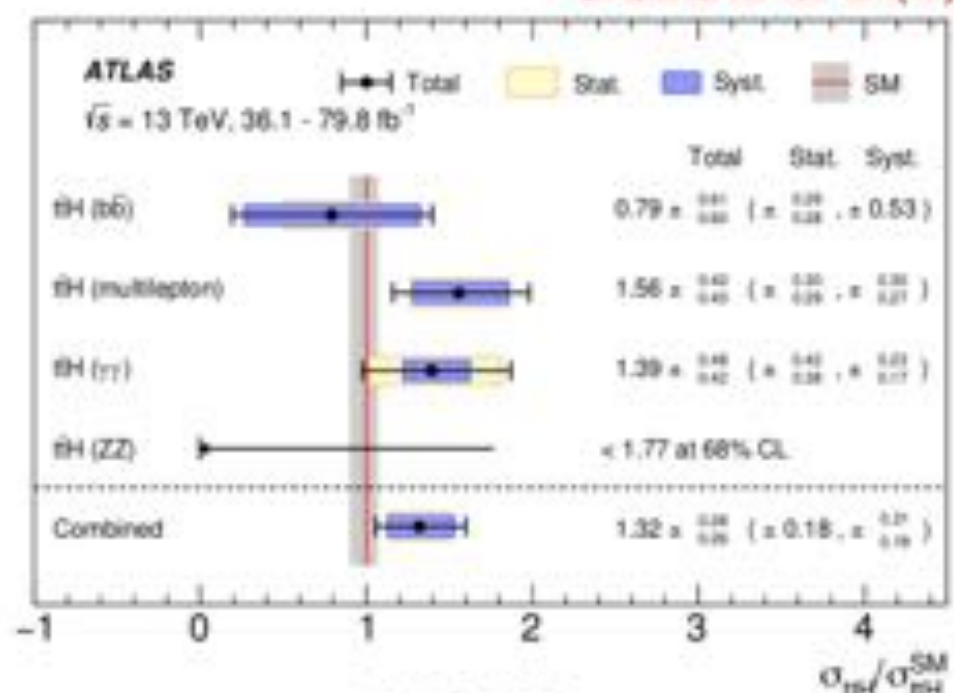

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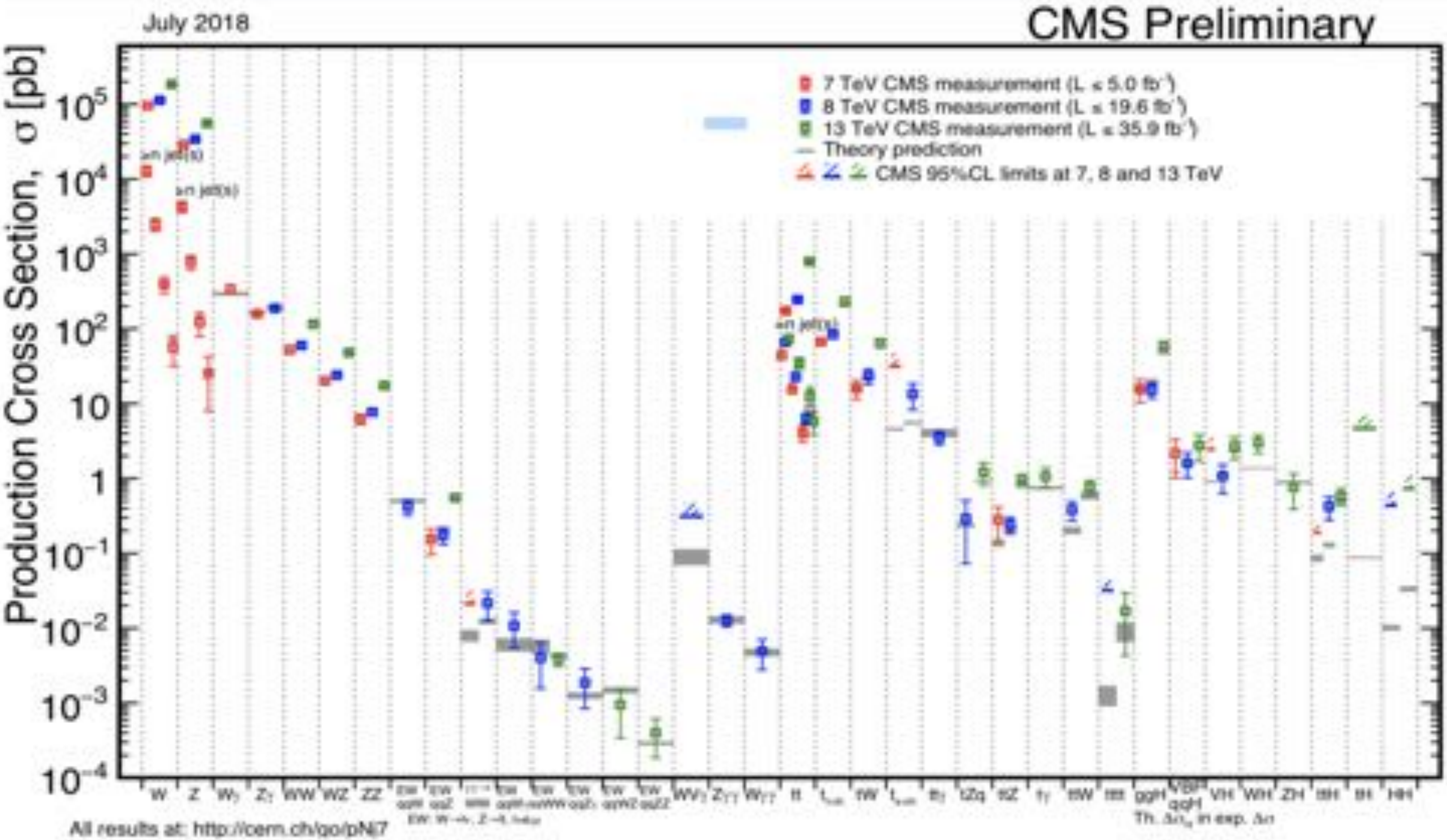
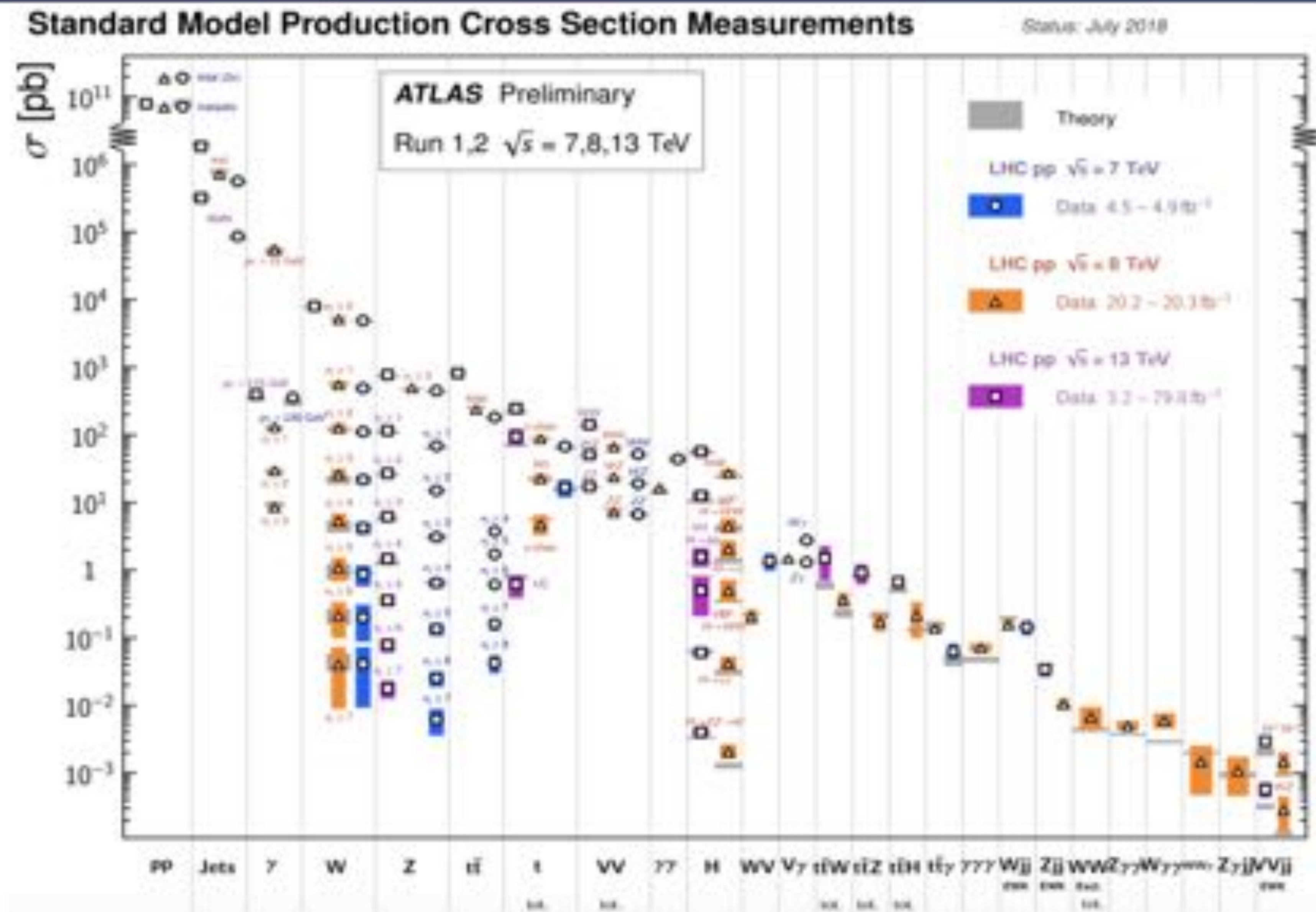
SM: not only Higgs



- Many precision measurements going on on other sectors: top, EWK, etc
- Cross sections, masses, spin, etc
- See Guillaume B. who will talk about the tau spin measurement

SM: not only Higgs



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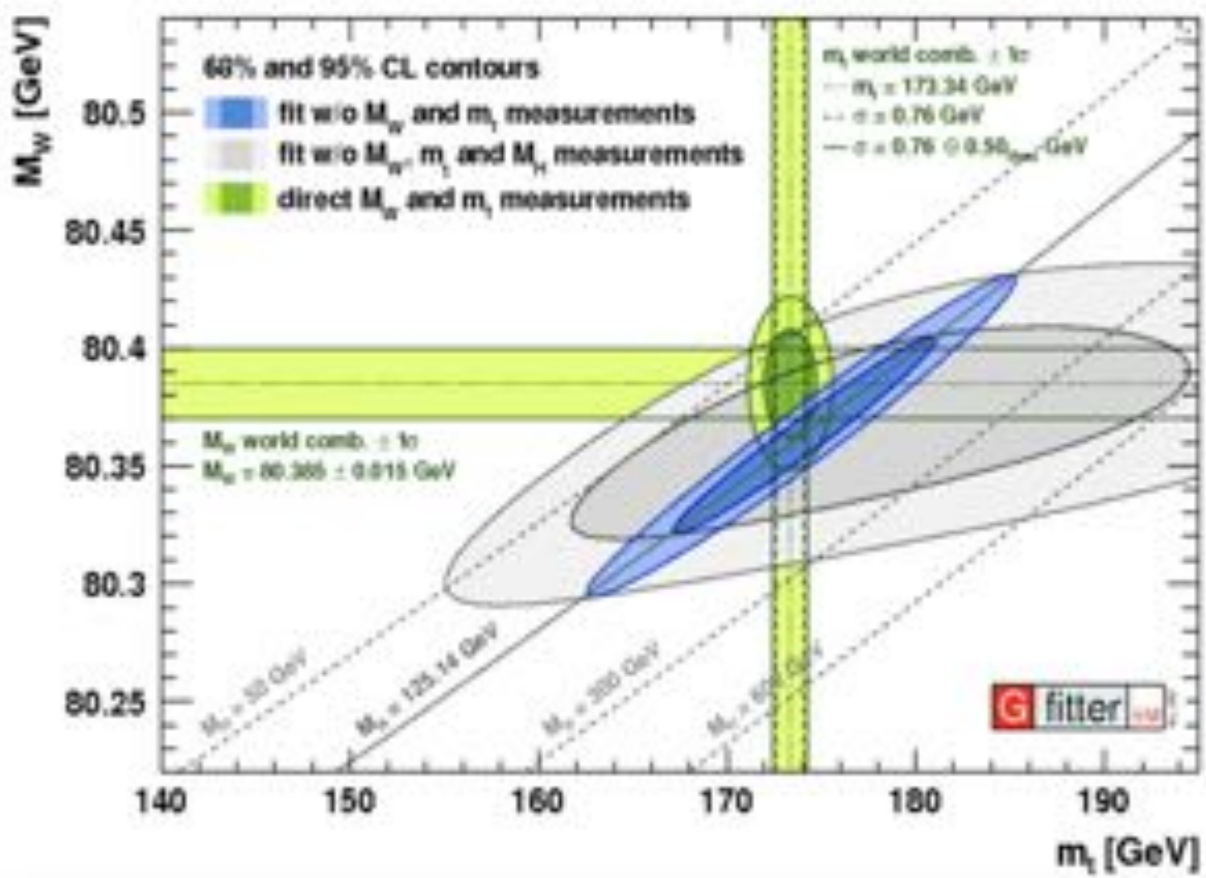
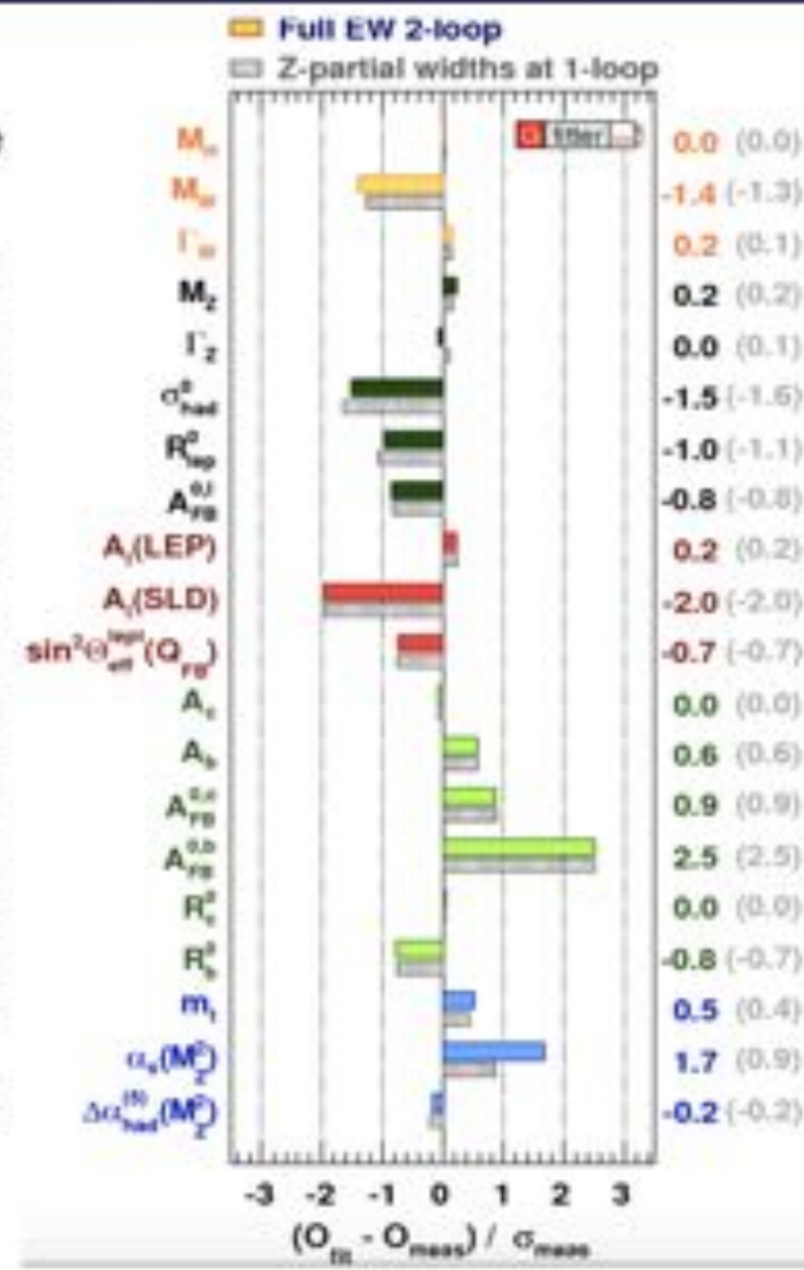
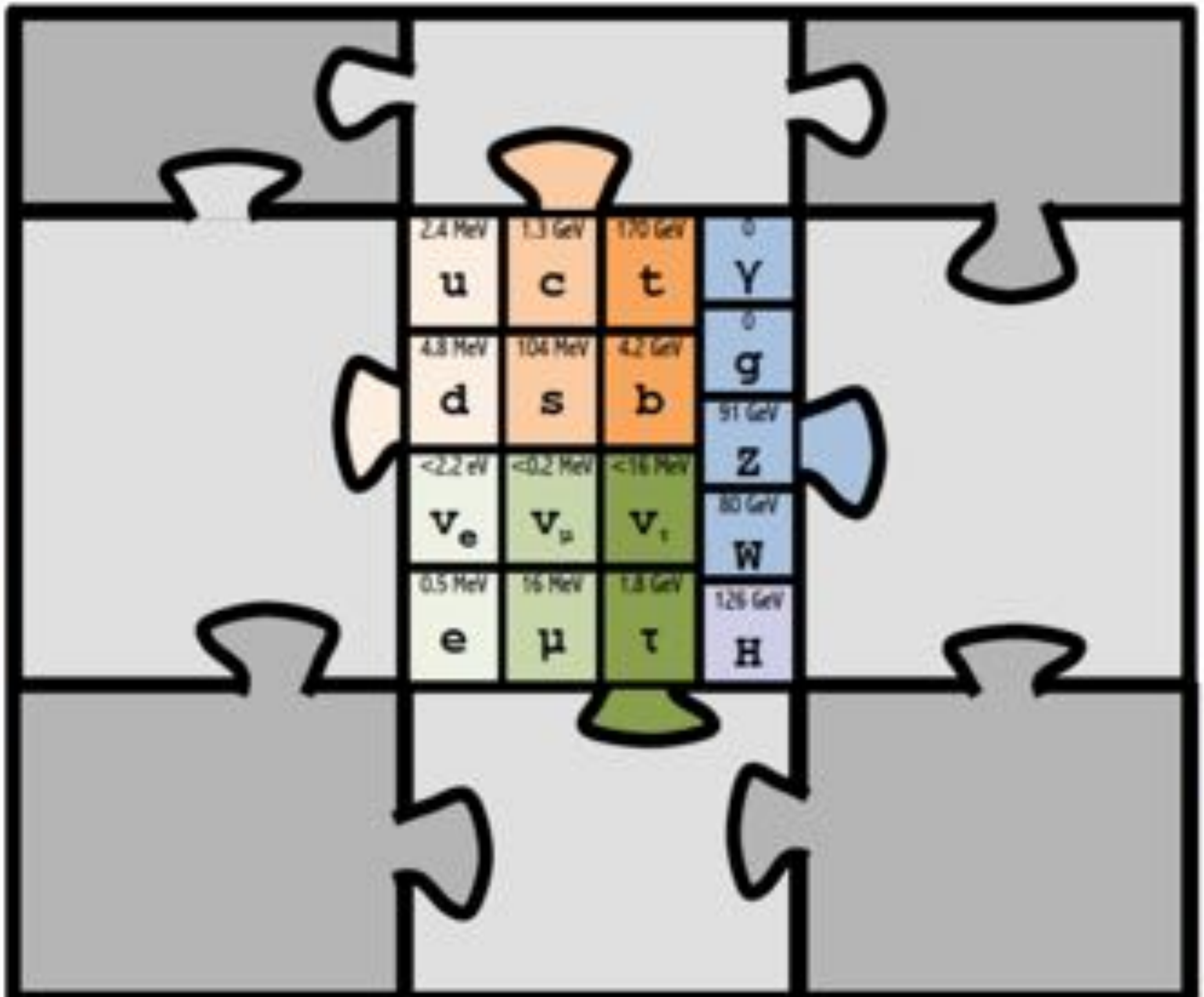
Coherence tests of the SM

- Many SM measurements
- We can test the coherence of the SM combining those





Is there something else beyond the SM?



El Modelo Estándar (MS)

¿Una pieza del rompecabeza del universo?

- Tomorrow morning we will discuss about direct searches of new particles/forces
- The SM is a laboratory itself for indirect searches!

Merci

Gracias

Thanks

Backup

Production modes and decays studied

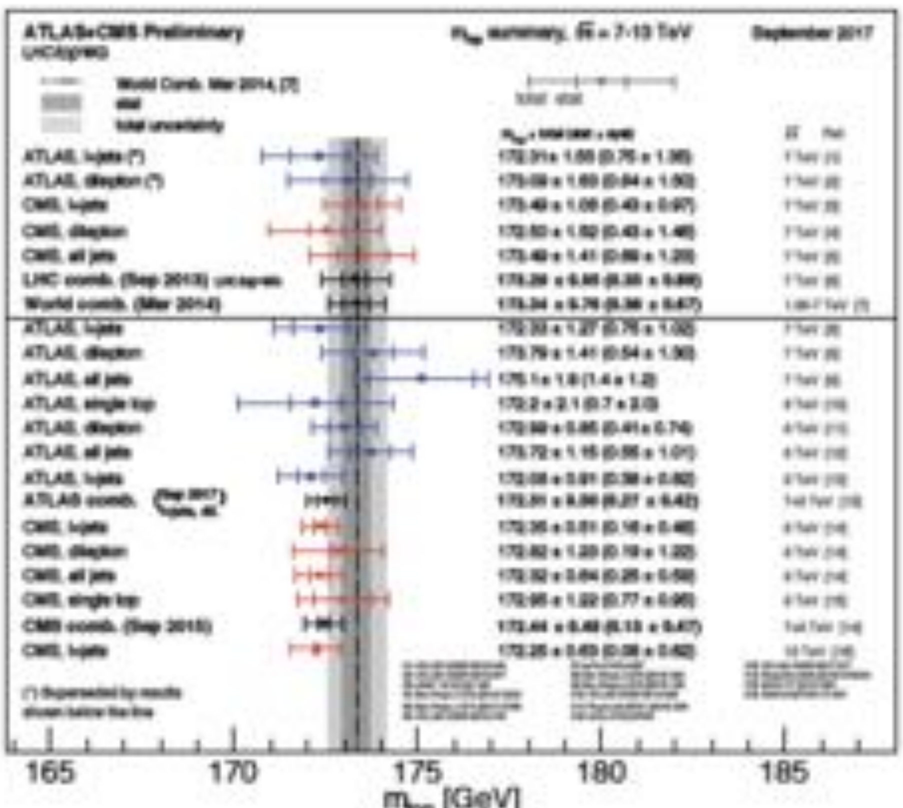
observed (run 2) investigated rare decay	Untagged (ggF mostly)	VBF	VH	ttH
Combination of decays				
H→γγ				
H→ZZ*→4l				
H→WW*→2l2ν				
H→ττ	(Boosted)			
H→bb	(Highly Boosted)			
H→μμ				
H→cc				
H→Zγ				
H->invisible				

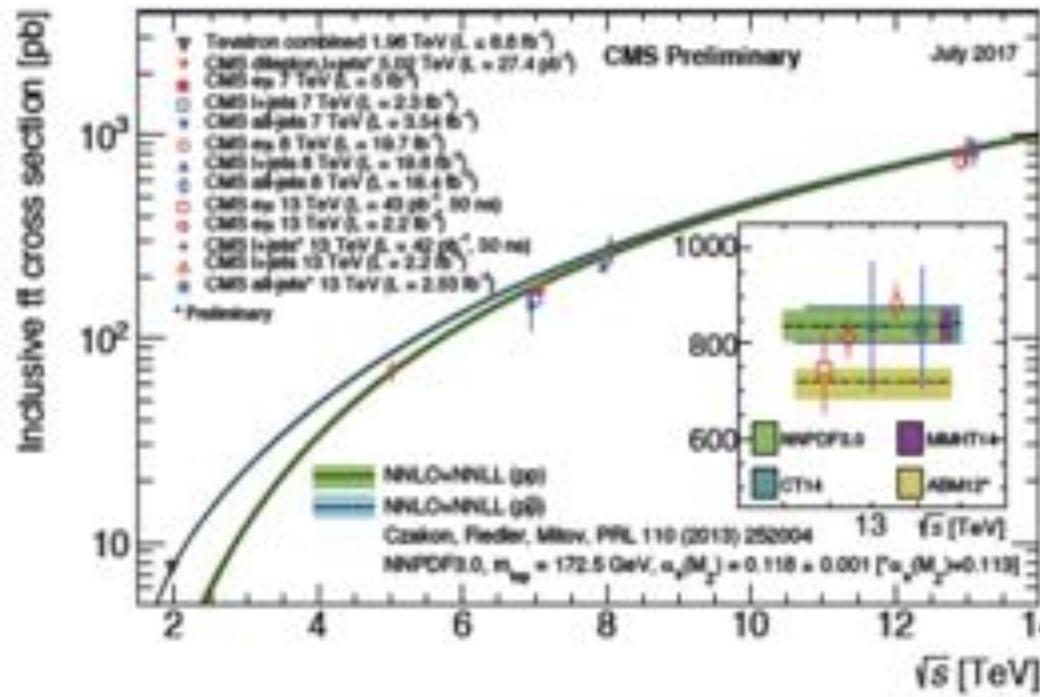
Each decay*Production mode combination involves usually several analysis categories to improve sensitivity

Main backgrounds usually derived or checked with data control regions

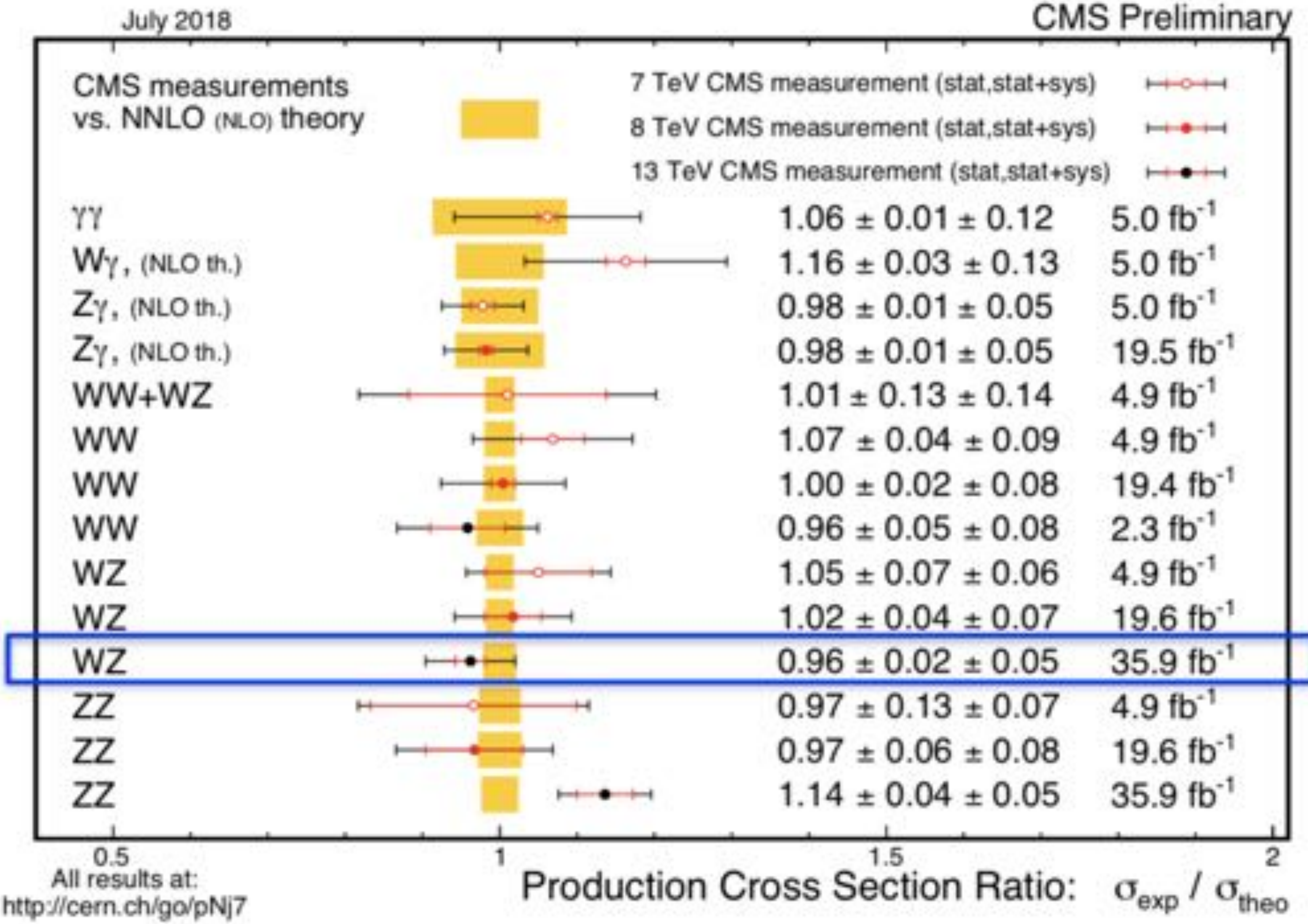
Top physics

- LHC is a top factory, a lot of measurements of cross section and mass

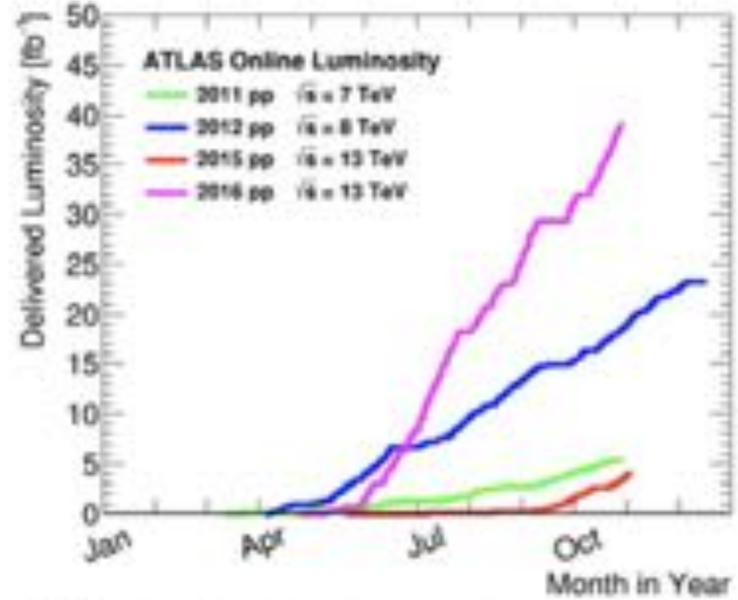




- Top is the heaviest known particle. If new physics exists, it's expected to couple with the mass
- **Top sensitive to new physics**
- Top rare processes ttZ, ttbb, … are important background for various analyses (ttH)


July 2018
CMS Preliminary
CMS measurements
vs. NNLO (NLO) theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
γγ 1.06 ± 0.01 ± 0.12 5.0 fb-1
Wγ, (NLO th.) 1.16 ± 0.03 ± 0.13 5.0 fb-1
Zγ, (NLO th.) 0.98 ± 0.01 ± 0.05 5.0 fb-1
Zγ, (NLO th.) 0.98 ± 0.01 ± 0.05 19.5 fb-1
WW+WZ 1.01 ± 0.13 ± 0.14 4.9 fb-1
WW 1.07 ± 0.04 ± 0.09 4.9 fb-1
WW 1.00 ± 0.02 ± 0.08 19.4 fb-1
WW 0.96 ± 0.05 ± 0.08 2.3 fb-1
WZ 1.05 ± 0.07 ± 0.06 4.9 fb-1
WZ 1.02 ± 0.04 ± 0.07 19.6 fb-1
WZ 0.96 ± 0.02 ± 0.05 35.9 fb-1
ZZ 0.97 ± 0.13 ± 0.07 4.9 fb-1
ZZ 0.97 ± 0.06 ± 0.08 19.6 fb-1
ZZ 1.14 ± 0.04 ± 0.05 35.9 fb-1
0.5
1
1.5
2
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo

- **Weak mixing angle extraction @8 TeV**
  - CMS EPJC 78 (2018) 701; ATLAS-CONF-2018-037
- **Triple-differential Drell-Yan @8 TeV**
  - ATLAS JHEP 12 (2017) 059
- **Forward Z → τ+τ− @ 8 TeV**
  - LHCb arXiv:1806.05008



- **Inclusive WZ production @13 TeV**
  - ATLAS-CONF-2018-034, CMS-PAS-SMP-18-002
- **Electroweak diboson production @13 TeV**
  - WZ: ATLAS-CONF-2018-033, CMS-PAS-SMP-18-001
  - ZZ: CMS PLB 774 (2017) 682
  - WW: CMS PRL 120 (2018) 081801; ATLAS-CONF-2018-030
- **γγ → ll with proton-tagging @13 TeV**
  - CMS+TOTEM JHEP 1807 (2018) 153
- **Light-by-light scattering @5 TeV Pb+Pb**
  - ATLAS Nature Phys. 13 (2017) 852; CMS-PAS-FSQ-16-012