Introduction to The Standard Model*

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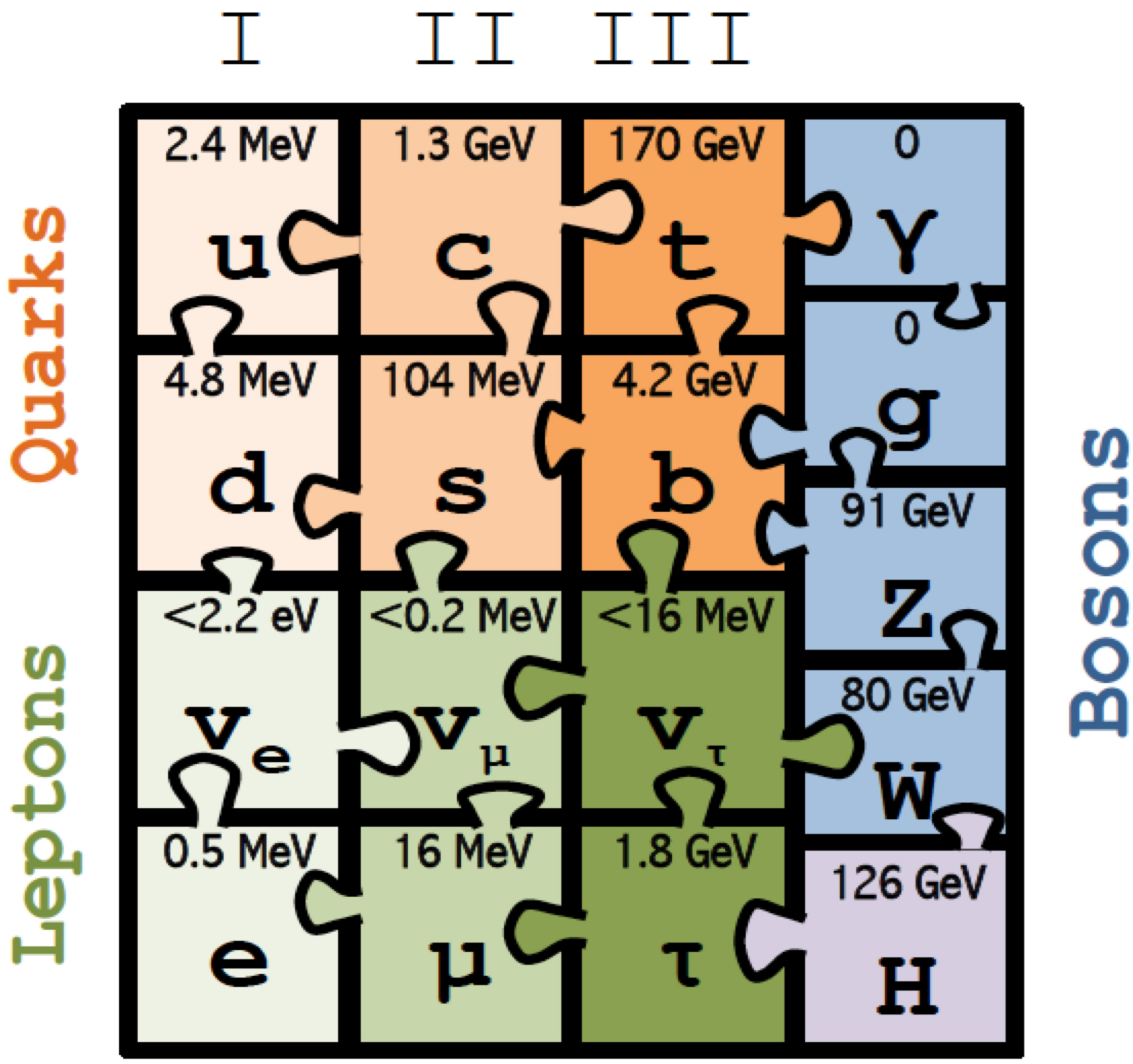
** A very biased introduction from an experimentalist!*

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) ← Electroweak

- 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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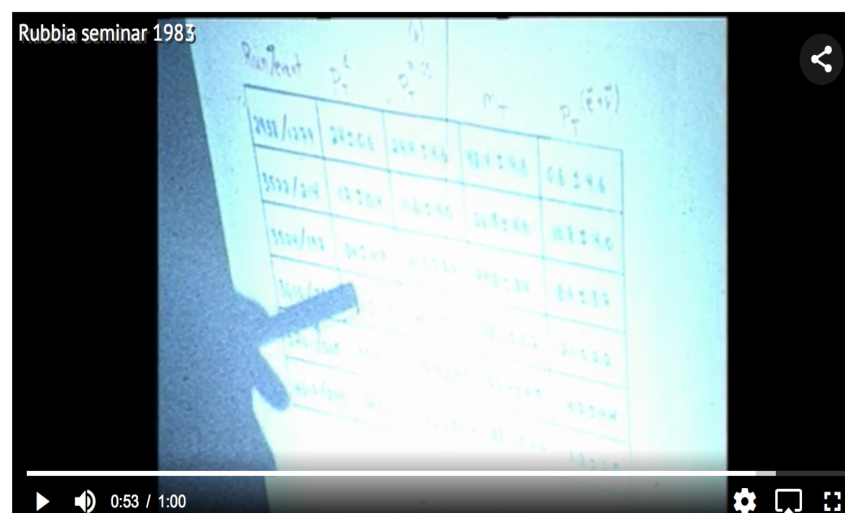
- In 1983 UA1 and UA2 announced the discovery of a massive W boson



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

The one-to-one relation between the couplings and the masses of gauge bosons (at Tree level) introducing the week mixing angle!

$$\tan\theta_W = \frac{g'}{g}$$

$$m_W = \frac{gv}{2}$$

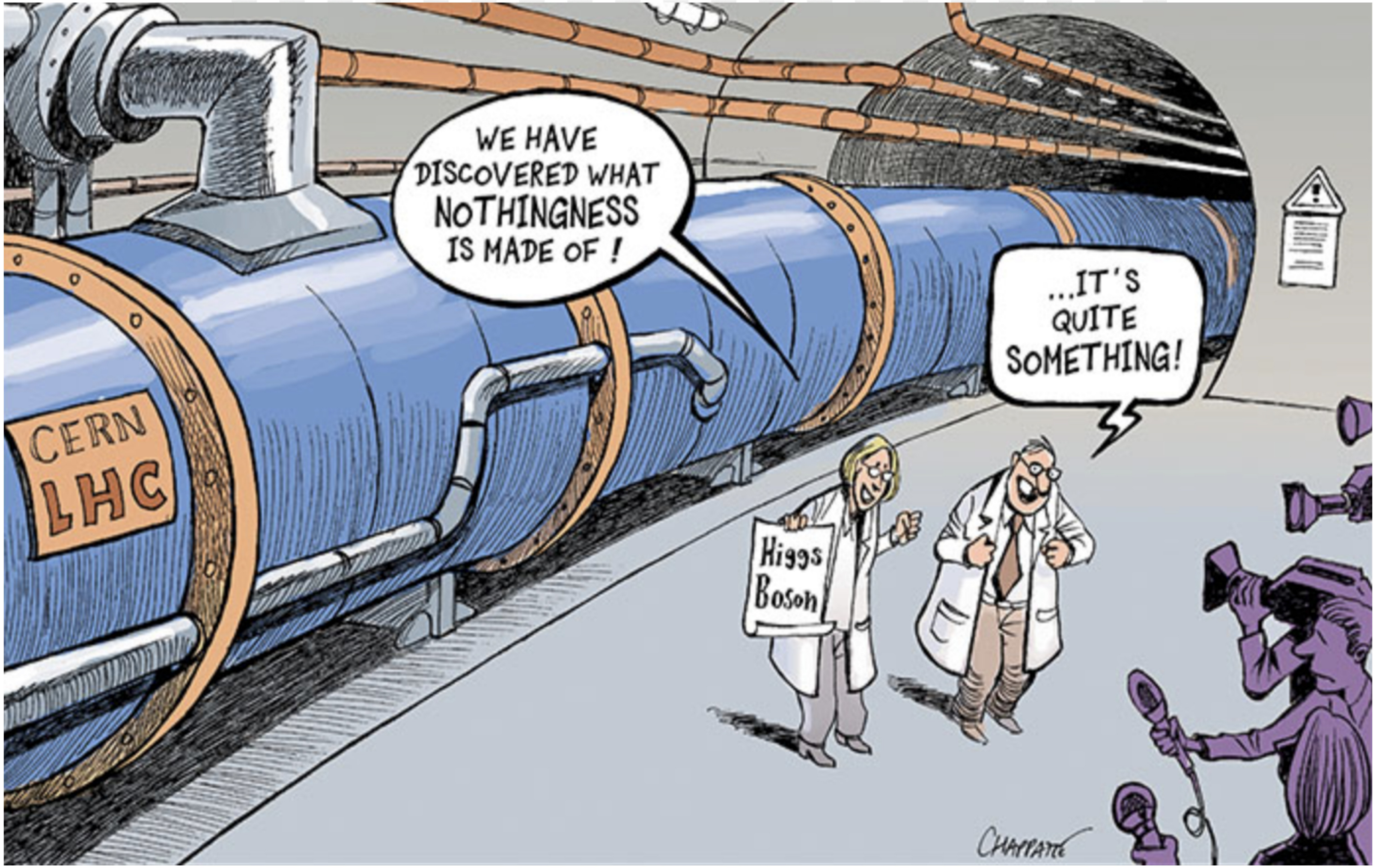
$$m_Z = \frac{gv}{2\cos\theta_W}$$

$$m_\gamma = 0$$

- *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

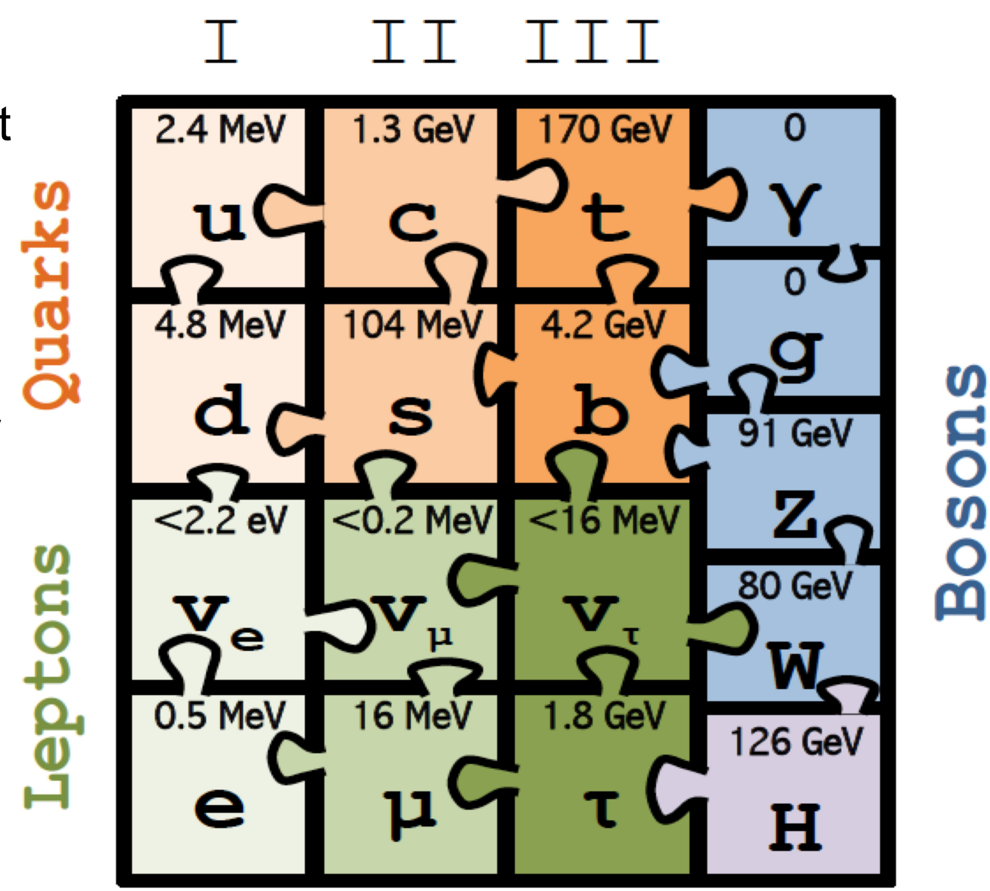
- The Higgs boson is the particle corresponding to the Higgs field

The Standard Model (SM)

Global overview

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

Top physics:
- A special kind of quark
- Decays before hadronizing t → Wb



Flavour physics:
- Quark and lepton flavor physics: mixings and couplings, symmetry principles violation
- Understanding the matter-antimatter asymmetry

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:
- Is the discovered particle the one predicted by the SM?

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

The Standard Model (SM)

Roadmap for main precision measurements @LHC

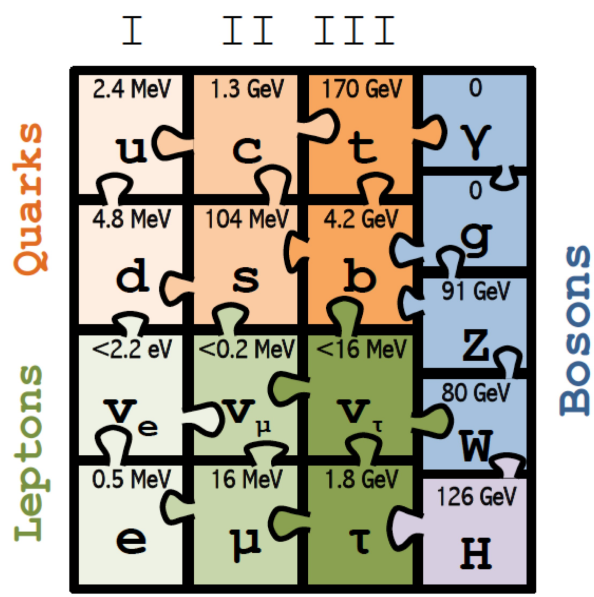
Several fundamental parameters coming in focus at the LHC

Couplings
e.g. Multibosons, VBS, four tops, Vtb, Higgs
VBF W/Z, exclusive l+l-, differential σ(tt)

Symmetry Conservations
e.g. Lepton universality
CP(T) in tt

α_S
e.g. Jet production, σ(tt)
Splitting scales, sub-structure

m_t
Direct and indirect Measurements
If the SM is all there is up to Planck scale, mtop pushes nature to a rim



m_W
Direct measurement
$p_T(V)$
At loop-level mW receives corrections from the top quark and the Higgs

$\sin\theta^2_W$
e.g. DY angular coefficients
A_{FB}

The Standard Model (SM)

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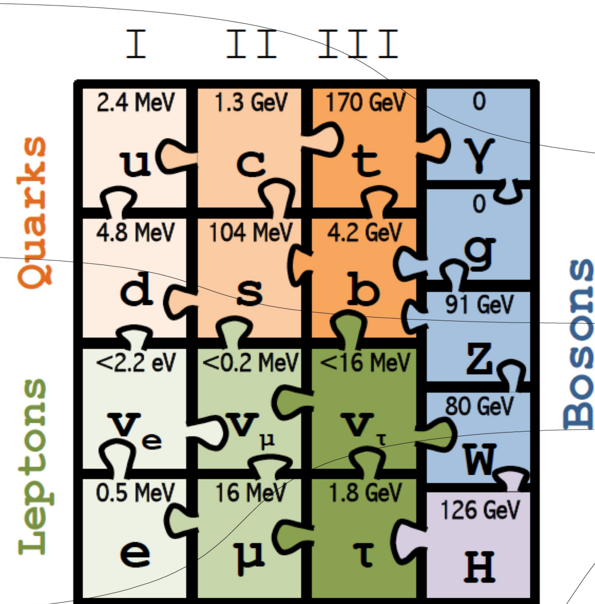

New physics?
Measuring with a purpose:
Disclose (if and) where new physics is

α_s
e.g. Jet production, σ(tt)
Splitting scales, sub-structure

m_t
Direct and indirect Measurements
If the SM is all there is up to Planck scale, mtop pushes nature to a rim

m_W
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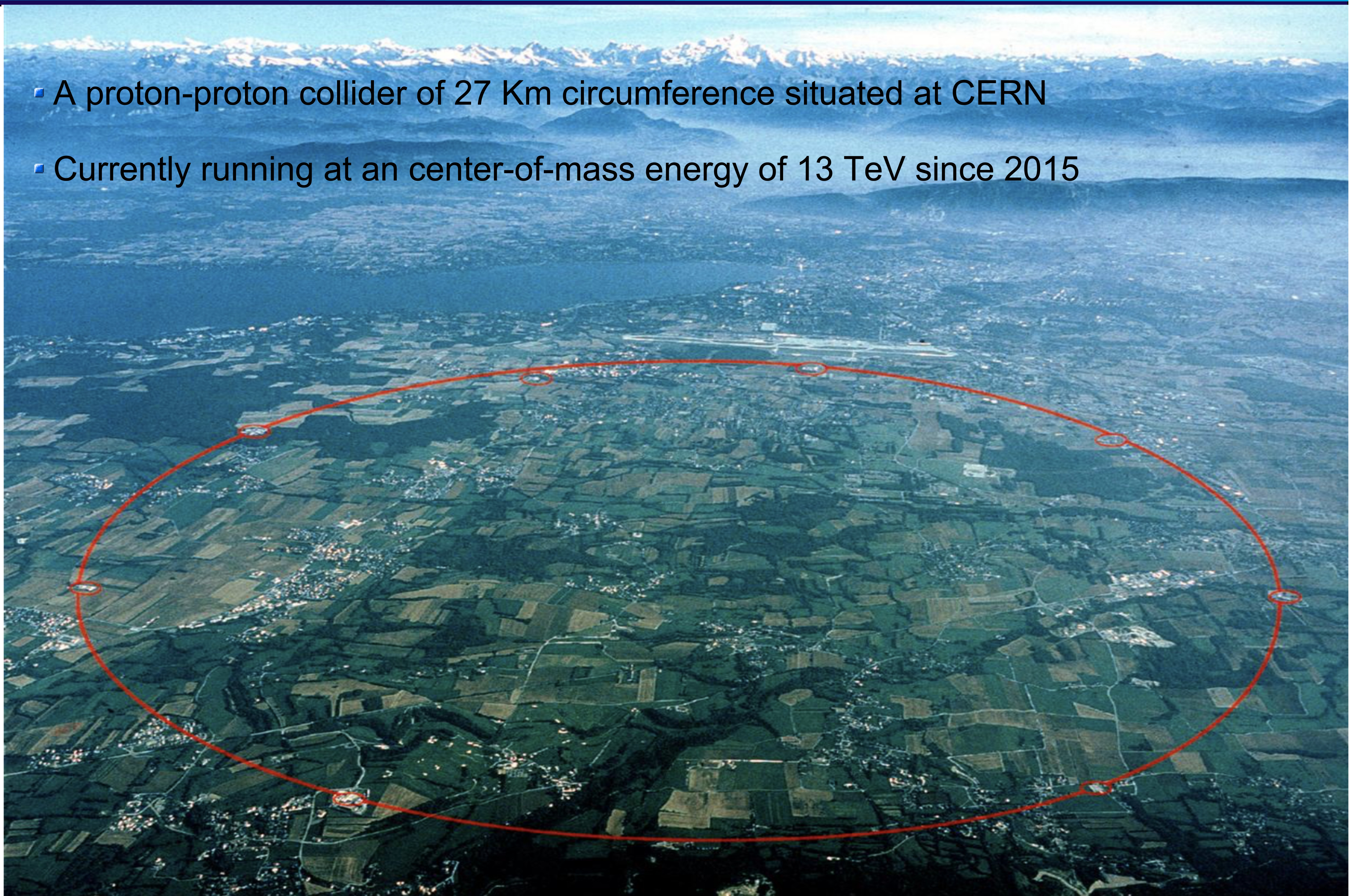
e.g. DY angular coefficients
A_{FB}

So how do we study all these particles?

The current tools: The Large Hadron Collider (LHC)

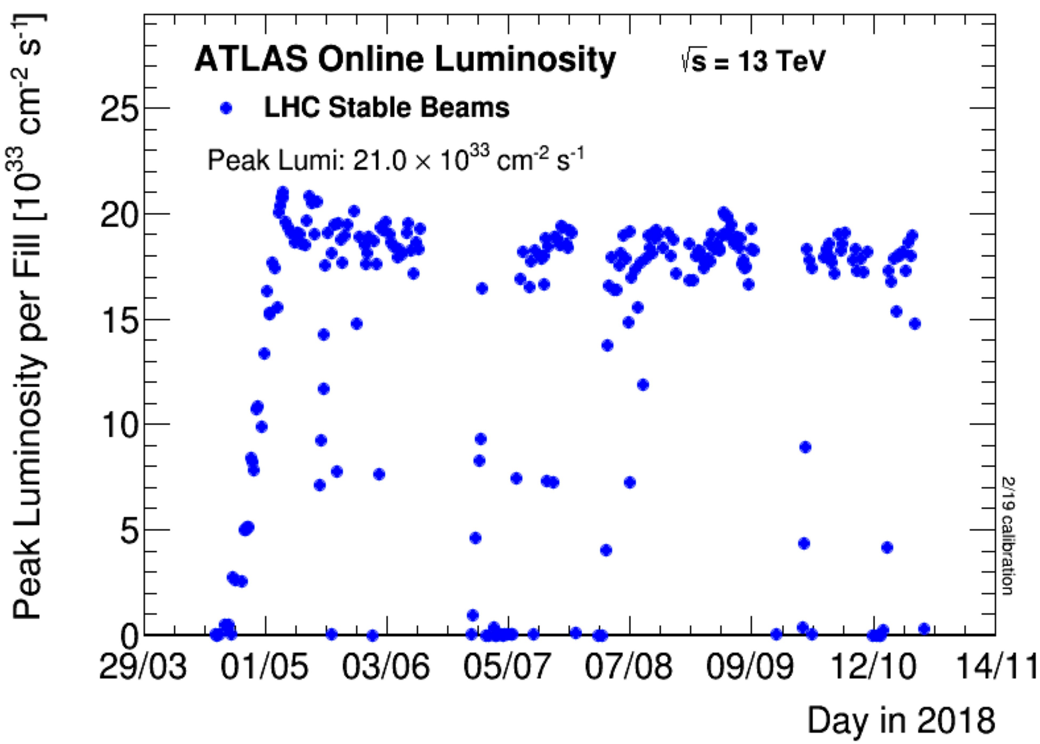
- A proton-proton collider of 27 Km circumference situated at CERN
- Currently running at an center-of-mass energy of 13 TeV since 2015

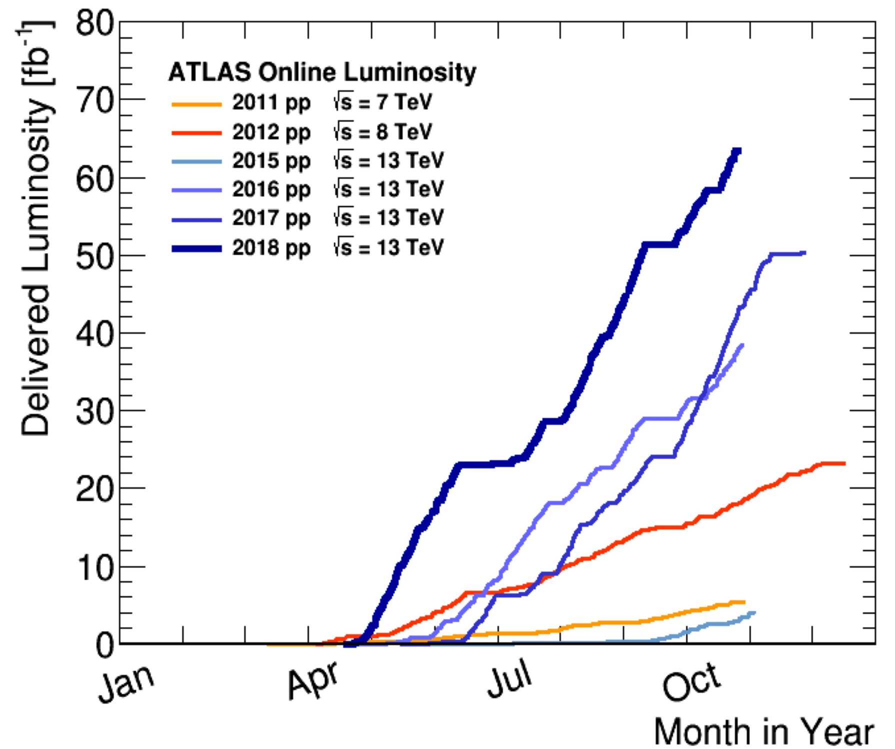


So how do we study all these particles?

LHC performance

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





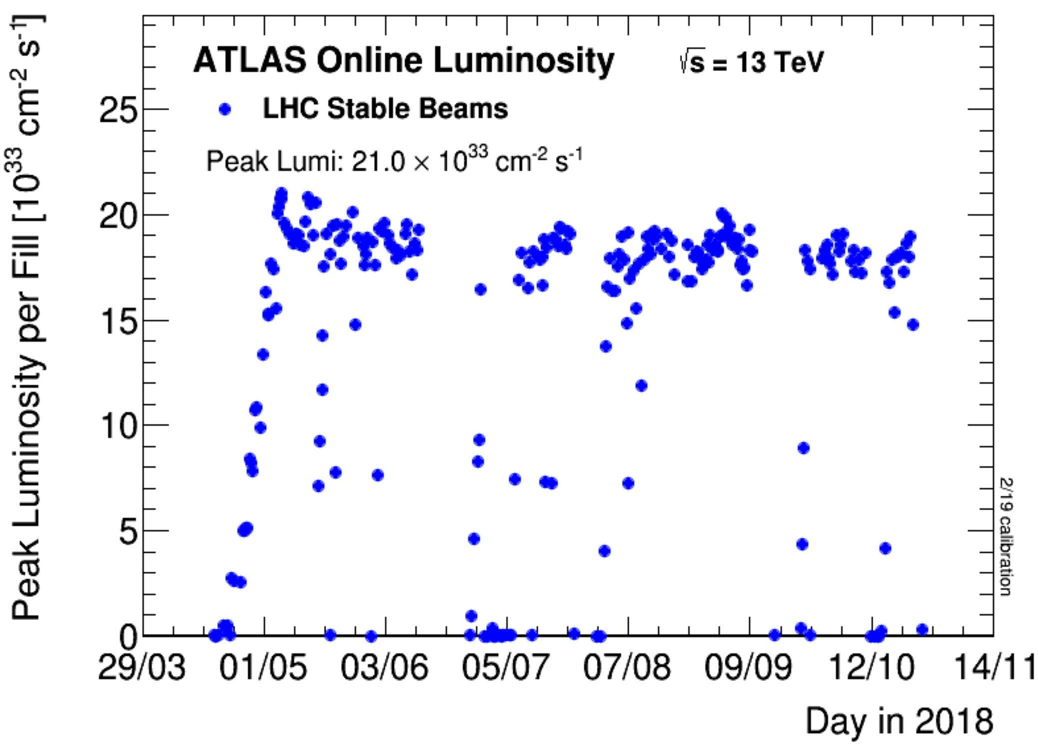
Peak luminosity twice larger than LHC design luminosity!

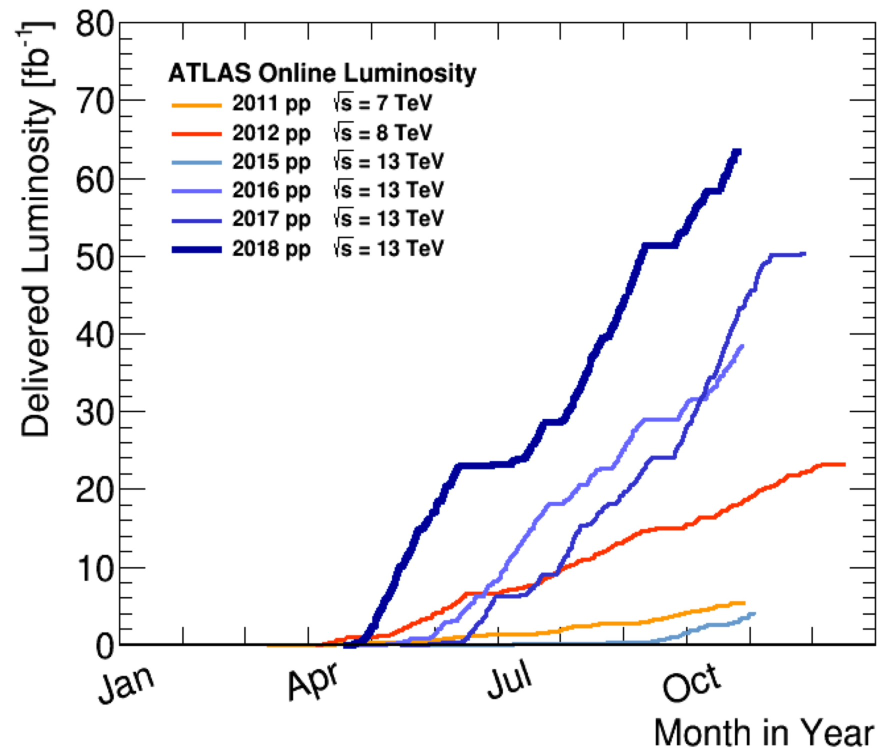
fb^{-1} is a measure of the amount of data collected =~10^{12} proton-proton collisions. Used to translate σ into a total number of events. For the SM Vh with h→bb process, σ~1305 fb → in 100/fb of collected data, we expect a total of 130500 events

So how do we study all these particles?

(Outstanding) LHC performance

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



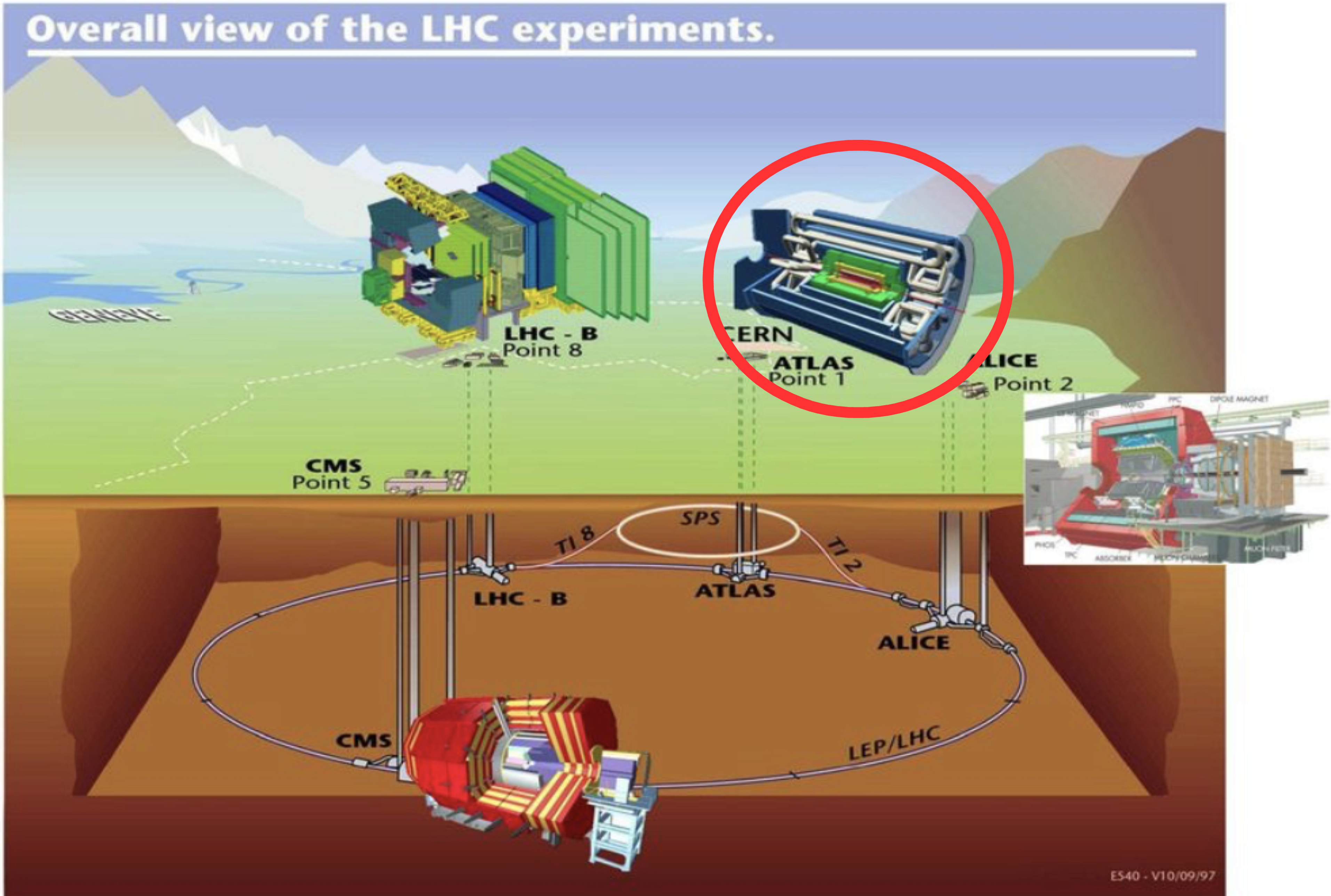


Future integrated luminosity goals:

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

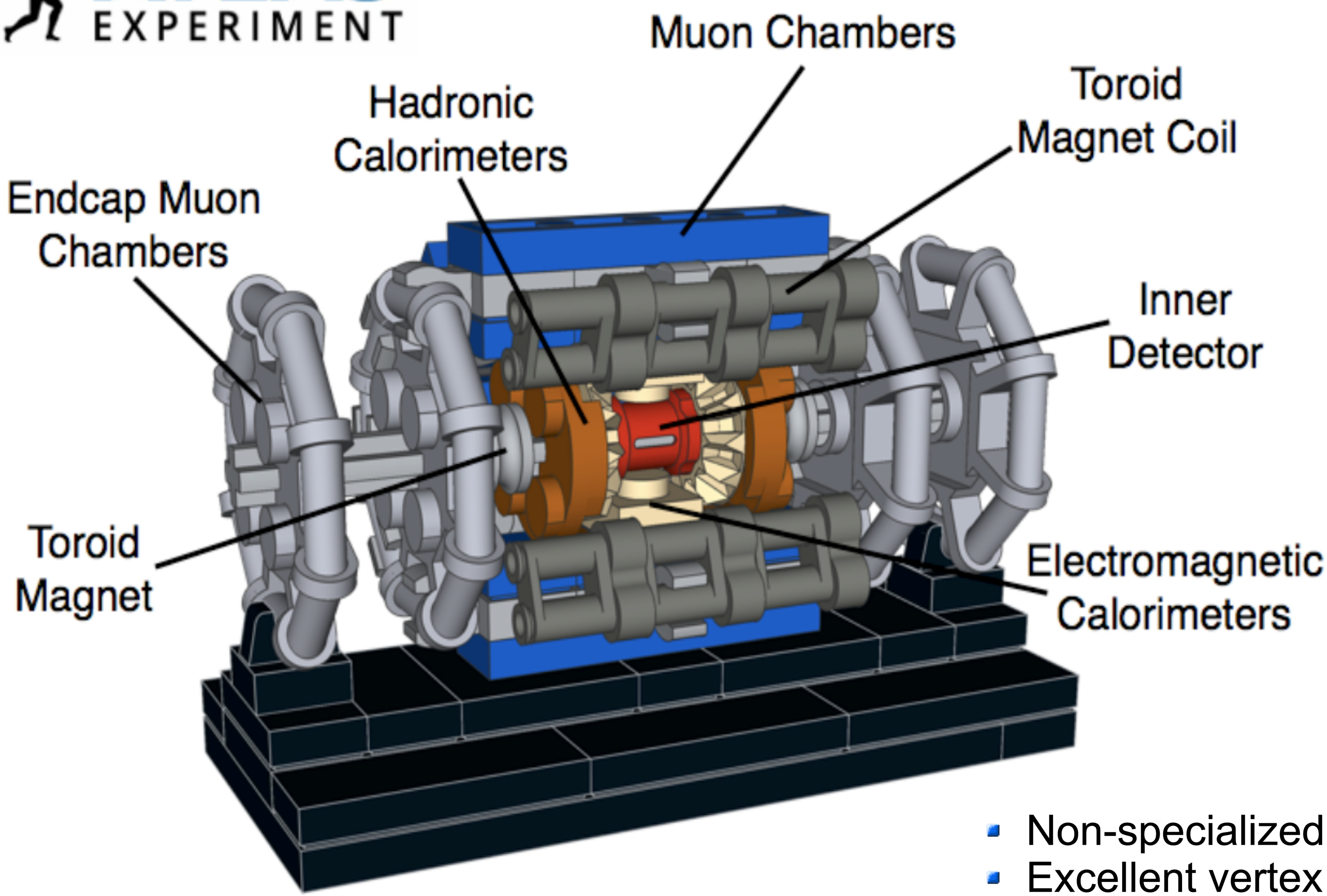
So how do we study all these particles?

The particle detectors



So how do we study all these particles?

The ATLAS detector

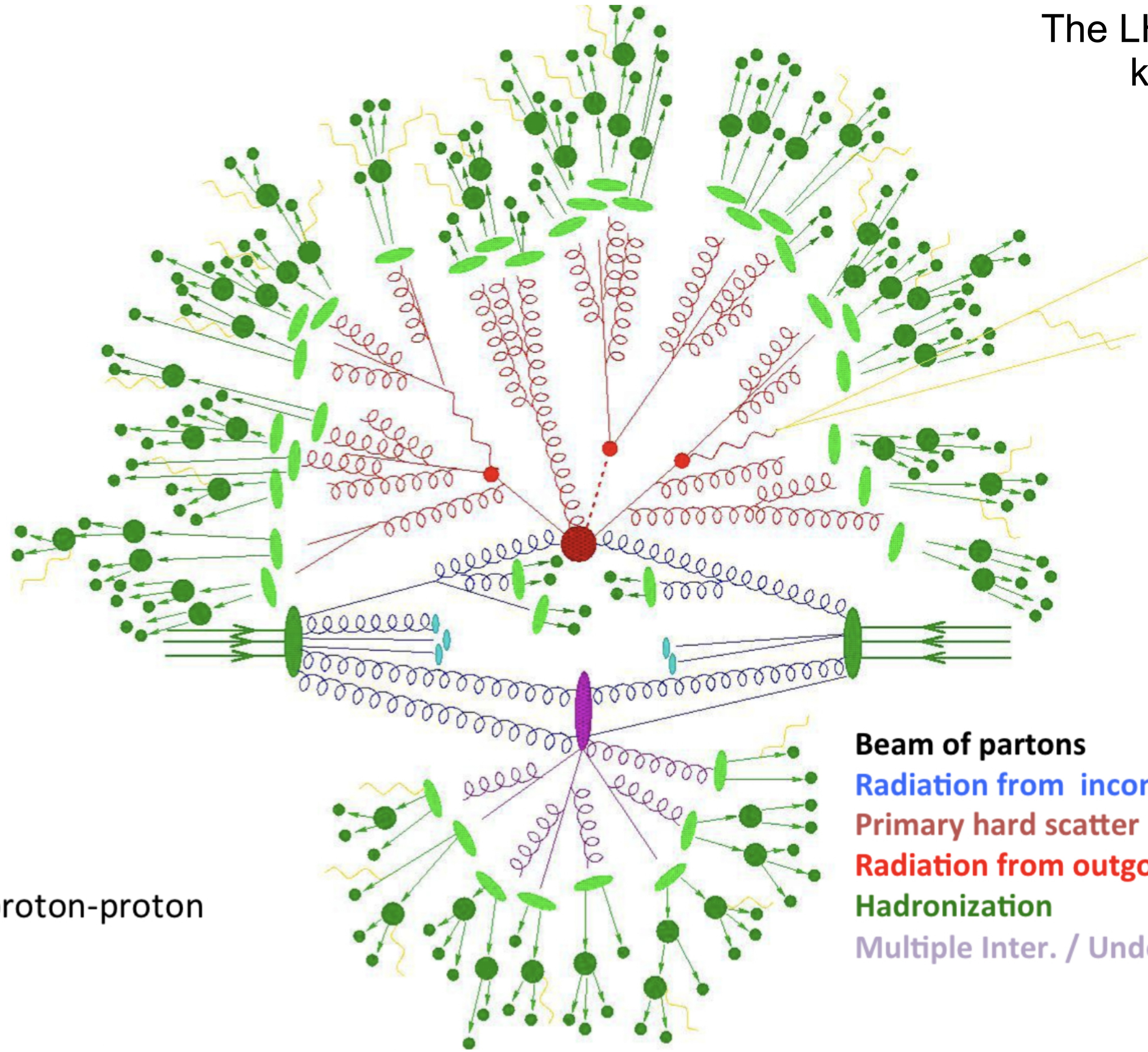


- Non-specialized detector
- Excellent vertex and tracking systems
- Large coverage for muon detection
- Excellent calorimetry with extended coverage

So how do we study all these particles?

The collisions

The LHC is a QCD kingdom



Beam of partons

Radiation from incoming partons

Primary hard scatter

Radiation from outgoing partons

Hadronization

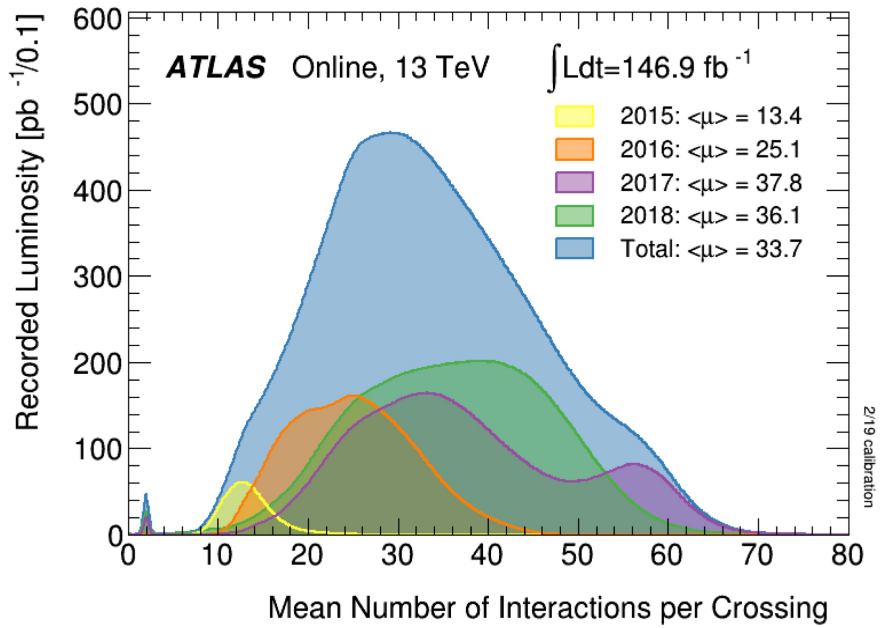
Multiple Inter. / Underlying event

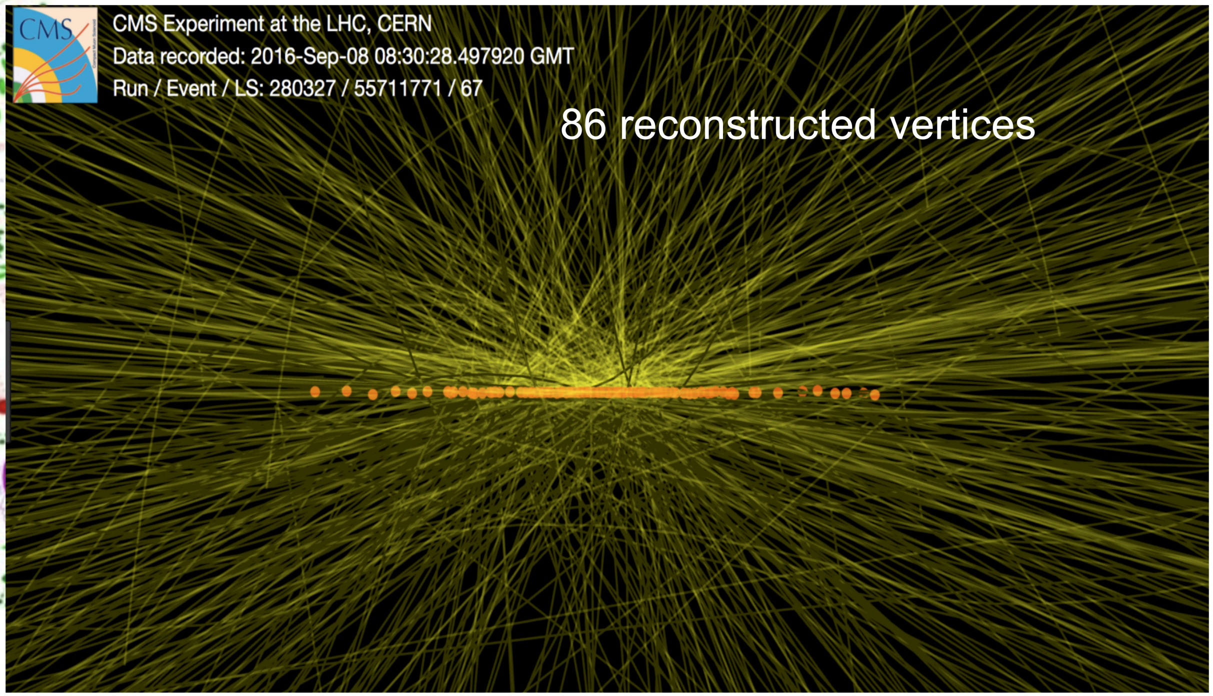
Typical proton-proton collision

So how do we study all these particles?

The collisions

High Lumi
=
high pileup

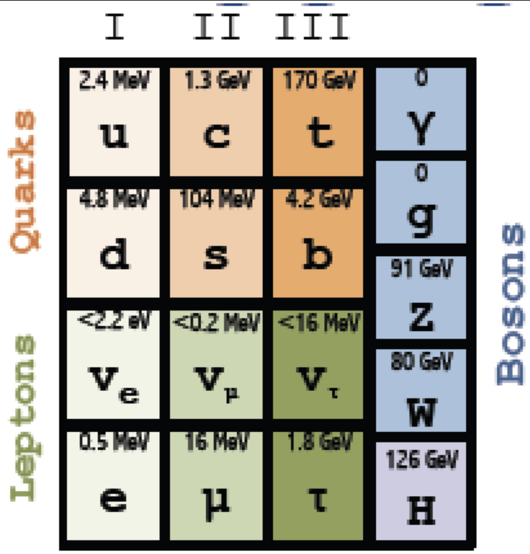


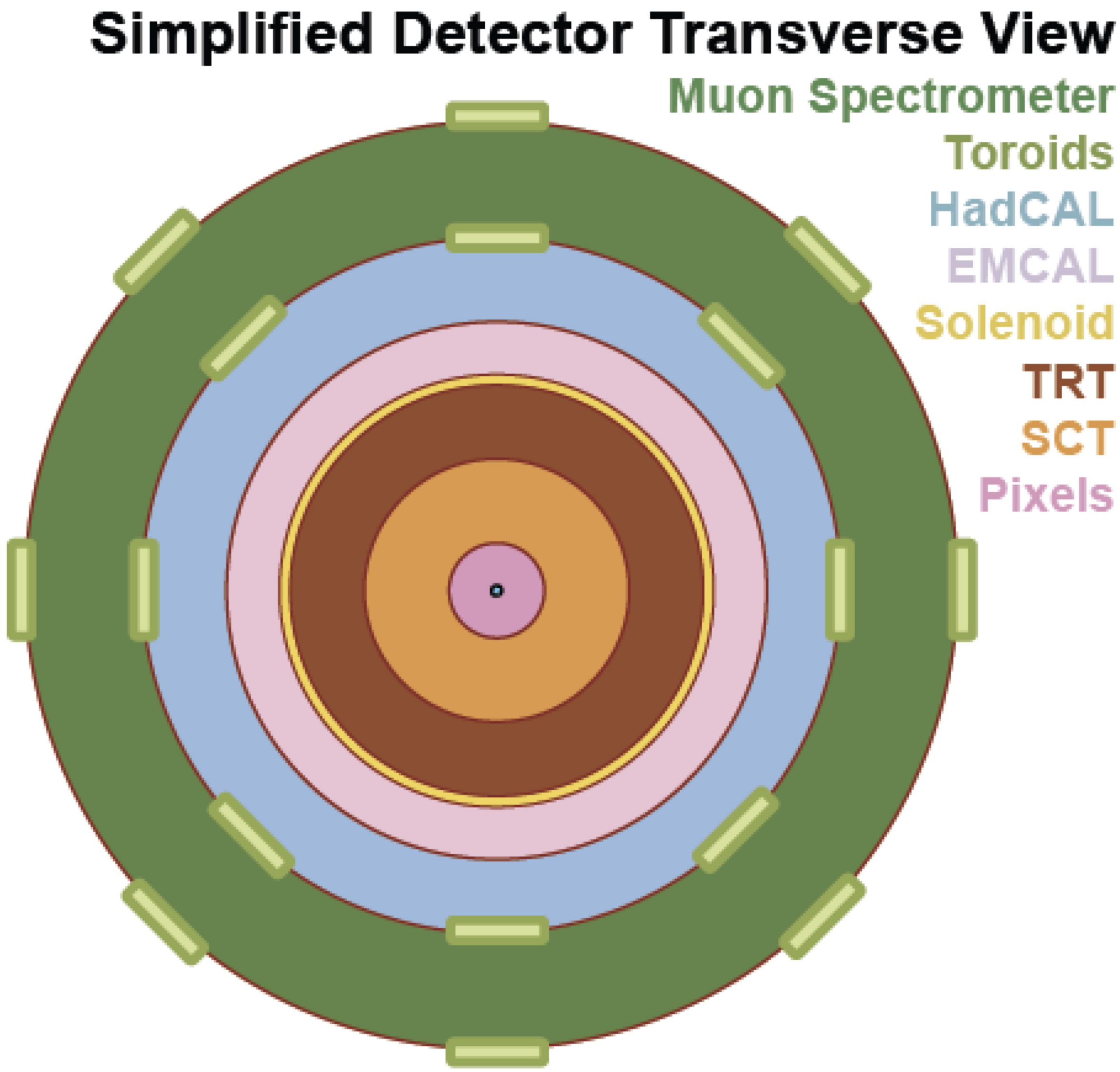


Impressive detectors

So how do we study all these particles?

How do we detect the particles?





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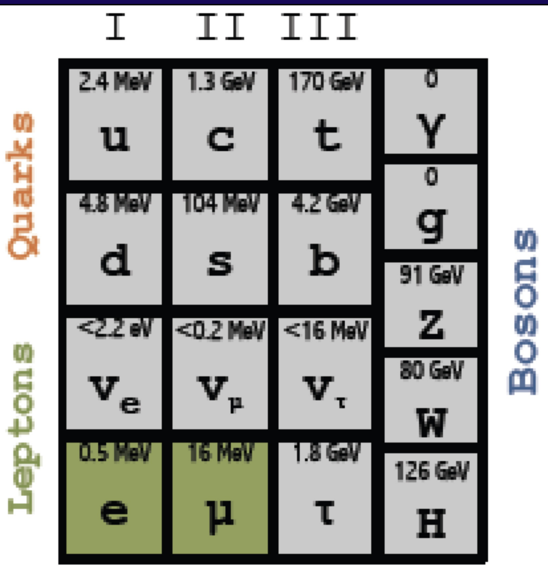

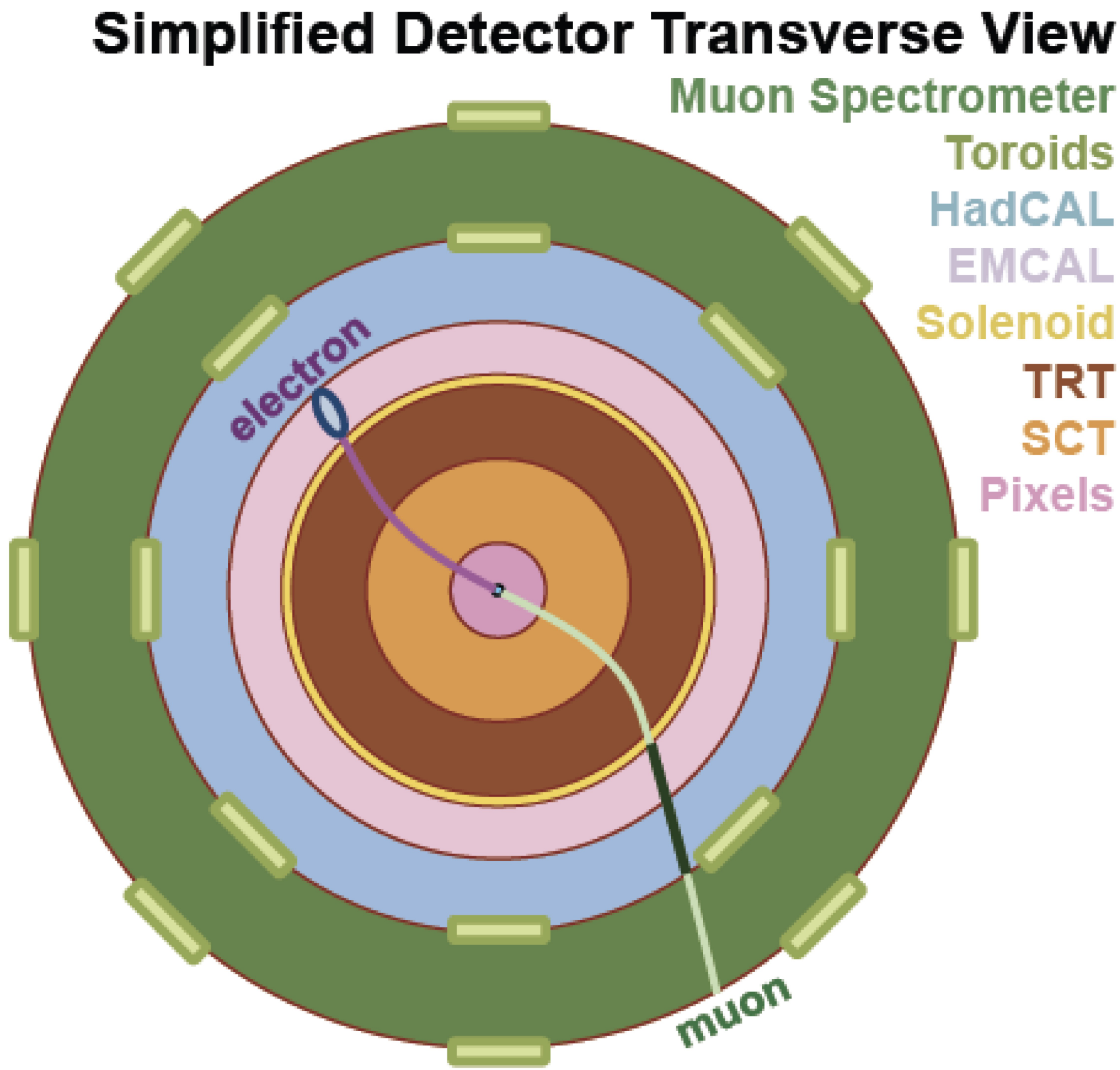

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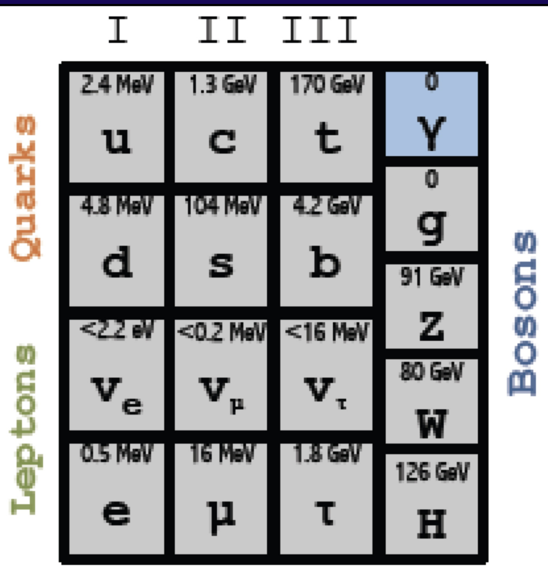

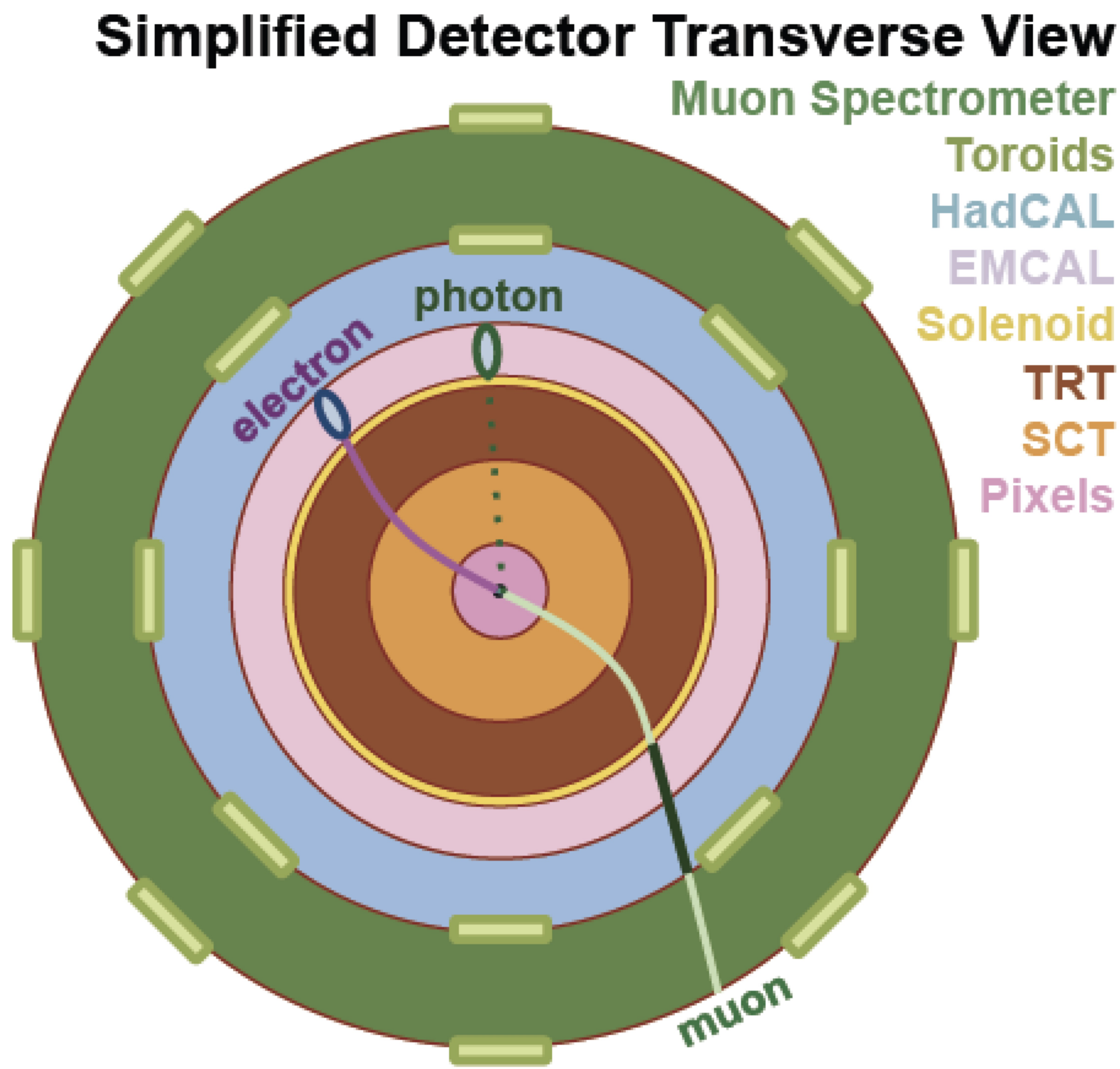

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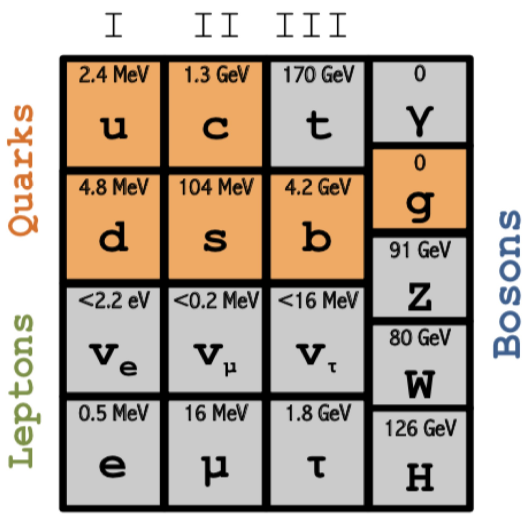
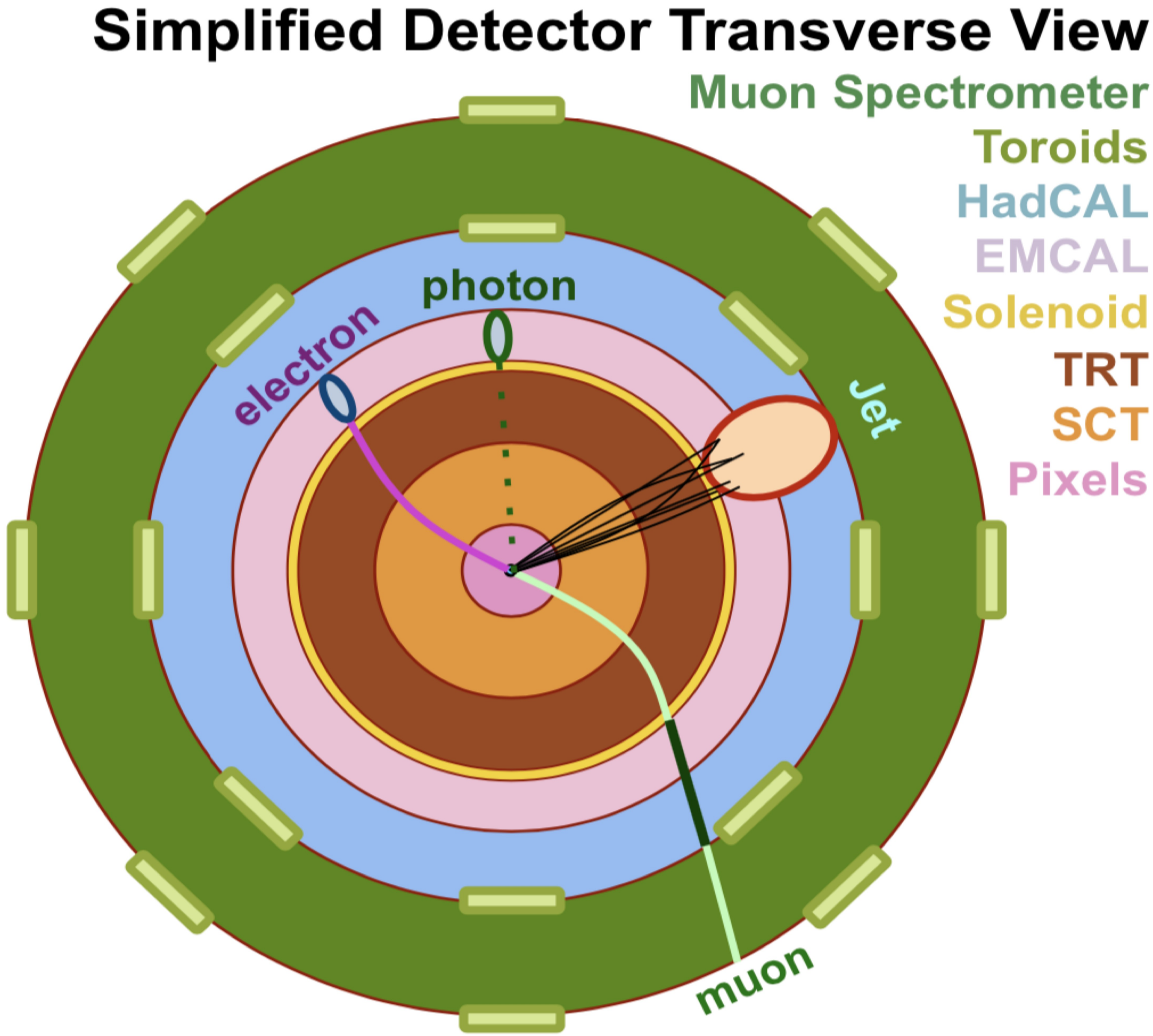
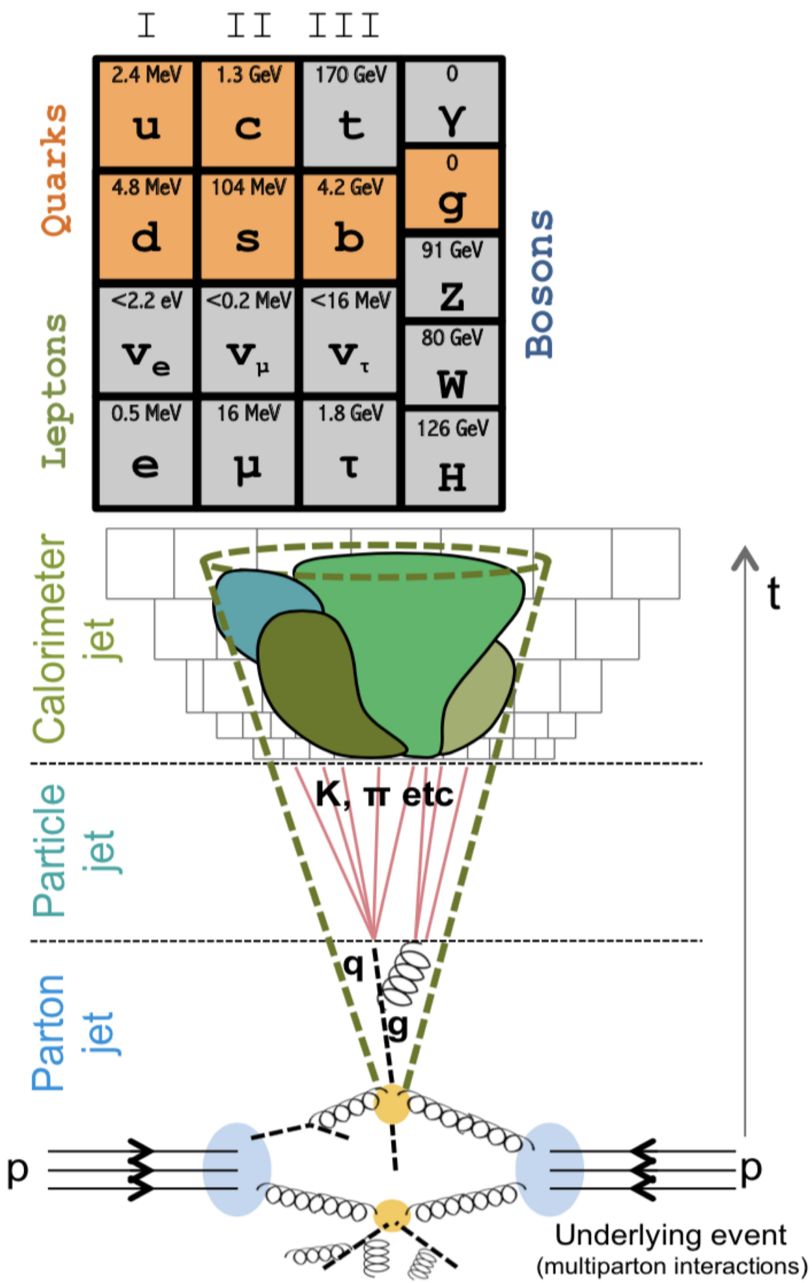


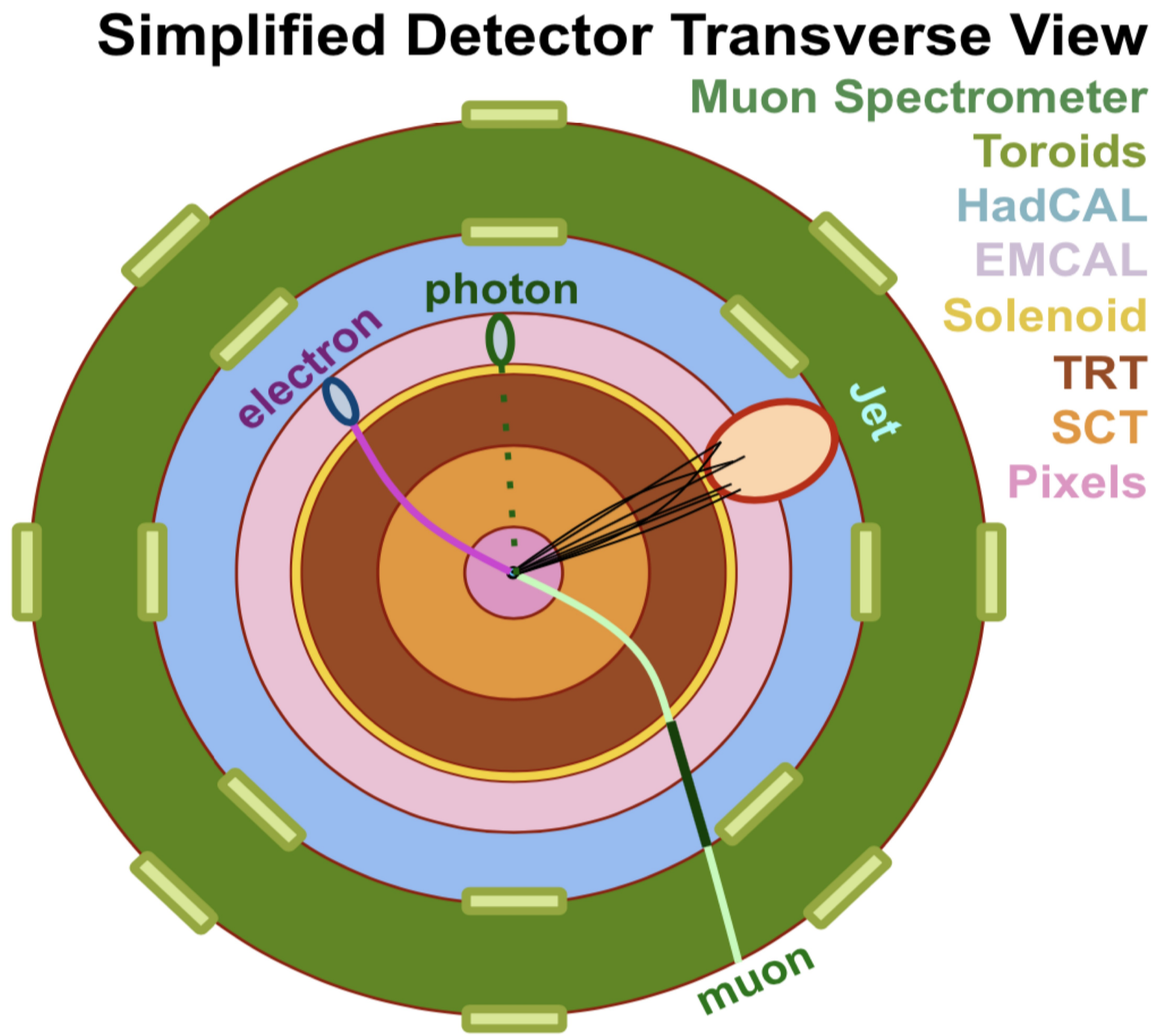


- Bare quarks,isolated gluons are colored objects and can't be observed isolated
- Radiate, eventually reconnect to the rest of the event evolve to create colorless final states
- end fragmenting to a directed flow of hadrons ⇨ jet

So how do we study all these particles?

How do we detect the particles?



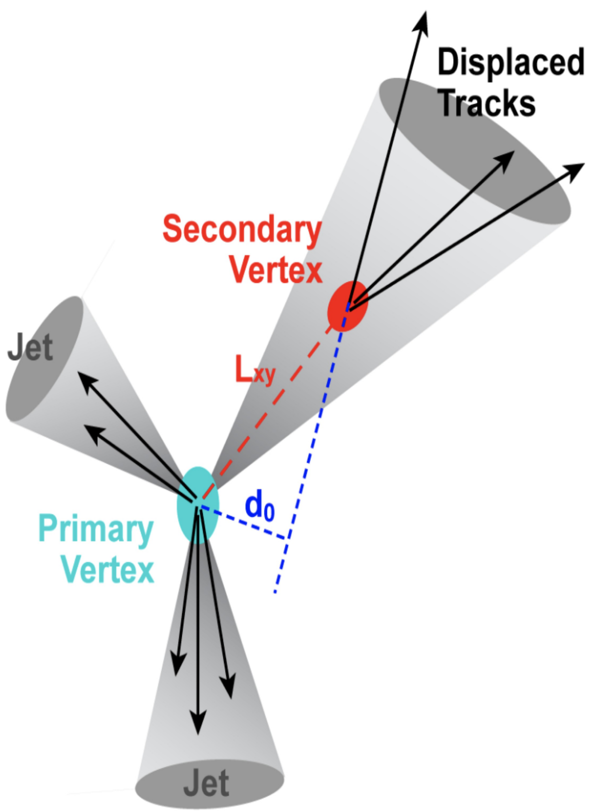


- Different algorithms used to combine inputs and reconstruct jets, eg. anti-kT, soft-drop
- Inputs can be from truth level, calorimeter, inner tracker and calorimeter+inner tracker (eg. PFlow)

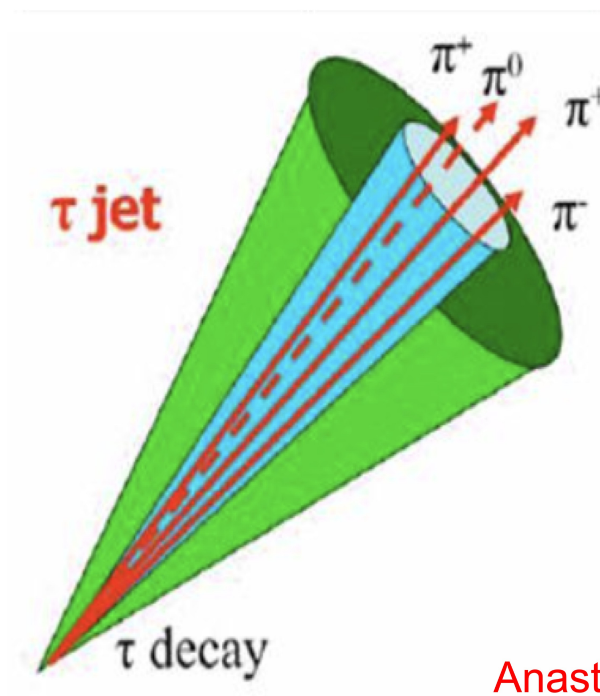
So how do we study all these particles?

Some of them are harder to identify/measure

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



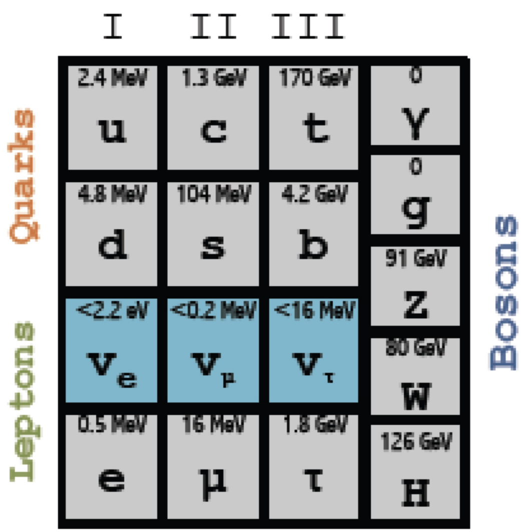
Tau leptons decay to hadrons and form jets: usually narrower jets with less tracks

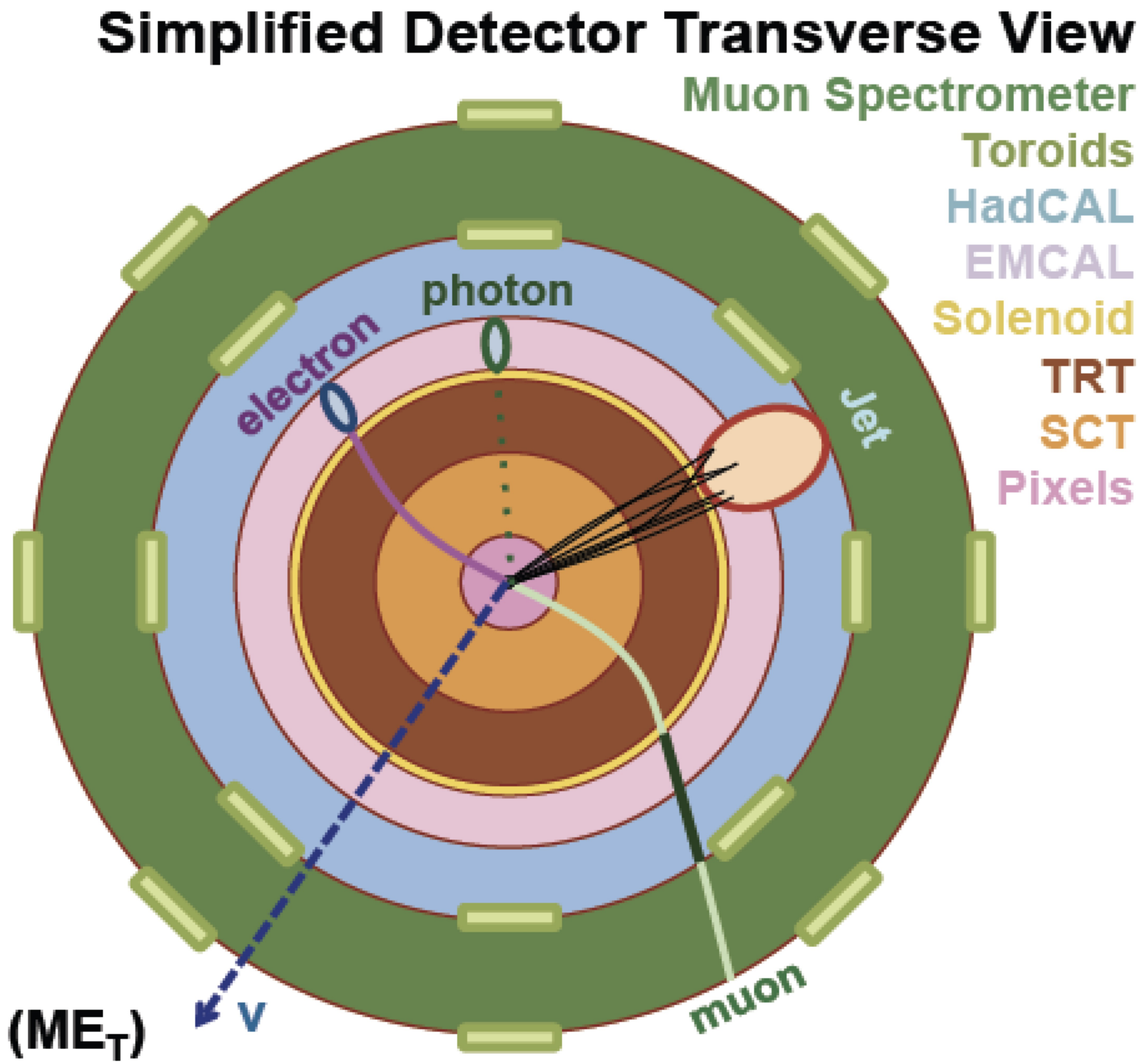


Anastasia will discuss about ways of identifying hard scatter jets in the forward region of the detector!

So how do we study all these particles?

How do we detect the particles?





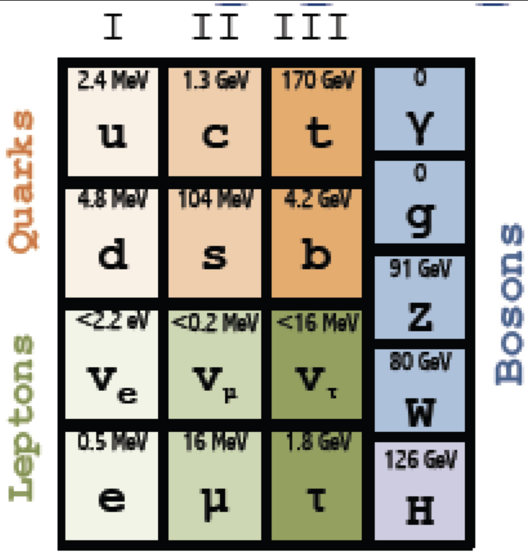
In the transverse plane:

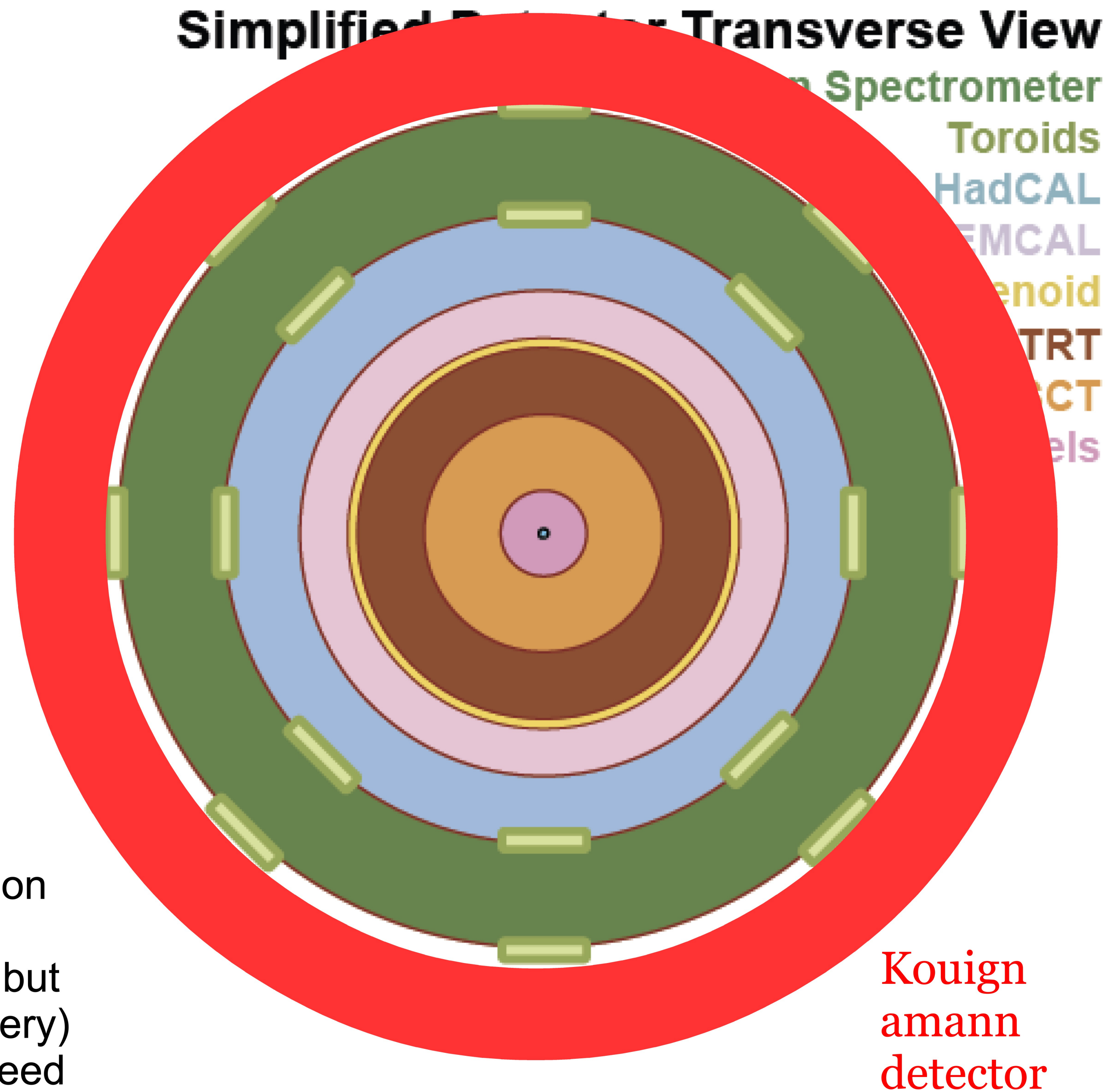
$$\sum \vec{p}_T = 0$$

Missing Transverse Momentum (ME_T)

So how do we study all these particles?

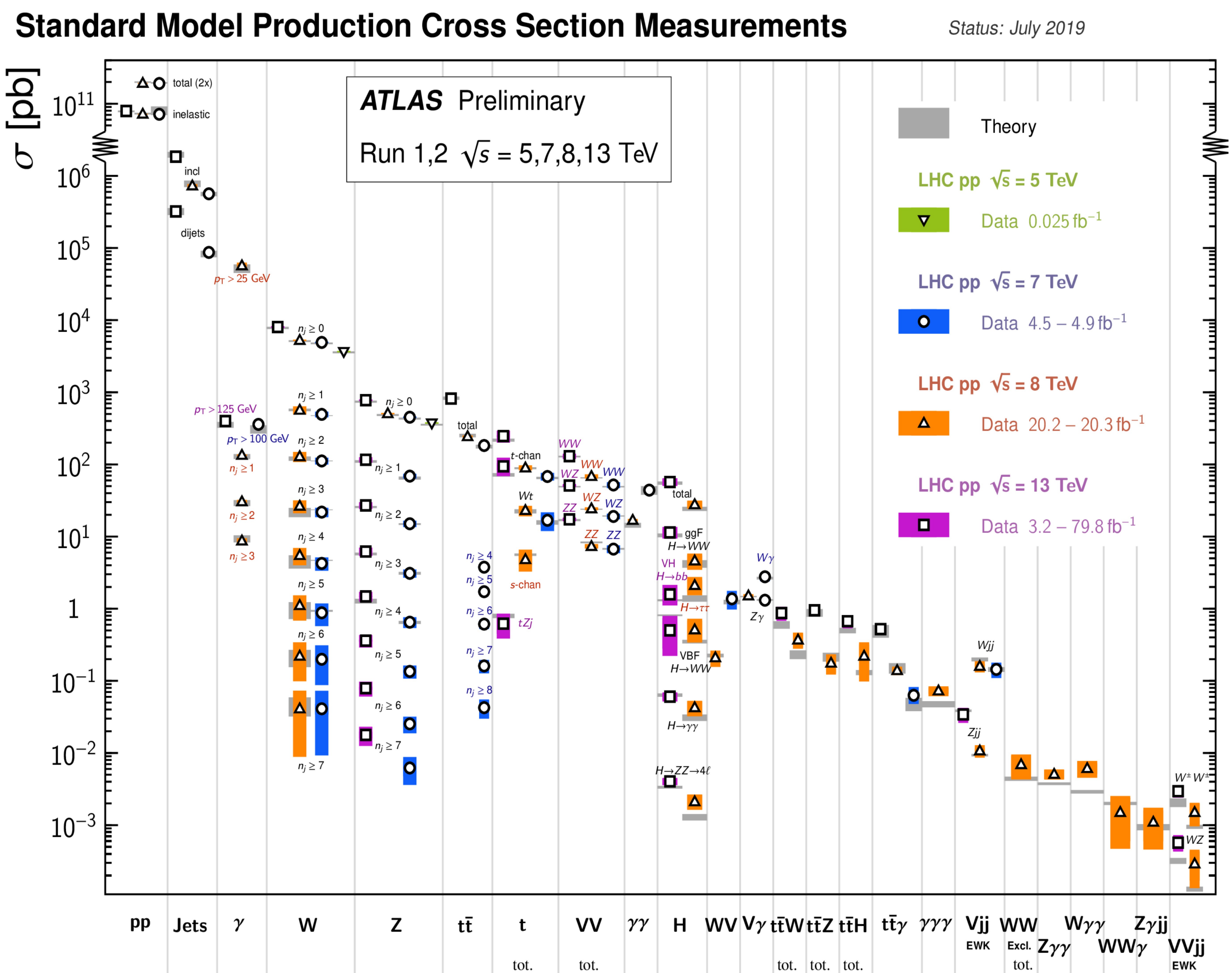
How do we detect the particles?





- Kouign amann do not interact strongly, rarely undergo hard collision with atomic nuclei
- They interact electromagnetically but they are so much heavier (and buttery) that electrons and muons! So we need an special butter-detector for them

The SM works!

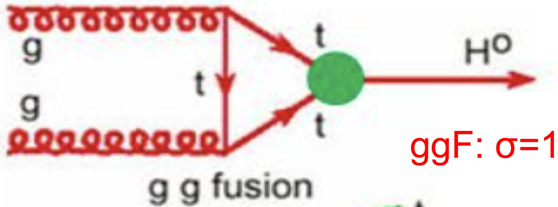


- Many precision measurements going on in different SM sectors
- Cross sections, masses, spin, etc

A Higgs boson was discovered in 2012

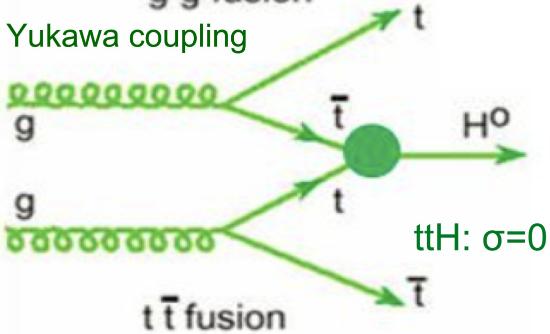
Higgs physics @LHC in a nutshell

Main production mode at LHC

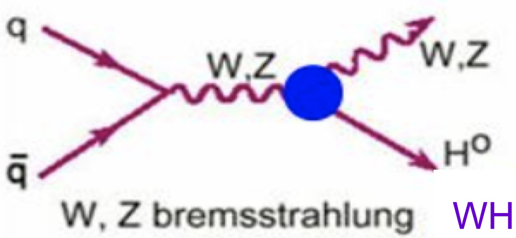


ggF: σ=19.2 pb

Yukawa coupling

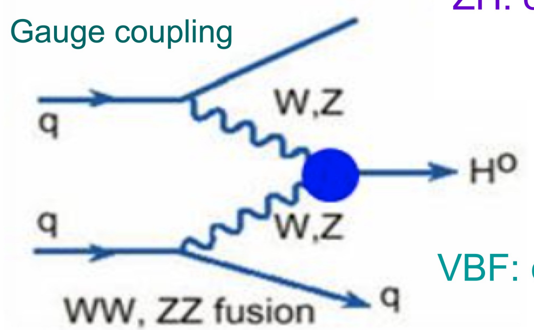


ttH: σ=0.13 pb



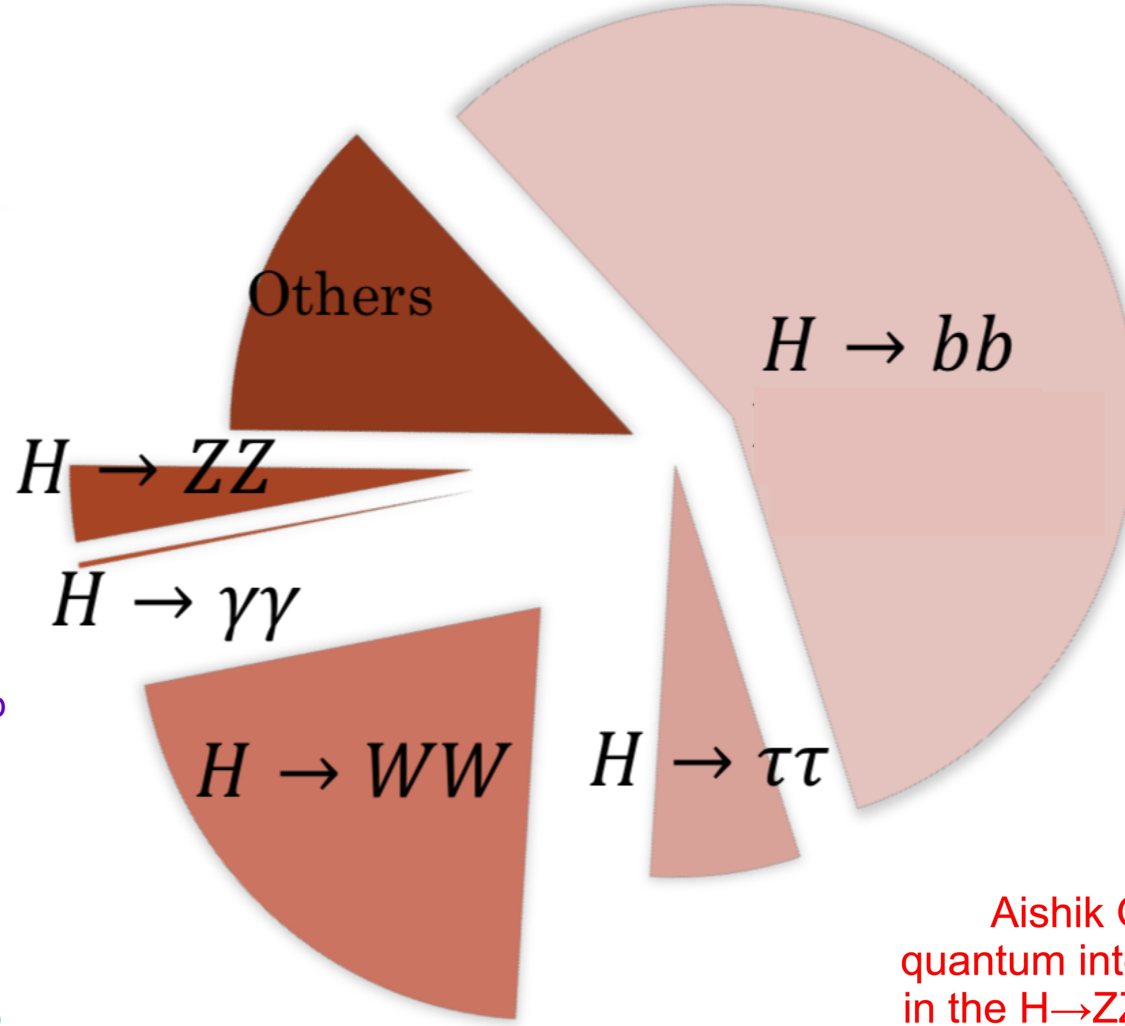
WH: σ=0.7 pb
ZH: σ=0.4 pb

Gauge coupling



VBF: σ=1.6 pb

Which production mode or/and decay is the best?



Aishik Ghosh for
quantum interference
in the H→ZZ with ML

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

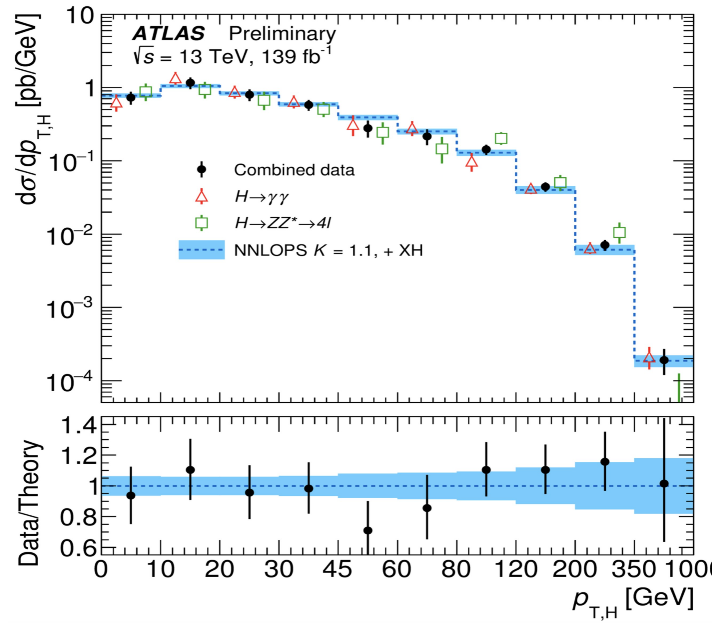
Higgs physics @LHC in a nutshell

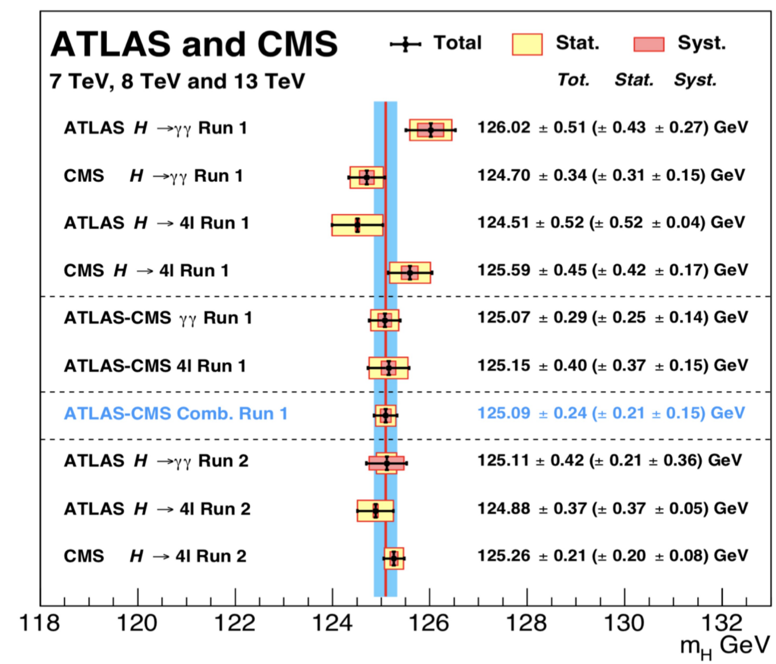
- Higgs physics today:
  - Observed production modes:
    - Gluon gluon fusion (Run-1)
    - VBF (Run-1) and ttH (Run-2)
  - Observed decay modes
    - To bosons: H→ZZ, H→WW, H→$\gamma\gamma$
    - To fermions: H→$\tau\tau$, H→bb

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

- Other Higgs-related physics still on search mode: rare decays and double Higgs

ATLAS-CONF-2019-032

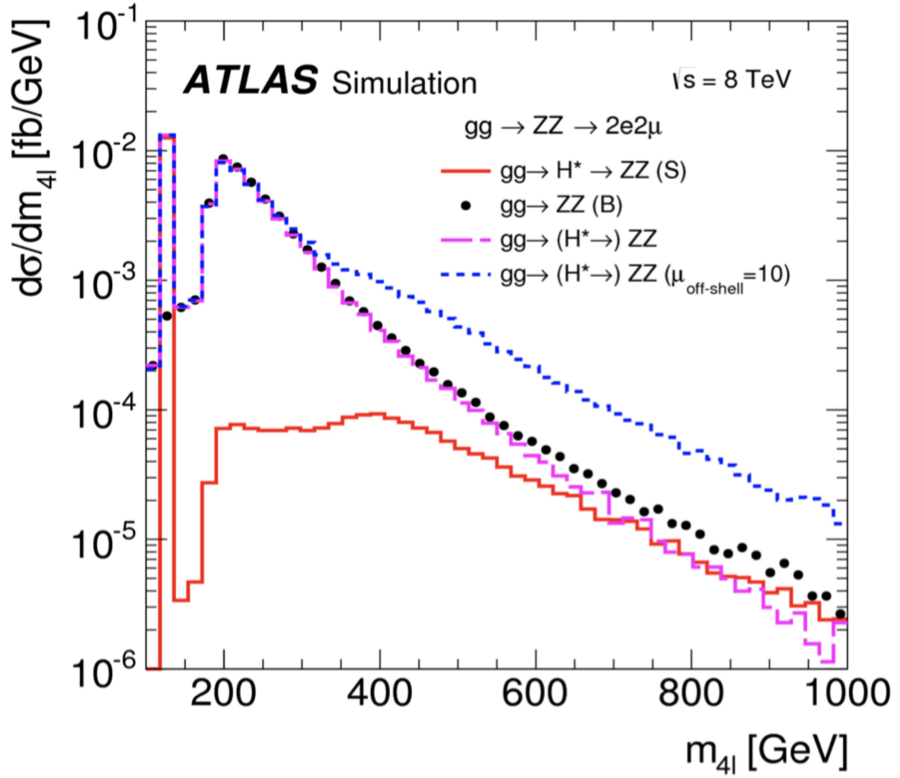




Higgs physics @LHC in a nutshell

- Higgs measurements in the on-peak region are consistent with SM expectations
  - On-shell affected by an ambiguity between the Higgs couplings and the total Higgs width: $\sigma_{i\to H\to f} \sim g_i^2 g_f^2/\Gamma_H$

- Disentangling this ambiguity would make it possible to constrain (or even measure?) the total Higgs boson width at the LHC)
  - Width is about 4 MeV, much smaller than the experimental resolution of the Higgs boson mass measurement
  - Use the off-shell! → the cross-section dependence on the total Higgs width is negligible, providing a unique opportunity to measure the absolute Higgs boson couplings
  - The off-shell Higgs boson couplings can then be correlated with the on-shell cross-sections to provide an indirect constraint on the total Higgs boson width (assuming SM!)



Highly non trivial due to:

- The negative interference

- The large other backgrounds

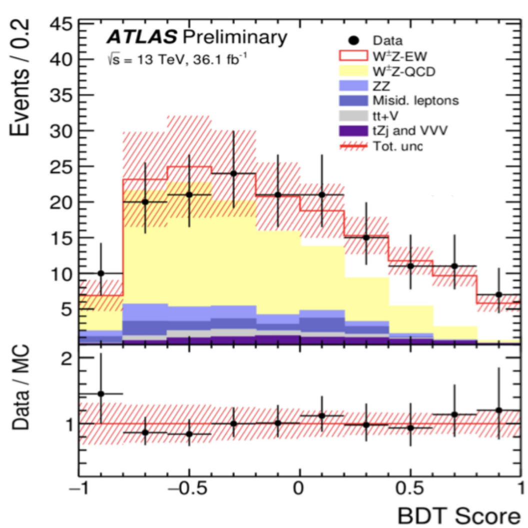
EWK physics @LHC in a nutshell

- Single and diboson production are at the center of a very rich measurement program: cross-sections, W mass, PDF constraints...

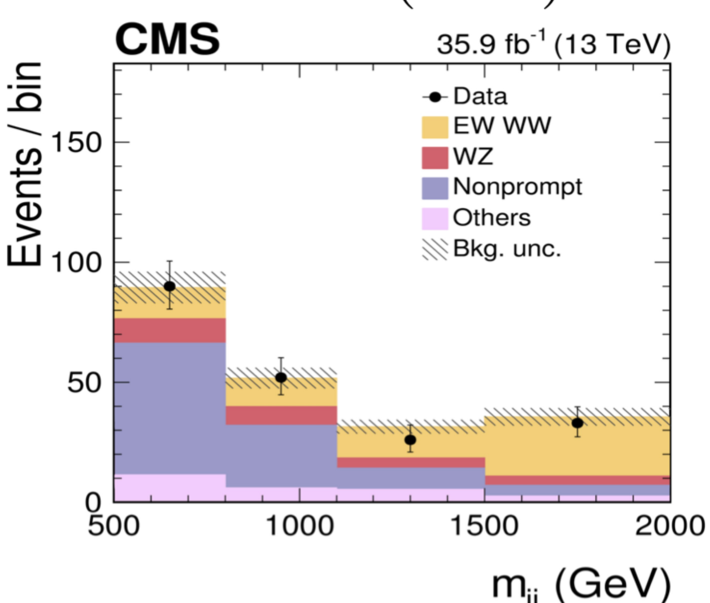
- They constitute background for many analyses and therefore its understanding is crucial

- Anastasia Kotsokechagia will briefly talk about one important process: EW Vector Boson Scattering process and its relationship with jet performance!
    - Unambiguously observed by both ATLAS and CMS (at more than 5σ) in the same sign WW mode. Evidences in the WZ mode
    - Used to constrain anomalous gauge couplings

WZ $5.6\sigma\ (3.3\sigma)$



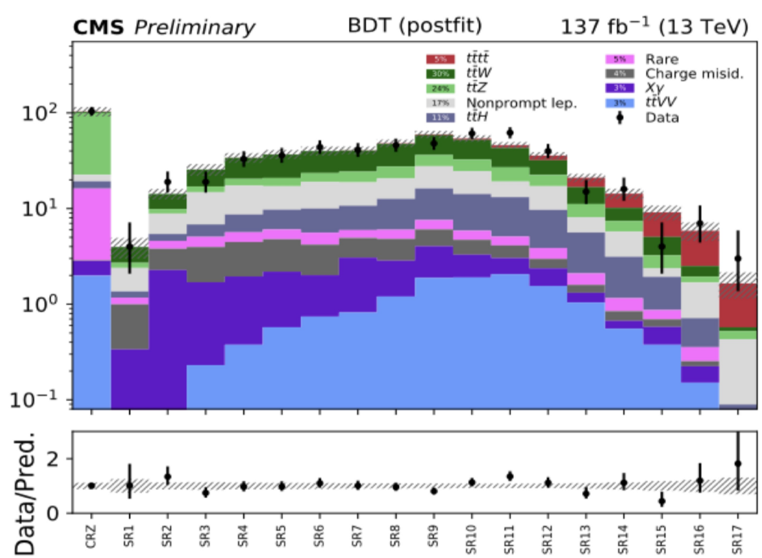
WW $5.5\sigma\ (5.7\sigma)$

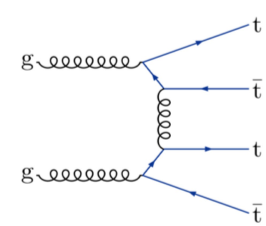


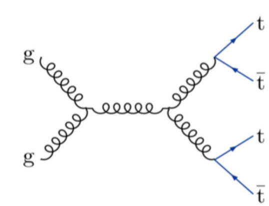
Top physics @LHC in a nutshell

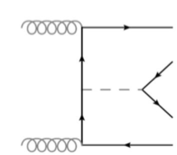
- The LHC is a top machine
  - Several precise results including cross-sections, mass and other properties
- It is a background for many analyses:
  - Hadronic and leptonic decays, depending on the W decay
  - Used as calibration candle for many performance studies like b- or W-tagging

- Measurement of rare processes like ttZ, ttbb and four tops. This last one will be presented by Lennart Rustige
  - Four tops is a very rare process (~10 fb) sensitive to the top Yukawa coupling (here using same sign dilepton, 3-leptons and 1 lepton+jets)!









Observed 2.6σ

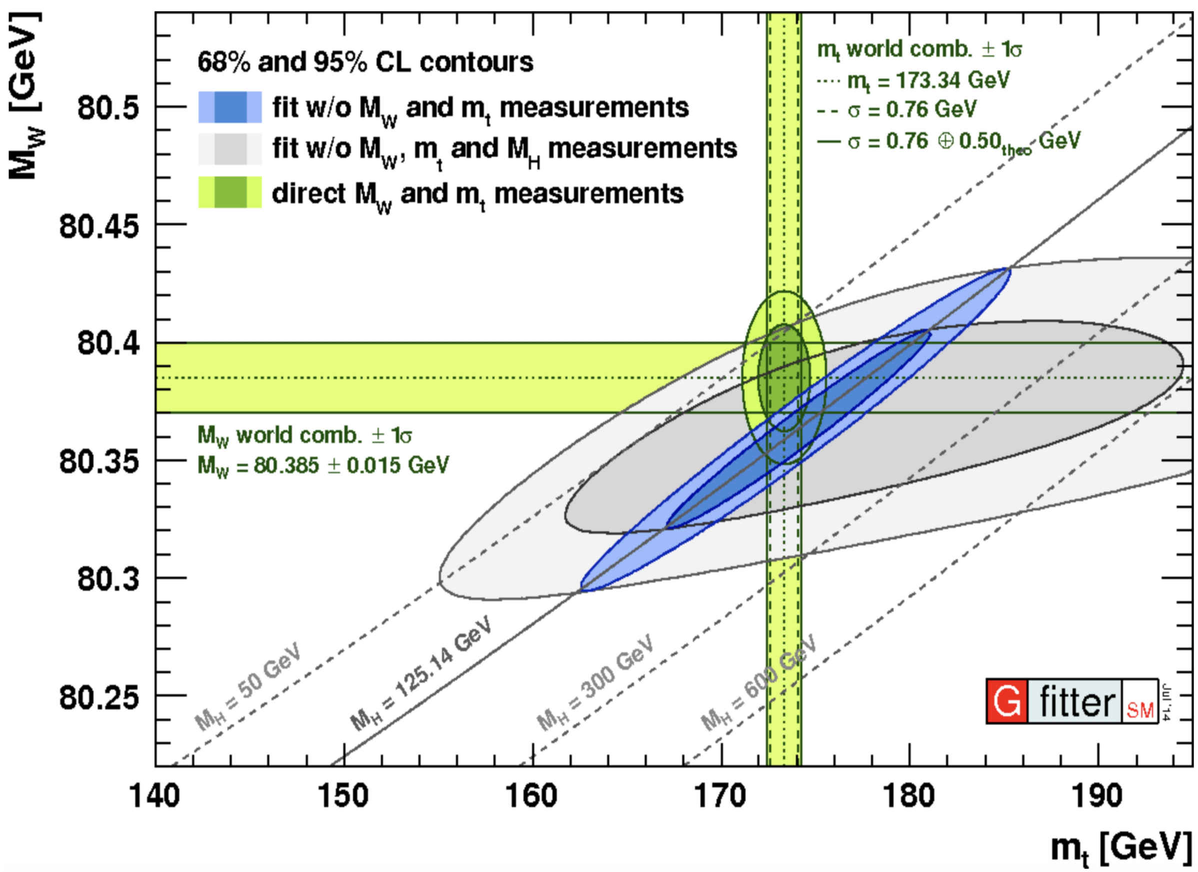
Expected (2.7σ)

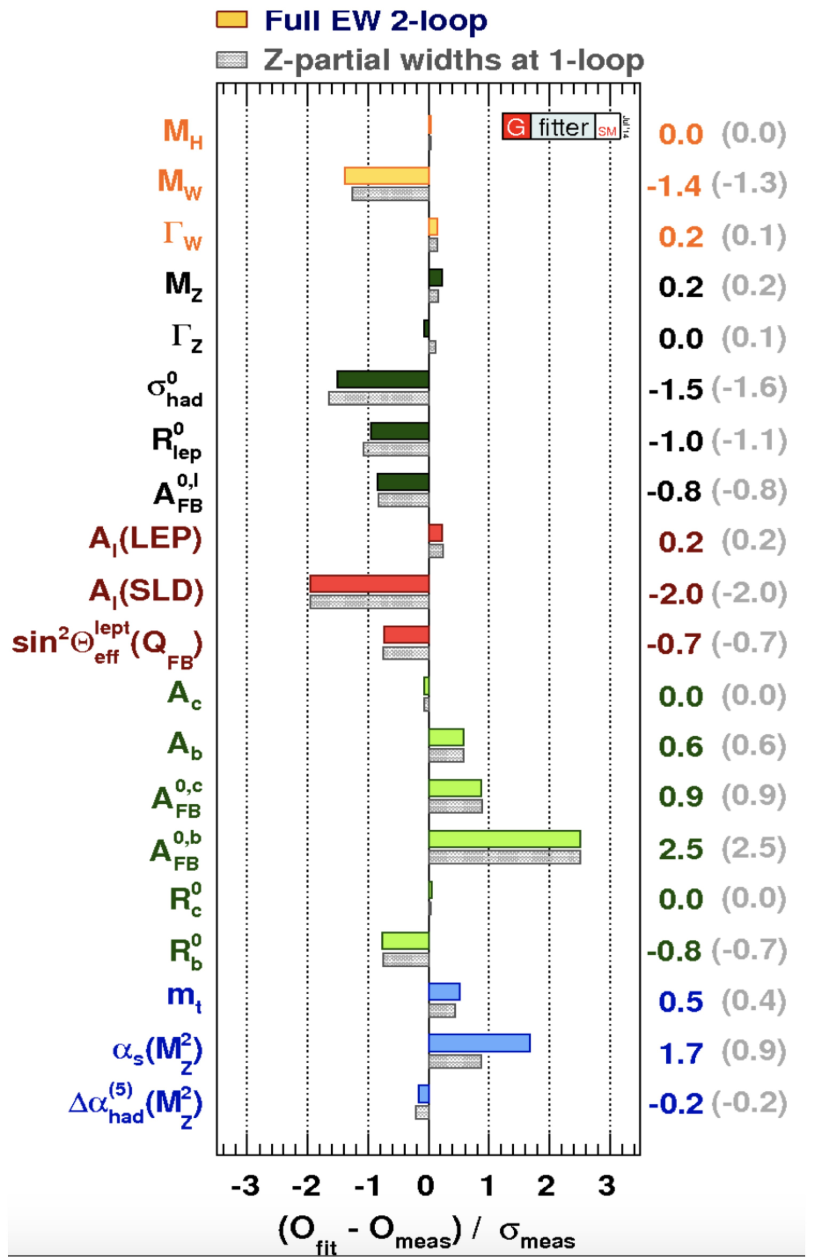
Limit on the top-Yukawa coupling:

$$y_t/y_t^{SM} < 1.7$$

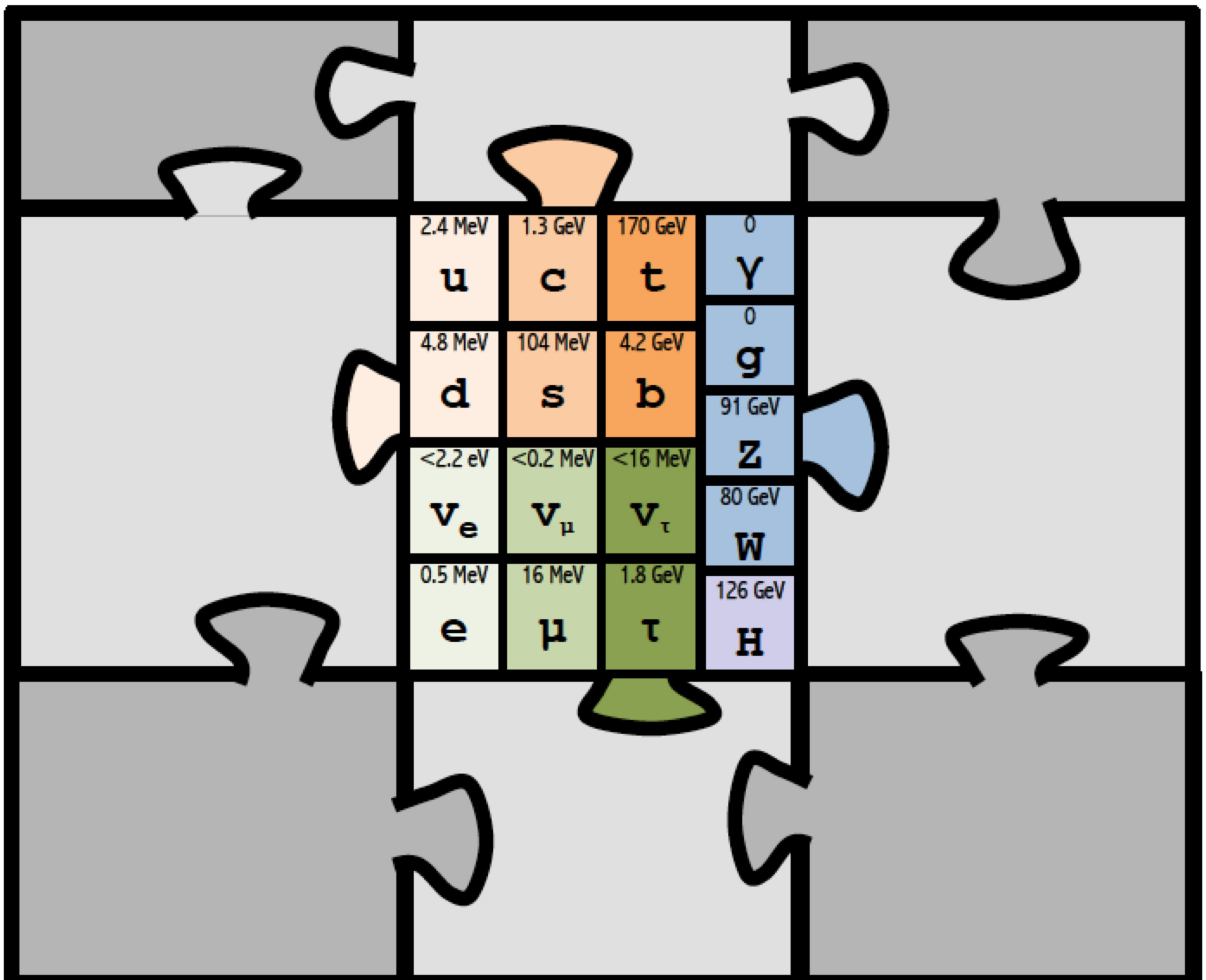
Coherence tests of the SM

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





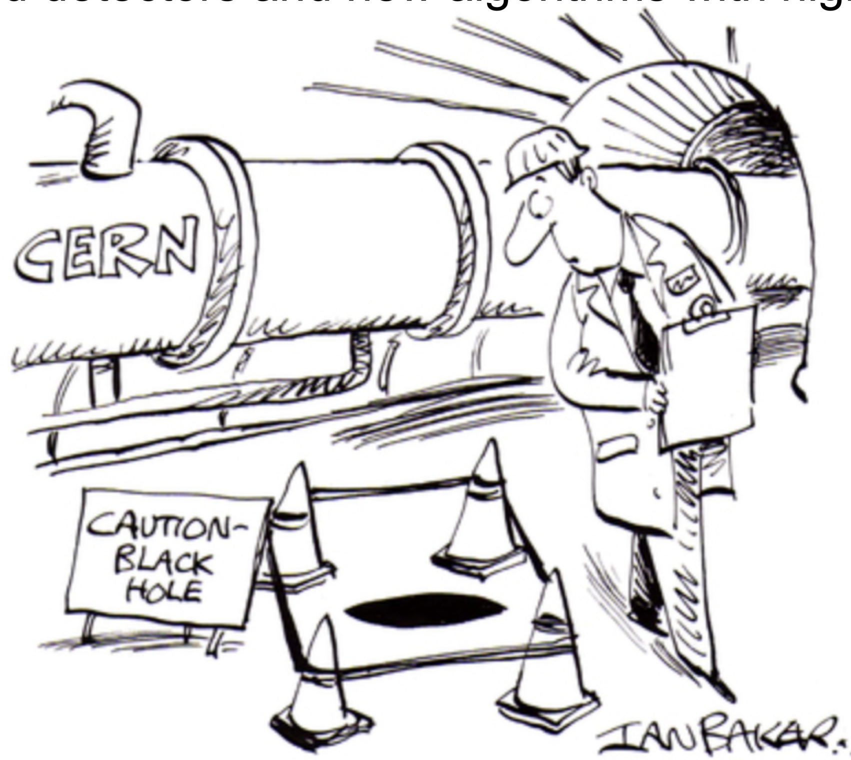
Is there something else beyond the SM?



Is there something else beyond the SM?

- Next Thursday and Friday we will discuss about direct searches of new particles/forces. But the best use of data by joining forces on searches/measurements
  - The SM is a laboratory itself for indirect searches!

- Potential to improve in the future crucially relies on:
  - Aggressive tuning of PDFs, low pT phenomenology
  - Improvements from theory on higher-order MCs and predictions
  - performance of upgraded detectors and new algorithms with high pileup

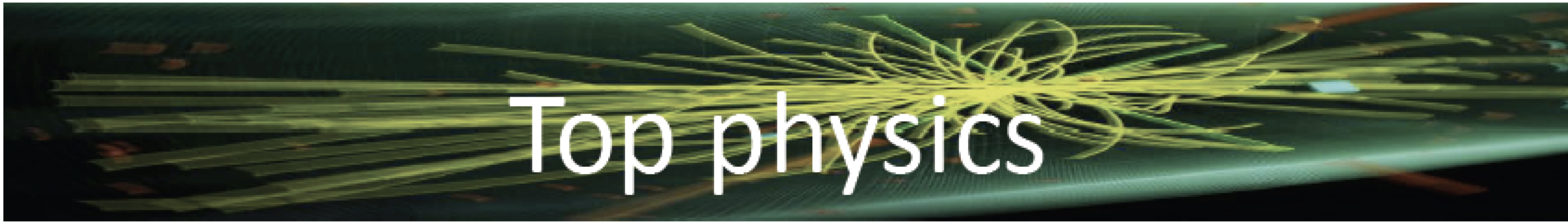


Merci

Gracias

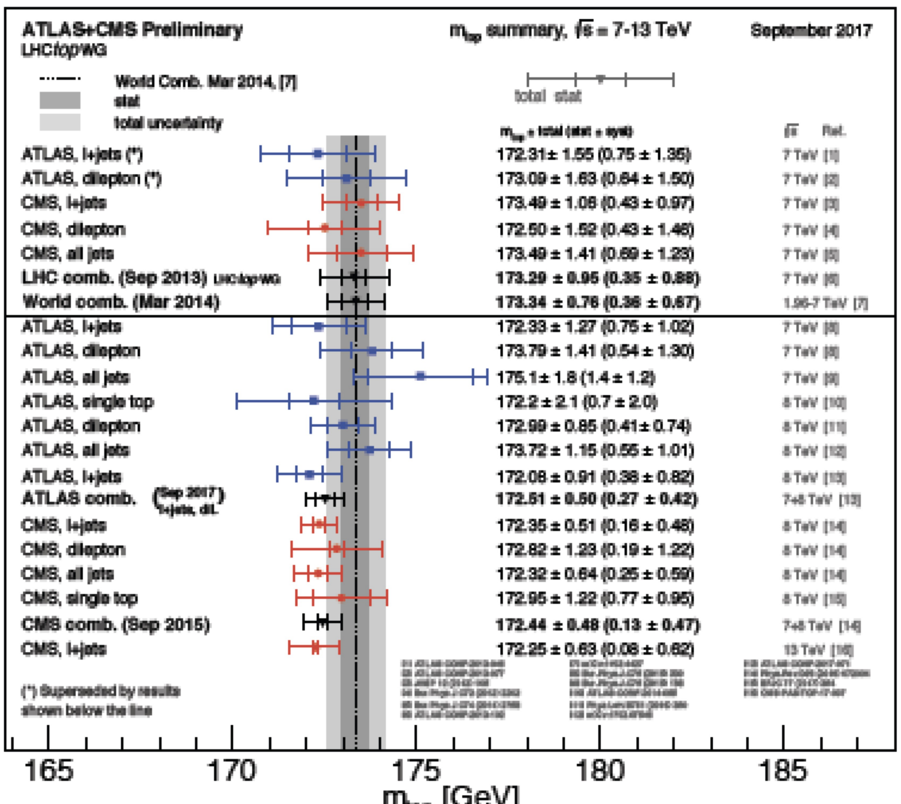
Thanks

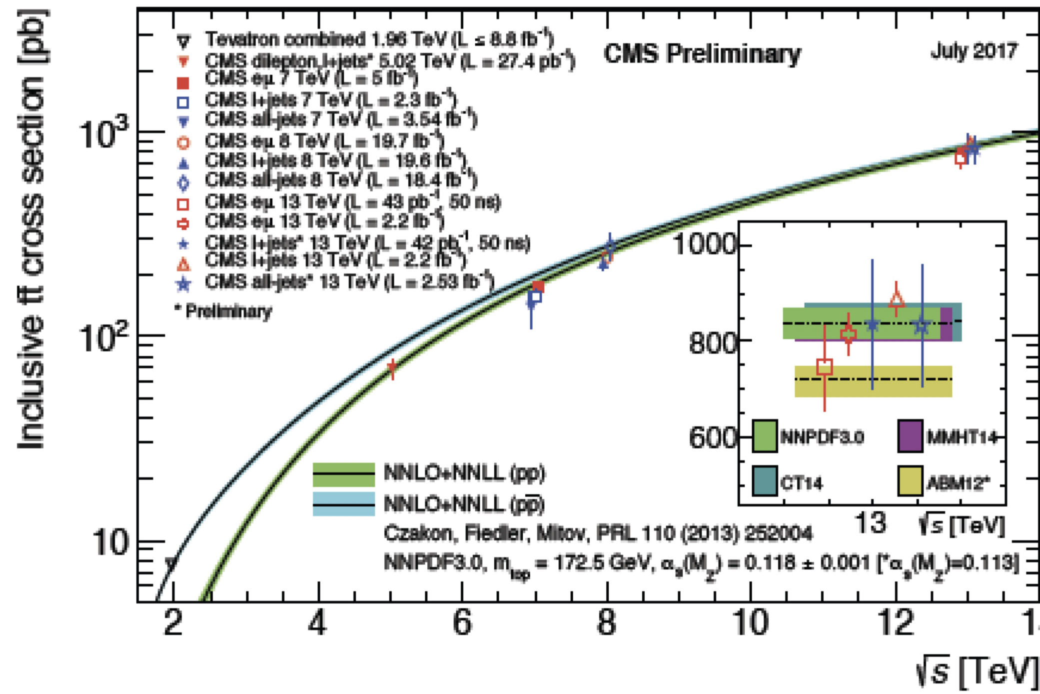
Backup



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)