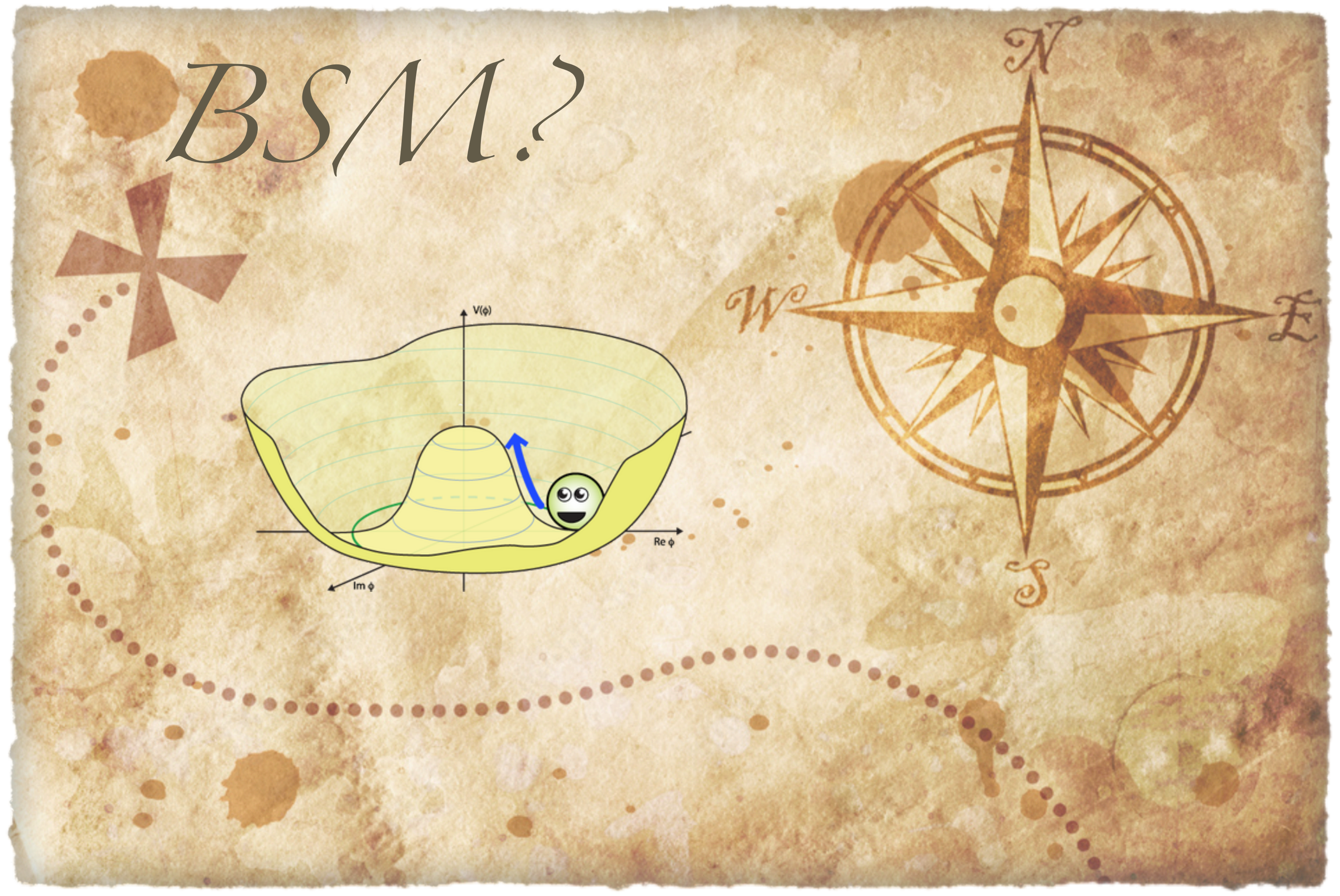
HEP / KEAL
@
NICPB / KBFI

cern.ch/bl4s
10th anniversary
powered by CERN & DESY

COMETA

CMS



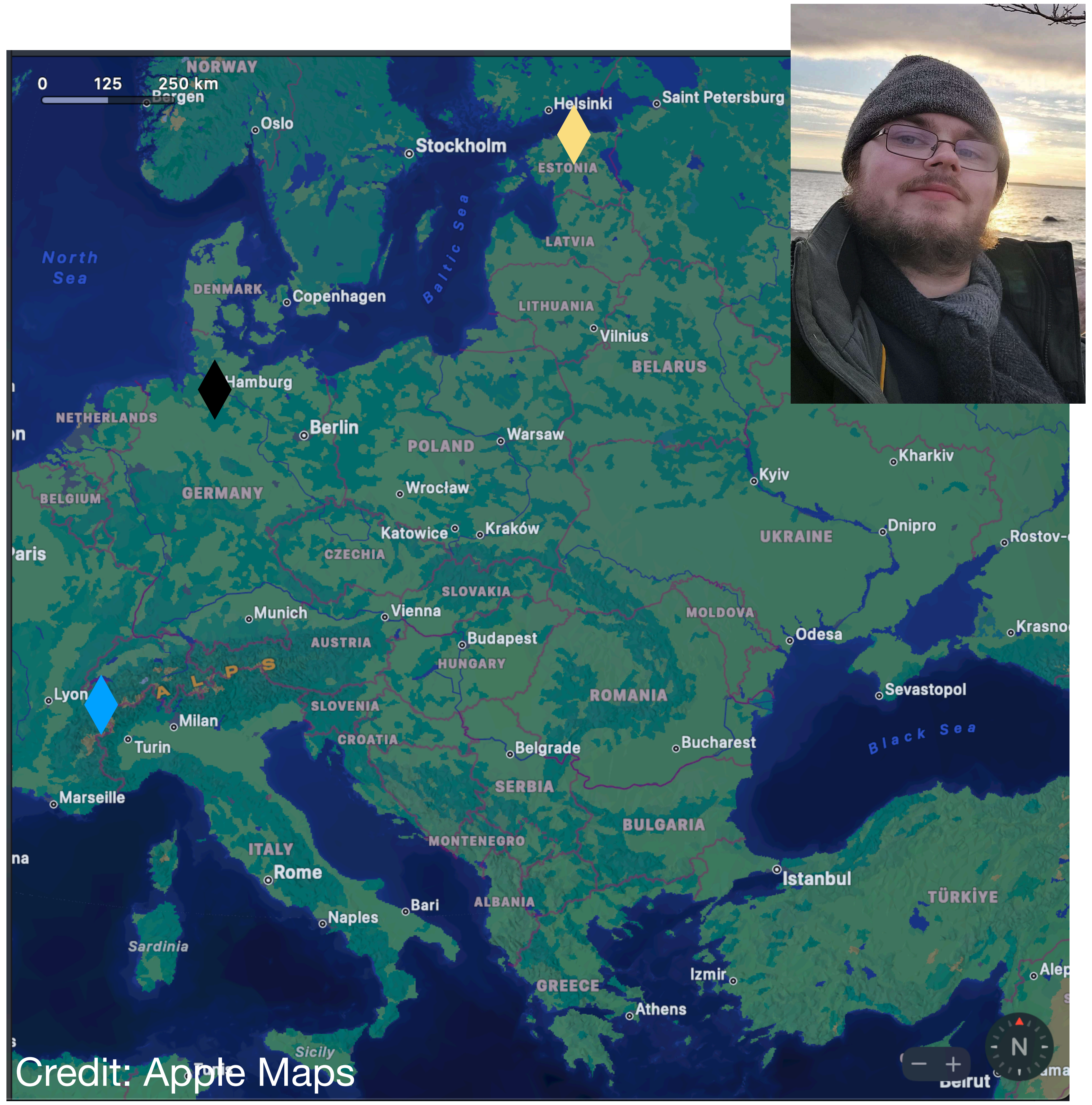

# Higgs physics on the edge

**Torben Lange (KBFI Estonia)**
**BL4S 2024 | CERN 20.09.2025**
**torben.lange@cern.ch**

Euroopa Liit
Euroopa Sotsiaalfond
Eesti
tuleviku heaks
Euroopa Liit
Siseministeerium
Eesti Teadusagentuur
Estonian Research Council
RVTT3 & TK202 “Fundamental Universe”

# Who am I?

- Torben Lange a particle physicist
- Studied in Hamburg 2012-2022 (B.Sc. - PhD.) ♦
- Worked half a year at CERN (2018) ♦
- Moved to Tallinn end of 2021 as a PostDoc
- Currently senior researcher in Tallinn, Leading the CMS analysis efforts in Estonia @KBFI
- Mostly focused on rare Higgs boson processes since 2015 and Di-Higgs production since 2019



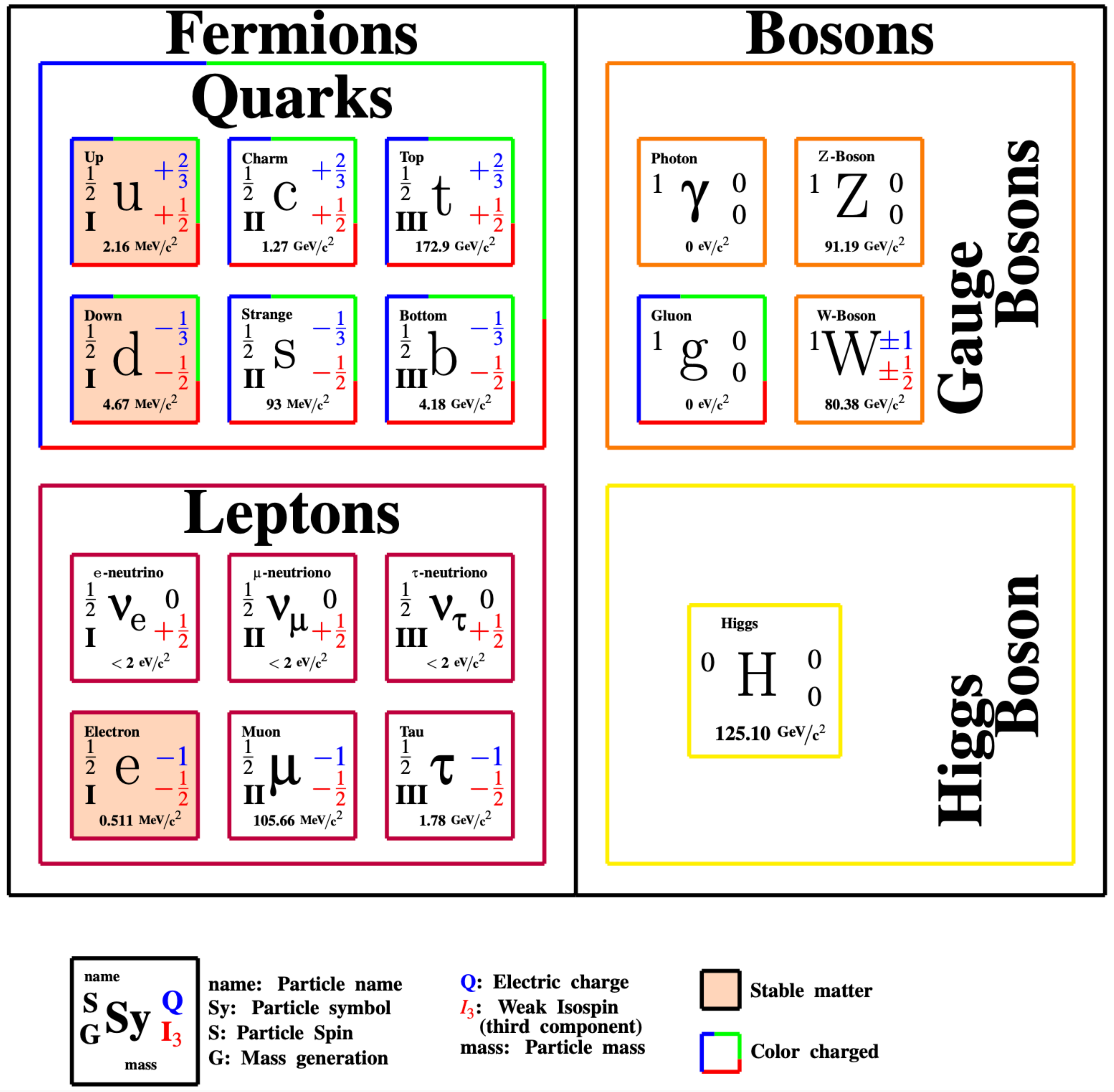
# Particle physics?

Credit: CERN (Daniel Dominguez, Arzur Catel Torres)

# Particle physics?

- Explaining the world via the interaction of the smallest particles
- Similar to periodic table in Chemistry, we have the Standard Model (SM)
- Matter is made up of leptons and quarks (fermions) interacting via bosons
- These interactions explain three our of four main forces: weak, strong and electromagnetic

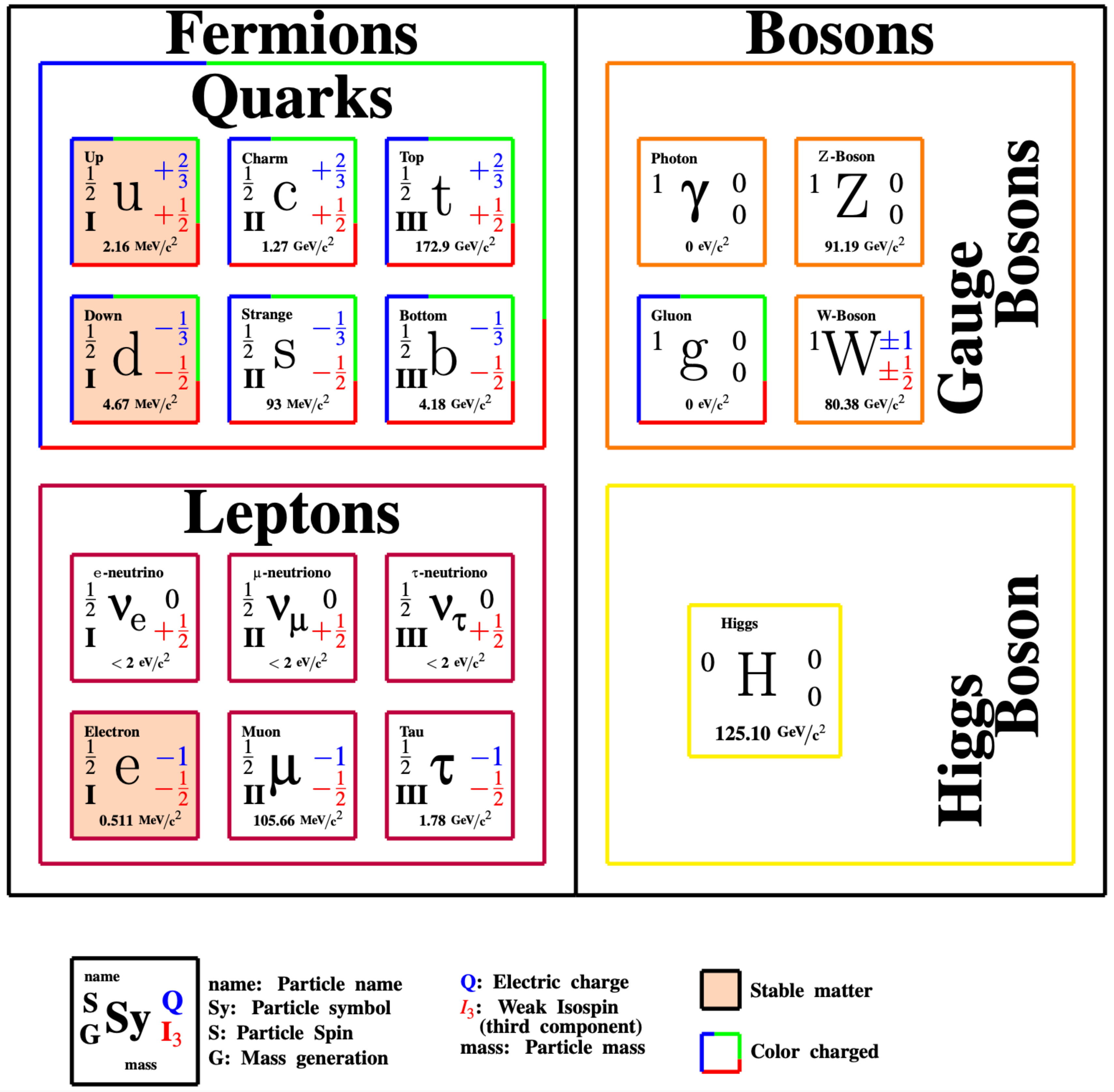
Credit:Thesis T.Lange



# Particle physics?

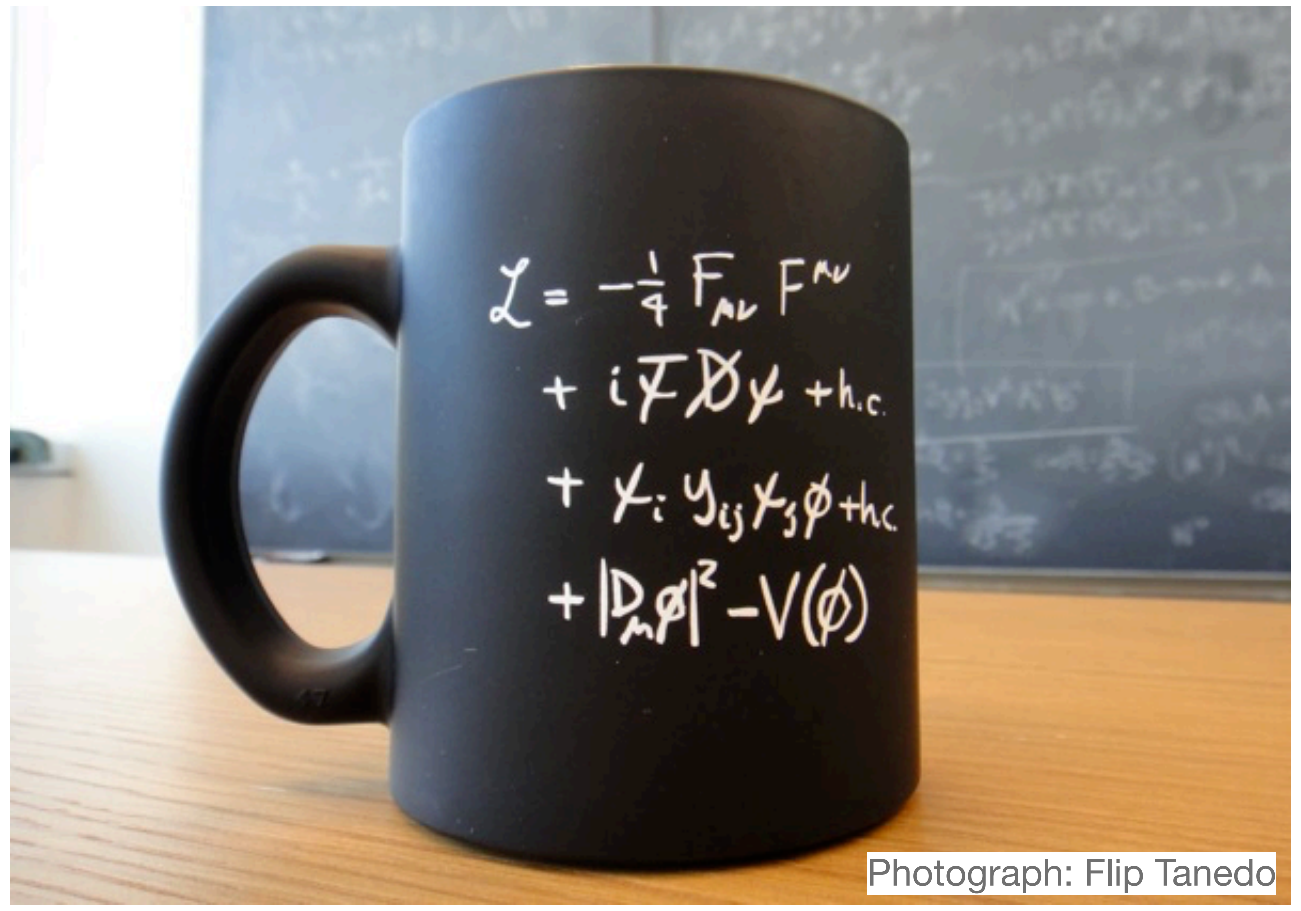
Credit:Thesis [T.Lange]

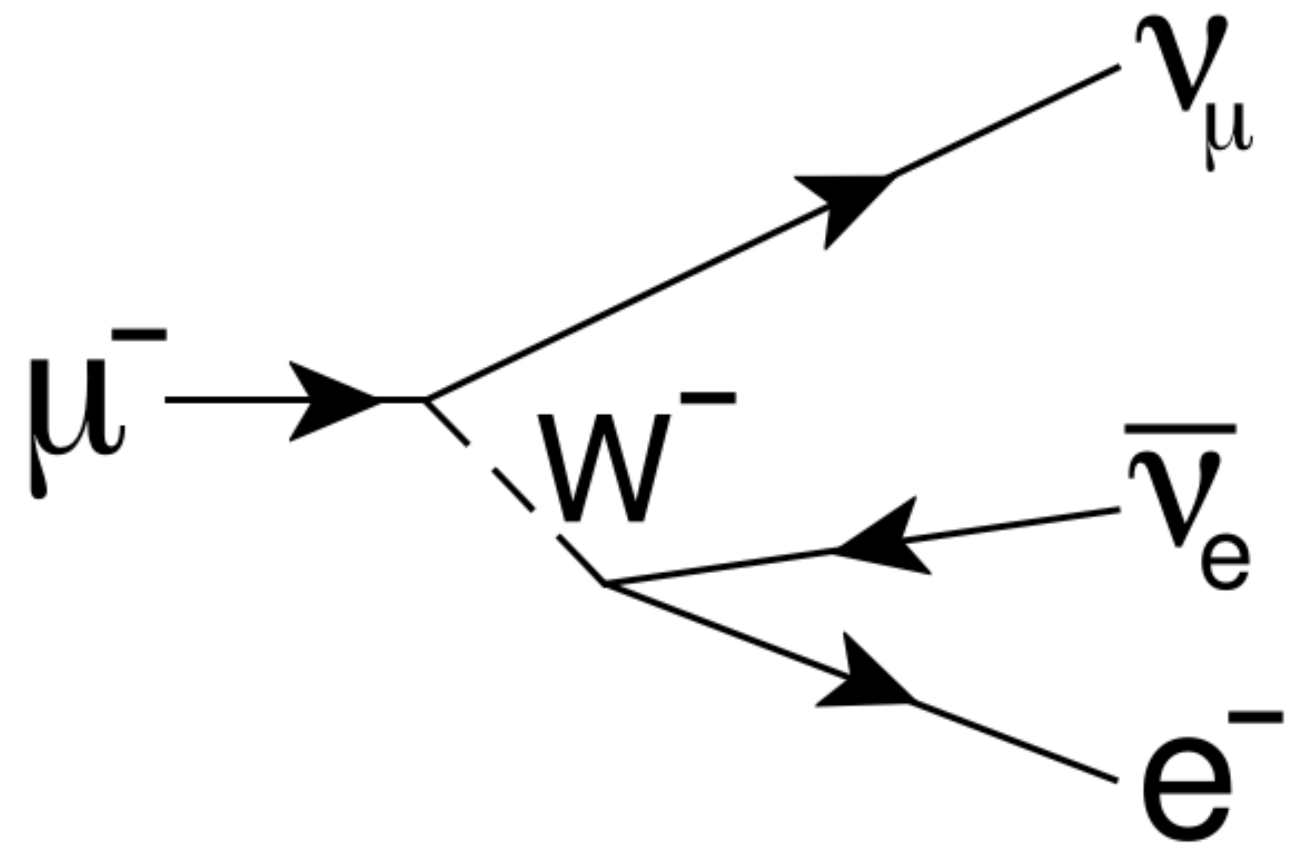
- Electromagnetic force: Everyday life from chemistry to magnets and electricity, binds electrons to atomic nuclei, also the reason why you don't fall through the floor
- Strong force: Binds atomic nuclei together counteracting the electromagnetic force on small scales -> strong
- Weak force: Radioactivity and fusion, allows fundamental particles to change
  e.g muon->electron or up -> down quark, this leads atoms to decay but also allows for fusion inside stars



# Particle physcis?

- Behind all of this is a lot of complicated math
- Simple interactions can be several dozen pages of integrals worth of math in the lowest order approximation
- Thankfully for experimentalist like me, we can draw Feynman diagrams out of easy to understand building blocks that correspond to precomputed integrals
- Theory gives us rules how to draw these, what processes to expect and at which rate


Photograph: Flip Tanedo

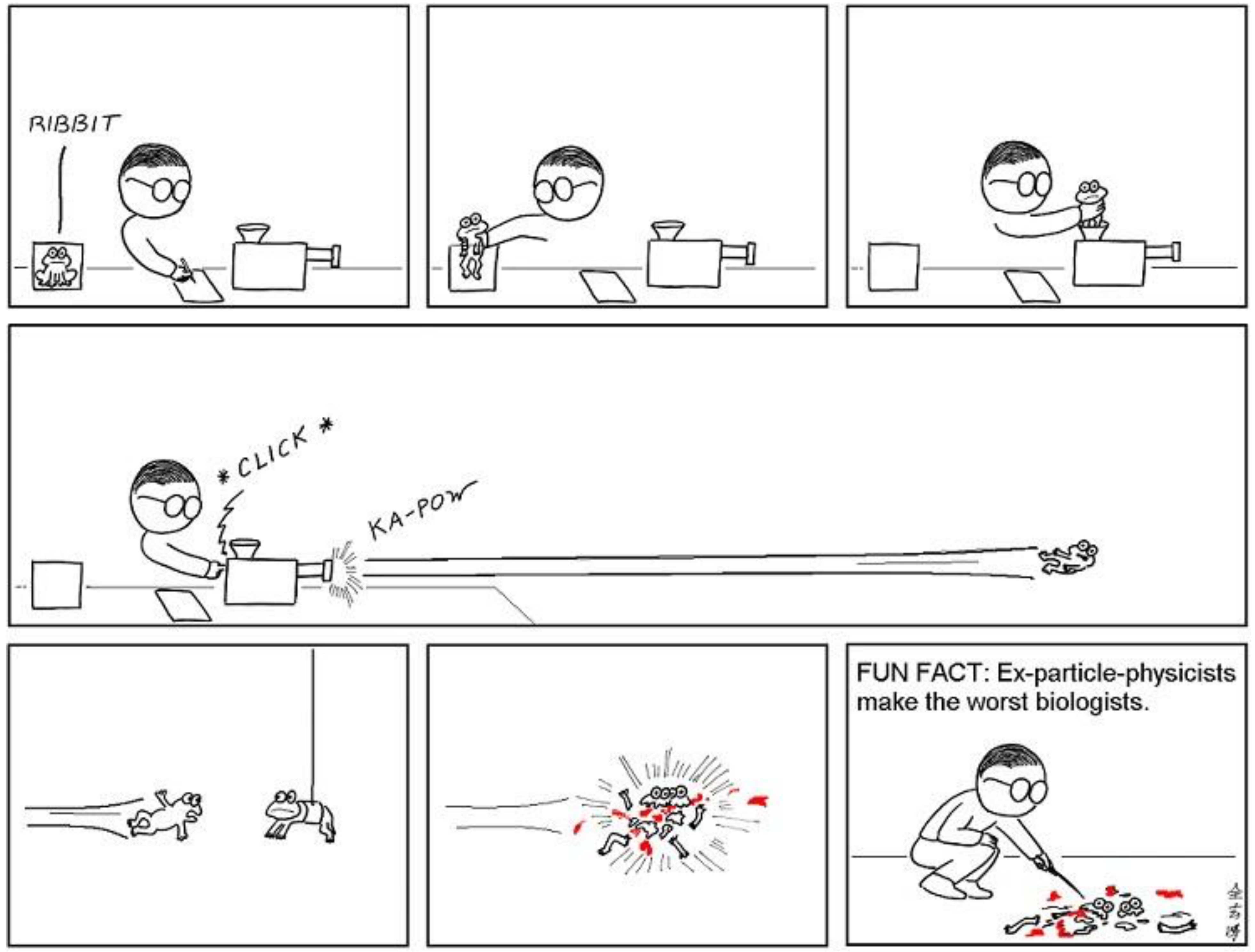


# Particle physcis?

How do we learn (more) about all this?

# Particle physcis?

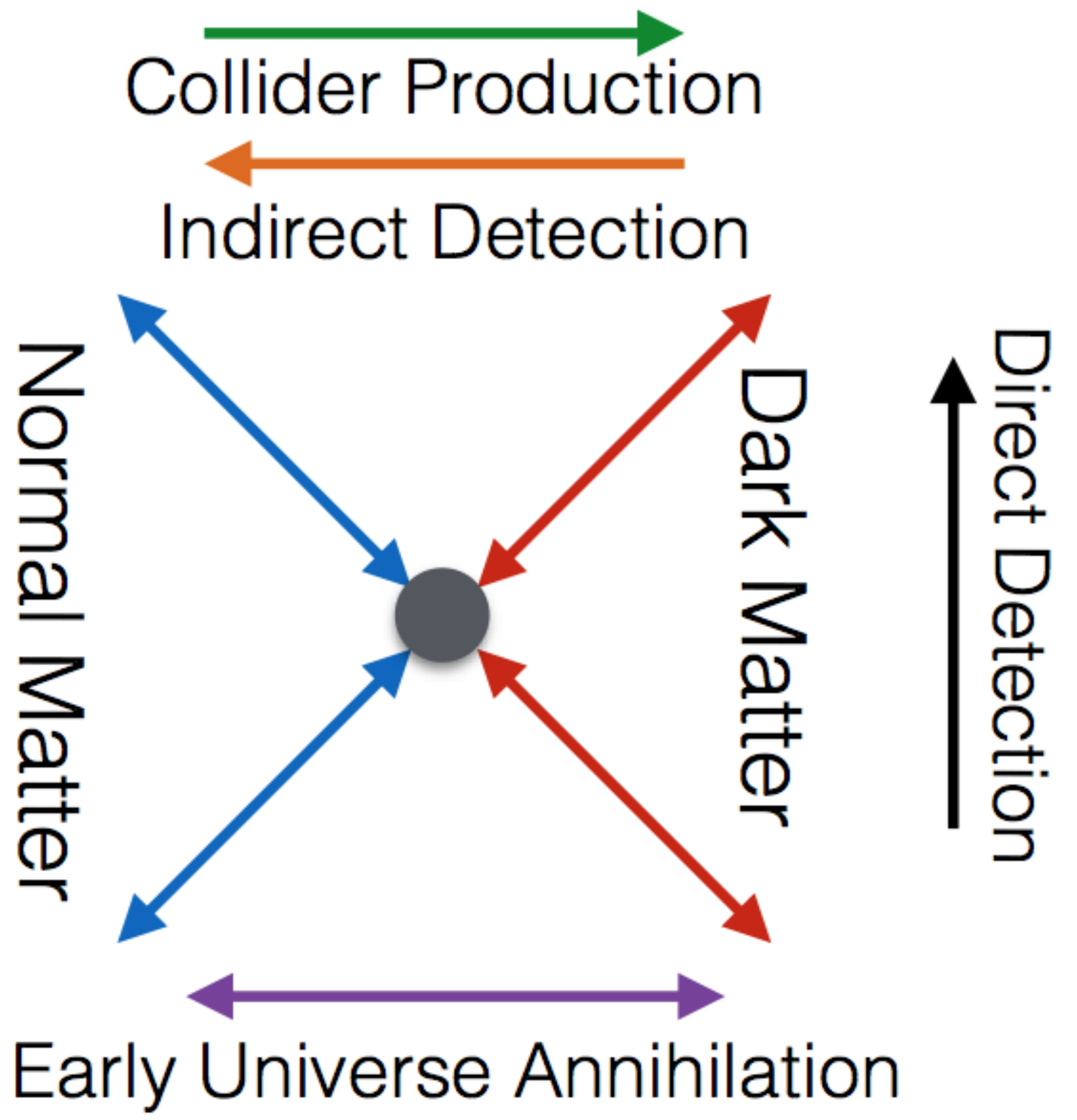
Credit: Abstruse Goose: High-Energy Biology




How do we learn (more) about all this?

# Particle physcis?

Example:
Searching for a new particle / Dark Matter

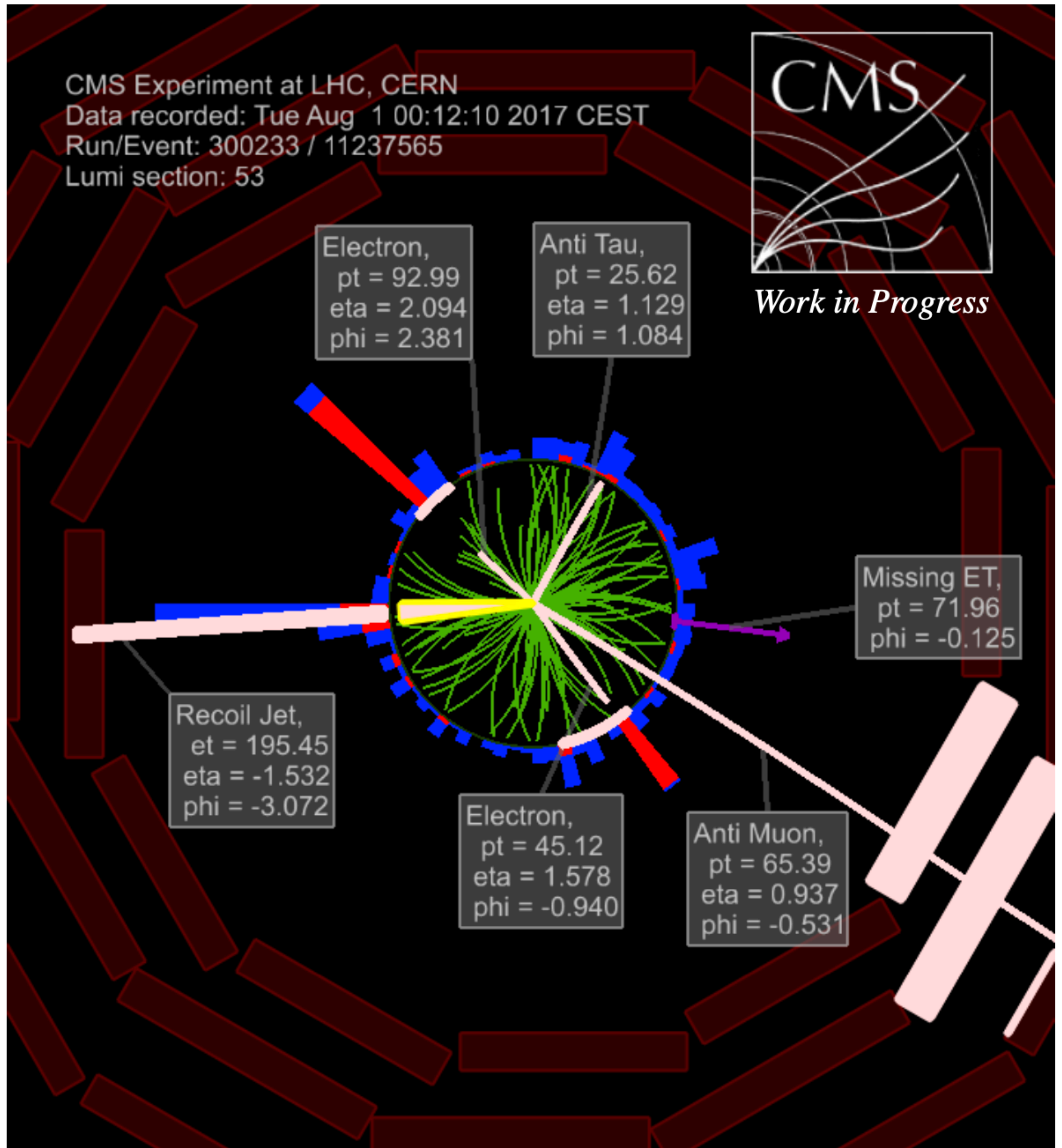



Credit: Mathew Buckley

How do we learn (more) about all this?

# Colliders/LHC/CMS

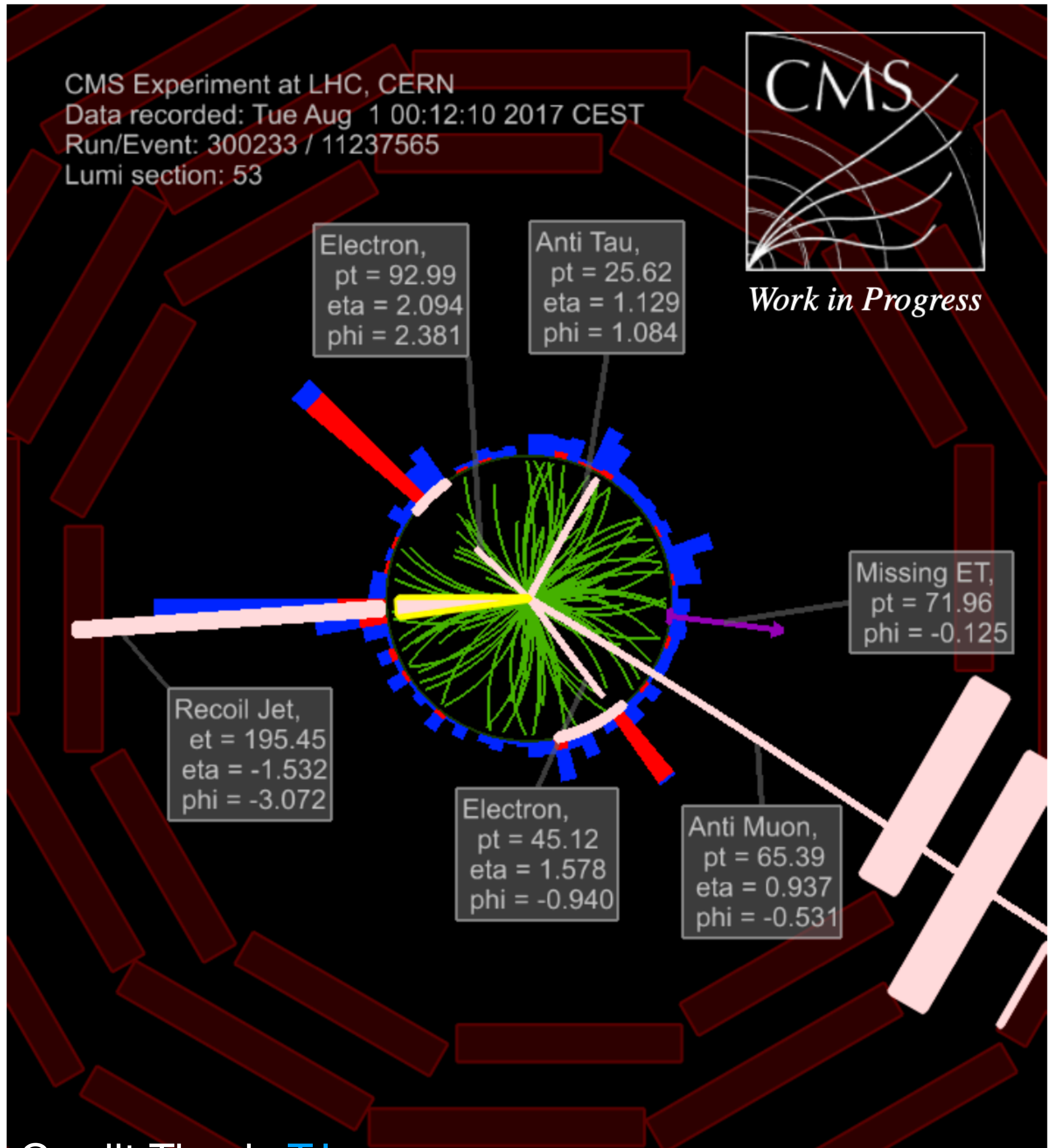
- We collide particles such as protons (hydrogen nuclei), electrons, positrons and muons at particle colliders
- The resulting collisions produce an explosion of hundreds to thousands of particles recorded by our experiments such as CMS
- We then analyze these “events”, reconstructing different particles coming out of the collision



Credit:Thesis T.Lange

# Colliders/LHC/CMS

- Based on this reconstruction, we can select a certain class of events we are interested in e.g. based on the number and energy of the resulting particles
- For this selection using statistic methods we then can compare the probability of different hypotheses I.e if its more likely that a certain process is present or not
- Example from the video: Higgs boson discovery



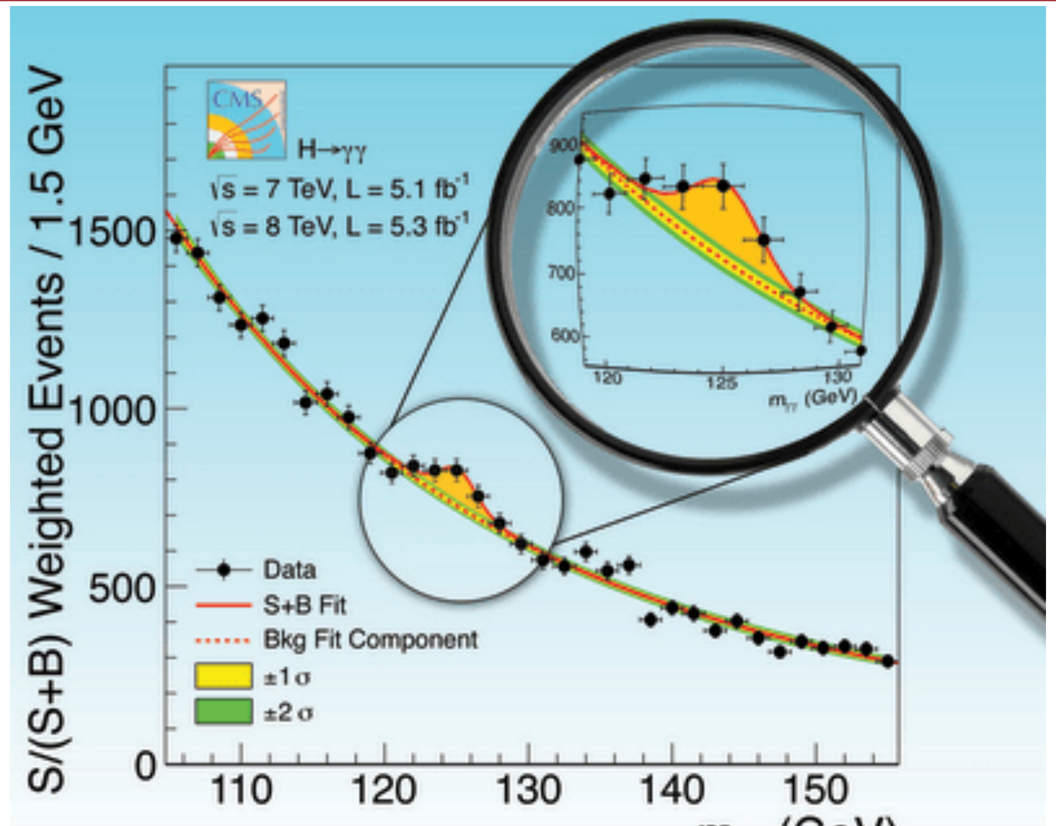
Credit:Thesis T.Lange

# Colliders/LHC/CMS

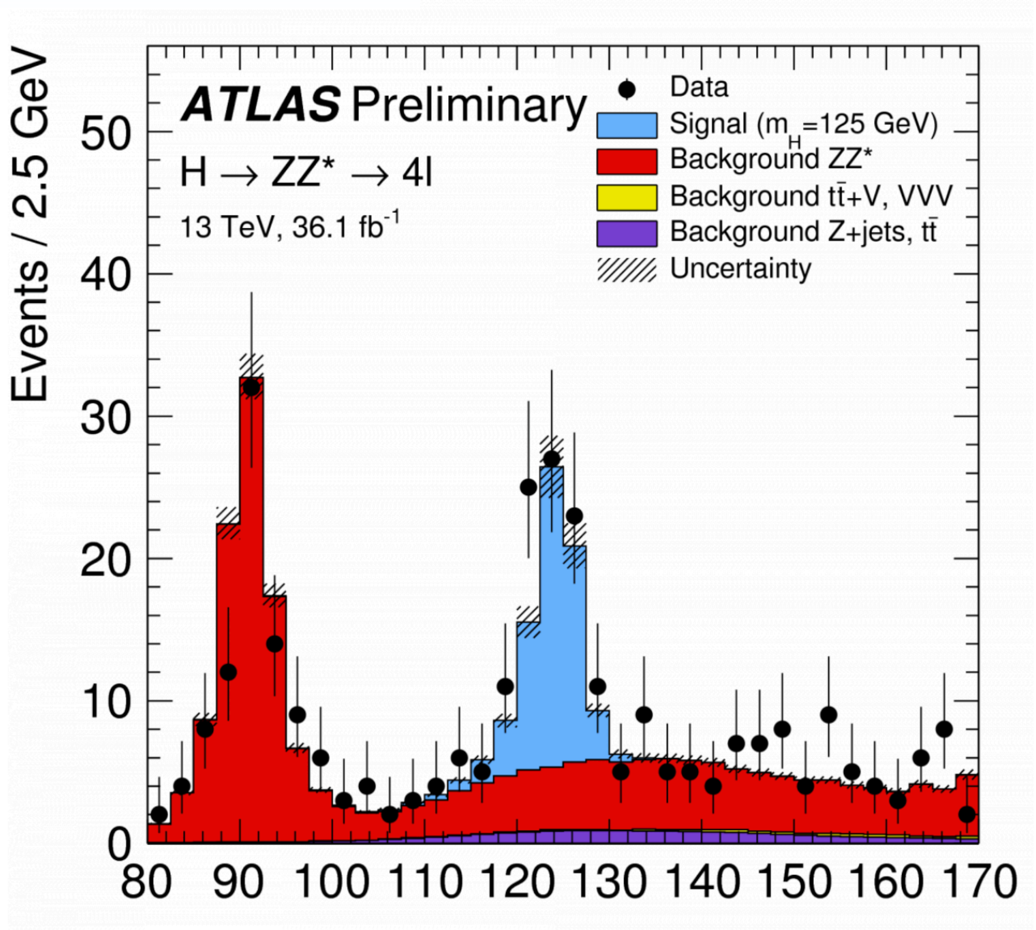
- Based on this reconstruction, we can select a certain class of events we are interested in e.g. based on the number and energy of the resulting particles

- For this selection using statistic methods we then can compare the probability of different hypotheses I.e if its more likely that a certain process is present or not

- Example from the video: Higgs boson discovery



Credit: CMS

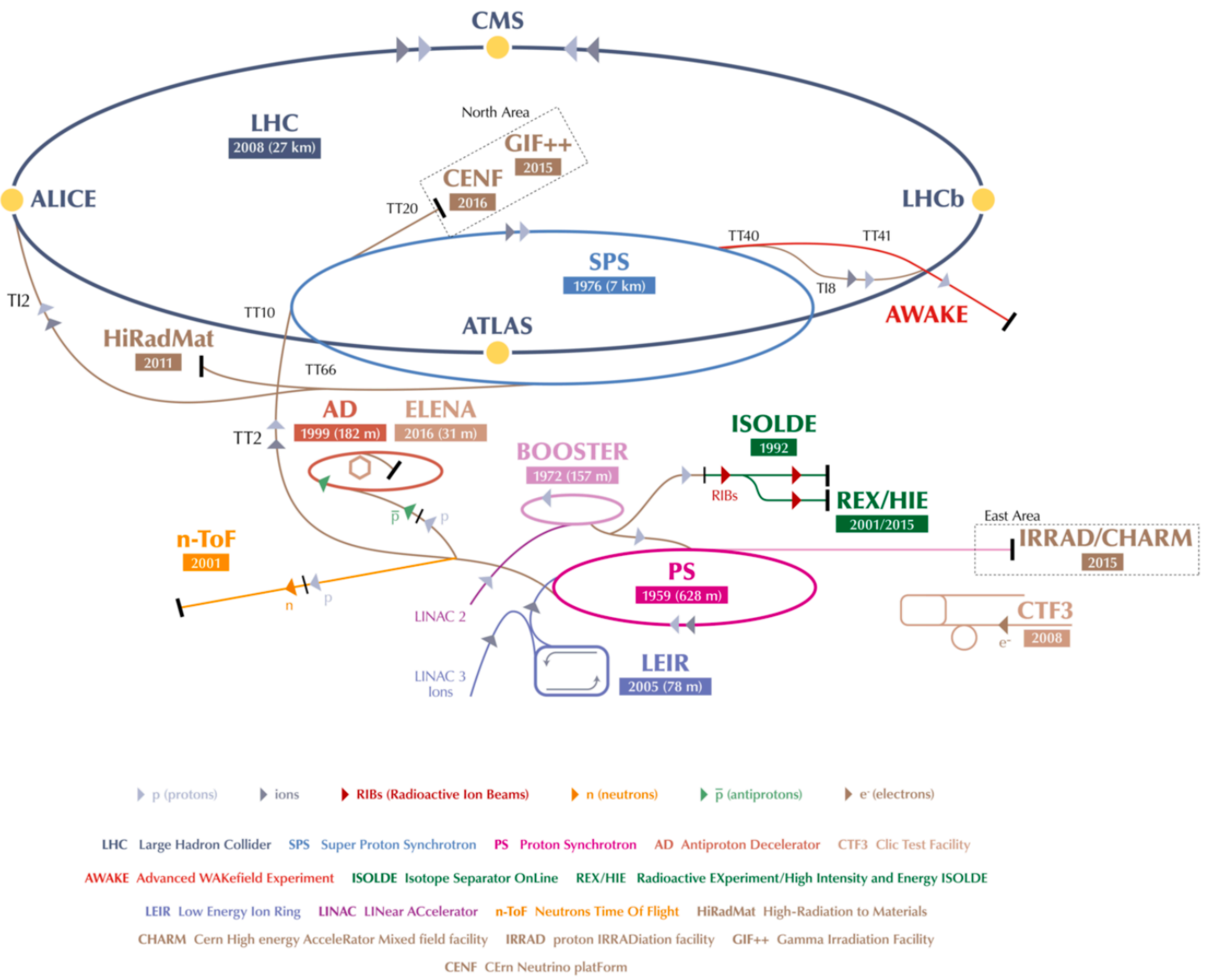


Credit: ATLAS

# Colliders/LHC/CMS

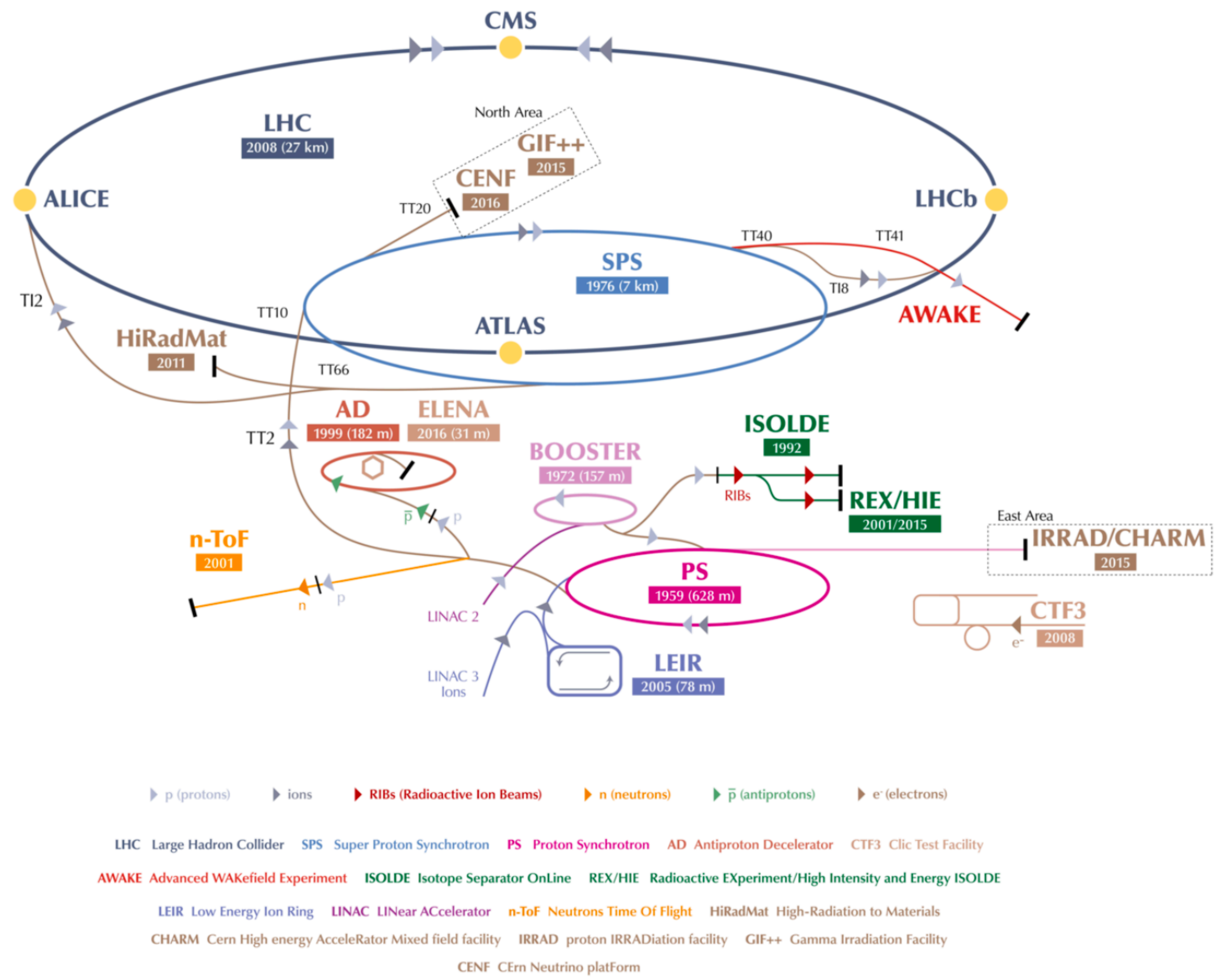
- We usually have two type of colliders, hadron colliders like the LHC and lepton colliders
- Hadron colliders use composite particles like protons at the highest energies allowing to probe all sorts of physics and with a large amount of data
- Lepton colliders on the other hand, while featuring lower energy, offer “cleaner” collisions, allowing for easier to analyze events and subsequently high precision
- I.e Discovery vs. precision machine

Credit: CERN



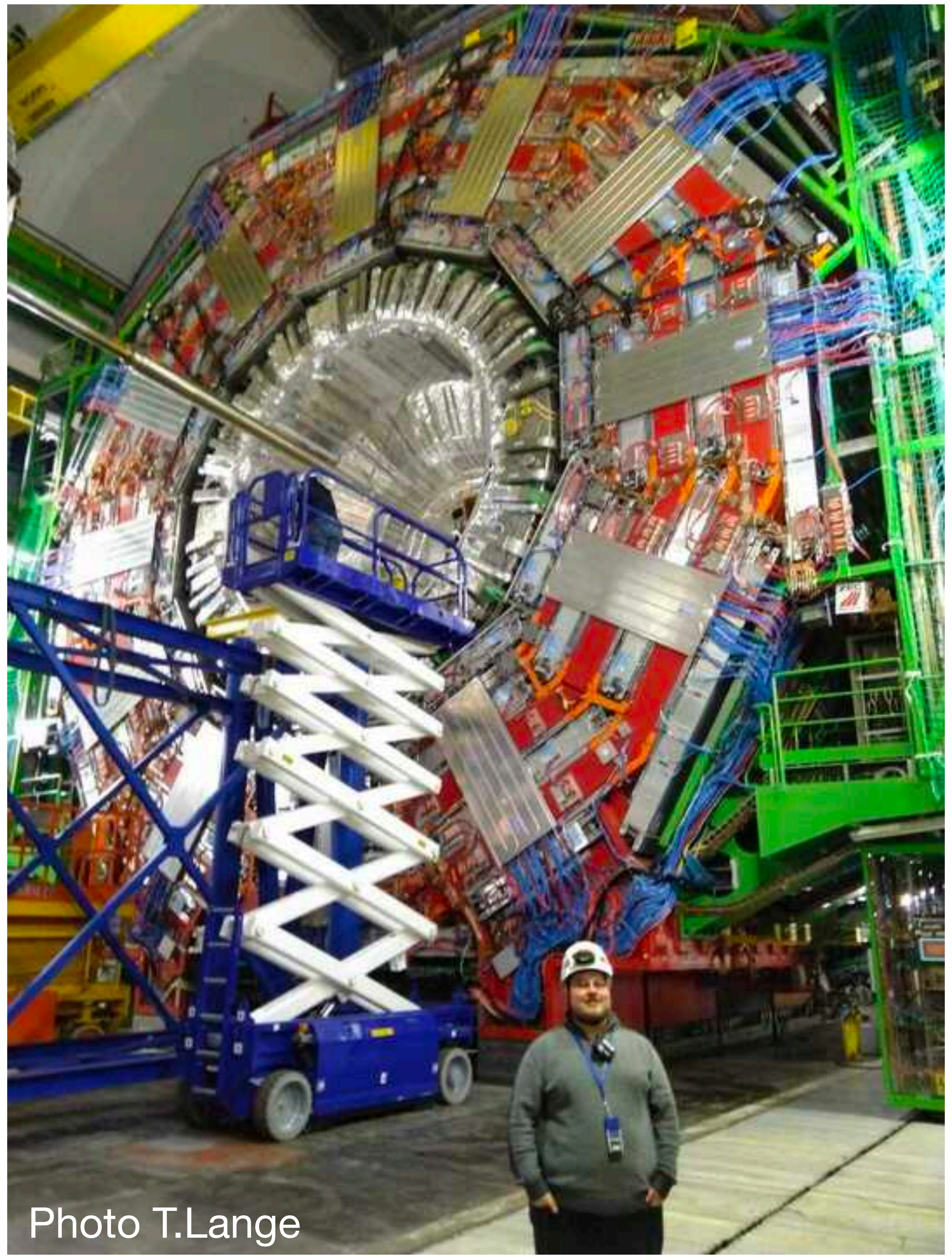
# Colliders/LHC/CMS

- To achieve the high energies at the LHC, a whole chain of accelerators is needed
- LHC is a circular collider, allowing to collide packages of particles repeatedly at a high rate
- This is not possible with leptons (at these energies) due to energy losses for lighter particles $m_{proton} >> m_{electron}$



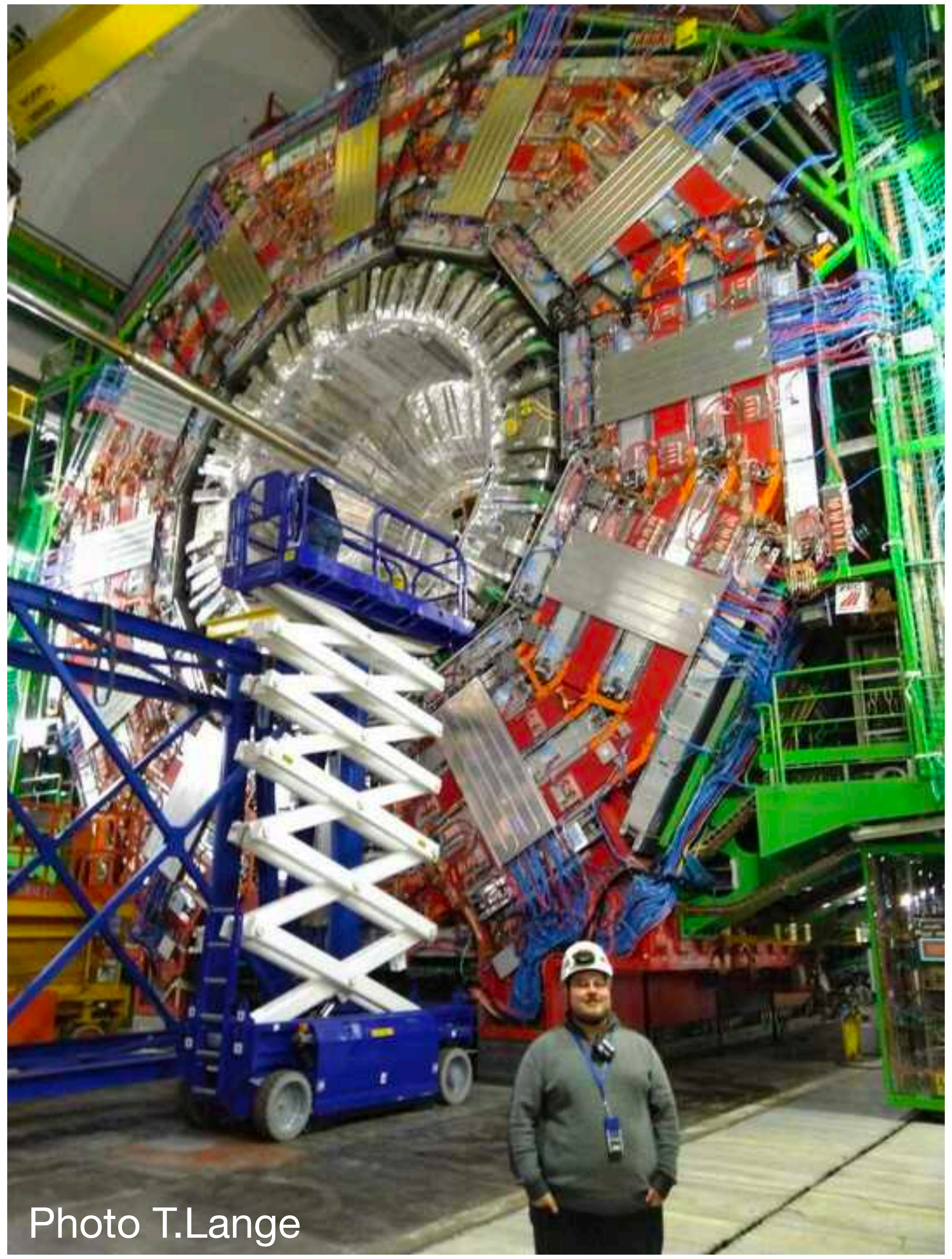
# Colliders/LHC/CMS

- LHC collides these packages of $10^{11}$ protons more than 600 million times per second at each interaction point/experiment
- In each of these crossings up to 70 actual proton-proton collisions happen
- Of these we read out about 100k/s and record/analyze a few 100/s
- Trigger recognizes interesting events to read out/record and make the amount of data manageable



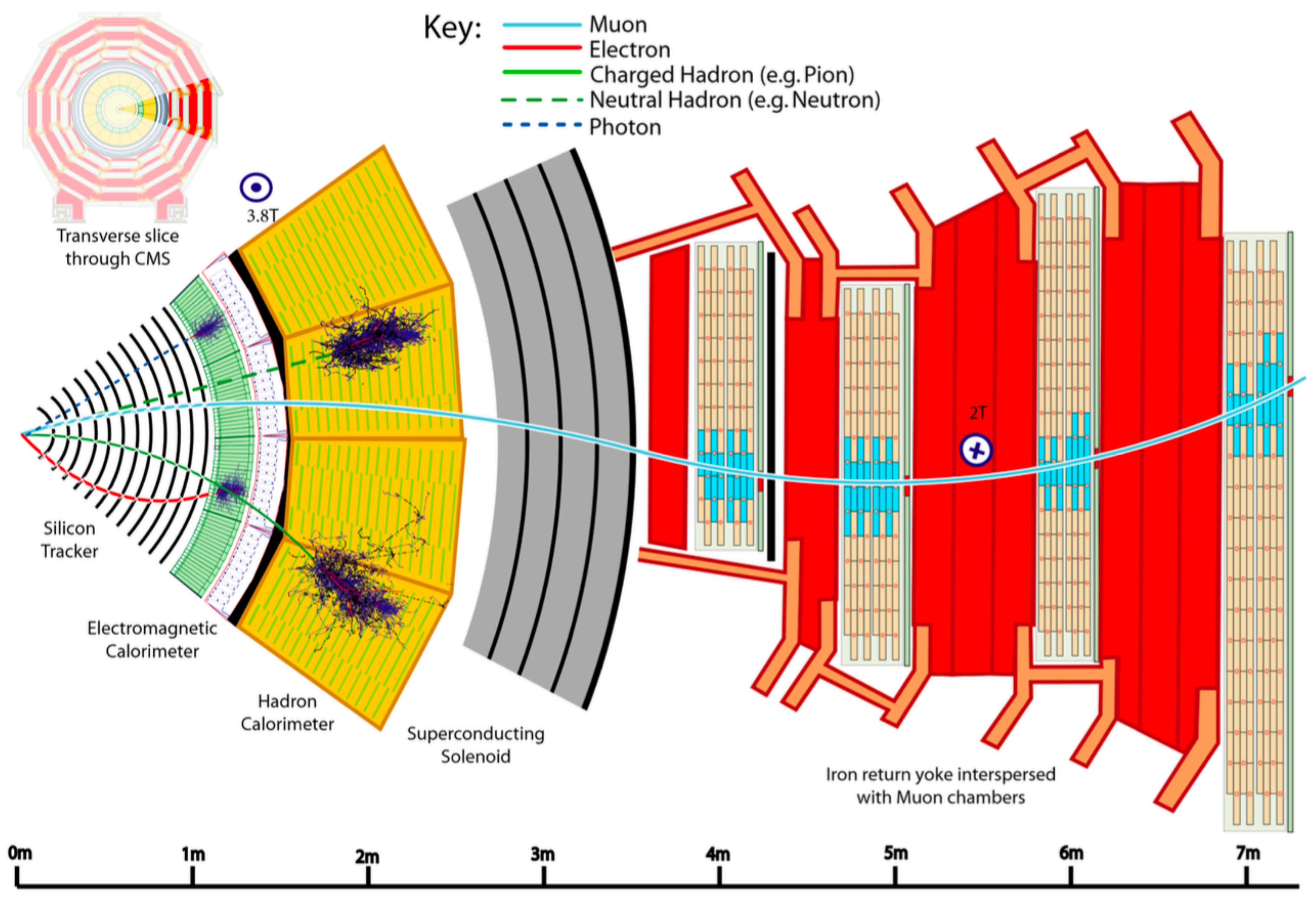
# Colliders/LHC/CMS

- The CMS experiment sits at one of the LHCs collision points
- Together with ATLAS one of the “general purpose” experiments
- ALICE and LHC-b more focussed on specific physics (In interactions and b-quarks/jets)



# Colliders/LHC/CMS

- Collisions produce hundreds/thousands of particles
- Higher energetic ones travel through most of the detector outward from the collision point
- Depending on their interactions with different parts of the detector we can identify them
- Similar to the detectors you have seen: Trackers + Calorimeters, Magnet to bend charged particles

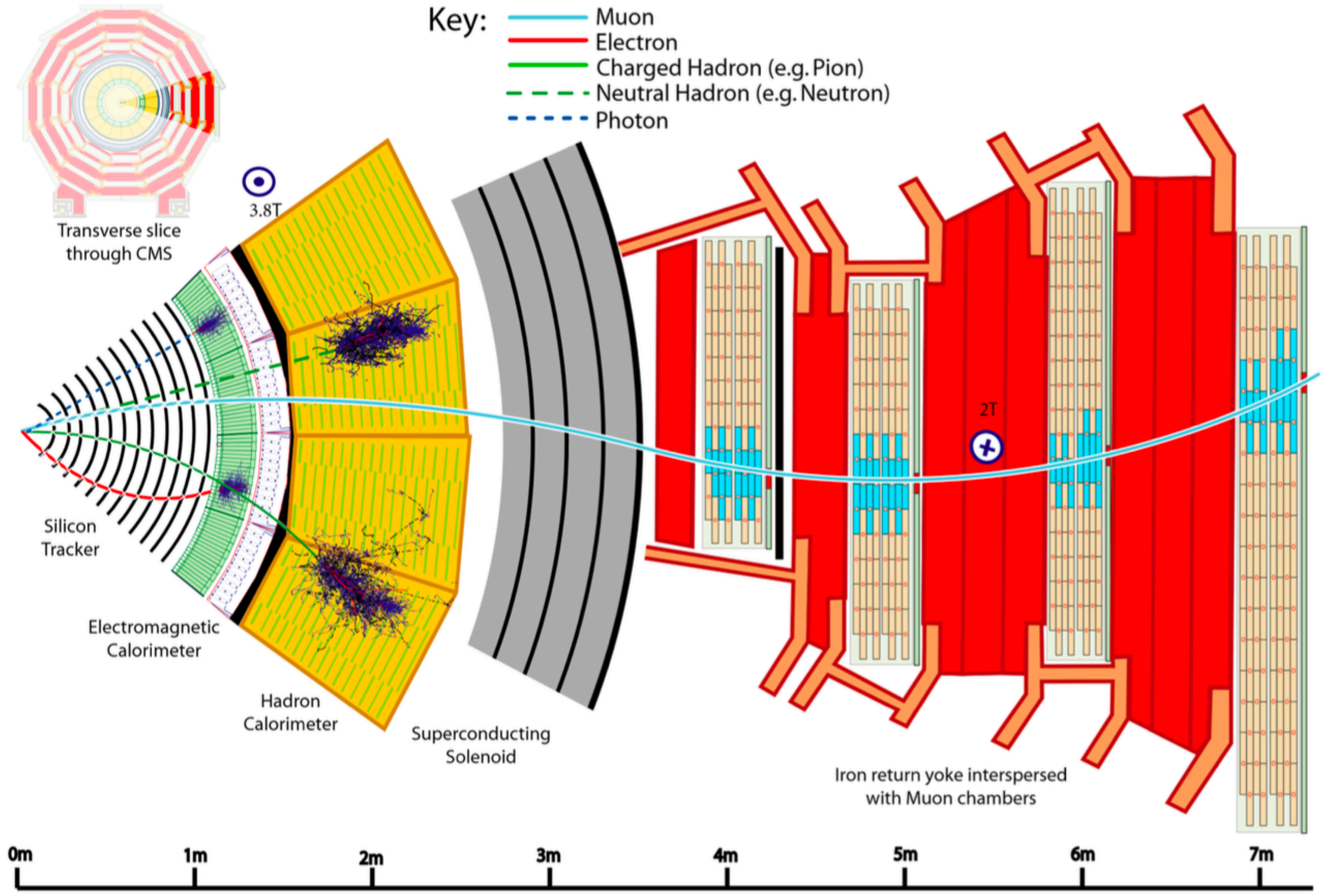



Credit: CMS

# Colliders/LHC/CMS

- Depending on the processes we are interested in, different particles are produced, most of them decaying almost instantly

- However, combining the different particles we can reconstruct, we can also reconstruct these fast decaying ones that produced them (or the ones that produced them, like the Higgs: H->WW->$\mu\mu$ + Neutrinos)



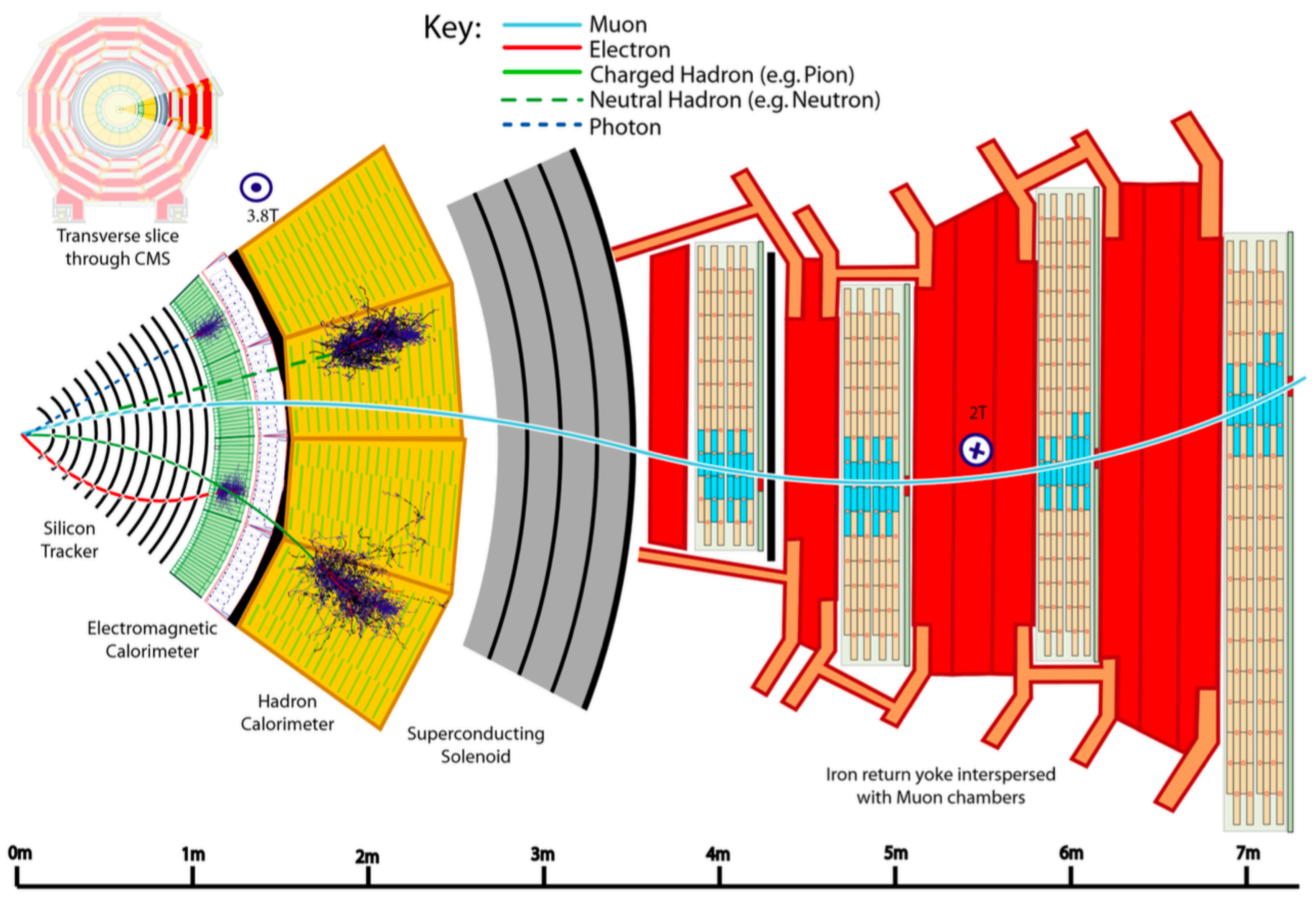

Credit: CMS

# Colliders/LHC/CMS

- Often we use machine learning (ML) both for both reconstruction of these particles as well as identifying events of interest

- I.e events that more likely contain our process of interest (signal) compared to other processes (background)

- To store/analyse all these events, produce simulation for signals and backgrounds that help us in terpreting our results and train said ML, we distribute data around the whole globe




Credit: CMS

# Particle physics?

Lets watch again and see if we understand better!

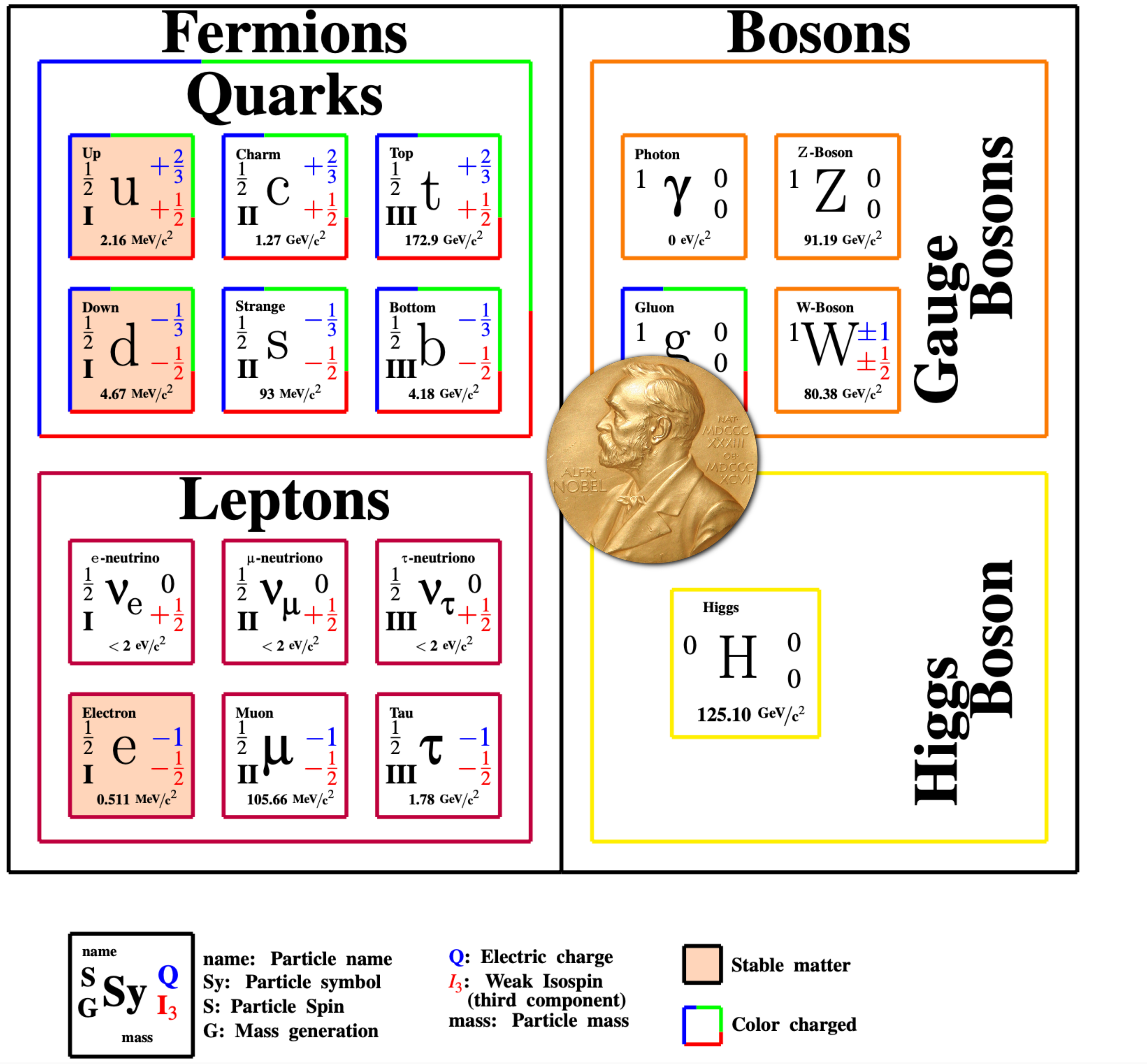
Questions so far?

Credit: CERN (Daniel Dominguez, Arzur Catel Torres)

# Higgs boson?

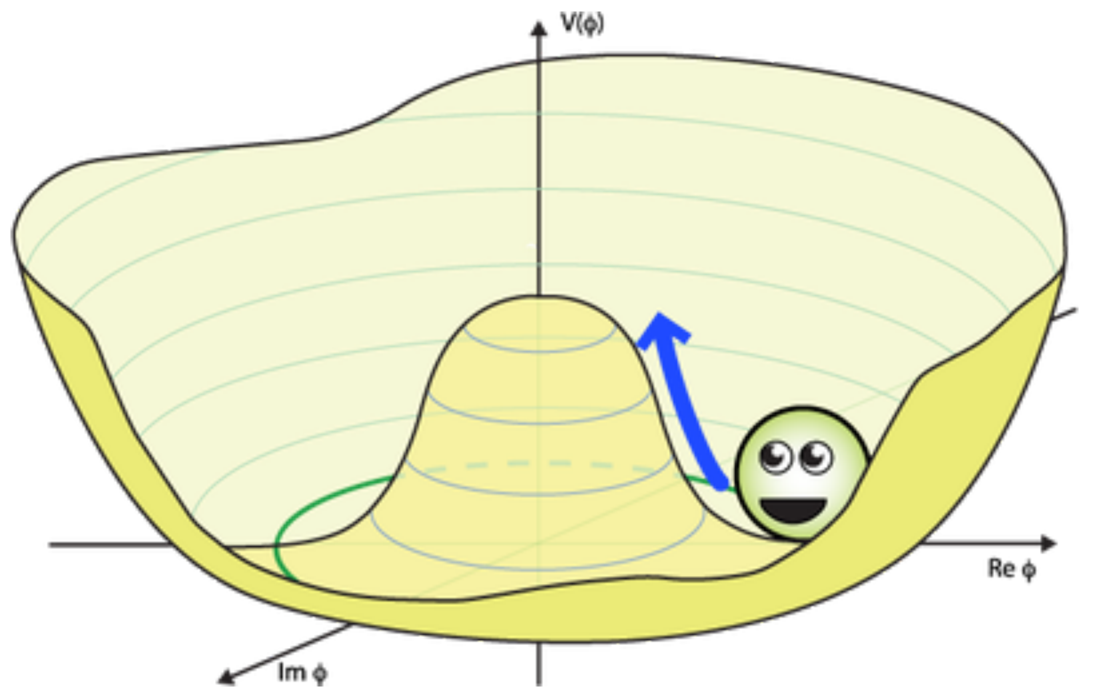
- Fundamental part of the SM
- For a self consistent model fermions and bosons should be massless
- Particles however have mass -> We need an additional ingredient
- The Higgs mechanism provides that and after long search the corresponding boson was found in 2012 leading to a Nobel prize five decades after its inception!

Credit:Thesis T.Lange

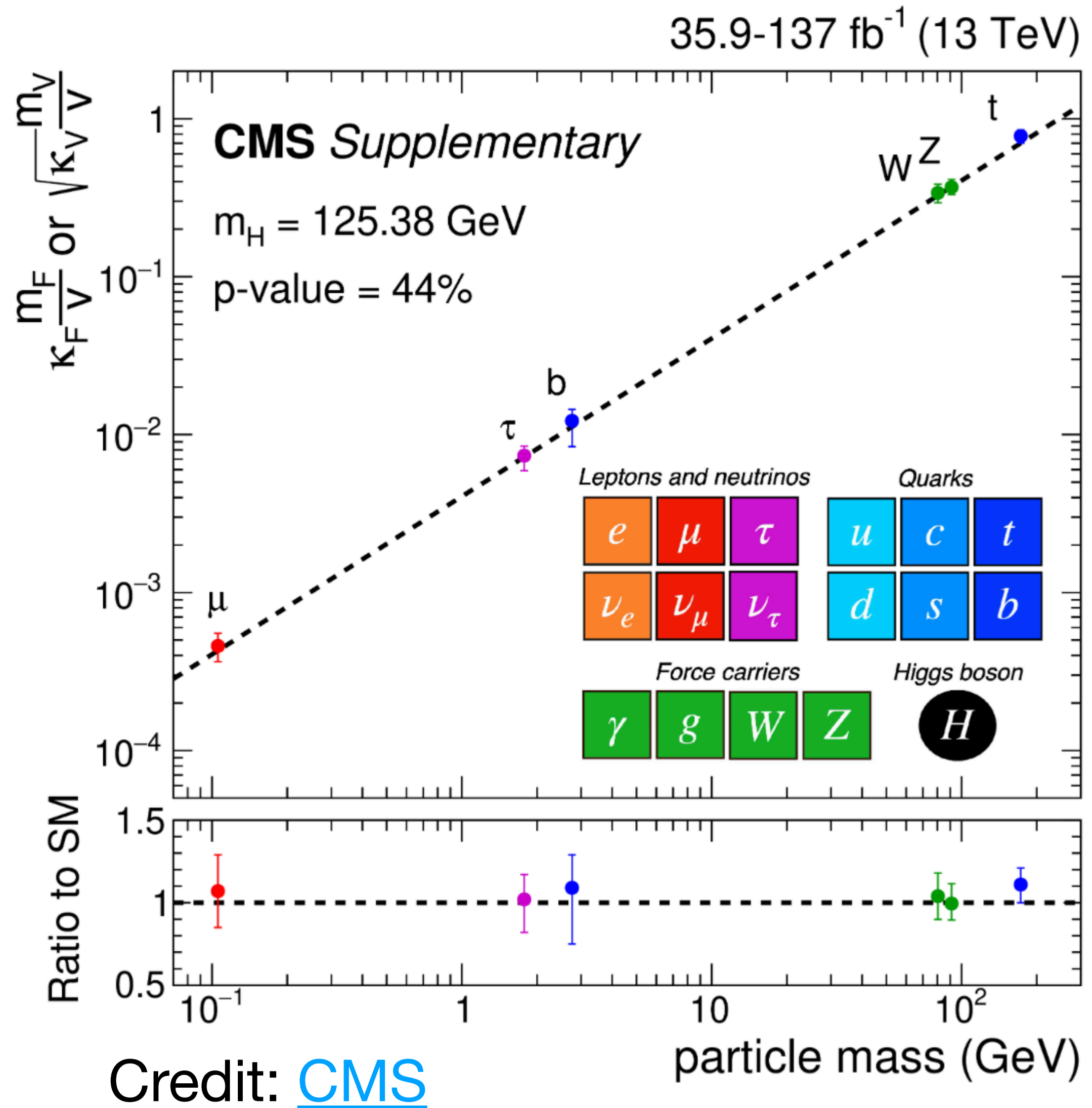


# Higgs boson?

- Last fundamental particle found so far
- Well known by know, meany quantities measured
- If there is more we need to look at some of the rarest processes known to mankind
- 2000 times rarer than the production of a single Higgs, we have the simultaneous production of two (O(4000) in 3 years compared to 600 mio/s)
- These events tell us about the Higgs boson self coupling, the underlying Higgs potential and the future of the universe!

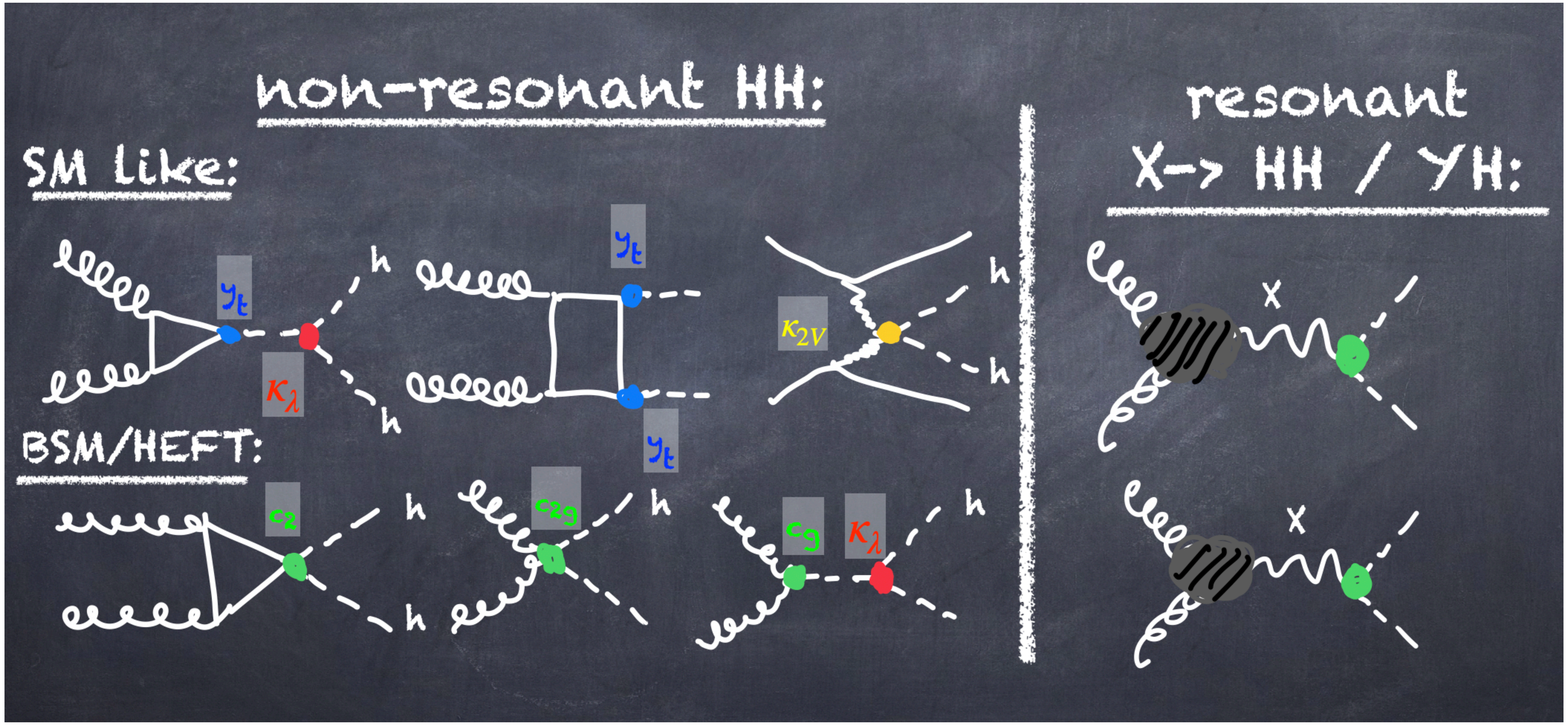



Credit: Netzwerk Telchenwelt

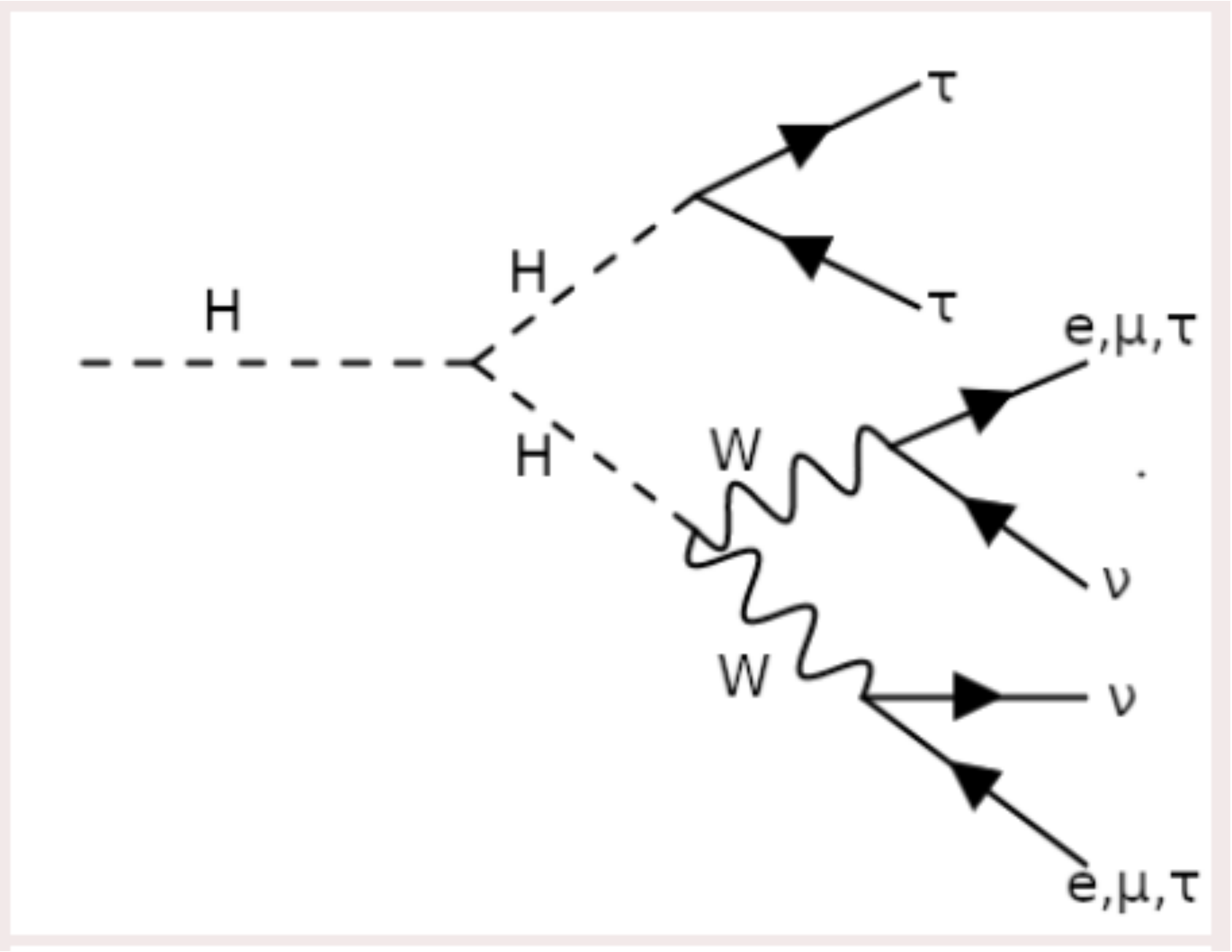


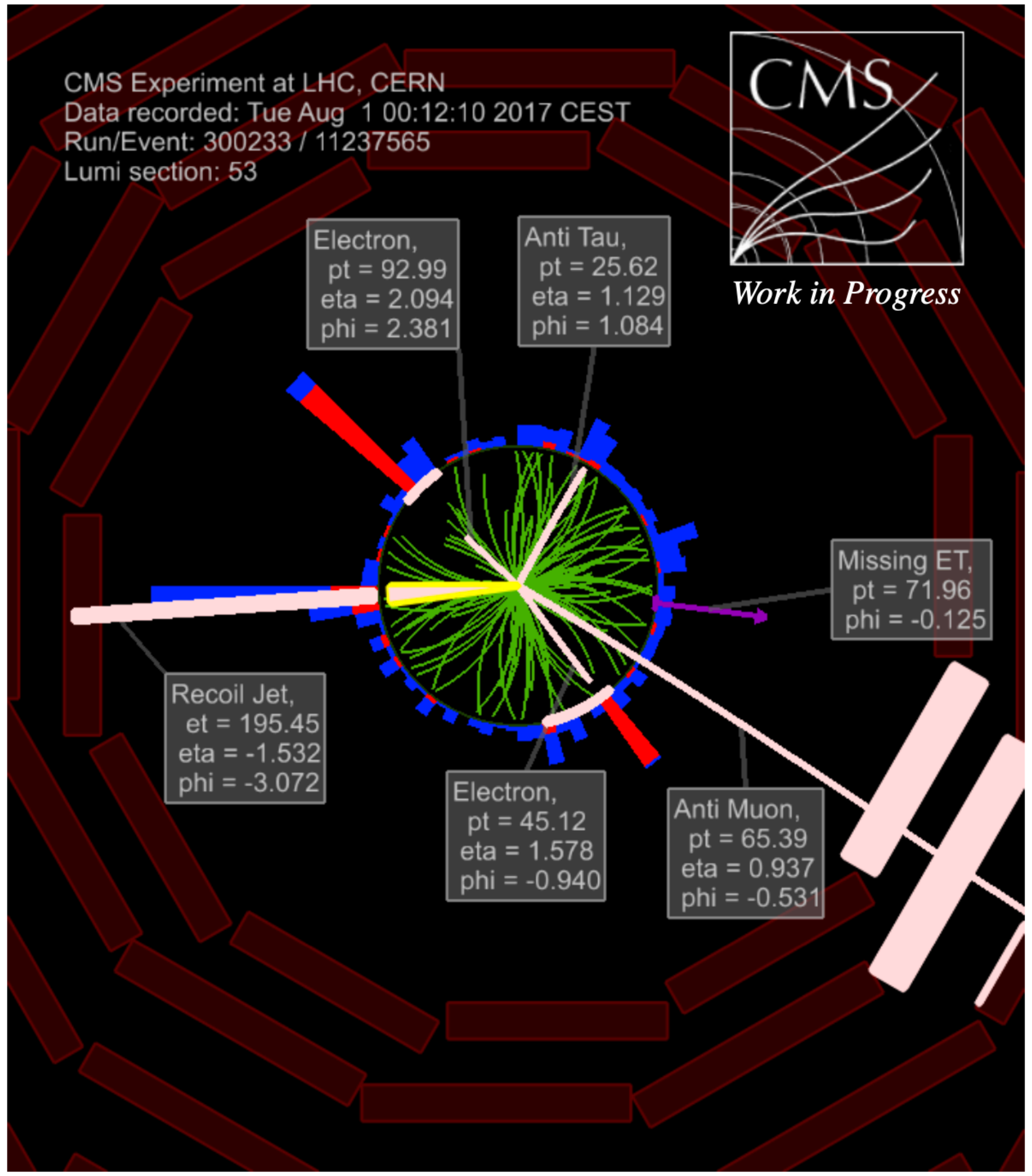

Credit: CMS

# Higgs boson pairs?

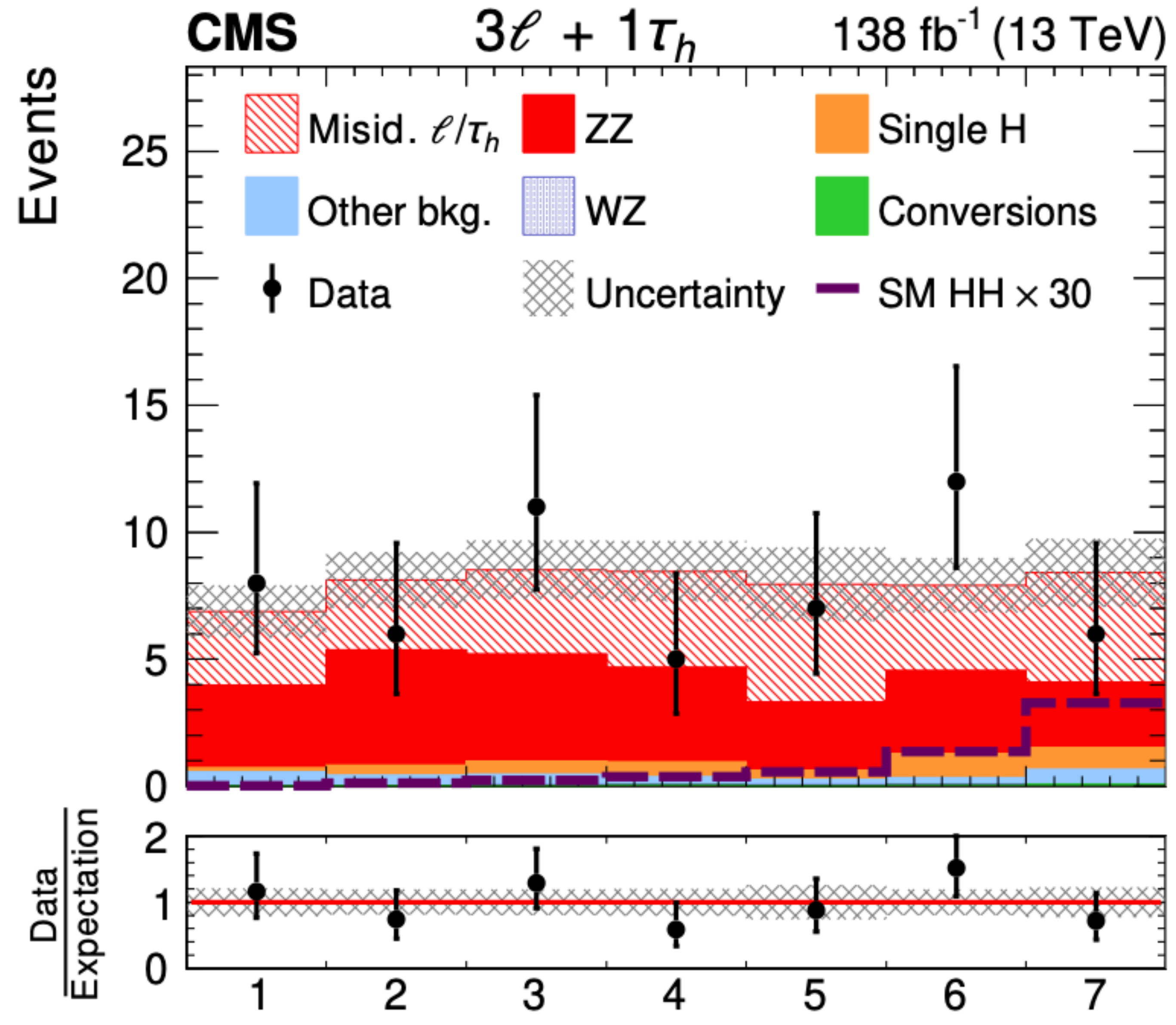


# Higgs boson pairs?



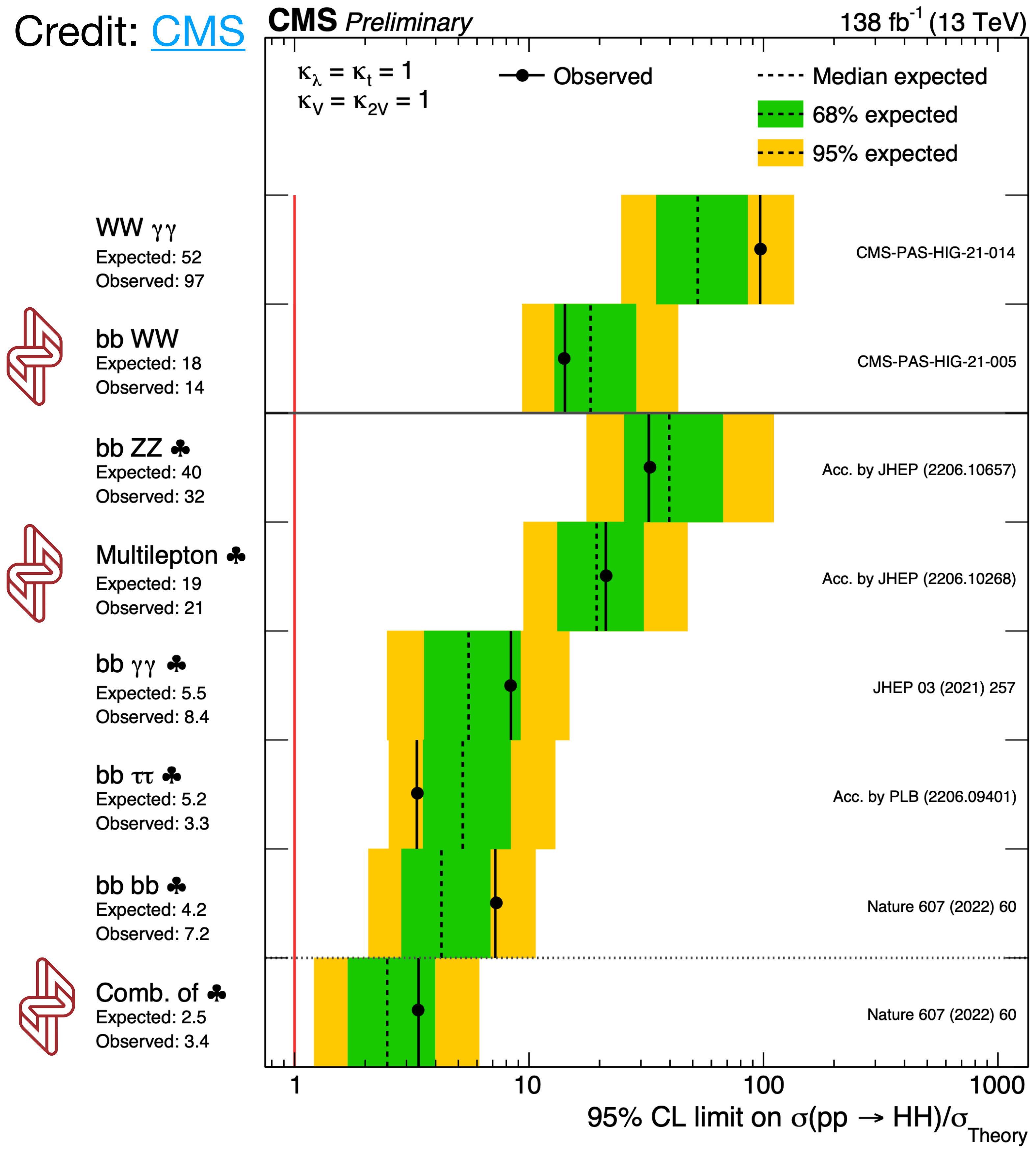

Credit:Thesis T.Lange



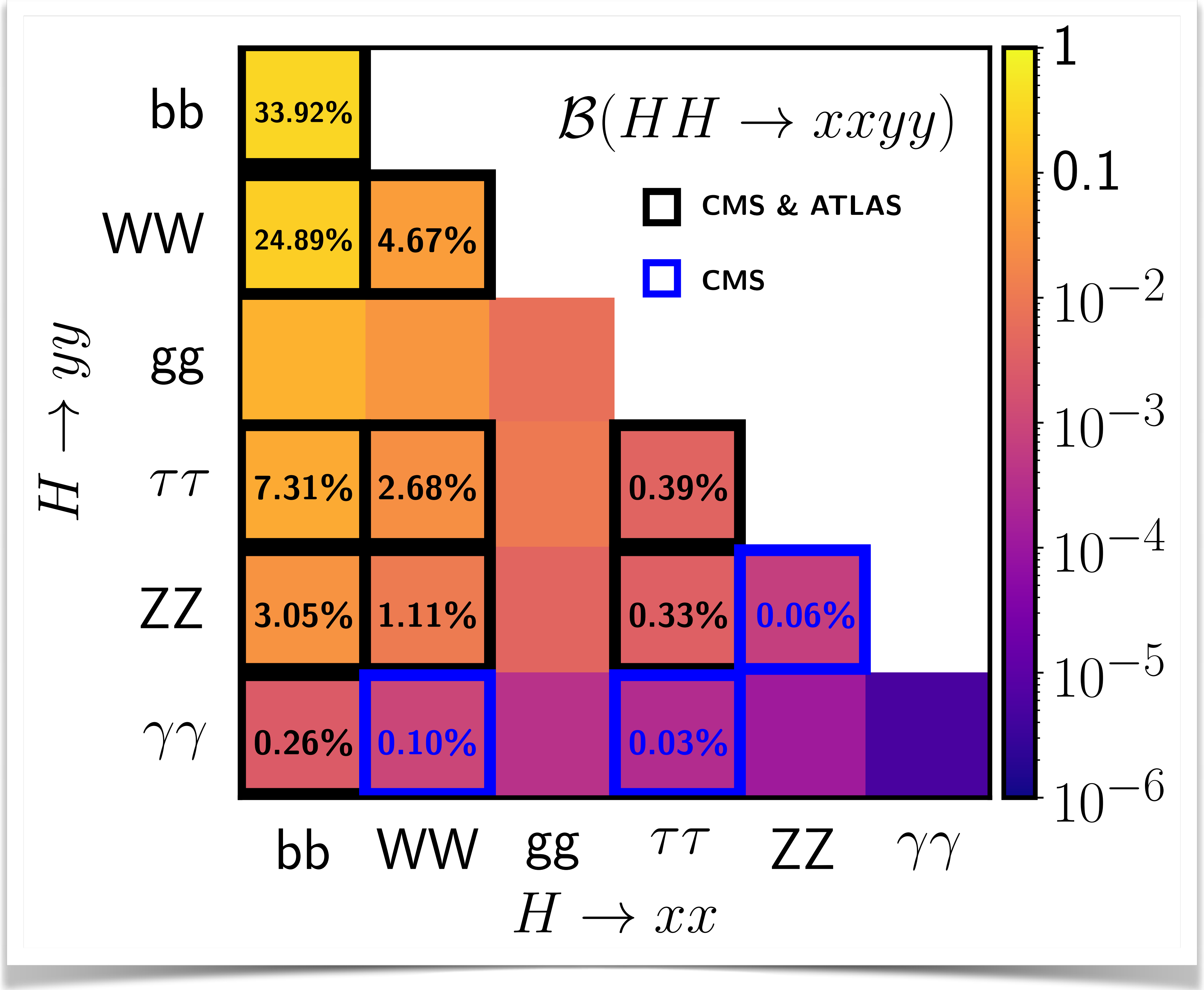

Credit: CMS

# Higgs boson pairs?

Credit: CMS




$+\ \tau\tau\gamma\gamma + VHH \rightarrow bb + bbWW^*(boosted) + \ldots.$




Credit: CMS+ATLAS

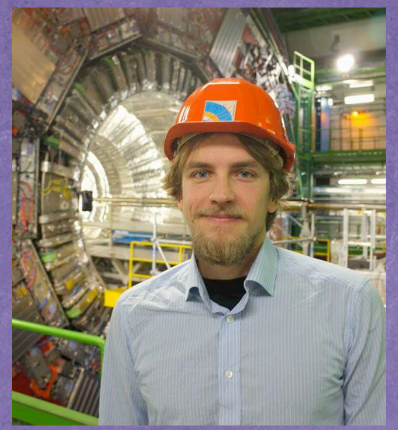
# KBFI experimental HEP group

Mario

Group Head

Torben

Christine



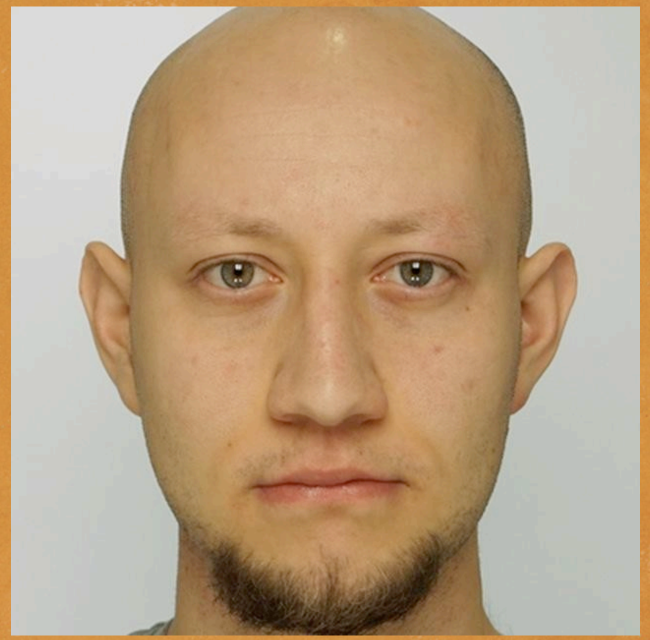
Joosep

Senior Scientist

Lauri

IT/Computing

Laurits



Sven

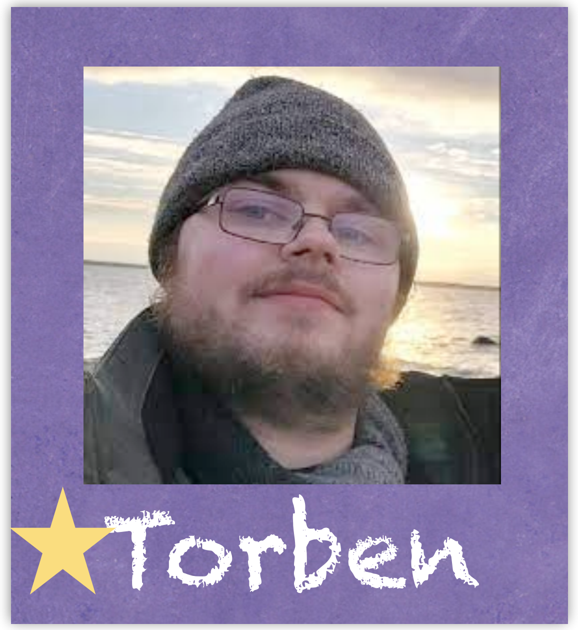
Norman

Postdocs and PhD. students

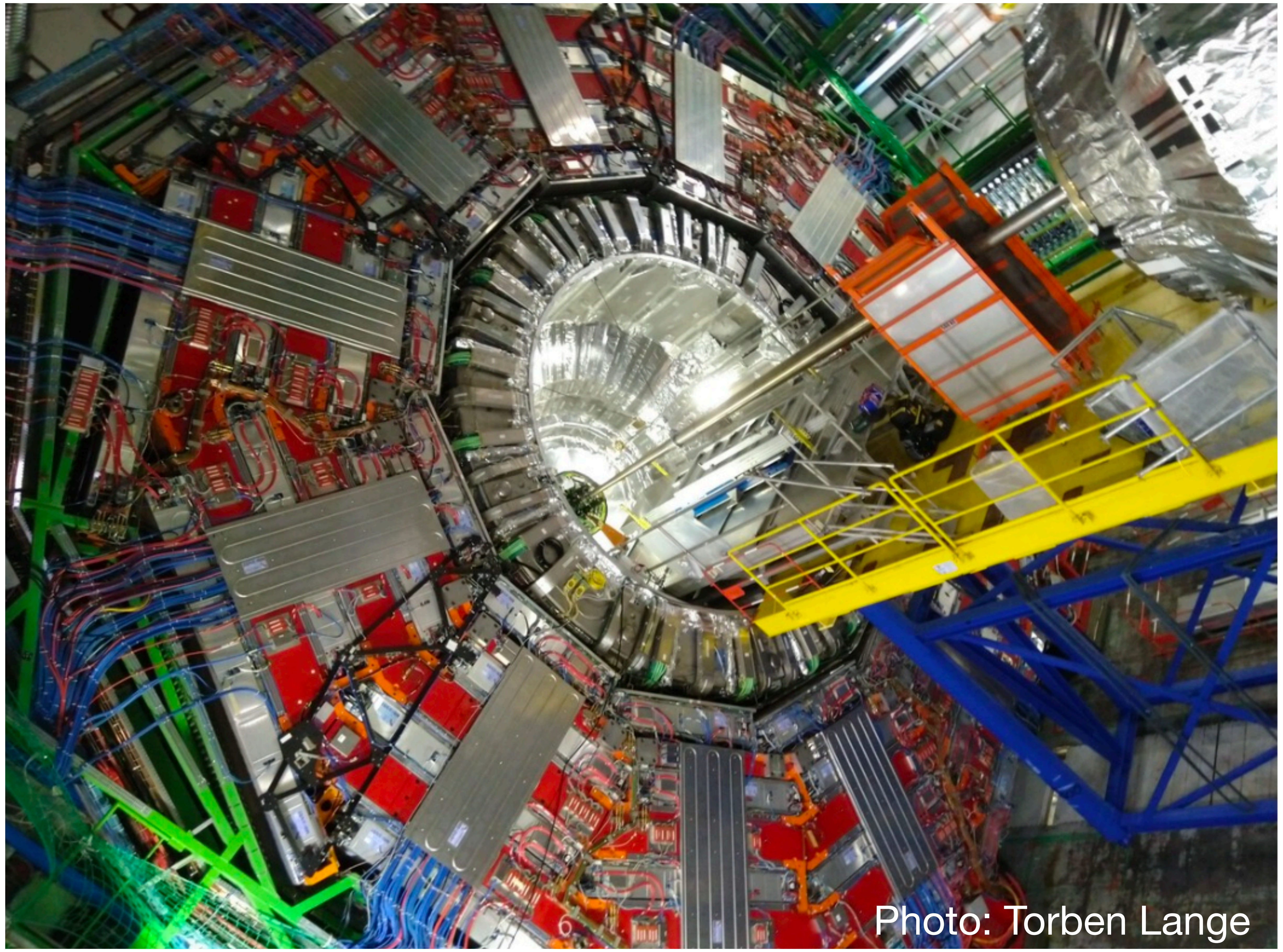
We also have a large theory group working on particle physics, astronomy and gravitational waves, feel free to contact us for more information!

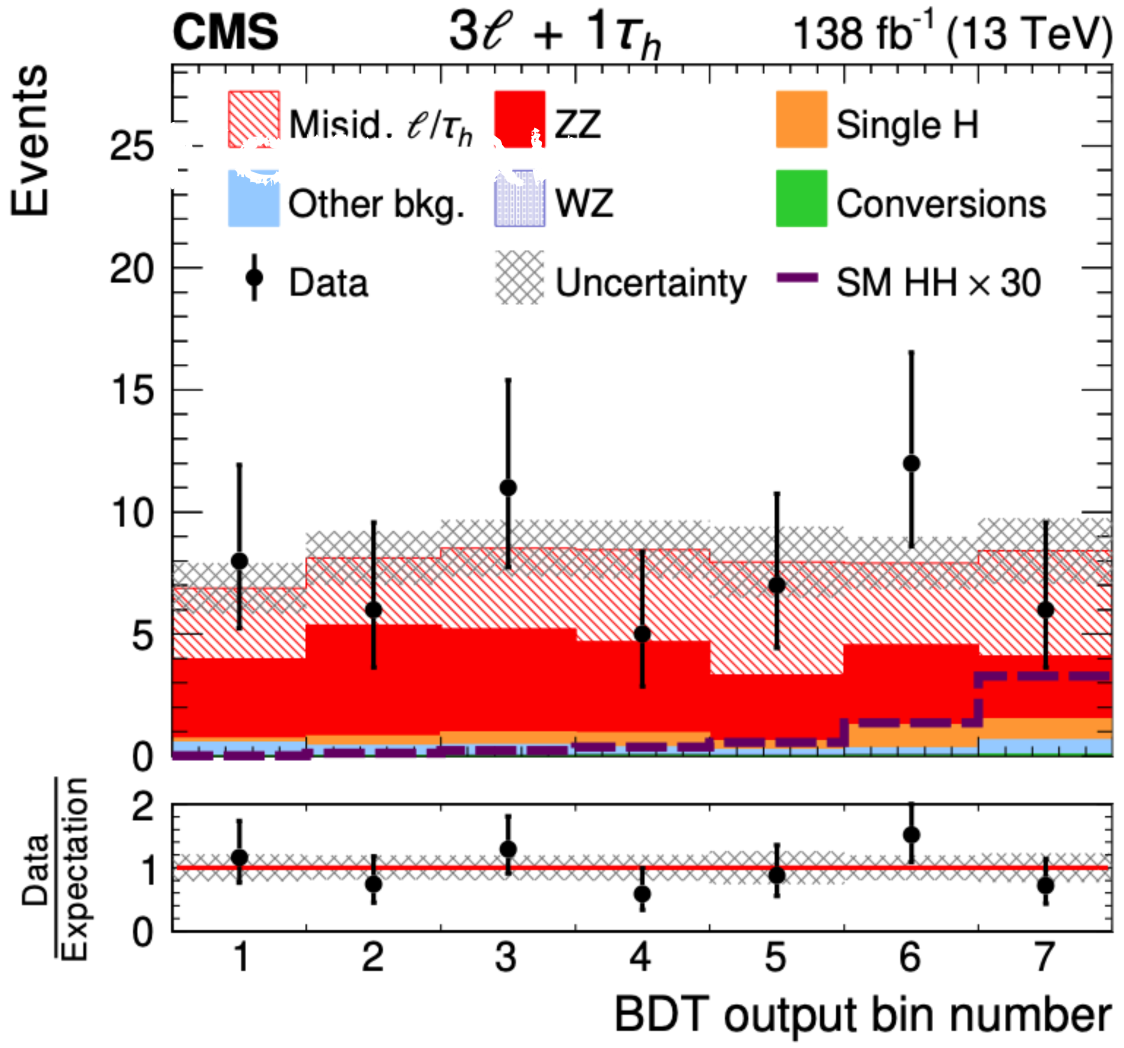
# KBFI experimental HEP group

## CMS Data analysis, on the hunt for more Higgs!

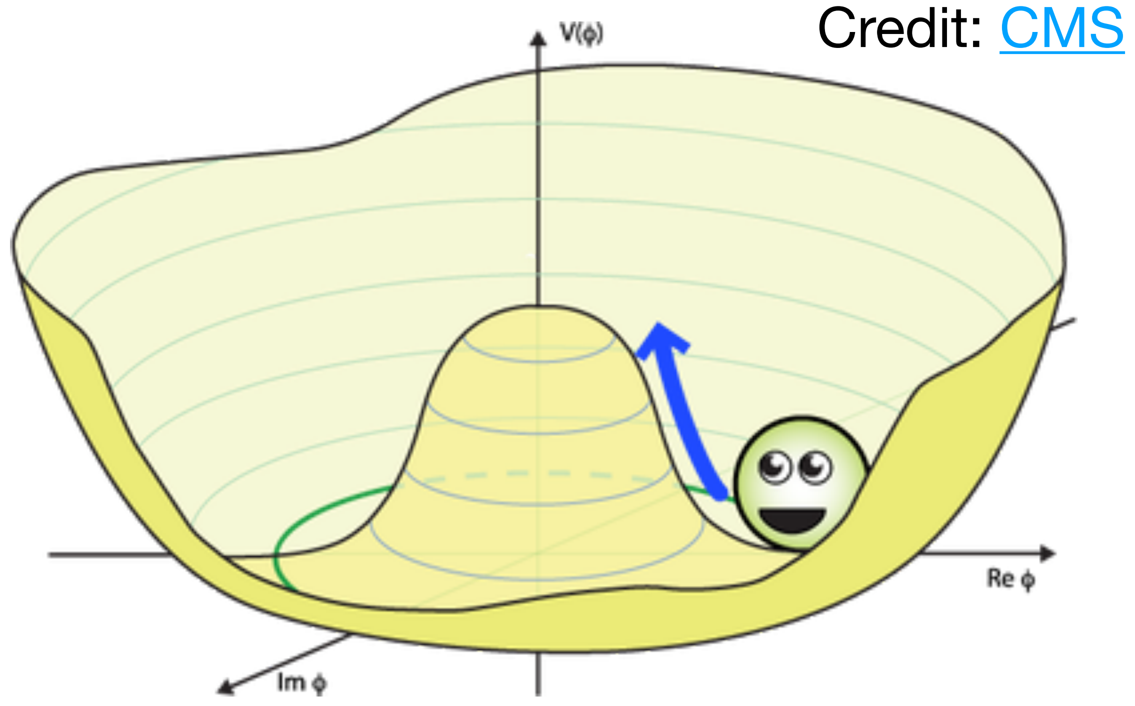







Credit: [CMS]

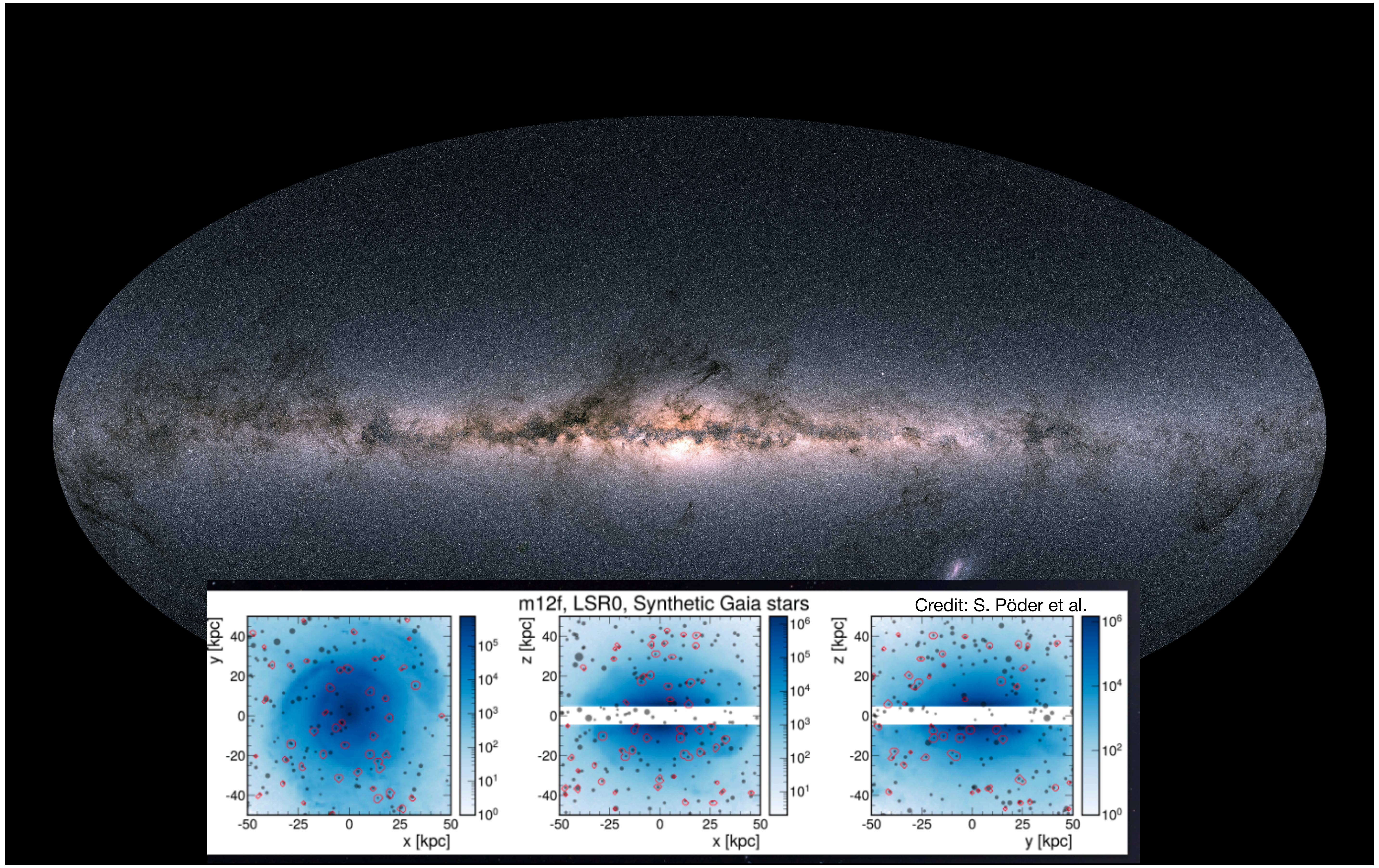



Credit: [Netzwerk Teilchenwelt]

# KBFI experimental HEP group

## ML+GAIA, on the hunt for Dark Matter!



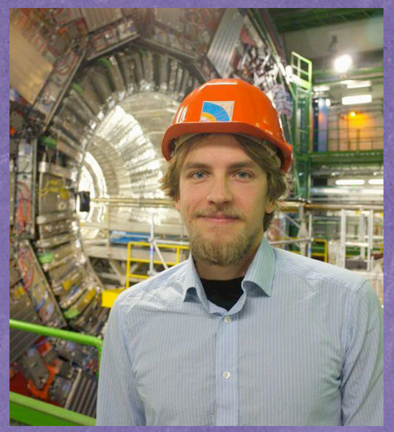




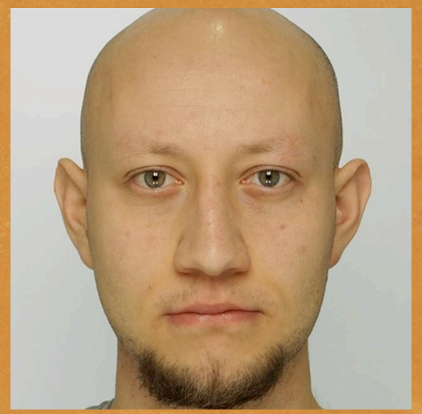
Credit: ESA/Gaia

# KBFI experimental HEP group

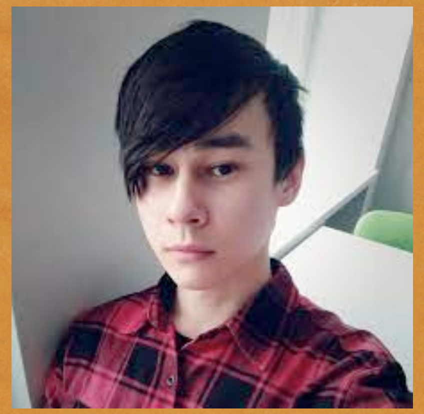
## Particle reconstruction with ML - hunting the architecture for all!



★ Joosep

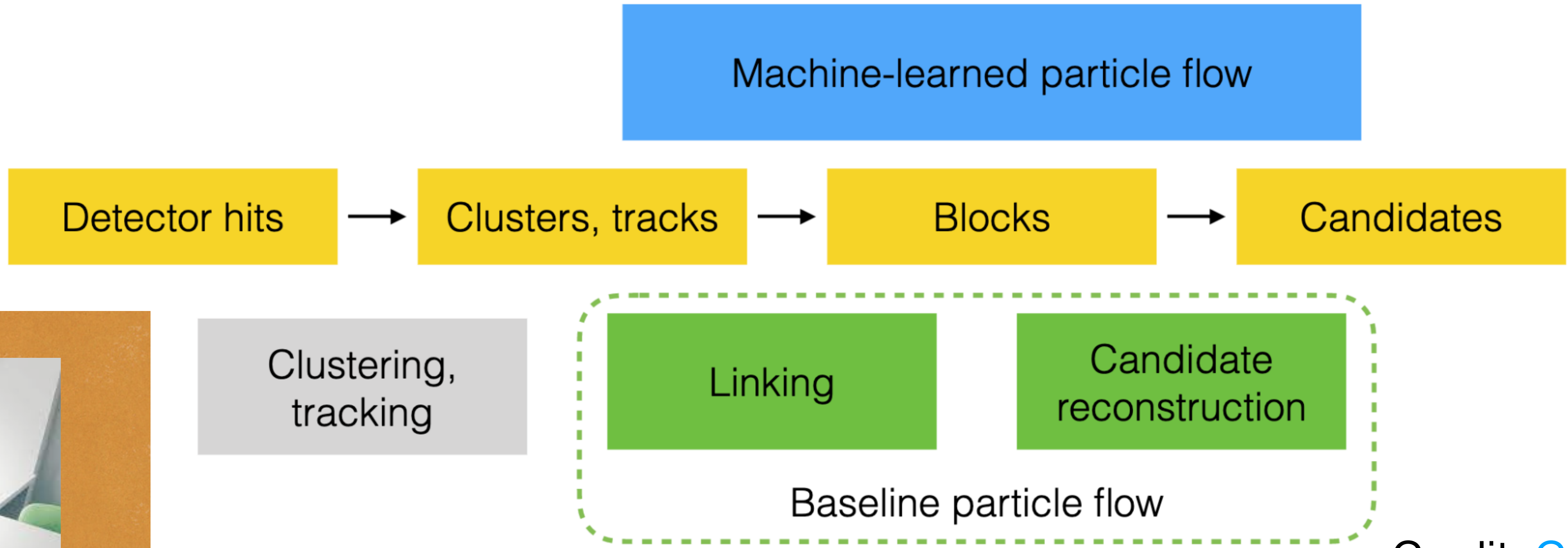


Laurits



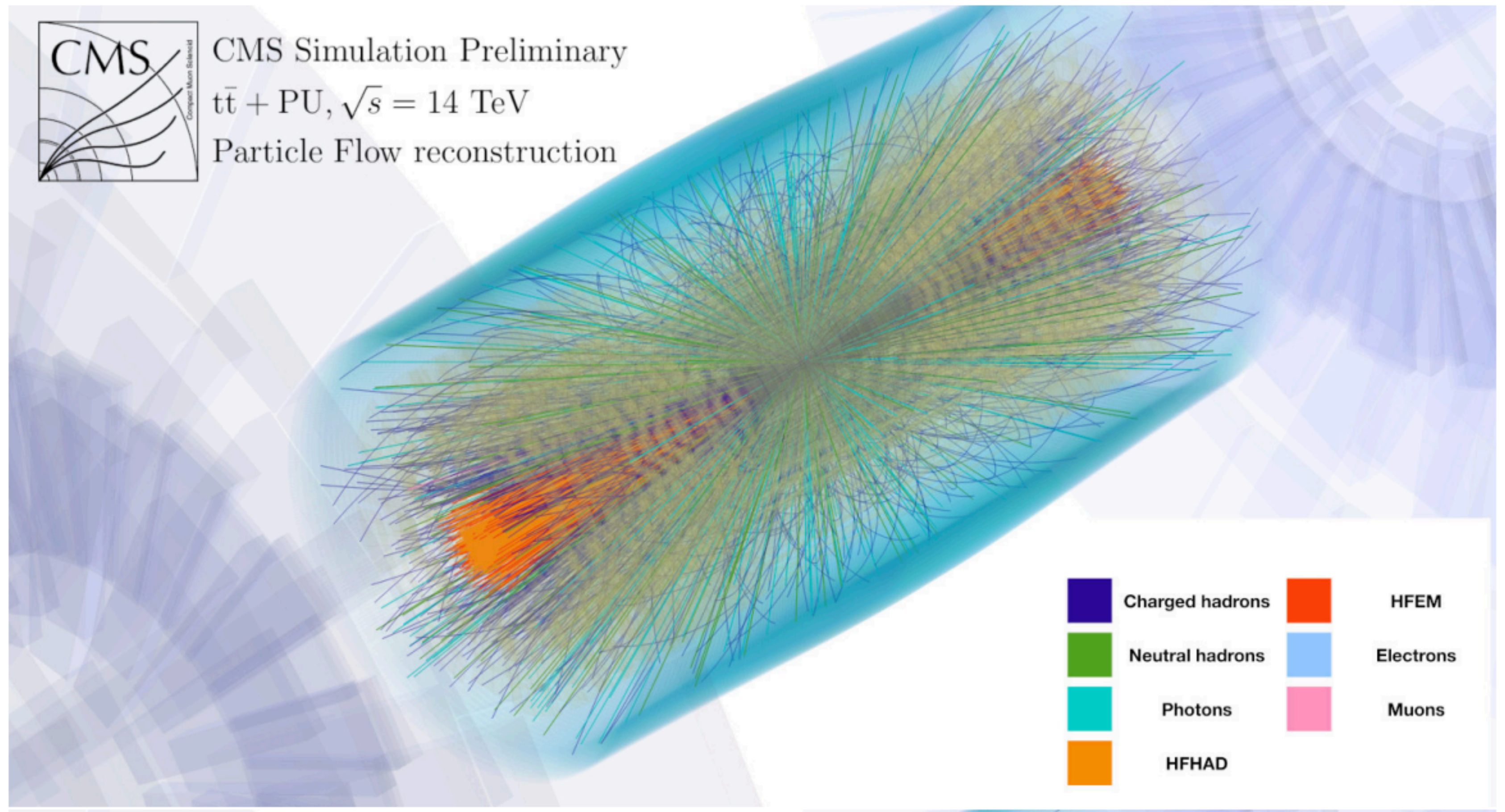
Norman

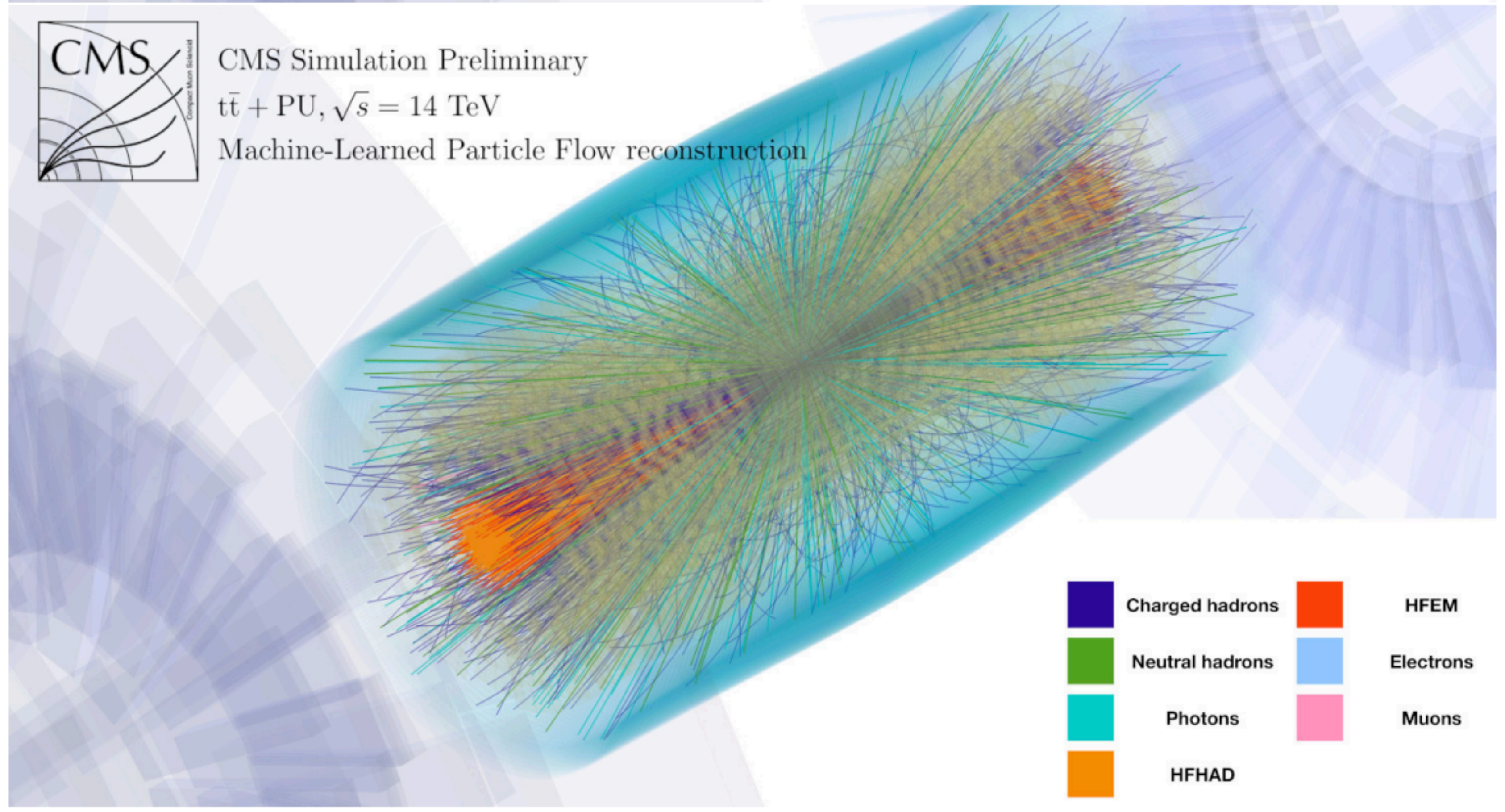
Torben




Credit: CMS

+ Tau reconstruction at FCC
+ Foundation models in HEP
+ more to come



# KBFI experimental HEP group

## L1 trigger development, hunting the speed limit!

Christine

+

TAL TECH

# Conclusion

- Particle physics == Understanding the interaction of the smallest particles with the fundamental forces dictating life
- We do that e.g. though collider experiments such as CMS at the LHC
- Still, not all mysteries are solved, we know our current models are not complete
- Looking for the Higgs might be one way to find the next puzzle piece
- We have a lively particle physics community in Estonia and we are doing our part in the quest of understanding mother nature and the universe!