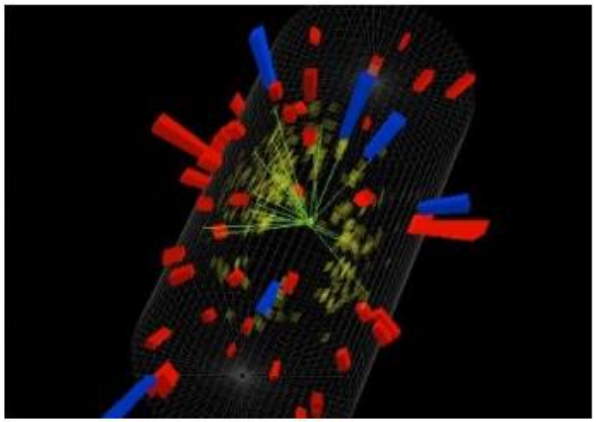
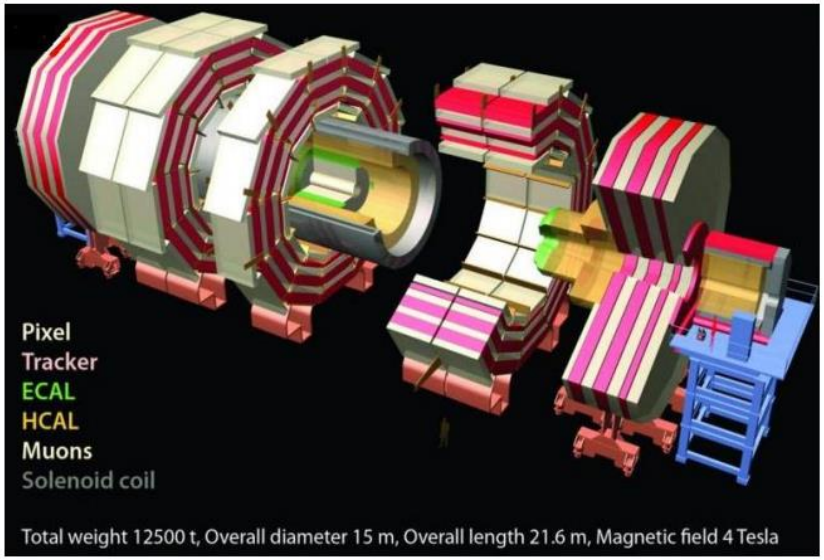
# High Energy Physics and the CMS WZH Masterclass






INTERNATIONAL MASTERCLASSES

hands on particle physics

Fermilab

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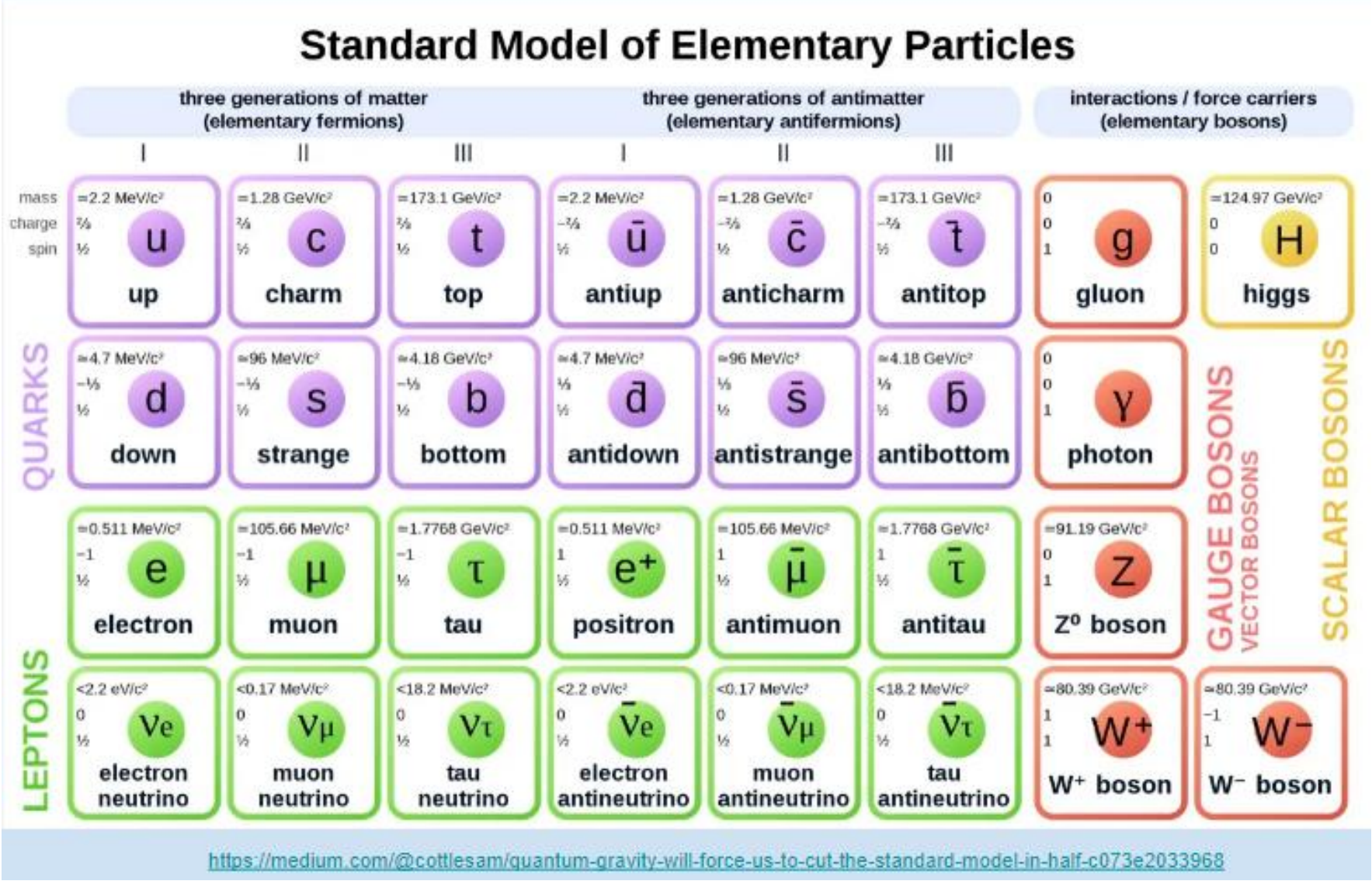
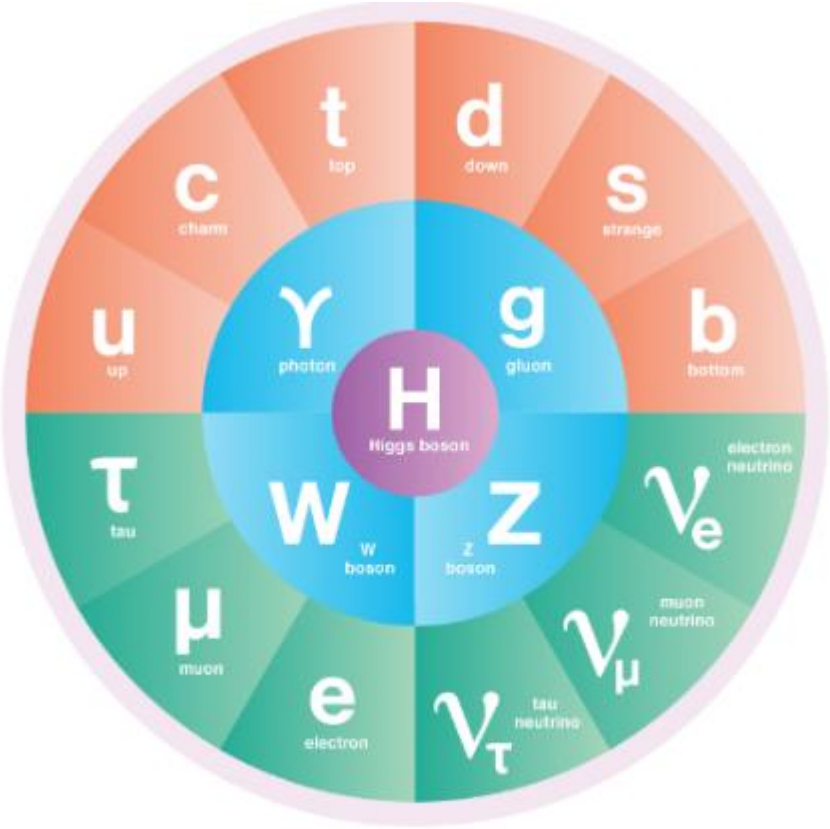
QUARKNET

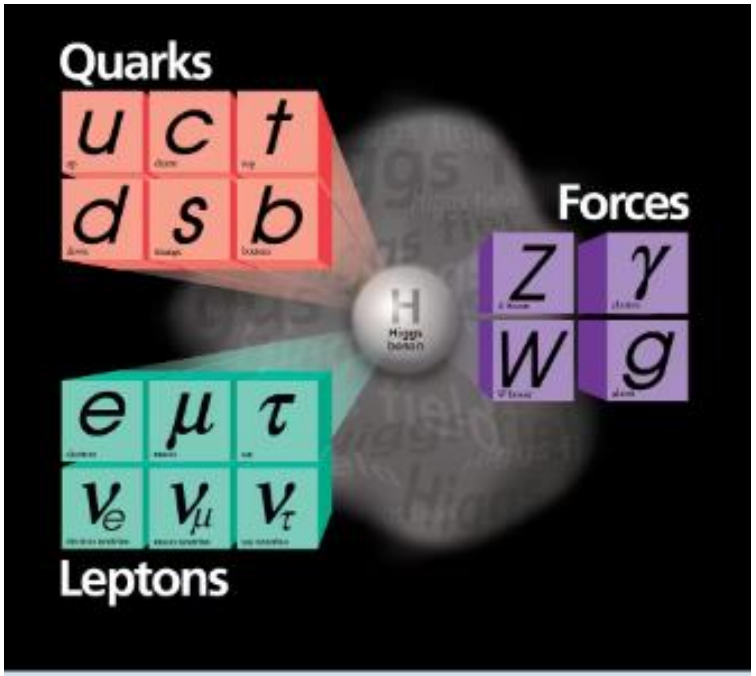



https://medium.com/@cottlesam/quantum-gravity-will-force-us-to-cut-the-standard-model-in-half-c073e2033968

QUARKNET



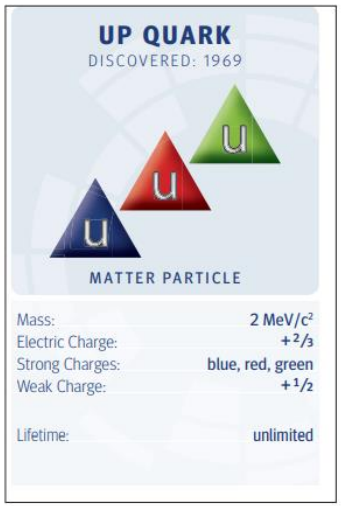

https://www.energy.gov/science/doe-explainsthe-standard-model-particle-physics

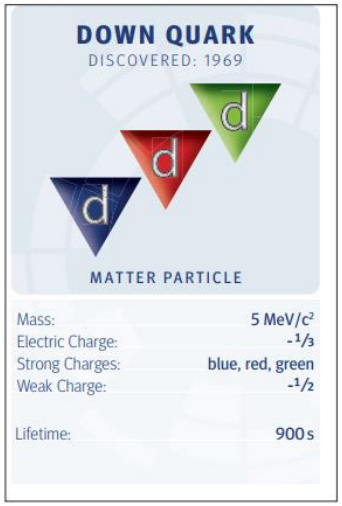


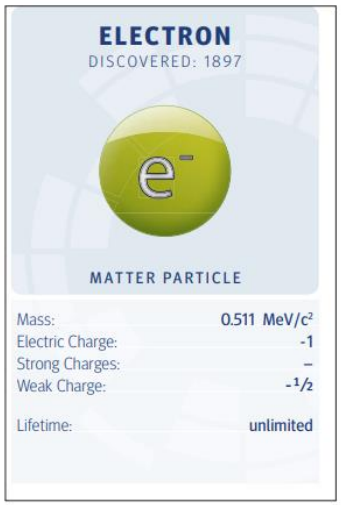

https://theconversation.com/the-standard-model-of-particle-physics-the-absolutely-amazing-theory-of-almost-everything-9470

# We know a few things

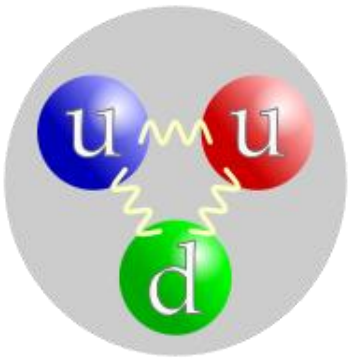
## All chemistry from just a few particles?

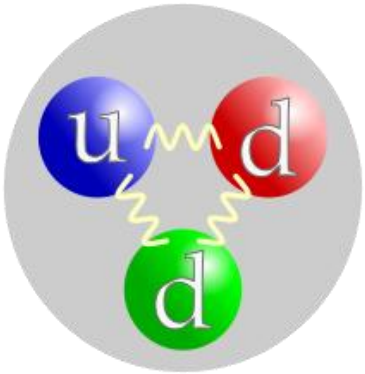


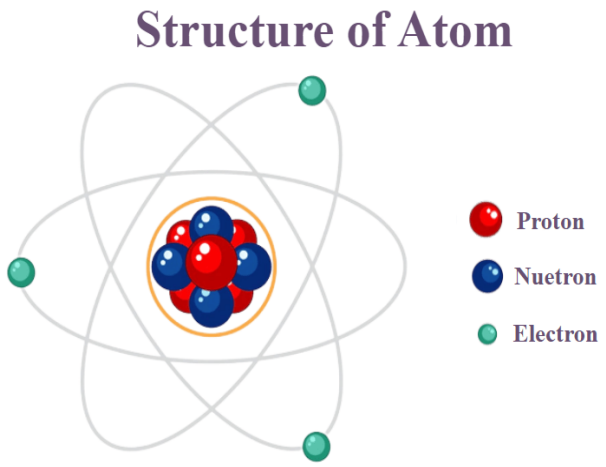




protons and neutrons




*Is that all?*

*Maybe not.* →

# Really? We have questions.

## What holds the atom together?





And what about these?

# More questions.

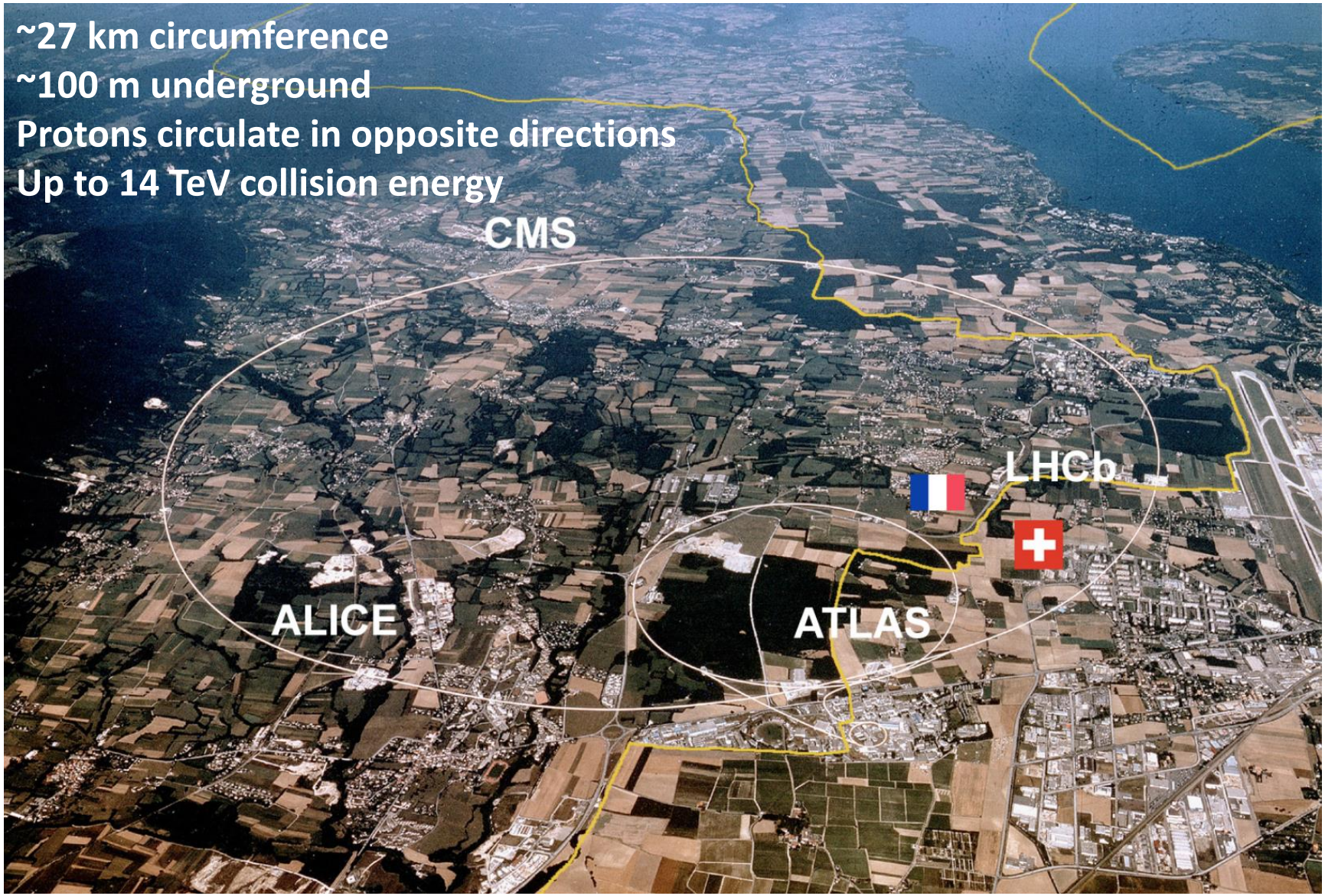
## Like antimatter…

# What shall we do?

**Let’s throw things at each other and study them to see what happens.**


# Activity break

# Large Hadron Collider @ CERN



# The LHC and the new physics

**Generic Design**

Cylinders wrapped around the beam pipe

From inner to outer . . .

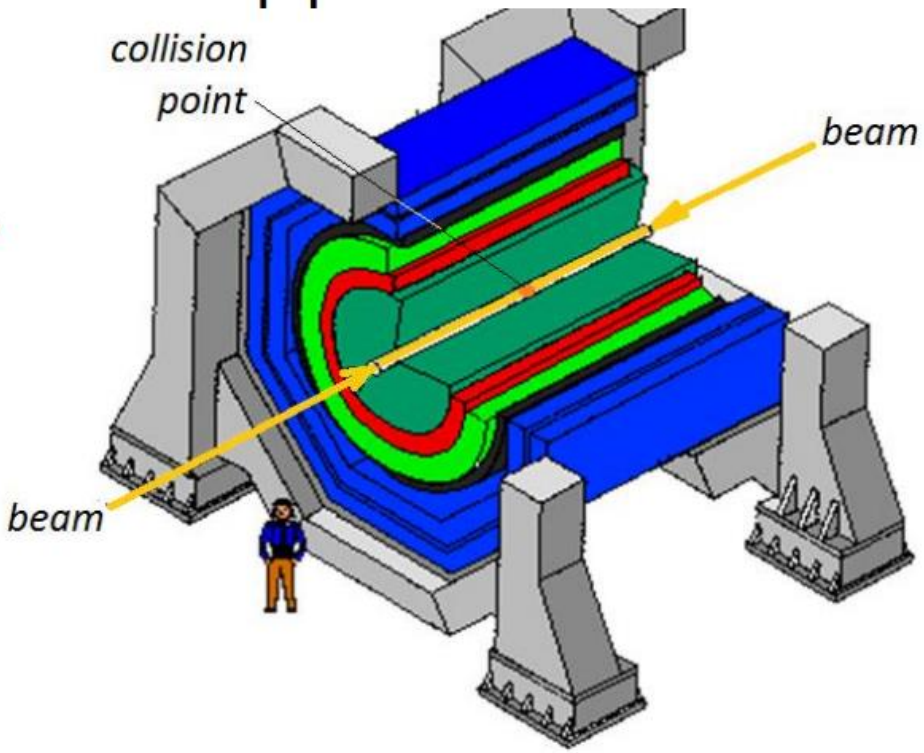
Tracking

Electromagnetic calorimeter

Hadronic calorimeter

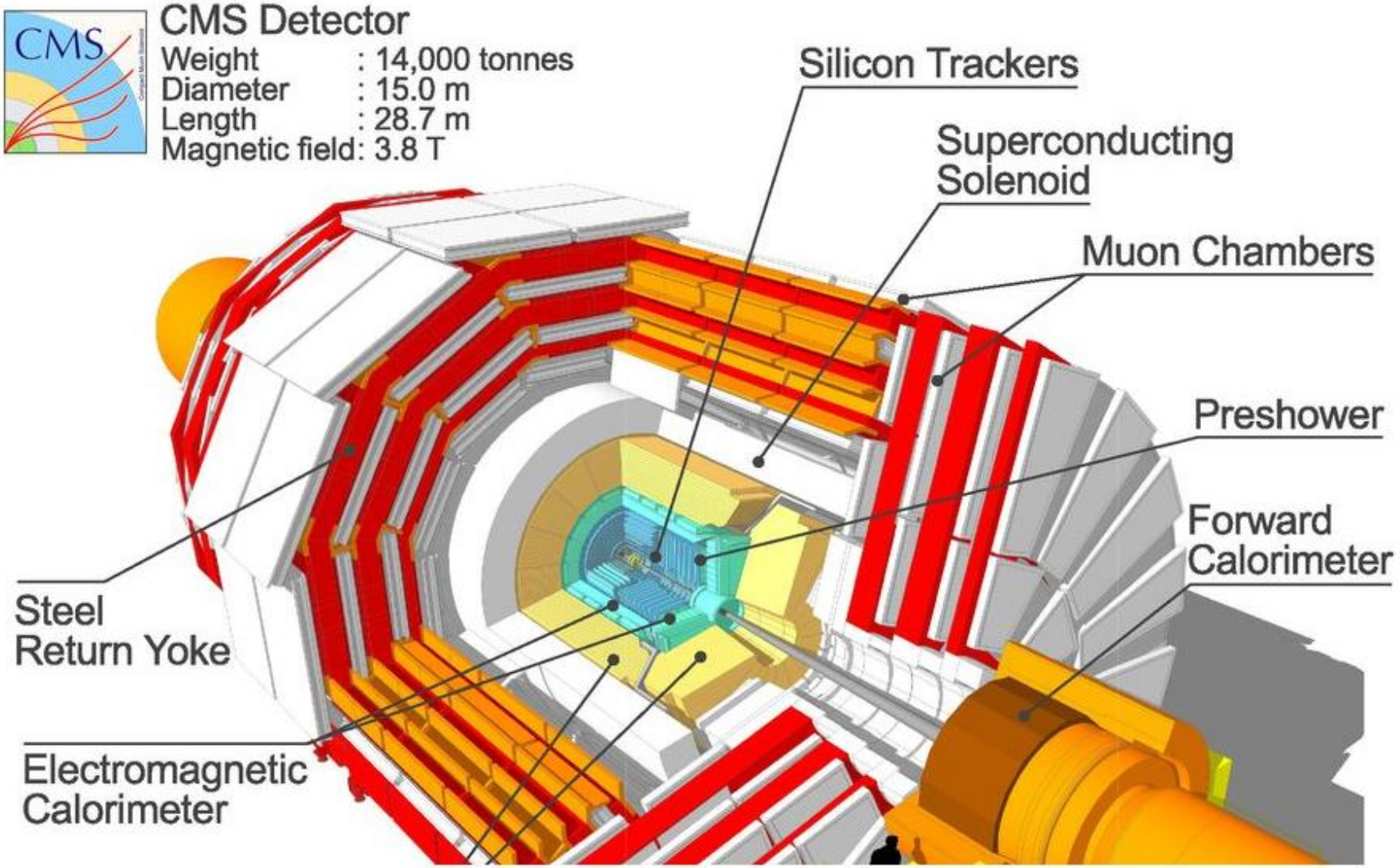
Magnet*

Muon chamber




* *location of magnet depends on specific detector design*

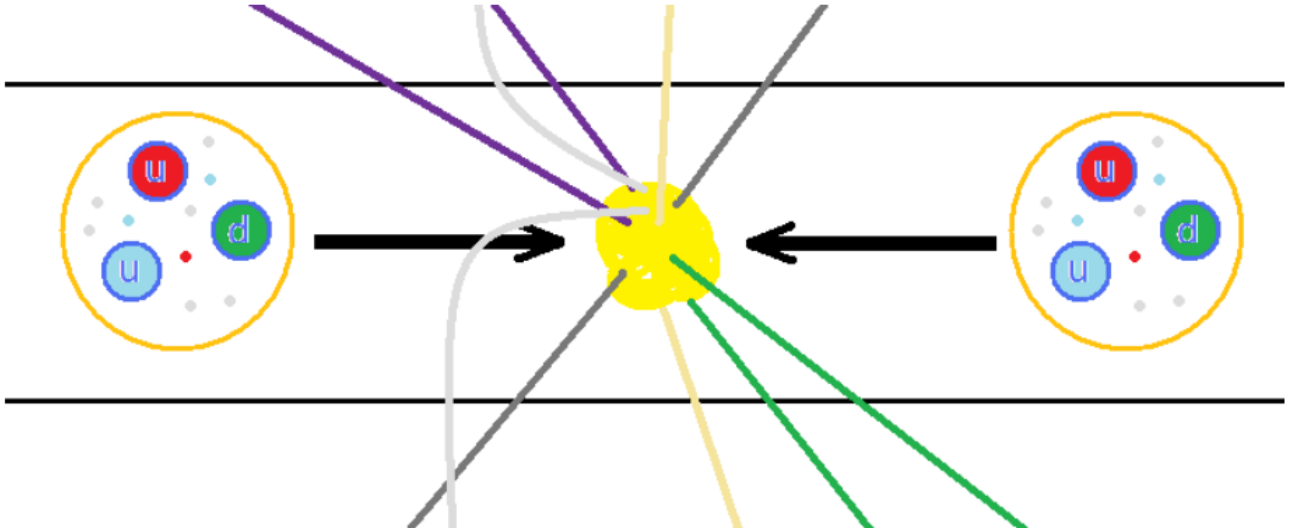
# The Compact Muon Solenoid (CMS)



# Protons collide inside CMS

**The LHC accelerates protons to almost 7500 times the energy equivalent of their mass. The protons circulate in opposite directions and collide in the center of CMS.**

**But protons are not just particles: they are more like bags of quarks and gluons. When protons collide, all sorts of very short-lived particles can be made from all that energy.**



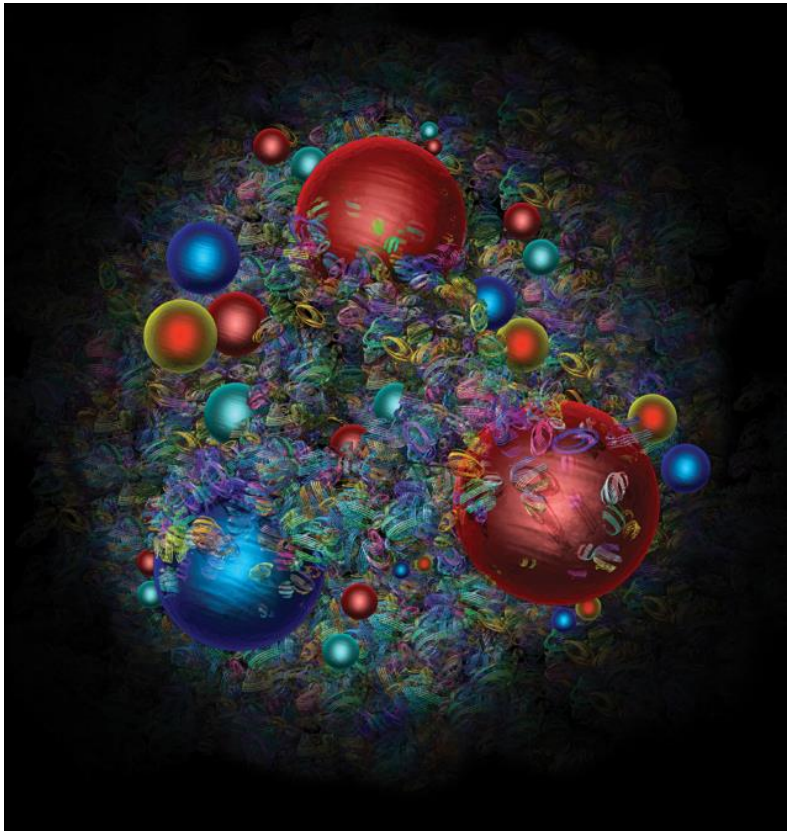
# What do the protons tell us?

**We learn from what proton collisions produce:**

***W bosons* give us clues to the proton structure…and they also present a mystery.**

***Z bosons* decay (sort of) like lighter particles but are also needed to sort out Higgs data.**

***Higgs bosons*, well, are Higgs bosons, the new kid on the block!**

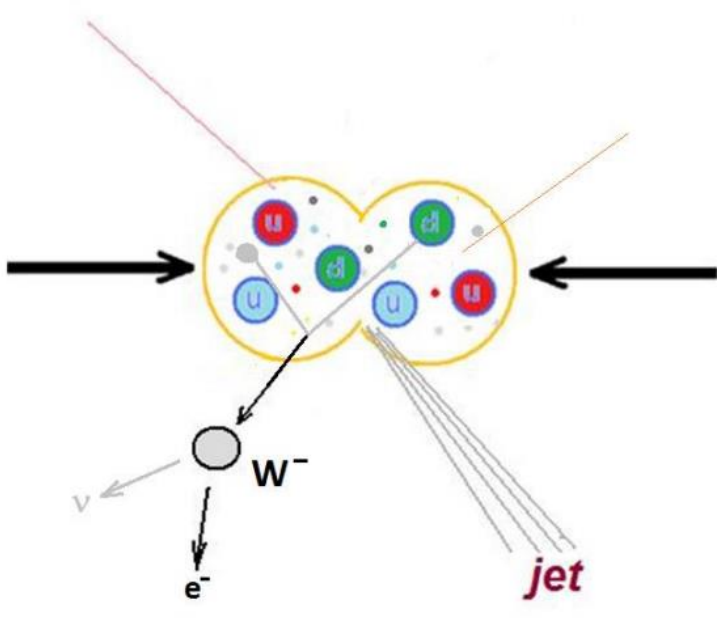


*Artist's image of a proton from CERN Courier.* Learn more here and even more here.

# One-lepton events

**The + or – charged W boson enables radioactive decay by transforming neutrons into protons.**

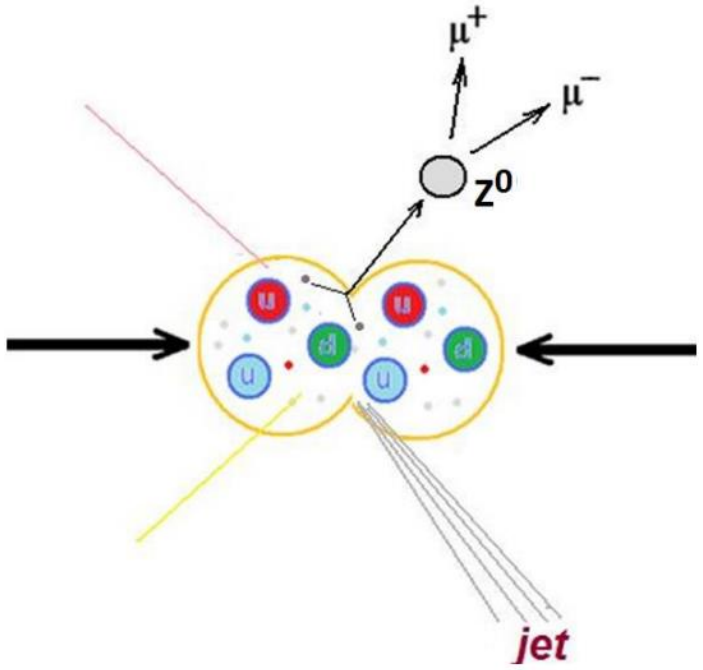
**It decays into a neutrino and another lepton. Since CMS cannot detect the neutrino directly, we can call this a one-lepton event.**

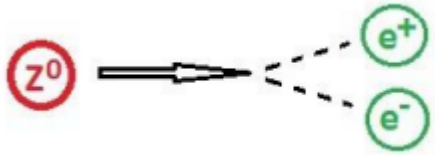


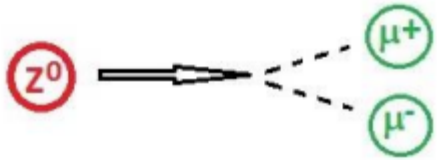

# Two-lepton events

**The Z boson is a neutral cousin of the W. It enables the "weak neutral current".**

**It decays into two leptons of the same type but opposite charge – electron and positron or muon and antimuon. It has other decay paths but we are not looking for these.**



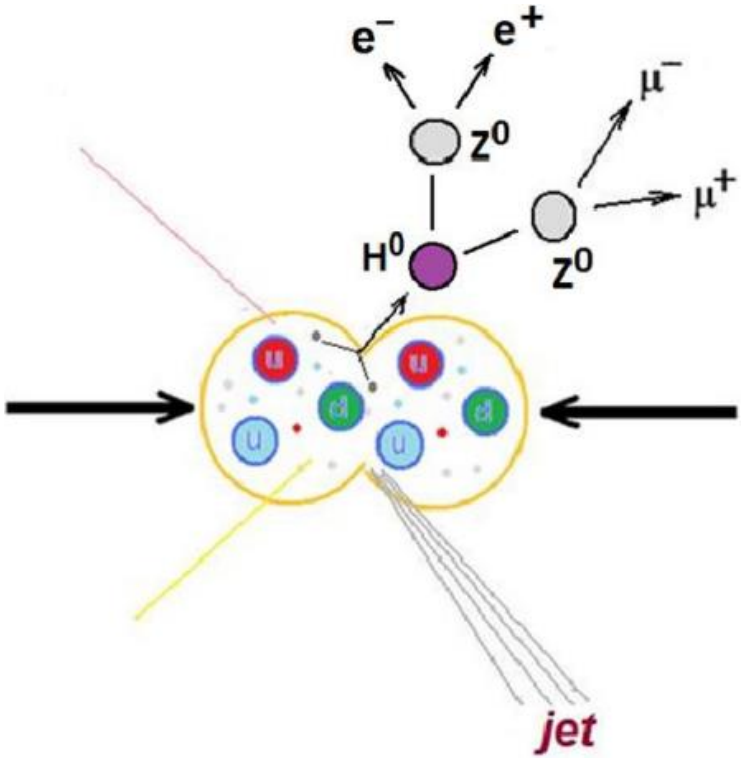



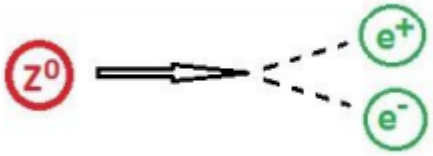



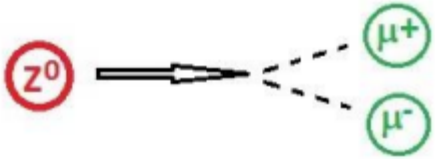
# Four-lepton events

**The Higgs boson is an expression of the field that gives other particles mass.**

**One decay mode of the Higgs is into two Z bosons, which themselves promptly decay. Thus we can get 2 muons and 2 electrons *or* 4 muons *or* 4 electrons.**



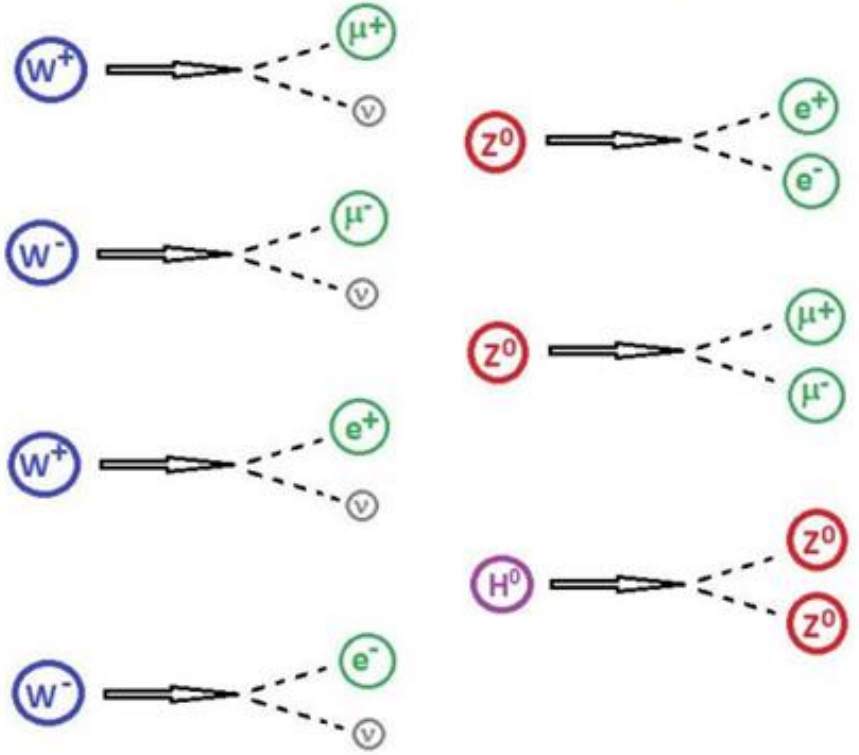



# Decay summary

Because bosons only travel a tiny distance before decaying, CMS does not "see" them directly.

CMS *can* detect :

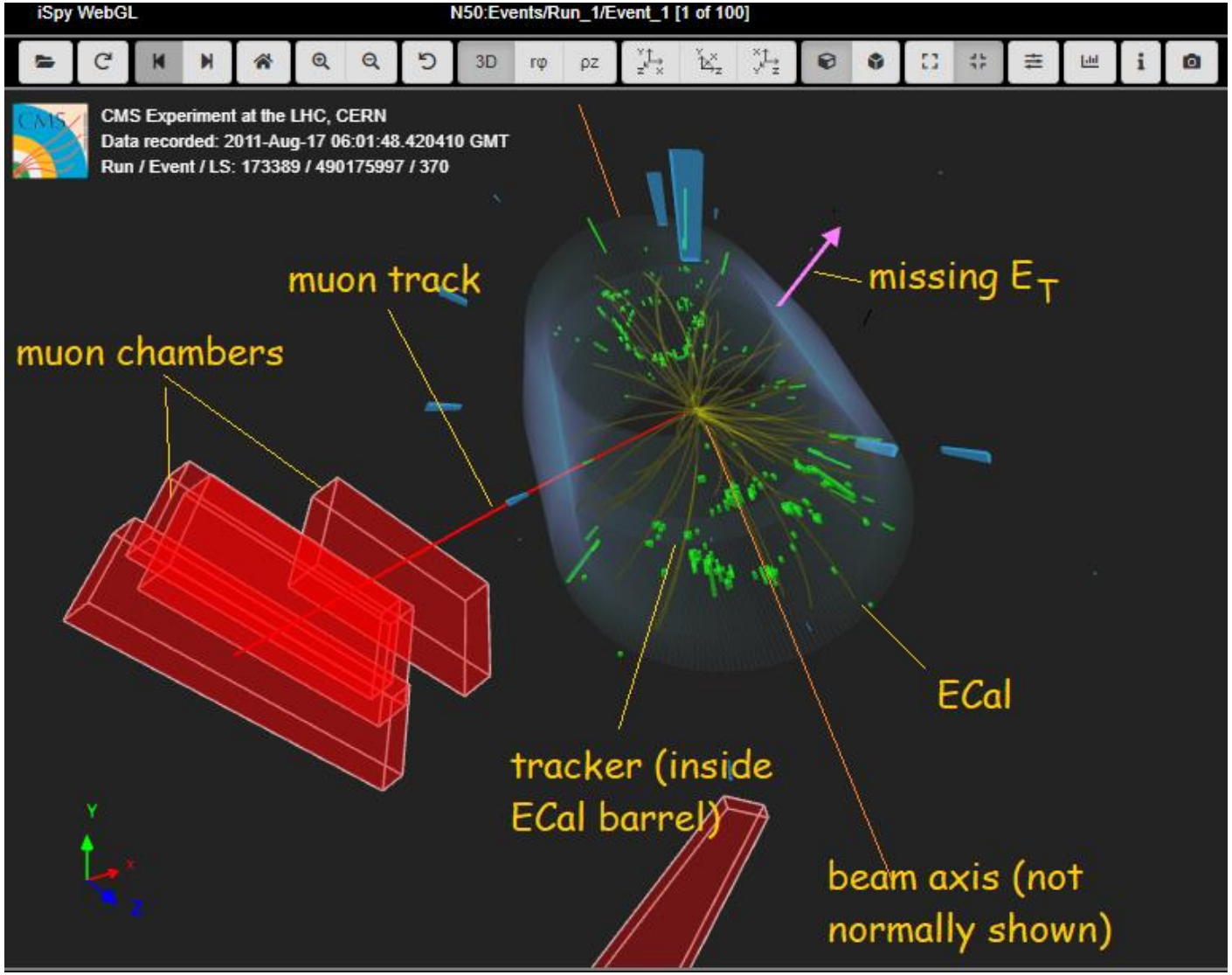
- electrons
- muons
- photons




CMS can infer:

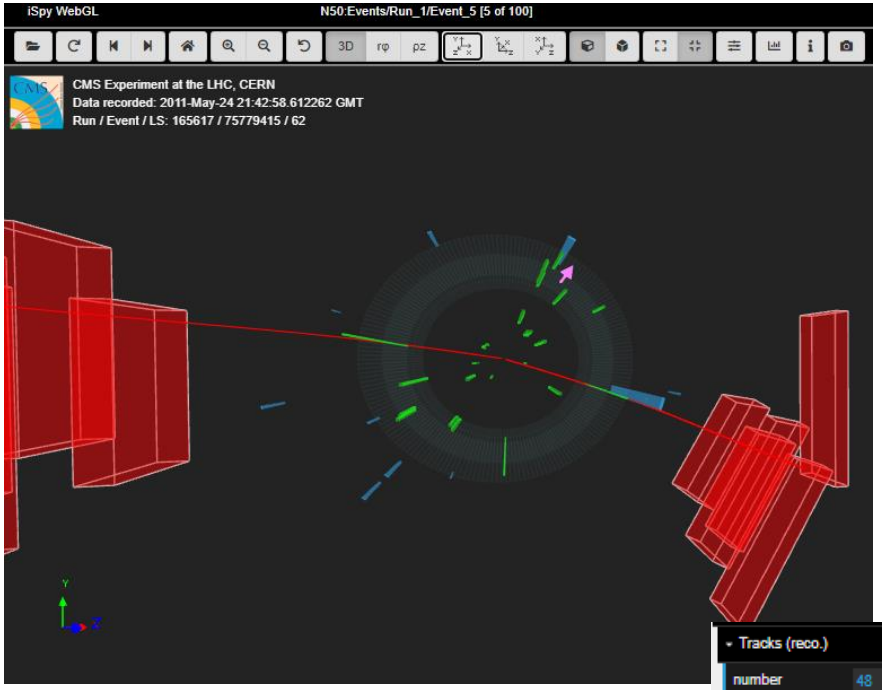
- neutrinos from "missing energy"

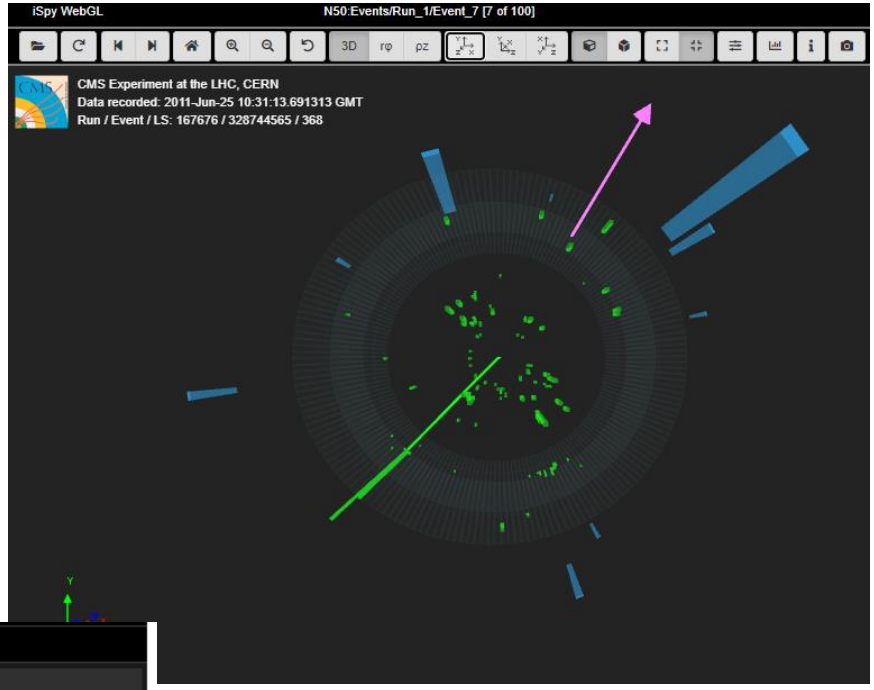
# iSpy event display for CMS

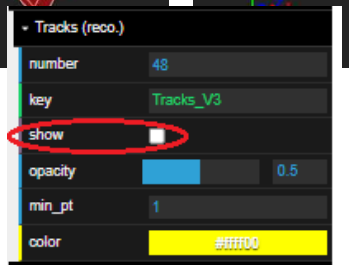


# 1, 2, or 4 leptons?

**Which of these events is 1-, 2-, or 4-lepton? Which flavors of leptons? What else do you see?**




Note Tracks (reco) turned OFF.

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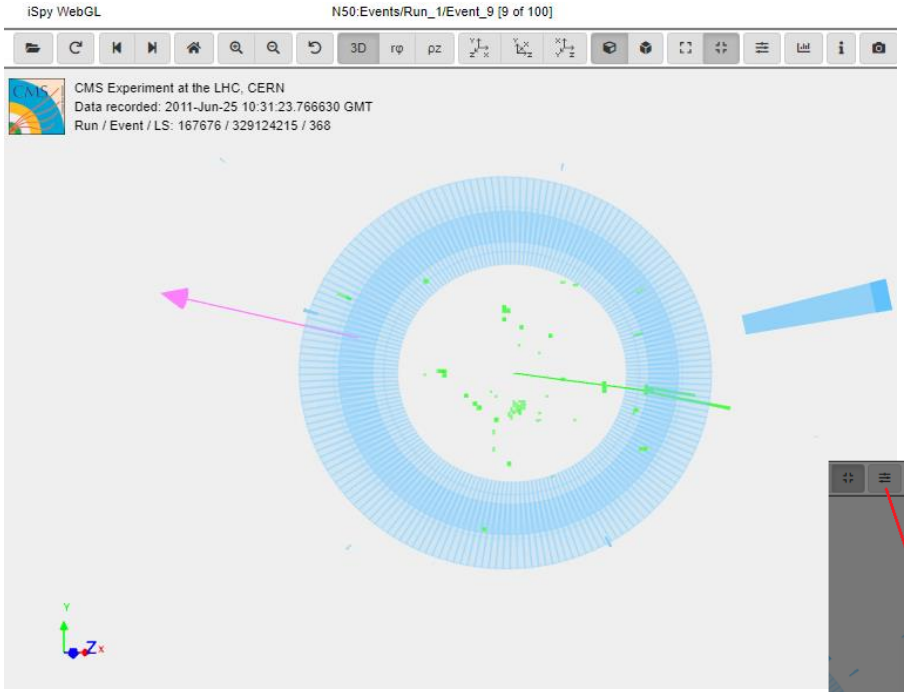
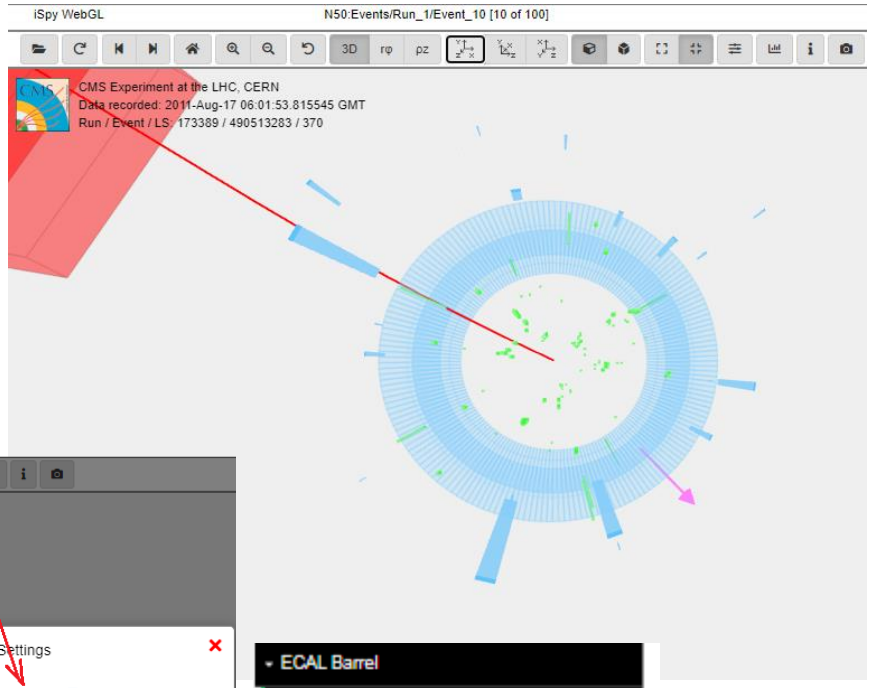
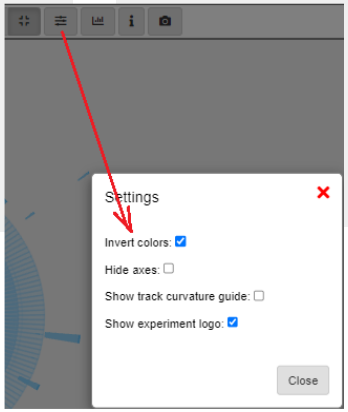
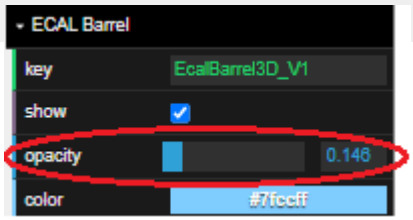



**Note Inverted Colors and increased ECal Barrel opacity.**



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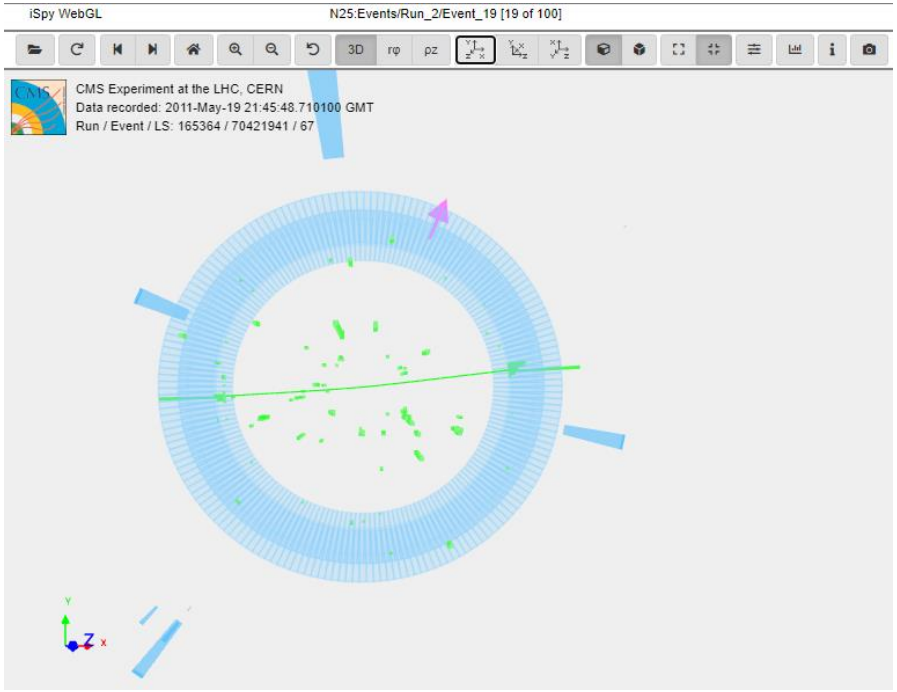


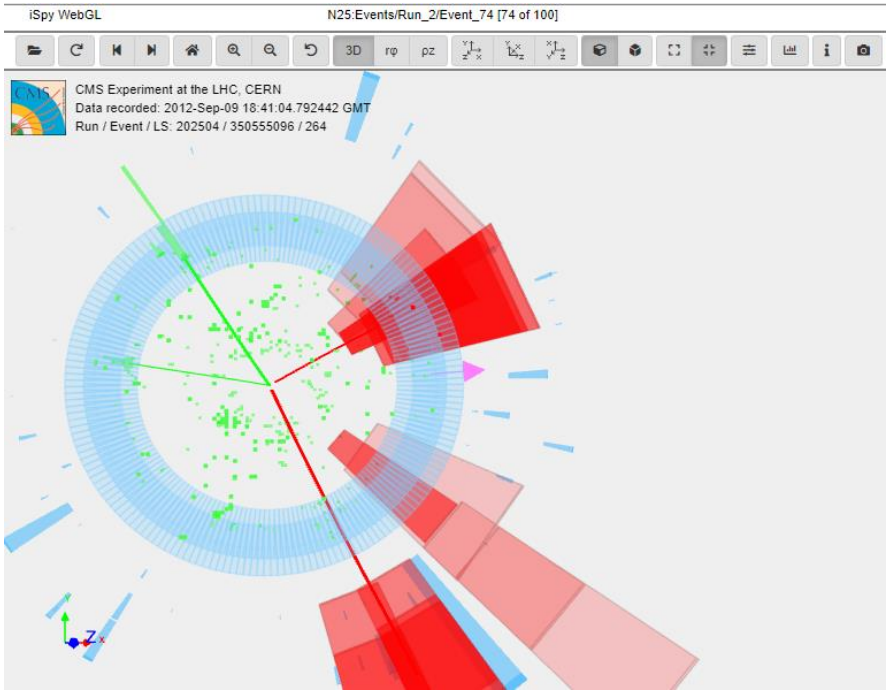

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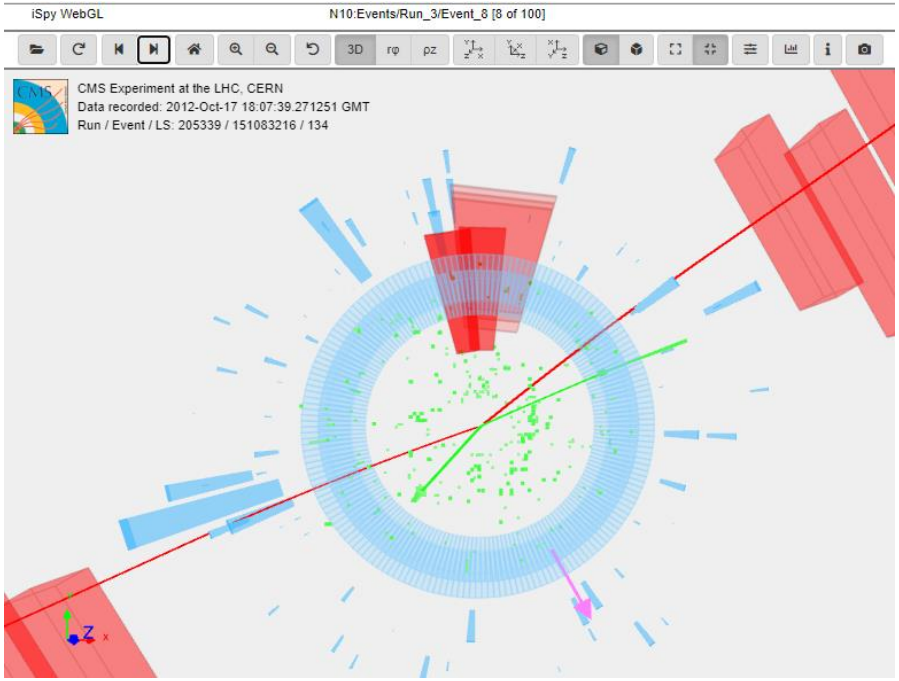


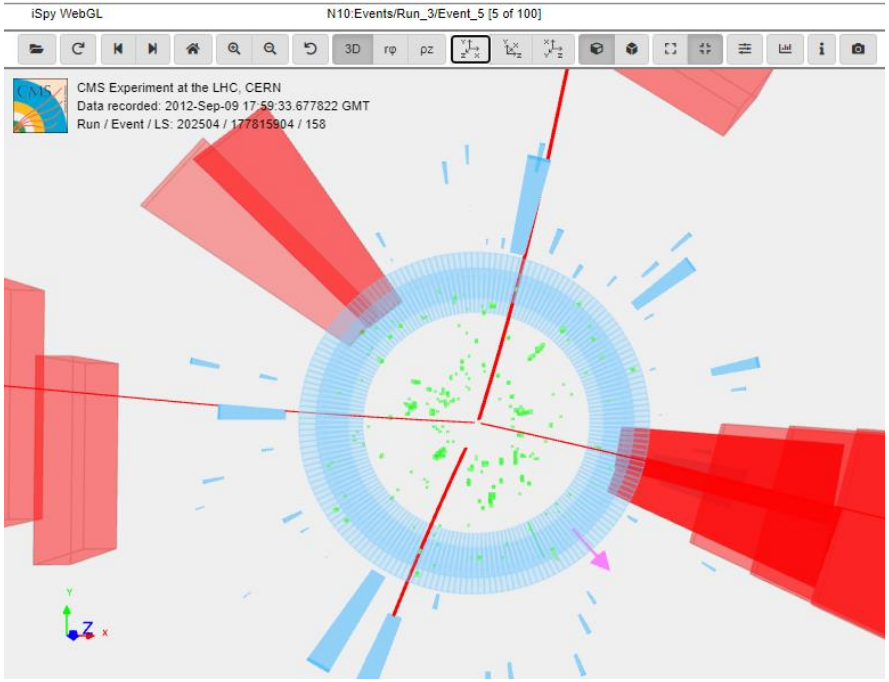

# Google Sheet analysis

Sandbox CMS Masterclass Analysis Sheet

File Edit View Insert Format Data Tools Extensions Help

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z | AA | AB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Event ID Nos. | | Final State - choose only one per row | | | | | | | Primary State - choose only one per row | | | | | If NP, enter | | Lepton counts | | | | W boson counts | | | | | | | Event |
| 2 | File | Event | e-nu | mu-nu | ee | mumu | 4e | 4mu | 2e2mu | W+ | W- | W± | NP | Zoo | Mass (GeV) | | e | mu | e/mu | | W+ | W- | W± | W+/W- | | Zoo | | Display |
| 3 | 25.1 | 1 | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | | | 14 | 17 | .82 | | 1 | 3 | 1 | 0.333333 | | 0 | | |
| 4 | | 2 | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | 2.28 | | ±3.74 | ±4.12 | | | ±1. | ±1.73 | ±1. | | | | | |
| 5 | | 3 | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | 87.15 | | | | | | | | | | | | | |
| 6 | | 4 | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | 4.79 | | | | | | | | | | | | | |
| 7 | | 5 | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | 6.74 | | | | | | | | | | | | | |
| 8 | | 6 | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 9 | | 7 | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | 3.71 | | | | | | | | | | | | | |
| 10 | | 8 | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | 7.30 | | | | | | | | | | | | | |
| 11 | | 9 | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | 86.43 | | | | | | | | | | | | | |
| 12 | | 10 | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | 276.26 | | | | | | | | | | | | | |
| 13 | | 11 | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | 243.15 | | | | | | | | | | | | | |
| 14 | | 12 | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | 88.47 | | | | | | | | | | | | | |
| 15 | | 13 | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 16 | | 14 | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 17 | | 15 | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 18 | | 16 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 19 | | 17 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 20 | | 18 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 21 | | 19 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 22 | | 20 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 23 | | 21 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 24 | | 22 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 25 | | 23 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 26 | | 24 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 27 | | 25 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |
| 28 | | 26 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | | | | | | | | | | | | | | |