JAVIER DUARTE

OCTOBER 9, 2020

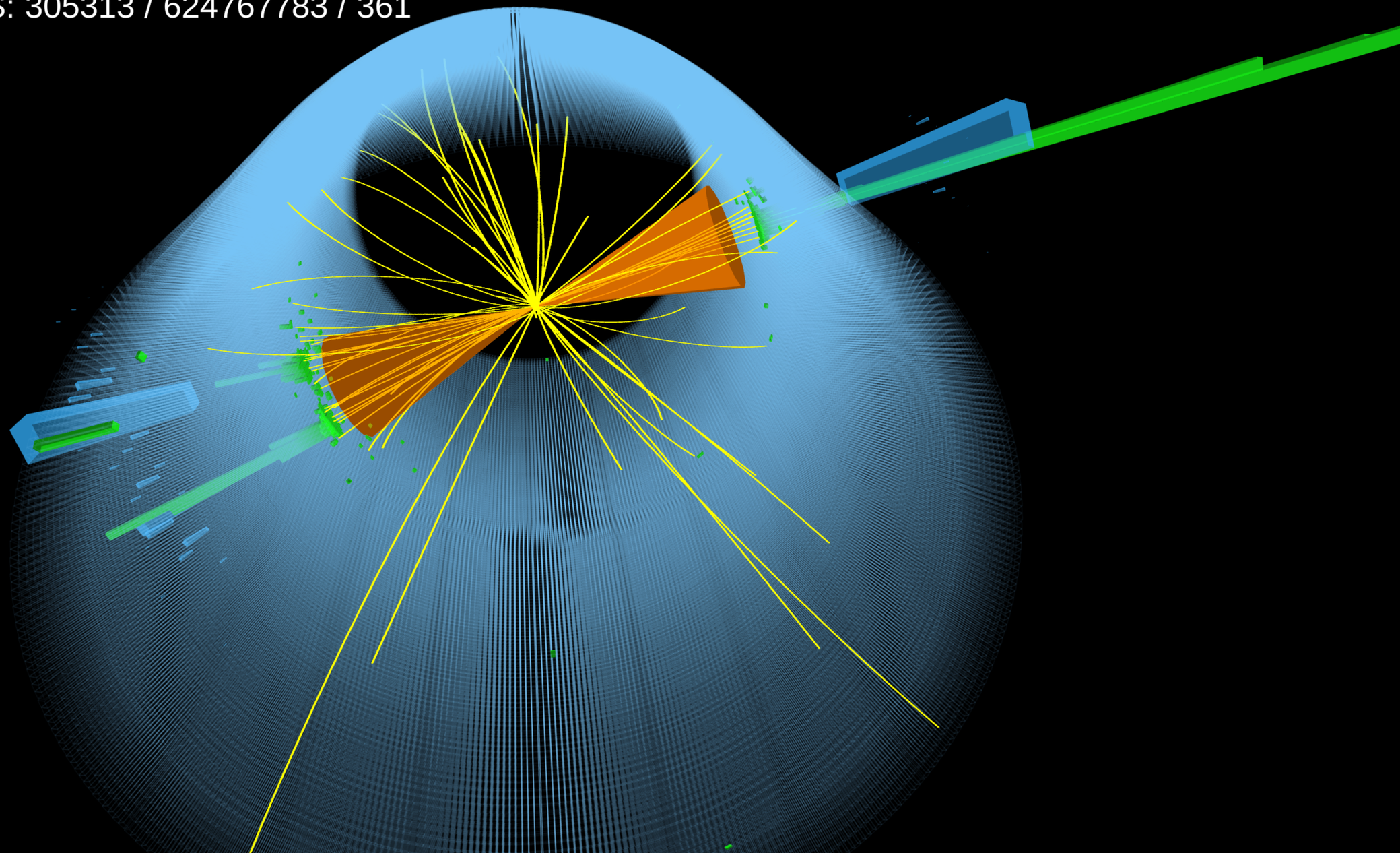
UCSD PHYSICS 191

PARTICLE PHYSICS AND MACHINE LEARNING AT THE CERN LHC & CMS

CMS Experiment at the LHC, CERN

Data recorded: 2017-Oct-20 03:55:39.135168 GMT

Run / Event / LS: 305313 / 624767783 / 361



WELCOME TO PHYSICS 191

- Goal: Introduction to research topics across physics. Opportunity for you to find potential labs to work in
- Lectures: 1:00-1:50 pm every Friday
- Attendance policy: Taking for credit? Attend most guest lectures and ask questions! I will record attendance for each class
- Webpage: Canvas: https://canvas.ucsd.edu/courses/19858 and Indico: https://indico.cern.ch/event/956641/
- Zoom: https://ucsd.zoom.us/j/98503442947
  General: Sign in with your full first and last name as listed on the class roster.
  Video: Turn on your video when possible. It is helpful to be able to see each other, just as in an in-person class.
  Audio: Mute your microphone when you are not talking. Use a headset when possible. If you own headphones with a microphone, please use them. Be in a quiet, distraction-free place when possible.
  Chat: No disrespect or hate speech.
  Recording: I will record each lecture for the benefit of students in different timezones.
  Discussion: Ask questions!

SCHEDULE

- Oct. 9 – Introduction; Javier Duarte
- Oct. 16 – Alex Frano
- Oct. 23 – Kam Arnold
- Oct. 30 – Mattia Serra
- Nov. 6 – Shelley Wright
- Nov. 13 – Liang Yang
- Nov. 20 – Chunhui Du
- Dec. 4 – Yizhuang You
- Dec. 11 – Tongyan Lin

PERSONAL BIO

- Originally from Cúcuta, Colombia
- Raised in Coram, NY (Long Island)

PERSONAL BIO

- Originally from Cúcuta, Colombia
- Raised in Coram, NY (Long Island)
- Undergrad at MIT (2006–2010)

PERSONAL BIO

*REU = Research Experience for Undergraduates

- Originally from Cúcuta, Colombia
- Raised in Coram, NY (Long Island)
- Undergrad at MIT (2006–2010)
  - Came to Fermilab as a Nevis REU* student (summer 2007)

PERSONAL BIO

*REU = Research Experience for Undergraduates

- Originally from Cúcuta, Colombia
- Raised in Coram, NY (Long Island)
- Undergrad at MIT (2006–2010)
  - Came to Fermilab as a Nevis REU* student (summer 2007)
  - Went to CERN as a Michigan REU* student (summer 2009)

PERSONAL BIO

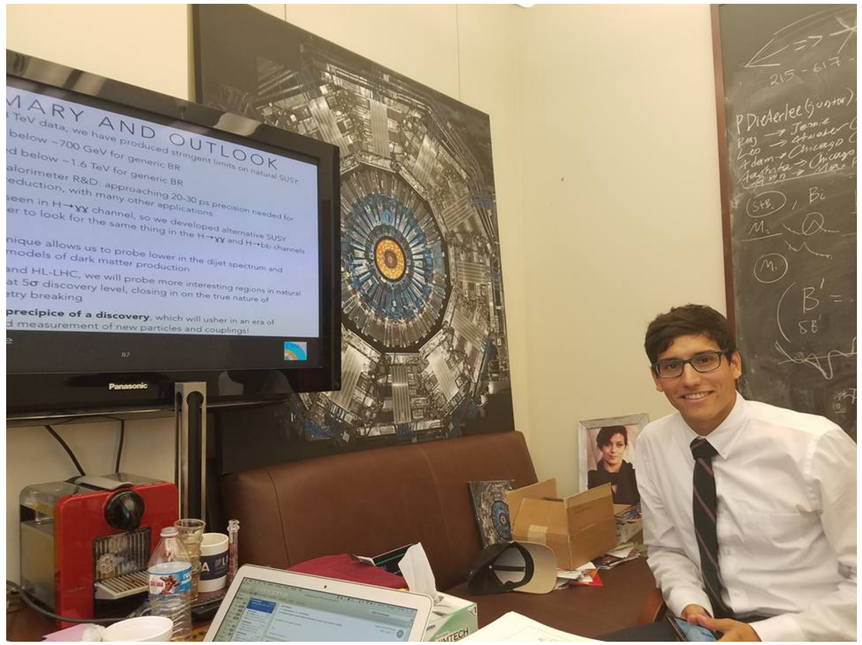
*REU = Research Experience for Undergraduates

- Originally from Cúcuta, Colombia
- Raised in Coram, NY (Long Island)
- Undergrad at MIT (2006–2010)
  - Came to Fermilab as a Nevis REU* student (summer 2007)
  - Went to CERN as a Michigan REU* student (summer 2009)
- Technical instructor for MIT Junior Lab (2010–2011)

PERSONAL BIO

*REU = Research Experience for Undergraduates

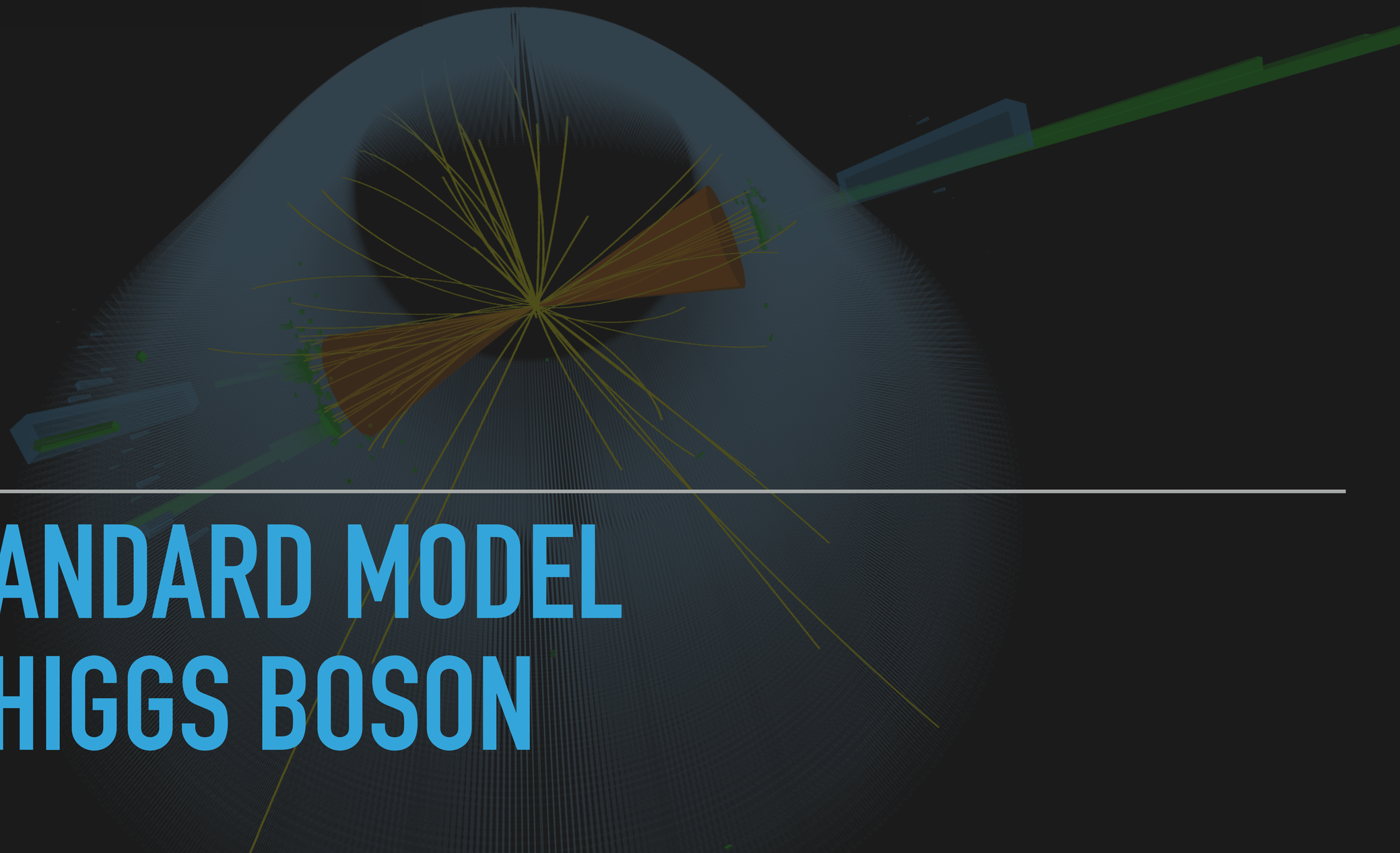
- Originally from Cúcuta, Colombia
- Raised in Coram, NY (Long Island)
- Undergrad at MIT (2006–2010)
  - Came to Fermilab as a Nevis REU* student (summer 2007)
  - Went to CERN as a Michigan REU* student (summer 2009)
- Technical instructor for MIT Junior Lab (2010–2011)
- Grad student at Caltech/CERN (2011–2016)



PERSONAL BIO

*REU = Research Experience for Undergraduates

- Originally from Cúcuta, Colombia
- Raised in Coram, NY (Long Island)
- Undergrad at MIT (2006–2010)
  - Came to Fermilab as a Nevis REU* student (summer 2007)
  - Went to CERN as a Michigan REU* student (summer 2009)
- Technical instructor for MIT Junior Lab (2010–2011)
- Grad student at Caltech/CERN (2011–2016)
- Lederman fellow at Fermilab (2016–2019)
- Assistant professor at UCSD (2019–Present)

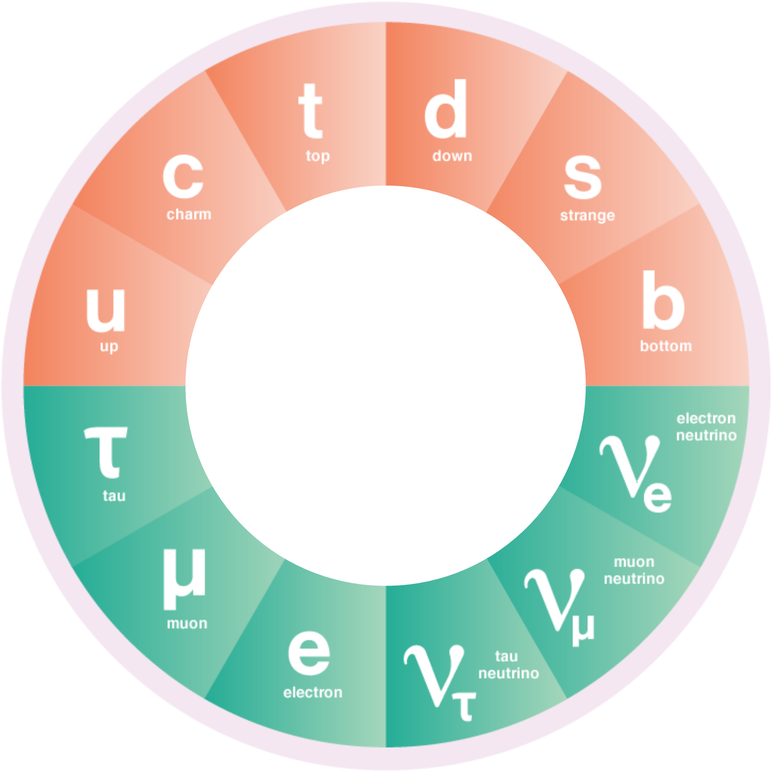


THE STANDARD MODEL & THE HIGGS BOSON

THE STANDARD MODEL (OR WHY STUDY THE HIGGS BOSON?)

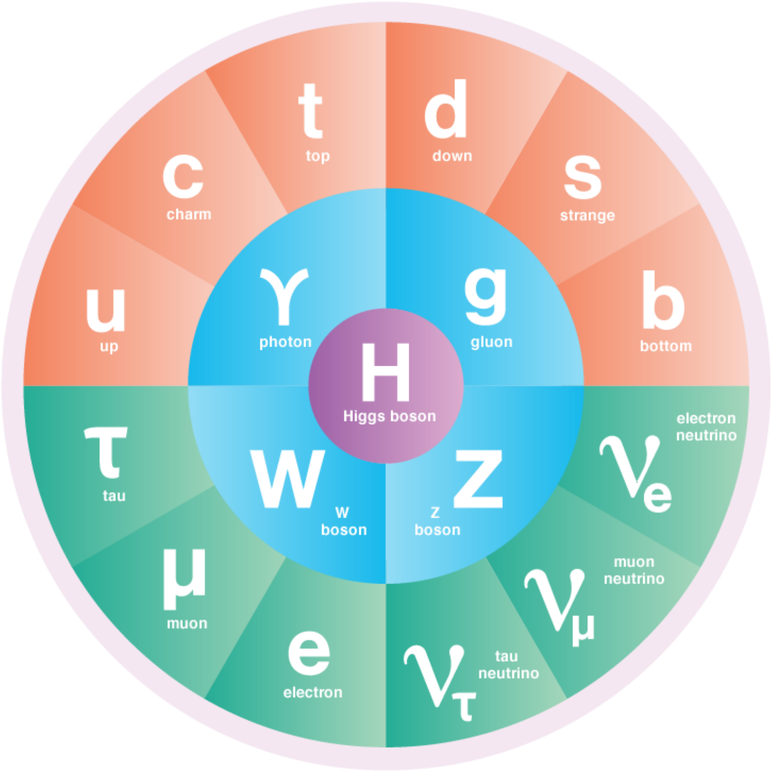
particles

THE STANDARD MODEL (OR WHY STUDY THE HIGGS BOSON?)



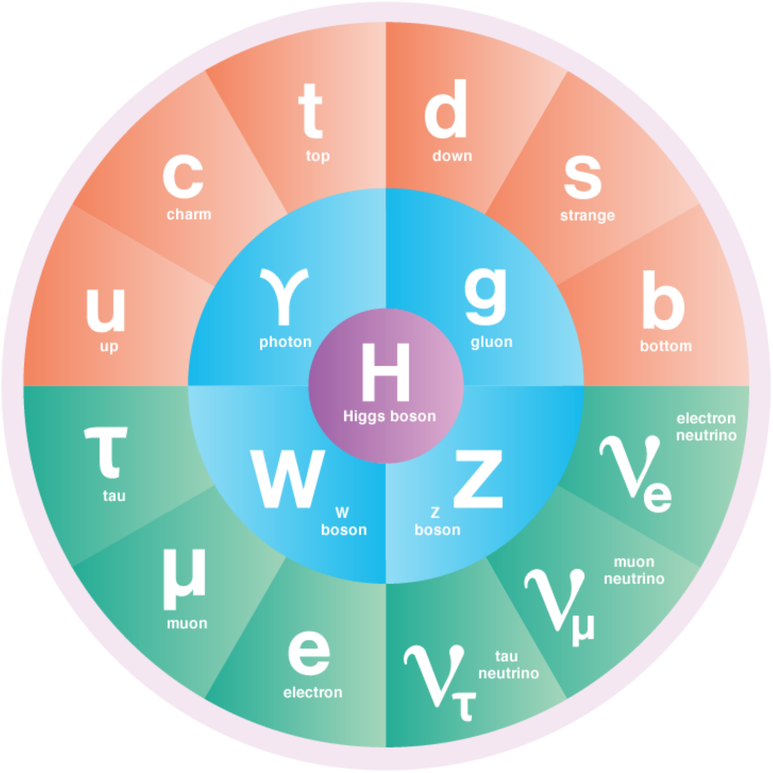
particles

THE STANDARD MODEL (OR WHY STUDY THE HIGGS BOSON?)



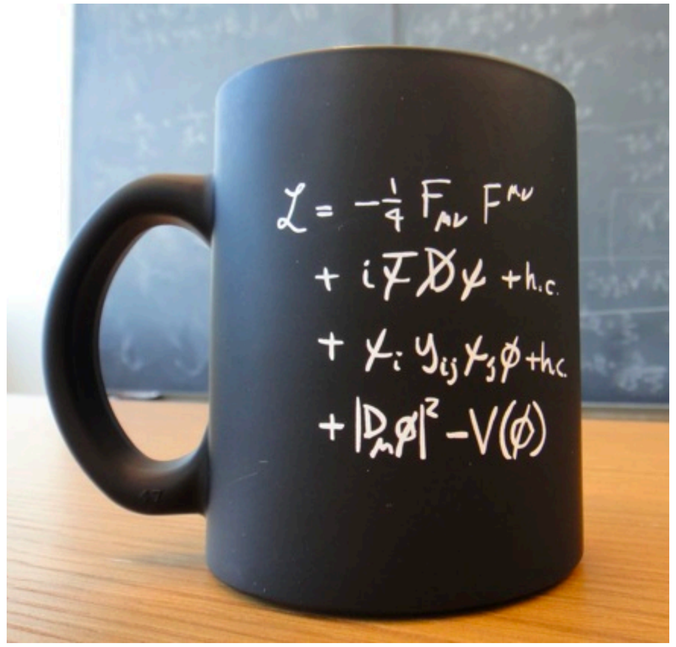
particles

THE STANDARD MODEL (OR WHY STUDY THE HIGGS BOSON?)



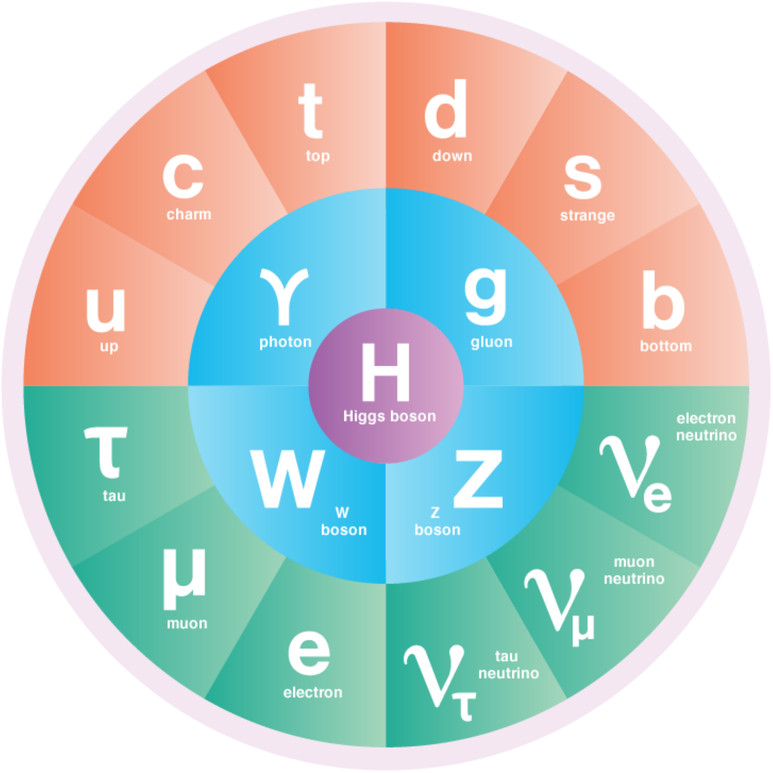
particles

+



interactions

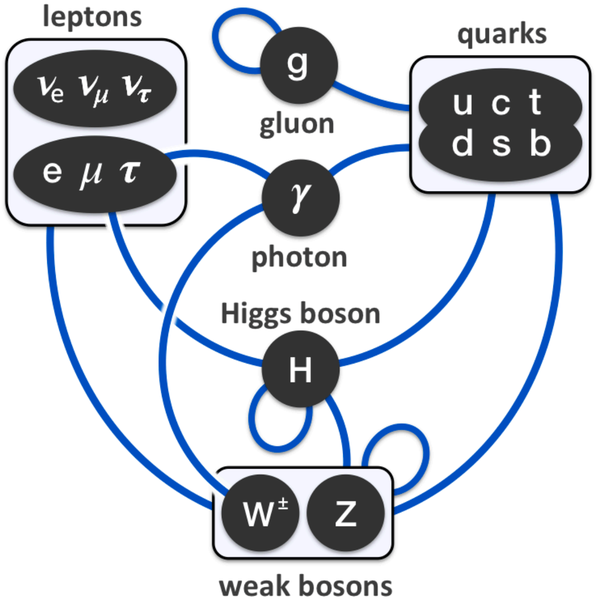
THE STANDARD MODEL (OR WHY STUDY THE HIGGS BOSON?)



particles

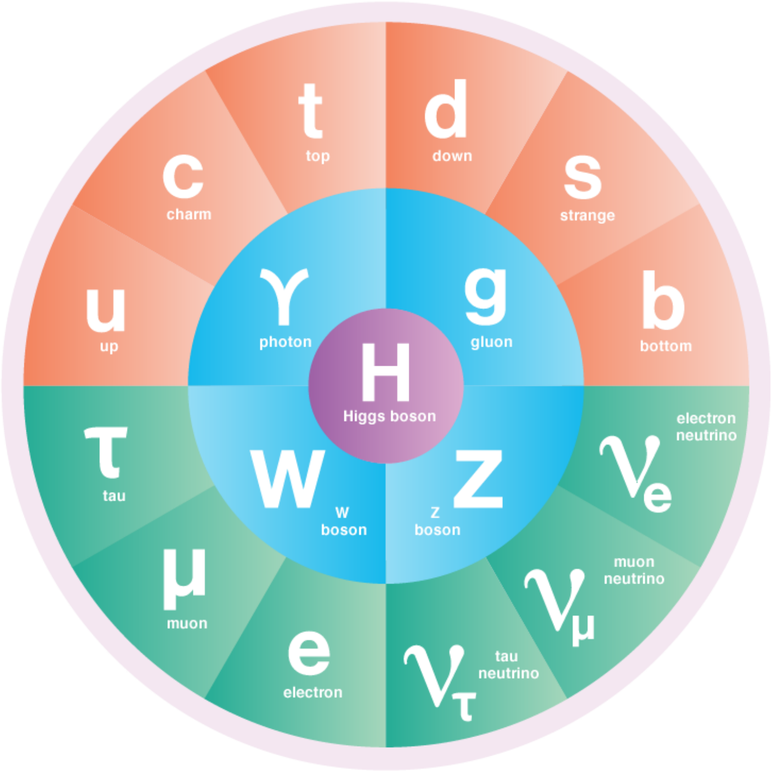
+

terms of L → links (*couplings*) between particles



interactions

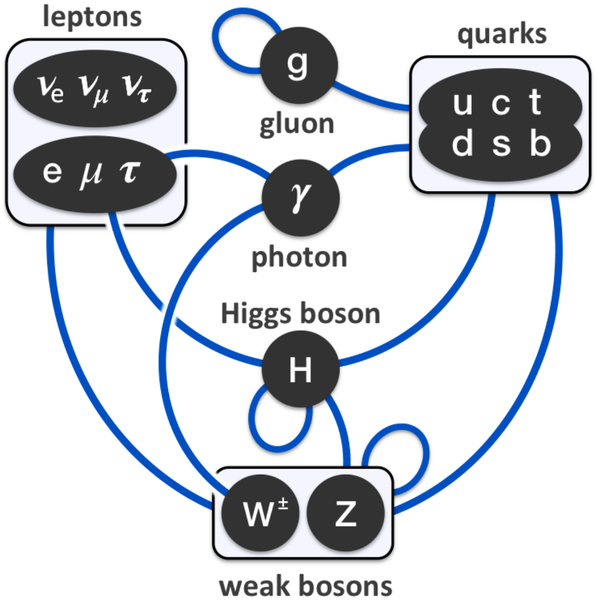
THE STANDARD MODEL (OR WHY STUDY THE HIGGS BOSON?)



particles

+

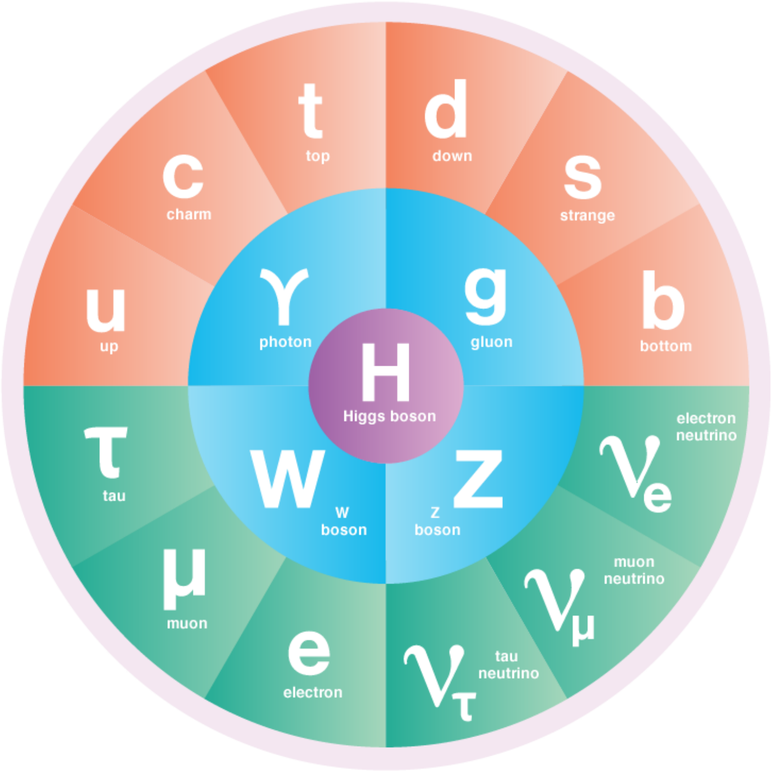
terms of L → links (*couplings*) between particles



interactions

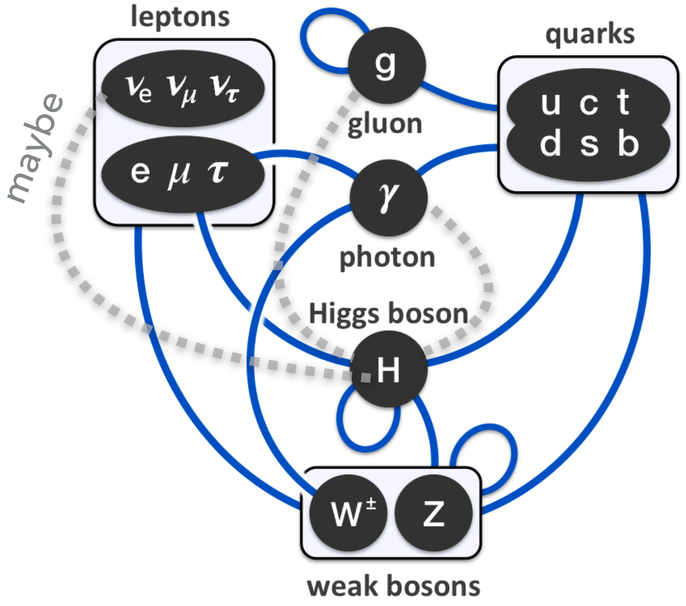
- But there has to be more to it! SM does not explain **dark matter**, **neutrino masses**, and the **matter-antimatter asymmetry**…

THE STANDARD MODEL (OR WHY STUDY THE HIGGS BOSON?)



+

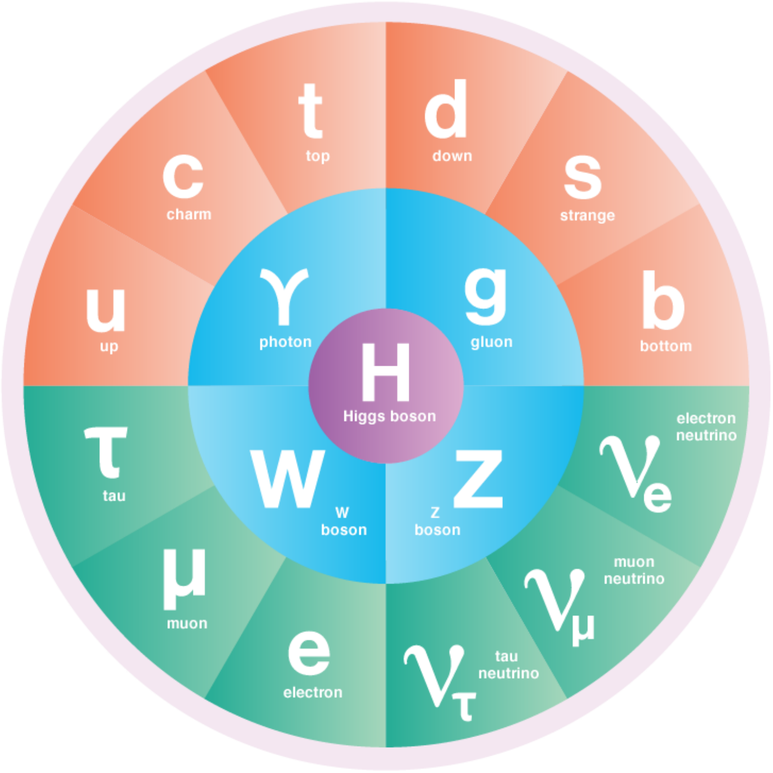
terms of L → links (*couplings*) between particles



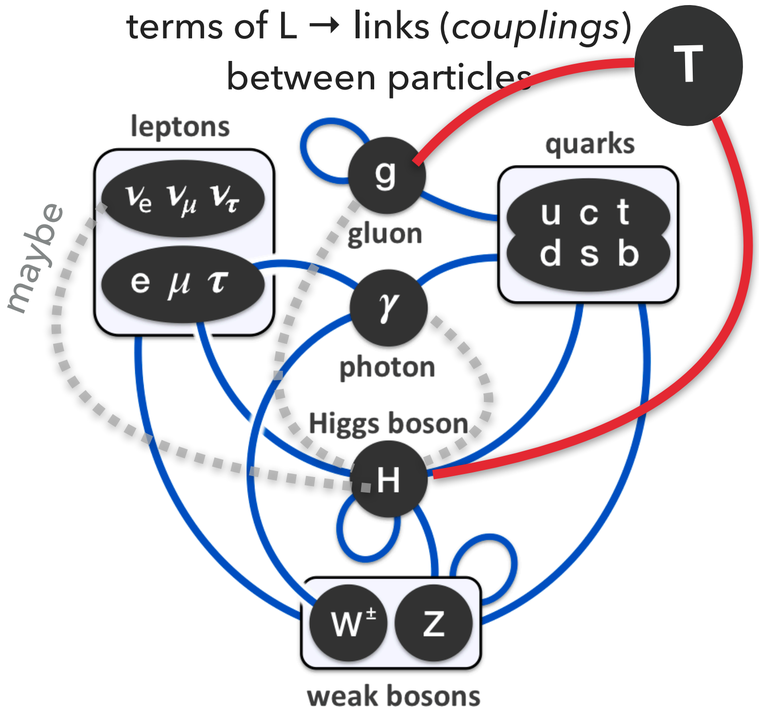
particles *interactions*

- But there has to be more to it! SM does not explain **dark matter**, **neutrino masses**, and the **matter-antimatter asymmetry**…
- Higgs boson is the ***centerpiece:*** all particles interact with it

THE STANDARD MODEL (OR WHY STUDY THE HIGGS BOSON?)



+



particles *interactions*

- But there has to be more to it! SM does not explain **dark matter**, **neutrino masses**, and the **matter-antimatter asymmetry**…
- Higgs boson is the ***centerpiece:*** all particles interact with it
- May be a link to new particles or interactions

HIGGS FIELD ANALOGY

https://www.youtube.com/watch?v=joTKd5j3mzk

HIGGS FIELD ANALOGY

https://www.youtube.com/watch?v=joTKd5j3mzk

HIGGS FIELD ANALOGY

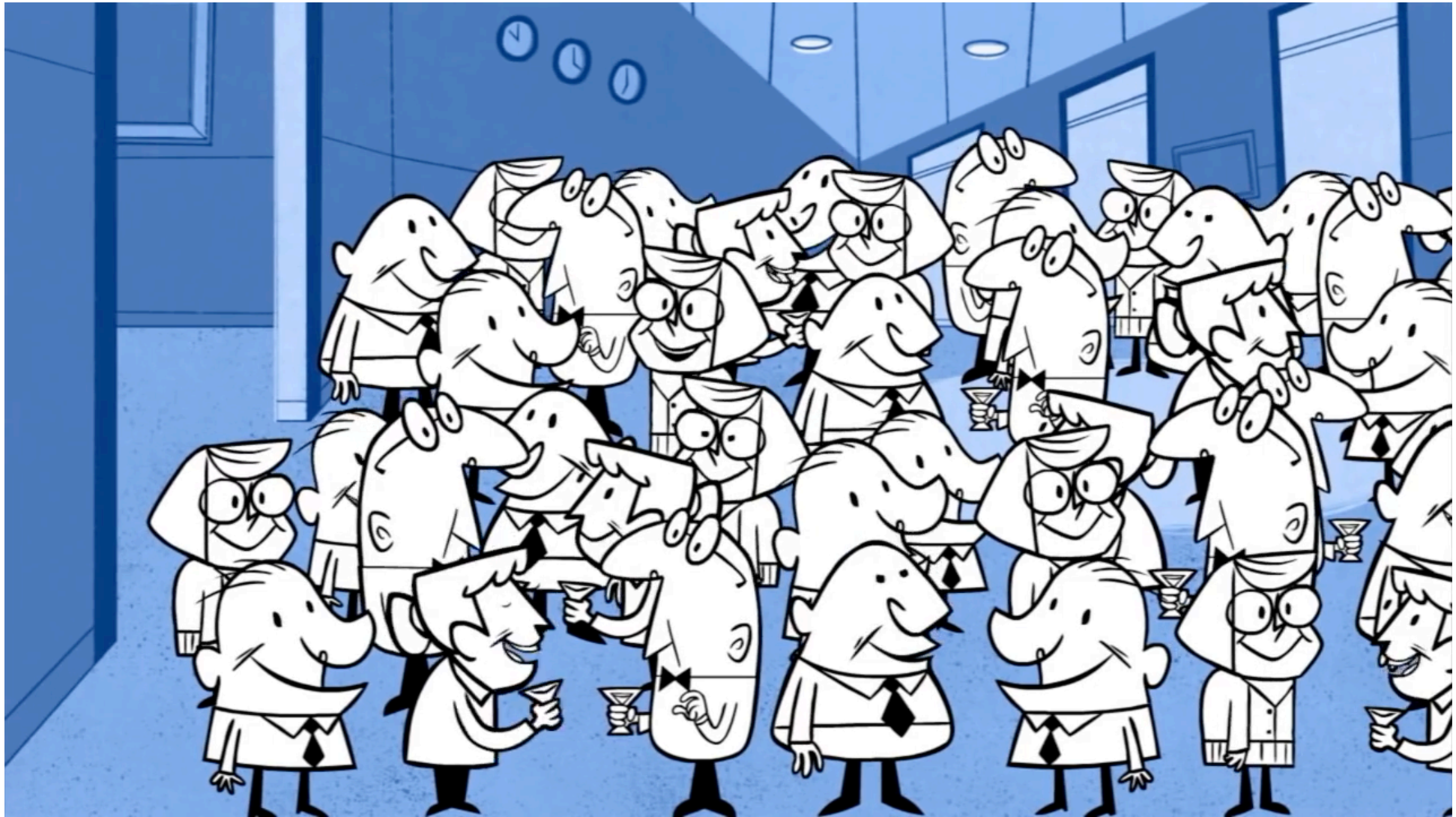
https://www.youtube.com/watch?v=joTKd5j3mzk

HIGGS FIELD ANALOGY

https://www.youtube.com/watch?v=joTKd5j3mzk

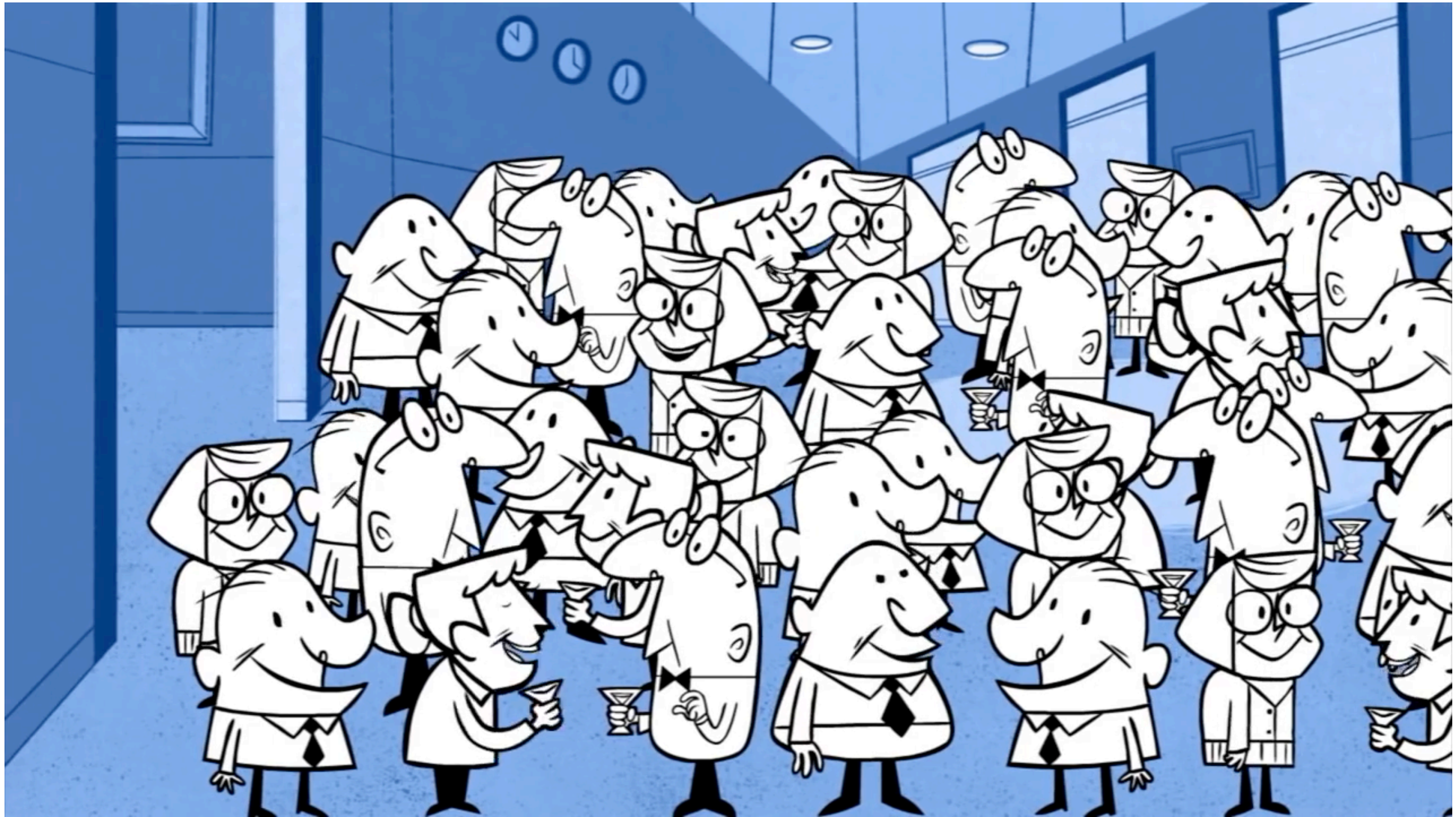
HIGGS FIELD ANALOGY

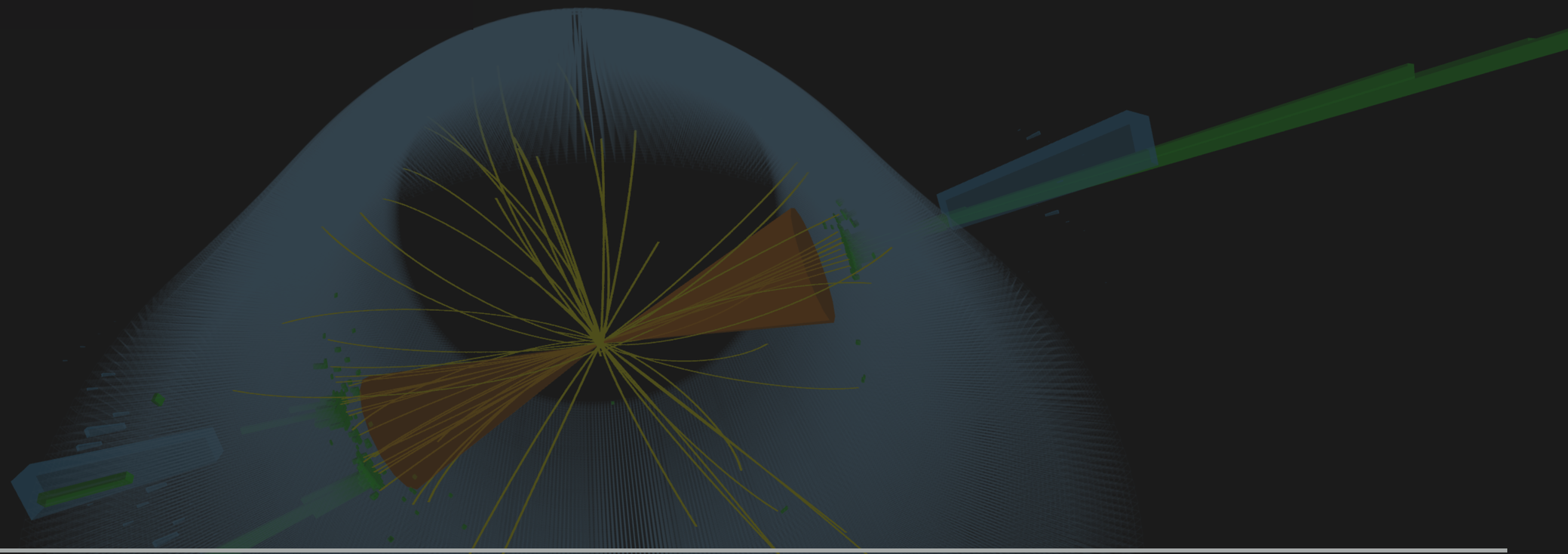
https://www.youtube.com/watch?v=joTKd5j3mzk



HIGGS FIELD ANALOGY

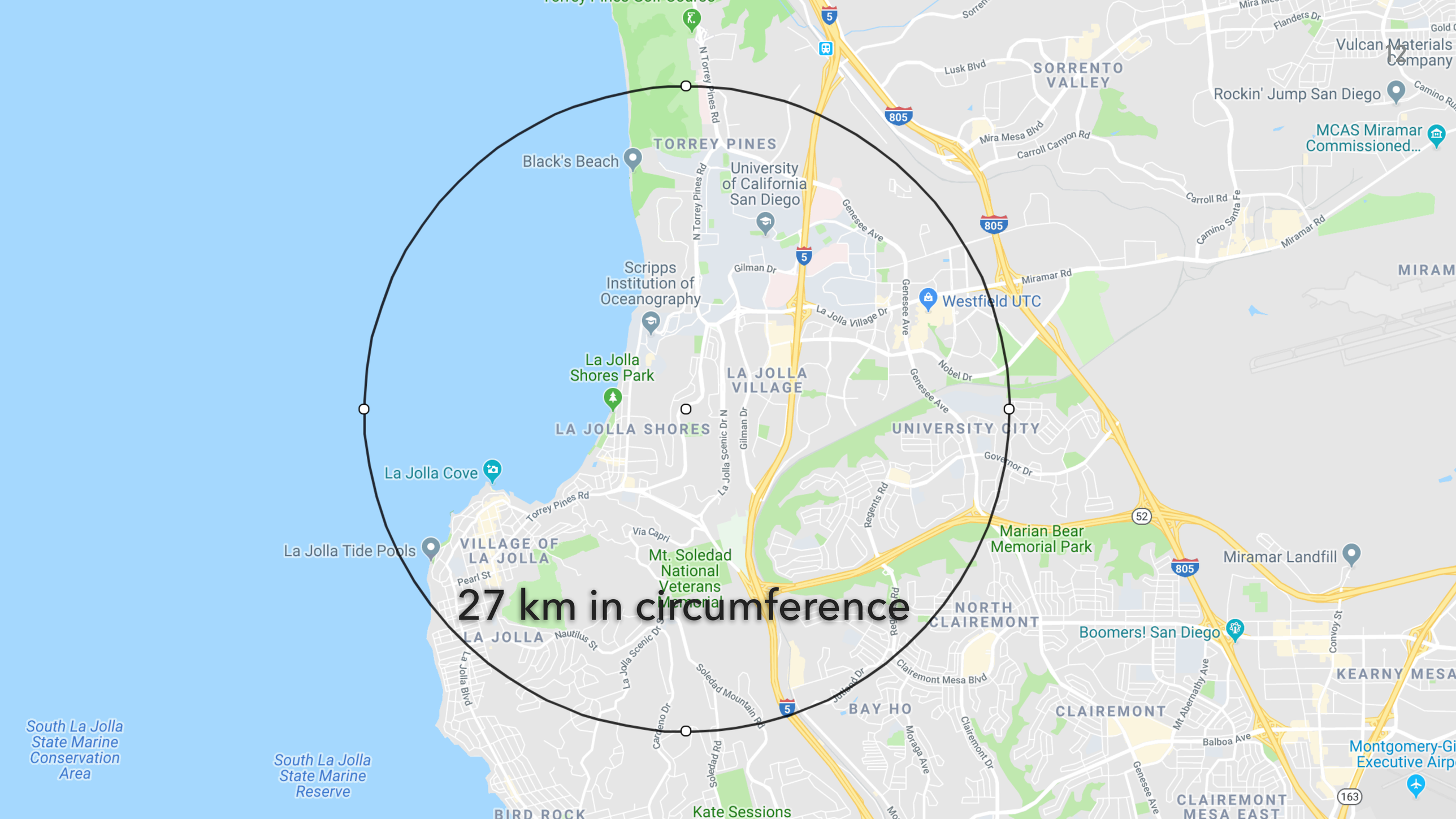
https://www.youtube.com/watch?v=joTKd5j3mzk





LARGE HADRON COLLIDER & COMPACT MUON SOLENOID


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km


27 km in circumference
TORREY PINES
Black's Beach
University of California San Diego
Scripps Institution of Oceanography
La Jolla Shores Park
LA JOLLA SHORES
LA JOLLA VILLAGE
UNIVERSITY CITY
Westfield UTC
SORRENTO VALLEY
Rockin' Jump San Diego
MCAS Miramar Commissioned...
Vulcan Materials Company
La Jolla Cove
La Jolla Tide Pools
VILLAGE OF LA JOLLA
Mt. Soledad National Veterans Memorial
Marian Bear Memorial Park
Miramar Landfill
NORTH CLAIREMONT
Boomers! San Diego
LA JOLLA
BAY HO
CLAIREMONT
KEARNY MESA
CLAIREMONT MESA EAST
South La Jolla State Marine Conservation Area
South La Jolla State Marine Reserve
BIRD ROCK
Kate Sessions
Montgomery-Gi Executive Airp
Torrey Pines Rd
N Torrey Pines Rd
Genesee Ave
Gilman Dr
La Jolla Village Dr
Nobel Dr
Governor Dr
Regents Rd
Miramar Rd
Carroll Canyon Rd
Mira Mesa Blvd
Lusk Blvd
Flanders Dr
Carroll Rd
Camino Santa Fe
Via Capri
Pearl St
Nautilus St
La Jolla Scenic Dr N
La Jolla Scenic Dr S
La Jolla Blvd
Cardeno Dr
Soledad Mountain Rd
Soledad Rd
Jutland Dr
Clairemont Mesa Blvd
Moraga Ave
Clairemont Dr
Mt Abernathy Ave
Balboa Ave
Convoy St
5
805
52
163

THE LARGE HADRON COLLIDER

13

THE LARGE HADRON COLLIDER

13

proton-proton collider @ 13 TeV center-of-mass energy

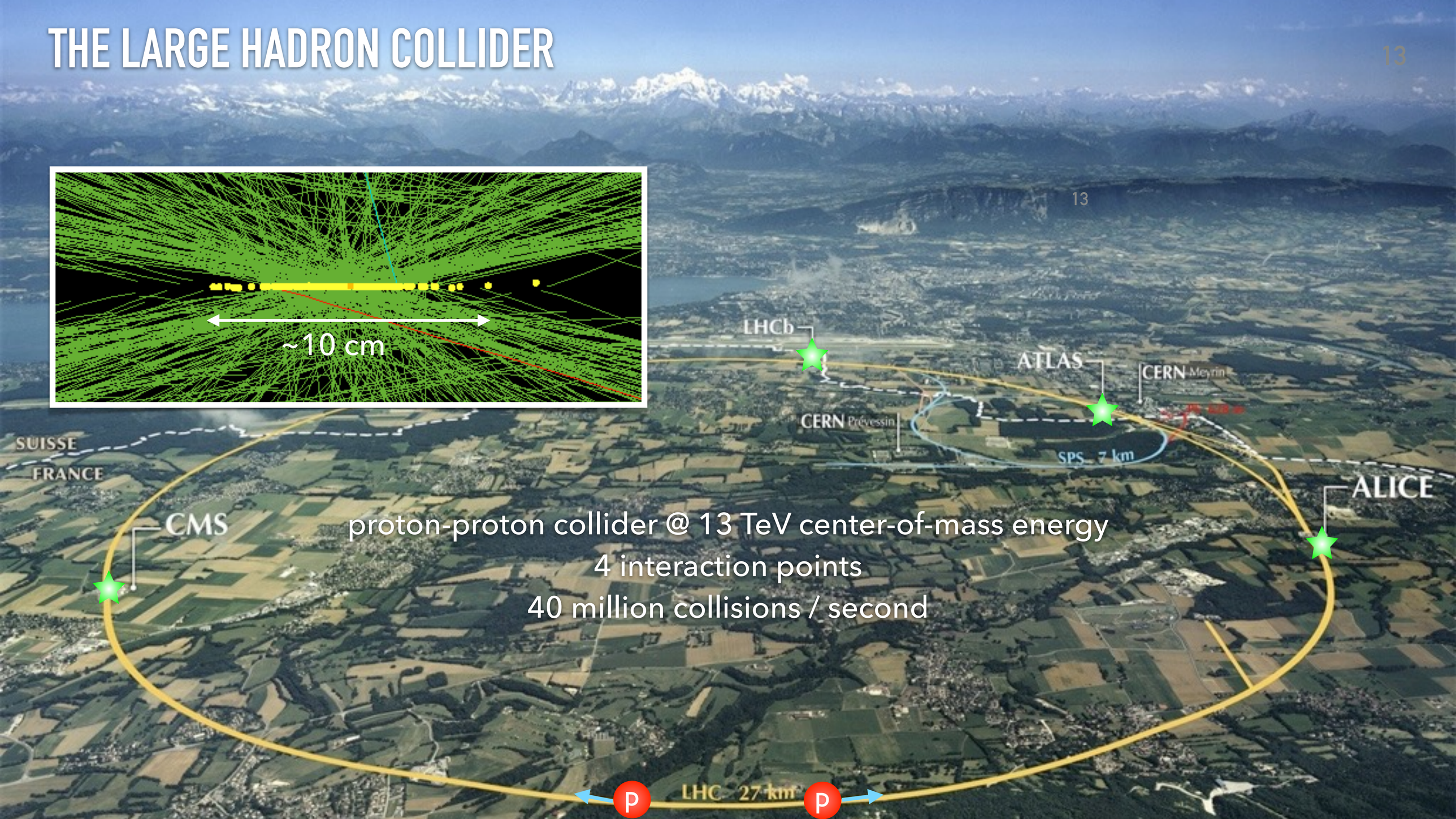
THE LARGE HADRON COLLIDER

13

proton-proton collider @ 13 TeV center-of-mass energy

4 interaction points

THE LARGE HADRON COLLIDER

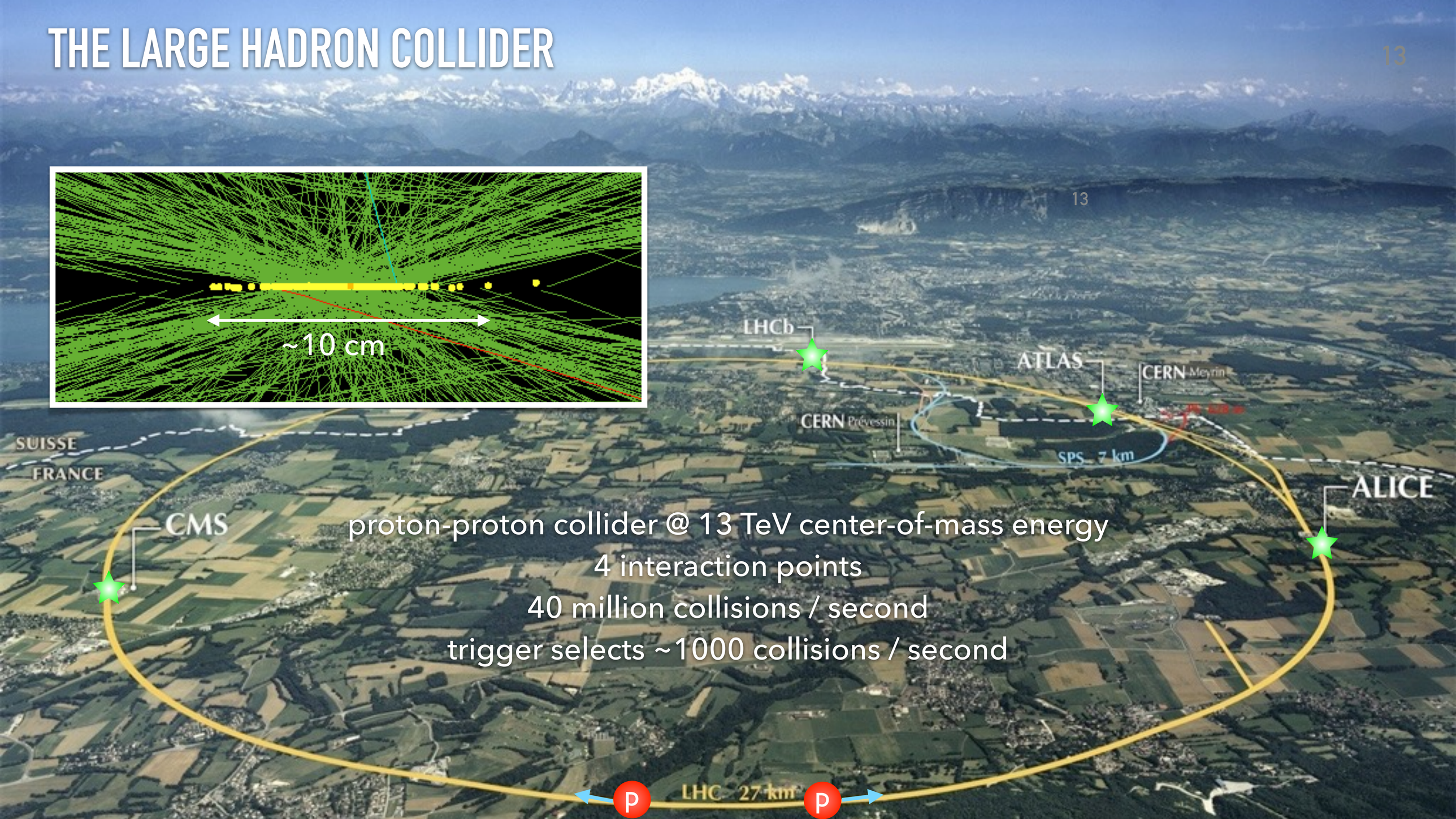


proton-proton collider @ 13 TeV center-of-mass energy

4 interaction points

40 million collisions / second

THE LARGE HADRON COLLIDER



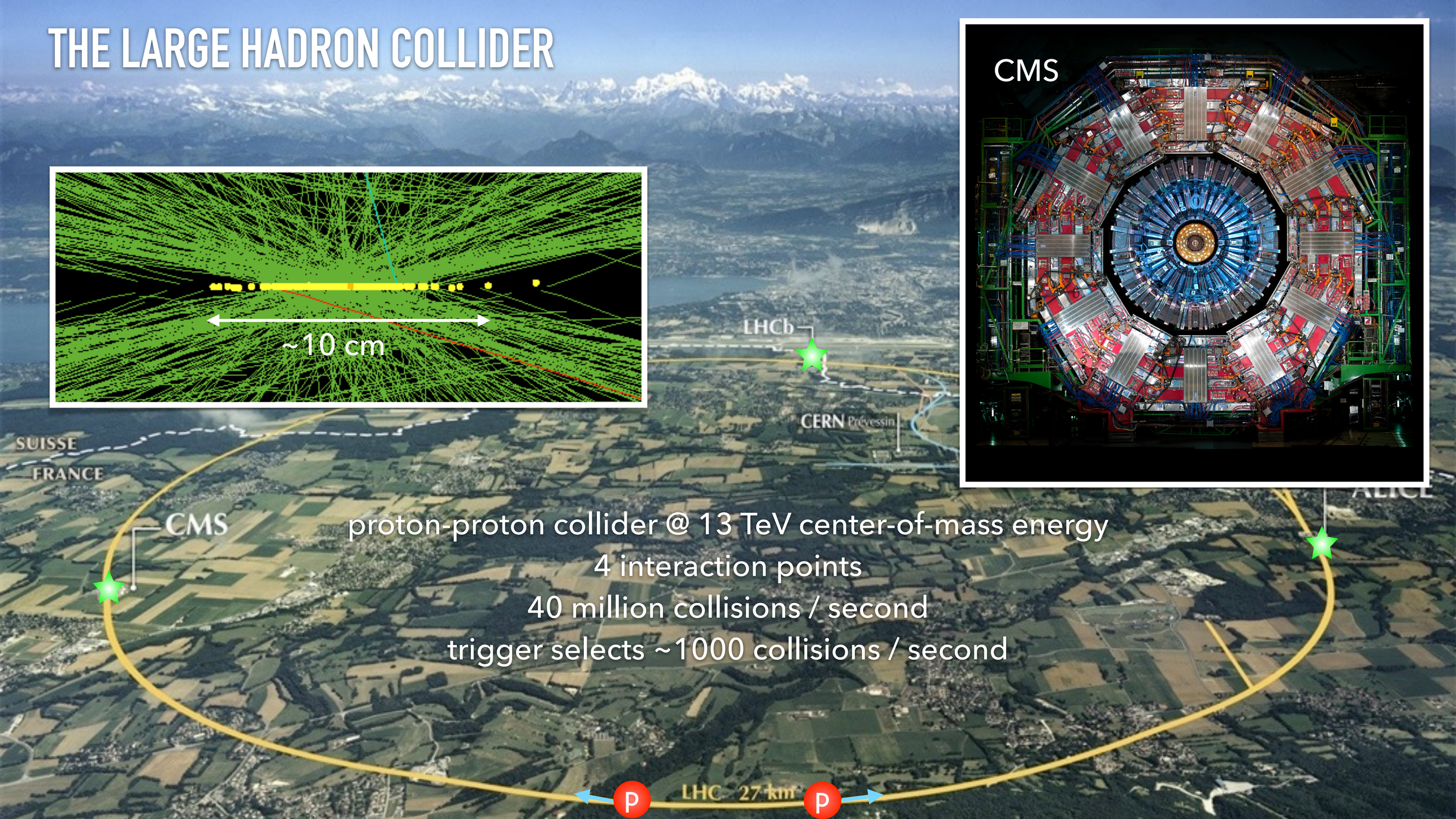
proton-proton collider @ 13 TeV center-of-mass energy

4 interaction points

40 million collisions / second

trigger selects ~1000 collisions / second

THE LARGE HADRON COLLIDER



proton-proton collider @ 13 TeV center-of-mass energy

4 interaction points

40 million collisions / second

trigger selects ~1000 collisions / second

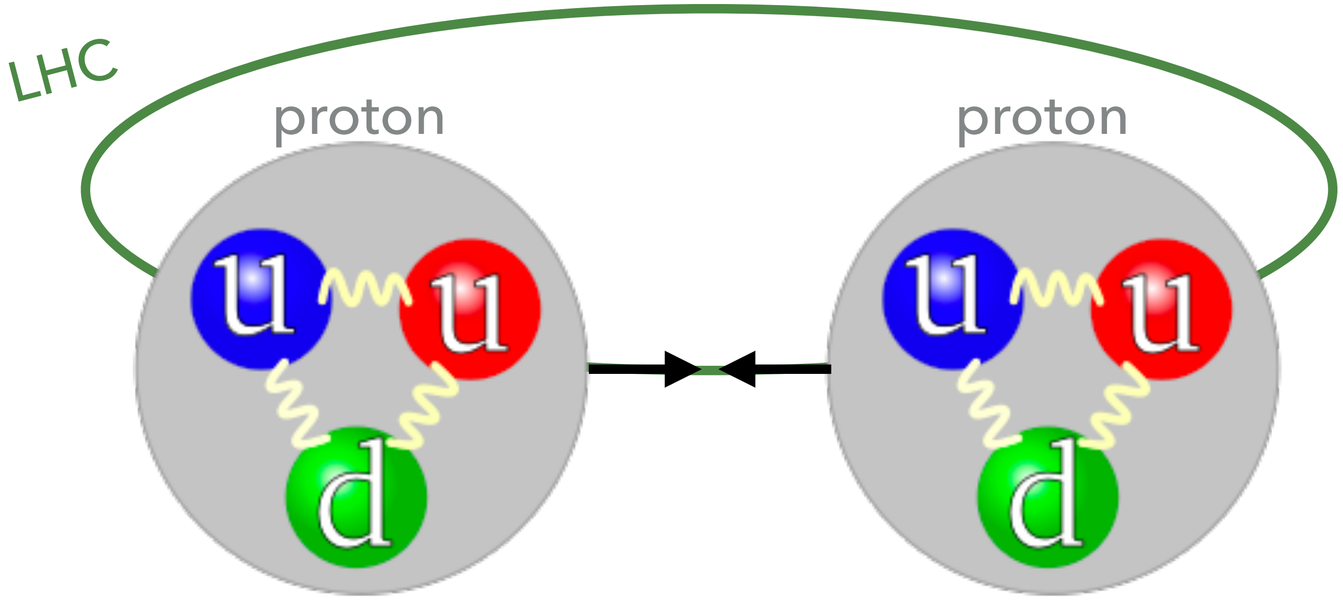
LARGE HADRON COLLIDER

https://www.youtube.com/watch?v=pQhbhpU9Wrg

LARGE HADRON COLLIDER

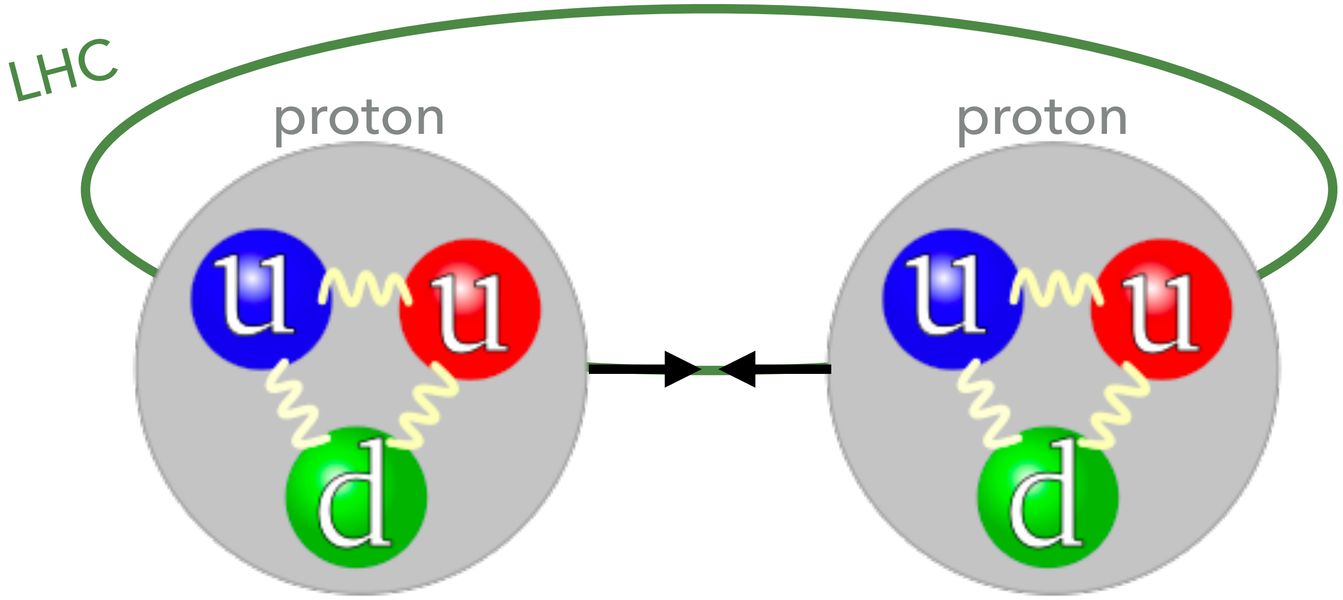
https://www.youtube.com/watch?v=pQhbhpU9Wrg

HOW DO WE PRODUCE HIGGS BOSONS AT THE LHC?



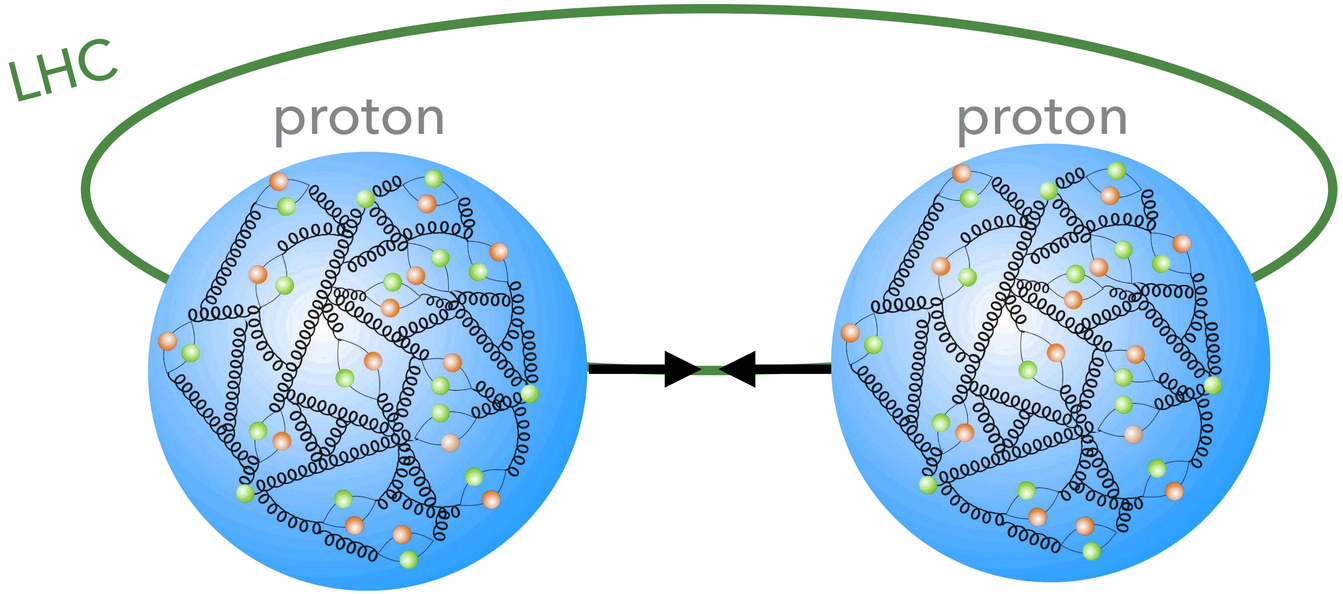
HOW DO WE PRODUCE HIGGS BOSONS AT THE LHC?

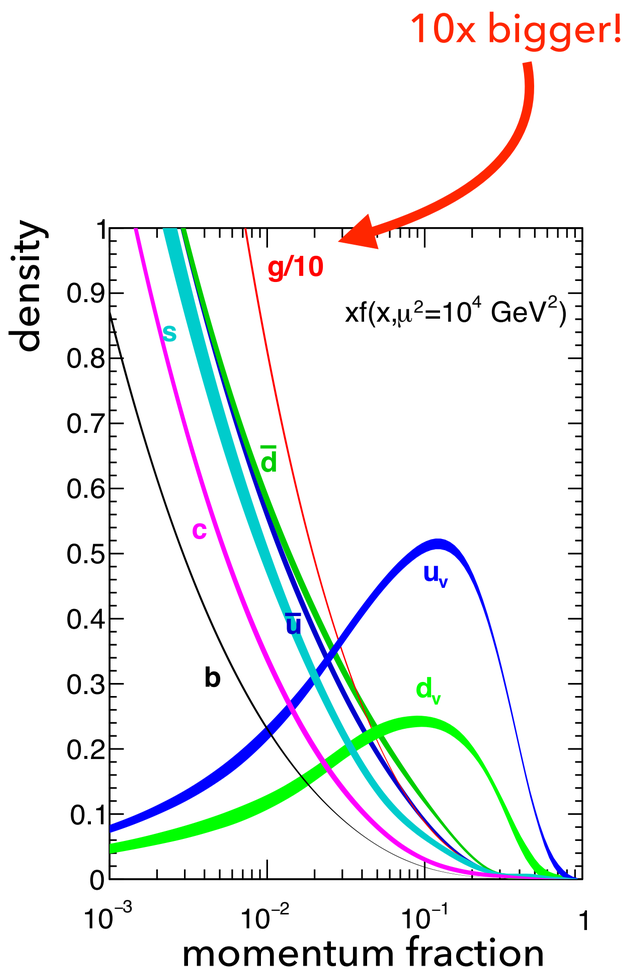
- LHC collides protons = uud + virtual quarks & gluons



HOW DO WE PRODUCE HIGGS BOSONS AT THE LHC?

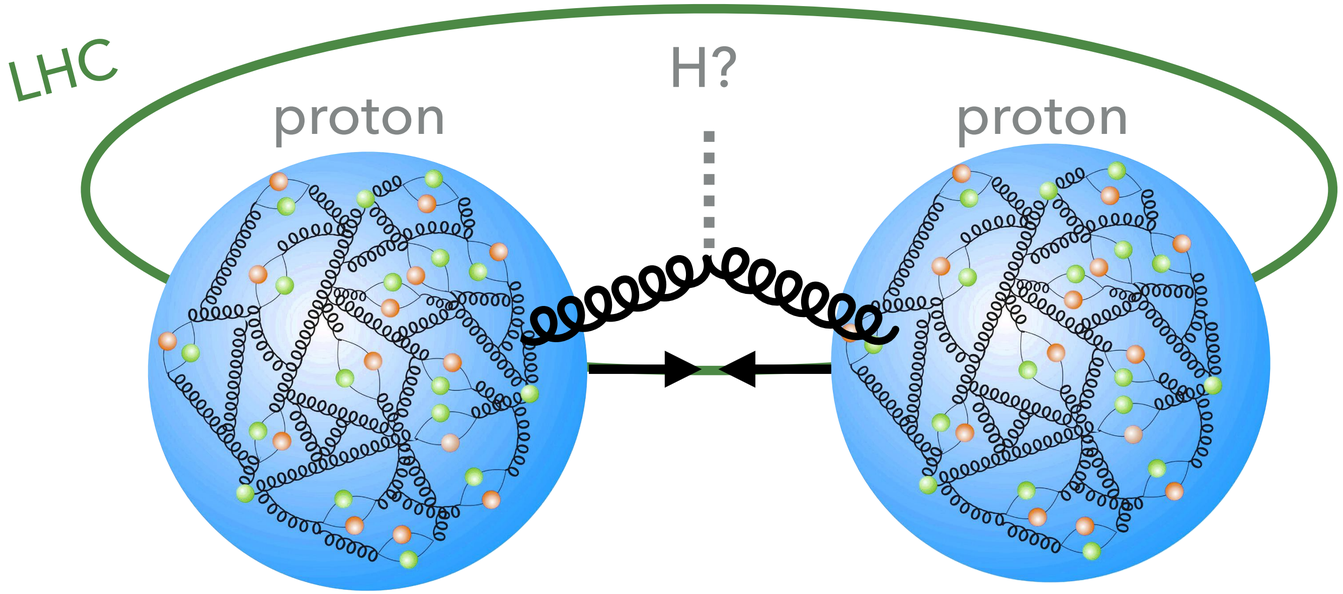
- LHC collides protons = uud + virtual quarks & gluons
- Gluons have the biggest density in the proton

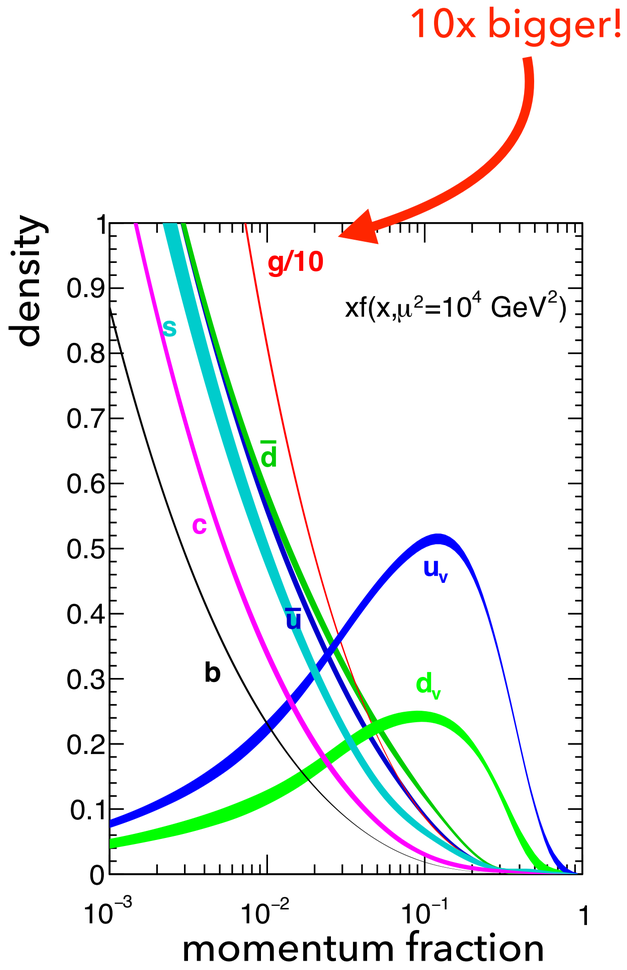




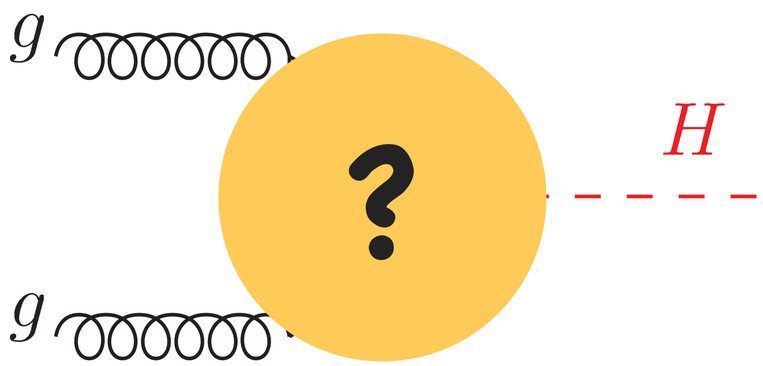
HOW DO WE PRODUCE HIGGS BOSONS AT THE LHC?

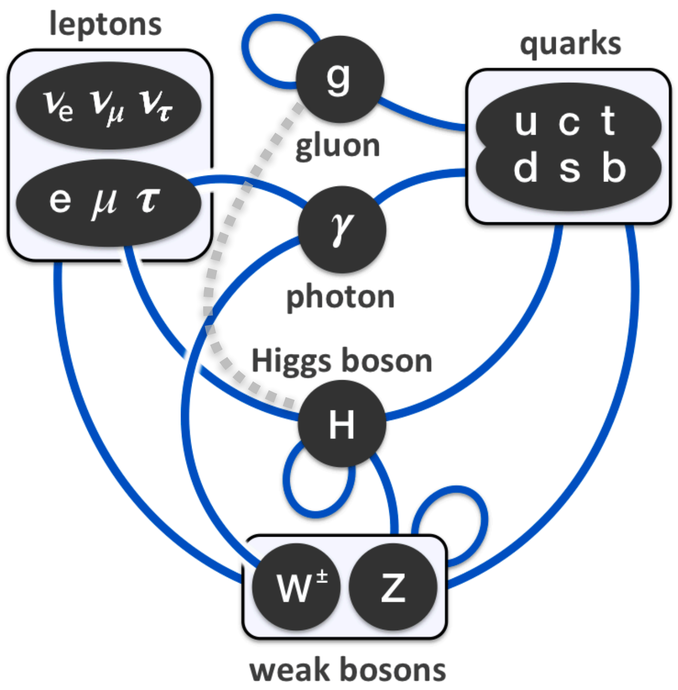
- LHC collides protons = uud + virtual quarks & gluons
- Gluons have the biggest density in the proton
- Can we collide gluons to make a Higgs boson?





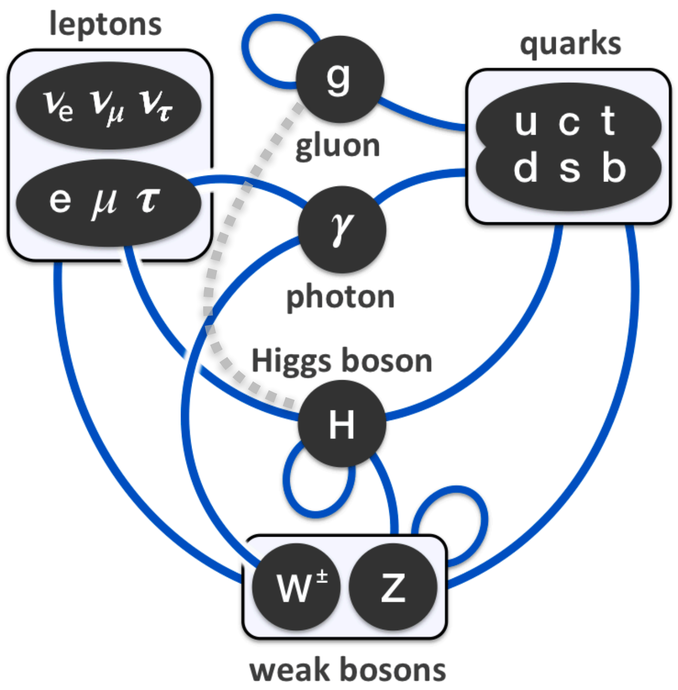
HOW DO WE PRODUCE HIGGS BOSONS AT THE LHC?

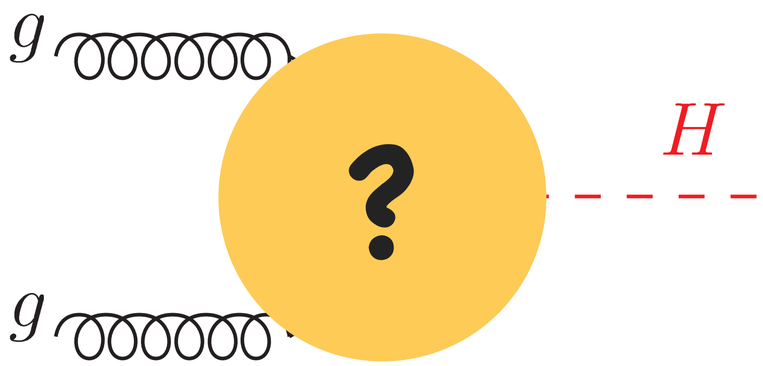




HOW DO WE PRODUCE HIGGS BOSONS AT THE LHC?

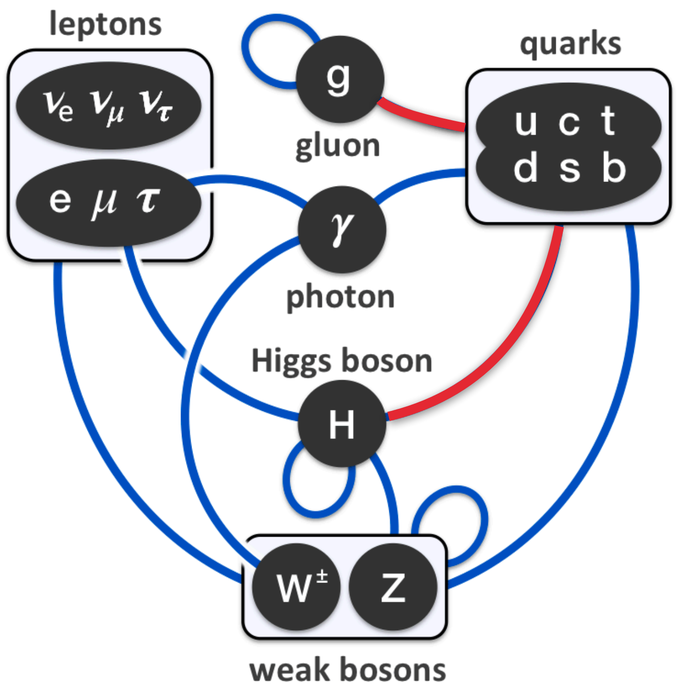
- Interactions can be "generated" through *virtual (intermediate) particles*

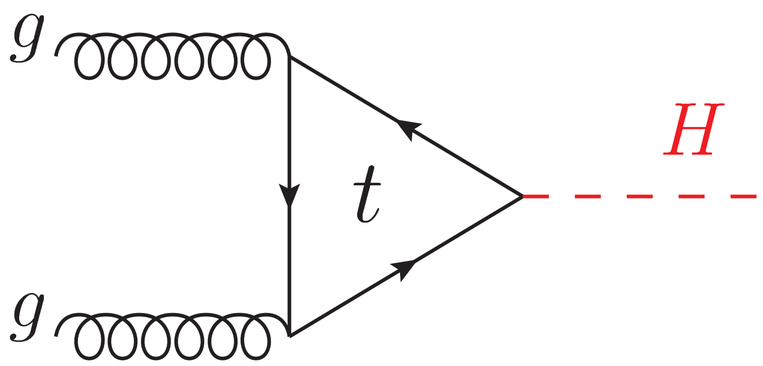




HOW DO WE PRODUCE HIGGS BOSONS AT THE LHC?

- Interactions can be "generated" through *virtual (intermediate) particles*
- Biggest contribution in the SM is from the **top quark**

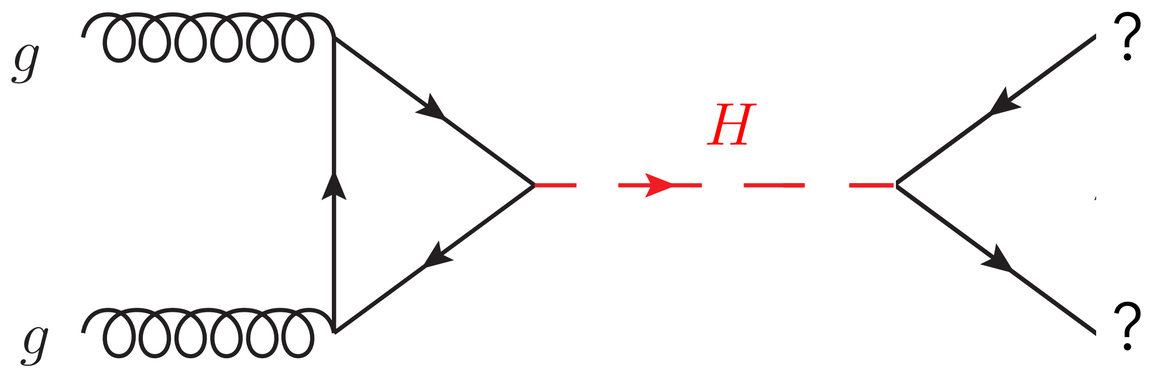


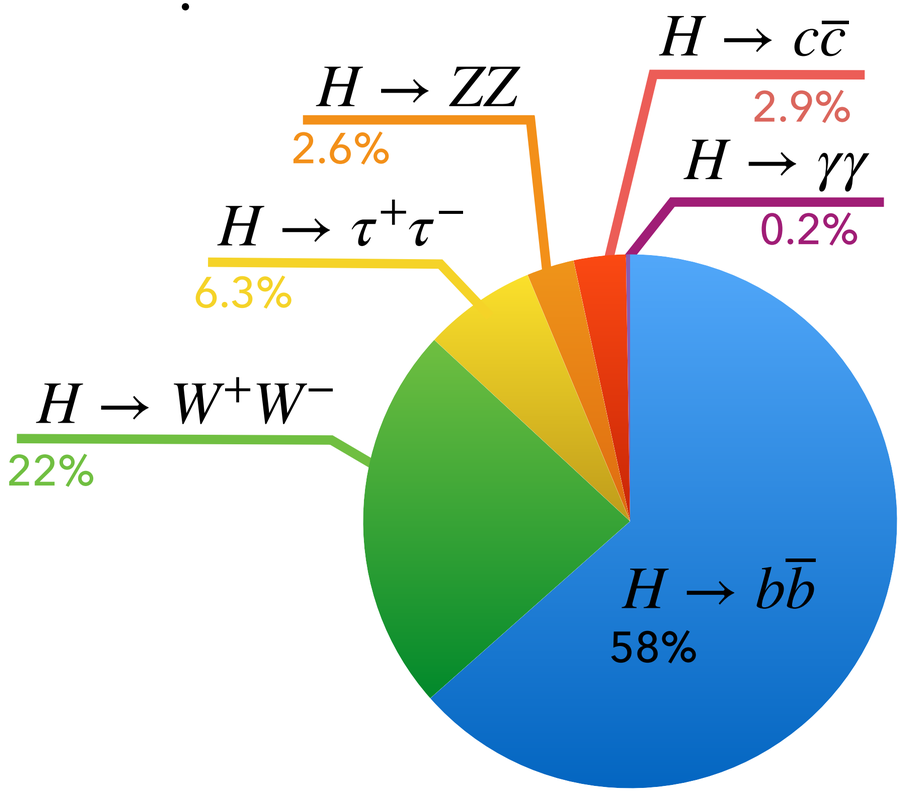


HOW DO WE DETECT HIGGS BOSONS?

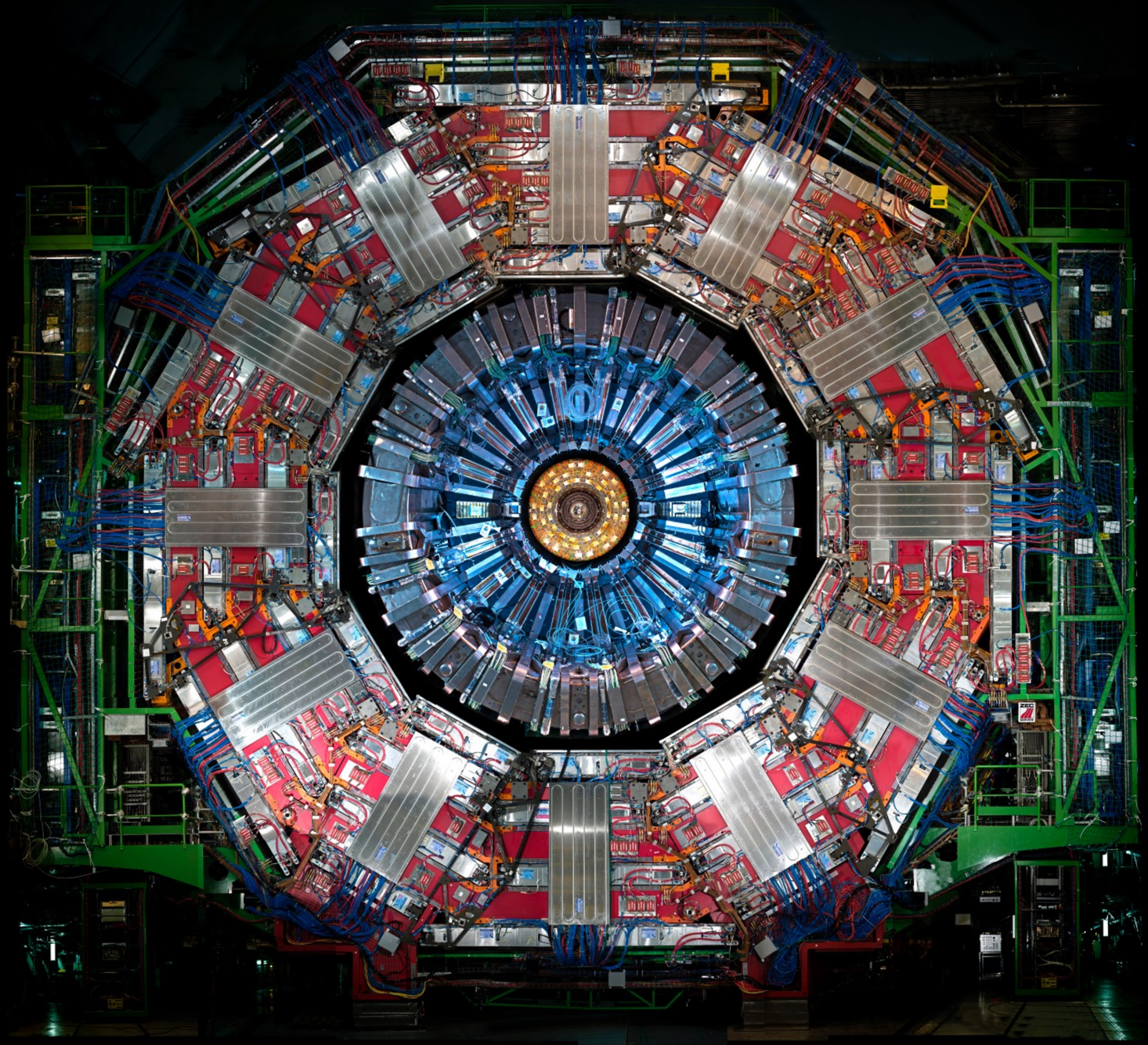
produce detect

(87%)



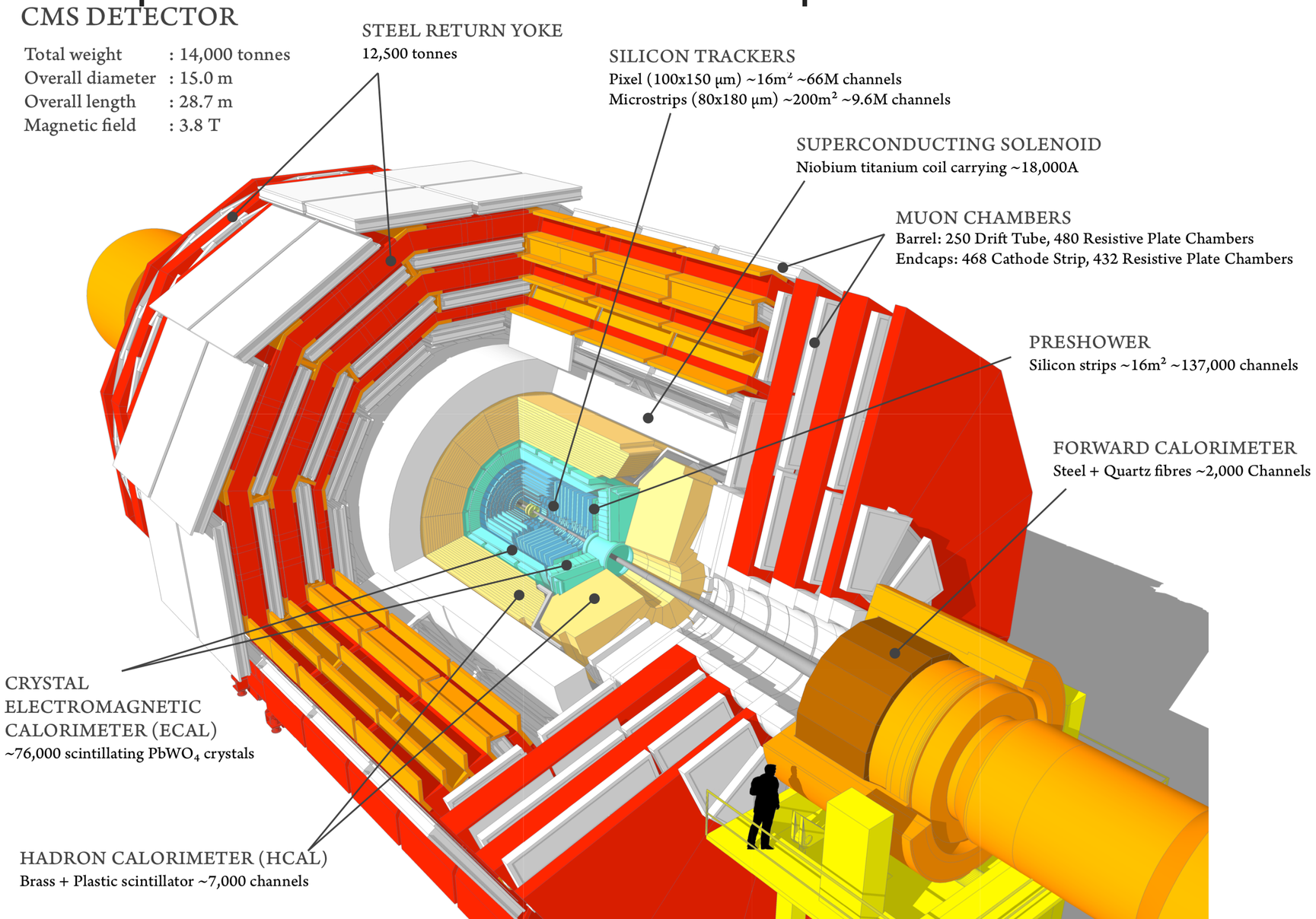


- H→γγ and H→ZZ have small rate but are very "clean"
- H→bb is large, but more difficult due to large backgrounds



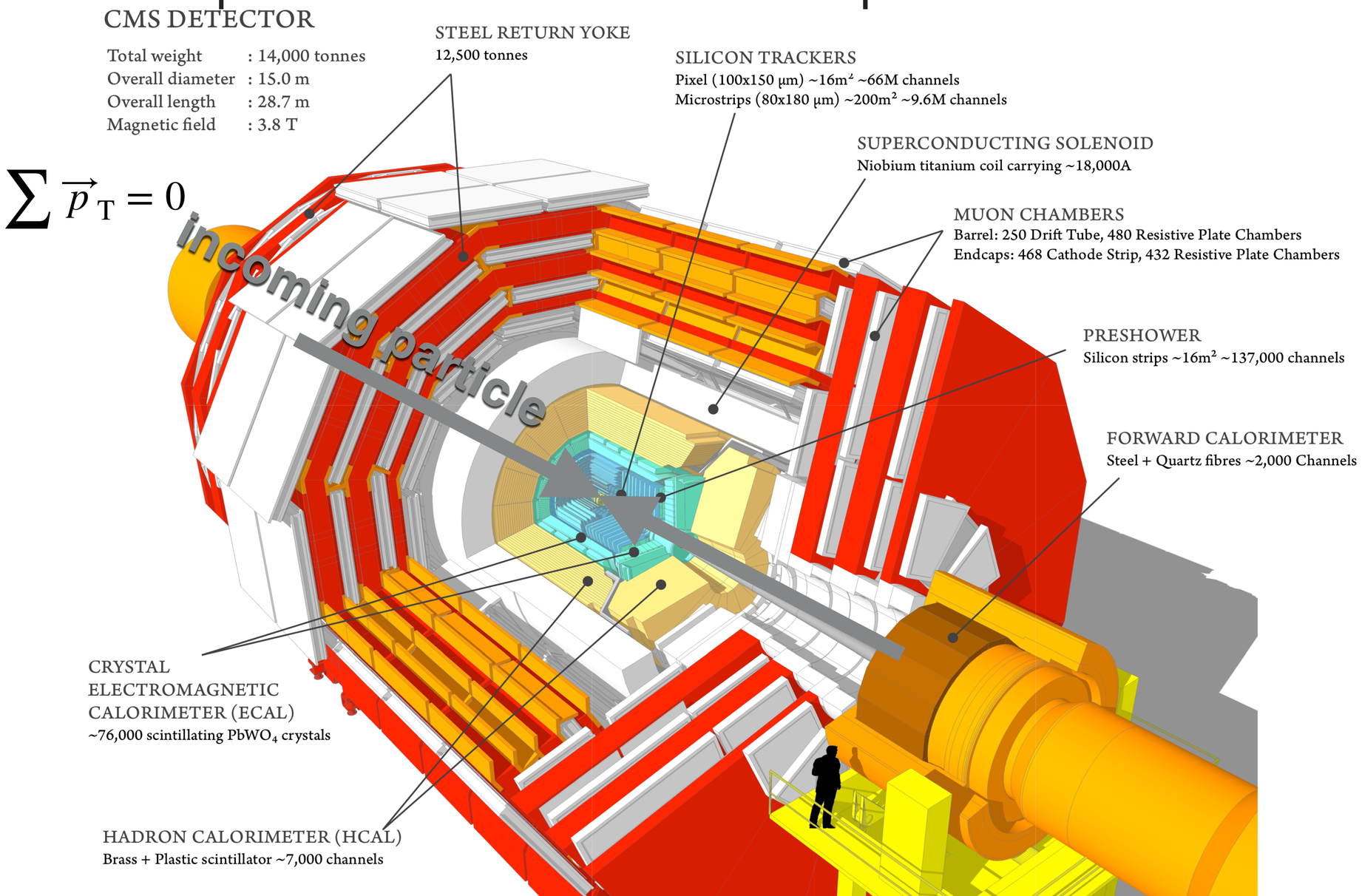
COMPACT MUON SOLENOID

- Specialized components to measure different particles



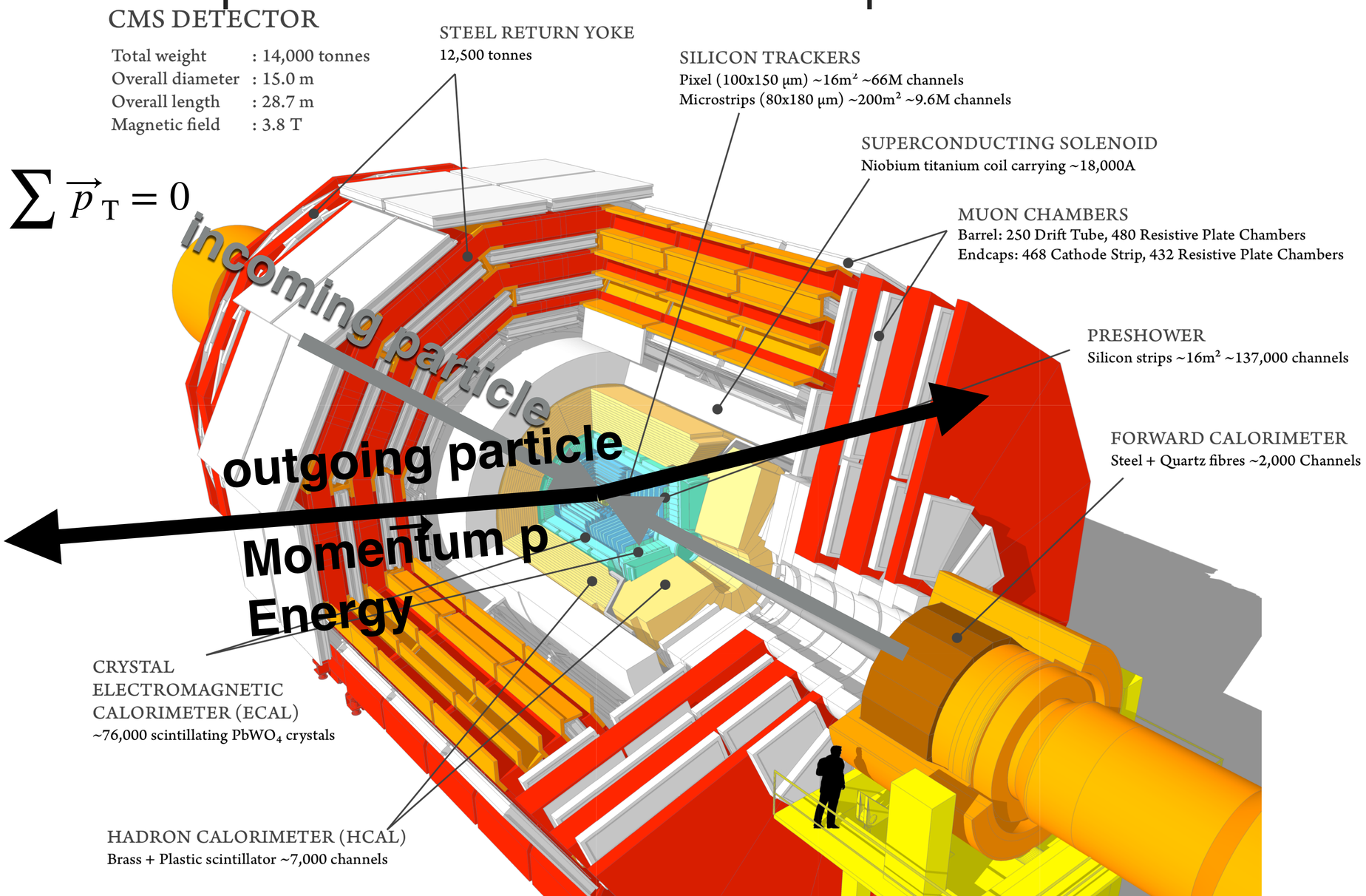
COMPACT MUON SOLENOID

- Specialized components to measure different particles



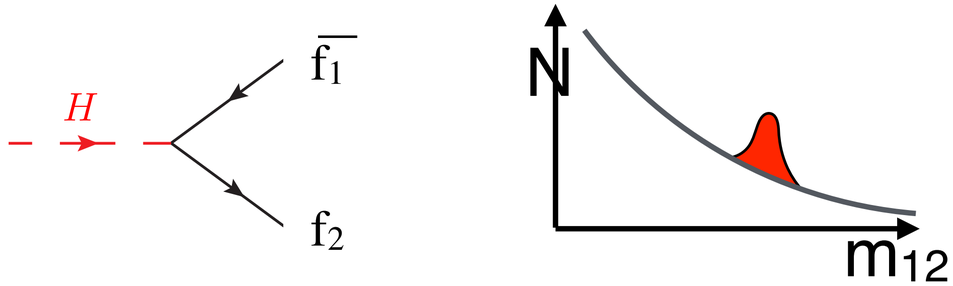
COMPACT MUON SOLENOID

- Specialized components to measure different particles



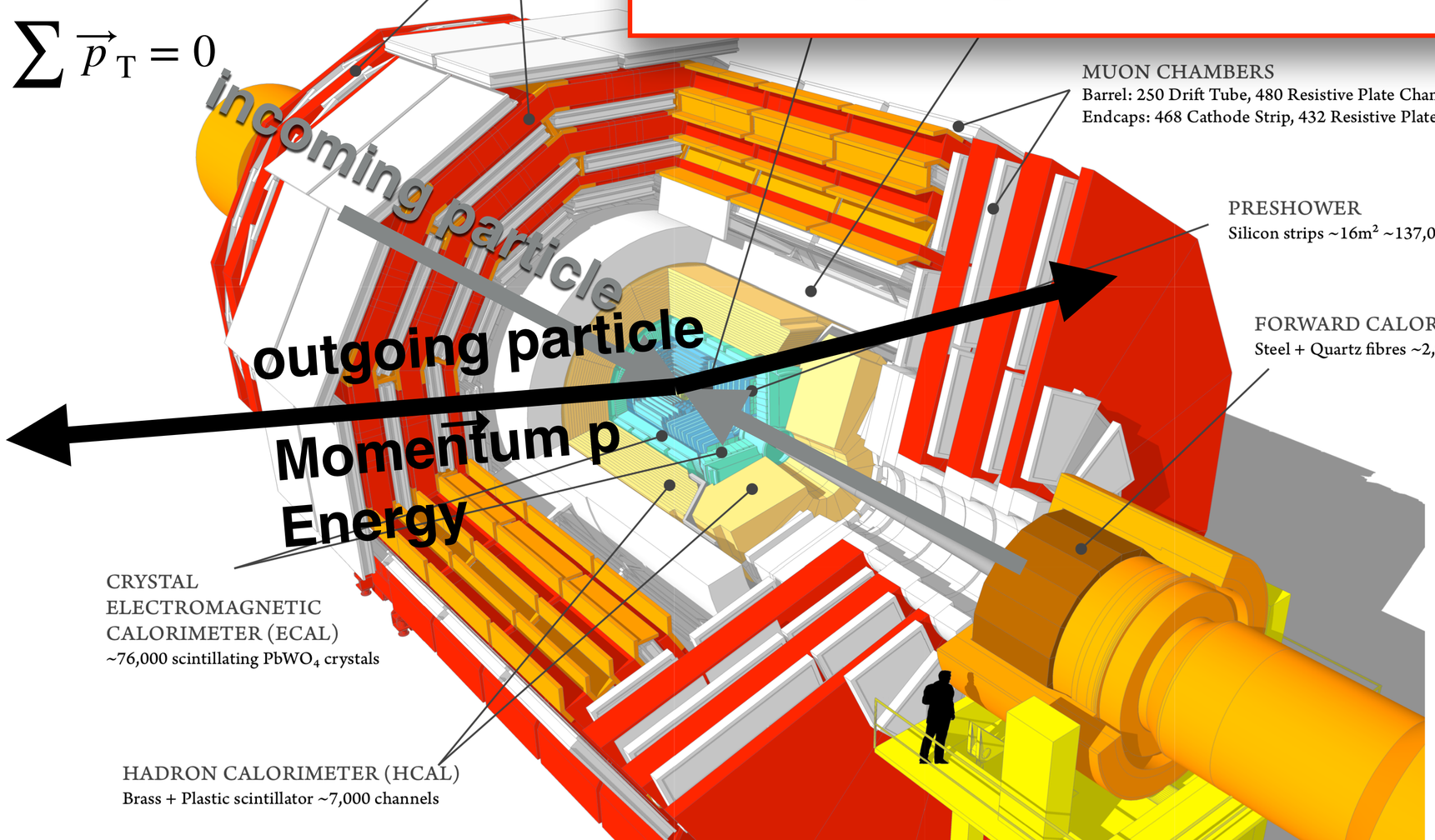
COMPACT MUON SOLENOID

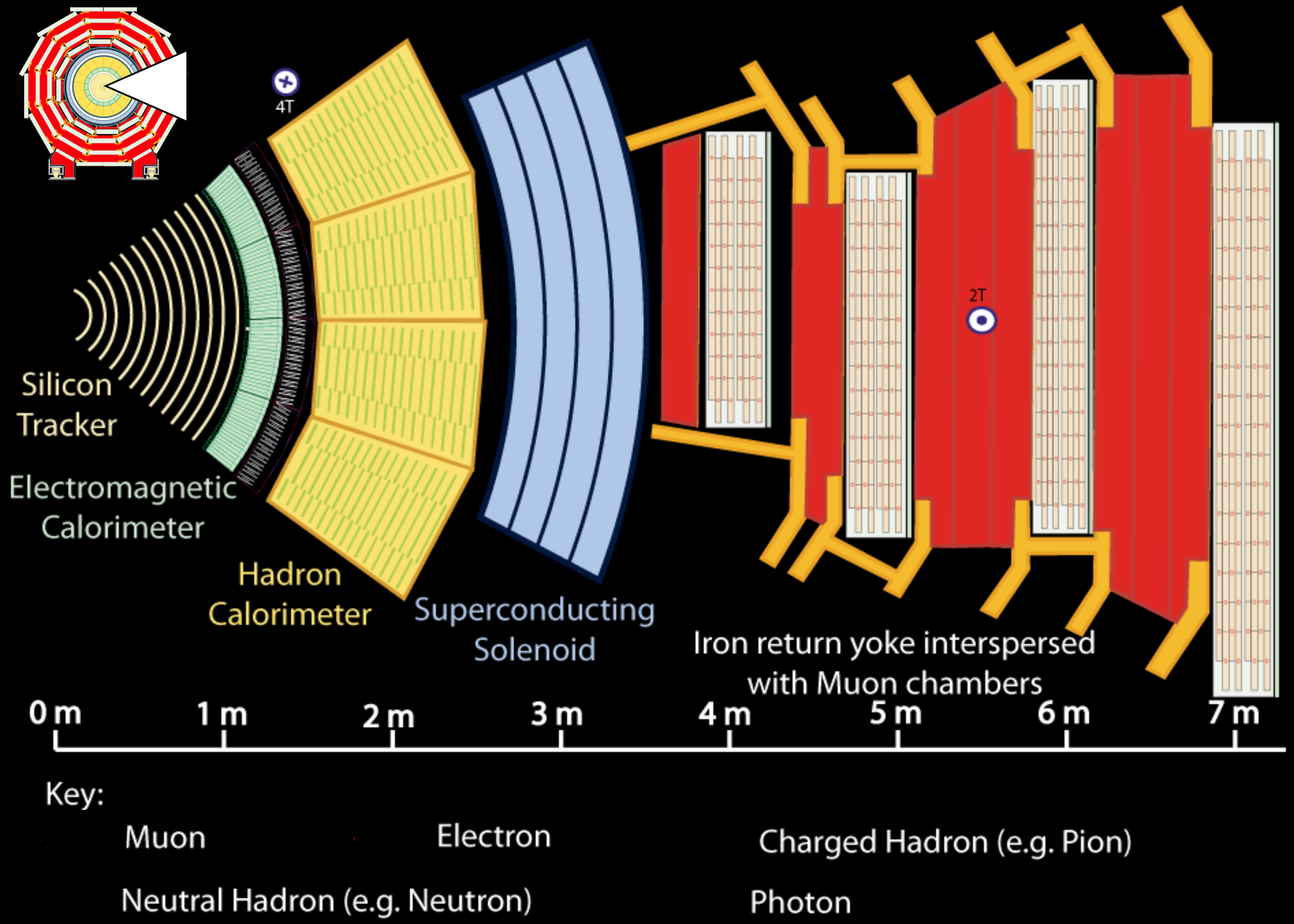
- Specialized components to mea

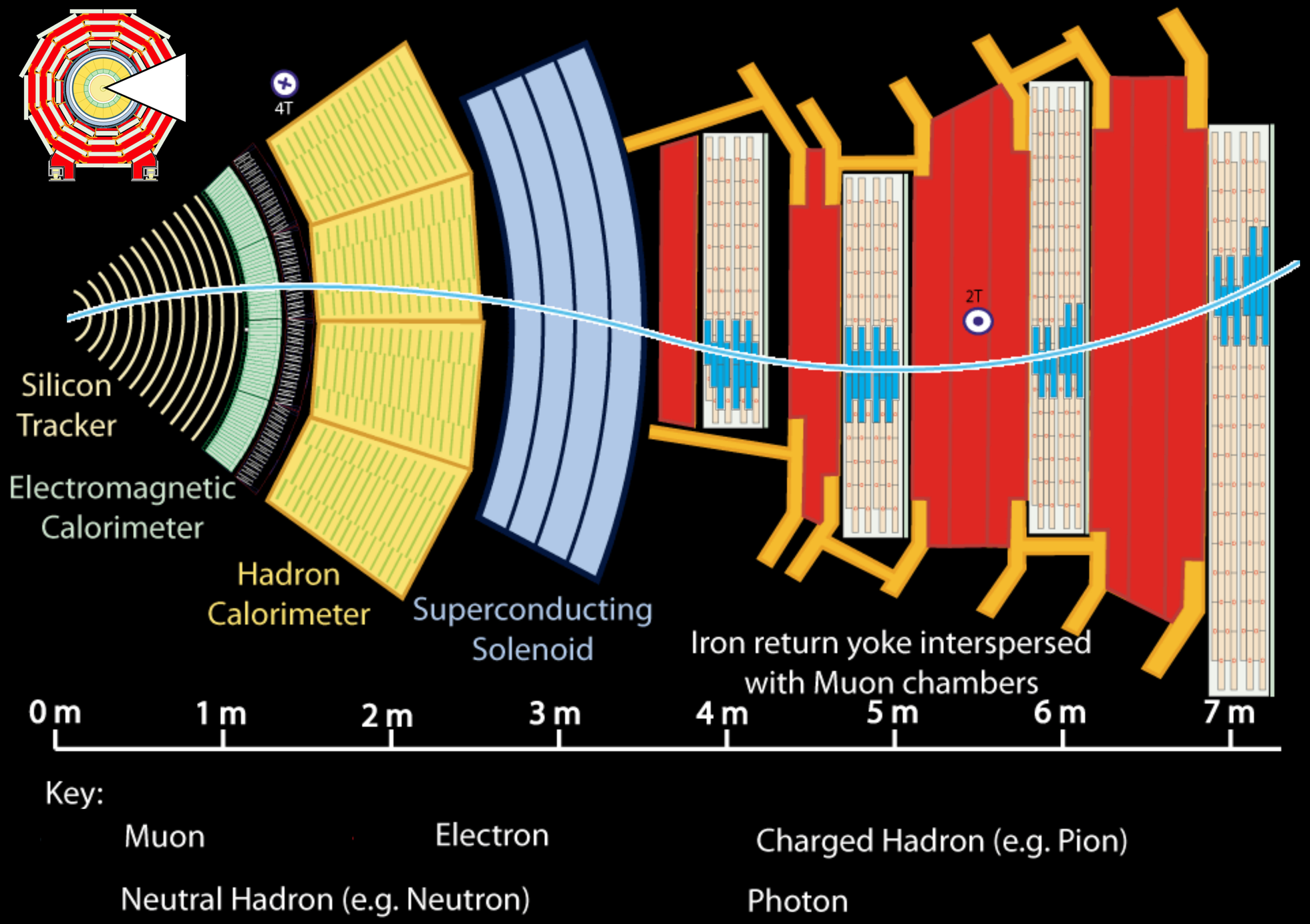


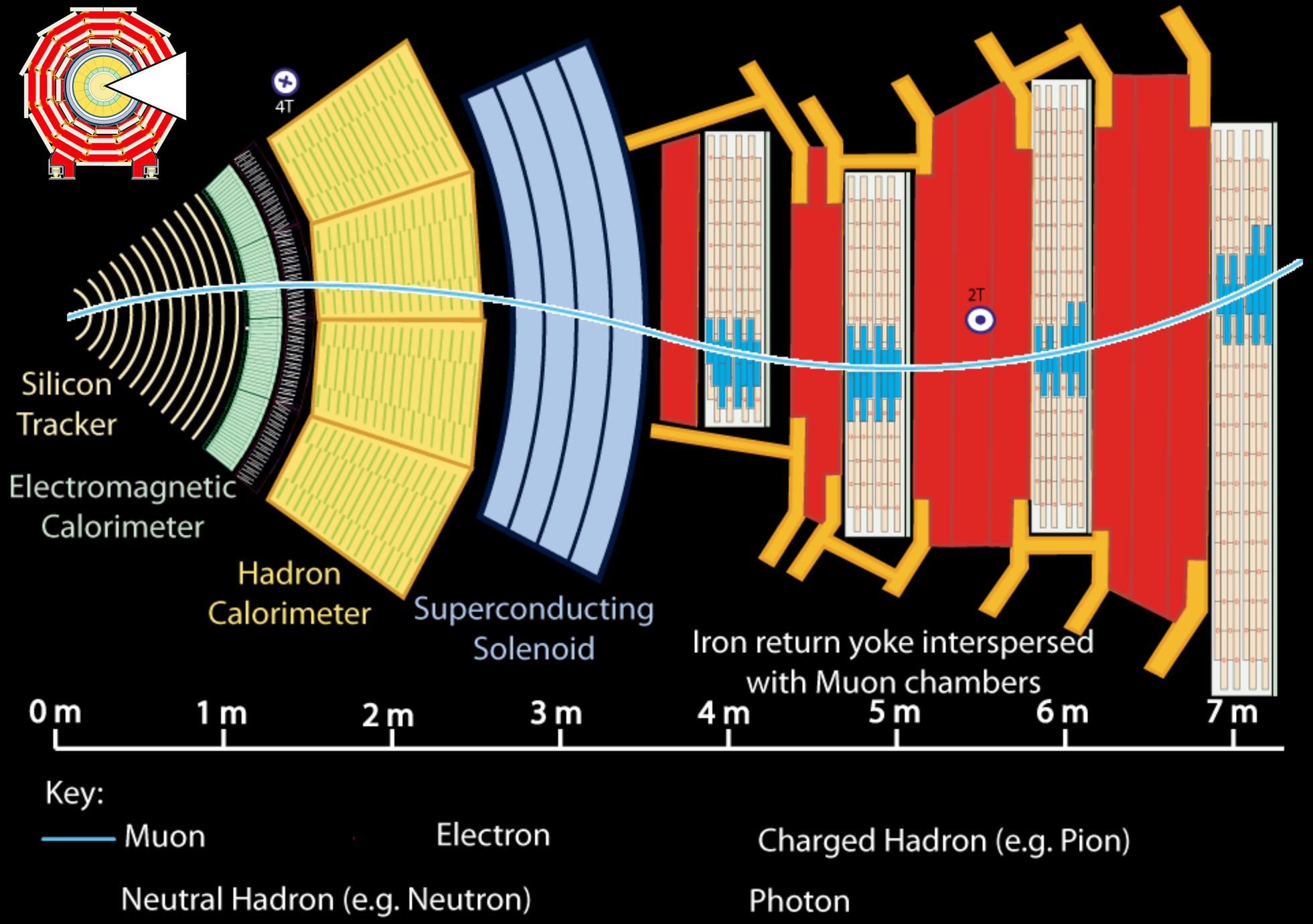
$$m_H^2 = m_1^2 + m_2^2 + 2(E_1E_2 - \vec{p}_1 \cdot \vec{p}_2)$$

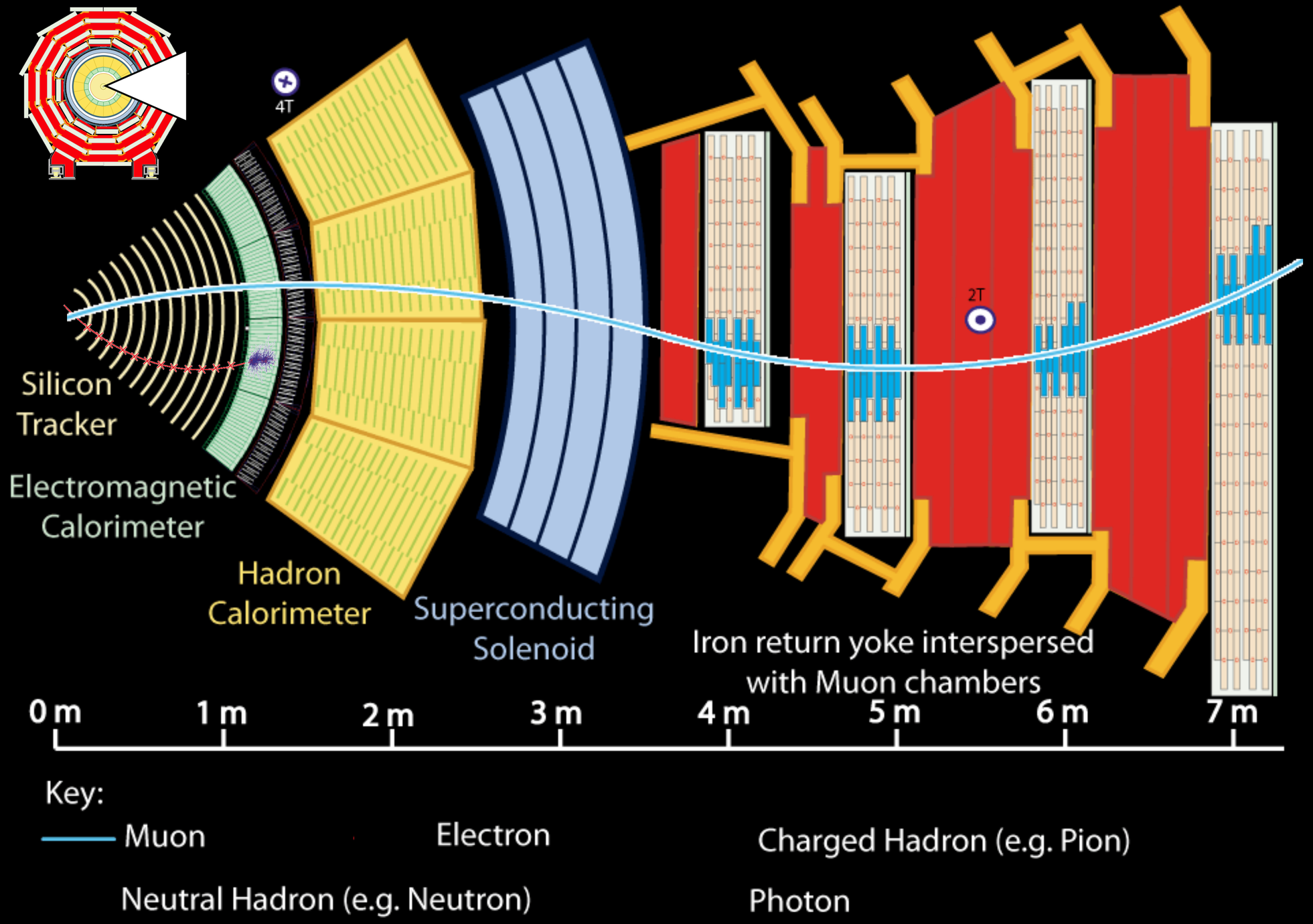
$$\sum \vec{p}_T = 0$$

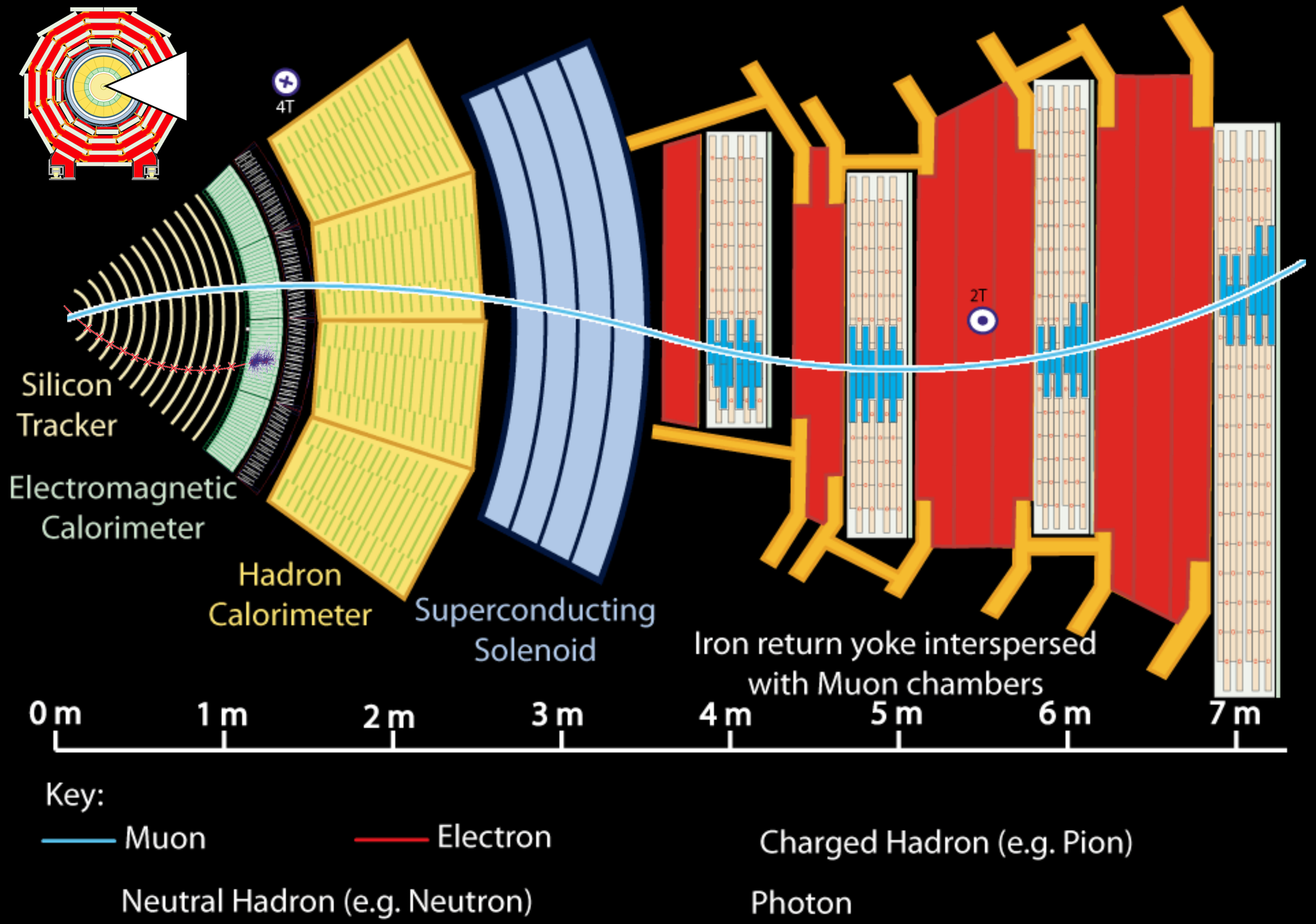


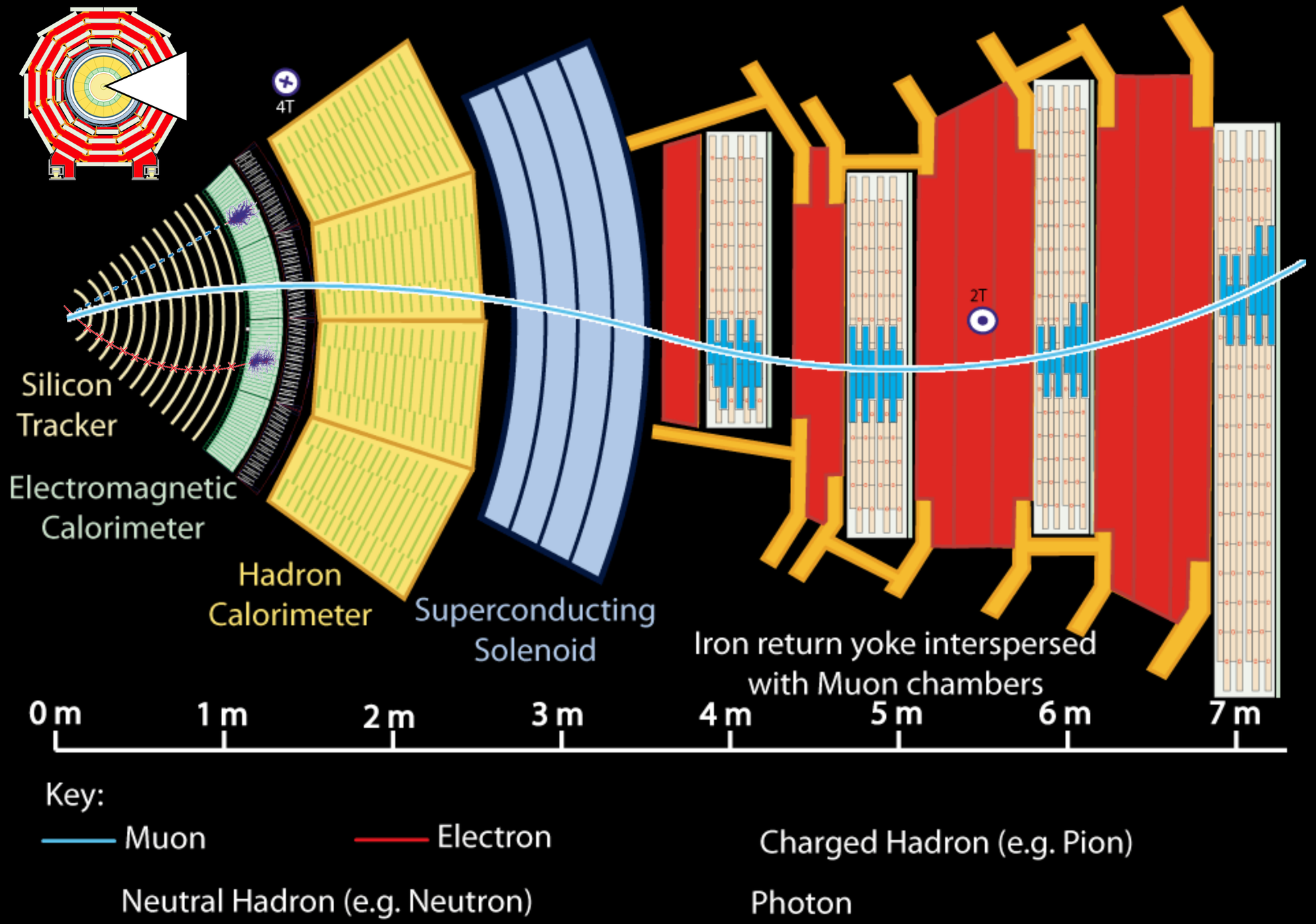

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

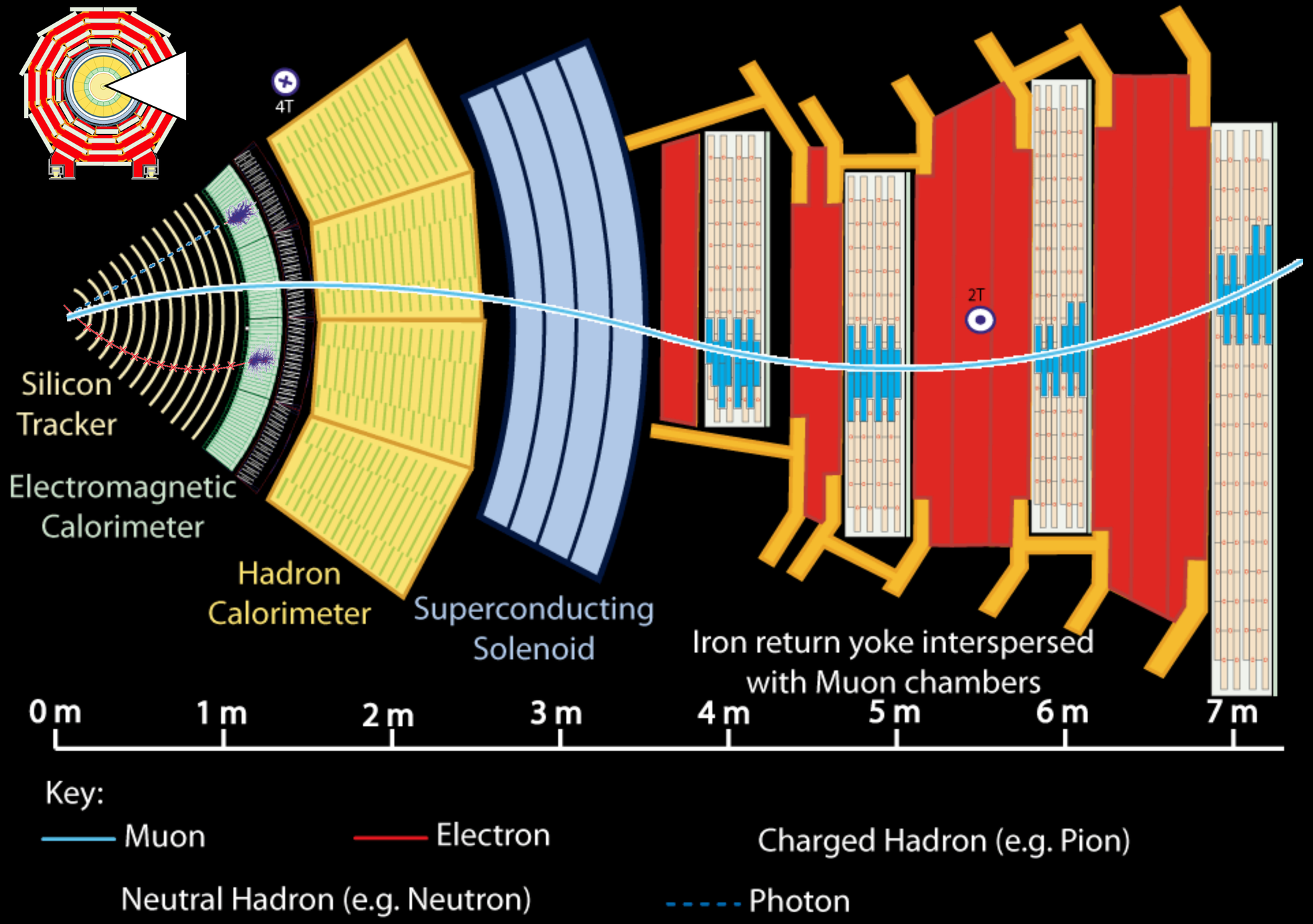

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

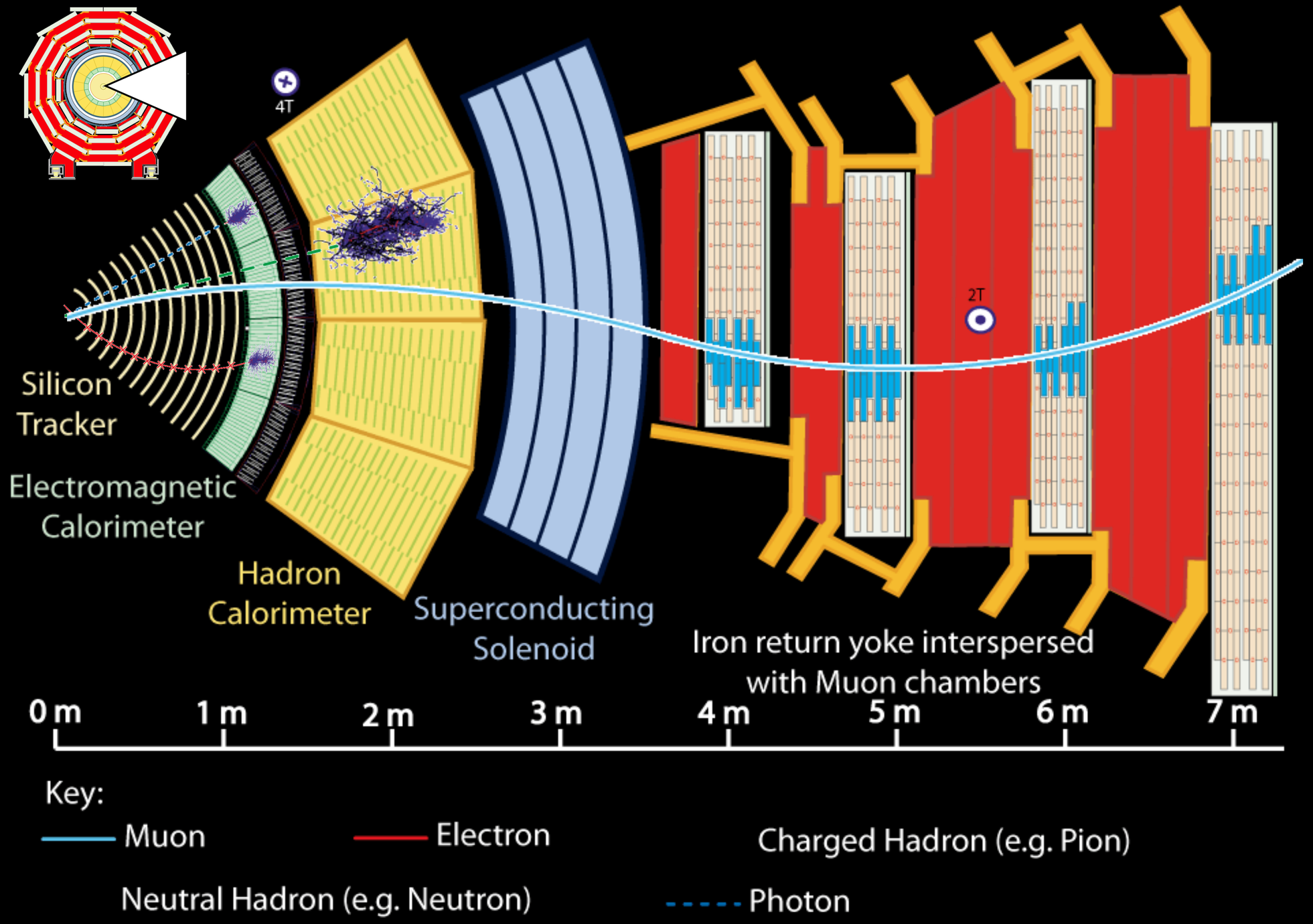

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

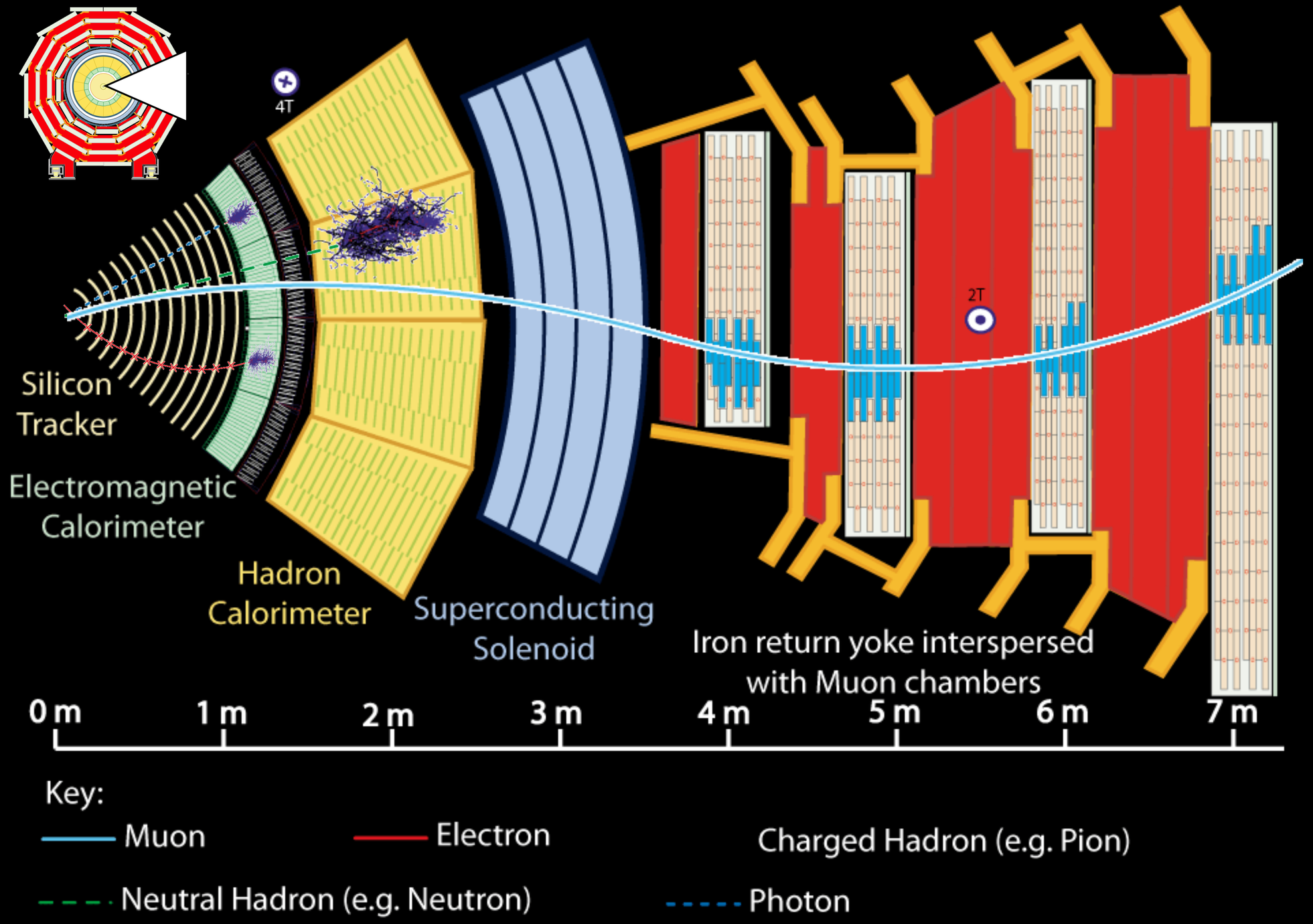

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

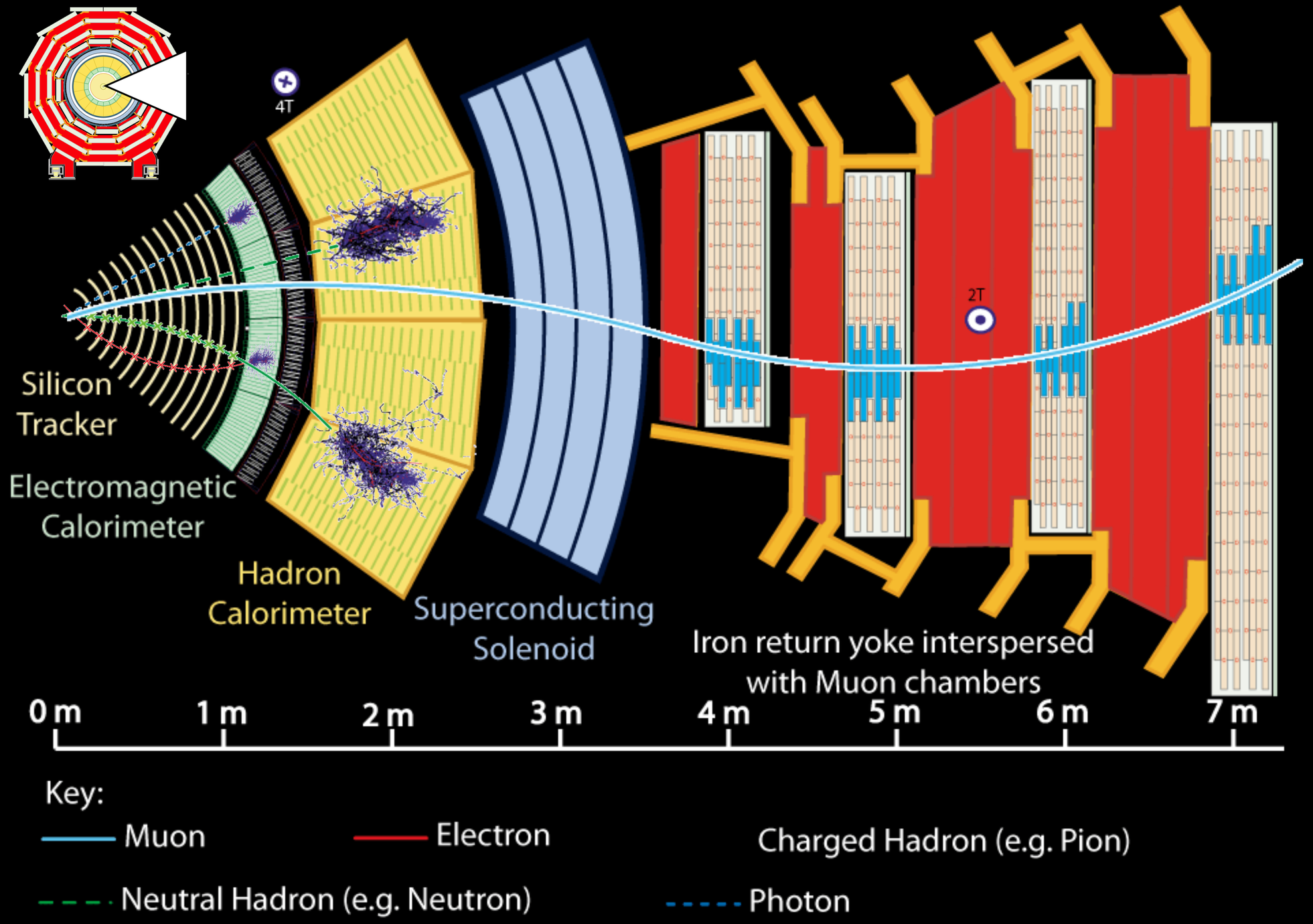

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

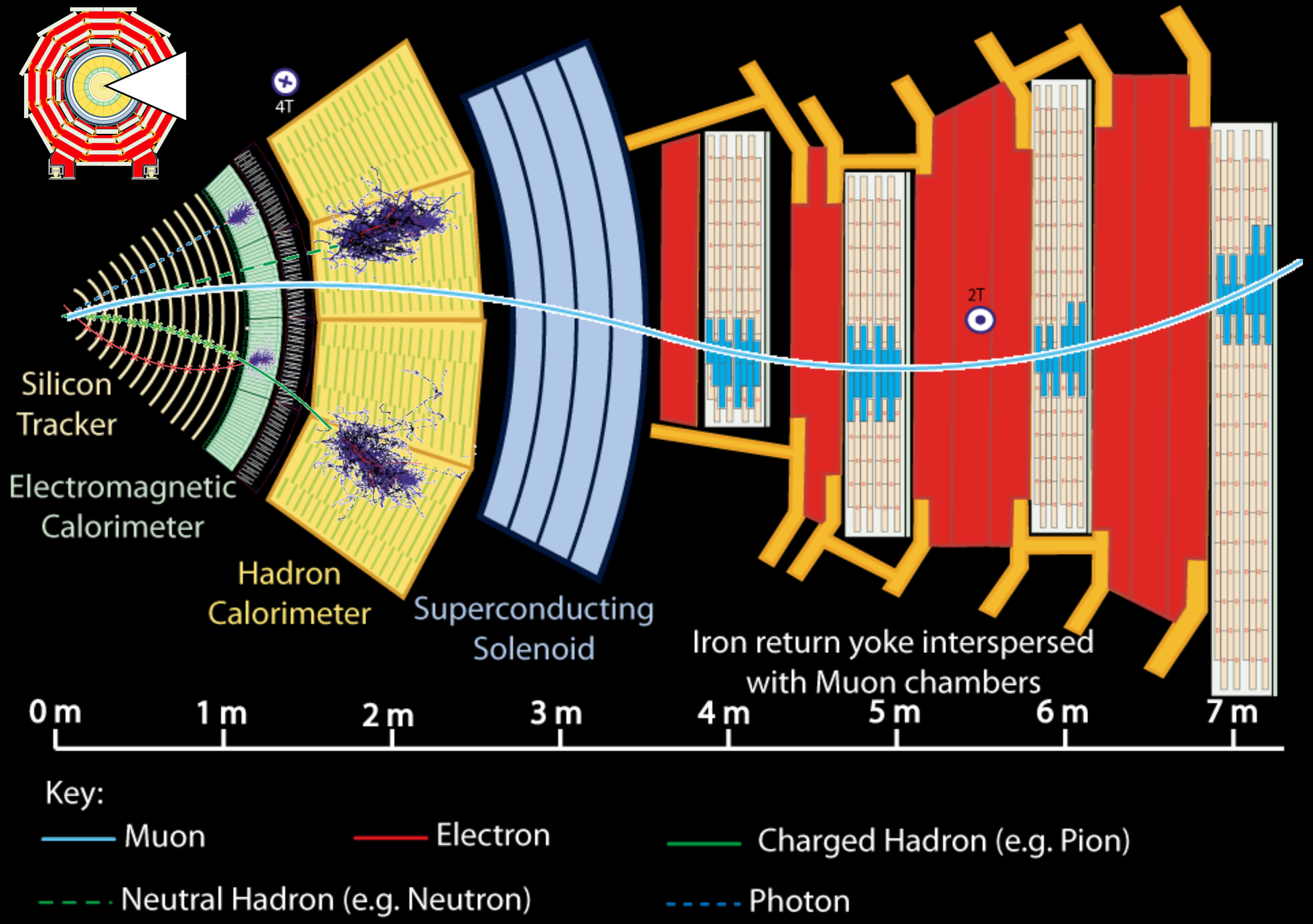

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

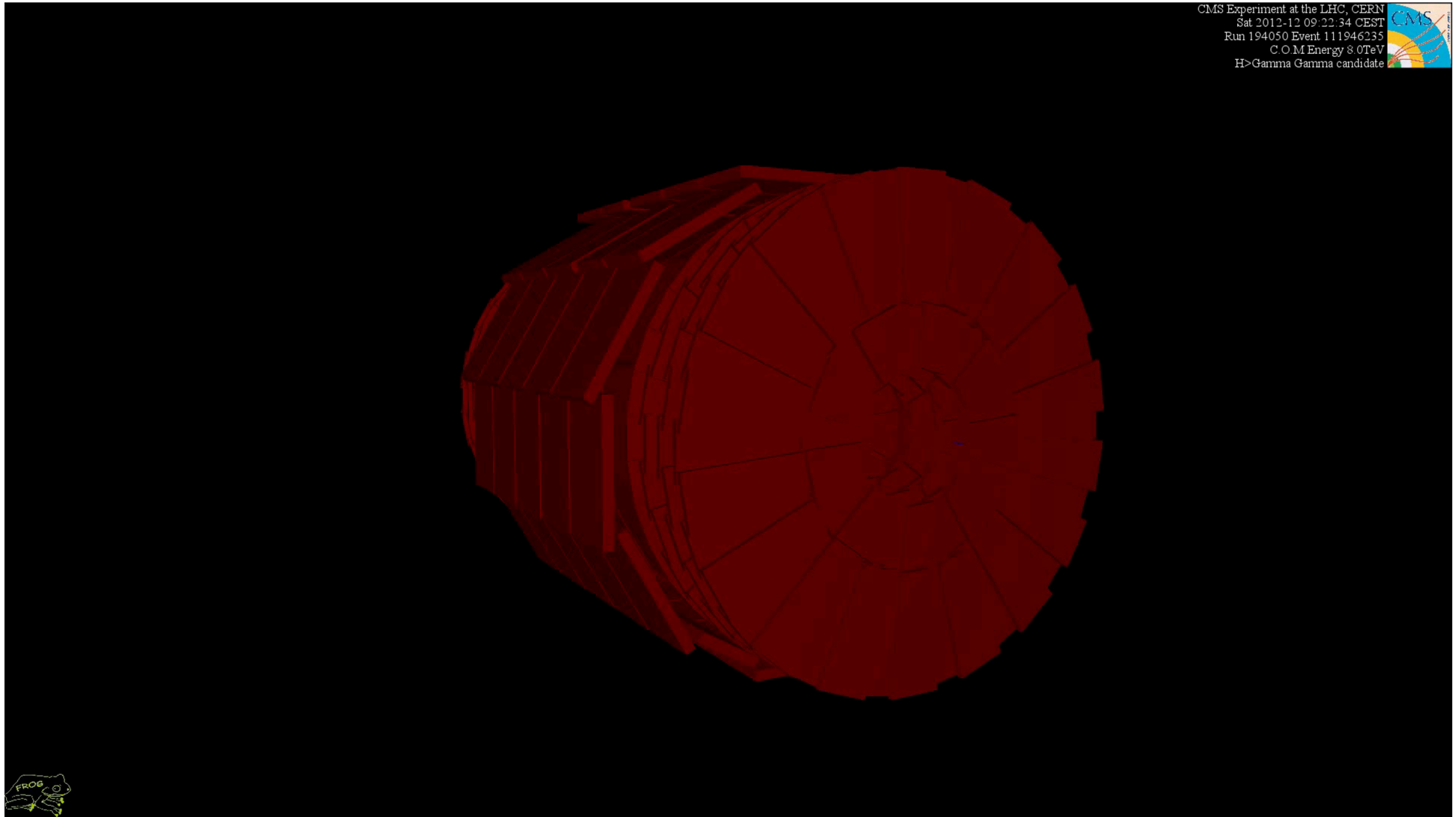

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

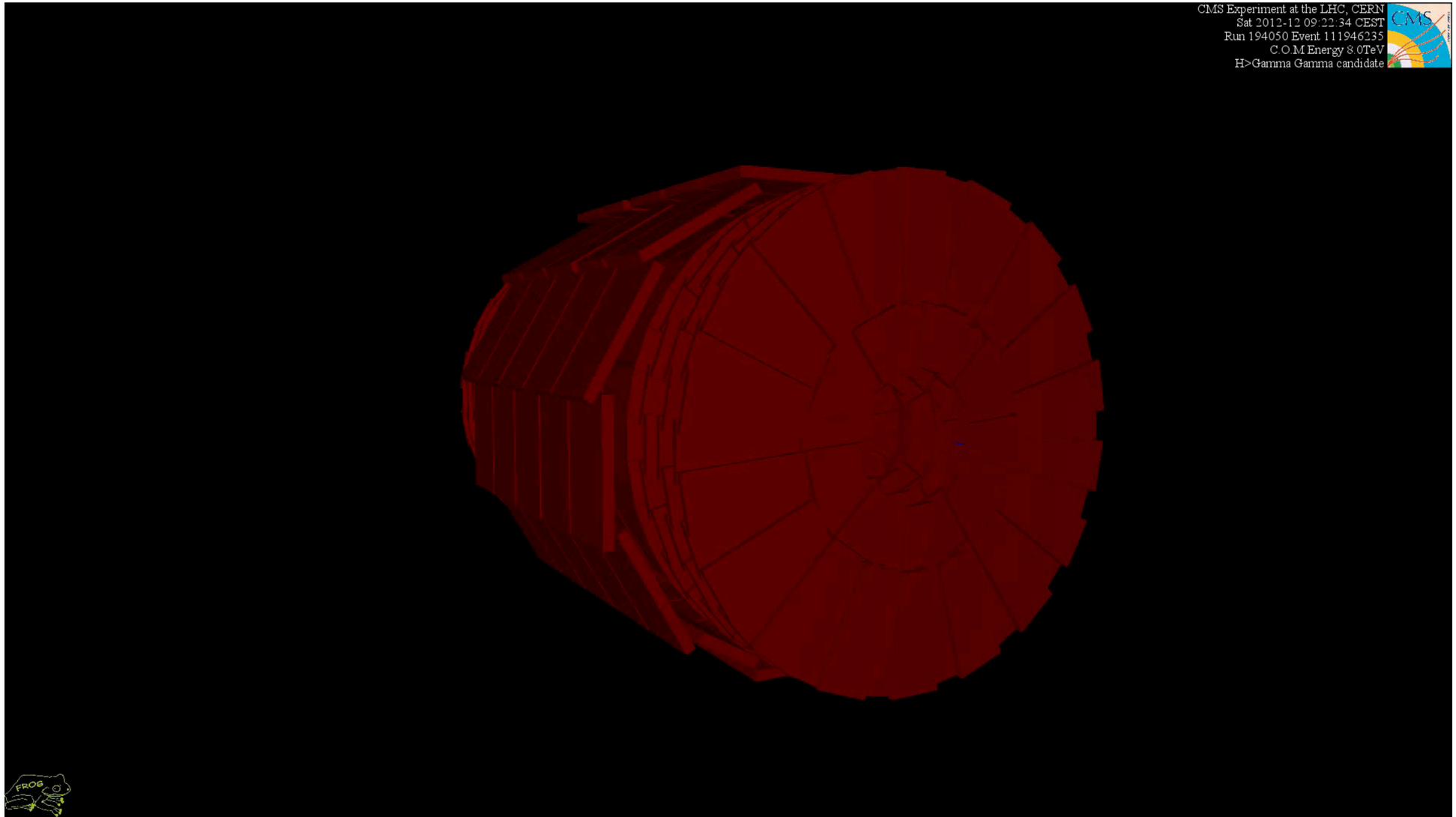
HIGGS BOSON

https://www.youtube.com/watch?v=psMpabzGuLo

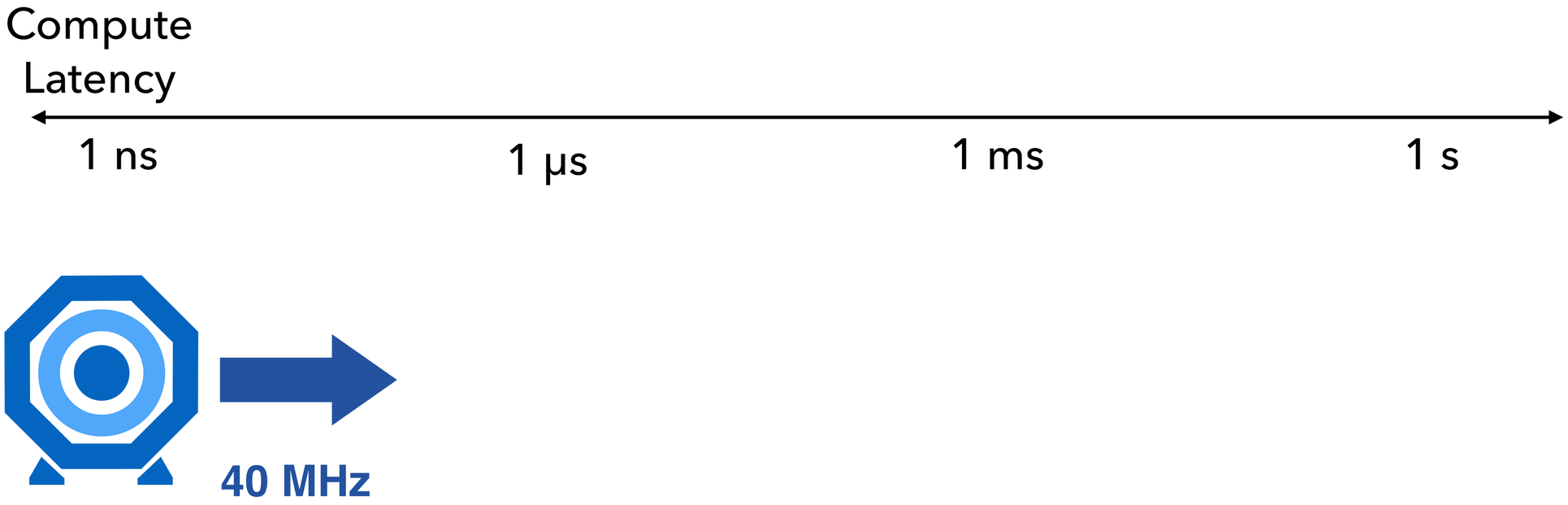


HIGGS BOSON

https://www.youtube.com/watch?v=psMpabzGuLo



LHC EVENT PROCESSING



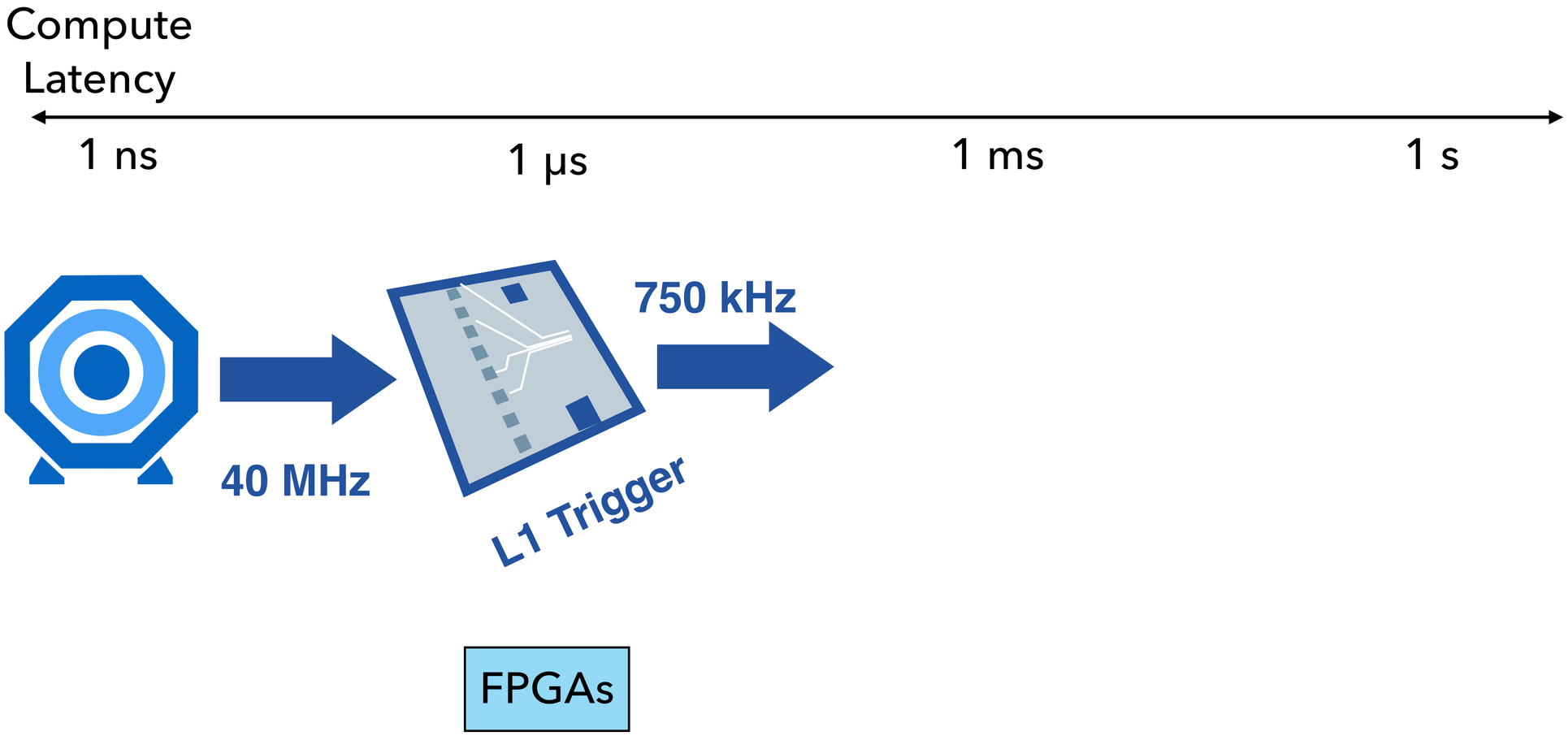
Challenges:

Each collision produces O(10^3) particles

The detectors have O(10^8) sensors

Extreme data rates of O(100 TB/s)

LHC EVENT PROCESSING



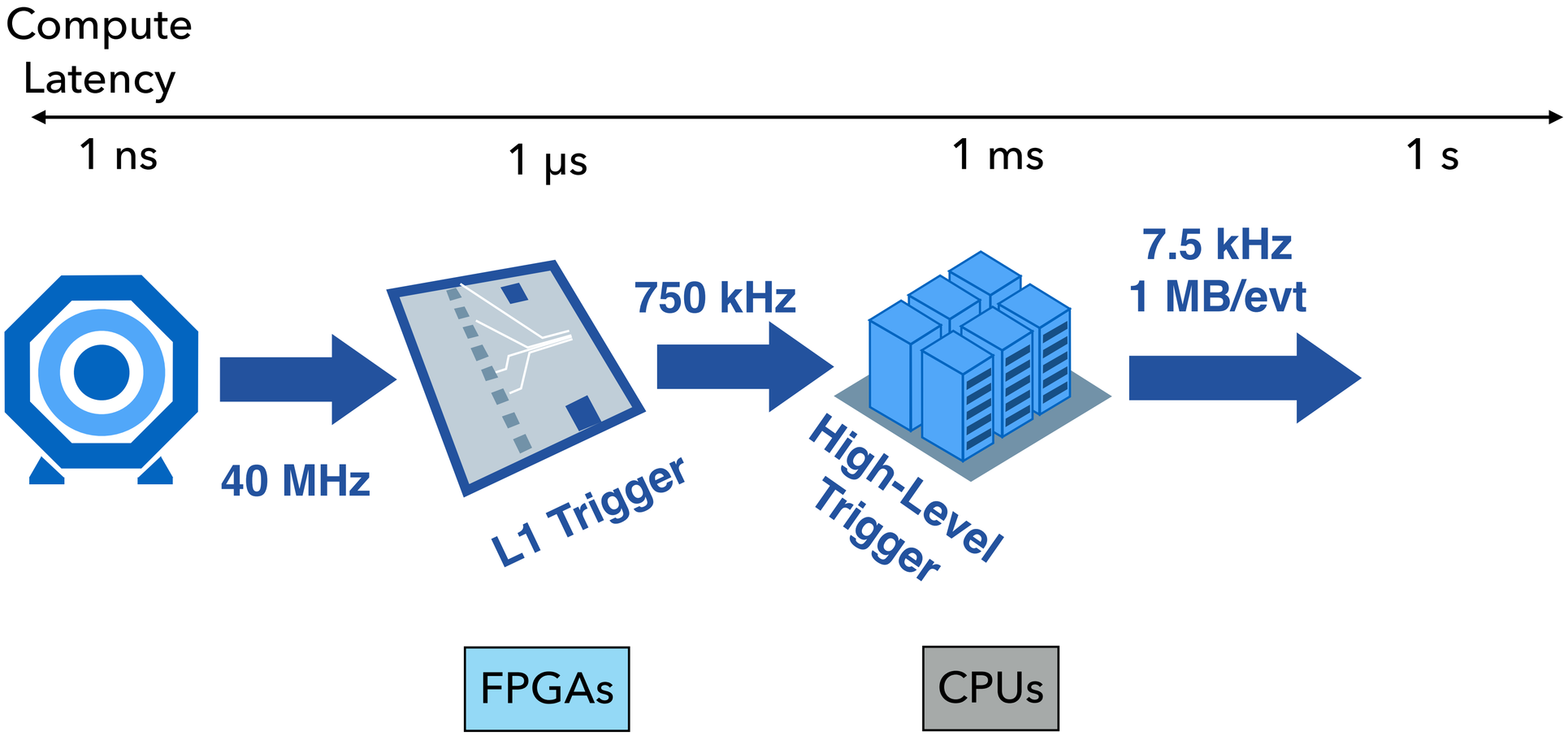
Challenges:

Each collision produces O(10^3) particles

The detectors have O(10^8) sensors

Extreme data rates of O(100 TB/s)

LHC EVENT PROCESSING



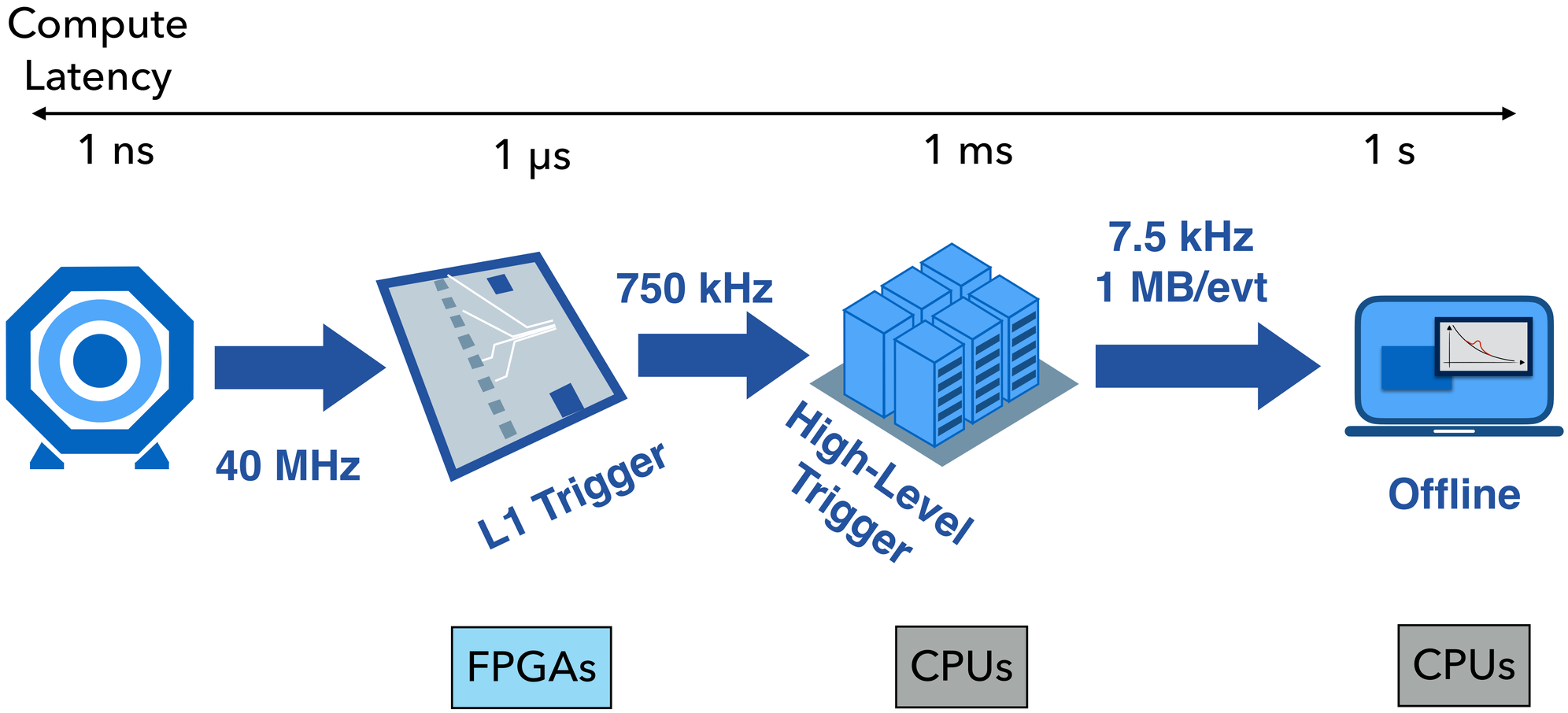
Challenges:

Each collision produces O(10^3) particles

The detectors have O(10^8) sensors

Extreme data rates of O(100 TB/s)

LHC EVENT PROCESSING



Challenges:

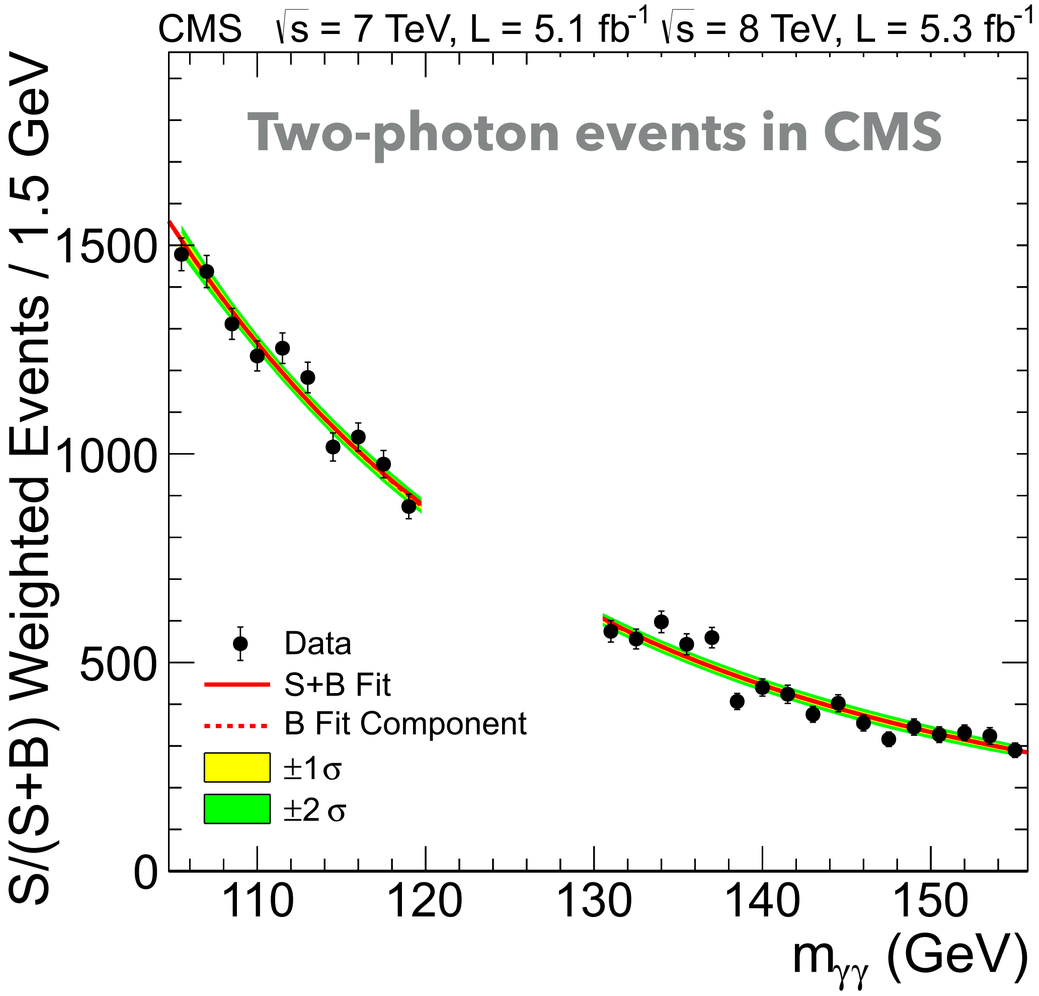
Each collision produces O(10^3) particles

The detectors have O(10^8) sensors

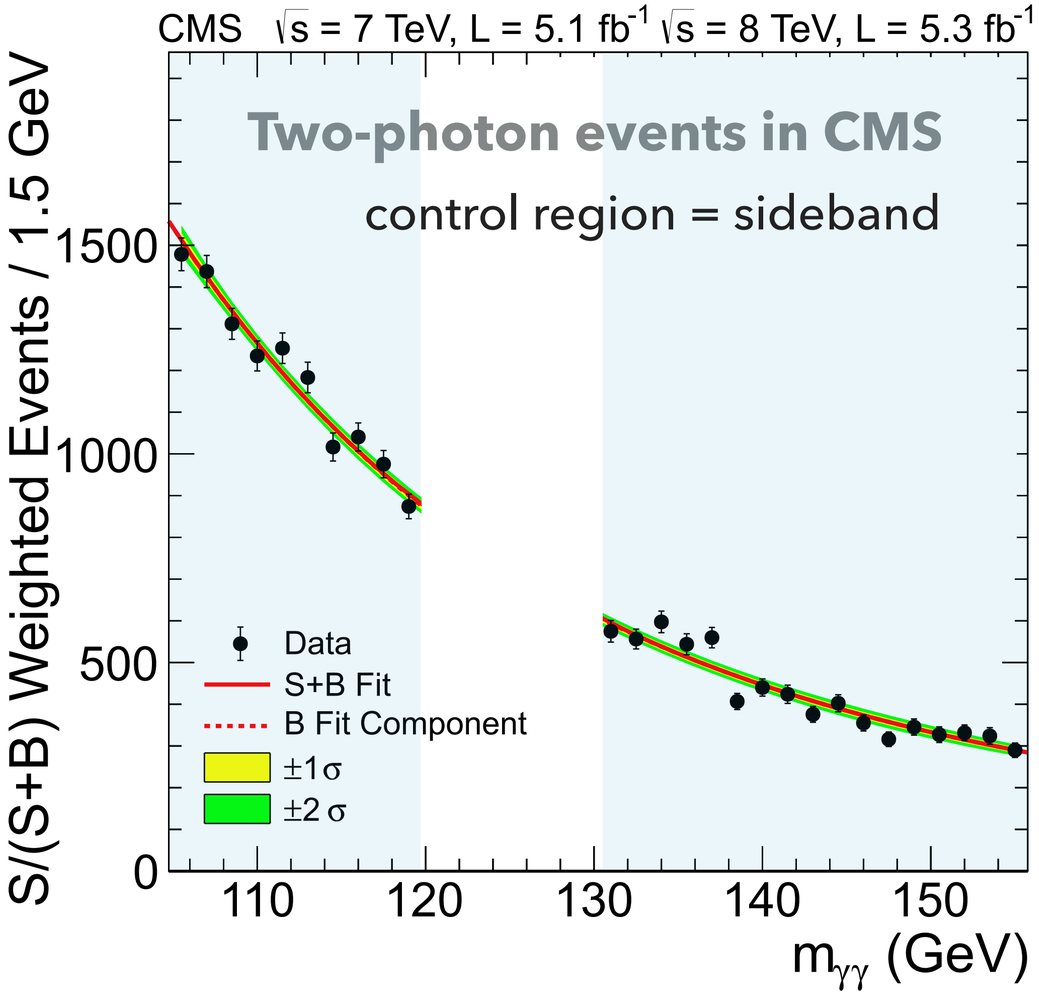
Extreme data rates of O(100 TB/s)

HIGGS BOSON & SEARCHES FOR NEW PHYSICS

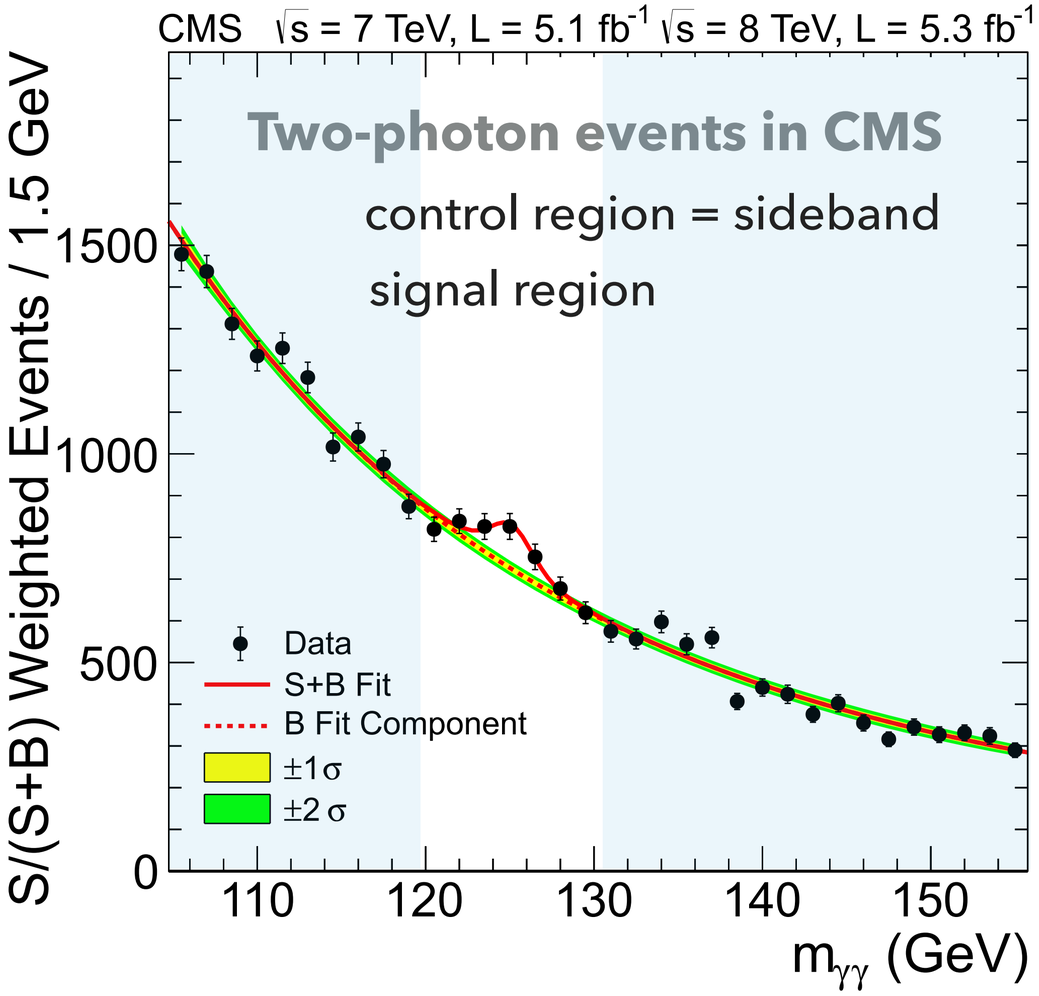
HIGGS BOSON DISCOVERY



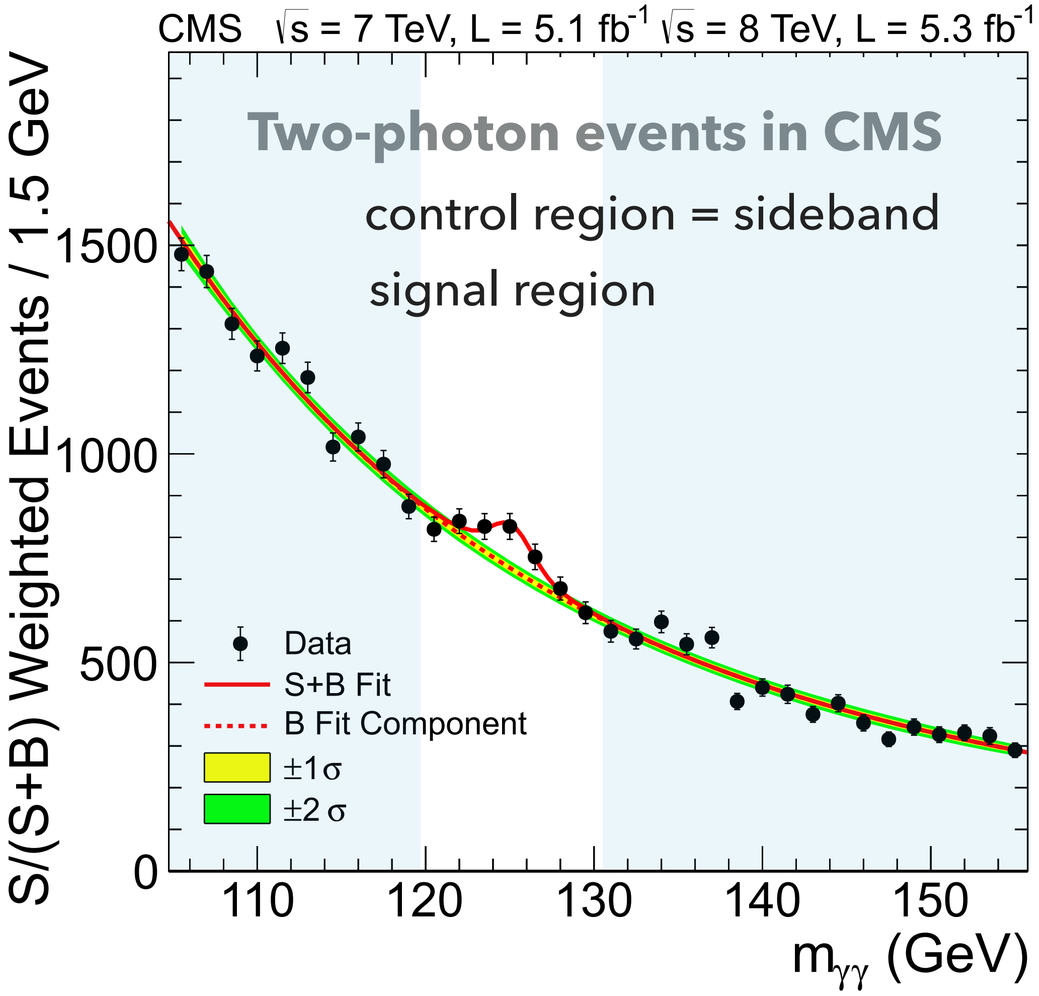
HIGGS BOSON DISCOVERY



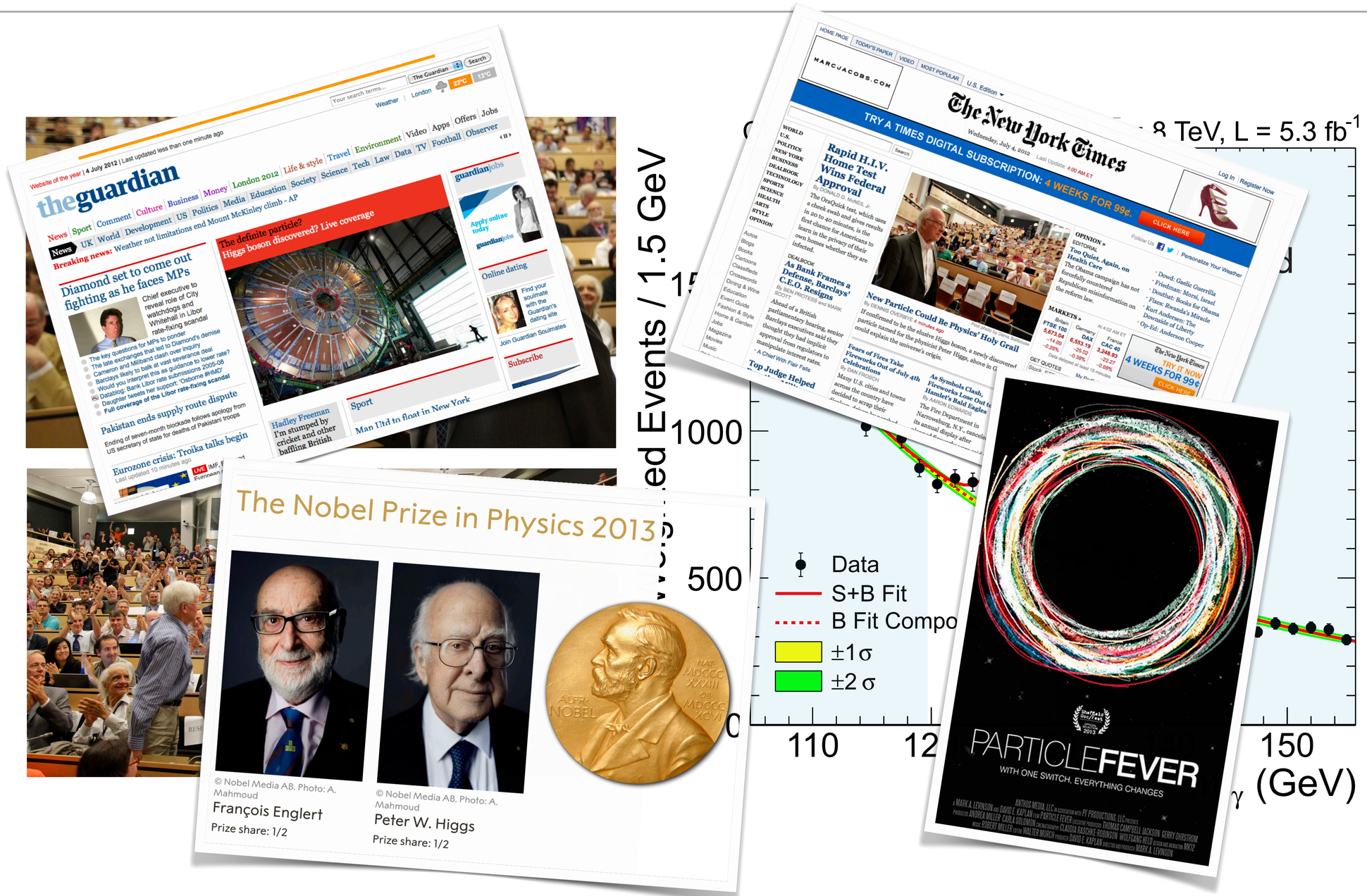
HIGGS BOSON DISCOVERY



HIGGS BOSON DISCOVERY



HIGGS BOSON DISCOVERY



WHY SEARCH FOR NEW PHYSICS?

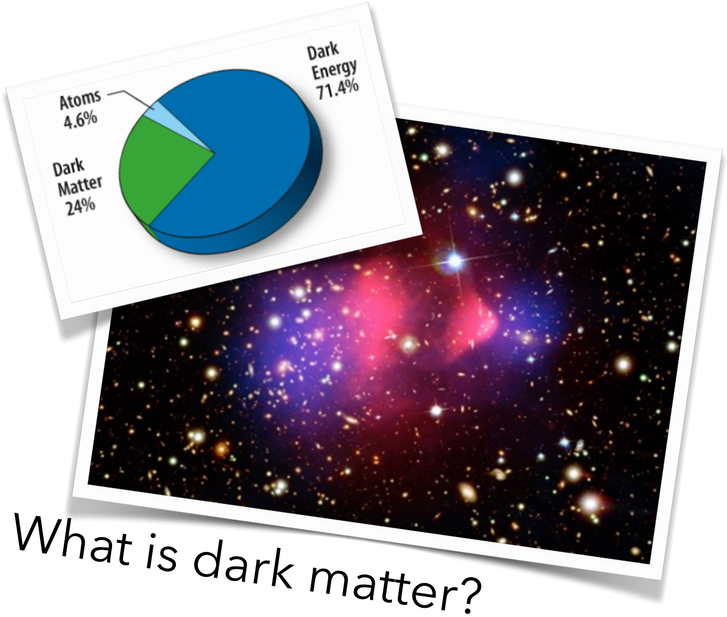
- Because we know the standard model is *incomplete*…

Quantum gravity?
Why is electroweak scale much smaller than the Planck scale?

WHY SEARCH FOR NEW PHYSICS?

- Because we know the standard model is *incomplete*…

Quantum gravity?
Why is electroweak scale much smaller than the Planck scale?

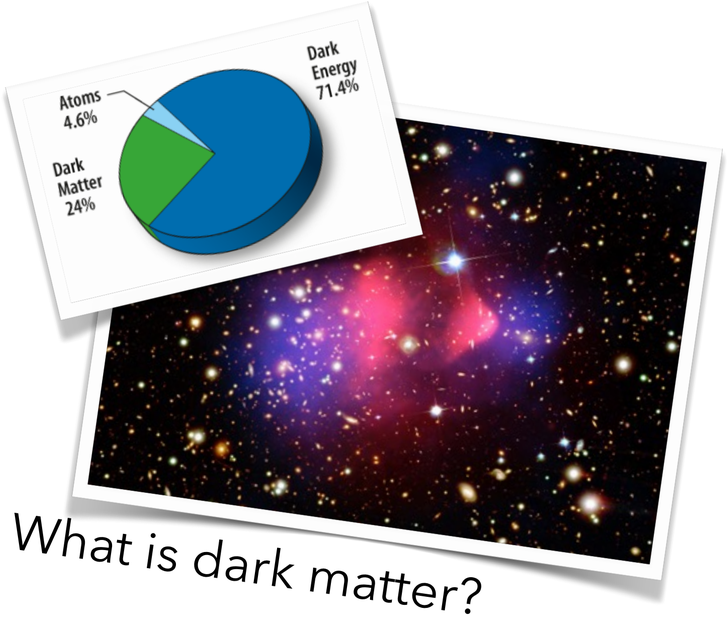


What is dark matter?

WHY SEARCH FOR NEW PHYSICS?

- Because we know the standard model is *incomplete*…

Quantum gravity?
Why is electroweak scale much smaller than the Planck scale?

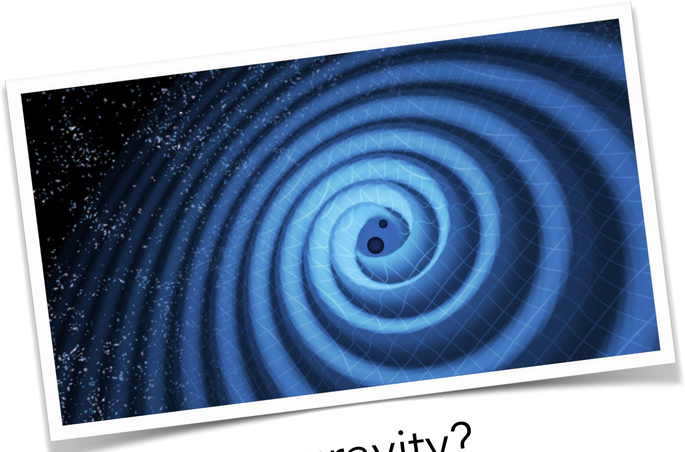


What is dark matter?

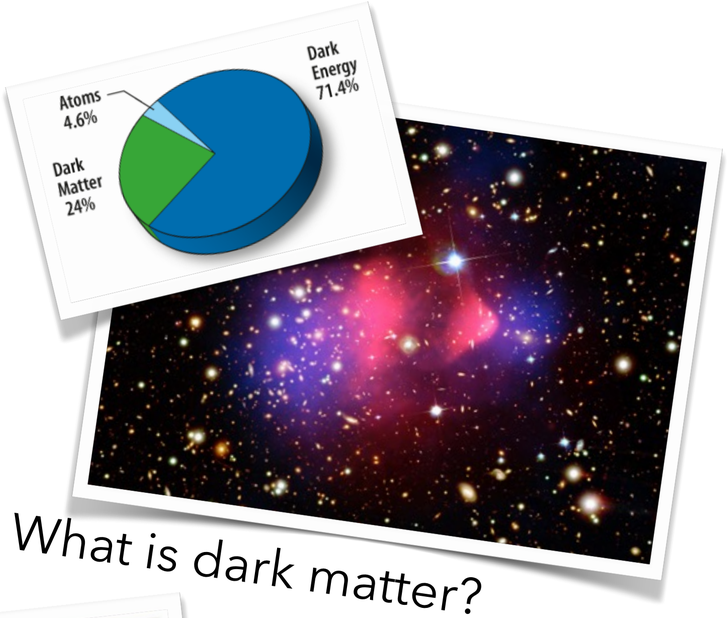
Matter-antimatter asymmetry?

WHY SEARCH FOR NEW PHYSICS?

- Because we know the standard model is *incomplete*…

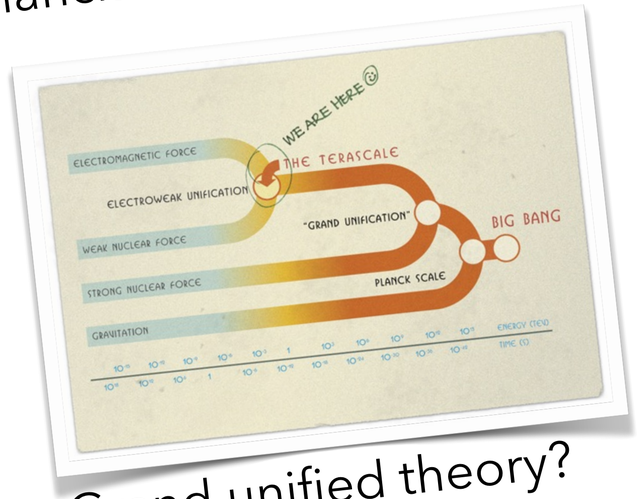


Quantum gravity?
Why is electroweak scale much smaller than the Planck scale?



What is dark matter?

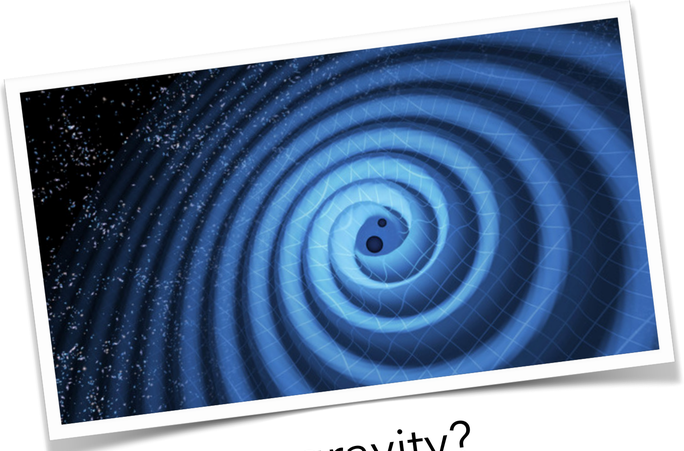
Matter-antimatter asymmetry?



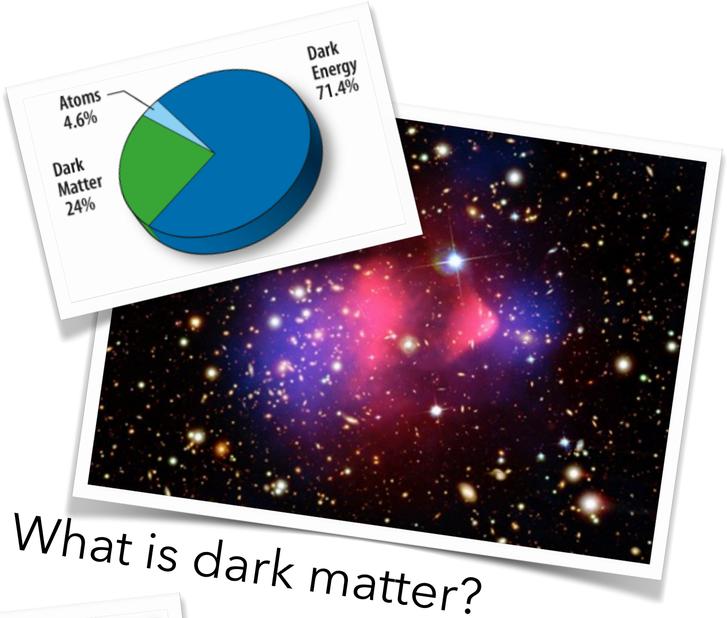
Grand unified theory?
Theory of everything?

WHY SEARCH FOR NEW PHYSICS?

- Because we know the standard model is *incomplete*…

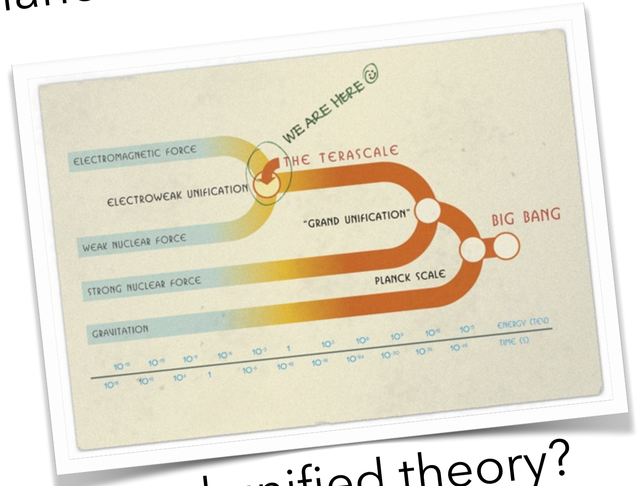


Quantum gravity?
Why is electroweak scale much smaller than the Planck scale?



What is dark matter?

Matter-antimatter asymmetry?



Grand unified theory?
Theory of everything?

Neutrino mass?

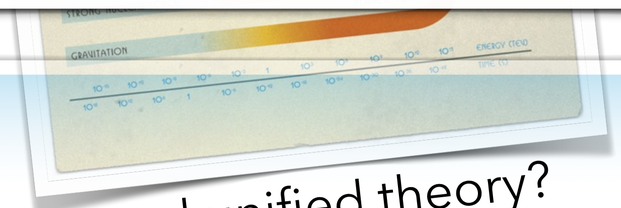
WHY SEARCH FOR NEW PHYSICS?

- Because we know the standard model is *incomplete*…

MANY OPEN QUESTIONS….

AND MANY POSSIBLE SOLUTIONS! HOW CAN WE LOOK FOR THEM?

Matter-antimatter asymmetry?



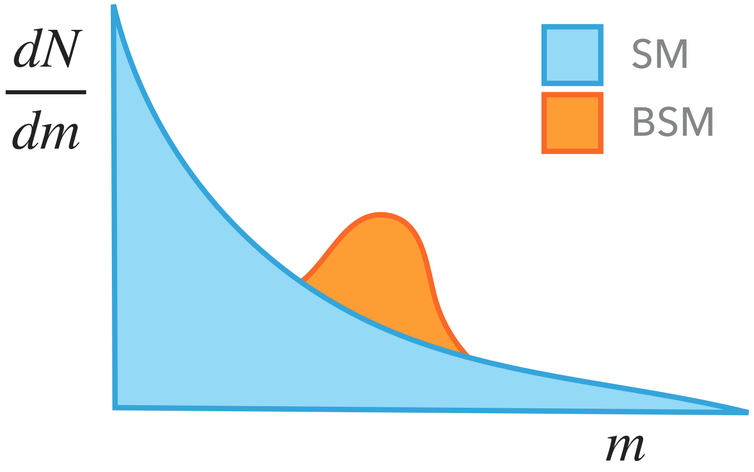
Grand unified theory?
Theory of everything?

Neutrino mass?

HOW DO WE LOOK FOR NEW PHYSICS?

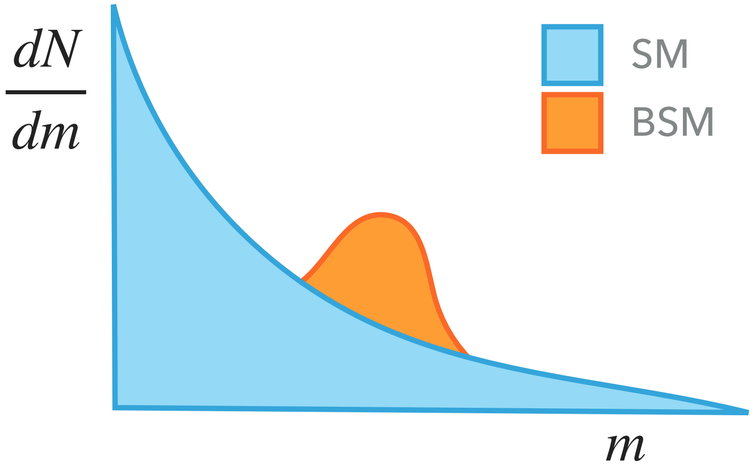
HOW DO WE LOOK FOR NEW PHYSICS?

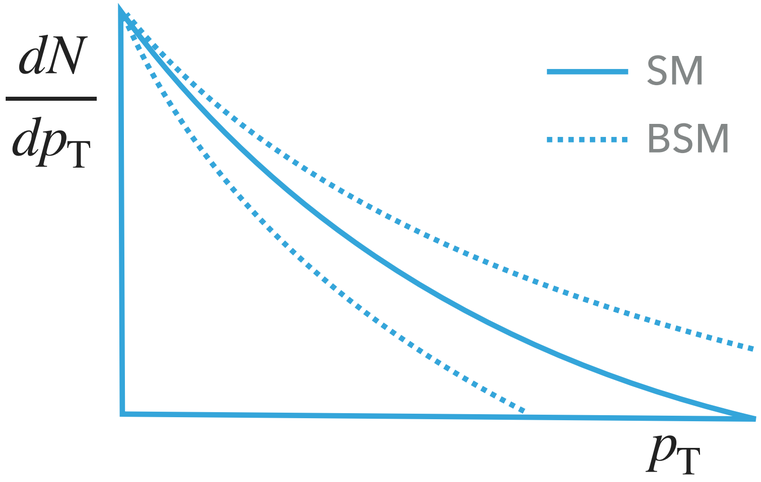
- **Direct searches**: produce and observe a new particle or interaction



HOW DO WE LOOK FOR NEW PHYSICS?

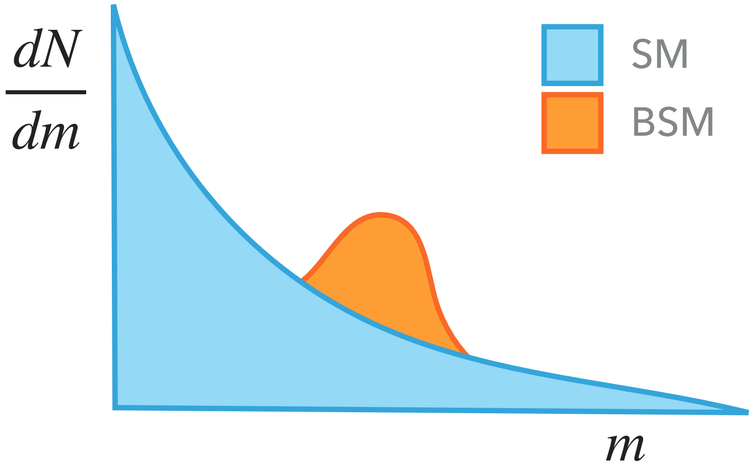
- **Direct searches**: produce and observe a new particle or interaction
- **Indirect searches**: measure known standard model particles and interactions to look for deviations

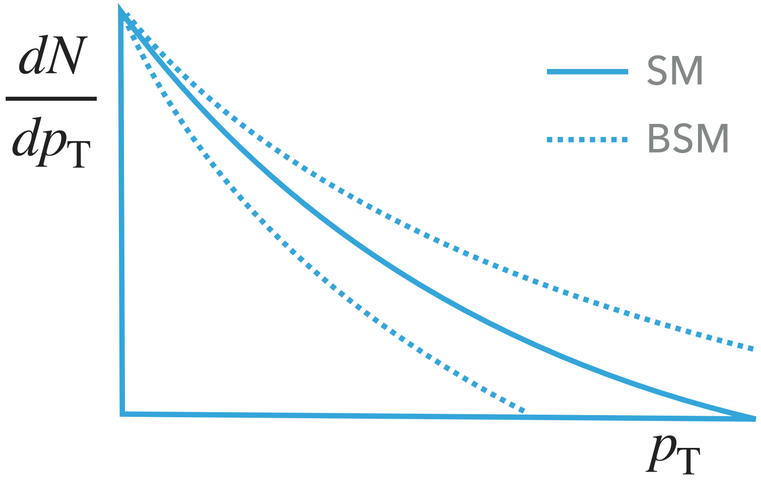




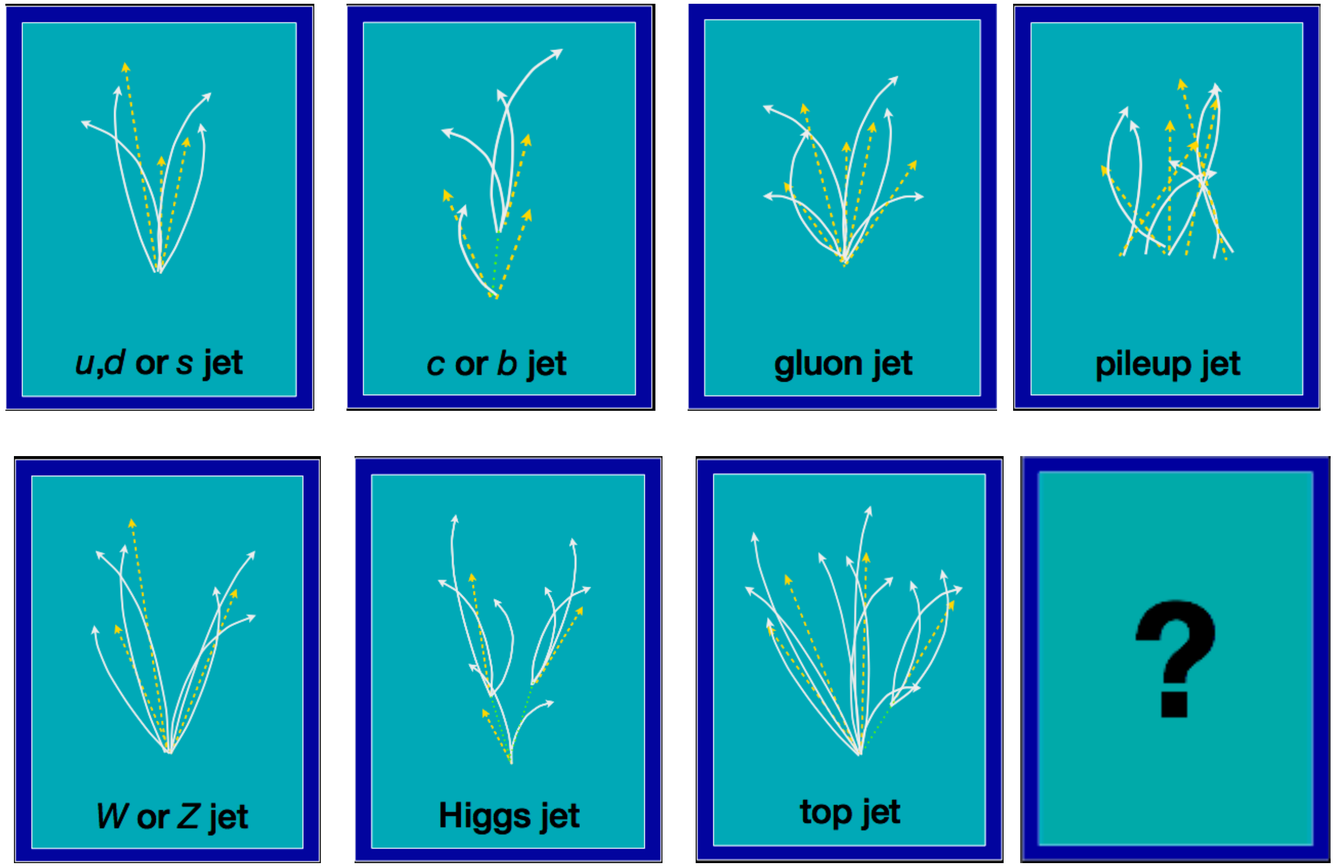
HOW DO WE LOOK FOR NEW PHYSICS?

- **Direct searches**: produce and observe a new particle or interaction
- **Indirect searches**: measure known standard model particles and interactions to look for deviations
- **Machine learning** is becoming more important to searches… Can even do *anomaly detection*





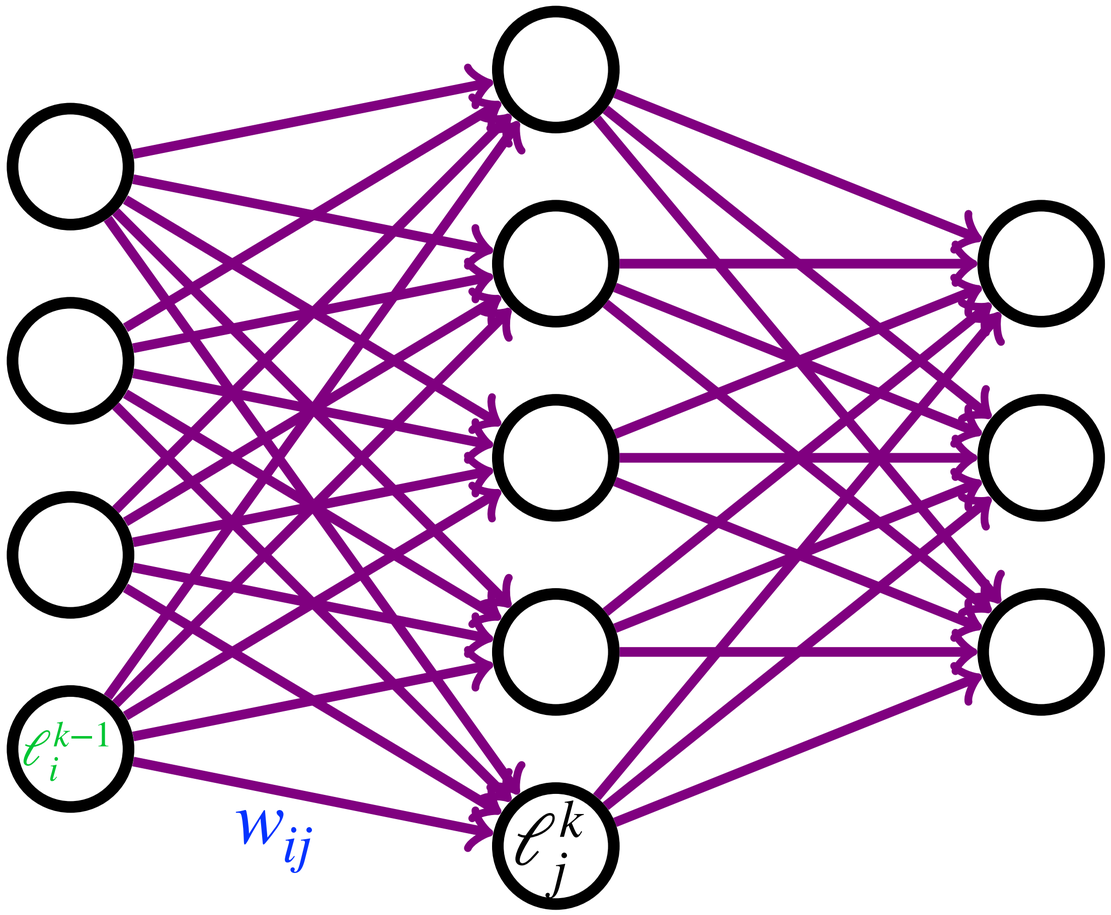
EXAMPLE: JET "TAGGING"



- Use machine learning to classify jets

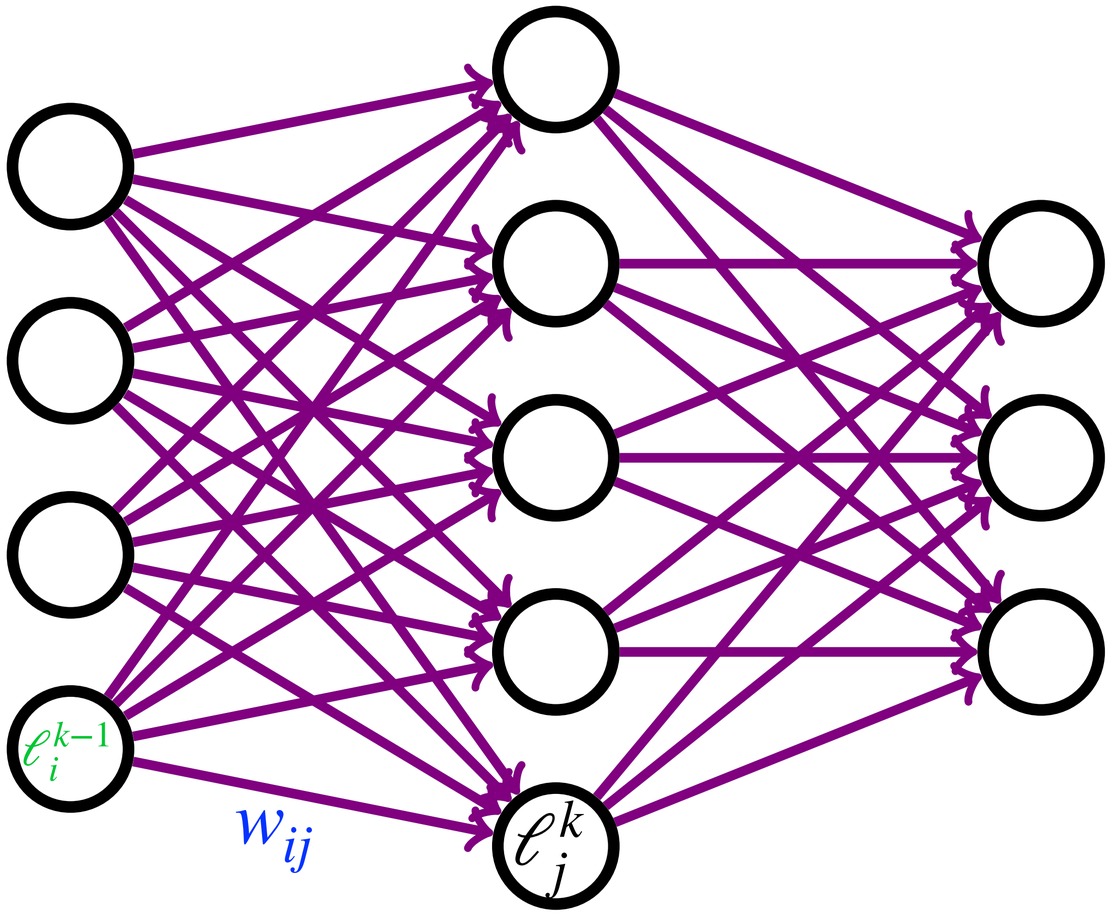
NEURAL NETWORK

$$\ell_j^k = \phi\left(\sum_i w_{ij}\ell_i^{k-1} + b_j\right)$$



NEURAL NETWORK

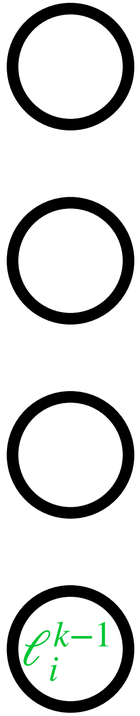
- Classic fully connected architecture $\ell_j^k = \phi\left(\sum_i w_{ij}\ell_i^{k-1} + b_j\right)$



NEURAL NETWORK

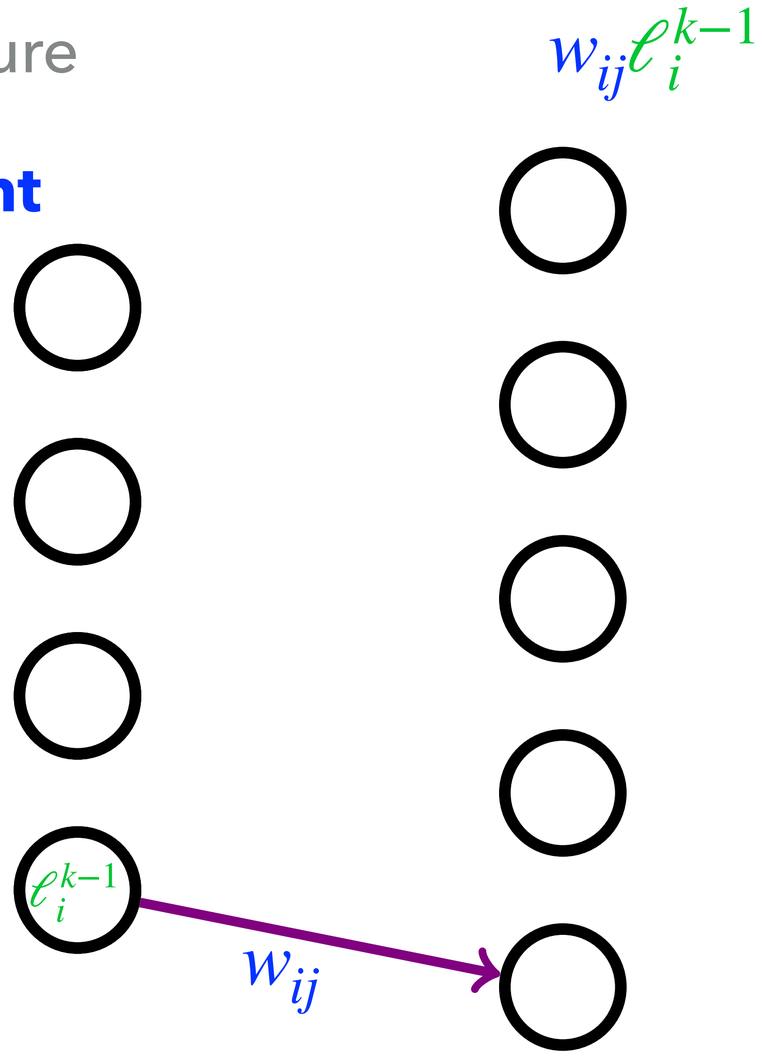
- Classic fully connected architecture

ℓ_i^{k-1}



NEURAL NETWORK

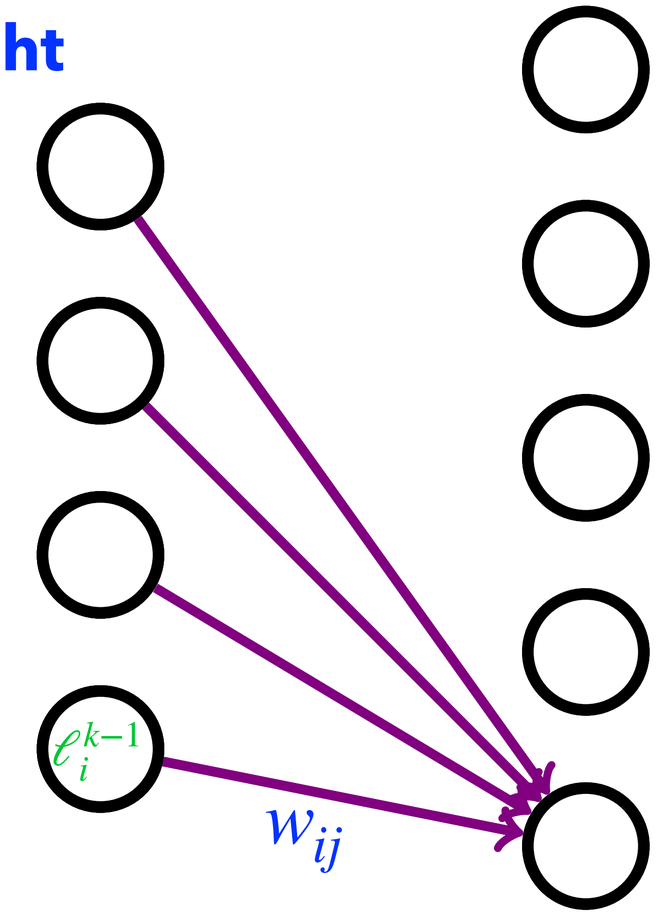
- Classic fully connected architecture
- Each **input** multiplied by a **weight**



NEURAL NETWORK

- Classic fully connected architecture
- Each **input** multiplied by a **weight**
- **Weighted** values are summed, **bias** is added

$$\sum_i w_{ij} \ell_i^{k-1} + b_j$$

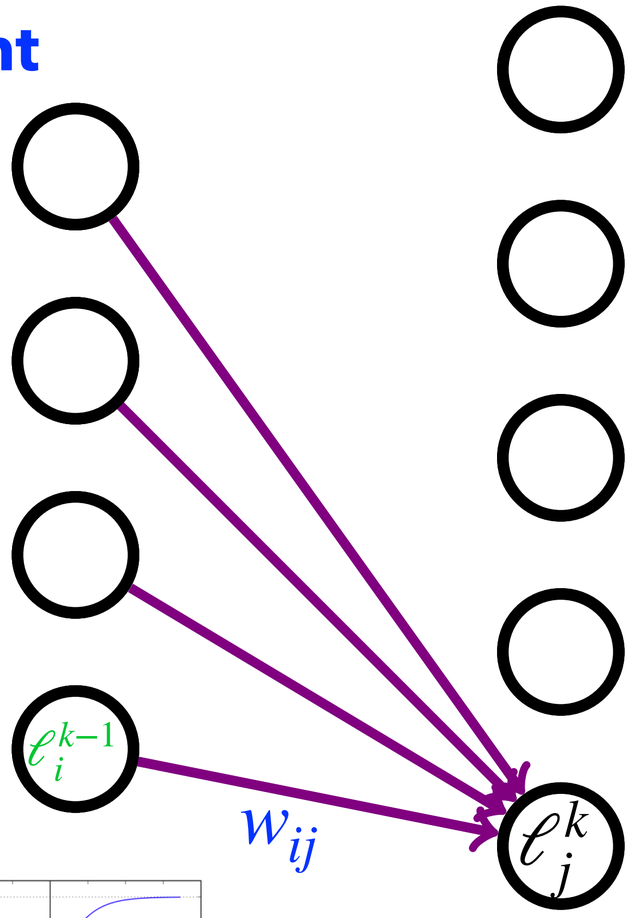


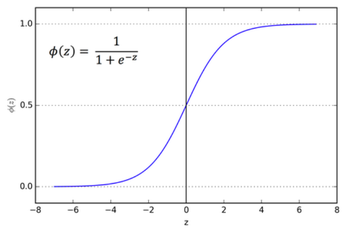
NEURAL NETWORK

- Classic fully connected architecture

$$\ell_j^k = \phi\left(\sum_i w_{ij}\ell_i^{k-1} + b_j\right)$$

- Each **input** multiplied by a **weight**
- **Weighted** values are summed, **bias** is added
- Nonlinear **activation function** is applied



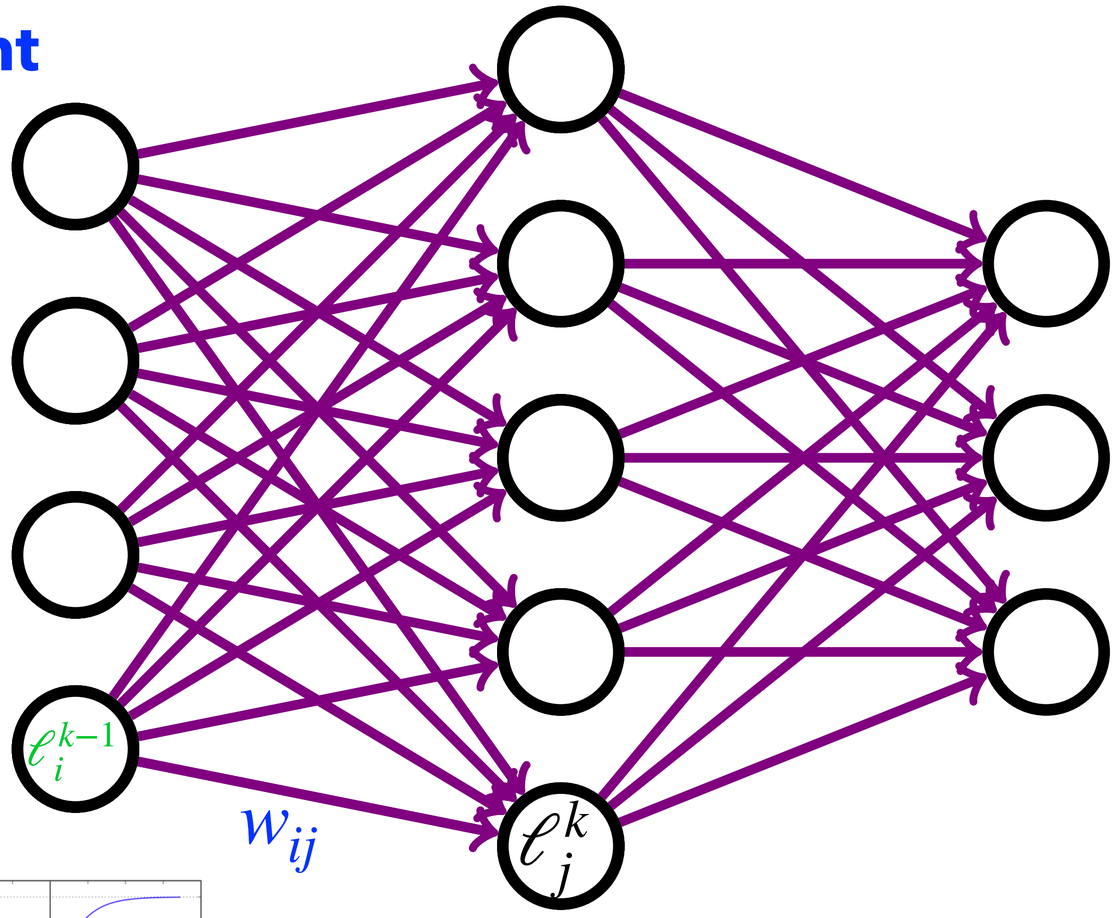


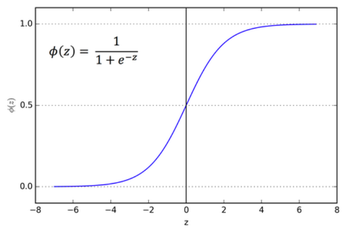
NEURAL NETWORK

- Classic fully connected architecture

$$\ell_j^k = \phi\left(\sum_i w_{ij}\ell_i^{k-1} + b_j\right)$$

- Each **input** multiplied by a **weight**
- **Weighted** values are summed, **bias** is added
- Nonlinear **activation function** is applied



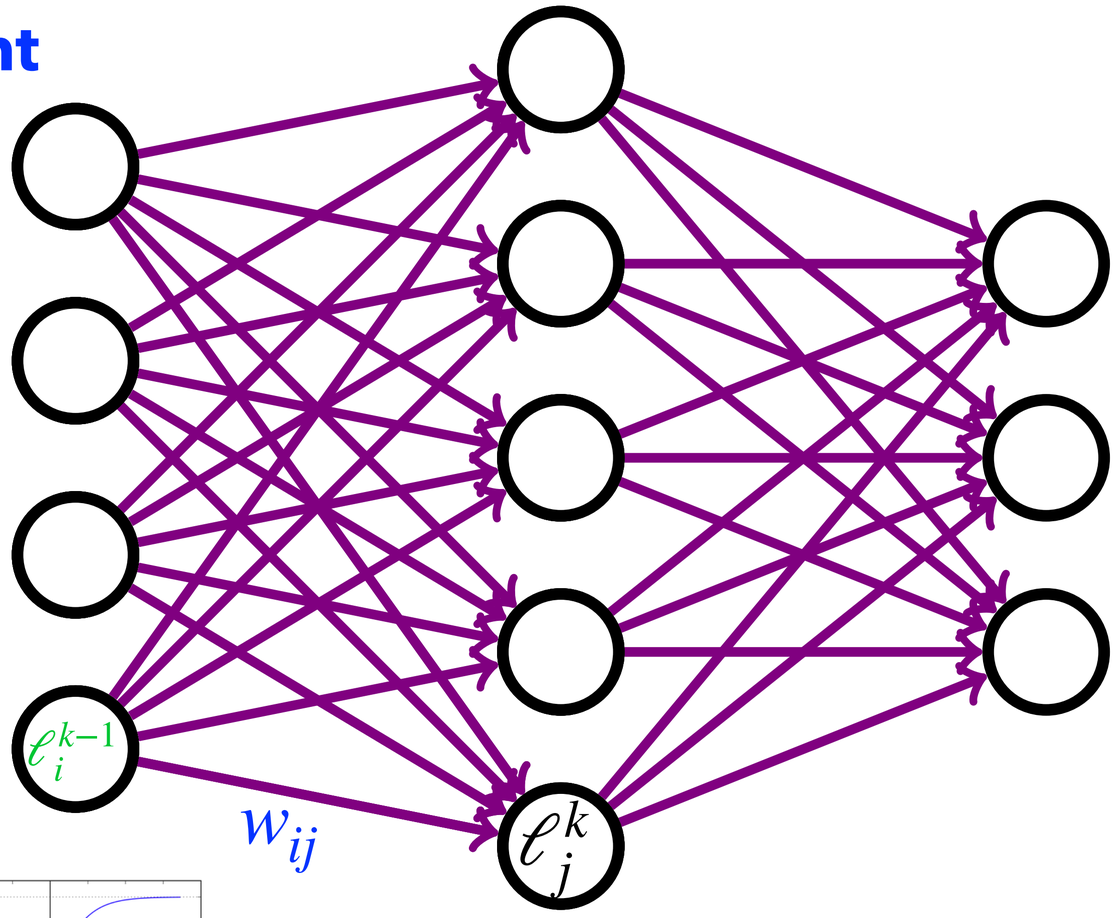


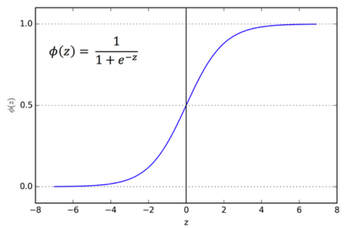
NEURAL NETWORK

- Classic fully connected architecture

$$\ell_j^k = \phi\left(\sum_i w_{ij}\ell_i^{k-1} + b_j\right)$$

- Each **input** multiplied by a **weight**
- **Weighted** values are summed, **bias** is added
- Nonlinear **activation function** is applied
- Trained by varying the **parameters** to minimize a loss function (quantifies how many mistakes the network makes)



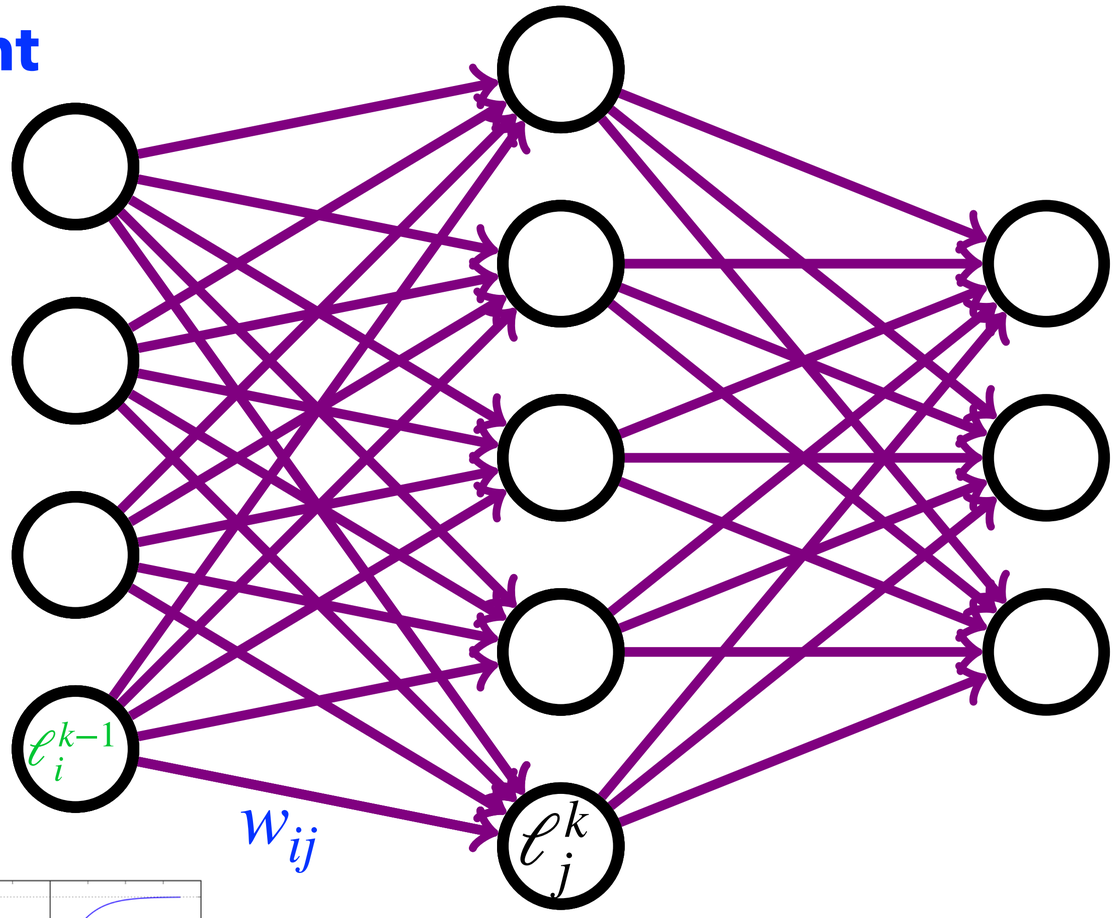


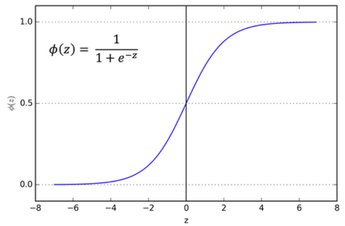
NEURAL NETWORK

- Classic fully connected architecture

$$\ell_j^k = \phi\left(\sum_i w_{ij}\ell_i^{k-1} + b_j\right)$$

- Each **input** multiplied by a **weight**
- **Weighted** values are summed, **bias** is added
- Nonlinear **activation function** is applied
- Trained by varying the **parameters** to minimize a loss function (quantifies how many mistakes the network makes)

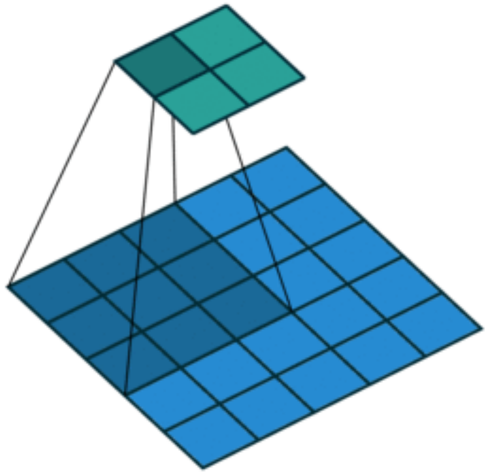




A sufficiently "wide" neural network can approximate any function!

DEEP NEURAL NETWORK: RESNET-50

- ResNet-50 is a deep convolutional neural network
  - inputs (pixels) are locally grouped and the same set of weights is applied to each patch
  - 50 hidden layers
  - state-of-the-art performance for natural images

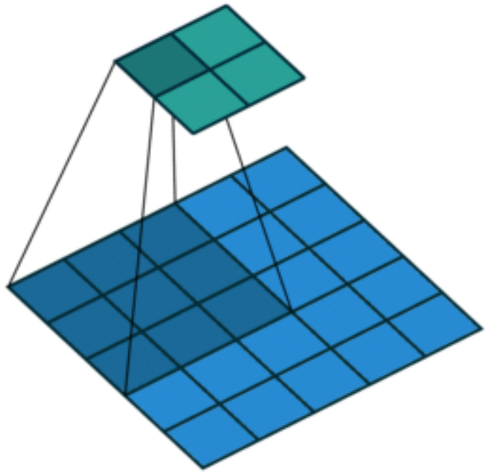


African elephant from Wikipedia

```
ResNet-50 predictions:

African elephant: 90%
Tusker: 6%
Indian elephant: 3%
```

DEEP NEURAL NETWORK: RESNET-50

- ResNet-50 is a deep convolutional neural network
  - inputs (pixels) are locally grouped and the same set of weights is applied to each patch
  - 50 hidden layers
  - state-of-the-art performance for natural images

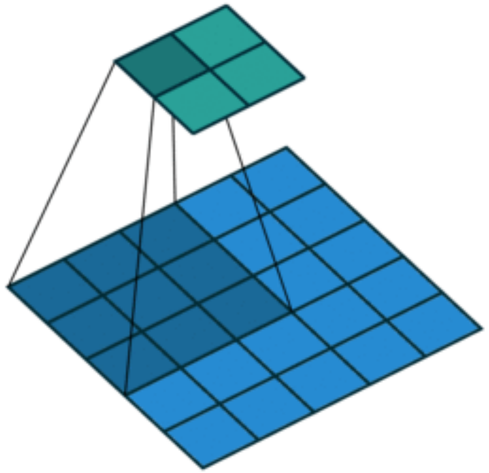


African elephant from Wikipedia

```
ResNet-50 predictions:

African elephant: 90%
Tusker: 6%
Indian elephant: 3%
```

DEEP NEURAL NETWORK: RESNET-50

- ResNet-50 is a deep convolutional neural network
  - inputs (pixels) are locally grouped and the same set of weights is applied to each patch
  - 50 hidden layers
  - state-of-the-art performance for natural images



African elephant from Wikipedia

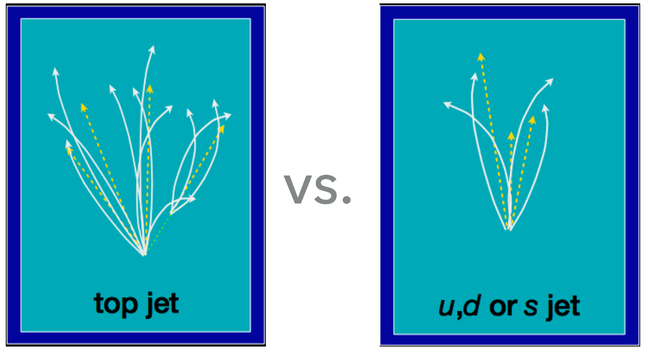
```
ResNet-50 predictions:

African elephant: 90%
Tusker: 6%
Indian elephant: 3%
```

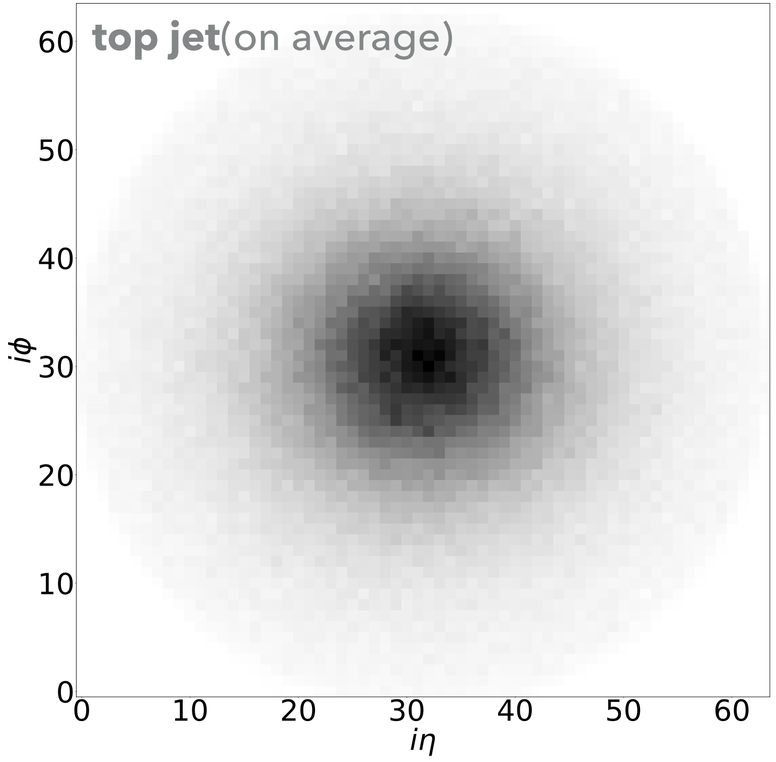
My puppy: whippet mixed with ???

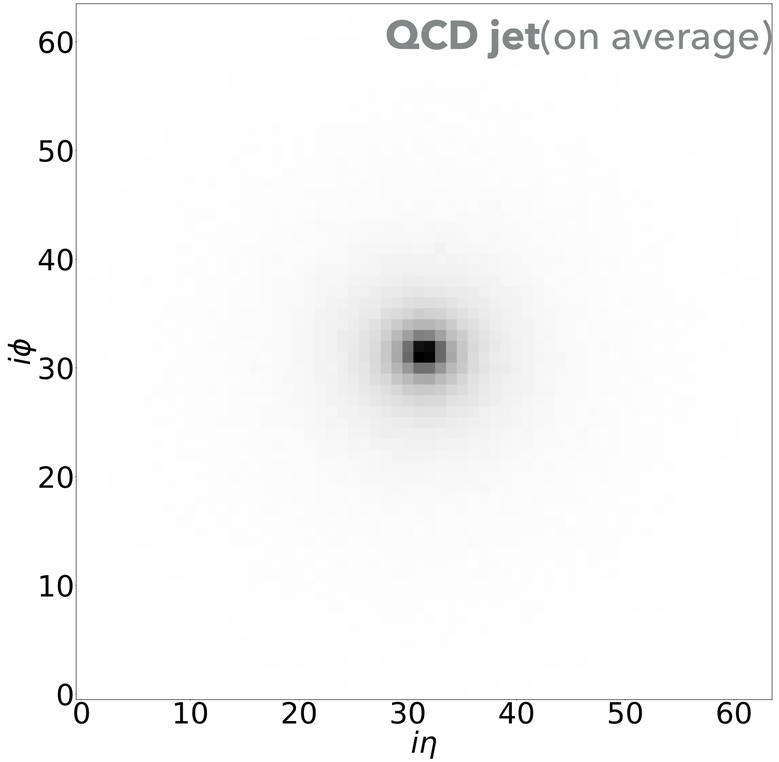
```
ResNet-50 predictions:

Whippet: 47%
Italian greyhound: 20%
Rhodesian ridgeback: 18%
```

JET VISION?

- Train ResNet-50 to identify the origin of jets
- Jet images = pixelated versions of calorimeter hits in 2D (η, ϕ)

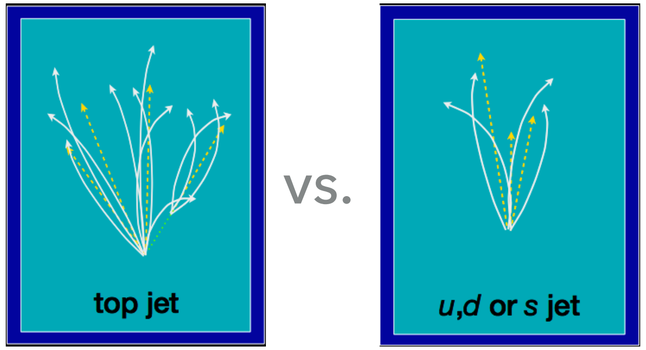


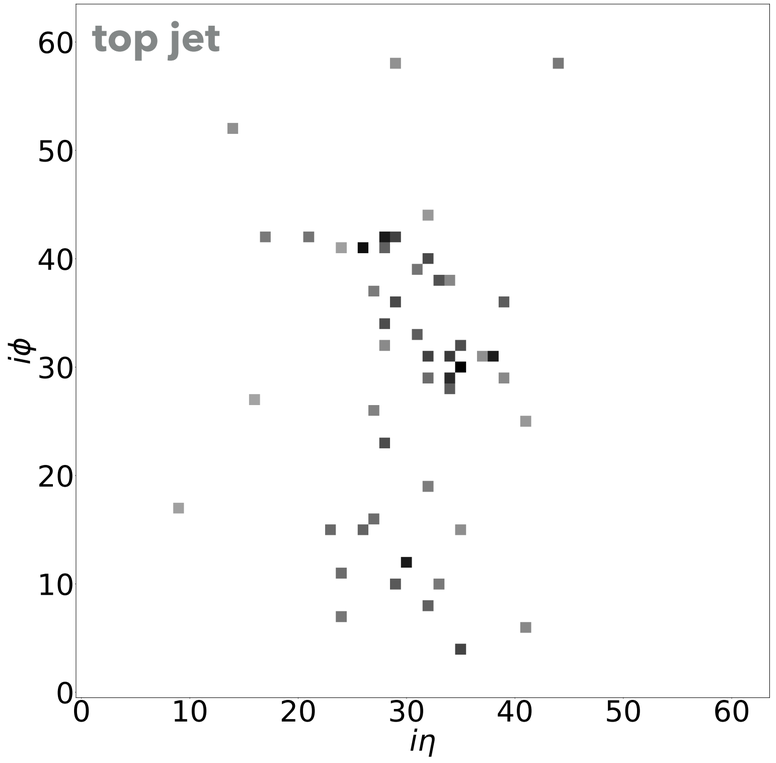


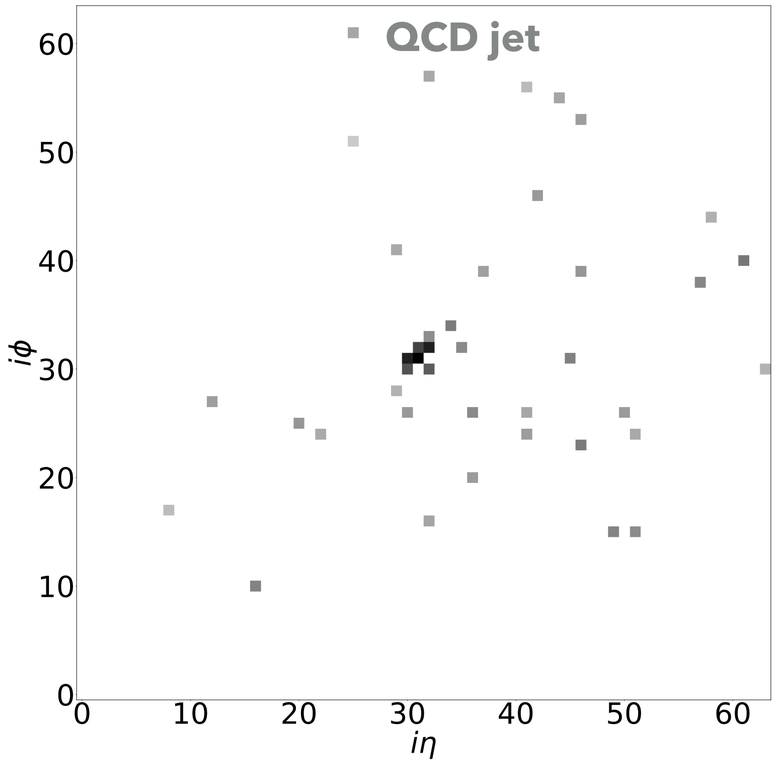


JET VISION?

- Train ResNet-50 to identify the origin of jets
- Jet images = pixelated versions of calorimeter hits in 2D (η, ϕ)

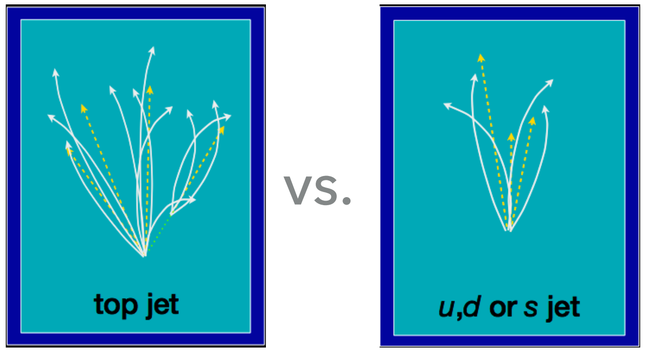


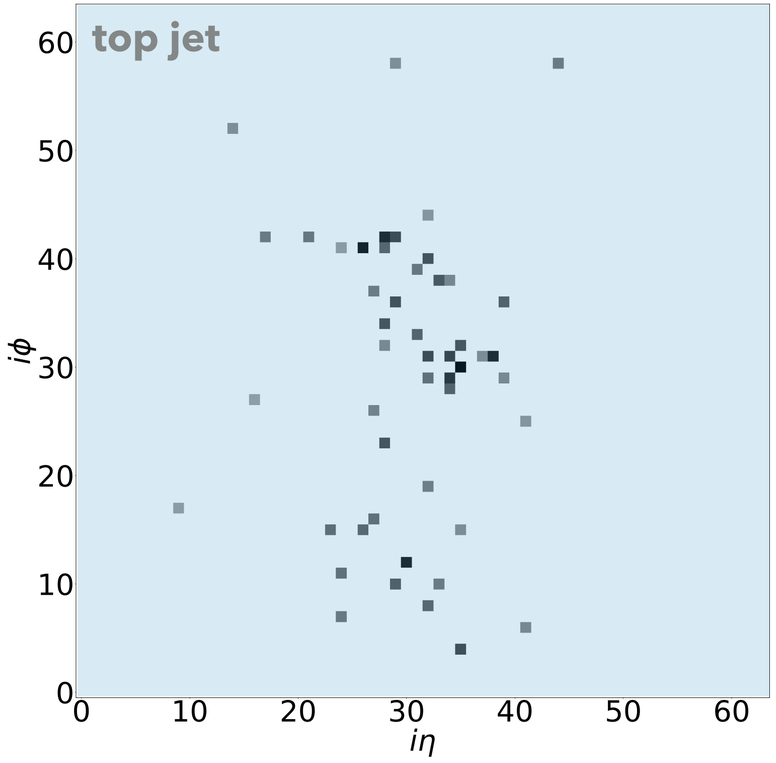


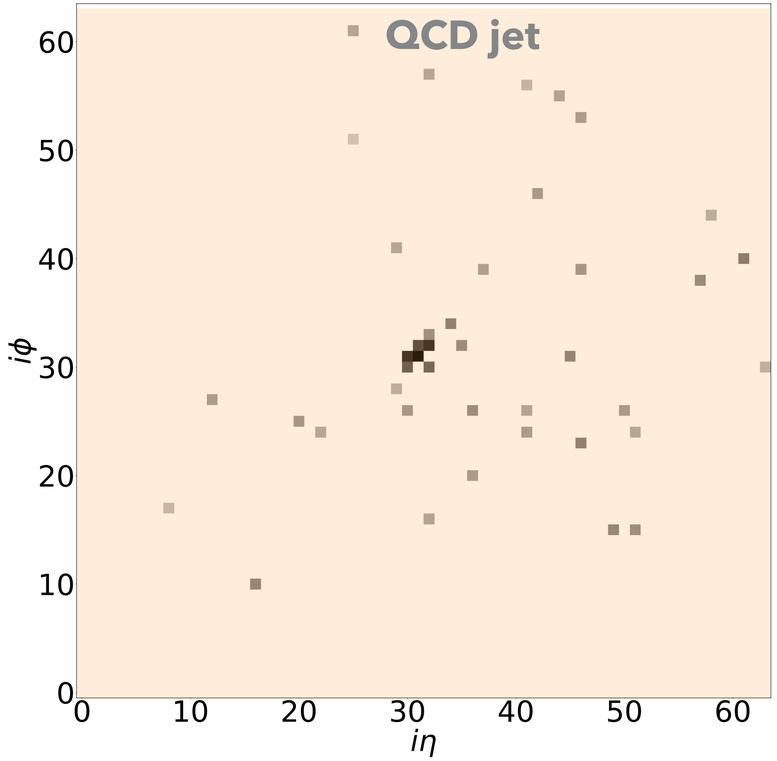


JET VISION?

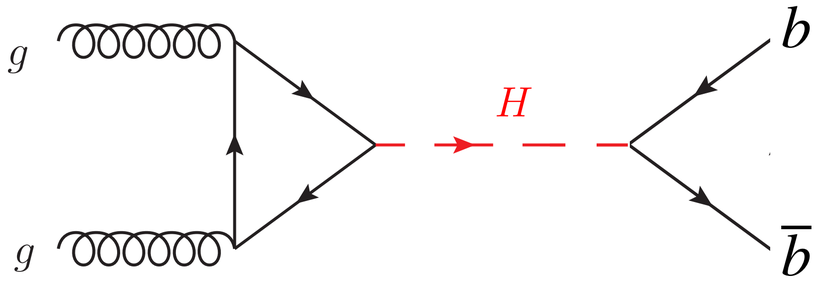
- Train ResNet-50 to identify the origin of jets
- Jet images = pixelated versions of calorimeter hits in 2D (η, ϕ)

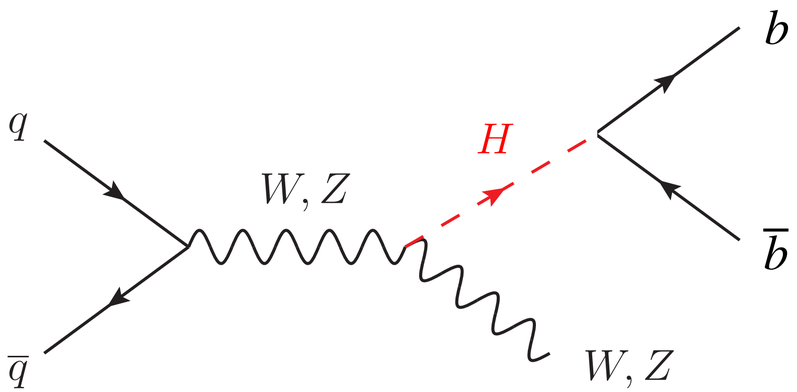






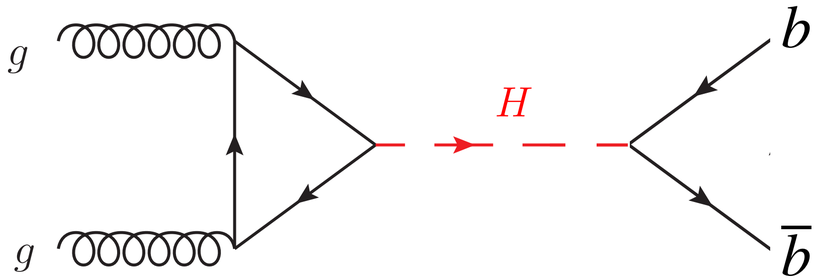
HIGGS BOSON TO BOTTOM QUARKS?

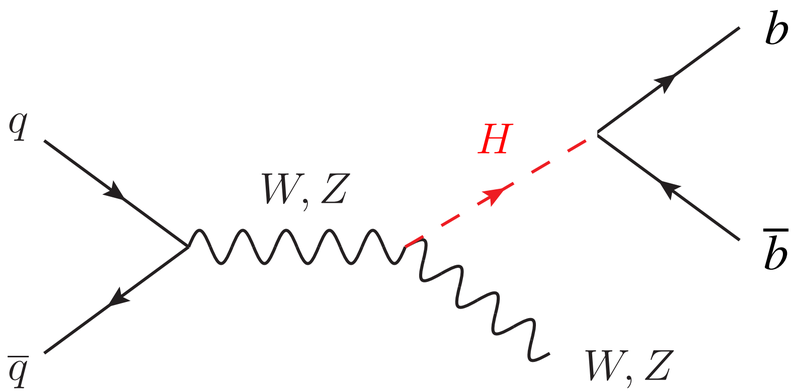




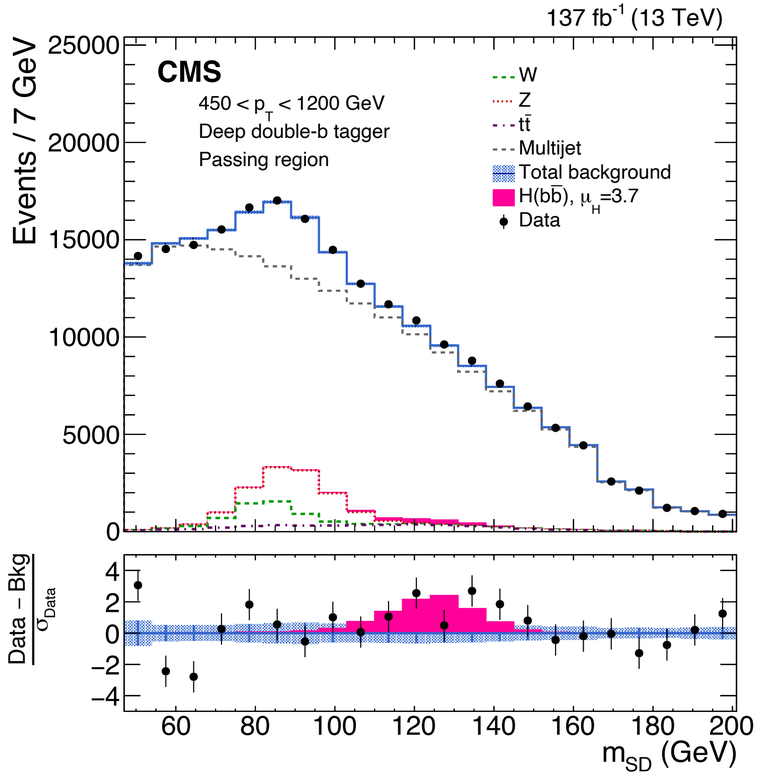
- Can we use ML techniques like this to observe the Higgs boson decaying to bottom quarks?

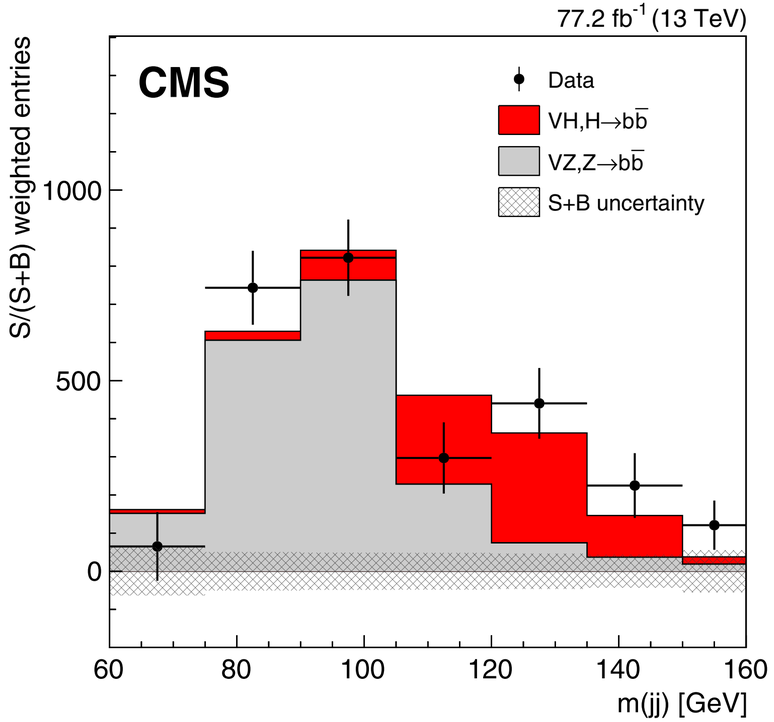
HIGGS BOSON TO BOTTOM QUARKS? YES!





DEEP NEURAL NETWORK

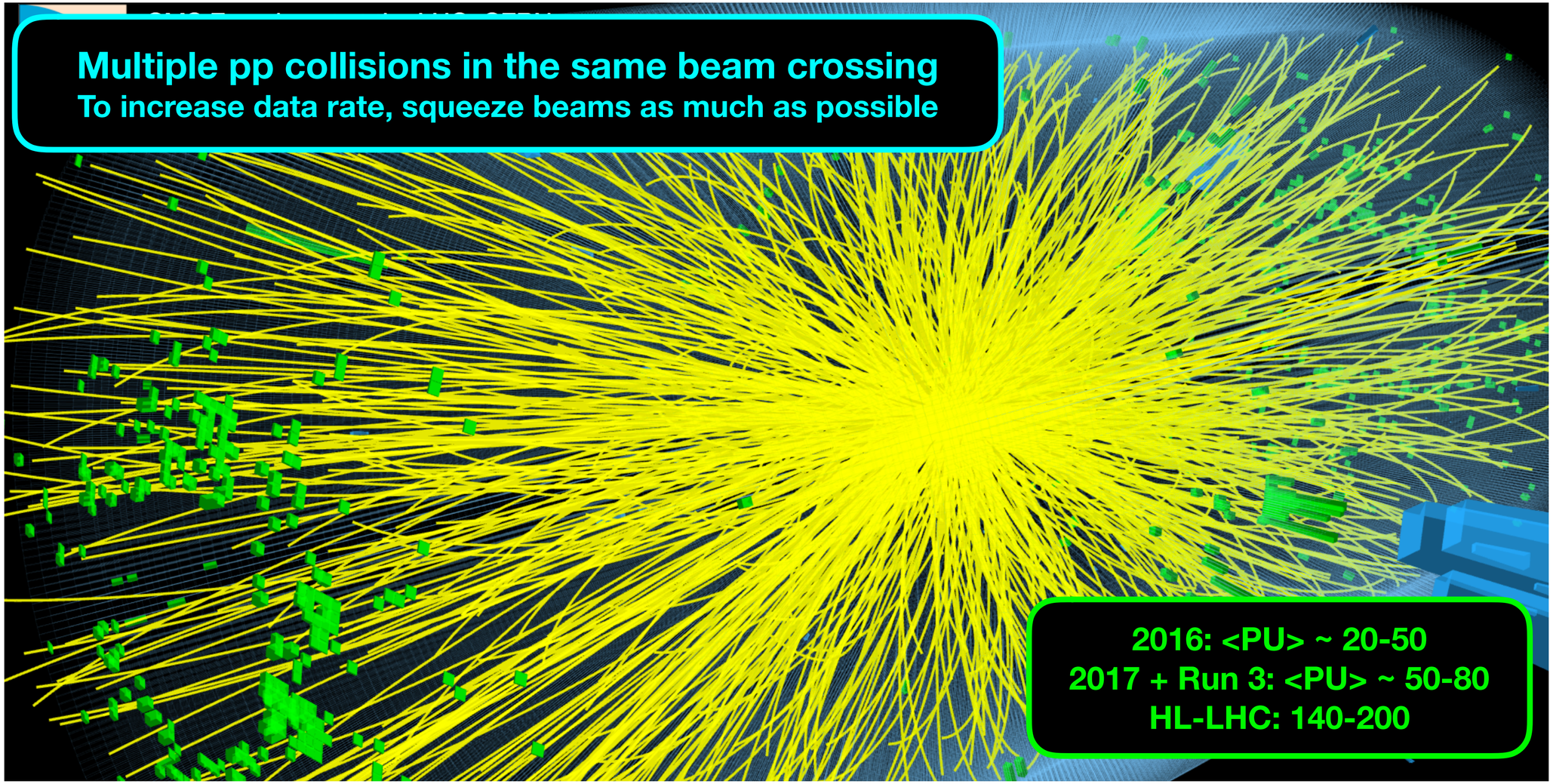


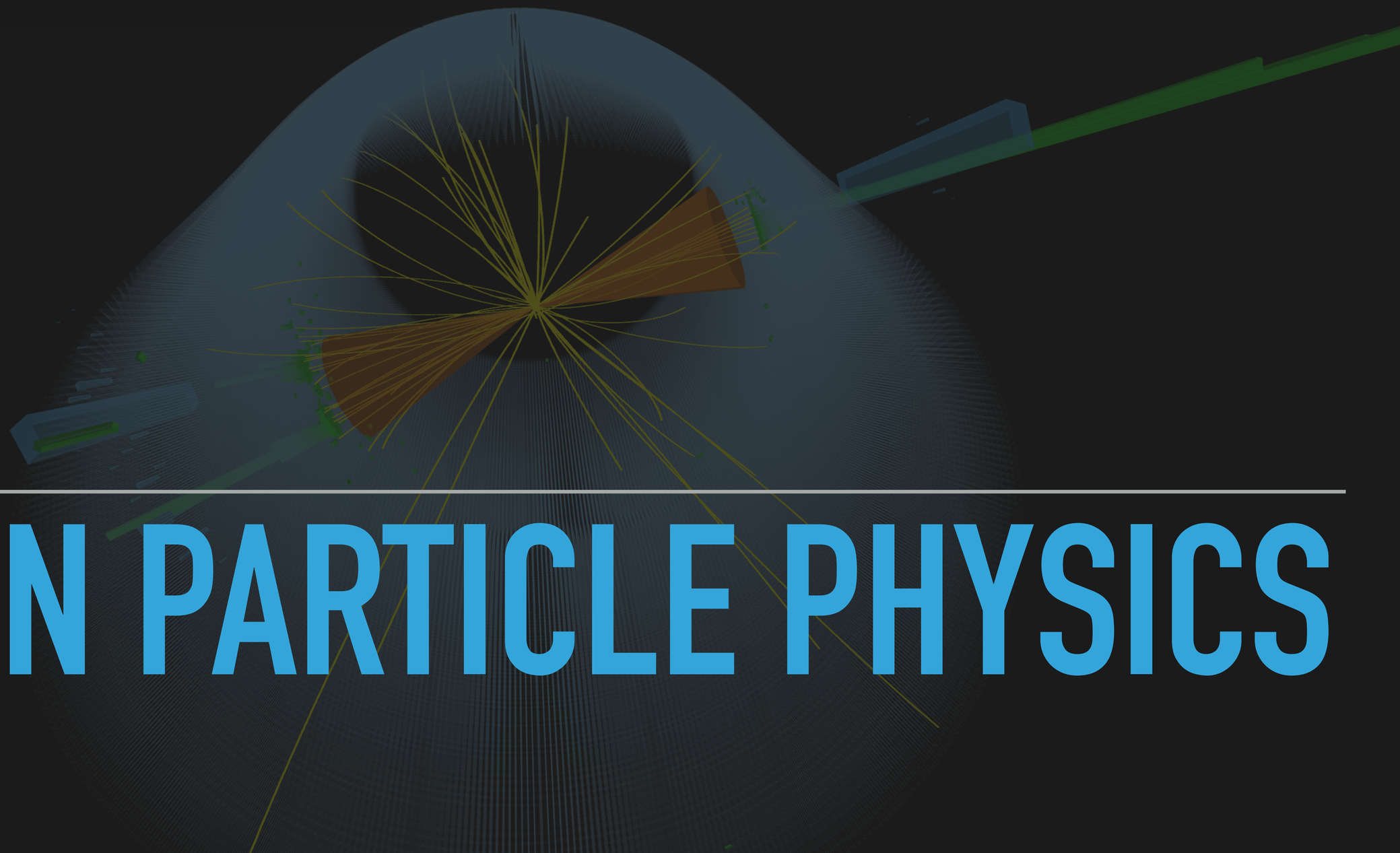


BOOSTED DECISION TREE

WHAT'S NEXT: HIGH LUMINOSITY LHC IN 2026

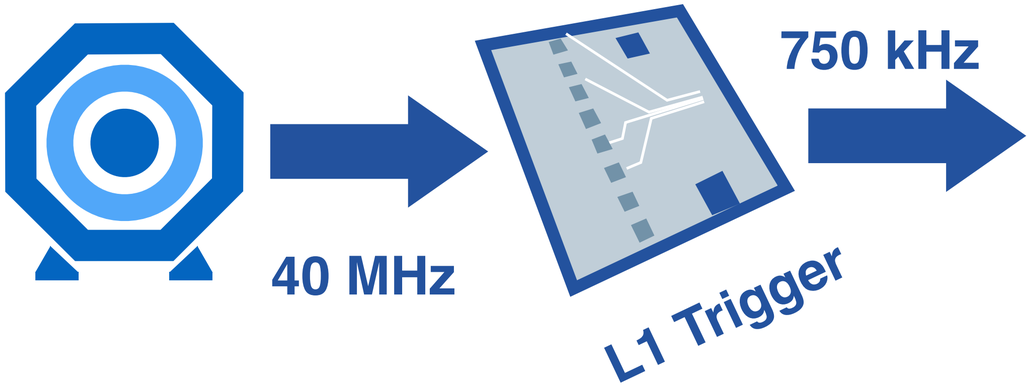
- High luminosity: increased event rate and many more simultaneous collisions (pileup)!
- Pileup + new detectors (= more complex data) challenge our **trigger** and **reconstruction**



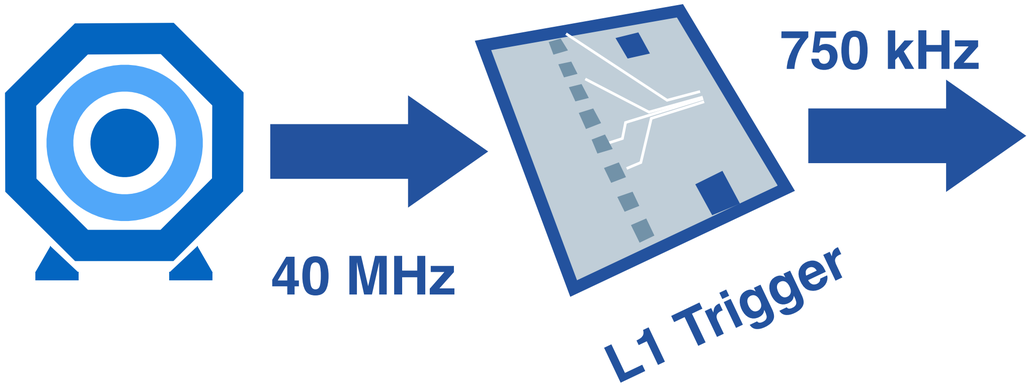


ML IN PARTICLE PHYSICS

LEVEL-1 TRIGGER

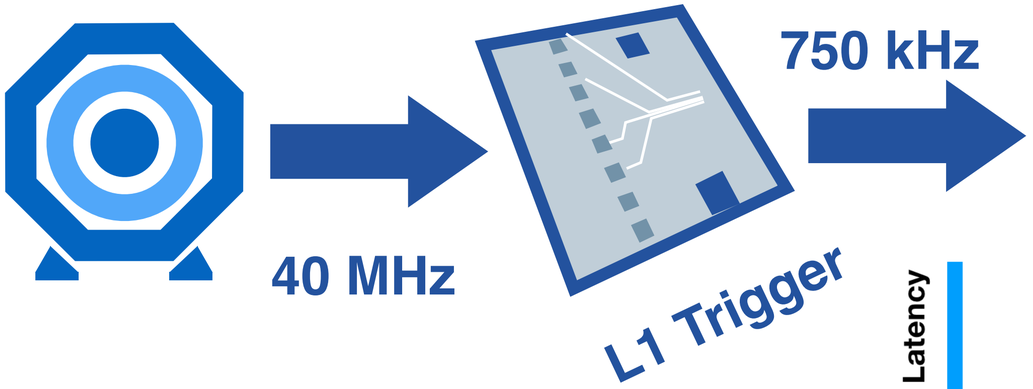


LEVEL-1 TRIGGER

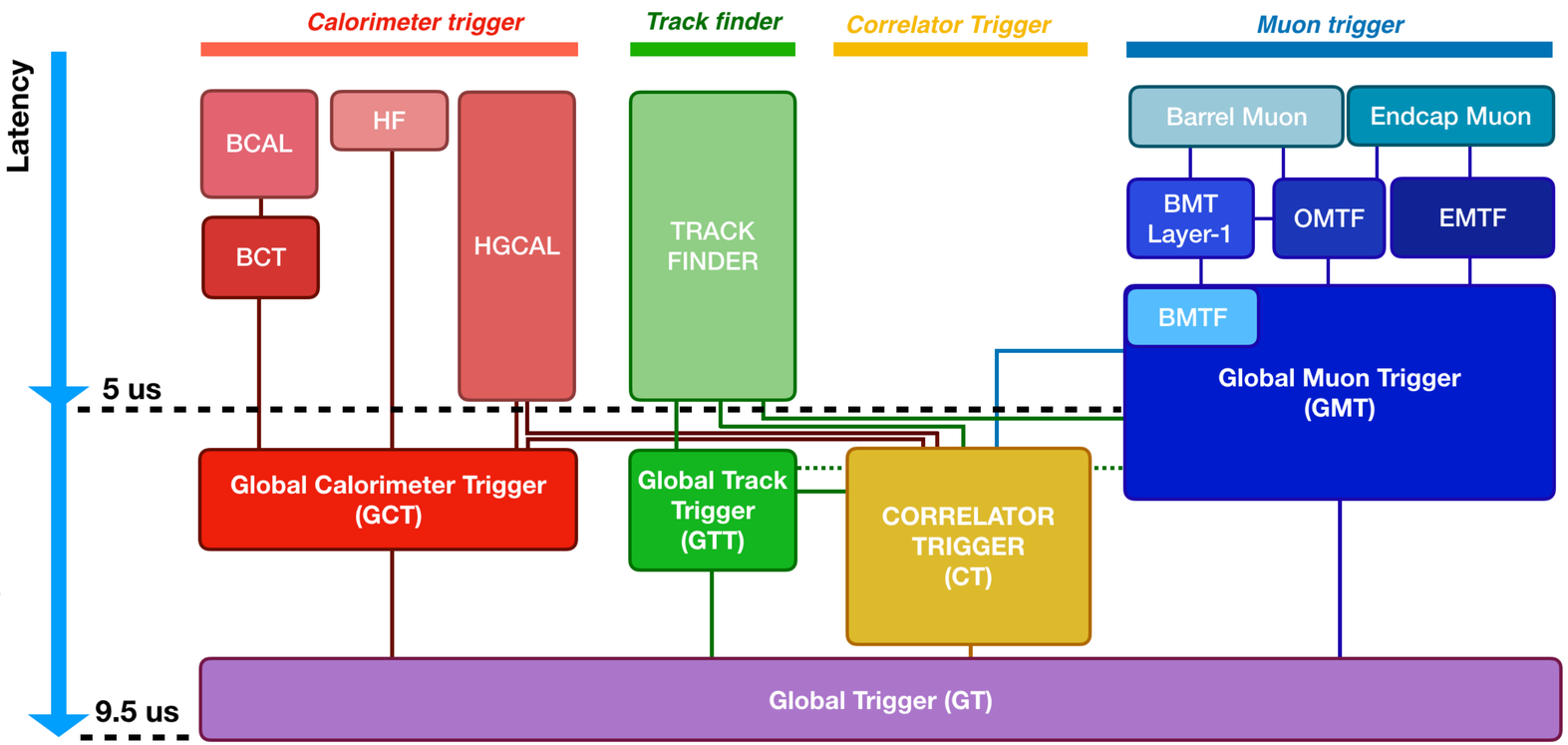


- Upgraded Level-1 Trigger:
  40 MHz → 750 kHz

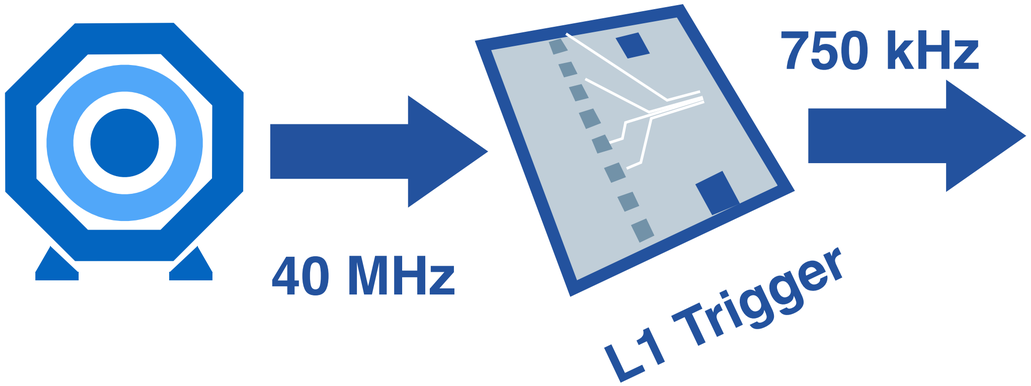
LEVEL-1 TRIGGER

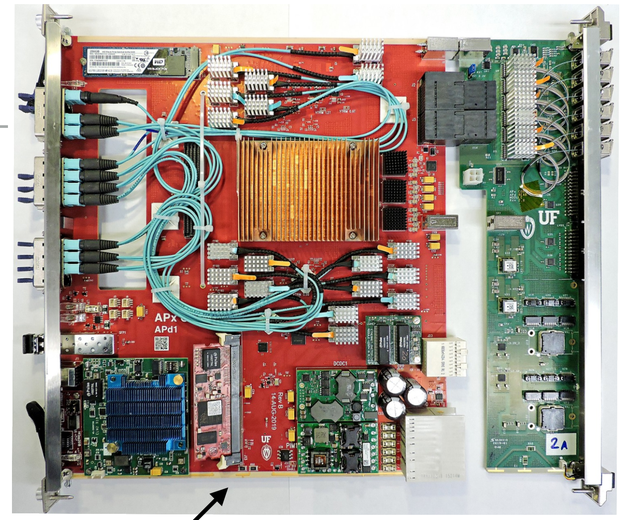


- Upgraded Level-1 Trigger: 40 MHz → 750 kHz
- Reconstruct all events and reject 98% of them in ~12.5 μs

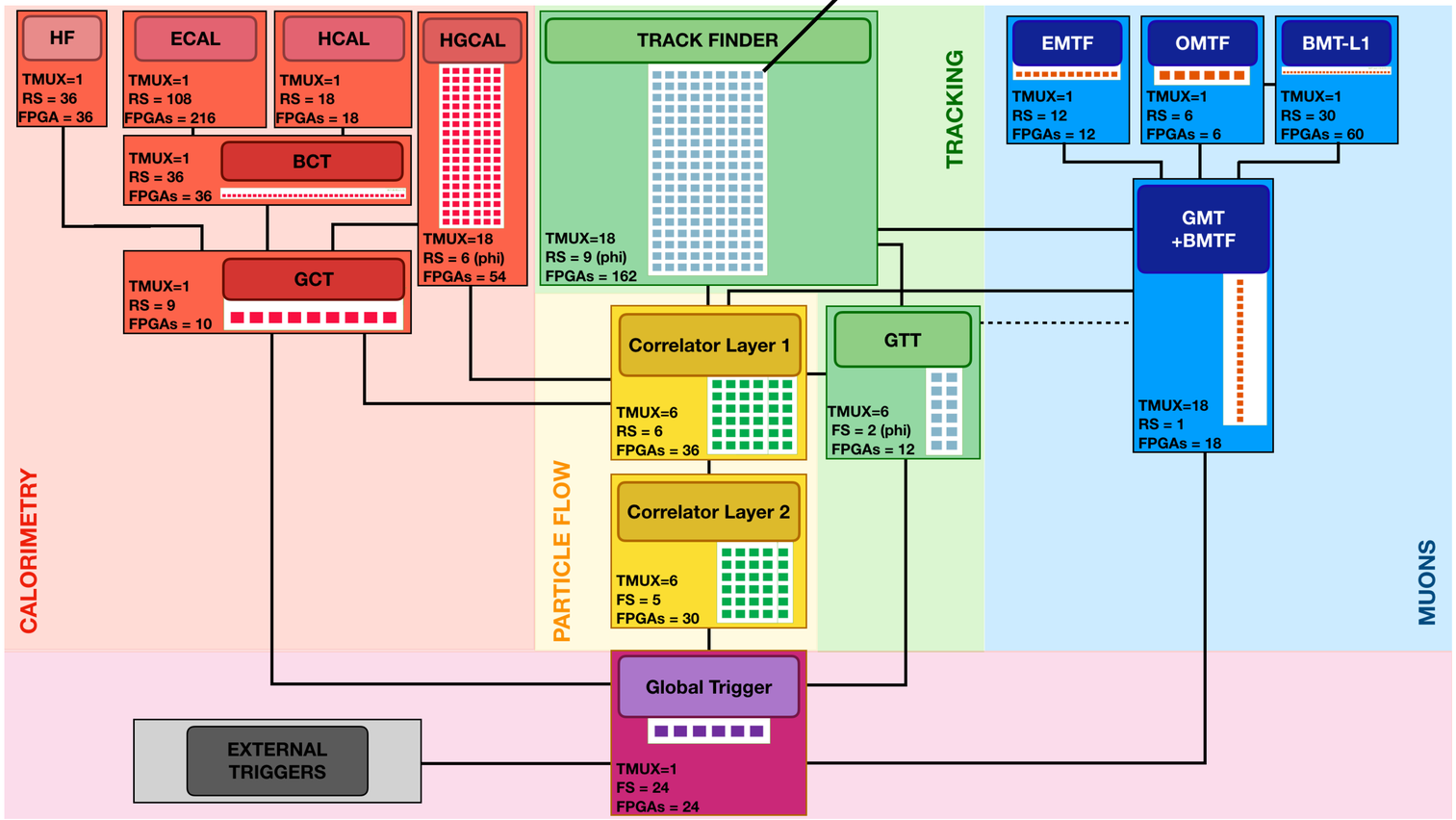


LEVEL-1 TRIGGER



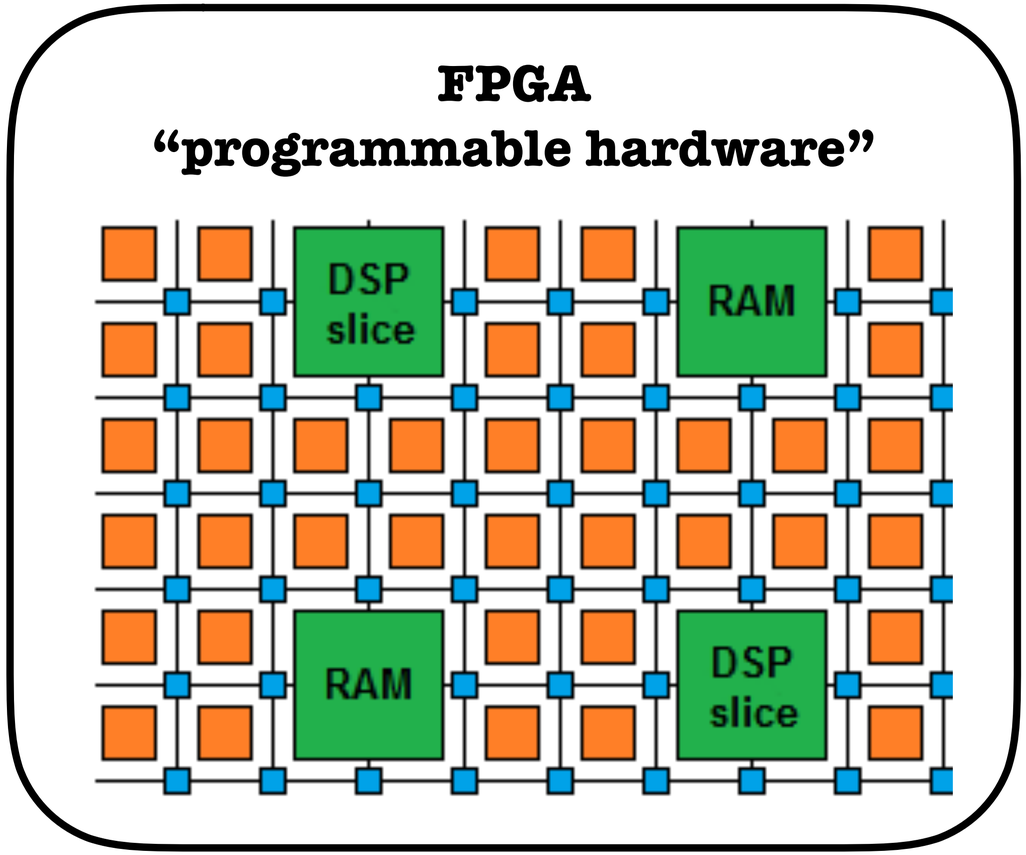


- Upgraded Level-1 Trigger: 40 MHz → 750 kHz
- Reconstruct all events and reject 98% of them in ~12.5 μs
- Latency necessitates all **FPGA** design (729 FPGAs!)



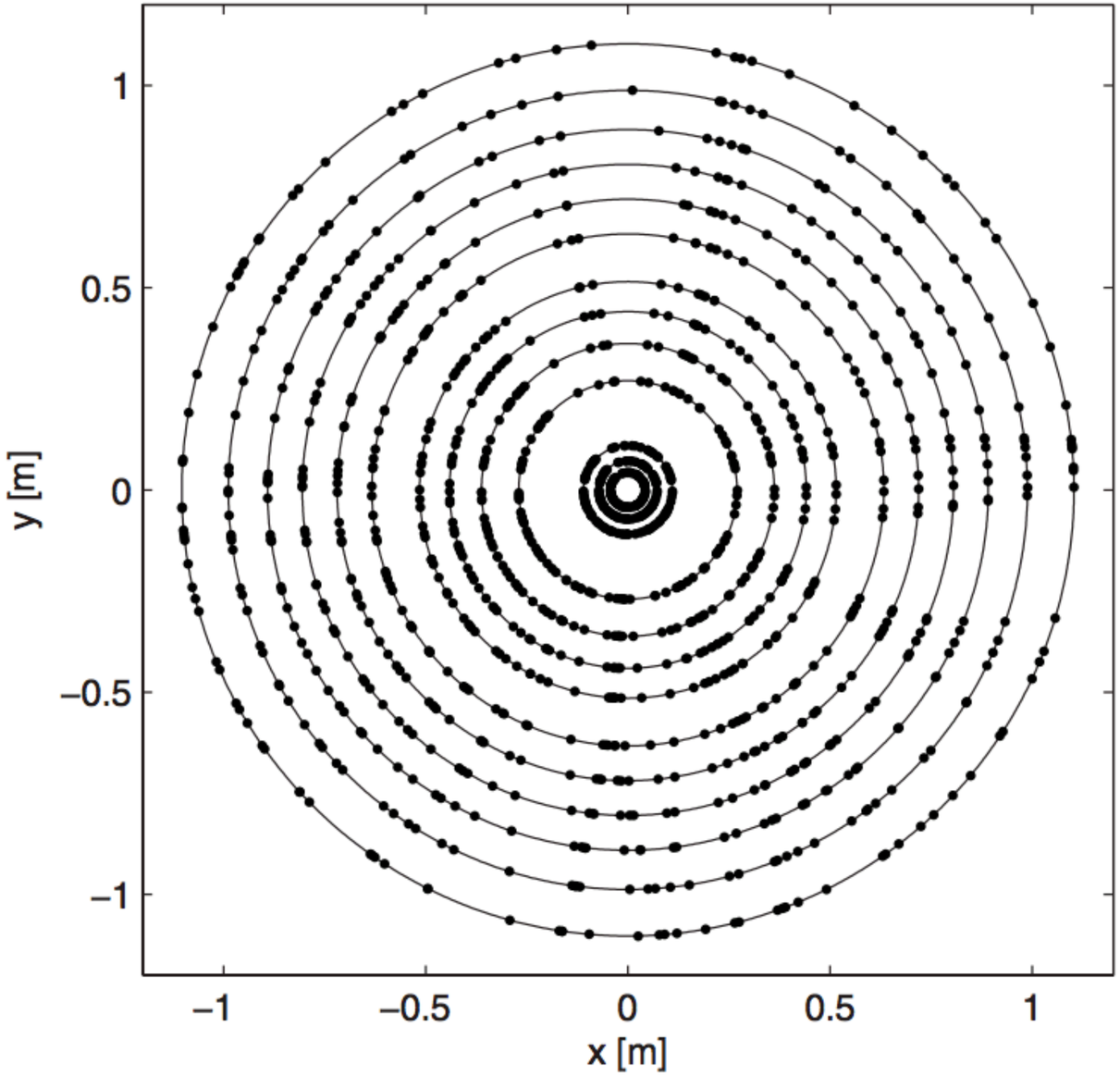
FPGAS: REPROGRAMMABLE HARDWARE

- Pros:
  - Reprogrammable interconnects between embedded components that perform multiplication (DSPs), apply logical functions (LUTs), or store memory (BRAM)
  - High throughput: O(100) optical transceivers running at O(15) Gbps
  - Massively parallel
  - Low power
- Cons:
  - Requires domain knowledge to program (using VHDL/Verilog)



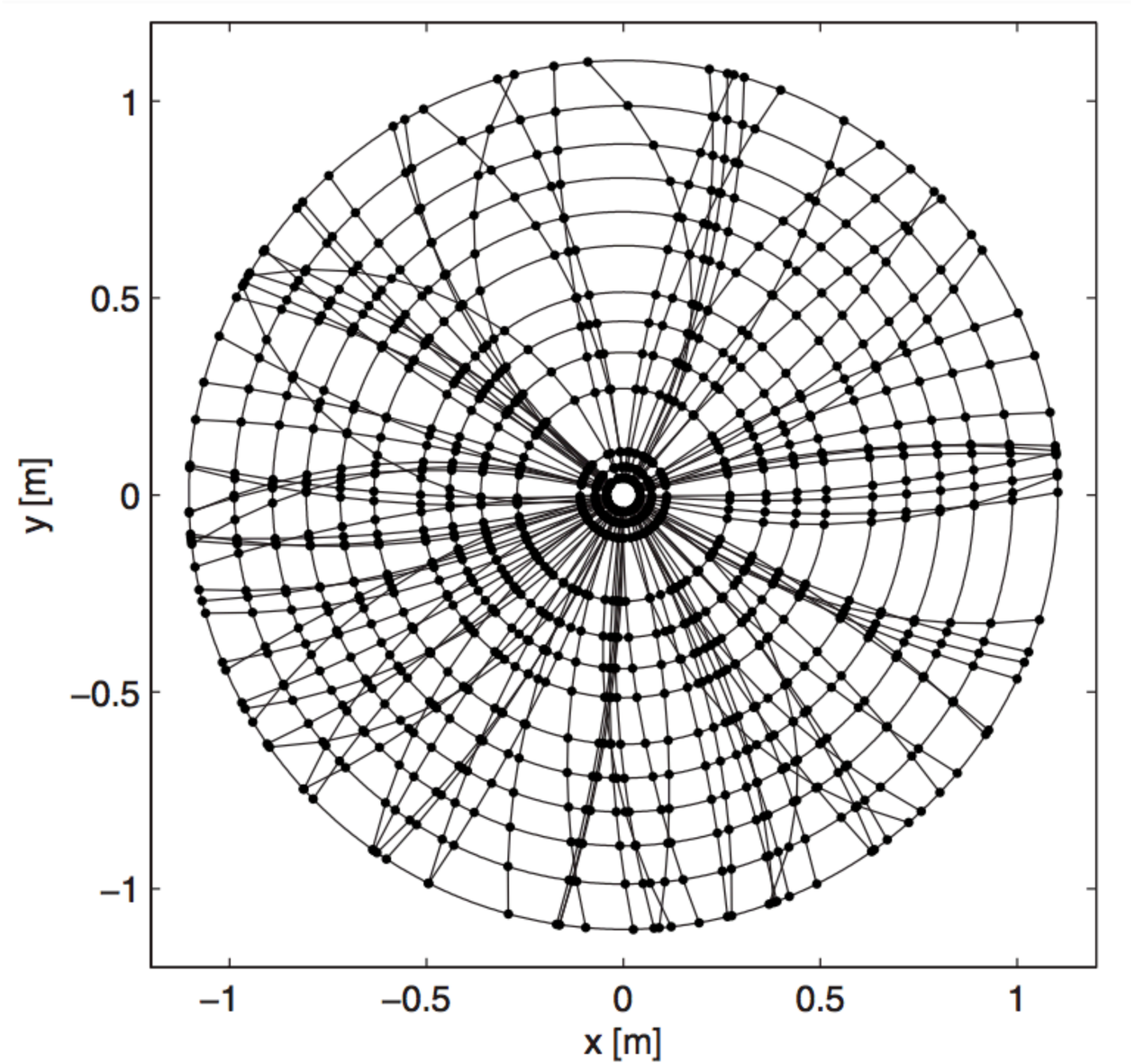
TRACKING (CONNECTING THE DOTS)

- Particle tracking is a classic reconstruction task
- From a set of hits sampled sparsely in 3D, reconstruct the helical trajectories of particles
- Traditional algorithms scale badly with the number of hits
- New algorithms (based on **graph neural networks**) may be able to do better

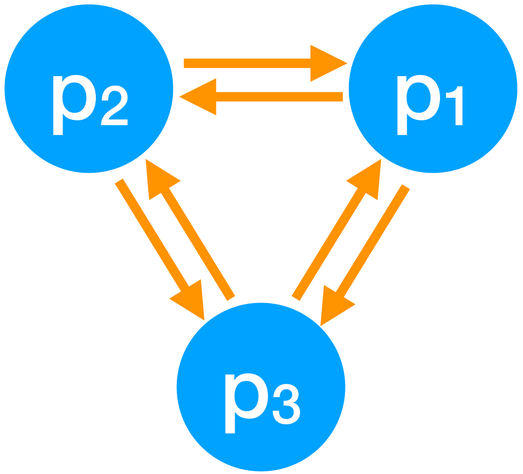


TRACKING (CONNECTING THE DOTS)

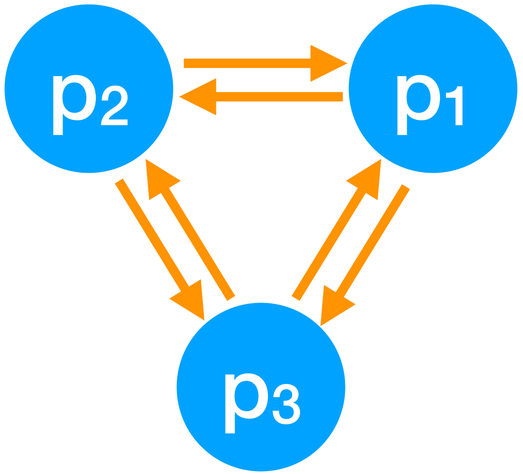
- Particle tracking is a classic reconstruction task
- From a set of hits sampled sparsely in 3D, reconstruct the helical trajectories of particles
- Traditional algorithms scale badly with the number of hits
- New algorithms (based on **graph neural networks**) may be able to do better



GRAPH NEURAL NETWORKS

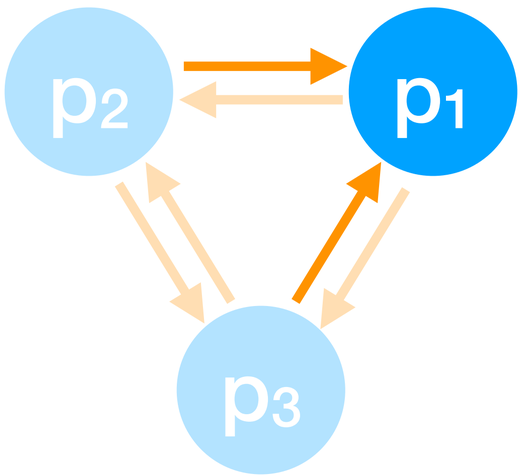


GRAPH NEURAL NETWORKS



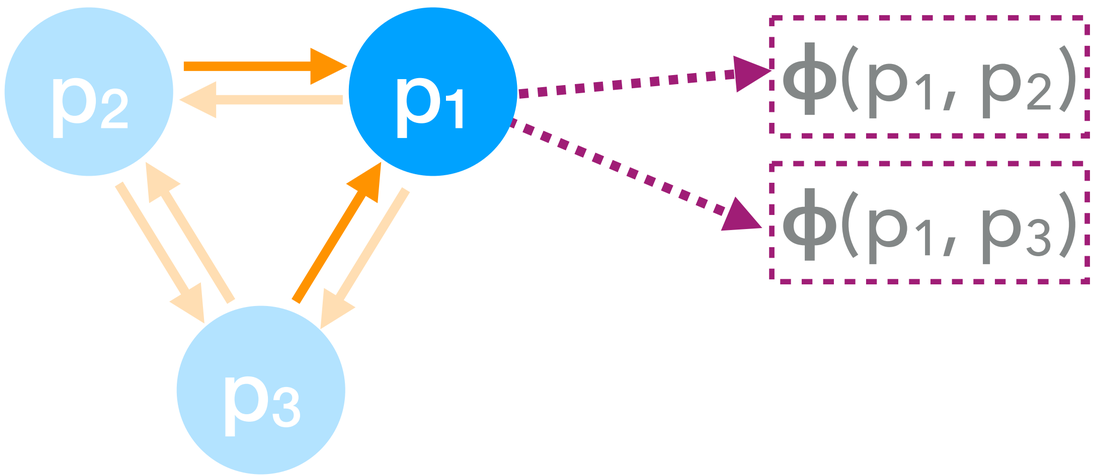
- A **graph** is a set of objects and their connections

GRAPH NEURAL NETWORKS



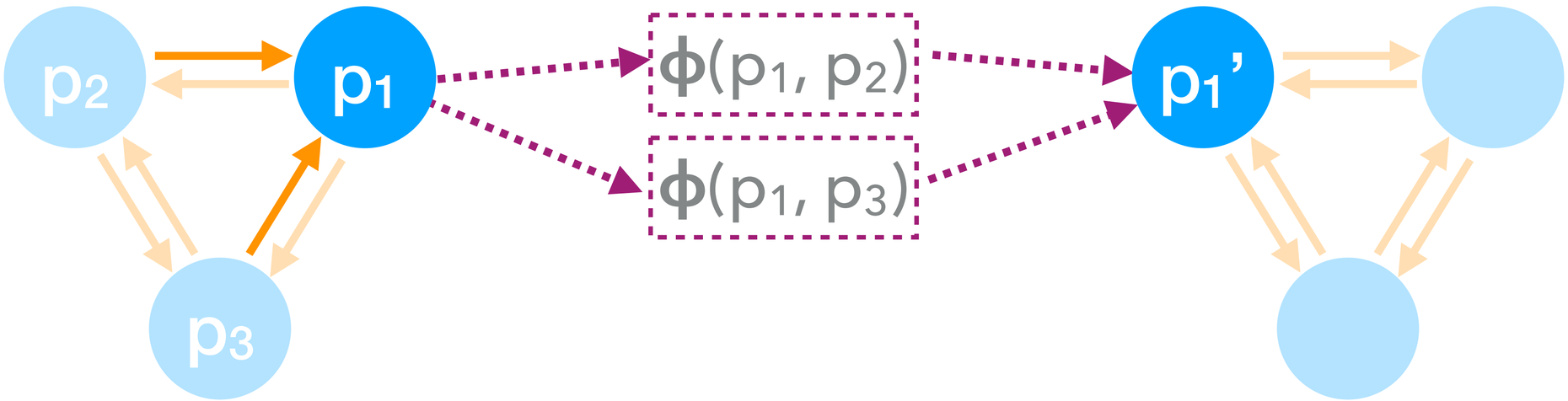
- A **graph** is a set of objects and their connections

GRAPH NEURAL NETWORKS



- A **graph** is a set of objects and their connections
- NN is evaluated on **pairs** of connected objects to produce a **message**

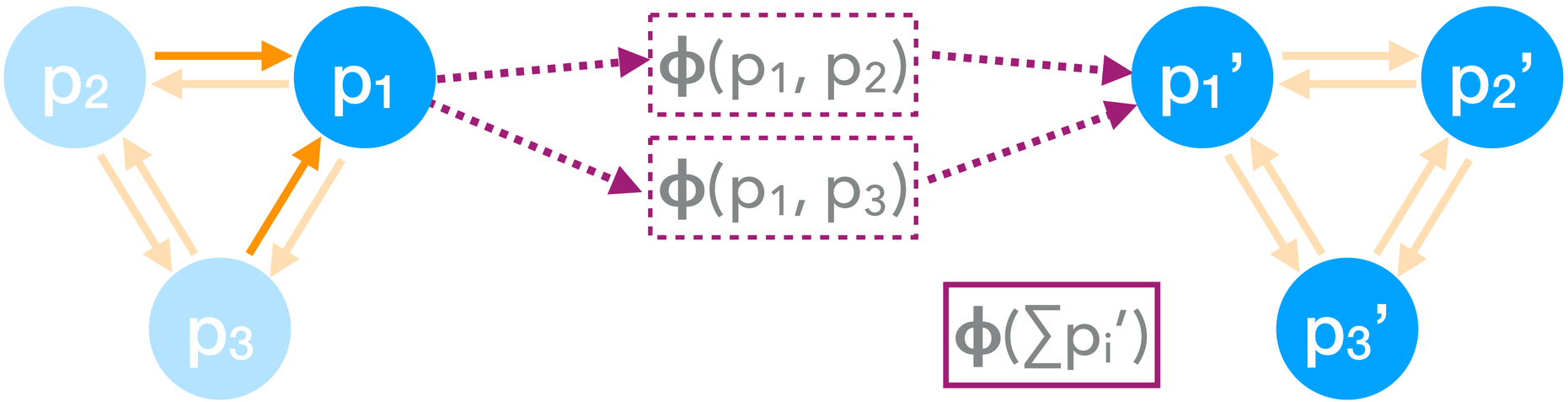
GRAPH NEURAL NETWORKS



- A **graph** is a set of objects and their connections
- NN is evaluated on **pairs** of connected objects to produce a **message**
- **Messages** are communicated from nearest neighbors (and summed*) to **update** the graph's features

*sum preserves permutation invariance

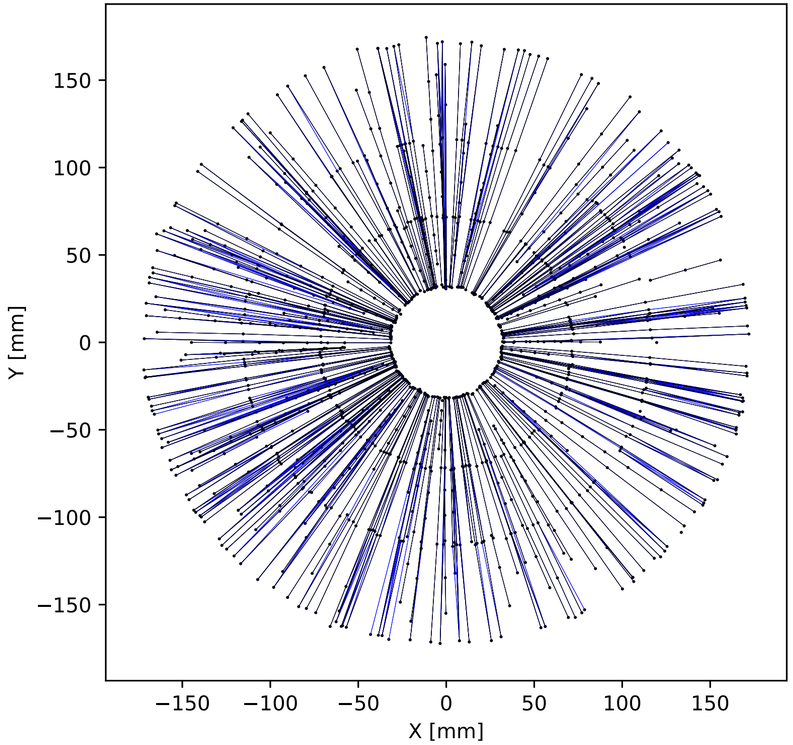
GRAPH NEURAL NETWORKS

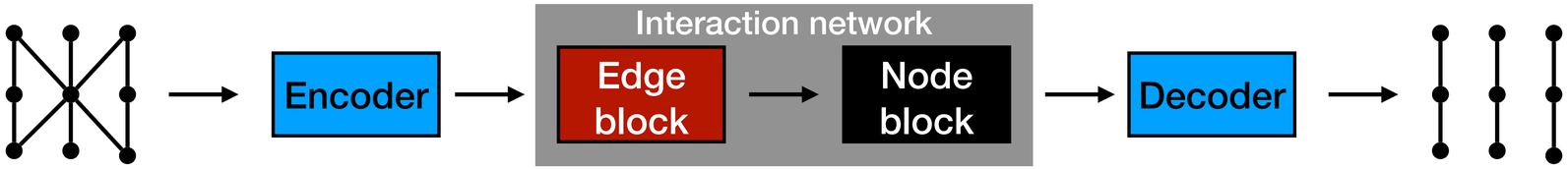


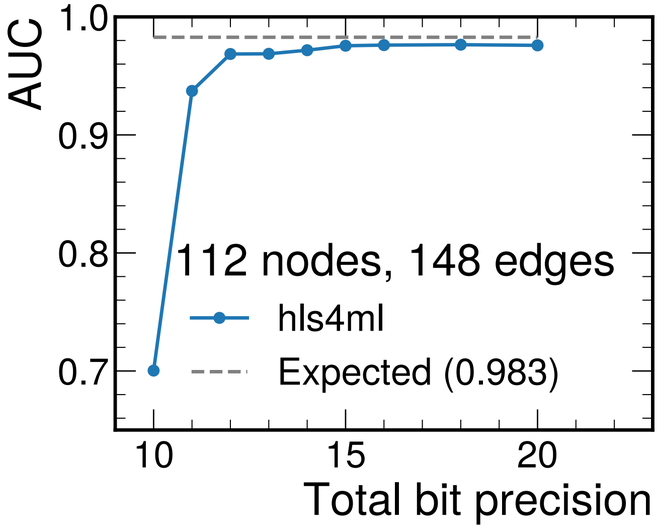
- A **graph** is a set of objects and their connections
- NN is evaluated on **pairs** of connected objects to produce a **message**
- **Messages** are communicated from nearest neighbors (and summed*) to **update** the graph's features
- Node-level, edge-level or graph-level **outputs** can be computed based on the updated hidden representations of the graph

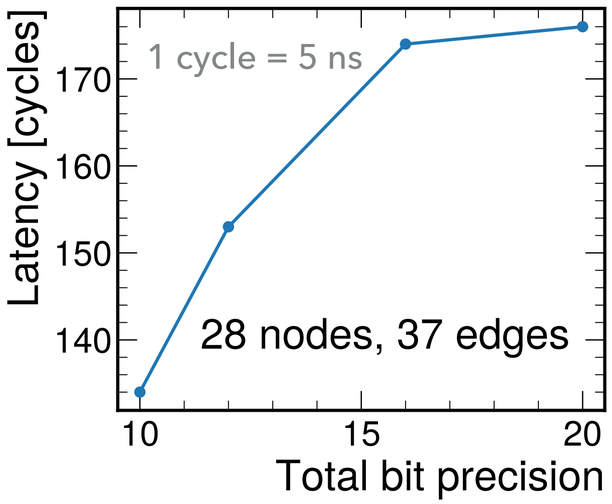
*sum preserves permutation invariance

GRAPH NEURAL NETWORKS ON FPGAS FOR PARTICLE TRACKING

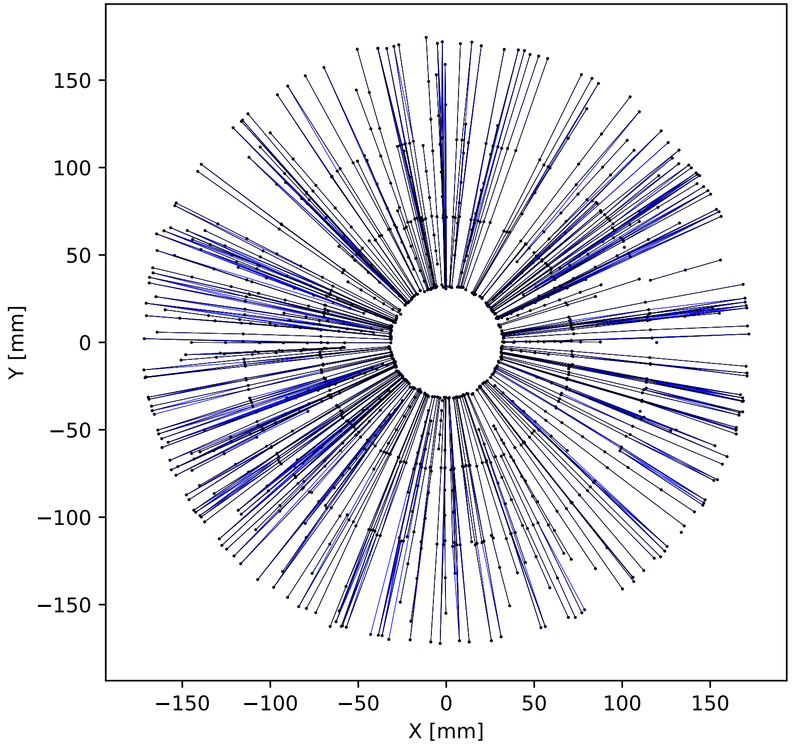


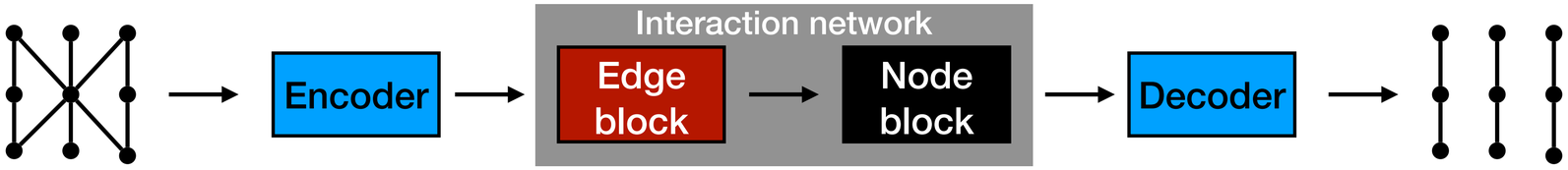


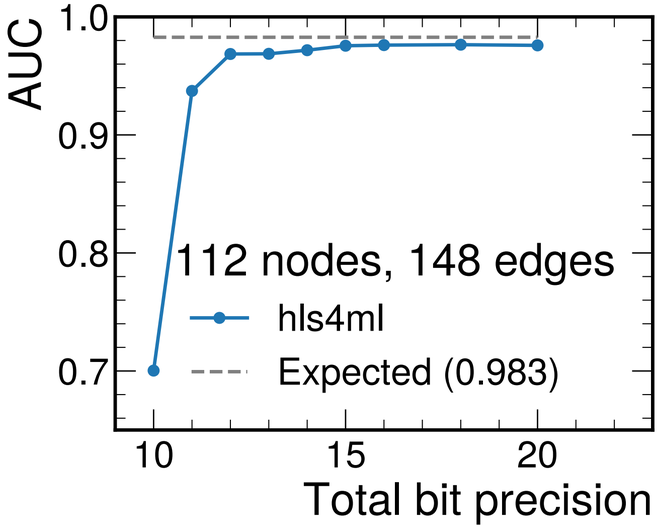


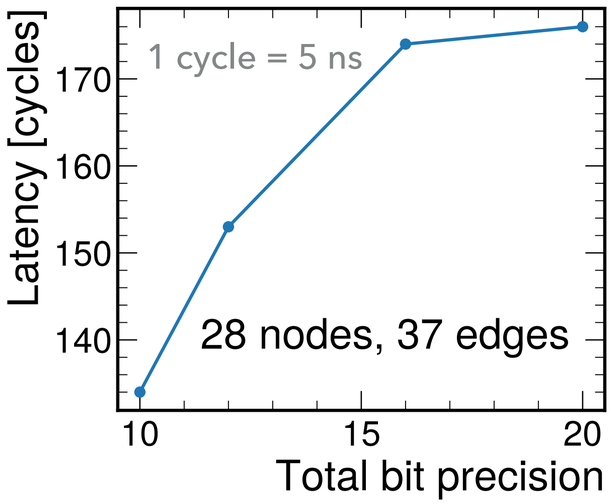


GRAPH NEURAL NETWORKS ON FPGAS FOR PARTICLE TRACKING



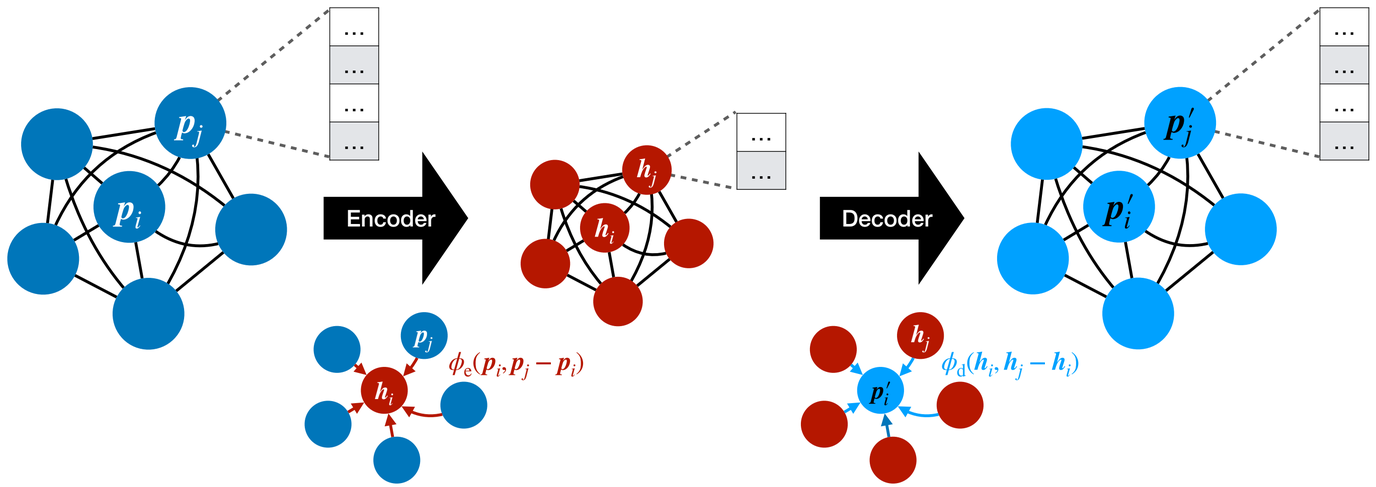


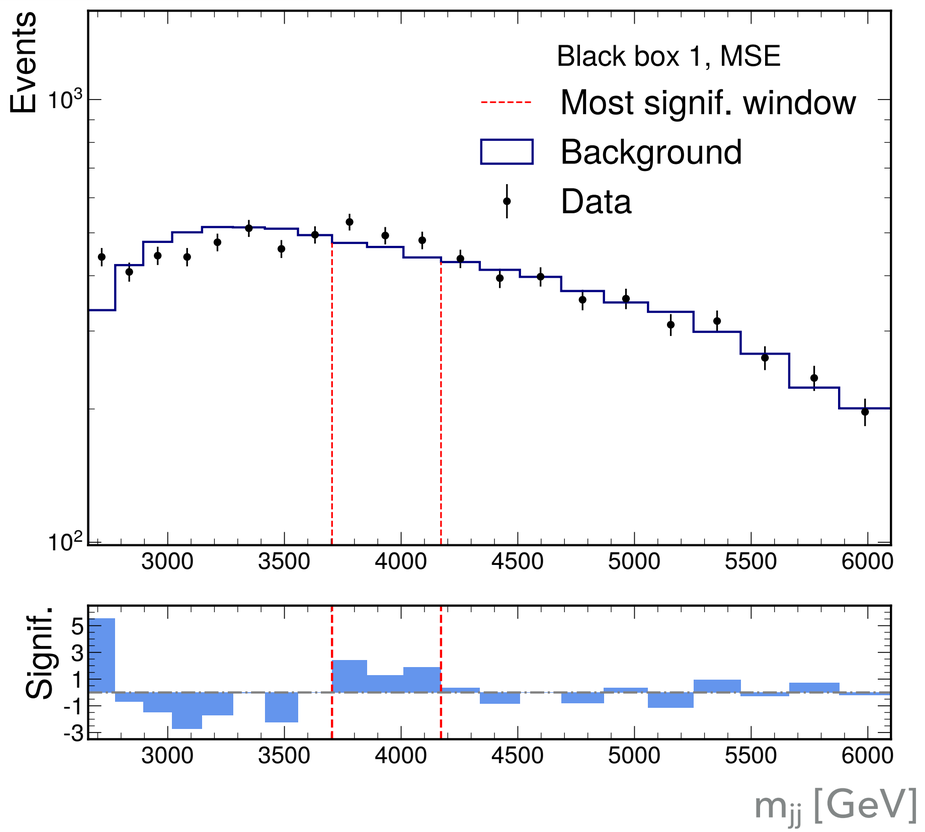




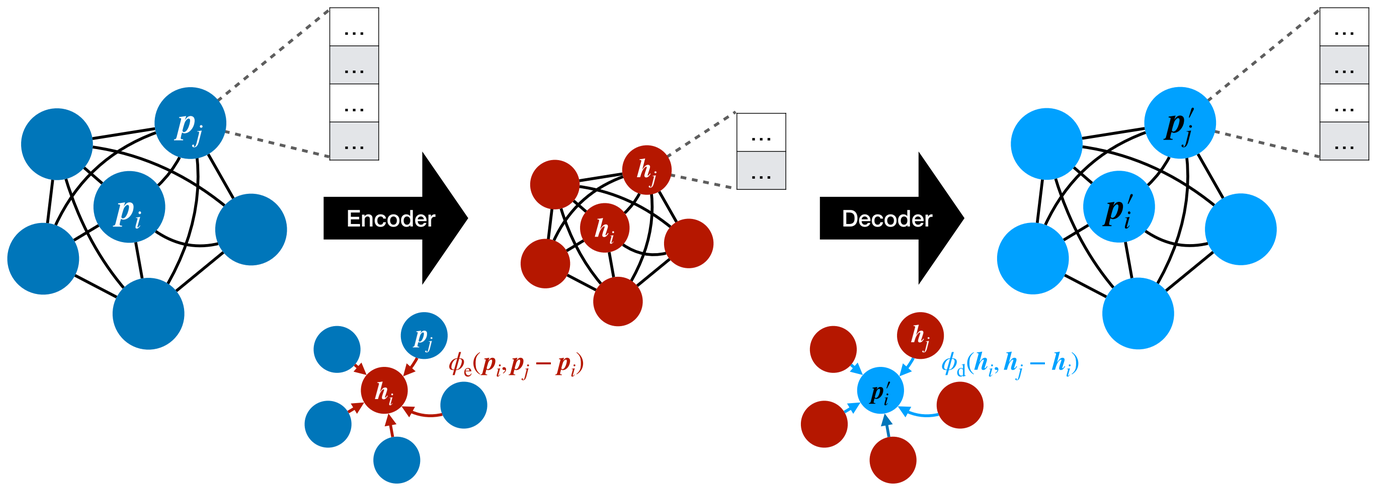
- Undergrad. summer student (IRIS-HEP fellow) project to implement a GNN on an FPGA for particle tracking
- Found it can complete a tracking task in < 1 microsecond

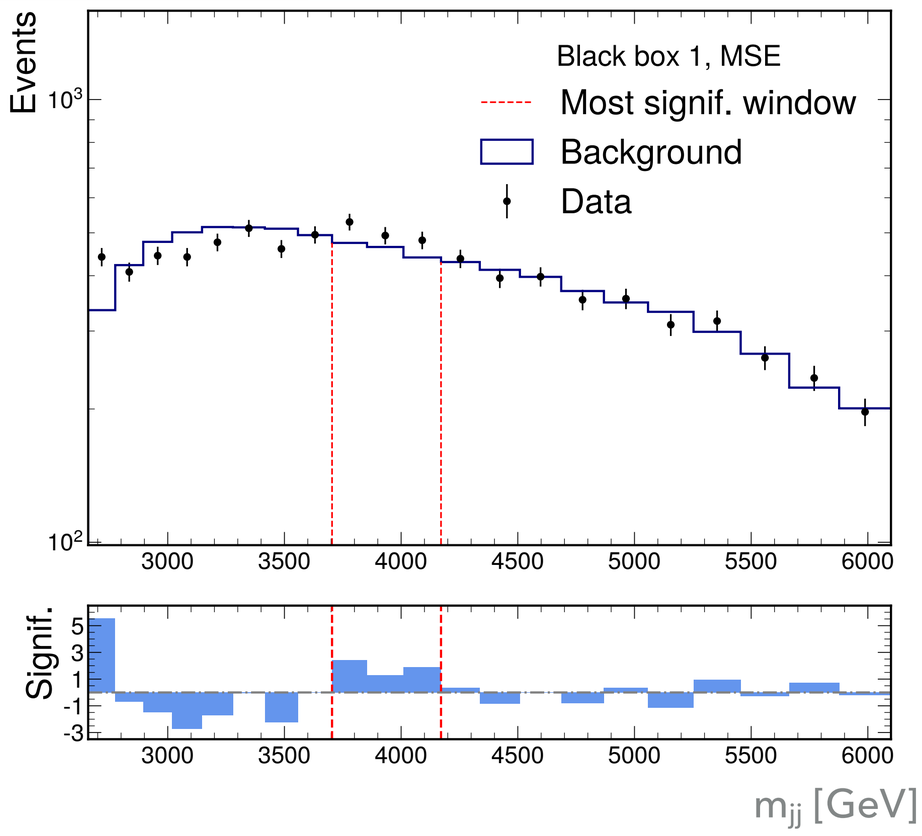
PARTICLE GRAPH AUTOENCODER FOR ANOMALY DETECTION





PARTICLE GRAPH AUTOENCODER FOR ANOMALY DETECTION



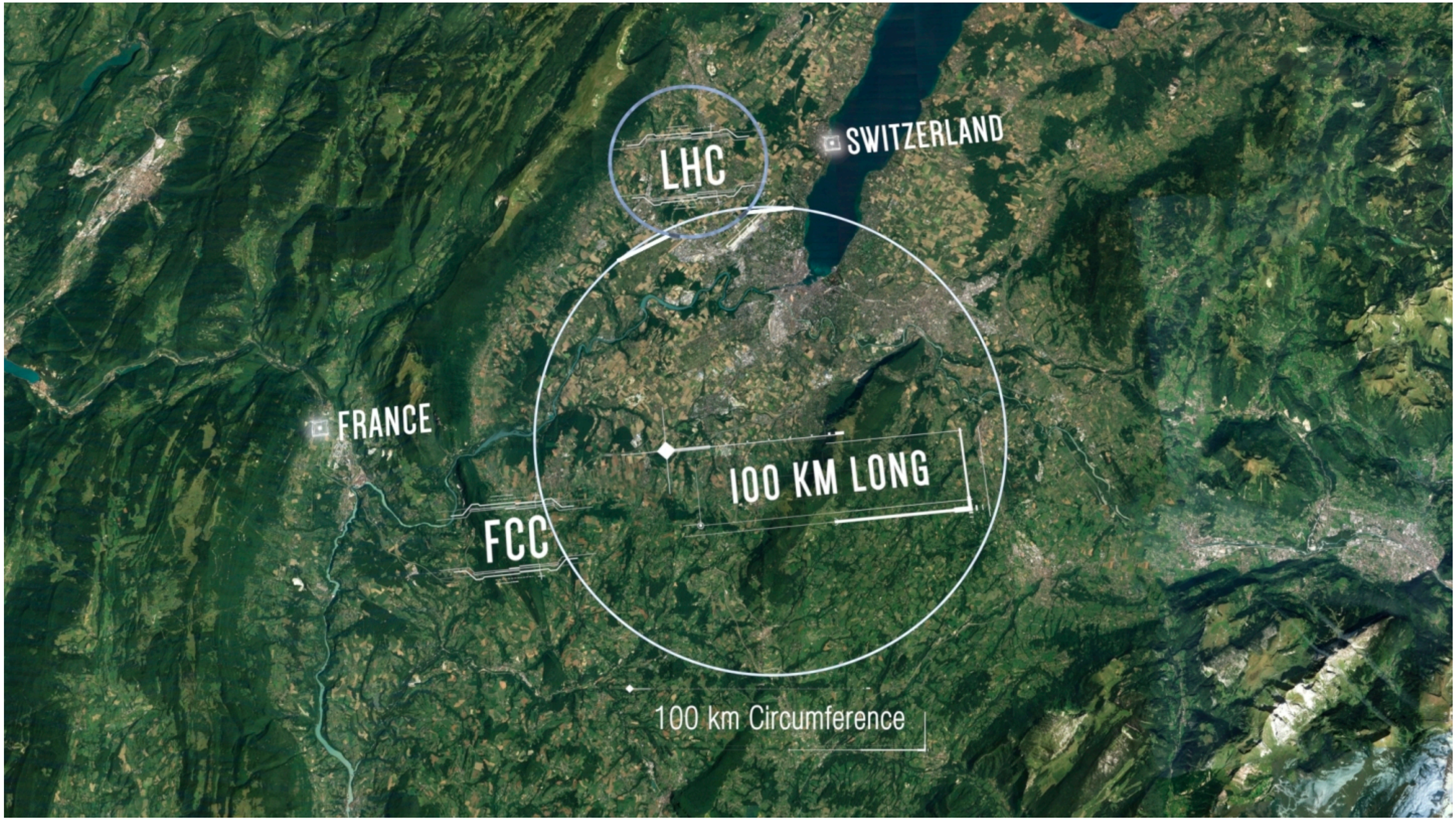


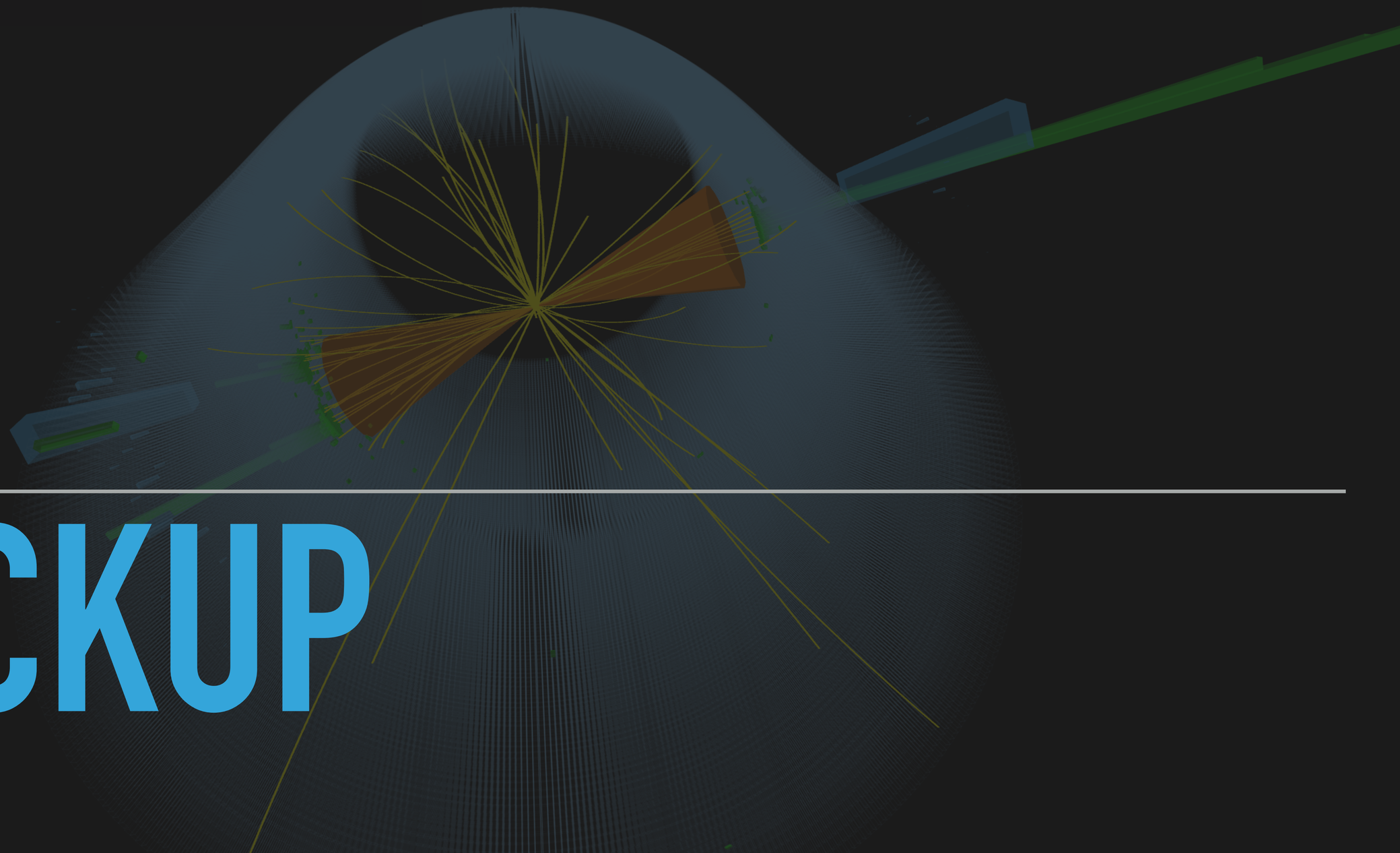
- Autoencoders compress data to a smaller representation and reconstruct it
  - Apply it to particles (E, ***p***): train autoencoder on known SM data
- Undergraduate summer student (TRELS) project found it to be effective on a mock dataset with a known signal injected at ~3800 GeV

SUMMARY

- Many interesting ML applications in particle physics!
- Intersection of two fields that is very fast paced
- If this sounds interesting to you, let me know!
  - No prior experience in ML or particle physics necessary; just a desire to learn it “on the job”

FUTURE COLLIDERS





BACKUP