Quarknet CMS Masterclass

University of Rochester, March 23, 2012

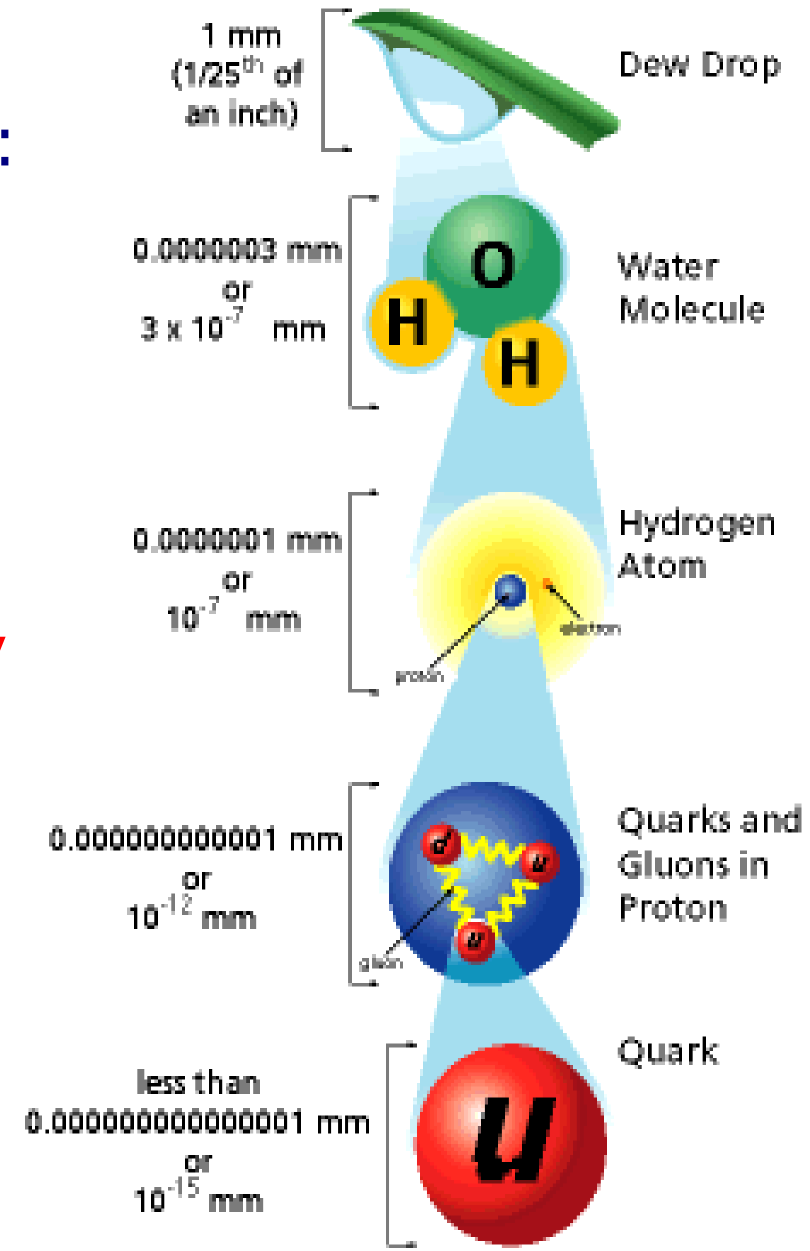
Analyzing CMS events

- Questions in Particle Physics
- Introducing the Standard Model
- The Large Hadron Collider
- The CMS detector
- W and Z bosons: decays
- iSpy event display
- Goals for today:
  - Select W and Z candidates
  - Measure W^+/W^- ratio
  - Measure e/μ ratio
  - Measure Z boson mass

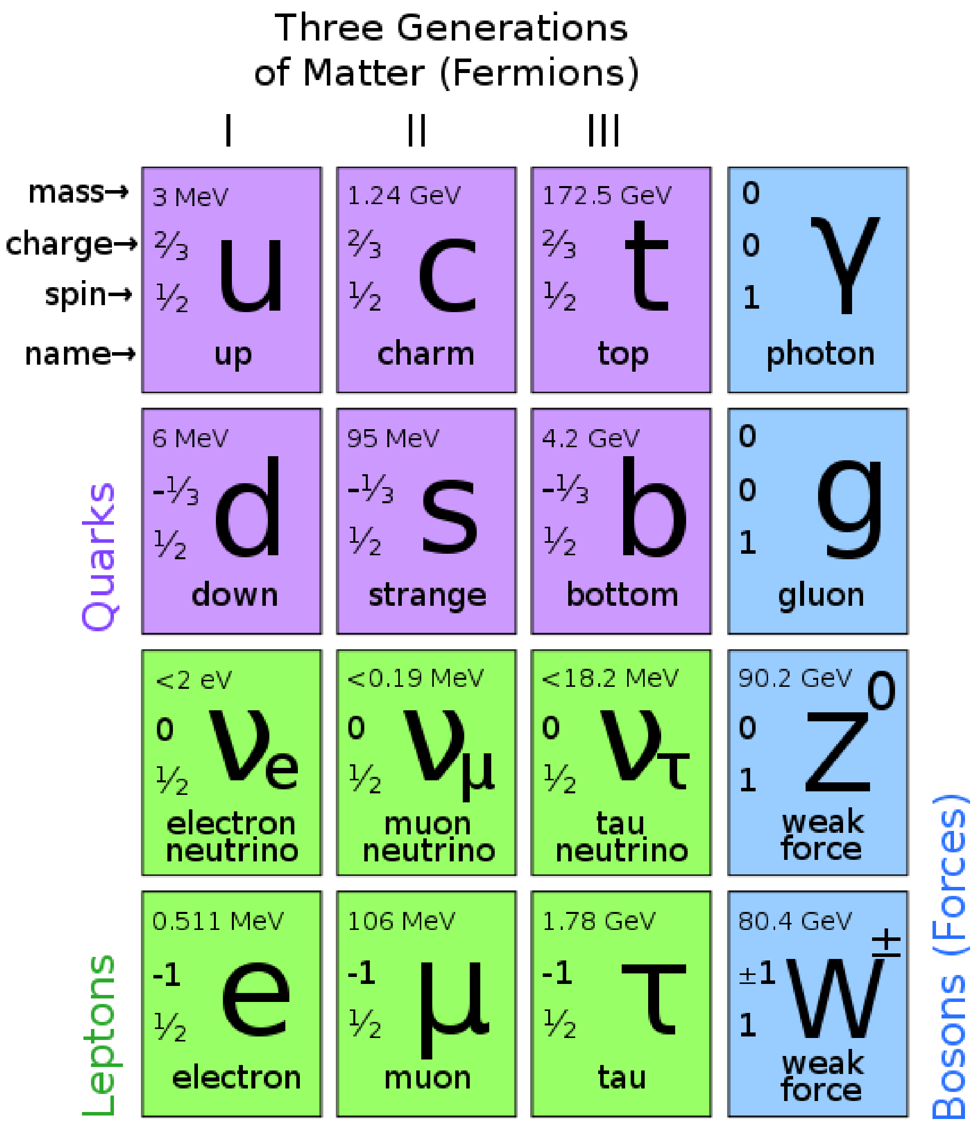
Arán García-Bellido

Particle Physics

- The quest for the nature of matter
- Questions we are trying to answer:
  - What is matter made of?
  - How do the constituents interact?
  - Are there new particles?
  - Are fundamental particles really fundamental?
  - What is the origin of mass?
  - Why is there more matter than antimatter in the Universe?
  - What is dark matter?
  - Why is gravity so weak?



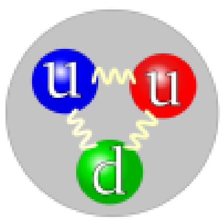
The Standard Model of Particle Physics: 3 families of matter and 4 forces



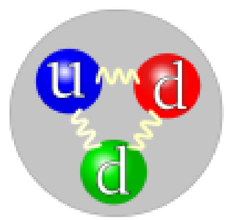
- A beautifully simple picture:
  - **12** particles make up **matter**
  - Come in three families
  - **4** particles describe **forces**
  - \+ the same number of **antiparticles**
- Describes all known matter and forces (except **gravity**!)
- Powerful predictions
- A triumph of 20th century physics
- But we still haven't found why particles have mass! **Higgs boson?**
- Many other questions...

Building a Universe

- We only need **up** and **down quarks**, together with **electrons** to build ALL the matter we see around us

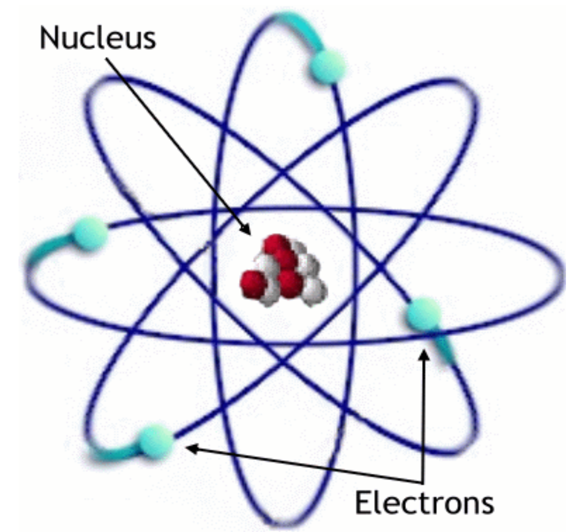


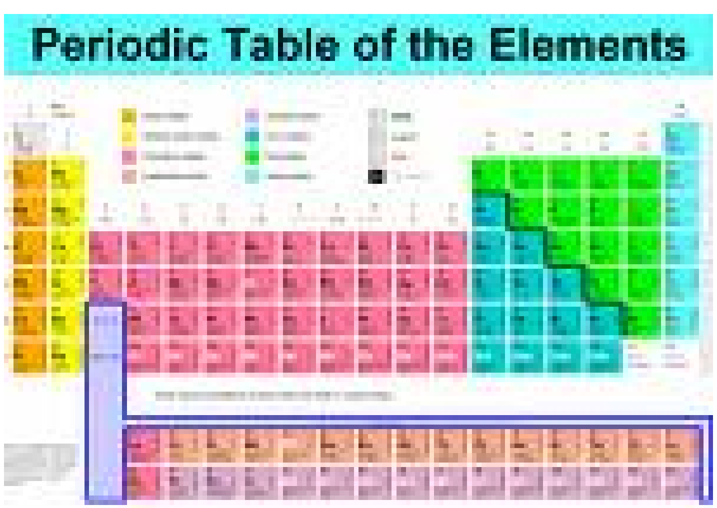
proton



neutron

electron

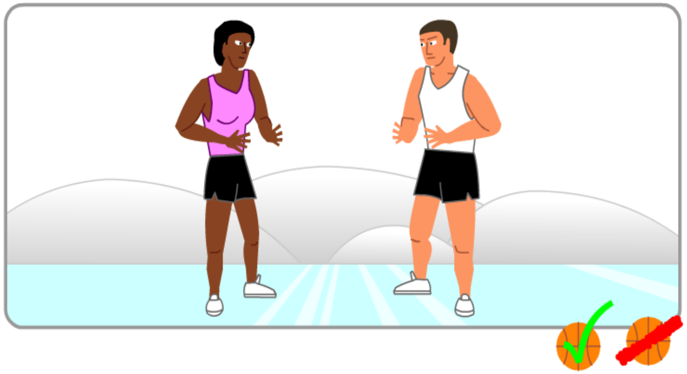




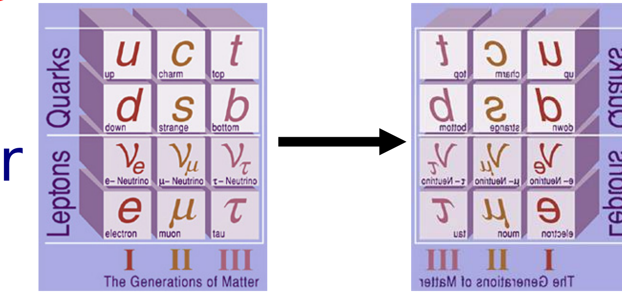
Four forces explain everything!

Force	Acts on	Carrier	Range	Strength
Gravity	mass	graviton?	Long: $1/r^2$	10^{-39}
Weak nuclear	fermions	W, Z	10^{-18} m	10^{-5}
Electromagnetism	charge	photon	Long: $1/r^2$	10^{-2}
Strong nuclear	Quarks, gluons	gluons	10^{-15} m	1

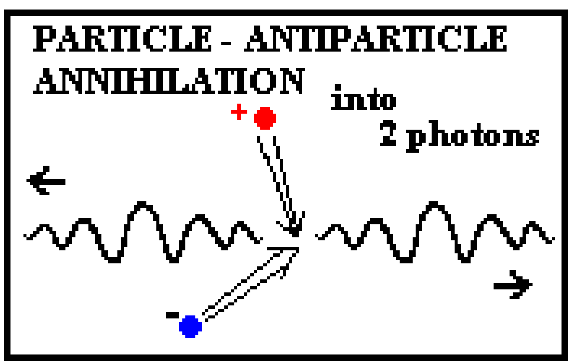
- But what is our dynamical quantum theory of the interactions?
- Theory of **force carriers**
  - All 4 forces above are "mediated" by an exchange of force carrying particles
  - Exchange of particle means interacting particles exchange momentum ➔ that's a force: $F = m\Delta v/\Delta t$

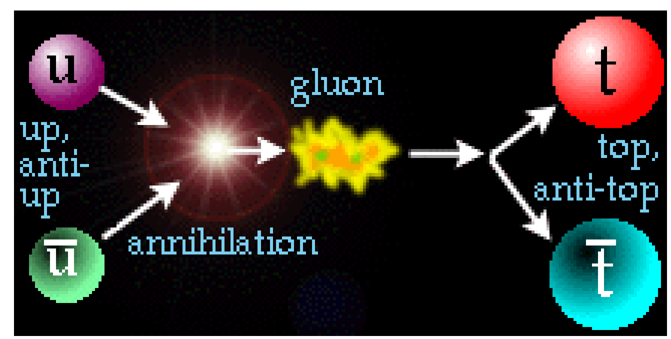


Antimatter… is really weird



- All particles have antiparticles!
- Antimatter has the same properties as matter
  - Same mass, same spin, same interactions
  - But opposite electric charge
- Has another weird property…
  - It can annihilate with matter to create pure energy!
  - Or, conversely, energy can create matter and antimatter pairs. $E=mc^2$



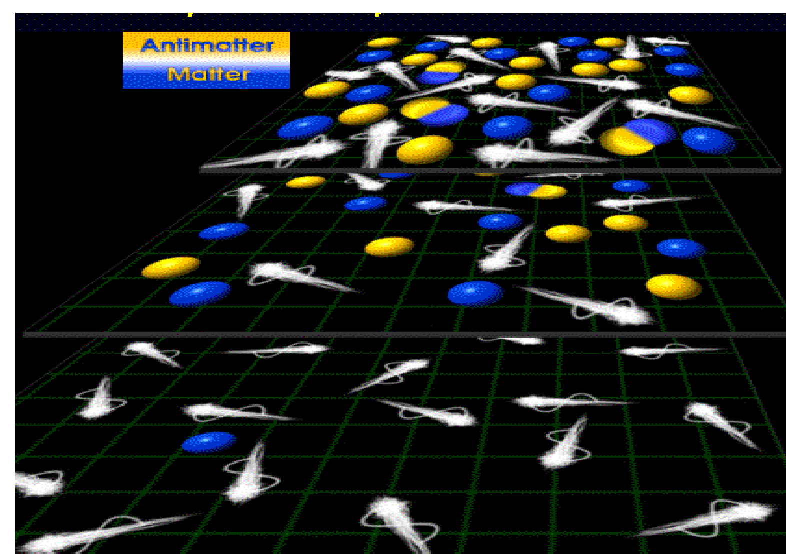


- So you might ask: The Universe was born with the same amount of matter as antimatter…. where is all the antimatter?

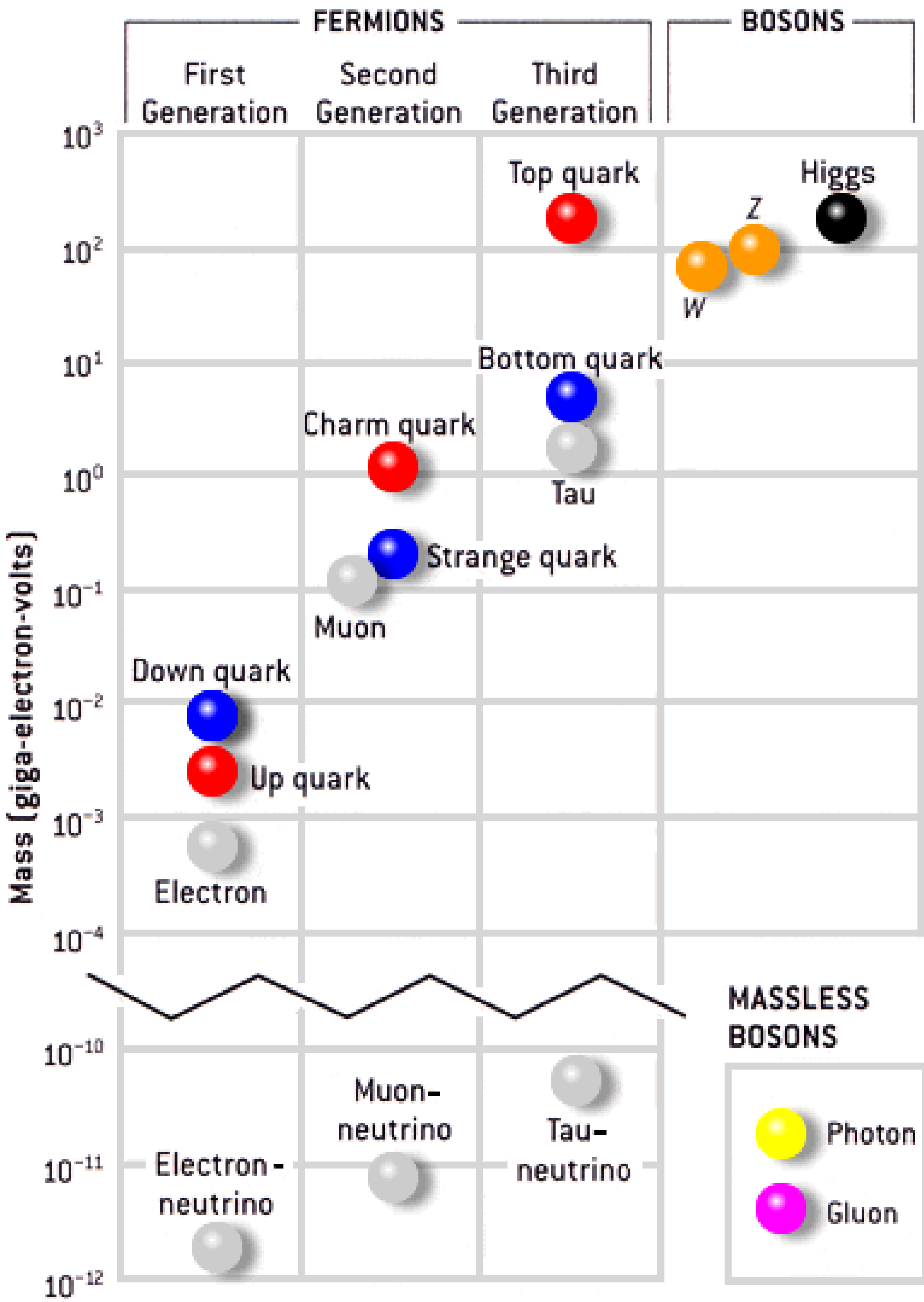
Why is the Universe made of matter?

- Good question: if the Universe started with same amount of matter and antimatter, where is the antimatter?
  - Look for annihilations of stars and antimatter stars
  - As far away as we can tell, today there aren’t big matter and antimatter collisions

- We don't know why this is true yet!
- Active field of research
- There must be a basic matter-antimatter asymmetry in one of the forces of Nature

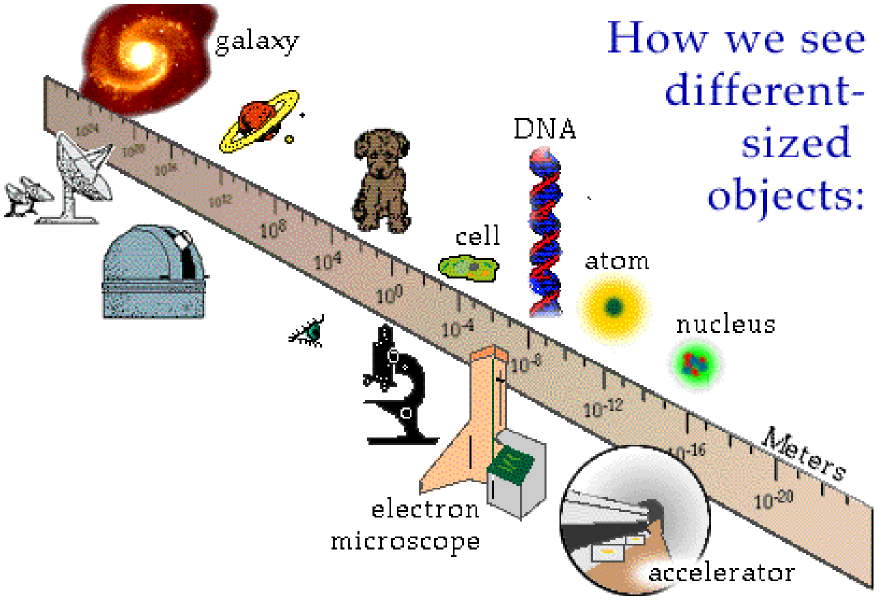


The Standard Model under attack



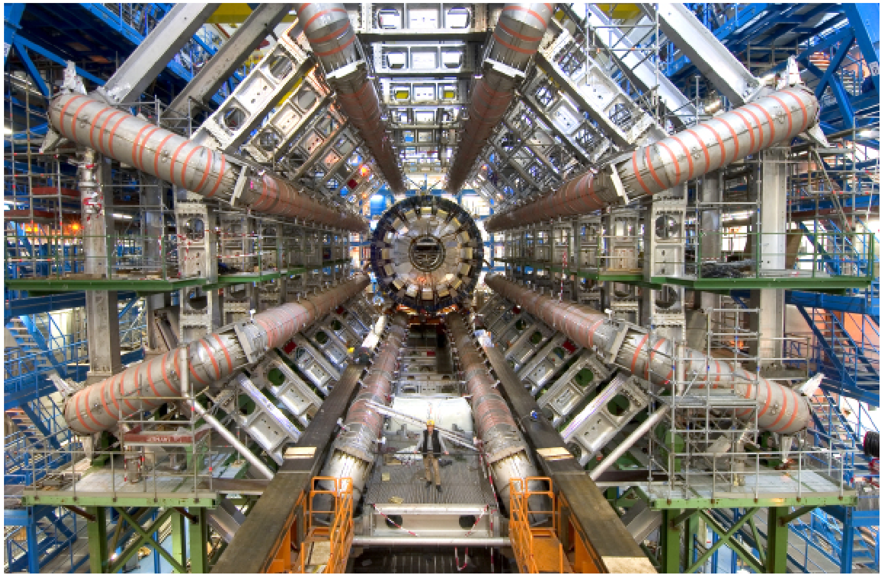
- The SM is a fantastic success: not a single break over many years of extremely precise measurements
- But recently: Neutrino masses, dark matter
- So we know it is not a complete description of Nature
- Many unanswered questions:
  - Why three generations?
  - Is the Higgs mechanism actually responsible for the particles' masses?
  - Why that hierarchy of masses?
  - What's with so many free parameters?
  - Gravity is not in the picture
  - Unification of three couplings is not possible

Particle Physics experiments require



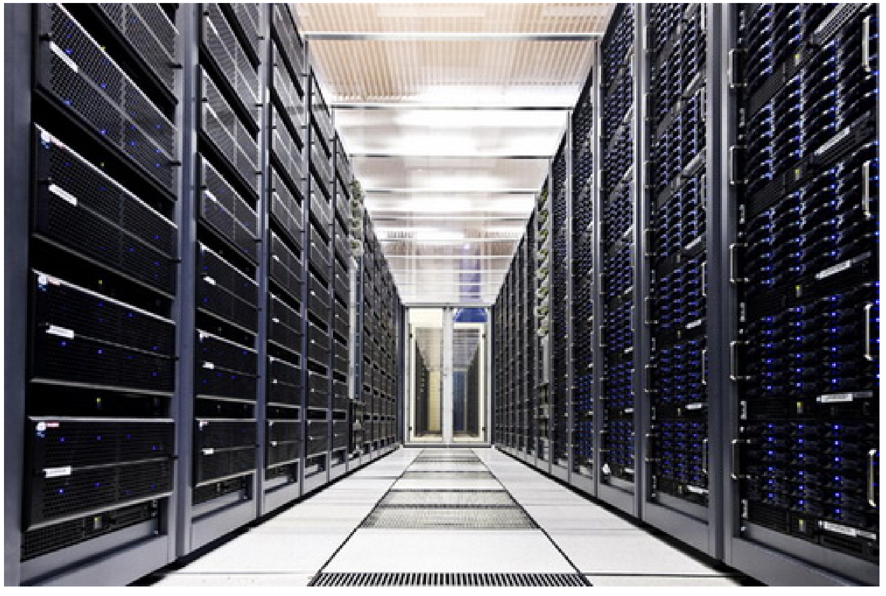
- **Accelerators**: powerful machines to accelerate particles to extremely high energies and bring them into collision

Particle Physics experiments require



- **Accelerators**: powerful machines to accelerate particles to extremely high energies and bring them into collision
- **Detectors**: gigantic instruments that record the particles that come out of the collision

Particle Physics experiments require



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- **Computing grids**: to collect, store, distribute and analyze the vast amount of data produced by the detectors

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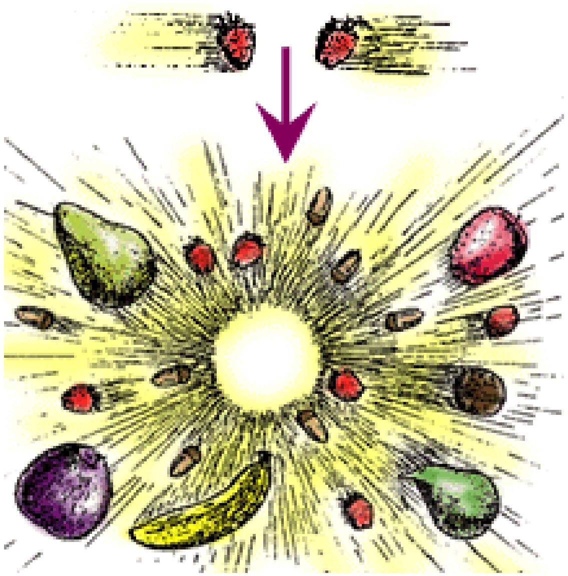
- **Accelerators**: powerful machines to accelerate particles to extremely high energies and bring them into collision
- **Detectors**: gigantic instruments that record the particles that come out of the collision
- **Computing grids**: to collect, store, distribute and analyze the vast amount of data produced by the detectors
- **People**: worldwide collaboration of scientists, engineers, technicians and support staff to design, build and operate such complex instruments

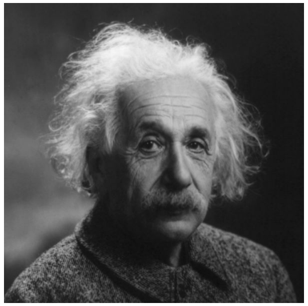
WELCOME TO THE LHC

PROTONS → ENERGY → NEW PARTICLES

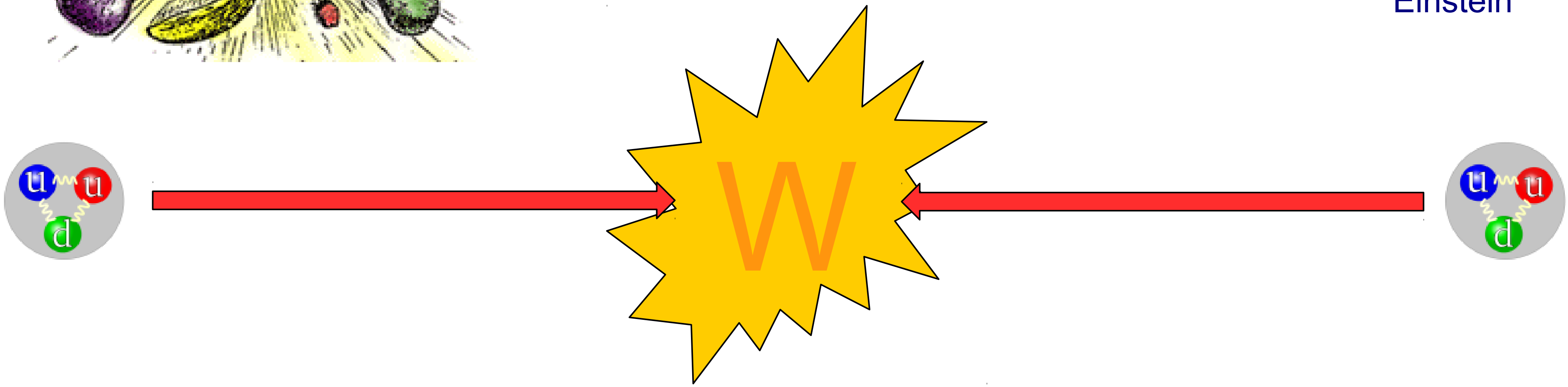
- Convert the energy given to accelerated protons to create new, heavy particles



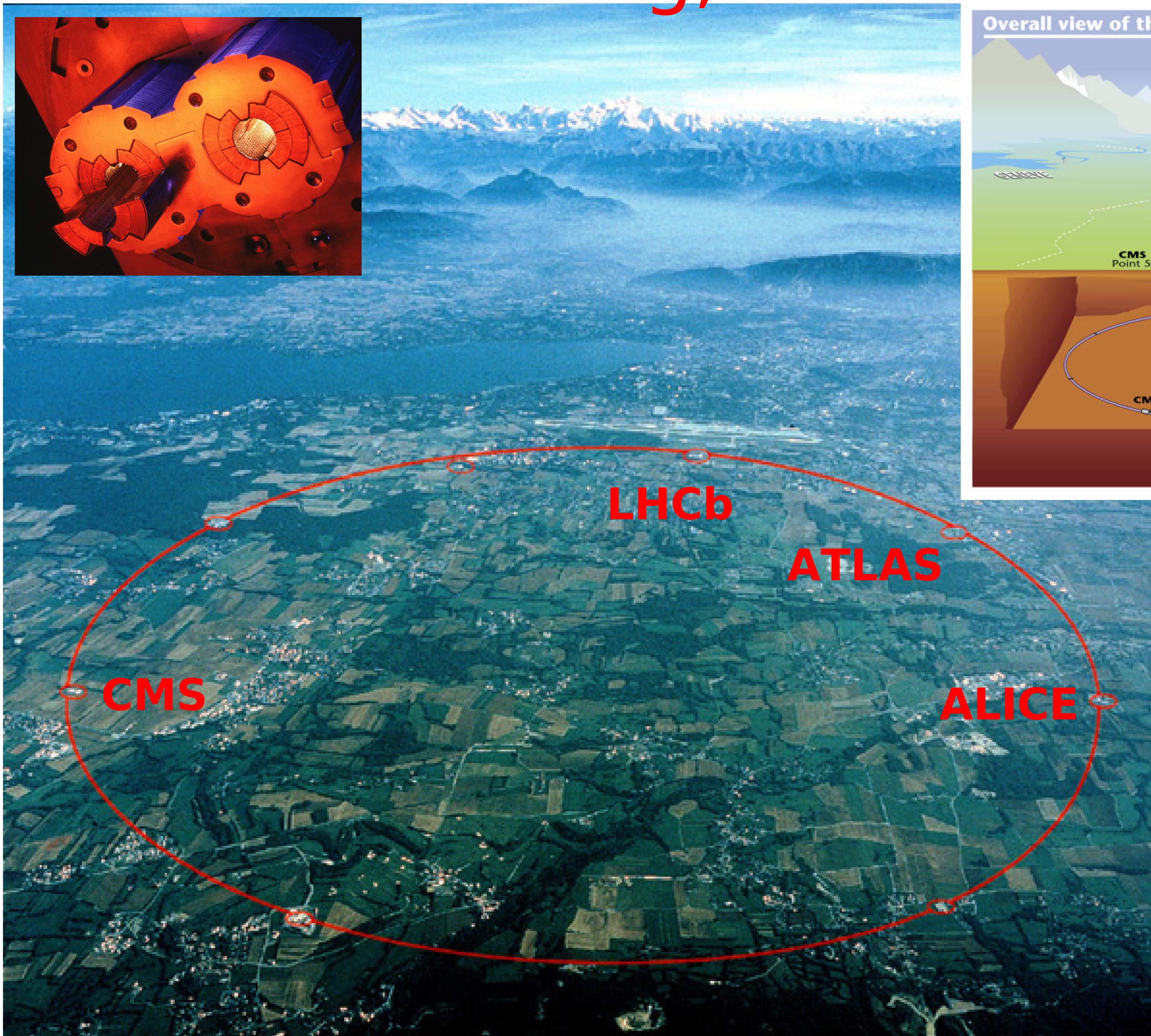
$$E=mc^2$$

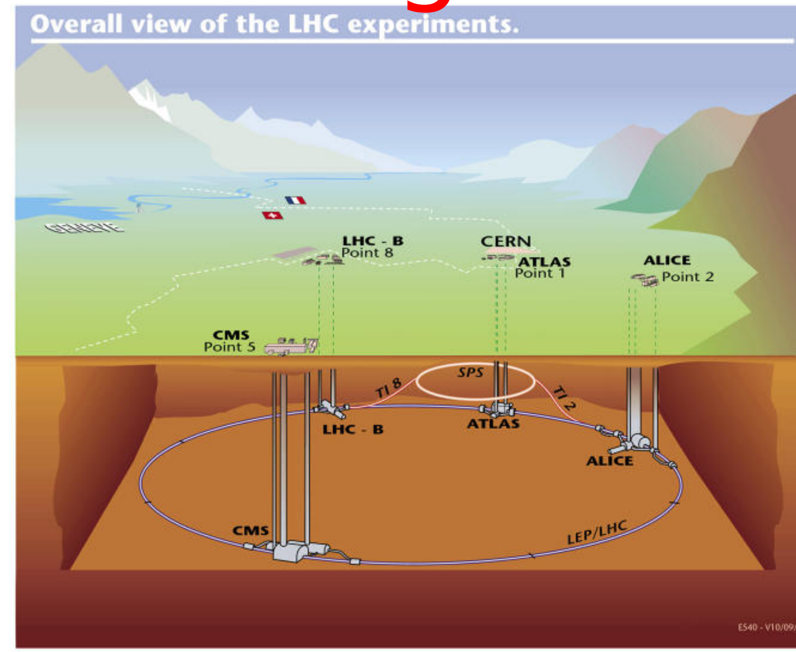


Einstein



LHC: 27 km long, 100 m underground





- Collides two beams of protons (3.5 TeV each)
- 9300 magnets
- 1.9 K
- 10^{-13} atm
- 4 detectors

Trillions of protons travel the 16.5-mile-long tunnel

- Only $2 \cdot 10^{-9}$ grams of Hydrogen consumed each day
- Protons are accelerated by powerful electric fields
- Using a chain of accelerators, protons go from 1 GeV at rest to 3500 GeV
- Like taking a 100 kg person and accelerating them until they weigh 350 ton

(That's 0.999999991c)

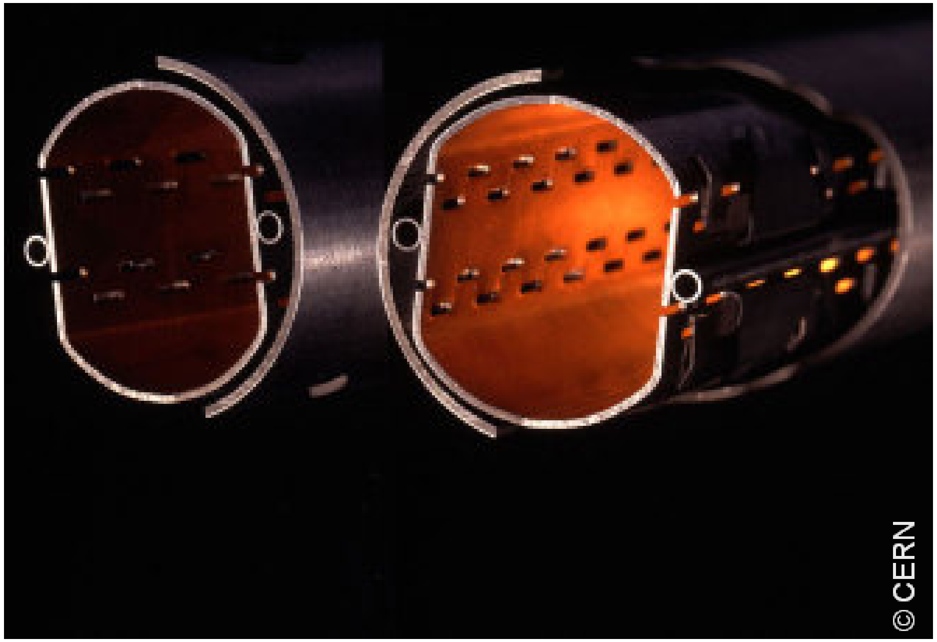
11,000 times a second

(that's 670,626,025 mph)

Particles travel in vacuum at 10^{-13} atm

- The beampipes are evacuated to allow protons to travel freely

More atmosphere on the moon than in the LHC



16.5 mi of ultra cold

- Protons are guided around their circular orbits by powerful superconducting magnets operating at 1.9°K = -456°F

Colder than the vacuum of outer space

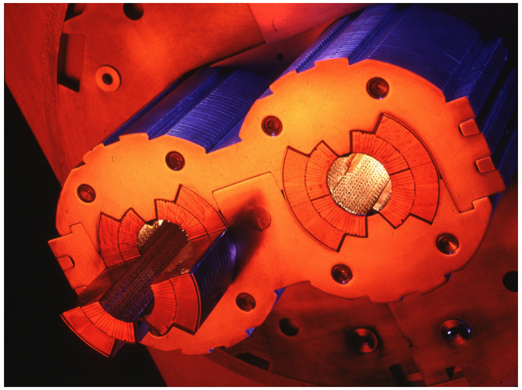
LHC by the numbers

LHC	Everyday life
362 MJ Energy stored by all protons in LHC	361 MJ USS Ronald Reagan at 5.6 knots
43,000 tons LHC magnets combined weight	88,000 tons USS Ronald Reagan weight
$4.4bn cost of building the LHC	$4.5bn cost of the USS Ronald Reagan
8.3 T Magnetic field in one magnet	$5 \cdot 10^{-5}$ T Earth's magnetic field
120 MW CERN's power consumption	1000 MW Typical breeder reactor power

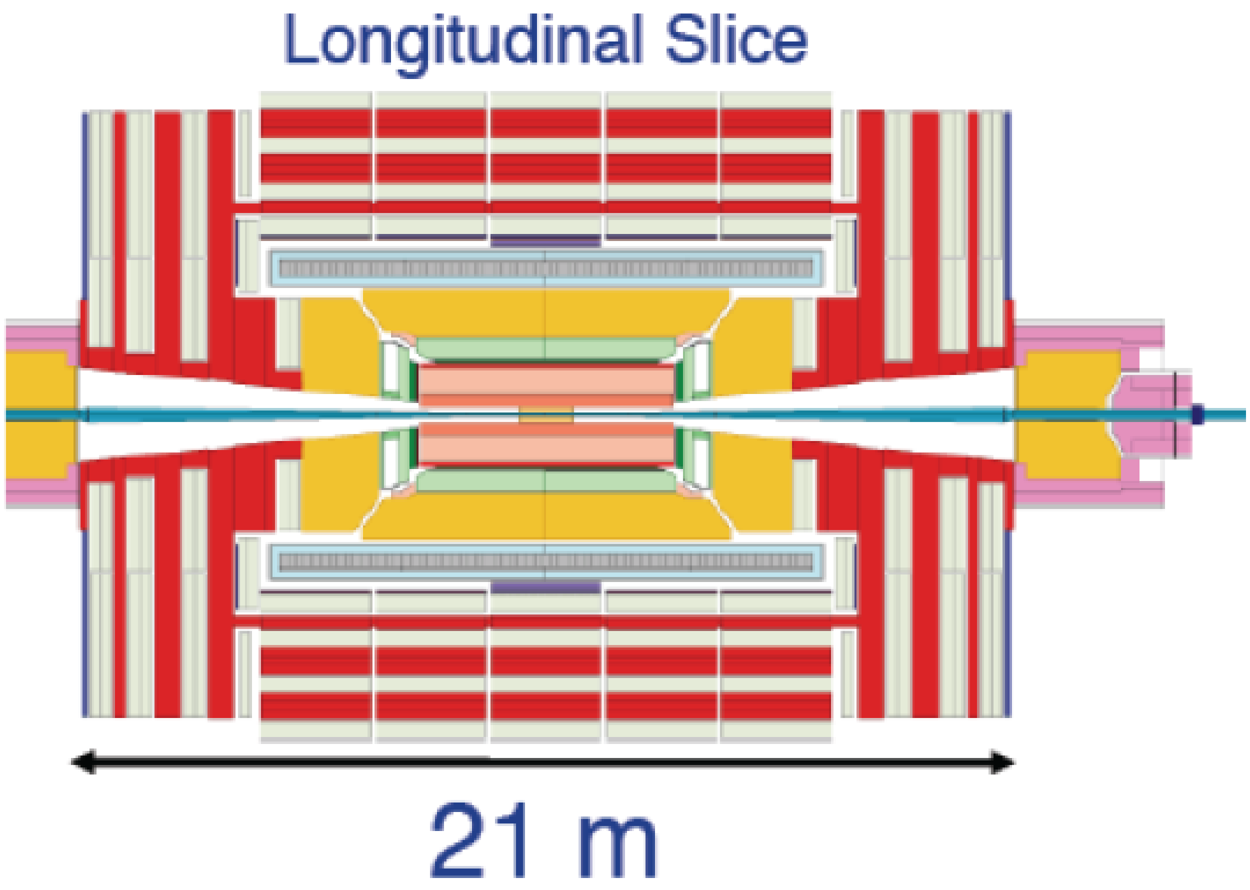

USS Ronald Reagan

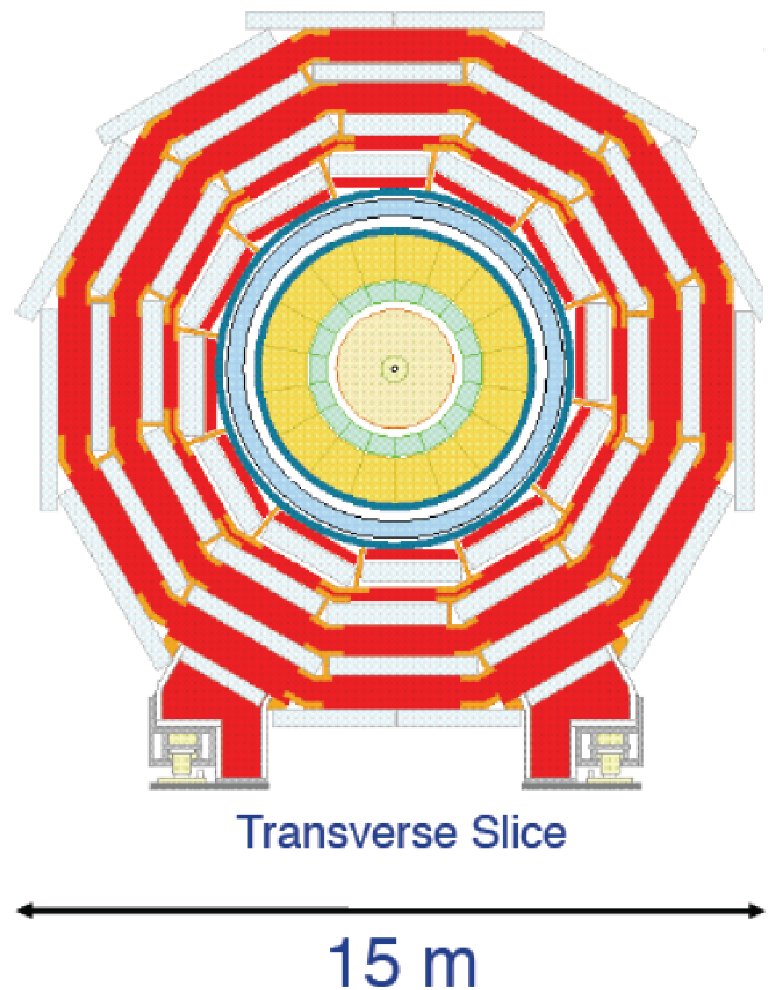

15 m long magnet being lowered into the tunnel

Dipole magnet with the two beampipes

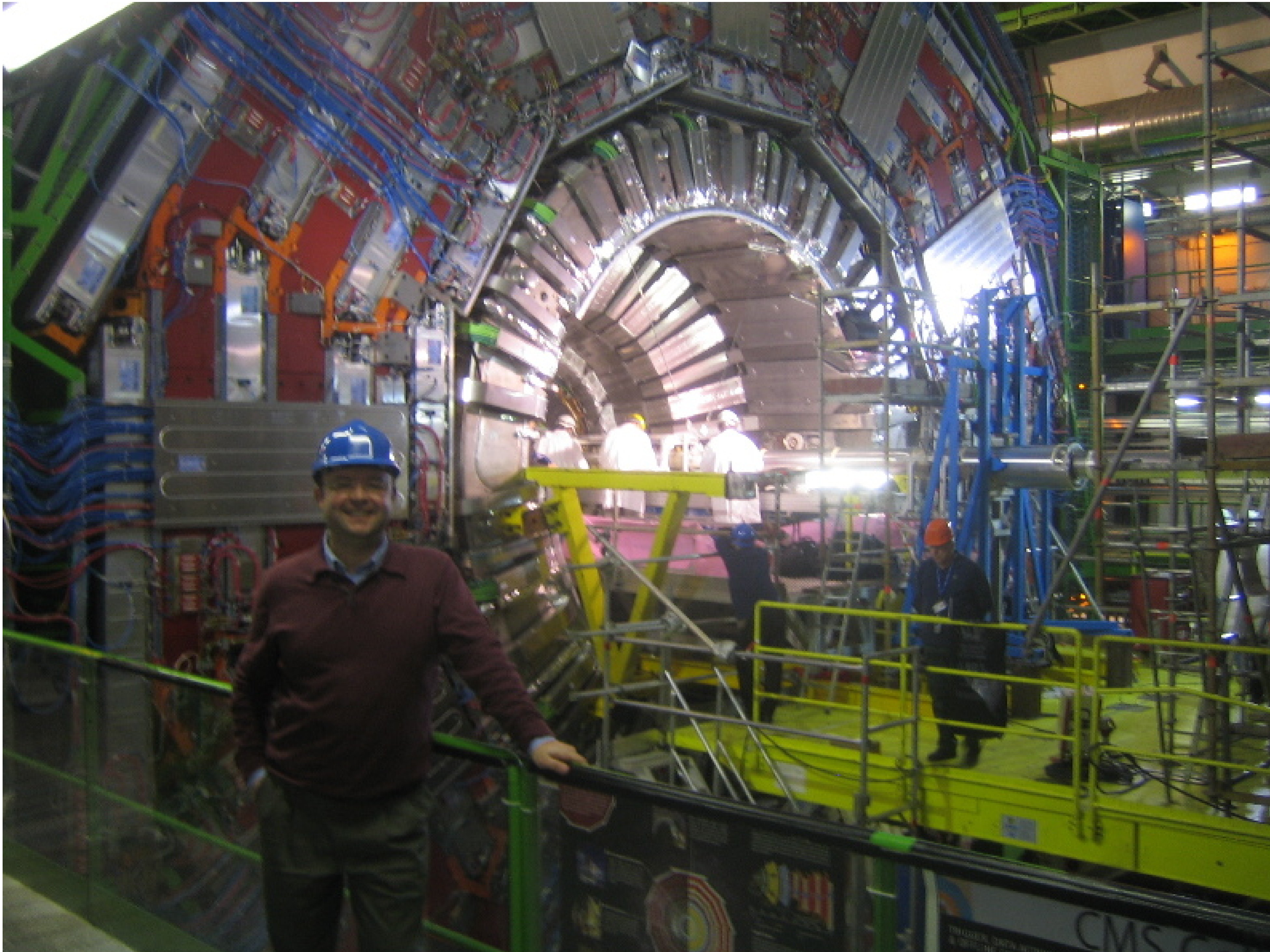


CMS detector





- 14000 tonnes
- ~80 million readout channels
- Taking data with 92% efficiency

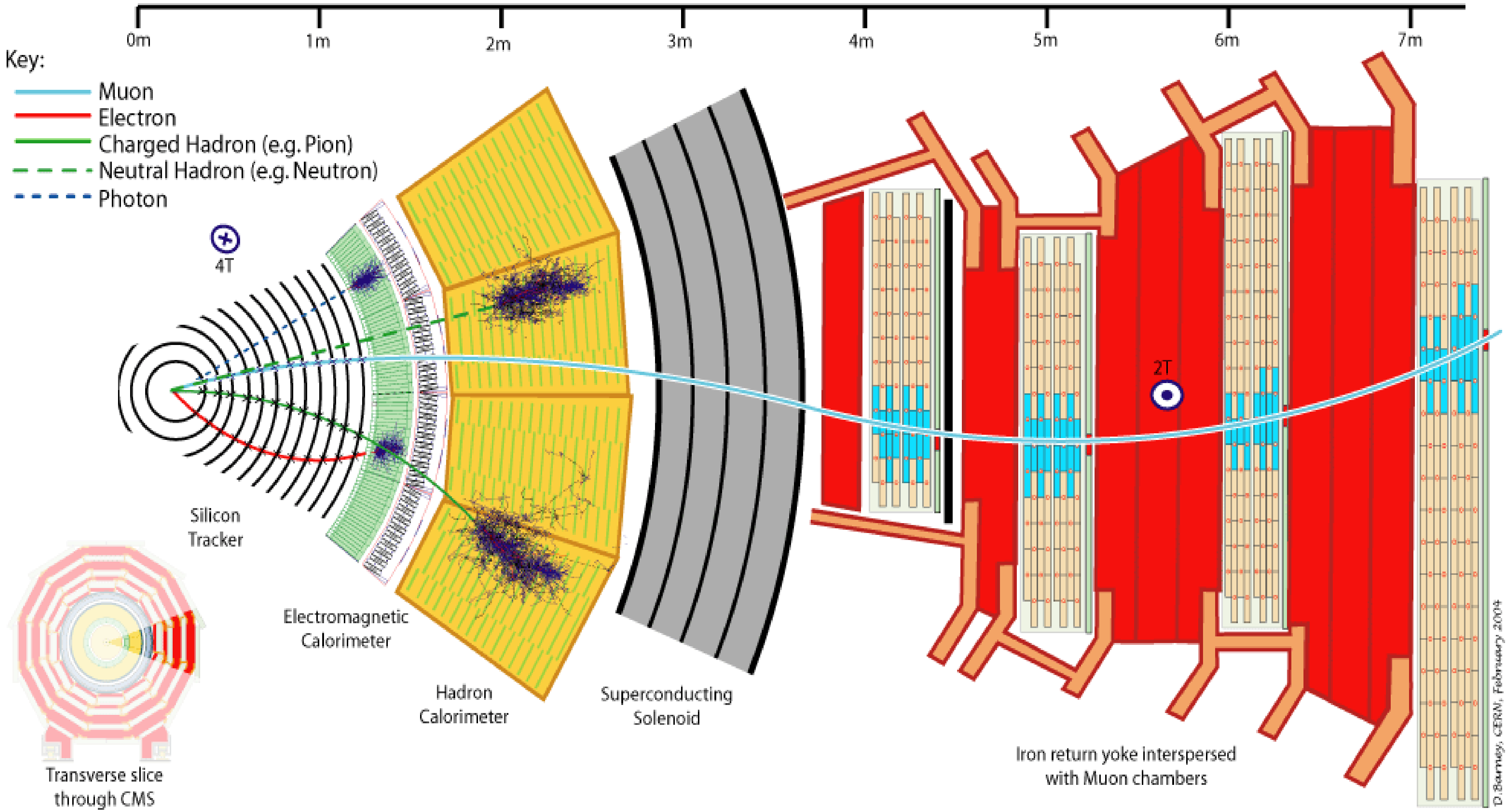


CMS solenoid magnet

Magnetic length	12.5 m
Free bore diameter	6 m
Central B Field	4 T
Weight	12,000 ton
Temperature	4.2° K
Nominal current	20 kA
Radial Pressure	64 atm
Stored energy	*2.7 GJ*

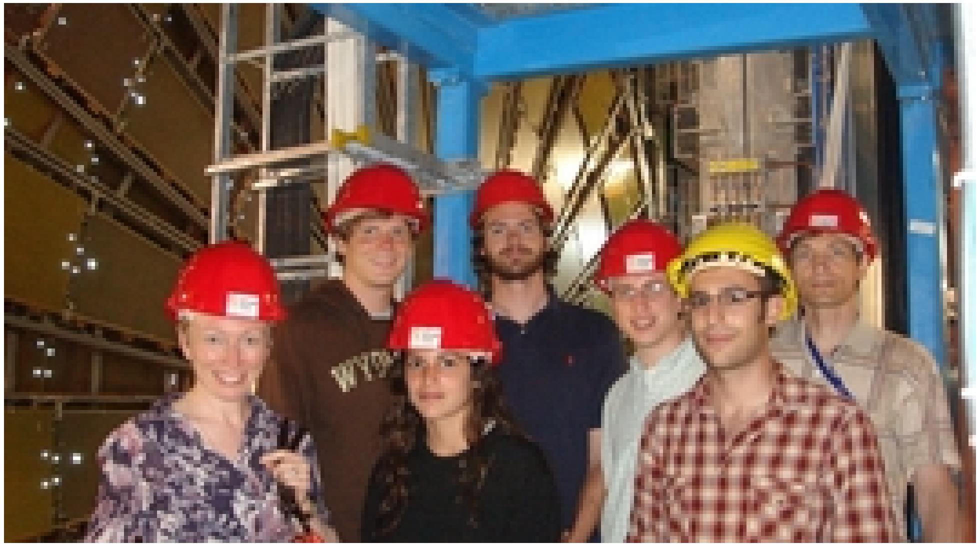
USS Ronald Reagan (88,000 tons) at 20 mph

Particle detection in CMS

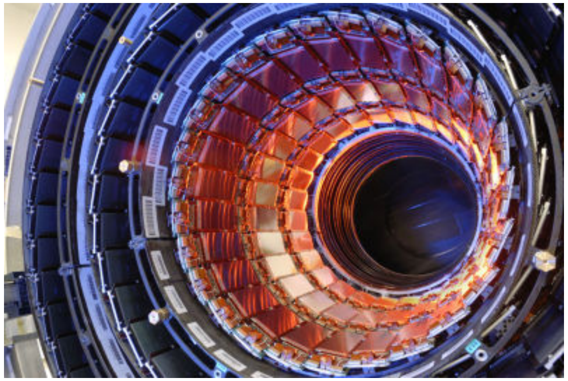


https://cms-docdb.cern.ch/cgi-bin/PublicEPPOGDocDB/RetrieveFile?docid=97&version=1&filename=CMS_Slice_elab.swf

UR contributions to CMS



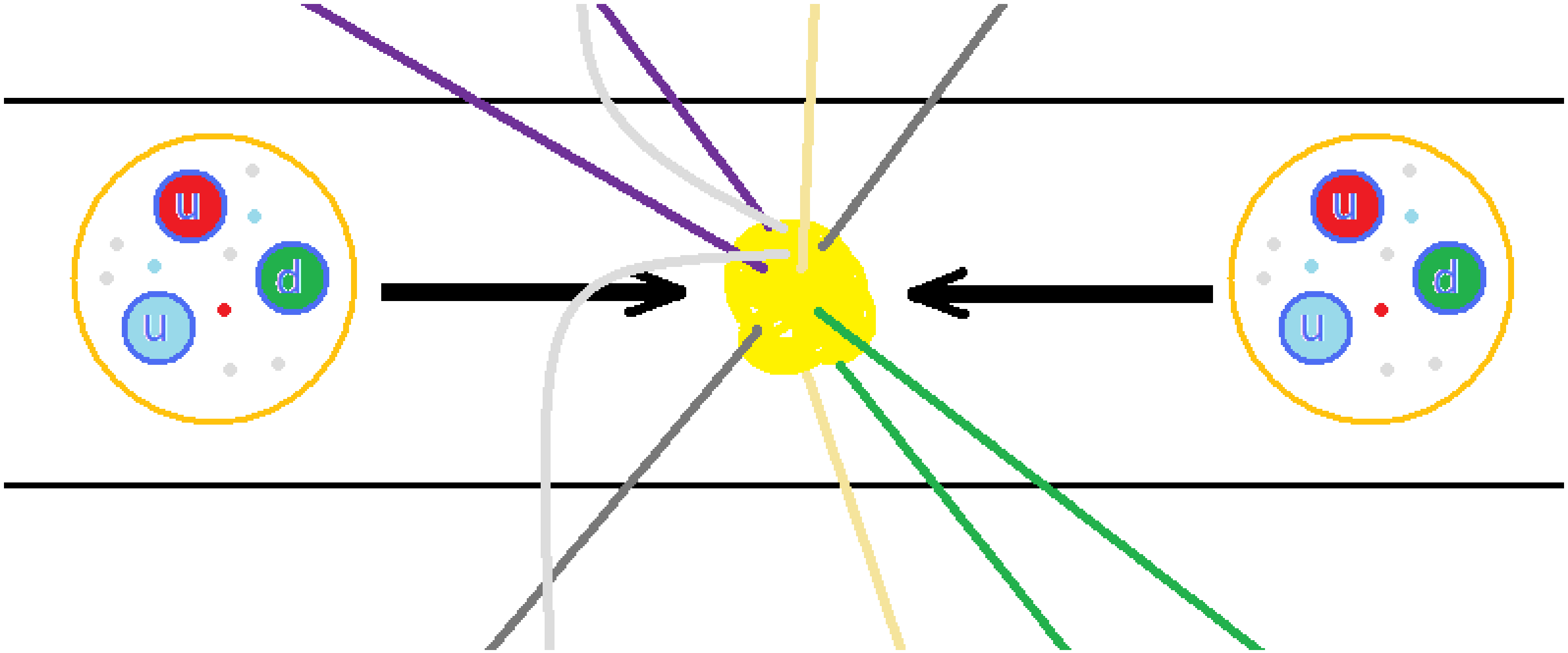
- 4 faculty, 4 senior scientists, 2 engineers, 5 postdocs, 4 grad
- **Hadronic calorimeter**: design, construction, commissioning
  - 70,000 plastic scintillator tiles
- **Silicon detector**: prototyped, tested, and commissioned Si modules
  - 200 square meters of Si (100 kg)



Energy and particle mass

If each beam proton has energy 3.5 TeV...

- The total collision energy is 2 x 3.5 TeV = 7 TeV
- But each particle inside a proton shares only a small portion of the 3.5 TeV
- So a newly created particle's mass ***must be*** smaller than the total energy

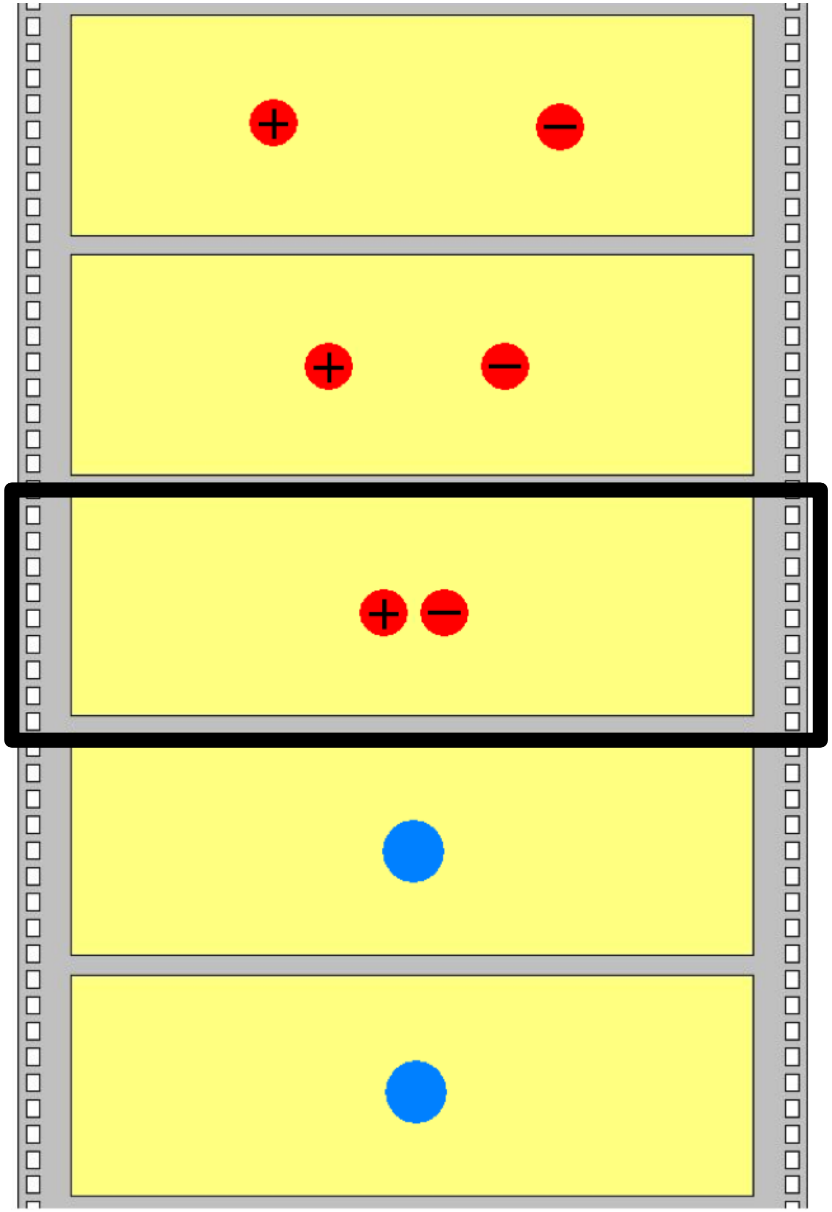


Particle decays

The collisions create new particles that promptly decay. Decaying particles *always* produce lighter particles.

Conservation laws allow us to see patterns in the decays.

Try to name some of these conservation laws.

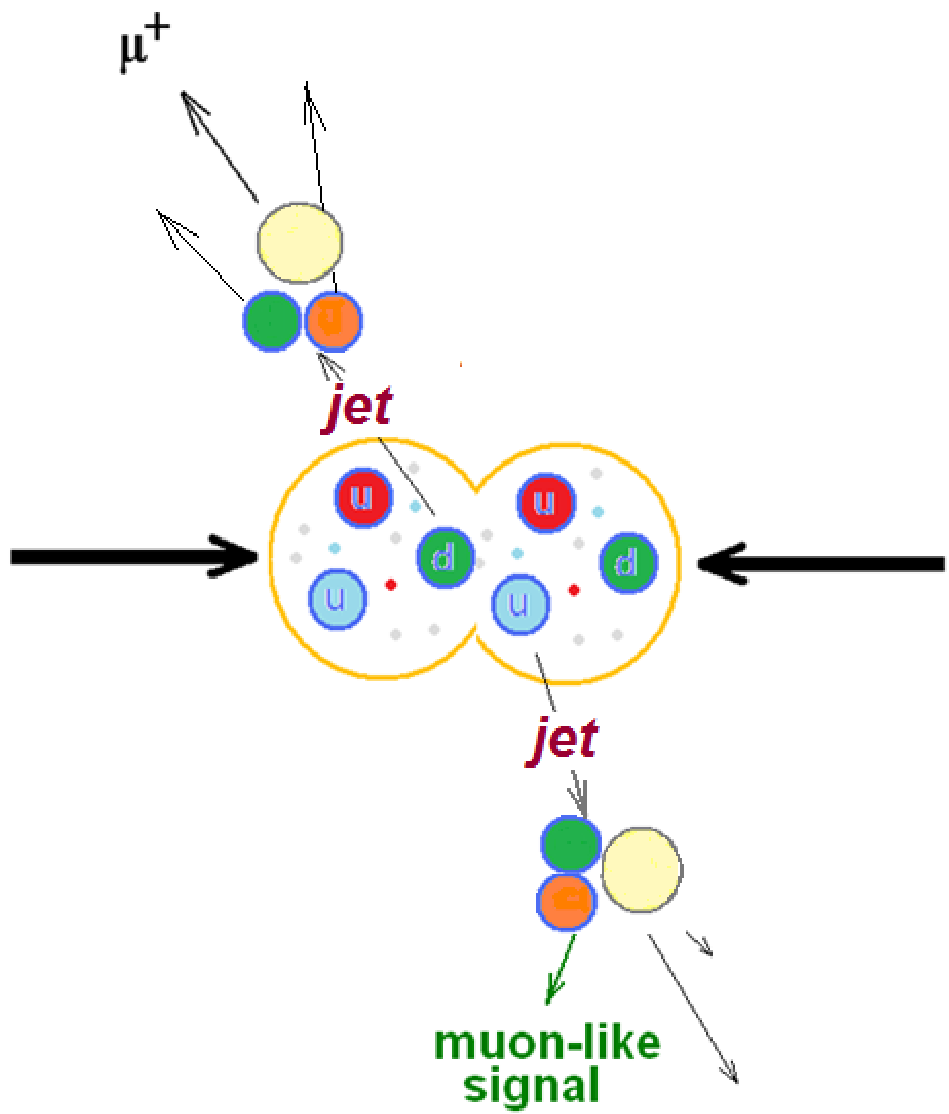


Background events

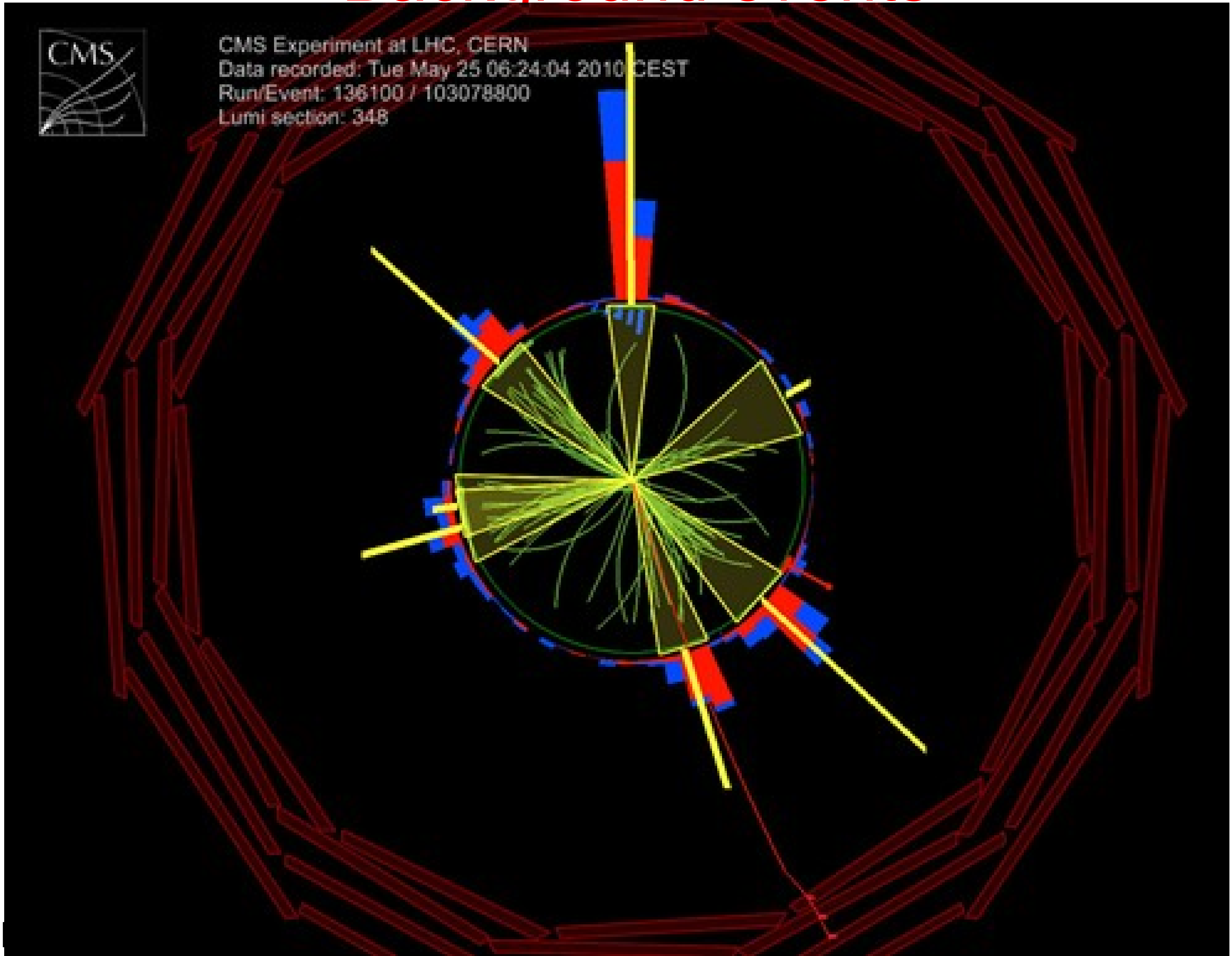
Quarks are scattered by proton collisions.

As they separate, the binding energy between them converts to sprays of new particles called ***jets.*** Electrons and muons may be included in jets.

Software can filter out events with jets beyond our current interest.



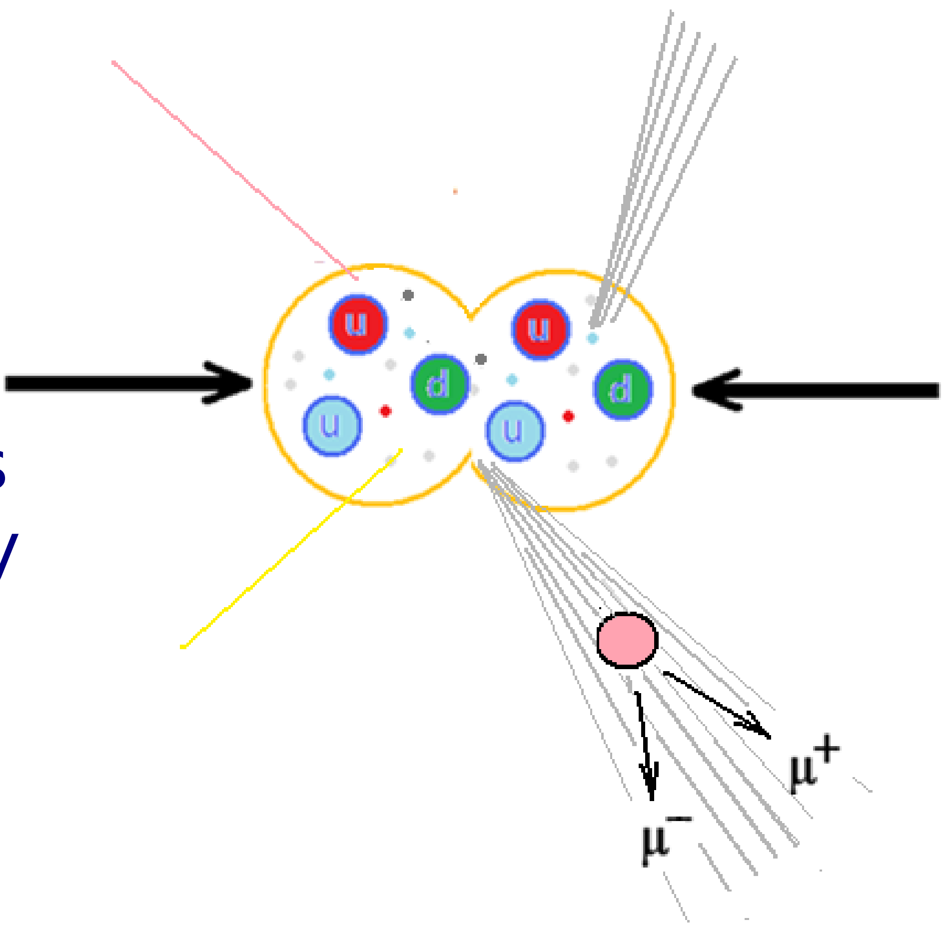
Background events



W and Z particles

We are looking for the mediators of the ***weak interaction:***

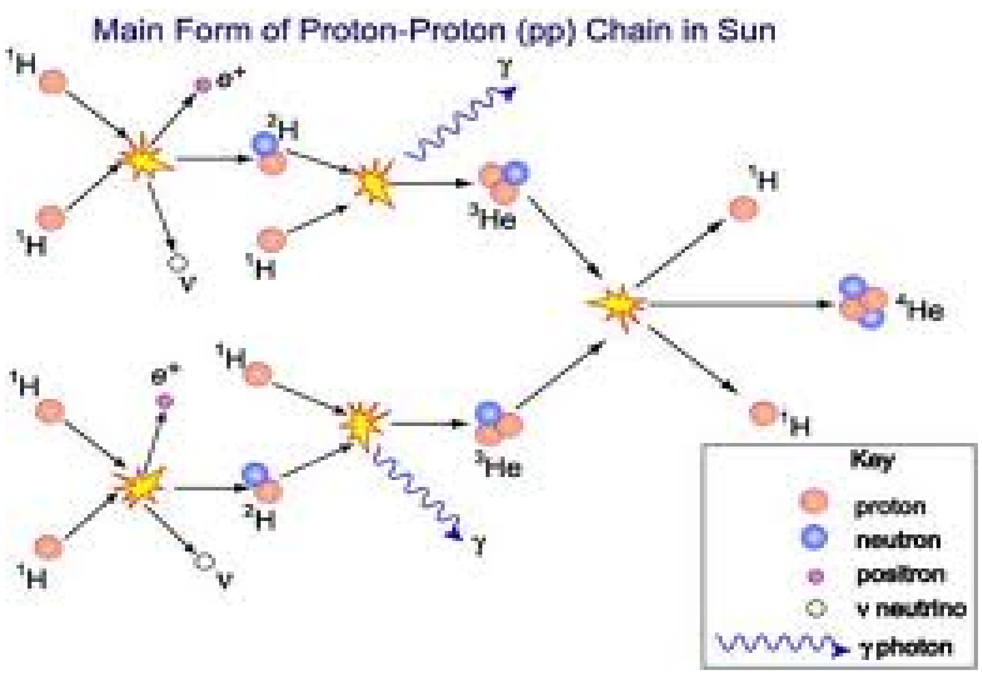
- electrically charged ***W⁺ boson,***
- the negative ***W⁻ boson,***
- the neutral ***Z boson***.

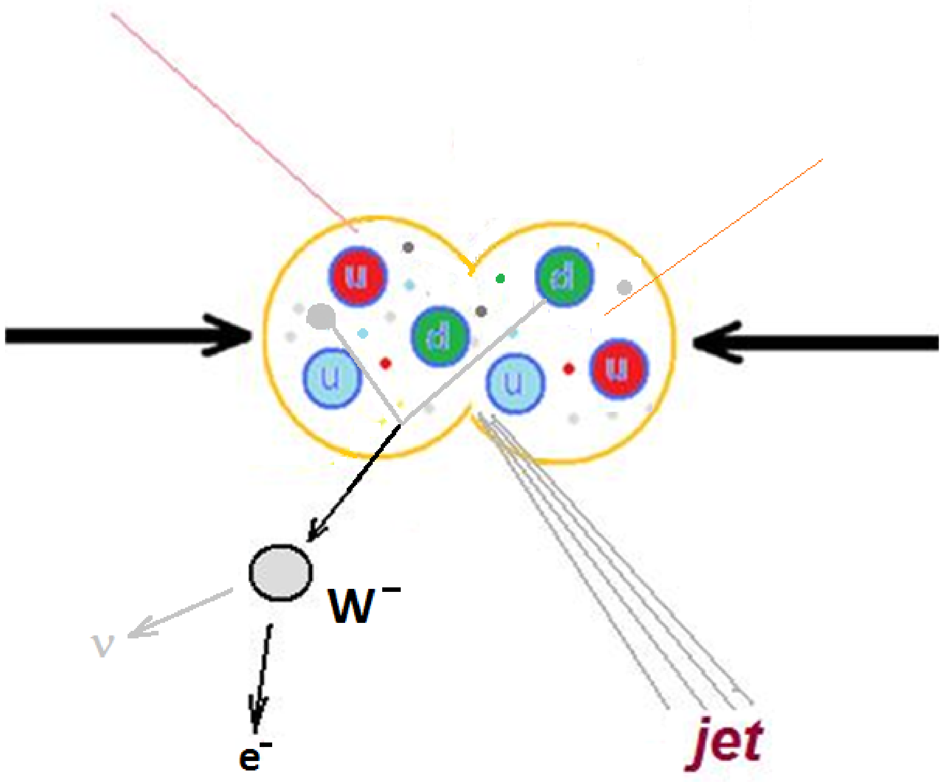


Unlike electromagnetic forces carried over long distances by massless photons, the weak force is carried by massive particles which restricts interactions to very tiny distances (10^{-18} m)

W bosons

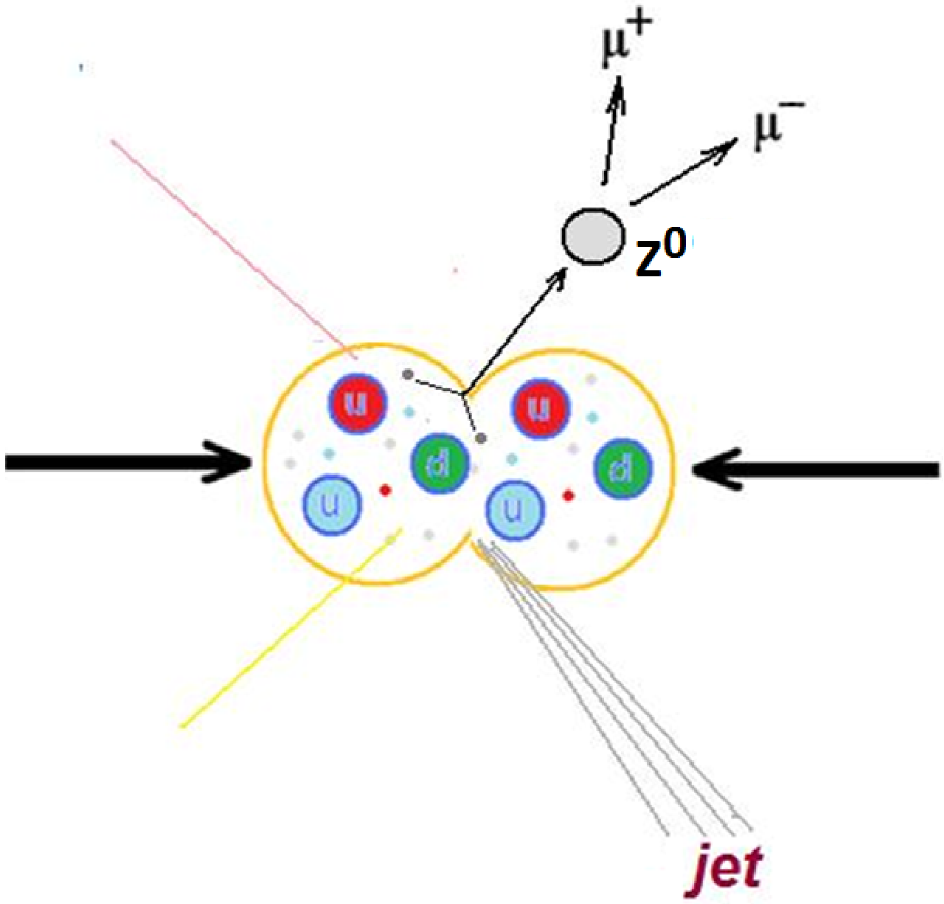
- The W bosons are responsible for radioactivity by transforming a proton into a neutron, or the reverse.
- They are also responsible for the Sun being able to shine!





Z bosons

- Z bosons are similarly exchanged but do not change electric charge.
- Collisions of sufficient energy can create W and Z or other particles.



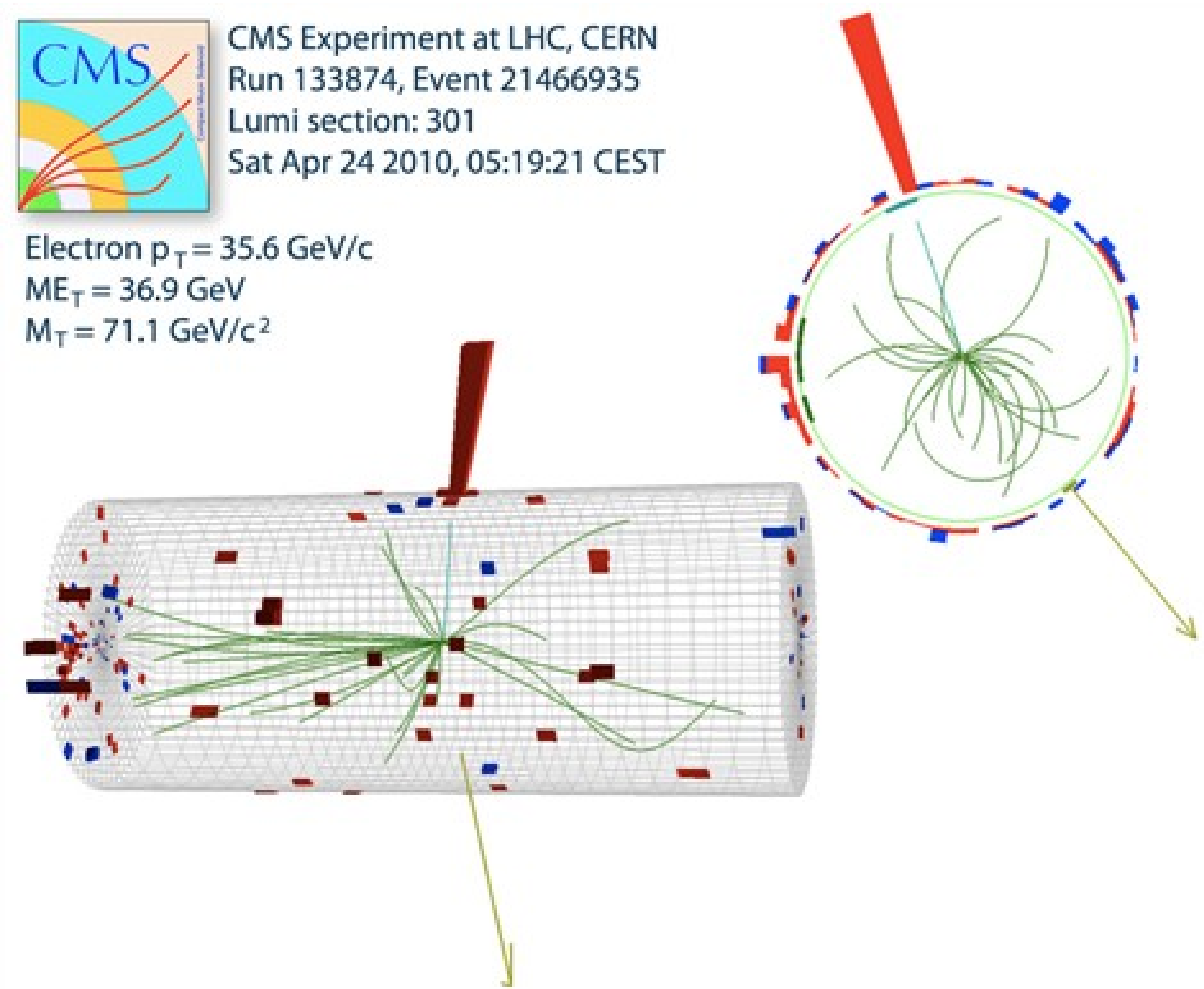
W and Z decays

Because W and Z only travel a tiny distance before decaying, CMS does not “see” W or Z bosons directly. CMS detects the decay products:

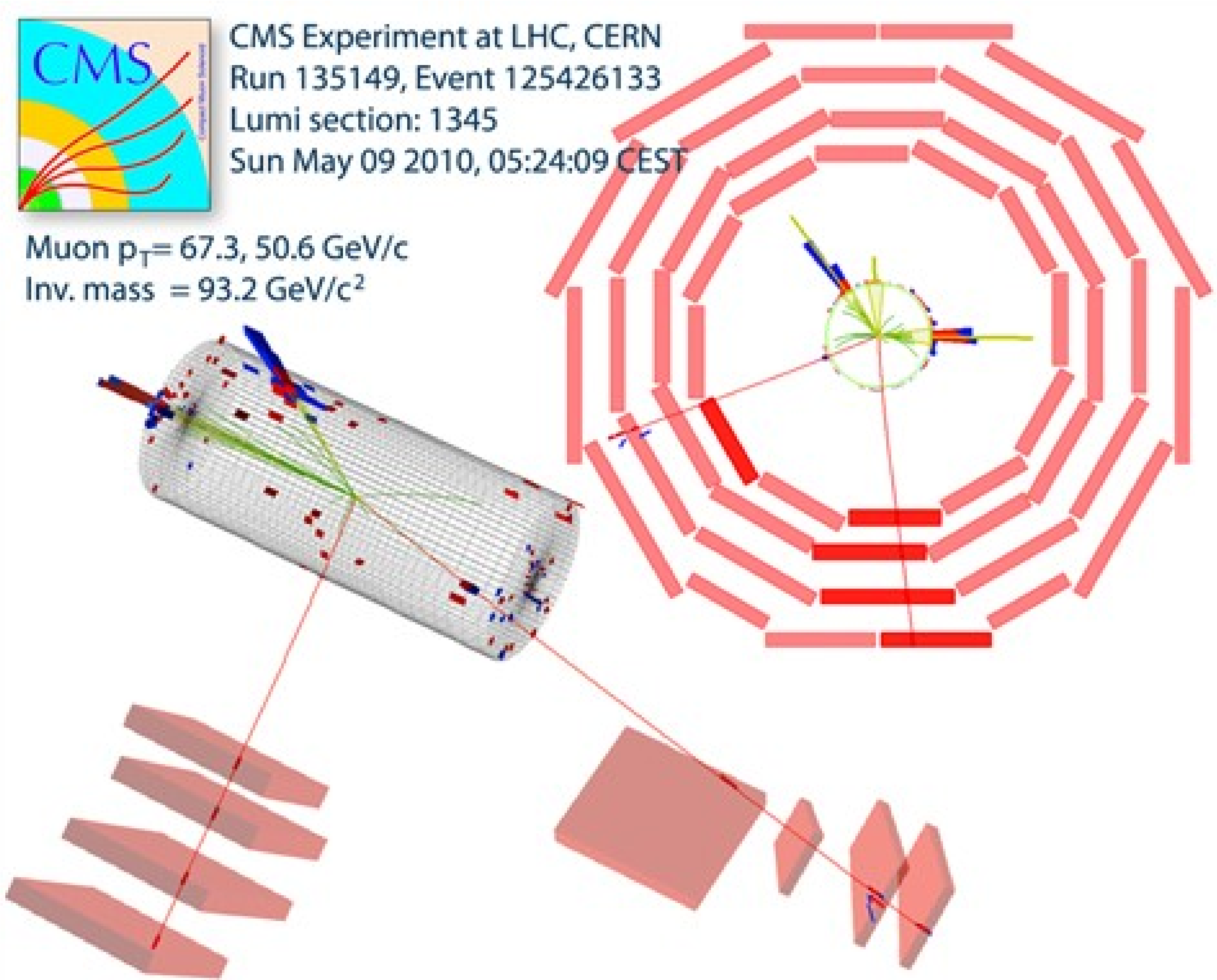
CMS *can* detect :
- electrons
- muons

CMS can infer:
- Neutrinos from “missing energy”

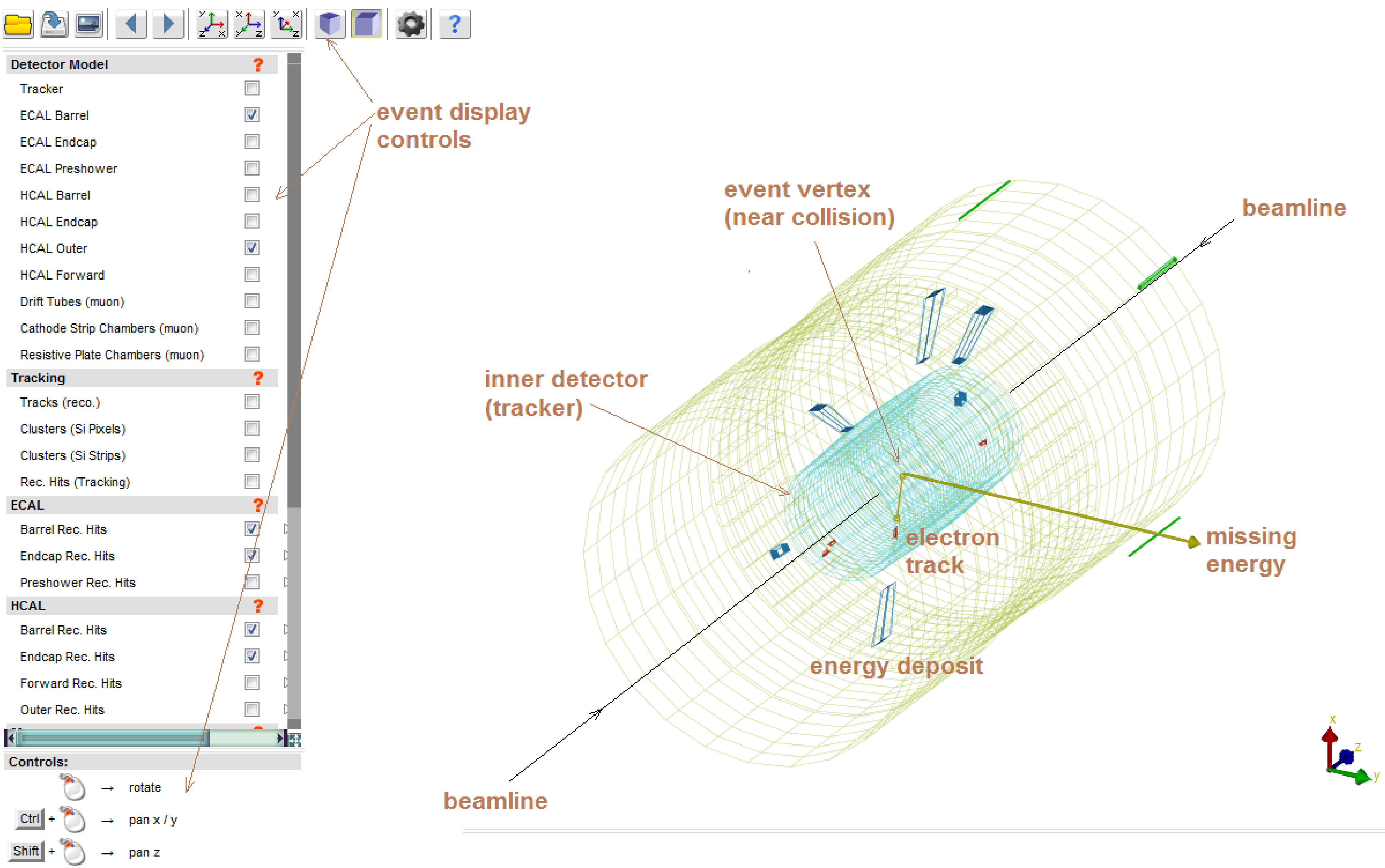
Example: W → eν event



Example: Z → μμ event



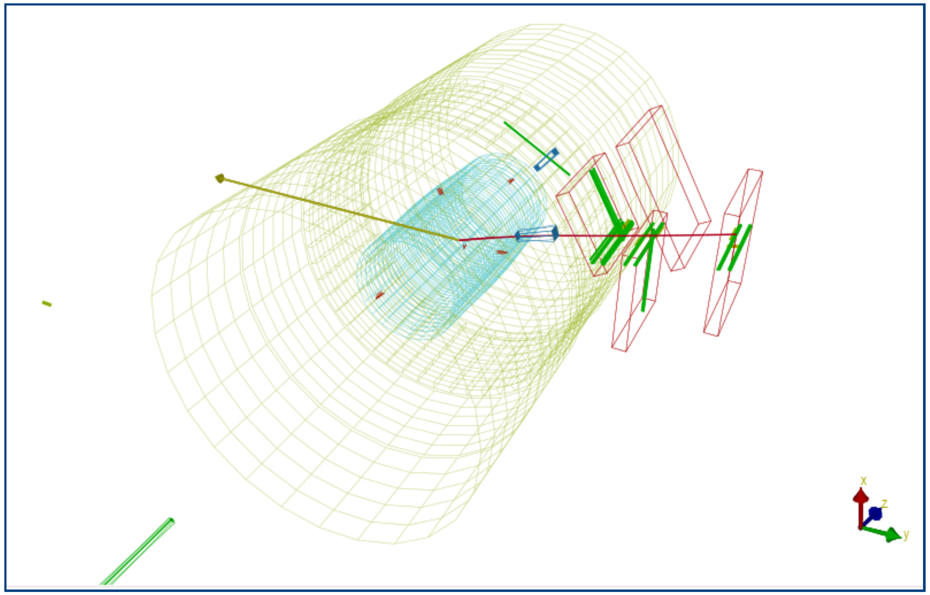
iSpy Online

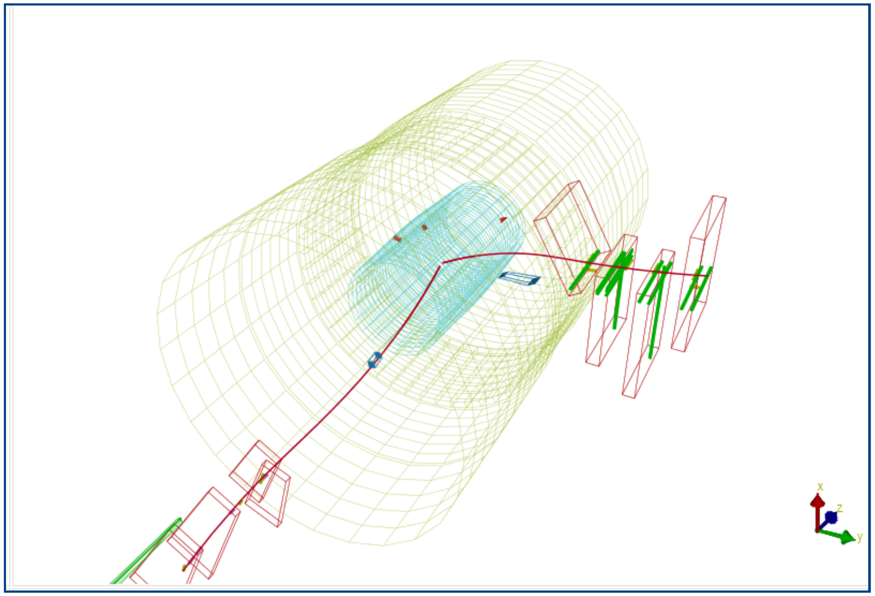

Detector Model
Tracker
ECAL Barrel
ECAL Endcap
ECAL Preshower
HCAL Barrel
HCAL Endcap
HCAL Outer
HCAL Forward
Drift Tubes (muon)
Cathode Strip Chambers (muon)
Resistive Plate Chambers (muon)
Tracking
Tracks (reco.)
Clusters (Si Pixels)
Clusters (Si Strips)
Rec. Hits (Tracking)
ECAL
Barrel Rec. Hits
Endcap Rec. Hits
Preshower Rec. Hits
HCAL
Barrel Rec. Hits
Endcap Rec. Hits
Forward Rec. Hits
Outer Rec. Hits
Controls:
→ rotate
Ctrl + → pan x / y
Shift + → pan z
event display controls
event vertex (near collision)
beamline
inner detector (tracker)
electron track
missing energy
energy deposit
beamline

Today's Task

Use new data from the LHC in iSpy to test performance of CMS:

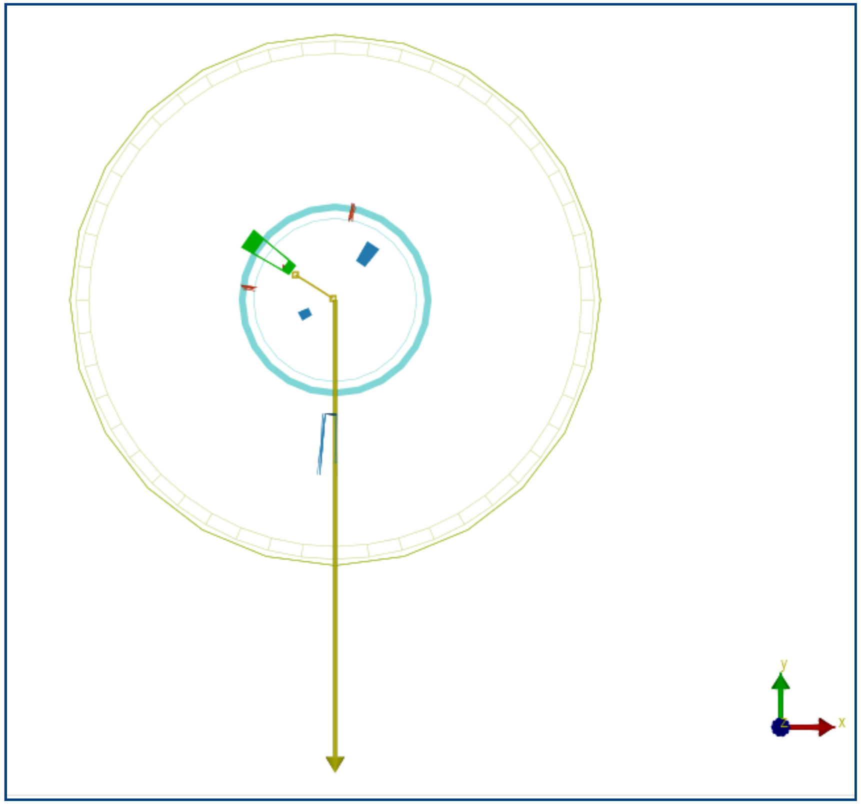
- Can we distinguish W from Z candidates?

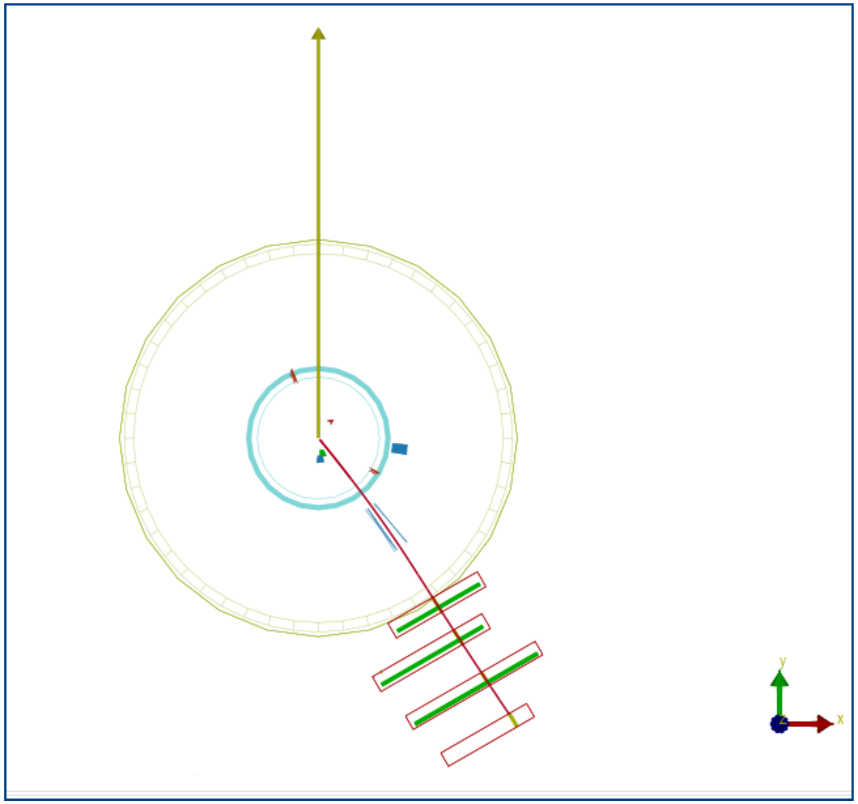




Today's Task

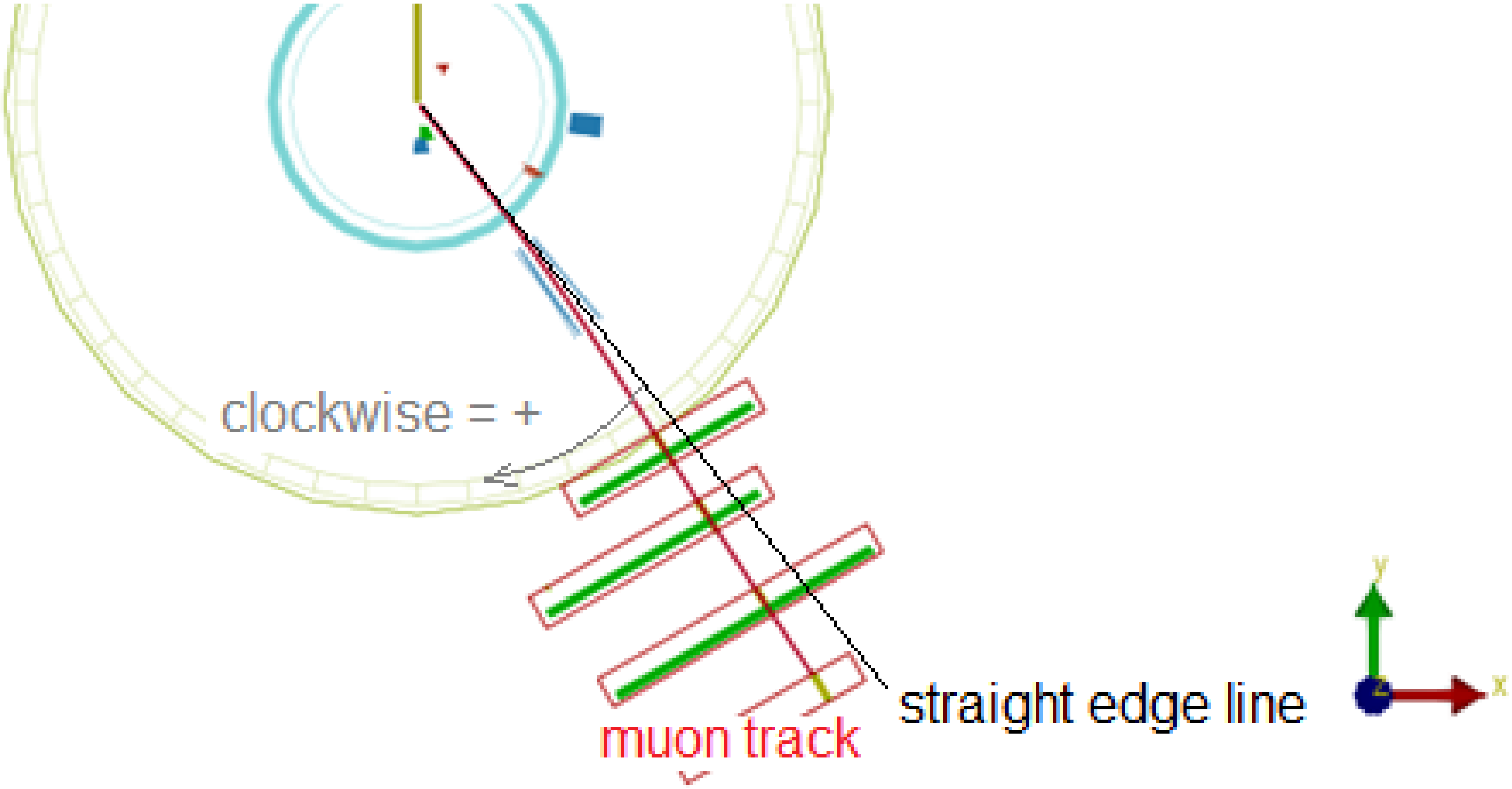
- Can we calculate the e/μ ratio?





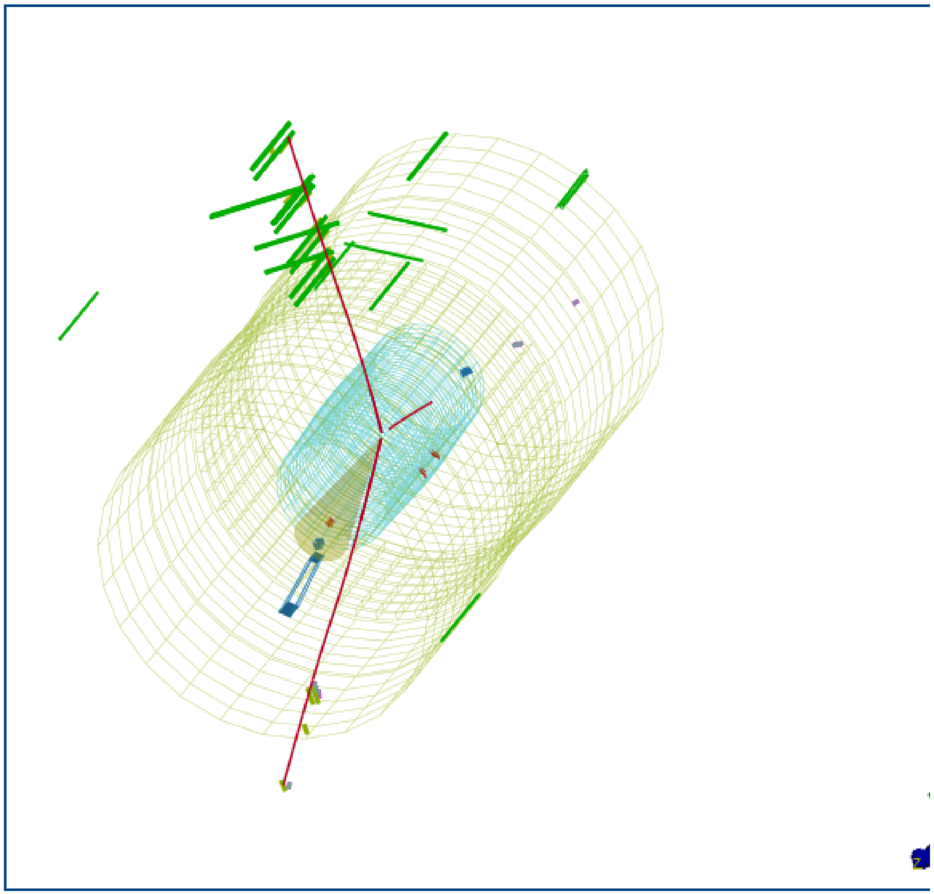
Today's Task

- Can we calculate a W^+/W^- ratio for CMS?

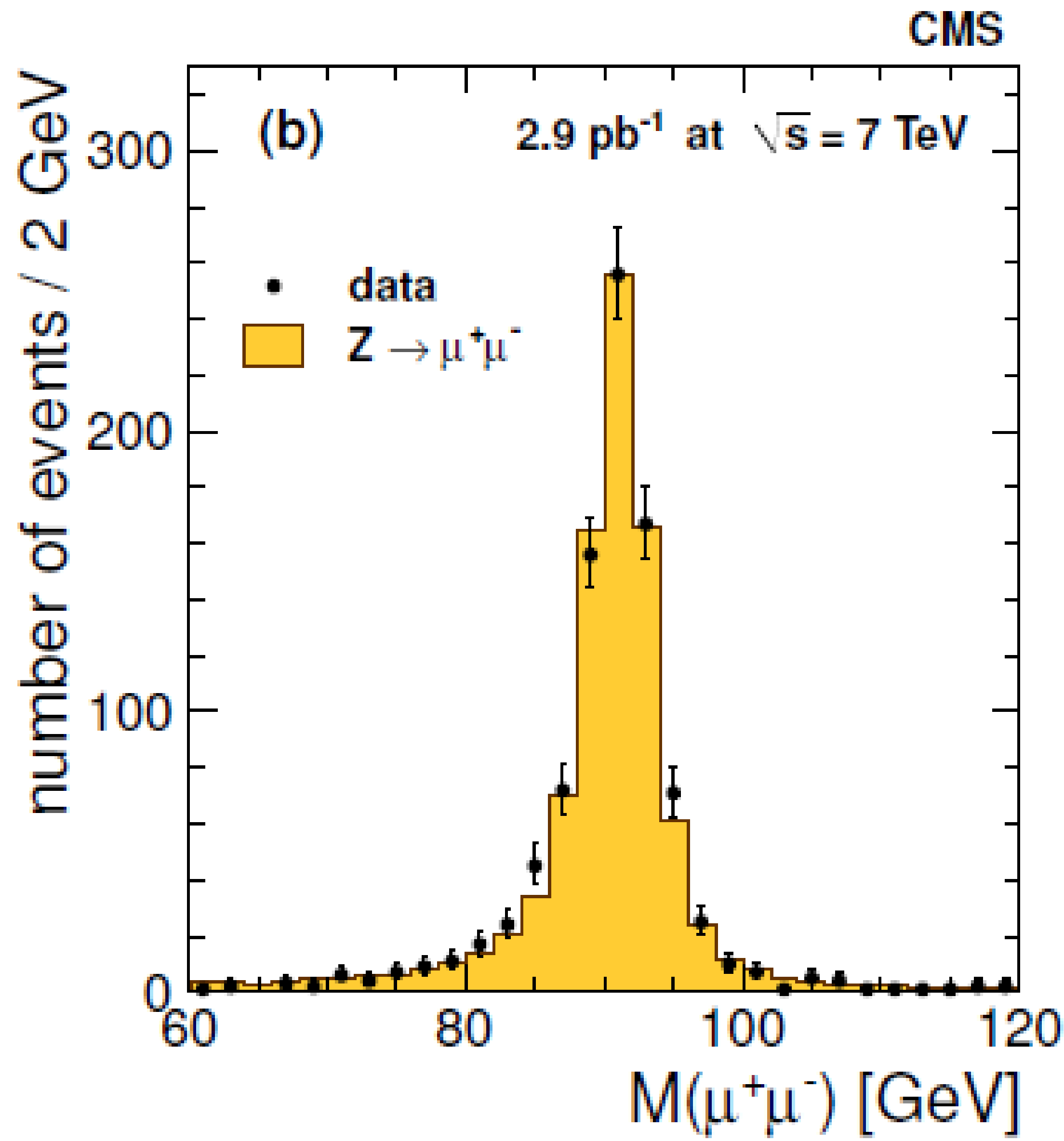


Today's Task

- Can we make mass plot of Z candidates?

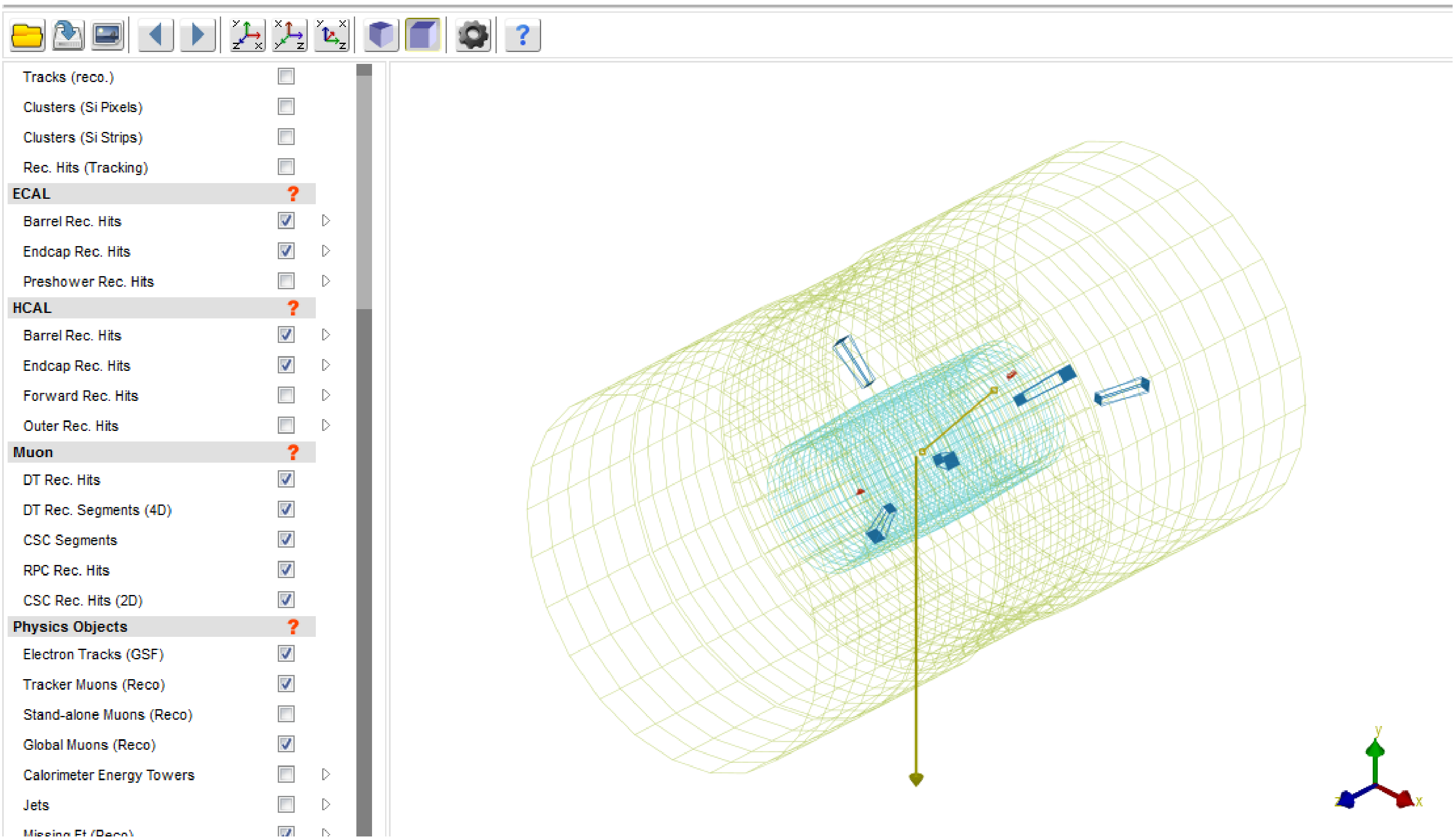


EvNo	E1	px1	py1	pz1	pt1	eta1	phi1	Q1
128943239	72.89895	13.36098	-26.087	66.74727	29.3095	1.5612	-1.09746	



Try some real events

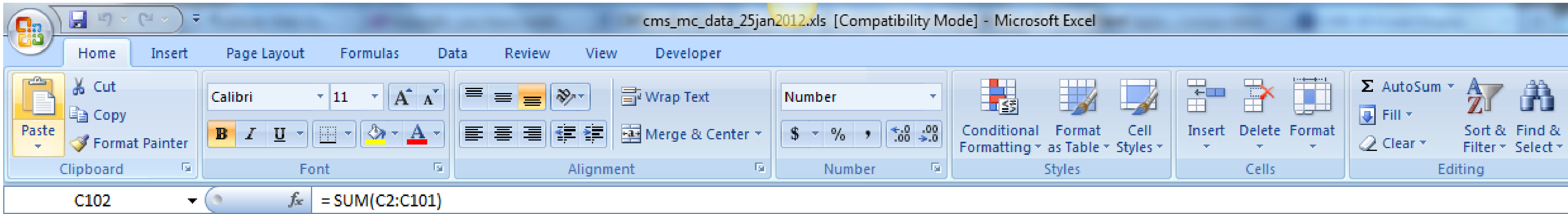
http://www18.i2u2.org/elab/cms/event-display/



- Are the observable lepton tracks muons or electrons?
- Is this a W candidate or a Z candidate? Or is it a "zoo" event?
- If it is more likely a W, is it W+ or W-?
- If it is more likely a Z, what is the invariant mass in GeV (from the spreadsheet)?

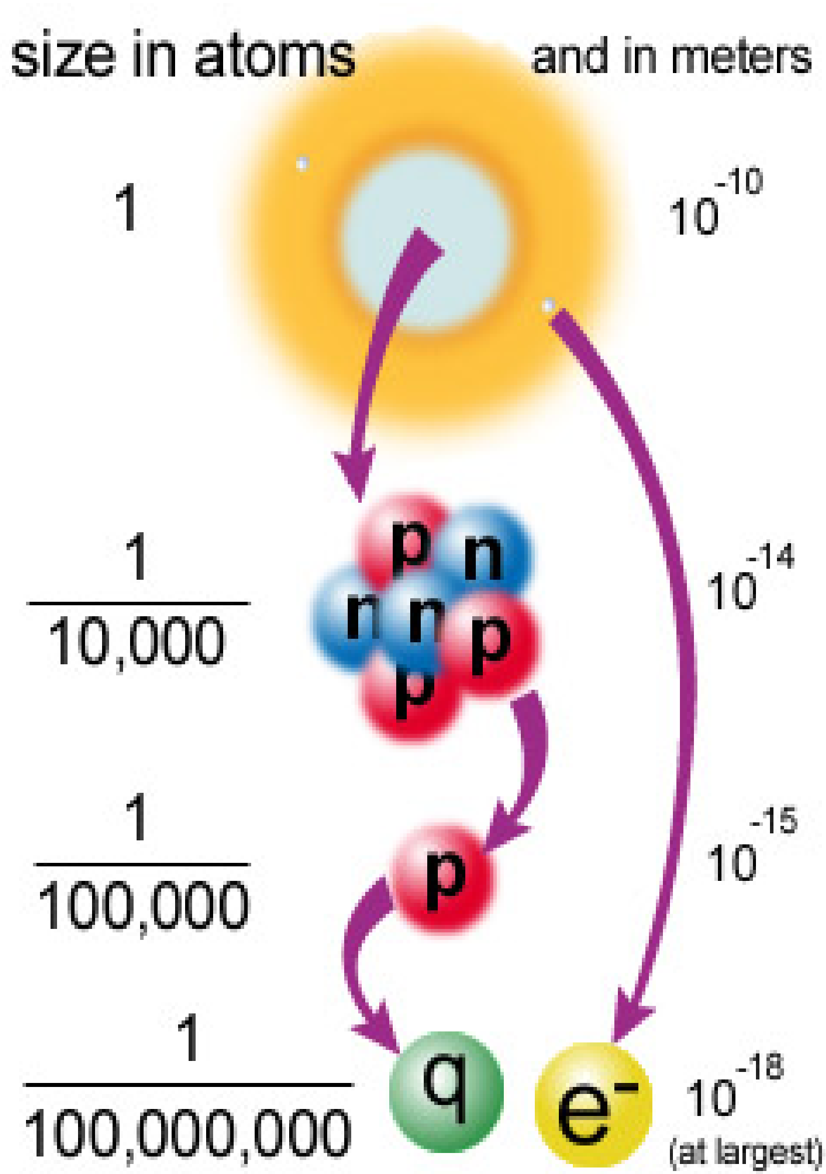
Recording event data

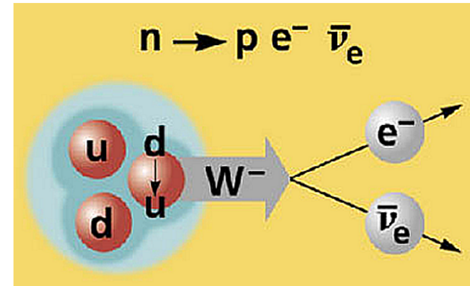
http://www.editgrid.com/qn-nd/qnmasterclasses/CMS_WZ_rochester



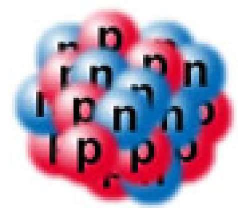
	A	B	C	D	E	F	G	H	I	J	K	L	M
1	MC No	Ev No	electron	muon	W+ cand	W- cand	W cand	Z cand	"zoo"	Z mass	Zmass list		**Student Instructions**
2	X.01	X X X X X	1									1	Find the file in iSpy_online or iSpy_dvd that corresponds to this tab.
3	X.02	X X X X X		1	1							2	Start with the first event.
4	X.03	X X X X X		1	1							3	Make sure Event Nos. match on the display and in the spreadsheet row.
5	X.04	X X X X X	1						1			4	Determine if the tracks are electron or muon.
6	X.05	X X X X X		1	1							5	Put a 1 under **electron** or **muon**.
7	X.06	X X X X X	1			1						6	If the event is a W candidate, determine if it is W+ or W-.
8	X.07	X X X X X	1					1		80.55	80.55	7	Put a 1 under **W+ cand**, **W- cand**, or (if you cannot tell charge) **W cand**.
9	X.08	X X X X X		1		1						8	If the event is a Z candidate, put a 1 under **Z cand** instead.
10	X.09	X X X X X		1	1							9	If you indicate Z cand, a mass will appear in green under Z mass.
11	X.10	X X X X X	1						1			10	If you cannot tell what the particle is, put a 1 under **"zoo"**.
12	X.11	X X X X X	1						1			11	Go to the next event. Repeat Instructions 3-10 until this tab is done.
13	X.12	X X X X X	1		1							12	You will find the sums in line 102 in blue.
14	X.13	X X X X X	1			1						13	Find your row on the Results page (your tab number under **mc_no**).
15	X.14	X X X X X		1	1							14	Copy the sums onto the Results page under **electron-->"zoo"** in your row.
16	X.15	X X X X X		1	1							15	Totals for your Institute will update in purple on Results line 21.
17	X.16	X X X X X		1	1							16	Return to your mc_xx tab.
18	X.17	X X X X X	1			1						17	*Manually* copy numbers under **Z mass** to under **Zmass list** w/no spaces.
19	X.18	X X X X X		1	1							18	Copy your Zmass list (numbers only).
20	X.19	X X X X X		1	1							19	Go to Results tab. Find **Z cand masses** (line 21, left).
21	X.20	X X X X X	1				1					20	Find the last number entered in the column under **Z cand masses**.
22	X.21	X X X X X							1			21	Paste your list under that last number.
23	X.22	X X X X X	1		1							22	Go back and check your own totals in blue and the ratios below in red.
24	X.23	X X X X X		1	1							23	Discuss with others - create a buzz.
102		Sums -->	48.00	52.00	38.00	24.00	10.00	11.00	16.00	74.96			
103													
104			e/mu	W+/W-									
105		Ratios -->	0.923077	1.583333									

Summary

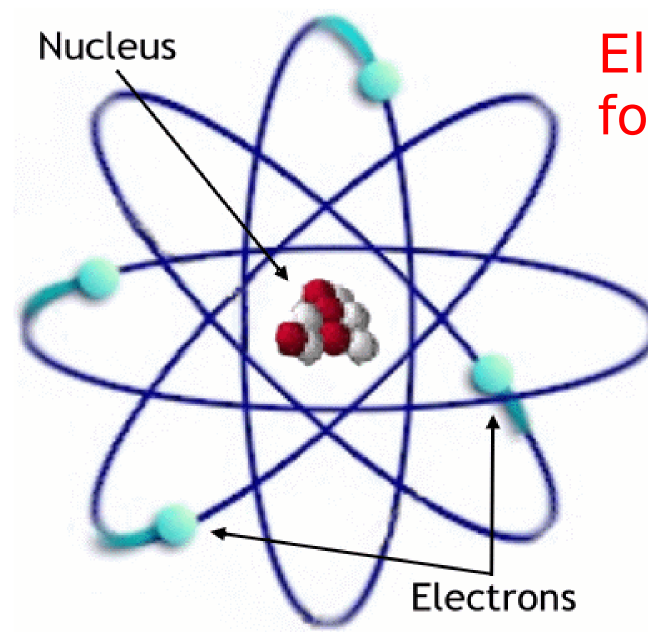




Weak force



Strong force



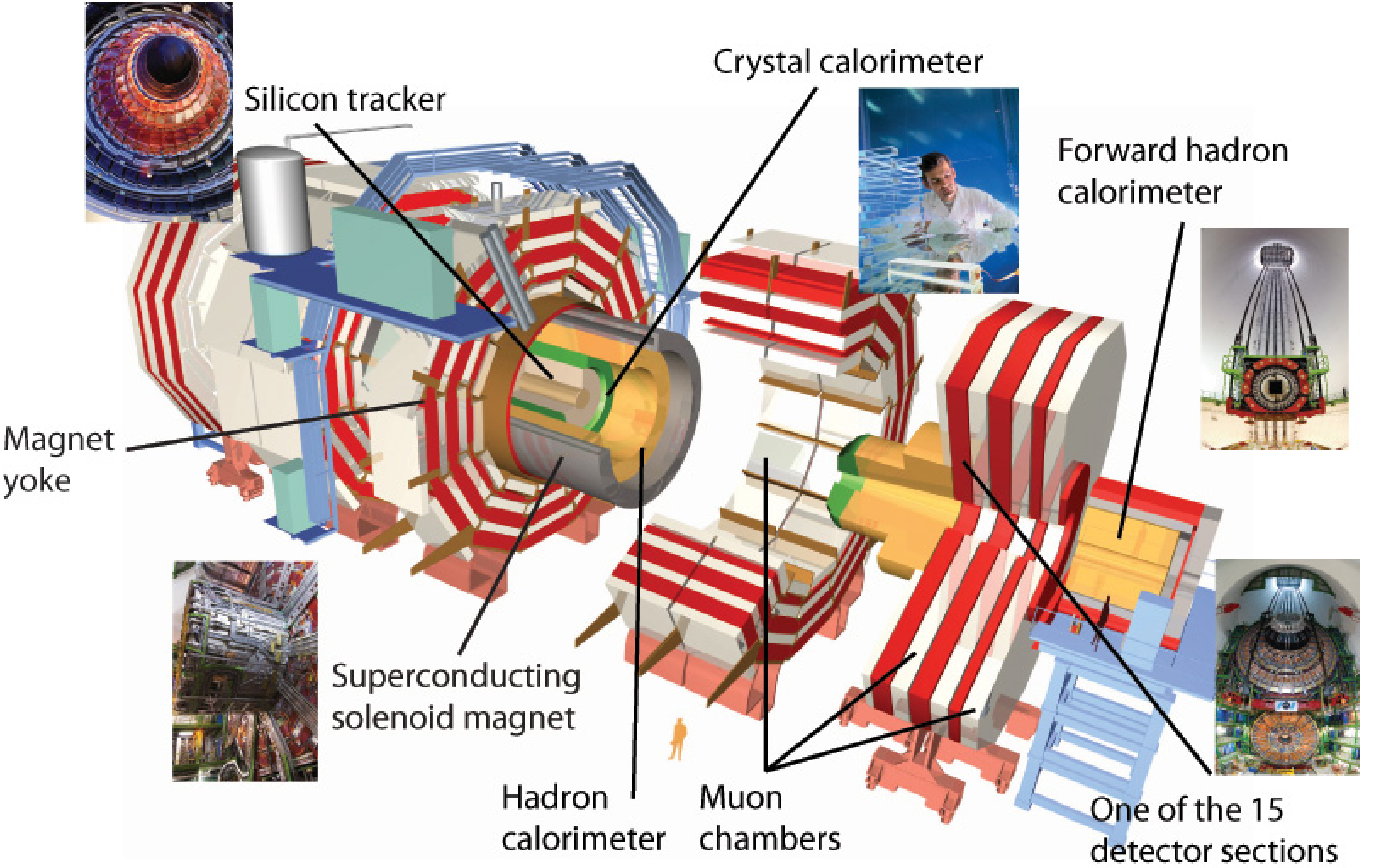
Electromagnetic force

Links

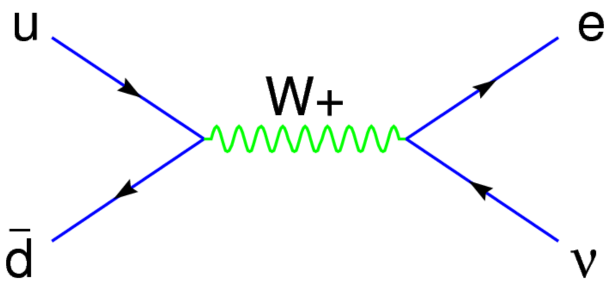
- http://www.interactions.org
- http://particleadventure.org
- http://pdg.lbl.gov
- http://public.web.cern.ch/public/
- http://www.fnal.gov/
- http://www.er.doe.gov/production/henp/np/index.html
- http://www.science.doe.gov/hep/index.shtml
- http://www.cern.ch

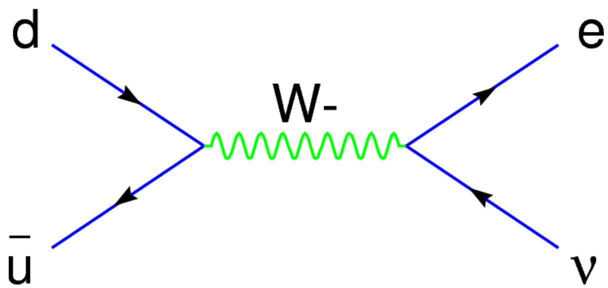
Extras

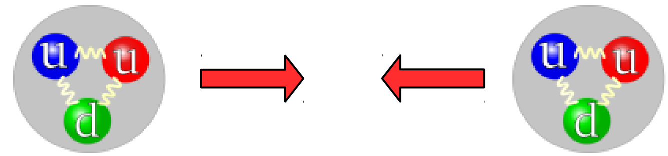
CMS subdetectors

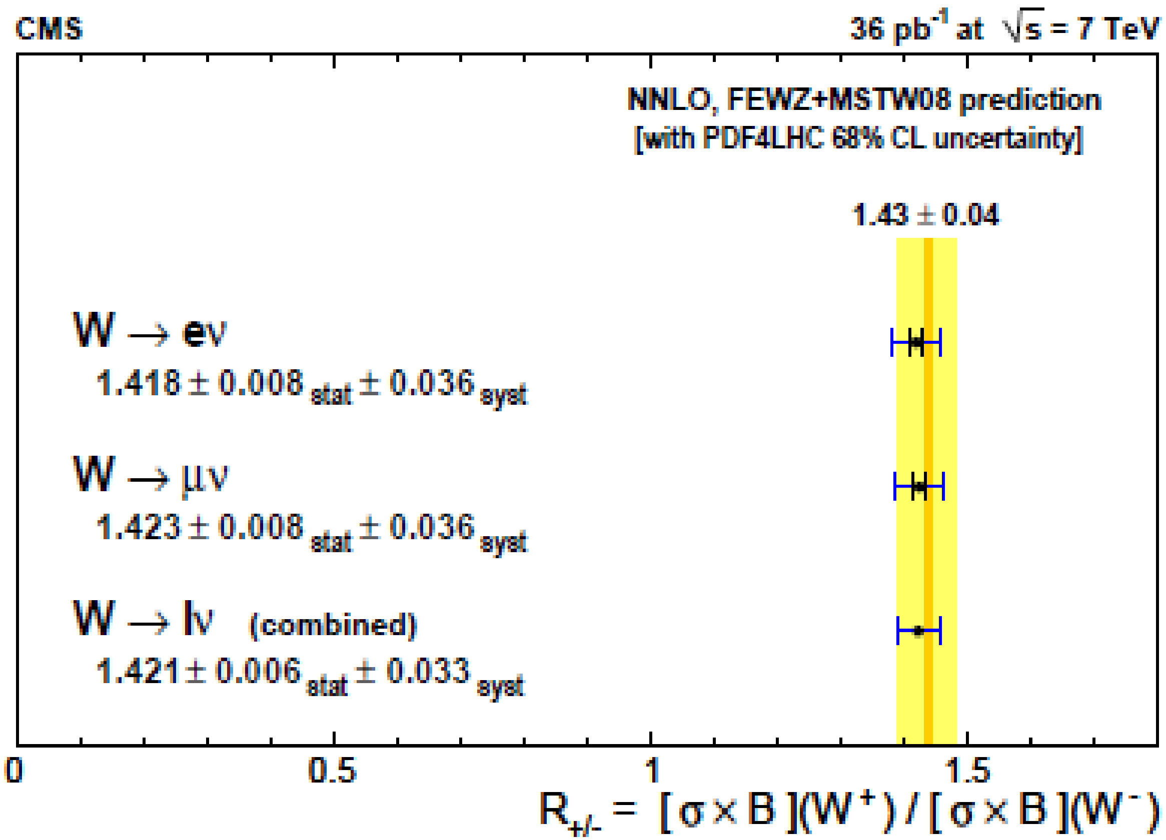


W^+/W^- ratio at the LHC









To produce a W^+: need u and $\bar{d}$

To produce a W^-: need $\bar{u}$ and d

But we collide protons (uud) against protons:

It is easier to produce W^+ than W^- (because there are more u quarks than d quarks)

Z mass shape

- The width of a particle: a quantum phenomenon
- Γ is the spread in measured energy due to Heisenberg's Uncertainty Principle (ΔE Δt > h/2)