Particle Physics 2011

Luis Anchordoqui

Bibliography

F. Halzen and A. D. Martin,
"Quarks and Leptons:
An Introductory Course in Modern Particle Physics,"
(John Wiley & Sons, New York, 1984)

V. Barger and R. J. N. Phillips,
"Collider Physics,"
(Addison-Wesley, 1987)

J. D. Bjorken and S. D. Drell,
"Relativistic Quantum Mechanics,"
(McGraw-Hill, 1964)

Advanced book:
M. E. Peskin and D. V. Schroeder
"An Introduction to Quantum Field Theory"
(Addison-Wesley, 1995)

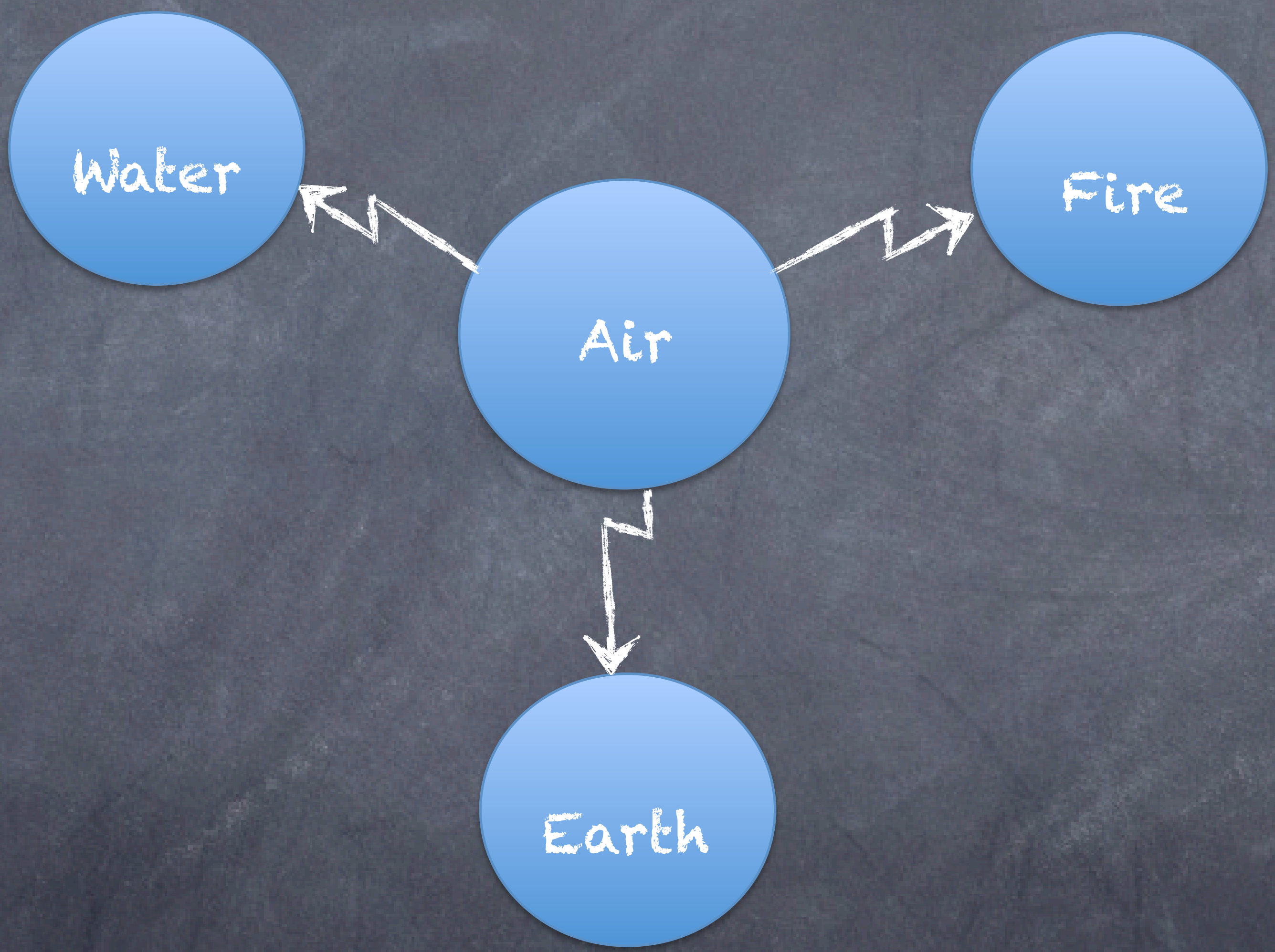
Lecture notes available at http://arXiv.org/abs/0906.1271

For latest updates see Particle Data Group (PDG)
http://pdg.lbl.gov/

What is the world made of?

Present-day particle physics research represents man's most ambitious and most organized effort to answer this question

Earlier answers to this riddle included the solution proposed by Anaximenes of Miletus



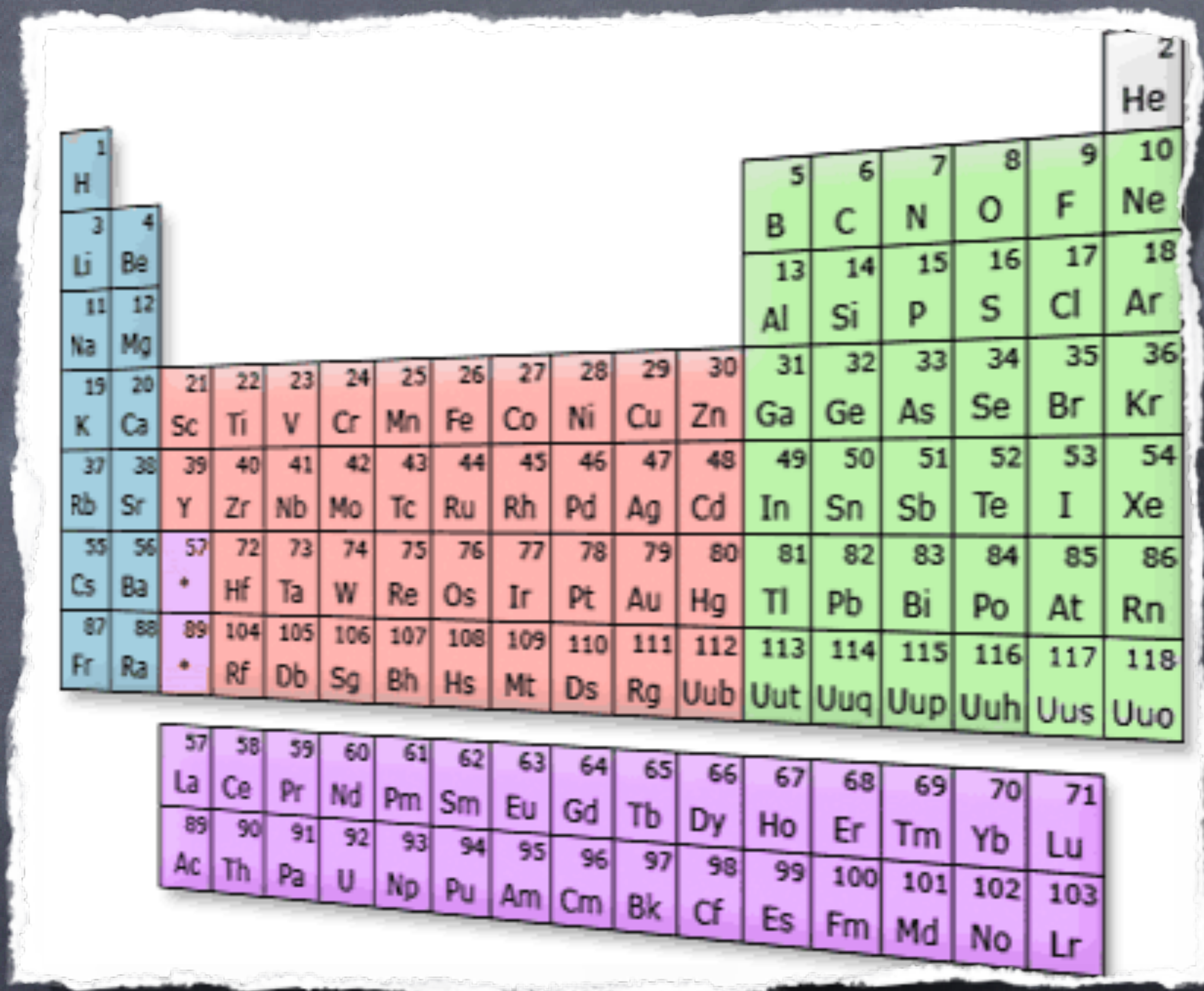
In the original version of the theory ☛ all forms of matter are obtained by condensing or rarefying air

Later ☛ a "chemistry" was constructed using the four elements

air-earth-water-fire

Periodic Table

Everyone is familiar with answer Mendeleev came up with 25 centuries later



☛ which now contains well over 100 chemical elements

Viewpoints

- Anaximene's model of fundamental structure of matter is clearly conceptually superior because of its simplicity and economy in number of building blocks

- It has one fatal problem: it is wrong!

- Mendeleev's answer is right ☛ but it is too complicated to represent the "ultimate" or fundamental solution

- The proliferation of elements and apparent systematics in organization of periodic table strongly suggest substructure

- We know now that elements in Mendeleev's table are indeed built up of more fundamental electrons and nuclei

Building Blocks and Interaction Rules

Today ☛ accepted model for elementary particle physics views quarks and leptons as basic constituents of ordinary matter

particles interact via four known basic forces

➢ gravitational, electromagnetic, strong, and weak ➢

that can be characterized on the basis of following four criteria:

- types of particles that experience force
- relative strength of force
- range over which the force is effective
- nature of particles that mediate force (photons, gluons, W, Z, graviton)

Comparison of the (approximate) relative force strengths

Relative strength of four forces
for two protons inside a nucleus

Type	Relative Strength	Field Particle
Strong	1	gluons
Electromagnetic	10^{-2}	photon
Weak	10^{-6}	$W^{\pm}\ Z^{0}$
Gravitational	10^{-38}	graviton

Though gravity is most obvious force in daily life
☛ on a nuclear scale it is weakest of four forces and its effect at particle level can nearly always be ignored

From grey stones to colored quarks

Beware of quantum ducks
quark quark quark...

fractionally charged spin-1/2 strongly interacting objects
which are known to form composites
collectively called hadrons

$$\left\{ \begin{array}{lll} q\bar{q} & \text{(quark + antiquark) mesons} & \text{integral spin} \to \text{Bose statistics} \\ qqq & \text{(three quarks) baryons} & \text{half-integral spin} \to \text{Fermi statistics} \end{array} \right\}$$

Quark Quantum Numbers

There are six different types of quarks known as flavors

name	symbol	Q	B	S	c	b	t
up	u	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
down	d	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0
strange	s	$-\frac{1}{3}$	$\frac{1}{3}$	-1	0	0	0
charm	c	$\frac{2}{3}$	$\frac{1}{3}$	0	1	0	0
bottom	b	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	-1	0
top	t	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	1

charge Q, baryon number B, strangeness S, chram c, "beauty" or bottomness b, and "truth" or topness t

(antiquarks have opposite signs of electric charge, baryon number, strangeness, charm, bottomness, and topness)

QCD

Quarks are fermions with spin-1/2
and therefore should obey exclusion principle

Yet for three particular baryons ($\Delta^{++} = uuu$, $\Delta^{-} = ddd$
and $\Omega^{-} = sss$) all three quarks would have same quantum
numbers and at least two quarks have their spin in same
direction because there are only two choices
☛ spin up ($\uparrow$) or spin down ($\downarrow$)

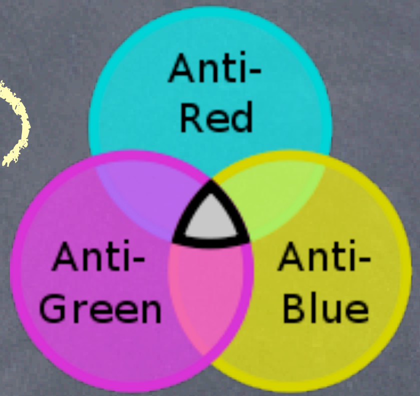
This would seem to violate exclusion principle!

Not long after quark theory was proposed it was suggested
that quarks possess another "charge" which enables them
to interact strongly with one another

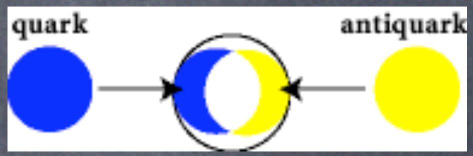
This "charge" is a three-fold degree of freedom which
has come to be known as color ☛ field theory has taken
on name of quantum chromodynamics or QCD

Baryons and Mesons

- Each quark flavor can have three colors usually designated red, green, and blue
(antiquarks are colored antired, antigreen, antiblue)



- Baryons are made up of three quarks ☛ one with each color
- Mesons consist of a quark-antiquark pair of a particular color and its anticolor e.g.

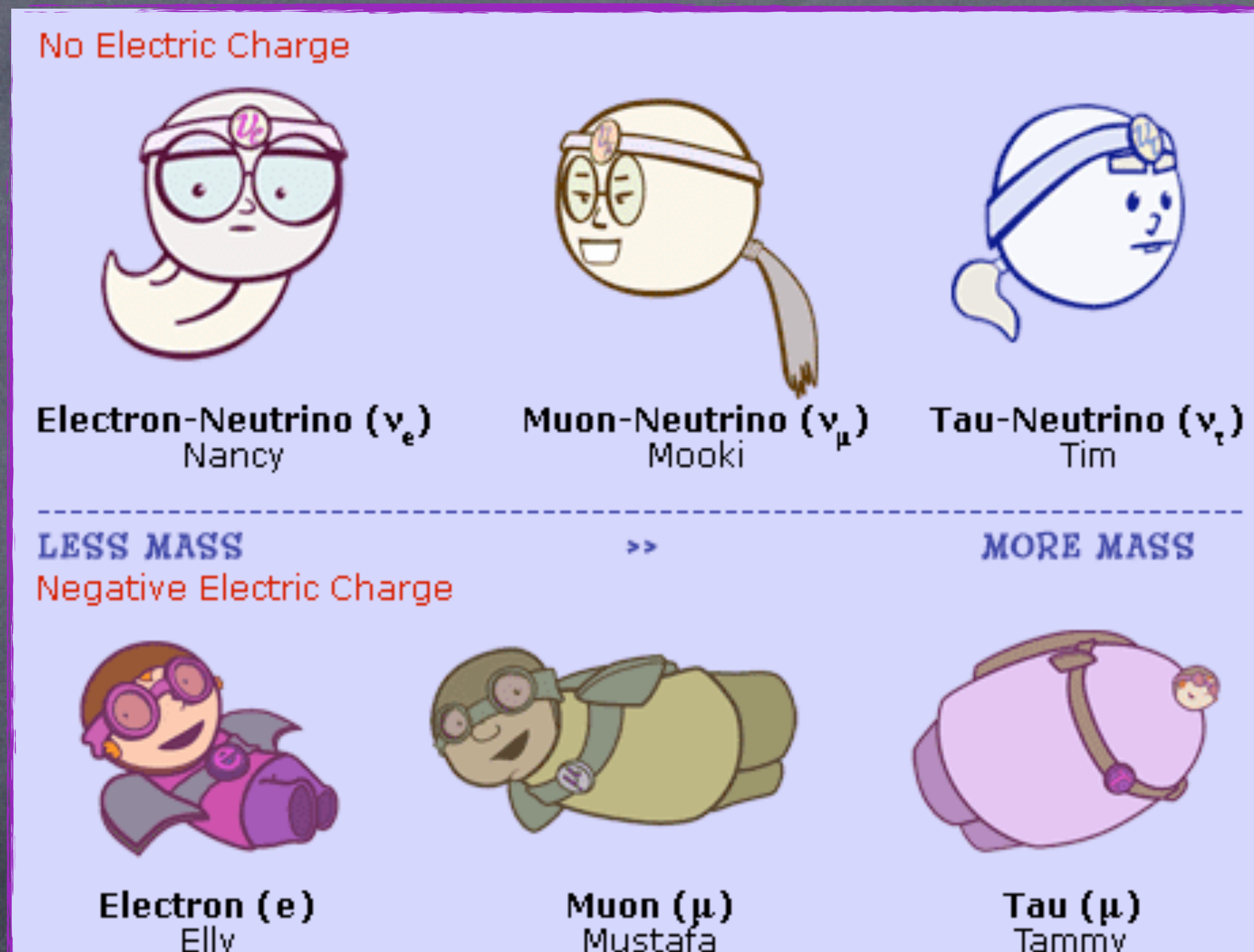


- Both baryons and mesons are thus colorless or white
- Because color is different for each quark ☛ it serves to distinguish them and allows exclusion principle to hold
- Even though quark color was originally an "ad hoc" idea ☛ it soon became central feature of theory determining force binding quarks together in hadrons

Leptons

Leptons are fractionally spin-1/2particles which do not strongly interact

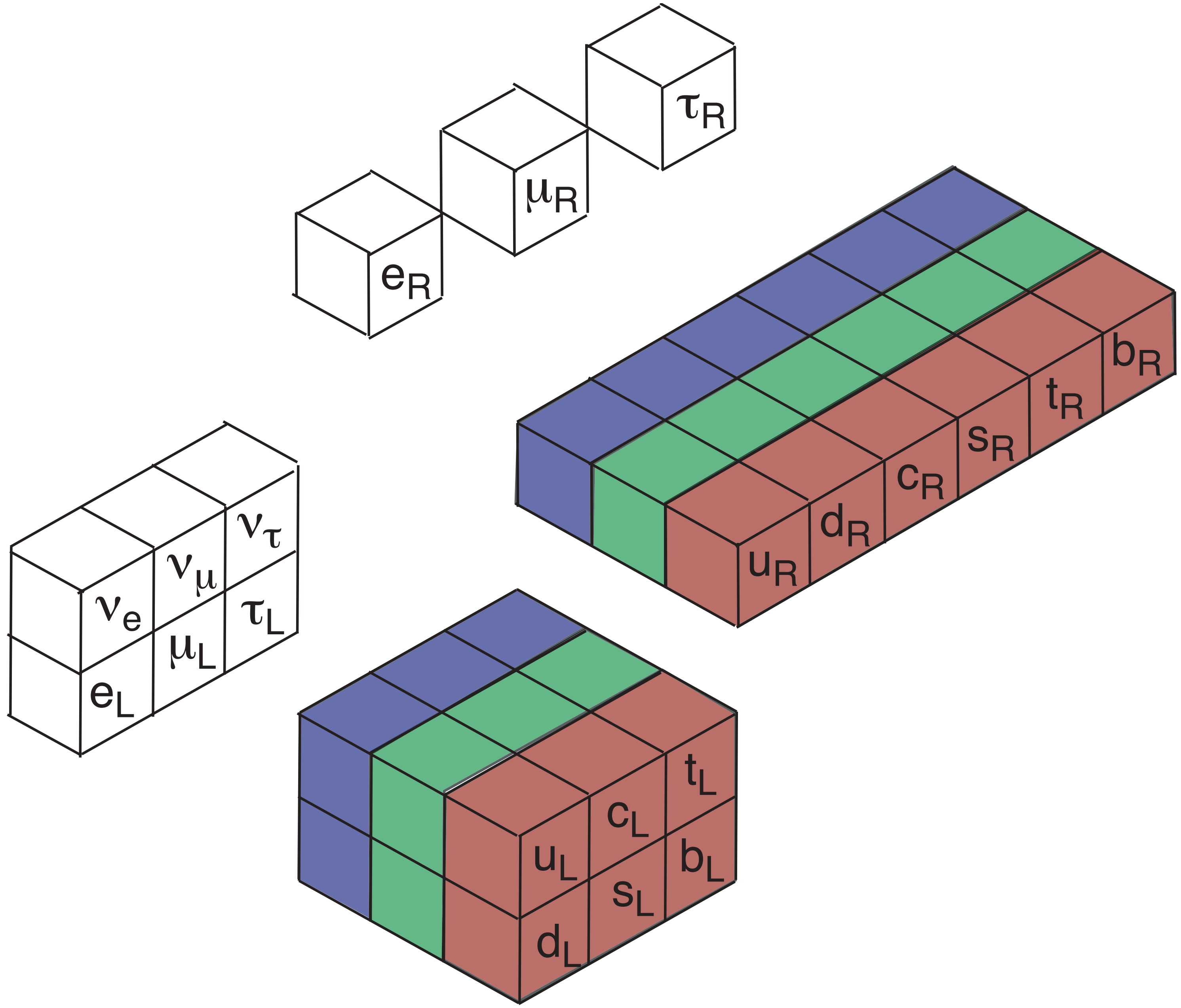
they come in three flavors:



$$m_e = 0.510998910 \pm 0.0000000013 \text{ MeV} \quad m_\mu = 105.658367 \pm 0.000004 \text{ MeV} \quad m_\tau = 1776.84 \pm 0.17 \text{ MeV}$$

Each flavor has an associated neutrino

Quarks & Leptons



Left handed doublets and right-handed singlets of quarks and leptons that inspire the structure of electroweak theory

Natural Units

Unless otherwise stated ☛ we work with natural (particle physicist's) Heaviside-Lorentz (HL) units with

$$\hbar = c = k = \varepsilon_0 = \mu_0 = 1$$

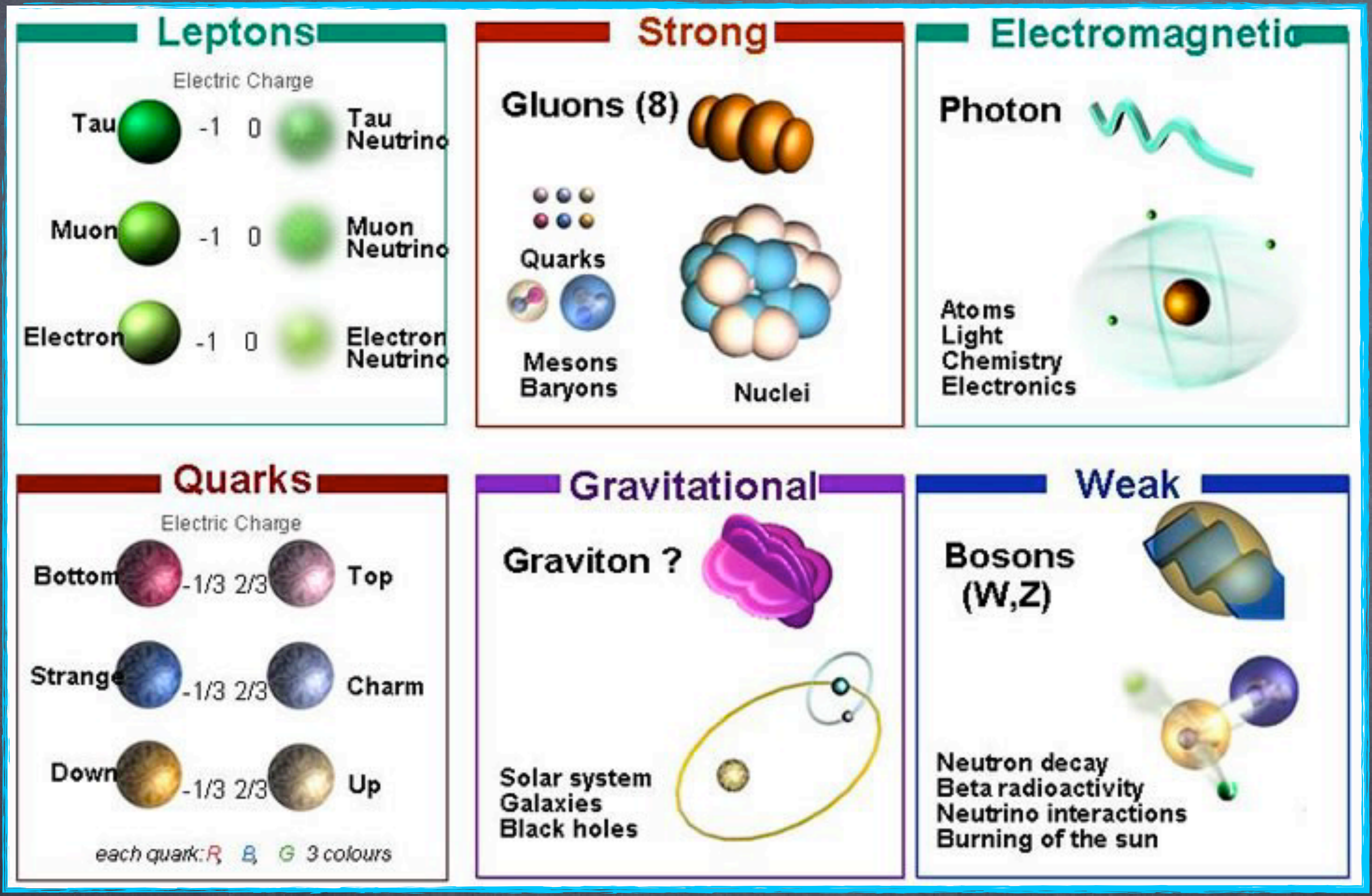
The fine structure constant is ☛ $\alpha = e^2/(4\pi\varepsilon_0\hbar c) \simeq 1/137$

All SI units can then be expressed in electron Volt (eV) ☛ namely

$$\begin{array}{llllll} 1\ \mathrm{m} & \simeq 5.1 \times 10^{6}\ \mathrm{eV}^{-1} & 1\ \mathrm{s} & \simeq 1.5 \times 10^{15}\ \mathrm{eV}^{-1} & 1\ \mathrm{kg} & \simeq 5.6 \times 10^{35}\ \mathrm{eV} \\ 1\ \mathrm{A} & \simeq 1244\ \mathrm{eV} & 1\ \mathrm{G} & \simeq 1.95 \times 10^{-2} \mathrm{eV}^2\,, & 1\ \mathrm{K} & \simeq 8.62 \times 10^{-5}\ \mathrm{eV} \end{array}$$

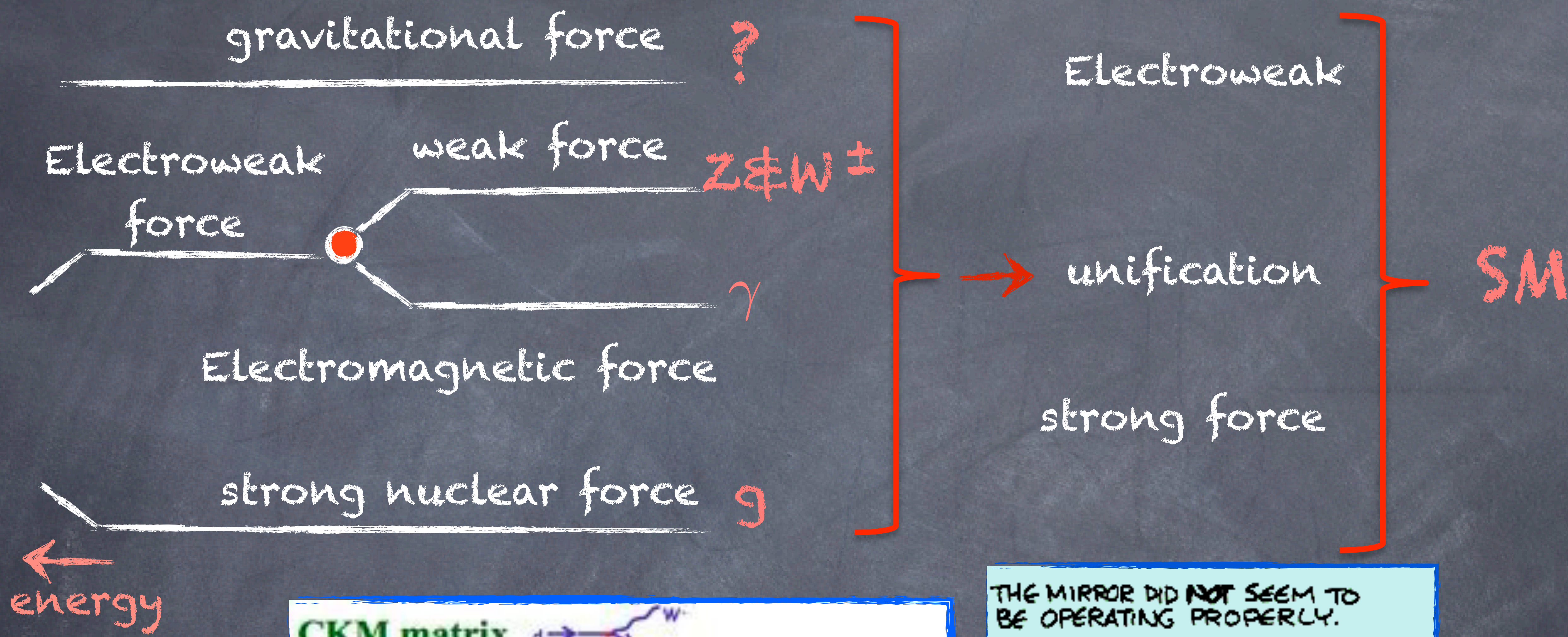
$\hbar c = 0.1973\ \mathrm{GeV\ fm}$ with $1\ \mathrm{fm} = 10^{-15}\ \mathrm{m}$

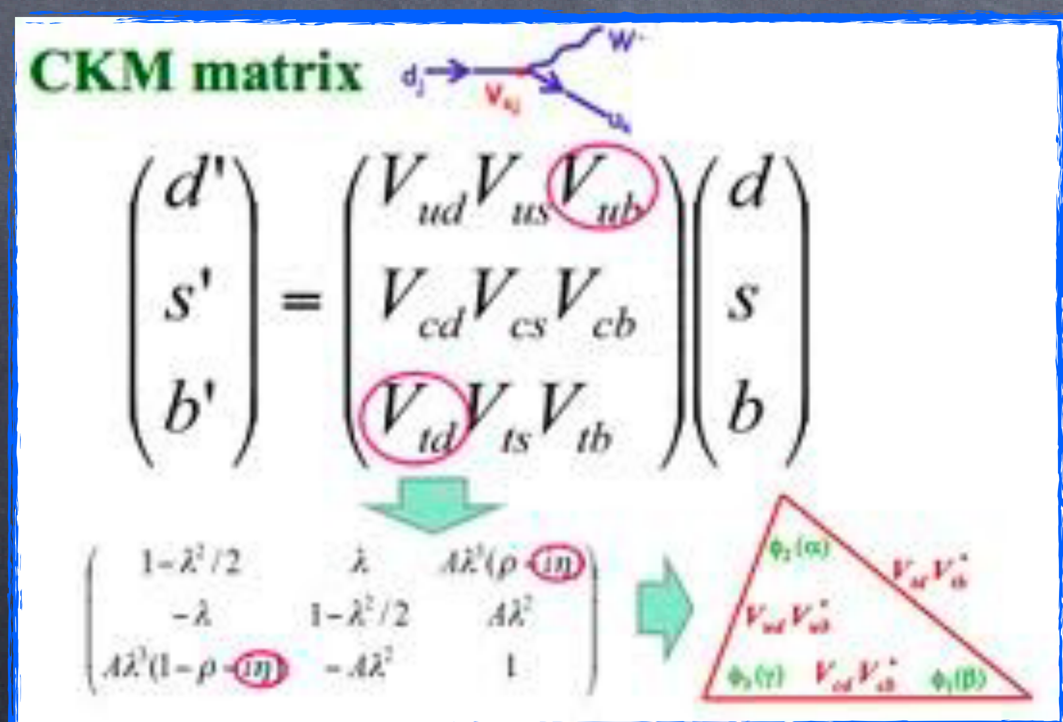
What we know experimentally



Matter and interactions that manifest down to distances of order $(10^{-3} - 10^{-4})\ \mathrm{fm} \sim \dfrac{\hbar}{(0.2 - 1)\ \mathrm{TeV}}$

and our theoretical understanding





CP violation

Some experimental limitations of the SM

Where is the Higgs?

Is SM the right place for neutrino masses?

What about dark matter?

Direct detection of WIMPs

CRESST

- In recent talks by members of the CRESST collaboration, a 4.6σ excess over known backgrounds has been reported (paper expected soon)
- The excess events appear in the oxygen band, implying a low WIMP mass
- The best fit point was reported to be m=13 GeV, with σ=3x10^{-40} cm^{2}, although these values are likely to be surrounded by considerable error bars
- Official results and corresponding paper are planned for TAUP meeting in September

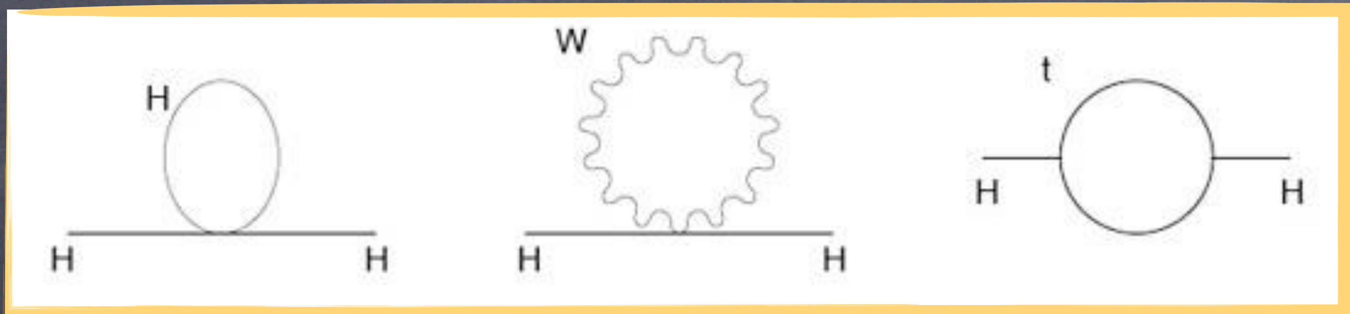
This slide is courtesy of Dan Hooper (presented at SUSY 11, 08/31/11)

Press conference call for September 6 ☛ i.e today!!!

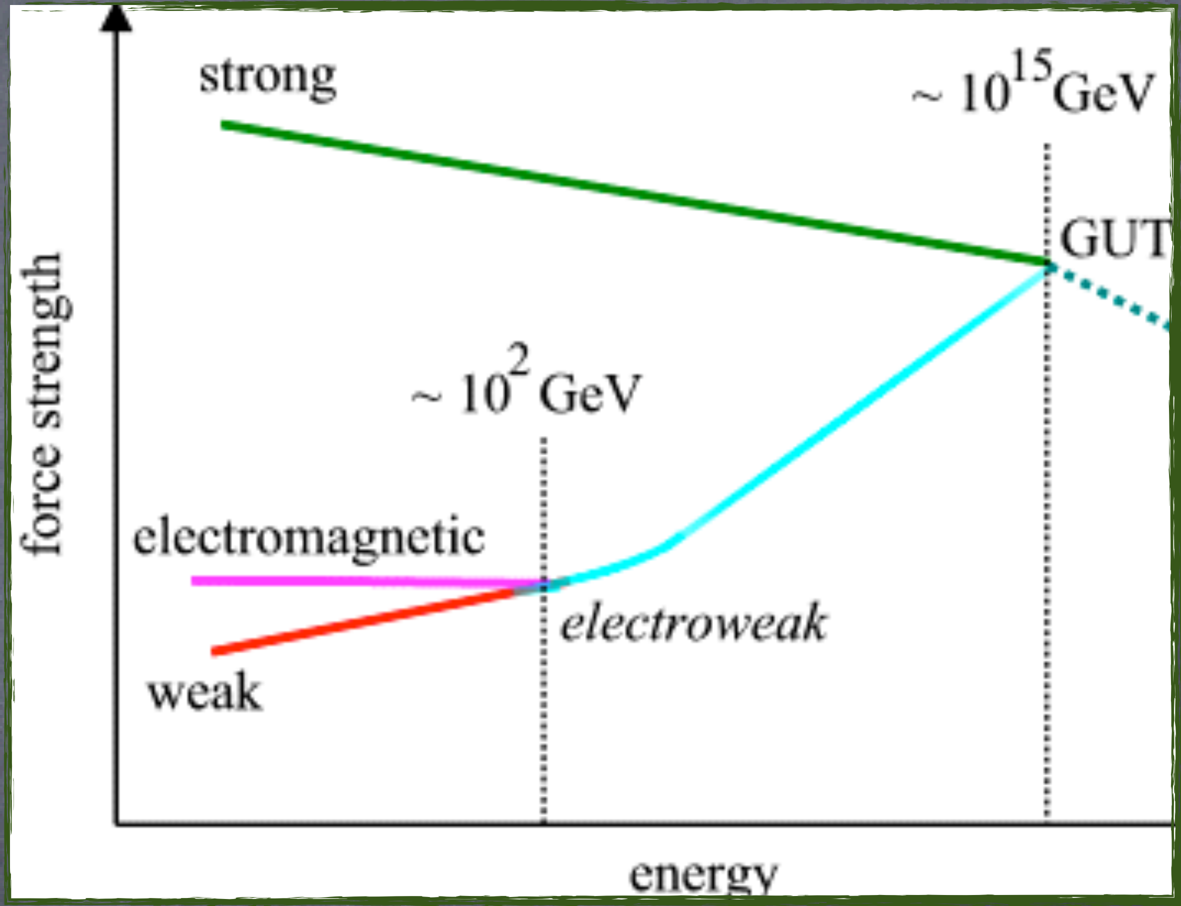
CRESST's signal region ☛ http://arXiv.org/abs/0906.1271

in considerable tension exclusion with limits from XENON and CDMS

Some theoretical limitations of the SM



Hierarchy problem
($m_H < 1\text{TeV}$ is 'unnatural')



It does not even consider the gravitational force as part of the game

Strong interactions are not really 'unified' within SM

Why several fermion families?
Why three?
Why so many parameters (19)?

REPETITION
REPETITION
REPETITION

Particle Colliders

Since the years after World War II particle accelerators have been a principal means of investigating structure of nuclei

Accelerated particles are projectiles that probe interior of nuclei/proton they strike and their constituents

Important factor is that faster moving projectiles can reveal more detail about nuclei

Wavelength of incoming particles is given by de Broglie's wavelength formula $\lambda = h/p$ showing that ➡ the greater the momentum p of bombarding particle ☛ the shorter the wavelength and the finer the detail that can be obtained

Scattering Cross Section

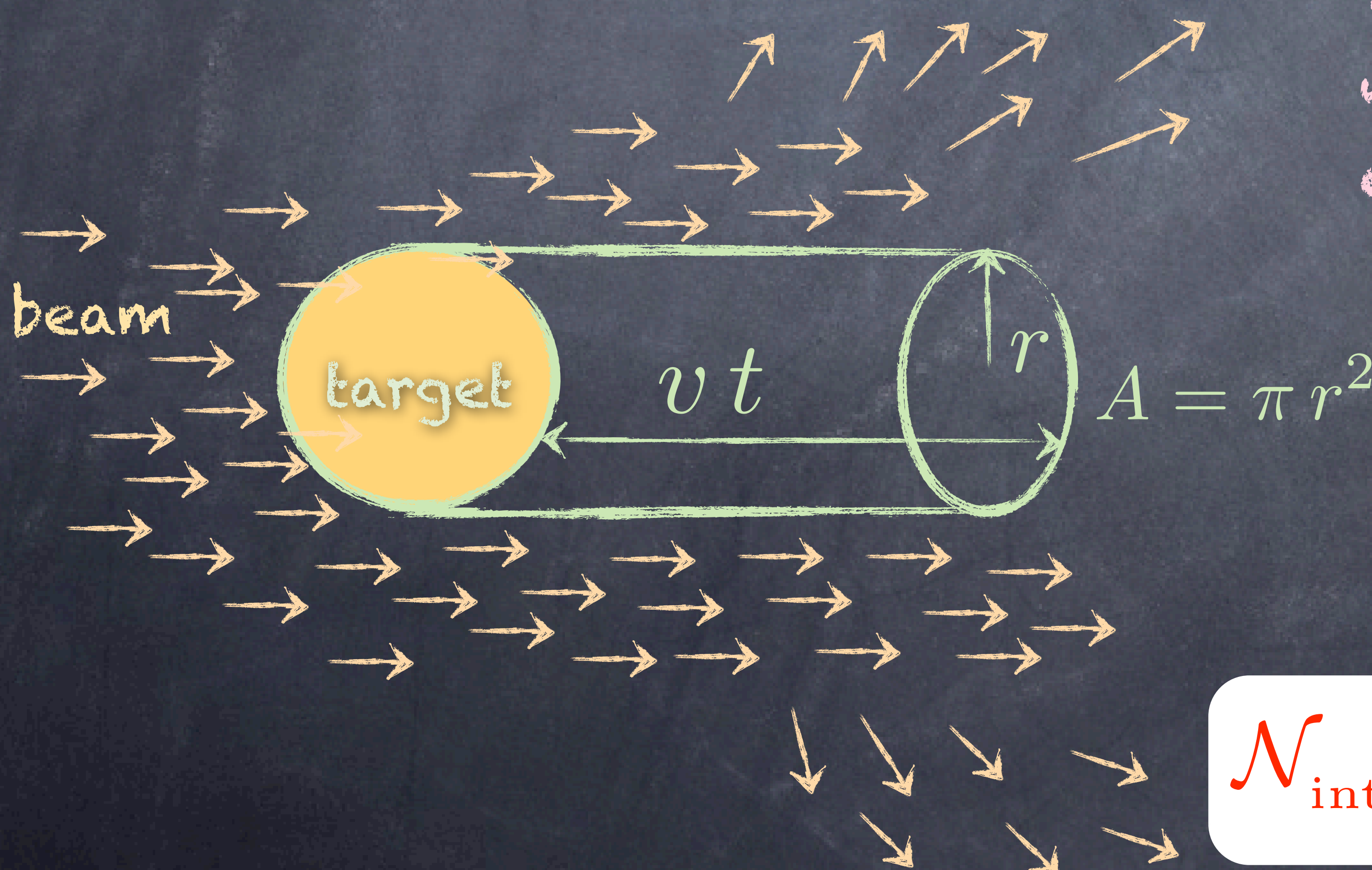
➢ hypothetical area expressing likelihood of interaction between particles

Concept derived from purely classical picture of (large number of) point-like projectiles directed to area that includes a solid target

interaction occurs (with 100% probability) if projectile hits solid and not at all (0% probability) if it misses

☛ total interaction probability for single projectile defined as ratio of area of the section of the solid to total targeted area

(area of the section of the solid) → cross section ☛ σ



Particles that have been scattered would have been located in cylinder had sphere not been there

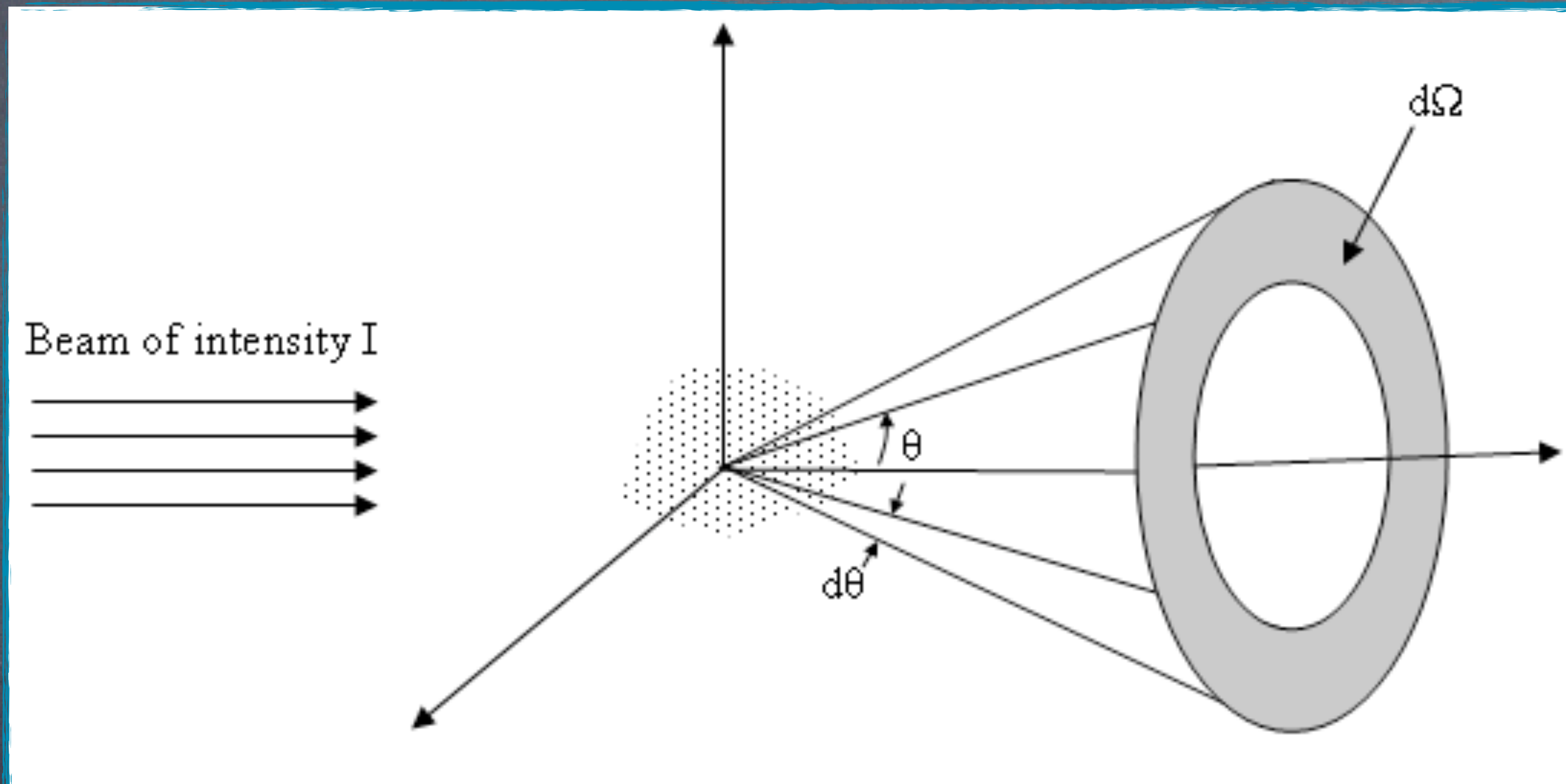
$$N_{\text{interactions}} = n_{\text{beam}}\, V$$

$$V = A\, L$$

In a time t the beam of particles travel a distance $L = v\, t$

$$\mathcal{N}_{\text{interactions per unit time}} = n_{\text{beam}}\, \pi\, r^2\, v$$

Differential Scattering Cross Section



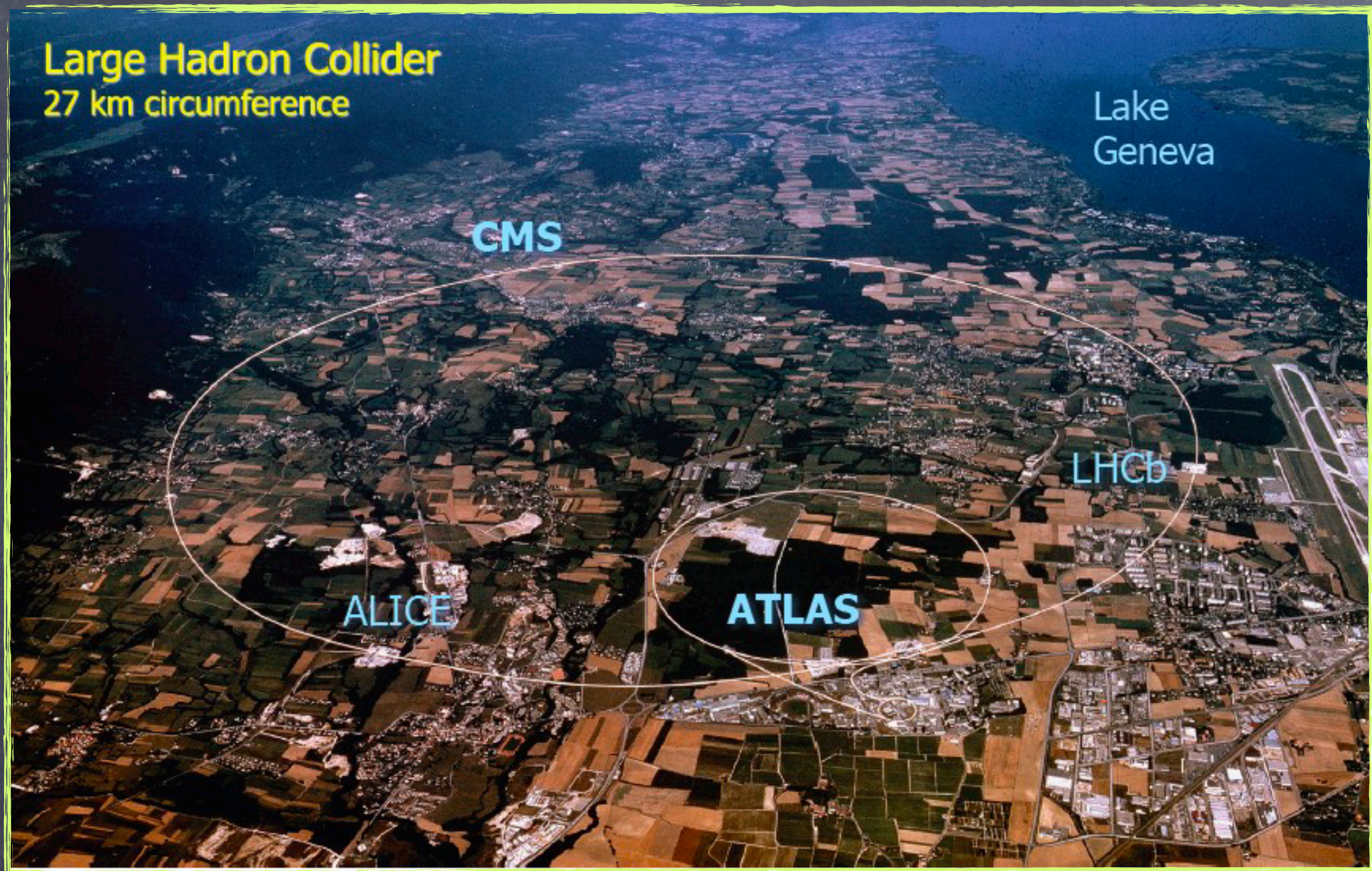
cross section unit ☛ barn $1\ \mathrm{b} = 10^{-28}\ \mathrm{m}^2$

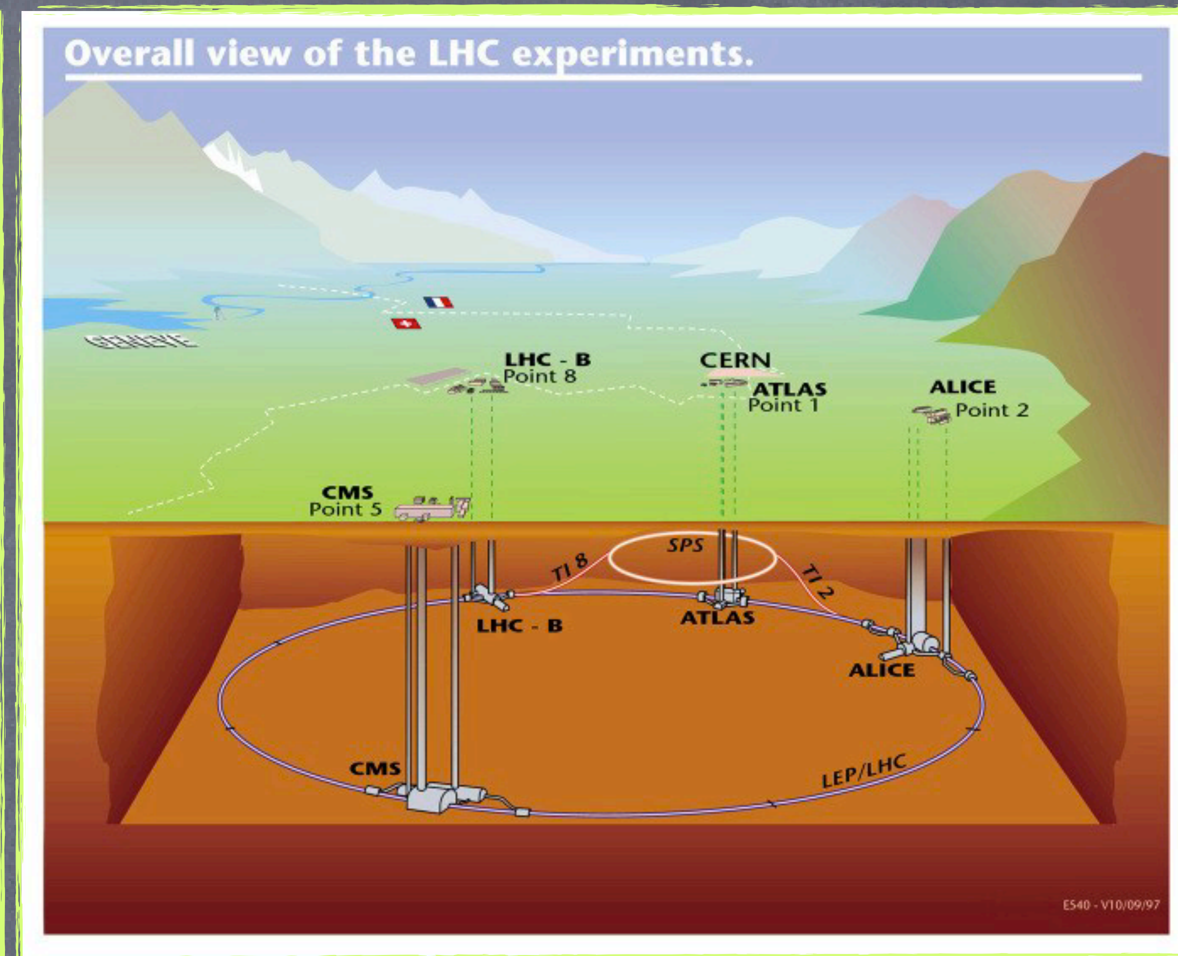
Large Hadron Collider vs Tevatron

- ❒ Proton-proton collider
- ❒ Max. $\sqrt{s}$ = 14 TeV (currently $\sqrt{s}$ = 7 TeV)
- ❒ Peak luminosity $10^{34}\ cm^{-2}\ s^{-1}$ (already reached: $2\ 10^{32}\ cm^{-2}\ s^{-1}$)

- ❒ Proton-antiproton collider
- ❒ Max. $\sqrt{s}$ = 1.96 TeV
- ❒ Peak luminosity $\sim 4\ 10^{32}\ cm^{-2}\ s^{-1}$

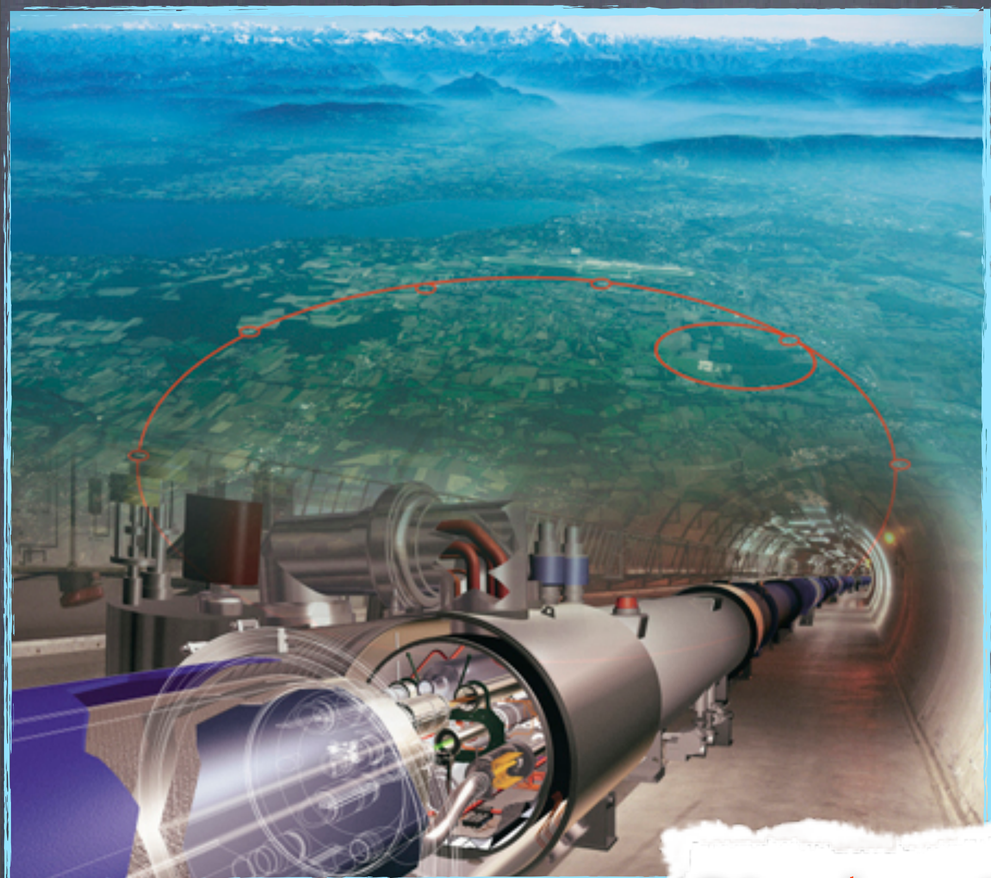
LHC





- Major objective: discover/study Higgs particle
  - For all masses up to 1 TeV in a Standard Model scenario
- It is designed to look for generic new physics signals at the TeV scale:
  - High center-of-mass energy ($\gtrsim$ 1TeV) in collisions between elementary constituents

LHC7



Proton-proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$

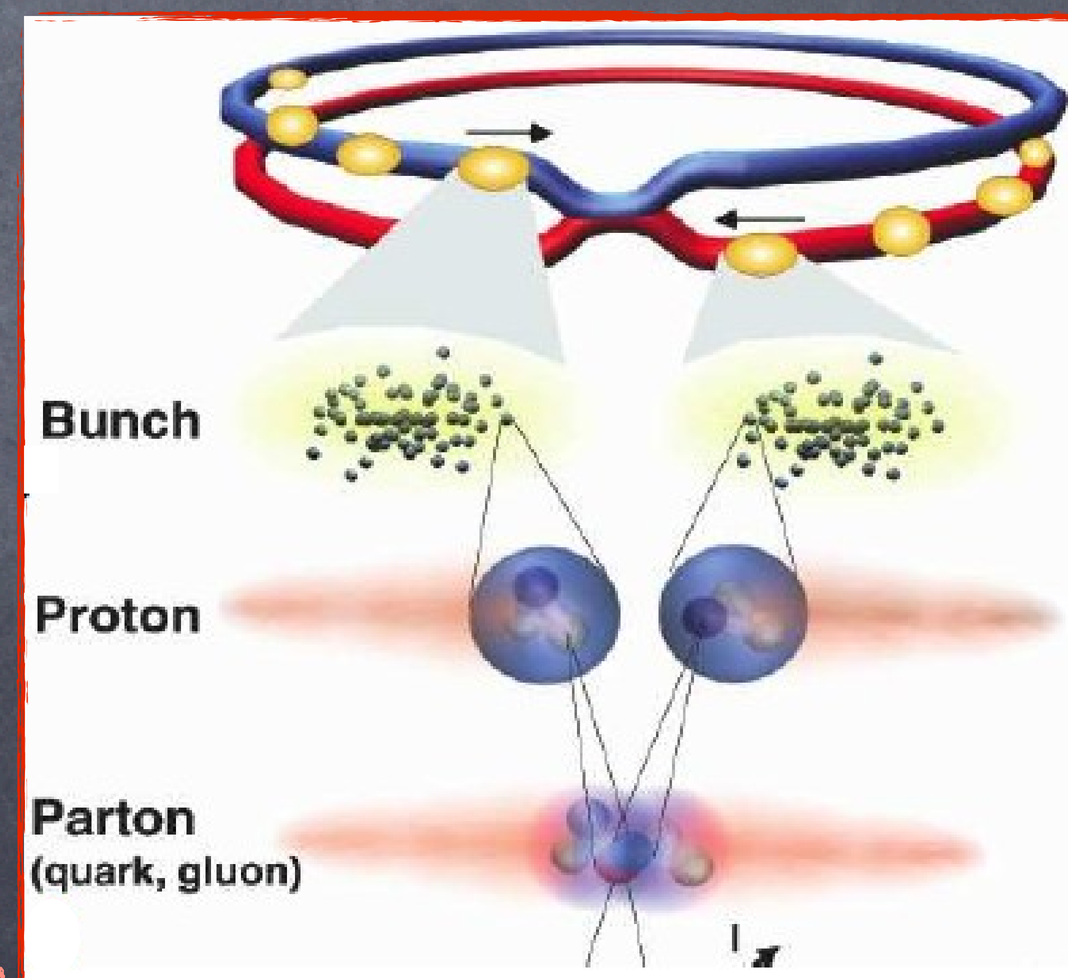
From March 30th until 6th November

(initial tests & physics at $\sqrt{s} = 0.9,\ 2.36\,\mathrm{TeV}$ by end 2009)

Pb-Pb collisions at $2.76\,\mathrm{TeV}$/ nucleon

during 1 month (8th Nov-16th Dec 2010)

Dipoles=15m long, 35 Ton
Provide 8.3T in LHC



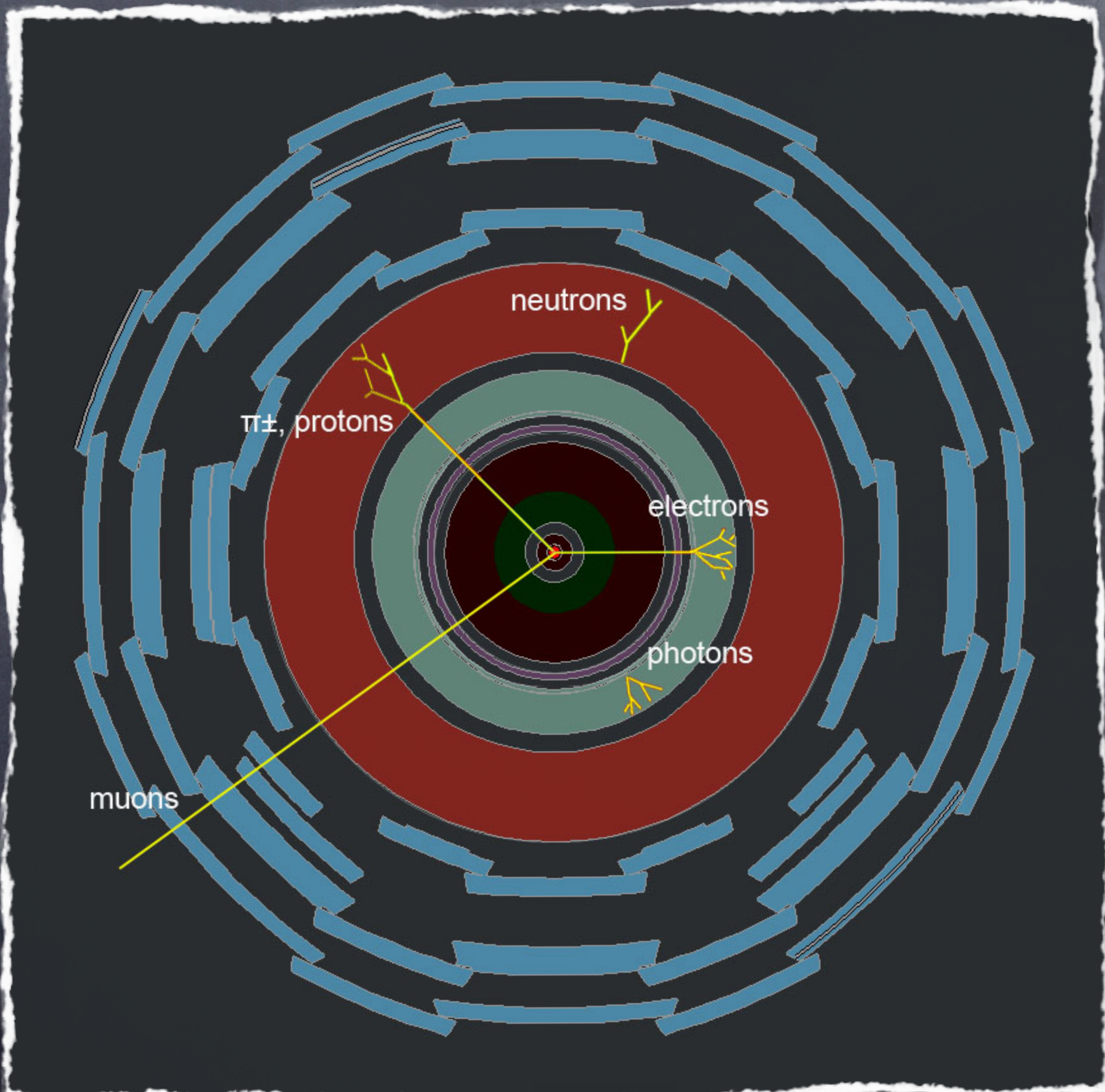
Largest superconducting magnet system:

~8000 magnets (1232 dipoles, 400 quadrupoles,....)

refrigerated with liquid He at 1.9 K

Great technological challenge in many aspects (magnets, cryogenics, vacuum,...)

LHC calorimeter



tracking chamber

electromagnetic calorimeter

hadron calorimeter

muon chamber

Two general-purpose experiments: ATLAS & CMS

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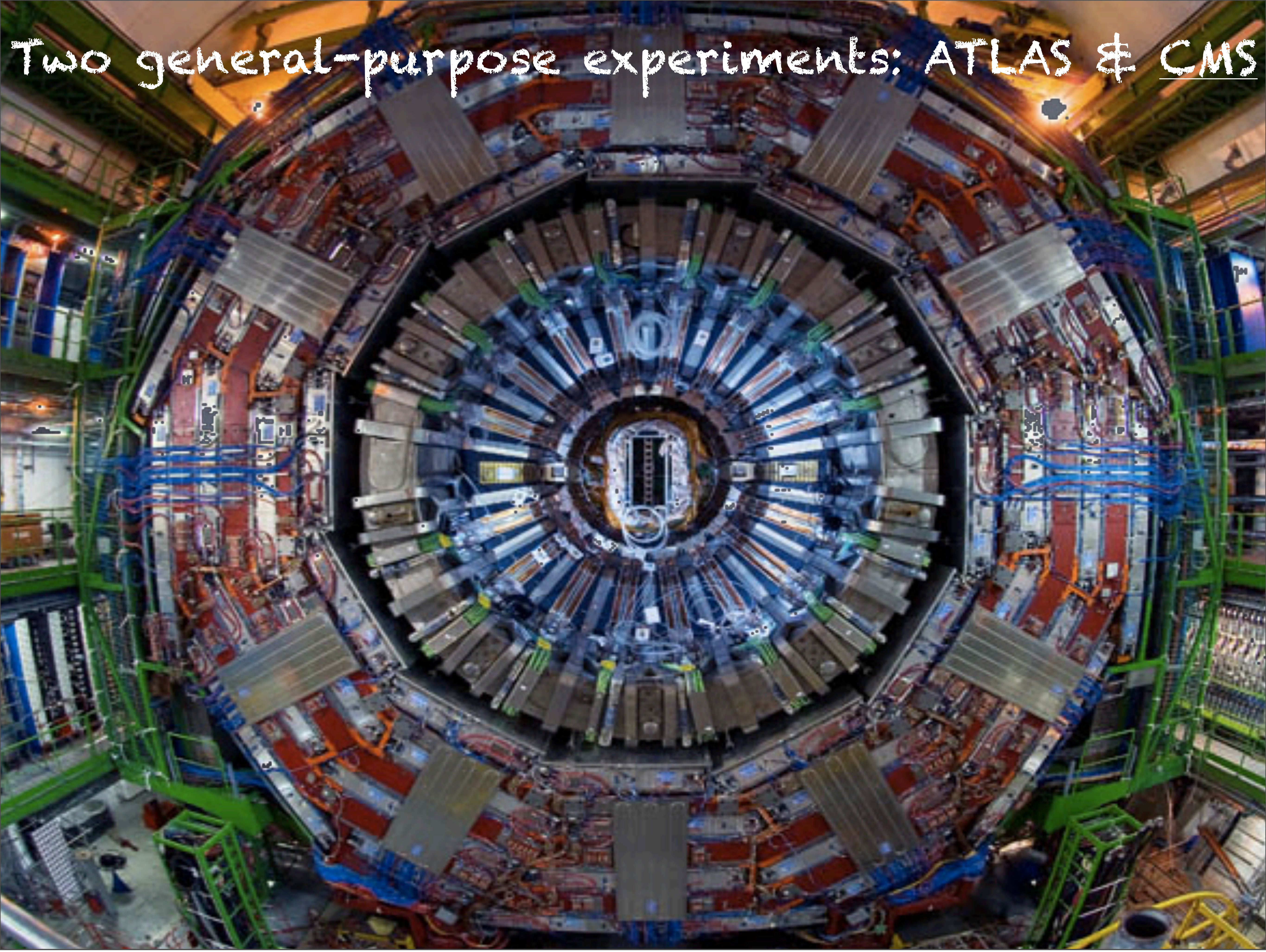
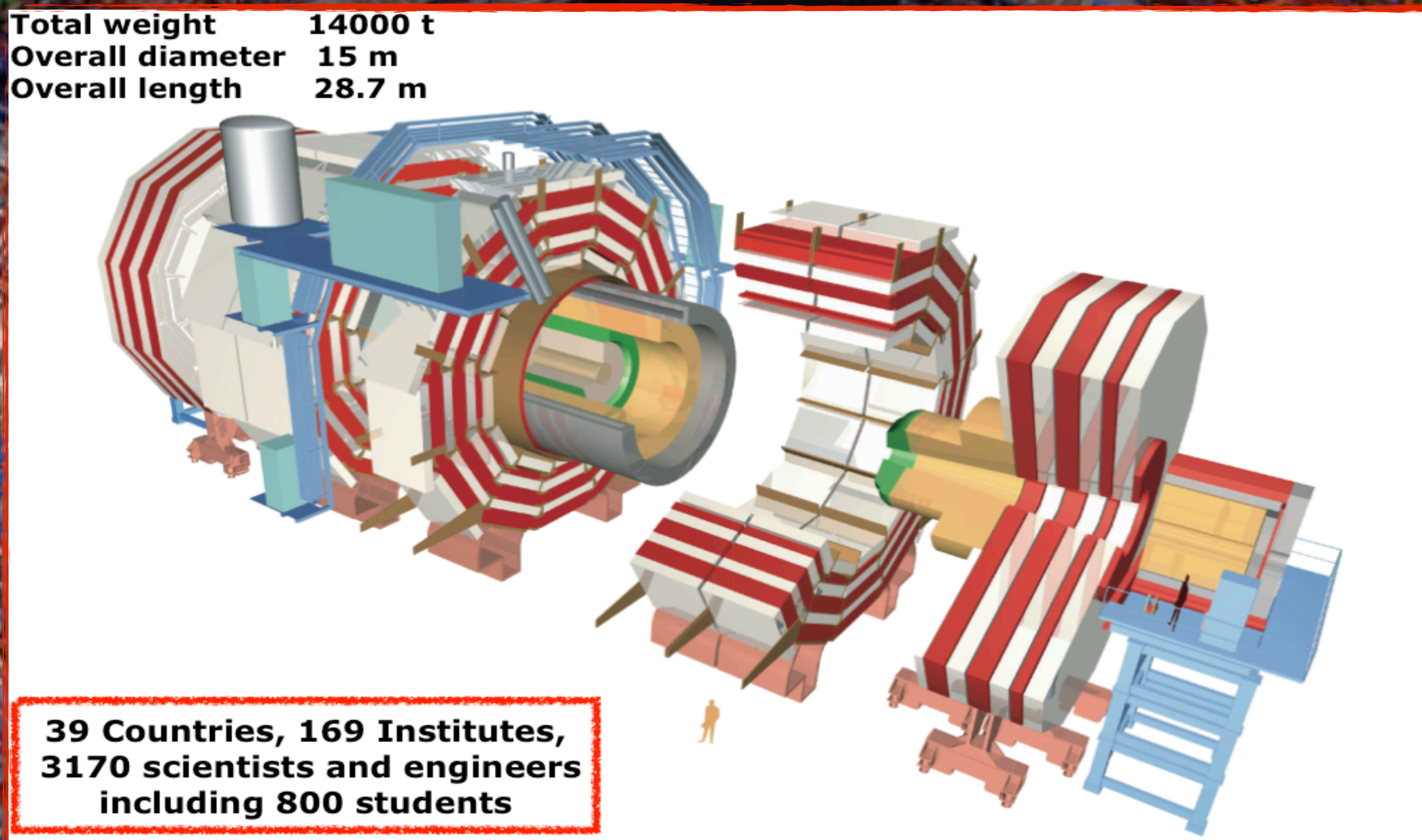


Two general-purpose experiments: ATLAS & CMS



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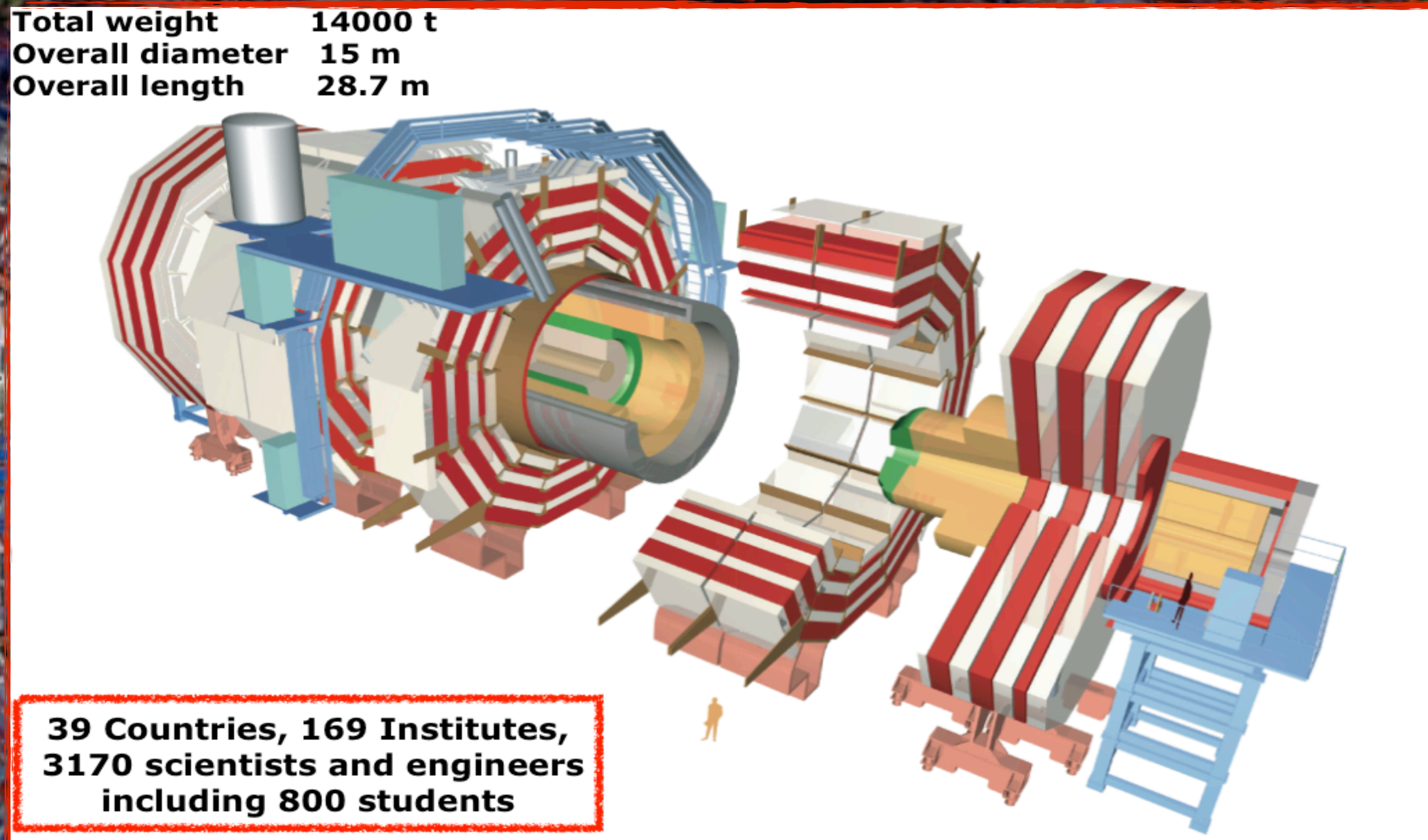

Emphasis on excellent resolution (energy, momentum, mass) of electrons, photons, muons

Two general-purpose experiments: ATLAS & CMS

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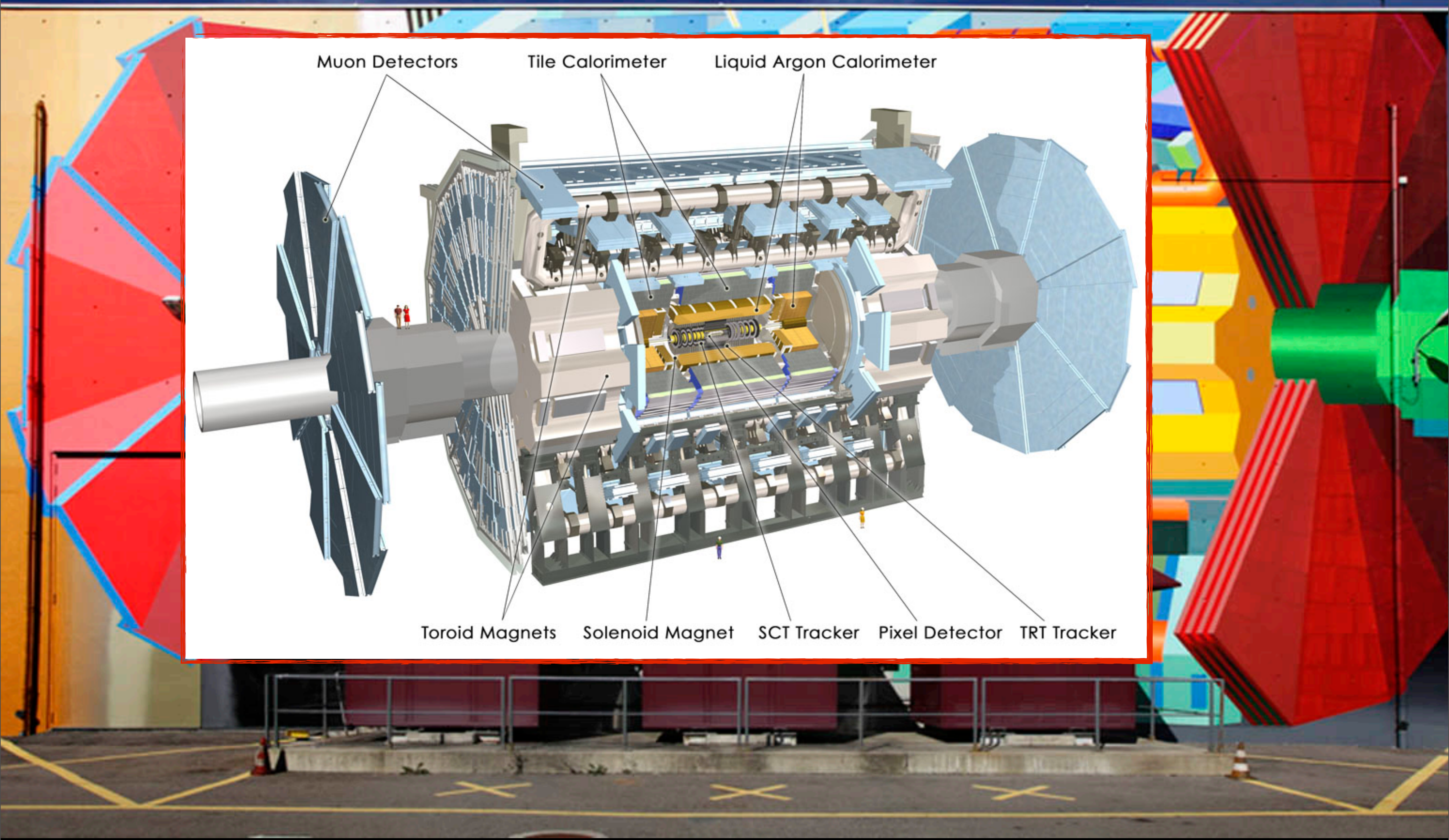
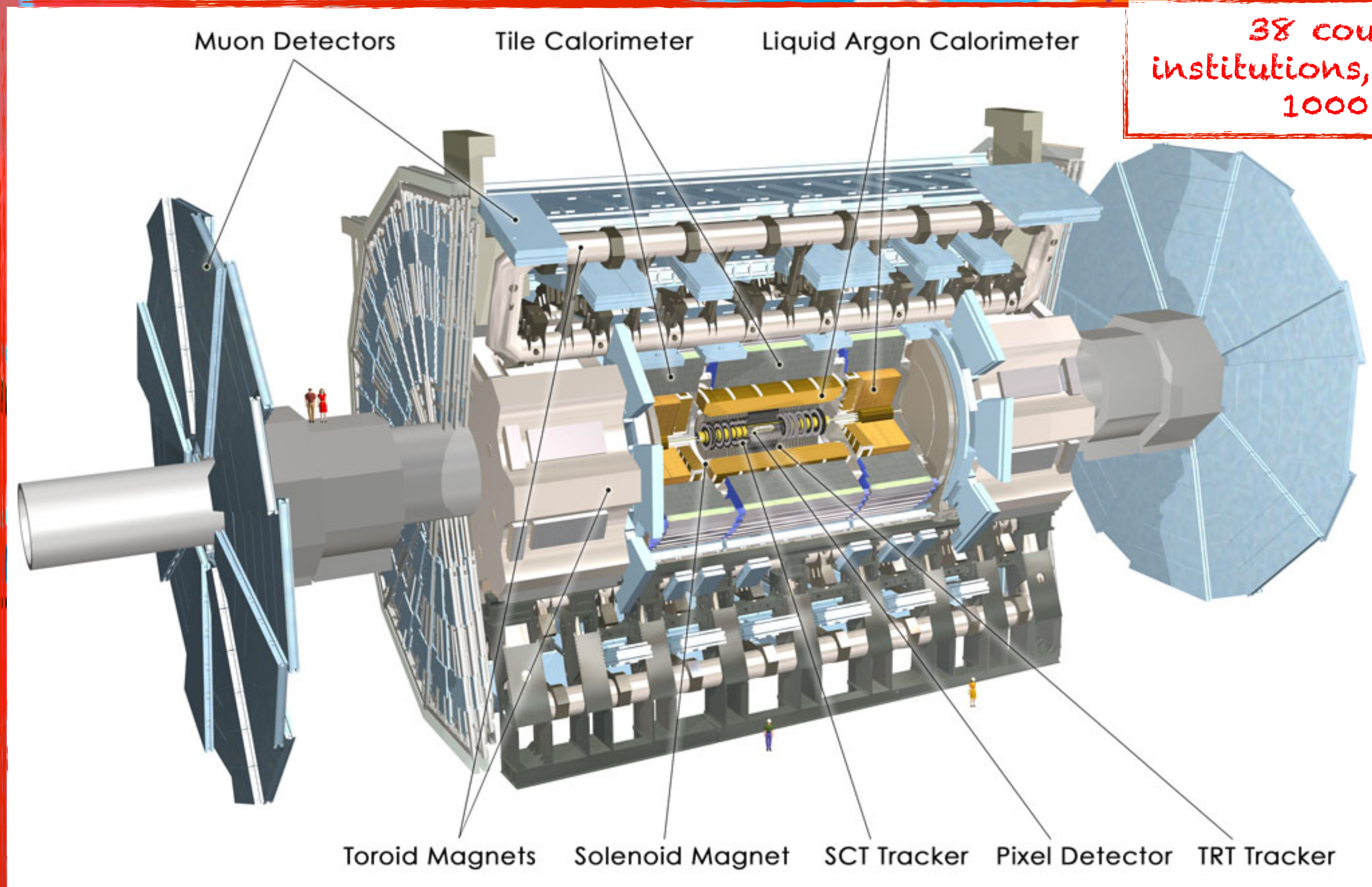


Two general-purpose experiments: ATLAS & CMS

38 countries, 174 institutions, 3000 scientists, 1000 students



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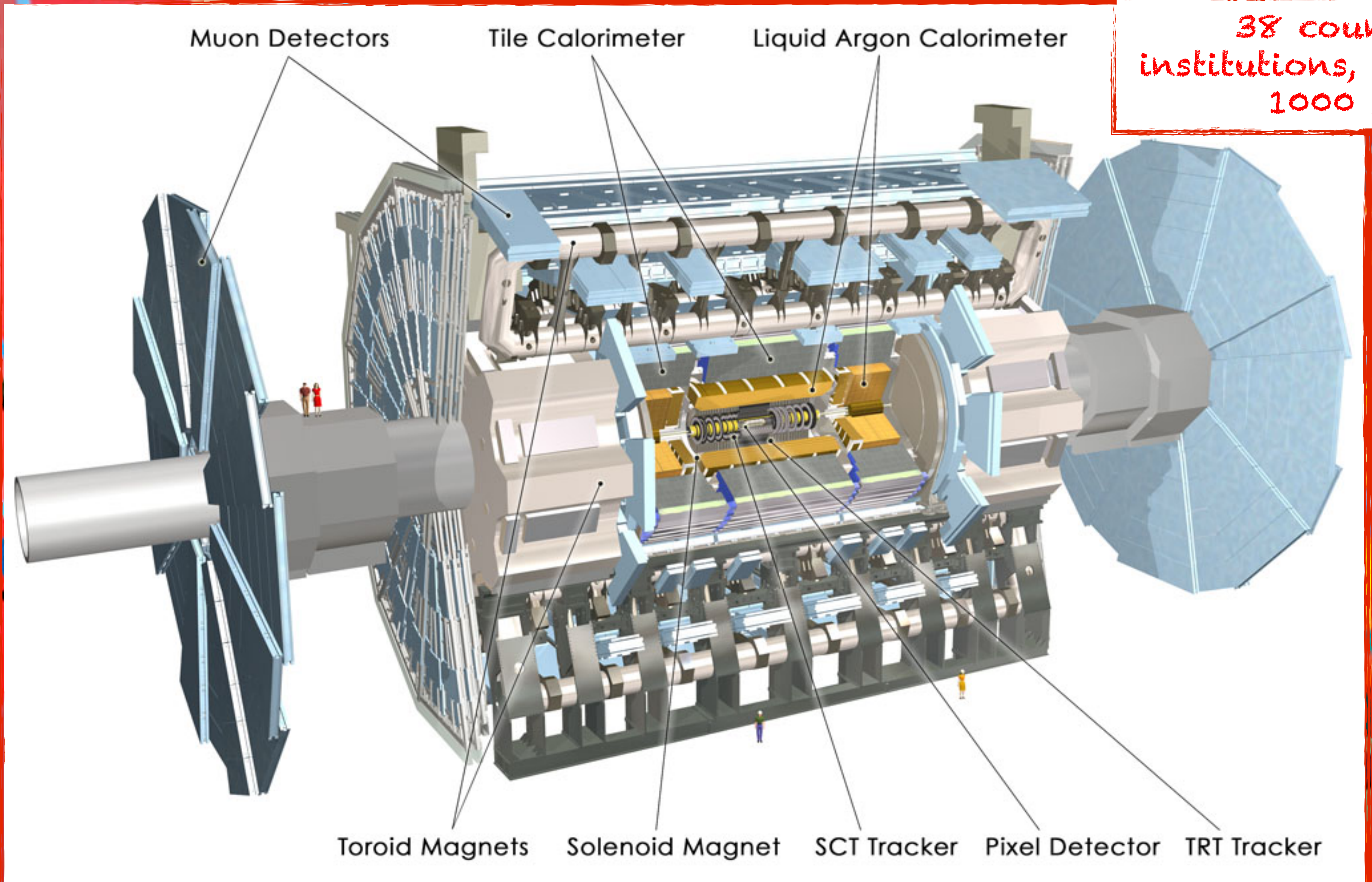
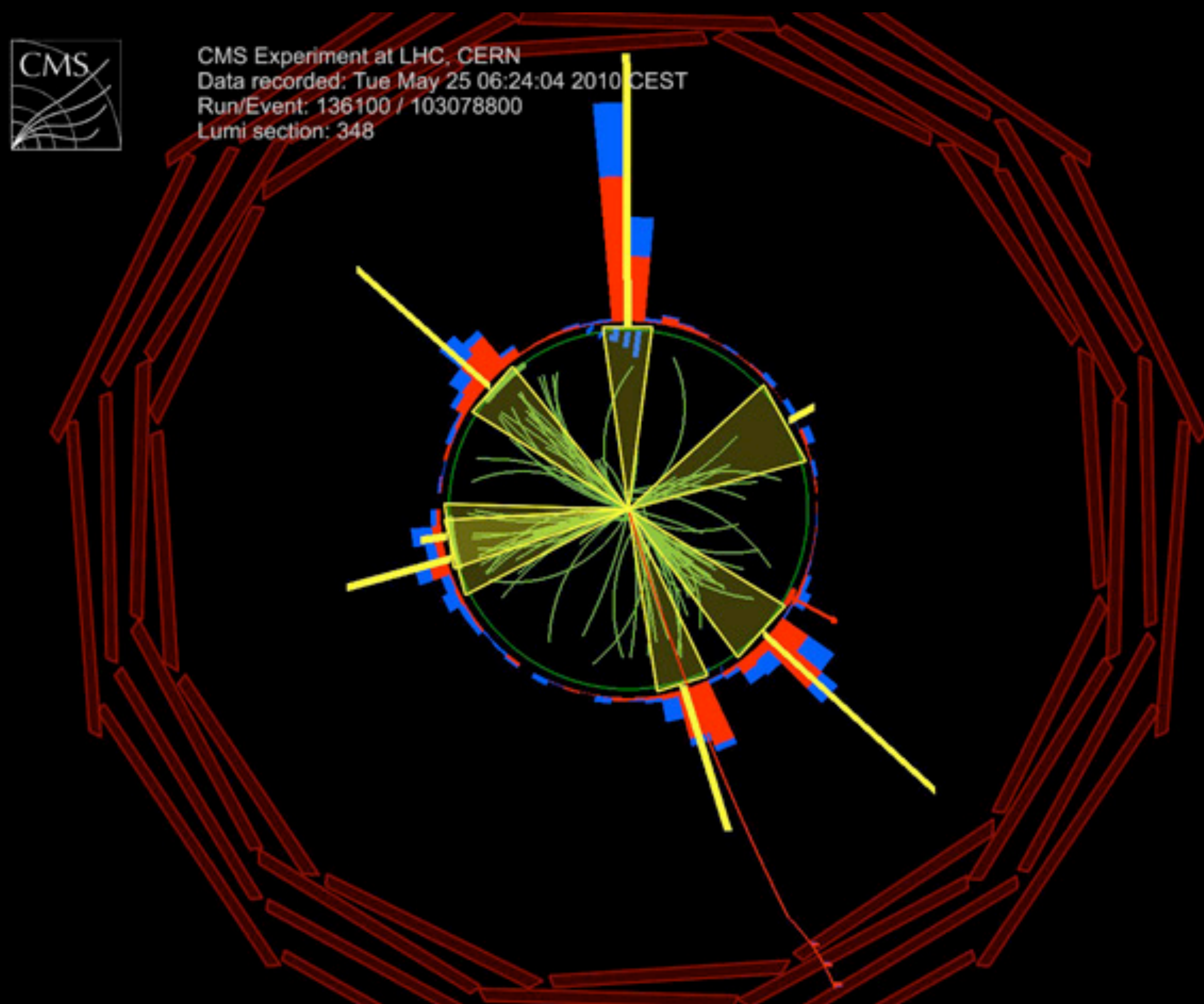


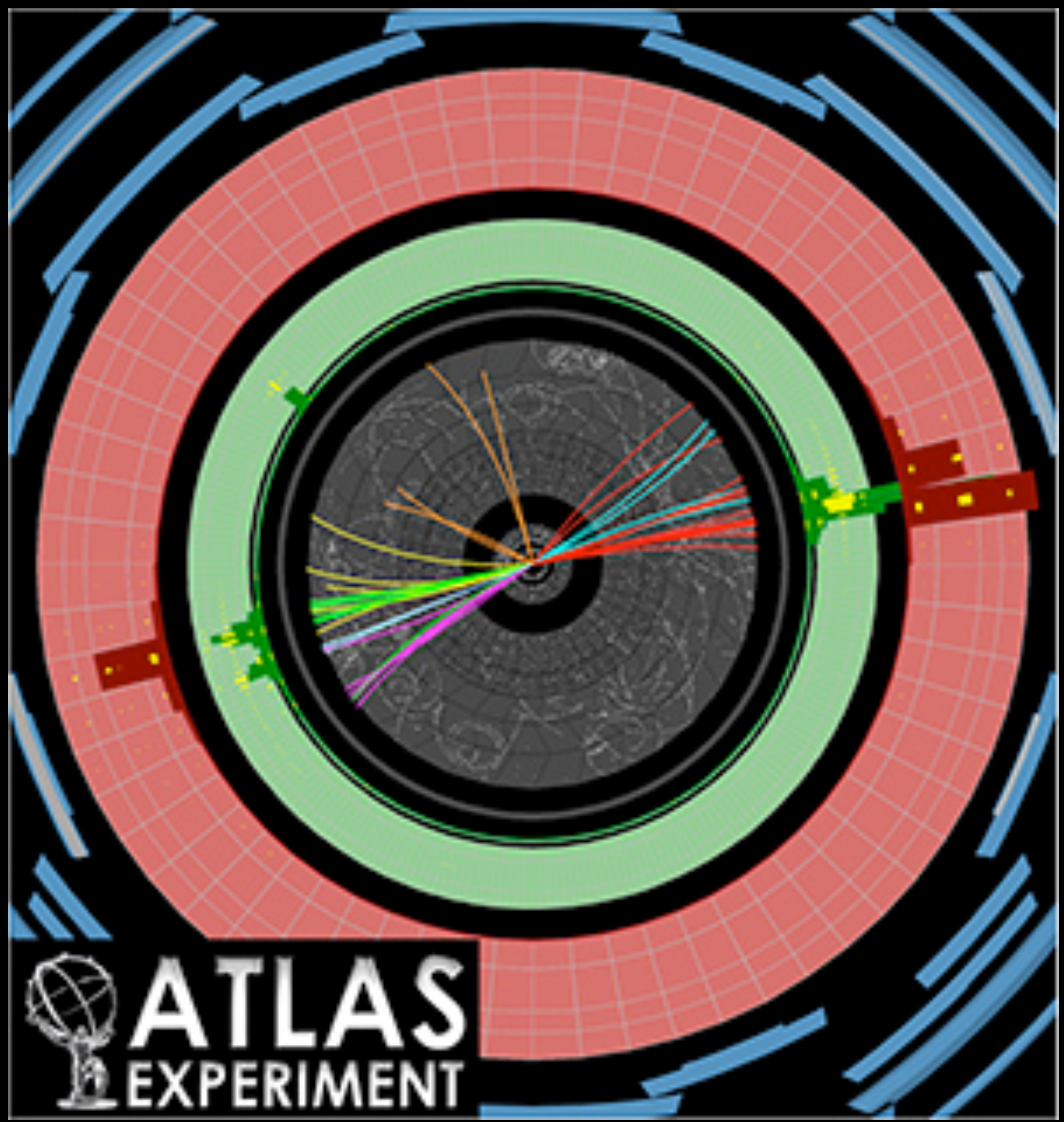
38 countries, 174 institutions, 3000 scientists, 1000 students

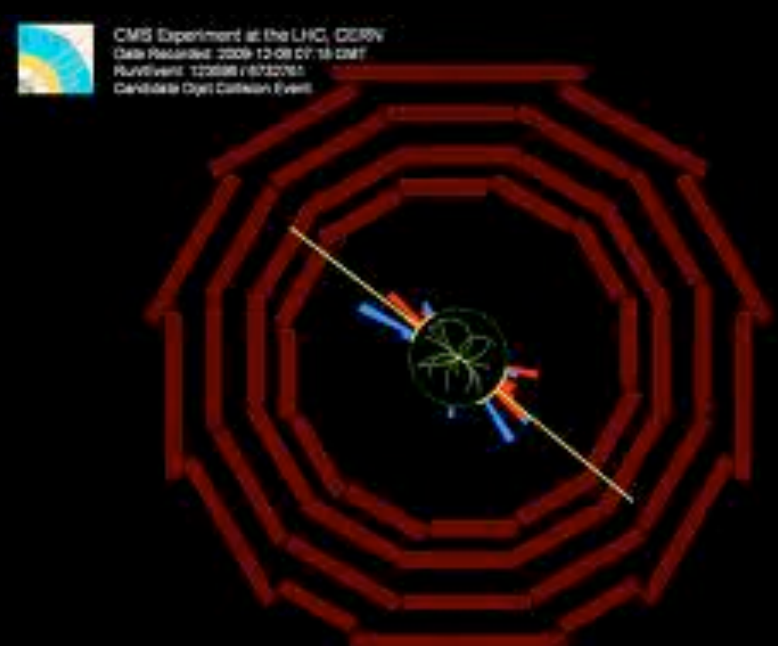
Emphasis on excellent jet and missig-E_T (MET) resolution, particle identification and standalone muon reconstruction

LHC7 data



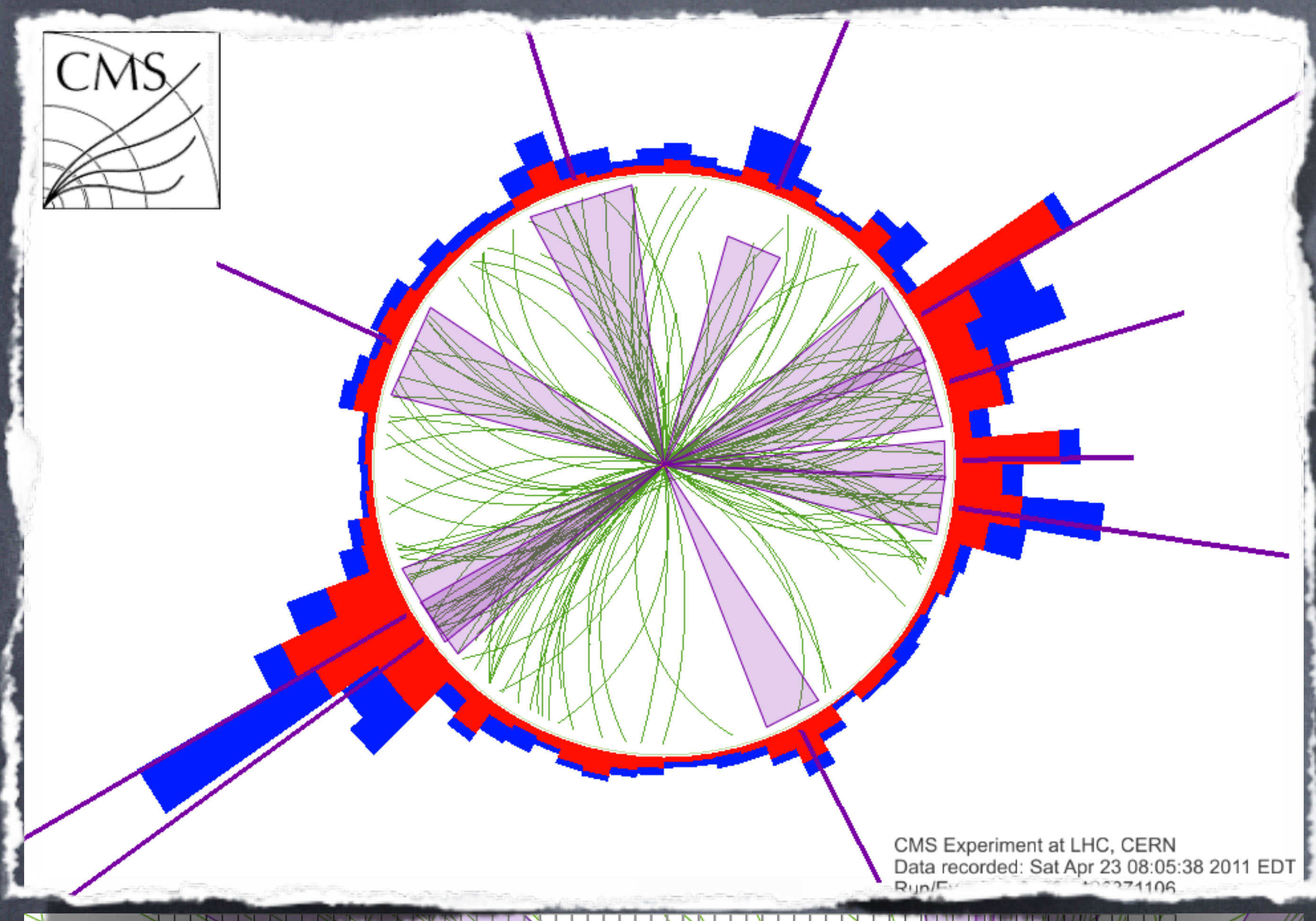
multijet event





dijet events

CMS multi-jet event

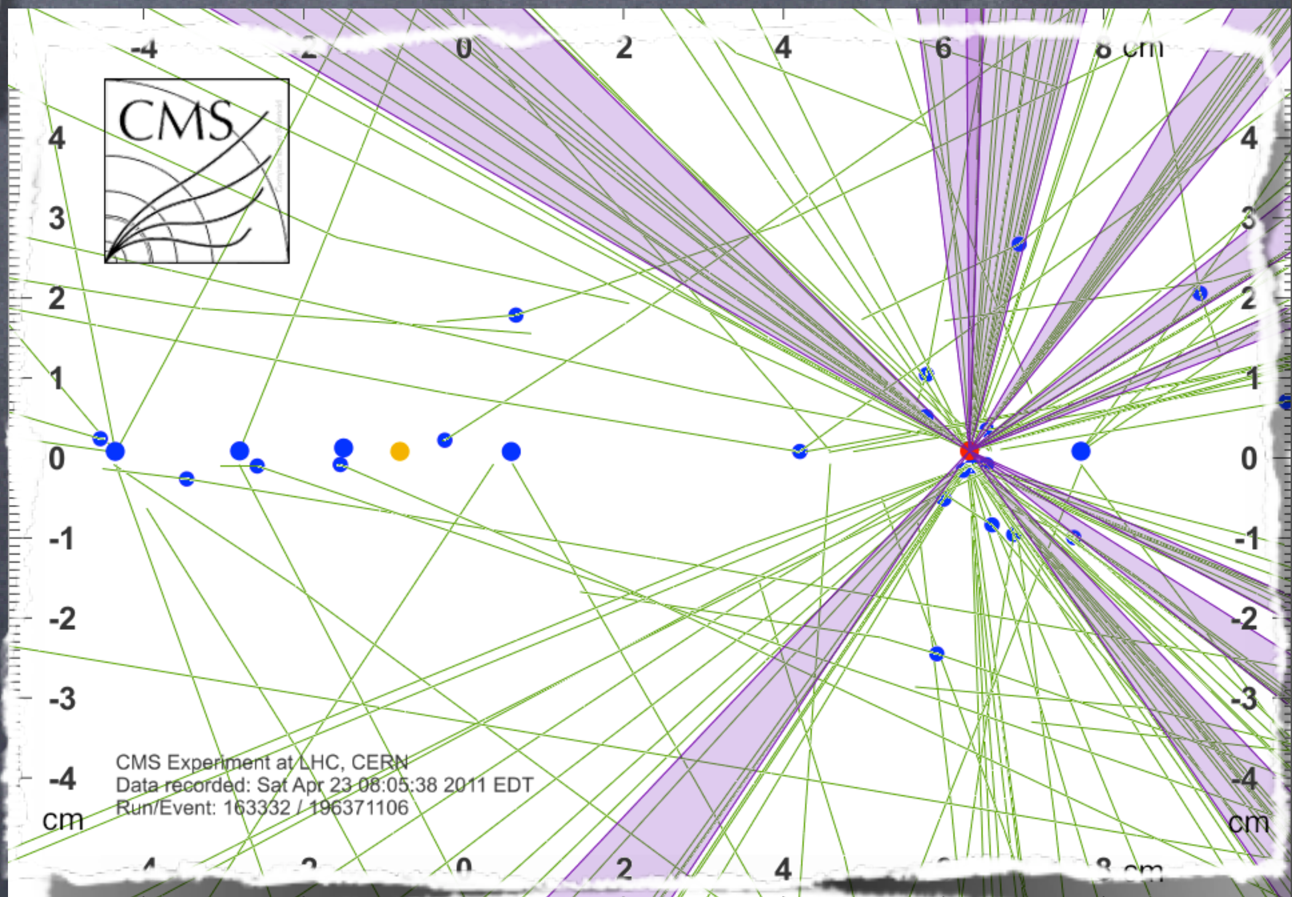


Transverse view of event with 10 objects (jets) highlighted with magenta cones

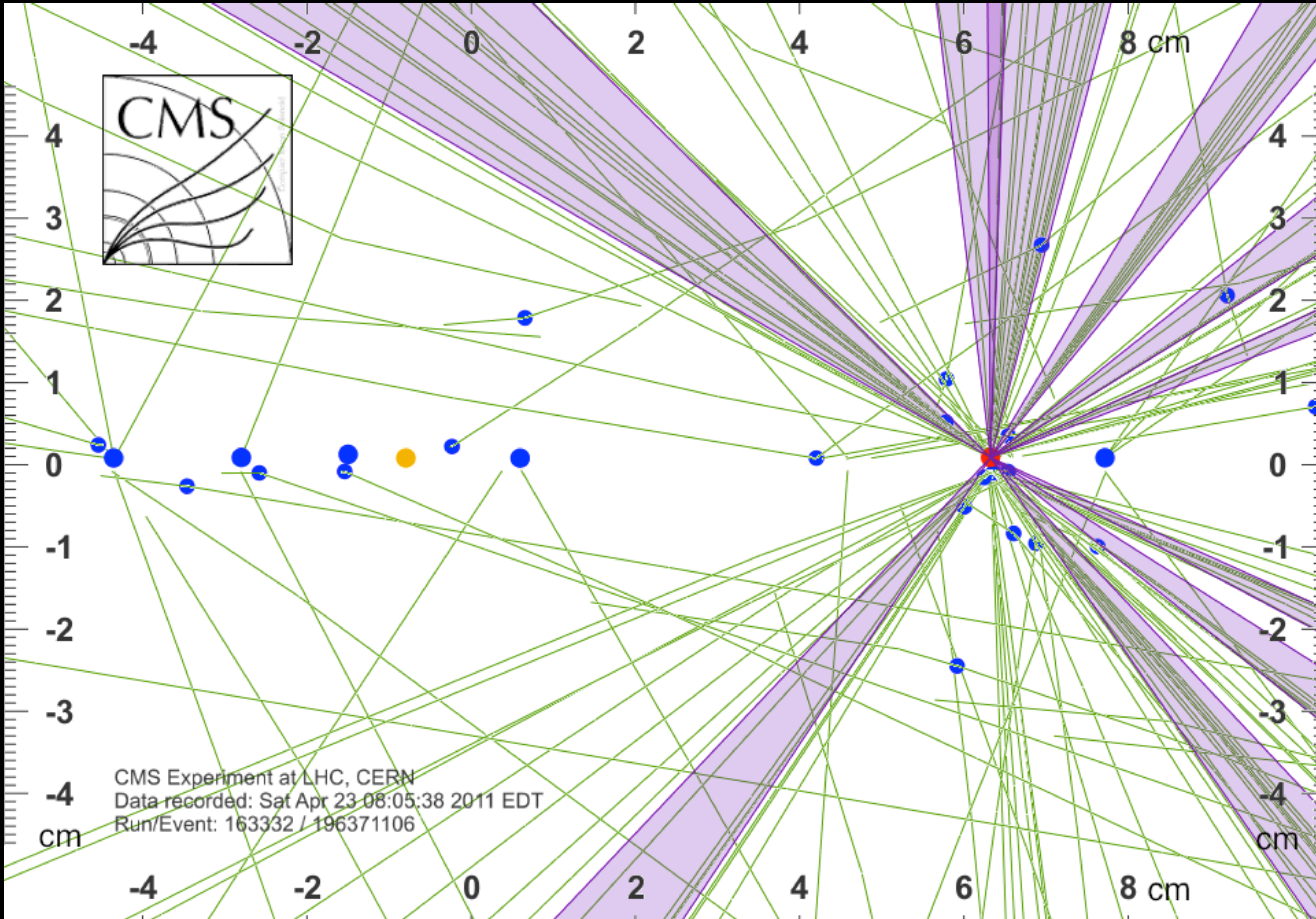
Zoom on vertex region in view parallel to beam-line

All jets come from same primary vertex (red dot) despite number of pile-up vertices (blue dots)

Nominal beam-spot position is shown with an orange dot

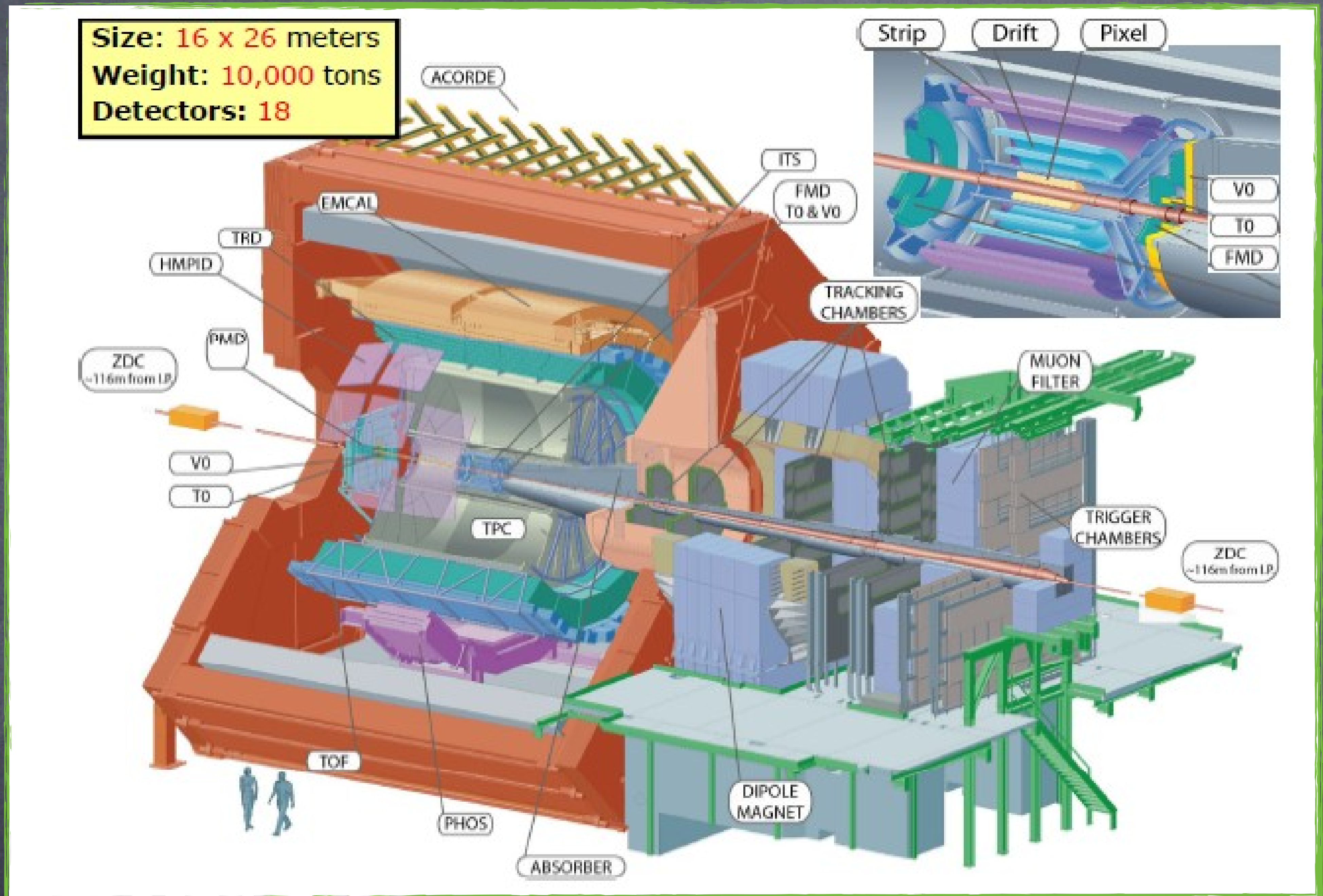


CMS Multi-jet event (cont'd)



ALICE & LHCb

Heavy ion collisions at LHC: ALICE

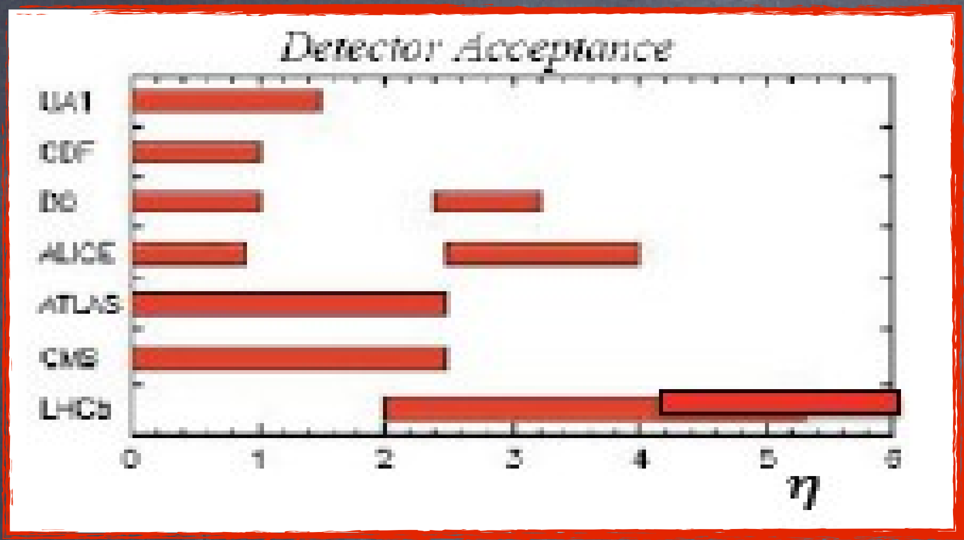


Many different sub-detectors
some of them covering small solid angle
but very specialized in particle identification/counting
for heavy ion collisions

Studies in the b sector at LHC: LHCb

LHCb is General Purpose Detector in the forward direction ($2 < \eta < 6$)

(designed to take data @ $2 \times 10^{32}\,cm^{-2}\,s^{-1}$)



$$\eta = -\ln\tan(\theta/2)$$

angle wrt beam direction

[see PDG]

LHCb is fully instrumented to provide:

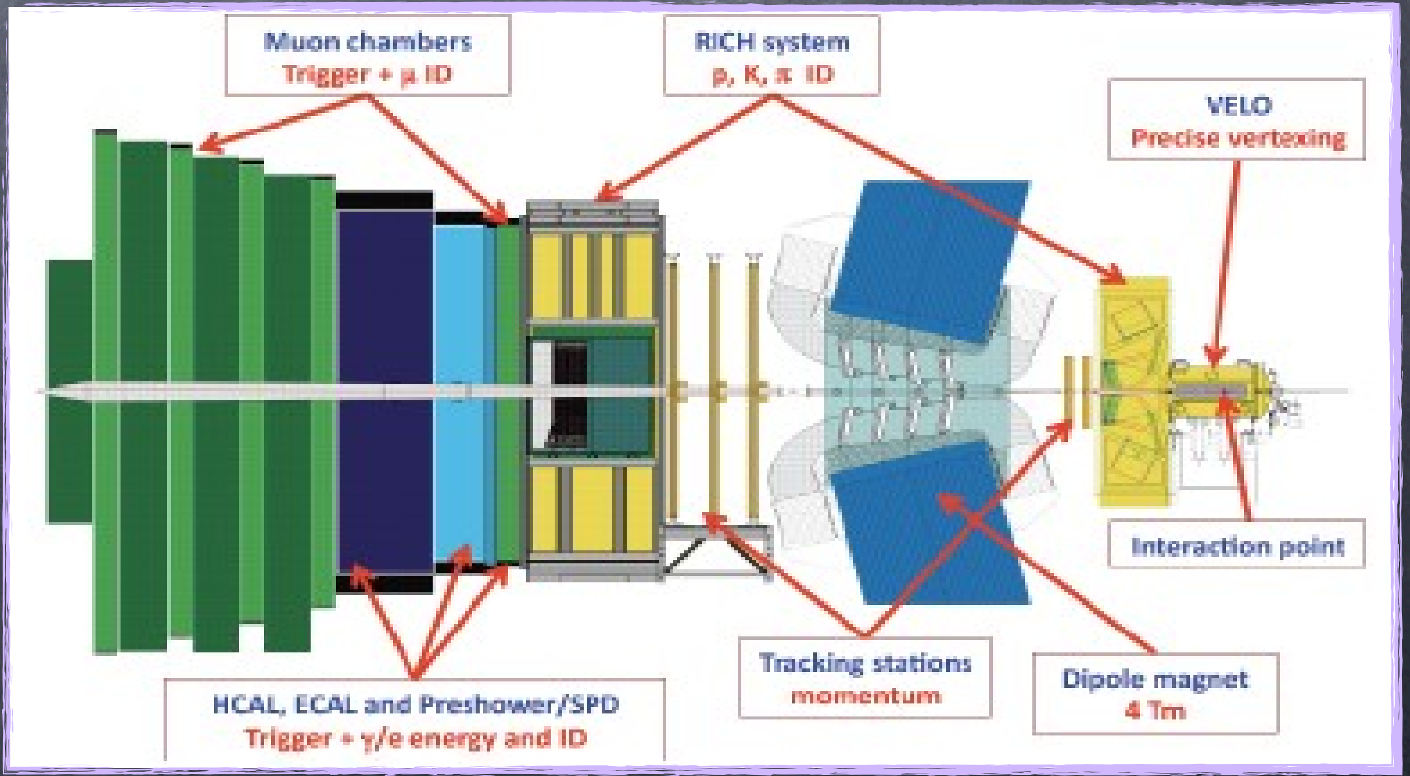
- Vertexing
- Tracking
- PID (hadron, muon, electron, photon)

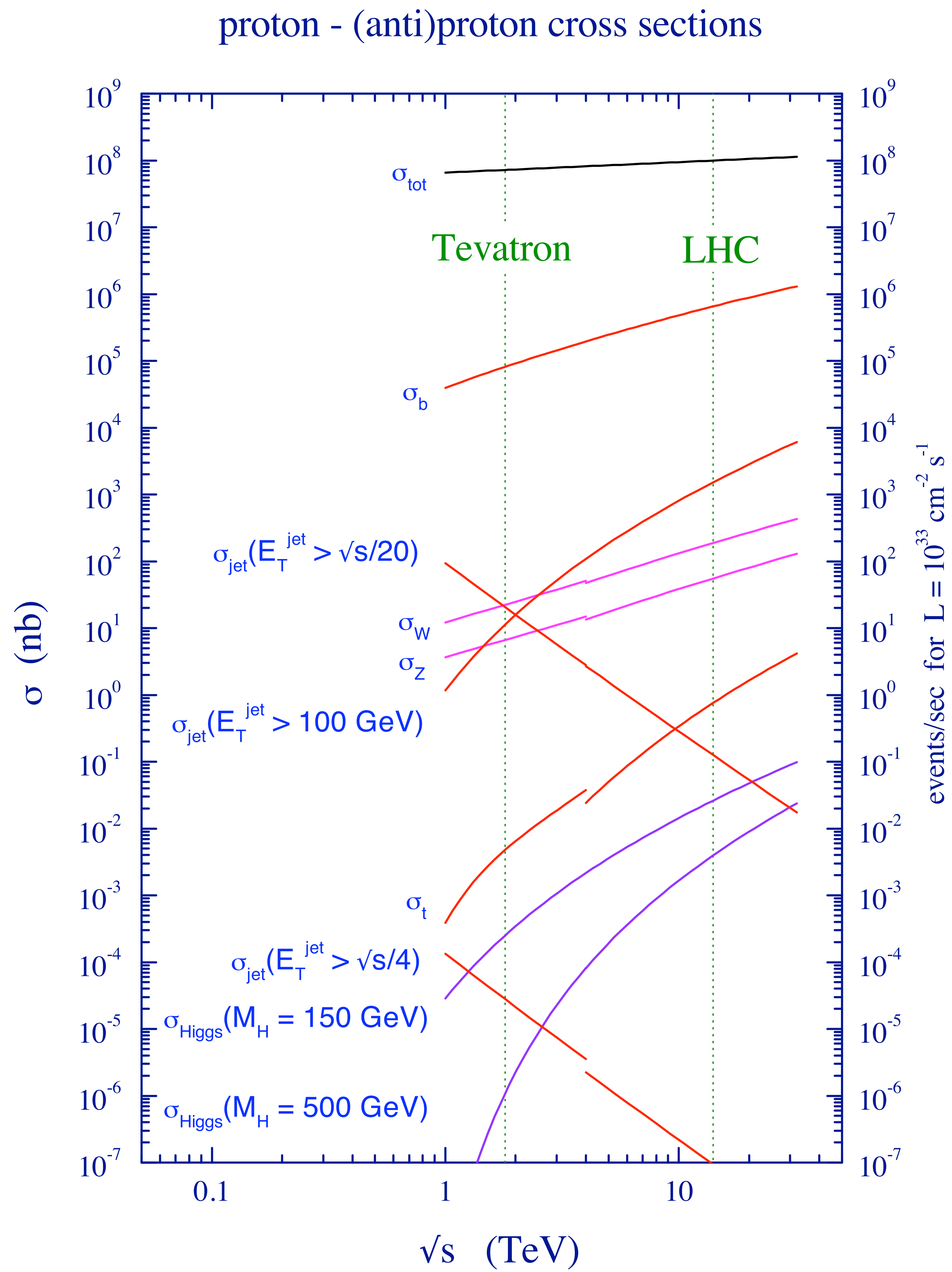
&

Flexible Trigger to low p_T particles

Well suited for flavor physics:

* Large bb (& cc) cross sections
* All B hadron species available
* Long decay flight
  ~ 1 cm for b hadrons





Thursday, September 8, 2011

Provisional Course Outline

(Please note this may be revised during the course to match coverage of material during lectures, etc.)

1st week: Lagrangian Field Theory

2nd week: Dirac Equation & Perturbation Theory

3rd week: Gauge Symmetries & Higgs Mechanism

4th week: Standard Model of Particle Physics

5th week: Electrodynamics of Spinless Particles

6th week: Electrodynamics of Spin ½ Particles
(beyond the trees ☛ dimensional regularization)

7th week: Structure of Hadrons, Deep Inelastic Scattering, Parton Model

8th week: Midterm-exam (October 27)

9th week: QCD Improved Parton Model

10th week: Electroweak Theory
(charged and neutral currents - radiative corrections)

11th week: Neutrino Oscillations

12th week: Midterm-exam (December 1)

13th week: New Physics at the TeV-scale? What about dark matter?


That's all Folks!