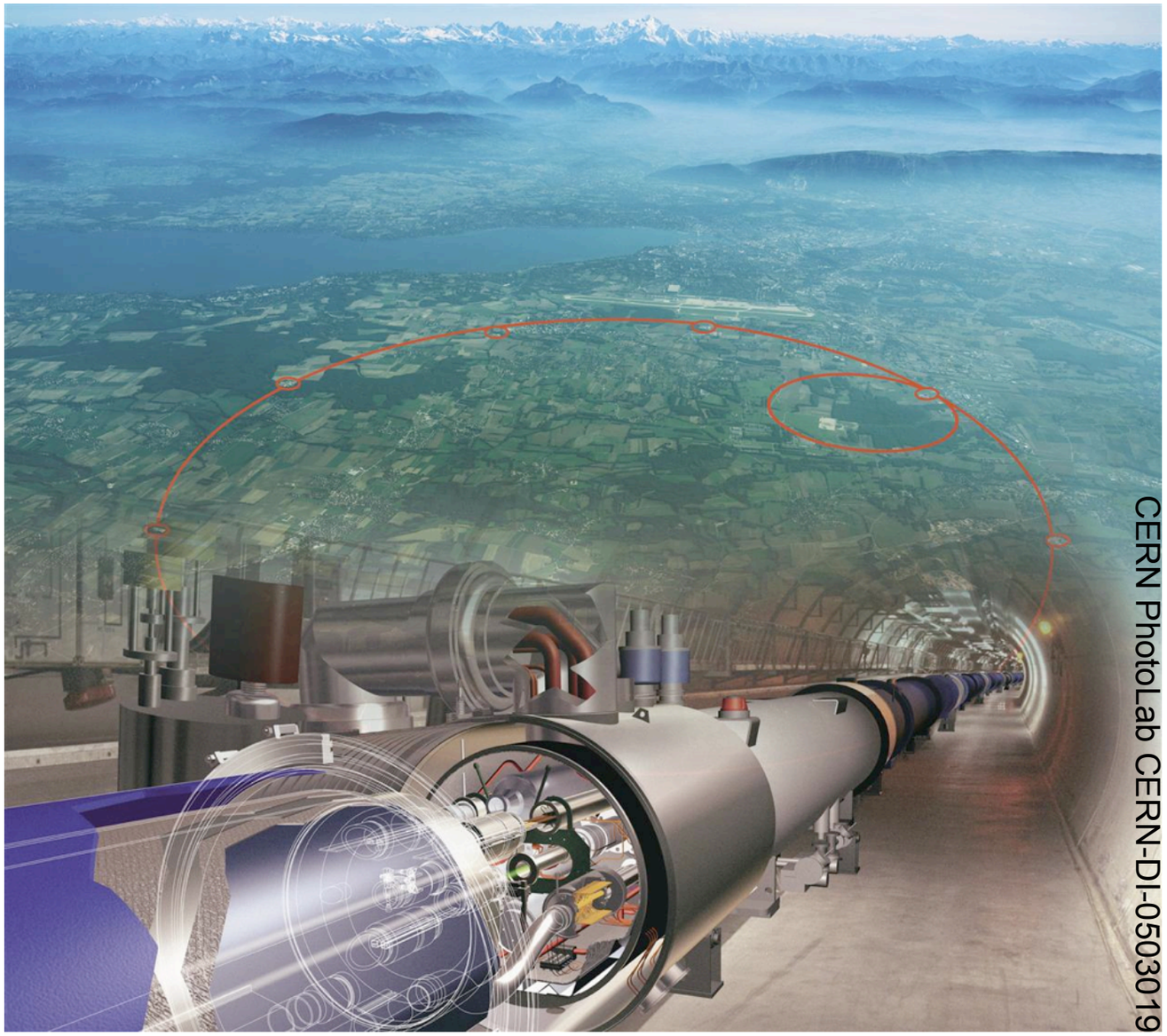
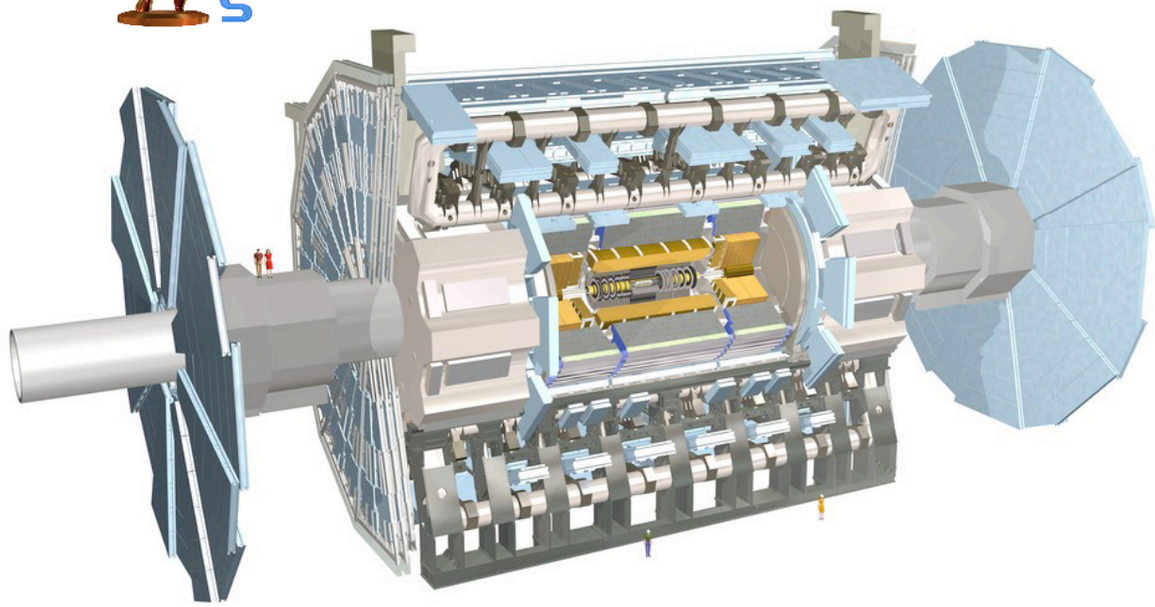
Probing the secrets of the Universe with the Large Hadron Collider and the ATLAS detector



Matter and space exploration at the smallest scale



Michel Lefebvre
University of Victoria, Canada
and LAPP, Annecy-le-Vieux, France

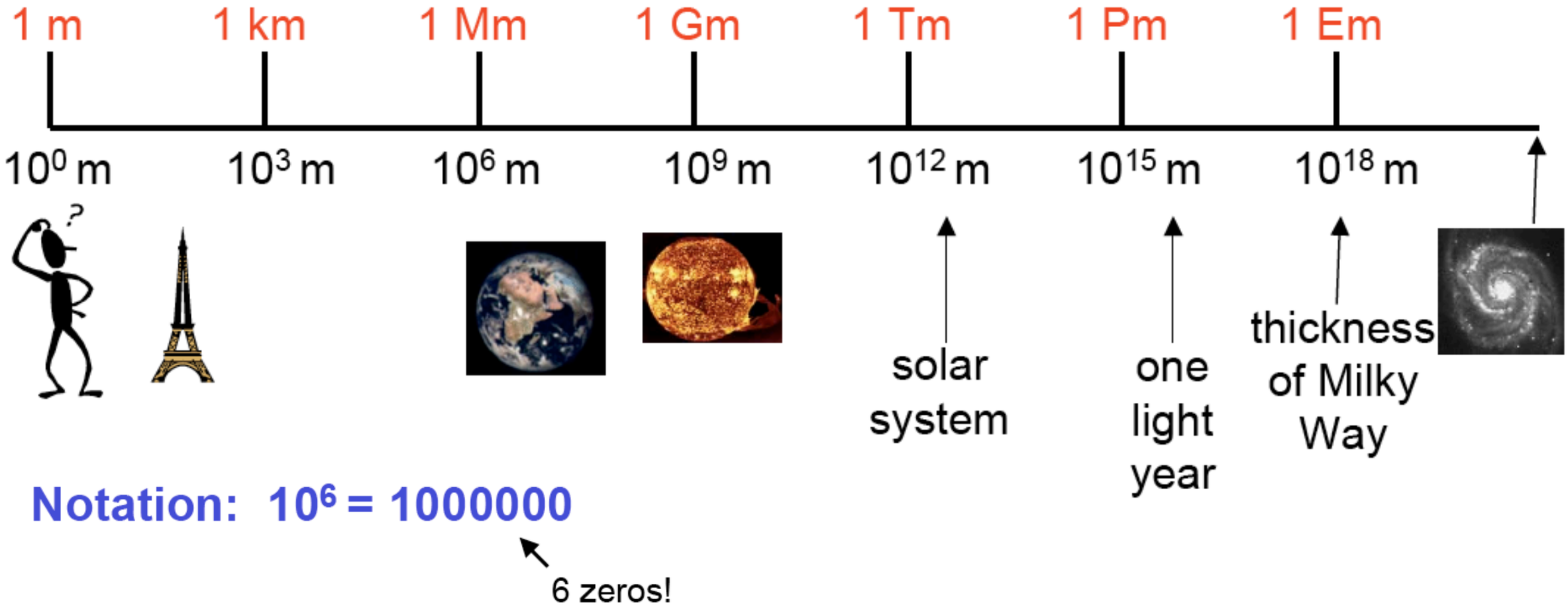
ASX Symposium
University of Toronto
28 January 2011

Abstract

The Large Hadron Collider, located near Geneva, Switzerland, is in operation since just over a year. With its 27 km long tunnel and related accelerator complex, it is the largest scientific tool ever made, and it now allows scientists to probe the very fabric of nature to unprecedented depth through the study of particle collisions. ATLAS is the largest particle detector at the LHC. Over 3000 scientists from around the world, including many from Canada, have collaborated for nearly twenty years in the design, construction, and now operation of the ATLAS detector.

Our current understanding of the fundamental laws of nature is remarkable, but many important questions remain. What is the origin of mass? Are there extra dimensions of space? Can all fundamental forces be unified? What is the nature of dark matter? This talk will briefly describe the Large Hadron Collider, the ATLAS detector and its scientific programme, the latest results, and future prospects.

Length Scales

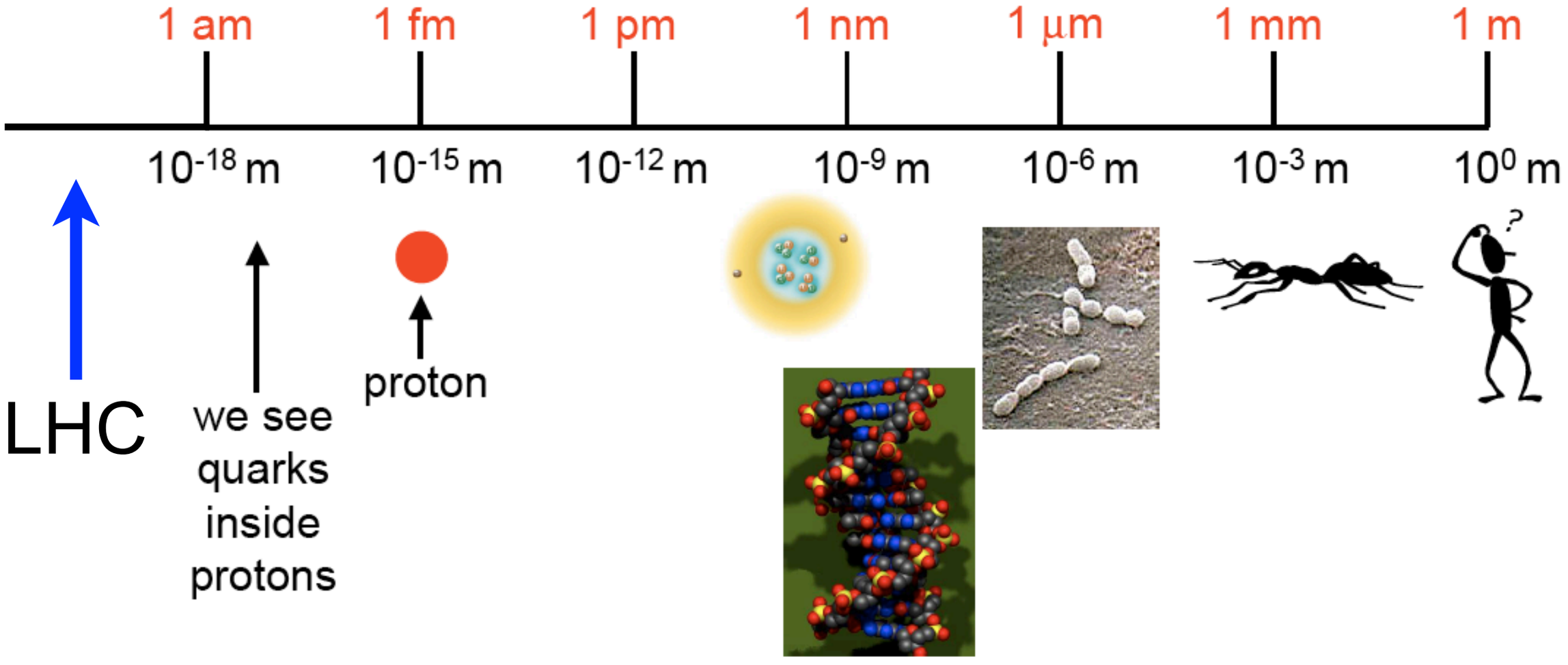


Notation: $10^6 = 1000000$

6 zeros!

Astrophysics explores matter and space in its largest dimensions

Length Scales



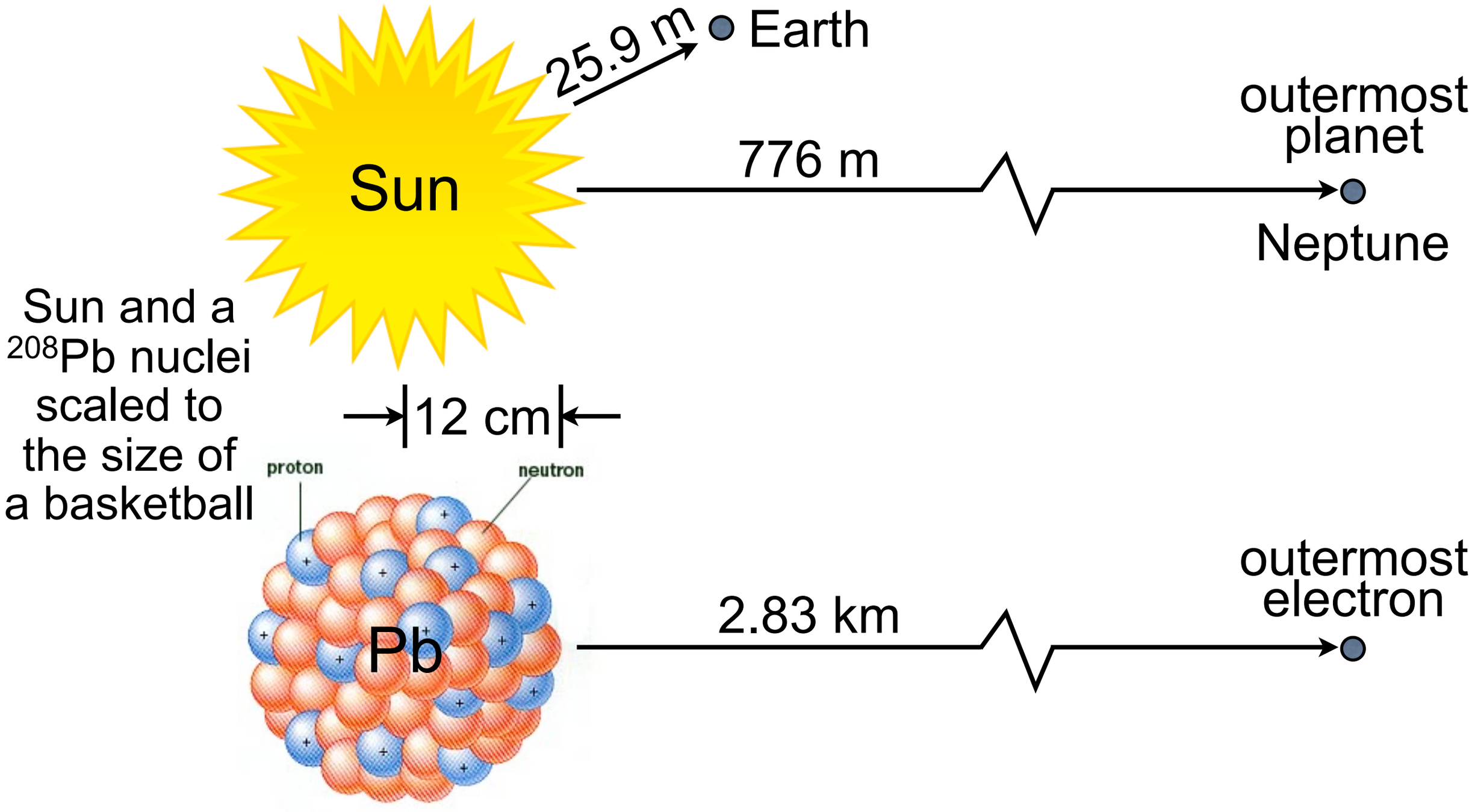
Notation: $10^{-6} = 0.000001$

6^{th} decimal place!

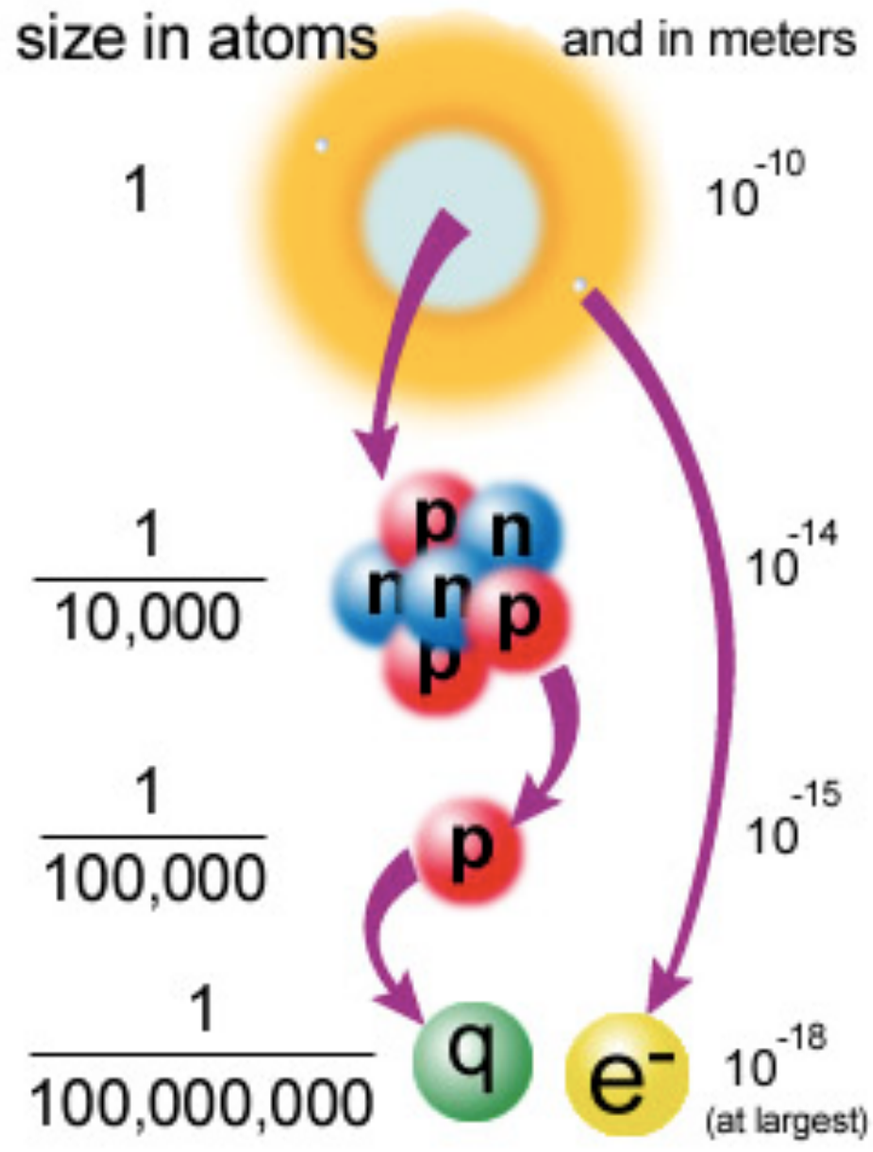
Particle Physics explores matter and space in its smallest dimensions

Length Scales

Relative scale of the solar system and an atom of lead



Inside the Atom



"Nothing exists except atoms and empty space; everything else is opinion."

Democritus (ca. 460 BC - ca. 370 BC)

Now looking smaller still!

The Big Questions

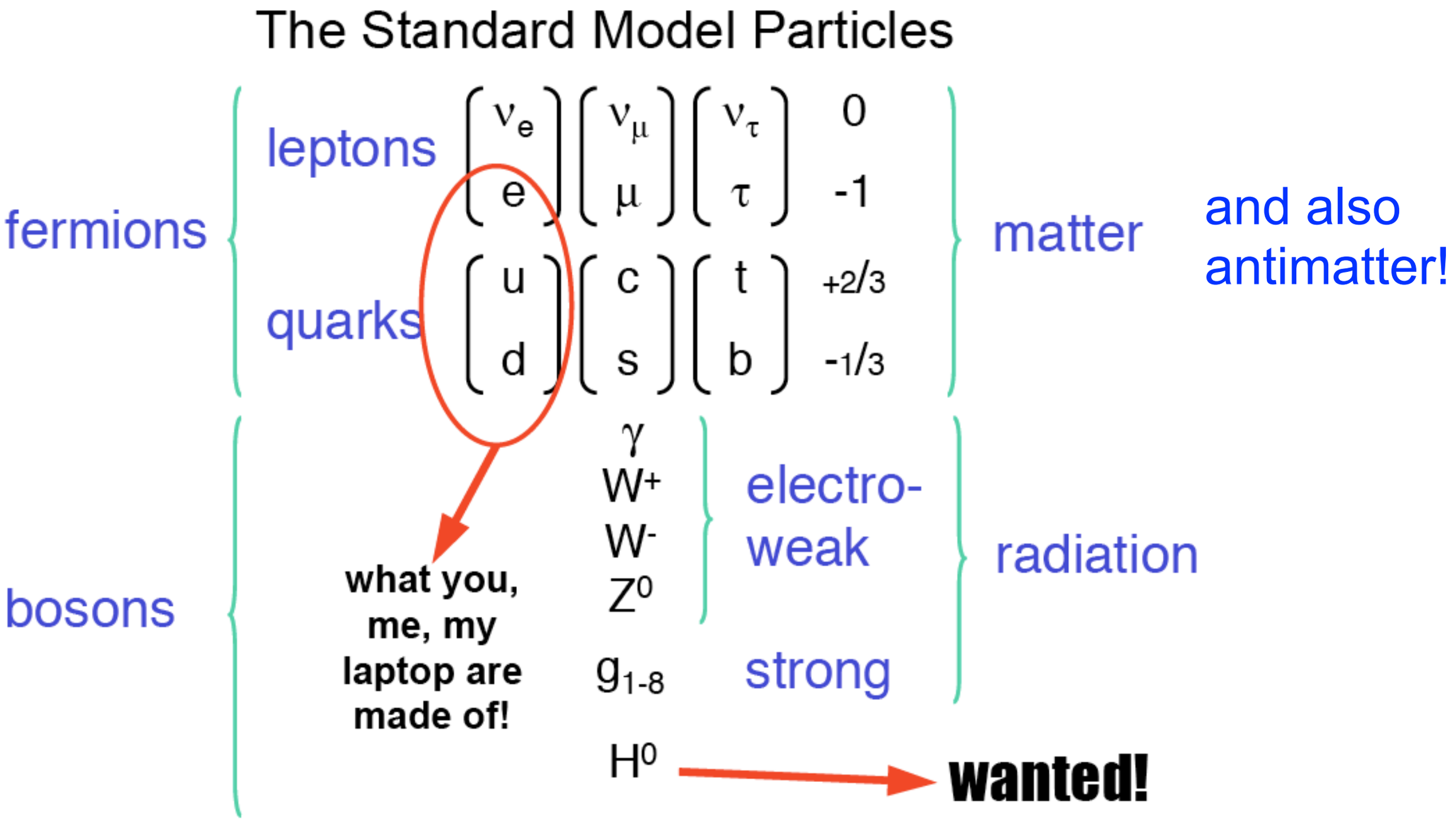
- What is the origin of Mass?
- What is the nature of Dark Matter?
- Why is there more matter than antimatter?
- Can all forces be unified?
- Are there other spatial dimensions?
- Are fundamental particles fundamental?
- Why three families of quarks and leptons?
- Is SuperSymmetry realized in Nature?
- What is Dark Energy?

Elements: Building Blocks of Chemistry

Group #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period																		
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

* Lanthanoids	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
** Actinoids	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Particles: Fundamental Building Blocks



quarks form hadrons: p(uud), n(udd), $\bar{\pi}^-$(ud)

quarks and gluons are called partons

Fundamental Masses

γ, g
massless

Depicted with mass proportional to volume of sphere!

ν_e, ν_μ, ν_τ
have small masses

e

μ

τ

u

c

t

Z

W

d

s

b

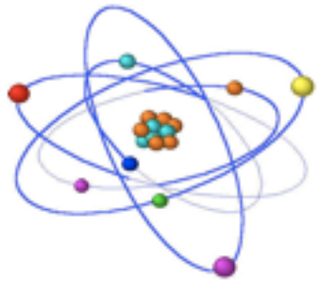
Fundamental Forces

	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

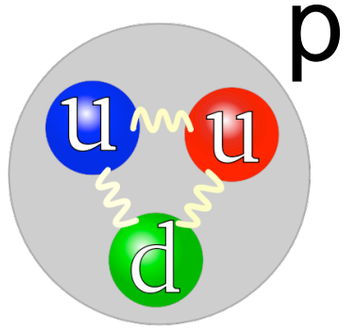
http://www.particleadventure.org/

slow H burning rate of the Sun

distinguishes left from right!



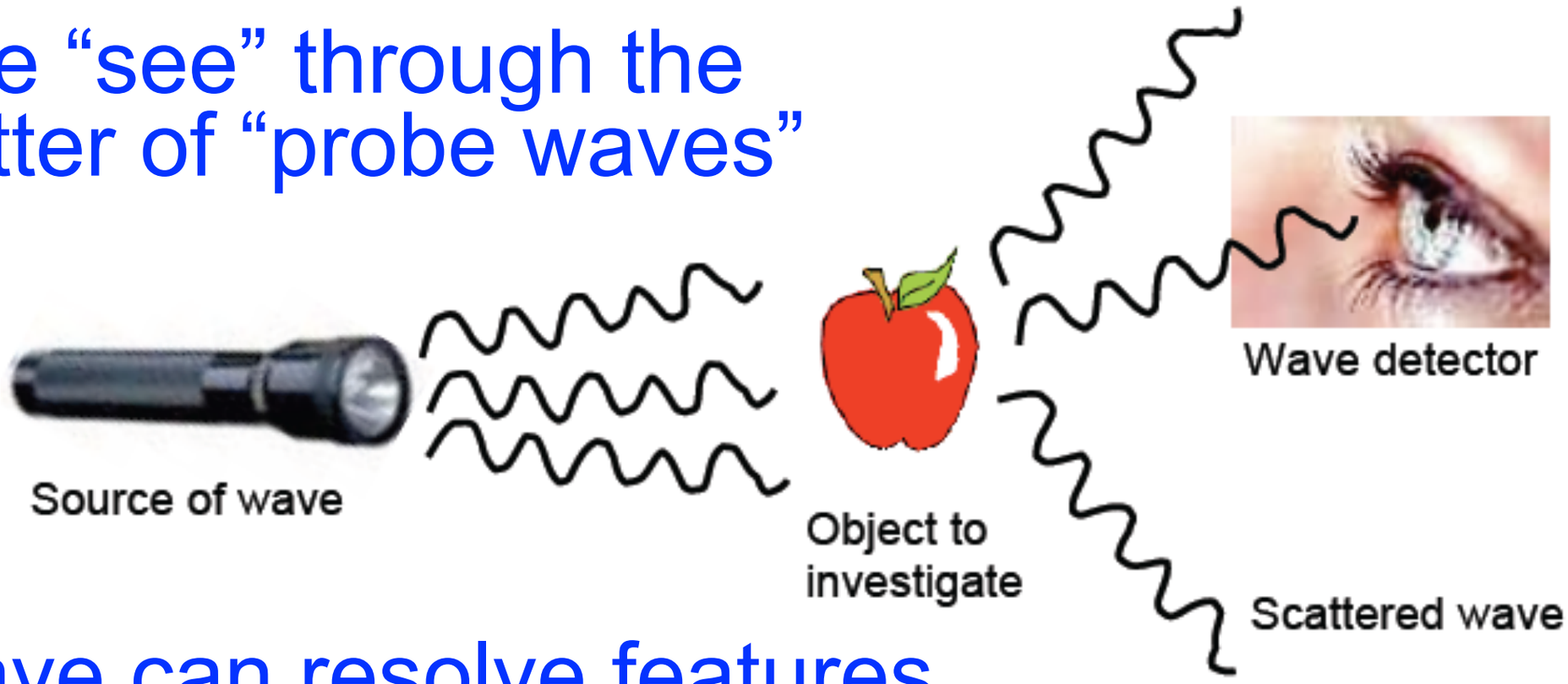
p



the nuclear force is a residual of the strong force

Scattering Experiments

We “see” through the scatter of “probe waves”

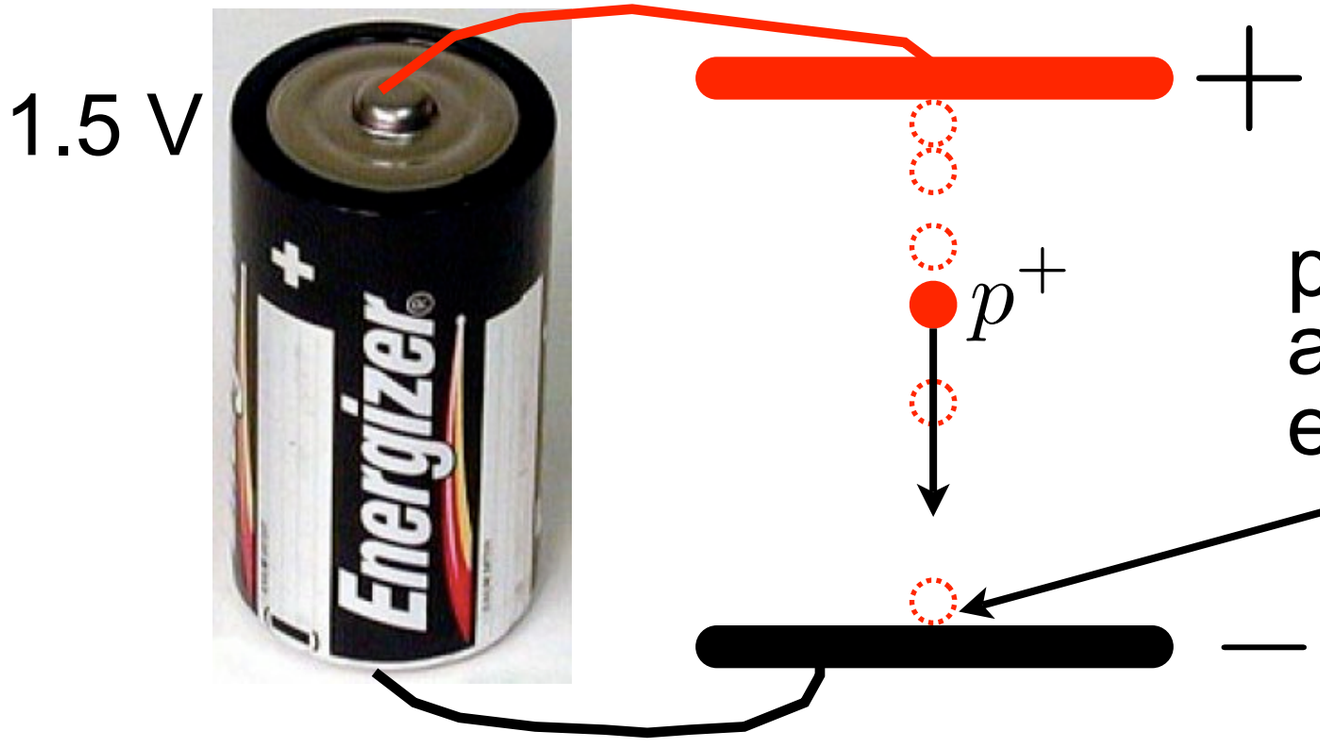


The wave can resolve features about the size of its wavelength

use particle “matter waves”: $\lambda = \dfrac{hc}{E}$ for $E \gg mc^2$

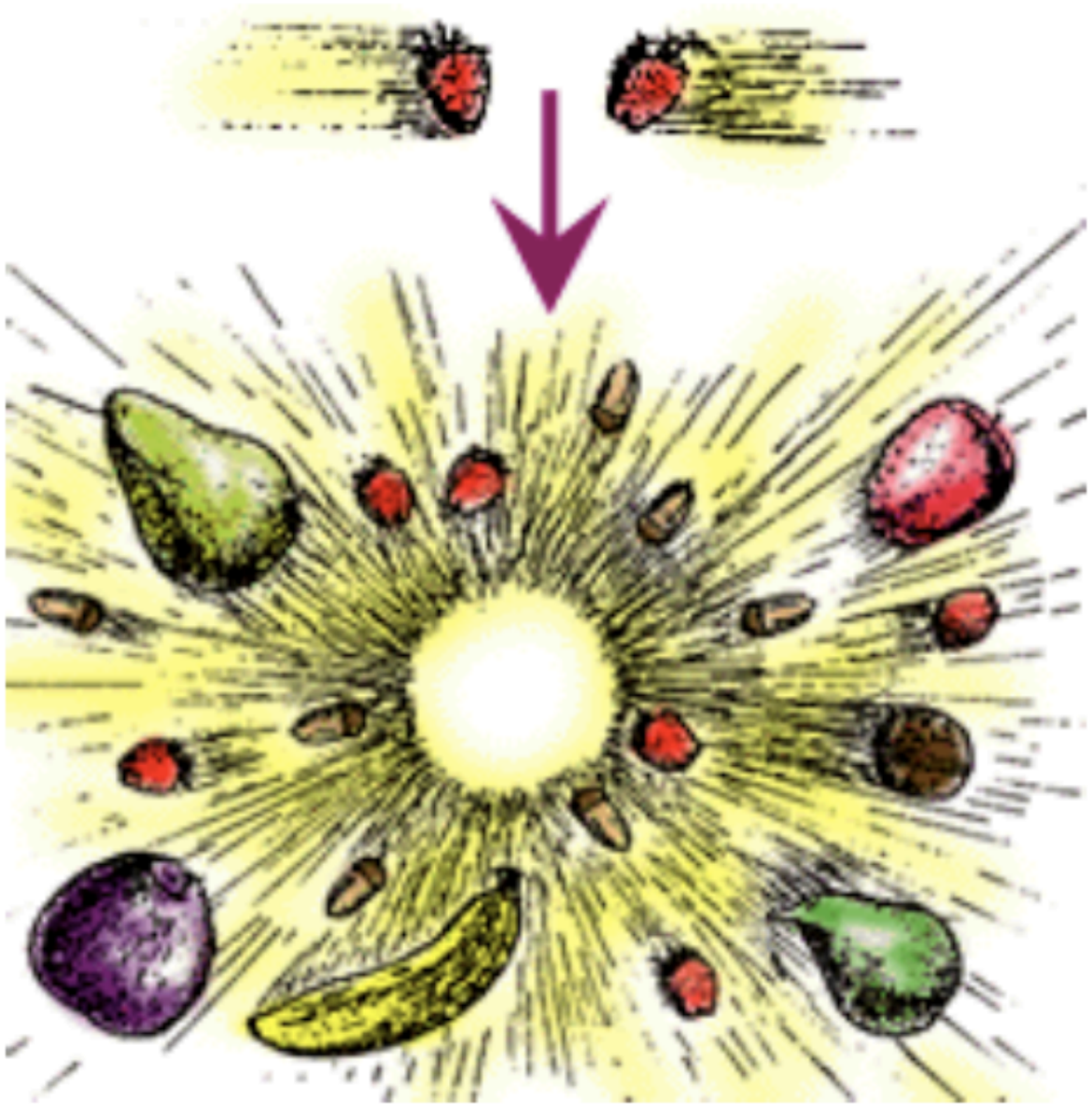
High energy particle ⇔ small matter wave!

Accelerating



- Here the proton gains 1.5 eV of energy
- Charged particles can also be accelerated using electromagnetic waves to reach much higher energies
  - 1 MeV = 1,000,000 eV
  - 1 GeV = 1,000,000,000 eV ~ mc^2 for proton!
  - 1 TeV = 1,000,000,000,000 eV

Colliding

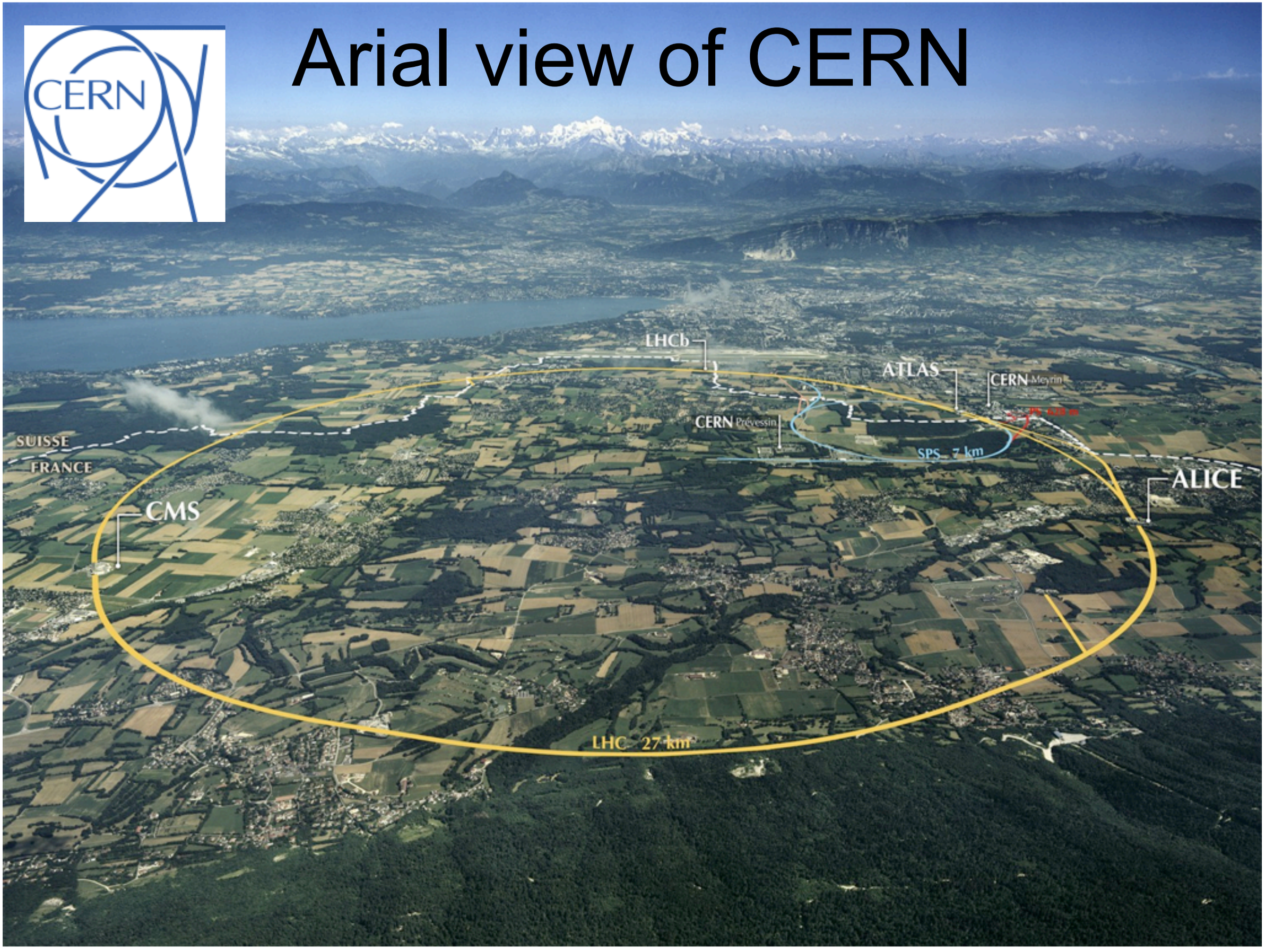


Particles and antiparticles, perhaps new and unknown ones, can be produced from the pure energy available after the collision

$$E = mc^2$$

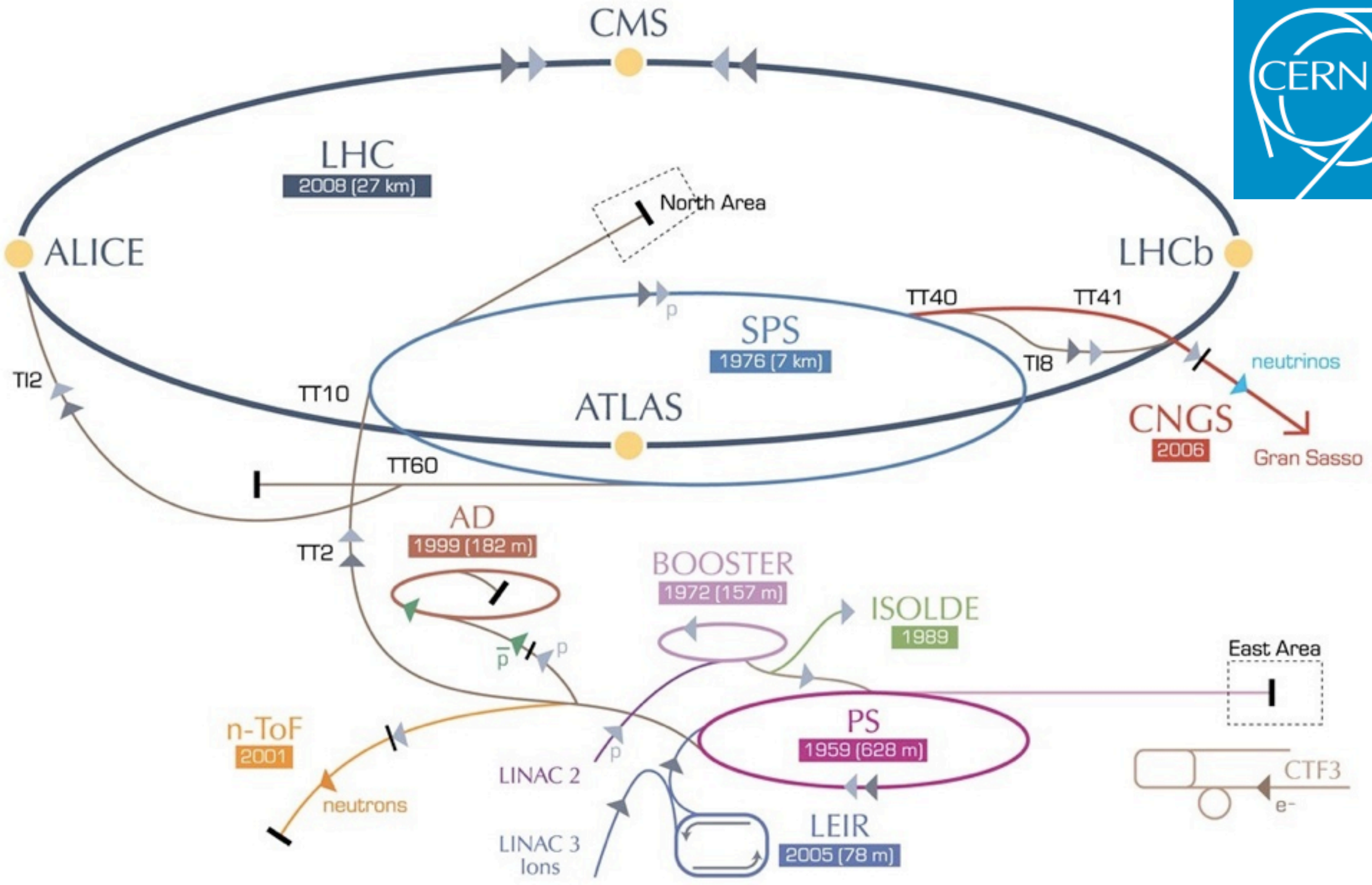
New particles signal new physical laws!

Arial view of CERN



CERN PhotoLab CERN-MI-0807031

CERN's Accelerator Complex



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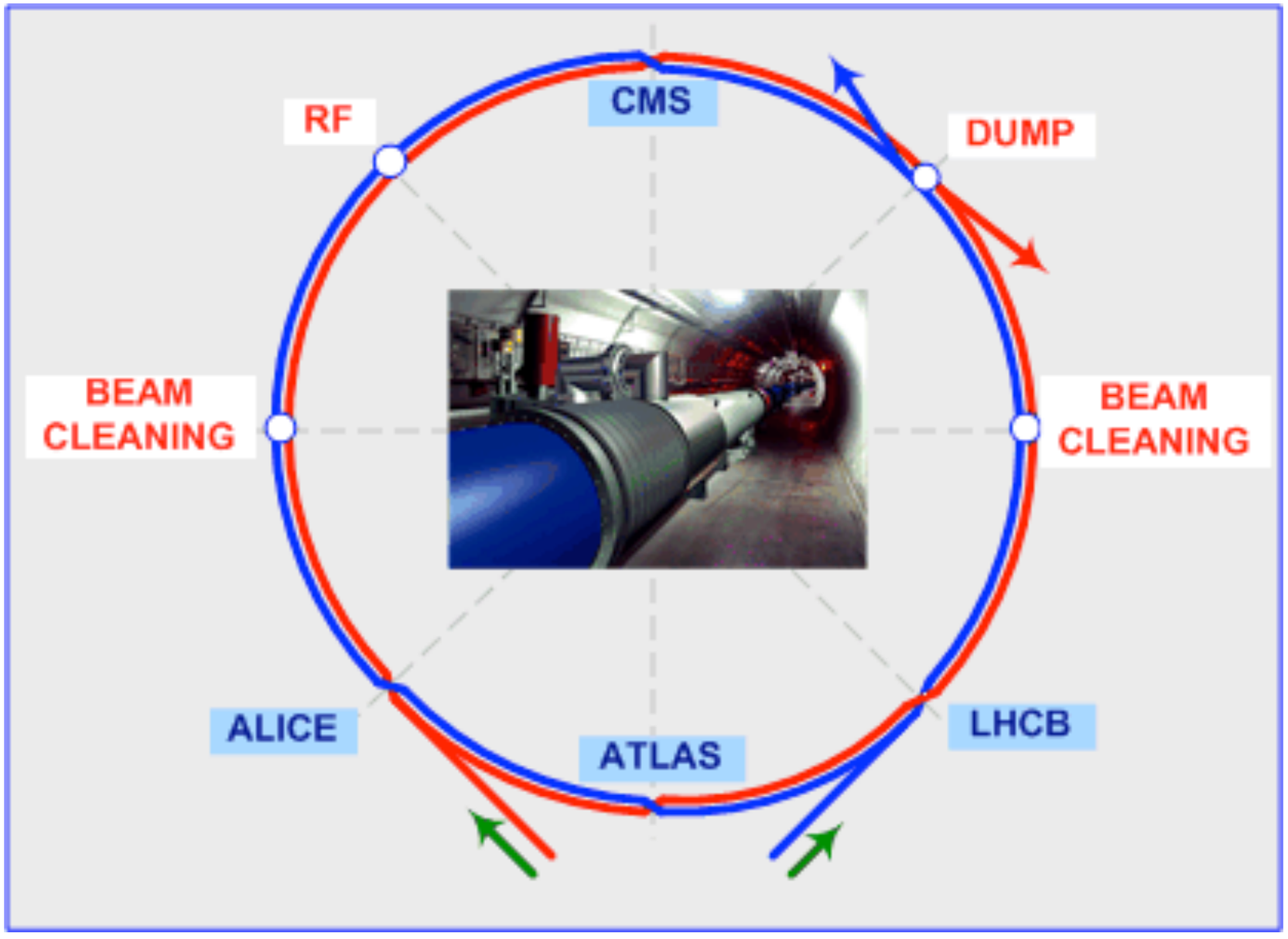
Large Hadron Collider



http://lhc.web.cern.ch/lhc/

- 4 major experiments: ATLAS, CMS, ALICE, LHCB
- Radio Frequency acceleration at one point on the ring
- Beam dump area at one point on the ring

Getting around in the LHC

The ATLAS Experiment at CERN, http://atlas.ch

LHC Design Parameters

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1×10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

http://cdsweb.cern.ch/collection/Official%20Press%20Brochures

Large Hadron Collider

- proton-proton collider
  - design energy: 7 TeV proton beams; 14 TeV collisions
  - design luminosity: 10^{34} $cm^{-2}s^{-1}$
  - high energy?
    - one pp collision has energy of a mosquito in flight
    - but stored energy per beam is 362 MJ
      - about 1000 light cars going at 100 km/h !!!
  - 2010: 7 TeV collisions @ up to 2 x 10^{32} $cm^{-2}s^{-1}$
    - highest energy human-made particle collisions!

- heavy ion collider
  - design energy: 2.76 TeV/N beams; 5.52 TeV/N collisions
  - 2010: 2.76/N TeV Pb-Pb collisions @ up to 3 x 10^{25} $cm^{-2}s^{-1}$
    - ^{208}Pb, 82 protons, 126 neutrons

History of the Universe

proton-proton physics at the LHC corresponds to conditions around here

Inflation

BIG BANG

possible dark matter relicts

cosmic microwave radiation visible

t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15

10 -10 s
10 15
10 2

10 -5 s
10 12
10 -1

10 2 s
10 9
10 -4

3x10 5 y
3000
3x10 -10

10 9 y
15
10 -12

12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)

Today

Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole

Heavy ions physics at the LHC corresponds to conditions around here

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

http://www.particleadventure.org/

Large Hadron Collider Milestones

- 1981: approval of the Large Electron-Positron collider, with its 27 km tunnel
- 1983: discovery of the W and Z bosons at the CERN SPS
  - hadron machines can do great discoveries!
- 1984: LHC feasibility study
- 1989: start of proto-collaborations to build detectors
- 1991: CERN agrees that the LHC is the right machine for the future
- 1994: approval of the LHC

- 2008: Sep 10th, first 0.45 TeV beam circulation in the LHC
- 2008: Sep 19th, electrical fault, material damage, operations halted
- 2009: Nov 23rd, first 0.45 TeV on 0.45 TeV proton collisions
- 2010: Mar 30th, first 3.5 TeV on 3.5 TeV proton collisions
  - 7 TeV collisions: 2010/03/30 - 2010/11/04
- 2010: Nov 8th, first 1.38 TeV/N on 1.38 TeV/N lead ion collisions
  - 2.76 TeV/N lead ion collisions: 2010/11/08 - 2010/12/06
- 2011: resume LHC operations

Historical Picture

The WWW was invented at CERN in the late 80's

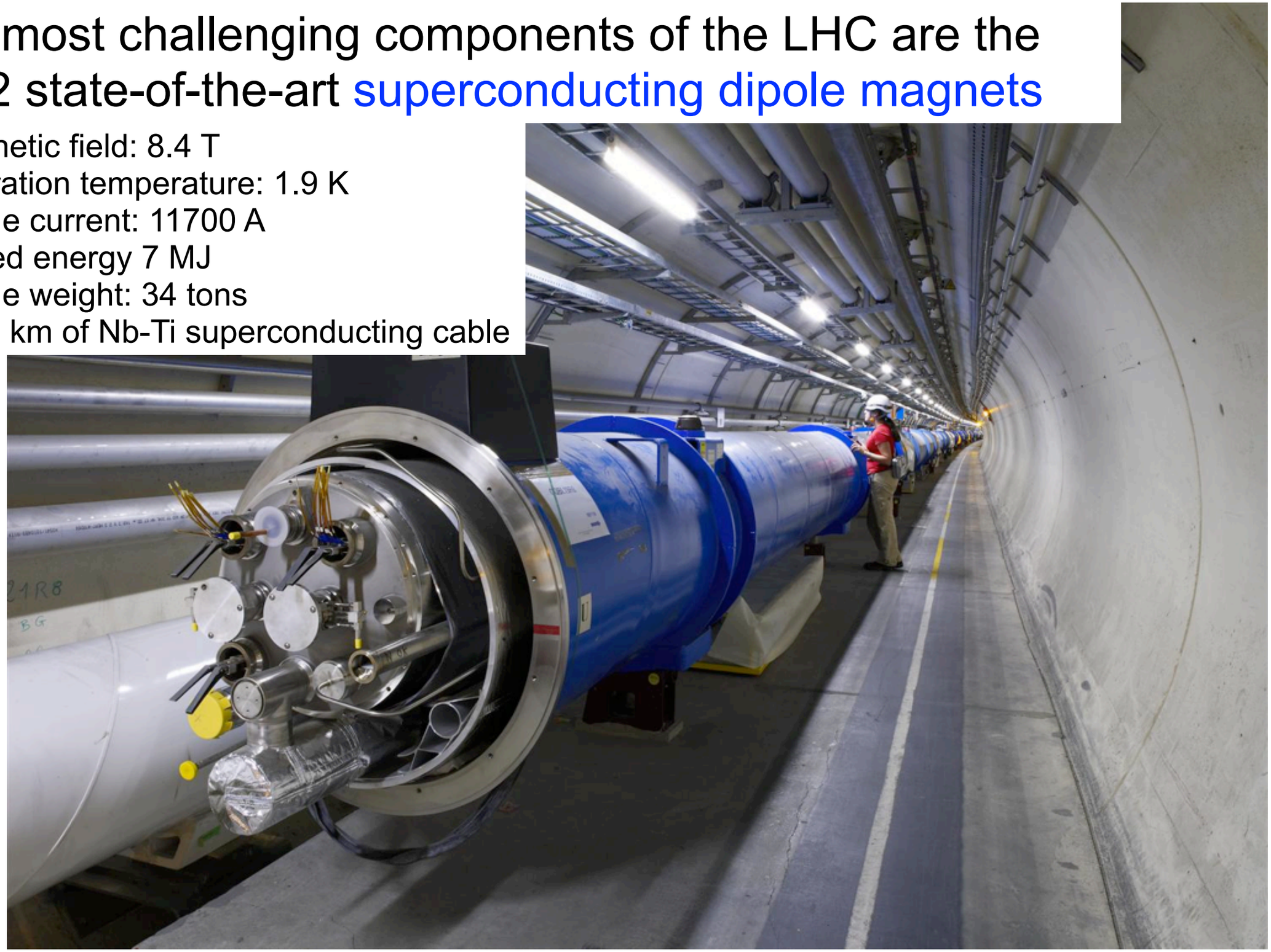
The LHC was already a hot topic!

The first photographic image on the Web in 1992!

The LHC Dipole Magnets

The most challenging components of the LHC are the 1232 state-of-the-art superconducting dipole magnets

- Magnetic field: 8.4 T
- Operation temperature: 1.9 K
- Dipole current: 11700 A
- Stored energy 7 MJ
- Dipole weight: 34 tons
- 7600 km of Nb-Ti superconducting cable



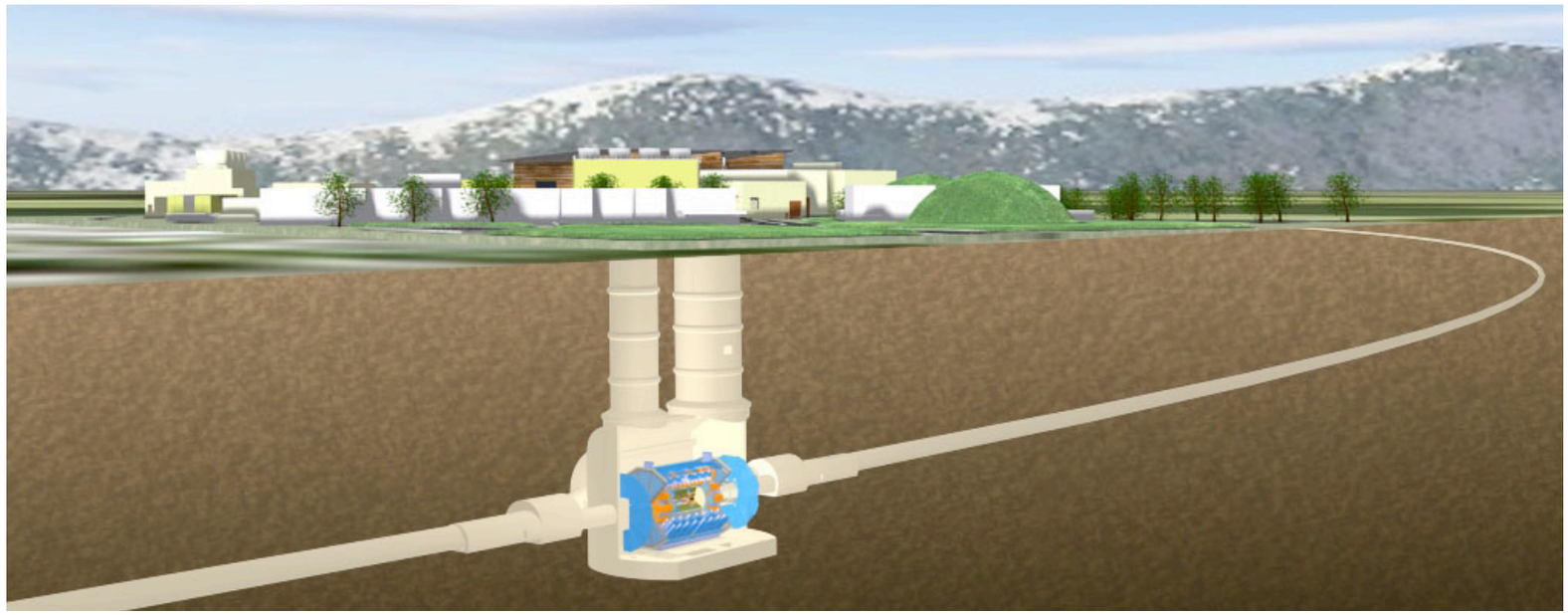
CERN PhotoLab

Canada and the LHC

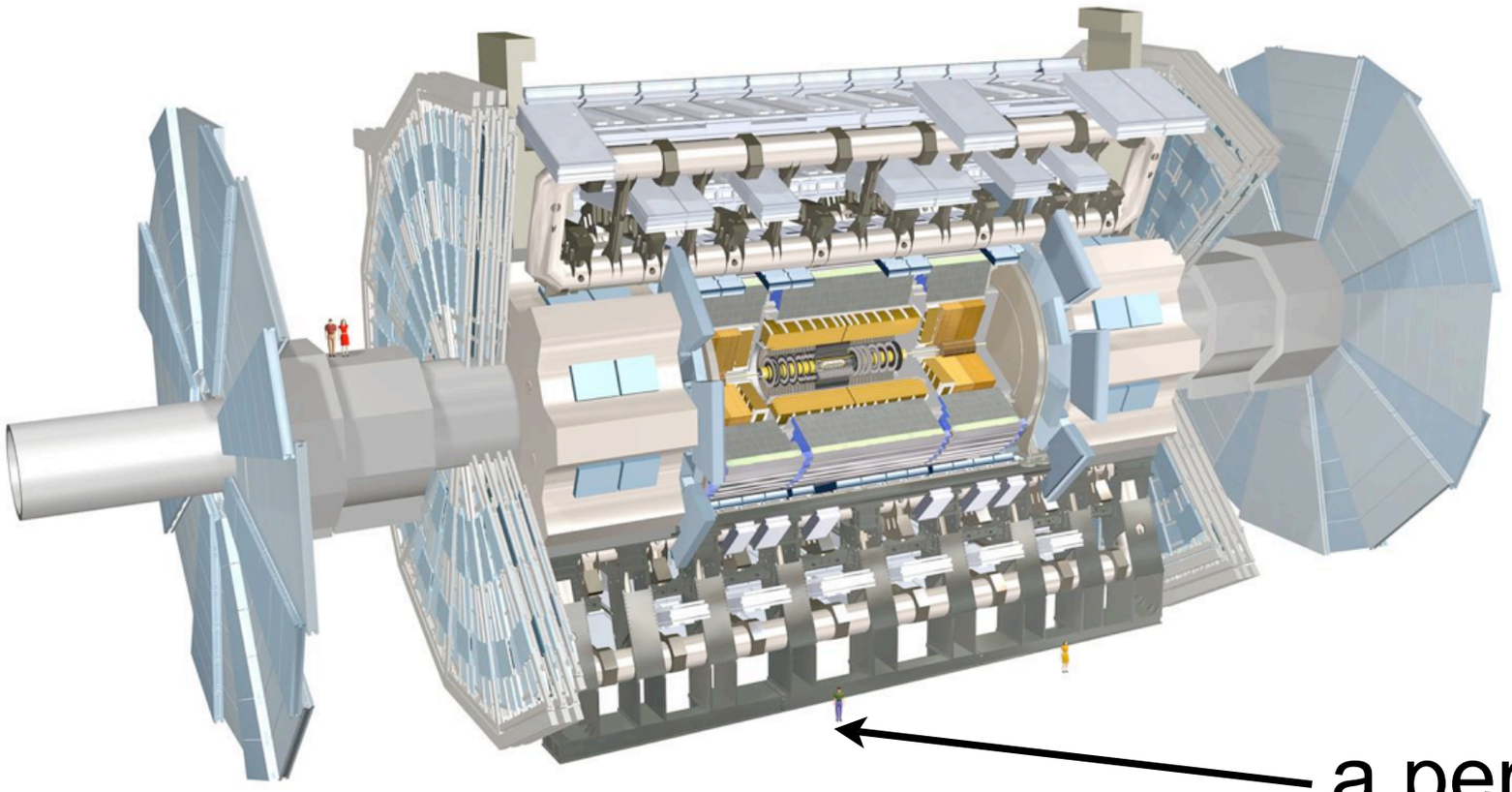
Canada made important contributions to the LHC machine: warm insertions and injector upgrades, with TRIUMF engineering

48 + 4 warm twin-aperture quadrupoles for cleaning insertions

The ATLAS Detector at the LHC

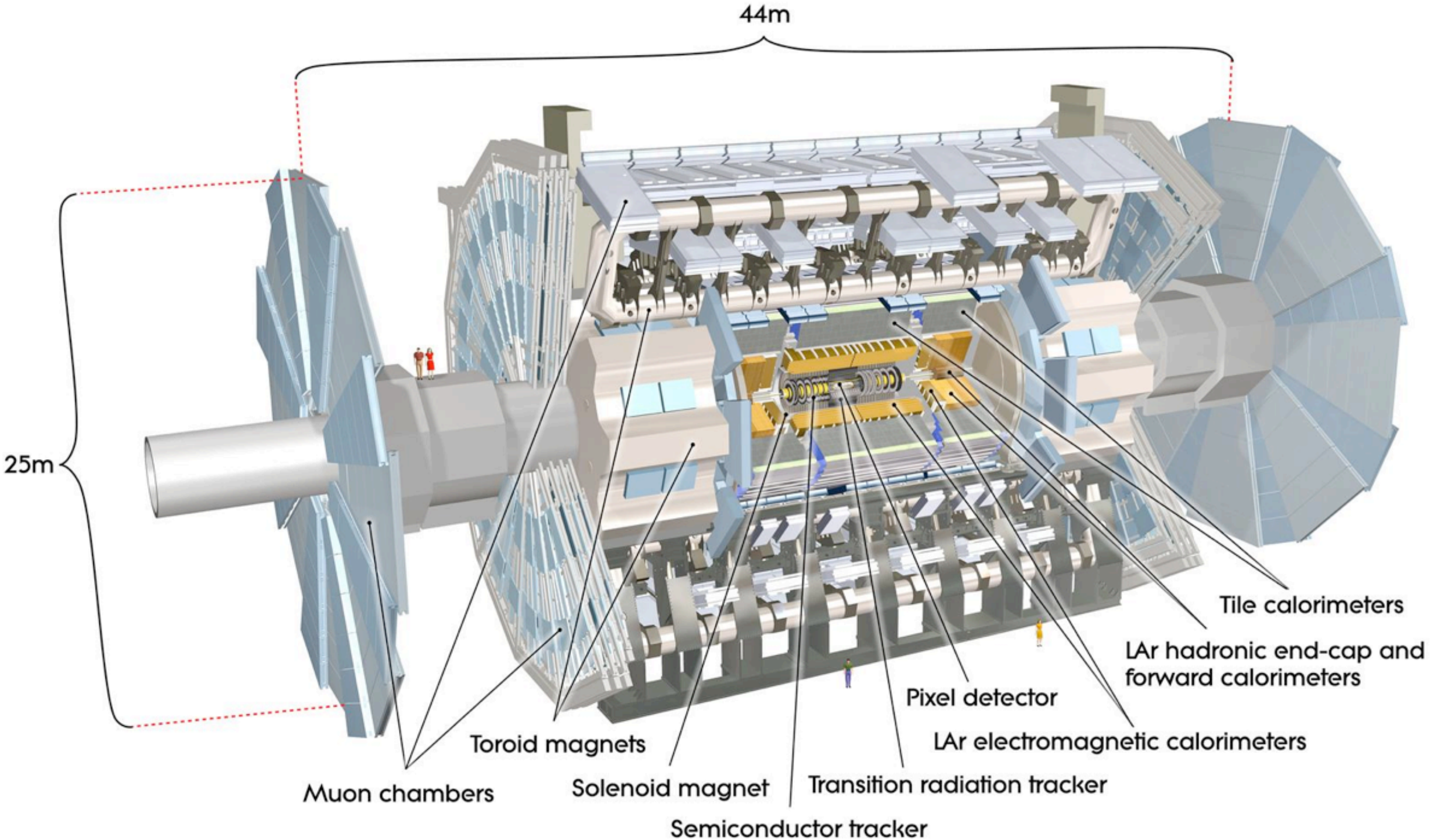


The ATLAS Experiment at CERN, http://atlas.ch

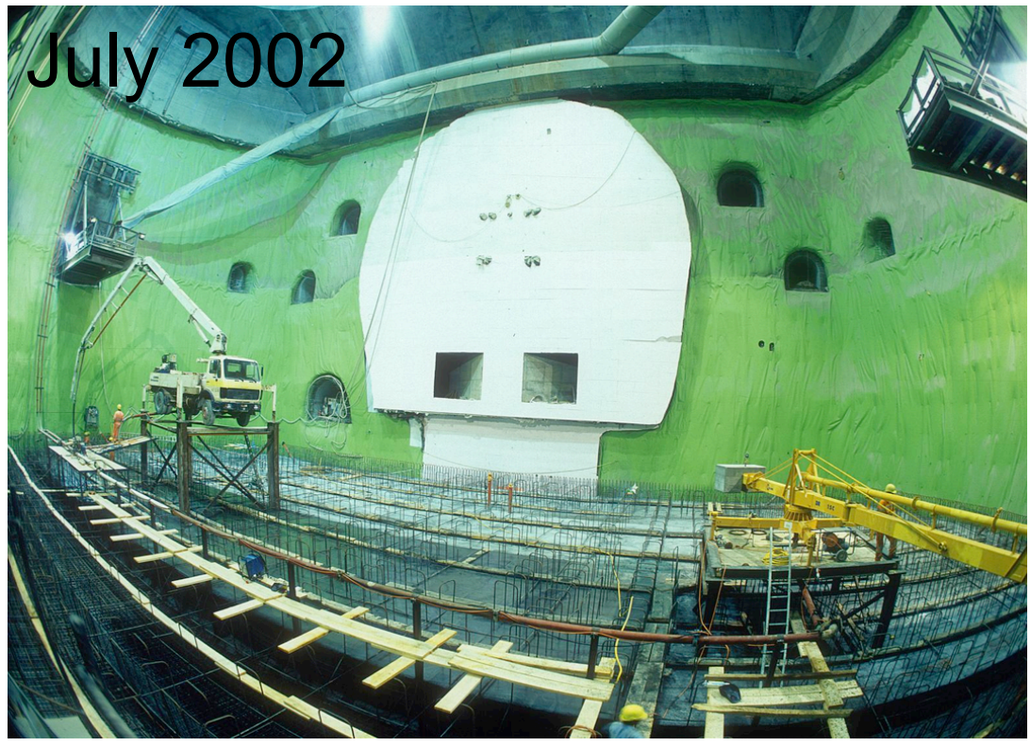


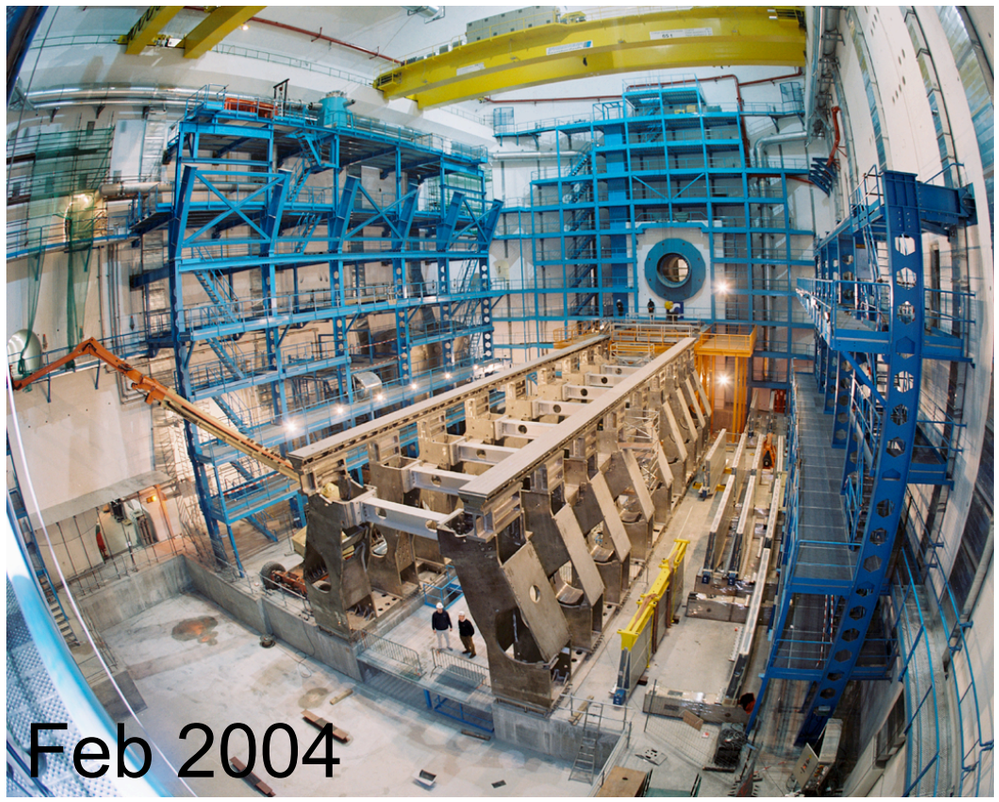
a person!

The ATLAS Detector



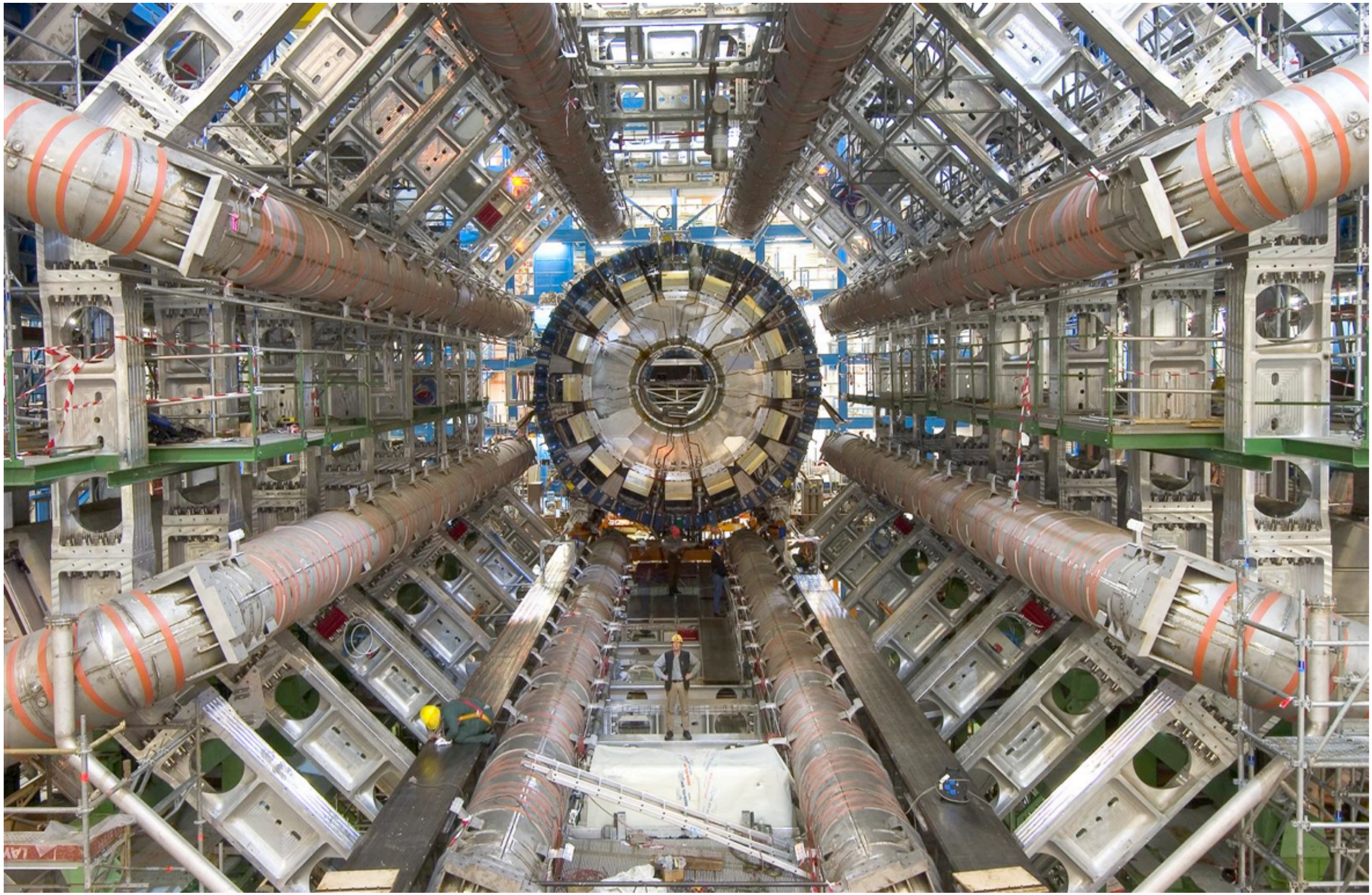
ATLAS Cavern





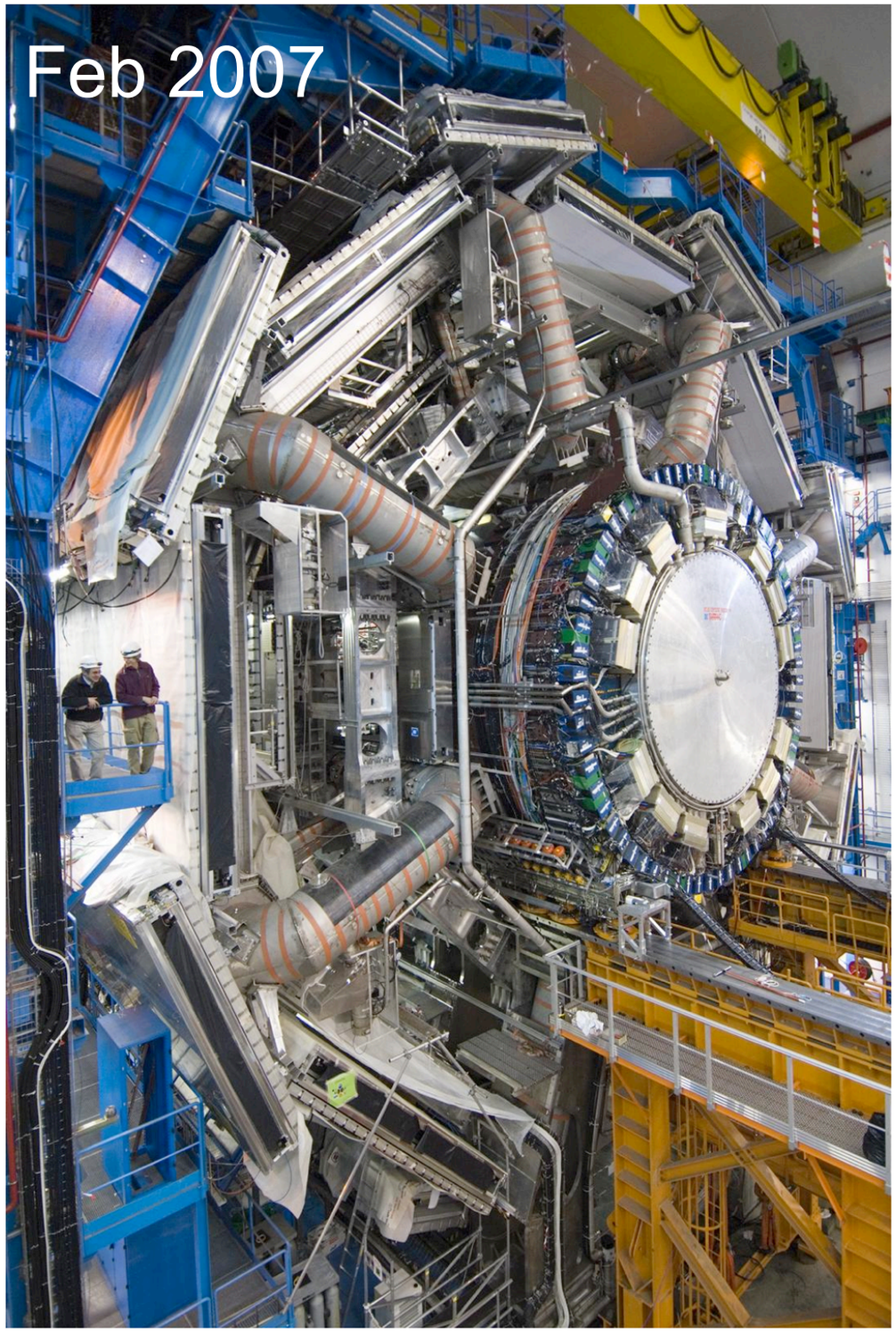
The ATLAS Experiment at CERN, http://atlas.ch

ATLAS Detector Construction (Nov 2005)

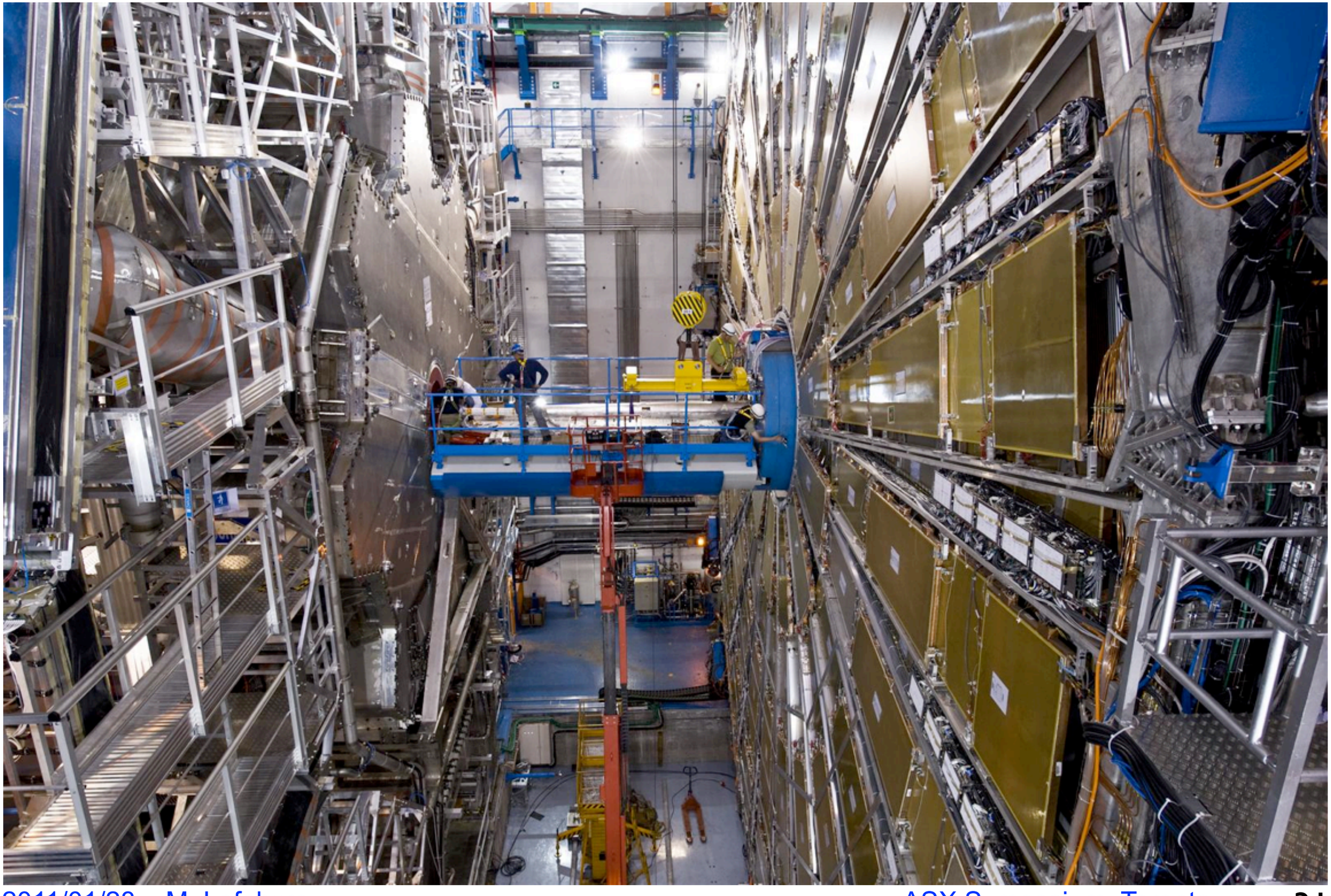


The ATLAS Experiment at CERN, http://atlas.ch

Moving the Calorimeters in Place



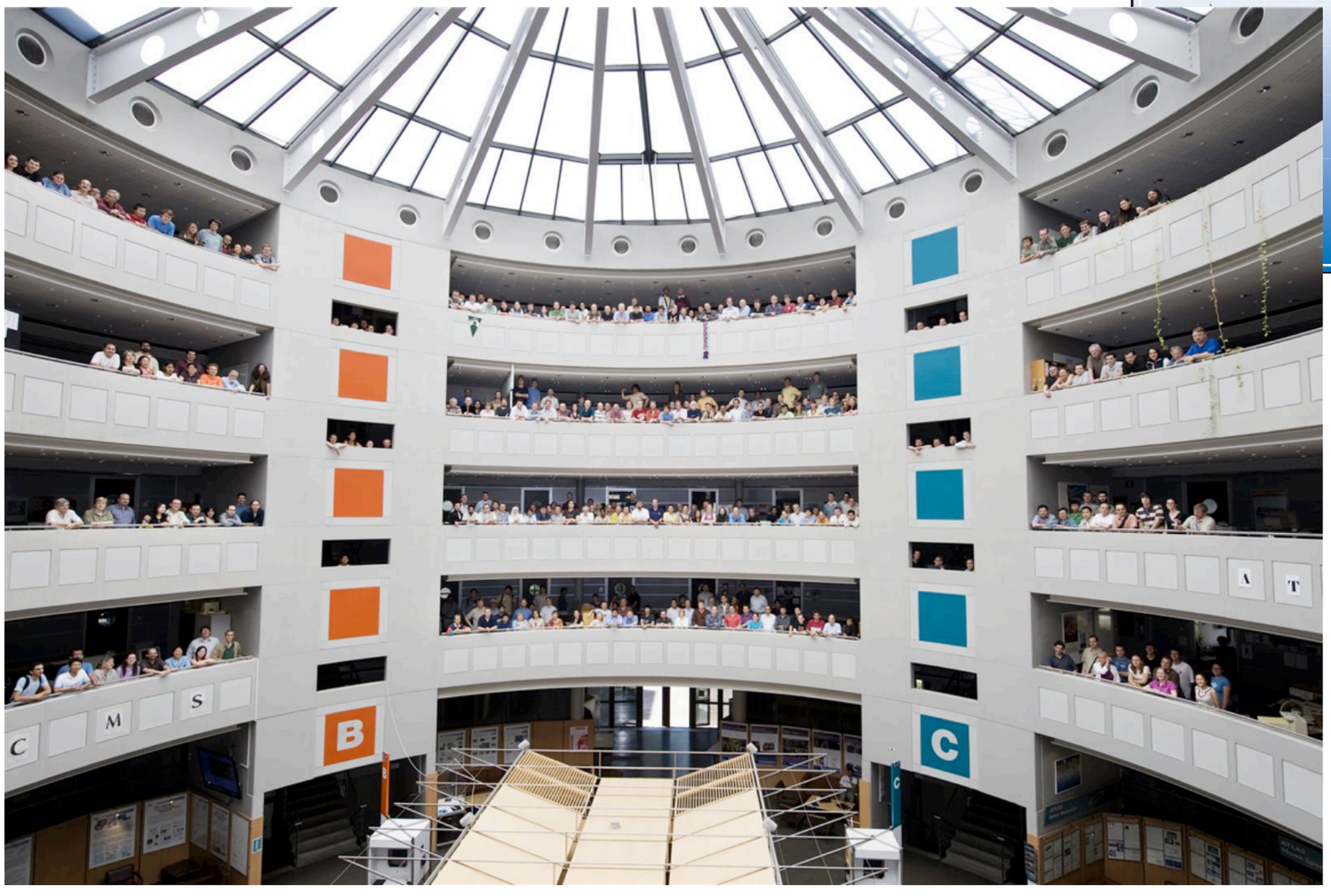
Closing of LHC Beam Pipe (16 June 2008)



The ATLAS Experiment at CERN, http://atlas.ch

The ATLAS Collaboration

- 38 countries
- 174 institutions
- 3000 scientific participants
  - about 1000 students



ATLAS
EXPERIMENT
http://atlas.ch

ATLAS and Canada

Alberta
Carleton
McGill
Montréal
Regina
SFU
Toronto
TRIUMF
UBC
Victoria
York

- Over 150 Canadian scientists participate in the ATLAS experiment
- ATLAS Canada Collaboration
  - Founded in 1992 — ML, UVic
  - Spokesperson (94-07) — Bob Orr, UofT
  - Spokesperson (07-) — Rob McPerson, UVic/IPP
  - Deputy — Dugan O'Neil, SFU
  - Physics Coordination — Pierre Savard, UofT/TRIUMF
  - Computing Coordination — Reda Tafirout, TRIUMF
- Contributions to the ATLAS detector construction
- Contributions to the LHC construction (TRIUMF)
- TRIUMF, Canada's nuclear and particle physics laboratory located in Vancouver, is playing an important role
  - http://www.triumf.ca/

ATLAS Control Room: first LHC collisions!

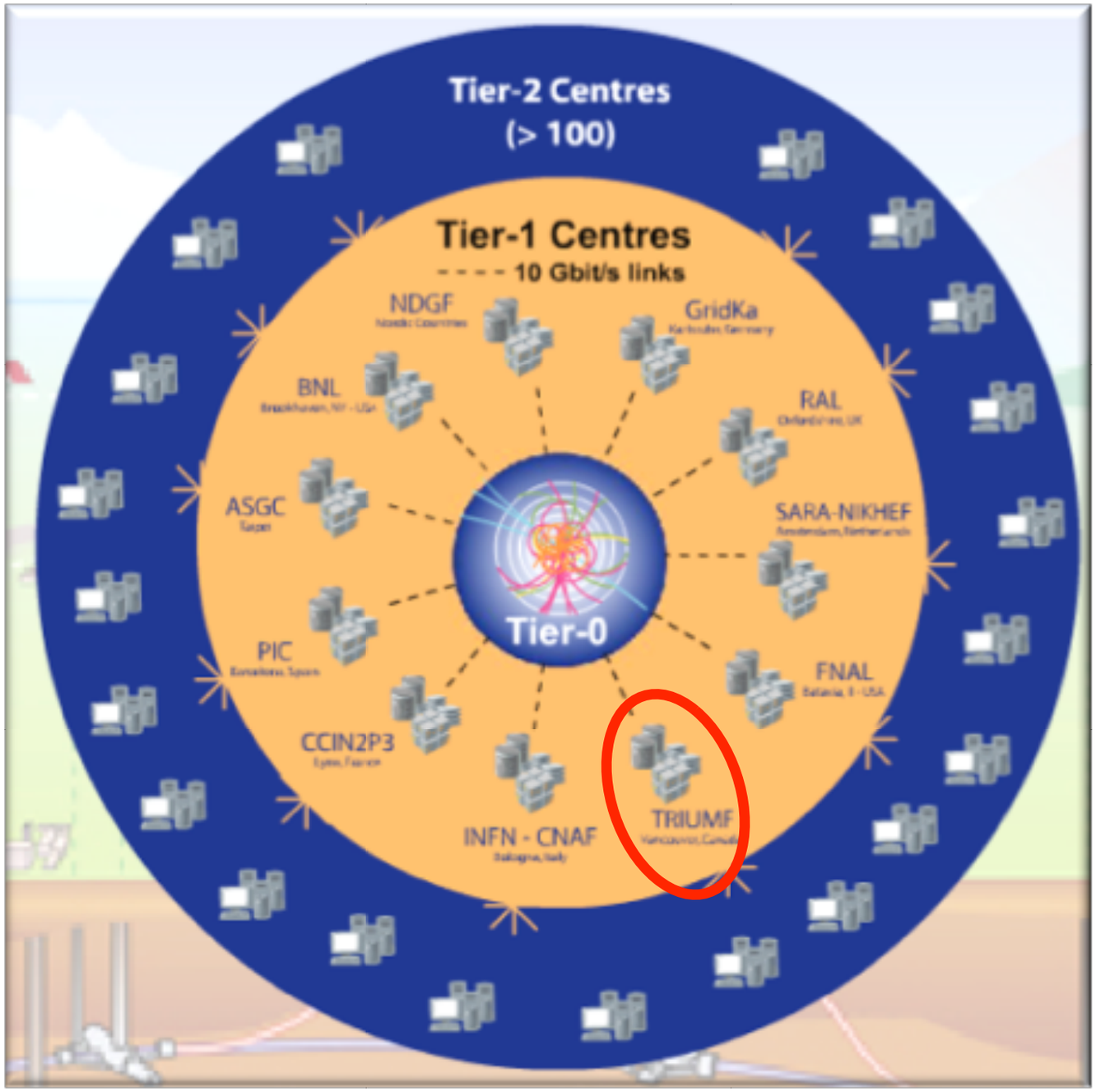
The ATLAS Experiment at CERN, http://atlas.ch

ATLAS Control Room: first 7 TeV

The ATLAS Experiment at CERN, http://atlas.ch

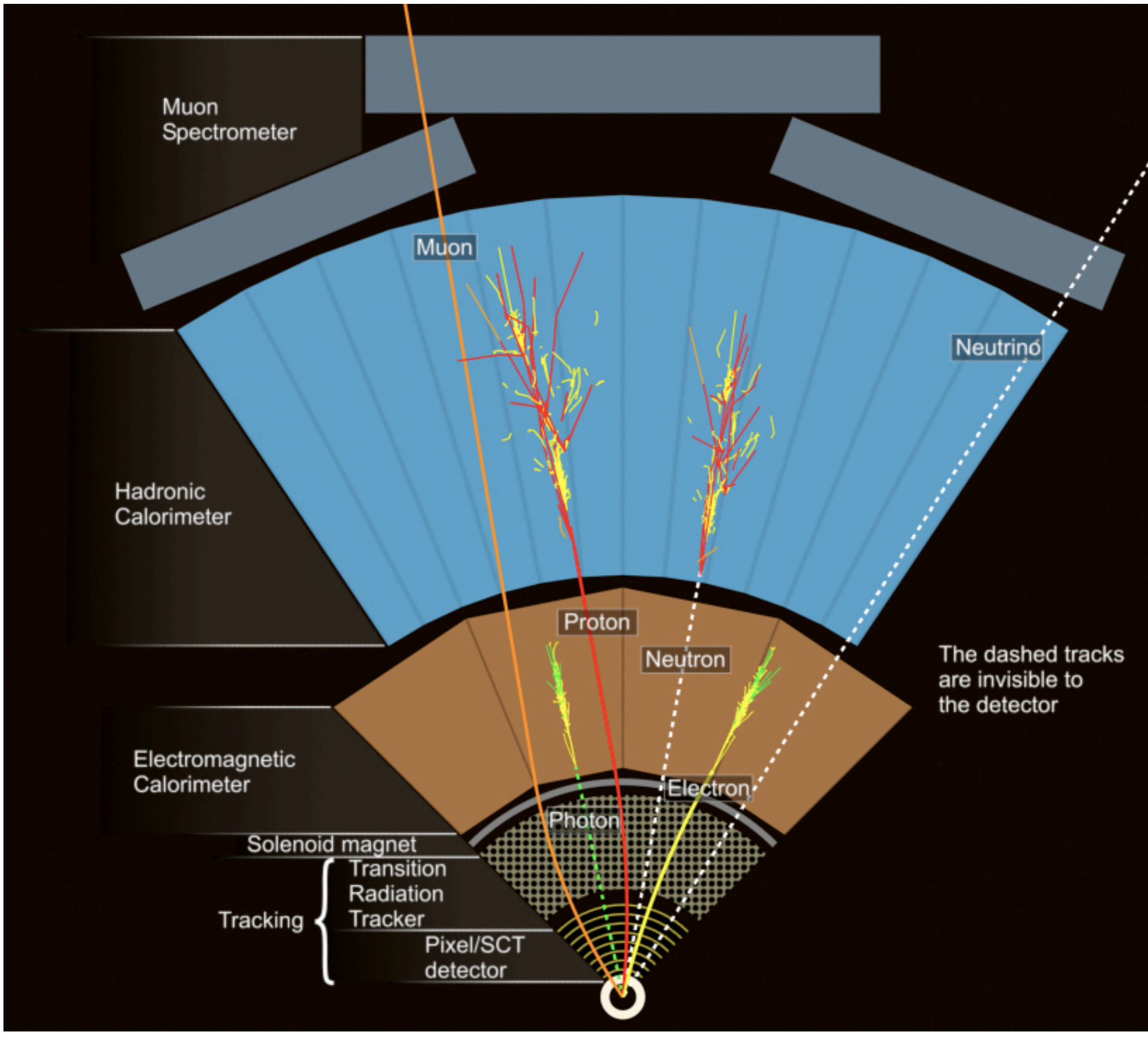
The Worldwide LHC Computing Grid

http://lcg.web.cern.ch/LCG/public/



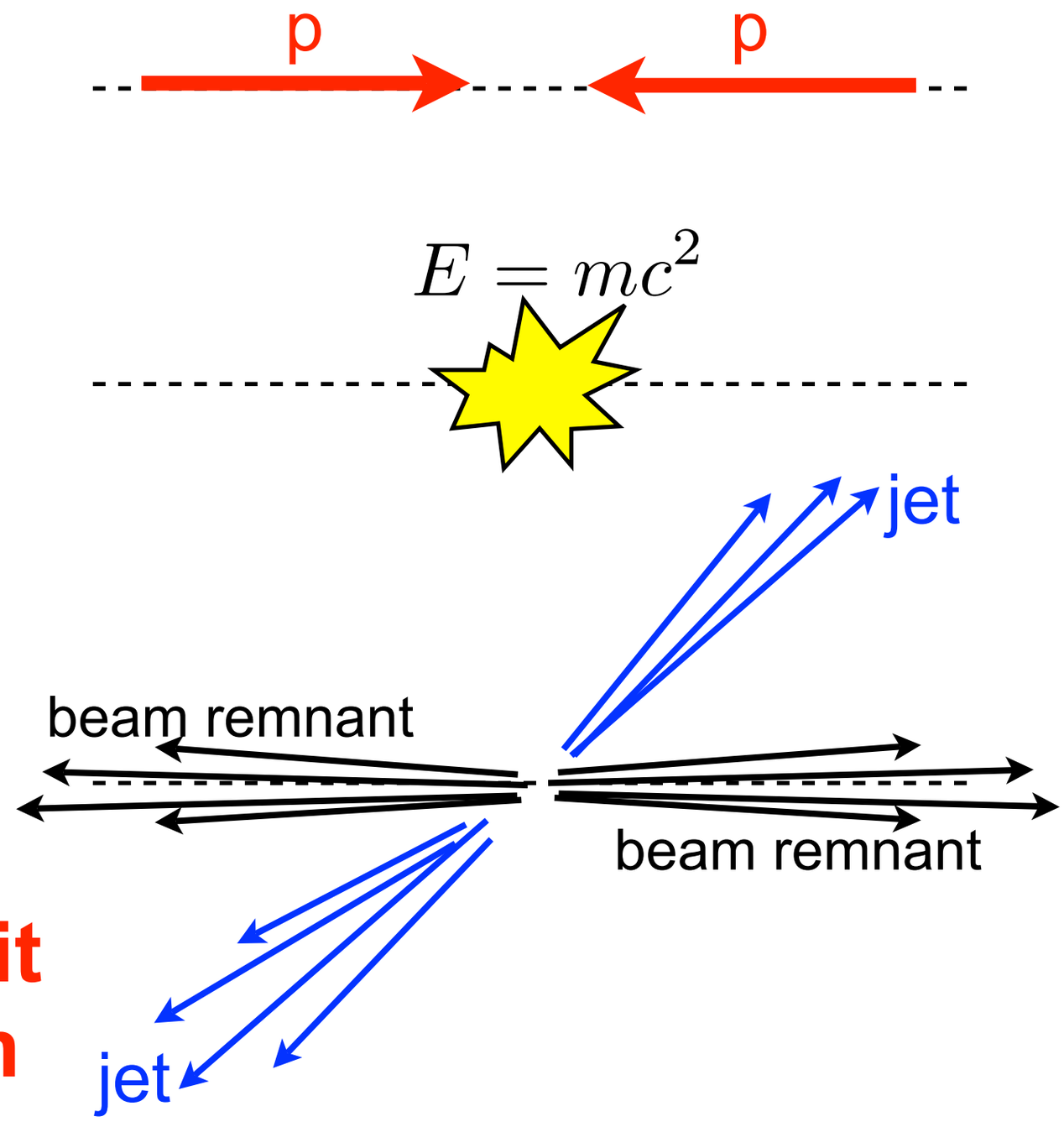
- Tier 0 (CERN)
  - data recording
  - initial data reconstriction
  - data distribution
- Tier 1 (11 centres)
  - one at TRIUMF, Canada
  - permanent storage
  - re-processing
  - analysis
- Tier 2 (federation of about 130 centres)
  - simulation
  - user analysis

Particle Identification in ATLAS



Two-jet Production

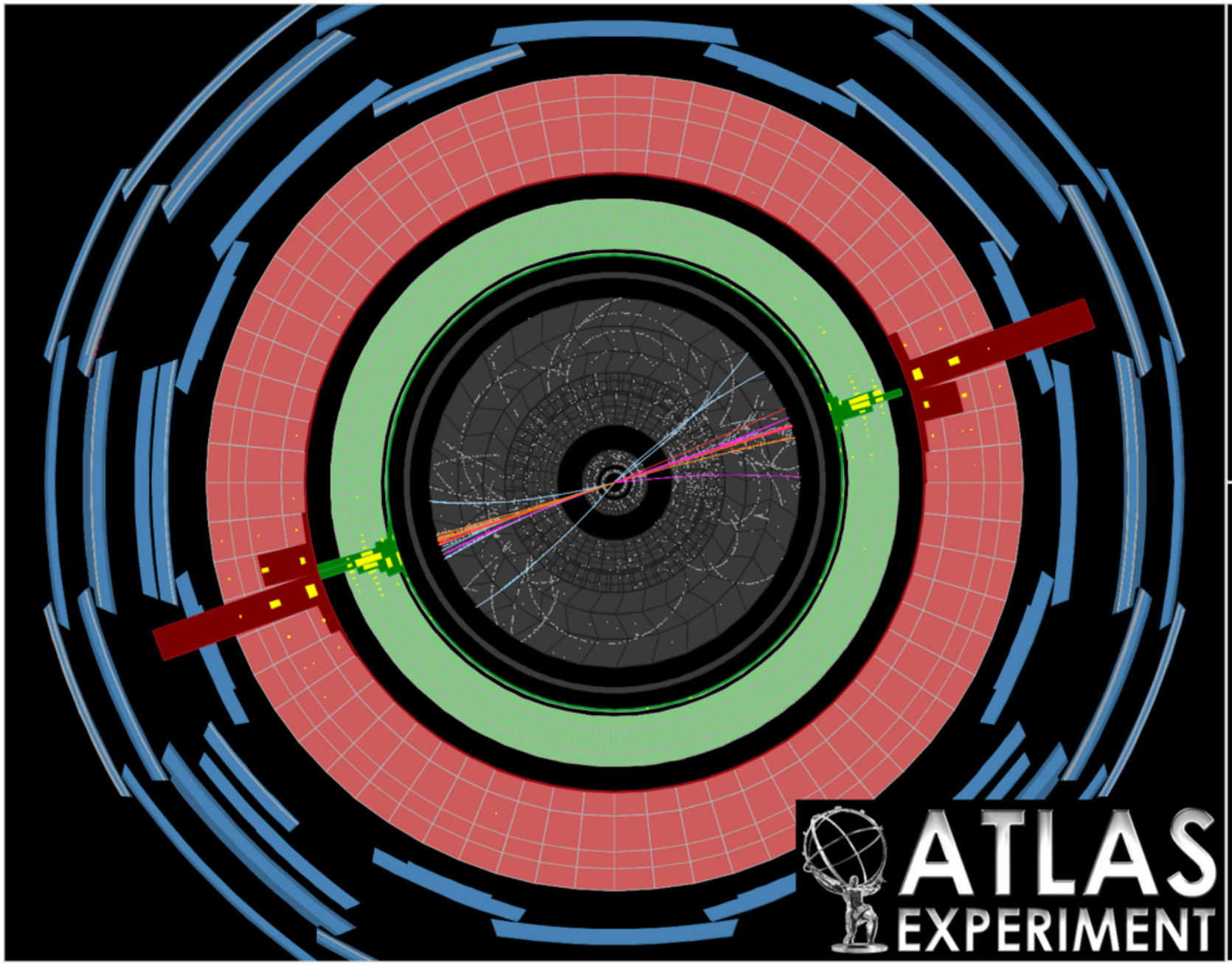
- In high energy proton-proton collisions, we often have the scattering of two partons (quarks and gluons)
  - two jets in the final state
- Study of two-jet events allows to look for parton substructure
  - recall Rutherford scattering: atomic nucleus
  - recall electon-proton scattering: proton structure

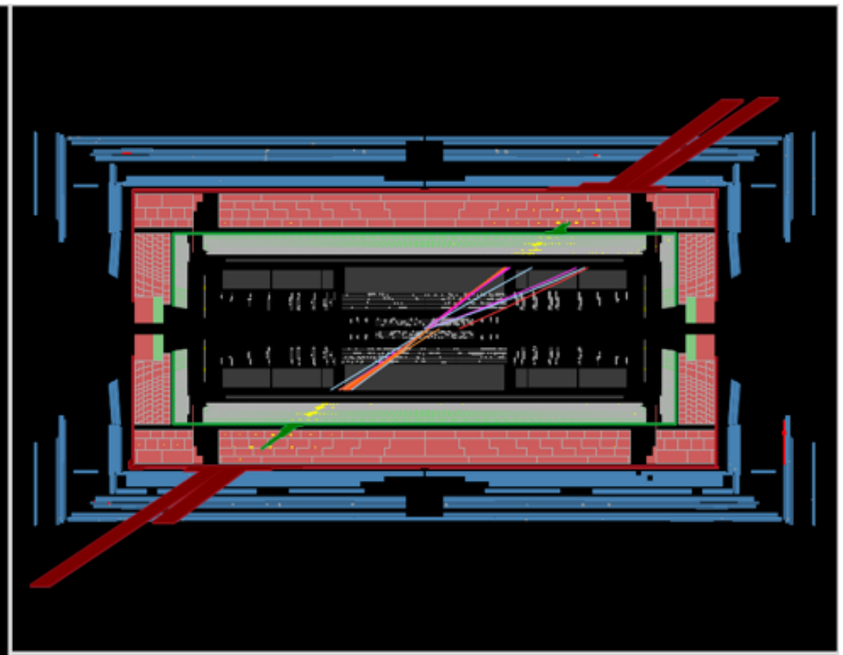


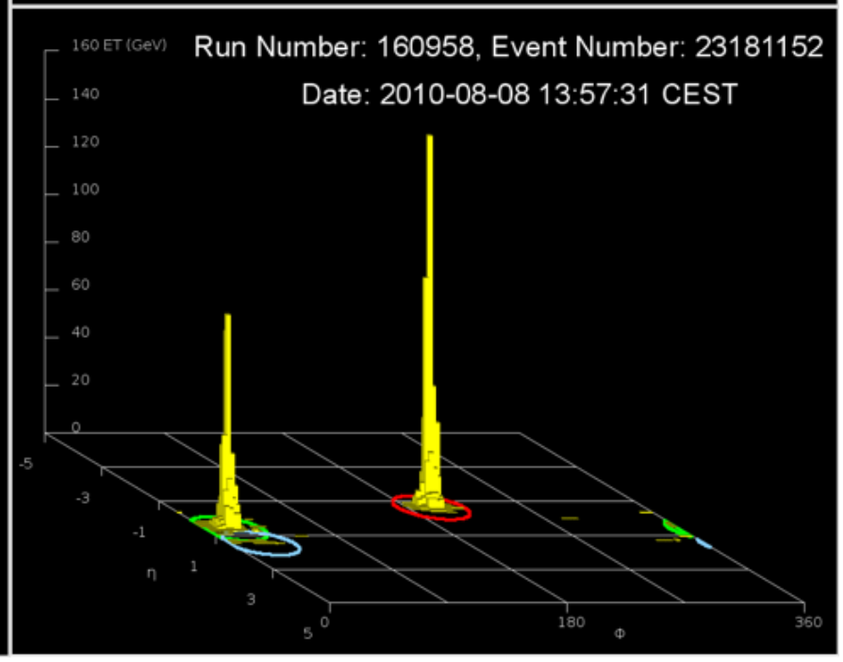
Recent ATLAS result: if quarks have a structure, it is smaller than 6 x 10^{-20} m

Phys. Lett. B694 (2011) 327-345

Two-jet Event

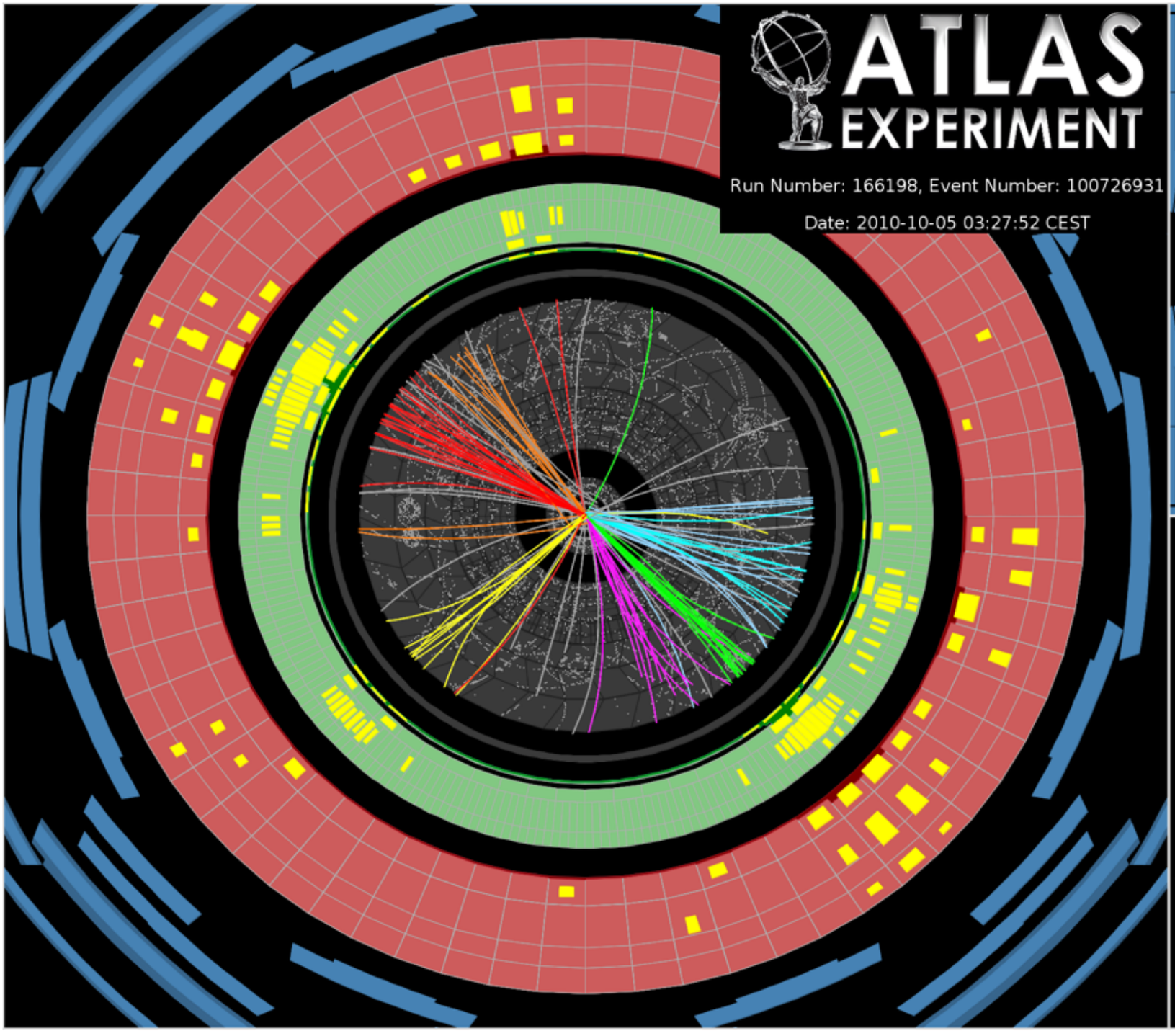


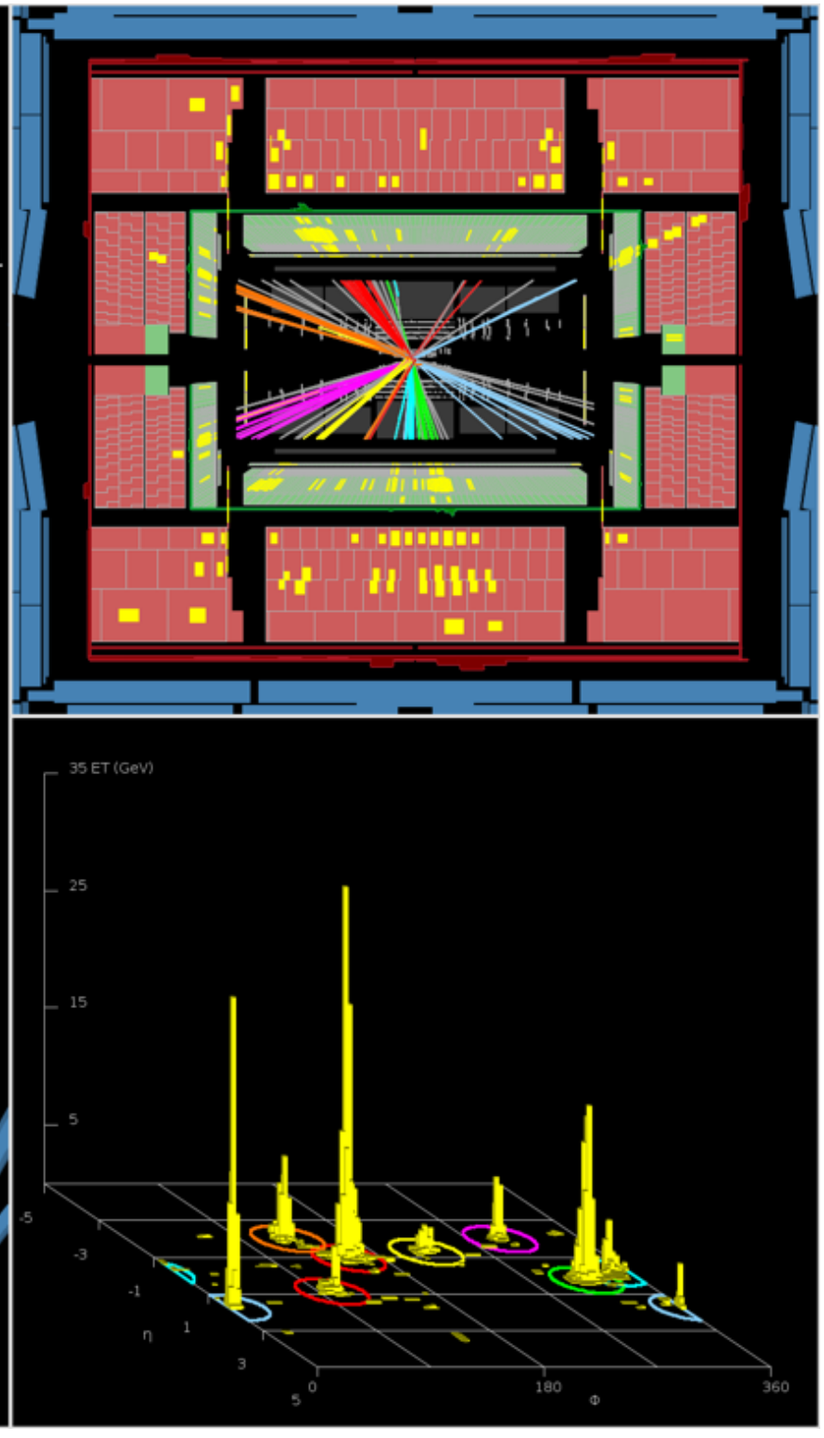




p_T of jets: 890 GeV, 760 GeV, 30 GeV

Multi-jet Event

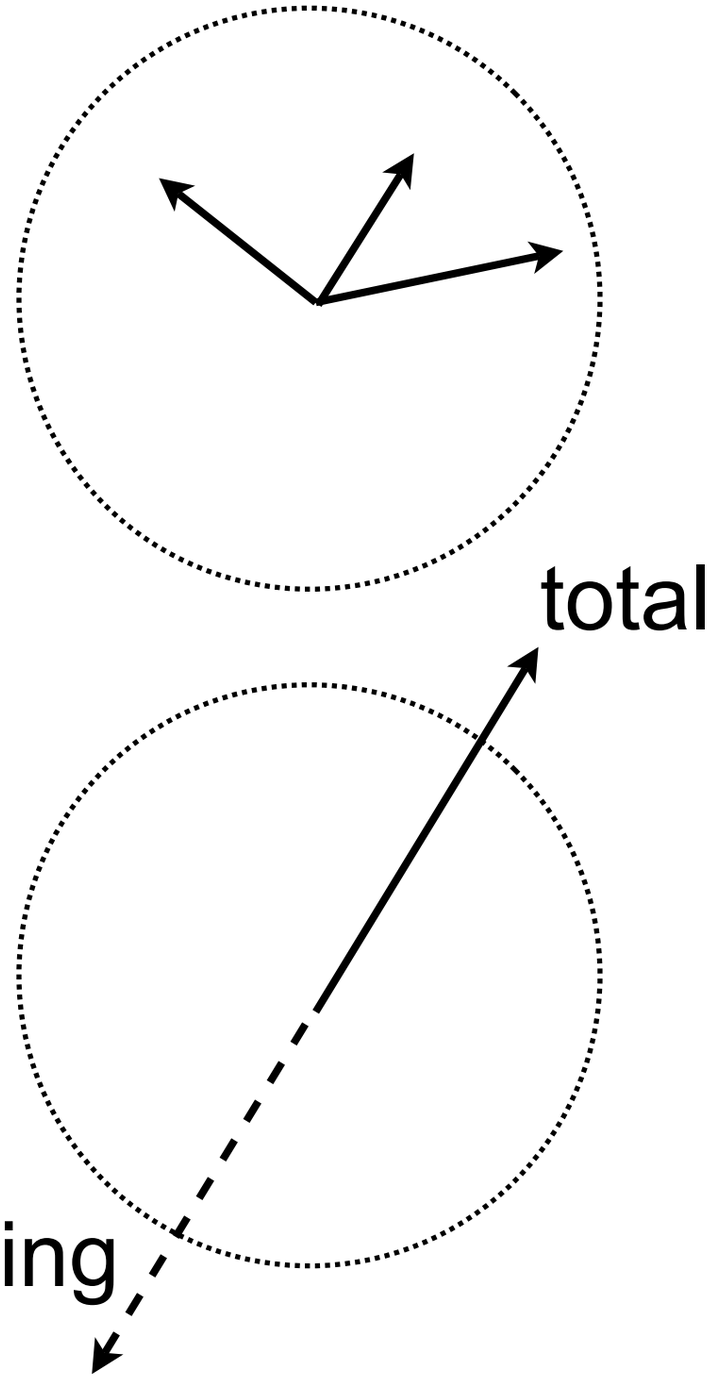




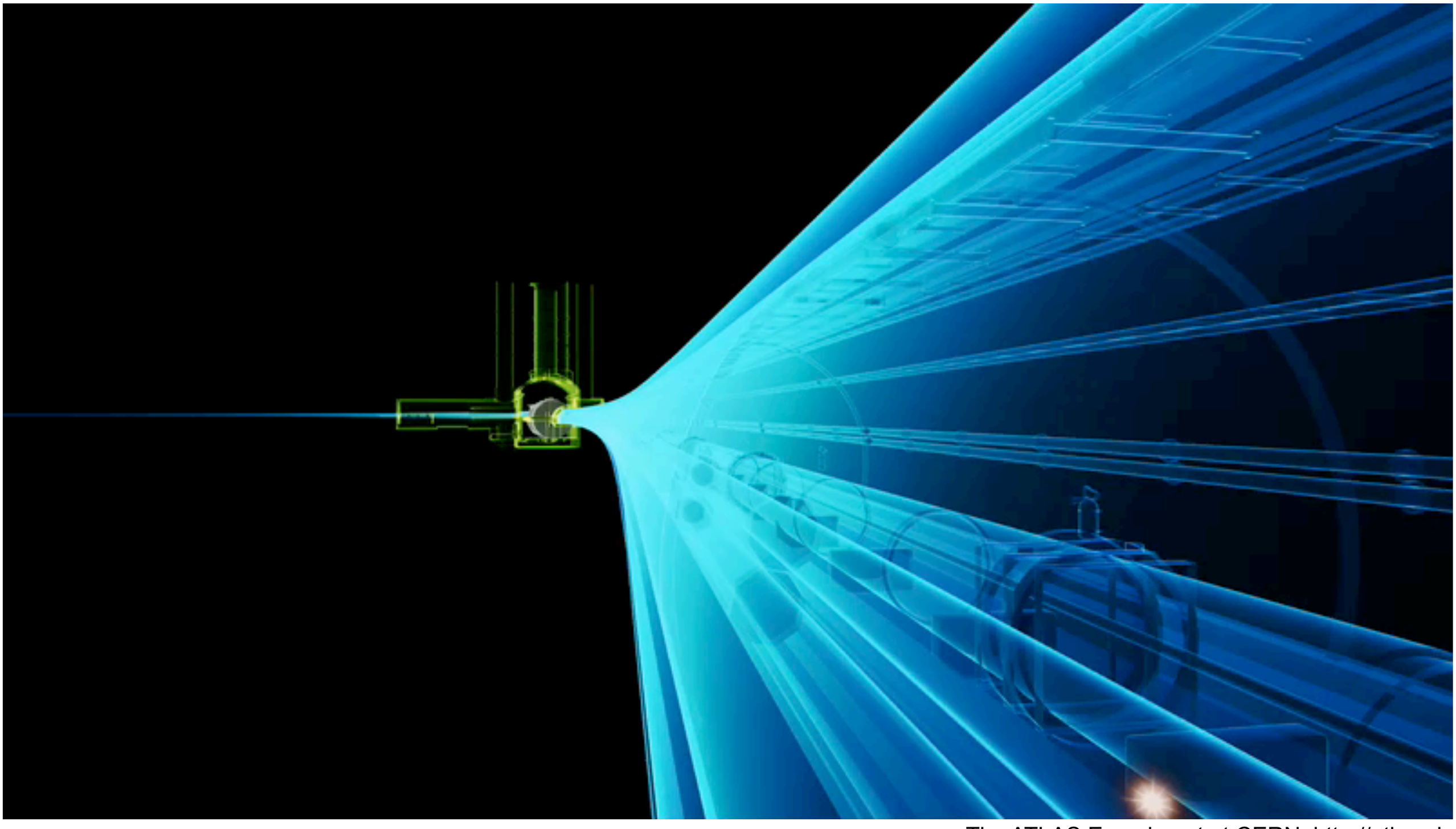
This event has 8 jets with p_T > 60 GeV !

Missing Transverse Energy

- No net momentum in the transverse plane
- But some particles cannot be detected
  - e.g. neutrinos... dark matter, escape in other dimensions!
- Infer particle from missing energy
  - “missing transverse energy”
  - how neutrinos were discovered!
- MET is an important observable!
  - essential to many measurements



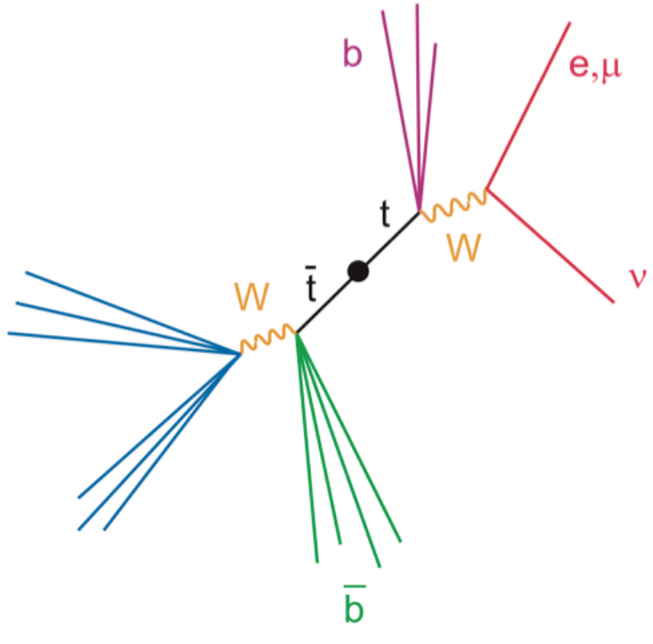
Animation of a real W→ev candidate

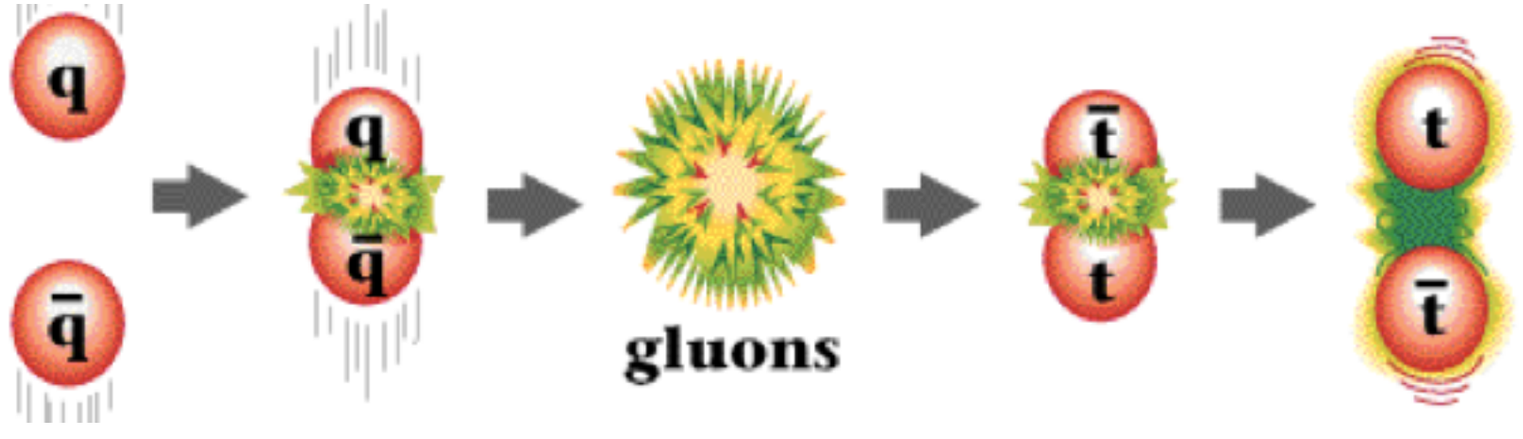


The ATLAS Experiment at CERN, http://atlas.ch

Top Quark Production

http://www.particleadventure.org/

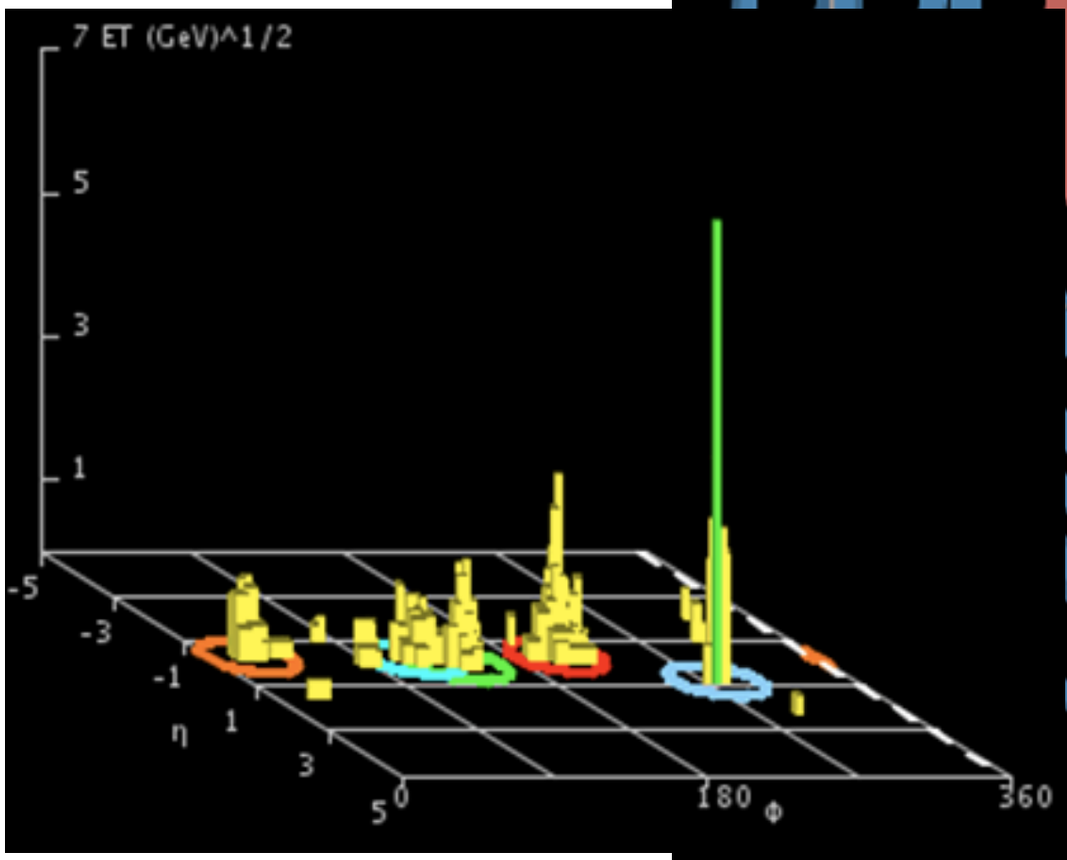


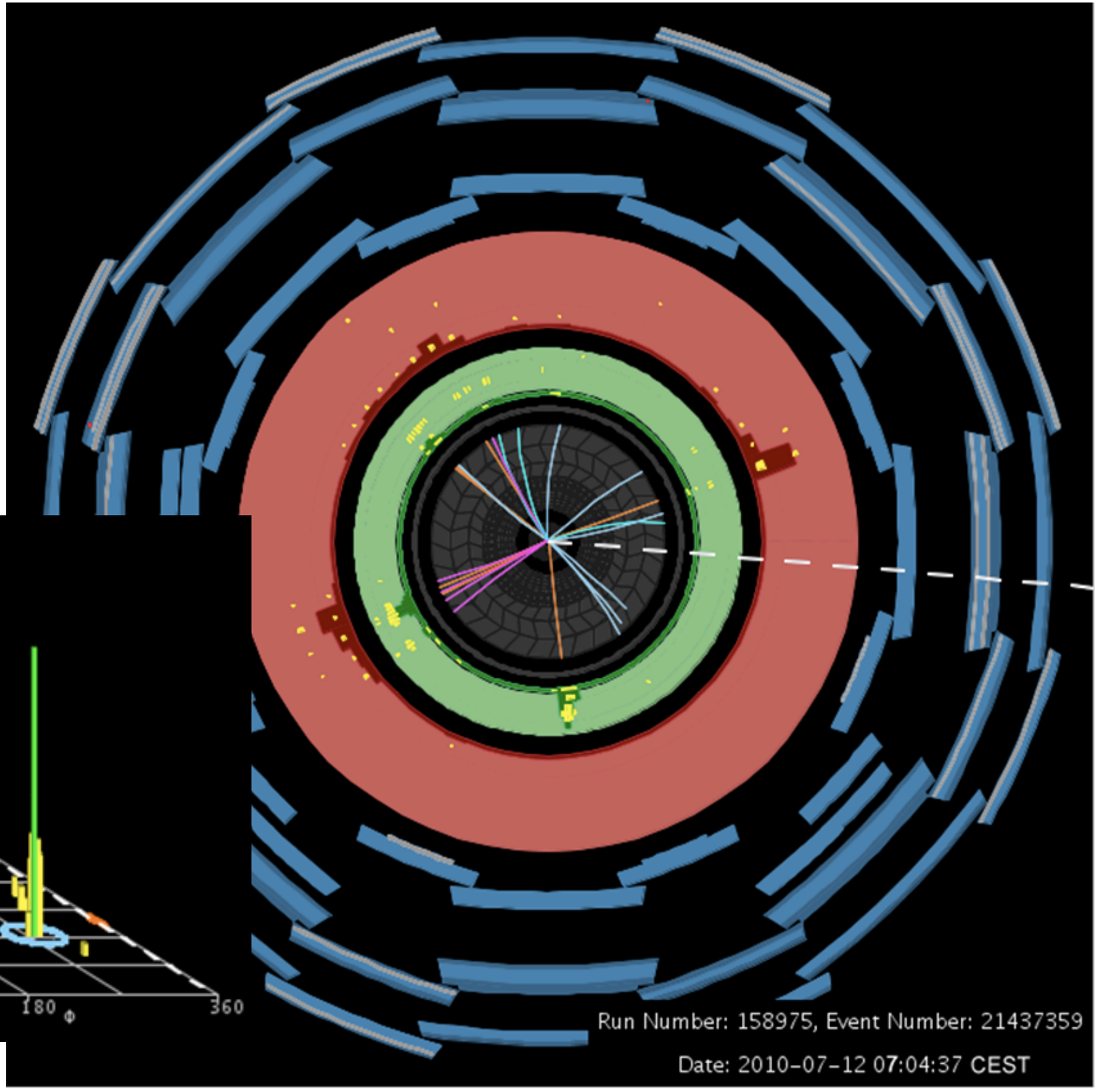


Top quarks are now observed in ATLAS!

Top

- electron
  - p_T = 41.4 GeV
- MET = 89.3 GeV
- 4 jets p_T > 20 GeV
  - 1 tagged as b-jet





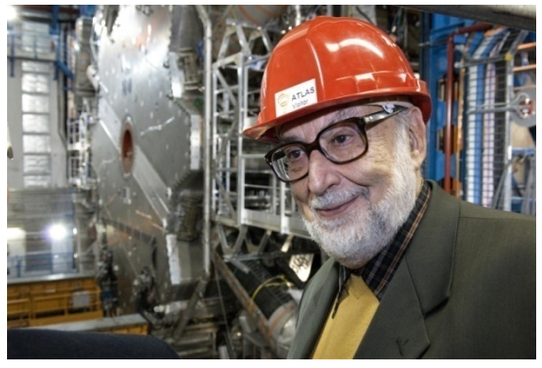
ATLAS-CONF-2010-063

The Higgs Boson

- Why particles (and matter) have mass?
- Whay are particle masses so different?
- The mystery of mass could be solved with the Higgs mechanism, which predicts the existence of (at least) one new elementary particle, the Higgs particle(s).
  - theory 1964 (P. Higgs, R. Brout, F. Englert)

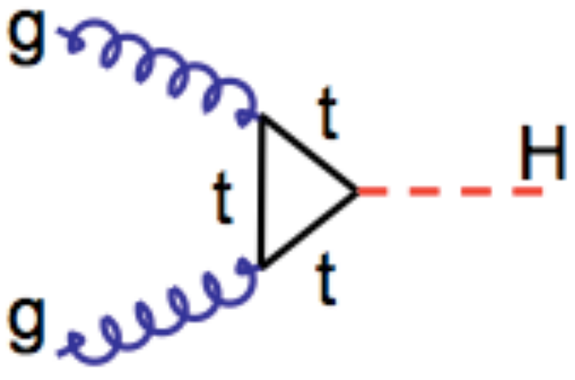
Peter Higgs visiting ATLAS
April 2008

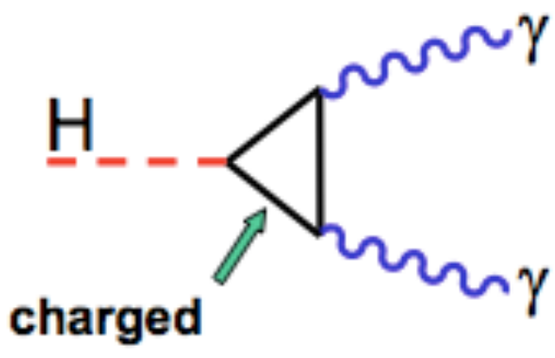
The Higgs particle (H) has been searched for at accelerators for decades, and not found yet.

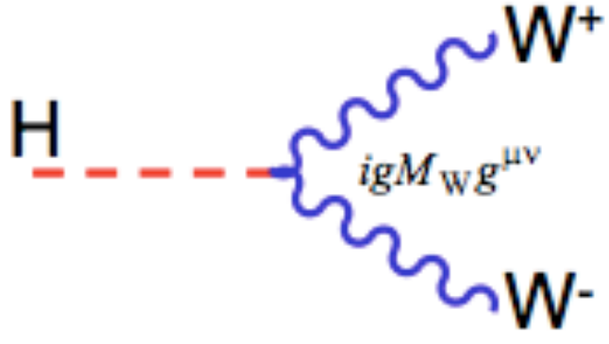


François Englert

If it exist, the LHC will have sufficient energy to produce it!!

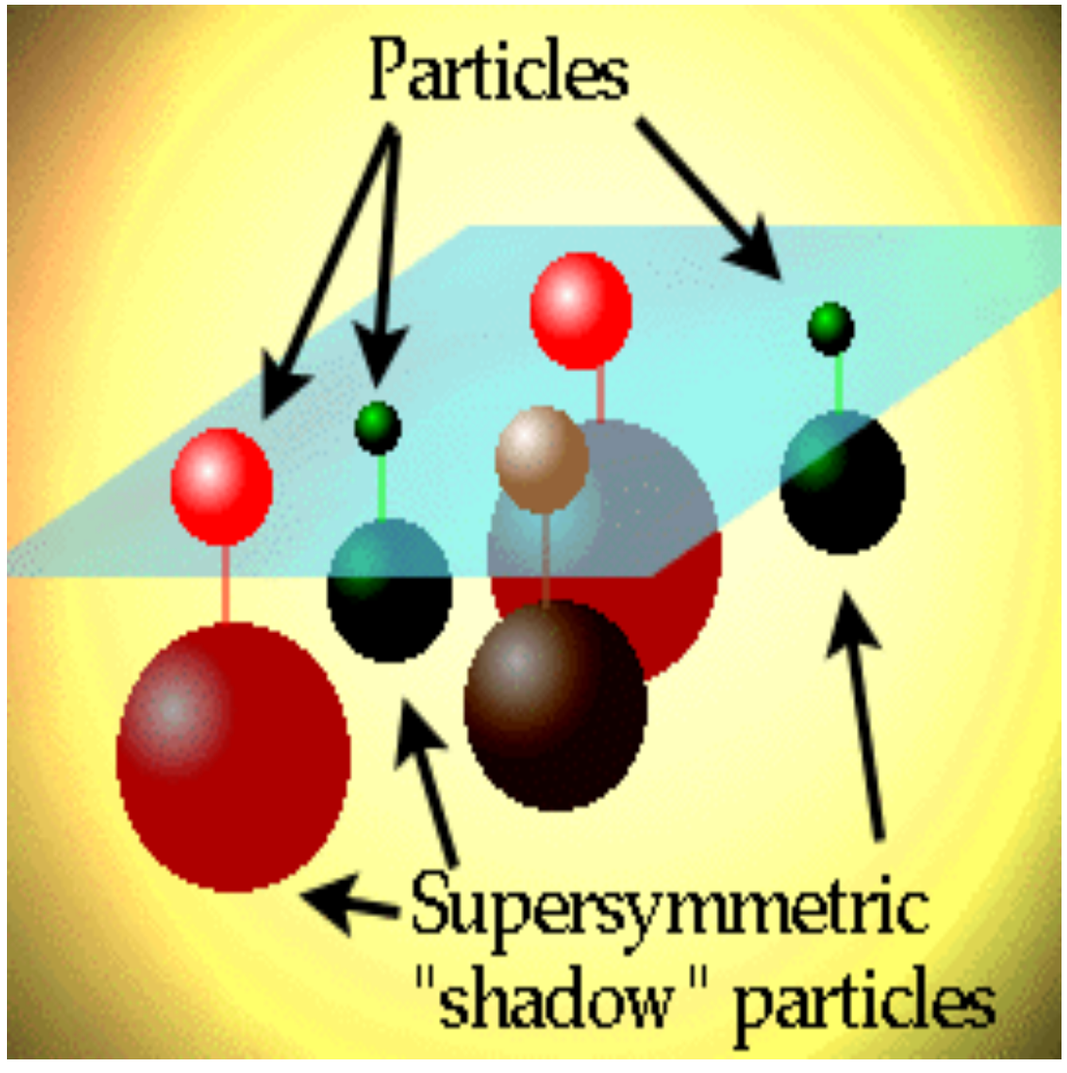




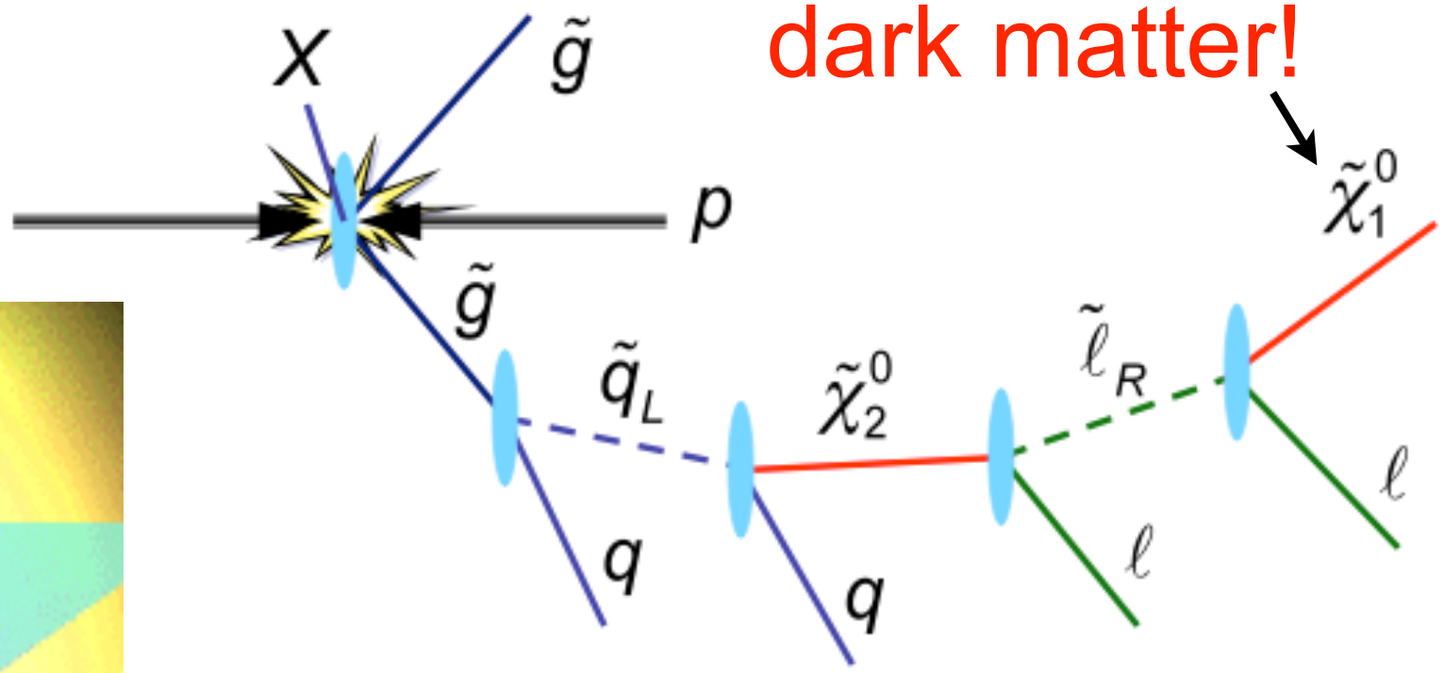


Supersymmetry

- Theoretical idea: extended symmetry of Nature
  - Wess and Zumino, 1974
  - establishes a symmetry between fermions (matter) and bosons (forces)



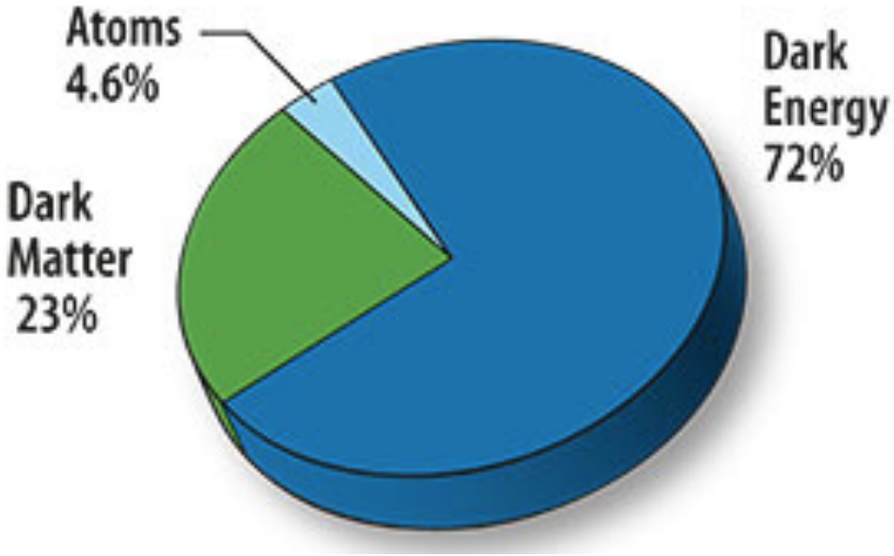
candidate for dark matter!



- Required in most theories of new physics
- Predicts super-partners of all particles!
  - "sparticles",not yet found: broken symmetry
- Many possible signatures sought for at the LHC!

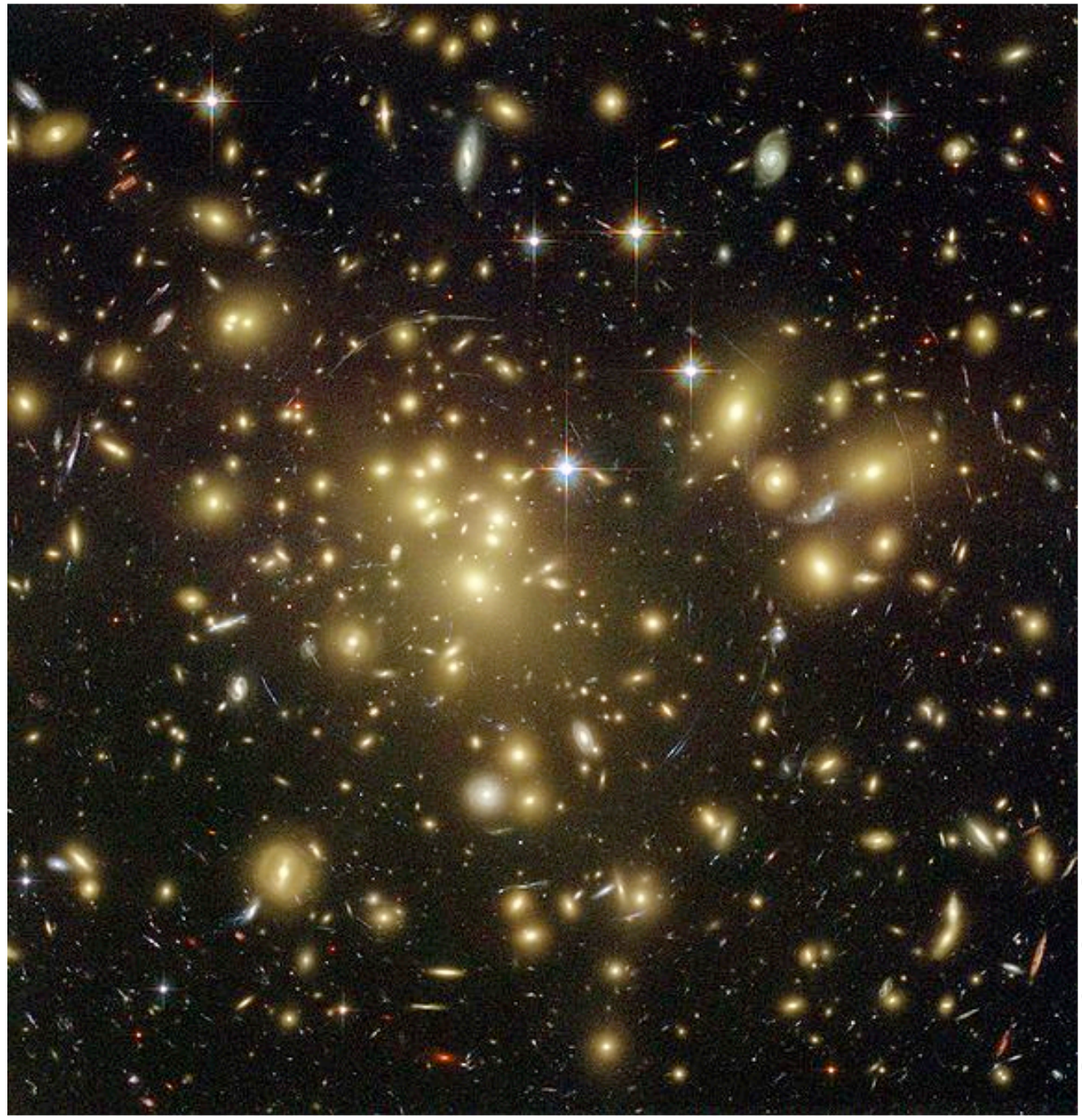
Dark Matter

- Many independent evidence of dark matter
  - most of all matter is of an unknown nature!!



NASA / WMAP Science Team

- Dark Matter candidates includes new particles that could be produced at the LHC
  - lightest supersymmetric particle



NASA and ESA

Strong gravitational lensing observed in Abel 1689 indicates the presence of Dark Matter

Where is the Antimatter?

NASA, Andromeda, M31

- When matter meets antimatter, they annihilate and emit gamma rays

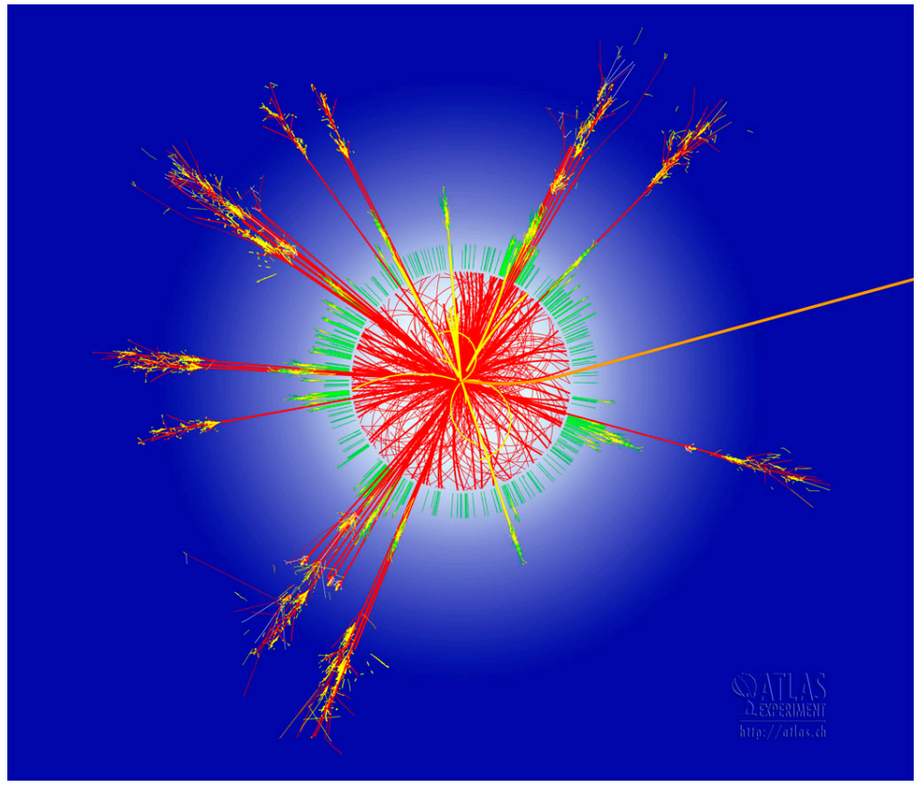
  example: $e^+ + e^- = \Upsilon + \Upsilon$

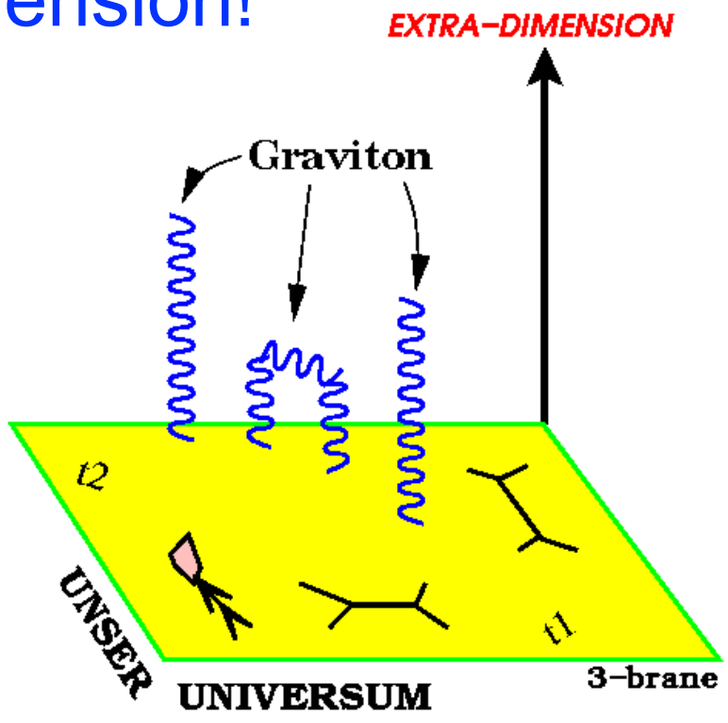
- Gamma rays would be produced at the boundary between matter and antimatter regions in the Universe

- Almost all matter visible from Earth seems to be made of matter, not antimatter
- At baryogenesis: 1,000,000,001 - 1,000,000,000
  - and we're the 1!
- Requires matter and antimatter to be produced at different rate
  - this can be tested at the LHC

Extra Space Dimensions

- Theoretical idea
  - why is gravity so weak?
- Gravity may propagate in extra spatial dimensions
  - but strong effects could be seen only at very small distances, reachable in p-p collisions at the LHC
  - some energy may escape in extra dimension!

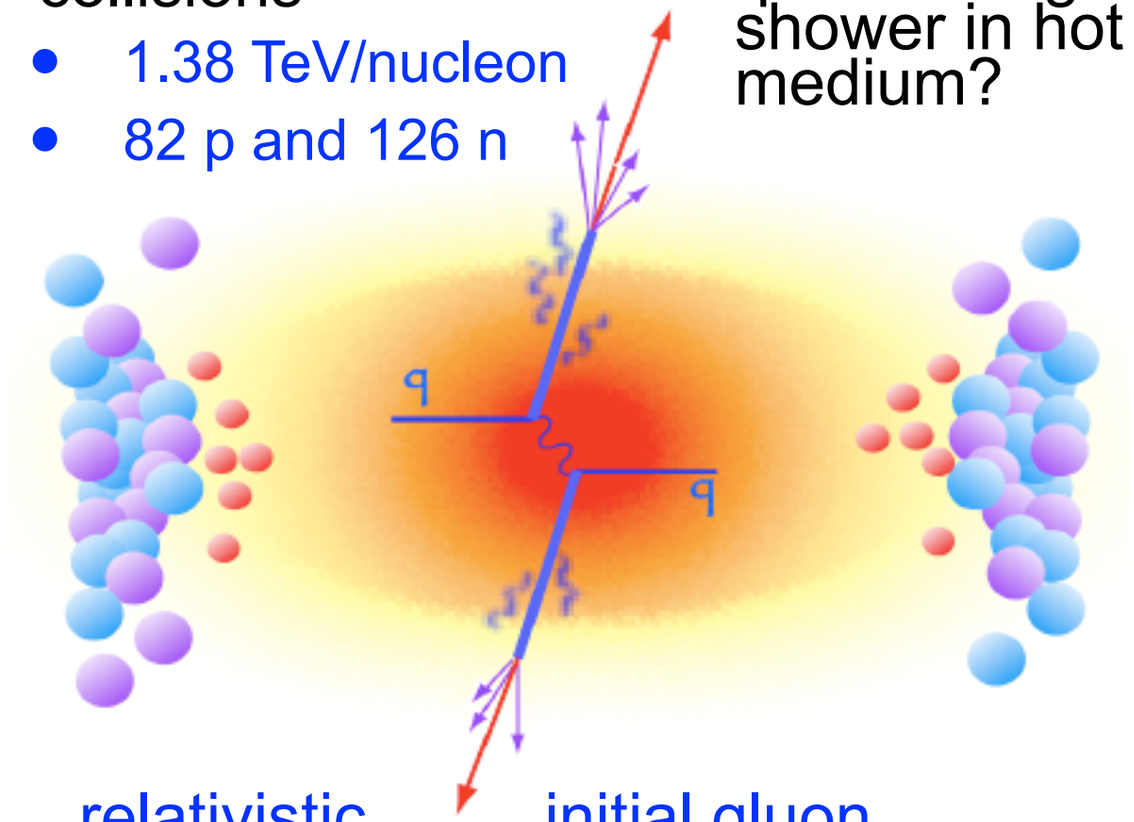




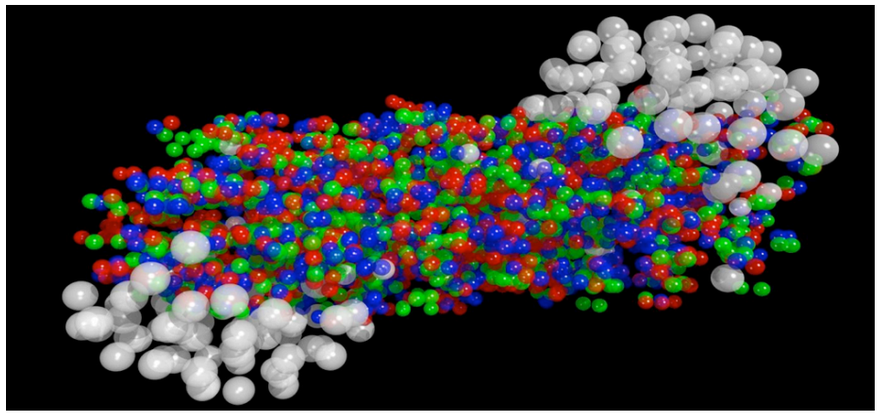
- Could allow the production of microscopic higher-dimensional black holes
  - with characteristic signatures!
  - decay instantly through Hawking radiation

Heavy Ions Collisions

- Pb-Pb nuclei collisions
  - 1.38 TeV/nucleon
  - 82 p and 126 n



- Key question: how do quark and gluon shower in hot dense medium?

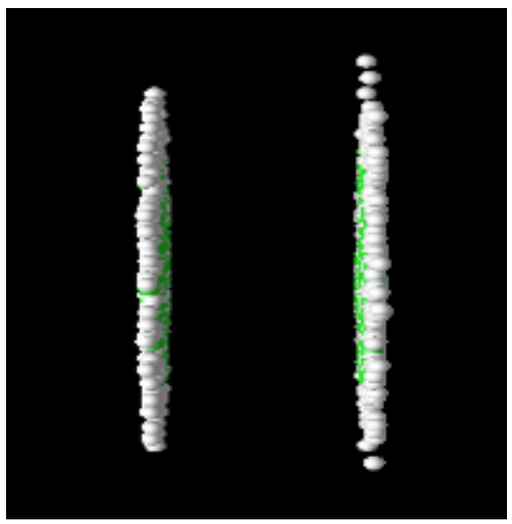


Simulation: quarks in red, blue and green; hadrons in white; after 6 x 10^{-22} s

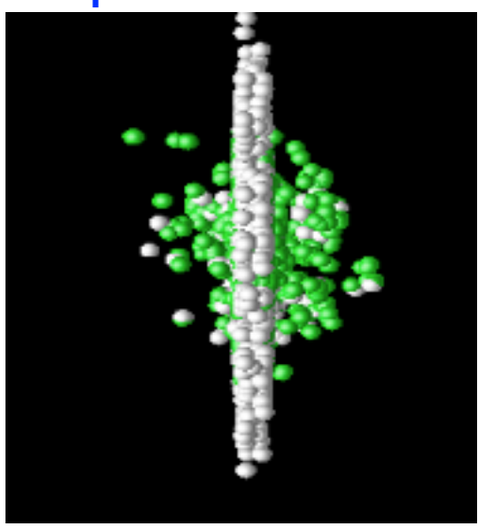
CERN PhotoLab CERN-EX-0002010

- Study high energy and high density state of matter
  - quark gluon plasma?

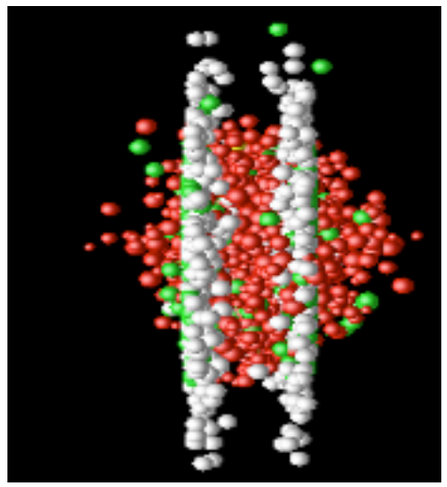
relativistic contraction!



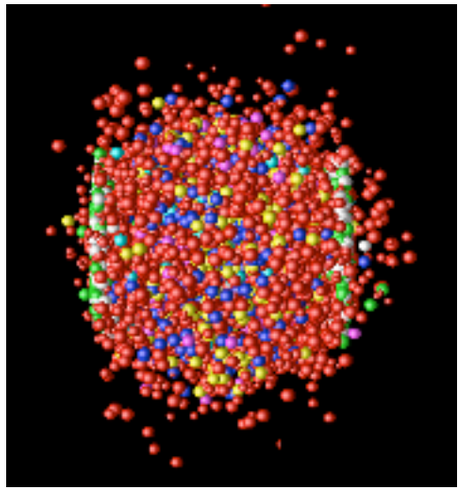
initial gluon production



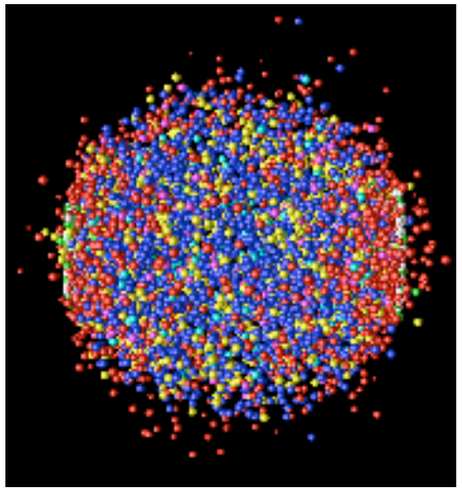
rapid thermalization

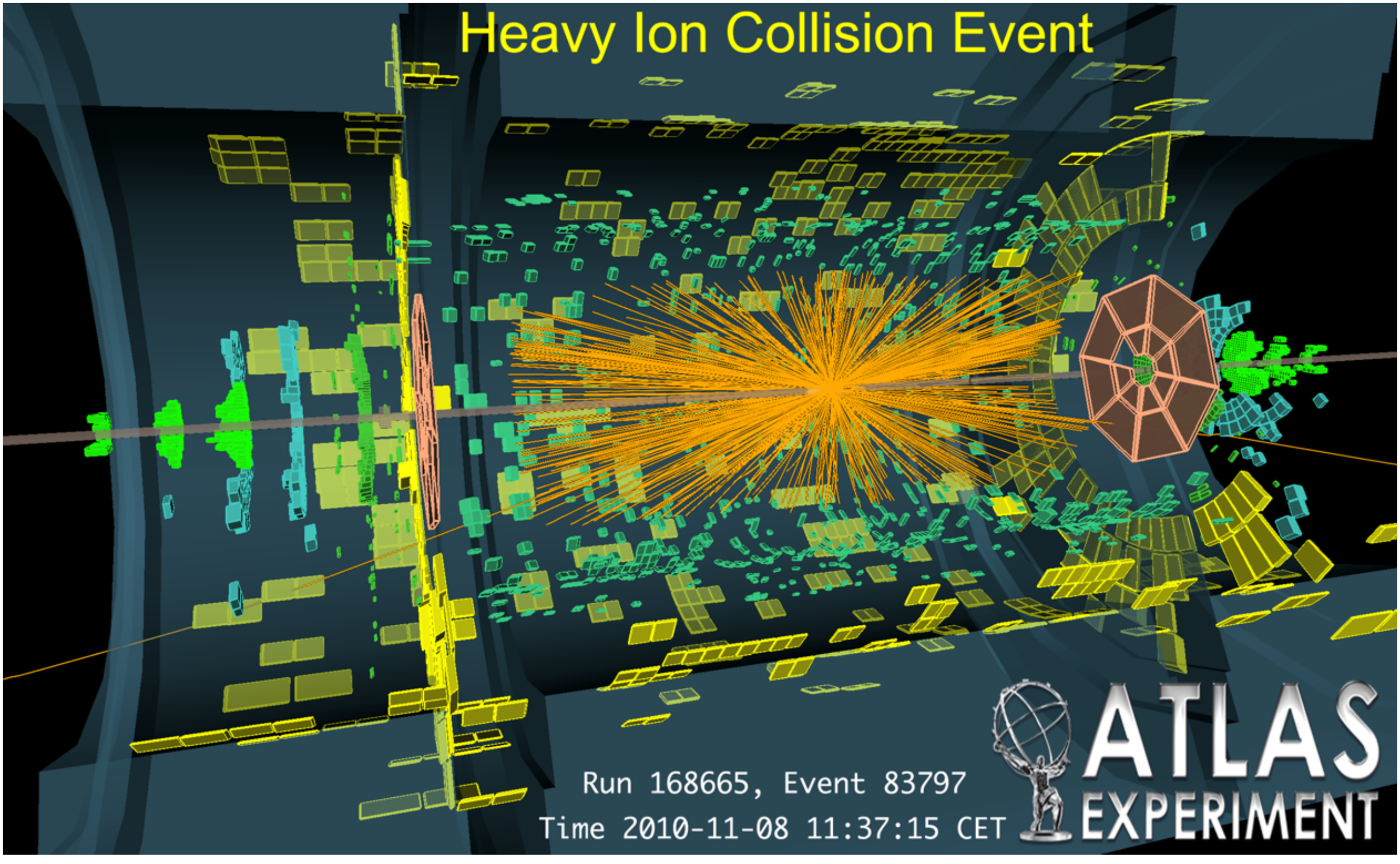


collective evolution

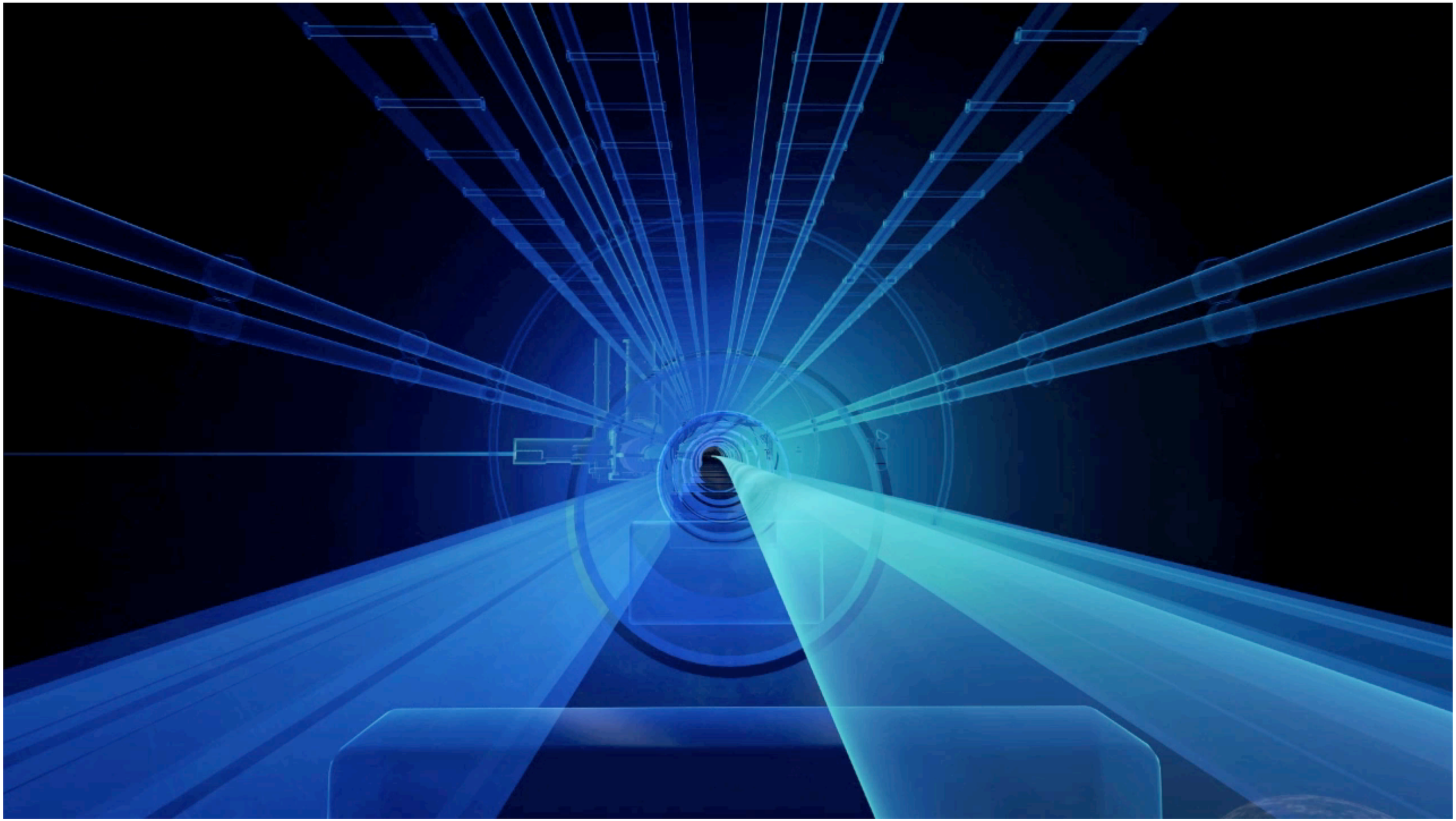


hadronization



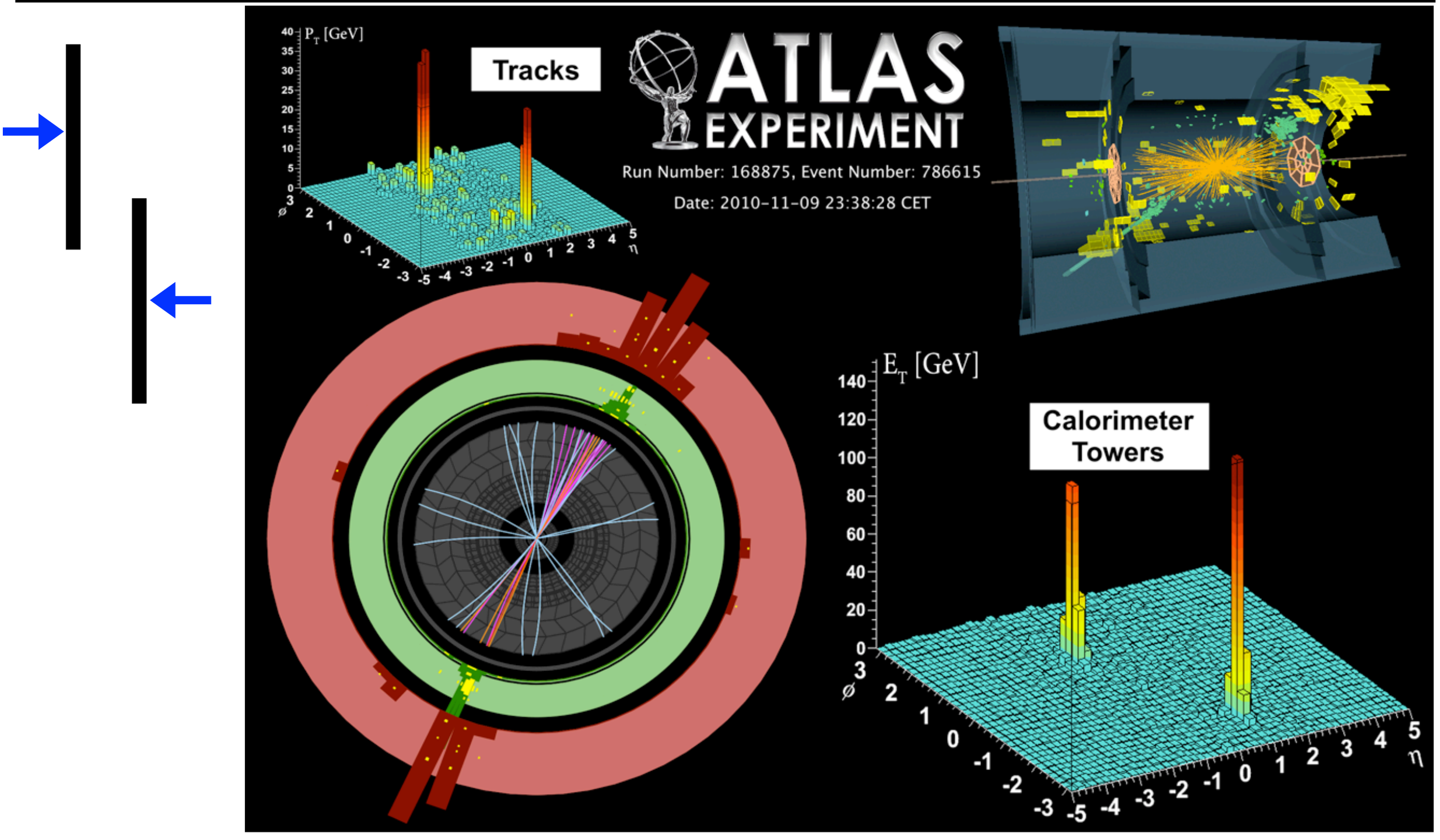

Heavy Ion Collision Event
Run 168665, Event 83797
Time 2010-11-08 11:37:15 CET
ATLAS
EXPERIMENT

Animation of a real Pb-Pb event



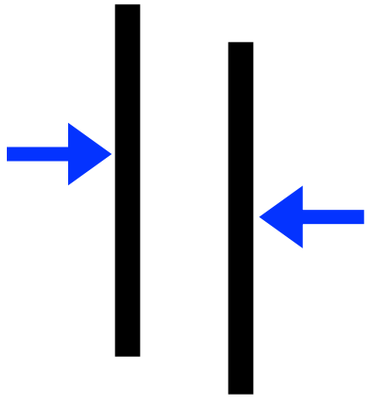
The ATLAS Experiment at CERN, http://atlas.ch

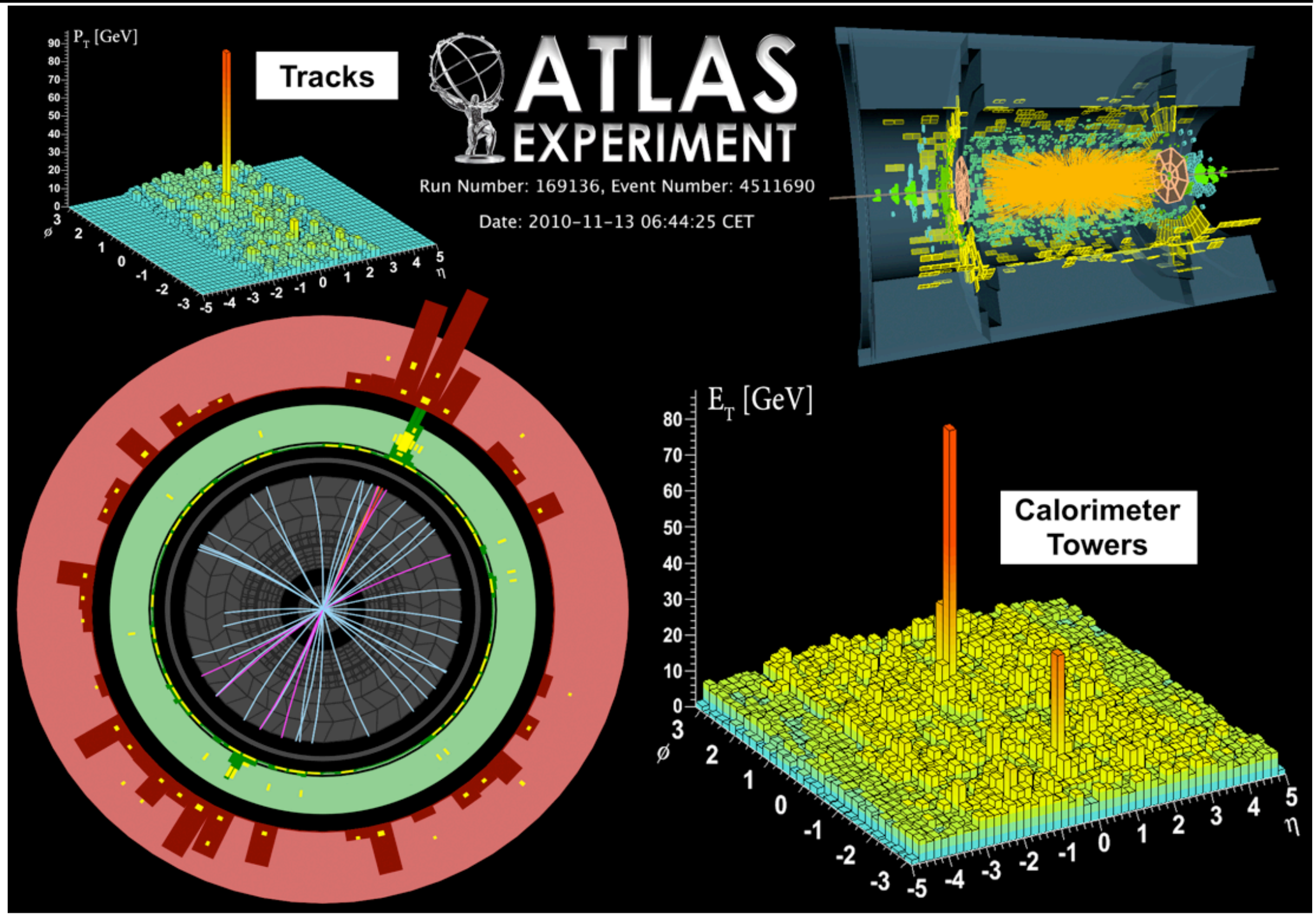
Symmetric Jet Production



"Peripheral"collision, smaller number of particles produced

Asymmetric Jet Production



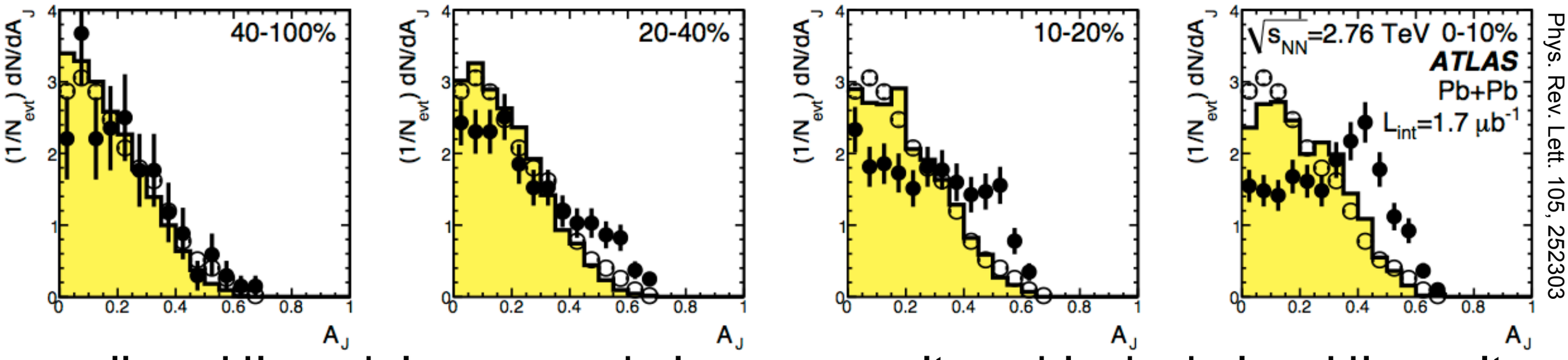


"central"collision, larger number of particles produced

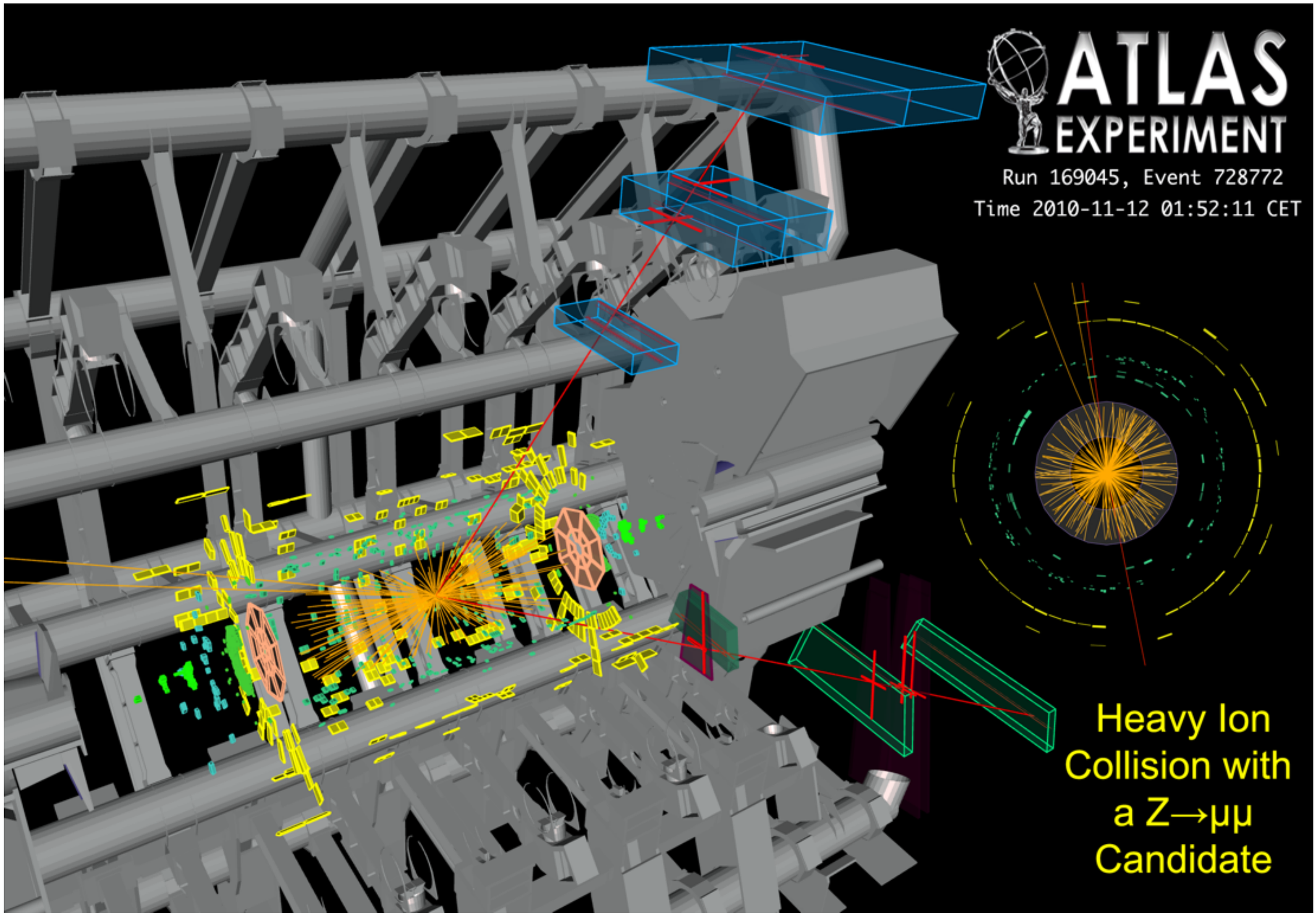
Jet Quenching

- ATLAS observes jets that lose a surprising amount of energy, signalling interactions with the medium more intense than ever seen before
  - "jet quenching"
- May bring new insight to the primordial universe where a hot, dense medium of quarks and gluons may have prevailed
- This result can be quantified in terms of the jet imbalance

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$



yellow: HI model; open circles: pp results; black circles: HI results

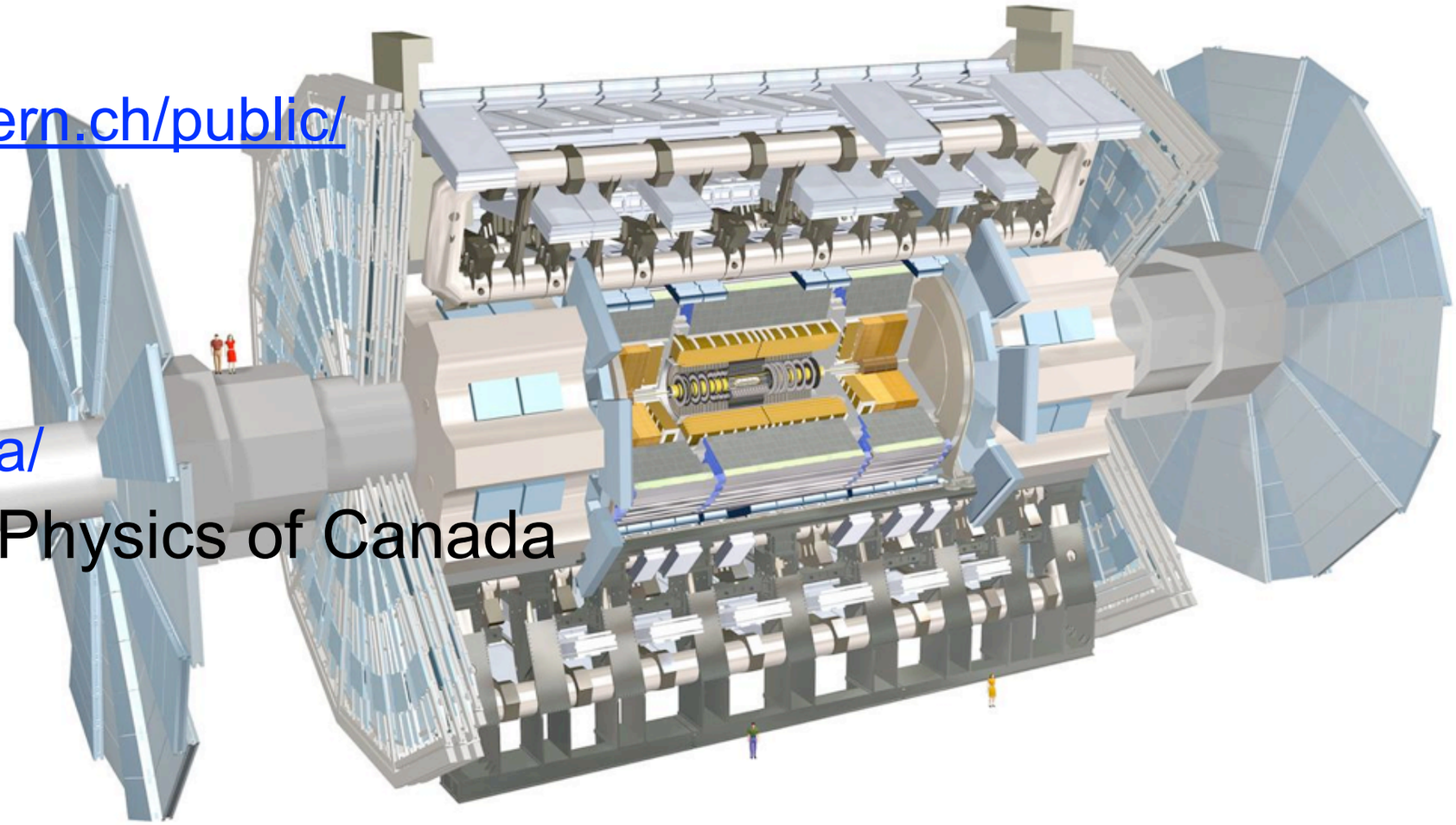

ATLAS
EXPERIMENT
Run 169045, Event 728772
Time 2010-11-12 01:52:11 CET
Heavy Ion
Collision with
a Z→μμ
Candidate

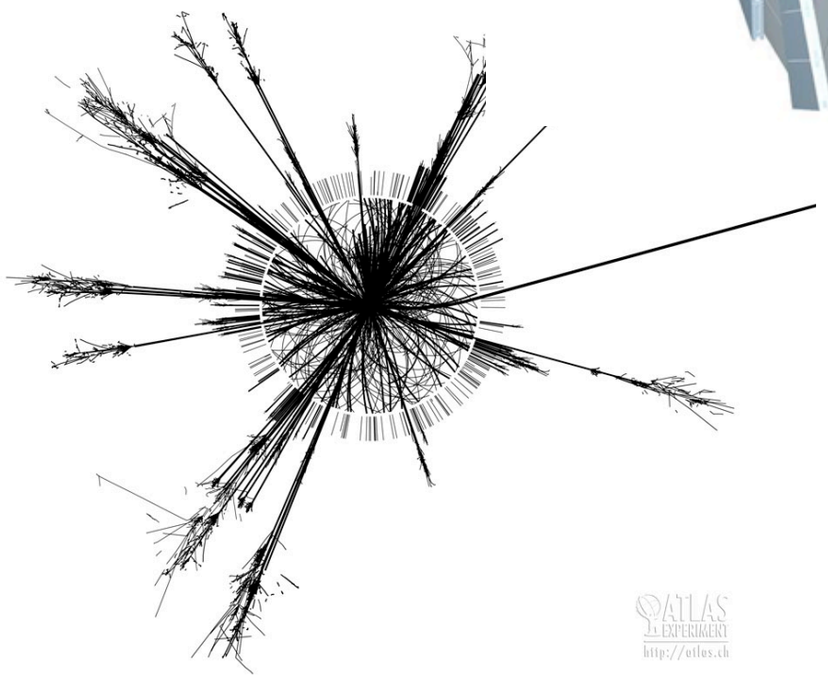
Prospects

- The Large Hadron Collider opens a new window onto the Universe
  - probing Nature most fundamental laws
  - many connections with Cosmology
- 2010 was a very successful year
  - highest energy proton-proton collisions ever produced
  - exciting heavy ions collisions results
- The ATLAS detector performing very well
  - already many publications and many more in progress
  - strong Canadian contribution
- LHC to resume operation very soon
  - likely at 7 TeV, and then 8 TeV in 2012 (decision next week)
- Looking forward to many years of data harvest
  - plans for LHC improvements
  - plans for detector improvements

Stay tuned!

- CERN
  - http://public.web.cern.ch/public/
- ATLAS
  - http://atlas.ch/
- TRIUMF
  - http://www.triumf.ca/
- Institute of Particle Physics of Canada
  - http://www.ipp.ca/





Funding support for ATLAS-Canada is gratefully acknowledged: NSERC, NRC and CFI.