The Experimental Program at the LHC: Probing the Standard Model

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LIP Lisbon

May 16, 2017

- ✓ Introduction
- ✓ The Large Hadron Collider
- ✓ The experiments
- ✓ Detector commissioning
- ✓ Re-discovering the standard model at the LHC (hadron interactions, minimum bias, jets, W/Z, top)

Agenda

Title: “Searches for BSM physics at the LHC”

Tentative agenda:

- Experimental program at the LHC (today, 3pm)
- SM, and Top quarks as probe to New Physics (Wed. 10:30am, 3pm)
- Higgs boson and beyond (Thu. 10am)

- Searches for New Physics (Thu. 4pm) - seminar

Evaluation

Seminar (Friday morning at 10am)

Review and present a seminar from one of these topics:

- di-Higgs production, CMS-HIG-17-002: https://cds.cern.ch/record/2256096/files/HIG-17-002-pas.pdf
- inclusive Z measurement, JHEP 01(2011)080: http://arxiv.org/pdf/1012.2466
- charged Higgs, JHEP11(2015)018: https://arxiv.org/pdf/1508.07774.pdf
- Higgs observation, Science 338(2012)1569: http://science.sciencemag.org/content/338/6114/1569.full.pdf

Experimental particle physics

Particle physics is a modern name for century-old effort to understand the basics laws of physics

Edward Witten

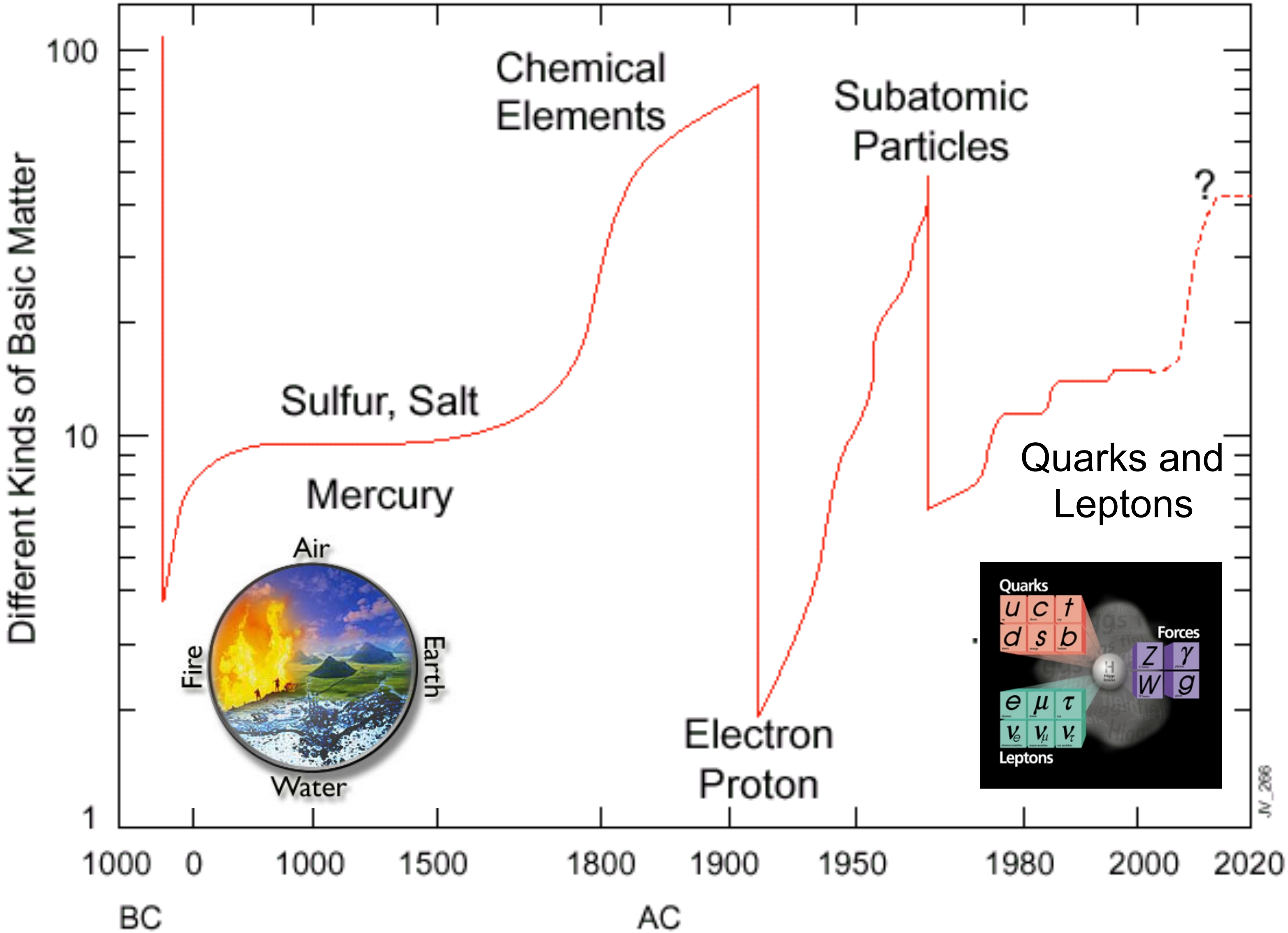
Questions:

- What are the elementary constituents of matter?
- What are the forces that determine their behavior

Experimentally

- Get particles to interact and study what happens

Constituents of matter

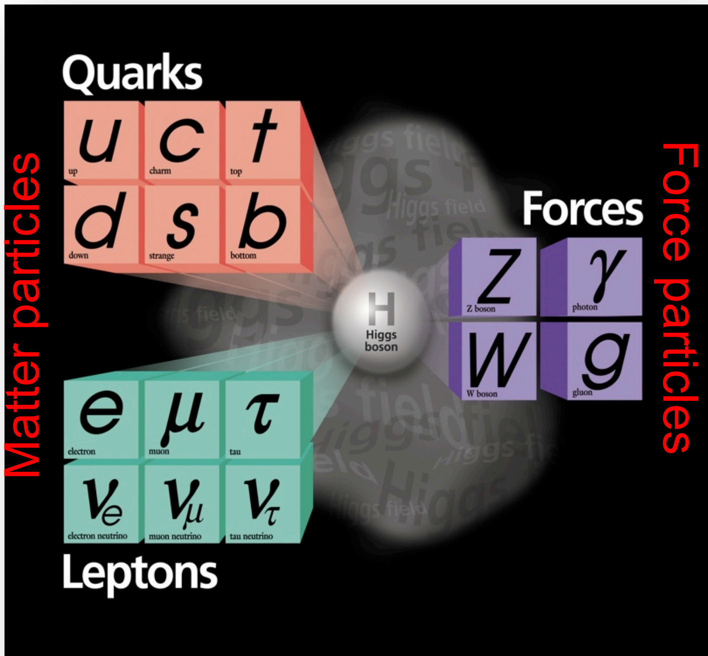


The Standard Model

Over the last ~100 years: combination of Quantum Field Theory and discover of many particles led to

the Standard Model of particle physics

as a new "periodic table" of fundamental elements



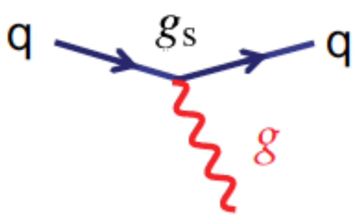
One of the greatest achievements of 20th Century Science

$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4}H^4 + \frac{g^2}{4}(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu)(\lambda^2 + 2\lambda H + H^2) + \sum_{l,q,q'}(\frac{m_l}{\lambda}\bar{l}l + \frac{m_q}{\lambda}\bar{q}q + \frac{m_{q'}}{\lambda}\bar{q}'q')H$$

Standard Model interactions

The interaction of gauge bosons with fermions is described by the SM

STRONG



Only quarks

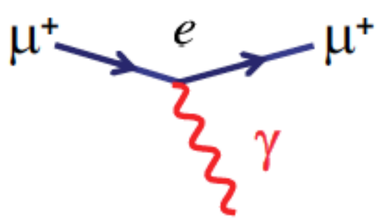
Never changes flavour

$\alpha_S \sim 1$

Gluons

massless

EM



All charged fermions

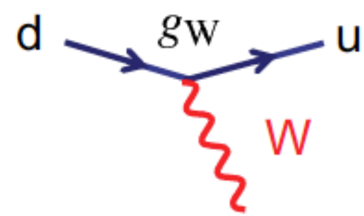
Never changes flavour

$\alpha \simeq 1/137$

Photon

massless

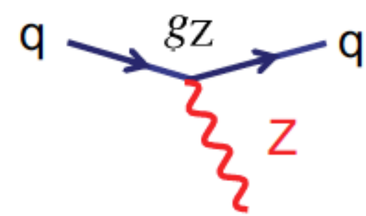
WEAK CC



All fermions

<u>Always</u> changes flavour

WEAK NC



All fermions

Never changes flavour

$\alpha_{W/Z} \sim 1/40$

W+, W-

very massive

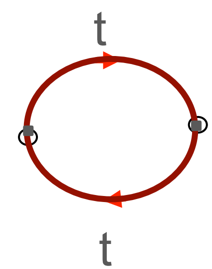
Z^0

very massive

Quantum Field Theory

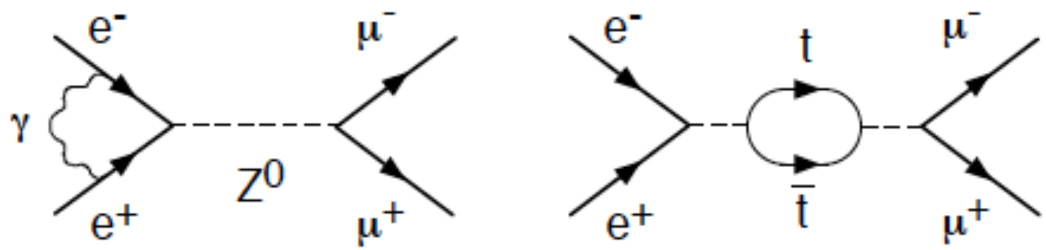
A particle-antiparticle pair can pop out of empty space ("vacuum") and vanish back into it

- These are virtual particles



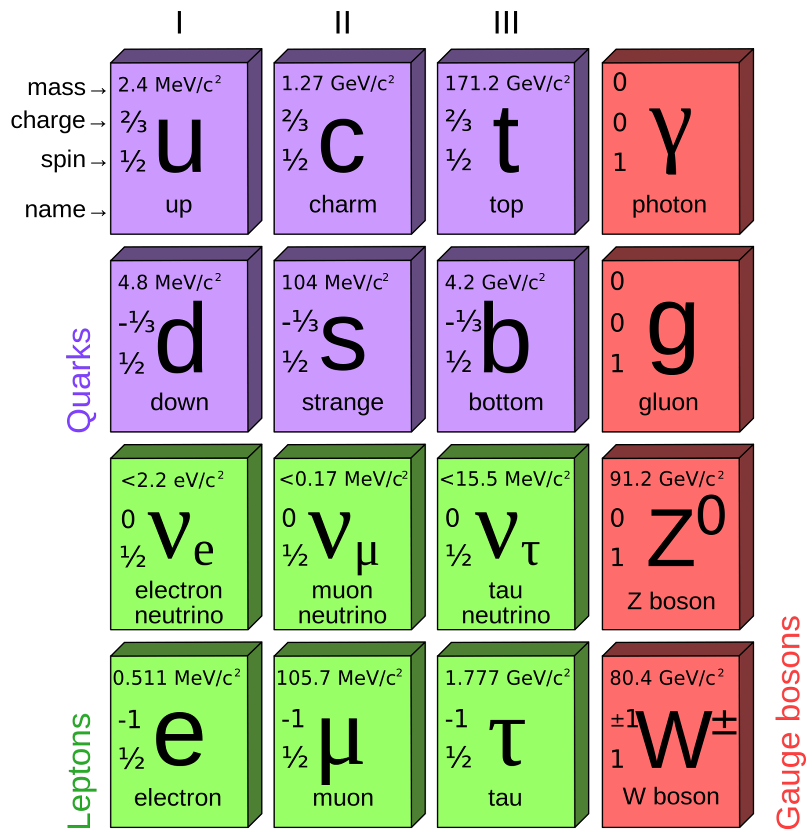
Vacuum fluctuations involving top quarks

- Other examples

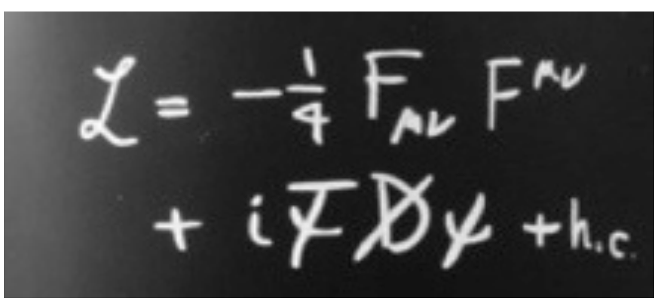


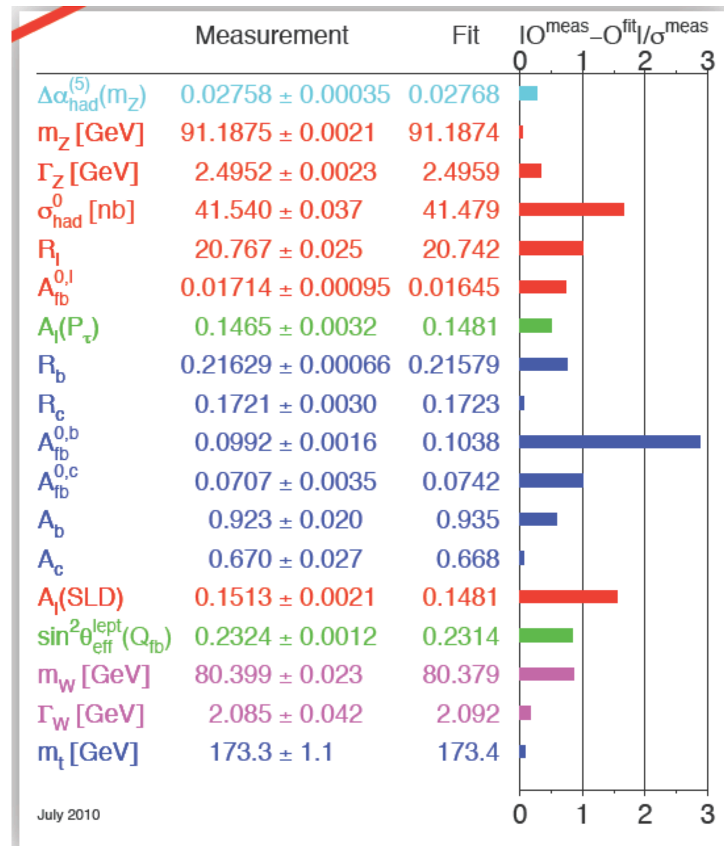
- It has far-reaching consequences
- Structure of the Universe depends on particles that do not exist in the usual sense

SM confirmed by data



STANDARD MODEL OF ELEMENTARY PARTICLES





Confirmed at sub 1% level!

What is missing?

- On the way to the modern theory of quarks, leptons, force fields, and their quanta
- The equations only made sense if all the bosons, and all the quarks and leptons, had no mass and moved at the speed of light!

The Higgs

In the simplest model, the interactions are symmetrical and particles do not have mass

Symmetry between electromagnetic and weak interactions is broken:

- Photons are massless
- W,Z have mass ~80-90 GeV

Higgs mechanism:

mass of W and Z results from the interactions with the Higgs field

Added bonus

- Non-zero average value of the Higgs field can also give masses to quarks, electrons, muons, and all point-like particles

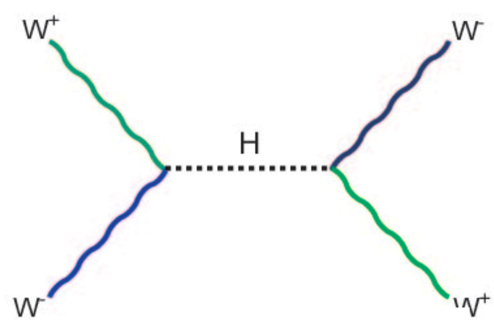
- Old theoretical problem affecting quantum theory of weak force:

Probability of two Ws interacting becomes >1 at high energies (>1TeV)

- This is solved by the Higgs field

$$\lim_{E\to\infty} \mathcal{A} \propto E^2$$

$+$



$$\lim_{E\to\infty} \mathcal{A} \propto \text{const.}$$

Terascale

- The SM would fail at high energy without the Higgs particle or other “New Physics”

- Based on the available data and on general theoretical insight it was expected that New Physics would manifest at an energy of about 1 TeV

⇒This is accessible at the LHC for the first time

Beyond the Standard Model

The SM answers many of the questions about the structure of matter. But SM is not complete; still many unanswered questions:

a) Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

b) What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

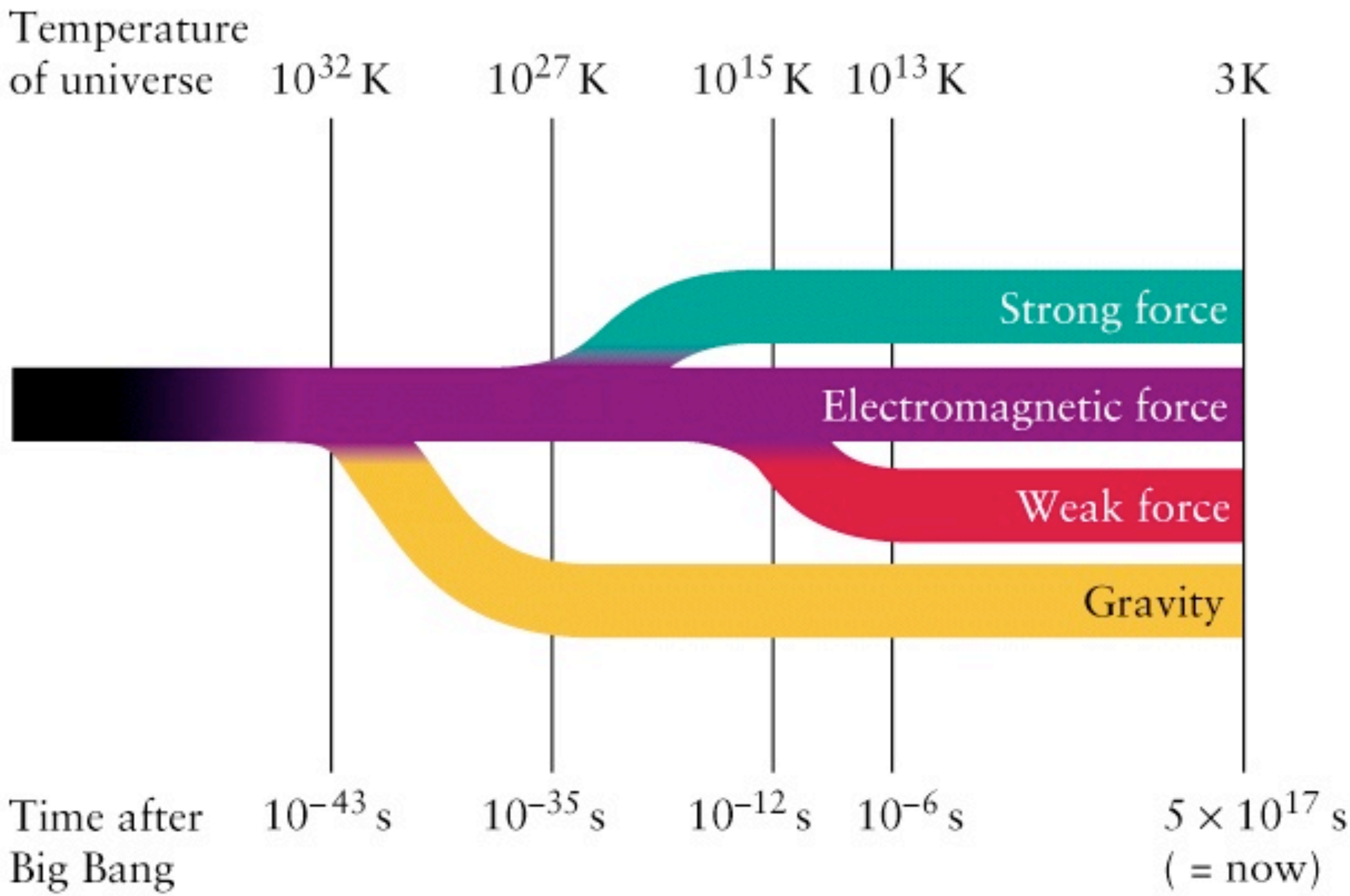
c) Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

d) Why are there three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

e) How does gravity fit into all of this?

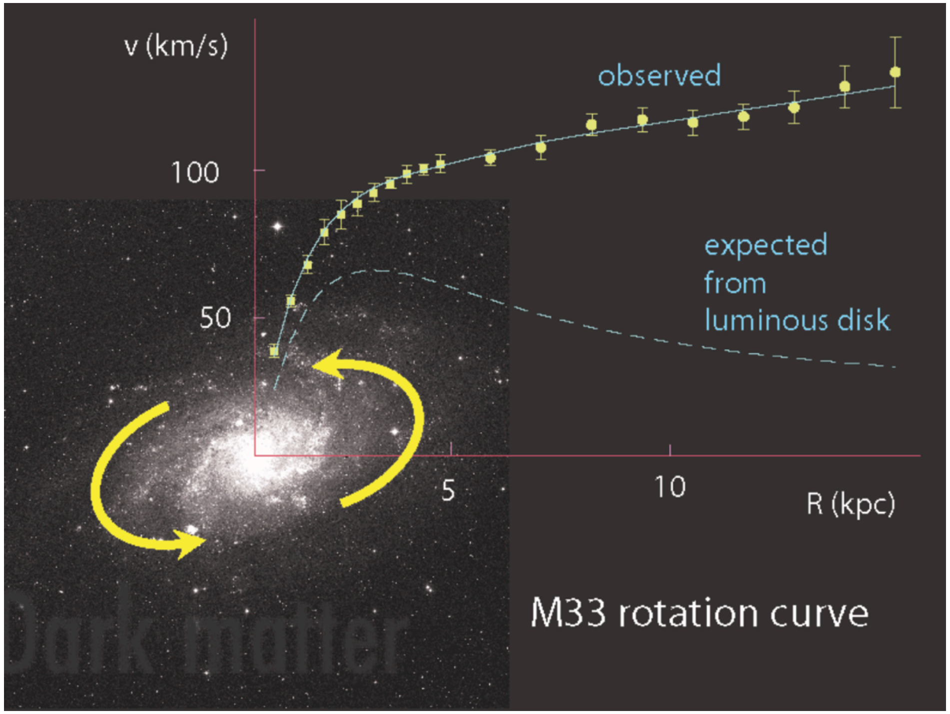
Forces and expansion of the Universe

$E = k \cdot T$ $\quad k = 8.62 \cdot 10^{-5}$ eV K^{-1}



Dark side of the Universe

- We know that ordinary matter is only ~4% of matter-energy in the Universe
- What is the remaining 96%?

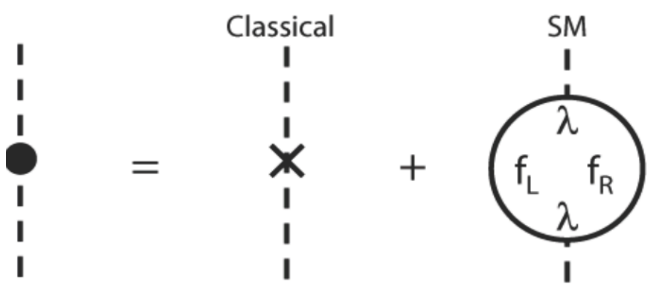


The LHC may help to solve this problem, by discovering dark matter

Higgs and hierarchy problem

In the SM, the Higgs mass is a big problem

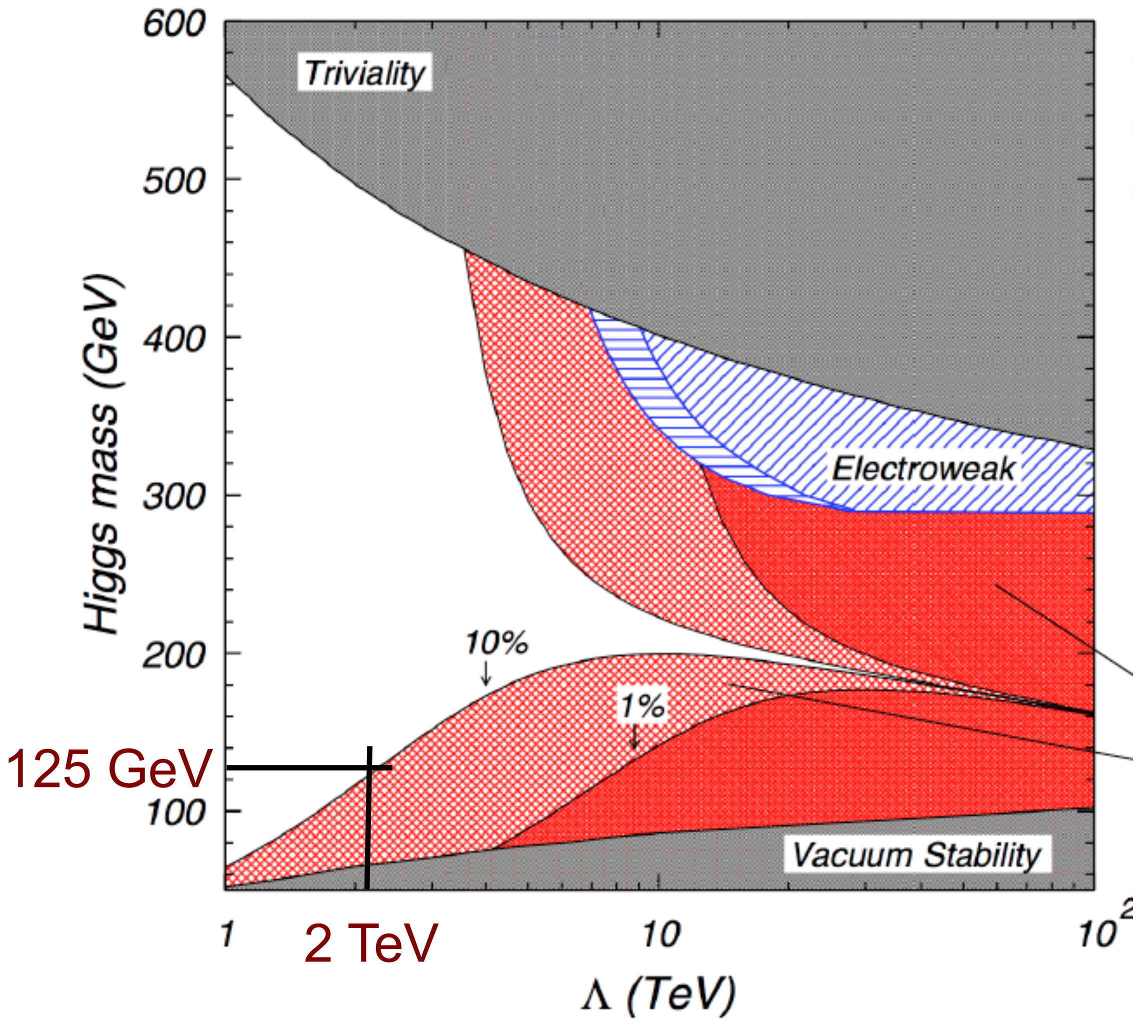
- Virtual particles in quantum loops contribute to the Higgs mass
- Contributions grow with Λ (upper scale validity of the SM)
- Λ could be large – e.g. the Planck scale (10^{19} GeV)
- Miraculous cancellations are needed to keep the Higgs mass <1TeV



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots,$$

This is known as the hierarchy problem

New Physics at the TeV scale?



Naturalness implies Supersymmetry or another 'New Physics' below ~ 2 TeV

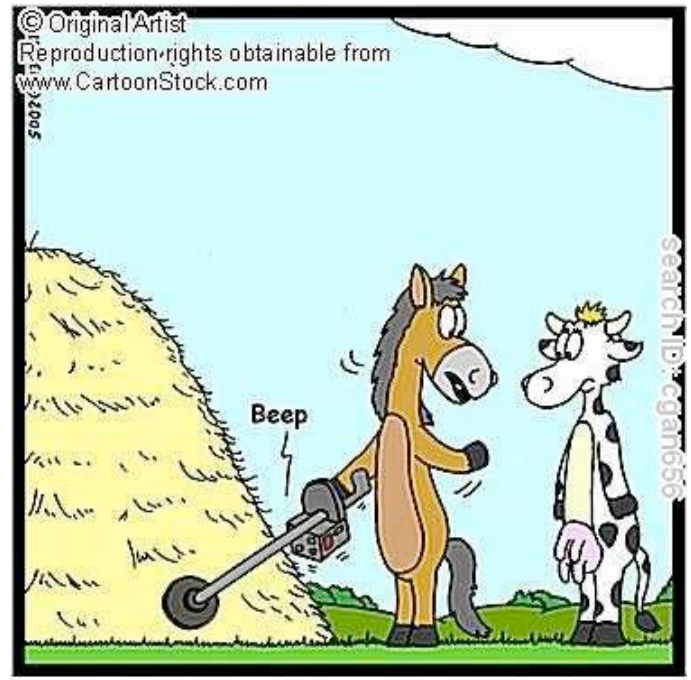
Excluded to avoid fine-tuning

Λ – Scale of New Physics

Many possible theories

There are many models that predict New Physics at the TeV scale, accessible at the LHC

- Supersymmetry (SUSY)
- Extra Dimensions
- Extended Higgs sector, e.g. in SUSY models
- Grand Unified Theories, SU(5), O(10), E6, …
- Leptoquarks
- New Heavy Gauge bosons
- Compositeness



You were right: There's a needle in this haystack...

⇒And it could be found at the LHC

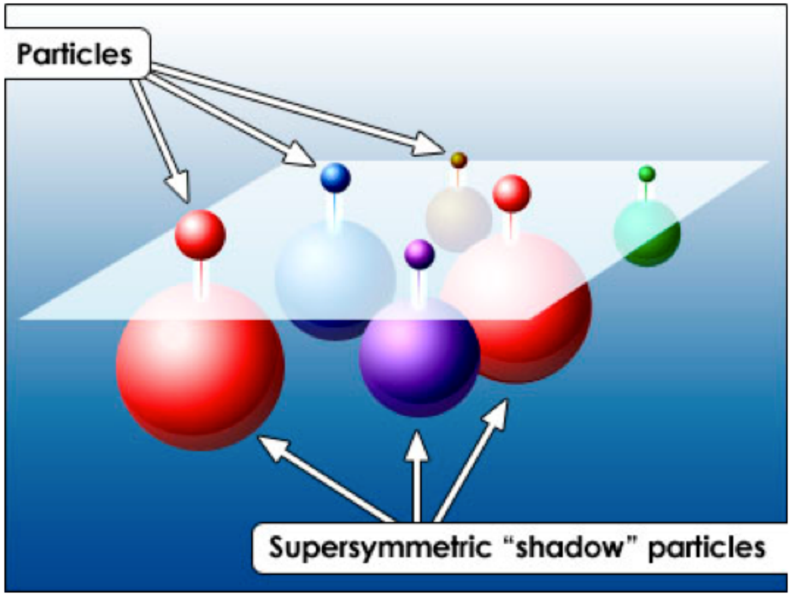
SUSY

A new fundamental symmetry was proposed in the attempt to unify gravity with other fundamental forces

- Every fermion should have a massive “shadow” boson
- Every boson should have a massive “shadow” fermion

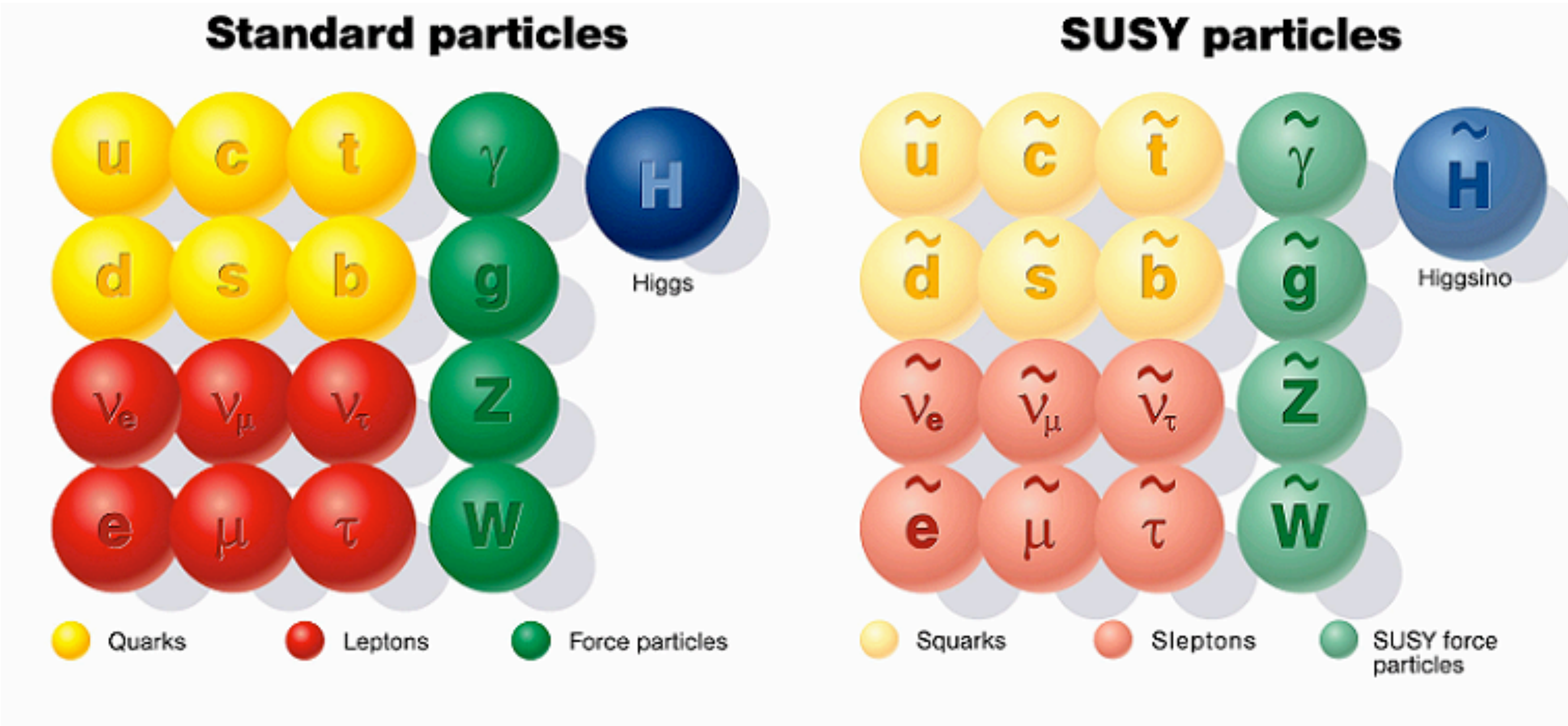
⇒This relationship between fermions and bosons is called supersymmetry (SUSY)

No supersymmetric particle has yet been found, but LHC experiments could detect SUSY particles



SUSY

Double the table with a new type of matter?



Heavy versions of every quark and lepton
Supersymmetry is broken

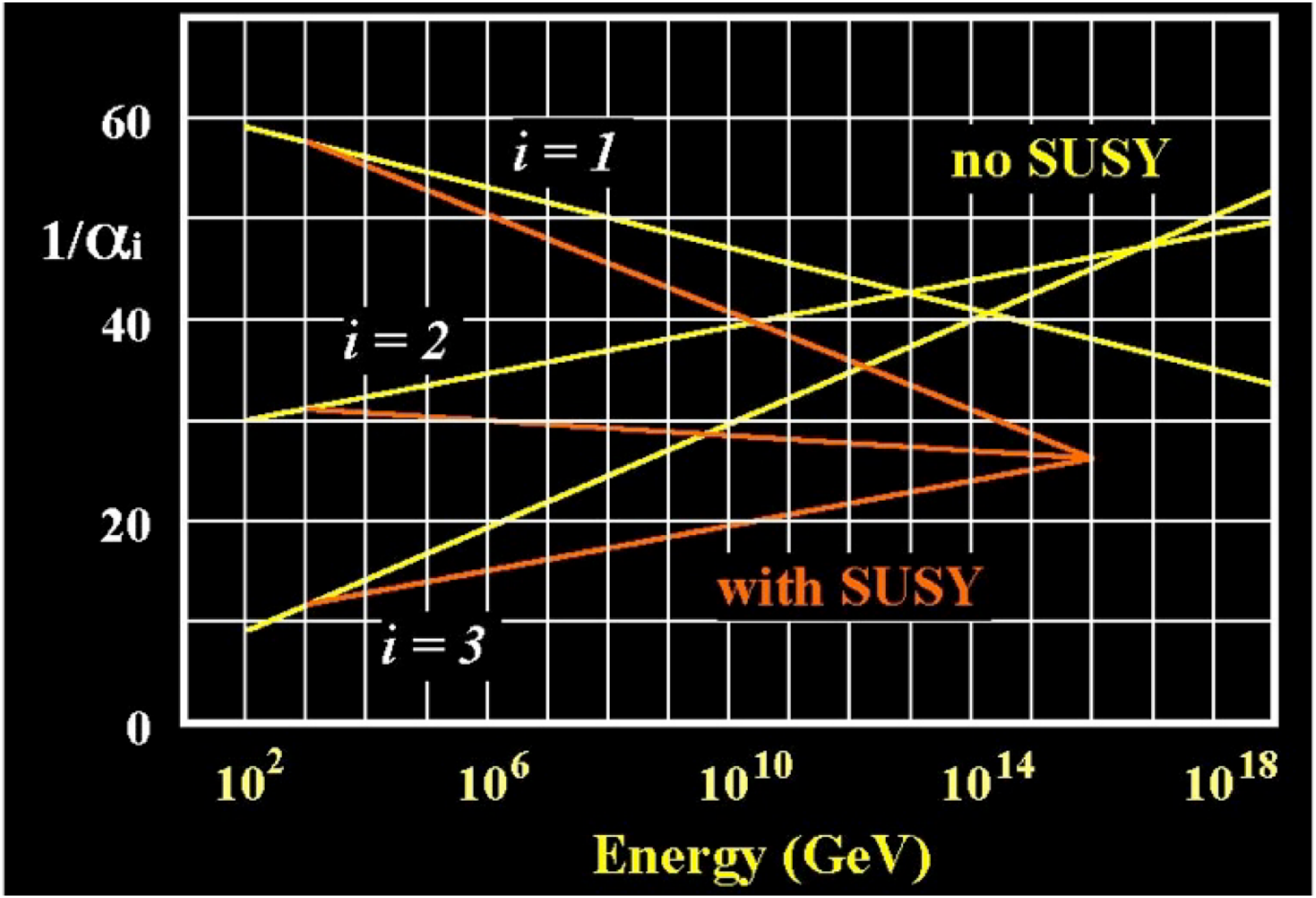
Could DM be SUSY particles?

- For every "normal" force quanta (boson), there are SUSY partners

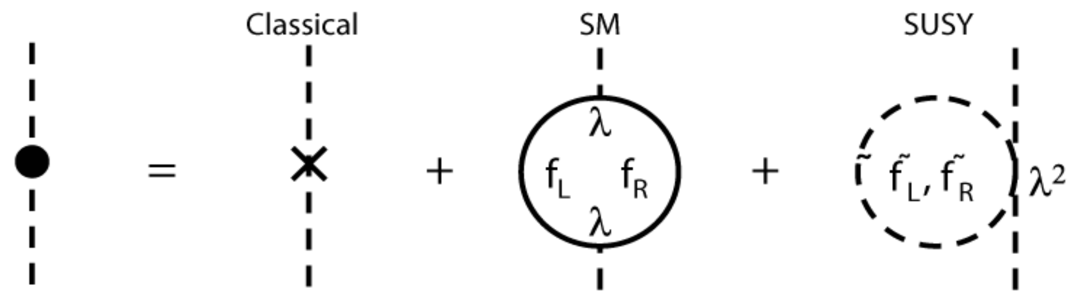
photon	photino
W, Z bosons	Wino, Zino
gluon	gluino
Higgs boson	higgsino

- These "…inos" are prime suspects to be the galactic dark matter
- Relics from the Big Bang!

Unification?



SUSY and the Higgs mass



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

Higgs mass:

- Correction has quadratic divergence!
- Λ a cut-off scale – e.g. Planck scale

Cancellation

$$\begin{aligned} m_h^2 &= (m_h^2)_0 \boxed{- \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2} + \ldots \\ &\approx (m_h^2)_0 + \boxed{\frac{1}{16\pi^2}(m_{\tilde f}^2 - m_f^2)\ln(\Lambda / m_{\tilde f})} , \end{aligned}$$

SUSY can fix this:

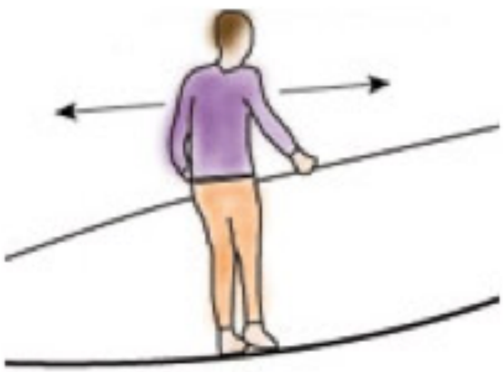
- Need superpartners at mass ~1-2TeV
- Otherwise the log term becomes too large, which would require more fine-tuning

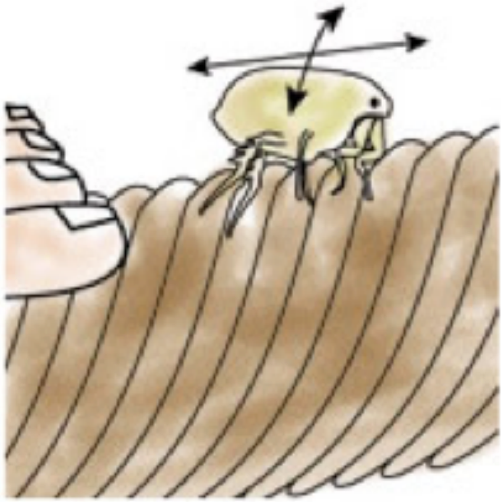
Extra Dimensions

- Space-time could have more than 3 space dimensions. Extra dimensions could be very small and undetected until now

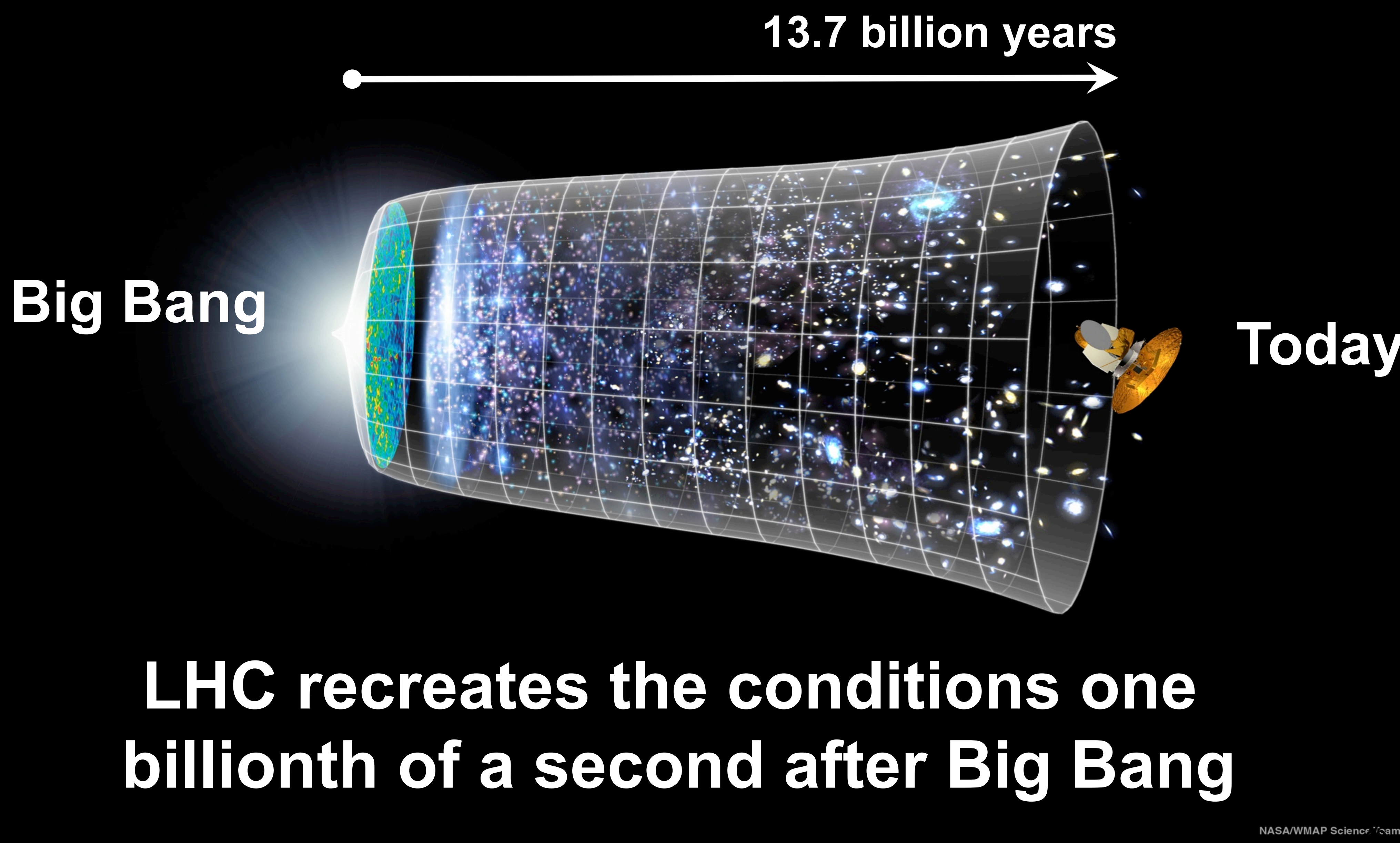
- How can there be extra, smaller dimensions?

- Acrobat can move forward/backward along the rope: 1-dim
- Flea can move forward/backward and sideways: 2-dim
  - One of these dimensions is a small closed loop

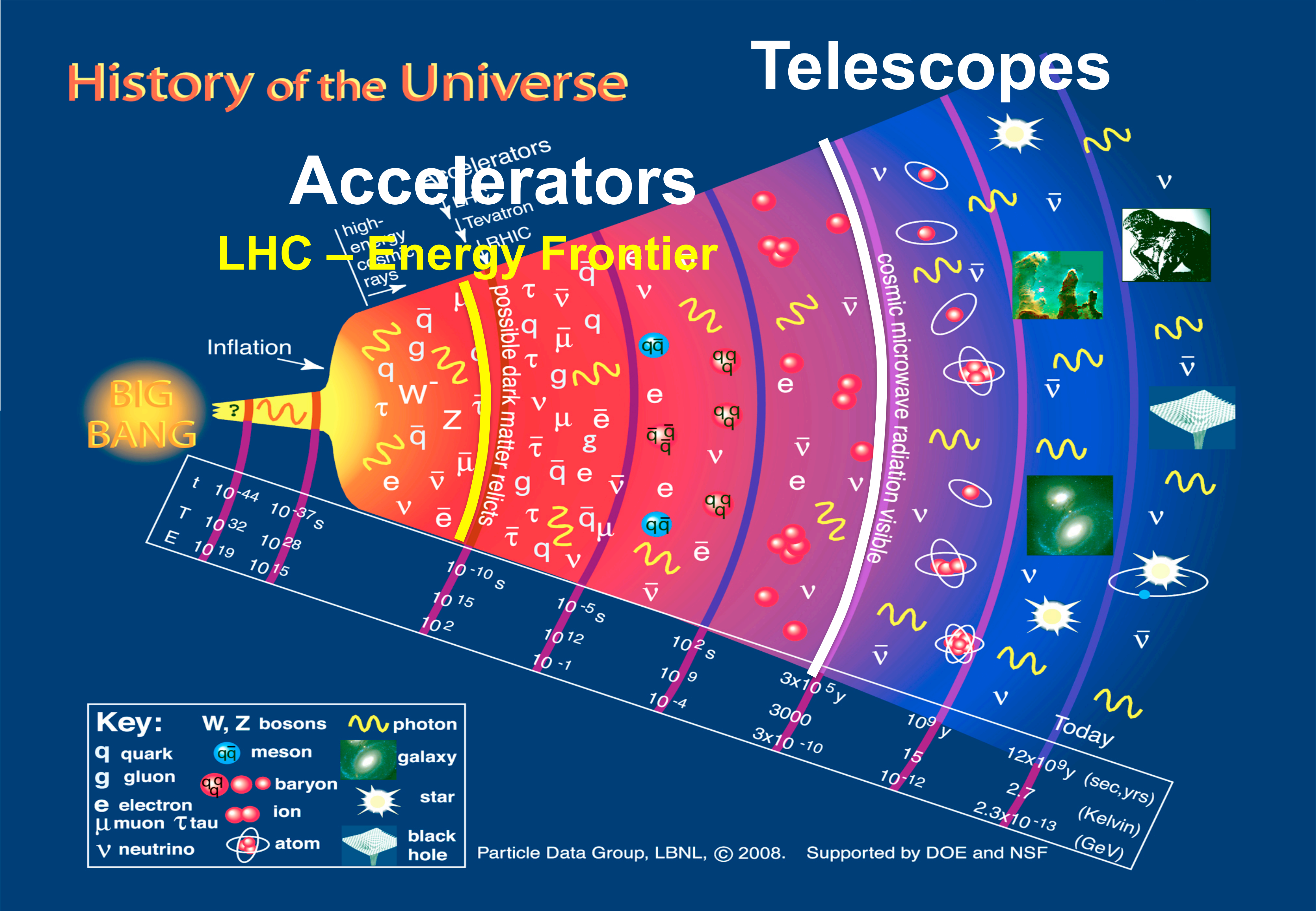




Timeline of the Universe



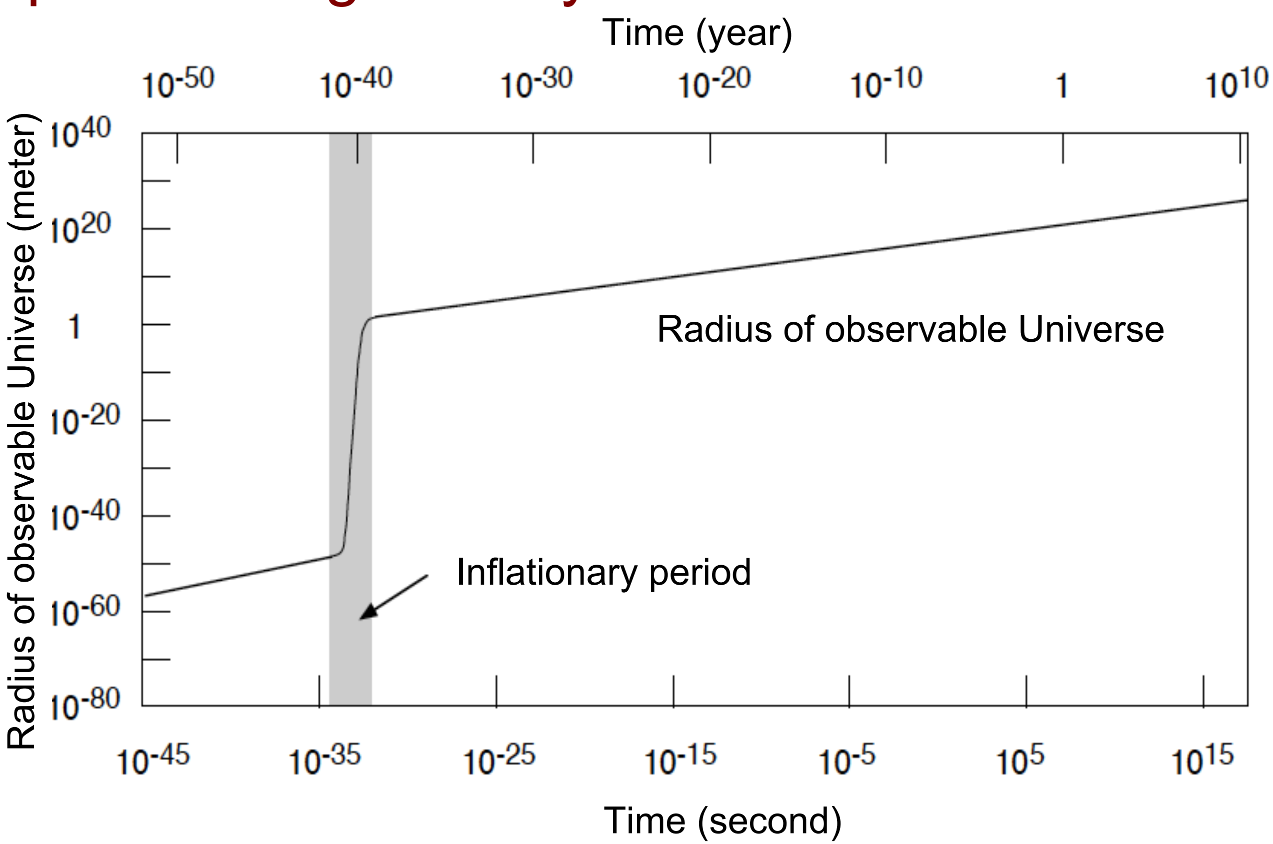
LHC recreates the conditions one billionth of a second after Big Bang



History of the Universe
Telescopes
Accelerators
LHC – Energy Frontier
accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
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
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008.
Supported by DOE and NSF

Cosmological Inflation

- In the very early Universe, space undergoes a dramatic exponential expansion
- Explains why Universe has uniform temperature (~3K) and flat space-time geometry

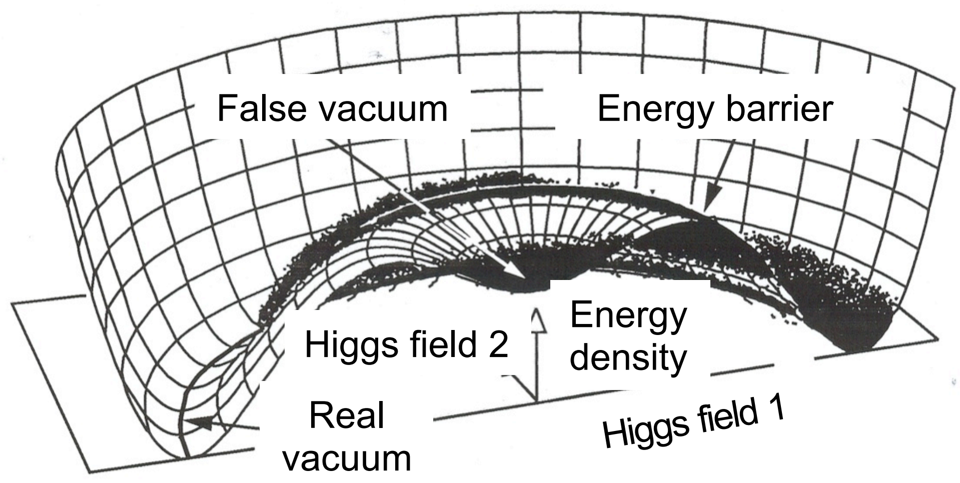


The inflation theory was developed independently in the late 70's by Alan Guth, Alexey Starobinsky, and others

Higgs-like field and inflation

- While the energy density of the Higgs field is positive, the Universe expands at accelerated rate (inflation)
- Inflation stops when the Higgs field decays to the real vacuum
- The energy released by the Higgs field is converted to matter particles

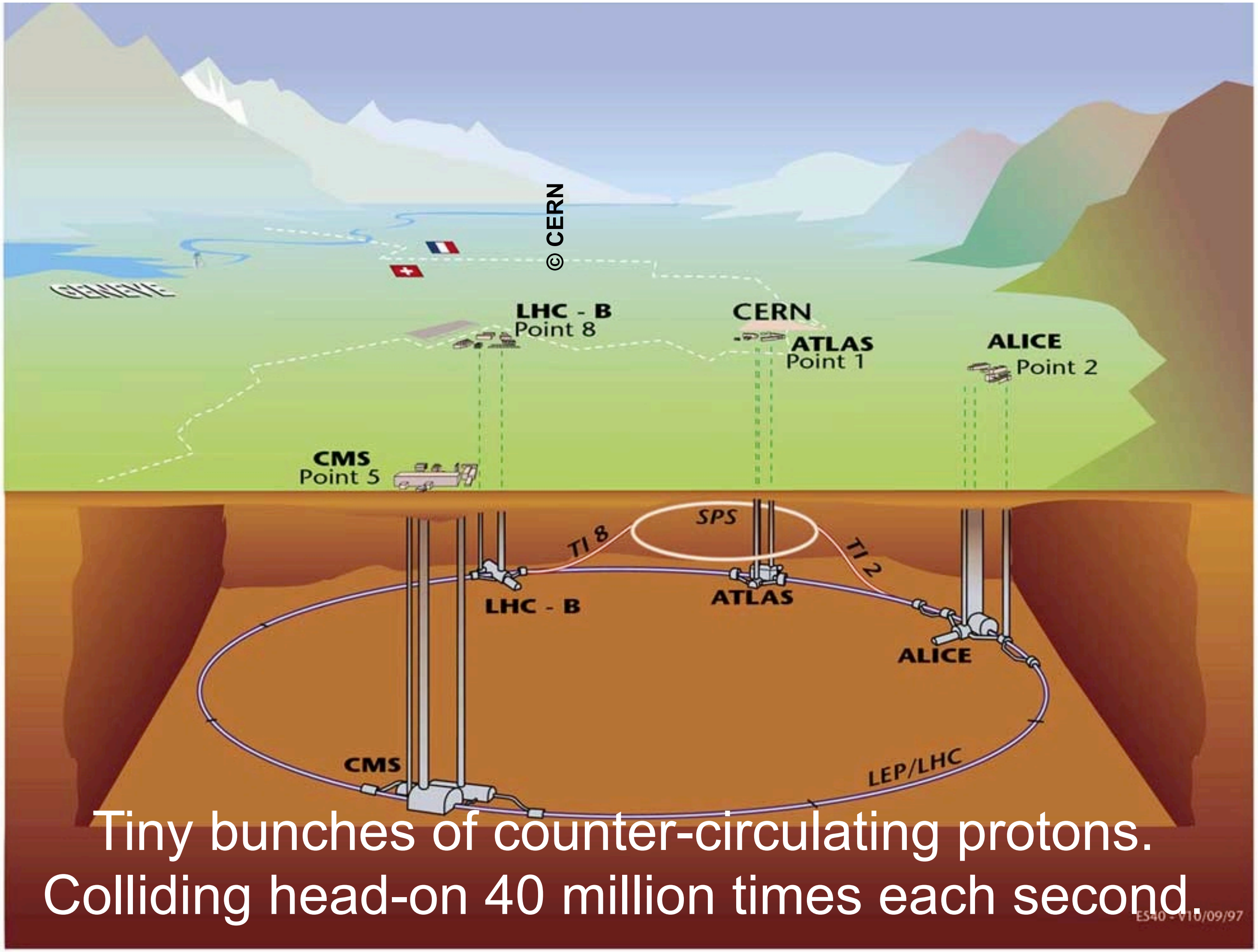
At the origin of the Universe, the energy density of a Higgs-like field is positive



The Large Hadron Collider

Accelerators and experiments

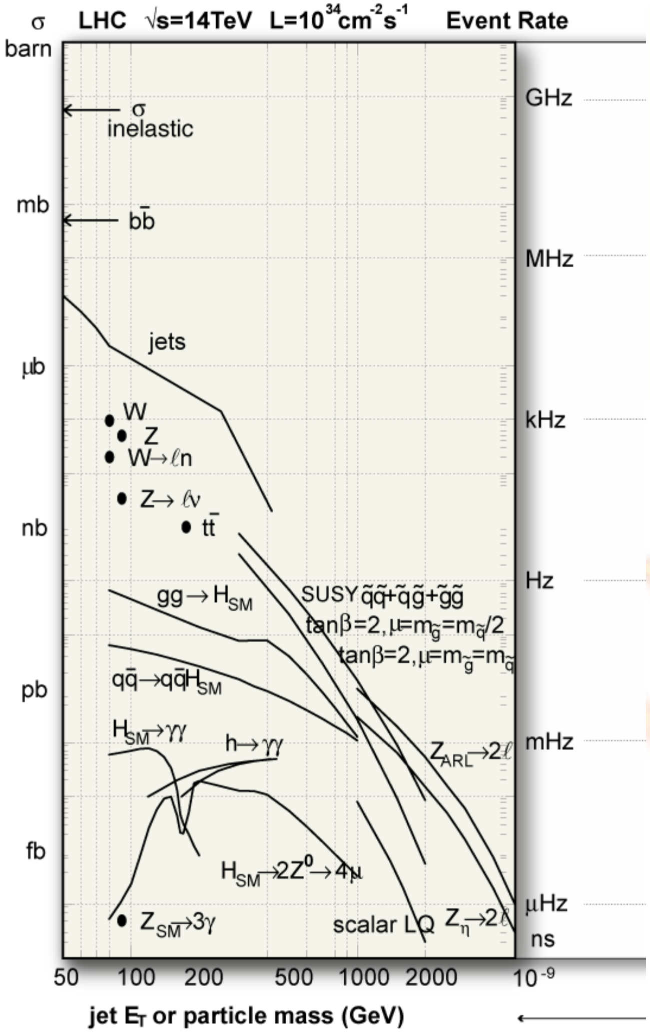
Accelerator and experiment layout

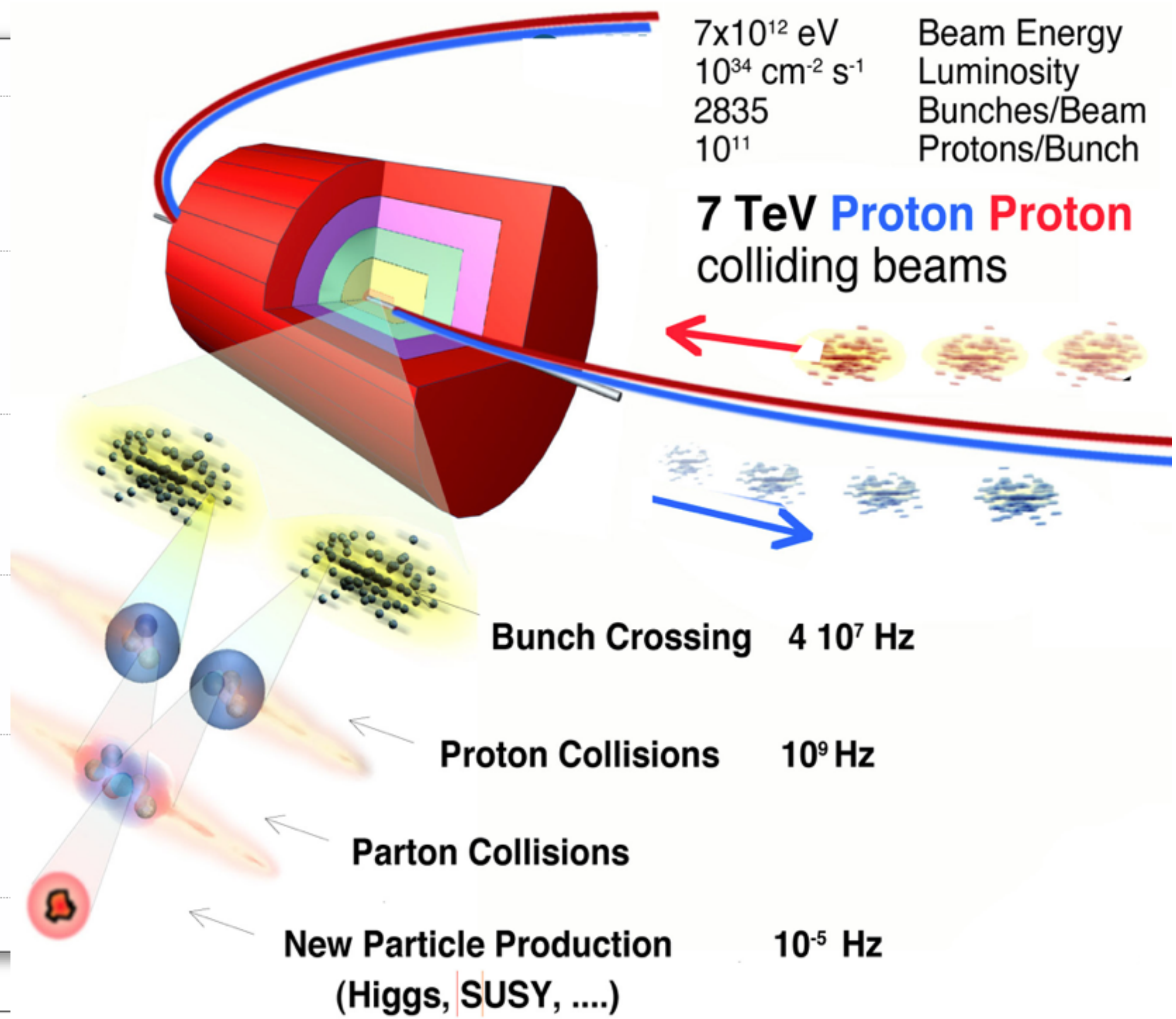


Tiny bunches of counter-circulating protons.
Colliding head-on 40 million times each second.

Proton collisions at the LHC

LHC collisions in 2011-2012: 7-8 TeV, 2015-2017 at 13TeV





Select 1 event in 10,000,000,000,000

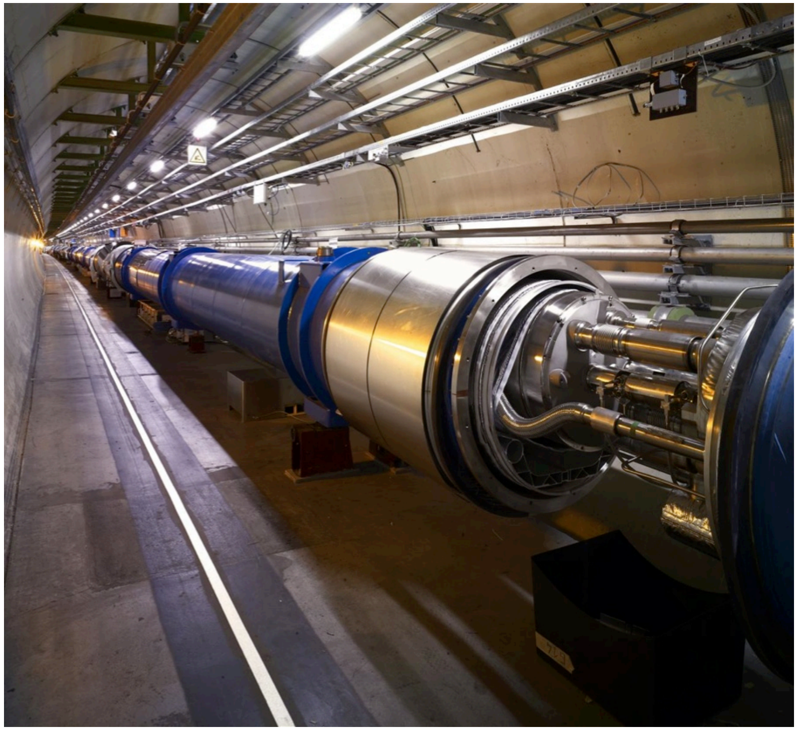
Accelerator challenges

Relative to the Tevatron (Fermilab, USA)

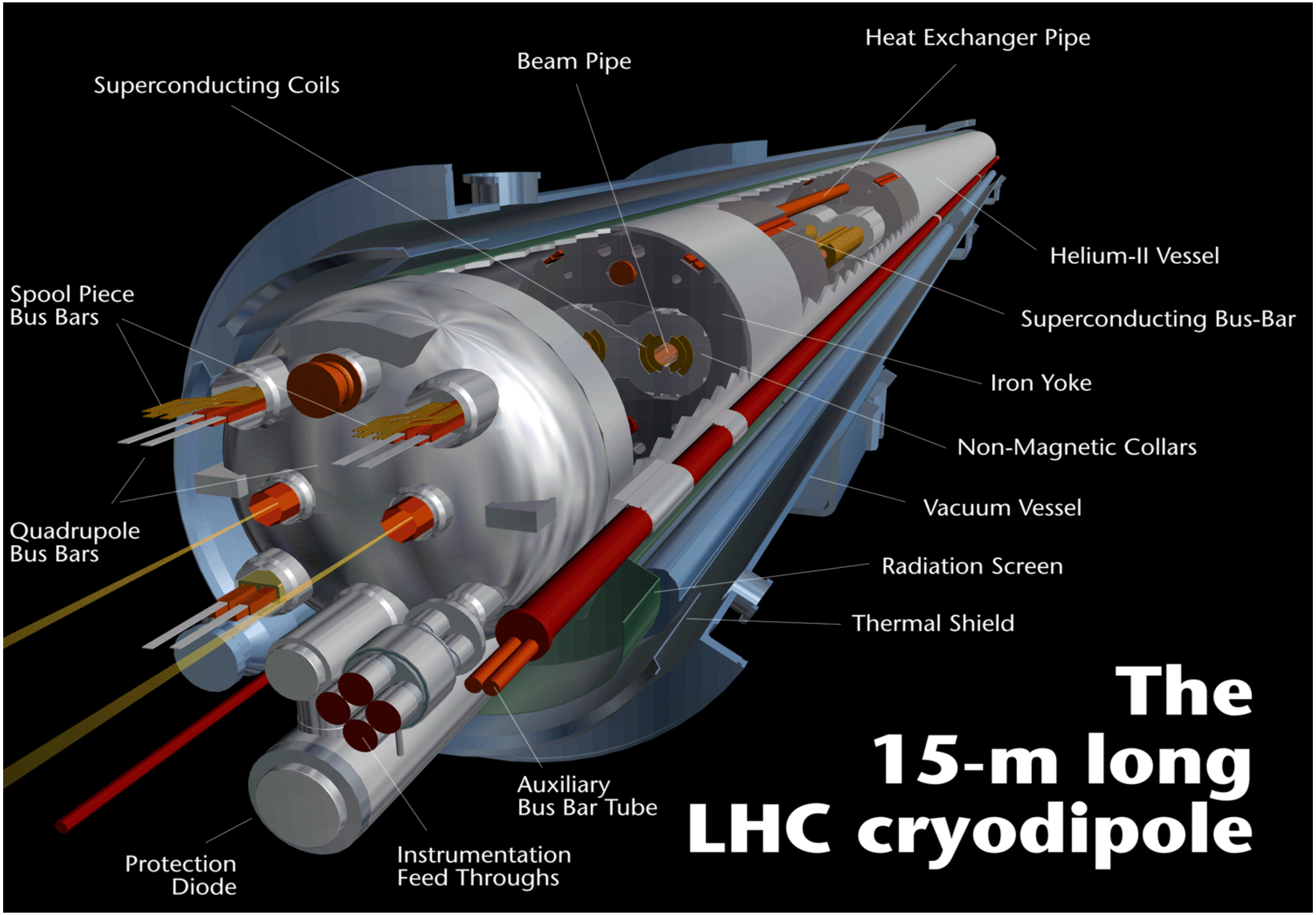
- Energy (14 TeV) x 7
- Luminosity (10^{34} $cm^{-2}s^{-1}$) x30

- Superconducting dipoles 8.3 T
- Operating temperature 1.9K (-271 C)
- More than 2000 dipoles
- 100 tons of liquid Helium

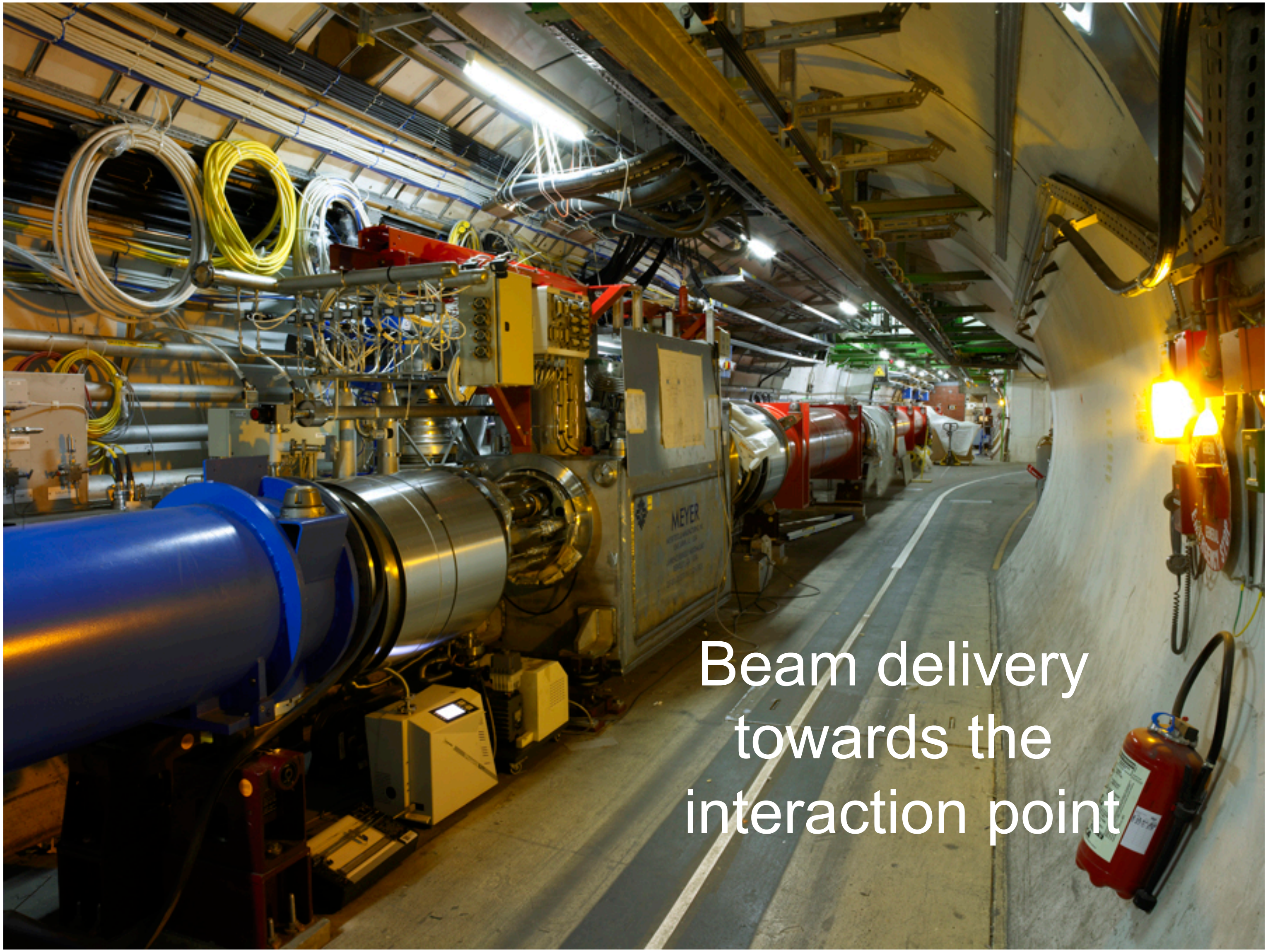
- Stored energy per beam: 350 MJoule
- Energy of a train of 400 tons at 150 Km/h
- LHC power consumption 120 MW



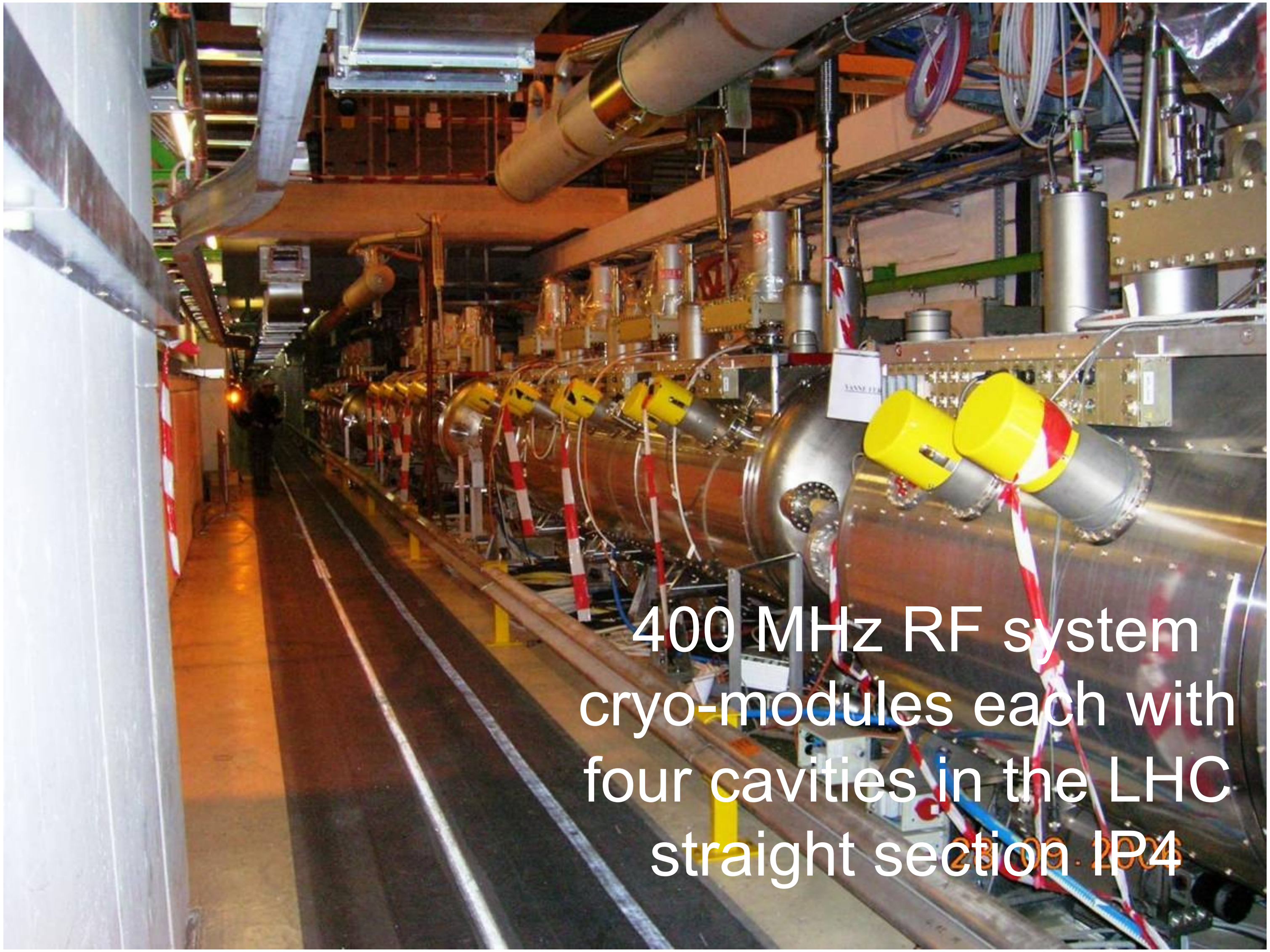
Superconducting magnetic dipole



In the tunnel

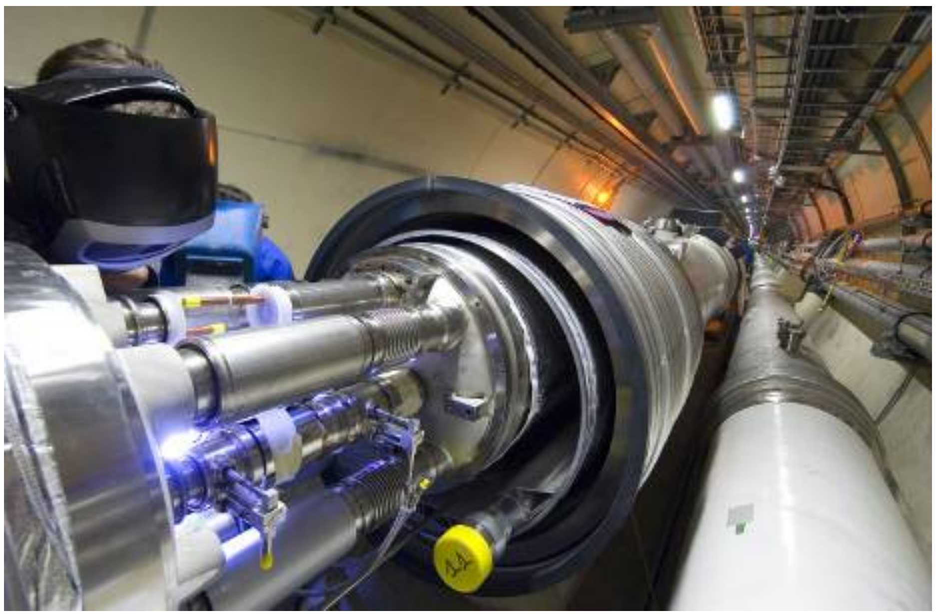


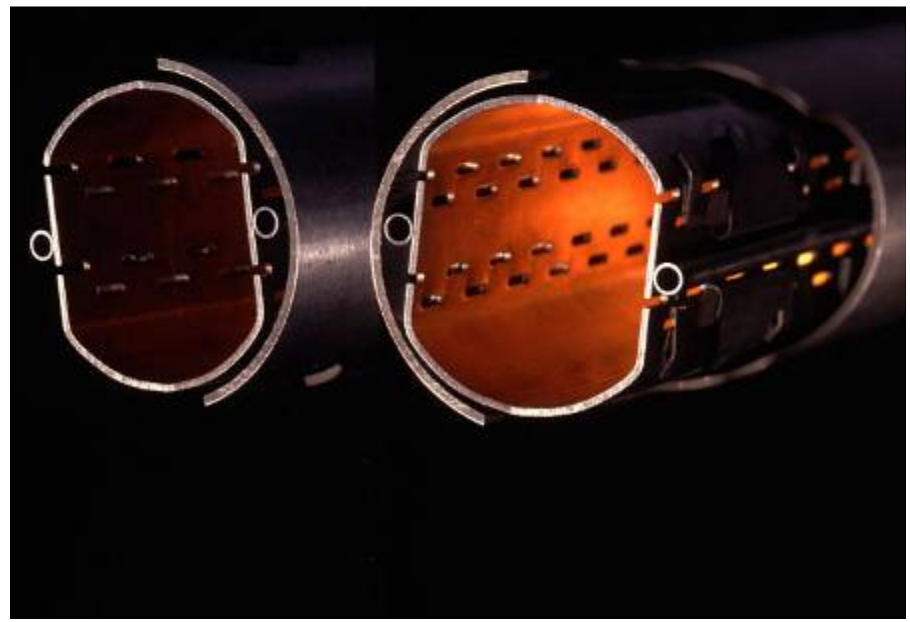
In the tunnel



It is empty!

- Air pressure inside the two 27Km-long vacuum pipes (10^{-13} atm) is lower than on the Moon



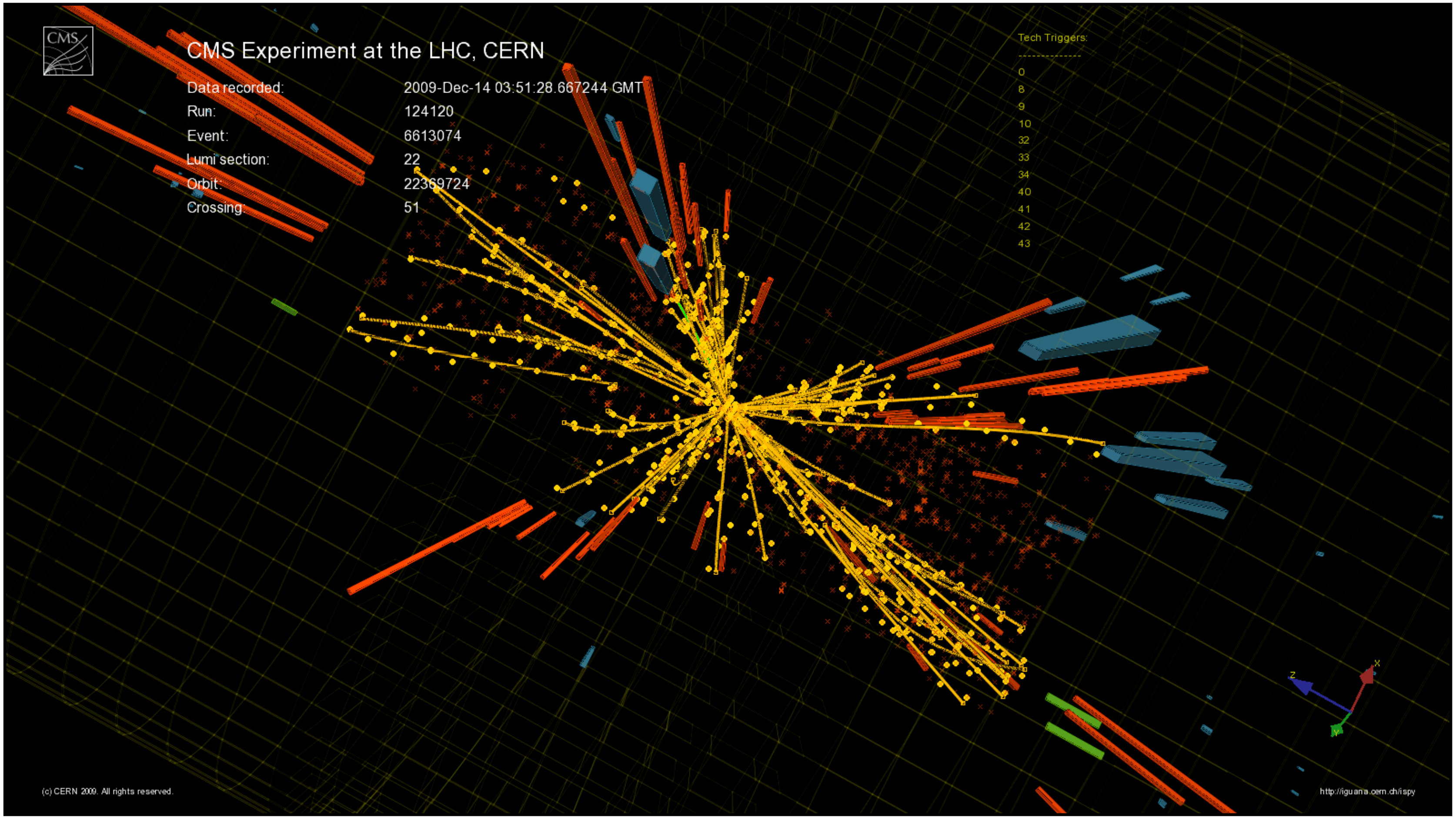


It is cold!

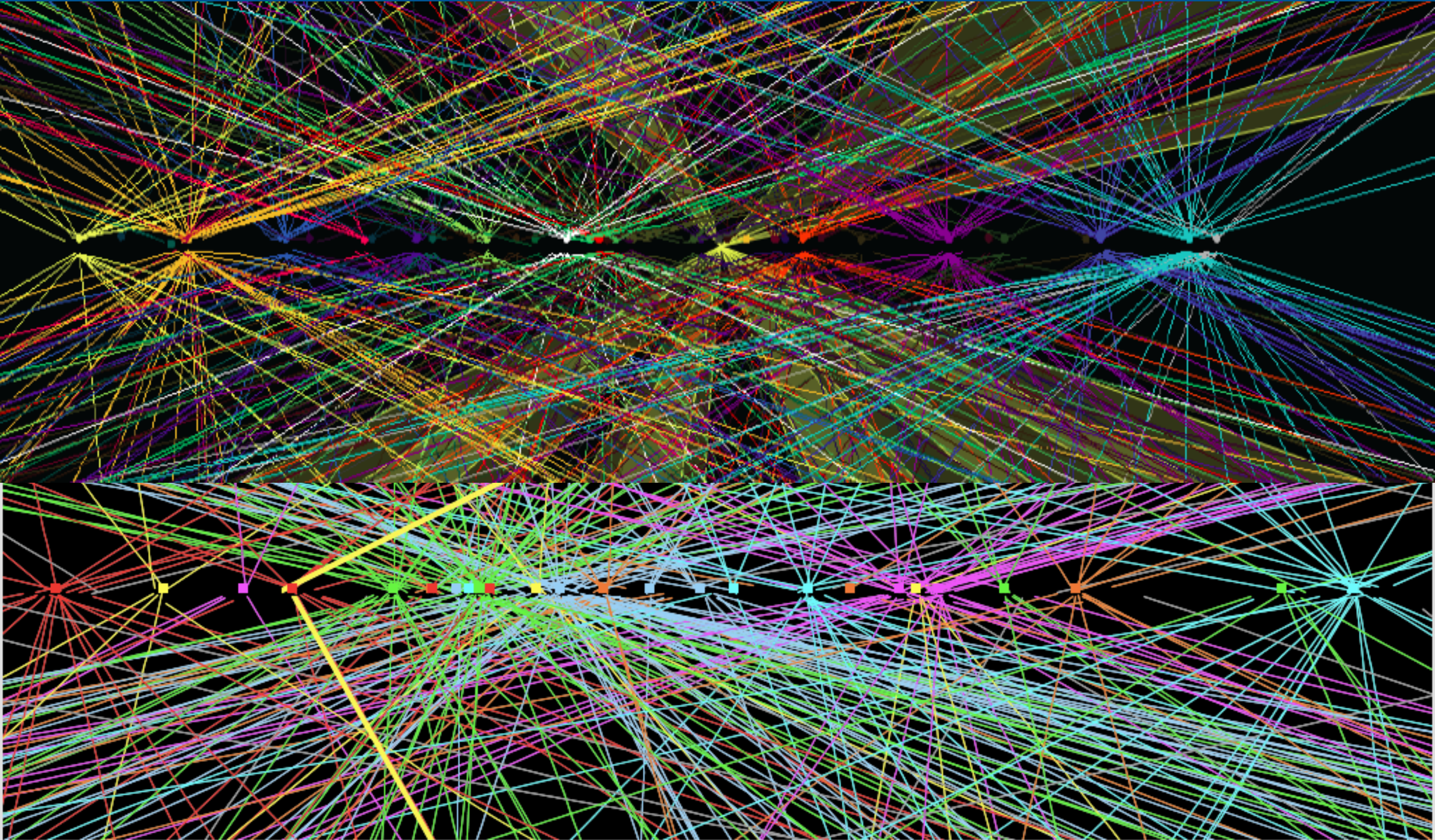
- 27 Km of magnets are kept at 1.9K, colder than outer space, using over 100 tons of liquid Helium

It is hot!

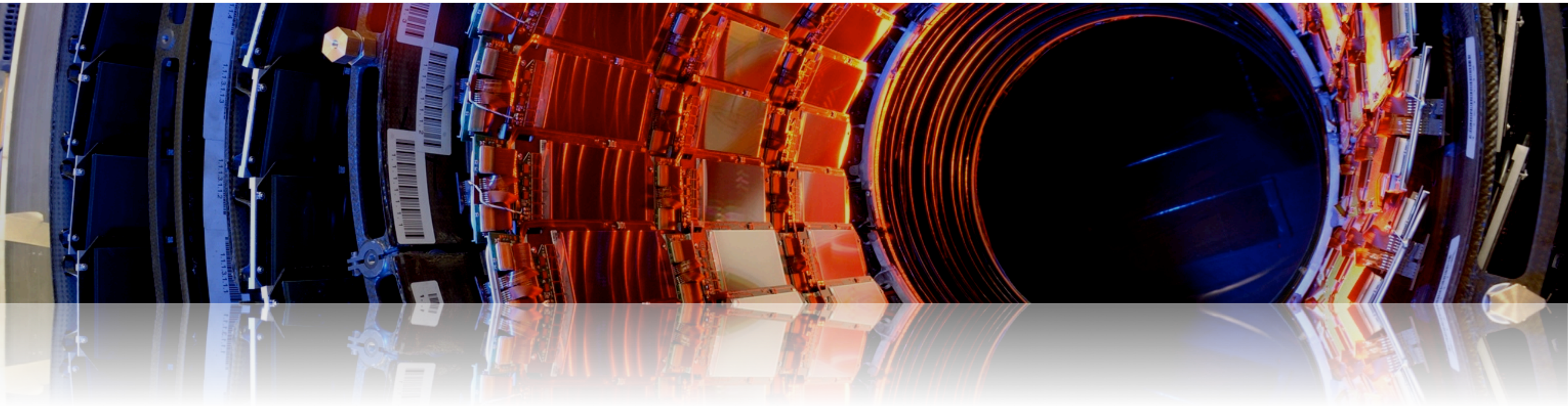
- In a tiny volume, temperatures one billion times hotter than the center of the Sun



…under difficult conditions



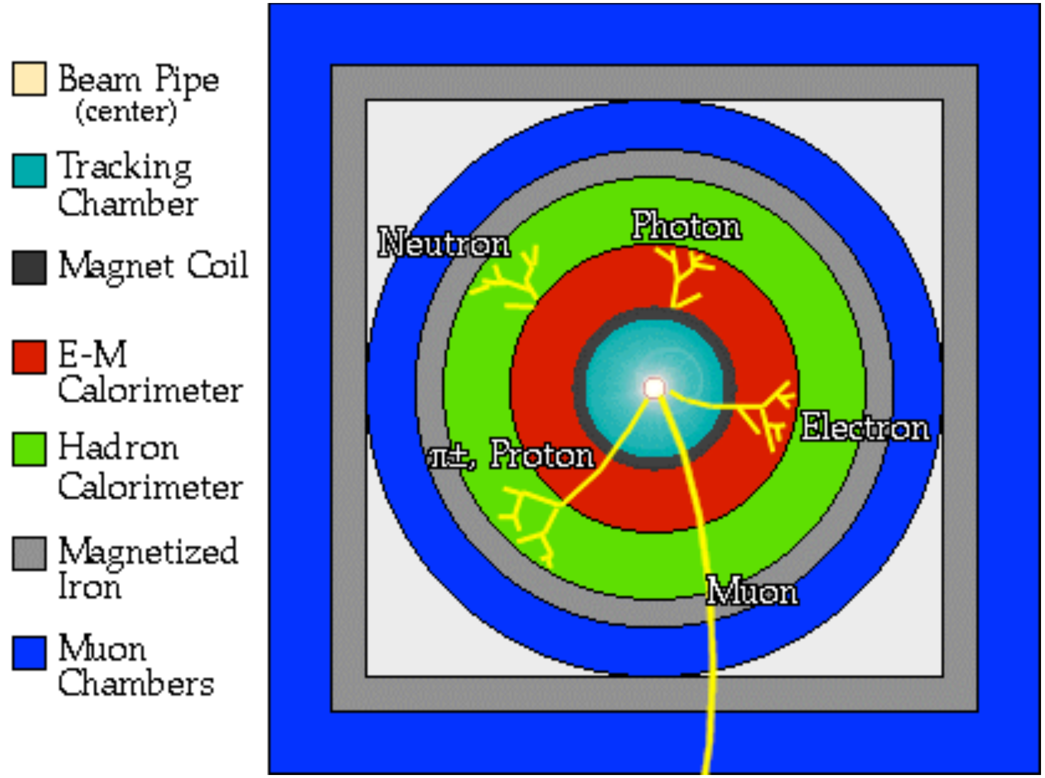
The Experiments



General purpose experiments

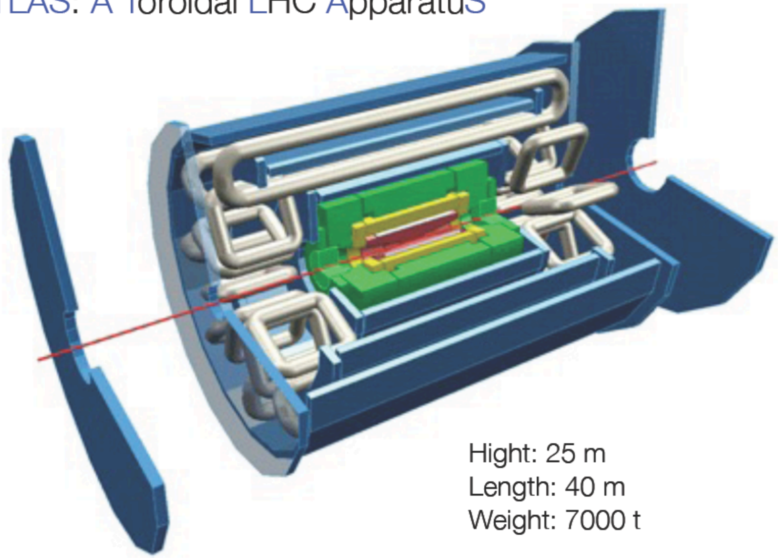
- Advanced detectors with many layers, each designed to perform a specific task
- Together, these layers allow to identify and precisely measure the properties of all stable particles produced in collisions

- Photons, electrons, muons, quarks (i.e. jets of particles), neutrinos (i.e. missing energy), etc.
- Design guided by physics

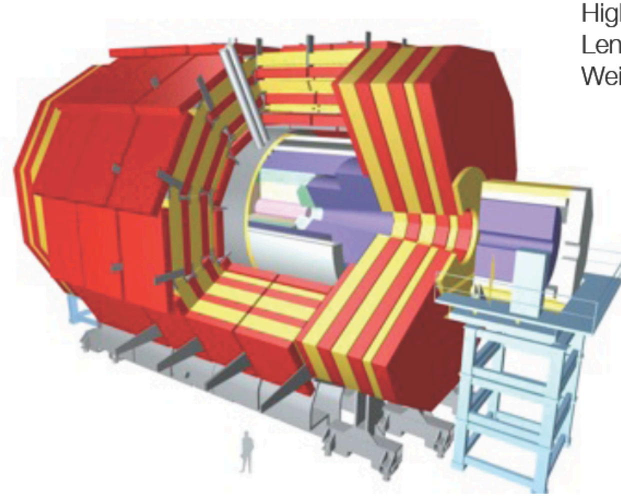


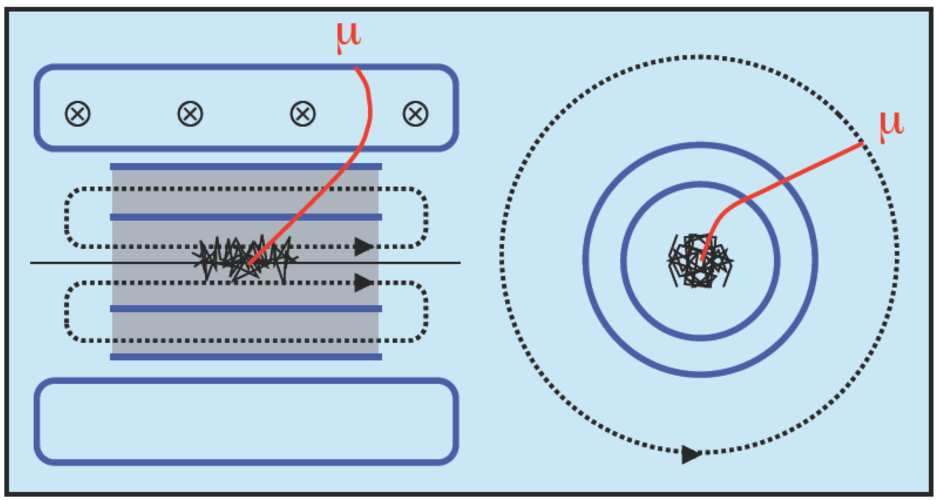
ATLAS and CMS

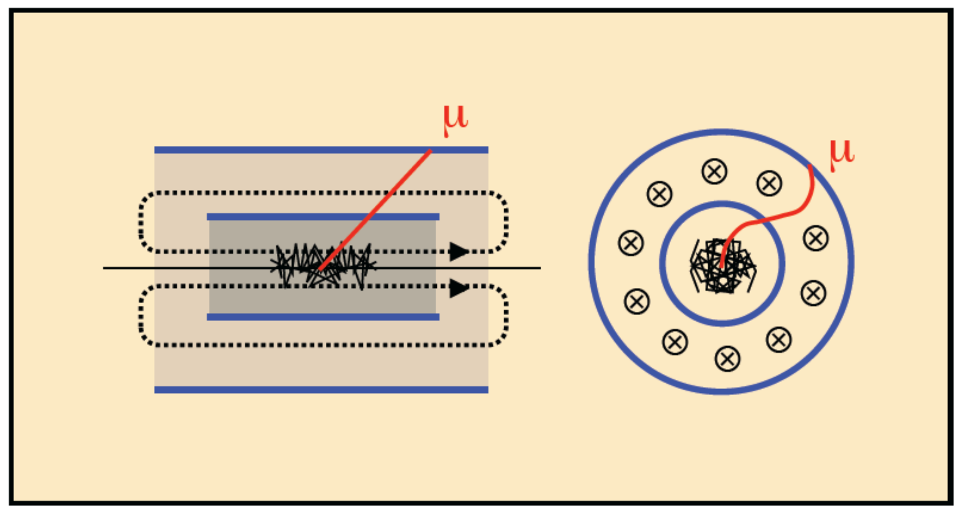
ATLAS: A Toroidal LHC ApparatuS

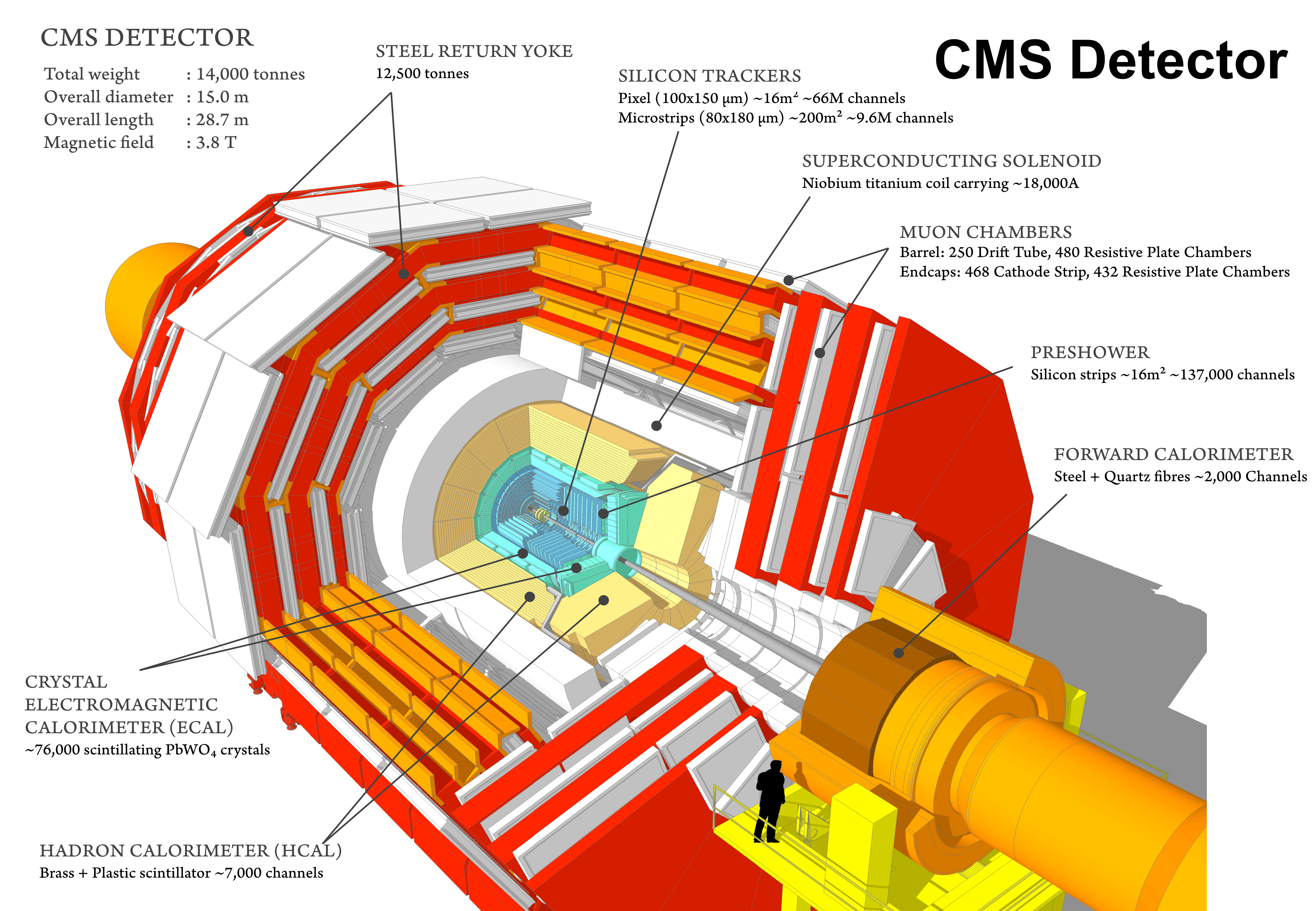


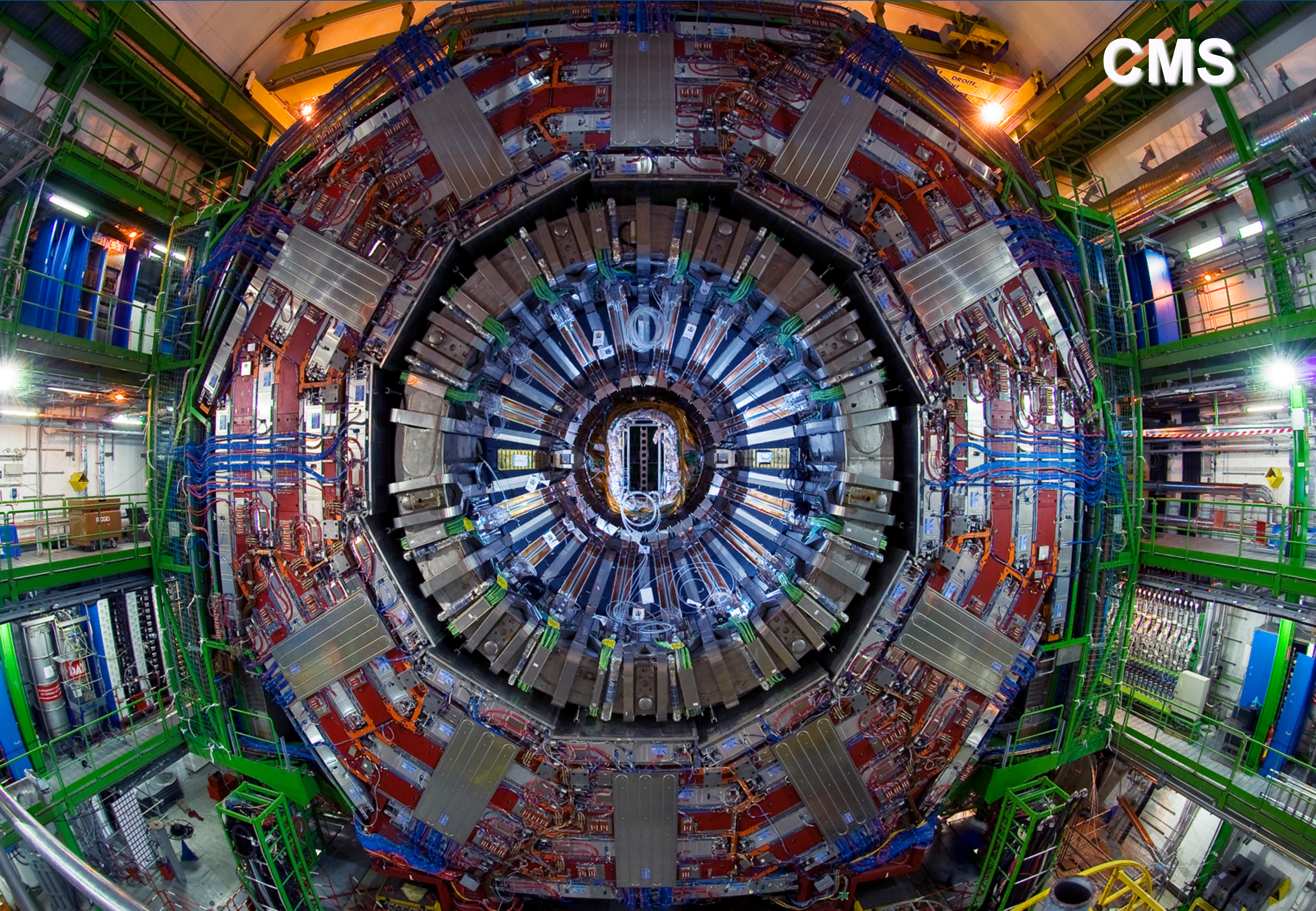
CMS: Compact Muon Solenoid



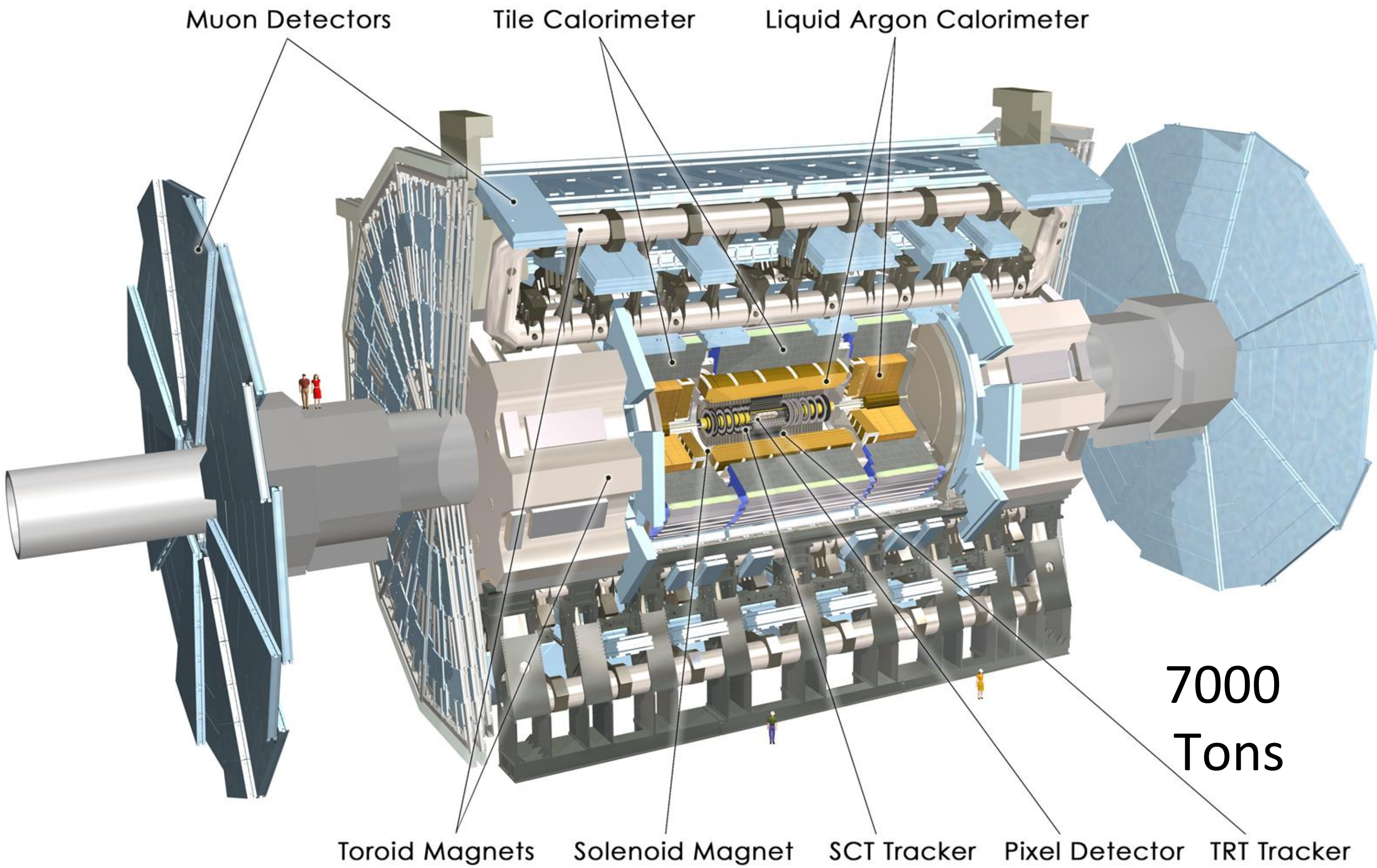





CMS Detector
CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

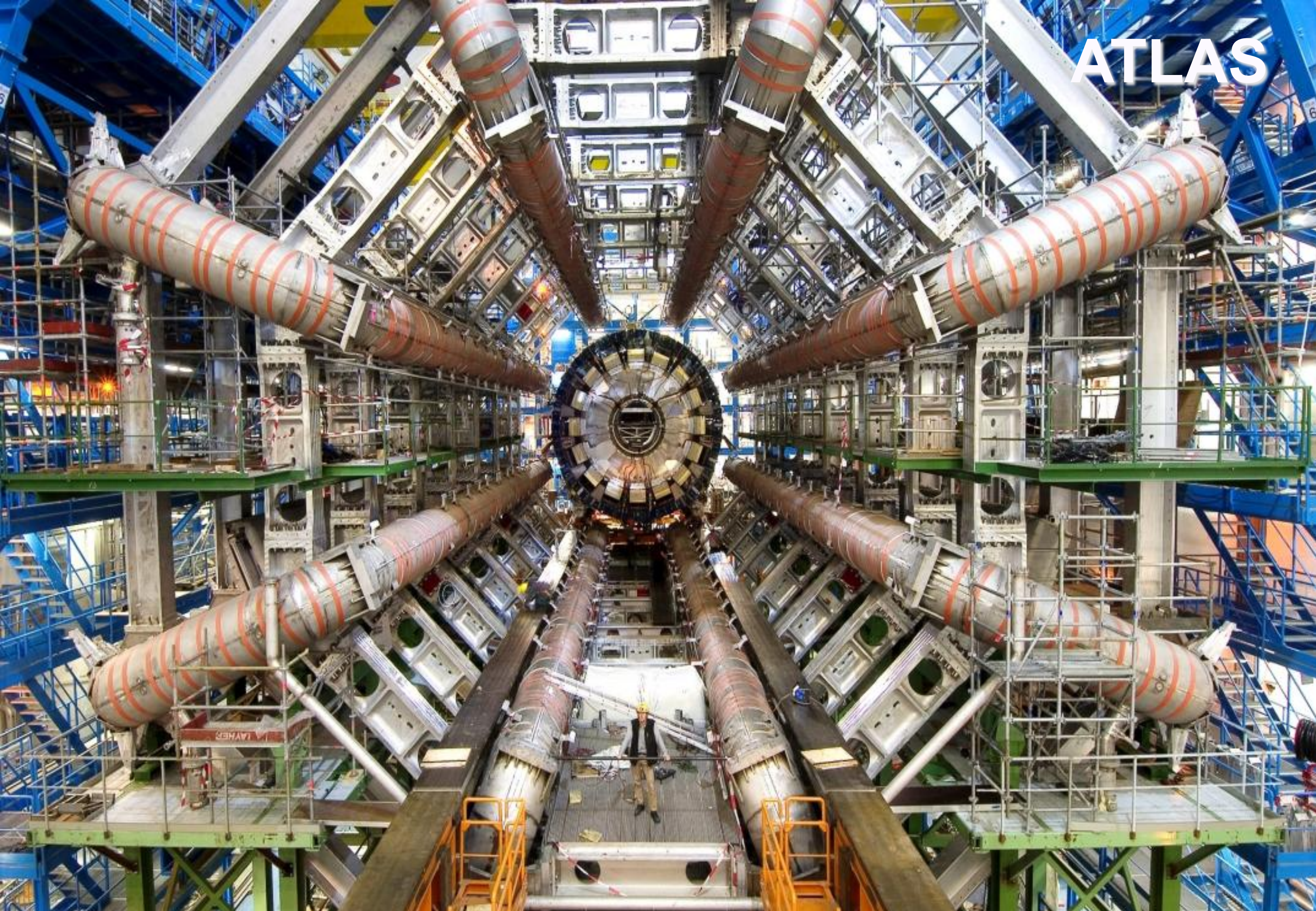

CMS

ATLAS

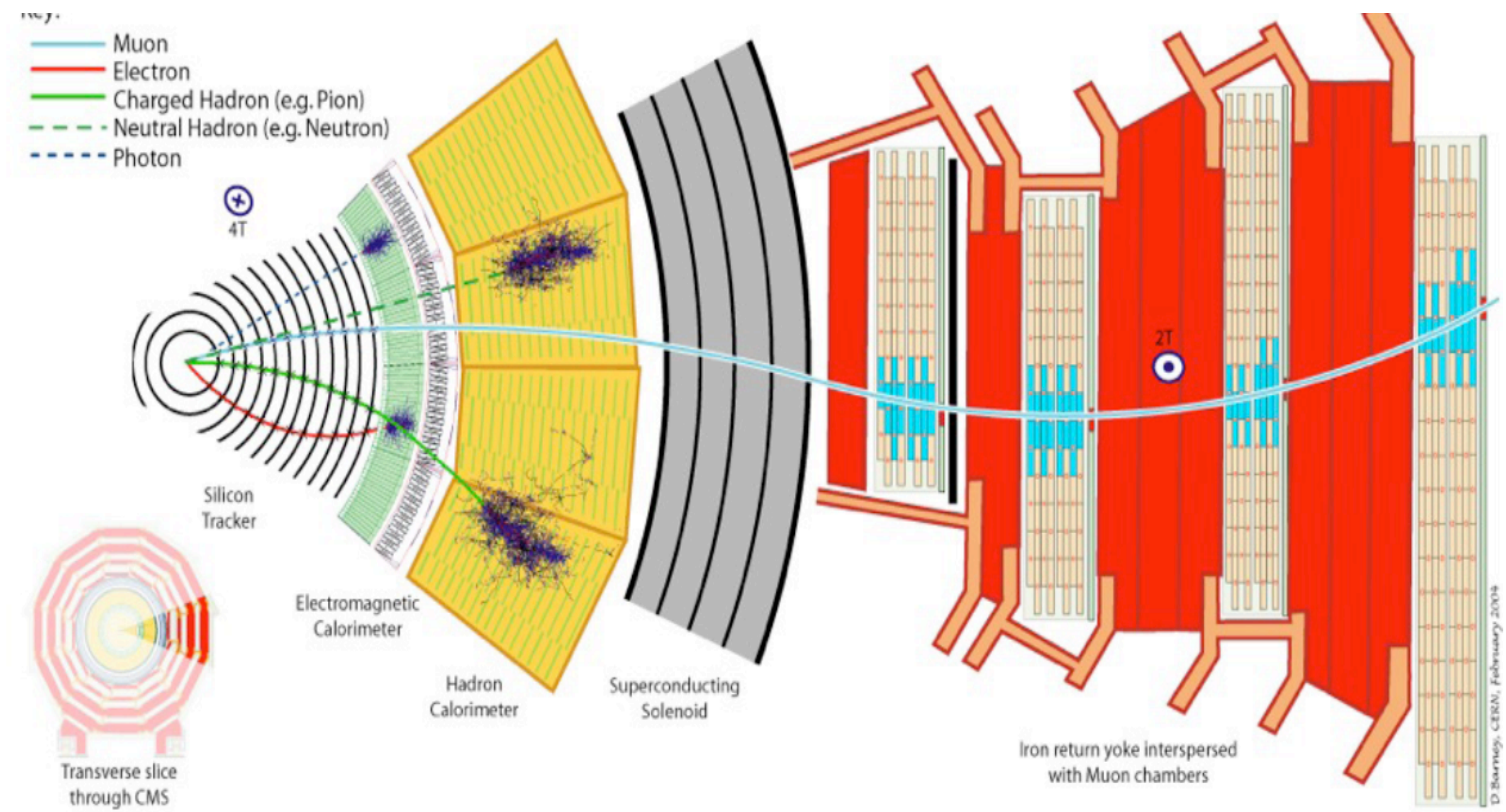


24 m

7000
Tons

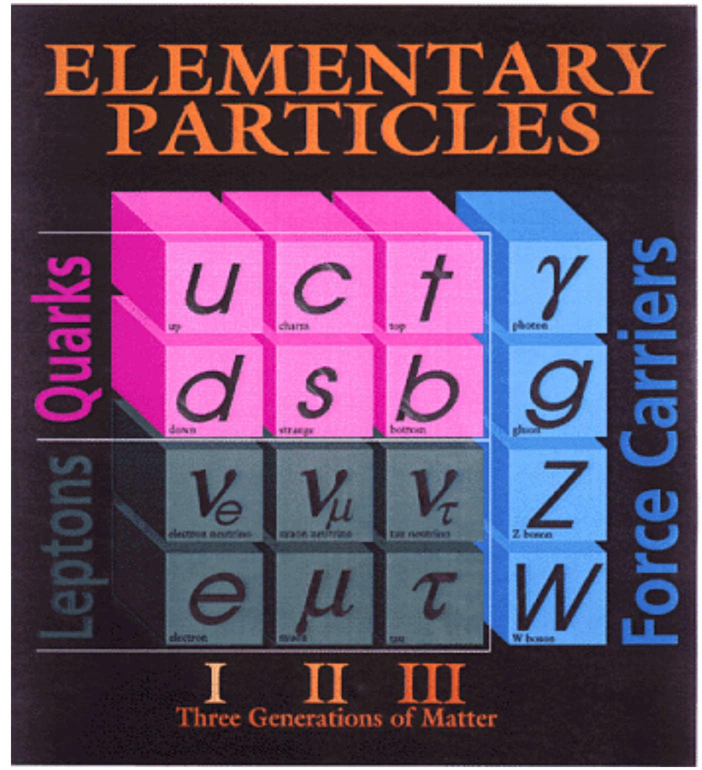

ATLAS

Particle detection



What can we detect?

- Directly observable particles must:
  - Undergo strong or EM interactions
  - Be sufficiently long-lived to pass the detectors
- We can directly observe:
  - Electrons, muons, photons
  - Neutral or charged hadrons
  - Pions, protons, kaons, neutrons,...
  - analyses treat jets from quark hadronization collectively as single objects
  - Use displaced secondary vertices to identify jets originating from b-quarks
- We can indirectly observe long lived weakly interacting particles (e.g. neutrinos) through **missing transverse energy**



What can we detect? (cont.)

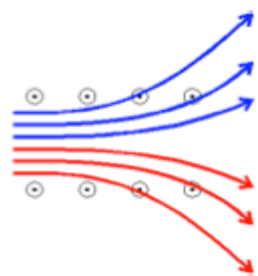
- Short-lived particles decay to long-lived ones
- We can only ‘see’ the end products of the reaction, but not the reaction itself
- In order to reconstruct the production/decay mechanism and the properties of the involved particles, we want the maximum information

Particle properties

Which properties do we want to measure?

- Energy (calorimeter)
- Momentum (tracking)
- Charge (tracking)
  - Direction, bending in magnetic field
- Life-time (tracking)
- Mass:

$$\left.\begin{array}{c} E \\ \vec{p} = \begin{pmatrix} p_1 \\ p_2 \\ p_3 \end{pmatrix} \end{array}\right\} \begin{pmatrix} E \\ \vec{p} \end{pmatrix}$$



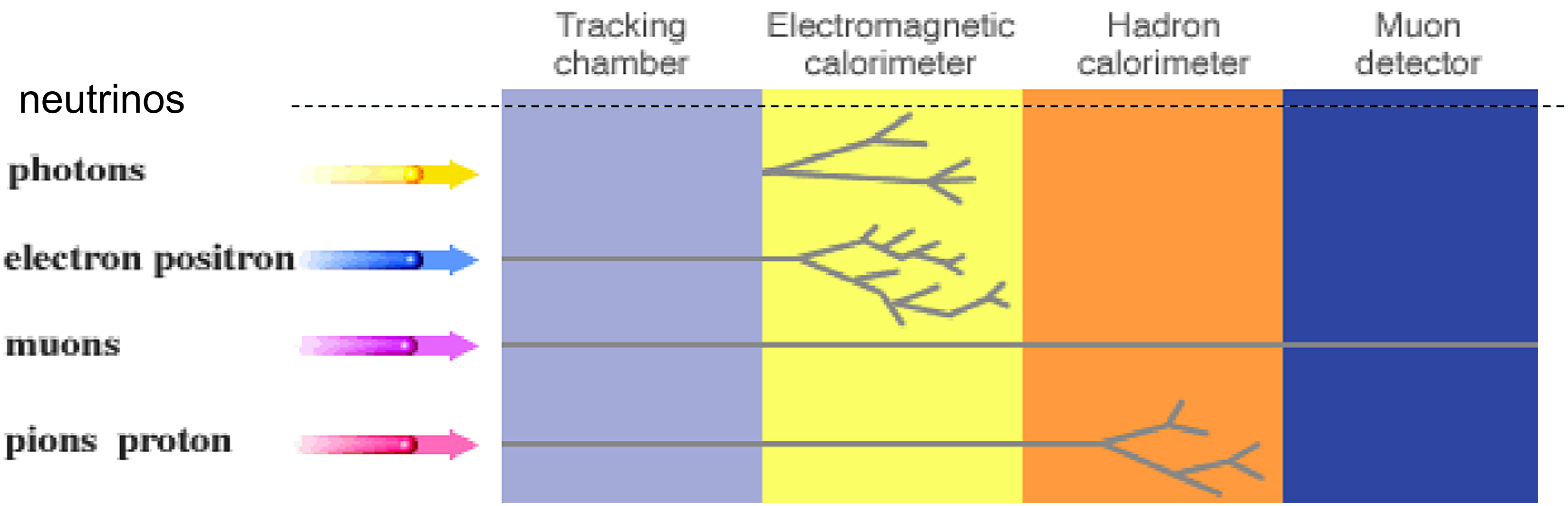
$$F = q \cdot v \cdot B = m \cdot \tfrac{v^2}{R}$$

$$\Rightarrow q \cdot B \cdot R = m \cdot v = |\vec{p}|$$

$$E^2 = m^2 \cdot c^4 + \vec{p}^2 c^2 \Rightarrow m = \frac{\sqrt{E^2 - \vec{p}^2 c^2}}{c^2}$$

Passage of particles

- "Onion"-like structure
- Each layer measures E and/or p of particles
- Redundancy of measurements



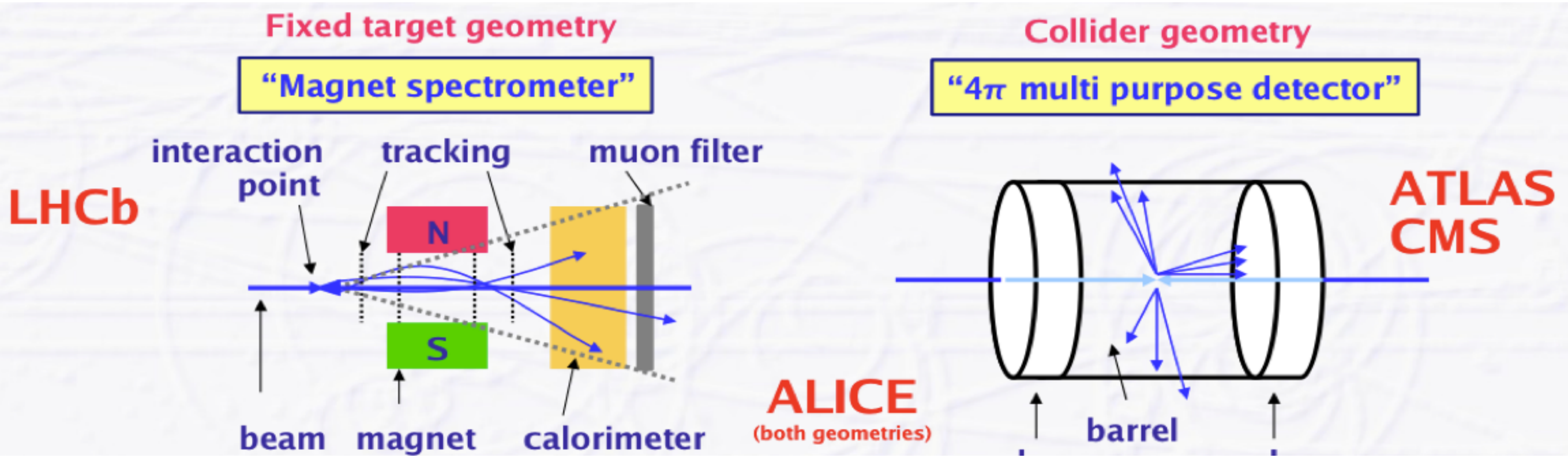
Missing ET
undetected
neutrinos...

Energy measurement
total absorption of showers

momentum measurement
(curvature in magnetic field)

Muon detection
measure momentum

Fixed target vs Collider

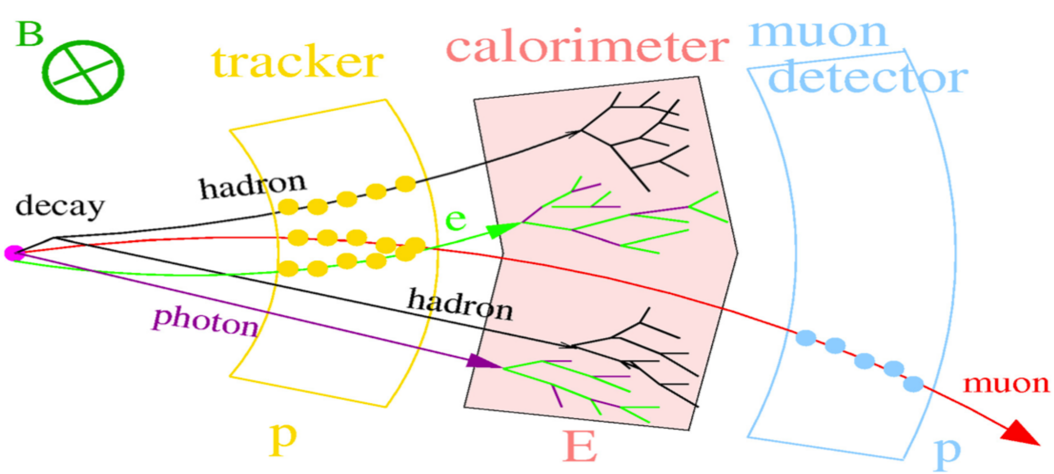


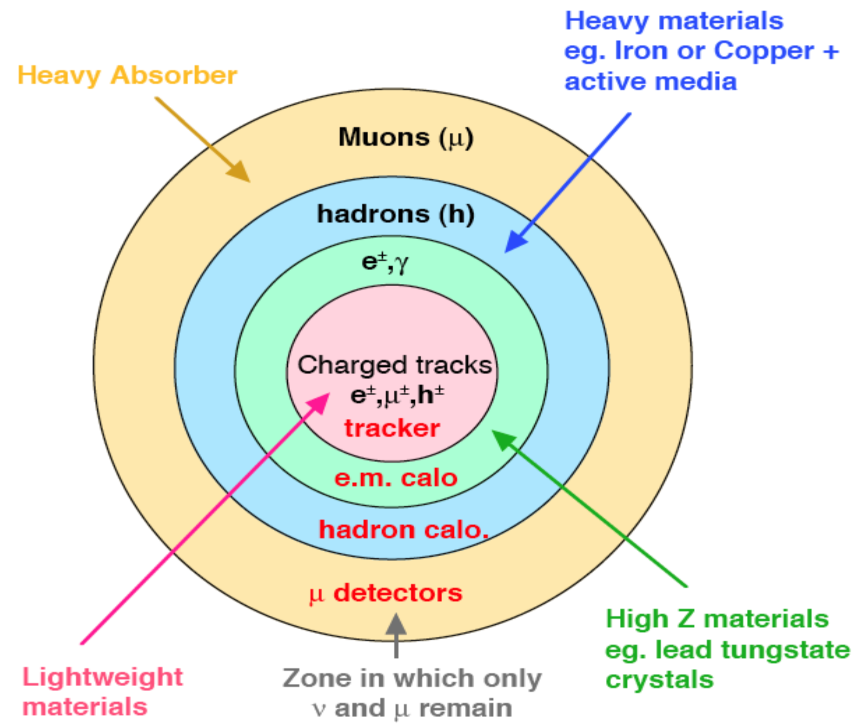
$$\sqrt{s} = E_{\mathrm{cm}} = \left[m_1^2 + m_2^2 + 2E_1 m_2\right]^{\frac{1}{2}}$$

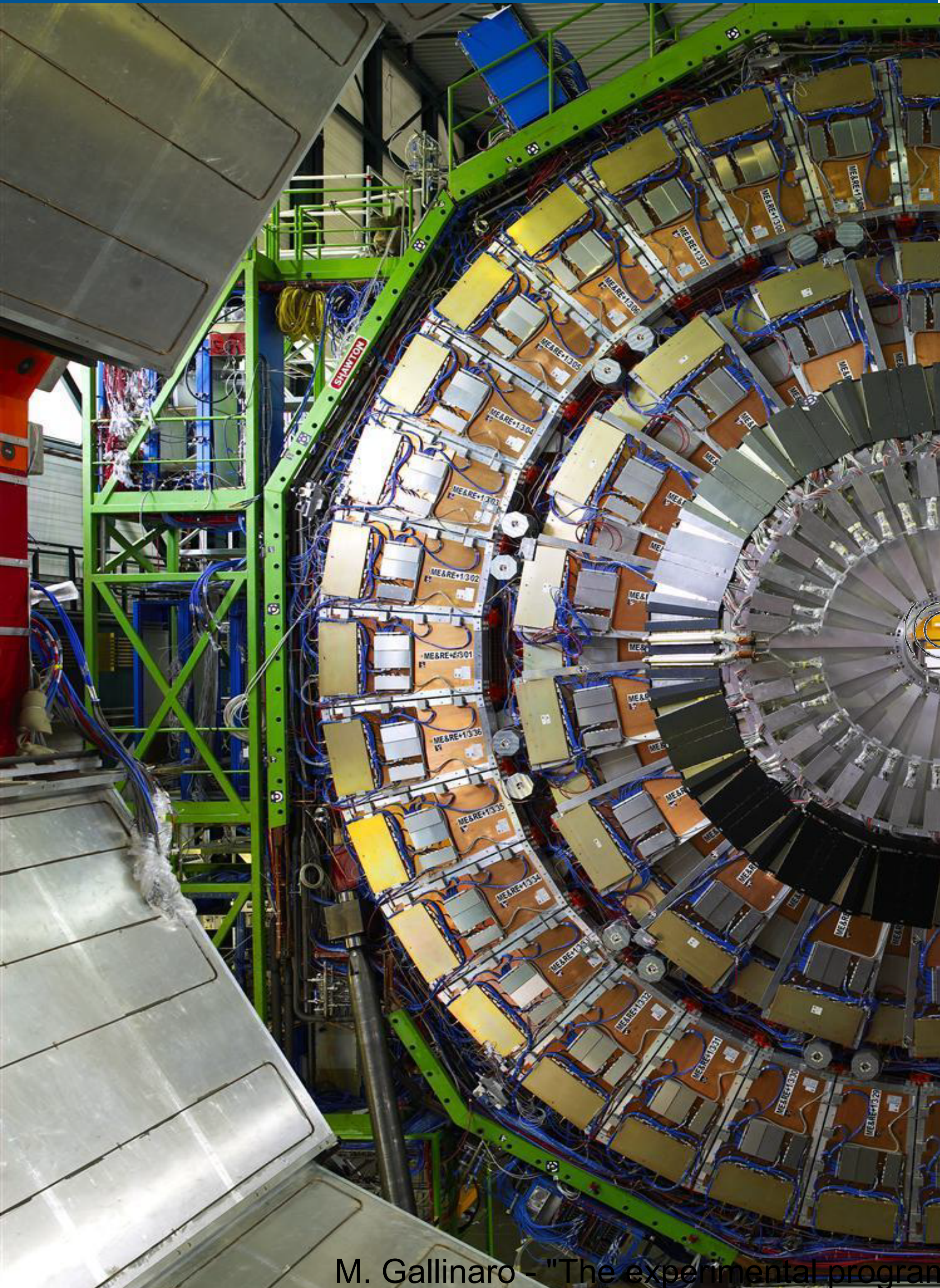
$$E_{\mathrm{cm}} = 2E$$

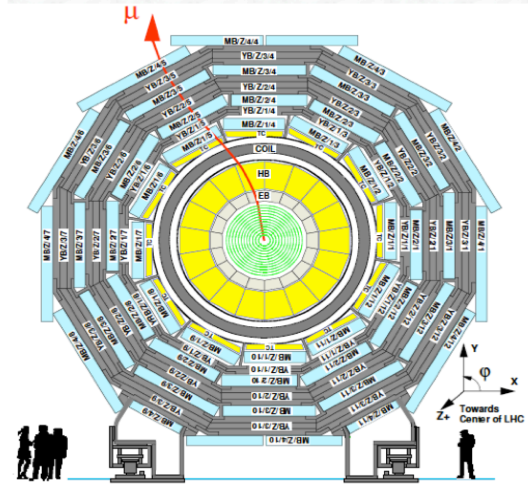
Detector layers

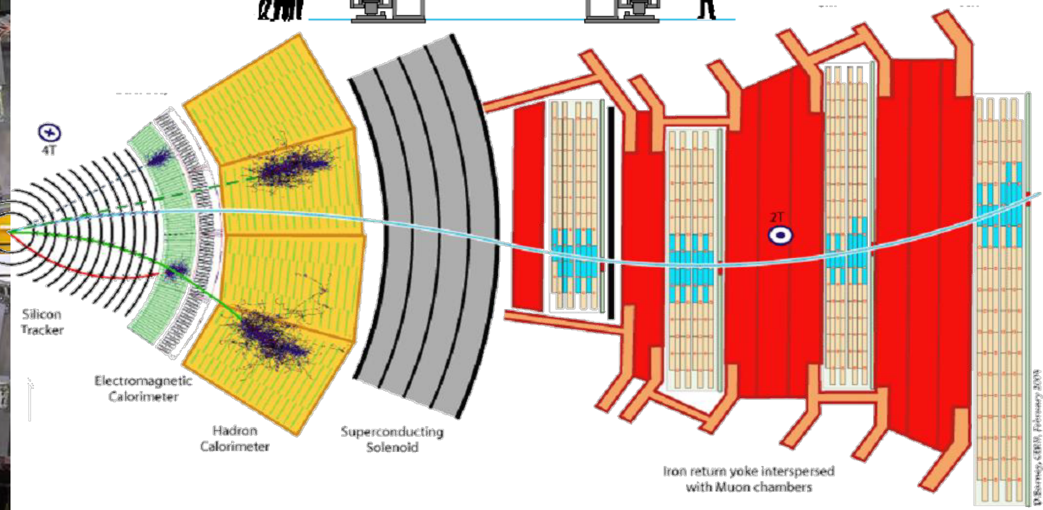
- Inner tracking
  - Measure charged particle (momentum)
- Magnetic field:
  - Measure momentum
- Calorimeters
  - Measure energy of all particles
- Outer tracking
  - Measure muons



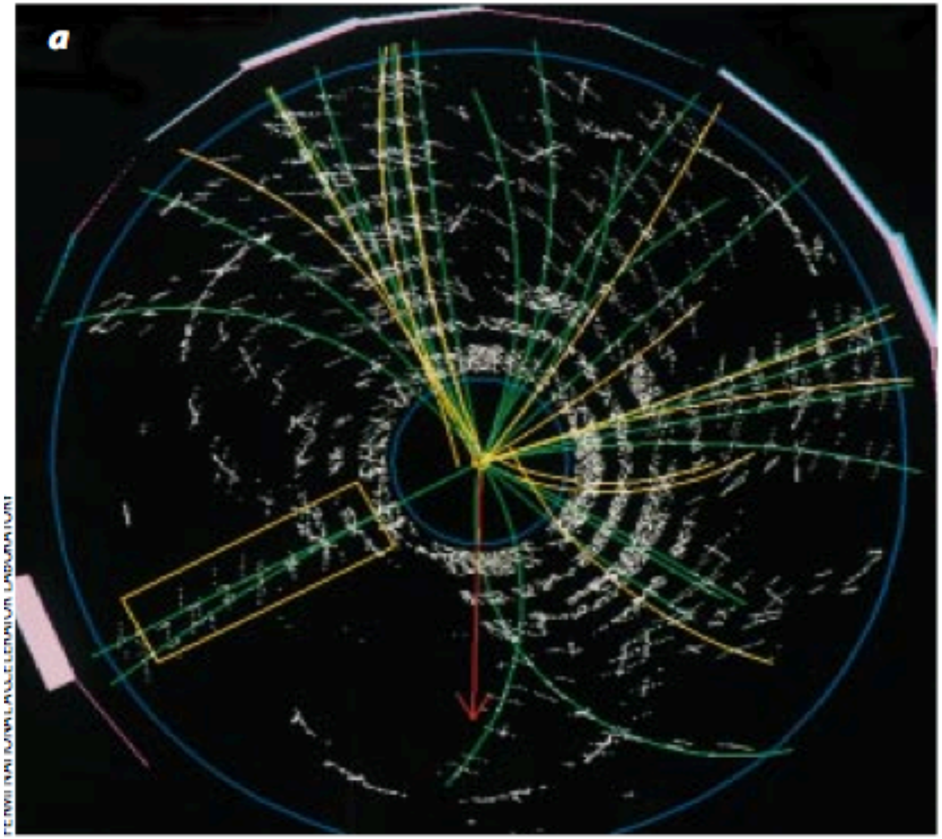


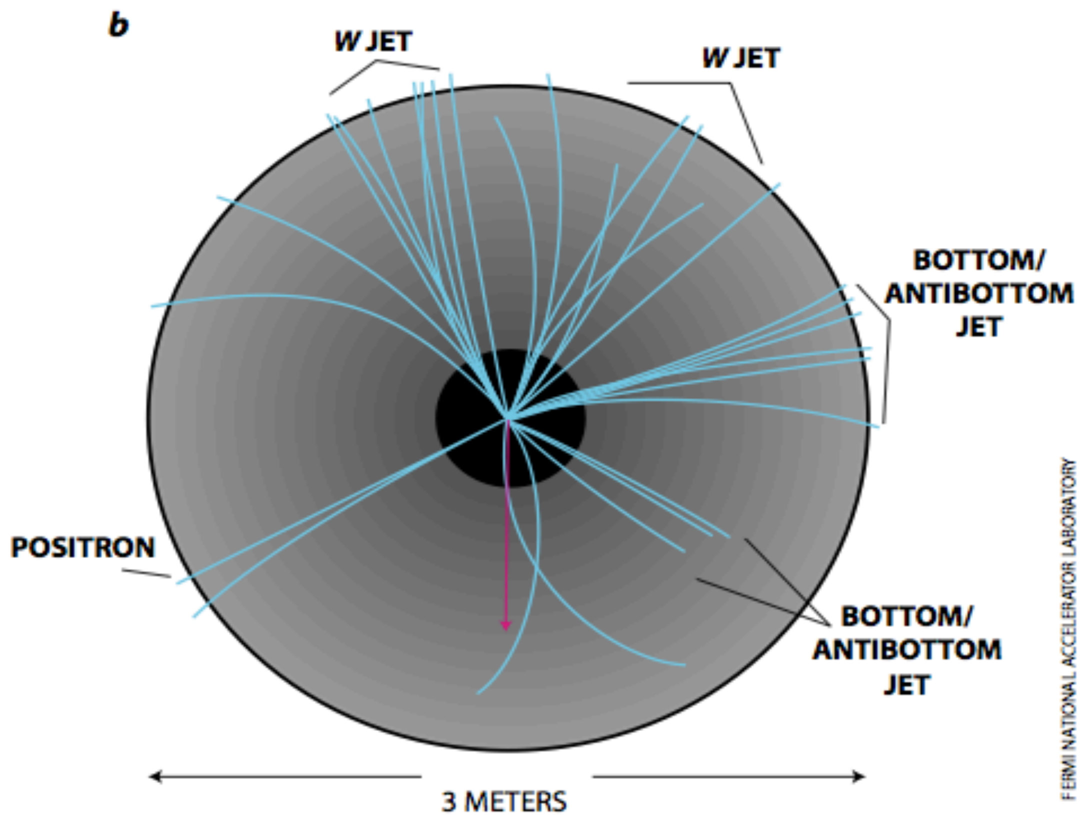



μ
COIL
HB
EB
Towards Center of LHC


4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers

From Picture to Reconstruction

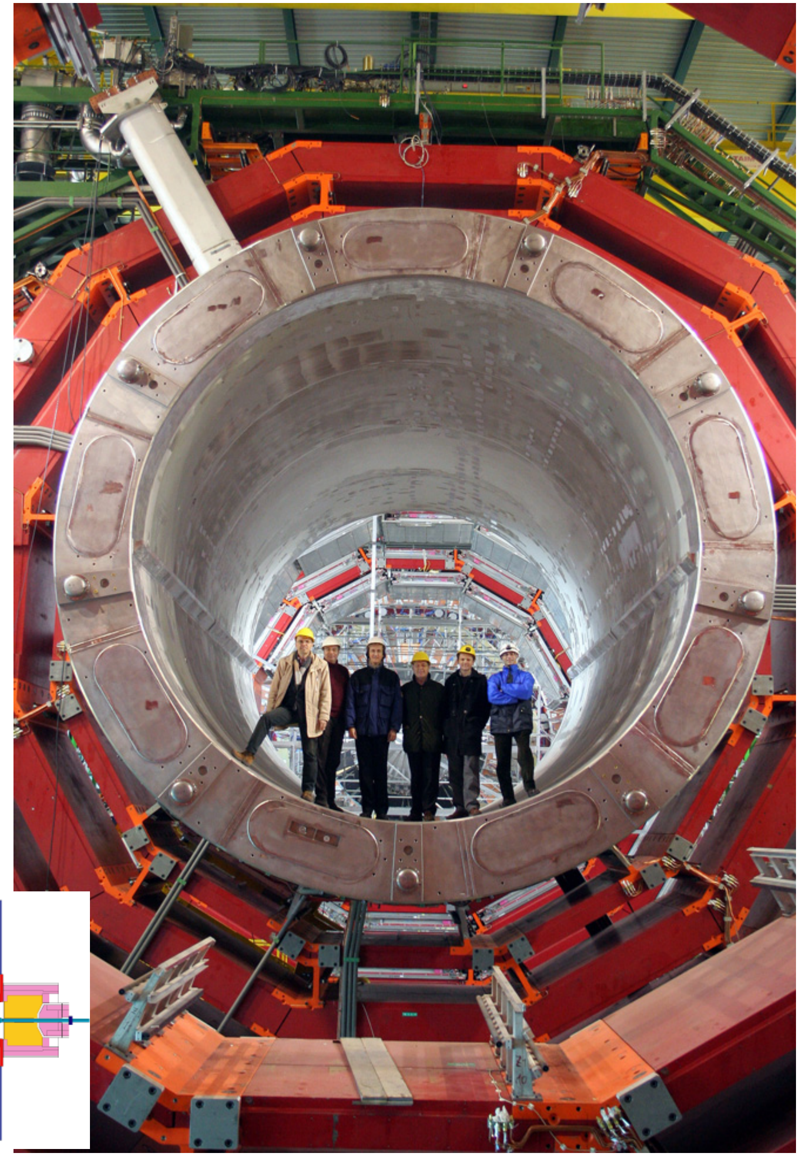




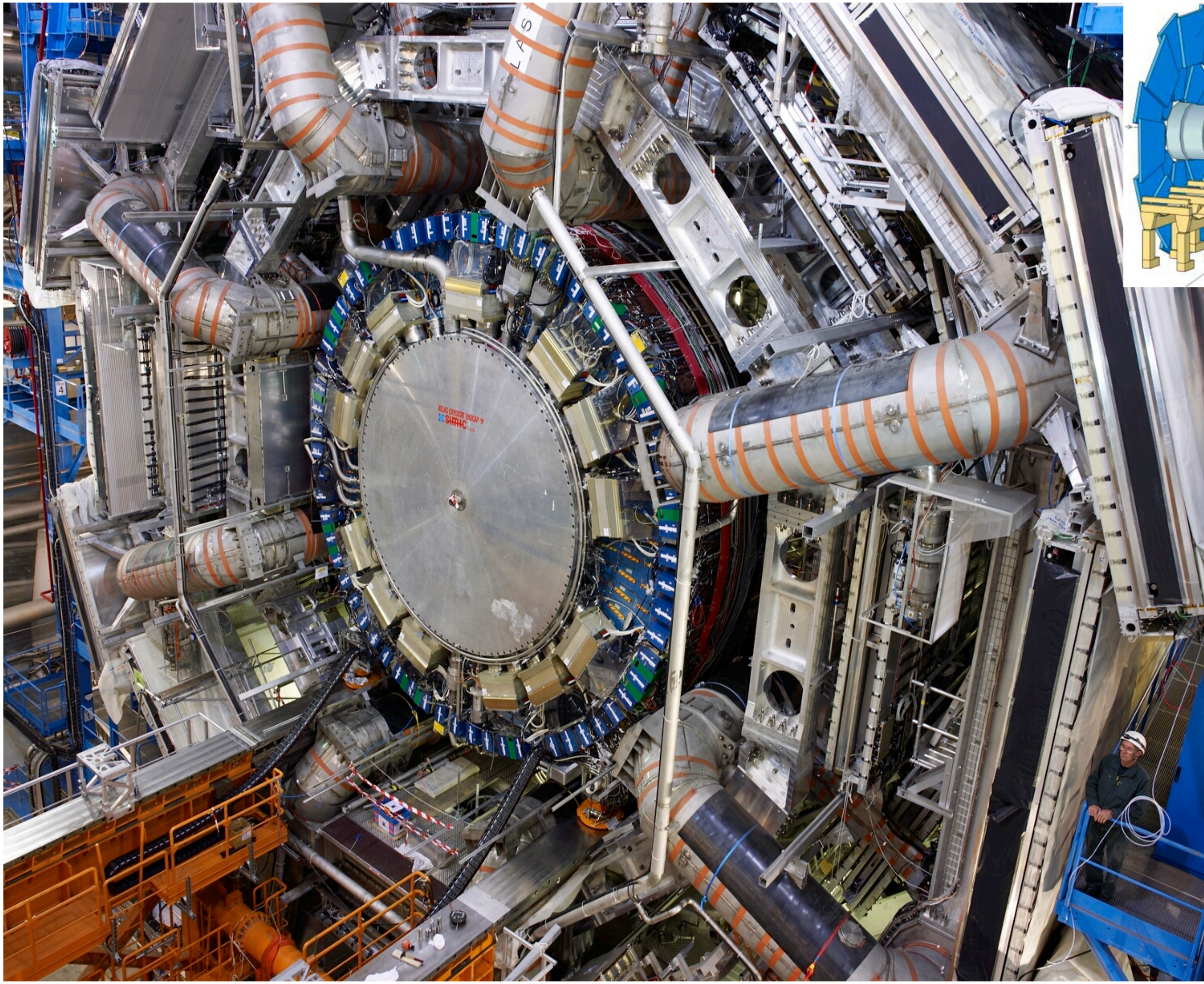
Detector R&D, construction:1993-2008

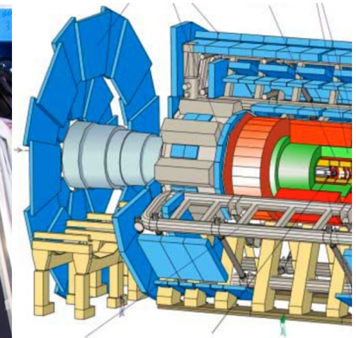
Superconductor solenoid at 3.8 Tesla

- It weighs 12,000 tons
- 100,000 times stronger the the Earth's
- Cooled to -268.5C (as in outer space)
- Stores energy to melt 18 tons of gold

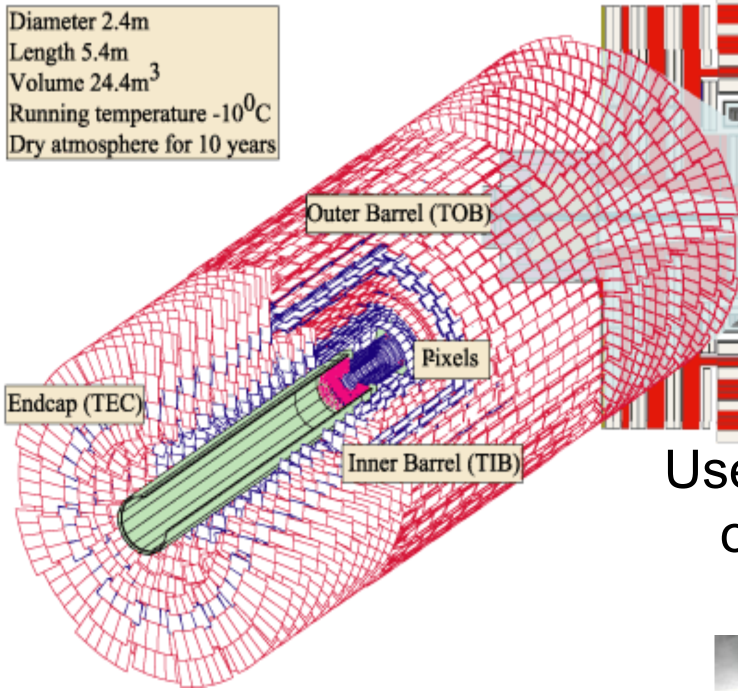


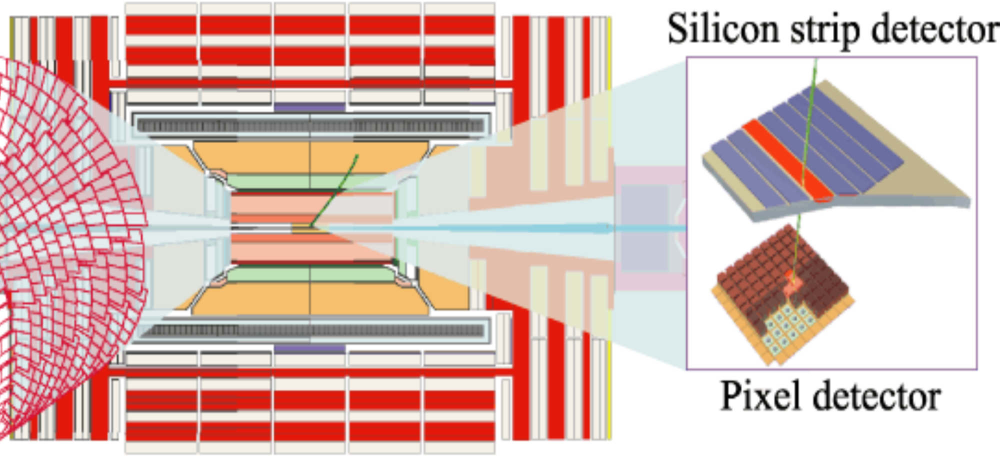
ATLAS Toroidal System





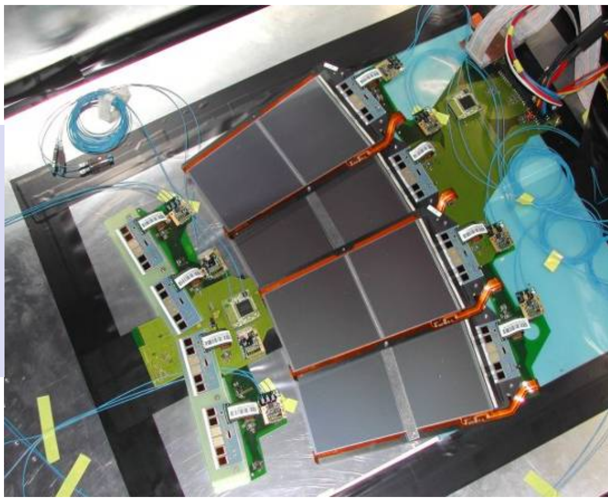
Silicon Tracker

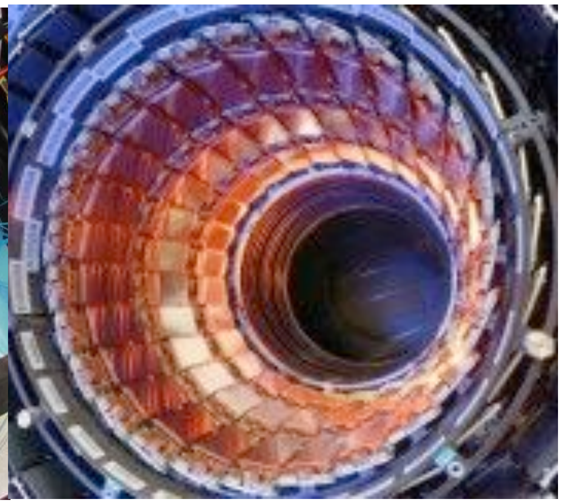




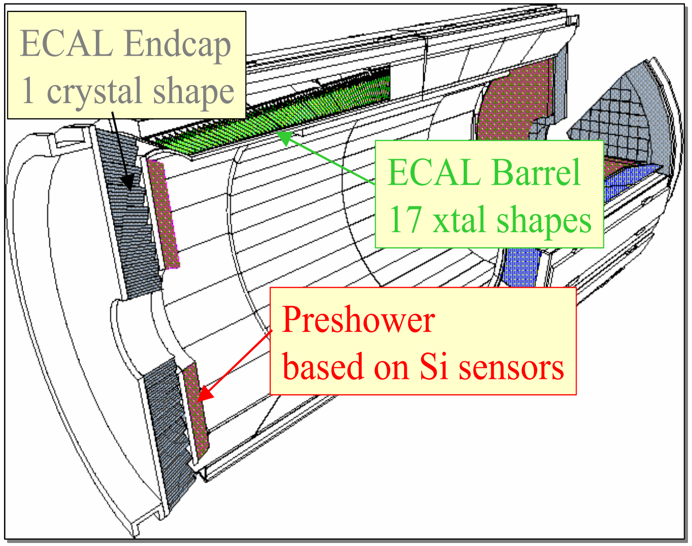
Used to reconstruct the trajectories of thousands of charge particles produced in the collisions

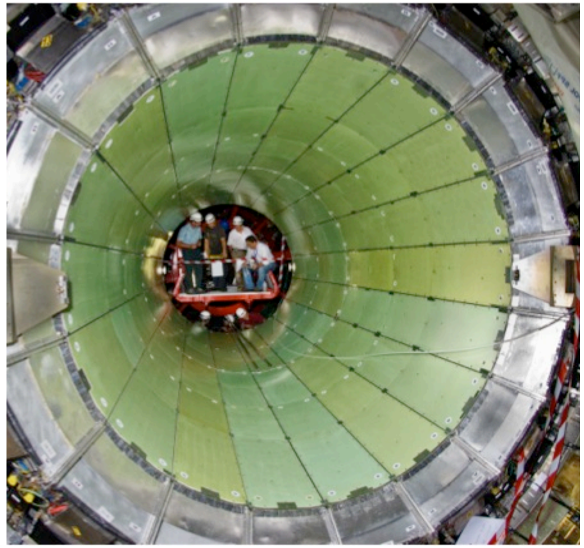
214m^2 silicon sensors
11.4 million silicon strips
65.9 million silicon pixels

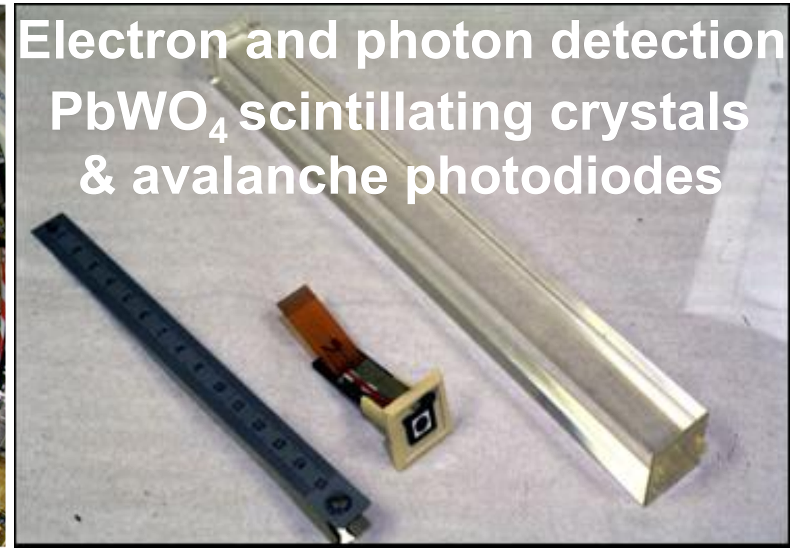


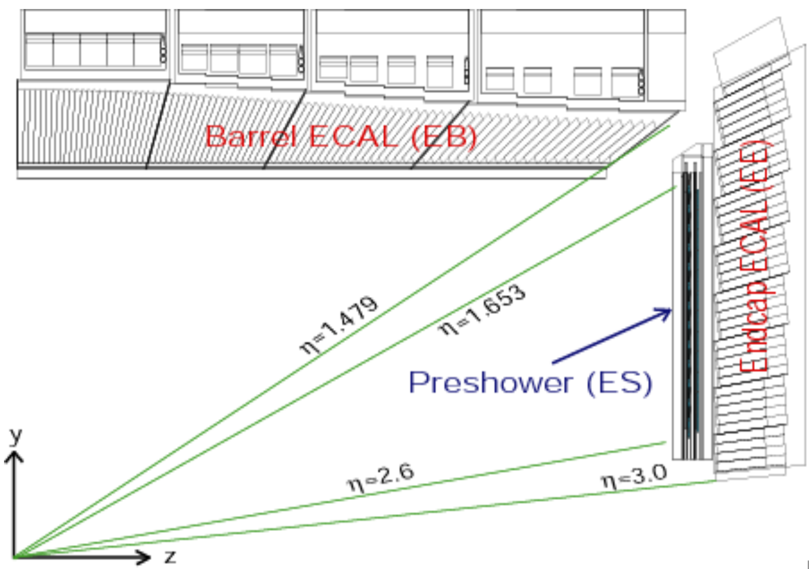


ECAL Electromagnetic Calorimeter







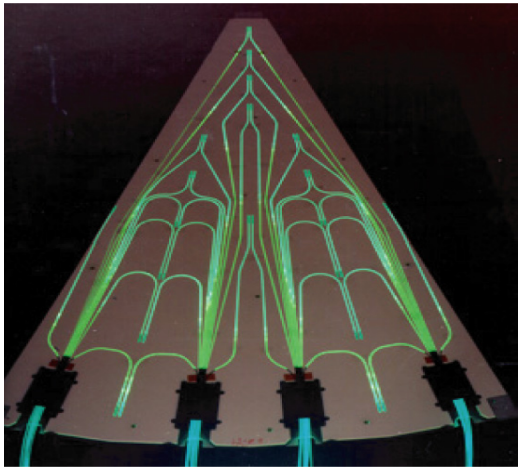


Design Goal: Measure the energies of photons from a decay of the Higgs boson to precision of ≤ 0.5%

Parameter	Barrel	Endcaps
# of crystals	**61200**	**14648**
Volume	**8.14m^3**	**2.7m^3**
Xtal mass (t)	**67.4**	**22.0**

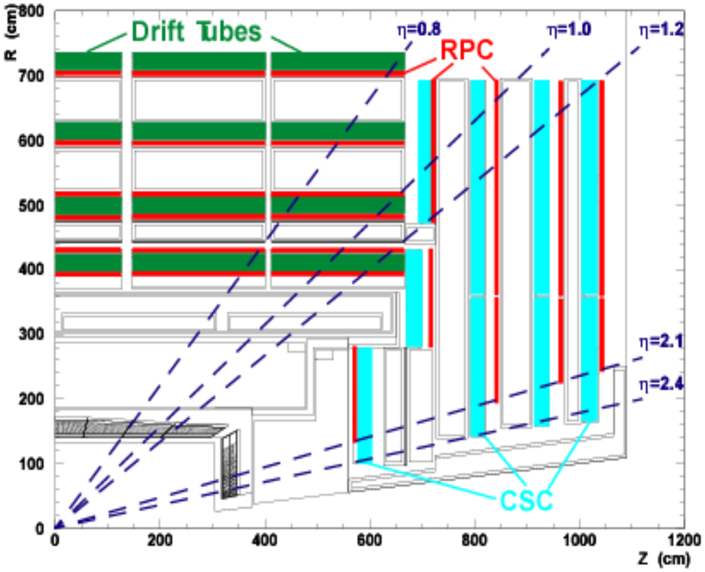
HCAL Hadronic Calorimeter

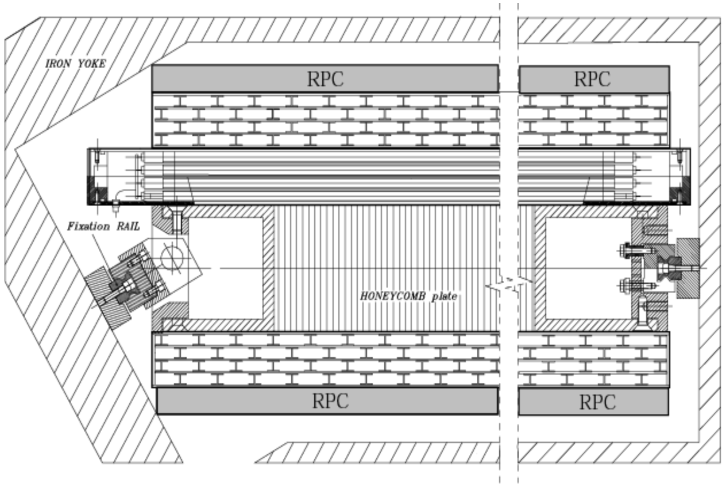
- Detection of hadrons:
  - Protons, neutrons, pions, etc.
- CMS HCAL (barrel, endcap, forward)
- Plastic scintillator and brass
- Quartz fibers and steel



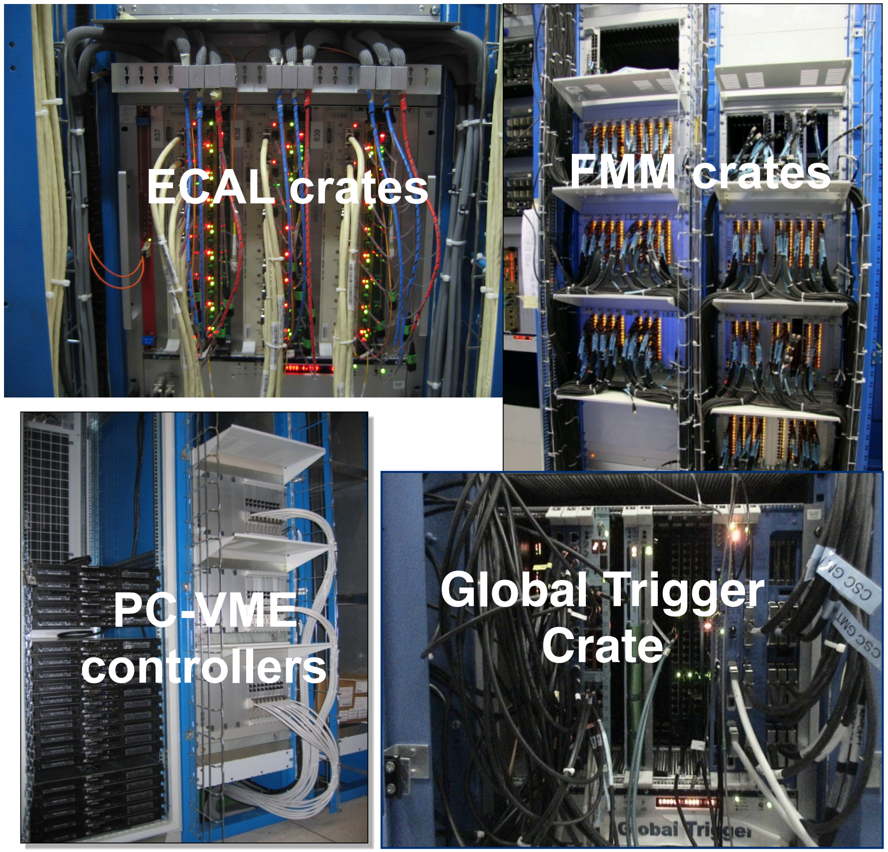
Muon detectors

- Drift tubes (DT)
- Cathode Strip Chambers (CSC)
- Resistive Plate Chambers (RPC)

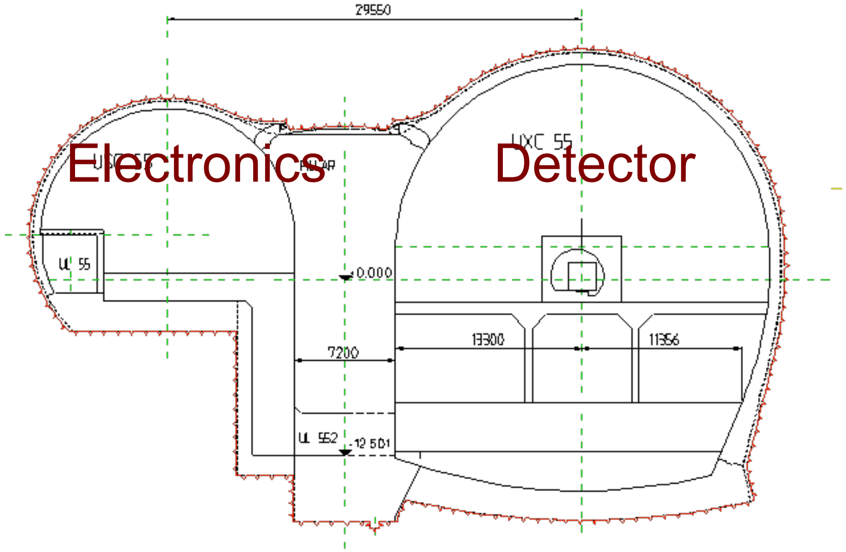


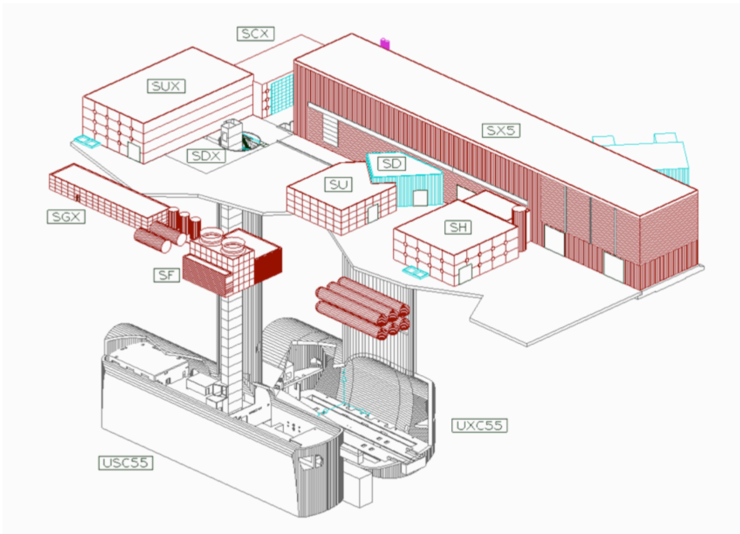


Trigger and electronics



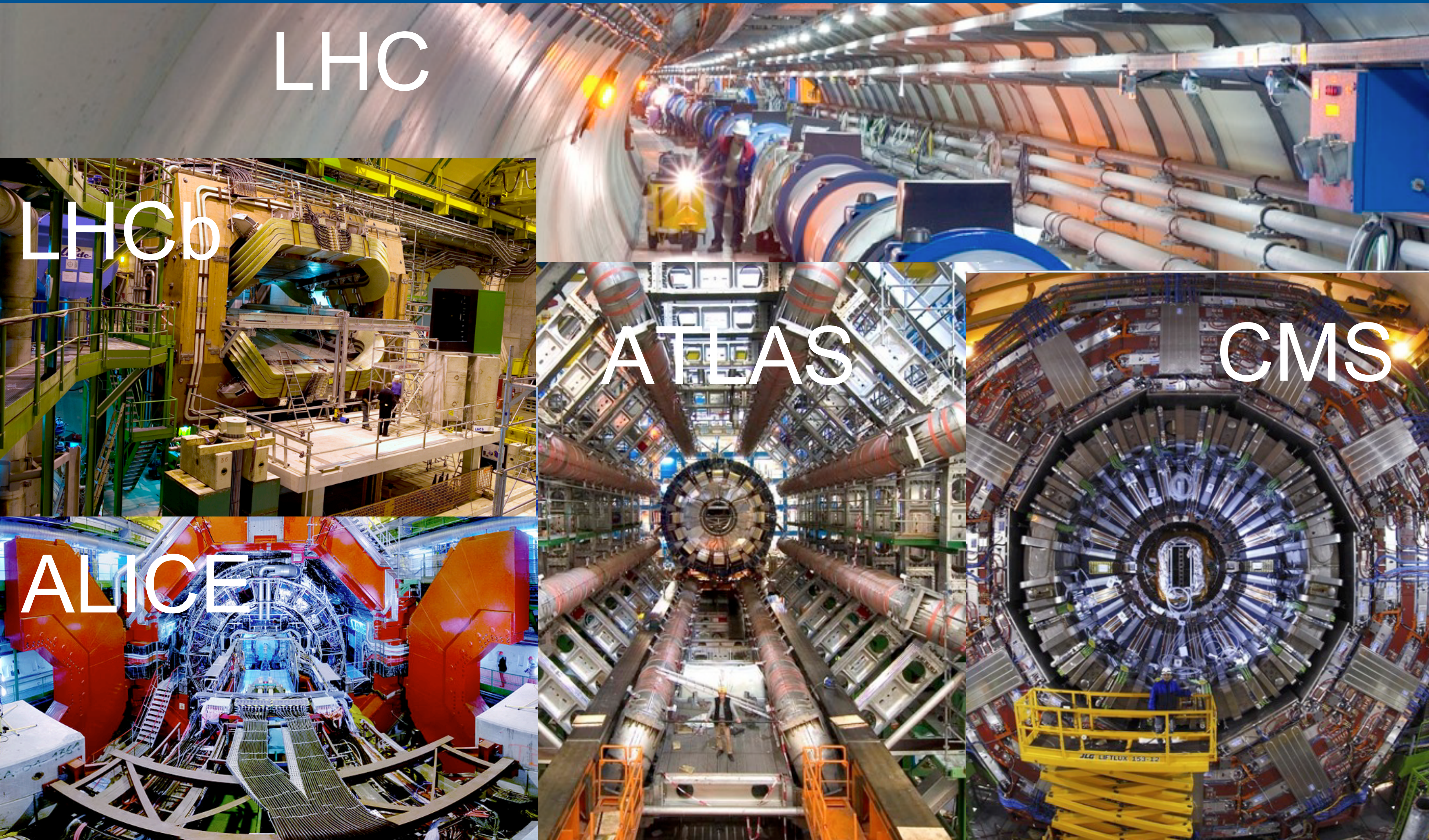
Underground caverns





- Electronics systems in the Service Cavern
- About 150 racks occupy two floors
- Most electronics is custom-built

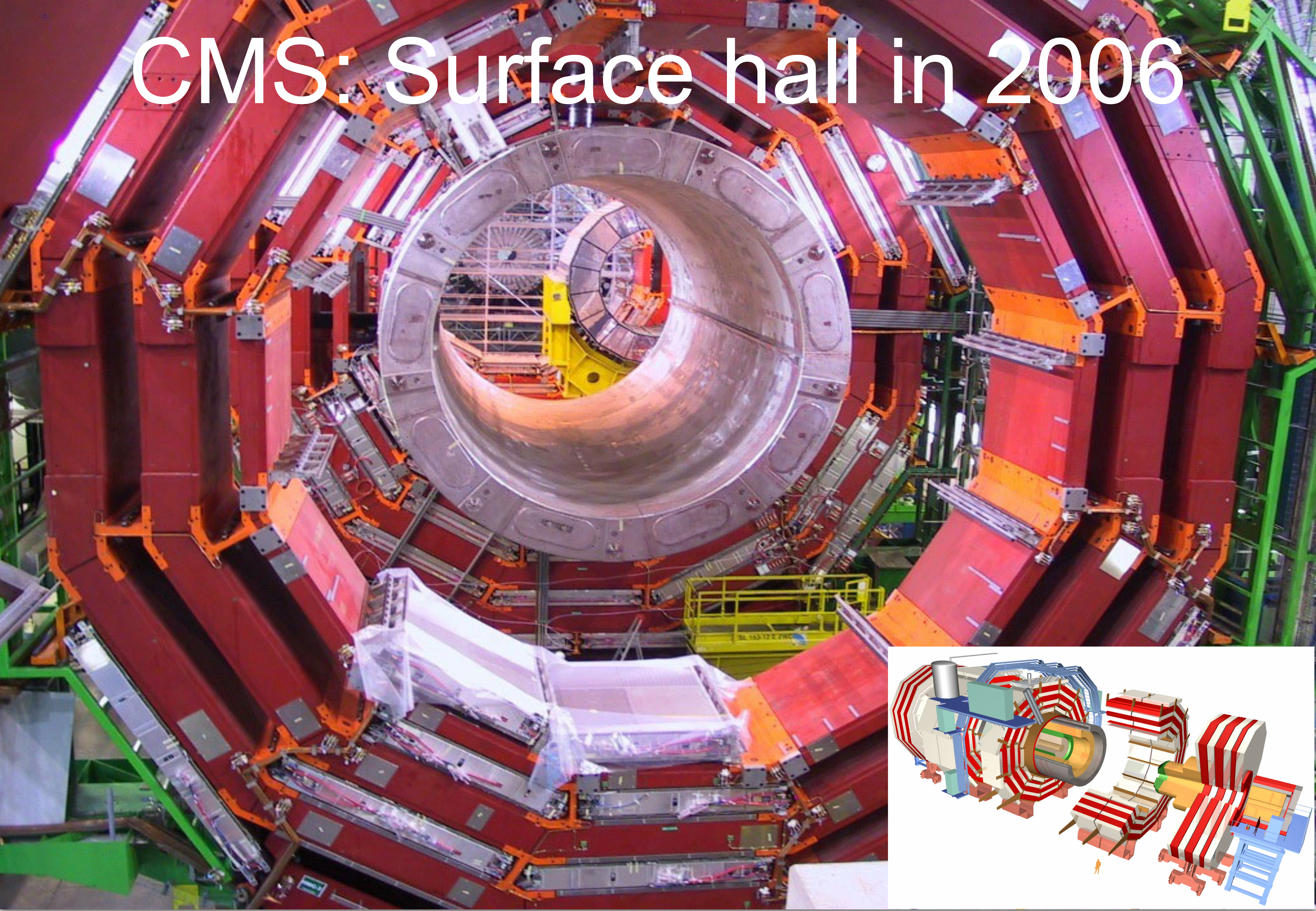
LHC accelerator/detectors



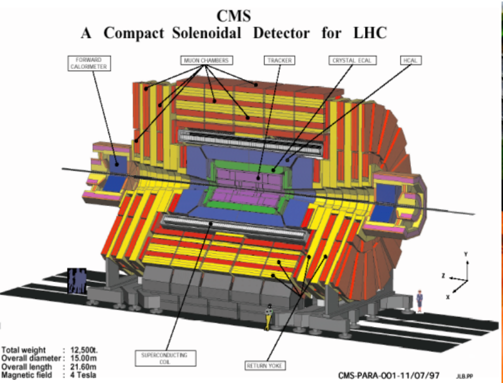
CMS: Surface site in 2000

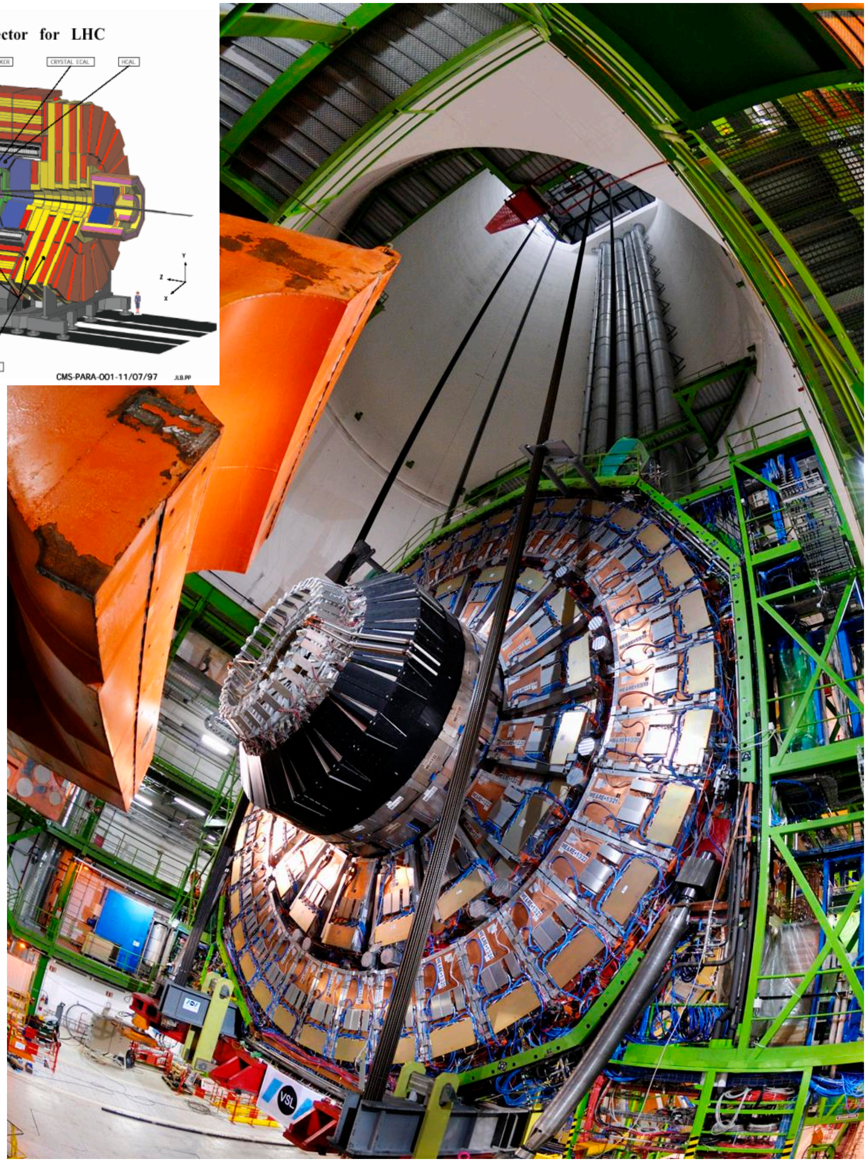
2004: CMS detector cavern

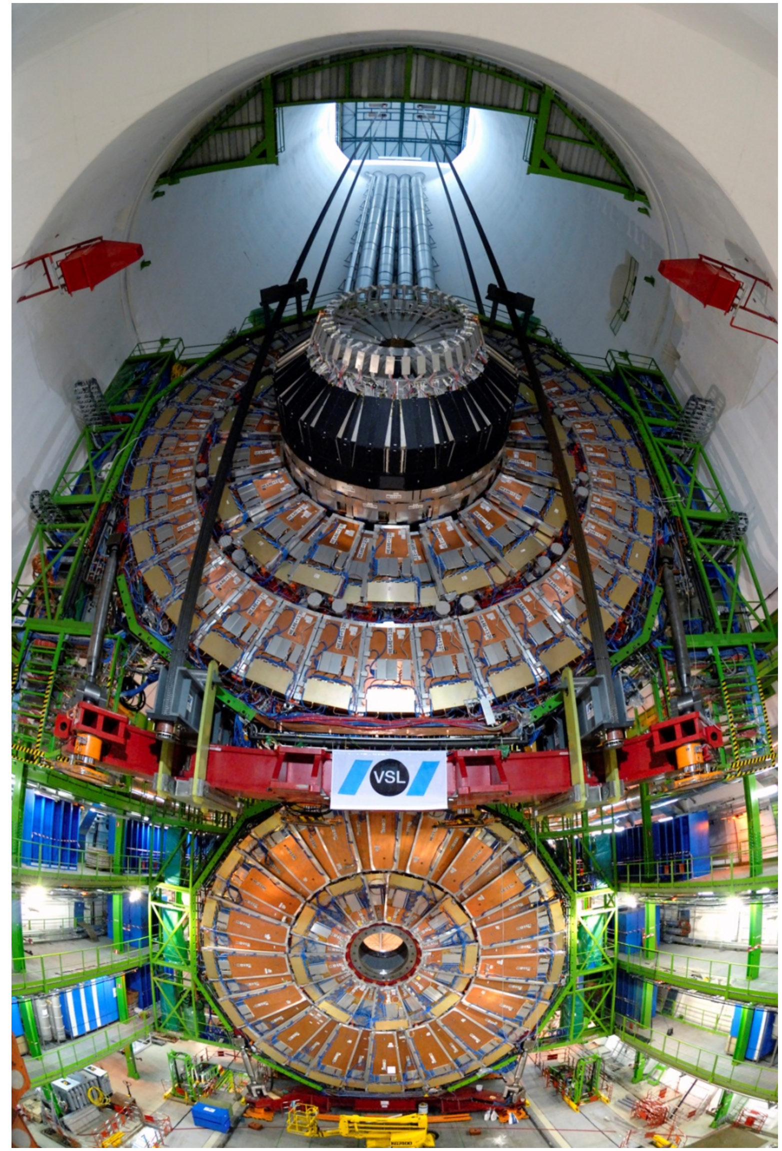
CMS: Surface hall in 2006



2007: lowering the detectors

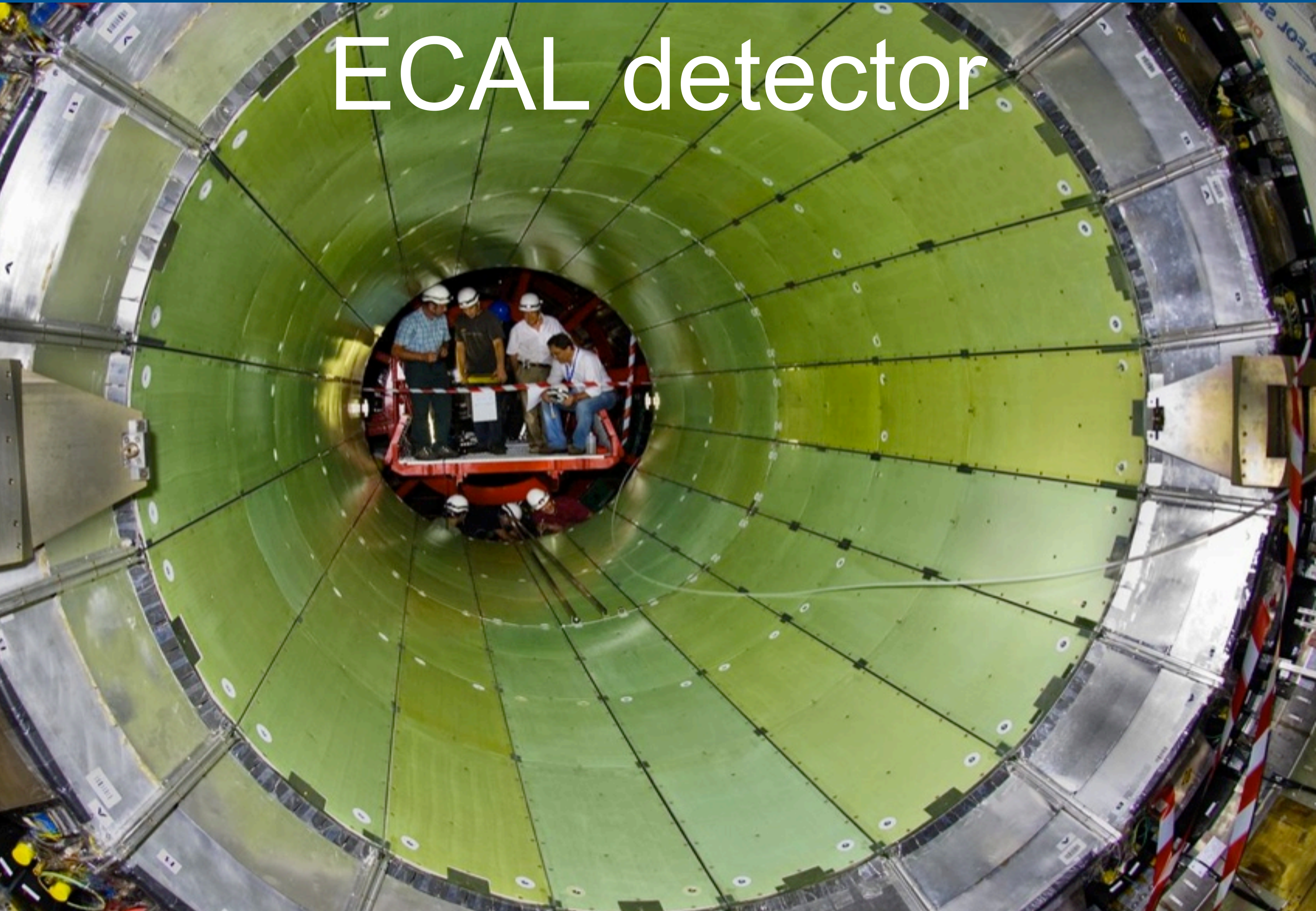




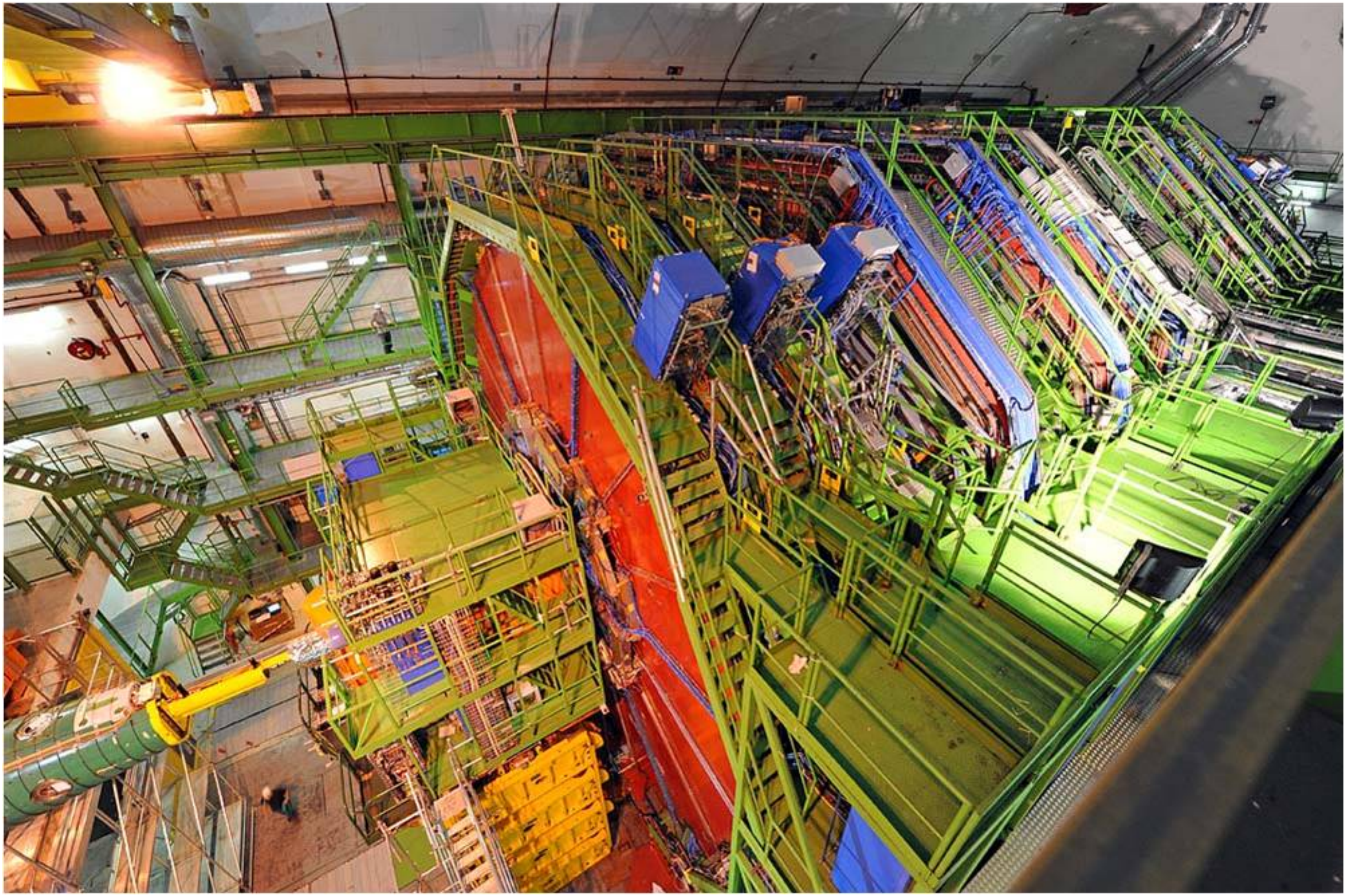


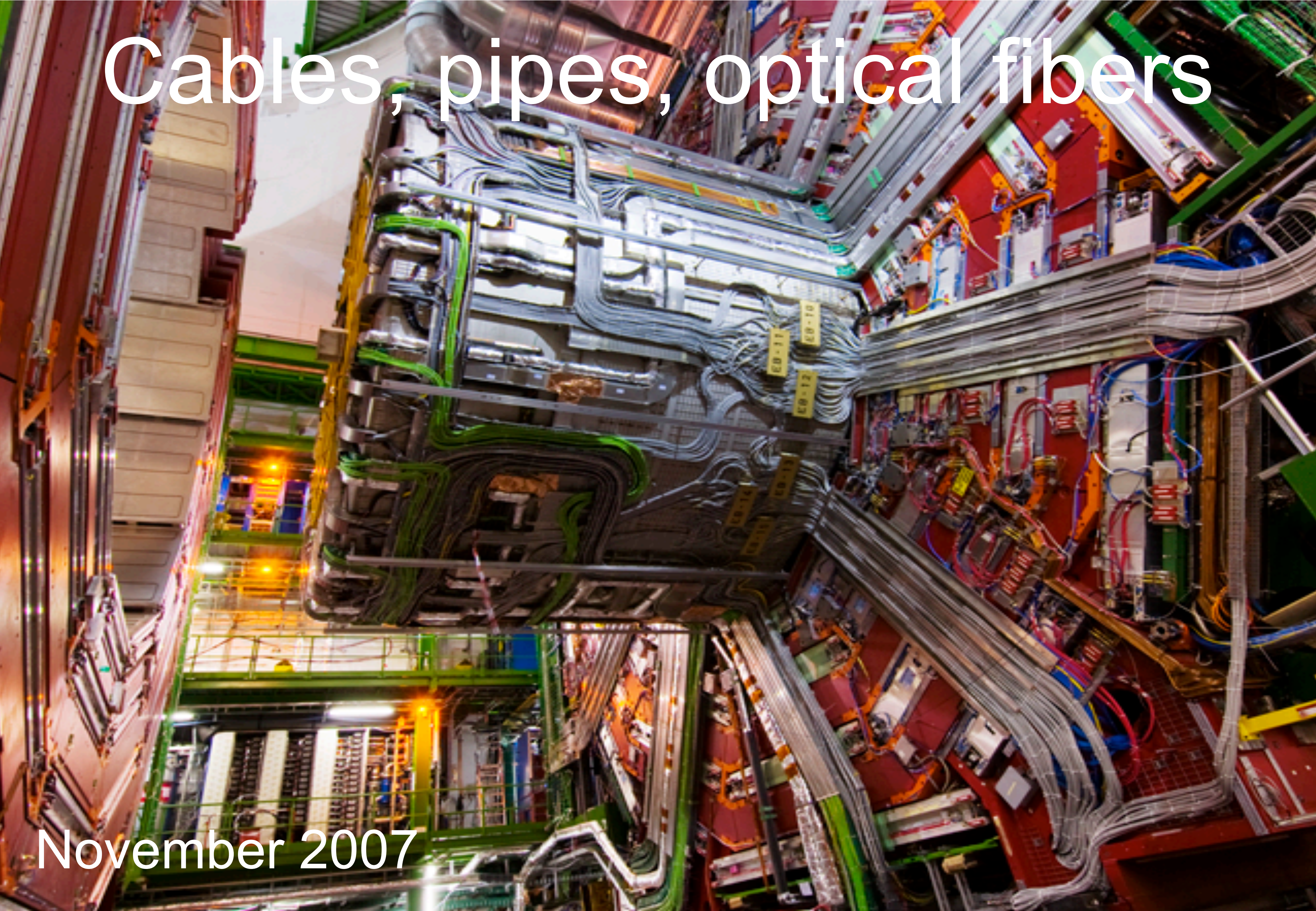

Spectacular operation in 2007
The CMS was lowered to the collision hall in Feb. 2007
…started the travel at 6 am….

ECAL detector

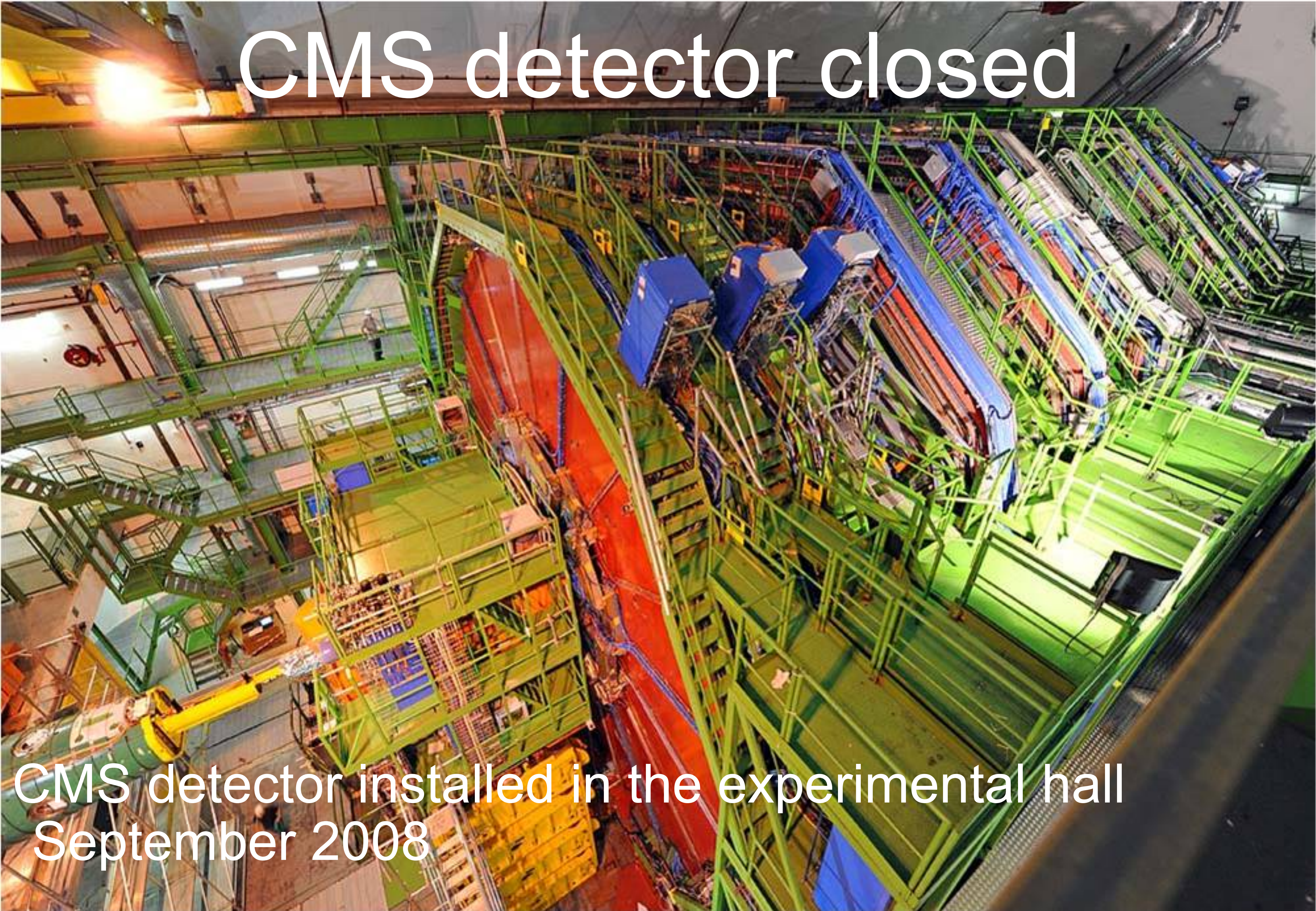


Sept. 2008: Ready for beams




Cables, pipes, optical fibers
November 2007

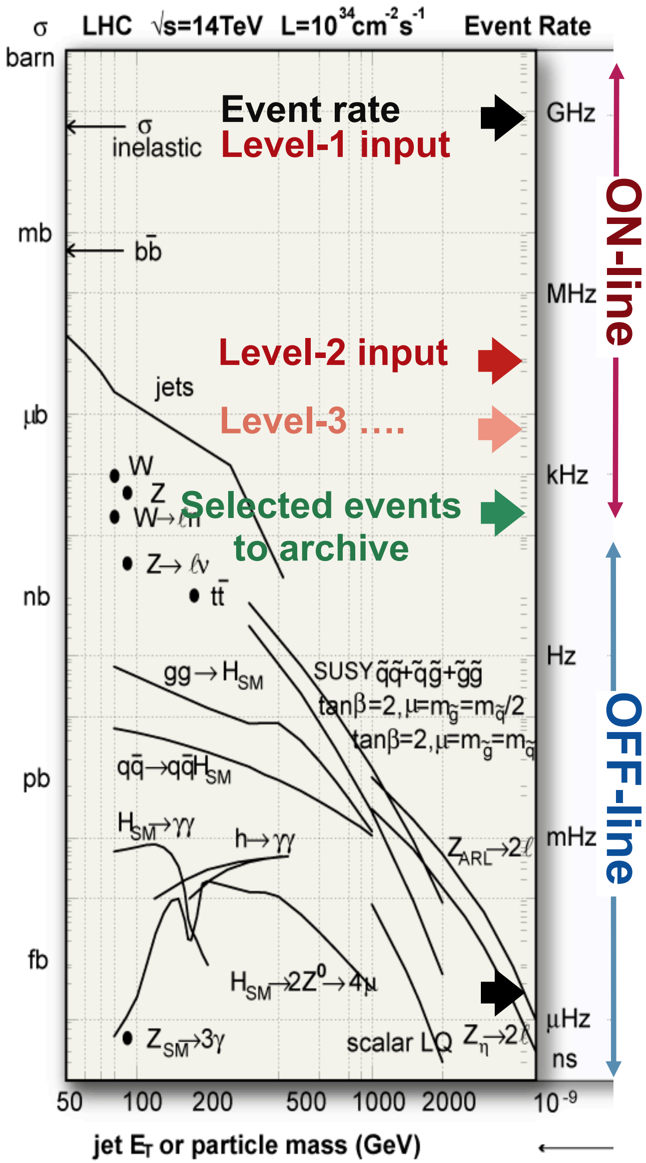
CMS detector closed

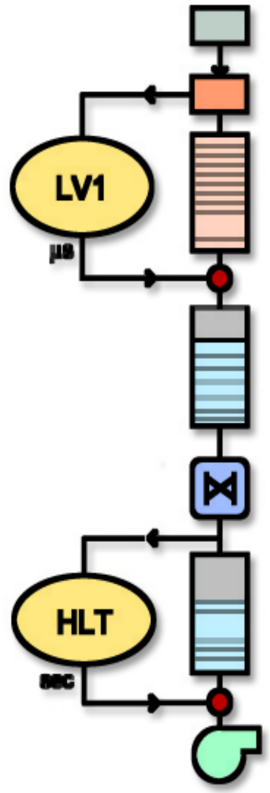


CMS detector installed in the experimental hall
September 2008

First collisions at 7 TeV
A big step up in energy

Trigger



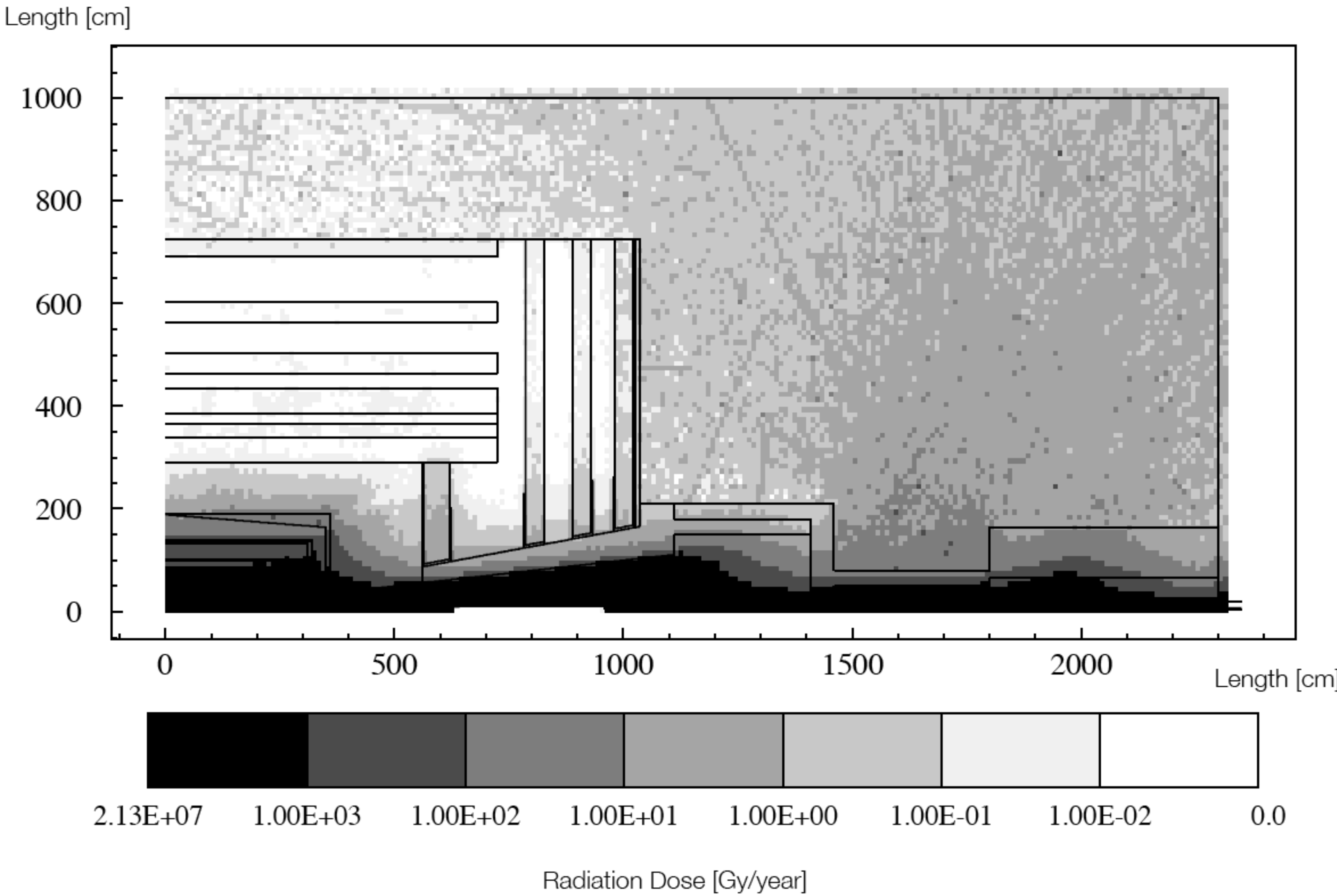


Trigger system decide if the event is interesting to be recorded

Two-step process:
- Level 1: dedicated hardware processors
- High level: computer farm

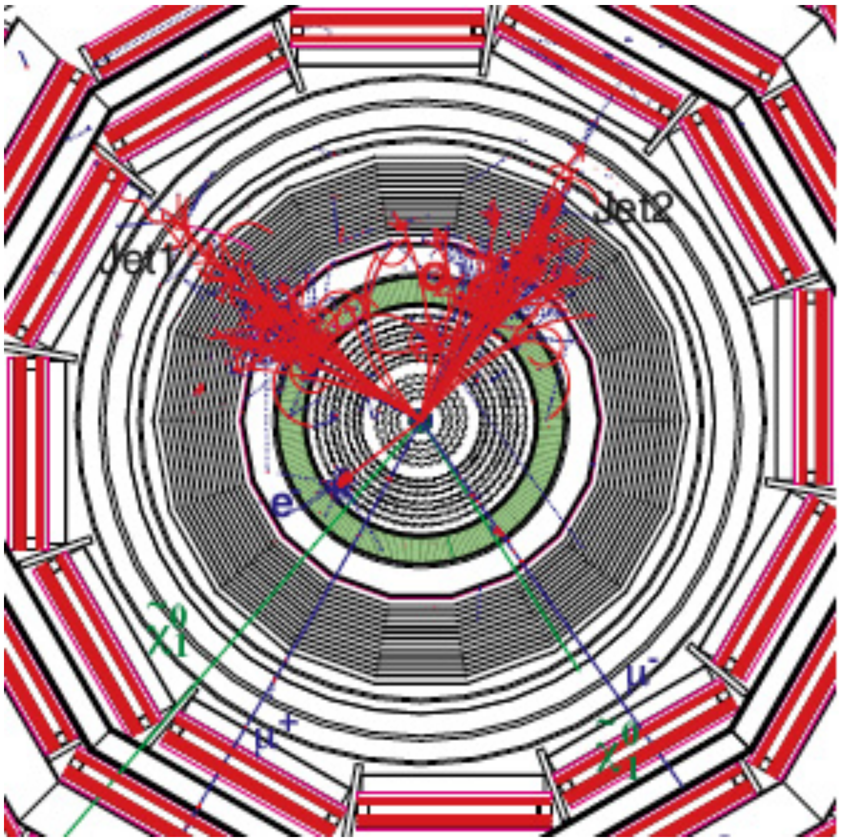
Trigger computer farm

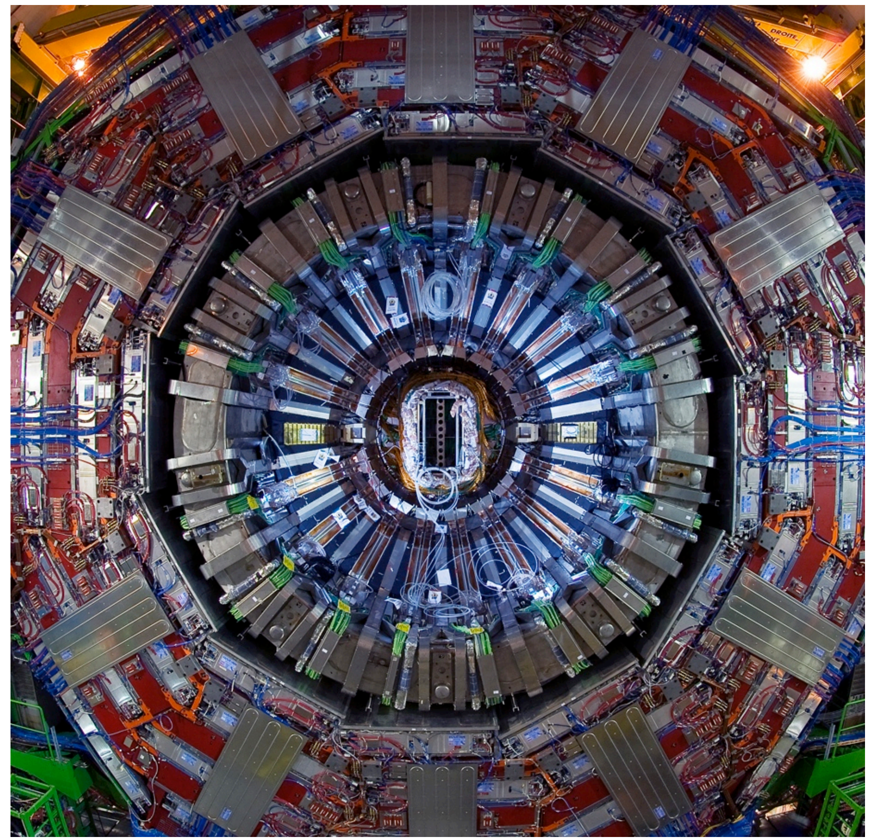
High radiation levels



How did we prepare for discoveries?

Simulation of proton-proton collision
making two dark matter particles





From partons to jets

From partons to
color neutral hadrons:

Fragmentation:

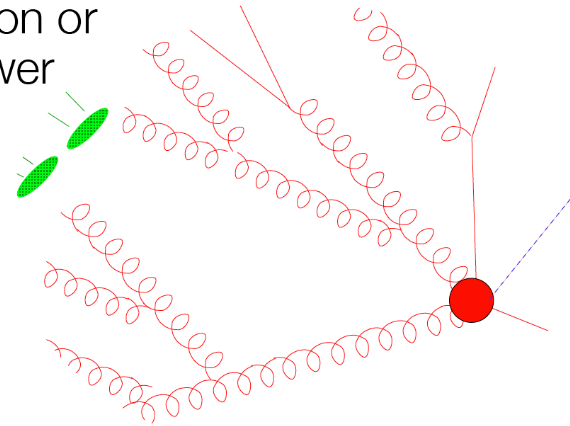
Parton splitting into other partons
[QCD: re-summation of leading-logs]
[“Parton shower”]

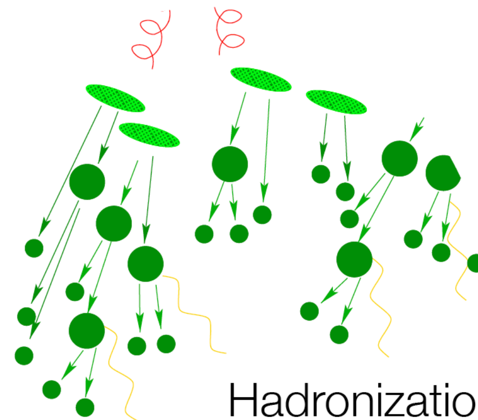
Hadronization:

Parton shower forms hadrons
[non-perturbative, only models]

Decay of unstable hadrons
[perturbative QCD, electroweak theory]

Fragmentation or
Parton Shower





Hadronization &
Decays

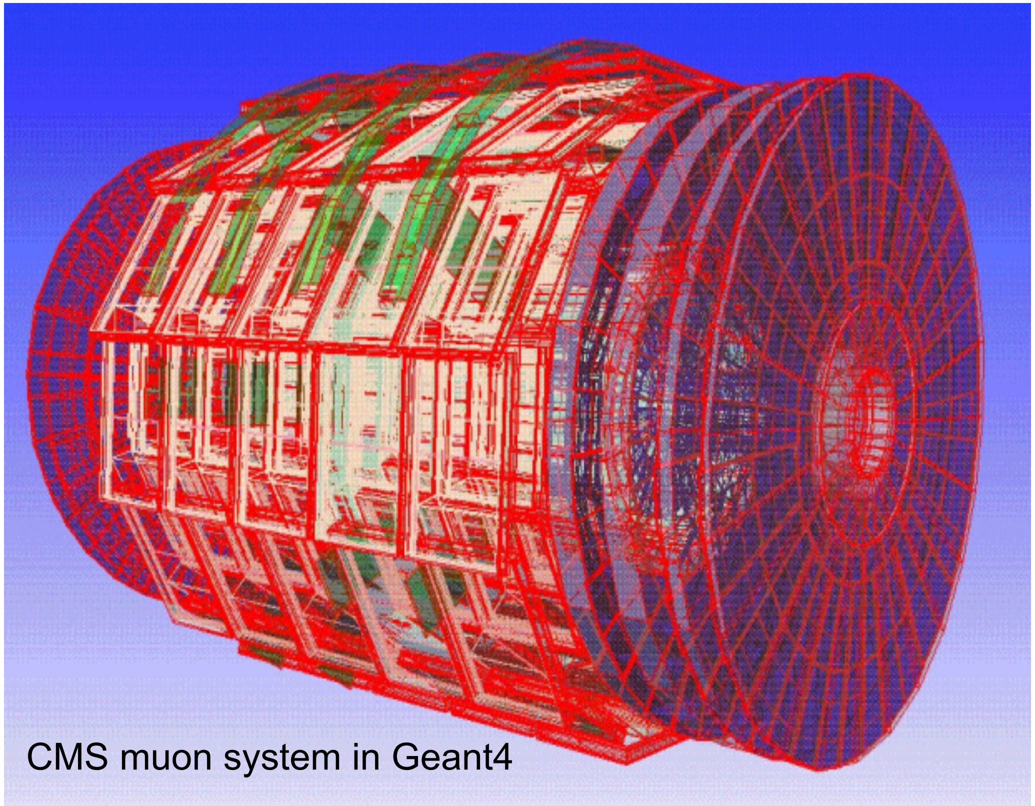
Detector simulation

GEANT
Geometry And Tracking

Detailed description of detector geometry
[sensitive & insensitive volumes]

Tracking of all particles through detector material ...

➛ Detector response



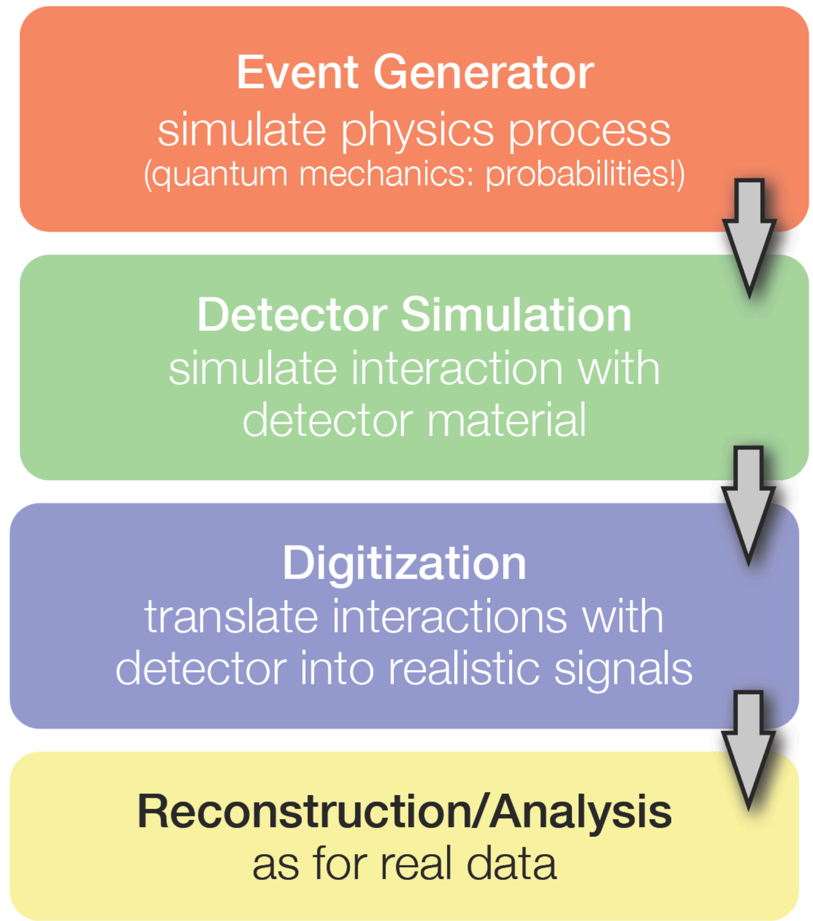
CMS muon system in Geant4

Developed at CERN since 1974 (FORTRAN)
[Today: Geant4; programmed in C^{++}]

Monte Carlo simulation

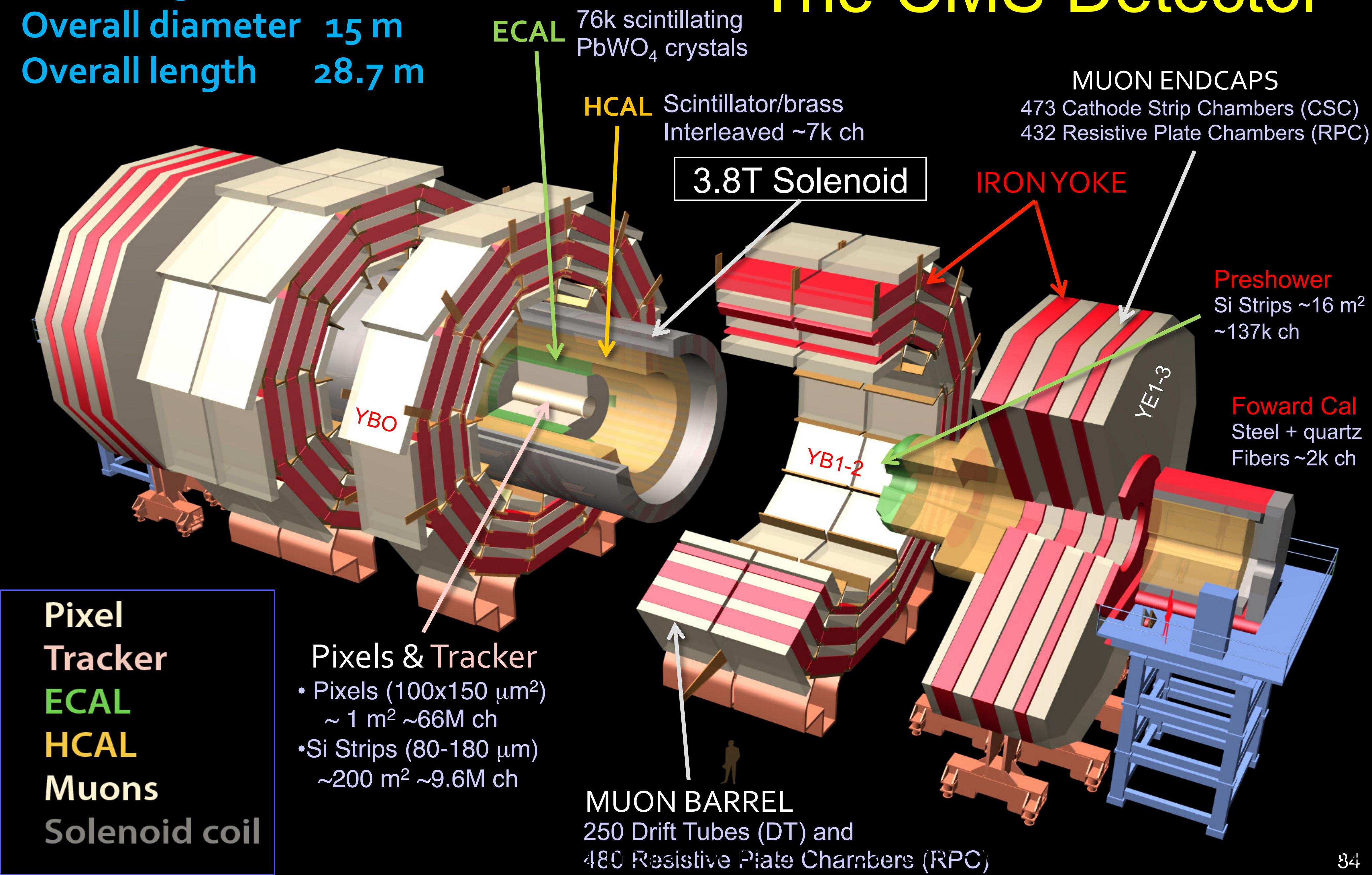
Simulation

- Numerical process generation based on random numbers
- Very powerful in particle physics
- Event generation
  - Pythia, Herwig, Isajet, Sherpa …
  - Hard partonic subprocess + fragmentation, hadronization, decay
- Detector simulation
  - Geant …
  - Interaction, response of all particles produced …

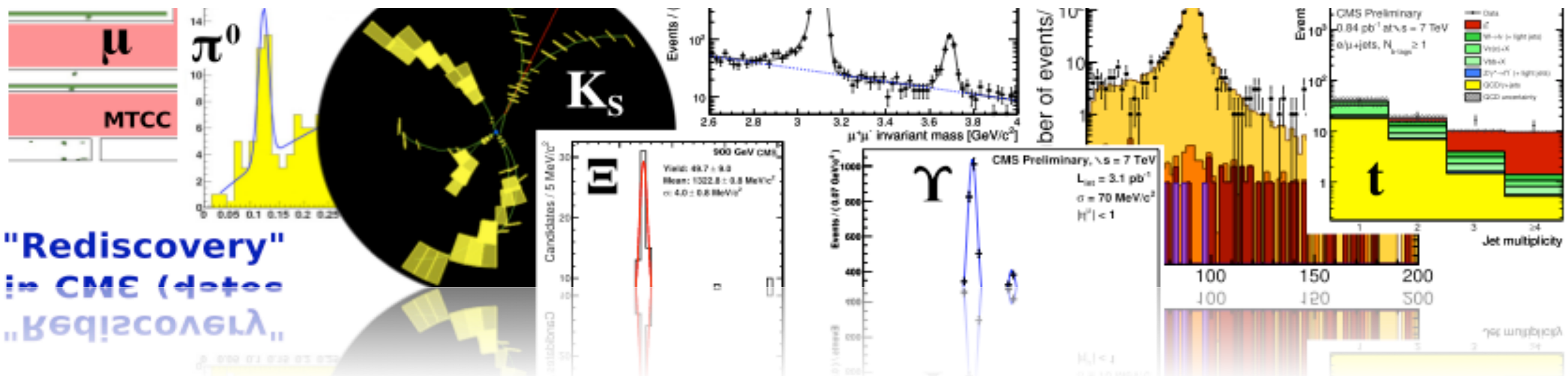


The CMS Detector

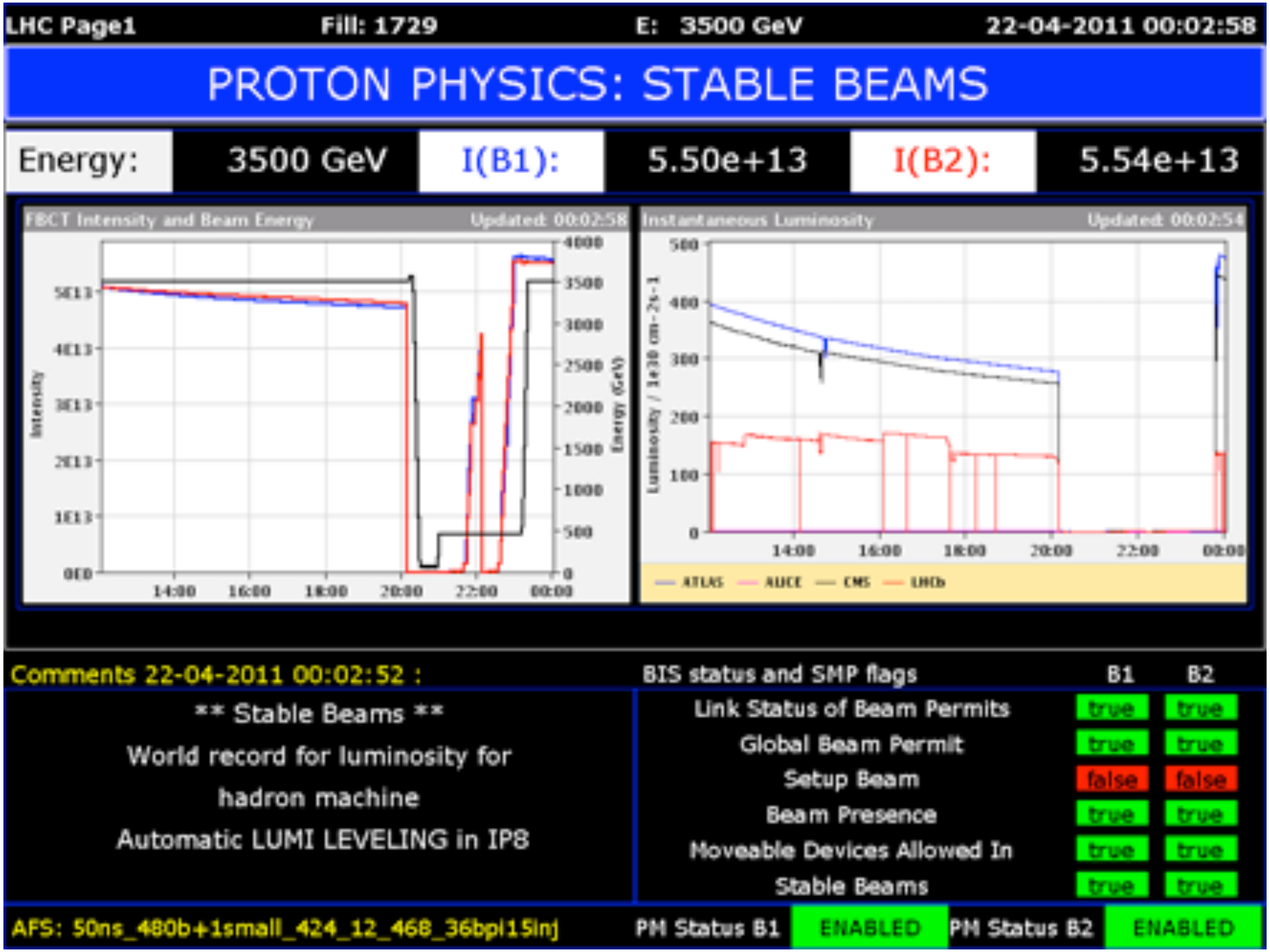
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m



Detector commissioning



LHC Page 1: stable beams



Experiment's control rooms

Cessy: Master Control Room

Fermilab: Remote Operations Center

Meyrin: CMS Data Quality Monitoring Center

Any Internet access

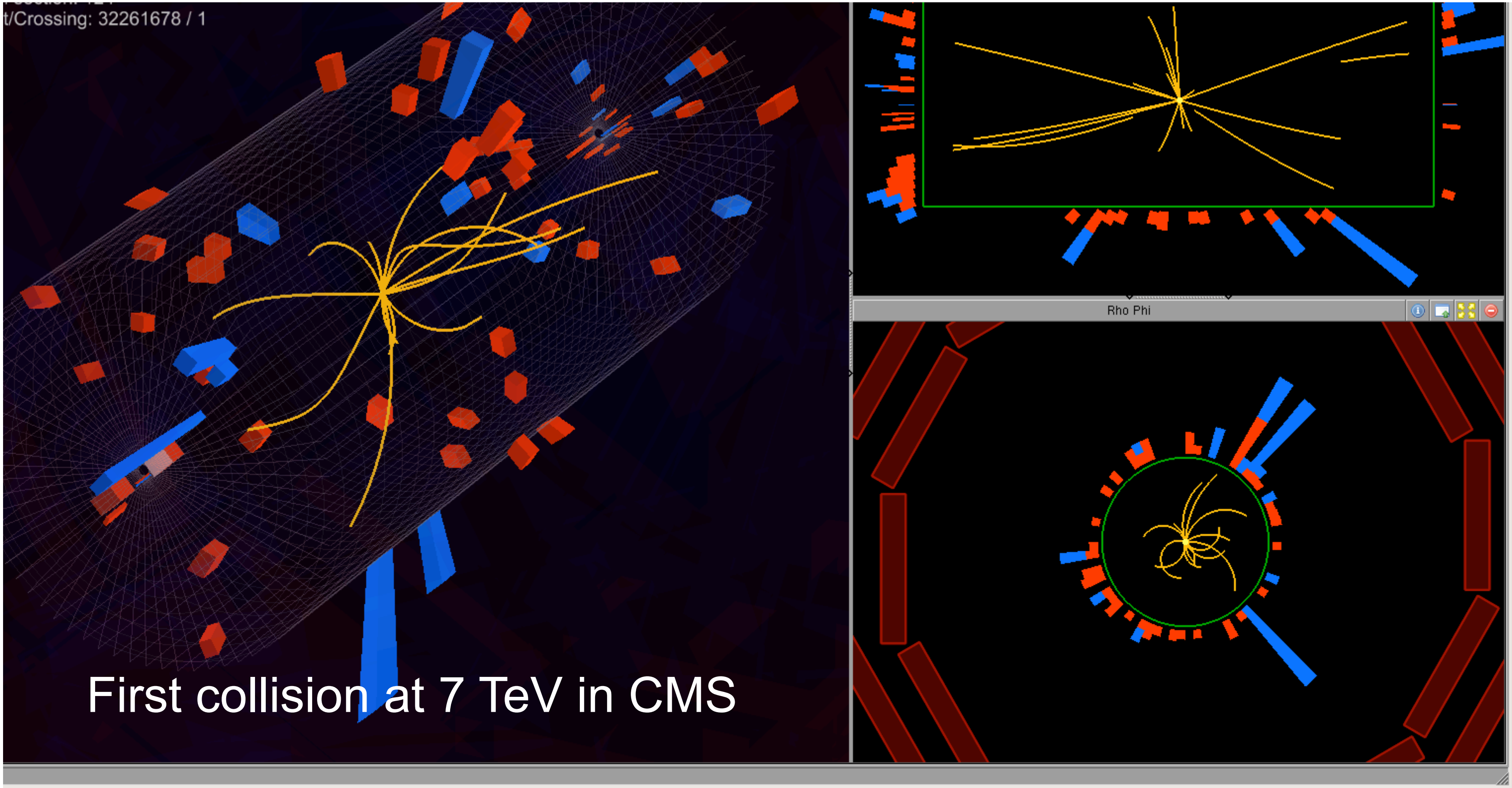
CMS Experiment

2009: first collisions at LHC

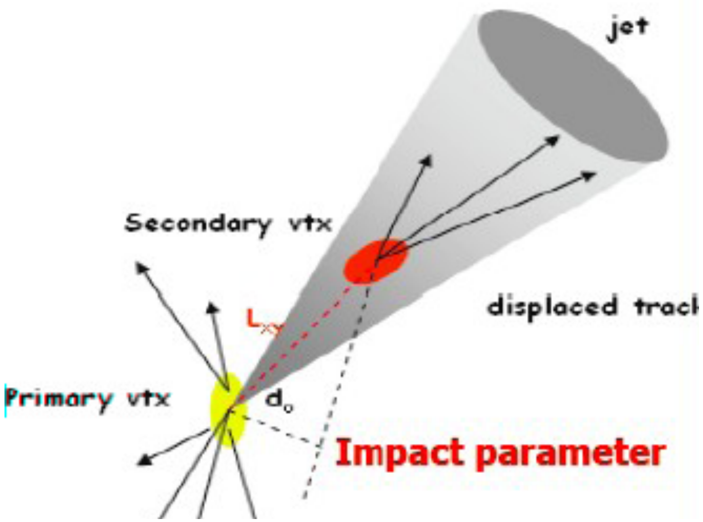
November 23, 2009
First collisions at 900 GeV

December 14, 2009
First collisions at 2.36 TeV

March 30, 2010
First collisions at 7 TeV

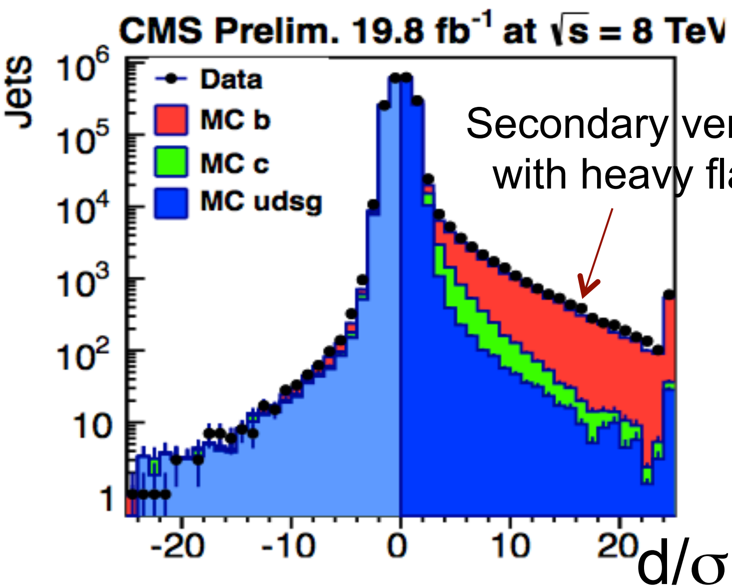


Tracking



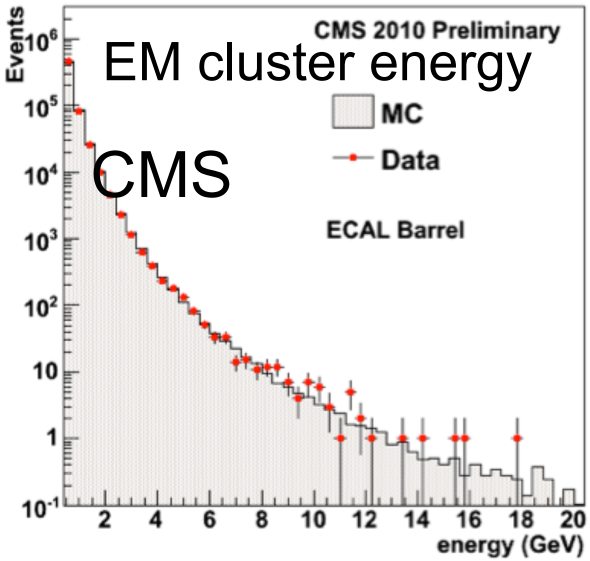
- Variables relevant for b-tagging
- Lifetime: τ_b~1-2 psec
- Reduction of backgrounds
- Secondary vertex tagging

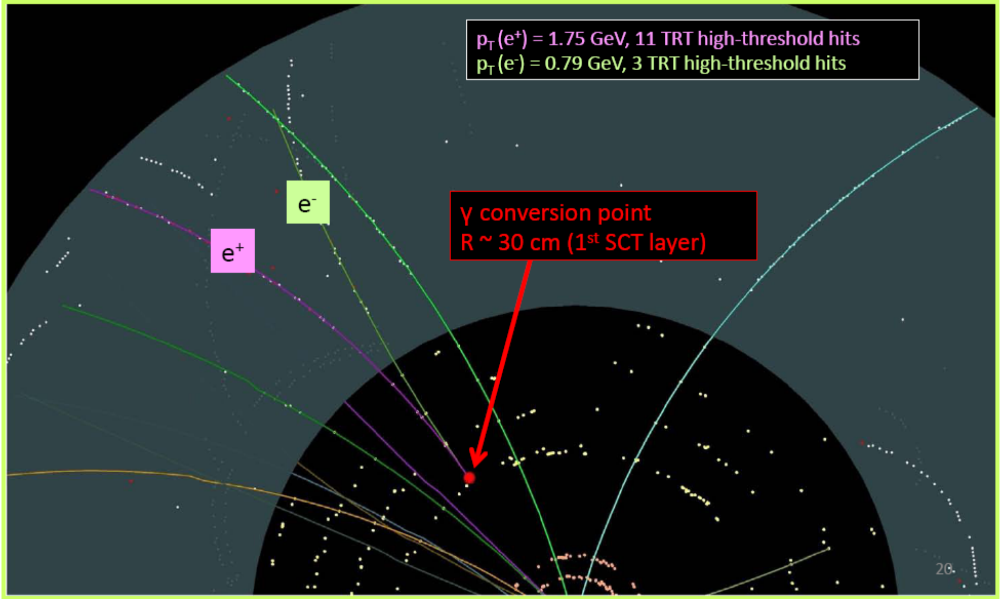
($b \to l \nu_l X$)

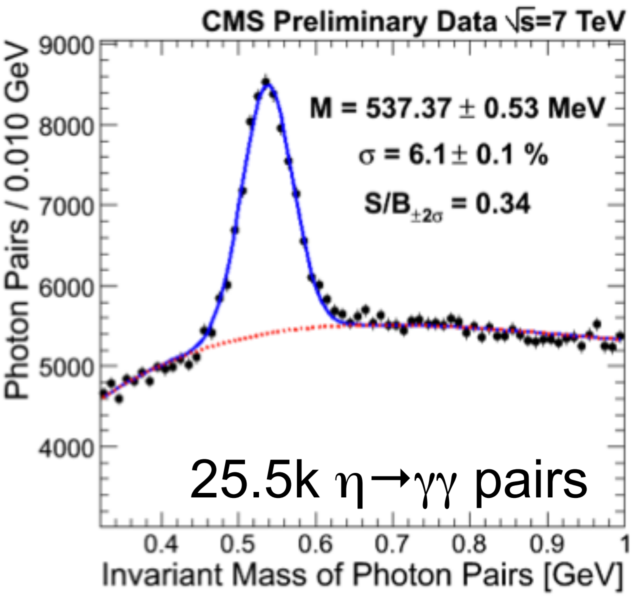


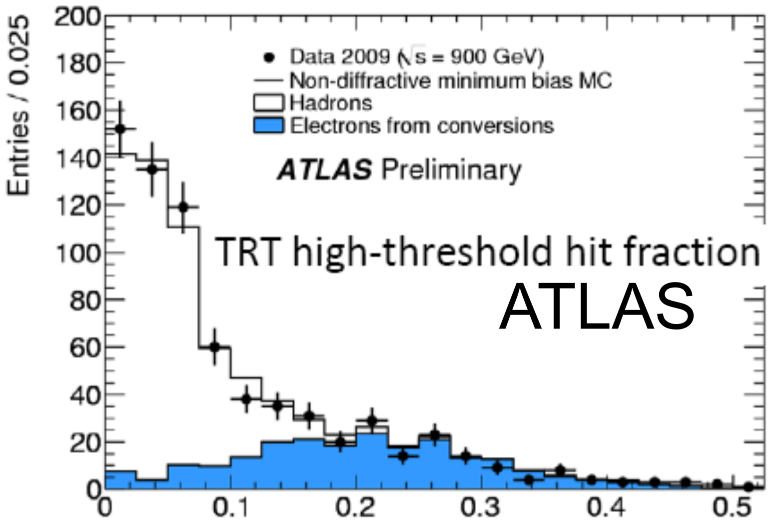
Secondary vertices compatible with heavy flavor production

Photons and electrons

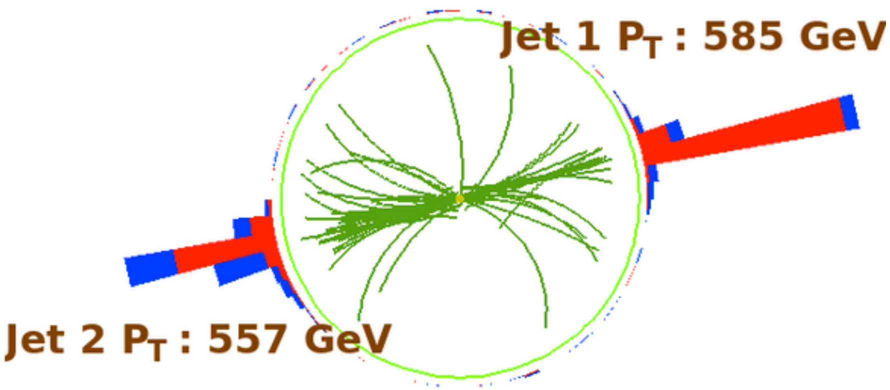


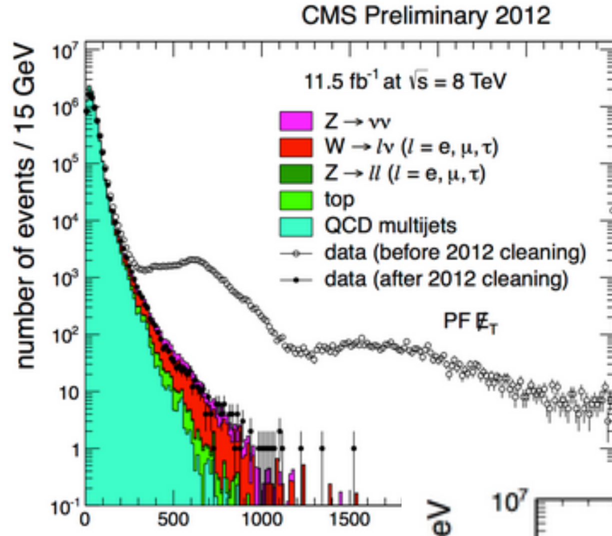


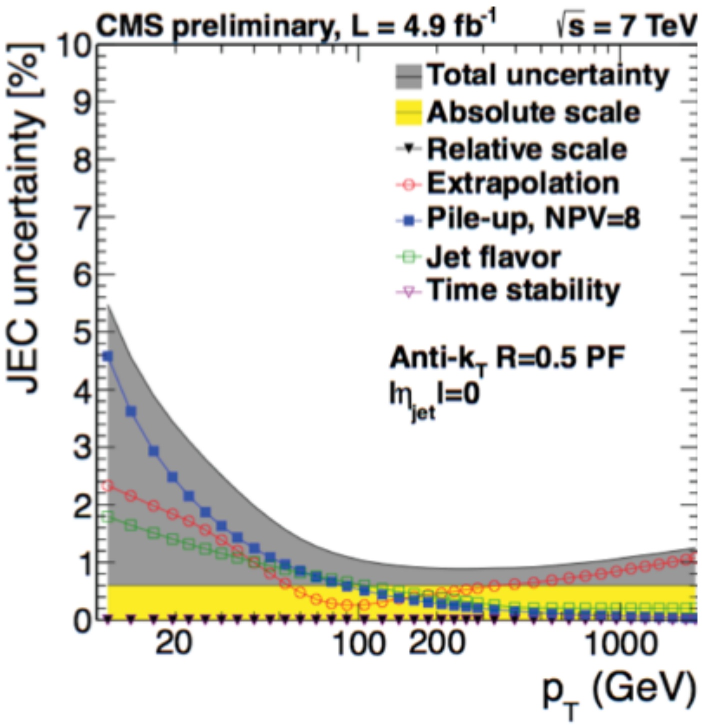


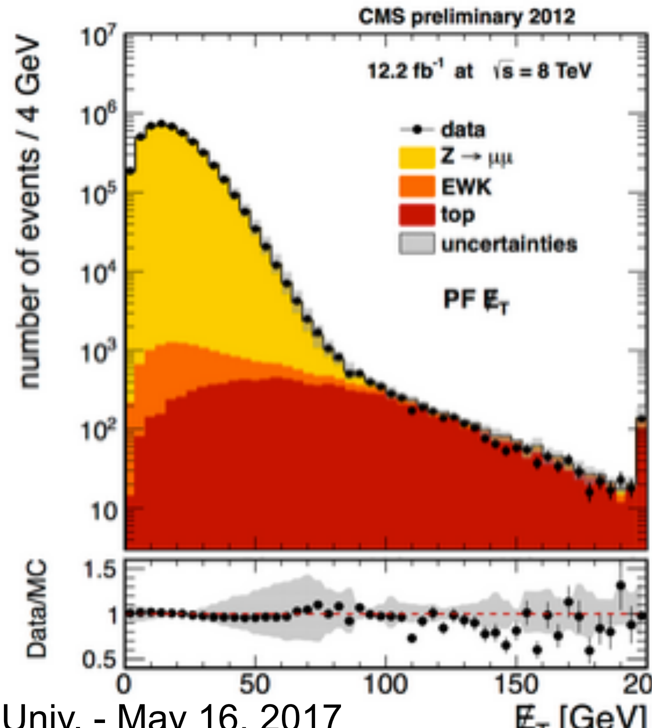


Jets and missing transverse energy



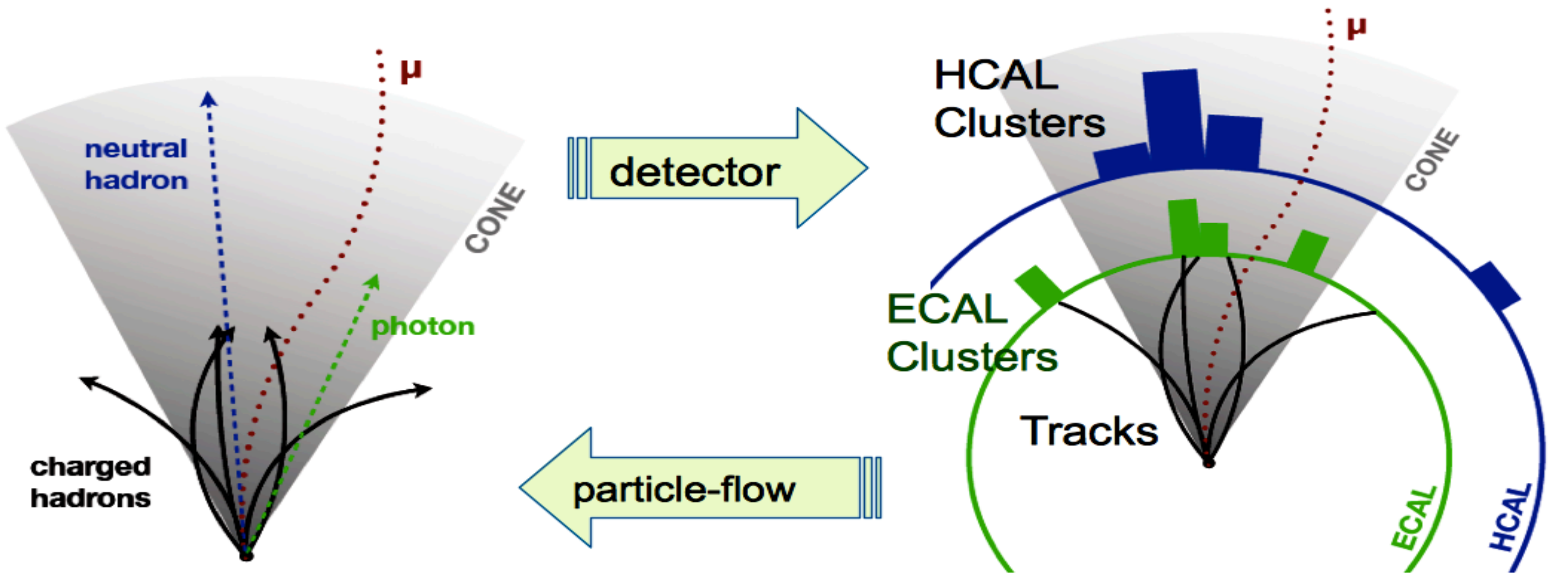




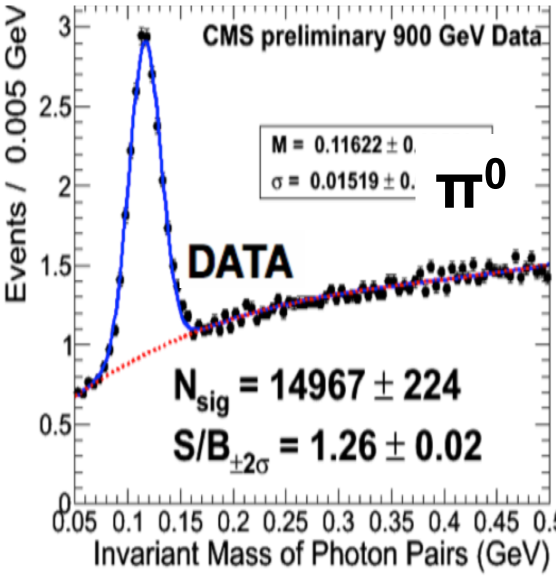


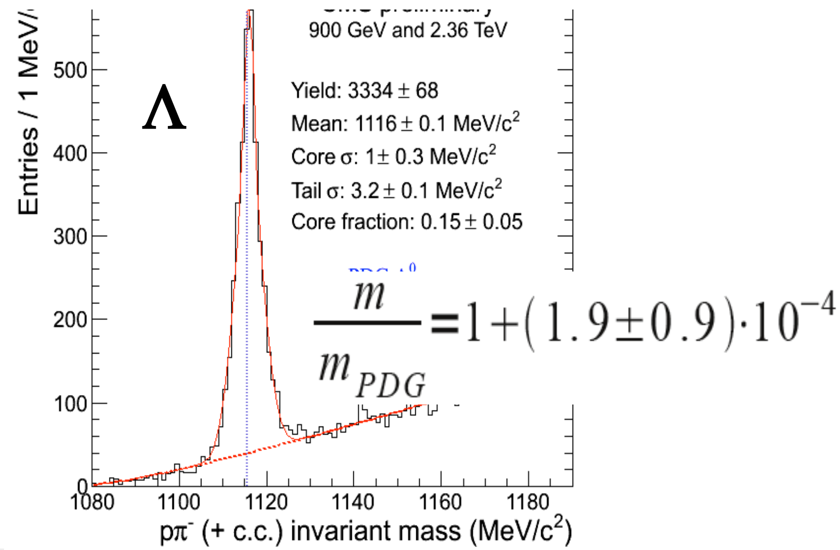
Particle Flow event reconstruction

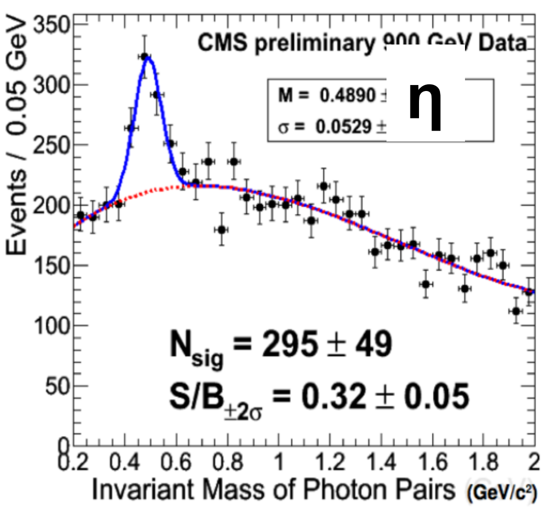
- Particle Flow (PF) combines information from all subdetectors to reconstruct particles produced in the collision
  - charged hadrons, neutral hadrons, photons, muons, electrons
  - use complementary info. from separate detectors to improve performance
  - tracks to improve calorimeter measurements
- From list of particles, can construct higher-level objects
  - Jets, b-jets, taus, isolated leptons and photons, MET, etc.

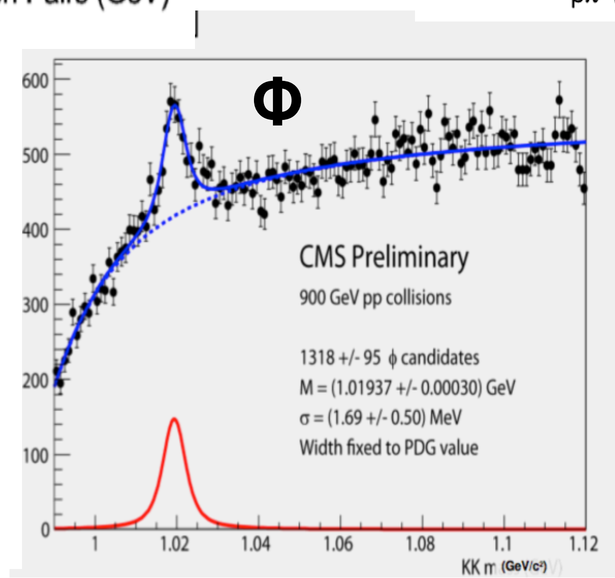


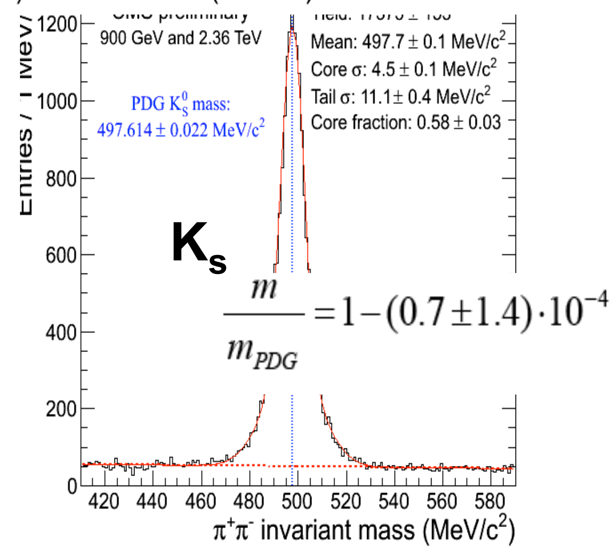
Rediscovery of resonances



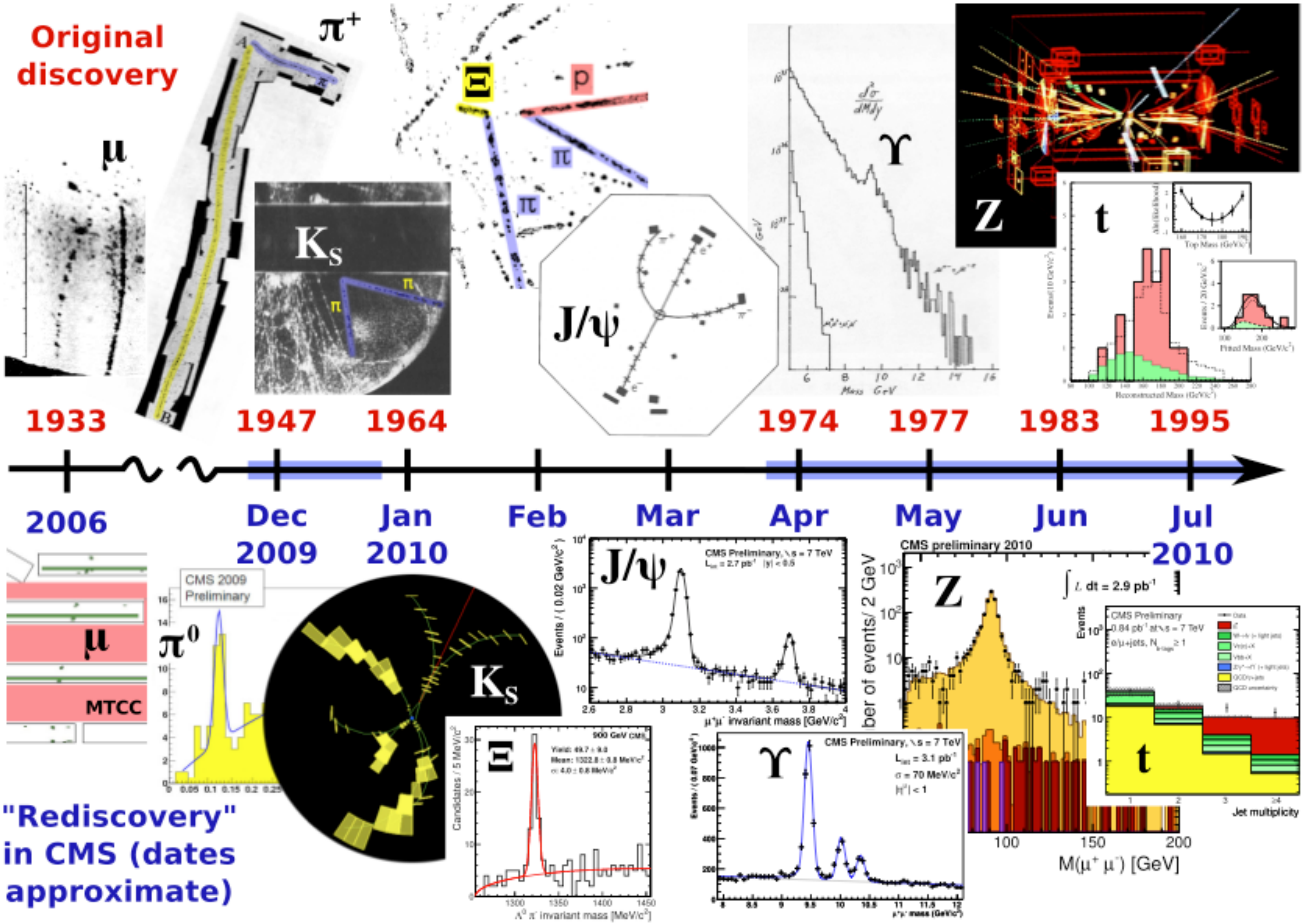








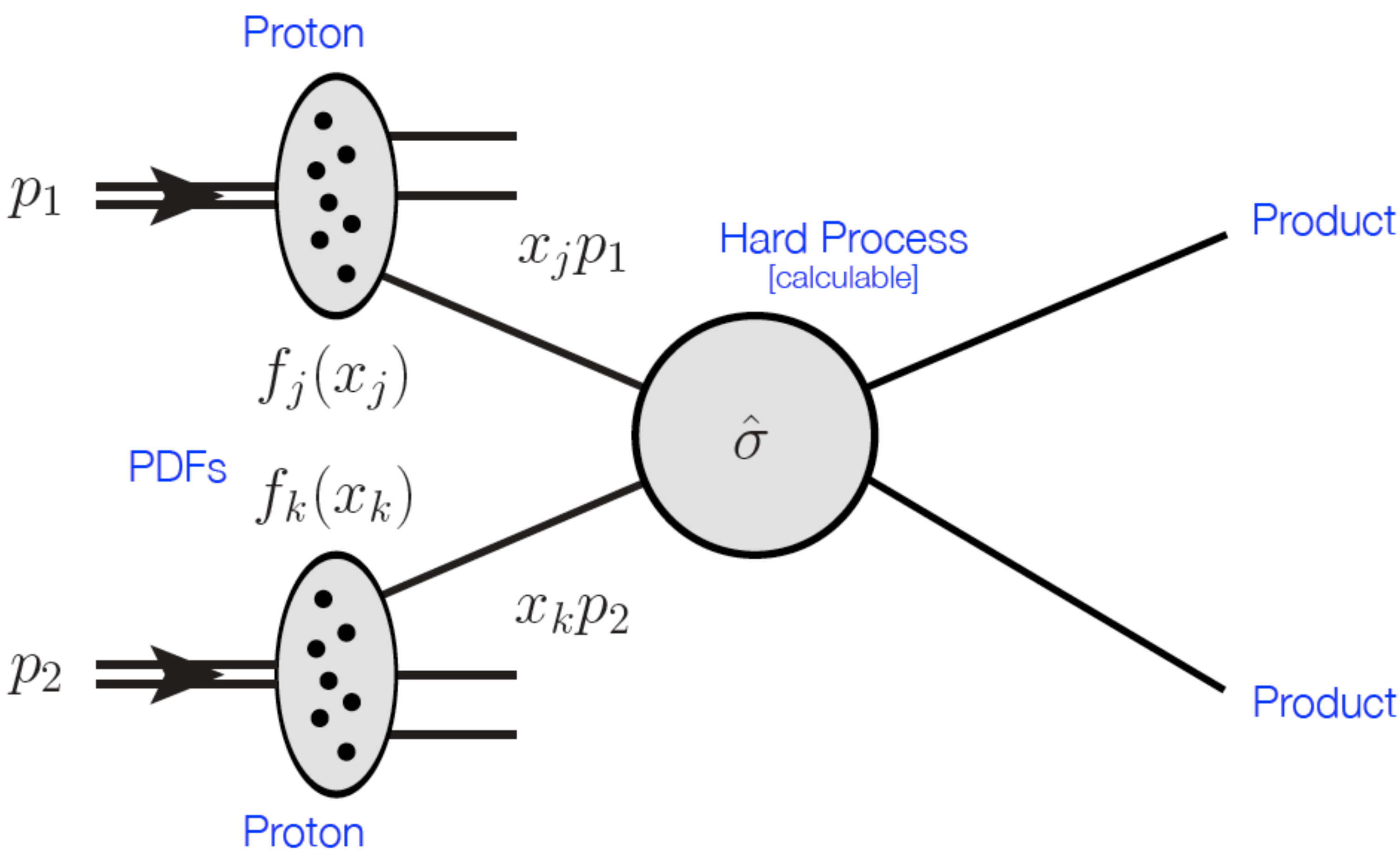
Re-discovery of the SM at the LHC



The standard model at the LHC

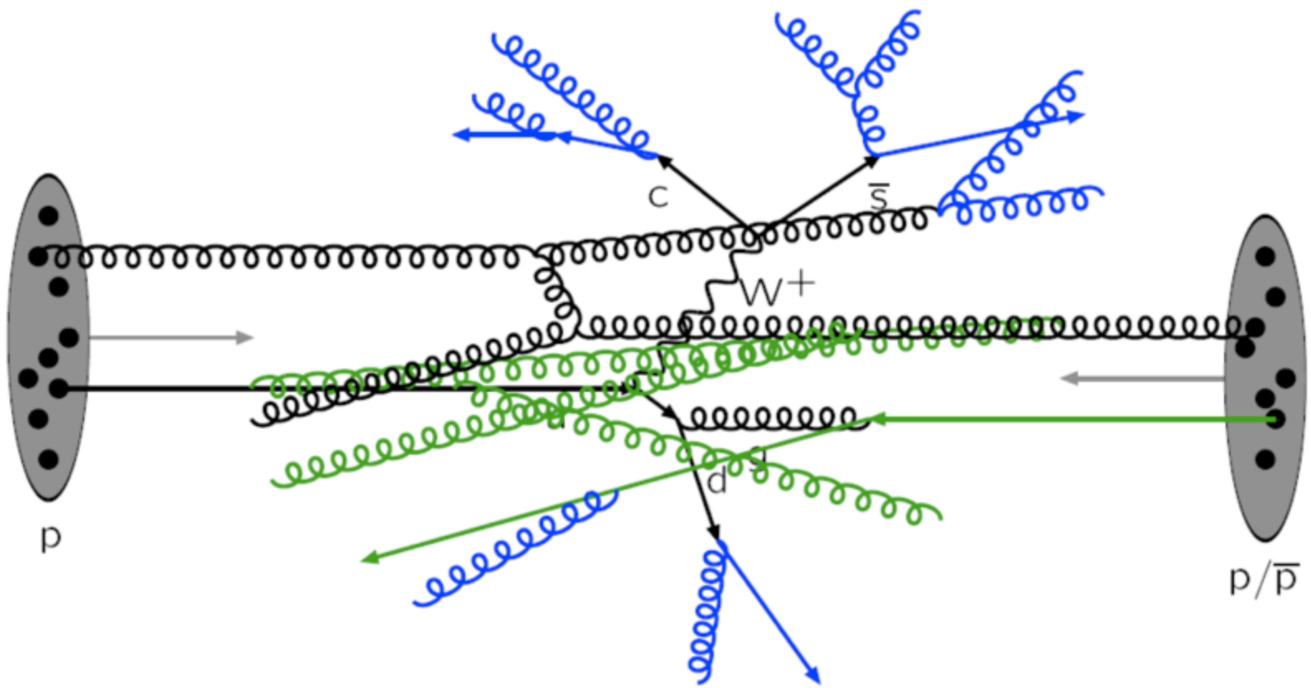
- Hadron interactions
- Monte Carlo generators
- Luminosity and cross section measurements
- Minimum bias events
- Jet physics
- W and Z physics

Hadron interactions: pp scattering



Proton-proton scattering at LHC

- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction ["underlying event"]



Cross section measurement

Number of observed events

Number of background events *(from data, calculated from theory)*

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int L dt}$$

Acceptance *(experimental: detector, efficiencies)*

Luminosity *(determined by amount of data, accelerator, triggers, etc)*

Luminosity determination

Absolute:

- From LHC parameters: van-der-Meer scans, standard candles:
  - $pp \to Z/W \to ll/l\nu$ (needs cross section)
  - $pp \to \gamma\gamma \to \mu\mu/ee$
  - Optical theorem: σ_{tot} (needs fwd det.)
  - Elastic scattering

accuracy: ~10%

accuracy: ~5-10%

accuracy: ~1%?

accuracy: ~2-3%

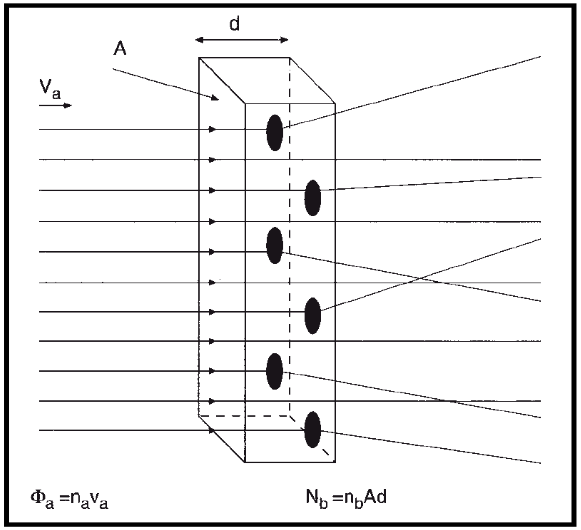
accuracy: ~2-3%

Relative:

- Particle counting (i.e. Cherenkov counters): needs calibration to absolute luminosity

Goal: accuracy of 2-3%

Cross section and Luminosity



$$\Phi_a = \frac{\dot{N}_a}{A} = n_a v_a$$

Φ_a : flux
n_a : density of particle beam
v_a : velocity of beam particles

$$\dot{N} = \Phi_a \cdot N_b \cdot \sigma_b$$

$\dot{N}$: reaction rate
N_b : target particles within beam area
σ_a : effective area of single scattering center

$$L = \Phi_a \cdot N_b$$

L : luminosity

$$\dot{N} \equiv L \cdot \sigma$$

$$N = \sigma \cdot \underbrace{\int L\, dt}_{\text{integrated luminosity}} \qquad \sigma = N/L$$

Collider experiment:

$$\Phi_a = \frac{\dot{N}_a}{A} = \frac{N_a \cdot n \cdot v/U}{A} = \frac{N_a \cdot n \cdot f}{A}$$

$$L = f \frac{n N_a N_b}{A} = f \frac{n N_a N_b}{4\pi\sigma_x\sigma_y}$$

LHC:

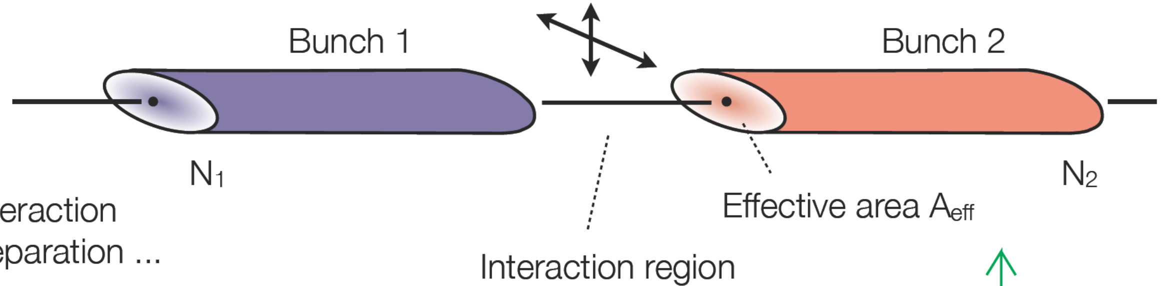
N_x	~	10^{11}
A	~	.0005 mm^2
n	~	2800
f	~	11 kHz
L	~	10^{34} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

N_a : number of particles per bunch (beam A)
N_b : number of particles per bunch (beam B)
U : circumference of ring
n : number of bunches per beam
v : velocity of beam particles
f : revolution frequency
A : beam cross-section
σ_x : standard deviation of beam profile in x
σ_y : standard deviation of beam profile in y

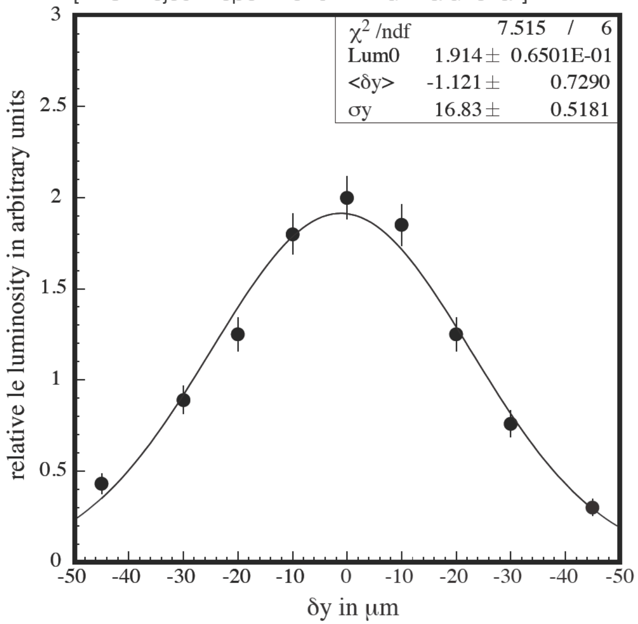
Van-der-Meer separation scan

Determine beam size ...

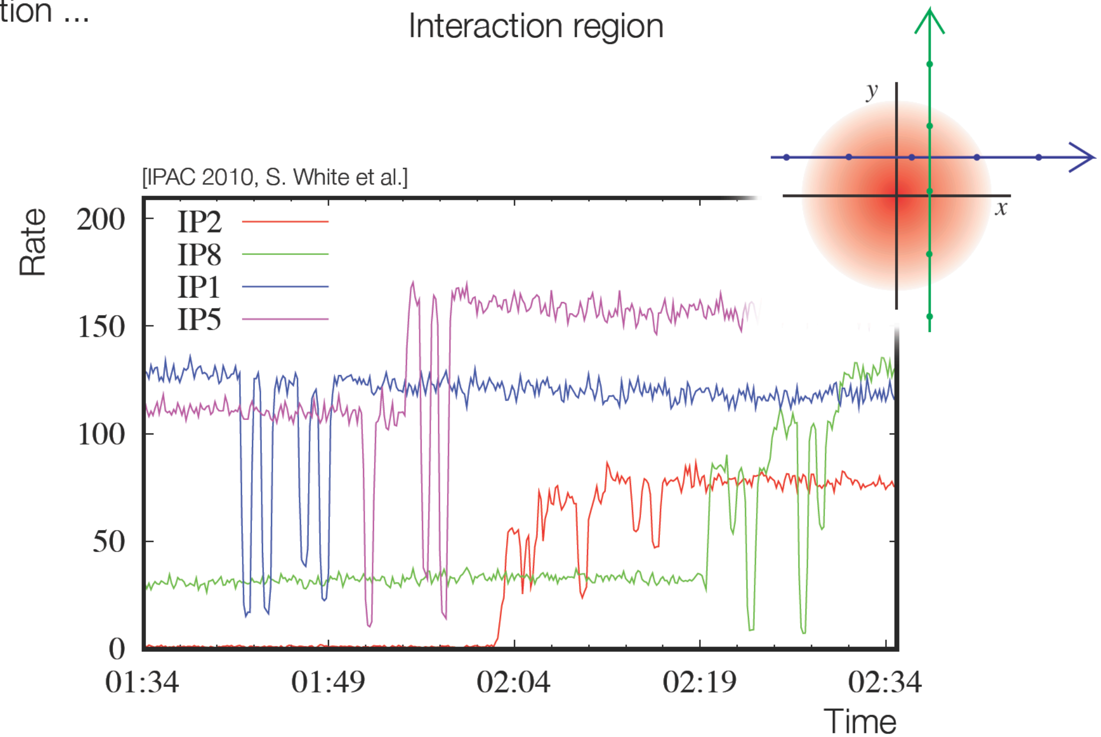
measuring size and shape of the interaction region by recording relative interaction rates as a function of transverse beam separation ...



[LHC Project Report 1019: H. Burkhardt et al.]



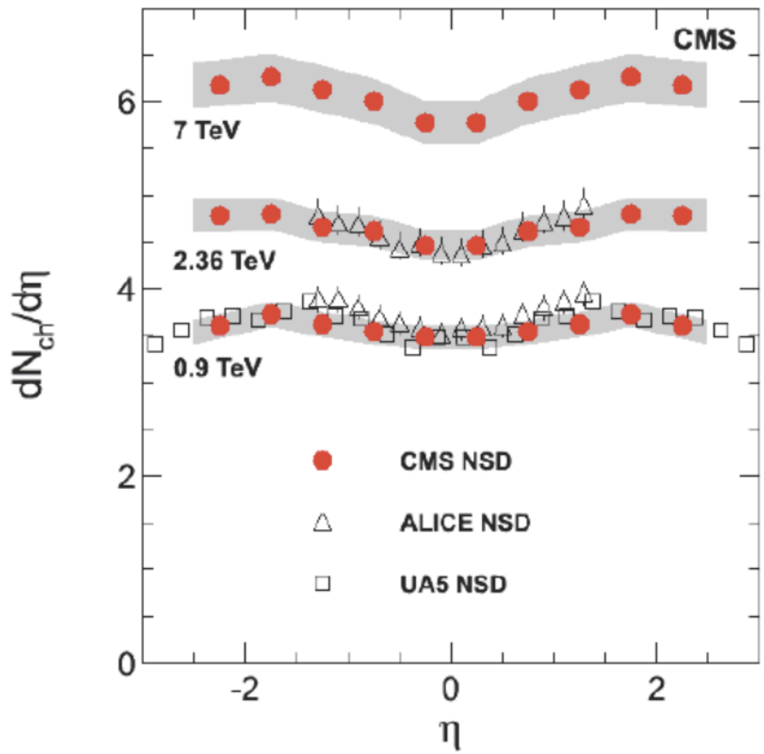
$$\frac{L}{L_0} = \exp\left[-\left(\frac{\delta_x}{2\sigma_x}\right)^2 - \left(\frac{\delta_y}{2\sigma_y}\right)^2\right]$$

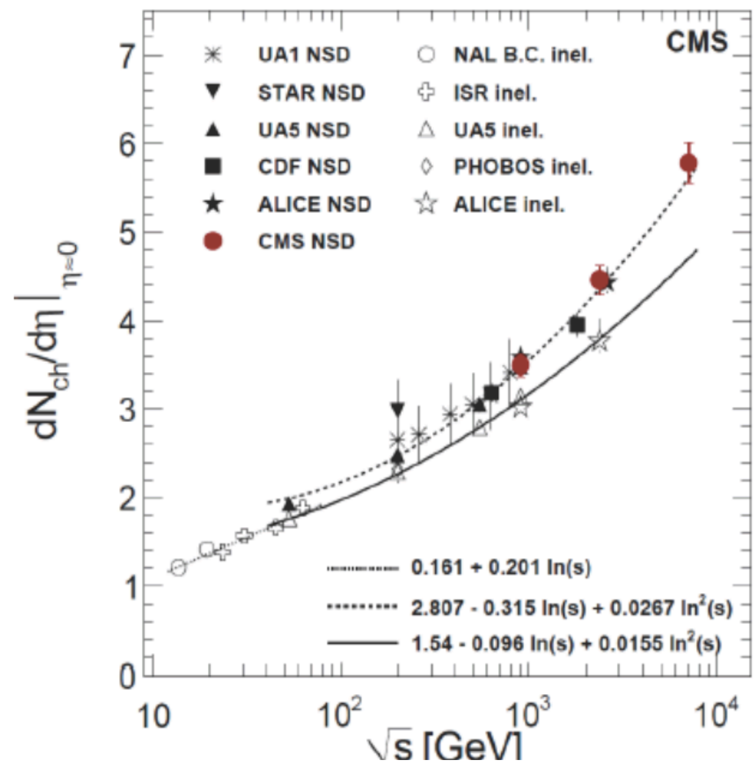


First optimization scans at LHC performed for squeezed optics in all IPs [November 2009].

Minimum bias events

- Particle density in minimum bias events
- Soft QCD (p_T threshold on tracks: 50 MeV)

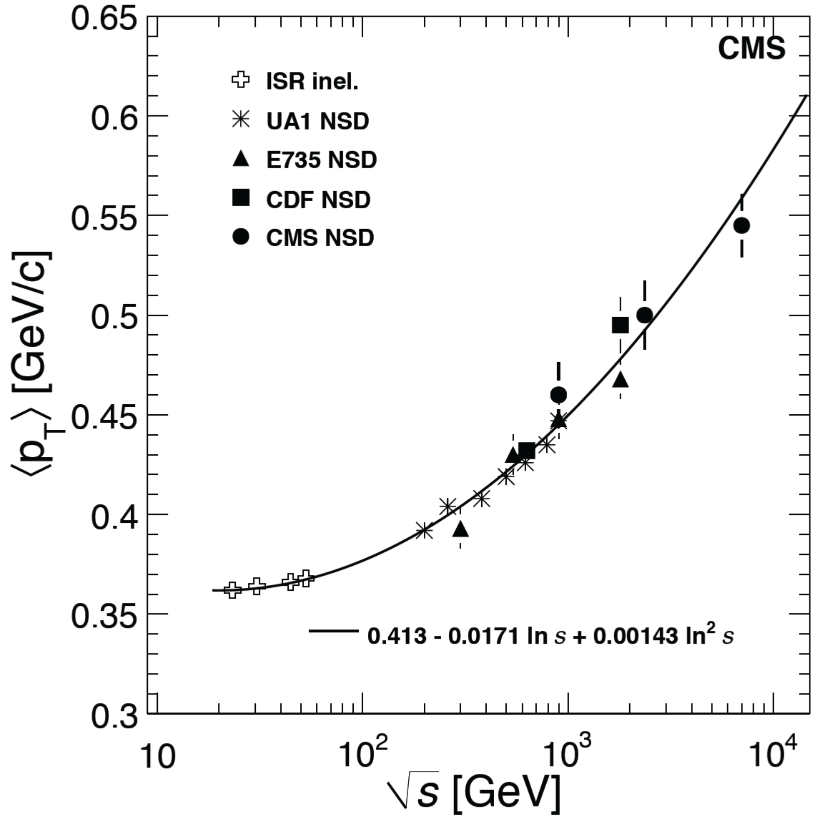




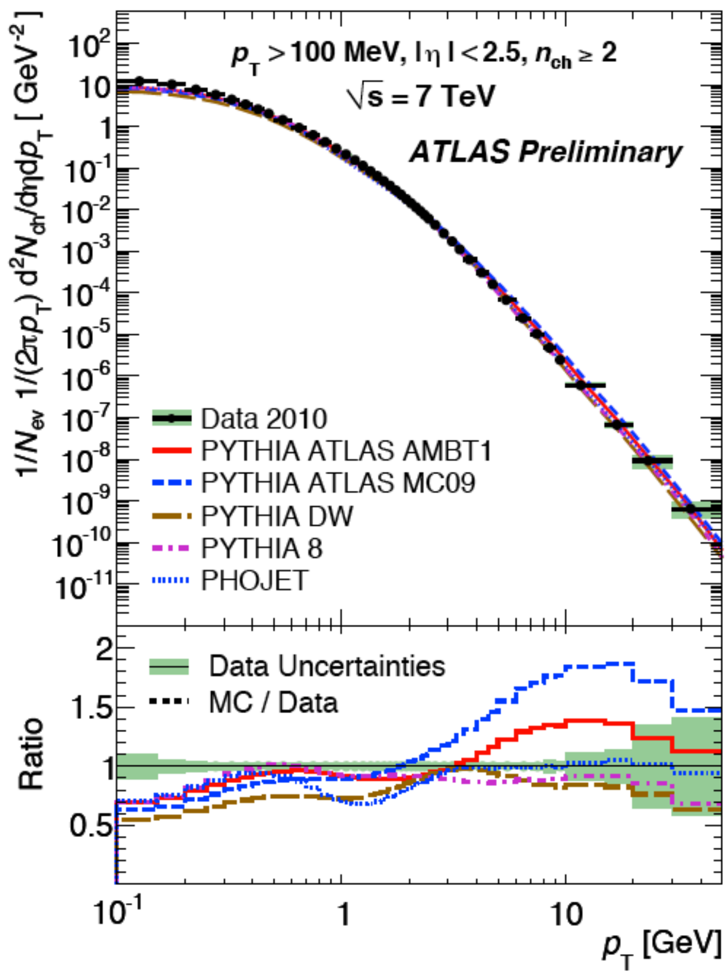
Tuning of MC generators needed

Charged particle p_T spectrum

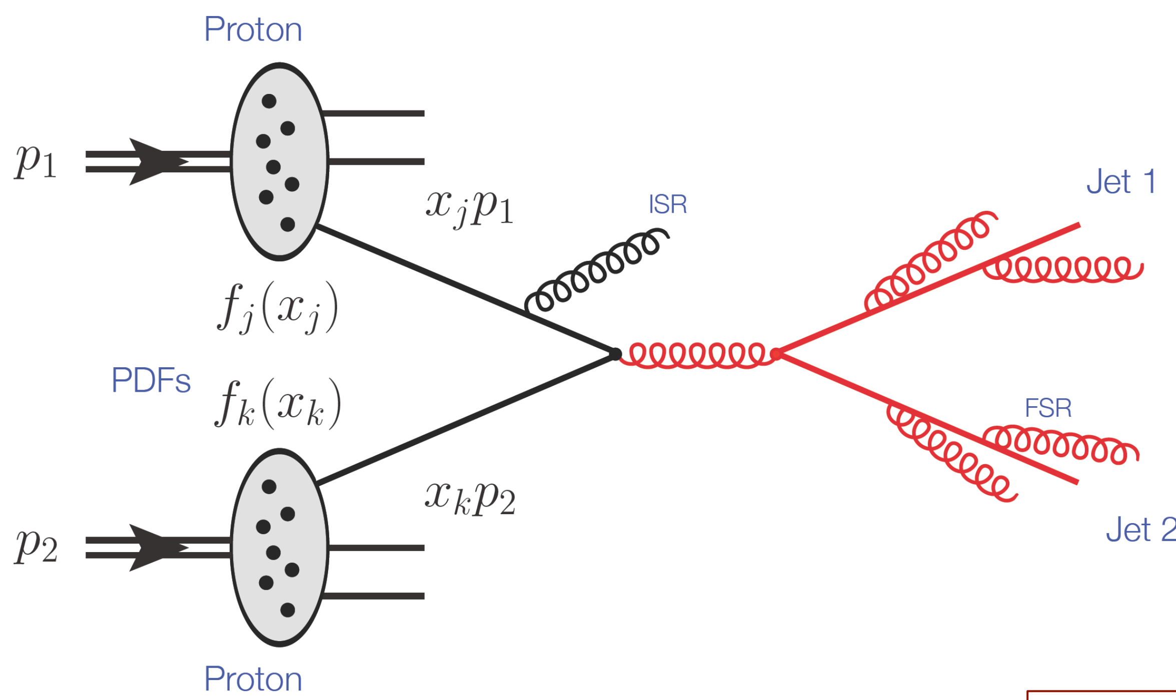
$<p_T>=0.545\pm0.005(\text{stat.})\pm 0.015 (\text{syst.})$ GeV

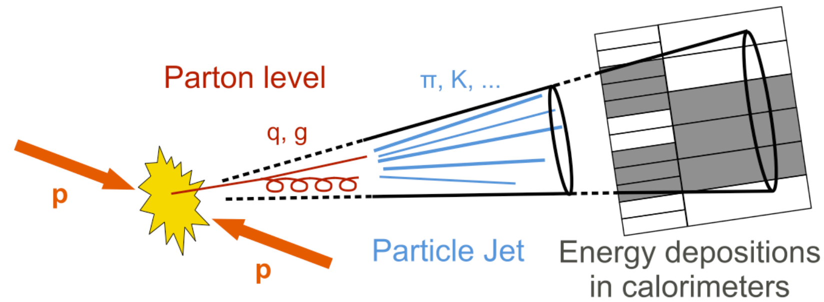


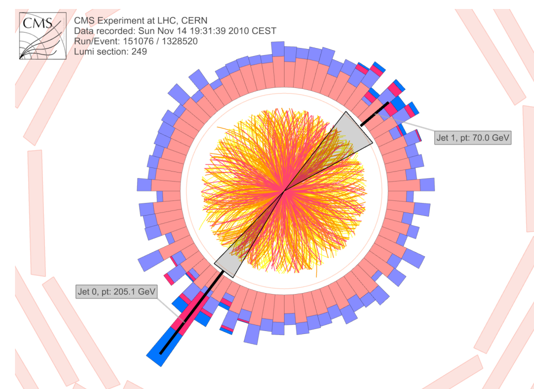
dN_{ch}/dp_T



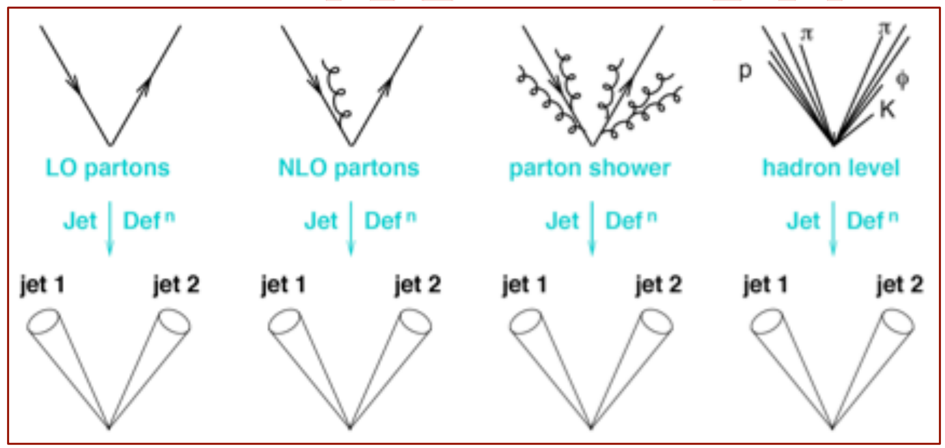
Jet production at LHC





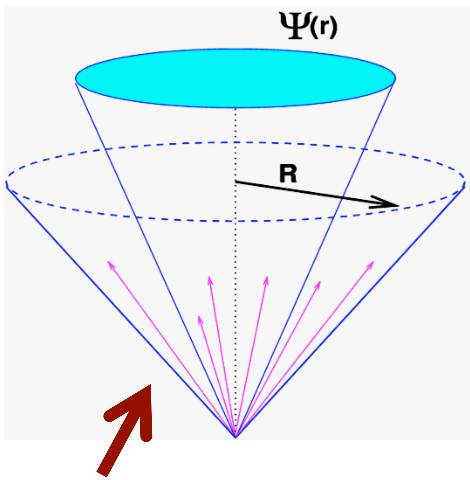


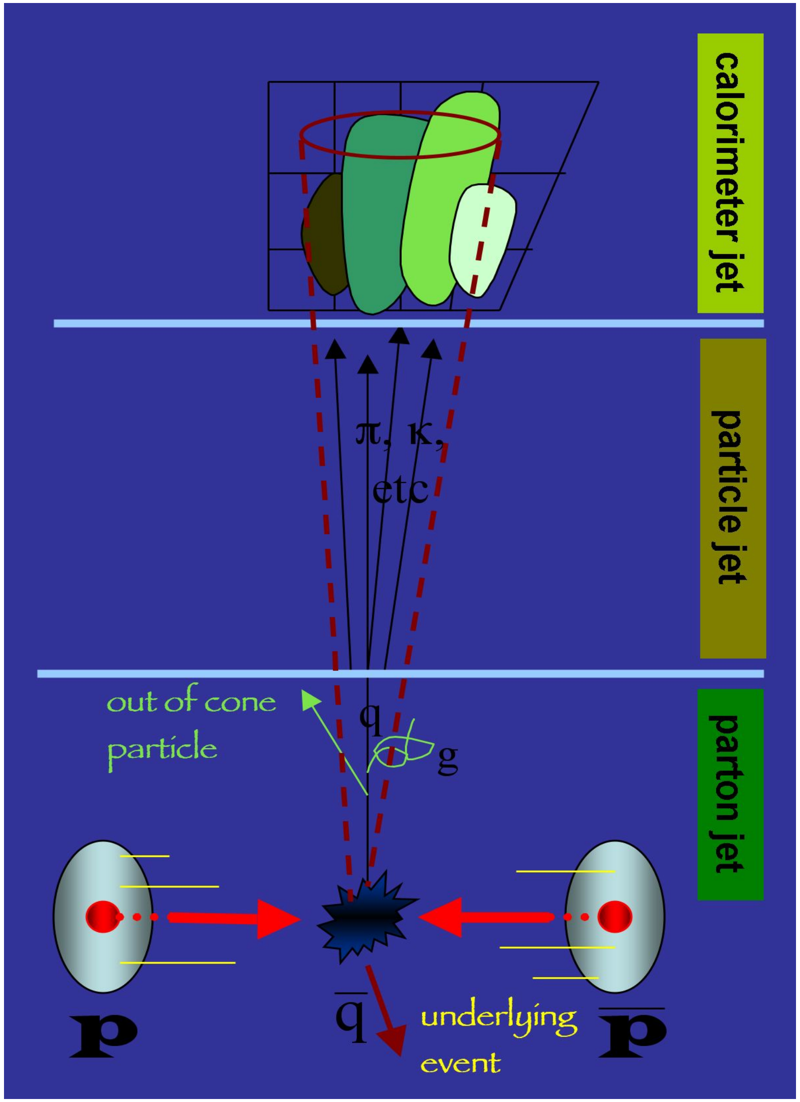
Available up to NLO, first NNLO calculations becoming available



Jet production at LHC (cont.)

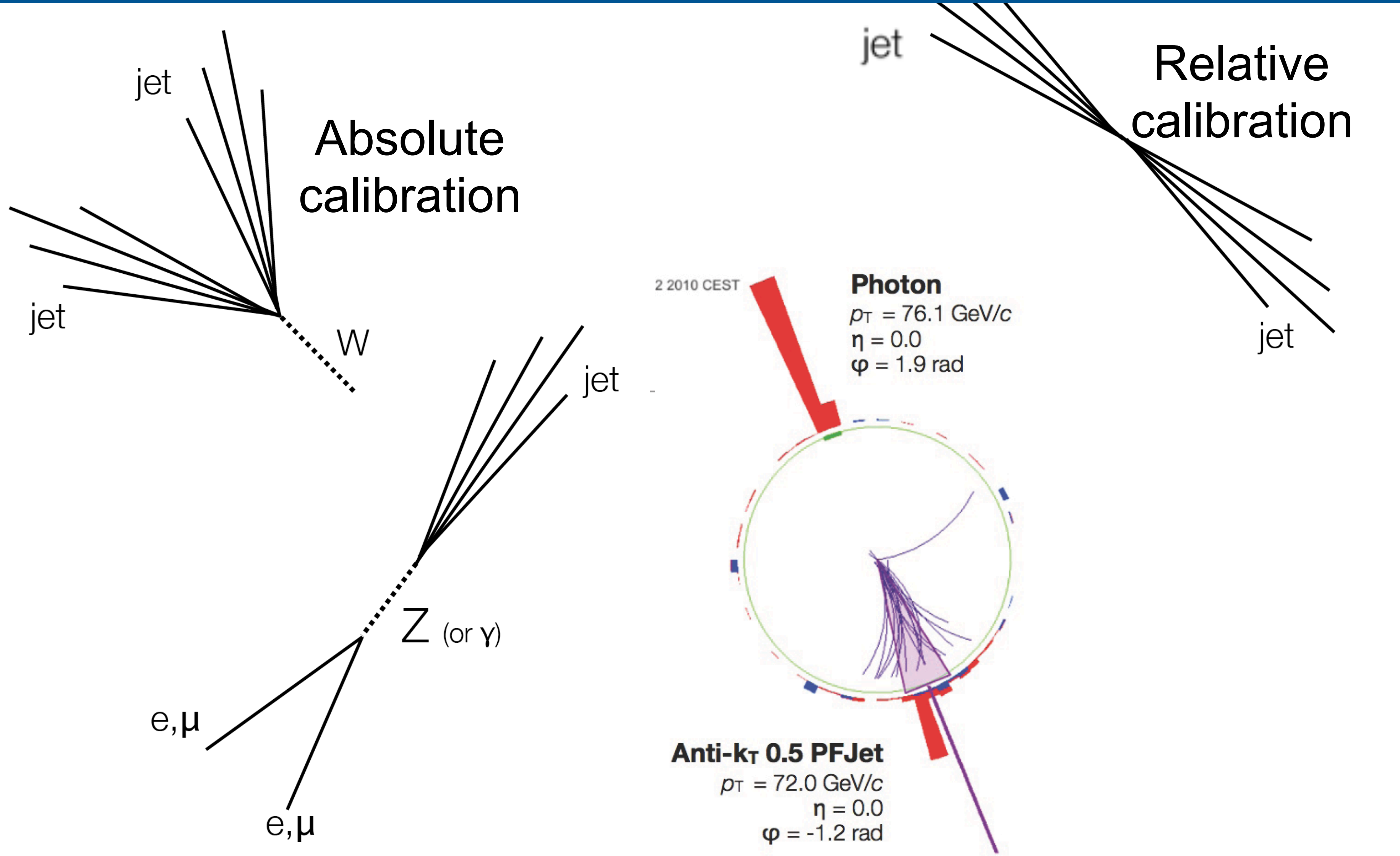
- Processes creating jets are complicated
  - Parton fragmentation, with electromagnetic or hadronic showering in the detector
- Jet reconstruction is difficult
- Jet energy scale and reconstruction is large source of uncertainty





- Measure energy in a “cone”

Jet energy calibration



Inclusive jet distribution

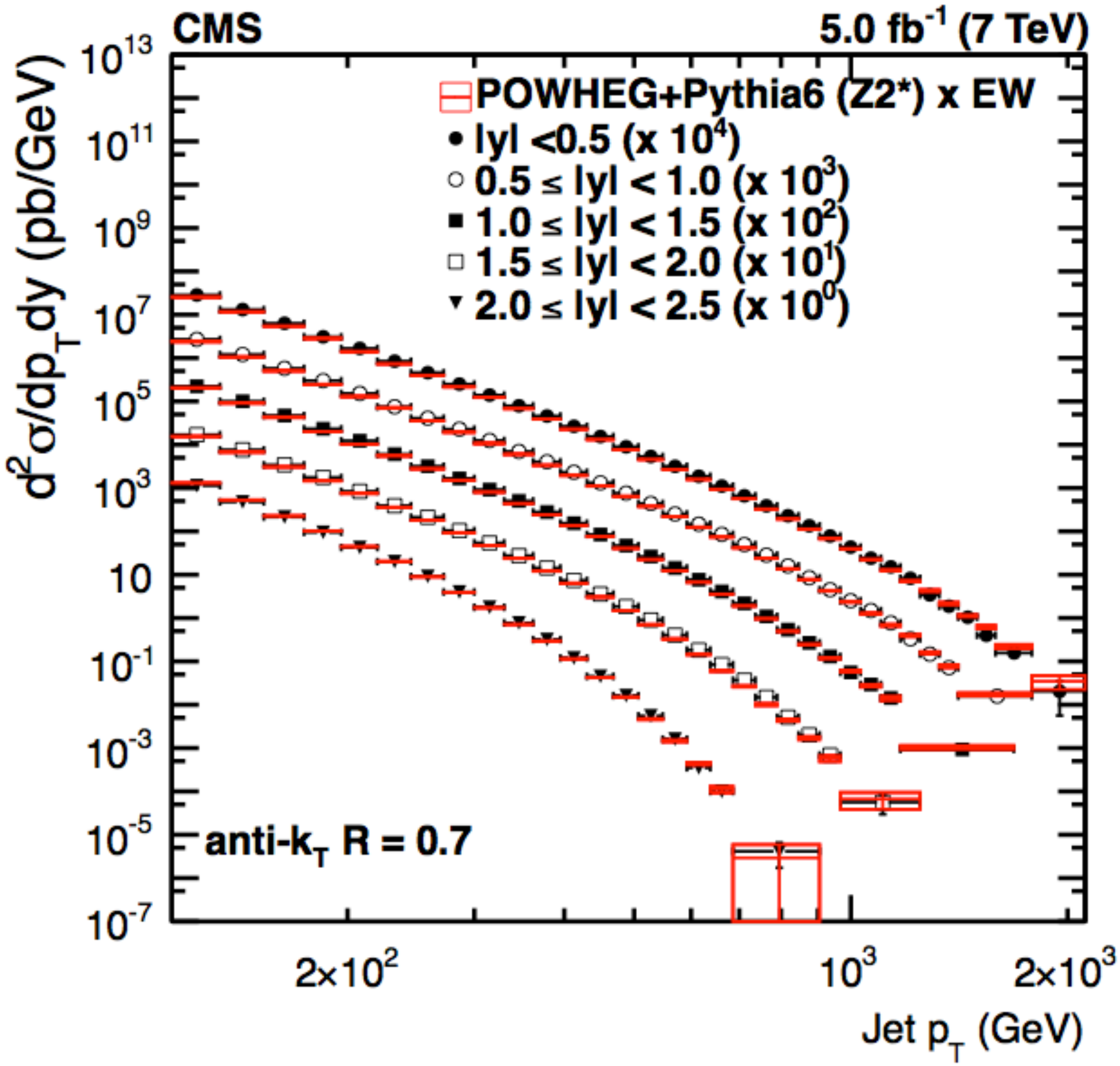
arXiv:1106.0208, arXiv:1410.6765

Cross section is huge (~Tevatron x 100)

Very good agreement with NLO QCD over nine orders of magnitude

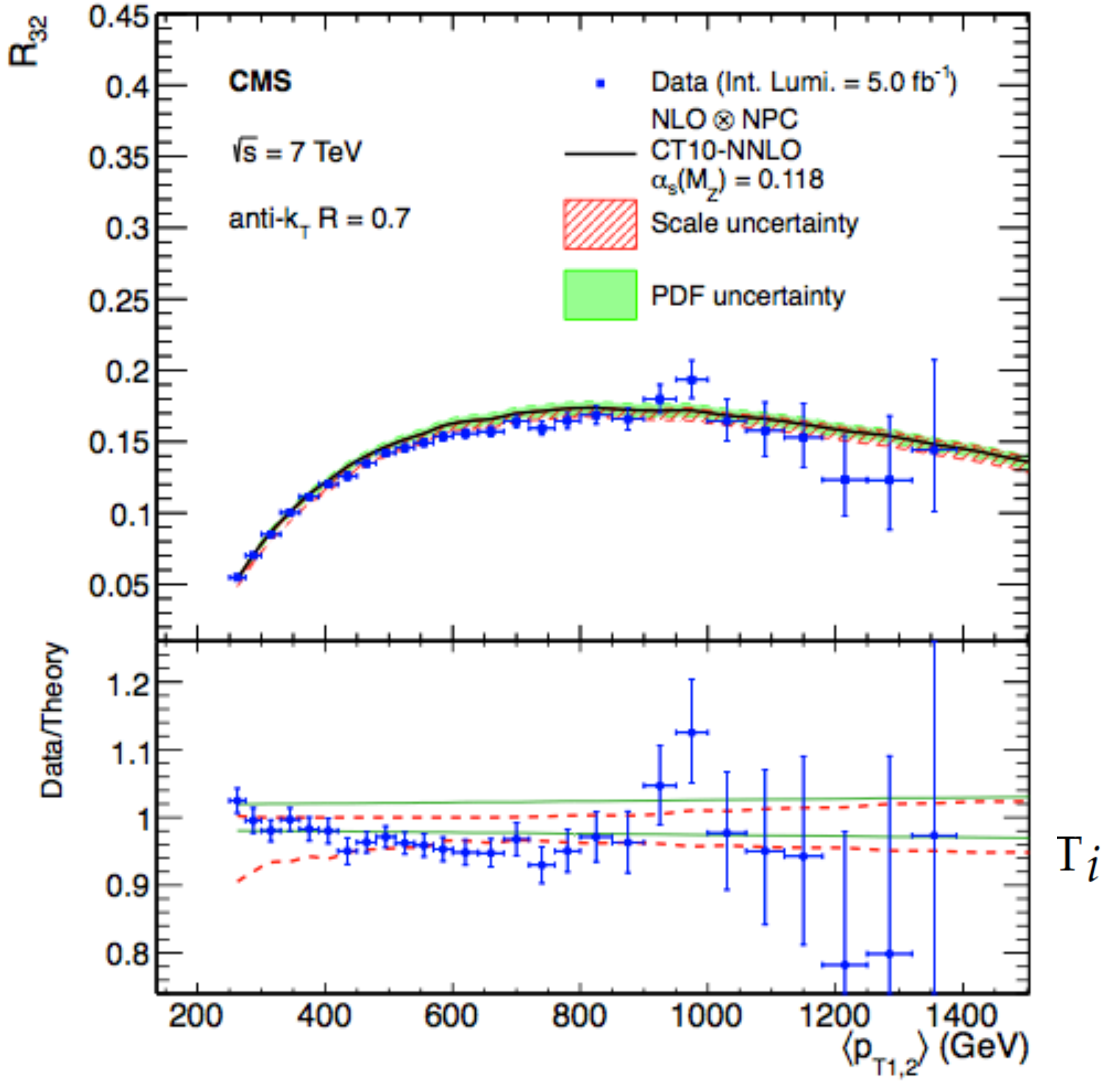
P_T extending from 20 to 2000 GeV

Main uncertainty:
- Jet Energy Scale (3-4%)



Inclusive cross section: 3-to-2 jet ratio

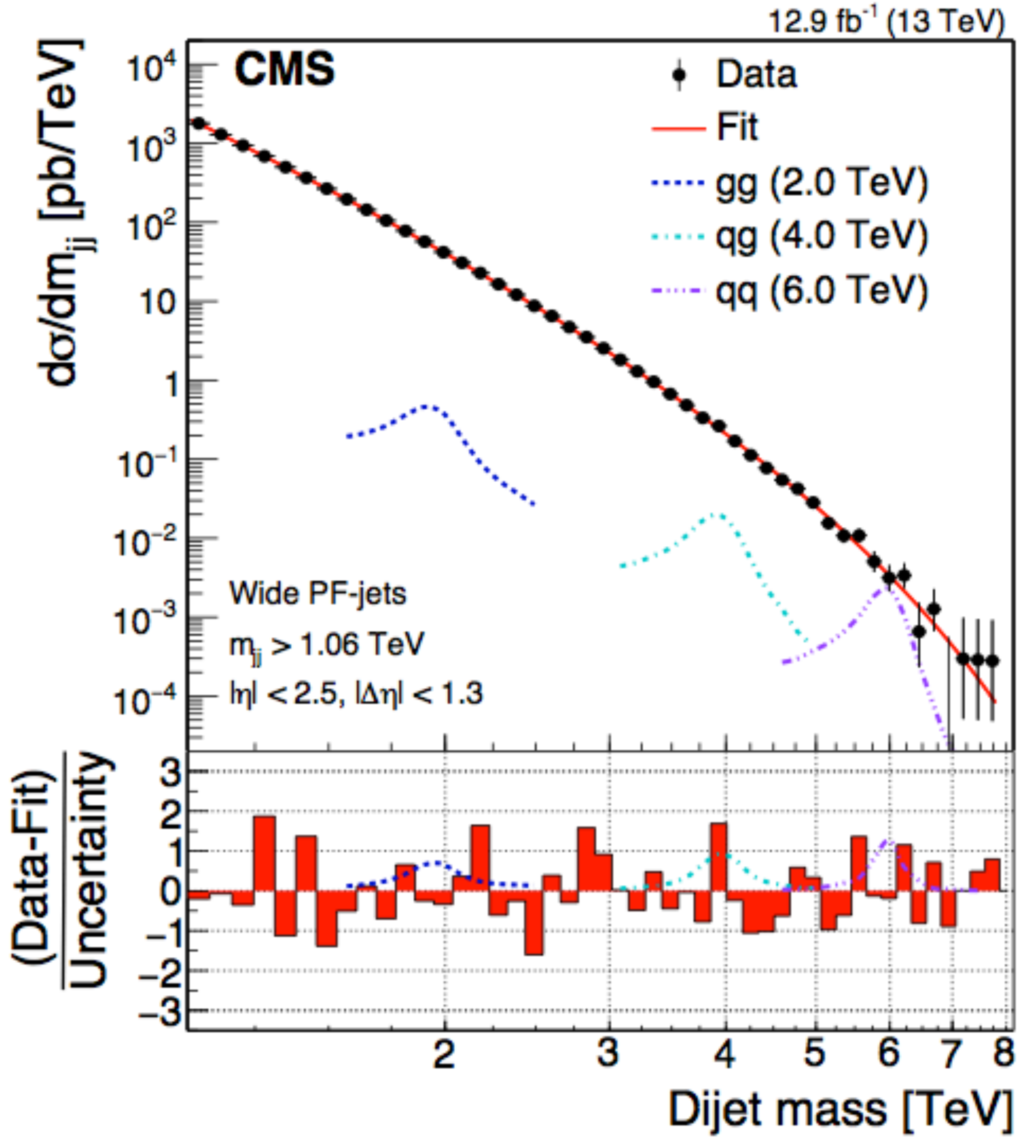
arXiv:1304.7498



Dijet mass

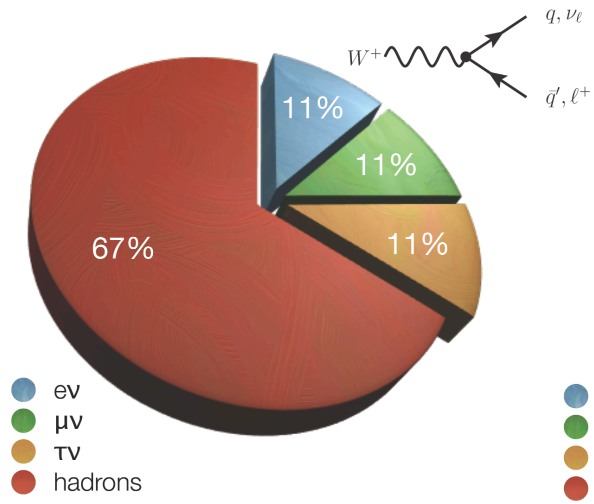
arXiv:1611.03568

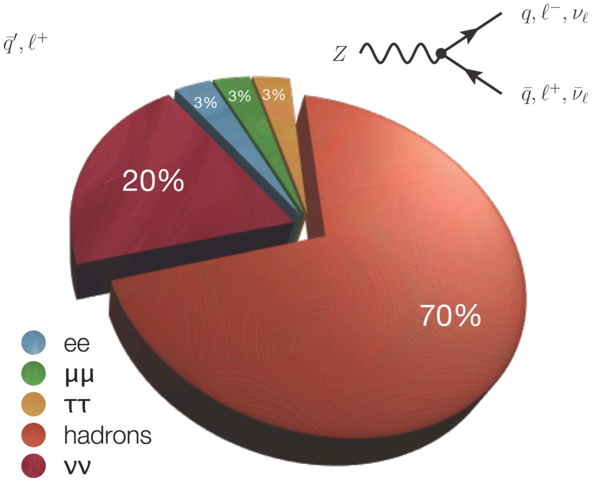
Very early search for numerous BSM resonance searches:
string resonance, excited quarks, axi-gluons, colorons, E6 diquarks, W' and Z', RS gravitons, DM

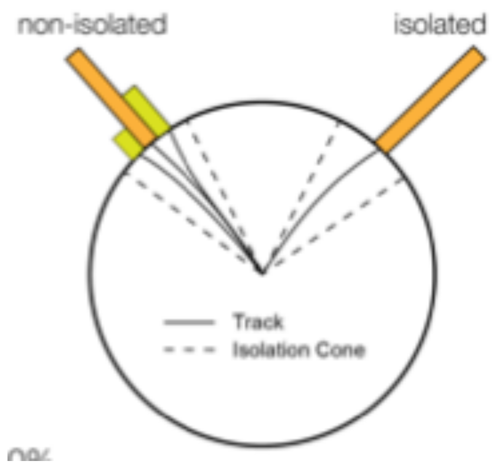


W and Z bosons

- Leptonic decays (e/μ): very clean, small branching fractions
- Hadronic decays: two-jet final state, large QCD background

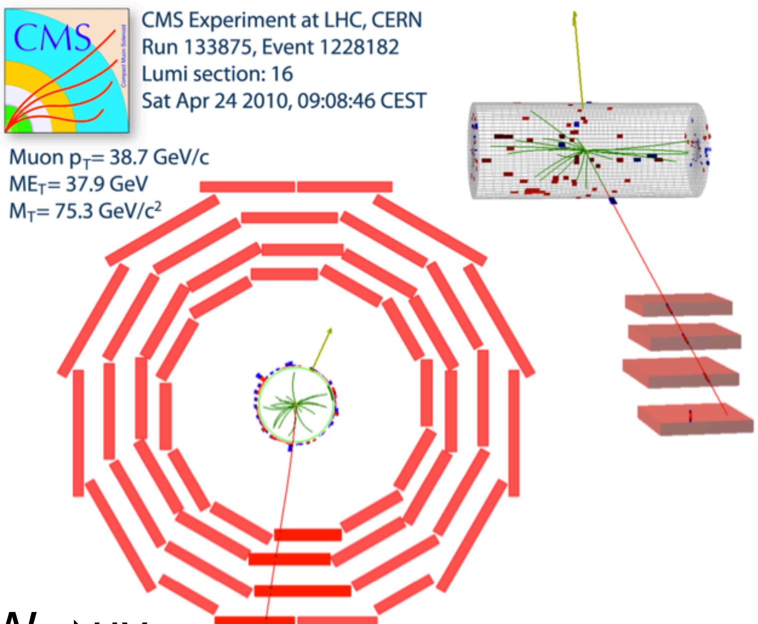




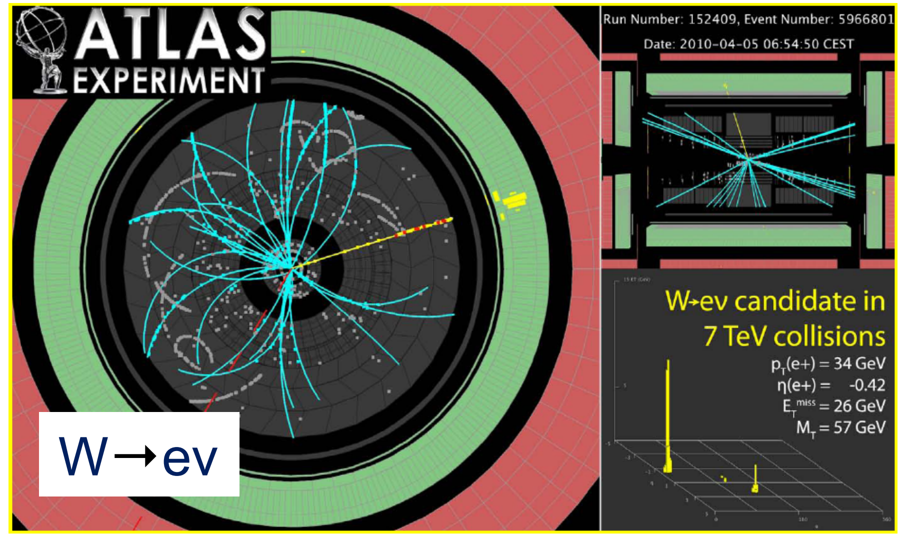


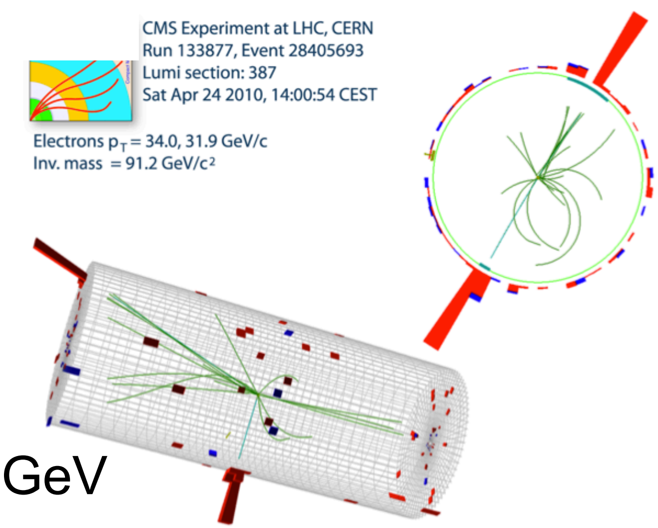
- Isolated high-p_T leptons: starting point of many analyses
  - Good rejection of QCD backgrounds
  - Jets reconstructed as "leptons": fakes
  - "Tracking" vs "calorimeter" isolation

W and Z bosons (cont.)



W→μν



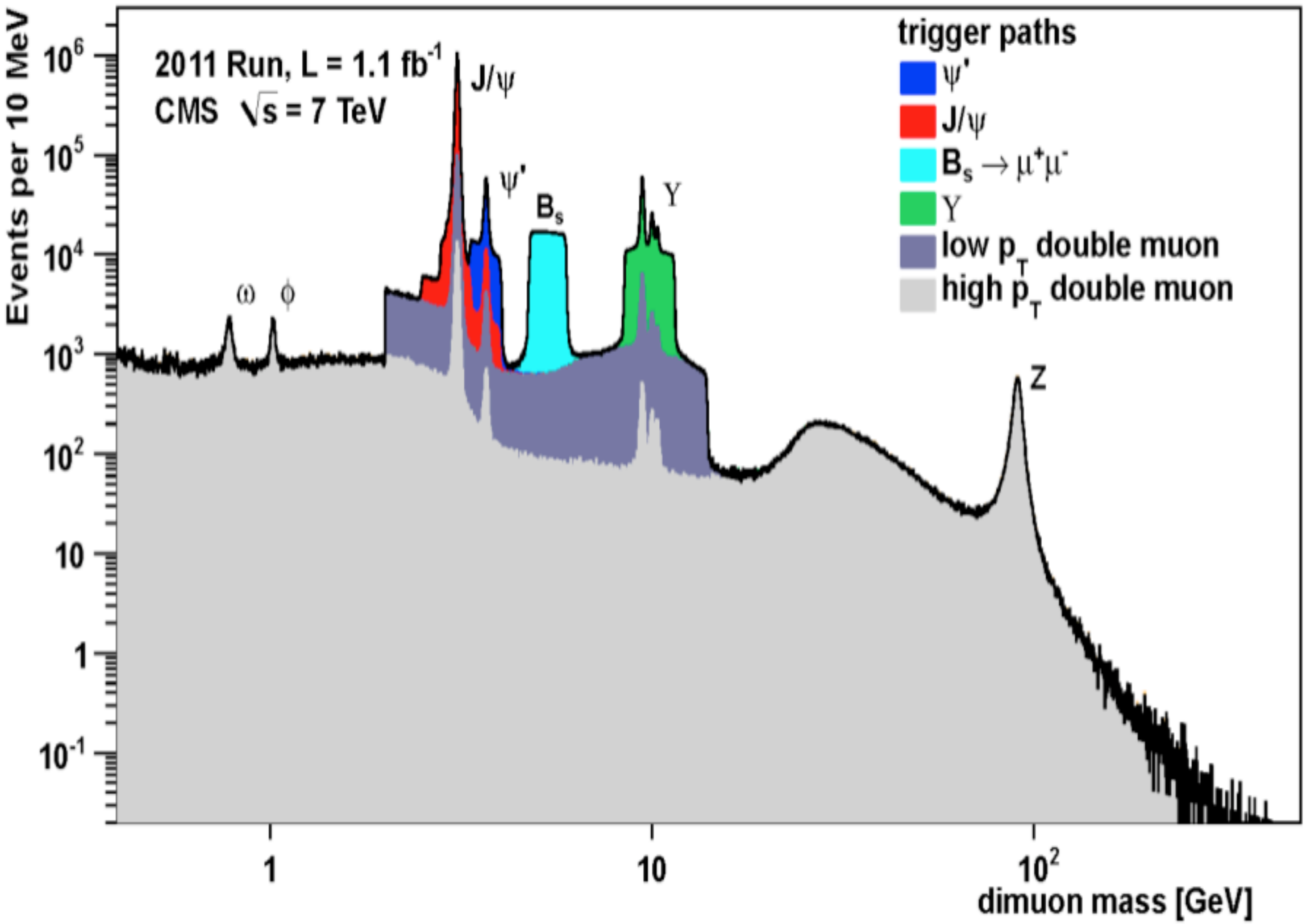


Z→ee:

Mass= 91.2 GeV

Di-muon mass spectrum

arXiv:1206.4071



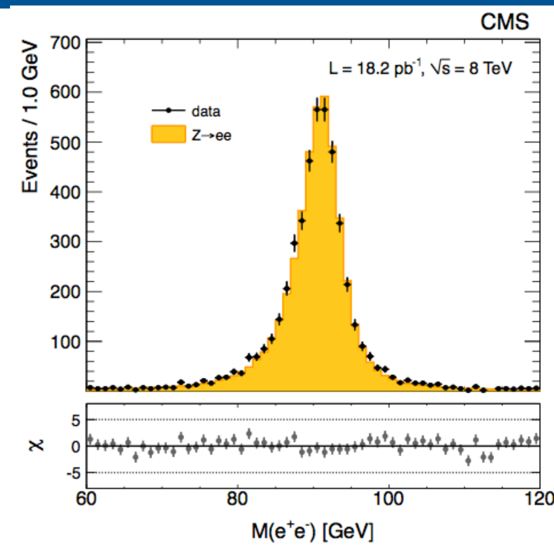
W/Z production

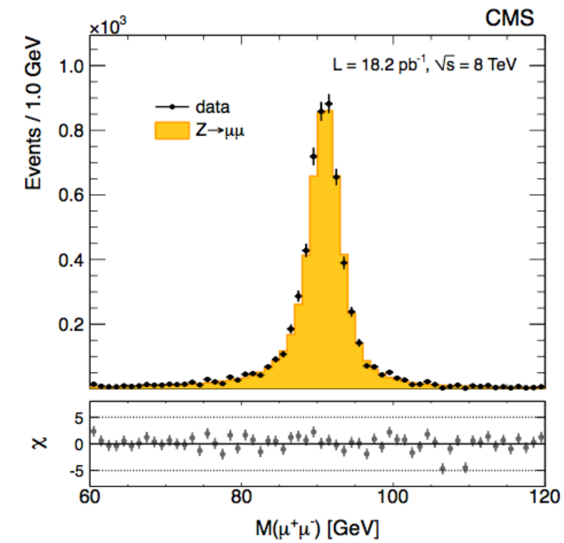
arXiv:1402.0923, arXiv:1510.07488

- Select isolated electrons and muons

- W: investigate transverse mass m_T
- Z: dilepton invariant mass

Z boson

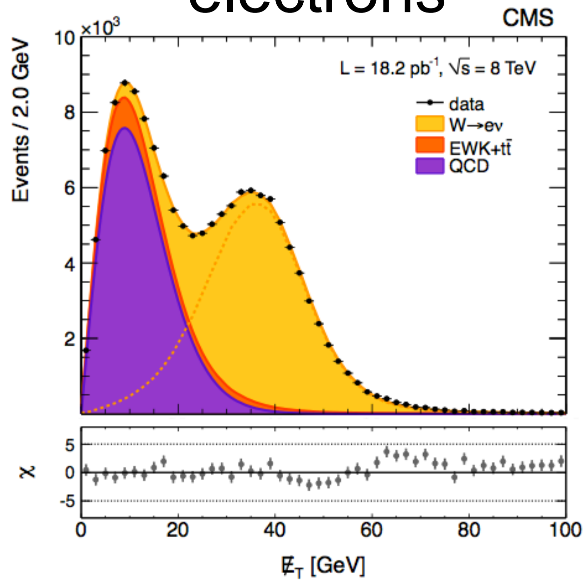


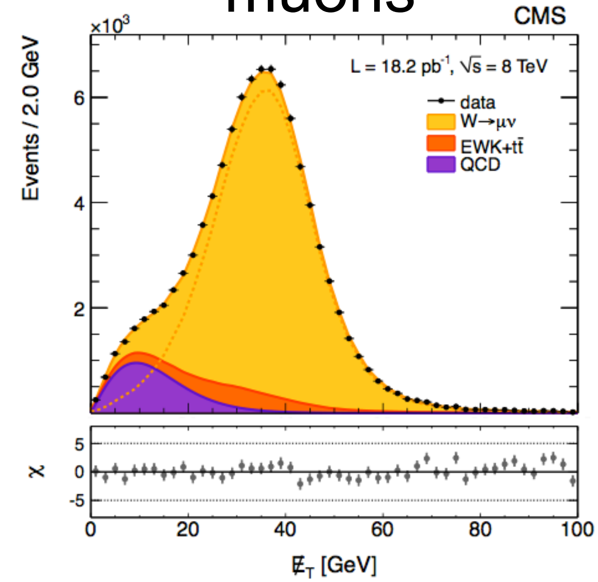


electrons

muons

W boson



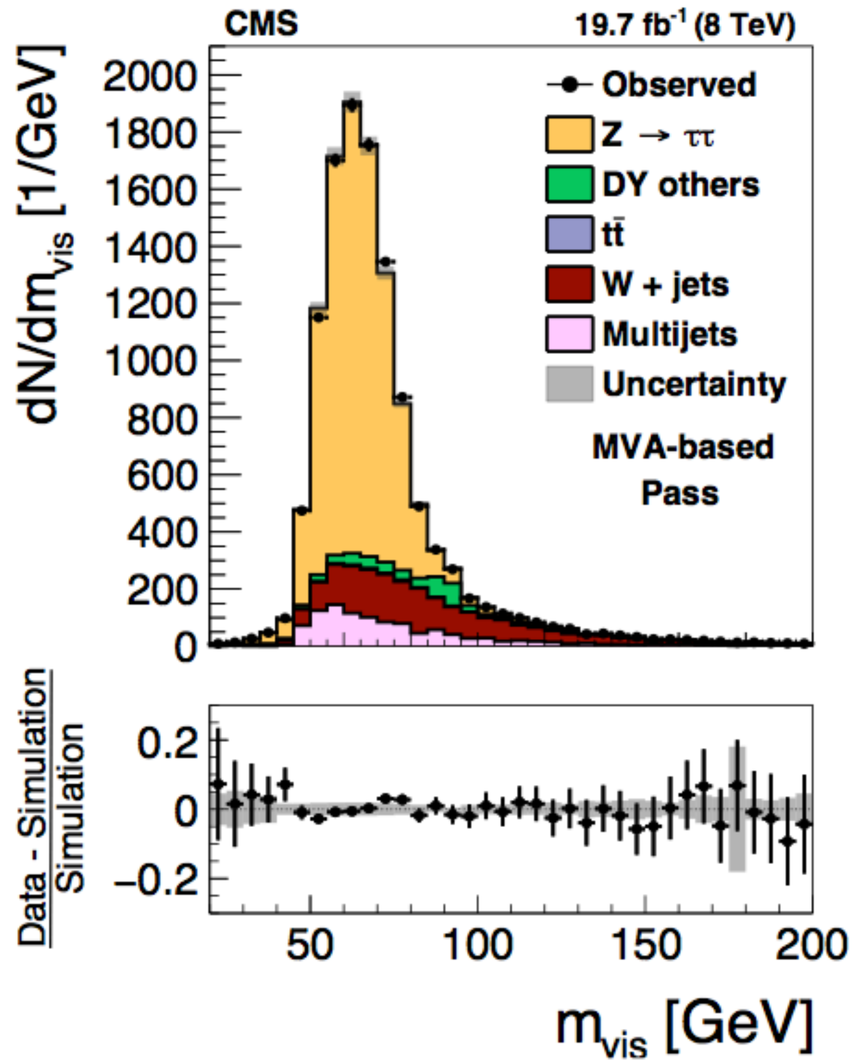


W/Z production (cont.)

arXiv:1402.0923, arXiv:1510.07488

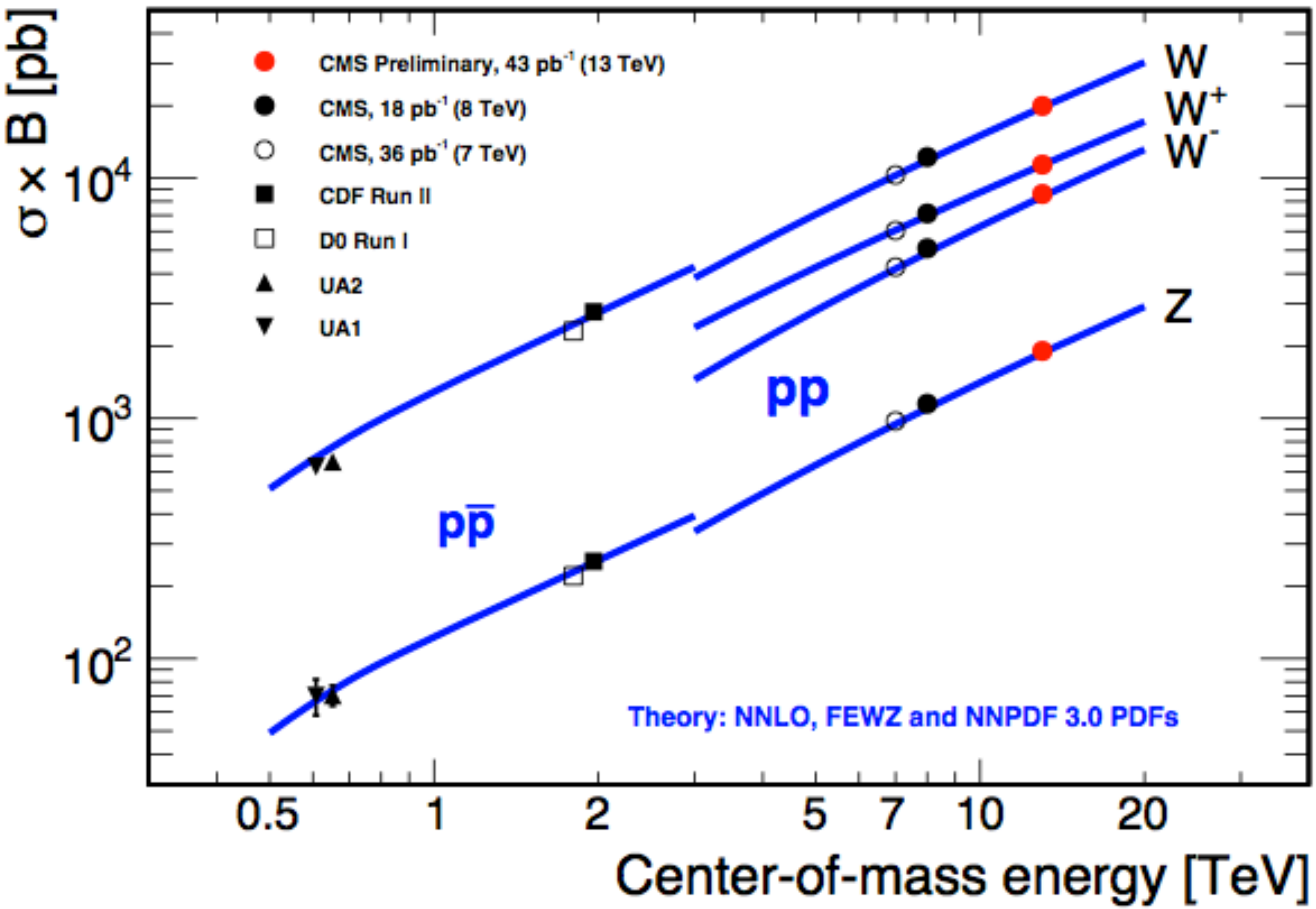
- Select isolated electrons and muons, and taus

- W: investigate transverse mass m_T
- Z: dilepton invariant mass



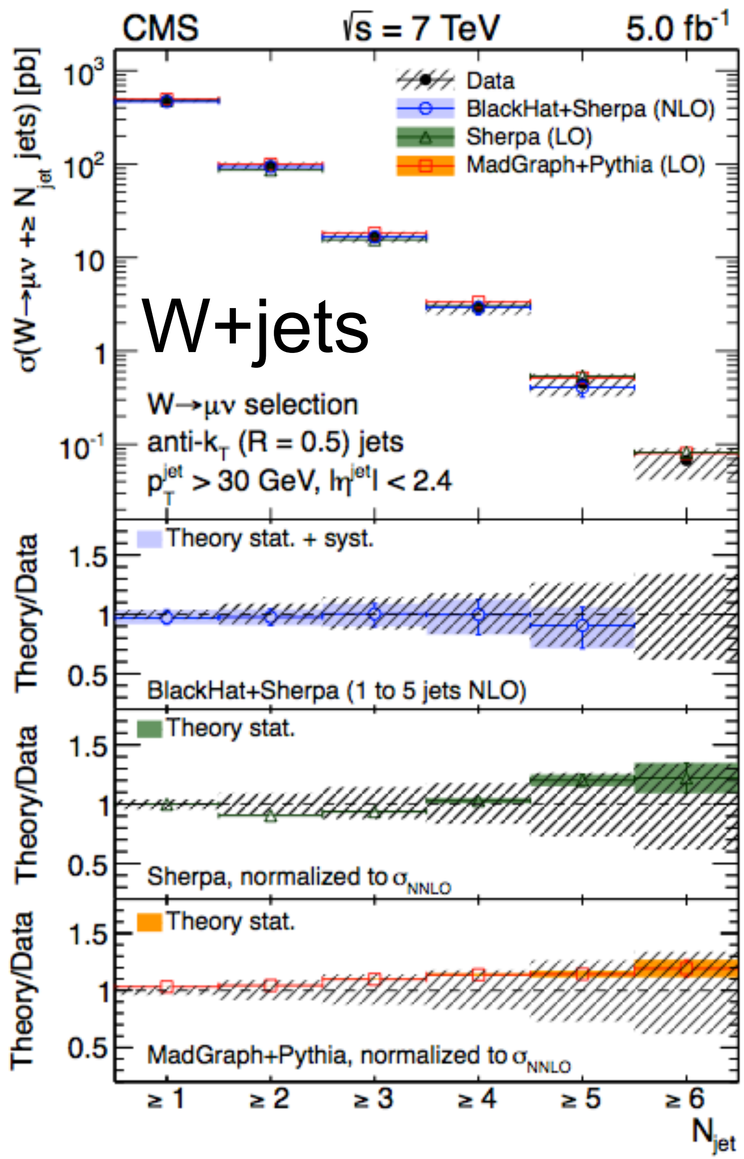
W/Z cross section vs √s

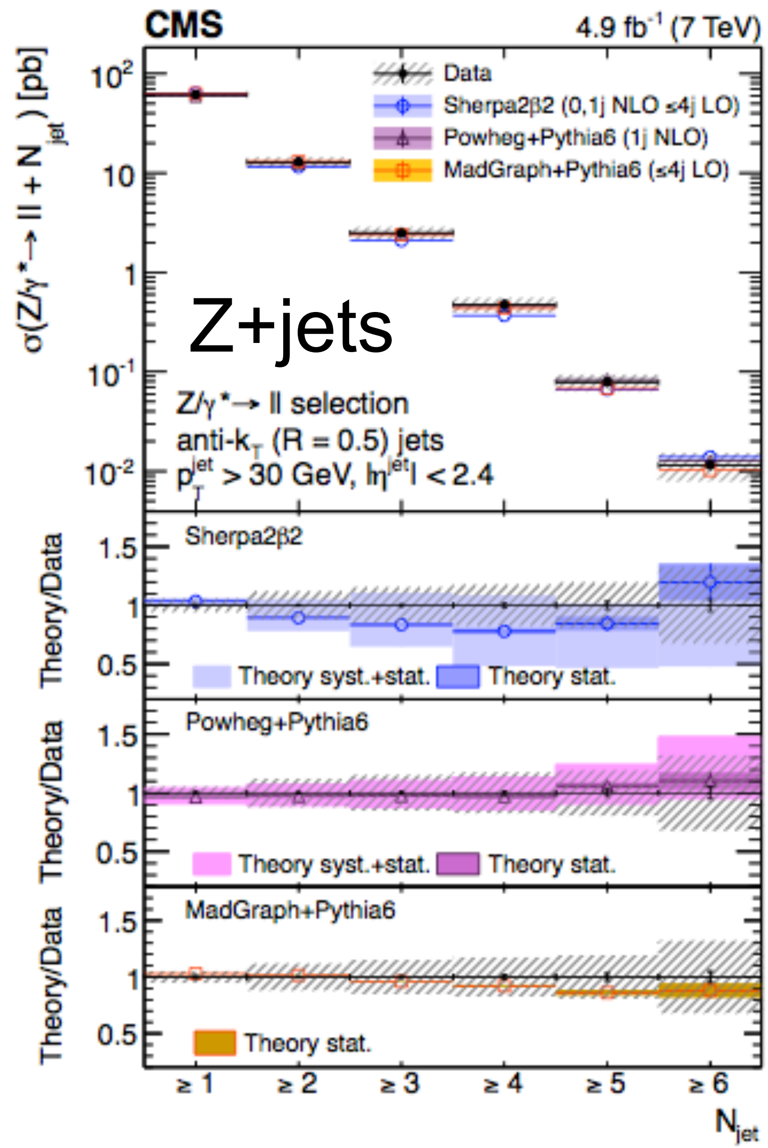
arXiv:1012.2466, CMS-SMP-15-004



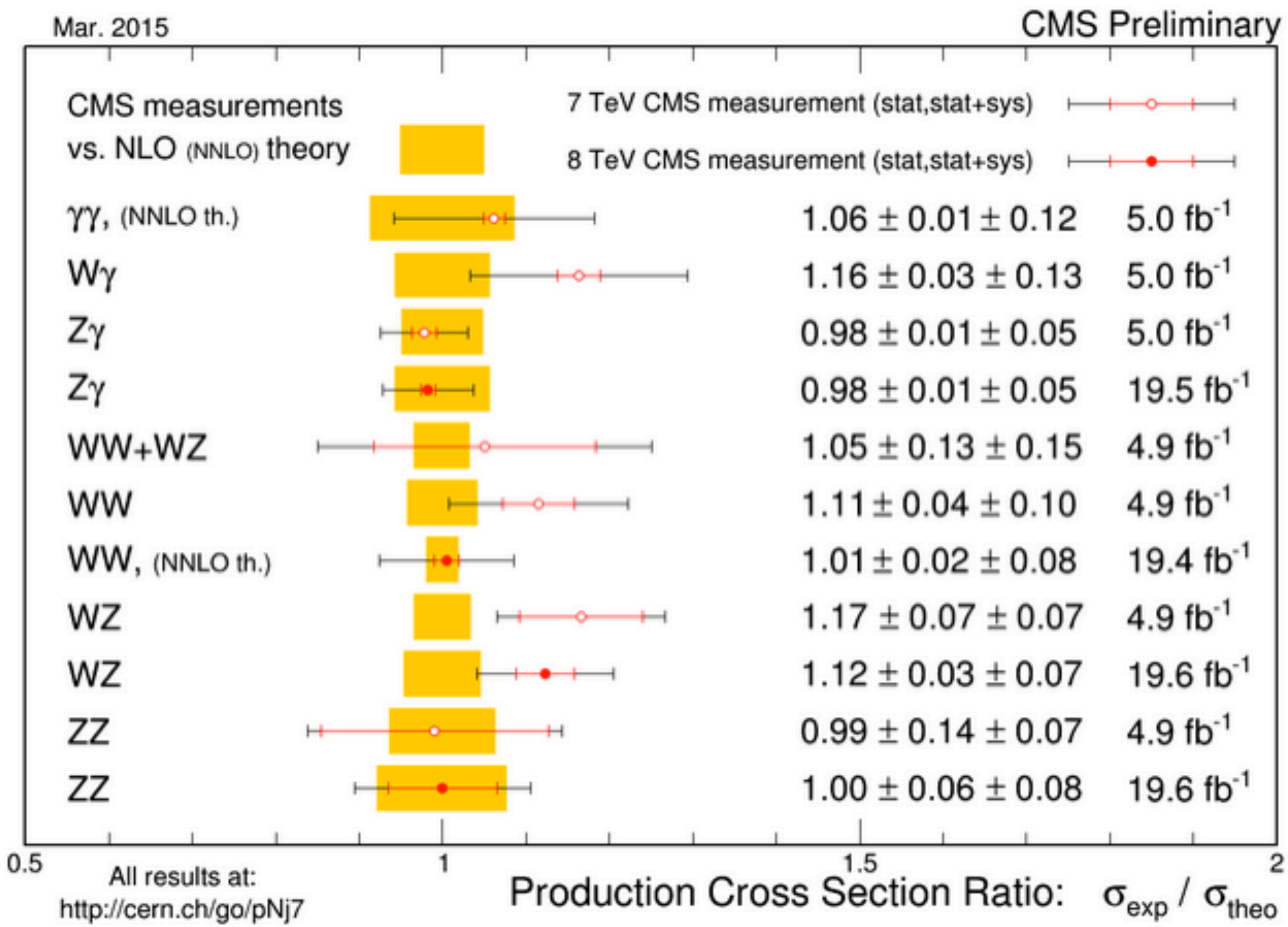
W/Z+jets

arXiv:1406.7533, arXiv:1408.3104



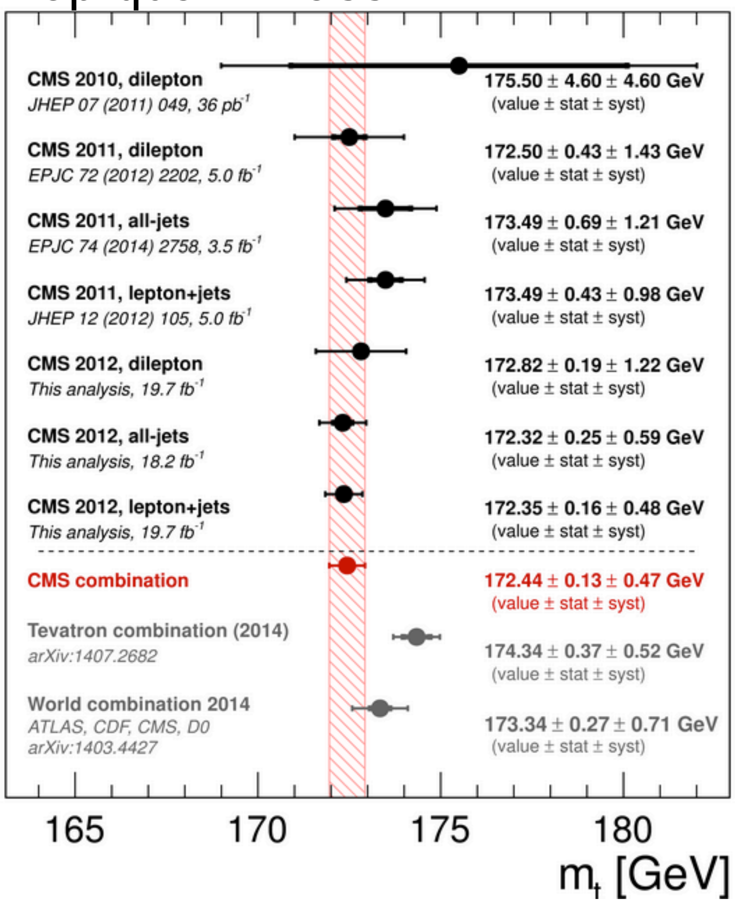


Diboson cross section measurements

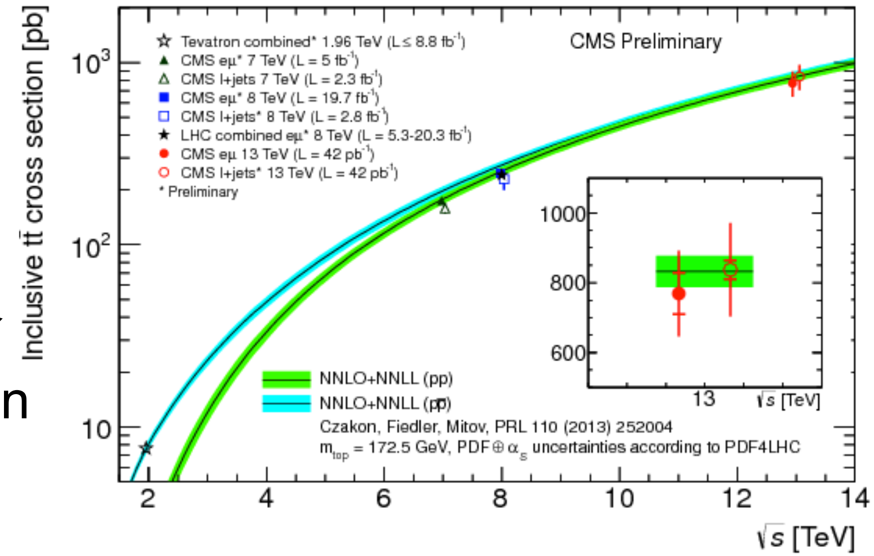


Top quark physics

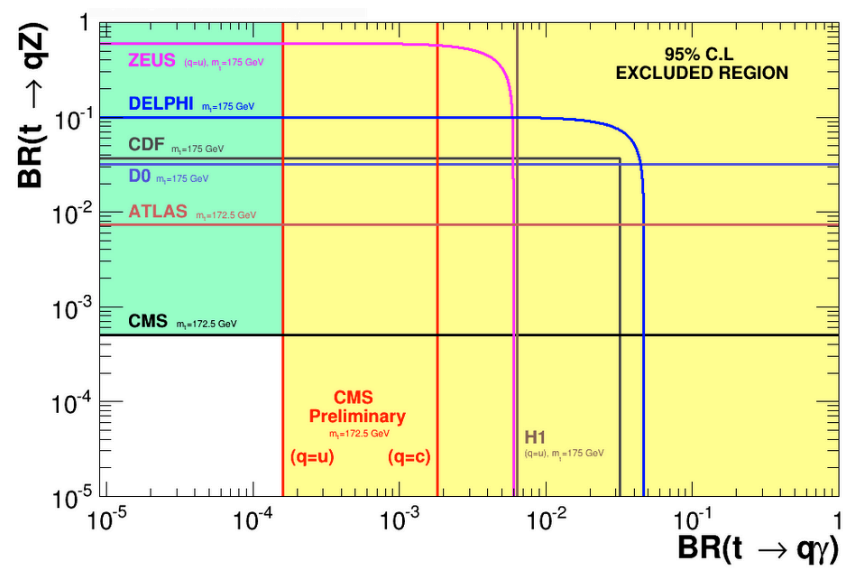
Top quark mass



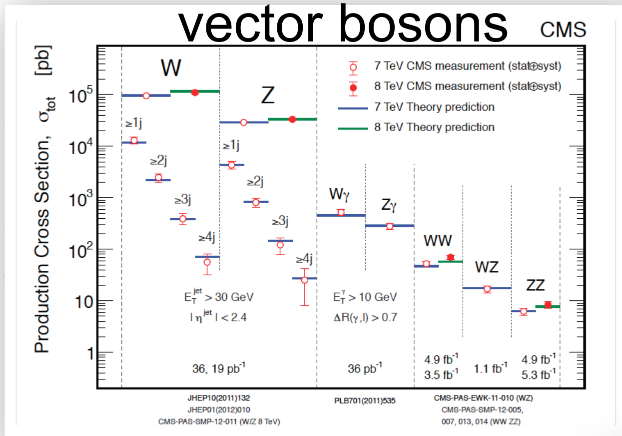
Cross section

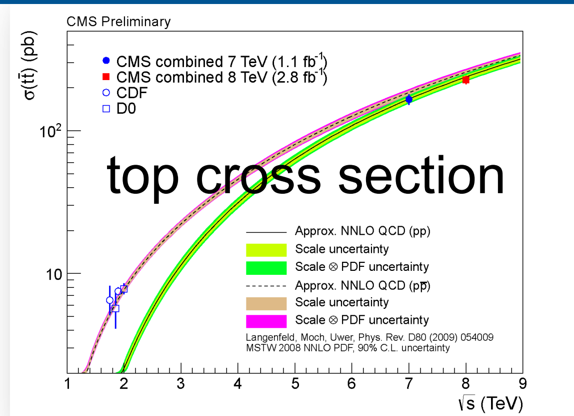


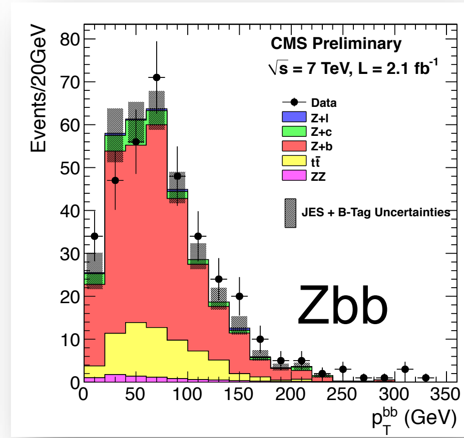
Rare decays

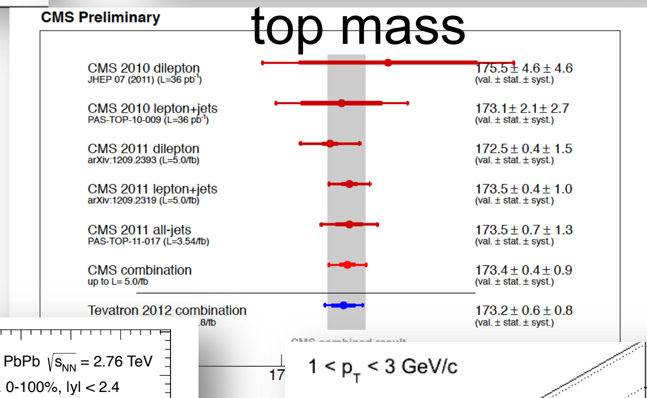


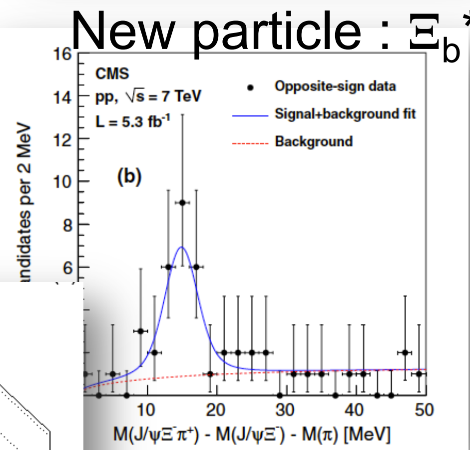
…and more physics results

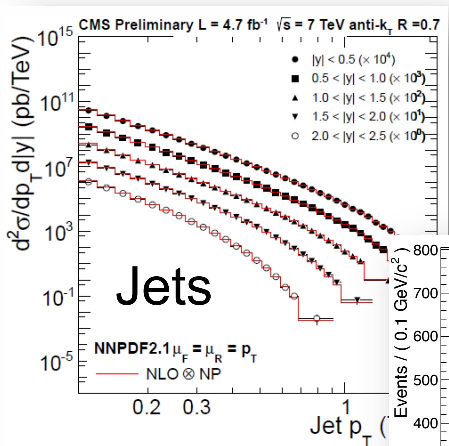


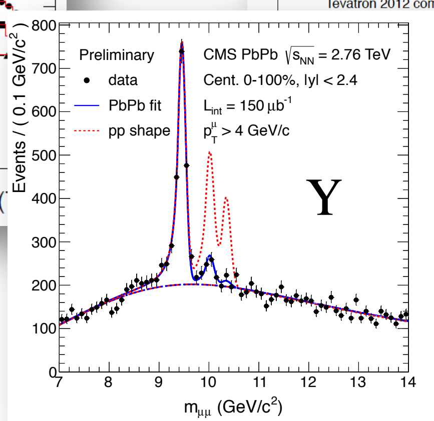


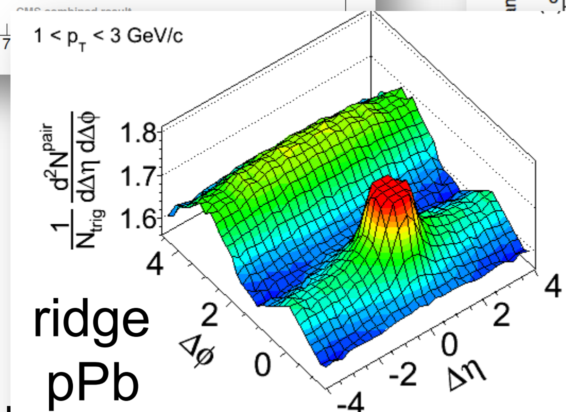






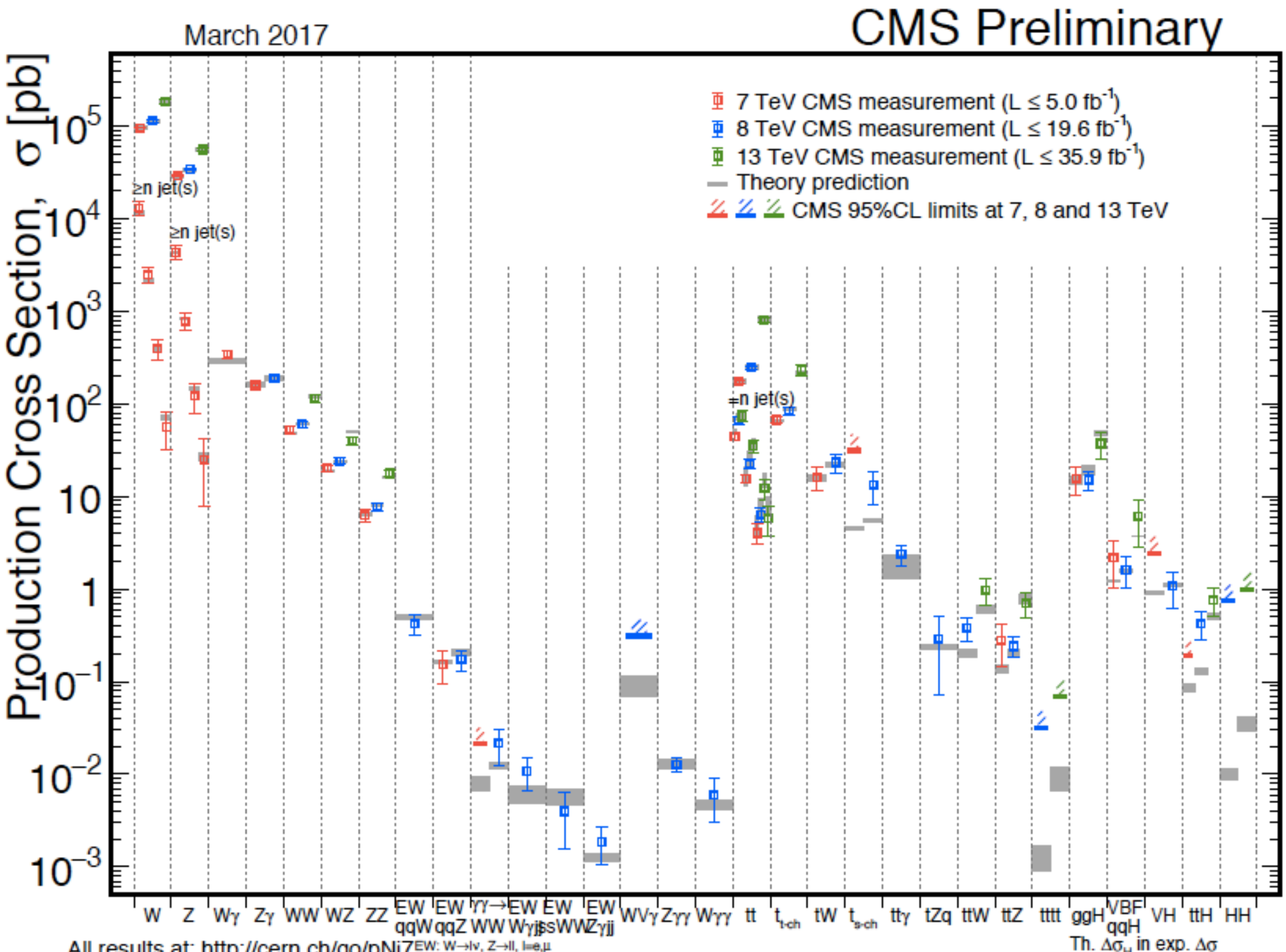




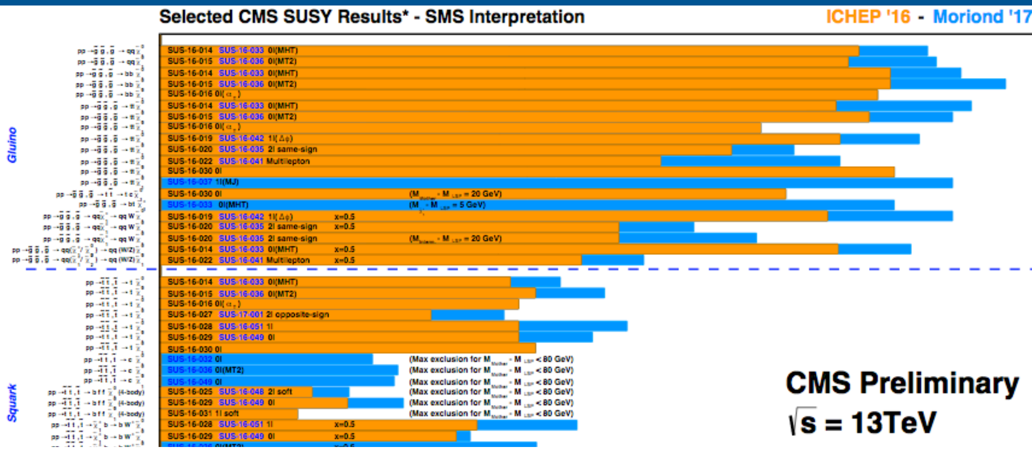


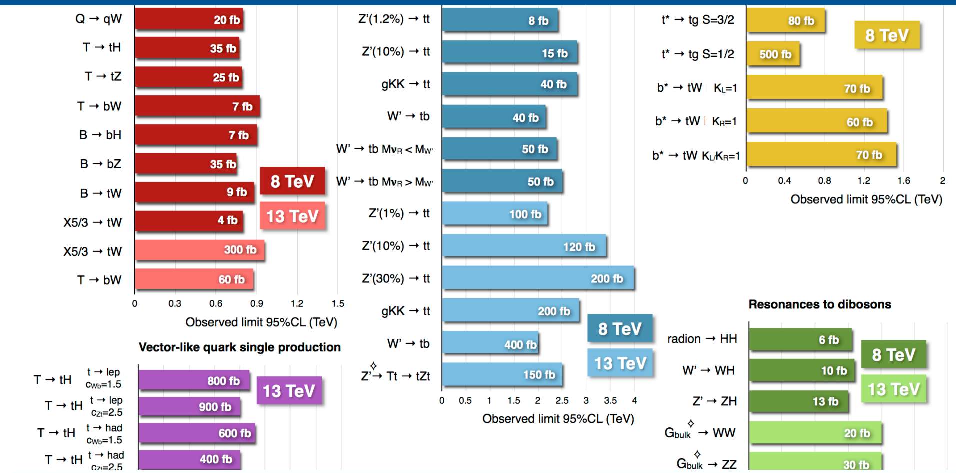
More than 900 papers from LHC

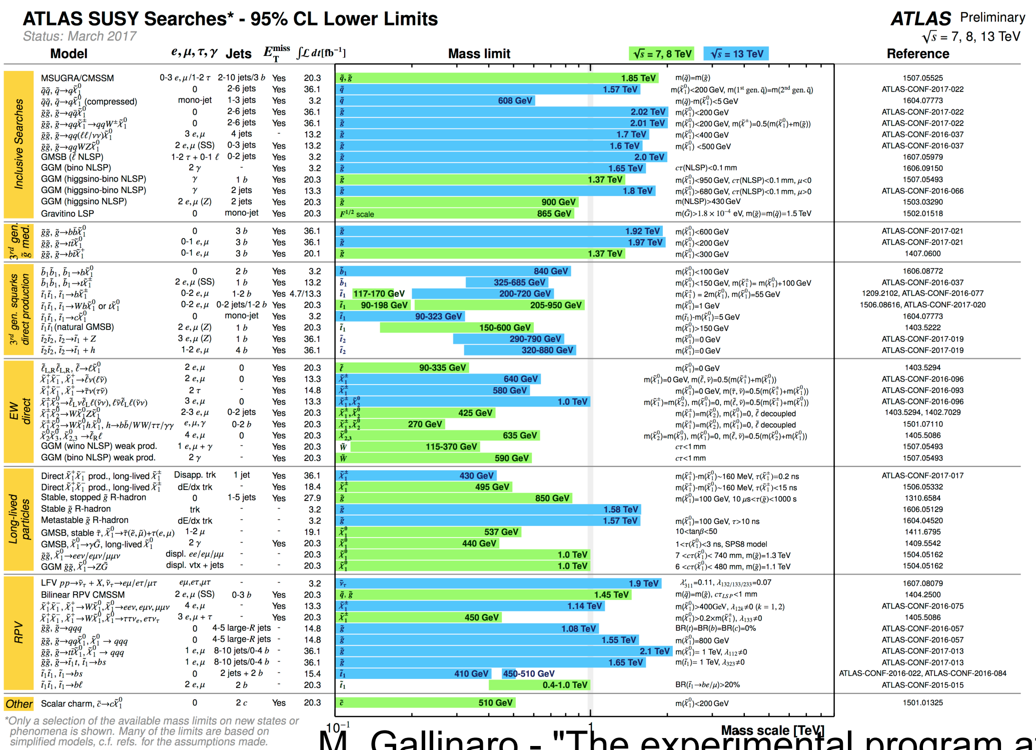
SM measurements

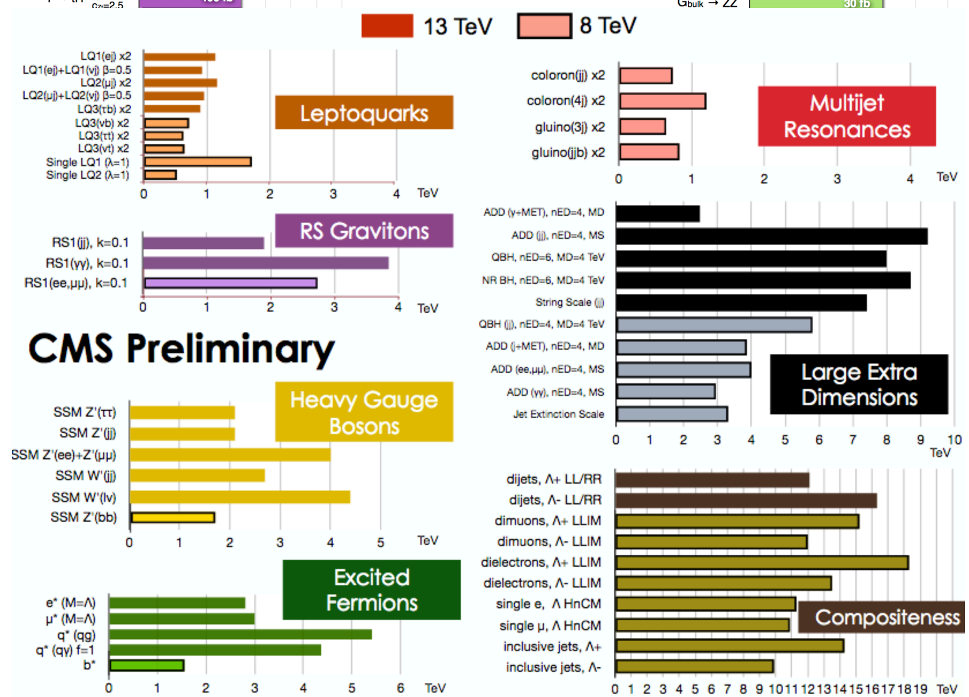


Probing the SM in many ways









Summary

- LHC experimental physics program is well under-way
- Experiments taking data with good efficiency
- Running well, with plenty of data still to come
- Rediscover the SM to calibrate/understand detector performance
- Probe the SM to test hints of New Physics
- Experimental challenges ahead