Course on Physics at the LHC

LIP Lisbon, January - June 2012

Program

The standard model of particle physics	2 lectures	30 January - 13 February
Detector physics and experimental methods	2 lectures	6, 27 February
Top quark and heavy flavor physics	4 lectures	5, 12, 19, 26 March
Statistical methods in data analysis	1 lecture	2 April
Standard model Higgs and beyond	5 lectures	16, 23, 30 April - 7, 14 May
Super symmetry	3 lectures	21, 28 May - 11 June
Matter at high density and temperature	2 lectures	18, 25 June

The lectures will take place between 17:00 and 18:30 at LIP, Av. Elias Garcia, 14 r/c, 1000 Lisbon - Portugal

J. Varela, LIP/IST
January 30, 2012

More info at

http://idpasc.lip.pt/LIP/events/2012_lhc_physics

Introduction

Specialized course on the Physics at the Large Hadron Collider organized by LIP in the framework of IDPASC.

The objective of the Course is to introduce the physics, analysis methods and results on the physics of the LHC experiments.

Emphasis is placed on the search for new physics, in particular phenomena at the basis of the electroweak symmetry breaking.

Benchmark channels in proton-proton collisions will be discussed in detail:

- identification of the objects involved
- signal and background properties
- background estimation and S/B discriminants
- estimation of systematical errors
- extraction and interpretation of the final results

Program

The standard model of particle physics

2 lectures Prof. J. Varela , 30 Jan, 13 Feb

Detector physics and experimental methods

2 lectures Dr. A. David 6, 27 Feb

Top quark physics

4 lectures Dr. M. Gallinaro, Prof. A. Onofre, 5, 12, 19, 26 Mar

Statistical methods in data analysis

1 lecture Dr. P. Bargassa 2 Apr

Standard model Higgs and beyond

5 lectures Dr. P. Silva, Dr. A. David, Dr. P. Muino, 16, 23, 30 Apr, 7, 14 May

Supersymmetry

3 lectures Dr. P. Bargassa 21, 28 May, 11 Jun

Matter at high density and temperature

2 lectures Prof. J. Seixas 18, 25 Jun

Required background

The course is intended for under-graduate or graduate students having basic training in Particle Physics:

Basic concepts
Elementary constituents of matter and interactions. Quantum numbers and conservation rules. Spin and symmetry groups. Relativistic kinematics. Cross-section. Natural units. Mass and lifetime. Resonances.

Structure of matter
Elastic scattering and form factors. Inelastic scattering experiments. Nucleon structure functions. Scale invariance. Quark model. Parton distribution functions. Introduction to QCD.

Fundamental interactions
Introduction to QED. Fermi interaction. Parity violation. Currents V-A and weak doblets. W and Z bosons. Cabibbo angle. Neutral currents. Electroweak interaction. Gauge symmetries. The Higgs mechanism. Weinberg-Salam model. CP violation.

Background bibliography

F. Halzen and A.D.Martin, ' Quarks and Leptons ', John Wiley and Sons (1984)

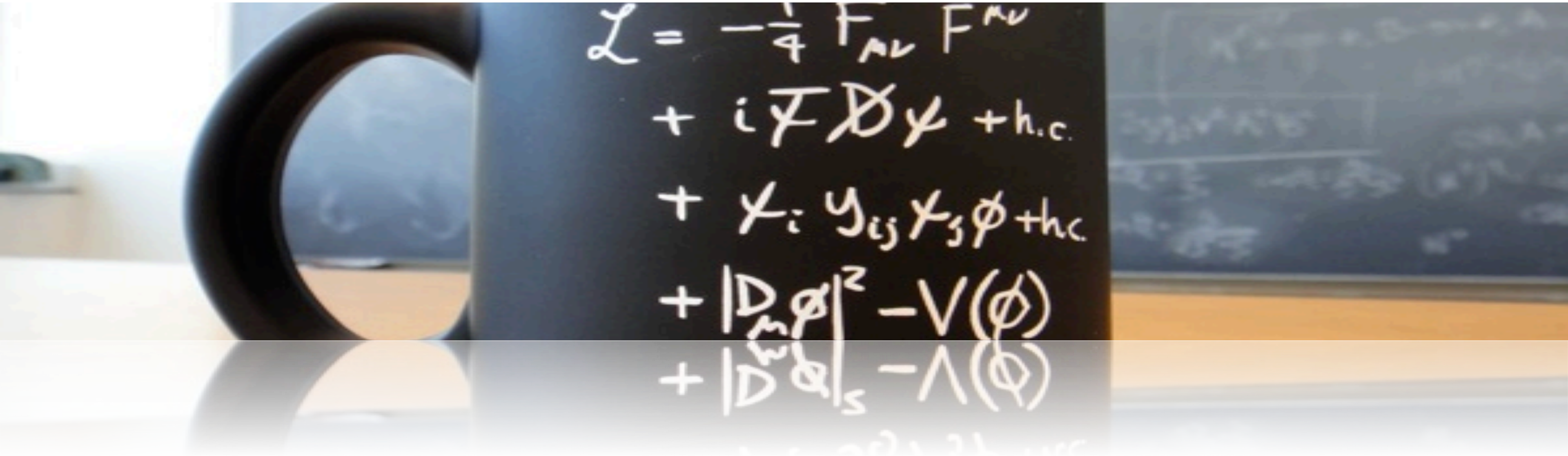
D. Griffiths, ' Introduction to Elementary Particles ', John Wiley and Sons (1987)

B.R.Martin, G. Shaw, ' Particle Physics ', John Wiley and Sons (1999)

Lecture 1

1. The LHC physics case
2. The LHC experimental program
3. Experimental challenges
4. Hadron interactions
5. Luminosity and cross-section measurements

The LHC physics case



The Standard Model

Is a beautiful model for describing the fundamental particles and fields and their interactions

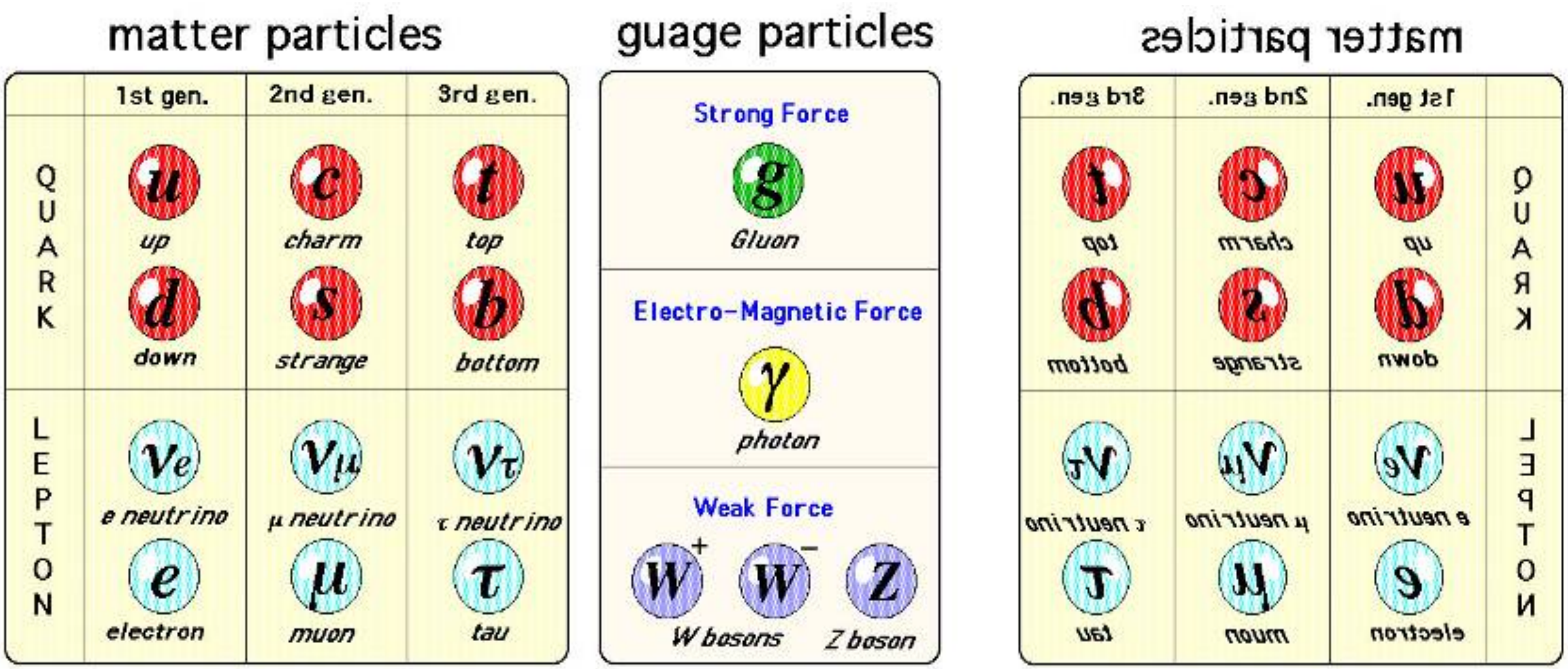
It provides a quantitative description of all experimental results so far

But:

The model requires the introduction of a new field (Higgs field) and corresponding particle (‘the Higgs’)

This particle has never been found by an experiment

The Standard Model

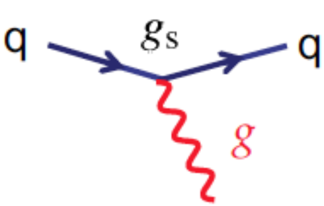


$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4}H^4 + \frac{g^2}{4}\left(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu\right)(\lambda^2 + 2\lambda H + H^2) + \sum_{l,q,q'}\left(\frac{m_l}{\lambda}\bar{l}l + \frac{m_q}{\lambda}\bar{q}q + \frac{m_{q'}}{\lambda}\bar{q}'q'\right)H$$

Standard Model interactions

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

STRONG

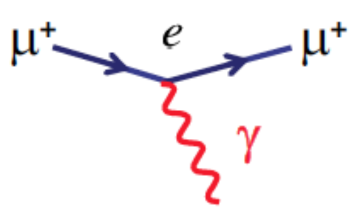


Only quarks

Never changes flavour

$\alpha_S \sim 1$

EM

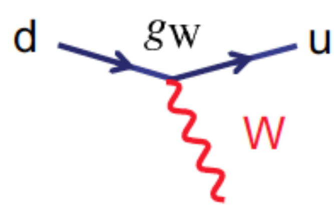


All charged fermions

Never changes flavour

$\alpha \simeq 1/137$

WEAK CC



All fermions

<u>Always</u> changes flavour

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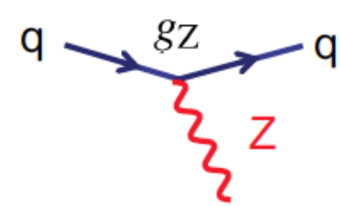


All fermions

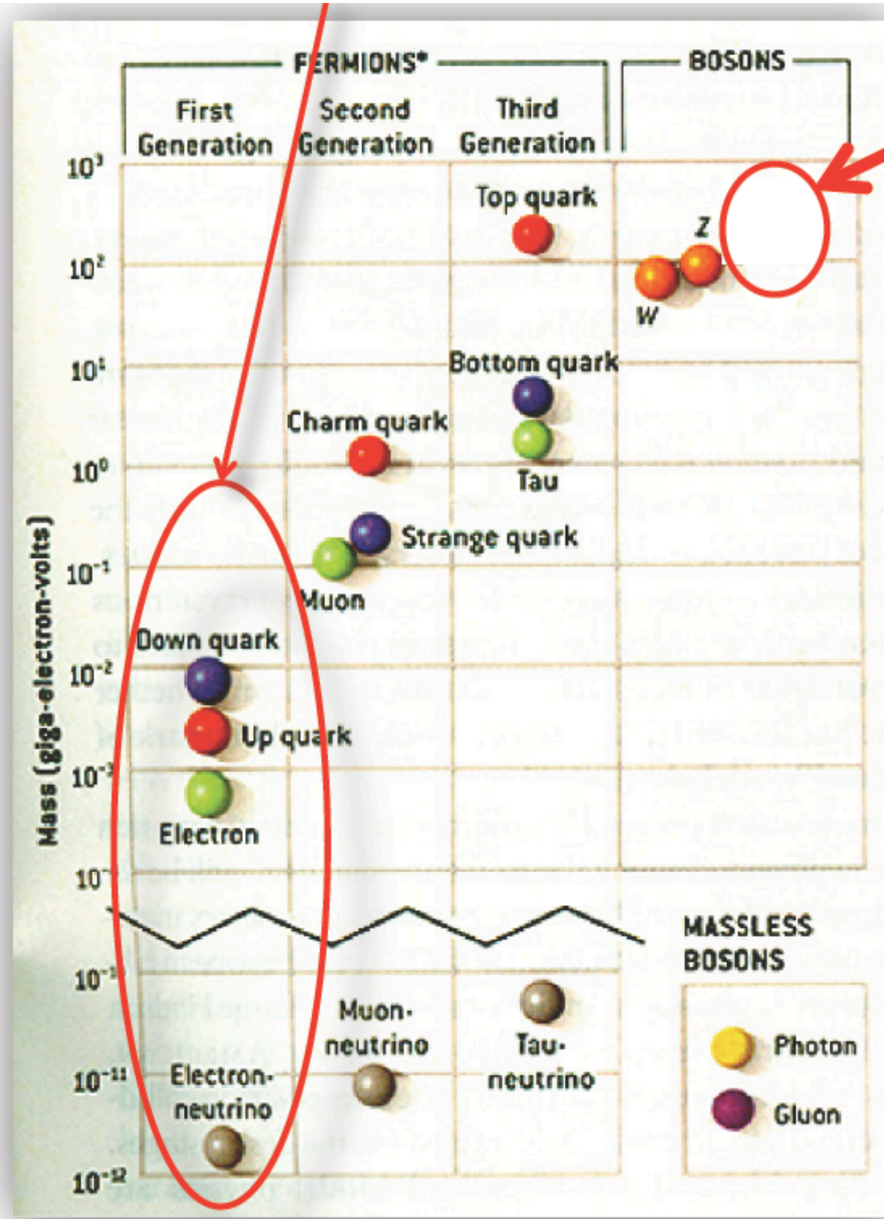
Never changes flavour

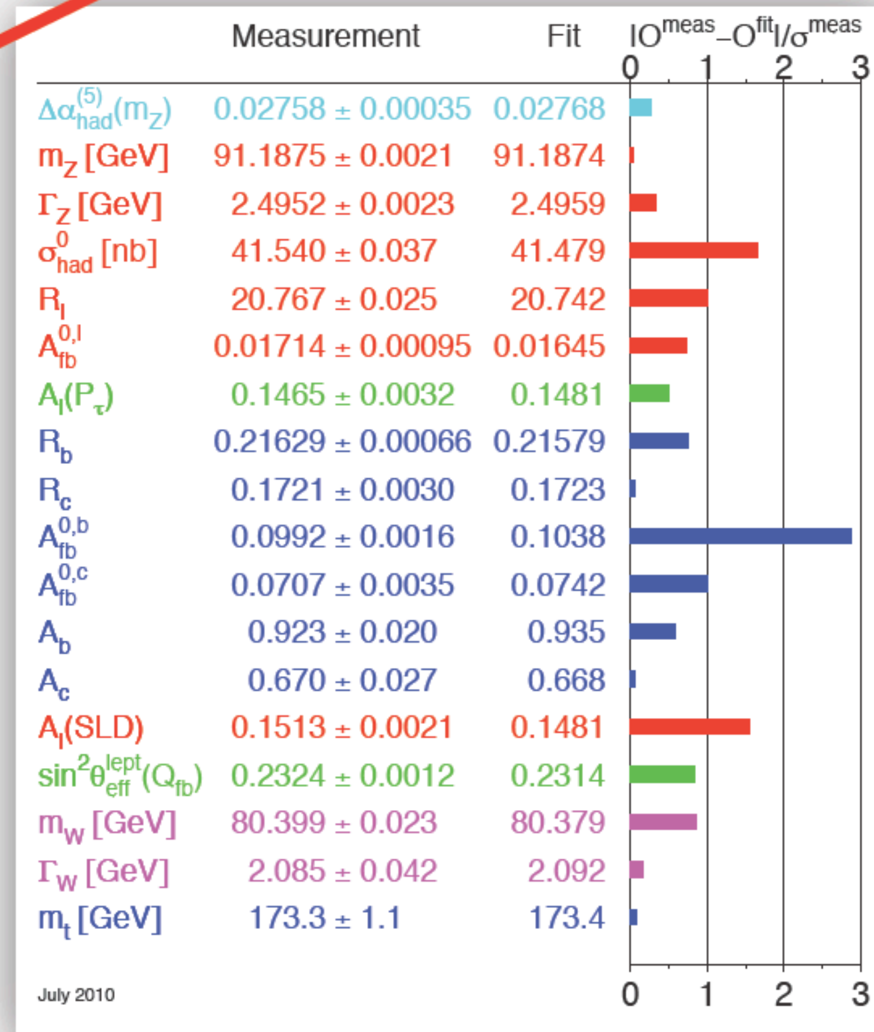
$\alpha_{W/Z} \sim 1/40$

The Standard Model

1 Missing piece: Higgs

Normal matter





	Measurement	Fit	$\|O^{meas}-O^{fit}\|/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^{0} [nb]	41.540 ± 0.037	41.479	
R_l	20.767 ± 0.025	20.742	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038	
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.399 ± 0.023	80.379	
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.3 ± 1.1	173.4	

July 2010

Confirmed at sub 1% level!

The Higgs and the origin of mass

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

The symmetry between the electromagnetic and the week interactions is broken:

- Photon do not have mass
- W, Z do have a mass ~ 80-90 GeV

Higgs mechanism:

mass results from the interactions with the Higgs field

The Terascale

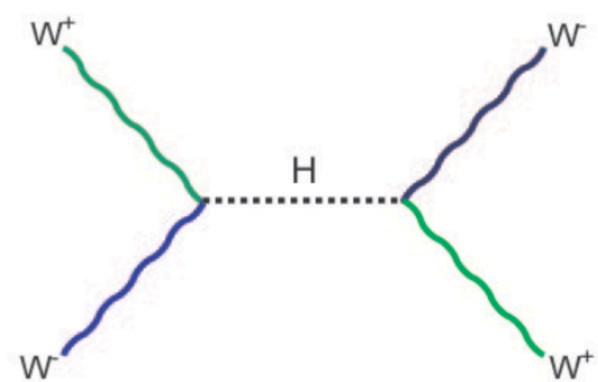
The Standard Model would fail at high energy without the Higgs particle or other ‘new physics’

Based on our present understanding and on quite general theoretical insights we expect the ‘new physics’ to manifest at an energy around or below

1 Tera-electronVolt = 10^{12} electronVolt

accessible at the LHC for the first time

Higgs fixes WW scattering



W^-W^+ scattering via Z/γ

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

Probability > 1 at Energy~ 1.7 TeV !

Unitarity violation

Introduce Higgs:

$\phi^\dagger = 2^{-1/2}(\phi_1 - i\phi_2, H - i\phi_o)$

w/ a very general potential

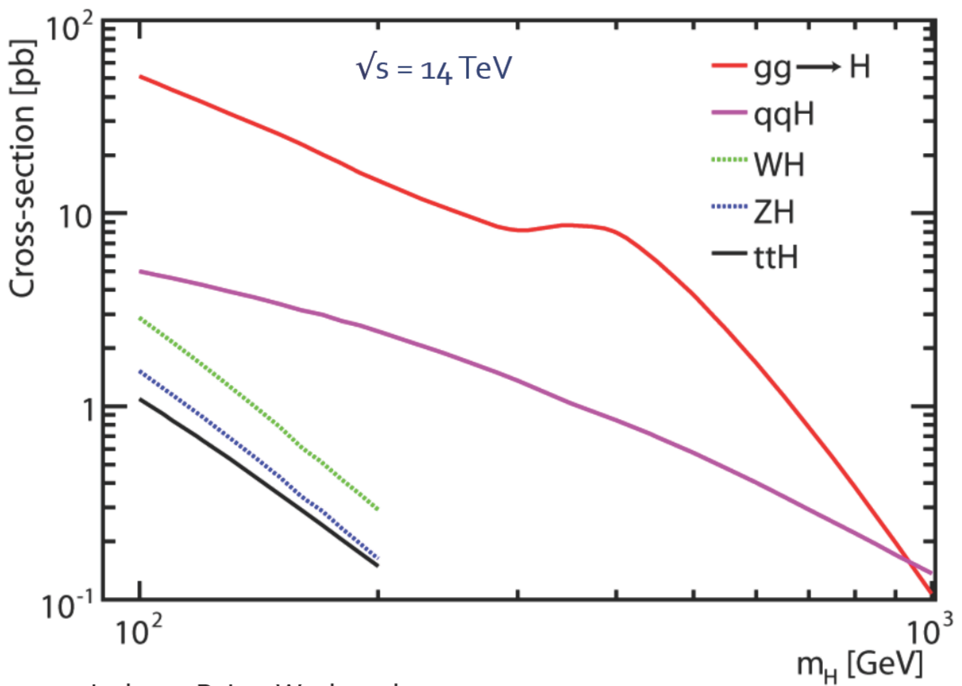
$V(\phi) = \mu^2 \phi\phi$

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

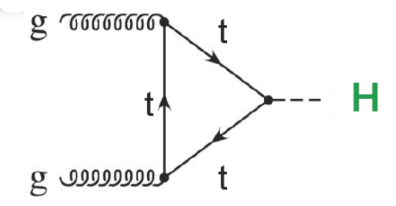
Problem fixed:

Provided $M_H \leq 1$ TeV ~ $[8\pi\sqrt{2}/(3G_F)]^{1/2}$

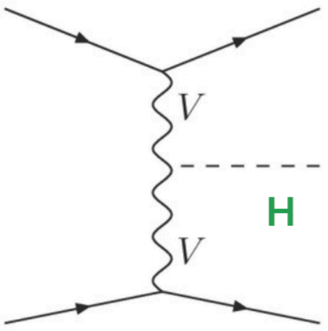
SM Higgs production at LHC



Dawson, Jackson, Reina, Wackeroth



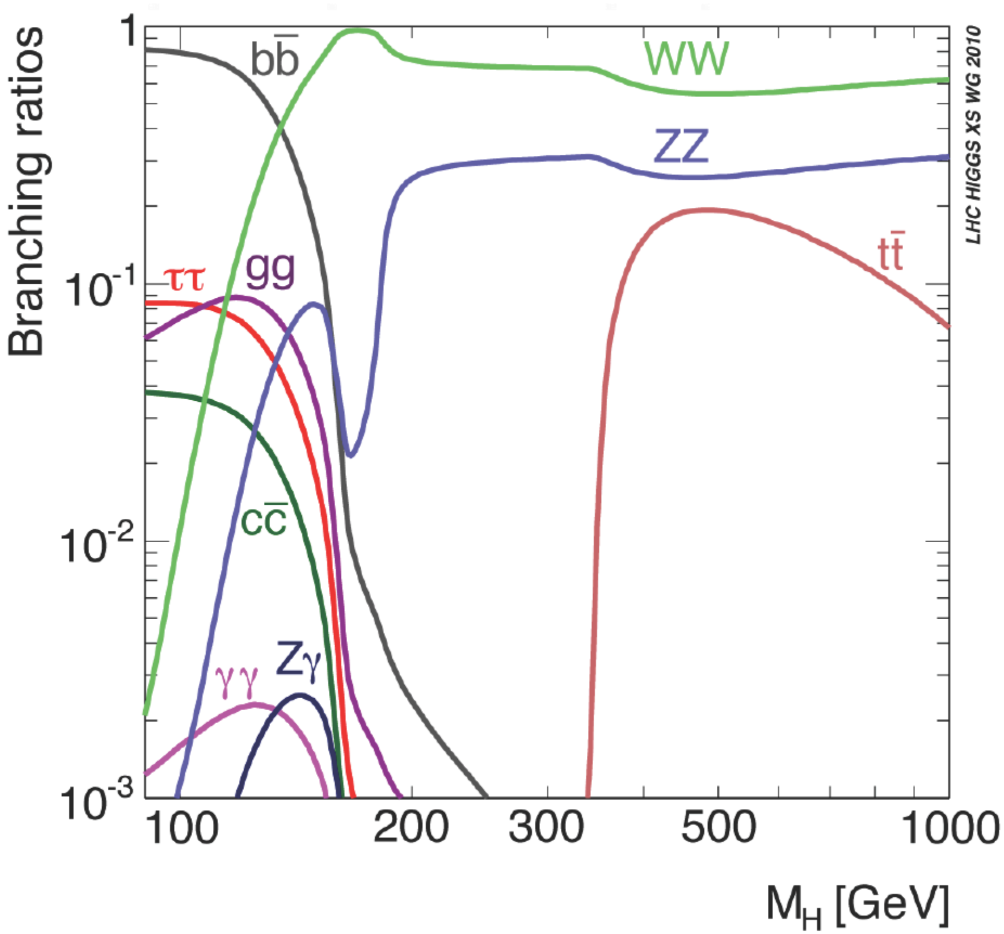
Gluon fusion



Vector Boson fusion

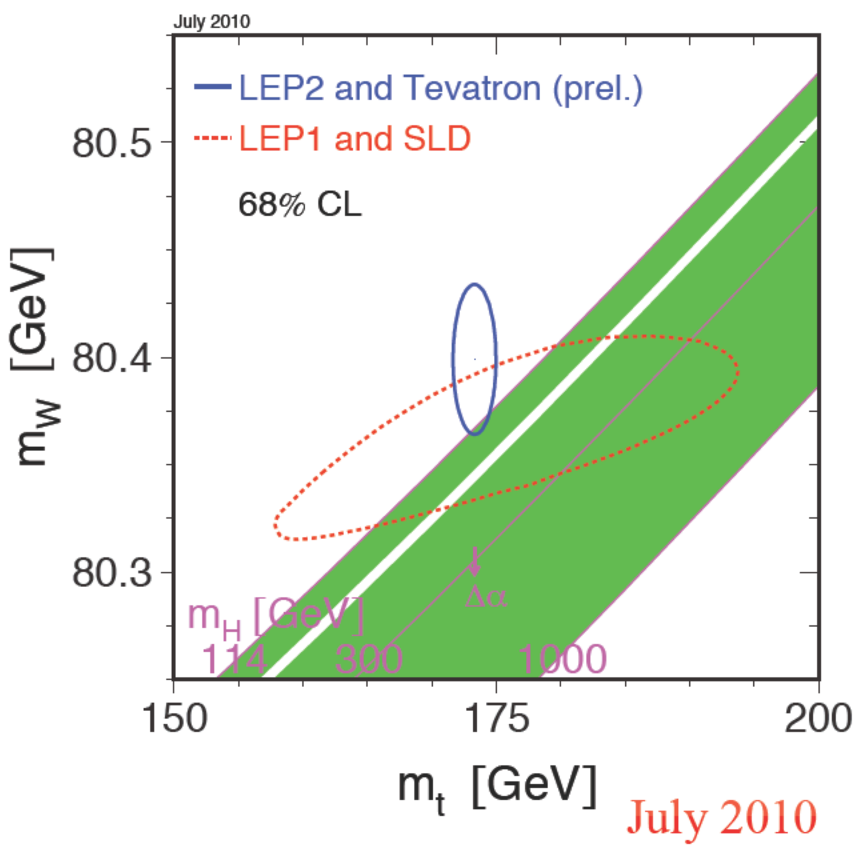
- Gluon fusion is dominant in the entire m_H mass range
- Vector boson fusion is the next most important

Standard Model Higgs decays



Relation of Higgs, top and W masses in SM

- Higgs, top and W masses are interdependent in the SM
- Precise measurements of top and W mass allow to predict Higgs mass



As of July 2010

- M_t=173.3±1.10 GeV
- M_W=80.399±0.023 GeV

➔ $M_H=89^{+35}_{-26}$ GeV

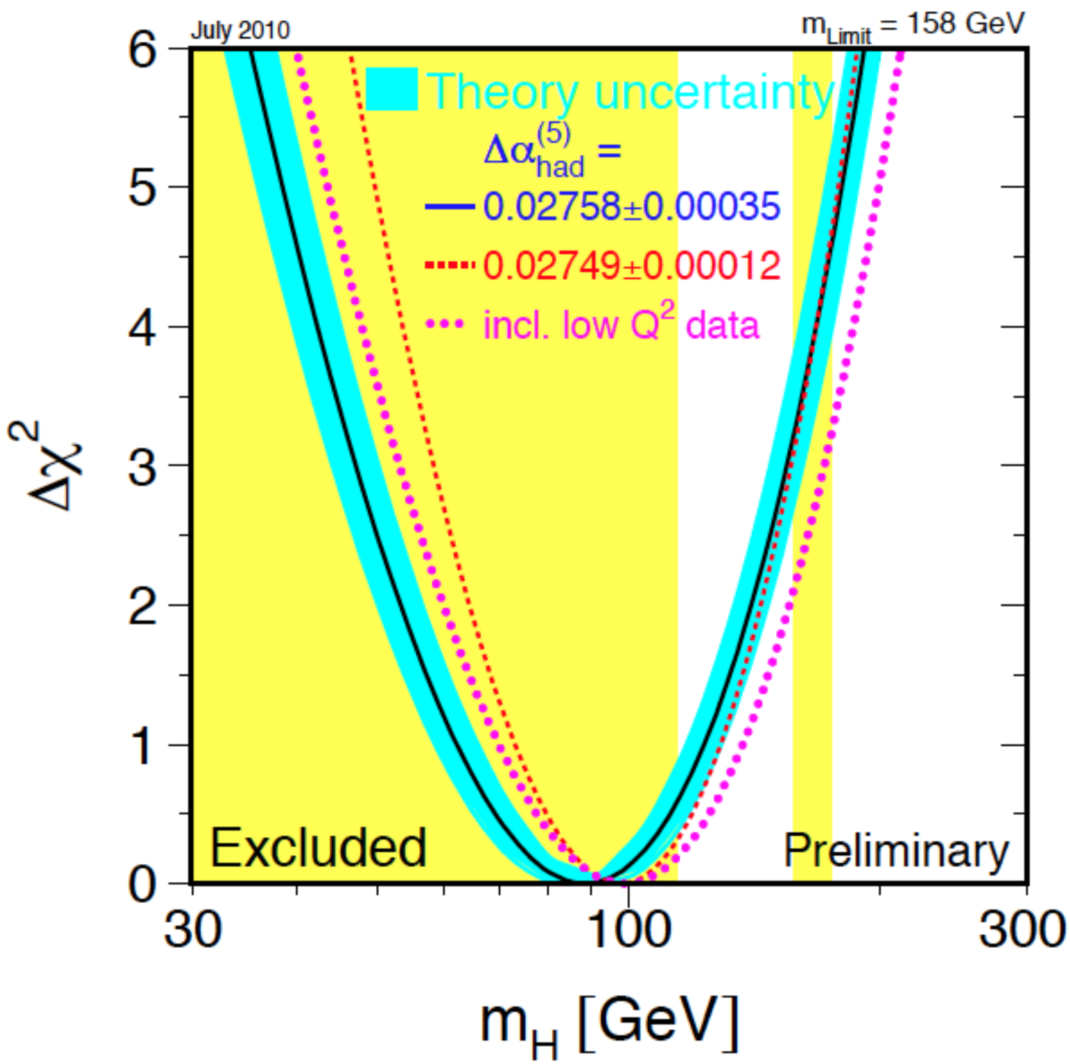
➔ M_H<158 GeV @95% CL

From direct searches at LEP:

- M_H>114 GeV (LEP)

Tevatron excludes 158 to 173 GeV (2011)

The Higgs mass from SM fits



EW-Fits:

$M_H = 89^{+35}_{-26}$ GeV

$M_H < 158$ GeV @ 95% CL

From direct search at LEP:

$M_H > 114$ GeV

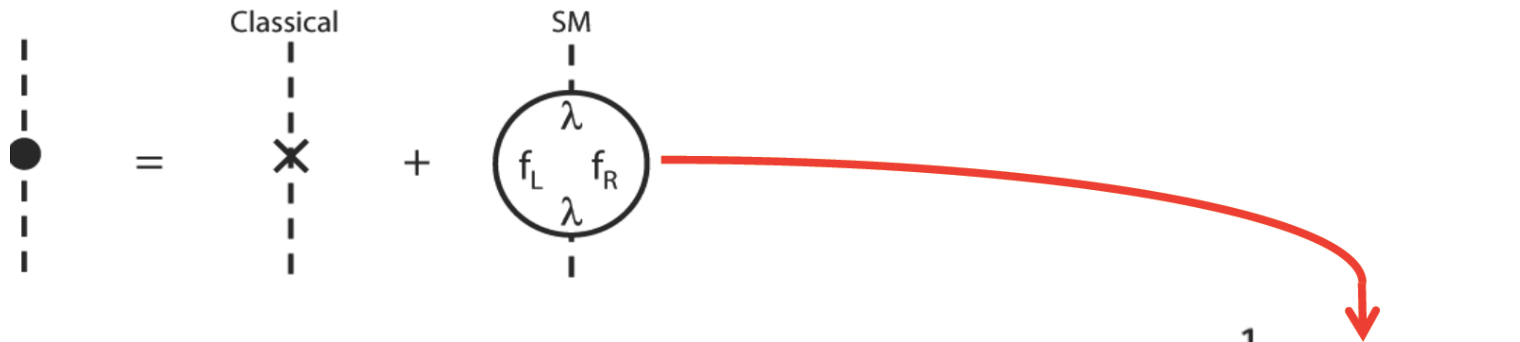
@ 95% CL

From direct search at Tevatron:

$158 > M_H > 175$ GeV

@ 95% CL

Higgs and hierarchy problem



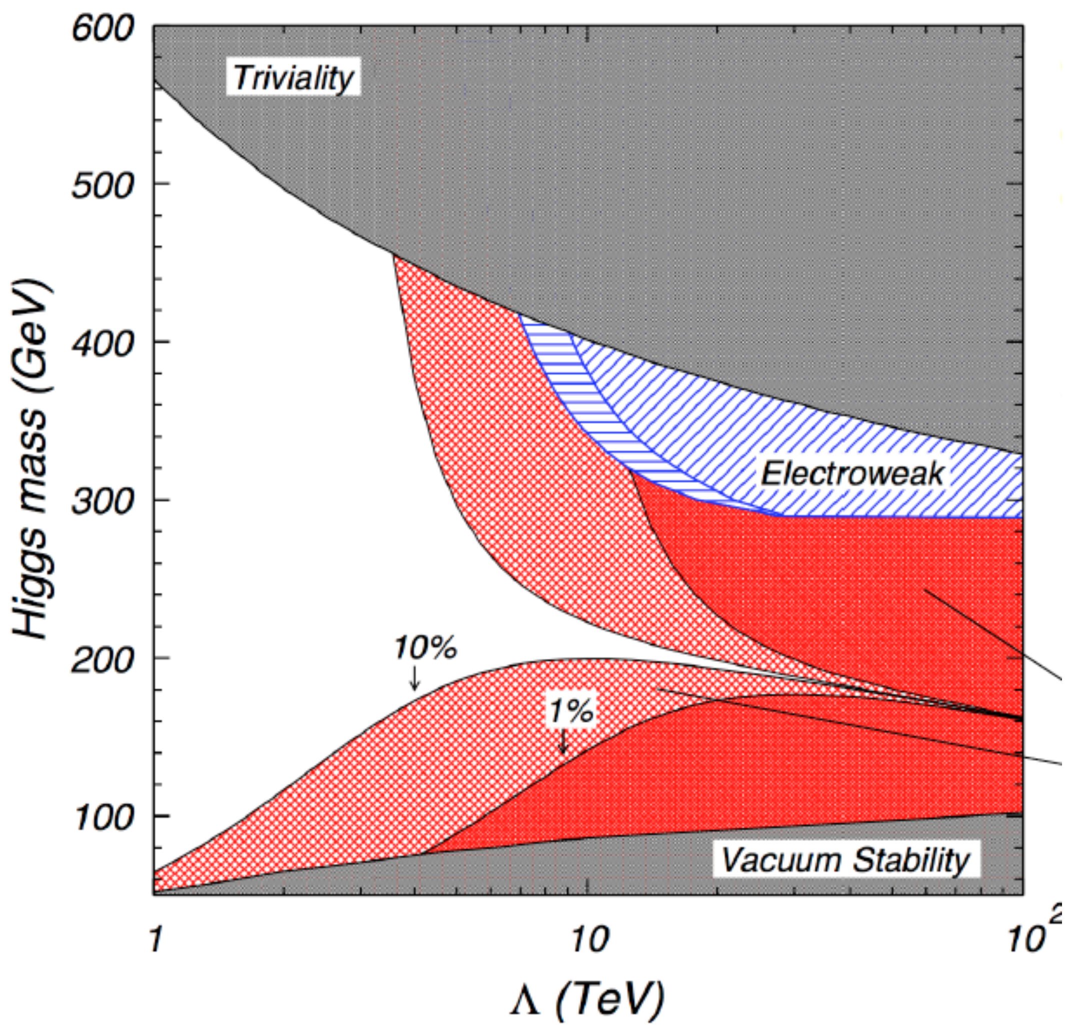
$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

Higgs mass is a huge problem:

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

This is known as the gauge hierarchy problem

New physics at a few TeV?



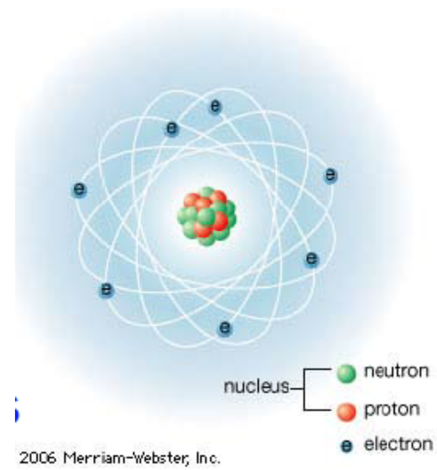
Excluded to avoid fine-tuning

The periodic table of the elements

By the end of the 19th century, scientists had characterized many “elements” indivisible in chemical reactions leading to the modern “periodic table”

Mendeleev spotted gaps and predicted that elements would be found to fill it

Group → / ↓Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
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 UUb	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
Lanthanides				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
Actinides				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



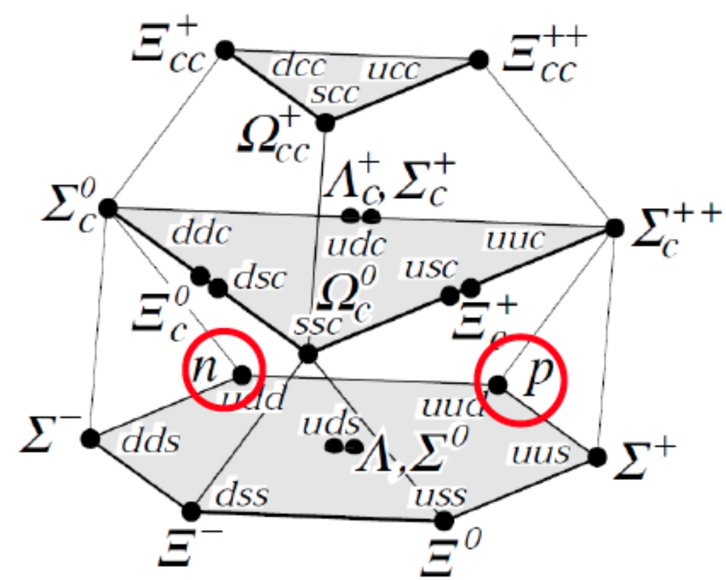
1913-32: Each atom has electrons orbiting a nucleus made of protons and neutrons.

The quark model

Physicists discovered dozens of “elementary particles” similar to proton and neutron

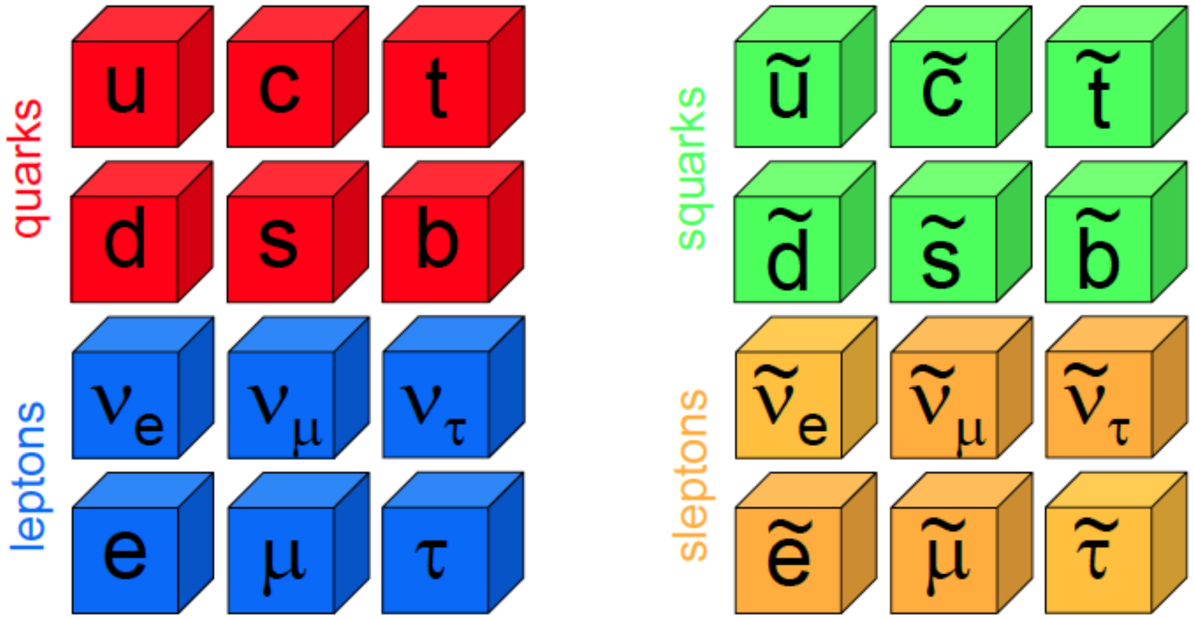
Tables had gaps, the whole periodic table story repeats one level down

Quarks:
u, d, s, c: up, down, strange, charm



Supersymmetry

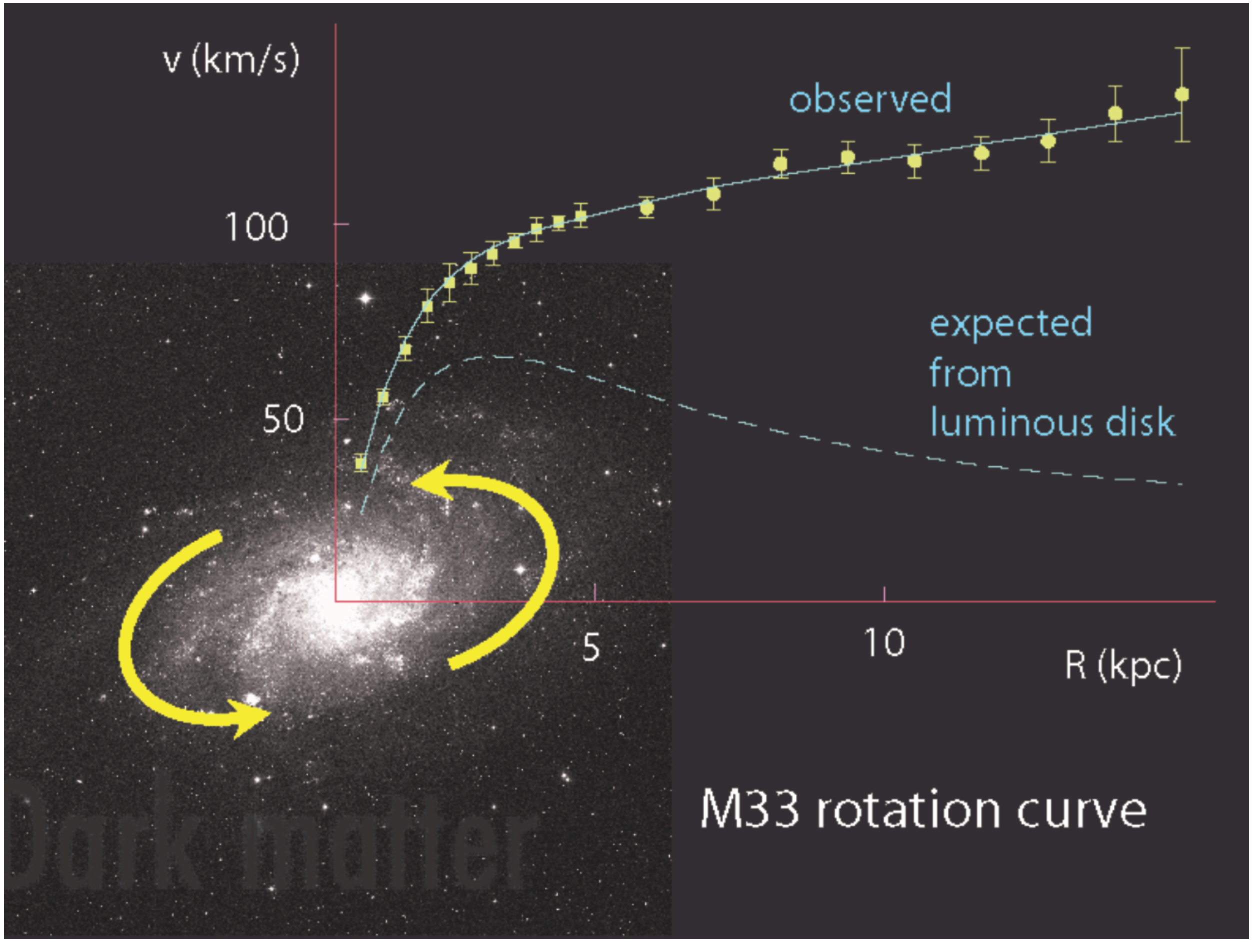
Double the whole table with a new type of matter?



Heavy versions of every quark and lepton

The dark matter problem

We know that ~25% of the matter in the universe is dark matter (ordinary matter is ~4%)



New physics at LHC?

There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

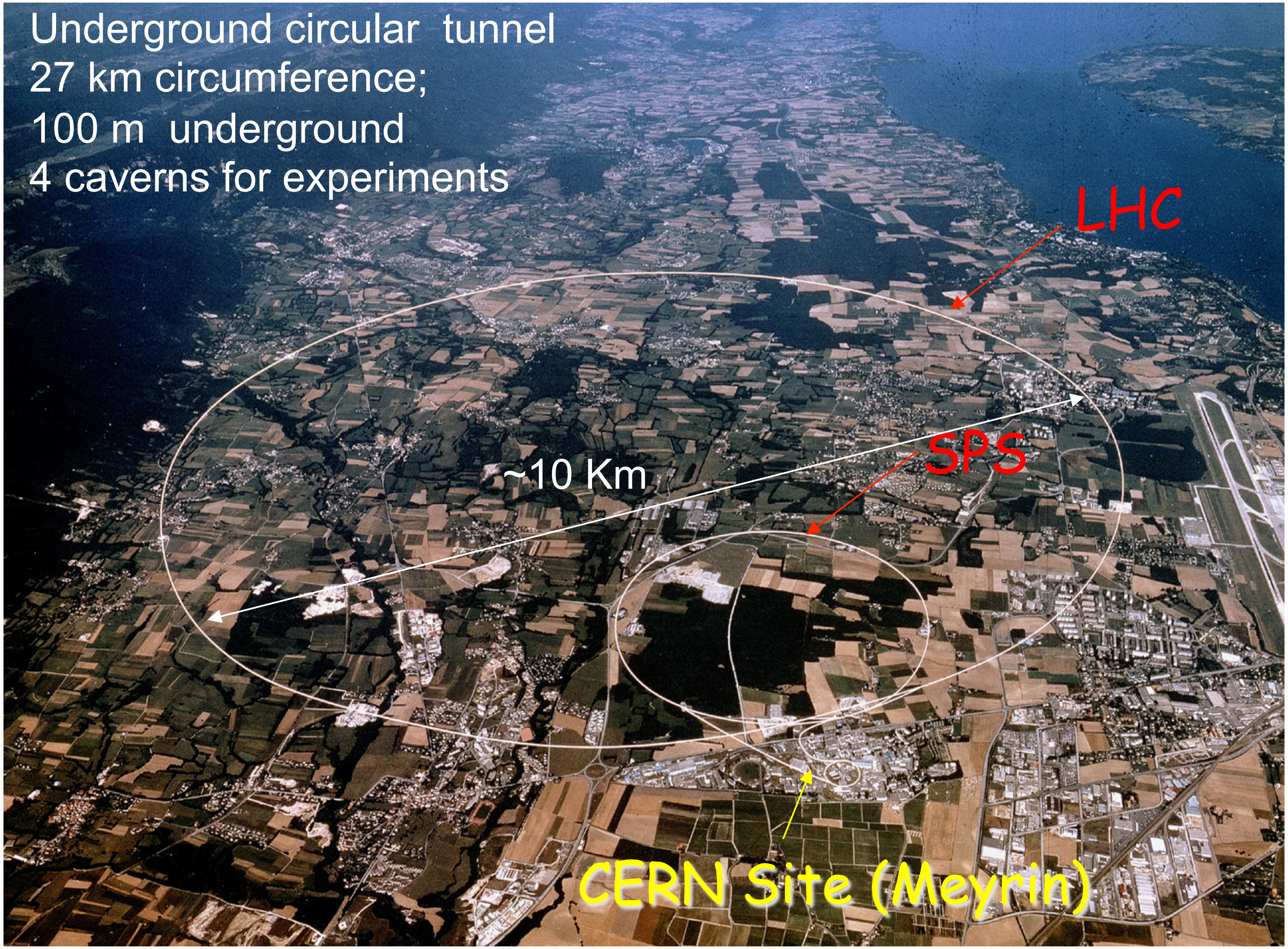
- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, …)
- Leptoquarks
- New Heavy Gauge Bosons
- Technicolour
- Compositeness

Any of this is what the LHC hopes to find ...

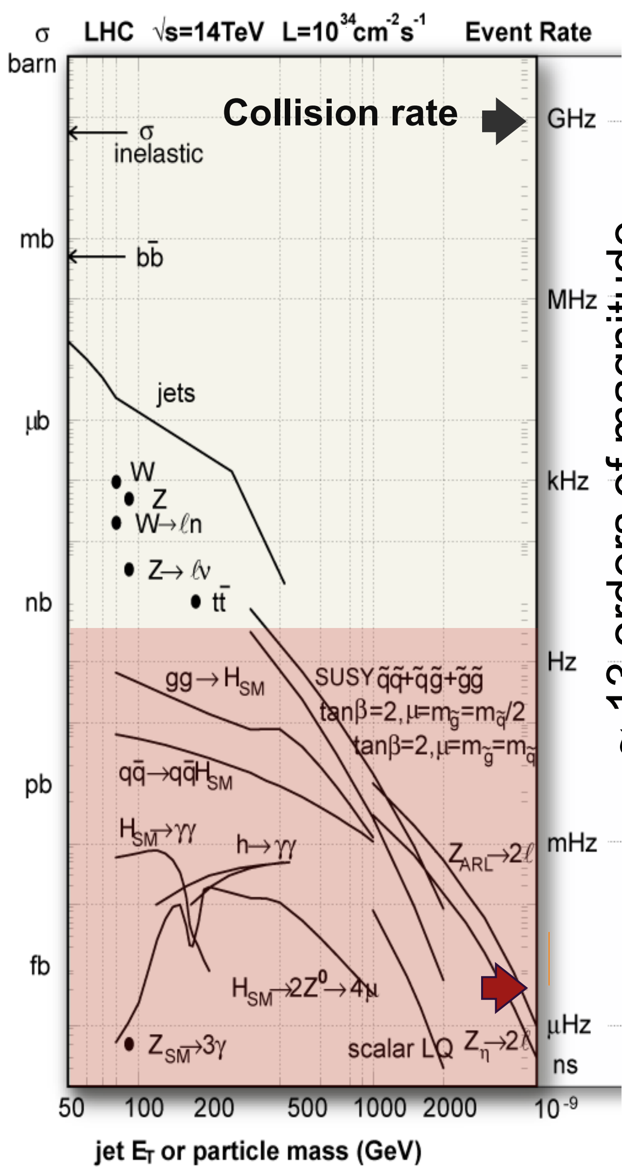
... apart from the Higgs

The LHC experimental program

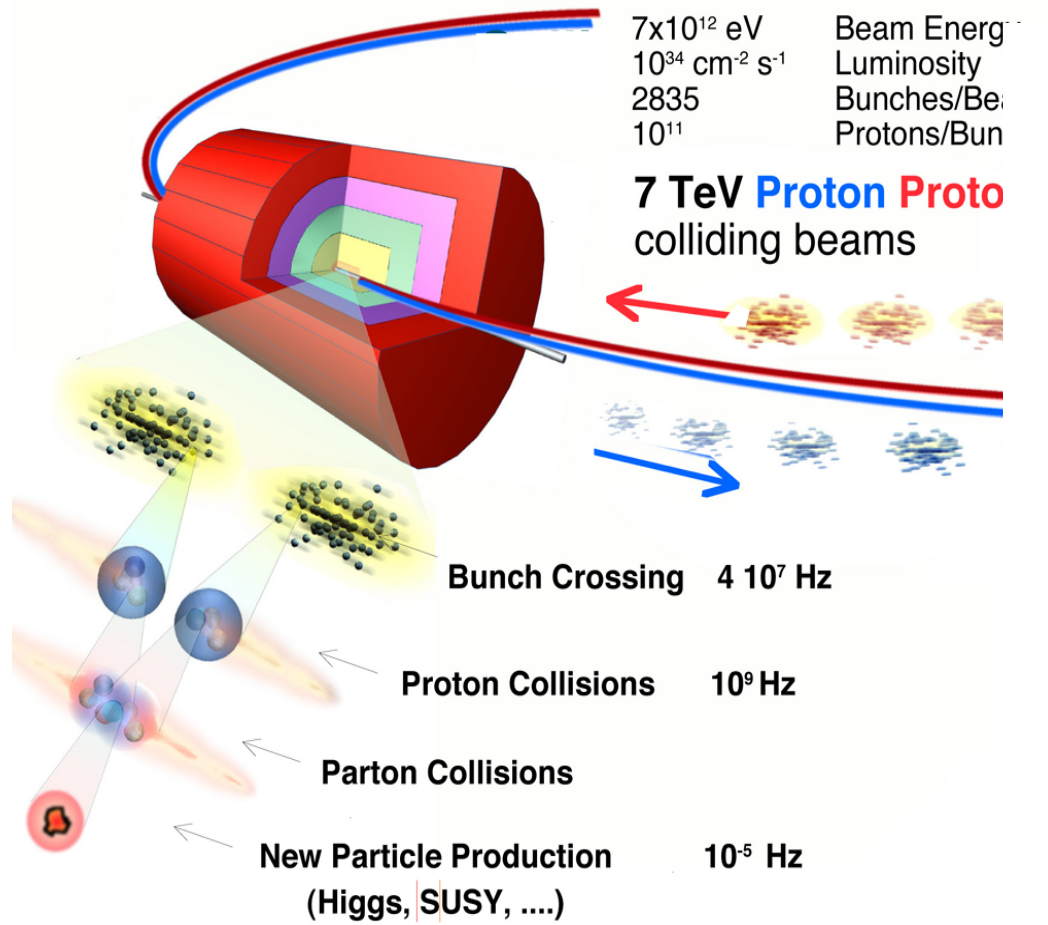
Accelerator and Experiments



Proton-proton collisions at LHC



~ 13 orders of magnitude



LHC 2010-12:

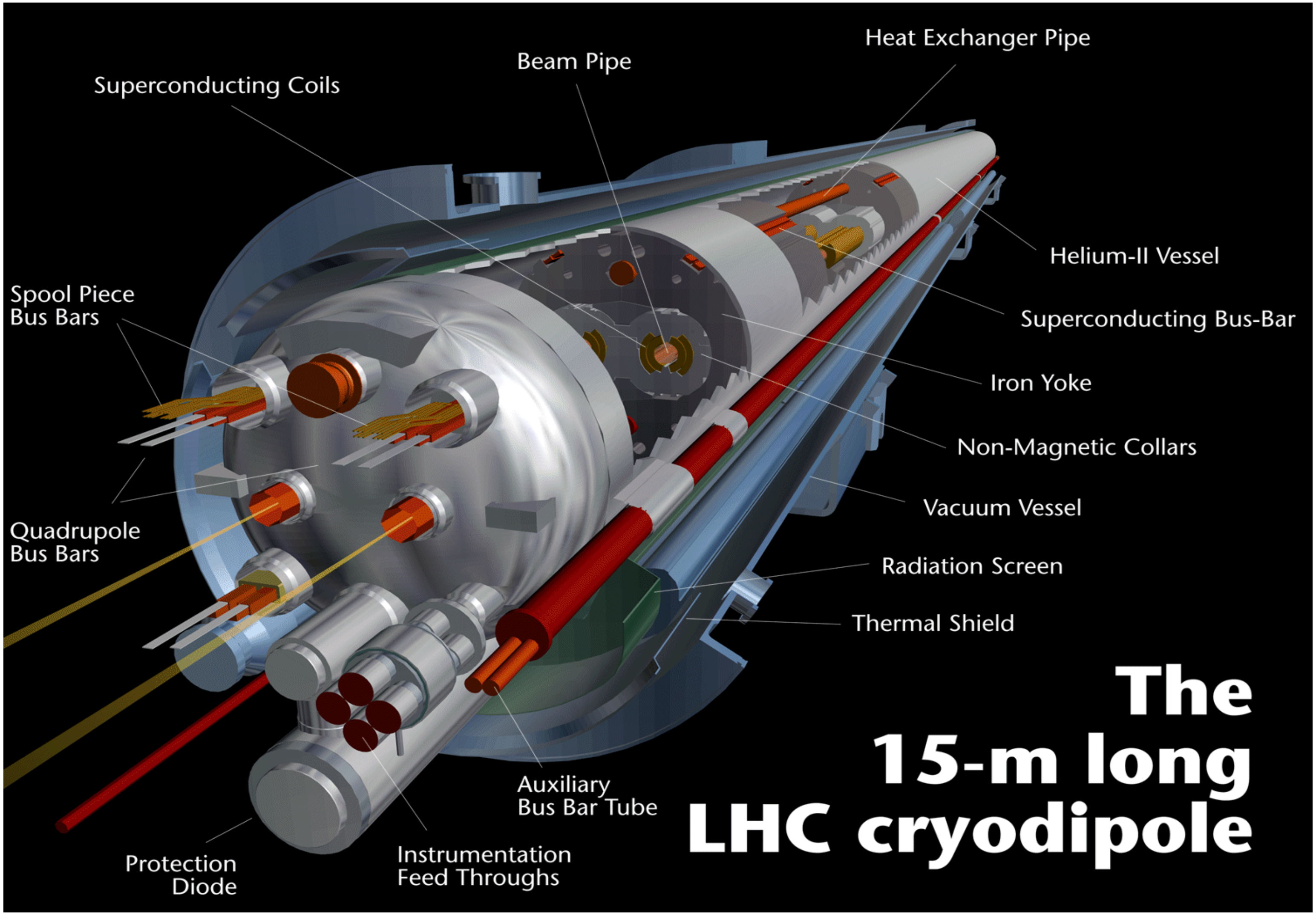
Collision Energy	7 TeV
Luminosity	10^{32-34} $cm^{-2}s^{-1}$

Heavy ion collisions: Pb-Pb 2.76 GeV/nucleon

Accelerator challenges

- Superconducting 8.3 T dipoles (operating temperature 1.9K)
- Focusing superconduting quadrupoles
- Collimation (350 MJ stored energy per beam)
- The huge size of the system
- More than 33,000 tonnes of ‘cold mass’
- 27 km of cryogenic distribution line

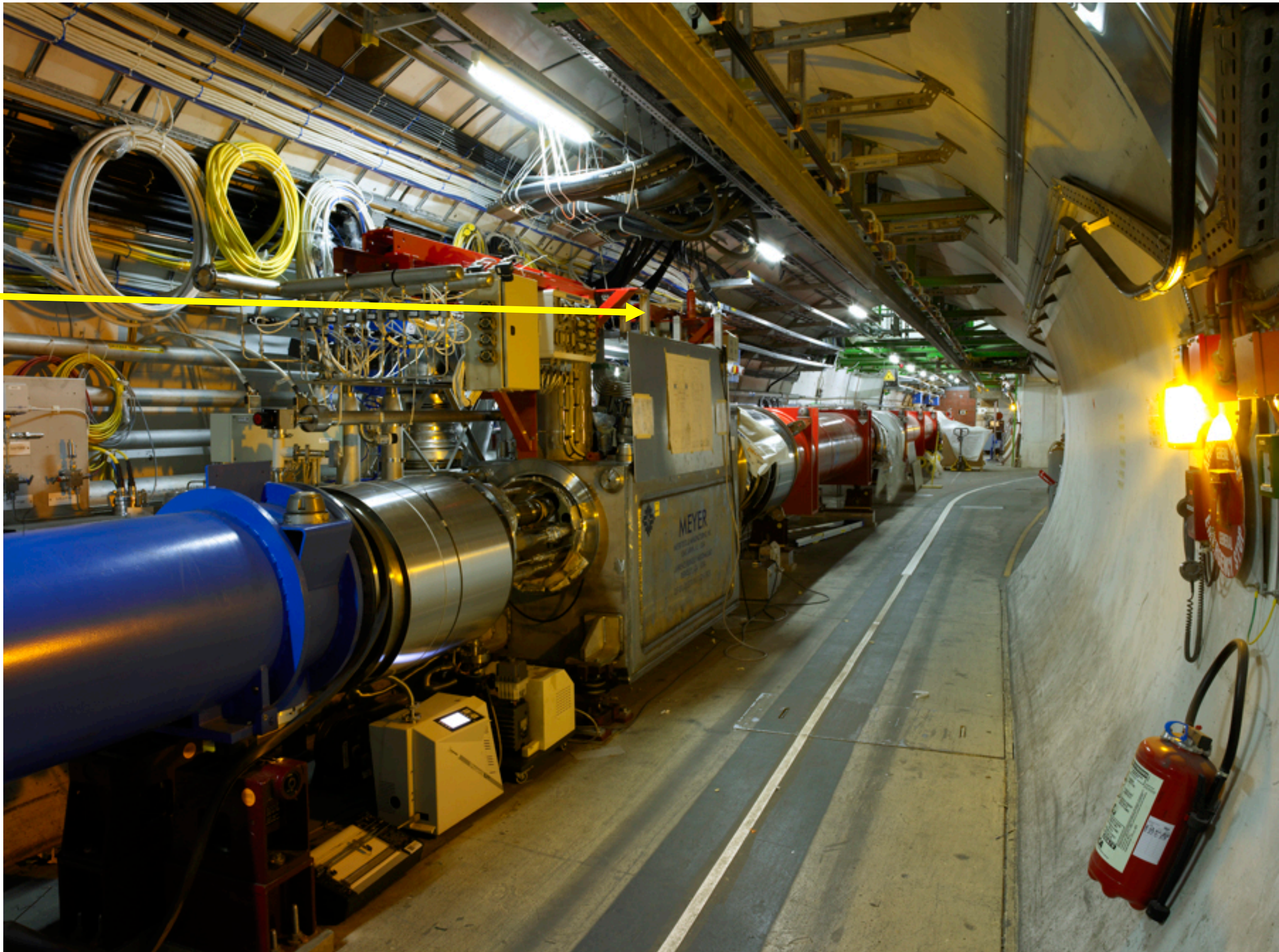
Superconducting dipole



In the tunnel

Beam delivery towards interaction point

Current distribution using High Temperature Supercondutor current leads

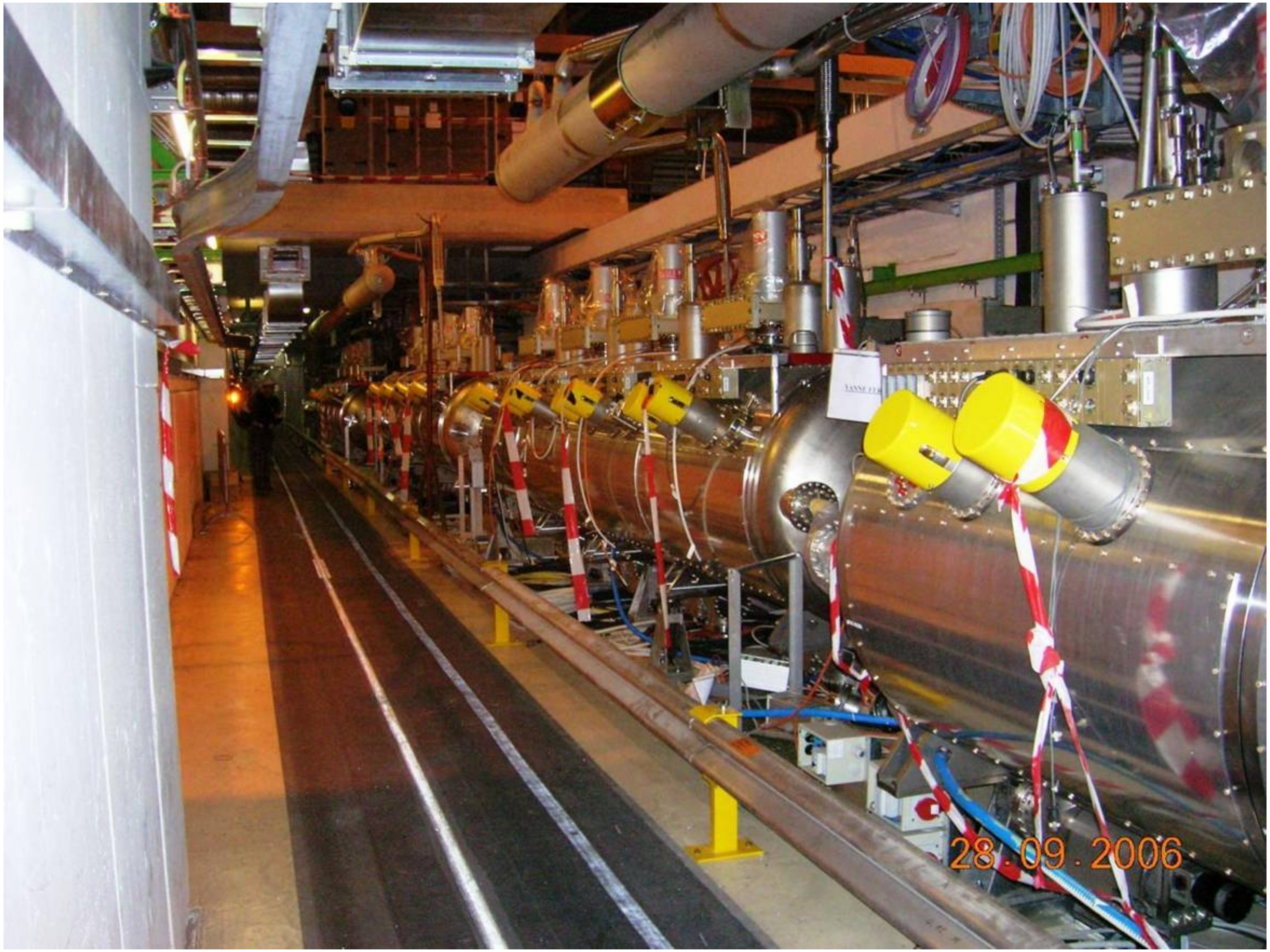


In the tunnel

RF cavities

cryo-modules each with four cavities in the LHC straight section IP4

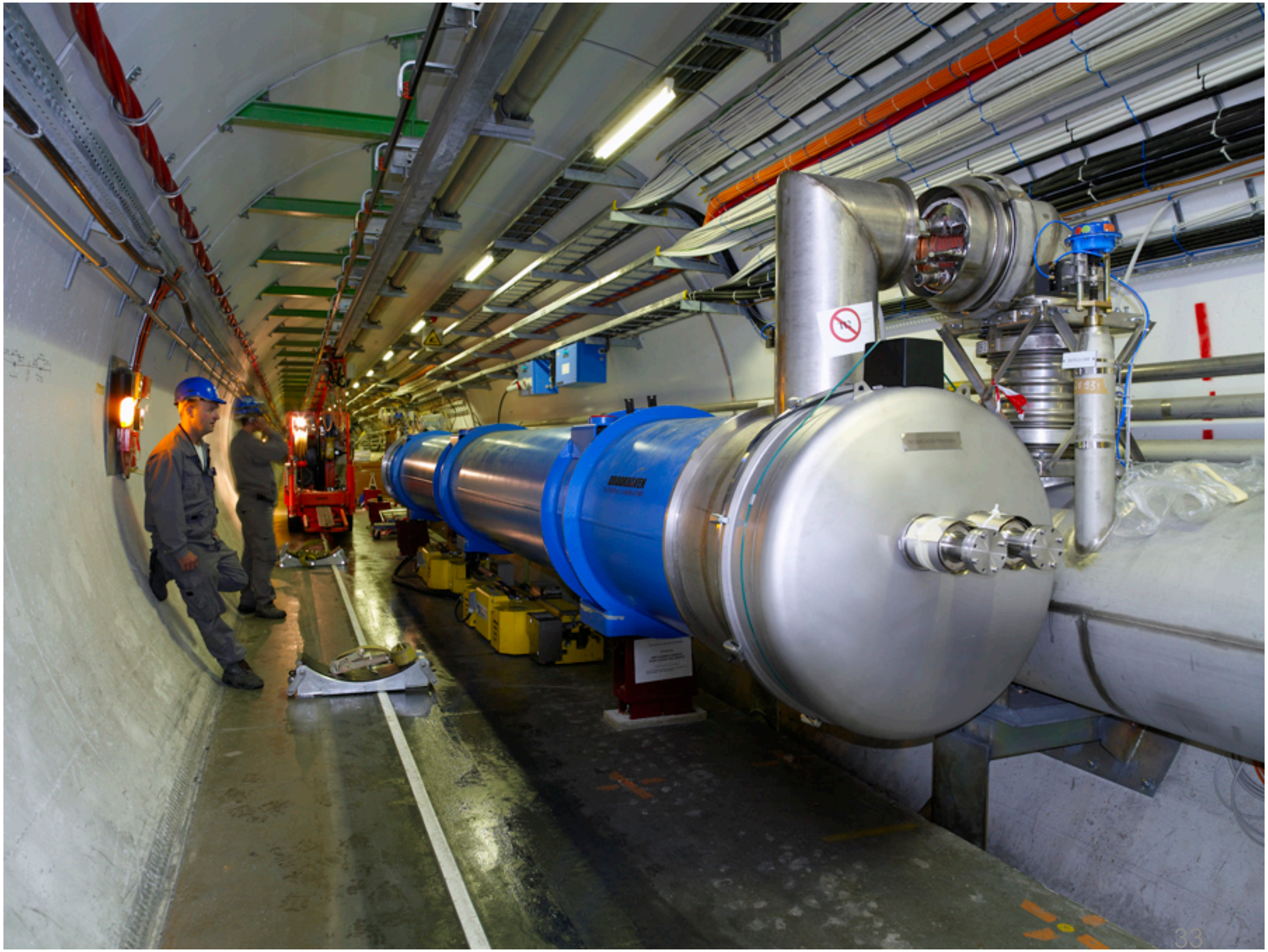
400 MHz RF system



In the tunnel

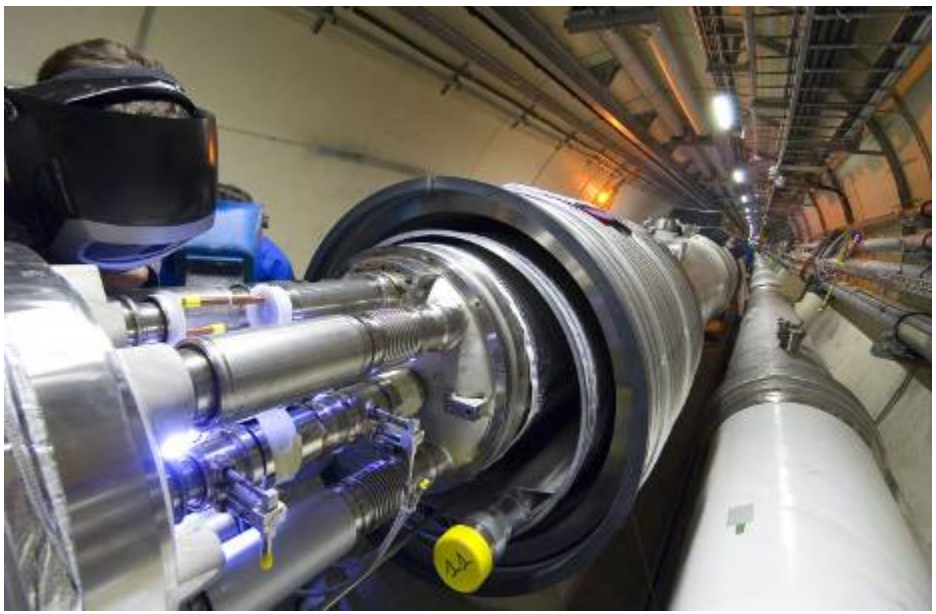
Jumper connecting cryogenic distribution line and magnets (once every ~100 m)

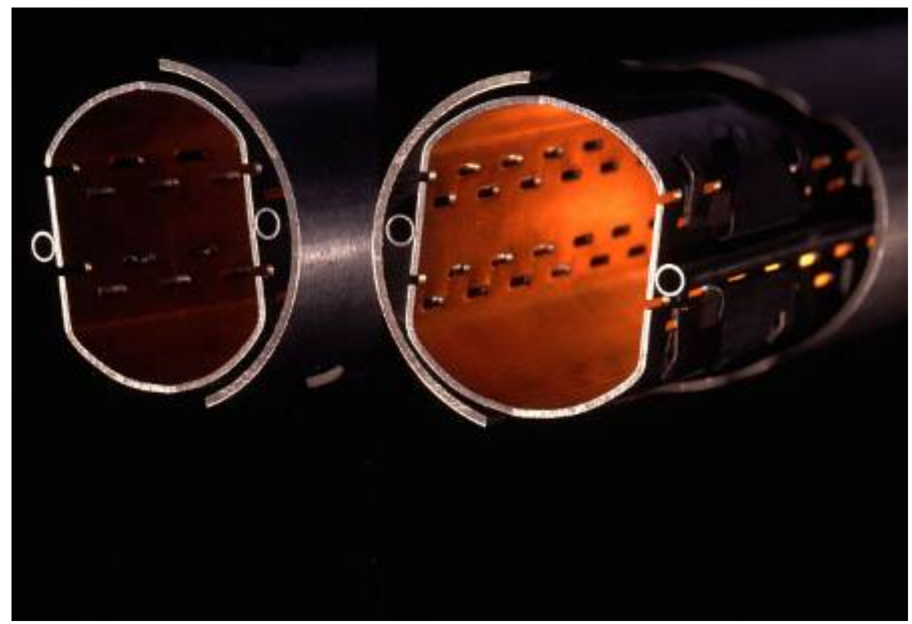
(early photo)



It’s Empty!

Air pressure inside the two 27Km-long vacuum pipes is lower than on the moon.



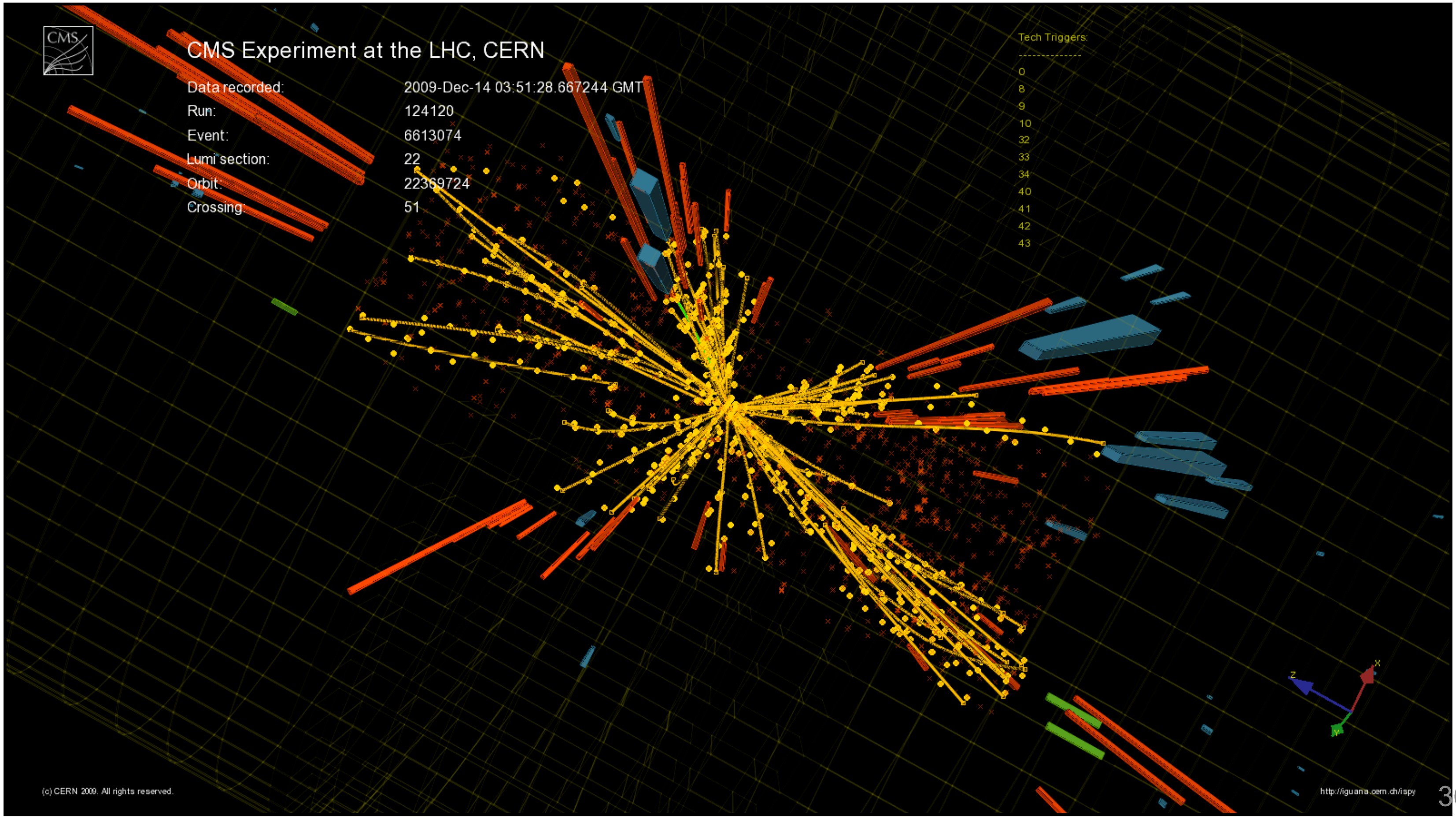


It’s Cold!

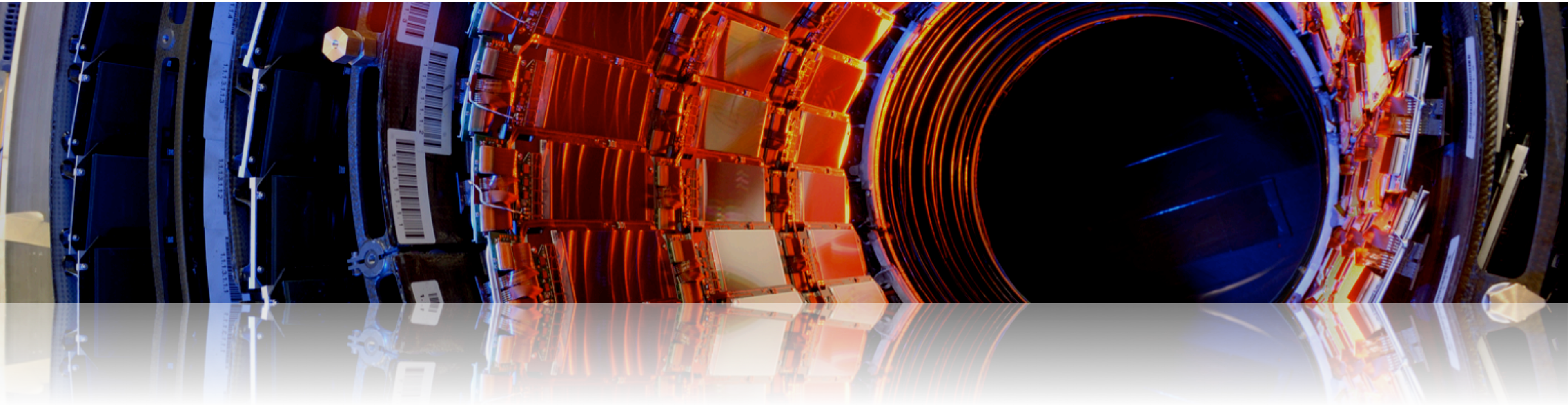
27 Km of magnets and connections are kept at 1.9 ^{o}K, colder than outer space, using over 100 tons of liquid helium.

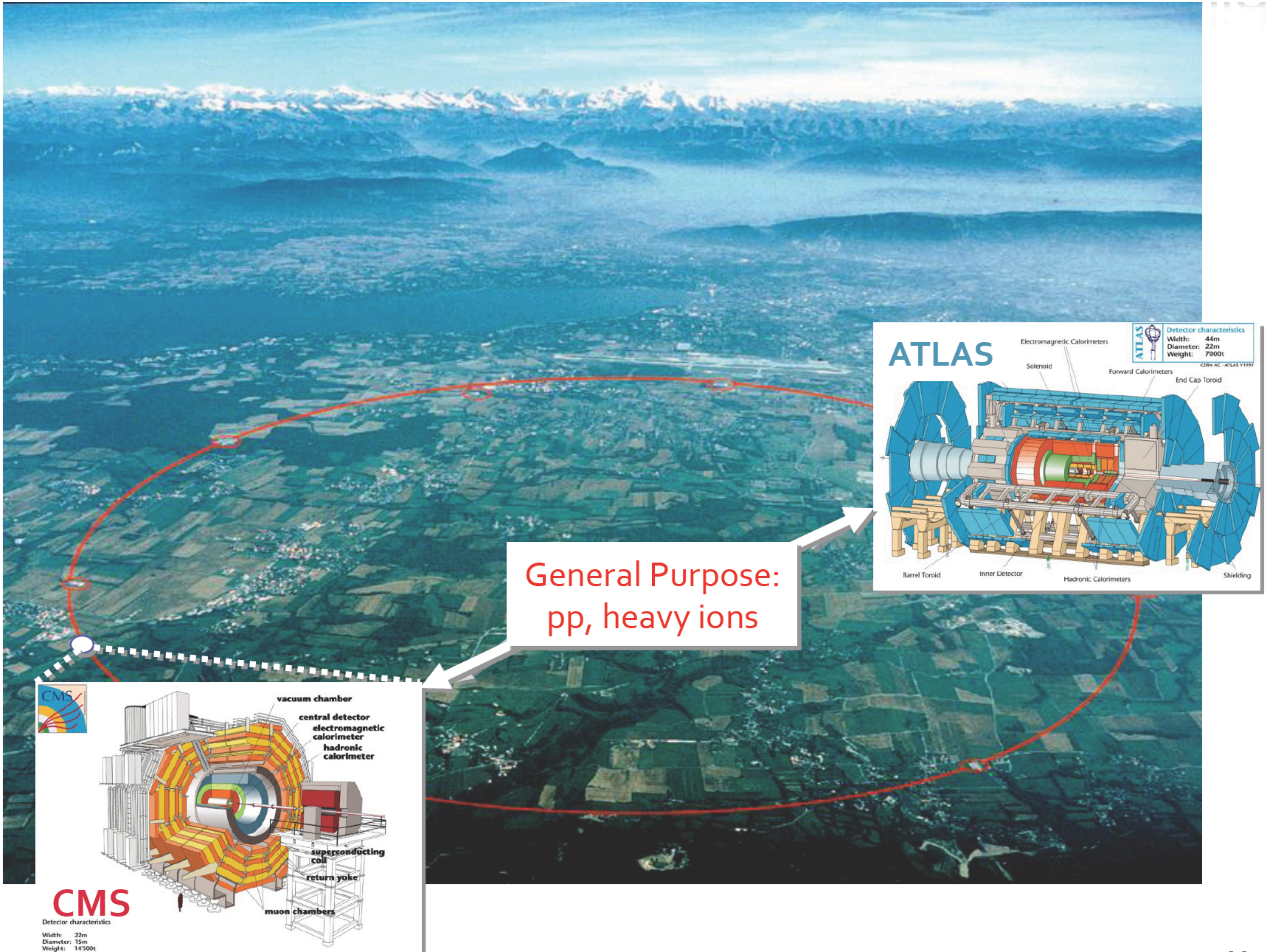
It’s Hot!

In a *tiny* volume, temperatures one billion times hotter than the center of the sun.



The Experiments

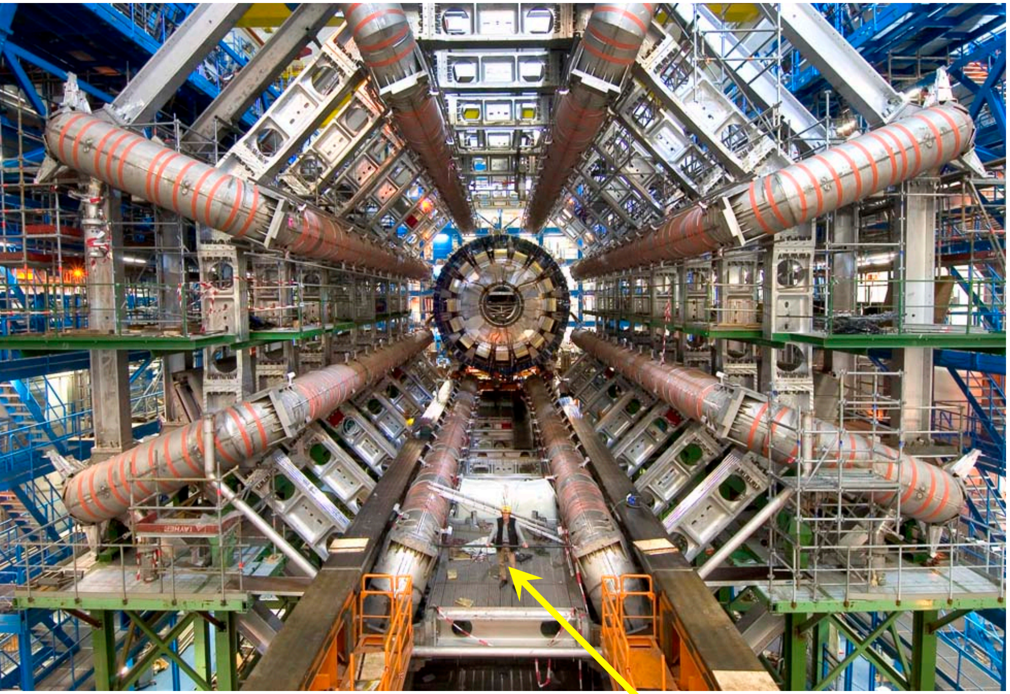


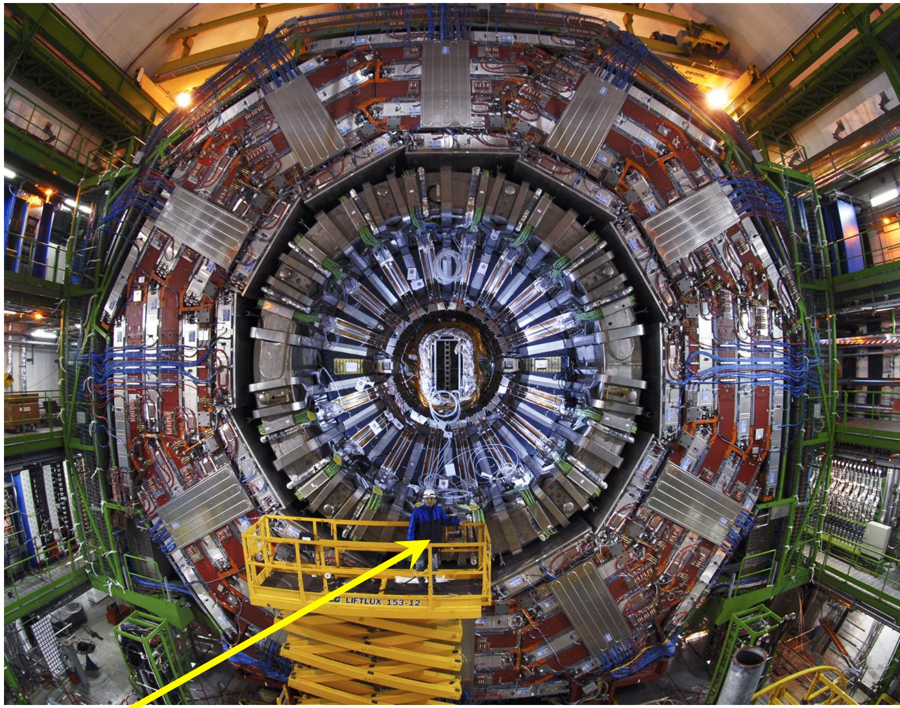

General Purpose:
pp, heavy ions
ATLAS
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
CMS
Detector characteristics
Width: 22m
Diameter: 15m
Weight: 14'500t

It’s huge!

Largest, most complex detectors ever built

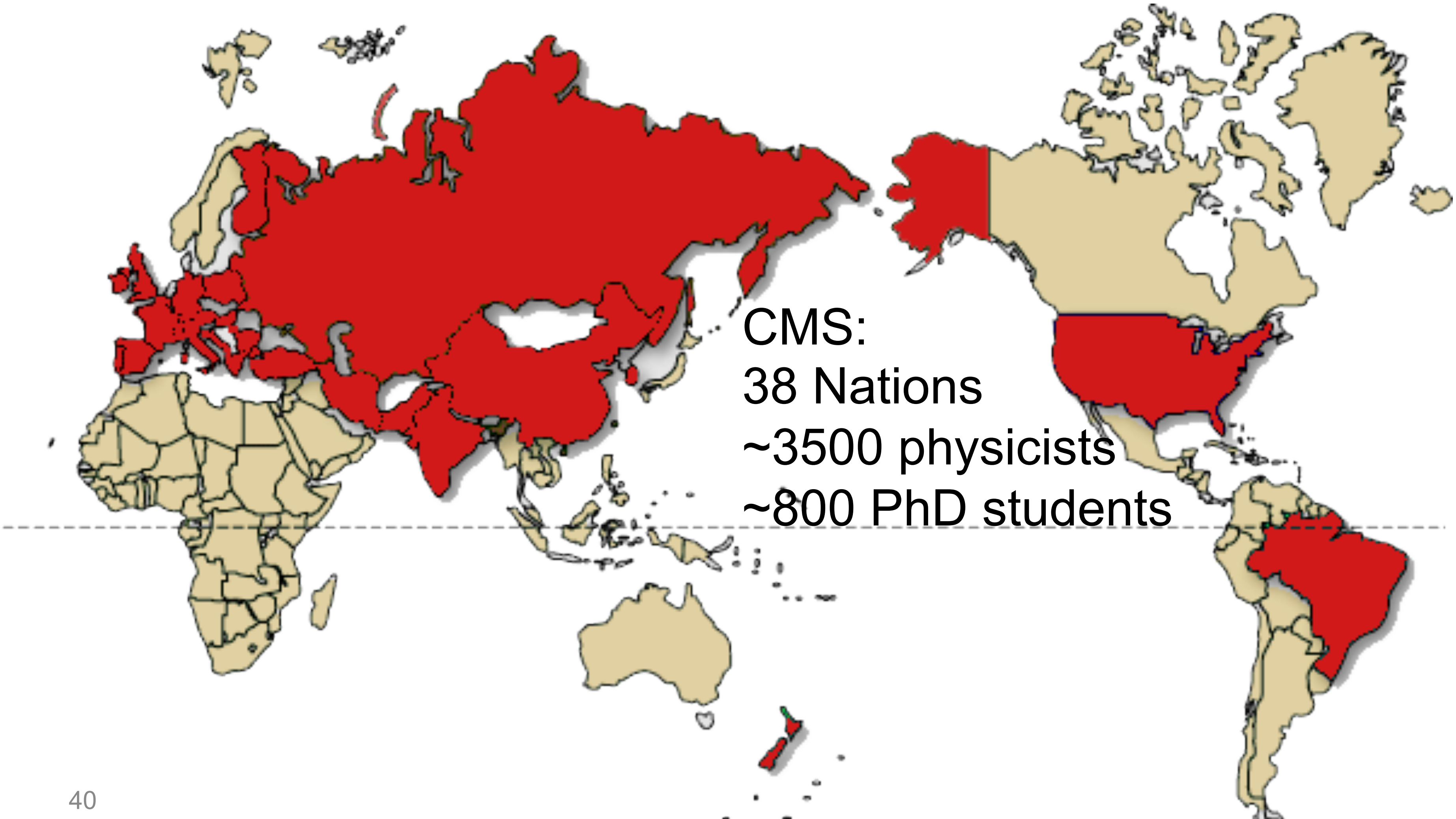
Study tiniest particles with incredible precision





(people)

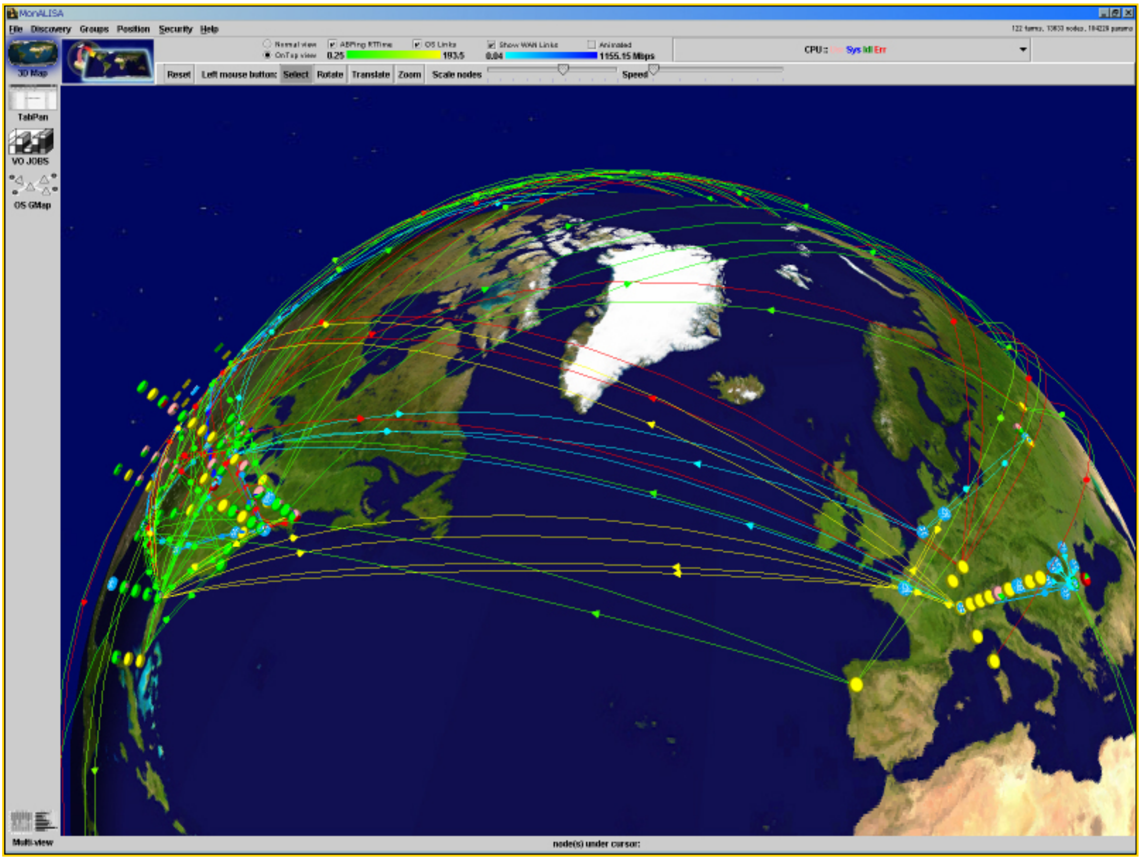
World-wide collaborations



CMS:
38 Nations
~3500 physicists
~800 PhD students

It’s complex!

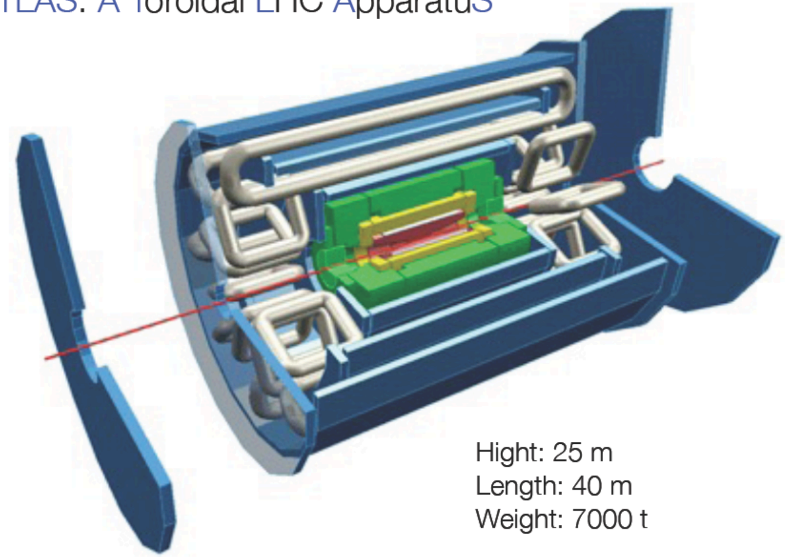
Worldwide LHC Computing Grid connects 100,000 processors in 34 countries with ultra-high-speed data transfers



Millions of Gigabytes of data each year.

Two concepts

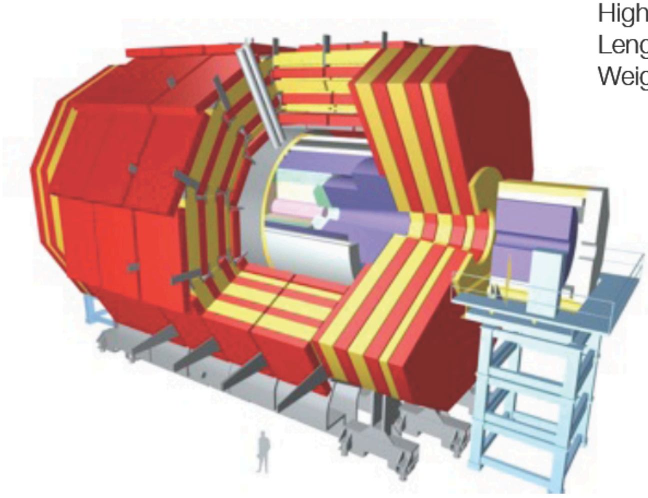
ATLAS: A Toroidal LHC ApparatuS

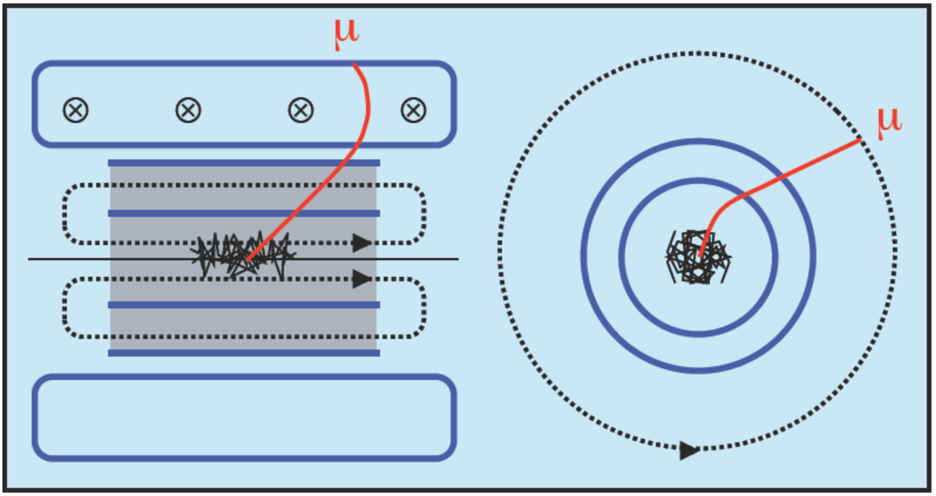


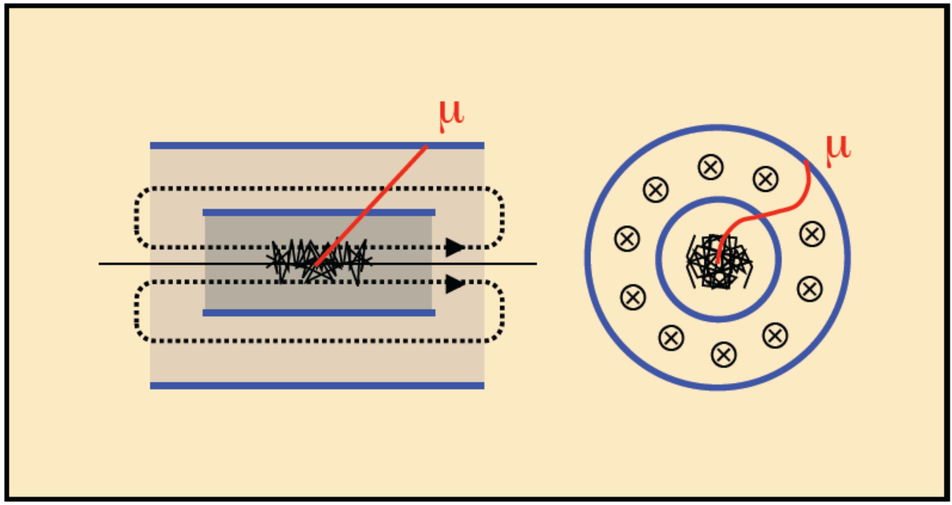
Hight: 25 m
Length: 40 m
Weight: 7000 t

CMS: Compact Muon Solenoid

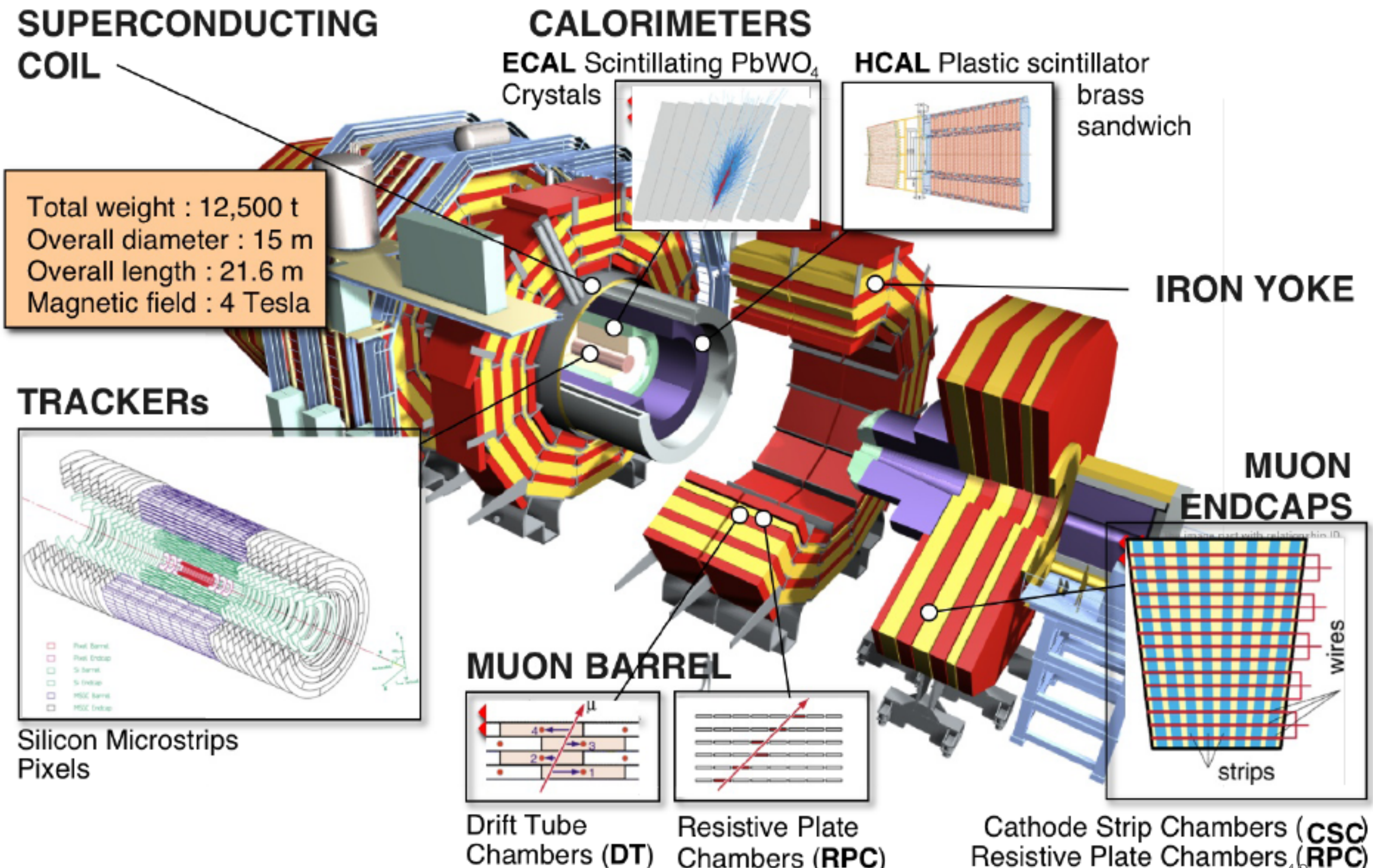
Hight: 15 m
Length: 22 m
Weight: 12500 t

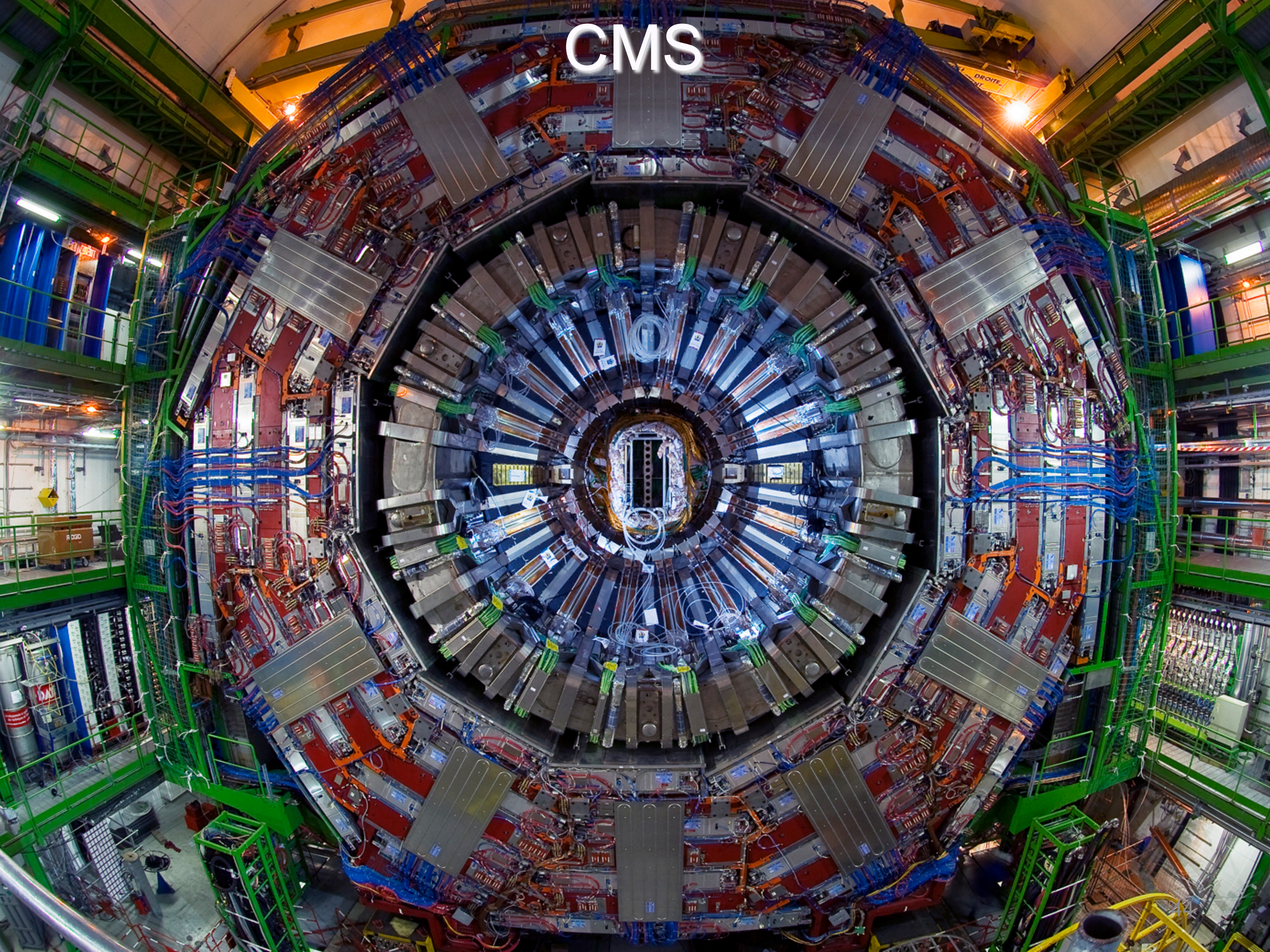




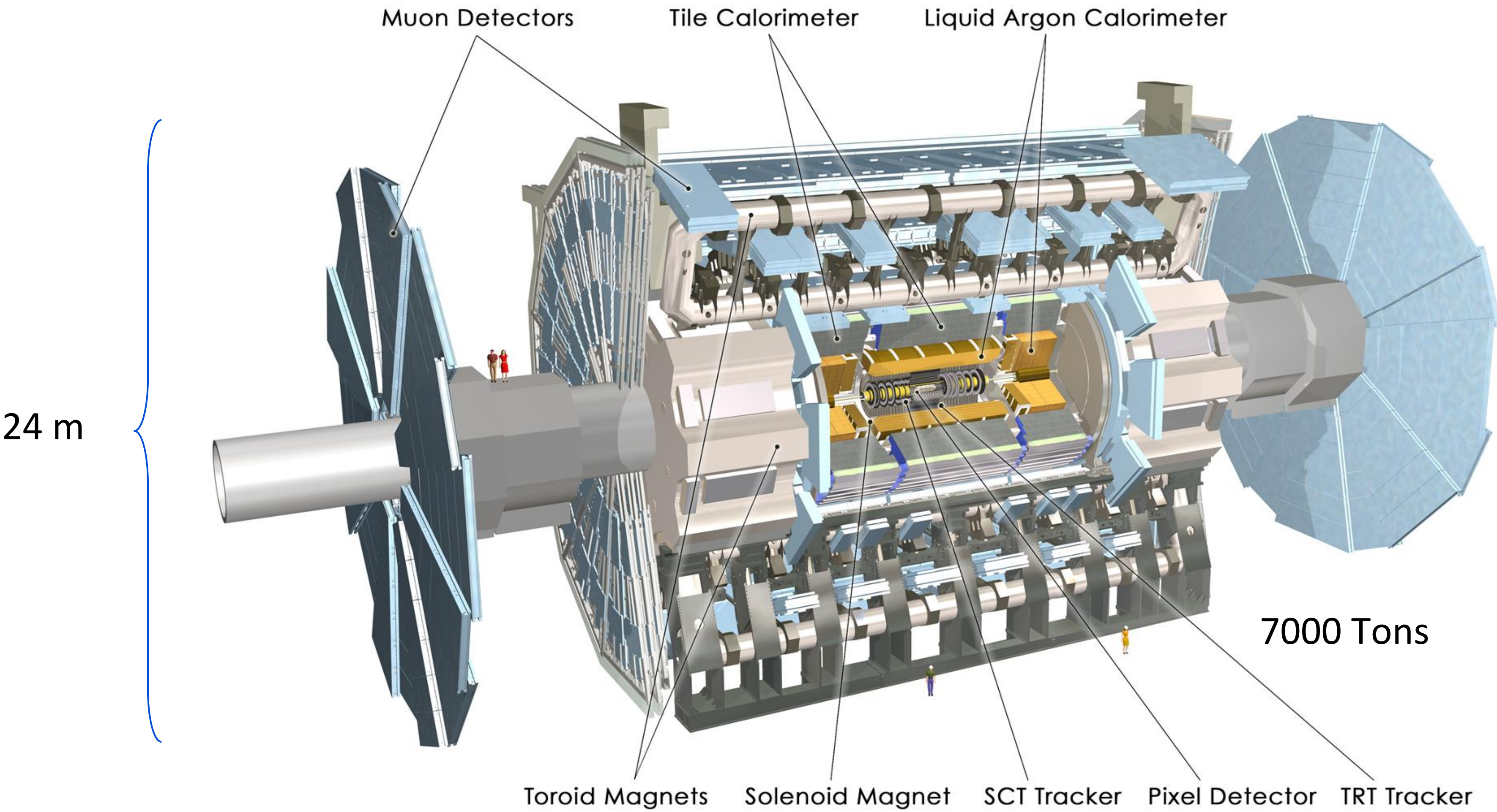


CMS detectors

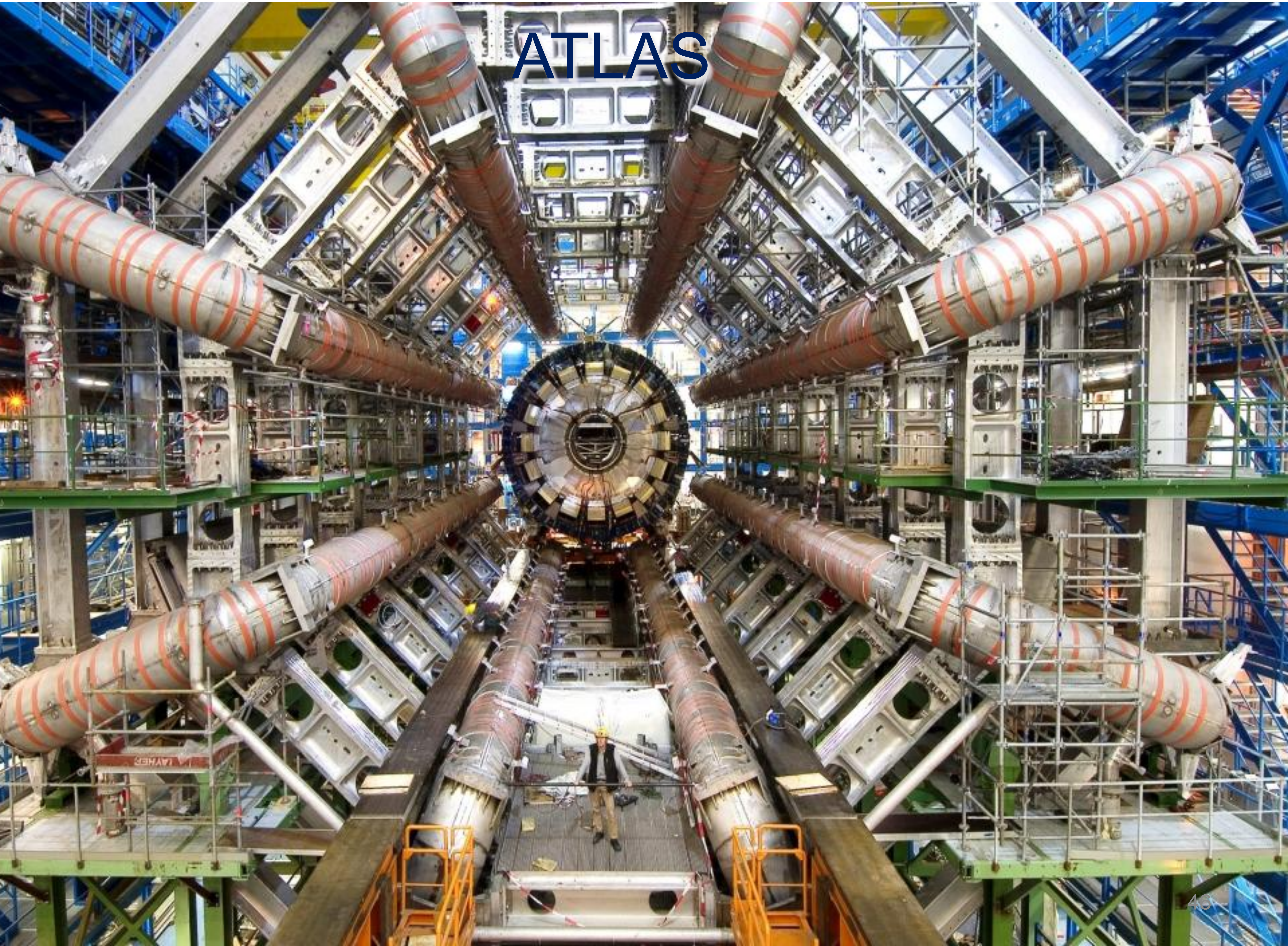



CMS

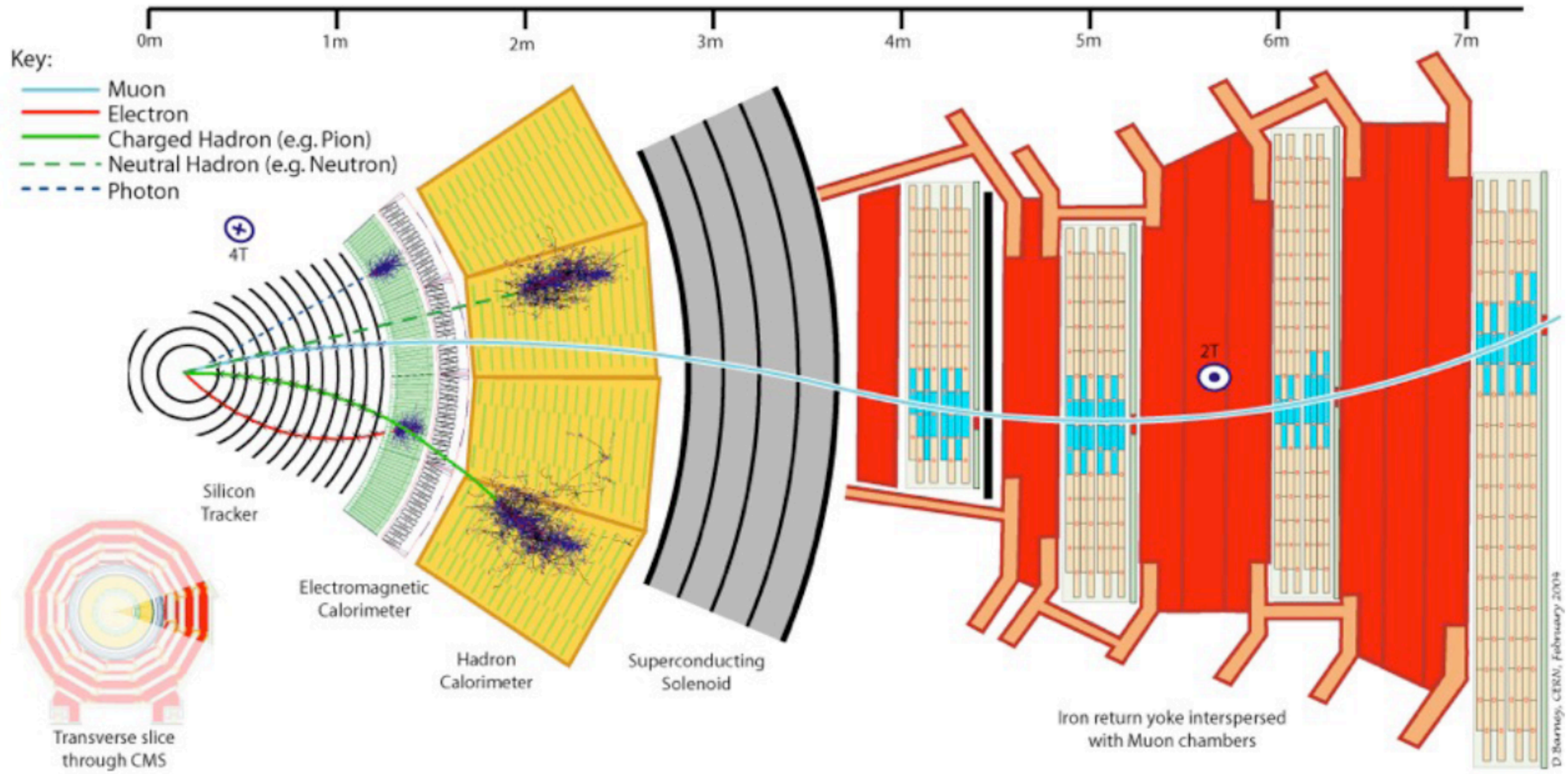
ATLAS detectors



ATLAS



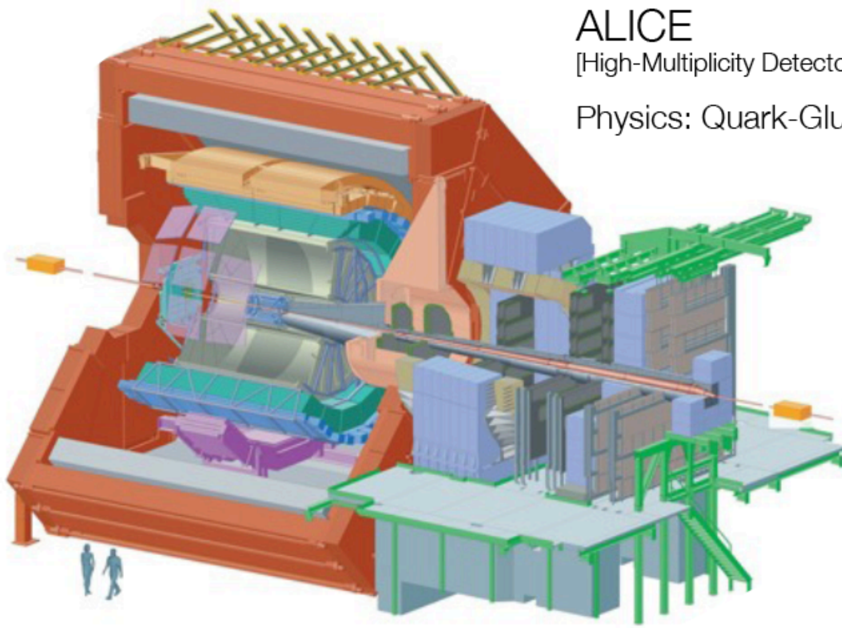
Detection of hadrons, $e^\pm$, γ and $\mu^\pm$



ATLAS vs. CMS

ATLAS		CMS
Silicon pixels; Silicon strips; Transition Radiation Tracker; 2 T magnetic field	Inner Detector	Silicon pixels, Silicon strips, 4 T magnetic field
Lead plates as absorbers; active medium: liquid argon; outside solenoid	Electrom. Calorimeter	Lead tungsten ($PbWO_4$) crystals; both absorber and scintillator; inside solenoid
Central region: Iron absorber with plastic scintillating tiles; Endcaps: copper and tungsten absorber with liquid argon	Hadronic Calorimeter	Stainless steel and copper with plastic scintillating tiles
Large air-core toroid magnet; muon chambers: drift tubes and resistive plate chambers; 0.5 T magnetic field	Muon Chambers	Magnetic field from return yoke (solenoid field: 4 T); muon chambers: drift tubes and resistive plate chambers

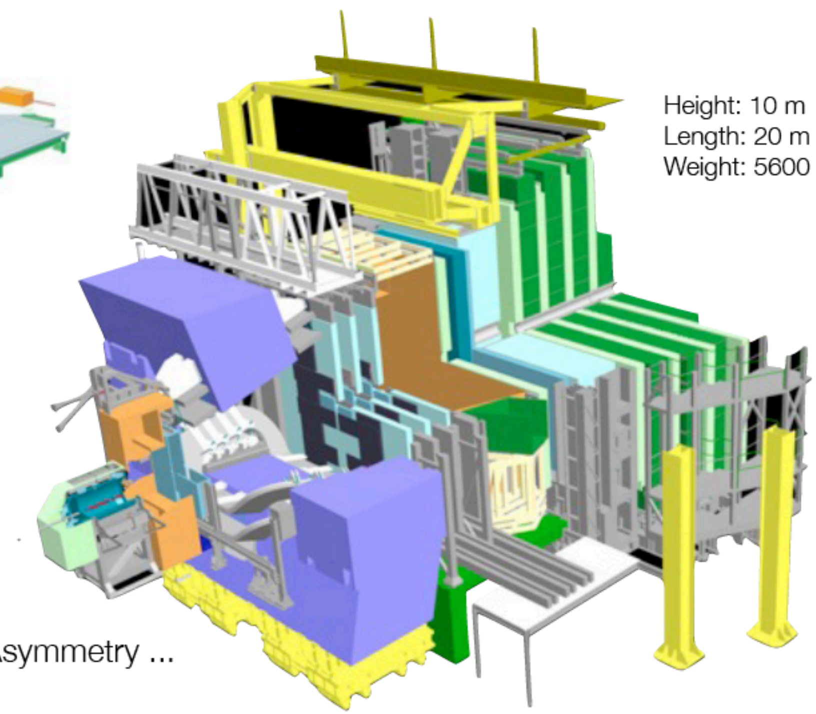
ALICE & LHCb



ALICE
[High-Multiplicity Detector]

Physics: Quark-Gluon Plasma ...

Height: 16 m
Length: 25 m
Weight: 10000 t



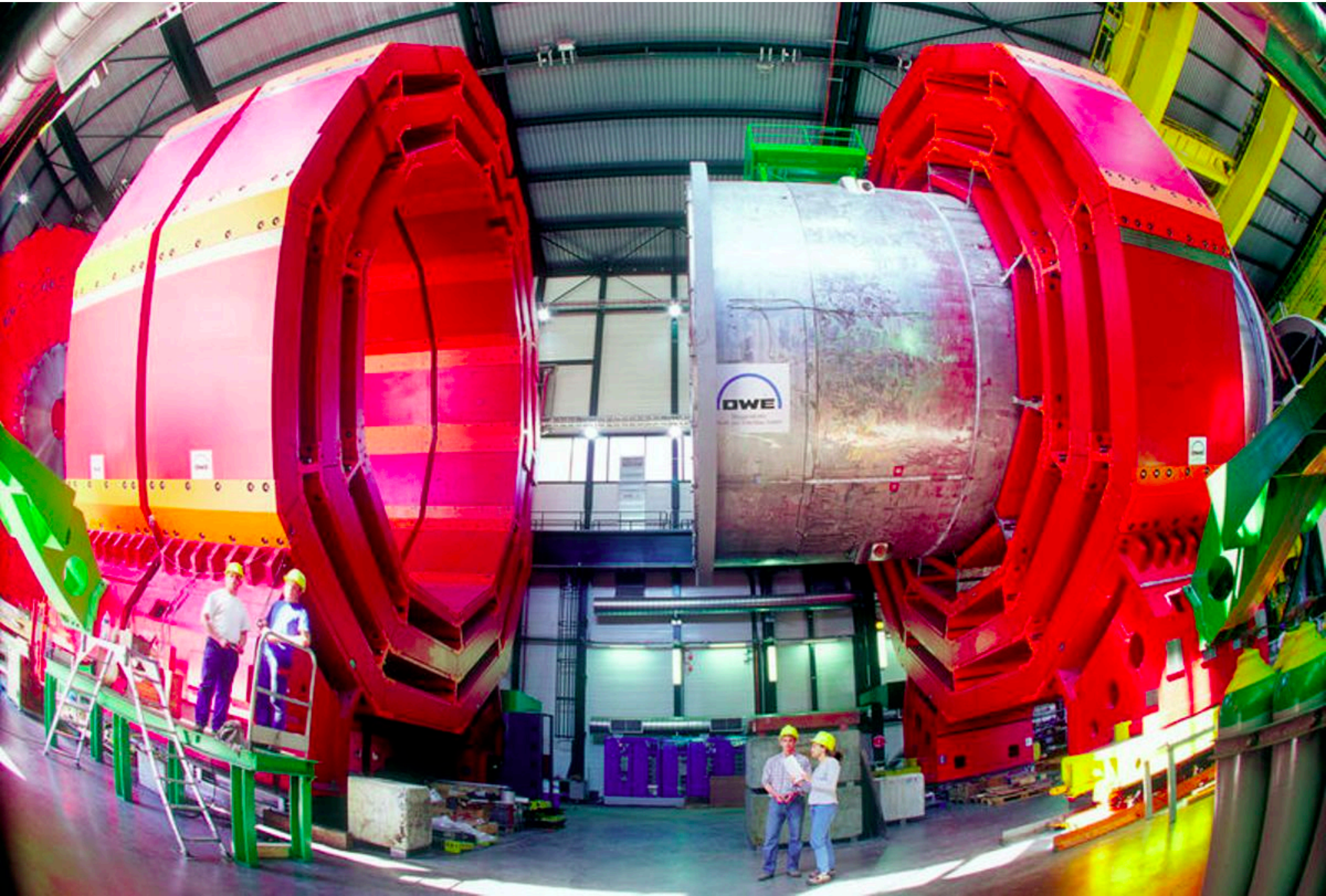
Height: 10 m
Length: 20 m
Weight: 5600 t

LHCb
[Forward Spectrometer]

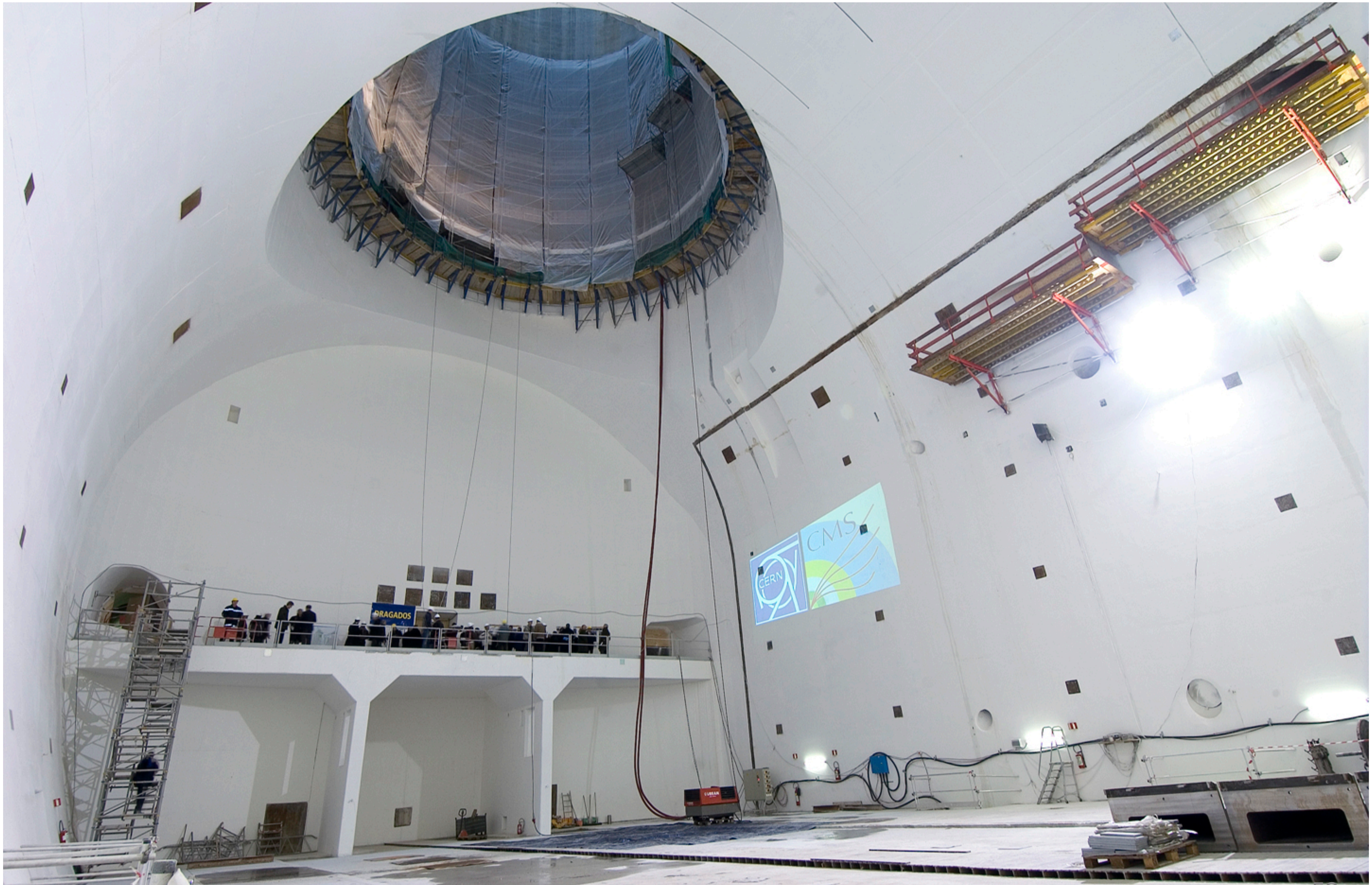
Physics: Matter/Antimatter-Asymmetry ...

1995-2006: Detector R&D and construction

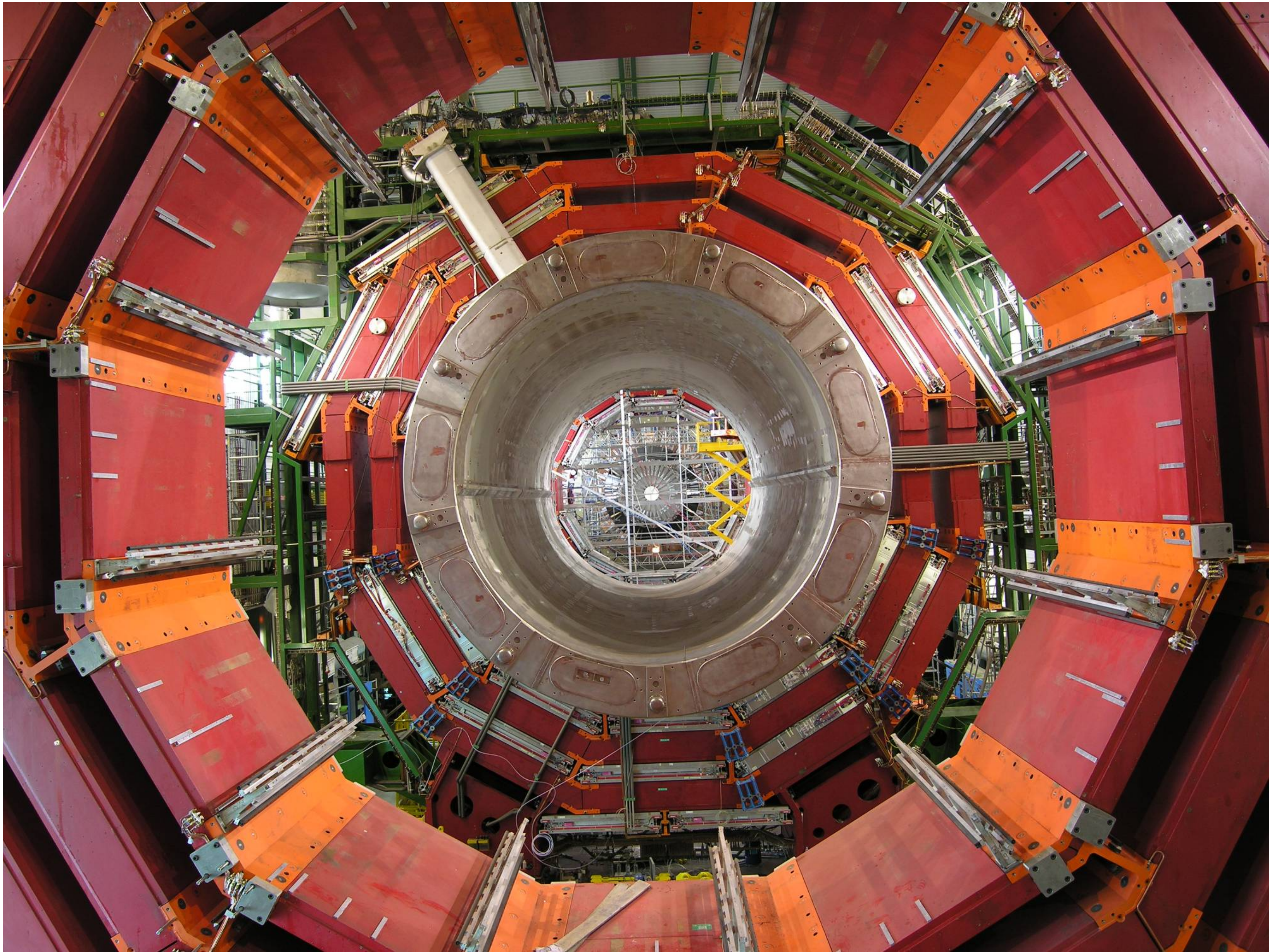
2002: CMS iron yoke assembly in surface hall



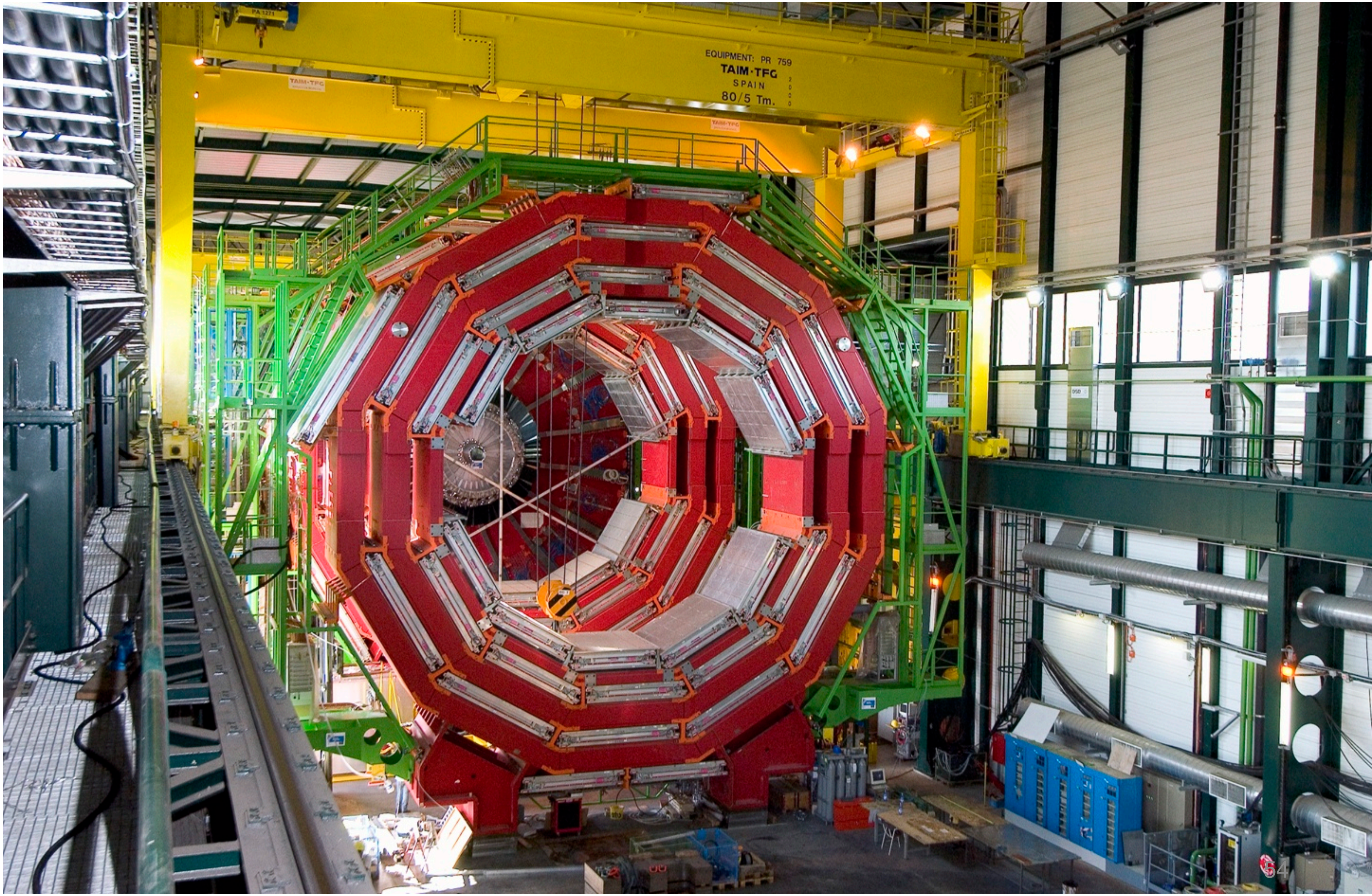
2004: CMS detector cavern



2005: Superconducting solenoid installed

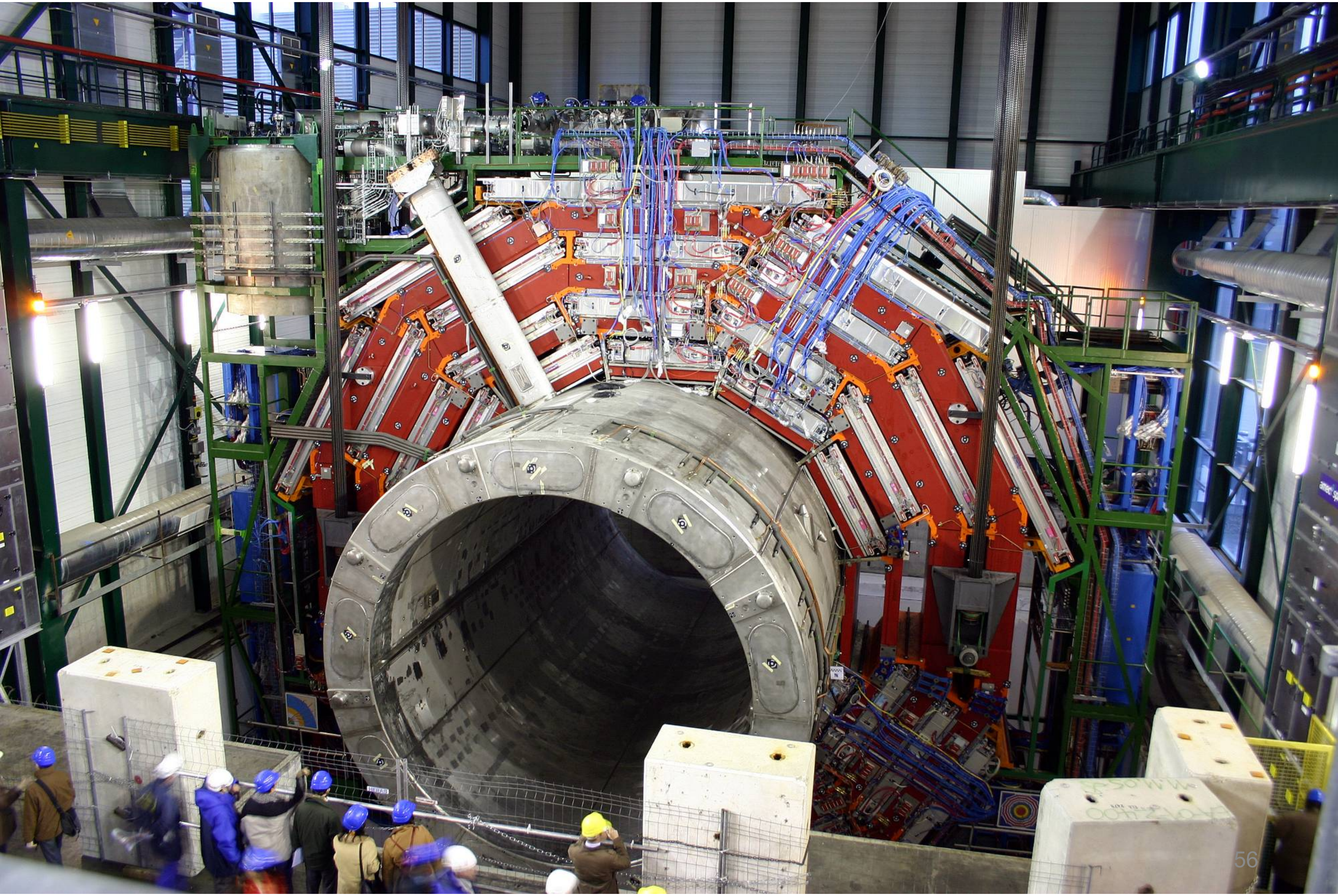


2005-06: Muon chambers inserted in iron yoke

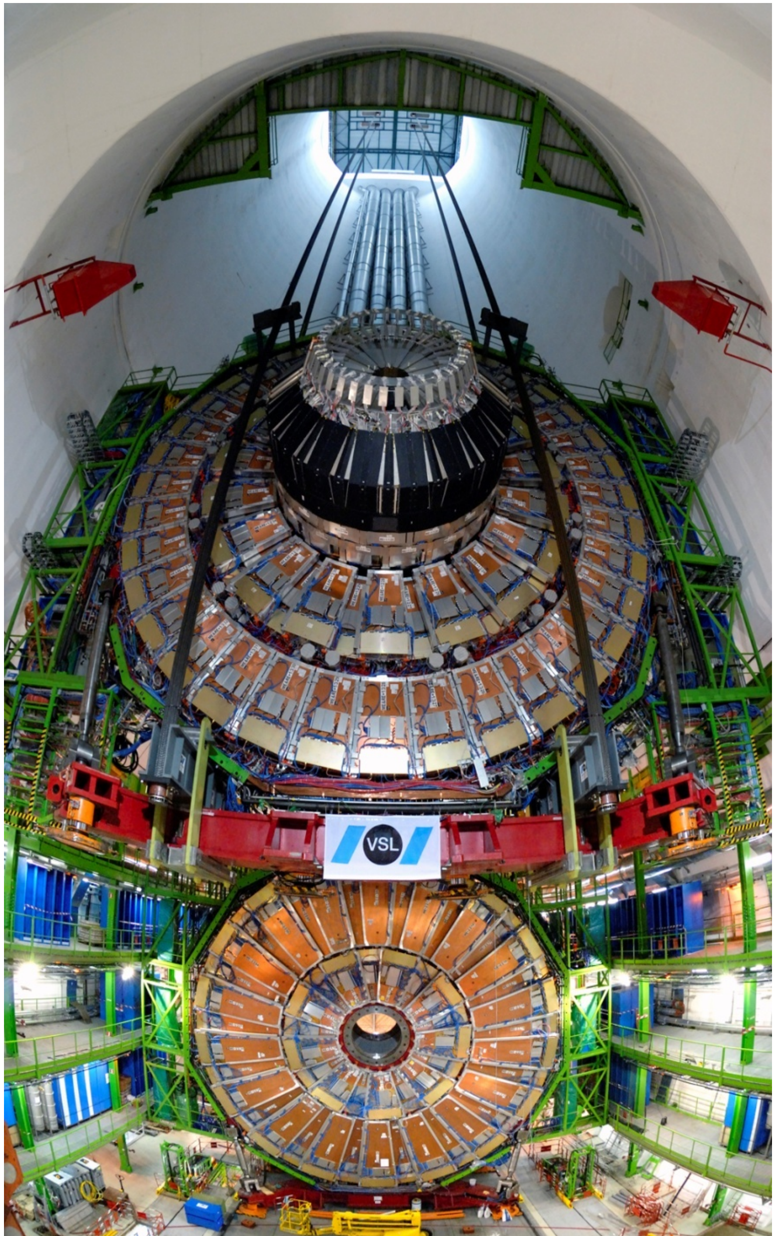


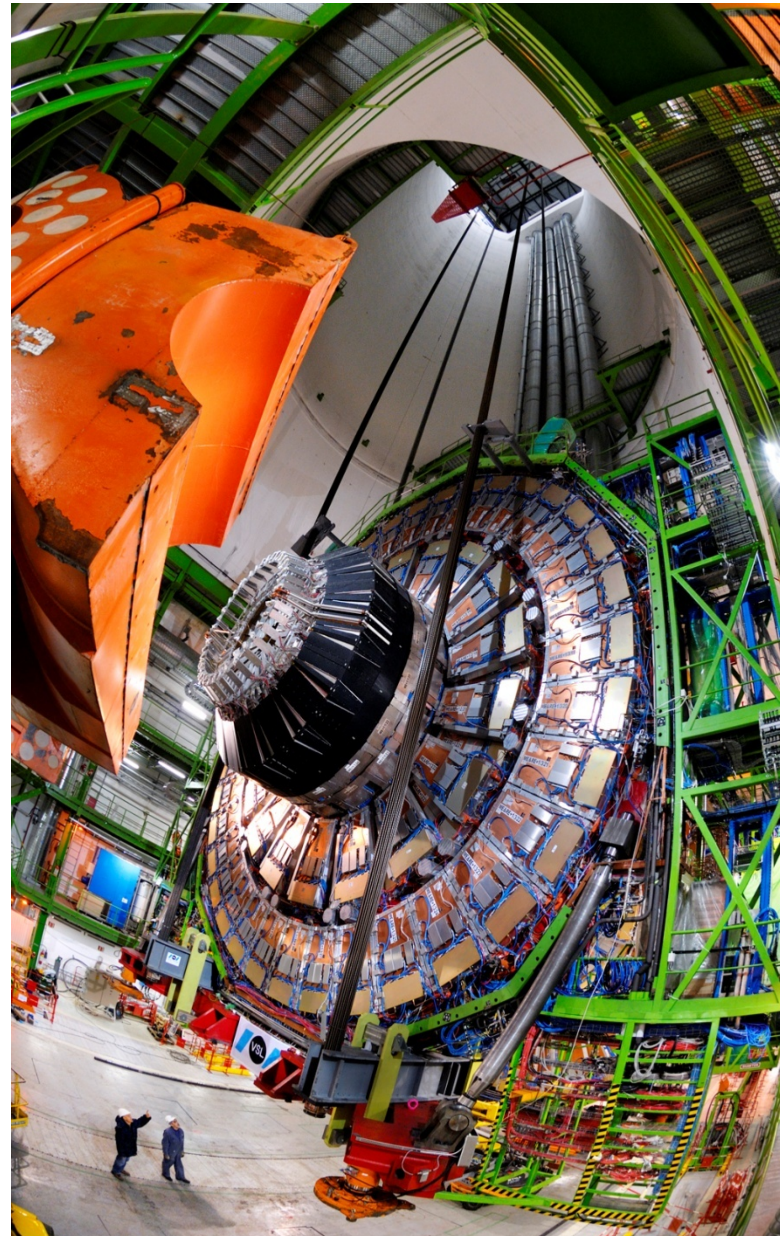
2006: Magnet test on the surface

2007: Lowering central wheel

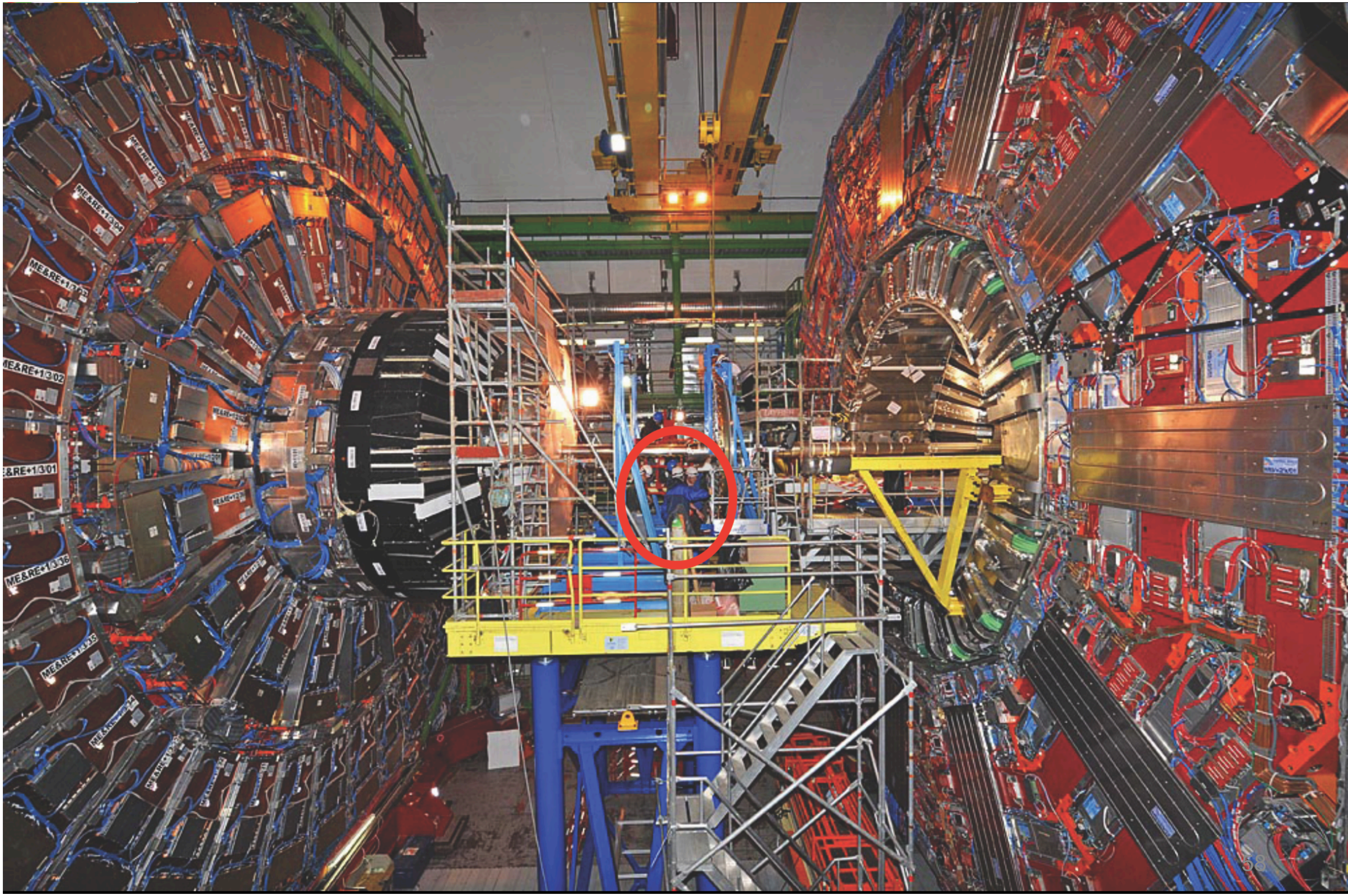


2007: Lowering the endcap wheels

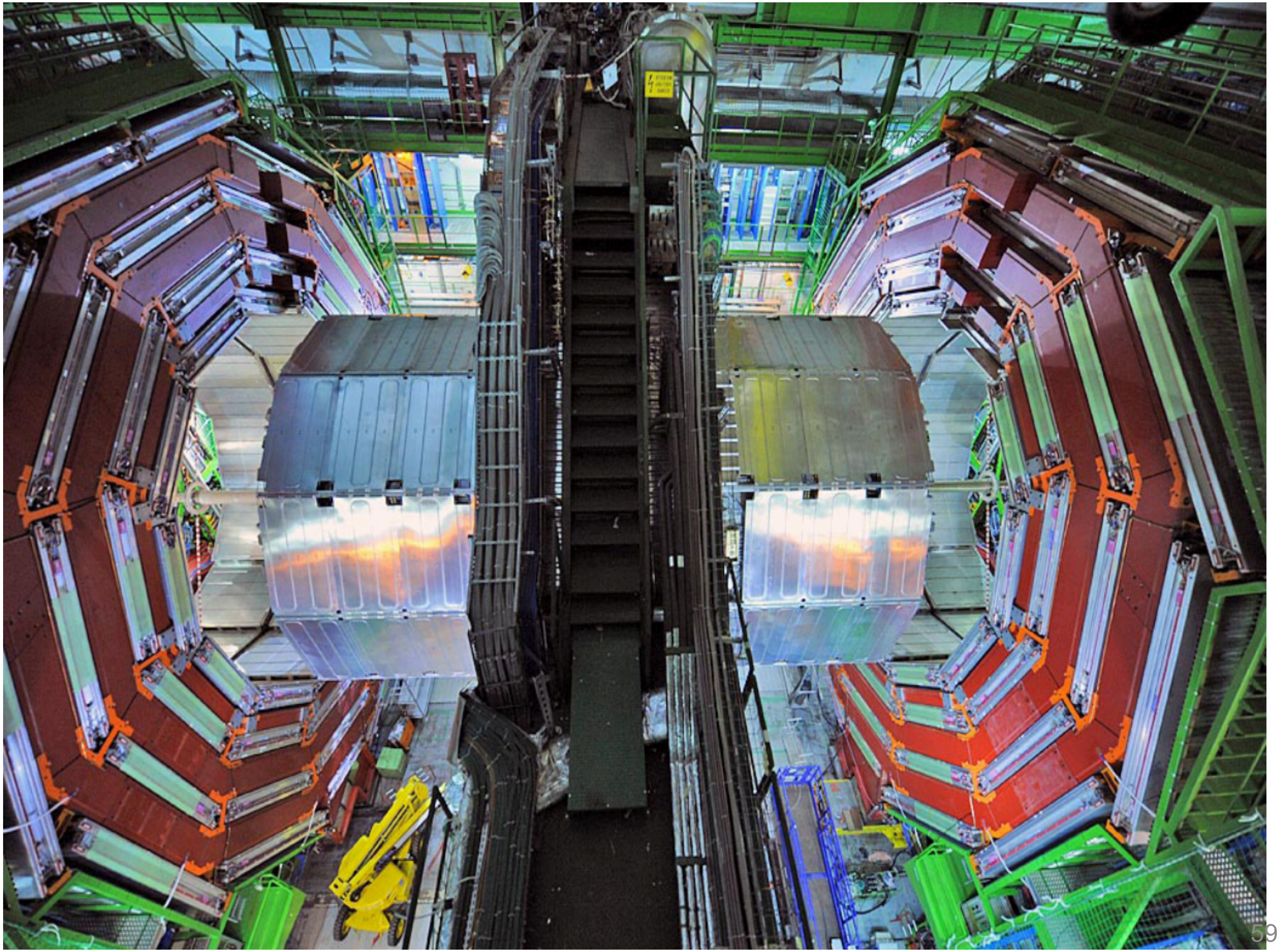




2007-08: Installation in the cavern

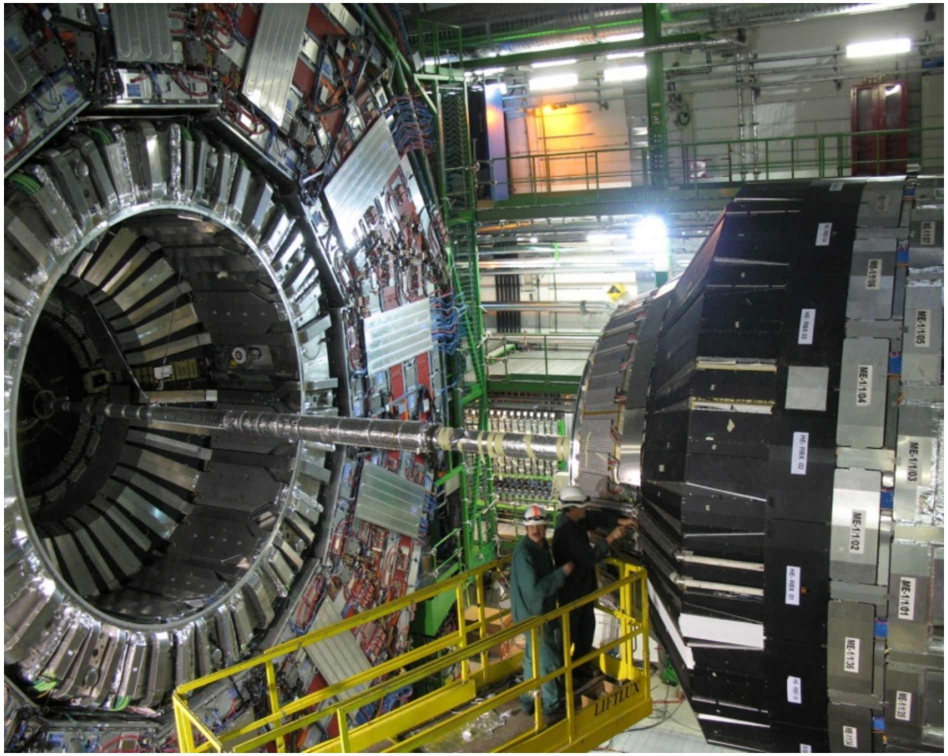


2008: CMS ready to close

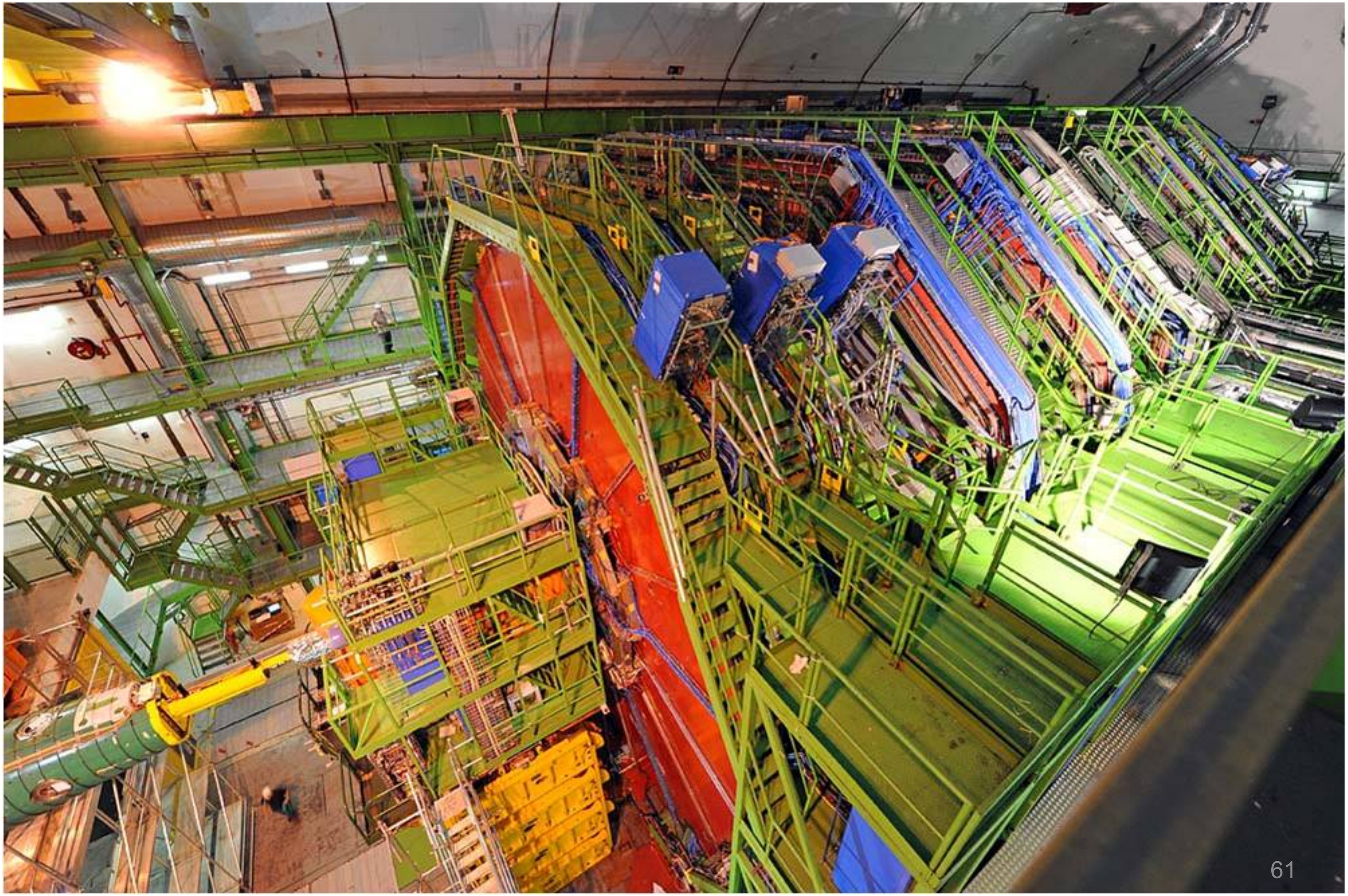


2008: CMS closing up…

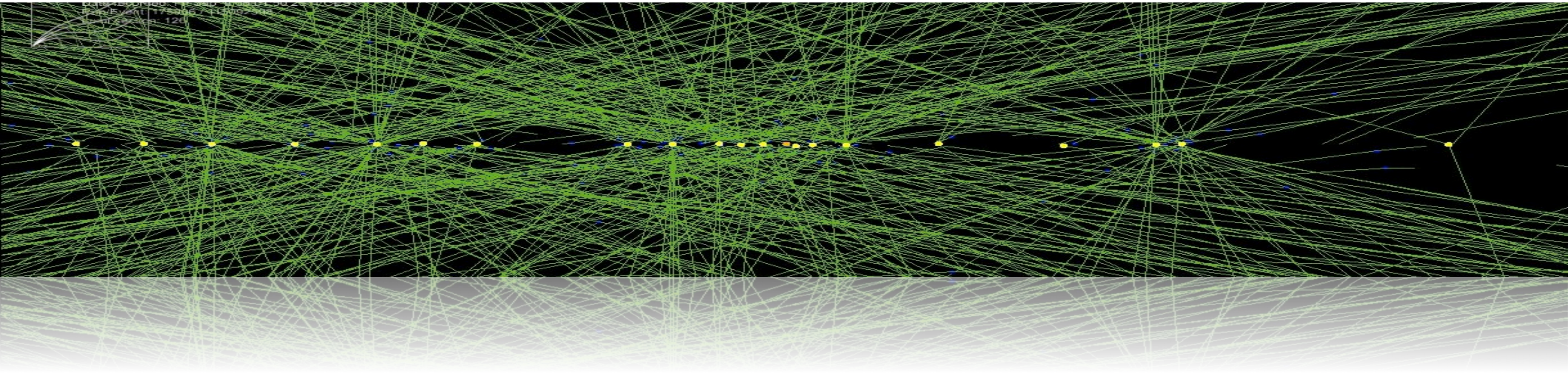
CMS closed: August 08



2008: CMS detector ready for beams



Experimental challenges



LHC pp-Interaction Rate

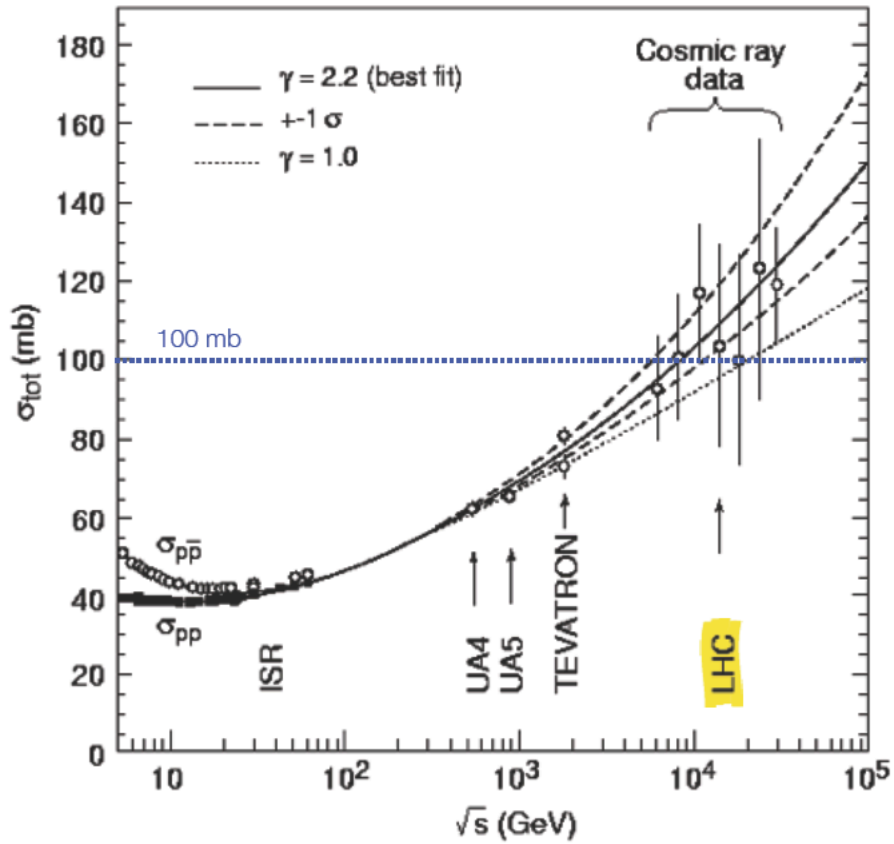
Luminosity:

$L = 10^{34}\ cm^{-2}s^{-1}$
$= 10^{7}$ Hz/mb

Cross section:

$\sigma \approx 100$ mb

➡ $N = L\sigma \approx 1$ GHz

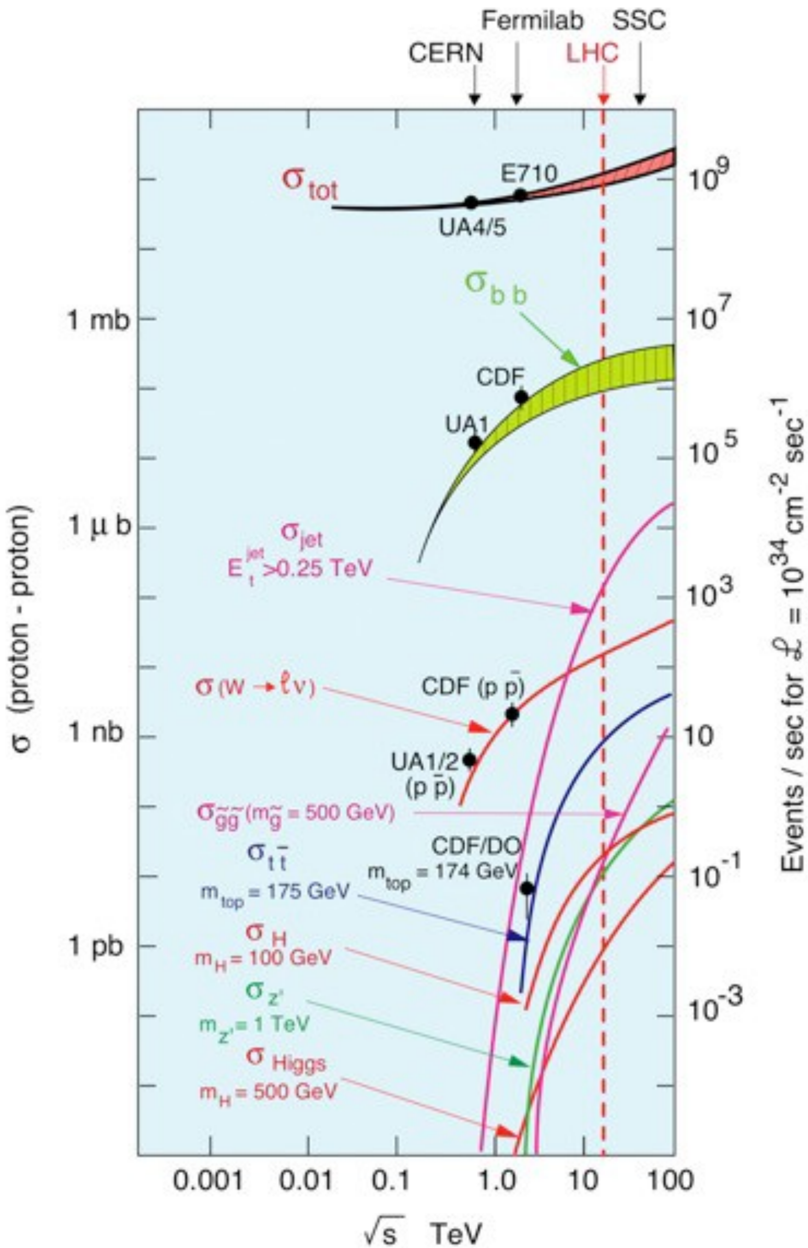


However:

Bunch crossing rate: 40 MHz
∴ Interactions/crossing ~ 25

This is a real challenge !

Proton-proton cross-sections



10^9 Events/sec
[1 Mbyte/Event]

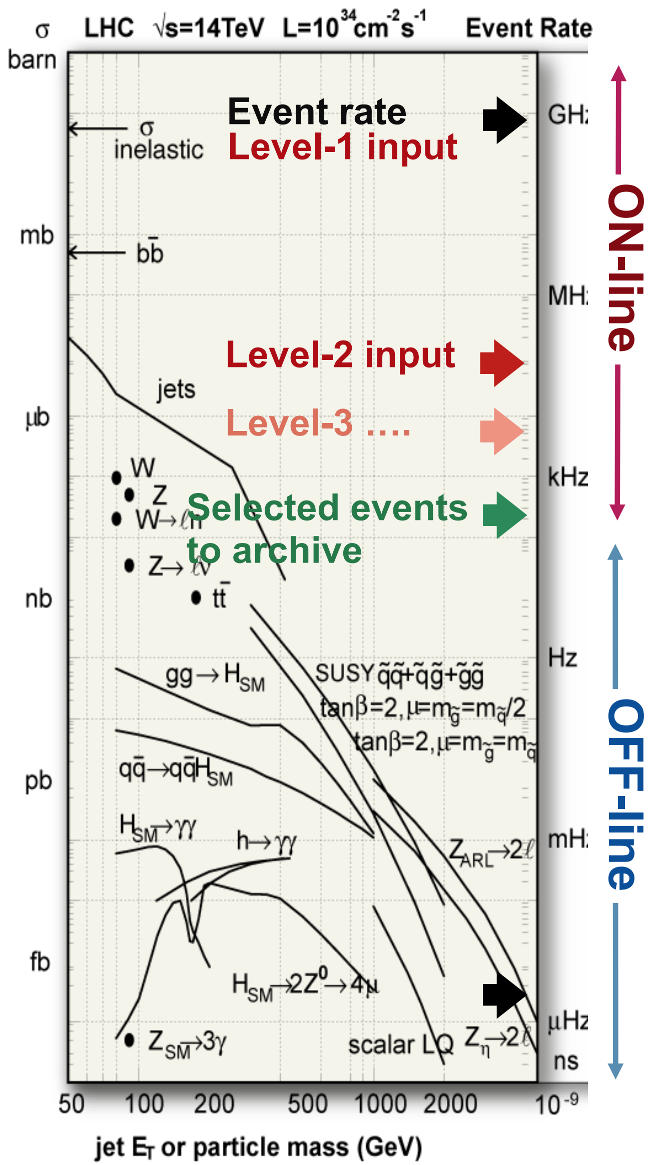
Efficient
rate reduction needed

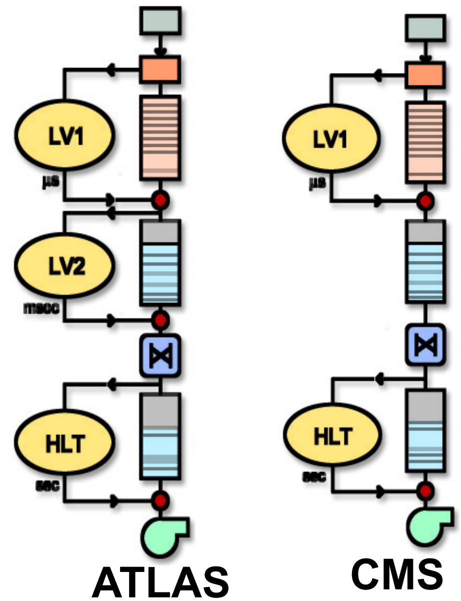
[Storage rate: 100 Hz]

10 Events/min
[$m_H \approx 100$ GeV]

with 0.2% $H \rightarrow \gamma\gamma$
1.5% $H \rightarrow ZZ$

Multi-level trigger





On-line requirements

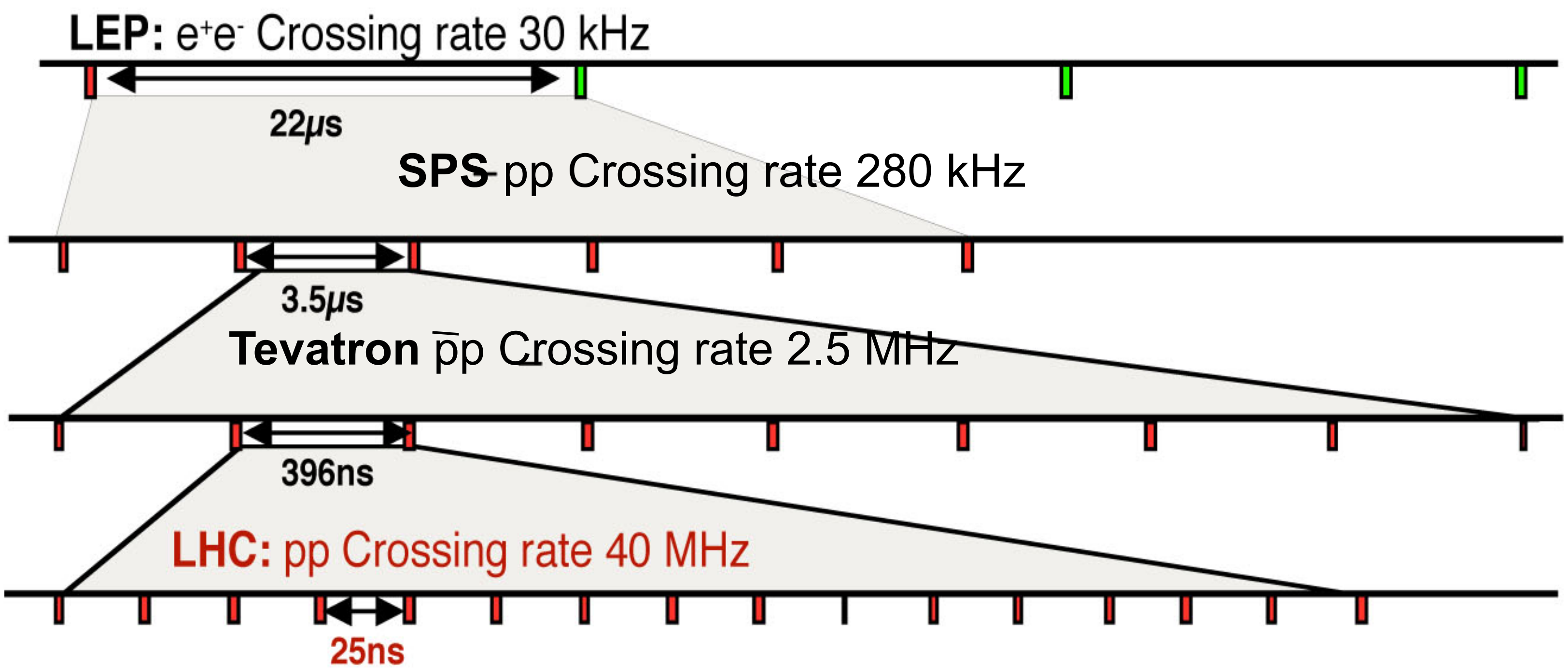
Crossing rate	40 MHz
Event size	1 Mbyte
Level-1 Trigger input	40 MHz
Level-2 Trigger input	100 kHz
……	
Mass storage rate	~300 Hz
Online rejection	99.999%

DAQ design issues

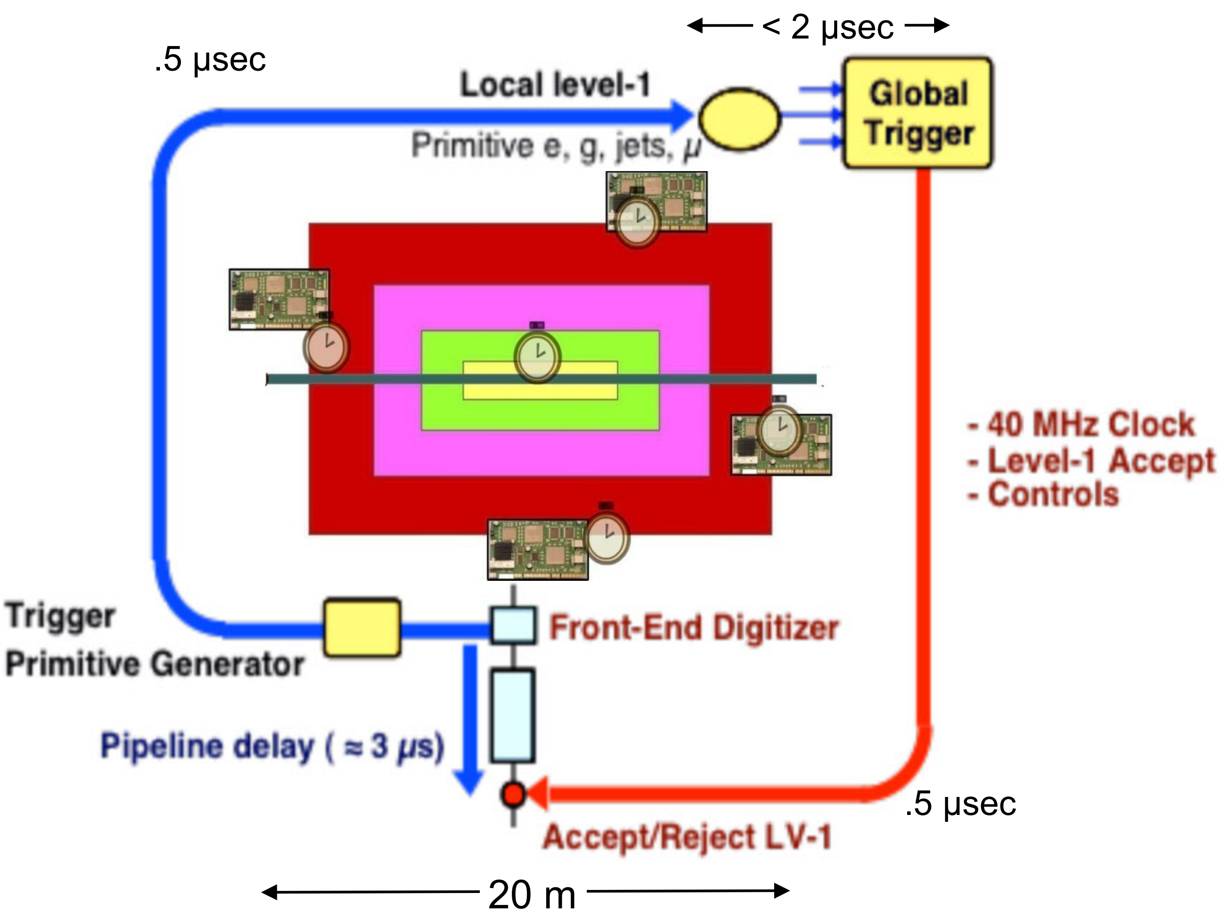
Data network bandwidth (EVB)	~ Tb/s
Computing power (HLT)	~ 10 Tflop
Computing cores	~ 10000
Local storage	~ 300 TB

Bunch crossing frequency

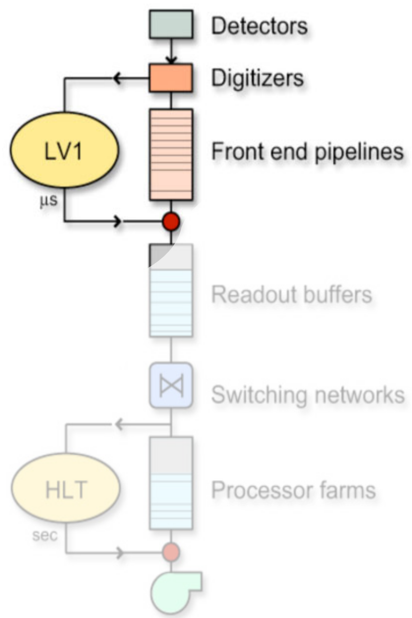
	(2012)
▪ LHC has 3564 bunches (2835 filled with protons)	1400
▪ Crossing rate is 40 MHz	20 MHz
▪ Distance between bunches: 27km / 3600 = 7.5m	15.0 m
▪ Distance between bunches in time: 7.5m / c = 25ns	50 ns
▪ Proton-proton collision per bunch crossing: ~ 20	<35



Level 1 trigger and front-end readout

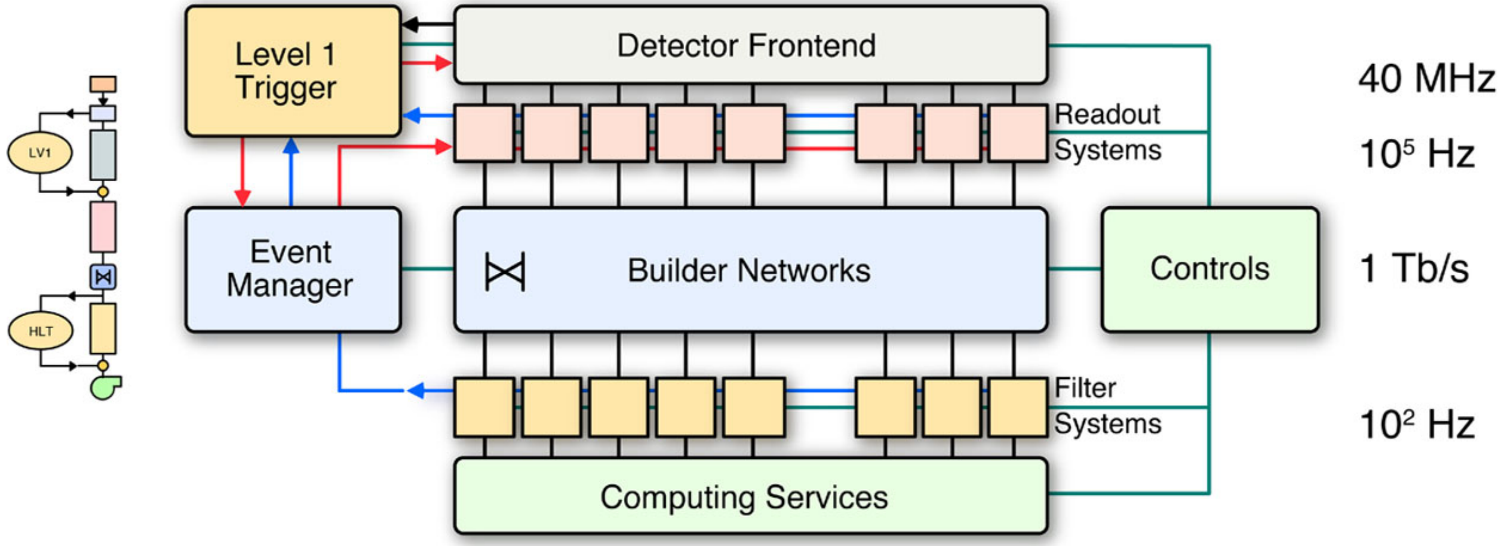


Front-end pipeline readout



- 40 MHz digitizers and pipeline readout buffers (128 steps ~ 3 μs)
- 40 MHz Level-1 trigger (massive parallel pipelined processors)
- High precision (~ 100ps) timing, trigger and control distribution

High level trigger



- High Level Triggers (HLT)
- HLT (~5000 CPUs) accesses full event info seeded by L1 objects
- HLT: available 100 ms per event
- Flexibility: full event info and offline reconstruction after L1
- Large data throughput in event builder network (1 Tb/s)

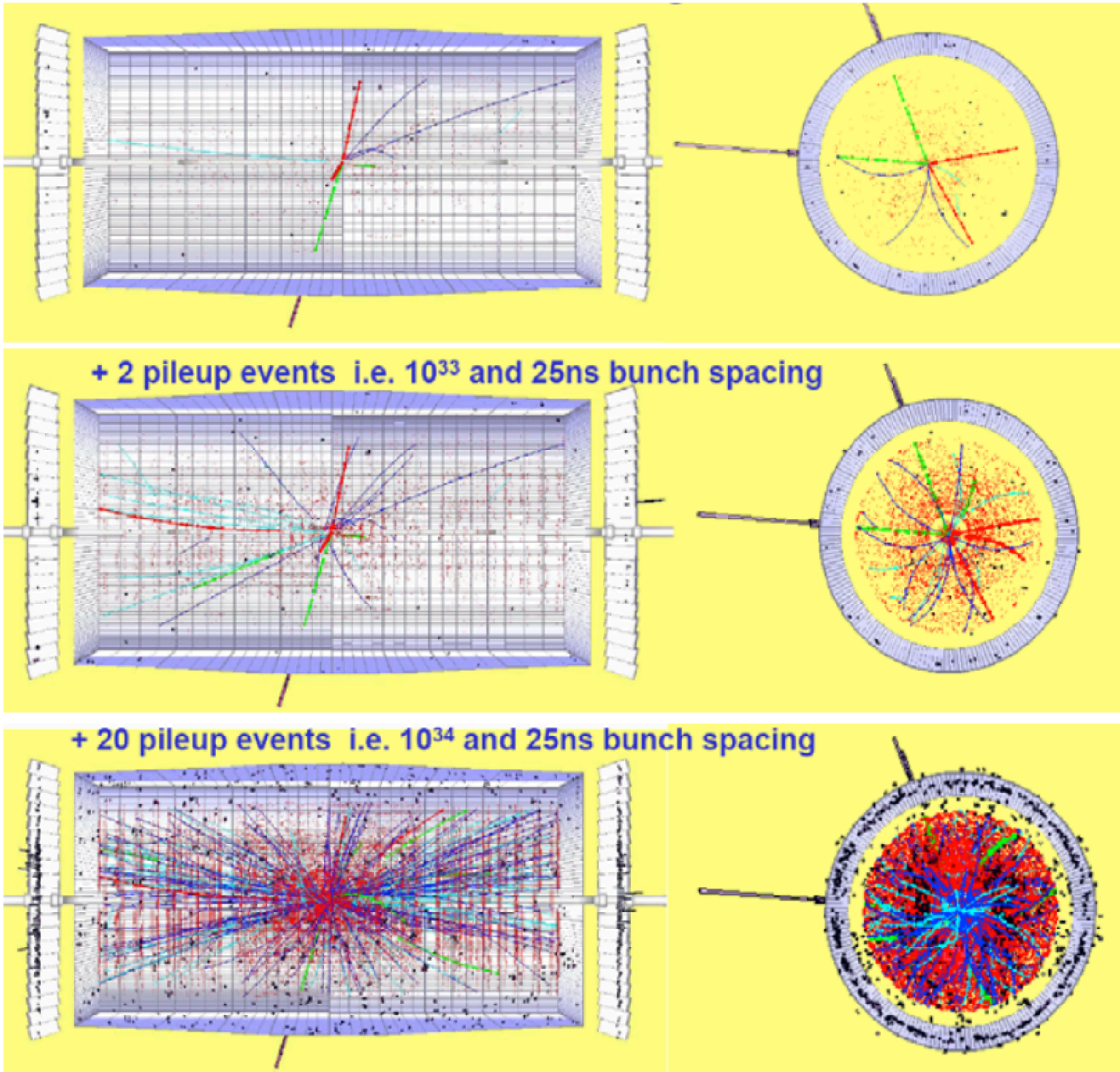
Triggers and event selection

- Select processes that produce particles with high transverse energy
- Examples at $5.x10^{33}$ $cm^{-2}s^{-1}$
    - Single lepton and photon triggers (P_T ~ 30 GeV)
    - Multiple lepton and photon triggers (P_T ~ 15 GeV)
    - Missing transverse energy (P_T ~ 50-100 GeV)
    - Multiple jet triggers (P_T ~ 50-100 GeV)
- About 100 trigger conditions in L1 trigger table
- About 400 trigger conditions in HLT trigger table

2011 Physics Proton Trigger Menu (end of run L = $3.3\ 10^{33}$ $cm^{-2}s^{-1}$)

ATLAS	Offline Selection	Trigger Selection		L1 Rate (kHz) at 3e33	EF Rate (Hz) at 3e33
		L1	EF		
Single leptons	Single muon > 20GeV	11 GeV	18 GeV	8	100
	Single electron > 25GeV	16 GeV	22 GeV	9	55
Two leptons	2 muons > 17, 12GeV	11GeV	15,10GeV	8	4
	2 electrons, each > 15GeV	2x10GeV	2x12GeV	2	1.3
	2 taus > 45, 30GeV	15,11GeV	29,20GeV	7.5	15
Two photons	2 photons, each > 25GeV	2x12GeV	20GeV	3.5	5
Single jet plus MET	Jet pT > 130 GeV & MET > 140 GeV	50 GeV & 35 GeV	75GeV & 55GeV	0.8	18
MET	MET > 170 GeV	50 GeV	70GeV	0.6	5
Multi-jets	5 jets, each pT > 55 GeV	5x10GeV	5x30GeV	0.2	9
TOTAL				**<75**	**~400 (mean)**

Event pileup in beams crossing



Example: $Z \rightarrow \mu\mu ee$
[Golden Higgs Decay]

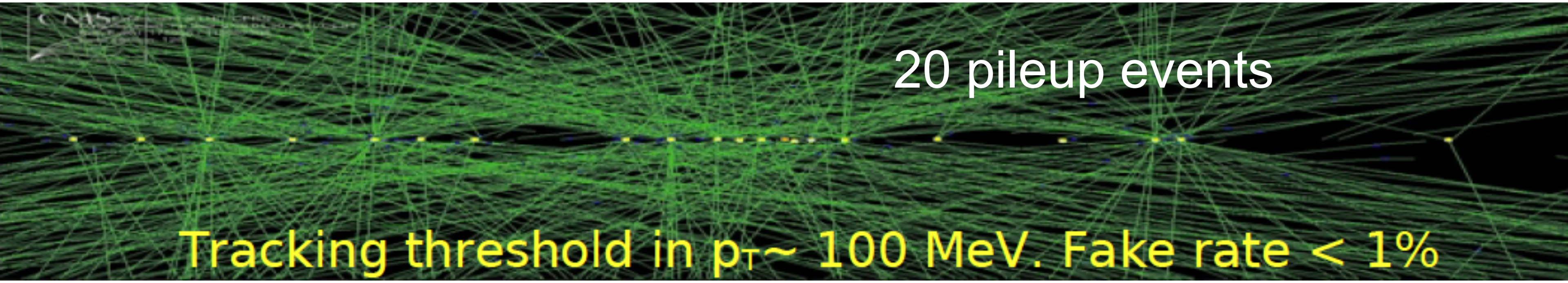
Low lumi
[First year]

High lumi

Monte Carlo simulation

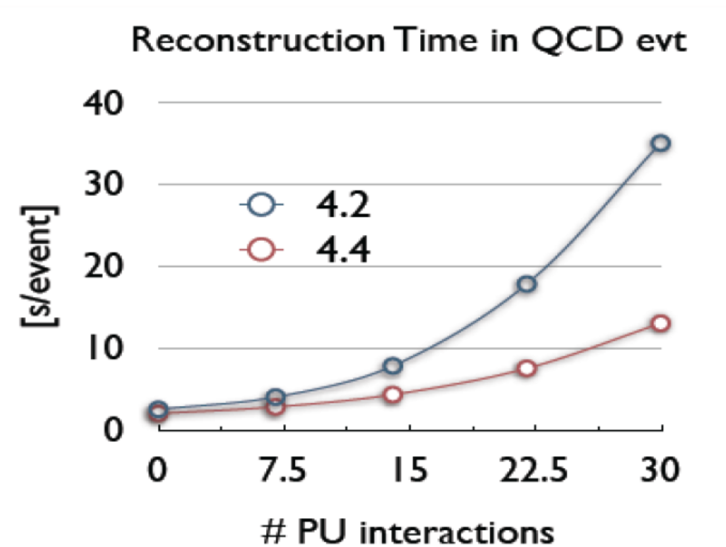
Event pileup in 2011-12

- In 2011 luminosity increased from 10^{32} $cm^{-2}s^{-1}$ up to $3.5x10^{33}$ $cm^{-2}s^{-1}$
- Bunch crossing spacing of 50 ns implies two times more pile-up (same beam current divided by two times fewer bunches)
- At the end of 2011 pileup was 15 events per crossing on average
- In 2012 luminosity may reach $7.x10^{33}$ $cm^{-2}s^{-1}$, corresponding to 30 pileup events

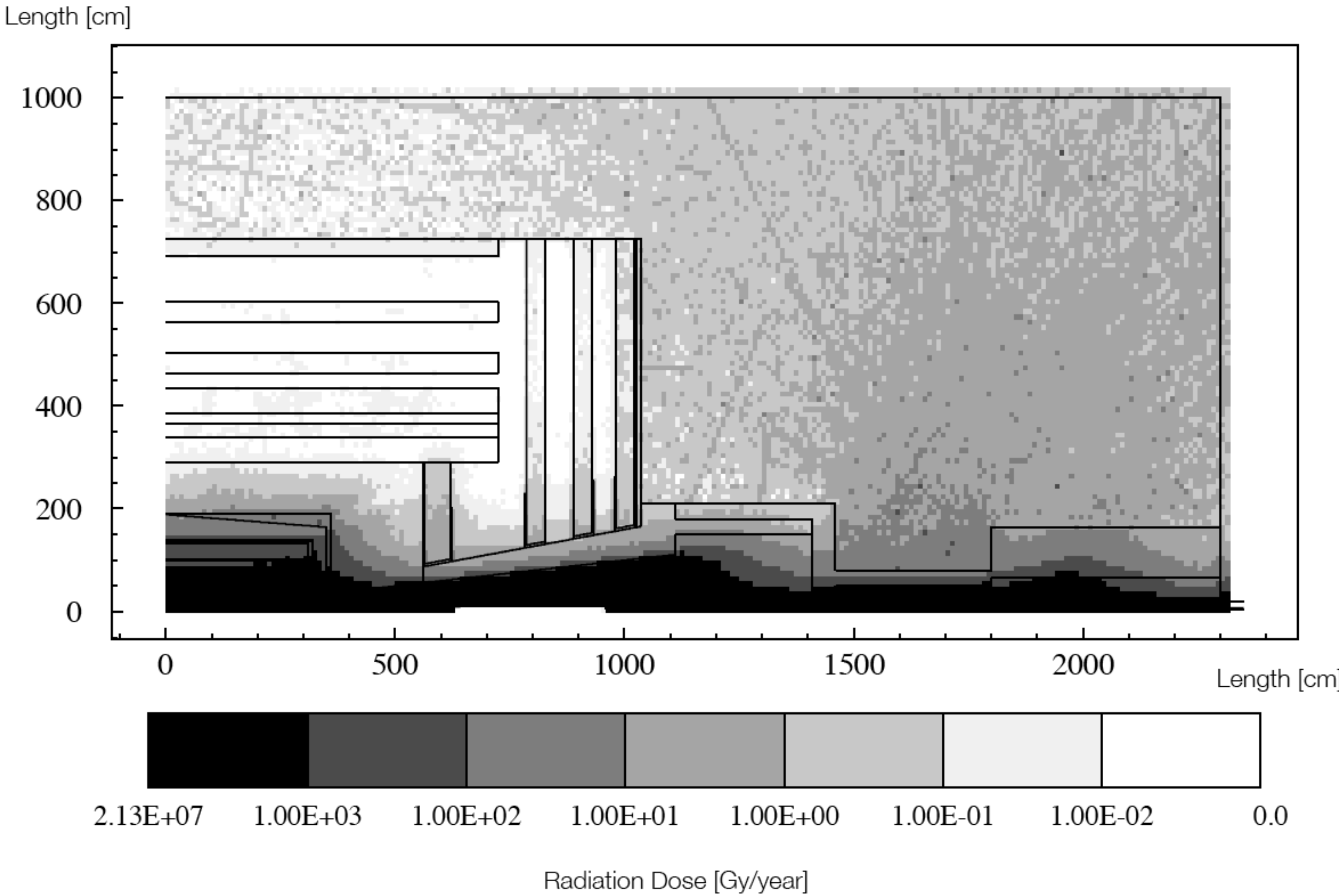


Event pileup, trigger and data analysis

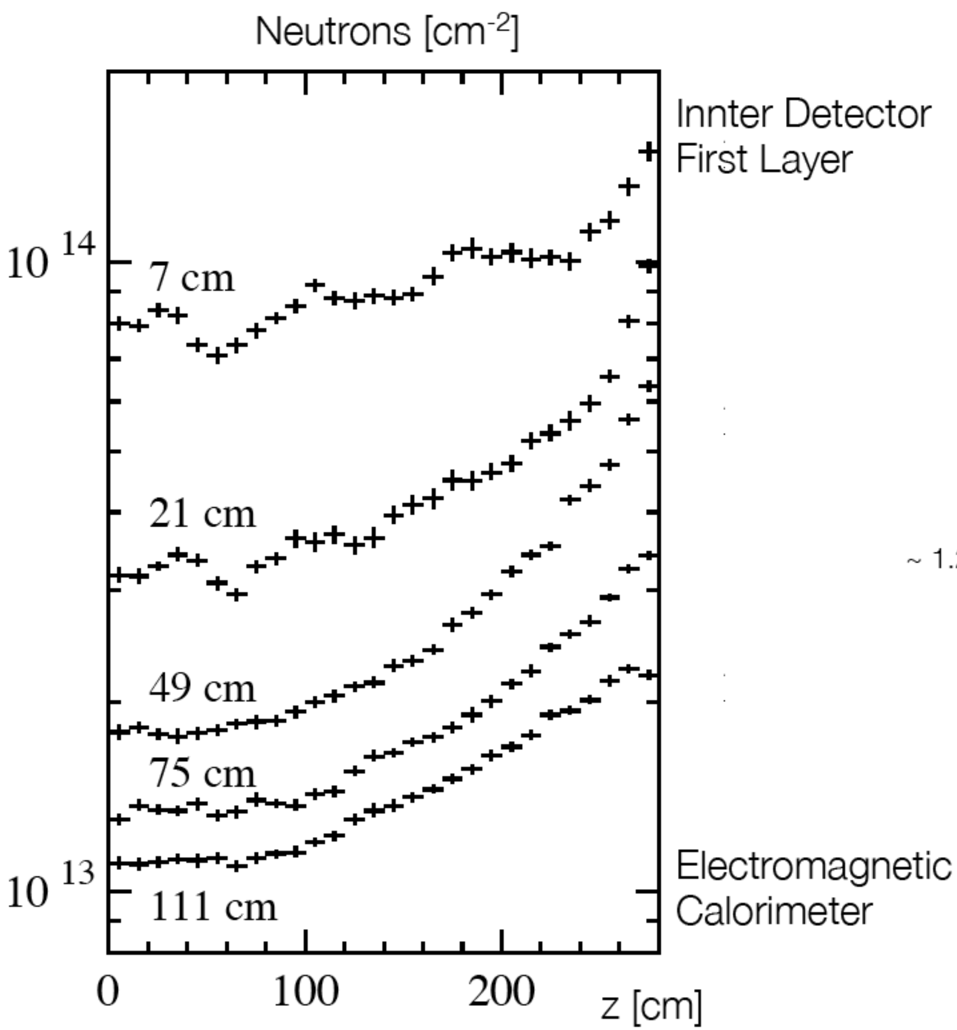
- Most p-p collisions (minimum bias) produce particles with low P_T (~0.5 GeV)
- Hard collisions produce objects (lepton, jets) with high P_T (> 20 GeV)
- High pile-up (> 10) has strong effects on trigger and data analysis:
  - Trigger rate of jets and missing energy
  - Jet reconstruction and energy scale (pileup subtraction)
  - Primary vertex identification
  - Lepton isolation efficiency
  - Tracking occupancy and reconstruction
  - etc.

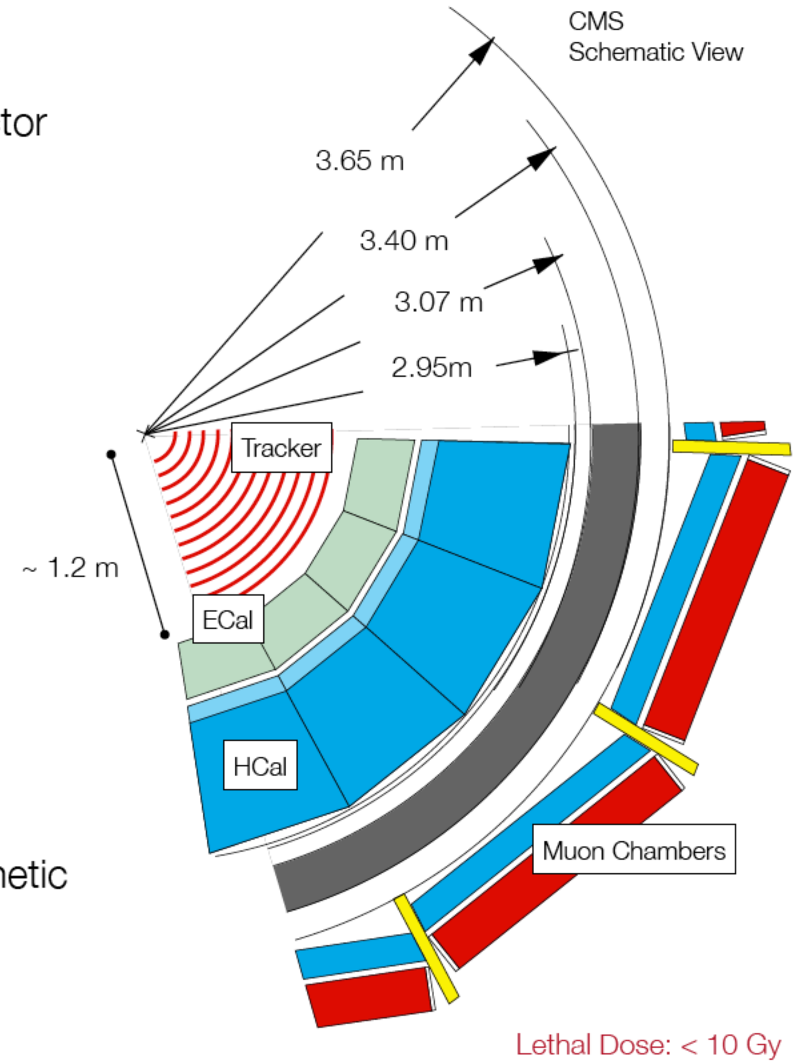


High radiation levels

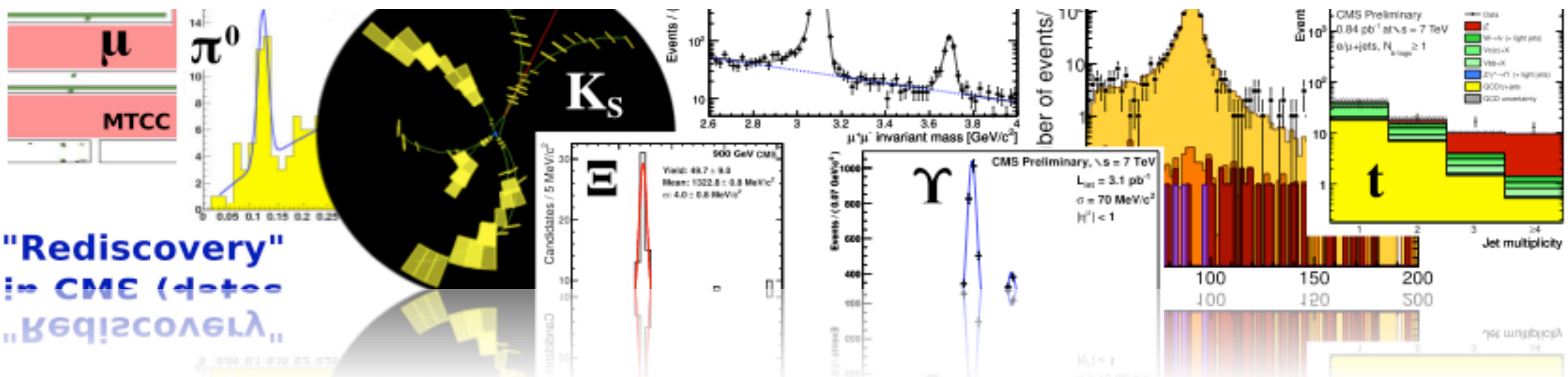


Radiation hard detectors and electronics





Detector commissioning and rediscovery of the SM

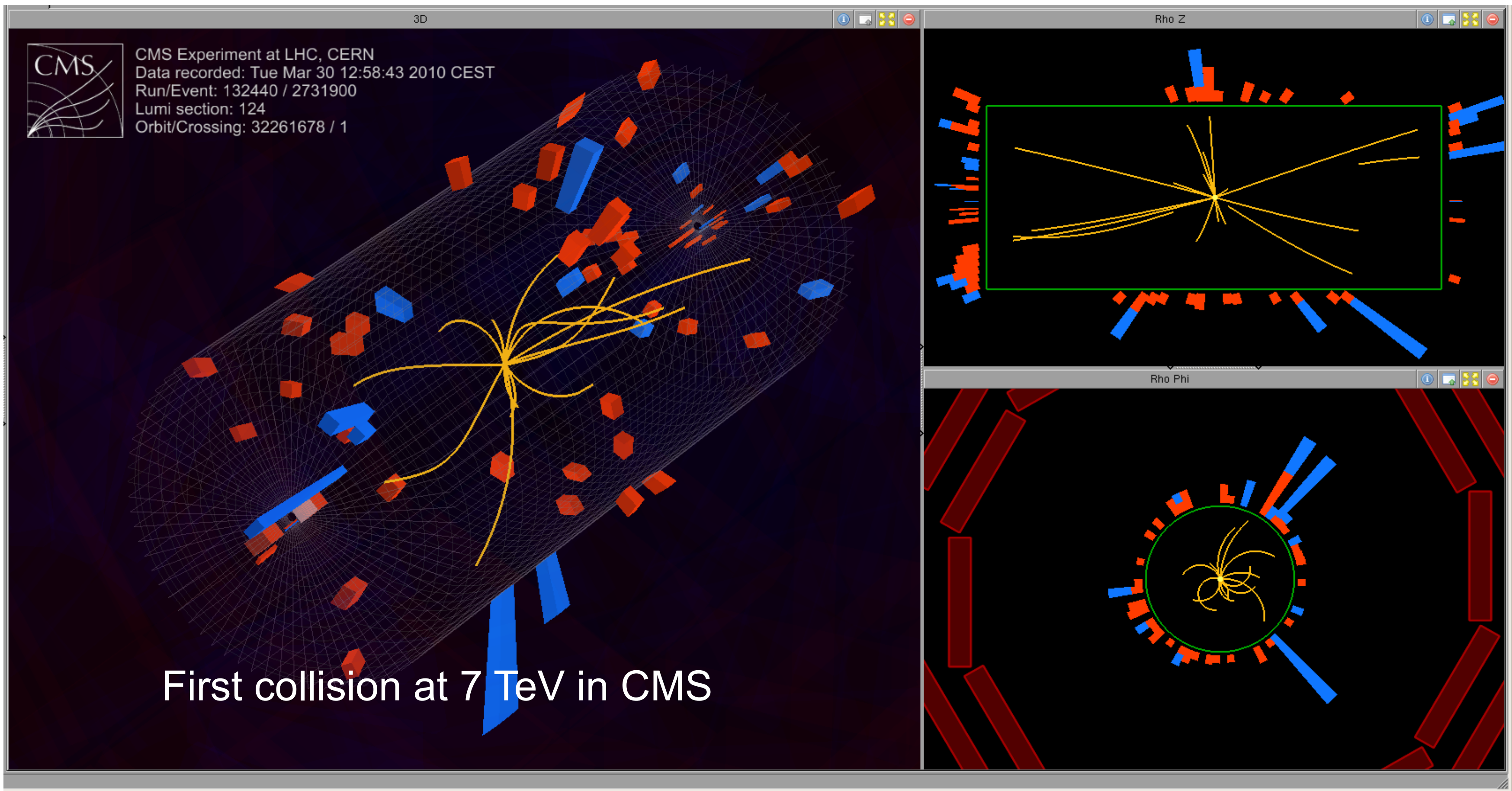


2009: First p-p collisions at LHC

November 23, 2009
First collisions at 900 GeV

December 14, 2009
First collisions at 2.36 TeV

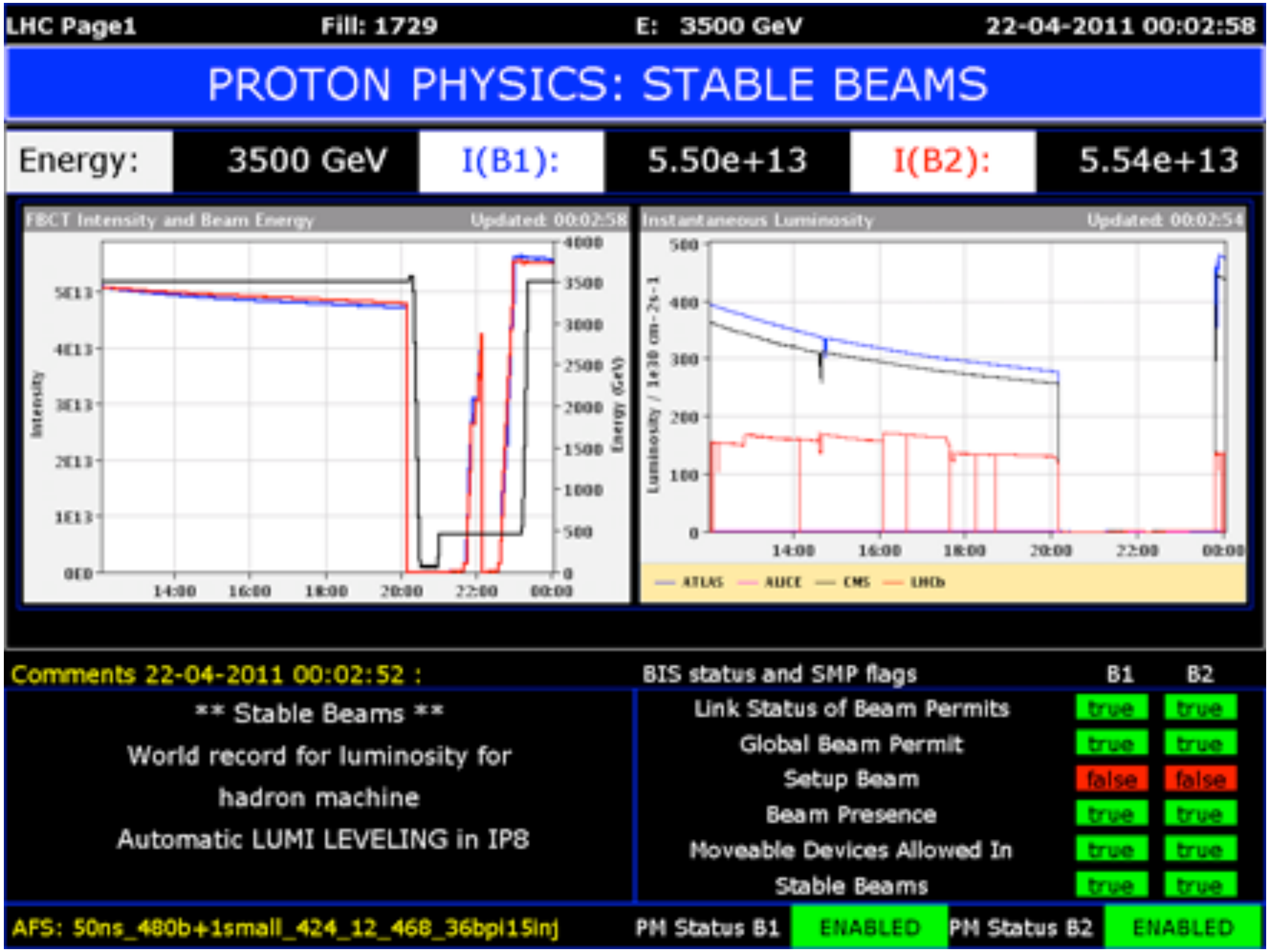
March 30, 2010
First collisions at 7 TeV



...unforgettable moments

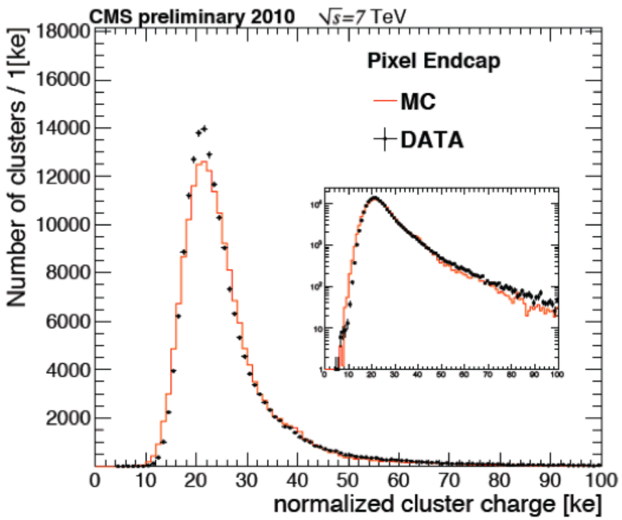
LHC Page 1: ramp

LHC Page 1: stable beams

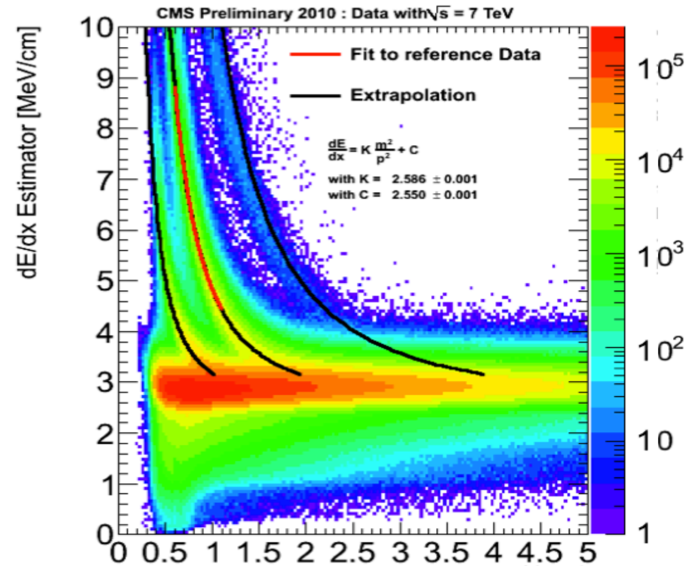


Tracking performance

Pixel cluster charge

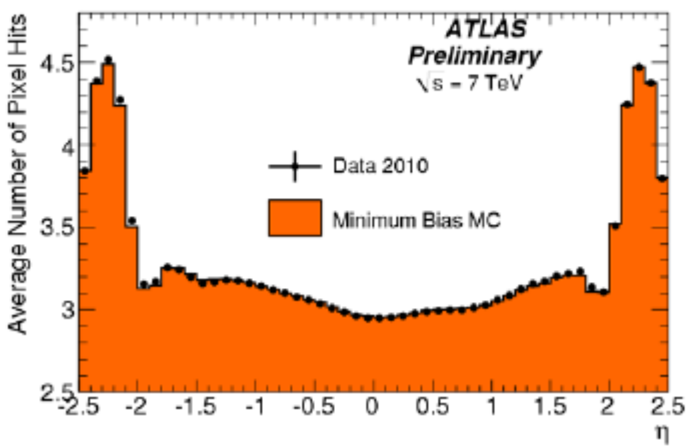


de/dx in the strips



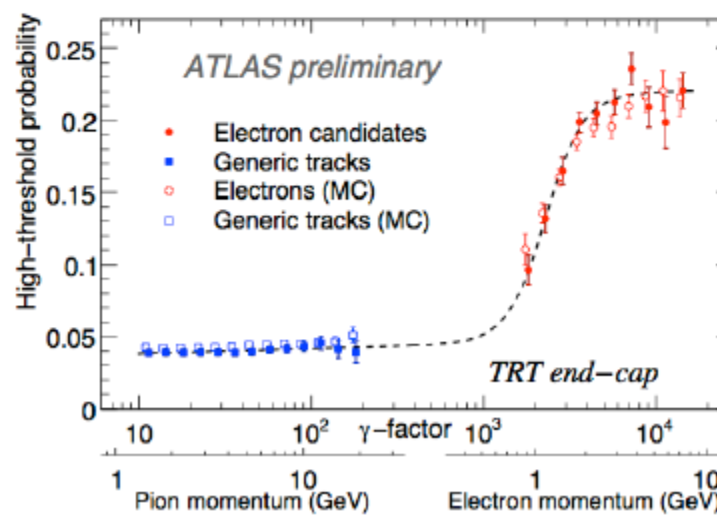
CMS

Pixel Det.



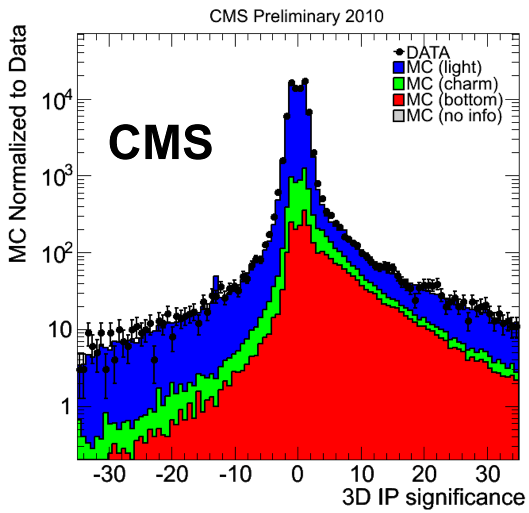
ATLAS

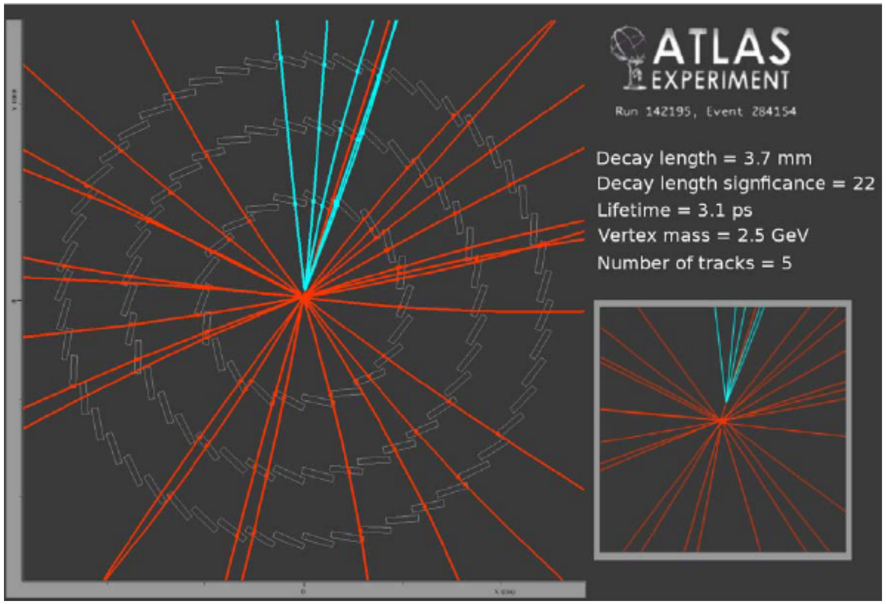
TRT Det.

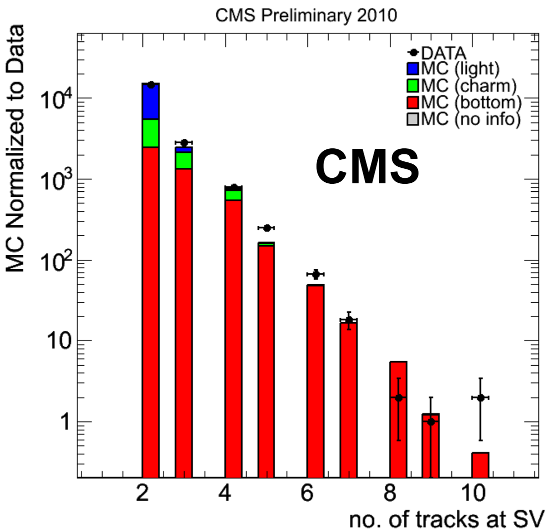


Tracking: secondary vertices

Basic variables relevant for B-tagging are well described by the simulation



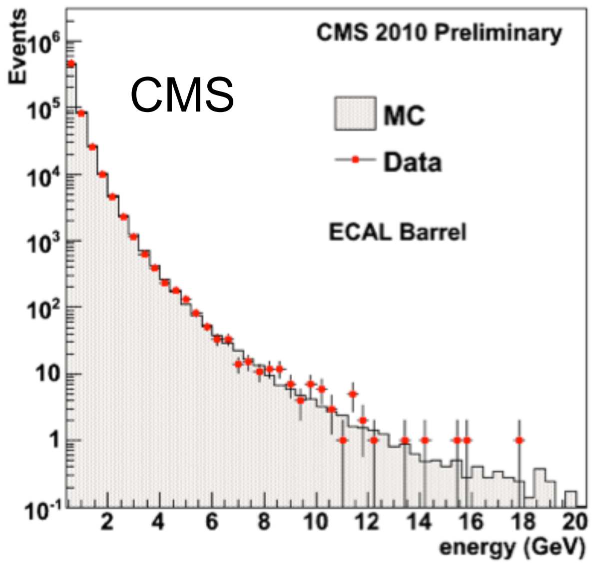


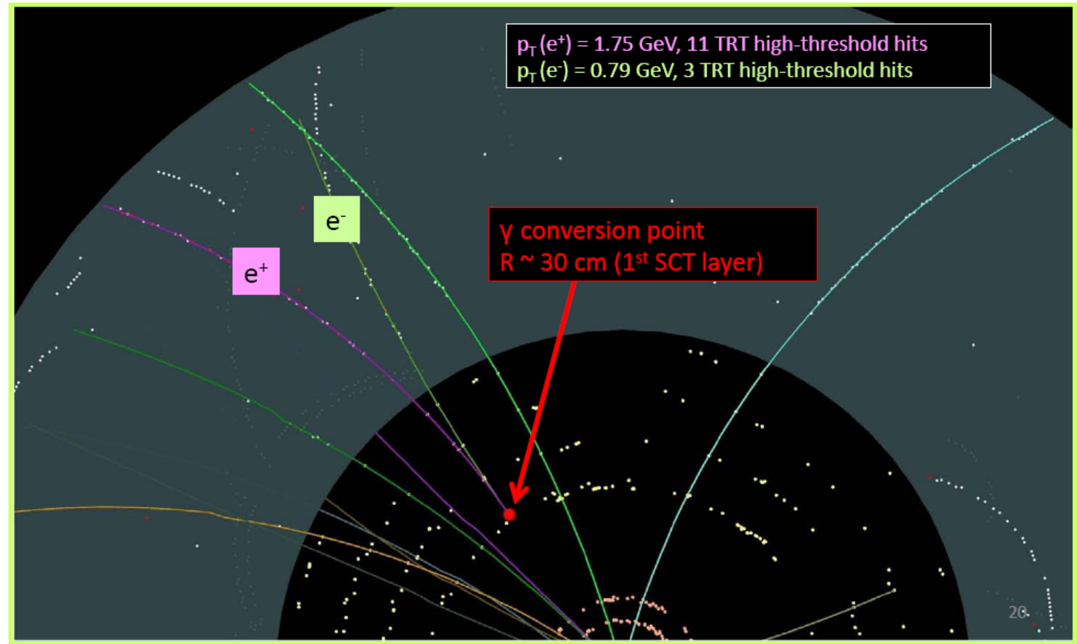


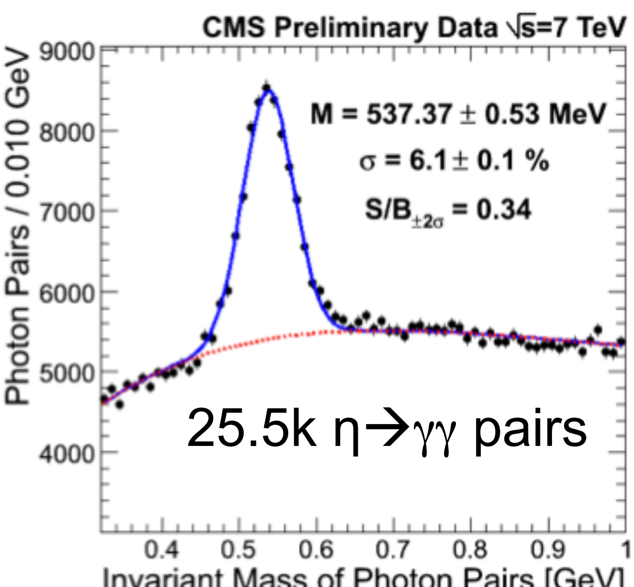
Secondary vertices compatible with heavy flavor production

Photons and electrons

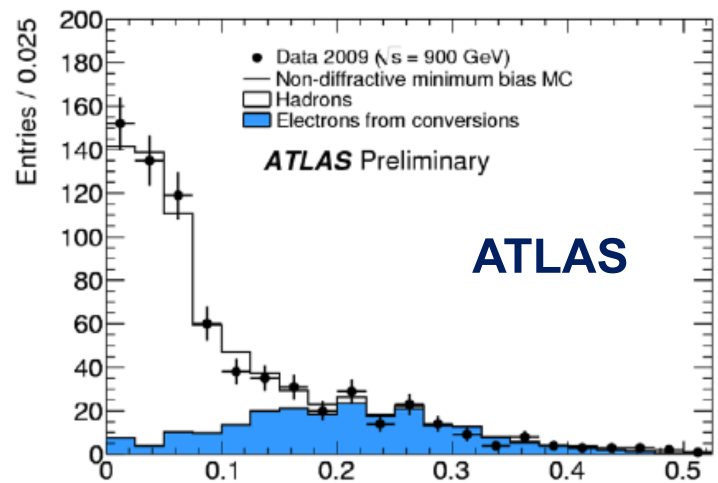
EM cluster energy



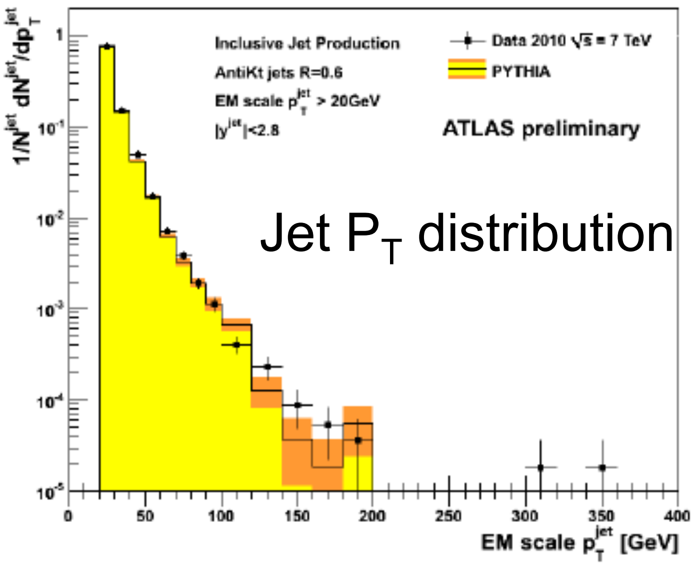




TRT high-threshold hit fraction

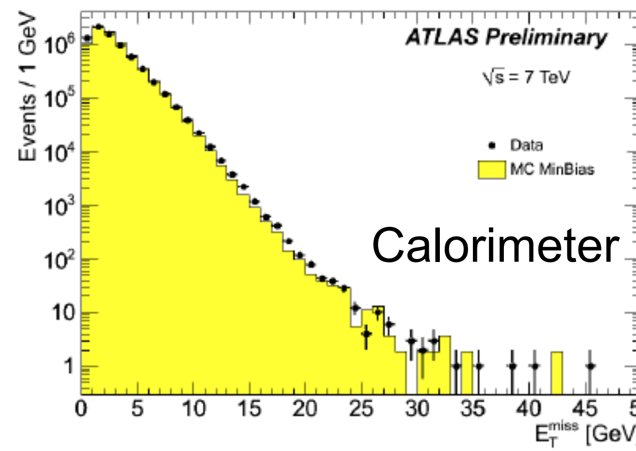


Jets and missing energy

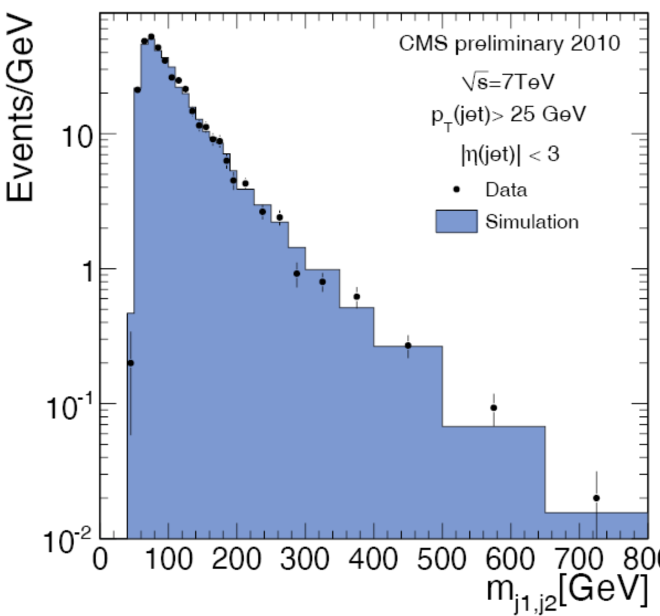


ATLAS

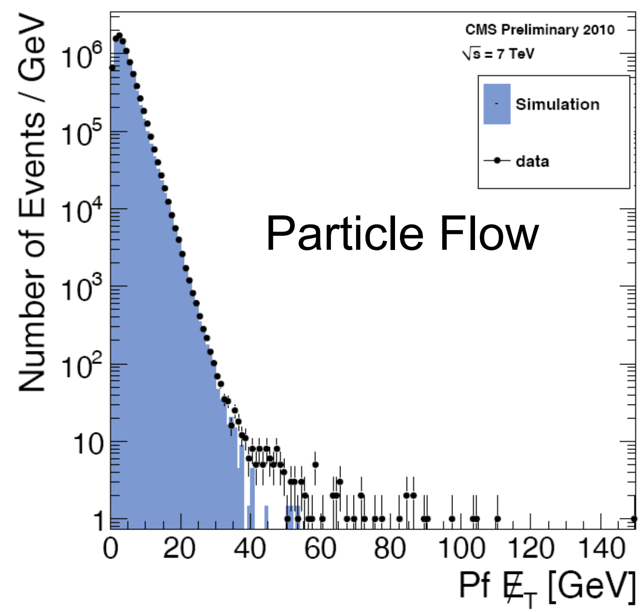
Missing Transverse Energy



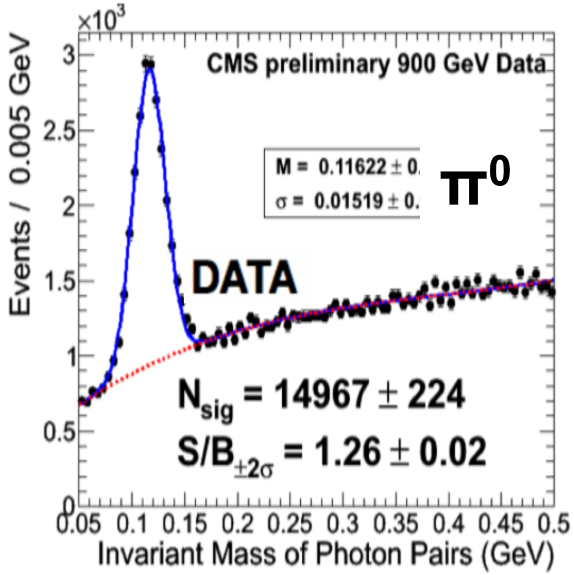
Di-jet mass

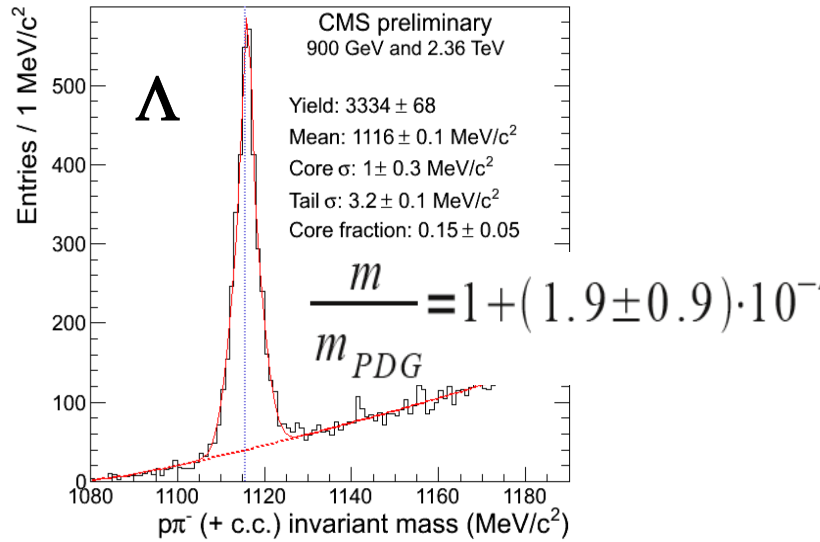


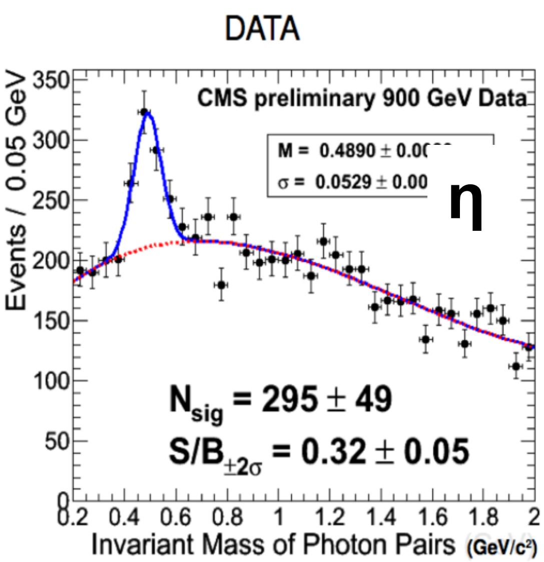
CMS

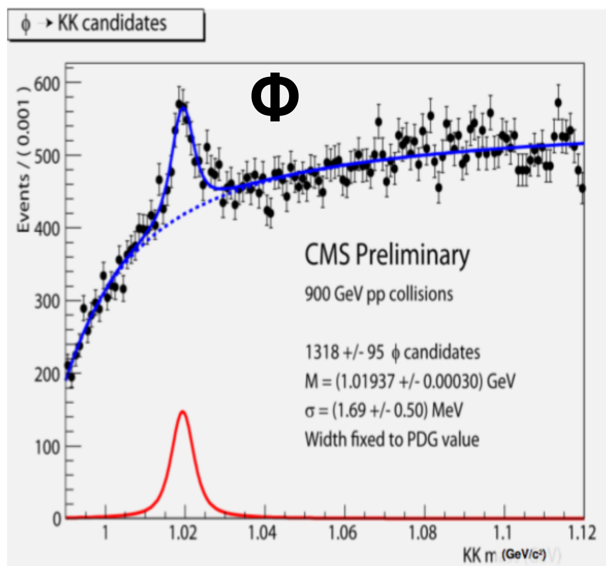


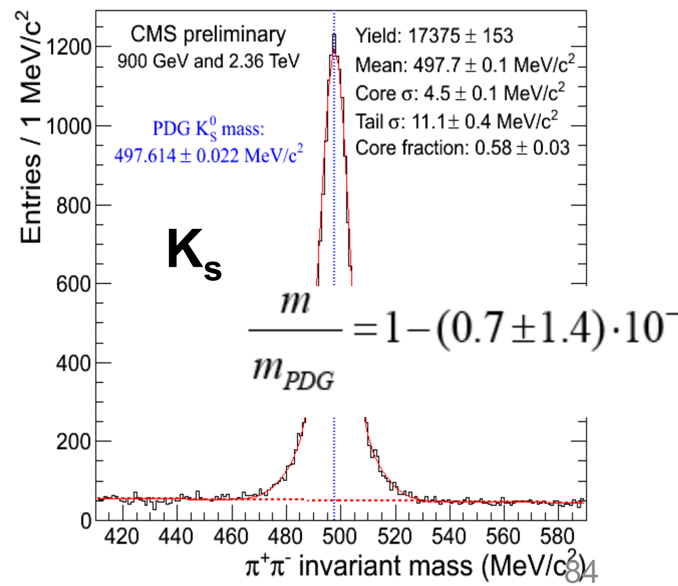
Rediscovery of resonances



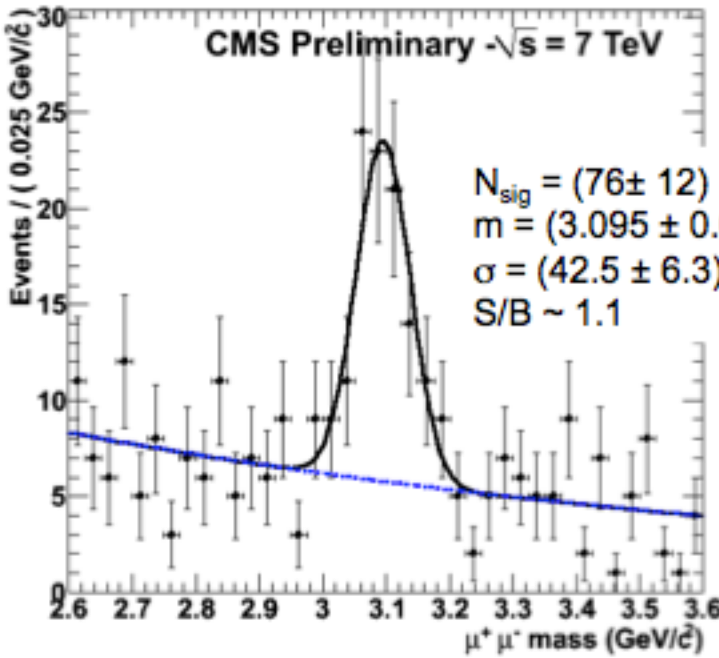








J/ψ’ s decaying into muons

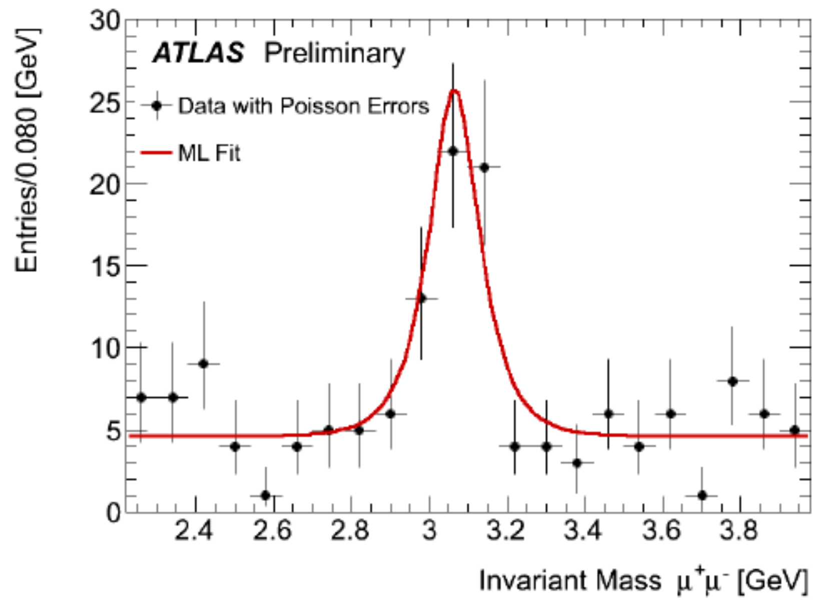


CMS

Gaussian-mean mass: 3.06±0.02 GeV

Resolution: 0.08±0.02 GeV

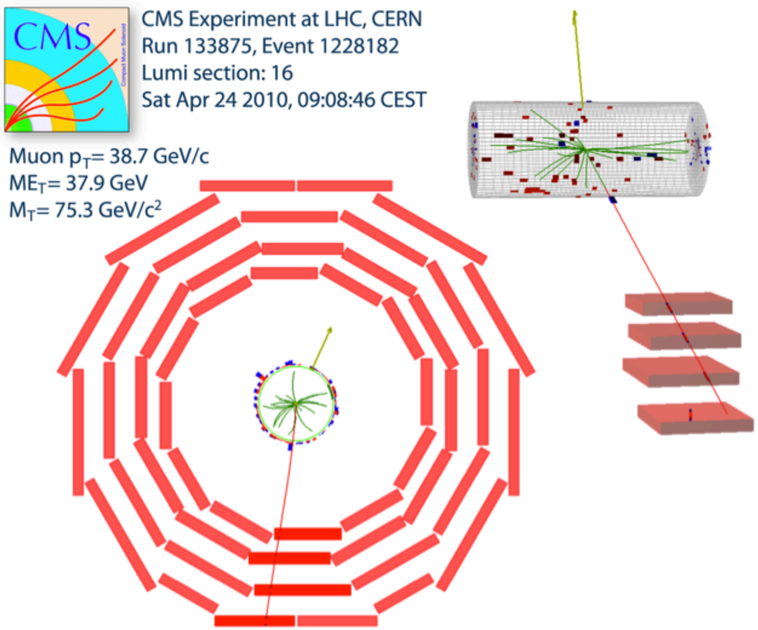
Number of signal events: 49±12



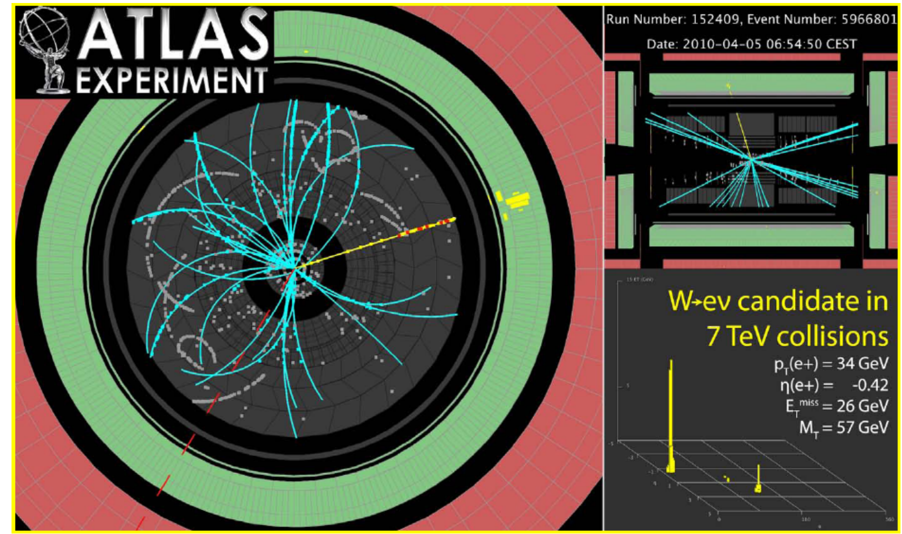
ATLAS

W and Z Bosons

W→μν

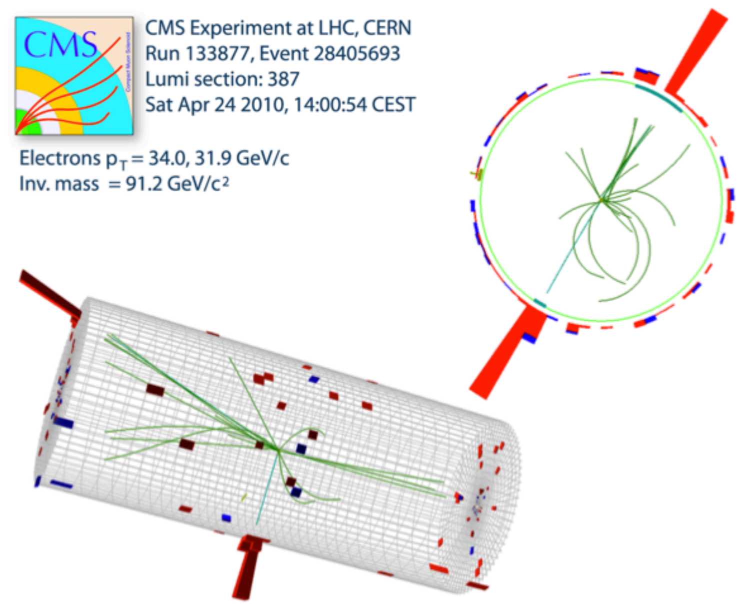


W→eν

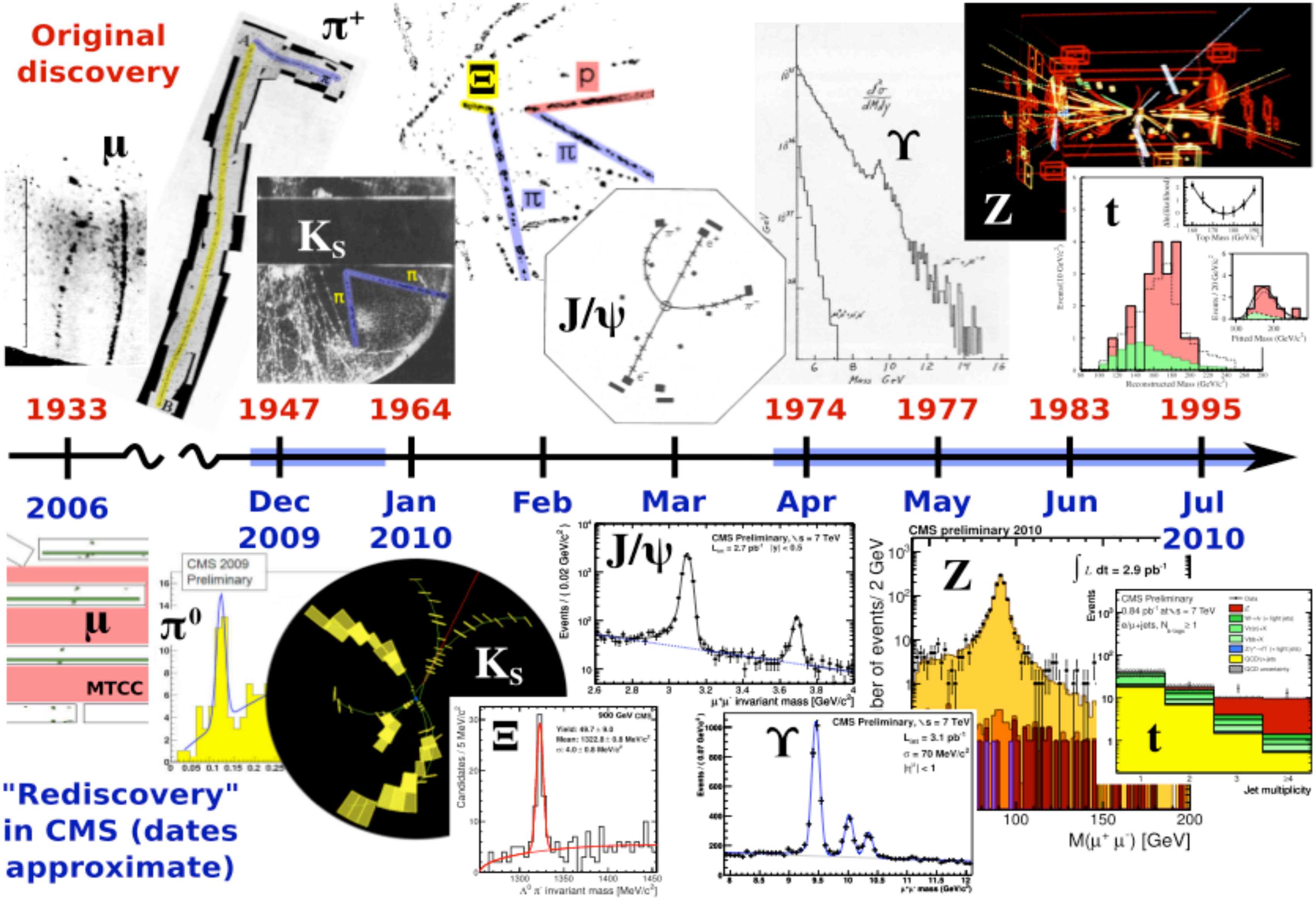


Z→ee:

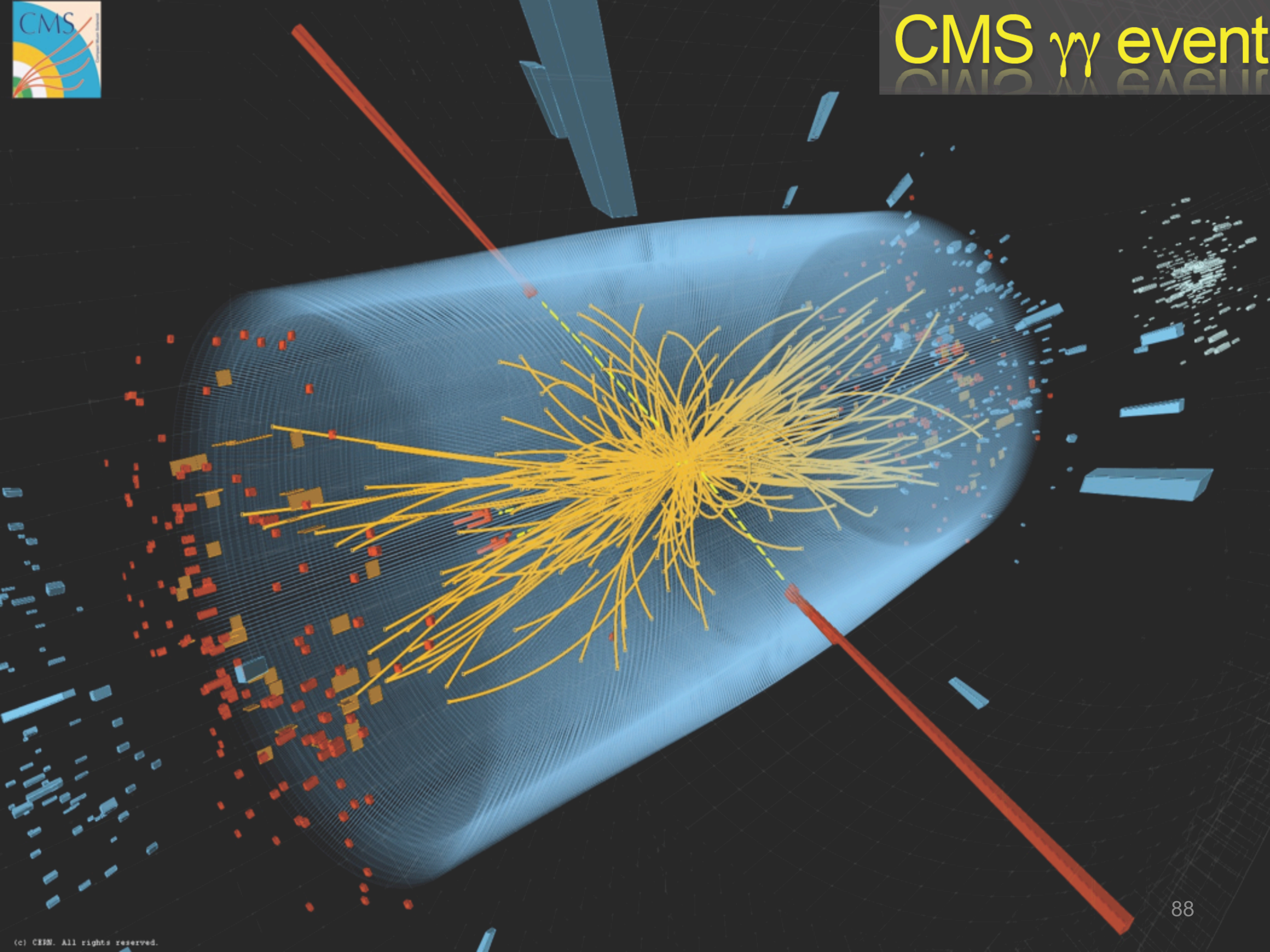
Mass= 91.2 GeV/c2



Rediscovery of the Standard Model

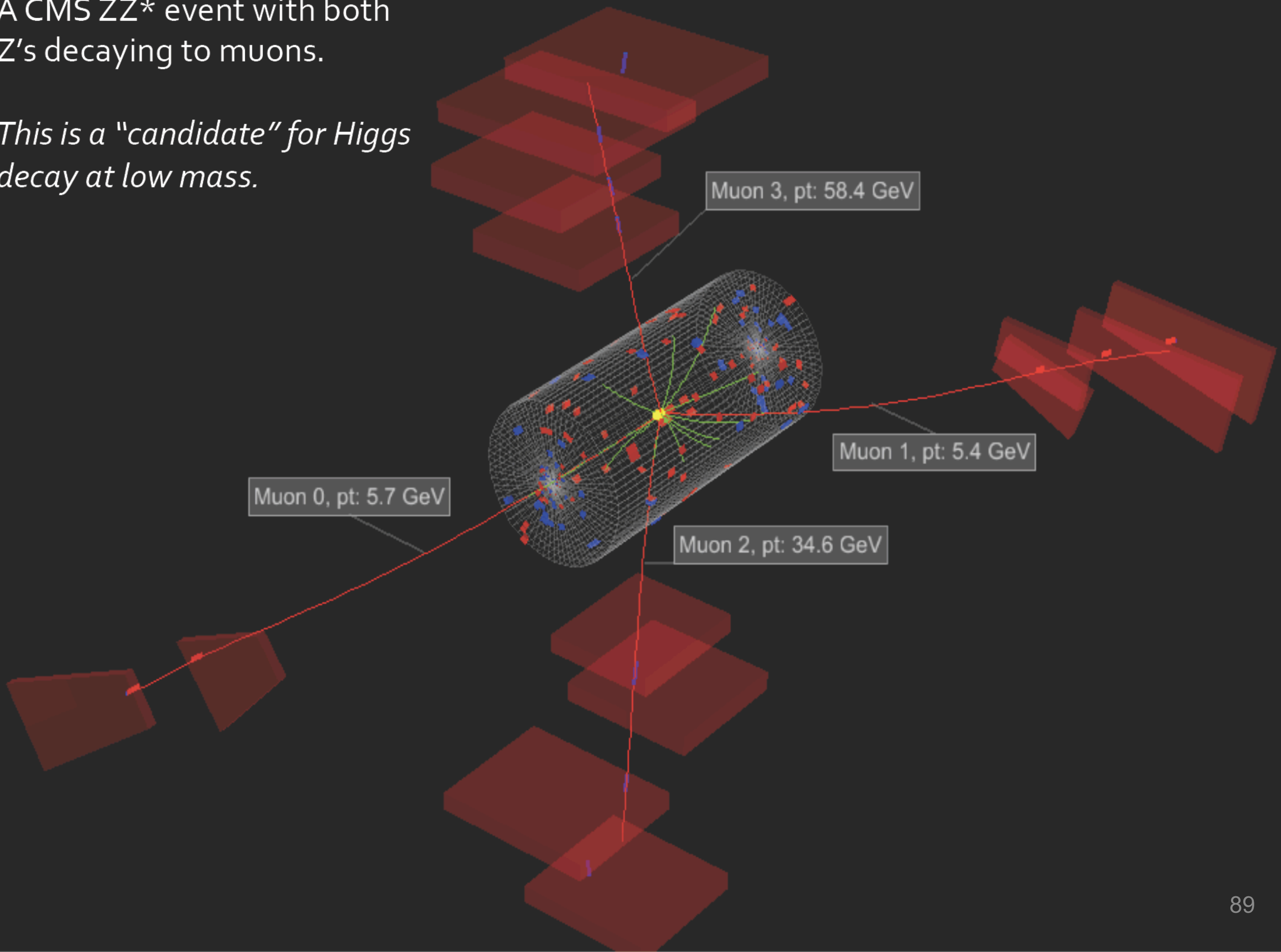


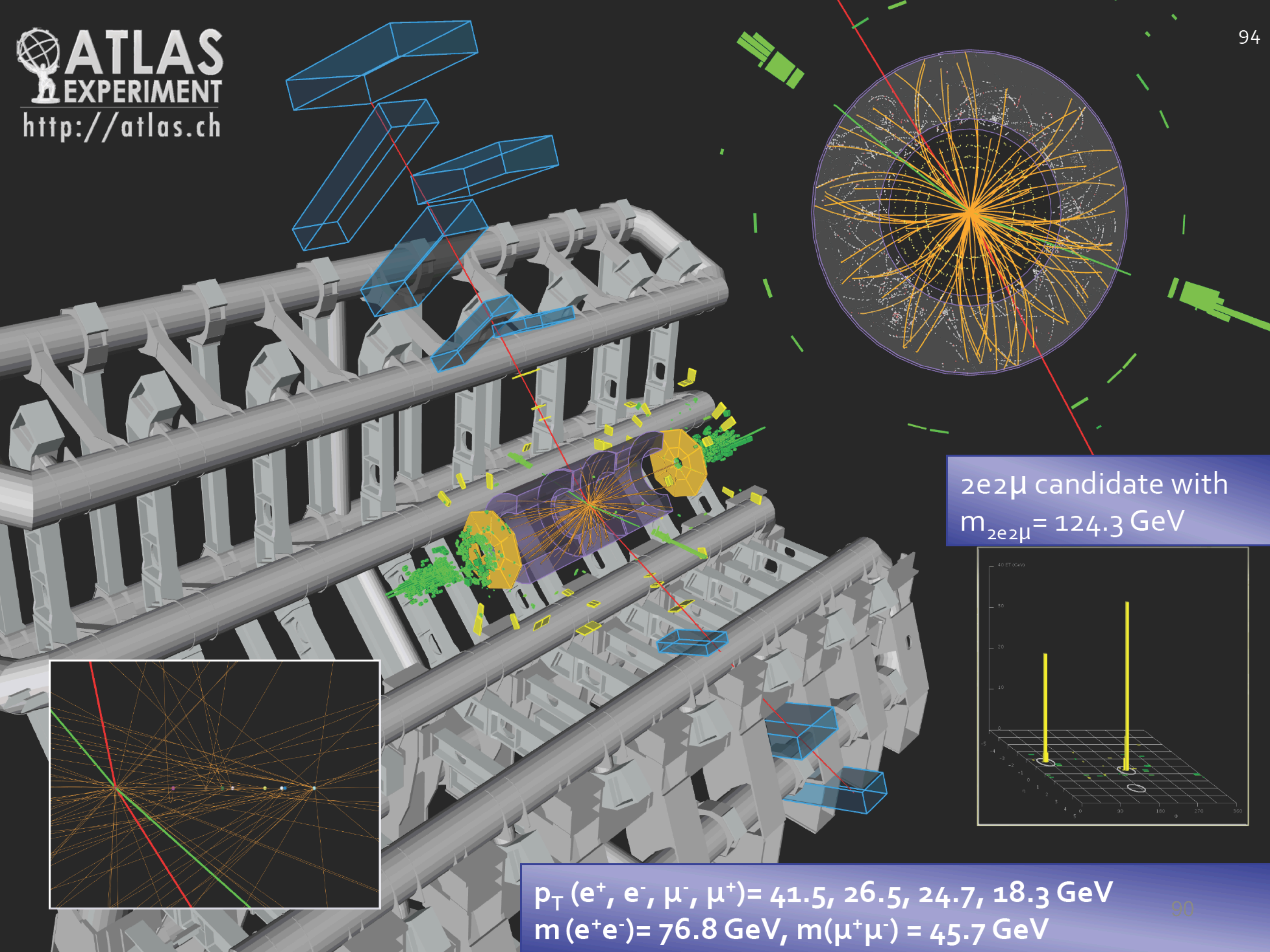
CMS $\gamma\gamma$ event



A CMS ZZ* event with both Z's decaying to muons.

This is a "candidate" for Higgs decay at low mass.




ATLAS
EXPERIMENT
http://atlas.ch
2e2μ candidate with
$m_{2e2\mu}$ = 124.3 GeV
p_T (e^+, e^-, μ^-, μ^+)= 41.5, 26.5, 24.7, 18.3 GeV
m (e^+e^-)= 76.8 GeV, m($\mu^+\mu^-$) = 45.7 GeV

End of Lecture 1