CERN – A Gateway to Science and Technology

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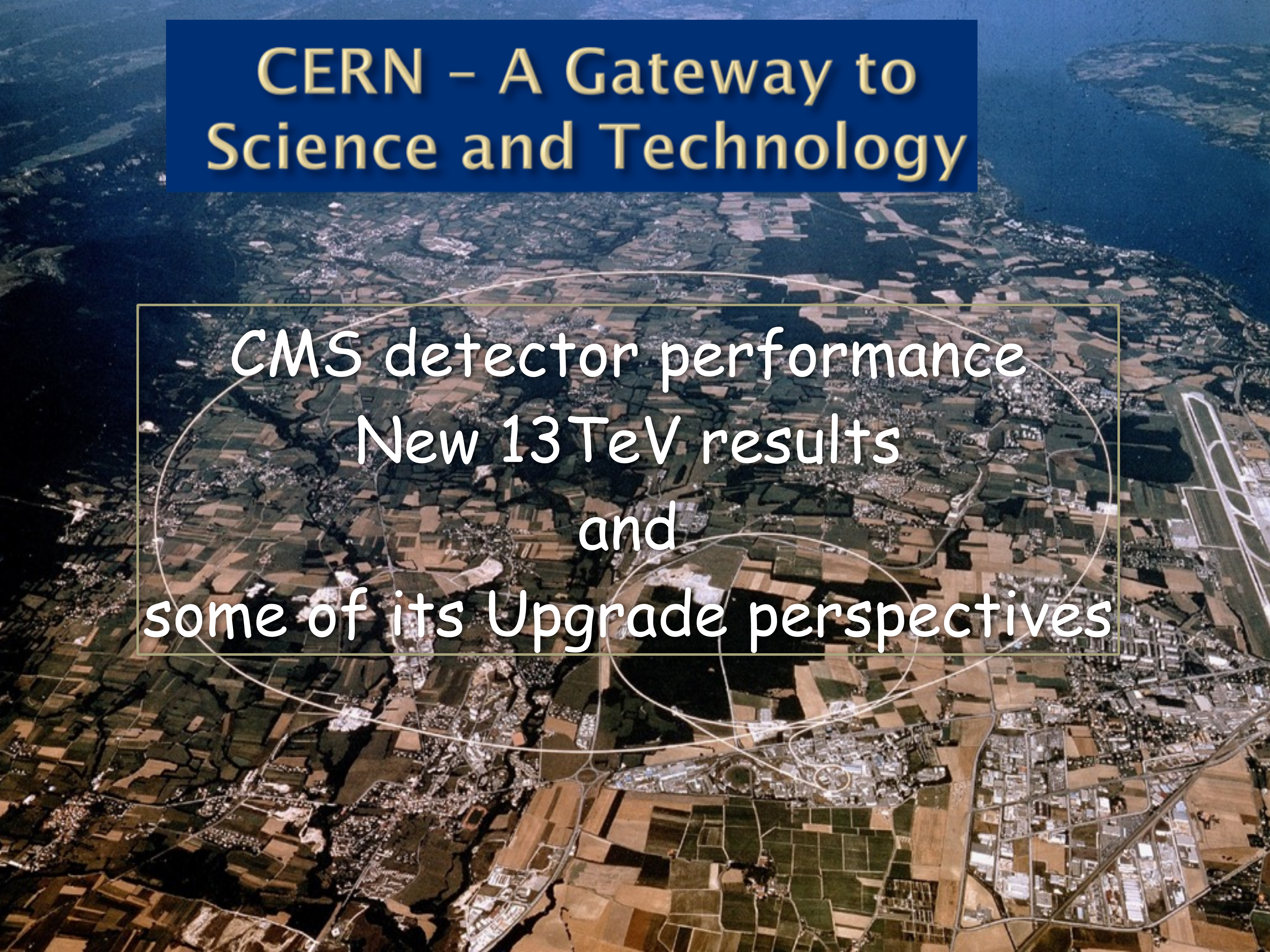

CMS detector performance
New 13TeV results
and
some of its Upgrade perspectives

CERN – A Gateway to Science and Technology

CMS detector performance
New 13TeV results
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some of its Upgrade perspectives

CNRS Centre National de la Recherche Scientifique

IN2P3

Ecole Polytechnique

CERN – A Gateway to Science and Technology

CMS detector performance New 13TeV results and some of its Upgrade perspectives

Ludwik Dobrzynski

Laboratoire Leprince Ringuet - Ecole polytechnique - CNRS - IN2P3

Split - 14 September 2015

Centre National de la Recherche Scientifique

IN2P3

Ecole Polytechnique

CERN – The European Organization for Nuclear Research

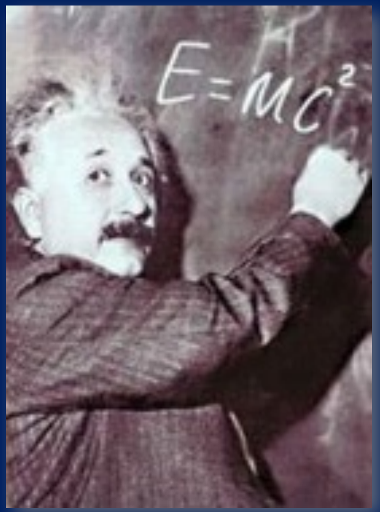
The Mission of CERN

Innovation
Education
CERN
uniting people
Research

The Mission of CERN

- Push forward the frontiers of knowledge

  E.g. the secrets of the Big Bang …what was the matter like within the first moments of the Universe's existence?



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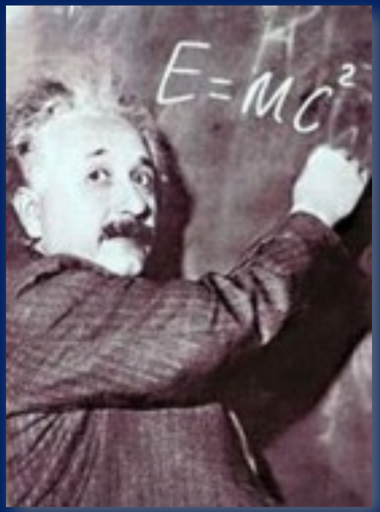
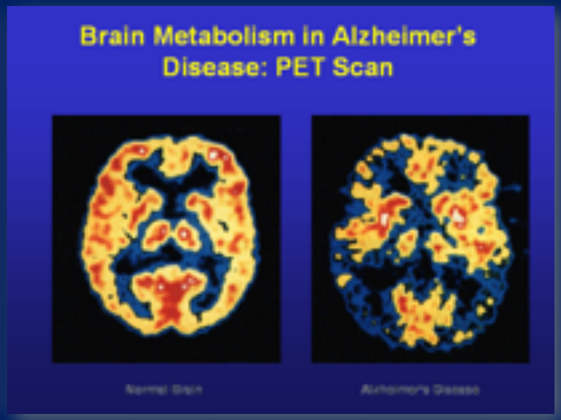


- **Develop** new technologies for accelerators and detectors

Information technology - the Web and the GRID

Medicine - diagnosis and therapy



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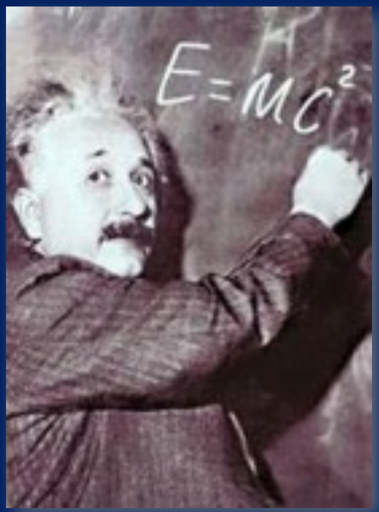

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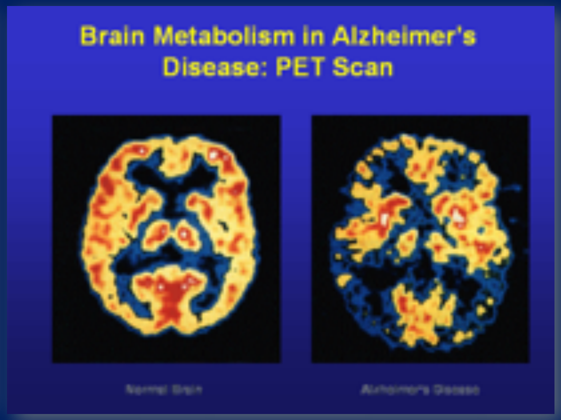
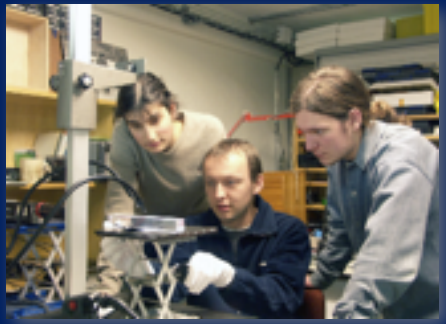


- **Train** scientists and engineers of tomorrow



Innovation
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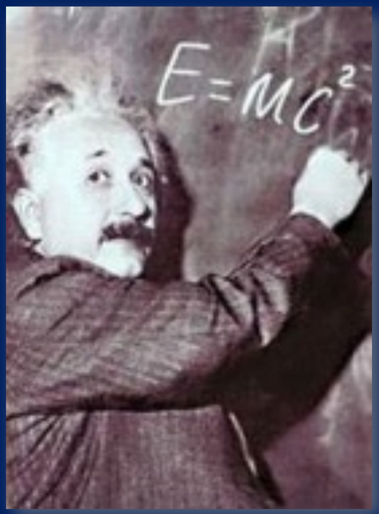
The Mission of CERN



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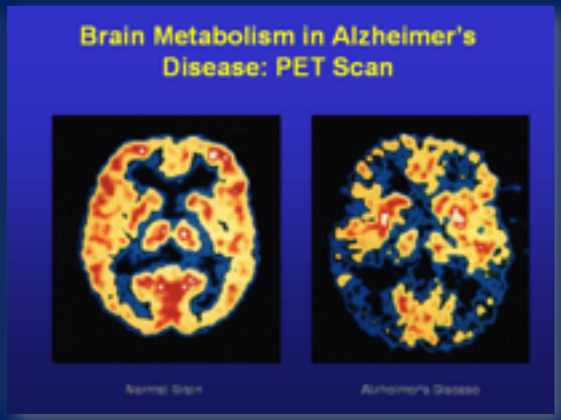

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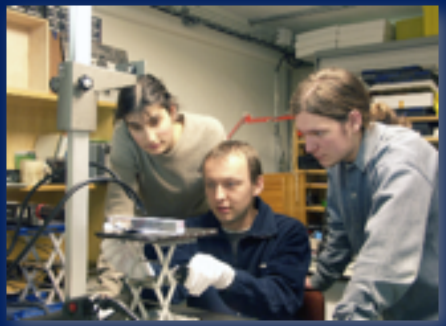

- Train scientists and engineers of tomorrow

- Unite people from different countries and cultures

CERN was founded 1954: 12 European States

"Science for Peace"

Today: 21 Member States

Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

Candidate for Accession: Romania

Associate Member in Pre-Stage to Membership: Serbia

Applicant States for Membership or Associate Membership: Brazil, Croatia, Cyprus, Pakistan, Russia, Slovenia, Turkey, Ukraine

Observers to Council: India, Japan, Russia, Turkey, United States of America; European Commission and UNESCO

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~ 2300 staff
~ 1600 other paid personnel
~ 10500 scientific users
Budget (2014) ~1000 MCHF

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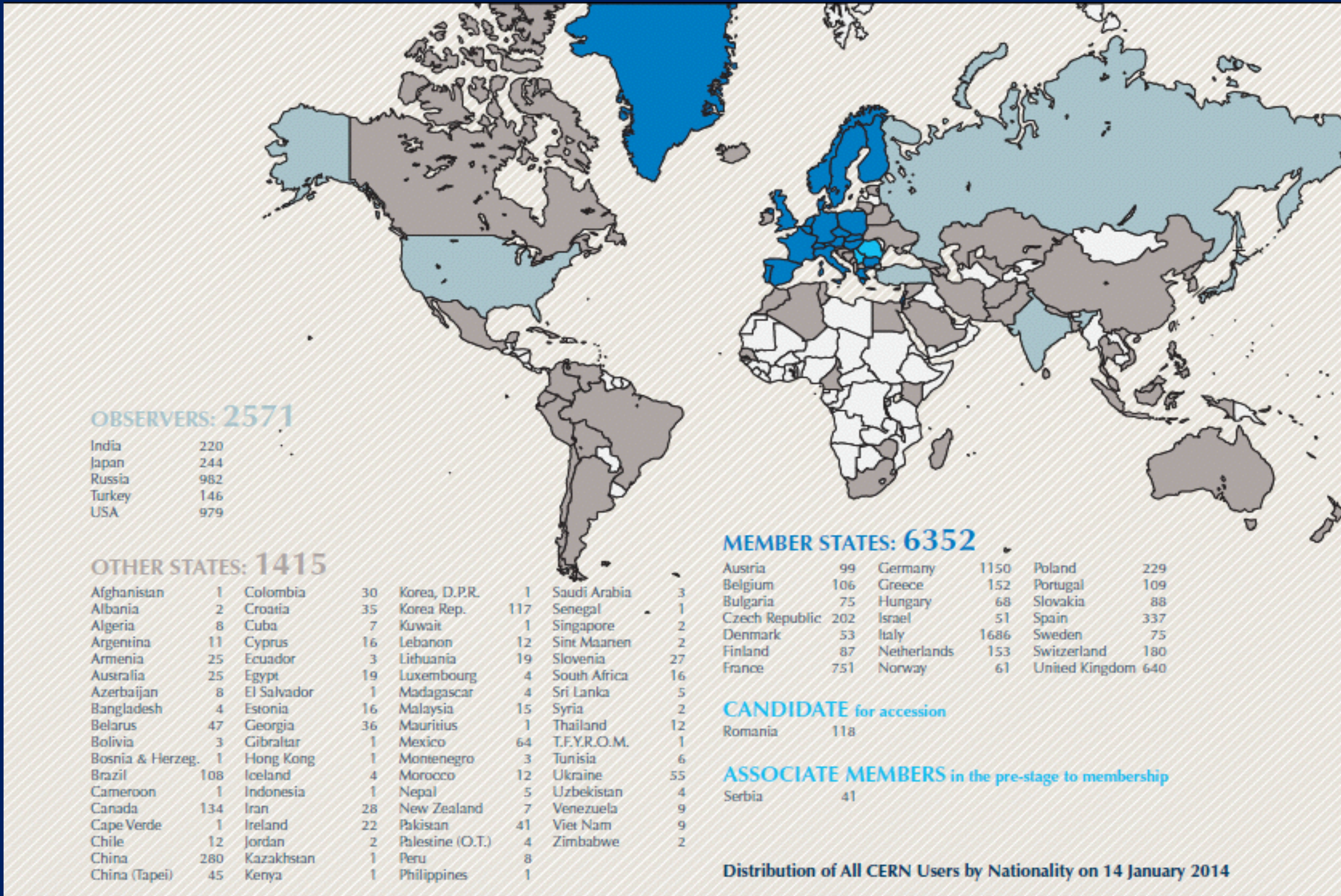
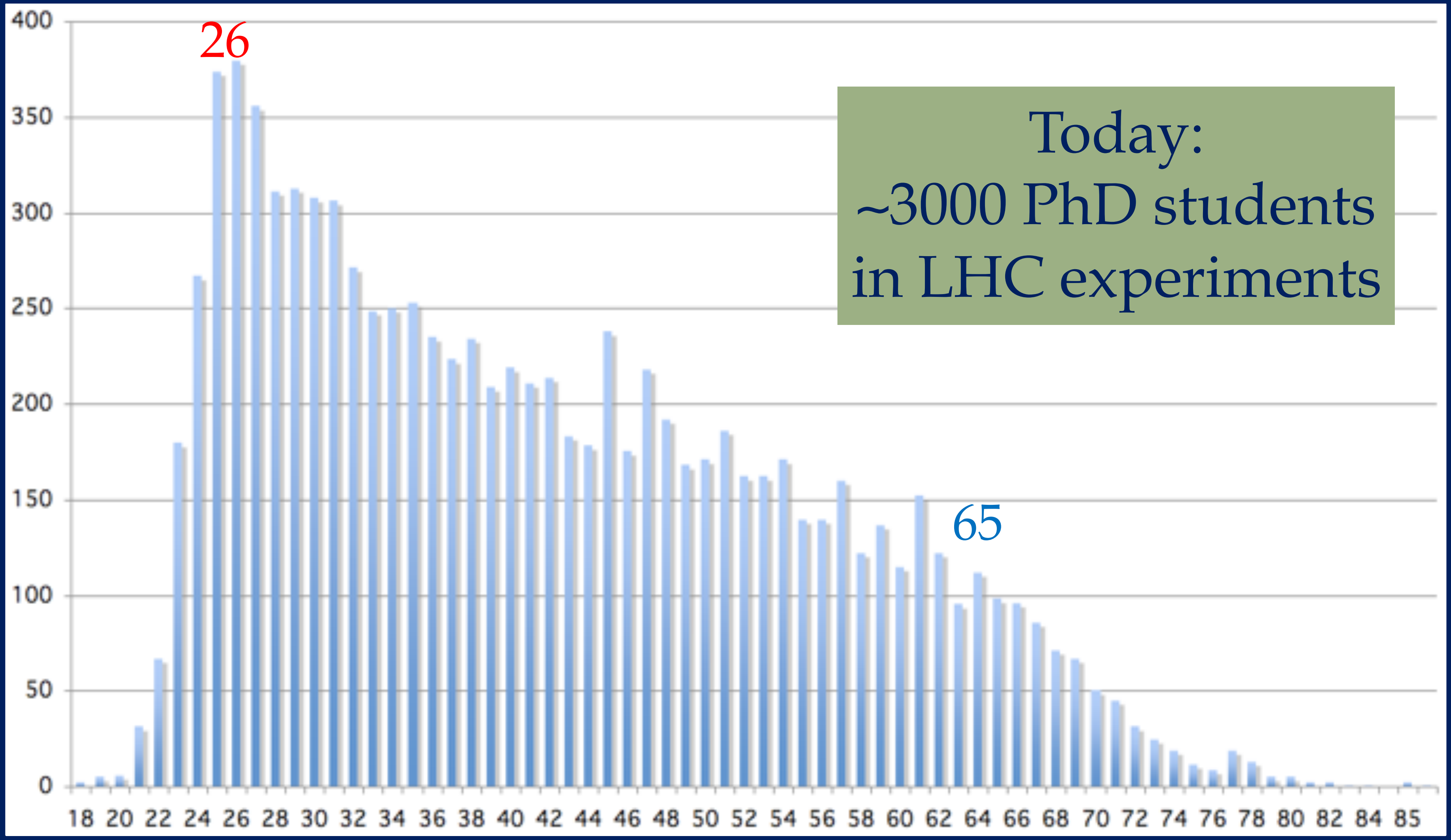
CERN – building bridges across continents



Age Distribution of Scientists

- and where they go afterwards

Survey in March 2009



Today:
~3000 PhD students
in LHC experiments

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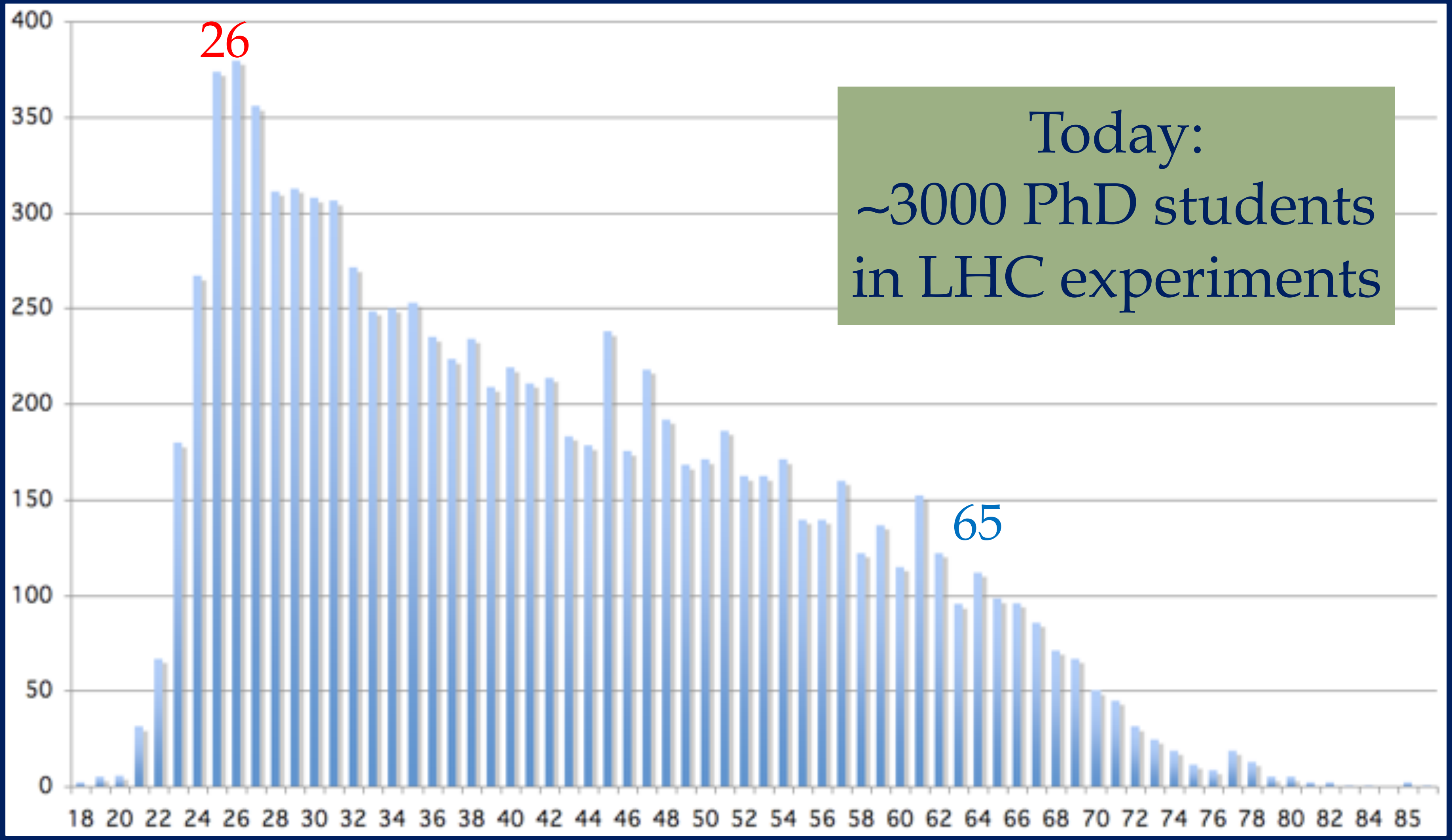

They do not all stay: where do they go?

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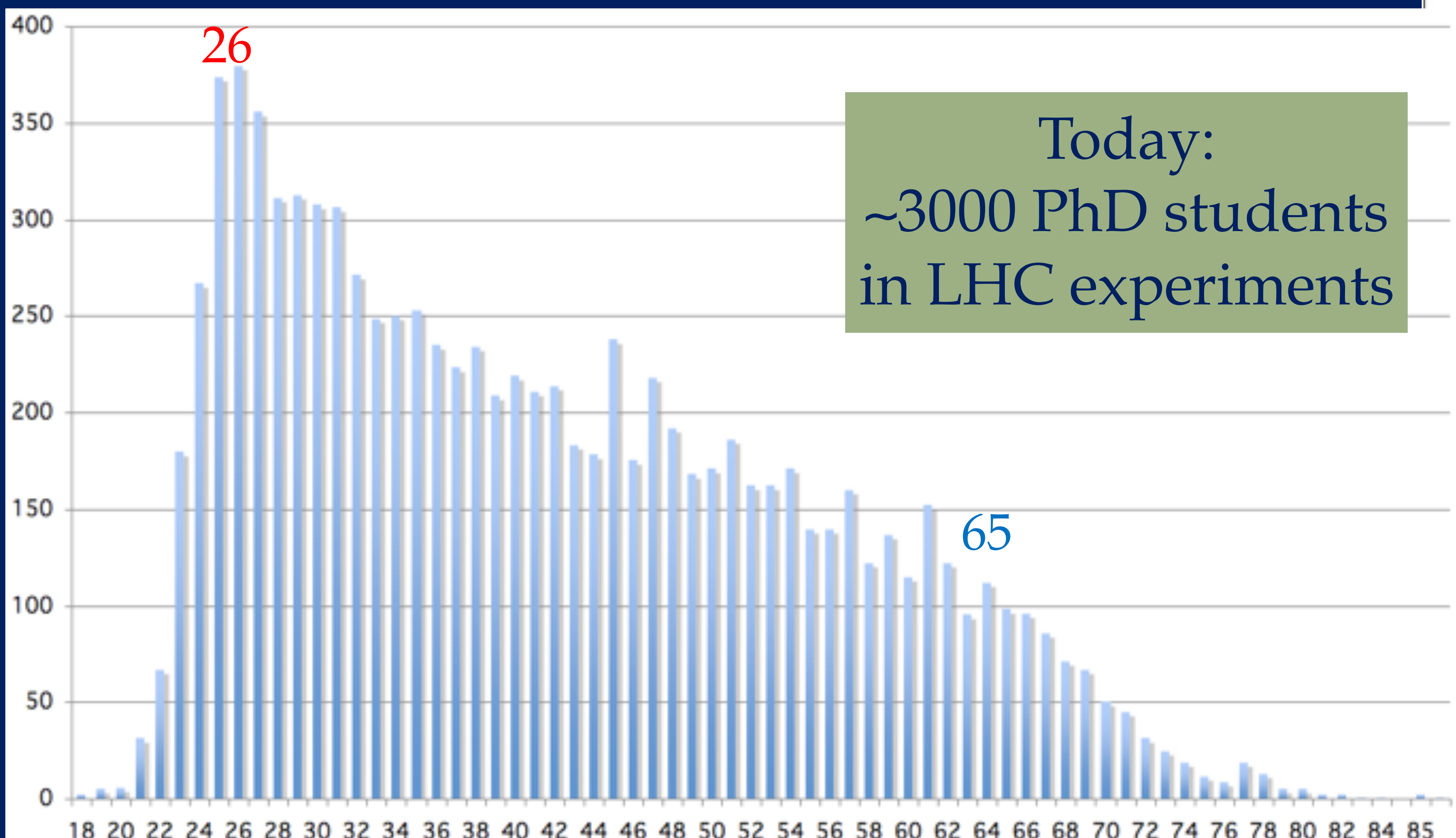

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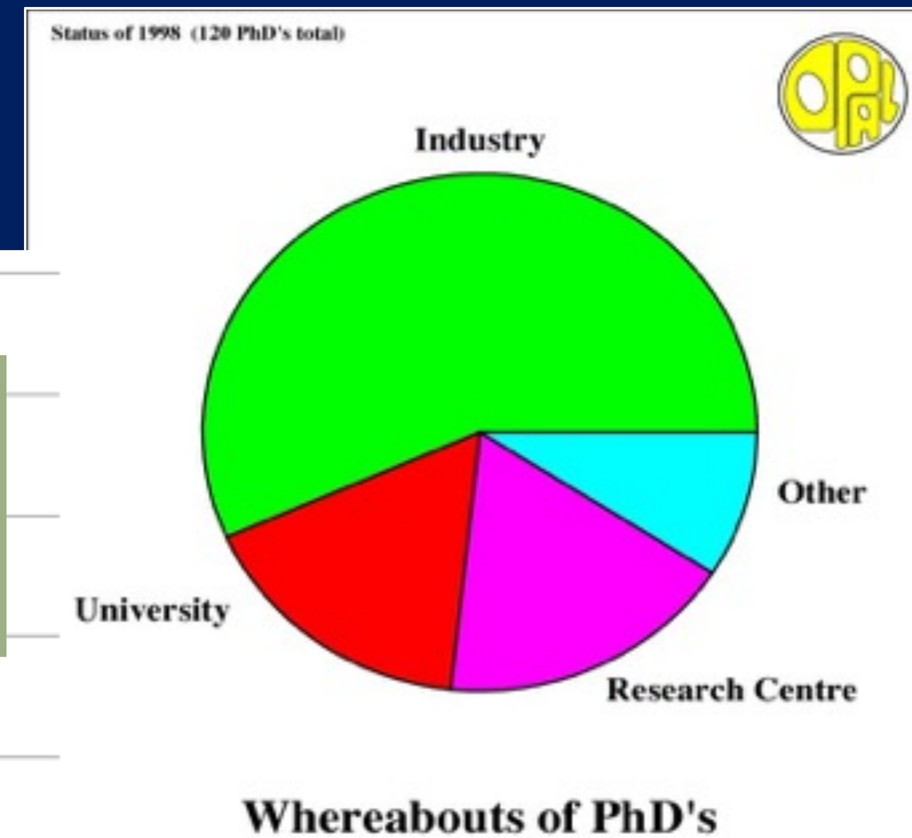
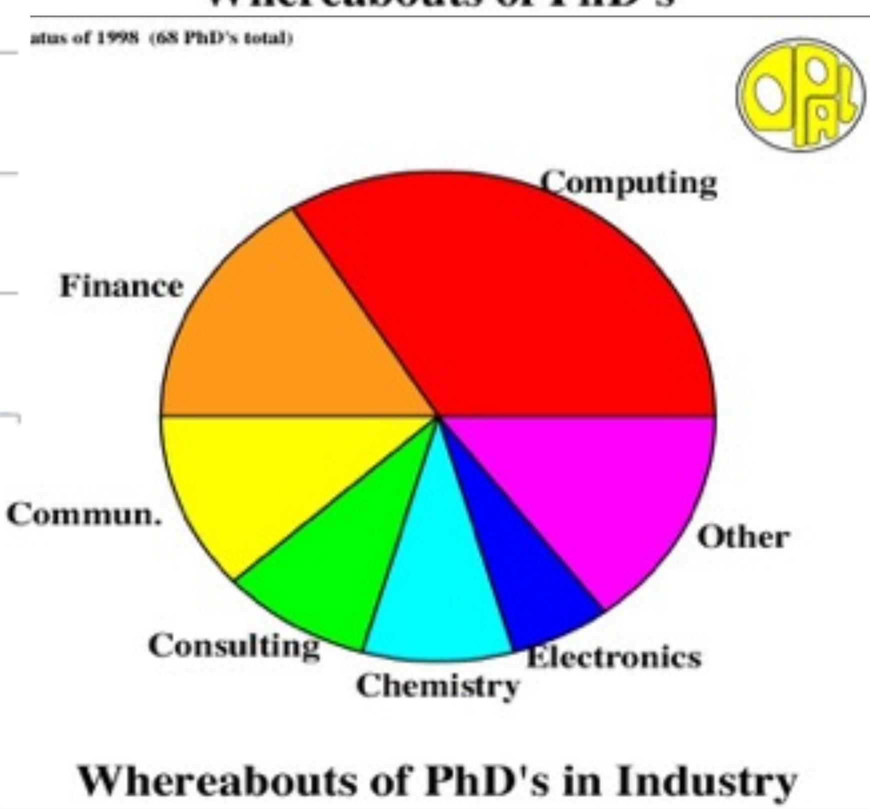




Knowledge and Technology Transfer

CERN: Particle Physics and Innovation

- Interfacing between fundamental science and key technological developments

Innovation Education
CERN
uniting people
Research

CERN: Particle Physics and Innovation

- Interfacing between fundamental science and key technological developments

- CERN Technologies and Innovation

Accelerating particle beams

Detecting particles

Large-scale computing (Grid)

CERN Technologies and Innovation

Example – Medical Applications

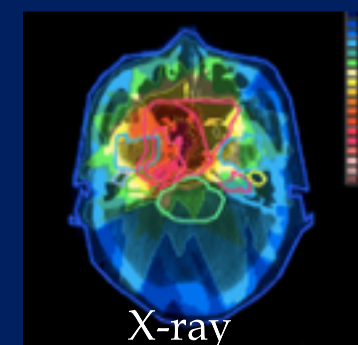
Combining Physics, ICT, Biology and Medicine to fight cancer

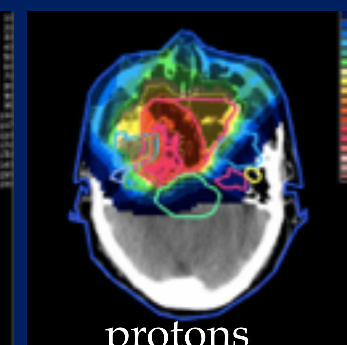
Accelerating particle beams

~30’000 accelerators worldwide

~17’000 used for medicine

Hadron Therapy





Leadership in Ion Beam Therapy now in Europe and Japan

>70’000 patients treated worldwide (30 facilities)

>21’000 patients treated in Europe (9 facilities)

CERN Technologies and Innovation

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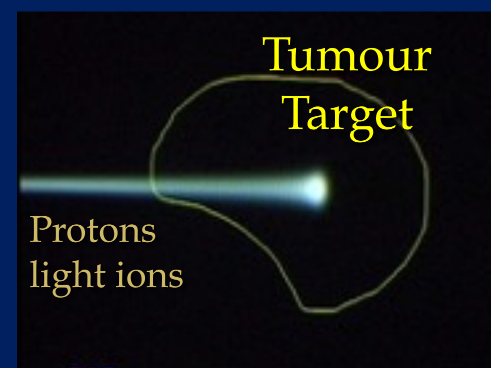

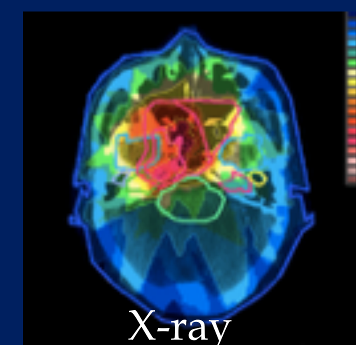

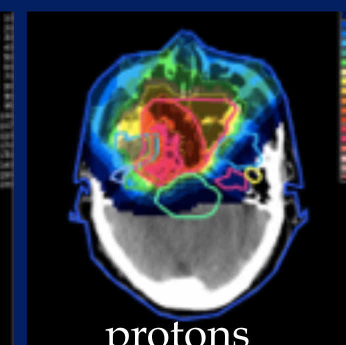

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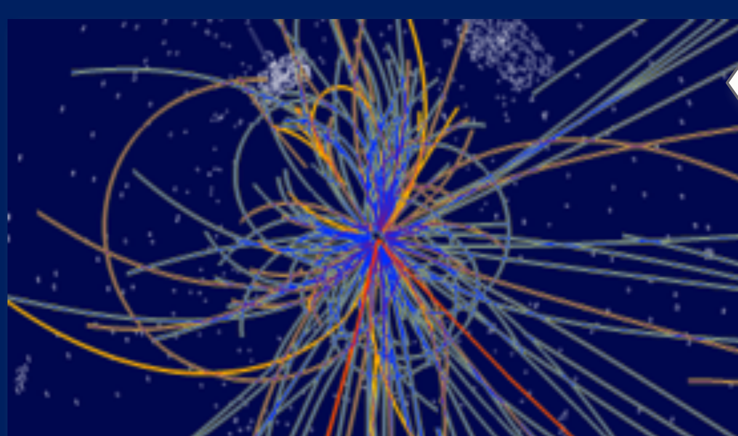
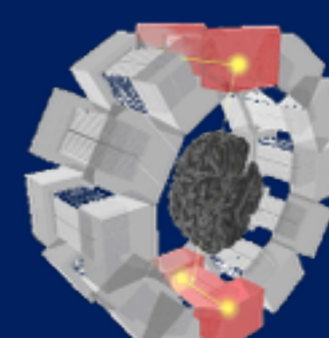


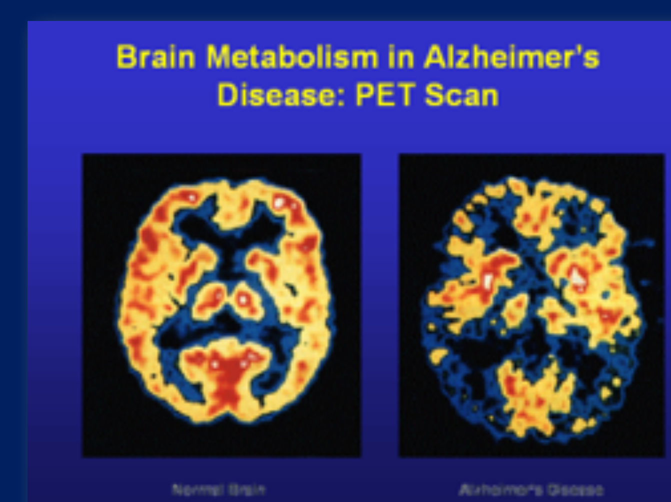
Detecting particles

Imaging

PET Scanner

Clinical trial in Portugal for new breast imaging system (ClearPEM)





Breaking the Wall of Communication
25 years ago: the Web was born

Breaking the Wall of Communication
25 years ago: the Web was born

Tim Berners-Lee

29

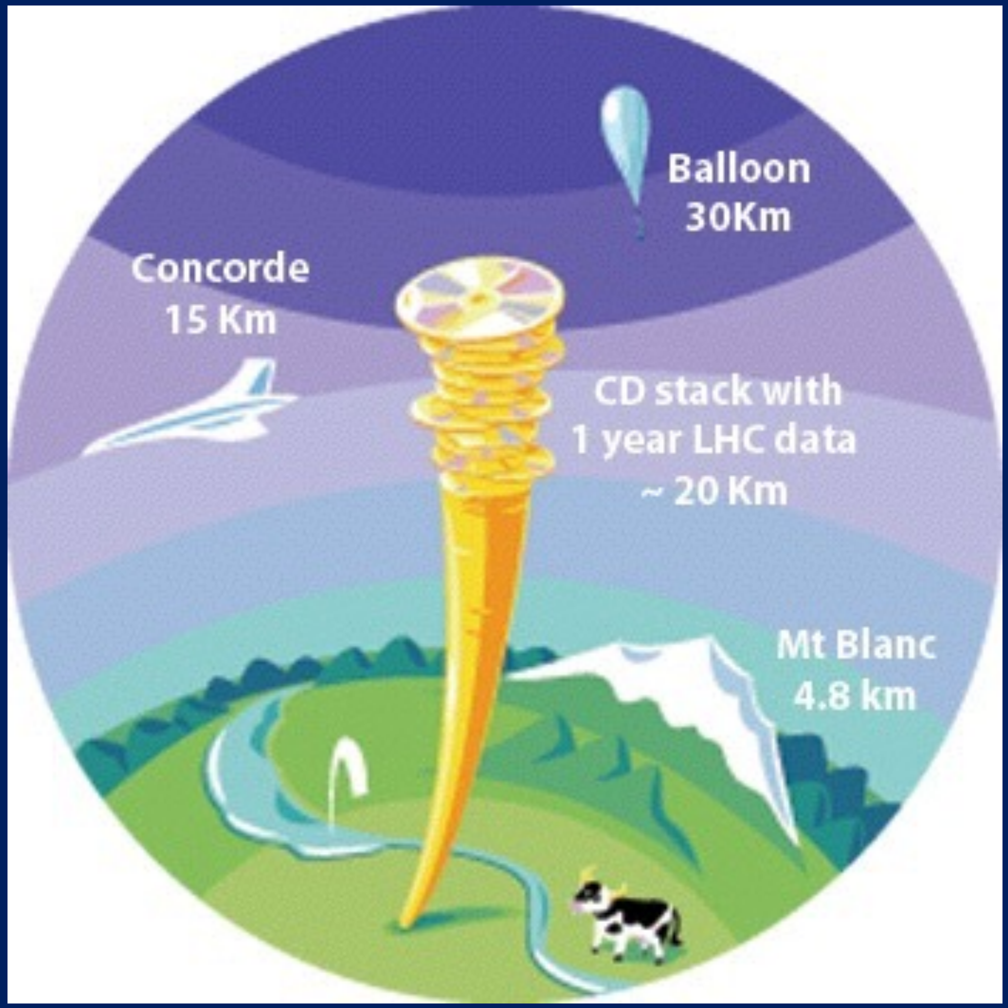
Breaking the Wall of Communication
25 years ago: the Web was born

Tim Berners-Lee

. . . and today ?

The LHC Data Challenge

- Experiments were anticipated to produce about 25 Million Gigabytes of data each year (~30 million CDs!).
- LHC data analysis requires a computing power equivalent to ~100,000 of today's fastest PC processors.
- => Requires many cooperating computer centres, as CERN can only provide ~20% of the capacity.



GRID Computing

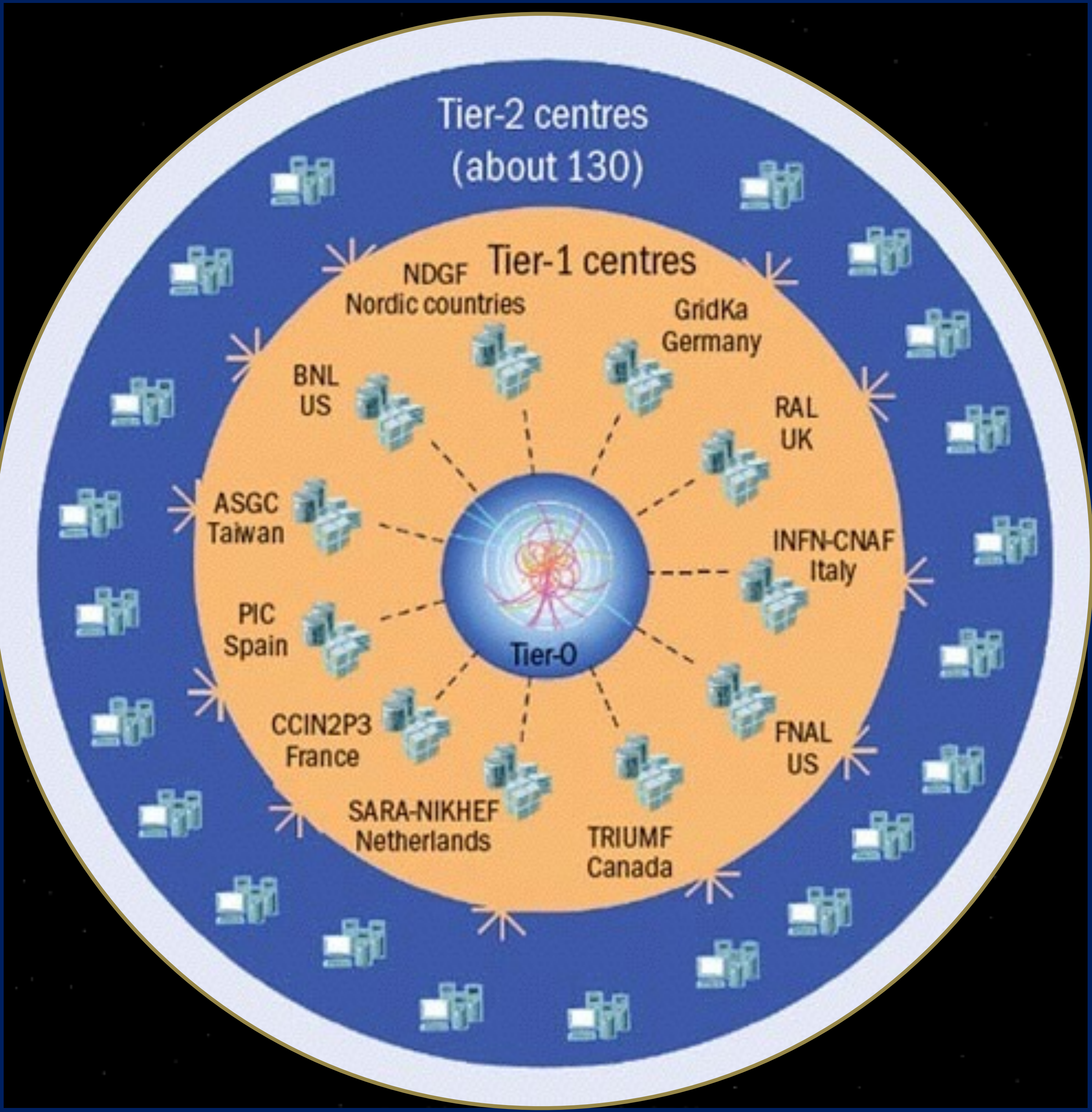
The Worldwide LHC Computing Grid

The Worldwide LHC Computing Grid

WLCG:
An International collaboration to distribute and analyse LHC data

Integrates computer centres worldwide that provide computing and storage resource into a single infrastructure accessible by all LHC physicists

The Worldwide LHC Computing Grid



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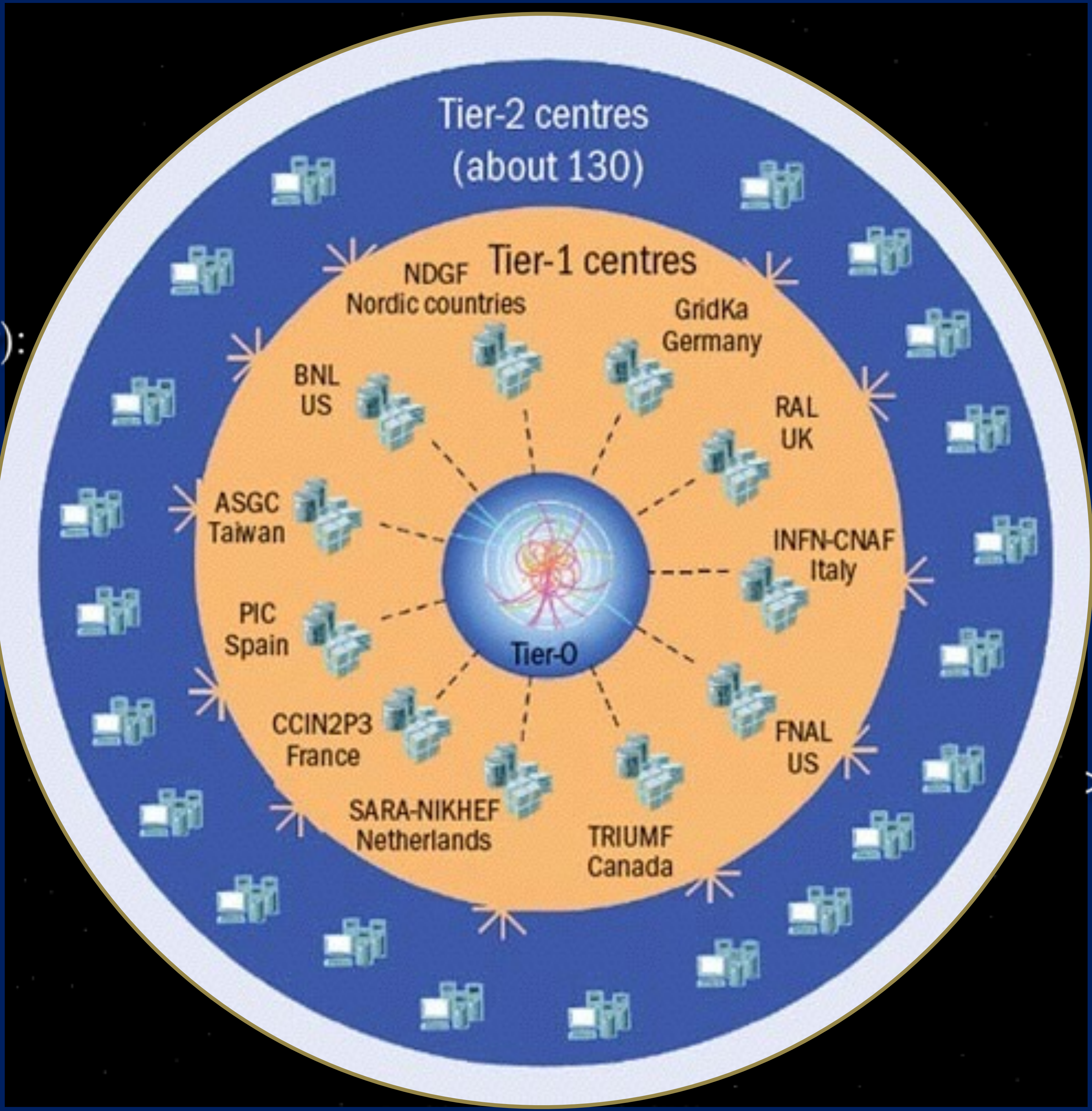
The Worldwide LHC Computing Grid

Tier-0
(CERN and Hungary): data recording, reconstruction and distribution

Tier-1: permanent storage, re-processing, analysis

Tier-2: Simulation, end-user analysis



nearly 160 sites,
35 countries

~250’000 cores

173 PB of storage

> 2 million jobs/day

10 Gb links

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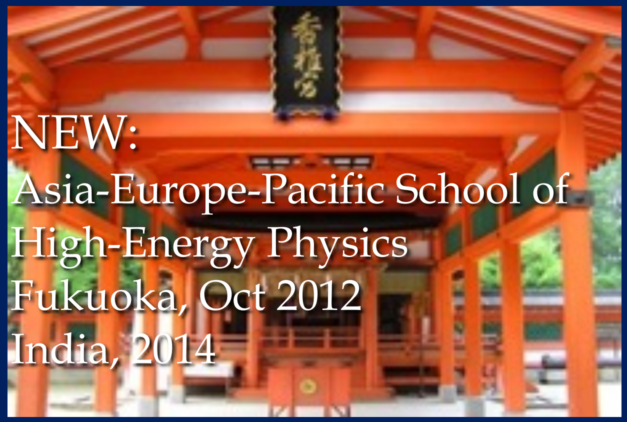
CERN Education Activities



NEW:
Asia-Europe-Pacific School of High-Energy Physics
Fukuoka, Oct 2012
India, 2014

Latin American School
Natal, Brazil, 2011
Arequipa, Peru, 2013

Scientists at CERN
Academic Training Programme

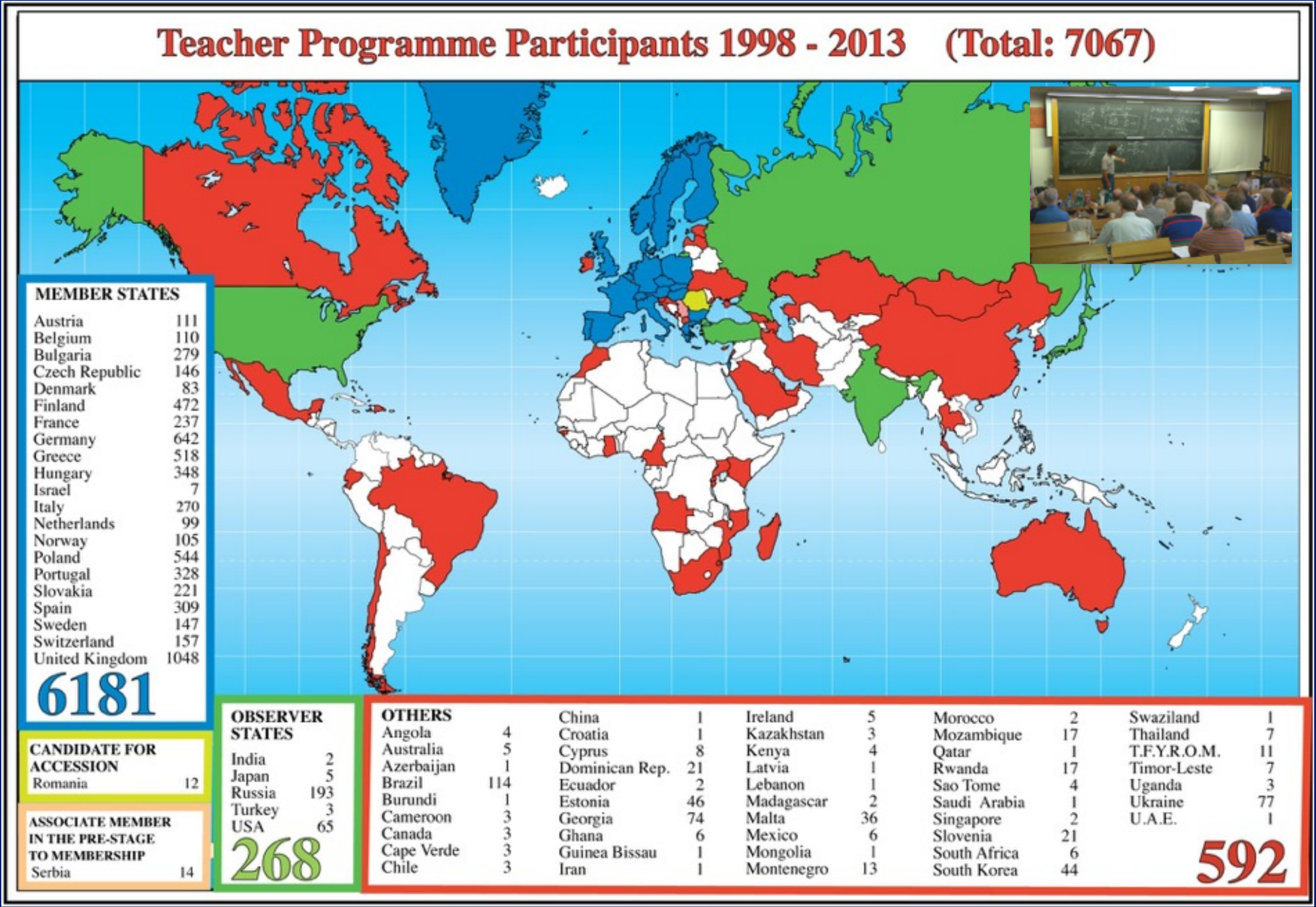
Young Researchers
CERN School of High Energy Physics
CERN School of Computing
CERN Accelerator School

CERN School of Physics
Hungary, June 2013

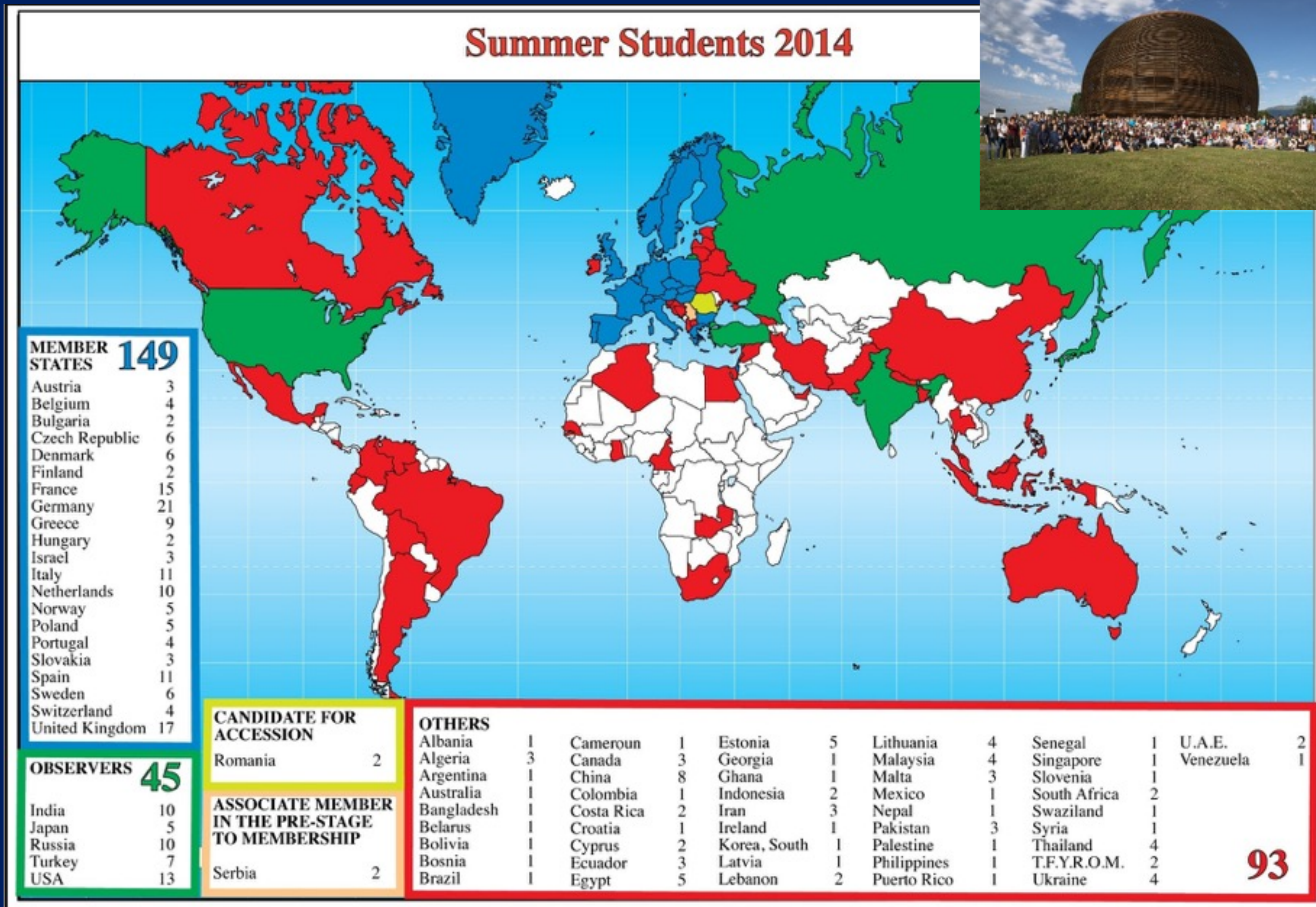
Physics Students
Summer Students
Programme

CERN Teacher Schools
International and National
Programmes

CERN Teacher Programme

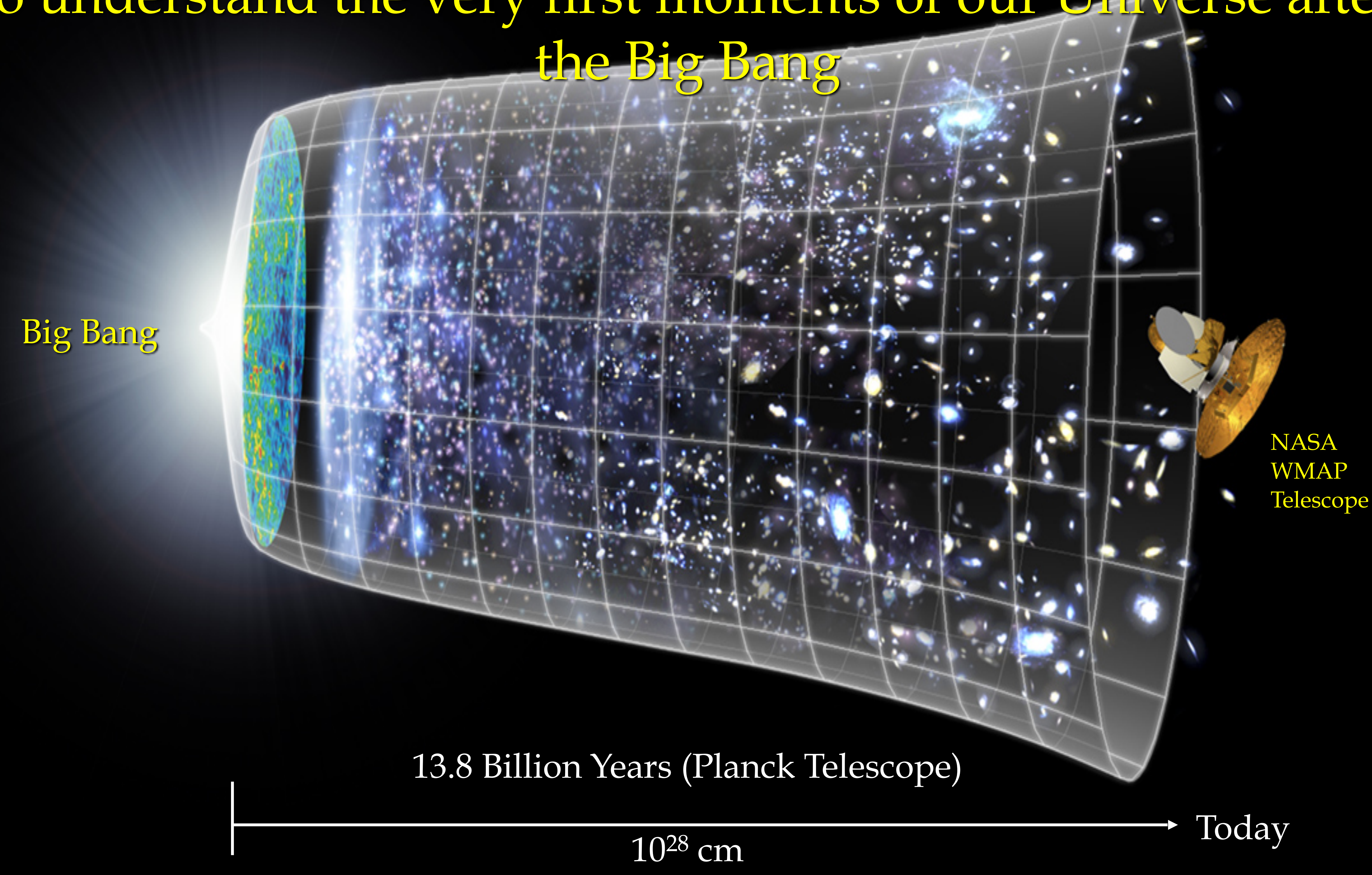


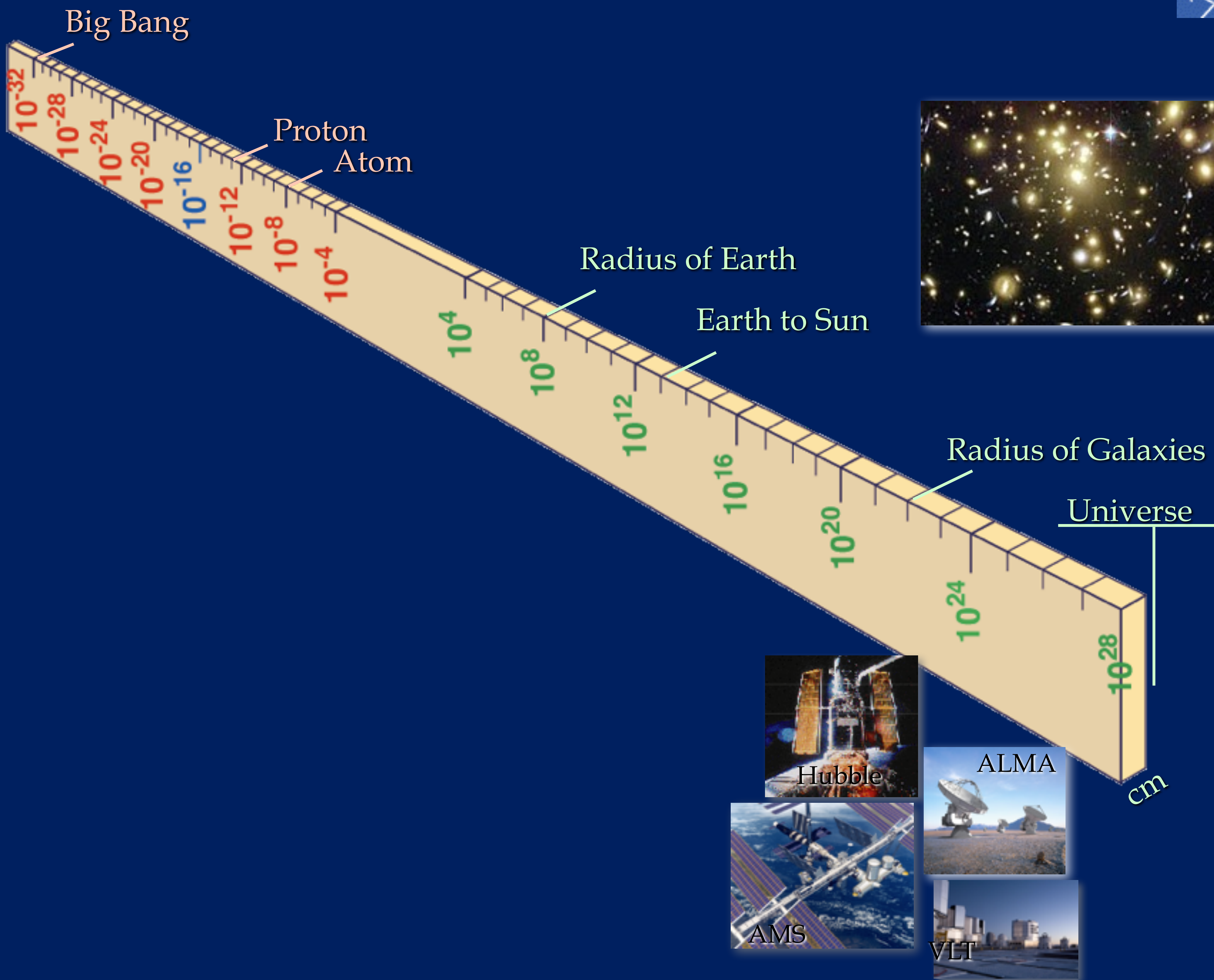
Summer Students 2014

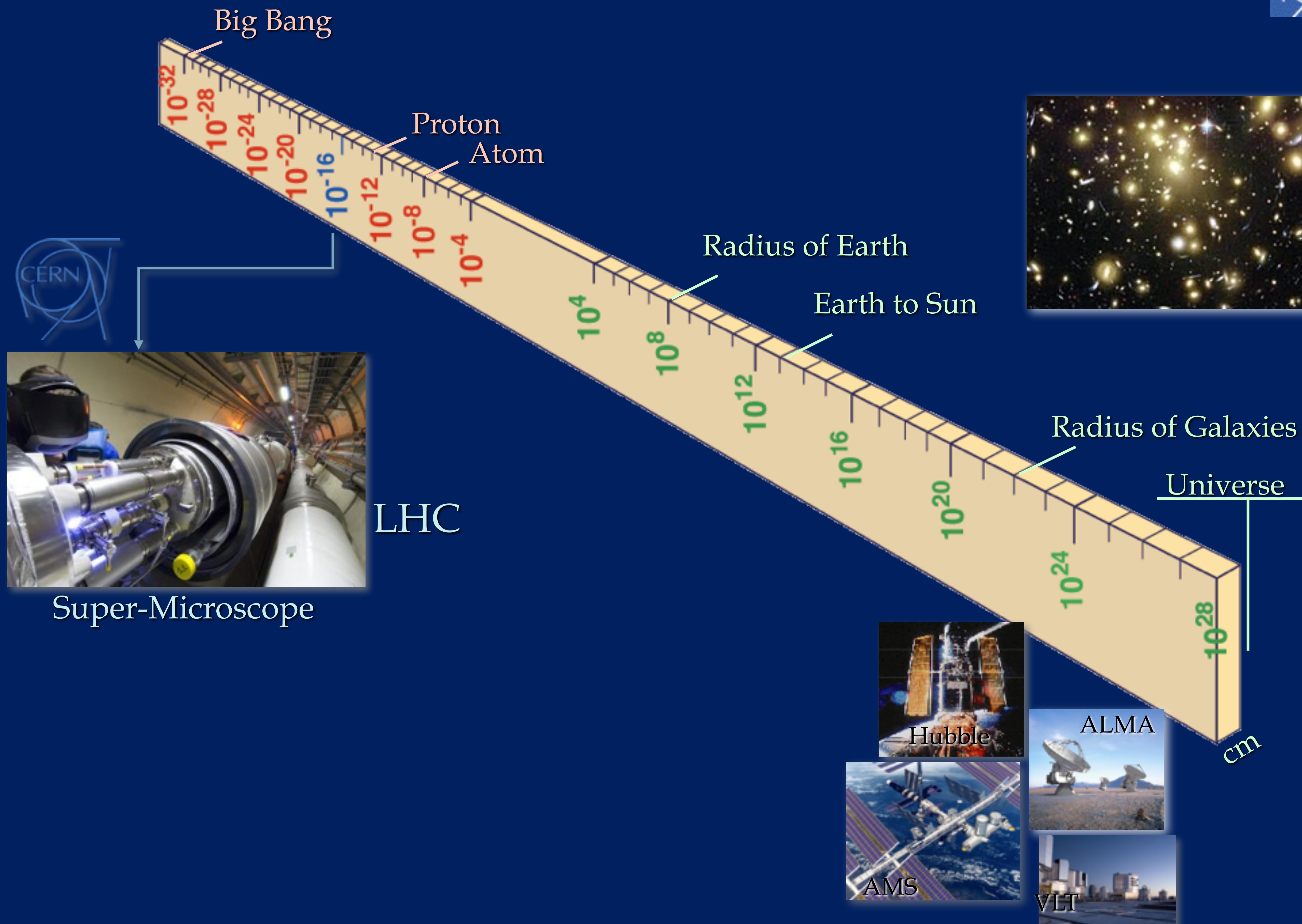


Discovery Science

Scientific Challenge:
to understand the very first moments of our Universe after the Big Bang




Big Bang
Proton
Atom
Radius of Earth
Earth to Sun
Radius of Galaxies
Universe
10^{-32}
10^{-28}
10^{-24}
10^{-20}
10^{-16}
10^{-12}
10^{-8}
10^{-4}
10^{4}
10^{8}
10^{12}
10^{16}
10^{20}
10^{24}
10^{28}
cm
Hubble
ALMA
AMS
VLT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AMS
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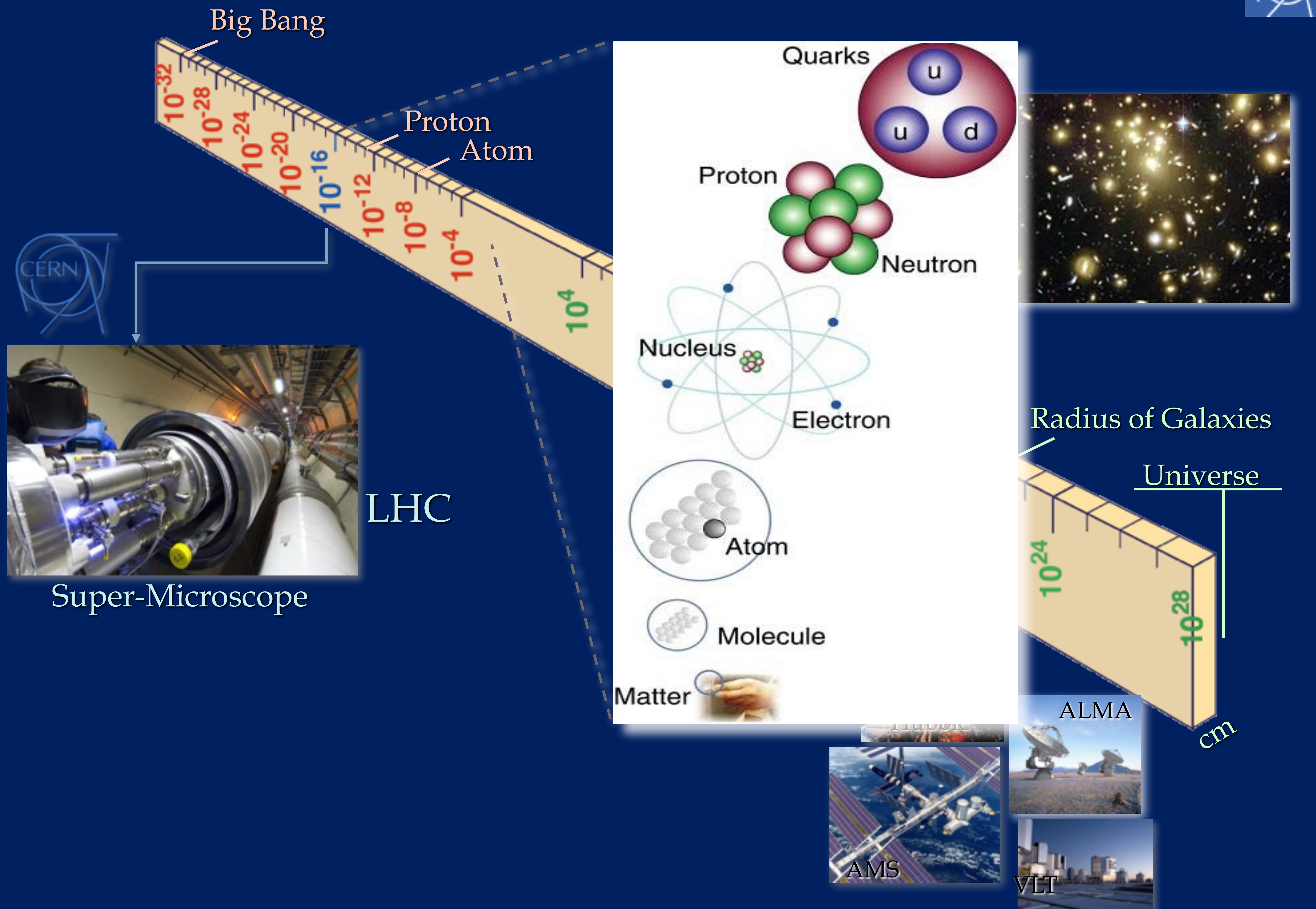

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Quarks
u
u
d
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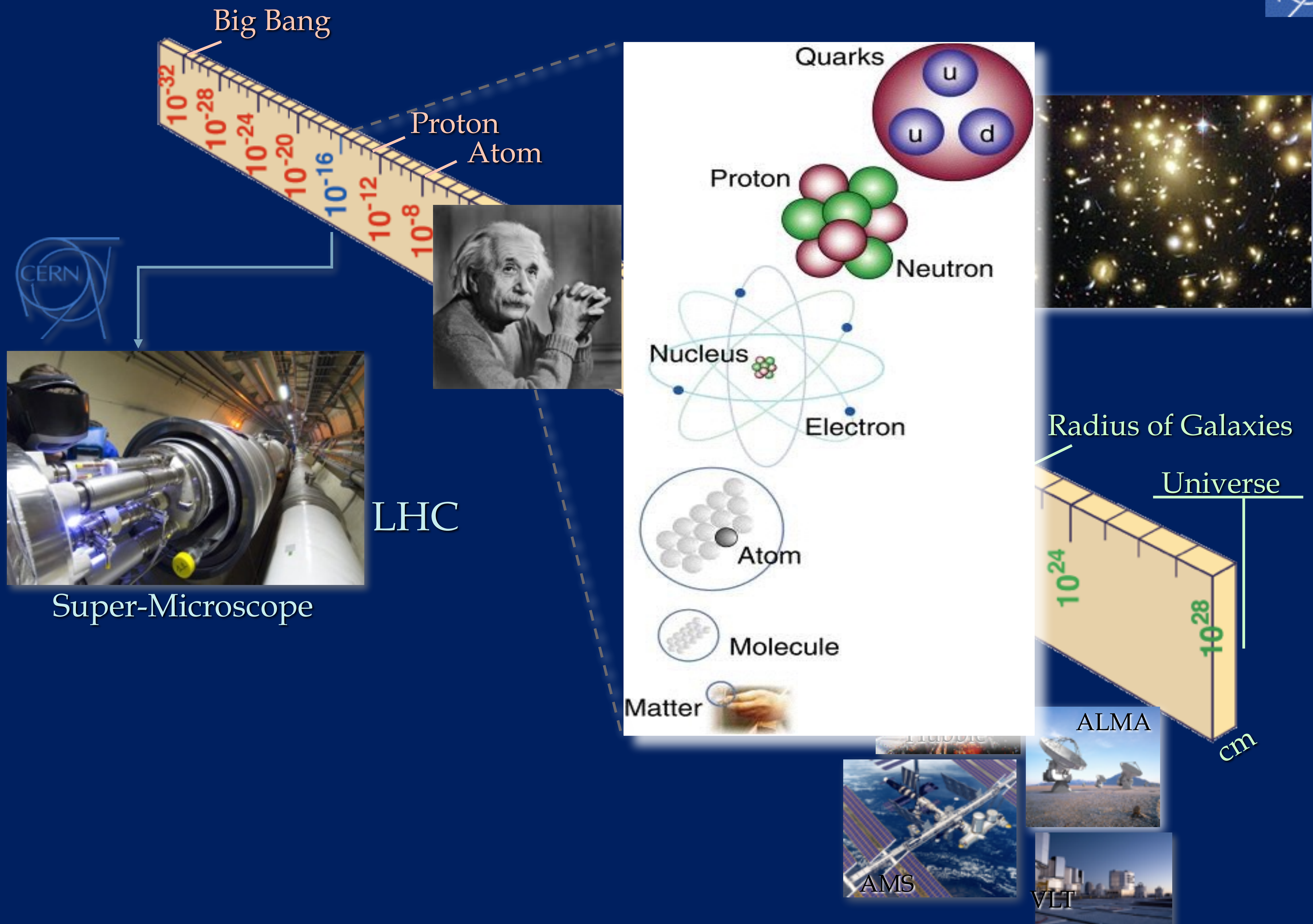
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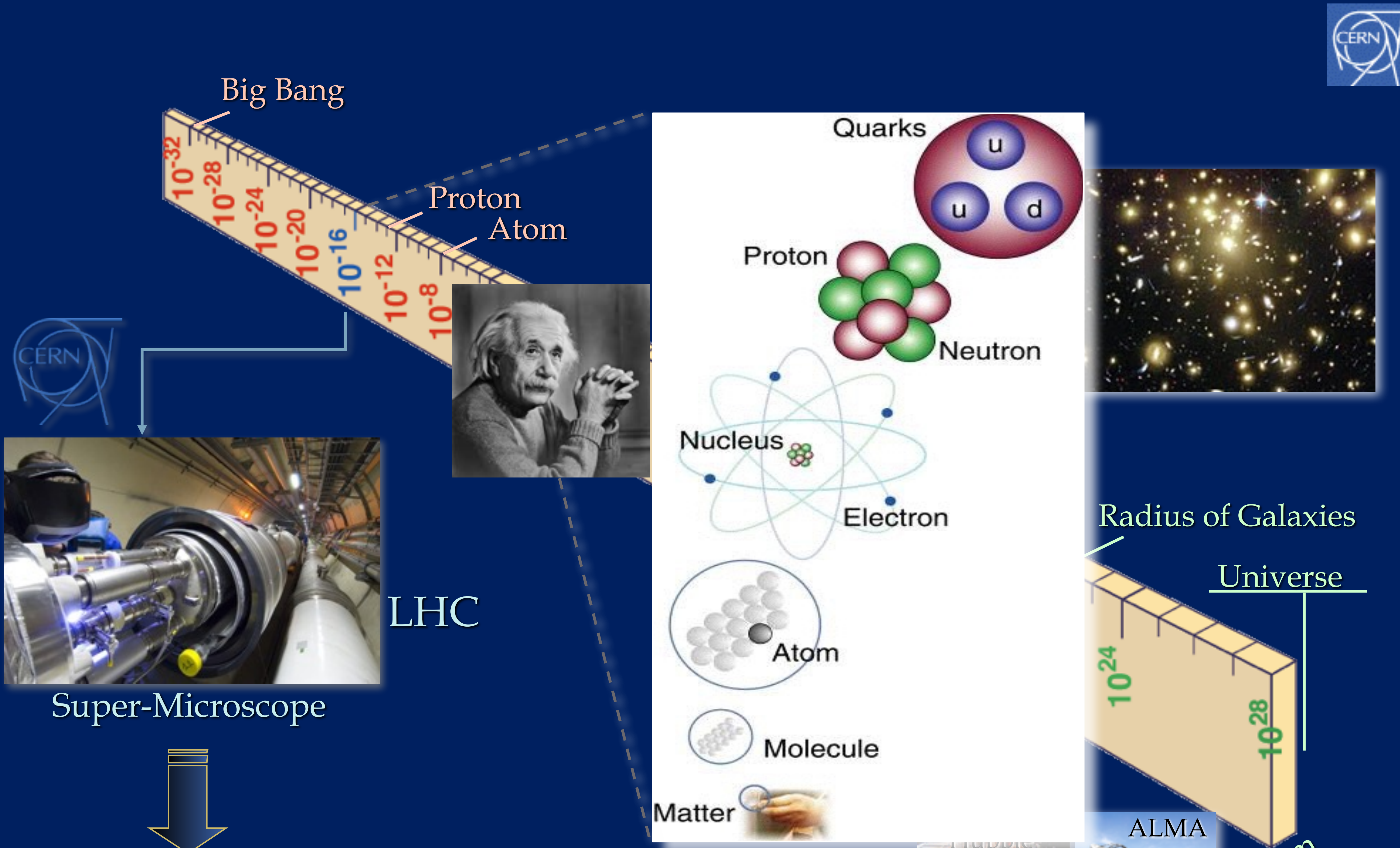
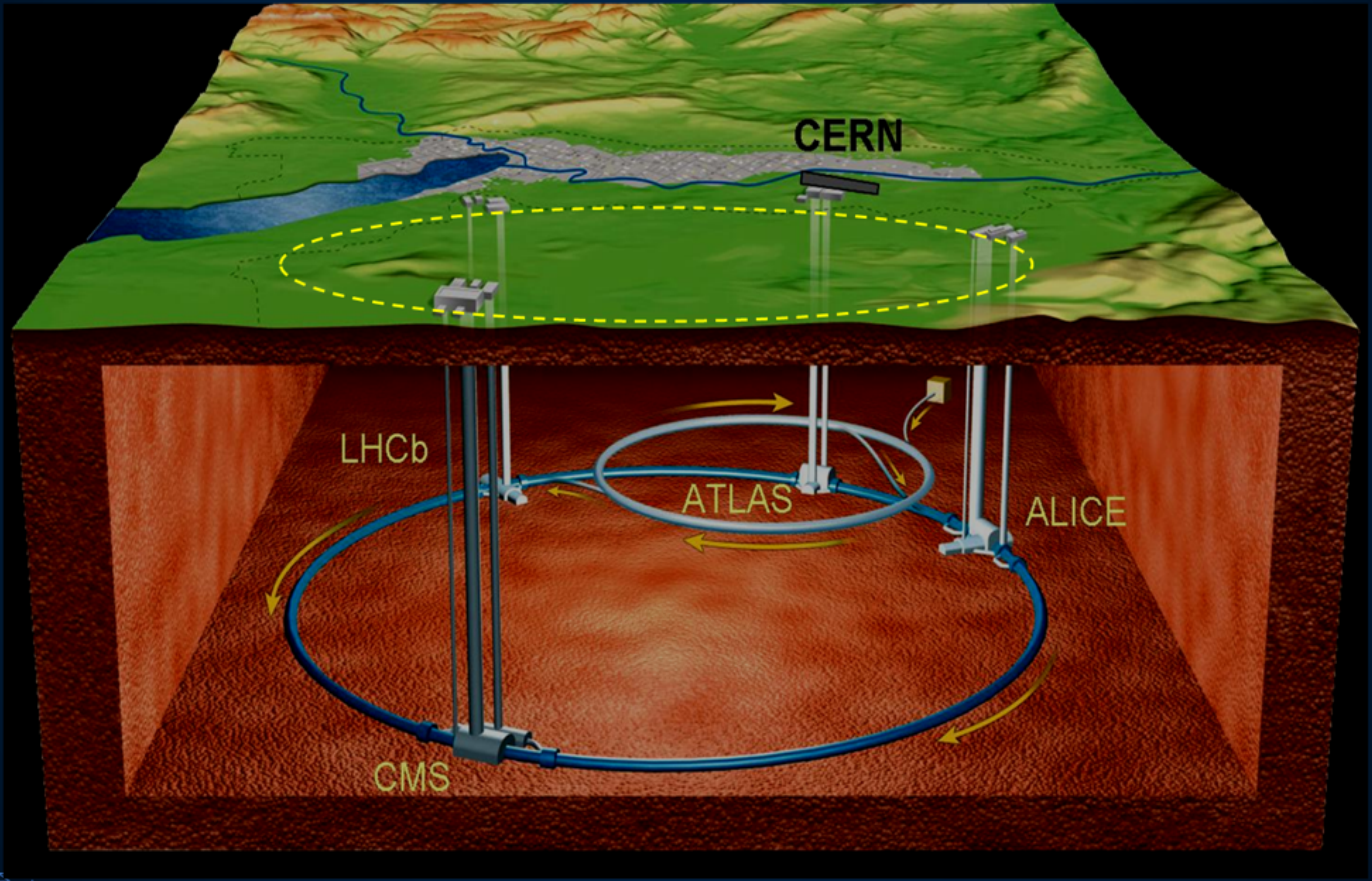


Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology

The
Large Hadron Collider

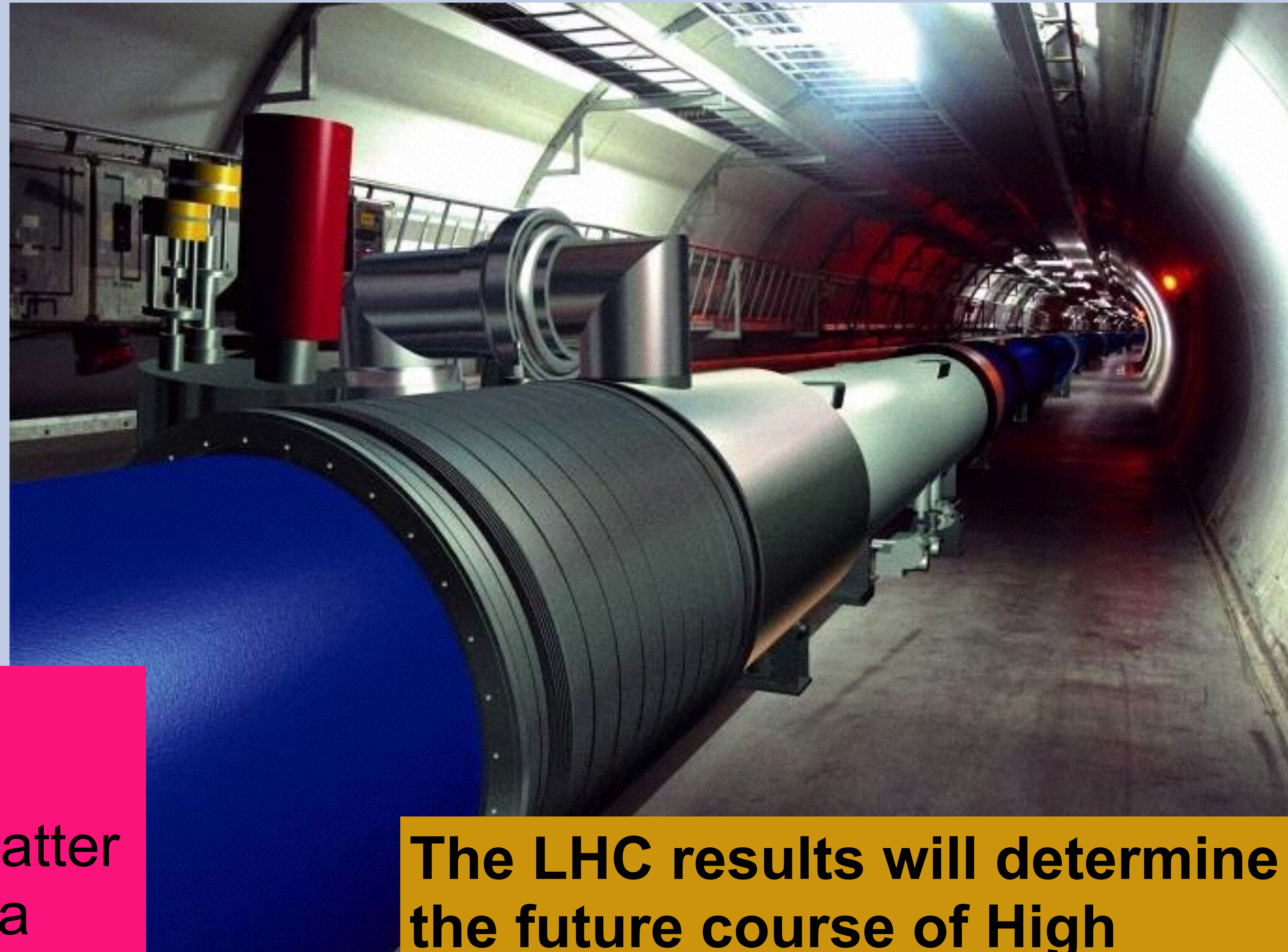
LHC – Large Hadron Collider



LHC - Large Hadron Collider

7 TeV + 7 TeV

Luminosity = $10^{34} cm^{-2} sec^{-1}$



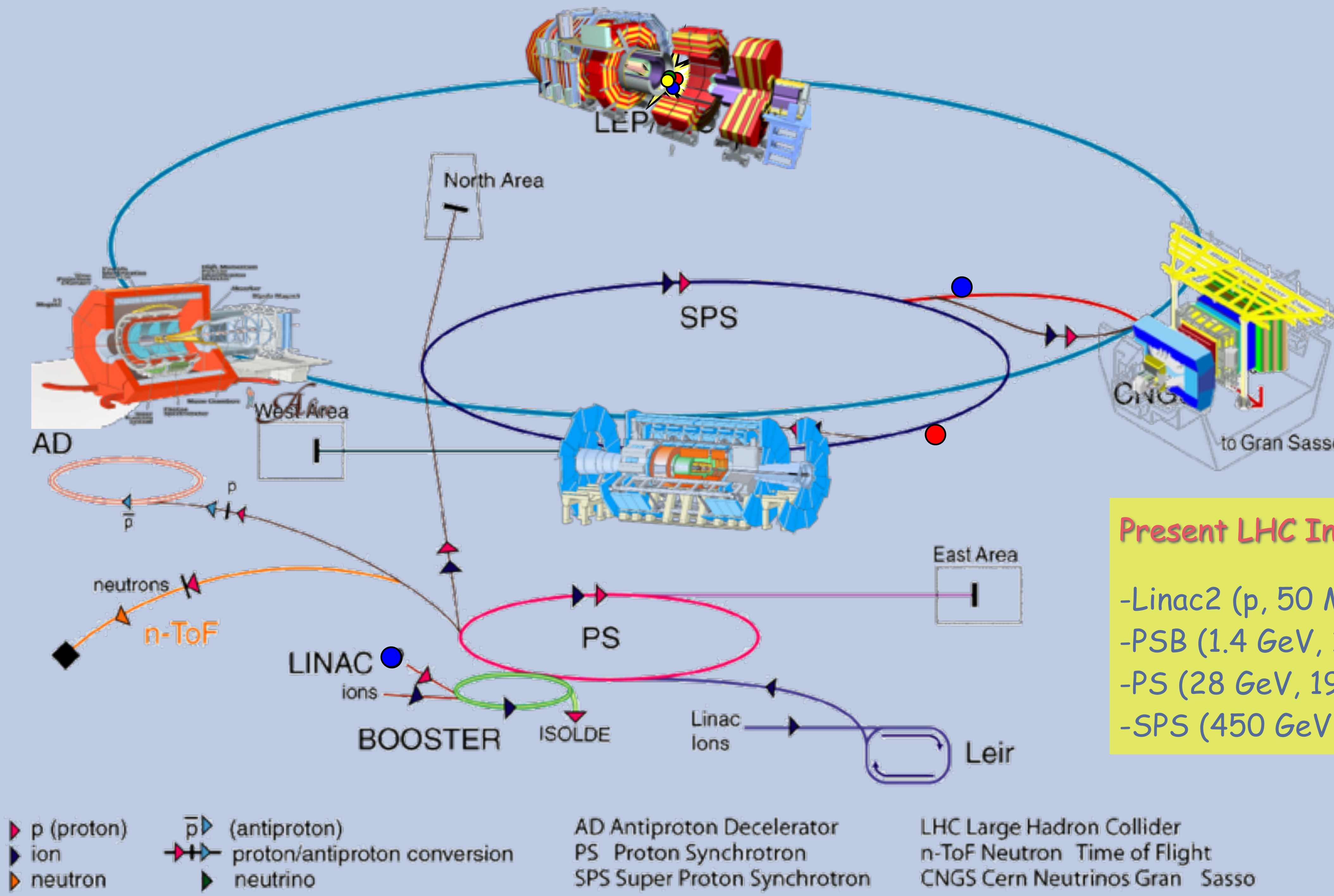
Primary targets:

- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

The LHC results will determine the future course of High Energy Physics

The large Hadron Collider

Collision of proton beams… …observed in giant detectors

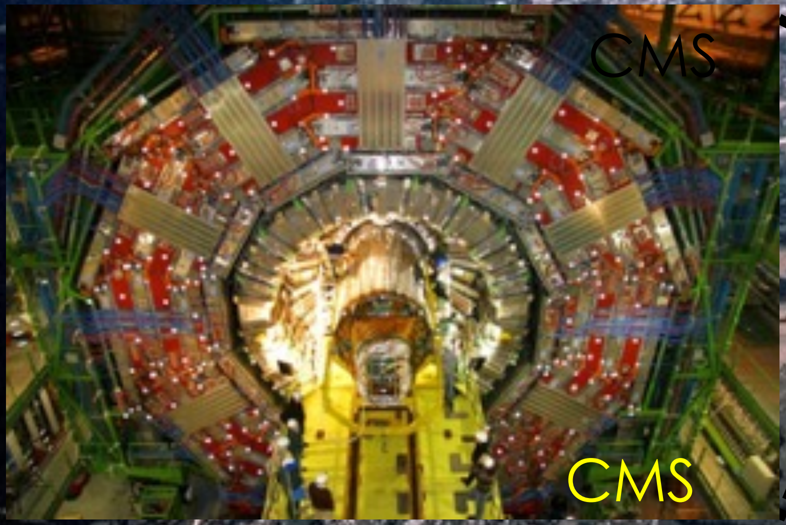


Present LHC Injectors

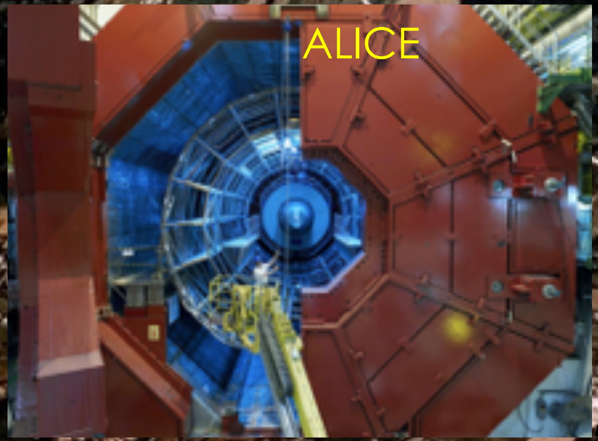
-Linac2 (p, 50 MeV, 1978)
-PSB (1.4 GeV, 1972)
-PS (28 GeV, 1959)
-SPS (450 GeV, 1976)

Enter a New Era in Fundamental Science

Start-up of the Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.

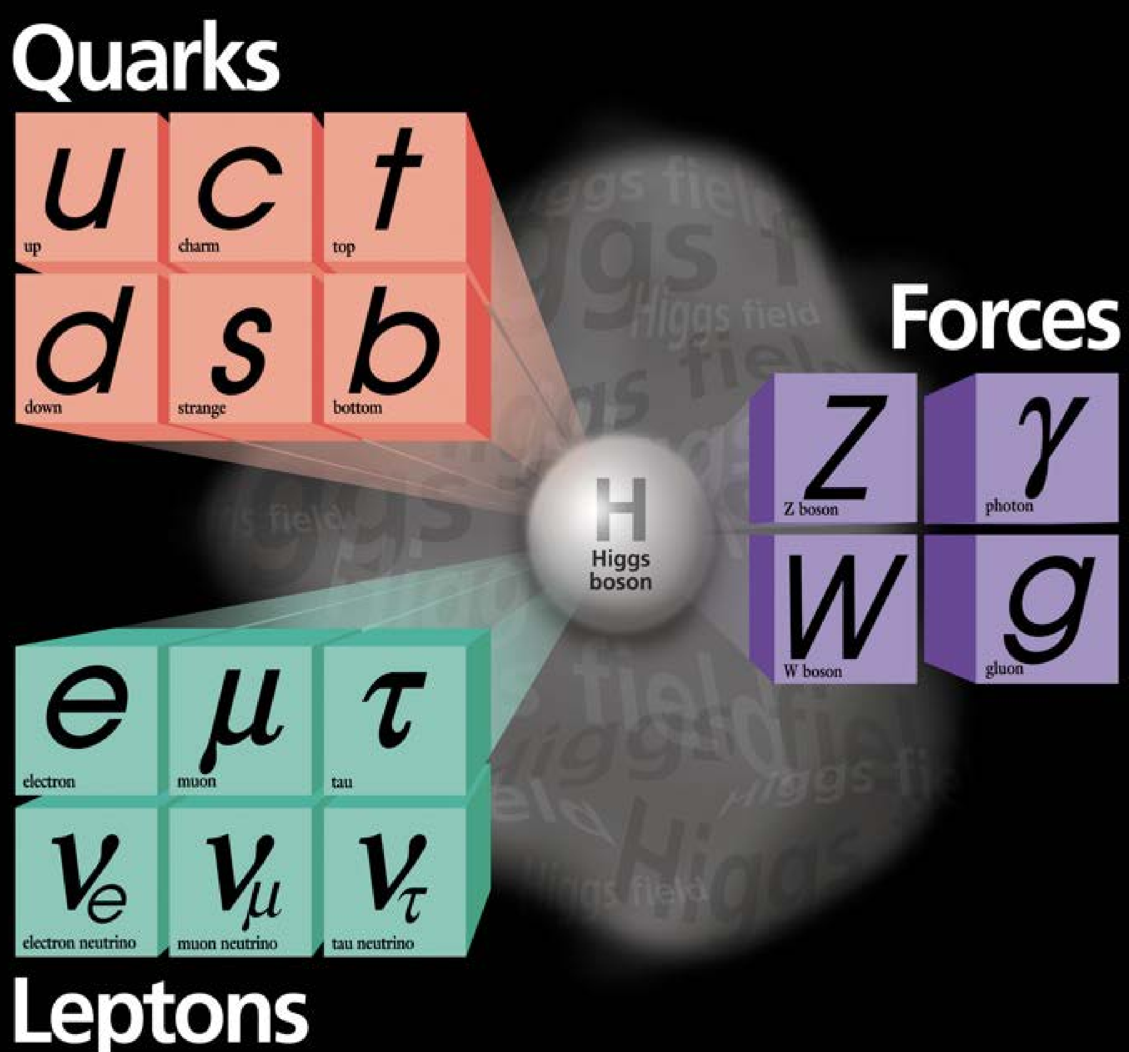


Exploration of a new energy frontier
Proton-proton collisions at E_{CM} up to 14 TeV

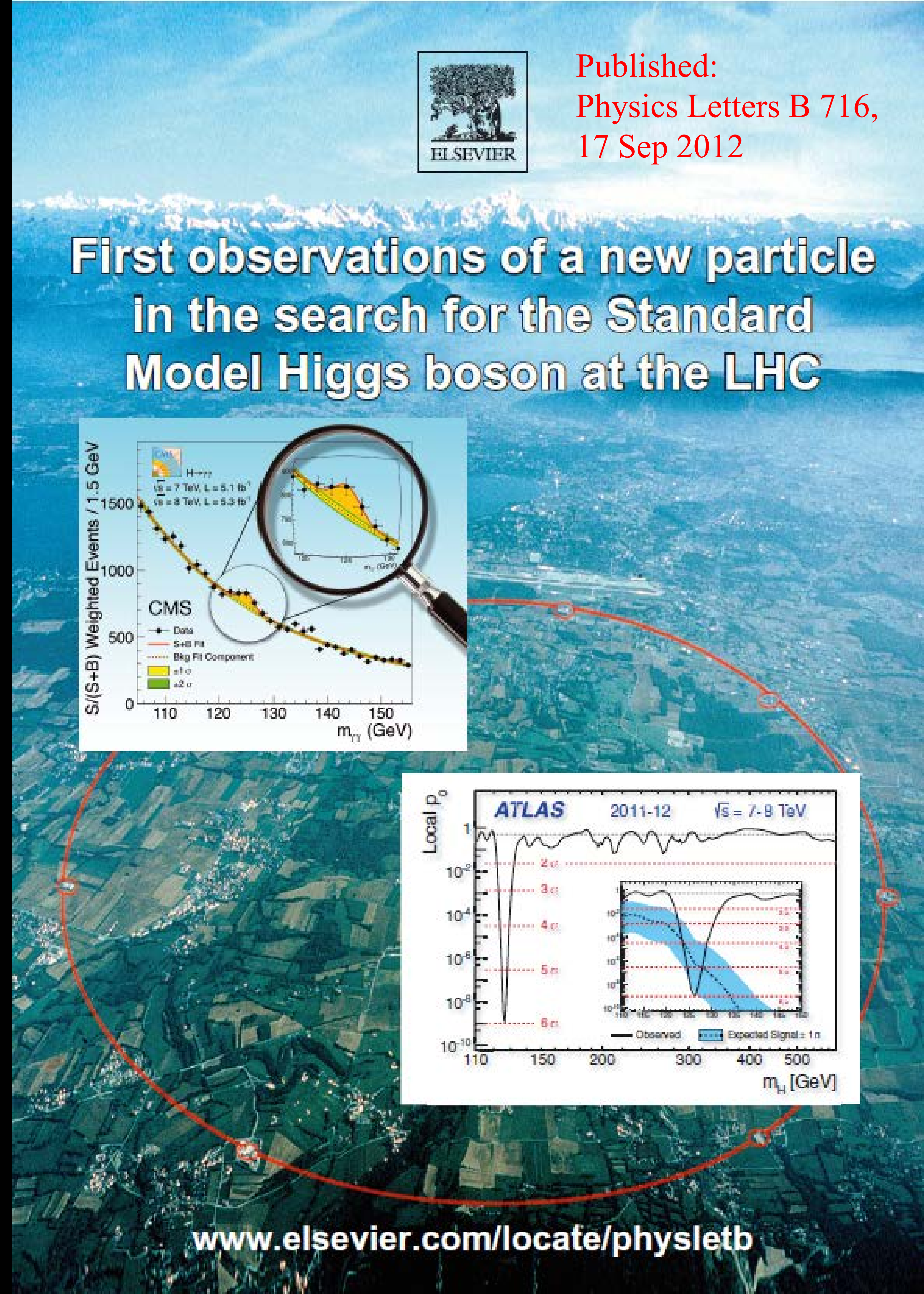


The discovery of the **Higgs particle** – the most important result from LHC (currently)

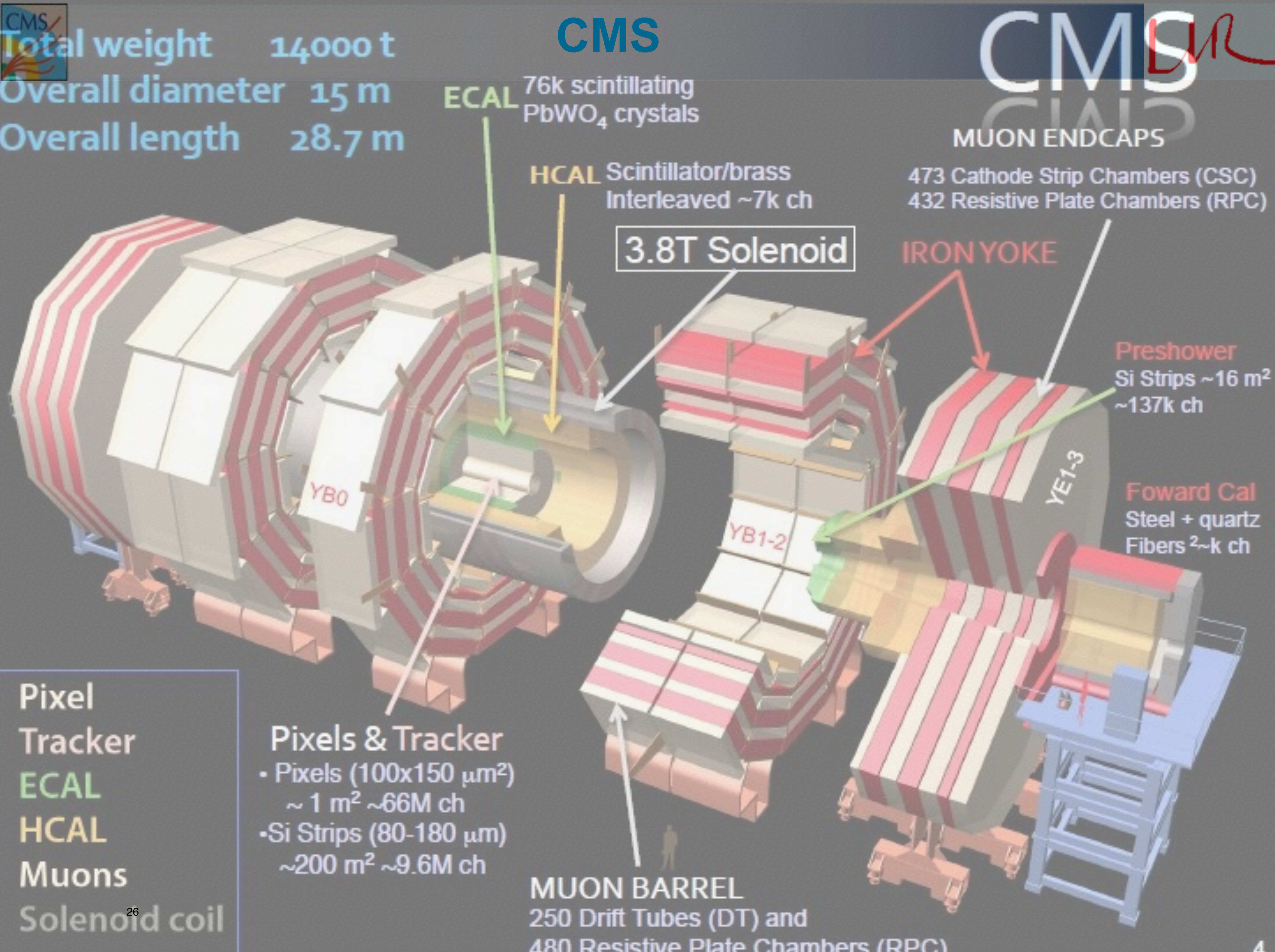
4.07.2012



Published:
Physics Letters B 716,
17 Sep 2012

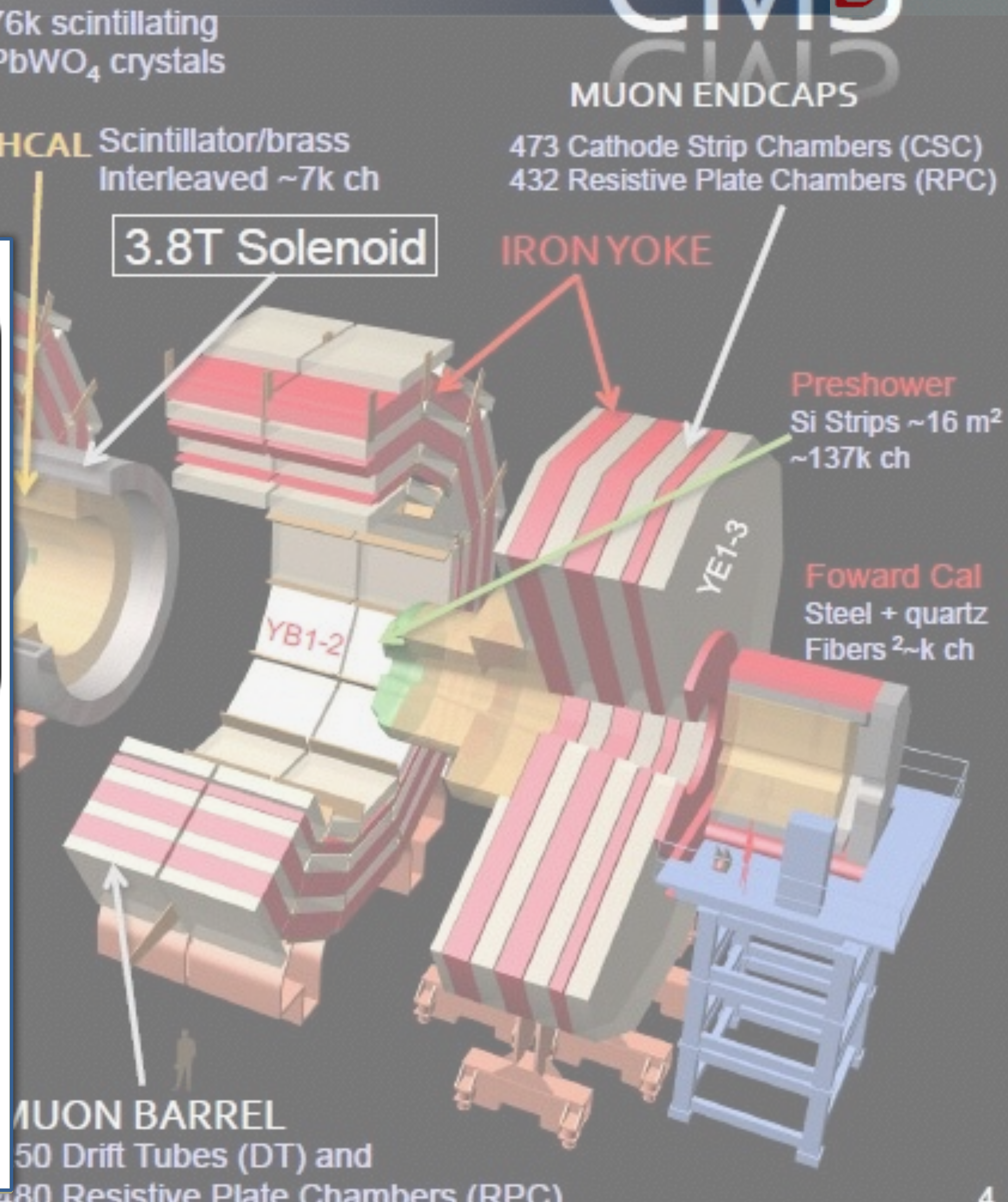


CMS



Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
ECAL
76k scintillating
$PbWO_4$ crystals
HCAL
Scintillator/brass
Interleaved ~7k ch
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
3.8T Solenoid
IRON YOKE
Preshower
Si Strips ~16 m^2
~137k ch
Foward Cal
Steel + quartz
Fibers ^{2}~k ch
YB0
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 ~66M ch
•Si Strips (80-180 μm)
~200 m^2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

CMS



The design goals of CMS:

1. A very good and redundant muon system
2. The best possible ECAL consistent with 1)
3. A high quality central tracking to achieve 1) and 2)
4. A financially affordable detector

-3.8T solenoid 13m long, 6m diameter
- high eta HCAL coverage
-Silicon based inner tracking system supplementing all types of reconstr.

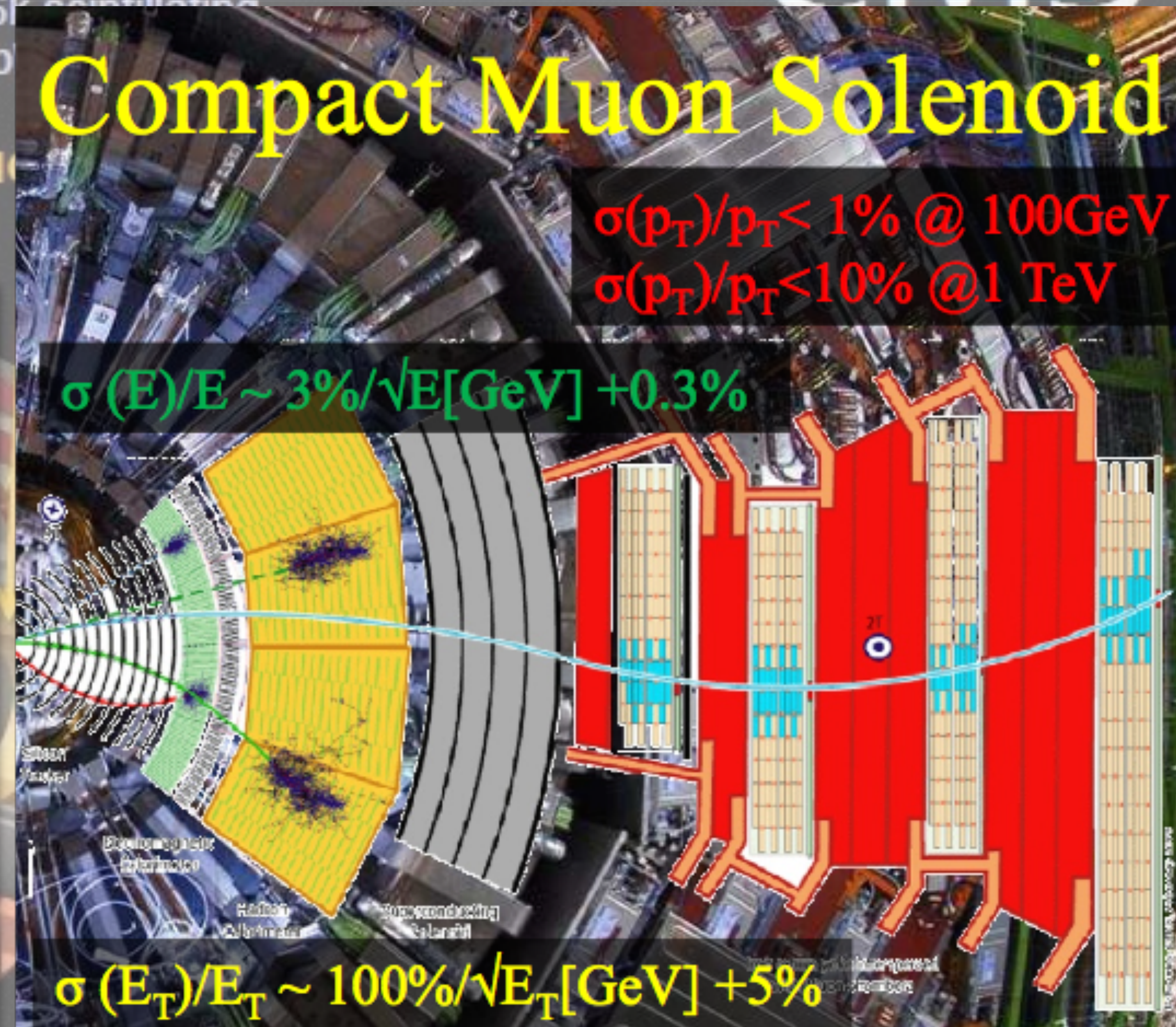
Powerful reconstruction of:

μ, e/γ, τ-jets, jets, MET

(+tracks, vertices)

CMS

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



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-Silicon based inner tracking system supplementing all types of reconstr.

Powerful reconstruction of:

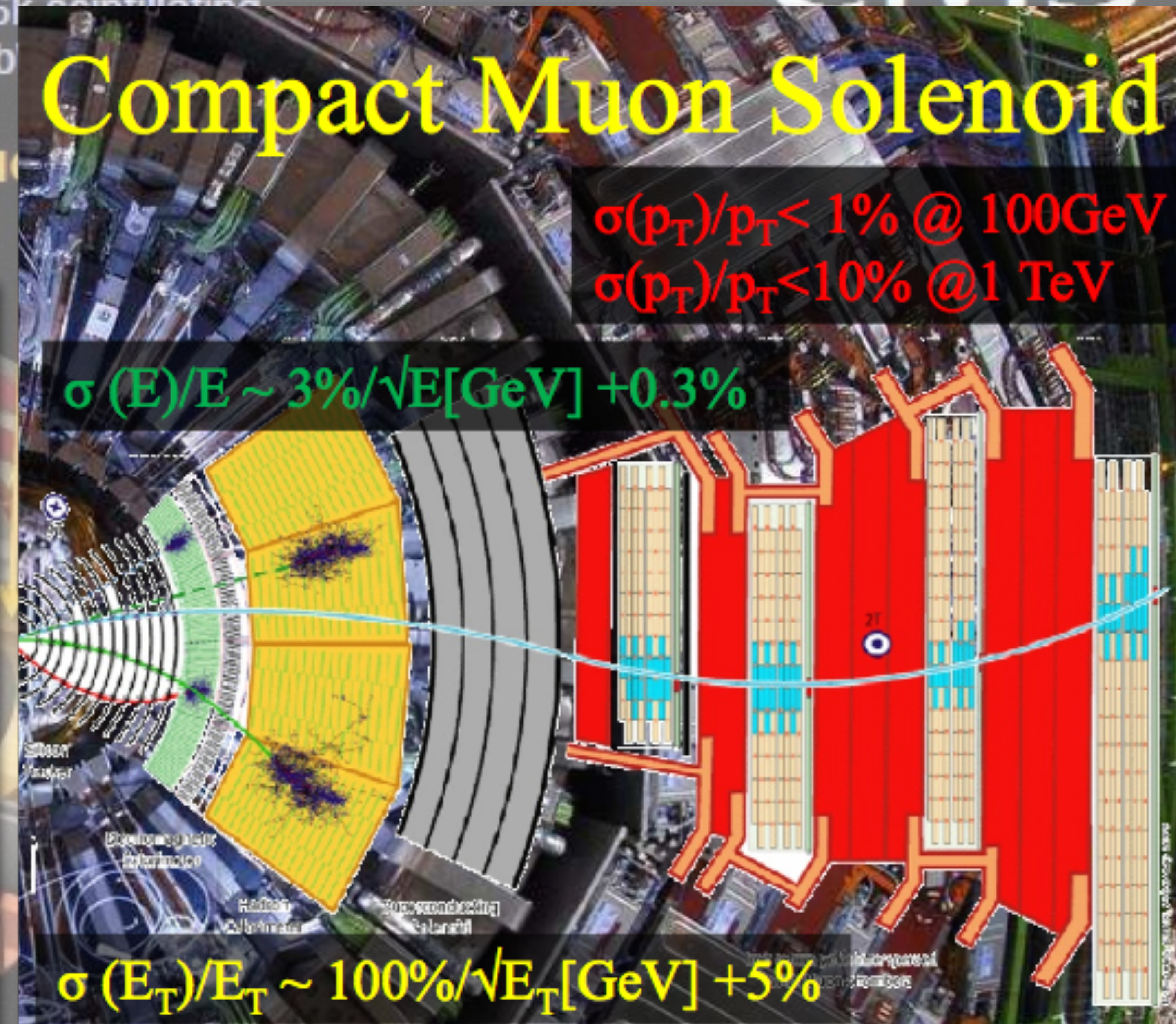
μ, e/γ, τ-jets, jets, MET

(+tracks, vertices)

MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

CMS

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



The design goals of CMS:

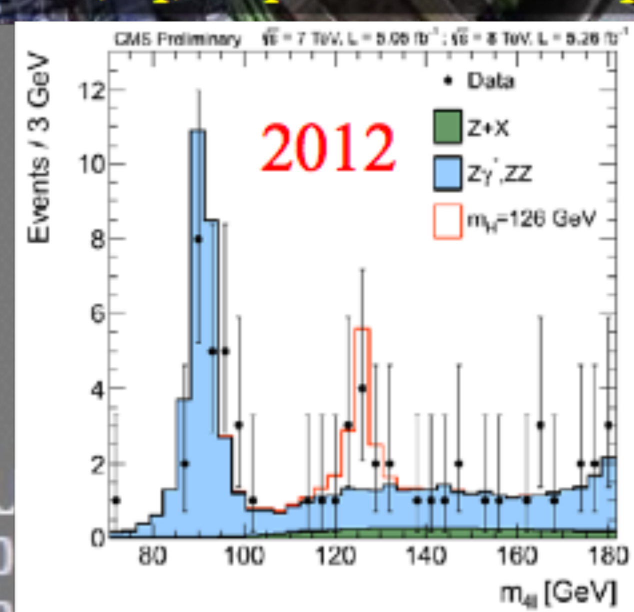
1. A very good and redundant muon system
2. The best possible ECAL consistent with 1)
3. A high quality central tracking to achieve 1) and 2)
4. A financially affordable detector

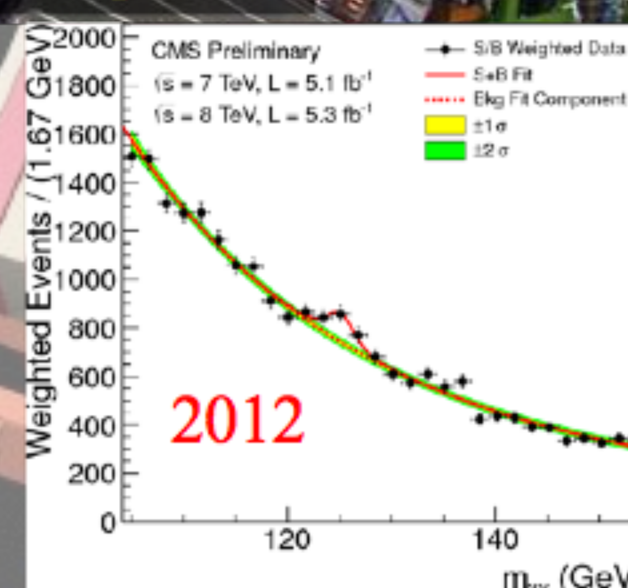
-3.8T solenoid 13m long, 6m diameter
- high eta HCAL coverage
-Silicon based inner tracking system supplementing all types of reconstr.

Powerful reconstruction of:

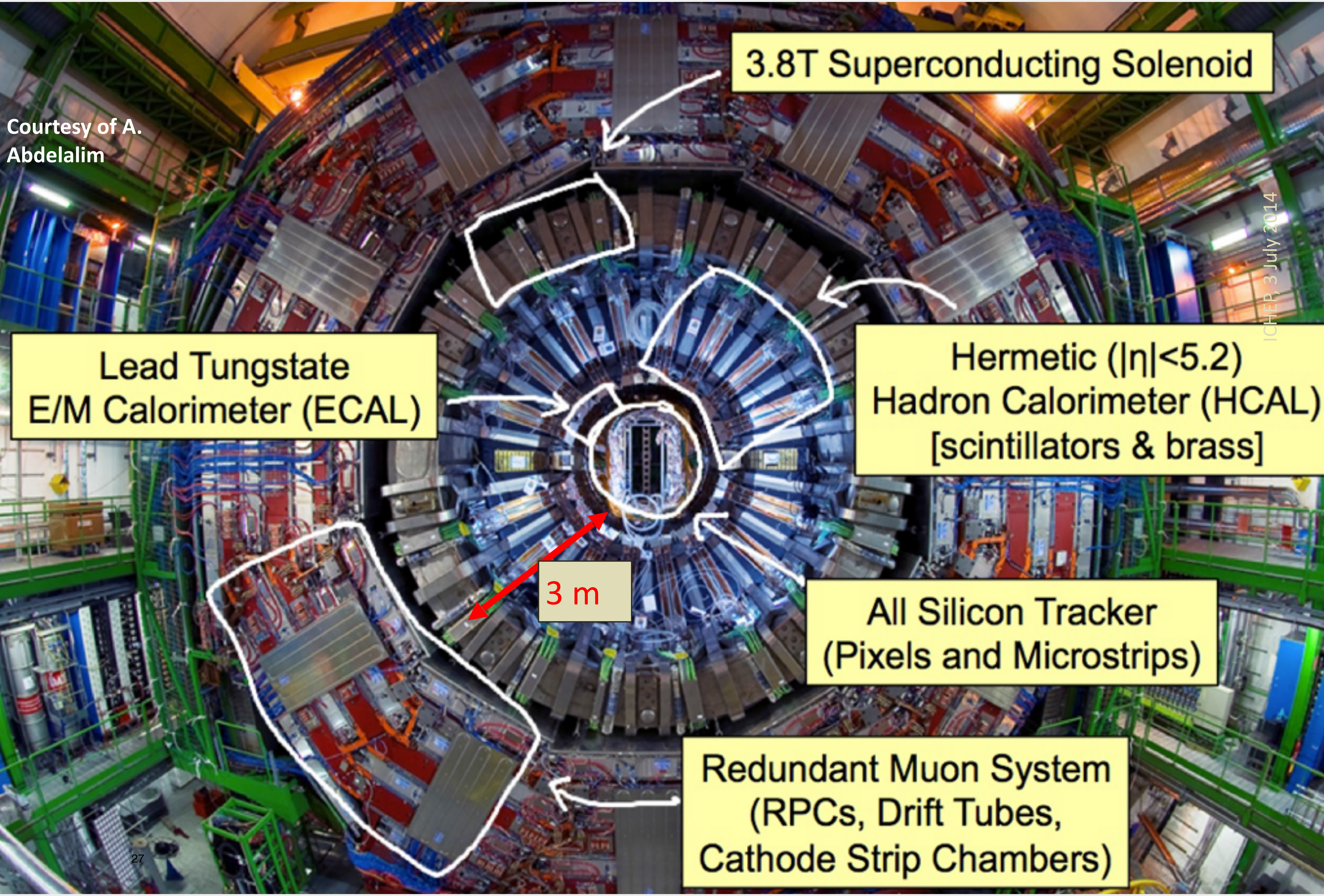
μ, e/γ, τ-jets, jets, MET

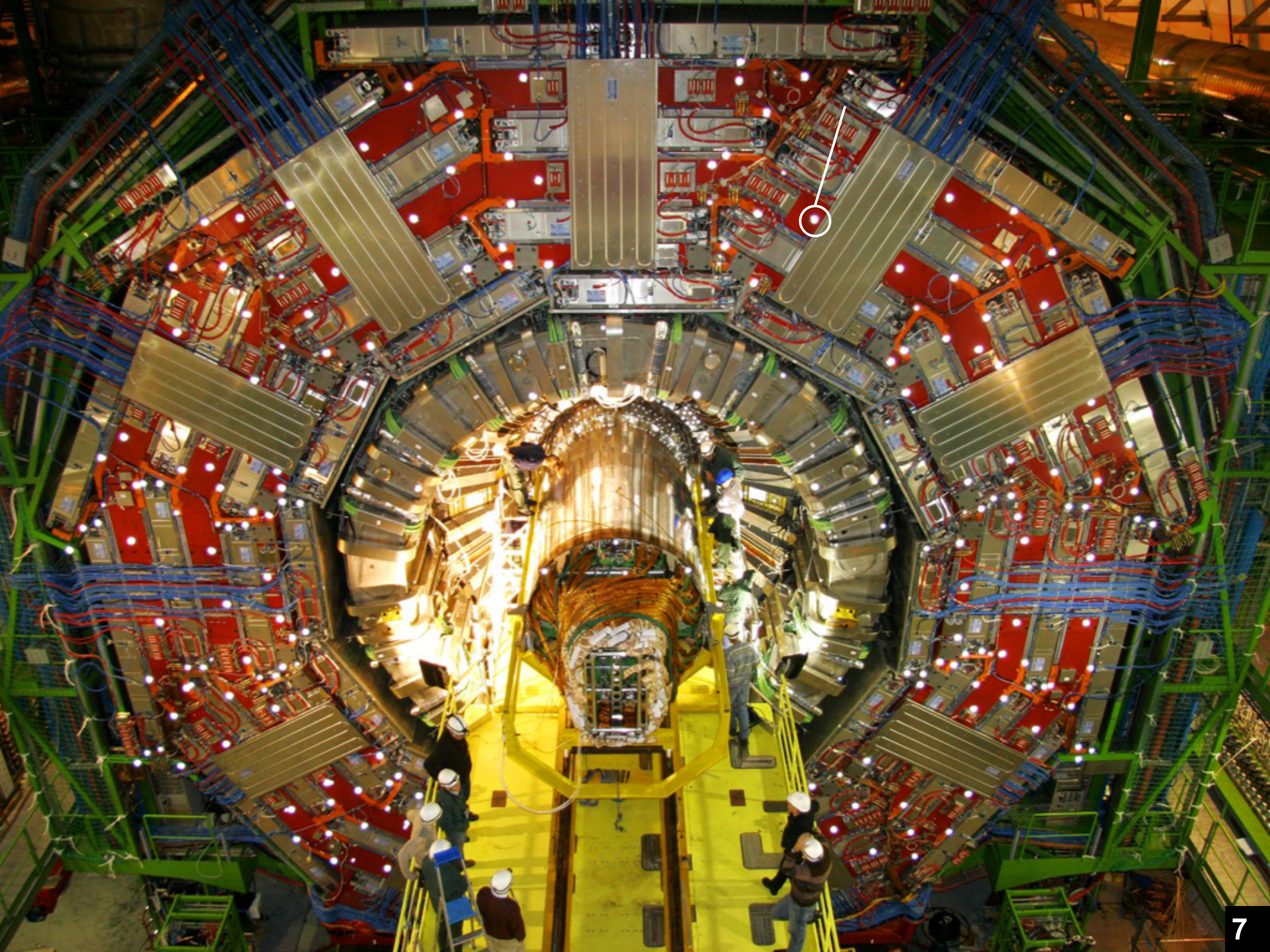
(+tracks, vertices)





The real CMS detector





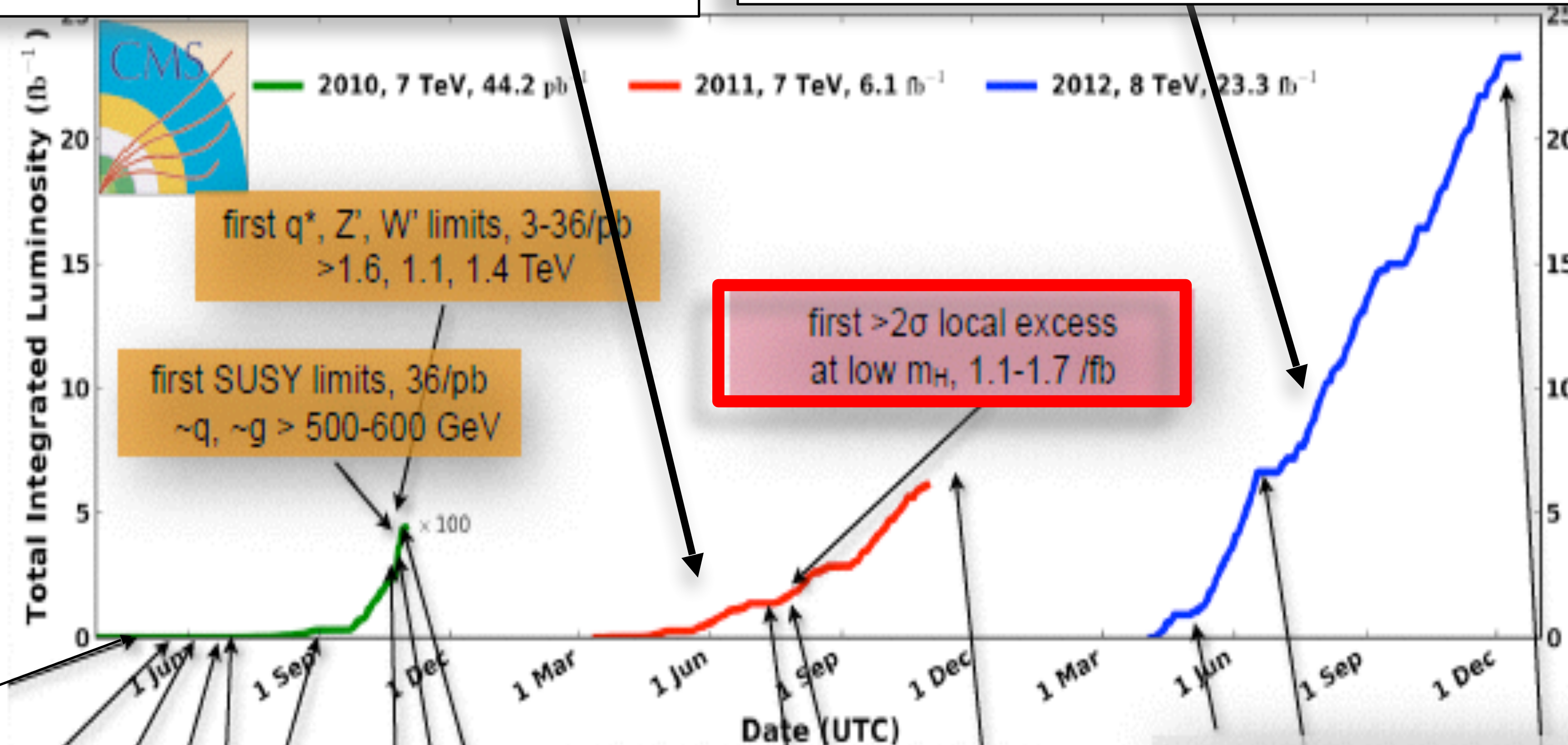
Plenty of barrel muons in online display!

100 Khz barrel muons (all pt)

2009 running:

- Hard to see anything apart from min bias in the displays.
- Serious analysis to find muons in the barrel.

What a run!



first q*, Z', W' limits, 3-36/pb >1.6, 1.1, 1.4 TeV

first SUSY limits, 36/pb ~q, ~g > 500-600 GeV

first >2σ local excess at low m_H, 1.1-1.7 /fb

repeating the program at 8 TeV

first MinBias / UE studies, particle multiplicities

first incl. b x-section, 8/nb δ ~ 15 %

first incl. jet x-section, PF jets 60/nb δ ~ 20-30%

first incl. W/Z x-sections, 200/nb δ ~ 4-6%, +11% lumi

first incl. J/Ψ x-section, 100/nb δ ~ 20%

first top xsec, 3/pb δ ~ 40%

first single top xsec, t-chan., 36/pb δ ~ 36%

first m_{top}, 36/pb Δ ~ 6.5 GeV

first WW xsec, 36/pb δ ~ 40% first limit on HWW

first ZZ xsec, 1.1 /fb δ ~ 40%

going more differential, e.g. Z/W + j,b,c

first significant limit on $B_s \to \mu\mu$, BR<1.9x10^{-8}

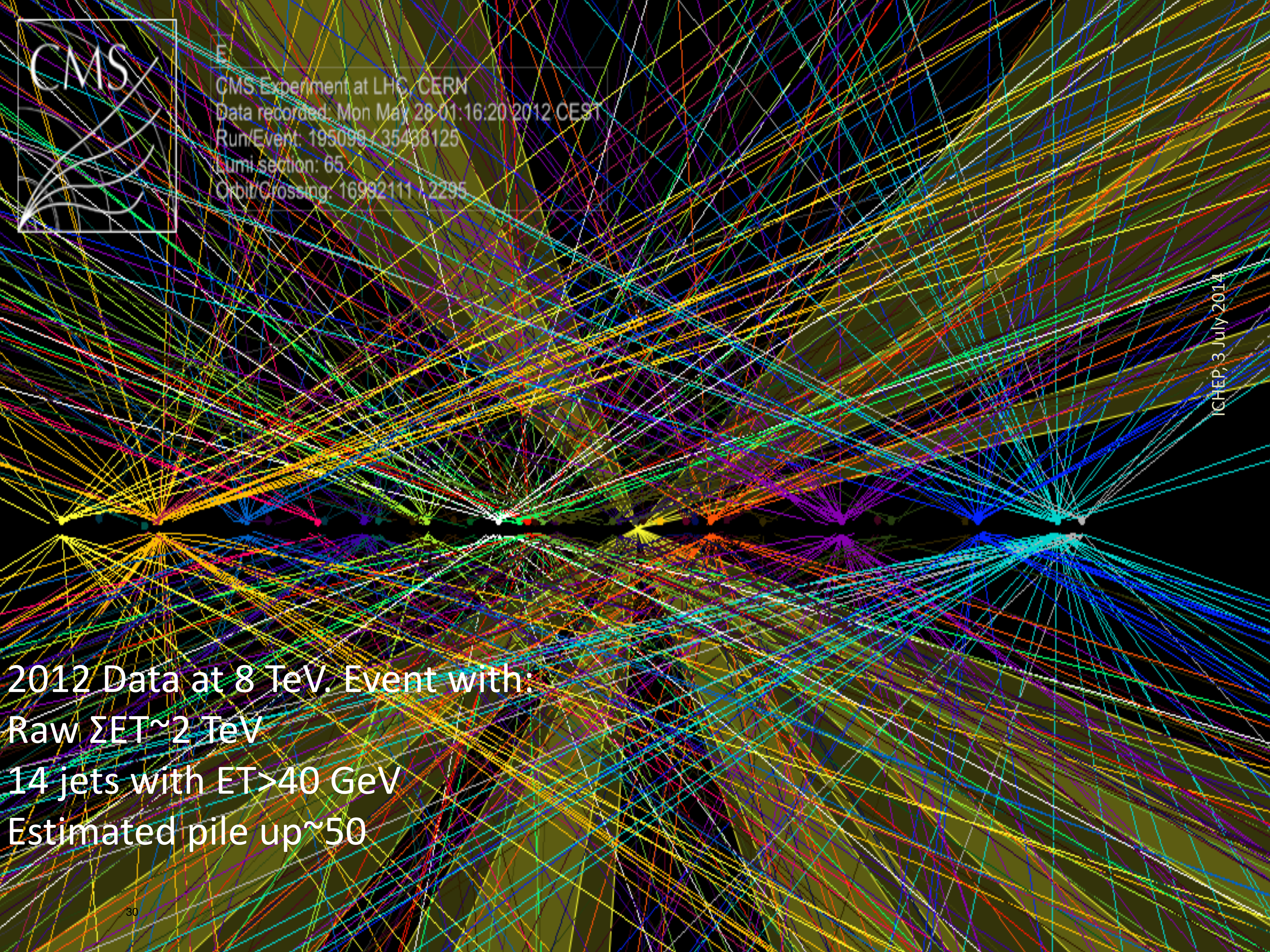
first particle discovered by CMS: Ξ_b

BSM searches continue, limits pushed

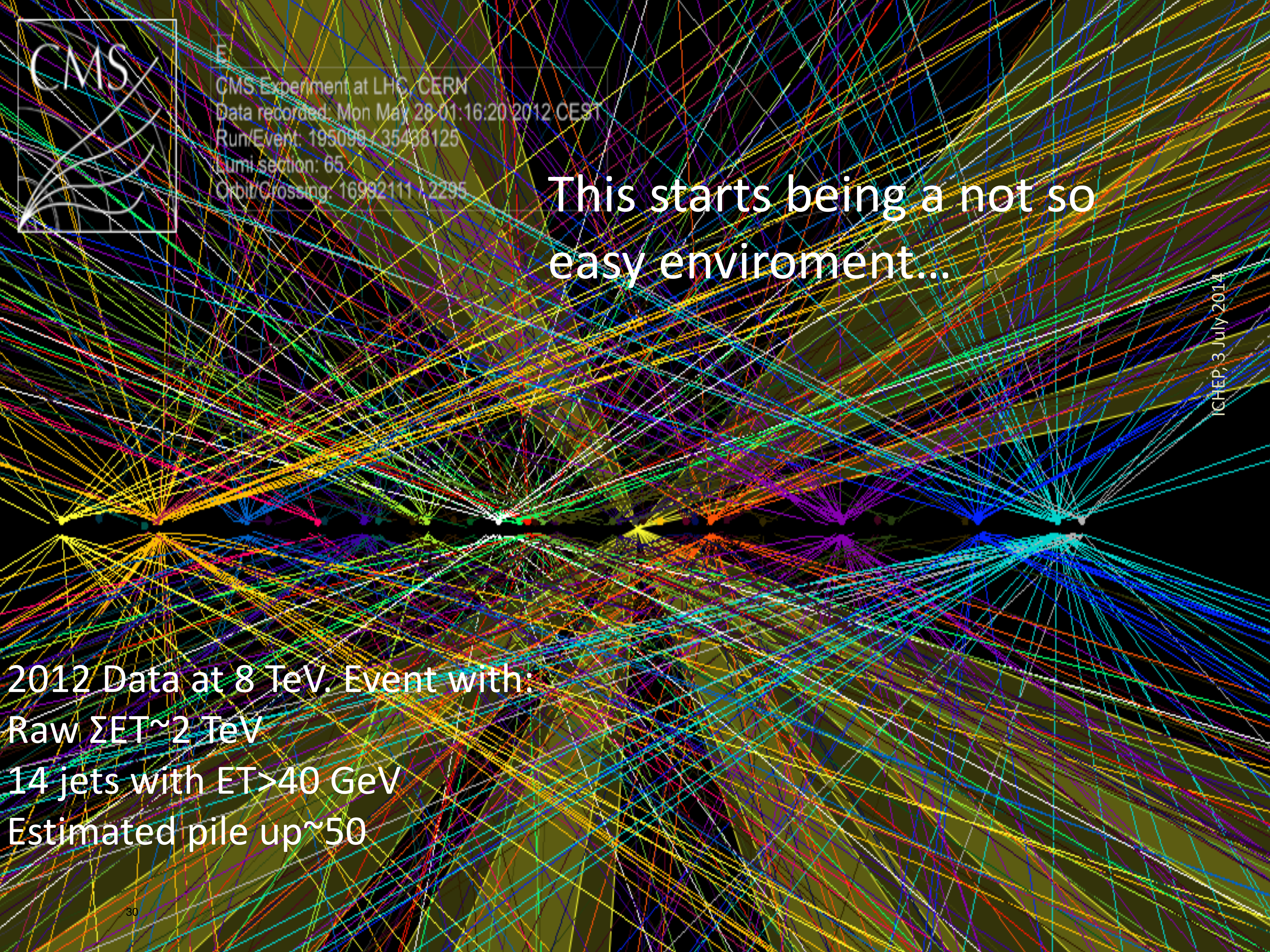
a new boson is announced, 5 /fb

first spin parity analysis of the boson, 17 /fb

δ .. relative uncert   Δ .. absolute uncert.   G. Dissertori



2012 Data at 8 TeV. Event with:
Raw ΣET~2 TeV
14 jets with ET>40 GeV
Estimated pile up~50



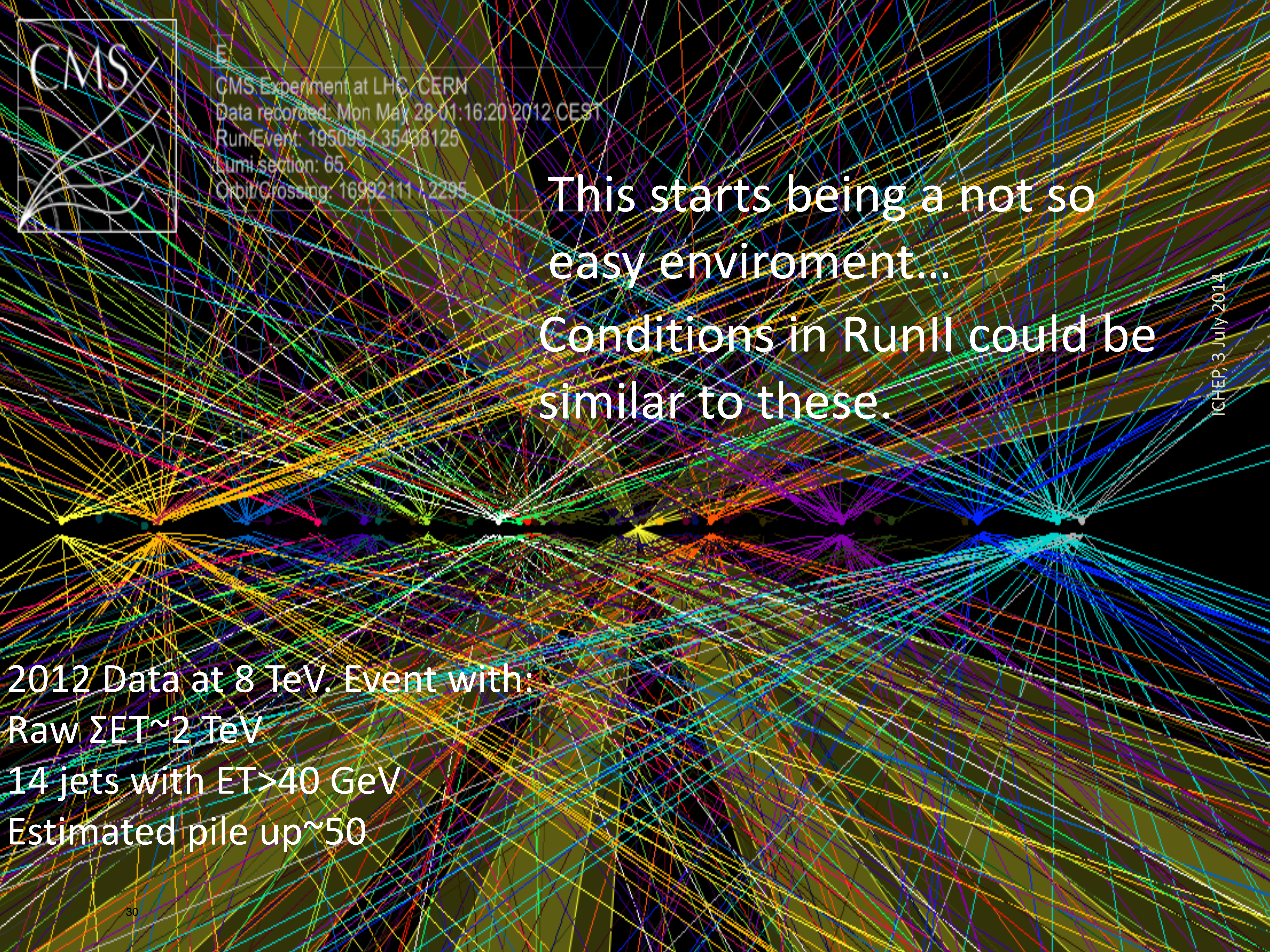
This starts being a not so easy enviroment…

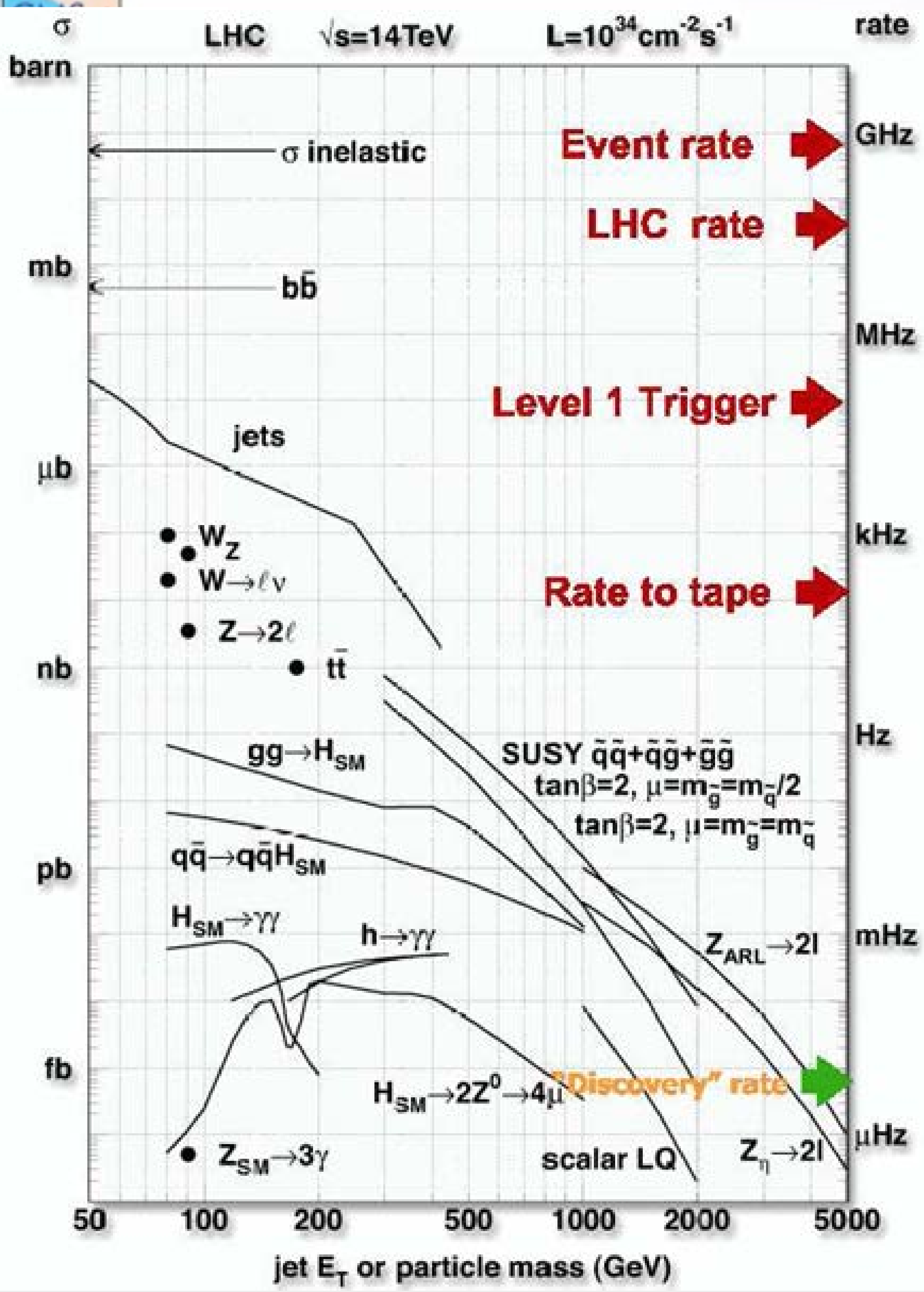
2012 Data at 8 TeV. Event with:

Raw ΣET~2 TeV

14 jets with ET>40 GeV

Estimated pile up~50


CMS
E
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
This starts being a not so easy enviroment...
Conditions in RunII could be similar to these.
2012 Data at 8 TeV. Event with:
Raw ΣET~2 TeV
14 jets with ET>40 GeV
Estimated pile up~50



CMS: Event processing

Level-1: dedicated hardware, data available with reduced granularity, no tracker data

HLT: computer farm, ~13kCPU, all data, algorithm paths seeded by L1, with reconstruction similar to offline

(up to 450 paths: physics obj. and complex alg.)

object L1	threshold (GeV)
Single μ	16
$(\lvert\eta\rvert < 2.1)$	12
Single e/γ	20
Single Isolated e/γ	18
Single jet	128
Double μ	10, 0
Double e/γ	13, 7
Double jet	56
Double τ_{jet}	44
$e/\gamma \oplus \mu$	12, 3.5
	7, 12
H_T	150
E_T^{miss}	40
E_T^{tot}	300

CMS trigger reduce # of p-p interactions from: $2 \cdot 10^7$ Hz (input) through $\leq$ 100 kHz down to:

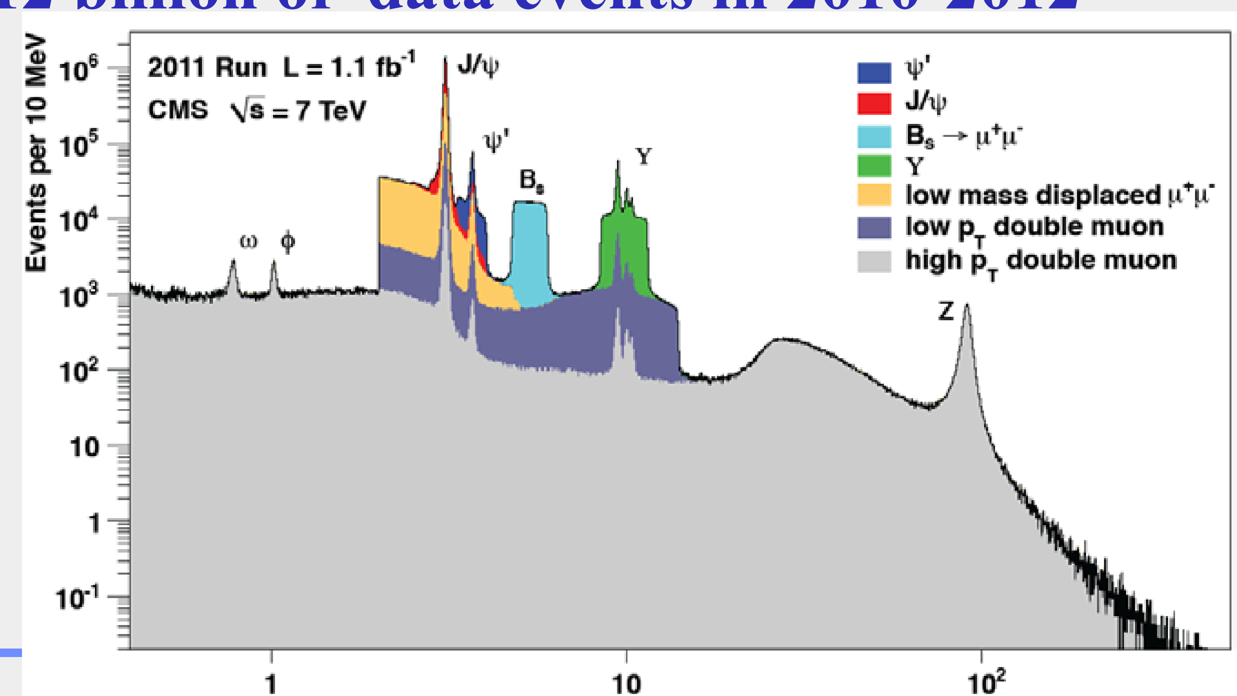
~300-500 Hz "core data" – main Physics program

(+ ~300-600 Hz "parked" for later analysis + 1kHz "scouting")

More than 12 billion of data events in 2010-2012

Reconstruction: Standalone detector based reconstruction but also **Particle Flow** (attempts to reconstruct individually each particle in the event, prior to the jet clustering, based on information from relevant sub-detectors.

→ better reconstruction of the jets, E_T, MET, tau)



Computing and Data handling

Reconstructed events

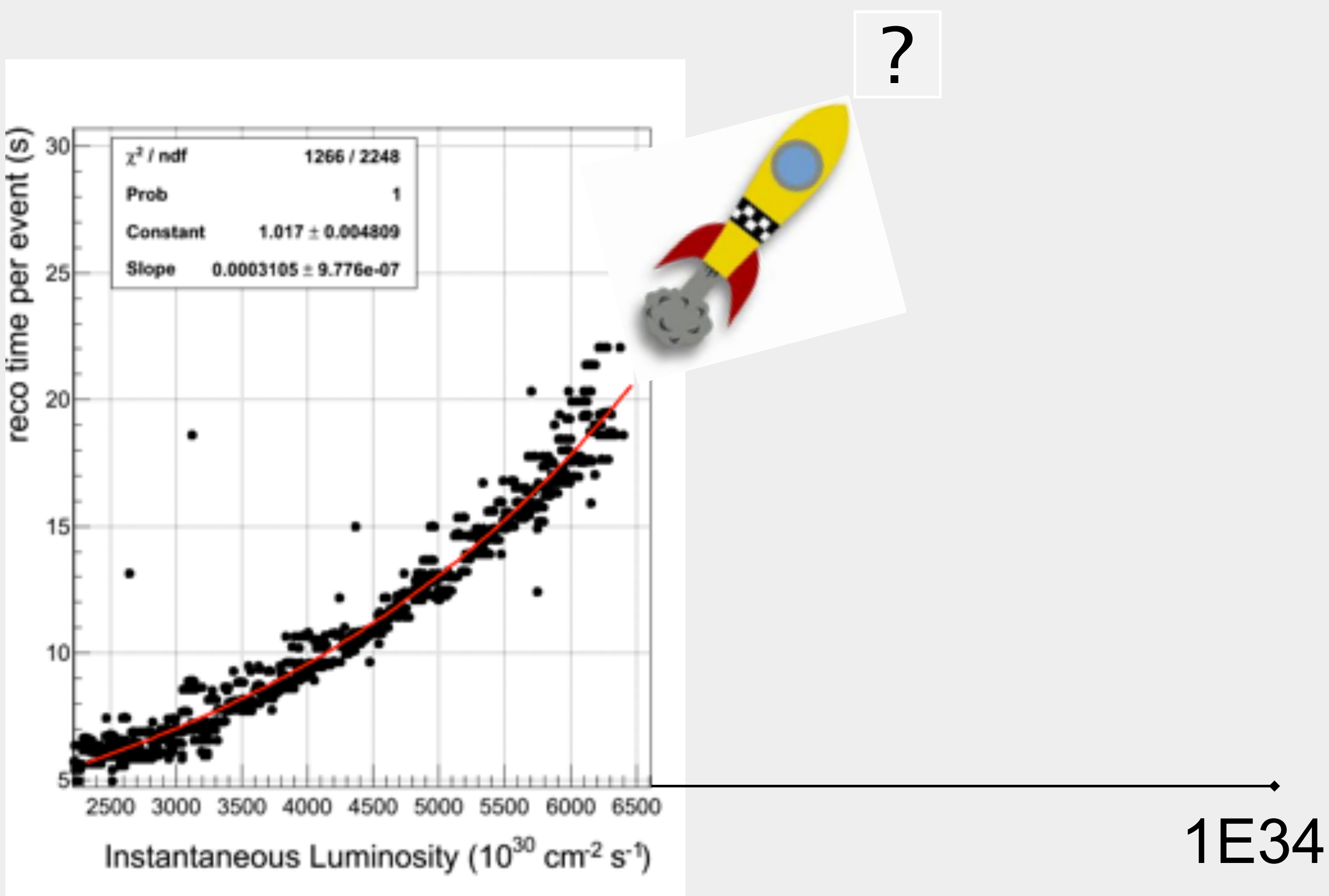
- 20 billion simulated events
- 12 billion data events

Data volume

More than 25PB moved to Tier-1s

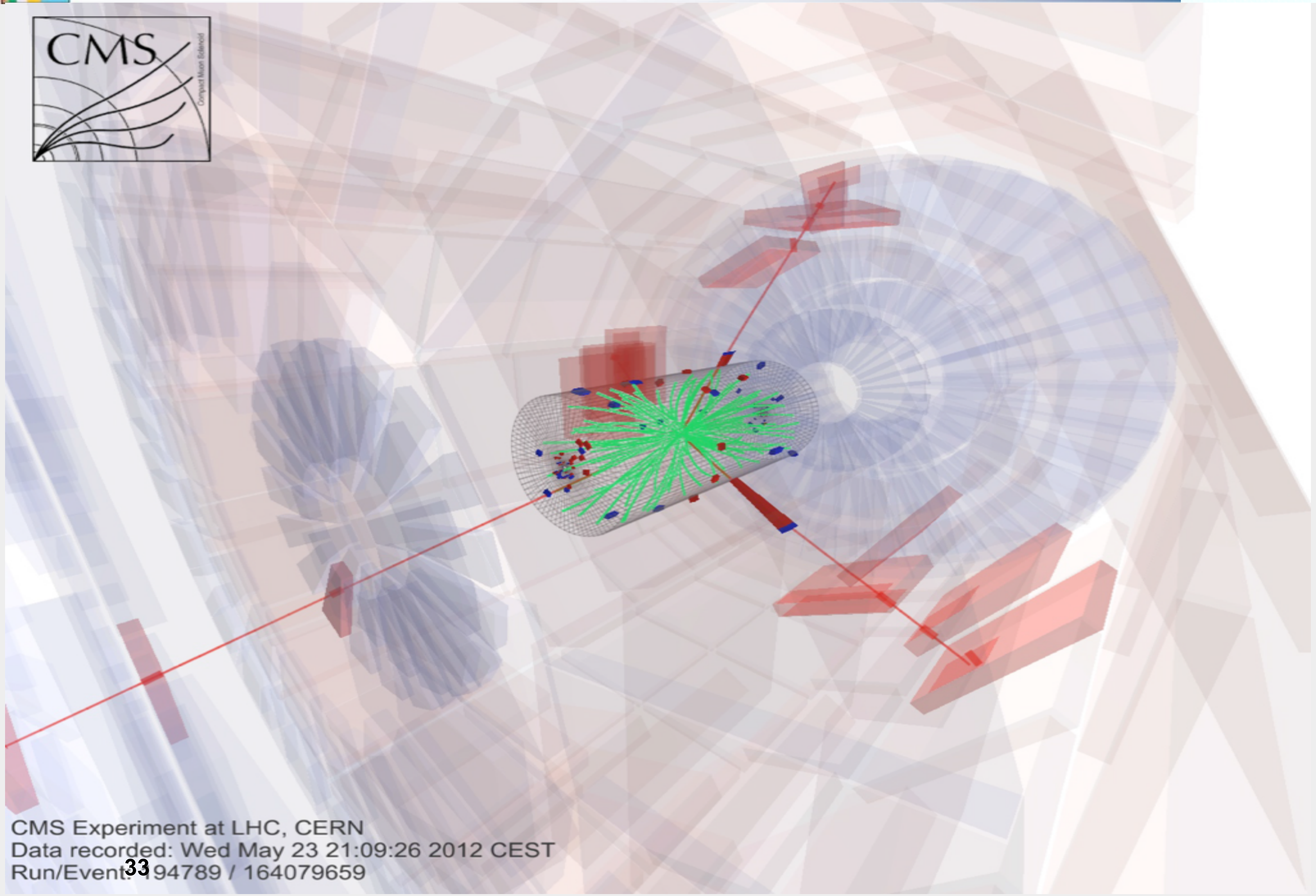
70PB moved to Tier-2s

- Improvements in the reconstruction code to cope with pile up
- Reconstruction time per event reduced by maintaining the physics performance.
  - Non-linear with PU ➔explodes

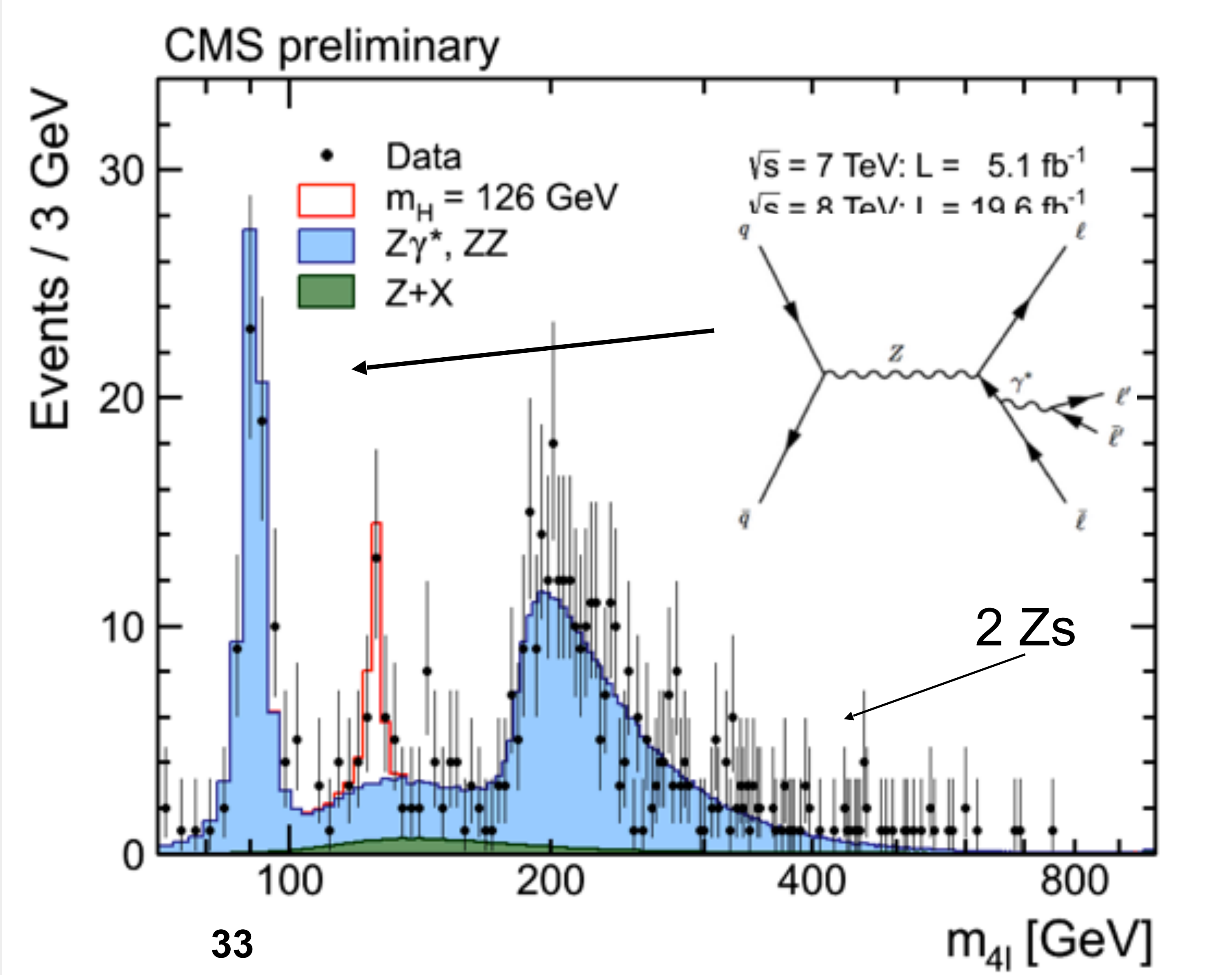


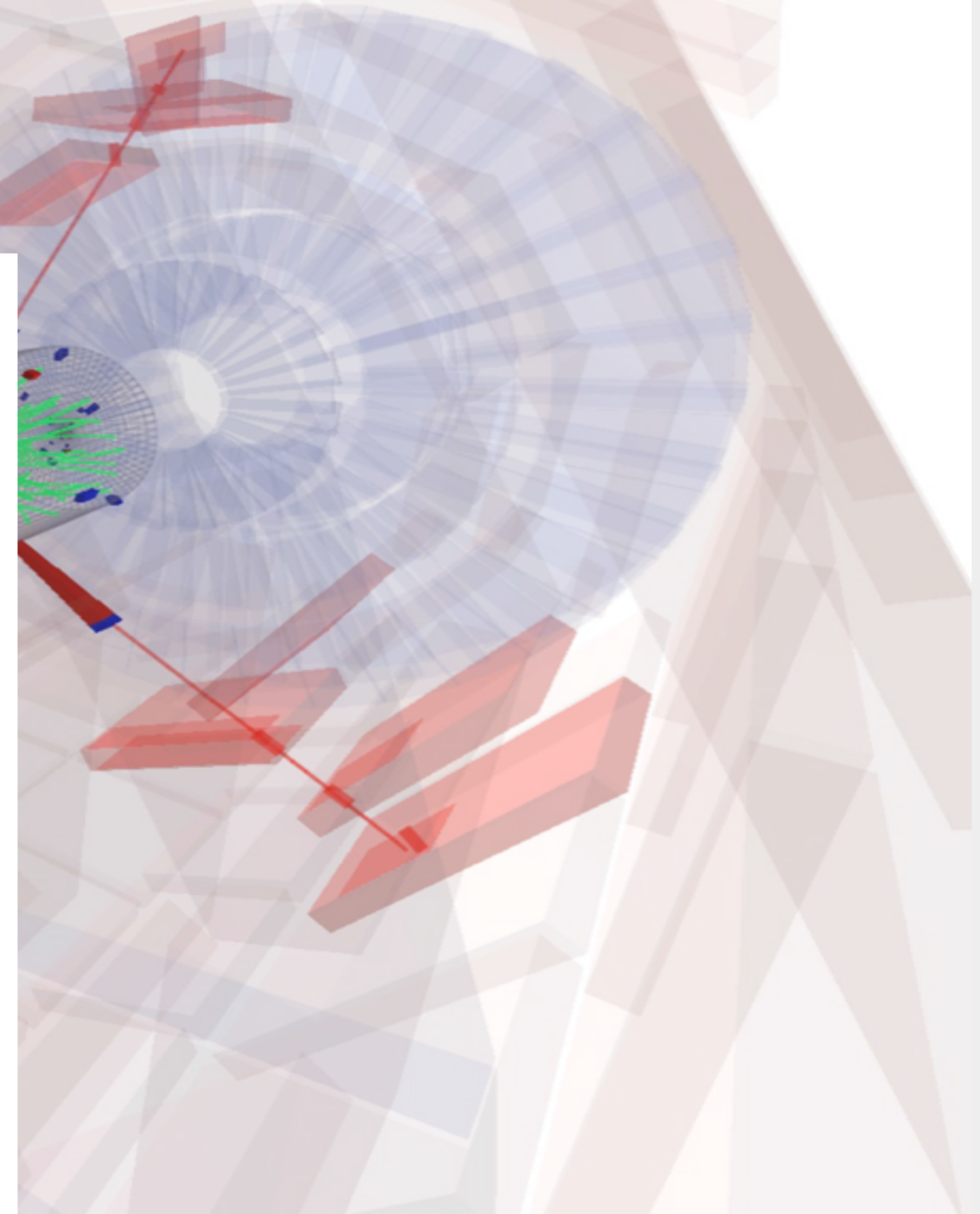
Quite a challenge:
All things equal,
2015 computing
needs increase x10

CMS in action: H->4 lepton

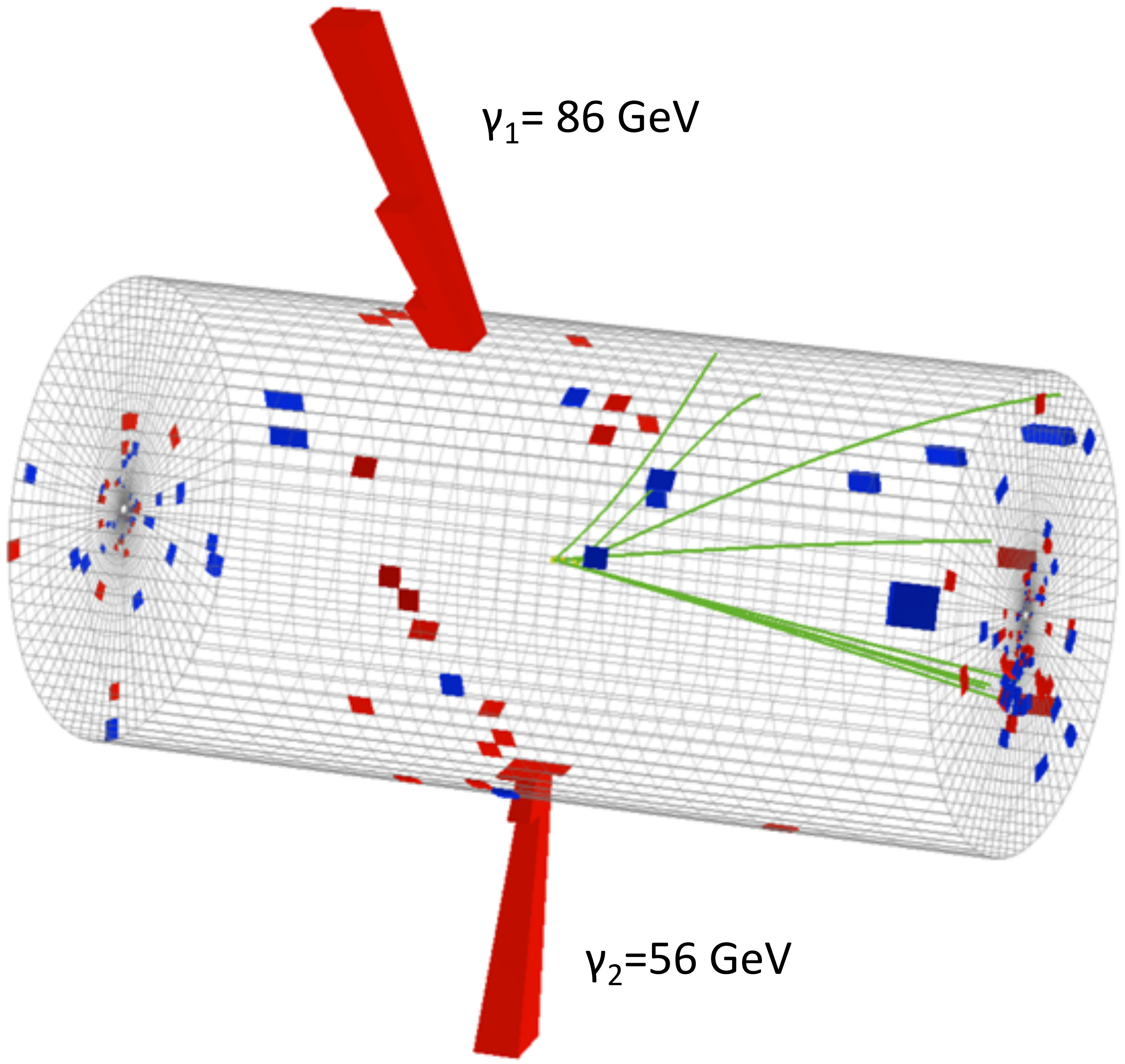


CMS in action: H->4 lepton

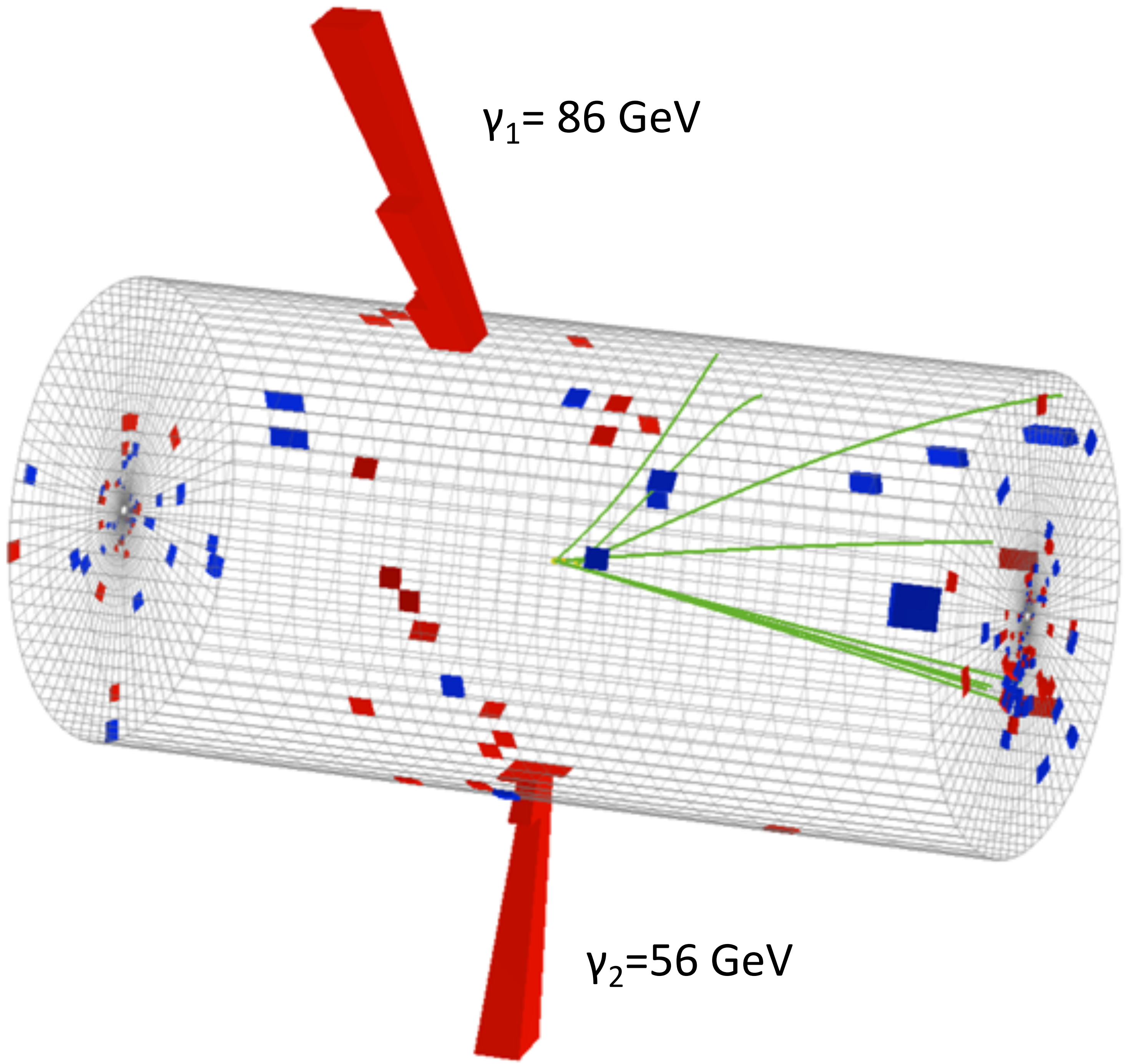




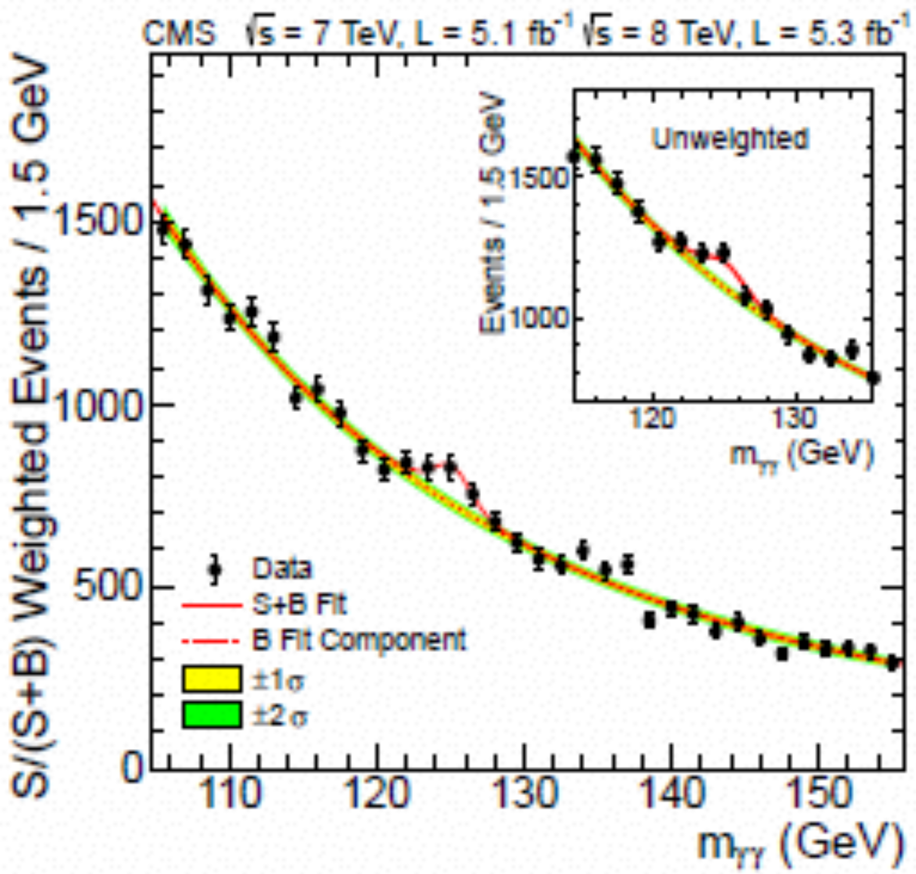
CMS in action: H->2γ



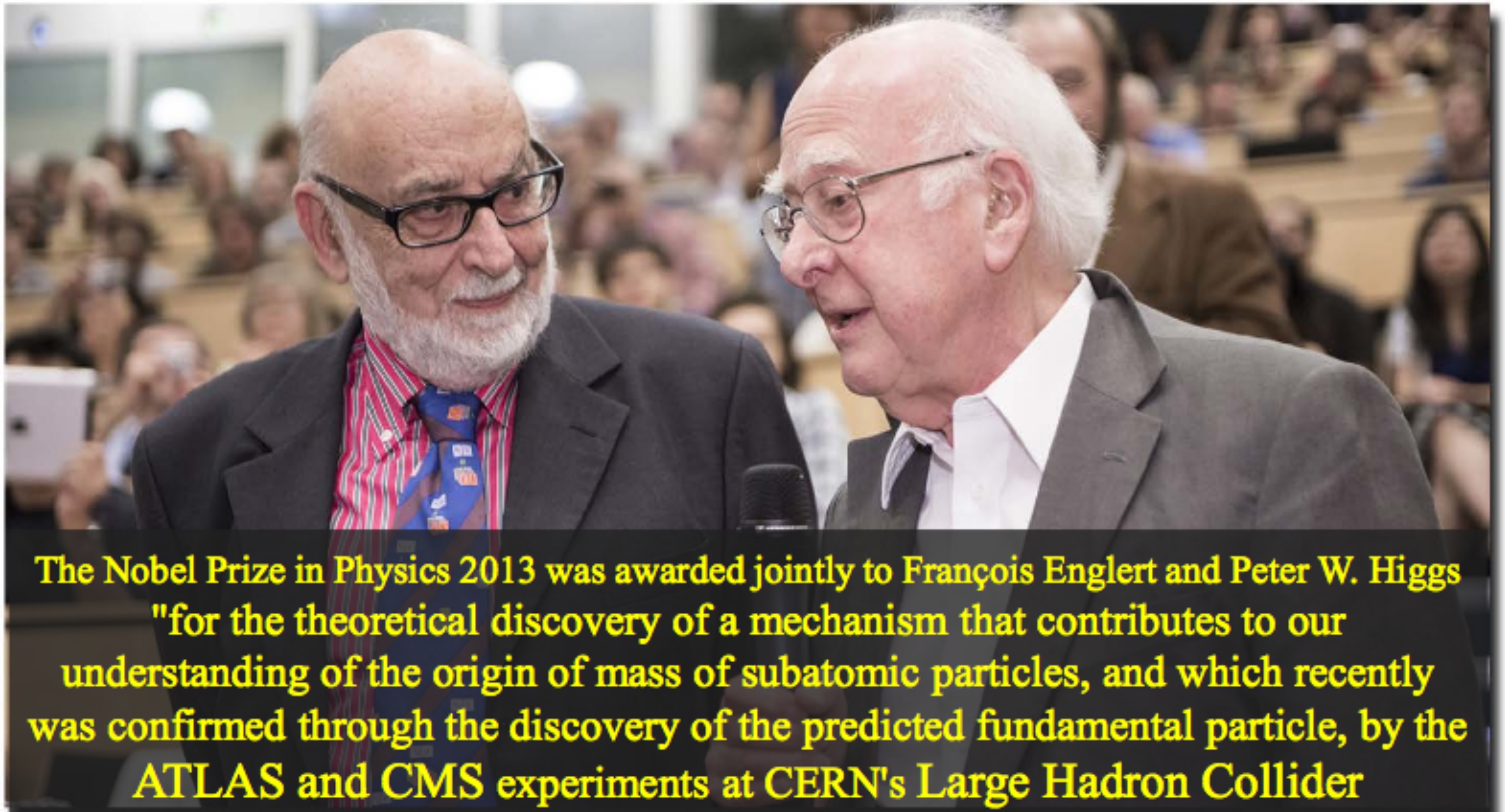
CMS in action: $H \to 2\gamma$

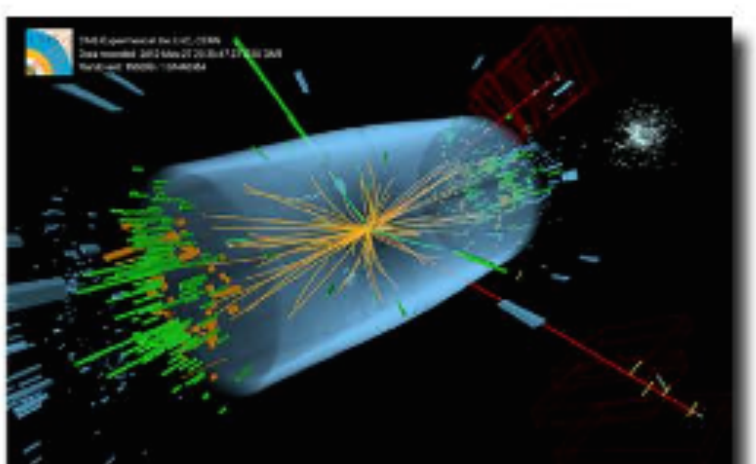


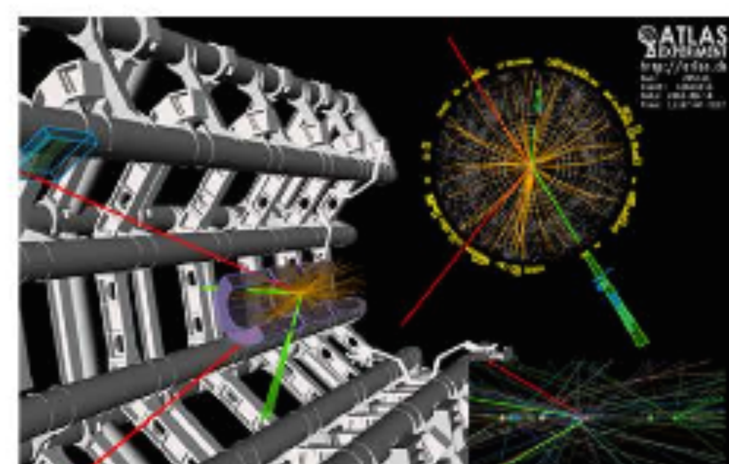
CMS Collaboration,
Phys. Lett. B716 (2012) 30-61



The Nobel Prize in Physics 2013





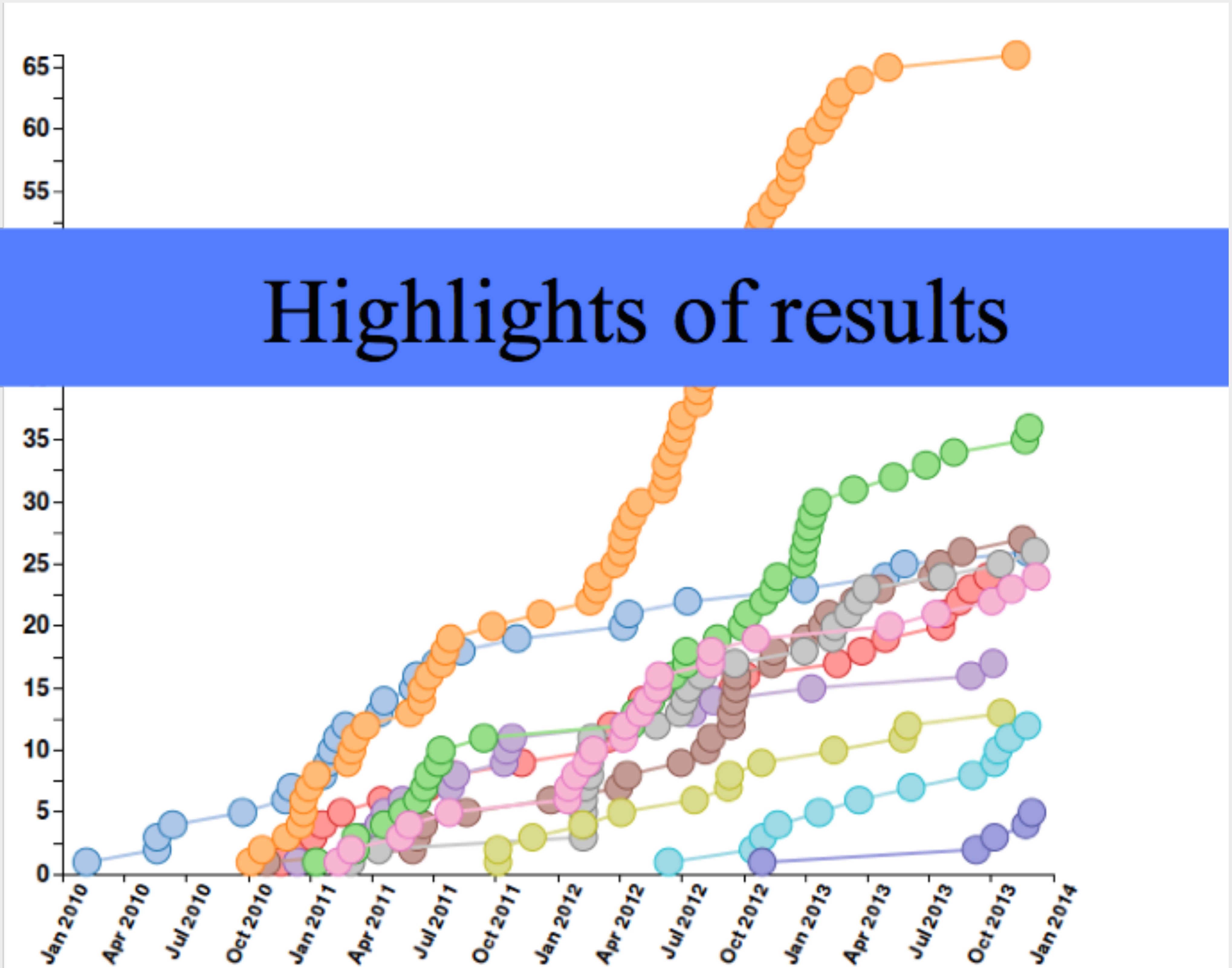


Show all | Total | QCD | Exotica Searches | Supersymmetry | B Physics | Electroweak

Top Physics | Heavy Ion | Higgs | Forward Physics | Standard Model | Beyond the SM: B2G

275 papers published (1 Jan 2014)

Highlights of results

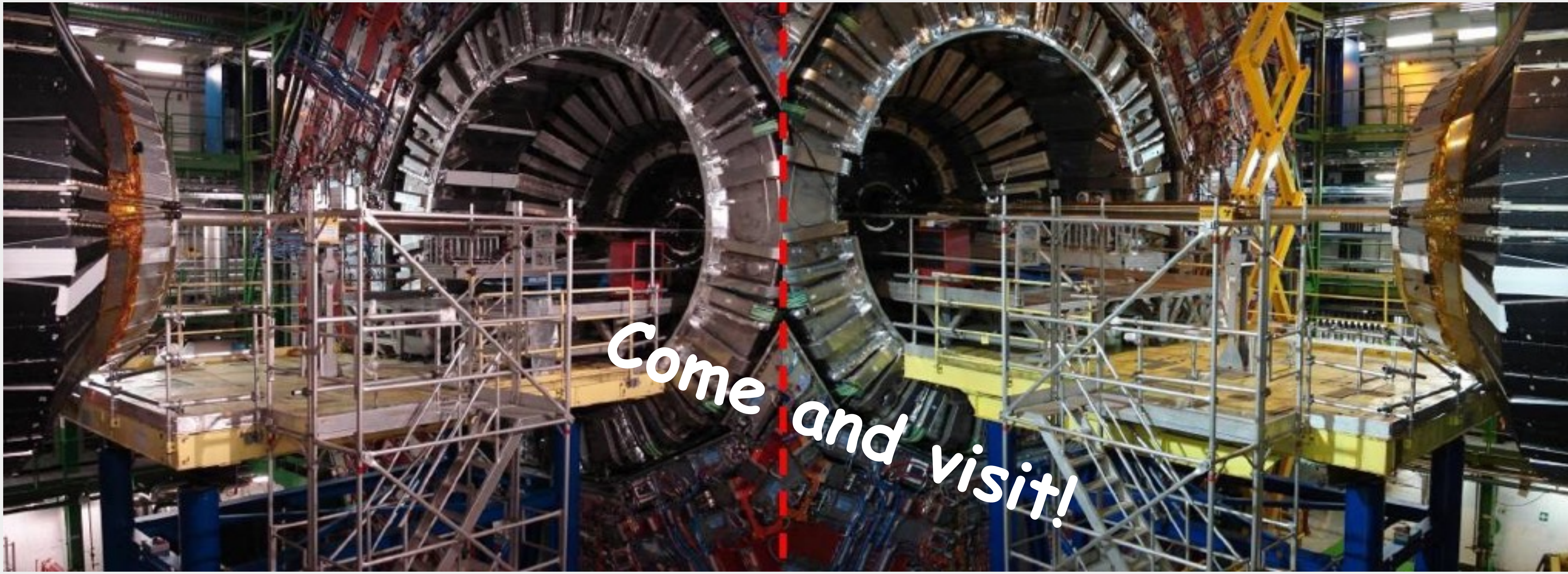


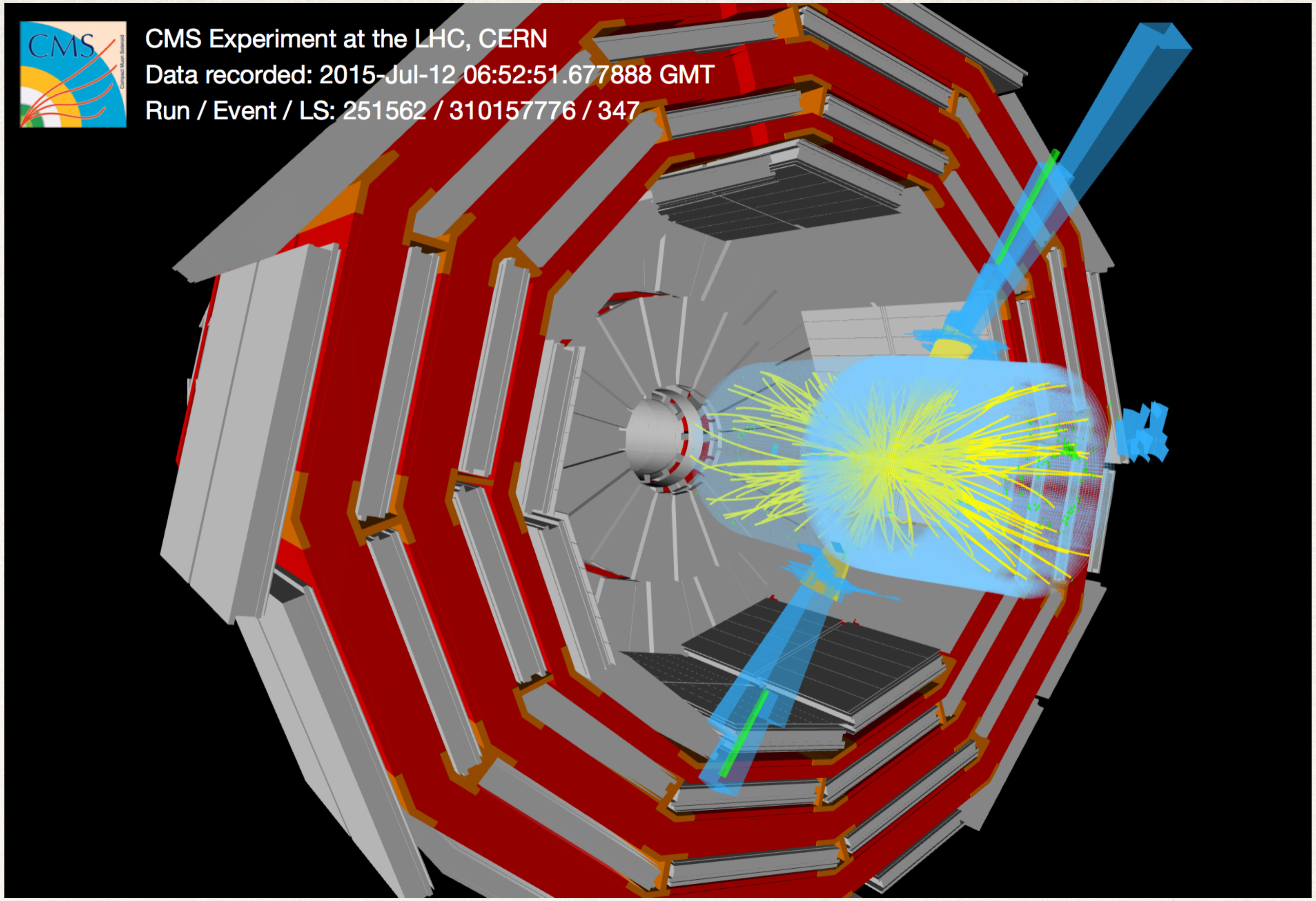
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

- Excellent performance of CMS detector during Run I
  - Tracking, vertexing
  - Lepton identification
  - Jet and MET reconstruction
  - Triggering capabilities

  - And final physics performance!

2013-2014 : Detector open for maintenance and upgrade

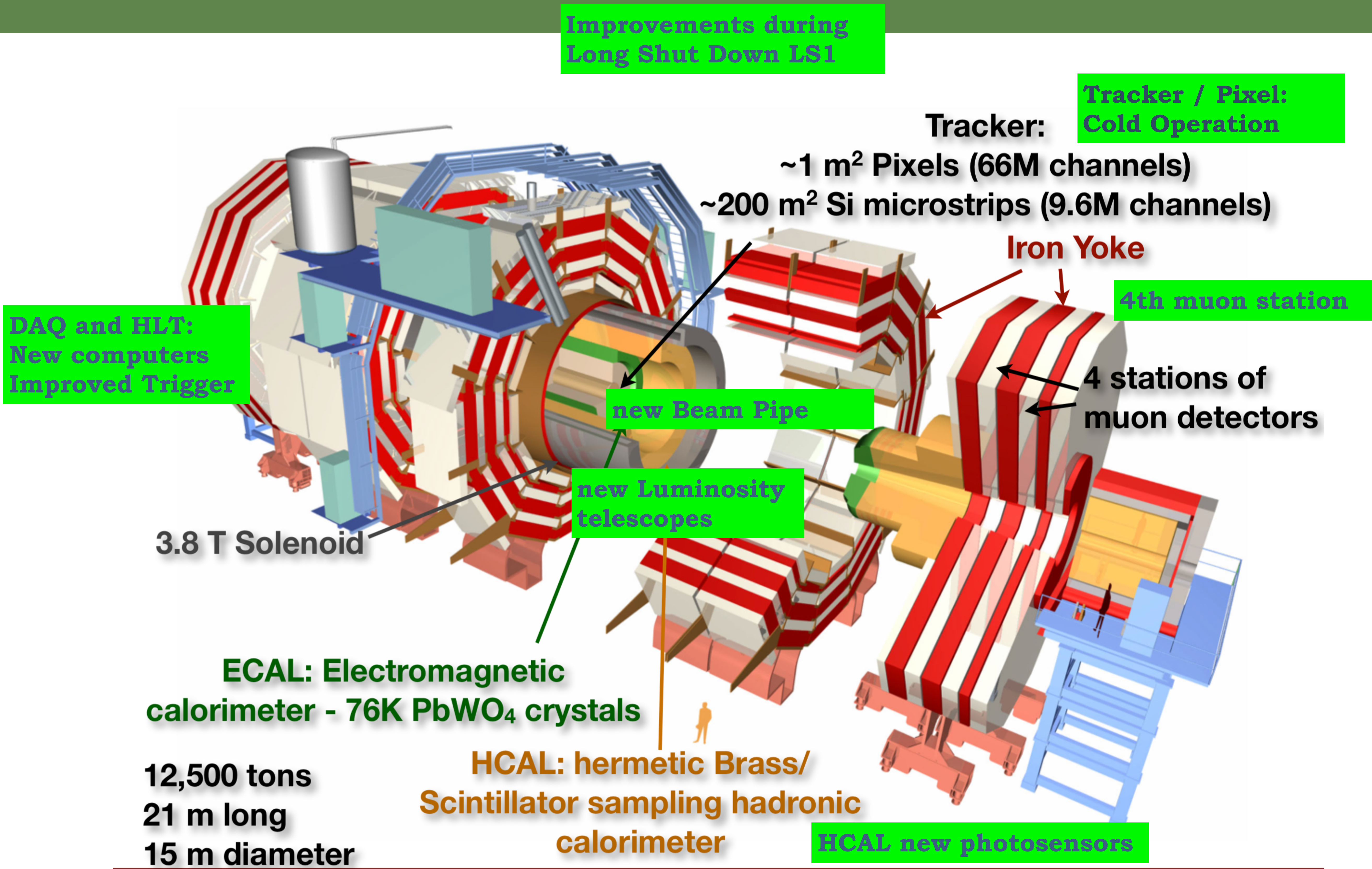




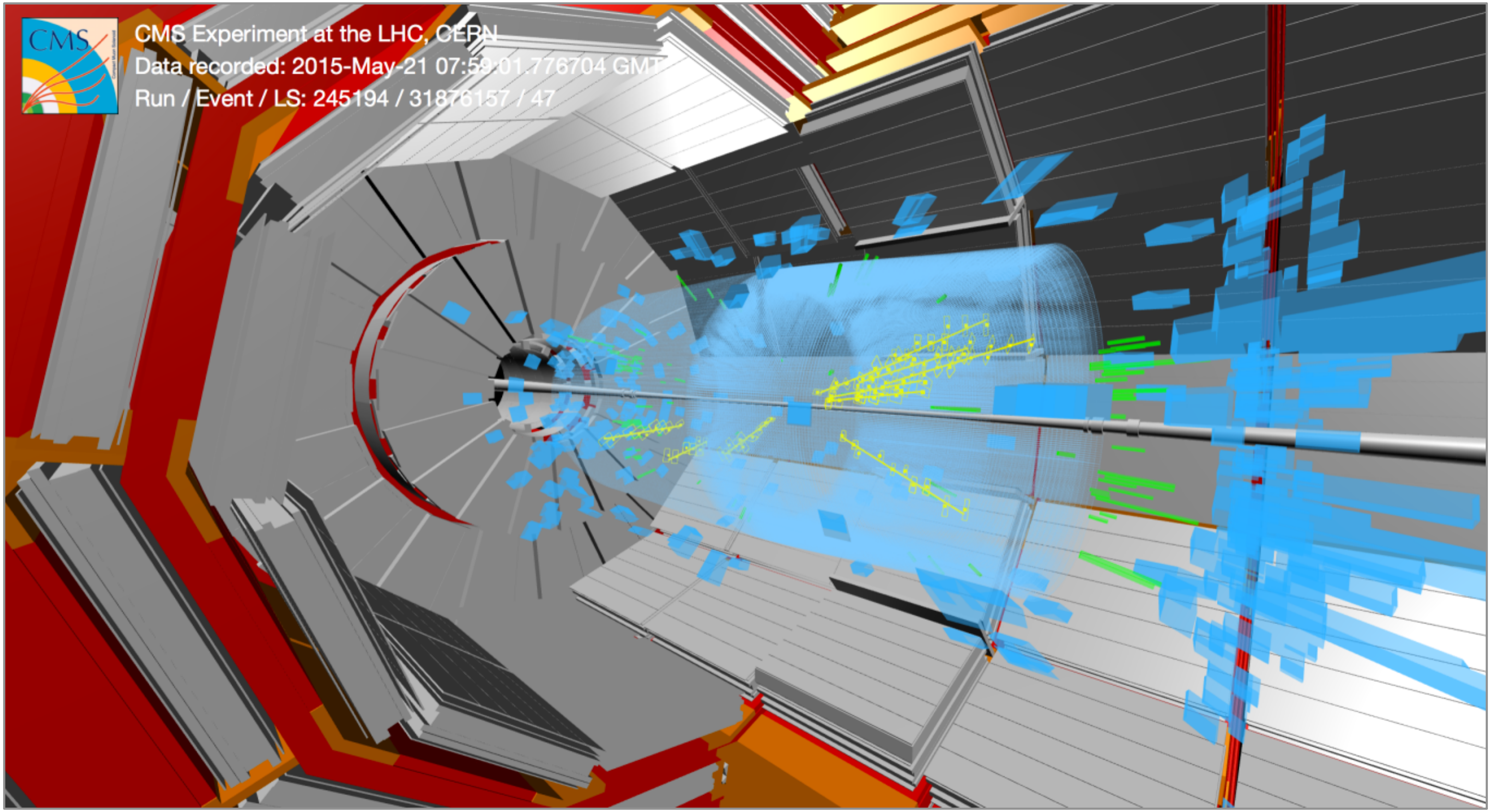
CMS: First look at 13 TeV data

Paolo SPAGNOLO on behalf of the CMS Collaboration

CMS detector for Run2



First Physics collision @ 13 TeV



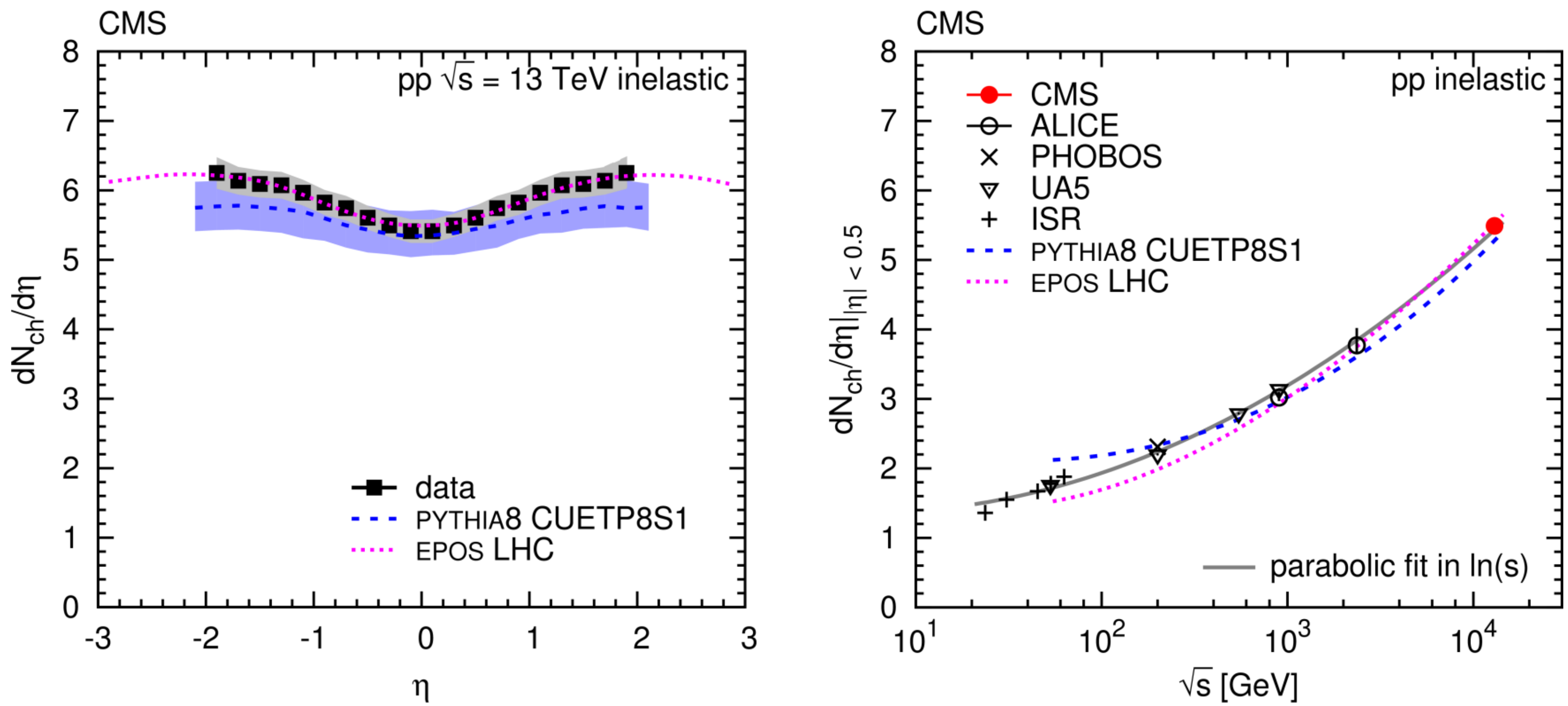
First CMS publication @ 13 TeV

First paper from LHC @13 TeV

First paper, submitted to PLB few weeks after the first collision http://arxiv.org/abs/1507.05915

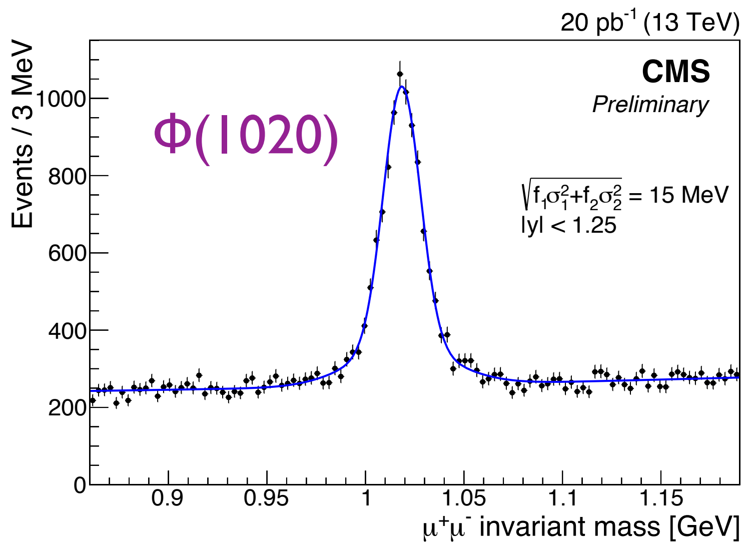
Pseudorapidity distribution of charged hadrons in proton-proton collisions at √s = 13 TeV

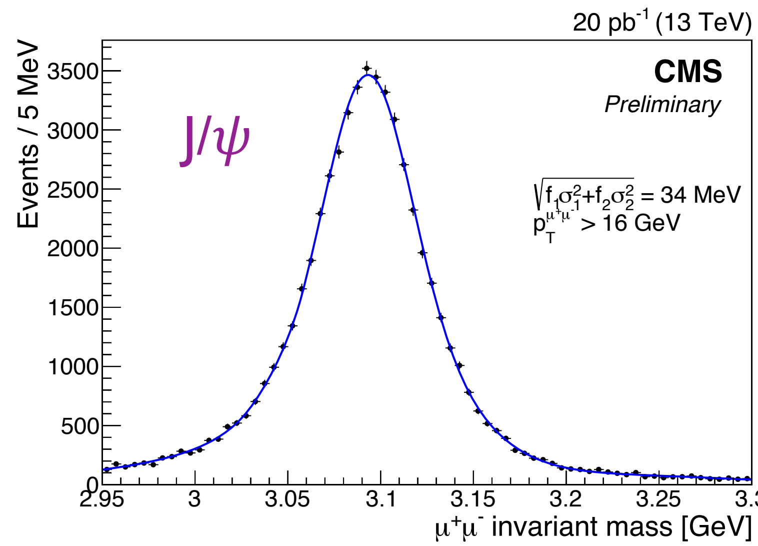
$dN_{ch}/d\eta||\eta|<0.5 = 5.49 \pm 0.01$ (stat) ± 0.17 (syst)

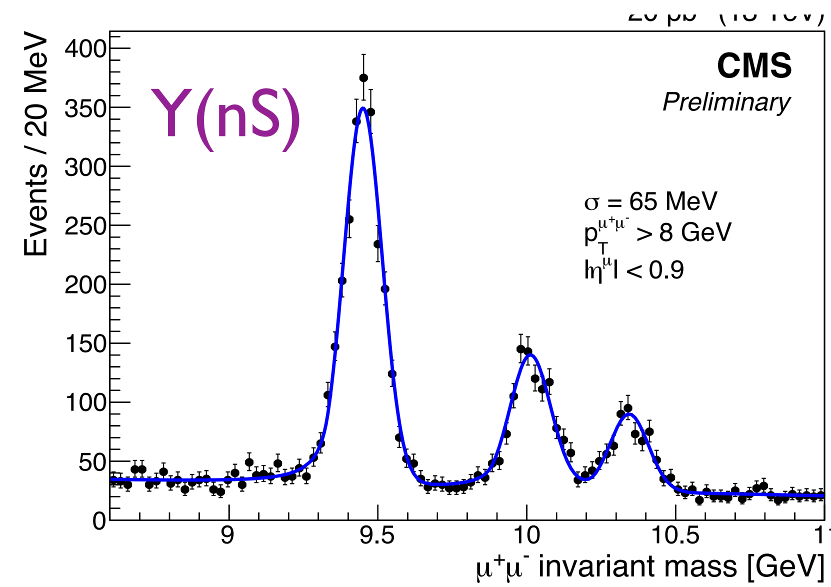


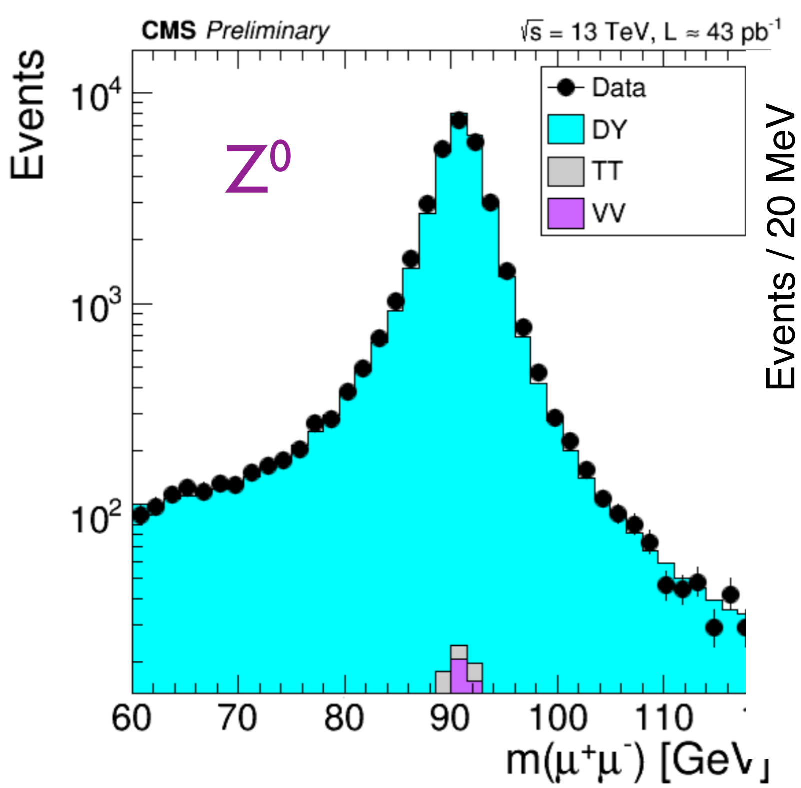
- measured in CMS in a special early run @13 TeV taken on June 7th (~1h30′) with B = 0 T
- dN/dη vs √s gives an handle on the relative weight of soft and hard scattering contribution
- both EPOS (better) and PYTHIA8 compatible with data

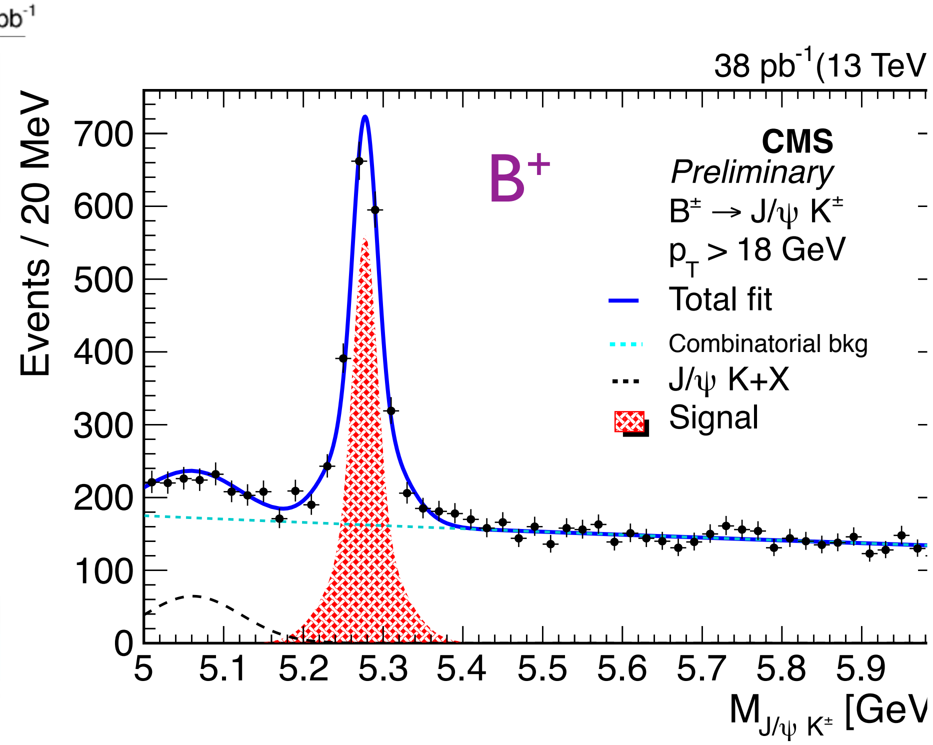
Di-muon spectroscopy:
standard candles resonances and first B mesons

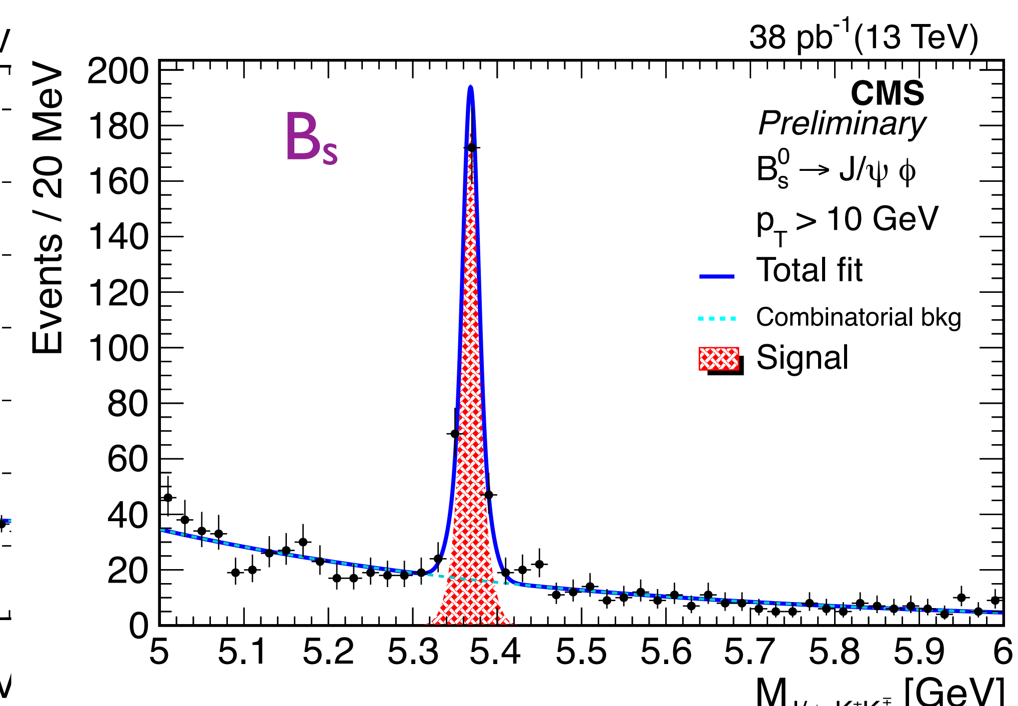




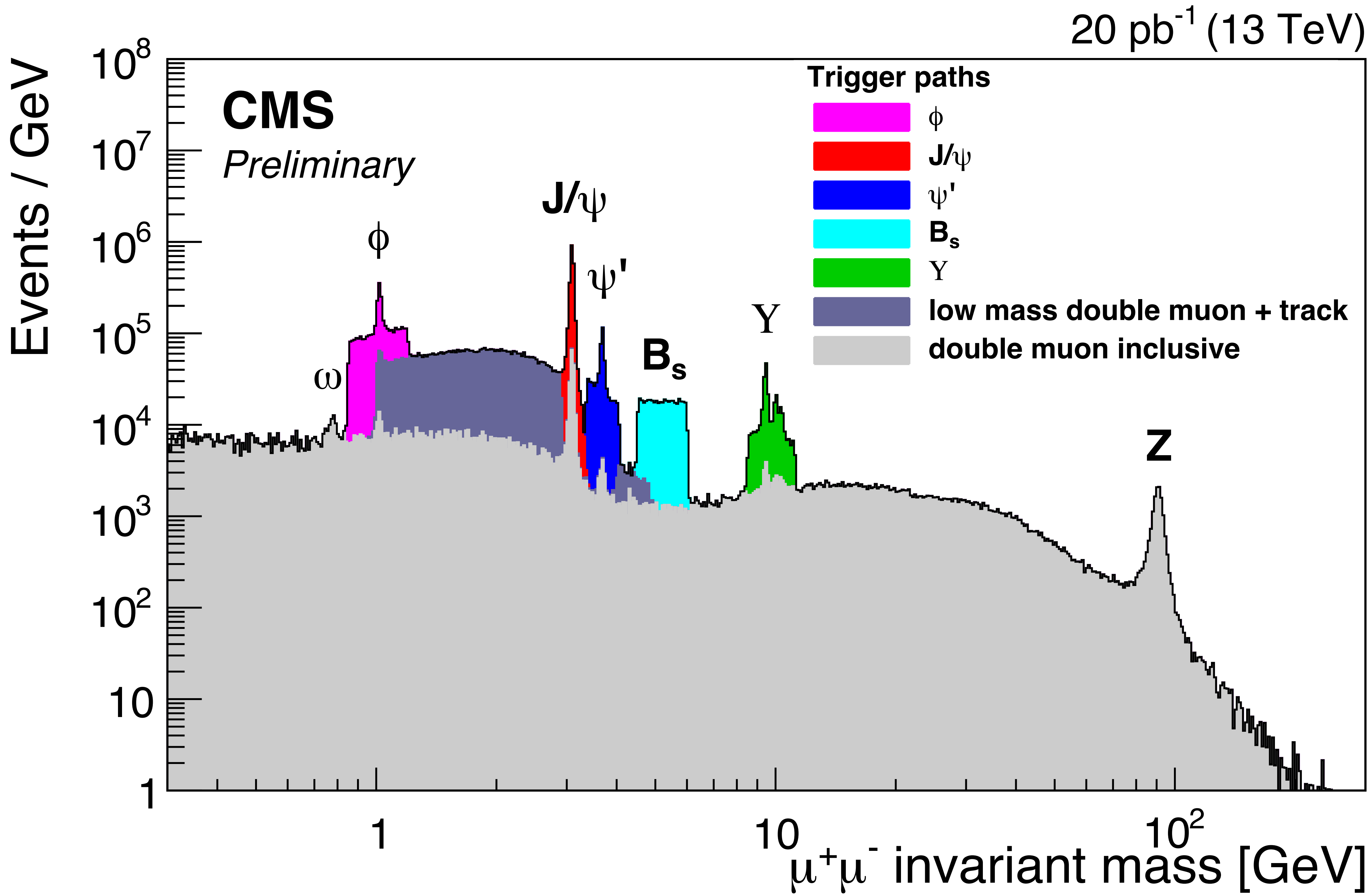








Di-muon spectroscopy: standard candles



Top pair cross-section measurement

inclusive σ_{tt}(13TeV)= 772 ± 60 (sta) ± 62 (sys) ± 93 (lum) pb

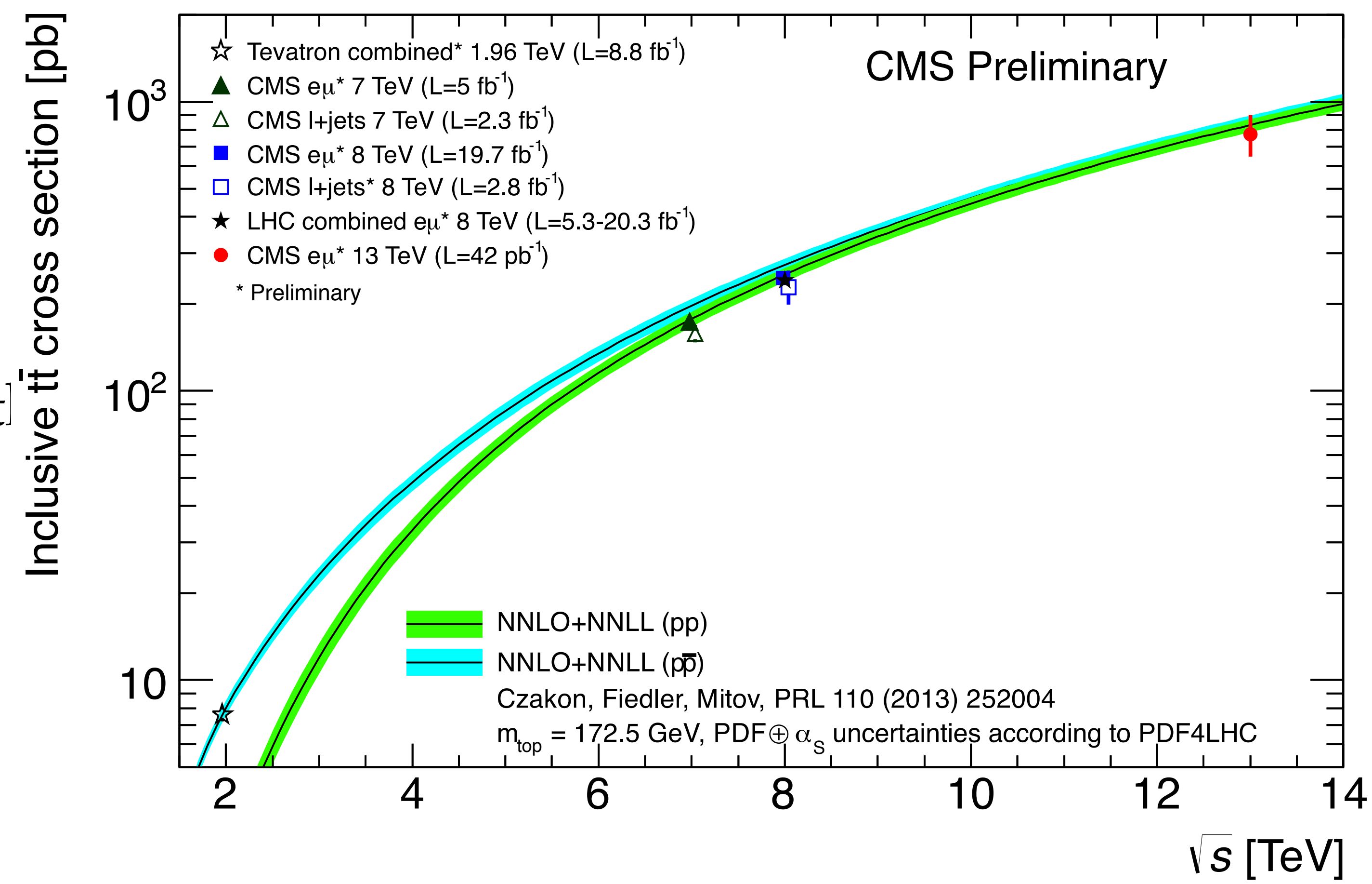
CMS PAS TOP-15-003

Integrated lumi= 42 pb^{-1}

- all validated data from 50 ns run

Selection

- At least 2 good (OS) leptons (1e and 1μ)
- pt(lept)> 20 GeV and |η|< 2.4
- If more than 2 good leptons, the two wit highest pt are retained
- Di-lepton invariant mass > 20 GeV
- At least 2 jets (anti-kT R = 0.4)
- pt(jets)> 30 GeV and |η|< 2.4

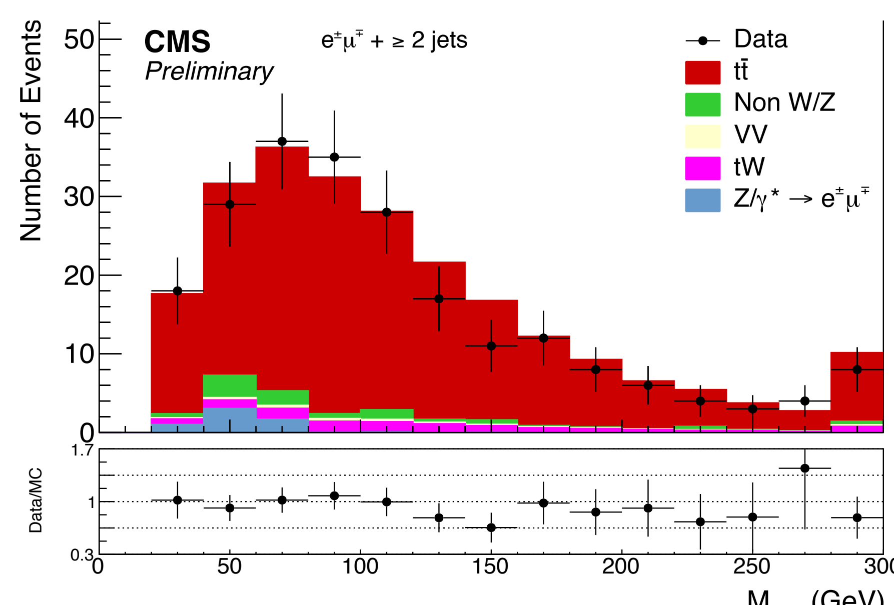


From Run1 data NEW RESULTS

(CMS TOP 13-004)

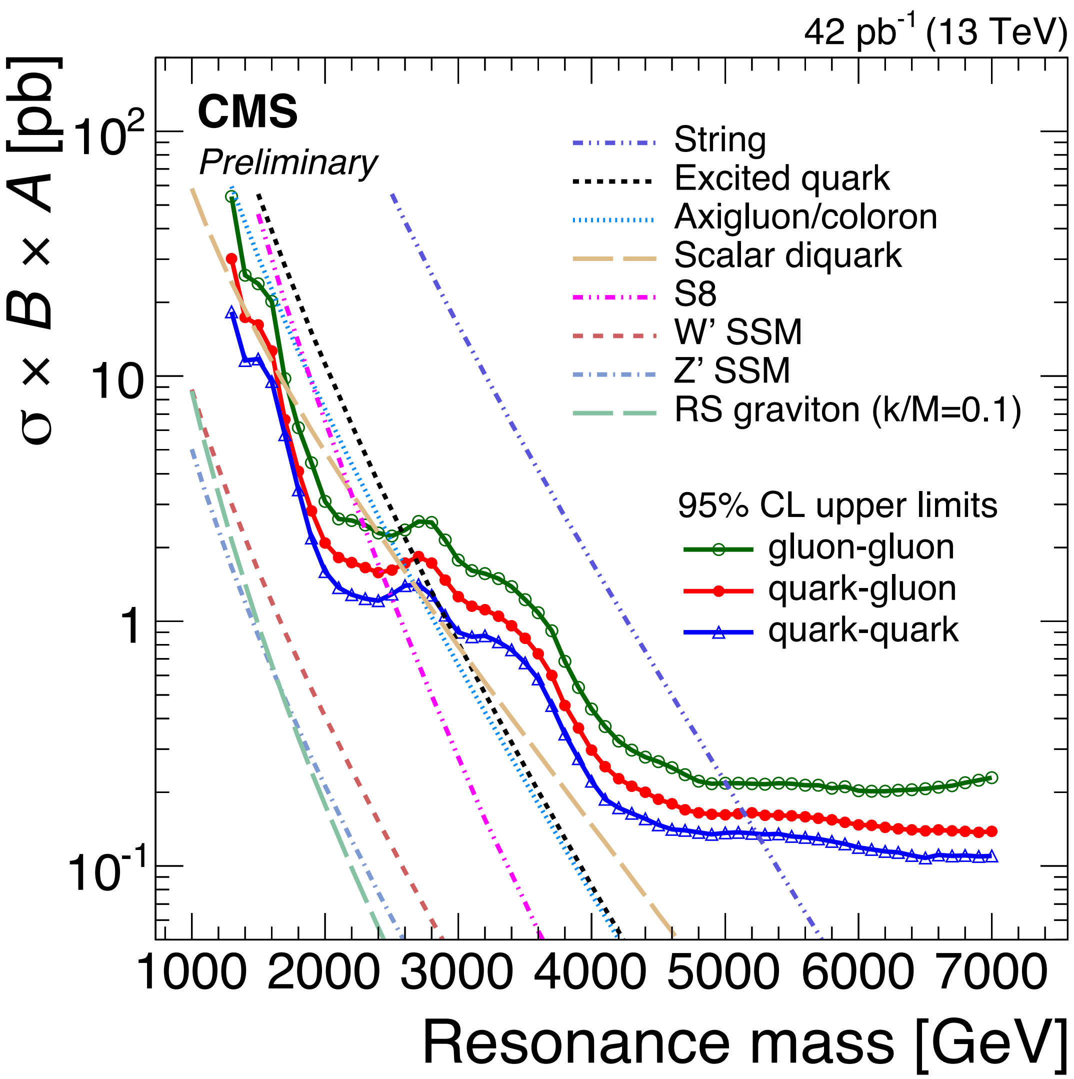
σ_{ttbar} = 174.5 ± 2.1 (stat)$^{+4.5}_{-4.0}$ (syst) ± 3.8 (lumi) pb at √s = 7 TeV

σ_{ttbar} = 245.6 ± 1.3 (stat)$^{+6.6}_{-5.5}$ (syst) ± 6.5 (lumi) pb at √s = 8 TeV



Allow to extract the pole mass from NNPDF30 PDF to be $m_{t,pole}$ = 173.6$^{+1.7}_{-1.8}$ GeV

Di-jet resonance search



CMS PAS EXO-15-001

- Observed limits at 95% CL on cross section of qq, qg, gg resonances
- Get worse when there are gluons in the final state because radiation increases and resolution degrades
- Extend to 7 TeV in di-jet mass for the first time
- plateaus at high mass due to absence of events

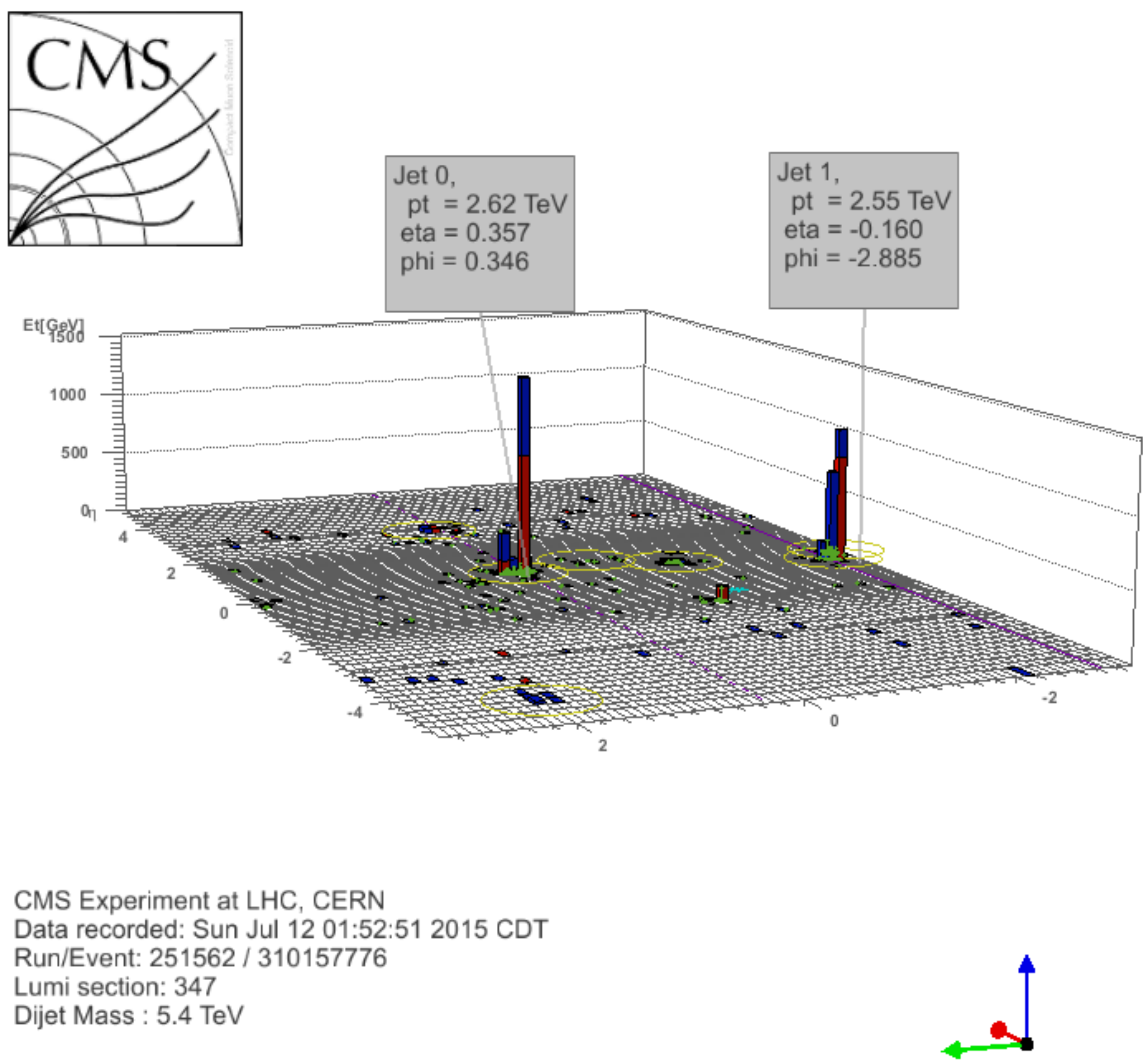
Confirms Run2 is already more sensitive than Run1 for M> 5 TeV

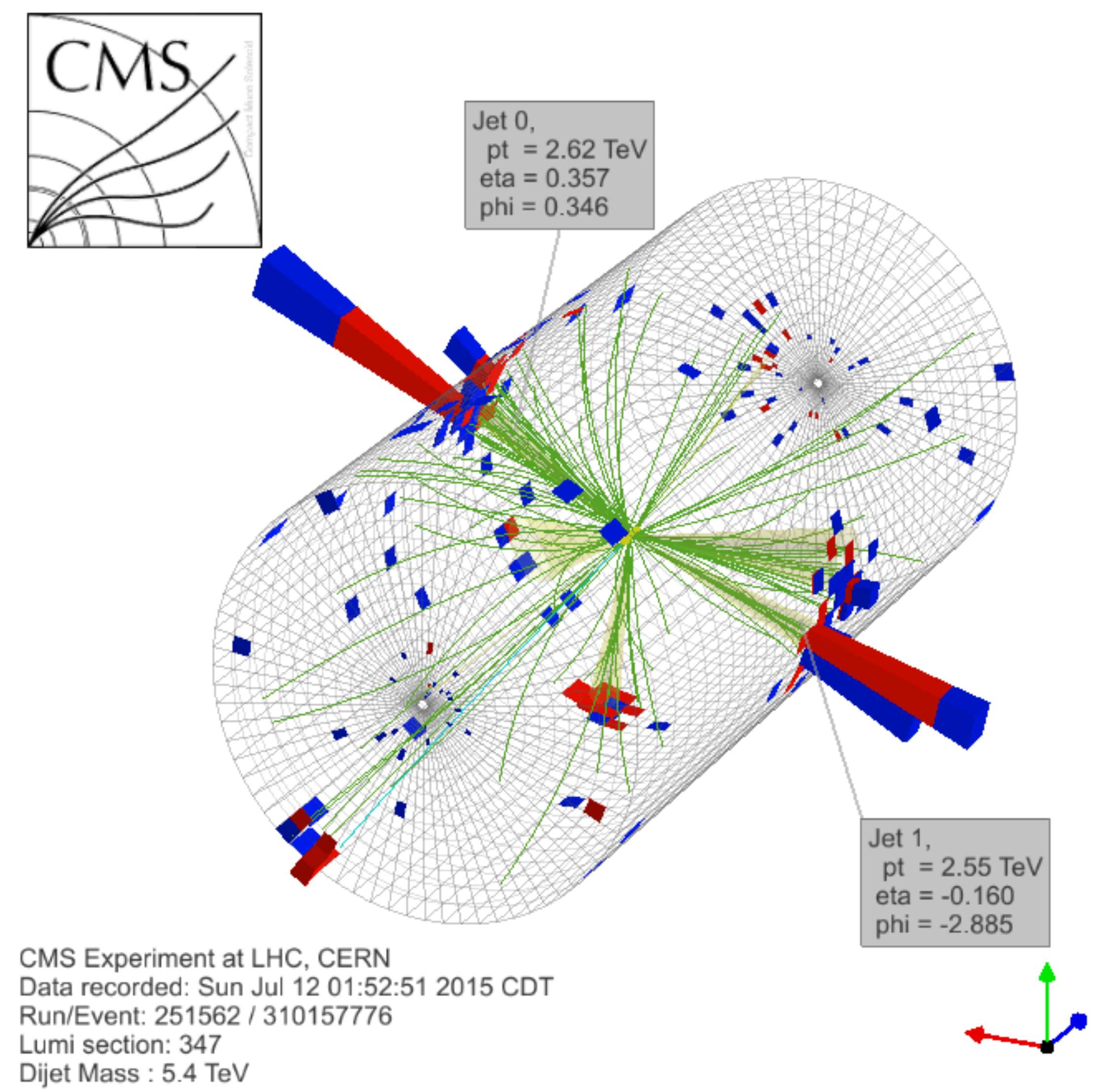
Model	Mass Limits (TeV)			
	Run 1 (20 fb^{-1})		Run 2 (42 pb^{-1})	
	Observed	Expected	Observed	Expected
String Resonance (S)	5.0	4.9	5.1	5.2
Excited Quark (q*)	3.5	3.7	2.7	2.9
Axigluon (A) / Coloron (C)	3.7	3.9	2.7	2.9
Scalar Diquark (D)	4.7	4.7	2.7	3.3
Color Octet Scalar (S8)	2.7	2.6	2.3	2.0

Di-jet resonance search

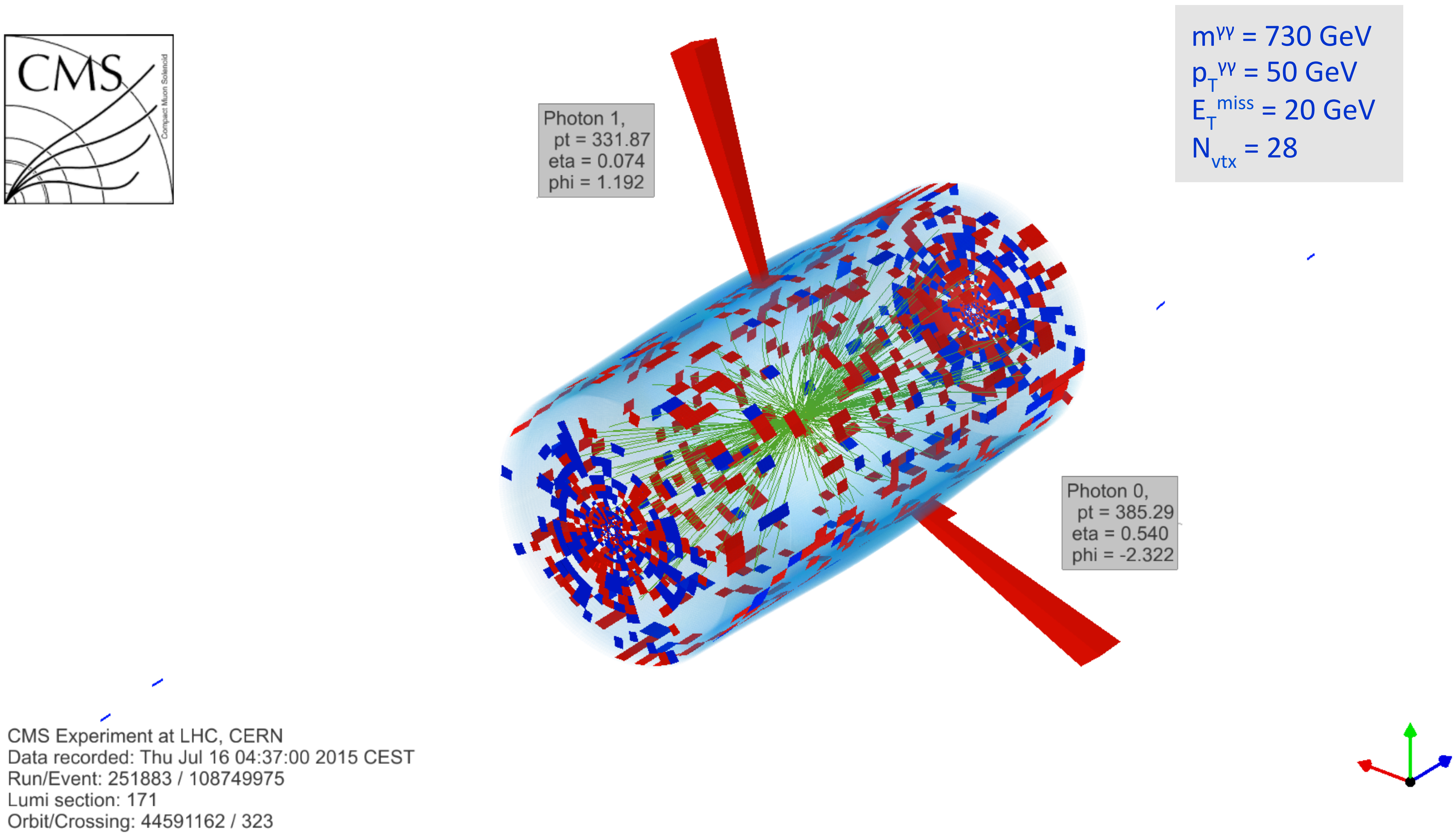
Highest Mass di-jet event M =5.4 TeV

CMS PAS EXO-15-001





Event display of the highest mass di-photon candidate (M = 730 GeV)

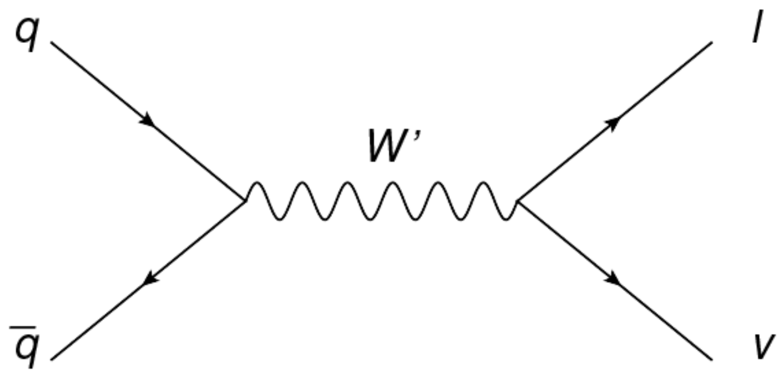


Photon selection

p_T> 100 GeV and |η| <2.5 with at least one candidate in the ECAL Barrel with |η| <1.4442

isolated photons with shape in ECAL compatible with prompt photon

Muon + MET resonance Search



Muon selection

Good-quality isolated high-p_T muon with p_T> 55 GeV and |η| <2.4

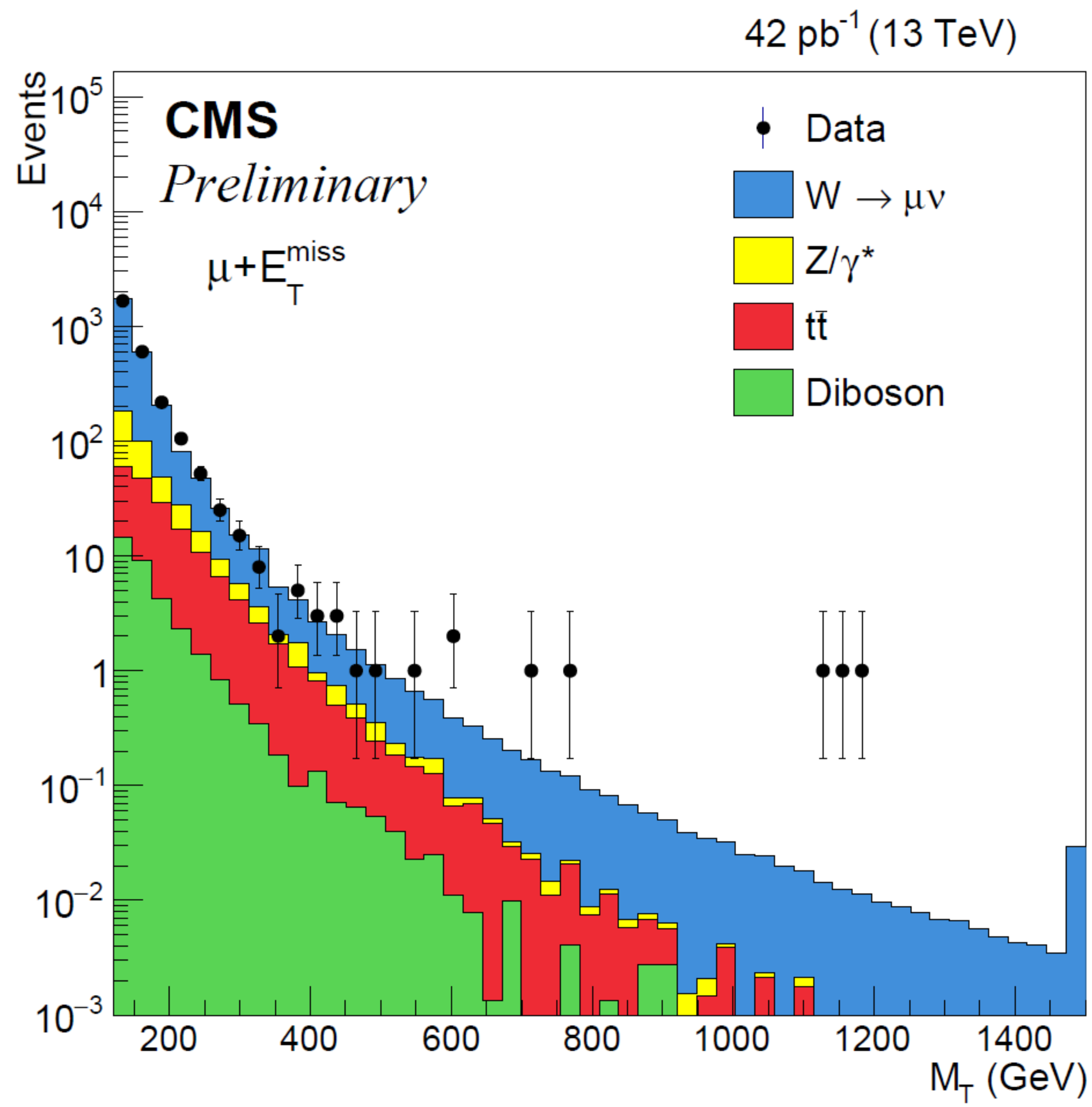
Event selection

- Single high-p_T muon accompanied by a large missing transverse energy (E_T^{miss}).
- Events containing additional muons with p_T> 25 GeV are vetoed
- Kinematic selection:

$0.4 < p_T(\mu)/ E_T^{miss} < 1.5$

$\Delta\Phi(\mu, E_T^{miss}) > 2.5$

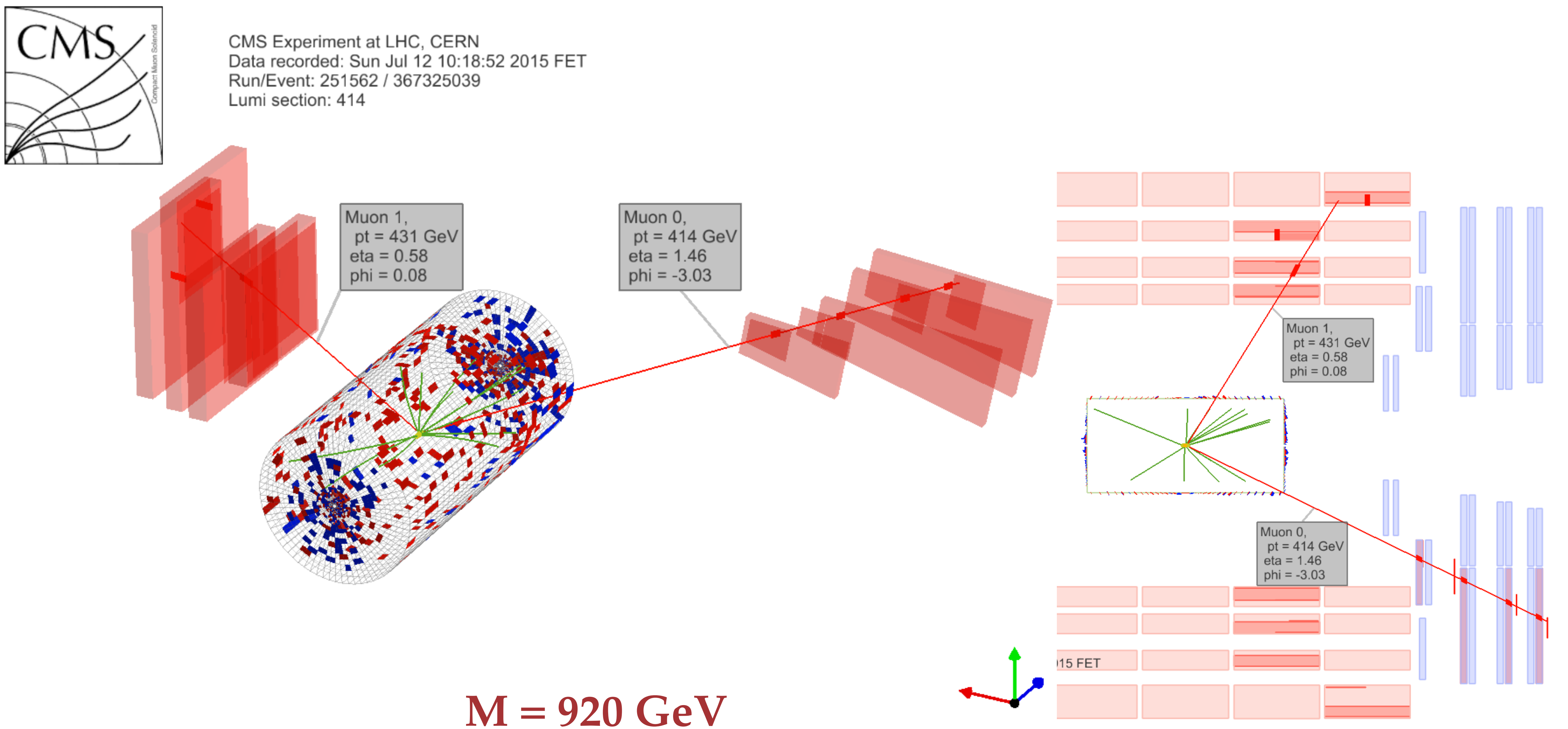
Early Alignment used in data



transverse mass

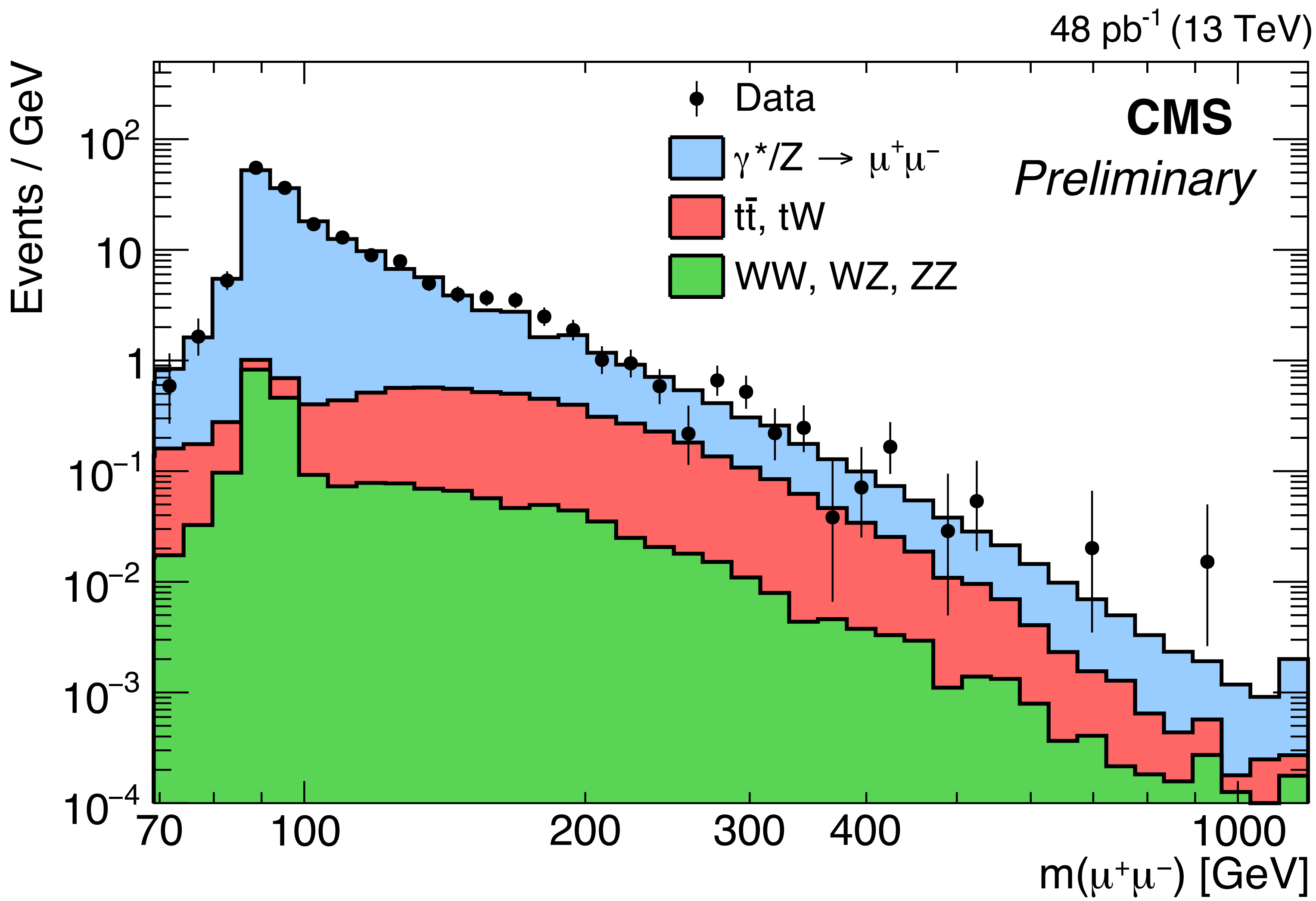
last bin includes overflow

Di-muon resonance search

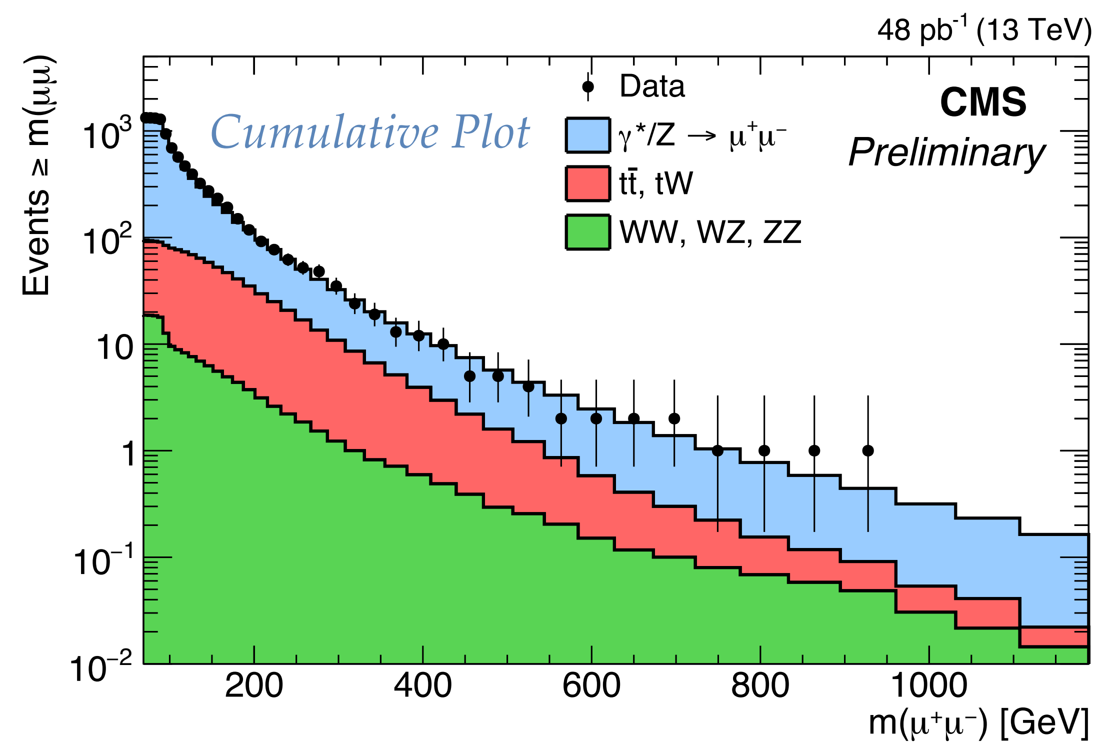


M = 920 GeV

Di-muon resonance search



last bin includes overflow



Highest mass event = 920 GeV

Early alignment of Muon system and Tracker used in data

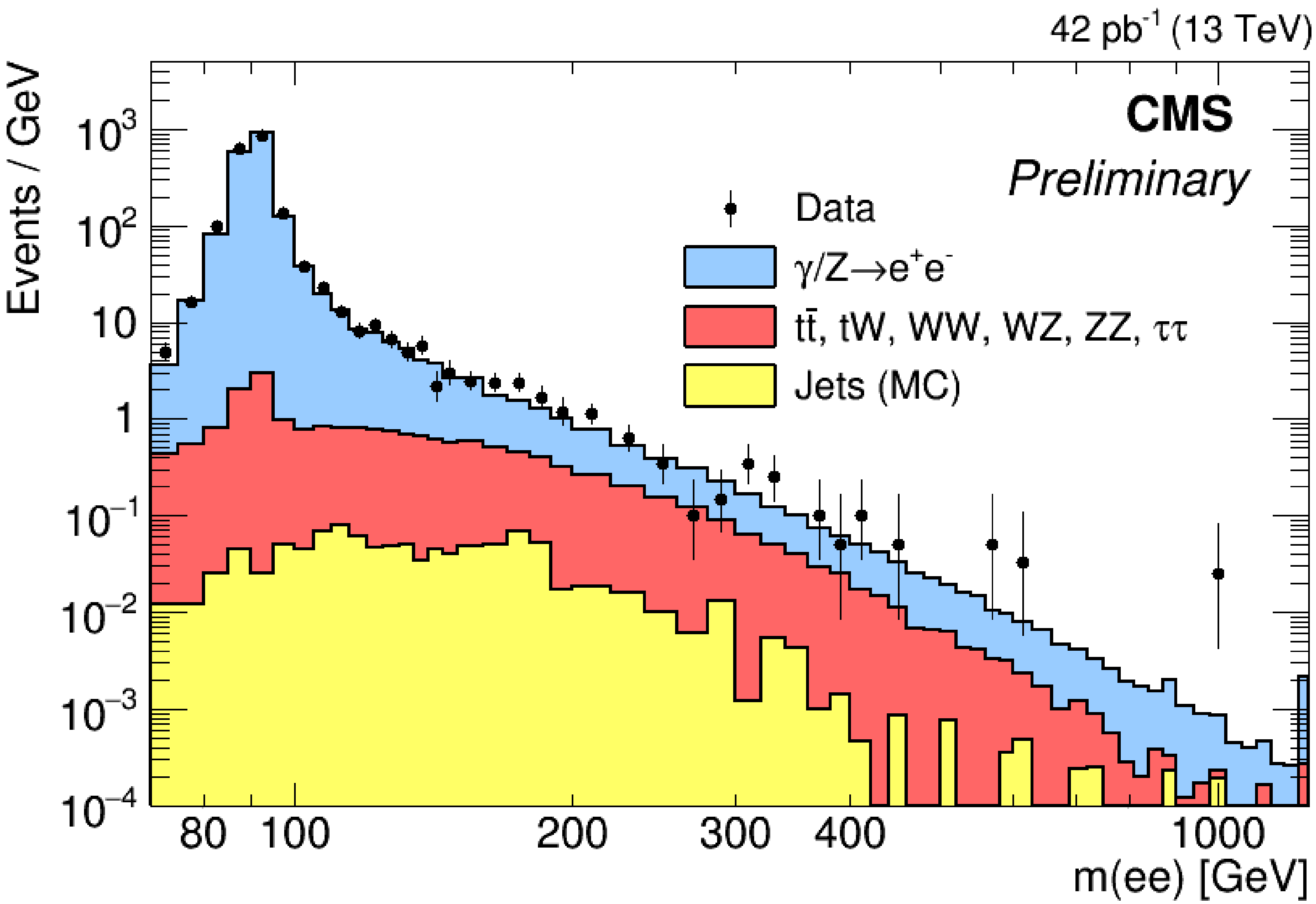
contribution from di-jets negligible and not shown

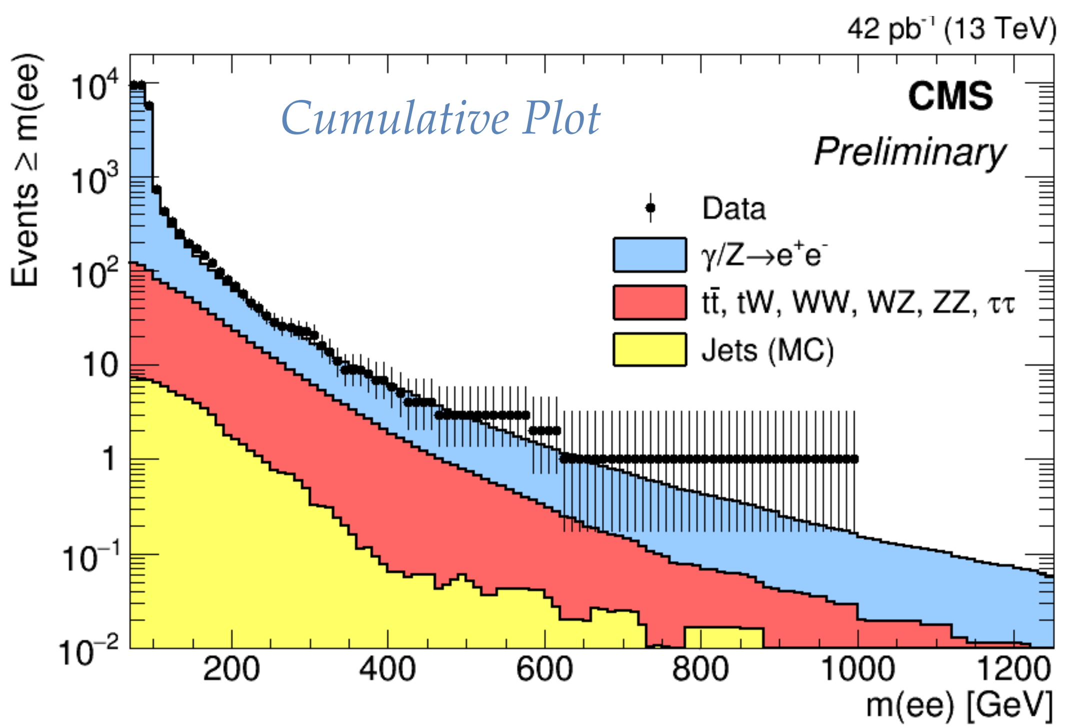
2 isolated muons muons are required to satisfy:

$p_T > 48$ GeV and $|\eta| < 2.4$

MC samples: aMC@NLO for Drell-Yan, POWHEG for ttbar and dibosons

Di-electron resonance search





last bin includes overflow

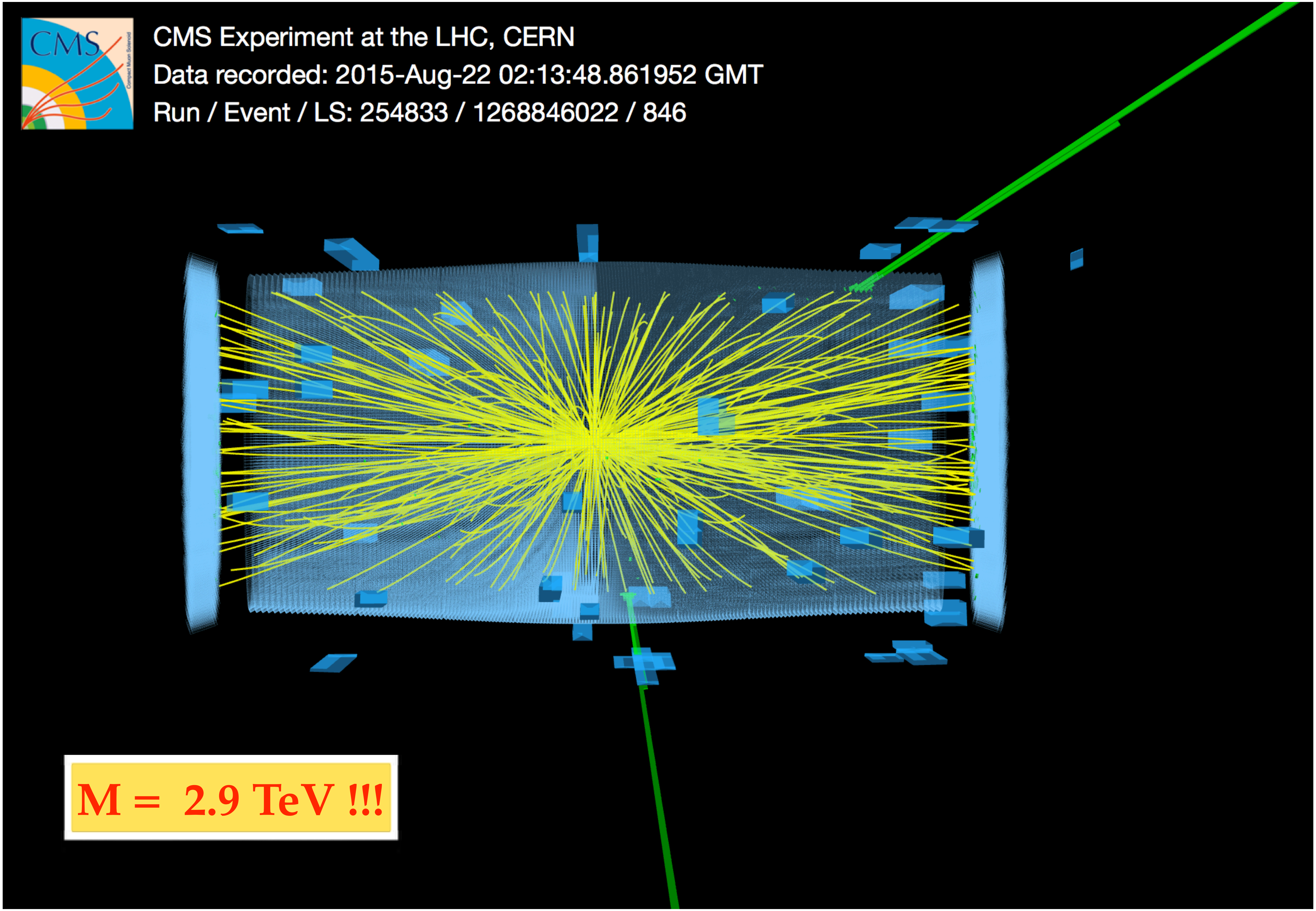
Highest mass event ~ 1 TeV

Run1 Limit for SSM Z′ < 2.9 TeV

Run1 sensitivity will be reached after about 2 fb^{-1}

2 electrons in ECAL with $E_T > 35$ GeV and at least one electron in the ECAL barrel

($|\eta| < 1.4442$ or $1.566 < |\eta| < 2.5$ with one electron within $|\eta| < 1.4442$)


CMS Experiment at the LHC, CERN
Data recorded: 2015-Aug-22 02:13:48.861952 GMT
Run / Event / LS: 254833 / 1268846022 / 846
M = 2.9 TeV !!!

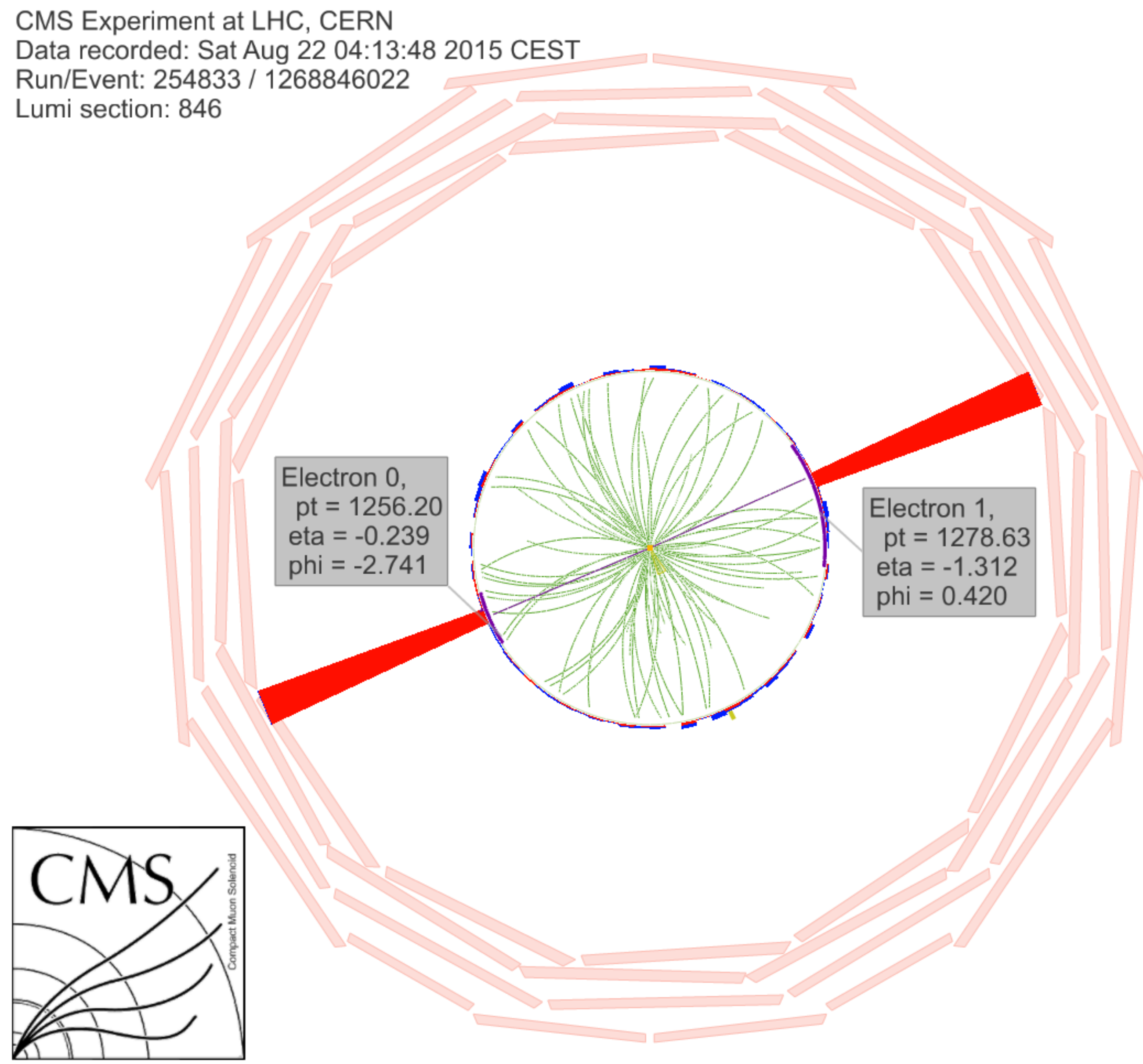
Di-electron resonance search

In the additional 25 pb^{-1} data @13 TeV and 50 ns processed last Wednesday:

An event with a di-electron mass of 2.9 TeV has been observed

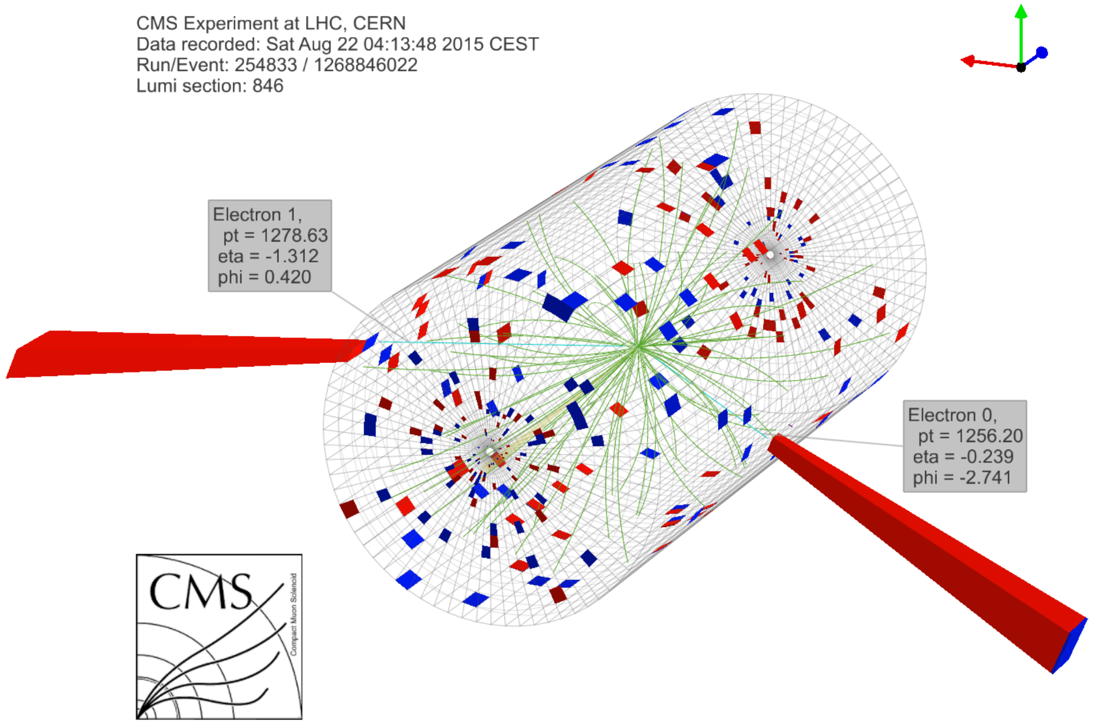
The event consists in two perfectly balanced electrons and no other significant activity

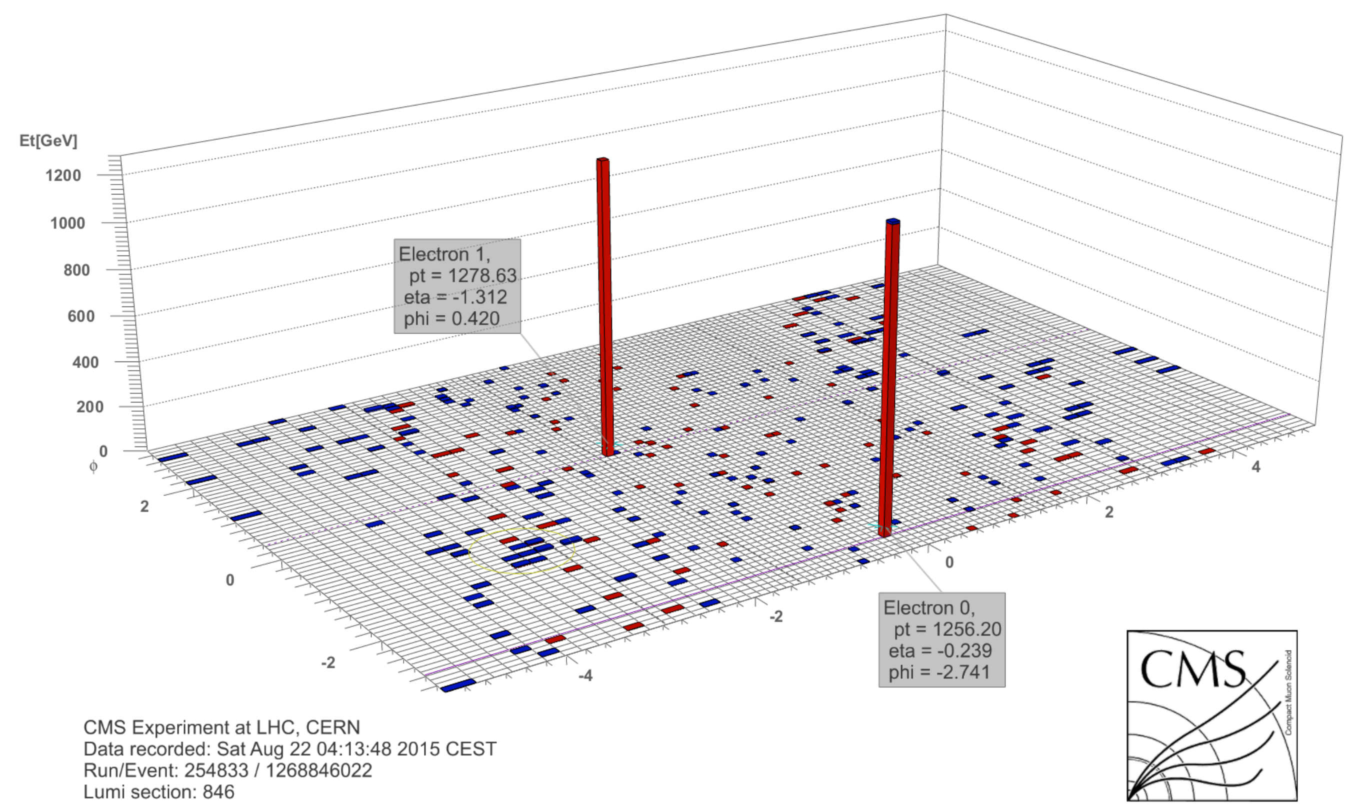
M = 2.9 TeV !!!



Di-electron resonance search

M = 2.9 TeV !!!





Conclusions

- Successful operation in 2010 - 2012 runs at √s- 7 and 8 TeV
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- Large number of analysis and publications from many CMS physics groups
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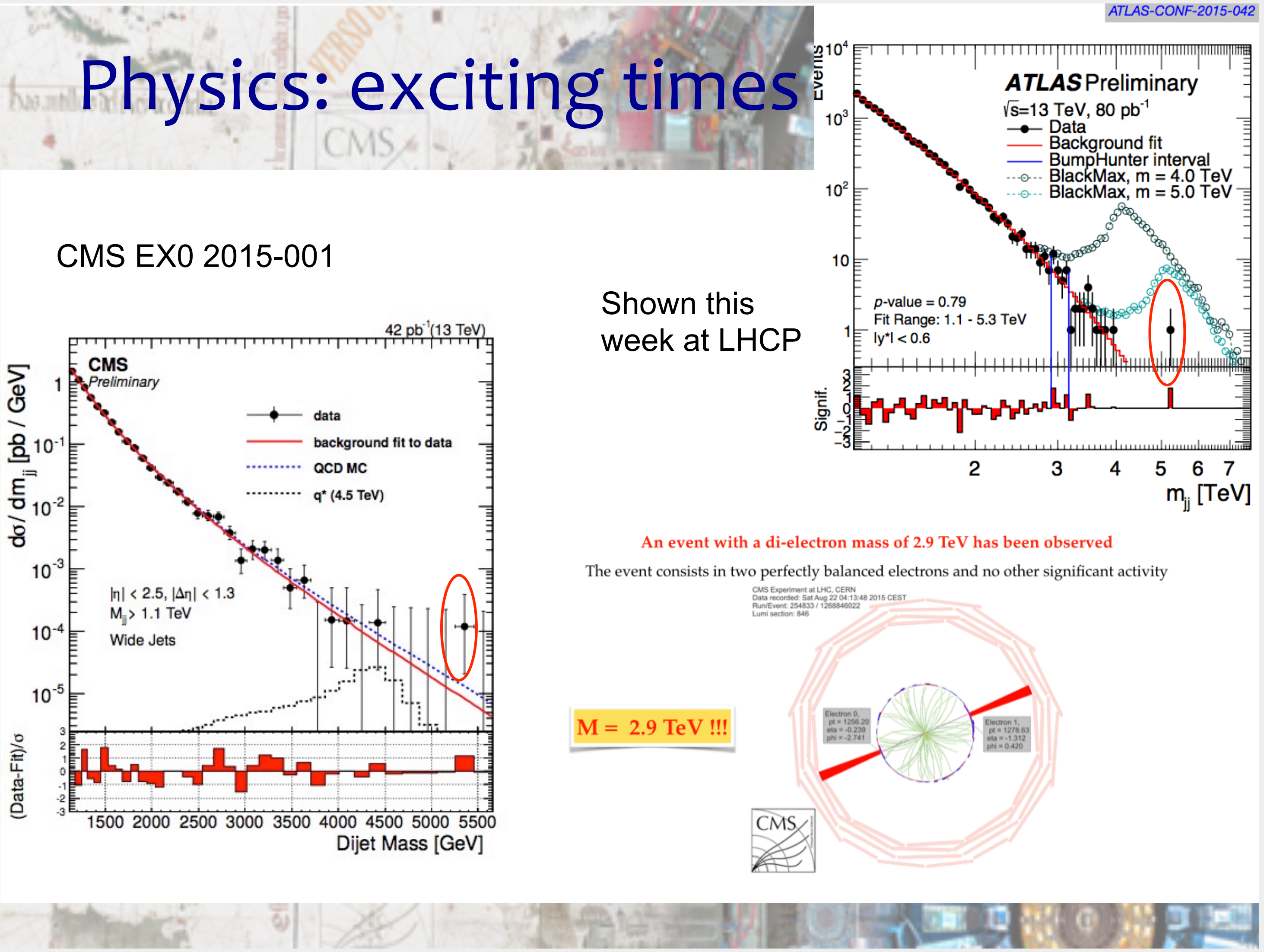

Conclusion (2)

- CMS is (~continuously) improving and upgrading to take advantage of the increasing LHC energy and luminosity
  - The LS1 projects are nearly complete
  - Upgrades to tracking and trigger will happen during Run 2
  - Further upgrades during LS2 to improve calorimeter granularity, trigger
  - R&D is underway for upgrades for HL-LHC

The CMS upgrade program aims to fully exploit the LHC physics potential