CMS @ LHC: Status and plans

A Look at Recent Results and into the Future

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HELMHOLTZ GEMEINSCHAFT

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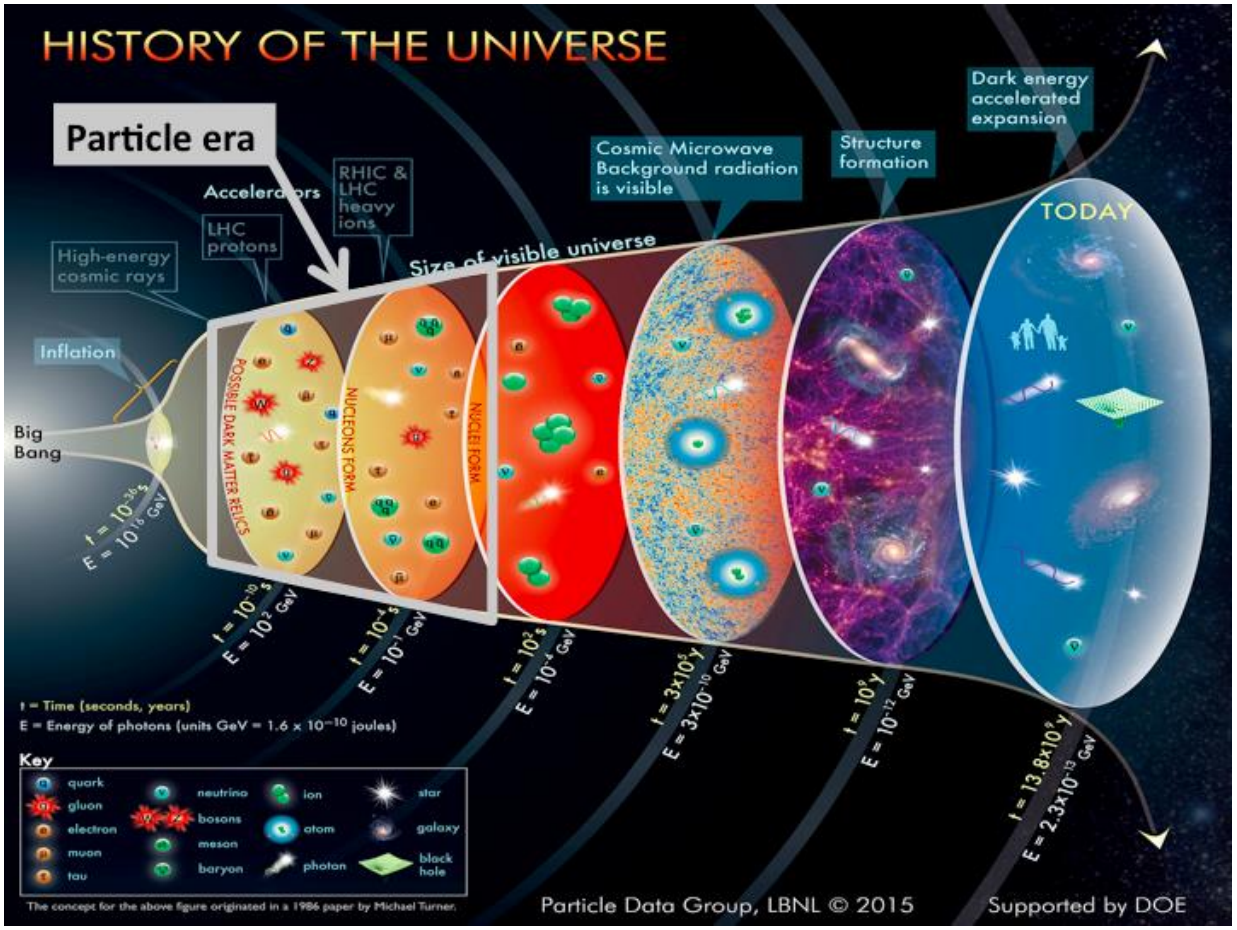
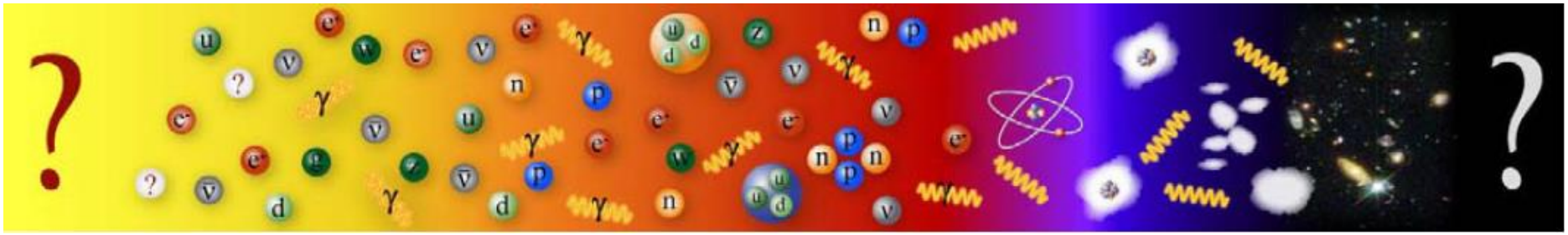
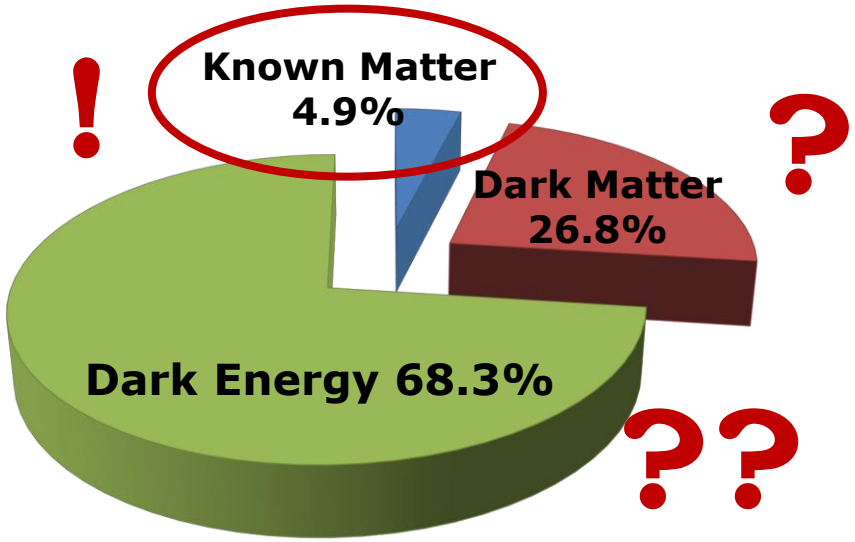
Our Mission



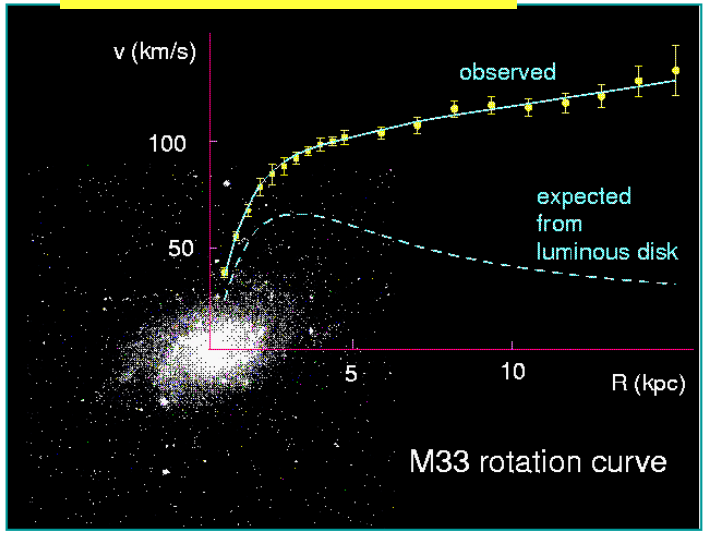
- **Identify fundamental particles**
- **Discover the fundamental laws of nature**
- **Understand the development of the Universe**

What is our Universe made of ?



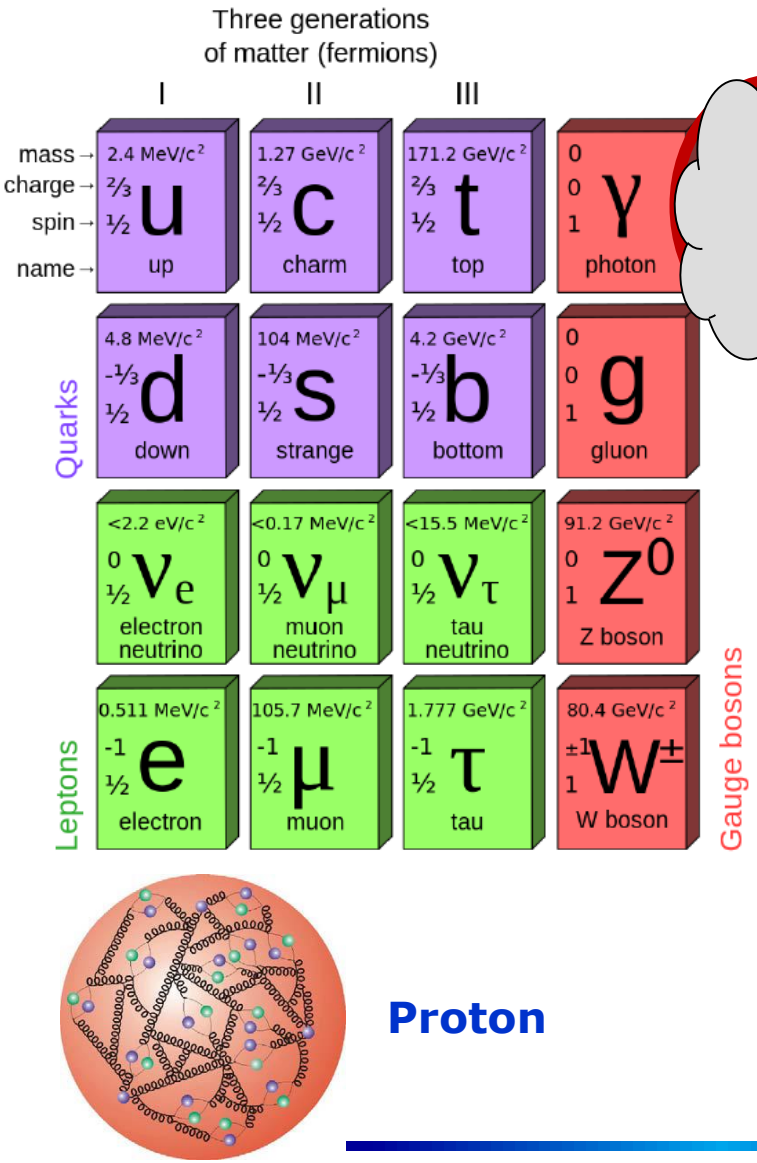


Galaxy rotation curves
(1933 – Zwicky)



Can we conclude from the familiar to the unknown ?
Are there deviations from predictions ?
Need highest precision to be able to find out!

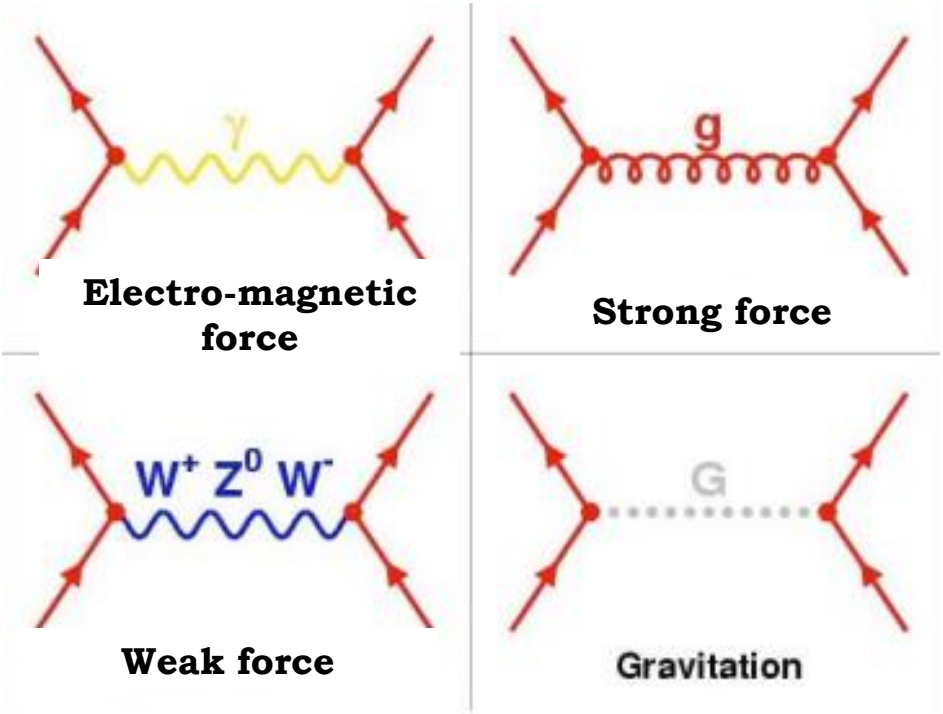
The Standard Model



Proton

Four fundamental forces:

- **Electro-magnetic force**
- **Strong force**
- **Weak force**
- **Gravitation**



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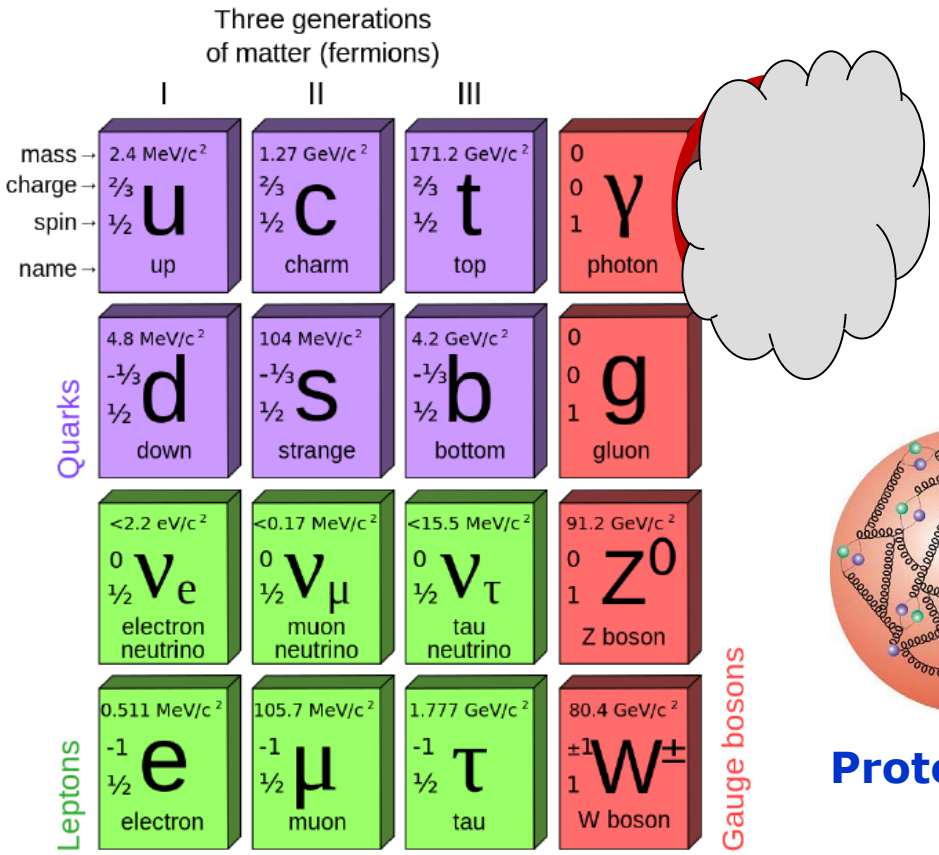

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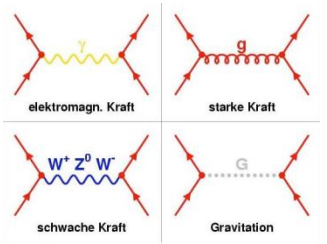
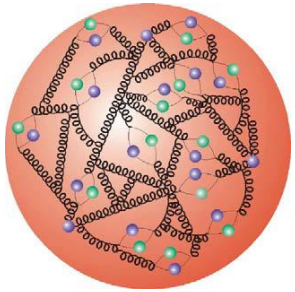
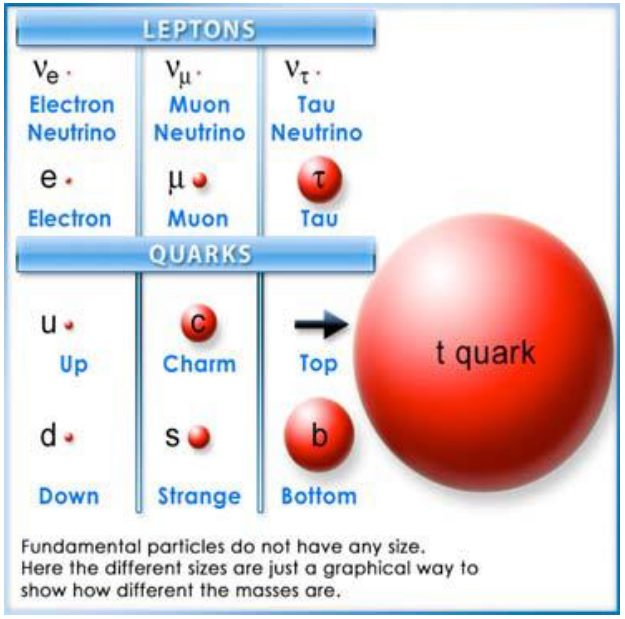




Proton



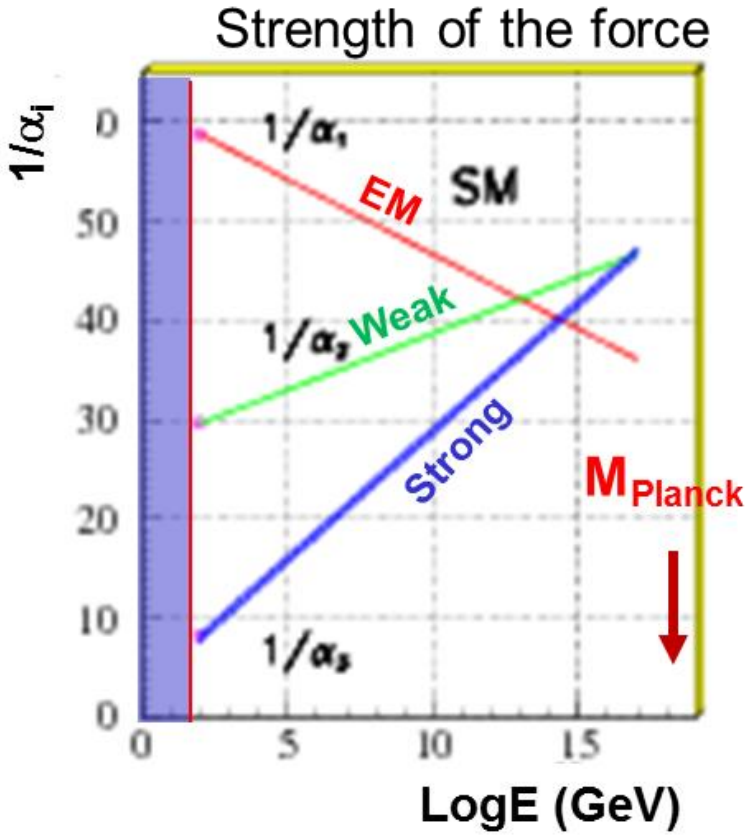
In the standard model all particles are mass-less.

Only through the interaction with the Higgs field they obtain their masses.

Is the Standard Model the ultimate solution ?

Important open questions:

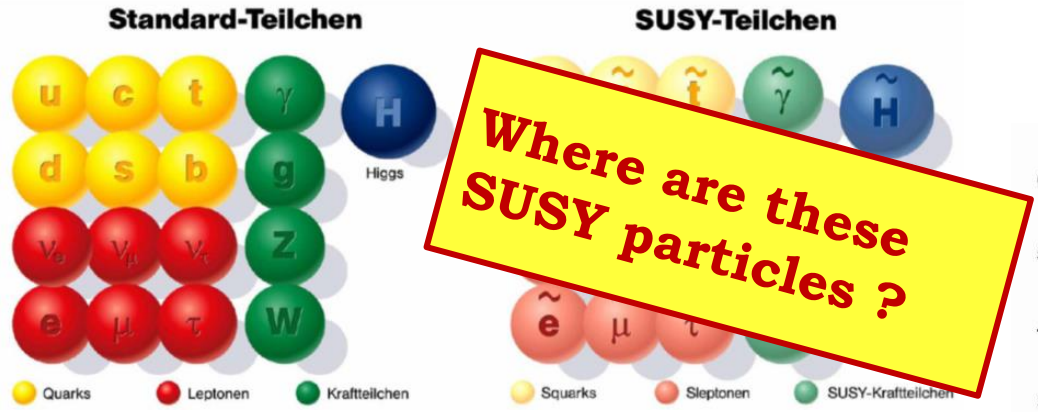
- **Why do the masses differ by more than 13 orders of magnitudes ?**
- **Do the fundamental forces unify ?**
- **What about gravity? Does a unified "World Equation: The Theory of Everything" exist?**
- **What is dark matter ?**
- **What is dark energy ?**



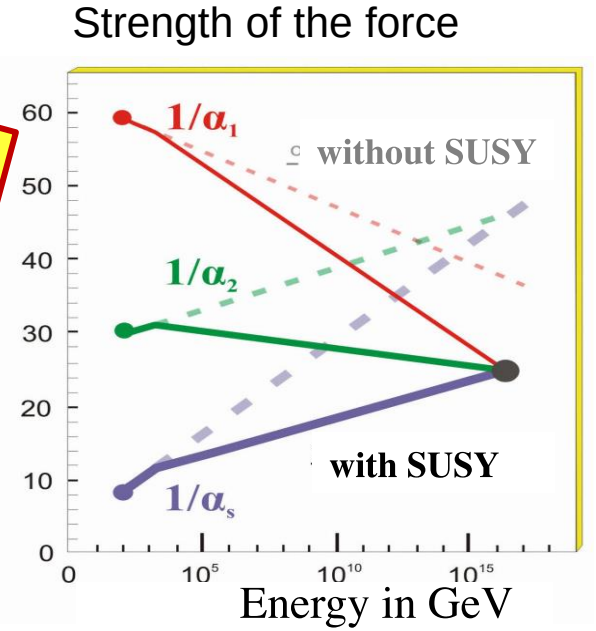
One potential solution: SUSY

Supersymmetry:

- **Each elementary particle obtains a SUSY partner**

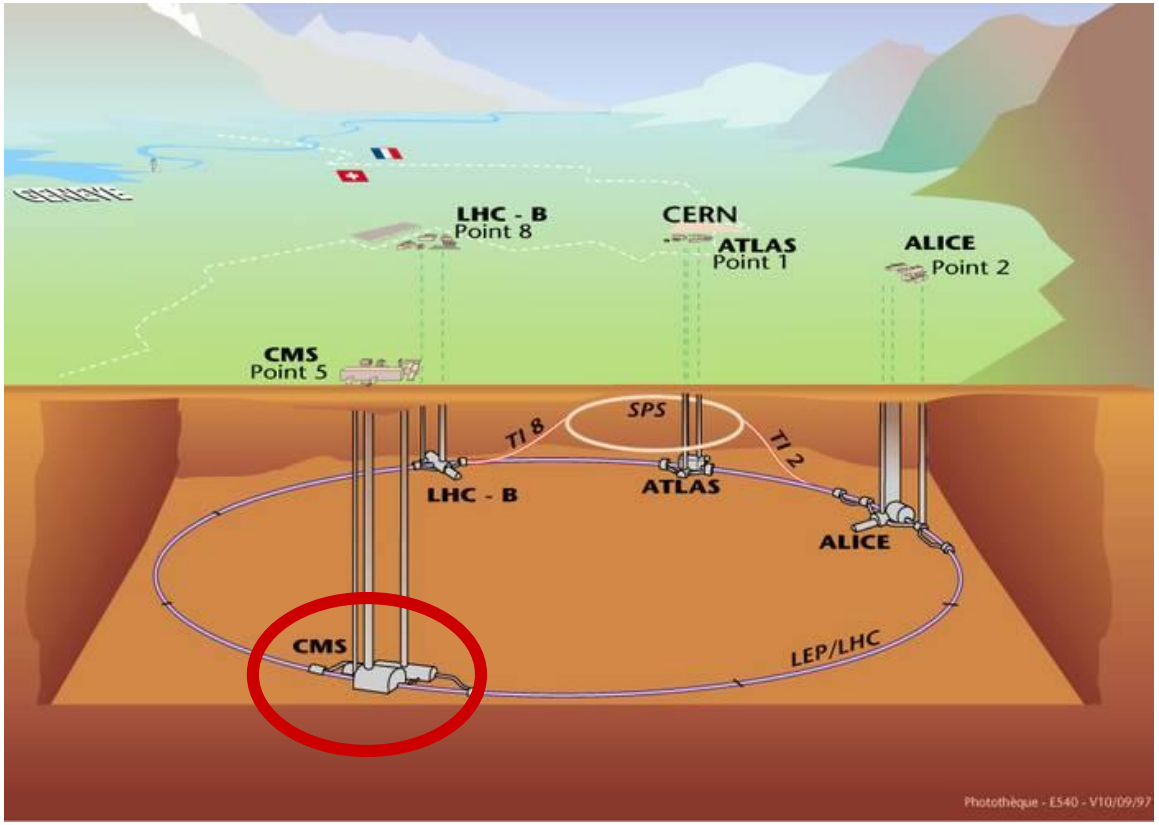


- **There are different flavors of the basic idea, which include a different number of new parameters**



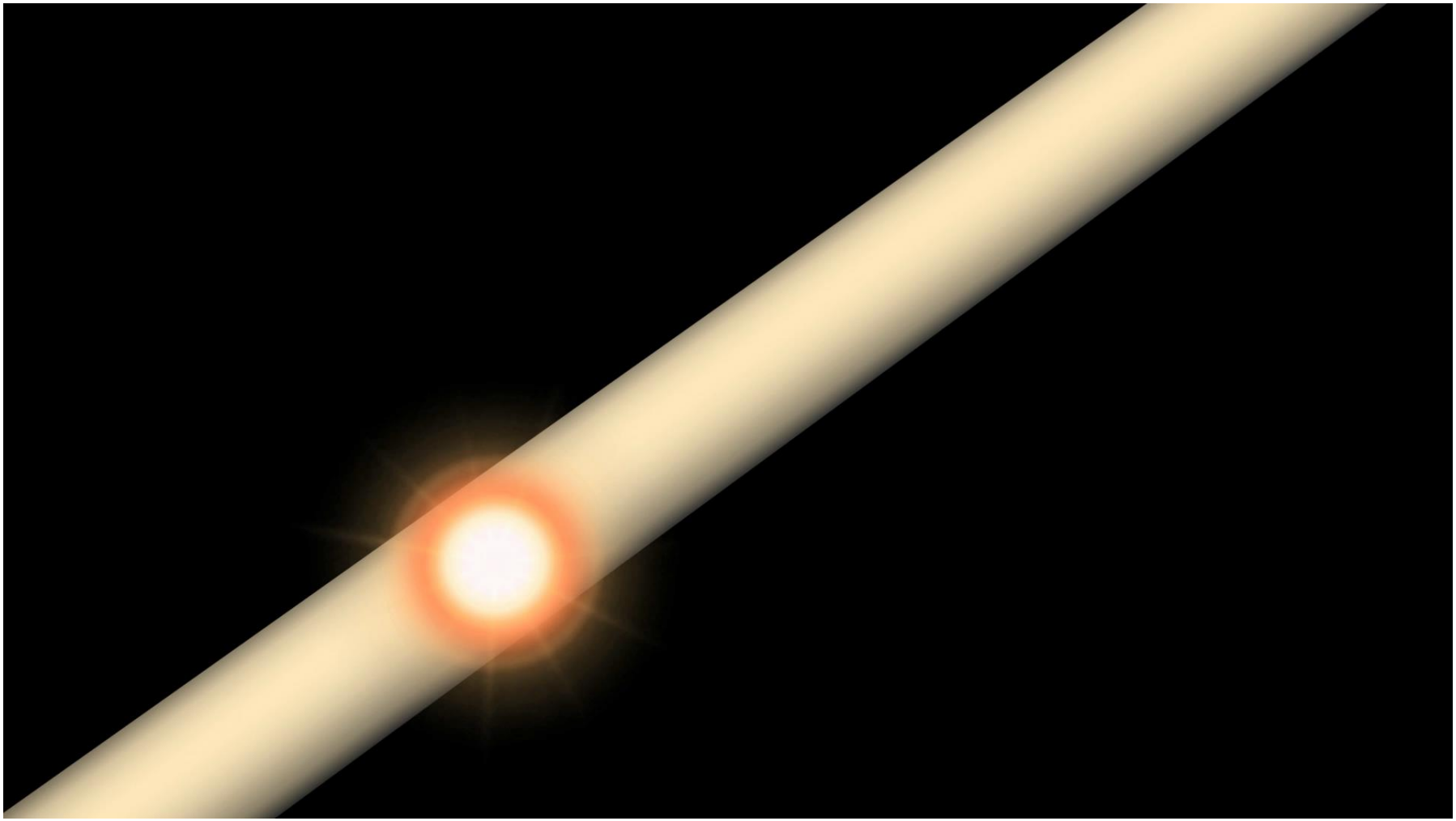
- ✓ **Neutrinos have mass**
- ✓ **Unification of forces**
- ✓ **Gravitation is included**
- ✓ **Lightest SUSY particle → candidate for dark matter**

High-Tech in Global Collaboration



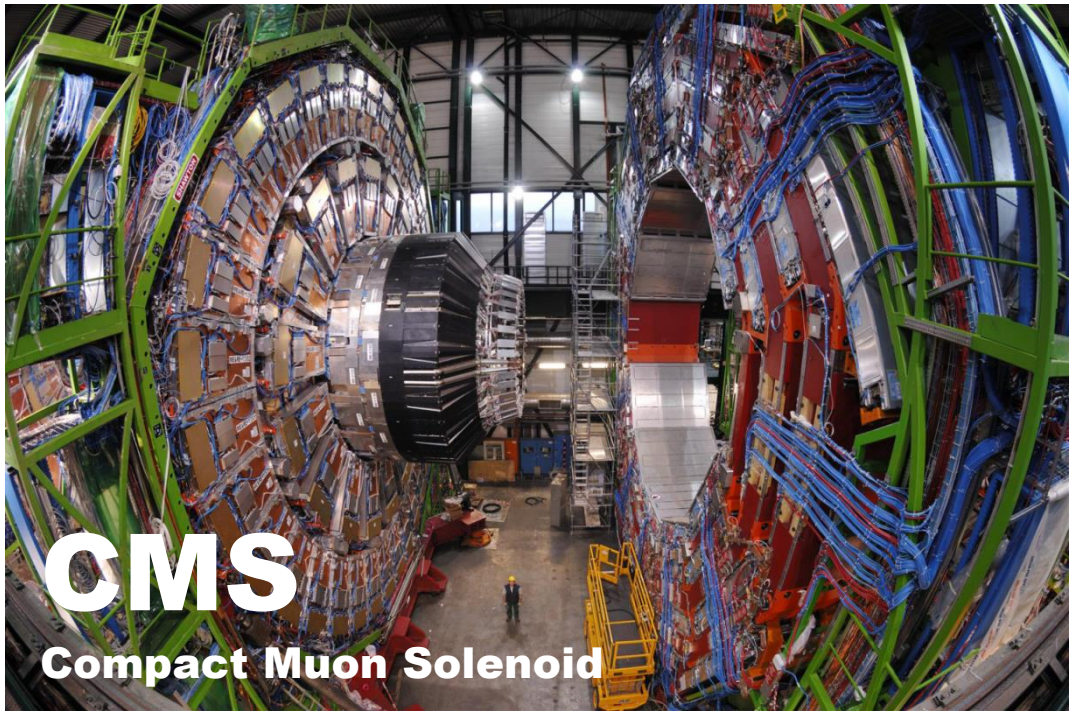
- 27 km long
- 9000 magnets, 2000 super-conducting
- colder than outer space
- proton-proton collisions with 8 → 13 TeV world record
- Lead-Lead, as well as proton-Lead collisions

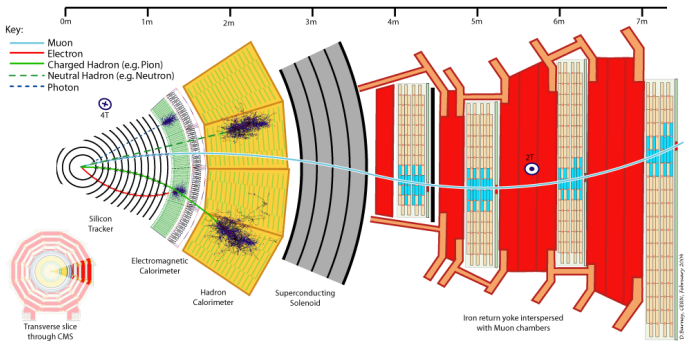
Collisions @ LHC

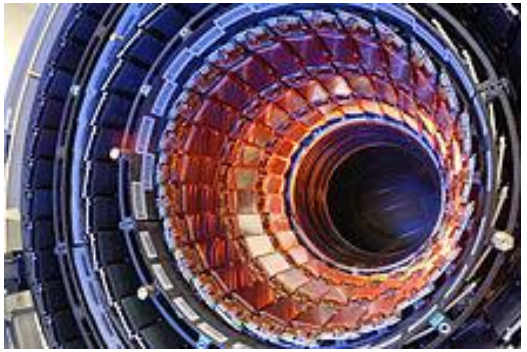


Copyright CERN

High-Tech in Global Collaboration



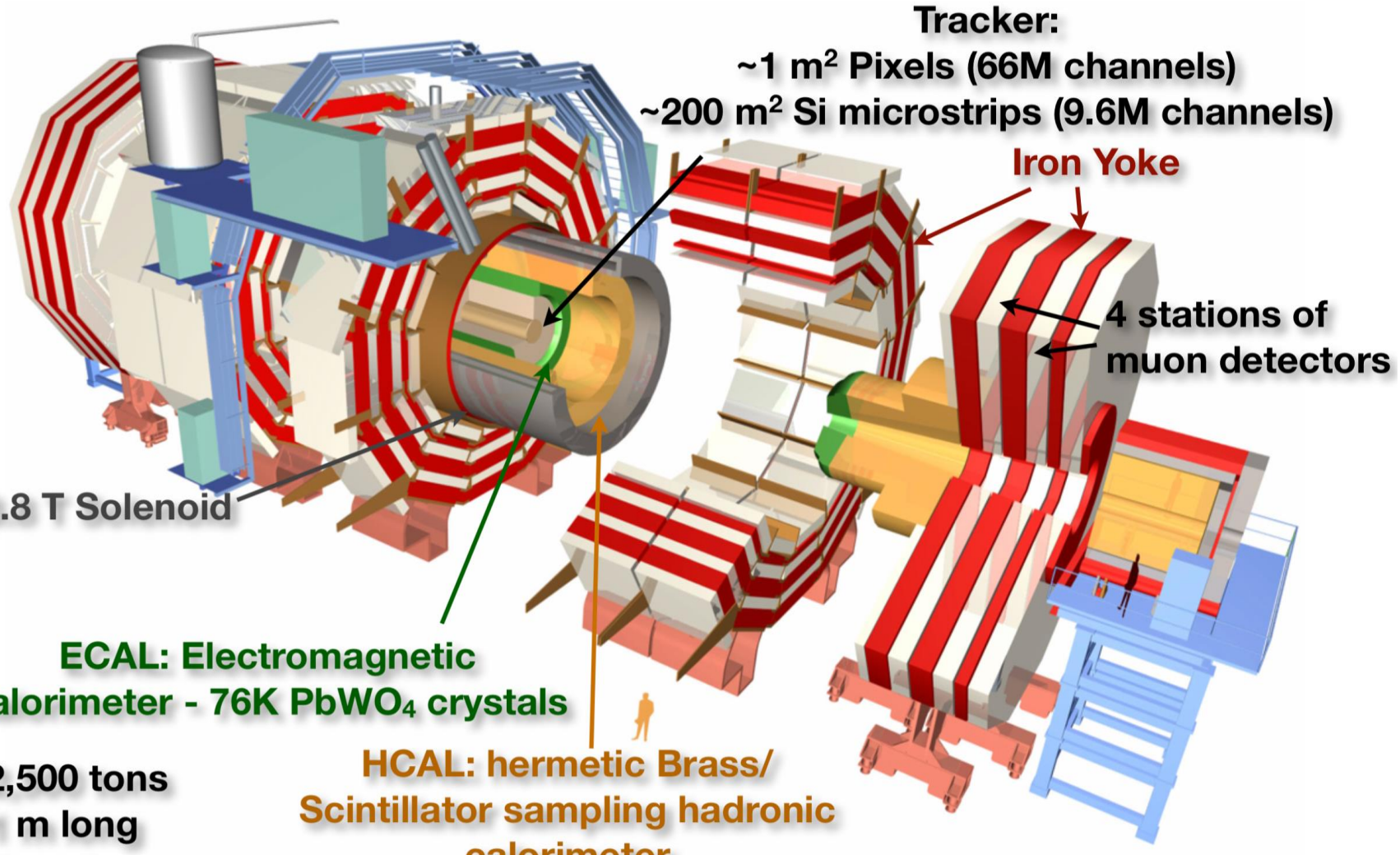




- **Large:** 21 m long, 15 m ∅, 14 000 t (> Eiffel Tower!)
- **Micro:** Tracking with hair-fine Si-strips and pixels with a precision of 20 micro-m
- **Many:** >5200 members, 1900 physicists, 1800 students, 950 engineers and technicians
- **Global:** 203 institutes from 45 countries

- **One Goal: Find out what our Universe is made of !**

The CMS Experiment



LHC: Fascinating Science

Google at the LHC start in 2008

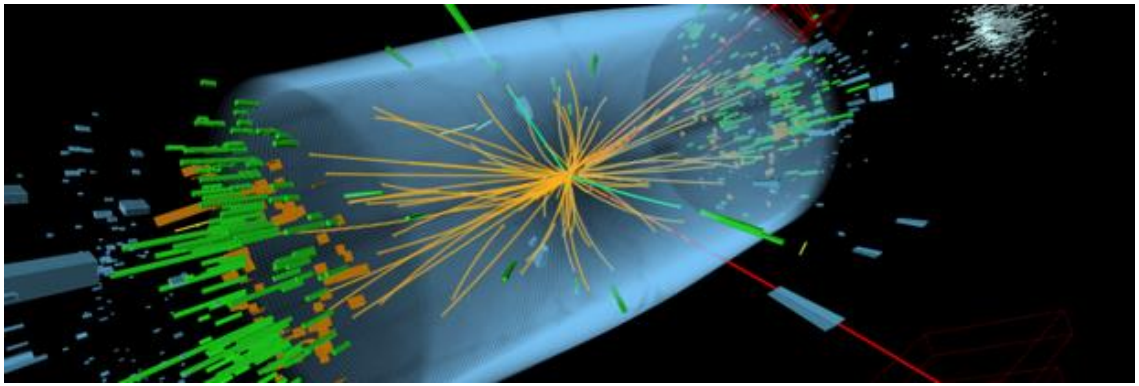
Higgs Discovery in Juli 2012

The long way to the Higgs Boson

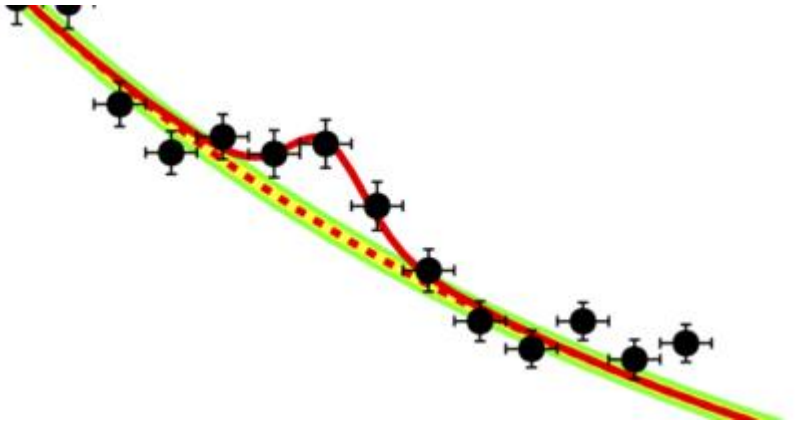
Proposed in 1964 by Peter Higgs and other colleagues.

Almost 50 years searches at many colliders with higher and higher energies.

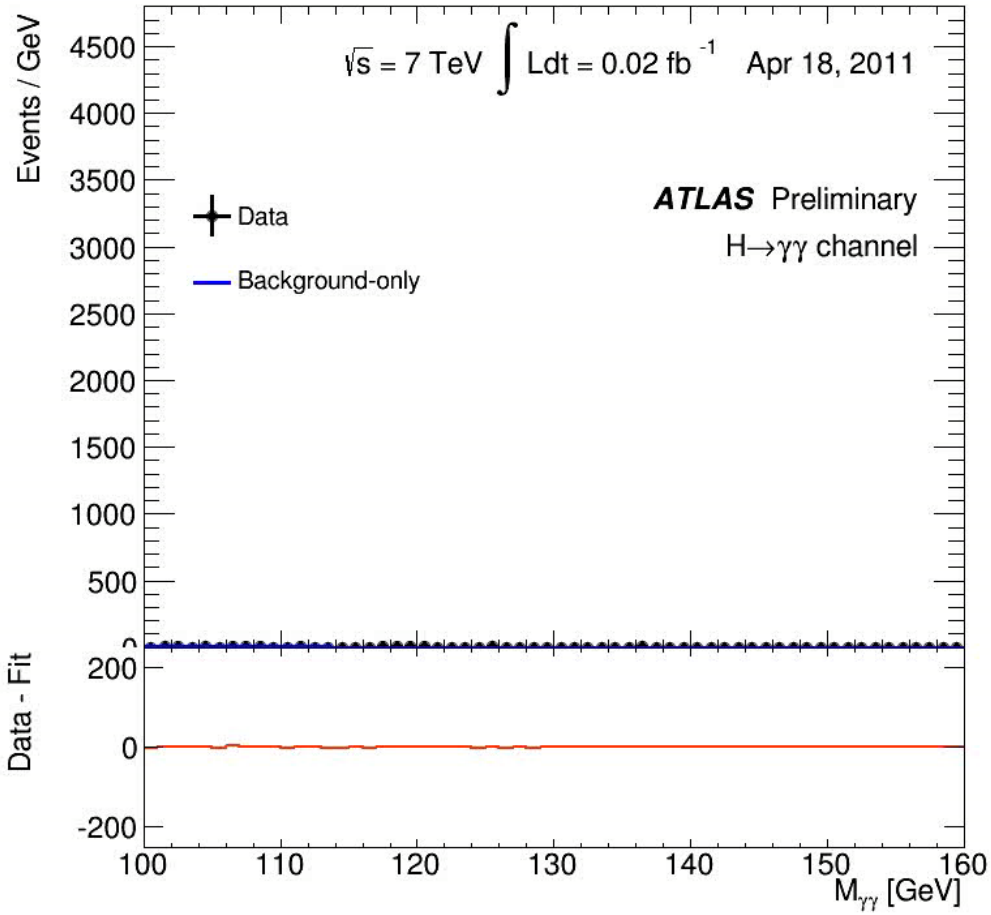
4.July 2012: Announcement of the discovery of a particle that resembles



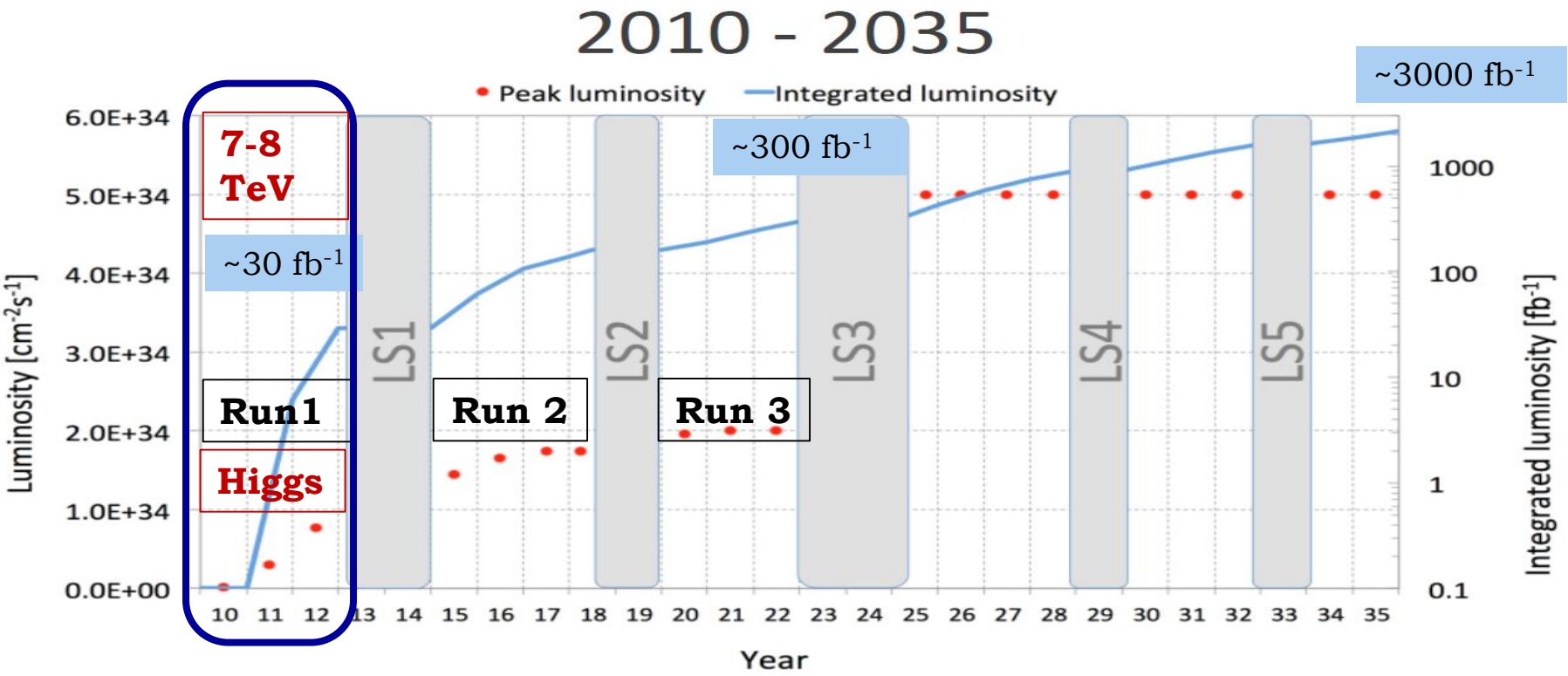
the Higgs Boson at the Large Hadron Collider by ATLAS and CMS



Discoveries need many data!



The Harvest of Run 1



Major Achievement: Higgs discovery and characterization

→Mass, spin, coupling, …

Top Quark: LHC is a top quark factory

→High precision measurements: mass, decays, spin…

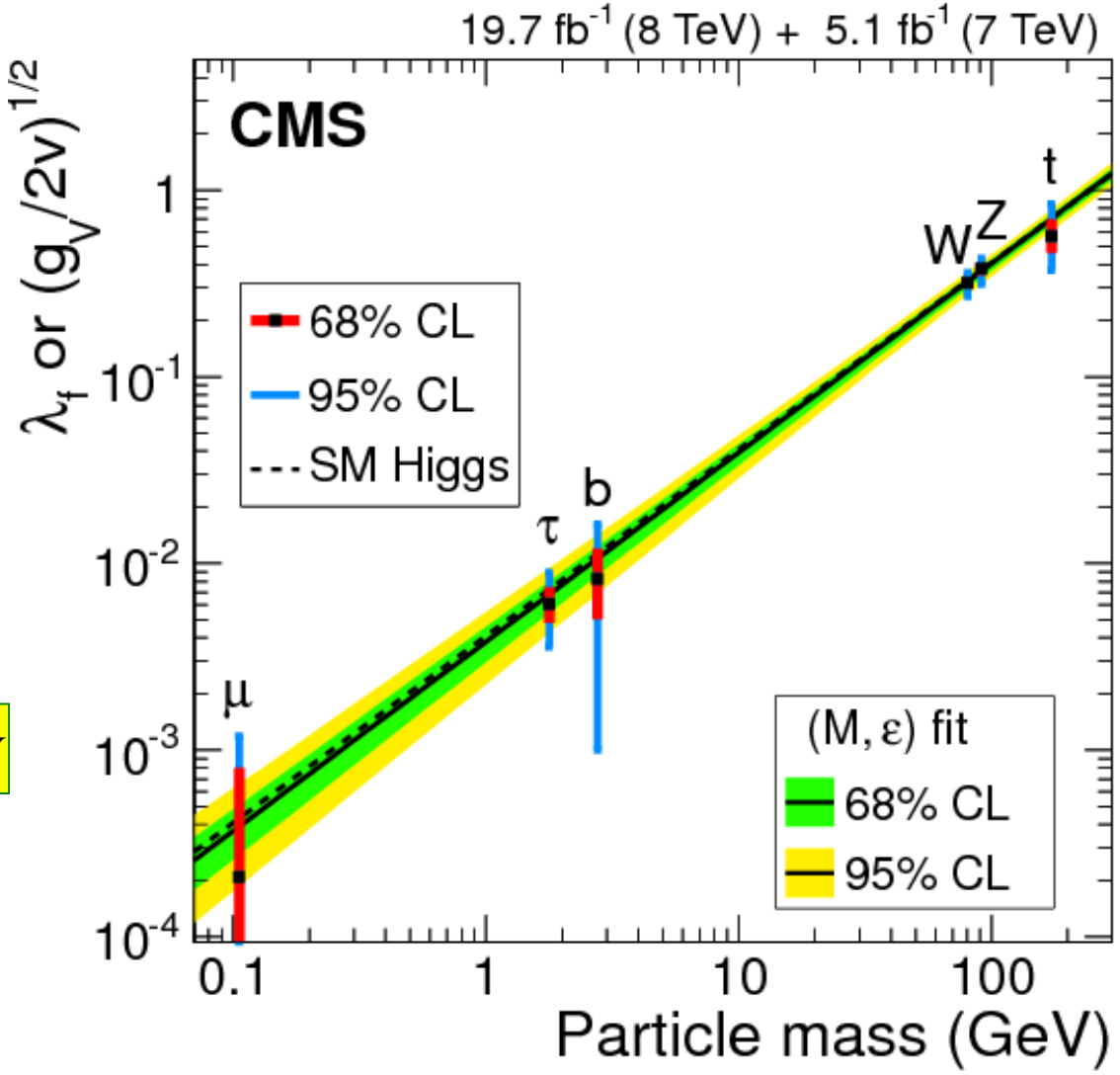
Searches for SUSY and other exotic particles beyond the SM

→Many limits for masses and couplings set.

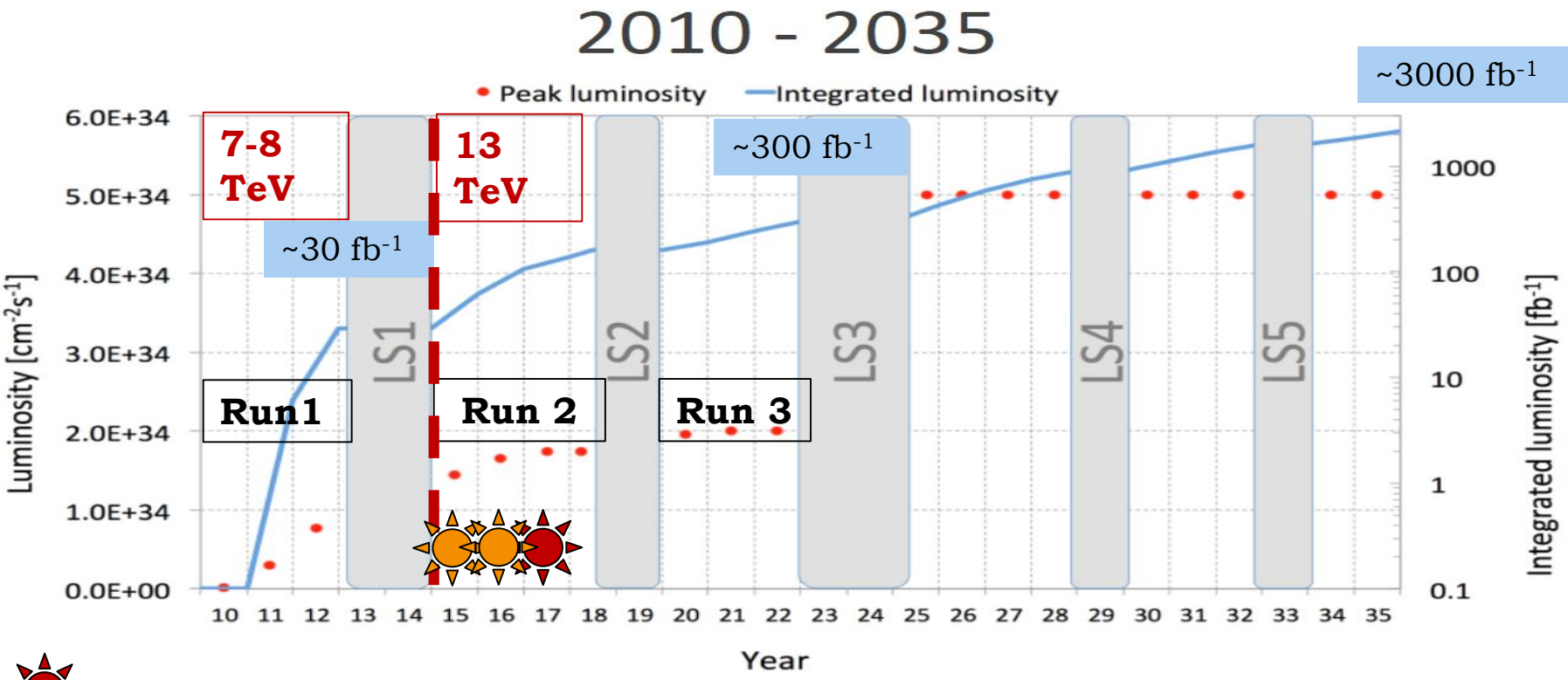
CMS Higgs Combination (Run 1)

- **Five main decay channels all published**
- **All results consistent with SM Higgs**

$$m_H = 125.02\ ^{+0.26}_{-0.27}\ (stat.)\ ^{+0.14}_{-0.15}\ (syst.)\ GeV$$



The Present @ LHC



: **new world-record energy and much more statistics**

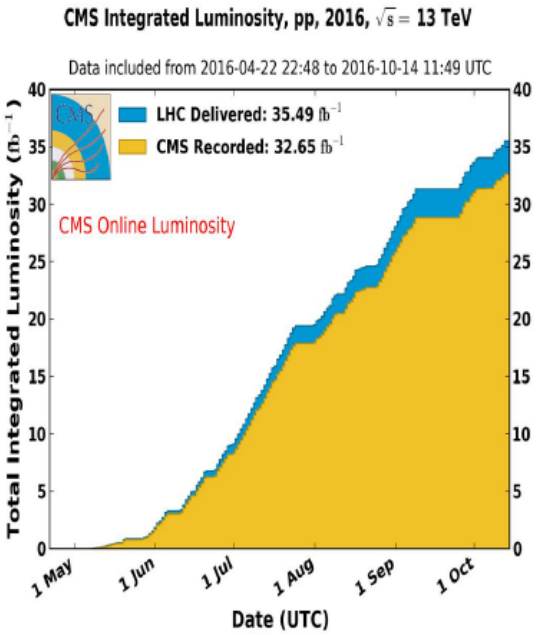
→ **Opening the window to unexplored territories for much higher masses of unknown particles and forces**

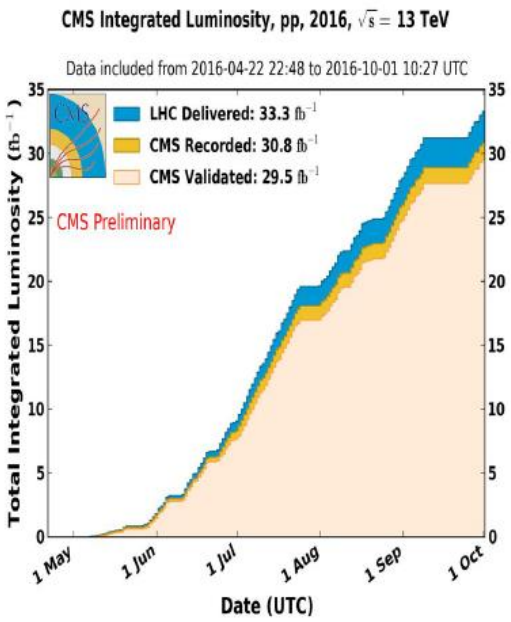
→ **New Physics**

→ **Dark Matter ? SUSY ? Extra-Dimensions ?**

→ **Precision measurements of the Higgs, top, …**

CMS Performance in 2016





- **LHC has exceeded DESIGN Luminosity**
- **LHC has much higher availability than expected**
- **CMS recording efficiency is holding steady at 92.5%**

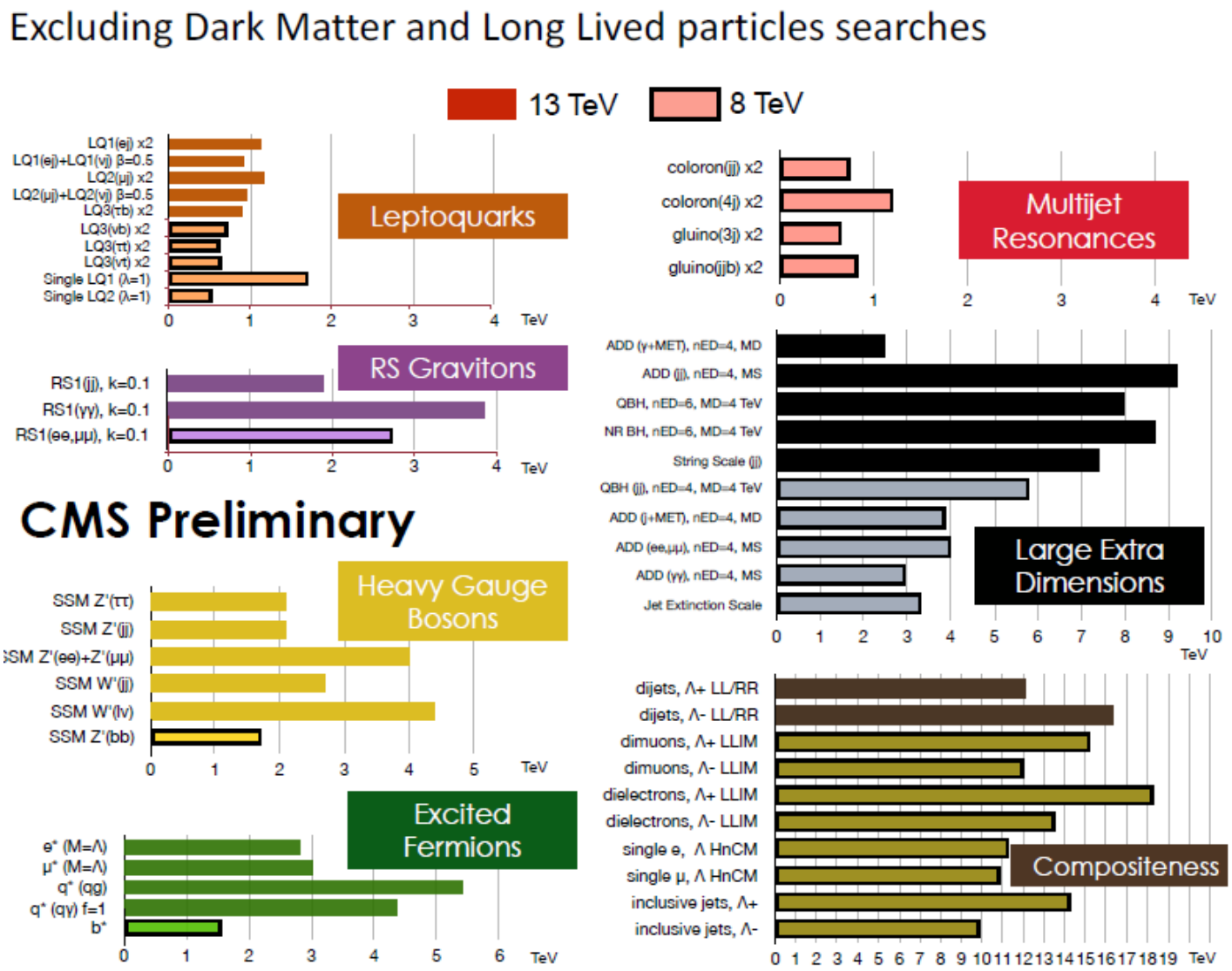
Data validated for all analysis is ~95% of recorded

Goal for 2016 was 25 fb^{-1} now almost 40 fb^{-1} on tape
Much more data to analyze! ☺

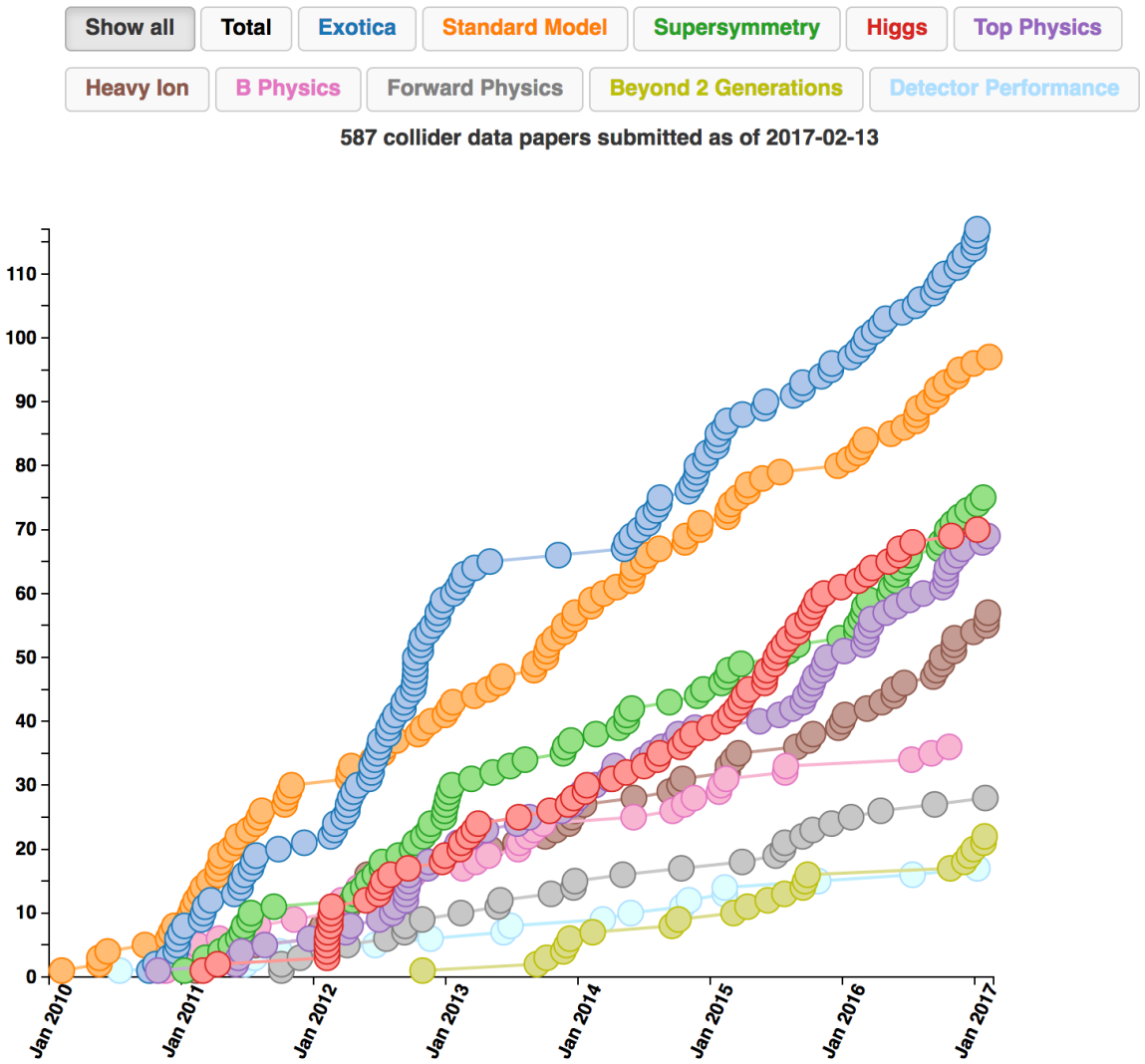
Searches for New Physics - Run 2

Keep watching out !

Took only less than 10% of the data expected for Run 2 up to 2018 !



Many Scientific Publications



- **587 papers submitted**
- **Run2: 209 public results, 68 papers submitted**
- **Publication rate steady at ~2.5/week**
- **All information:**

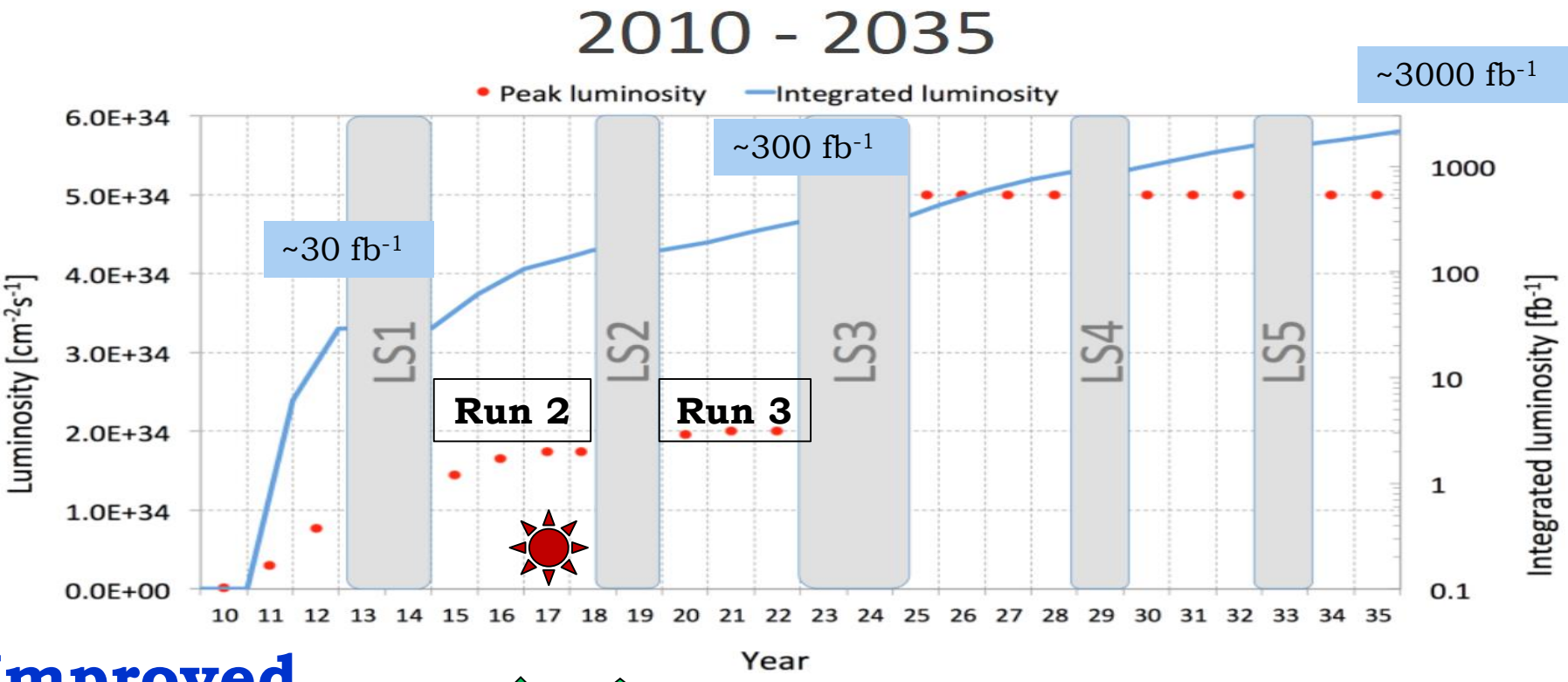
http://cms-results.web.cern.ch/cmsresults/public-results/publications/

CMS @ LHC: Status and plans

And Now ?

What next ?

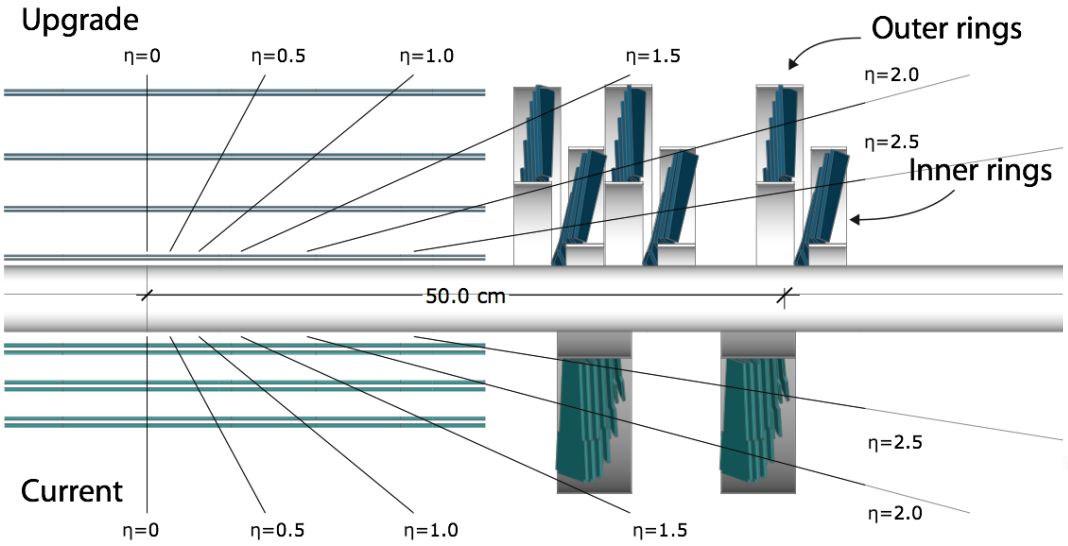
Future @ LHC - Phase I Upgrade

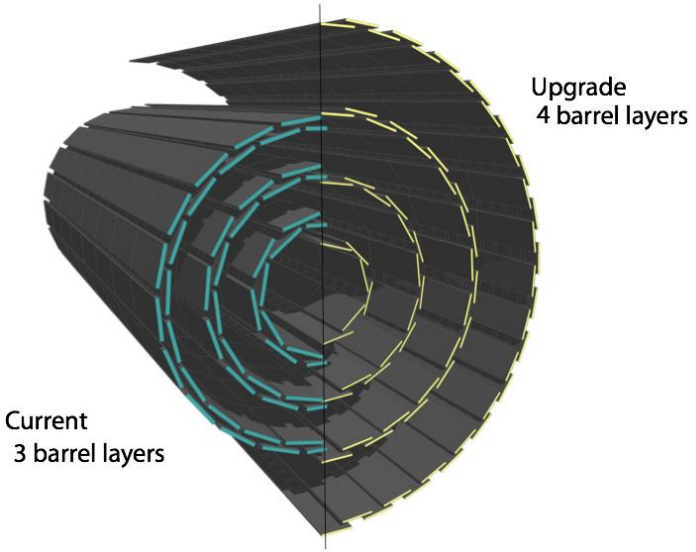


Improved detectors

Phase I Construction

Phase I – Pixel Upgrade



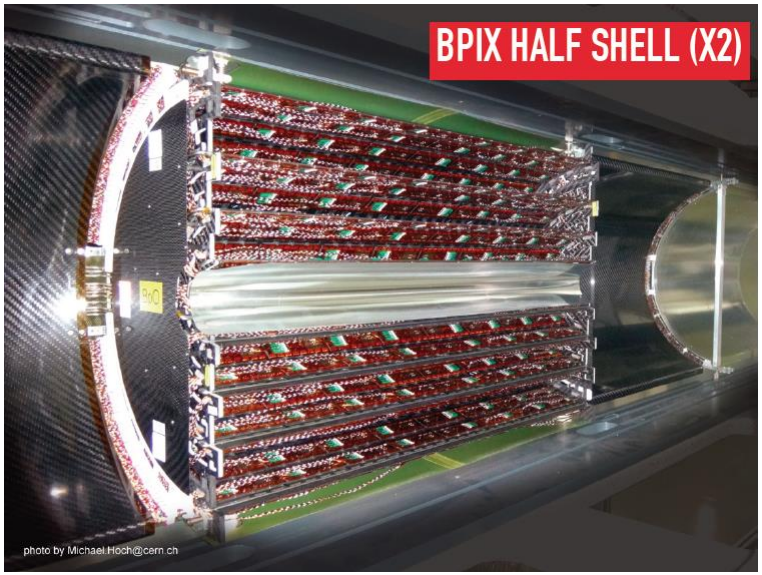


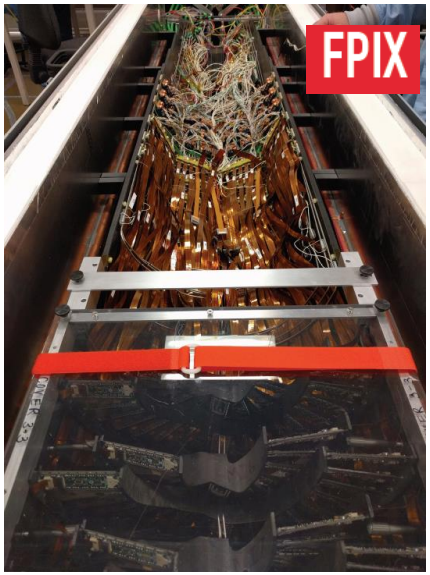
- **4 layers/3 disks** (1 more space-point extended range from lower to larger radius)
  - 3 cm inner radius
- **New readout chip** (recovers inefficiency at high rate and pileup)
- **Less material** (CO_2 cooling, new cabling and powering scheme (DC-DC))

  - Tolerate rates up to PU 100
  - Survive Integrated Luminosity of 500 fb^{-1} (5x 10^{15} neq/cm^2)
    - layer 1 exchange after 250 fb^{-1}
  - Improved track resolution and efficiency, and reduce fake rate

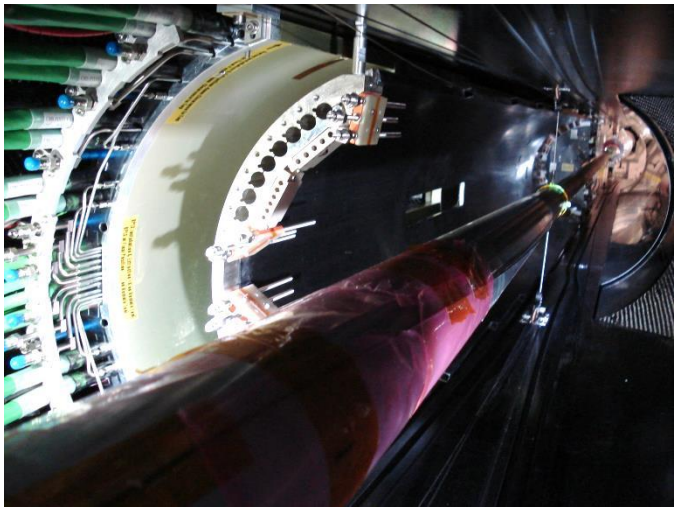
- **Installation in extended Year End Technical Stop 2016-17 - NOW !**

Installation of the new Pixel

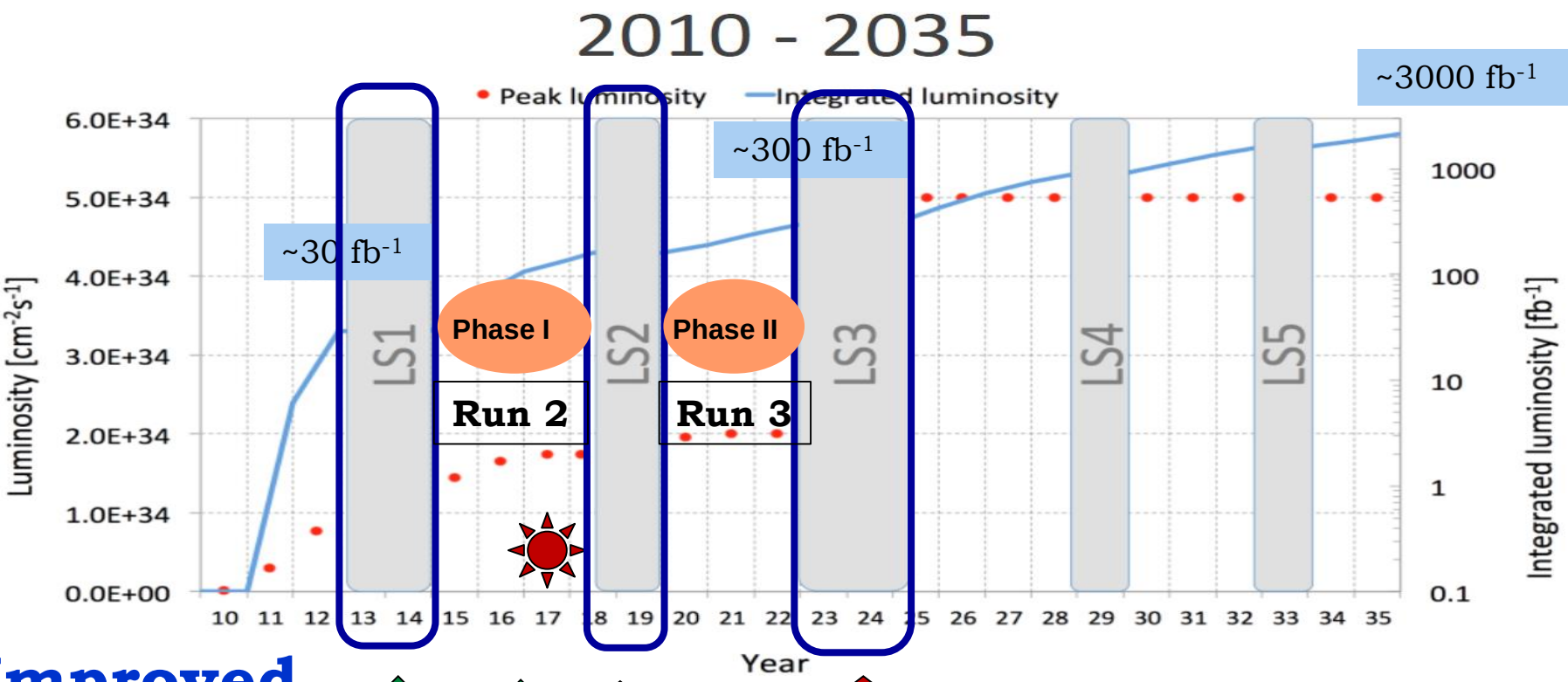




Barrel pixel far side + Fpix mockup



Future @ LHC



Improved detectors

Ready ☺ **Phase I**

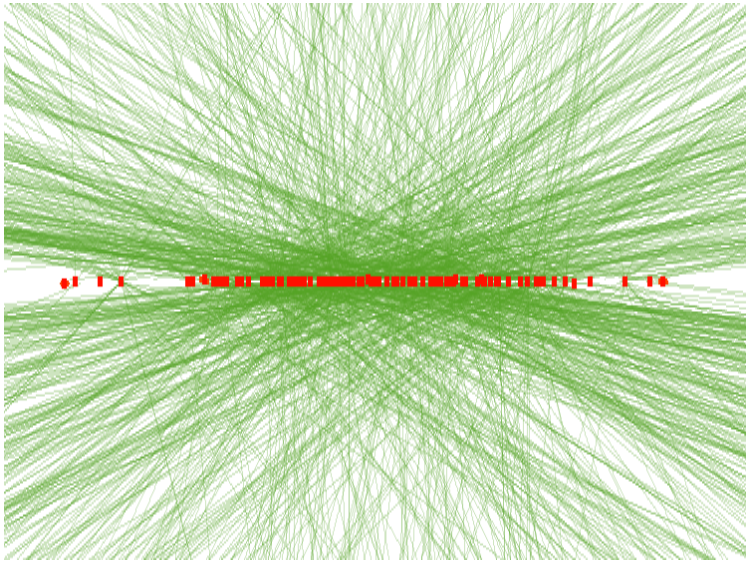
Construction **Phase II**

Challenges @ LHC

- **Highest Energies**
- **Most Intense Beams**

} **extreme particle flow**

  - **Pile up 20 → 50 → 200 → complex analyses**
  - **Extreme radiation hardness of detectors**
  - **Extreme high readout rate (DAQ, Computing)**

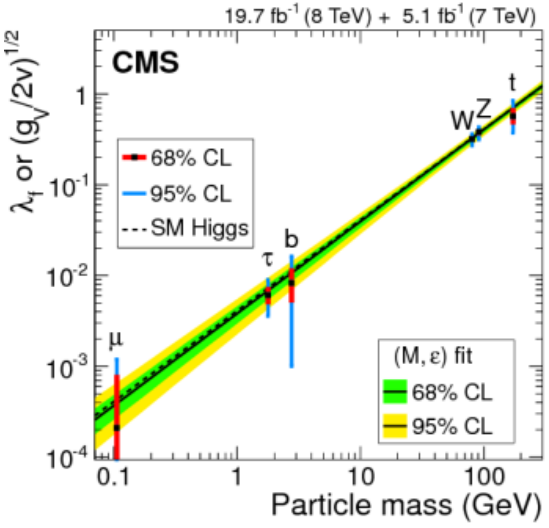


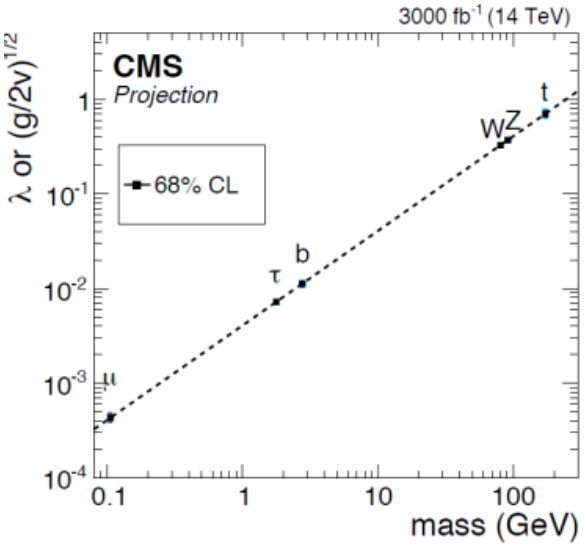
Event display showing reconstructed tracks and vertices of a simulated top-pair event with additional 140 interactions overlaid for the Phase-II detector

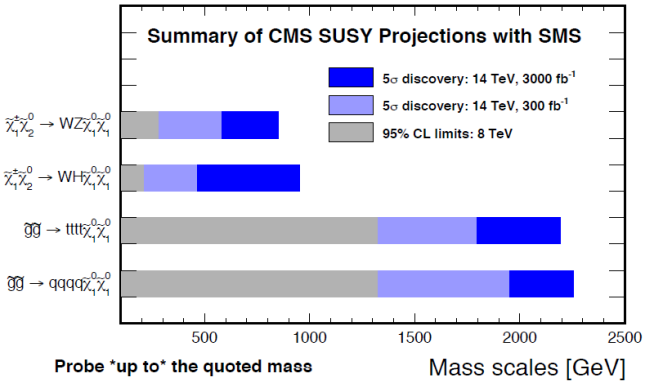
- **Need new technologies and clever ideas: detectors, computing, analyses**

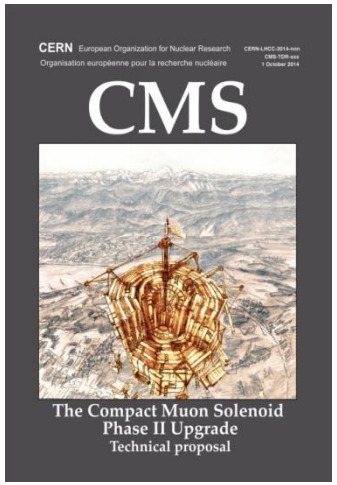
High Luminosity LHC

Physics Topics: Higgs Physics , Searches









Technical Proposal for the CMS Phase II Upgrade:

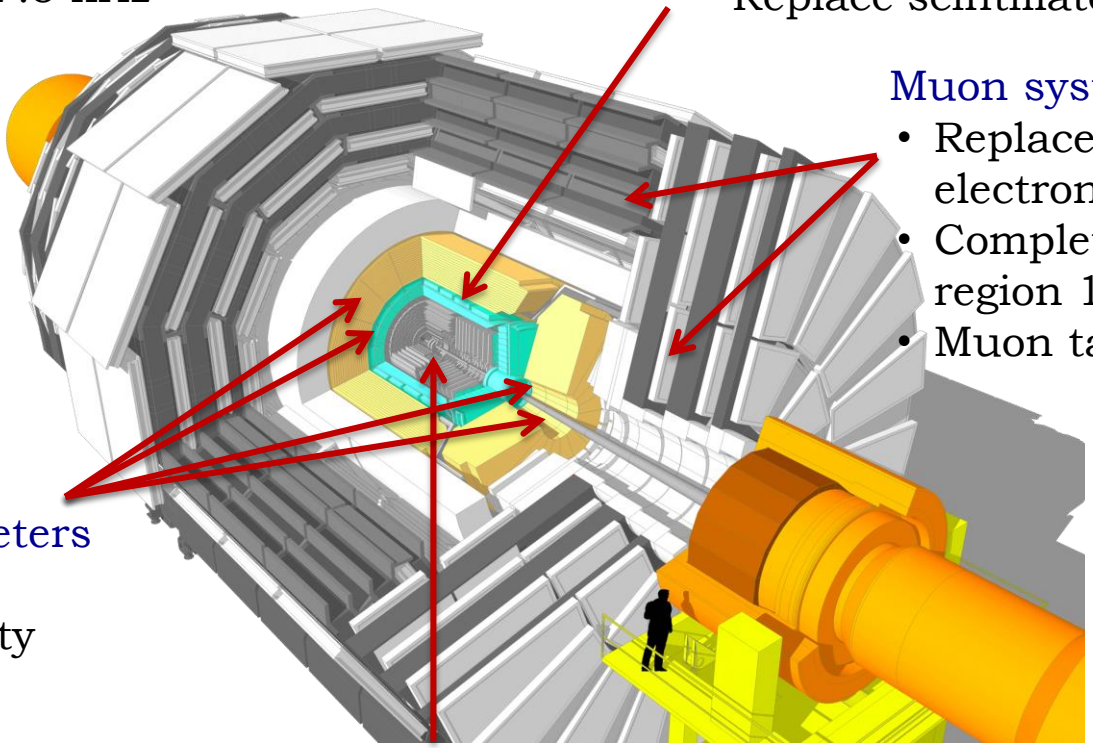
- **Physics motivation**
- **Detector Upgrades & Performance**
- **Core Costs**

CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886

CMS Phase II Upgrades

Trigger/HLT/DAQ
- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output ≃7.5 kHz

Barrel EM & hadronic calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8∘C)
- Replace scintillator layers

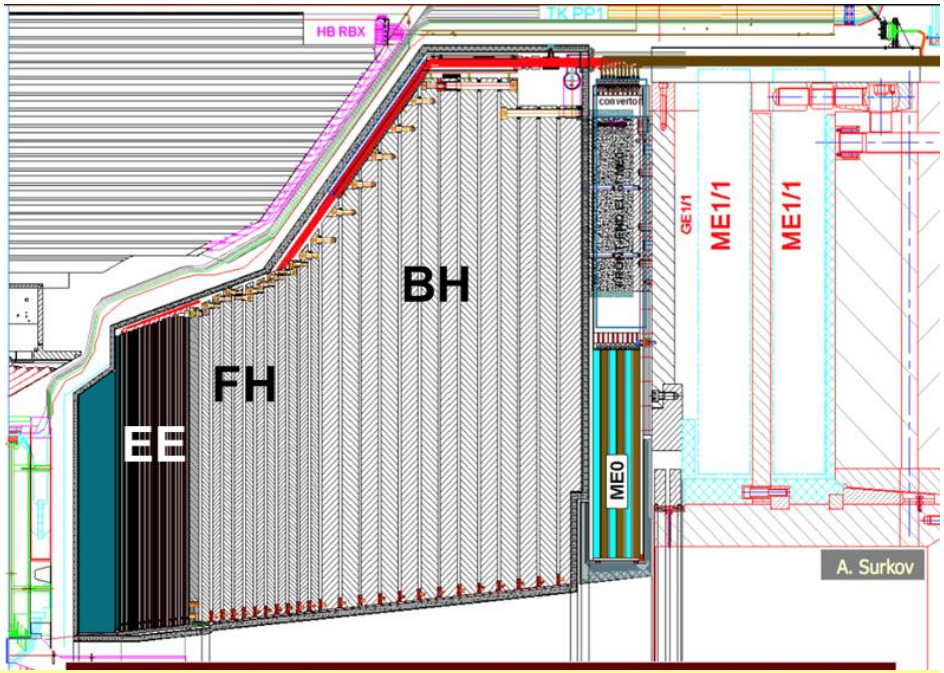


Muon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

Endcap Calorimeters
- rad. tolerant
- high granularity
- 3D capability

Replace Tracker
- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to $\eta = 3.8$

EndCap Calorimeter Design



Novel Approach to Calorimetry with particle flow

Key parameters:

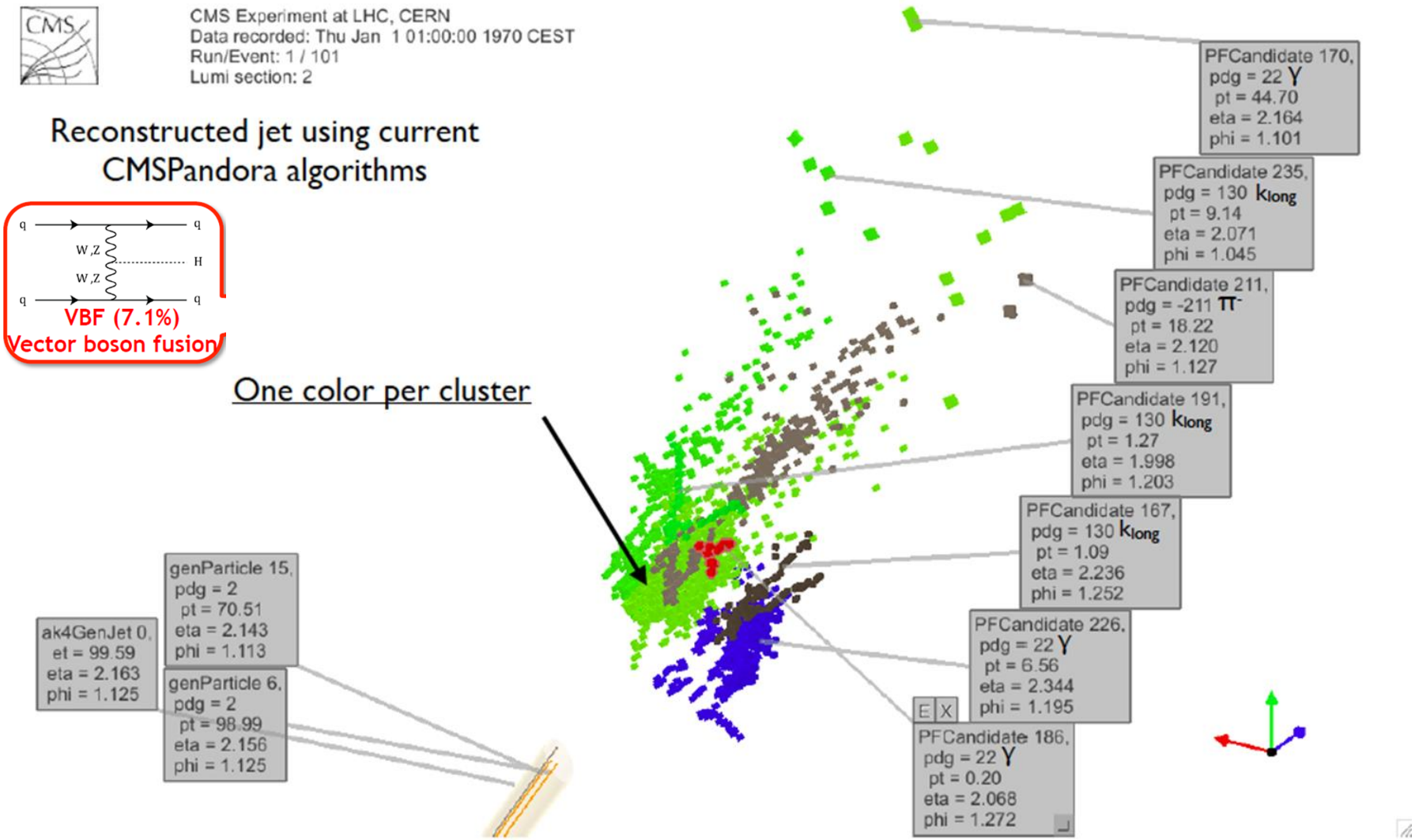
- *593 m^2 of silicon*
- *6M ch, 0.5 or 1 cm^2 cell-size*
- *21,660 modules (8" or 2x6" sensors)*
- *92,000 front-end ASICS.*
- *Power at end of life 115 kW.*

System divided into three separate parts:

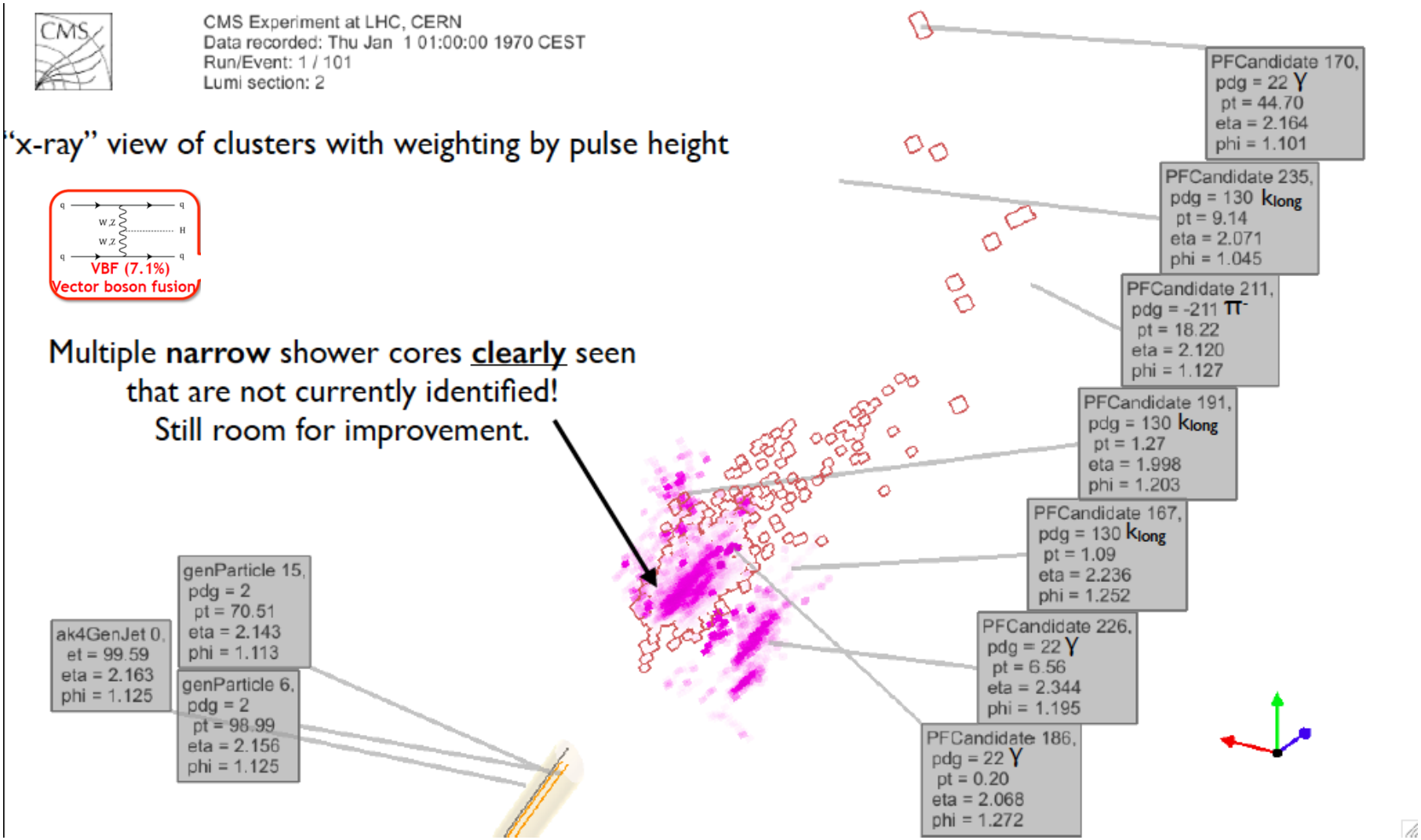
EE – Silicon with tungsten/Pb absorber – 28 sampling layers – 25 X_o + ~1.3 λ
FH – Silicon with SS absorber – 12 sampling layers – 3.5 λ
BH – Scintillator with SS absorber – 12 layers – 5.5 λ

EE and FH are maintained at – 30°C. BH .

EC Reconstruction: VBF Jets

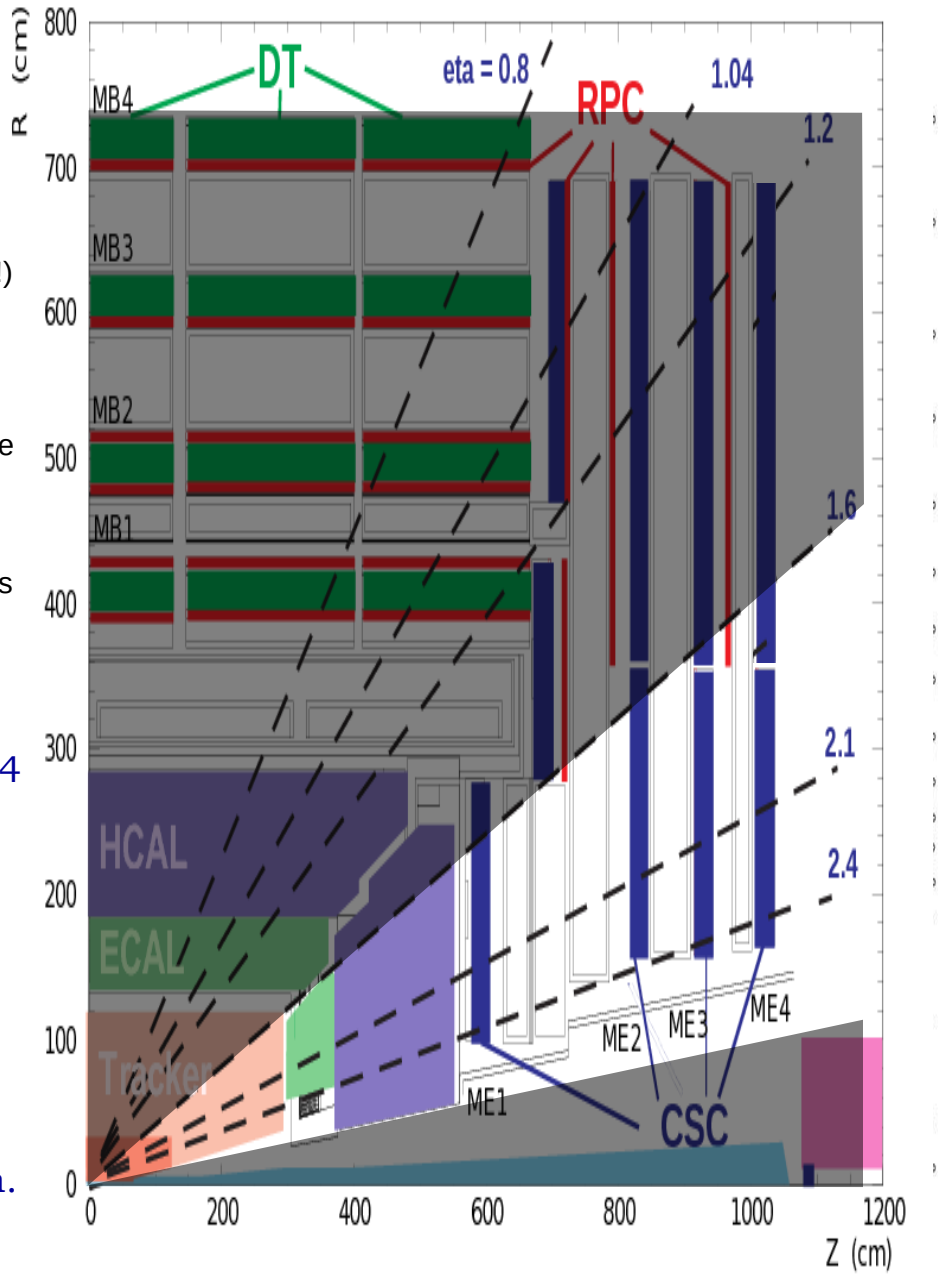


EC Reconstruction: VBF Jets

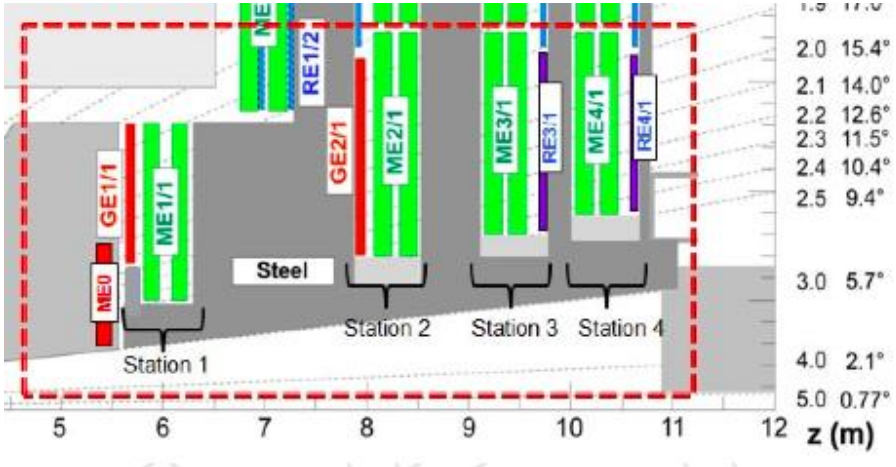


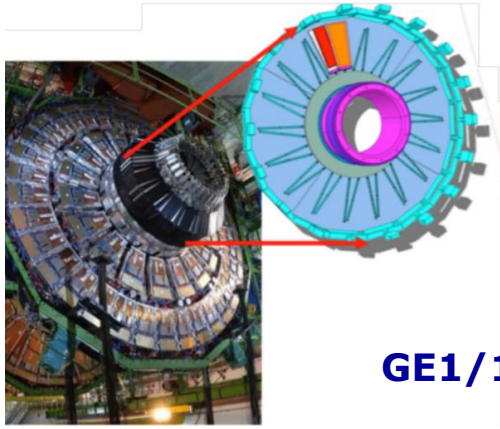
Muon System

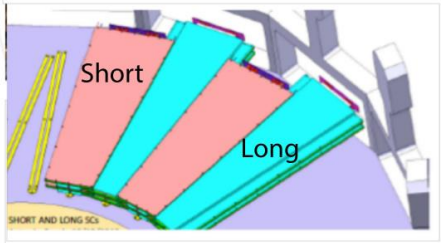
- **Existing System**
  - Chambers expected to cope with the higher particle rates
    - New gas mixtures under discussion (CF4 , greenhouse rules!)
  - Drift tube (DT) electronics
    - not radiation-hard, cannot sustain trigger acceptance rate of 1MHz
    - All mini-crates, housing readout and trigger electronics, will be replaced
  - CSC electronics
    - Cannot cope with trigger latency of 12.5μs & higher data rates
- **Additional Muon Chambers in the End-Cap: most difficult region**
  - presently no redundancy in region $1.6<|\eta|<2.4$
    - but: high rates, low magnetic field, high fake rates
  - need to add fast, high-resolution detectors to improve trigger momentum selectivity and reconstruction
    - Gas-Electron-Multiplier (GEM): GE1/1 (LS2 installation) and GE2/1
    - improved RPCs in RE3/1 and RE4/1
  - Very forward extension $2.0<|\eta|<3.0$ with a muon tagger (ME0) to match tracker extension.



New Muon Chambers



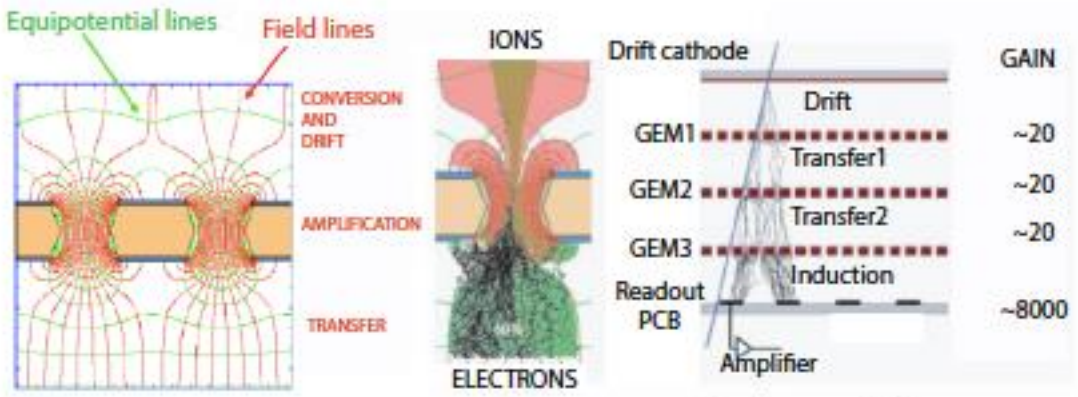


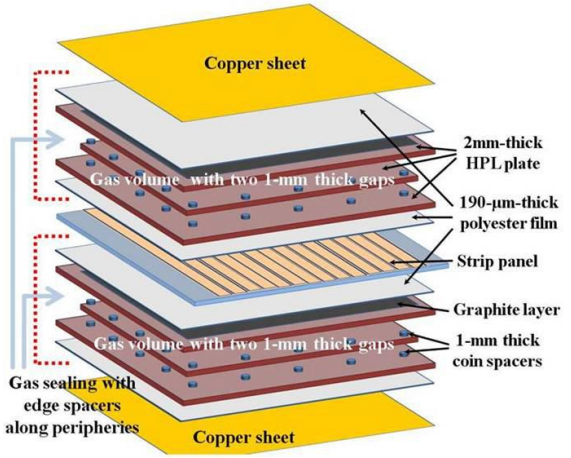


GE1/1

iRPCs to increase rate capability to few kHz
- low resistivity bakelite or glass – multi-gap new FE readout

A pairs of triple GEM in GEM1/1 and GEM2/1
6 triple GEMs in ME0 (few 100 µm resolution)





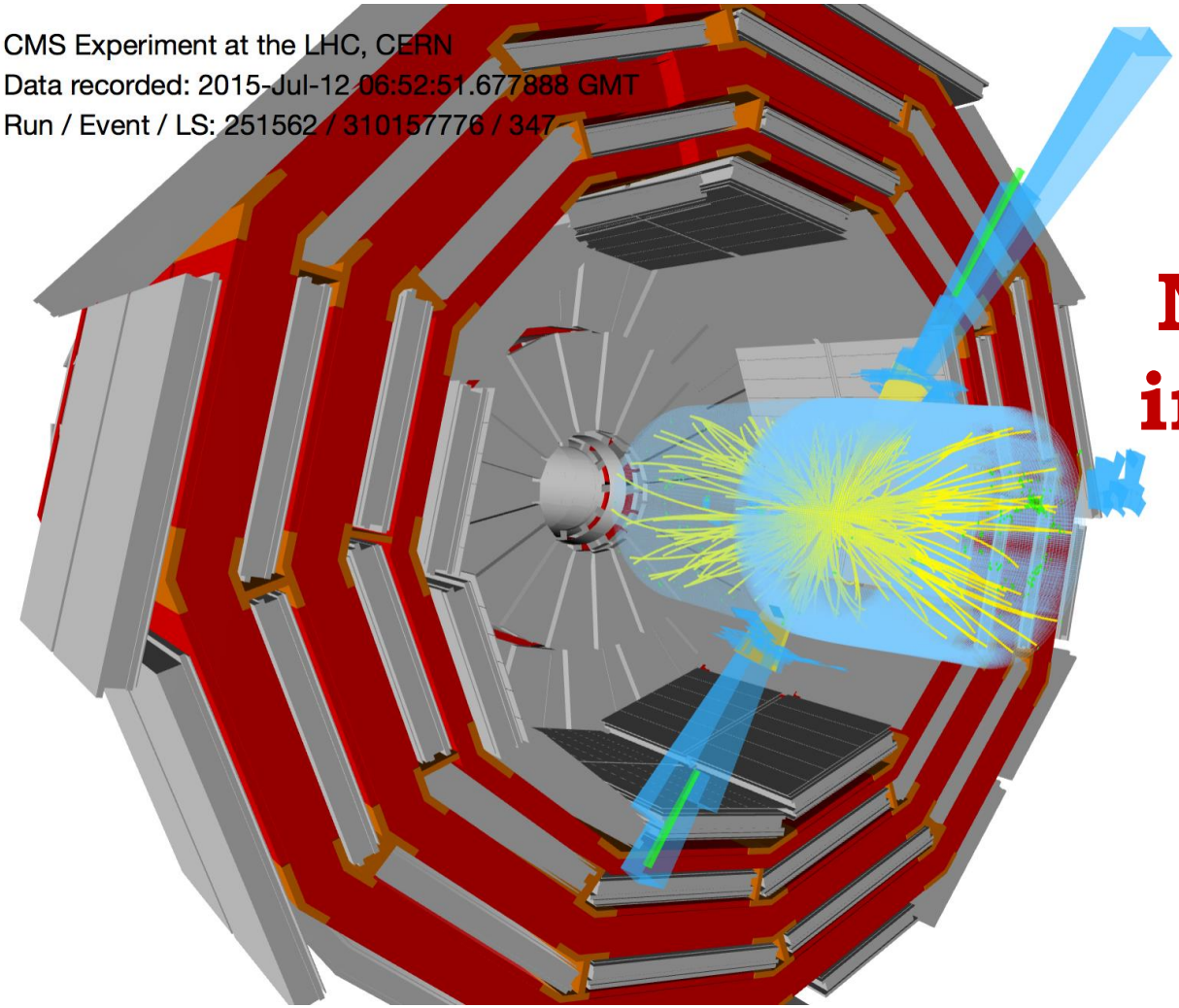
Summary

- Overwhelming harvest from Run 1 Data
- Detector improvements in LS 1 paying off
- LHC with its Experiments is in discovery mode
  - Extremely good LHC performance and data colllection
  - Improved detectors, trigger and reconstruction algorithms leading to high precision results
- 2015 & 2016 data in Run 2 delivered novel insights
- 2017 data taking in preparation
- Road to the future paved
  - Phase I upgrades proceeding well
  - Phase II technical proposal approved & funding looks ok

Summary

- **Participating in CMS means:**
  - **Exciting physics**
  - **Employing and developing novel technologies**
  - **High-Level training and participation of engineers and computing experts**
  - **Enabling technology transfer**
  - **Being attractive for students and offer international education**

Our Future has just started



Let‘s see, what Nature has in stock for us !

Any Questions ?

BACKUP