Compact Muon Solenoid (CMS) Status

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International Symposium on Higgs Boson and Beyond Standard Model Physics (ISHBSM)

Shandong University, Weihai

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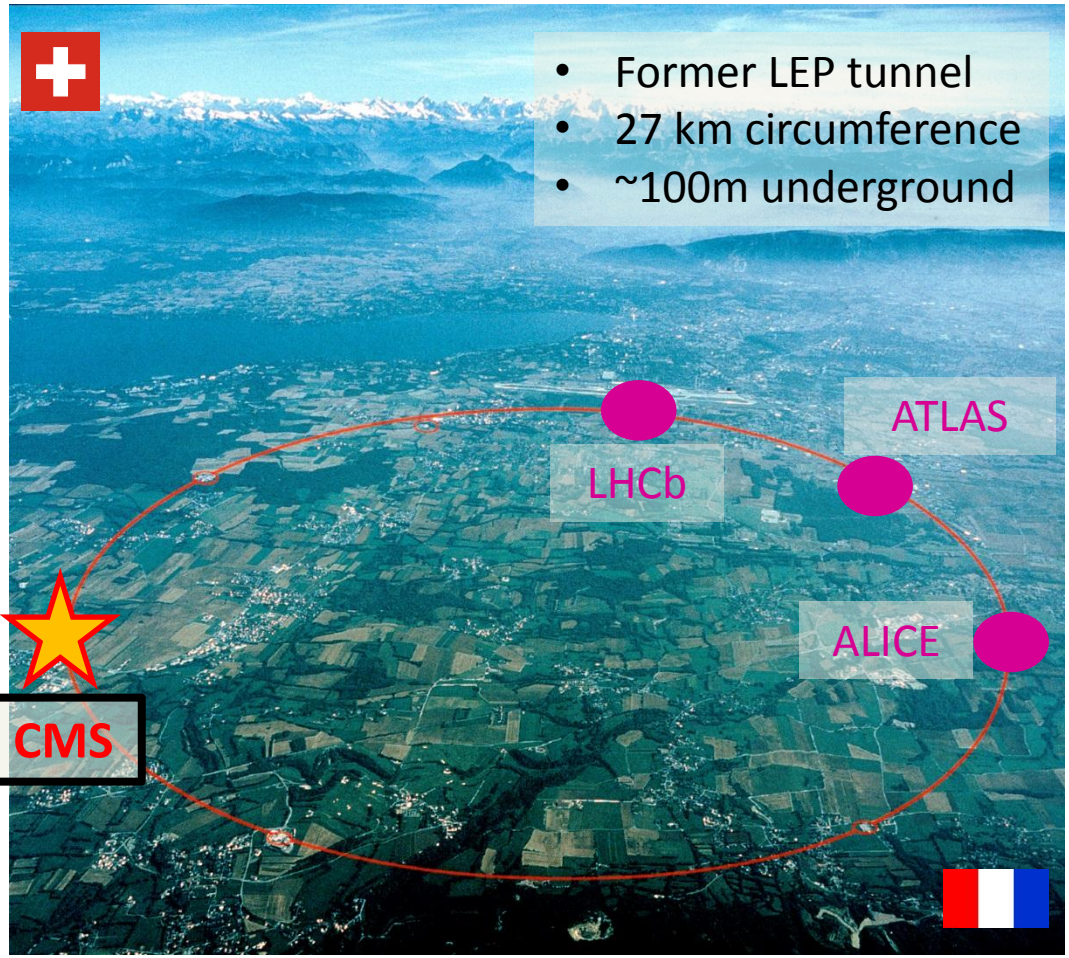
http://indico.ihep.ac.cn/e/ishbsm

Large Hadron Collider (LHC) @ CERN

Multi-purpose hadron collider: p+p, Pb+Pb, p+Pb



Searches for new physics at four Interaction Points (IP)

CMS and ATLAS…

- General purpose detectors to study Higgs & search for physics Beyond the Standard Model

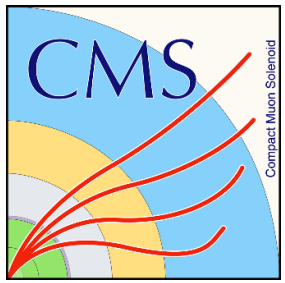
LHCb…

- Detailed studies of b-quark

ALICE…

- The heavy ion experiment

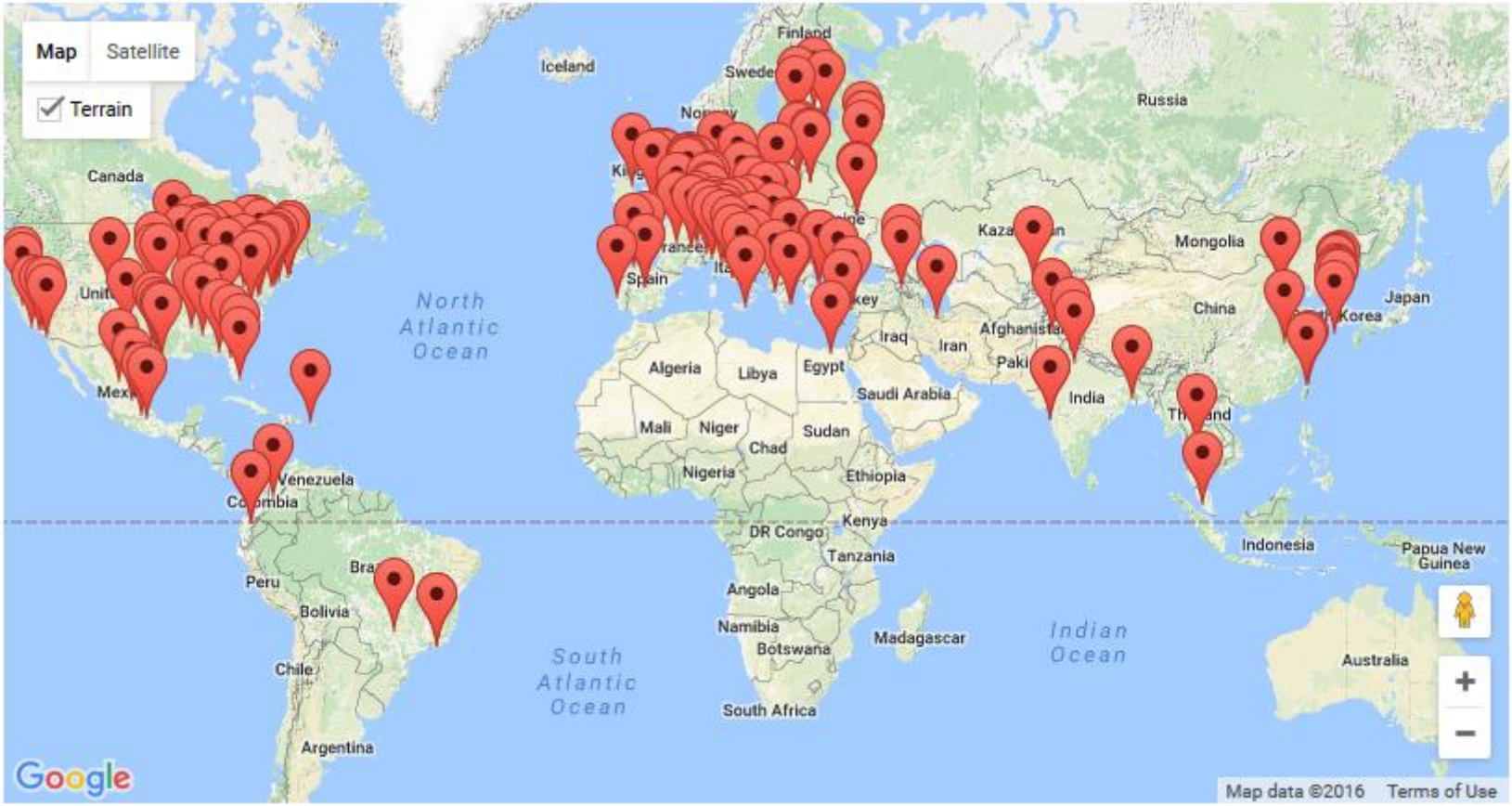
This talk:



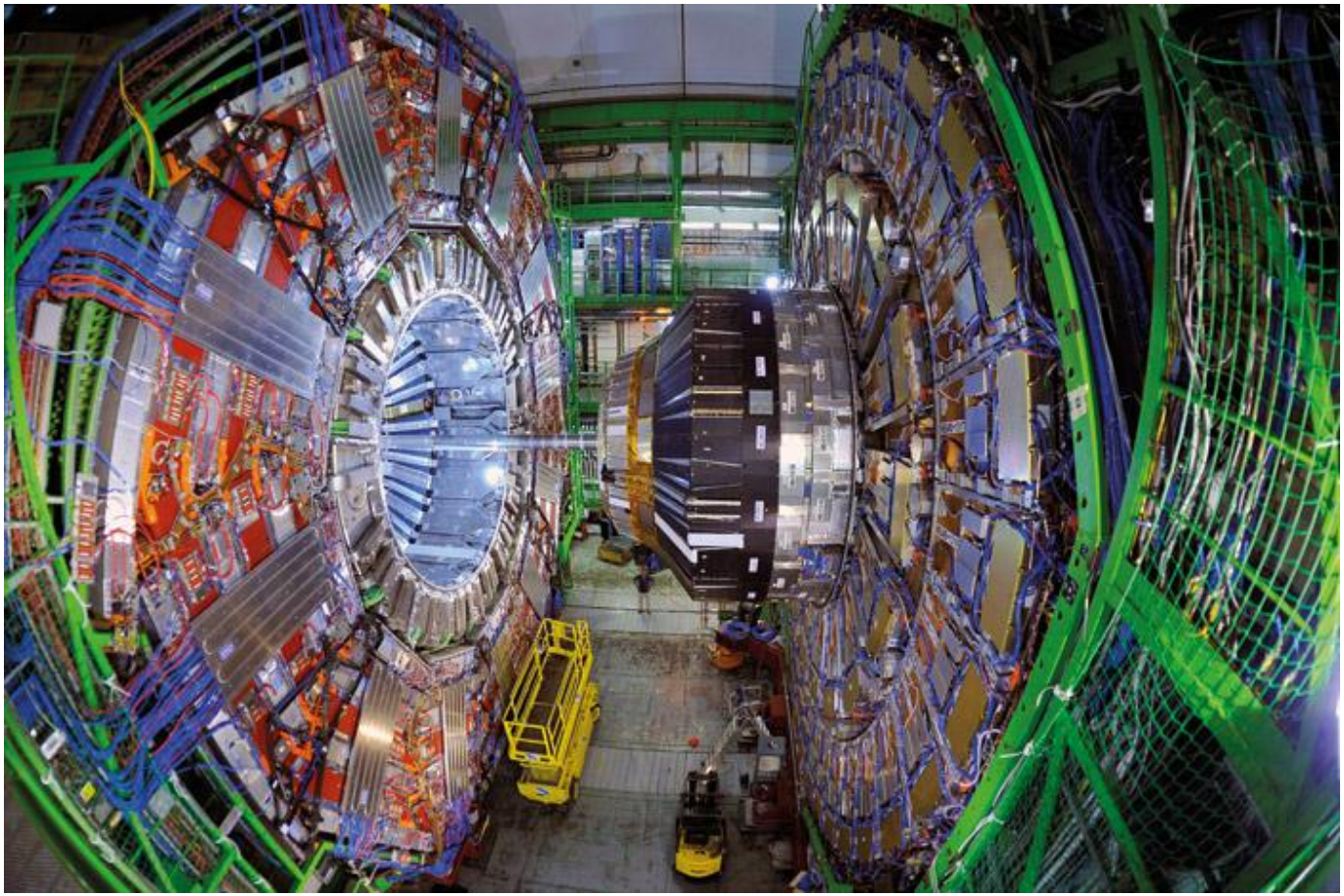
Outline

- Reminder of the CMS detector
  - Design and functionality
- Essential aspects of Run-2
  - Operational efficiency
  - Detector performance
- CMS detector upgrades
  - Motivation: pileup
  - Status of Phase-1

CMS is designed, built, operated, calibrated, and physics results extracted by … an international collaboration



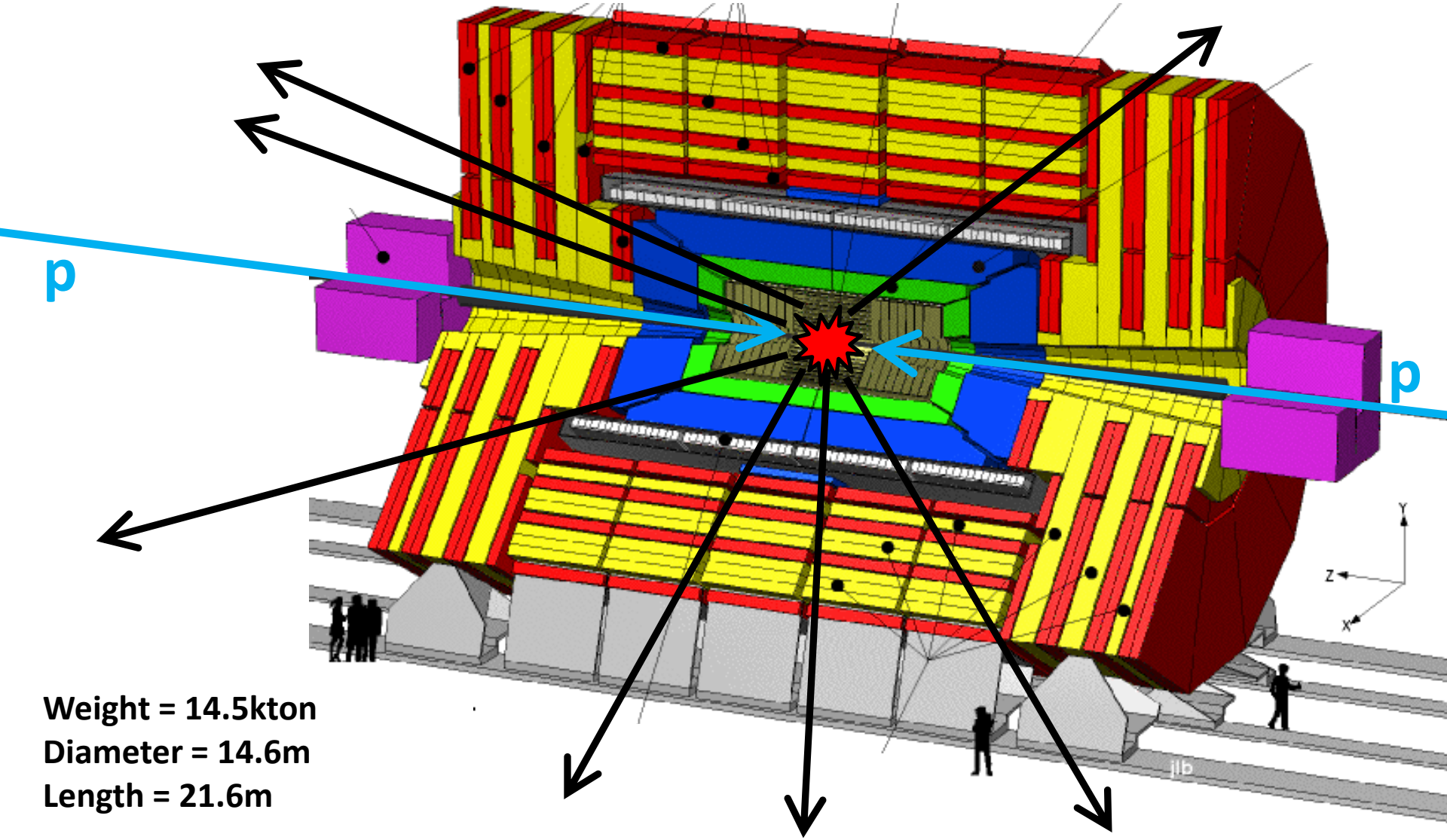
CMS is a beautiful detector…



… with a functional design

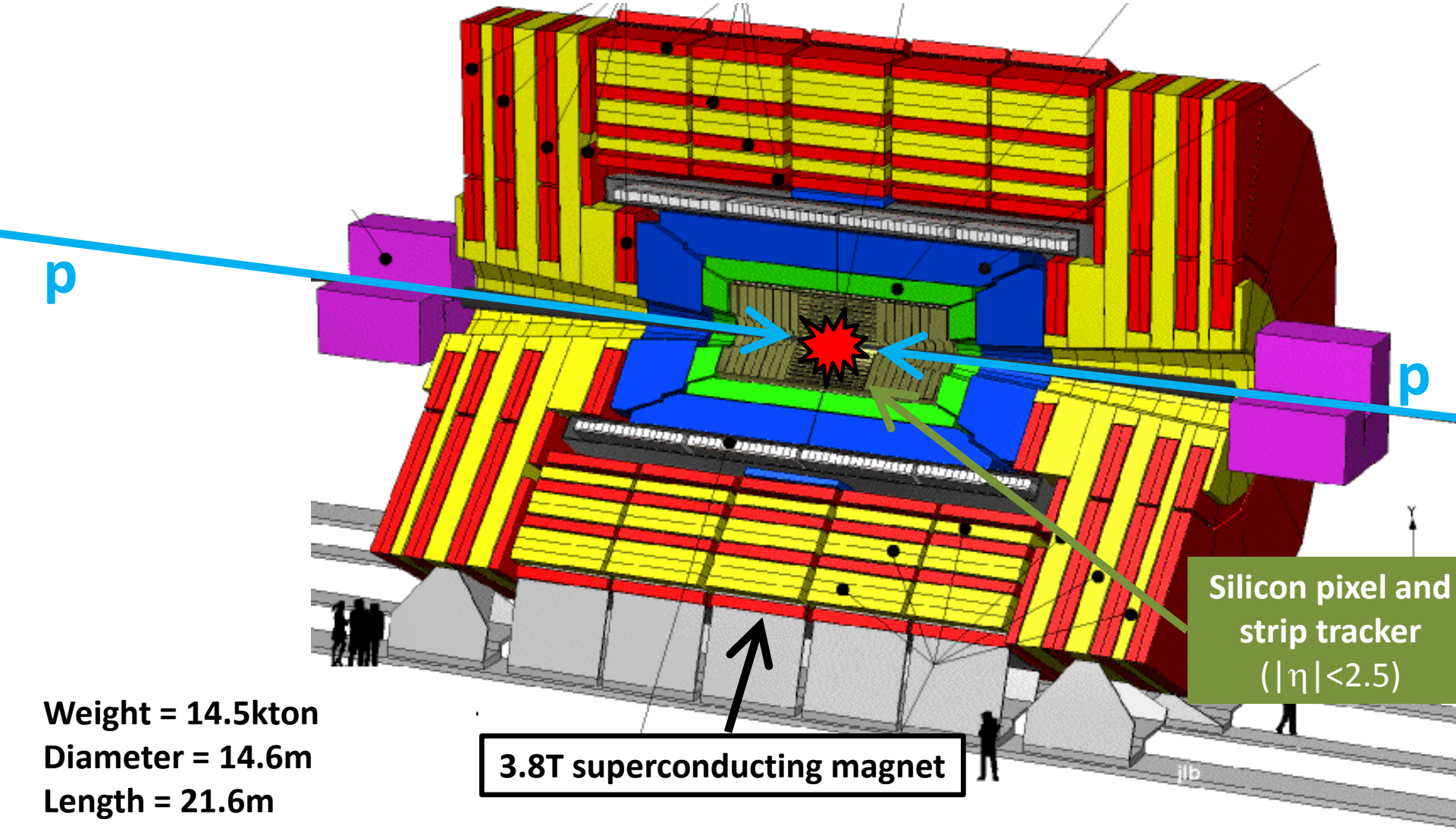
Compact Muon Solenoid detector

Protons collide in the center of the CMS detector…
On their way out, particles encounter the following…



Weight = 14.5kton
Diameter = 14.6m
Length = 21.6m

Compact Muon Solenoid detector



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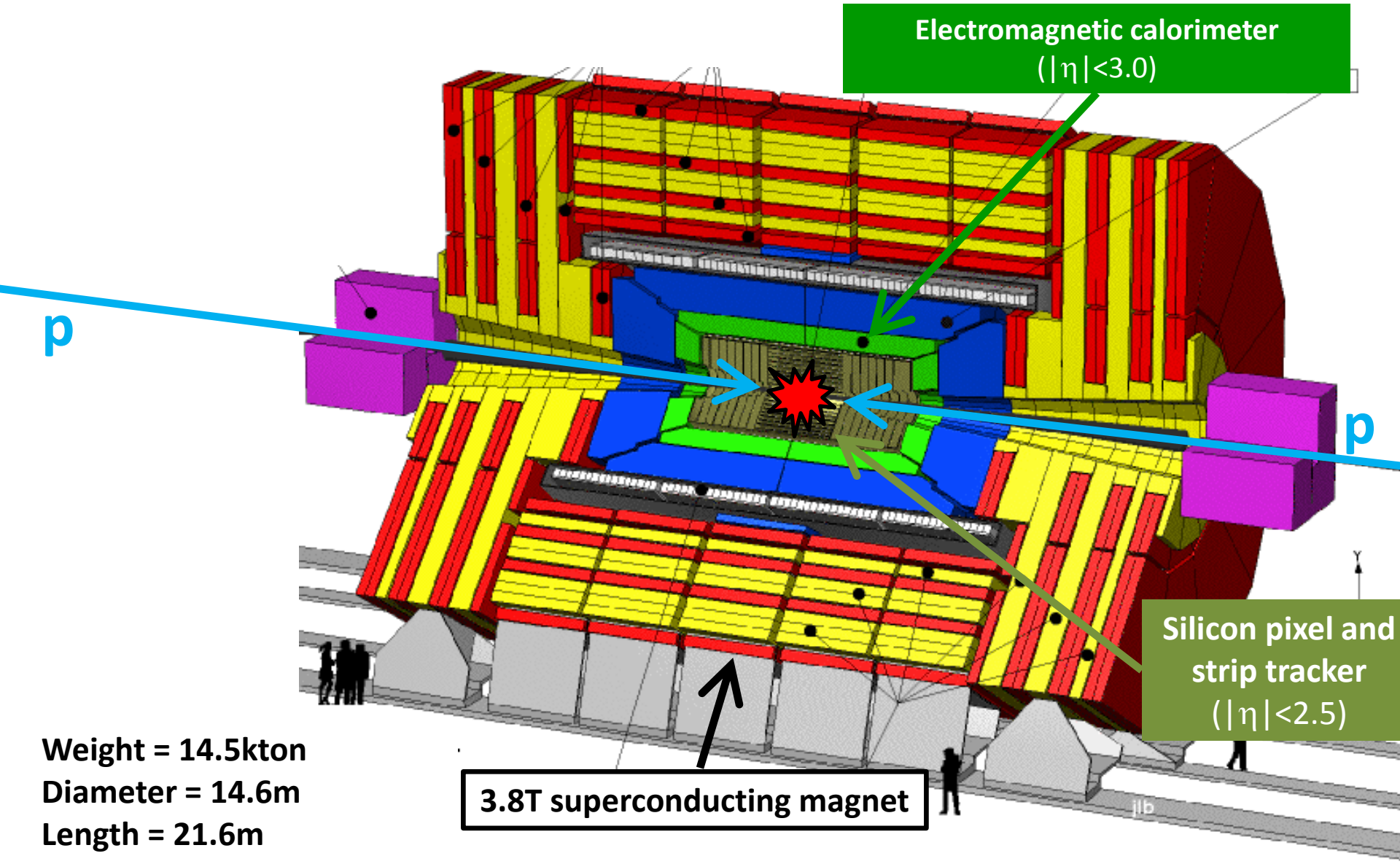
Compact Muon Solenoid detector



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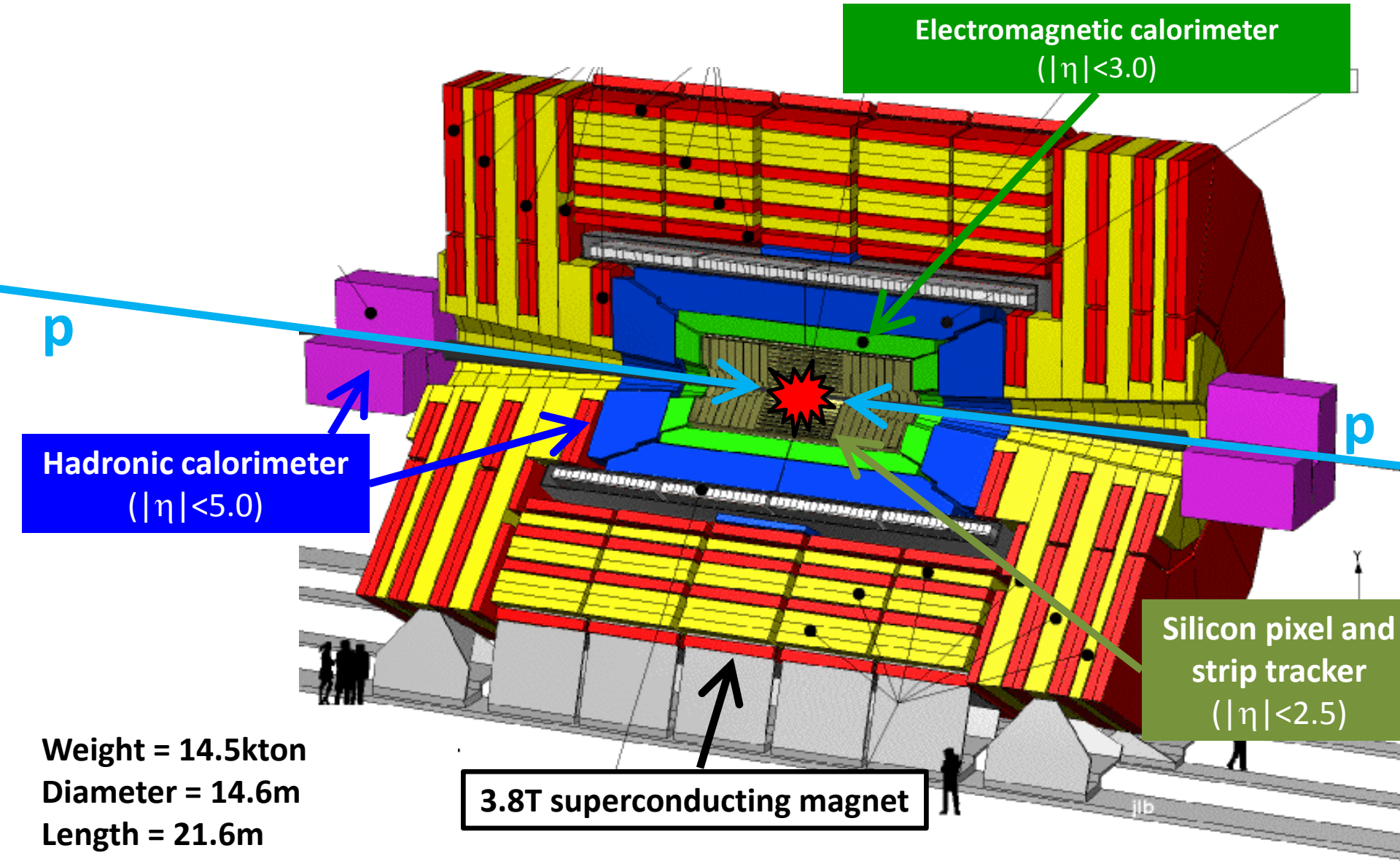
Compact Muon Solenoid detector



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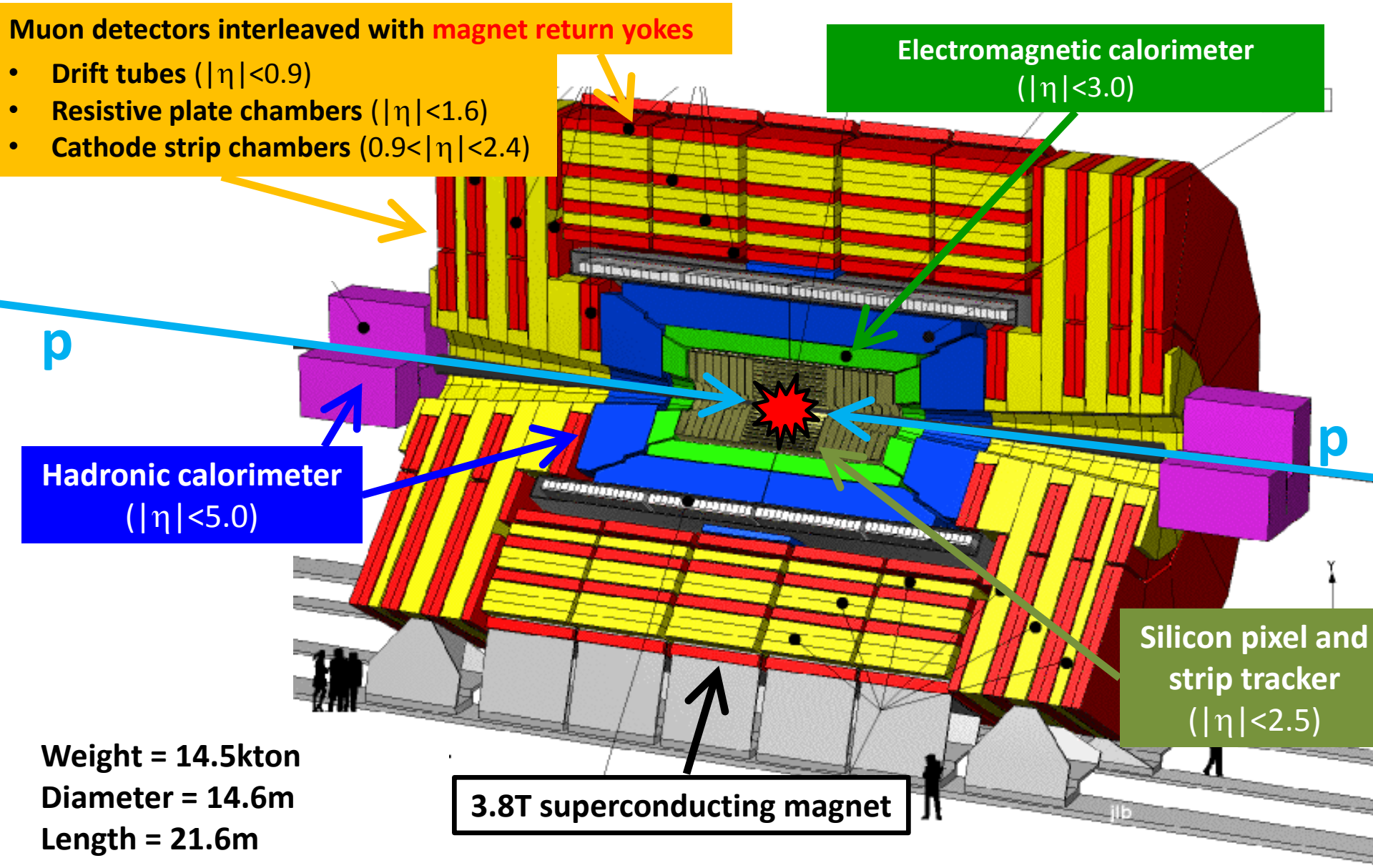
Compact Muon Solenoid detector

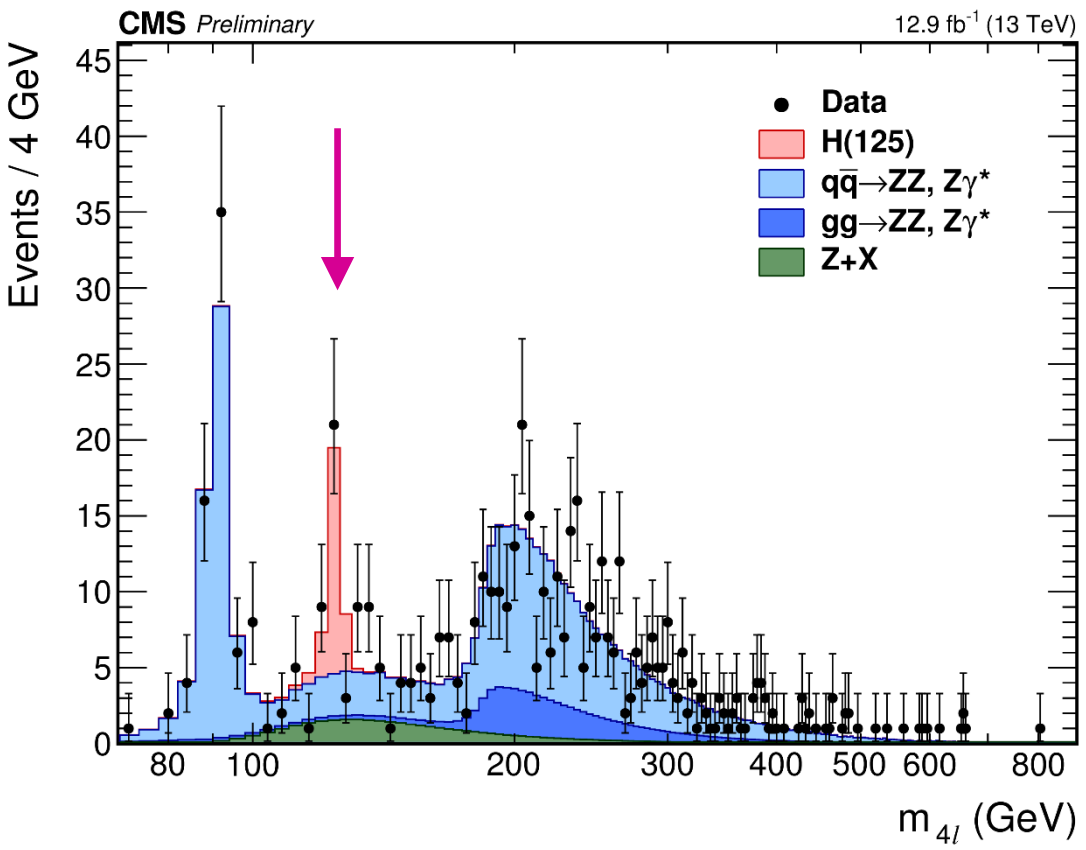


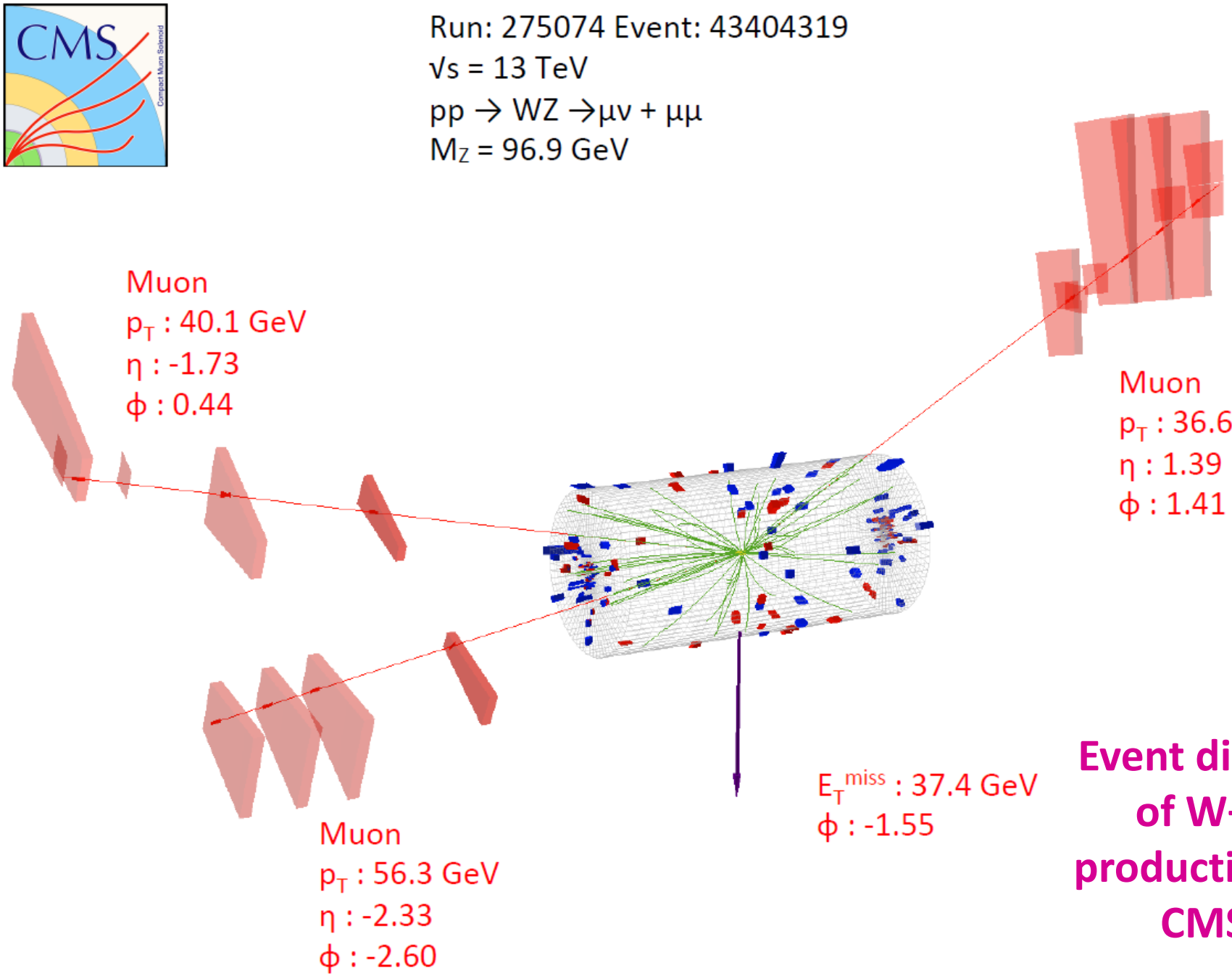
CMS goal: discover new physics

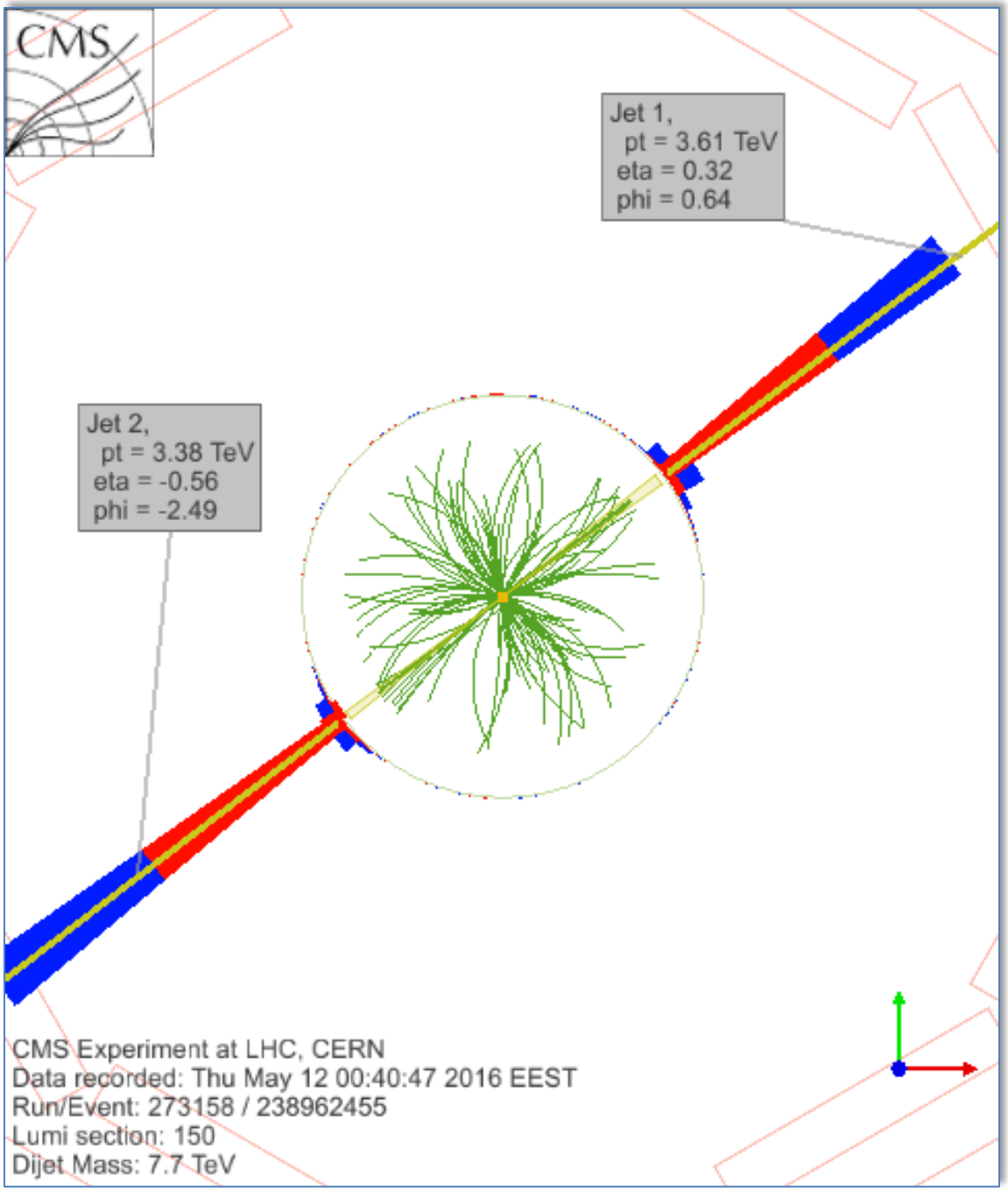
- Some of the observables to be detected include…
  - H → Z + Z → 4 leptons
  - H → γ + γ
  - H → τ + τ → l + jet
  - Z′ → $e^+ + e^-$?
  - Missing E_T, di-jets, heavy Ions
- Over 70 new results so far in 2016…

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/ICHEP-2016.html

Higgs rediscovery at √s=13 TeV




Run: 275074 Event: 43404319
√s = 13 TeV
pp → WZ →μν + μμ
M_Z = 96.9 GeV
Muon
p_T : 40.1 GeV
η : -1.73
ϕ : 0.44
Muon
p_T : 36.6 GeV
η : 1.39
ϕ : 1.41
Muon
p_T : 56.3 GeV
η : -2.33
ϕ : -2.60
E_T^{miss} : 37.4 GeV
ϕ : -1.55
Event display of W+Z production at CMS



Event display of back-to-back jets with largest invariant mass seen at CMS (M_{jj} = 7.7 TeV)

Summary so far…

- We have seen a short reminder of…
  - What CMS was designed for
  - Rediscovery of the Higgs
  - Potential to see large invariant masses

- Next we move to a taste of…
  - LHC and CMS Operations
  - CMS detector performance

LHC increase lumi Run-1 → Run-2

$$L = \frac{N^2 k_b f g}{4\pi e_n b^*} F$$

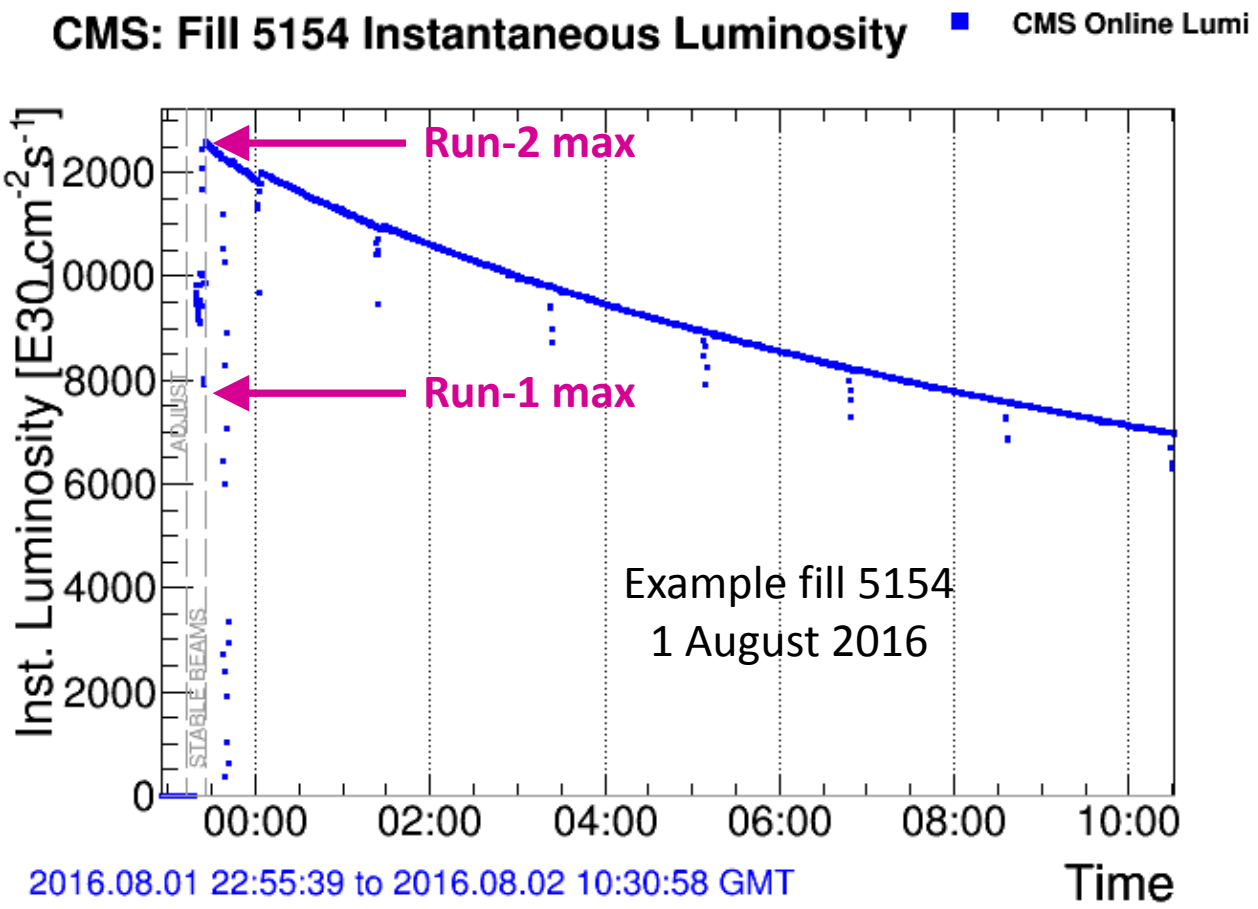
N	Number of particles per bunch
k_b	**Number of bunches**
f	Revolution frequency
ε_n	**Normalized emittance**
F	Reduction factor due to crossing angle
β*	**Beta function at Interaction Point**

Increase number of bunches by reducing spacing between bunches (50ns → 25ns)

Reduce transverse size of the beams in the injectors

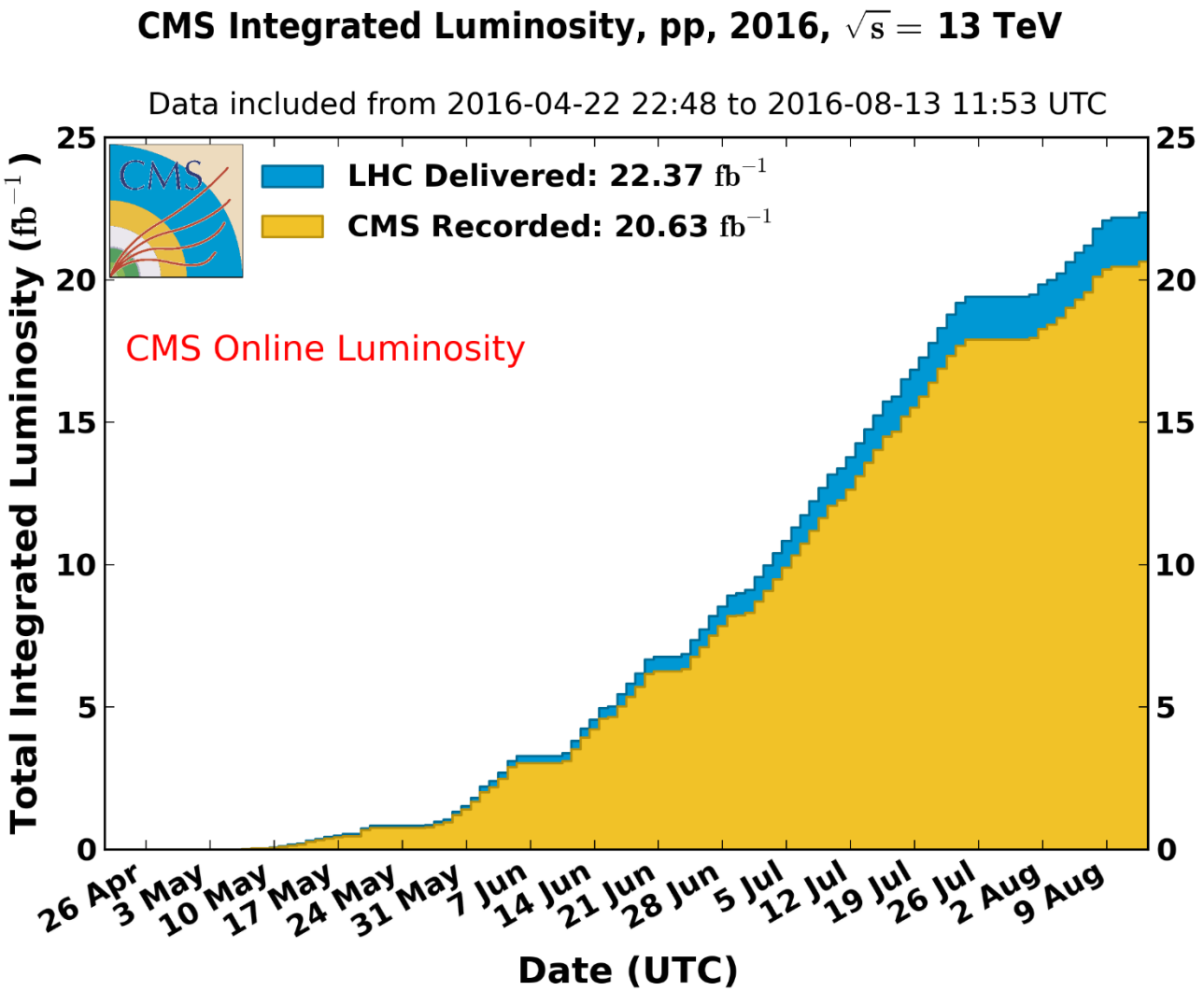
Decrease the "focal length" at CMS (60cm → 40cm)

LHC “typical” fill



Maximum peak lumi in Run-2 = **1.6x** Run-1 max (so far)

With increased lumi, LHC is delivering at record pace



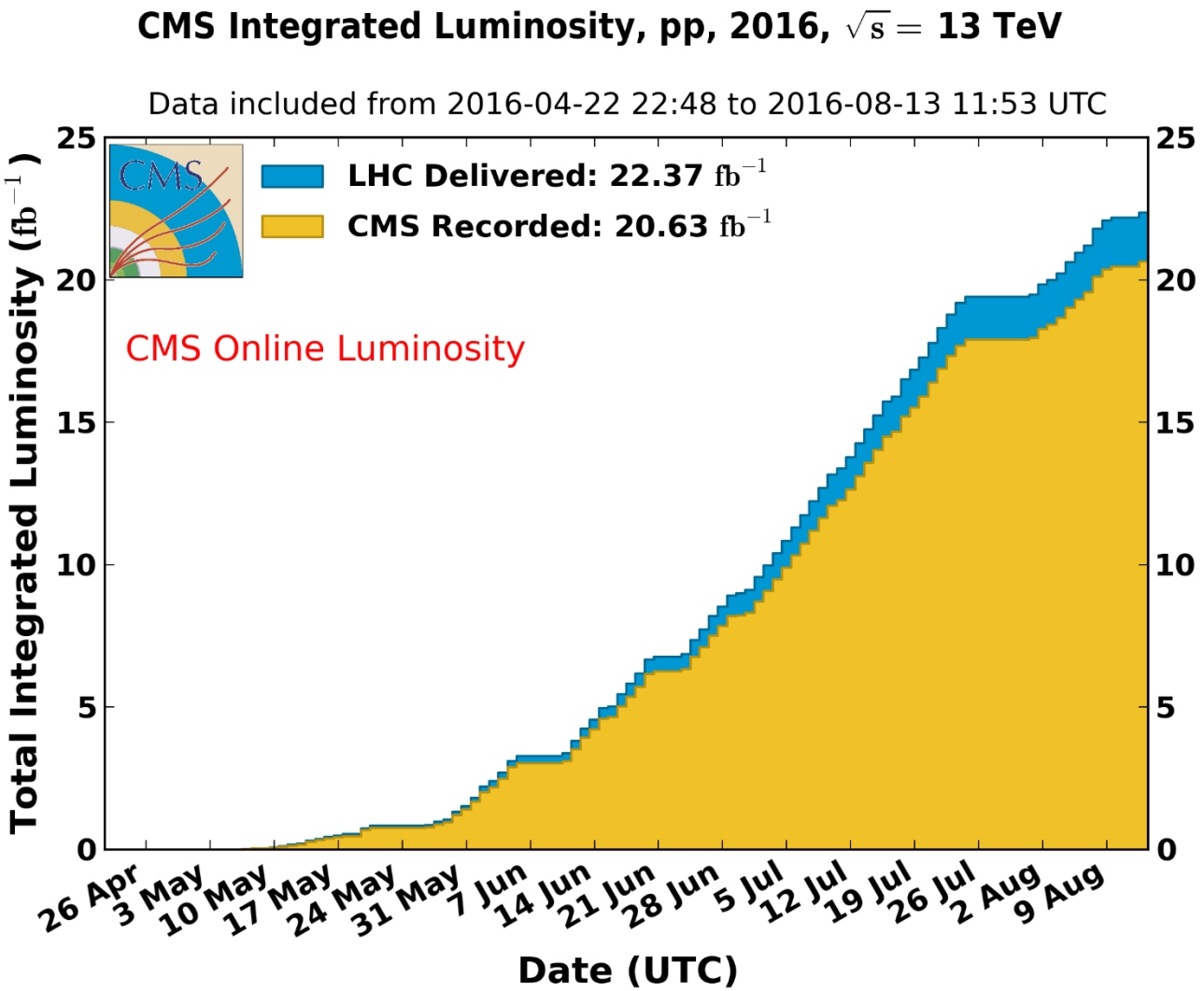
https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

So far in 2016, LHC has delivered 22 fb^{-1}

There are 8 more weeks of running left in 2016…

If LHC continues at the same pace, could deliver 30-40 fb^{-1} in 2016

With increased lumi, CMS continues to collect data efficiently



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

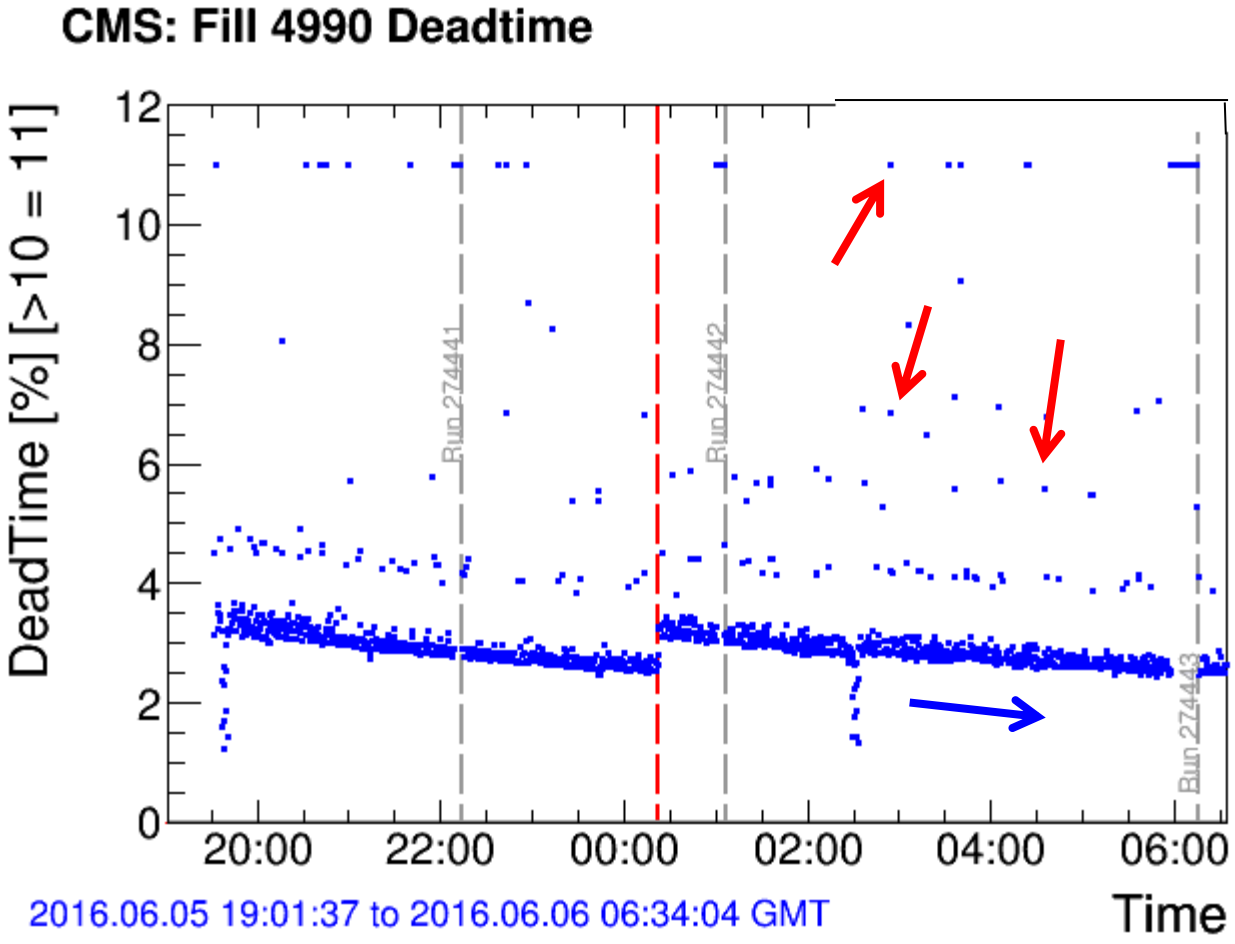
2016 CMS data collection efficiency is 92.2%

CMS has complex machinery in place to automatically keep data collection running to achieve this high efficiency

… next page →

CMS running efficiency “deadtime” dominated

CMS “dead” = running but triggers vetoed

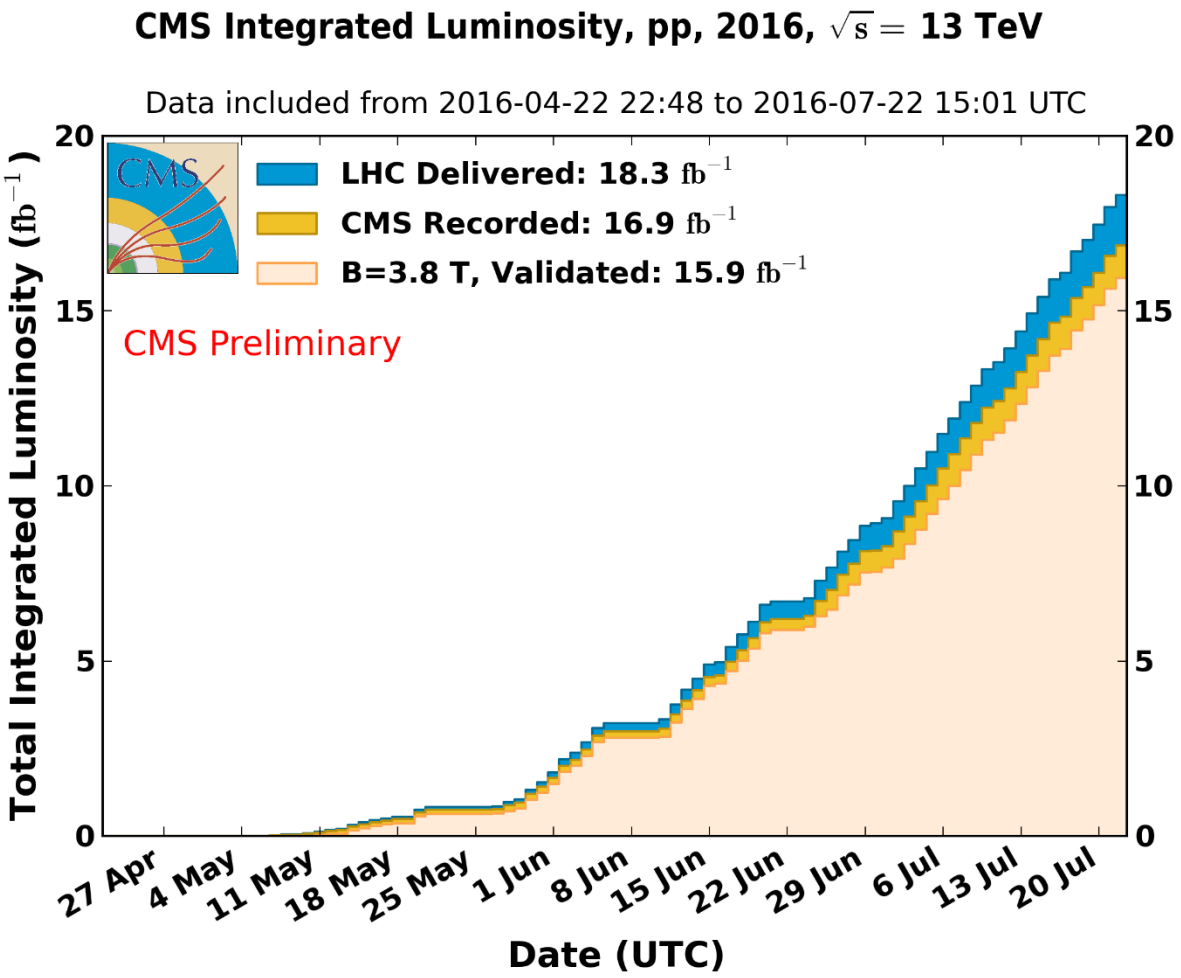


Typical “deadtime” ~3%
→ decreases with trigger rate and lumi

When soft errors occur (radiation)
→ recovery action automatically initiated

… deadtime increases temporarily, then CMS keeps on running…

CMS collects high quality data efficiently



94% of logged data certified good for every analysis

Most data which are not "Gold" are due to (isolated) infrastructure issues

For results @ ISHBSM…

- **15.0/fb delivered**
- **13.8/fb recorded (92%)**
- **12.9/fb "Golden" (93.5%)**

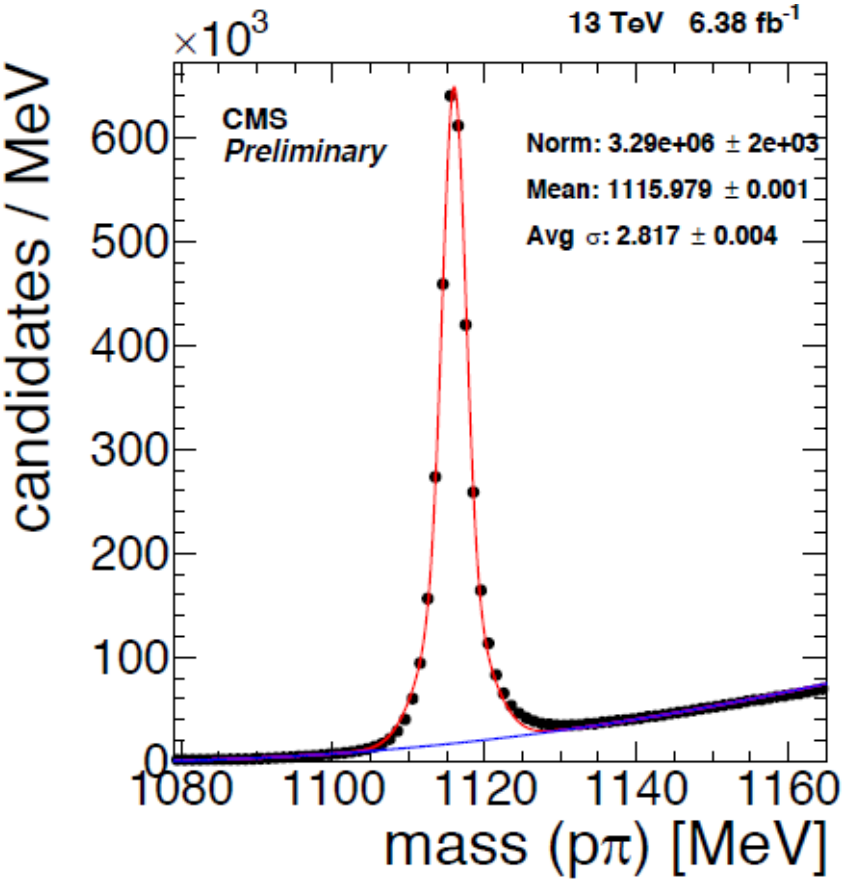
https://twiki.cern.ch/twiki/bin/view/CMSPublic/DataQuality

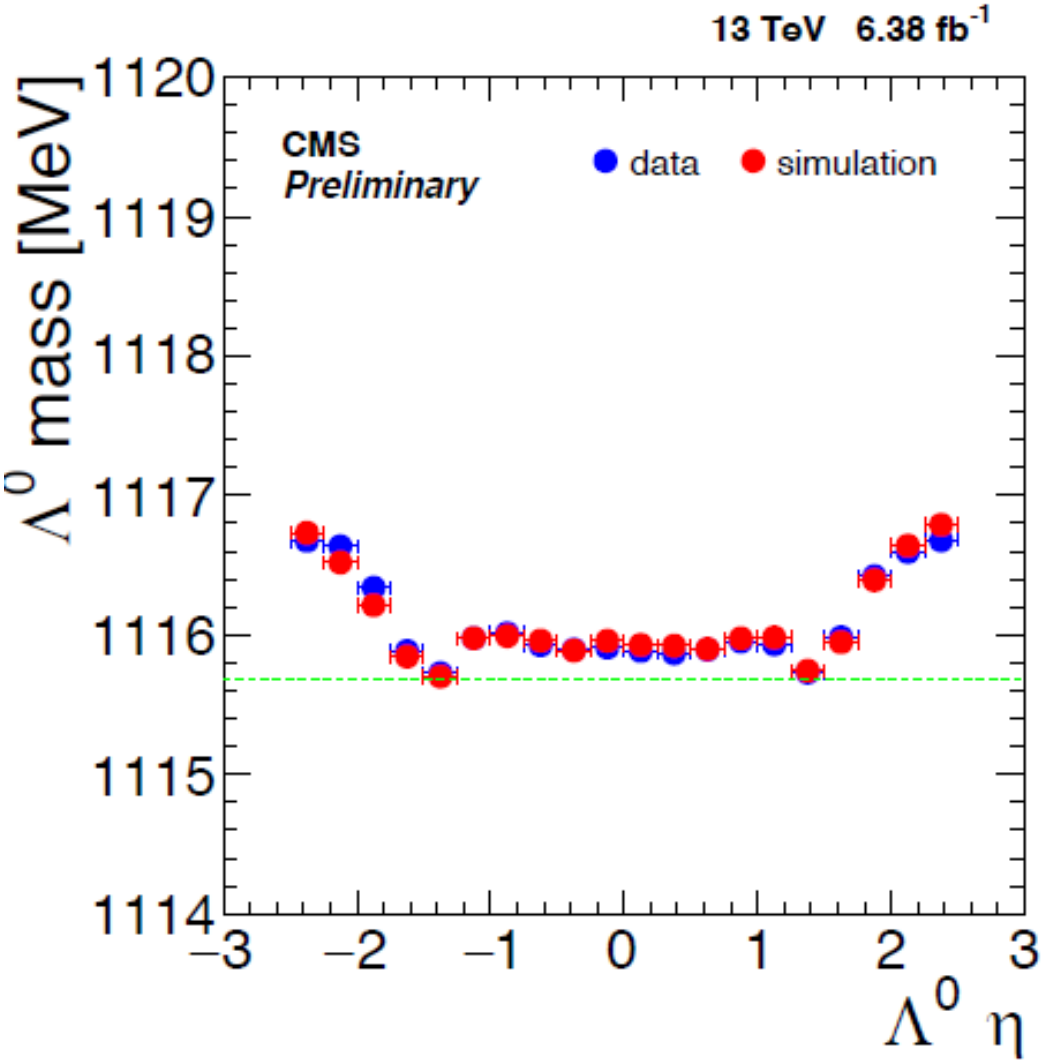
CMS detector performance

Next slides give a taste of the quality of CMS subsystems…

… using physics standard candles to quantify their performance

CMS Silicon Tracker: vertex reconstruction

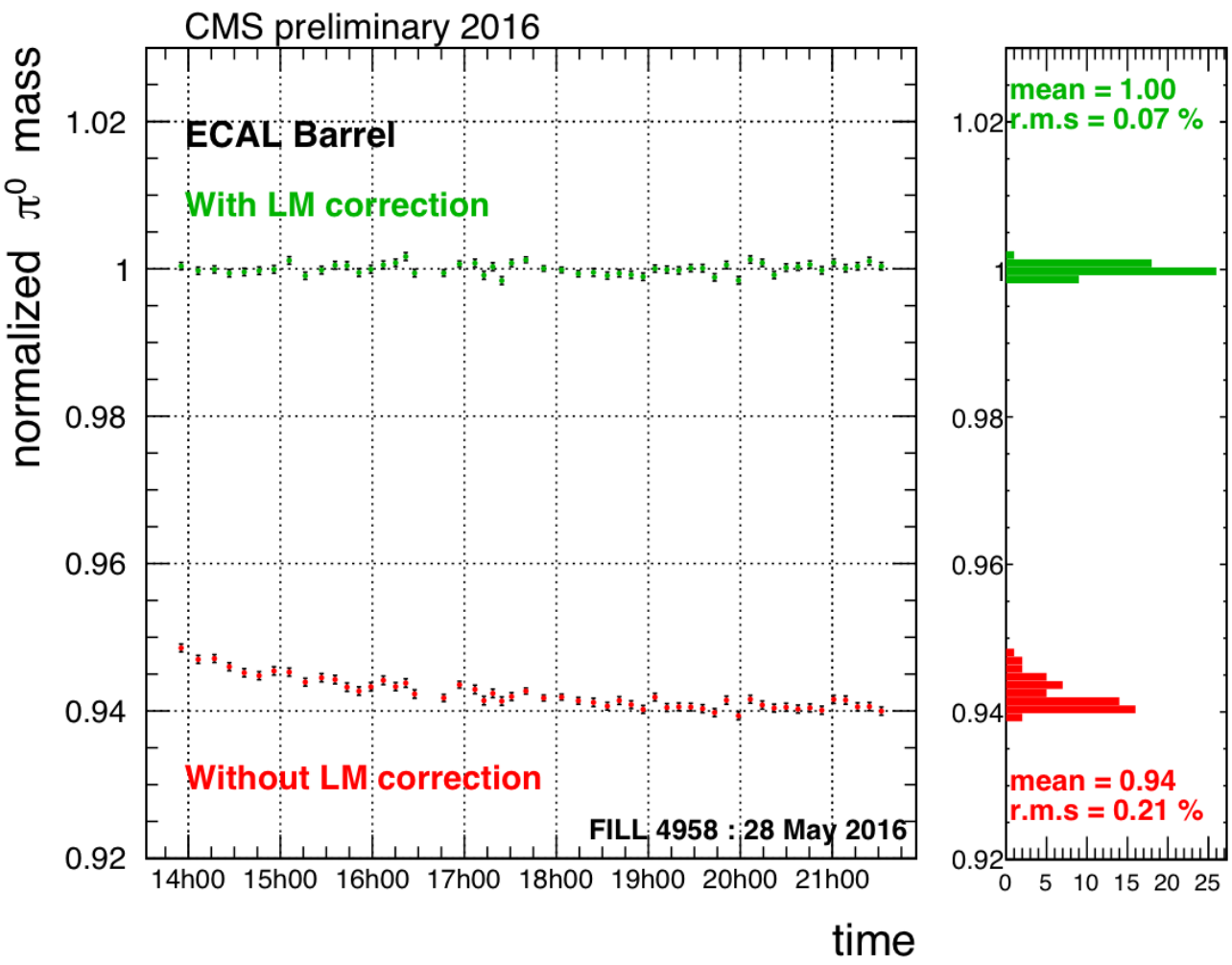


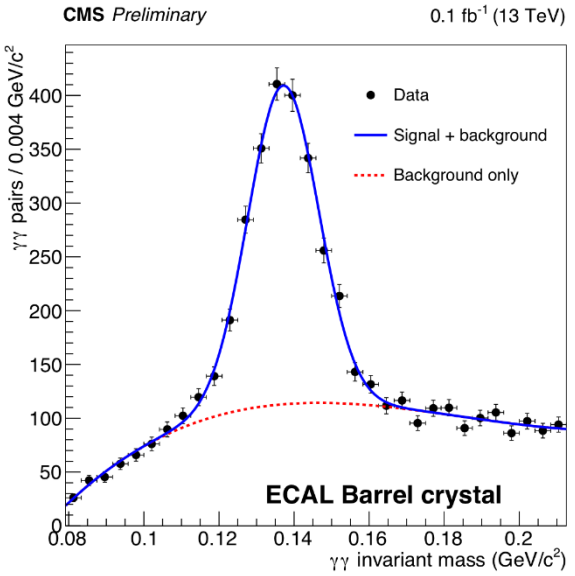


Λ^0 mass dependencies well described by simulation:

η, φ, p_T, decay length

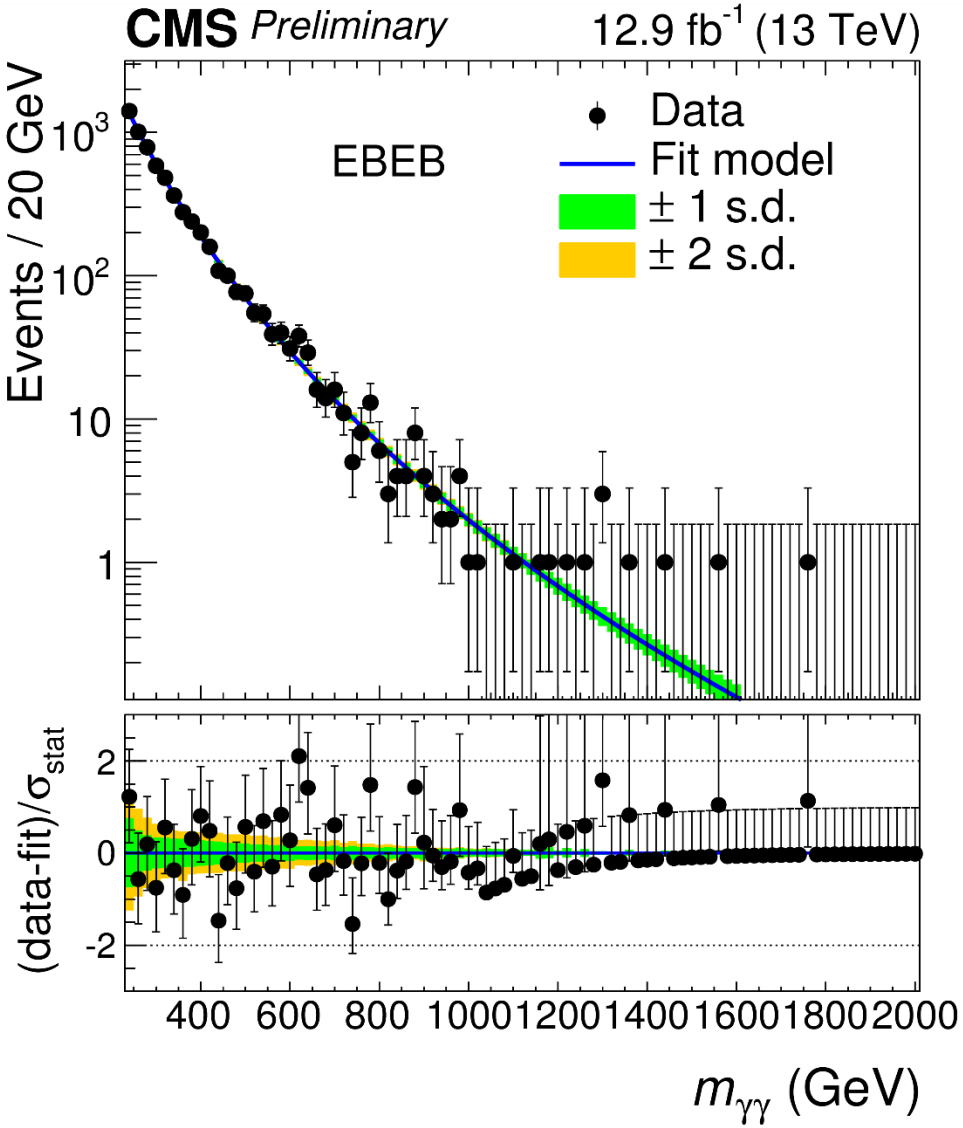
CMS Electromagnetic Calorimeter: calibration and resolution (1/2)





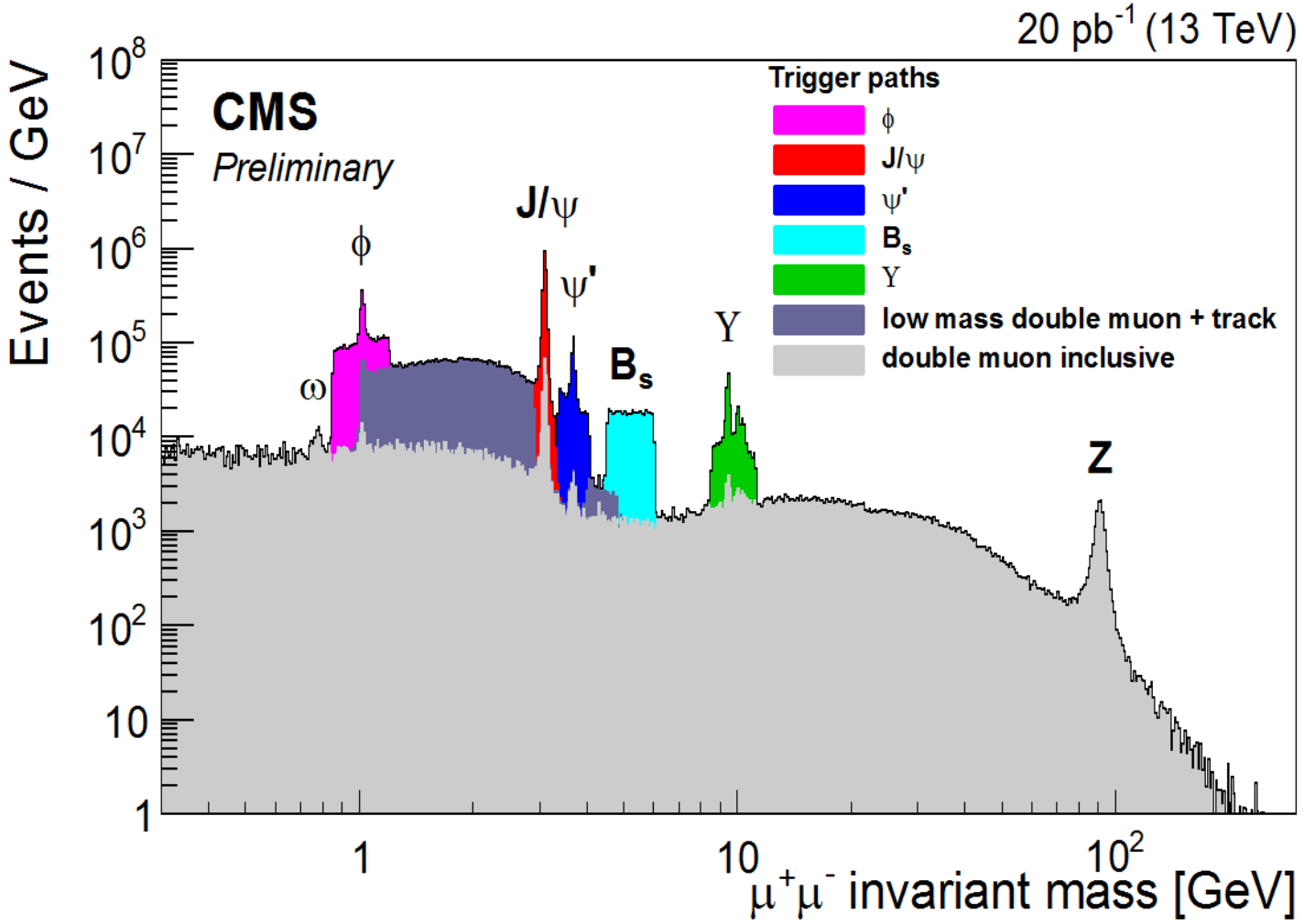
ECAL calibration uses a laser to monitor and correct for transparency loss

CMS Electromagnetic Calorimeter: calibration and resolution (2/2)



The mild excess near Mγγ~750 GeV reported by CMS with 2012 and 2015 data is not confirmed with 2016 data

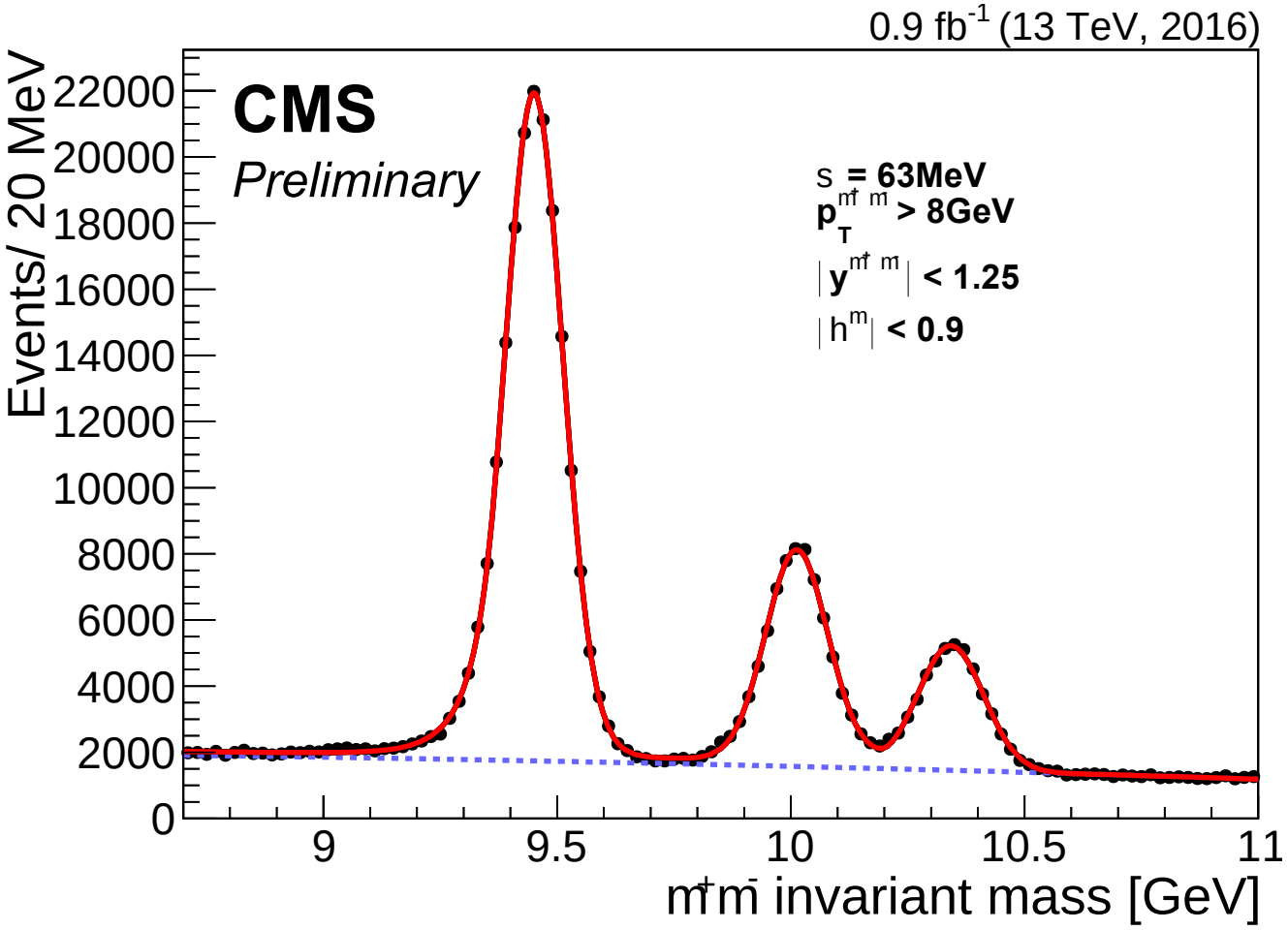
CMS Muon Chambers: Drift Tubes, Resistive Plate, and Cathode Strip (1/2)



CMS muon detectors cover a wide range of kinematics

… this plot comes directly from the High Level Trigger selection of muons "out of the box"…

CMS Muon Chambers: Drift Tubes, Resistive Plate, and Cathode Strip (2/2)



… with excellent resolution, to boot…

(Heavy ion physicists study the suppression of the Υ(nS) states)

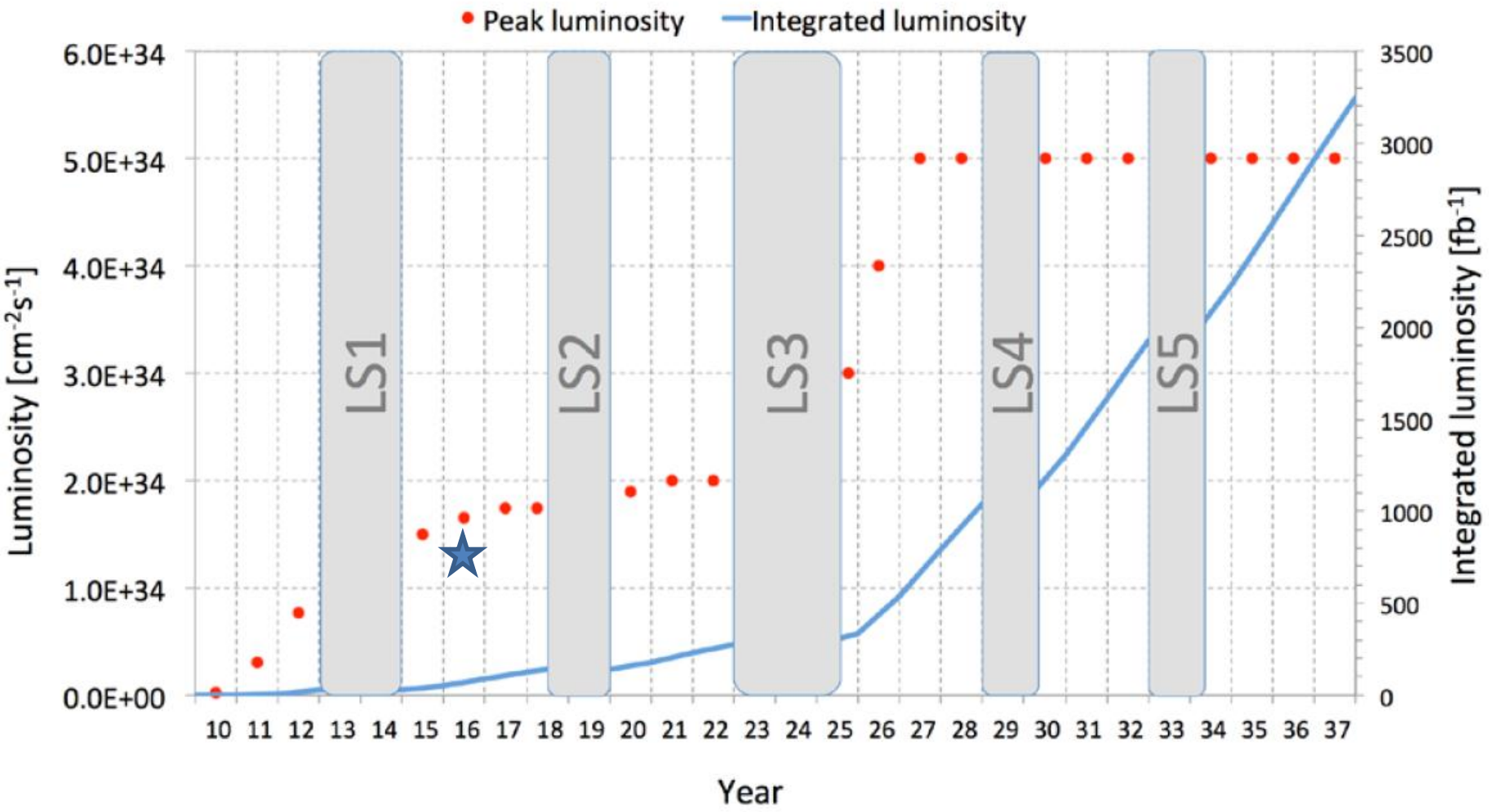
Summary so far…

- Compared to Run-1, LHC has increased the instantaneous luminosity by ~160%
- CMS continues to collect high quality data efficiently with highly performant subsystems, even under more demanding collision conditions
- What is going to happen as LHC continues to increase the luminosity?

Next page…

Expectations: long term

From M. Lamont (CERN) at Moriond 2015
(https://indico.in2p3.fr/event/10819/session/3/contribution/109/material/slides/0.pdf)



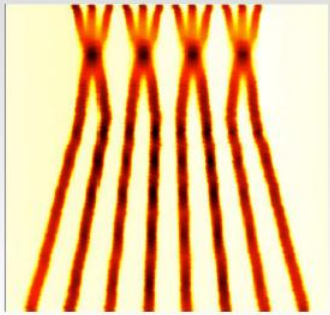
LHC baseline for Run 2

From talk by M. Lamont (CERN) at EPS
(https://indico.cern.ch/conferenceOtherViews.py?confId=218030&view=standard#2013-07-23)

Run II – post LS1

- Energy: 6.5 TeV
- Bunch spacing: 25 ns
  - pile-up considerations
- Injectors potentially able to offer nominal intensity with even lower emittance

BCMS = Batch Compression and Merging and Splitting

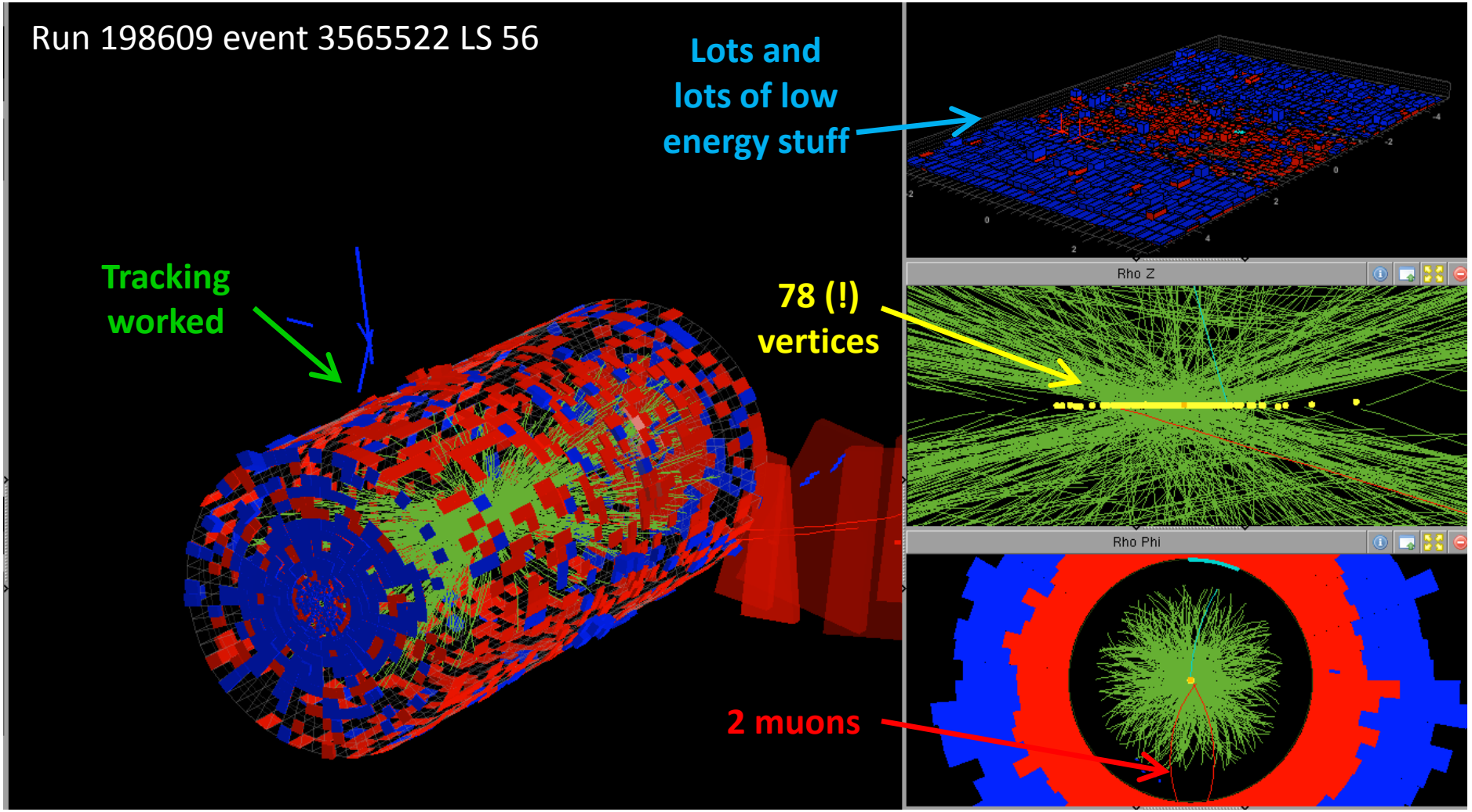


	Number of bunches	Ib LHC FT[1e11]	Emit LHC [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi per year [fb^{-1}]
25 ns BCMS	2590	1.15	1.9	1.7e34	49	~45

18

As the lumi increases, the **pileup** increases

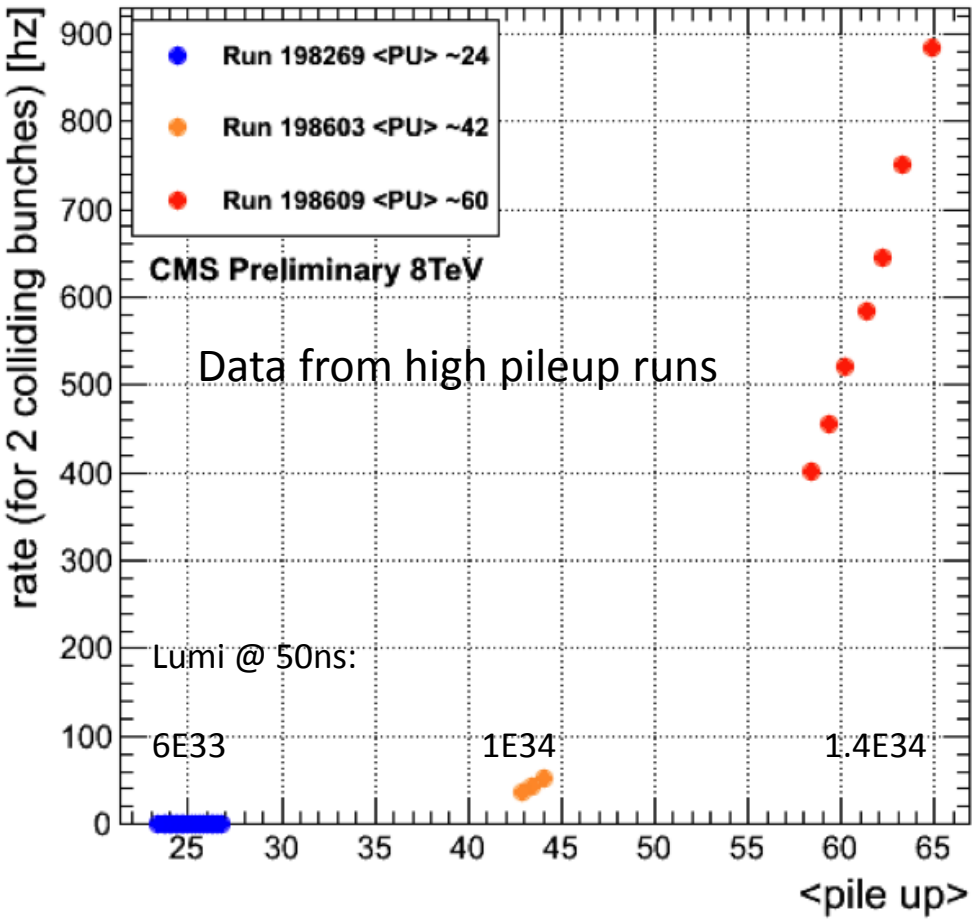
From a test fill in 2012…



http://cms.web.cern.ch/news/reconstructing-multitude-particle-tracks-within-cms

Example: Phase-0 L1 Trigger w/high pileup

From test fill in 2012: triggers of clustered hadronic energy > 200 GeV



For some Run-1 triggers, rate could increase by 1000x for pileup increase of 2.3x

Need to upgrade Trigger for Run-2!

CMS upgrades the detector to handle expected increases in pileup…

- "Phase-1" underway: dates for operation are…
  - 2016: added processing power to the Level-1 (L1) trigger
  - 2017: add another layer of silicon tracking (Pixels)
  - 2017-2018: refine granularity of hadron calorimeter

- "Phase 2": Technical Design Report being fleshed out
  - Likely to include tracking, trigger, calorimeter, muon… in other words, most of CMS!

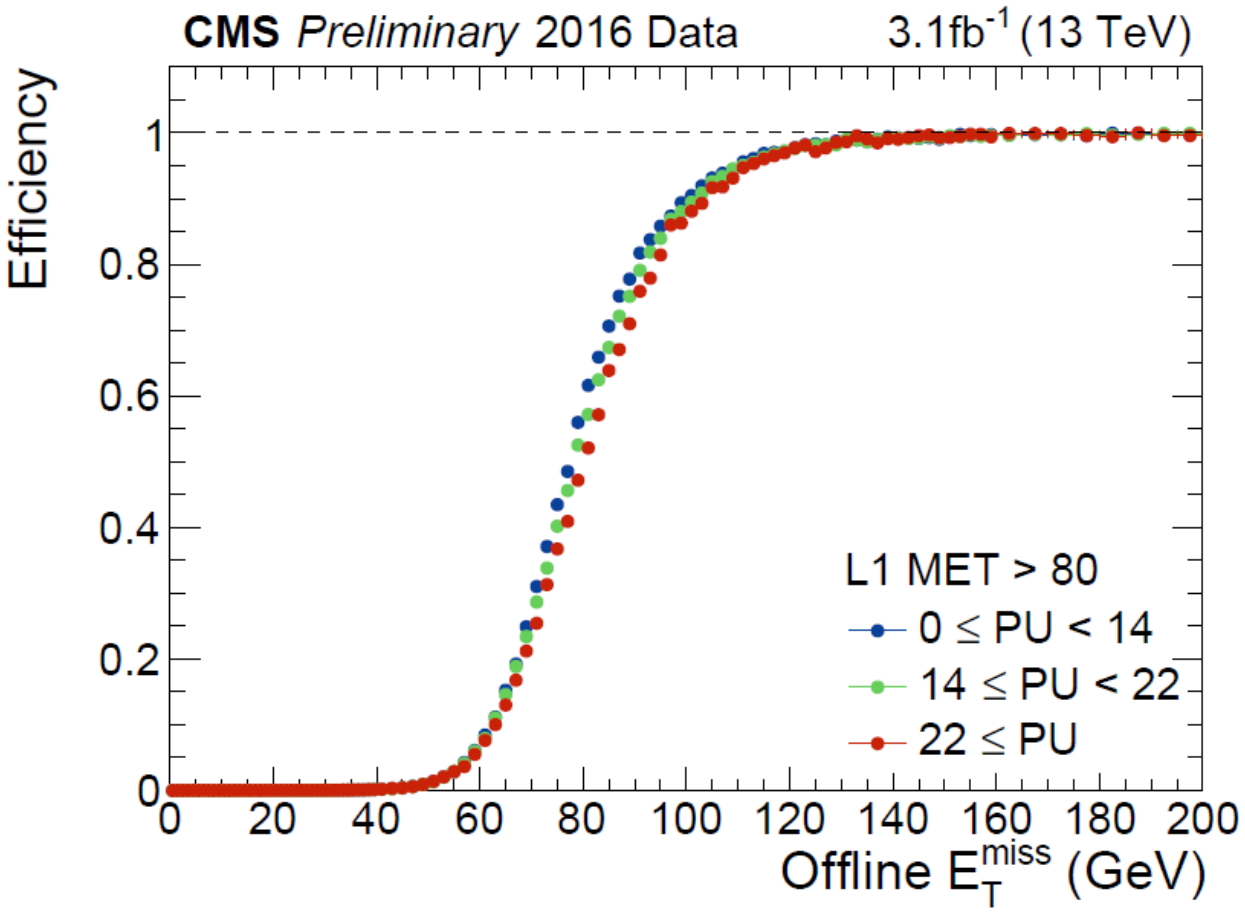
Next couple of slides touch the Phase 1 upgrade…

Summary: L1 trigger Phase-1 upgrade

- **Concept:** use optical fiber to transport high resolution data to large FPGAs mounted on electronics with a small footprint (uTCA telecommunications standard)
  - Subtract pileup event-by-event
  - Improve tau identification
  - Improve position resolution
  - Optimize muon tracking

- **Upshot: the CMS Level-1 trigger upgrade has been operational since the first collisions of 2016**

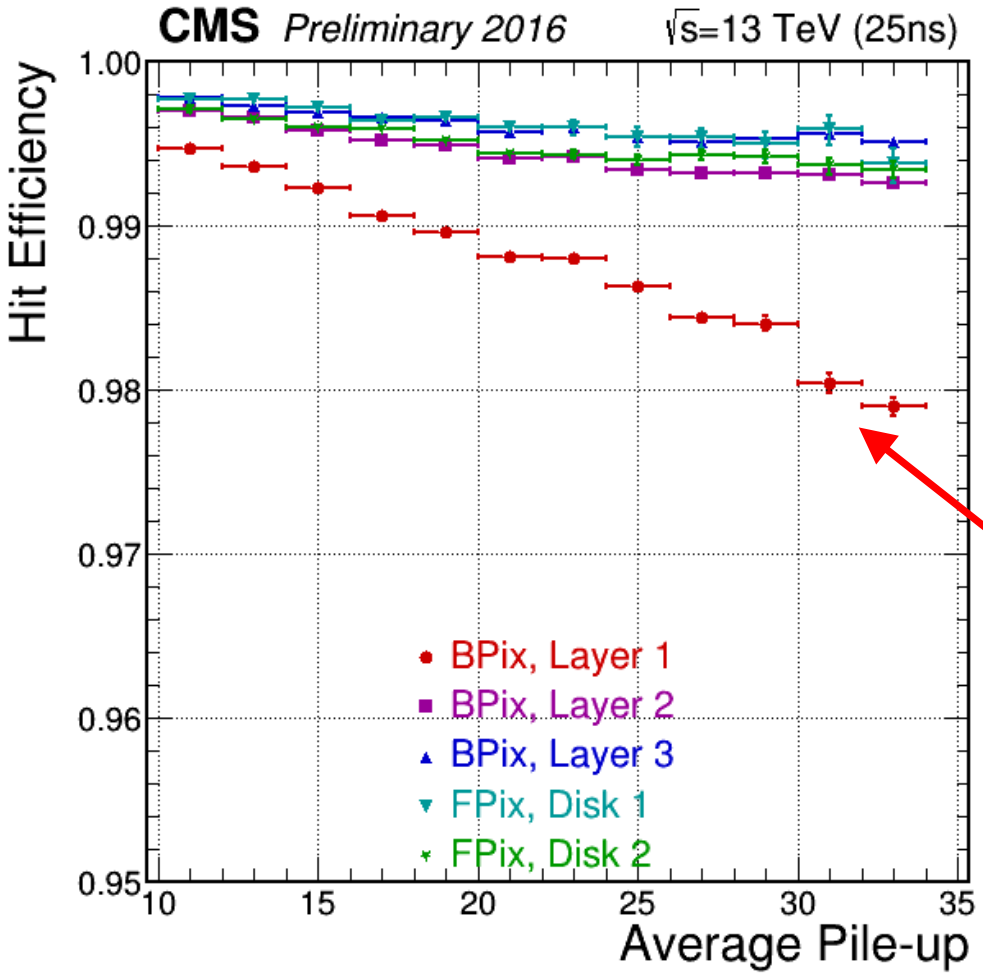
Example of improvement with Phase-1 upgrade of L1 Trigger



With Phase-1 upgrade, Missing transverse energy trigger remains efficient even as pileup increases

2017: CMS Pixel Phase-1 upgrade to be installed

Example of limitation in Phase-0 Pixels:
"dynamic inefficiency" at high pile up + trigger rates



Phase-1 pixels to have…

- One more layer but reduced material
- Improved readout chip to improve efficiency with pileup
  - (this will go away!)

Summary and Conclusion (1/3)

- CMS and LHC operating extremely well in Run-2
  - For $\sqrt{s}$=13 TeV results at this ISHBSM…
    - 15.0 fb^{-1} delivered by LHC
    - 13.8 fb^{-1} recorded by CMS
    - 12.9 fb^{-1} certified as good for all analyses
- "Phase-1" upgrades in process of being installed to handle higher pileup/lumi
  - Already installed for 2016: Level-1 Trigger
  - To be installed 2017-2018: Pixels +Hadron Calorimeter
- "Phase-2" upgrade planning underway

Please enjoy ISHBSM plenary talks by CMS speakers! (2/3)

- Higgs boson production and decays
  - Mingshui Chen (IHEP)
- BSM Higgs searches
  - Li Yuan (Beihang University)
- SUSY searches
  - Teruki Kamon (TAMU)
- Exotics searches
  - Huaqiao Zhang (IHEP)
- Di-Higgs and prospects (ATLAS+CMS)
  - Martino Dall'Osso (INFN-Padova)

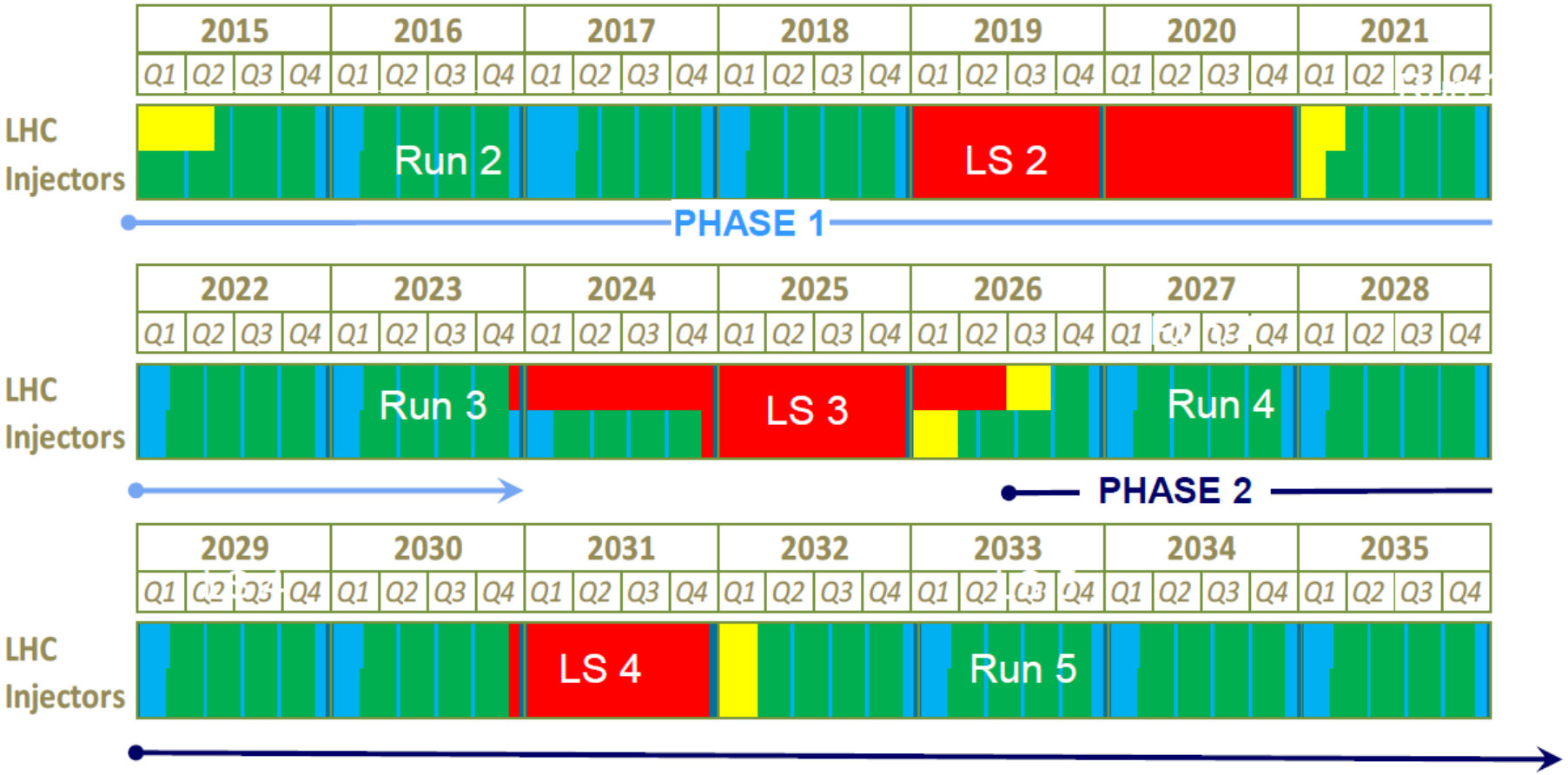
Please enjoy ISHBSM parallel talks by CMS speakers! (3/3)

- Measurement of differential and integrated fiducial cross sections for Higgs boson production in the four-lepton decay channel in pp collisions at $\sqrt{s}$ = 7, 8, and 13 TeV
  - Ahmad Muhammad (IHEP)
- Search for heavy resonances decaying to WW in semileptonic channel at CMS
  - Huang Huang (Peking U)
- Electroweak W+γ production in association w/two jets at $\sqrt{s}$=8 TeV
  - Daneng Yang (Peking U)
- Search for heavy neutral Higgs in di-boson final state
  - Tongguang Cheng (IHEP)
- Search for displaced leptons in the e-μ channel at CMS
  - Bingxuan Liu (OSU)

Backup slides

LHC roadmap: according to MTP 2016-2020 V2

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC



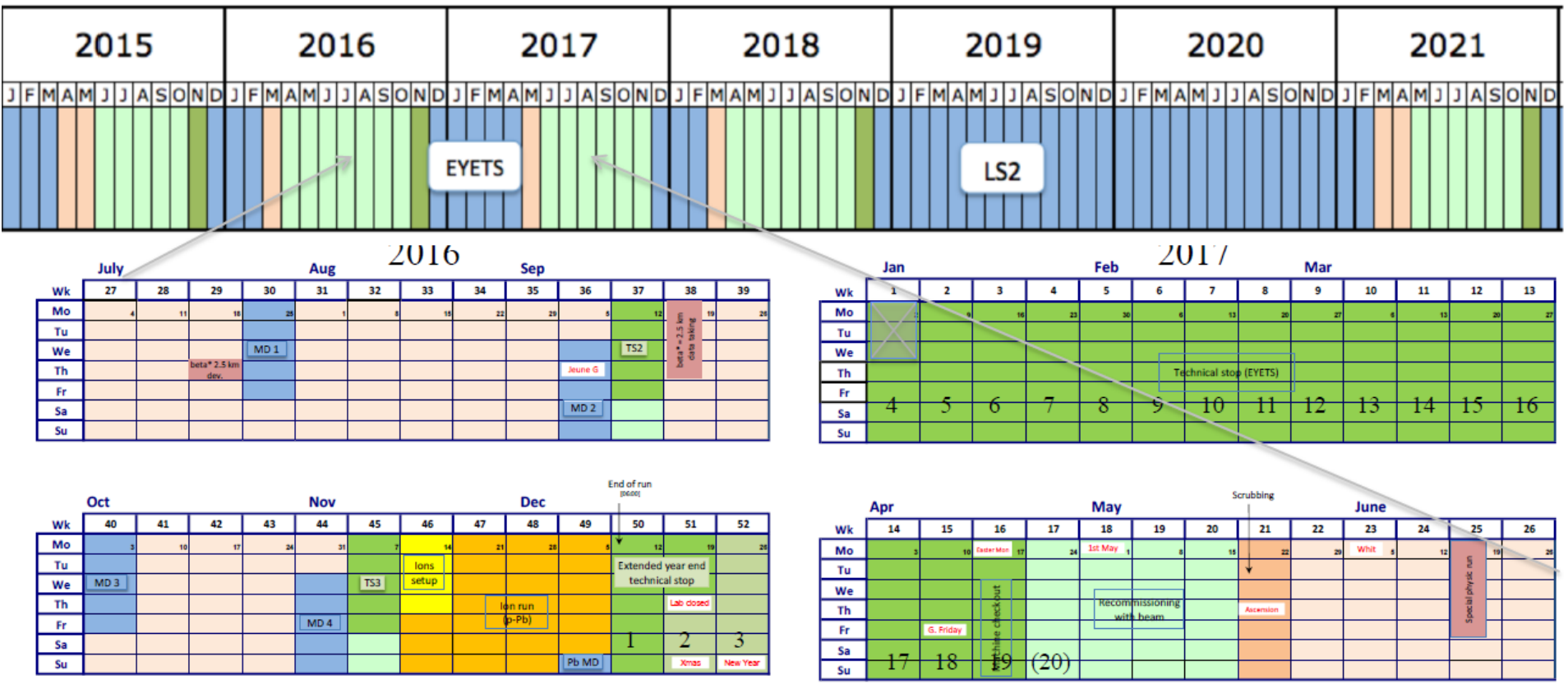
https://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-long-term.htm

Technical Coordination

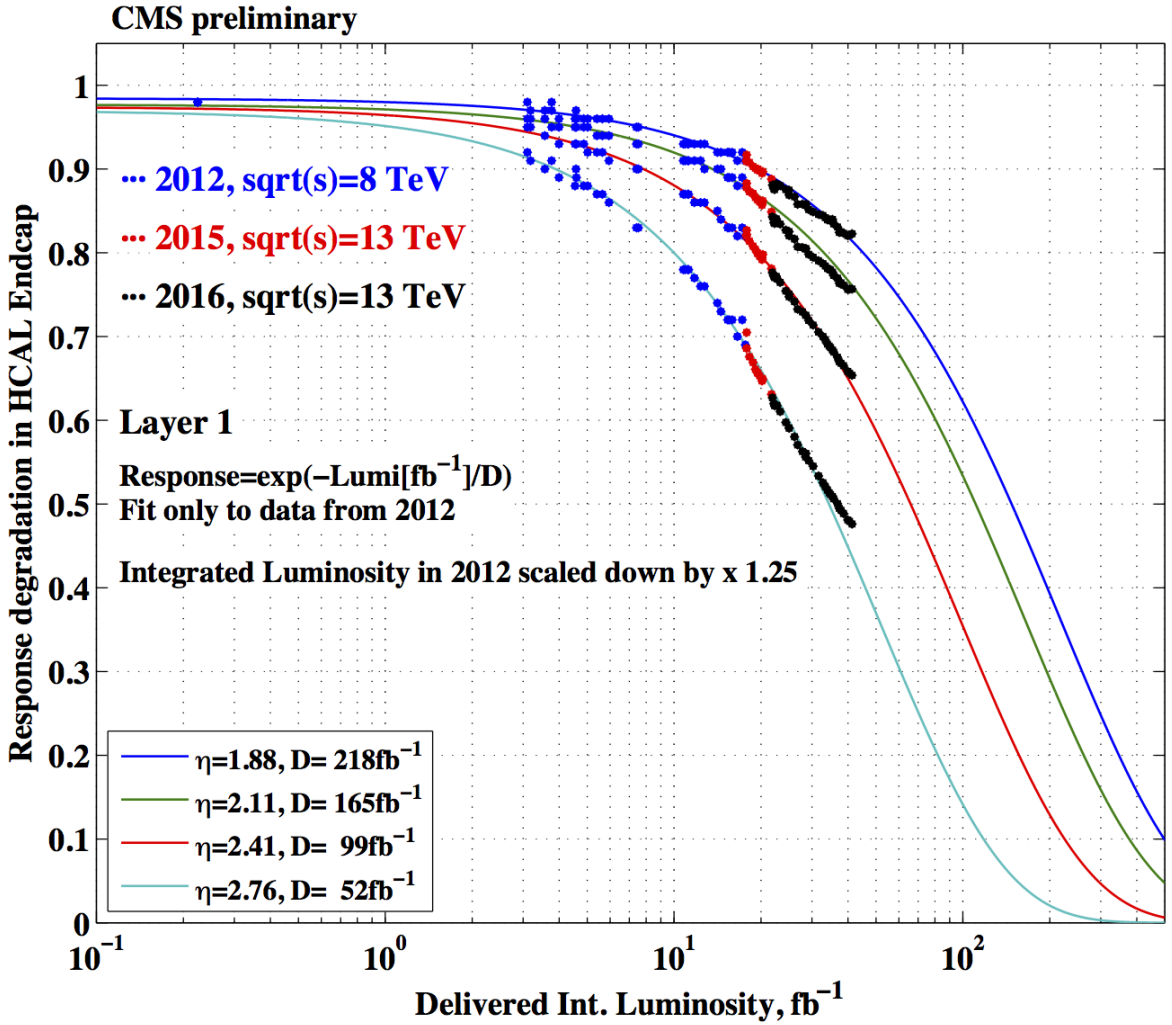
CMS in EYETS 2016-17

Extended Year End Technical Stop:

Requested by CMS for installation of the CMS Phase 1 pixel tracker (originally targeted for LS2)



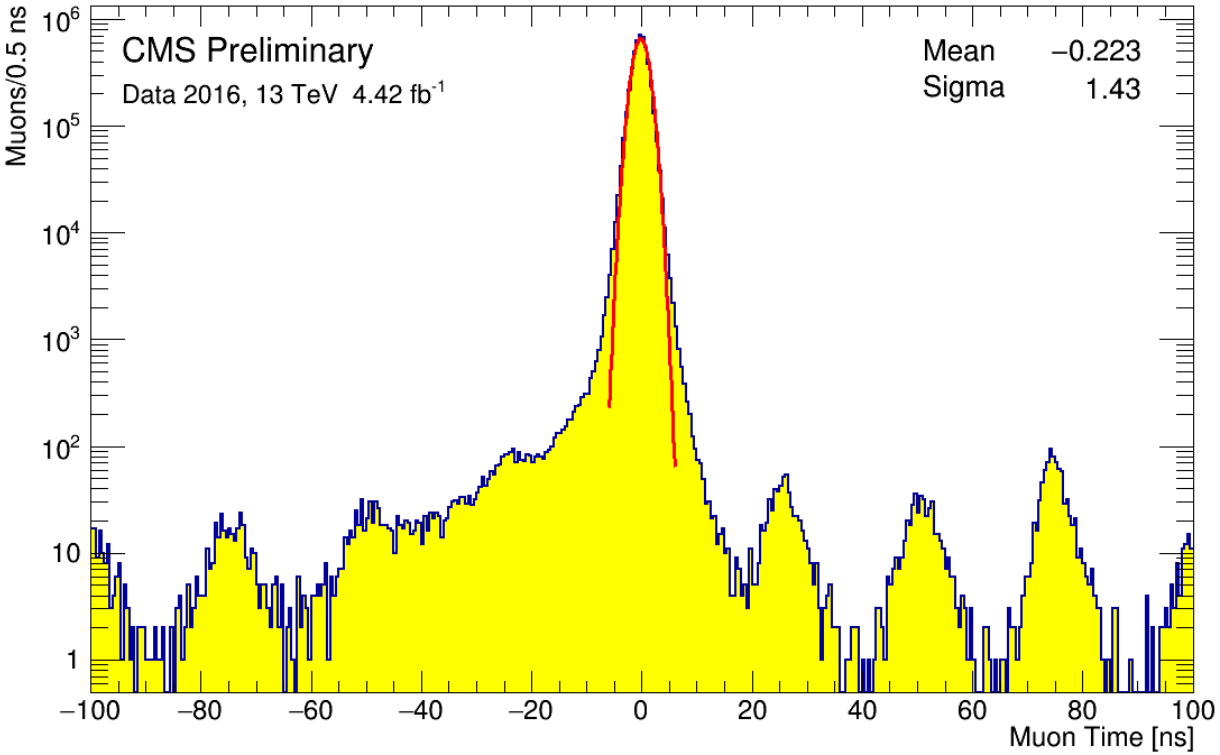
Radiation damage in endcap of Hadron Calorimeter



Plan to accelerate installation of upgrade hadronic endcap to mediate radiation damage as a result of excellent LHC performance

Plan to install in 2016-2017 Extended Year End Technical Stop (Dec 2016-May 2017)

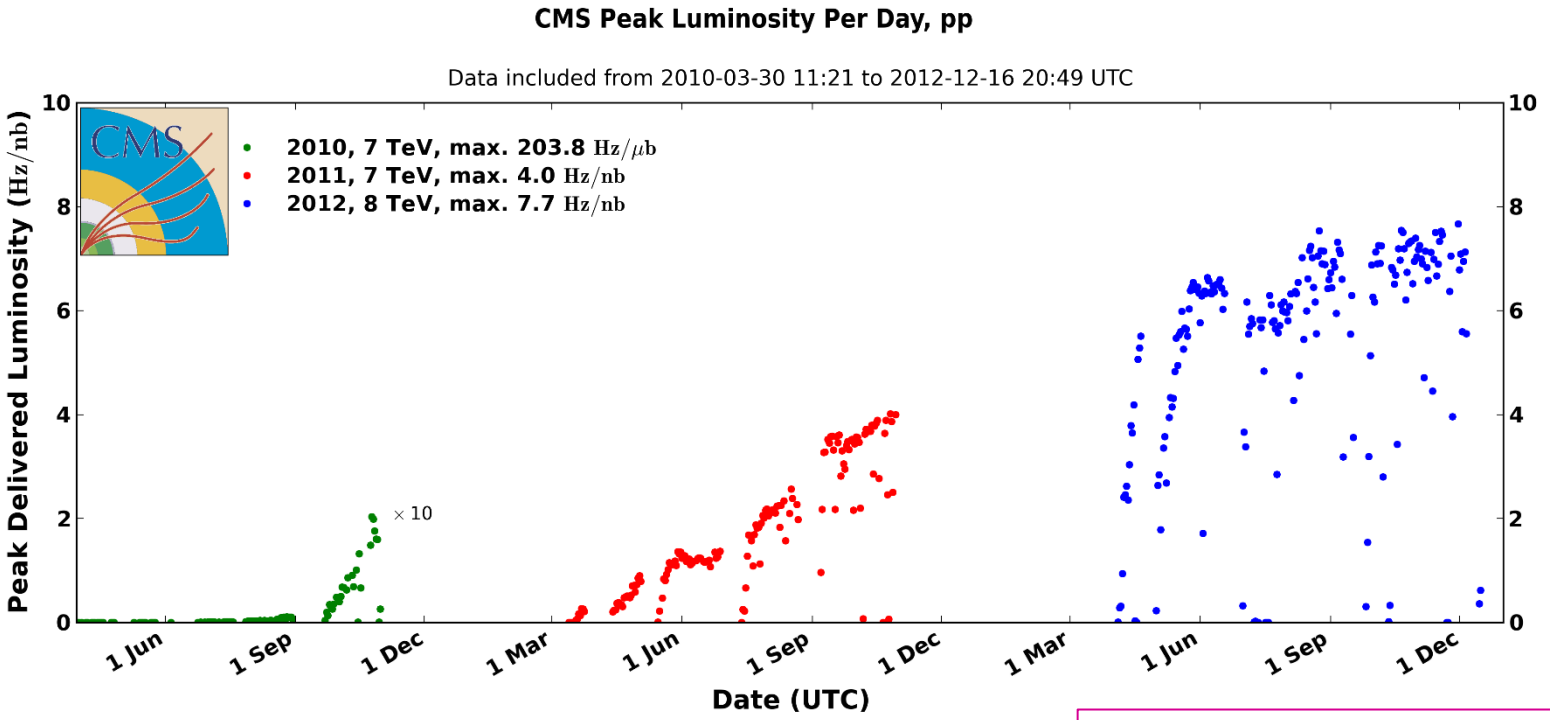
CMS Drift Tubes: accurate timing



Time resolution clearly shows the 25ns bunch spacing of LHC collisions

Luminosity increases during Run-1

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



Run-1 peak performance numbers

- Max. inst. lumi = $7.7 \times 10^{33}/cm^2/s$ (design = 1×10^{34})
- Number of bunches = 1380 (design ~ 2200)
- Bunch spacing = 50ns (design = 25ns)

From the point of view of peak instantaneous luminosity *per bunch*, LHC Run-1 **exceeded the specs by ~140%**