



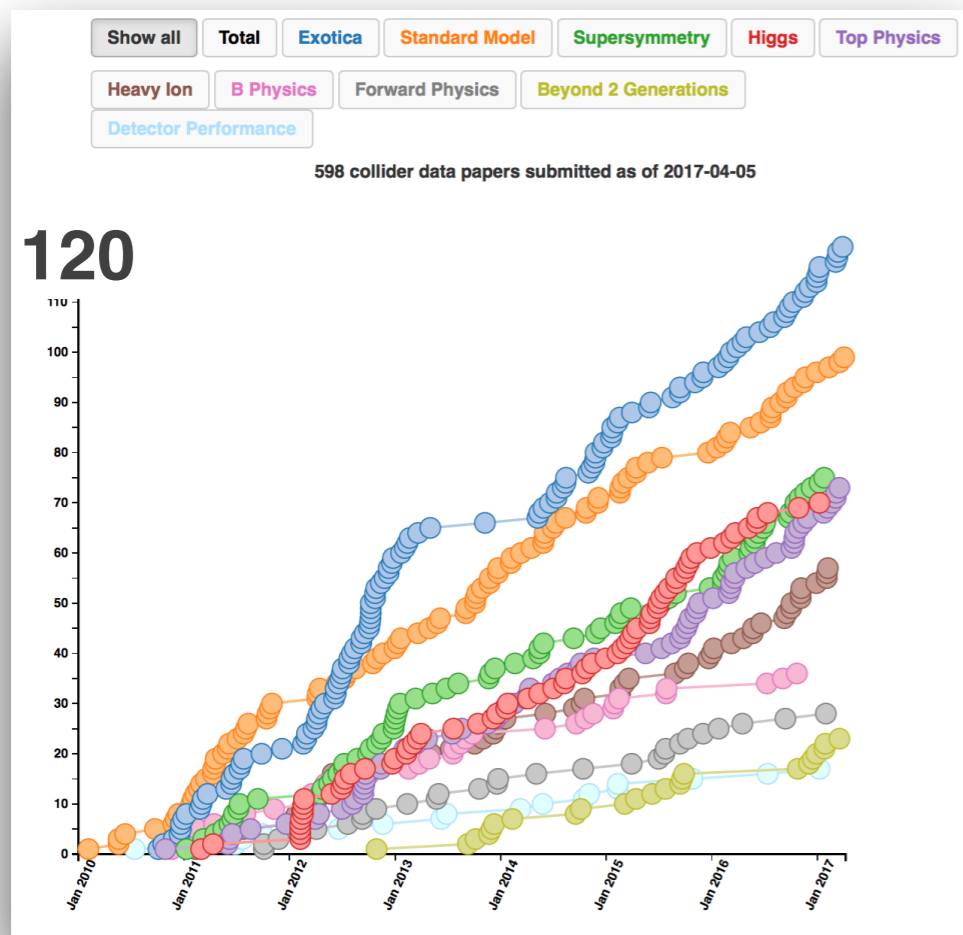
Large Hadron Collider: from LHC-Run2 to the HE-LHC

Anadi Canepa and Sergo Jindariani for the Energy Frontier Group

April 10th 2017

The LHC

- **The LHC addresses three out of the five science drivers identified by P5**
- **The broad and diverse physics program allows to explore the energy frontier**
- **CMS and ATLAS > 1000 journal publications**



The Science Drivers

Five intertwined Science Drivers provide compelling lines of inquiry that show great promise for discovery.

+ Use the Higgs boson as a new tool for discovery. ✓

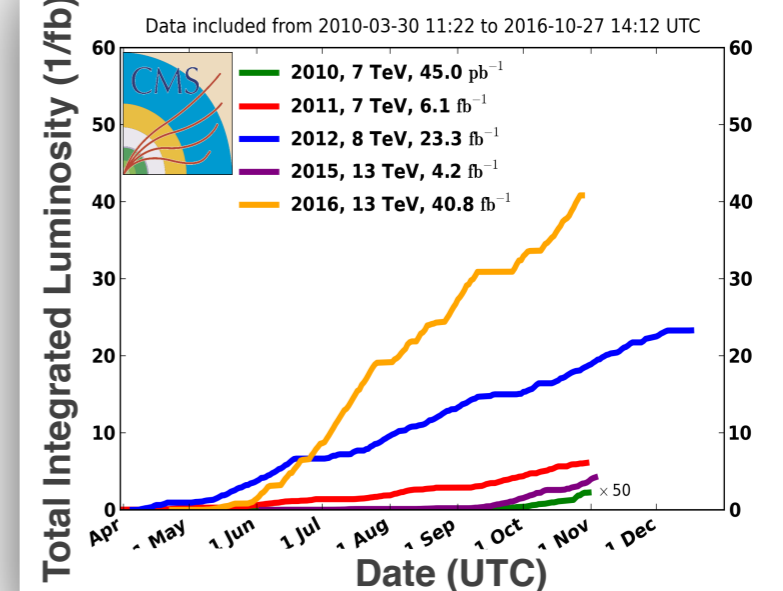
+ Pursue the physics associated with neutrino mass.

+ Identify the new physics of dark matter. ✓

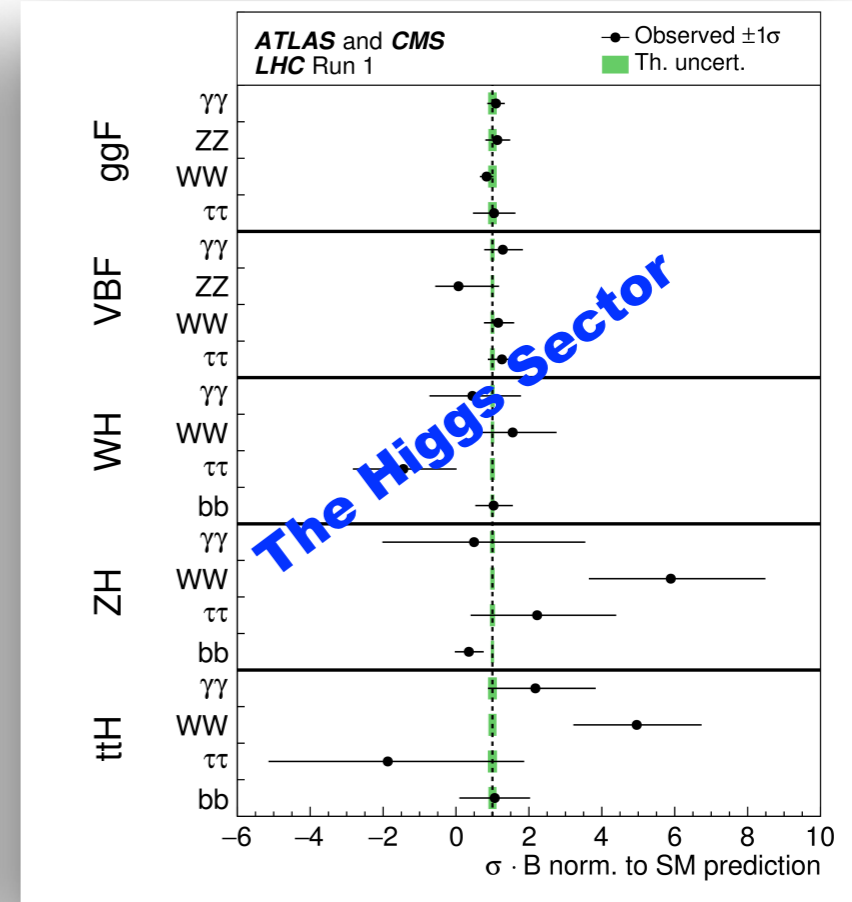
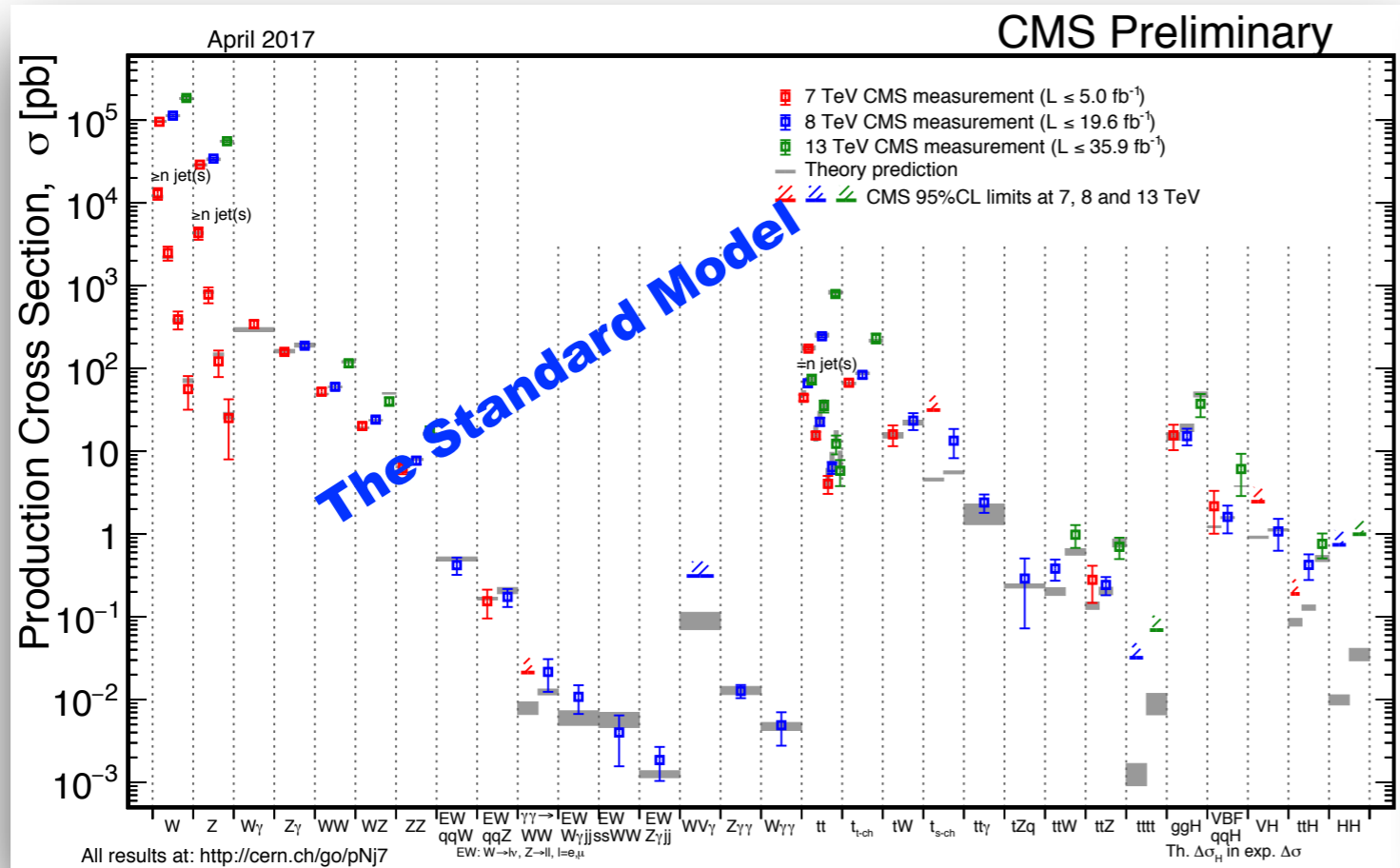
+ Understand cosmic acceleration: dark energy and inflation.

+ Explore the unknown: new particles, interactions, and physical principles. ✓

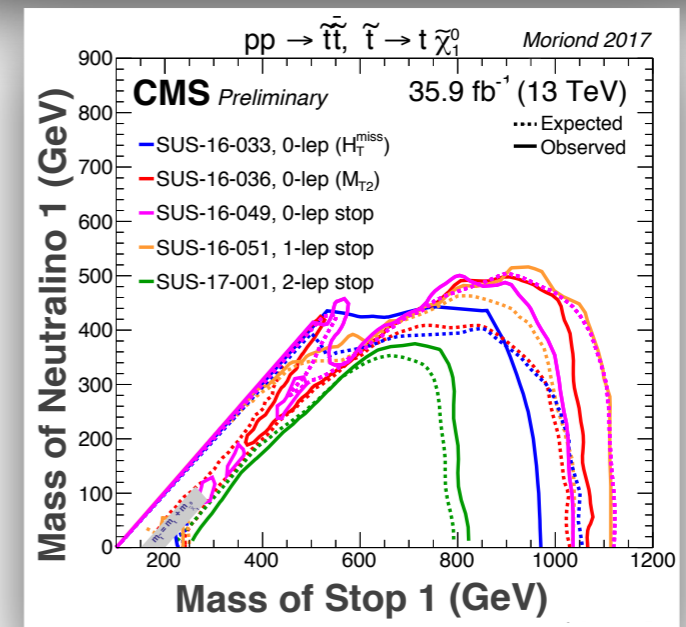
CMS Integrated Luminosity, pp



Physics Today



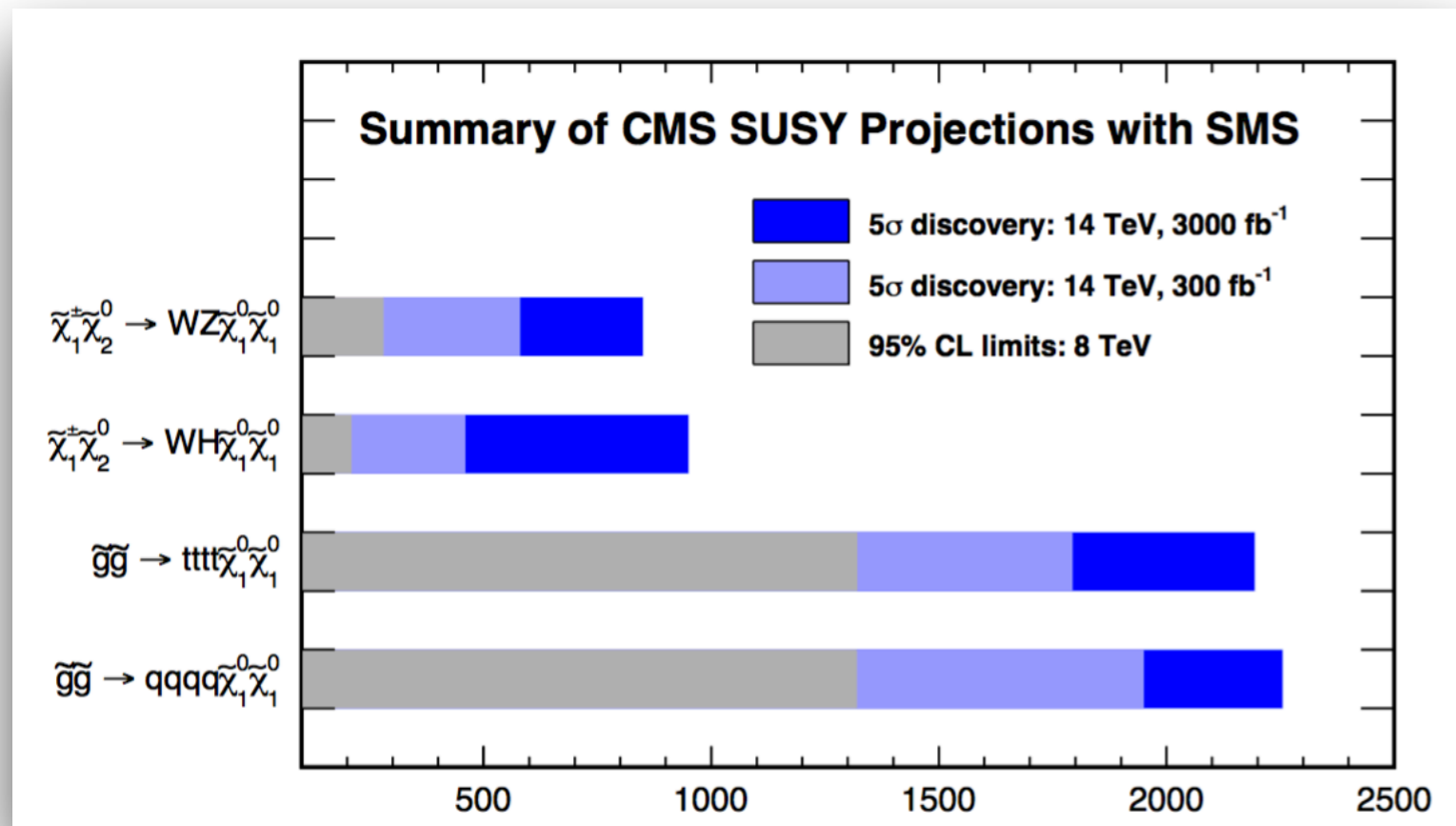
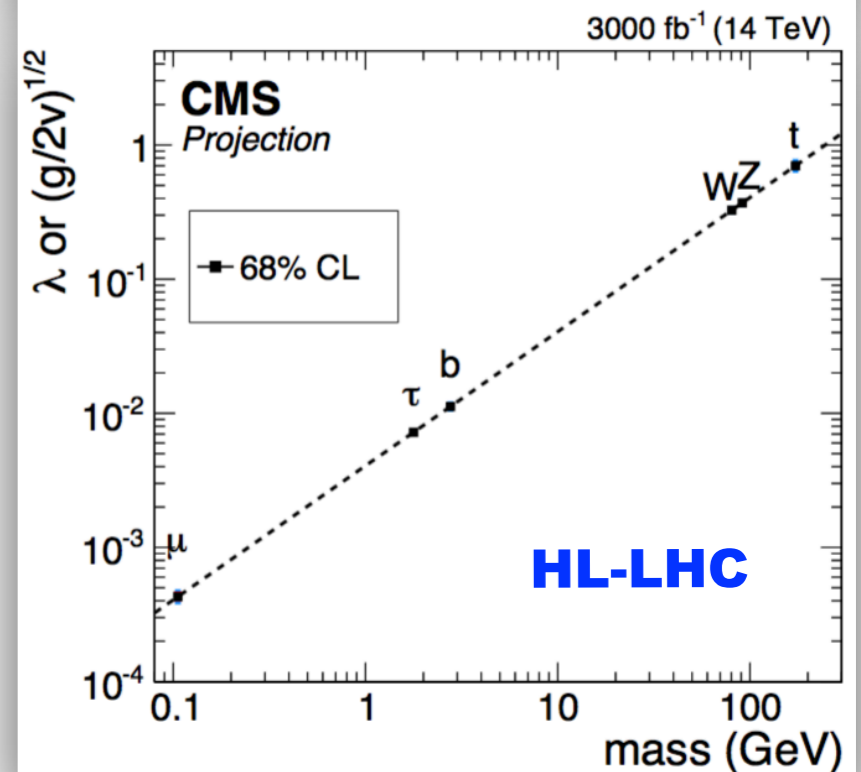
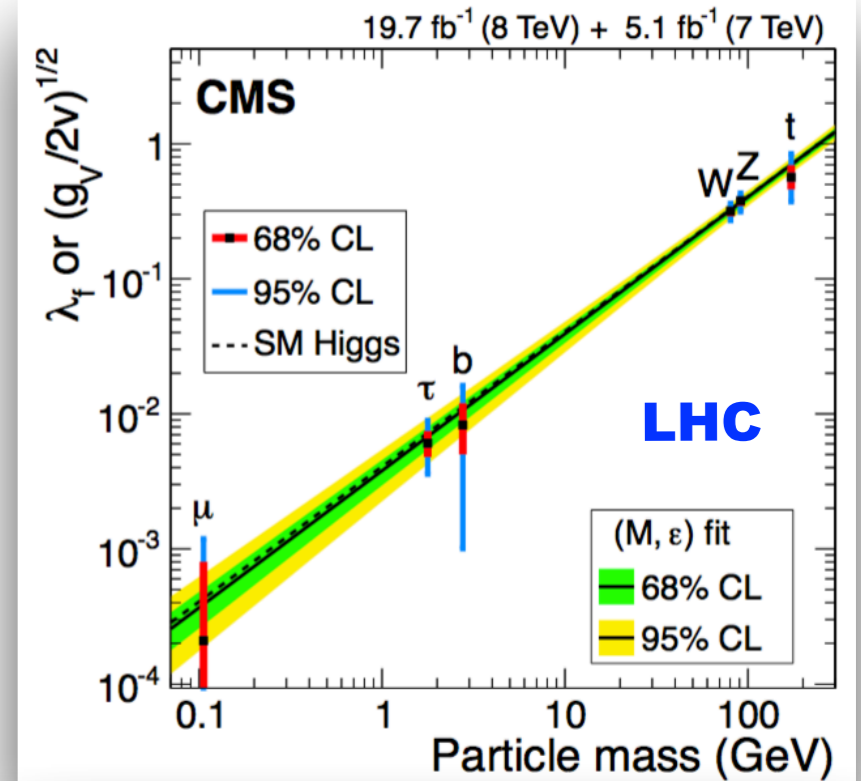
- **Direct searches for New Physics**
- **SUSY as an example**
- **Indirect searches for New Physics via precision measurements of the Higgs sector**
(and EWK, top, B, etc. sectors)



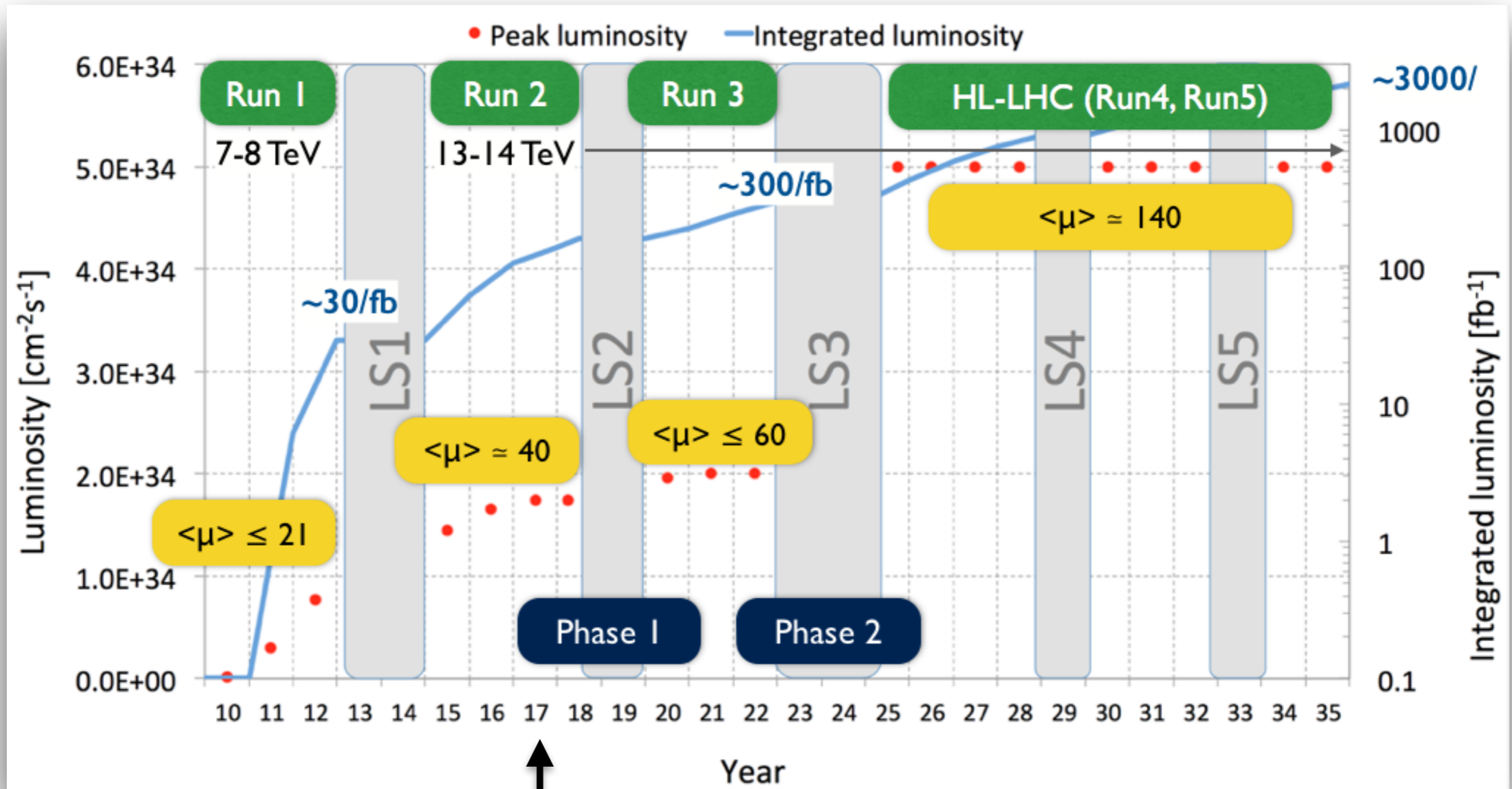
Why HL-LHC?

Extend the LHC discovery potential

- measurements of the Higgs couplings (from % to sub-% level)
- direct searches for few-TeV New Physics



The Evolution of the LHC into the HL-LHC



↑
We are here

Fermilab at the LHC

- **Superconducting magnets for the accelerator**
- **Construction and upgrade of the CMS detector**
- **Comprehensive physics program**
- **Host of US-CMS LHC Physics Center**
- **Host of Tier-1 center**
- **Host of Remote Operations Center**
- **Project management of the US-CMS**



The image shows a screenshot of the Fermilab website. The top navigation bar includes links for Home, Contact, Phone Book, Fermilab at Work, Jobs, and We are 50. Below this, a secondary navigation bar lists About, Science, Newsroom, Come visit us, and Resources for. The main content area features a large, close-up photograph of the CMS detector's internal structure, showing a central vertical pipe surrounded by complex, multi-layered components. Below the image, the headline reads "A new gem inside the CMS detector" in a large blue font. Underneath the headline, a sub-headline states: "U.S. scientists have embedded sophisticated new instruments in the heart of a Large Hadron Collider experiment."

The technological challenge at the HL-LHC

Unprecedented number of collisions per bunch crossing (up to 200)
and radiation dose / neutrino fluence

The pileup challenge

Events taken at random
(filled) bunch crossings

2010

O(2) Pile-up events
150 ns inter-bunch spacing

2011

O(5-10) Pile-up events
50-75 ns inter-bunch spacing

2012

O(20-30) Pile-up events
50 ns inter-bunch spacing

Design value exceeded!

*A leading driver of
innovation in hardware
and algorithms @ LHC*

**HL-LHC: Expect
pileup ~ 140
and probably
much higher**

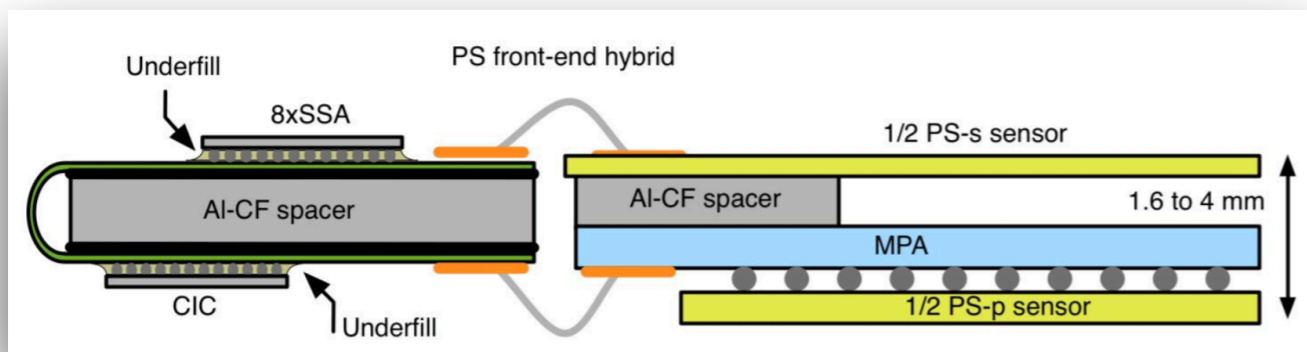
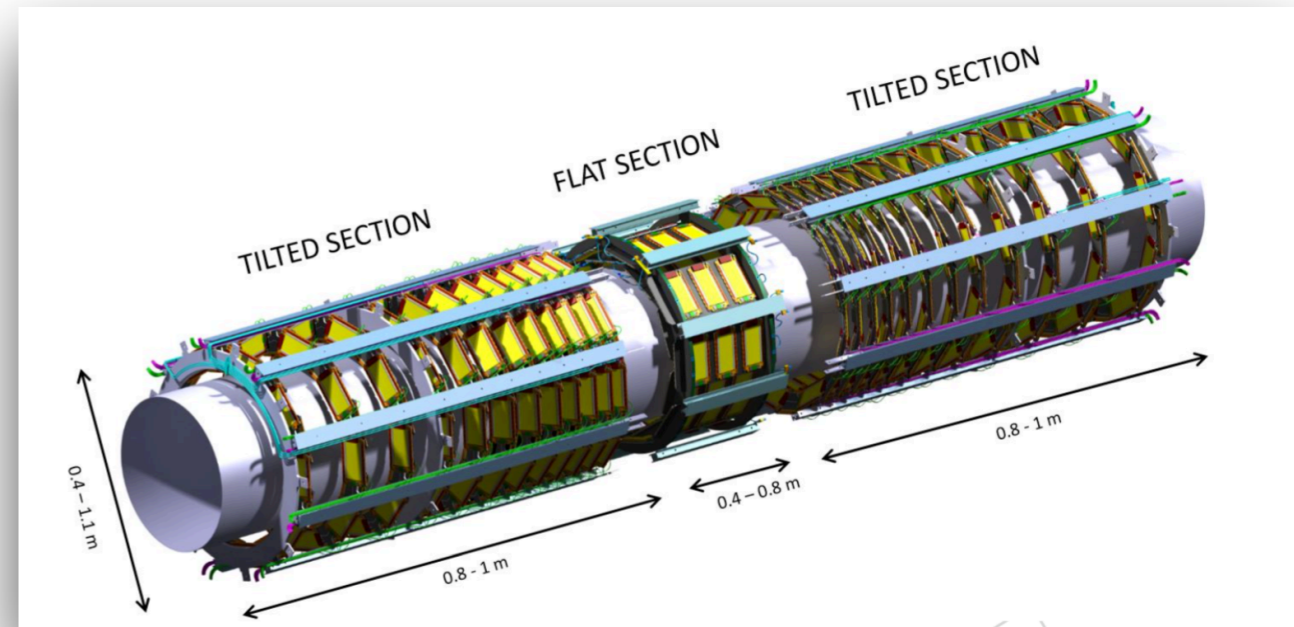
**Extreme radiation
hardness and very high
granularity detectors
are the keys to enable
particle identification at
CMS in this challenging
environment**

Courtesy of J. Incandela

Tracking at 40MHz: the Phase 2 Tracker of CMS

New $>200 \text{ m}^2$ silicon tracker:

- silicon sensors with **10x radiation hardness**
- **4x granularity & larger coverage ($>250\text{M}$ channels)**
- capability to provide **tracking info at 40 MHz** for the first time at Hadron Colliders (setting the basis for future machines)



pT Module

Local measurement of track momentum done by 'pT' modules at 40MHz (high density folded hybrids, digital front-end electronics)

Triggering at 40MHz: the Phase 2 Track Trigger of CMS

The performance of current Level-1 trigger will be highly compromised by high pileup

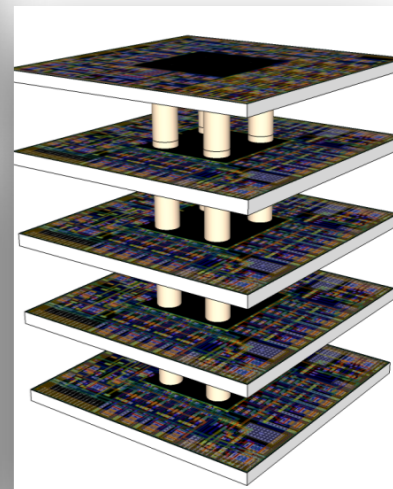
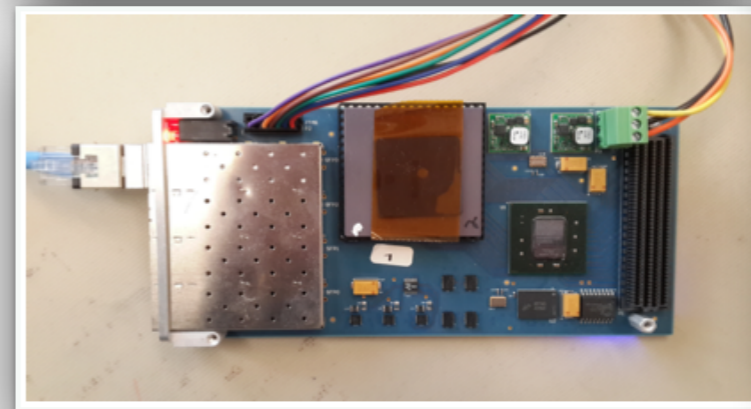
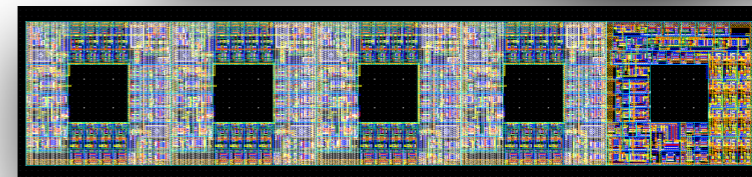
- higher thresholds leaving interesting physics out

Use Silicon Tracker data and Particle Flow reconstruction in Level-1 trigger

- Large bandwidth (**~100 Tbps**)
- small latencies (**~10 microseconds**)
- R&D in high speed electronics and fast pattern recognition

High speed links, modern FPGAs etc.

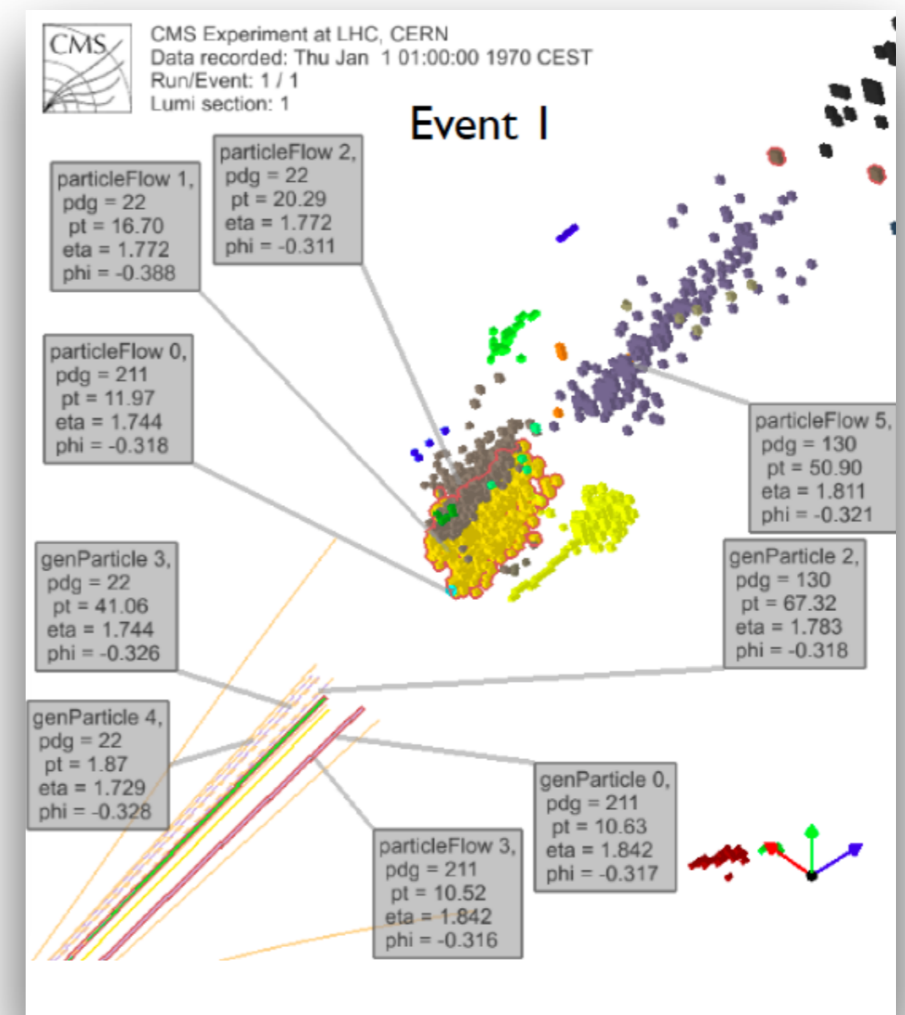
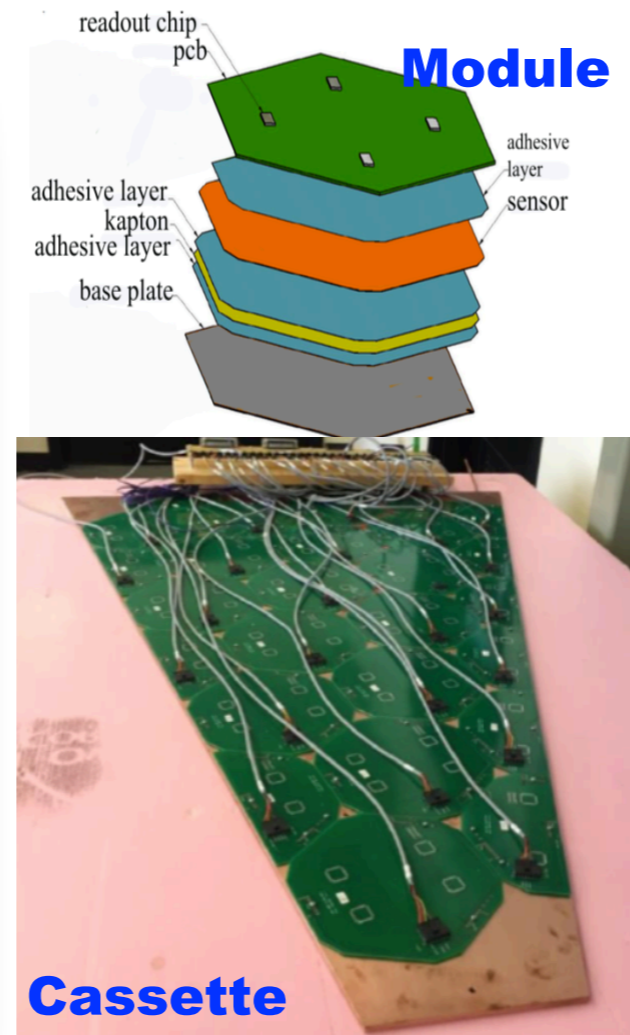
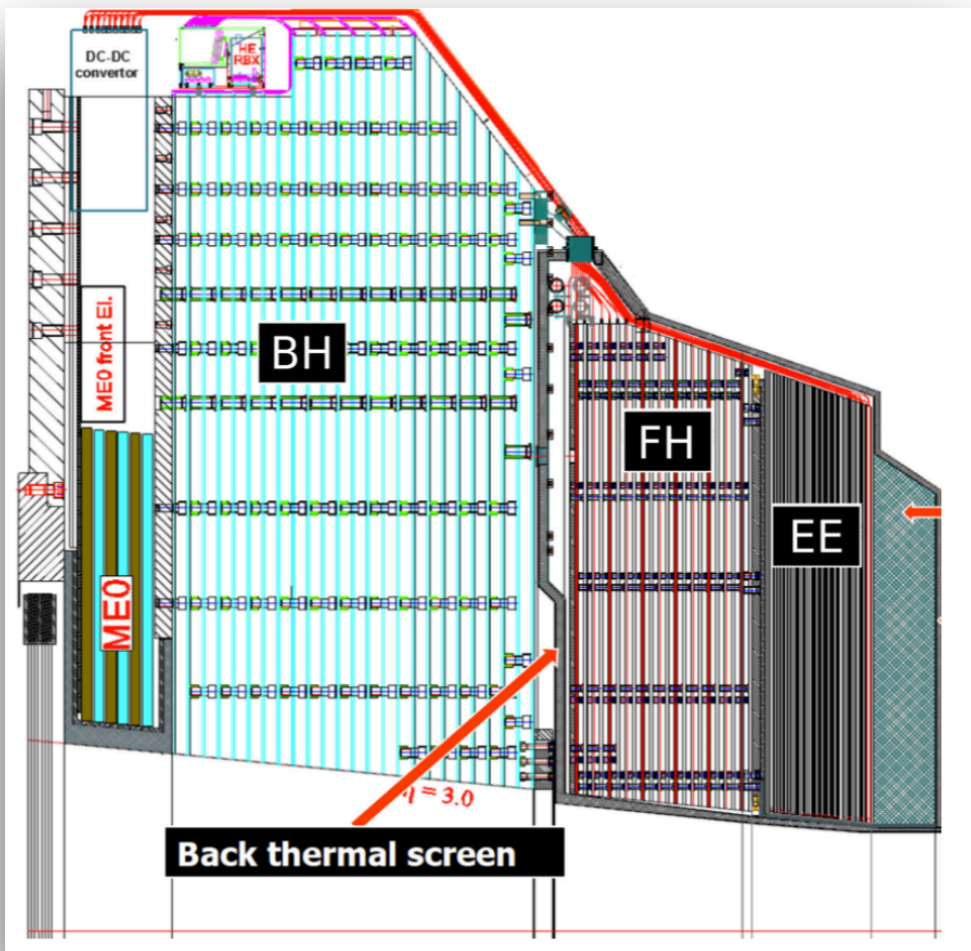
Technology useful for future high energy/intensity



Imaging Jets: the Phase 2 High Granularity Calorimeter of CMS

Innovative choice, a 6M-channel silicon based calorimeter:

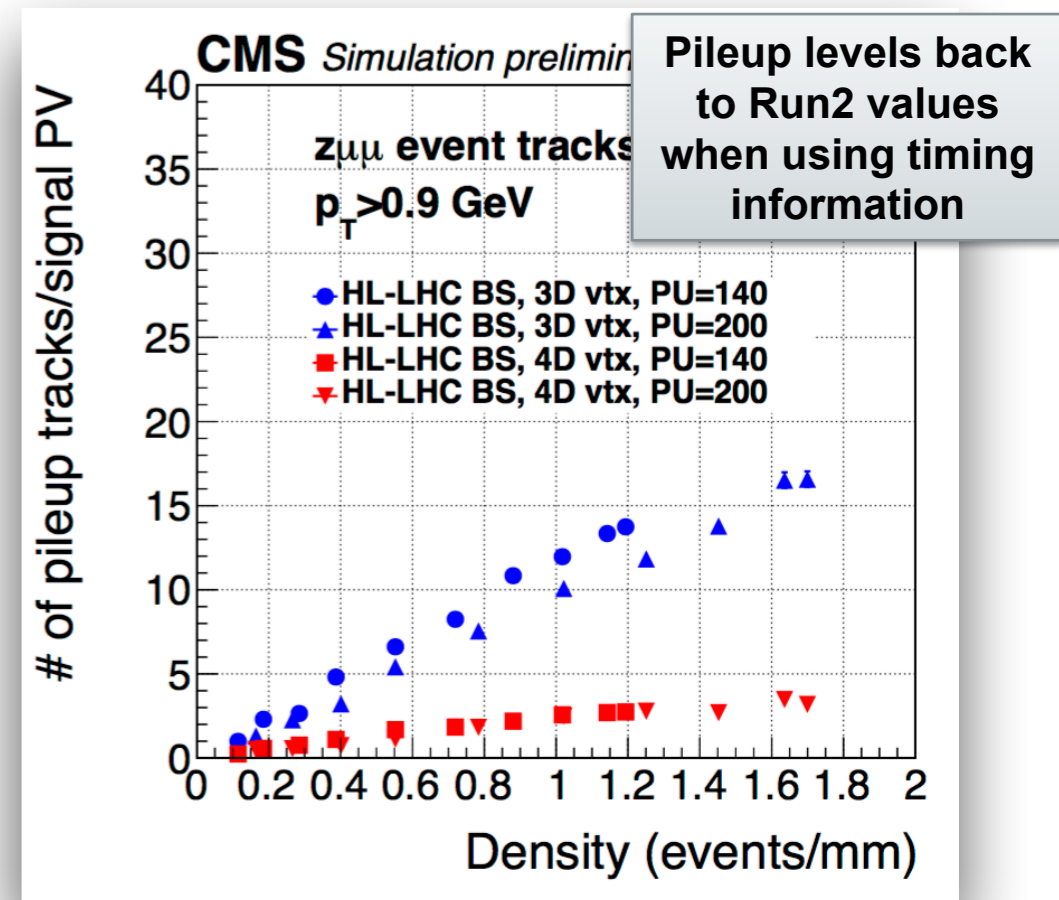
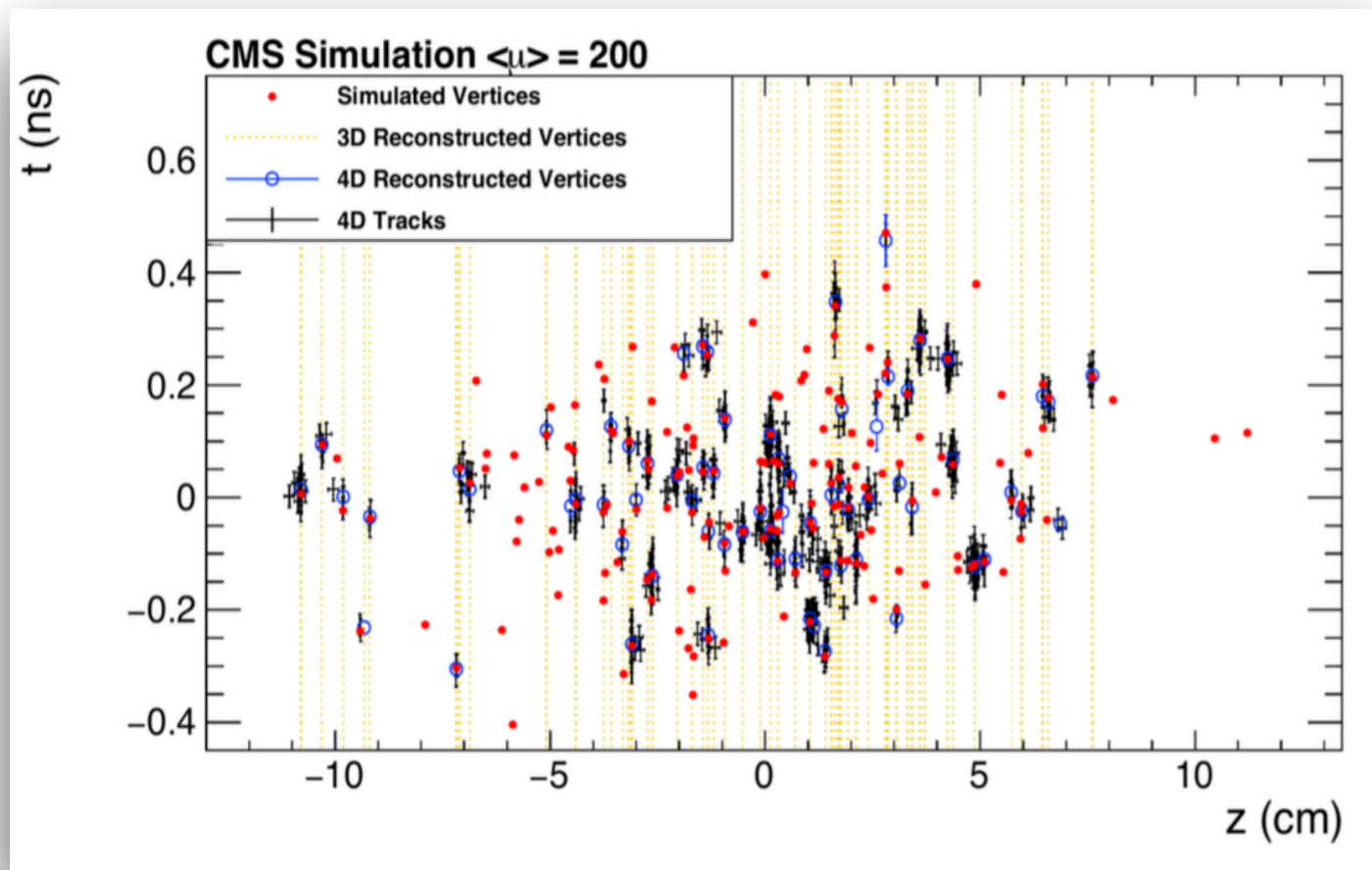
- radiation hard sensors
- providing timing information for pile up suppression
- extending tracking to calorimetry with 3D reconstruction of showers



Timing at the HL-LHC: a timing detector at CMS

Pile-up is THE challenge at the HL-LHC

Timing information allows to further separate hard-scatter collisions from pileup collisions happening close by in z



Technological challenges: radiation hardness of sensors and stability of clock distribution, could be revolutionary for hadron collider detectors

LARP

**Main objectives of HL-LHC: operate the machine up to 2035-37 and produce
10x the luminosity reach of first 10 years of LHC operation**

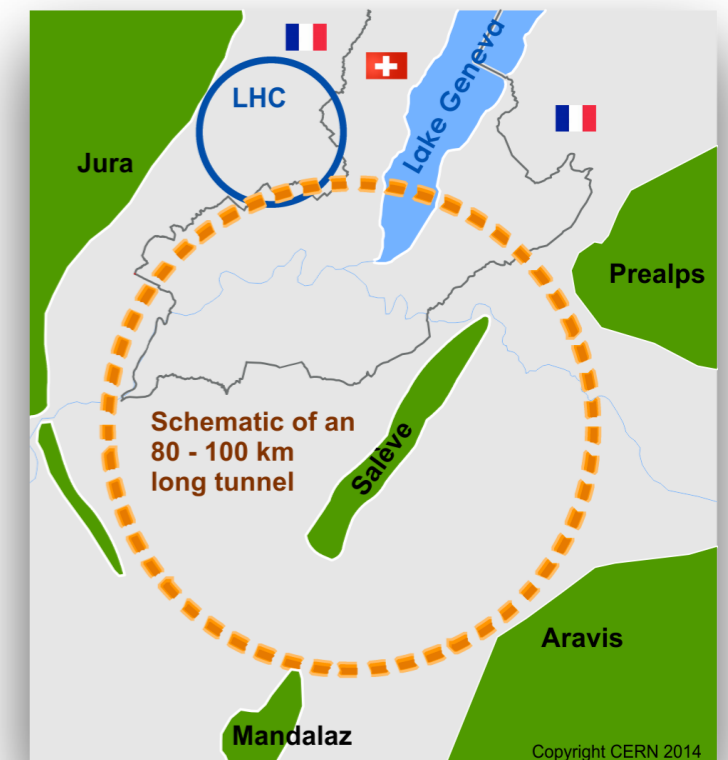
- **Contributions of the US: Large Aperture IR Quadrupoles and Crab Cavities**
- **LARP achieved excellent performances on short/long coils and magnets**
- **Recently the LARP/JLAB Collaboration demonstrated good successes on the front of completion & testing of DQW and RFD Crab Cavities for HL-LHC**



HE-LHC

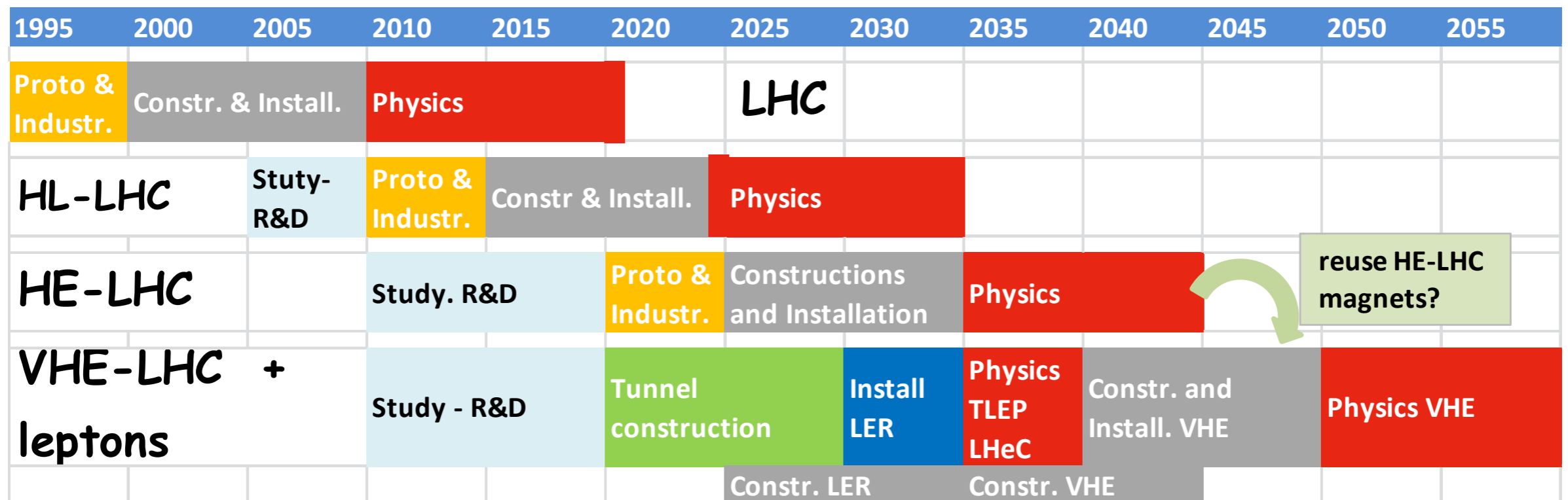
Future Circular Collider collaboration continues effort on high-field collider in LHC tunnel (2035-)

- Yellow Report CERN-2011-1
- Energy of 25+ TeV, Luminosity $25 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Based on 16-T dipoles developed for FCC-hh
- Extrapolation from (HL-)LHC and from FCC developments
- Extend reach for new physics by approximately a factor of 2 in masses
- Can detectors be largely reused ?
- Goal for the FCC collaboration to complete CDR by the next European Strategy update in 2018/2019



Sketch schedule

From presentation by F. Zimmermann in 2013



Additional Material

Phase 1 Upgrade of the CMS detector

Level 1 trigger

Conversion from VME to uTCA system (optical links and FPGAs)

Hadron Calorimeter

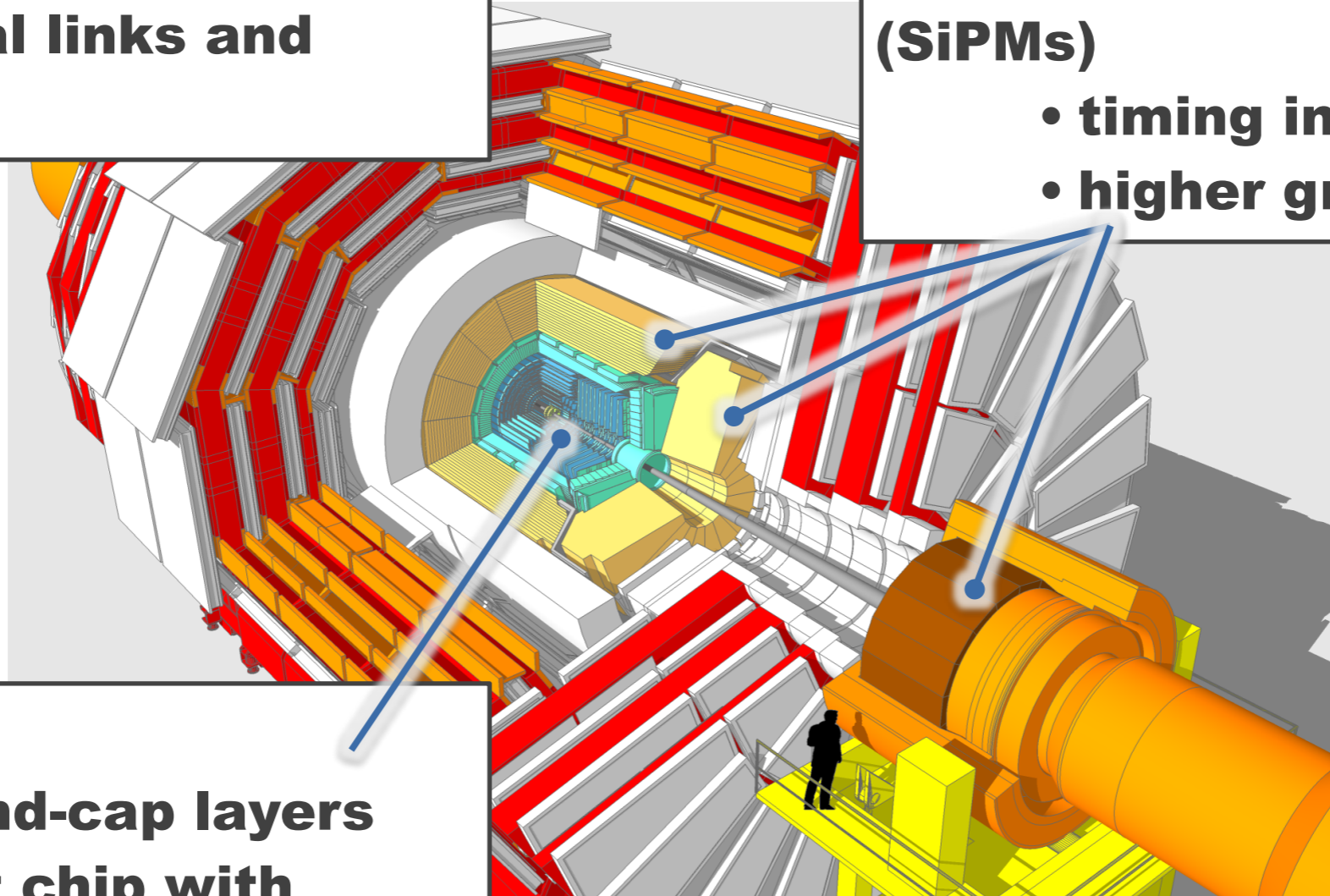
New “front-end” photosensors (SiPMs)

- timing information
- higher granularity

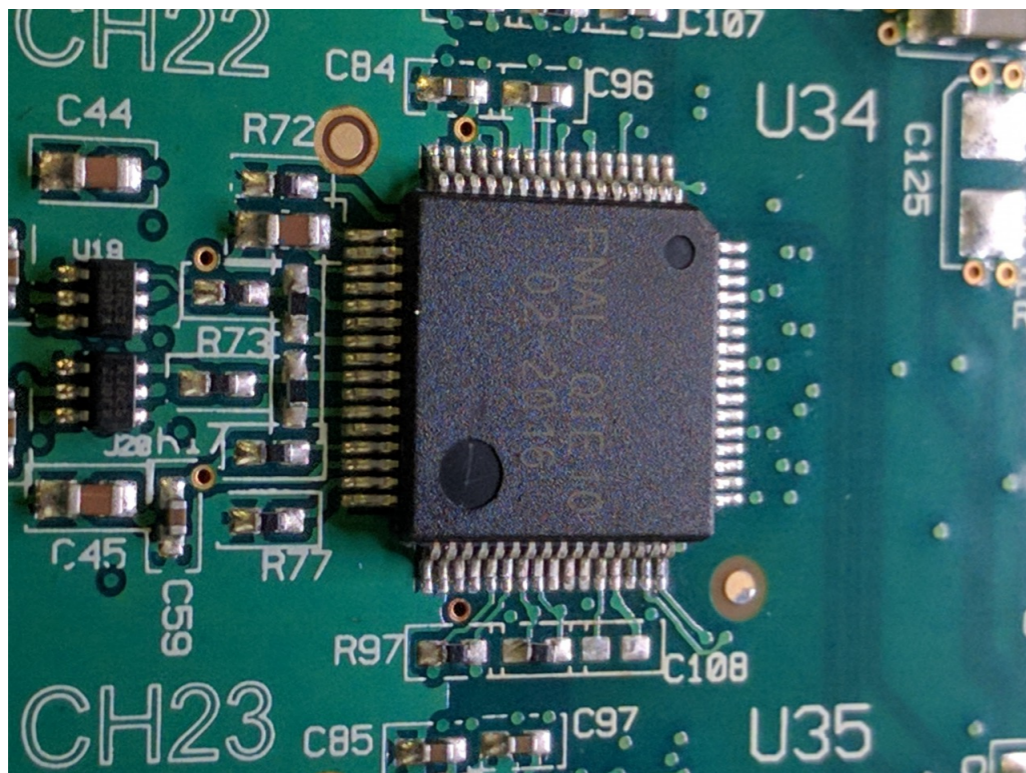
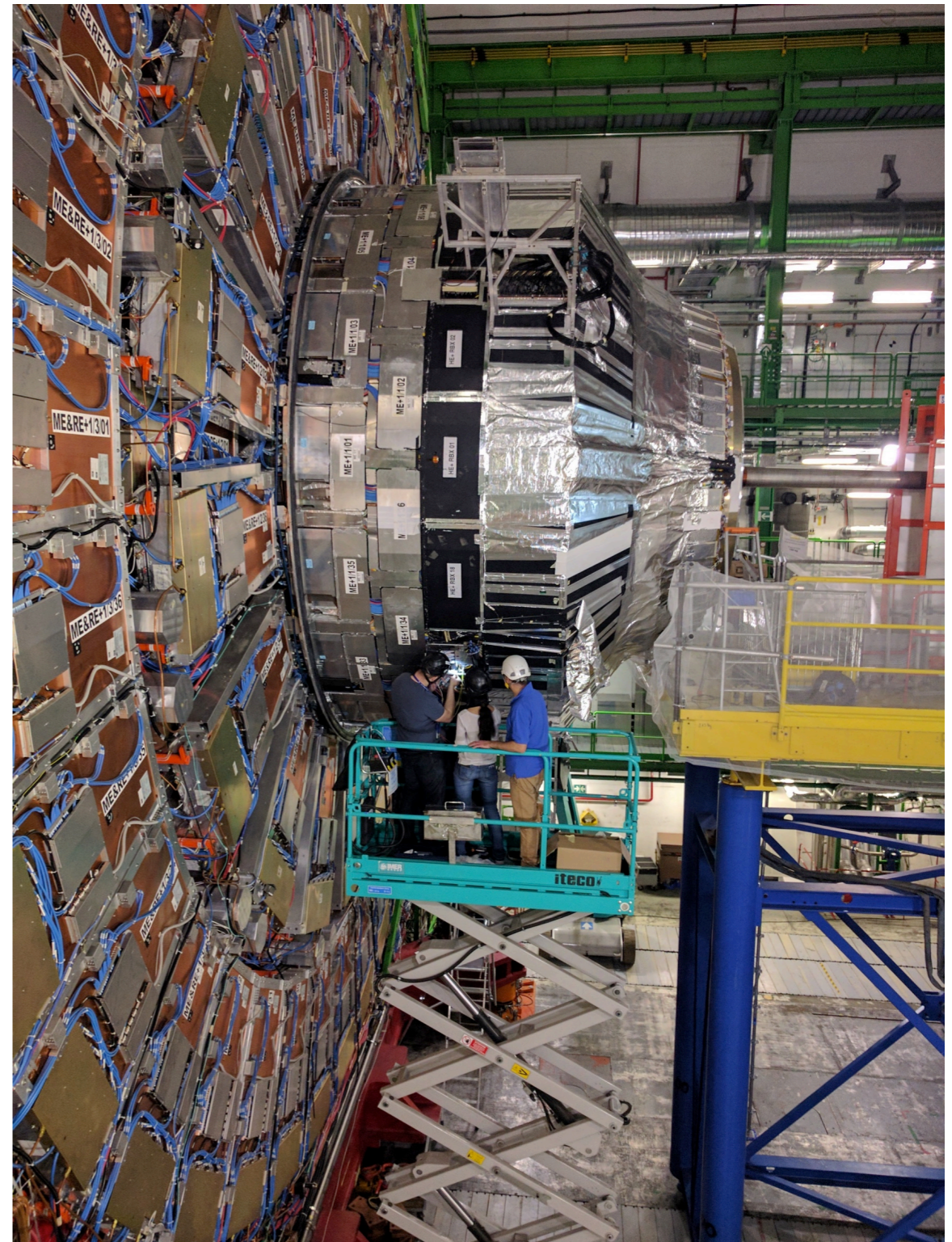
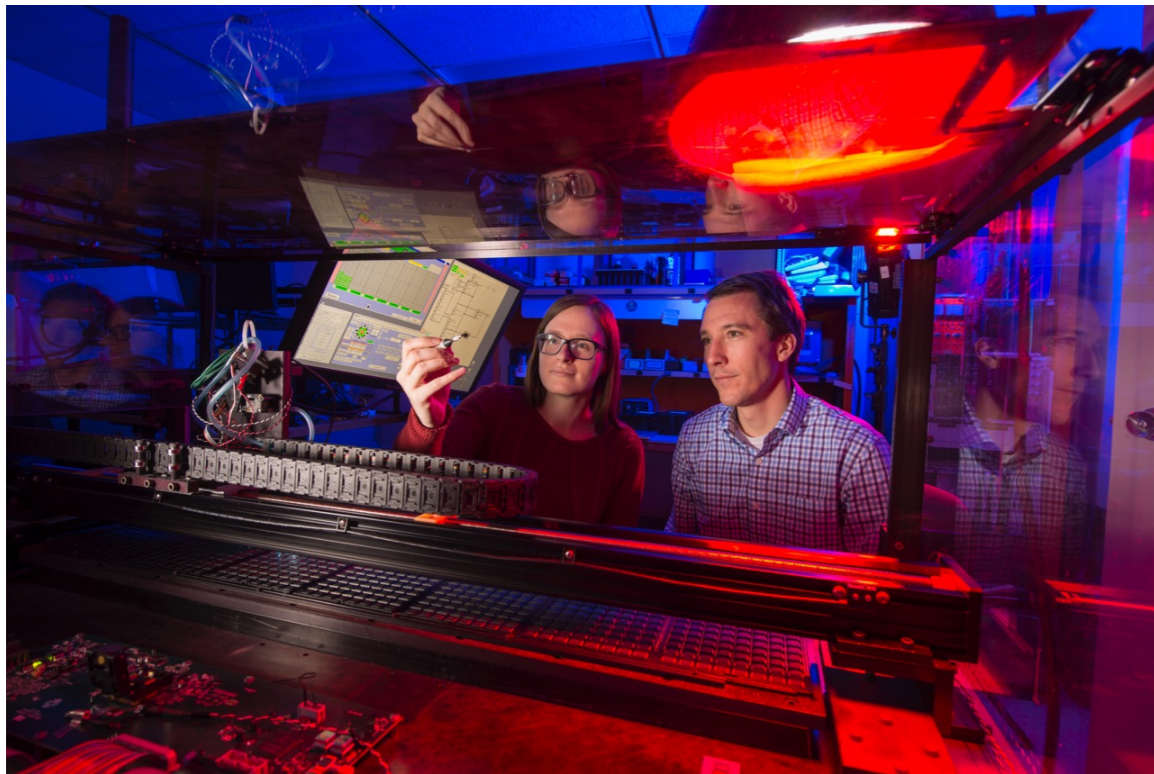
Pixel Detector

4 barrel & 3 end-cap layers

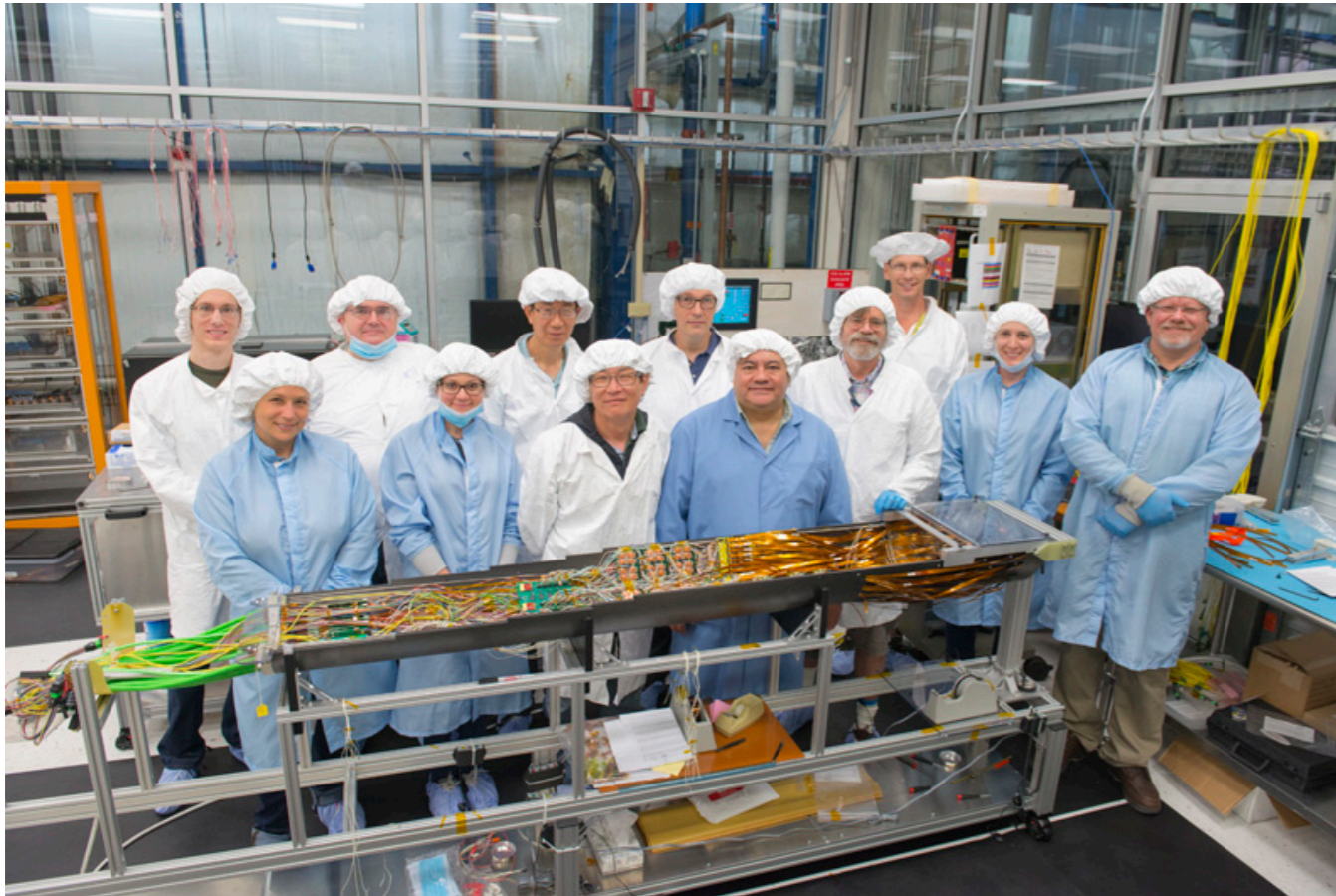
- readout chip with deeper buffers, higher speed
- less mass



Phase 1 Upgrade of the CMS detector



Phase 1 Upgrade of the CMS detector



HL-LHC AUP

- HL-LHC Accelerator Upgrade Project (AUP) has received formal CD-0 (Mission Need) Approval in March 2016.
- HL-LHC AUP Management Team in TD
- HL-LHC AUP gearing up for CD-1 (Cost & Schedule Range) Review in August 2017.
 - HL-LHC AUP Production Plans for both Magnets and Cavities foresee major involvement from TD technical resources
 - Coil Production, Magnet Cold Mass Assembly, Cryostat Assembly and Final Test
 - Crab Cavities Production, processing and testing

Collider reach for Gluinos in Natural SUSY

