CMS Test Beams

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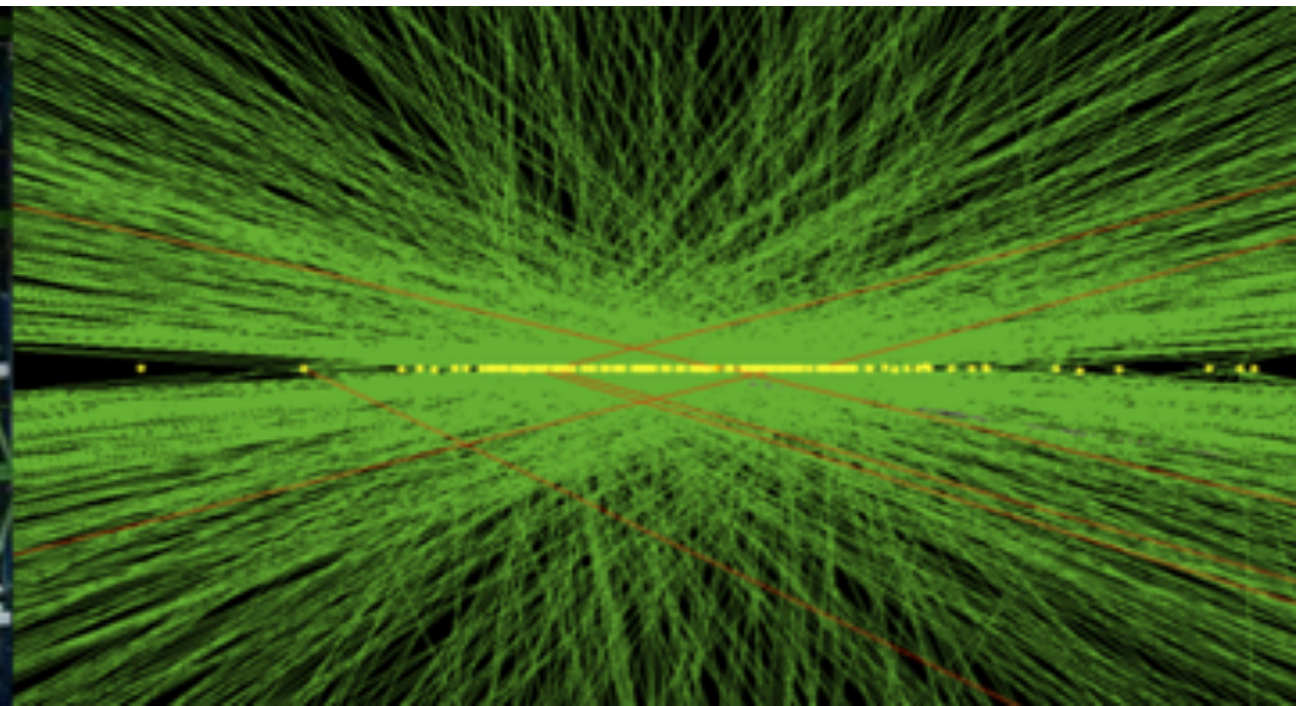
Fermilab Test Beam Committee Meeting

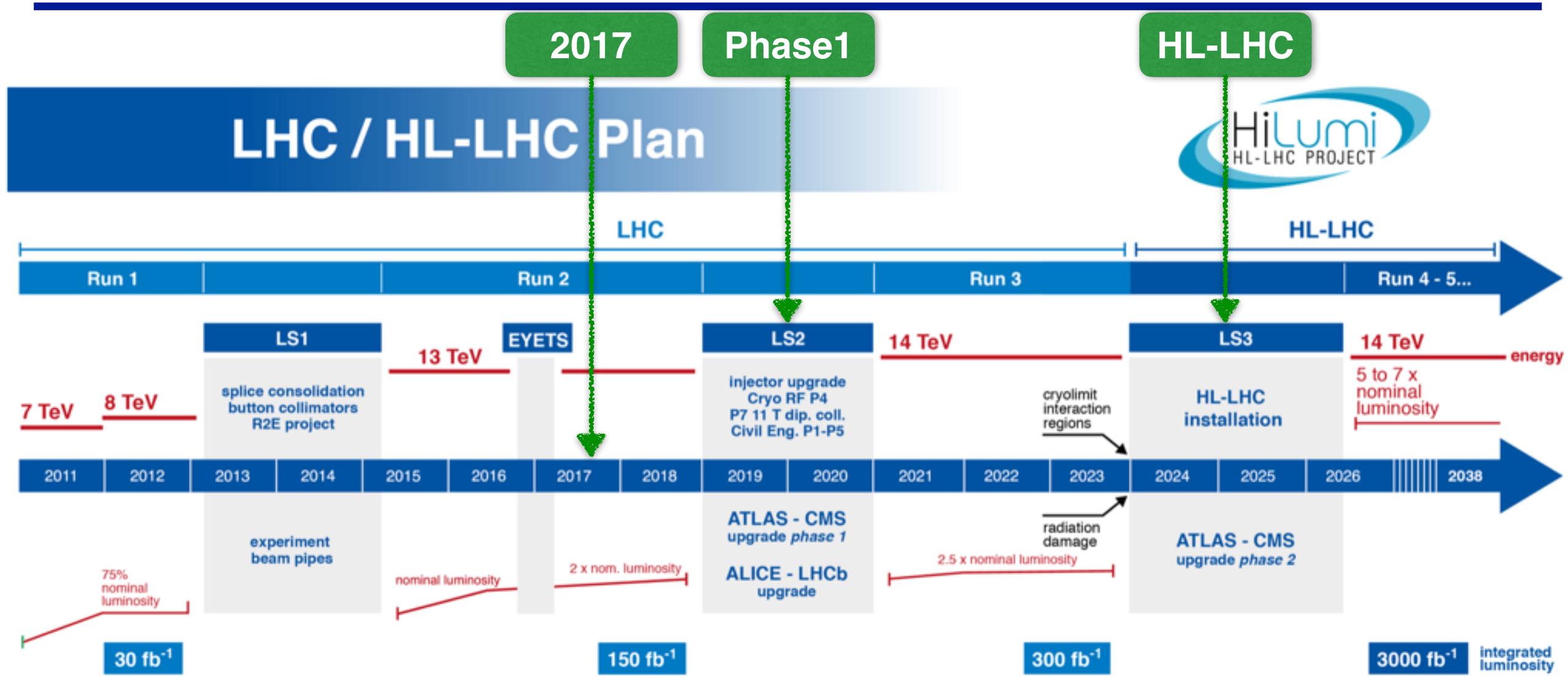
November 3 2017

Fermilab at CMS and CMS at Fermilab

- **FNAL at CMS is researching on 3 out of 5 science drivers identified by P5**
- FNAL is the largest group in US and 2nd largest in CMS
  - more than 100 people active at Fermilab
  - host lab for CMS Operations and Upgrades
  - Joel Butler current CMS spoke-person
- FNAL personnel are active in: data analysis, operations, Phase 1 upgrades, Phase 2 upgrades, computing (Host of US Tier-1, largest of all T1s)
- **FNAL is essential to the success of CMS (and thus of Fermilab and CERN)**
  - **commitment to support test beams for the Phase 2 upgrades**



Upgrade Schedule



Pile-up ~30

Pile-up ~60

Pile-up ~200

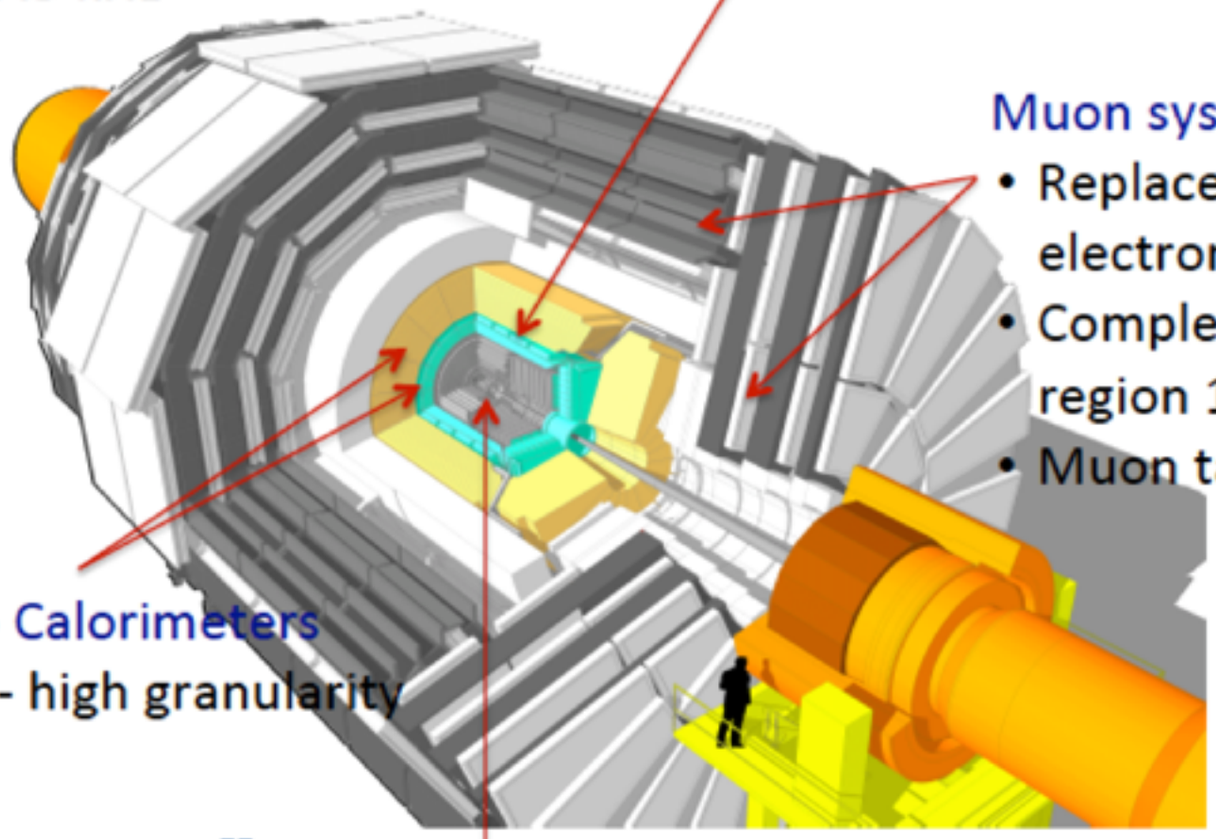
Phase 2 Upgrades of the CMS Detector

Trigger/HLT/DAQ

- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output ≈7.5 kHz

Barrel EM calorimeter

- Replace FE/BE electronics
- Lower operating temperature (8◦)



Muon systems

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

Replace Endcap Calorimeters

- Rad. tolerant - high granularity
- 3D capability

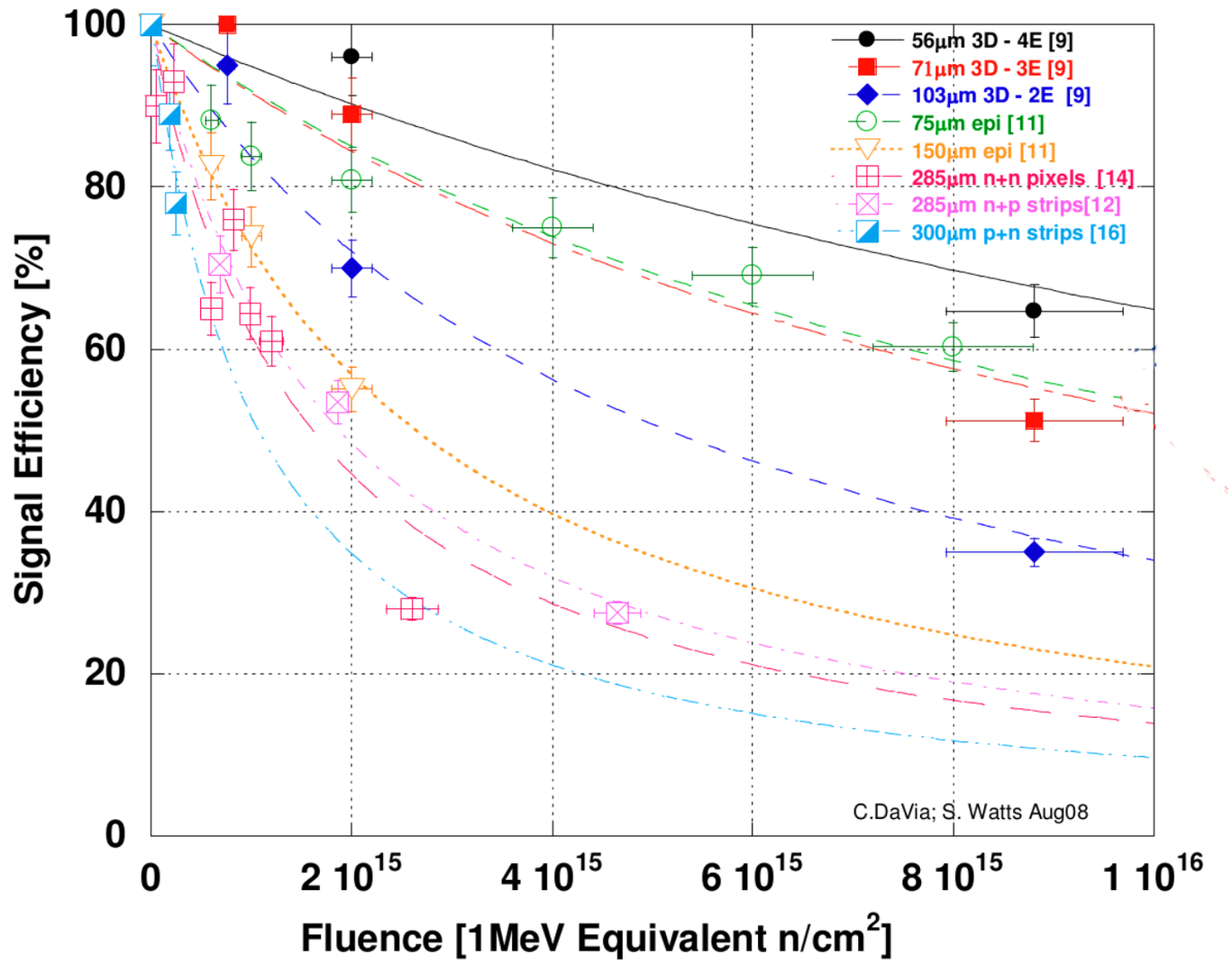
Replace Tracker

- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to η ~4 (TFPIX)

+ Novel Timing Detector

HL-LHC Requirements

- At 3 cm from the interaction point the radiation fluence of $2x10^{16}$ neq/cm^2!!!!!
- Today's pixel sensor technology cannot survive these conditions
- All detectors will be exposed to very high radiation environment



Fermilab

T-992 Experiment at Fermilab

- Our goal is to test the next generation prototypes for the HL-LHC upgrade before and after irradiation to compare the performances and understand if we have a technology capable of withstanding the enormous fluences.

- Big global effort on Sensor R&D for the HL-LHC
  - RD42 (diamond)
  - 3D consortium (3D sensors)
  - ATLAS, CMS and LHCb

- Test beams are essential to study the characteristics of sensors after irradiation, measuring efficiencies and charge collection to make sure that the newly designed structures behave as expected

- It is also important to test in real beam conditions the new Read Out Chips (ROCs) designed for these new sensors

- CMS Pixel and Outer Tracker Phase II are just two of the main participants of this challenging R&D effort

The Pixel detector

- Over the past **4 years** different sensors technologies have been investigated:
  - 3D Silicon sensors
  - Diamond
  - Thin silicon

- The FTBF telescope is an essential tool with bandwidth and resolution and efficiency that are not matched in any test beam around the world

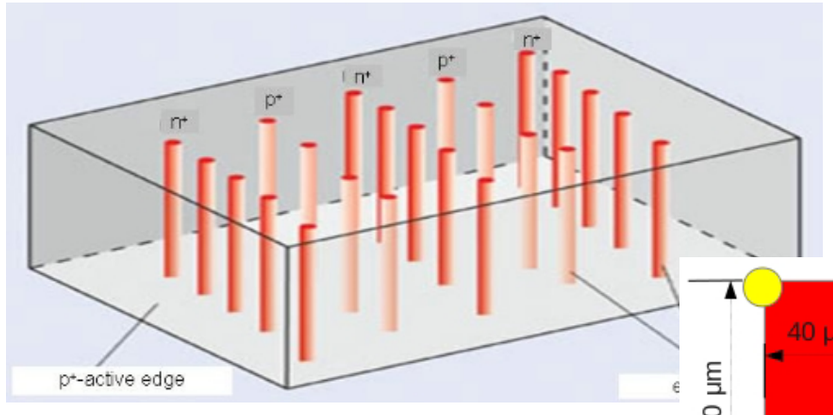
- The 120 GeV bunched proton beam offers a unique opportunity to test the timing of the ROCs and the sensor's resolution with little multiple scattering allowing to resolve precisely design structures at the level of few μm

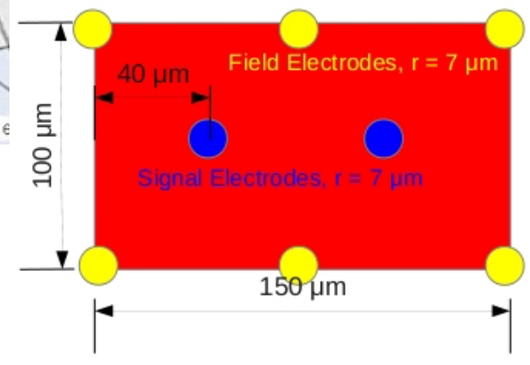
- Pixel collaborators are coming at least twice a year to test their sensors and ROCs before and after irradiation

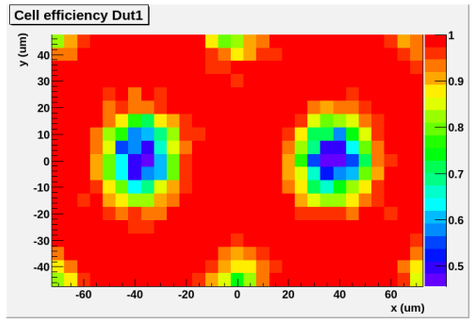
- Sensors are tested after production. They are then irradiated to very high doses and then retested again

- **Uniqueness of the facility demonstrated by having achieved reliable results over the course of the years**

- **Many published papers helped the whole pixel sensor R&D community to narrow down the winning technologies to build the next generation of pixel detectors!**



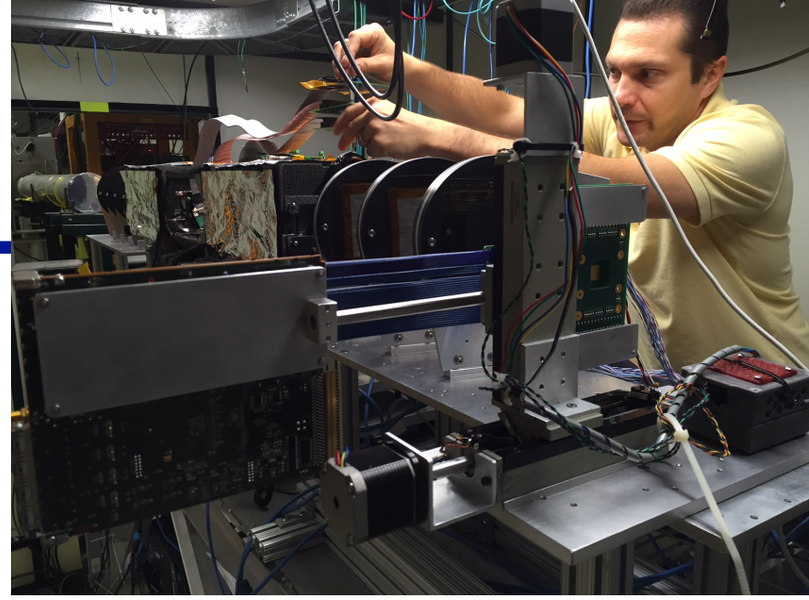




Fermilab

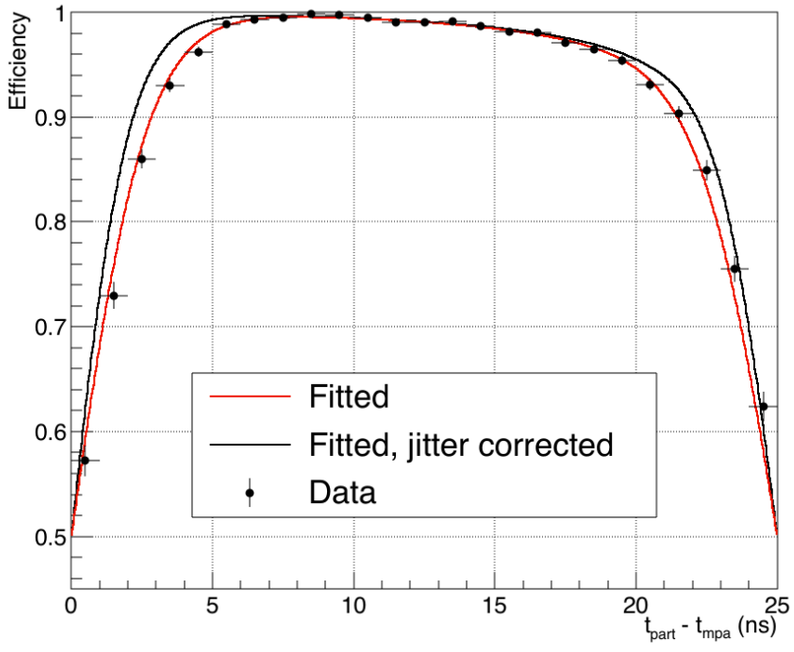
The Outer Tracker (1)

- New >200 m^2 silicon outer tracker essential to the success of the HL-LHC
- USCMS will build > 4000 modules (30% of the outer tracker)
- **Many places to do test beams, but FTBF is the best instrumented and supported**
  - **3-4 test beams in 2016 and 2017**
- TDR results for pixel-strip module R&D <u>are exclusively from FTBF</u> (TDR needed to get the LHCC approval of Outer Tracker)
- An excellent match to the US CMS leadership role in pixel-strip module development
- European CMS colleagues realize the value of FTBF and are coming here for their tests



First PS R&D module (made in the US)

First timing measurement with particles of the PS ASIC prototype (made with FTBF data)



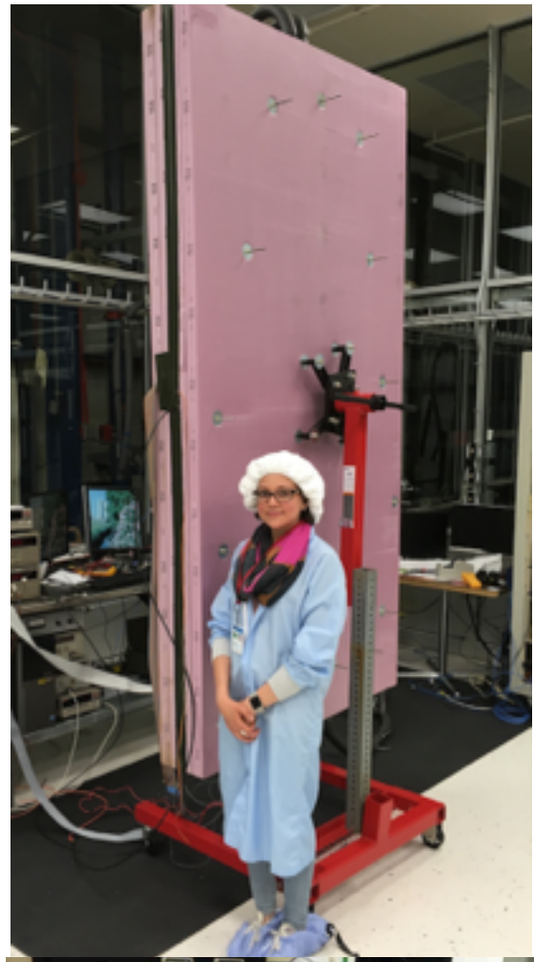
The Outer Tracker (2)

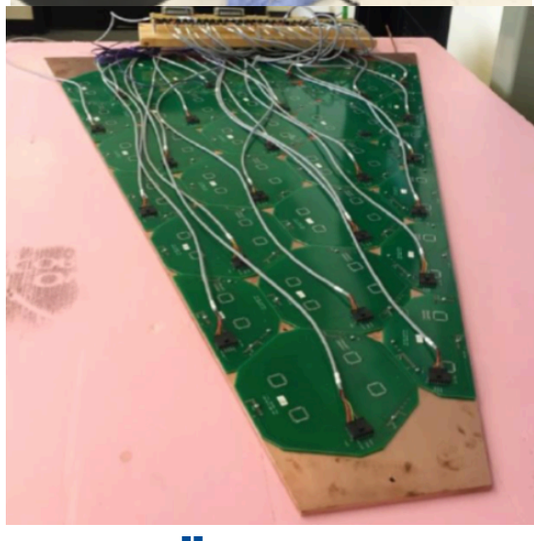
- **Devices for tests in remaining months of 2017**
  - minimodule (US CMS test beam)
  - 2S full size module (official CMS test beam - 8 colleagues from Europe)
- 2018-2019 are critical for the OT: pre-production components are coming in and we need to make every effort to verify the design with real particle in real beam
  - Lot of ambitious design features: FE ASIC inter-communication, hit pair reconstruction @40 MHz, 10Gbps DAQ, etc
  - Some are the core of the US contribution to the OT, i.e. Macro-Pixel-Sub-Assembly (MaPSA) and OTSDAQ
- **Devices for tests in 2018**
  - First SSA and MaPSA tests with beams
  - First Pixel-Strip mini-module prototype validating inter-ASIC communication and stub formation
  - Pixel-Strip pre-production modules
  - Strip-Strip pre-production modules

  - No available test beam slots at CERN in the next few months so results of the upcoming FTBF test beam for OT are a crucial validation of the design of the new ROC that will be tested for the first time in a beam here!

The High Granularity Calorimeter

- Novel calorimeter in the forward region capable of imaging jets
  - essential to cope with unprecedented level of pile expected at HL-LHC
- FNAL will assemble 360 cassettes, each containing ~40 8” silicon modules
- **US CMS responsible for module and cassette production**
- **It is critical for the US to carry out test beams of the prototypes**
- In 2016, 4 weeks of test beam
  - test of the 1st HGCAL modules
- New campaigns expected in 2018
  - 3 generations of front end chip expected, all must be tested

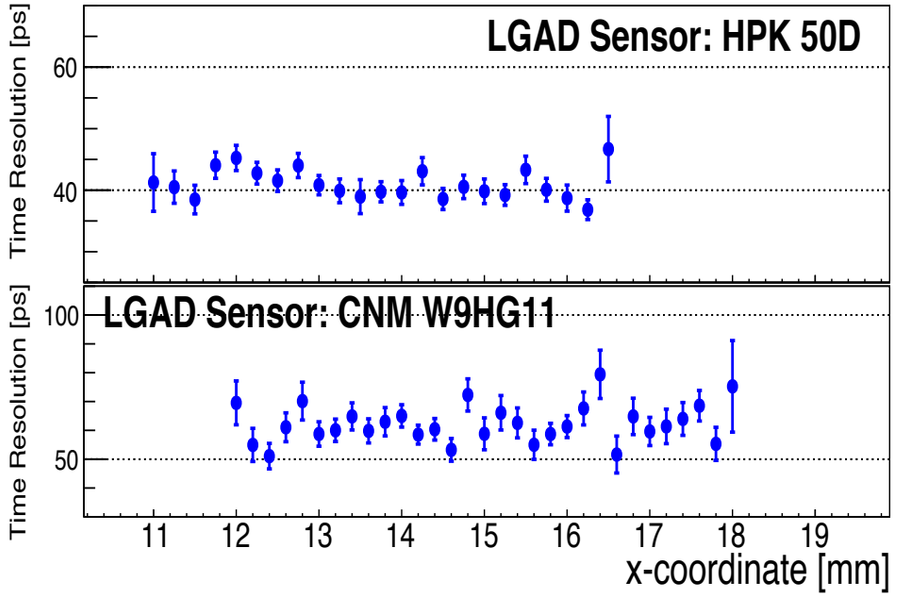




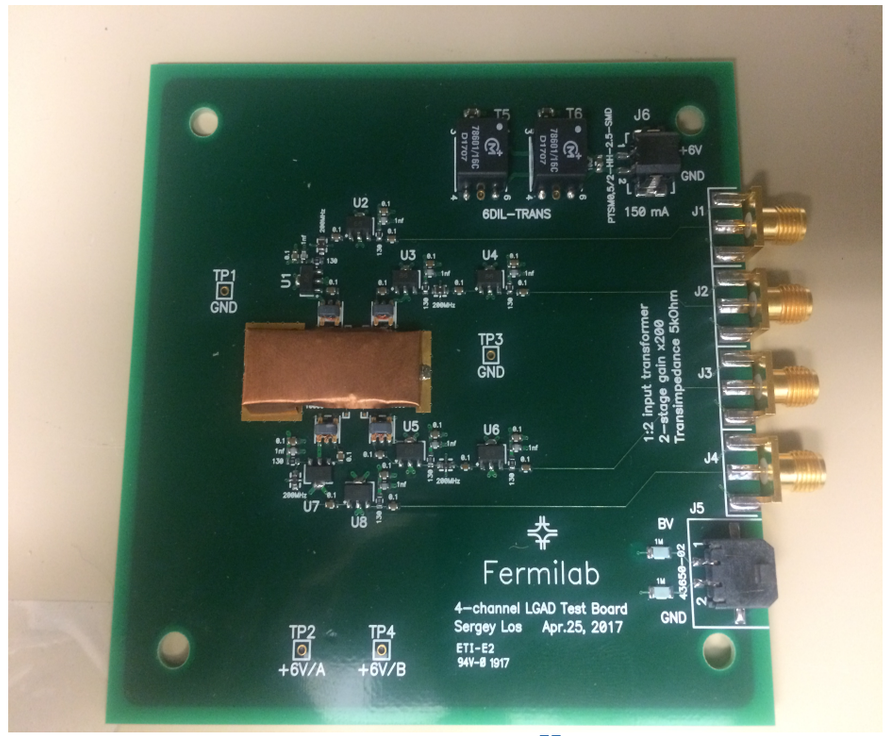
The Timing Detector

- **Adding the 4th dimension to CMS, measuring the timing of particles' arrival allows to further suppress the pile up**
- **FNAL is leading the R&D of the LGAD silicon sensors and readout ASICs for the End-cap timing detector**
- Collaborative effort between CMS and ATLAS institutions
  - Test beam campaign in May 2017: **ATLAS+CMS**
    - Close collaboration with Hamamatsu, CNM, FBK
    - Publication submitted to NIM A
- Thanks to unique pixel telescope in the FTBF, for the first time we looked at the behavior between pixels
  - Quantified the size of the dead area, sensors uniformity, working on the next generation with manufacturers

Time resolution across sensor surface



Readout board designed at FNAL

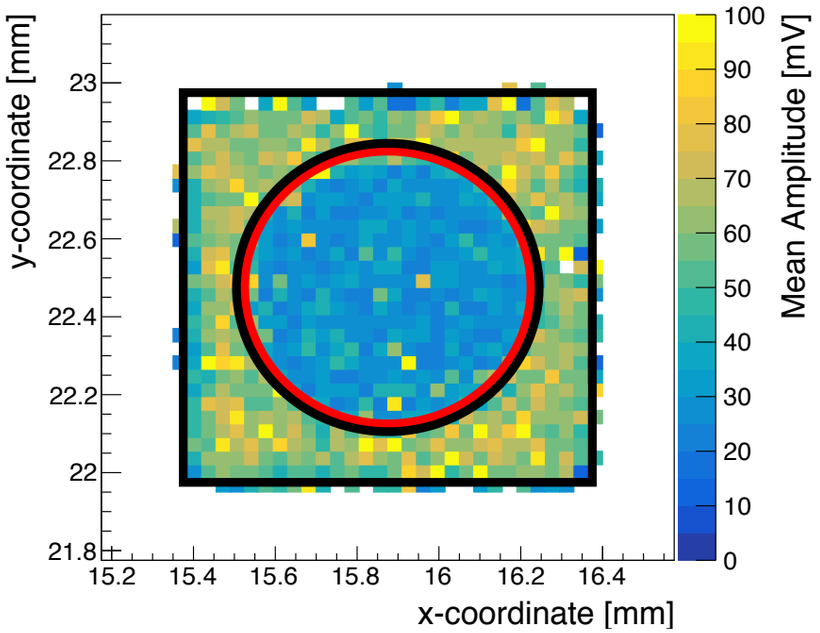


The Timing Detector

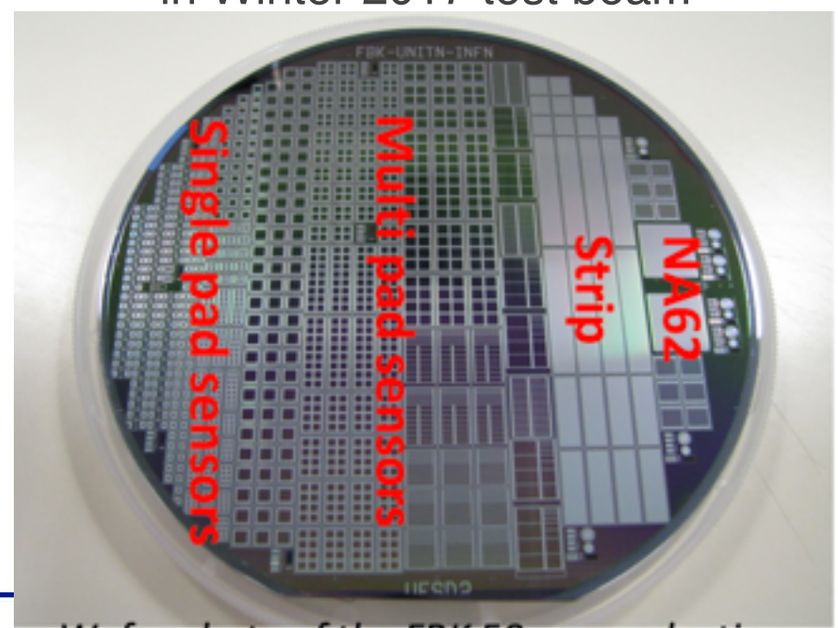
- FTBF has been a critical facility for timing detectors
  - > 10 publications on timing R&D in the last 3 years

- **Testbeam in Winter 2017**
  - **Barrel Timing detector: SiPM+LYSO**
    - University of Virginia, Caltech, Notre Dame, Princeton, Northeastern
  - **Endcap Timing Detector**: **LGAD silicon sensors**
    - FNAL, Caltech, UC Santa Barbara, University of Helsinki, University of Torino
- **TDR preparation in 2018**
  - 2 more test beams already scheduled in 2018
- FNAL plays a leading role in sensor and ASIC development: **more test beams will be needed in the coming years!**

Time resolution across irradiated sensor surface: gain dependance on metal on the surface



New sensors from FBK to be tested in Winter 2017 test beam



Wafer photo of the FBK 50μm production

Summary

- CMS will be upgraded in preparation for the HL-LHC

- The FTBF facility is CRITICAL for the success of CMS, Fermilab, CERN
  - As a support facility for the high priority Fermilab projects (Outer Tracker, HGCAL, Timing)
  - As a user support facility for US CMS (Fermilab is the host lab for US CMS, CERN relies heavily on Fermilab for the successful completion of the US CMS project)
  - As a user facility for the International CMS

- *Important: CERN won't have beam in 2019-2020, exactly when the Phase 2 projects are transitioning from prototyping to production*
  - *Unique opportunity for Fermilab as the US national lab for particle physics to continue to lead in the next years*

Collaborators

- Pixels

  INFN Milan, INFN Torino, INFN Firenze, INFN Lecce, Purdue University, Cornell University, University of Colorado, The University of Tennessee

- Outer tracker

  Fermilab, UCSD, DESY, Louvain, Bristol, IC London, Vrije Universiteit Brussel, CERN, Rutgers, Brown, Rochester

- HGCAL

  University of Minnesota, Northwestern University, Texas Tech University, CMU

- Timing

  UC Santa Cruz, University of Kansas, Caltech, FNAL, Northeastern University, University of Torino, UC Santa Barbara, University of Helsinki, Princeton