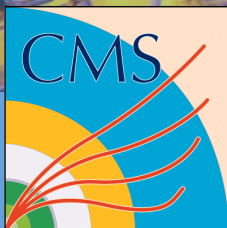


The CMS performance and Upgrade plans

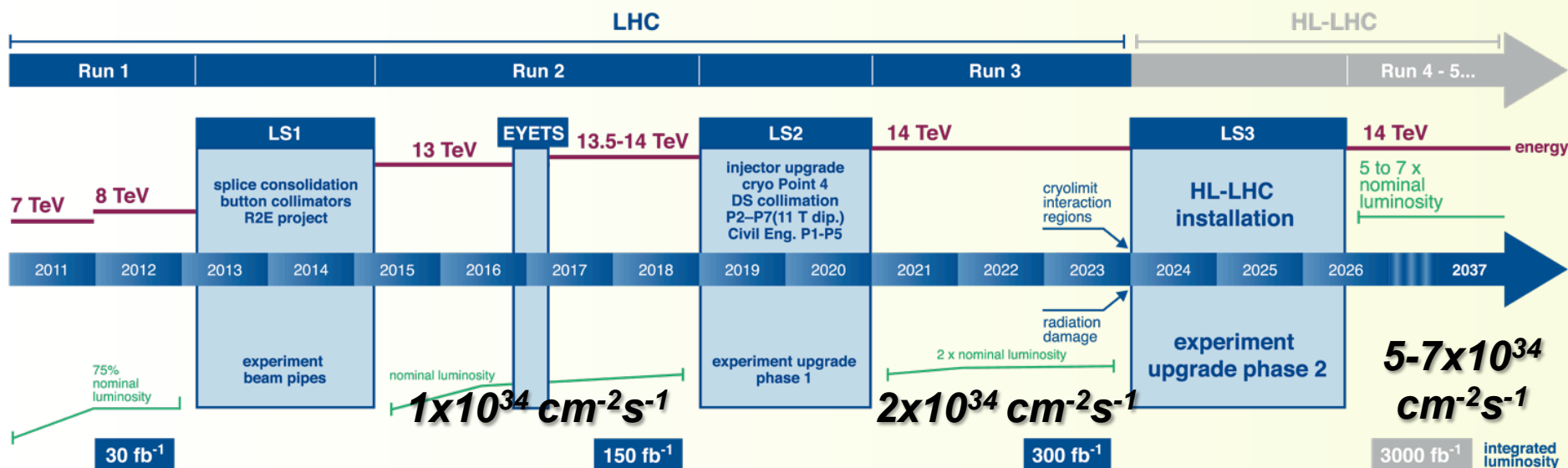
Alexandre Zabi
for the CMS collaboration

LHC Days 2016 Split Croatia



The LHC Roadmap

LHC / HL-LHC Plan



Phase I (until 2023): Ongoing, collecting data delivered with high luminosity from the LHC
 → Consolidating CMS on the way

Phase II (starts 2024): R&D and tests of first designs
 → CMS getting ready

OUTLINE

CMS performance and the Phase I upgrade:


The CMS detector is **recording efficiently** the data delivered by the LHC. The detector is being **consolidated to maintain the performance** through the whole of Phase I

- ***Operations of the detector at high-luminosity***
- ***Performance on single objects***
- ***Impact of these performance on physics***
- ***The Phase I Overview (lots of R&D preparing HL-LHC program)***

The CMS Phase II upgrade:

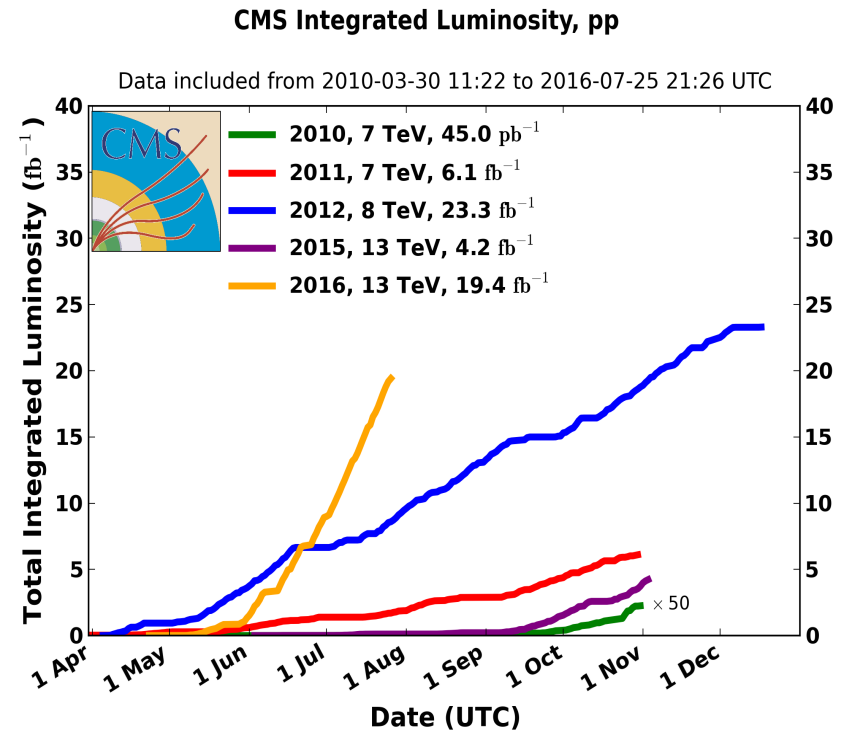
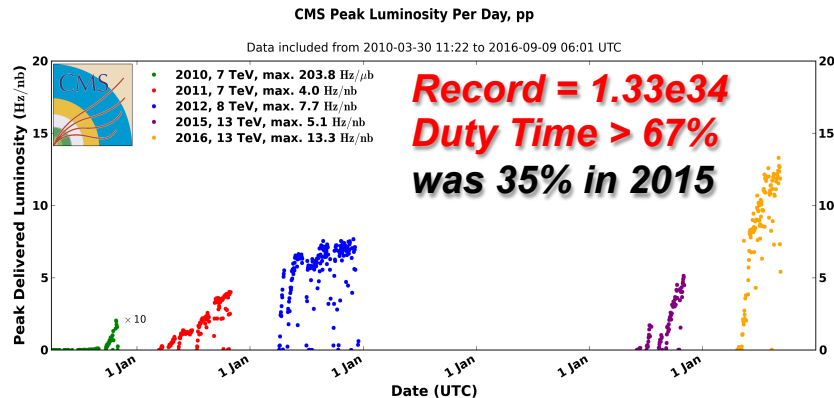
As we go toward the **HL-LHC**, the CMS detector will **undergo major changes** to maintain a level of performance similar to the one of Phase I in the much harsher environment:

- ***Replacement of the tracking and part of the calorimeters***
- ***Improved Muon system***
- ***New Readout, DAQ and Trigger electronics***



CMS Performance and the Phase I Upgrade

CMS & the LHC



Data Taking conditions & performance:

- **LHC peak lumi $1.33 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$**
→ delivering @ record pace 30-40 fb⁻¹ end of 2016. PU < 25 >
- **CMS Data taking efficiency: 92.5%**
92% of logged data good for analyses
Typical “Deadtime” ~3%.
→ Complex machinery in place to keep data collection running

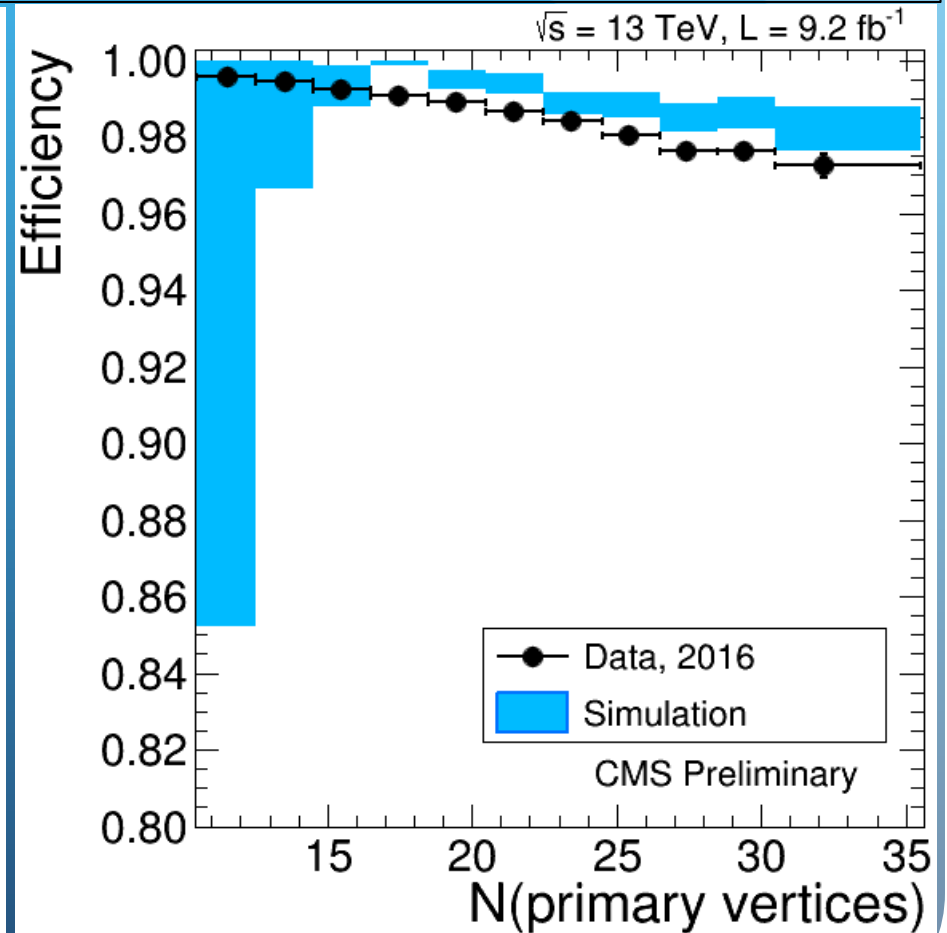
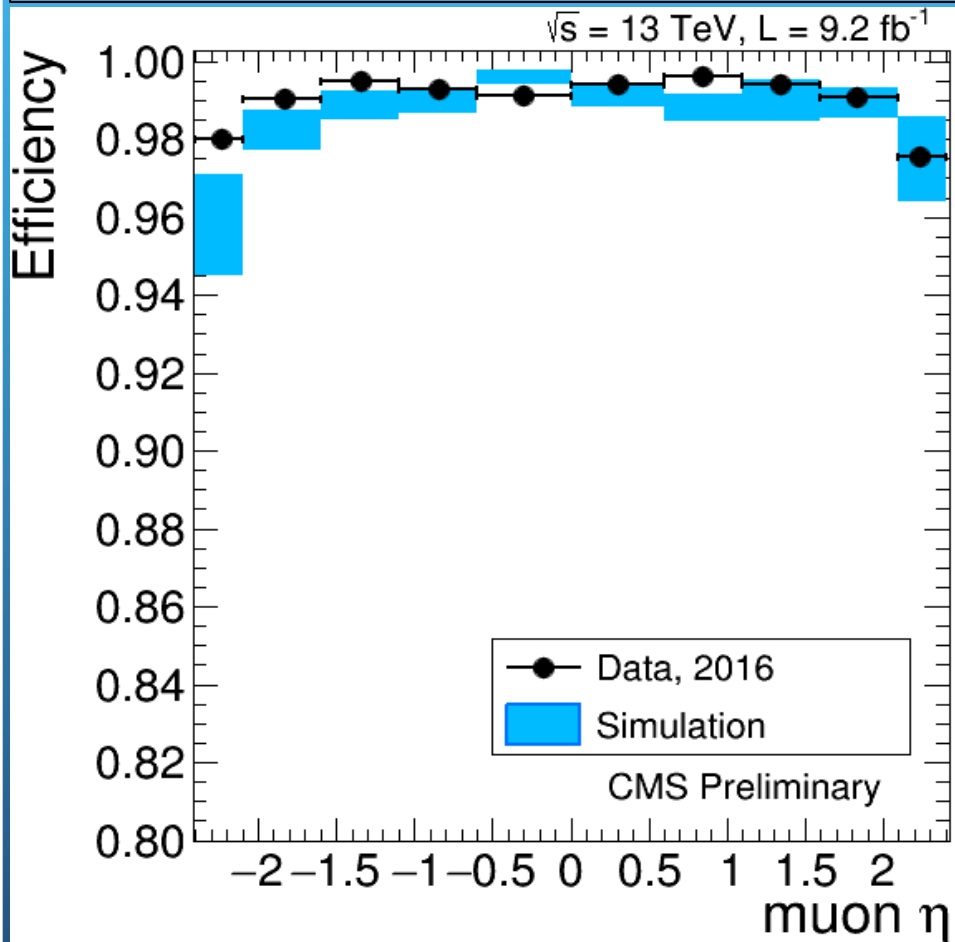
Amazing performance of the LHC, which exceed even the most optimistic performance estimate!

→ **Thanks and congratulations to the LHC team**

Physics Objects

Muon reconstruction

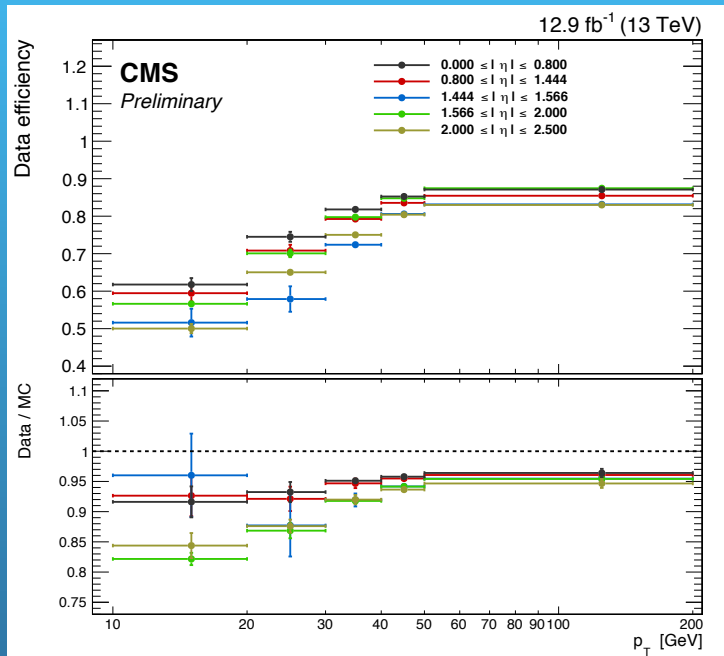
Improved reconstruction for Run II to face high lumi and pile-up



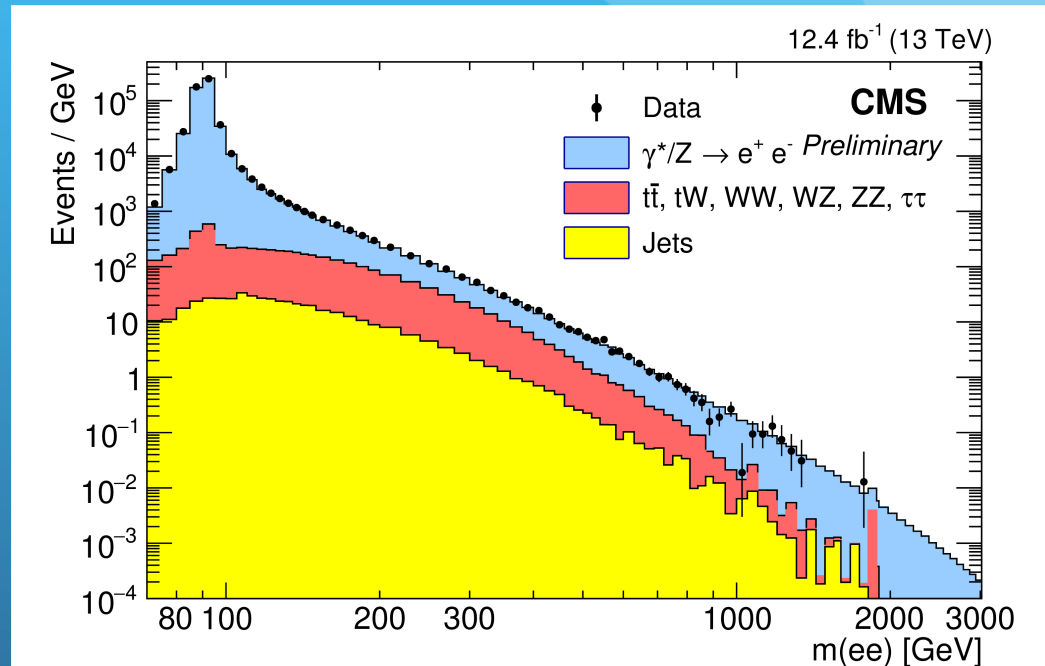
CMS-DP-2016-043

Physics Objects

Electron/Photon reconstruction



Electron Identification



M_{ee} invariant mass

Excellent reconstruction, ID & Iso performance CMS-DP-2016-049

→ Electron reconstruction > **96%**, Identification MVA > **90%** (p_T>50 GeV)

→ Photon identification MVA > **90%** (p_T>50 GeV)

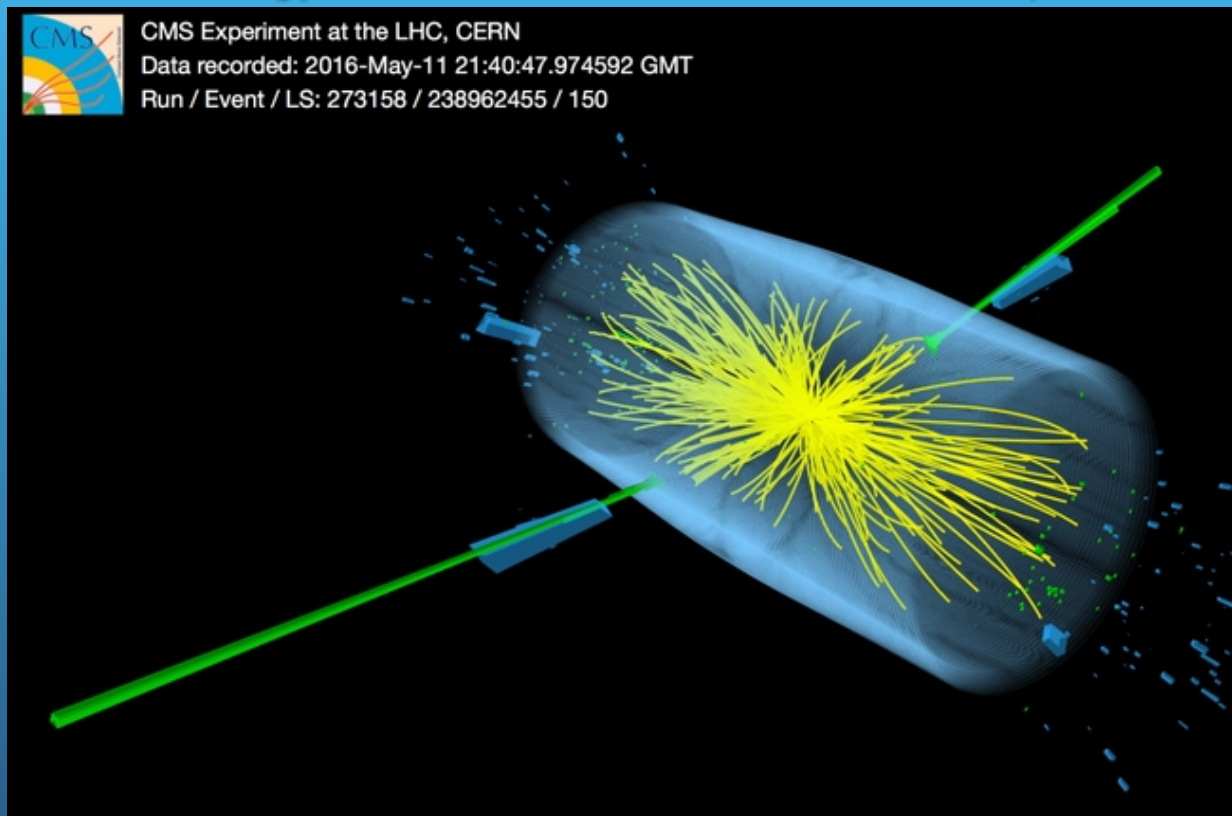
Physics Objects

Highest reconstructed Jet invariant mass

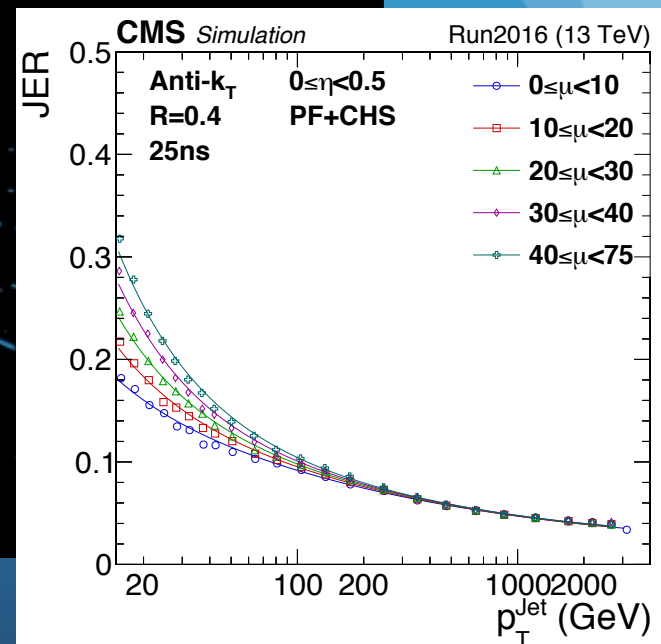
→ Jet energy scale and correction made independent of PU ($p_T > 100$ GeV)



CMS Experiment at the LHC, CERN
Data recorded: 2016-May-11 21:40:47.974592 GMT
Run / Event / LS: 273158 / 238962455 / 150



Invariant mass reconstructed → 7.7 TeV

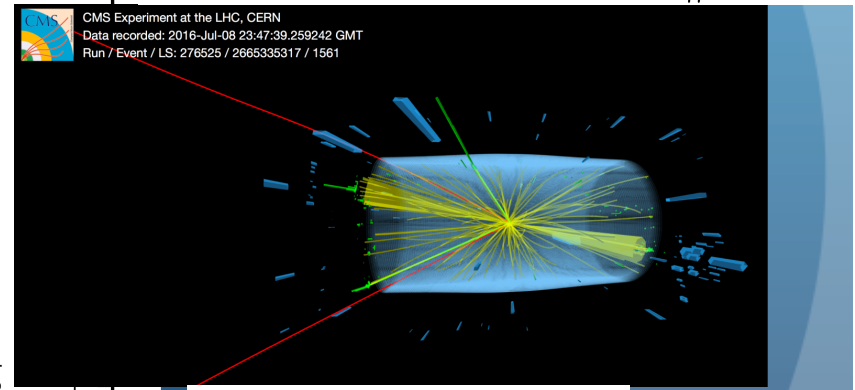
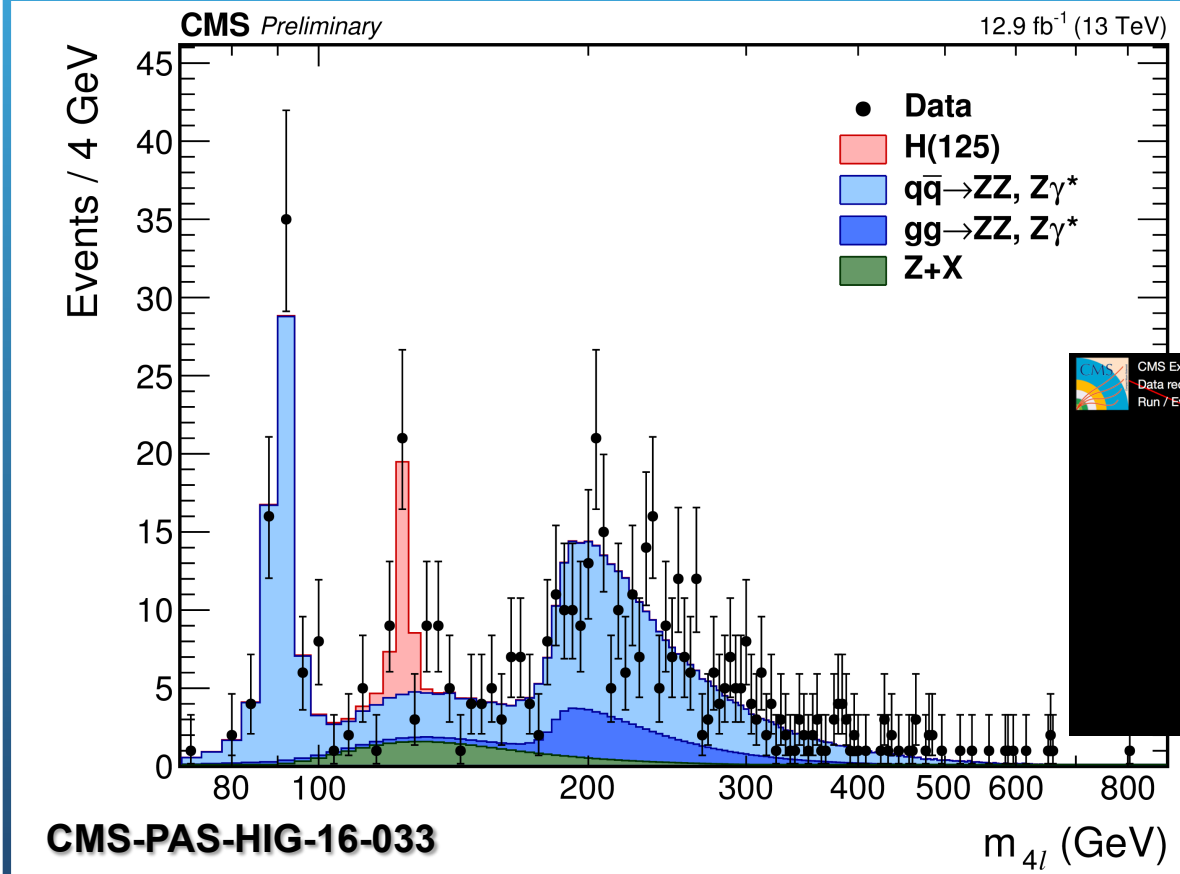
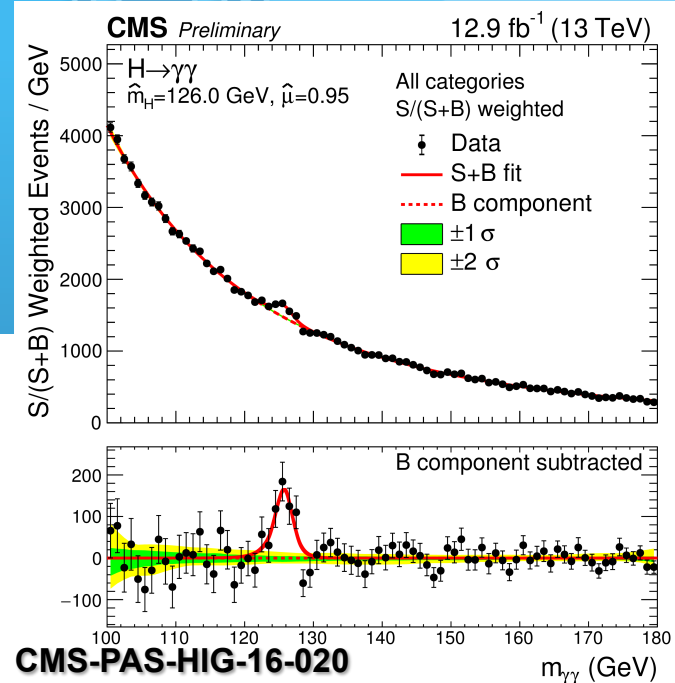


CMS-DP-2016-020

Higgs @ 13 TeV

Higgs signal @ 13 TeV

→ Given the excellent performance on single object reconstruction, *the Higgs signal @ 13 TeV has been successfully rediscovered!*



CMS Phase I Upgrade

CMS



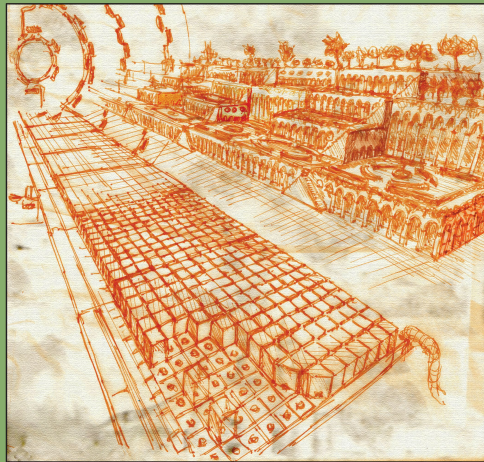
CMS TECHNICAL DESIGN REPORT
FOR
THE LEVEL-1 TRIGGER UPGRADE

L1 Trigger Upgrade

- *Completed in 2016*
- *Upgrade muon&Calo*
- *μ TCA & Large FPGA*

LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES CERN-LHCC-2012-016
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS CMS-TDR-011
7 September 2012

CMS



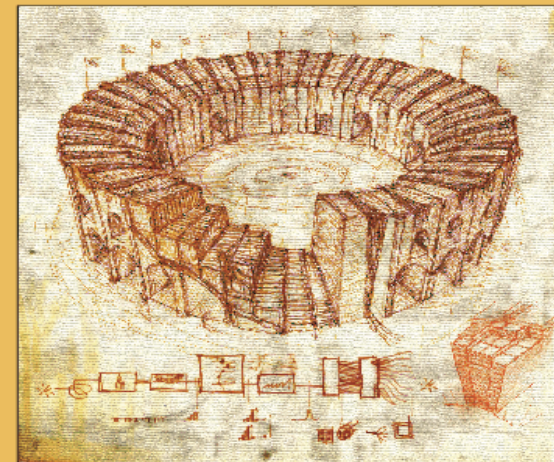
CMS TECHNICAL DESIGN REPORT
FOR
THE PIXEL DETECTOR UPGRADE

Pixel Upgrade (2017)

- *4 Layers Barrel*
- *4 Disks forward*
- *High Rate readout*

LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES CERN-LHCC-2012-015
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS CMS-TDR-010
26 September 2012

CMS



CMS TECHNICAL DESIGN REPORT
FOR THE PHASE 1 UPGRADE
OF THE HADRON CALORIMETER

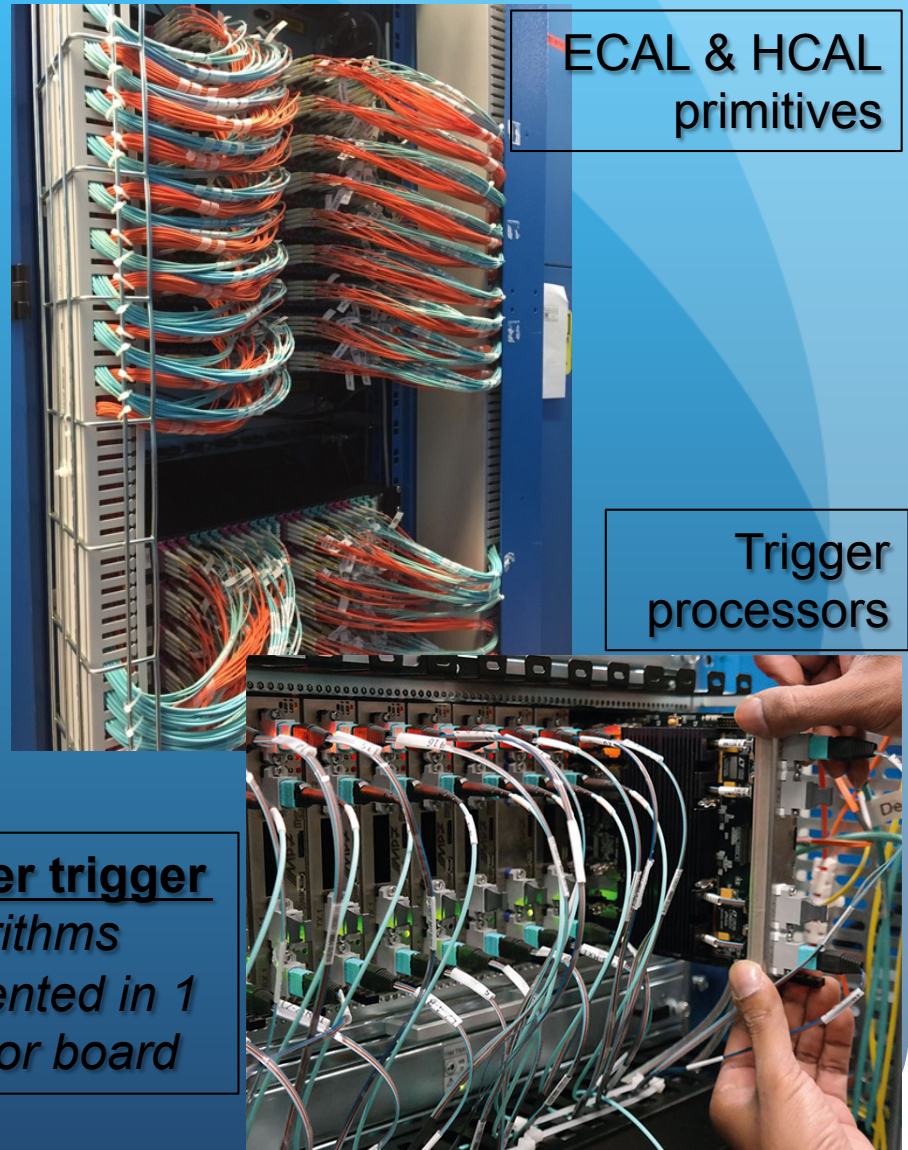
HCAL Upgrade (2015-18)

- *Change Photodetector*
- *Change Front & Back-End electronics*

L1 Trigger Upgrade

L1 Trigger Upgrade

- Use of *modern technology*: architecture using μ TCA & FPGA
- *Improved granularity*: Full tower granularity from ECAL & HCAL
- *High-speed optical links*: All input data transmitted @ high speed
- *Processing 1000Tb/s using Time-Multiplex-Trigger architecture*
- Trigger installed in stages and commissioned in 2015. Fully operational in 2016
- *Increased selectivity @ L1 for physics*

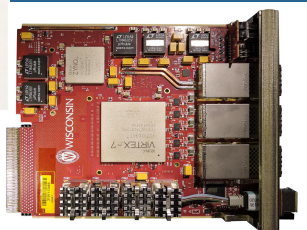


ECAL & HCAL primitives

Trigger processors



MP7



CTP7

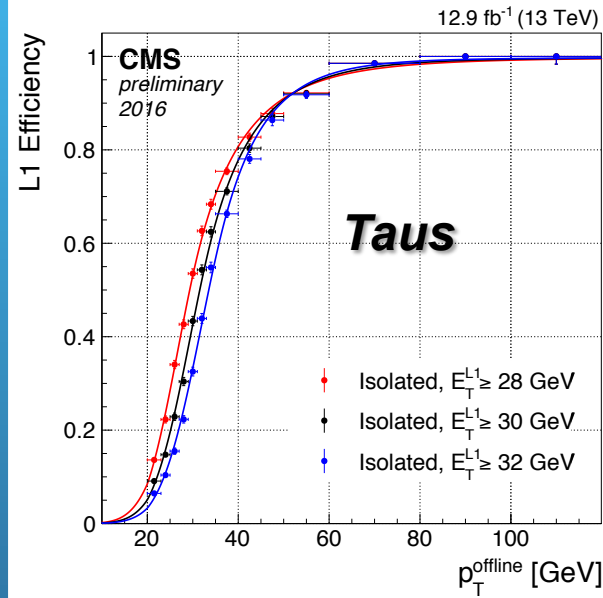
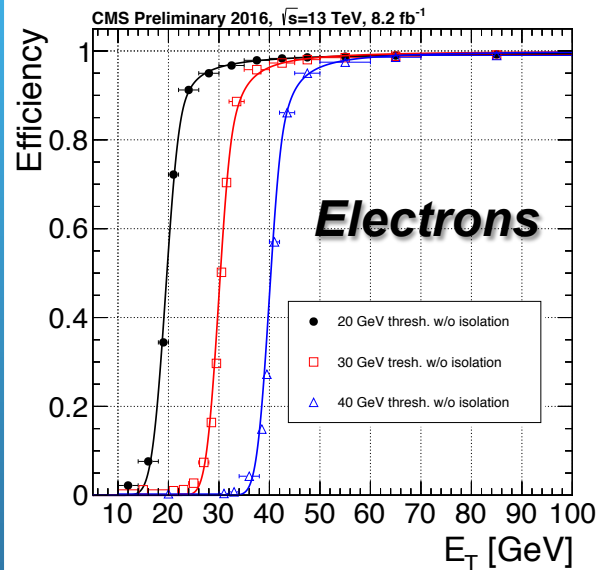
Calorimeter trigger

- All algorithms implemented in 1 processor board

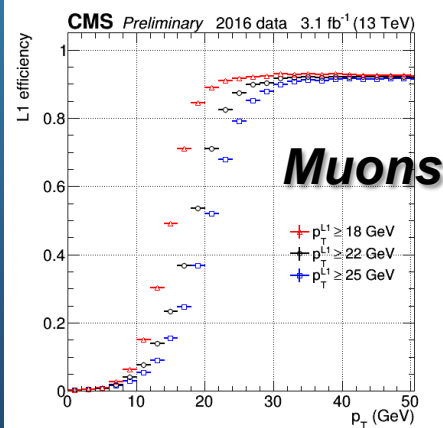
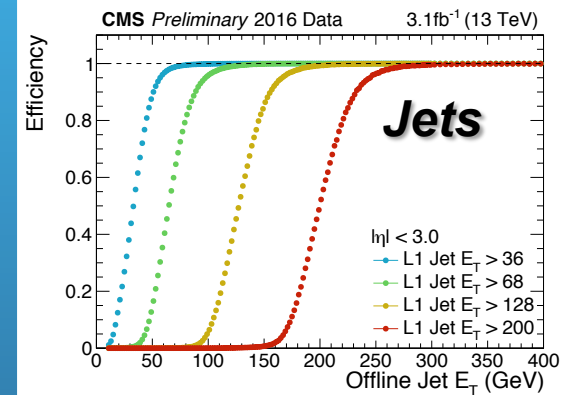
Triggering Performance

Trigger architecture upgrade in stages as lumi goes up

→ **Maintain thresholds for Physics using sophisticated algorithms @ L1**



CMS-DP-2016-044



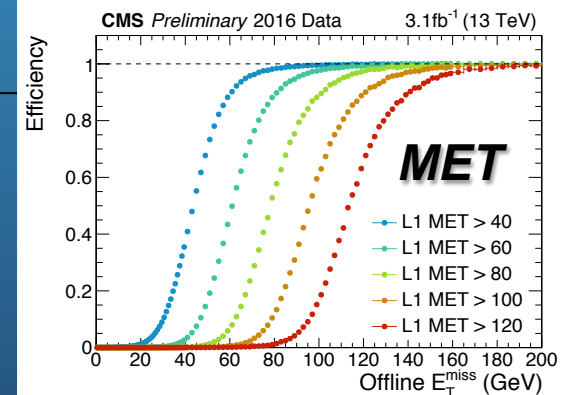
Complete New L1 system

→ **100 kHz w/ 280 Algorithms**

→ Example of typical paths. EWK:
SingleIsoEG26,28 OR SingleEG40

Higgs: DoubleEG18_16 (20_10),

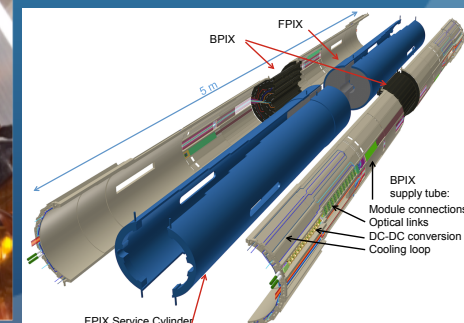
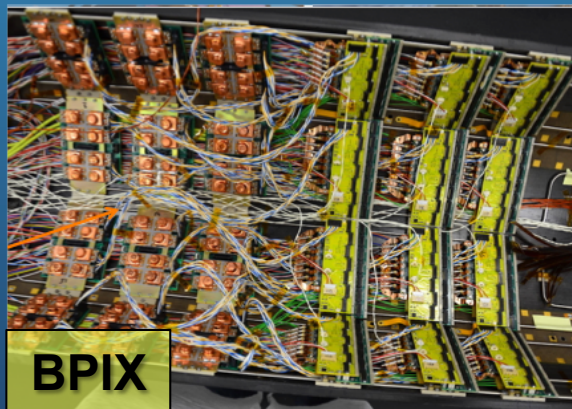
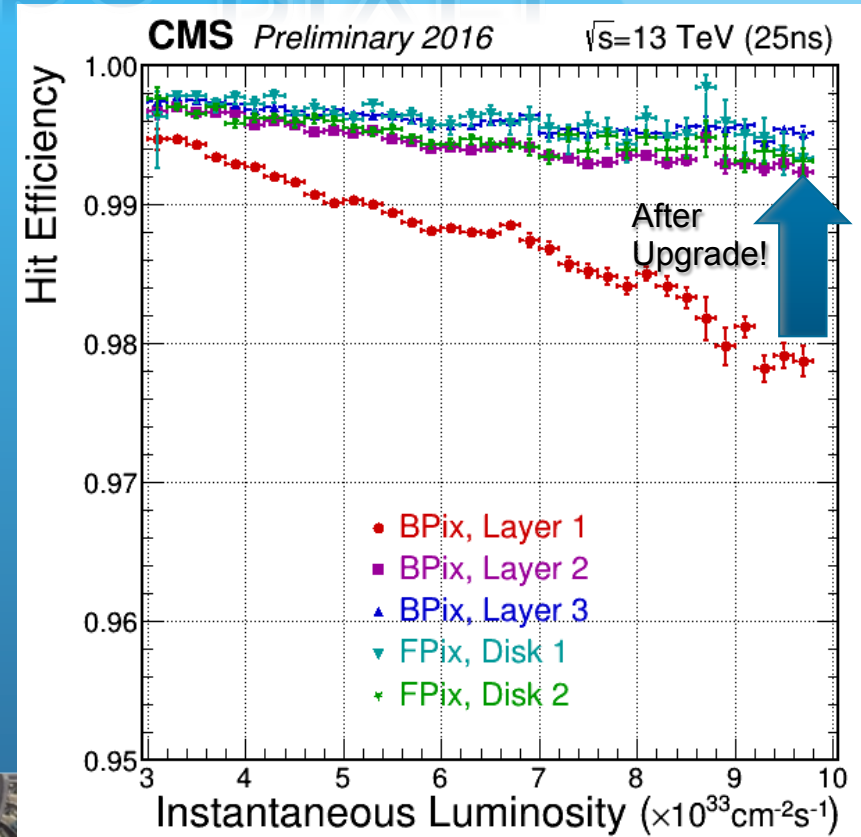
TripleEG14_10_8 and DoubleIsoTau28



Plans for the PIXEL

Pixel Upgrade for Phase I

- **Additional Layer in Barrel and Endcap** → 4 Hits in $|\eta| < 2.5$
→ Reduce fake rate & improved track resolution and reco efficiency
- **New Front-End Electronics**
→ Efficient operation @ high rate and multiplexing of data increase bandwidth
- Commissioning of the system ongoing with 2016 collision Data
- Installation in 2017



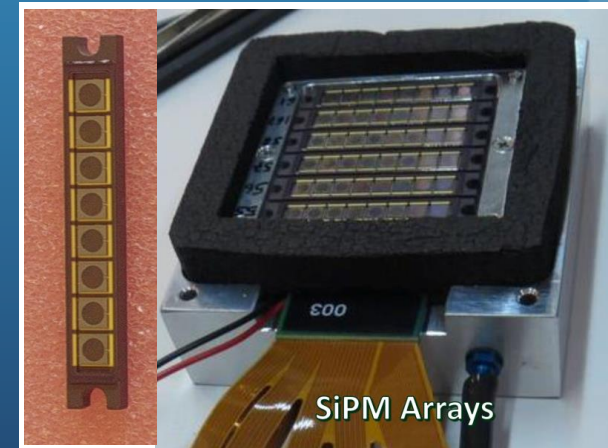
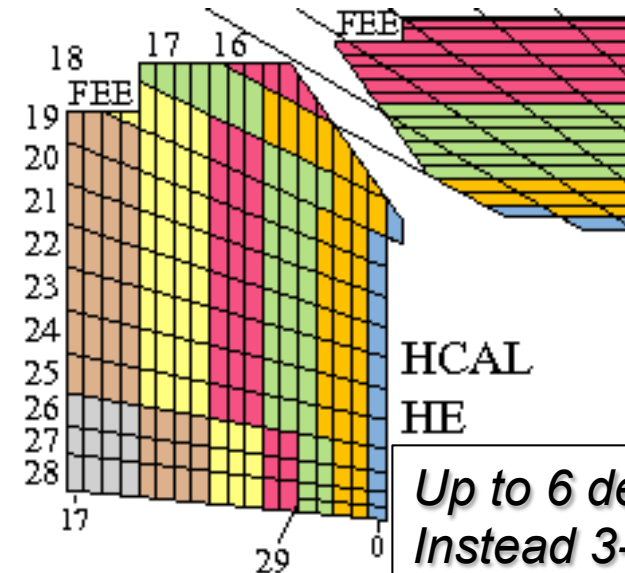
Plans for the HCAL

HCAL Upgrade

- **Photodetectors replacement:** HPD replaced by SiPM in Barrel, Endcap & Outer Hadronic Calorimeters (2017)
 - Better Signal/Noise
 - Insensitive to Magnetic Field
- Forward Calorimeter:** multi-anode PMT replace single-readout PMT (2015) (removal of anomalous signals, 2017)
- **Readout Electronics:** replaced
 - **Front-End:** need electronics to readout SiPM + More robust, redundant clock system, Extended dynamic + timing info
 - **Back-End:** Use μ TCA architecture
Latency & rate for HL-LHC
 - commissioned in 2016

→ More information from Salavat's presentation

New segmentation with SiPMs+QIE11

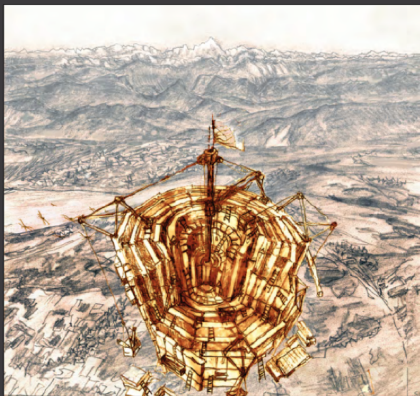


CMS Phase II Upgrade

CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

CERN-LHCC-2015-010
LHCC-P-008
CMS-TDR-15-02
1 June 2015

CMS



The Compact Muon Solenoid
Phase II Upgrade
Technical proposal



LHC Phase II: Physics Case

The goal of the Phase II HL-LHC and CMS physics program:

→ **Higgs (couplings, rare decays, field structure, unitarity through Vector Boson Scattering VBS etc.), SUSY, Dark matter etc..**

How do we plan to approach Phase II?:

→ **Physics Program** : require specific performance
(at least at the level of Phase I if not improved)

→ New Tracking, New Calorimetry & New Muons

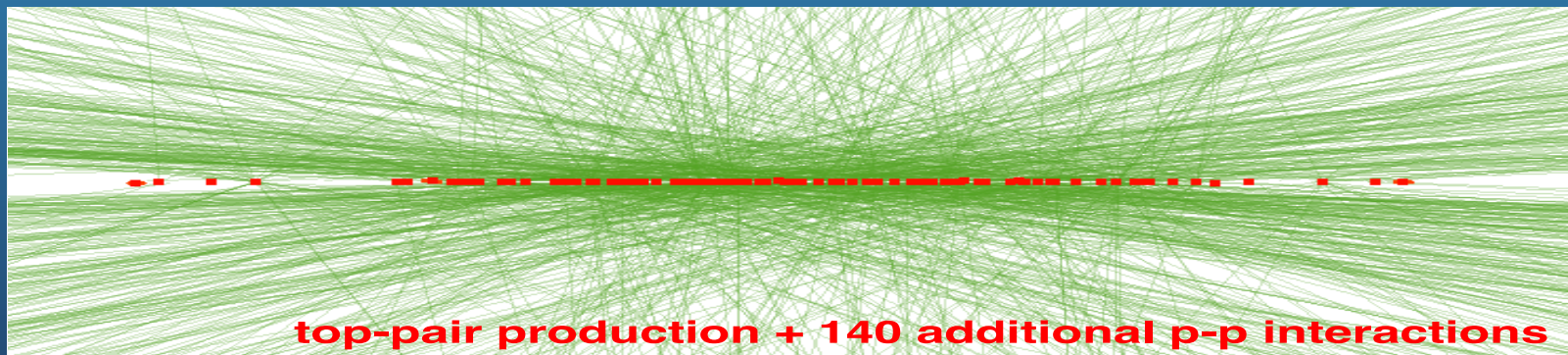
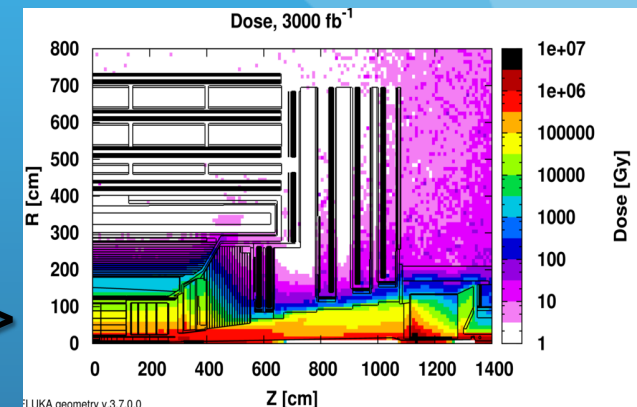
→ **Adapt to HL-LHC harsh conditions: $5e34$ PU<150>**

- **High granularity Tracker and Calorimeters**

→ very high particles multiplicity/Radiation damage

- **Increased throughput for DAQ** → Scales up with PU

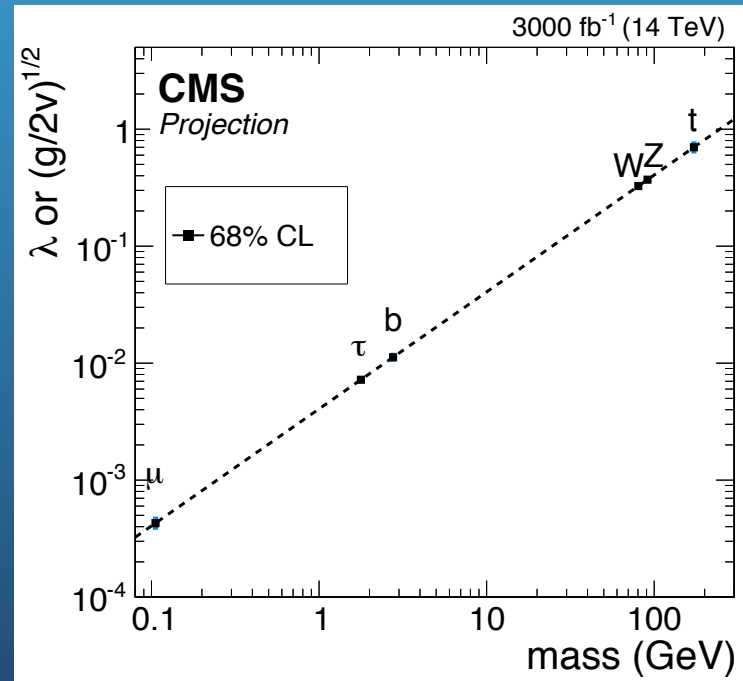
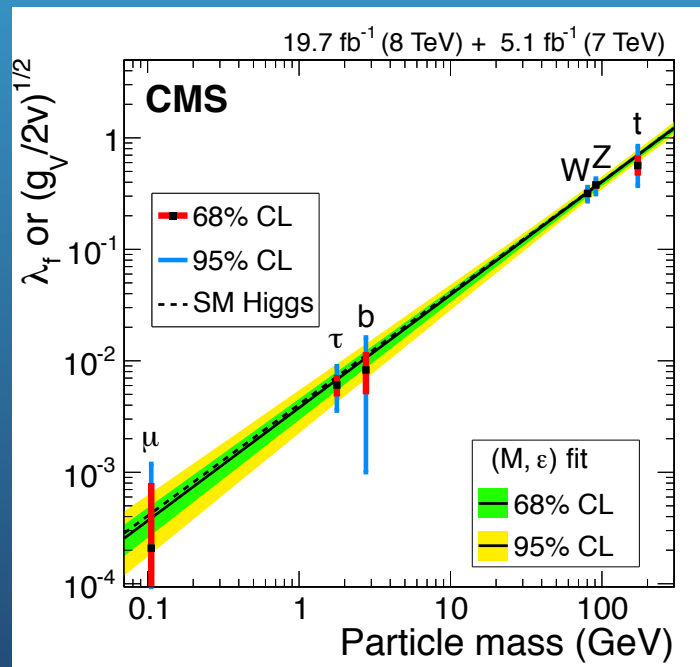
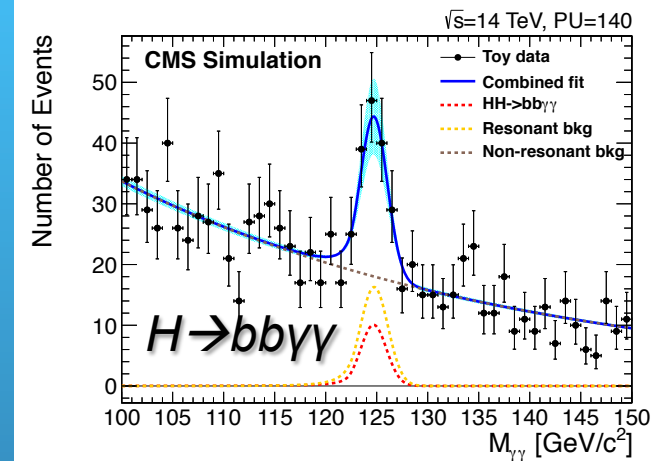
- **Combined Track-Calo for the Trigger Selection** → Rate/PU



Phase II Physics Highlights

HIGGS:

- $O(%)$ couplings to fermions & bosons
- Rare decays $H \rightarrow \mu\mu$
- Double Higgs
- VBF and HW, HZ production modes
- Triple-gauge coupling, quartic-gauge coupling



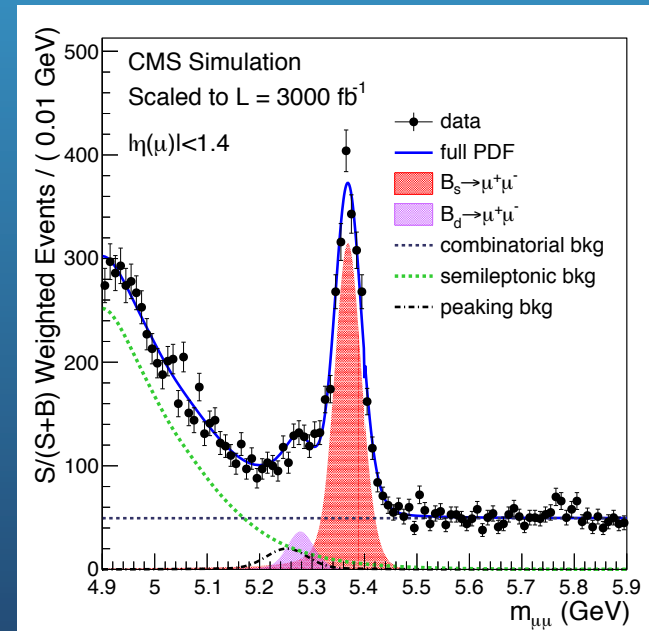
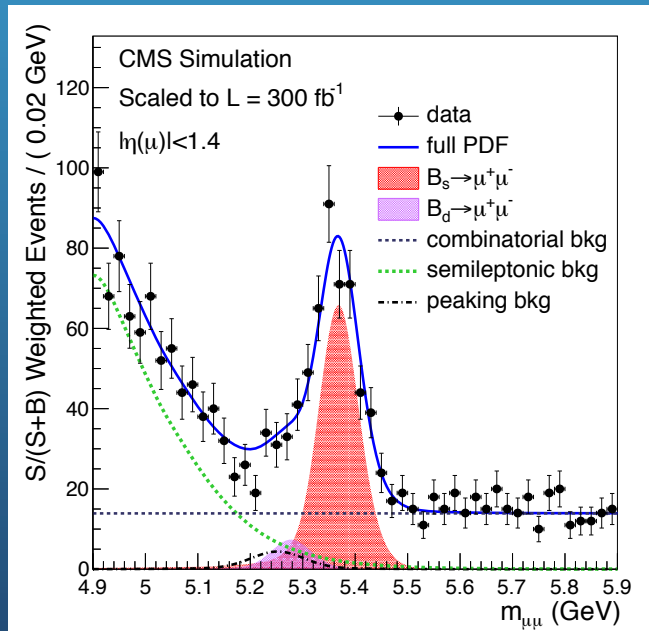
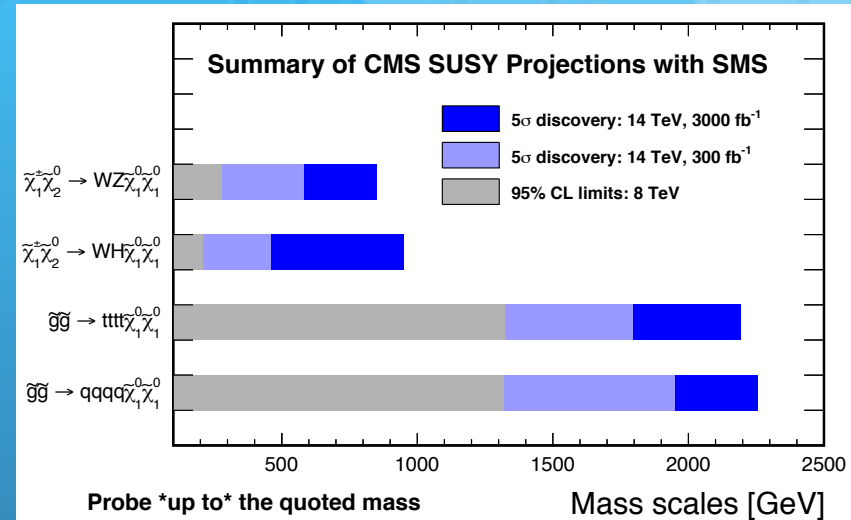
Phase II Physics Highlights

Standard Model Physics:

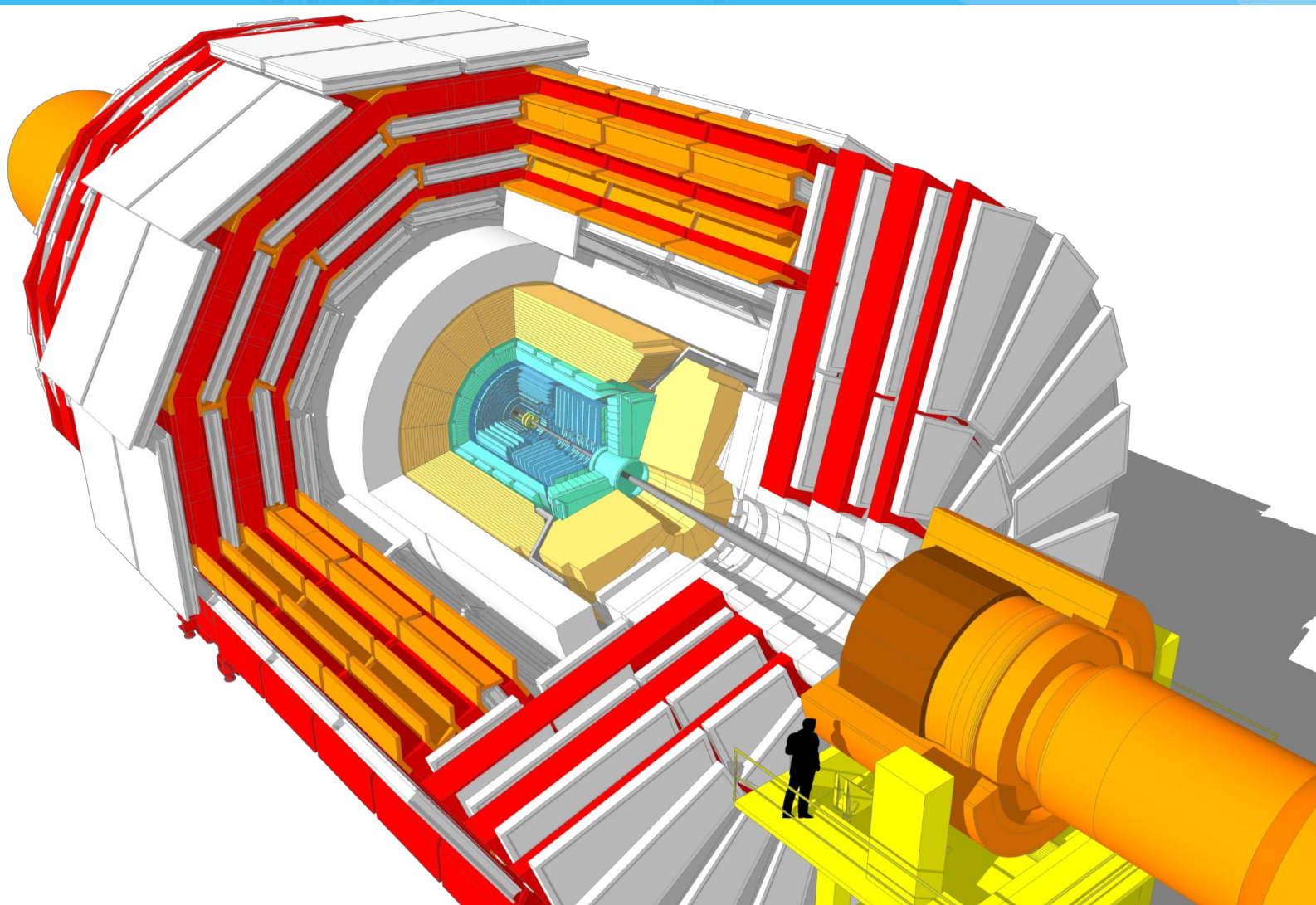
- Rare $B_{s,d}$ decays
- Vector Boson Scattering (VBS)

SUSY and beyond:

- Scan to level of multi TeV
- Dark matter : mono-object signature (jet, vector boson etc,)



Phase II Detector overview



Phase II Detector overview

Muon System

- New DT/CSC BE/FE electronics
- GEM/RPC coverage in $1.5 < |\eta| < 2.4$
- Muon-tagging in $2.4 < |\eta| < 3.0$

Barrel Calorimeter

- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator

Endcap Calorimeter

- High-granularity calorimeter
- Radiation-tolerant scintillator
- 3D capability and timing

Tracker

- Radiation tolerant, high granularity, low material budget
- Coverage up to $|\eta|=3.8$
- Track-trigger at L1

Trigger and DAQ

- Track-trigger at L1
- L1 rate $\sim 750\text{kHz}$
- HLT output $\sim 7.5\text{kHz}$

Muons

WFOU2

- *Extended coverage*
- *New Readout*
- *Introducing GEM*

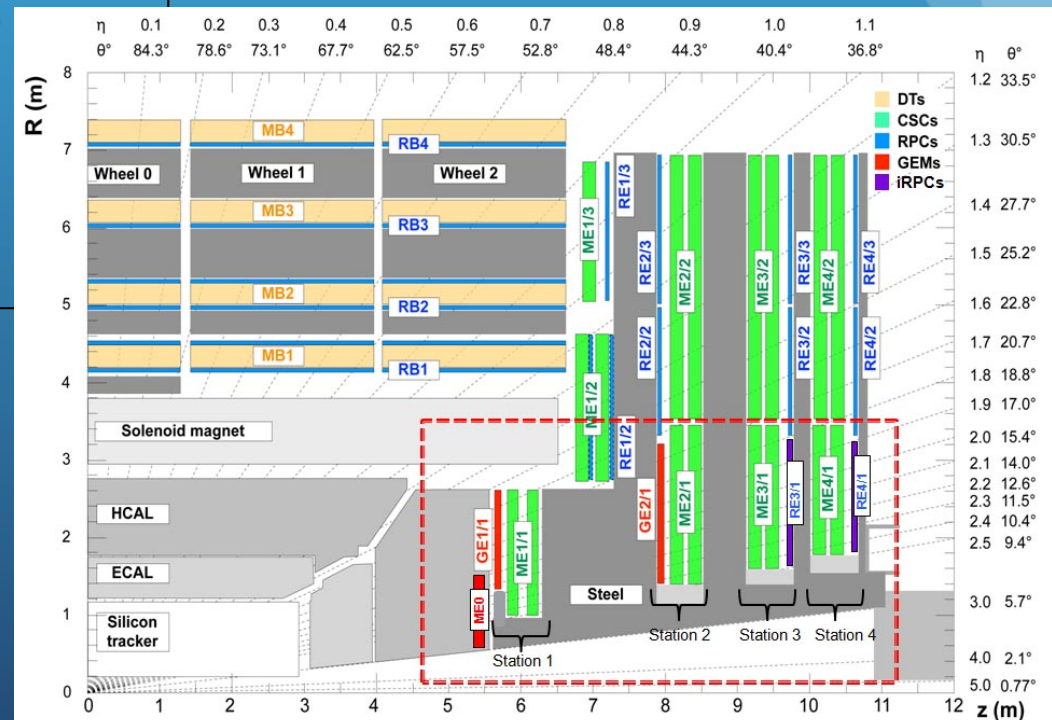
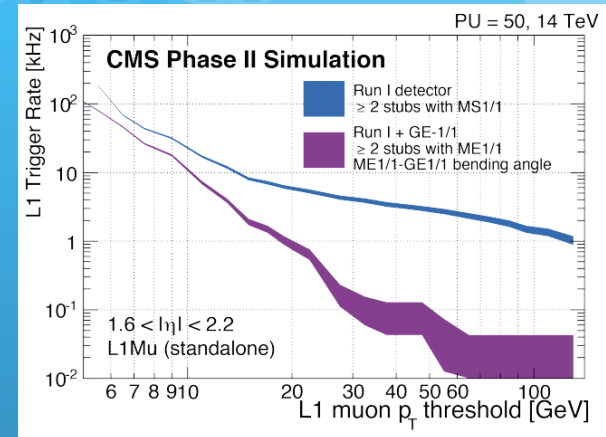
Muon System

Muon system for Phase II (DT, RPC, CSC)

- **Need to maintain low threshold for physics and extend coverage**
- **Extension of the muon system**
Coverage up to $|\eta| \sim 2.4$ to benefit from the extension of the tracker, HGC & new L1 trigger features
- **New GEM chambers (finer pitch):** improve reconstruction, improve triggering, timing info helps PU mitigation
→ Extend Muon tagging to $|\eta| = 3$

Readout & Gas

- **Replacement DT and CSC readout** (impact of radiation and dead time in current trigger)
- **Gas mixture: changed in RPC and CSC**

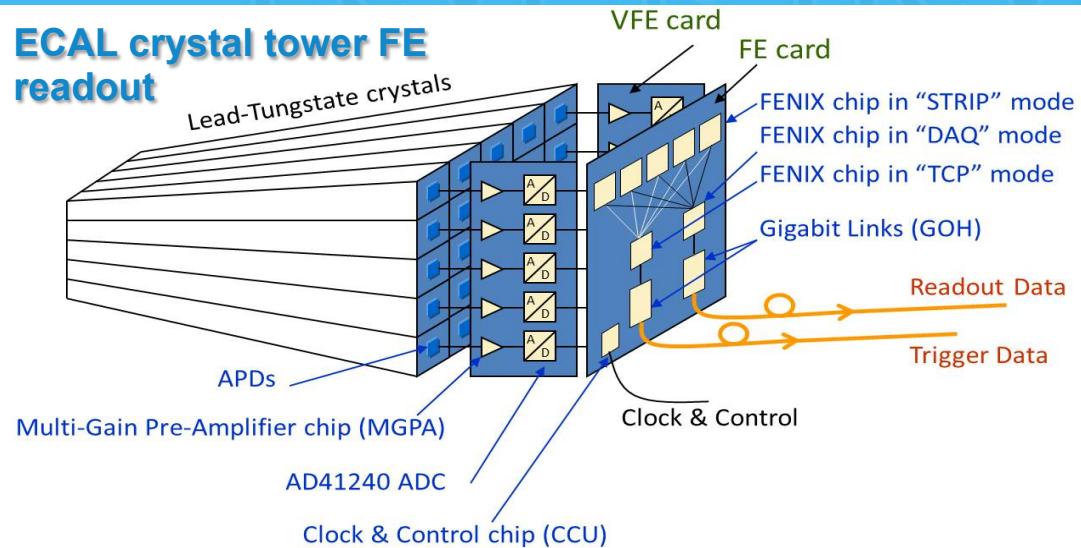


Calorimetry

- *Combine information with tracker*
- *New electronics*
- *Imaging Calorimeter*

ECAL & HCAL Barrel

ECAL crystal tower FE readout



Electromagnetic calorimeter

- **New Front-End and Back-End electronics** → meet new Trigger Specifications (including crystal level info), improve "spike" rejection and mitigate PU effect (timing).
- **Full study of ECAL longevity** → Dark currents in APD reduced by operating @ 8°

Hadronic Calorimeter

- **Replacement of inner layers**
 - Use radiation-tolerant plastic scintillator
 - Replacement of "megatiles"
 - Readout: HPD replaced by SiPM during Phase I) & New Front-End Electronics
- **New Back-End electronics**: probably merged with ECAL (using xTCA)

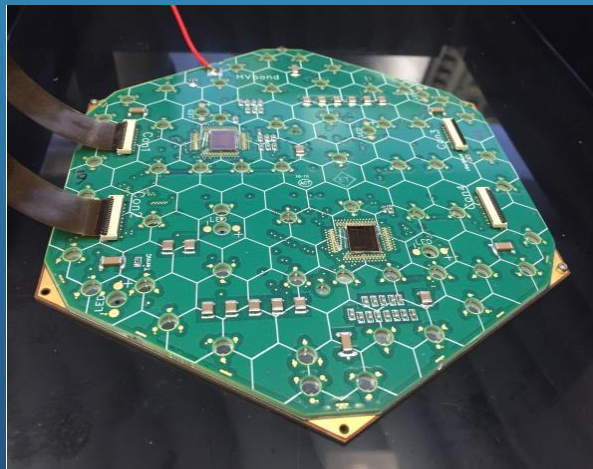
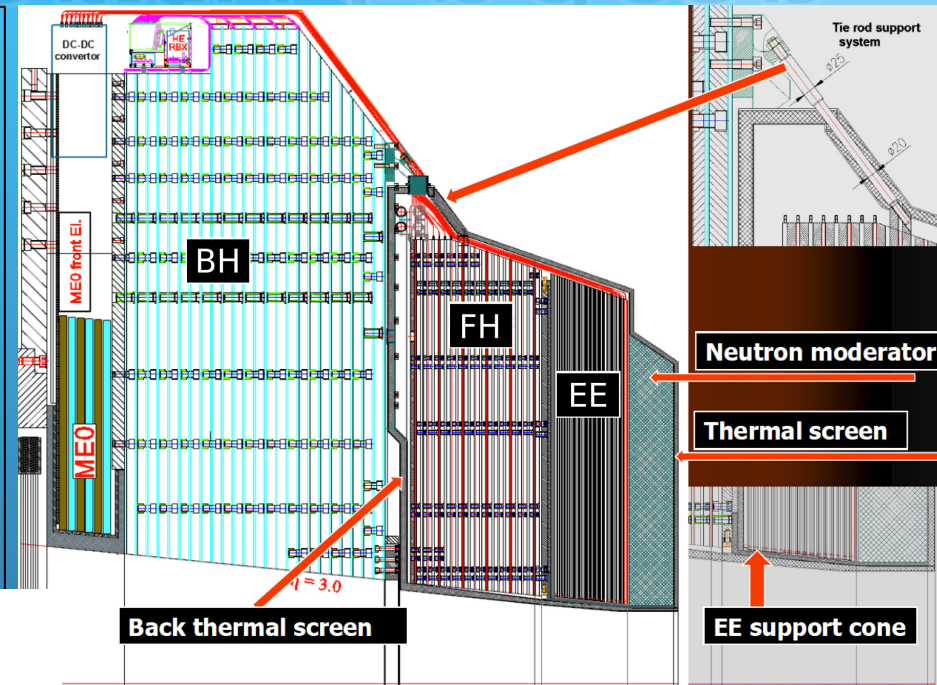


Installation of a central megatile

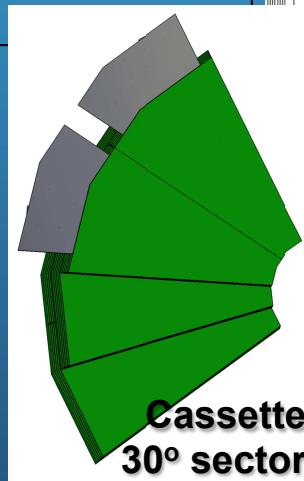
High-Granularity Endcap

Complete replacement of the Endcap calorimeters → **Target high performance for physics objects in high PU (imaging calorimeter)**

- **Silicon-Tungsten** sampling calorimeter inspired from the ILC-CALICE Design
 $EE=26 X_0$, 1.5λ . FH (Si-Stainless Steel)= 3.5λ BH (Plastic-Steel)= 5λ
- **Highly segmented**: EE(28 layers), FH(12) = 6.1M Channels



Module & Readout chip (SKIROC2-CALICE)
 First test beam ongoing



Cassette
 30° sector

Lots of interesting ongoing R&D

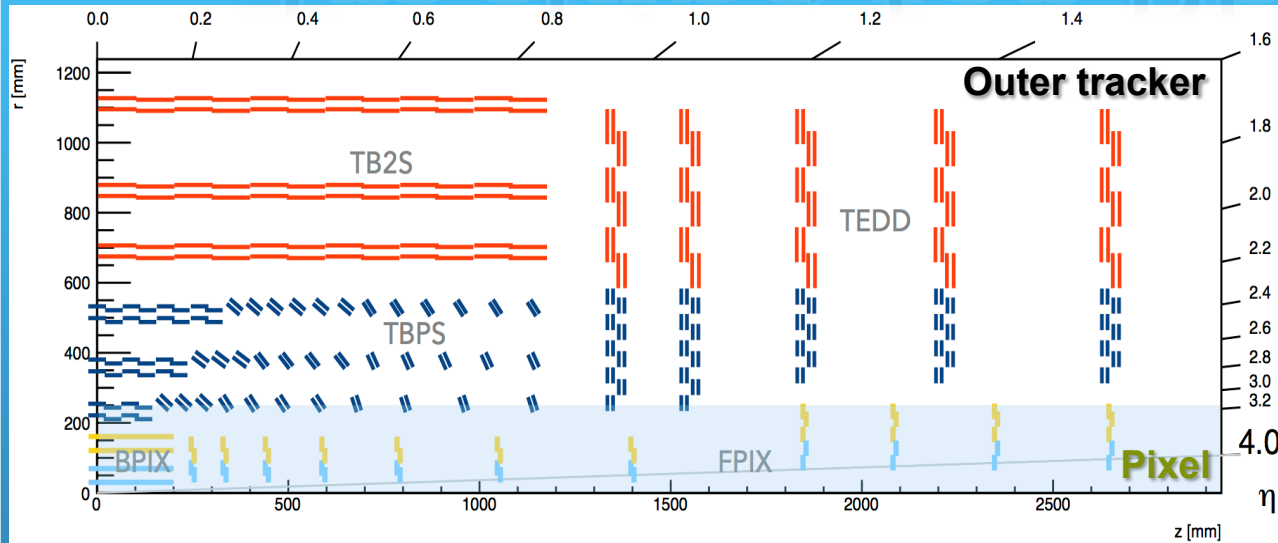
- **Challenging project in many aspects** (mechanics, readout, trigger, reconstruction etc.)
- **Performance**: 20% of Stochastic term & 0.7% of constant term
- **Timing, data transfer etc.**



Tracking

- ❑ *Radiation Tolerant*
- ❑ *Higher Granularity*
- ❑ *Low material budget*

Tracking for Phase II



Outer tracker

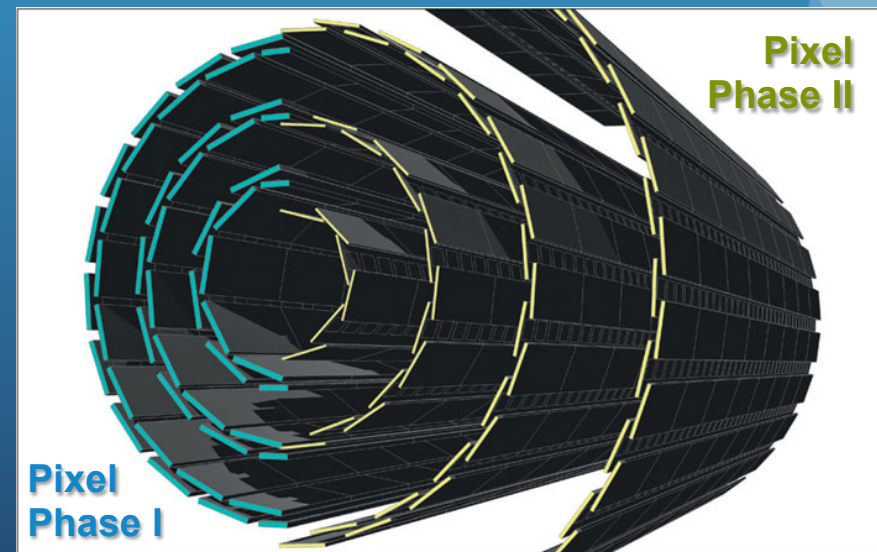
- **Higher Granularity**
→ 4 x Phase I
- **6 Barrel layer & 5 EndCap disks**
→ Double Si Layers (trigger purpose)
- **Increased acceptance**
→ Up to $|\eta| < 3.2$

Pixel Detector

- **Increased acceptance & high granularity**
→ Up to $|\eta| < 4$ (11 Disks)
- **Huge sensor R&D: 4m^2 vs 2.7m^2 in Phase I, inner layer 3cm from beam**

Operation & Readout electronics

- Readout @ **750 kHz and comply with $12.5 \mu\text{s}$ trigger latency**
- Operation @ **-30° & -20° for Pixel**





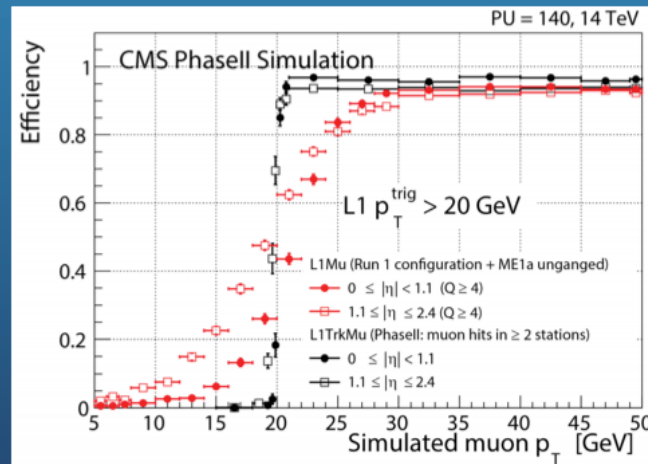
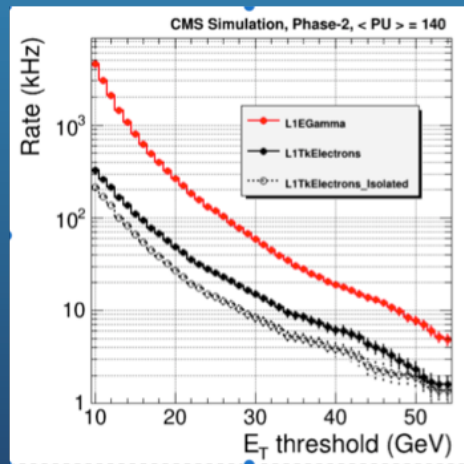
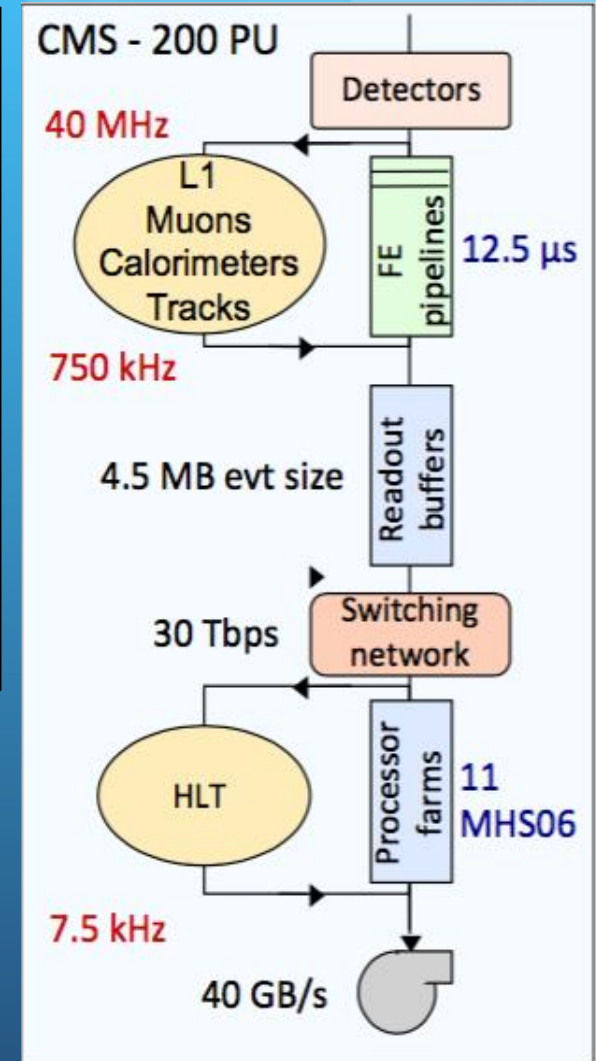
DAQ & Trigger

- *Increase bandwidth*
- *Increase selectivity*
- *Handle Rate/PileUp*

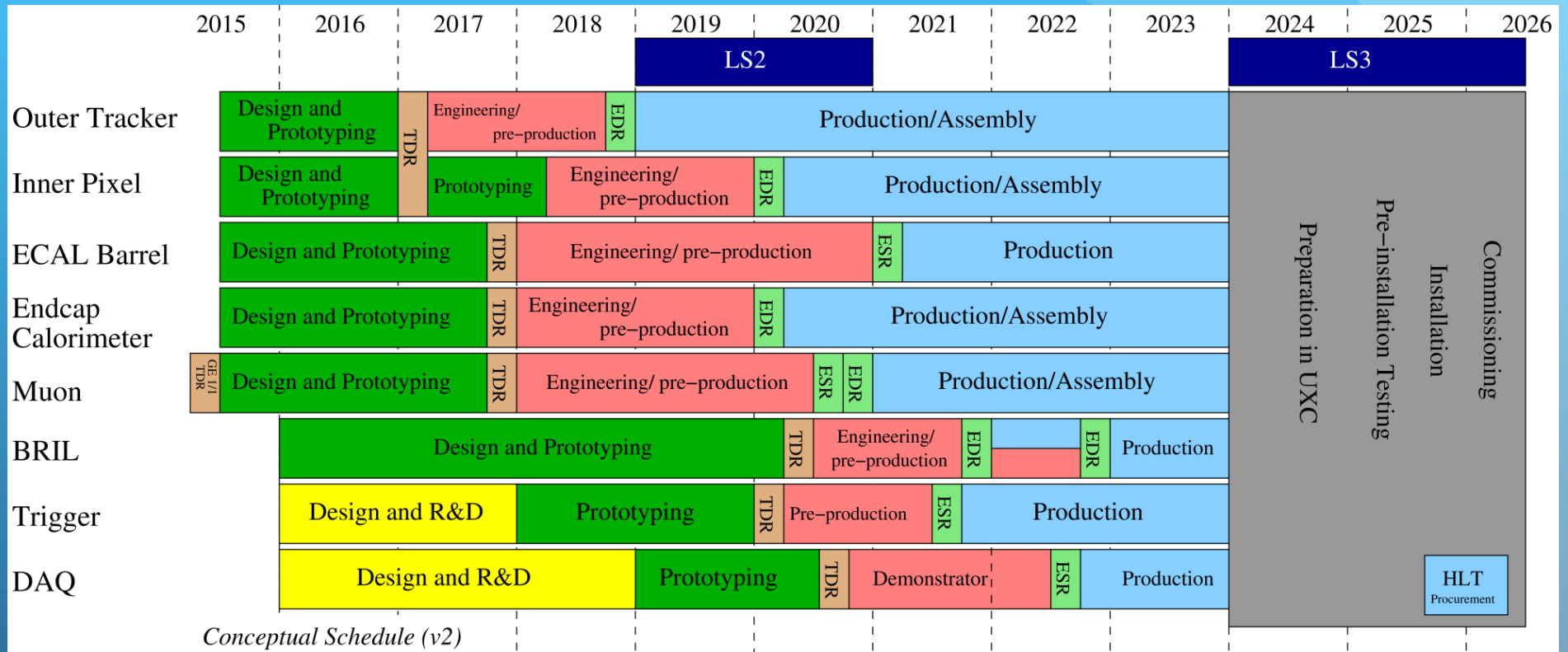
DAQ & Trigger for Phase II

Keep physics performance for HL-LHC

- **More features and flexibility to L1**
 - Introducing a track trigger & fine info (ECAL crystal)
 - Bandwidth = **750kHz** & Latency **12.5 μs**
 - Architecture based on xTCA
- **Combination of info:** increase selectivity and reduce fake. PU mitigation technique
- **Powered-up HLT&DAQ:**
 - HLT Output Rate = **7.5 kHz** (vs 1kHz in Run II)
 - Increase bandwidth (**800 links @ 100 Gb/s**)
 - **30 Tb/s** Throughput



Upgrade Schedule



Technical Design reports expect by 2017

Focusing now finalizing R&D, prototyping and tests

Summary & Outlook

Current data taking with CMS :

- *CMS recording data efficiently and following LHC unprecedented instantaneous luminosity increase.*
- *Should reach 30 to 40 fb⁻¹ by the end of the year*
- *Already benefiting from improvements deployed during LS1 (2013-2015)*

CMS capitalizing on Phase I Upgrade:

- *Phase I upgrade includes important changes to the Trigger/DAQ, Pixel and HCAL*
- *Deployment with aggressive schedule to keep up with luminosity increase*
- *Lots of useful R&D to prepare for Phase II*

Phase II program well under way:

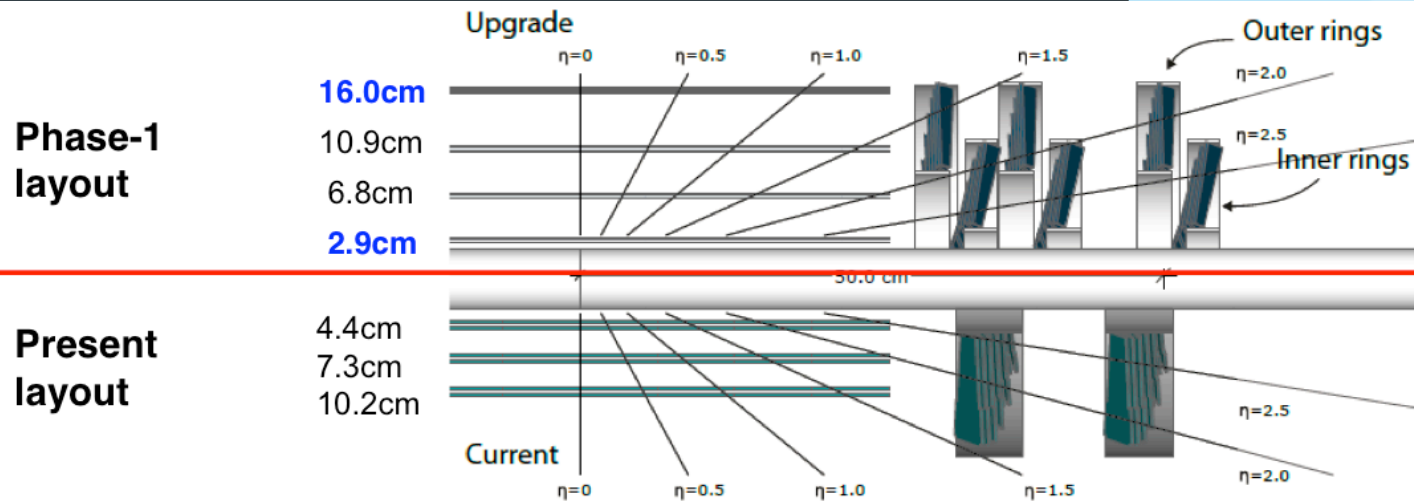
- *CMS will go under major changes of all subsystems including readout, Trigger and DAQ → deal with high Pile-Up and radiations*
- *Introducing new technologies at every steps of the detection process and data handling*
- *Challenging and exciting R&D program: many opportunities to innovate*
- *Exciting physics program ahead! Need a successful upgrade to achieve it !*

BACK UP MATERIAL



Pixel Upgrade

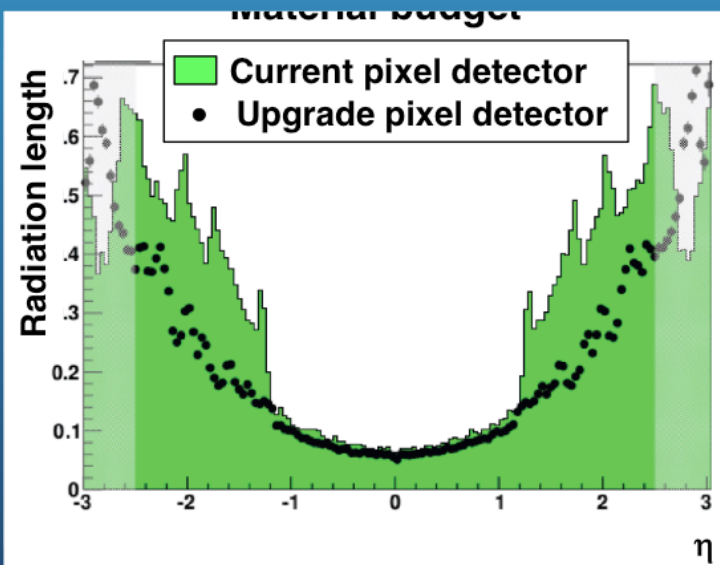
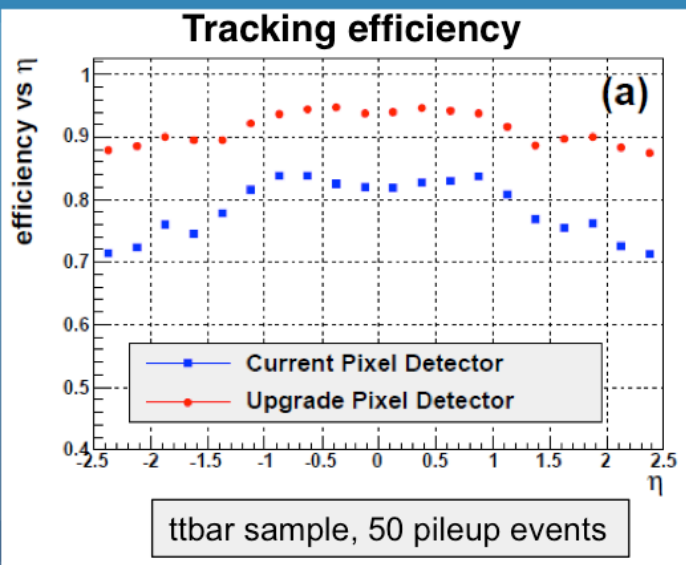
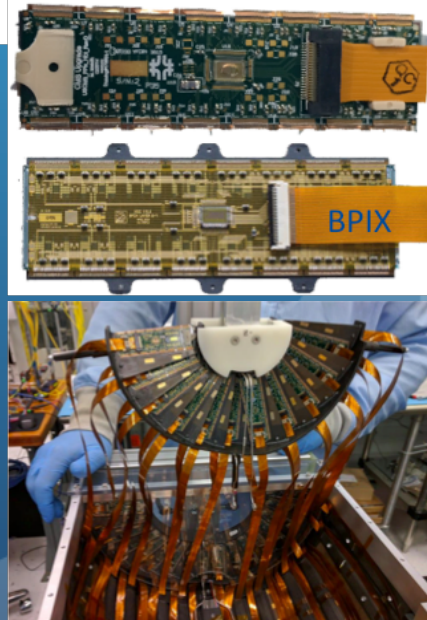
1 Disk + few FPIX modules installed since LS1



1856 modules
124M pixels

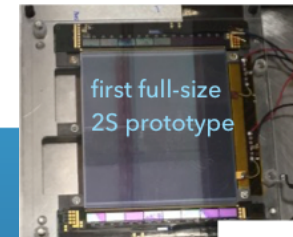
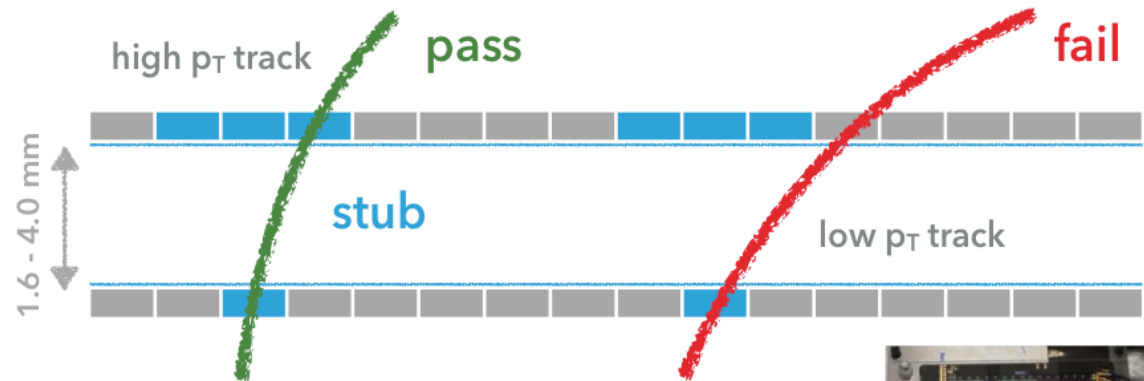
Cell size reduced 6x

1440 modules
66M pixels



OUTER TRACKER UPGRADE

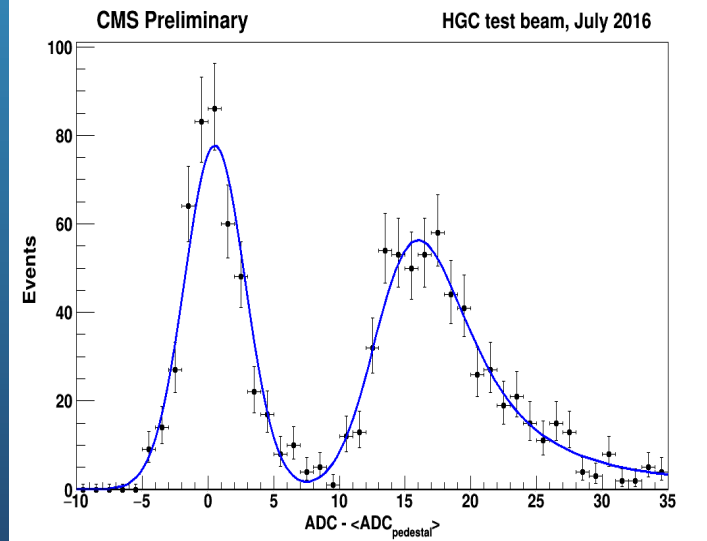
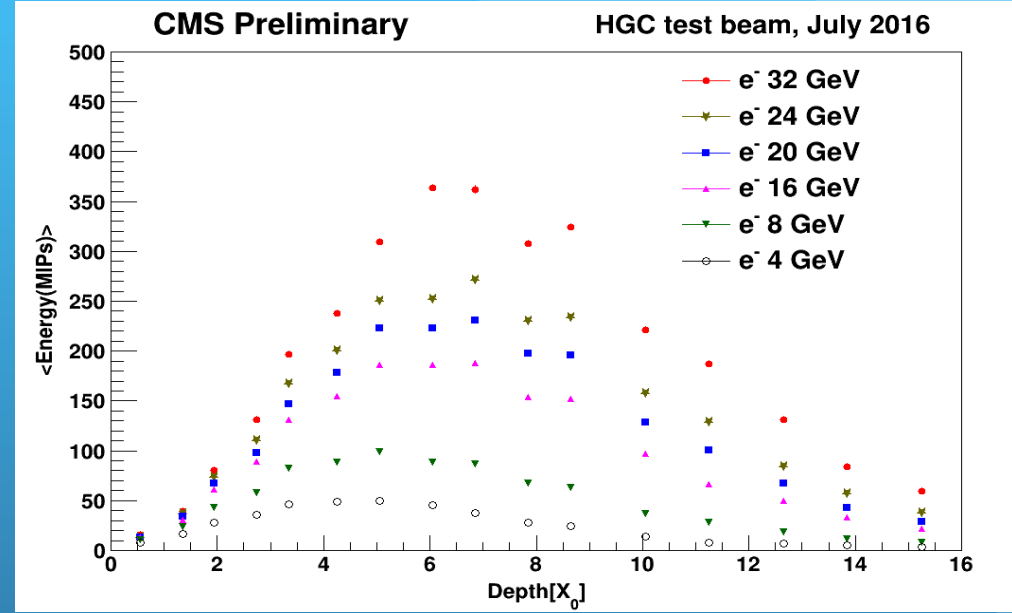
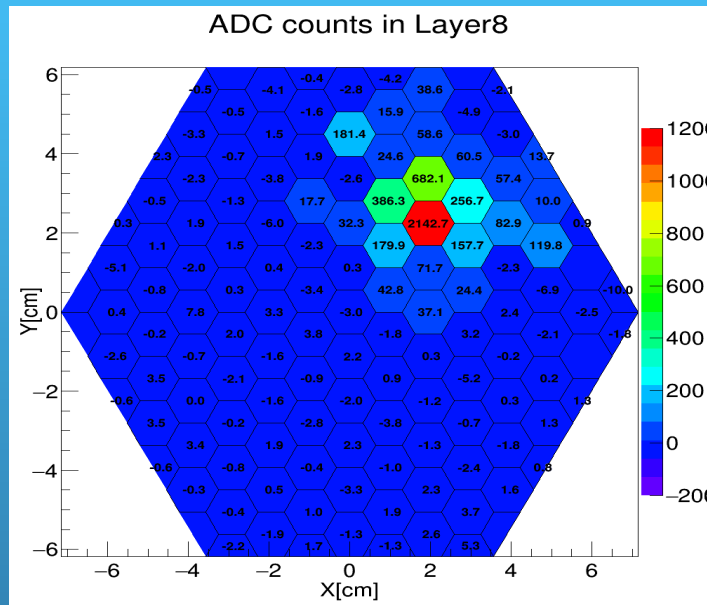
- ▶ contribution to L1 trigger requires **tracker data at every BX (40 MHz)**
- ▶ all hits would exceed bandwidth -> data reduction at the front end
- ▶ detect **high-momentum tracks** on module by **correlating hits** on 2 appropriately spaced sensors -> **"STUB"**



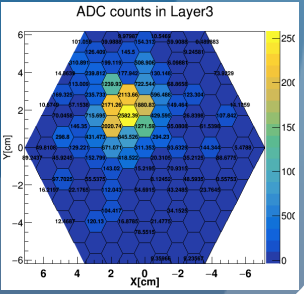
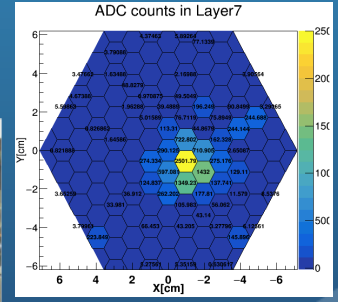
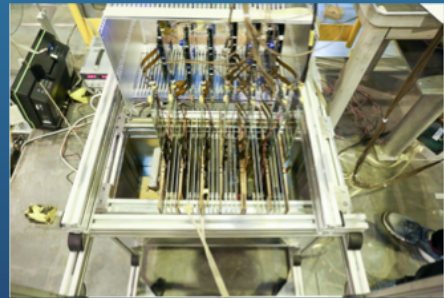
Track-Trigger challenge

- **Passing only stub information from the Front-End to track finder**
 - reduce rate by x10 (still 10k stubs/BX@140PU)
- **Tracking reconstruction:**
 - Associative Memory (ASIC)
 - Time-Multiplexed Trigger (FPGA)
 - Tracklet-based FPGA

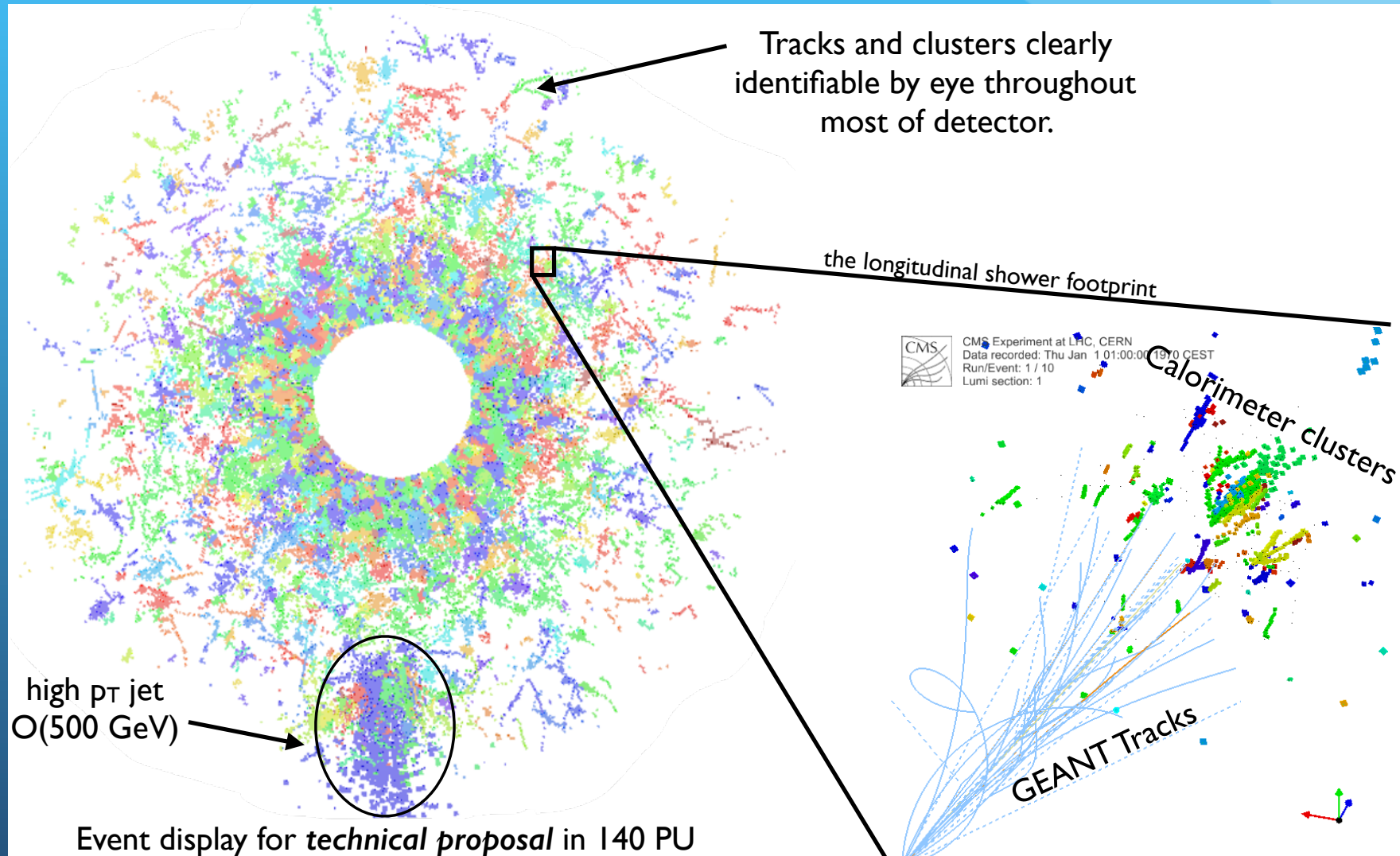
ENDCAP UPGRADE: HGC



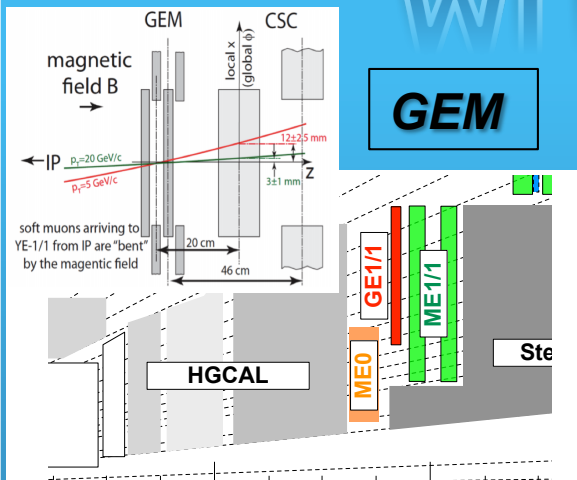
Test Beam results @ FNAL/CERN



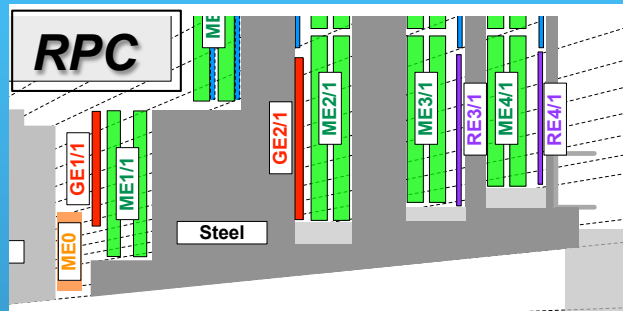
ENDCAP UPGRADE: HGCD



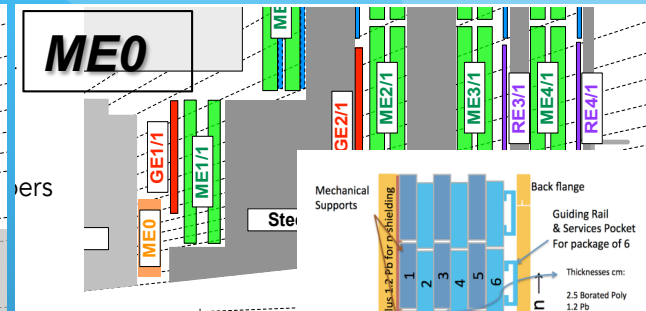
MUON UPGRADE



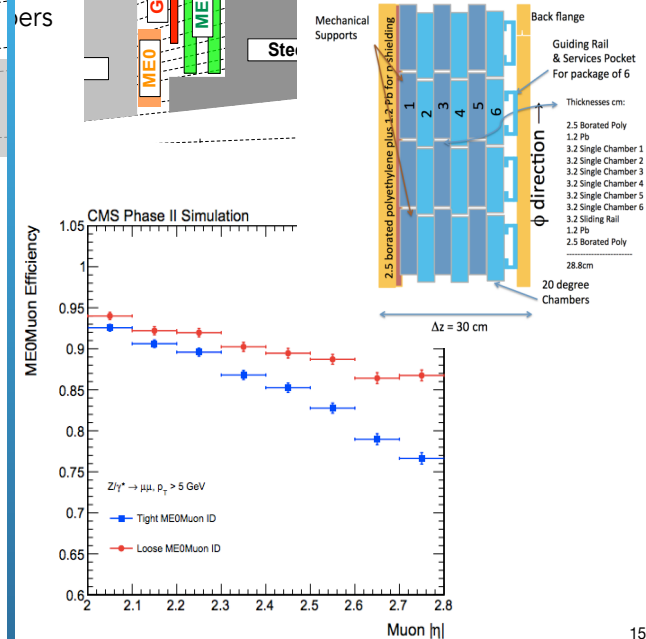
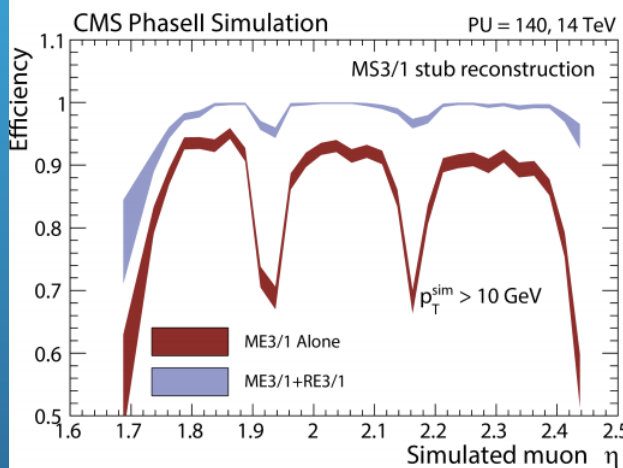
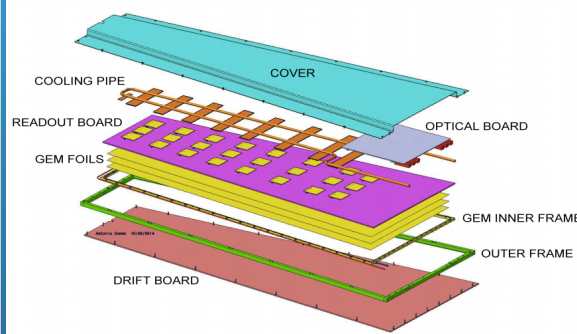
GEM



RPC



ME0



- $1.6 < |\eta| < 2.2$
- Using bending angle between GE1/1 and CSC-ME1/1: reduce the rate by a factor 4

- $1.6 < |\eta| < 2.4$
- Restore redundancy
- Improve design
- Timing 100ps reduce rate from neutrons

- Forward Muon tagger $|\eta| < 3$
- Trigger capabilities
- Combined with Pixel and HGCAL info