CMS UPGRADE STATUS AND OUTLOOK

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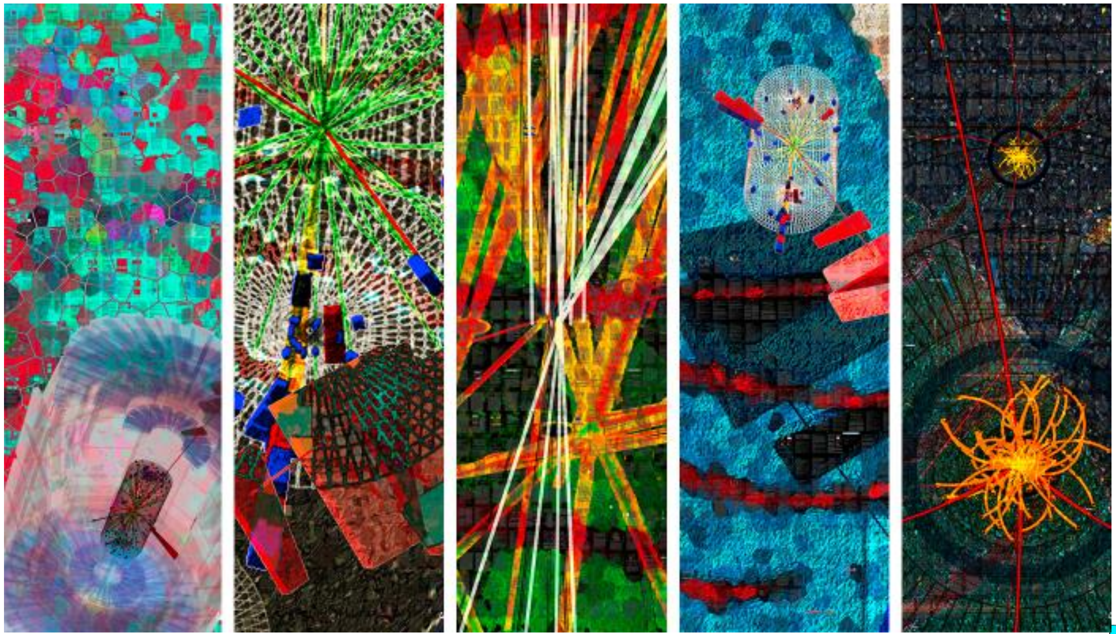
Brown University

ECFA 2016 Workshop,
Aix-les-Bains,
Oct 3-6, 2016



Outline

- Physics reach at the HL-LHC
- Detector Upgrades to achieve the physics goals
- Performance of the upgraded detector
- Near term outlook
- Summary

PHYSICS REACH @ HL-LHC

Why HL-LHC?

- The need to explore the TeV scale provides a strong physics case for HL-LHC
  - Currently no direct evidence of new physics.
  - Standard Model works beautifully – possibly beyond the TeV scale.
  - Naturalness argument and low mass of Higgs boson provide strong motivation for new particles and/or interactions at the TeV scale.
  - The standard model does not provide a dark matter candidate
- Answers to many key questions in HEP may lie at the TeV scale
- HL-LHC will deliver 3/ab (x100 today's data sample). This will allow us to:
  - Study the Higgs boson in detail
    - Discriminate between possible BSM scenarios
  - Measure rare SM processes
  - Search for new particles/phenomena at the TeV scale
    - Top partner could provide solution to the hierarchy problem
    - Dark matter candidate
  - Investigate properties of new particles observed during Run2 & 3!.

Strategy for HL-LHC projections

- Select measurements from the recent Run2 analyses
  - Extrapolate to (300) 3000/fb
  - Consider effects of high pileup (PU) conditions and detector performance, based on the CMS Phase II Technical Proposal (TDR-15-002; LHCC-P-008)
  - This selection is only a subset to highlight detector performance.
- Scenarios for systematics
  - Scenario 1+
    - Theory uncertainties same as in the corresponding Run2 analyses.
    - Experimental systematics same as reference analysis.
    - Effects of higher PU and detector upgrades on the future performance are accounted for.
  - Scenario 2+
    - Theory uncertainties reduced by 50%.
    - Experimental systematics scale as $1/\sqrt{\int L dt}$ until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector.
    - Possibly reasonable assumption as large data sets allow to constrain systematics in situ.
    - PU effects and projections for detector performance are taken into account.
  - Stat only: included in some cases to highlight the ultimate reach
  - Earlier projections (arxiv:1307.7135) scaled all systematics with $1/\sqrt{\int L dt}$
  - These estimates give guidance on:
    - Which experimental systematics are limiting the measurement?
    - How to constrain systematic effects better?
    - What are the requirements for the detector?

Updated projections (since Technical Proposal)

- Higgs boson
  - H→γγ, H→ZZ: signal strength, fiducial and differential cross sections
  - Anomalous couplings
  - Double Higgs production
  - VBF H→ Invisible
  - MSSM Φ→ττ
- SM measurements
  - FCNC in t+γ
  - top mass measurement
  - vector boson scattering
  - $B_s \rightarrow \phi\phi$+4K
- Searches for new particles
  - W'→ tb, Z' → tt
  - Dark matter (monojet)
  - VLQ T → tH

Tuesday morning Physics Session :

Miguel Vidal:
"Updated studies for Higgs measurements"

Markus Cristinziani:
Updated studies for SM measurements

Niels Tuning:
Heavy flavour physics at high luminosity

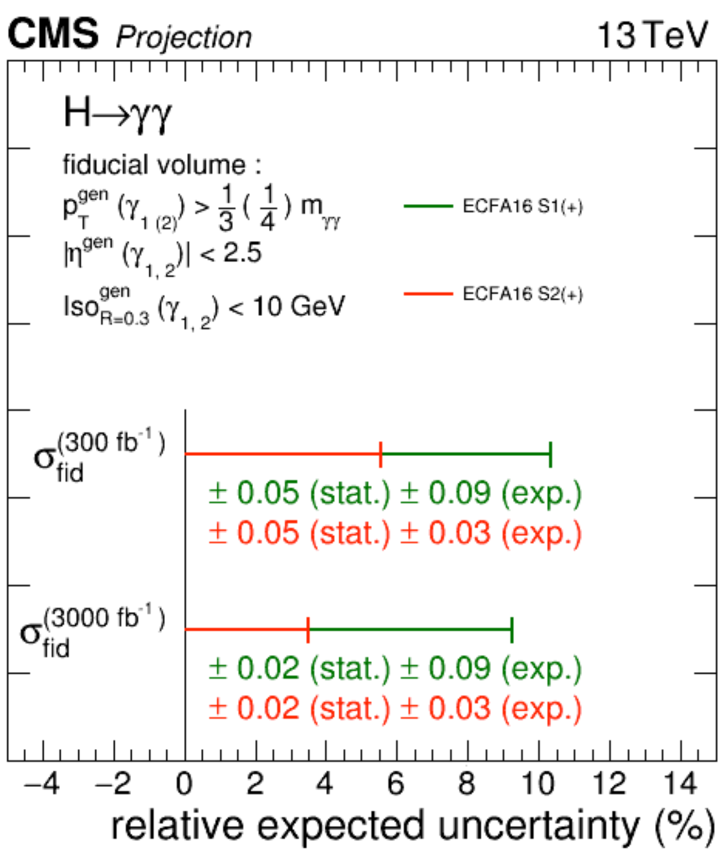
Kerstin Hoepfner :
Updated projections for BSM searches

This selection is only a subset to highlight detector performance.

Higgs Cross Section Projections

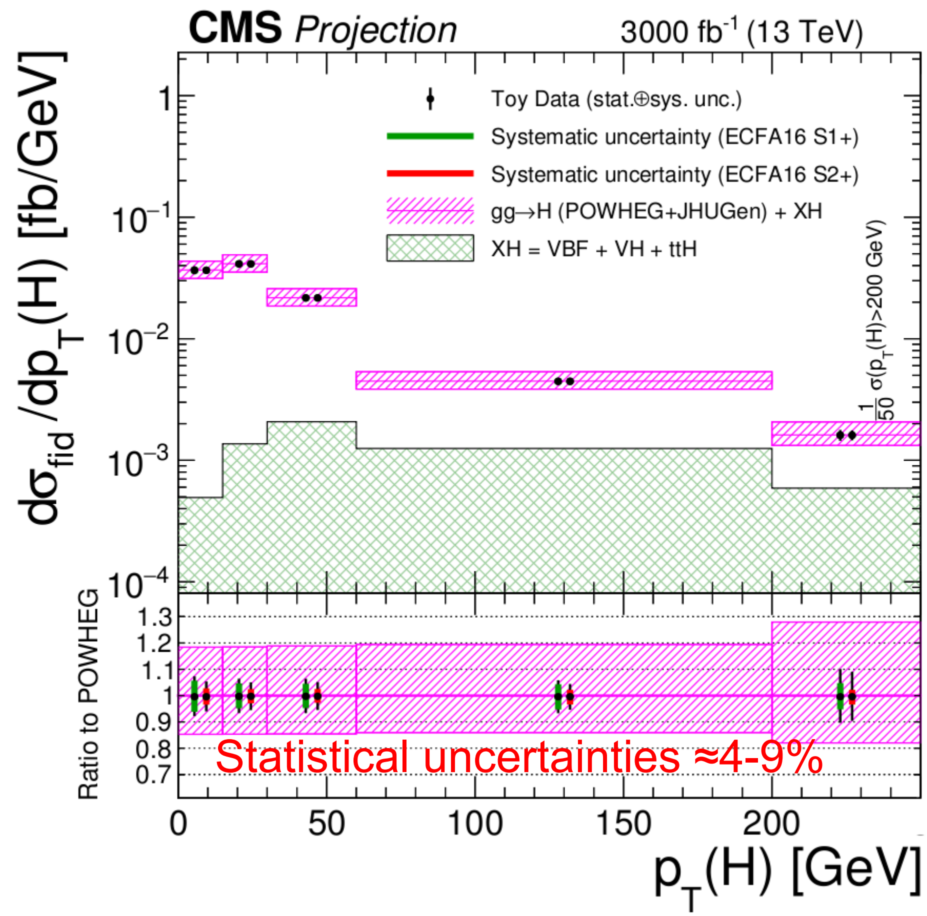
Fiducial Cross Section (H→γγ)

- Statistically limited but less dependent on model assumptions
- With increased integrated luminosity this measurement will become important



Differential $p_T(H)$ Cross Section (H→ZZ)

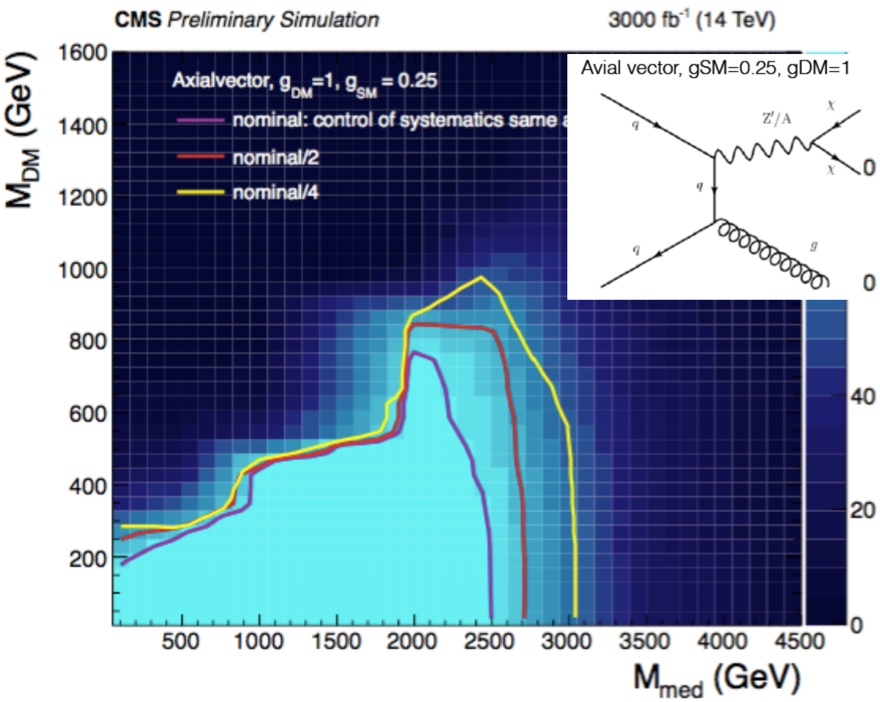
- More detailed comparison with SM predictions



Kerstin Hoepfner – Tuesday morning
"Updated projections for BSM searches"

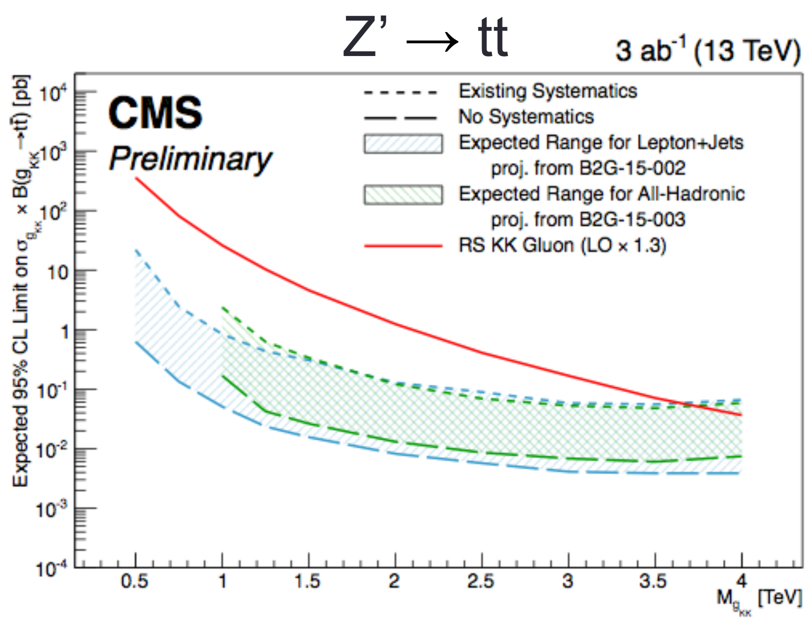
Exploring the TeV scale

- Search for dark matter in monojet events
  - Axial vector mediator
  - Suppressed in direct detection
    - Collider: complementary sensitivity
  - Exclusion possible up to 3 TeV
  - Sensitive to missing pT resolution



- Search for heavy new resonances
  - Z' → tt
  - W' → tb
  - Exclusion possible beyond 4 TeV
  - Sensitive to b-tagging performance and jet substructure for boosted jets

Z' → tt

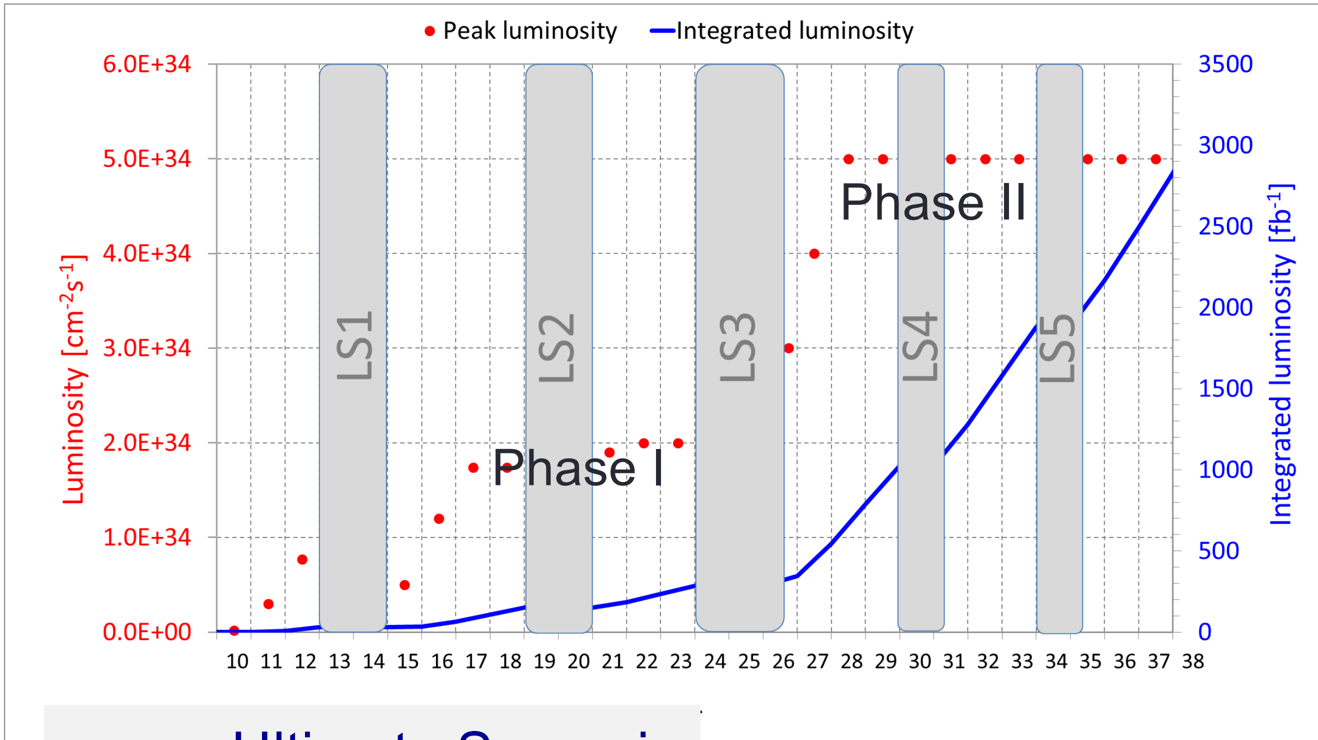


DETECTOR UPGRADES TO ACHIEVE THE PHYSICS REACH

Detector requirements

- Reconstruct all the standard physics analysis objects with high efficiency, low fake rate, and high resolution.
- Requires excellence in every corner
  - Increased acceptance at high η
  - Excellent electron, photon, muon and jet reconstruction
  - tracking of charged hadrons, measurement of electromagnetic energy, muon and electron reconstruction.
  - excellent missing Et resolution
  - Boosted jet identification (W/Z/Higgs/Top jet tagging).
  - b-quark tagging, precision reconstruction of primary and secondary vertices.
- For precision measurements and observations of very rare processes need to at least maintain current performance for all physics objects!

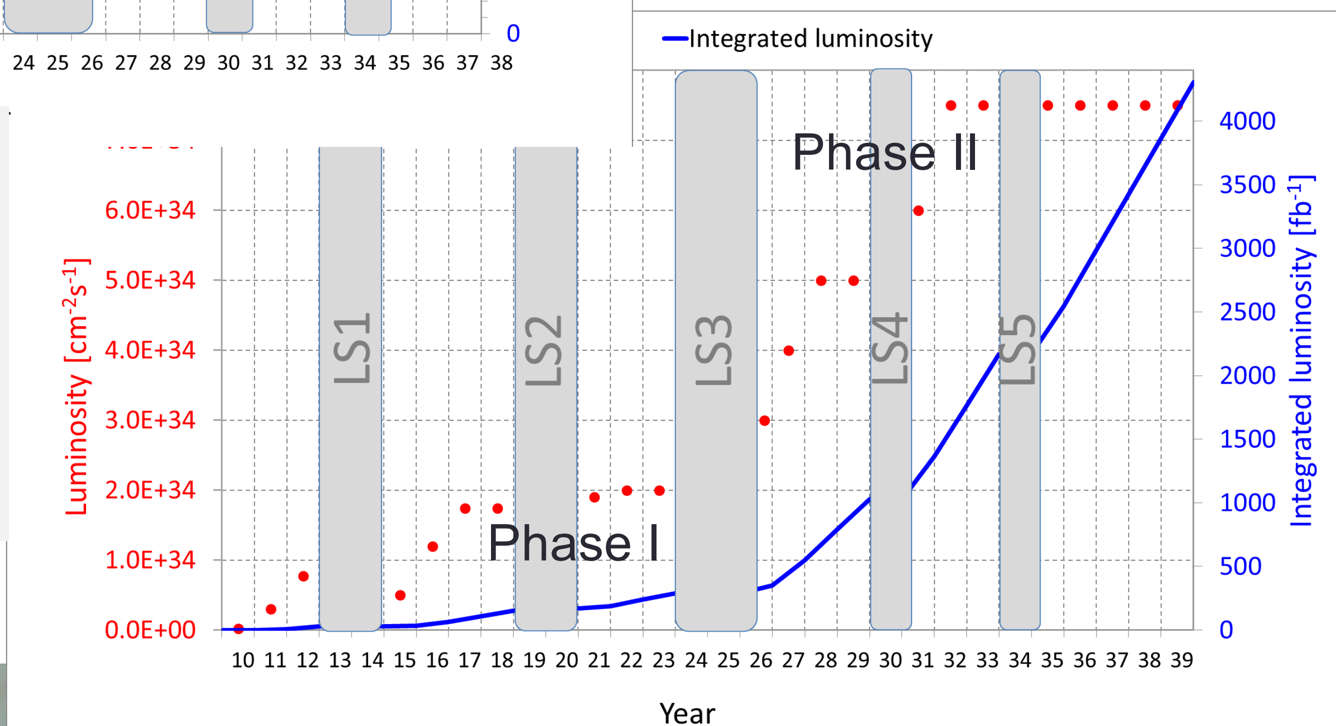
Luminosity Profile for LHC/HL-LHC



Nominal Scenario
Luminosity leveled at
5 x 10^{34} Hz/cm^2 ,
Pile-up <μ> = 140

Ultimate Scenario
7. 5 x 10^{34} Hz/cm^2 ,
Pile-up <μ> = 200

→ ≃ 25% increase in integrated luminosity



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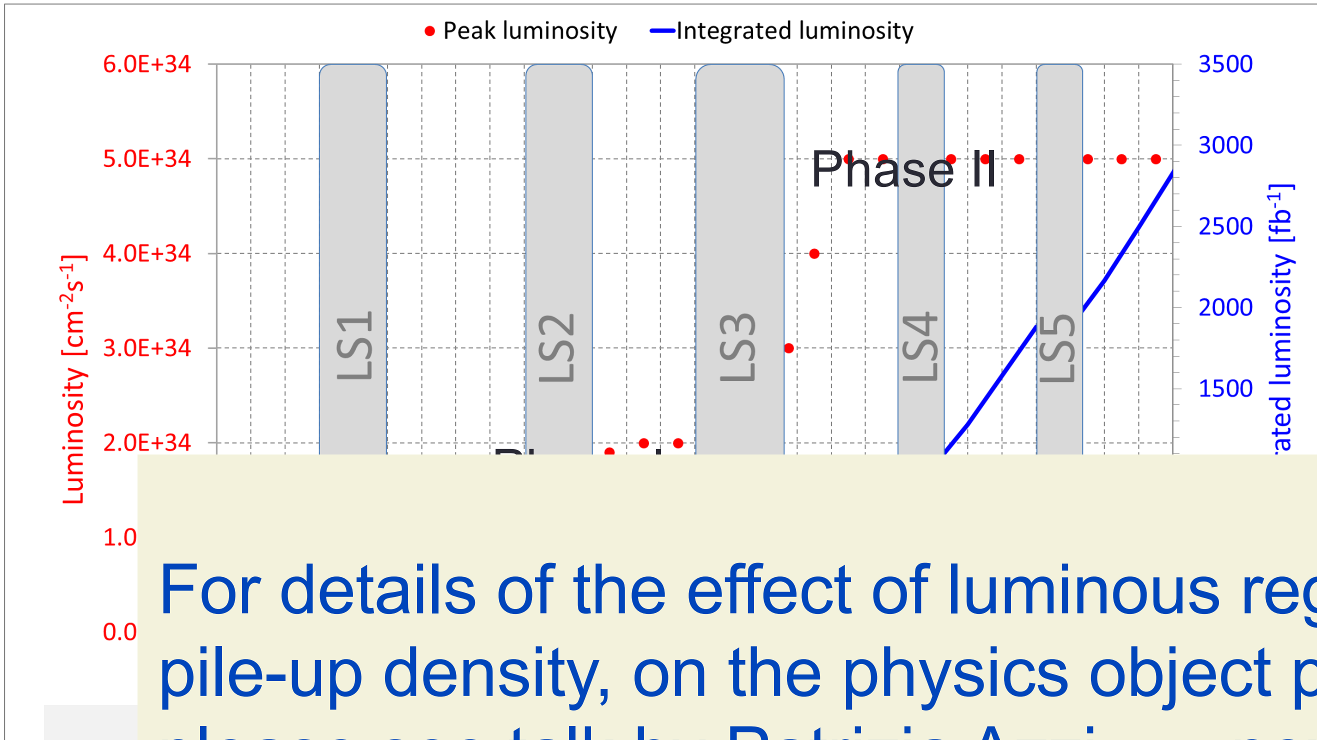
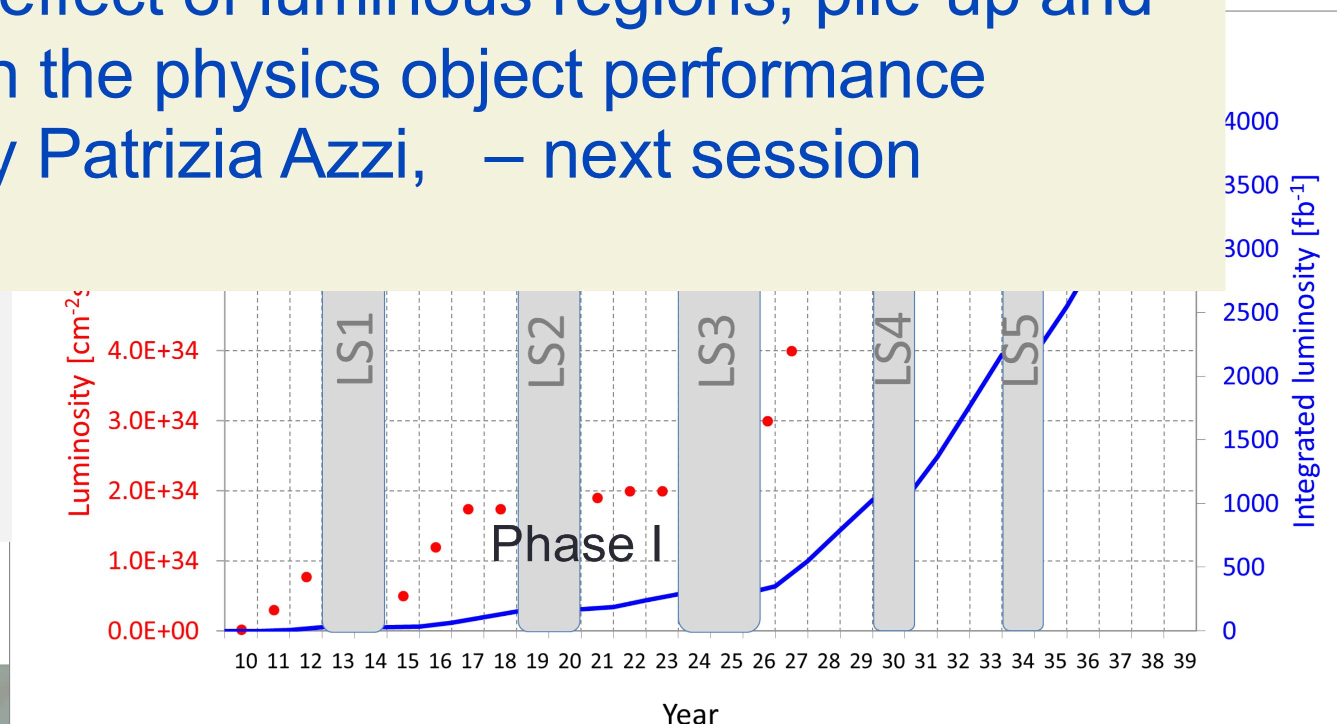


Nominal Scenario
Luminosity leveled at
5×10^{34} Hz/cm^2 ,
Pile-up <μ> = 140

For details of the effect of luminous regions, pile-up and pile-up density, on the physics object performance please see talk by Patrizia Azzi, – next session

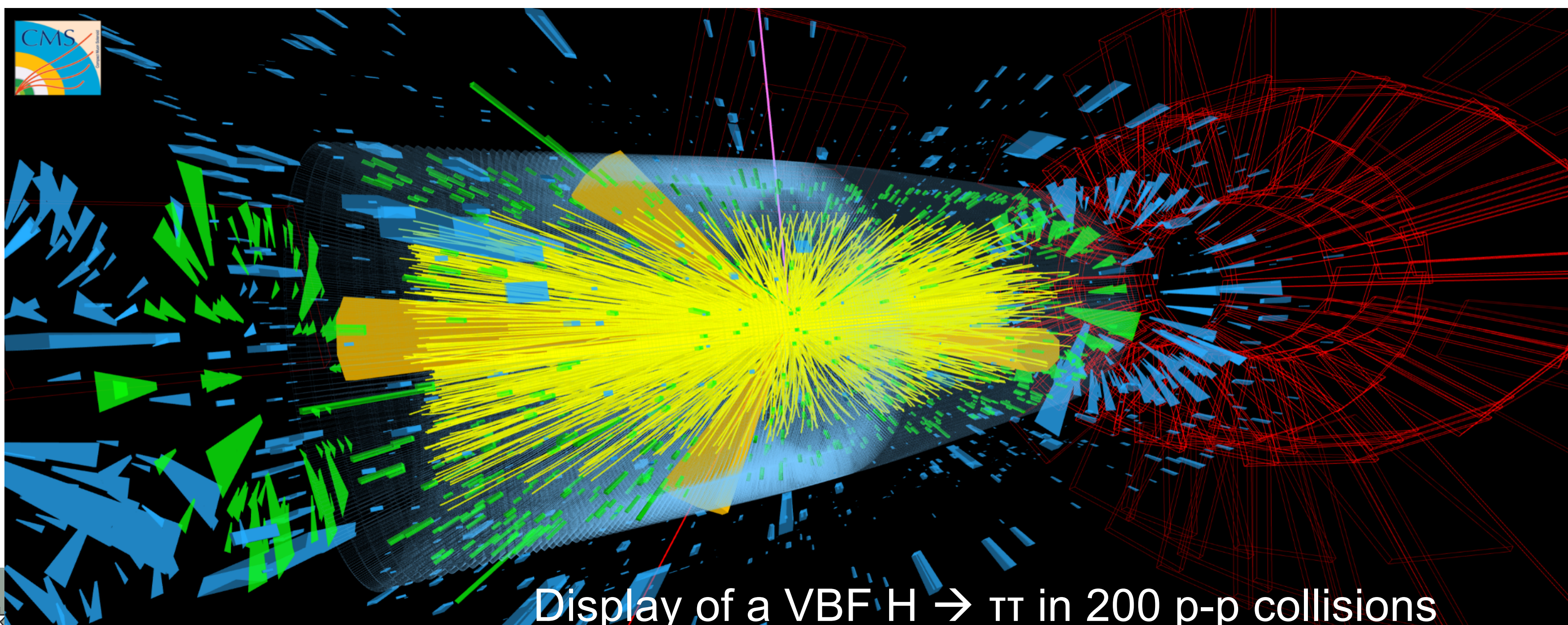
Pile-up <μ> = 200

→ ≃ 25% increase in integrated luminosity



Main challenges

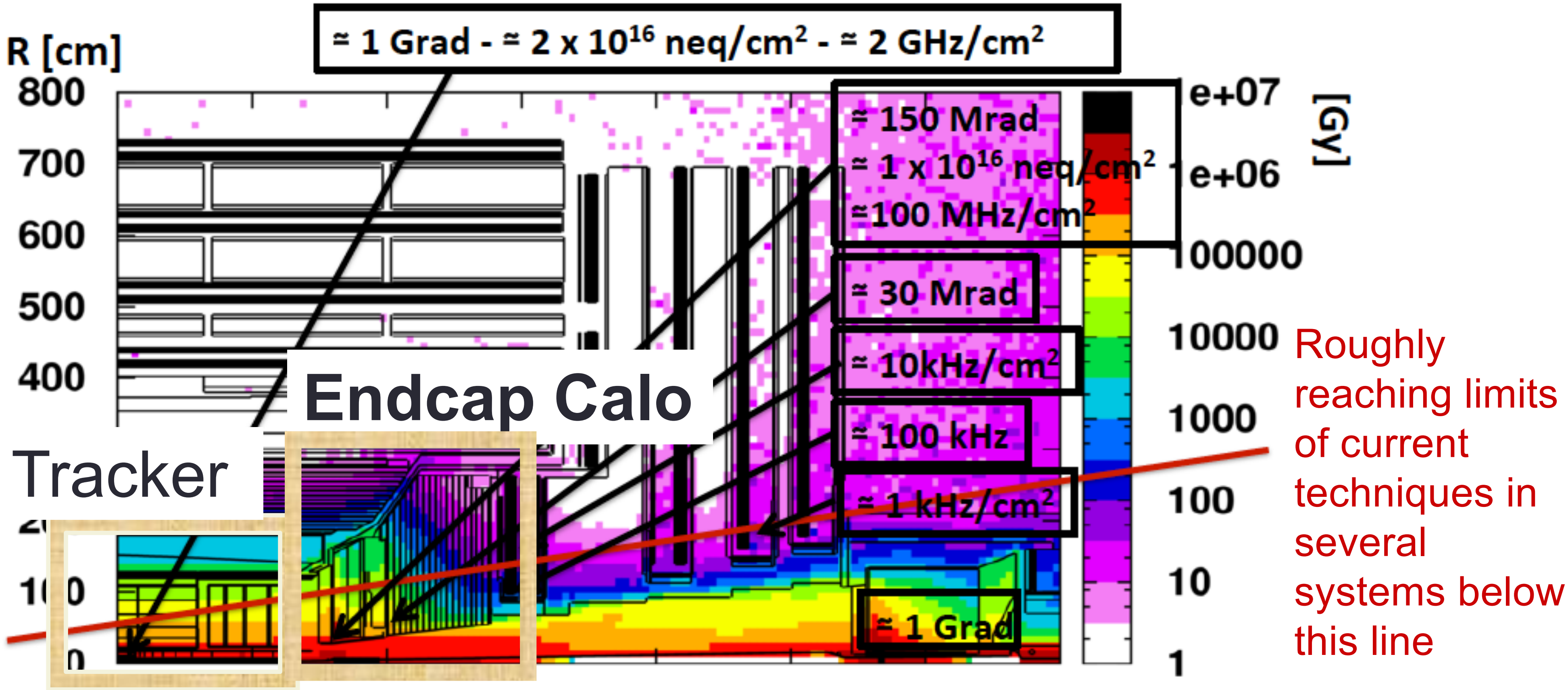
- Pileup
  - Increases the combinatorial complexity and rate of fake tracks
  - Adds extra energy to calorimeter measurements
  - Increases the amount of data that has to be read out in each BX
- Pileup Mitigation
  - High granularity detectors (trackers, calorimeters) needed to identify particles associated with the primary hard scatter collision vertex with high efficiency
  - Precise timing measurement can unambiguously associate both tracks and neutral energy clusters to each vertex, providing ultimate pileup mitigation (under study).



Display of a VBF H → ττ in 200 p-p collisions

Main challenges

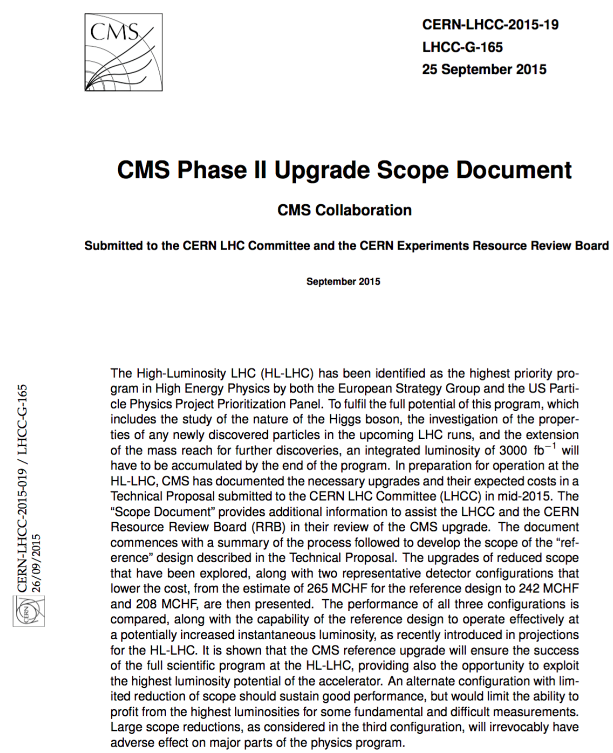
- Radiation damage
  - Detector elements and electronics are exposed to high radiation dose
  - Degrades signal, & limits life time of detectors
  - Requires new tracker, and endcap calorimeters, new forward muons
  - And replacement of most of the readout systems



CMS radiation dose map, neutron equivalent fluence and particle rates for luminosities of 3000 fb^{-1} (integrated) and 5 x 10^{34} Hz/cm^2 (instantaneous)

In 2015

- We submitted the technical proposal and the scope document summarizing
  - The design of the proposed upgrades
  - The performance of the detectors and object reconstruction in high pileup environment
    - Investigated different sub-detector designs and their performance with <pile-up>=140 & 200. The reference design is well suited for 140 PU and provides smooth degradation up to the ultimate value.
  - The increase in physics reach with 3000fb-1 and enhanced detector granularity and acceptances



CERN-LHCC-2015-19
LHCC-G-165
25 September 2015

CMS Phase II Upgrade Scope Document

CMS Collaboration

Submitted to the CERN LHC Committee and the CERN Experiments Resource Review Board

September 2015

The High-Luminosity LHC (HL-LHC) has been identified as the highest priority program in High Energy Physics by both the European Strategy Group and the US Particle Physics Project Prioritization Panel. To fulfil the full potential of this program, which includes the study of the nature of the Higgs boson, the investigation of the properties of any newly discovered particles in the upcoming LHC runs, and the extension of the mass reach for further discoveries, an integrated luminosity of 3000 fb^{-1} will have to be accumulated by the end of the program. In preparation for operation at the HL-LHC, CMS has documented the necessary upgrades and their expected costs in a Technical Proposal submitted to the CERN LHC Committee (LHCC) in mid-2015. The "Scope Document" provides additional information to assist the LHCC and the CERN Resource Review Board (RRB) in their review of the CMS upgrade. The document commences with a summary of the process followed to develop the scope of the "reference" design described in the Technical Proposal. The upgrades of reduced scope that have been explored, along with two representative detector configurations that lower the cost, from the estimate of 265 MCHF for the reference design to 242 MCHF and 208 MCHF, are then presented. The performance of all three configurations is compared, along with the capability of the reference design to operate effectively at a potentially increased instantaneous luminosity, as recently introduced in projections for the HL-LHC. It is shown that the CMS reference upgrade will ensure the success of the full scientific program at the HL-LHC, providing also the opportunity to exploit the highest luminosity potential of the accelerator. An alternate configuration with limited reduction of scope should sustain good performance, but would limit the ability to profit from the highest luminosities for some fundamental and difficult measurements. Large scope reductions, as considered in the third configuration, will irrevocably have adverse effect on major parts of the physics program.

CERN-LHCC-2015-019 / LHCC-G-165
26/09/2015

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

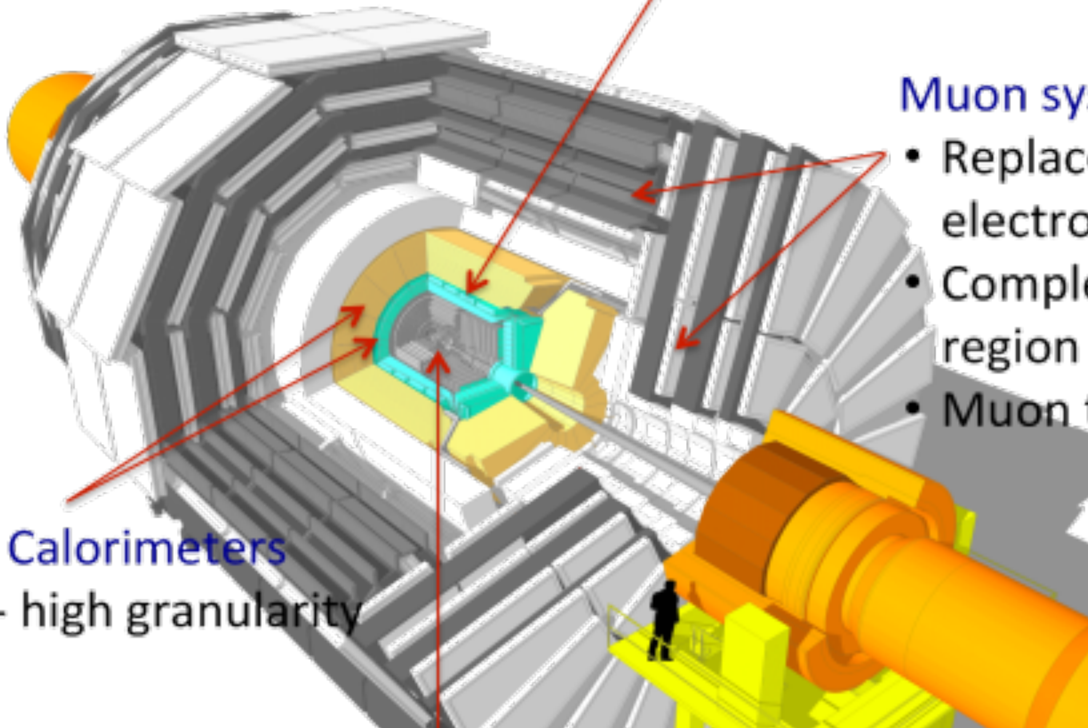
CERN-LHCC-2015-019
https://cds.cern.ch/record/2055167

Summary of CMS HL-LHC 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 calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8◦)

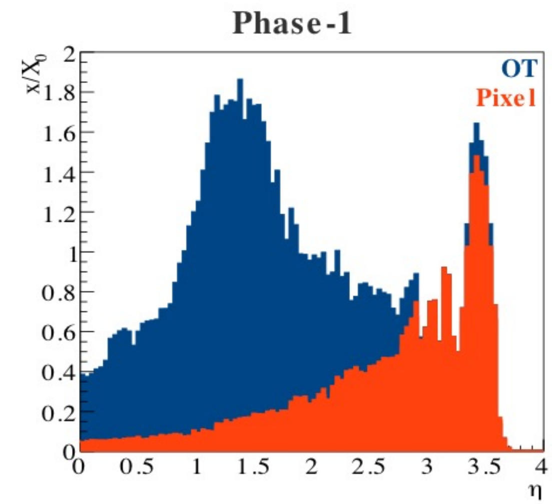
Muon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$



Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

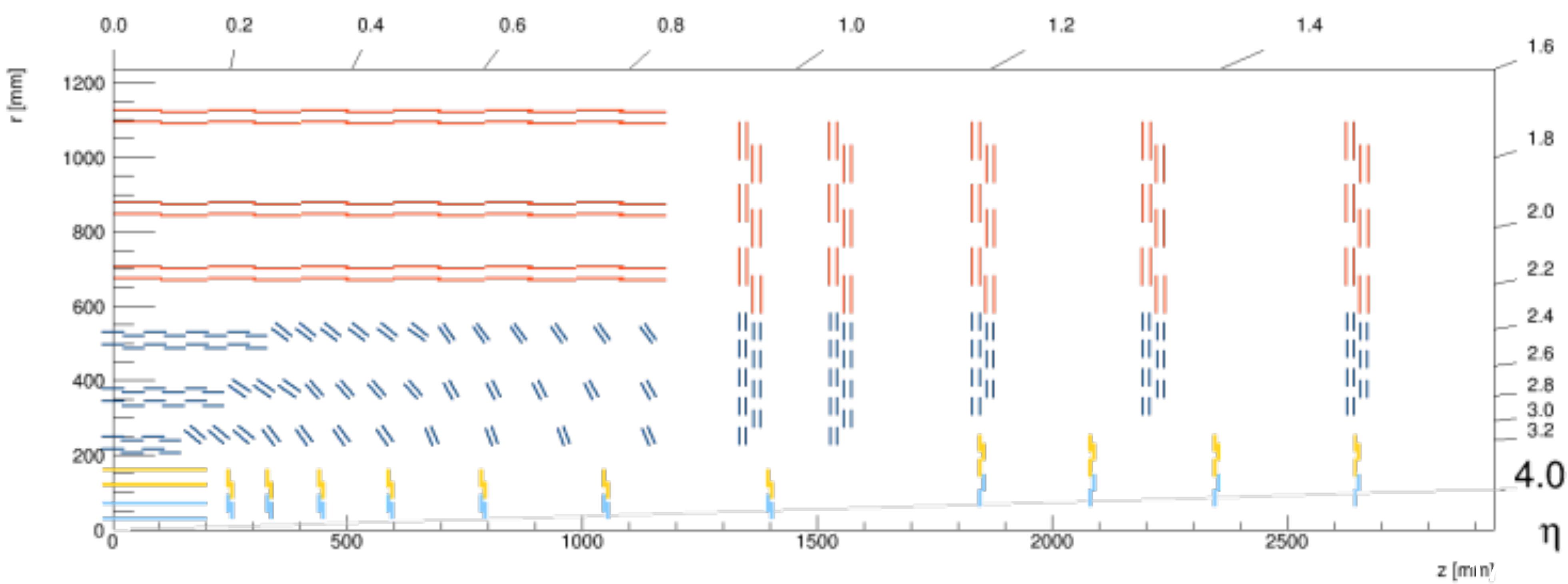
Replace Tracker
- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to $\eta = 3.8$

CMS phase 2 Tracker

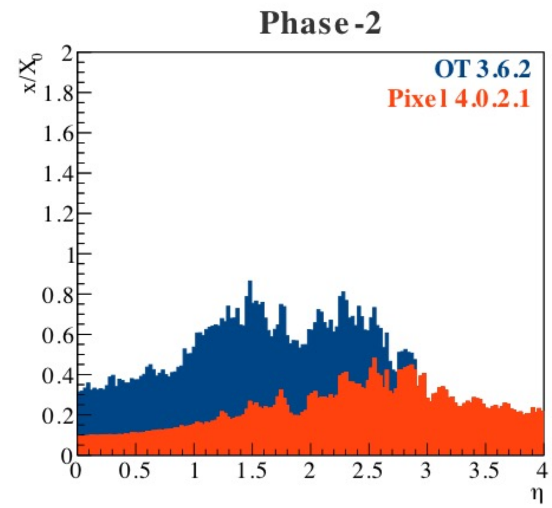


- Specifically designed to provide inputs to L1 Trigger
  - Level 1 track-trigger finds tracks with pT≥2 GeV
- Outer tracker (6 layers, 5 disks)
  - Two-layer p_T-modules provide inputs to level 1 trigger
  - High granularity, efficient track reconstruction for >140 PU
- Pixel detector (4 layers, 11 disks)
  - Extended coverage with disks to |η|<4
  - Thin planar sensors 100μm or 3D sensors;
  - Small pixels (50x50 or 25x100 μm^2)
- Improved material budget and radiation tolerance

See talk by:
Stefano Mersi: Design Optimization CMS Tracker, Wednesday Morning



CMS phase 2 Tracker



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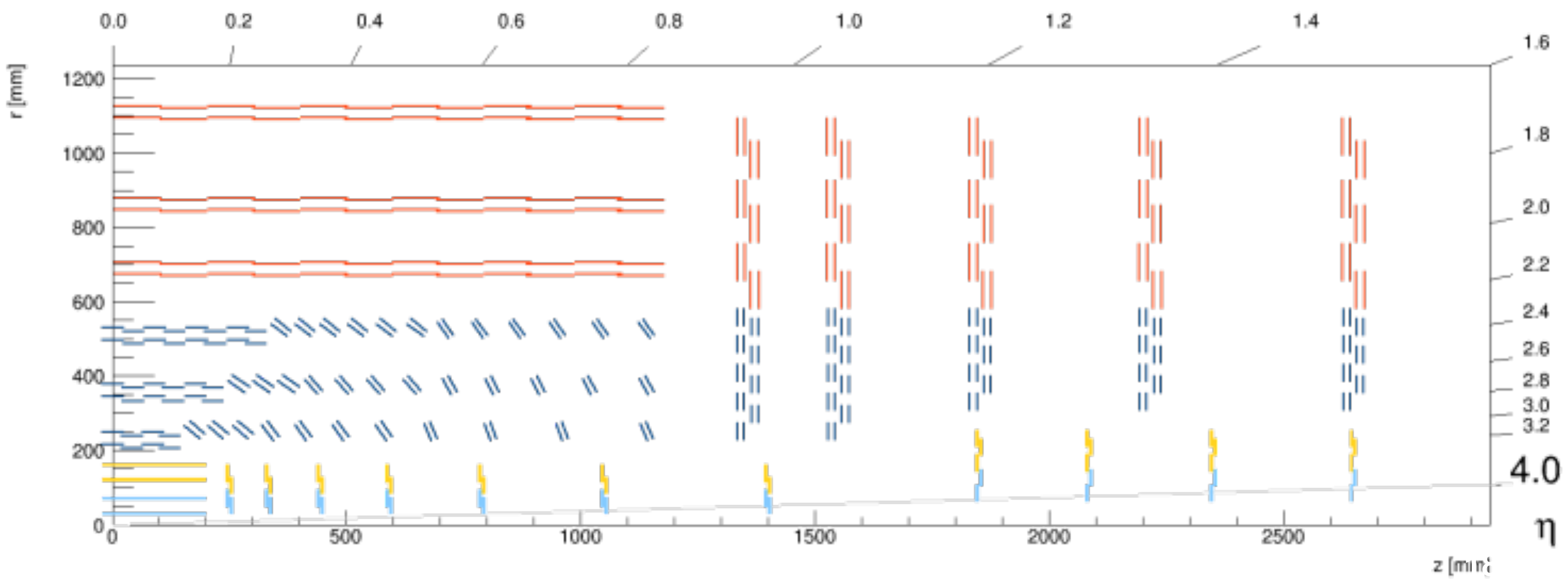
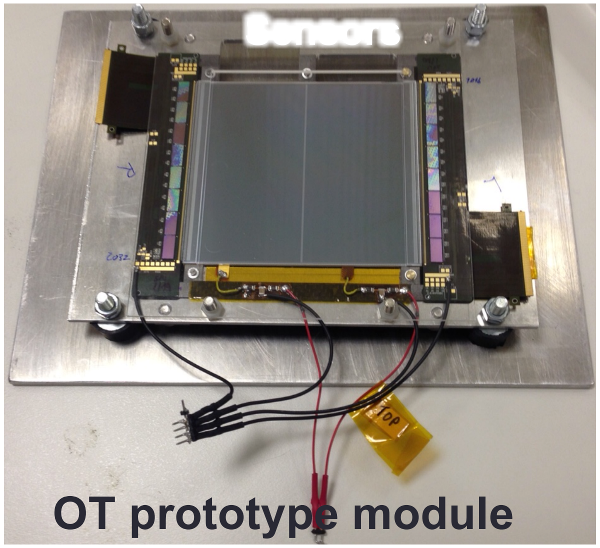


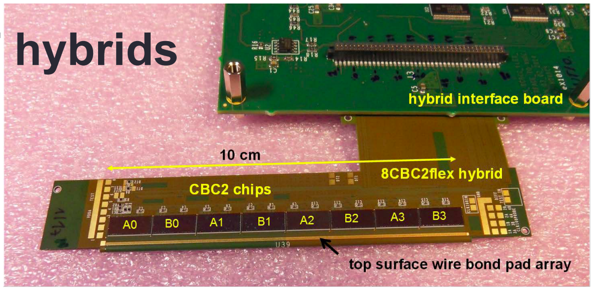
CMS phase 2 Tracker

- Outer tracker
  - Sensors
    - R&D of material and technology complete.
  - Modules
    - Design and assembly procedures are being established.
    - Prototype modules tested in beam tests.
  - Hybrids
    - Designs and prototypes exist, development with 3 suppliers
  - Readout ASICs
    - 65nm CMOS
    - First prototype with reduced functionality exists
    - Full scale chip under design, to be submitted in spring 2017
- Pixel detector
  - Sensors
    - R&D program of planar and 3D sensors in progress
    - Assessing radiation tolerance and optimizing design
  - Read Out Chip
    - Development in 65 nm in common with ATLAS: RD53
  - Replacement of inner layer/ring considered as an option to mitigate effect of radiation damage

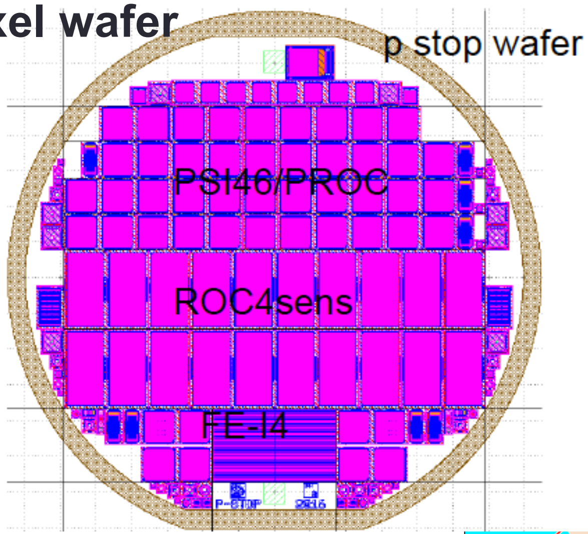
CMS Strip Tracker R&D: Alexander Dierlamm
CMS Pixel Tracker R&D: Julia Thom
Wednesday Morning



OT hybrids



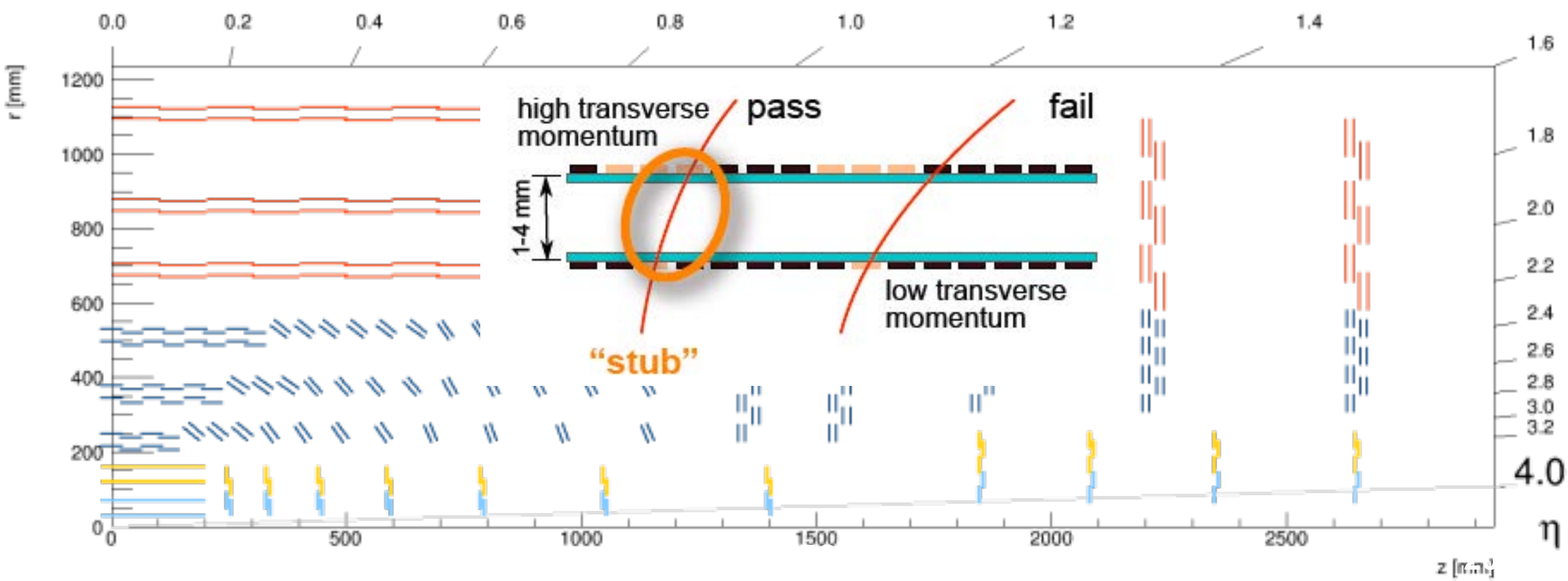
Pixel wafer



CMS phase 2 Track Trigger

Thursday afternoon:
Level-1 track finding at CMS:
Louise Skinnari

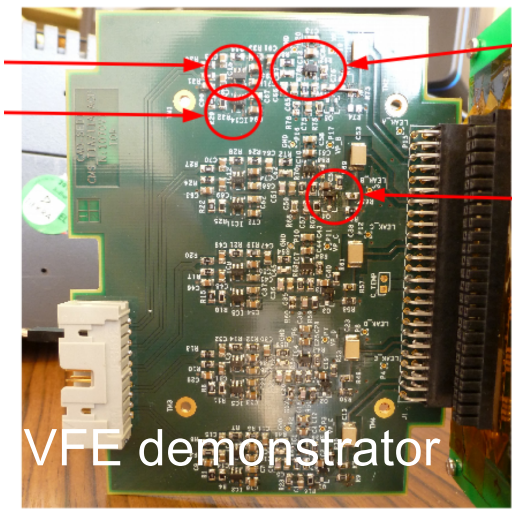
- Outer Tracker pT modules
  - 2 sensors, spaced by few mm and read out into same chip
  - Measure bending of particles in high B-field & filter data on detector to select hit pairs from tracks with pT ≳ 2 GeV
  - Transfer to back end at 40 MHz
- Several design options for track reconstruction in back-end electronics
  - ASIC based associative memories + FPGA
  - FPGA based projective binning using Hough transform
  - FPGA based tracklet building and combined chi squared track fit
  - Demonstrators by end of year

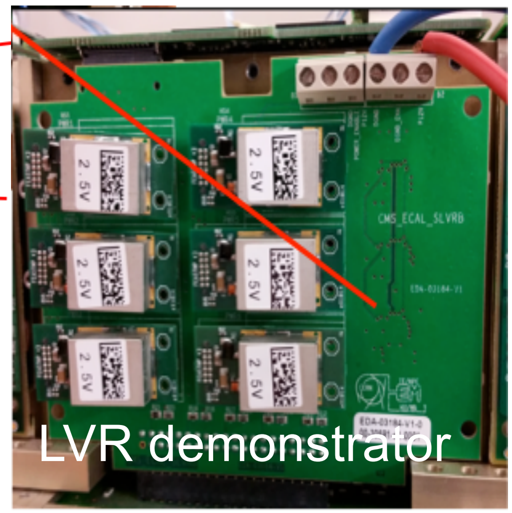


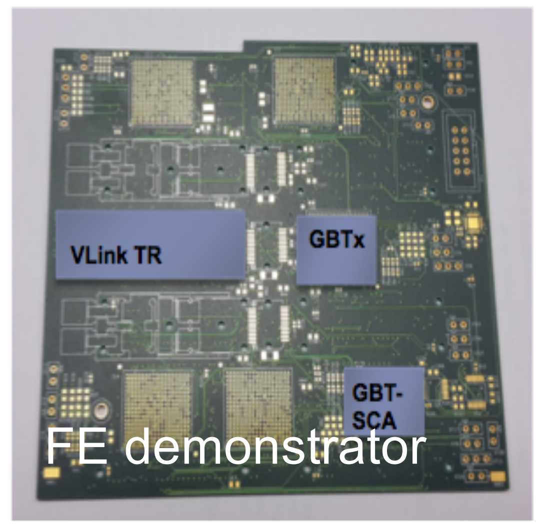
Barrel Calorimeter design optimisation: Colin Jessop
Wednesday afternoon

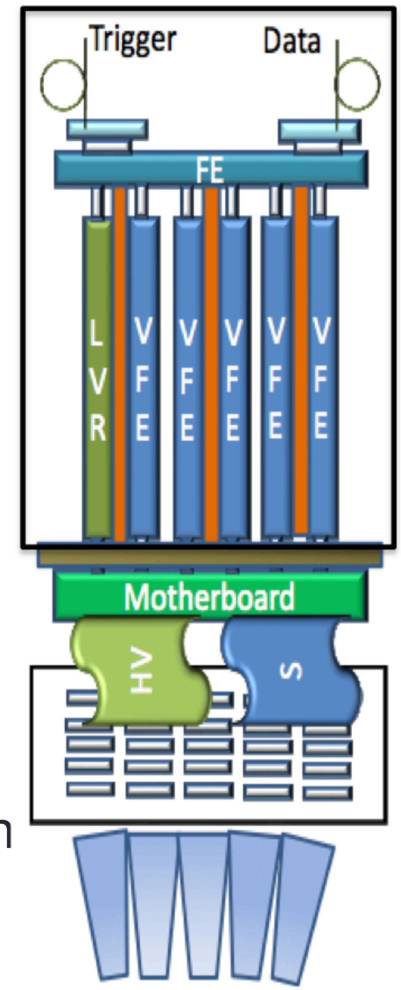
CMS phase 2 Barrel EM Calorimeters

- New readout to provide full granularity to hardware trigger to improve isolation
- New Very Front-End pre-amplifier and ADC to mitigate noise/background effects and improve time resolution
- Operate photodetectors cold (T ≃ 8°C) to reduce noise from radiation aging of APD.





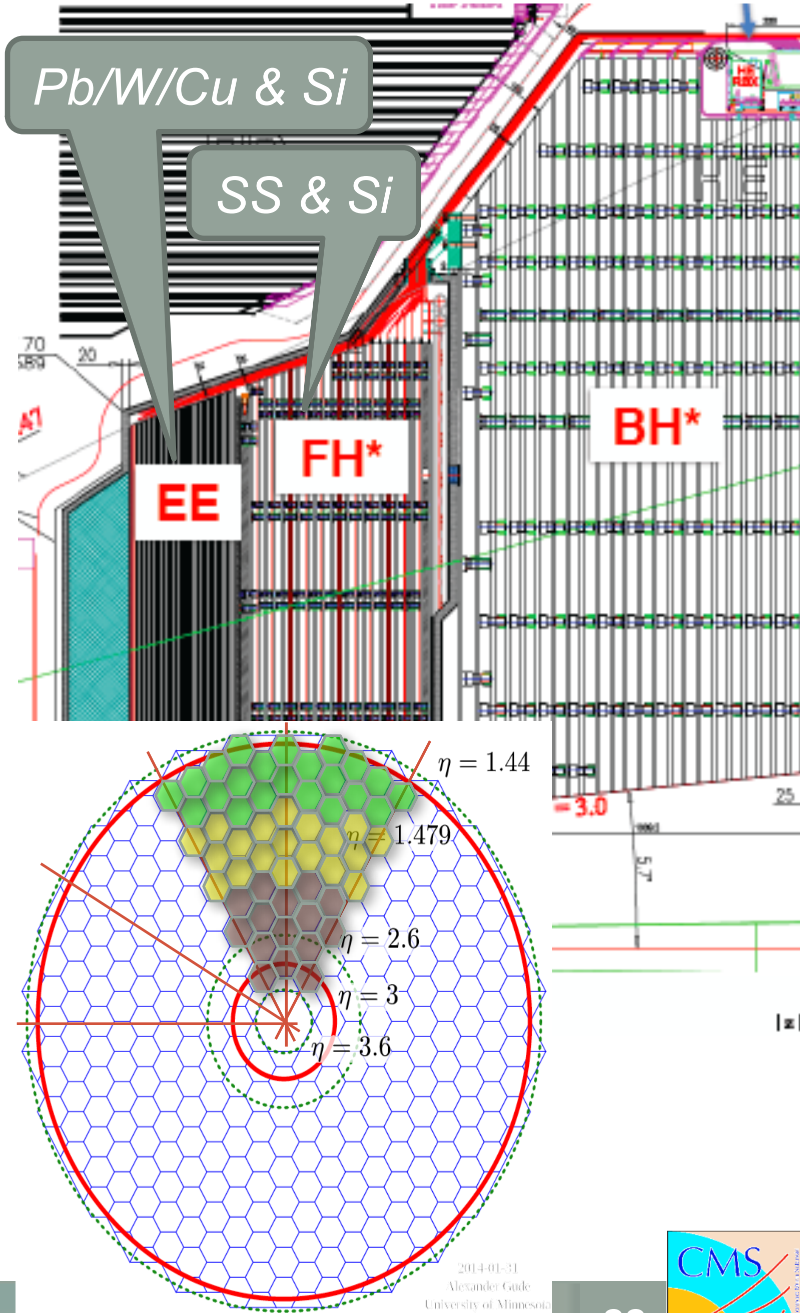




- Demonstrator boards for VFE (with discrete components), FE with 5Gbps GBT and LV with DC/DC converters are ready for test
- Preliminary test beam results indicate ~ 30 ps timimg resolution with crystal + APDs could be reached at E ≳ 30 GeV

CMS phase 2 Endcap Calorimeters

- New High Granularity Calorimeter using silicon sensors to allow detailed 4D (space-time) reconstruction of showers
- Electromagnetic Calorimeter:
  - 28 layers of W/Pb/Cu total of >25 Xo, 1.5λ
  - 380 m^2 of silicon pad detectors, 4.3M channels
- Front Hadronic Calorimeter
  - 12 layers of SS/silicon (3.5λ), 209 m^2 of Si, 1.8M ch.
- Hexagonal silicon sensors
  - 3 active thicknesses (100/200/300 μm) depending on radius
  - 0.5 - 1 cm^2 pads for 100 - 200/300 μm
- Operation at -30^{o}C using CO_2 Cooling (to mitigate Si sensor radiation issues).



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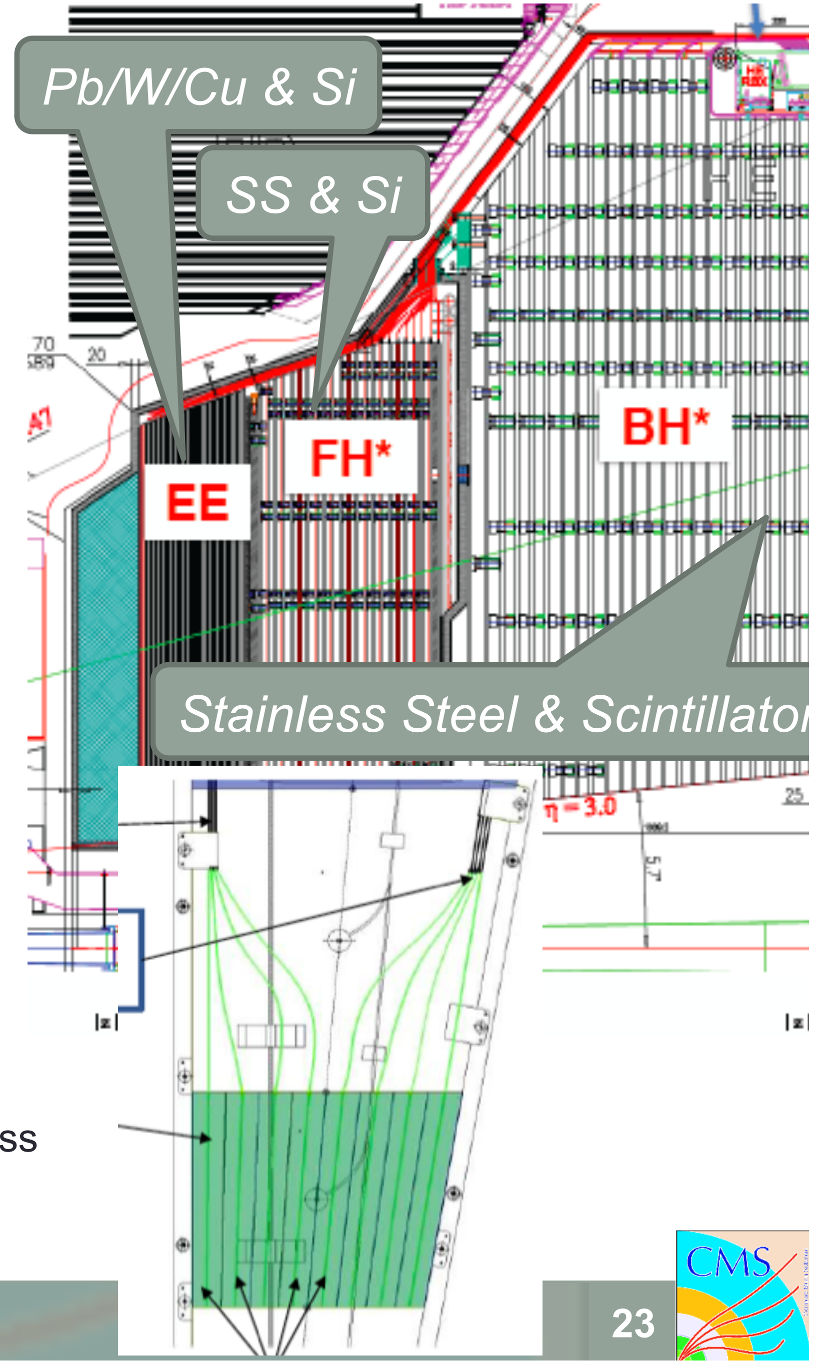
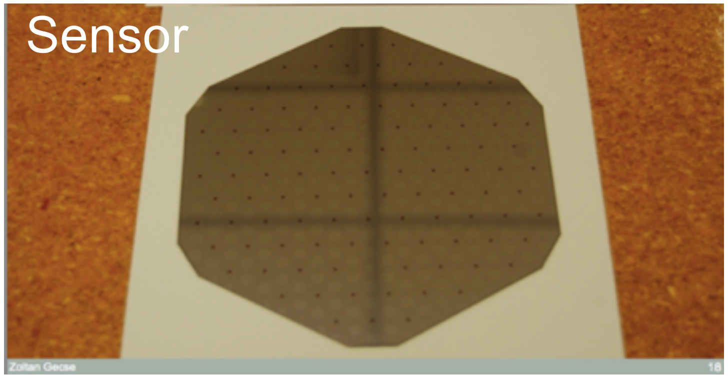
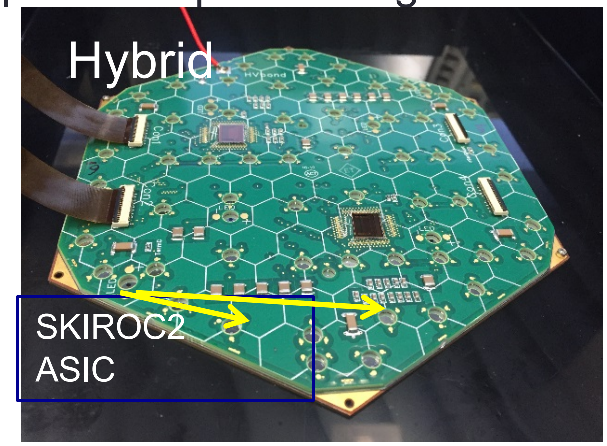
  - 0.5 - 1 cm^2 pads for 100 - 200/300 μm
- Operation at -30^{o}C using CO_2 Cooling (to mitigate Si sensor radiation issues).
- Backing calorimeter
  - Five interaction lengths (e.g. sampling of 0.4λ).
  - Radiation levels lower→ use plastic scintillator & stainless steel



CMS phase 2 Endcap Calorimeters

- Si-sensors R&D ongoing
  - high quality 6” p-in-n sensors received
  - multiple geometries & other designs on 6” & 8” n-in-p orders proceeding



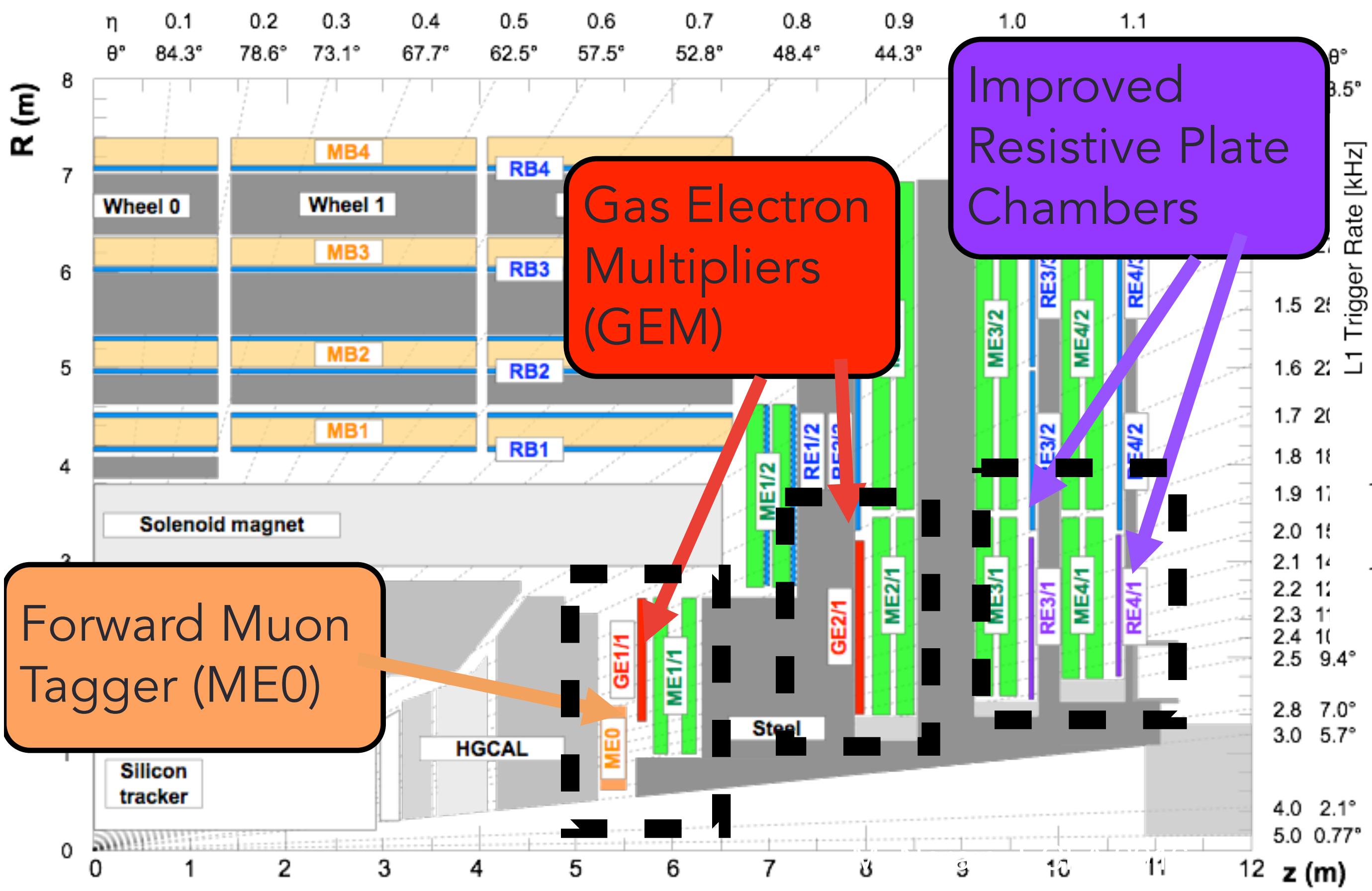


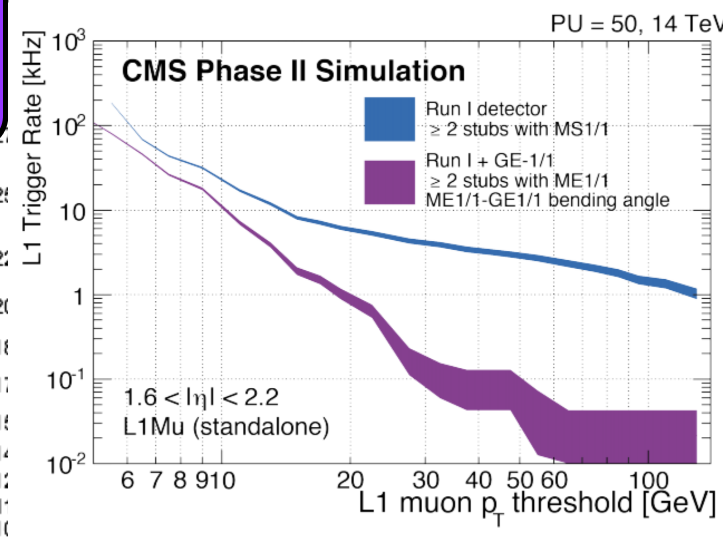
- Frontend Electronics R&D
  - SKIROC2 (from CALICE with slow shaping) readout ASIC used in this year’s beam test
  - Submit various designs of HGROC analogue part in 130nm technology by end of 2016
  - Submit first 64-channel ASIC with full functionality by June 2017.
- Test beams in 2016: EE proto at FNAL & CERN, 2017: EE + FH at CERN
- Measured time resolution: $\simeq$20 ps with 10 MIP signal in a single unirradiated pad
- Mechanical structure
  - Baseline design: carbon-fiber alveolar structure with 30° cassettes inserted (CALICE).
  - Alternative: with full disk design (non-insertable cassettes).
  - Baseline choice for TDR to be made by the end of 2016

Design and optimisation considerations
Anna Colaleo, thursday afternoon

CMS phase 2 Muon system

- Maintain excellent triggering, ID/reco, & resolutions under harsher HL-LHC conditions
  - Existing detectors: barrel DT and endcap CSC electronics upgrade for 40 MHz readout
  - New chambers to complete forward region at $1.6 < \eta < 2.4$ region
    - GEM detectors — reduces trigger rate by factor of 2-4 or more
    - iRPC chambers — high rate, and timing resolution to reject background
  - Forward muon tagger — ME0 - Coverage up to $\eta = 3$



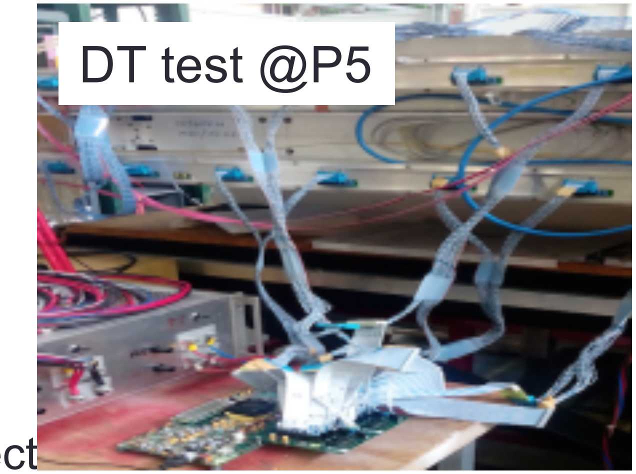


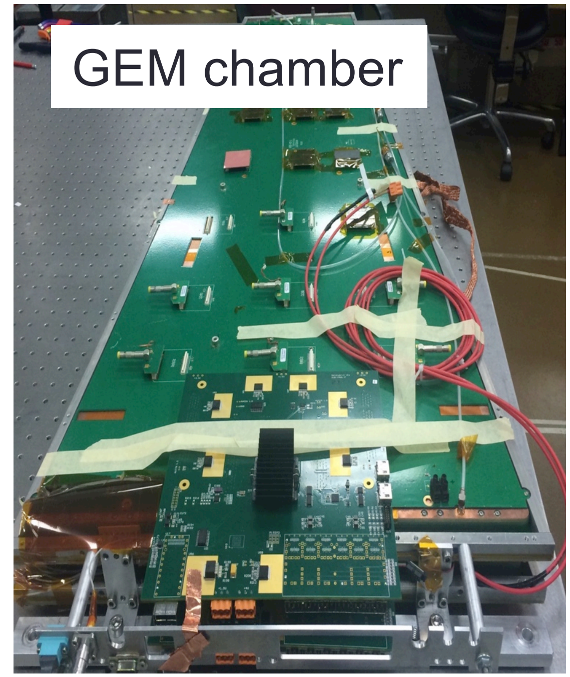
CMS phase 2 Muon system

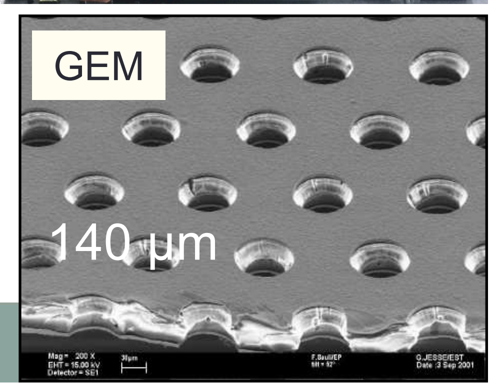
- Current focus is on design optimization
- Drift tubes
  - DT chamber on surface at Point 5 is being equipped with upgraded prototypes to collect cosmic ray muons
  - Longevity and gas tests at GIF++ to confirm margins and select eco-friendly gas mixtures

- iRPCs
  - Increased rate capability, 2.0 kHz/cm^2 vs present 0.3 kHz/cm^2.
  - Plan to use low resistivity Glass and Bakelite, and double or multi-gap designs for high timing accuracy
  - Promising results with small and large prototypes

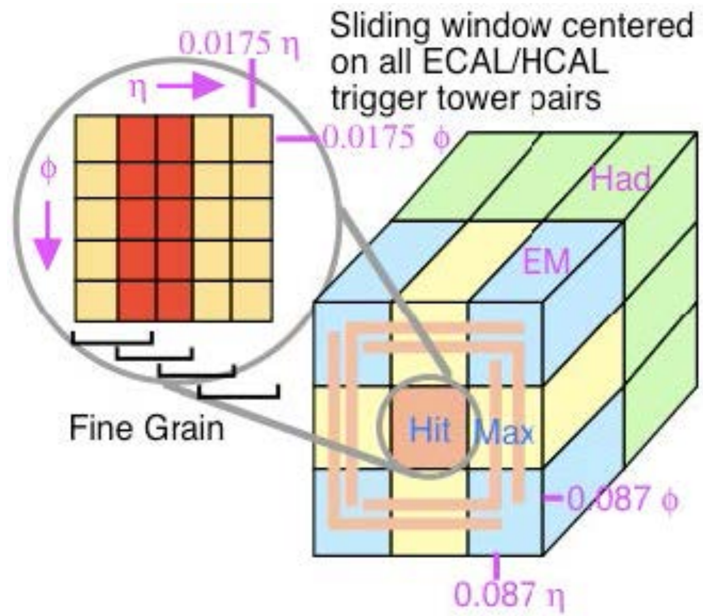
- GEM detectors
  - Install pilot system during EYETS2016
    - 5 super chambers
    - 10 detectors already assembled, now under certification
    - Unique opportunity to gain experience and fine tune mass production, commissioning, online and everything else
  - Full installation in LS2







CMS phase 2 trigger

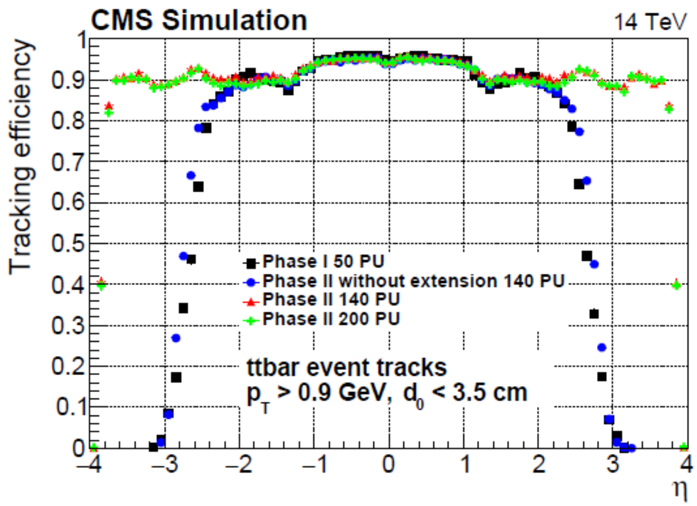


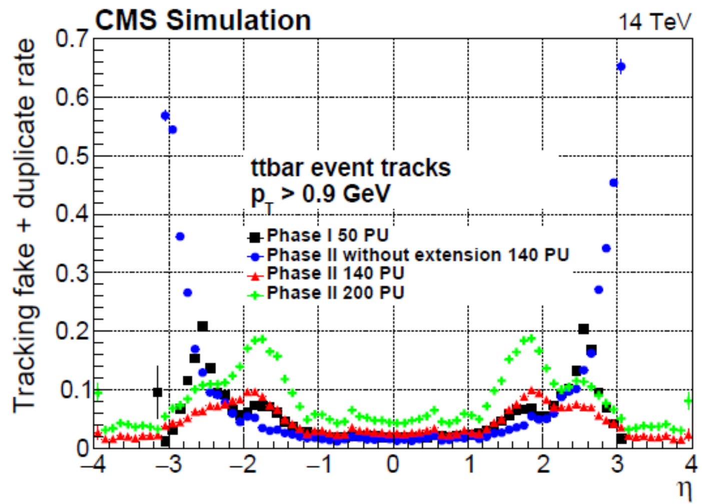
- Replace ECAL frontend electronics
  - Allows L1 latency of 12.5 μs
  - Provides individual crystal level information
    - not 5x5 sums
- L1 track trigger
  - Lepton p_T & isolation, jets, vertex
- New L1 Trigger (Calorimeter, Muon, Global) to incorporate
  - Track trigger
  - Finer calorimeter cluster information
  - Additional muon coverage for |η|>1.5
  - Muon & calorimeter seeds for track match
- L1 accept rate of 750 kHz @200 PU
  - Larger acceptance and lower thresholds
- HLT output rate of 10 kHz
  - Limited by downstream computing

PERFORMANCE OF THE UPGRADED DETECTOR

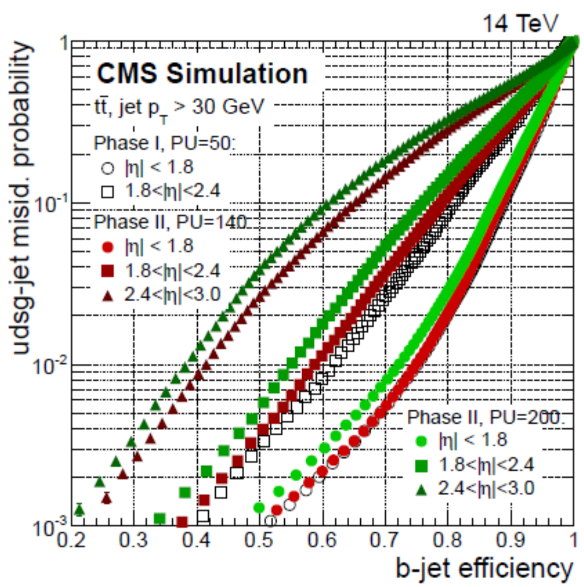
Effect of pileup on track efficiency, b-tagging

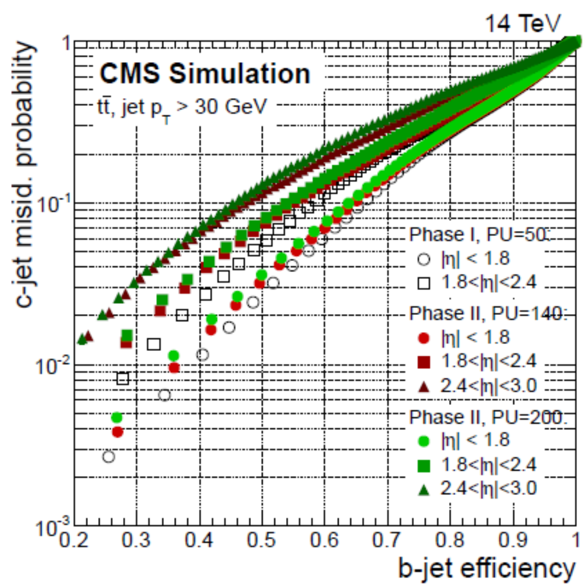
- $t\bar{t}$ events with 140 PU (●) and 200 PU (●) LHCC-P-008





- $t\bar{t}$ events with 140 PU (●■▲) and 200 PU (●■▲)

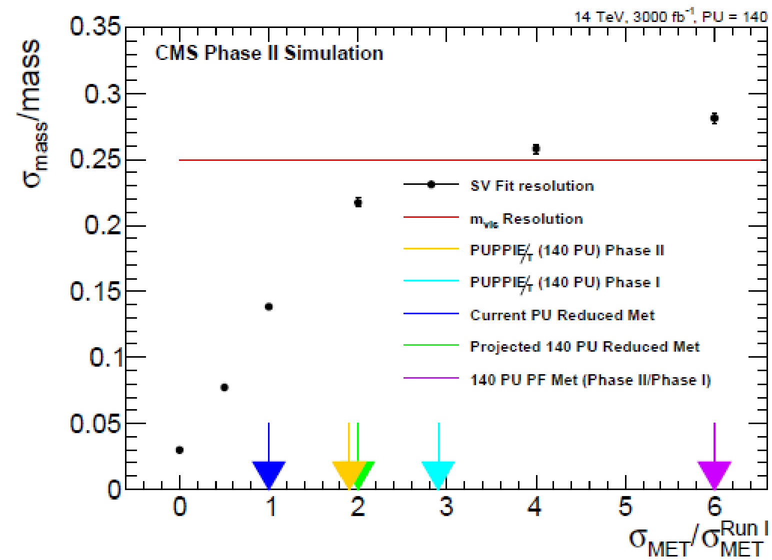




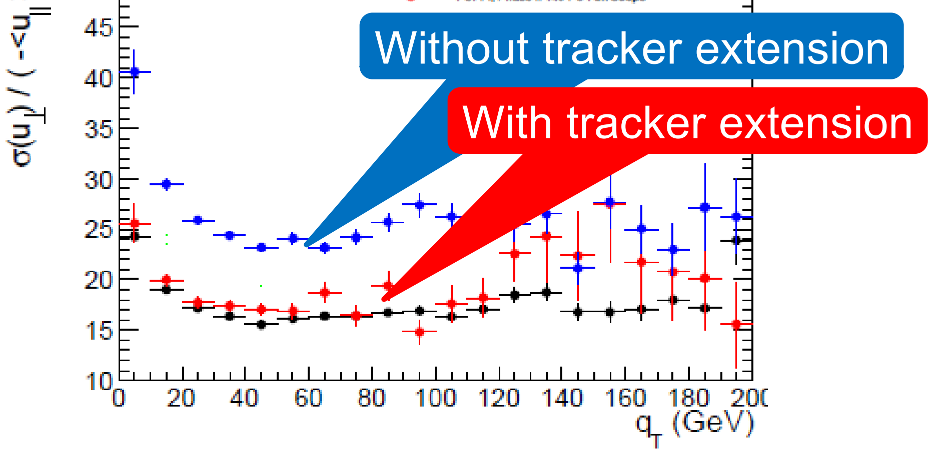
H → ττ - missing p_T resolution

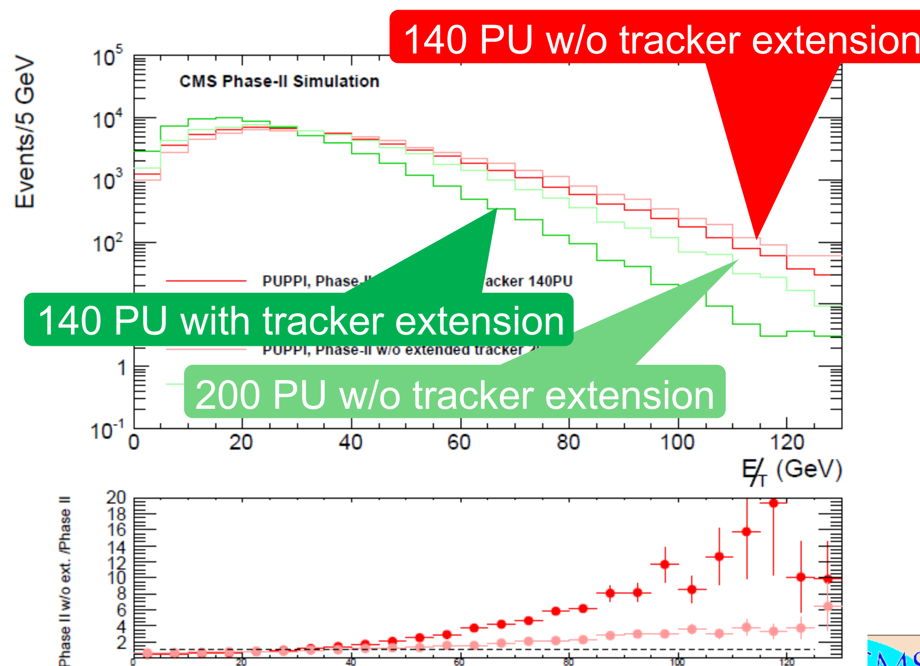
LHCC-P-008

- $m_{\tau\tau}$ resolution depends on missing p_T
- Missing p_T resolution
  - Extended tracker coverage in η
  - Pileup mitigation



Perpendicular recoil of Z bosons

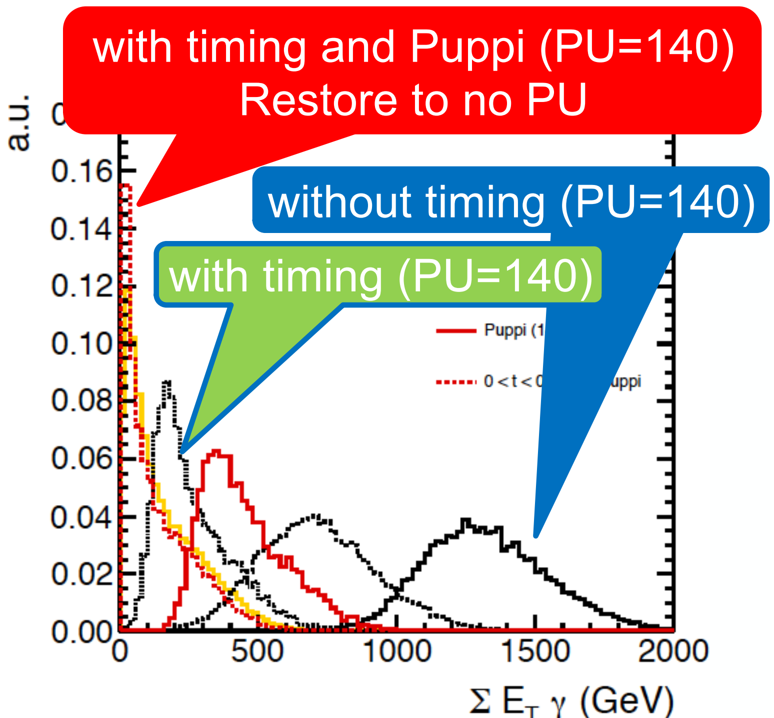




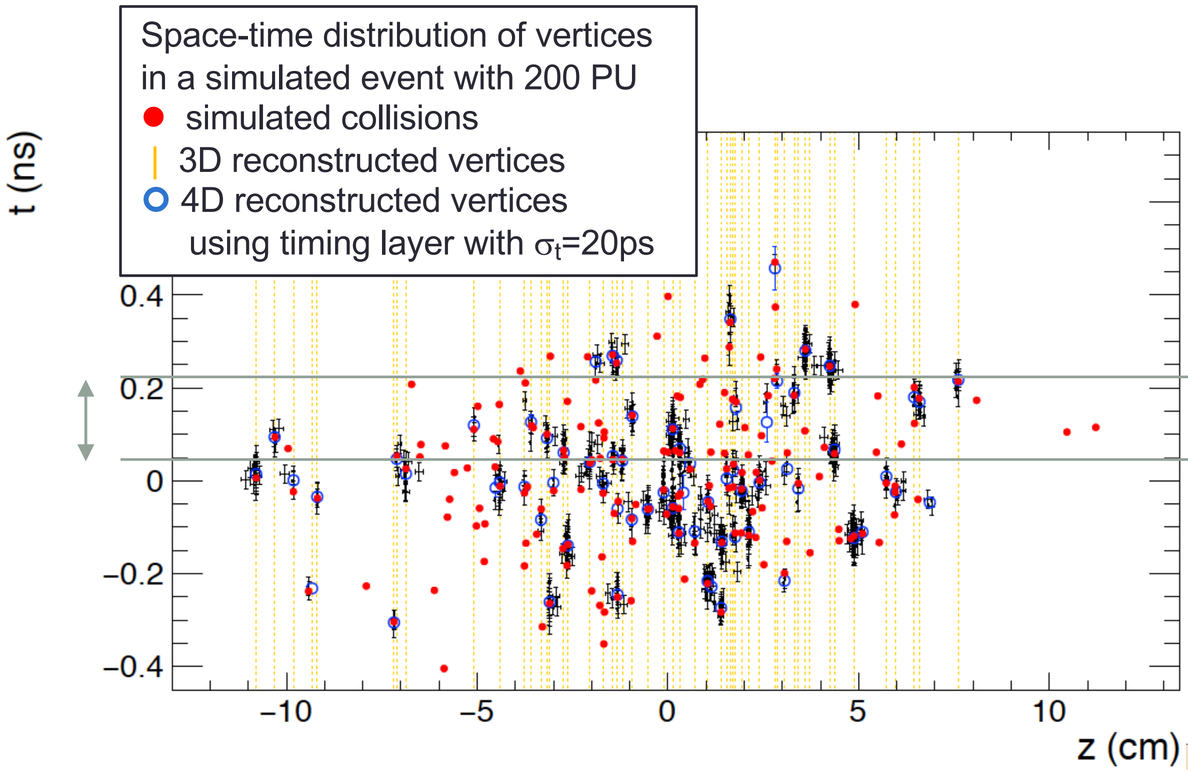
NEAR TERM OUTLOOK

Pileup Mitigation with time information

- Interaction vertices are distributed in z (rms ≈ 5 cm) and time (rms ≈ 170 ps)
- If tracks and calorimeter signals had a time stamp with ≈ 30 ps resolution, one could restrict the time interval around the hard interaction to reduce the contributions of pileup interactions
- Time information is an integral part of the barrel and endcap calorimeter upgrades.
- Currently investigating the feasibility of a dedicated timing detector for tracks



Missing pT performance with time information



Extend Performance Studies

- Major Effort current underway to:

- Define and implement the complete description of the geometry of the baseline detector in full simulation
- Digitization and Local reconstruction of hits and clusters

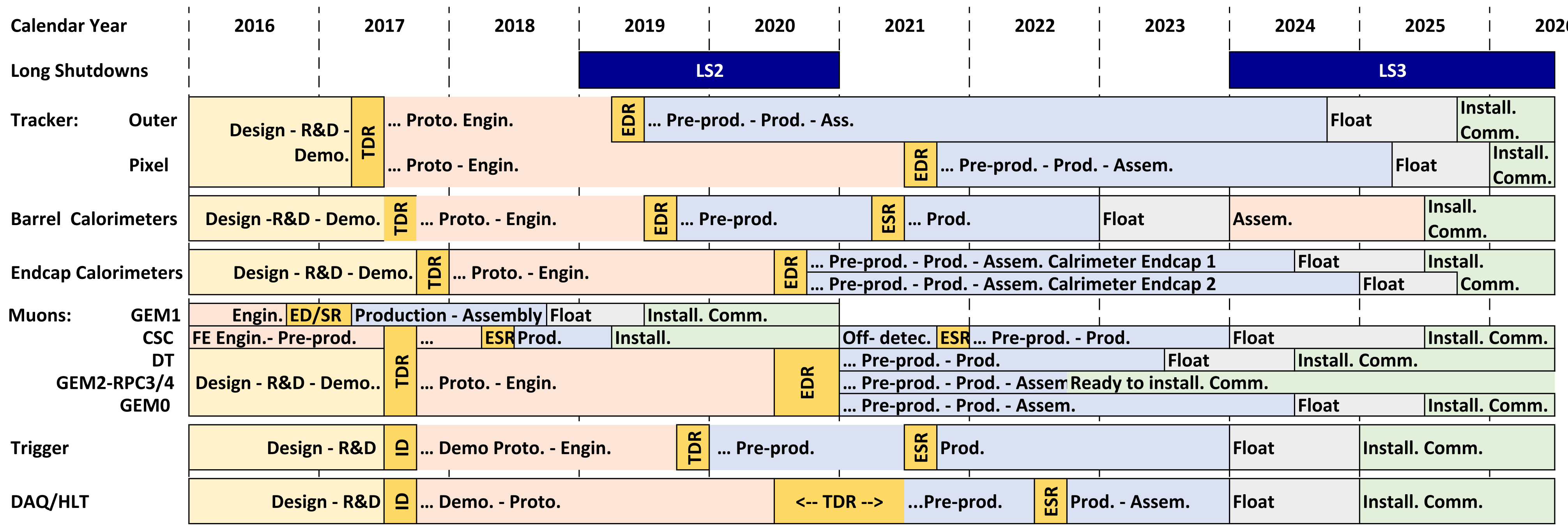
- Implement the object reconstruction algorithms
- Develop object selection and identification algorithm

- Develop and tune pile-mitigation algorithms
- Optimization, and validation will be the focus

- Study performance in Pileup $\langle\mu\rangle$ = 140 & 200 scenarios
  - talks on object performance:
  - Erica Brondolin: tracking, vertexing, b and tau tagging (Wed. morning)
  - Alexx Perloff: e/gamma, jets and missing Et (Wednesday afternoon)
  - Alexei Safanov: muons (Thursday morning)

Milestones & Timelines

- Tracker TDR
  - May 2017: pre-view document; end of June 2017: provide CMS approved version - including cost and responsibilities
  - Nov. 2017: final approval of the Tracker TDR
- Barrel Calorimeters and Muons TDRs
  - Sep. 2017: provide CMS approved TDRs - including cost and responsibilities
  - Feb. 2018: final approval of the BC and Muons TDRs
- Endcap Calorimeter TDR
  - Nov. 2017: provide CMS approved TDR - including cost and responsibilities
  - May. 2018: final approval of the Endcap Calorimeter TDRs



Summary

- In the coming 15 years LHC will continue to increase its luminosity
  - Goal is to accumulate an integrated luminosity of 3000/fb
  - 140-200 pileup interactions/crossing
- Compelling program of precision measurements in Higgs sector and exploration of the TeV scale via heavy new particle searches
  - Requires low trigger thresholds, excellent resolution and maximal acceptance
- Main challenge is mitigation of large number of pileup interactions
  - Trigger – more bandwidth, new capabilities (eg track trigger)
  - Increased detector granularity and acceptance in η
  - Timing measurements will add an additional dimension to pileup rejection
- Baselines for the upgraded detectors have been defined
  - Technologies for detectors are identified/demonstrated
  - Several innovations compared to current detectors to withstand large scale and harsh environment
  - R&D now focused on finalizing specifications and prototyping/engineering - 2 to 4 years effort to start of production

References

- ECFA 2016 DPS Note: add XYZ ref
- CMS Collaboration, “Technical Proposal for the Phase-II Upgrade of the Compact Muon Solenoid”, Technical Report CERN-LHCC-2015-010, LHCC-P-008, 2015.
- CMS scope document LHCC-G-165, 2015.
- Higgs Working Group Report of the Snowmass 2013 Community Planning Study, arXiv:1310.8361 [hep-ex]
- Slides of previous talks by colleagues
  - Some of which I have shamelessly borrowed from (many thanks).