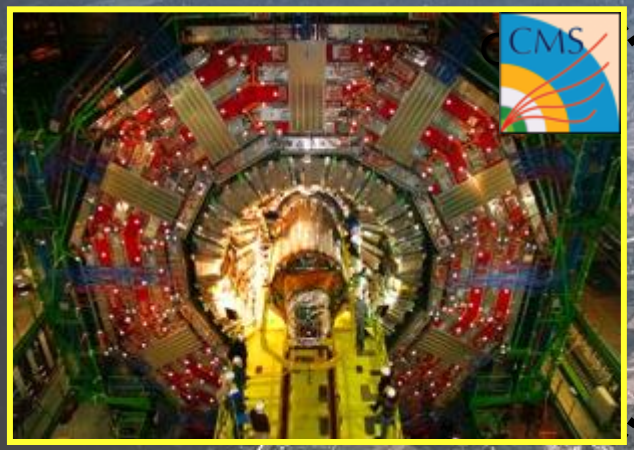
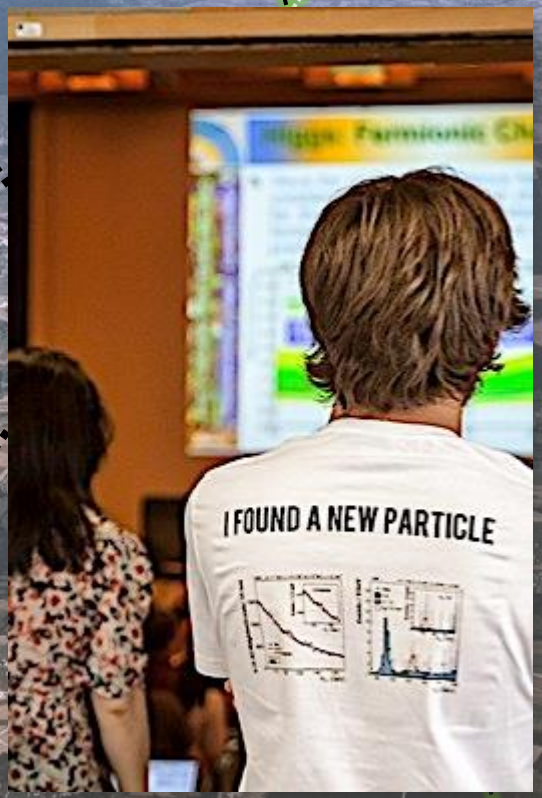
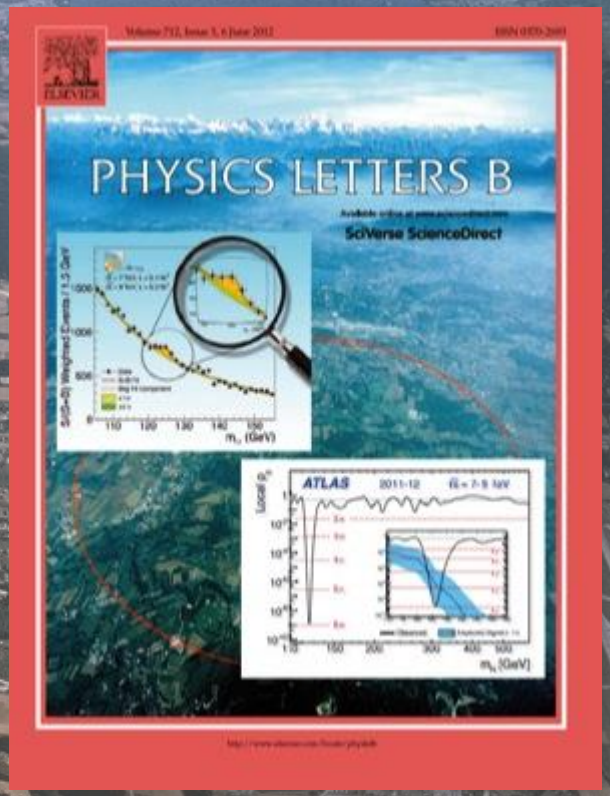
May 20'th 2014

CMS UPGRADES FOR HL-LHC: SELECTED HIGHLIGHTS

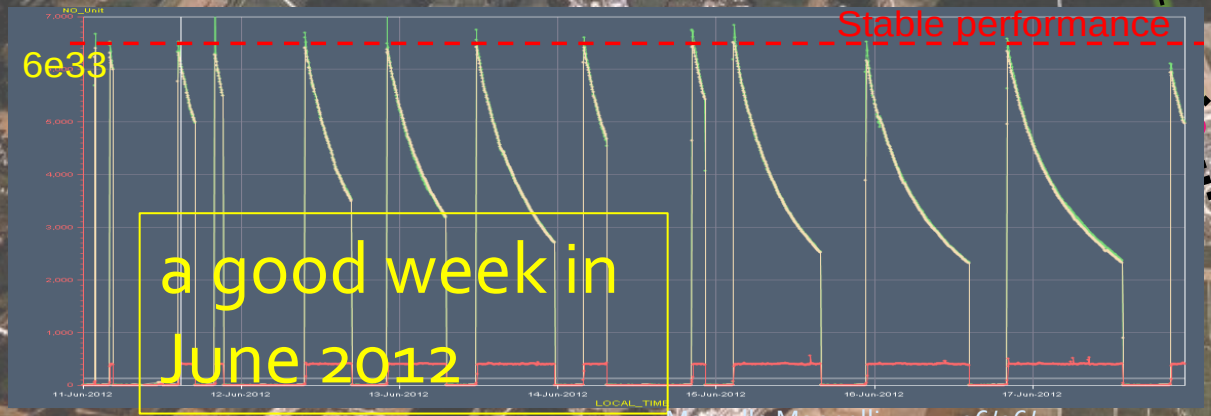
So Far So Good

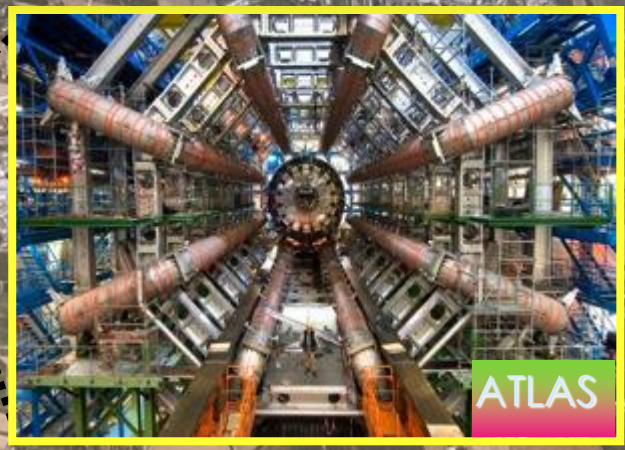






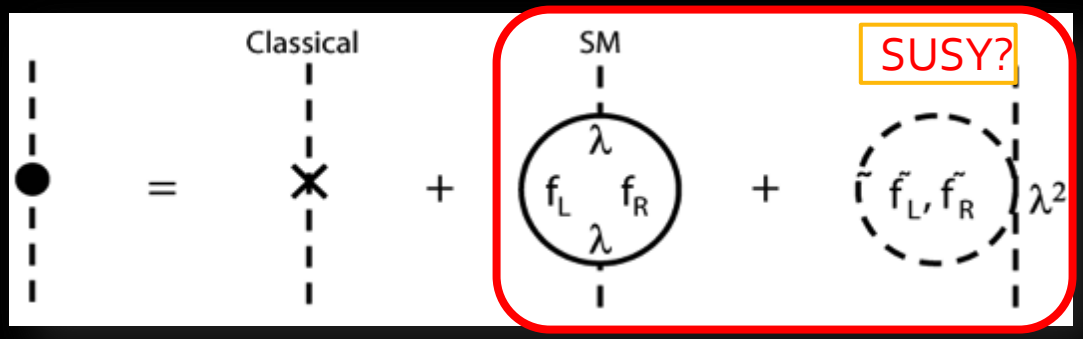
2011 ~ 5fb^{-1} + 2012 ~ 25fb^{-1}
For each ATLAS and CMS





And this is just the beginning!

Post-discovery landscape

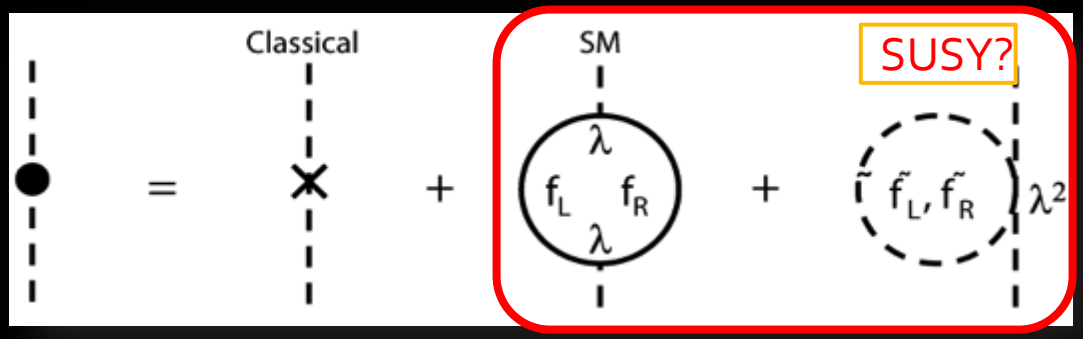


- Higgs Discovery ⇒ Hierarchy problem no longer hypothetical
  - Corrections to the Higgs mass appear to want to be at the Planck scale
  - Is the universe incredibly fine-tuned?

- How do we resolve this issue?
  - SM partners especially 3rd generation & EWK Bosons ⇒ Naturalness
  - New phenomena related to the true Planck scale being much lower
  - …

- These are experimentally testable at the LHC
  - e.g. naturalness even fine-tuning a bit requires partners at the TeV scale

Post-discovery landscape



- Higgs Discovery ⇒ Hierarchy problem no longer hypothetical
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- How do we resolve this issue?
  - SM partners especially 3rd generation & EWK Bosons ⇒ Naturalness
  - New phenomena related to the true Planck scale being much lower
  - … **Dark Matter…. Dark Energy…. ???**

- These are experimentally testable at the LHC
  - e.g. naturalness even fine-tuning a bit requires partners at the TeV scale

14TeV LHC and HL-LHC

With ~30fb^{-1} at 6-7TeV no low hanging fruit for New Physics, and yet we know the picture is not complete…

- The LHC Run 2, with 300fb-1 at 13~14TeV will open a new window for discovery
- Across a mass range crucial for Naturalness

But this is still only scratching the surface

14TeV LHC and HL-LHC

HL-LHC, with 3'000fb^{-1} at 13~14Tev will bring high intensity frontier physics to the energy frontier

- Precision SM, EWSB and Higgs studies as probes for BSM physics
- Further extend potential for direct discovery and characterization of BSM physics
  - Extend mass reach by ~ 1TeV
  - Open broad scope for rare, unusual processes

14TeV LHC and HL-LHC

ESWG: "Europe's top priority should be the exploitation of the full potential on the LHC including the high-luminosity upgrade of the machine and the detectors with a view to collecting ten times more data than in the initial design, by around 2030

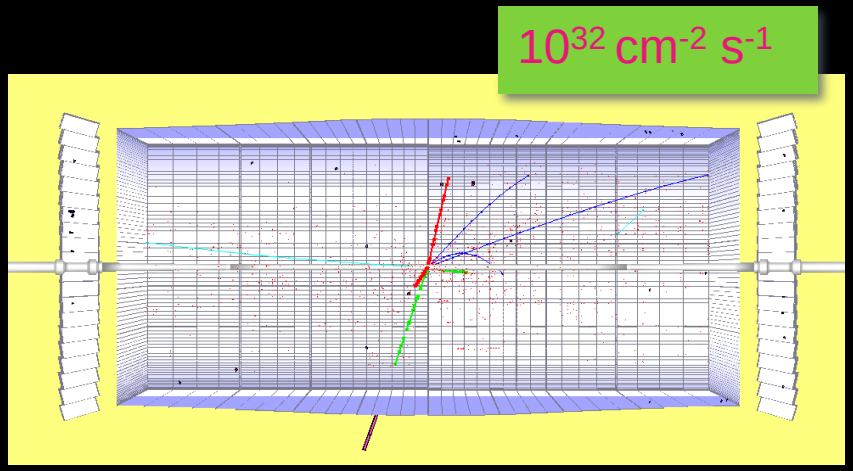
- Precision SM, EWSB and Higgs studies as probes for BSM physics
- Further extend potential for direct discovery and characterization of BSM physics
  - Extend mass reach by ~ 1TeV
  - Open broad scope for rare, unusual processes

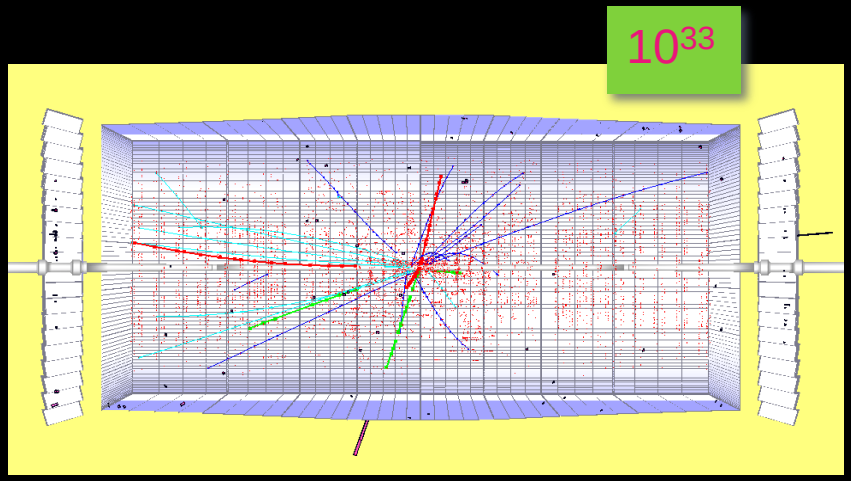
HL-LHC Physics Drivers

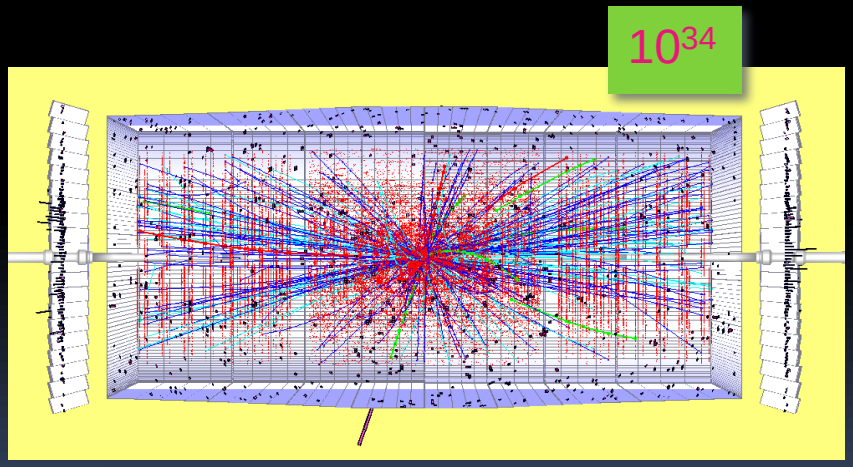
This is Very Challenging: it requires

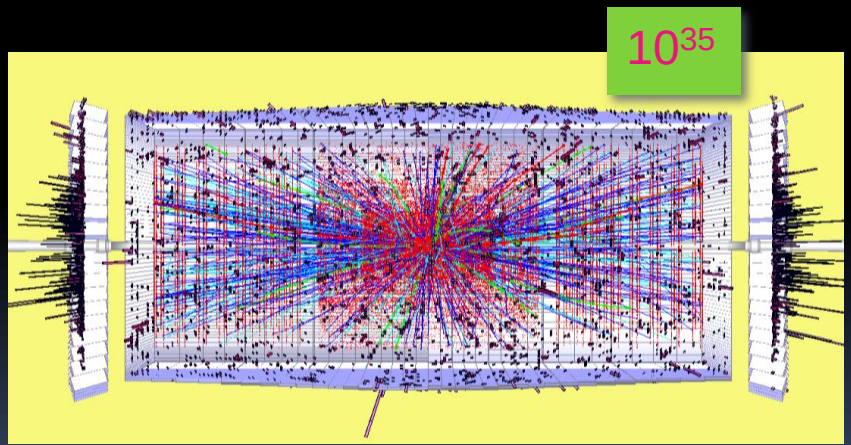
- Precision measurements of physics objects
  - Leptons (e, μ, τ), γ, Jets, b (c) quarks, MET
- Accurate reconstruction of complex event topologies to identify
  - W/Z, top, VBF, etc.
- Over the full range from low to high p_T
  - In a very high rate and high pile-up environment

HL-LHC Challenges









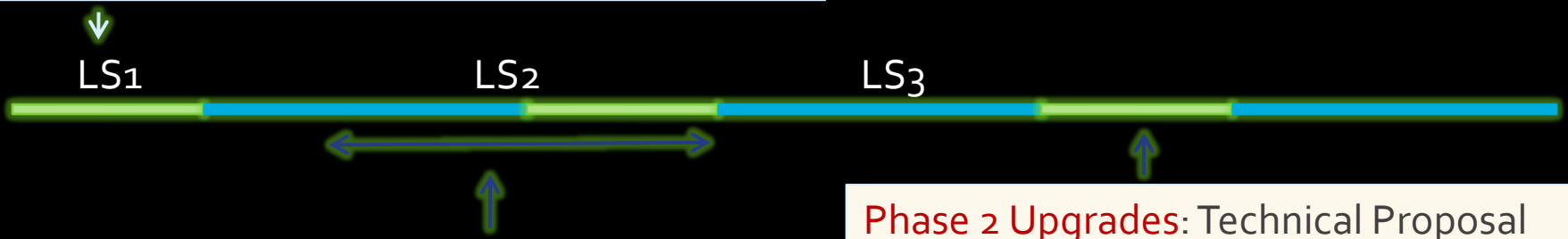
HL-LHC presents increased challenges for Triggering, Tracking and Calorimetry, in particular for low to medium P_T objects

Upgrade Strategy: CMS

LS1 Projects & Upgrades:

- Completes muon coverage (ME4)
- Improve muon trigger (ME1), DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD → SiPM)
- A lot of consolidation work

Complete original detector
Address operational issues
Start upgrade for high PU



Phase 1 Upgrades:

- New Pixels, HCAL SiPMs and electronics, and L1-Trigger
- Preparatory work during LS1:
  - new beam pipe
  - test slices of new systems

Maintain/Improve performance at high PU

Phase 2 Upgrades: Technical Proposal forthcoming (Sept 2014)

- Further Trigger/DAQ upgrade
- Barrel ECAL Electronics upgrade
- Tracker replacement/ Track Trigger
- End-Cap Calorimeter replacement
- Tracker & possible End-Cap Calo, Muon extension
  - From $|\eta| = 3$ to $|\eta| \sim 4$

Maintain/Improve performance at extreme PU
Sustain rates and radiation doses

CMS Phase I Upgrade Strategy

Phase 1 Upgrades:

Maintain performance at high PU

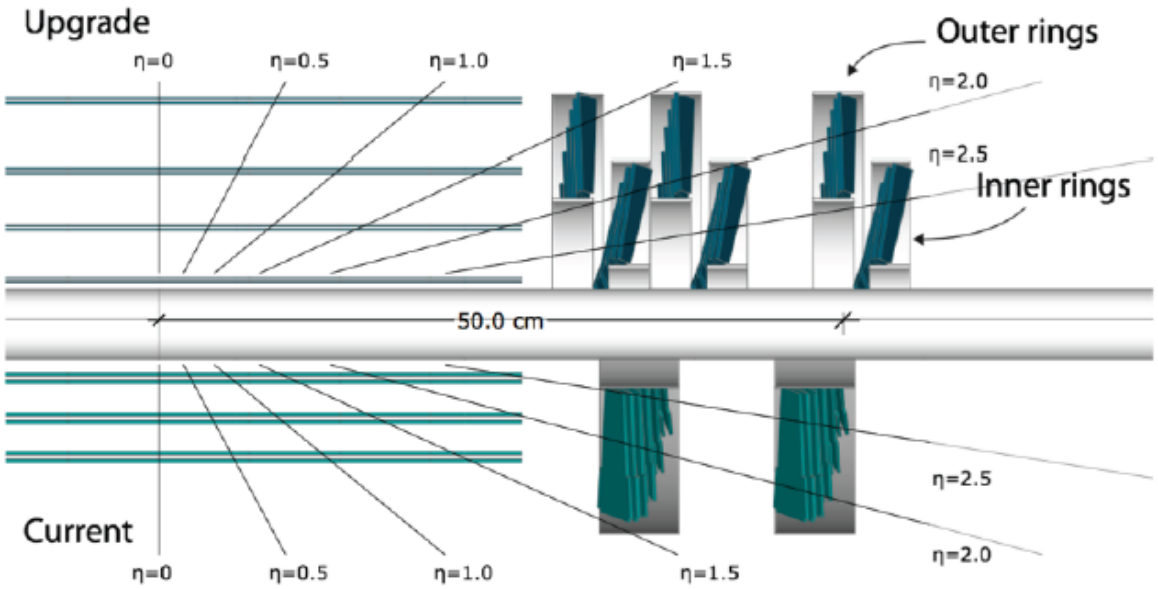
- New Pixels
- HCAL SiPMs and electronics Upgrade
- L1-Trigger Upgrade

- Preparatory work during LS1:
  - new beam pipe
  - test slices of new systems

Phase I CMS Inner Pixel Upgrades

Phase I CMS 4 layer Inner Pixel

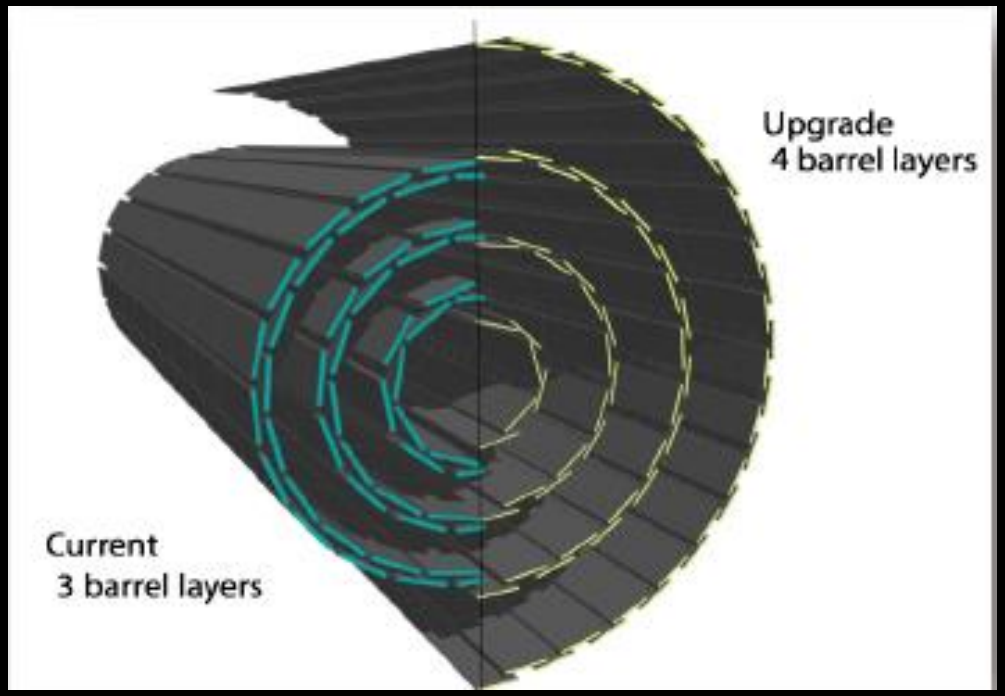
- 4^{th} barrel layer at r =16 cm, 3^{rd} disk at z = ±51.4 cm
- 4-hit coverage up to |η| ~ 2.5
- Smaller radius of innermost barrel layer from 4.4 cm to 3 cm : New beam pipe with smaller diameter

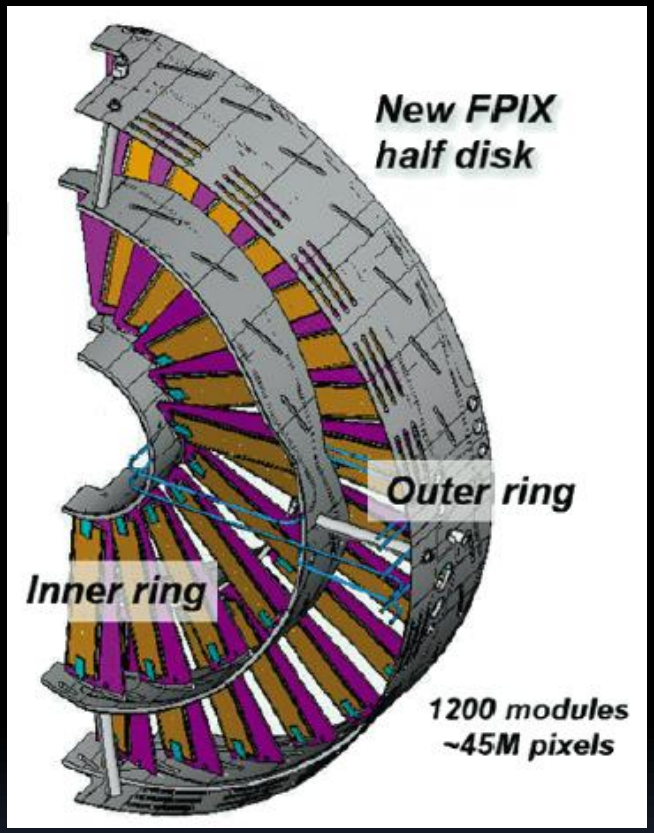


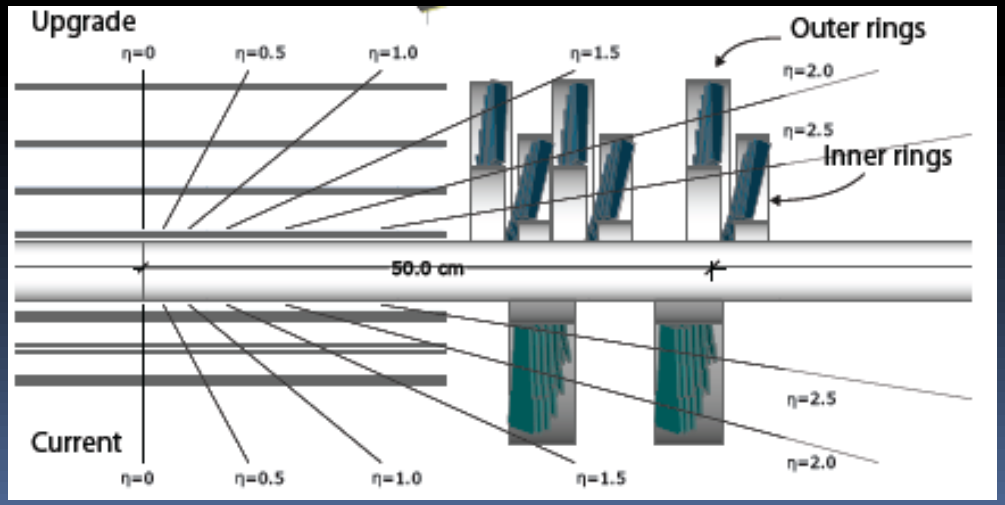
Targets of Pixel Upgrade: (To be installed in end of 2016 extended technical stop)

- Baseline L = $2x10^{34}$ $cm^{-2}sec^{-1}$ & 25ns → 50 pileup (50PU)
- Tolerate L = $2x10^{34}$ $cm^{-2}sec^{-1}$ & **50ns** → 100 pileup (100PU) , with reduced performance
- Survive Integrated Luminosity of 500fb^{-1}

Phase I CMS 4 layer Inner Pixel







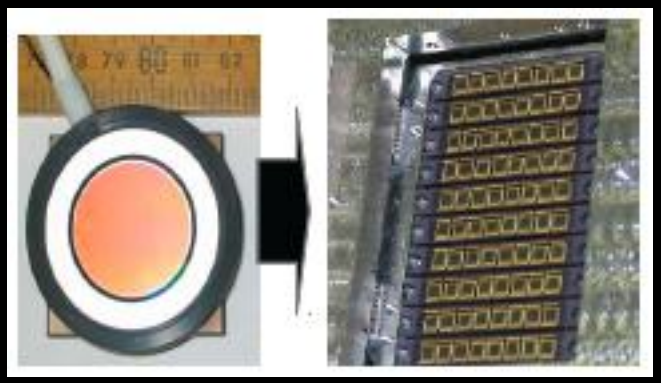
Phase I CMS HCAL Read-Out Upgrades

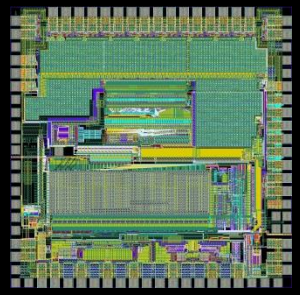
Phase I CMS HCAL Read-Out Upgrades

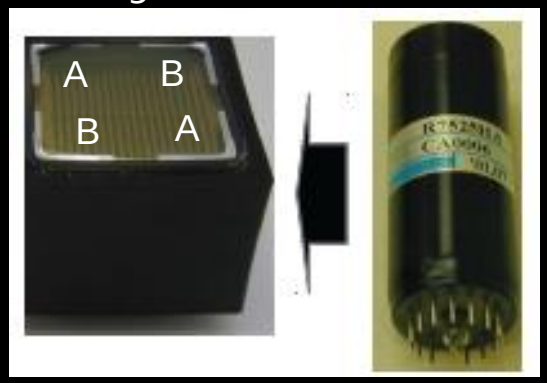
Replace Photo-transducers to
reduce noise & improve performance
Implement new FE Chip

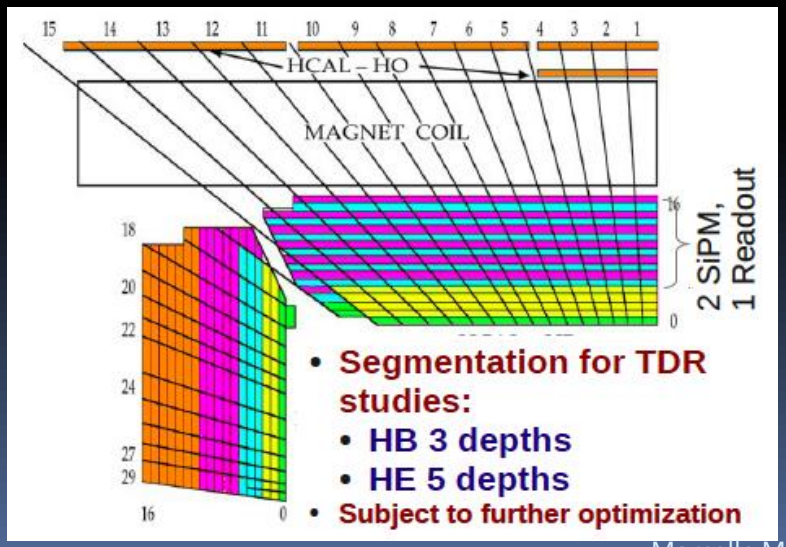
HB/HE/HO
From HPD to SiPM's

HF
From single to multi-anode PMT's



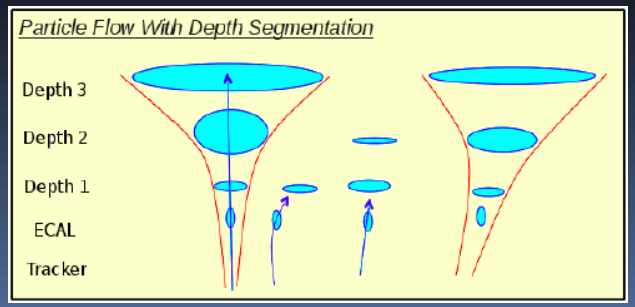






Use SiPM's to increase HB/HE Depth Segmentation

- Improved PF Hadronic shower localization
  Provides effective tool for pile-up mitigation
  at high luminosity
- Mitigate radiation damage to scintillator & WLS fibers

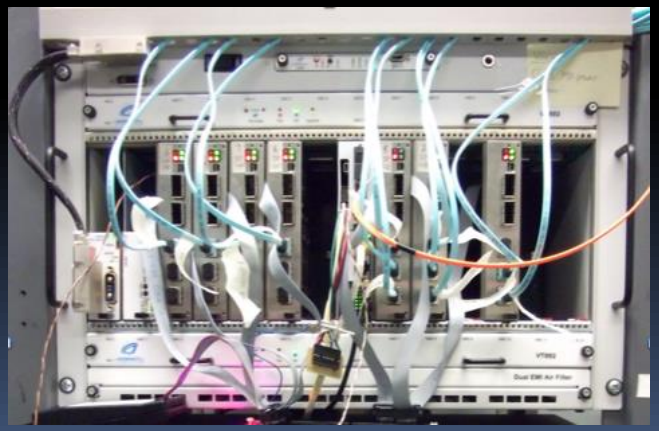


Phase I CMS Trigger Upgrades

Phase I CMS Trigger Upgrades

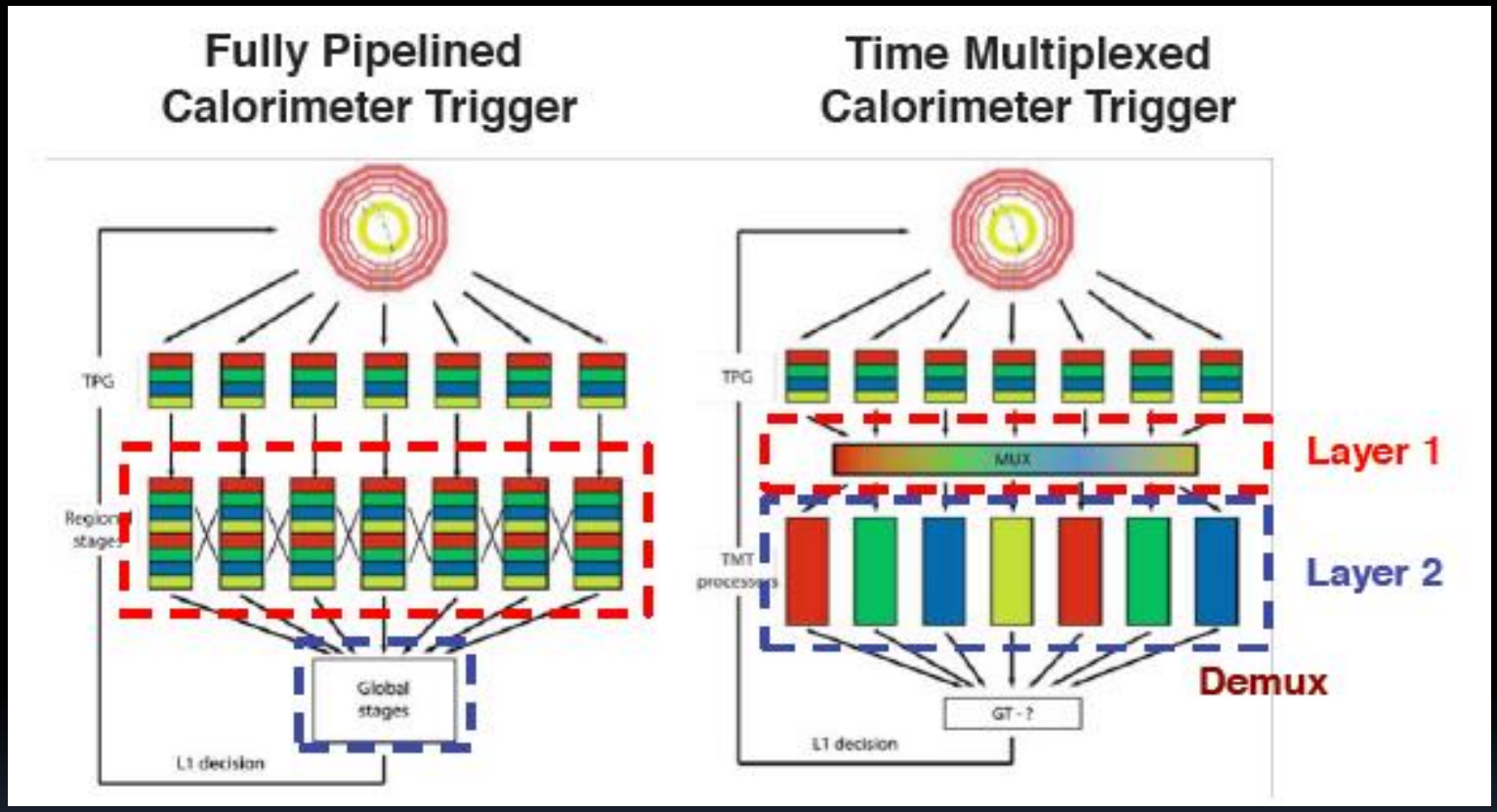
- **Modern FPGAs and µTCA backplane technology for high bandwidth and processing power - new architecture for calorimeter with a full event in one processor**
  - This allows higher calorimeter granularity and earlier combination of muon systems to provide better precision on trigger objects and more sophisticated selection algorithms
- e, γ and µ isolation and jet finding with PU subtraction
- τ finding with narrower cone
- new algorithms with correlated quantities (e.g. invariant mass…)

MP7 board Virtex 7 and 72 I/O links at 10Gpbs



Demonstrator of Calorimeter trigger in µTCA crate

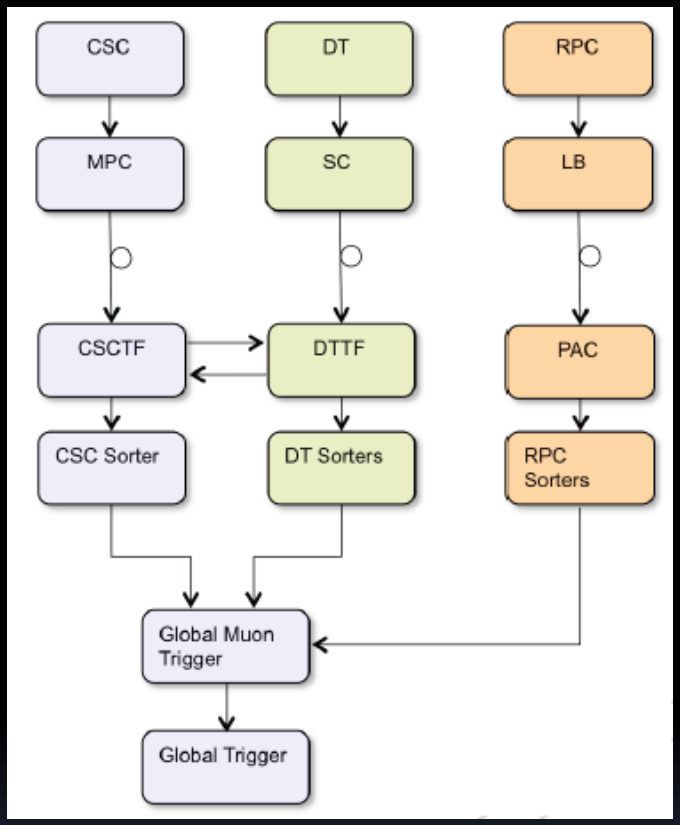
Phase I CMS Calo Trigger Upgrade

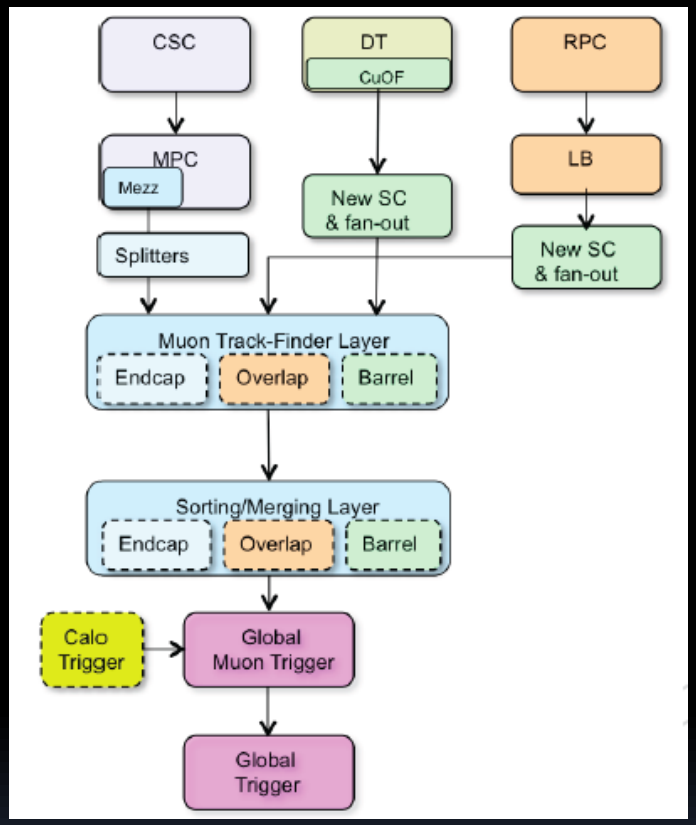


Layer 1 is optimized for backplane connectivity; Layer 2 for front-panel optical bandwidth

Access full granularity ECAL/HCAL Trigger Tower granularity for clustering, isolation etc.

Phase I CMS Muon Trigger Upgrade

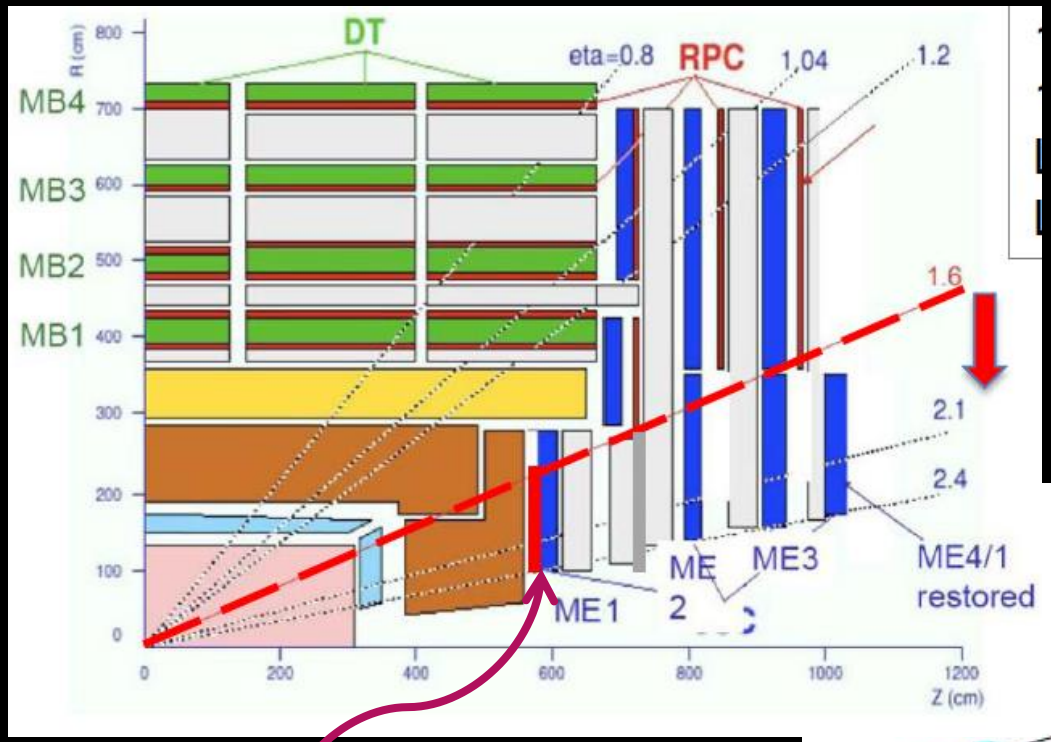


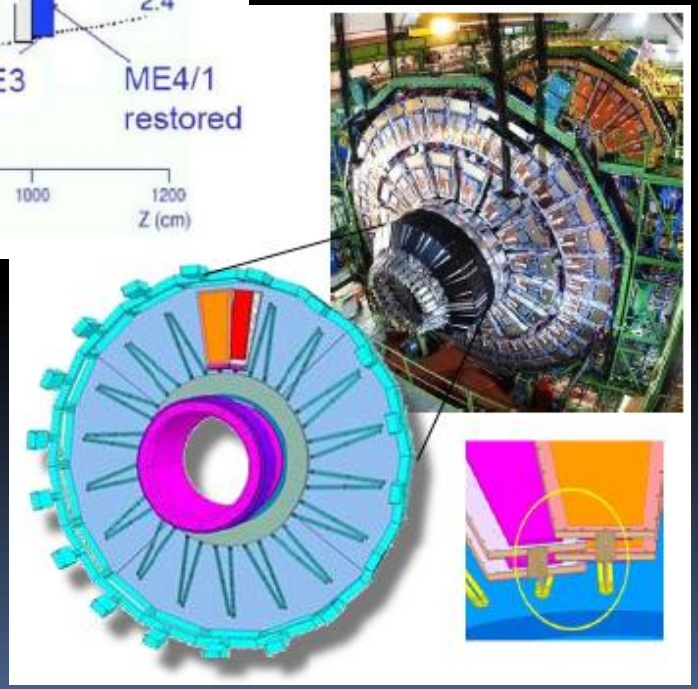


The present muon trigger system has separate CSC, DT & RPC μ track finders

Upgrade allows merging of CSC, DT & RPC segments for combined μ track finding
=> Improved robustness and efficiency

CMS GE1-1 Muon Trigger Upgrade

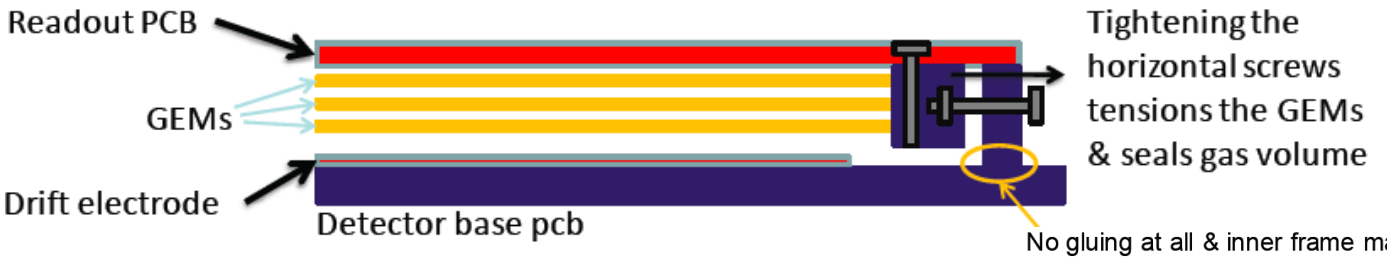




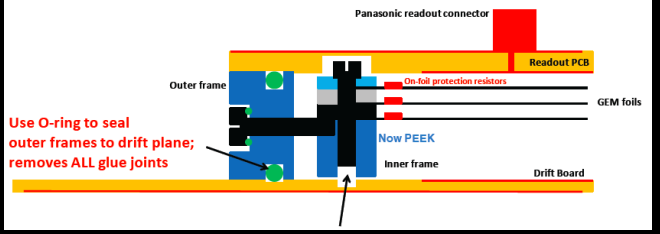
New GE1-1 GEM Muon Station
Combined with ME1 can
Substantially improve p_T determination
To reduce trigger rate

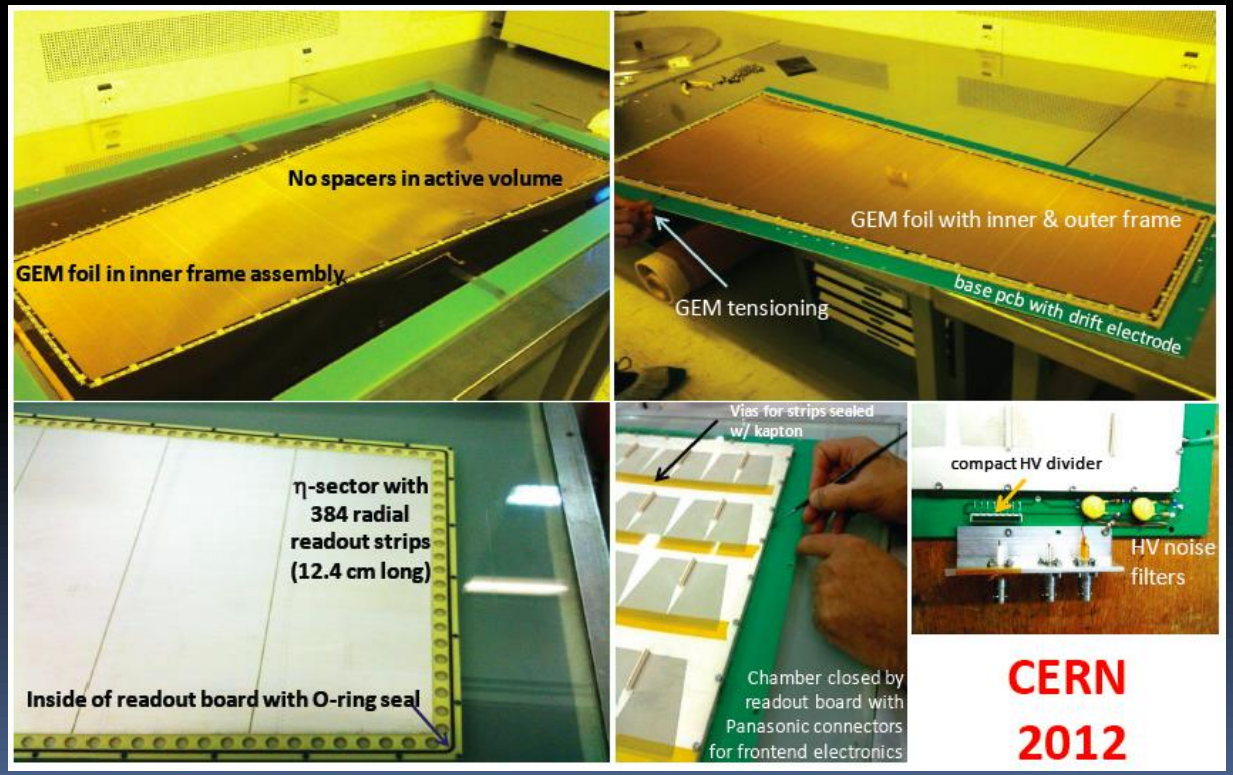
CMS GE1-1 Muon Trigger Upgrade

Current state-of-the-art: Self-stretching assembly sans spacers (CERN)



No gluing at all & inner frame made from PEEK:





CMS Phase II Upgrade Strategy

Phase 2 Upgrades:

Maintain performance at extreme PU

Sustain rates and radiation doses

- Further Trigger / DAQ upgrade
- Barrel ECAL Electronics upgrade
- Tracker replacement / Track Trigger
  - Extend Tracking to $|\eta| \sim 4$
- End-Cap Calorimeter replacement
  - Study option for EE/HE & Muon extension to $|\eta| \sim 4$

CMS Phase II Upgrade Strategy

Phase 2 Upgrades:

Maintain performance at extreme PU

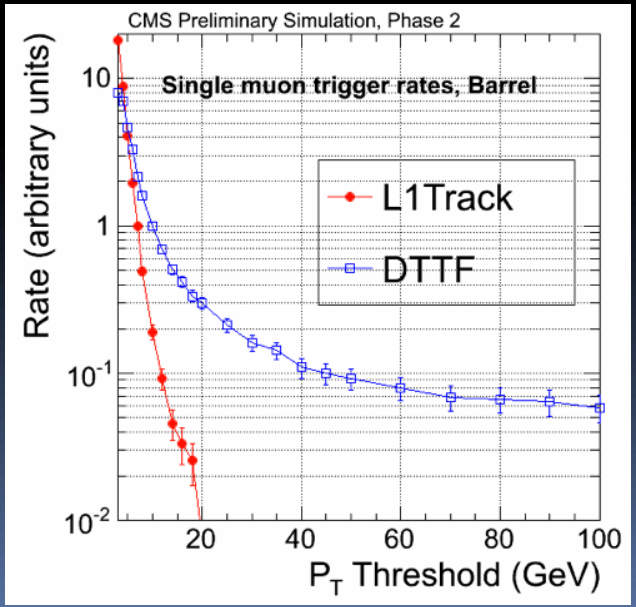
Sustain rates and radiation doses

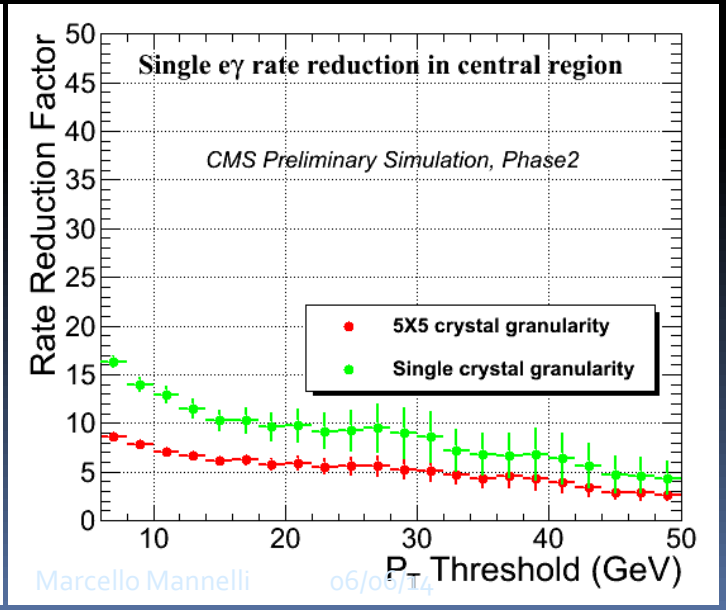
Technical Proposal forthcoming: September 2014

Phase II CMS further Trigger/DAQ Upgrades

Trigger/DAQ upgrades

- Track trigger will reduce rates through
  - High momentum resolution of leptons - sharp thresholds
  - Isolation for e/γ/μ/τ - reduce background
  - Association of particles to same primary or secondary vertex - reduce combinatorial effect of PU in multi-particle/jet triggers
- Together with crystal level ECAL info
  - Gain ~ 10 for lepton triggers => retain low trigger thresholds

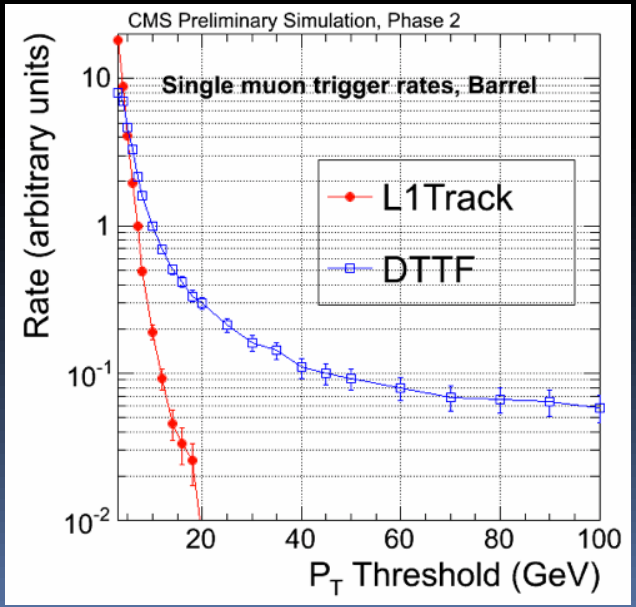


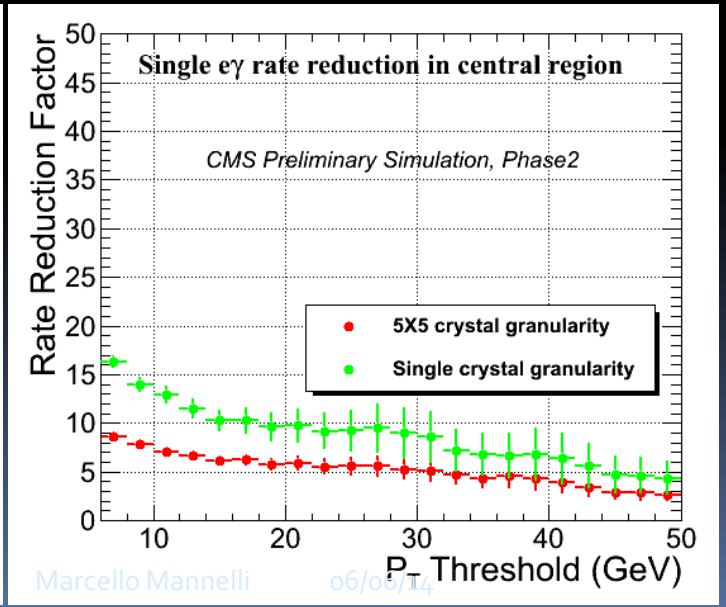


Lepton trigger rate reduction by a factor 5 to 10 with improved ECAL L1 granularity and L1 Tracking

Trigger/DAQ upgrades

- Increase of L1 bandwidth from 100 kHz to 500/1000 MHz will provide flexibility
  - Robustness to higher Luminosity and PU
  - Ability to allocate bandwidth for "exotics"
- Computing trigger output at 10 kHz - preserve present rejection rate



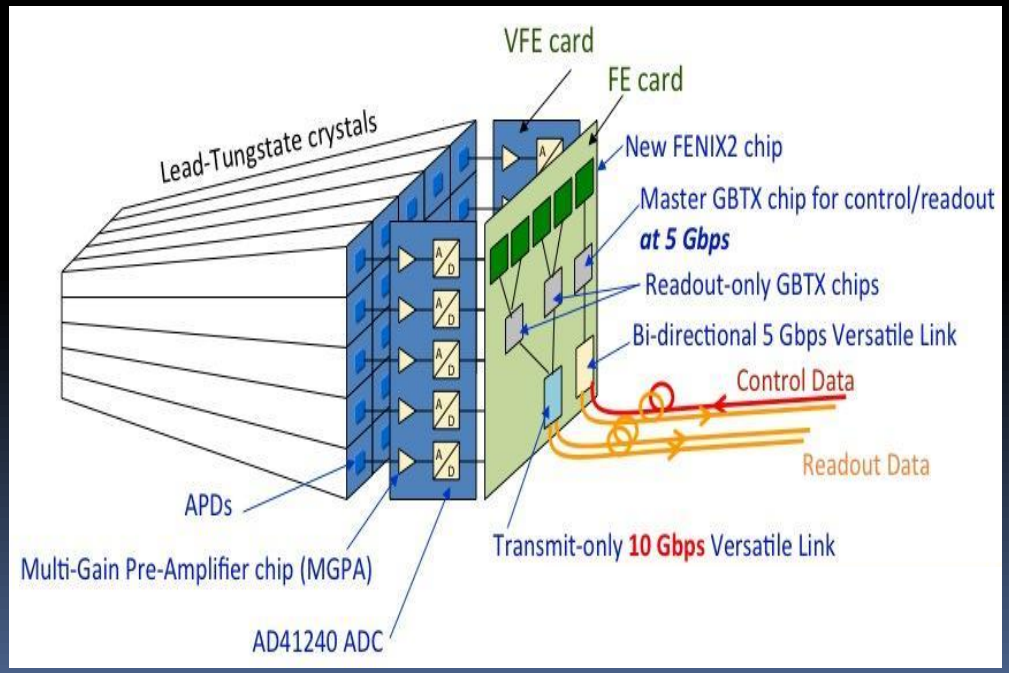


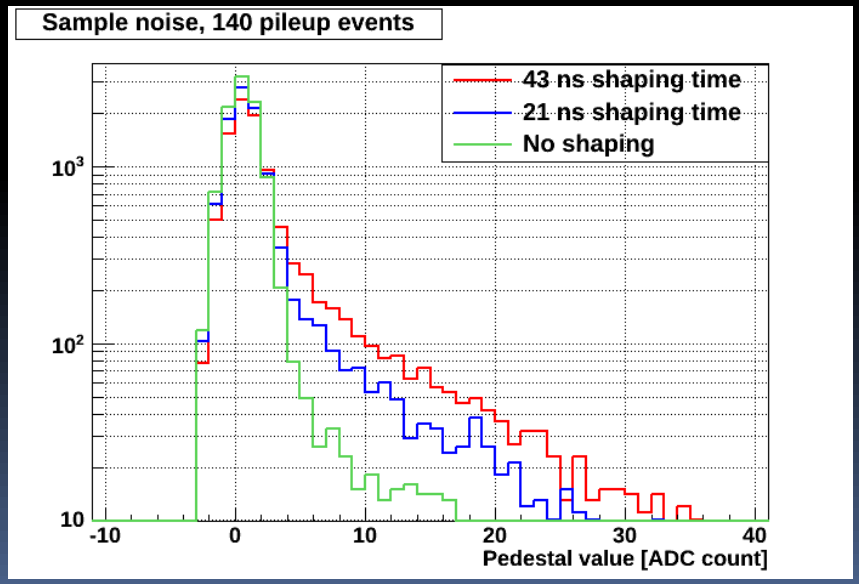
Lepton trigger rate reduction by a factor 5 to 10 with improved ECAL L1 granularity and L1 Tracking

Phase II CMS Barrel ECAL Read-Out Upgrades

R&D for the ECAL Barrel FE electronics

- VFE board with improved shaping - noise/PU mitigation, spike rejection
- FE board with data transfer at 40 MHz and crystal granularity for trigger
  - Investigating commercial versus custom design
  - Need to develop 10Gbps GBTx to minimize cost





Phase II CMS Tracker/Tracking Trigger

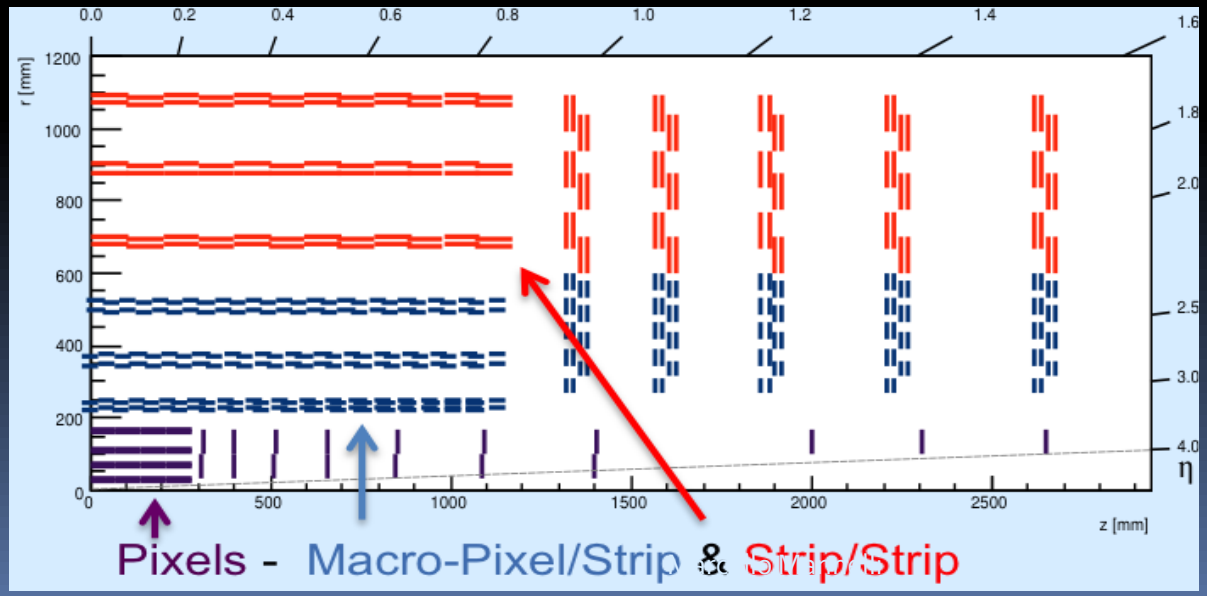
Phase II CMS Tracking Trigger

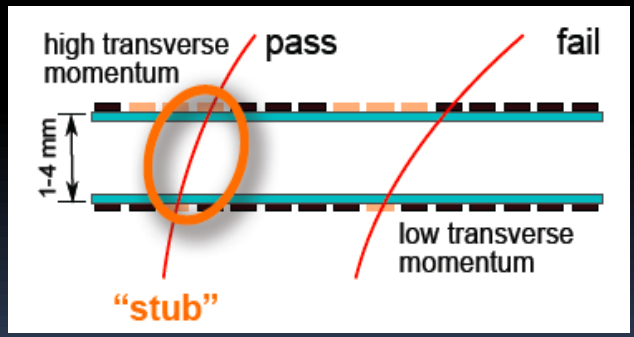
- Design modules with p_T discrimination
  - Correlate hits in two closely-spaced sensors to provide vector (stub) in transverse plane: angle is a measure of p_t
  - Exploit the strong magnetic field of CMS
- Level-1 "stubs" are processed in the back-end
  - Form Level-1 tracks, p_T above 2~2.5 GeV
  - To be used to improve different trigger channels
- L1 Track Trigger back-end architectures under study
  - FPGA "seeded" patter recognition vs Associative Memory

Tracker conceptual design

- Powerful concept to implement tracks in hardware trigger
  - 2 sensor modules to select track "stubs" of $p_T \geq 2$GeV for trigger readout (40MHz)
  - Strip-Strip (SS) in outer layers and Macro Pixel-Strip (PS) in inner (z meas.)

- Extension of Pixel coverage up to $|\eta| \sim 4$

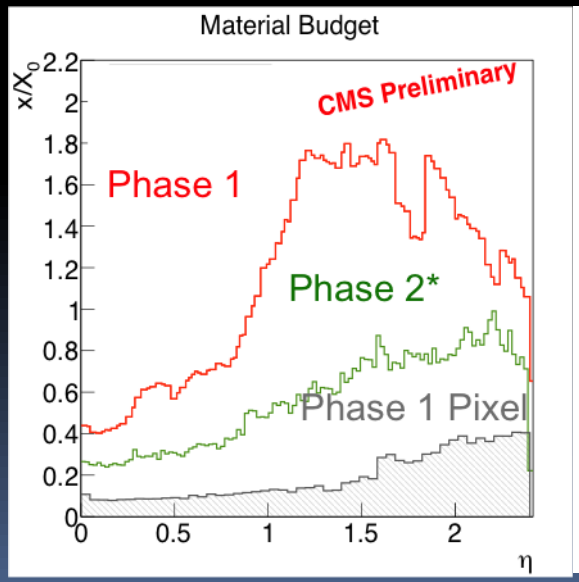


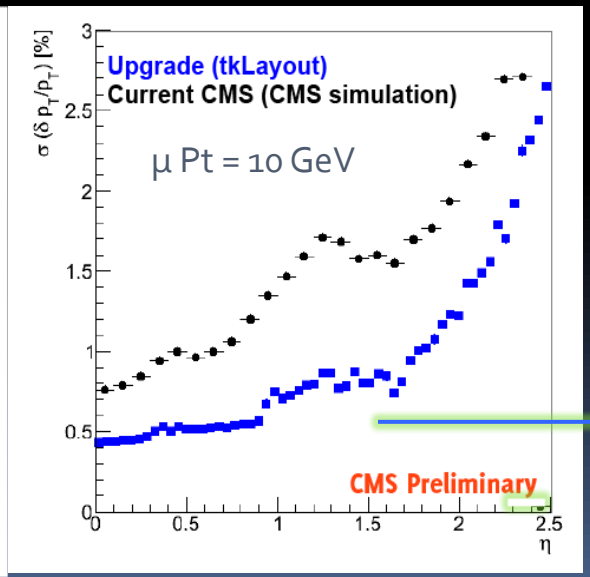


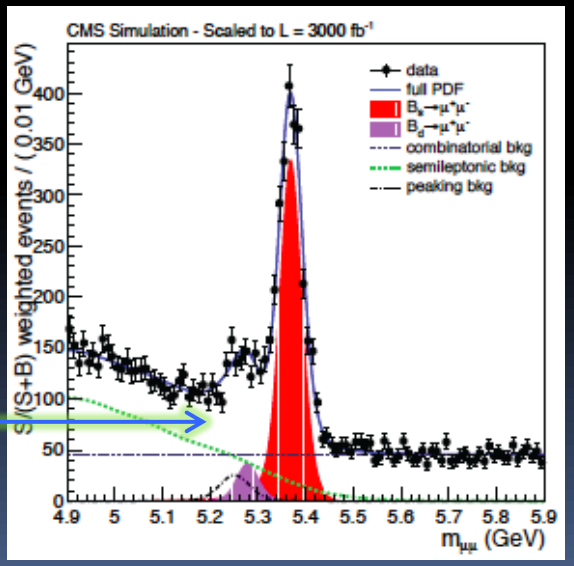
Concept for on detector selective data readout

Tracker conceptual design

- Lighten up!
  - DC-DC powering scheme, CO_2 cooling, low mass assemblies
- Reduced material within Tracker Volume
  - Improved track p_T resolution & reduce rate of γ conversion
  - ex. HH -> bbγγ; ttH -> γγ ; H -> μμ - $B_{s,d}$ -> μμ…

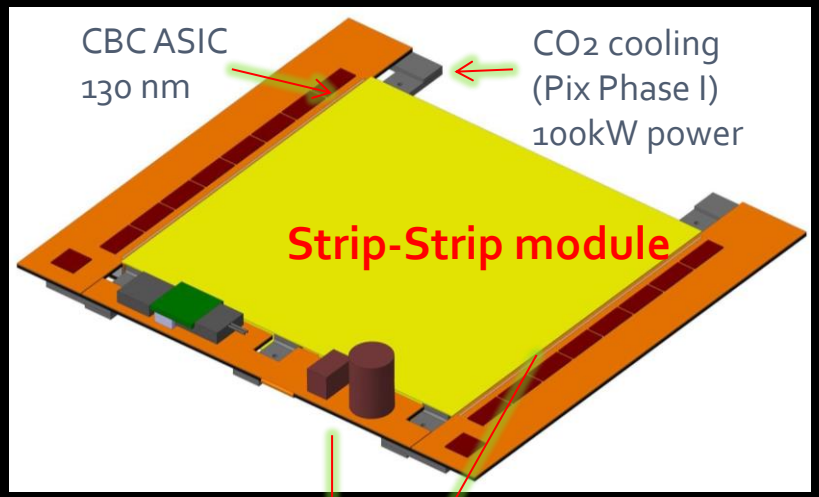




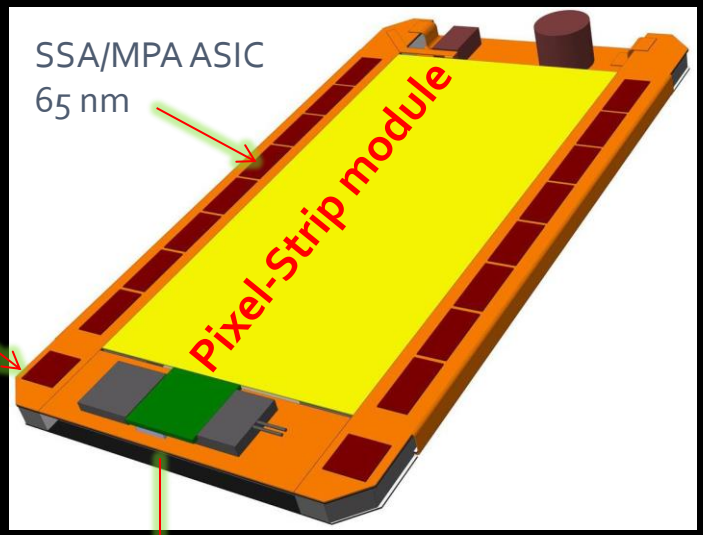


R&D on Tracker Modules

Light module assembly - validated with FEA - building mock-up

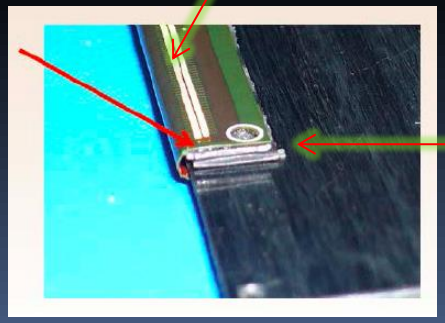


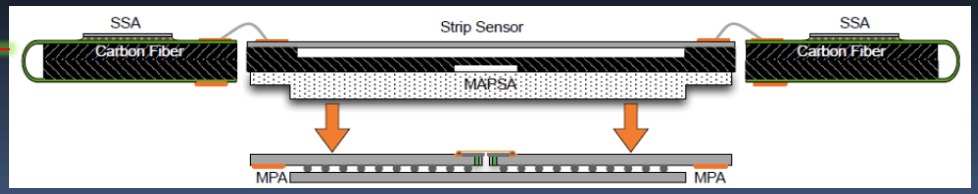
Concentrator ASICs
130 and/or 65 nm



DC-DC conversion
based on pixel Phase 1

GBT 65 nm & Optical Link
low power – compact packaging wo connector





Flex hybrid - Flip-Chip assembly - possibly TSV for inter-chip connection

R&D on Tracker Modules

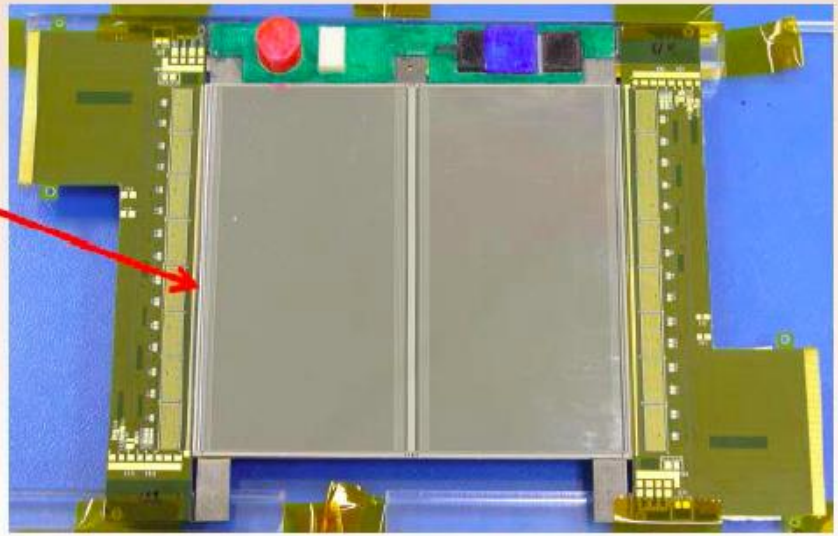
Alan Honma

2S 1.8mm prototype module

We have produced a 2S 1.8mm mechanical dummy module:

1. Based on Al-CF pieces produced by Novapack
2. Used current dummy silicon sensors (200um thickness)
3. Used an unloaded hybrid with our own fold-over (to get correct thickness).
4. Tested support, rigidity, flatness of hybrid prototype
5. Tested bondability – very good, needed handmade bonding jigs but bonding was smooth, fast and of good quality: <20 minutes to bond the >2000 wires.
6. Our design looks practical for a large scale production (so far)

1016 strip bond wires + 6 bias wires (and same on bottom side)



23 May 2014

7

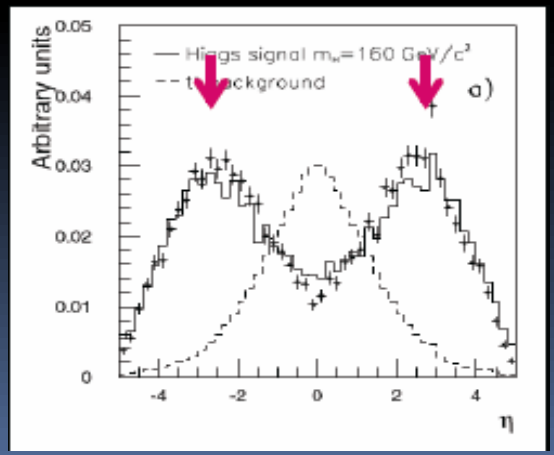
Phase II CMS End-Cap Calorimeter Upgrade

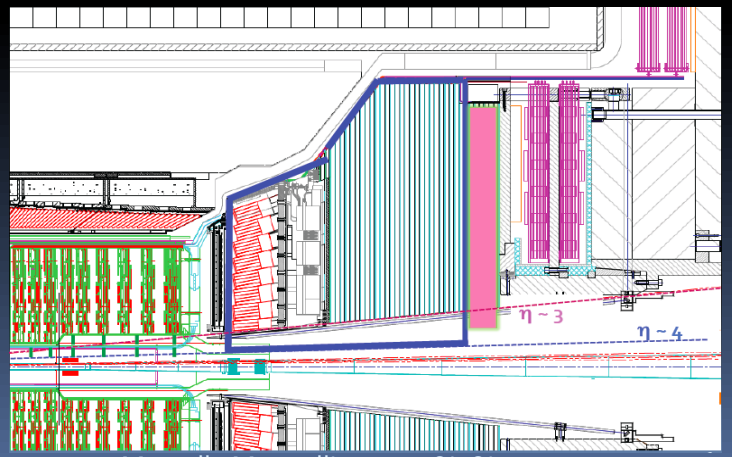
Phase II CMS End-cap Calorimetry

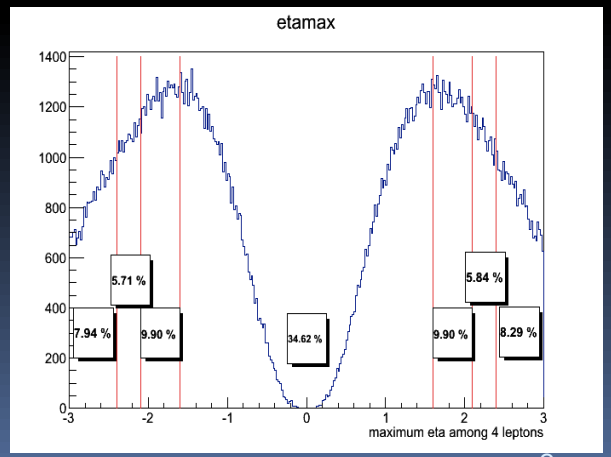
CMS needs to replace End-cap Electromagnetic and Hadronic calorimeters for Phase 2 due to radiation damage

Opens new possibilities for Calorimeter design and envelope to

- Retain EM resolution, optimize for Particle Flow - Jet/MET
- Study Option of extended EE/HE coverage, to |η|~4
  - Provide uniform detector response beyond the peak of VBF jets, matched with extended Tracker coverage
  - Compact Muon coverage extension in shadow of new EE/HE





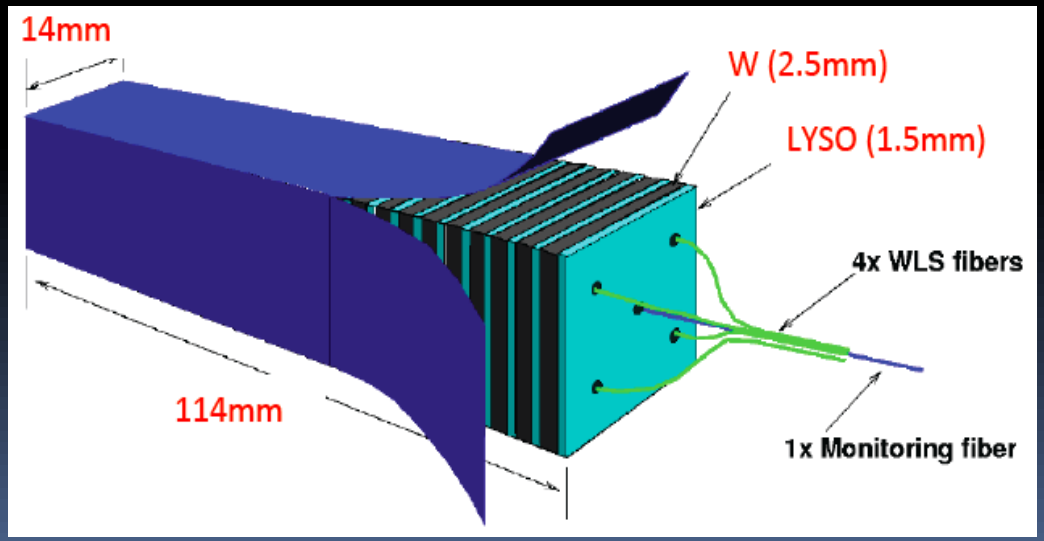


Phase II CMS End-cap Calorimetry

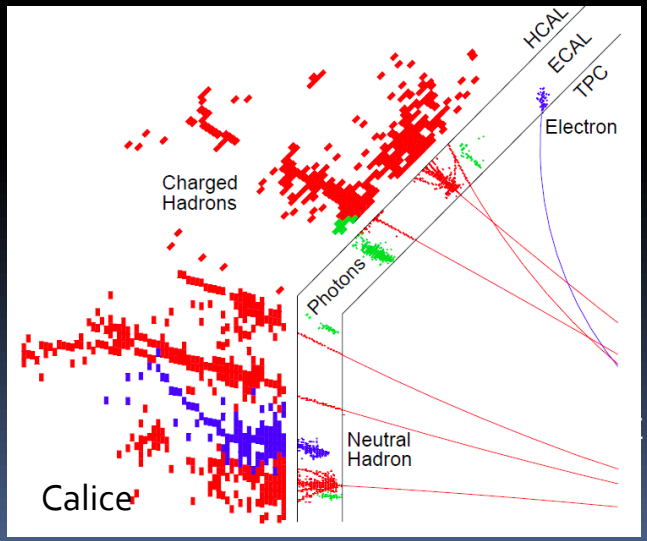
CMS needs to replace End-cap Electromagnetic and Hadronic calorimeters for Phase 2 due to radiation damage

Two concepts currently under study:

- An Electromagnetic End-cap (EE) calorimeter built in a Shashlik design and a Hadronic End-cap (HE) Calorimeter rebuild
- A High Granularity CALorimeter (HGCAL) integrating EE and HE functions (CALICE concept) with a Back HE to capture energy tails



EE Shashlik concept



HGCAL concept

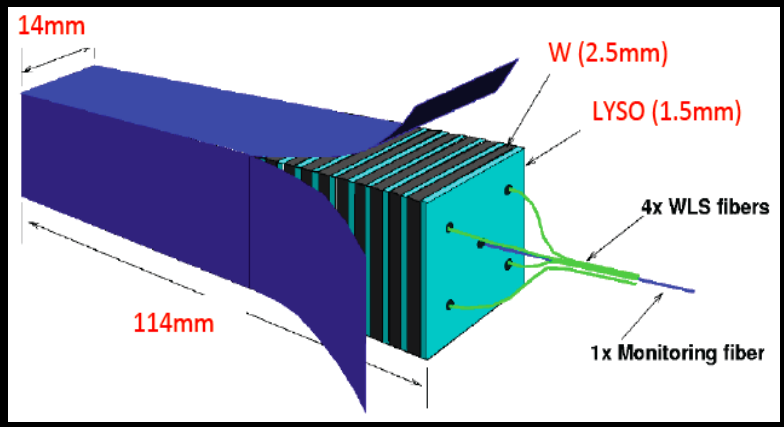
EE Shashlik and HE re-build

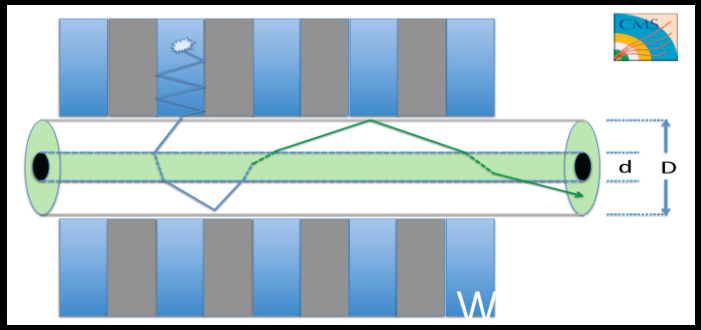
EE Shashlik

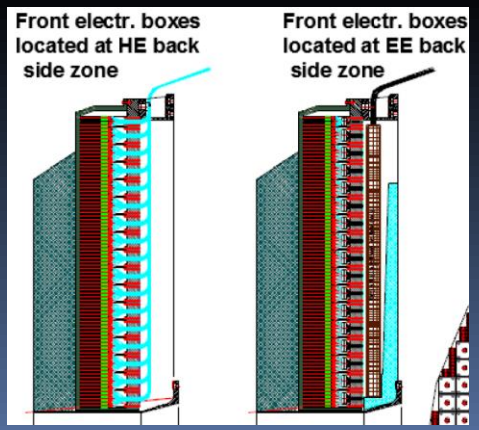
- W-absorber and Crystal LYSO 28 plates
  (CeF_3 a possible alternative)
  - Very compact ~ 11 cm long
  - Small Moliere radius (14 mm) and
  - Fine granularity (14 mm^2) to mitigate pile-up
  - High light yield for good e/γ energy resolution
    ~ 10%/sqrt(E) + 1%

- Readout with
  - 4 WLS Capillaries (scintillating fibers CeF_3)
  - Calibration Fiber (1 per module)
  - GaInP(SiPM) Photosensors (4 per module)

- No depth segmentation
  - But investigating extraction of a signal near shower max with precise timing - WLS with scintillating dye on quartz core







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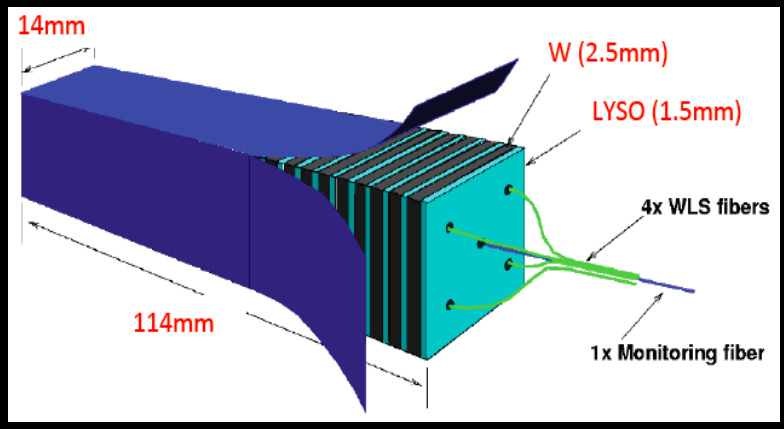
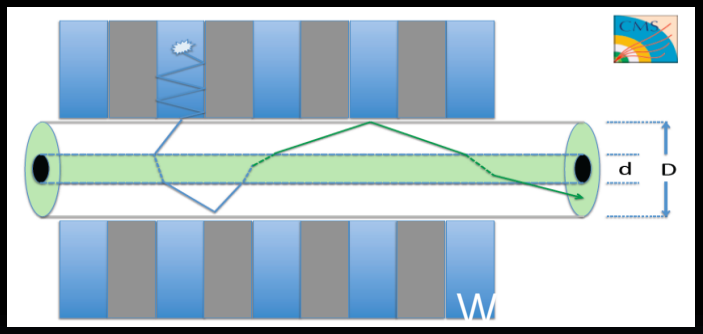
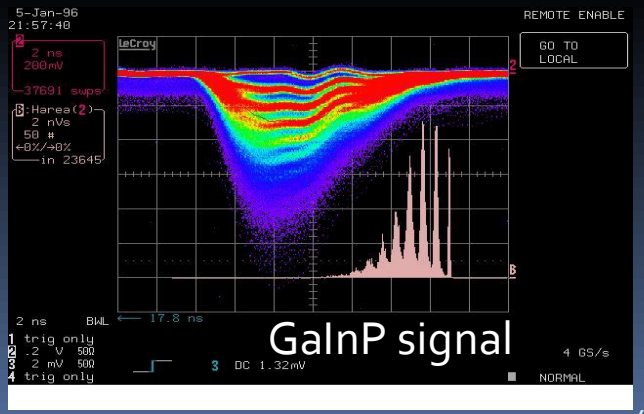
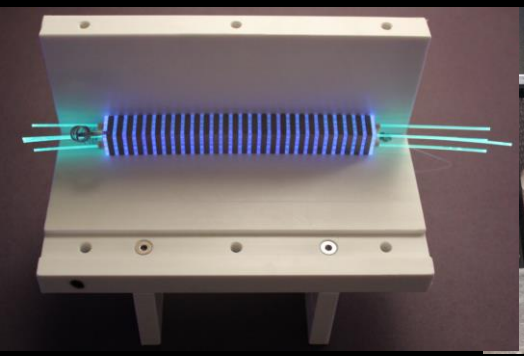




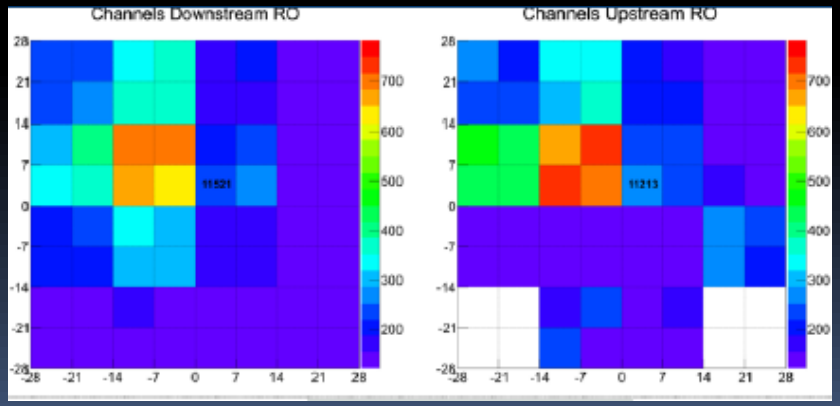


EE Shashlik beam tests

- First test of a 4x4 modules prototype
  - 364 LYSO crystals (final configuration)
  - WLS readout at both ends with SiPMs
  - Laser calibration in central fiber



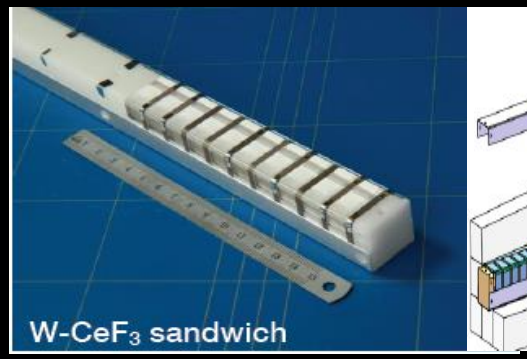
- 120 GeV protons

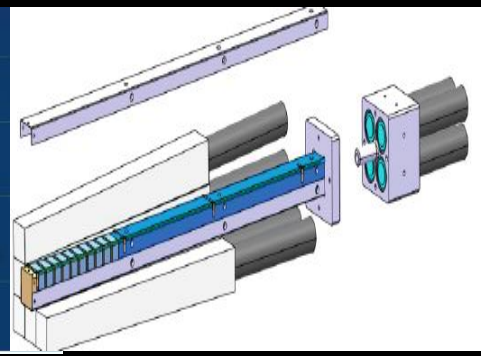


Downstream and upstream signals

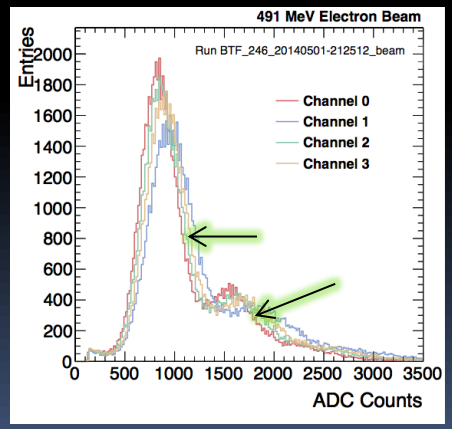
- Analysis of data in progress

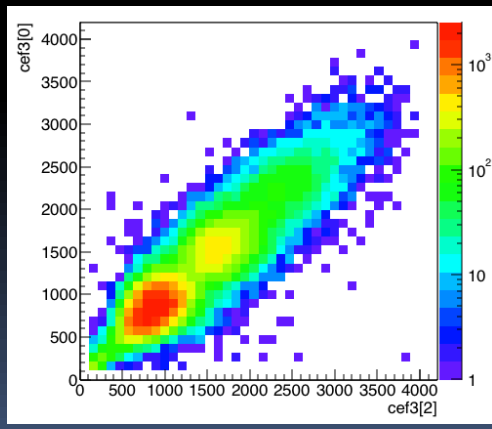
- First test of a CeF_3 modules
  - 10 x (3.1 mm W + 10 mm CeF3)
  - Scintillating fibers readout with PMTs





- 500 MeV electrons



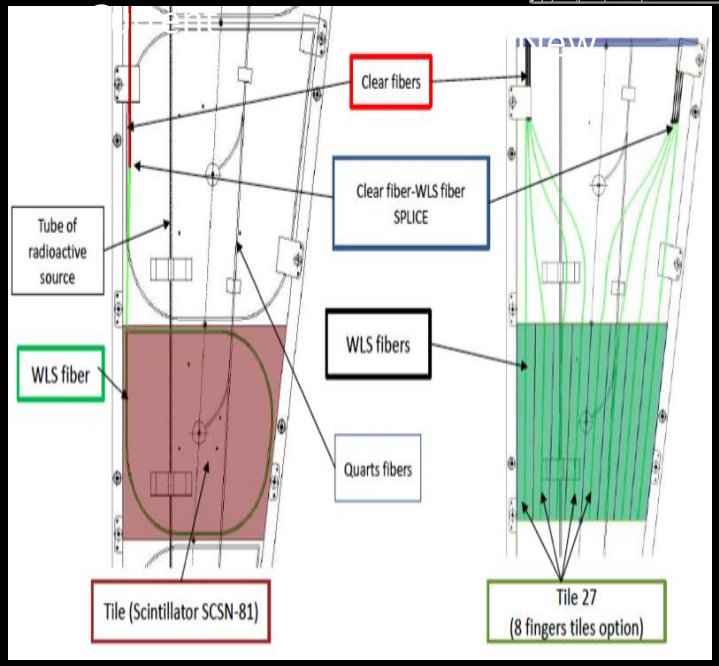


Raw signal (left) and correlation (right)

- Analysis of data in progress

EE Shashlik and HE re-build

- HE re-build
  - Higher granularity in (η/ϕ) x 2 & longitudinal & extension towards EE Shashlik (resolution)
  - Scintillating tiles in brass with finger WLS to reduce light path
  - Investigating liquid scintillators or radiation tolerant scintillating fibers quartz/glass/ crystals doped with Ce3 for innermost region



- Irradiation tests
  - MIP signal in green, blue and liquid-scintillator tiles (Jun. Jul.)
    - square and finger tiles equipped with red/orange WLS fibers
  - Intend to test total doses from 50 krad to 100 Mrad, with dose rates varying from 2 krad/hr to 5 Mrad/hr
    - Two facilities in US Ann Arbor (γ) and Maryland Co-60 125 kCi γ-ray and 200 kW TRIGA
    - Dubna (neutrons) - Kharkov (γ)

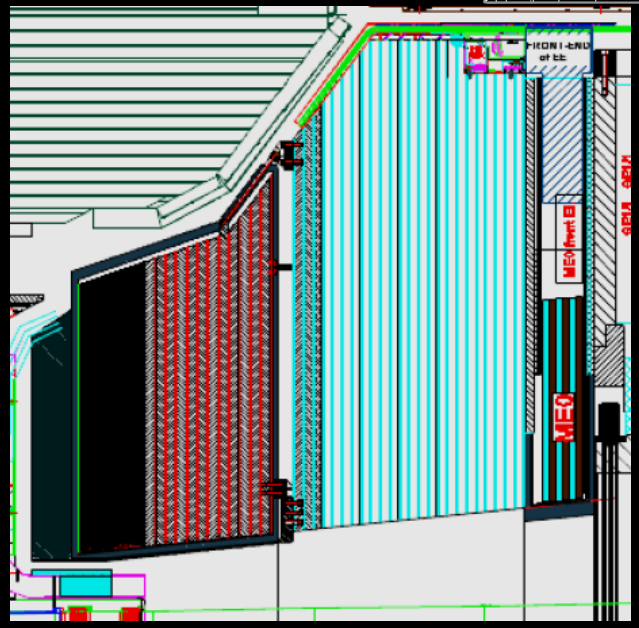
High-Granularity Calorimeter (HGCAL)

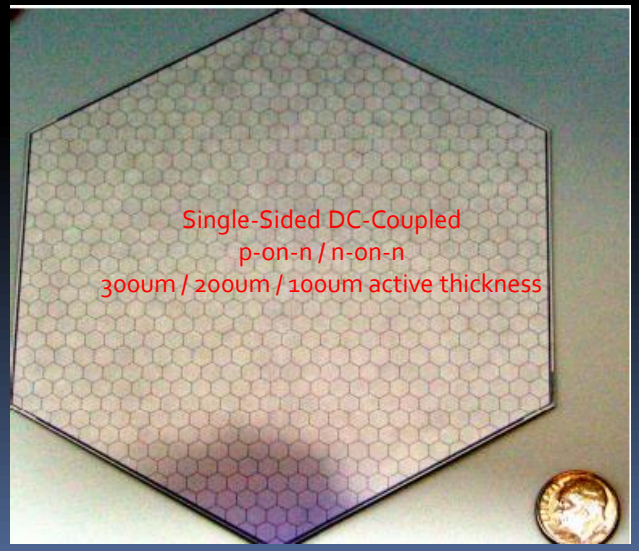
High Granularity Calorimeter

- ECAL: ~33 cm, 25 X0, 1□, 31 layers:
  - 11 planes of Si separated by 0.5 X0 of lead/Cu
  - 10 planes of Si separated by 0.8 X0 of lead/Cu
  - 10 planes of Si separated by 1.2 X0 of lead/Cu
- HCAL: ~66 cm, 4λ:
  - 12 planes of Si separated by 40 mm of brass
- Fine grain pads 0.5~1cm²
  - ~10M channels and 700m² of Silicon
- Back HCAL as HE re-build 5λ
  - With increased granularity

ΔE/E ~ 20%/√E; 3D shower reconstruction

- => Use detailed shower topology to mitigate PU effect





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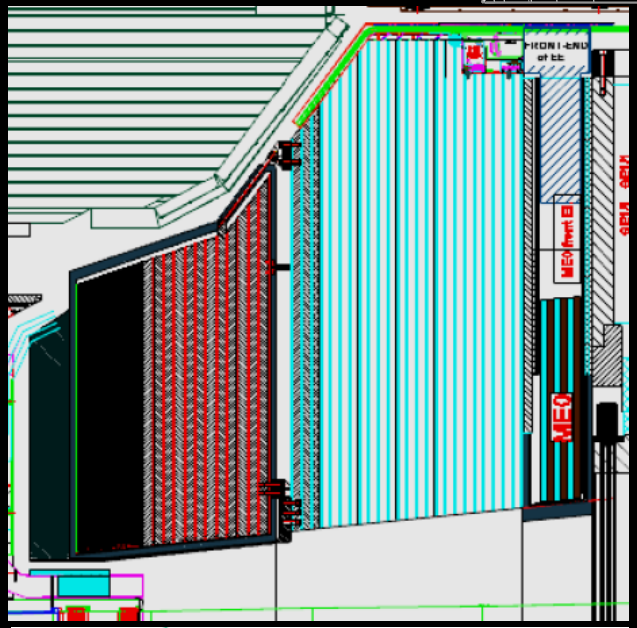
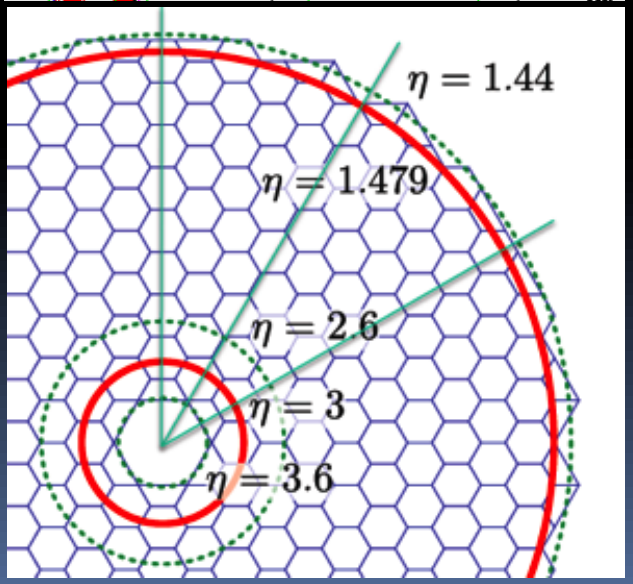
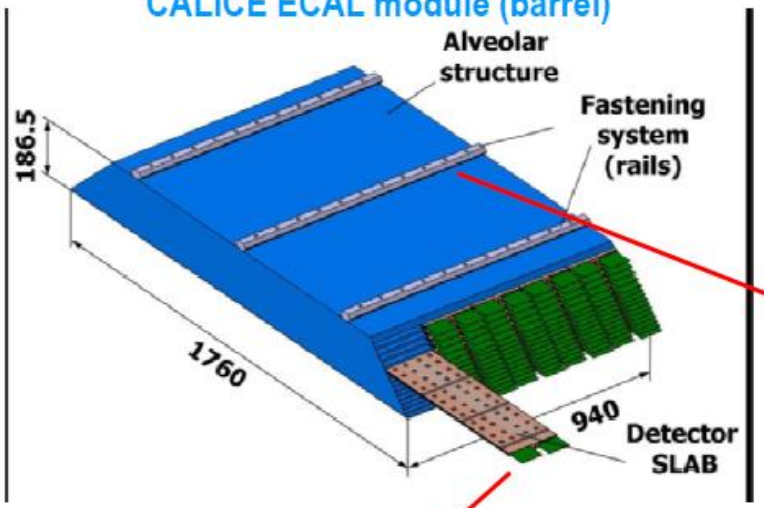




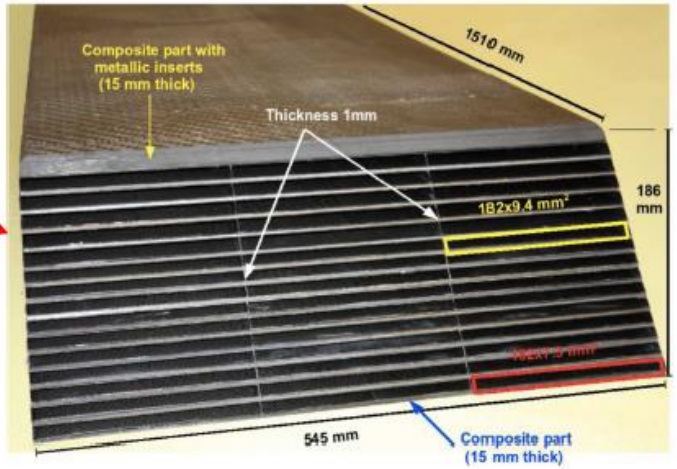
High-Granularity Calorimeter (HGCAL)

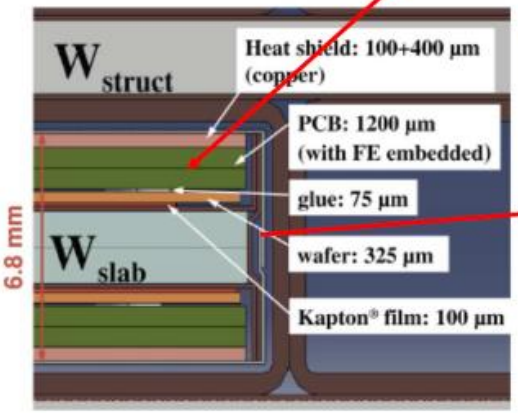
Reminder of the CALICE ECAL concept

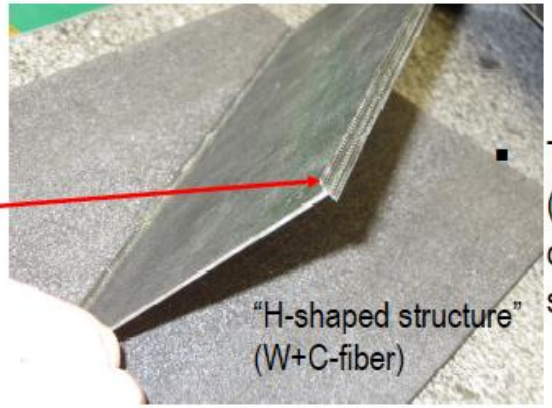
CALICE ECAL module (barrel)



- Half of the tungsten plates is incorporated into a self-supporting **alveolar composite structure** (carbon)



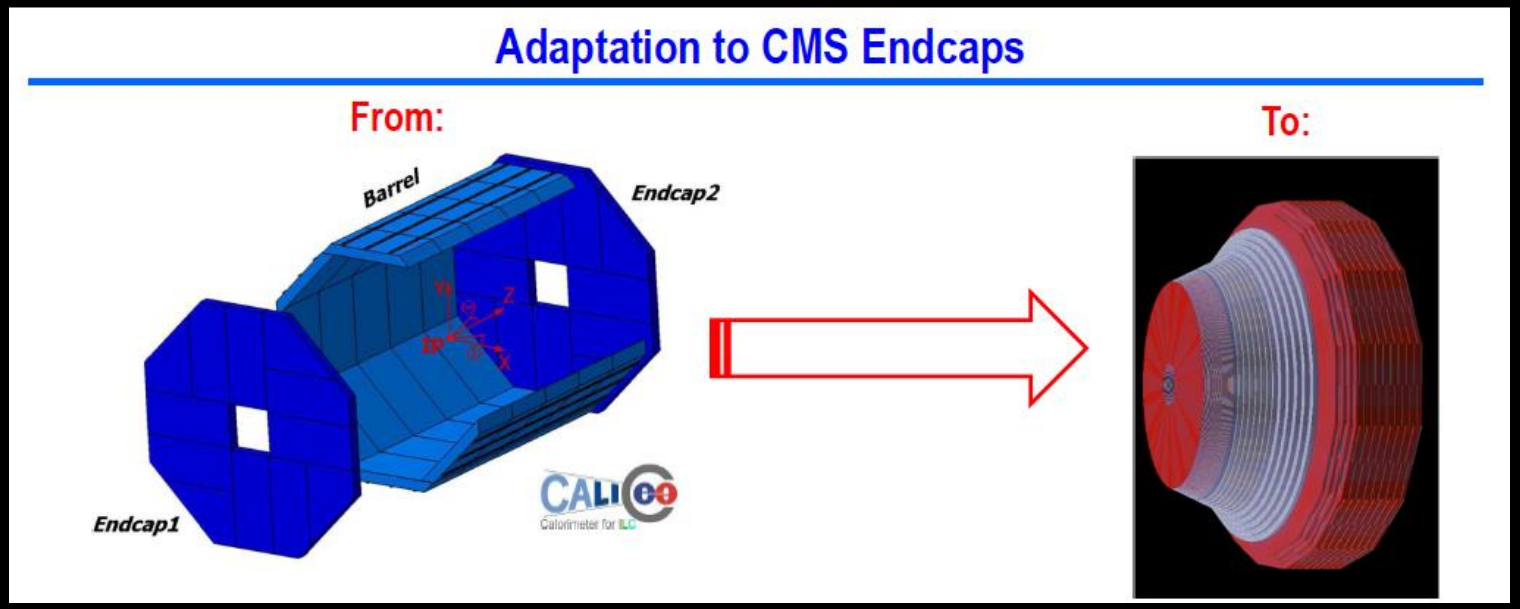


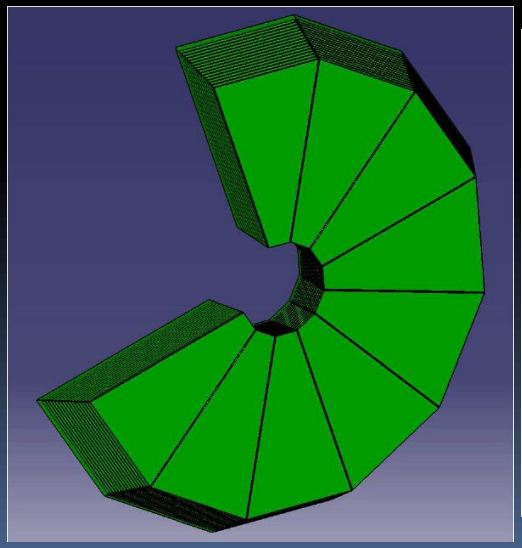


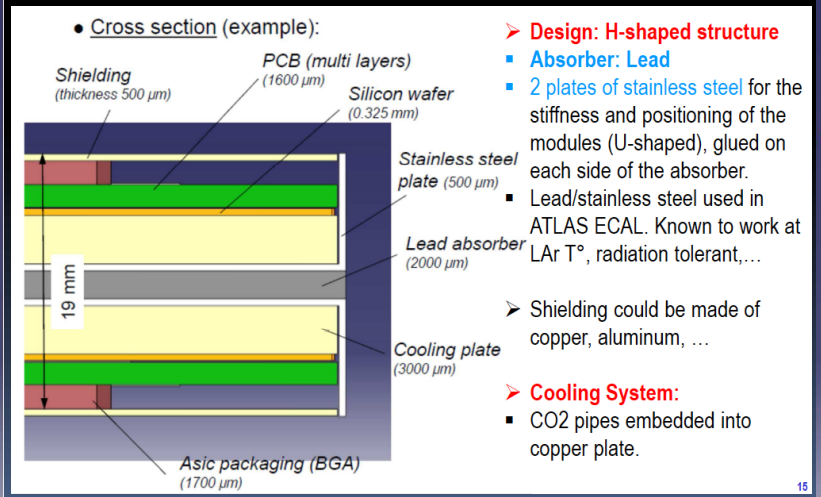
- The other half of the W plates in supports (H-shaped structure) called **detector SLAB (or "drawer")**, slide inside each cell.

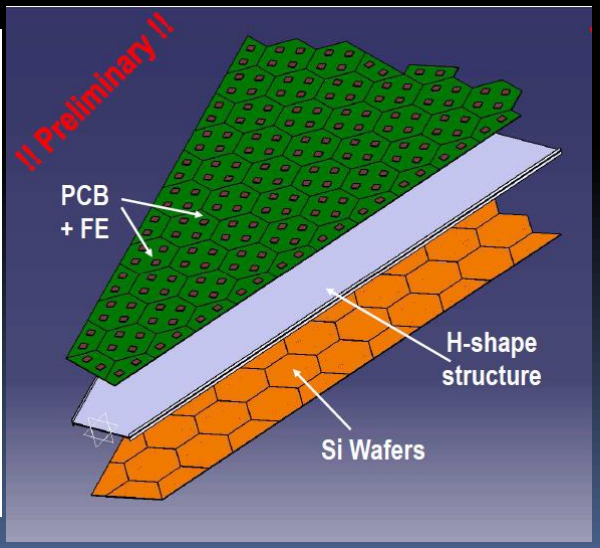
3

High-Granularity Calorimeter (HGCAL)

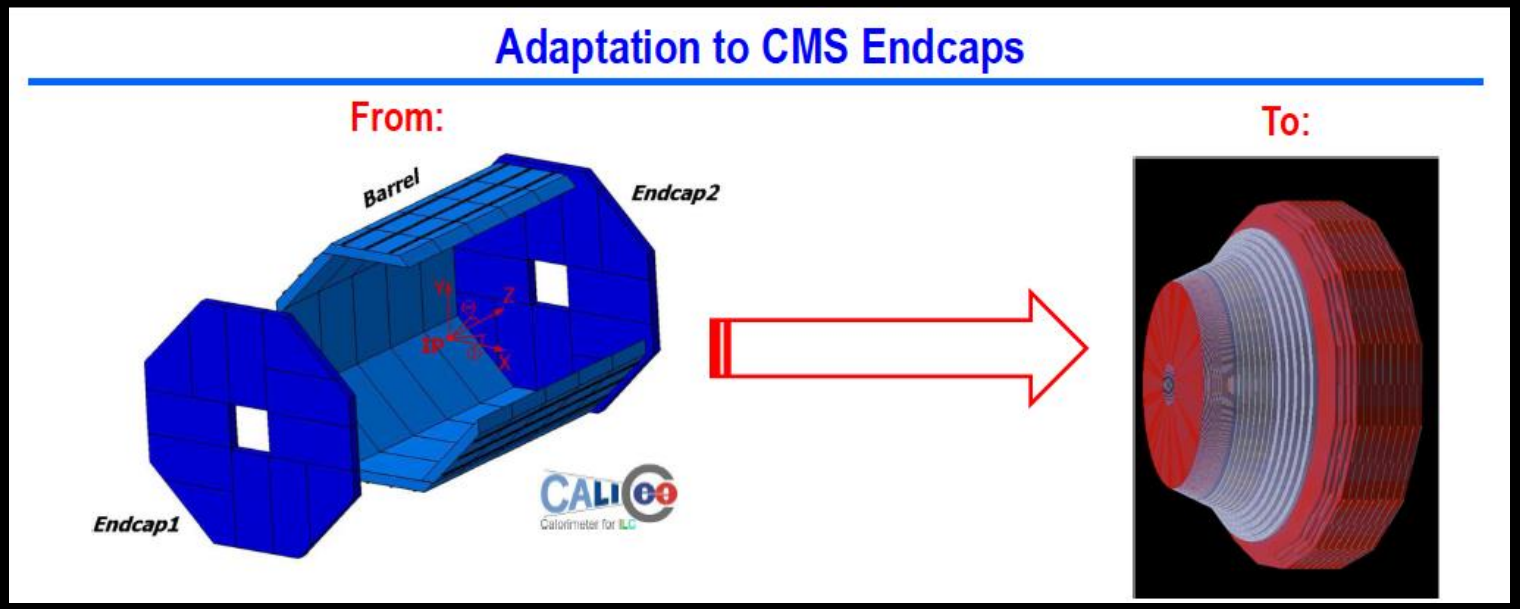








High-Granularity Calorimeter (HGCAL)

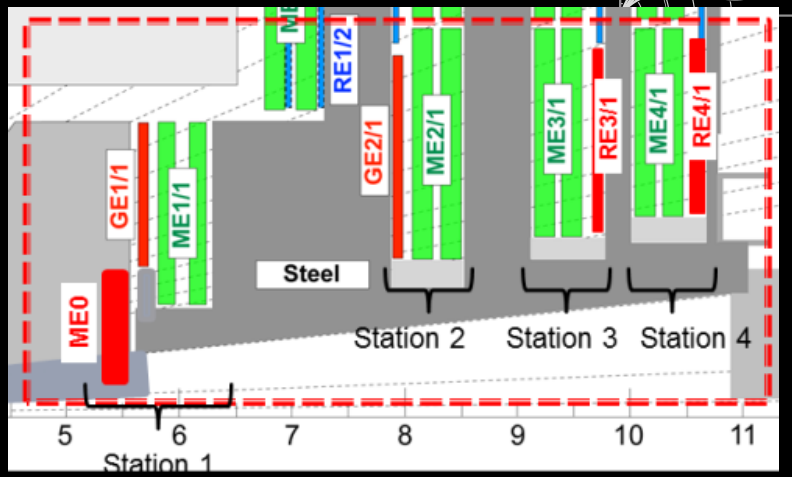


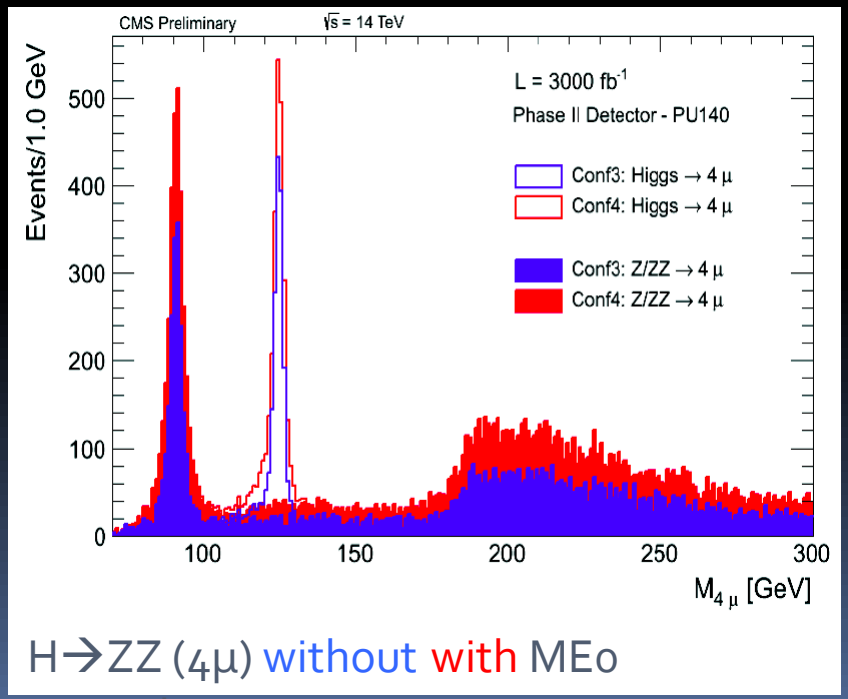
- Power consumption & Data rates
- Radiation and -30°C operating temperature
  - Thermal enclosure & services feed-troughs
- Profit from synergy with Tracker R&D
  - Sensors, cold operation & CO_2 cooling, Read-Out

Phase II CMS End-Cap Muon Upgrade

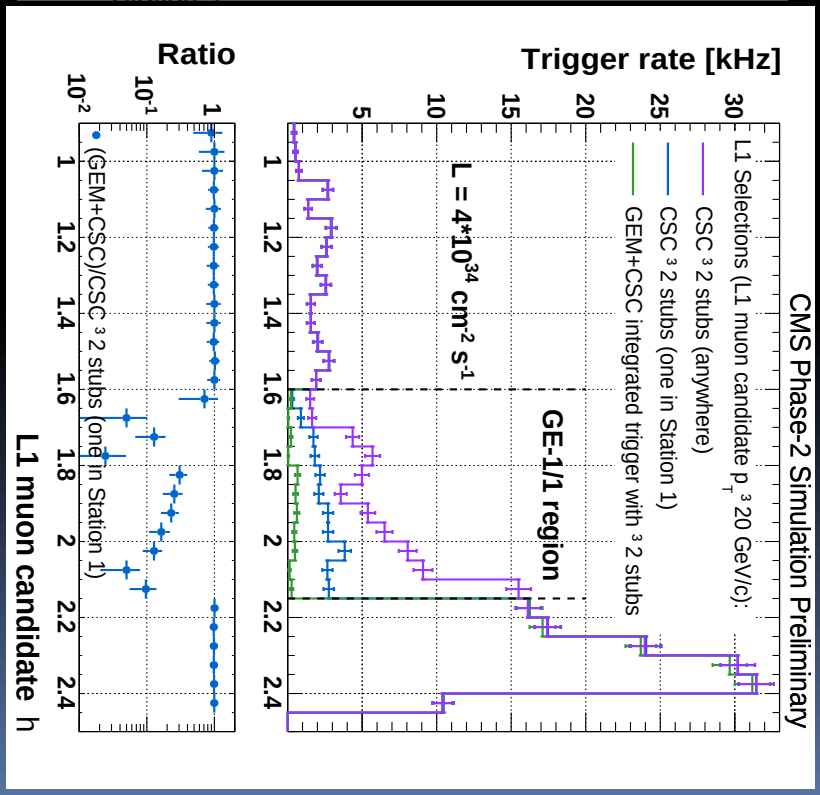
New forward Muon detectors

- Complete muon stations at $1.6 < |\eta| < 2.4$ to reduce trigger rates
  - GEMs in 2 first stations (improve Pt resolution)
  - RPCs in 2 last (timing resolution to reduce bkgd)
- Consider increase of the muon coverage up to $|\eta| \sim 4$
  - Coupled to extension of new calorimeter and pixel
  - Increase physics acceptance for multi- lepton final state





H→ZZ (4μ) without with MEo extension



Summary and Conclusions

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- The LHC Run I at 7TeV has resulted in the Discovery of a 125GeV Higgs Boson !
  - This completes the SM
- No evidence yet for New Physics
  - And yet we know there must be more to the picture
- The HL-LHC will allow thorough exploration of the TeV scale with a two-pronged approach
  - Precision SM, EWSB & Higgs physics, rare processes
  - Characterize and/or continue direct searches for BSM physics, including low cross-section

Summary and Conclusions

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CMS is preparing a program of Upgrades aimed at fully exploiting the HL-LHC physics potential

Backup

Backup

The CMS Detector

(shown open)

Total weight	14000 t
Overall diameter	15 m
Overall length	28.7 m

ECAL
76k scintillating $PbWO_4$ crystals

HCAL
Scintillator/brass
Interleaved ~7k ch

Muon endcaps
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)

3.8T Solenoid

IRON YOKE

Preshower
Si Strips ~16 m^2
~137k ch

Foward Cal
Steel + quartz
Fibers ^{2}~k ch

Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

Pixels & Tracker
- Pixels (100x150 μm^2)
  ~ 1 m^2 ~66M ch
- Si Strips (80-180 μm)
  ~200 m^2 ~9.6M ch

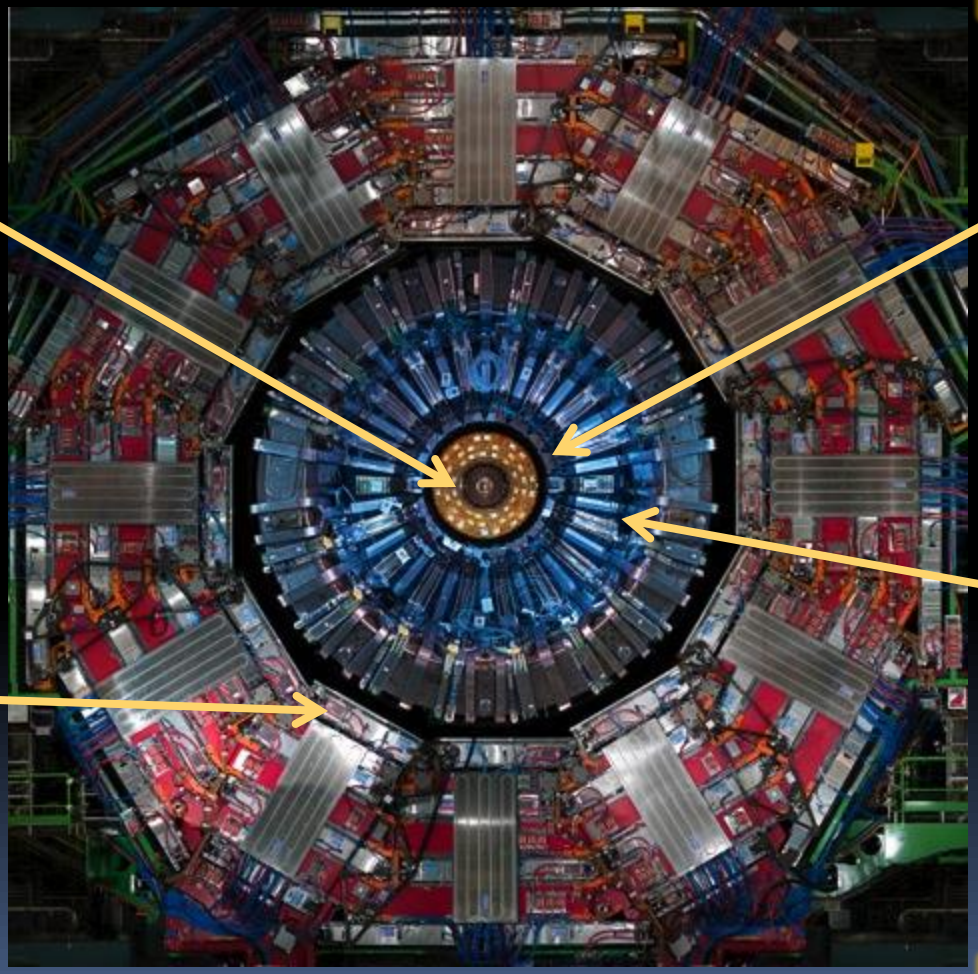
Muon Barrel
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

The CMS Detector

18 years in the making!

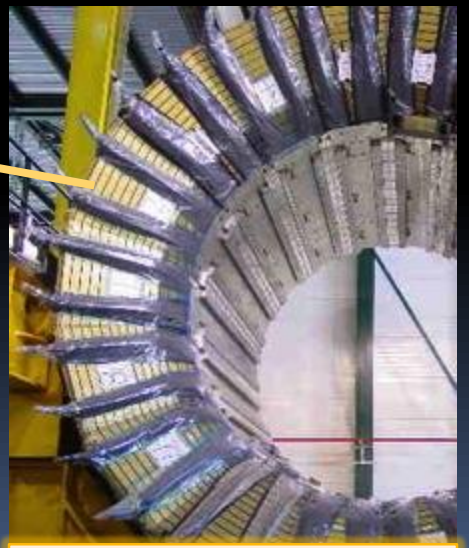
3000 scientists from 40 countries
800 Ph. D. Students!

Silicon Tracker



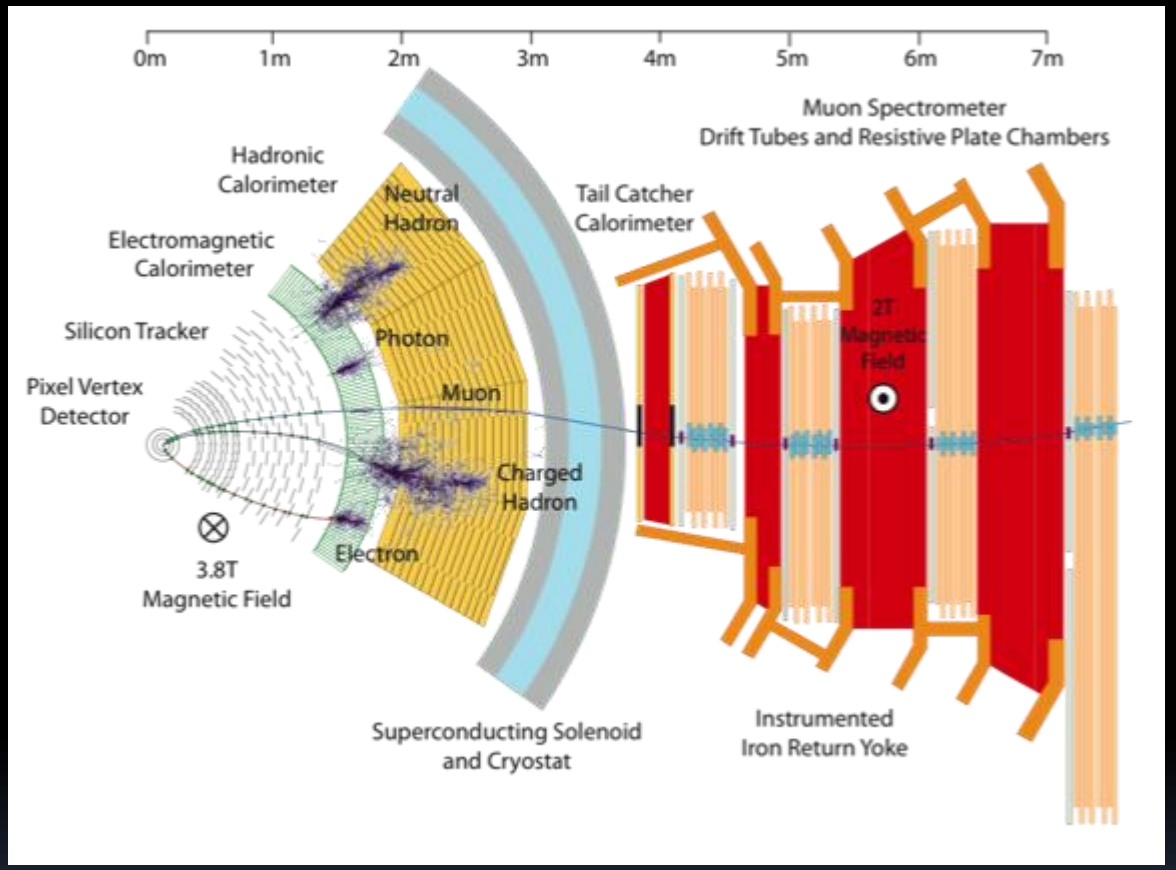
Scintillating Crystals

Gas ionization chambers



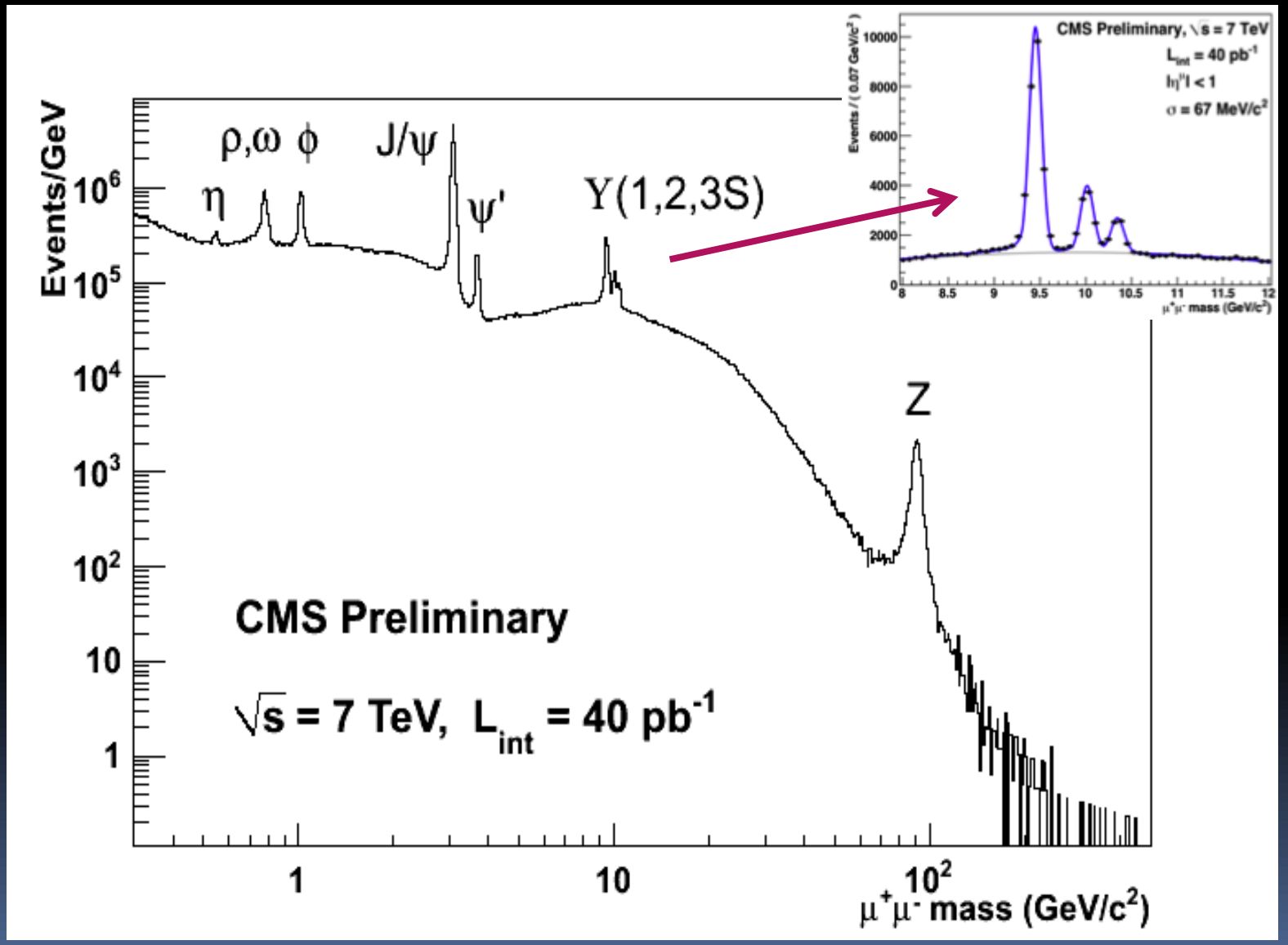
Brass plastic scintillator

Object Reconstruction with LHC Detectors

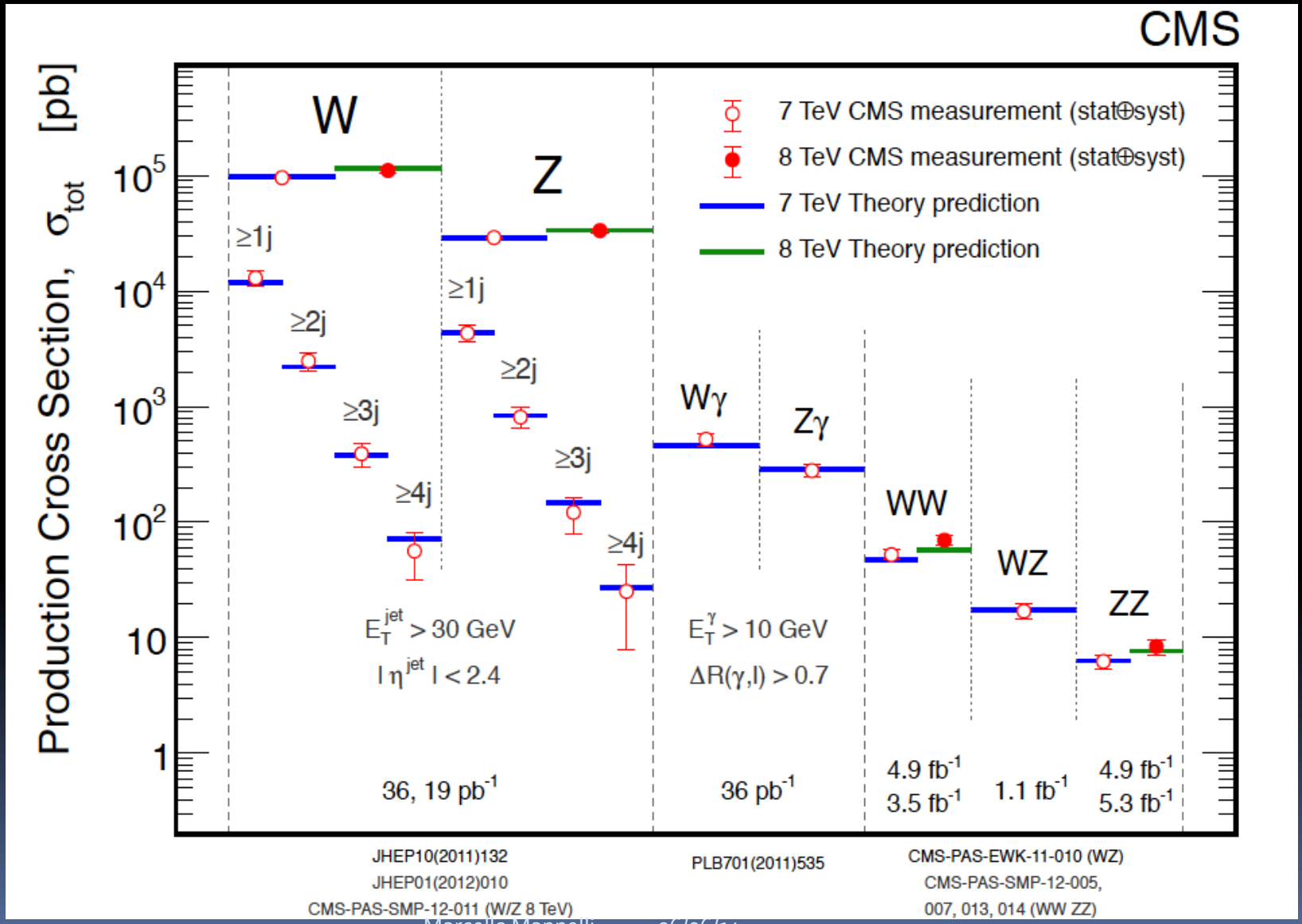


- Optimal combination of information from all sub-detectors: returns a list of reconstructed particles
  - e,μ,γ, charged and finally, neutral hadrons
- Used in analyses to reconstruct fundamental physical processes

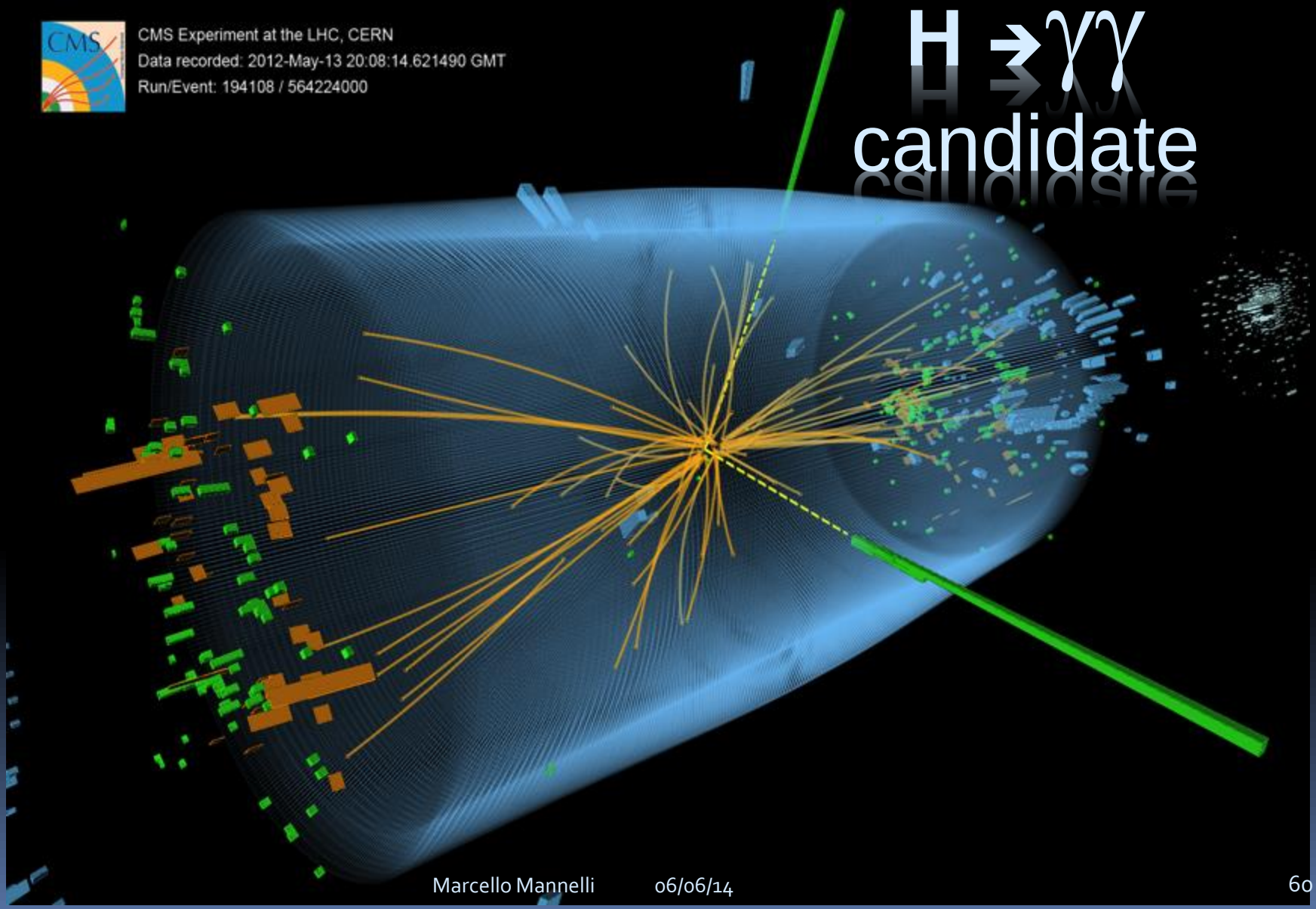
$\mu^+\mu^-$ Invariant Mass Spectrum



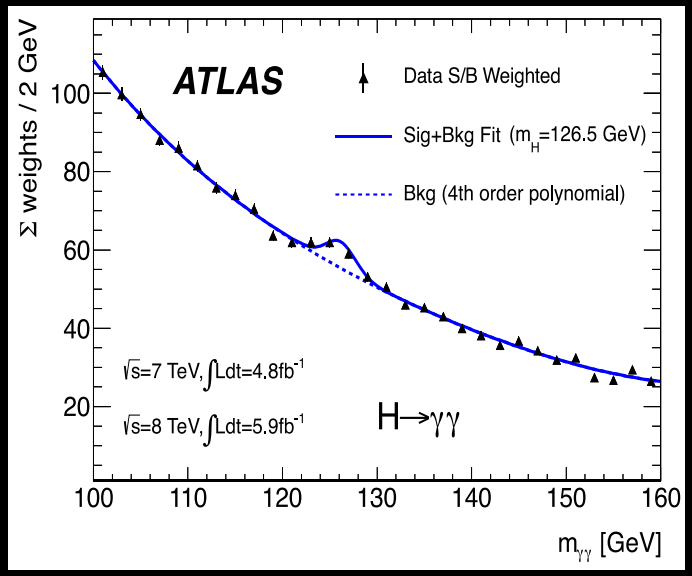
Mapping out the SM

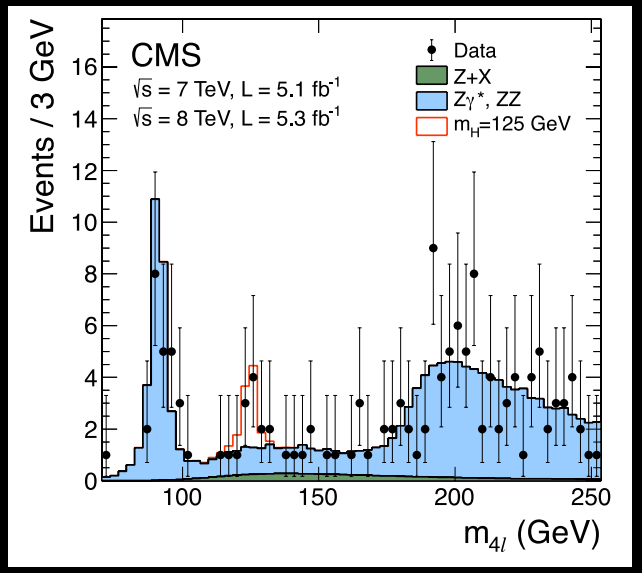


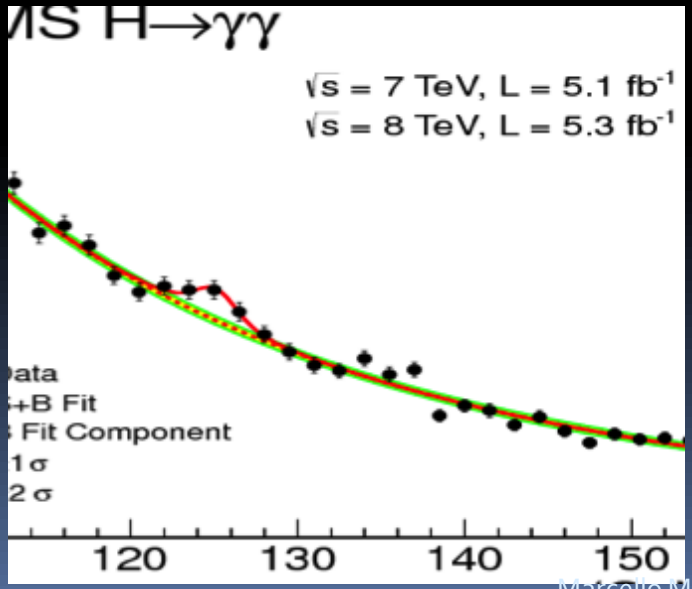
Decays into 2 Photons: H → 2γ

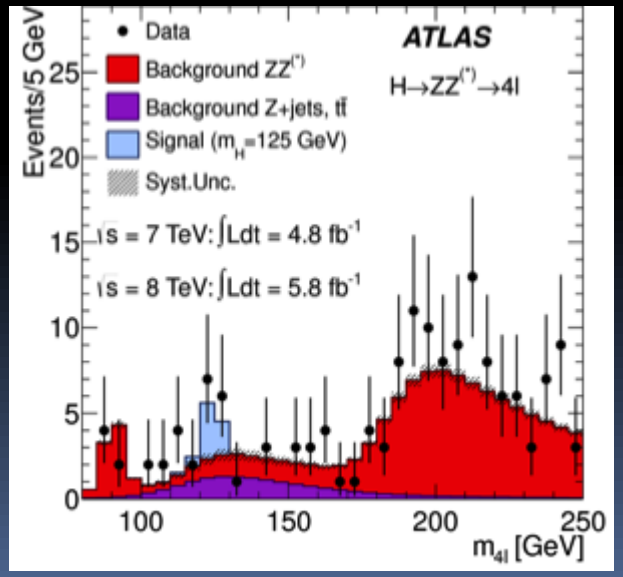


July 4th 2012: discovery of a boson with mass ~ 125 GeV



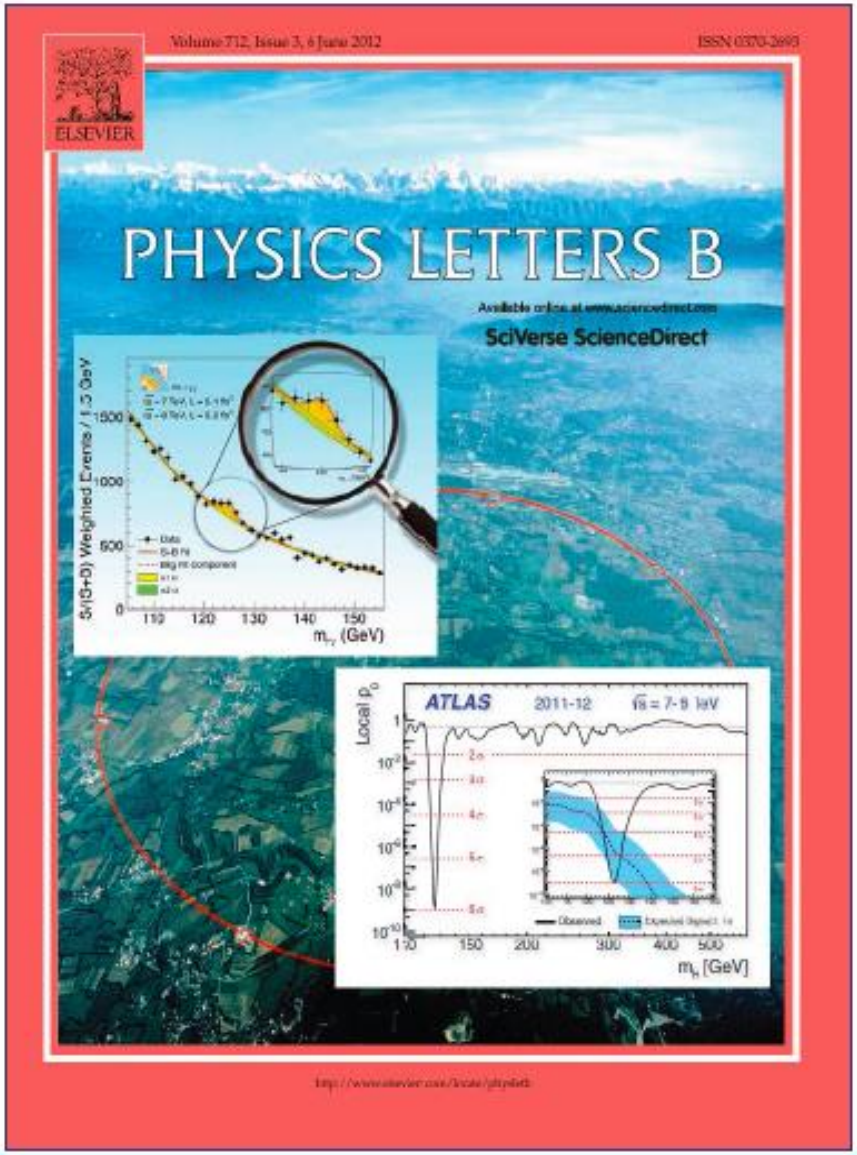




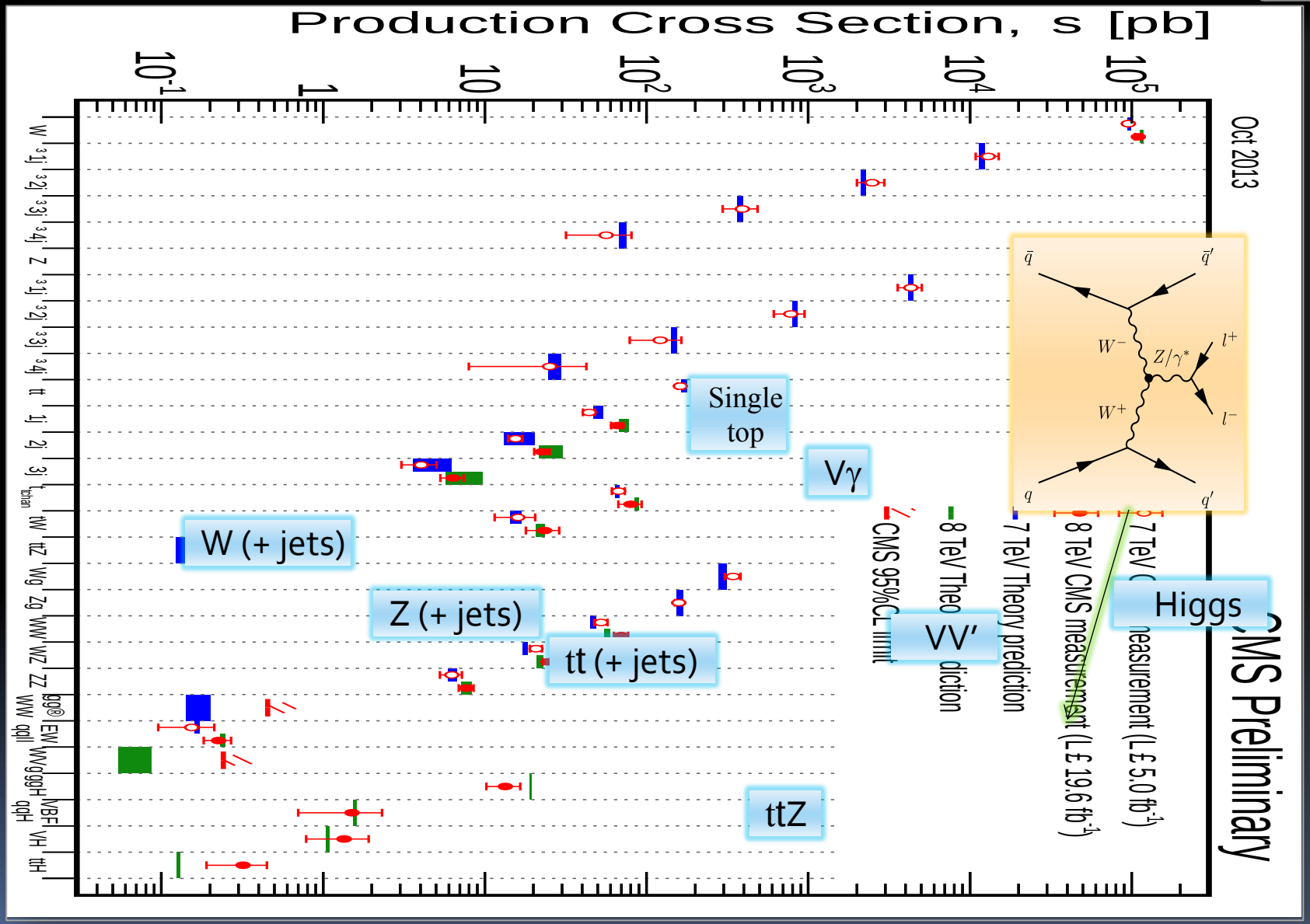


The highlight of a remarkable year 2012

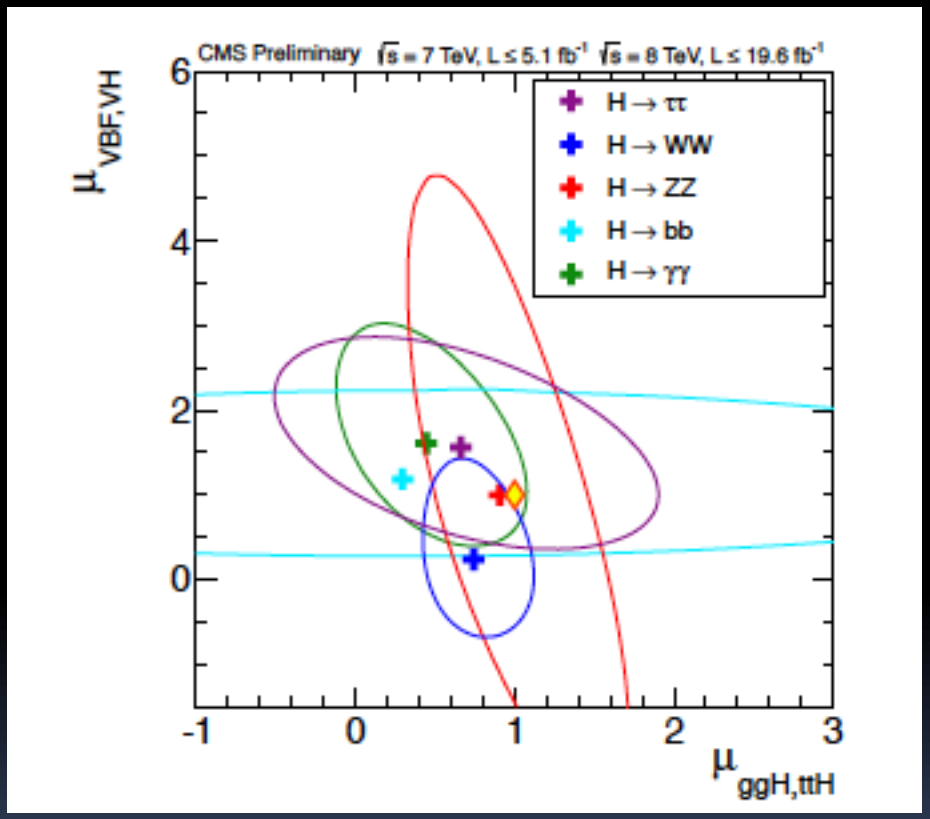
Rolf Heuer CERN-DG
January 2013

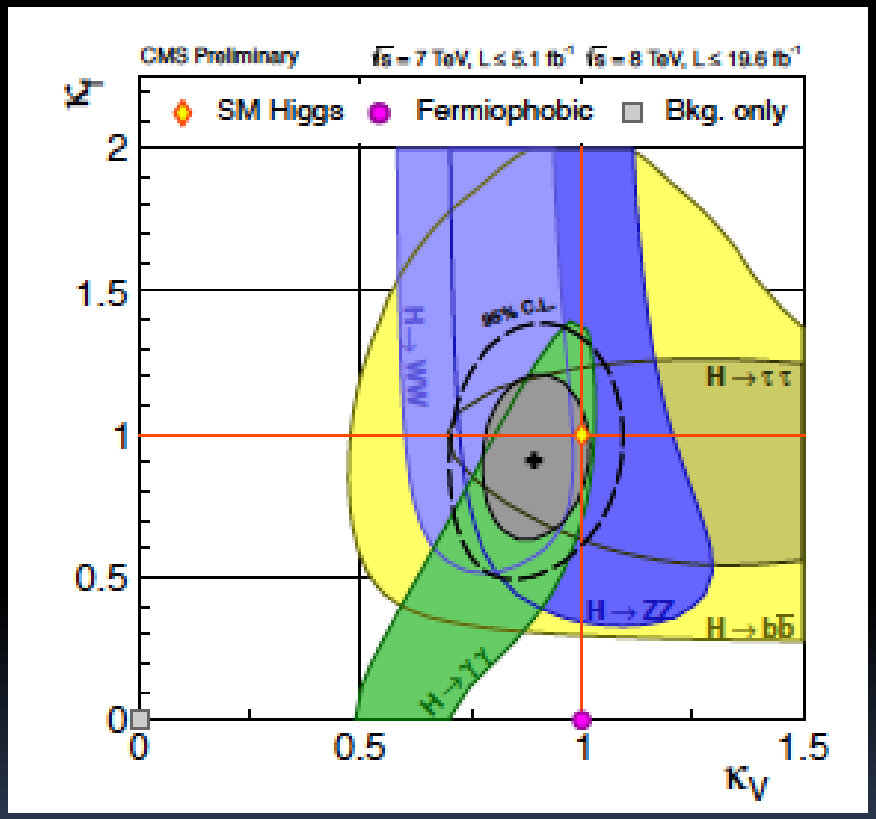


Mapping out the Higgs sector



Higgs Couplings





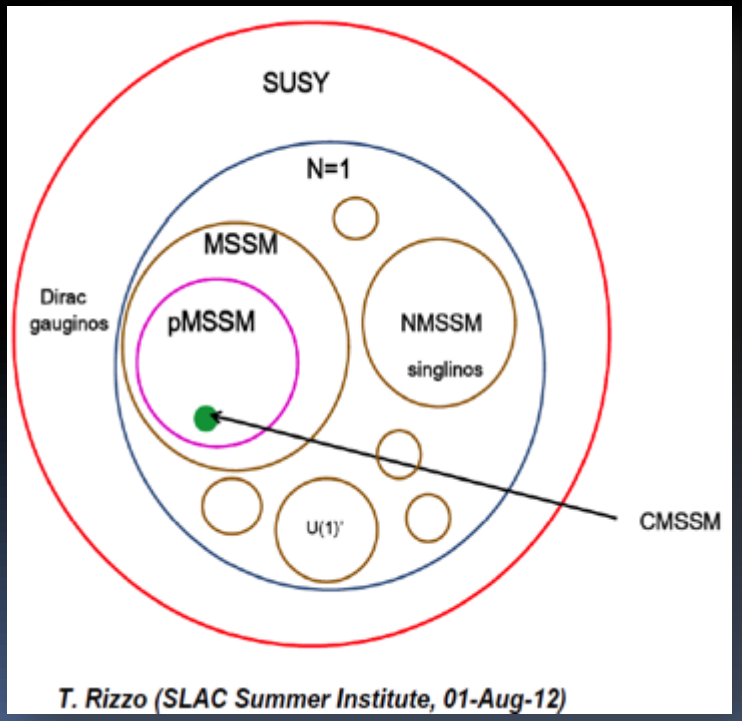
SUSY

- Much uncovered phase space
  - *It could be at low mass but hidden*
  - *Or at higher mass but still natural*
- If something new is seen,
  - the LHC can provide insights into the underlying physics
    - *e.g. lifetimes of long-lived particles provide info about the SUSY scale**
- Until something new is seen
  - We'll expand the constraints
    - *We can potentially make a significant statement (albeit not 100% definitive) on naturalness*

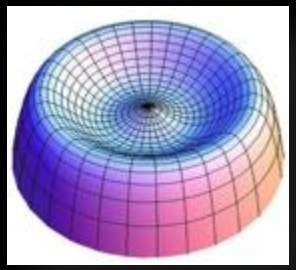
*N.Arkani-Hamed et al. arXiv:1212.6971v1

More reasons to like SUSY

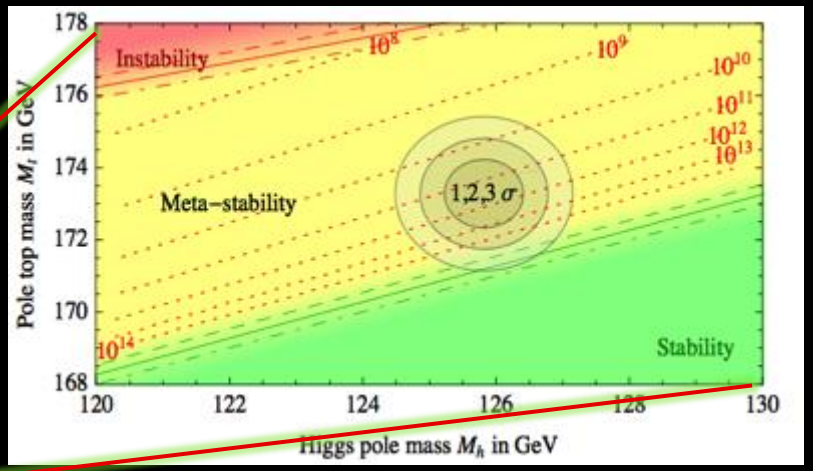
- ***Unifies couplings***
- ***Predicts SM-like Higgs m_h < 130 GeV***
- ***Dark matter candidates***
- ***Connects large Top mass to EWSB***

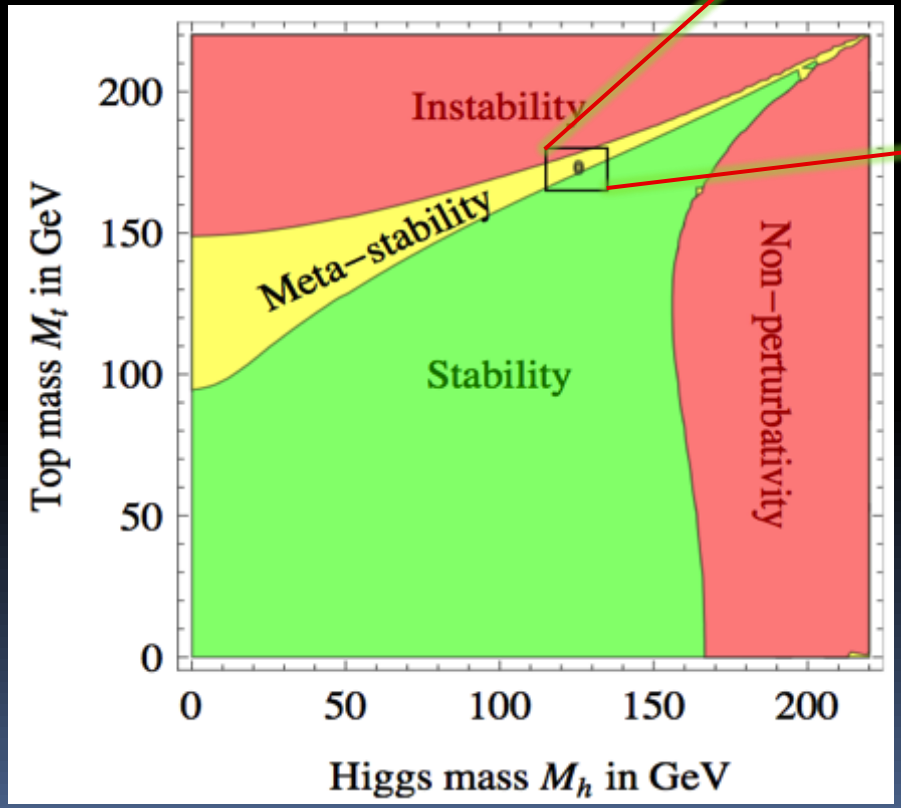


Precision physics, and the state of the Universe

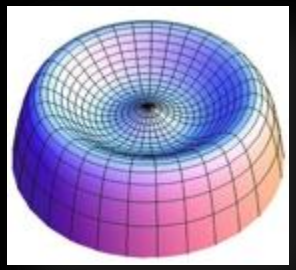


m_{top} ~ 173 GeV

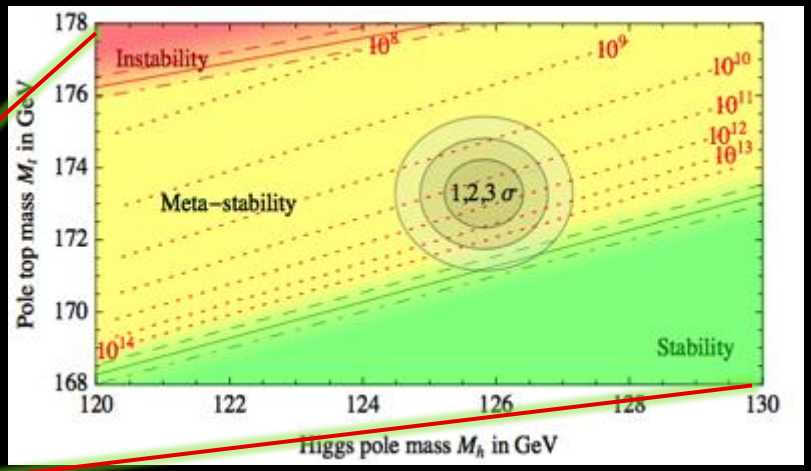


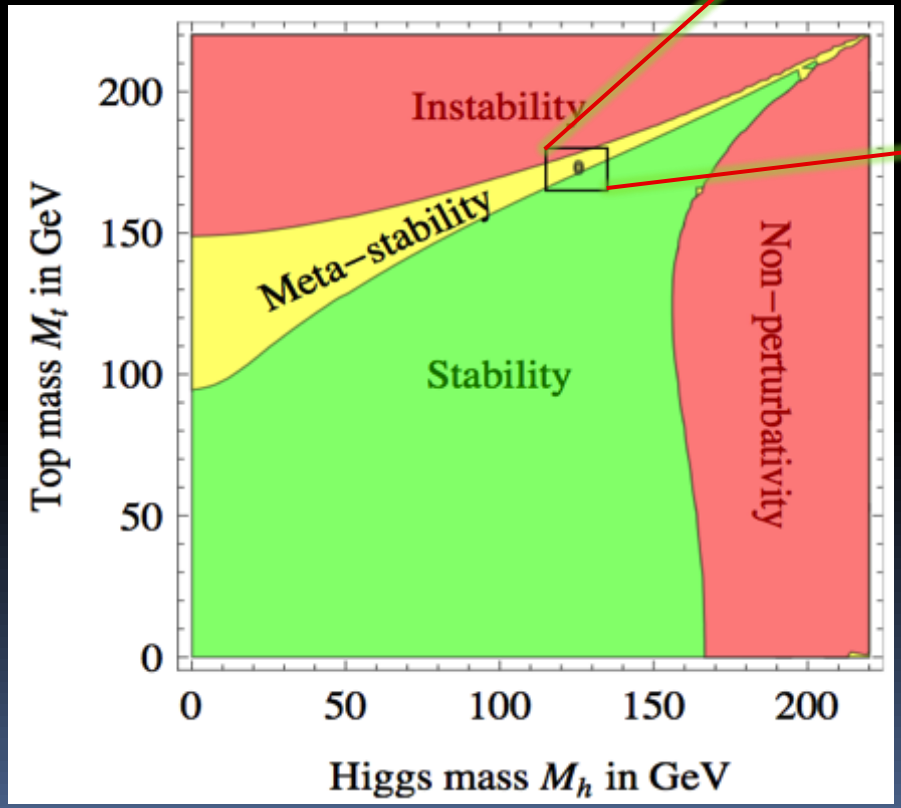


Precision physics, and the state of the Universe

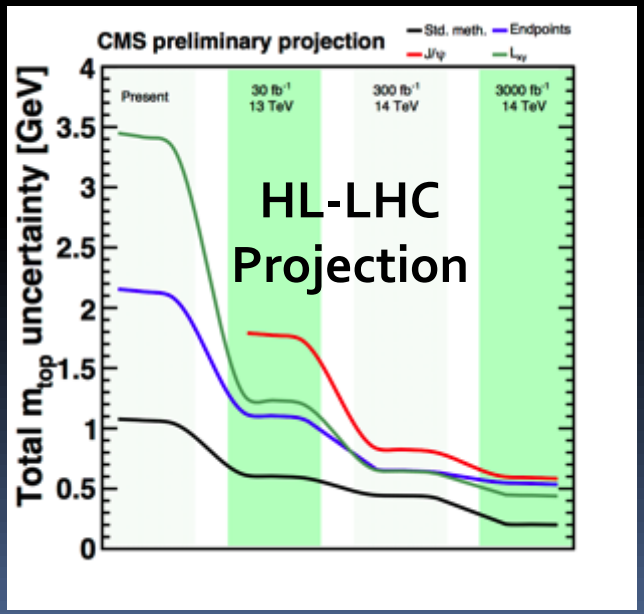


m_{top} ~ 173 GeV





3 ab^{-1}	Per expt.
Δm_t	~200 MeV
Δm_H	~ 50 MeV
$\Delta \Gamma_H$	<100 MeV?
Δm_W	~ 6 MeV



LHC

Rolf Heuer CERN-DG
January 2013

ESWG: "Europe's top priority should be the exploitation of the full potential on the LHC, including the high-luminosity upgrade of the machine and the detectors with a view to collecting ten times more data than in the initial design, by around 2030

Key message

There is a program at the energy frontier with the LHC for the next ~20 years:

13, then 14 TeV, design luminosity
14 TeV high luminosity (HL-LHC)

The Energy and Intensity Frontiers Meet

Phase I CMS Trigger Upgrades

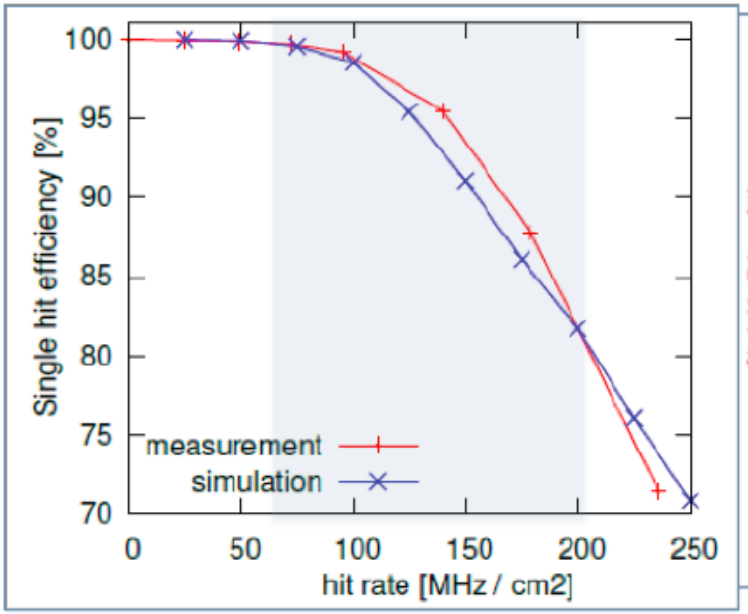
- Improve Muon Trigger Pt resolution in End-Caps
- Access higher Calorimeter Granularity
- Upgrade Trigger systems to use more powerful FPGA's
  - Better Trigger primitives and more sophisticated algorithms to maintain L1 accept rate at ~100kHz
- Tracking is not presently used in L1 Trigger, so plays a key role in L2 (HLT)
  - upgrade HLT farm & speed up track reconstruction

Phase I CMS 4 layer Inner Pixel

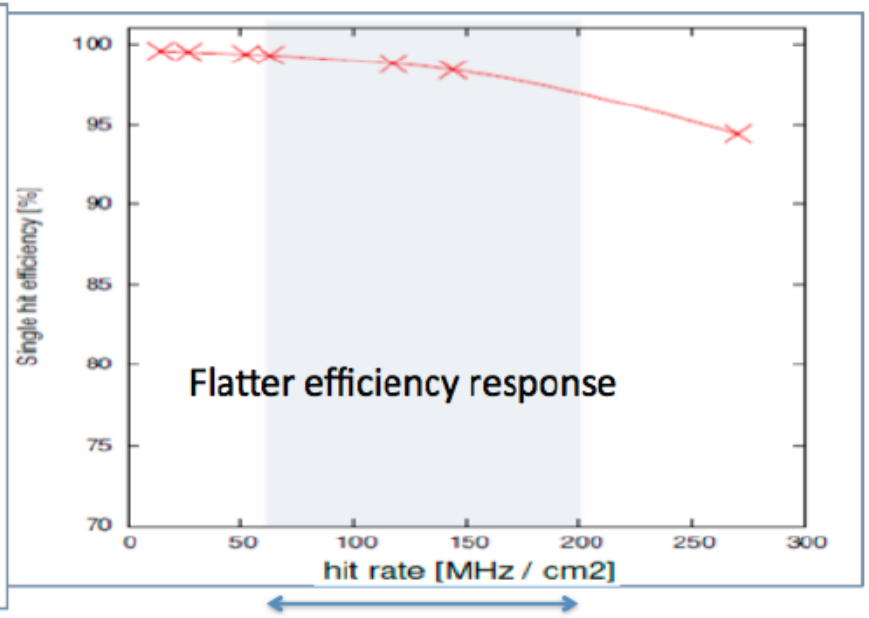
The Luminosity Cliff

- Expected fluence in the Innermost disk
  - The old and the new ROC are contrasted for the same geometry using x-rays

Current Pixel Detector

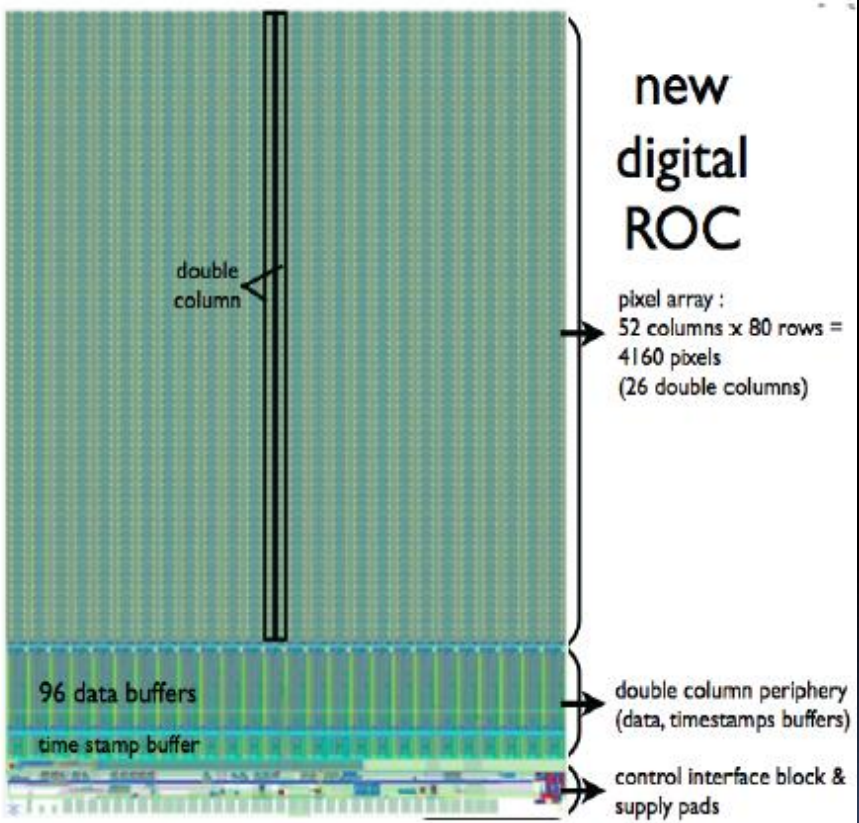


Upgrade Pixel Detector

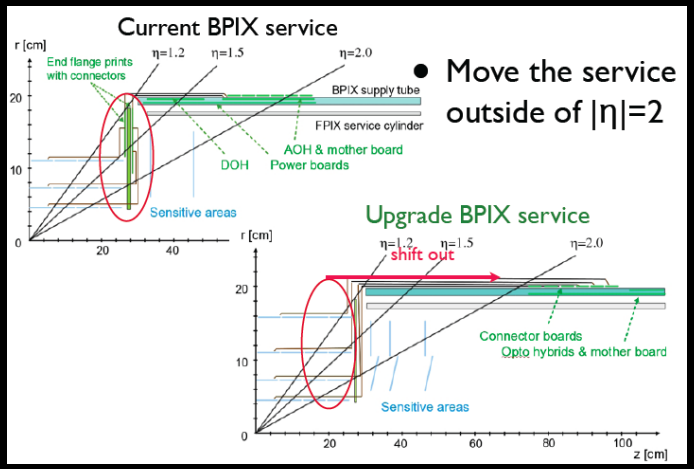


Phase I CMS 4 layer Inner Pixel

- Pixel Size: 100μm x 150μm
- Reduced data loss
  - increased time stamp / data buffers 12/32 → 24/80 to prevent overflow with high occupancy
  - Additional readout buffer (32->96) to reduce readout related data loss
- Increased readout link speed (40 MHz analog→160MHz digital) for pixel address and pulse heights
- Reduced pixel threshold of 1800e from present 3500e

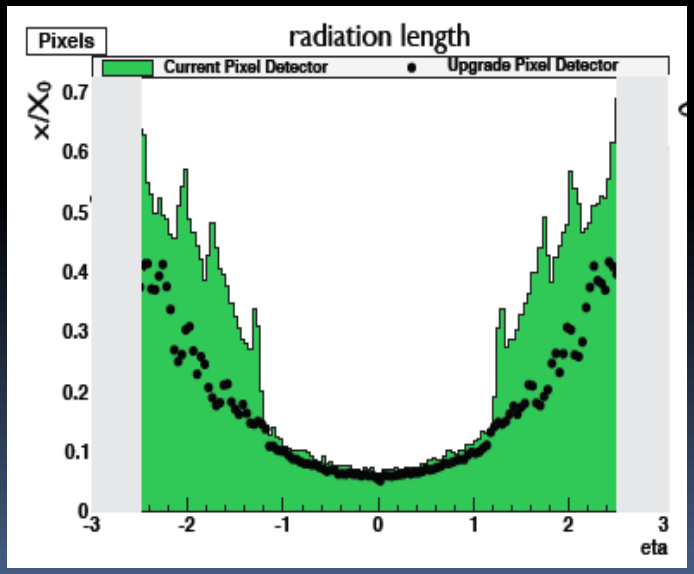


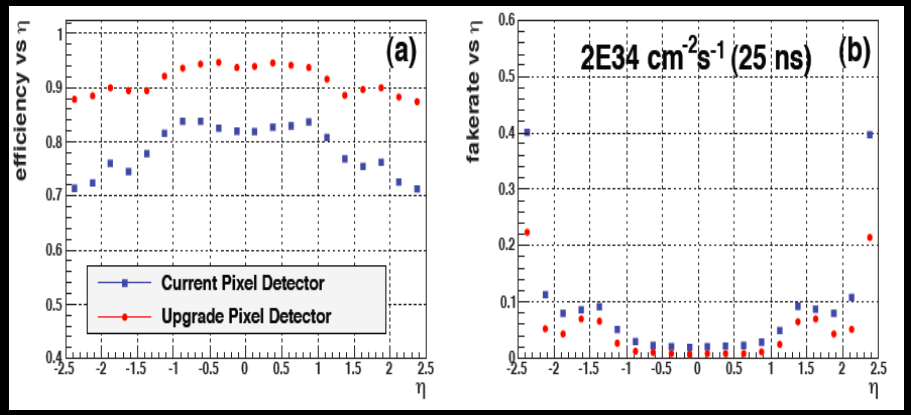
Phase I CMS 4 layer Inner Pixel

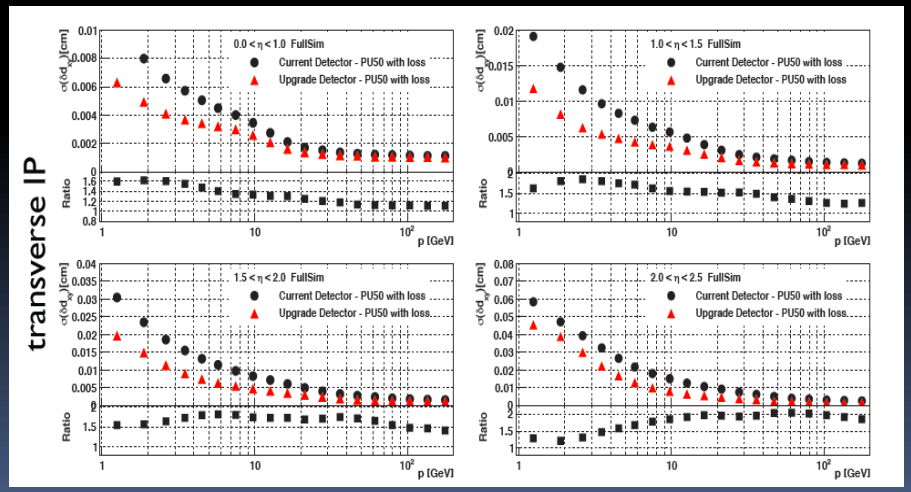


- Move the service outside of |η|=2

Minimize Material within Tracking Volume:
Optimize Performance of 4 Pixel Layer System

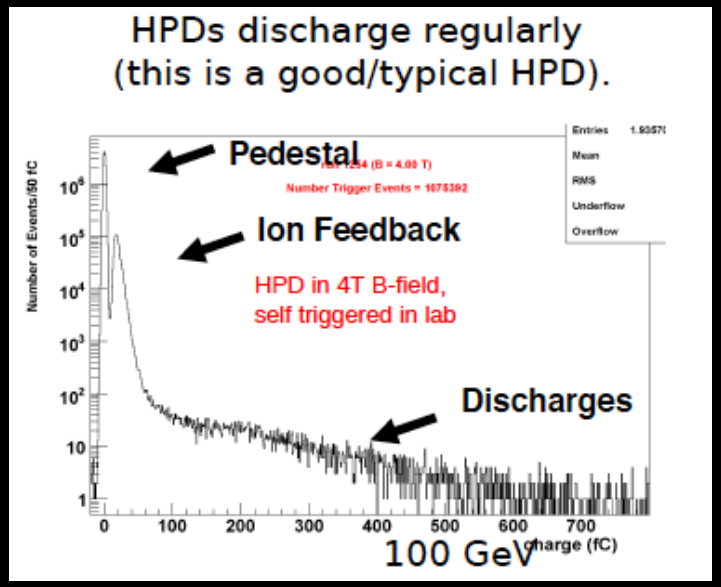


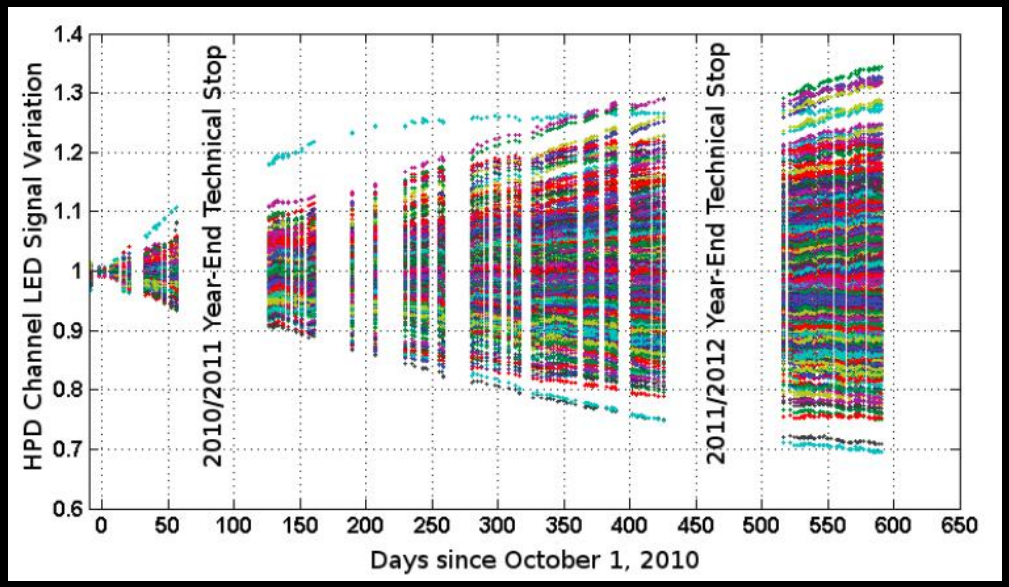


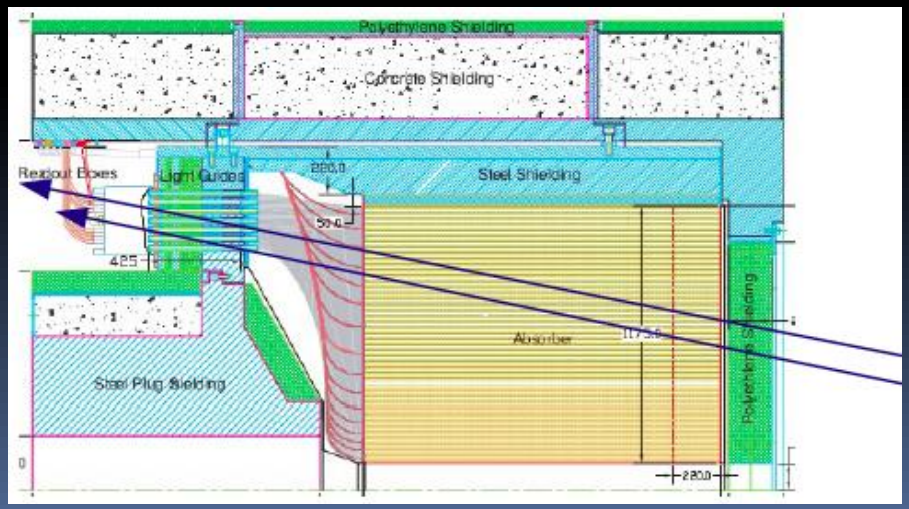


Phase I CMS HCAL Read-Out Upgrades

HB/HE Performance Concerns:
HPD discharges, and gain drift !



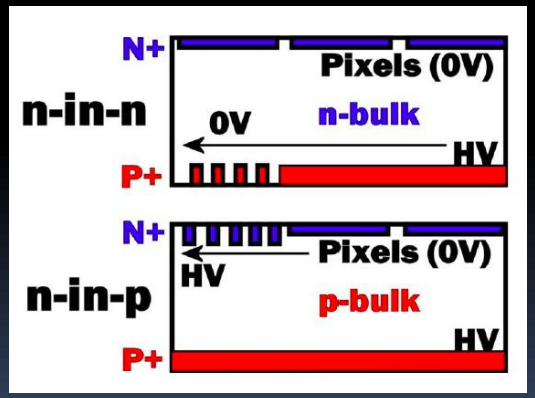


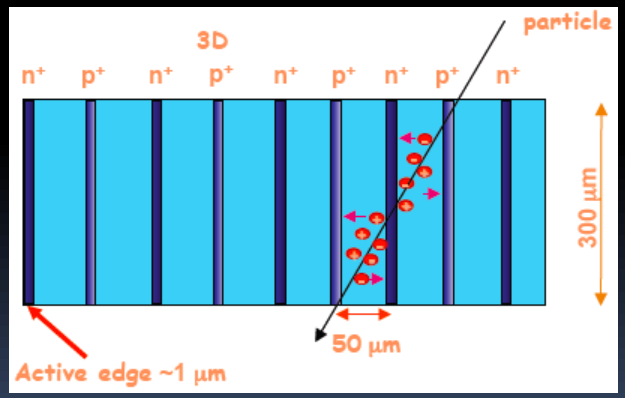


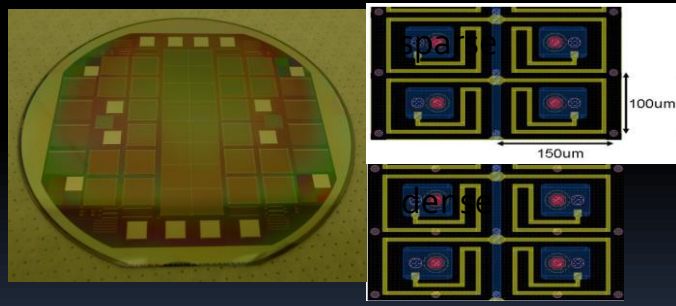
HF Performance Concerns:
Large signals from particles going directly through PMT window: cannot be usefully filtered with 25ns bunch-spacing

R&D on Phase II Silicon sensors

- For Pixels radiation tolerance up to $\gtrsim 10^{16} n_{eq}/cm^2$
  - Planar n-in-n and n-in-p technologies
    - 98% efficiency after $10^{16} n_{eq}/cm^2$
    - Study pixel geometry and thickness (~100μm)
  - 3D sensors
    - ATLAS IBL radiation tolerance up to $5x10^{15}$ n_{eq}
    - Study configuration and thickness (~100μm)







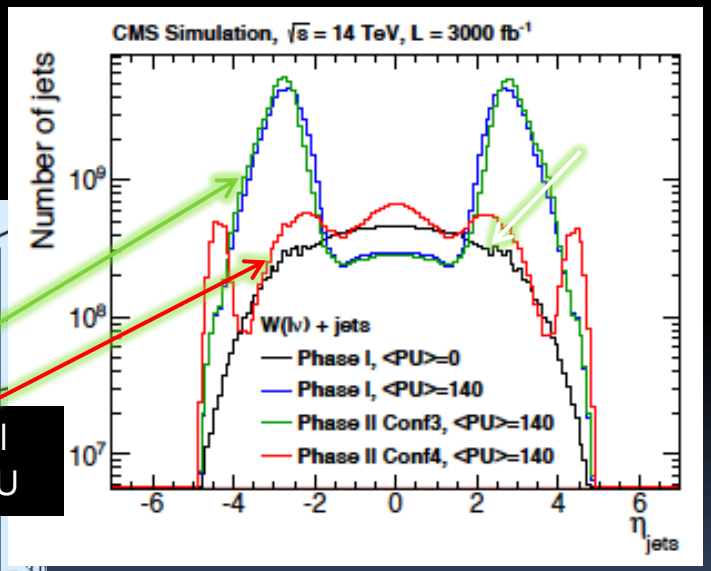
CNM 3D sensors

Phase II CMS Tracking Trigger

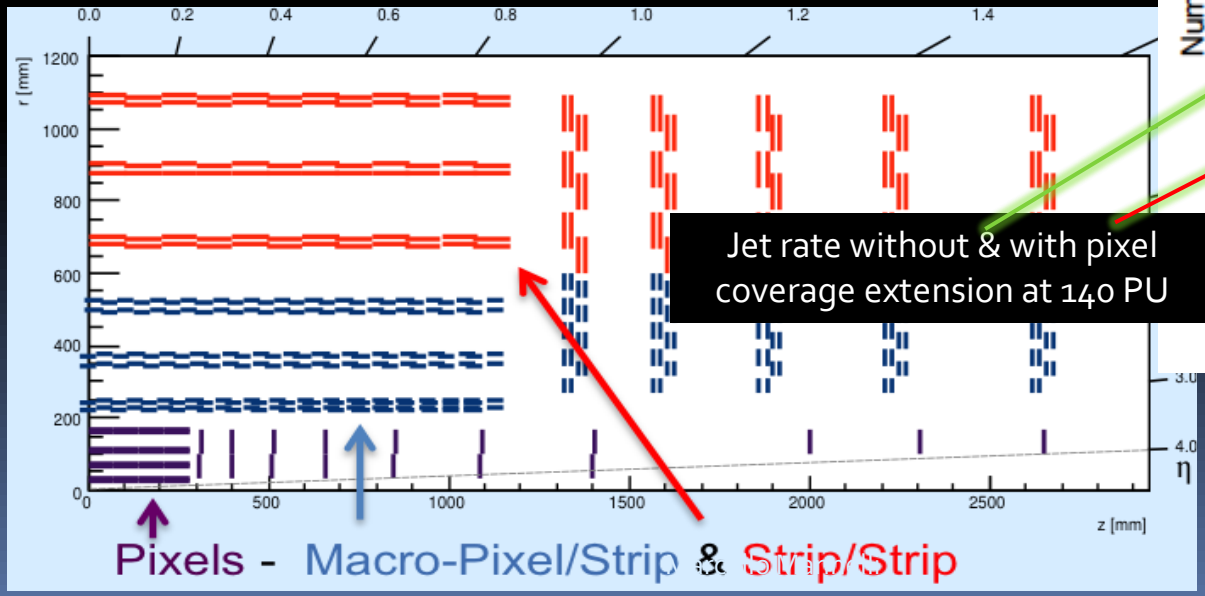
- Objective:
  - Reconstruct "all" tracks above 2 ~ 2.5 GeV
  - Identify origin along beam axis with ~ 1 mm precision
- Level-1 data require local rejection of low-pT tracks
  - Reduce bandwidth, and simplify track finding @ Level-1
  - Threshold of ~ 1÷2 GeV ⇒ data reduction of one order of magnitude or more
- Tracker modules provide both 40MHz "Level-1 data" and 100kHz "readout data"
  - Tracker & Tracking Trigger in one fully integrated system

Tracker conceptual design

- Extension of Pixel coverage up to |η|~ 4
  - Reduce rate of fake jets due to PU for VBF/VBS physics
  - Associate jets to tracks - vertex to mitigate pile-up effect
  - Expect significant improvements for all VBF processes: Higgs - BSM dark matter & for VBS

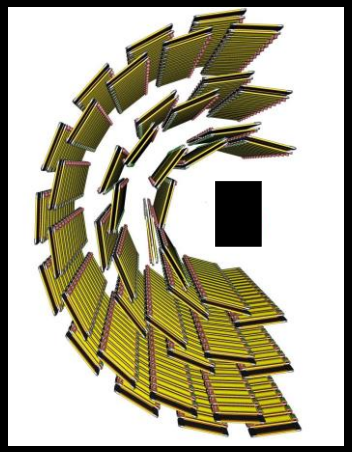


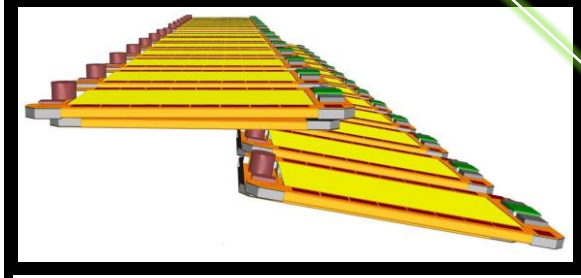
Jet rate without & with pixel coverage extension at 140 PU

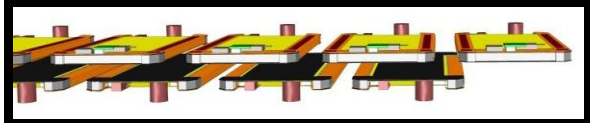


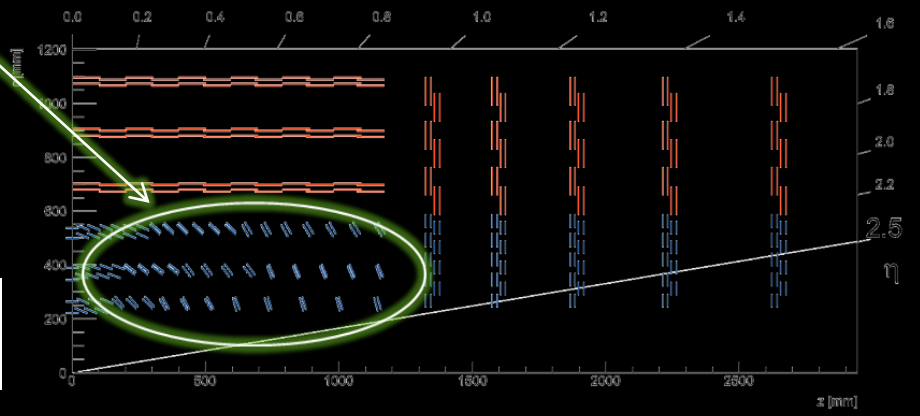
R&D on Outer Tracker

- Mechanical structures
  - Concept for outer barrel and endcap is selected
  - Decide inner barrel concept in 2014









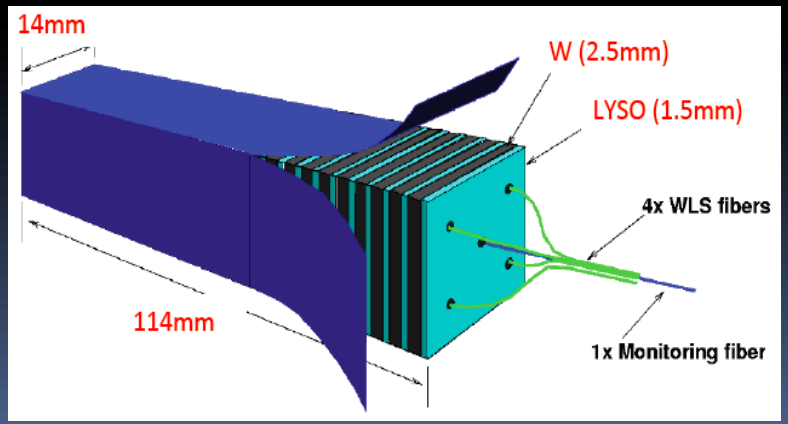
- CO_2 cooling
  - Need 100kW - build on pixel Phase 1 - common development with ATLAS
- Back-end electronics for trigger track reconstruction
  - Pattern recognition with Associative Memories or propagation from layer to layer in FPGA followed by fit in FPGA
    - demonstrators being developed - build on ATLAS FTK - existing high BW/ processing boards - generic R&D on custom AM ASICs
  - DAQ building on Phase 1 board developments for Pixel and Trigger

Phase II CMS End-cap Calorimetry

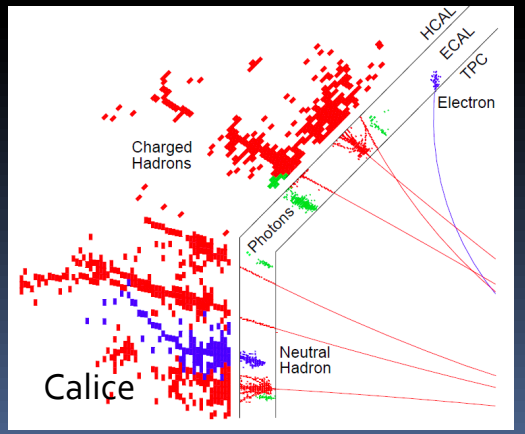
CMS needs to replace End-cap Electromagnetic and Hadronic calorimeters for Phase 2 due to radiation damage

Three concepts have been considered:

- An Electromagnetic End-cap (EE) calorimeter built in a Shashlik design and a Hadronic End-cap (HE) Calorimeter rebuild
- A Combined Forward CALorimeter (CFCAL) integrating EE & HE functions (DREAM/RD52 concept)
- A High Granularity CALorimeter (HGCAL) integrating EE and HE functions (CALICE concept) with a Back HE to capture energy tails



EE Shashlik concept



HGCAL concept

Plans for End-cap Calorimetry

From Jan. to Apr. 2014, a review committee investigated the potential of each concept to fulfill the CMS requirements for:

- physics performance;
- technical feasibility and integration within the existing CMS;
- completion of the project within the anticipated Phase 2 resources and schedule.

Conclusion was that:

- Current resources were insufficient to demonstrate three concepts on the required time scale to select final technical solution
- The CFCAL concept presented the highest technical and schedule risks

The collaboration has decided to continue studies and R&D* for the EE Shashlik plus HE-rebuild and the High Granularity CALorimeter

* also continue R&D (started for CFCAL) on radiation tolerant scintillating fibers
- could be solution in alternative Shashlik design & innermost part of HE

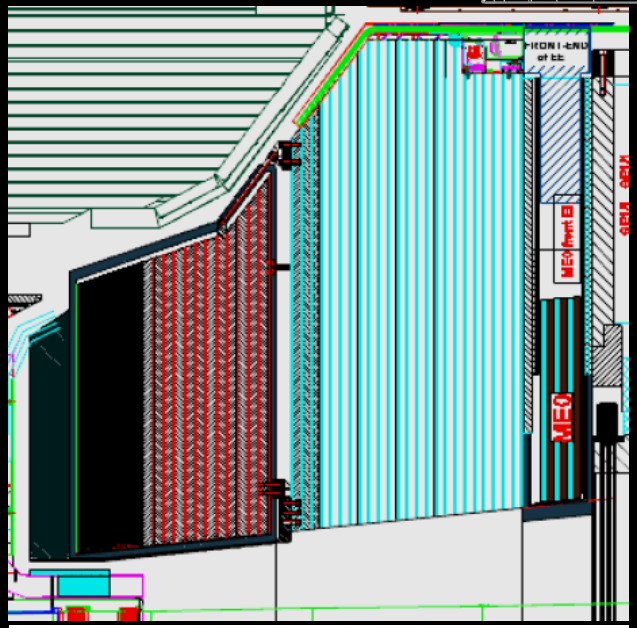
High-Granularity Calorimeter (HGCAL)

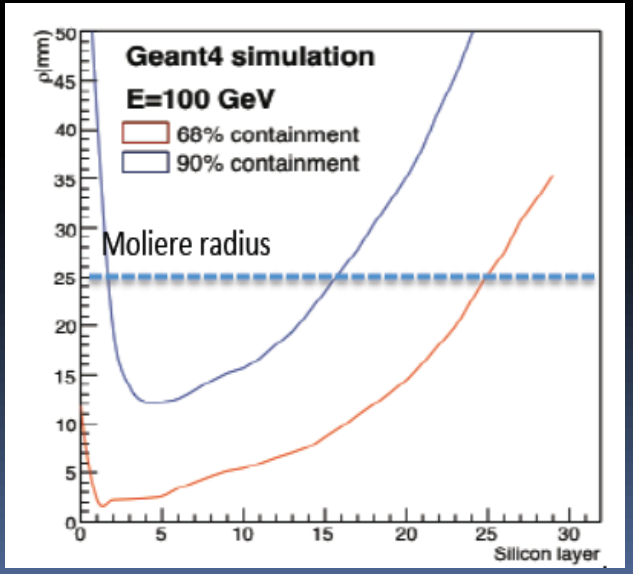
High Granularity Calorimeter

- ECAL: ~33 cm, 25 X0, 1□, 31 layers:
  - 11 planes of Si separated by 0.5 X0 of lead/Cu
  - 10 planes of Si separated by 0.8 X0 of lead/Cu
  - 10 planes of Si separated by 1.2 X0 of lead/Cu
- HCAL: ~66 cm, 4λ:
  - 12 planes of Si separated by 40 mm of brass
- Fine grain pads 0.5~1cm²
  - ~10M channels and 700m² of Silicon
- Back HCAL as HE re-build 5λ
  - With increased granularity

ΔE/E ~ 20%/√E; 3D shower reconstruction

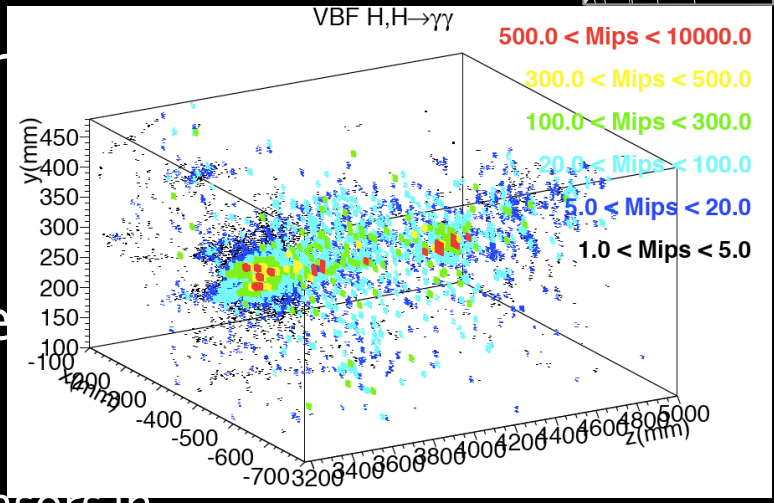
- => Use detailed shower topology to mitigate PU effect



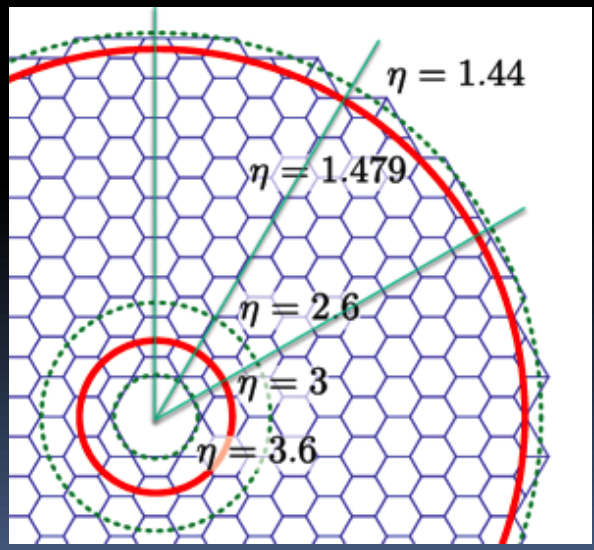


High-Granularity Calorimeter (HGCAL)

- $25X_0$ (1λ) Silicon-lead ECAL & 4λ silicon-br
  HCAL
  - Fine-grained pads ~1cm²
- Fine depth segmentation ~ 30/12 plane
  SiECAL/SiHCAL
  - 3.7/1.4 Mchannels & 420/250m² of siliconsensors in ECAL/SiHCAL
- Full shower topology to mitigate PU effect
- Back HCAL as HE-rebuild (lower radiation level)



VBF Jet (no PU)

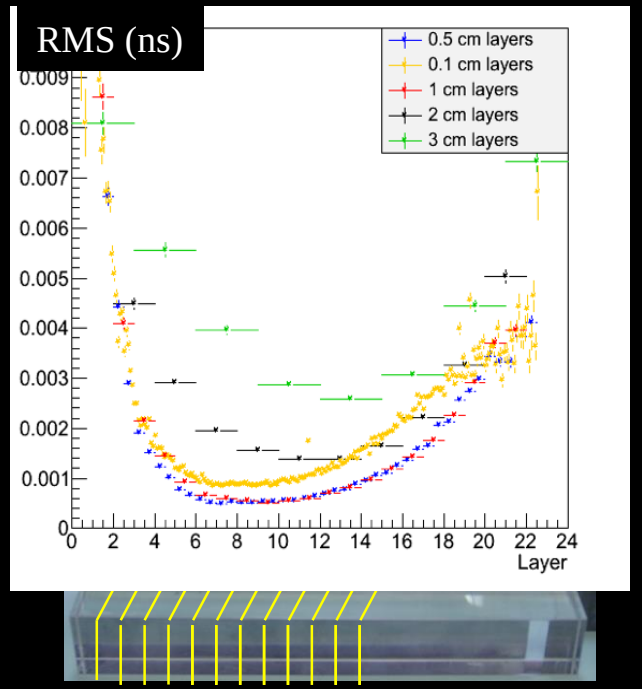


Tiling of 8" hexagonal Si-sensors modules

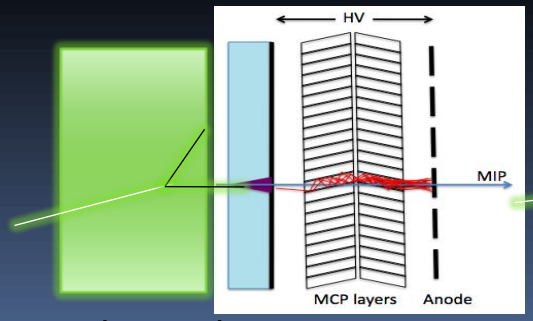
Precision timing

- Time of flight measurement could provide PU mitigation for neutrals
  - precision of ~ 10 ps allows energy deposit association to vertex in the range of ~ 1 cm
- Generic R&D on
  - PMT-MCP or "Ionization-MCP"
  - Silicon sensors : highly doped Si sensor
  - SiPM, HAPD

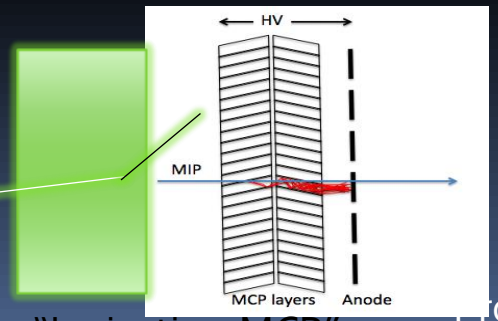
Could allow implementation in preshower or embedded layer or full calorimeter signal



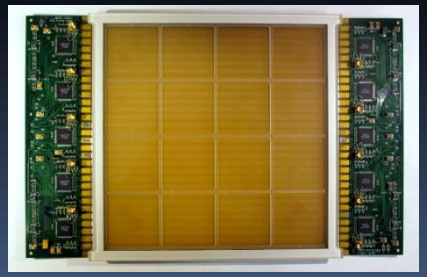
GEANT4 simulation crystals 1cm slices



Classical PMT-MCP



"Ionization-MCP"



Prototype waveform digitizer on a LAPPD mockup, 15 GS/s

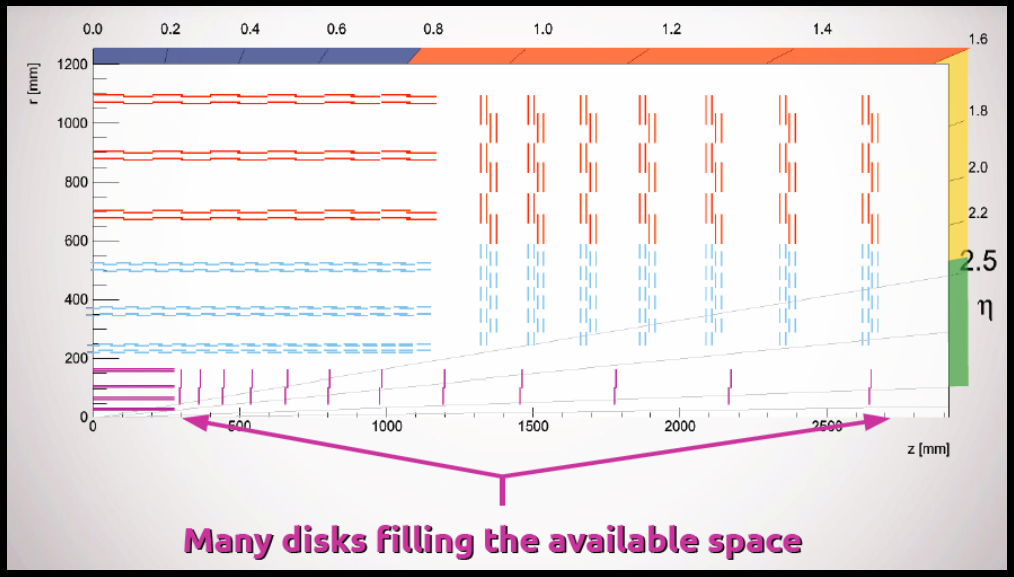
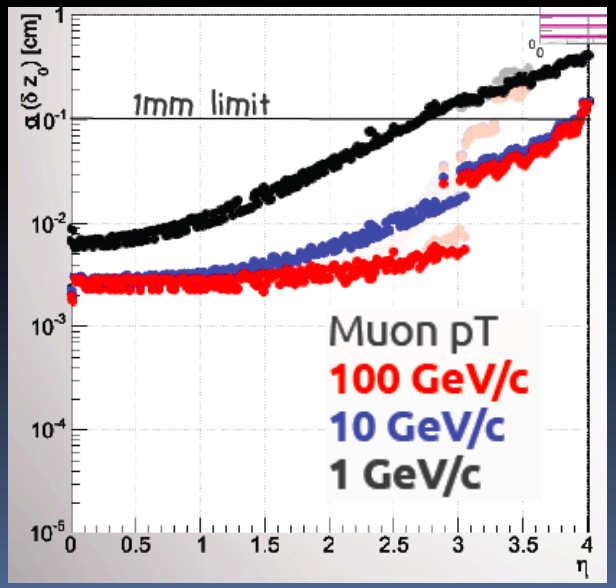
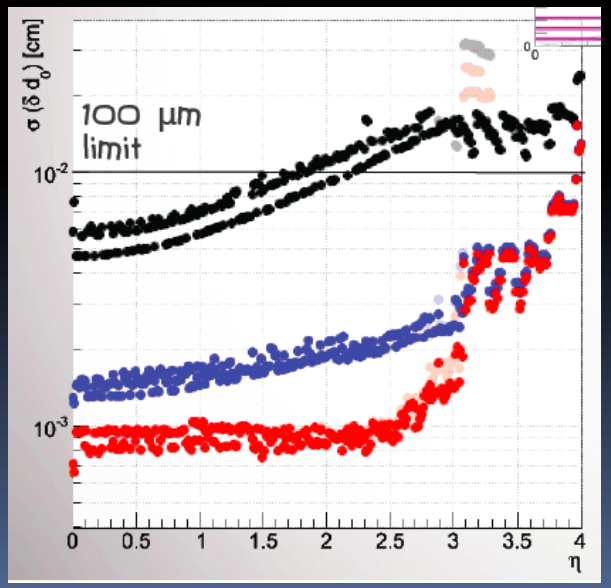
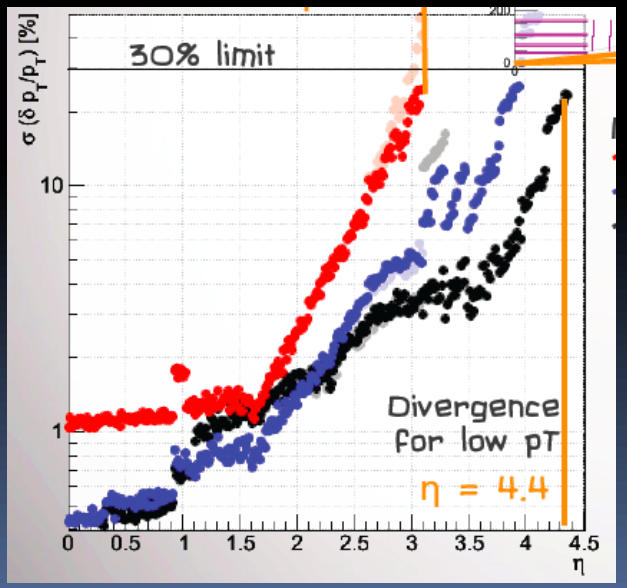
Phase II CMS Trigger/DAQ Upgrades

- A key goal of the CMS HL-LHC upgrade program is to maintain the acceptances of the key leptonic, photonic, and hadronic trigger objects such that the overall physics acceptance, especially for low-mass scale process like Higgs production, can be kept similar to the one in 2012.

- Two key focus points to accomplish this physics goal
  - The first one is the addition of a L1 Tracking Trigger for identification of tracks associated with improved calorimeter and muon trigger objects at L1.
  - The second is to study the option of a significant increase of L1 rate (up to 1MHz), L1 latency (up to 20us) and HLT output rate

Plans for End-cap Calorimetry

Milestones have been established to allow decision on final technical solution on a timescale of ~ 1 year:

- EE Shashlik + HE re-build :
  - Physics performance must be part of the Technical Proposal
  - Demonstrate with prototypes that expected performance can be achieved
  - Demonstrate radiation tolerant components both for EE Shashlik and HE
- HGCAL:
  - Demonstrate benefit of high granularity in physics performance
  - Perform engineering studies of critical design aspects
  - Confirm Si-Sensor radiation tolerance - in conjunction with tracker R&D

Extended Tracker Coverage