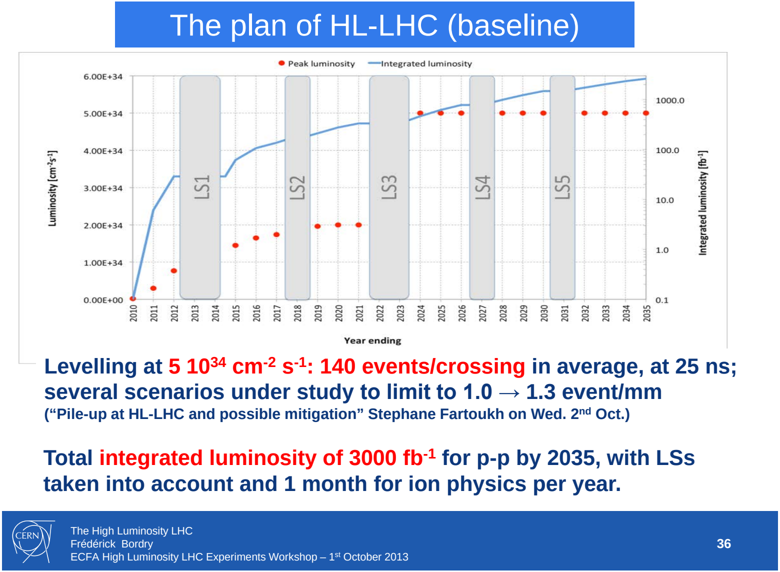
Upgrade Phase II – CMS

Federico Ferri for the CMS group

CSTS du SPP – November 13, 2013

- Introduction
- Overview of CMS Phase II upgrade
- Special guest: calorimetry, i.e. SPP-CMS plans for contributions

Introduction - LHC plans



The plan of HL-LHC (baseline)

Levelling at 5 10^{34} cm^{-2} s^{-1}: 140 events/crossing in average, at 25 ns; several scenarios under study to limit to 1.0 → 1.3 event/mm
(“Pile-up at HL-LHC and possible mitigation” Stephane Fartoukh on Wed. 2nd Oct.)

Total integrated luminosity of 3000 fb^{-1} for p-p by 2035, with LSs taken into account and 1 month for ion physics per year.

The High Luminosity LHC
Frédérick Bordry
ECFA High Luminosity LHC Experiments Workshop – 1st October 2013

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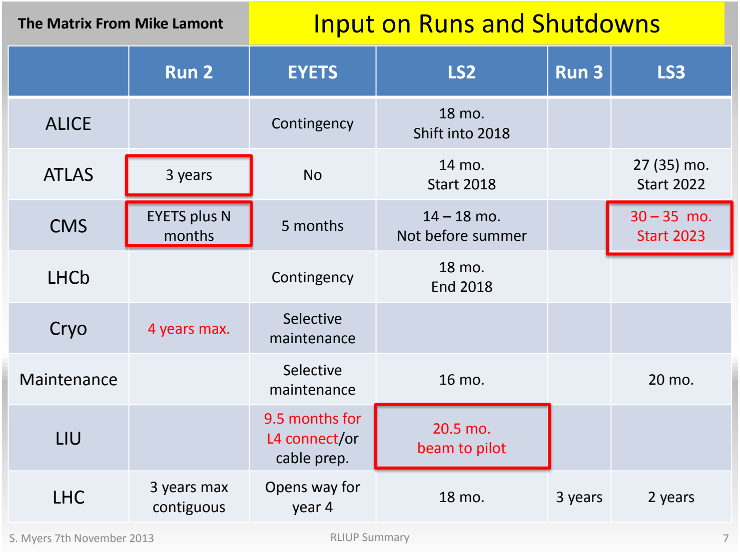
Introduction - LHC plans

Still conflicting requests

To make it “easy”: EYETS = End of Year Extended Technical Stop



The Matrix From Mike Lamont

Input on Runs and Shutdowns

	Run 2	EYETS	LS2	Run 3	LS3
ALICE		Contingency	18 mo. Shift into 2018		
ATLAS	3 years	No	14 mo. Start 2018		27 (35) mo. Start 2022
CMS	EYETS plus N months	5 months	14 – 18 mo. Not before summer		30 – 35 mo. Start 2023
LHCb		Contingency	18 mo. End 2018		
Cryo	4 years max.	Selective maintenance			
Maintenance		Selective maintenance	16 mo.		20 mo.
LIU		9.5 months for L4 connect/or cable prep.	20.5 mo. beam to pilot		
LHC	3 years max contiguous	Opens way for year 4	18 mo.	3 years	2 years

S. Myers 7th November 2013 RLIUP Summary 7

Introduction - LHC plans

Scenario 1 (S1)

LS2 (2018) lasts for 1.5 years, LS3 (2022) for 2 years

S2 = S1 delayed by 1 year

S3 = S2 delayed by 1 year

= S1 delayed by 2 years

Scenario 4 (S4)

LS2 (2018) lasts for 2 years, LS3 for 3 years

S5 = S4 delayed by 1 year

In 4 out of 5 scenarios LS3 starts already in 2023 or 2024. . .

	LS2=1.5y, LS3=2y			LS2=2.0y, LS3=3y	
Year	**S1**	**S2**	**S3**	**S4**	**S5**
2015	35	35	35	35	35
2016	50	50	50	50	50
2017	50	50	50	50	50
2018	🟨	50	50	🟨	50
2019	25	🟨	50	🟨	🟨
2020	60	25	🟨	25	🟨
2021	60	60	25	60	25
2022	🟨	60	60	60	60
2023	🟨	🟨	60	🟨	60
2024	150	🟨	🟨	🟨	🟨
2025	250	150	🟨	🟨	🟨
2026	250	250	150	150	🟨
2027	🟨	250	250	250	150
2028	200	🟨	250	250	250
2029	250	200	🟨	🟨	250
2030	250	250	200	200	🟨
2031	🟨	250	250	250	200
2032	200	🟨	250	250	250
2033	250	200	🟨	🟨	250
2034	250	250	200	200	🟨
2035	250	250	250	250	200
2036		250	250	250	250
2037			250	250	250
2038					250
Total	2580	2630	2680	2580	2630

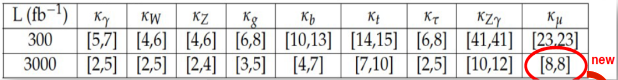
federico.ferri@cern.ch

Introduction - Non exhaustive physics case

Higgs physics

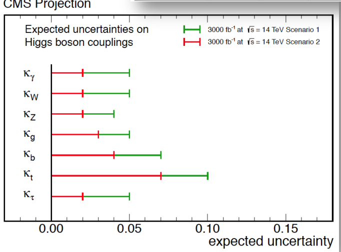
- Projections for Higgs couplings
  - 2-10% with HL-LHC
- Rare Higgs decays studied*
  - H → μμ at > 5σ with HL-LHC
- Low Mass Stops
  - Already with 300 fb^{-1}, discovery potential direct production mode up to ~900 GeV

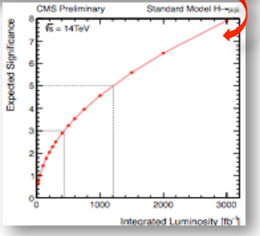
2-10% precision on Higgs couplings



L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

new



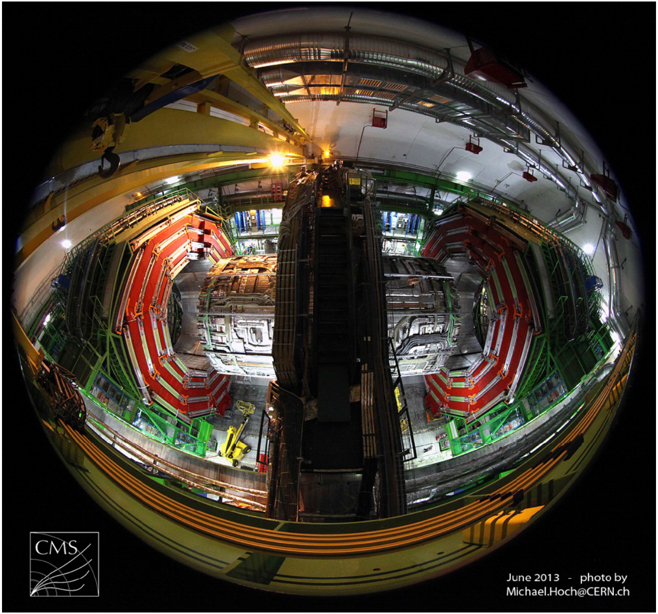


Introduction - Non exhaustive physics case

(Heavy) ions

- **Jets:** characterization of energy loss mechanism both as a testing ground for the multi-particle aspects of QCD and as a probe of the medium density
  - Differential studies of jets, b-jets, di-jets, γ/Z-jet at very high p_T (focus of **ATLAS** and **CMS**)
  - Flavour-dependent in-medium fragmentation functions (focus of **ALICE**)
- **Heavy flavour:** characterization of mass dependence of energy loss, HQ in-medium thermalization and hadronization, as a probe of the medium transport properties
  - Low-p_T production and elliptic flow of several HF hadron species (focus of **ALICE**)
  - B and b-jets (focus of **ATLAS** and **CMS**)
- **Quarkonium:** precision study of quarkonium dissociation pattern and regeneration, as probes of deconfinement and of the medium temperature
  - Low-p_T charmonia and elliptic flow (focus of **ALICE**)
  - Multi-differential studies of Υ states (focus of **ATLAS** and **CMS**)
- **Low-mass di-leptons:** thermal radiation γ (→ e^+e^-) to map temperature during system evolution; modification of ρ meson spectral function as a probe of the chiral symmetry restoration
  - (Very) low-p_T and low-mass di-electrons and di-muons (**ALICE**)

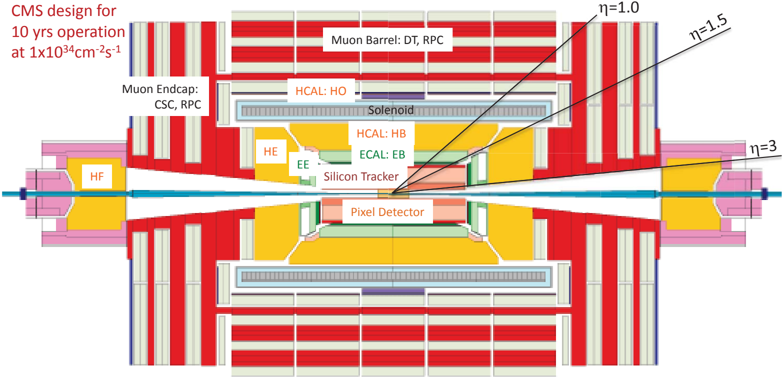
Introduction - CMS (right) now



June 2013 - photo by
Michael.Hoch@CERN.ch

federico.ferri@cern.ch

Introduction - CMS now



CMS design for 10 yrs operation at $1x10^{34}cm^{-2}s^{-1}$

Tracking

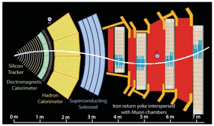
More than $220m^2$ surface and
76M channels (pixels & strips)
6m long, ~2.2m diameter
Tracking to |η|<2.4

Muon System

Muon tracking in the return field
Barrel: Drift Tube & Resistive Plate Chamb r
Endcap: Cathode Strip Chambers & RPCs

ECAL

Lead Tungstate ($PbWO^4$)
EB: 61K crystals, EE: 15K crystals



HCAL

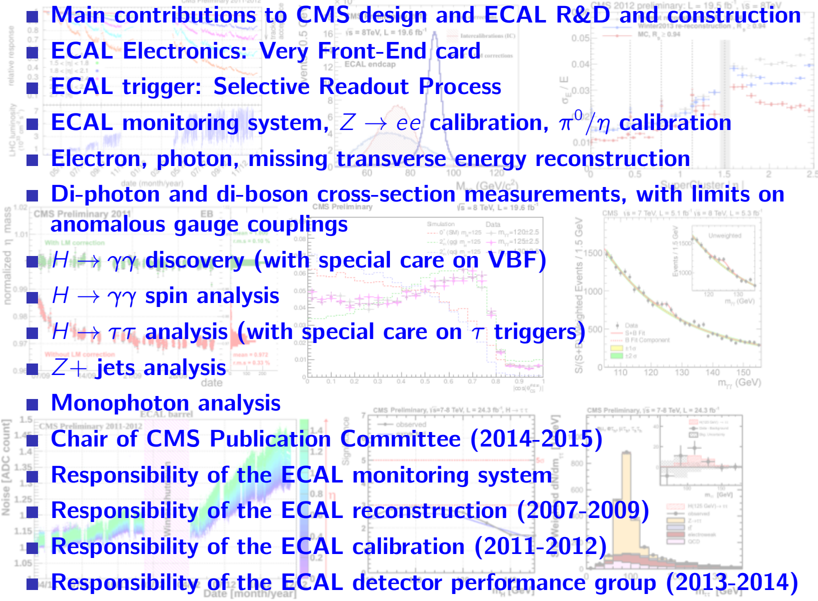
HB and HE: Brass/Plastic scintillator
Sampling calorimeter. Tiles and WLS fiber
HF: Steel/Quartz fiber Cerenkov calo.
HO: Plastic scintillator "tail catcher"

Trigger

Level 1 in hardware, 3.2μs latency ,100 kHz
ECAL+HCAL+Muon
HLT Processor Farm,1 kHz: Tracking , Full reco

federico.ferri@cern.ch

Introduction - CMS Saclay

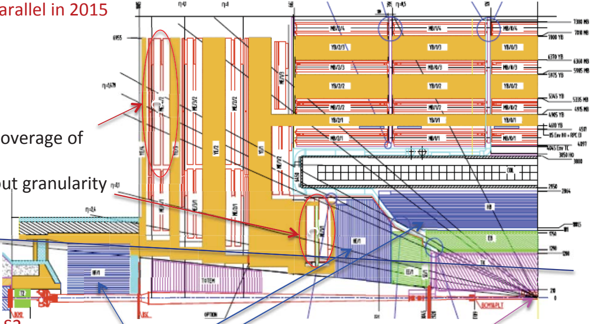


- **Main contributions to CMS design and ECAL R&D and construction**
- **ECAL Electronics: Very Front-End card**
- **ECAL trigger: Selective Readout Process**
- **ECAL monitoring system, $Z \to ee$ calibration, π^0/η calibration**
- **Electron, photon, missing transverse energy reconstruction**
- **Di-photon and di-boson cross-section measurements, with limits on anomalous gauge couplings**
- **$H \to \gamma\gamma$ discovery (with special care on VBF)**
- **$H \to \gamma\gamma$ spin analysis**
- **$H \to \tau\tau$ analysis (with special care on τ triggers)**
- **$Z+$ jets analysis**
- **Monophoton analysis**
- **Chair of CMS Publication Committee (2014-2015)**
- **Responsibility of the ECAL monitoring system**
- **Responsibility of the ECAL reconstruction (2007-2009)**
- **Responsibility of the ECAL calibration (2011-2012)**
- **Responsibility of the ECAL detector performance group (2013-2014)**
- **Responsibility of Monte Carlo for Standard Model group**

federico.ferri@cern.ch

Introduction - CMS Phase I upgrade

- No major changes foreseen till Phase II, besides the new Pixels
- Mainly maintenance and improvements in preparation for Phase II
- Electromagnetic calorimeter designed to work just fine up to the end of Phase I (300 fb^{-1})



Trigger/DAQ

→ New backend electronic systems

- Commission in parallel in 2015

Muon systems

→ Complete muon coverage of CSCs and RPCs

→ CSC higher read-out granularity

- during LS1

Forward proton spectrometer (PPS)

- staged from LS1 to LS2

Hadron calorimeters HF/HE/HB

→ Replace photo-detectors and read-out

- staged from LS1 to LS2

Pixel detector

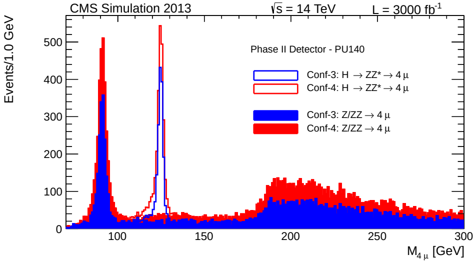
→ Full replacement

- EYETS in 2016-2017 (discussed)

General considerations for Phase II upgrades

- Define the minimal set of upgrades with the most cost-effective design
- Assumption: 300 fb^{-1} by the end of Phase I, 3000 fb^{-1} during Phase II

Maintain and possibly extend physics acceptance of key leptonic, photonics, trigger objects to keep it similar to 2012 (also for low-mass scale processes such as Higgs production)



- Trigger requirements driving most of the electronics upgrades
- Radiation sustainability is a must

Phase II: trigger

Goal: maintain the physics acceptances similar to the one in 2012

- add a **L1 tracking trigger** for identification of tracks associated with calorimeter and muon tracker objects
- use **finer granularity from calorimeter and muon triggers**: better isolation, p_T resolution, matching, topological precision
- **increase L1 rate, L1 latency, HLT output rate**

Strategy:

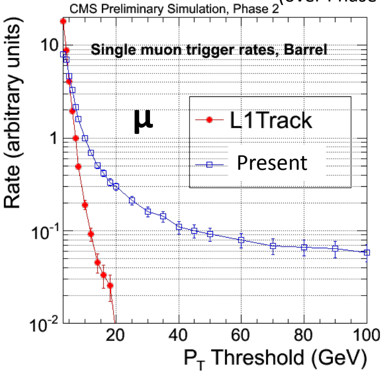
- **L1 rate**: 0.5 MHz with contingency of up to **1 MHz**
- L1 latency: 10 μsec (option to **20 μsec**) [now: 3.2 μsec up to 6.4 μsec]
  - current limitation is ECAL, otherwise up to 10 μsec already
- **Tracking trigger** + new calorimeter/muon/global trigger to use it
  - finer granularity for calorimetry
- **HLT** output rate: **10 kHz** (same reduction L1→HLT as present design)
  - DAQ HW & HLT processing compatible with Moore's law scaling until 2023

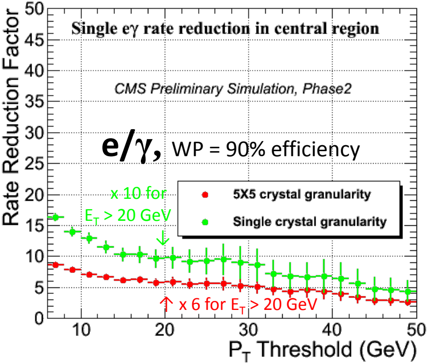
federico.ferri@cern.ch

Phase II: trigger

Example of reduction rates from L1 tracking informatio information (left) and single-crystal ECAL granularity (right)

(over Phase 1 Trigger, |η| < 1)





Matching Drift Tube trigger primitives with L1Tracks: **large rate reduction:**

> 10 at threshold > ~ 14 GeV.

Normalized to present trigger at 10 GeV.

Removes flattening at high P_t

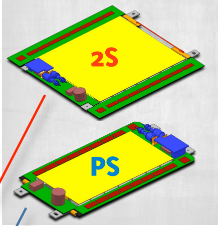
Rate reduction brought by matching L1 e/γ to L1Track stubs for | η | < 1.

Red: with current (5x5 xtal) L1Cal granularity.

Green : using single crystal-level position resolution improves matching

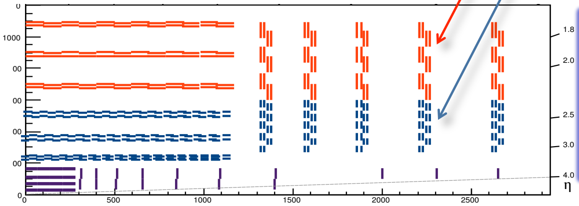
Phase II: tracker

- Higher granularity, less material
  - Track reconstruction at PU 140 and beyond
  - 2 sensor “Pt-modules” to provide L1 trigger information at 40 MHz for Pt≥2GeV
- Pixels: sensors 100 μm thick
  - Smaller pixels: ~30 x 100 μm
  - 4 barrel layers, 10 disks to cover up to |η| = 4
- R&D activities: All components
  - Sensors and readout electronics
  - Prototype of 2S modules ongoing
  - BE track-trigger with Associative Memories

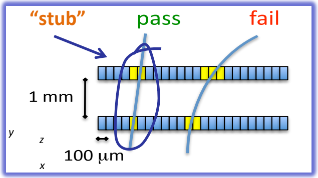


5 cm long strips (both sides)
90 μm pitch
P = 2.72 W
~ 92 cm^2 active area

2.4 cm long strips + pixels
100 μm pitch
P = 5.01 W
~ 44 cm^2 active area



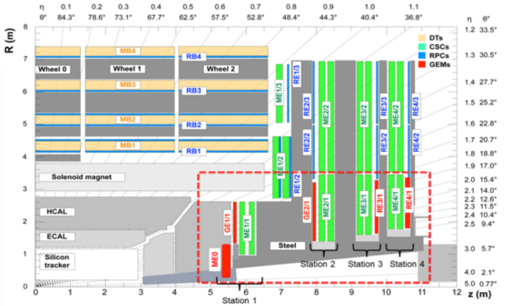
Trigger track selection in FE



Phase II: muons

- Performance, redundancy in high rate, high PU region
  - Completion of muon stations at 1.6 < |η| < 2.4 under study
    - GEMs 1st 2 stations (Pt resolution) Glass-RPC last 2 (timing to cut background)
  - Investigating coverage beyond |η| < 2.4

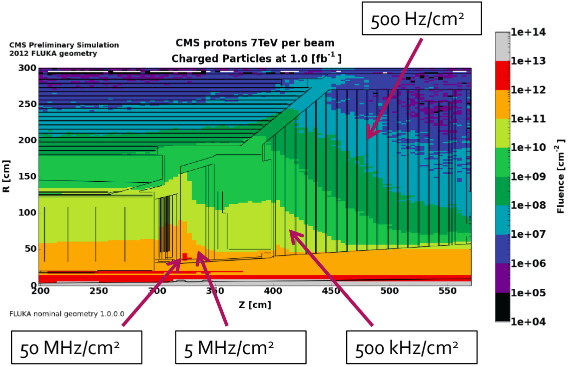
    GEM tagging station coupled with extended pixel tracking
- R&D activities well underway
  - GEM and Glass-RPCs
    - *Preparing demonstrator slice for GE1/1 (GEM), for 2016-17 YETs.*
    - *Desirable to install GE1/1 in LS2 for early operational experience and fake muon rejection in trigger*



Phase II: calorimetry

- **ECAL barrel crystals still fine up to 3000 fb^{-1}!**
- **ECAL electronics need replacement to comply with trigger requirements**
  - 1 MHz L1 + 20 μsec latency
- HCAL barrel also fine (photo-detectors and readout replaced in Phase I)

- At $5 \cdot 10^{34}$ we get 1 fb^{-1} in 5.5 hours!
- **Forward calorimetry to be replaced (both ECAL and HCAL)**



500 Hz/cm²

50 MHz/cm²

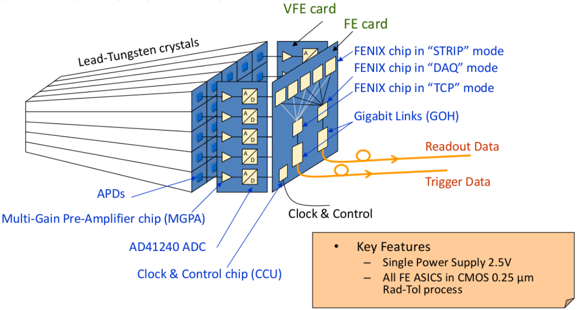
5 MHz/cm²

500 kHz/cm²

Current ECAL barrel electronics

Rate limitation:
200 kHz (FE)

Latency limitation:
6.4 μsec
(nominal 3.2 μsec)



- Key Features
  - Single Power Supply 2.5V
  - All FE ASICS in CMOS 0.25 µm Rad-Tol process

- signal from the 2 APD per crystals (analog OR)
  → MotherBoards
  → Very Front-End cards (VFE)
  → Front-End cards (FE)
- the MB distribute HV to APDs, LV to the VFE, signals to the VFE
- the VFE contains a 3 gains pre-amp/shaper and a 4-channel 12-bit ADC
- the FE collects data from VFE, calculates and sends trigger information (5 × 5 crystal granularity), stores data waiting for L1-accept, sends data on L1-accept
- the Low-Voltage Regulator card (LVR) regulates LV to 2.5 and 5 V, pass it to FE, and to VFE via the MB

Phase II: ECAL barrel electronics

Challenges:

- **age**: 20/30 years old at the HL-LHC start/end
- **noise**: expected increase of APD leakage current (parallel noise)
  - reconsider shaping time
  - reconsider signal dynamics, quantization step
- **pileup**: 140 pileup events at each crossing (in time pileup)
  - 140 pileup events from each previous crossing (OOT pileup)
- **APD** direct ionization ("**spikes**")
  - ≈ 1 per crossing at a luminosity of 5×10^{34}

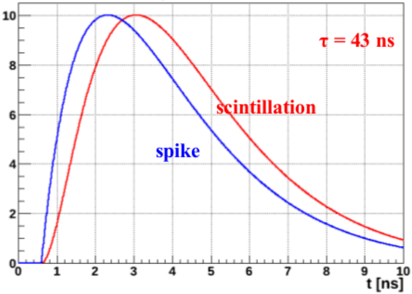
Strategy:

- **change of FE mandatory** to comply with trigger requirements
- profit from the super-module opening and **also change the VFE**
  - $15 - 20\%$ budget increase
- **change the off-detector electronics** (limited at 140 kHz) to comply with the trigger requirements and move to single crystal granularity at L1/HLT: trigger + Selective Readout Process, event builder, clock distribution [switch to μTCA]
  - also adapt the monitoring system
  - in collaboration with French groups (Lyon, LLR)
- **mechanical (severe) constraints** prevent from going further than VFE, e.g. no changes in APD readout are possible

Phase II: ECAL Very Front-End boards

- **Shaping time** from 43 ns to 21 ns:
  - noise reduction by as much as $\approx 30\%$ at 3000 fb^{-1}
  - factor of 2 reduction of OOT pileup tail
- **Dynamics** in the range 100 MeV to 2 TeV (14 bits)
  - 2×12 bits range: 100 MeV $\rightarrow$ 400 GeV, 500 MeV $\rightarrow$ 2 TeV ($\sigma_Q = 140$ MeV)

- Spike features, from direct APD ionization (no scintillation):
  - Dirac pulses
  - earlier timing
- **Tag spikes at early stages**:
  - inside the preamplifier (rising edge, pulse width before shaping)
  - after digitization (rising edge, maximum position …oversampling?)



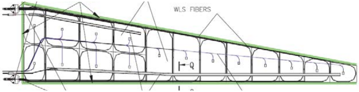
Also look at other developments in CMS (e.g. QIE10 for HCAL: no shaping) and evaluate modifications to suite the ECAL needs.

Phase II: forward calorimetry

Two approaches

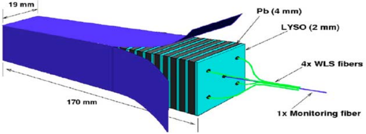
a) Maintain standard tower geometry - develop radiation tolerant solutions for EE and HE to deliver the necessary performance to 3000 fb^{-1}

- Build EE towers in eg. Shashlik design (crystal scintillator: LYSO, CeF)
- Rebuild HE with more fibers, rad-hard scintillators



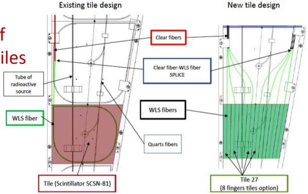
EE

- Rad tolerant WLS fibers (capillaries under development)
- Rad tolerant GaInP “SiPMs” (or fibers to high radius)



HE

- Development of radiation hard tiles



b) Study alternative geometry/concepts with potential for improved performance and/or lower cost. Two concepts under consideration

- Dual fiber read-out: scintillation & Cerenkov (DROC) – following work of DREAM/RD52
  - using doped/crystal fibers - allows e/h correction for improved resolution
- Particle Flow Calorimeter (PFCAL) – following work of CALICE
  - using GEM/Micromegas – fine transverse & longitudinal segmentation to measure shower topology

federico.ferri@cern.ch

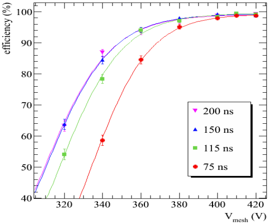
Phase II: forward calorimetry - ANR 1

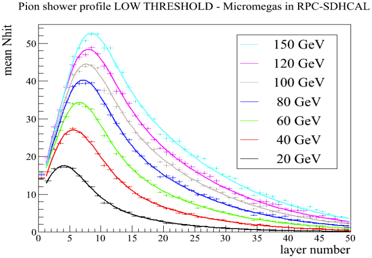
Sampling Calorimeter with Resistive Anode Micro-Megas for CMS (HL-LHC) and LC

State of the art:

LAPP Annecy Development:

- Semi-digital: 3 readout thresholds to improve energy resolution w.r.t. pure digital
- Large area prototype of 1x1 m^2 :
  → 6 Bulk PCBs with embedded MICROROC ASICs
  → 4 chambers with pad size of 1cm^2
- Integrated into a 50-layer calorimeter at CERN
  → Measured longitudinal profiles
  → Efficiency, response and linearity

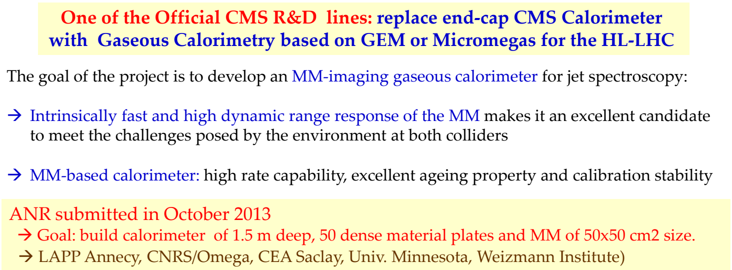




Phase II: forward calorimetry - ANR 1

Sampling Calorimeter with Resistive Anode Micro-Megas for CMS (HL-LHC) and LC

ANR request: 270 k€ (≈ 70-80 k€ for Irfu) all material



One of the Official CMS R&D lines: replace end-cap CMS Calorimeter with Gaseous Calorimetry based on GEM or Micromegas for the HL-LHC

The goal of the project is to develop an MM-imaging gaseous calorimeter for jet spectroscopy:

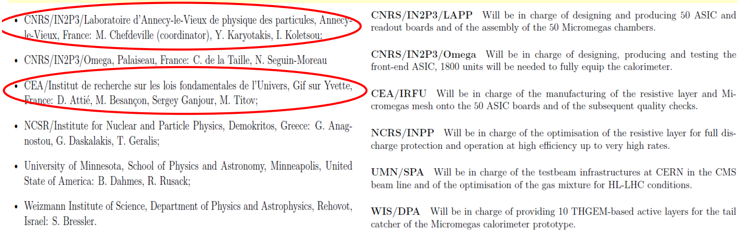
→ Intrinsically fast and high dynamic range response of the MM makes it an excellent candidate to meet the challenges posed by the environment at both colliders

→ MM-based calorimeter: high rate capability, excellent ageing property and calibration stability

ANR submitted in October 2013

→ Goal: build calorimeter of 1.5 m deep, 50 dense material plates and MM of 50x50 cm2 size.

→ LAPP Annecy, CNRS/Omega, CEA Saclay, Univ. Minnesota, Weizmann Institute)



- CNRS/IN2P3/Laboratoire d'Annecy-le-Vieux de physique des particules, Annecy-le-Vieux, France: M. Chefdeville (coordinator), Y. Karyotakis, I. Koletsou;
- CNRS/IN2P3/Omega, Palaiseau, France: C. de la Taille, N. Seguin-Moreau
- CEA/Institut de recherche sur les lois fondamentales de l'Univers, Gif sur Yvette, France: D. Attié, M. Besançon, Sergey Ganjour, M. Titov;
- NCSR/Institute for Nuclear and Particle Physics, Demokritos, Greece: G. Anagnostou, G. Daskalakis, T. Geralis;
- University of Minnesota, School of Physics and Astronomy, Minneapolis, United State of America: B. Dahmes, R. Rusack;
- Weizmann Institute of Science, Department of Physics and Astrophysics, Rehovot, Israel: S. Bressler.

CNRS/IN2P3/LAPP Will be in charge of designing and producing 50 ASIC and readout boards and of the assembly of the 50 Micromegas chambers.

CNRS/IN2P3/Omega Will be in charge of designing, producing and testing the front-end ASIC, 1800 units will be needed to fully equip the calorimeter.

CEA/IRFU Will be in charge of the manufacturing of the resistive layer and Micromegas mesh onto the 50 ASIC boards and of the subsequent quality checks.

NCRS/INPP Will be in charge of the optimisation of the resistive layer for full discharge protection and operation at high efficiency up to very high rates.

UMN/SPA Will be in charge of the testbeam infrastructures at CERN in the CMS beam line and of the optimisation of the gas mixture for HL-LHC conditions.

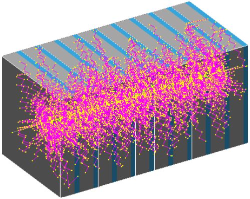
WIS/DPA Will be in charge of providing 10 THGEM-based active layers for the tail catcher of the Micromegas calorimeter prototype.

Phase II: forward calorimetry - ANR 2 (jeune)

Water Čerenkov Sampling Calorimeter for HEP

Design:

- `Pb` or `W` absorber
- water as active Čerenkov layer
  - very fast detector (vertexing and p-flow)
- Quantum-Dots as wavelength shifters
  - efficient and versatile
- several readout options:
  - Shashlik, single layer readout, new rad-hard photodetectors . . .



ANR request: ≈ 50 k€ of material + one 2-years post-doc.

Planning:

- Phase I: QD caracterization, dissolution tests (homogeneity, segregation)
- Phase II: prototype with variable active-layer thickness, optimization of QD concentration, photodetector studies, simulation
- Phase III: prototype with sampling calorimeter of 20 radiation lengths
- Phase IV: study of calorimeter for the CMS forward region

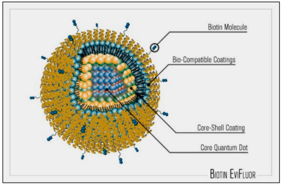
federico.ferri@cern.ch

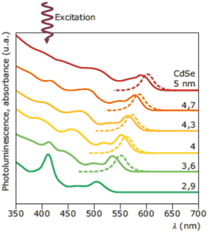
Phase II: forward calorimetry - ANR 2 (jeune)

Water Čerenkov Sampling Calorimeter for HEP

- Need a wavelength shifter to optimise the Čerenkov light collection and minimise the active layer thickness
  - Čerenkov spectrum $\sim \frac{1}{\lambda^2} \Rightarrow$ high collection at low λ, e.g. UV band
  - wavelength shift to be tuned to photodetector efficiency

- Nanocrystals composed of inorganic semiconducting materials (CdSE, InGaP, C, Si) with confined pairs of electron- and electron-hole
- Wide absorption spectrum
- Emission in few ns with a tunable wavelength proportional to the QD size
- Very low concentration to be used (few nanomole / litre)
- Widely used in solar cell optimisation, biology, electronics and optoelectronics, . . .



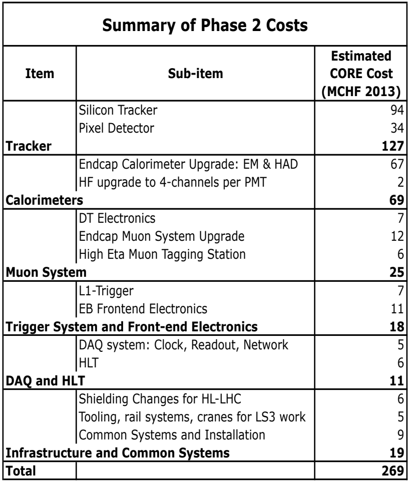


federico.ferri@cern.ch

Cost exercise

- Used reasonable assumptions
  - Materials, channel counts, etc.

    No contingency included
- Breakdown of costs
  - Replacement of radiation damaged detectors ~ 75%
  - Retaining performance in very high pileup environment ~ 15%
  - Extending coverage < 10%
- Staging under study
  - Options are limited



Summary of Phase 2 Costs

Item	**Sub-item**	**Estimated CORE Cost (MCHF 2013)**
	Silicon Tracker	94
	Pixel Detector	34
Tracker		**127**
	Endcap Calorimeter Upgrade: EM & HAD	67
	HF upgrade to 4-channels per PMT	2
Calorimeters		**69**
	DT Electronics	7
	Endcap Muon System Upgrade	12
	High Eta Muon Tagging Station	6
Muon System		**25**
	L1-Trigger	7
	EB Frontend Electronics	11
Trigger System and Front-end Electronics		**18**
	DAQ system: Clock, Readout, Network	5
	HLT	6
DAQ and HLT		**11**
	Shielding Changes for HL-LHC	6
	Tooling, rail systems, cranes for LS3 work	5
	Common Systems and Installation	9
Infrastructure and Common Systems		**19**
Total		**269**

N.B. Total CMS costs for Phase I is 65 MCHF, fully covered already.

Outlook

- **ECAL designed for no upgrades in Phase I (300 fb^{-1})**
- **Time schedule till LS3 far from being definite**
  - conflicting requests
  - very likely at least one year of delay, i.e. from 2022 to 2023
  - R&D opportunity: no need to freeze design upgrades at this stage
- Phase II: **ECAL barrel electronics upgrade**
  - excellent expertise at Irfu (SPP & SEDI), mutual interests matched
    - digital electronics: TRAPS, LILA (trigger and Selective Readout); analogue electronics LDEF (VFE)
  - can bring significant improvements w.r.t. current electronics
- Phase II: **forward calorimetry upgrade** → two ANRs submitted
  - consolidated technology at Irfu, collaborative effort
  - innovative concept of calorimetry, affordable price
  - evaluate the best path during the forthcoming months
  - no need to rush decisions at this stage
- **Exciting program of *pp* and ion physics ahead of us**

federico.ferri@cern.ch