CMS Upgrades

Aldo Penzo, INFN
(on behalf of CMS)

LHC: On a fast track! initial → Standard → SUPER

[Luminosity (cm^{-2} s^{-1}): 10^{32} → 10^{34} → 10^{35}]

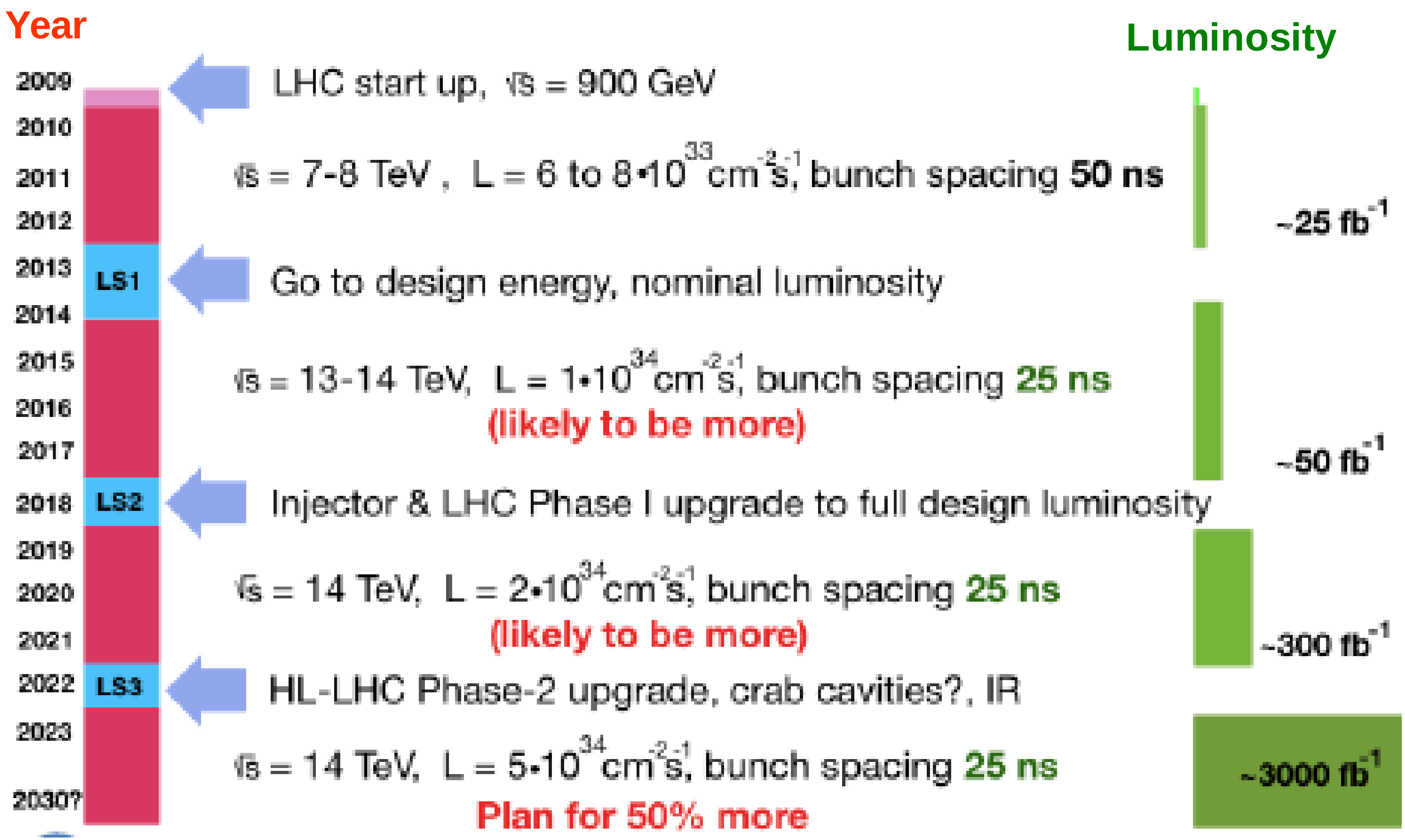
Experiments: *All you can eat!*

[$15x10^6$ gigabytes of data annually]

Soon will hit limits: PU, DAQ, RD…

Need MAINTENANCE and UPGRADE

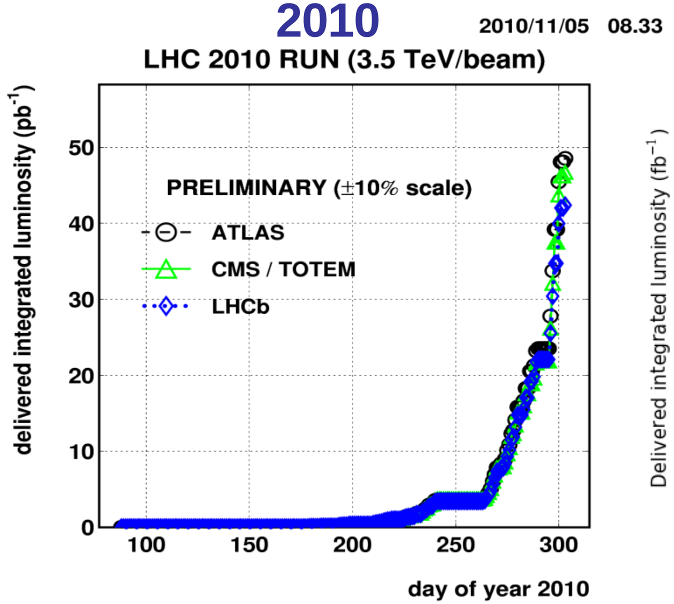
LHC Timeline



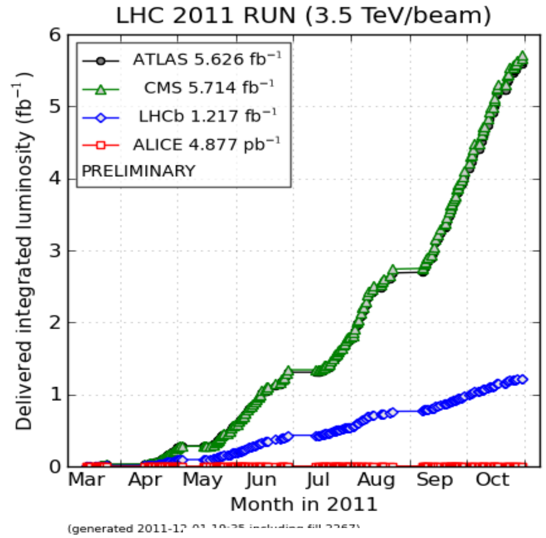
- See previous speaker: Stephen Hillier

LHC startup

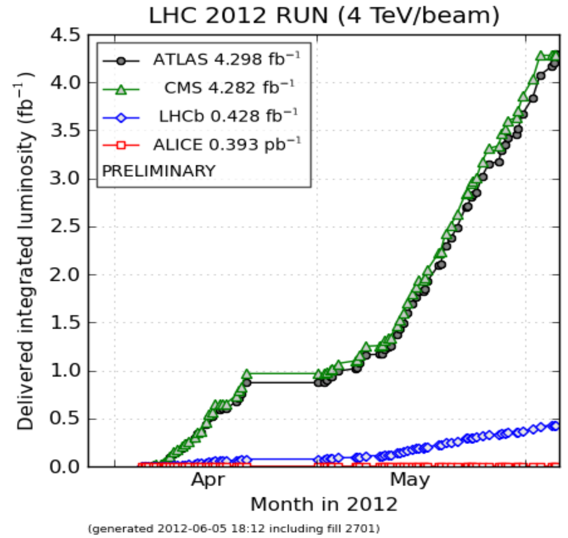
2010



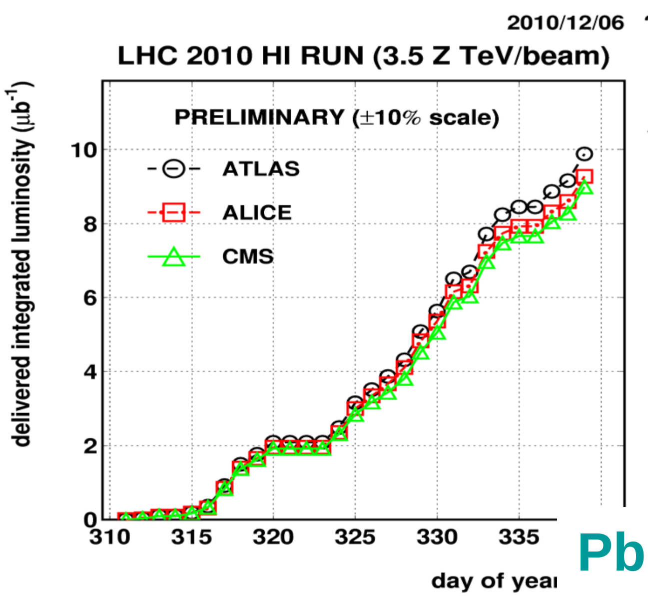
2011

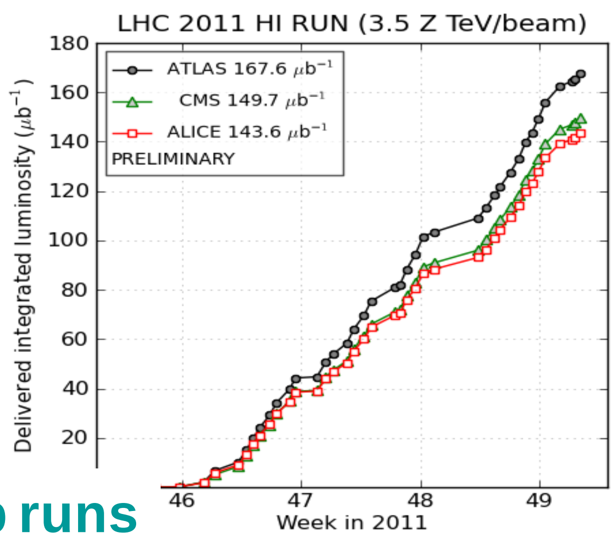


2012



pp runs

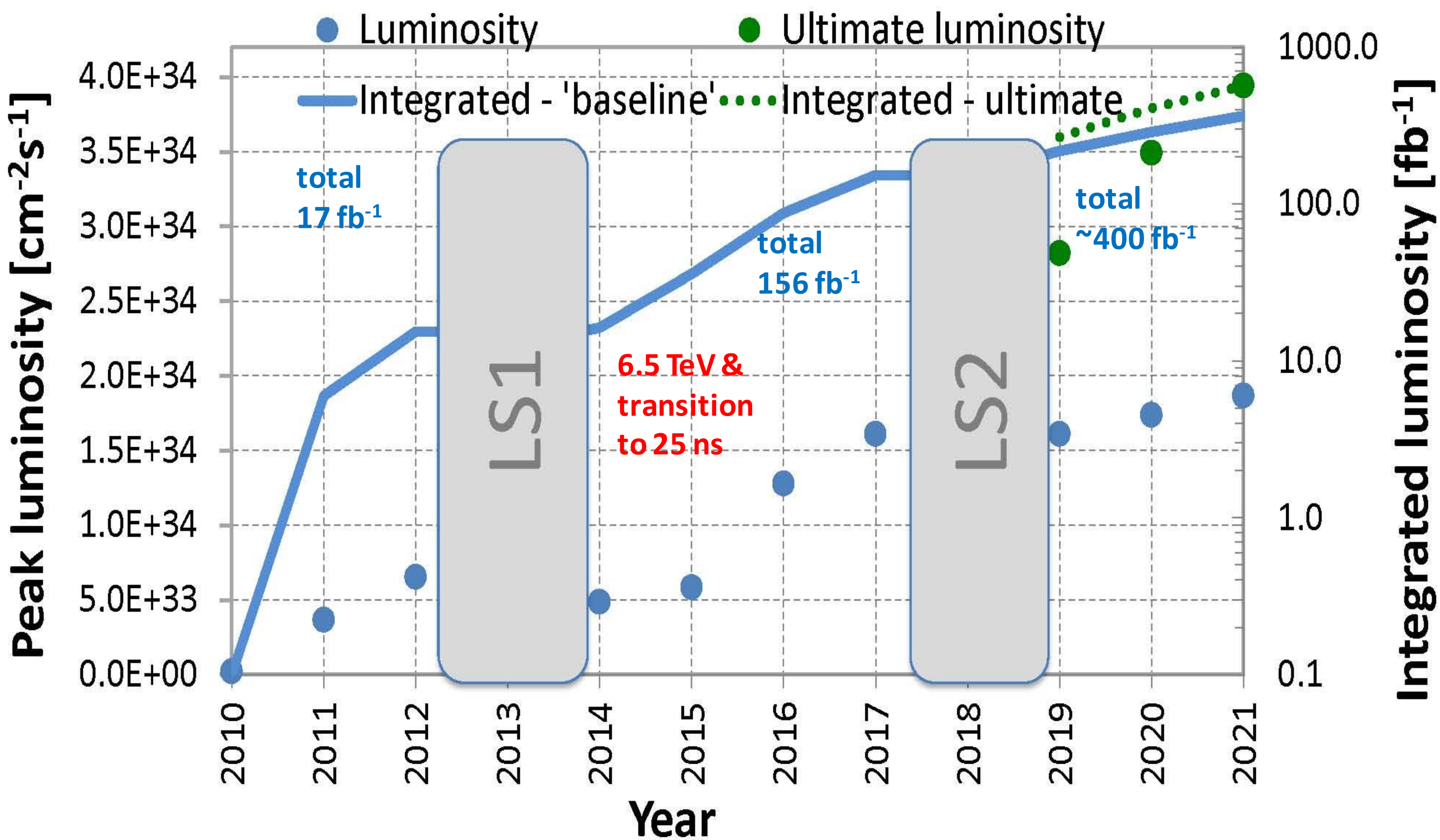




Pb runs

Both proton and lead runs have successfully started in 2010 and the experiments are aiming at collecting a sizeable amount of data before the first long shutdown

LHC Luminosity progress



In the next stage (HL-LHC) the machine should be capable of delivering 1E35cm^{-2}s^{-1}, operated with luminosity-leveling at a steady 5E34, and delivering a total of 3000fb-1. The start of HL-LHC is usually expected at the third LHC long shutdown (LS3); by that time something like 500fb^{-1} should have been accumulated…

LHC beam parameters

	design	October 2011	end 2012 ?	2016 ??
Beam energy	7 TeV	**3.5 TeV**	**4 TeV**	**6.5 TeV**
transv. norm. emittance	3.75 μm	**2.5 μm**	**2.5 μm**	**3.5 μm**
beta*	0.55 m	1.0 m	0.7 m	0.5 m
IP beam size	16.7 μm	24 μm	19 μm	17 μm
bunch intensity	1.15×10^{11}	**1.5×10^{11}**	**1.6×10^{11}**	**1.2×10^{11}**
# colliding bunches	2808	1331	1350	2800
bunch spacing	25 ns	**50 ns**	**50 ns**	25 ns
beam current	0.582 A	0.335 A	0.388 A	0.604 A
rms bunch length	7.55 cm	9 cm	9 cm	7.6 cm
full crossing angle	285 μrad	240 μrad	240 μrad	260 μrad
"Piwinski angle"	0.64	0.37	0.51	0.61
peak luminosity [$cm^{-2}s^{-1}$]	10^{34}	**3.6×10^{33}**	**7.4×10^{33}**	**1.3×10^{34}**
average peak pile up*	25	**18**	**36**	**30**

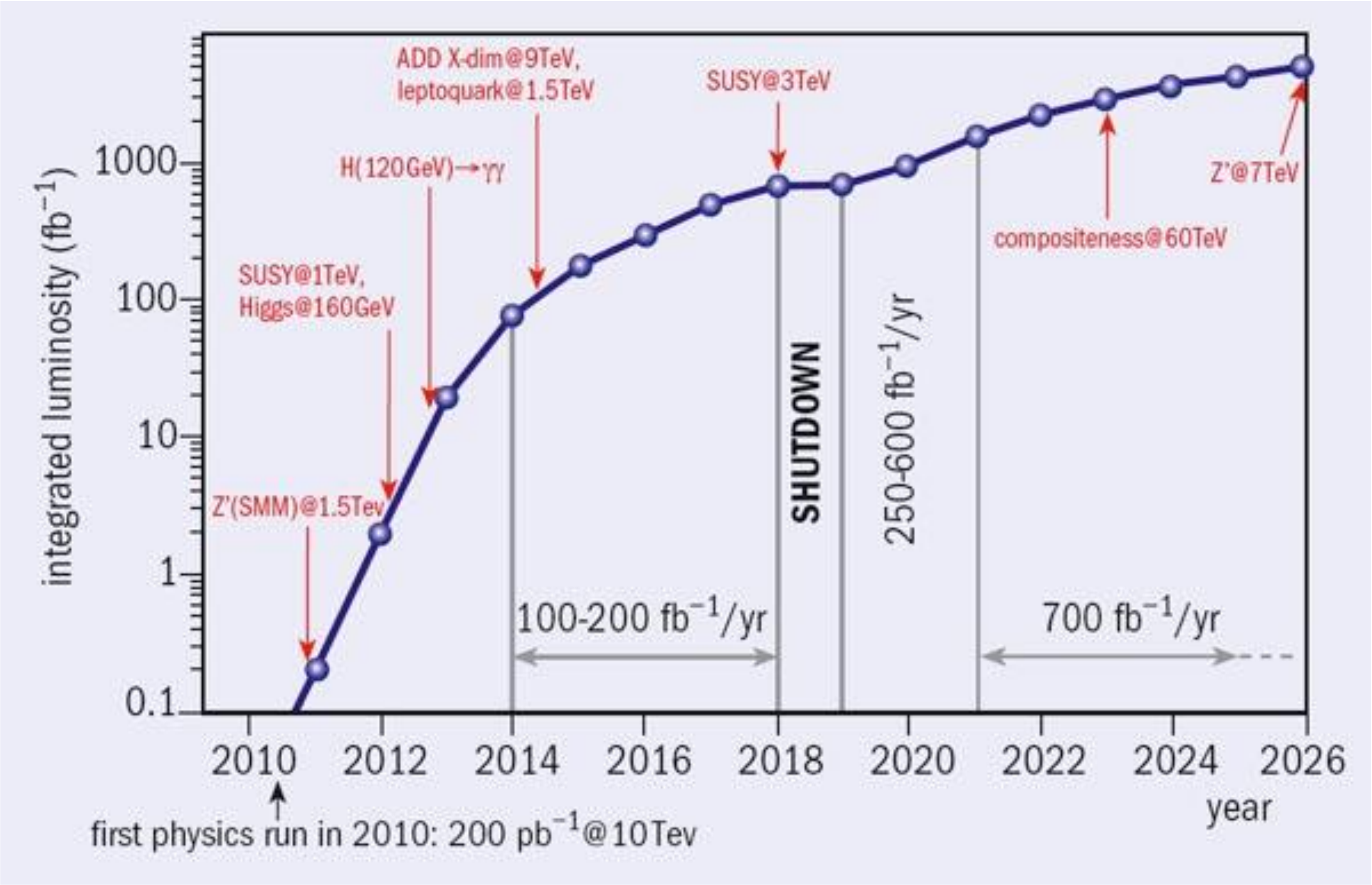
(* with σ ~ 80 mbarn)

Overall LHC Injector Upgrade Planning

	Linac4	PS injector, PS and SPS	Beam characteristics at LHC injection
2011 - 2012	Continuation of construction…	• Beam studies § simulations • Investigation of RCS option • Hardware prototyping • Design § construct equipment • TDR	25 ns, 1.2 10^{11}p/b, ~2.5 mm.mrad 50 ns, 1.7 10^{11}p/b, ~2.2 mm.mrad 75 ns, 1.2 10^{11} p/b, $\leq$ 2 mm.mrad
2013 – 2014 (Long Shutdown 1)	• **Linac4 beam commissioning** • **Connection to PSB ?**	• PSB modification (H^- injection)? • PSB beam commissioning ? • Modifications and installation of prototypes in PS and SPS	
2015 - 2017	• Progressive increase of Linac4 beam current	• If Linac4 connected: increase PSB brightness progressively • Some improvement of PS beam (Injection still at 1.4 GeV) • Design & construction for PS injector, PS and SPS • Beam studies	• Limited gain at LHC injection (pending PSB (or RCS), PS and SPS hardware upgrades)
2018 (Long Shutdown 2)		• **Extensive installations in PS injector, PS and SPS** • **Beam commissioning**	
2019 –2021			**After ~1 year of operation: beam characteristics for HL-LHC…**

(R. Garoby, 24 June 2011)

Luminosity vs Physics



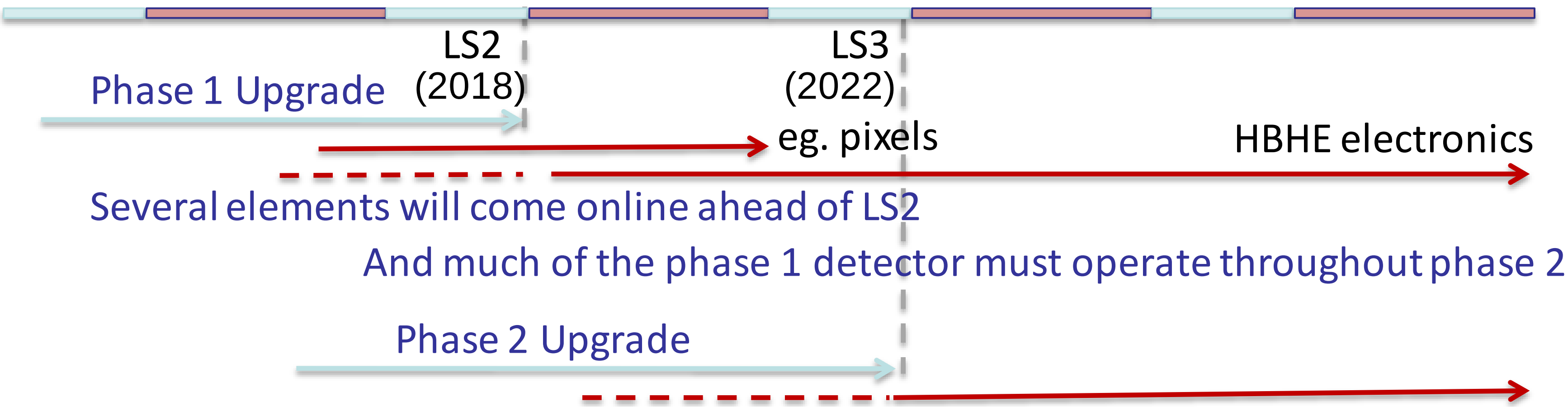
- D. Denegri, Mugla (2005)

CMS Upgrade Strategy

- *Expect an almost continuous multi-step increase in LHC performance, through a series of running periods and shutdowns*
- *CMS need to follow the LHC progress and long term schedule in order to plan and implement interventions on the detector*
- *Taking place concurrently with operations and analysis, upgrades represent extra strain on budget/manpower*
- *Clear – cut priorities:*
- *Data taking and analysis → Physics*
- *Excellent standard of performance*
- *Compelling Physics Case*
- *Enabling Technologies*

Upgrade Planning

CMS Phase 1 and Phase 2

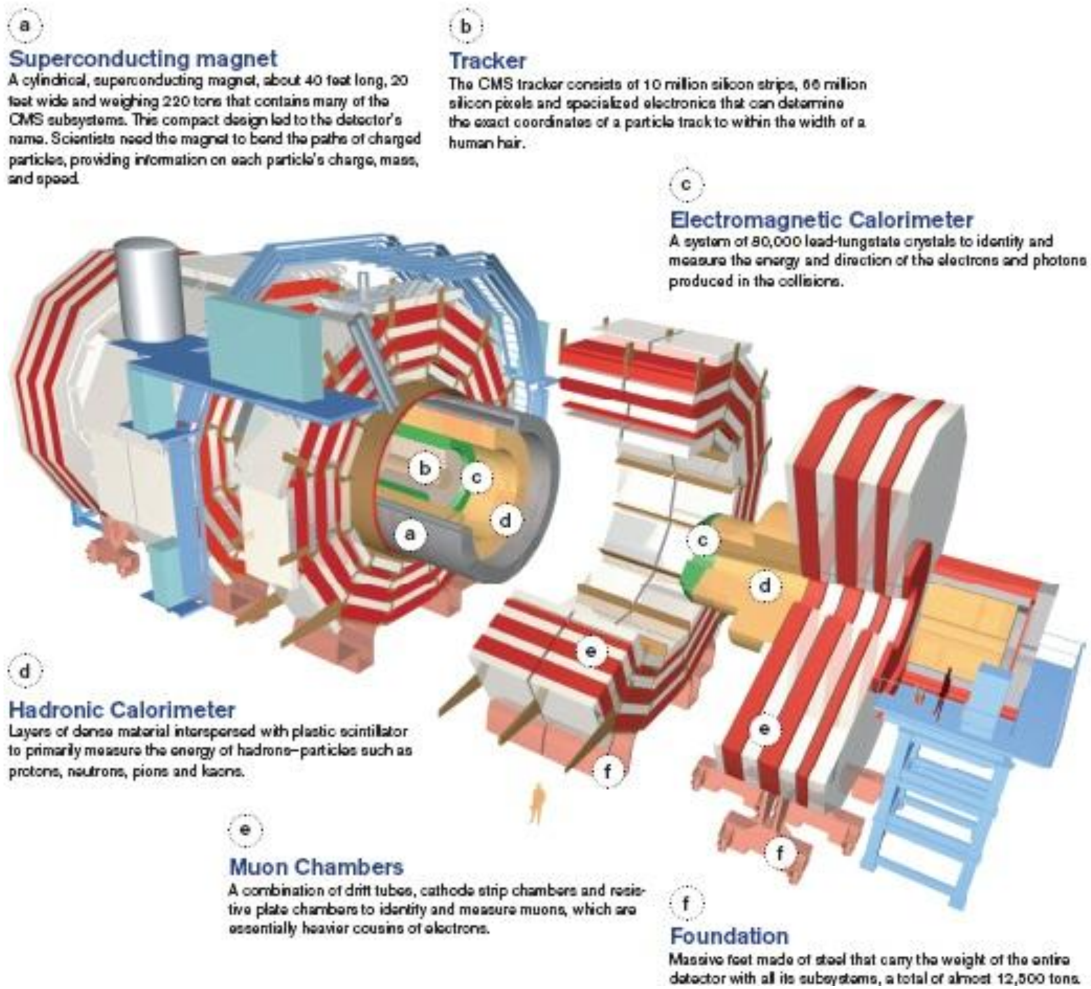


Several original systems will be part of Phase 2 detector. Must predict aging well

- *The CMS Upgrade Program is based on the scope of Phase 1 and Phase 2 outlined in the Technical Proposal (2010)*
- *This two-phase approach is needed for planning and funding, but real life may not be so clear-cut.*

The next 10 years to Phase 2 will not be like the construction period – the ongoing program is itself a major “distraction”

Main parts of CMS

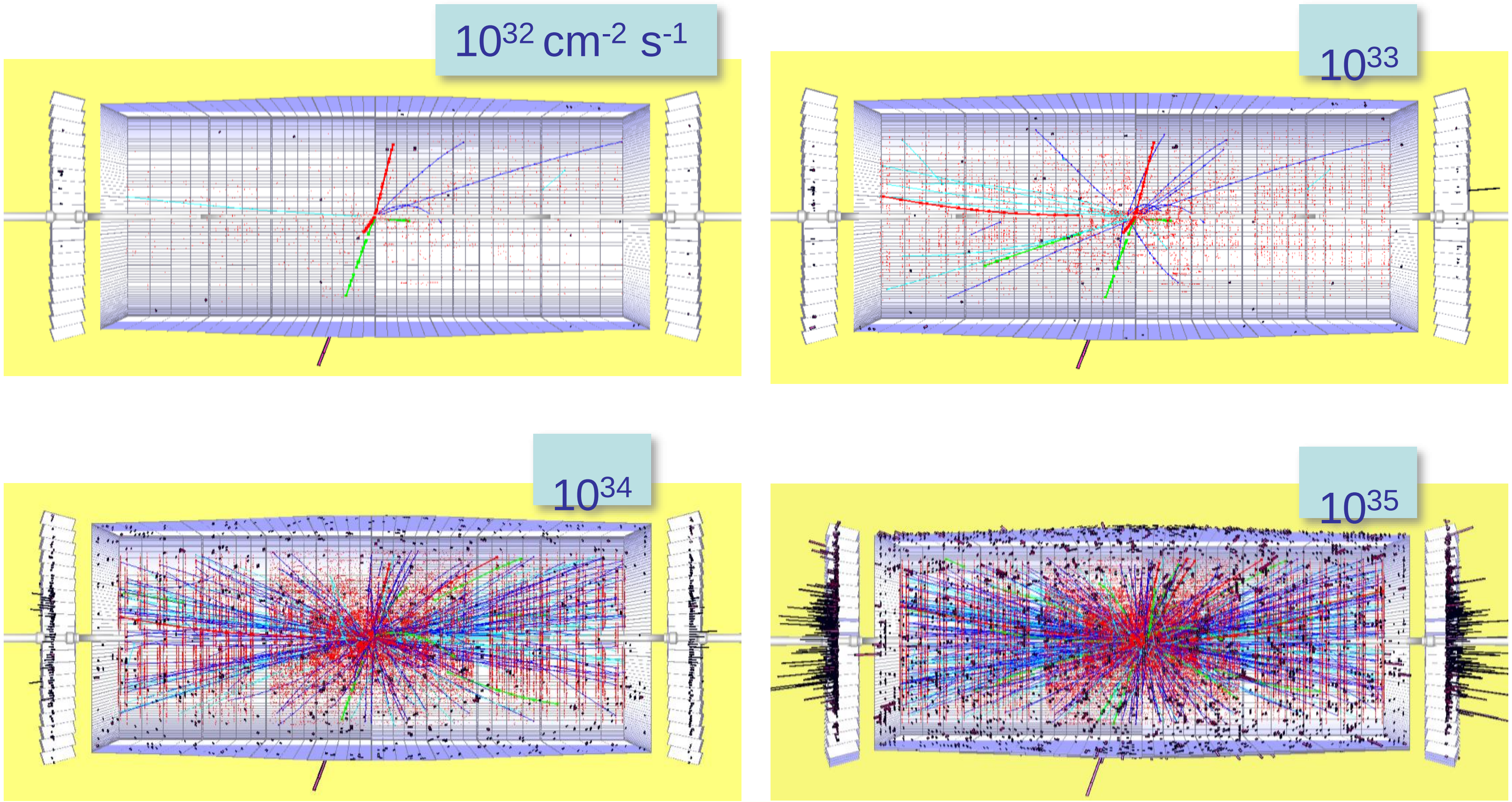


Upgrade Projects

- ***Tracker***
  - ***Pixel phase 1***
  - ***Tracker phase 2***
- ***Calorimeters***
  - ***ECAL - HCAL***
  - ***DT - CSC - RPC***
- ***L1 Trigger***
- ***DAQ***
- ***Infrastructures***

About CMS status and present performances see Daniel Teyssier

Activity in CMS vs Luminosity



- *Events' pile-up represents limit to maximum luminosity*

CMS Upgrade Plans

– Phase 1

- 2013: Smaller diameter beampipe
- 2013: HO replacement of HPDs with SiPMs
- 2013: HF photo-detectors
- 2013: ME1/1 CSC Electronics
- 2013: ME4/2 CSC Chambers
- 2013: ME4/2 RPC Chambers
- 2016: Calorimeter Trigger
- 2016: Muon Track Finder Trigger
- 2016: Global Trigger
- 2016: HB/HE photo-detectors and readout electronics
- 2016: Pixel Detector with 4 Layers and smaller mass

– Phase 2

- 2020: New Tracker
- 2020: New Forward Calorimeters (ECAL & HCAL)

Why

Prep for pixel upgrade

Remediation

Remediation

Remediation

Recover coverage

Recover coverage

Improved performance

Improved performance

Improved performance

Remediation

Improved performance

Remediation/Improvement

Remediation

Tracker and Pixels

New Tracker being designed with:

- *Higher granularity*
- *Enhanced radiation hardness*
- *Improved Tracking performance*

- *L1 Track finding capability*
- *Reconstruct tracks above ~ 2.5 GeV*
- *With ~ 1mm z- resolution*

- ***Draft schedule for delivery in LS3***

Pixel upgrades in 2 phases:

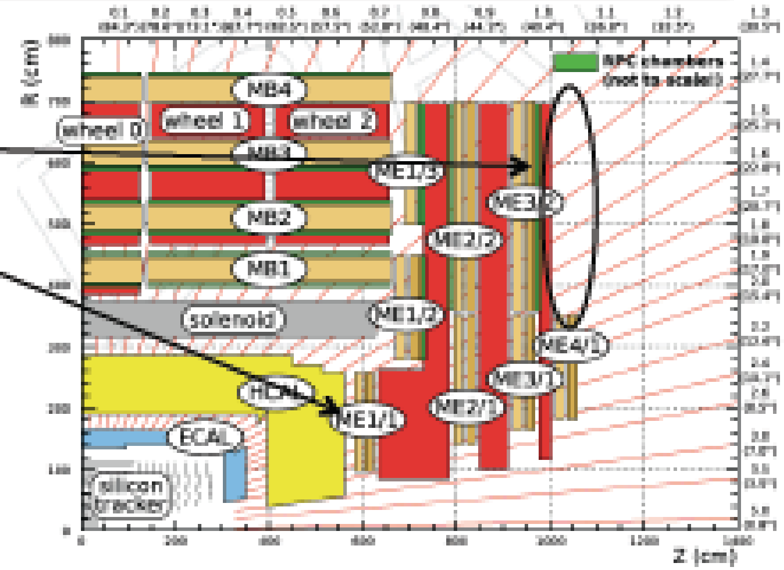
- *2016: Pixel with 4 Layers and smaller mass*
- *The inner layer of Phase 1 Pixel detector exposed to very high level of irradiation. (Lifetime < 2 years at luminosity L=200 fb^{-1})*

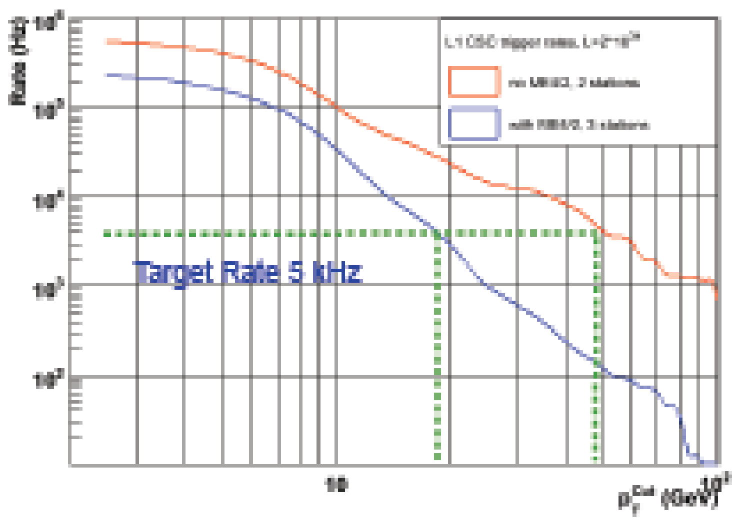
Muon System

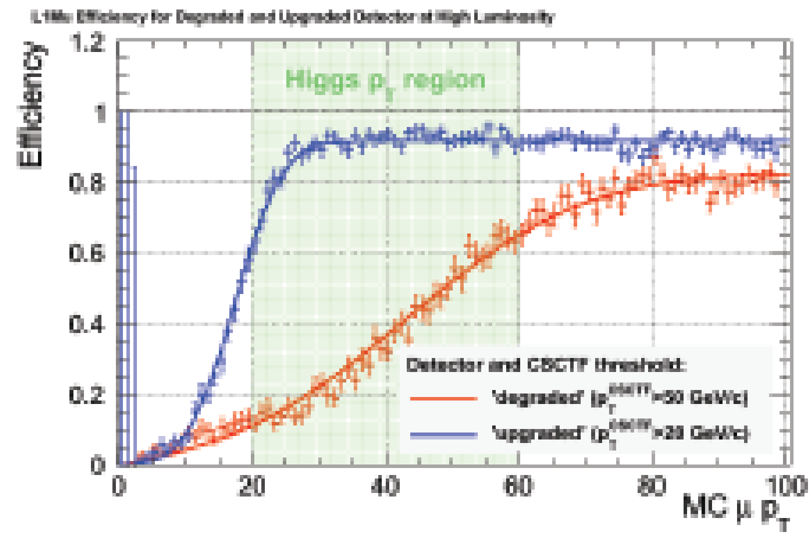
LS1 Muon Upgrade Highligths

New features

- CSC and RPC: ME4/2 (1.25< | η | <1.8)
  - → More hits - improved precision
- CSC: M1/1 (2.1< | η | <2.4) new digital boards and trigger cards
  - → Higher granularity – improved precision
- DT new trigger readout board and relocation of sector collector from UXC55 to USC55







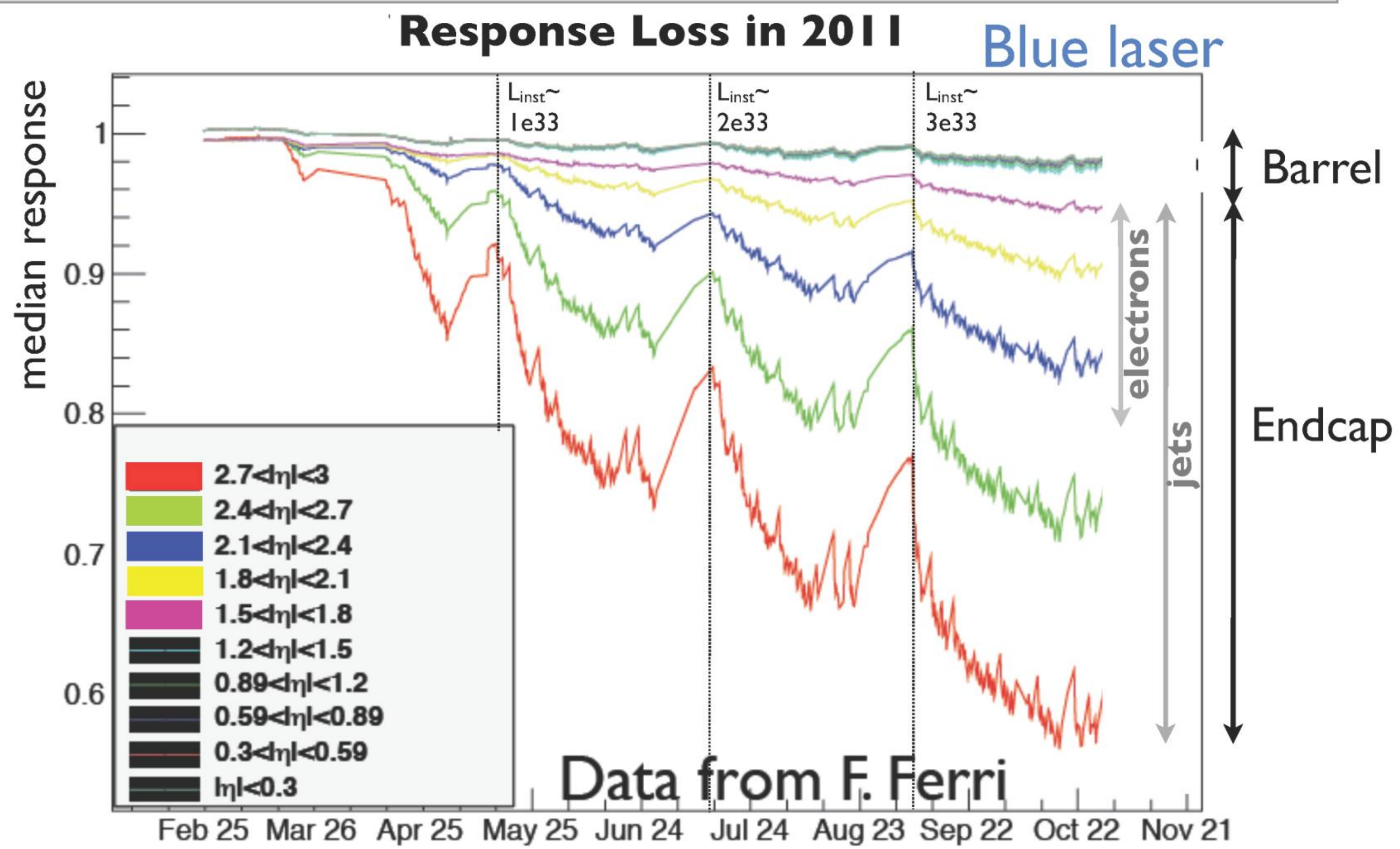
Electromagnetic Calorimeters

- **Performance of ECAL may be degraded due to radiation damage**
  - Crystal transparency losses
    - Electromagnetic damage: fast partial recovery at room temperature; full recovery at ~200°C; dominates crystal transparency losses in 2011/12
    - Hadronic damage: ~no recovery at room temp.; can be fully annealed at high T (>300°C) or partially with lower T (≥50°C) and/or optical "bleaching"; will dominate after ~1×10^{13} hadrons/cm^2
  - Photodetector degradation
    - VPTs: photocathode & faceplate degradation (drop in detection efficiency) – long-term studies in Brunel and Virginia (and effects included in performance predictions for EE)
    - APDs: dark current increases; spikes
  - Silicon sensor (ES) charge collection efficiency decreases
  - Single Event Effects in electronics
    - Short/long term losses in overall efficiency

ECAL Response

5

Transparency measurements in 2011

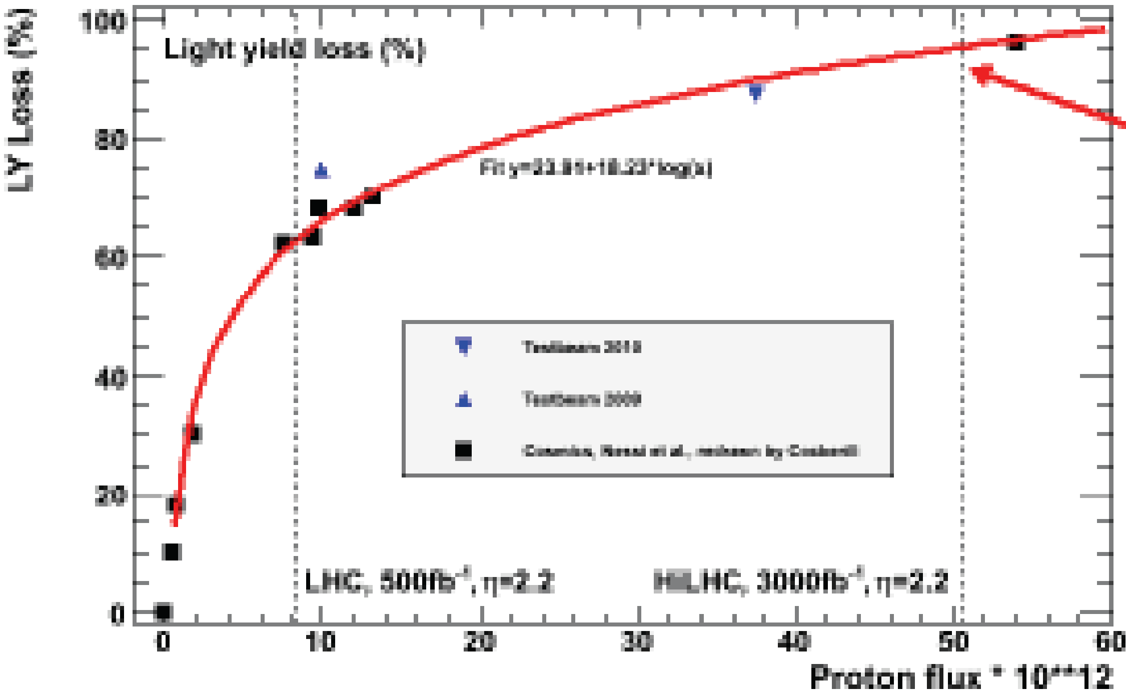


<u>Cycle of damage and recovery (beam off) evident</u>

Significant (~50%) losses seen in the inner eta ring of EE

Excellent quality of monitoring data following recalibration exercise

Hadron damage to lead tungstate crystals



~5% light remaining at eta = 2.2 for 3000 fb^{-1}

D. Cockerill

LY loss measured in cosmic ray test stand/H4 after exposure to 20 GeV/c proton flux
Cosmics test stand: EB crystal + bialkali PM.
H4: EE crystals + bialkali PMs

Fluence estimates at eta = 2.2 using Pushpa Bhat's MARS estimator
Fit: LY Loss = 23.91 + 18.23*log(fluence) %. Use this for ECAL resolution estimates.

[1] Nessi et al, NIMA 545 (2005) Table 3 and Fig.18 NIMA 564 (2006) Fig 3 (top)

ECAL Plans

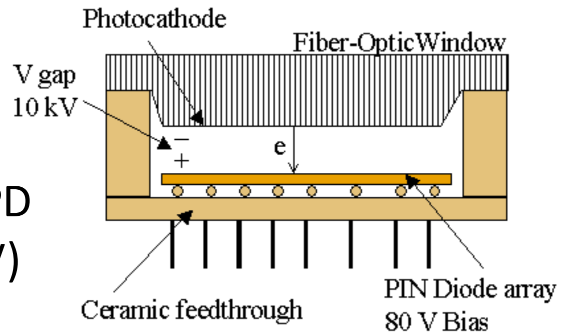
- **Phase 1**
  - EB will perform according to TDR specifications throughout phase 1 LHC operation with no interventions (even with spikes etc.)
  - EE + ES will perform well throughout phase 1 and even though the light collected in EE will be smaller in 2022 than now, the performance is not expected to degrade significantly
- **Phase 2**
  - EB will function throughout phase 2 LHC operation with no interventions foreseen
  - EE + ES will almost certainly be functional throughout phase 2 operation but with some performance degradation

- ECAL groups involved in “Forward Calorimetry Task Force”

Hadron Calorimeters

- HCAL upgrades anticipate over LHC Luminosity increase to remove major limitations and risks coming from photodetector technologies that instrument the current HCAL detectors
  - Hybrid PhotoDiode (HPD) breakdown was first identified in MTCC 2006 in the first major immersion of CMS in magnetic field; this affects HB, HE and HO
  - HF anomalous pulses from MIP/shower interactions in PMT photocathode window were first quantified in testbeam
  - mitigation schemes based on calorimeter tower manifolding to parallel readout channels were very effective to reduce this backgound, and will be implemented systematically in the upgraded system

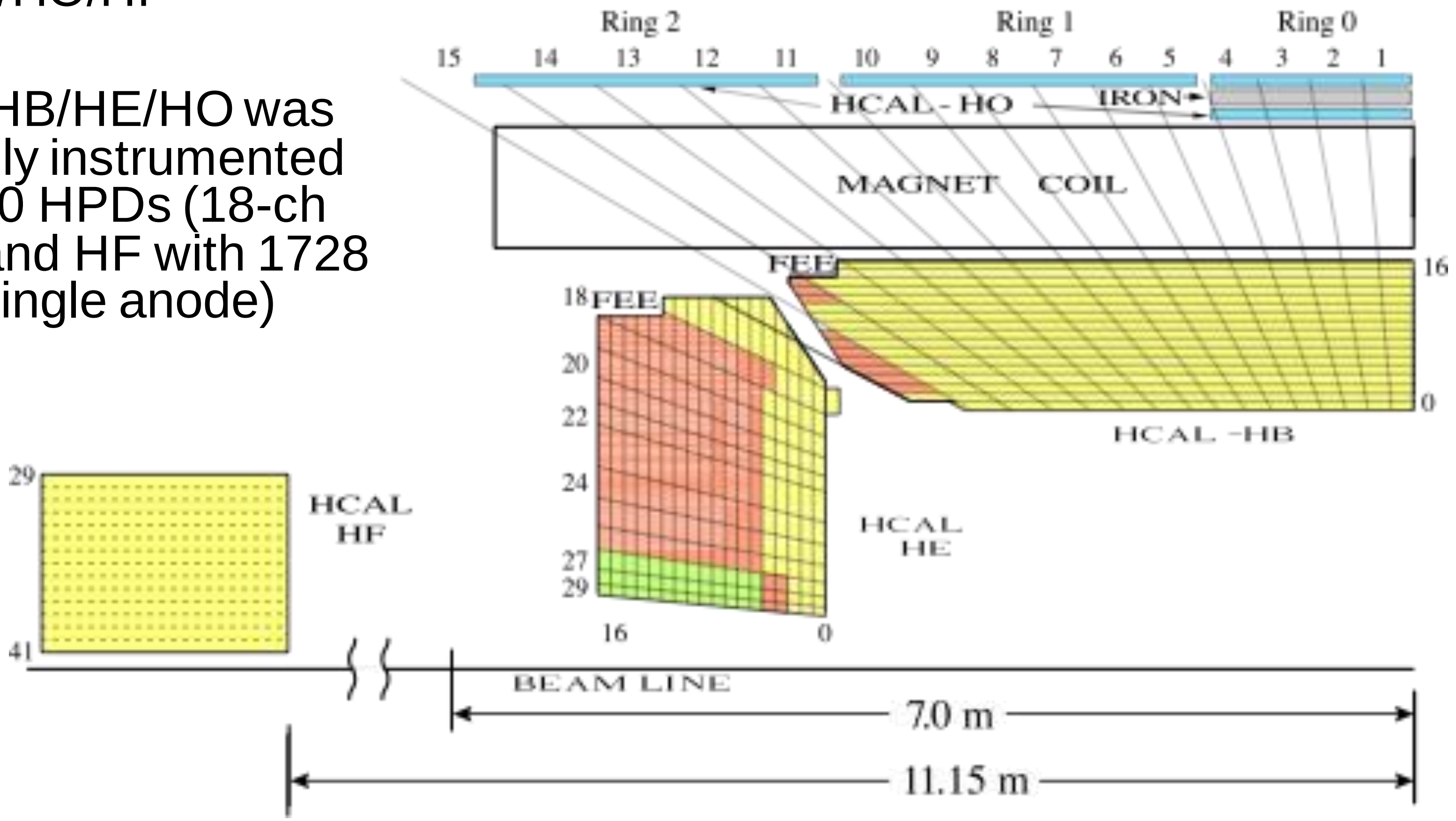
HB/HE/HO HPD
(HV - many kV)



HF PMT
(thick glass)

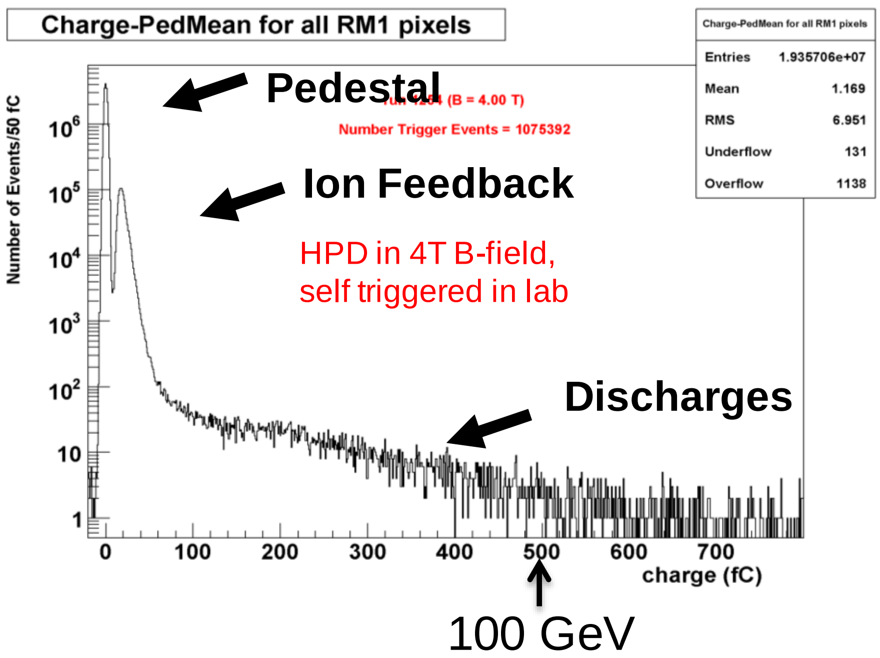
HCAL HB/HE/HO/HF

- 10 units of rapidity and a large fraction of the 10λ containment of the CMS calorimeters come from HB/HE/HO/HF
- HCAL HB/HE/HO was originally instrumented with 420 HPDs (18-ch each) and HF with 1728 PMT (single anode)

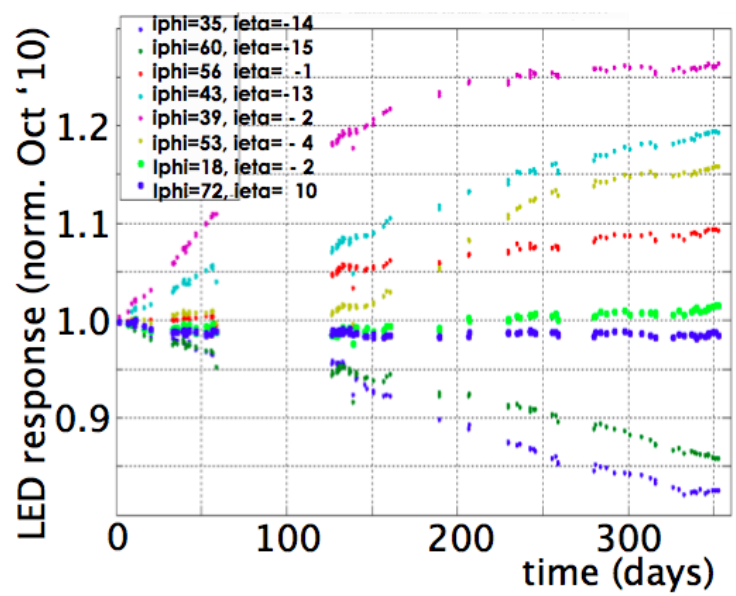


HPD Problems

HPDs discharge regularly from time to time. But 10-15% of those mounted in CMS HCAL will discharge uncontrollably and destructively if operated at ~1-2 Tesla



Are HPDs slowly destroyed with collisions?
Why their gains drifted by up to 10-30% with time in 2011?



(see also C. Tully, Upgrade Week, May 2012)

HCAL Upgrade Plan

- ***LS1, ETS(2015/16) and LS2***

- New PMT (multi anode) for **HF (during LS1)**
- Avoid background from PMT windows
- 32 such PMTs already in place (Oct-2010, Feb-2012)

- **HO (during LS1)** then in HE/HB (during LS2)
- !Replace HPDs with SiPMs
- Higher gain (reduced noise effects, pulse shape usage), avoid discharges
- Improve granularity of segmentation depth segmentation (in HE/HB**) (during LS2)**
- better isolation and particle ID, improved calibration

- New Front Ends **(2015/16 for HF, LS2 for HBHE)**
- 8 bit multi-scale ADC and 6 bit rising edge TDC allows Anomalous signal rejection at 25ns BX

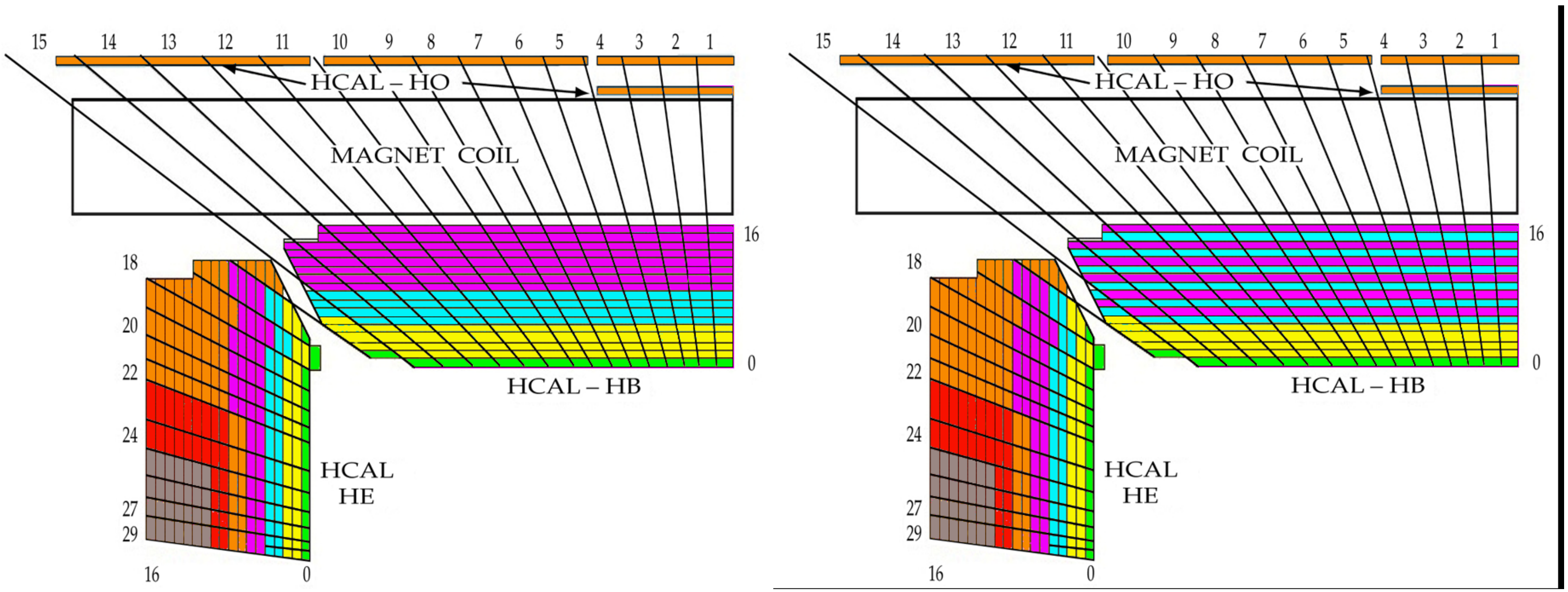
- New Back-Ends **(LS1 for HF, LS2 for HBHE)**

High Luminosity LHC

HE/HB (during LS2)
Photosensors: increased noise at 4.5 ab-1 (@ T=20 C)
scintillator damage in front/high eta region of HE:
some layers in the corner of HE will be completely black
!HF:
!Quartz fiber damage in HF: at highest eta only 1/3 of signal left, but can be re-calibrated
new PMTs less sensitive to beam exposure, but more data needed to predict long-term behavior

HCAL longitudinal segmentation

- New photo-detectors allow finer segmentation of readout in depth
- New segmentation – more robust against damage to inner scintillator layers



Color code represents the layers that are grouped into separate readout channels. The left scheme maximizes resolution by concentrating separate readout channels to groups of layers where the energy density is highest. The right scheme maximizes redundancy and robustness of the calorimeter by providing two rear readout channels with interleaving sampling of the hadronic showers.

SiPM for HCAL

New SiPM photo-sensors for the CMS HCAL Phase-I Upgrade.

Currently working with 6 SiPM producers: Hamamatsu, Zecotek, CPTA, KETEK, FBK, NDL. Hamamatsu , Zecotek, FBK and KETEK bench- and beam- tested at CERN

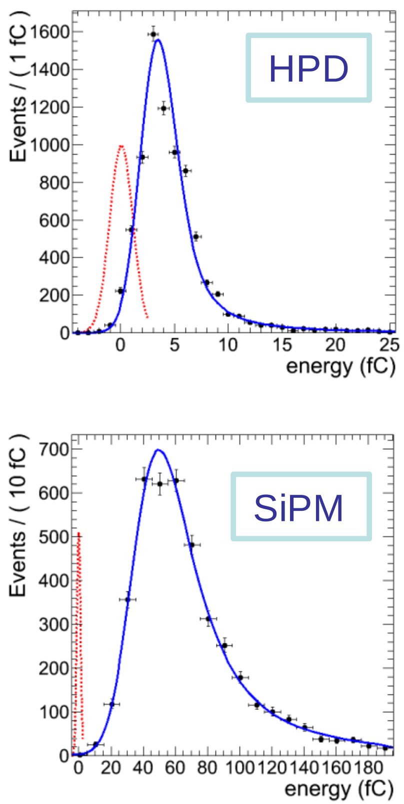
Significant progress on the development of large dynamic range, fast, radiation hard SiPM for CMS achieved over the last 2 years.

Requirements of the CMS HCAL Phase-I Upgrade.

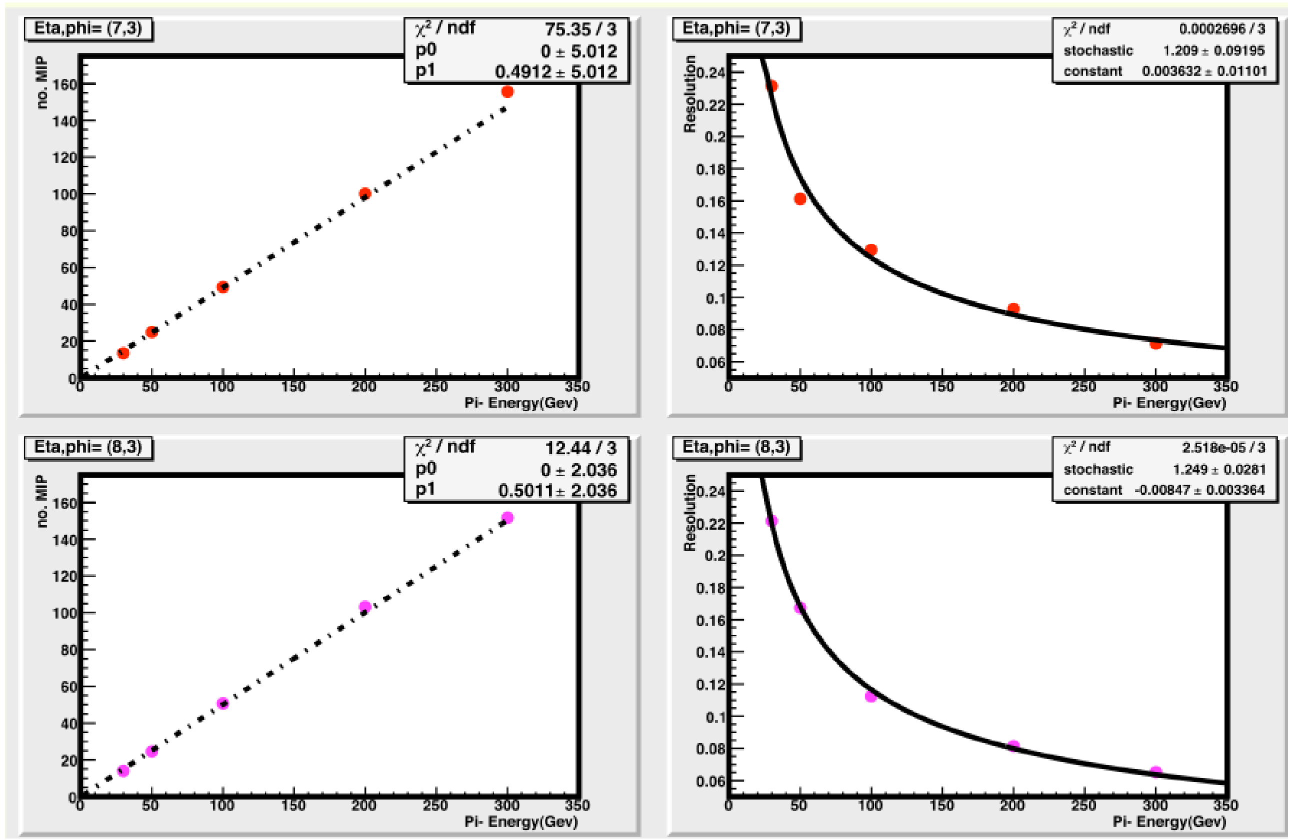
- High PDE(515 nm): 15 - 30%
- Number of pixels (effective pixels): >15 000 1/mm2
- Fast pixel recovery time: 5 – 100 ns (depends on the pixel density)
- Good radiation hardness > 3*1012 n/cm2 (10 years of SLHC) - Gain*PDE change < 20% - noise < 1 MIP at 50 ns integration time
- Low optical cross-talk between cells <10%
- Low sensitivity to neutrons < 10-5 1/n at 30 p.e. threshold?
- Low temperature coefficient < 5%/C
- High reliability

SiPM vs HPD

SiPM have 2-3 orders of magnitude higher gain and photo-detection efficiencies than HPDs and do not have the discharging behavior of HPDs in intermediate magnetic fields



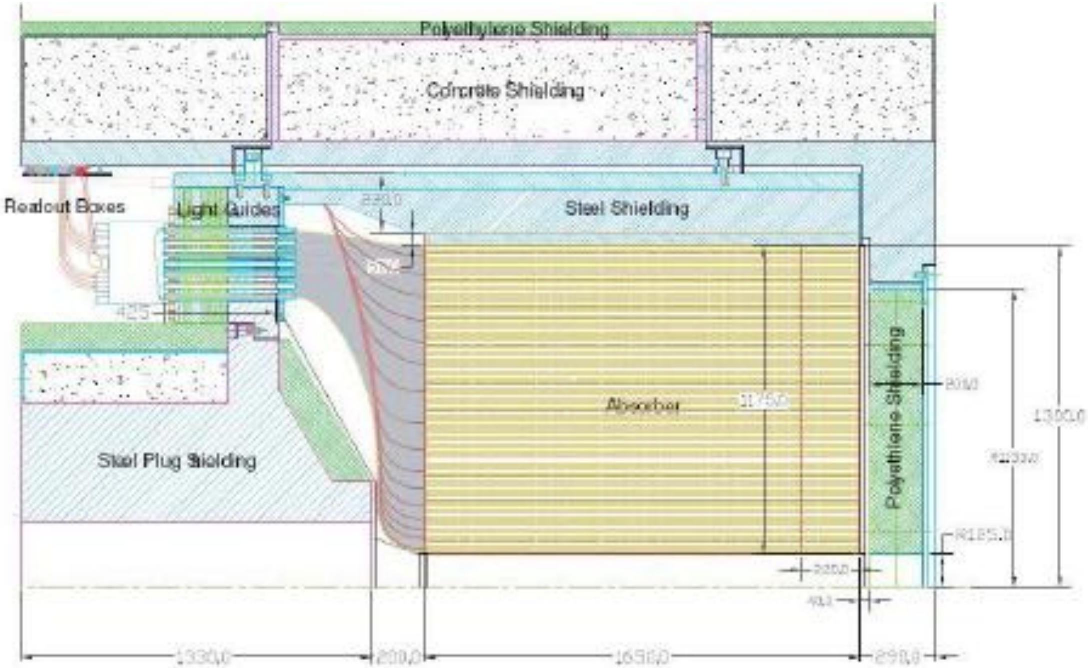
Muon response

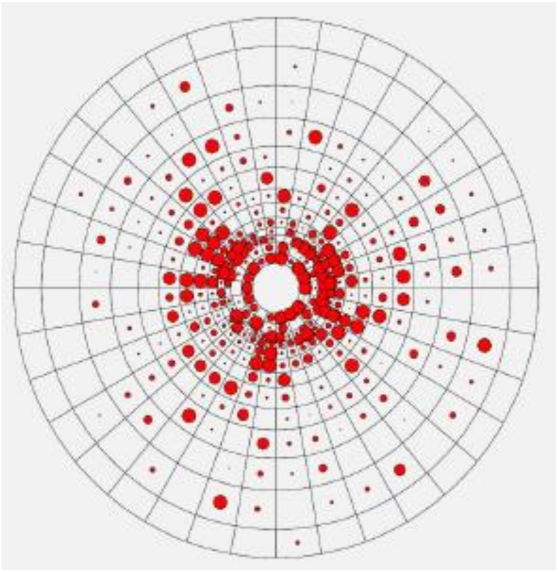


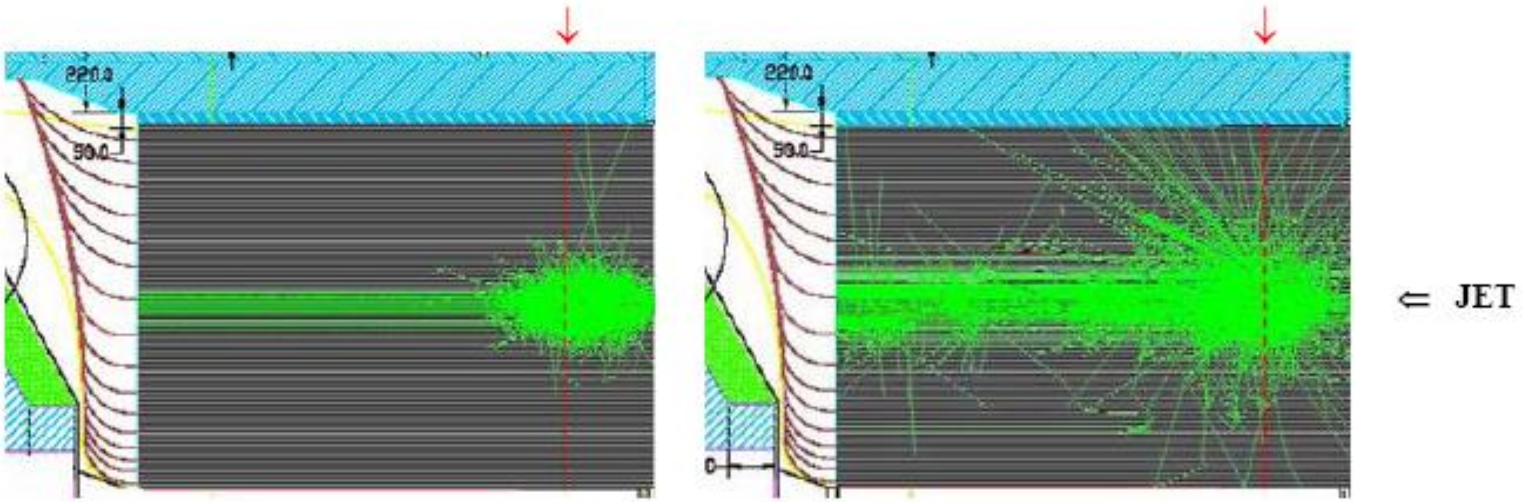
Hadron response (linearity and resolution)

Results of test beam with SiPM (mainly HPK)

HF structure and properties





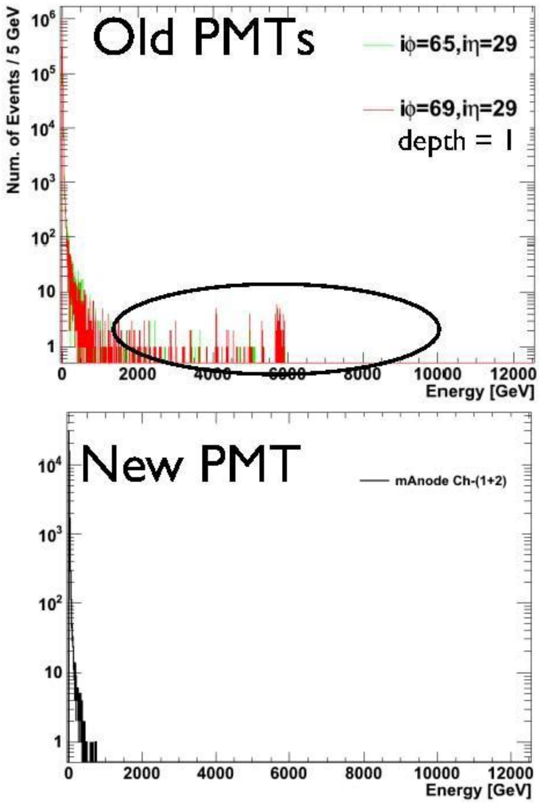


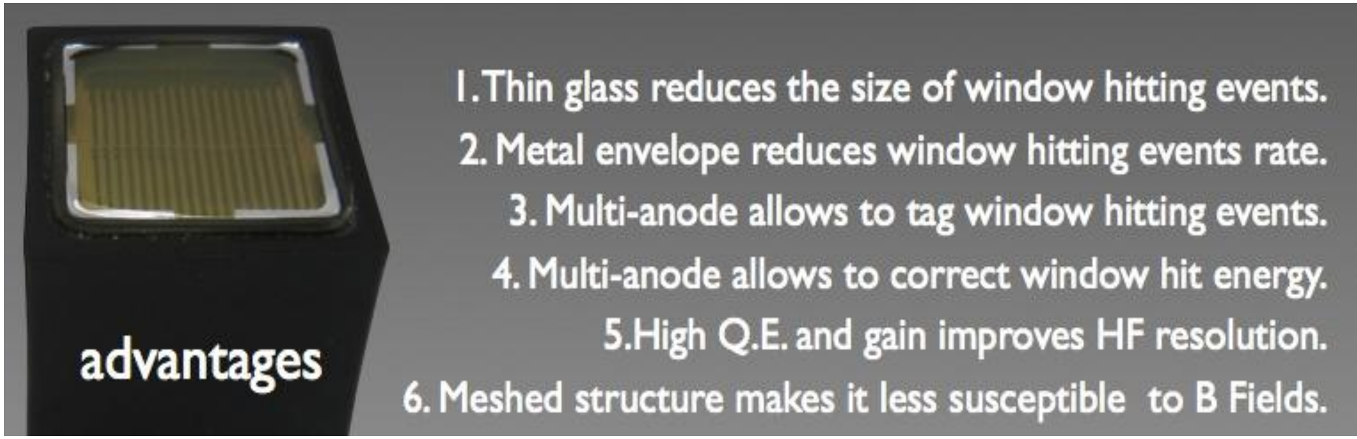
100 GeV electron shower

100 GeV proton shower

HF PMT Replacement

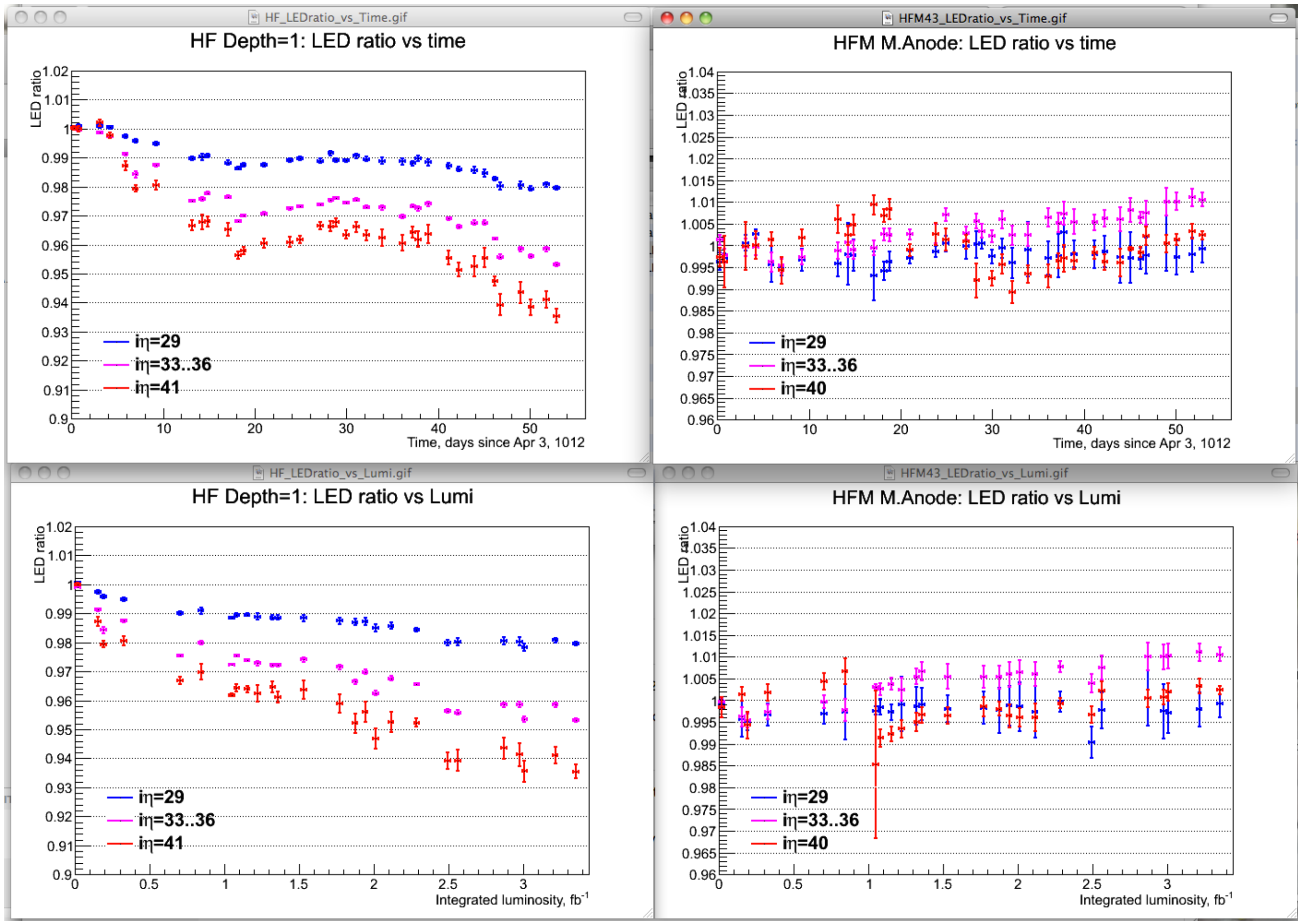
Present PMTs (thick windows and walls) give large (>10 TeV) beam-induced, fake signals. R7525 will be replaced during LS1 by new, thin window, metal wall, multianode PMTs R7600 that will have much lower beam-induced noise. At present LHC (50ns) bunch spacing) noise is filtered in HF exploiting timing information.
In post-LS1 era, LHC will most likely operate at 25ns bunch spacing and present scheme will not be possible.





HF PMT gain loss

old PMTs (R7525) | new PMTs (R7600)



- Old PMTs exhibit systematic gain loss vs Integrated Luminosity
- New PMTs (24 installed in Feb-2012) show no signs of gain changes so far (3mo, 3.5fb-1)

Radiation Damage of Quartz Fibers

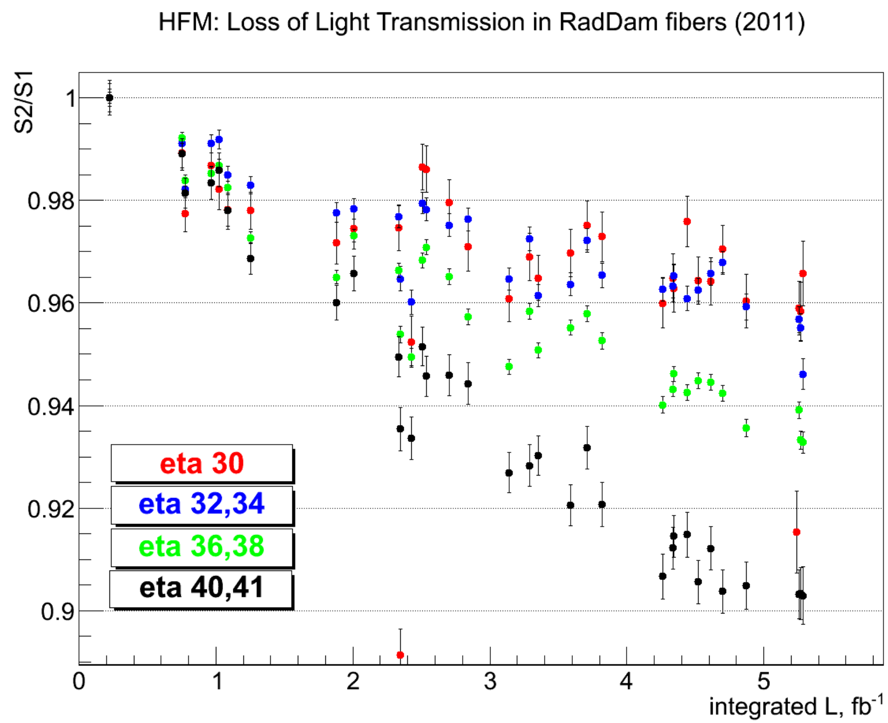
Decrease of HF signal and RADDAM effect versus dose in HF quartz fibers from Kerem Cankoçak et al. NIM A 585 (2008) 20-27

with $\alpha = 1.44$ dB/m $\beta = 0.44$ L = 1.65 m

$I(D,\lambda)/I(0,\lambda) = \exp[-(L/4.343)\,\alpha(\lambda)\,(D/D_s)^{\beta(\lambda)}]$

Dose (Mrad)	0.01	0.1	0.5	1.0	10.0	100	1000
A (dB/m)	0.025	0.069	0.097	0.190	0.523	1.44	2.754
I(D)/I(0) SIGNAL	0.991	0.974	0.964	0.930	0.820	0.579	0.351
I(D)/I(0) RADDAM	0.981	0.949	0.929	0.866	0.672	0.335	0.123

04/20/2012 CMS HCAL-DPG JP Merlo



Doses for integrated Lumi of 5 fb-1
R= 13cm: 1.5 Mrad- 0.2 Mrad
R= 50cm: 0.1 Mrad- 0.01 Mrad
R=100cm: 0.01 Mrad- 0.001 Mrad

Consistency between RadDam data and predictions from NIM A 585 (2008) 20-27

FCAL : Options & Choices

At the stage of R&D and MC studies

Structure:

- Shashlik
- Sampling
- Tile Calorimeter

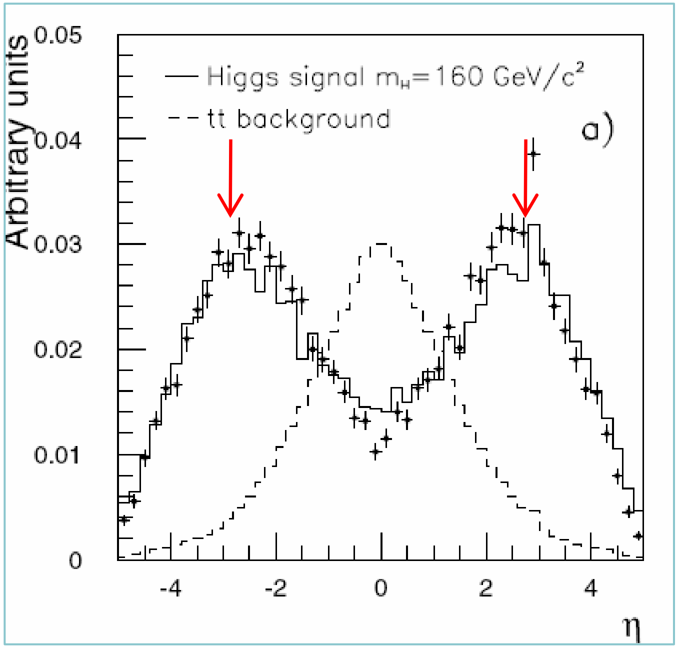
- Materials
  - Crystal ++
    - Which crystal LYSO, …
- Software for studies to make a choice
  - Geometry in CMSSW
  - Detailed simulation for calorimetric aspects
  - Fast simulation for physics case
- Difficulties
  - Radiation Damage
  - Pile-up

Integrated Approach

Endcap and Forward Region

- The Forward Calorimeter Task Force (where do we go with EE, HE, and HF?)
- Simulations and studies of longevity of present endcap& forward detectors
- Simulations comparing design concepts, and R&D on rad-hard technologies
- New Working Group (what should a fully integrated forward region be?)
  - Integrated approach driven by physics and objects, including muons, tracking (vertex or track counting in jets), precision timing to help with PU …
  - Triggering: forward with central
  - Consider new geometries, avoid cracks
  - And the “other” constraints – like present detector, design for shielding and access

In order to help to isolate the jets which go ~ forward, having emitted a virtual W, the |y| of the jets is centered on |y| ~ 3. Unfortunately, this is at the present HE/HF boundary.



Trigger Upgrade

- Motivation
  - Electronics technology advances can give us enhanced capabilities
    - More sophisticated algorithms, improved resolution
      - Unfortunately, input to trigger hardware does not change much (for calorimeter system)
  - Physics driven:
    - HLT like capabilities
    - Improved resolution to sharpen thresholds
    - Improved purity for identification
    - Cross-triggers with more sophistication
    - Angular correlations, Invariant masses
    - Better quality corrections
    - Pileup handling – background subtraction
  - Presently the program is more driven by technology rather than physics goals – needs prompt correction
- New option: Tracking Trigger (adding tracker to L1 trigger)

Technical Coordination

LS1-4: Radiological protection

Dose rate predictions (FLUKA), 1 mo cooling (AB from Huhtinen, Muller, Vincke…

Region	LS1	EYETS 16-17	LS2	LS3	LS4
Tracker BH	12 µSv/h	35 µSv/h	50 µSv/h	65 µSv/h	125 µSv/h
EE(high η)	0.25 mSv/h	0.75 mSv/h	1 mSv/h	1.25 mSv/h	2.5mSv/h
HF(high η)	5 mSv/h	15 mSv/h	20 mSv/h	25 mSv/h	50 mSv/h
TAS region	≤15mSv/h	≤45mSv/h	≤60mSv/h	≤75mSv/h	≤150mSv/h
Expt cavern	<0.5 µSv/h	<1.5 µSv/h	<2 µSv/h	<2.5 µSv/h	<5 µSv/h

In fact measured dose rates in the far forward seem lower than predicted by a factor 3-5
-arguably within the FLUKA systematic, but probably due to underestimated magnetic field.
-needs to be checked.

Away from the forward beampipe, the simulation seems good to 30% , verify in LS1

Tracker change in LS3: key personnel have 30 hours in close proximity for 2 mSv
ECAL dismantling in LS3: <2 hours in proximity for 2mSv → remote handling reqd.
TAS removal in LS3 < 1 minute in proximity for 2 mSv → !!!!!

Summarizing…

- EB and HB are expected to survive through Phase 2. To be confirmed…
- Muon chambers are expected to survive beyond LS3
- At high η ECAL and HCAL degradation in the endcap will be a challenge
- The emphasis will be on improved calibrations to extend their use
- For HE: depth segmentation will allow weighting to compensate
- EE will be very difficult to operate/calibrate by LS3
- Phase 2 technologies may be applied to extend longevity of phase 1 detector
- The Pixel Detector is one example
  - In ~2016 a second inner layer replacement, to survive >500 fb^{-1}
- Probably the trigger upgrades will need to be phased to span Phase 1-2
- For Phase 2, ageing will be driving the upgrade program
  - Tracker (silicon and pixels): needs to be replaced >500fb^{-1}
    - Opportunity to provide track trigger. What η range?
  - HF: even with new PMTs, TDCs, and 2-anode readout, by LS3 HF may be struggling with backgrounds. Fiber darkening may complicate calibration, and lead to loss of higher η
  - Endcap calorimeters: EE and HE will likely need to be replaced/augmented ay high η

- ***RELIABLE CALIBRATIONS SHOULD ALLOW PROPER CORRECTIONS***

Backup Slides

2011 LHC records

	CMS	ATLAS
peak stable luminosity delivered	3.55×10^{33} cm^{-2} s^{-1}	3.65×10^{33} cm^{-2} s^{-1}
maximum luminosity in one fill	123.13 pb^{-1}	122.44 pb^{-1}
maximum luminosity in one day	135.65 pb^{-1}	135.45 pb^{-1}
maximum luminosity in 7 days	537.9 pb^{-1}	583.5 pb^{-1}
maximum colliding bunches	1331	1331
maximum #events / bunch crossing	19.94	17.5
longest time in stable beams for 1 fill	26 h	26 h
longest time in stable beams for 1 day	19.9 h (82.9%)	21.9 h (91.2%)
longest time in stable beams for 1 week	107.1 h (63.7%)?	107.1 h (63.7%)
longest time in stable beams for 1 month	232.2 h	232.2 h
fastest turnaround to stable beams	2.1 h	2.1 h

More about LHC upgrades

- **In 2012 we may expect addtitional 10/fb at 4 TeV with maximum pile up ~36 (50 ns spacing)**
- **From 2014 run with 25 ns spacing at 6.5 TeV**
- **By 2017 we may have ~150/fb and by 2021 ~400/fb with maximum pile-up <50**
- **connection of LINAC4 might help for 50-ns operation, but could give highest luminosity with rather high maximum pile up (70-170)**
- **maximum luminosity is determined by acceptable pile up (no head-on beam-beam limit!)**
- **leveling could be applied systematically to limit the pile up**
- **enhanced satellites would give low & high pile up events**
- **LHC will exceed design luminosity; 2021: time for HL-LHC**

Longevity of Detectors

- EB and HB are expected to survive through Phase 2. To be confirmed?
- Muon chambers are expected to survive beyond LS3
- At high η ECAL and HCAL degradation in the endcap will be a challenge
- The emphasis will be on improved calibrations to extend their use
- For HE: depth segmentation will allow weighting to compensate
- EE will be very difficult to operate/calibrate by LS3
- Phase 2 technologies may be applied to extend longevity of phase 1 detector
- The Pixel Detector is one example
  - In ~2016 a second inner layer replacement may be done, if Phase 1 detector has to survive >500 fb^{-1}
- Probably the trigger upgrades will need to be phased to span Phase 1-2
- For Phase 2, ageing will be driving the upgrade program
  - Tracker (silicon and pixels): needs to be replaced >500fb^{-1}
    - This is well predicted - extensive test beam and radiation studies
    - Opportunity to provide track trigger. What η range?
  - HF: even with new PMTs, TDCs, and 2-anode readout, by LS3 HF may be struggling with backgrounds. Especially for the trigger. Fiber darkening will complicate calibration, and lead to loss of higher η
  - Endcap calorimeters: EE and HE will likely need to be replaced/augmented ay high η

Tracker and Pixels

- **Basic requirements and guidelines**

- Radiation hardness: ultimate integrated luminosity ~ 3000 fb-1
- (To be compared with original ~ 500 fb-1)

- Granularity: resolve up to 200÷250 collisions/bunch crossing
- (Nominal 5×1034 cm-2 s-1 @ 40 MHz gives ≥ 100 collisions
- Maintain occupancy at the few % level
- Improve tracking performance

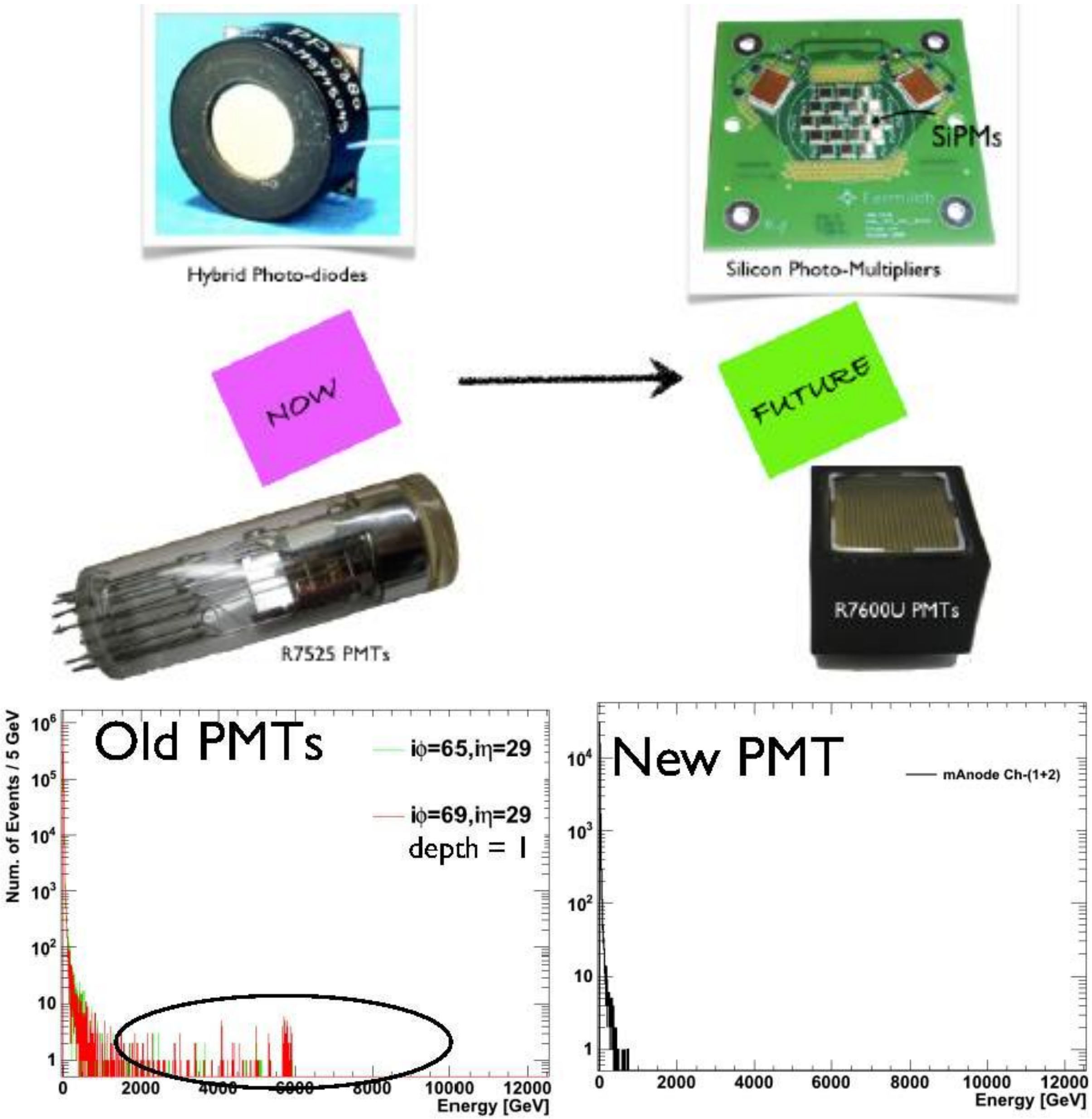
- Reduce material in the tracking volume
- Reduce rates of nuclear interaction, γ conversions, bremsstrahlung…

- Reduce average pitch
- Improve performance @ low (and high) pT

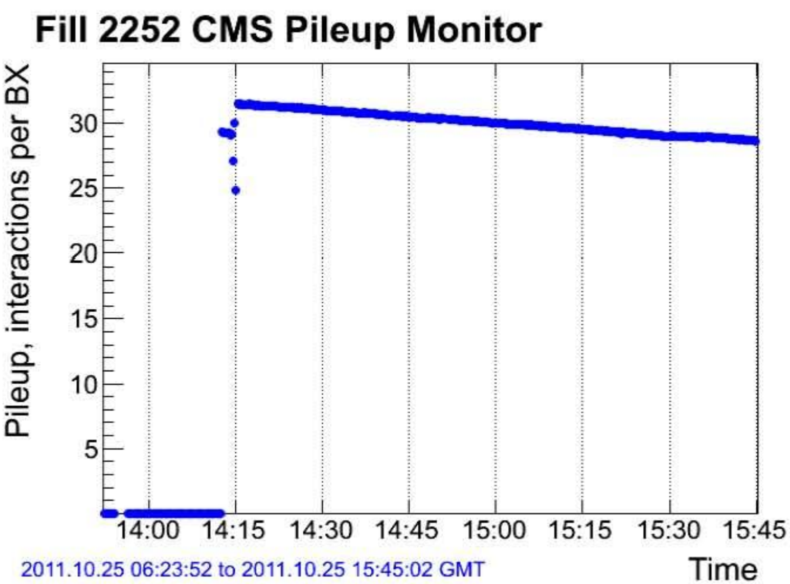
- New option: Tracking Trigger (adding tracker to L1 trigger)

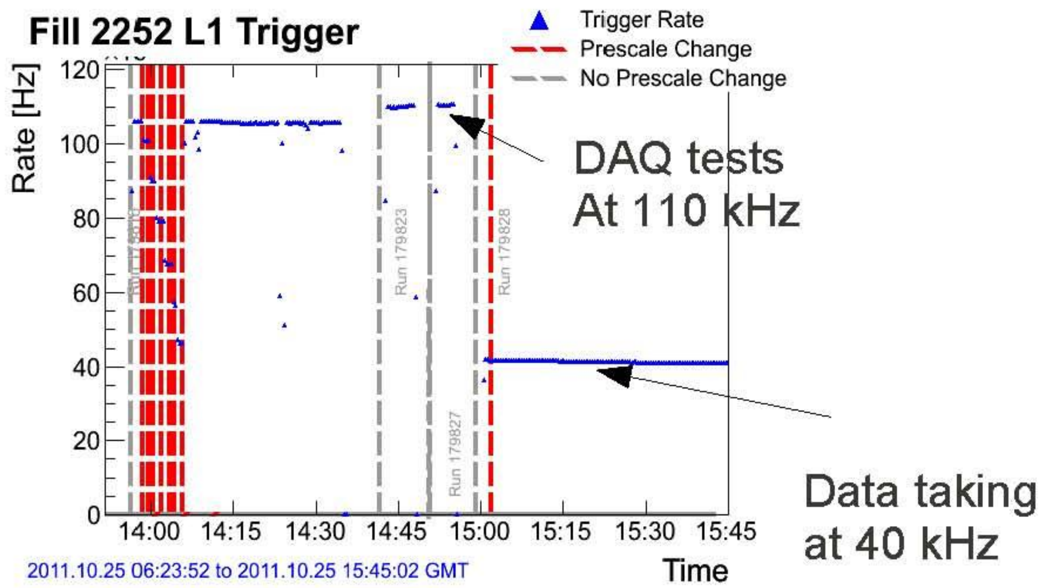
- **Substantially higher channel count!**

HCAL Photodetector Replacement



CMS high pile-up tests





- With a PU of >30 at the start of the fill we ran at 110 kHz L1 trigger rate – no limitation seen by the DAQ bandwidth.
- Without modifications to the readout we can operate at 7e33 Hz/cm2 with 50 ns bunch spacing.

(A. Ryd, LMC112)