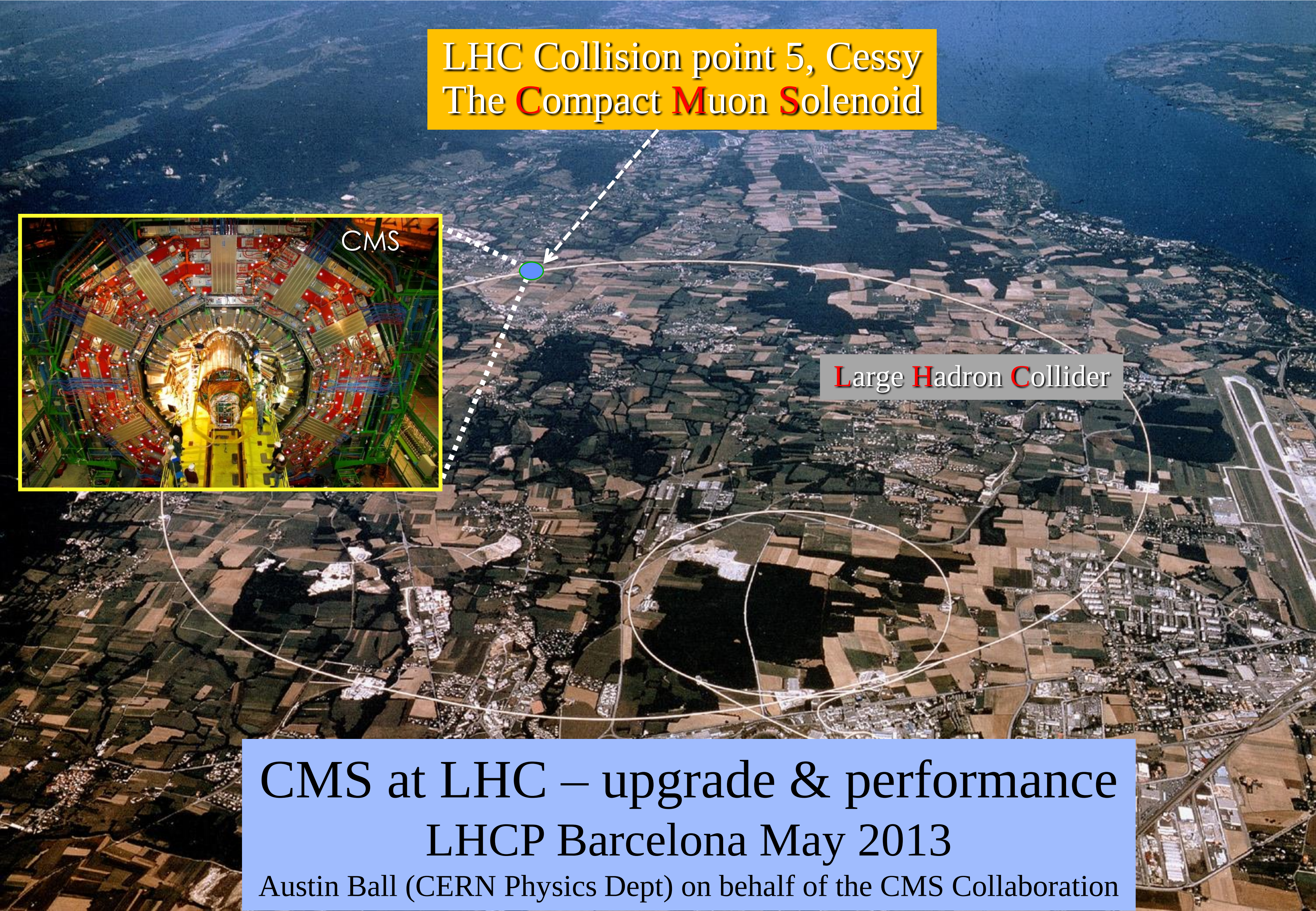
LHC Collision point 5, Cessy
The Compact Muon Solenoid



CMS at LHC – upgrade & performance

LHCP Barcelona May 2013

Austin Ball (CERN Physics Dept) on behalf of the CMS Collaboration

The CMS experiment: looking ahead

The recent exciting discovery presents challenges and opportunities:

a) low mass

b) high enough mass that many different decay modes yield distinguishable signatures.

—> Fruitful LHC physics programme far into the future:

$\int L.dt$ —> 300fb^{-1} —> 3000fb^{-1} (2015 —> mid 2030's)

—> Implications for CMS experimental apparatus:

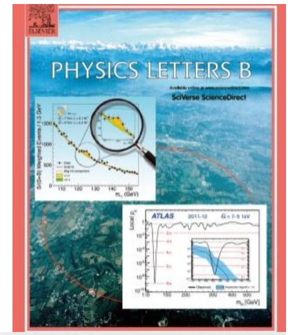
i) must maintain present capabilities at low momentum & low energy to extract max. physics from the discovery.

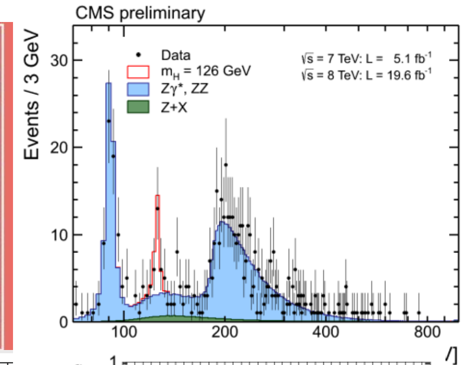
ii) must also maintain capability to search for high mass, rare particles.(eg something counteracting the effect of quantum corrections to the Higgs mass: heavier SUSY ? not seen yet, extra dimensions? .. etc)

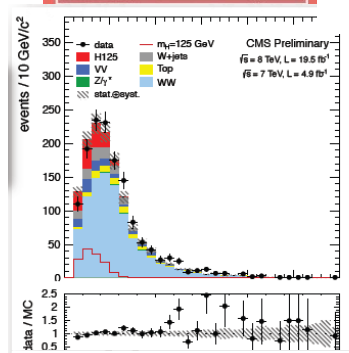
-at highest useable luminosity (rare processes, precision)

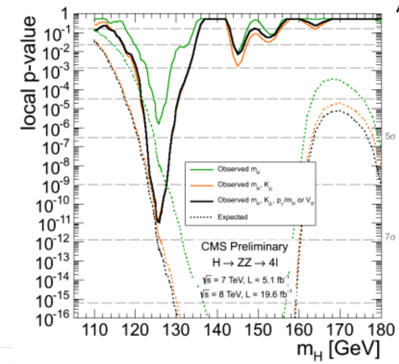
-at consequently very high pileup and radiation load

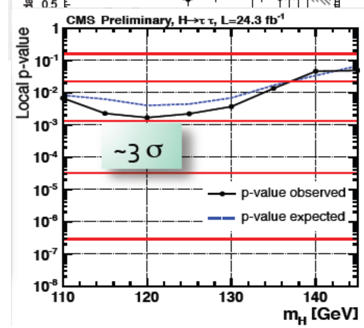
-over a period much longer than design lifetime!!

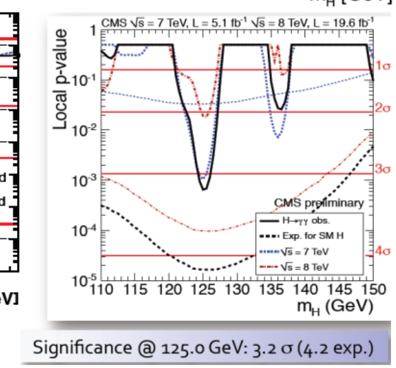




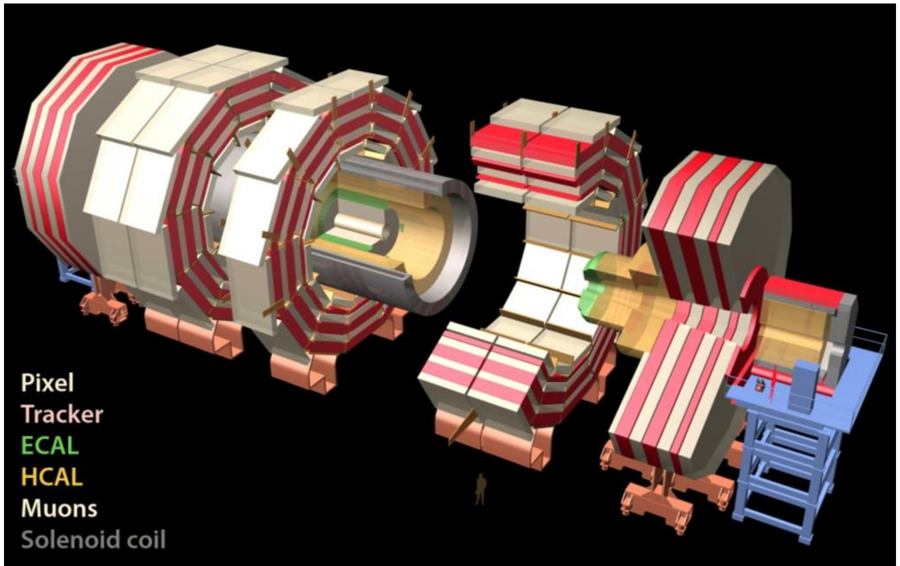


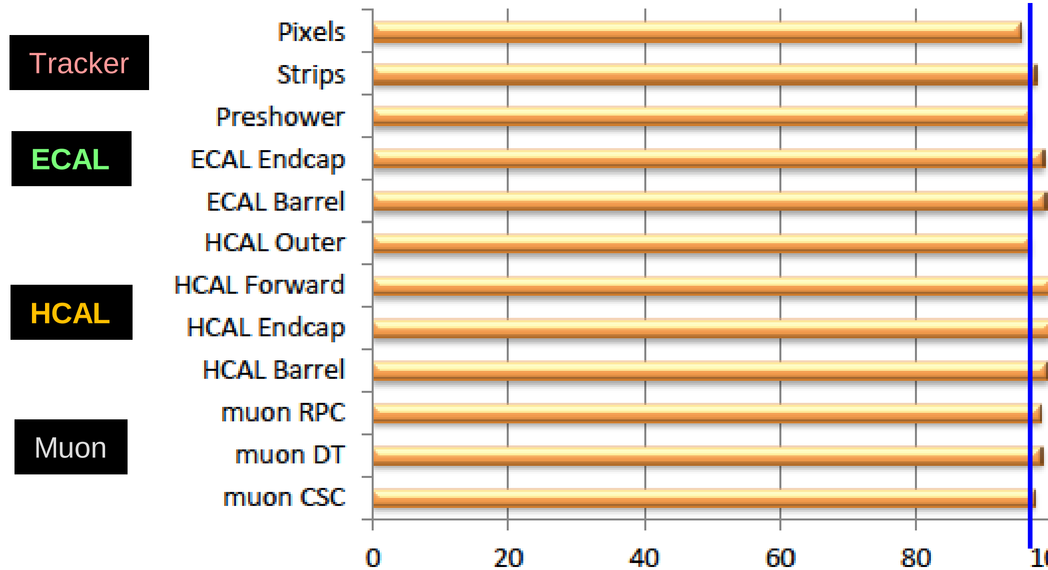




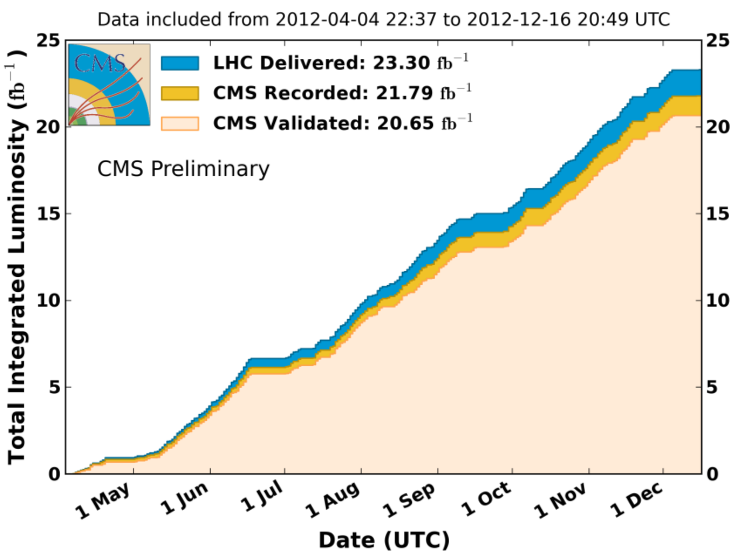


CMS: 2010-13 data-taking performance





Subsystem active fraction **≥98%**



Negligible & stable fraction of dead channels

Good recording efficiency 93.6% (2012)
90.5% (2011)

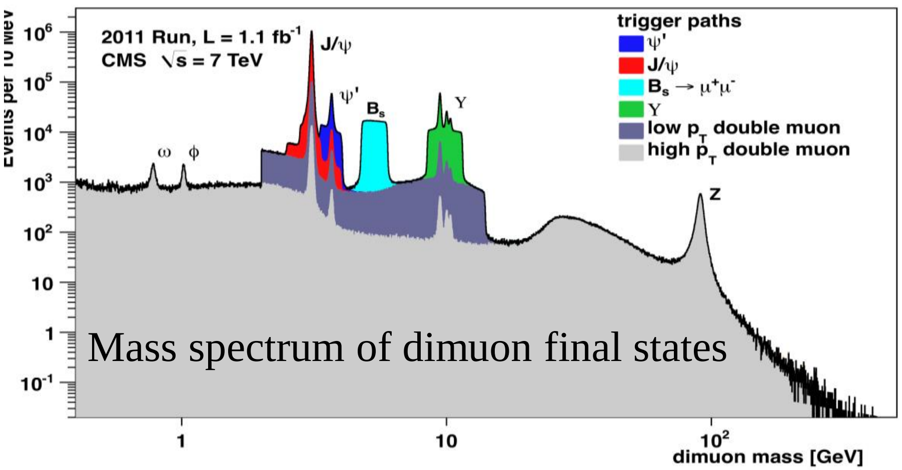
Efficient trigger with adequate bandwidth

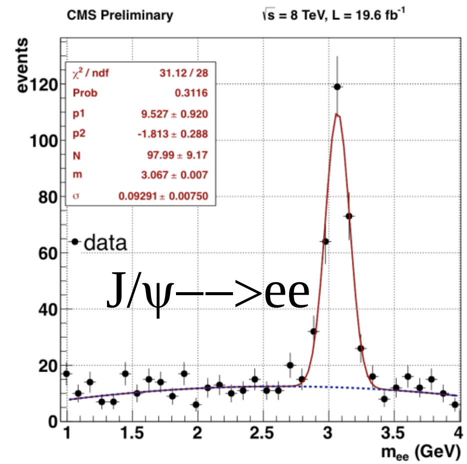
7 x 10^9 collisions recorded (out of 10^{15})

Adequate computing resources for rapid DQM and analysis

Painstaking calibration —> design performance

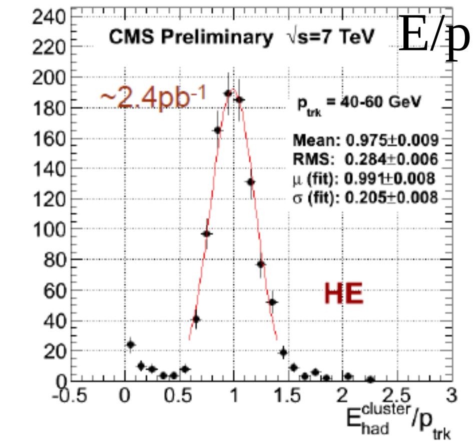
Momentum measurement and lepton identification



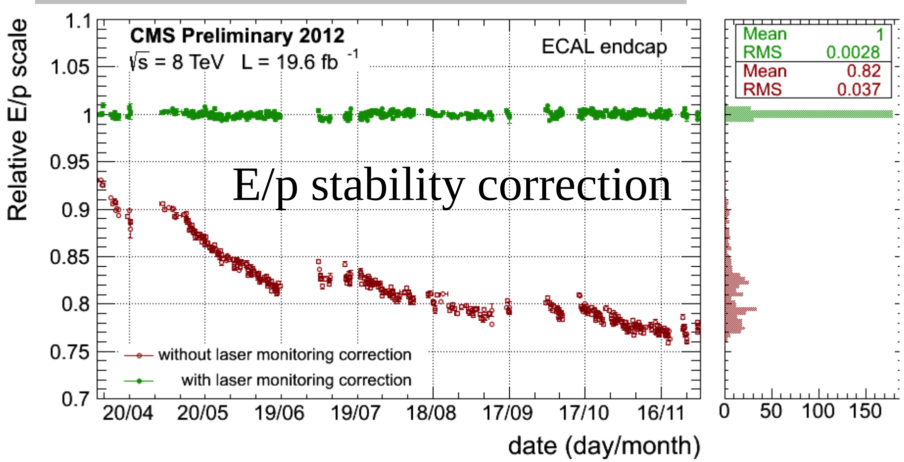


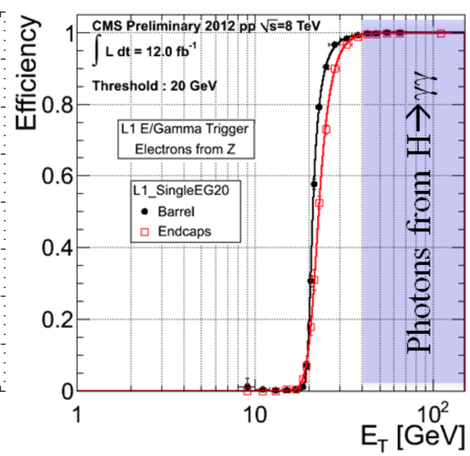
Hadron calorimetry

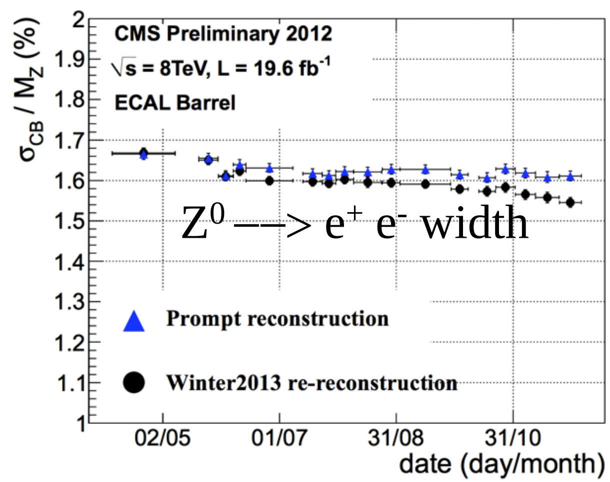
Isolated track trigger (after bias removal)



Electromagnetic calorimetry



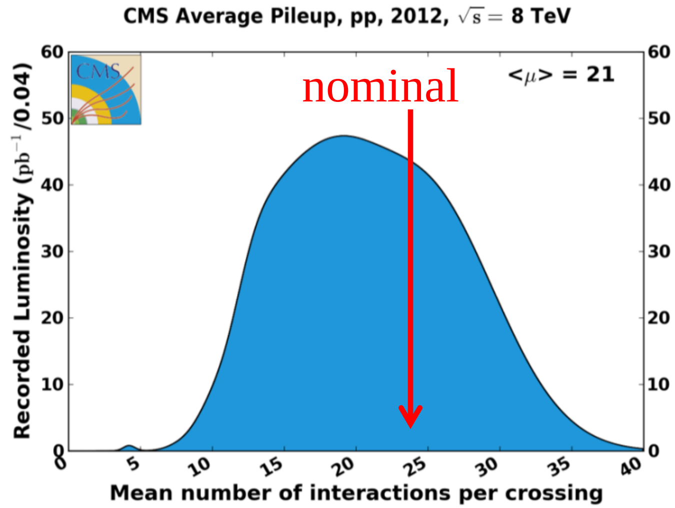


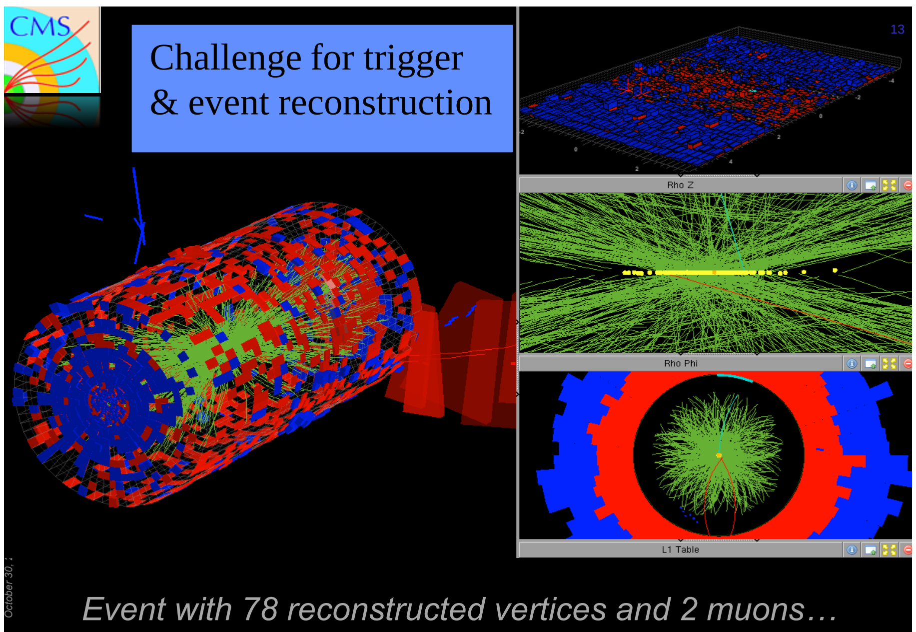


LHC & CMS : 2010-12

LHC operating at ~ ½ nominal p-p design energy
80% nominal luminosity
……*but twice nominal bunch spacing*

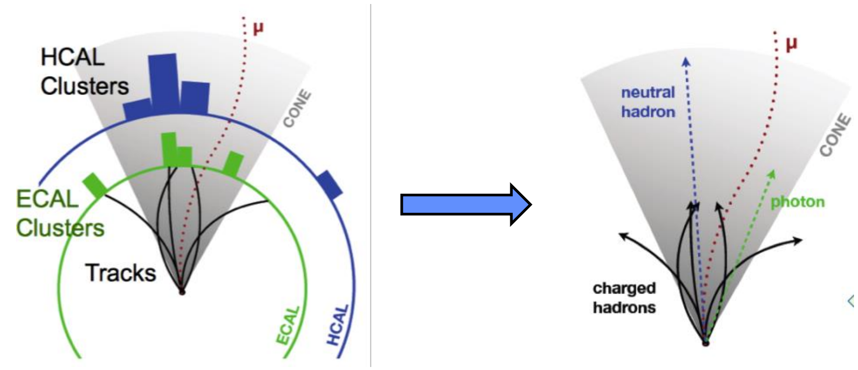
Detectors experience:
< nominal "out-of time" pile up
overlapping signals from adjacent bunch-bunch collisions
but ≥ **nominal "in-time" pile-up**
overlapping multiple p-p collisions within a bunch-bunch collision.





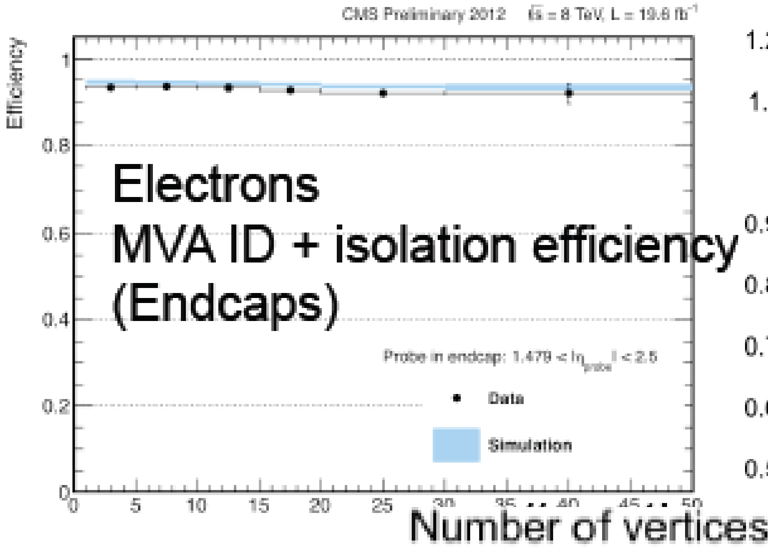
Event with 78 reconstructed vertices and 2 muons…

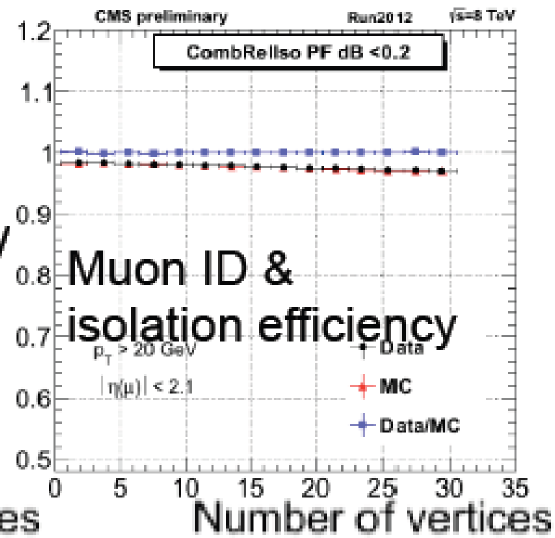
taste of future expected as lumi at 25ns increases.

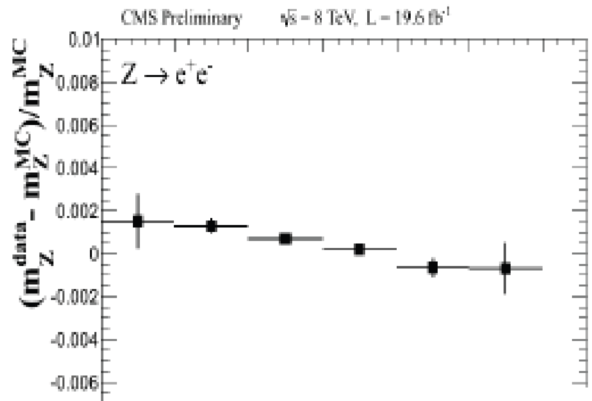


Particle flow paradigm (combining detector info for best reconstruction and energy resolution) very powerful in combatting pile-up.

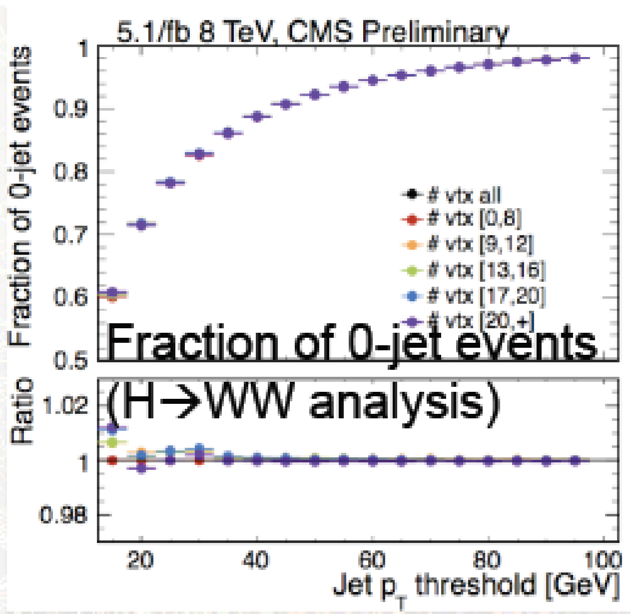
Stability against pile-up: examples





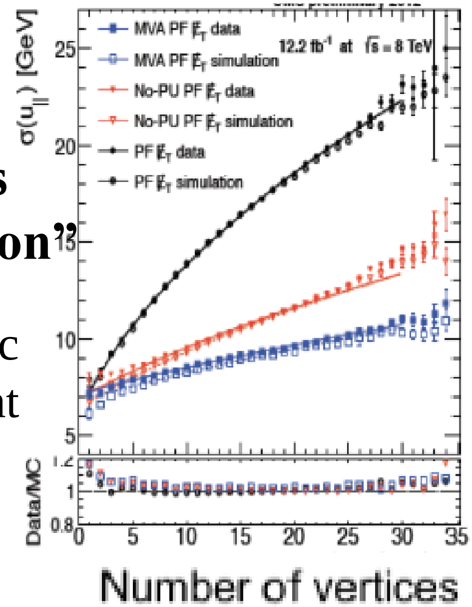


Z mass stability: $Z^0 \longrightarrow e^+ e^-$



“E_T miss Resolution”

(est from hadronic energy component recoiling against reconstructed $Z^0 \rightarrow \mu^+\mu^-$)

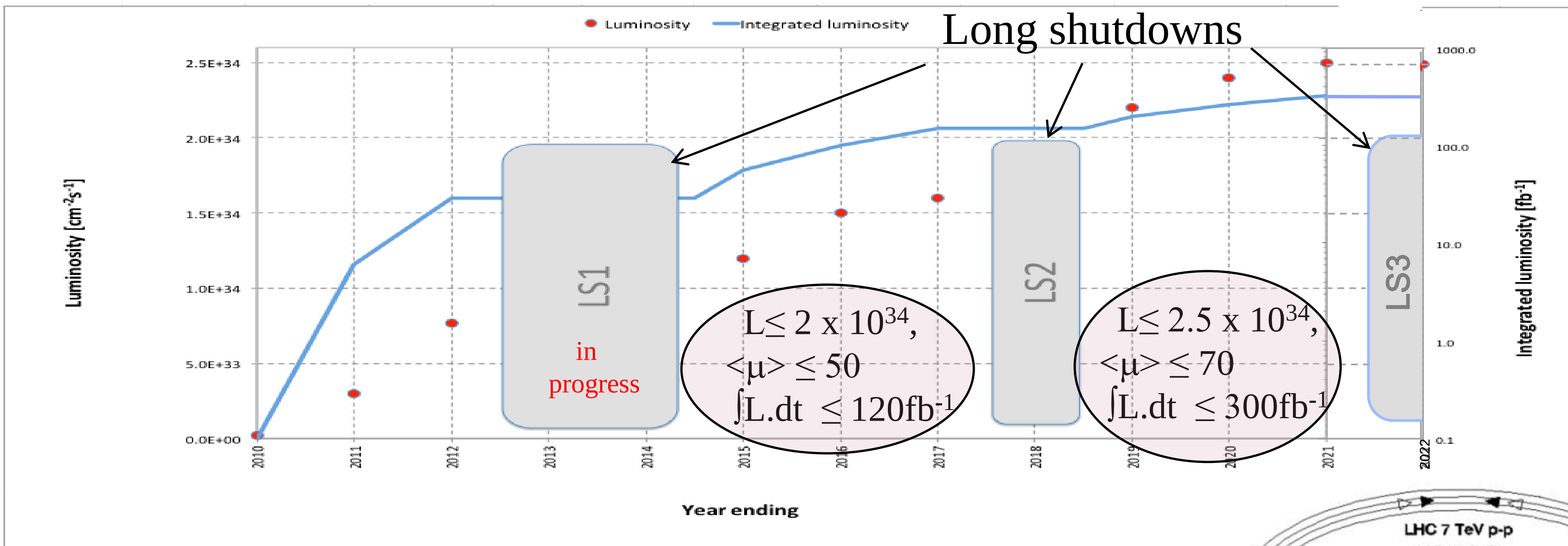


uncorrected

} 2 pileup correction algorithms

LHC : the next decade

LHC is outperforming its design: *performance on the way to 300fb^{-1} will exceed nominal*



LS1 —> LHC "nominal" lumi

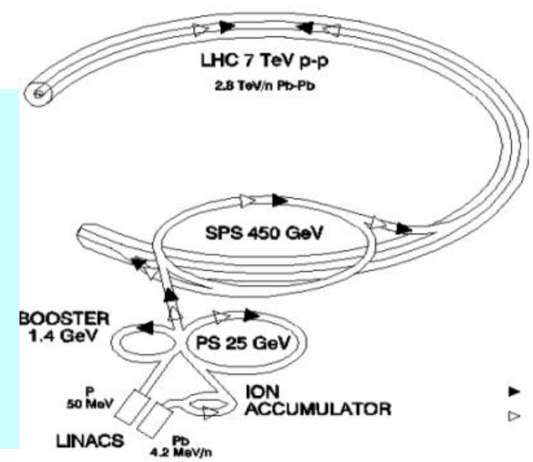
Consolidation - Splice repair: Ecm 8→14 TeV
- R2E mitigation programme

Injector chain
- Batch compression in PS
- Scrubbing in SPS & LHC (e-cloud mitigation)
- 50→25ns bunch spacing

LS2 :—> LHC "ultimate" lumi

Consolidation: R2E programme

Injector chain:
- New Linac 4 connected
- PSBooster-PS: 1.4→2 GeV
- RF upgrades in PS and SPS



CMS physics programme: the next decade

Higgs studies —–> a certain priority .....is this “Higgs” “The Higgs” or what?

Improved measurements of:
i) mass
ii) spin
iii) signal strengths and couplings

new studies with ~ 300fb^{-1}
iv) search for rare decay modes
v) increasingly precise measurements of the relative strengths of the couplings

Besides that

i) Search for new physics resonances, missing E_T signatures ....

ii)Top physics, LHC as top factory —–> study rare decays & measure couplings

iii)Precision electroweak studies (eg search for anomalous TGC’s).

iv)Study of forward processes such as vector boson fusion and diffractive scattering

—–> must deliver the same detector performance as 2012, in more hostile conditions

CMS: Phase 1 upgrades

CMS was designed for: 10 years of $L= 10^{34}$ $cm^{-2}s^{-1}$ (25ns) and for $\int L.dt \leq$ 500fb-1
: annual cycle of 7 months operation, 5 months maintenance

[NB The detector operated from 2009 until 2013 has some design features not yet installed]

The **"Phase 1 consolidation and upgrade"** programme is focused on:
-adapting CMS to better exploit the predicted best LHC performance.
-taking account of the physics landscape already revealed.

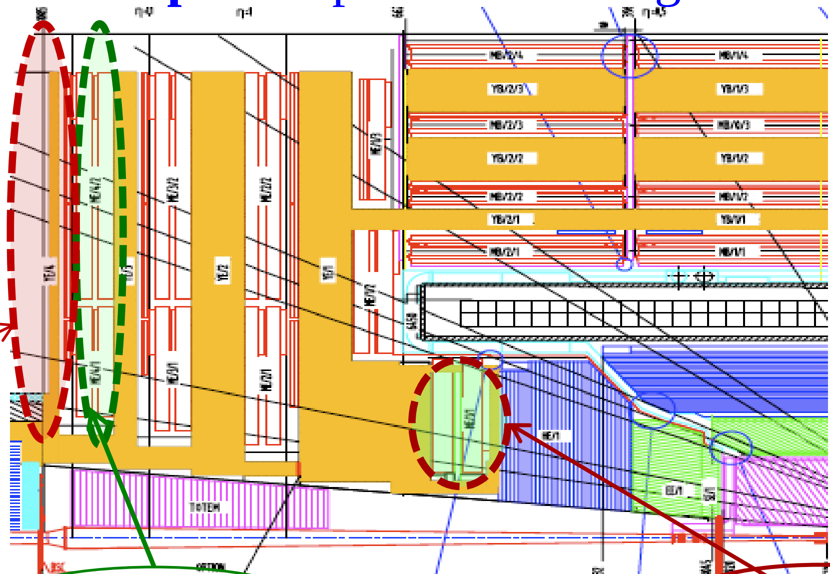
"Phase 1 programme" includes
-completion of the detector designed for $L= 10^{34}$ $cm^{-2}s^{-1}$
-correction of weaknesses exposed by operating experience
-consolidations towards an eventual 25 year operating life
-improvements for operation at $L= 2.0 \times 10^{34}$ (25ns)
eventually tolerating $\leq 2.5 \times 10^{34}$ and beyond

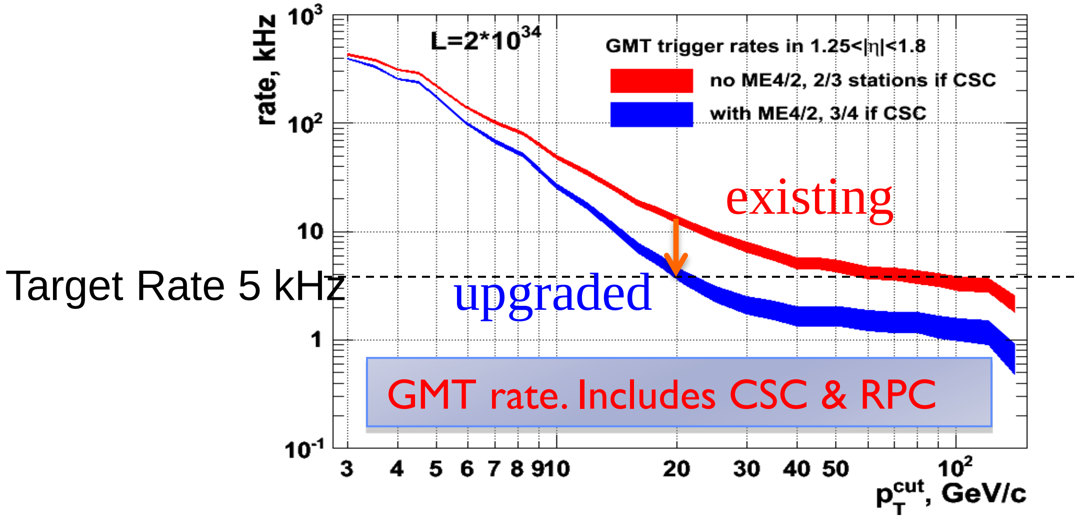
(*notable improvements over design performance :pixel tracker, HCAL readout & L1 trigger)*

Phase 1 upgrade is underpinned by the work planned for LS1 – well underway.
will continue: in year-end stops, in shutdown LS2 & parallel with data collection

Muon detector

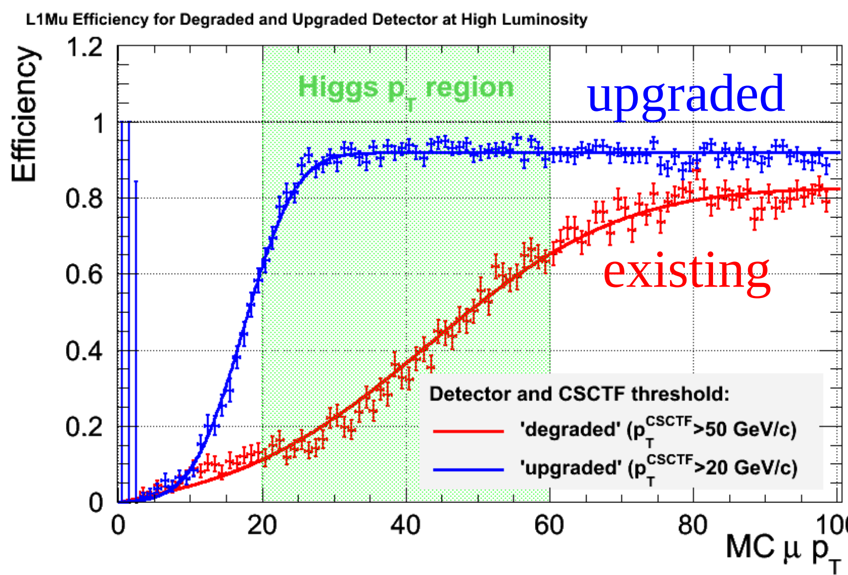
Endcap : complete TDR design in LS1 -- needed for nominal lumi and above.





4'th station (CSC & RPC) & 1'st station (CSC)

- L4 restores control of trigger rate via p_T threshold.
- new 14m shield disk: protects new L4 station

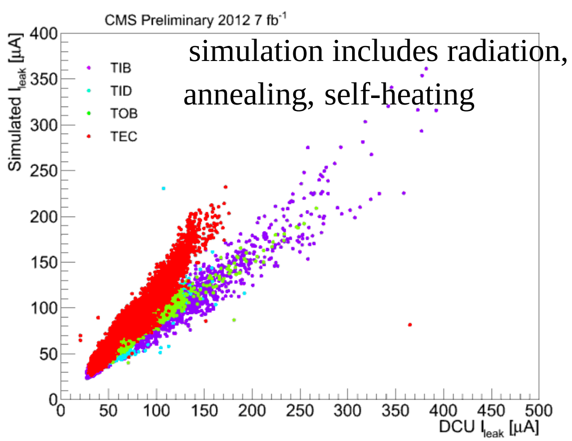


1st CSC station; restore de-scoped granularity
enhance rate capability

Barrel: on board electronics mods **in LS1**

partially replace obsolete trigger cards & move key readout card out of expt cavern (maintainability)

Tracking: strip tracker - colder operation

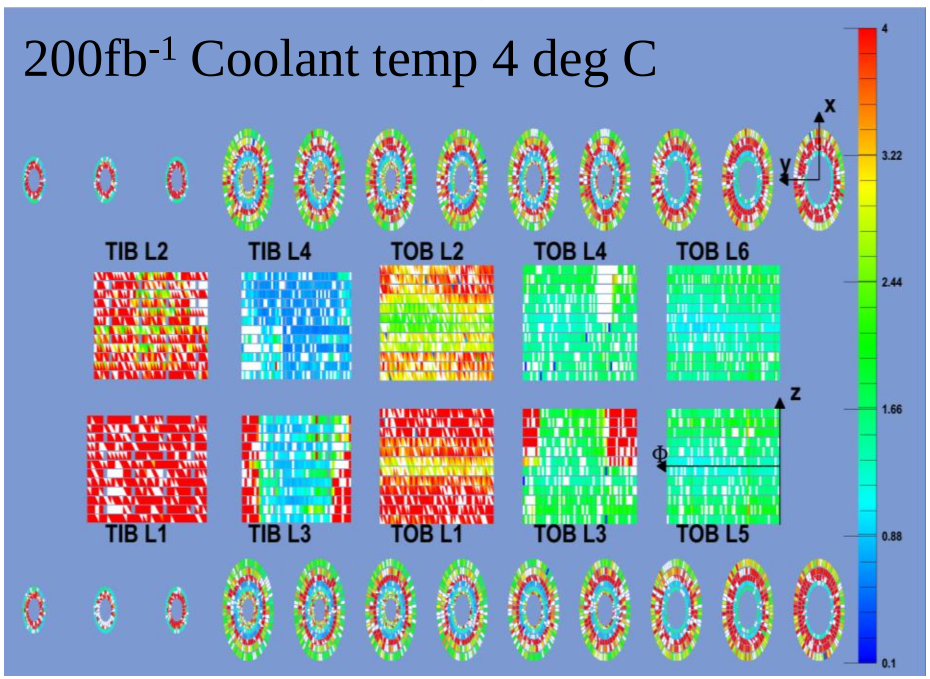


Main concern: increase of sensor leakage current with $\int L.dt$
some modules have compromised cooling
limiting current about 4 mA per module

Sophisticated simulation - reproduces observations quite well
- predicts status after $200fb^{-1}$

—-> Performance badly affected at 2013 working temp (4 deg C)

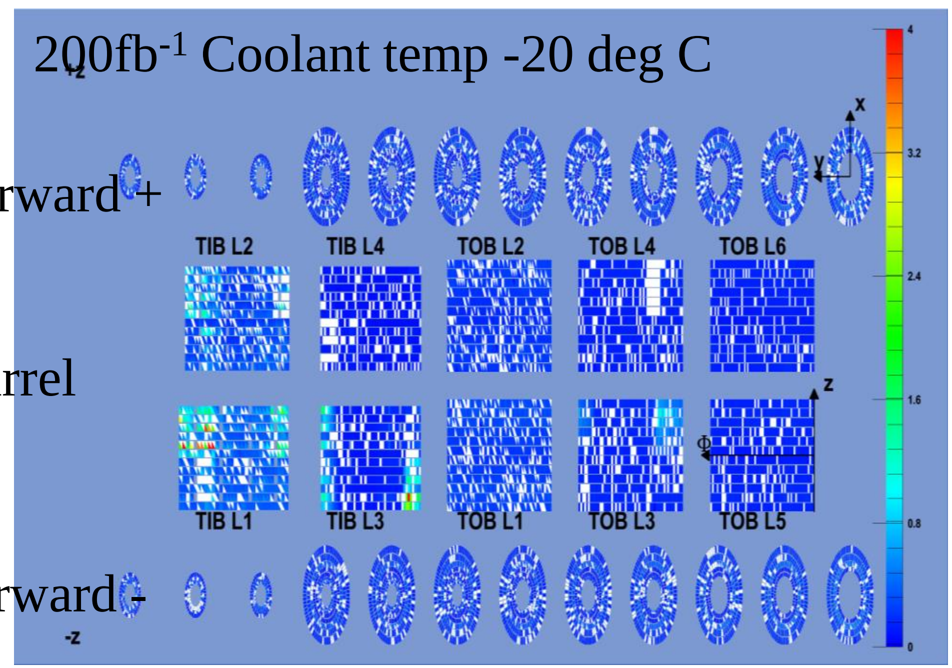
—-> Target - 20deg C for 2015 onwards ***(every 7deg halves $I_{leakage}$)***



forward +

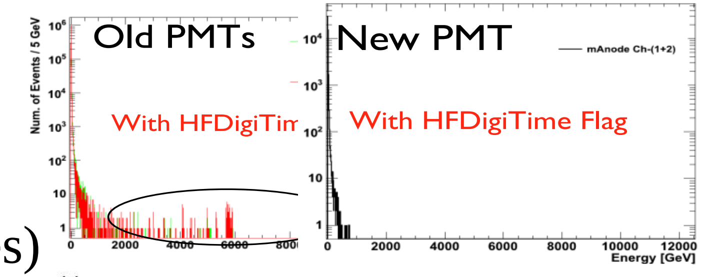
barrel

forward -

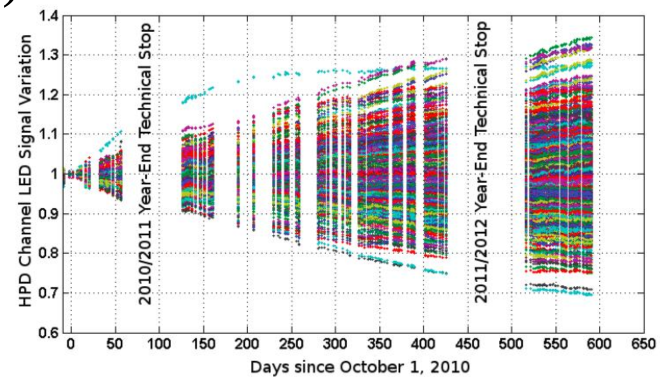


Hadron Calorimetry: change photodetectors & readout

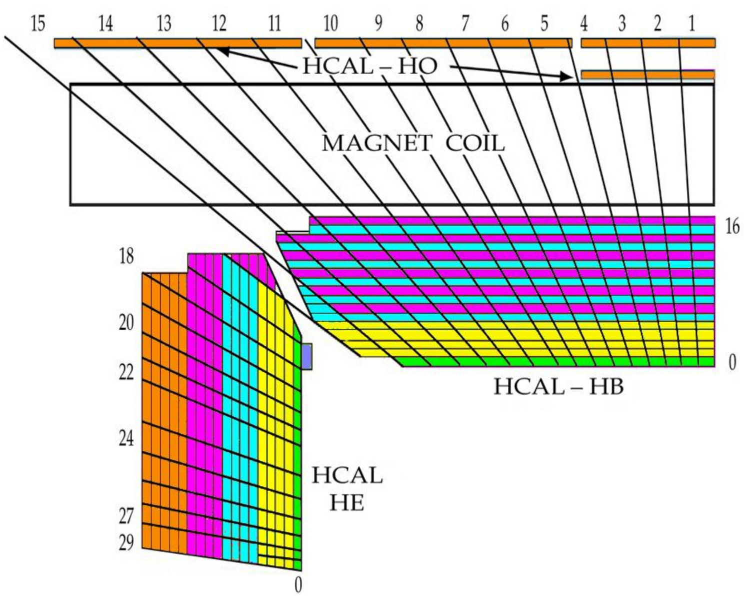
Forward HCAL (HF) : change phototube to multi-anode
Reduce anomalous signals (beam /punch-through)
significantly reduced contamination of "missing E_T"



Outer HCAL (HO): replace HPD's (B-field tolerance issues) by SiPM's (in LS1)
+ new front end package later.

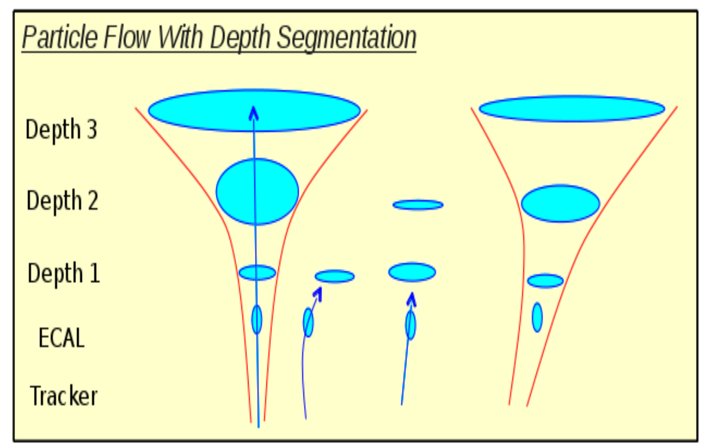


Barrel and Endcap HCAL (HB/HE) :
HPD gain variations worsening: replace by SiPM's

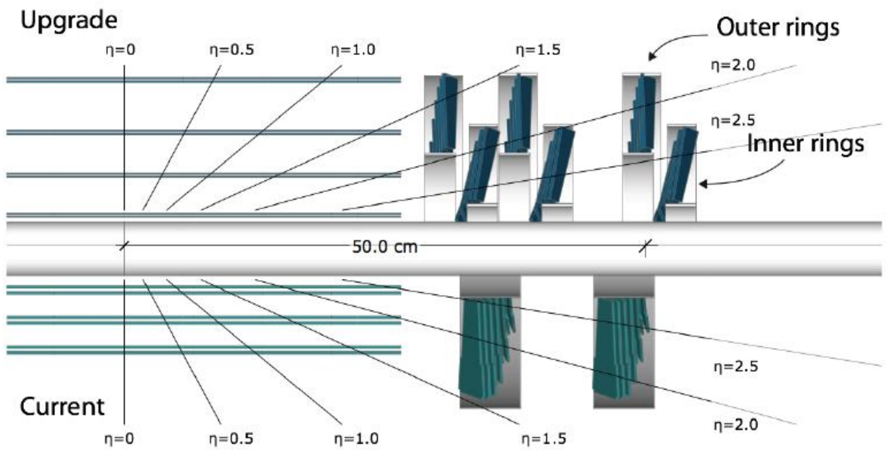


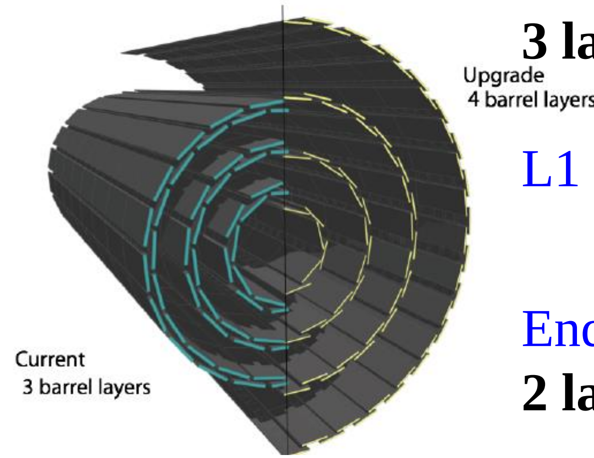
+ new readout, allowing for depth segmentation

- -better background rejection, using timing
- -exploit longitudinal shower development
- -improve calibration, shower recon, isolation, trigger



Tracking: pixel tracker upgrade





Barrel:

3 layers ––> 4 layers

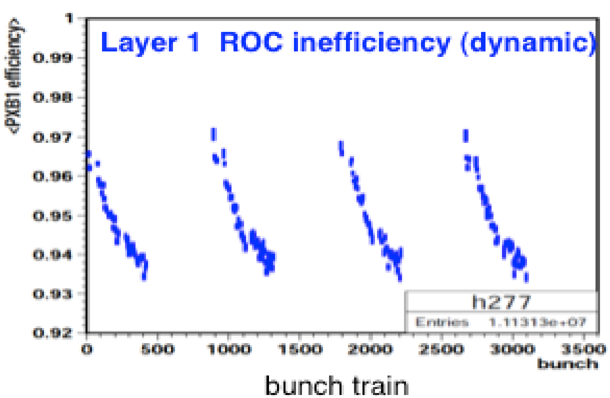
L1 : closer to beamline

: replaceable (250fb^{-1}?)

Endcap:

2 layers ––> 3 layers

Chip buffer depth limitation



Cure high data rate limitation in existing detector

More robust tracking (efficiency, track seeding, impact parameter resolution, lower fake rate) especially valuable at high pileup.

Dramatically reduced material, especially in fwd direction.

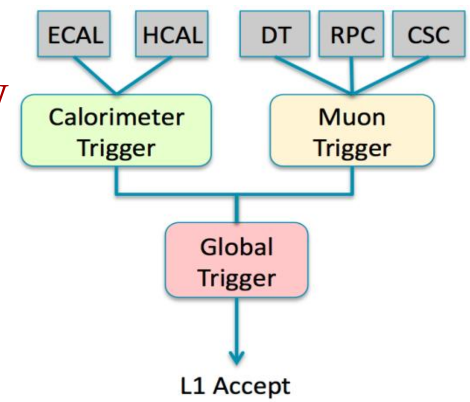
Install in 2016-17 end-of-year stop

but, depends on new infrastructure installed in LS1:

- reduced diameter central beampipe
- two-phase CO_2 cooling plant and distribution.

Level 1 Trigger

Front-end electronics currently limits the L1-trigger rate to <100 kHz.
Upgrade to keep same physics acceptance (**Higgs** & Searches!) as now
at nominal E_{cm} & 2.5 x nominal lumi & <pile-up> =70, until LS3



Target improvements:

- e and γ isolation, with pileup subtraction
- jet finding, with pileup subtraction
- tau finding, with much narrower cone
- muon p_T resolution in difficult regions
- calorimeter isolation of muons, with pileup subtraction
- global trigger: bring the HLT functionality to L1

Implementation:

Upgrade entire L1-Trigger using 3 standard types of boards

-high bandwidth (10Gb/s) optical links for all I/O

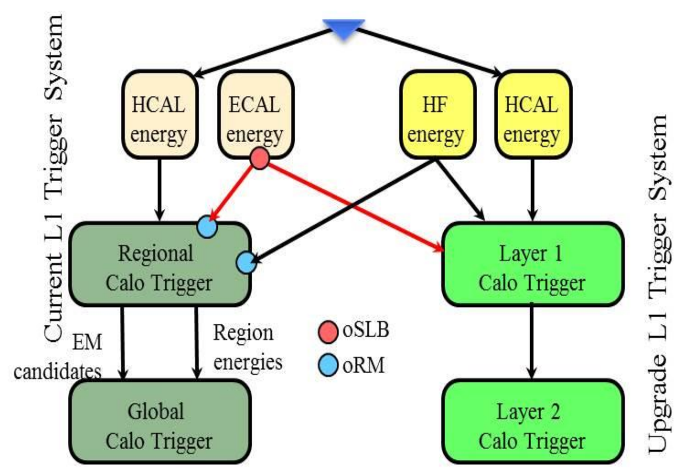
-large FPGAs (Xilinx Virtex-7) and memory

-all in industry standard μTCA architecture

—> more compact, more capable, more flexible

Multi-stage upgrade, keeping current trigger in parallel

eg Calorimeter trigger



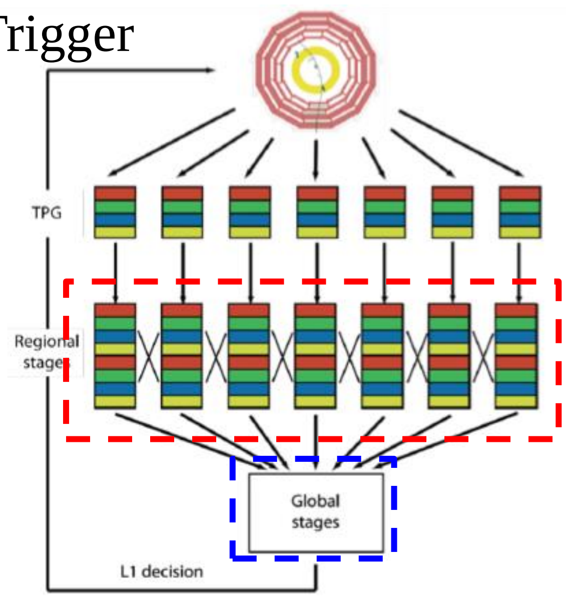
Level 1 trigger: details

- Calorimeter Trigger: Higher granularity, improved algorithms (isolation, feature information), calorimeter & muons integrated for μ isolation
- Muon Trigger: Consolidated track-stub finding, (from DT,CSC and RPC segments) improved coverage for overlap regions, more "roads"
- Global Trigger: More powerful object algorithms with larger FPGAs and LUTs

Flexibility: different architectures possible by re-configuring FPGA's

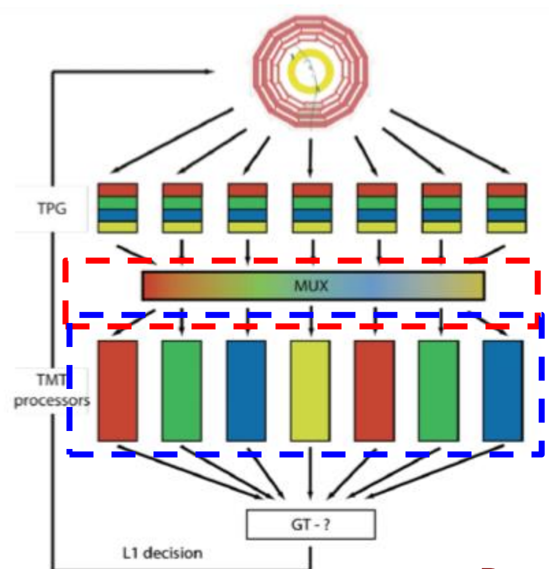
eg Calorimeter Trigger

Fully Pipelined Calorimeter Trigger



Similar to current L1
All algorithms applied in regions

Time Multiplexed Calorimeter Trigger



Layer 1

Layer 2

Upgrade baseline

Demux

Stream entire event to each processor
Each processor runs every algorithm

Phase 1: Computing for event reconstruction

Compared with 2012, using same algorithms:

CPU needed in 2015 [assume 1.5 x 10^{34} $cm^{-2}s^{-1}$ (25ns)]

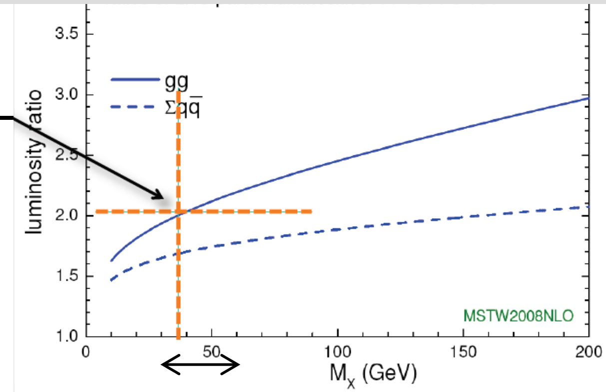
x 2 (at least) from trigger rate (8TeV ––> ~ 14 TeV)

x 2 from out of time pile-up (or lumi levelling)

x 2.5 from in-time pile-up

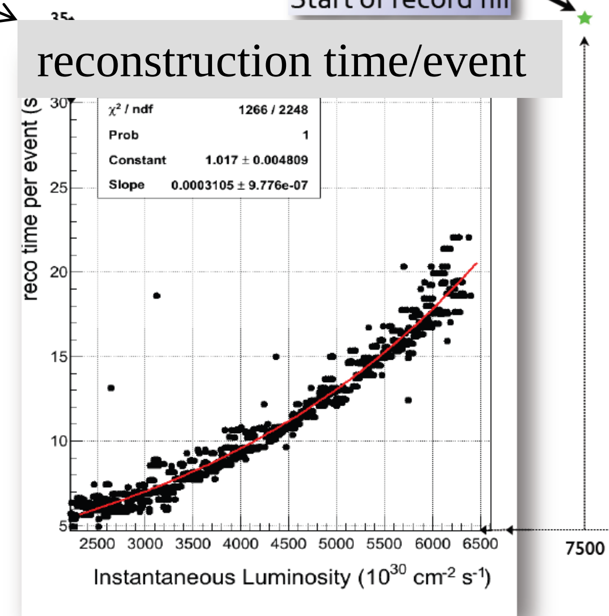
TOTAL x 10 more CPU needed!!!

Parton luminosities 8TeV/14TeV



Off the chart: Start of record fill

reconstruction time/event



Tackle by:

Improving trigger resolution= selectivity : better signal/background

Rewrite core software: more performant, adapted for parallelism

Automate resource allocation for higher time efficiency

Make use of opportunistic computing resources (cloud)

––> aim for x 5 via these improvements

––> x 2 to find from increased dedicated computing resources

Other Phase 1

During LS1:

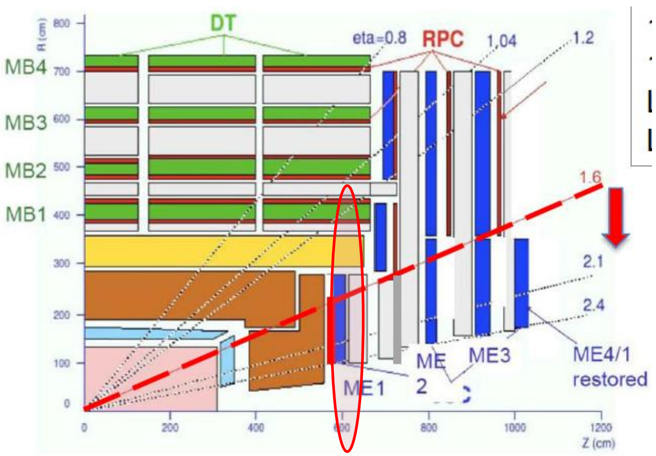
vital work on common systems to underpin reliability & longevity + make provision for detector upgrade

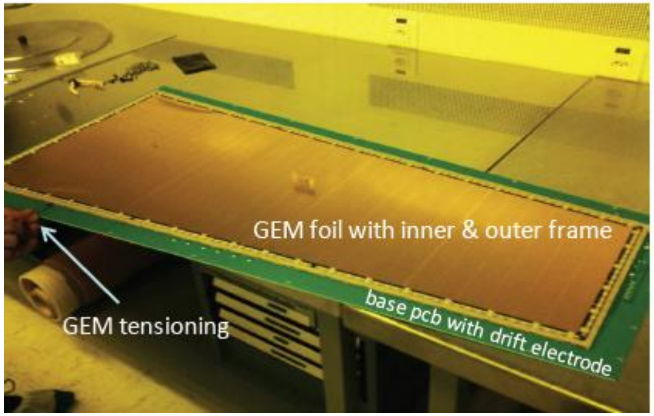
- -magnet cryogenics and cooling
- -beampipe
- -opening/closing/moving system
- -electrical system UPS extension
- -radiation shielding
- -beam and luminosity monitors

comprehensive DAQ & controls revision with up-to-date electronics & provision for Phase 1 upgrade detectors

Proposals under Review:

Addition of GEM layer to 1'st endcap muon station in LS2.





Technology likely to also find application in Phase2

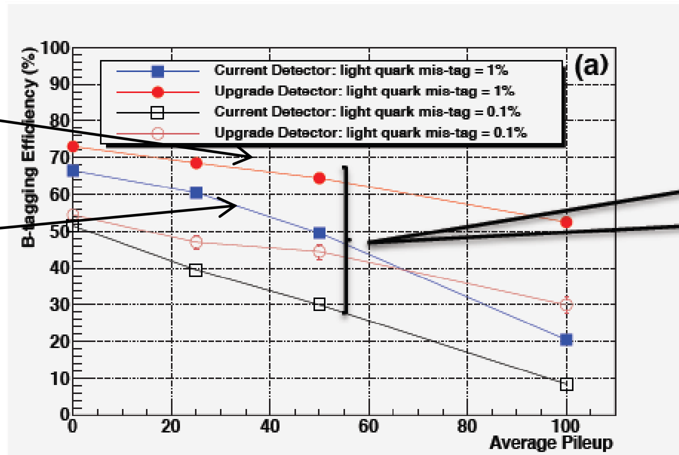
Proton spectrometer in 200-240m region
with precision tracking and timing to measure the scattered protons

Phase 1 improvements: sample performance

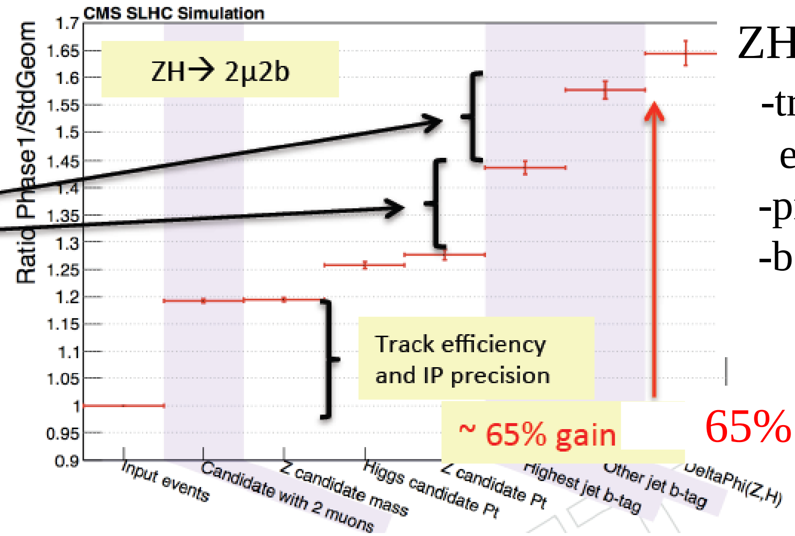
Pixel

upgrade

current

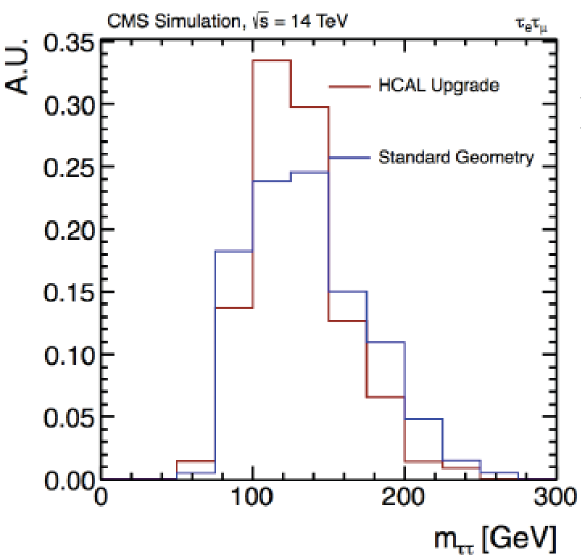


b-tag efficiency vs pile-up



ZH —> μμbb
- -tracking efficiency
- -precision in i/p.
- -b-tag efficiency

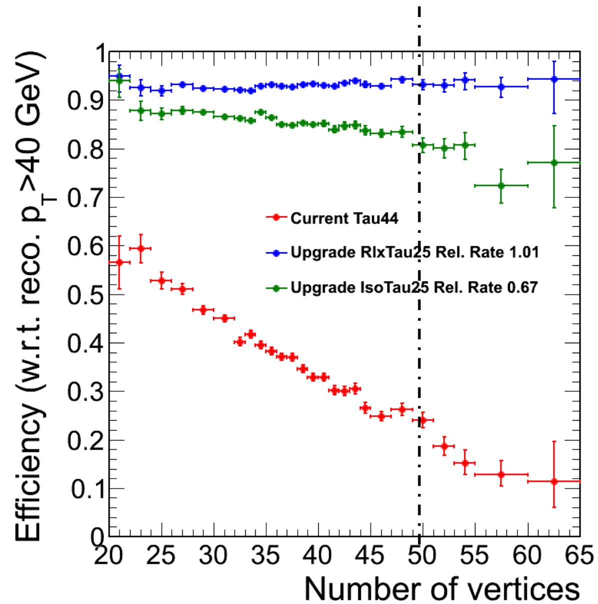
65% gain in effic.



HCAL electronics

H —> tau tau (VBF)
- -better MET resolution
- -forward jet tagging
- -better lepton id

25% better resolution
sig/backgr x 2.4



L1 trigger

efficiency of an L1 tau trigger (cf reconstr) vs pileup

x 3.5 @ 50 pileup

>300fb^{-1} —–> 3000fb^{-1} ?

Data from 2015+ —–> new pointers to physics reach expected from further x 10 in ∫L.dt.

..but a reliable focus would be continued studies of the "Higgs" already found with < 30fb^{-1}

i) super-precise measurements of the relative strengths of the couplings

From CMS input to ESPP

CMS (prelim)	Uncertainty (%)			
Coupling	300 fb^{-1}		3000 fb^{-1}	
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Systematics: Unchanged Scaled

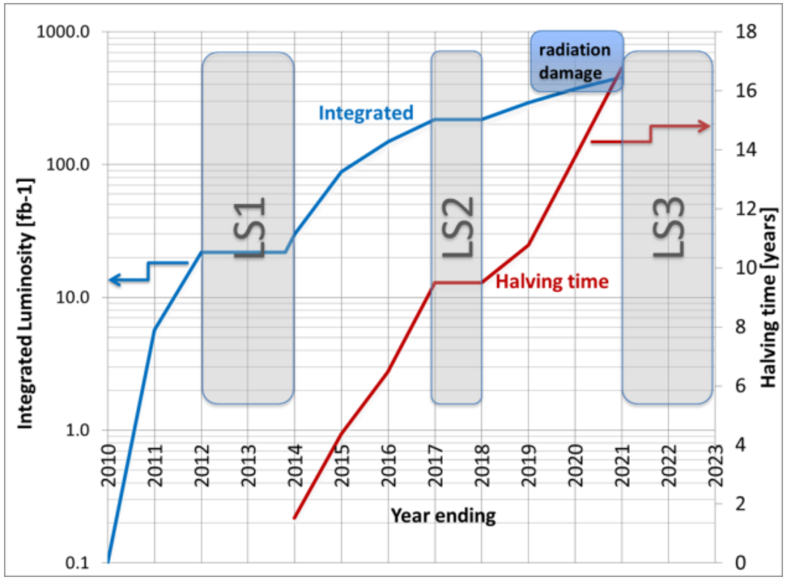
i)Preliminary simulations show that the factor 10 in lumi could dramatically reduce uncertainties.

Evolution of systematics is important:
Assume theory systematics could be halved
1/√lumi achievable if determined from data?

ii) continued search for rare decay modes

ii) measurement of the self coupling (maybe 3 σ measurement per expt for 3000fb^{-1})?
(the strength of the Higgs potential itself)

HL-LHC : 3000 fb^{-1} by 2030's…



"Halving-time" needed to reduce statistical errors by a factor of 2 becomes very long after LS3.

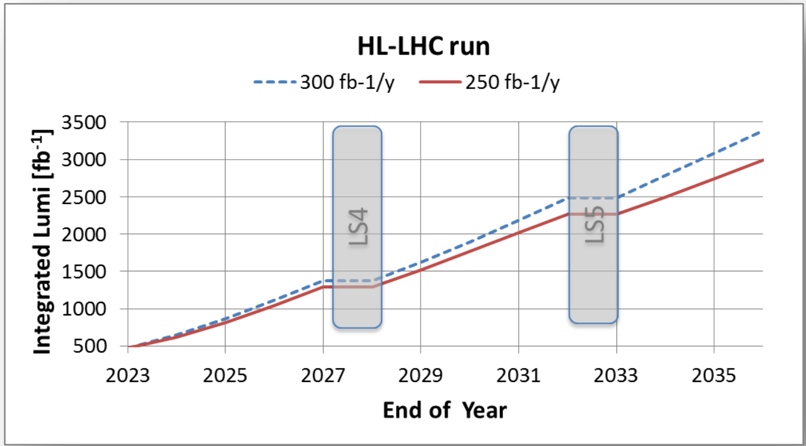
For 3000fb^{-1}, need to upgrade LHC —–> HL-LHC

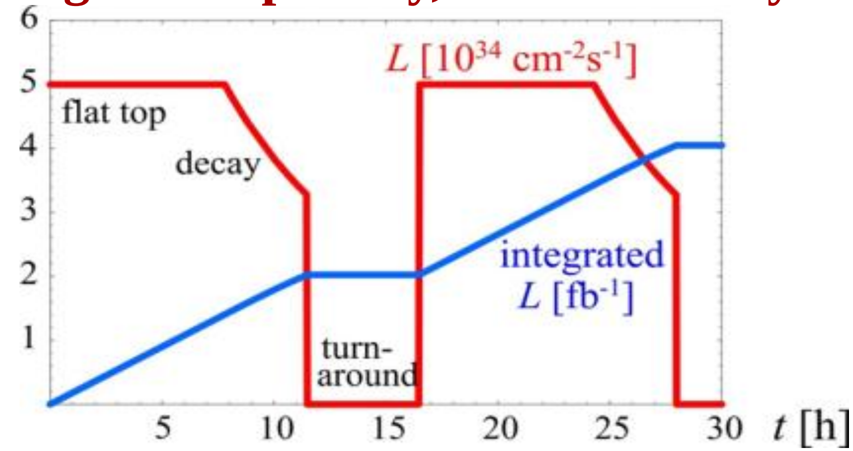
—–> New low-β quads with higher aperture
New collimator system
Uprated radiation tolerance, abort system

—–> Luminosity levelled to limit max pile-up
Bunch-crossing adjustment (crab cavities)

—–> Luminous region tuned for min pile-up density

Target 3fb^{-1} per day, 60% efficiency





CMS for HL-LHC era : Phase 2 upgrades

Phase1 upgraded detector: designed to survive L= 2.5 10^{34} $cm^{-2}s^{-1}$ (25ns) and $\int L.dt \leq 500fb^{-1}$

—> soft threshold for major changes due to radiation damage expected at t ≥ LS3.

Silicon Tracker: increase in leakage current (mitigated from LS1 by lower temperature)
increase in depletion voltage (mitigated by low "temperature history")
eventually cannot be compensated for an increasing number of modules

Calorimeters: darkening of scintillating crystals (ECAL), tiles (HCAL) and fibres (HF)
routinely compensated now, but *eventually lack of light destroys performance*

—> rates and (sustained) pileup at HL-LHC begin to compromise trigger & event recon.

L1 Trigger & HLT action needed to maintain efficiencies (down to low p).
- integrate tracking info into L1-Global Trigger Associated memory processors?
- increase L1 latency (20 μs ?) and output rate (1 MHz?) + HLT output rate (1kHz?)
  ⤷ requires revising detector front-end electronics - costly & time-consuming.

New or extended detectors, conceived for particle flow and pile-up mitigation

Phase 2 upgrade being researched now [Tech. Proposal 2014]
aim for a system levelled 5.0 x 10^{34} $cm^{-2}s^{-1}$, $\int L.dt \leq 3000fb^{-1}$, $<\mu>$ ~120 -140

Phase 2: new strip tracking system

Rad-tolerant sensors + ASICS in 65 nm process

Increased granularity and spatial resolution
- resolve up to 200 collisions per bx
- occupancy maintained at few %
- better high p_T performance

Reduced material (fewer layers, CO_2 cooling)
- better low p_T performance
- reduced secondary interactions

Input to L1 trigger : enhance event recon. at L1

-reject low p_T ($\leq$ 2GeV) charged particles locally

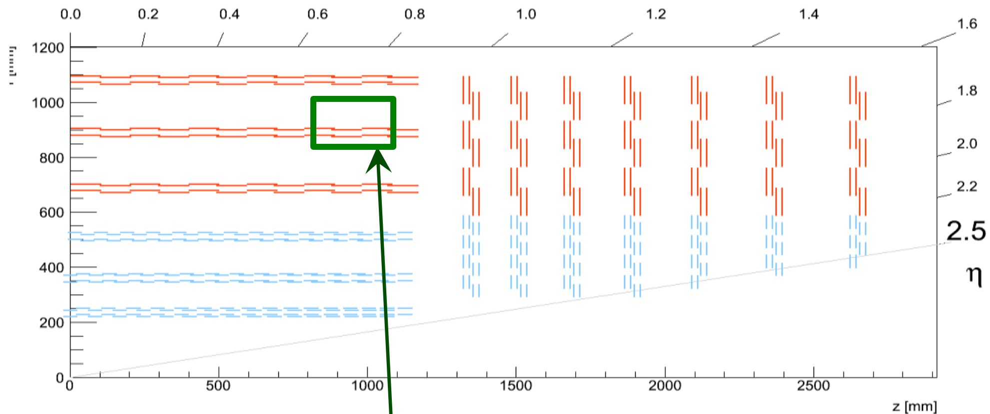
-read-out accepted signals every bx (ie at 40MHz)

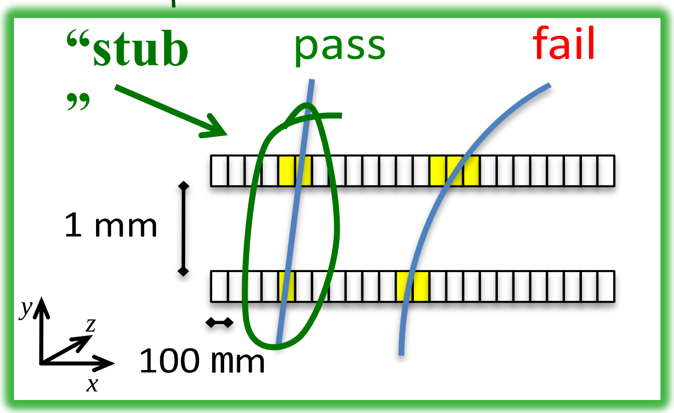
-reconstruct tracks above 2GeV @ L1

(few % p_T resolution, ≤1mm z resolution at ip)

Various geometries being investigated, eg: 6(7) layers arranged in superlayer pairs,

- option for "long barrel"

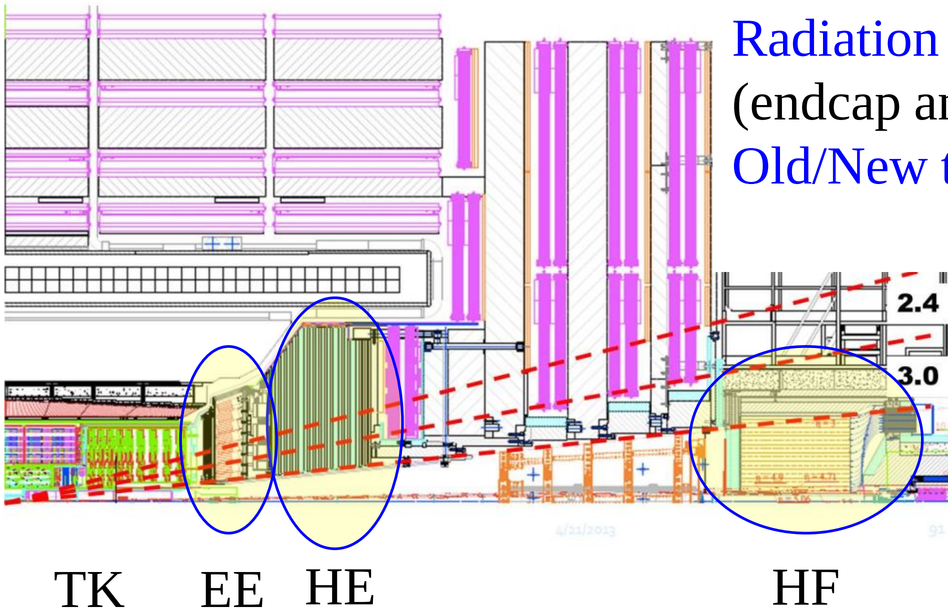




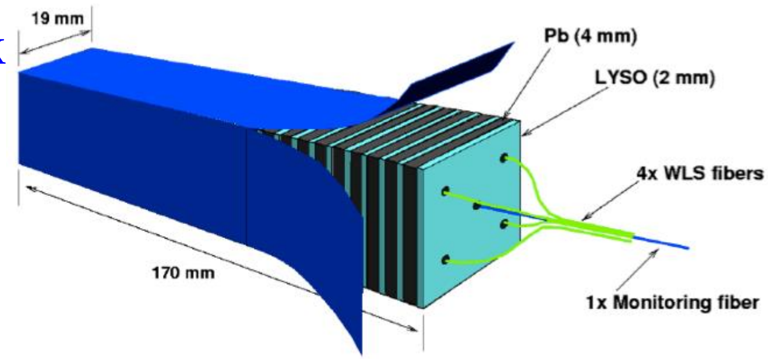
—> control μ,e,jet, E_T miss rates at hi lumi and pileup

Phase 2: endcap & forward regions

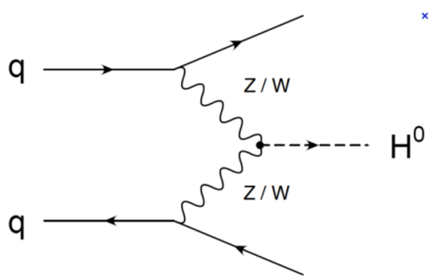
Radiation damage & pileup effects increase with η.
(endcap and forward calorimeters will need to be revised).
Old/New technology options: R & D ongoing
performance being simulated



eg Shashlik for EE

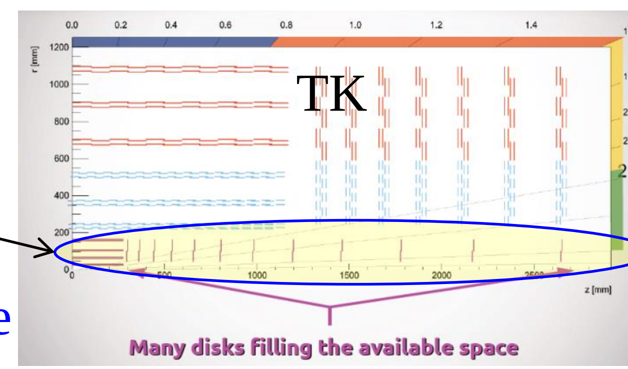


eg sensors with 10ps timing to combat pileup

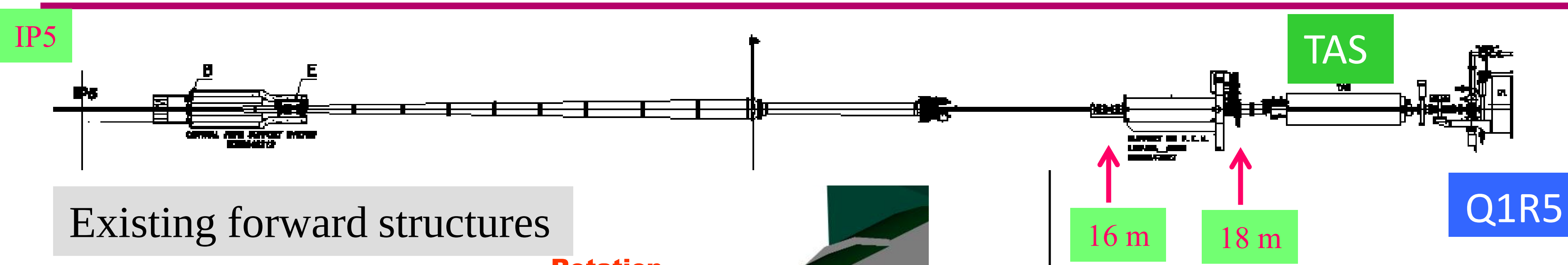


VBF process and $W_L W_L$ scattering:
(tag jets peak at current HE/HF boundary)

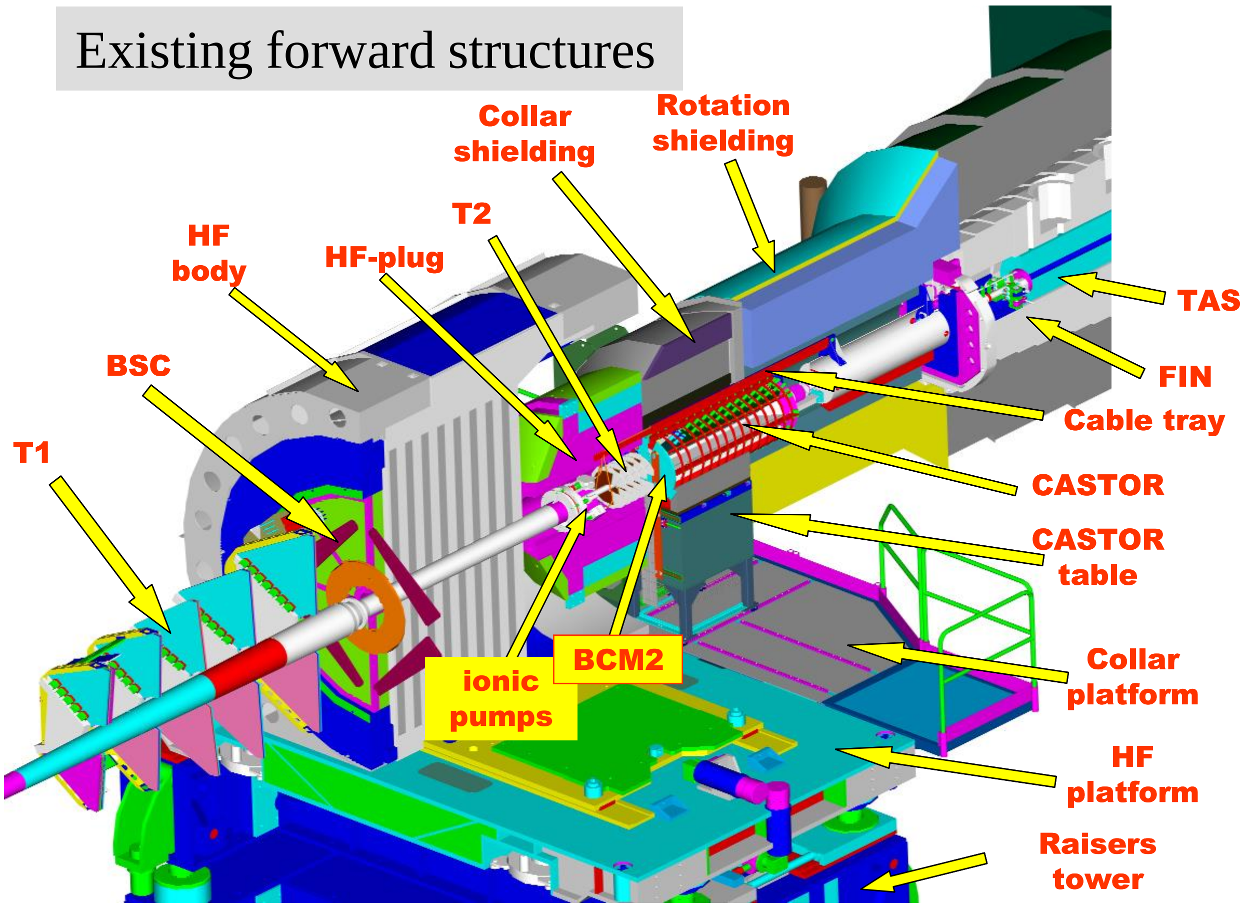
Consider extending tracking to higher η
to assist in pile-up mitigation (particle flow)
& link up with possible extended μ coverage
to improve acceptance for H ––> 4 leptons



Phase 2: Forward regions & Machine Interface



Existing forward structures



LS 3 Mandatory:

-new Q1,2,3 with larger aperture

—-> Larger aperture TAS

—-> Larger aperture CT2 & FWD pipes (to match larger aperture quads)

—-> Shielding revision for larger TAS and for 7 x 10^{34}

LS 3 Likely:

-Revision of beam monitoring

-Re-work of support structure, opening system & maintenance scenarios. (Contemporary with likely replacement of endcap/forward calorimeters, their possible extension to higher η, plus addition of tracking/timing detectors)

Phase 2: other considerations

High bandwidth DAQ evolution matched to upgraded detector back end electronics

HLT Architecture evolution :multi-core CPUs and Moore's Law? or dedicated processors?
(standard multi-CPUs likely OK – but work to optimize code)

Corresponding worldwide computing infrastructure

Obsolescence & end of lifecycle replacements: control systems technology
common systems & infrastructure

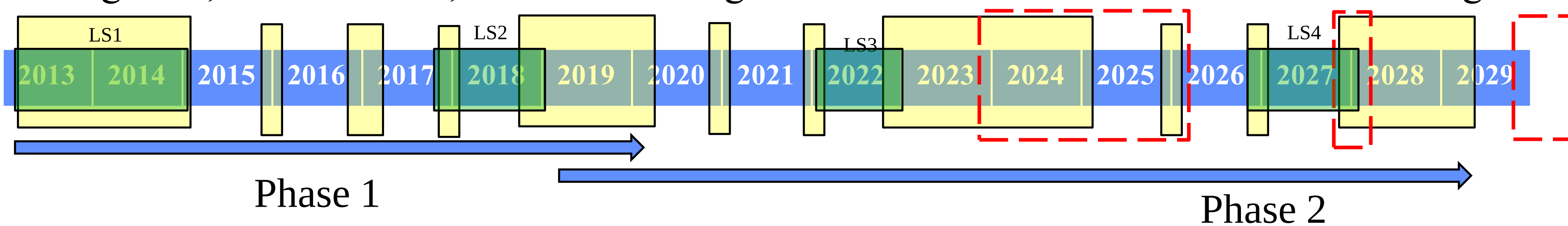
Practical timeframe for Phase 2 upgrades influenced by:

Physics landscape revealed at Ecm = 13-14 TeV

Updated estimates of LHC performance evolution + Phase 1 detector longevity

ALARA : forward systems, beampipe, TAS and shielding highly activated at HL-LHC.
—> replace/revise as early as practicable … or after extended cooling time.

Logistics, resource flow, shutdown timing/duration realities…variants not hard to imagine:



Conclusion

Excellent LHC performance delivering ~1/10 of the nominal ∫L.dt target,
- CMS detector system and analysis chain performed as well or better than designed

Now anticipate intensive study of a Higgs boson at low mass + search programme
—–> maintain present performance over a huge dynamic range,
in face of increasing radiation damage & pile-up.

Taking account of this & known physics landscape, plus operating experience in 2010-12,
CMS is making a well-defined programme of "Phase 1"upgrades
—–> exploit the predicted LHC performance in delivering 300-500 fb^{-1}
—–> consolidate the prospects for further exciting discoveries

For even higher precision measurements and the search for very rare processes
—–> need v. large amounts of high quality *recorded and analysable* (integrated) luminosity
. —–> HL-LHC matched by Phase 2 detector upgrades now under study
After Phase 2 upgrades. including replacement of radiation damaged detectors,
—–> CMS capable of recording up to 300 fb^{-1}/yr in the harsh environment of HL-LHC .

The enthusiasm, dedication and expertise of CMS members will continue to be the key ingredient for success!

Acknowledgements & references

Acknowledgements
I have liberally borrowed material from many CMS collaborators, but particular thanks to Dave Barney, Didier Contardo, Joe Incandela, Jordan Nash, Jeff Spalding, Frank Hartmann.

Some Relevant references:

CMS Technical Proposal for Phase 1 Upgrades:
https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=2717&version=15&filename=p1utp1a_auto.pdf

CMS Phase 1 Pixel Detector Upgrade Technical Design Report:
https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=5669&version=22&filename=pixuptdr_final.pdf

CMS Phase 1 Hadron Calorimeter Upgrade Technical Design Report:
https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=5952&version=66&filename=hcaluptdr-final.pdf

Additional Material

Assume we are seeing the SM Higgs –
Define a general set of Coupling scale factors

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2$$

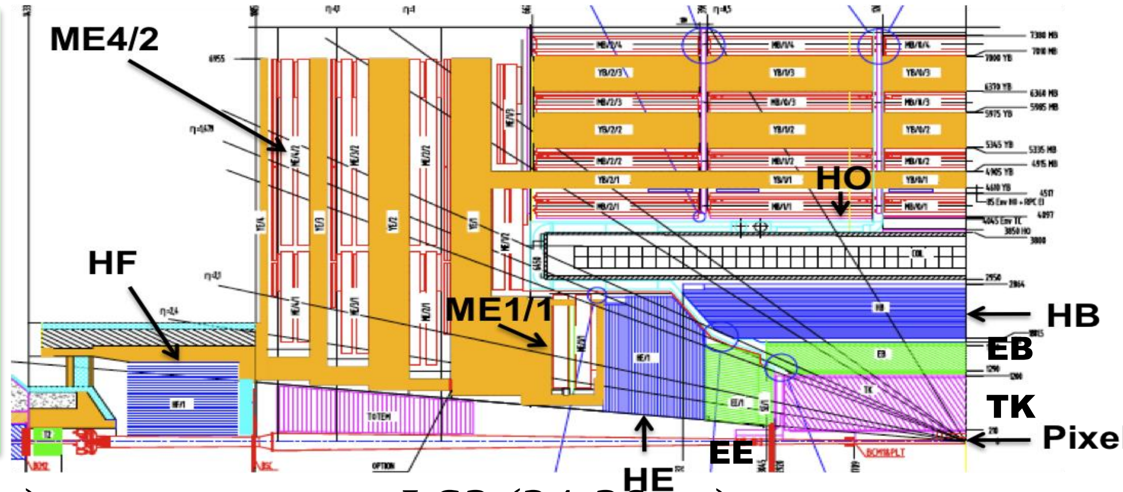
$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

http://arxiv.org/abs/1209.0040v1

CMS detector upgrades summary

Phase 1: in production for LS1

- Complete muon coverage (4'th endcap layer)
- Improve muon operation (1'st endcap layer), and barrel drift tube electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPM)
- DAQ1 → DAQ 2
- Consolidate common systems for long-term



LS1(22mo) LS2 (14mo) LS3 (24-36mo)

Phase 1: up to end LS2 (LOI app. Sep 12)

- TDR's approved:4 layer Pixel tracker (install in YEETS 2016-17), HCAL electronics/granularity
- TDR in 2013: L1-Trigger
- Preparatory work during LS1
  - New beam pipe (for 4 layer pixel tracker)
  - Test slices: *Pixel(CO2 cooling), HCAL, L1-trig*
  - Install ECAL optical splitters
    - *L1-trigger upgrade in parallel with run.*

Phase 2 Upgrades (Tech.Proposal in 2014)

- Tracker Replacement, Track Trigger
- Endcap/Forward region improvements : Calorimetry, Muon system and tracking
- Further Trigger upgrade
- Further DAQ upgrade
- Many obsolescence/lifetime replacements
- Shielding/beampipe for higher LHC aperture

LHC (nominal) vs HL-LHC (25ns) parameters

https://espace.cern.ch/HiLumi/PLC/default.aspx

Parameter	nominal	25ns
N_b	1.15E+11	2.2E+11
n_b	2808	2808
N_{tot}	3.2E+14	6.2E+14
beam current [A]	0.58	1.11
x-ing angle [μrad]	300	590
beam separation [σ]	9.9	12.5
β^* [m]	0.55	0.15
ε_n [μm]	3.75	2.50
ε_L [eVs]	2.51	2.51
energy spread	1.20E-04	1.20E-04
bunch length [m]	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	18.5
IBS longitudinal [h]	61 -> 60	20.4
Piwinski parameter	0.68	3.12
Reduction factor 'R1*H1' at full crossing angle (no crabbing)	0.828	0.306
Reduction factor 'H0' at zero crossing angle (full crabbing)	0.991	0.905
beam-beam / IP without Crab Cavity	3.1E-03	3.3E-03
beam-beam / IP with Crab cavity	3.8E-03	1.1E-02
Peak Luminosity without levelling [$cm^{-2}\ s^{-1}$]	1.0E+34	7.4E+34
Virtual Luminosity: Lpeak*H0/R1/H1 [$cm^{-2}\ s^{-1}$]	1.2E+34	21.9E+34
Events / crossing without levelling	19 -> 28	210
Levelled Luminosity [$cm^{-2}\ s^{-1}$]	-	5E+34
Events / crossing (with leveling for HL-LHC)	*19 -> 28	140
Leveling time [h] (assuming no emittance growth)	-	9.0

Pile-up

Often quantified as: mean of Poisson distribution of number of events per beam crossing:

$$\mu = \sigma_{inel} \frac{L}{k_b\, frev}$$

Lumi, # bunches, 11.245 kHz

σinel ? —> should be x-section for processes which can give hits in detector
eg CMS uses an "effective σ *inel*" of 69.4 mbarn
—> best agreement between simulated & observed distribution of # of vertices.

Sensitivity of a detector system, including online triggering, to pile-up is:

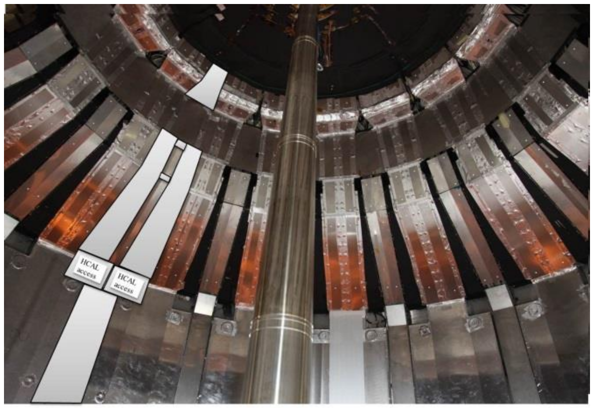
- not linear
- different for different experiments
  ..or even different detectors within the same experiment
- not well described by the mean of a pile-up Poisson distribution
  .. tails are particularly troublesome

Effect on physics efficiencies/backgrounds etc depends heavily on the process being studied.

Density of event vertices along luminous region (& in precise collision time) is important
—> analysis aims to associate each track/cluster to vertex with particular z and t

Tracking system: colder operation

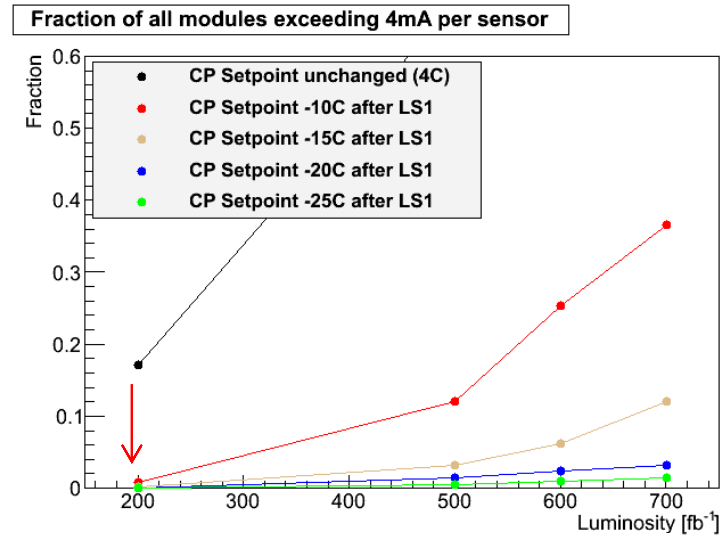
Humidity seals



Dry gas plant (N_2 or air)

LS1 programme includes

- revision of the $C_6 F_{14}$ cooling plant & distribution
- major re-sealing work to control the environment (humidity) inside the tracker volume, with follow-up possible in LS2.
-installation of dedicated dry gas production plant.



Tracking efficiency simulation:

200fb^{-1}, pileup 50, using estimate of max number of "dead" modules

––> upgraded pixel compensates most of the predicted loss.