The CMS Upgrade

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for the CMS Collaboration

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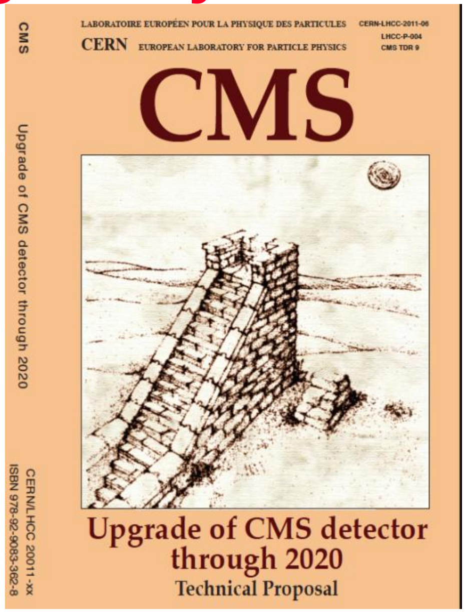
Outline

1. LHC performance so far
2. <u>LHC luminosity upgrade plan</u>
3. CMS at Present: what it does and goals of the upgrade
4. Challenges of high luminosity
5. The CMS upgrade plans, Phase 1 – through early 2020s
    1. Muon System
    2. Pixel Detector
    3. Hadron calorimeter
    4. Trigger
6. A peek at Phase 2: after the early 2020's
    1. Tracking Trigger
    2. Forward Calorimetry
3. Conclusions



http://cdsweb.cern.ch/record/1355706?ln=en

1. Luminosity at the LHC

The quantity "Luminosity" captures many machine parameters into one number with units of $cm^{-2}s^{-1}$ such that

 # interactions = Luminosity x cross section (cm^2) x running time(s)

$$L = \frac{N_b^2 n_b f_r \gamma}{4\pi \varepsilon_n \beta^*} F$$

- Each beam consists of many bunches (N_b) ~2808, a few cm long, 25ns spacing
- To maximize the interaction rate
  - Maximize the number of particles in each bunch
  - Minimize transverse size (εxβ^*): highest density
  - Don't miss – collide close to 0º (F~1)
- At a given luminosity, fewer bunches →more interactions /bunch (a.k.a pileup)
  - Several interactions/bunch is a challenge to the experiment as they are all superimposed

Symbol	Quantity	Affected by
N_b	Number of particles per bunch	Injector chain
n_b	Number of bunches	Limited by electron cloud effect
f_r	Revolution Frequency	Property of LHC
ε_n	Normalized emittance	Injector chain
β^*	Beta function value at Interaction Point (IP)	Interaction region focusing system
F	Reduction factor due to crossing angle	Beam separation schemes

LHC design L=10^{34} cm^{-2} s^{-1}, ~20 interactions/crossing

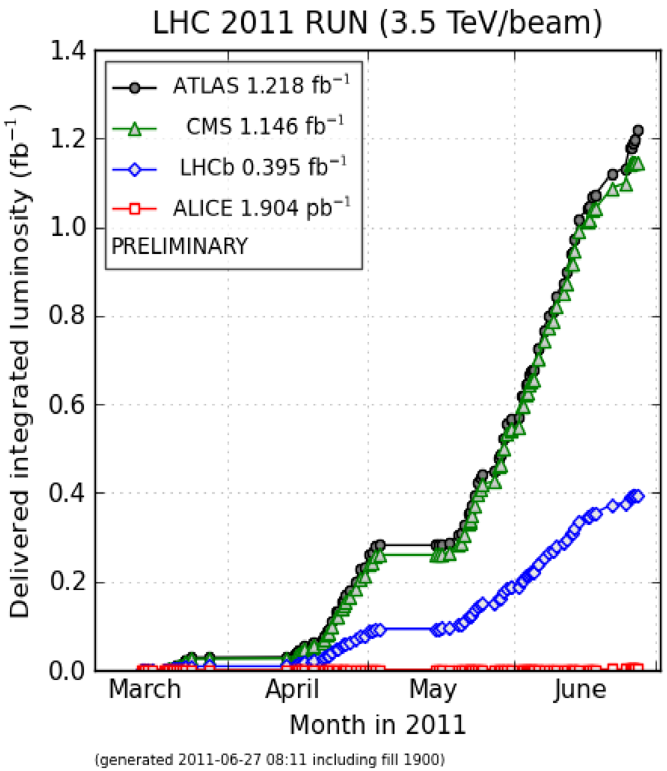
- Giving tens of interactions for a process with σ=1 fb per year

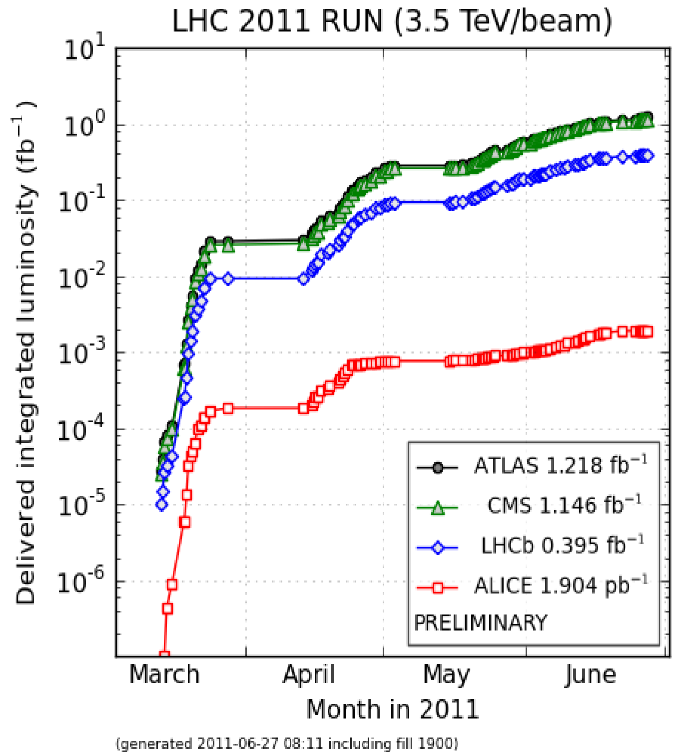
After CM energy, luminosity is the most important for physics

Luminosity calculator: http://lpc.web.cern.ch/lpc/lumi.html

1. LHC Progress

Integrated luminosity delivered to CMS >1fb^{-1} !





- Goal for this year was 1 fb^{-1} – we are already there!
- The LHC can now do ~1 fb^{-1}/month
- If the machine continues to progress we might reach 3-5 fb^{-1} by the end of 2011 and >10 fb^{-1} by end of 2012

1. LHC Status

- **Machine Development main achievements:**
  - **1380 bunches (1318 colliding at CMS) with 50 ns spacing;**
  - **Peak luminosity 1.27×10^{33} $cm^{-2}s^{-1}$.**
- **Bunches with a charge of 2.5E11 have been tested and they have worked well (design is 1.15E11).**
  - **Emittances of 1.5 μm(2.5 is design) achieved**
  - **Recent development: β^*= 1m could be possible this year.**
  - **No apparent showstopper for interbunch spacing of 25ns (tests will be done over summer)**
- **This machine could potentially reach (exceed) nominal luminosity very soon and go beyond it in the next run**
  - **But pile-up conditions could be very challenging**

> **•The LHC upgrade will increase the luminosity of the machine, producing more rare processes to study. This is simpler, less expensive and less disruptive than increasing the energy which would require all new magnets that are still being developed.**
>
> **•It is harder on the experiments because it implies more pileup!**

2. LHC draft 10 year plan Spring 2011

2. Luminosity predictions July 2010

ICHEP 2010

Super

Year	TeV	OEF	β*	Nb	Ib	Itot	MJ	Peak luminosity	Pile up	pb-1/day	Physics Days	Integrated (fb-1/year)	Total Int (fb-1)
2010	3.50	0.20	2.00	796	8.0E+10	6.4E+13	36.0	1.886E+32	1.264			0.1	0.07
2011	3.50	0.25	2.00	796	8.0E+10	6.4E+13	36.0	1.886E+32	1.264			0.98	1.04
LS 1												0.0	1.0
2013	6.50	0.20	0.55	796	1.15E+11	9.2E+13	96.1	2.632E+33	17.642			8.2	9.2
2014	7.00	0.20	0.55	1404	1.15E+11	1.6E+14	182.5	5.000E+33	19.0000	86.4	240.0	20.7	30.0
2015	7.00	0.20	0.55	2808	1.15E+11	3.2E+14	365.0	1.000E+34	19.0000	172.8	210.0	36.3	66.3
LS 2											0.0	0.0	66.3
2017	7.00							1.000E+34	19.0000	216.0	240.0	51.8	118.1
2018	7.00							1.701E+34	32.3251	411.6	240.0	98.8	216.9
2019	7.00							2.185E+34	41.5198	566.4	210.0	118.9	335.8
2020											0.0	0.0	335.8
2021	7.00	0.20	0.30	2808	1.70E+11	4.8E+14	539.6	4.006E+34	76.1197	692.3	150.0	103.8	439.7
2022	7.00	0.27	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1257.3	220.0	276.6	716.3
2023	7.00	0.27	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1257.3	220.0	276.6	992.9
2024	7.00	0.29	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	1290.0
2025	7.00	0.29	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	1587.1
2026	7.00							5.390E+34	102.4060	1350.5	220.0	297.1	1884.2
2027	7.00							5.390E+34	102.4060	1350.5	220.0	297.1	2181.3
2028	7.00							5.390E+34	102.4060	1350.5	220.0	297.1	2478.4
2029	7.00							5.390E+34	102.4060	1350.5	220.0	297.1	2775.5
2030	7.00							5.390E+34	102.4060	1350.5	220.0	297.1	3072.6

Already surpassed

Almost all of PHASE 1 running expected at peak $L > L_{nominal}$

In PHASE 2 may run with 50 ns bunch interval, so pile up may be 200!

2. Schedule Uncertainties

- The schedule has changed several times already. Other changes are under discussion
- What seems invariant is that there will be three “long shutdowns” of at least 1 year each, now referred to as LS1, LS2, and LS3.

PHASE 1

- LS1 will be for the repair of splices so the LHC can operate at 14 TeV and so it can reach full luminosity
- LS2 will be for experimenters to make changes to cope with peak luminosity $>2\times10^{34}$ cm^{-2} s^{-1} and integrated luminosity >300 fb^{-1}.

PHASE 2

- LS3 will occur after 2020 and there will be major revisions and rebuilds to both CMS and ATLAS to cope with 5×10^{34} cm^{-2} s^{-1} , luminosity leveled with a goal of integrating 3000 fb^{-1}.
  - Both CMS and ATLAS will have to replace the full tracking systems and many other devices
    - May last two years, driven by needs of the experiments

2. Take Home Message

- **The LHC is already a high luminosity machine**
  - **By the end of this year experiments will know lots about operation at high pileup**
- **The LHC is well on the way to achieve and exceed its luminosity goal of 1×10^{34} cm^{-2} s^{-1} with a wide space for optimization and tradeoffs**
- **We do not yet have, but may soon have, definitive information about new physics**

A luminosity upgrade that has been talked about for the last few years now seems to be definitely needed, maybe even sooner than expected!

The ultimate goals of the LHC may be raised if this success continues and may require some re-thinking of the upgrades I will be discussing today.

One can well ask, "how one can even plan under these circumstances?"

3. The upgrade starts with what CMS does today

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	−1	s strange	0.1	−1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	−1	b bottom	4.3	−1/3

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge	Name	Mass GeV/c^2	Electric charge
γ photon	0	0	g gluon	0	0
W^-	80.4	−1			
W^+	80.4	+1			
Z^0	91.187	0			

Heavy objects decay into lighter objects

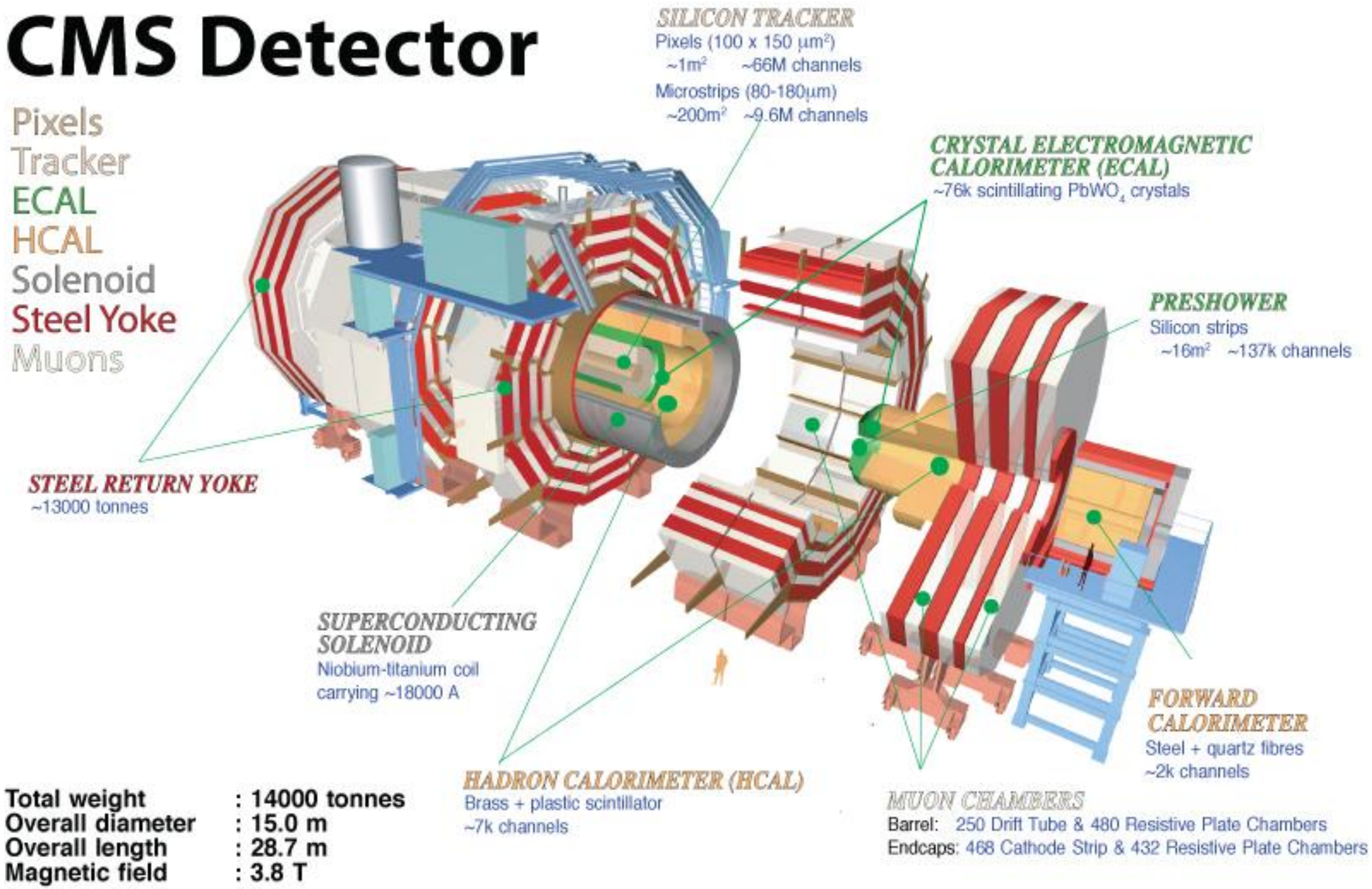
- **The “lighter objects” are the particles of the Standard Model**
  - **Photons, electrons, muons, τ leptons, jets (light quarks u,d, s and gluons)- especially “b-jets”, “charm jets”, “top”, Ws, and Zs**
    - **Only a few particles are stable enough to be measured directly: e,μ,γ, plus some hadrons: pions, kaons, protons, neutrons**
  - **Partons, quarks and gluons, manifest themselves as jets of particles so identifying “jets” and measuring their angle and energy becomes important**
- **It is a requirement for finding new physics to be able to measure all the known SM objects**

3. What else?

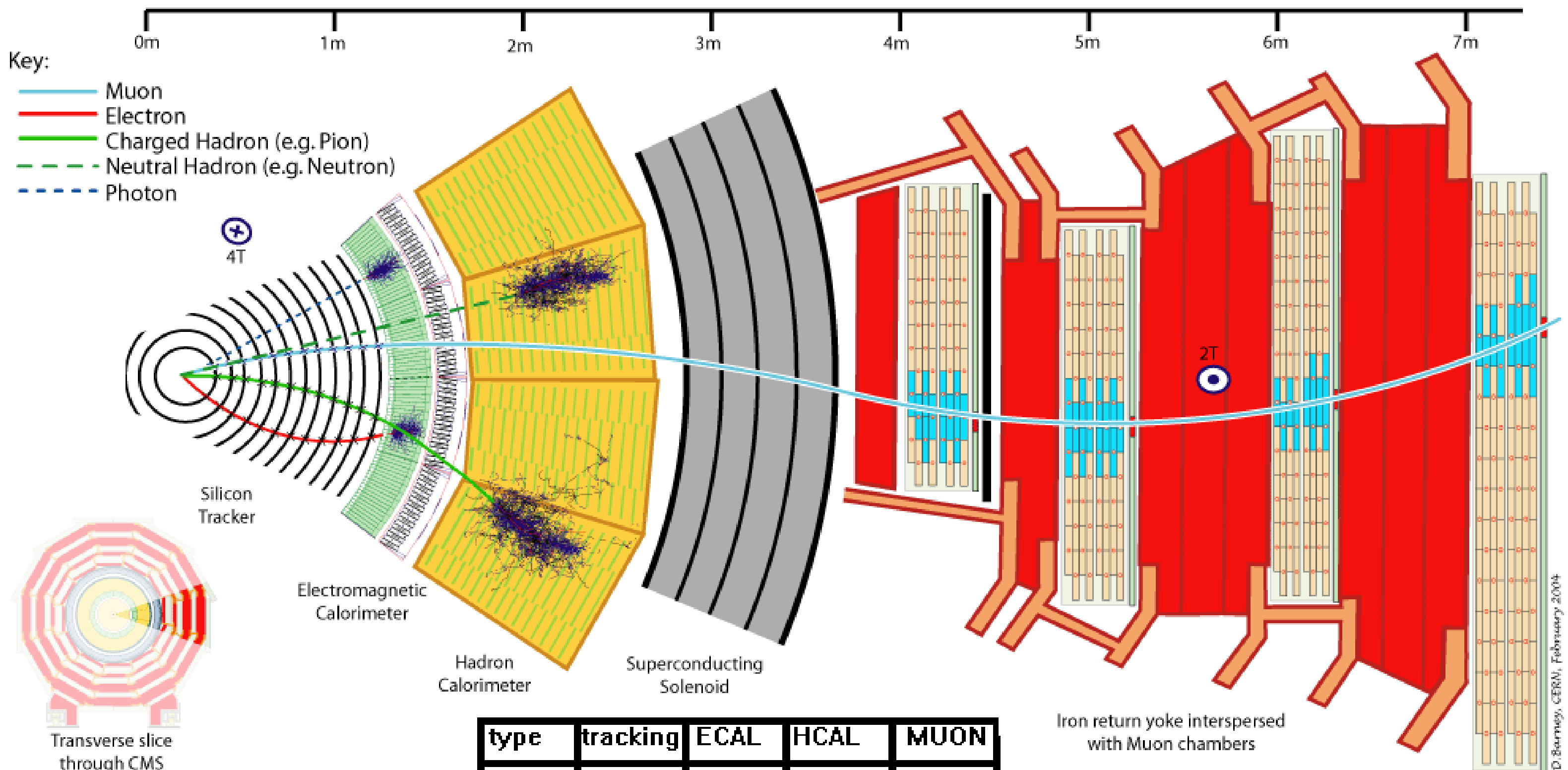
- Particles may leave the detector without interacting
  - Neutrinos are “known” SM particles that do that all the time
  - There may be NEW weakly interacting particles that behave similarly
  - These can be “detected” by observing missing transverse energy , “MET”, so it is a requirement to be able to detect it
    - This is a huge challenge since MET is a global variable in which a large number of signals, e.g. from the whole calorimeter are added together to look for an imbalance
      - Noise makes MET on the other side of the detector
      - Inefficiency makes MET on the same side of the detector

It is a requirement for finding new physics to be able to measure all the known SM objects and MET and this is what must be preserved at higher luminosities for the UPGRADES

3. CMS - The Compact Muon Solenoid



3. CMS Slice



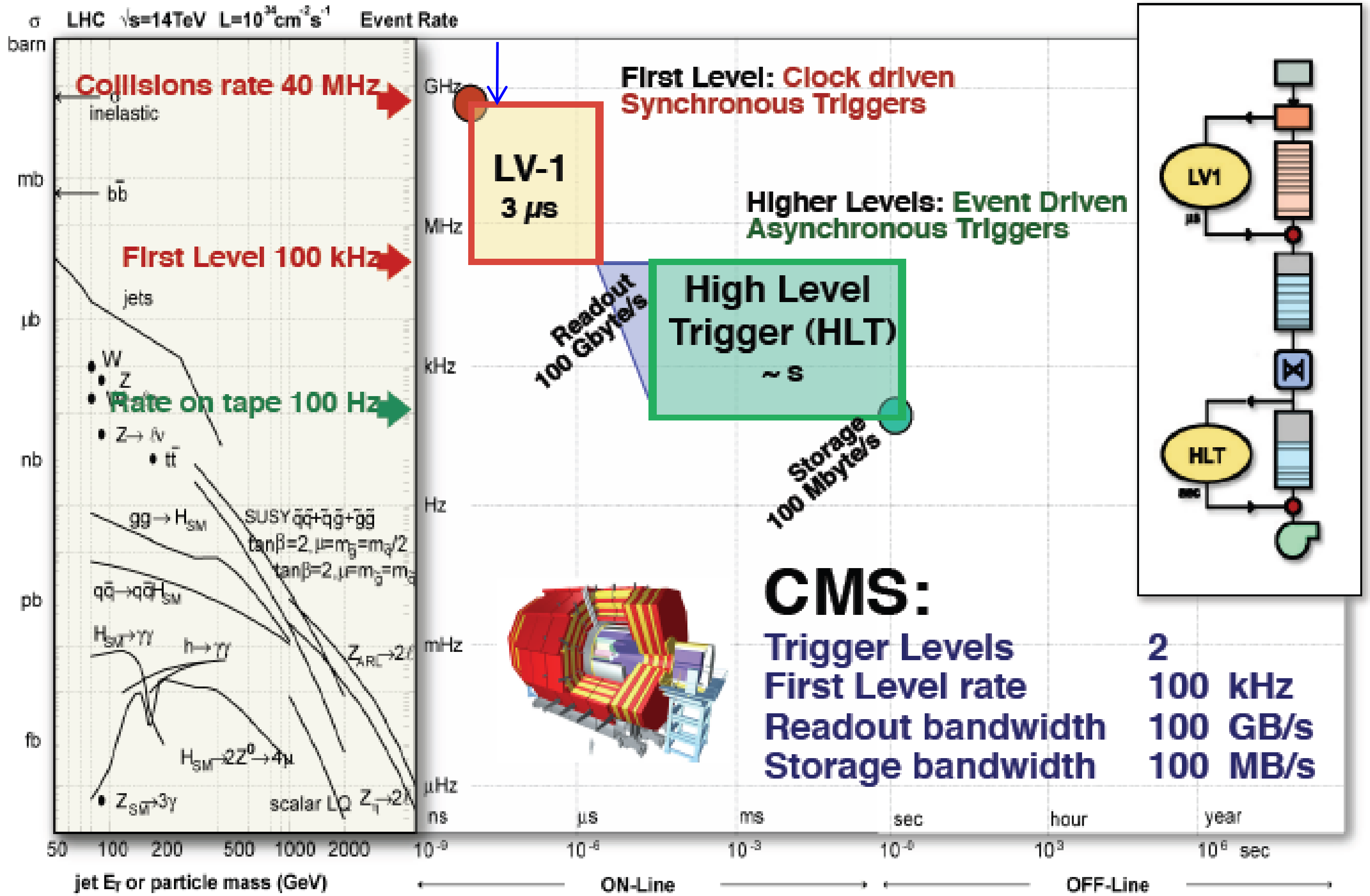
type	tracking	ECAL	HCAL	MUON
γ				
e				
μ				
Jet				
Et miss				

3. CMS Design Features

- **Very large solenoid – 6m diameter x 13 m long**
- **Tracking and calorimetry fit inside the solenoid**
  - **particles measured before they pass through the solenoid coil and cryostat, which would degrade their resolution**
- **Very strong field – 3.8 T**
  - **Excellent momentum resolution**
  - **Coils up soft charged particles**
- **Tracking chambers in the return iron track and identify muons**
  - **This makes the system very compact**
  - **Weight of CMS is dominated by all the steel and is 14,000 Tonnes**
- **A lead tungstate crystal calorimeter (~76K crystals) for photon and electron reconstruction**
- **Hadron calorimeters for jet and missing E_t reconstruction (provides coverage to η~5)**

- **Charged Particle Tracking is based on all-silicon components**
  - **A silicon pixel detector out to radius ~ 10-15 cm**
  - **A silicon microstrip detector from there out to 1.1 m**
  - **Small pitch gives CMS excellent charged particle tracking and primary and secondary reconstruction**
  - **High segmentation results in very low occupancy**
  - **Silicon detectors are very radiation hard**
- **Muon momentum is measured in the muon system but the best resolution comes from associating a silicon track, which has excellent momentum resolution ,with the muon track and doing a full fit. Challenge is to do this with high pileup → fine pitch→ low occupancy.**
  - **MAJOR DIFFERENCE BETWEEN ATLAS AND CMS.**
    - **It is why CMS is "compact" and ATLAS is so huge**

3. CMS Trigger and Data Acquisition (DAQ)



Level 1 is implemented in hardware with calorimetry and muon systems(not inner tracking)
Level 2 is a computer farm with full access to all event data and can run complex algorithms
In reality, the system can take more, We now run ~400 Hz and write and store 400MB/s

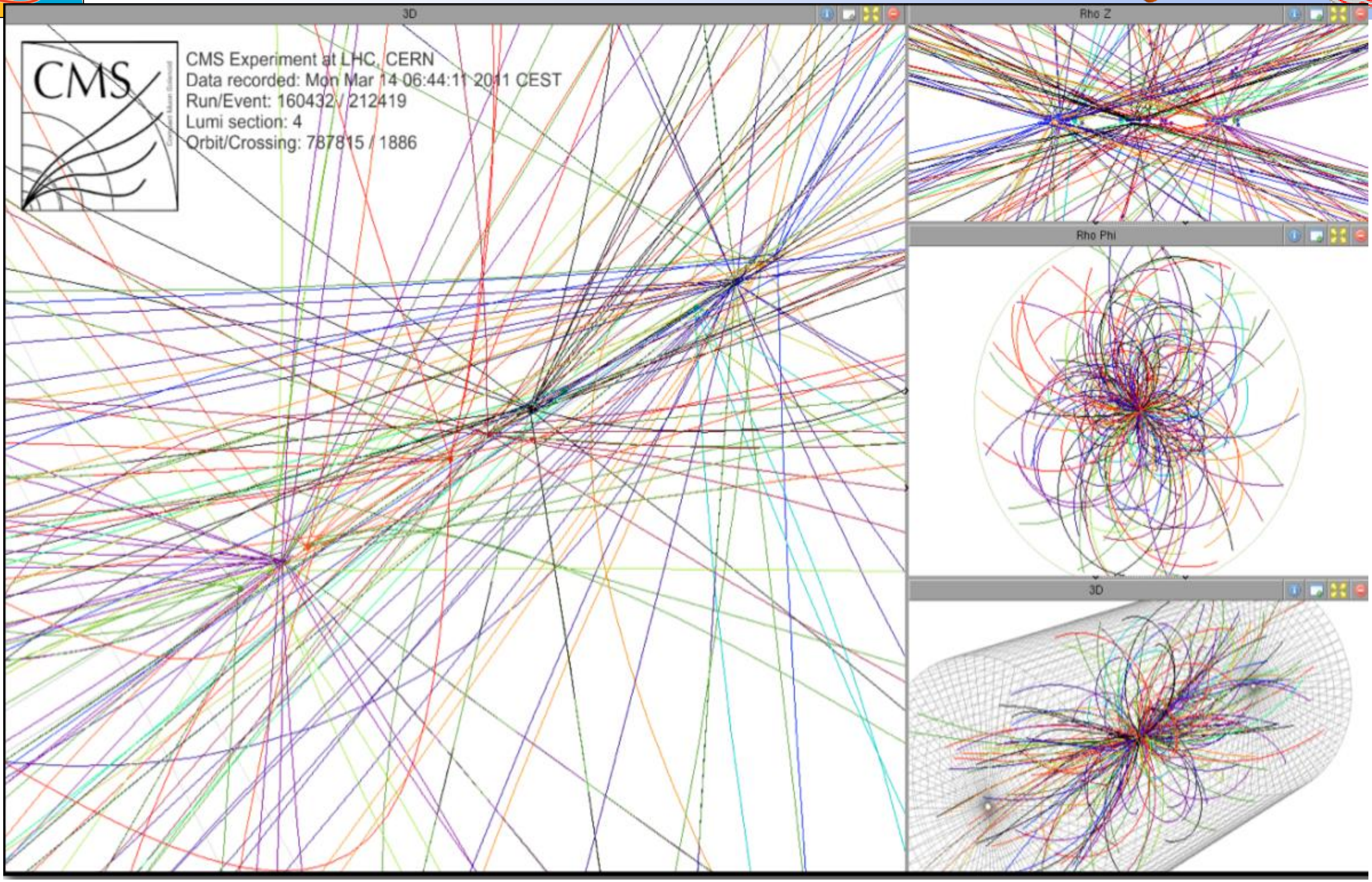
3. Goal of the CMS Upgrade

- The fundamental goal of the upgrade is to preserve the ability to reconstruct all the Standard Model objects and Missing E_t at higher luminosity than the original design, but which it now seems the LHC will reach
- The long shutdowns are the best time to make major changes to CMS
  - CMS can, however, do certain activities in so-called "technical stops" of a few months that typically occur each winter
- The goal is to return from each long shutdown with the upgrades needed to cope with the most challenging running conditions foreseen for the next long operating period (and hopefully subsequent ones)

4. Challenges of high luminosity

- Higher Occupancy (pileup) – hits on detector elements proportional to the number of interactions in crossing
- Radiation damage (integrated luminosity) – loss of efficiency due to
  - Charge trapping in silicon
  - Light absorption and scattering in optical detectors, such as crystals
  - Increased noise and dark current
- Pile-up
  - “in time pileup: Multiple interactions per crossing, which cause several events to be superimposed, all occurring at the same time
  - “Out of time pileup” or “spillover”: signals from a preceding crossing “spill-over” into the crossing of interest or the tail of the signal from the crossing of interest “spills over” into the next crossing

4. The new challenge: pile-up



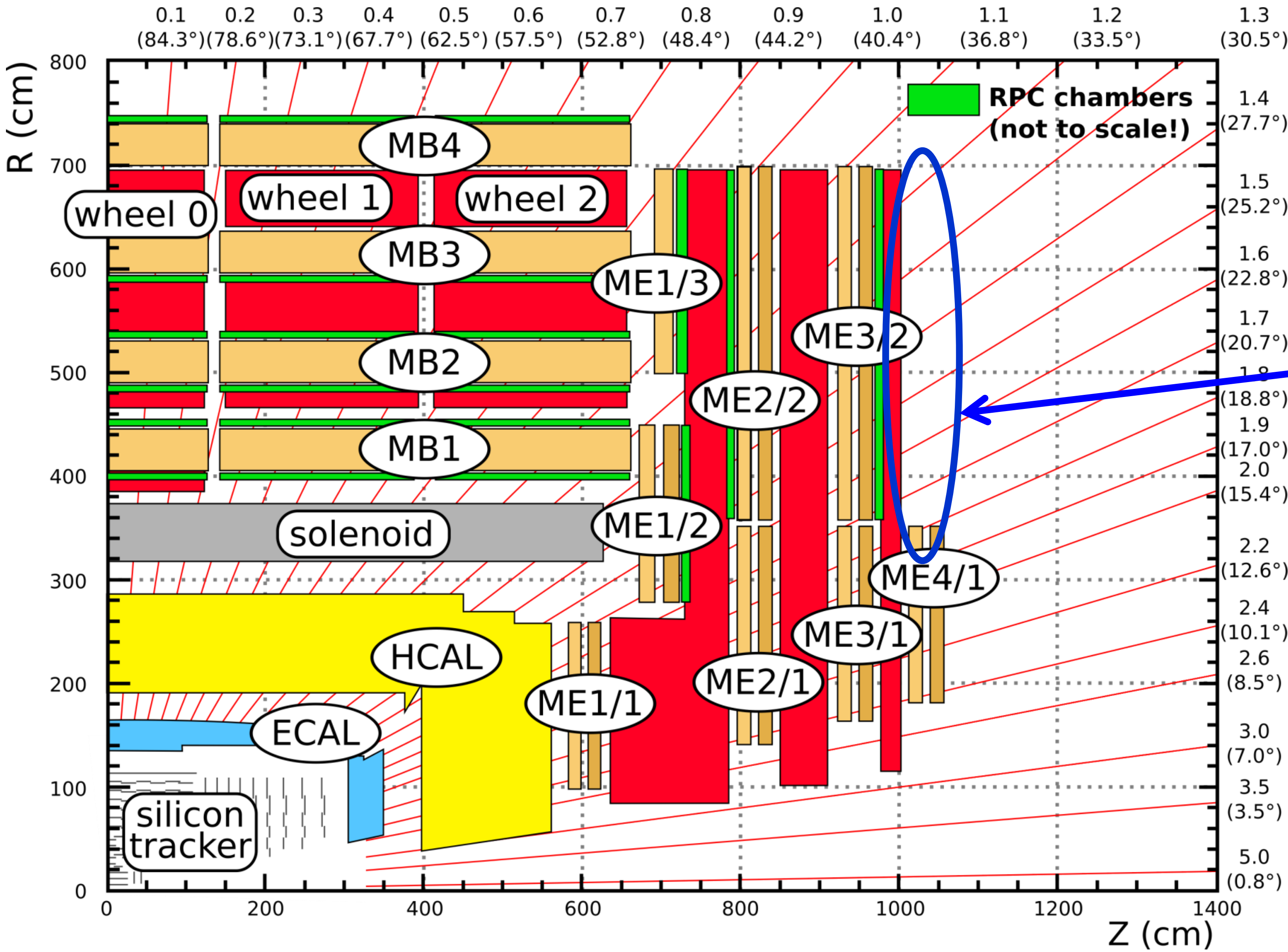
4. Challenges of high Pileup

- **Pileup causes**
  - **Pattern recognition problems**
  - **Energy sums, isolation, missing Et**
  - **Problems with pattern recognition at trigger, reconstruction, and analysis level**
  - **Larger event sizes and longer readout times**
  - **More data storage**
  - **More need for computer memory in cluster nodes, especially multicore nodes**
  - **More combinatorics→ more computing time for both high level trigger and offline analysis**

5.0 CMS Improvements and Upgrades Timeline

Shutdown	System	Action	Result	Physics
LS 1	Muon (ME42,ME11) uTCA trigger	CSC (Complex YB4 installation) New electronics	Improved μ trigger and reconstruction ($1.1<\|\eta\|<1.8$, $2.1<\|\eta\|<2.4$)	W acceptance WH, $H^{\pm} \rightarrow \tau\nu$
LS 1	Hadron Outer	Replace HPDs with SiPMs to reduce noise	Single μ trigger Tails of very high p_T jets	Muons from τ $Z/H \rightarrow \tau\tau \rightarrow \mu X$
LS 1	Hadron Forward	Install new PMT to reduce window hits	Forward jet tagging Improves MET	Vector-boson fusion H
LS 1	Muon YB4	New RP CSC (not funded)	Improved trigger at lower thresholds	Increase W acceptance
LS 1	Beam Pipe	Install new beam pipe	Easier pixel installation	b-tagging
LS 2	New Pixel system	Low mass 4 Layers, 3 Disks with new ROC	Reduces dead time Improves b-tag.	SUSY decay chains
LS 2	HCAL Barrel and Endcap uTCA trigger	Replace HPDs with SiPMs for longitudinal segmentation New electronics	Reduces pileup effects Improves MET Improves τ, e, γ clustering and isolation	SUSY $H \rightarrow \tau\tau$ $H \rightarrow ZZ \rightarrow ll\tau\tau$
LS 3	TRACKER New Trigger Endcap Calo.	Replace tracker Replace trigger ?	Maintain performance at high SLHC Lumi	Guided by early discoveries

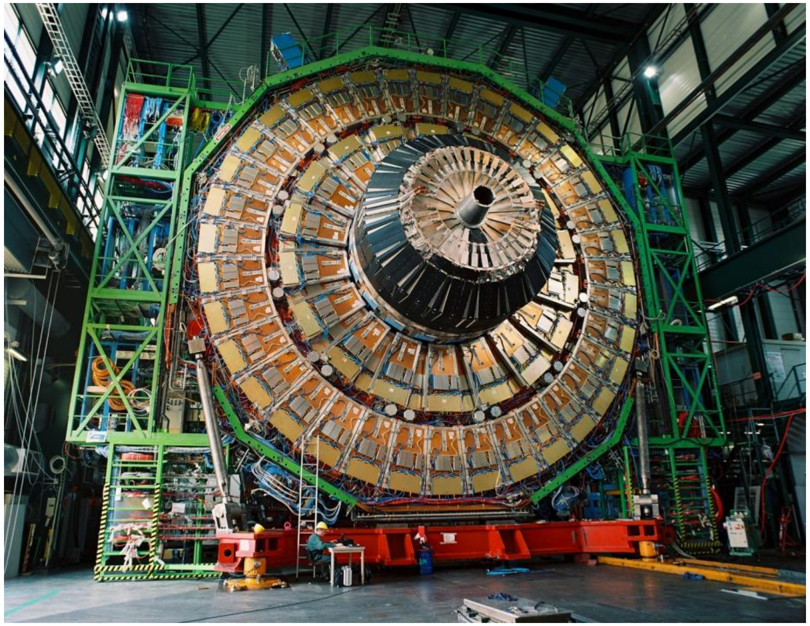
5.1 CMS Muon Detector

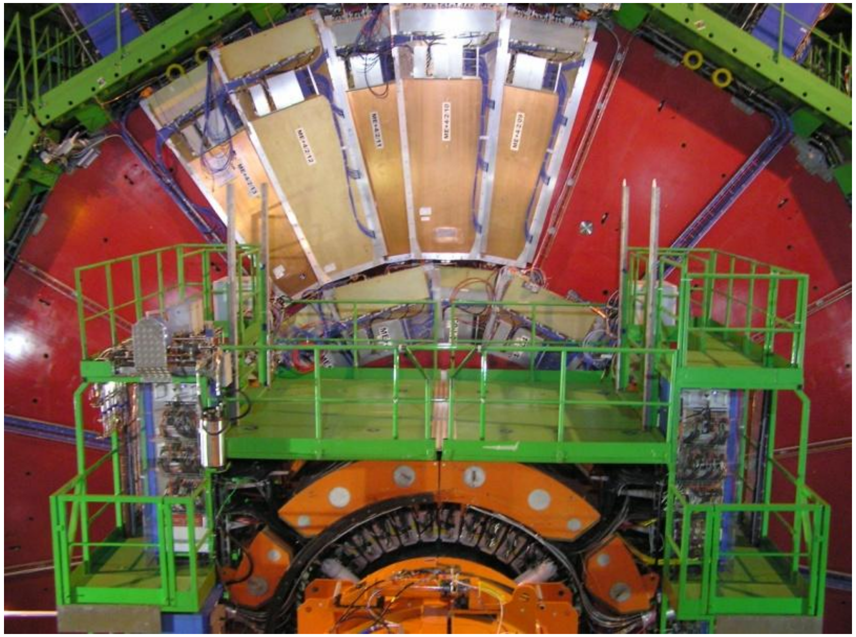


Missing 4th layer η 1.2-1.8

5.1 Muon systems

- **Three tracking technologies: Drift Tube (DT), Resistive Plate Chamber (RPC), and Cathode Strip Chamber (CSC)**
  - **Each pseudorapidity interval is covered by two of these subsystems**
  - **Muon triggers are the most robust vs pileup and MUST BE PRESERVED**
  - **The CSCs and RPCs had final ENDCAP stations descoped**
    - **This may barely work at 10^{34} $cm^{-2}s^{-1}$ with 25 ns bunch crossing but not a twice that luminosity or at 50 ns bunching spacing**
    - **Upgrade will complete 4 station endcap coverage for RPCs and CSCs**





5.1 CSC Upgrade

- **Scope**
  - **Original design unfinished – ME4/2 not built**
  - **72 ME4/2 chambers to complete system**
    - **Identical to chambers already built and working well**
    - **Increase redundancy of system**
    - **Efficient triggering at high luminosities**
  - **This provides a fourth segment for the muon trigger which allows CSC to maintain its effectiveness at high luminosity**

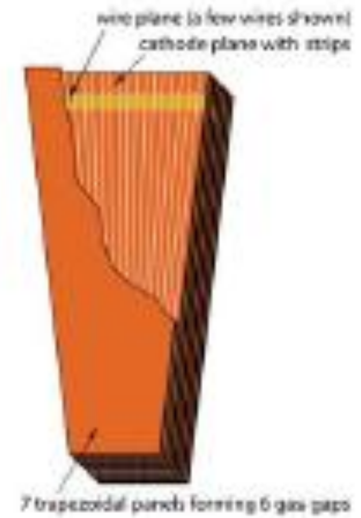
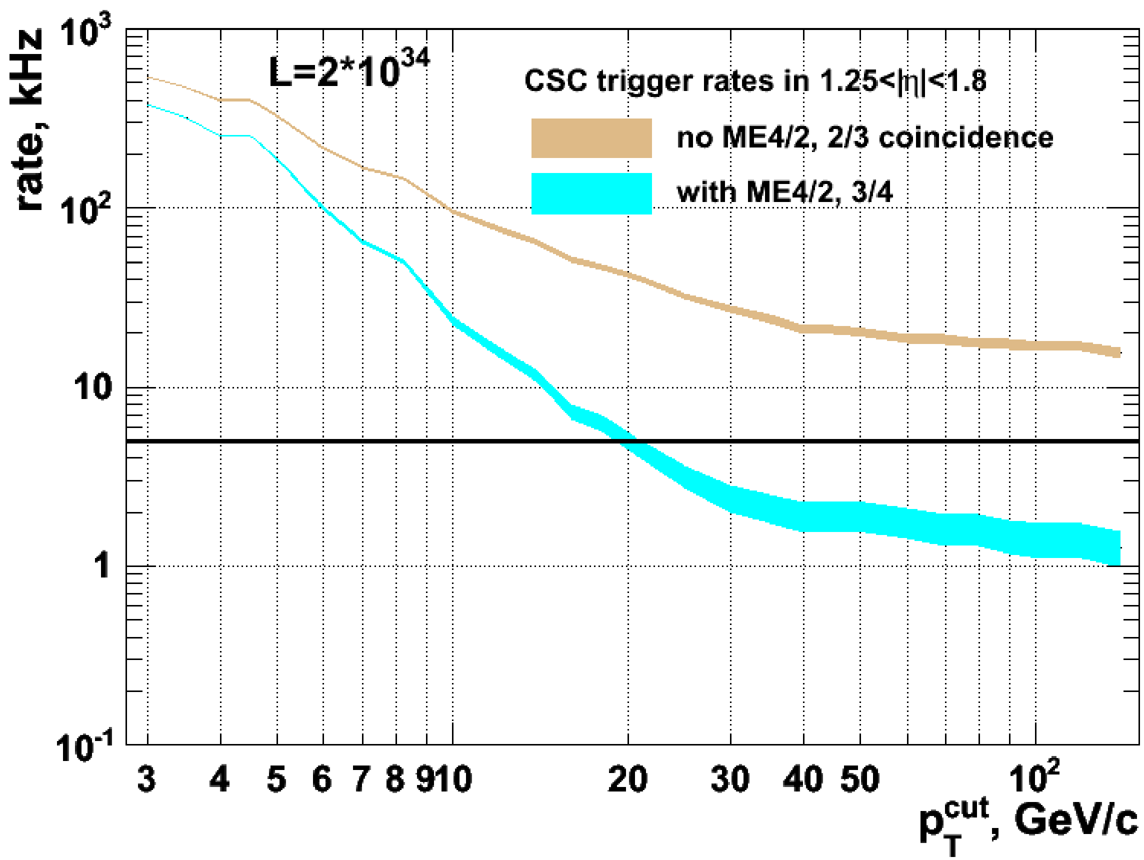


Figure 7.49: Layout of a CSC made of 7 trapezoidal panels. The panels form 6 gas gaps with planes of sensitive anode wires. The cut-out in the top panel reveals anode wires and cathode strips. Only a few wires are shown to indicate their azimuthal direction. Strips of constant $\Delta\phi$ run lengthwise (radially). The 144 largest CSCs are 3.4 m long along the strip direction and up to 1.5 m wide along the wire direction.

5.1 CSC Trigger Rates

- CSC chambers have 6 planes/chamber -- good ability to reject neutron hits
- Each station provides a “mini-vector” for calculation of momentum
- With 3 planes, use 2 out of 3 or 3 out of 3. The 2 out of 3 can get wrong momentum at high pileup
- Upgrade: Use of 3 out 4 and 4 out of 4 fixes this (never use just two stations)
- With ME4/2, the GMT rate is 5 kHz at 20 GeV/c threshold
- Without ME4/2, trigger rate/threshold is substantially higher

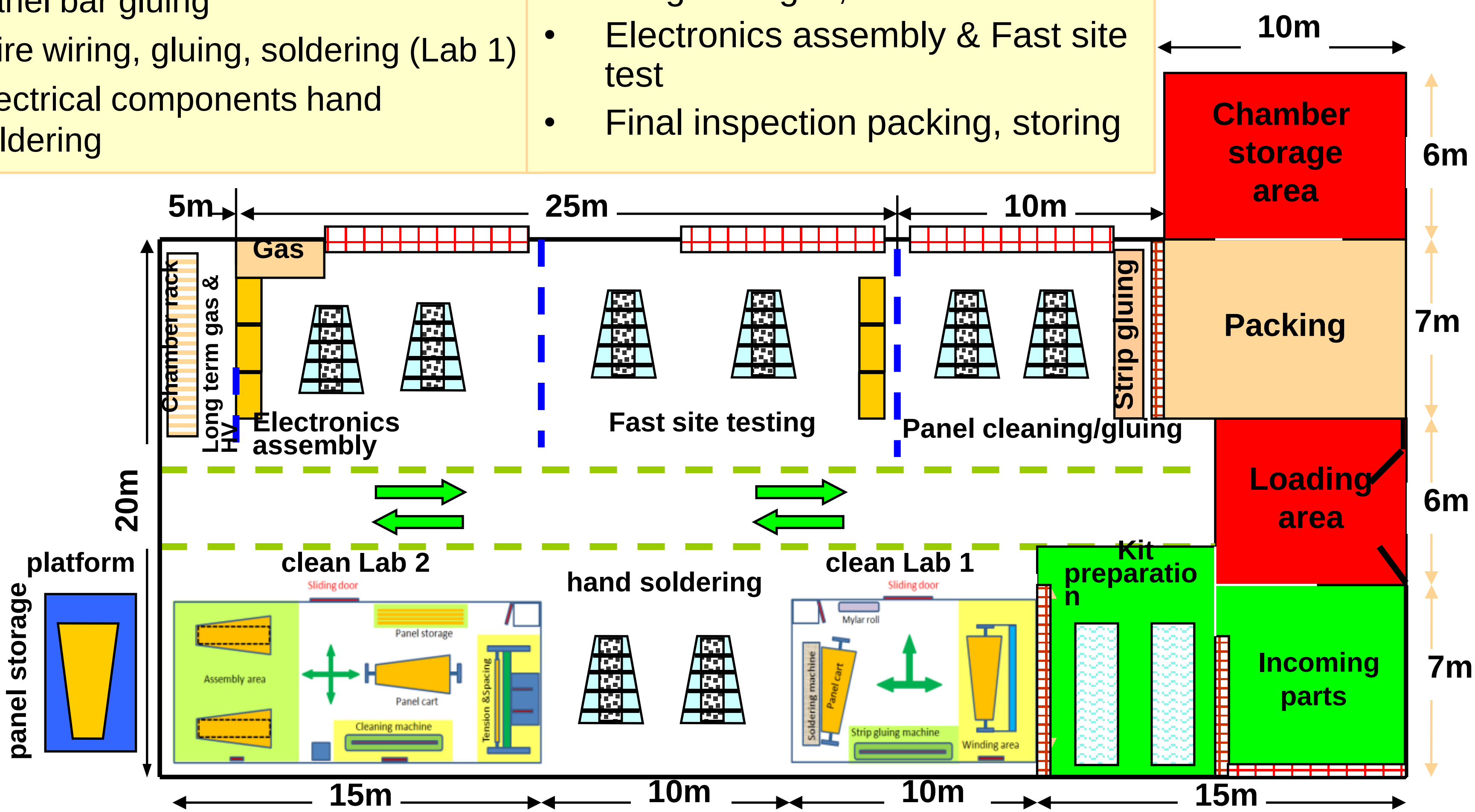


Muon trigger robustness in 1.2<|η|<1.8 depends critically on new station ME4/2

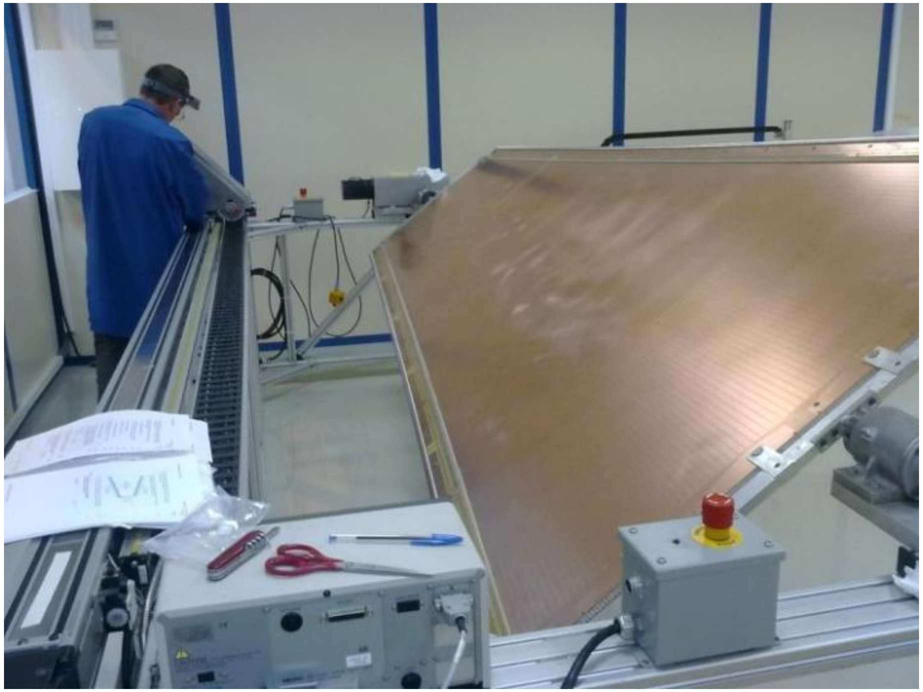
5.1 CSC production workflow at CERN Building 904 factory

- Incoming parts
- Kit preparation
- Panel bar gluing
- Wire wiring, gluing, soldering (Lab 1)
- Electrical components hand soldering

- Chamber assembly & test (Lab 2)
- Long term gas, HV tests
- Electronics assembly & Fast site test
- Final inspection packing, storing



5.1 Clean Room 1 - Winding



- About 1000 50µm thick AuW wires are winded on the anode panel with a ~3.16mm pitch. Total wire length ~2600 m per panel. Winding time: ~4h per panel. 200 µm thick field-shaping CuBe wires are tensioned (500g) and soldered beforehand
- Then, mylar fixation strips are glued onto the wire-end before wire soldering
- So far, we have successfully wound 2 anode panels and are ready to wind 3rd

5.2 RPC Upgrade

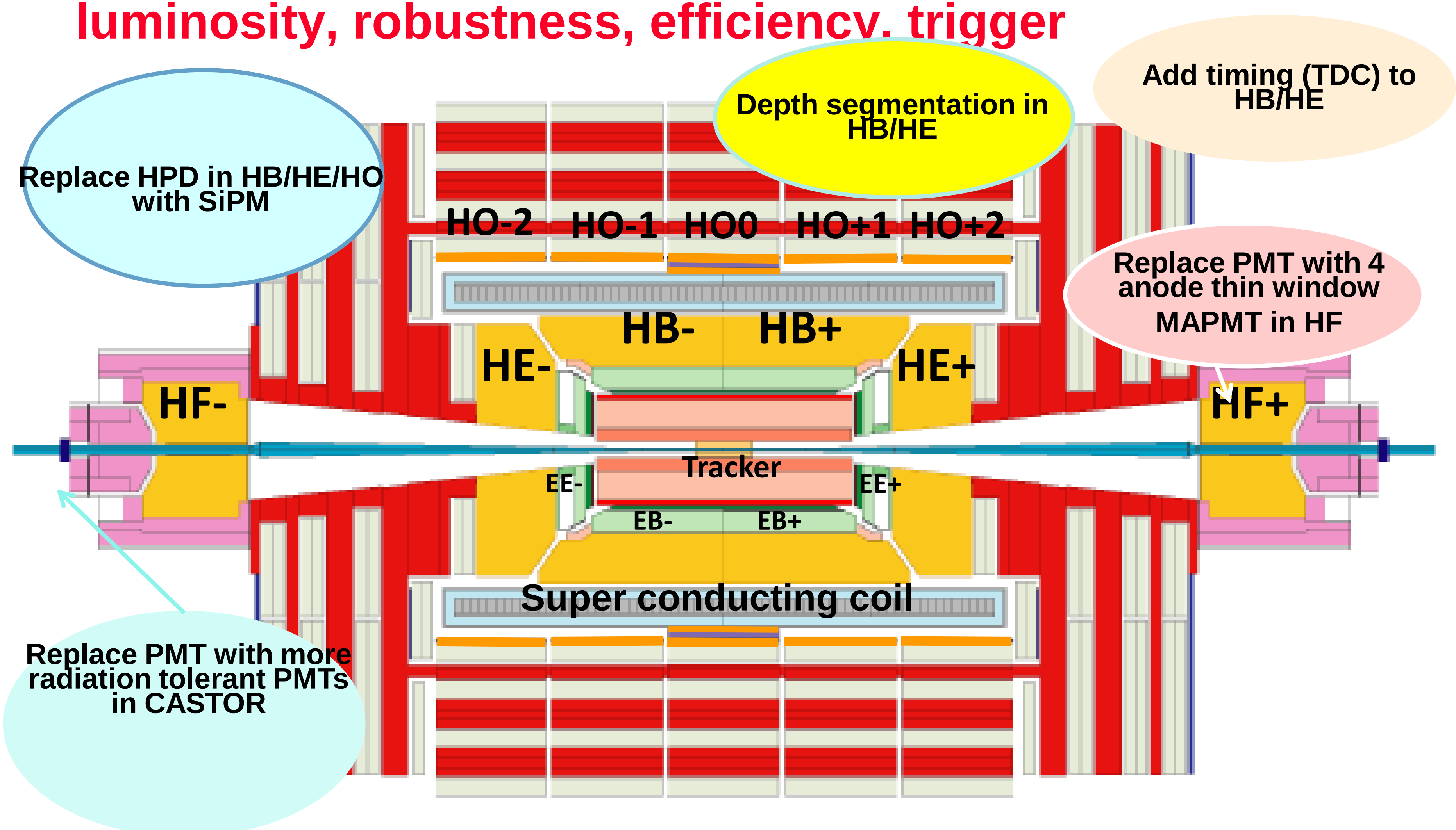
- **Original design unfinished**
  - **4th station never built**
- **At high luminosity redundancy essential**
  - **3 out 4 much better than 2 out of 3**
  - **Pattern recognition important**
  - **RPCs provide excellent timing in station 4**
- **Upgrade scope**
  - **Build RE4/2 and RE4/3 rings in station 4**
  - **Need 144 chambers – build 200 to have some spares**
  - **Phase 1: cover from η = 1.2 to η = 1.6**
  - **Phase 2: cover from η = 1.6 to η = 2.1 (maybe MPGD)**
- **Factory is also being set up in Building 904 at CERN right next to CSC factory**

5.2 HCAL Upgrade Overall Motivation

- **Current HCAL designed for 10 years for 10^{34} cm^{-2}s^{-1}**
  - **LHC upgrade calls for 10x exposure, substantial increase in luminosity**
- **Physics and detector considerations (all are related):**
  - **Pileup increase x10 (x20 if back off from 25ns to 50ns Beam Crossing)**
  - **Radiation damage and mitigation, especially to first few layers due to leakage from Electromagnetic Calorimeter**
  - **Impacts on the quality of the hardware-level trigger for a wide range of trigger paths**
  - **Preserve accurate MET and JET measurements**
  - **As luminosity increases, opens up possibilities for measurement of rare processes**
    - **Requires us to have a more robust way to mitigate rare backgrounds**
      - **Cosmics, halo, electronics "burps", limitations of the current HCAL transducers, other non-BX-related effects**
  - **Mitigate current known problems that threaten the physics contribution from HCAL**

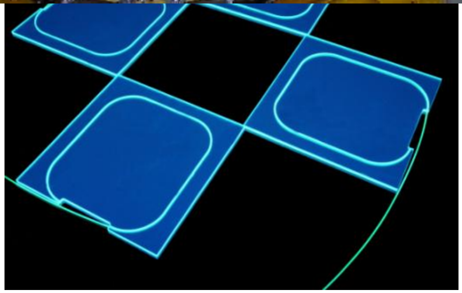
5.2 Upgrade to Hadron Calorimeters

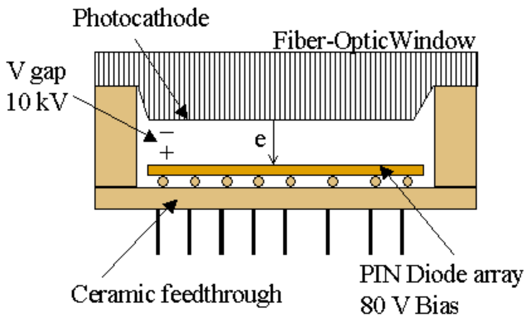
- **Upgrade driven by effect of peak instantaneous luminosity, robustness, efficiency, trigger**



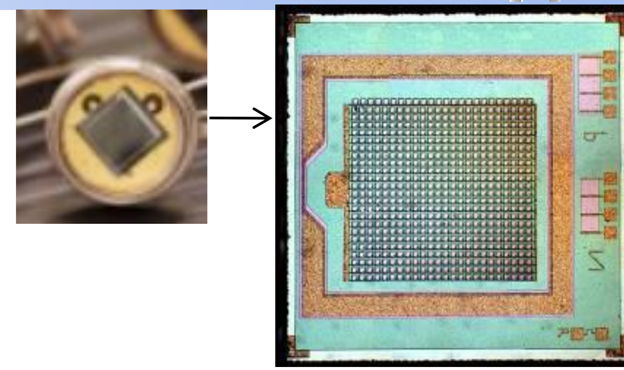
5.2 Replacement of HPDs with SiPMs

- Problems with HPDs (Hybrid Photodiodes)
  - Low gain (~1000) and poor S/N prevents
    - Splitting signal for longitudinal segmentation
    - Spitting signal for timing output
  - High Voltage (8-10 KV)
    - Causes breakdown, sometimes destructive
  - B-field behavior is complicated
  - This type no longer manufactured
- Replace with SiPMs (Silicon Photomultipliers)
  - Array of pixelized APDs operating in Geiger mode
    - few mm x few mm with up to 30,000 pixels
    - Output proportional to number of photons hitting pixels, delivered as one output/chip
    - Technology is new: <10 years old
      - ubiquitous in PET scanners

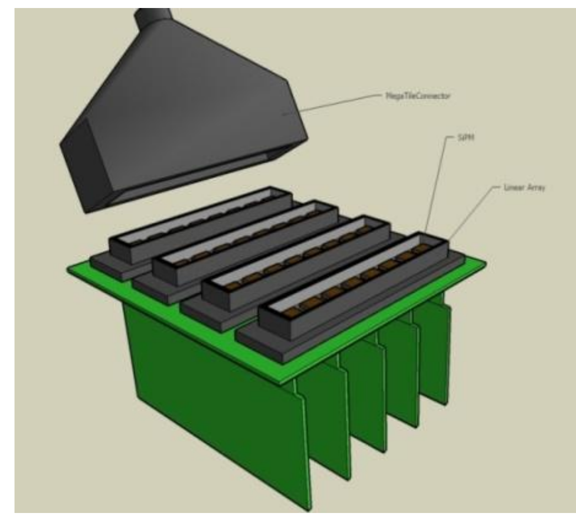




5.2 Silicon PM (SiPM)



- **Great advantages over current HPDs:**
  - **Not effected by magnetic fields**
  - **Low voltage (50-100V vs ~7k for HPD**
    - **No discharges and no vacuum (no ion feedback)**
  - **Higher gain (x50-x500) and QE (x2) over HPD**
    - **Replace HPD's w/SiPMs, S/N increase by x10!**
  - **"Digital" device. Pixels count photons**
    - **Linear up to high energy where >1 γ/pixel**
  - **Compact – several can fit in space of HPD and inexpensive**
- **Allows**
  - **longitudinal segmentation in HB/HE**
  - **Timing determination at hardware level**
  - **Vast simplification in implementation**
    - **Connector from detector has the fibers, plugs into coupler unit**
    - **Can replace with cheap 1x1 mm^2 SiPM array and gang electrically**

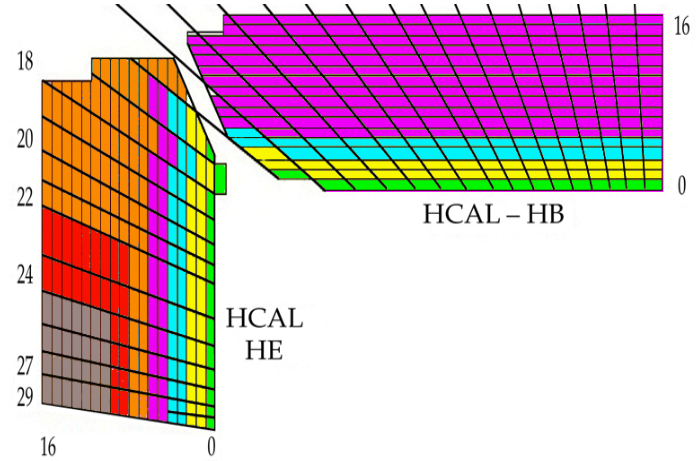


5.2 Key Issues for SiPM R&D

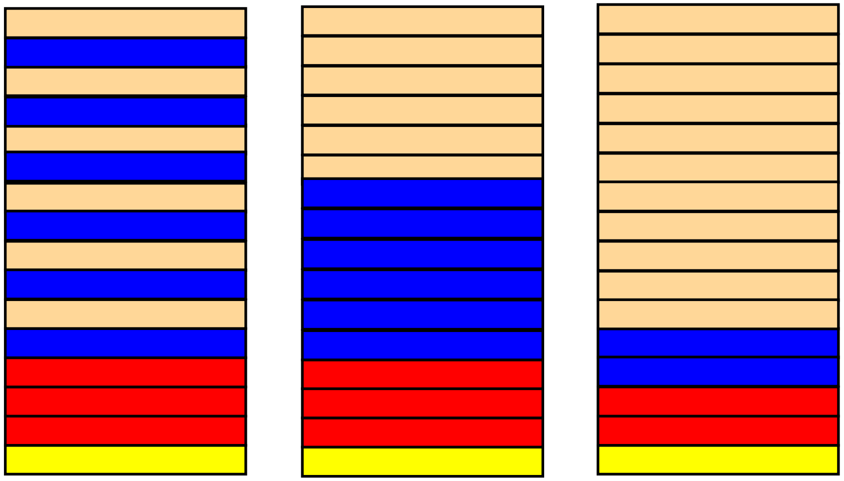
- **Key R&D issues:**
  - **Pixel recharging time: sufficiently short to not degrade measurements in subsequent bunch crossings**
  - **Pixel density for a given photo-detection area must provide required dynamic range and linearity for full range of expected signals**
  - **SiPM temperature and voltage stability adequately controlled to minimize cell-to-cell variation**
  - **Radiation tolerance to prevent long-term performance degradation from leakage current increase**
  - **Signal from a single neutron interaction should be minimized**
- **HB/HE: Each individual requirement has been met, and we may now have SiPMs that meet them all (still checking radiation hardness on recent devices)**
  - **Working with three vendors: Zecotek, Hamamatsu and FBK**
  - **Expect to demonstrate prototypes meet baseline specs by end 2011 or beginning of 2012**

5.2 More Depth Segmentation in HB/HE

- **SiPMs allows increase segmentation, providing:**
  - **Reweighting of inner layer, important for:**
    - **Correcting for radiation damage to inner layer**
    - **Mitigating underlying event punch-through, important for triggering on isolated electrons**
  - **Ganging can be implemented ad hoc in the electronics**
  - **Ongoing studies:**
    - **Various schemes, various optimizations, e.g. Physics Studies**
      - **what does 2 vs 3 vs 4 get us in rejecting various backgrounds**



Examples of longitudinal segmentation into 4 channels



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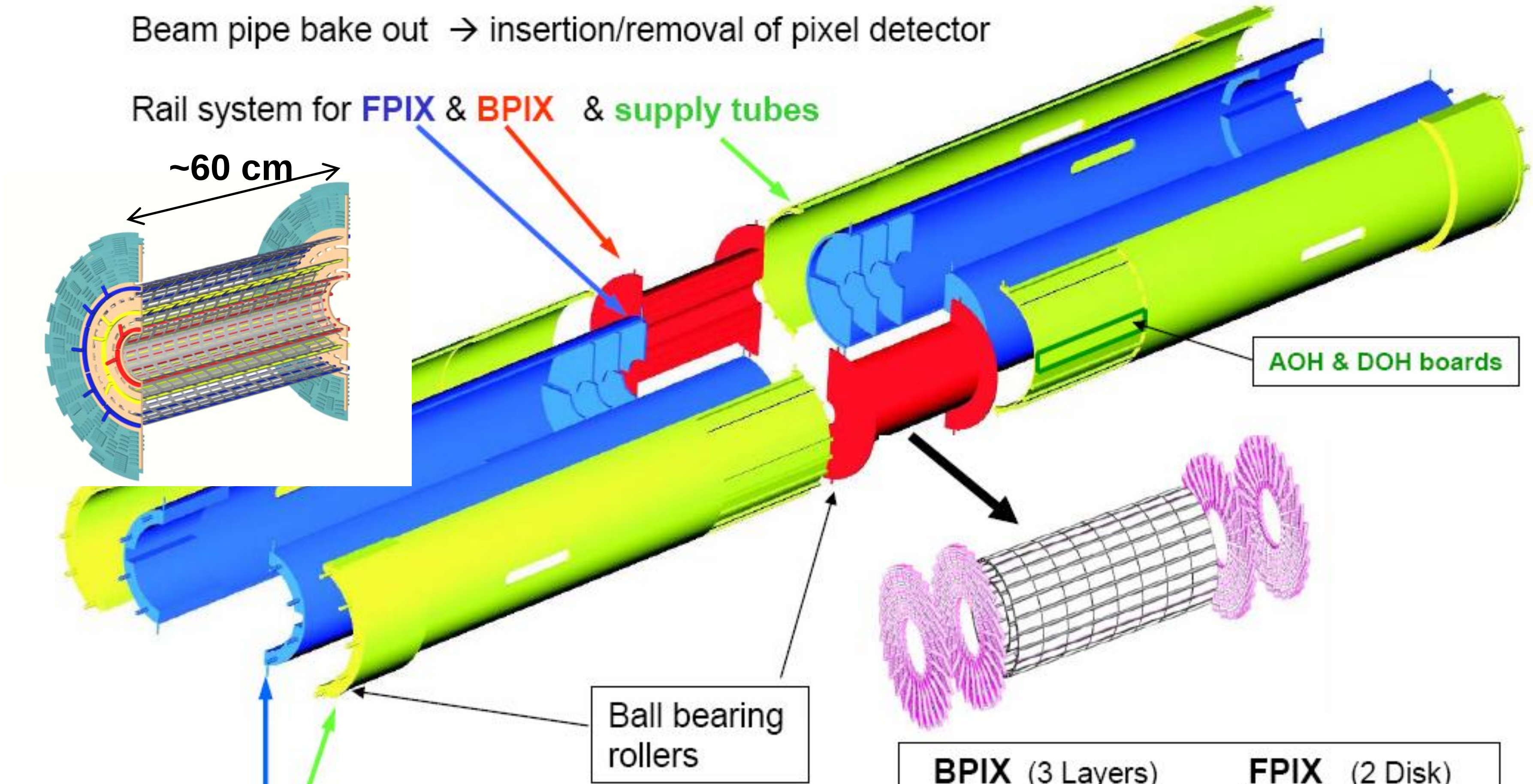
5.2 Improved Timing

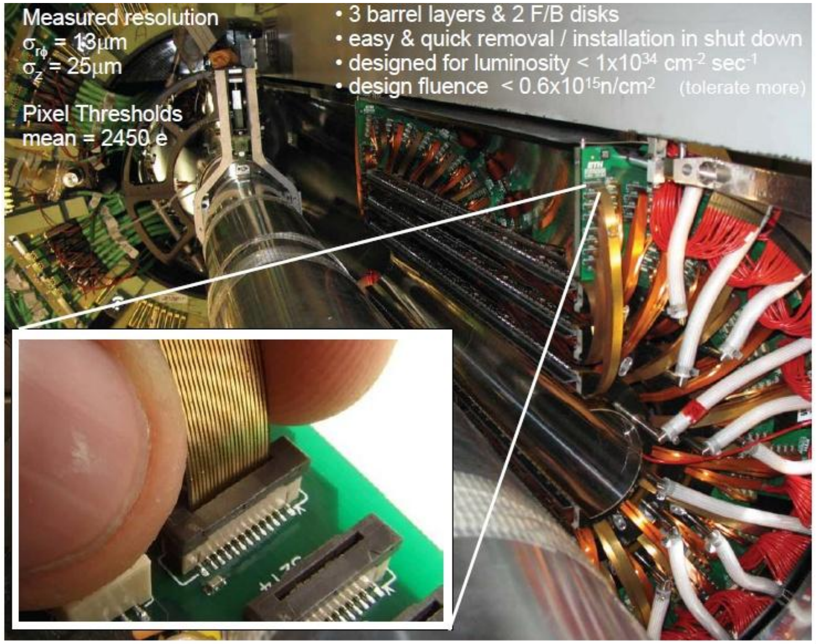
- HB and HE signals are ~3 BX full width
  - Well formed calorimeter signals currently provide offline sub-BX timing
    - Will disappear at higher luminosity
  - Hardware timing information will aid in identification of malformed signals from background and pileup
  - Will also allow redundancy and contribute to eliminating non-BX-related signals
- The Tevatron has background from cosmics and stray beam halo falling in coincidence with a real interaction
  - The Tevatron has only one crossing every 396 ns compared to one every 25 ns at the LHC
    - Need good timing to defend against higher backgrounds

5.3 The CMS Pixel System



BPIX (3 Layers)	FPIX (2 Disk)
672 Modules	96 Blades
96 Halfmodules	672 Plaquettes
11520 ROC	4320 ROC

5.3 Current Pixel Detector



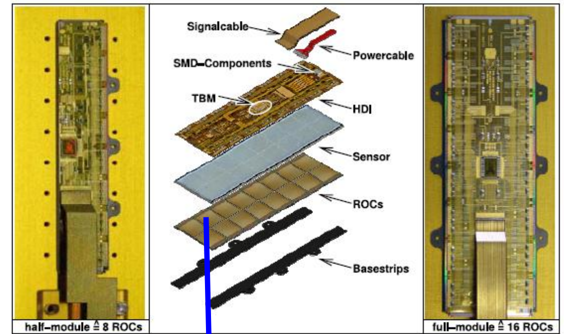
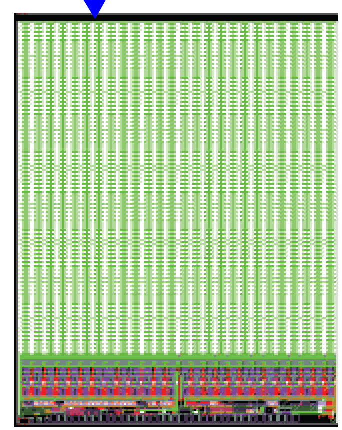


Figure 7: Exploded view (middle) of a barrel pixel detector fullmodule (right) and picture of an assembled half-module (left)

Each ladder:
16 readout chips (ROCs), each 8mm x 9mm
Reading out and controlling 4160 pixels, 100 µm x 150 µm



Current BPIX and FPIX are working well
- **>99% single hit efficiency**
- **13 µm resolution in r-ϕ.**
- **25 µm resolution in r-z**
- **Pixel threshold of 2450 electrons (~10% MIP)**
- **Easily removable during shutdowns**
- **Highly successful as “seed” for rest of tracking**
- **Finds (multiple) primary and secondary vertices**
- **Excellent b-tagging performance**

5.3 Problems at High Luminosity

- **Radiation hardness**
  - **Radiation tolerance of the pixel sensors is $6x10^{14}$ n/cm^2 (for full resolution, at $1x10^{15}$ n/cm^2 both resolution and efficiency become impaired)**
- **Buffer sizes (data loss at higher luminosities)**
  - **Readout is designed for 10^{34} cm^{-2} s^{-1} with 25 ns bunch crossing. If we continue to run at 50 ns bunch crossing, limited buffer on readout chips leads to 16% loss of efficiency on inner layer**
  - **At $2x10^{34}$ cm^{-2} s^{-1} with 50 ns bunch crossing, >50% of loss of efficiency on inner layer and significant losses on the next two layer**
- **B tagging and seeding capabilities**
  - **Becomes impaired due to efficiency loss and pulse height loss (which degrades charge sharing and hence position resolution)**
- **Material budget is also not good now, should not get worse, and hopefully will get better, in upgraded version**

5.3 The Pixel Upgrade Plan

•**New Layout: 4 layers and 3 disk/side**

Baseline Option: 4 layers/3 disks new 250 nm PSI46dig ROC

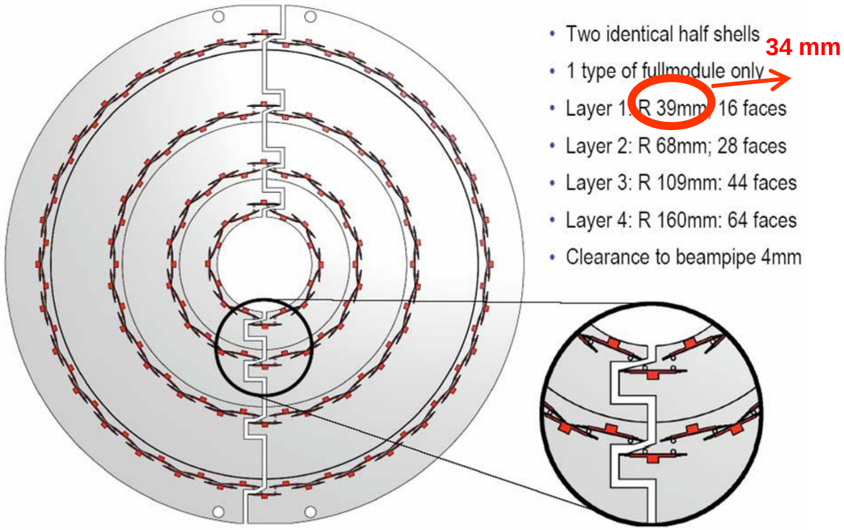
PSI46dig ROC: reduce data losses at high luminosity, more robust digital readout, protection mechanism against large clusters induced by beam background

Inner layers and inner disks: designed for easy and fast replacement.

Inner layer: closer to IR (from 44 mm present to possibly 39-34 mm)

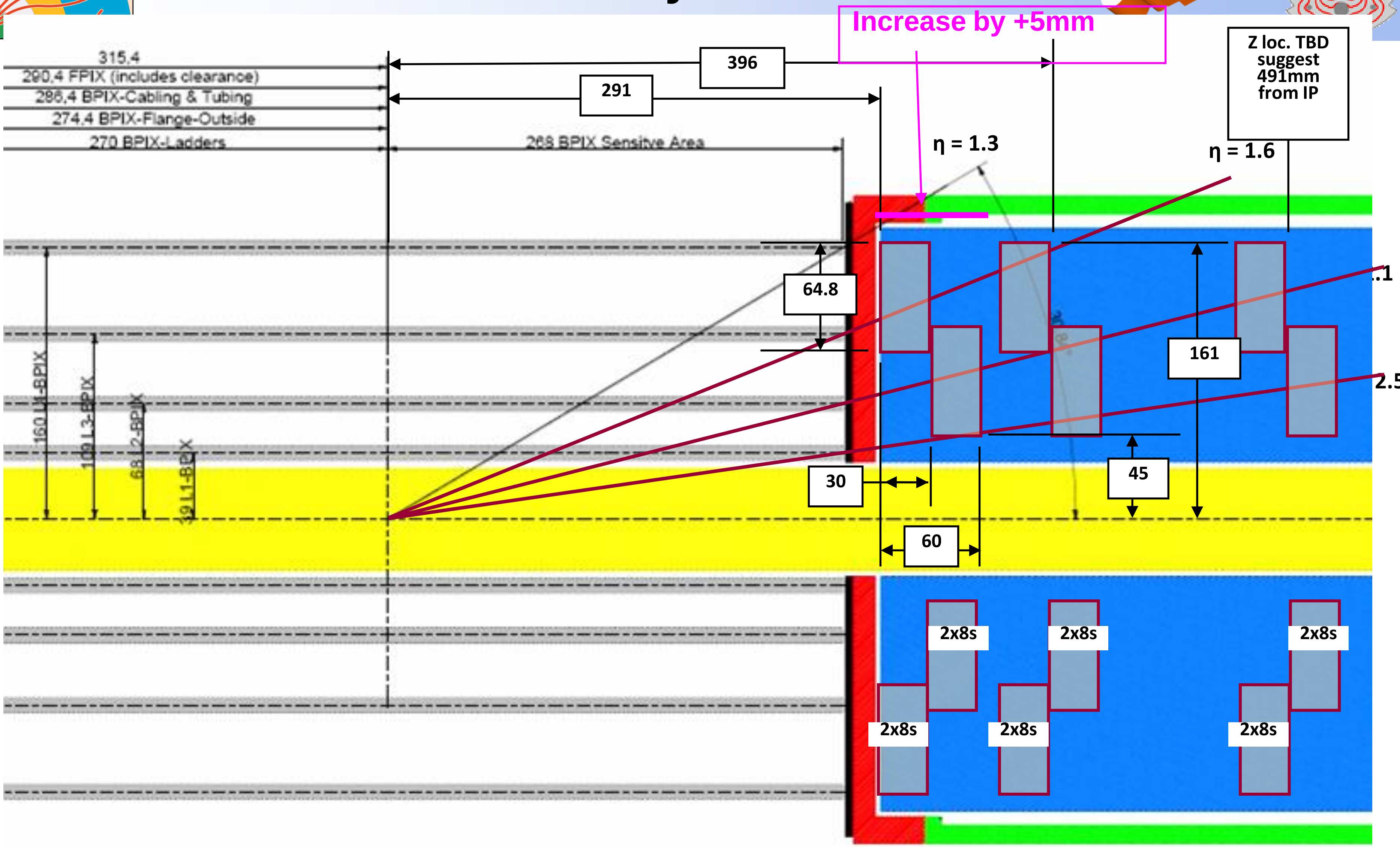
Outer layer and disks: closer to Tracker Inner (160 mm w.r.t 106 mm present detector)

Material budget: aim for major reduction (at least 60% reduction)



Fall forward line: Two inner layers/inner disks with better hit resolution and radiation tolerance New ROC chip optimized for lower thresholds, possibly able to digest higher rate, 50% pixel area (75µm x 100 µm or smaller) and thinner sensors

5.3 BPIX / FPIX Envelope Definition for 4 Hit Pixel System

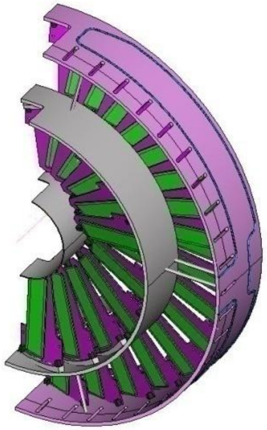


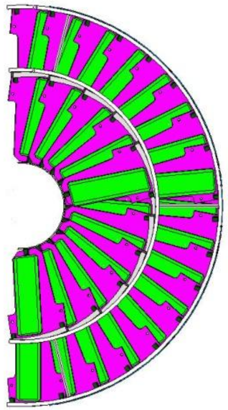
All Identical disks (1st and 2nd disks in locations to maximize 4-hit eta coverage)

6 disks = (6x68) outer + (6x44) inner = 672 2x8 modules (10752 ROCs)

5.3 Replacement Capability Material budget

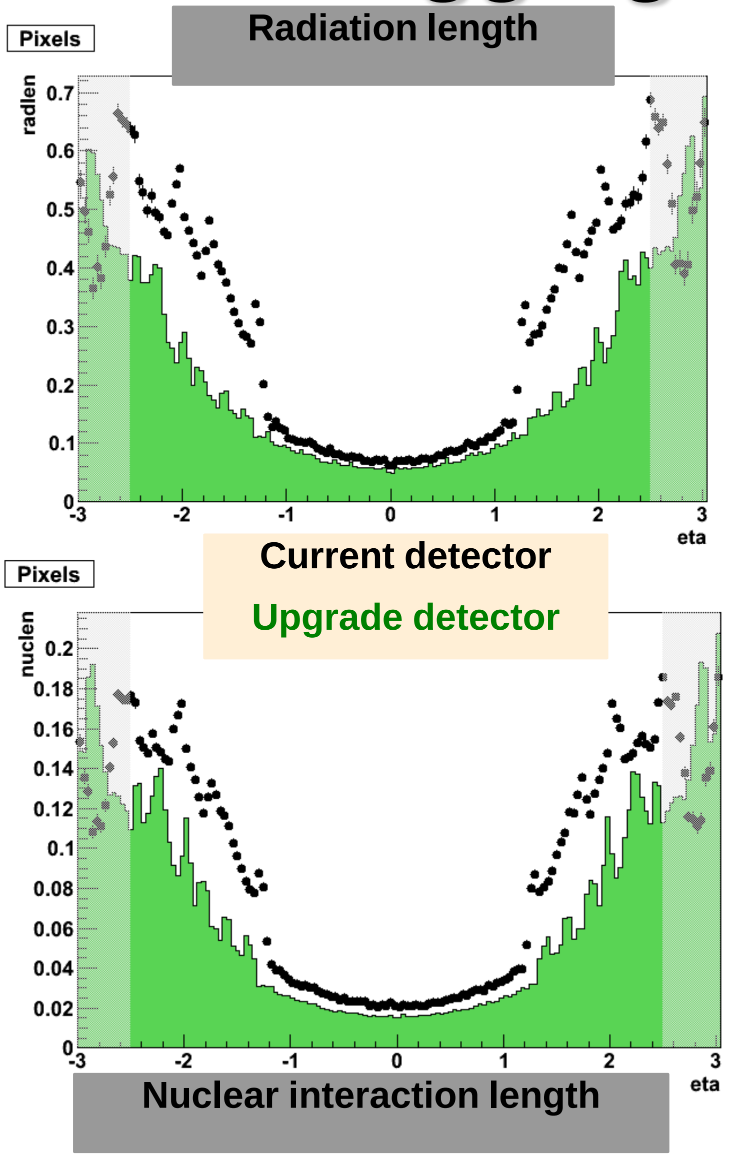
Inner portion will Experience radiation damage and can be removed separately and replaced in a short technical stop

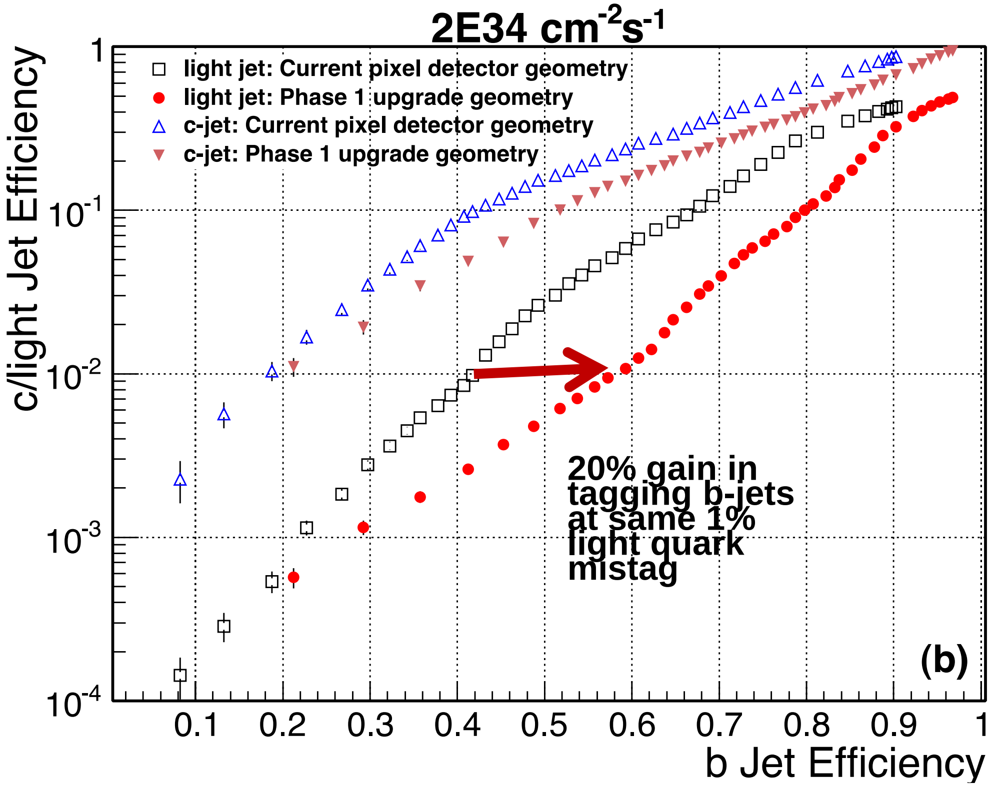




- Material Budget
  - New system has more electronic channels
  - To keep material lower than the existing detector
    - Use DC-DC conversion to bring less current into the detector to need less cooling
    - Use evaporative CO2 cooling which is more efficient and requires much less material than the existing C6F14 fluid system
    - Use new light weight materials
    - More as much of the support electronics out of the tracking volume to areas where it has no bad effects

5.3 Material Budget and B Tagging Performance





6.0 Phase 2 Upgrades

- Once the machine approaches $5X10^{34}$ cm^{-2} s^{-1} with 50 ns (or hopefully 25ns) beam crossings, there will be
- A pileup of
  - 200 interactions/crossing at 50 ns (easier for machine to achieve high luminosity)
  - 100 interactions/crossing at 25 ns (preferred by experiments).
- This leads to
  - Severe occupancy problems in the tracker
  - Radiation issues for the pixel sensors and the forward calorimeters
    - Must tolerate as much each year as they did for previous decade!
  - Severe breakdown of the Level 1 trigger
  - Need to expand the data acquisition system and the HLT
- This will require a substantial rebuild of much of CMS
  - Projected to take at least two years to install and commission
- Substantial R&D is needed to address the challenge
  - This R&D must be accomplished in the next ~3-4 years so one can start to build circa 2015 to be ready for installation circa 2021/22

6.1 The Case for Using Tracking in the L 1 Trigger

- At 2×10^{34} $cm^{-2}s^{-1}$, we will be using the full granularity and resolution of the muon system and calorimeters and will be able to trigger on the important physics efficiently (barely)
- When the luminosity goes above this, the Level 1 trigger rates are too high and the Level 1 trigger becomes inefficient
- The only move left, which can be shown to work with simulation and with data, is to add information from the inner tracker to the Level 1 trigger

Current Thresholds & Rates

- Extrapolation from data collected
  - For 2×10^{33} cm^{-2} s^{-1}
- Electron / Photon Trigger
  - Single: 30 GeV / 1.5 kHz
  - Double: 10 GeV / 1.4 kHz
- Muon Trigger
  - Single: 10 (25) GeV / 11 (4.1) kHz
  - Double: 5 GeV / 1.3 kHz

5/12/11 Sridhara Dasu (Wisconsin) 2

Realistic 5×10^{34} cm^{-2} s^{-1} Thresholds & Rates

- Extrapolation from data collected
  - For 5×10^{34} cm^{-2} s^{-1}
- Electron / Photon Trigger
  - Single: > 50 GeV / 20 kHz
  - Double: 30 GeV / 20 kHz
- Muon Trigger
  - Single: No control on threshold
  - Double: 20 GeV / 10 kHz
- Double triggers could have additional contribution from PU, but is not included above
- Are these acceptable for physics of HL-SLHC?

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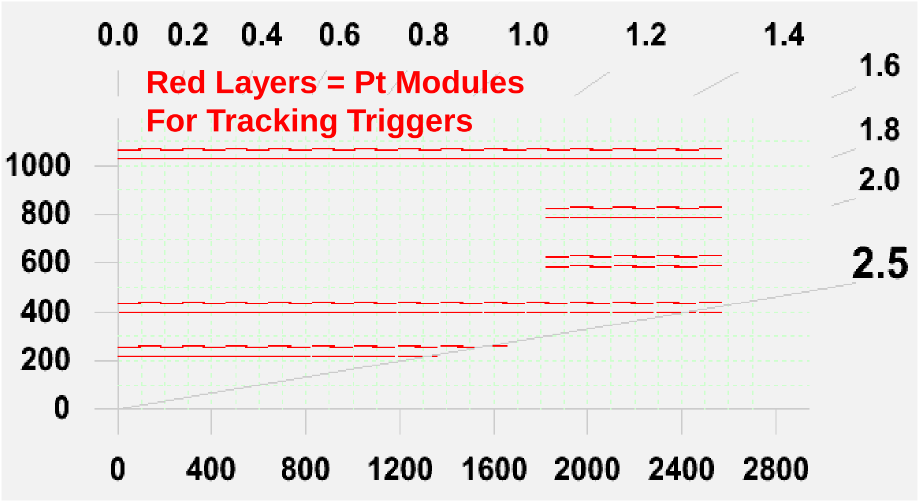
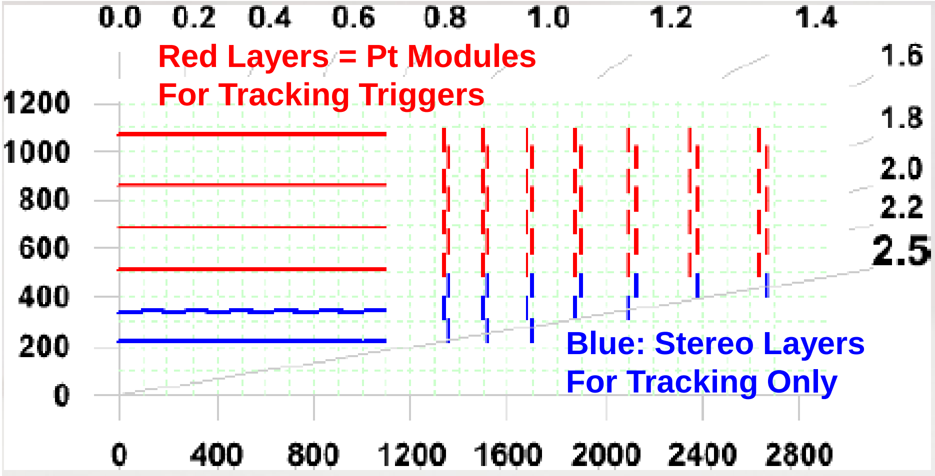
6.1 Rebuilding the Tracker

- The Tracker has to be rebuilt for higher luminosities because
  - The occupancy will be too high for good, efficient pattern recognition with pileup of 100->200
  - Radiation damage will become a problem at integrated luminosity > 500-700 fb^{-1} .
- It will need to be designed so it can be efficiently used in the Level 1 trigger
  - The new Tracker will probably have > 200M pixels, >100M strips
  - Getting all the hit data off the detector, several MBytes at 40 MHz, is not possible with any technology that we can envision
- The basic idea is to arrange the Tracker geometry so it is possible to identify hits of tracks of "moderate" P_t (above ~2 GeV/c) inside the Tracker volume with local electronics so only hits on that very small subset of tracks have to be moved off the detector to Level 1 electronics for fitting and correlation with signals from the calorimeter and muon detector
- One of several possible ideas is shown on the next two slides

6.1 Complementary Layouts

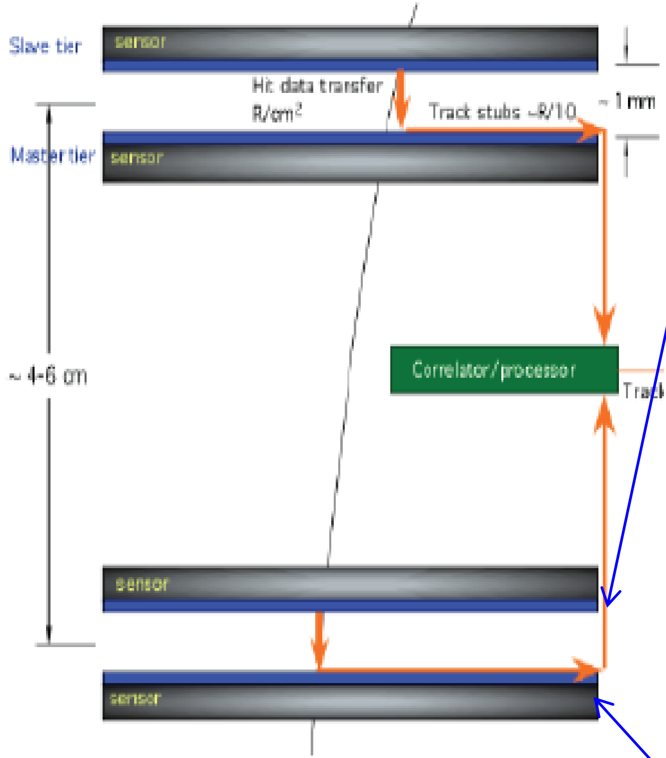
- **Complementary Layouts => compare qualitatively different possibilities**
  - **Long Barrels vs Barrels and End-Cap Discs**
  - **Strip and/or Pixelated Pt module deployment at different radii**
    - **Strip Pt modules limited to region above R ~ 50cm**
  - **Different arrangements (and number) of Pt Layers**
    - **Super Layers: closely spaced pairs of Pt Layers**
    - **Independent Pt layers**
    - **Different architectures & performance potential**

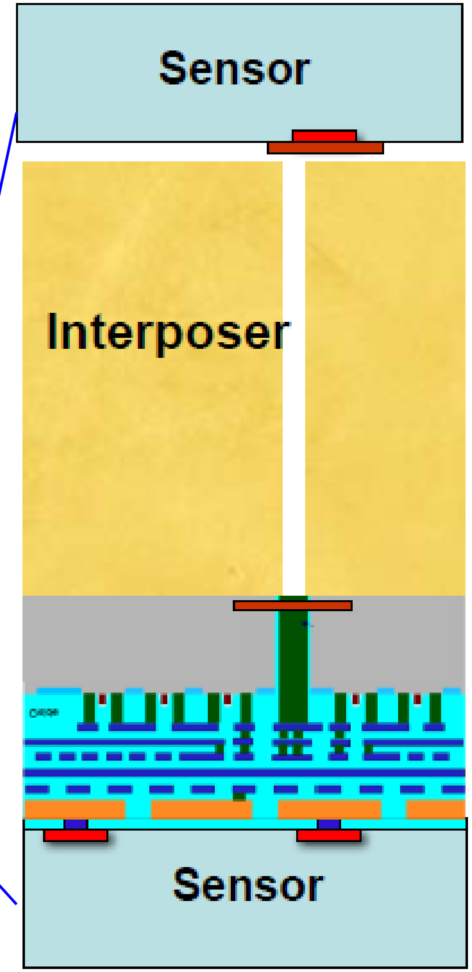




6.1 Trigger Scheme for Long Barrel

- Stack of two detectors separated ≈1mm in r
- Correlate hit information from both sensors on the detector
- Reject hits that do not have a match in the other detector, consistent with p_T>threshold
- Move selected hits to off-detector processor





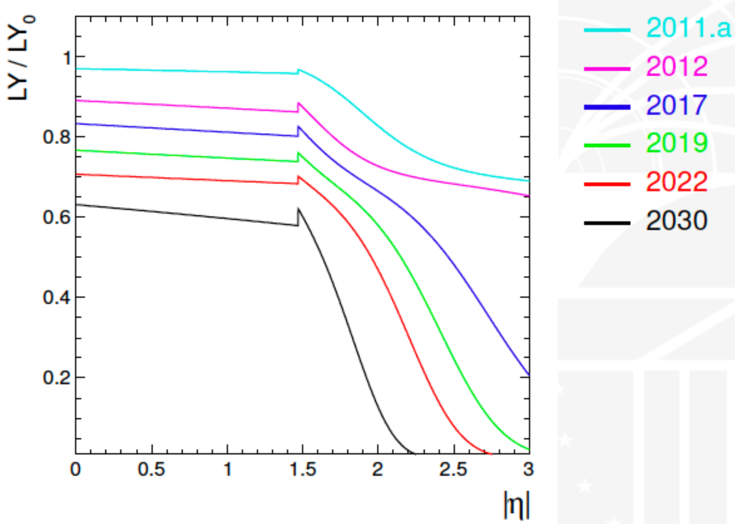
- techniques being developed by industry
- collaborate with industrial partners

6.2 Forward calorimetry: Loss of Light due to Radiation Damage vs η

Lead Tungstate scintillating crystal

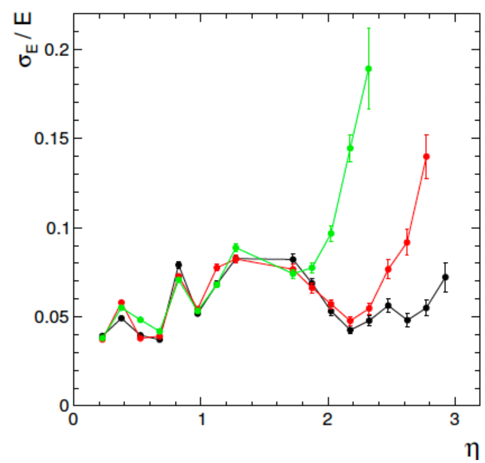
Radiation Damage in ECAL

Relative degradation of ECAL signal due to loss of Light Yield.



Energy Resolution for Photons

Average for all photon energies of the SUSY events



Resolution of basic clusters vs η:

- 0 fb^{-1}
- 500 fb^{-1}
- 3000 fb^{-1}

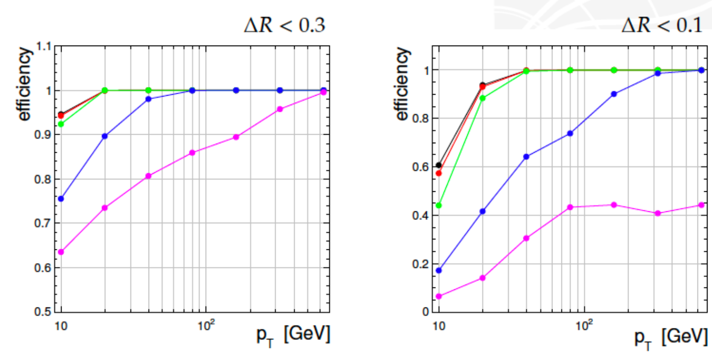
This plot is for SR and ZS ×2 of the nominal

Particle gun is a better choice for detailed studies

effects of rad. damage only

Efficiency of finding a jet with ΔR matching

- 2009
- 2017
- 2019
- 2022
- 2024



6.2 New Detector Materials for Calorimetry

- **Possible radiation-hard sensor options have been identified (not inclusive):**
  - **New Crystals - LYSO, CeF, etc** — **challenge (cost, availability)**
  - **Photodetectors - GaAs/GaInP** — **challenge (needs R&D/proceeding)**
  - **Tranparent Ceramics** — **challenge (need R&D/just beginning)**
  - **Crystal Fibers** — **challenge (needs R&D/ limited applicability)**
  - **Quartz plates**
  - **Liquid scintillator Calorimetry**
- **Possible radiation-hard photodetectors**
  - **Photodetectors – GaAs/GaInp – pixelated radiation hard Geiger –mode detectors, which need R&D that we are now undertaking**

7.0 Summary

- LHC is the first machine capable of exploring the whole range of phenomena up to ~1 TeV
- CMS is superbly designed to find how nature behaves at the Terascale for pileup ~20 interactions/crossing and a few hundred fb-1 integrated luminosity
- It is very credible that the LHC will exceed that and eventually run at peak luminosities that imply 100-200 interactions/crossing and produce integrated luminosity of 300 fb-1/year for another decade
- We have presented an incremental upgrade path to deal with the luminosity growth through 2020/2022
- We have indicated the necessity for rebuilds of major portions of the detector to handle the highest rates comparable
- The physics we learn from the first few years might influence the exact path we take for the Phase 2 upgrades
- The LHC will be the intensity frontier for the next twenty years so we need to preserve the ability of the experiments to take high quality data and learn as much as possible

Machine upgrade path

2013 Long shutdown 1 (18 month long):

- ***Repair magnet splices to allow operation at 14 TeV and improve collimation to permit operation at L=1 10^{34}***

2014-2017 (?) RUN (70 fb^{-1})
14 TeV run to explore Terascale physics at moderate luminosity

2017 (?) Long shutdown 2 (12 months long):

- ***Improve collimation to enable operation at L=2-3 10^{34}***
- ***Connect Linac4 into the injector complex***
- ***Upgrade the energy of the PS Booster to reduce the beam emittance***

PHASE 1: 2018- 2022 RUN (350 fb^{-1})
14 TeV high luminosity run to more thoroughly explore Terascale physics and to study in more detail new phenomena observed in the preceding runs using the upgraded detectors.

PHYSICS OF DISCOVERY

2022 (?) Long shutdown 3 (peak luminosity up to 5×10^{34} cm^{-2} s^{-1}) :

- ***Luminosity leveling***
- ***Crab Crossing Scheme***
- ***Early Separation Scheme***

HL-LHC: 3,000 fb^{-1} for PRECISION measurements

HE-LHC ?

Backup Slides

LHC performance

	2010/2011	Nominal
Energy [TeV]	3.5	7
beta* [m]	3.5, 3.5, 3.5, 3.5 m	0.55, 10, 0.55, 10
Emittance [microns]	**2.0 – 3.5 start of fill**	**3.75**
Transverse beam size at IP [microns]	around 60	16.7
Bunch current	**1.2e11**	**1.15e11**
Number of bunches	480	2808
Bunch crossing time (ns)	50	25
Peak luminosity [$cm^{-2}s^{-1}$]	5e32	1e34

We have already passed 10^{33} $cm^{-2}s^{-1}$

Detector Issues for Phase 1 Super

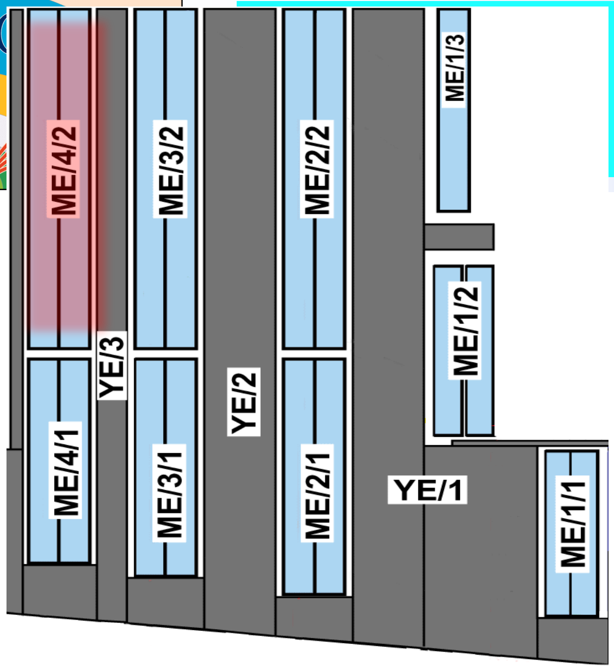
- Maintain the CMS detector physics performance expected at $L=10^{34}$ cm^{-2} s^{-1} at higher peak luminosities.
- Already 40 (80) interactions/crossing at $L=2\times10^{34}$ cm^{-2} s^{-1} and 25 (50) ns bunch crossing
- In Phase 1 the main concern is the increase in L_{peak}
  - Trigger performance degradation
    - Upgrades to the muon system and the hadron calorimeters aim to preserve the Level 1 trigger capability by providing it with more and higher quality inputs.
  - Decreases capability to discriminate electrons from jets
    - Implement longitudinal segmentation in hadronic calorimeter
  - Data losses due to latencies and limited buffering
    - Severe data losses in the inner pixel layer (>50% peak data loss at 2E34/cm^2/s with 50ns spacing)
    - Radiation damage will lead to loss of efficiency and poor position resolution in the inner pixel layer
- HL-LHC: radiation damage and higher L_{peak} lead to more serious issues.

CMS Upgrades ideal scenario

- 2013 Long Shutdown (LS1)

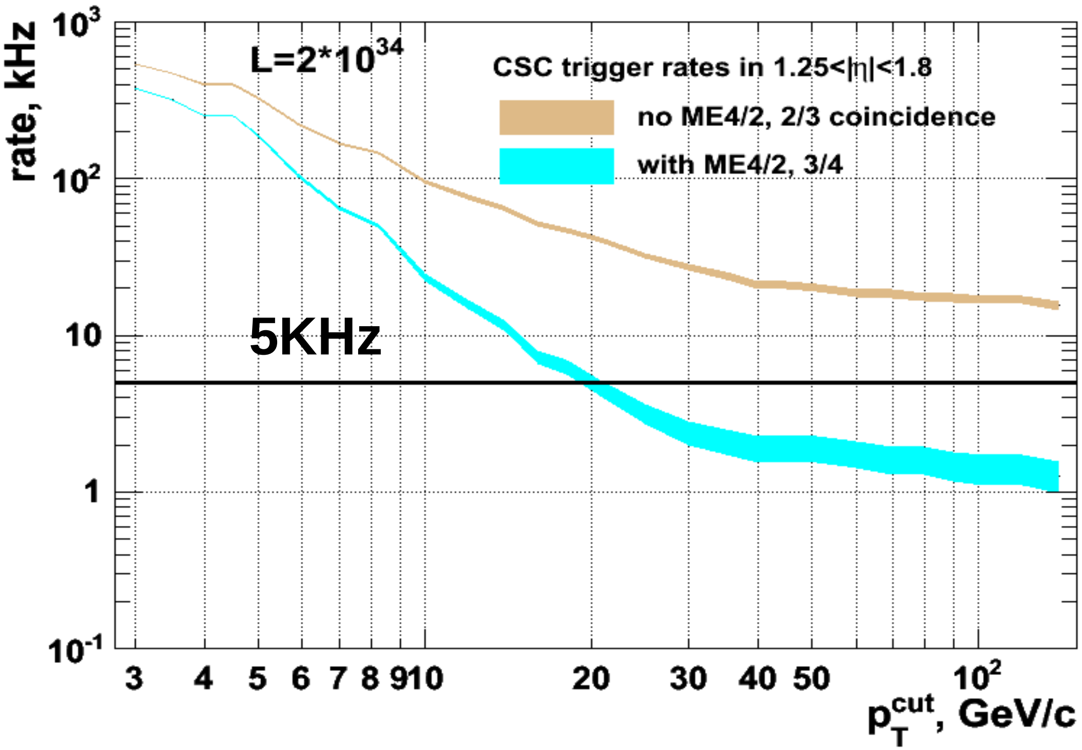
M&O
  - HO SiPMs (Hadronic Calorimeter Tail Catcher)
  - HF PMTs (Forward Hadron Calorimeter eta 3-5)
  - Installation of CSC muon systems
  - Pixel Luminosity Telescope (if not done in an earlier technical stop)
  - Install new beam pipe with 4.5 mm diameter
- 2017 ? Long Shutdown (LS2)
  - Install new pixel detector (it could also be done in a long technical stop before LS2)
  - Install HB/HE photo-detectors
  - Install new trigger system
- 2022?? Long Shutdown (LS3)
  - Install new tracking system
  - Major consolidation/replacement of electronics systems
    - Including potentially ECAL electronics
  - ECAL and HCAL Endcaps (subject of a task force)
  - Trigger and DAQ system upgrade

CSC Upgrade



- **Present System: 473 Cathode Strip Chambers covering both endcaps**
- **Proposed Upgrade: Add 67 new CSC chambers to complete the 4th station**
- **Muon Trigger robustness in 1.2<|η|<1.8**

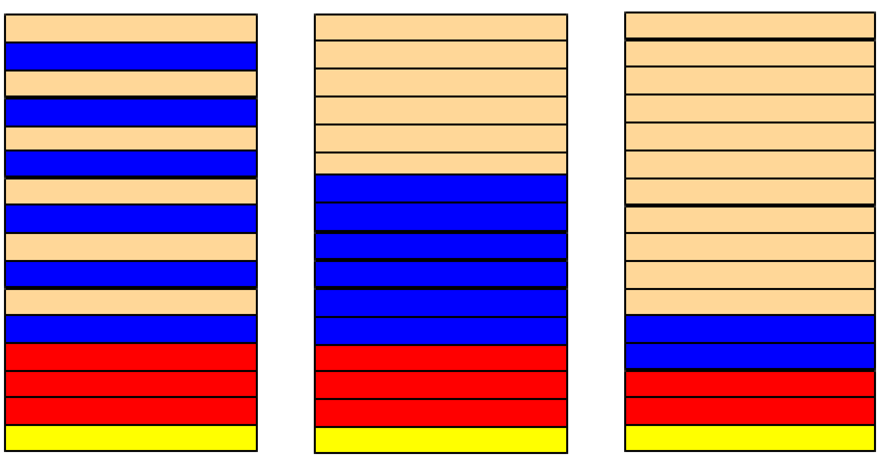
5 chambers already installed

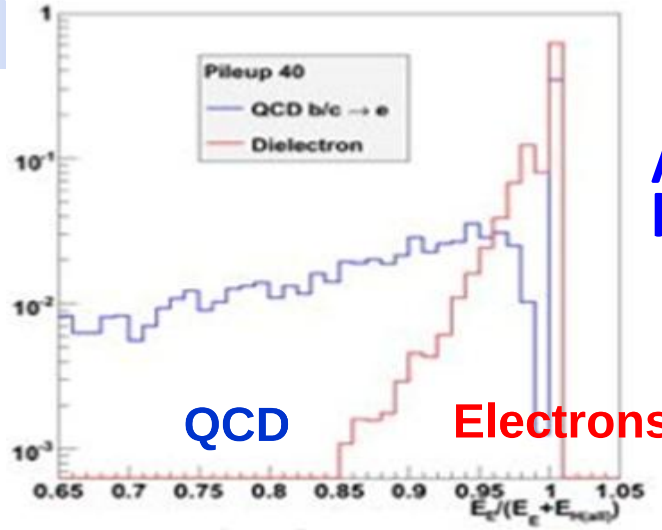


HCAL upgrade

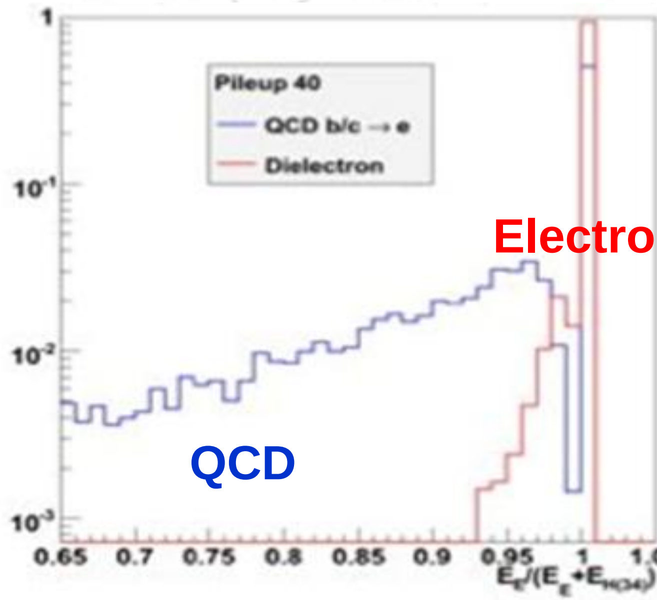
40 pileup events = 1E34 and 50 ns spacing

- **Replace HPD with higher performance SiPM in HB/HE**
- **Compact size of SiPMs allows depth segmentation in HB/HE**
  - **Redundancy for non-BX signals &channel failure**
  - **Reweighting of inner layer to:**
    - **Mitigate rad damage**
    - **Improve electron isolation**





All layers

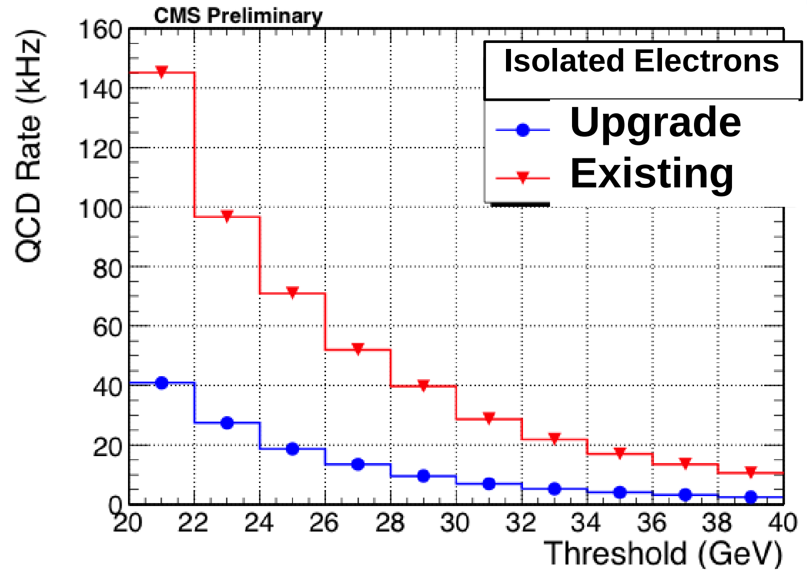


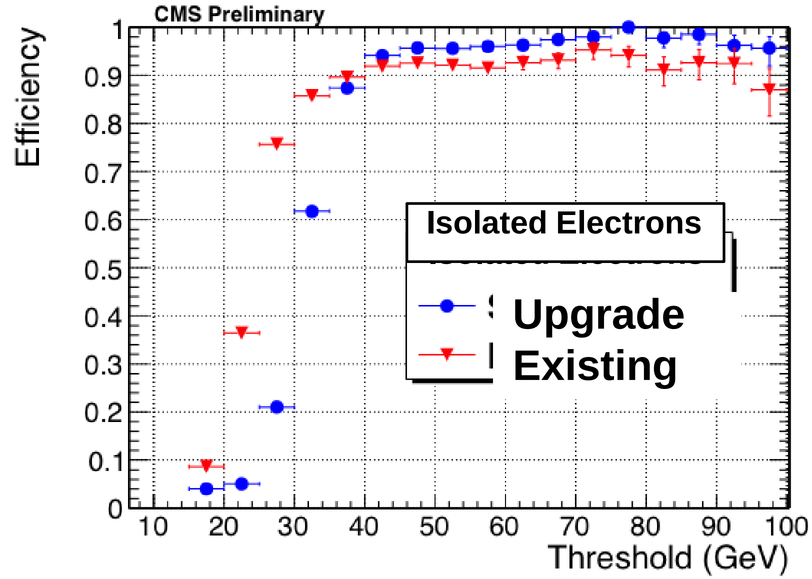
Excluding L0

- **Isolation of electrons and photons $E_{ECAL}/(E_{ECAL}+E_{HCAL})$ is impacted by pileup in Layer-0.**

CMS Trigger Upgrade

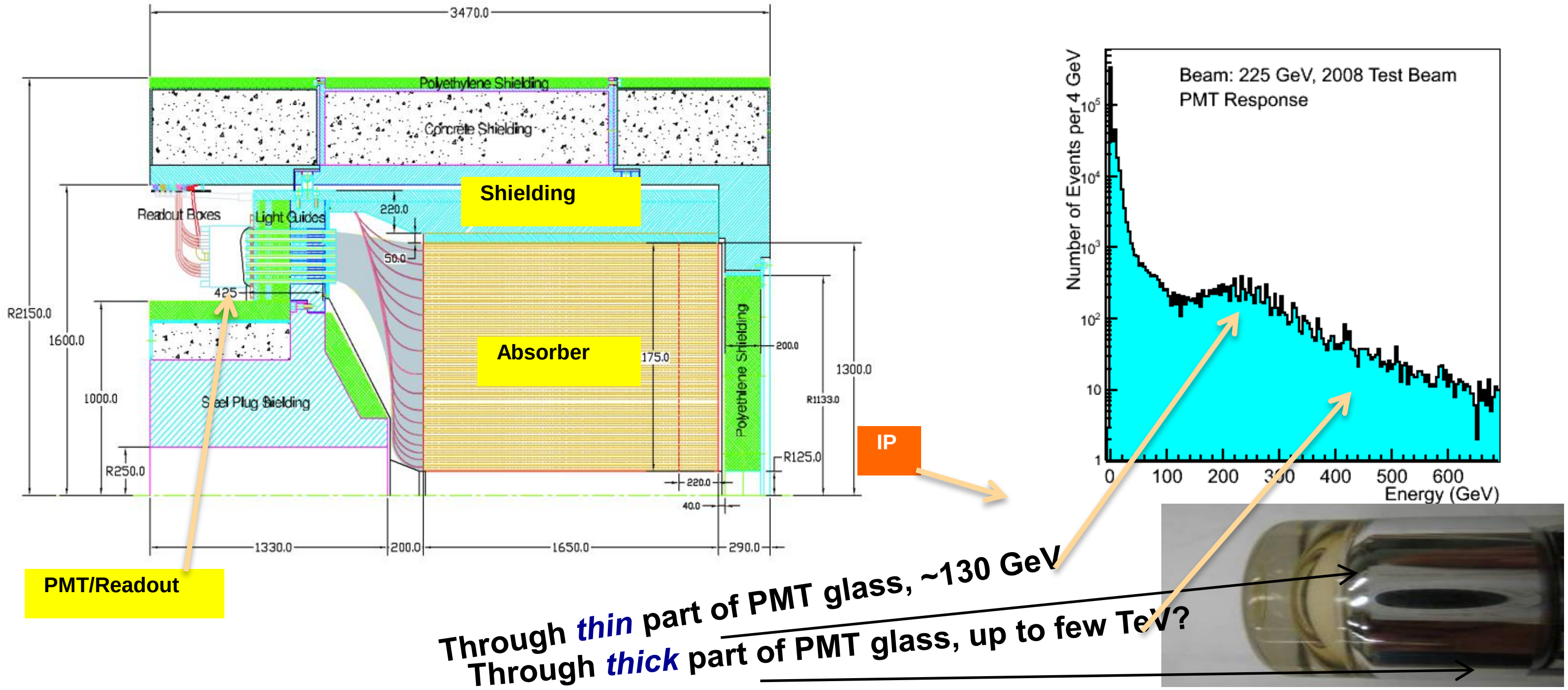
- **Constraints**
  - **Output rate at 100 kHz**
  - **Input rate increases x2 over LHC design (10^{34})**
  - **Number of interactions in a crossing (Pileup) goes up by x4 at 50 ns**
- **Strategy for Phase 1 Calorimeter**
  - **Present L1 algorithms inadequate above 10^{34} or 10^{34} w/ 50 ns spacing**
    - **Pileup degrades object isolation**
  - **Current FPGA technologies allow sophisticated cluster algorithms & isolation deal w/more busy events**
    - **Use full granularity of calorimeter trigger information**
  - **Factor of 2 reduction in rate as shown with initial L1 Trigger studies.**





HF Upgrade

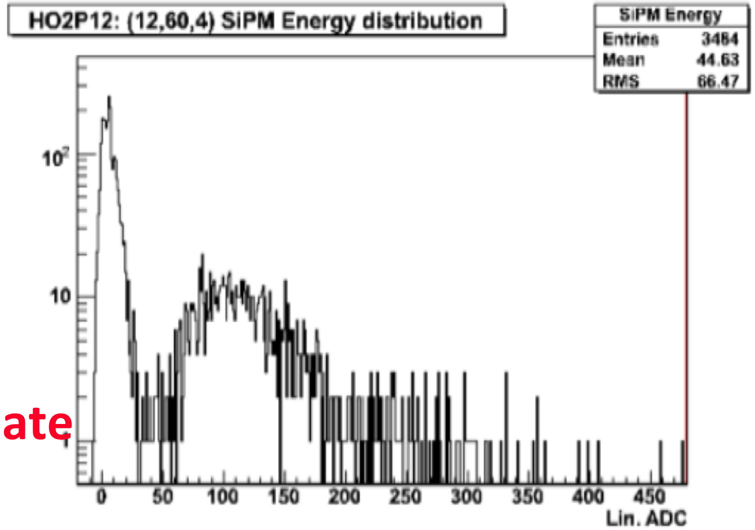
- **Steel absorber w/horizontal quartz fibers, detects cerenkov γs, few GeV/photon readout with high gain PMTs**



- **In collision data anomalous signals contaminate MET tail**
  - **Well known, studied in testbeam ("Window Events")**
- **Easy to mitigate using thin window PMTs with metal sides**

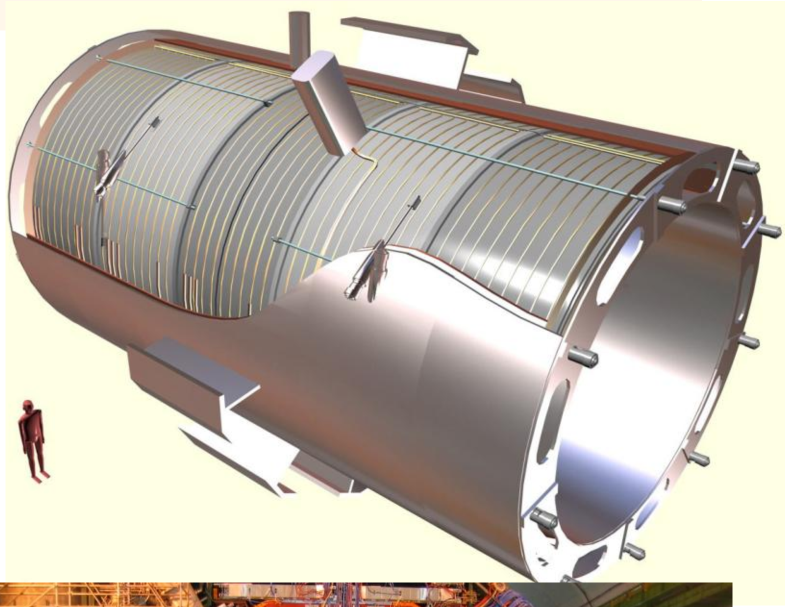
HCAL Outer (HO)

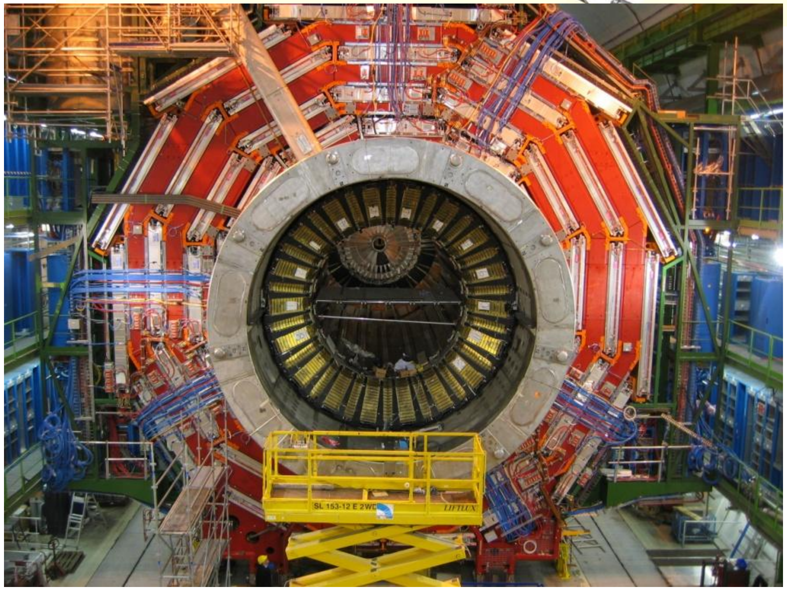
- HPDs susceptible to discharge at intermediate B-fields.
  - Mitigated by lowering gain but that causes problems with S/N for min-ionizing (muons) and reduced contribution to jet measurement
- Will replace HPDs with SiPMs (see below) for all HO for performance improvement and to provide a common system.
- Operated 2 RBXs with SiPMs in situ for the last year: shows 10x improvement in S/N for muons
- Dynamic range required for HO is met by current generation SiPMs and existing digitizer (QIE)
- 2012 Timeline:
  - Replace all HPDs with SiPM
  - Retrofit existing electronics for new SiPM
- Status
  - SiPM order placed, first production deliveries soon
  - Mechanics and electronics R&D finished
- Imperative: HPDs will likely not last, S/N inadequate for muon contribution
- Risks: very few, not a technically challenging fix



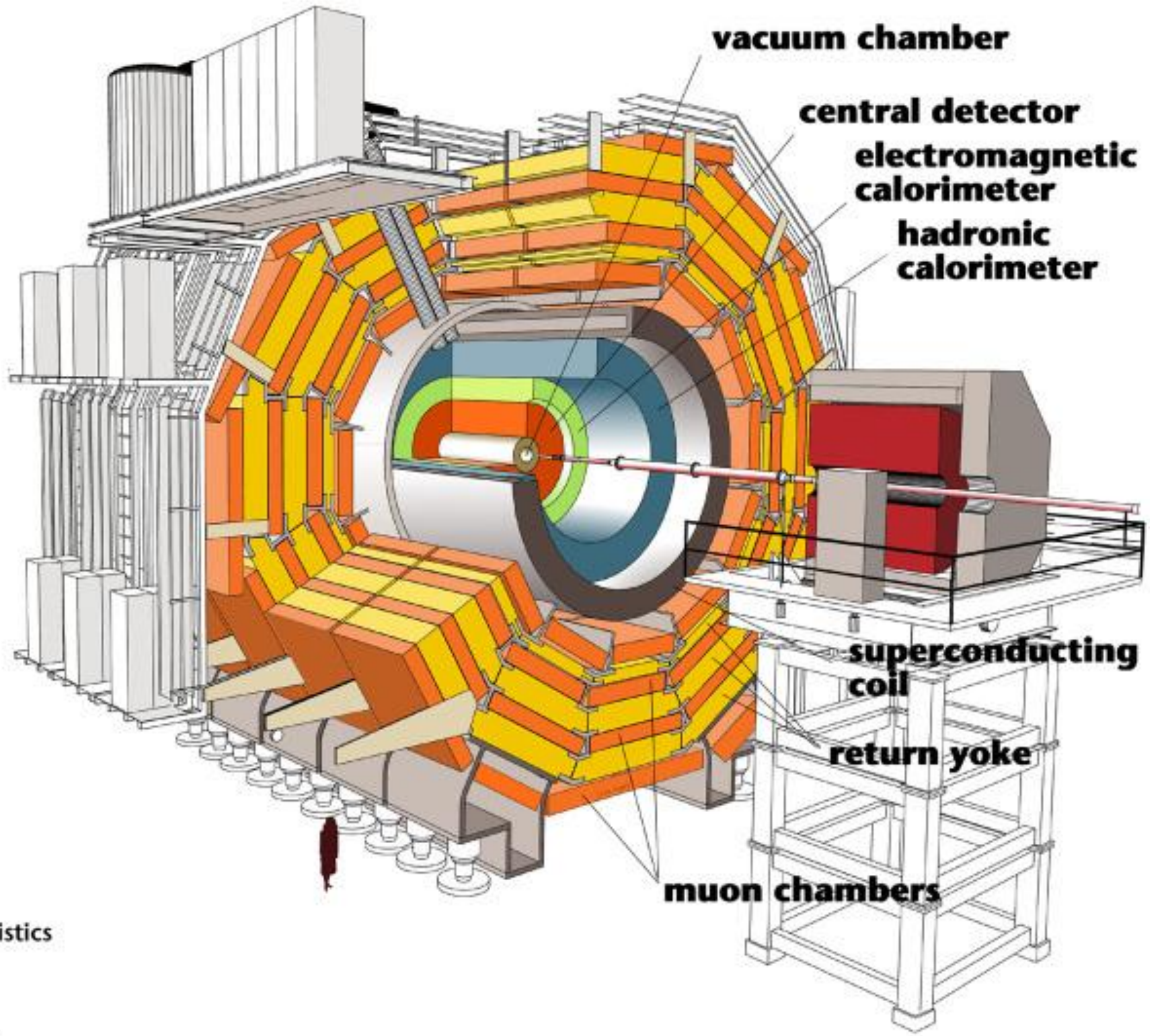
3. CMS Solenoid

- **Solenoid has the features described above**
  - **Large acceptance in the most promising region**
  - **Bends charged particles, allowing tracker to measure the transverse momentum. Optimal for measuring P_t in central region**
- **3.8 T magnet at 4^o K**
- **6 m diameter and 12.5 m long (largest ever built)**
- **220 t (including 6 t of NbTi)**
- **Stores 2.7 GJ — equivalent to 1300 lbs of TNT**





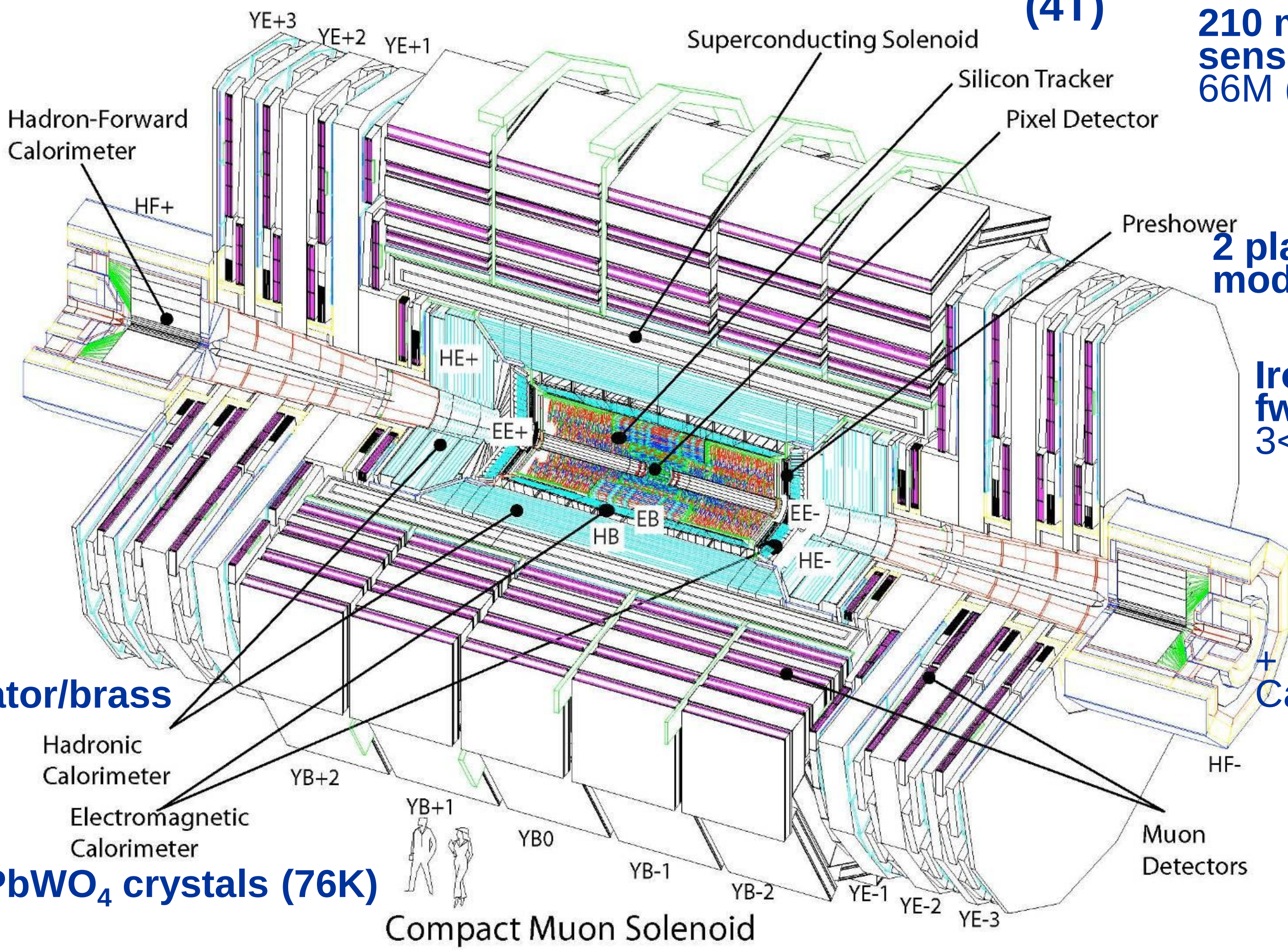
3. CMS - The Compact Muon Solenoid



Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

CMS - The Compact Muon Solenoid



(4T)

210 m^2 of silicon sensors: 9.6M (Str) & 66M (Pix) channels

2 planes of silicon modules for ECAL

Iron / Quartz fiber fwd calorimeter, $3<|\eta|<5$;

+ Castor, $5<|\eta|<6.55$

+ Zero Degree Calorimeter

Scintillator/brass

$PbWO_4$ crystals (76K)

Cathode Strip Chambers,

Drift Tubes, Resistive Plates