

The CMS Upgrade

LPC JTERM III

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Jan. 12, 2009



Outline



- **What is the LHC Accelerator Luminosity Upgrade?**
- **What are the core strengths and principles of the current CMS detector that must be preserved?**
- **What problems will the current version of the CMS detector encounter at higher luminosities?**
- **What considerations and constraints will shape the upgrade?**
- **Examples of the Phase I Upgrade**
 - **Pixels**
 - **Muons**
- **What are the challenges of the the Phase II Upgrade**

For many more details and for other subsystems refer to
CMS Upgrade Workshop, Nov 19-21, 2008:
<http://indico.cern.ch/conferenceDisplay.py?confId=41832>

Why are we having this talk?



- It will be a great challenge for CMS to simultaneously
 1. operate and maintain the detector to take good data
 2. analyze the data and extract the physics
 3. do the R&D and construct the upgraded CMS detector
- While younger physicists need to pay attention to items 1 and 2, they should try, if possible, to allocate some of their time and effort to the upgrades. The upgrade activity provides
 - An opportunity to understand the limits of the existing detector
 - An opportunity to participate in the design of a new detector
 - Most of us did not participate in the design of this CMS detector
 - Because you will soon be working directly with real data and will be adept at the simulation and analysis tools, you should be particularly effective. This is an extension of your normal work
 - Test beam and prototype work that will provide you with the knowledge and experience to contribute to the upgrade hardware
 - The upgrade will be a major activity (and source of funds) starting in 2011
- Physics will surely require us to implement these upgrades
 - to study in detail the phenomena seen at lower luminosity and
 - to look for new heavy or rare objects that require the very highest integrated luminosity

Best
State to be in!!!



Experimental Challenge for the Existing Detector



LHC Detectors are radically different from the previous generations

- **High Interaction Rate**

pp interaction rate **1 billion interactions/s**

Data can be recorded for only $\sim 10^2$ out of 40 million crossings/sec

Level-1 trigger decision takes $\sim 2\text{-}3\ \mu\text{s}$ and about 10^5 crossings/s pass it

⇒ **electronics need to store data locally (pipelining)**

- **Large Particle Multiplicity**

$\sim \langle 20 \rangle$ superposed events in each crossing

~ 1000 tracks stream into the detector every 25 ns

need highly granular detectors with good time resolution for low occupancy

⇒ **large number of channels ($\sim 100\text{ M}$)**

- **High Radiation Levels**

⇒ **radiation hard (tolerant) detectors and electronics**



LHC Upgrade scenarios



• **CERN has developed a TWO PHASE plan to increase the machine luminosity**

- **PHASE 1 will begin operations in 2013 with $L = 2-4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$**
 - No long shutdown needed
 - New interaction region (quadrupoles) and new linac “LINAC 4”
- **PHASE 2 to be decided in 2011 with $L = 8-10 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ by 2017/18**
 - Long, ~ 1.5 year, shutdown in 2017 driven by the experiments
 - New injectors (SPL + PS2)

Phase 1

1. No IR magnets of LHC will enter the $\pm 19 \text{ m}$ zone of the existing CMS
2. Beam crossing remains 25 ns -> 40-80 interactions/crossing!!

Phase 2

1. Beam crossing might be 25 ns or 50 ns
2. Pile-up can be up to 200 or 400 interactions per crossing!!!!!!
 - Very demanding to achieve the same performance of current detectors and TRIGGER with so much pileup
3. Might require further magnets within the experimental envelop

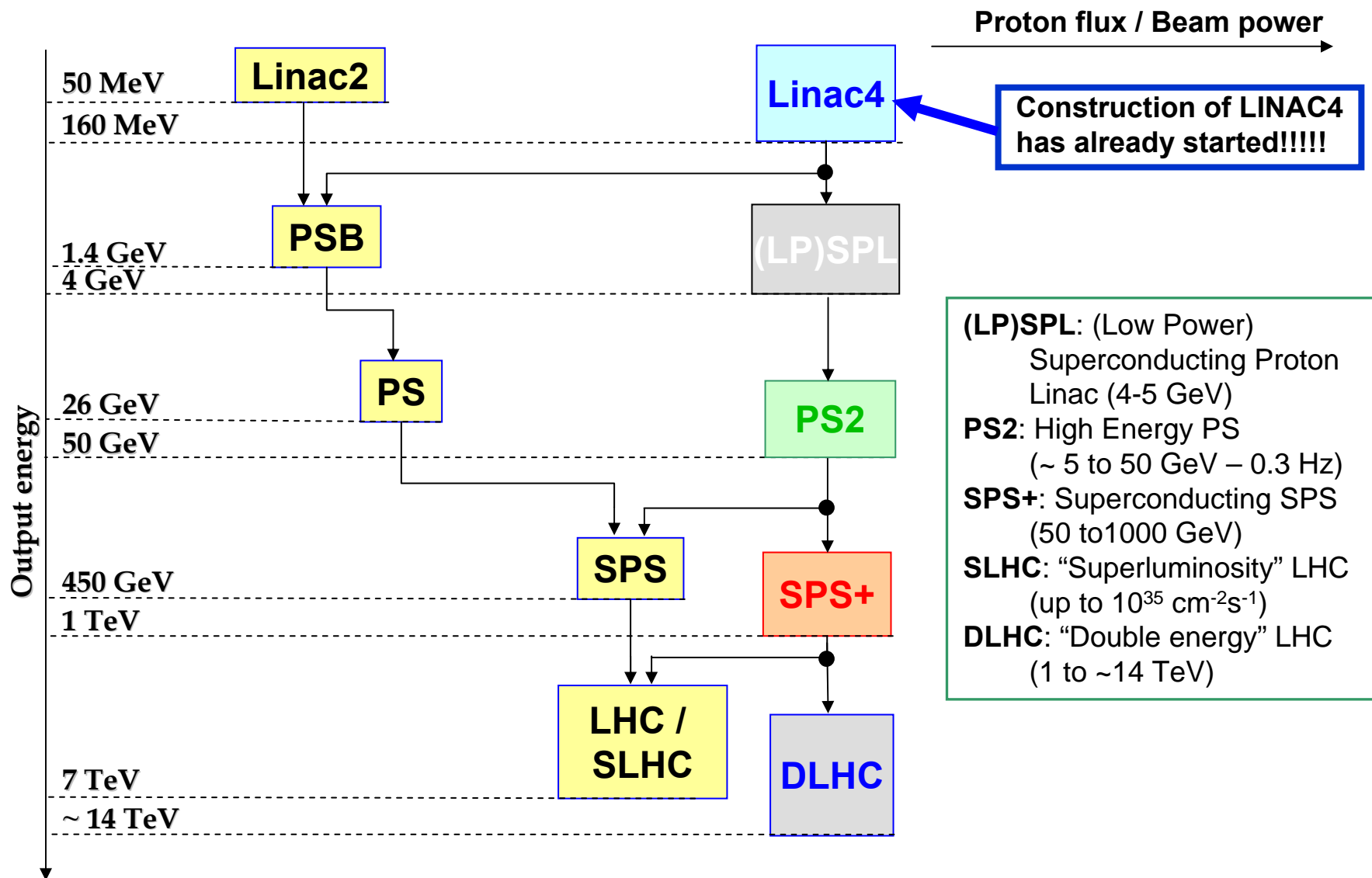
Luminosity Upgrades



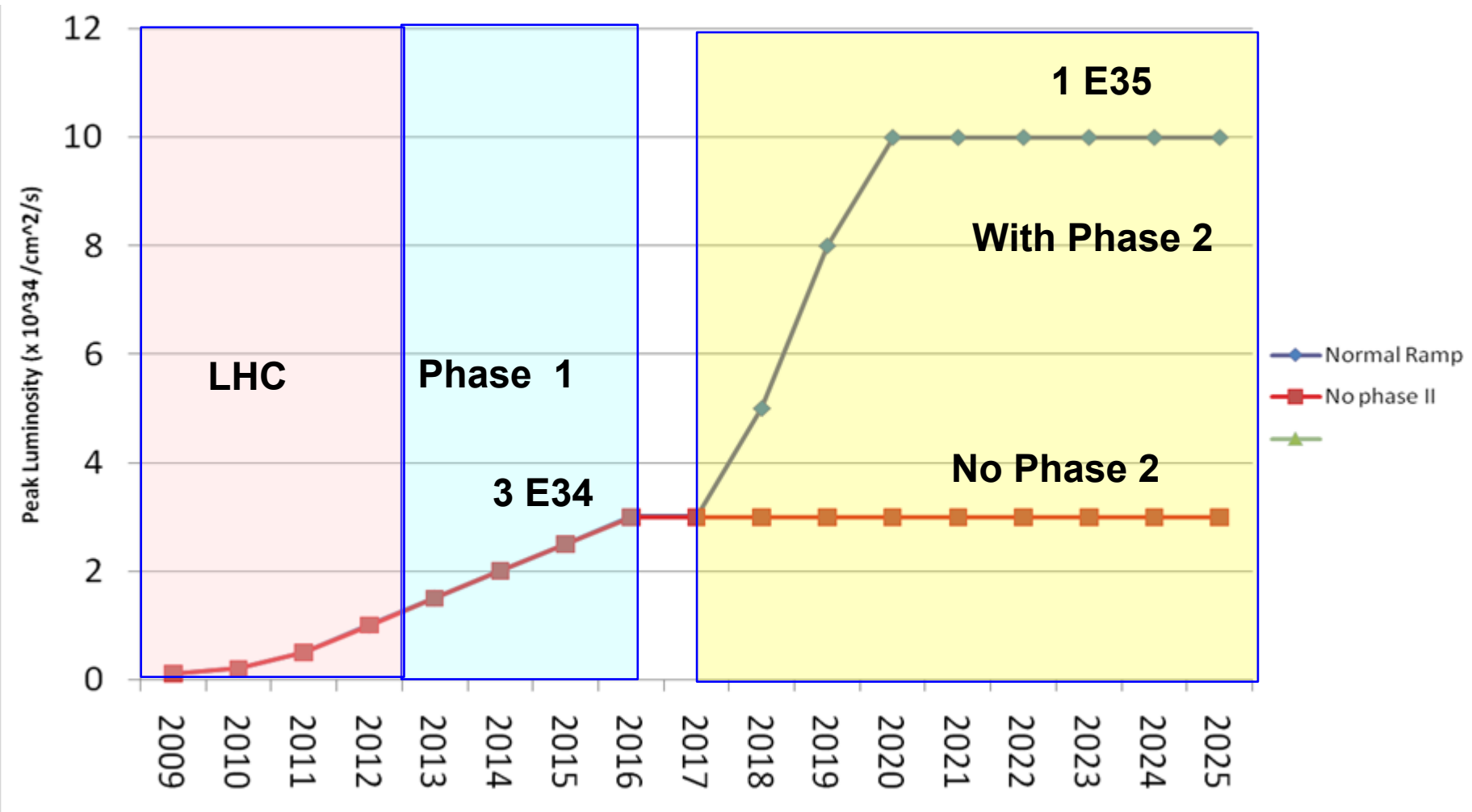
$$L \rightarrow \frac{N_b^2 n_b f_r \gamma}{4\pi \varepsilon_n \beta^*} F$$

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

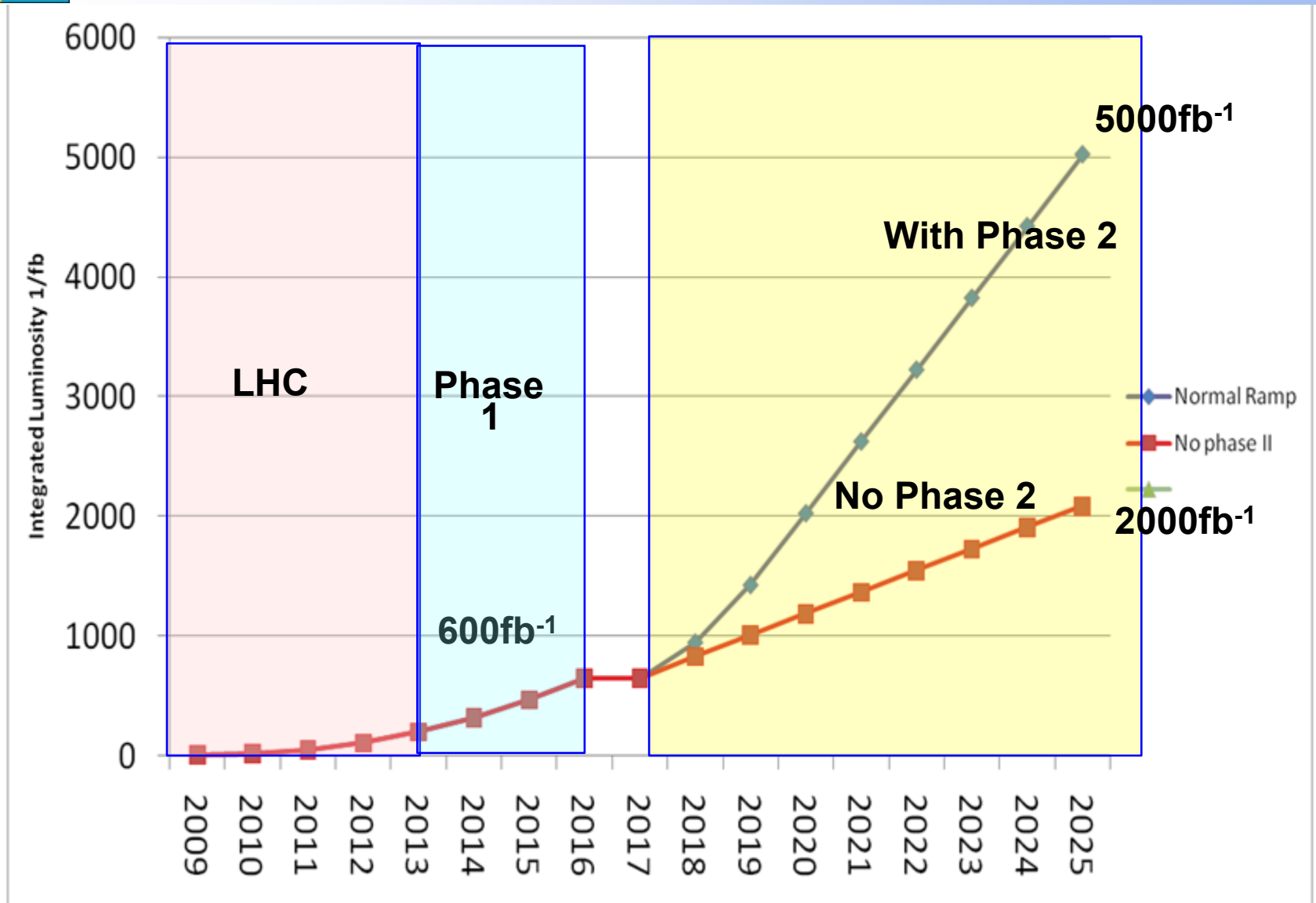
Present and Future Injectors



Peak Luminosity



Integrated Luminosity



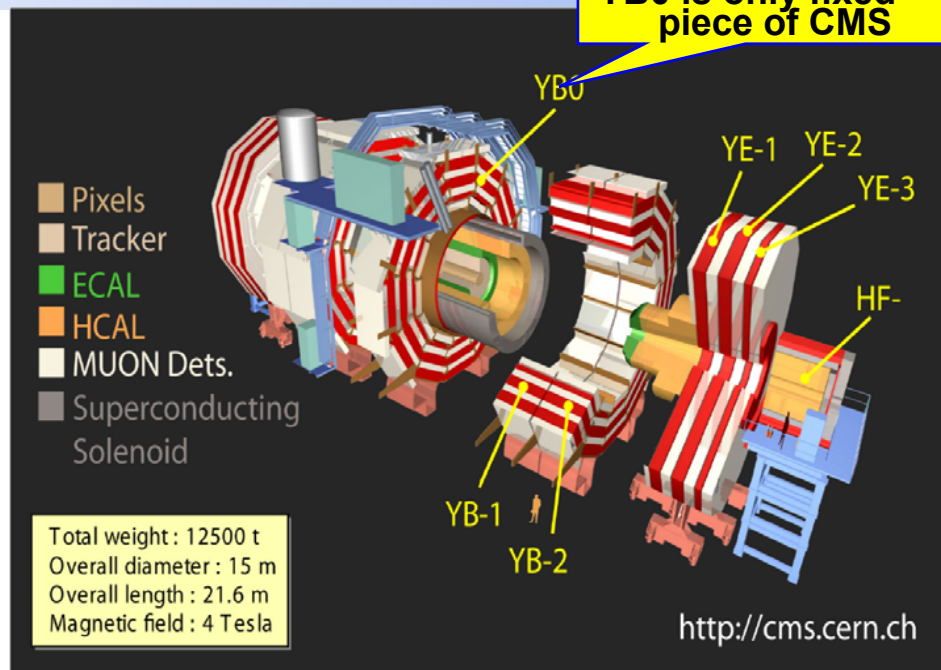


Key CMS Design Features



YB0 is only fixed piece of CMS

- Large solenoid ($d=6\text{m}$, $l=13\text{ m}$) with large 4 Tesla field
- Tracking and calorimetry are all inside the solenoid
 - Avoid having particles pass through cryostat which would degrade energy resolution
- Strong field
 - Coils up soft charged particles
 - Results in excellent momentum resolution
- Tracking chambers in the return iron yoke track and identify muons
 - This makes the system very compact
 - The weight is dominated by all the steel and is 12,500 Tonnes
- A lead tungstate crystal calorimeter ($\sim 80\text{K}$ crystals) for photon & electron reconstruction
- Hadron calorimeter for jet and missing E_t (weakly interacting particle)



- Tracking uses all-silicon components
 - A silicon pixel detector with 66 million pixels, out to $\sim 11\text{ cm}$
 - A silicon microstrip detector with 11 million strips, out to 1.2m
 - Excellent charged particle tracking and primary and secondary vertex reconstruction
 - High segmentation results in very low occupancy



Issues for CMS Upgrade

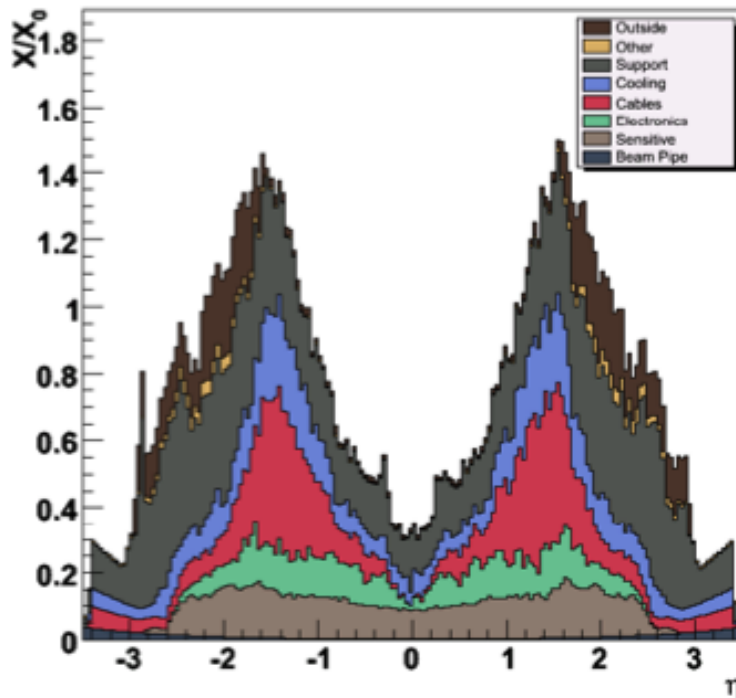


- The CMS Upgrade Plan is based on making changes to the detector that are needed to run for sustained periods at luminosities well above $10^{34}\text{cm}^{-2}\text{s}^{-1}$ of the original design and to achieve AT THE MINIMUM the same physics efficiency we designed to achieve at $10^{34}\text{cm}^{-2}\text{s}^{-1}$
- Issues that must be addressed
 - Radiation damage
 - Need more radiation tolerant sensors and electronics
 - High occupancy that affects reconstruction or triggering
 - Need more segmentation/channels
 - High occupancy that leads to overflow of buffers and to problems with data link bandwidth
 - Pileup that creates dead time or affects trigger
 - Pileup that causes problems in Missing E_t and isolation
 - Sensitivity to very rare events
 - “fakes” via accidentals often involving cosmic rays
- CMS is accessible and has been designed to be opened

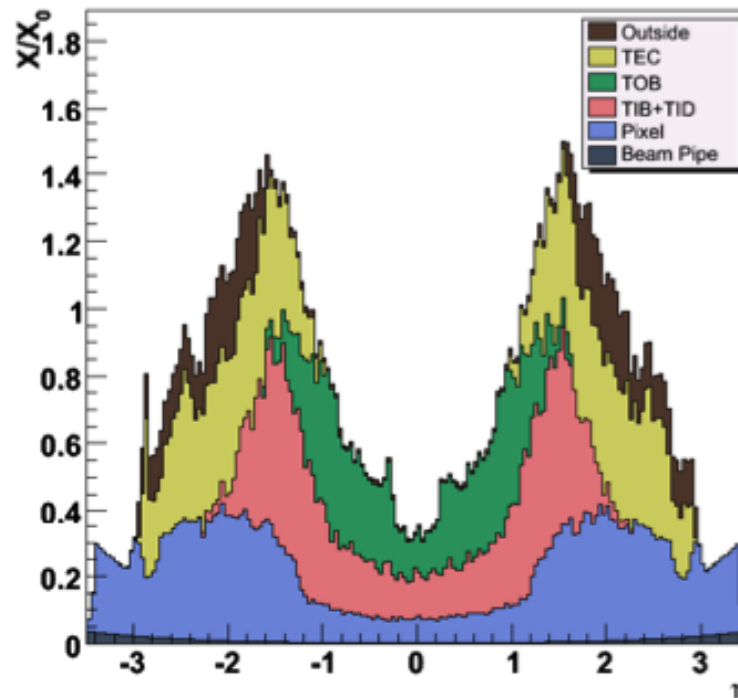
Material Budget



Tracker Material Budget



Tracker Material Budget



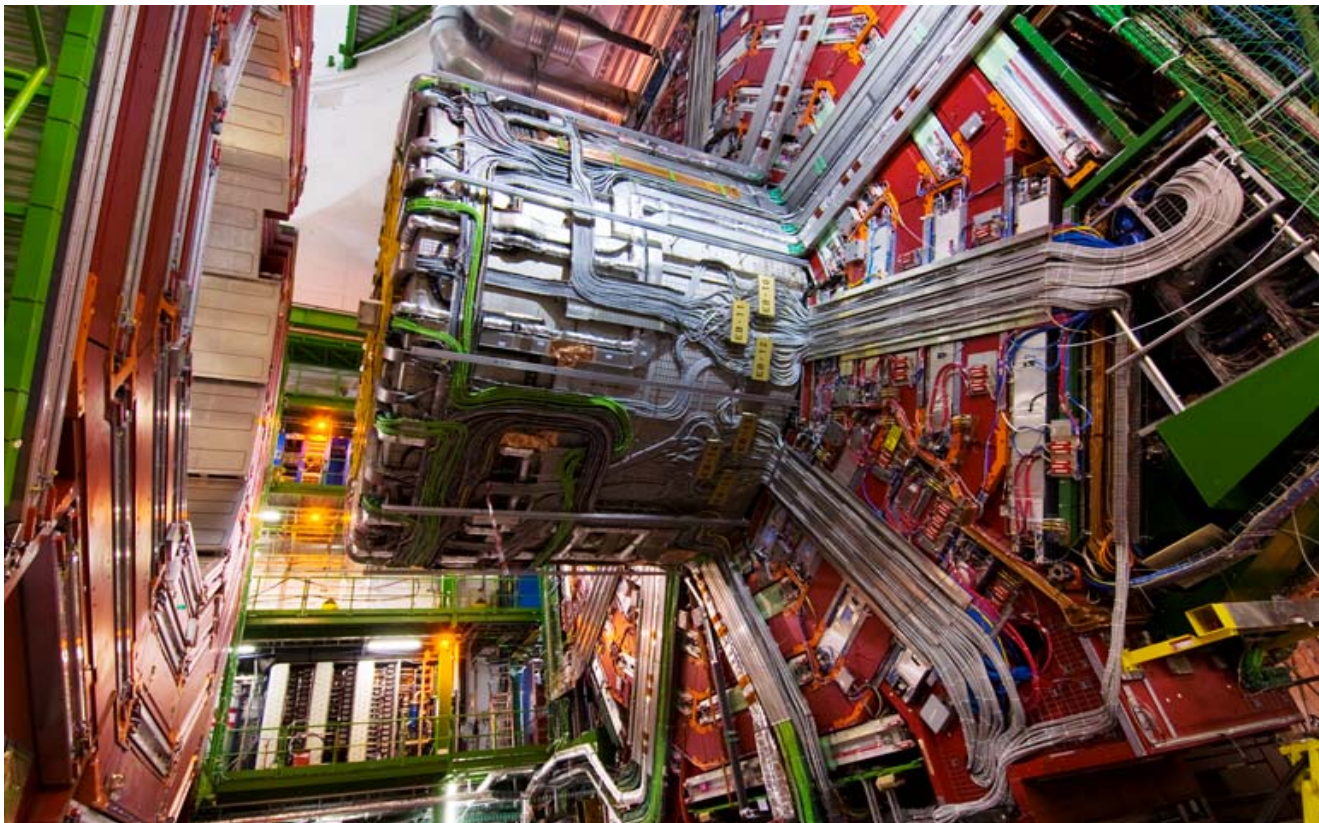
There is too much material in the CMS detector NOW.

Power, cooling, and the associated cabling and piping, along with mechanical supports dominate the material budget.

Many possible approaches to the upgrade will move in the direction of **INCREASING** the amount of **POWER** needed, and correspondingly the amount of **COOLING** required.

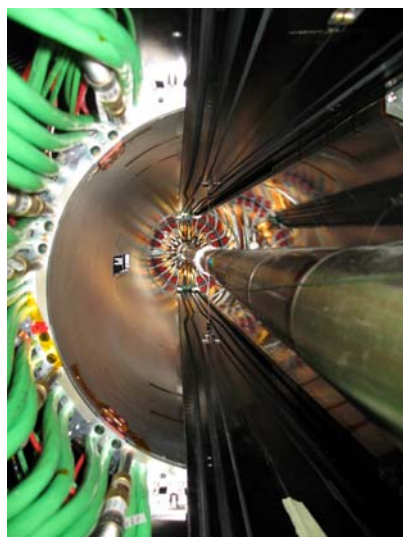
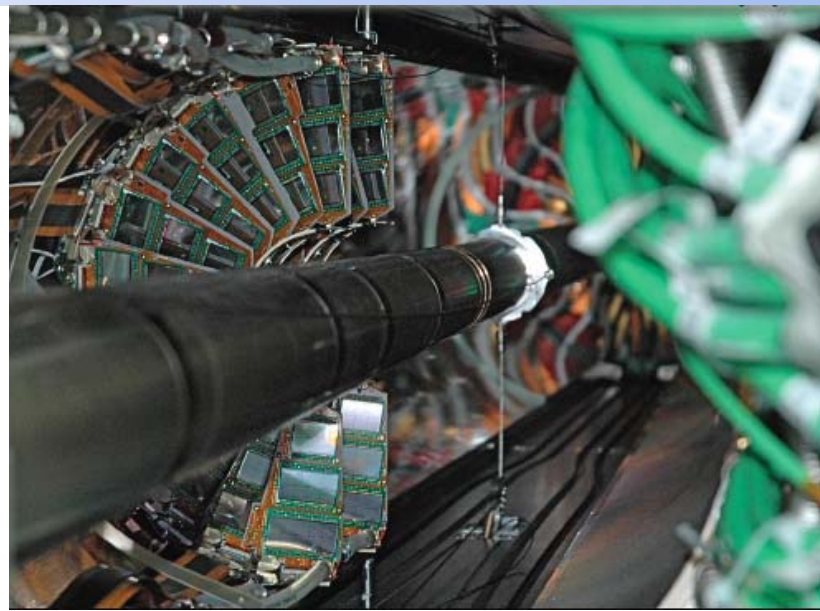
R&D in new materials and techniques is going to be required.

Constraints of Existing Installation



The cabling and piping infrastructure is very complicated and is constrained by the requirement that the detector must be closed. Replacing it would be time-consuming, expensive, and difficult especially after it is irradiated. It must largely be reused – e.g. rather than adding fibers to carry increased data rate, fibers will have to be driven at higher frequencies.

Ability to Upgrade in Small Steps



CMS was designed to be very modular

- Large, individual pieces were constructed above ground
- Once lowered, the pieces could be quickly put into the physical structure and hooked up up to preinstalled and pretested cables and utilities at well defined interfaces
- This modularity also makes it possible to open the detector during annual shutdowns and to have good access for maintenance
- In particular, the Pixel Detectors, which are most susceptible to radiation damage, clamshell around the beampipe and can be removed or reinserted and fully cabled in two weeks
 - This makes intermediate replacements and upgrades possible



Planning in an Uncertain Situation



- There are significant uncertainties in planning the upgrade
 - We don't REALLY know how the LHC luminosity will develop or when the upgrades will actually occur
 - There are still uncertainties in the details of the upgrades themselves
 - Bunch crossing frequency and number of interactions per bunch
 - Intrusion into the IR
 - We don't know enough about the actual performance of the existing detector, how it will behave at 10^{34} , how it will age under real world conditions, including upsets and environmental control problems
 - We don't know what the physics that emerges will require – it may weight detectors or detector characteristics differently than we believe
 - We don't have a perfect understanding of how technologies that might help us meet these challenges will develop
- Nevertheless we have to do work now because if the future develops even roughly as expected, we will need to have the design work and to be in position to prepare for construction of new components fairly soon
 - Making decisions too late means we won't be ready
 - Making decisions too soon means that we will have less performance than we could have had and maybe less than we need.

Reduced performance

Severe degradation

Component	1E34	3E34 (Phase 1)	10E34 (Phase 2)
TRACKER Pixel	OK	Rad/Occ: Replace/Add layers/disks	Rad/Occ: Full Replacement
TRACKER Strip	OK	OK	Rad/Occ: Full Replacement
ECAL Barrel	OK	OK	OK
ECAL Endcap	OK	OK	Rad high η : replace
HCAL Barrel	OK	Performance: Upgrade readout X4	No further action
HCAL Endcap	OK	Rad: Upgrade readout X4	Rad high η : new scintillators
HCAL Forward	OK	Rad: Upgrade readout X2	Rad/Occ: replace
HCAL Outer	HPD upgrade	No further action	No further action
MUON Drift Tube Barrel	OK	Change minicrates	Occ: upgrade electronics
MUON Cathode Strip chambers Endcap	OK	Occ: Add planes	Occ: upgrade electronics
MUON Resistive chambers Endcap	OK	Occ: Add planes	Occ: upgrade electronics
TRIGGER	OK	Maximal segmentation	Occ: tracking in trigger



US CMS Phase 1 Upgrade



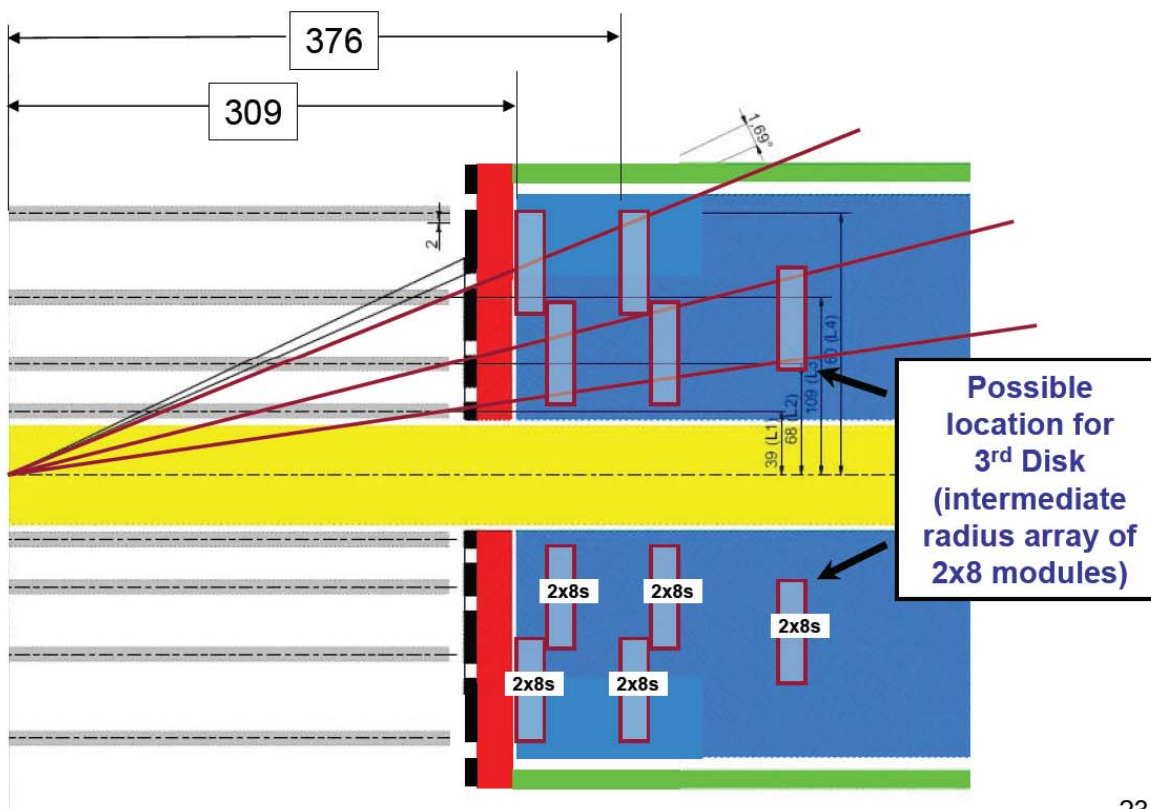
Detector	Comment
Pixel Detector	Replacement of the current system with 4 barrel layers and 3 forward disks; more radiation hard sensors; new readout chip to improve dead time; reduction of the material budget. Task shared with PSI and others.
HCAL	Implementation of longitudinal segmentation and precision timing to cope with the higher luminosities. Silicon Photomultipliers (SiPM) provide the high gain needed for segmentation and timing.
End Cap MUON	Addition of chambers in the 4th Endcap Muon layer (ME4/2) to add redundancy to reduce accidental rate and to preserve a low a P_T threshold for the L1 MuonTrigger; upgrade the layer 1 (ME1/1) electronics to include it in the trigger for added coverage.
TRIGGER	Rebuilding of the Trigger using new technologies, such as μ TCA technology (cell phone towers). This will permit flexible clustering and implementation of isolation algorithms. Both upgraded Calorimeter and Muon triggers would produce information for eventual combination with a tracking trigger information. PHASE 2 needs more – a TRACKING trigger
ECAL	New Trigger/readout receiver electronics to provide enhanced detailed information to the upgraded Regional Calorimeter Trigger

One Possible Layout of the Phase 1 Pixel Detector



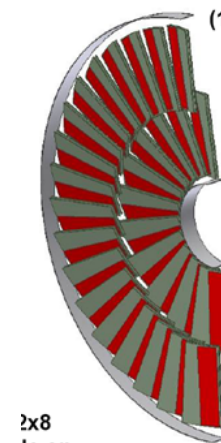
Locations for 1st and 2nd Large Disks

(to ensure four hits as acceptance angle increases beyond the third barrel layer)



Option 3:

(1) 2x8 module on each side of all outer and inner radius Blades

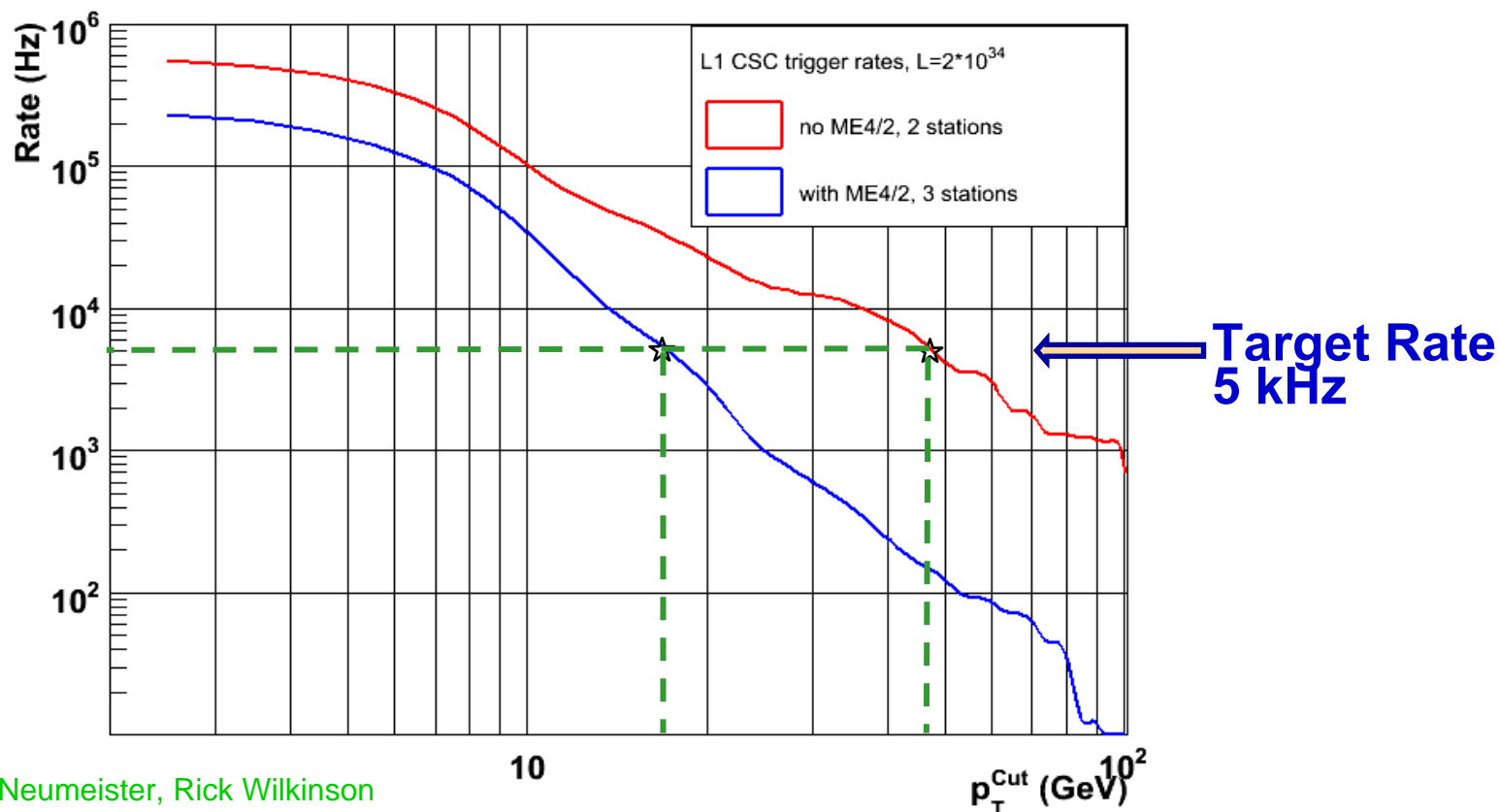


23

Triggering with the ME4/2 upgrade



- With the ME4/2 upgrade, we can still capture W, Z, top, etc. events
 - Below: trigger rate at $L=2 \cdot 10^{34}$ with ME4/2 (3/4 stations) versus without (2/3)
 - Triggering on n out of n stations is inefficient and uncertain
- The Level 1 trigger threshold is reduced from 48 \rightarrow 18 GeV/c (!)



Simulation and Stage 2

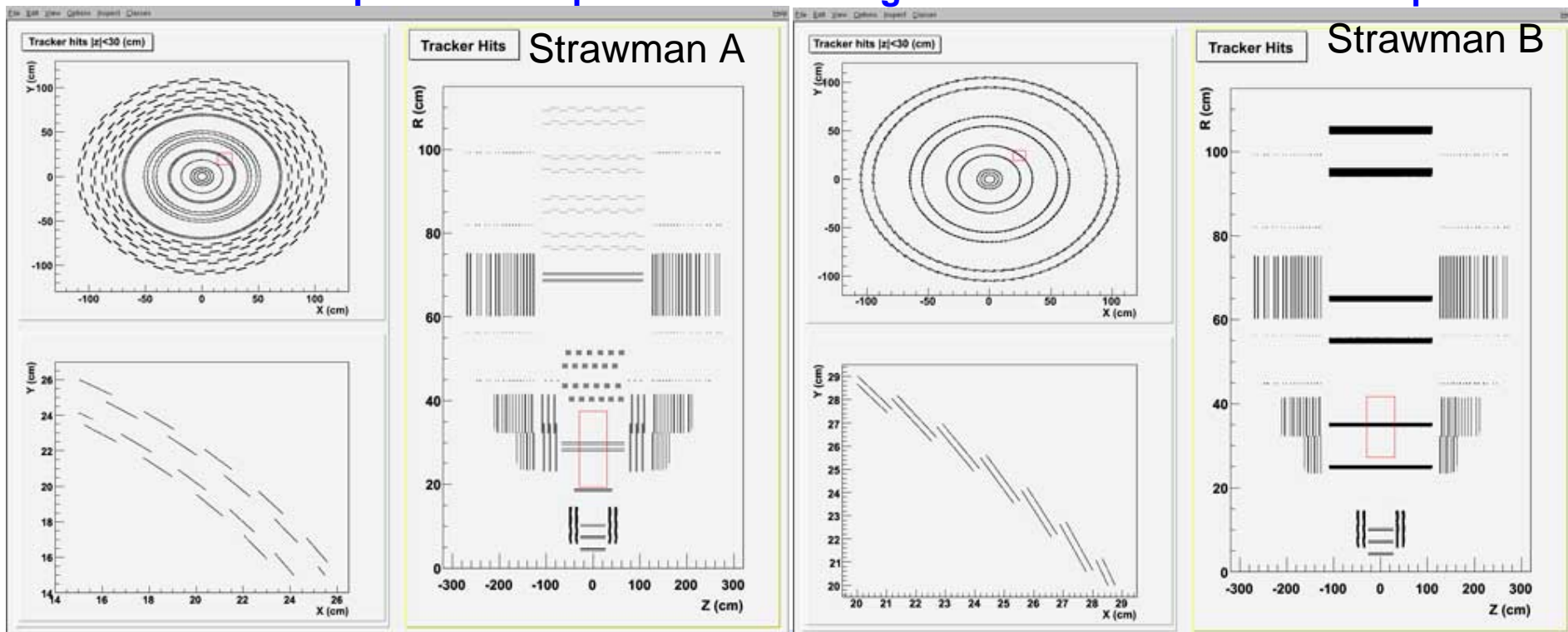


- **Stage 2 requires a complete replacement of the Tracker in order to**
 - Provide a Tracking Trigger at Level 1
 - Handle the higher occupancy and the radiation levels
- **The average number of interactions/crossing will be 200-400 (depending on bunch spacing)**
- **Since the maximum latency allowed will only be 6.4 Microseconds, this is a DAUNTING challenge**
- **The need to transport signals off the Tracker for triggers may add to the cabling, power and cooling problems and hence add material in the detector volume**
- **The GEOMETRY of the Tracker must be chosen to facilitate the “Trigger Mission”**
 - But the device must match the efficiency and resolution for tracking of the existing device
- **We need very detailed simulations - Intuition with this many interactions is not very good!**
- **Once we have a basic concept, we must do a rather complete engineering design to show it is buildable and will do the physics**
 - **A simulation that has the complete amount of material then has to be done to show it works**
- **If anyone likes a real challenge, this is IT!**

Geometry Issues



- We need to simulate different (tracking system) geometries to see which ones will make a suitable trigger
 - Strawman A has dedicated pixelated TRIGGER Layers followed by relatively continuous tracking similar to the existing detector
 - Strawman B also uses TRIGGER-like Layers at lower radii but more localized tracking at the larger radii
 - Both have planar endcaps. There is a “long barrel” version with no endcaps

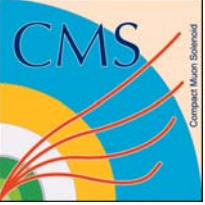


Summary



- These upgrades are incredibly challenging
- It will take an aggressive R&D program to design them – there is not much time!
- What is in it for students and post docs
 - These upgrades will be carried out by YOU
 - You should be involved in the design
 - The R&D program, including bench tests and test beams, will be the training program for constructing the upgrade
- There is synergy between work on existing detector and data and the Upgrade
 - We have much to learn from the existing detector
 - We have much to learn from the early physics
- New technologies being investigated for the upgrade may help solve problems with the existing detector

So while you are making great discoveries with the early data please try to follow the Upgrade and if possible to work on design, simulation, prototyping, bench and beam testing and, of course, construction!!!



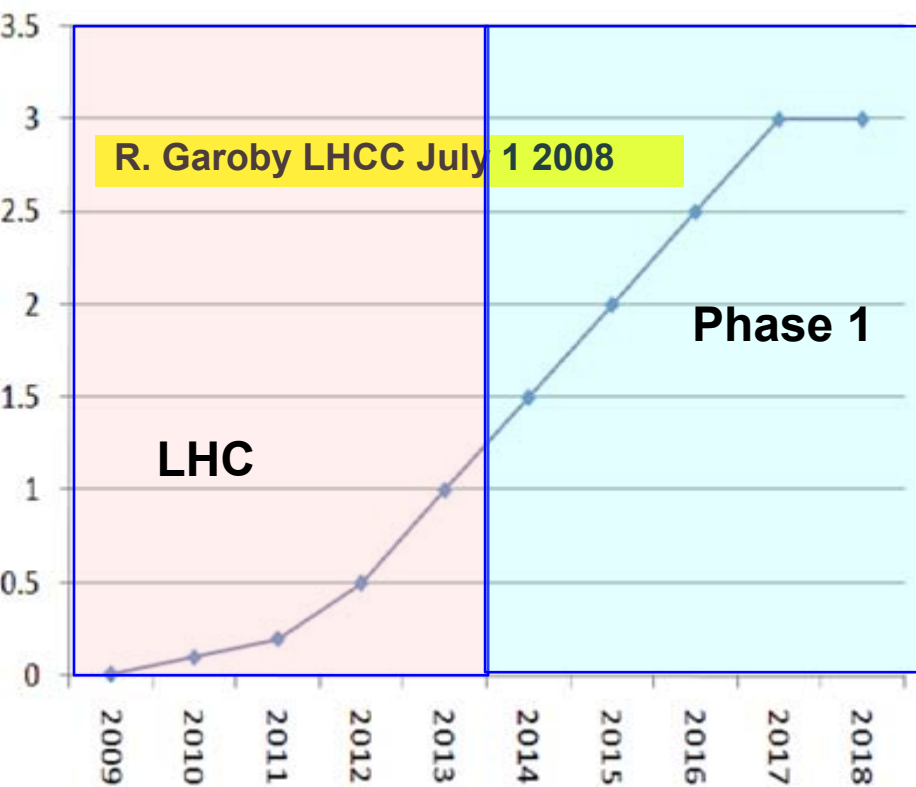
Backup Slides



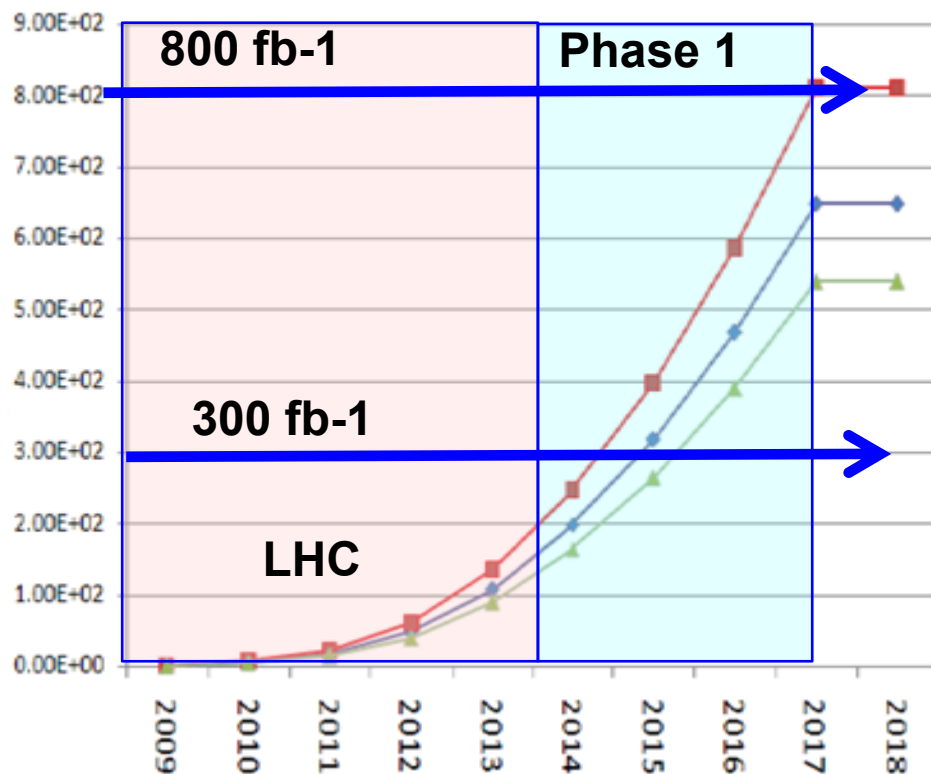
Luminosity assumptions



Peak Luminosity ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)

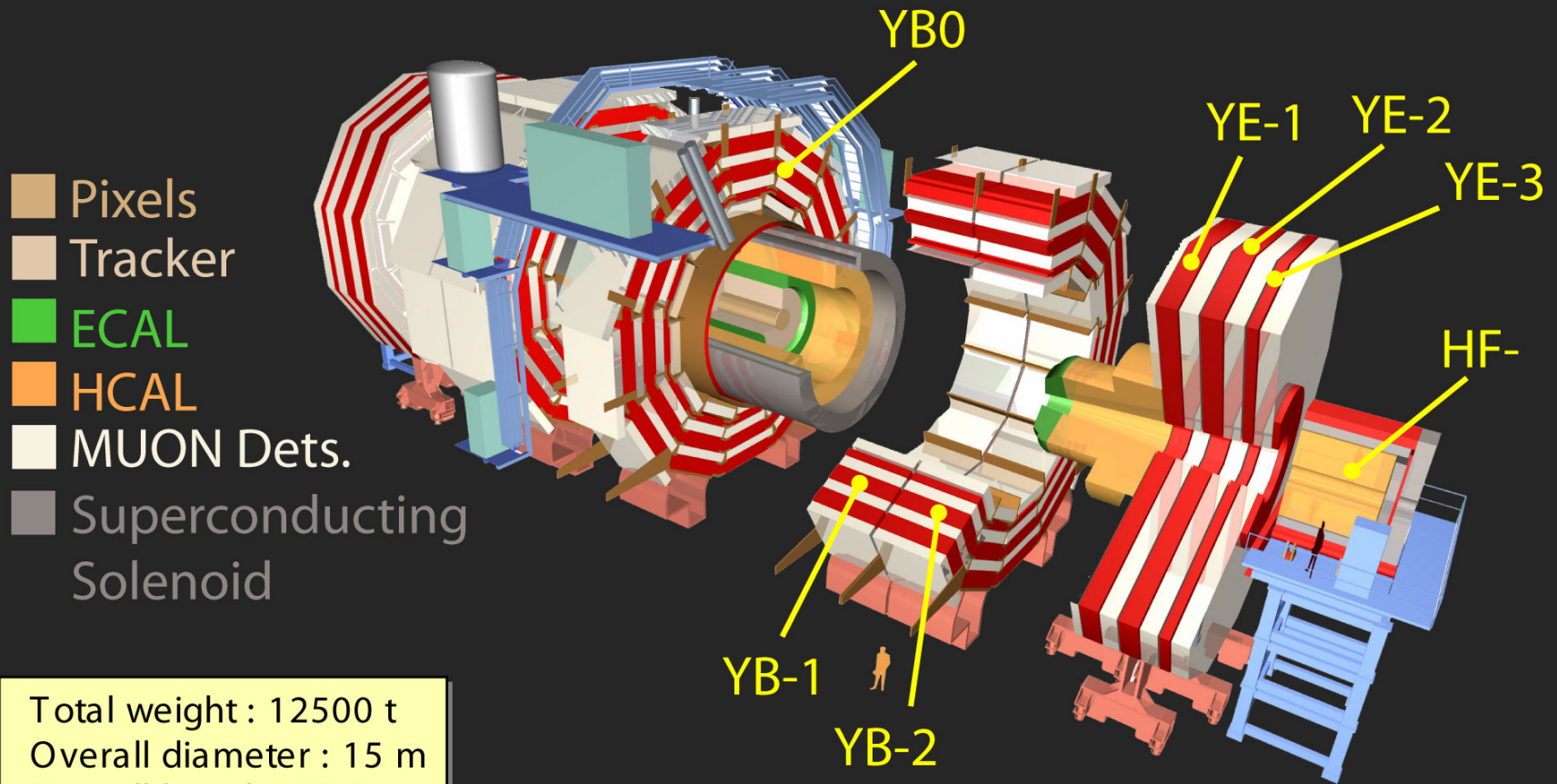


\int Luminosity (fb^{-1})



- Expected peak (left) and integrated luminosity (right). The normal (blue, presented by Garoby at LHCC), optimistic (red), and pessimistic (green) scenarios have been determined by varying the effective running time between 5M and 7.5 M second/year. We assume a shutdown in 2017 before the phase 2 upgrade, based on recent discussions with LHCC (could be 3 months earlier)

The CMS Detector



Total weight : 12500 t
 Overall diameter : 15 m
 Overall length : 21.6 m
 Magnetic field : 4 Tesla

<http://cms.cern.ch>

- **Provision of the required power and cooling to the front-end electronics is one of the major challenges for the SLHC.**
 - **potential supply current increase due to**
 - increased granularity i.e. channel count: factor ~20
 - extended front-end functionality: data reduction, L1 trigger
 - gigabit digital links
 - lower supply voltages in ≤ 130 nm ASIC technology
 - **potential supply current saving due to**
 - smaller detector capacitance per channel
 - **choice of front end power will be compromise between**
 - performance and functionality (ask for more power)
 - cooling power, silicon temperature, and cable cross section (ask for less power)
 - IF increased radiation induced sensor leakage current (x6) can be compensated by reduced temperature ($\Delta T = -14^\circ\text{C}$ gives x4) and reduced depleted silicon thickness (x2), then we could tolerate (w.r.t. thermal run-away) similar front end power as in current tracker
 - If the efficiency of the cooling system can be improved, power can be increased somewhat without making the material situation worse – need to use new approaches
- tracker upgrade to SLHC will at best keep front end power at current level, but almost certainly require significantly higher total front end current at lower voltage



BPIX Options for Phase 2 upgrade

R Horisberger May 2008










as 2008

<u>Option</u>	<u>Layer/Radii</u>	<u>Modules</u>	<u>Cooling</u>	<u>Pixel ROC</u>	<u>Readout</u>	<u>Power</u>
0	4, 7, 11cm	768	C ₆ F ₁₄	PS46 as now	analog 40MHz	as now
1	4, 7, 11cm	768	C ₆ F ₁₄	2x buffers	analog 40MHz	as now
2	4, 7, 11cm	768	CO ₂	2x buffers	analog 40MHz	as now
3	4, 7, 11cm	768	CO ₂	2x buffers	analog 40MHz μ-tw-pairs	as now
4	4, 7, 11cm	768	CO ₂	2xbuffer, ADC 160MHz serial	digital 320MHz μ-tw-pairs	as now
5	4, 7, 11, 16cm	1428	CO ₂	2xbuffer, ADC 160MHz serial	digital 640 MHz μ-tw-pairs	DC-DC new PS

Similar options for FPIX

- Heavy objects decay into lighter ones
 - New particles will decay into the elementary objects of the SM
 - Photons, electrons, muons, taus, jets (quarks and gluons)- especially “b-jets” and “charm jets”
 - If neutrinos or new weakly interacting particles are produced, there will be missing transverse energy (MET)
- Start by identifying and measuring (p or E) particles
 - Photons (γ) in ECAL
 - Electrons in tracker and ECAL
 - Muons make it to muon system
 - Jets in tracker, ECAL, and HCAL
 - Neutrinos, black holes, and possibly other particles leave no trace (missing Et)
- Isolation is a key issue to suppress backgrounds from QCD processes
- It must be possible to TRIGGER the detector to promptly select a small number of beam crossings ($\sim 100/\text{s}$) out of 40 million beam crossings/s with an average of 20 interactions/crossing

type	tracking	ECAL	HCAL	MUON
γ				
e				
μ				
Jet				
Et miss				

This is, of course, has to be done on a budget and take into account many risk factors

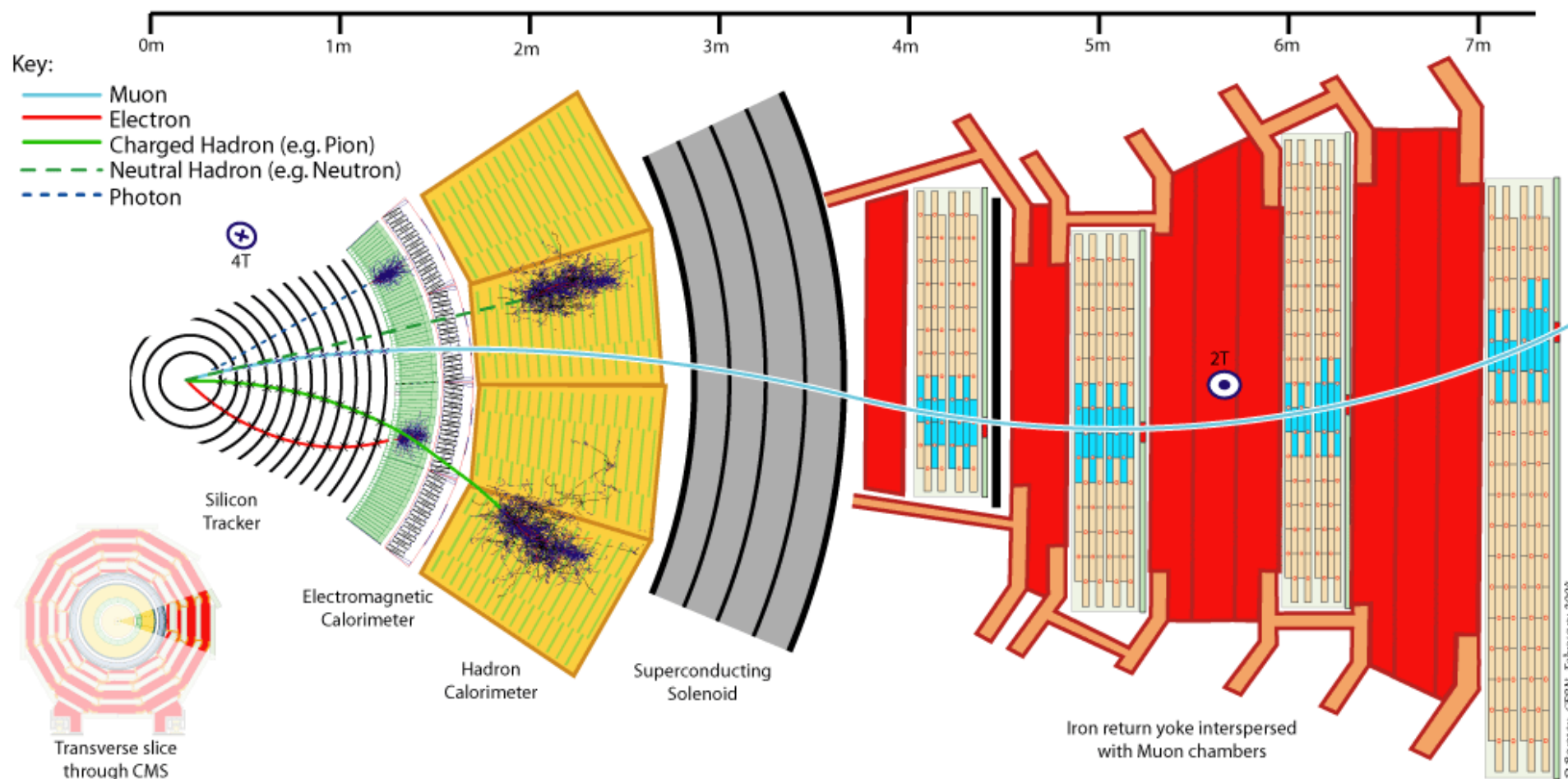
Different judgments led to two different solutions: ATLAS and CMS

CMS was designed to work beautifully at $10^{34} \text{ cm}^{-2}\text{-s}^{-1}$ and WILL DO SO

The goal of the DETECTOR UPGRADE is work as well or better as the luminosity rises



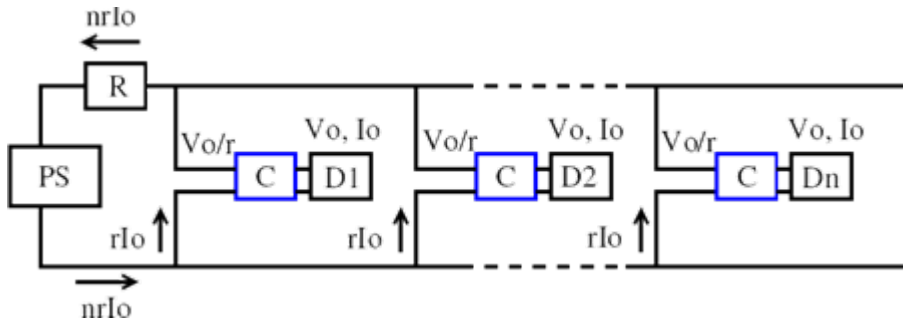
CMS Slice



Possible Powering Schemes for Phase 1



Parallel powering with DC-DC conversion

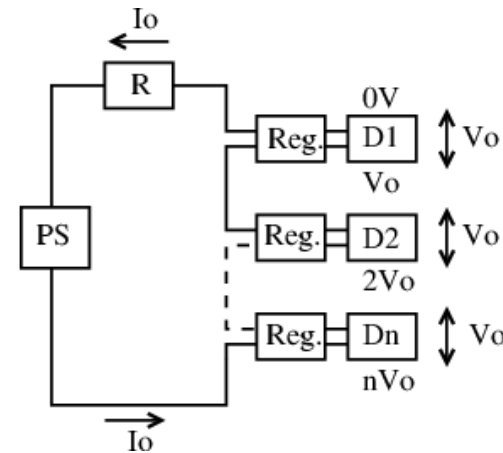


Conversion ratio $r = V_{out} / V_{in} \ll 1$

$$P_{drop} = R \cdot I_0^2 \cdot n^2 \cdot r^2$$

- + Classical grounding, readout & communication
- + Flexible: different voltages can be provided
- + Several conversion steps can be combined
- Radiation-hard, HV and magnetic field tolerant
- DC-DC converter to be developed
- Converter efficiency 70-90%
- Converters are switching devices ☐ noise
- Inductors must have air-cores ☐ noise

Serial powering



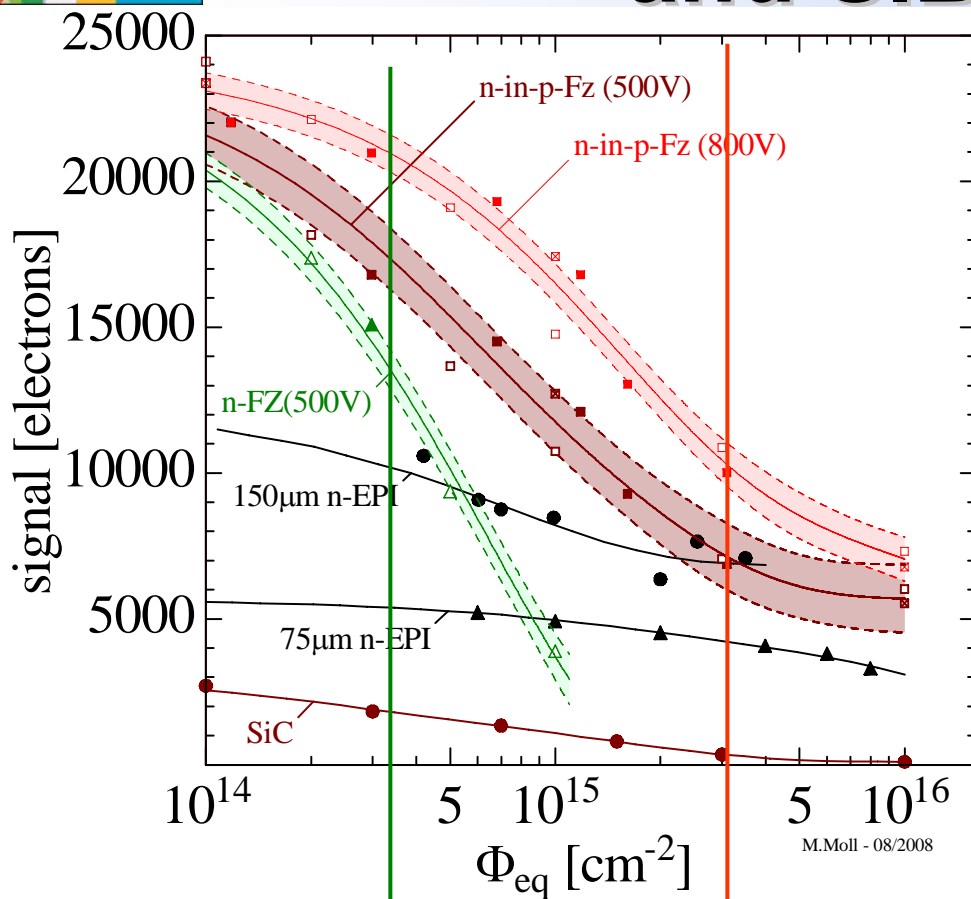
$$V_{drop} = R \cdot I_0$$

$$P_{drop} = R \cdot I_0^2$$

- + Many modules can easily be chained
- + No noise problems observed so far
- Each module has its own ground potential
- All communication must be AC-coupled
- Shunt regulator and transistor to take excess current and stabilize voltage
- ☐ Significant local inefficiency
- Safety issues

Sensors: RD50, RD39 and SIBT

Luukka



Silicon Sensors

- p-in-n (EPI), 150 μm [7,8]
- ▲ p-in-n (EPI), 75μm [6]
- n-in-p (FZ), 300μm, 500V, 23GeV p [1]
- n-in-p (FZ), 300μm, 500V, neutrons [1]
- n-in-p (FZ), 300μm, 500V, 26MeV p [1]
- n-in-p (FZ), 300μm, 800V, 23GeV p [1]
- n-in-p (FZ), 300μm, 800V, neutrons [1]
- n-in-p (FZ), 300μm, 800V, 26MeV p [1]
- ▲ p-in-n (FZ), 300μm, 500V, 23GeV p [1]
- △ p-in-n (FZ), 300μm, 500V, neutrons [1]

Other materials

- SiC, n-type, 55 μm, 900V, neutrons [3]

References:

- [1] p/n-FZ, 300μm, (-30°C, 25ns), strip [Casse 2008]
- [2] p-FZ, 300μm, (-40°C, 25ns), strip [Mandic 2008]
- [3] n-SiC, 55μm, (2μs), pad [Moscatelli 2006]
- [4] pCVD Diamond, scaled to 500μm, 23 GeV p, strip [Adam et al. 2006, RD42]
- [5] Note: Fluence normalized with damage factor for Silicon (0.62)
- [6] 3D, double sided, 250μm columns, 300μm substrate [Pennicard 2007]
- [7] n-EPI, 75μm, (-30°C, 25ns), pad [Kramberger 2006]
- [8] n-EPI, 150μm, (-30°C, 25ns), pad [Kramberger 2006]
- [9] n-EPI, 150μm, (-30°C, 25ns), strip [Messineo 2007]

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!

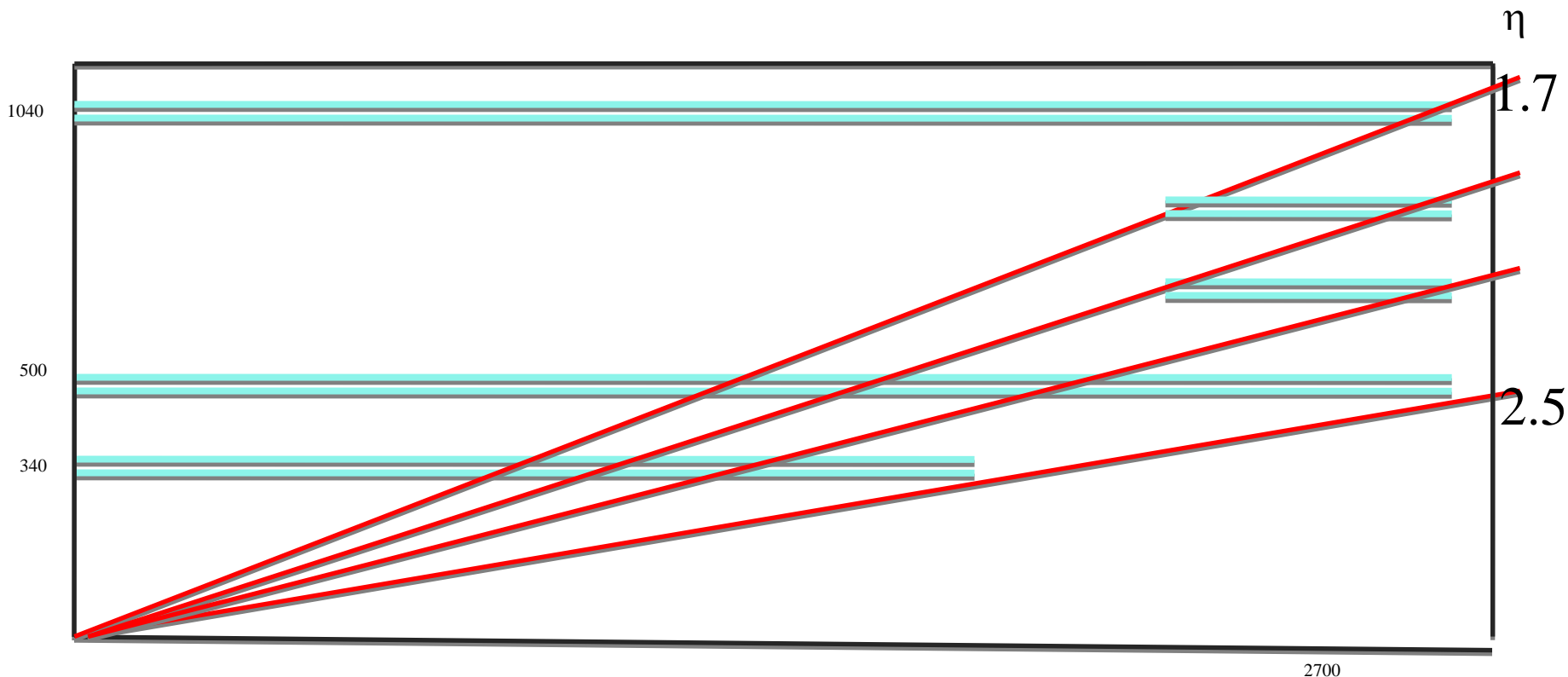
LHC

SLHC

n-in-p technology should be sufficient for Super-LHC at radii presently (LHC) occupied by strip sensors

highest fluence for strip detectors in LHC: The used p-in-n technology is sufficient

Layout for the Tracking Trigger Project

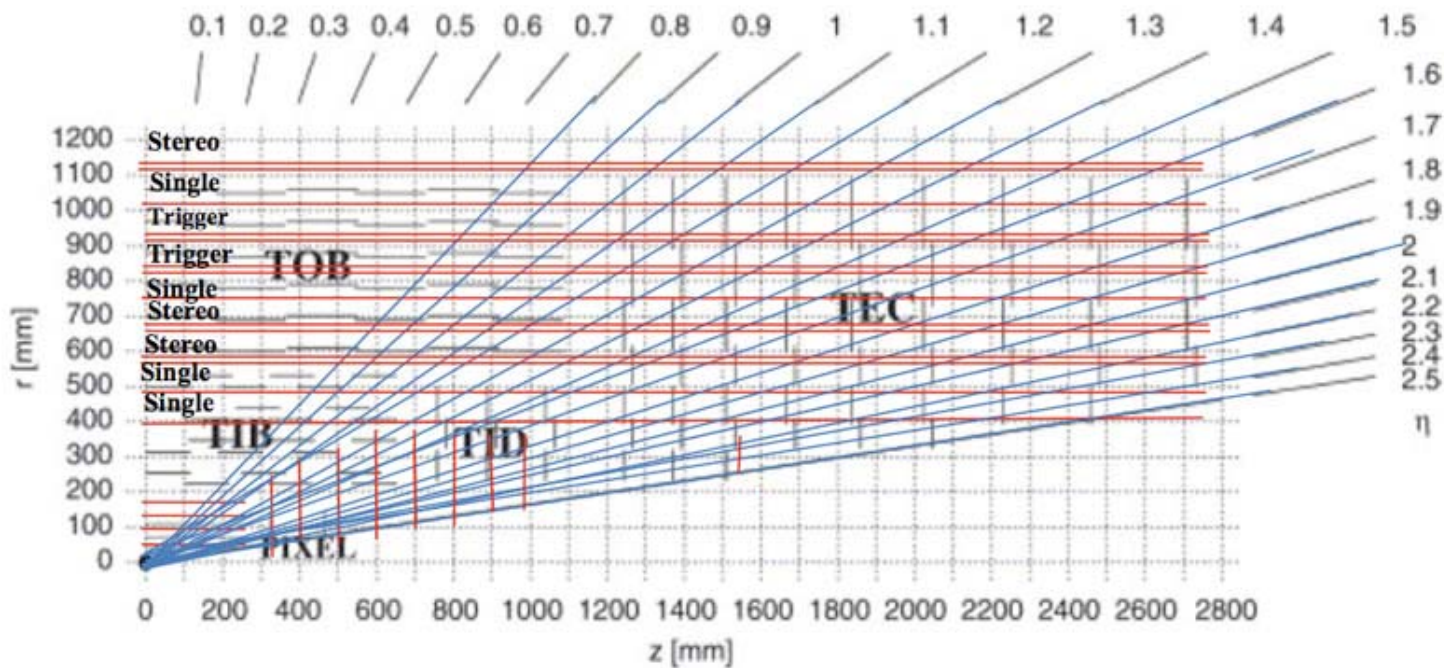


Long Barrel Layout: an aggressive “strawman” design whose development should be highly instructive
 (note: A “strawman is NOT a “baseline”)

Long Barrel Strawman



- Very long barrel strip detector idea presented by Wim de Boer in July Strawman discussion



Documents



Will we be ready for these dates?

