CMS Upgrade Issues

J. Nash   LHCC 23 September 2008

Topics

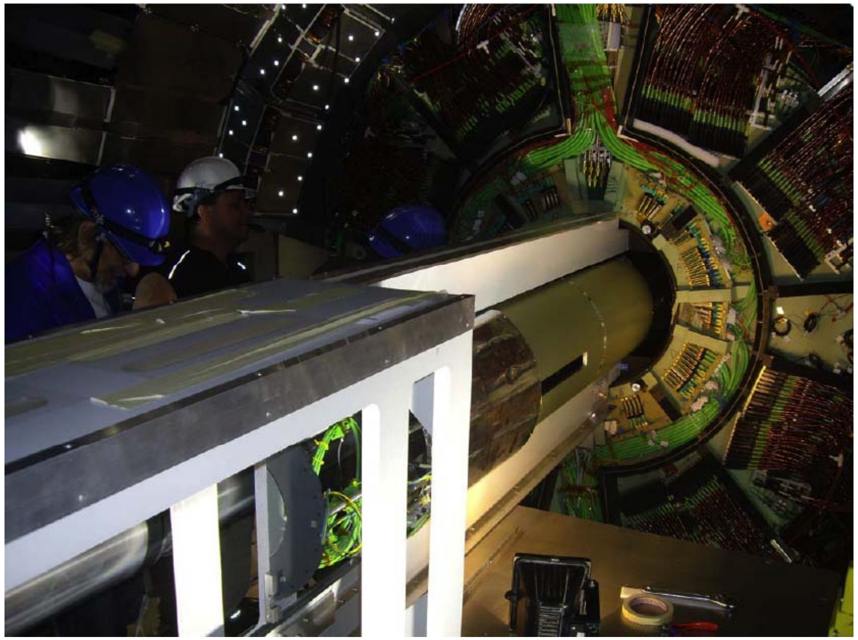
- Phase I tracking upgrades
- Brief glimpse at Phase II tracker progress
- Phase I Muons
- Phase I HCAL
- Phase I Trigger

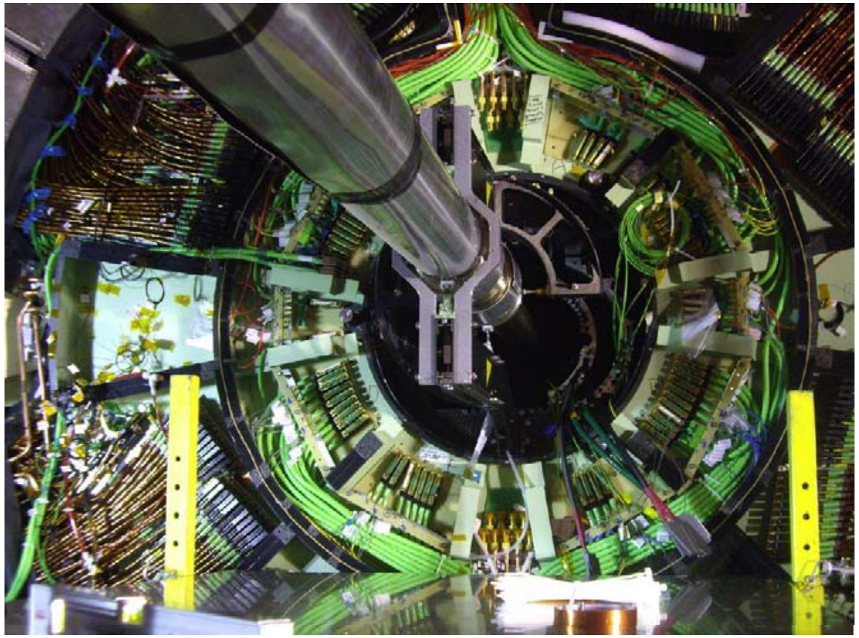
What are the key timescales/issues?

- Phase 1
  - How well do detector components handle the increasing luminosity?
    - Both instantaneous and integrated effects
  - What detector elements will need replacement/modification to cope?
    - Detectors will record >500 fb^{-1}, can they withstand this?
- Phase 2
  - What detector elements will need replacement?
  - What do machine plans imply for interaction regions
  - Is there a requirement for a long shutdown?
    - How long – 18 Months? (1 Full calendar year without beam +)
    - When – sometime after the middle of the next decade
      - Developing and building new tracking detectors will take many years
      - We have to plan this now in order to have any chance of running detectors with high luminosity
    - ATLAS and CMS now agree on the dates
      - No sense in having two long shutdowns
      - Reach 700 fb^{-1}(potential limit)
        - Likely 2017

CMS Pixel system can be removed in a very short time period

Trial insertion of Pixel system



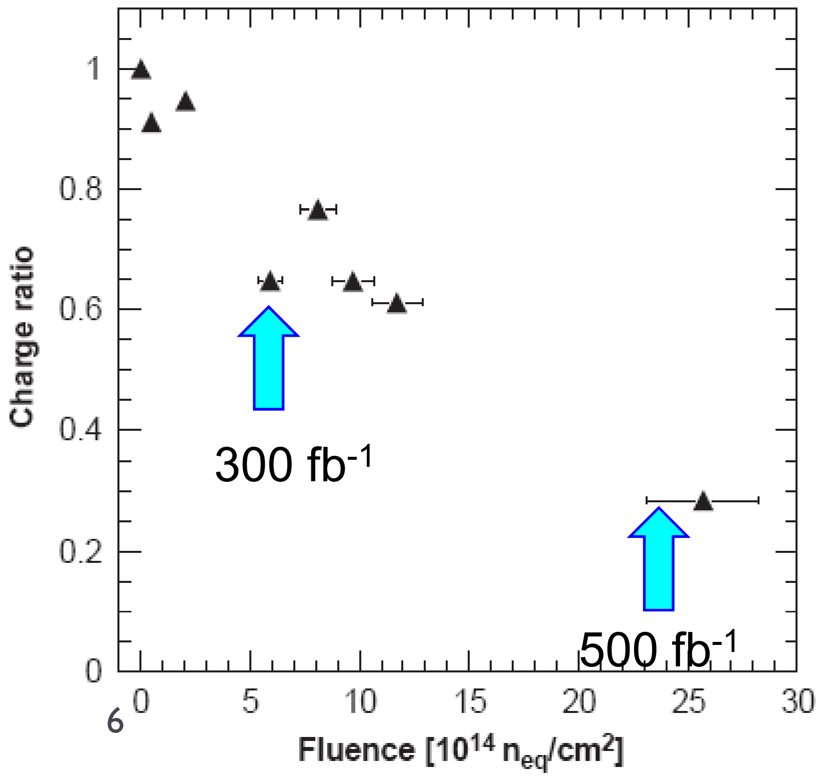


Insertion of the Pixel was done in a few hours

Limitations in Phase 1

Note that the table assumes L=60 fb^{-1} at 1×10^{34} $cm^{-2}s^{-1}$ but if machine works well we could get L=100 fb^{-1}/year at 1×10^{34} $cm^{-2}s^{-1}$ in 2012

- Radiation damage due to integrated luminosity.
  - Sensors designed to survive $6\times10^{14} n_{eq}/cm^2$ (~ 300 fb^{-1}).
  - n-on-n sensors degrade gradually at large fluences



Normal Ramp

Year	Peak Lumi ($\times 10^{34}$)	Annual Integrated (fb^{-1})	Total Integrated (fb^{-1})
2009	0.1	6	6
2010	0.2	12	18
2011	0.5	30	48
2012	1	60	108
2013	1.5	90	198
2014	2	120	318
2015	2.5	150	468
2016	3	180	648
2017	3	0	648
2018	5	300	948
2019	8	420	1428
2020	10	540	2028
2021	10	600	2628
2022	10	600	3228
2023	10	600	3828
2024	10	600	4428
2025	10	600	5028

Garoby LHCC July 1, 2008

Limitations in Phase 1

- Instantaneous luminosity

- Pixel dead time

high luminosity LHC: [10^{34}]

11 cm / 7 cm / 4 cm layer

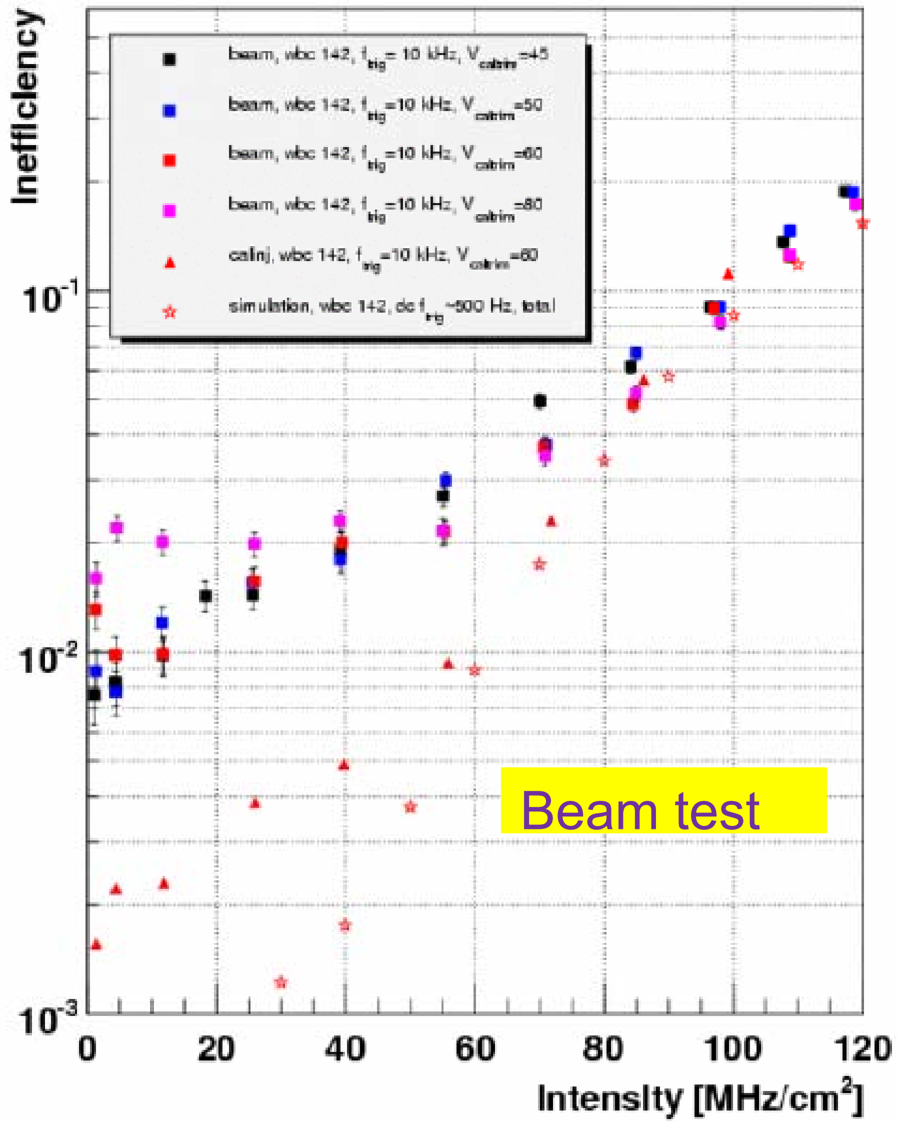
total data loss @ 100kHz L1A:

0.8%

1.2%

3.8%

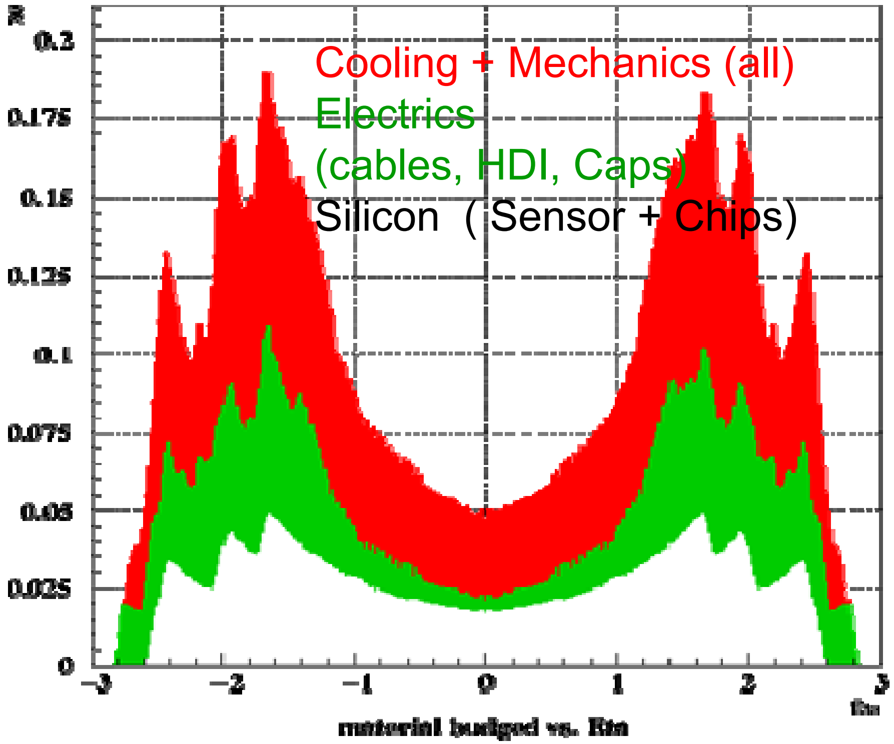
simulation



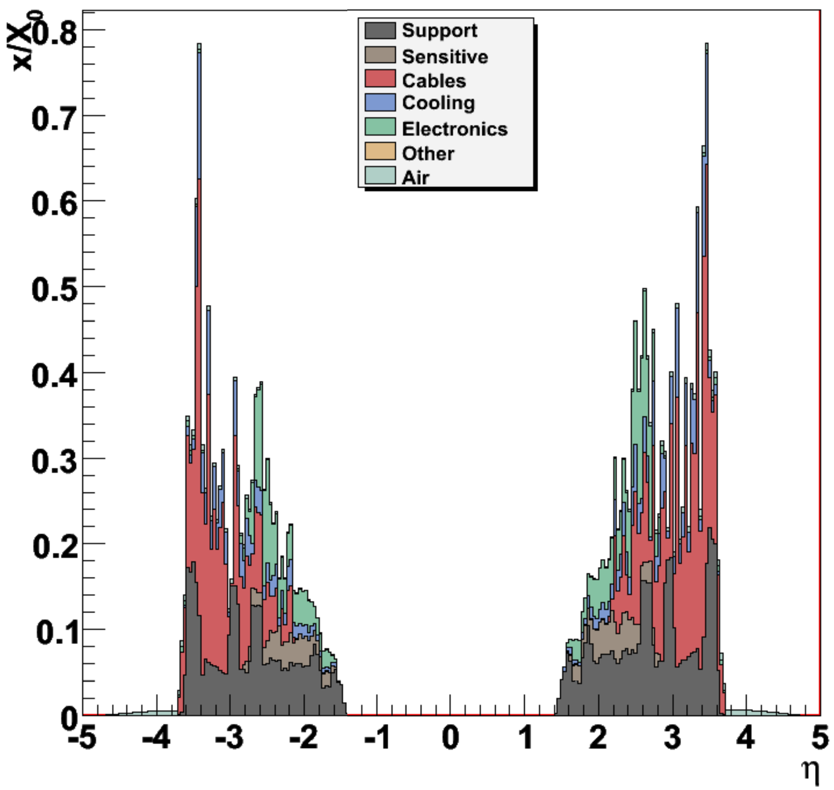
- Dead time will rise to ~12% due to increase in peak luminosity

Limitations in Phase 1

BARREL PIXELS



ENDCAP PIXELS



- Material budget both in endcap and barrel
  - Significant contribution from mechanical supports, cables

BPIX Options for 2013 replacement/upgrade – R. Horisberger

	Option	Layer/Radii	Modules	Cooling	Pixel ROC	Readout	Power
as 2008	0	4, 7, 11cm	768	C_6F_{14}	PS46 as now	analog 40MHz	as now
	1	4, 7, 11cm	768	C_6F_{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

Upgrade Plans

- Baseline: 3 layers (4 layer option) 3 disk in each endcap
  - Detector technology
- Single sided n-on-p sensors (more rad-hard) instead of n-on-n (fallback)
- Evaluating 3D sensors industrialization for innermost layer at 4 cm.
  - Readout Chip
- Double buffer size (in 250 nm CMOS extra 0.8 mm needed for chip periphery)
    - Minimal R&D. Design, verification, testing at high beam rates 8-10 months
    - Mechanical changes
- Further gains possible with 130 nm CMOS but R&D needed
  - Layout, mechanical assembly, and cooling (aim at material reduction of about a factor of 3 in barrel and 2 in forward)
- $C0_2$ cooling (as in VELO for LHCb)
- Low mass module construction and simplified thermal interfaces
- Further material reduction can be acheived with on module digitization:
    - R&D needed: It requires new ADC and Token Bit Manager changes

4th Layer option

- 4 layer system has 1.8x more modules than present 3 layer system

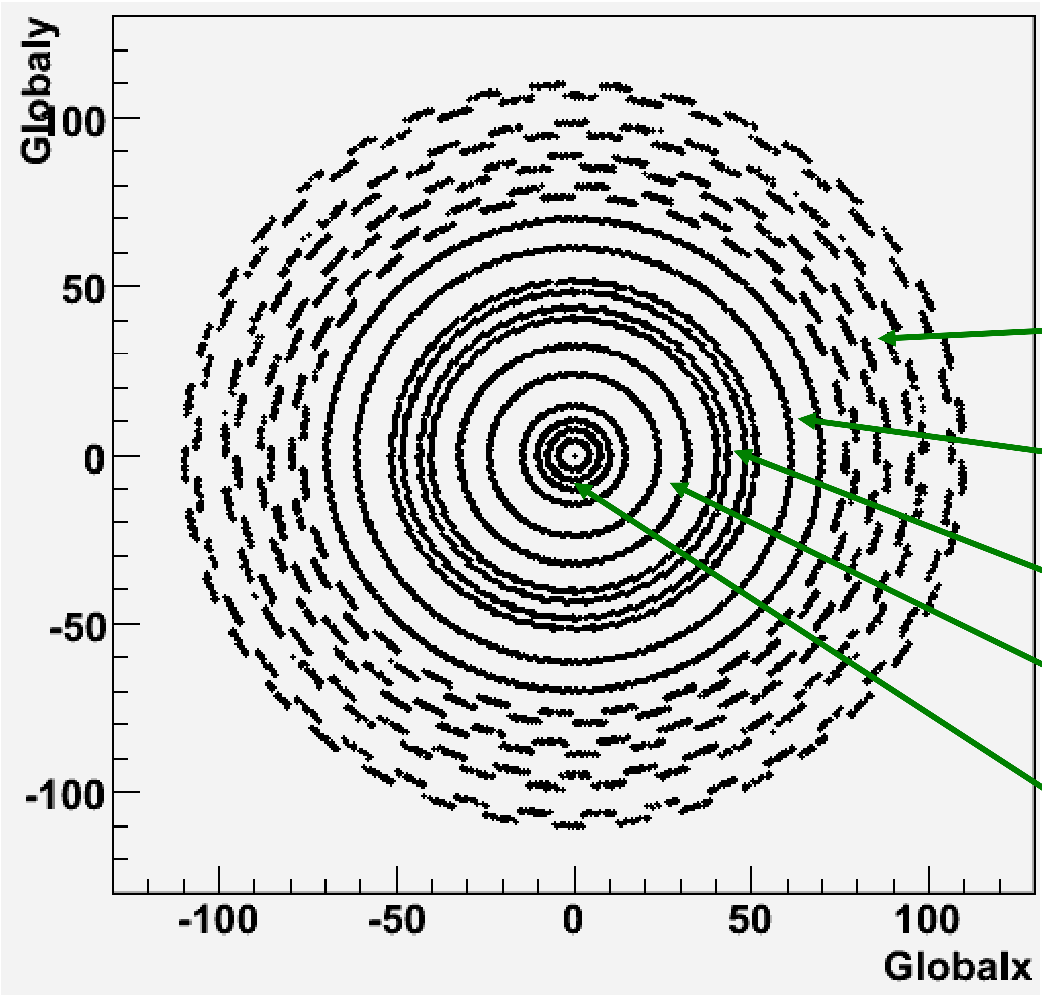
- Severe infrastructure constraints
  - DC-DC step down converters to bring more power through cables
  - high speed links to transmit 3.6x more data through same fibers
  - have advanced bi-phase cooling (e.g. CO_2) in same pipe x-section

Cost estimate for following system: (no half modules)

radius [cm]	length [#mod]	faces	#modules
16.0	10	64	640
10.4	8	42	336
7.3	8	30	240
4.4	8	18	144

- Nonetheless 4 layer system could :
  - Solve potential problems if inner silicon tracker layer fails
  - Strengthen pattern recognition in more complex events
  - Decision after we see first LHC data. It could be installed after 2013

Phase II Tracker : Strawman A



Strawman A r-phi view
(RecHit 'radiography')

4 TOB short strips
Remove 2

2 TOB strixels
Adjust chn count

2 TIB short strips
Remove 1

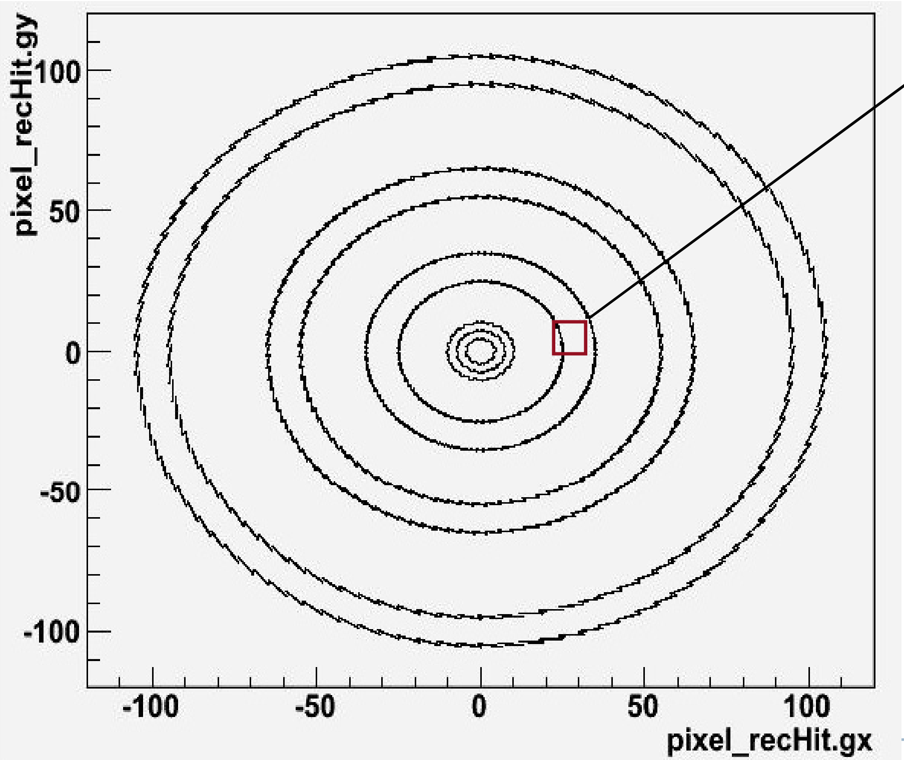
2 TIB strixels
Adjust chn count

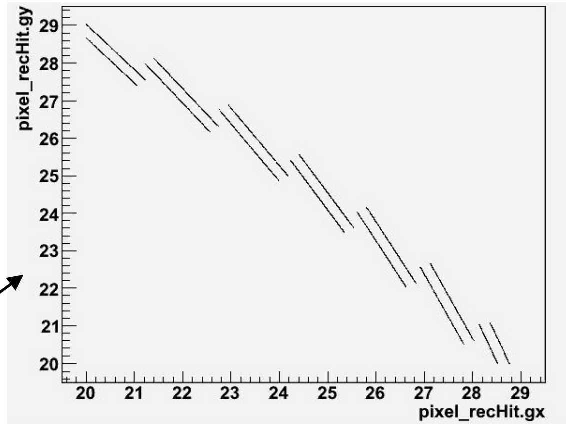
4 inner pixels

More Realistic Strawman B

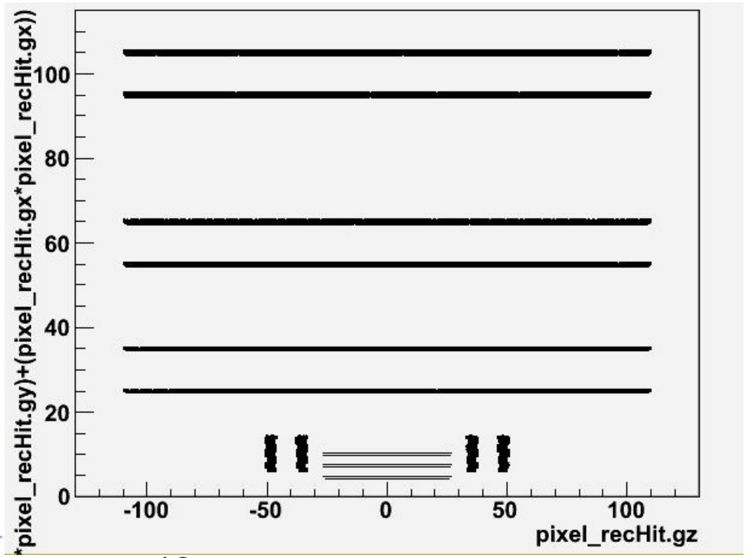
- Adjust granularity (channel count) of Strawman B layers
  - Keep the TEC for now until someone can work on the endcaps

Strawman B r-phi view
(RecHit 'radiography')





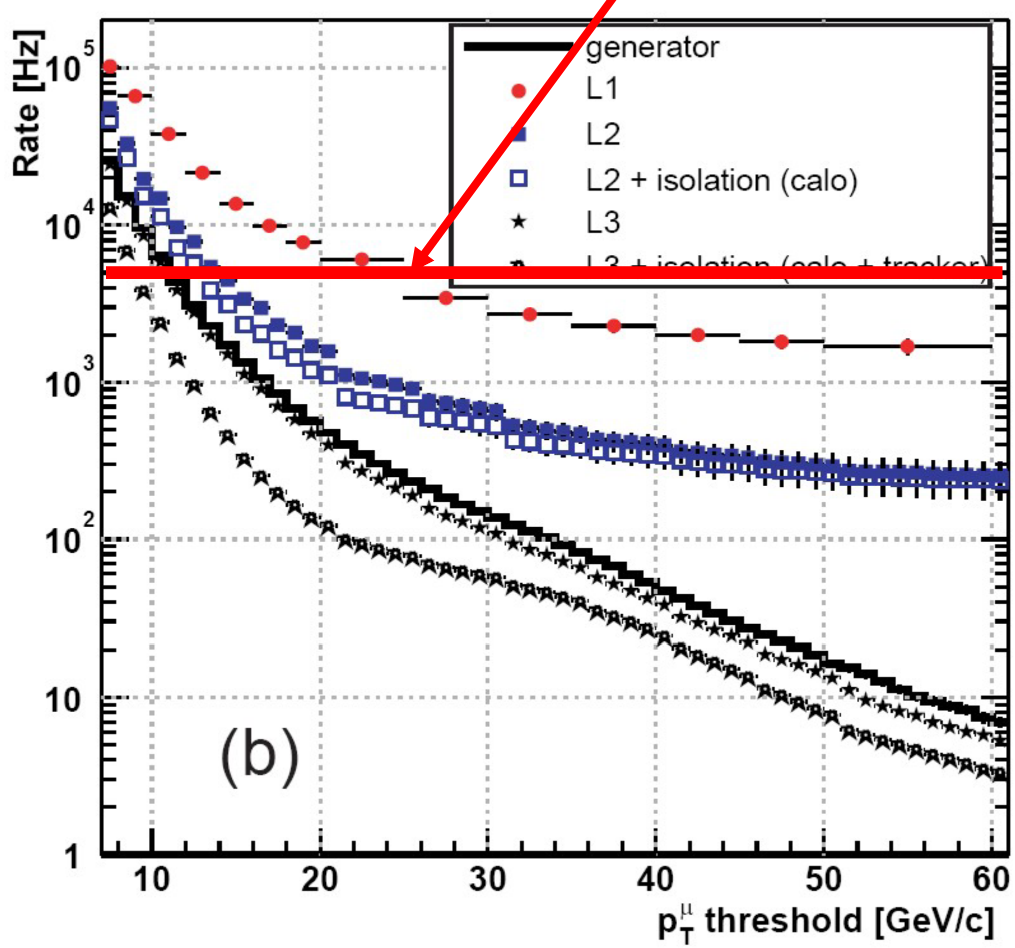
r-z view



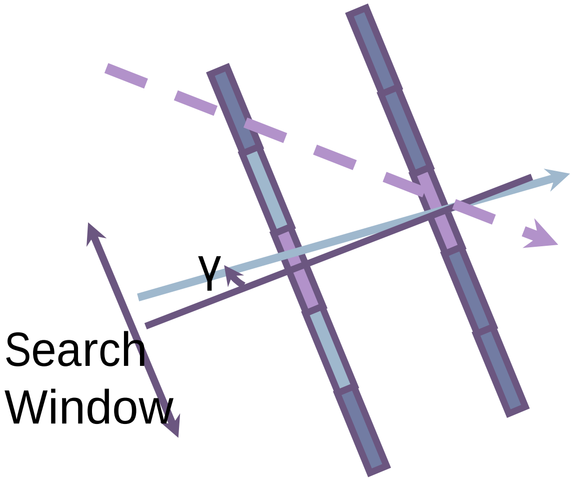
Phase II – Tracking Trigger

Level 1 Trigger has no discrimination for $P_T >\sim 20$ GeV/c

- The trigger/daq system of CMS will require an upgrade to cope with the higher occupancies and data rates at SLHC
- One of the key issues for CMS is the requirement to include some element of tracking in the Level 1 Trigger
  - One example: There may not be enough rejection power using the muon and calorimeter triggers to handle the higher luminosity conditions at SLHC
- Adding tracking information at Level 1 gives the ability to adjust P_T thresholds
- Single electron trigger rate also suffers
  - *Isolation criteria are insufficient to reduce rate at* $\mathcal{L} = 10^{35}\ cm^{-2}.s^{-1}$

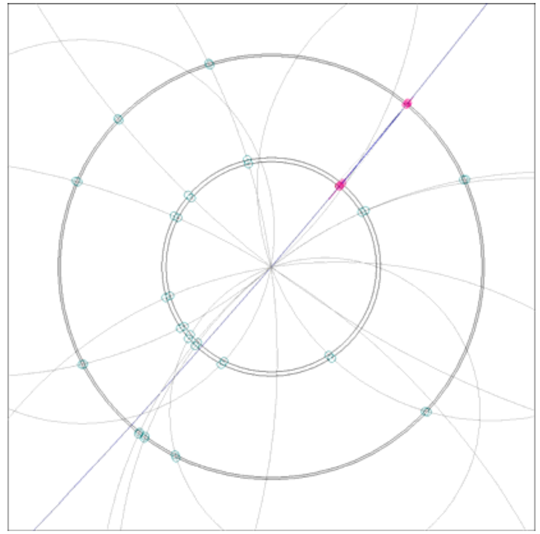


Concepts:Tracking Trigger



High momentum tracks are straighter so pixels line up

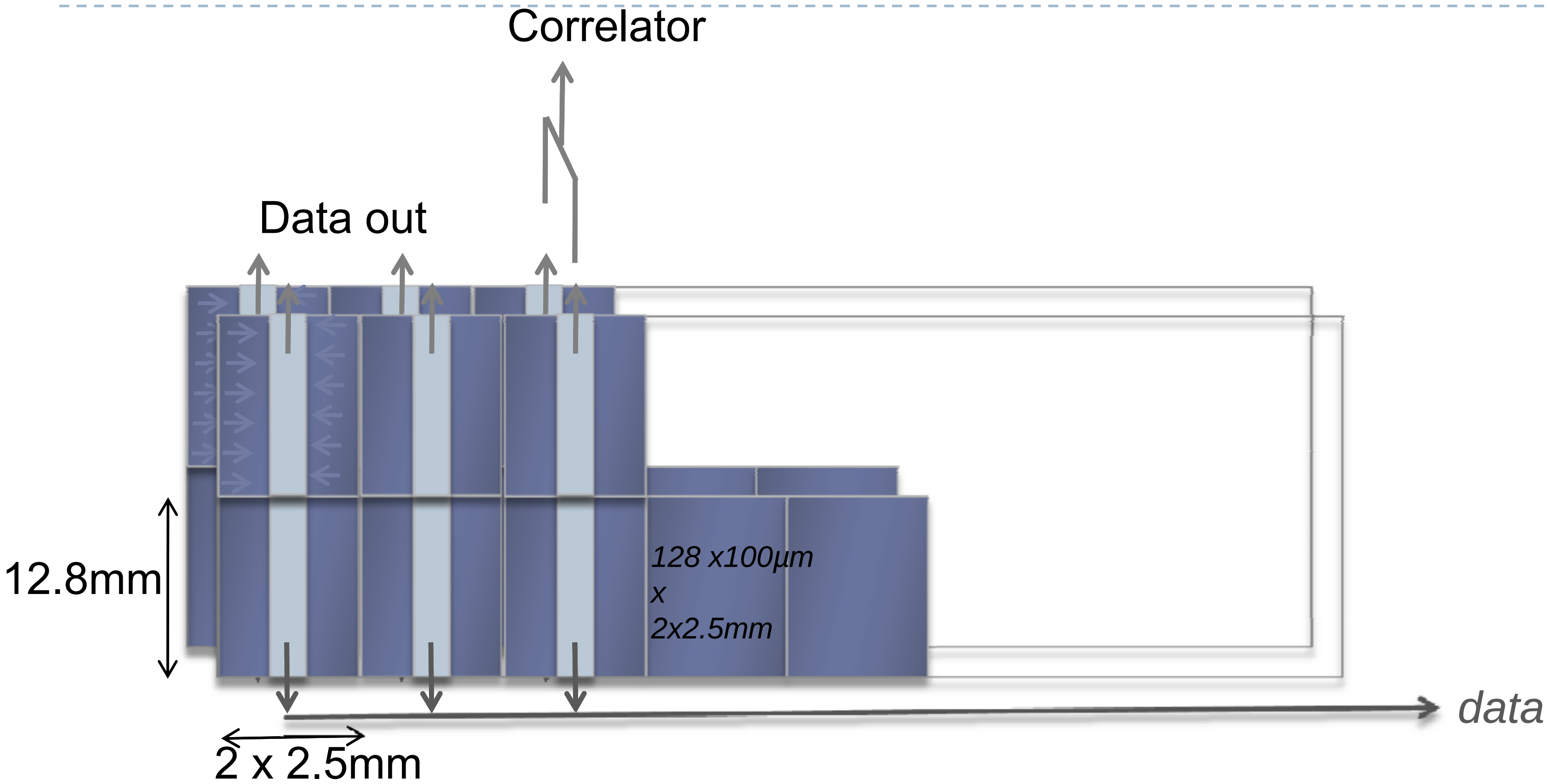
Pairs of stacked layers can give a P_T measurement



Geometrical p_T-cut - J. Jones, A. Rose, C. Foudas LECC 2005

- Why not use the inner tracking devices in the trigger?
  - Number of hits in tracking devices on each trigger is enormous
  - Impossible to get all the data out in order to form a trigger
  - How to correlate information internally in order to form segments?
- Topic requiring substantial R&D
  - “Stacked” layers which can measure p_T of track segments locally
    - Two layers about 1mm apart that could communicate
  - Cluster width may also be a handle

Example PT module

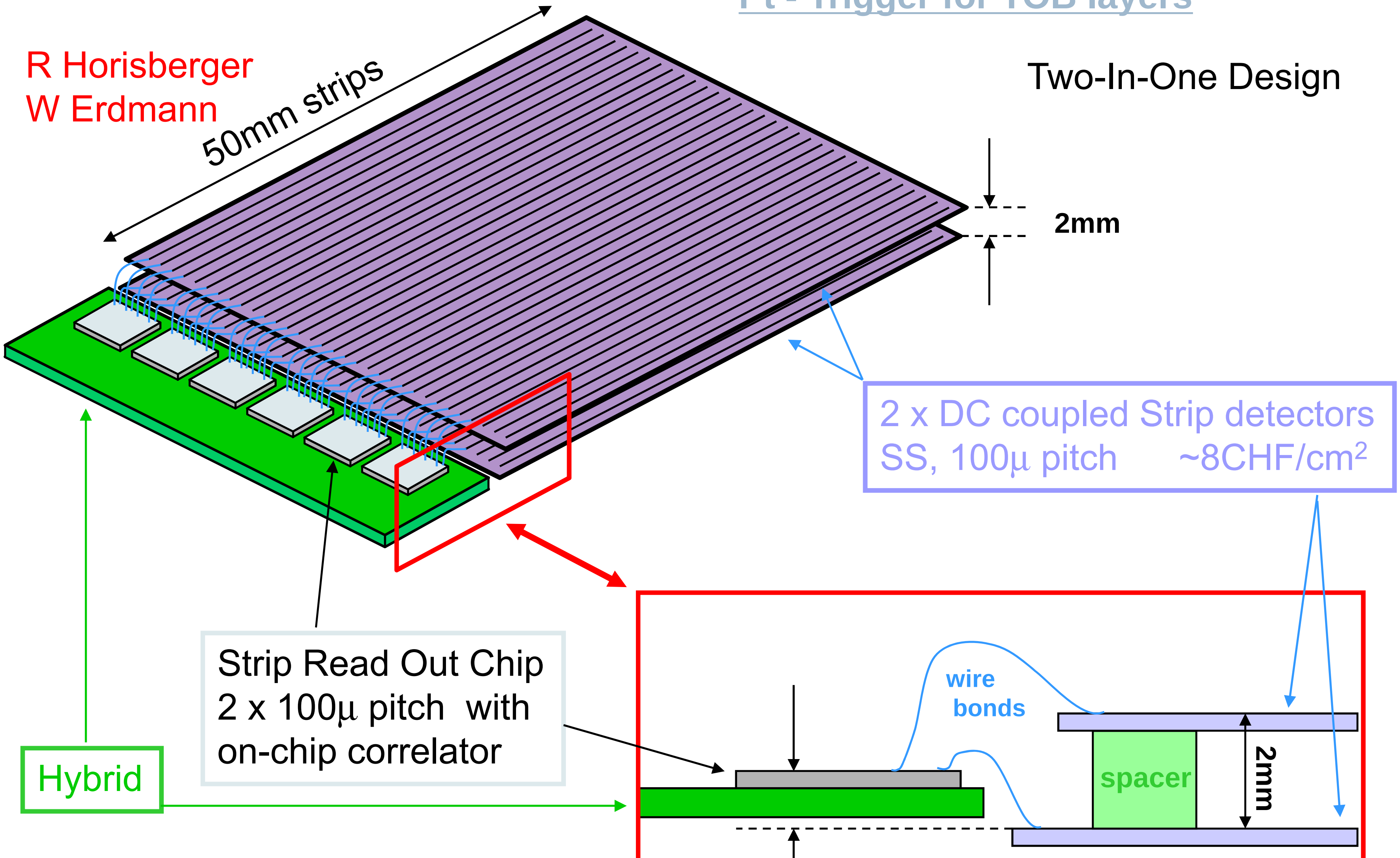


Such a design has potential for inexpensive assembly, using wire bonding, with low risk and easy prototyping

Pt - Trigger for TOB layers

R Horisberger
W Erdmann

Two-In-One Design

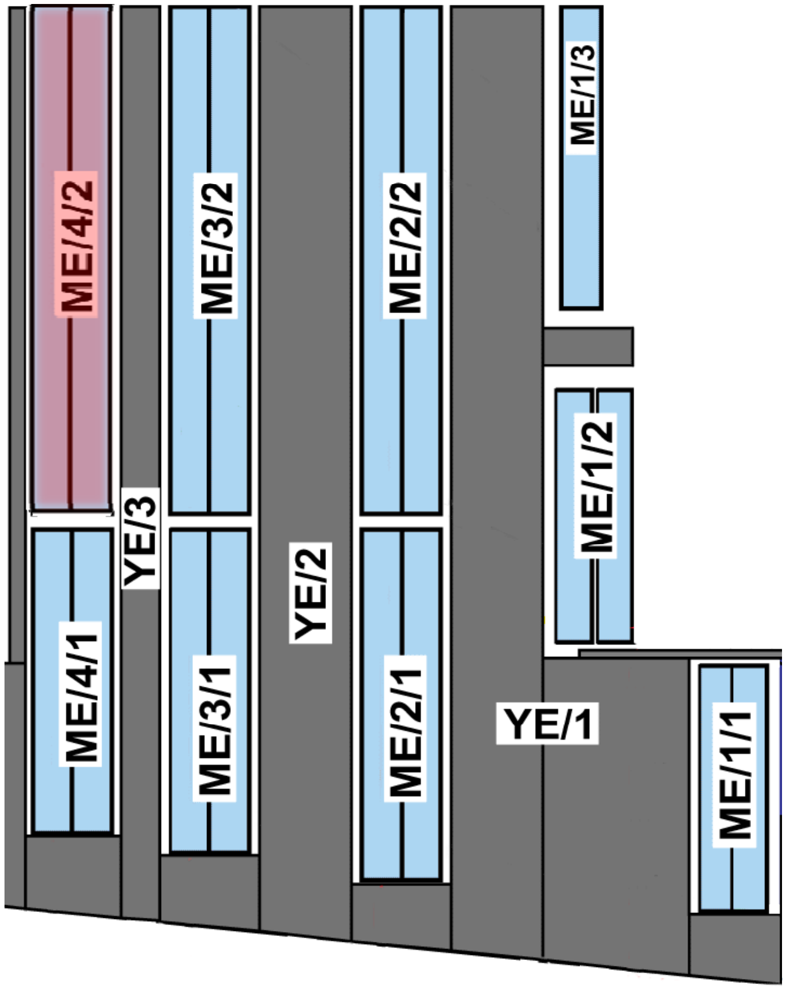


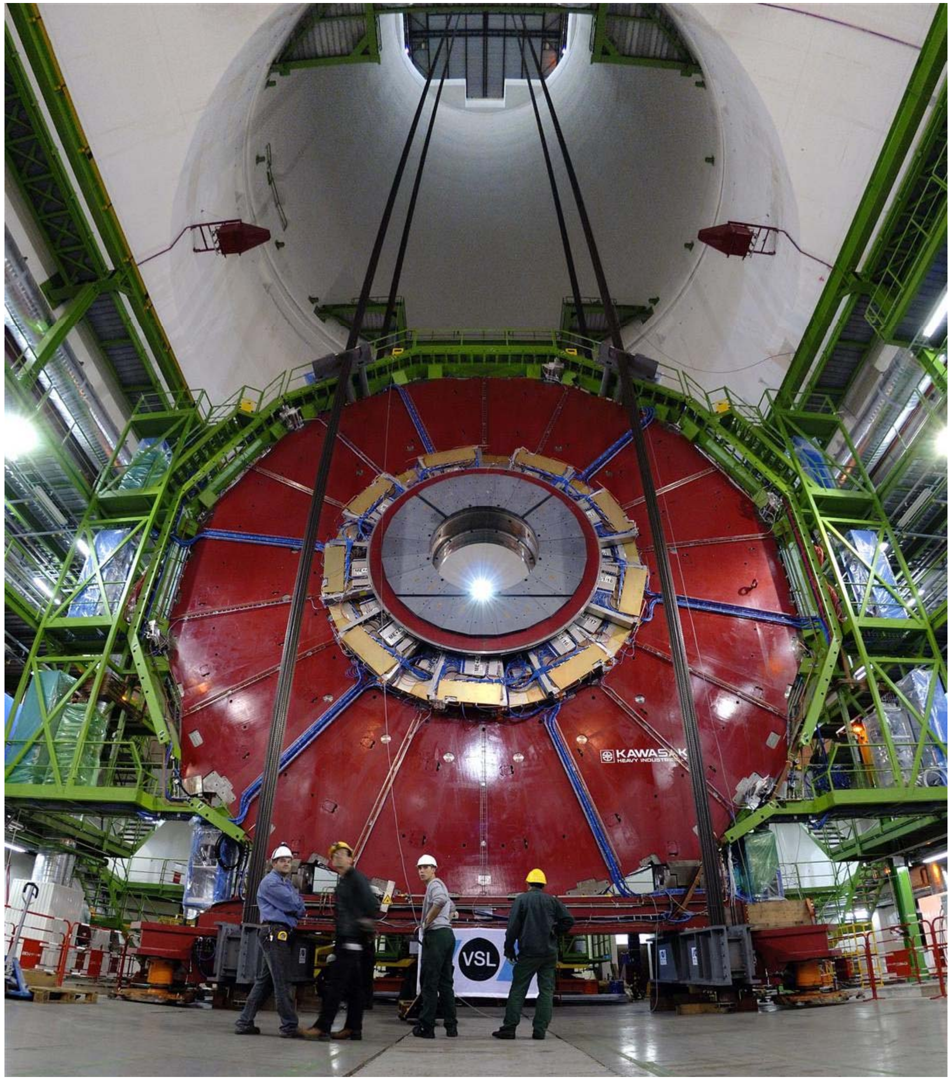
track angular resolution ~20mrad

→ good P_t resolution

Endcap CSC Muon Phase 1 Upgrade (ME4/2)

R-Z cross-section

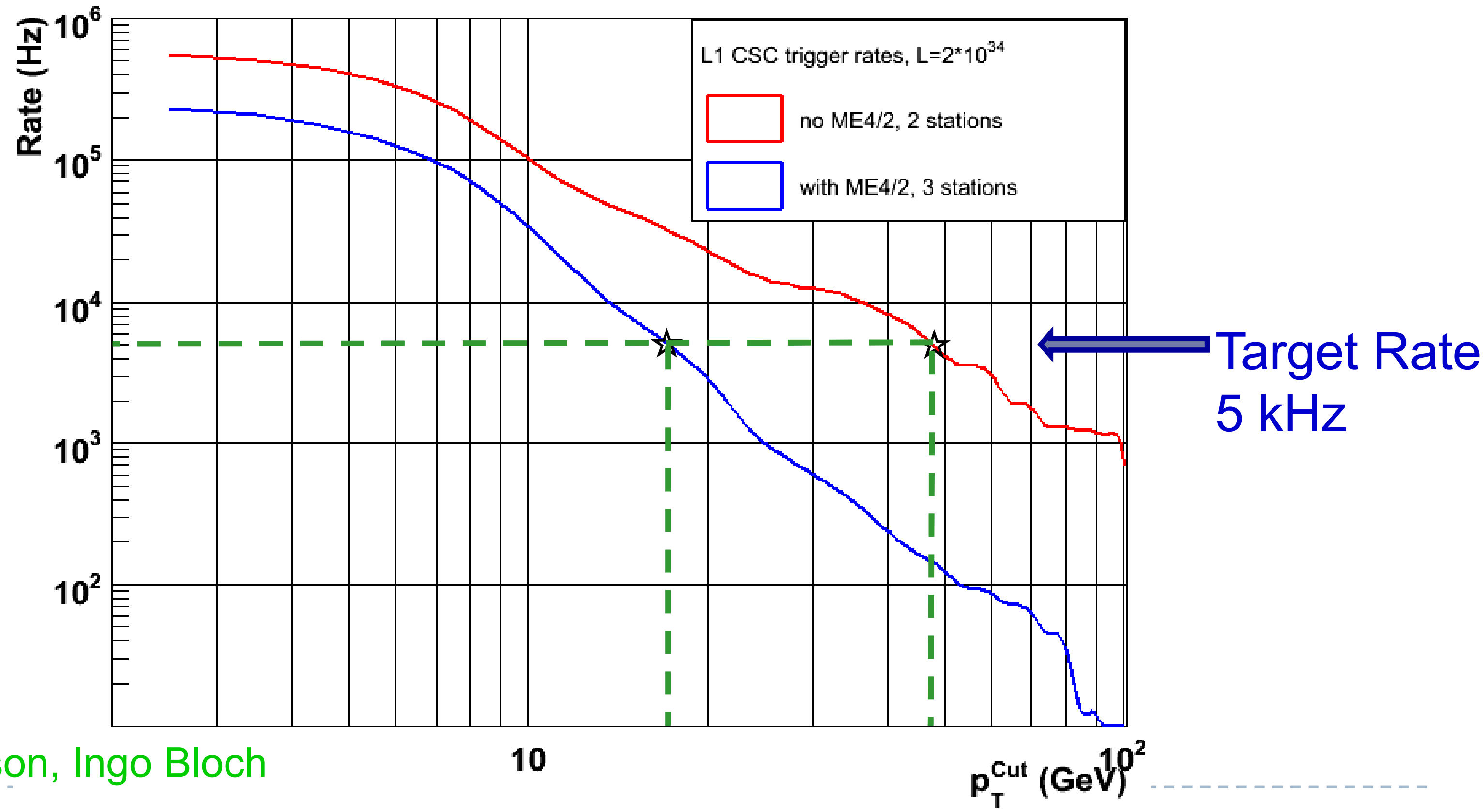




"Empty" YE3 ready for ME4/2

Phase 1 : Muons ME4/2 upgrade motivation

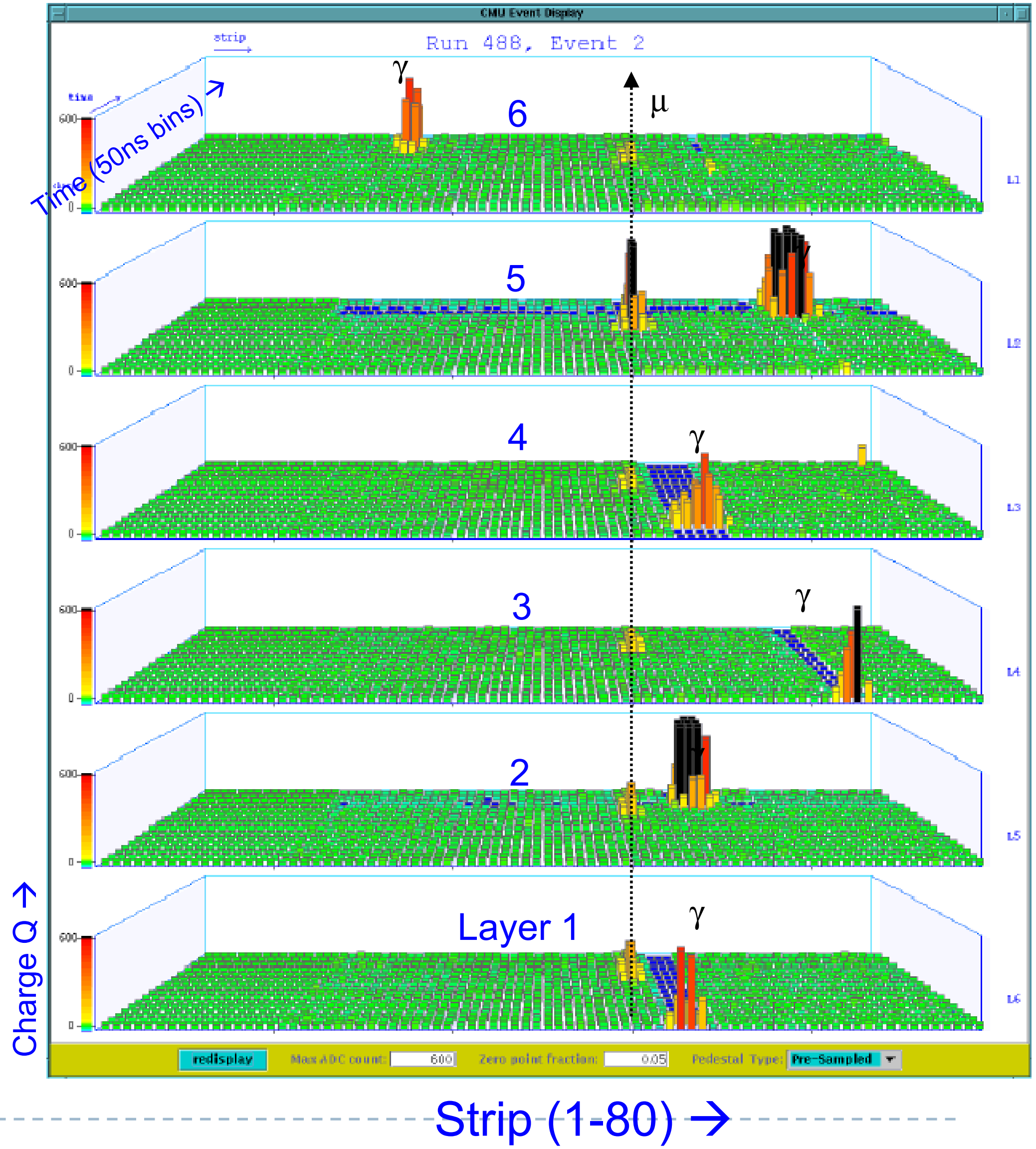
- Compare 3/4 vs. 2/3 stations:
  - (Triggering on *n* out of *n* stations is inefficient and uncertain)
- Recent simulation with & without the ME4/2 upgrade:
  - The high-luminosity Level 1 trigger threshold is reduced from 48 → 18 GeV/c



Rick Wilkinson, Ingo Bloch

Neutron backgrounds: another worry

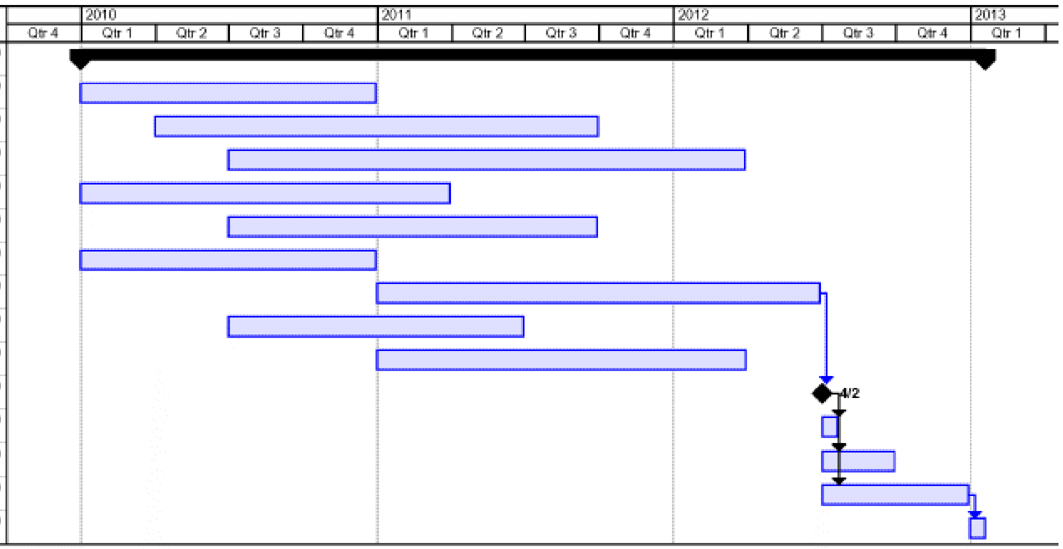
- A typical CSC chamber *event* at 10^{34} luminosity
  - From 1999 test beam study (Gamma Irradiation Facility)
- Actual rates known only after LHC running
- 4^{th} station: redundancy adds to trigger/ readout safety margin
  - Estimated ~3 for LHC



Schedule

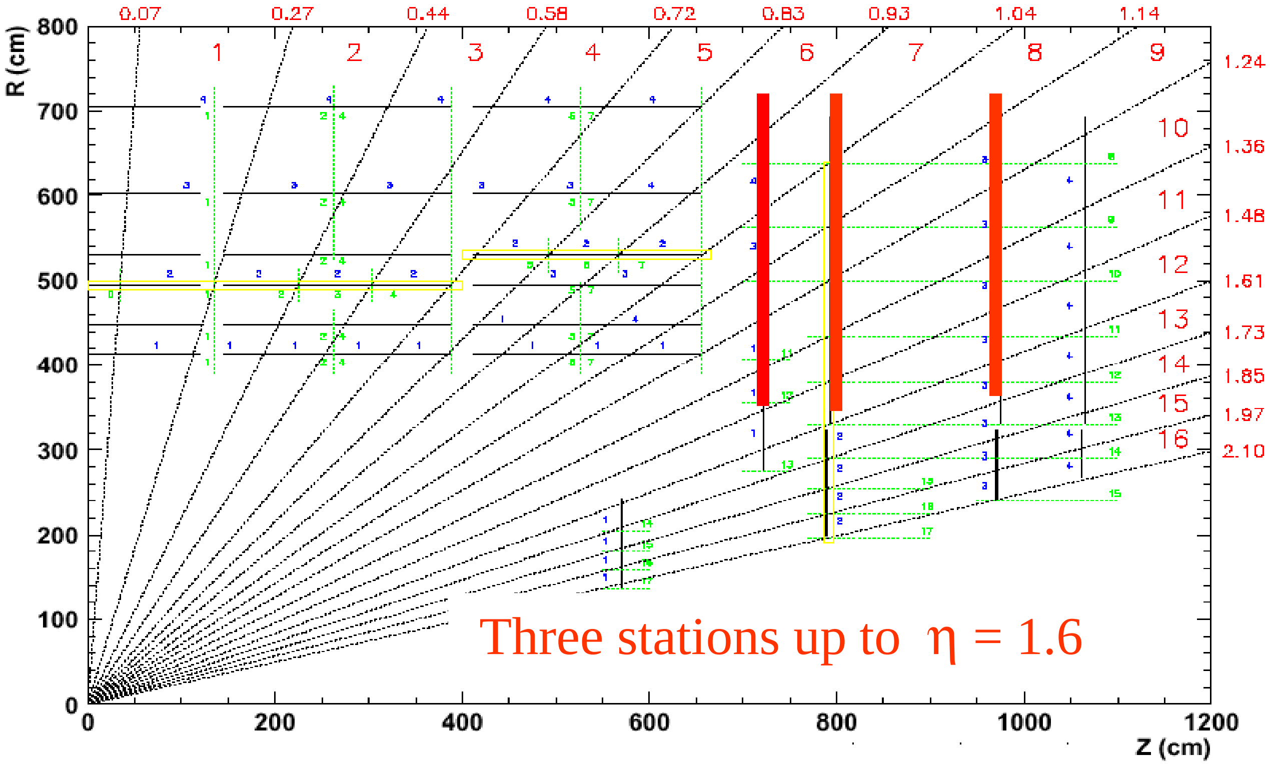
- Project covers three years from approval
- A few details:
  - Parts procurement can start any time (sooner=better)
  - Parts procurement → chamber production
  - Parallel to electronics R&D → production

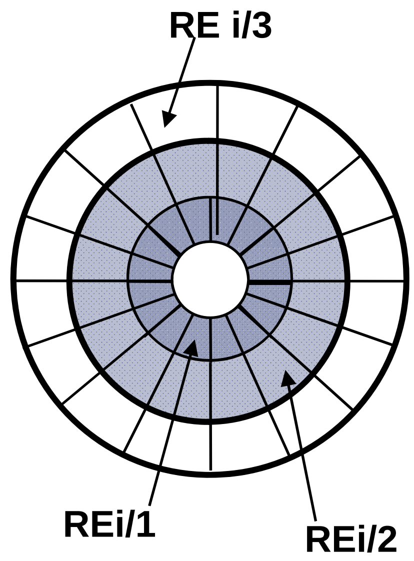
ID	WBS		Task Name	Duration	Cost 2008 ($K)
1	1		**Emu ME4/2 upgrade**	**797 days**	**$0.00**
2	1.1		ME4/2 Procure mechanical parts and panels	260 days	$2,027.90
3	1.2		ME4/2 Panel production	390 days	$345.00
4	1.3		ME4/2 Chamber assembly and shipping	455 days	$1,768.00
5	1.4		ME4/2 Procure electronics parts (non-CFEB)	325 days	$722.00
6	1.5		ME4/2 Produce electronics boards (non-CFEB)	325 days	$722.00
7	1.6		Pre-production CFEB-D	260 days	$192.00
8	1.7		ME4/2 Final assembly and test (FAST) at CERN	390 days	$313.00
9	1.8		Procure CFEB-D parts	260 days	$436.00
10	1.9		Produce CFEB-D boards	325 days	$436.00
11	1.10		Ready for start of ME4/2 chamber installation	0 days	$0.00
12	1.11		Installation of ME4/2 chambers (earliest date)	15 days	$0.00
13	1.12		Cabling and services for ME4/2 (earliest date)	65 days	$603.50
14	1.13		(Upgrade of ME1/1 with CFEB-D, earliest date)	130 days	$0.00
15	1.14		Install CFEBs on ME4/2 chambers (earliest date)	15 days	$0.00



The start up RPC endcap system

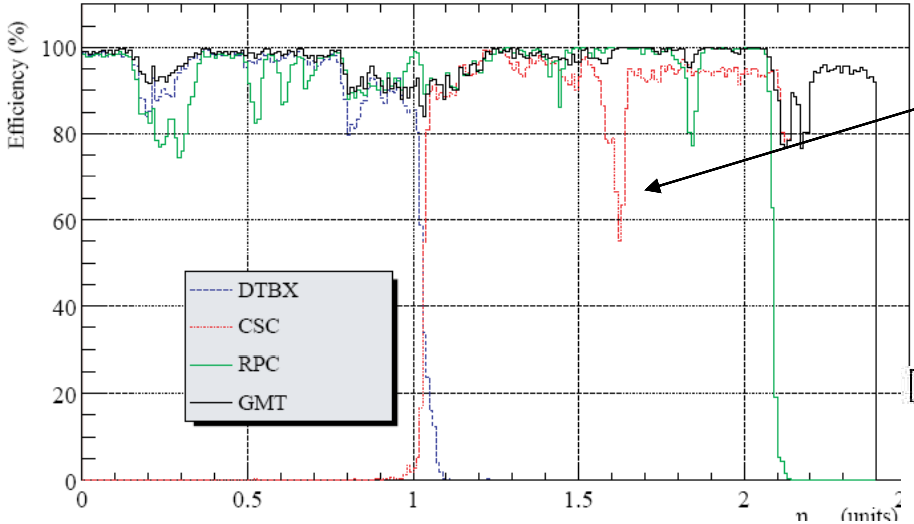
	RE 1/1	RE 1/2	RE 1/3	RE 2/1	RE 2/2	RE 2/3	RE 3/1	RE 3/2	RE 3/3	RE 4/1	RE 4/2	RE 4/3
No. of chambers	36*2	36*2	36*2	18*2	36*2	36*2	18*2	36*2	36*2	18*2	36*2	36*2





RPC trigger efficiency

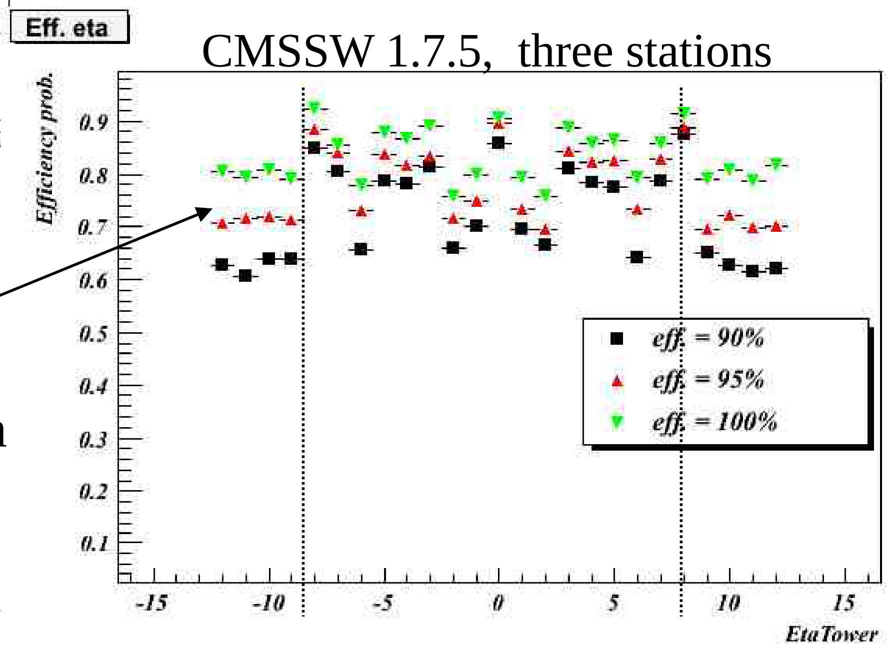
Trigger CMS TDR, four stations



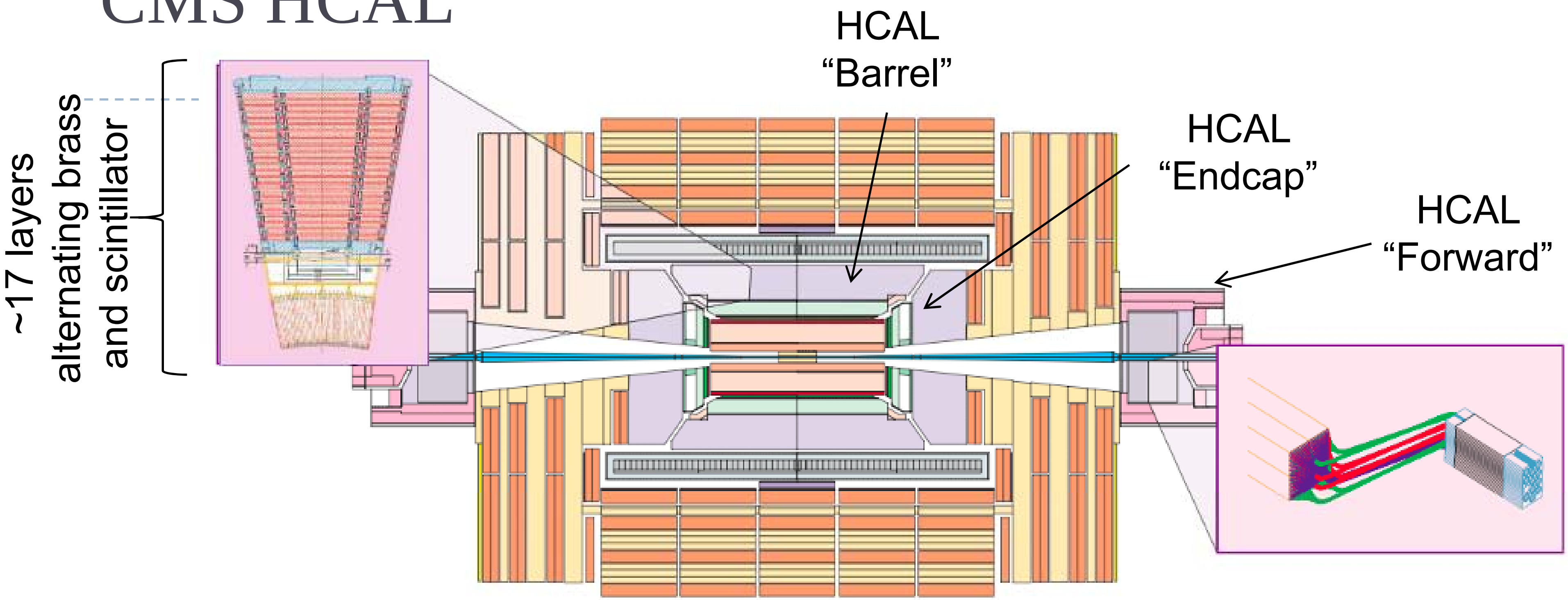
Importance of high η restoration

Importance of four stations restoration

CMSSW 1.7.5, three stations



CMS HCAL



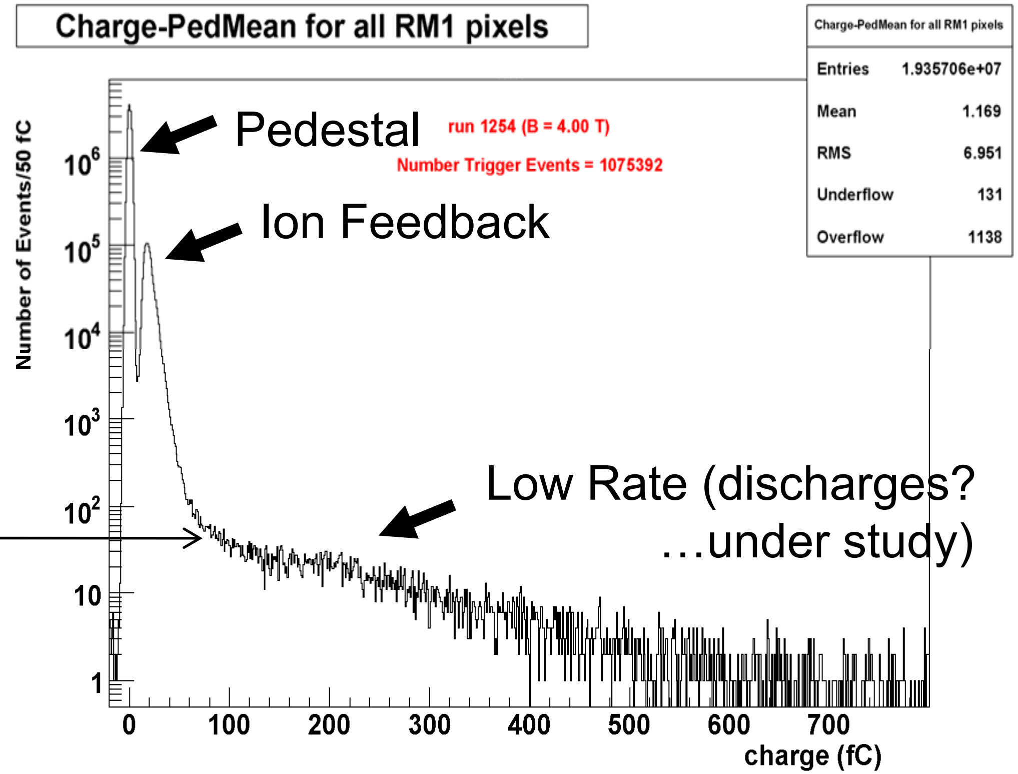
- Barrel and Endcap (inside CMS solenoid)
  - Brass absorber (surplus WWII Russian shells) with scintillator
  - (Hybrid) photodiodes (HPD) detect scint. light
    - Photo cathode with ~mm acceleration gap
    - Detection by PIN diodes

- Forward (extremely high rad levels, ~100Mrad/year!)
  - Steel absorber, quartz fiber detectors
  - Photomultiplier tubes collect Cherenkov light from fibers
  - 40% of CMS EM *and* HAD calorimetry!

Areas of exposure in current HB/HE

- Scintillator light from all layers in each tower are added together optically
  - No correction for higher radiation damage in inner layers
  - No way to vary weighting in separate layers to improve linearity of response and resolution
  - No redundancy to help ameliorate non-beam-crossing-related signals

- HPD noise issues
  - Can have big effect on trigger and resolution

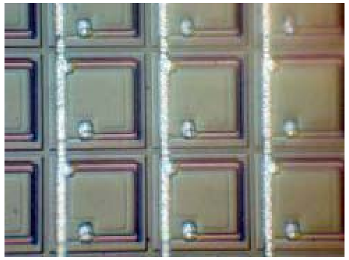


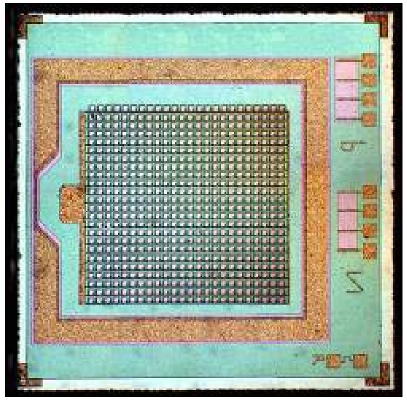
Front-end enhancement

- Increase longitudinal segmentation in HB and HE
  - Add redundancy, survive high luminosities, and surpass current HCAL capabilities
  - Self-imposed constraint, keep present digital fiber plant
- Replace HPDs (HB/HE) and PMTs (HF) with better technology
  - Array's of APDs
    - They call these "Silicon Photo Multipliers", or SiPMs
    - Were not available ~10 years ago when choice of HPDs had to be made
    - They are rad hard, cheap, small, flexible, higher gain, quieter
    - Will allow us to increase segmentation, add timing, avoid HPD noise issues
  - Used in commercial PET scanners, laser range finders, long distance fiber optic communications
- SiPMs allow longitudinal segmentation and timing capability to FE
  - Improves ability to reject backgrounds, reduce out-of-time pileup
    - At SLHC luminosities will have 400 events per crossing, way beyond original CMS specs

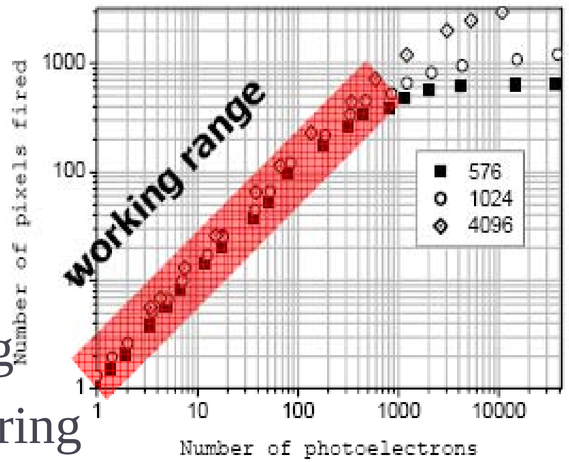
SiPMs

- Array of avalanche photo diodes ("digital" photon detection)
  - Array can be 0.5x0.5 up to 5.0x5.0 mm^2
  - Pixel size can be 10 up to 100µ
- All APDs connect to a single output
  - Signal = sum of all cells
- Are almost "off the shelf" parts



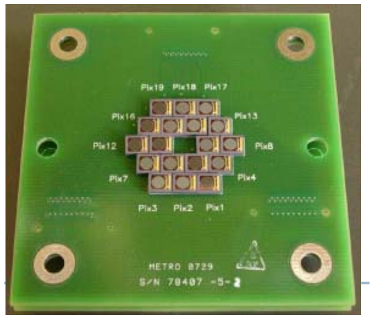


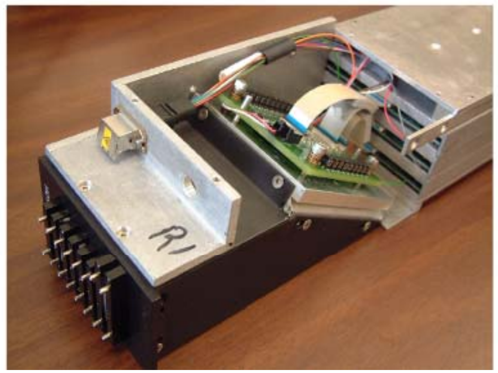
- If probability of photon in a single cell is small, signal is proportional to number of photons
  - Huge gain, high linearity
- Advantages over HPDs:
  - 28% QE (x2 higher) and 10^6 gain (x500 higher)
  - More light (40 pe/GeV), less photostatistics broadening
  - Very high gain can be used to give timing shaping/filtering



HO SiPM effort

- HO
  - Few layers outside magnet catch shower leakage behind HB
  - Also used to augment muon trigger
    - HPD gain not optimized for muons…marginal signal above pedestal
- Effort underway for past 3-4 years to investigate using SiPMs
  - Much experience accumulated already with these devices
  - They will be implemented for HO in FY10
  - Have already measured time to retrofit
    - Apply to HB/HE retrofit…not a problem, can meet LHC Phase 1 shutdown requirement

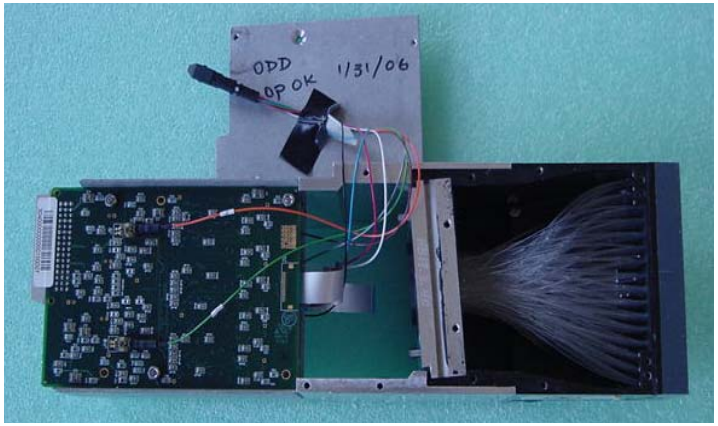


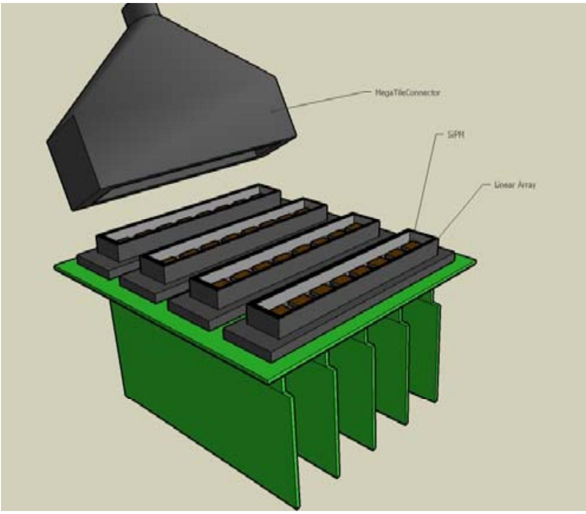


Taking Advantage of New Technology

- Current scheme in HB/HE/HO to change scintillator light to electrical signals is very complex
  - Physical mechanisms are labor intensive and delicate
  - Fiber electrical details are complex
- SiPMs allow vast simplification!
  - Connector from detector has the fibers, plugs into coupler unit
  - Can replace with cheap 1x1 mm^2 SiPM array, established technology, very cost effective

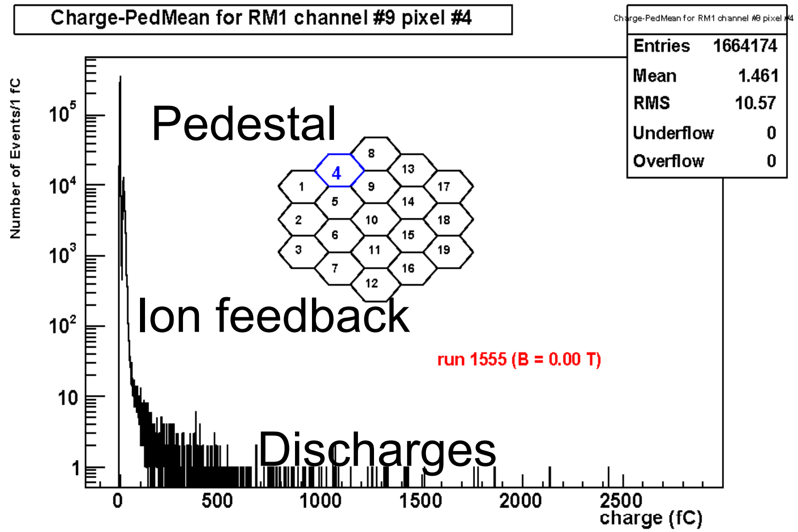
Under investigation – very exciting possibilities for a better, cheaper, more reliable upgrade to current design that meets our requirements

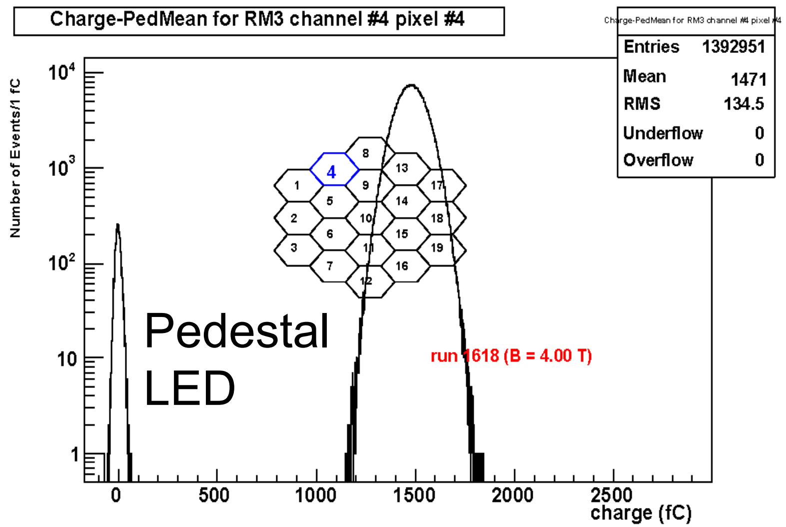




SiPM vs HPD

- Here we see a random HPD sampling
  - Pedestal, plus ion feedback, plus discharge noise
  - Honeycomb is the HPD array
- Test run with SiPM array
  - No ion feedback, no discharge!
  - Superimposed signal from LED
- SiPM gain >> HPD gain
  - For HPD, LED signal is near the ion feedback peak
- These are simply much better devices for a sampling calorimeter





SiPM R&D Issues

- Maturing technology driven by commercial sector
  - "Off the shelf"
- Half dozen vendors…R&D will evaluate to optimize for
  - Recovery (quench) time after avalanche
  - Thermal stabilization
  - Radiation hardness
    - We believe we have succeeded in finding a vendor to meet our charged and neutral particle radiation fluence specification
  - Dynamic range, linearity, number of pixels
- All issues are being systematically studied
  - Goal: have answers at end of the FY09

SLHC Phase 1 Level-1 Trigger (2-4 x 10^{34})

- Occupancy
  - Degraded performance of algorithms
    - Electrons: reduced rejection at fixed efficiency from isolation
    - Muons: increased background rates from accidental coincidences
- Trigger Rates
  - Try to hold max L1 rate at 100 kHz by increasing readout bandwidth
    - Avoid rebuilding front end electronics/readouts where possible
  - Implies raising E_T thresholds on electrons, photons, muons, jets and use of multi-object triggers, unless we have new information
- $\Rightarrow$ finer granularity & resolution of muon & calorimeter trigger information

SLHC Phase 1 & 2 Upgrade Level-1 Triggers

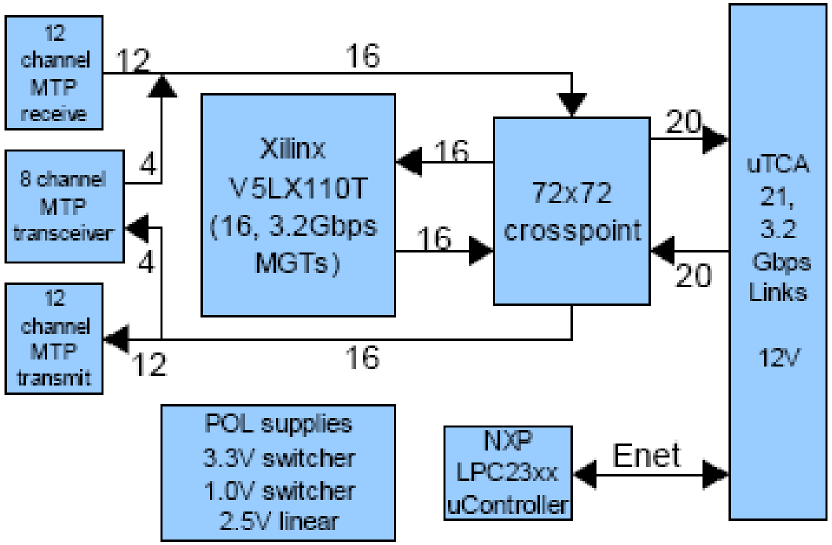
- Phase I
  - new information from use of more fine-grained information from calorimeter & forward muon triggers & improved algorithms exploiting this new information
- Phase 2
  - new information from introduction of tracking triggers.
- Phase I upgrade triggers designed so that they:
  - provide for a natural incorporation of tracking trigger information in Phase 2.
  - incorporate pixel trigger information & operate with this tracking trigger when it is available.
- Strategy:
  - Designing for tracking triggers from the beginning helps with rate reduction (due to finer granularity) and also provide valuable guidance in designing the final CMS L1 tracking trigger.

Phase 1 CSC Trigger Upgrade

- Occupancy increase → Muon Port Card becomes bottleneck
  - only allows 3 Local Charged Tracks per bunch crossing per sector.
- → 60 Muon Port Cards replaced.
  - higher bandwidth links → increase bandwidth from Port Card to Track-Finder
  - new Sector Processors require new optical receiver links,
- Sector Processors upgrade done once,
  - Meets requirements of SLHC Phase 2 although deployed with Phase I
  - Refined position info. from Track-Finder needed to match pixel/strip hits
  - Info. available on finer scale. More bits transmitted from Sector Proc. to new Sorter/Match Box for combination with pixel/tracker
- Muon Sorter (MS) → Sorter/match upgrade done once
  - Incorporate the ability to use pixel & tracker information in Phase 2.
  - Increase in dataflow into MS requires new backplane

Proto. Generic Trigger System

Concept for Main Processing Card



uTCA Crate and Backplane

- The Main Processing Card (MPC):
  - Receives and transmits data via front panel optical links.
  - On board 72x72 Cross-Point Switch allows for dynamical routing of the data either to a V5 FPGA or directly to the uTCA backplane.
  - The MPC can exchange data with other MPCs either via the backplane or via the front panel optical links.
- The Custom uTCA backplane:
  - Instrumented with 2 more Cross-Point Switches for extra algorithm flexibility.
  - Allows dynamical or static routing of the data to different MPCs.

Trigger Upgrade Hardware

- Calorimeter Trigger Upgrade
  - 10 μTCA crates with custom backplanes
  - 80 μTCA cards with high-speed optical links
  - Design provides for introduction of tracking trigger links and interface cards in phase 2
- Muon Trigger Upgrade
  - Replacement of 60 Muon Port Cards in VME peripheral crates on detector
  - Single μTCA crate with custom backplane
  - 8 μTCA cards with high-speed optical links
  - Design provides for introduction of tracking trigger links and interface cards in phase 2

Upgrade Scope

System	Phase 1	Phase 2
Pixel	New Pixel Detector (1 or 2 iterations?)	
Tracker	FEDs?	New Tracking System (incl Pixel)
HCAL	Electronics + PD replacement	HF/HE?
ECAL	TP (Off Detector Electronics) ?	EE?
Muons	ME4/2, ME1/1 ,RPC endcap, Minicrate spares, some CSC Electronics	Electronics replacement
Trigger	HCAL/RCT/GCT to μTCA	Complete replacement

Documents

Phase I Upgrades

- Concept
  - mid 2008
- LOI/TP
  - mid 2009
- TDR
  - Early 2010

Phase 2 Upgrades

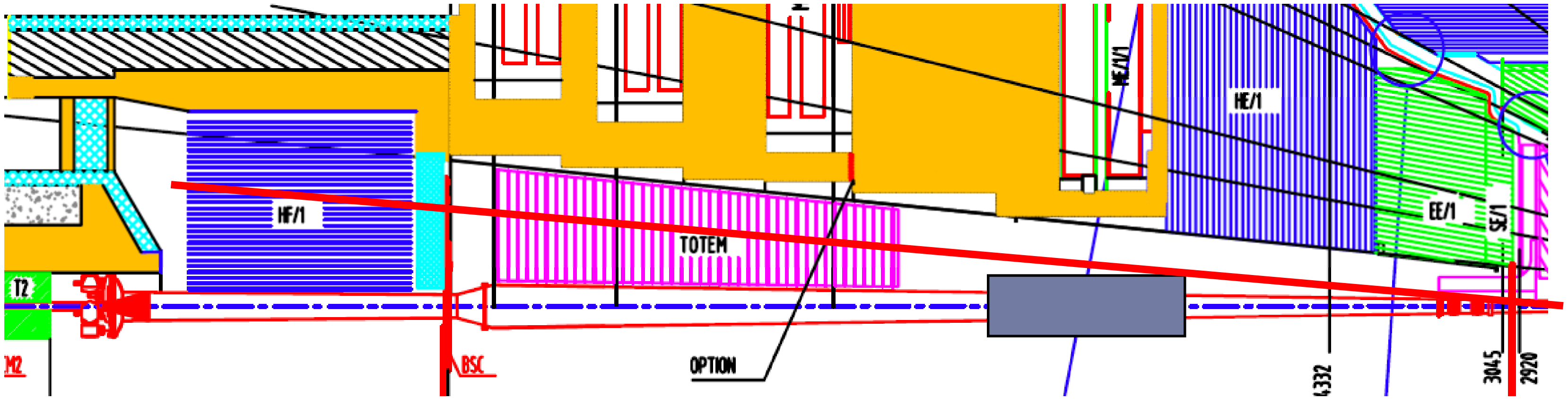
- Strawman
  - Mid 2009
- TP/LOI
  - Mid 2010
- TDR
  - 2012

Next Steps

- Produce an Integrated project plan for Phase I
  - Large number of systems expect to produce upgrades many of which involved interleaved installation issues
  - Some of these are already rather advanced and need to be integrated into the planning
- Define timescales/scopes for reviews of each upgrade
  - PDR > ESR/EDR > PRR?
- Request milestones/deliverables down to level … for each project
  - TDR > Production > Installation >
  - Start to track these milestones
    - Will require resources

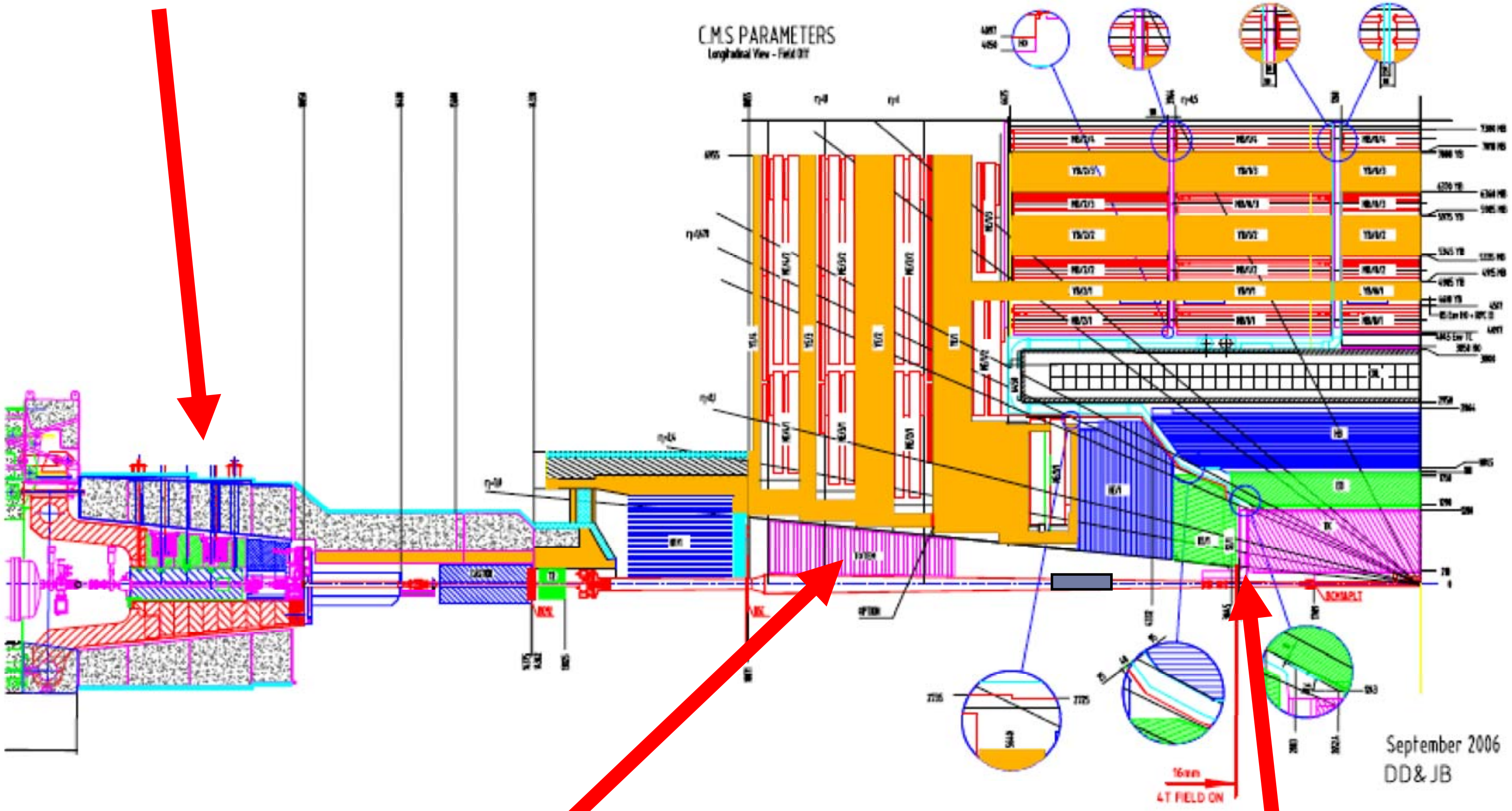
Implications of Early Separation

- Could we do this without replacing HF?
  - No way without obscuring part of the detector
  - But perhaps lower eta region still usable
- Will the HF still be useful at SLHC



What about maintenance?

Triplet moves closer to IP



These wheels move for maintenance

Either D0 has to clear the EE, or it has to move for maintenance

Conclusions

- CMS is progressing on defining the scope of phase 1 and phase 2 upgrades
- A substantial program of R&D is well underway
- The coming years will see development of detailed project plans for the upgrades
- Need to work with the LHCC to understand the transition from phase 1 to phase 2