CMS Upgrade for

SLHC

Lutz Feld, RWTH Aachen

DCMS Meeting Zeuthen Friday September 28, 2007

Outline

- Why upgrade LHC, and how
- Implications for CMS
- Necessary upgrades to
  - Tracker
  - ECAL
  - HCAL
  - Muon
  - Trigger/DAQ
- Organization and Schedule of CMS Upgrade
- German Contributions

Why do we need an Upgrade?

- LHC machine and detectors were designed to deliver 500 fb^{-1} at $L=10^{34}$ cm^{-2} s^{-1}

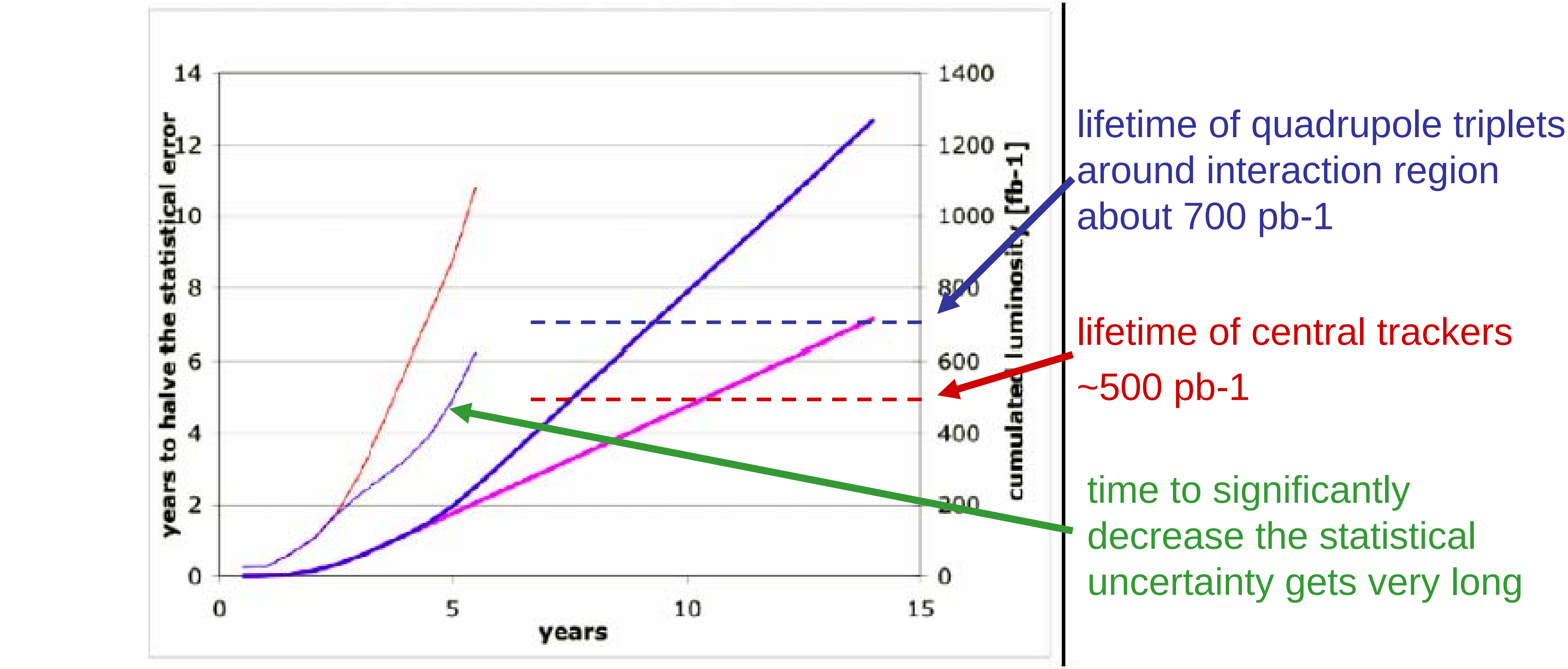


Figure 1.1: The thick lines on the right show integrated delivered luminosity (right hand scale) for two potential LHC running scenarios as a function of years from startup. The thin lines on the left (left hand scale) show the run-time required to halve statistical errors. [7].

- beyond 500 fb^{-1} an extension of LHC operation will be difficult and not profitable

→ Super-LHC: 10x instantaneous luminosity leading to 3000 fb^{-1}

Why do we need more than 500 fb^{-1} at all?

- impossible to give a firm answer before LHC data has been analyzed

- physics channels which profit from further increased statistics
  - triple and quartic gauge boson couplings (indirect evidence for new physics)
  - rare Higgs decays, Higgs Yukawa couplings
  - Higgs self couplings (measure potential shape: v)
  - WW and ZZ scattering (depends on Higgs mechanism)
  - rare top decays
  - SUSY: extended reach for squarks and gluinos, sparticle mass spectrum, measure sparticle spin
  - extended reach for new heavy gauge bosons
  - quark substructure

→ these measurements require precise measurements of electrons, muons, photons, jets and missing energy, as well as b and tau tagging

→ detector performance similar to current CMS is needed

What will change from LHC to SLHC?

- peak luminosity $L=10^{34}\ cm^{-2}\ s^{-1}$ → $L=10^{35}\ cm^{-2}\ s^{-1}$

- integrated luminosity 100 fb^{-1}/year → 1000 fb^{-1}/year

- replaced/new machine elements, also close to interaction regions → lower beta*

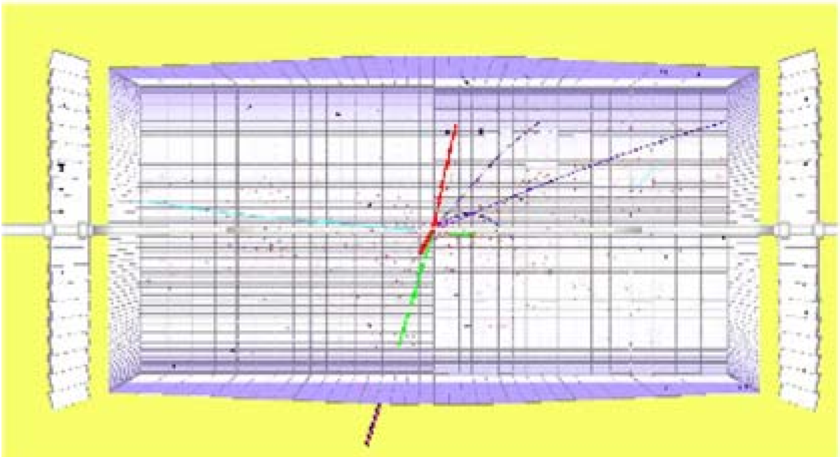
- modified bunch structure: no final decision yet, currently preference for 50 ns crossing rate of slightly longer bunches with more protons
  - 10, 12.5, 15 ns: heat load in LHC beam screen due to electron cloud too high (last resort if bunch charge or pile-up at 50 ns lead to unexpected problems
  - 25 ns: beam separation magnets inside the experiments much closer to IP than for 50 ns option
    → this is the fall-back

→ about 400 pp interactions on average in each bunch crossing

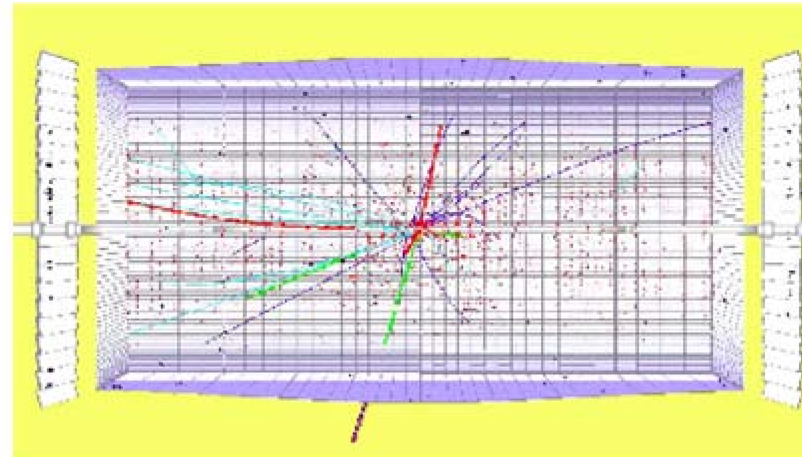
→ about 20,000 particles in the tracker per bunch crossing

- c.m. energy will remain at 14 TeV (increase to 28 TeV would require complete rebuilt of machine including s.c. dipoles with B=16T which do not exist)

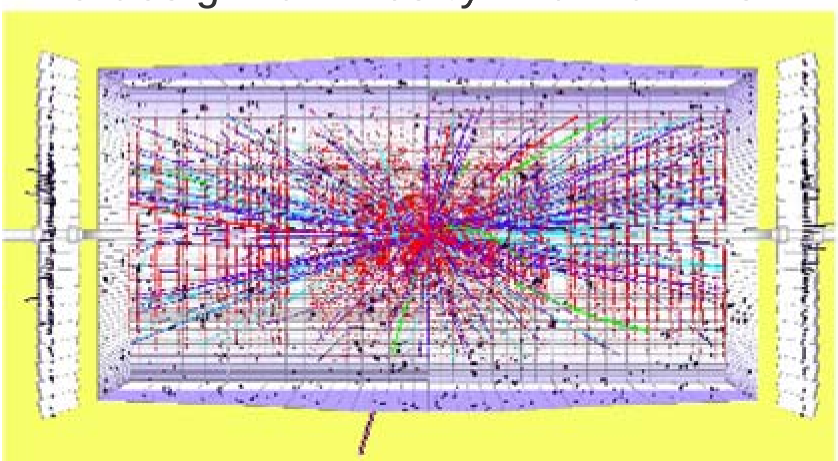
LHC start-up: 10^{32} cm^{-2} s^{-1}



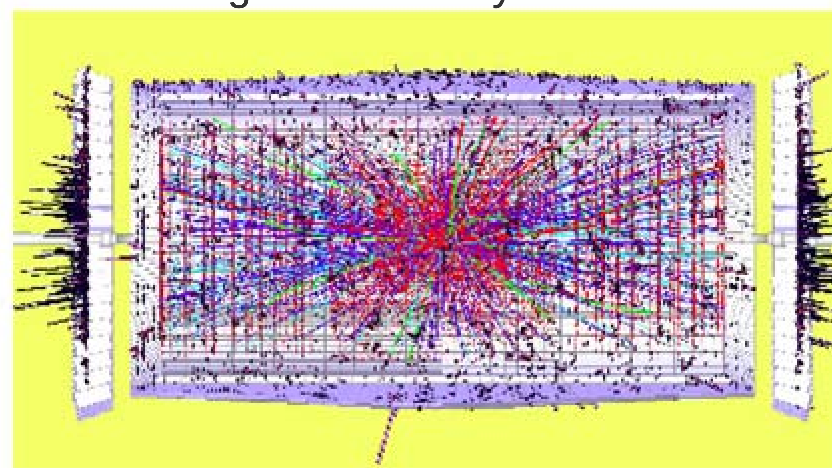
LHC first year: 10^{33} cm^{-2} s^{-1}



LHC design luminosity: 10^{34} cm^{-2} s^{-1}

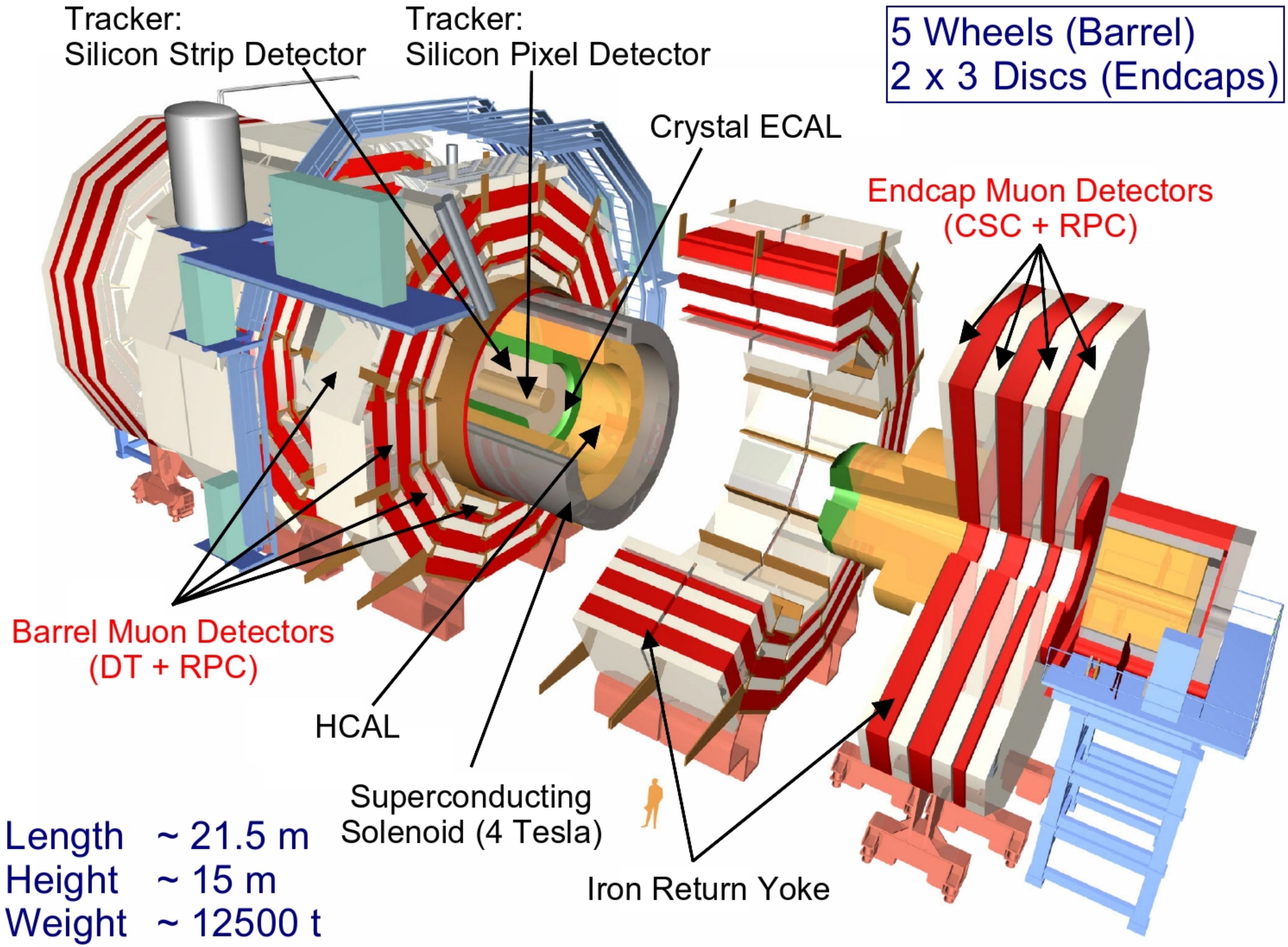


SLHC design luminosity: 10^{35} cm^{-2} s^{-1}



~20 soft interactions superimposed on interesting event

~200 soft interactions superimposed on interesting event
(actually, for 20 MHz operation the number of particles is twice as high)


Tracker:
Silicon Strip Detector
Tracker:
Silicon Pixel Detector
5 Wheels (Barrel)
2 x 3 Discs (Endcaps)
Crystal ECAL
Endcap Muon Detectors
(CSC + RPC)
Barrel Muon Detectors
(DT + RPC)
HCAL
Superconducting
Solenoid (4 Tesla)
Iron Return Yoke
Length ~ 21.5 m
Height ~ 15 m
Weight ~ 12500 t

Implications for CMS

- occupancies increase roughly by a factor of 20
- data rates increase roughly by a factor of 20
- radiation dose and fluence increase roughly by a factor of 20

Aim: preserve performance of CMS

(otherwise a factor of 10 in statistics would be rather useless)

- **Tracker** (pixel and strips): needs to be rebuilt
- **ECAL**: crystals and on-detector electronics should work at SLHC
- **HCAL**: HB ok, HE need replacement of scintillators, HF may be in conflict with new machine elements
- **Muon**: chambers ok, on-detector electronics may need upgrade
- **Trigger**: needs to be rebuilt

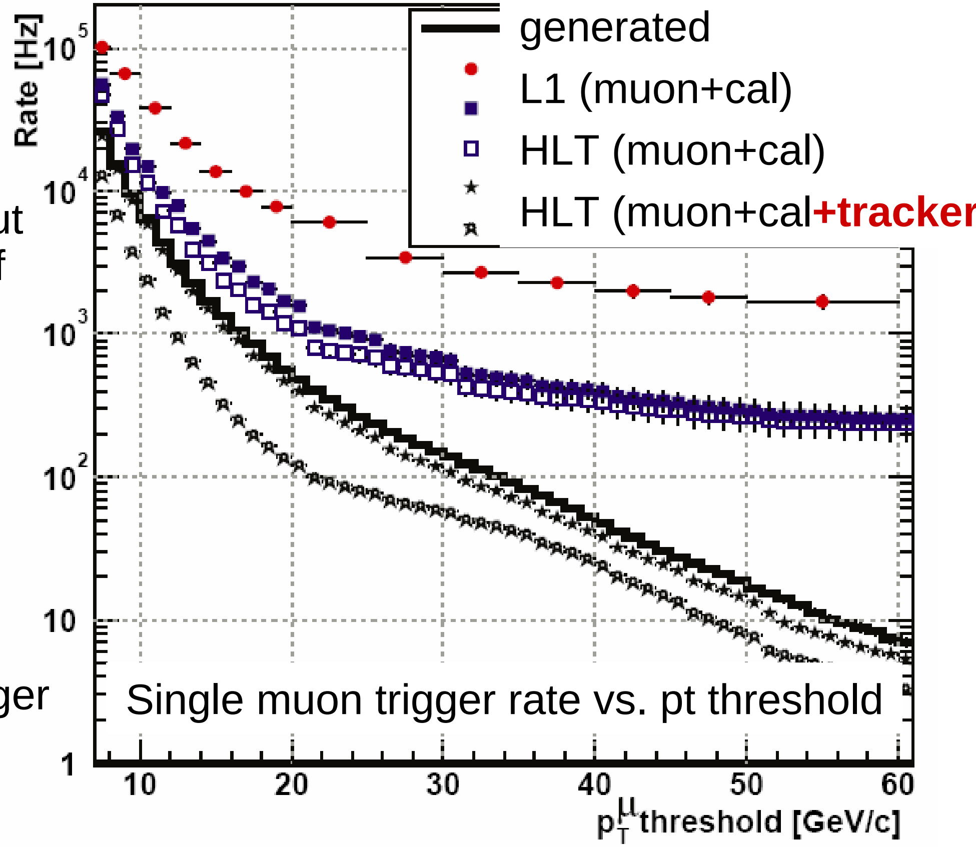
Trigger

- Level-1 trigger rate should remain at 100 kHz
- 20 times more occupancy has two main effects:
  - larger event size → **data reduction + higher bandwidth** (5-10 times)
  - current trigger algorithms provide less rejection at fixed efficiency (less isolation, more fake tracks, …)
    → need to **improve rejection**
- rejection cannot simply be improved by increased thresholds
  - momentum scale of important physics signals (like leptons from Z) will not change
  - limited detector resolution smears out p_t distributions such that reduction of trigger rate by increased cuts is very slow

→ add tracking information to L1 trigger
  - confirm muon, electron and photon candidates, improve resolution
  - reject fakes
  - distinguish primary vertices
  - do not require stand-alone track trigger

→ need to rebuild trigger system

- L1 latency will be doubled to 6.4 µs

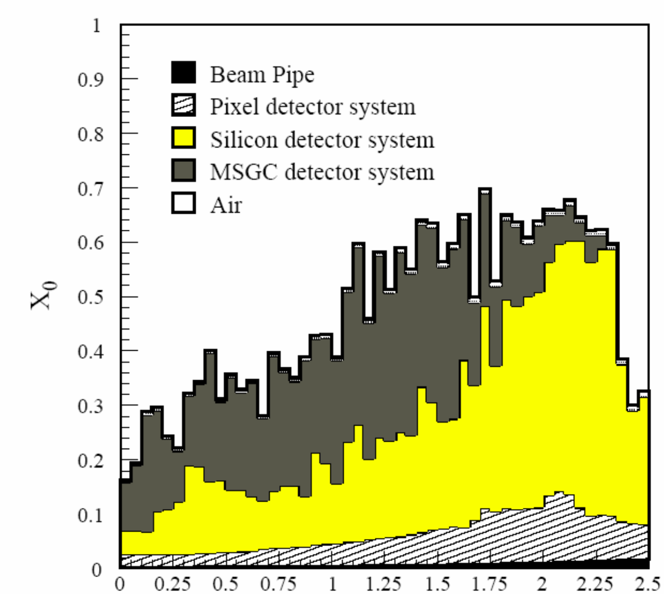


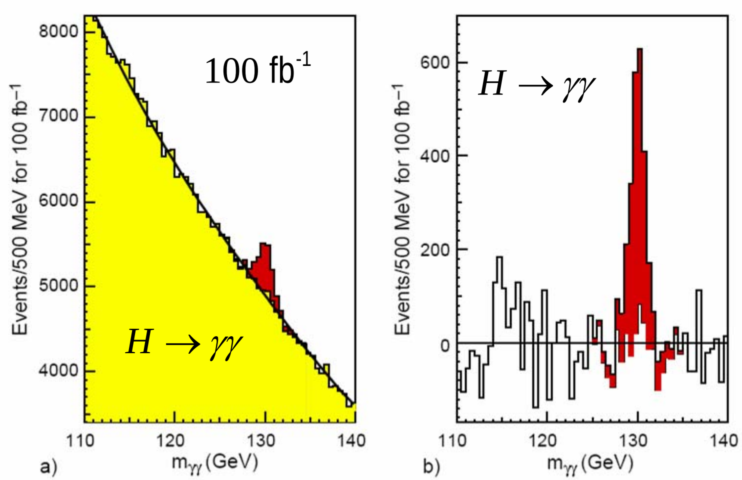
Tracker

- current CMS Tracker is highly efficient and precise
  → keep specifications for momentum and spatial resolution
- only one way to make it significantly better: **reduce material budget**
- operation of Tracker at the SLHC with equal or better performance requires
  - higher granularity to cope with 20 times increased occupancy
  - improved radiation hardness of sensors to survive increased radiation levels
  - improved read-out system to cope with increased hit rates and data volume, and to contribute to the L1 trigger
  - improved power distribution to supply more detector channels and allow usage of 0.13µm (or smaller) ASIC technology
  - reduced material budget
- simulations are needed

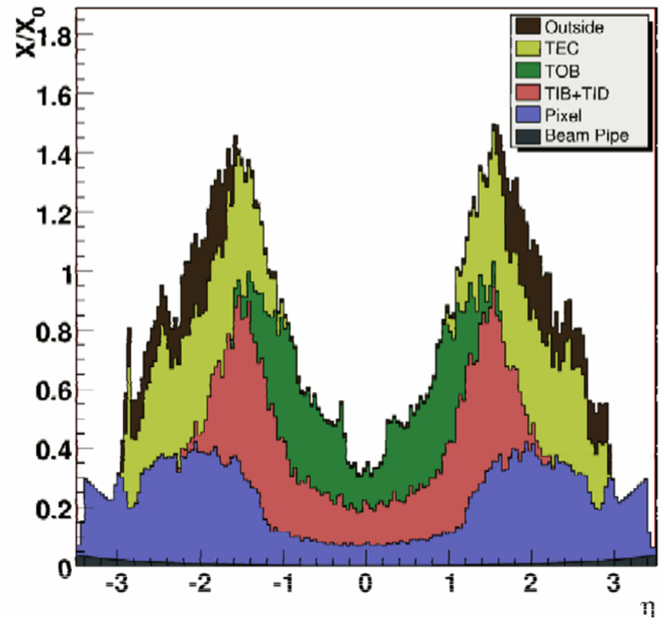
The Material Budget Nightmare

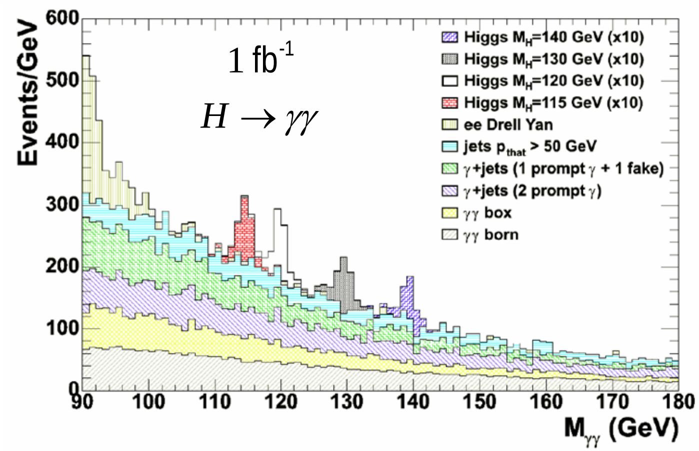
1997





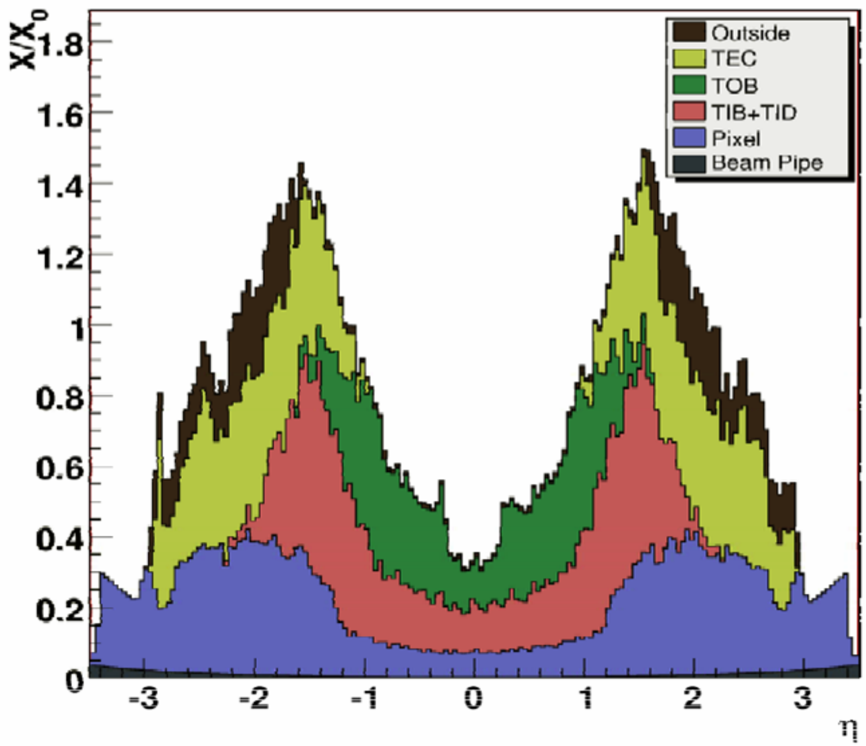
2006



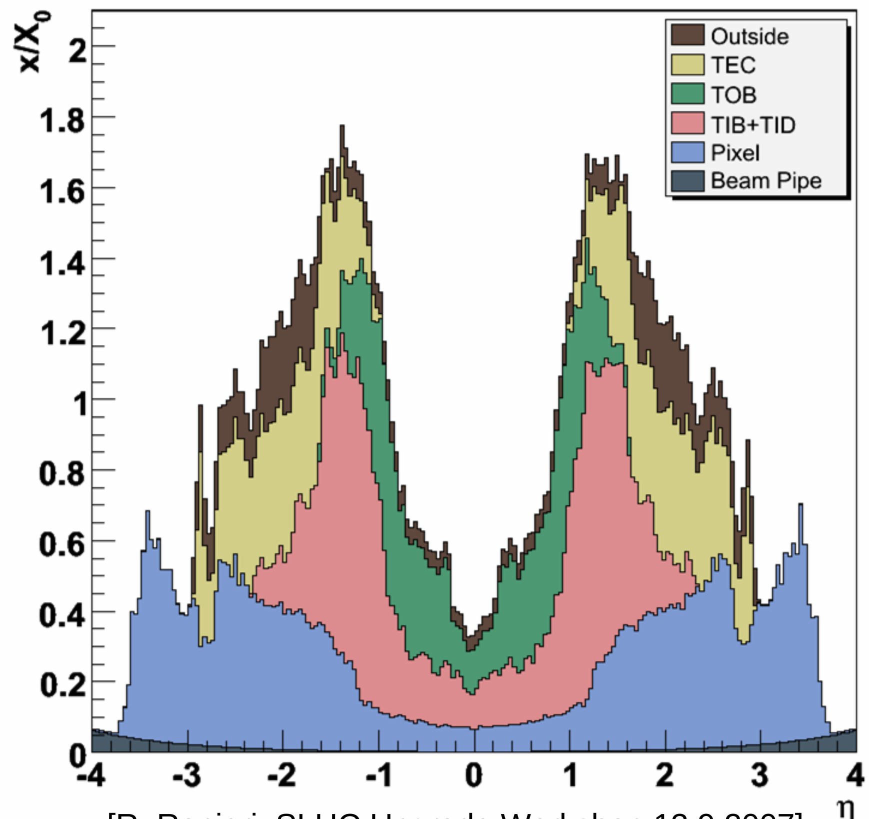


…continued

2006



2007



[R. Ranieri, SLHC Upgrade Workshop 13.9.2007]

Tracker material budget needs to be decreased in the upgrade
to the good of Tracker and ECAL!

Material Budget in the current Tracker

Element	Index	Total Mass	Mass Fraction
Nitrogen	0	3.87108 kg	0.00107488
Oxygen	1	365.756 kg	0.10156
Argon	2	51.9506 g	1.44251e-05
Hydrogen	3	114.589 kg	0.031818
Iron	4	49.7929 kg	0.013826
Carbon	5	1412.52 kg	0.392215
Manganese	6	331.092 g	9.19346e-05
Chromium	7	2.67785 kg	0.00074356
Nickel	8	10.4754 kg	0.0029087
Aluminium	10	585.763 kg	0.162649
Beryllium	11	760.09 g	0.000211055
Copper	13	494.673 kg	0.137356
Gold	14	442.466 g	0.00012286
Silicon	15	306.091 kg	0.0849924
Sulfur	16	7.27642 g	2.02045e-06
Phosphor	17	5.21479 g	1.44799e-06
Indium	18	1.07669 g	2.98966e-07
Lead	19	326.109 g	9.05509e-05
Tin	20	4.67424 kg	0.0012979
Barium	21	4.72014 kg	0.00131064
Titanium	22	24.3486 kg	0.00676089
Fluorine	23	192.615 kg	0.0534834
Silver	24	11.204 kg	0.00311102
Pix_Bar_Ring_HC25		45.2962 g	1.25774e-05
Bor 10	26	64.9296 g	1.8029e-05
Bor 11	27	285.69 g	7.93278e-05
Chlorine	28	73.206 g	2.03272e-05
Antimony	29	171.786 g	4.76999e-05
Bromine	30	9.00321 kg	0.00249993
Zinc	31	3.67327 kg	0.00101996
Sodium	32	970.164 g	0.000269386
Potassium	33	1.19481 kg	0.000331765
Cobalt	34	211.631 g	5.87636e-05
	Total Weight without Air 3601.39 kg		

[R. Ranieri, SLHC Upgrade Workshop 13.9.2007]

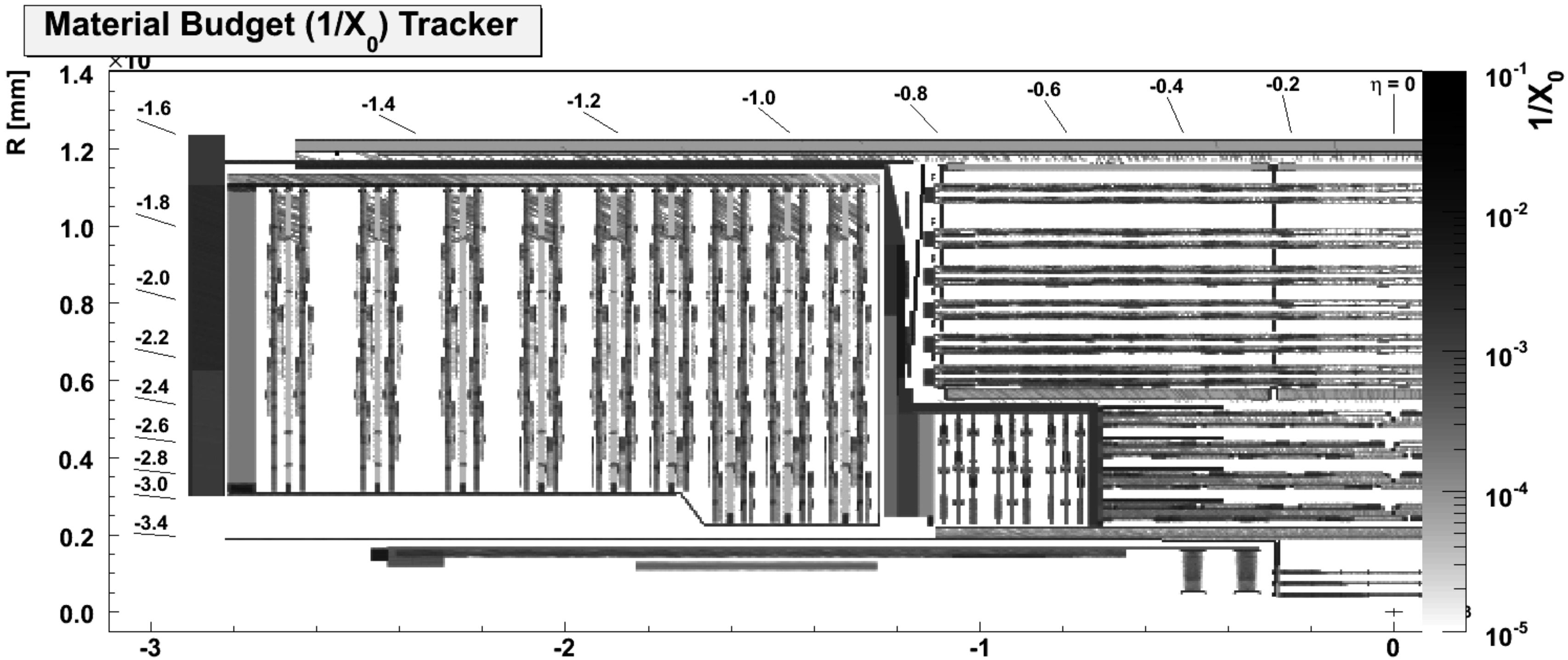
Material Budget in the current Tracker

	Support	Sensors	Cables	Cooling	Electronics
TIB/TID	18.2%	7.6%	46.0%	15.3%	12.9%
TEC	48.6%	11.9%	12.1%	19.5%	7.9%
TOB	30.9%	15.5%	17.8%	9.7%	26.1%
TST+TS+PP	15.8%	0	69.4%	14.8%	0.0%
STRIP	30.9%	10.7%	28.2%	15.3%	14.2%

[R. Ranieri, SLHC Upgrade Workshop 13.9.2007]

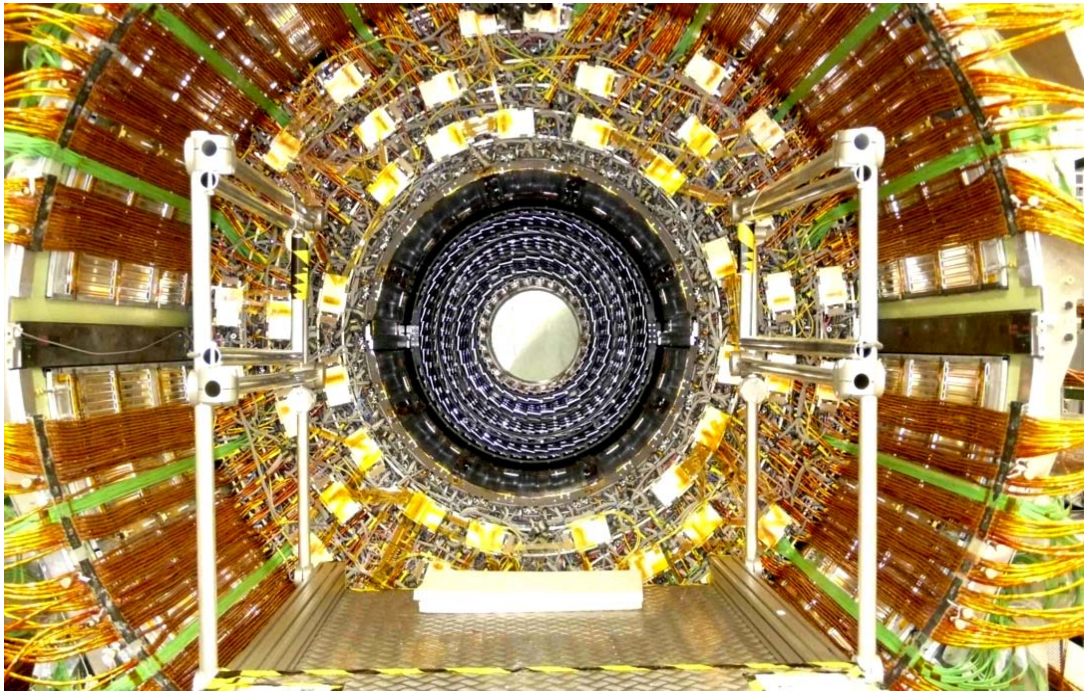
- sensors contribute only 10.7%
- big contribution by support structure, cables and cooling
- material budget obviously depends on system layout

$1/X_0$ ray of the CMS Tracker



[R. Ranieri, SLHC Upgrade Workshop 13.9.2007]

Material Budget Improvement Options



- less power
- less current
  (i.e. higher voltage)
  → smaller cable xsection
- fewer layers
- optimization of
  system layout
- optimization of materials
- modifications to cooling system

Radiation Hardness

- ionizing and non-ionizing radiation doses scale with integrated luminosity
  → factor 5-6 compared to LHC

Table 17. Hadron fluence and radiation dose in different radial layers of the CMS Tracker (barrel part) for an integrated luminosity of $2500\,\mathrm{fb}^{-1}$

Radius (cm)	Fluence of fast hadrons ($10^{14}\,\mathrm{cm}^{-2}$)	Dose (kGy)	Charged Particle Flux ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)
4	160	4200	5×10^8
11	23	940	10^8
22	8	350	3×10^7
75	1.5	35	3.5×10^6
115	1	9.3	1.5×10^6

[Eur. Phys. J. C 39, 293–333 (2005)]

- 0.25µm CMOS ASICs sufficiently radiation hard for SLHC
  BUT process may be no longer available in 10 years
  → work on 0.13µm has started,
  allows more features in the chip and lower power,
  BUT at reduced voltage (1.2 V vs. 2.5 V)

- silicon sensor leakage current increases by factor 5-6
  → a lot more power in the silicon and risk of thermal runaway
  → more efficient cooling, thin sensors, under-depleted operation, …

- depletion voltage of current sensor layouts would rise beyond reasonable limits
  → new sensor material and layout needed
  Options: p-type silicon, magnetic Czochralski silicon, … for outer layers
  inner layers need really new concepts (thin sensors, 3D, epi, diamond, …)

- last resort: replace inner layers every n years

Occupancy

- occupancy at SLHC will be ~20 times higher:
  → strip occupancy in current tracker would rise to about 30% on inner layers

- studies for heavy ion running of LHC indicate that pattern recognition and decent track reconstruction will be possible with current tracker at such high occupancies however: reduced efficiencies due to necessary pixel seeding, HIP effect on FE-electronics and FED common mode subtraction

- at any given radius the detector cell size needs to be reduced
  strips → short strips → long pixels → pixels

BUT

- present system cost: pixels 500 CHF/cm^2 strips 40 CHF/cm^2
  → need cost reduction for pixels: low cost bump bonding or new technology
  → careful analysis of required granularity (watch material budget)

- power density of pixels = 10 x strips
  → careful design + new powering scheme

Power

- power consumption inside current tracker: about 60 kW
- channel number will increase
- power per analogue channel will decrease, but probably not compensate increase in channel number
- increased logic (on chip data reduction, trigger logic) will increase power
- fast data links (GB/s or more) need power
- ASIC supply voltage will decrease (factor 2 for 0.25µm→0.13µm)
  → same power requires more current
- total power cable cross section is limited by cable channels in CMS
  cables are big contribution to material budget
  → can not increase currents, rather decrease them

→ new powering scheme needed: supply power at high voltage (e.g. 48V) into tracker (at much reduced current) and convert locally (DC-DC or serial)

L1 Trigger from Tracker

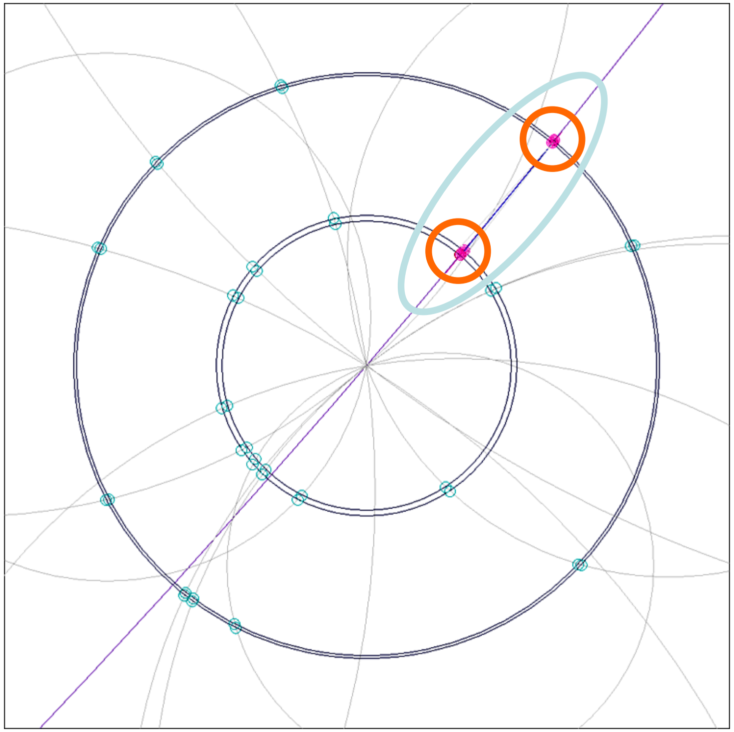
- extraction of L1 trigger information from tracker requires a completely new approach
- data processing on the detector will be necessary
- track stubs pointing to ECAL clusters or MUON tracks would be sufficient

→ **double layer** of pixel detectors with hit correlation logic

hit pairs of high p_t tracks point to IP

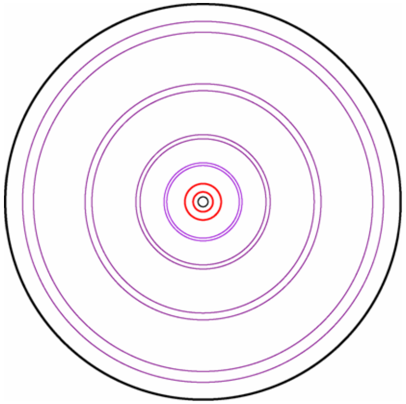
correlation = p_t cut

- binary read-out with off-detector processing could be an alternative

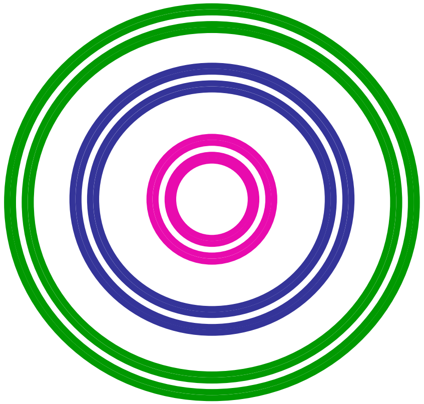


[J. Jones et al., http://www.imperial.ac.uk/research/hep/preprints/06-11.pdf]

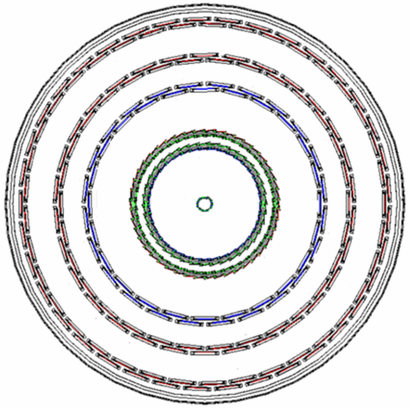
Straw Man Designs

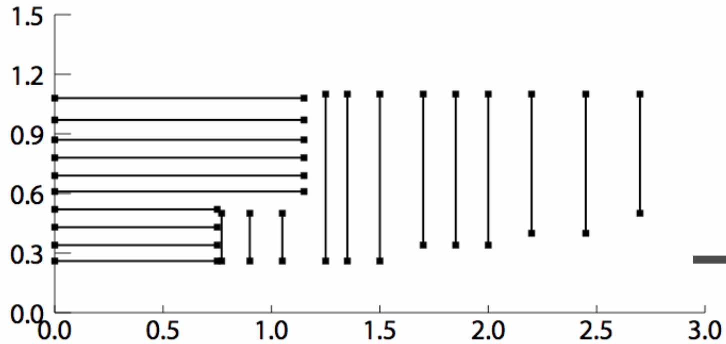


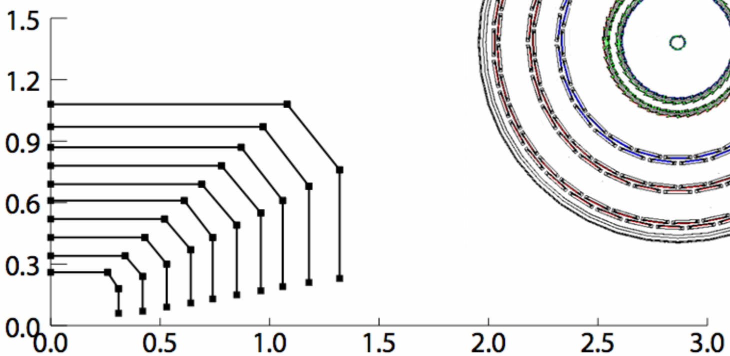
- many different proposals, no agreed baseline straw man design yet
- r < 20cm new pixel devices
  20cm < r < 60cm "cheap" pixel devices
  60cm < r current (short) strip devices



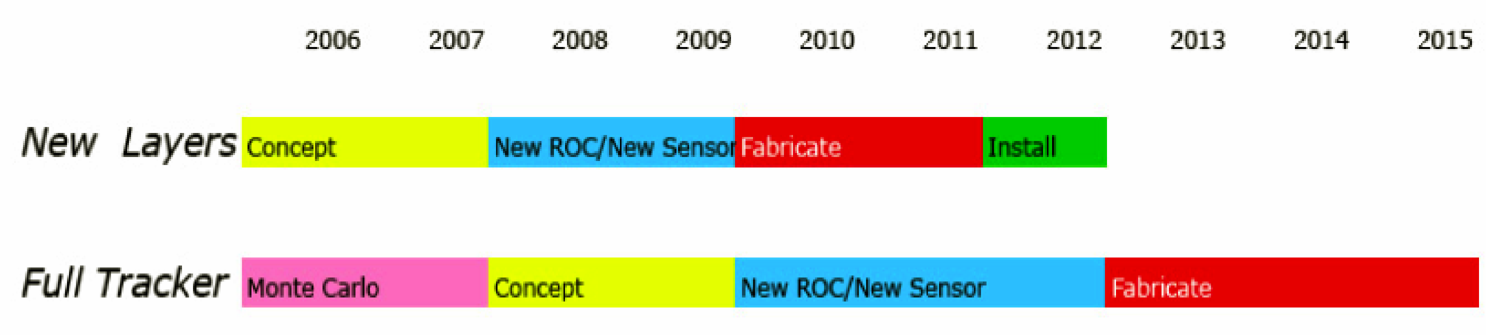
- probably 4 pixel layers
- double layers look promising (for the barrel)
- fewer layers seem to be sufficient
- end caps not really looked at
- current inner pixel layer needs to be replaced after ~4 years
  → could replace it by "pathfinder system" which tries out SLHC detectors







Timeline for Tracker Upgrade

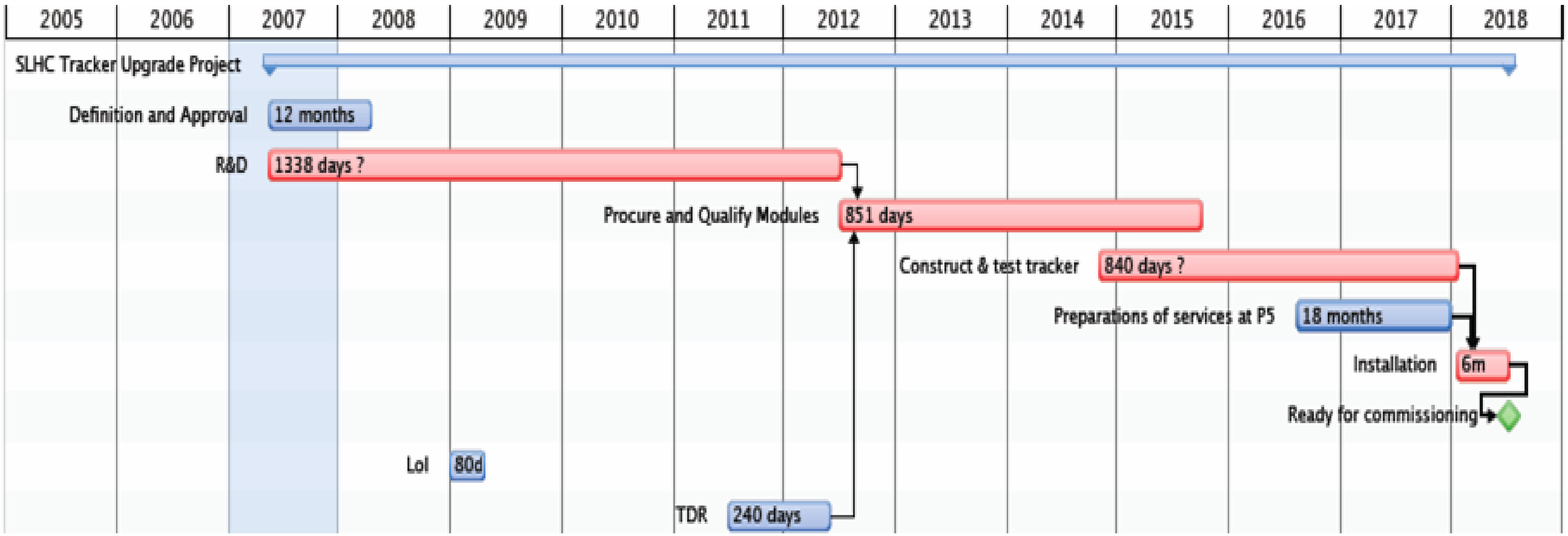


[CMS Expression of Interest in the SLHC, CERN/LHCC 2007-014]

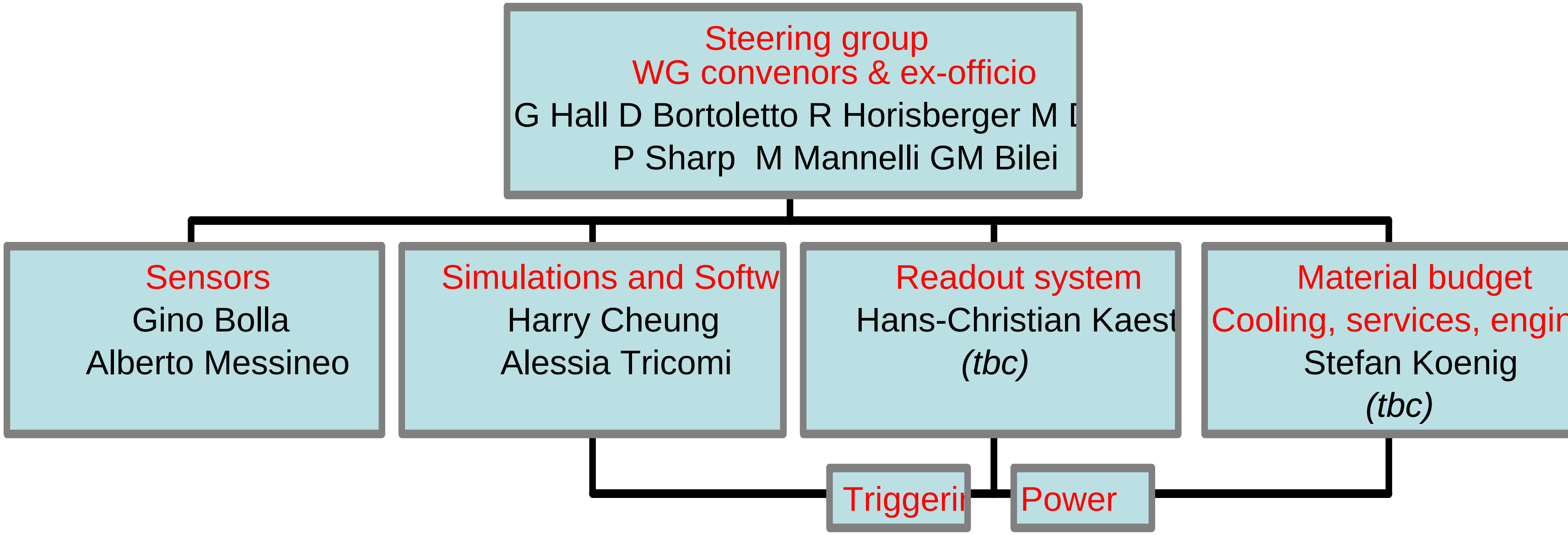
A more experience driven (and still optimistic) approach by Geoff Hall:

~10 years from now to operation, with possible breakdown:

5 years R&D - 2 years Qualification - 3 years Construction - 6 months Installation



Tracker SLHC Organization



- several upgrade workshops and working group meetings have taken place

- for further information see
  - SLHC Tracker web pages
    http://cmsdoc.cern.ch/Tracker/Tracker2005/TKSLHC/index.html
  - Tacker Upgrade Wiki pages
    https://twiki.cern.ch/twiki/bin/view/CMS/SLHCTrackerWikiHome
  - SLHC Tracker Simulation Hypernews Forum
    hn-cms-slhc-trackersim@cern.ch

Calorimeters

ECAL

- crystals tested to radiation levels beyond SLHC, somewhat reduced light yield
- APDs and VPTs should work at SLHC
- on-detector electronics tested to radiation levels beyond SLHC
- off-detector electronics needs update to cope with new bunch crossing frequency and new trigger and DAQ requirements
- preshower should be ok, but tests are needed

HCAL

- HB should be ok
- scintillators in HE will darken at SLHC radiation levels and need to be replaced; various options: scintillators, parallel plate chambers, silicon sensors, quartz plates, …
- improvement of HO by replacing HPDs by SiPMs
  (S/N would improve by factor 4)
- HF may need modifications depending on new machine elements inside CMS
- upgrade HCAL read-out electronics to higher bandwidth and finer trigger granularity

Muon System

- drift tubes (DT), cathod strip chambers (CSC) and resistive plate chambers (RPC) should work at SLHC rates
  - possible exception: RPCs at large rapidity

  → need R&D to check rate compatibility

- larger hit rate and increased radiation levels require major upgrades of
  - front-end electronics
  - trigger electronics
  - read-out electronics

Cost

Sub-Detector	Estimated Cost
Inner Tracker	30 MCHF
Outer Tracker	90 MCHfF
Level-1 Trigger	20 MCHF
DAQ	10 MCHF
Muons and Calorimters	10 MCHF
Infrastructure	15 MCHF
Total	175 MCHF

[CMS Expression of Interest in the SLHC, CERN/LHCC 2007-014]

CMS SLHC Organization

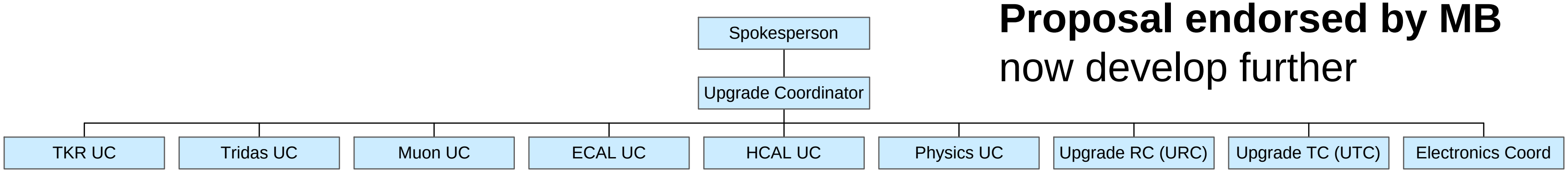
SLHC Task Force Co-chairs: of J. Nash and G. Tonelli

Members: Austin Ball, Philippe Bloch, Joel Butler, Marcos Cerrada, Geoff Hall, Mauro de Palma and Joao Varela.

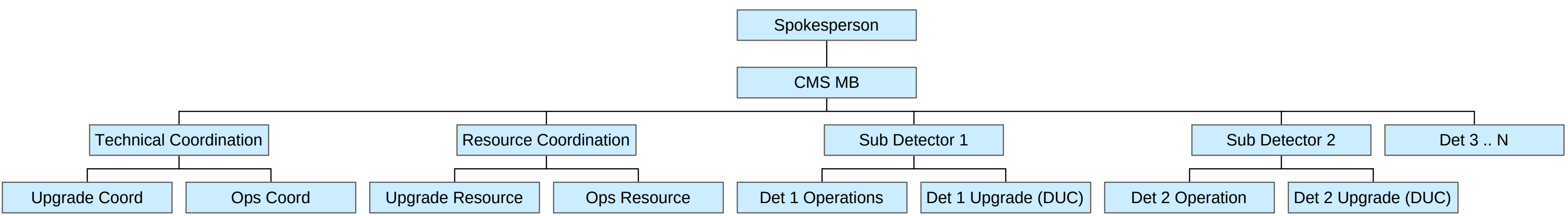
Mandate: To make proposals on how an Upgrades Project might be set up, particularly how it should be managed - the relationship of such a large undertaking to the ongoing activity of running CMS.

Upgrade Management Team

Proposal endorsed by MB
now develop further



Enlarged CMS Management Team



Upgrade PM or Co-ordinator (Wide Remit acting as CMS advocate of the upgrade)

Work with sub-detectors to ensure upgrade resources are adequate and balanced wrt operations and to help integrate new groups in Upgrade effort

Look at global upgrade issues (e.g. material budget, interaction with machine, physics capability)

Ensure R&D is appropriate and focused

[Jim Virdee, CMS Week Sep 2007]

R&D Proposals

- CMS has set up a review procedure to consider proposals for R&D, so they can be compatible with the experiment and to encourage funding agencies to back the ones which have CMS support. During the September 2005 CMS Week, the CB & MB approved the creation of the CMS SLHC Upgrades Steering Group

- one tracker related proposal has been submitted:

  Letter of intent for Research and Development for CMS tracker in SLHC era

  Lenny Spiegel (Fermilab), Jorma Tuominiemi, Jaakko Haerkoenen, Panja Luukka, Eija Tuominen, Sandor Czellar (Helsinki Institute of Physics, HIP), Martin Frey, Alexander Furgeri, Frank Hartmann, (Karlsruhe University), Vincent Lemaitre (Louvain University), Alexander Kaminski, Dario Bisello (University of Padova), Regina Demina, Yuri Gotra, Sergey Korjenevski (University of Rochester)

  Design, production, characterization, irradiation and test-beam measurements of silicon sensors on magnetic Czochralski.

- more proposals in the pipeline (e.g. R&D on powering by AC-Ib)

- approved proposals will help to obtain components and funding

Contributions and Plans of German Groups

- Current status, still in an early phase, will evolve.
- In many cases continuation of past activities.

	Projects	Status
Aachen IB	**Tracker**: system issues (powering, cooling, material), system design (modules, super-modules, support structure), construction and integration	starting
Aachen IIIA	**Computing** and **Tracker** and/or **Muon**	interested
Aachen IIIB	**Muon**: Test of Electronics	interested
DESY	Interests in **Tracker** (rad-hard sensors), **HLT/DAQ**, **Integration**	interested
Hamburg	**Pixel**: radiation hard sensor material and design, simulation of signal shape after irradiation	started
Karlsruhe	**Tracker**: radiation hard sensors, modules, system test, sensor QA, module and super-module production and tests	started

Summary

- CMS needs to be upgraded for operation at SLHC
- take into account what was learned during CMS construction and what will be learned during first years of operation
- upgrade plans are triggered by new requirements, not by deficiencies of current CMS detector systems
- main upgrade projects: Tracker and Trigger/DAQ
- R&D on SLHC upgrade needs to start now
- organization of upgrade project starts to take shape
- R&D groups are forming, join them or start a new project
  a lot of work and technical challenges are between us and the SLHC
- applications for the next BMBF Förderperiode (7/2009 – 6/2012) need to contain rather significant requests for SLHC since in 2012 the R&D has to be far advanced and close to a final design
- detector R&D for SLHC is fun, but…

official version: http://cmsdoc.cern.ch/cms/archives/07/LHCC/slhc-eoi-final.pdf