

LHC Phase II Upgrade R&D

ATLAS, CMS, LHCb

Lutz Feld, RWTH Aachen

KET-Jahrestreffen, Bad Honnef, 23. 11. 2013



*Europe's **top priority** should be the exploitation of the **full potential of the LHC**, including the high-luminosity **upgrade** of the machine and **detectors** with a view to collecting ten times more data than in the initial design, by around 2030.*

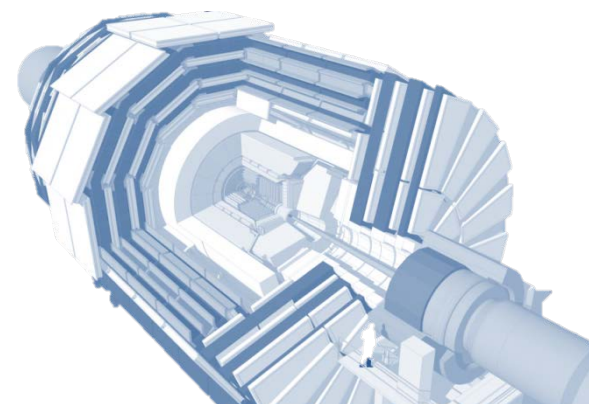
[European Strategy for Particle Physics Update 2013]

Phase II Upgrades

- from LHC design to ultimate performance
 - **luminosity** $1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \rightarrow 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ leveled (ATLAS + CMS),
 $4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1} \rightarrow 2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ (LHCb)
 - **integrated luminosity** 300/fb \rightarrow 3000/fb (ATLAS + CMS), 5/fb \rightarrow 50/fb (LHCb)
 - \rightarrow **new and more precise measurements, extended reach for discoveries**
IF detector performance can be preserved / improved
- the price to pay:
 - pile-up 20 \rightarrow 140-200 (ATLAS+CMS), 2 \rightarrow 5 (LHCb)
 - particle densities x5-10
 - radiation damage x10
- the casualties (radiation damage and/or performance loss)
 - pixel
 - tracker
 - trigger
 - end-cap calorimetry, electronics
 - end-cap muon system, electronics
- the brave (in general)
 - calorimetry
 - muon system
- when?
 - installation mainly in 'long shut down 3' currently foreseen 2022-2023 (ATLAS+CMS)
partly already in 'long shutdown 2' currently foreseen 2018 (LHCb)
 - **R&D NOW**

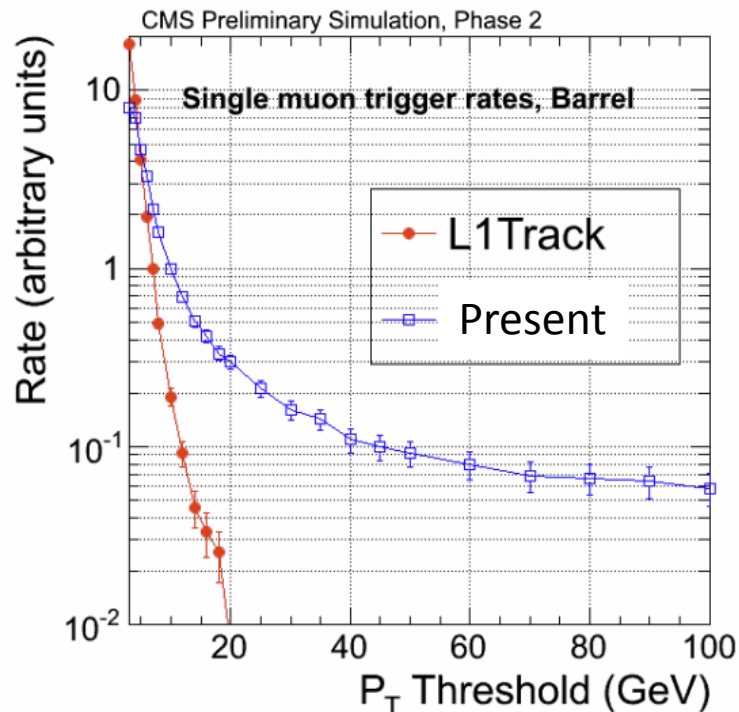
x5

x10

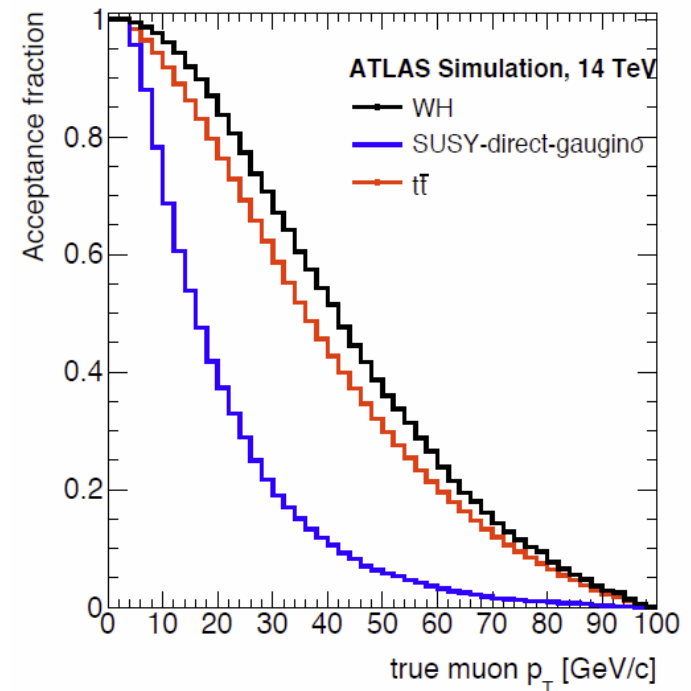


Trigger Challenge

- more luminosity → more interesting events but also more background
- only useful if interesting events can still be triggered and read-out
- high pile-up and particle densities lead to decreased resolution at trigger level
→ trigger rates increase beyond capacity of trigger/DAQ system



matching of muon system tracks with tracker tracks
→ improved precision of p_T measurement at trigger level
→ large rate reduction












simply increasing trigger thresholds
would kill the signal

General Survival & Improvement Concepts

- pile-up 20 → 140...200
 - association of tracks and calorimeter energies to individual vertices (up to high eta)
 - particle flow reconstruction
- particle densities x5-10 (ATLAS+CMS: 6'000 primary tracks per event)
 - finer granularity → more channels
- data rates (particles per event) x5-10
 - higher band-width (analogue→digital links)
- increased trigger rates (at fixed thresholds) due to degraded resolution and ambiguities
 - improve resolution of pt and E measurement at trigger level
 - use topological information
 - provide tracking information to L1 trigger
 - increase latency and acceptable trigger rates (LHCb: no trigger at all: 40 MHz read-out)
- radiation damage x10
 - more radiation hard detection elements (silicon, crystals)
- increased front-end power consumption
 - ASIC technology scaling 250nm → 130 nm → 65 nm to reduce power per transistor
 - improved powering and cooling
- reduce material budget inside detector volume
- changes to a running system
 - test new systems as early as possible (e.g. run new triggers in parallel to old ones, run pilot systems inside detectors)

new technologies needed
+ keep what works well
+ cost-effective solutions
+ keep logistics in mind (ALARA)

Phase II Upgrade Plans of Experiments

	ATLAS	CMS	LHCb
Pixel Vertex Det.	New BN, DO, GÖ, HD, MPI, SI, W 	New  HH	New (Velo)
Tracker	New, all silicon  B, DESY, FR	New, all silicon  AC, DESY, KA	New Fiber Tracker  AC, DO, HD Replace Upstream Tracker
			Replace RICH Electronics
Calorimeters	Replace Electronics  DD, MPI	Replace End-Caps Replace Electronics	Replace Electronics
Muon Syst.	Replace electronics  FR, MZ, M, MPI, WÜ	Extend End-Caps  AC Replace Electronics	Replace Electronics
Trigger	Upgrade  HD, MZ DESY, HD	Upgrade	Trigger-less

German groups are active in many of the key areas!

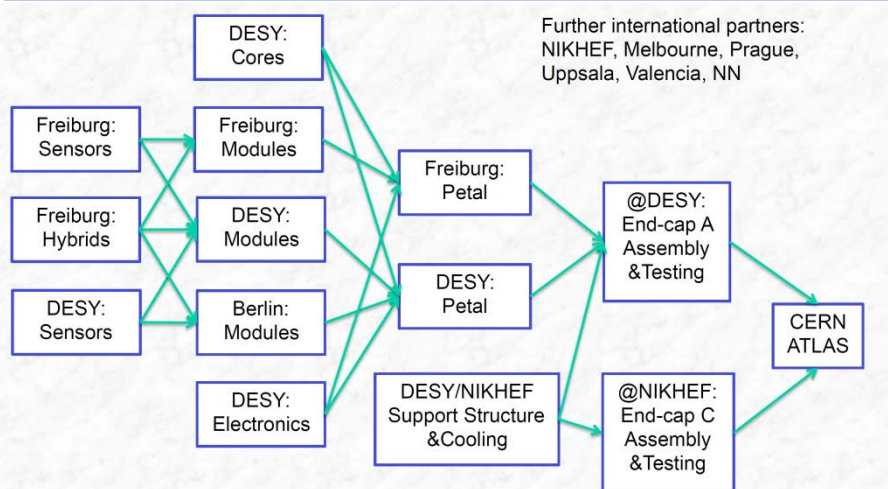
Cost (ATLAS,CMS; roughly):

- 50% Pixel+Tracker
- 20% Calorimeters
- 10% Muon Syst.
- 10% Trigger/DAQ
- 10% Common Fund

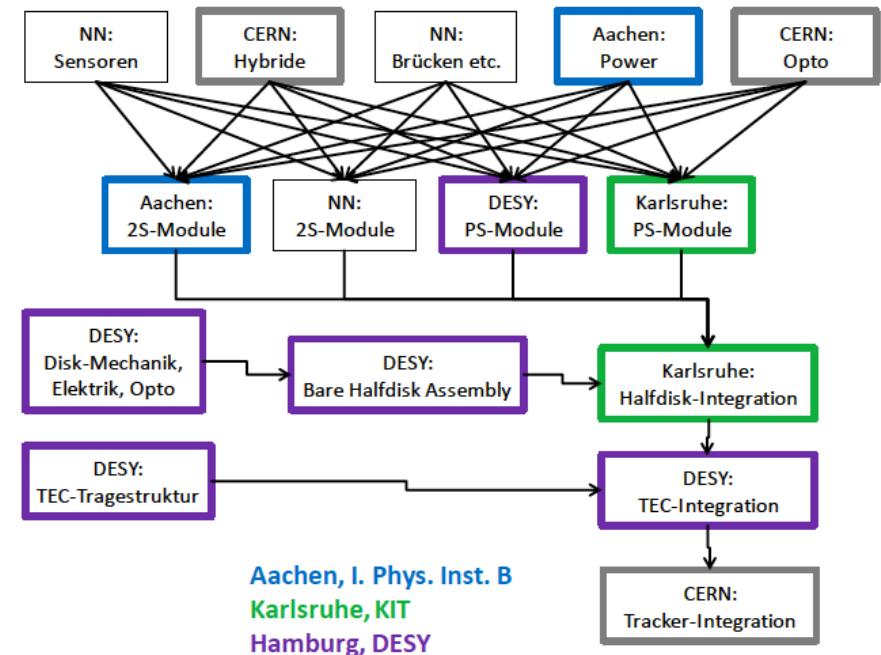
Upgrades are a joint effort of Universities, DESY, KIT and MPI

An example: Tracker End-Cap Construction

ATLAS

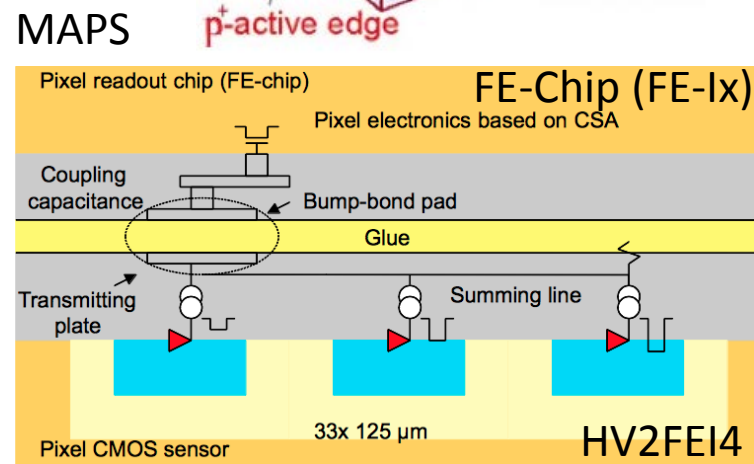
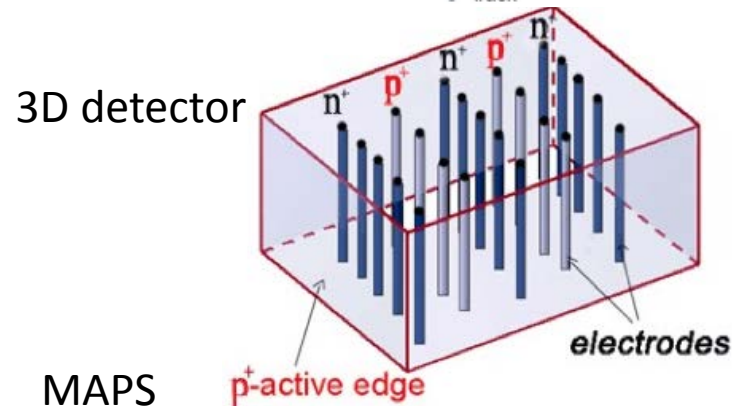
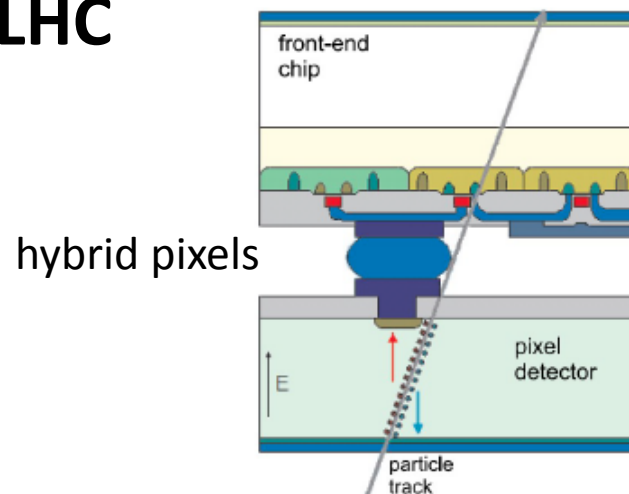


CMS



ATLAS + CMS Pixel Detectors at HL-LHC

- **extreme environment**
 - particle rates up to 1-2 GHz/cm²
 - fluence up to 2×10^{16} n_{eq}/cm²
 - Ionizing dose up to 10 MGy
- **hybrid pixels** (sensor layer + read-out layer)
- **smaller pixels** (e.g. 30μm x 100μm)
- **sensor materials under study**
 - thin planar silicon (100-200 μm)
 - 3D detectors (part of ATLAS IBL)
 - diamond
 - depleted MAPS (CMOS sensor with ~20μm depletion depth + pre-amplifier → S/N~100)
- **interconnection technologies**
 - bump-bonding (as today)
 - 3D integration
 - glue bonding?
- **front-end chip: new R&D collaboration (RD53)**
 - joint development of a pixel chip for phase II in **65nm** technology for ATLAS and CMS



ASIC technology scaling

normalized to 250 nm process

Generation [nm]	Cost / mask set	Cost / 8" wafer	Cost Proto/mm2	Density gates/[unit A]	Design Complexity	Power per gate
250	1.0	1.0	1.0	1	1	1.00
130	2.9	0.9	6.0	5	3-5	0.36
65	5.3	1.1	10.8	27	10-25	0.18
28	15.0	2.4	36.3	50	25-125	0.09

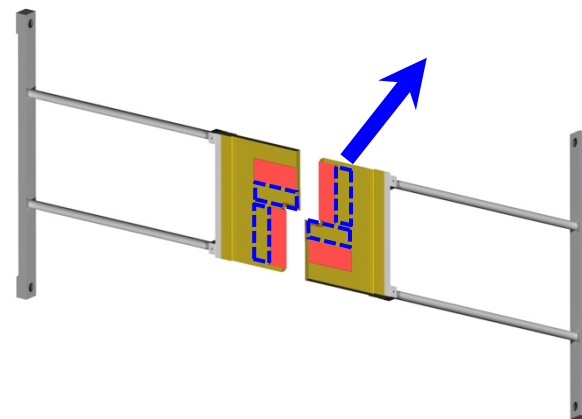
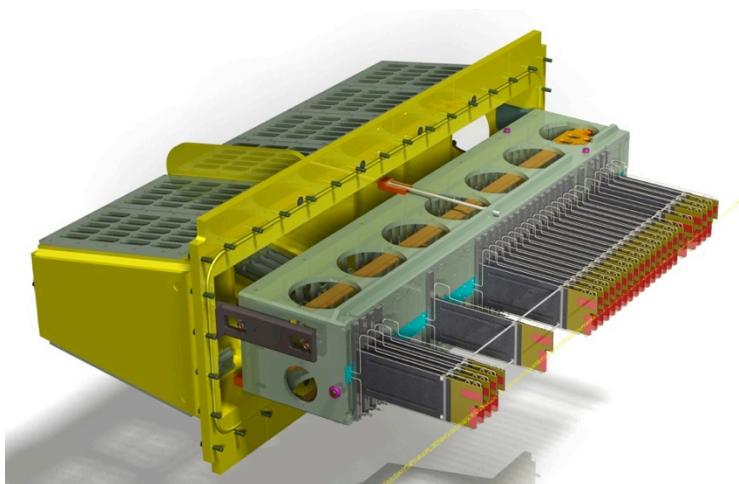
more functionality

reduced power
per transistor

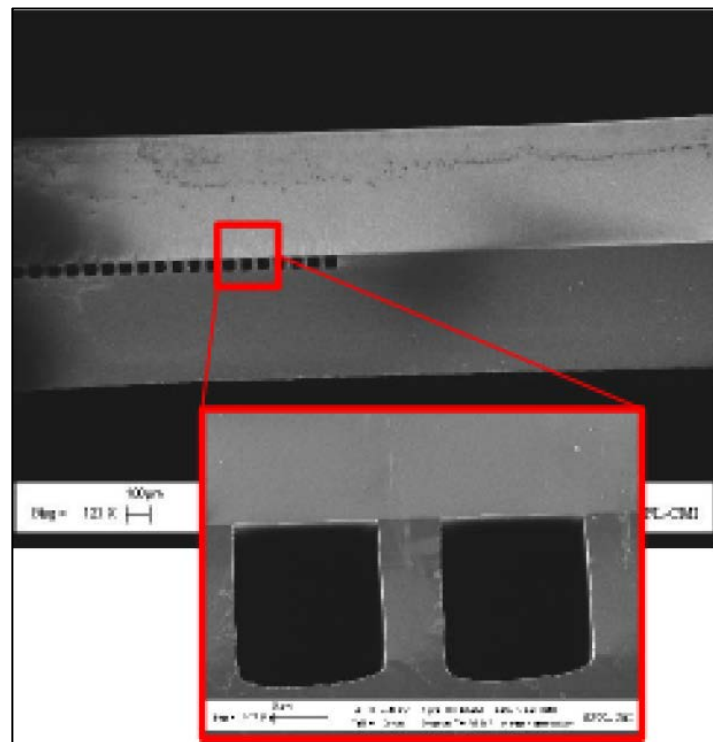
	.35 um Power	250 nm	180 nm	130 nm	65 nm	< 65 nm
Pixels (Hybrids)				✓	✓	✓
Pixels (Monolithic)			✓	✓	✓	
Si Trackers				✓	✓	
Calorimeters		✓		✓		
TPC				✓	✓	
MPGD				✓		
Links (Electrical and Optical)				✓	✓	✓
Embedded Power	✓		✓			

[Sandro Marchioro, ECFA HL-LHC Workshop Oct. 2913]

LHCb new VELO

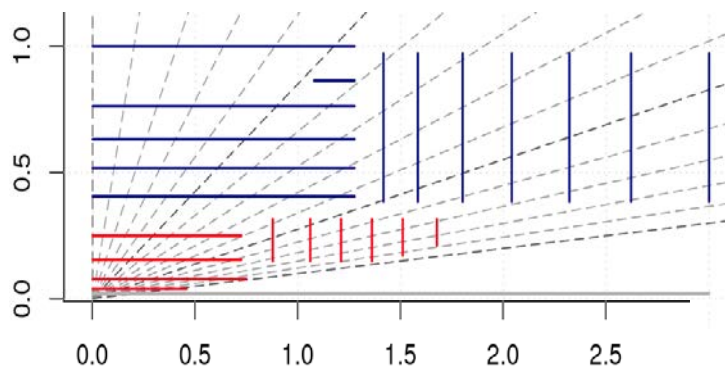


- strips \rightarrow pixels
- 8.2 mm \rightarrow 5.1 mm distance of active elements to LHC beam
- thinning of RF foil between sensors and primary LHC vacuum 300 μ m \rightarrow 150 μ m
- VeloPix ASIC (TimePix variant)
- micro-channel CO₂ cooling



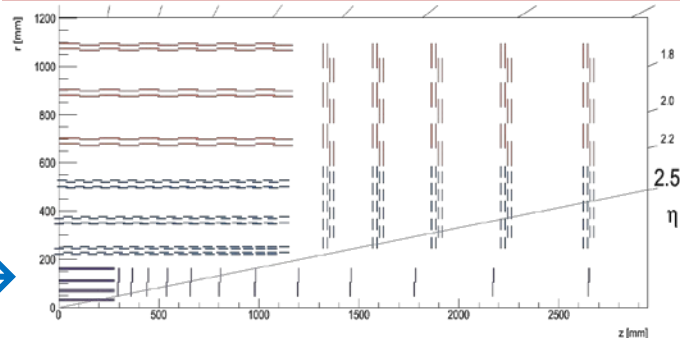
New ATLAS + CMS Trackers

ATLAS



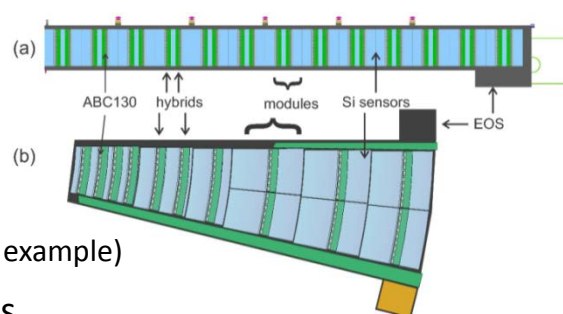
~5cm
 ← strips →
 ~2.5 cm
 ← pixels →

CMS

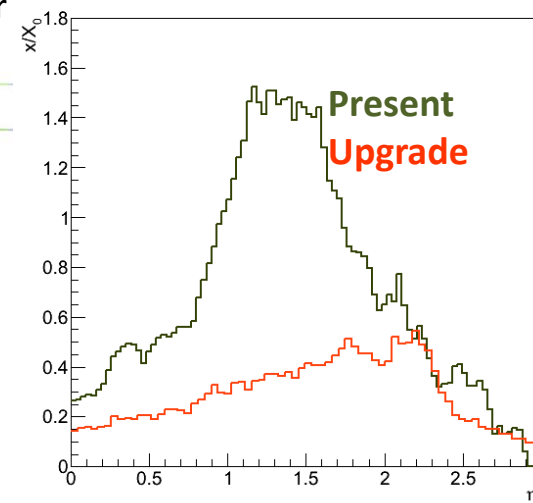


- all silicon outer trackers
- acceptance $|\eta| < 2.5$ ($|\eta| < 4$ under study in CMS)
- 5.5 / 6 barrel layers + 7 / 5 disks
- 2 sensors per module with
 - 40 mrad stereo angle (ATLAS)
 - pt logic (CMS)
- 200 m² of silicon (each)
- front-end power: 33kW → 58kW (CMS as example)
- much reduced material budget estimates
 - CO₂ cooling
 - DC-DC powering
 - lighter structures
 - relocation of services

staves and petals for ATLAS tracker



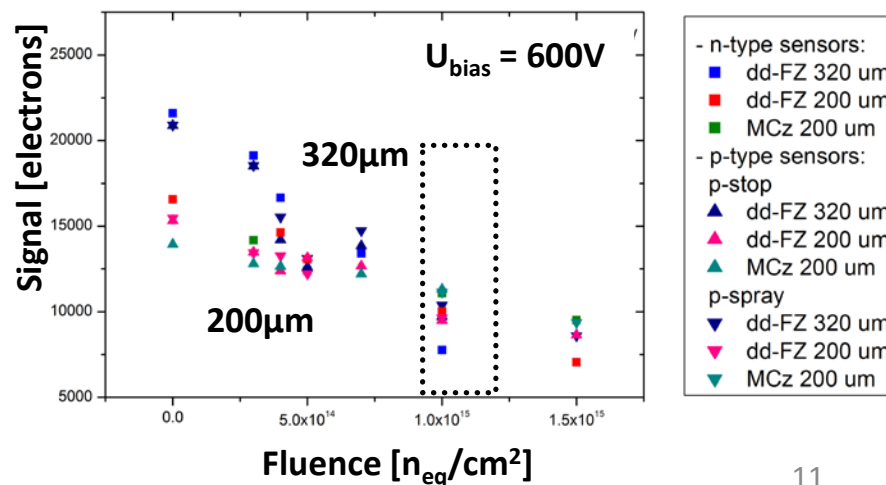
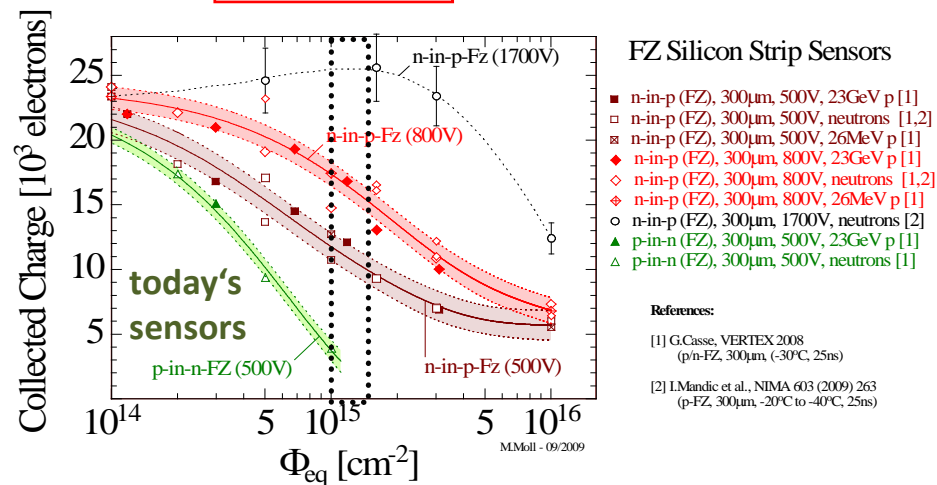
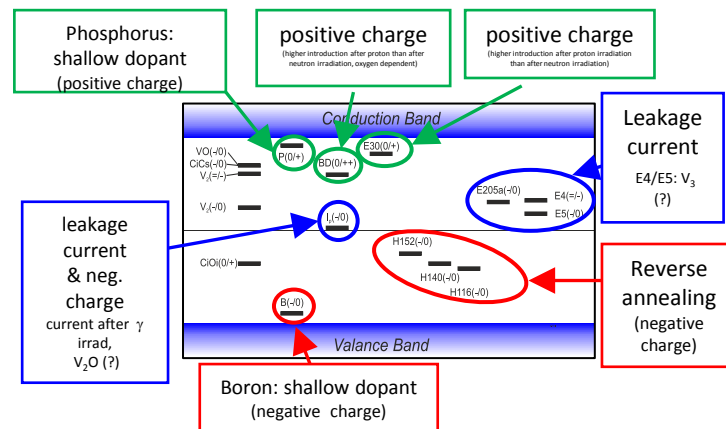
Material budget **estimate**
 (CMS outer tracker)



HGF-Alliance Project of ATLAS and CMS groups: “Enabling Technologies for Silicon Tracking detectors at HL-LHC” (PETTL)

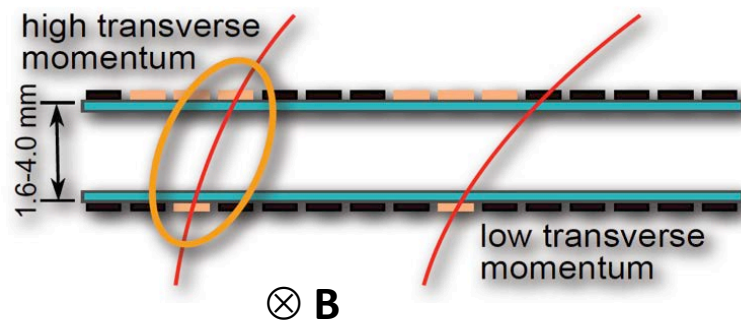
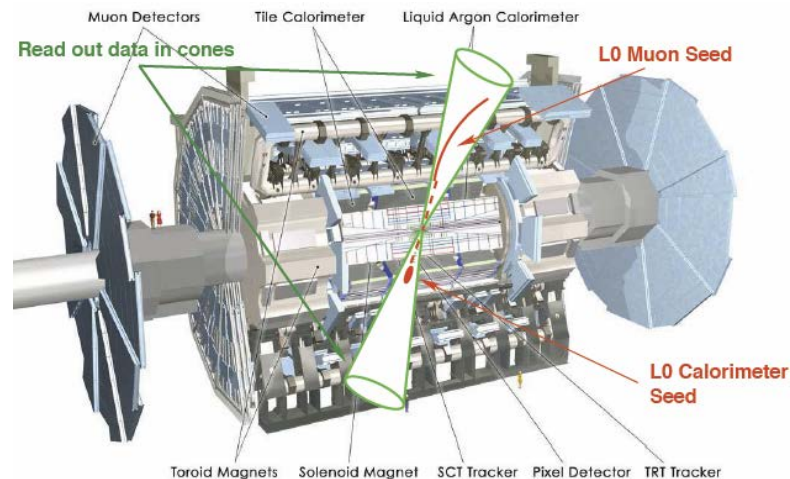
Silicon Strip Sensors

- up to around $1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ for ATLAS+CMS outer tracker
- detailed understanding of bulk defects in past years
- sensors used today would not deliver signal at the end of phase II
- beyond $10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ signal charge does not scale with the thickness
→ choose thin sensors
- design choices:
 - p-type substrates (today: n-type)
 - 200 ... 320 μm thickness
 - operation at up to 500...600V



Level 1 Track Trigger

- Benefits:
 - validate calorimeter or muon trigger objects (e.g. discriminate electrons from $\pi^0 \rightarrow \gamma\gamma$)
 - improve muon trigger pt measurement
 - check isolation of e , γ , μ or τ candidates
 - association to primary vertex
- ATLAS:
 - to be installed before Phase-II: FTK Fast Track Trigger: at L2, 25 μ s, pattern recognition with associative memories, track fitting in FPGAs
 - ‘pull architecture’
 - L0 trigger (Calo/Muon) reduces rate within $\sim 6 \mu$ s to $\gtrsim 500$ kHz and defines ‘regions of interest’ (Rois)
 - L1 track trigger extracts tracking info inside RoIs from detector FEs
- CMS:
 - ‘push architecture’ for outer tracker
 - track segment selection at front-ends based on pt measurement (at 40 MHz)
 - all tracks with $p_T > 2$ GeV
 - ~ 1 mm primary vertex resolution
 - pattern recognition and track fit at L1 in off-detector electronics (AM+FPGAs)
 - explore ‘pull architecture’ for pixel \rightarrow b tags at L1



Power

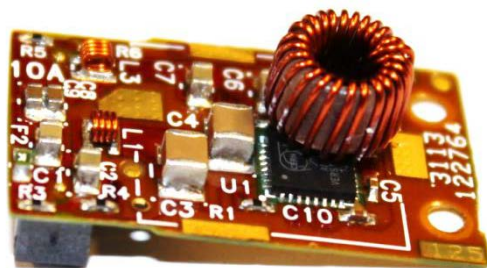
- higher channel density
- more functionality
- higher speed
- smaller chip technologies

front-ends need more power (x2)
at smaller voltages (:2)

- currents x4
- cable losses x16
- **no tracking at HL-LHC with today's powering scheme**
- new schemes also help to reduce material budget

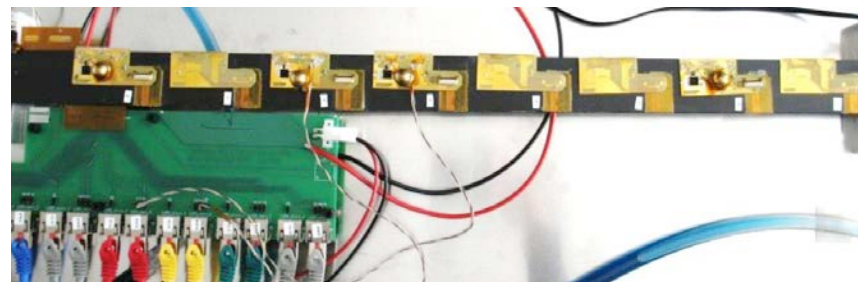
DC-DC conversion:

supply power at high voltage (~10V)



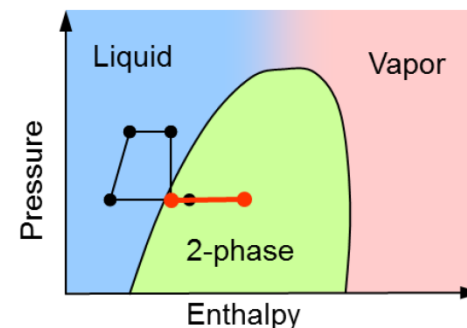
serial powering:

use same current in a chain of modules



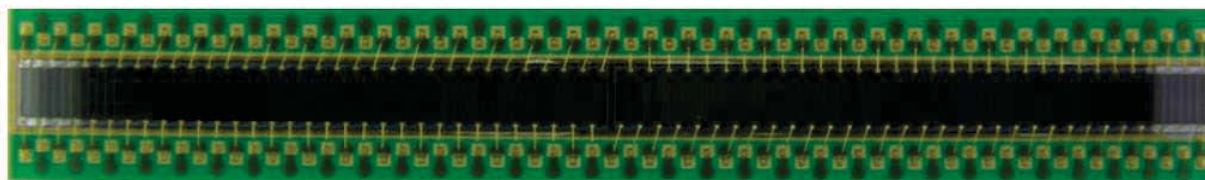
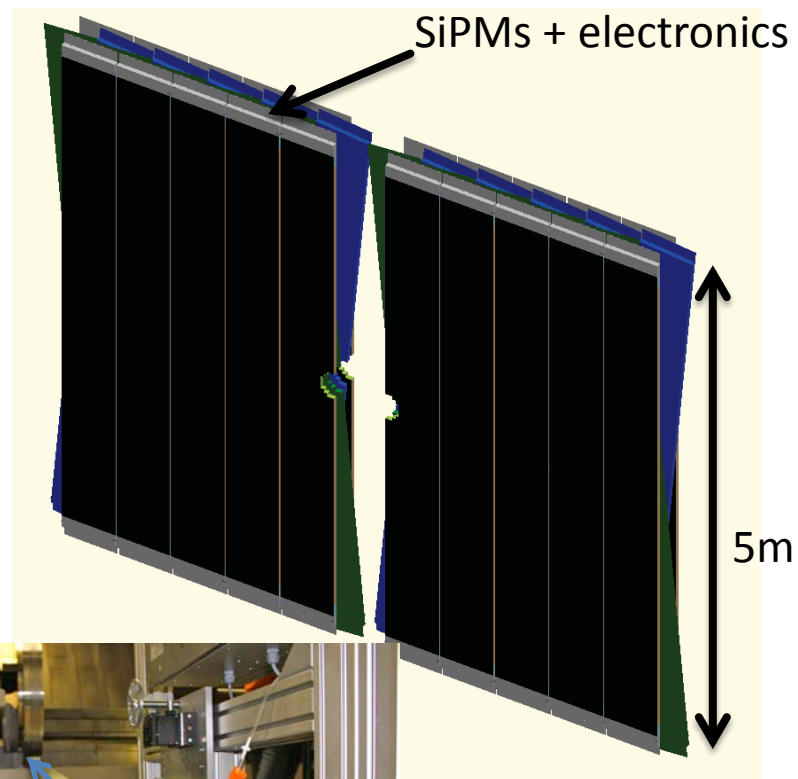
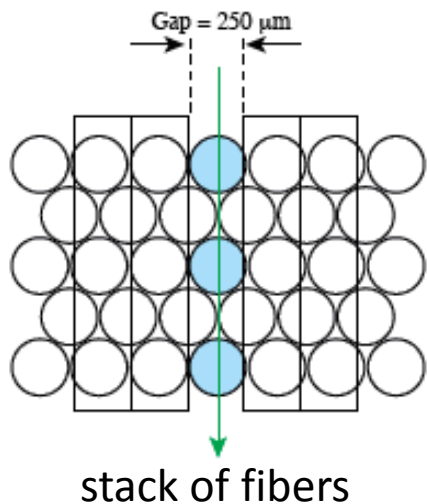
Cooling

- evaporative CO₂ cooling for all new pixel and tracking detectors
 - pioneered by LHCb Velo
 - 15...100 bar
 - 200...300 J/g instead of ~2 J/g in a mono-phase cooling system
- much thinner (~2 mm dia.) and longer pipes possible
- large material reduction



Fiber Tracker for LHCb

- scintillating fibers
+ silicon photo-multipliers (SiPMs)
- 2.5 m long fiber modules
- SiPMs and electronics at periphery
- new technology to equip large areas with fast and precise tracking detectors when particle densities are not too high



128x250 μm SiPM channels \rightarrow 50 μm resolution

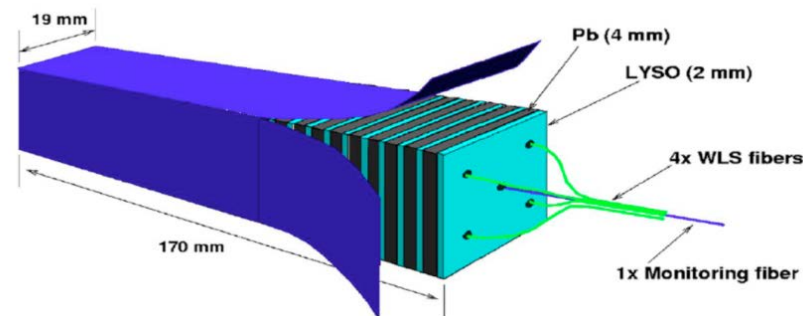
Calorimetry

ATLAS

- replace LAr + TileCal FE+BE electronics: 40 MHz digitization, inputs to L0/L1
- replace HEC cold preamps if required
- replace forward calorimeter if required

CMS

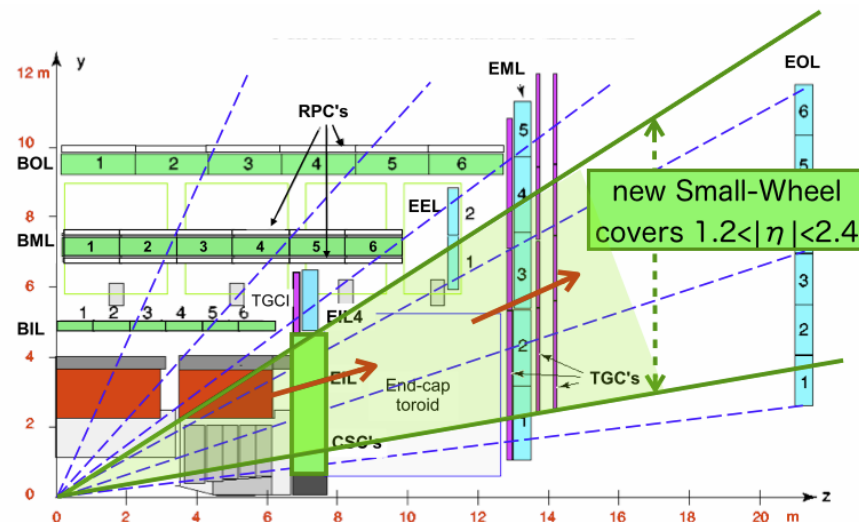
- full replacement of ECAL and HCAL end-caps
 - radiation induced loss of transparency
 - baseline: tower based sampling calorimeters
e.g. Lead-LYSO shashlik ECAL
+ HCAL with more read-out fibers
 - alternative option under study: integrated calorimeter
 - dual read-out calorimeter (scintillation + Cerenkov light (a la DREAM))
 - high granularity particle flow calorimeter (a la CALICE)
- extension of coverage from $|\eta| < 3$ to $|\eta| < 4$ is under consideration (VBF tagging)
- replace ECAL barrel electronics (crystal level granularity, 10 μ s latency, improved noise rejection)
- replace Hadron Forward calorimeter if required



Muon Systems

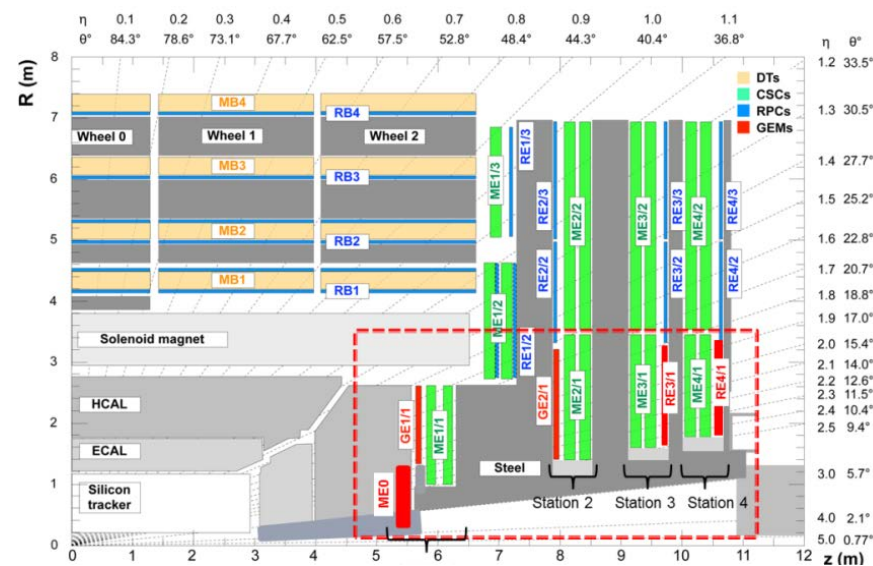
ATLAS

- detector chambers will work at HL-LHC
- upgrade FE electronics
 - accommodate L0/L1 trigger scheme
- improve L1 pt resolution
 - using MDT information seeded by RPC/TGC ROI



CMS

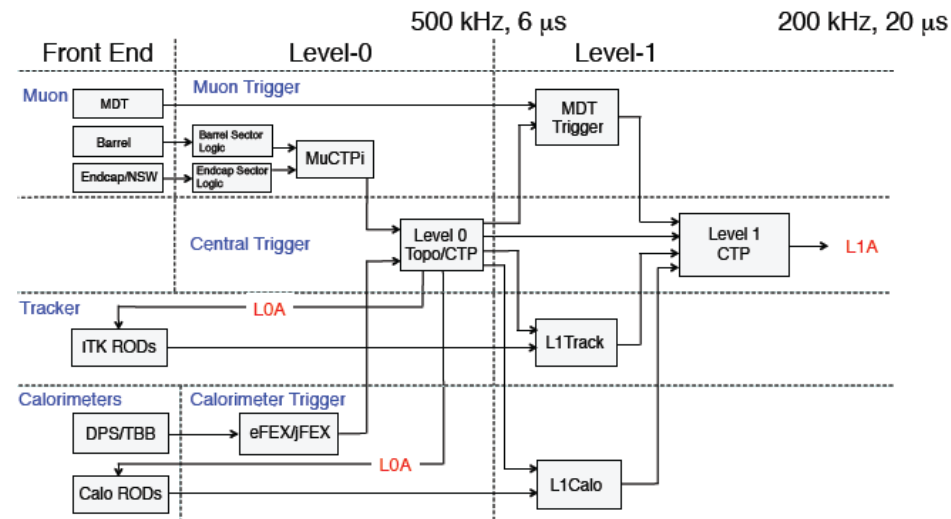
- detector chambers will work at HL-LHC
- completion with higher resolution muon stations at $1.6 < |\eta| < 2.4$ under study
 - GEMs and Glass-RPC
- investigating coverage beyond $|\eta| < 2.4$
 - GEM tagging station (ME0) coupled with extended pixel tracking
- replace electronics of DT 'minicrates' for radiation tolerance and higher trigger rates



Trigger

ATLAS

- already before phase II:
 - L1 Topological Trigger
 - High precision calorimeter L1 trigger
 - Fast tracking at L2
- split L1 into
 - L0: muon + calorimeters
 - up to 500kHz, $\sim 6\mu\text{s}$ latency
 - L1: muon + calorimeters + **track trigger**
 - up to 200kHz, $\sim 6+14\mu\text{s}$ latency
- HLT accept up to 5-10 kHz

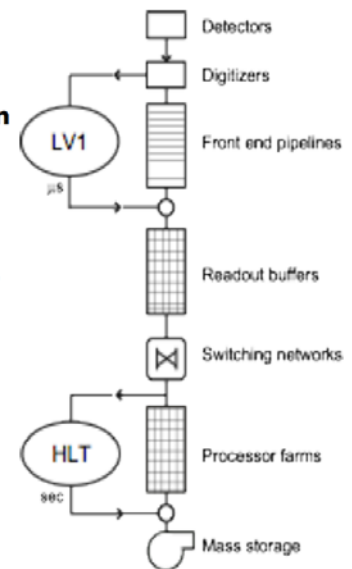


CMS

- increasing latency from $3.2\mu\text{s}$ to $10\mu\text{s}$ will allow integrating tracking into all trigger objects at L1
 - requires replacement of ECAL barrel electronics (+ pixel, tracker, ECAL end-cap rebuilt anyway)
- increase L1 accept rate from 100 kHz up to 1 MHz
- L1 tracking trigger
- new (finer segmented) L1 calorimeter, muon, global triggers
- HLT output rate of 10 kHz
 - maintain present HLT rejection factor

40 MHz CLOCK driven
Synchronous control loop

1 MHz EVENT driven
Asynchronous control loop



7th Annual Workshop

2-4 December 2013
Karlsruhe

Topics:

- Electroweak Phenomena and QCD
- Heavy Flavour Physics
- Searches for Higgs and Phenomena beyond the Standard Model
- Detector Technologies

Session on LHC Phase II Upgrade Plans in Germany at Alliance Workshop

Tuesday 03 December 2013

14:00 - 18:00	Detector Project: LHC Phase II Upgrade Plans in Germany Convener: Lutz Feld (RWTH Aachen)
14:00	Introduction 15' Speaker: Lutz Feld (RWTH Aachen)
14:20	ATLAS Pixel System 15' Speaker: Fabian Hügging (Universität Bonn)
14:40	CMS Pixel System 15' Speakers: Erika Garutti (University of Hamburg) , Erika Garutti (DESY)
15:00	ATLAS Tracking System 15' Speaker: Ulrich Parzefall (Uni Freiburg)
15:20	CMS Tracking System 15' Speaker: Alexander Dierlamm (Karlsruher Institut für Technologie)
15:40	Coffee Break 30'
16:10	ATLAS Calorimetry 15' Speaker: Olga Novgorodova (DESY)
16:30	ATLAS Muon System 15' Speaker: Oliver Kortner (Max-Planck-Institut für Physik)
16:50	CMS Muon System 15' Speaker: kerstin Hoepfner (RWTH Aachen)
17:30	LHCb 25'

Summary

- **phase II detector upgrades are essential to take full benefit of LHC luminosity upgrade**
- **challenging program, including lots of new technologies**
- **German groups are active in many of the key areas**
- **if you are looking for a great detector project: now is the time to join!**