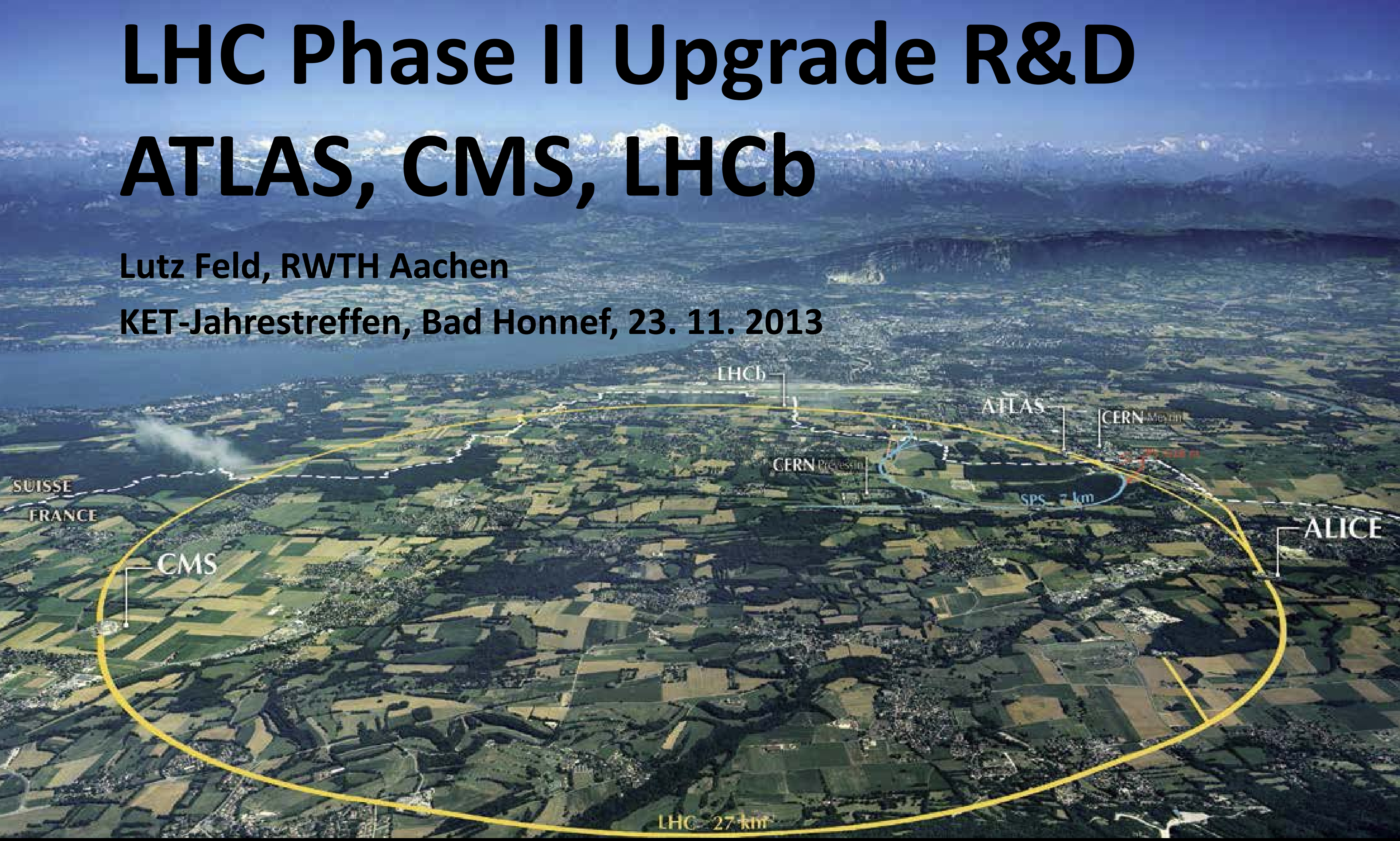
LHC Phase II Upgrade R&D
ATLAS, CMS, LHCb

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

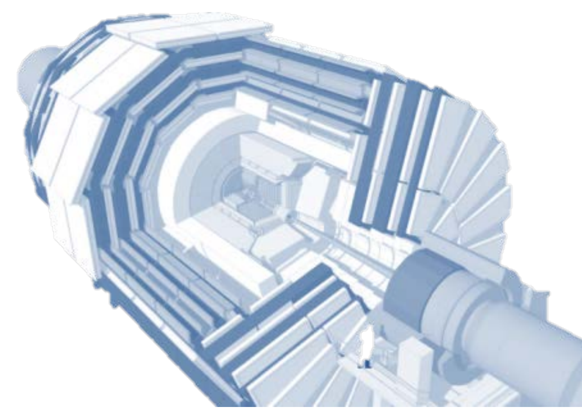
- from LHC design to ultimate performance
  - **luminosity** **$1x10^{34}$**$cm^{-2}s^{-1}$ → **$5x10^{34}$**$cm^{-2}s^{-1}$ leveled (**ATLAS + CMS**),
    $4x10^{32}$ $cm^{-2}s^{-1}$ → **$2x10^{33}$**$cm^{-2}s^{-1}$ (**LHCb**)
  - **integrated luminosity 300**/fb → **3000**/fb (**ATLAS + CMS**), **5**/fb→ **50**/fb (**LHCb**)

  → **new and more precise measurements, extended reach for discoveries**
  IF detector performance can be preserved / improved

x5

x10

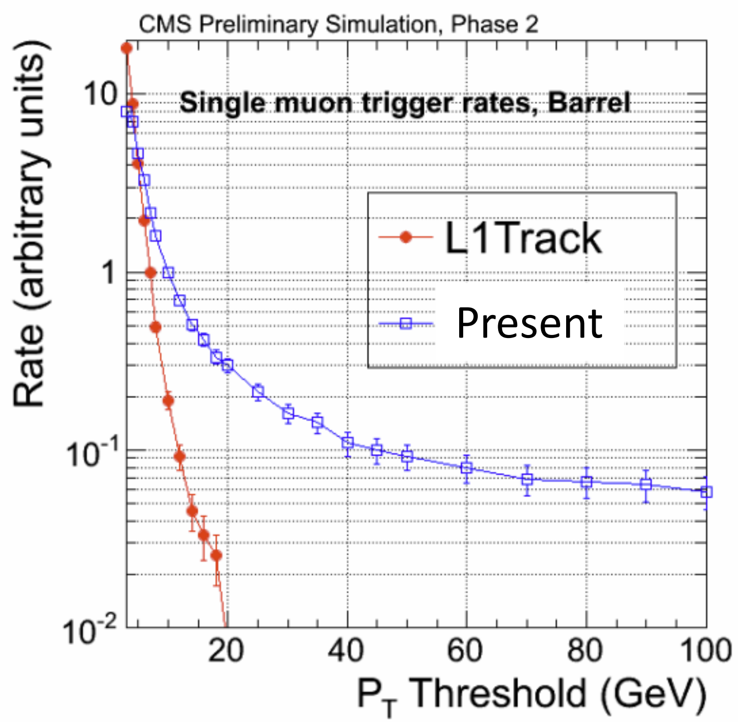
- the price to pay:
  - pile-up 20 → 140-200 (ATLAS+CMS), 2 → 5 (LHCb)
  - particle densities x5-10
  - radiation damage x10
- the casualties (radiation damage and/or performance loss)
  - pixel
  - tracker
  - trigger
  - end-cap calorimetry, electronics
  - end-cap muon system, electronics
- the brave (in general)
  - calorimetry
  - muon system

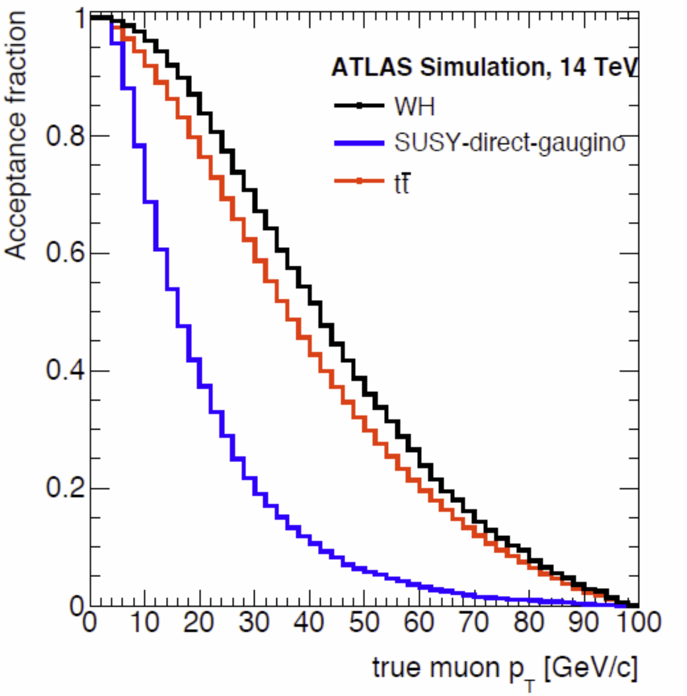


- when?
  - installation mainly in 'long shut down 3' currently foreseen 2022-2023 (ATLAS+CMS)
    partly already in 'long shutdown 2' currently foreseen 2018 (LHCb)
  - **R&D NOW**

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 pt measurement at trigger level
→ large rate reduction

simply increasing trigger thresholds would kill the signal

General Survival & Improvement Concepts

- finer granularity → more channels
- higher band-width (analogue→digital links)
- improve resolution, at trigger level
- provide tracking information to L1 trigger
- more radiation hard detection elements
- ASIC technology scaling 250nm → 130 nm → 65 nm
- improved powering and cooling
- reduced material budget

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 Replace Electronics AC	Replace Electronics
Trigger	Upgrade HD, MZ DESY, HD	Upgrade	Trigger-less

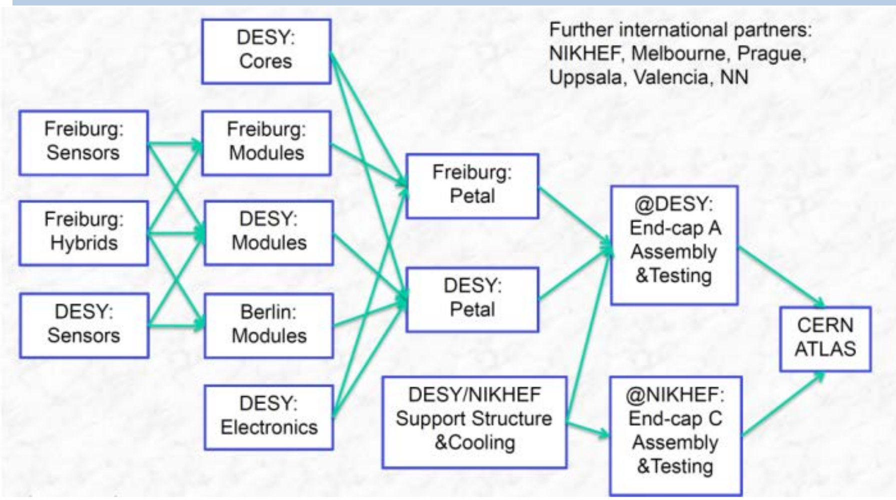
German groups are active in many of the key areas!

Cost (ATLAS,CMS; roughly):
- 50% Pixel+Tracker
- 20% Calorimeters
- 10% Muon Syst.
- 10% Trigger/DAQ
- 10% Common Fund

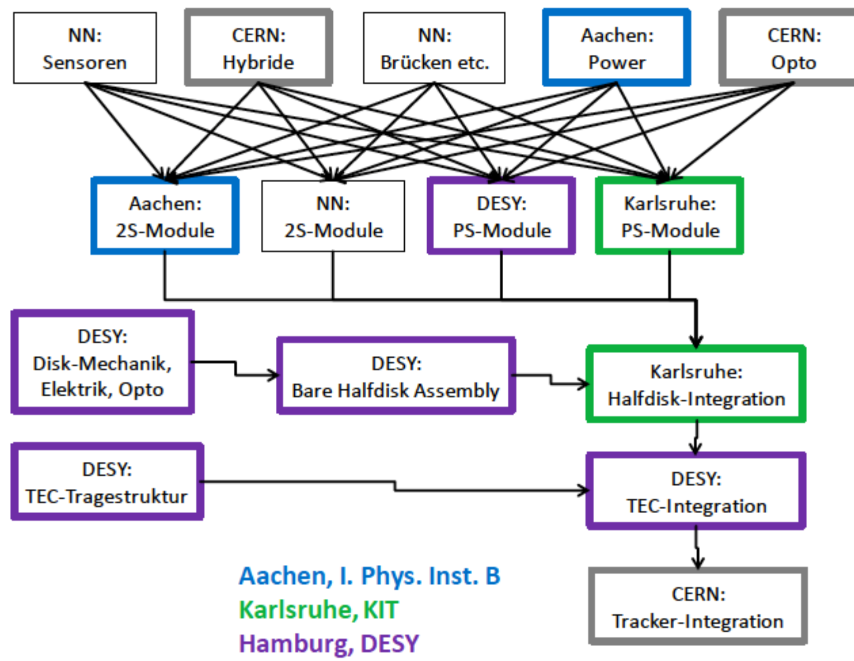
Upgrades are a joint effort of Universities, DESY, KIT and MPI

An example: Tracker End-Cap Construction

ATLAS



CMS



ATLAS + CMS Pixel Detectors at HL-LHC

- **extreme environment**
  - particle rates up to 1-2 GHz/cm^2
  - fluence up to 2×10^{16} n_{eq}/cm^2
  - Ionizing dose up to 10 MGy

→ **hybrid pixels** (sensor layer + read-out layer)

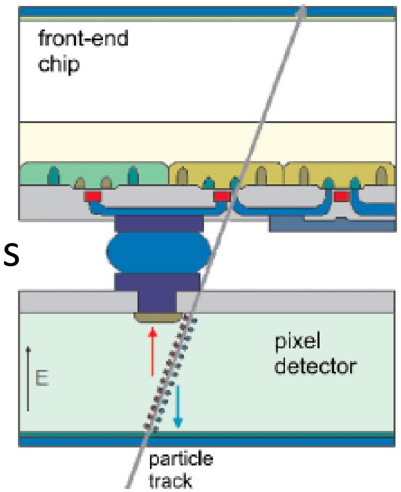
→ **smaller pixels** (e.g. 30µm x 100µm)

- **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)

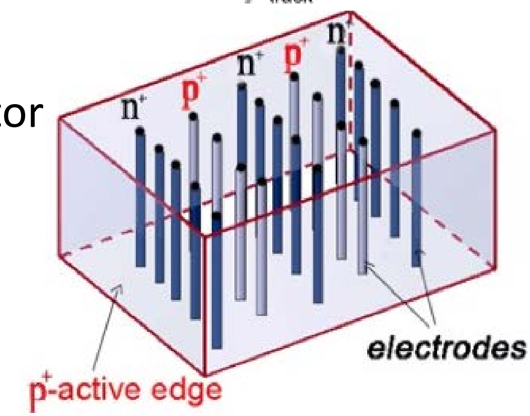
- **interconnection technologies**
  - bump-bonding (as today)
  - 3D integration
  - glue bonding?

- **front-end chip:** new R&D collaboration (**RD53**)
  - joint development of a pixel chip for phase II in **65nm** technology for ATLAS and CMS

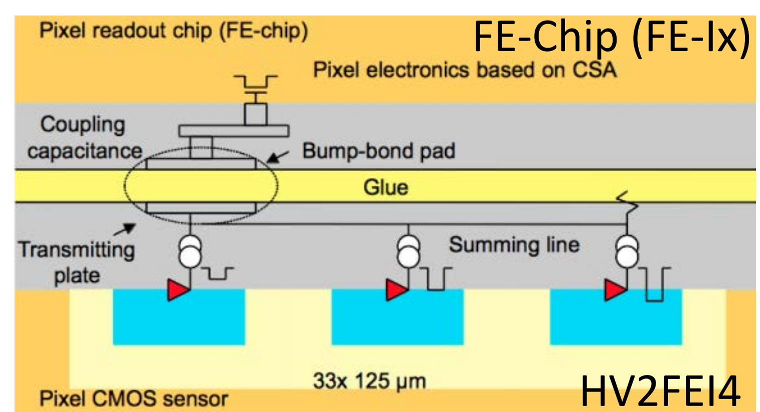
hybrid pixels



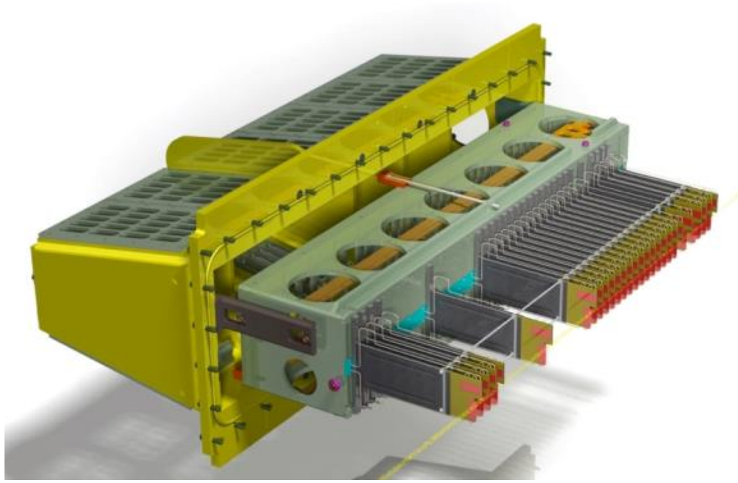
3D detector

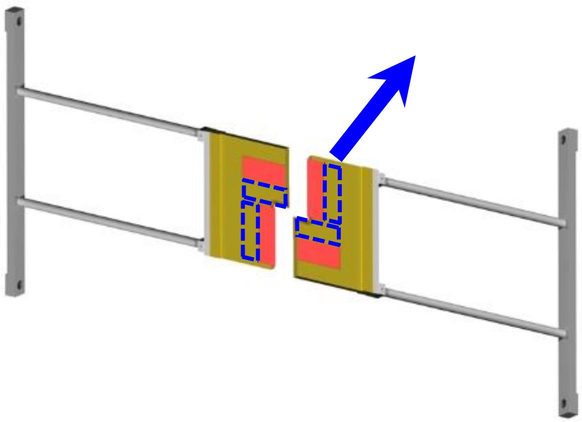


MAPS

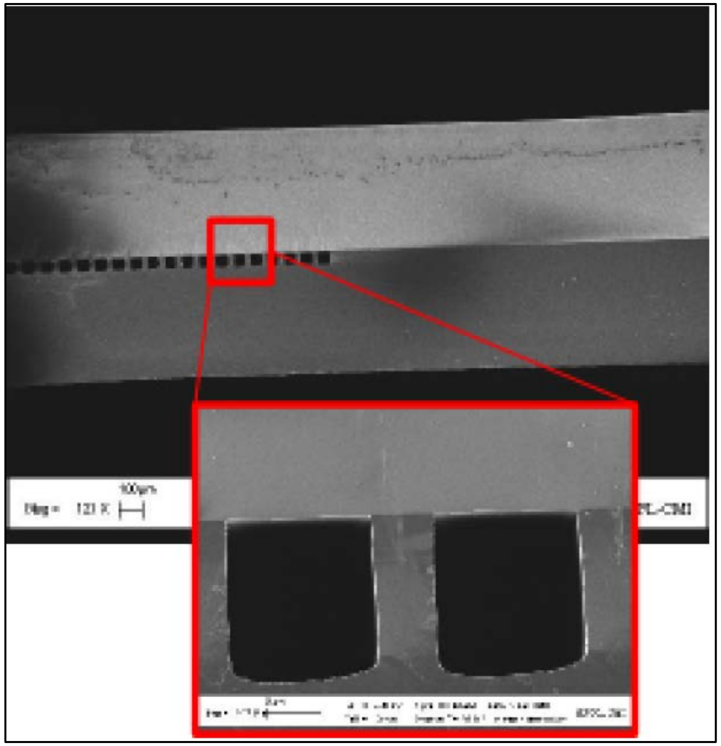


LHCb new VELO



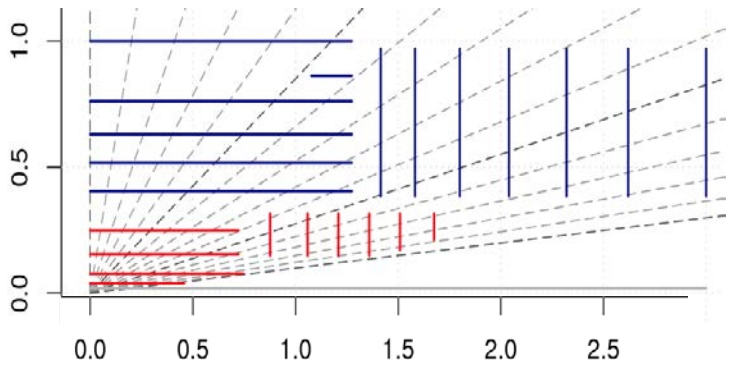


- strips → pixels
- 8.2 mm → 5.1 mm distance of active elements to LHC beam
- thinning of RF foil between sensors and primary LHC vacuum 300µm → 150µm
- VeloPix ASIC (TimePix variant)
- micro-channel CO_2 cooling



New ATLAS + CMS Trackers

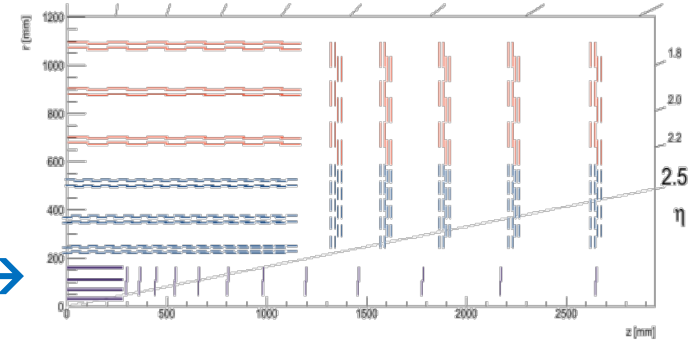
ATLAS



~5cm
← strips →
~2.5 cm

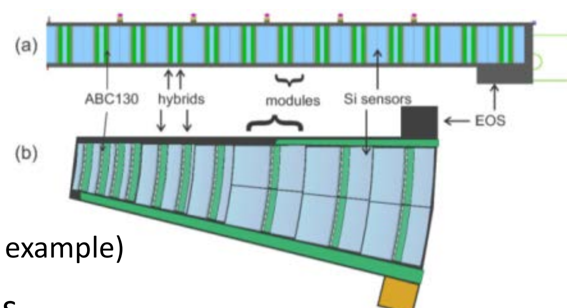
← pixels →

CMS

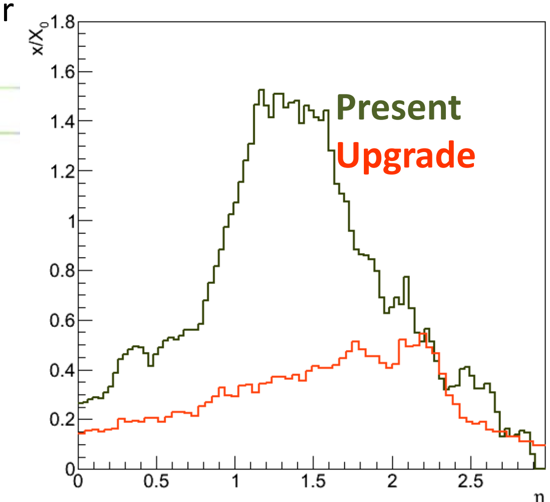


- all silicon outer trackers
- acceptance |η|<2.5 (|η|<4 under study in CMS)
- 5.5 / 6 barrel layers + 7 / 5 disks
- 2 sensors per module with
  - 40 mrad stereo angle (ATLAS)
  - pt logic (CMS)
- 200 m² of silicon (each)
- front-end power: 33kW → 58kW (CMS as example)
- much reduced material budget estimates
  - CO_2 cooling
  - DC-DC powering
  - lighter structures
  - relocation of services

staves and petals for ATLAS tracker



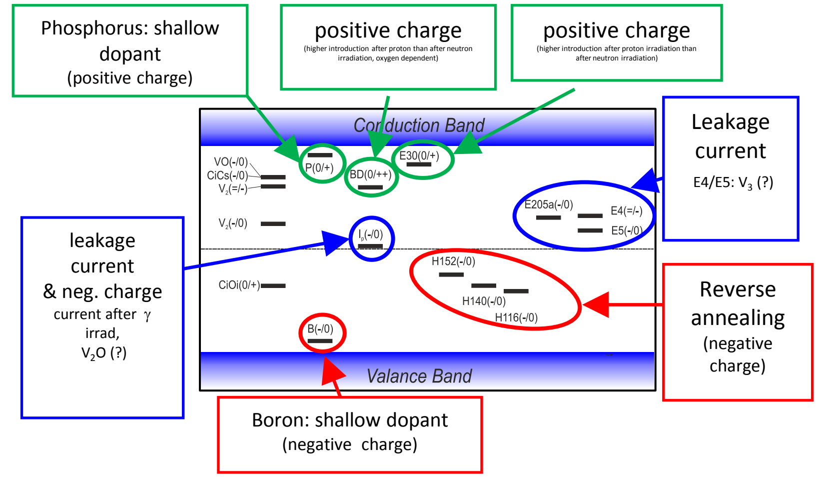
Material budget **estimate** (CMS outer tracker)

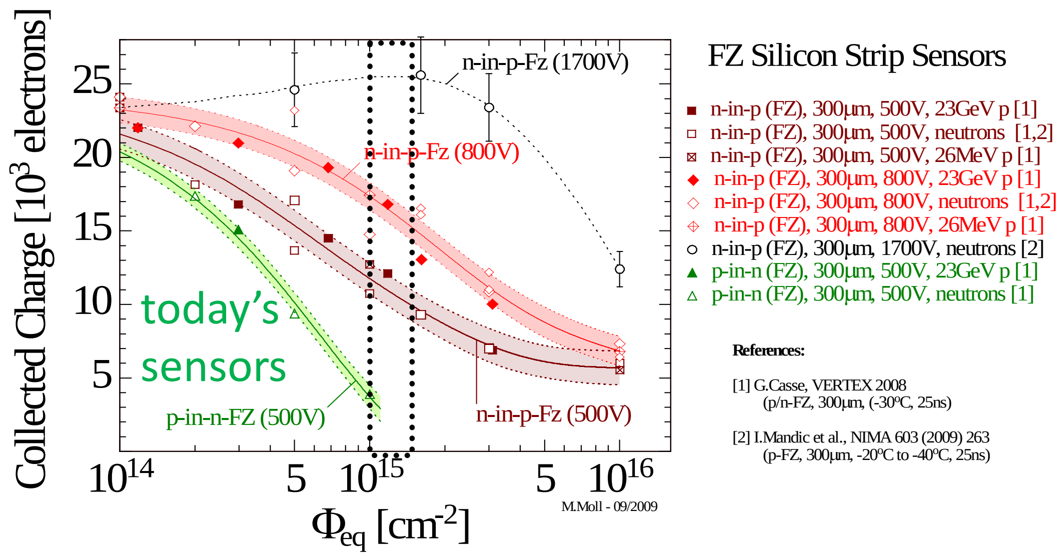


HGF-Alliance Project of ATLAS and CMS groups:"Enabling Technologies for Silicon Tracking detectors at HL-LHC" (PETTL)

Silicon Strip Sensors

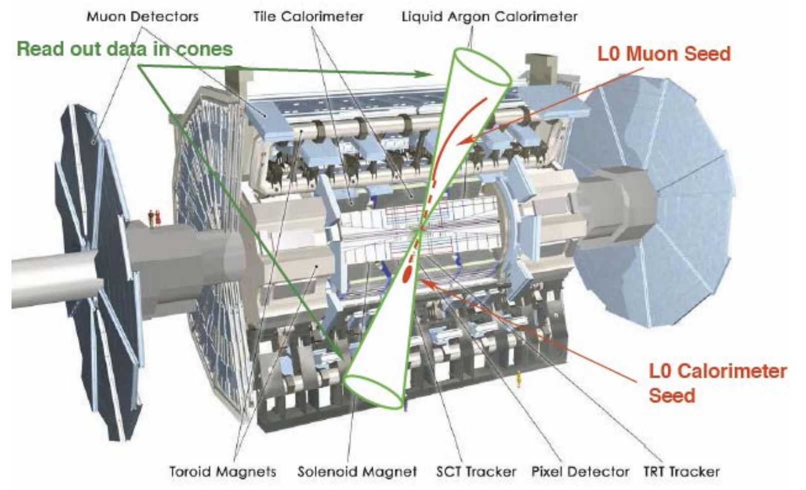
- up to around **1 x 10^{15}** n_{eq}/cm^2 for ATLAS+CMS outer tracker
- detailed understanding of bulk defects in past years
- sensors used today would not deliver signal at the end of phase II
- design choices:
  - p-type substrates (today: n-type)
  - 200 … 320 µm thickness
  - operation at up to 500…600V





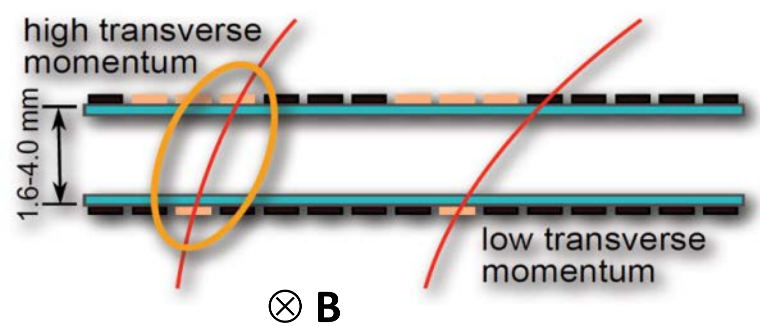
Level 1 Track Trigger

- 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, 25µs
  - '**pull** architecture'
    - L0 trigger (Calo/Muon) reduces rate within ~6 µs to ≳ 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
  - explore 'pull architecture' for pixel → b tags at L1

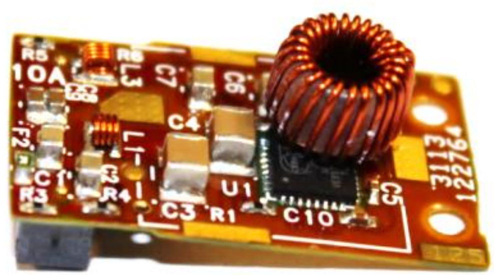


Power

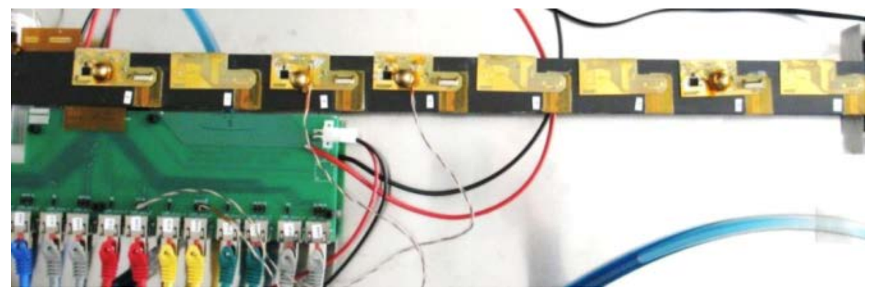
- higher channel density
- more functionality
- higher speed
- smaller chip technologies

→ **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)



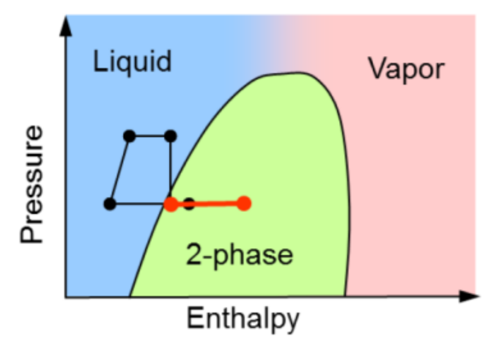
serial powering:
use same current in a chain of modules



Cooling

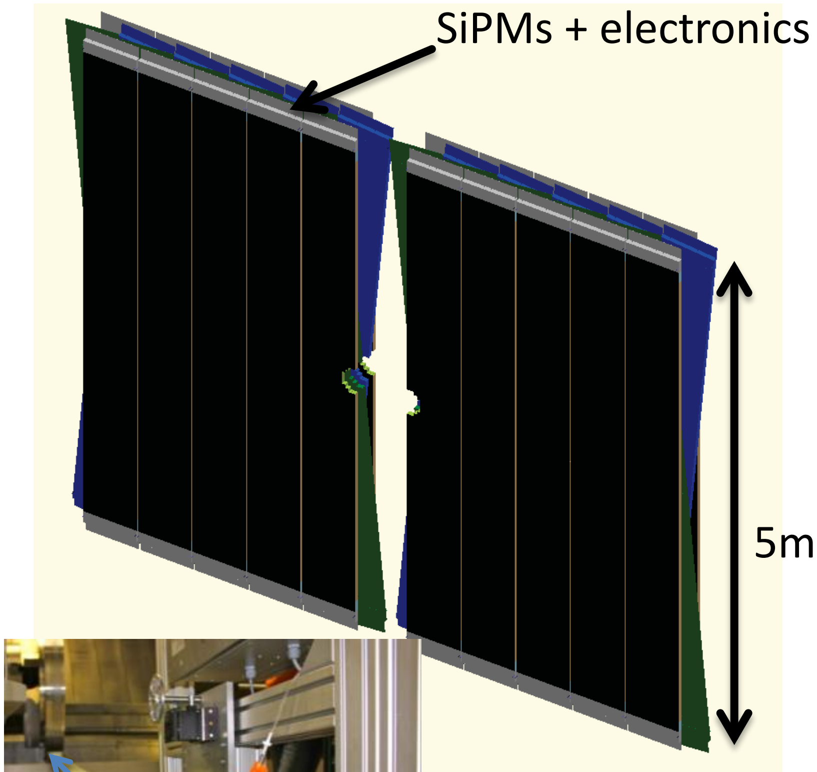
- evaporative CO_2 cooling for all new pixel and tracking detectors
- pioneered by LHCb Velo
- 15…100 bar
- 200…300 J/g instead of ~2 J/g in a mono-phase cooling system

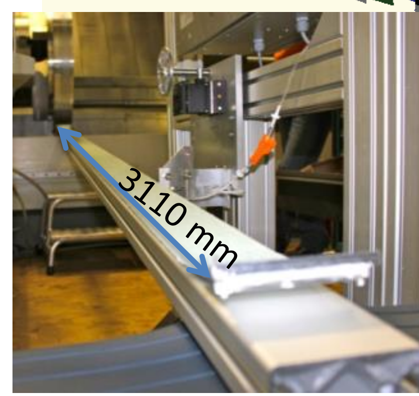
→ much thinner (~2 mm dia.) and longer pipes possible
→ large material reduction

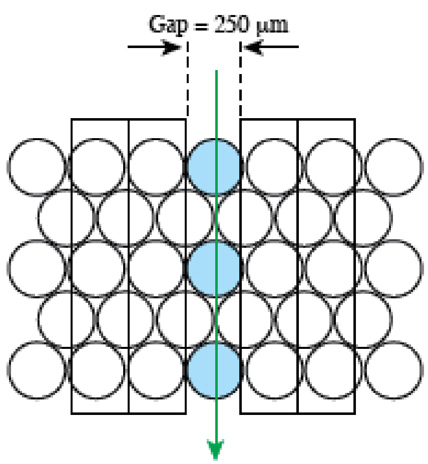


Fiber Tracker for LHCb

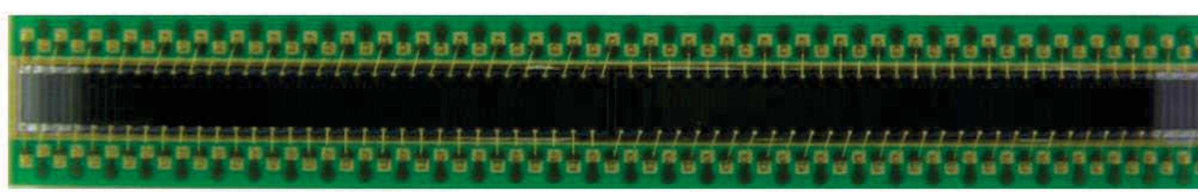
- scintillating fibers
  + silicon photo-multipliers (SiPMs)
- 2.5 m long fiber modules
- SiPMs and electronics at periphery
- new technology to equip large areas with fast and precise tracking detectors when particle densities are not too high







stack of fibers



128x250μm SiPM channels → 50 μm resolution

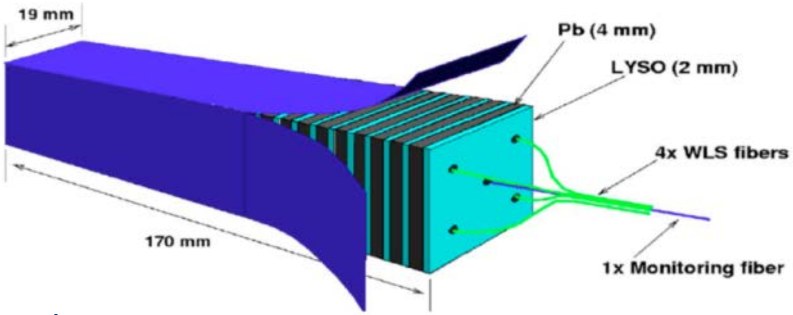
Calorimetry

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)

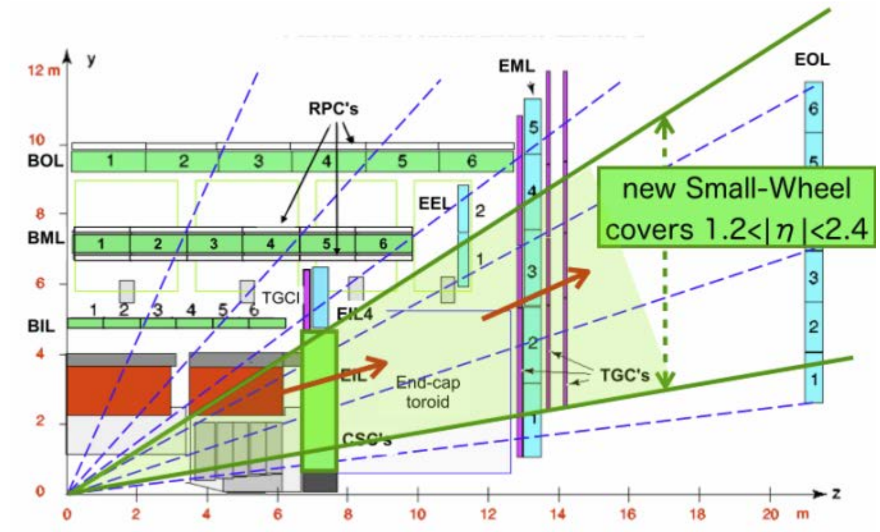


- extension of coverage from $|\eta|<3$ to $|\eta|<4$ is under consideration (VBF tagging)
- replace ECAL barrel electronics (crystal level granularity, 10µs latency, improved noise rejection)
- replace Hadron Forward calorimeter if required

Muon Systems

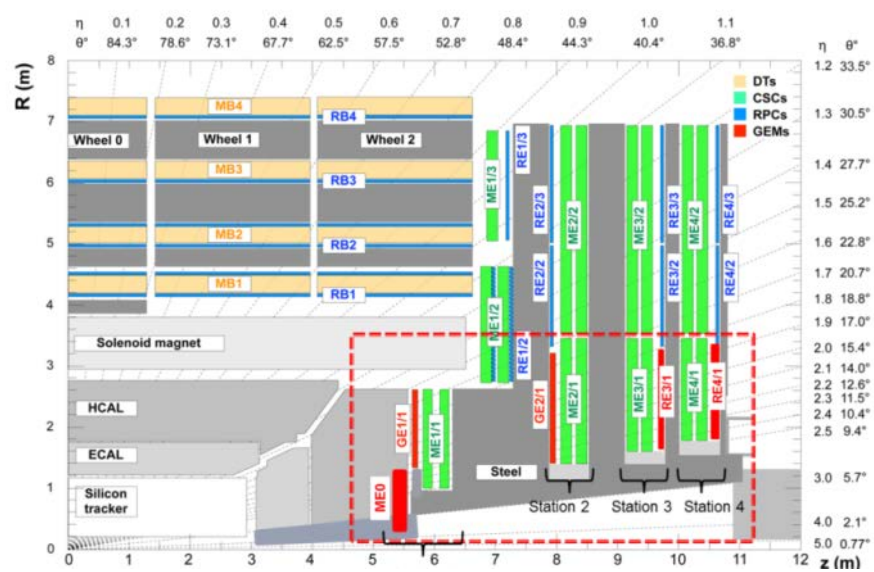
ATLAS

- 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

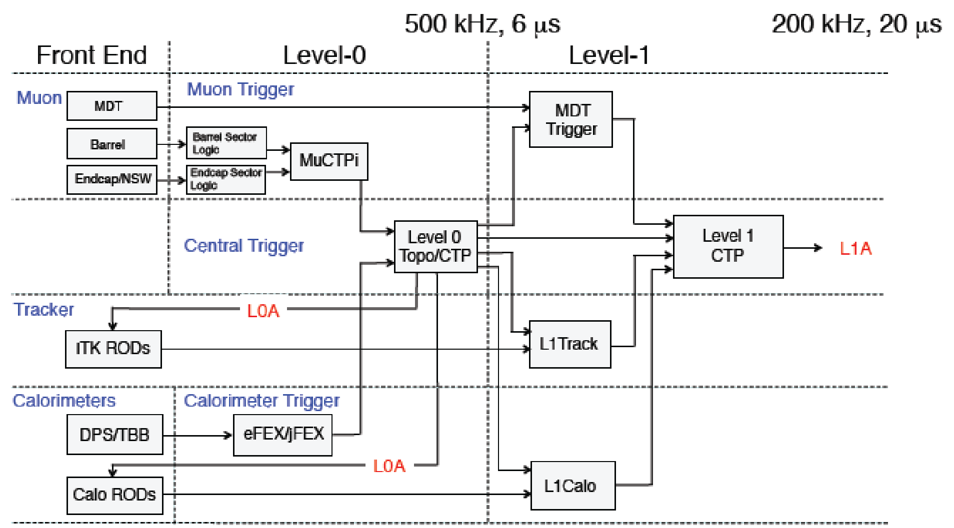
- detector chambers will work at HL-LHC
- completion with higher resolution muon stations at 1.6 <|η|<2.4 under study
  - GEMs and Glass-RPC
- investigating coverage beyond |η|<2.4
  - GEM tagging station (ME0) coupled with extended pixel tracking
- replace electronics of DT 'minicrates' for radiation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



Trigger

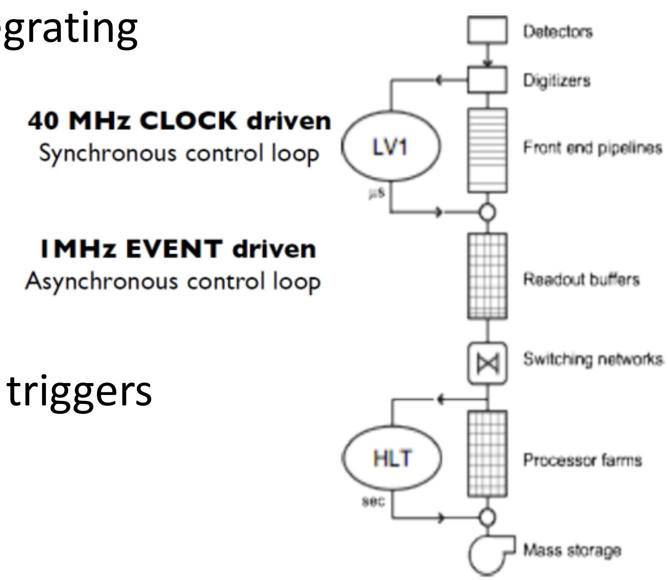
ATLAS

- 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, ~6μs latency
  - L1: muon + calorimeters **+ track trigger**
    - up to 200kHz, ~6+14μs latency
- HLT accept up to 5-10 kHz



CMS

- increasing latency from 3.2 μs to 10μs 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



Helmholtz Alliance

PHYSICS AT THE TERASCALE

Deutsches Elektronen-Synchrotron DESY +++ Karlsruher Institut für Technologie - Großforschungsbereich +++ Max-Planck-Institut für Physik München +++ Rheinisch-Westfälische Technische Hochschule Aachen +++ Humboldt-Universität zu Berlin +++ Rheinische Friedrich-Wilhelms-Universität Bonn +++ Technische Universität Dortmund +++ Technische Universität Dresden +++ Albert-Ludwigs-Universität Freiburg +++ Justus-Liebig-Universität Gießen +++ Georg-August-Universität Göttingen +++ Universität Hamburg +++ Ruprecht-Karls-Universität Heidelberg +++ Karlsruher Institut für Technologie - Universitätsbereich +++ Johannes Gutenberg-Universität Mainz +++ Ludwig-Maximilians-Universität München +++ Universität Regensburg +++ Universität Rostock +++ Universität Siegen +++ Julius-Maximilians-Universität Würzburg +++ Bergische Universität Wuppertal +++

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

Tuesday 03 December 2013

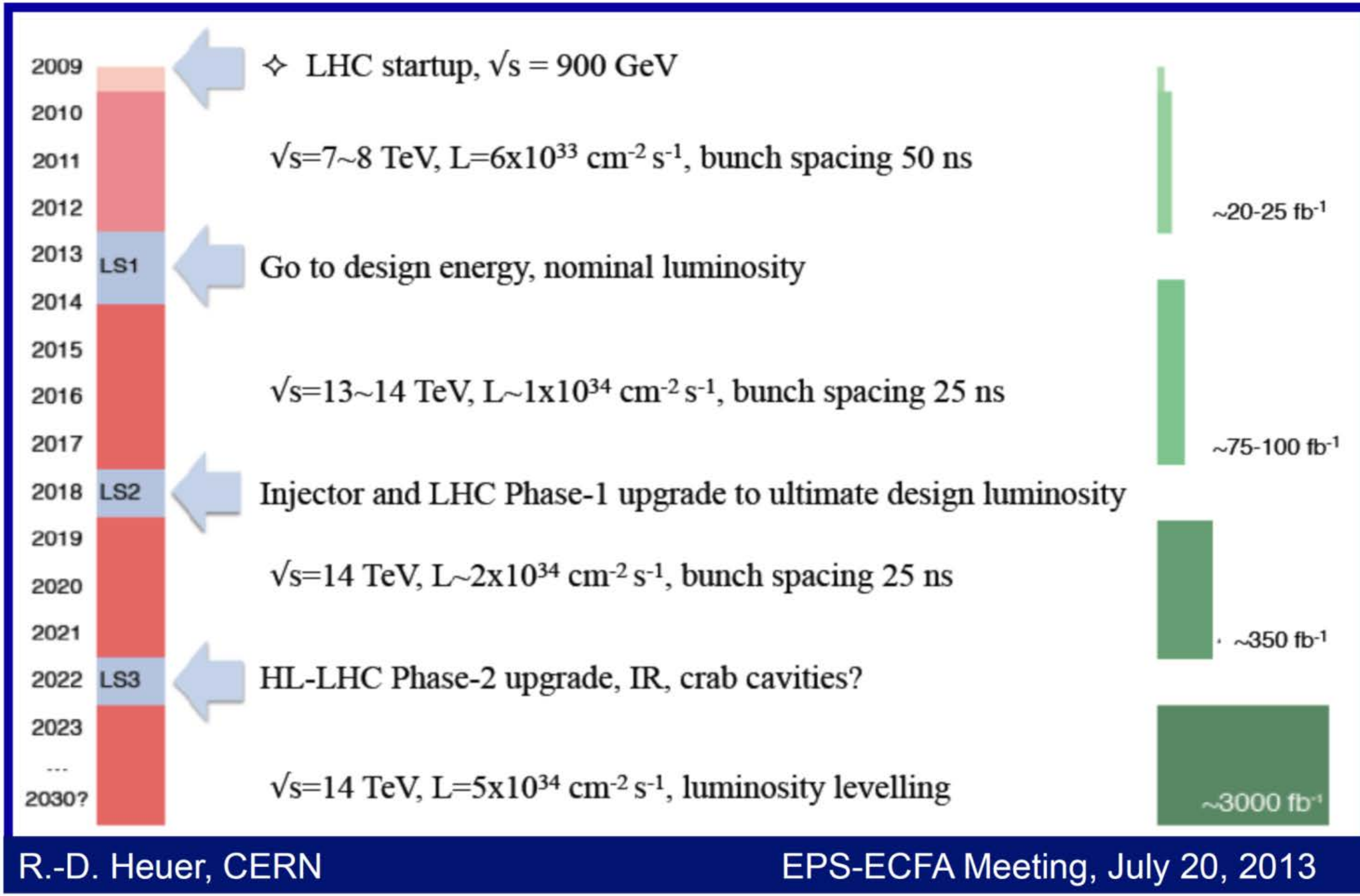
14:00 - 18:00 Detector Project: LHC Phase II Upgrade Plans in Germany

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!


2009
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2015
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2017
2018
2019
2020
2021
2022
2023
...
2030?
LS1
LS2
LS3
✧ LHC startup, √s = 900 GeV
√s=7~8 TeV, L=6x10^33 cm^-2 s^-1, bunch spacing 50 ns
Go to design energy, nominal luminosity
√s=13~14 TeV, L~1x10^34 cm^-2 s^-1, bunch spacing 25 ns
Injector and LHC Phase-1 upgrade to ultimate design luminosity
√s=14 TeV, L~2x10^34 cm^-2 s^-1, bunch spacing 25 ns
HL-LHC Phase-2 upgrade, IR, crab cavities?
√s=14 TeV, L=5x10^34 cm^-2 s^-1, luminosity levelling
~20-25 fb^-1
~75-100 fb^-1
~350 fb^-1
~3000 fb^-1
R.-D. Heuer, CERN
EPS-ECFA Meeting, July 20, 2013

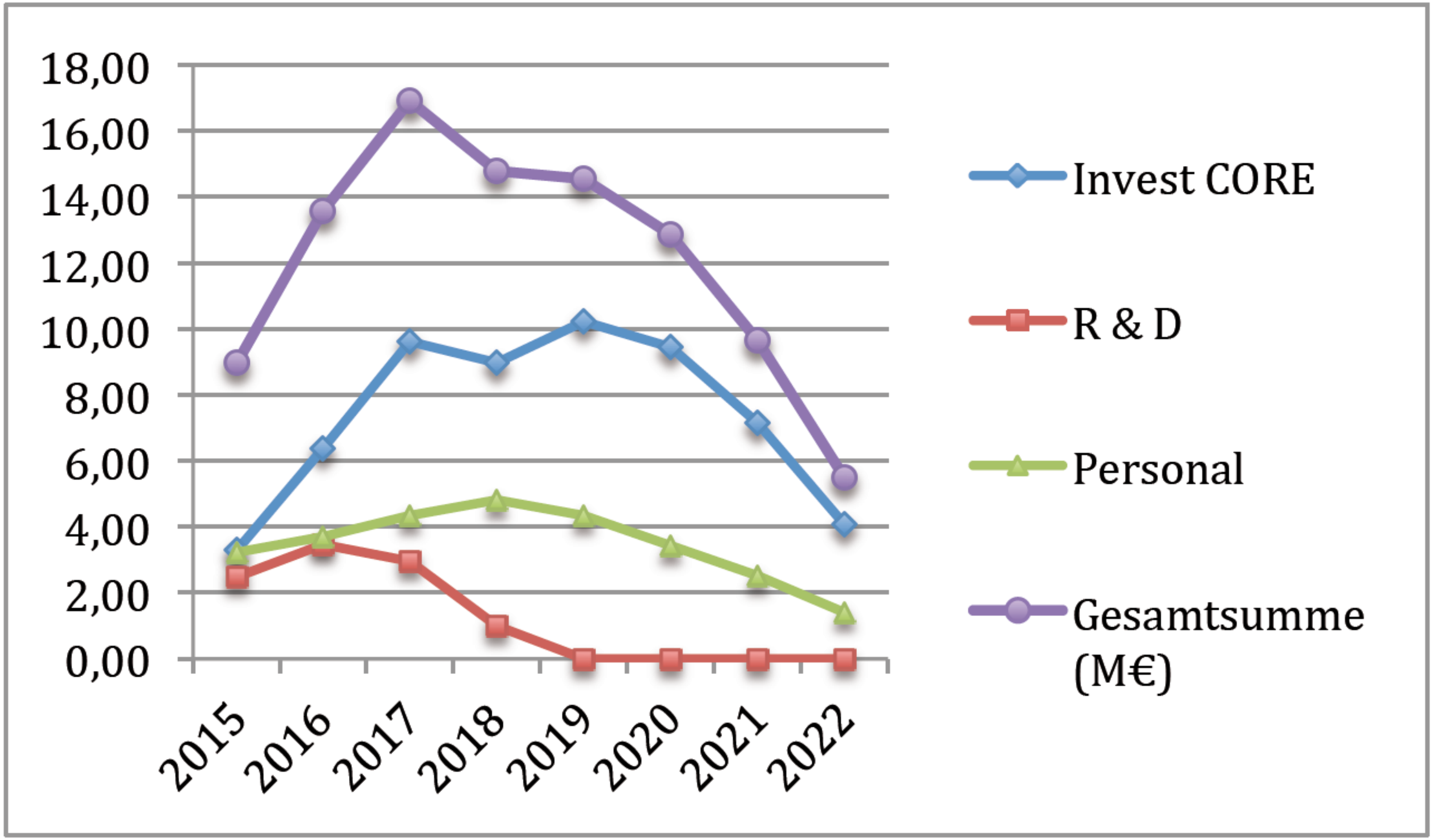
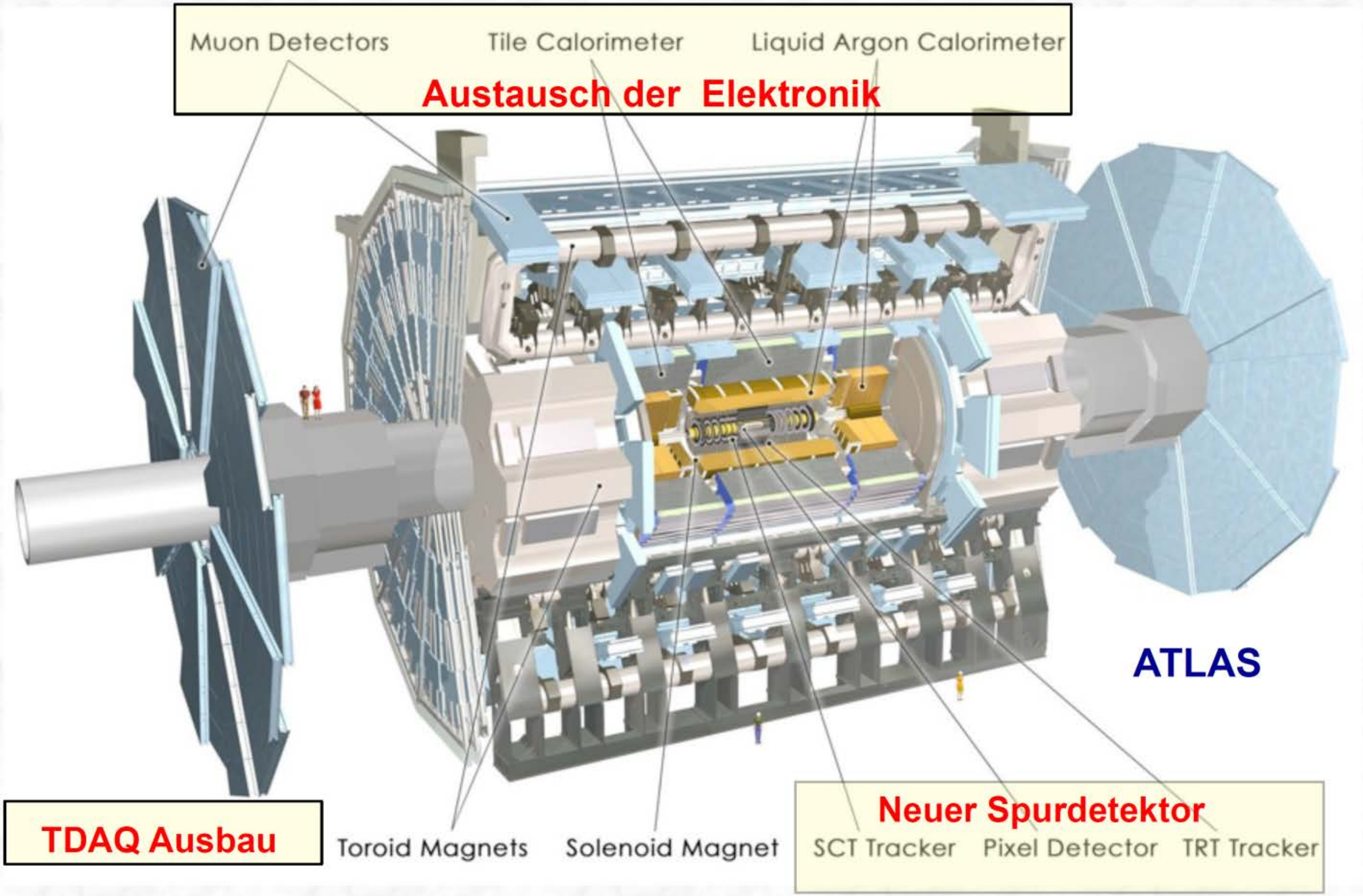


Abbildung 1: Zeitliches Profil des deutschen Anteils von 97 M€ an den Detektorkosten der vier LHC-Experimente.

ATLAS Detektor und Überblick über den Ausbau



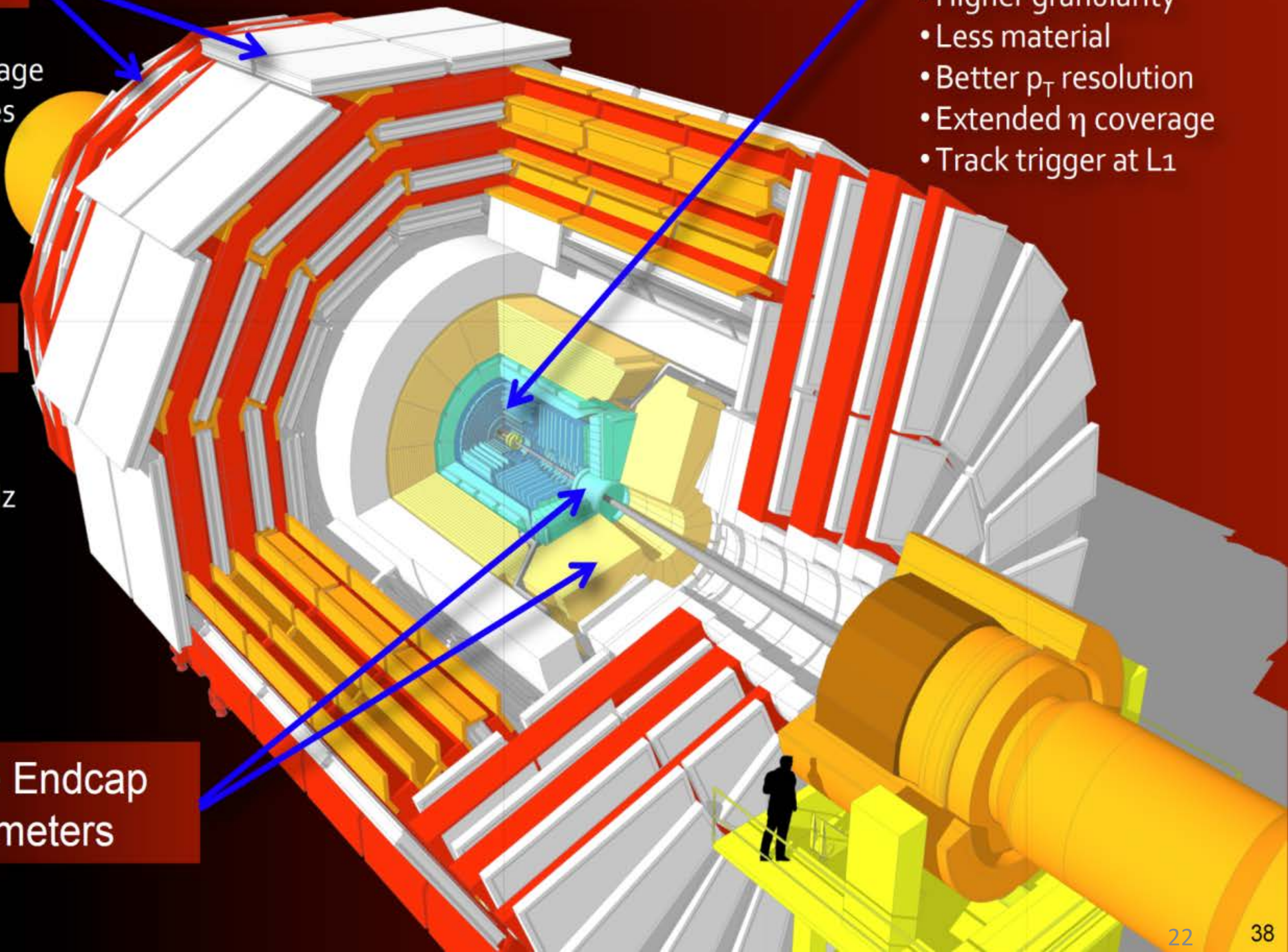
Phase 2 Upgrades

Muon system
- GEM Glass RPCs
- Extended η coverage
- New DT minicrates

Trigger/DAQ
- New FE and RO
- L1 up to 1 MHz
- HLT up to 10 KHz
- Tracking at L1

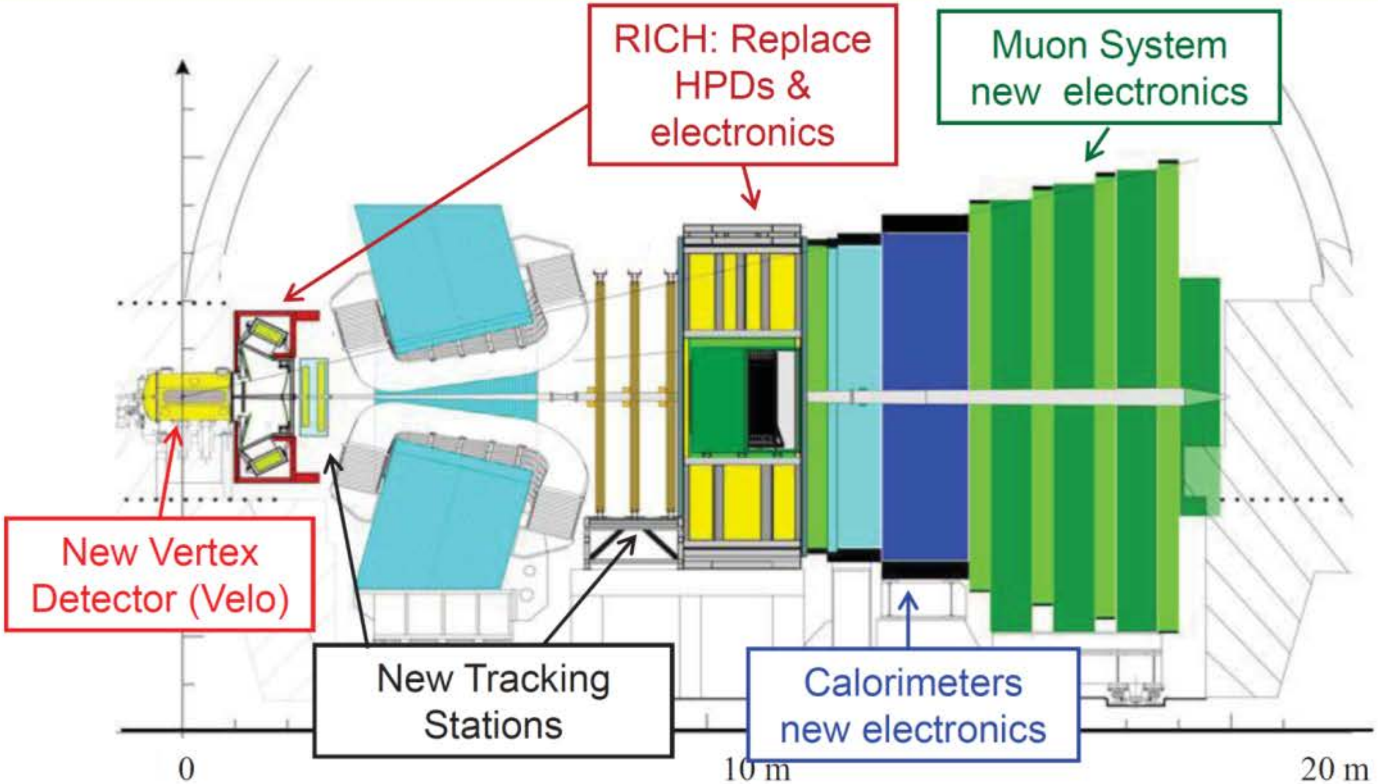
Replace Endcap Calorimeters

Tracker
- Higher granularity
- Less material
- Better p_T resolution
- Extended η coverage
- Track trigger at L1



LHCb

Upgrade Maßnahmen



- Upgrade ALLER Sub-Systeme auf 40 MHz Front-End (FE) Elektronik.
- Ersatz aller Systeme mit nicht-austauschbarer Elektronik: VELO, TT, RICH HPDs
- Neues Spursystem um erhöhter Multiplizität Rechnung zu tragen
- Neue Computing-Farm und neues Auslesenetzwerk