LHC Upgrades

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Outline

- Motivating the Upgrade
- Current machine planning
- Challenges for the detectors
- Upgrade plans of ATLAS, CMS, LHCb
  - **trackers**
  - **calorimetry**
  - **muons**
  - **trigger / DAQ**
- Concluding remarks and funding aspects

gross features

many projects still in development/discussion

Why an Upgrade ?

- We are doing fundamental science at the edge of success / failure.
- With the methods we have (i.e. colliding high energy protons) the signals we look for are perhaps 10^{11} times smaller than the background. Finding them is not automatically guaranteed.

Why an Upgrade ?

- We are doing fundamental science at the edge of success / failure.
- With the methods we have (i.e. colliding high energy protons) the signals we look for are perhaps 10^{11} times smaller than the background. Finding them is not automatically guaranteed.
- It therefore is absolutely mandatory – independent of our current ideas what we might find – to exploit the LHC machine and its physics to the utmost limit possible.
- The financial costs of the upgrade will be non-negligible, but still only a fraction of the past LHC investment.

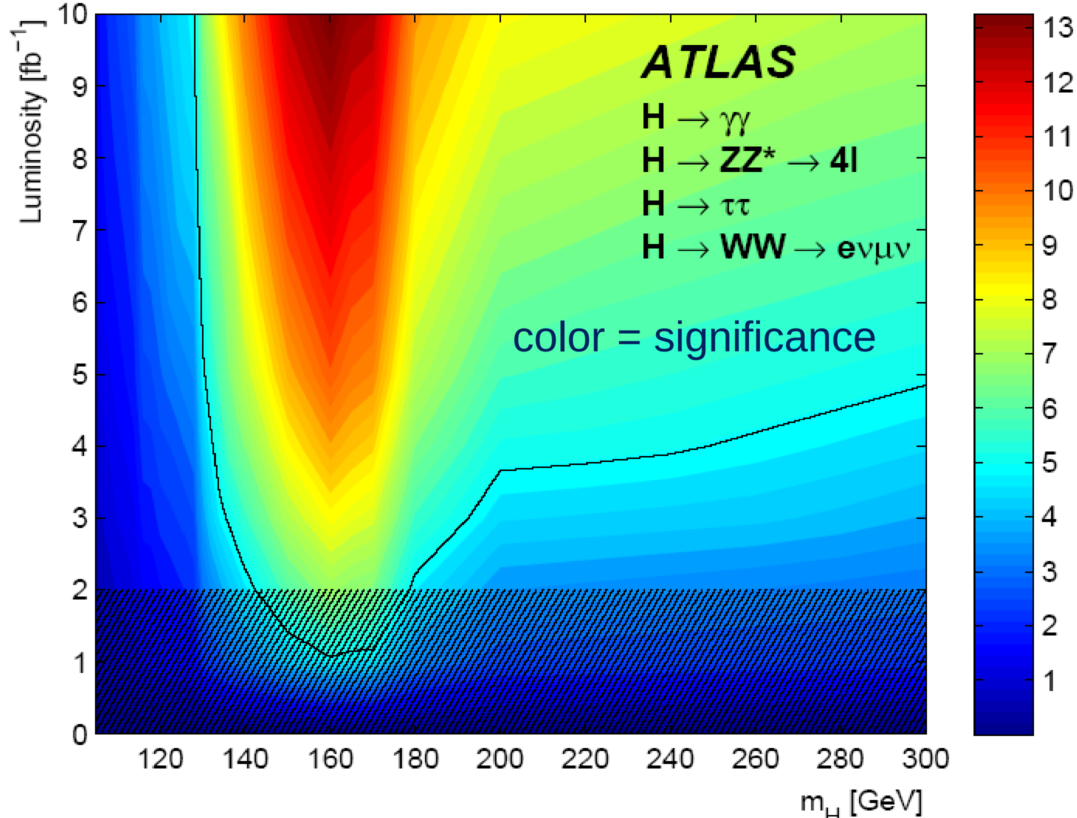
Why upgrade ?

1. The new discoveries hoped for will need a lot of data to understand their nature.

examples

- Higgs parameters
- SUSY – spectroscopy
- Triple gauge couplings
- VV scattering at ~1 TeV

2. In addition, the potential is significantly extended for (more difficult) physics discoveries

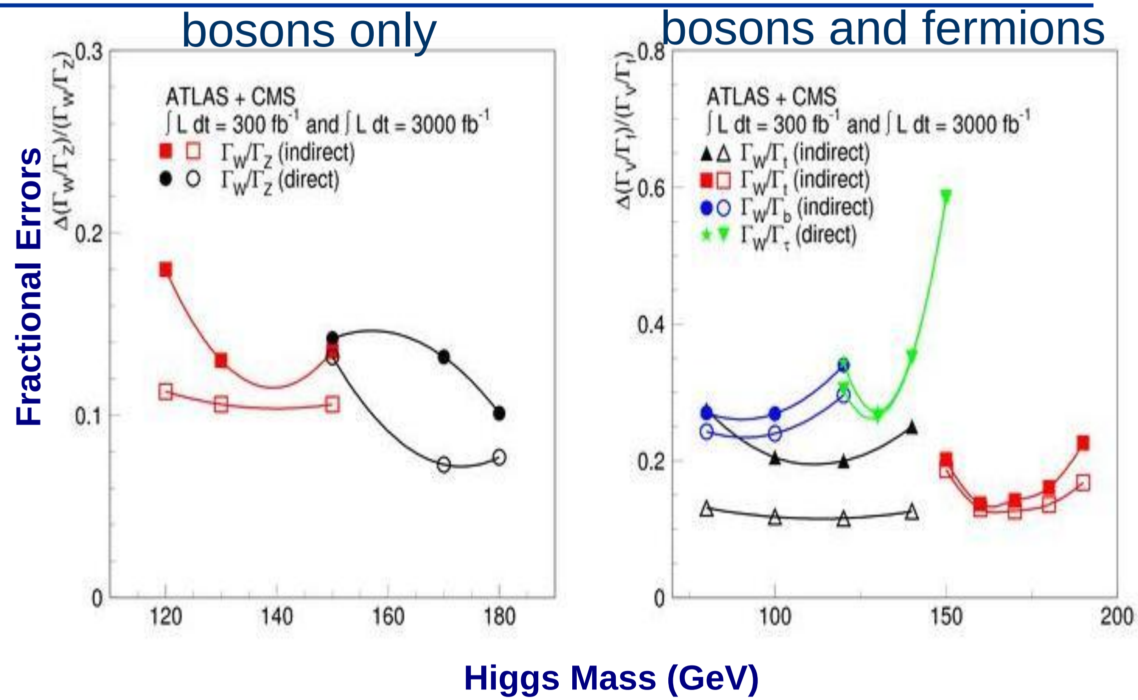


With ~10 fb^{-1} (~2015) a Standard Model Higgs will either be discovered or ruled out over a large mass range.

Need of course to see results of early LHC to know what will be important at the Upgrade, and finalize the physics case.

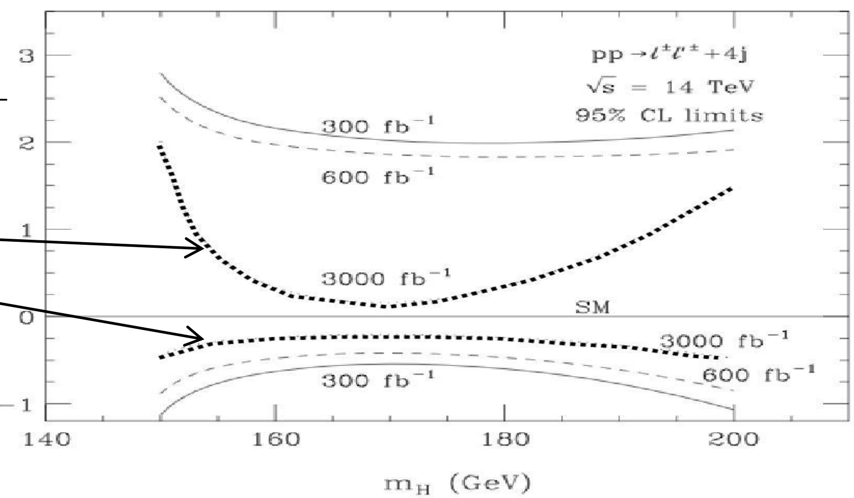
Example: Higgs parameters

- **couplings/partial widths to fermions and bosons**
  - 10% measurements in reach



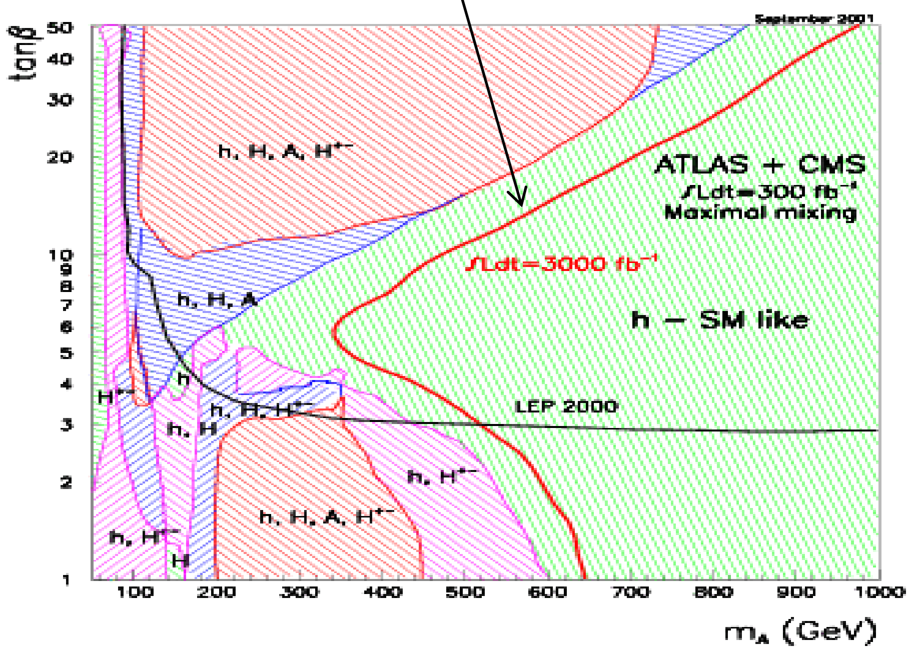
- **Higgs self coupling λ_{HHH}**
  - not possible at LHC
  - perhaps in reach at sLHC (study optimistic)

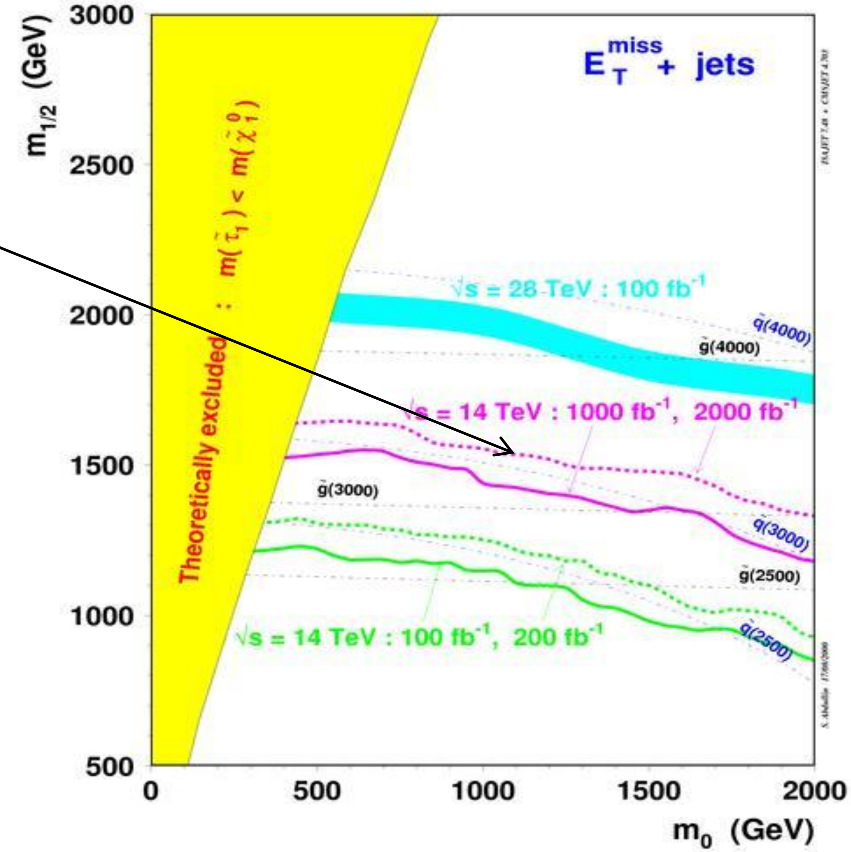
$$\Delta\lambda_{HHH} = \frac{\lambda - \lambda_{SM}}{\lambda_{SM}}$$



Example: SUSY

- If SUSY is not found soon, sLHC can extend the search to masses up to ~ 1.5 TeV
- If SUSY is discovered, then sLHC is needed for SUSY spectroscopy and multiple-Higgs searches

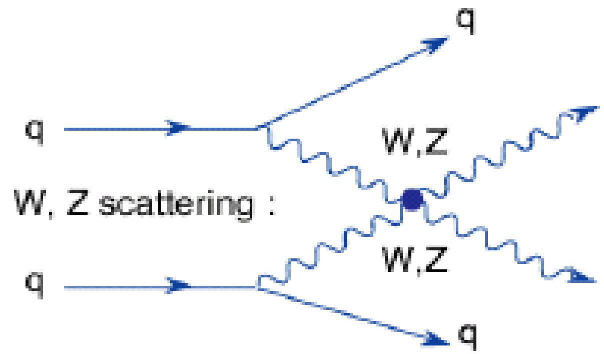


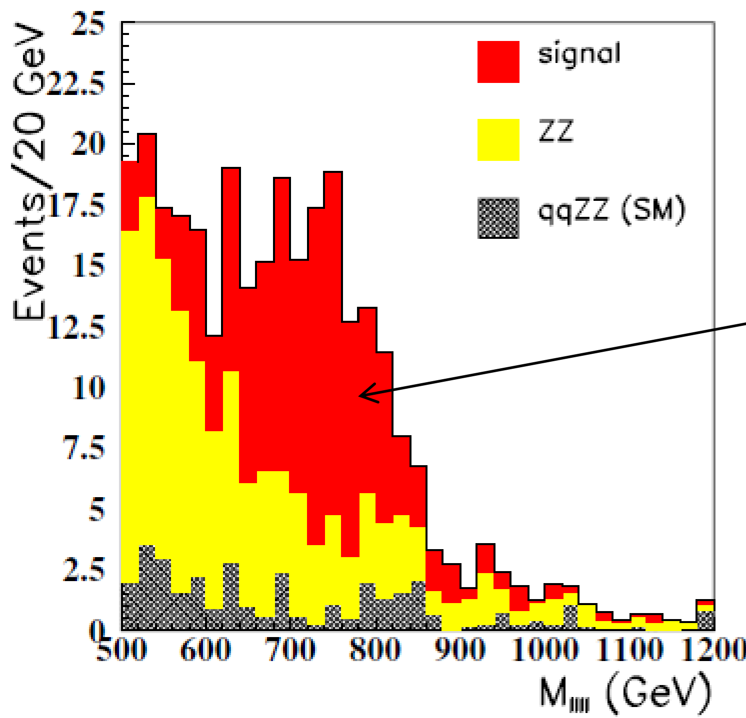


Example: VV scattering at high energies

If no Higgs is found, WW and ZZ scattering at 1TeV will tell what mechanism maintains unitarity in boson-boson scattering.

Effects will probably show up as new resonances with ~TeV masses visible with sLHC

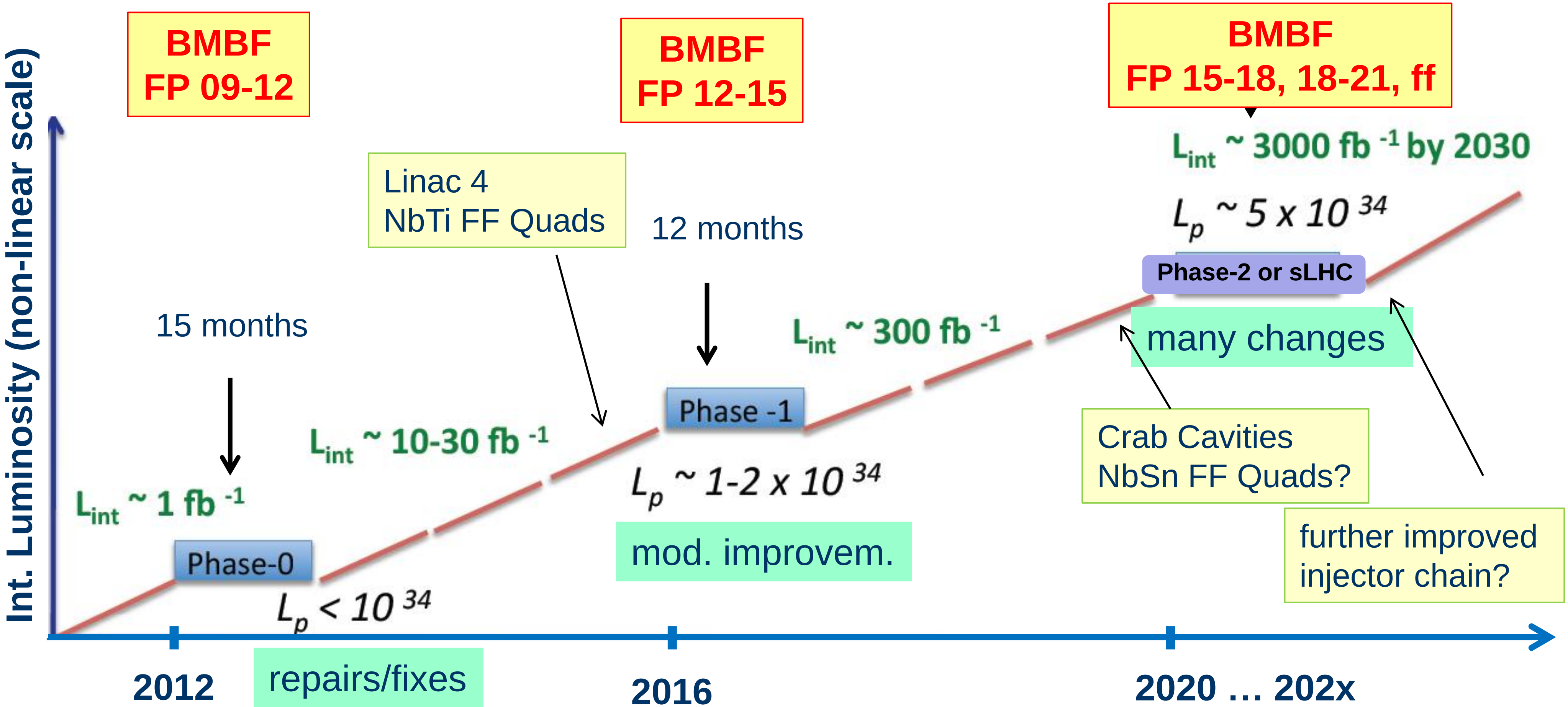




signal 750 GeV resonance

observable at sLHC <u>not at LHC</u>

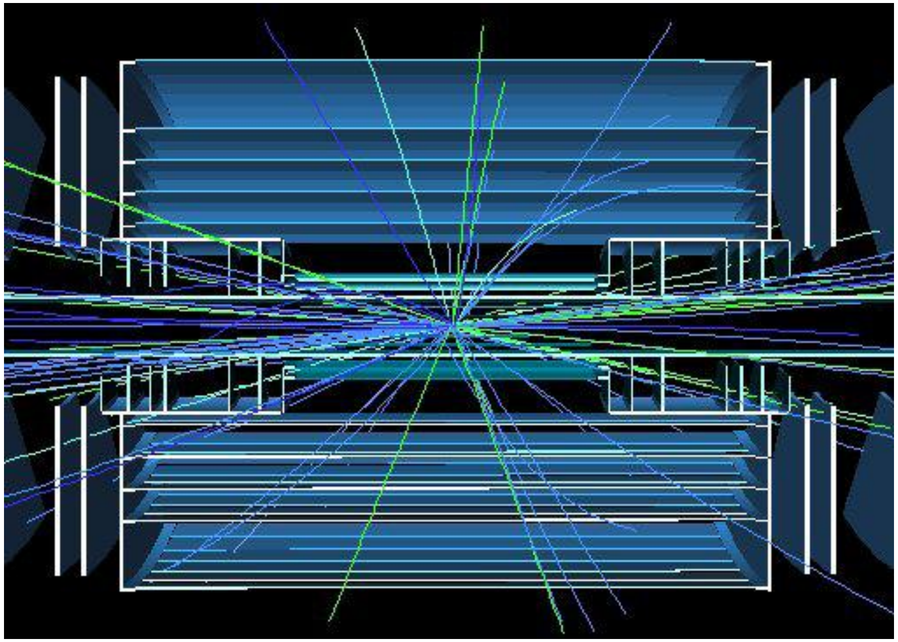
The LHC 10 year plan … 3 upgrade phases (0, 1, 2)



$N_{Higgs} = \frac{\sigma \cdot L_{int}}{\varepsilon} < 5$	few 100	few 1000	$>$ 50 000

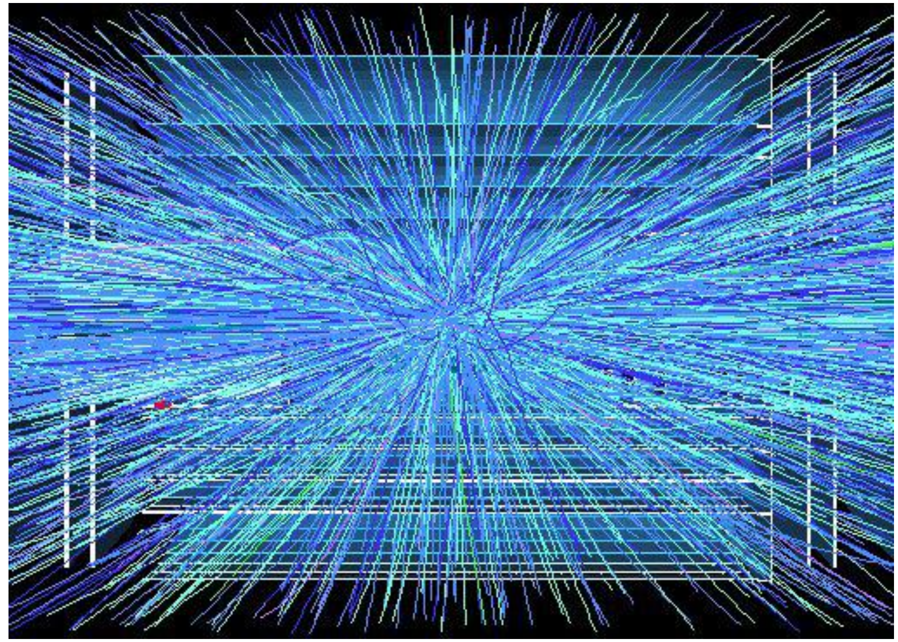
Challenges for the detectors …

$0.2 \times 10^{34}\ cm^{-2}s^{-1}$ (2013)



5 collisions per BX

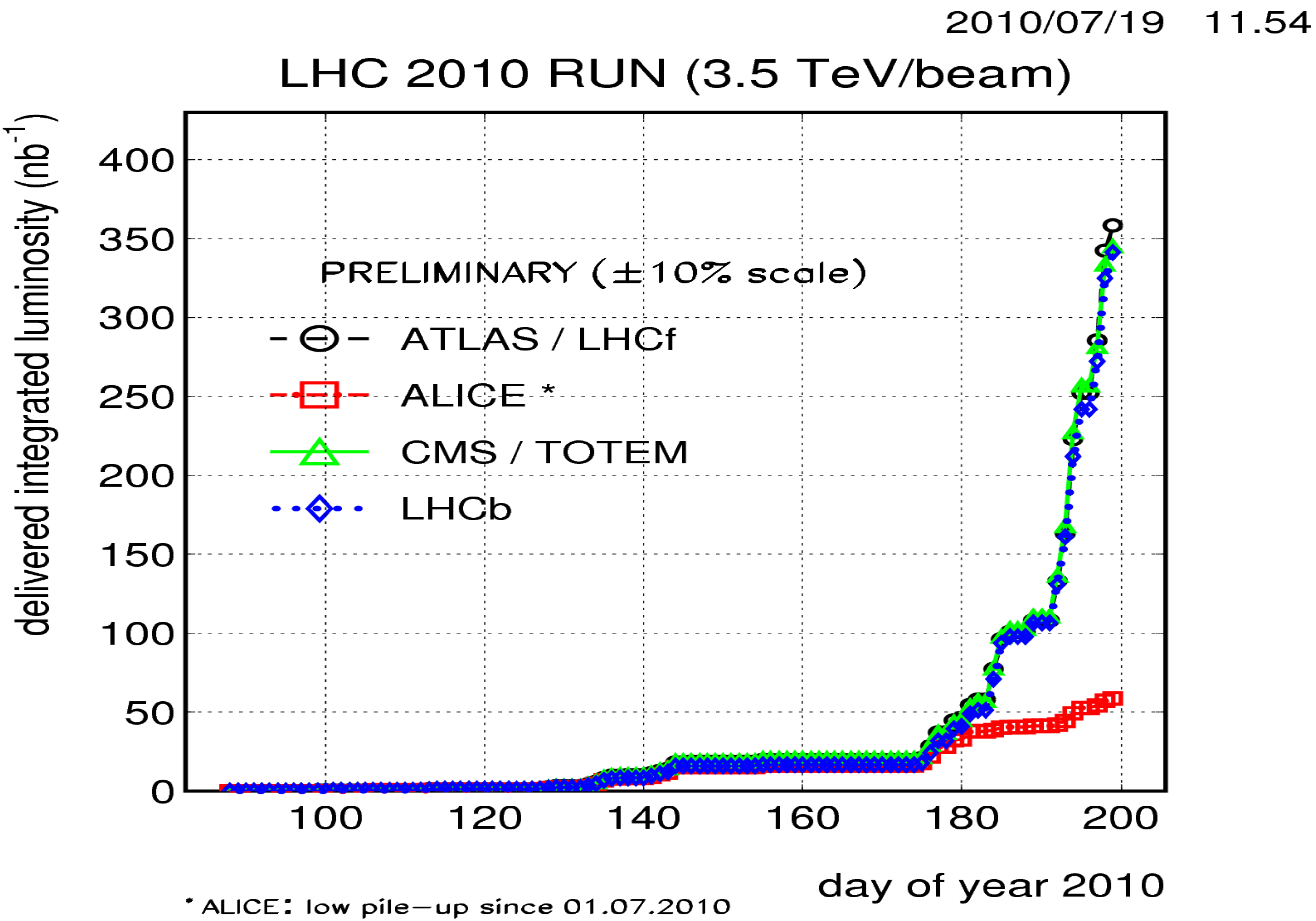
$1 \times 10^{35}\ cm^{-2}s^{-1}$(>2025 ?)



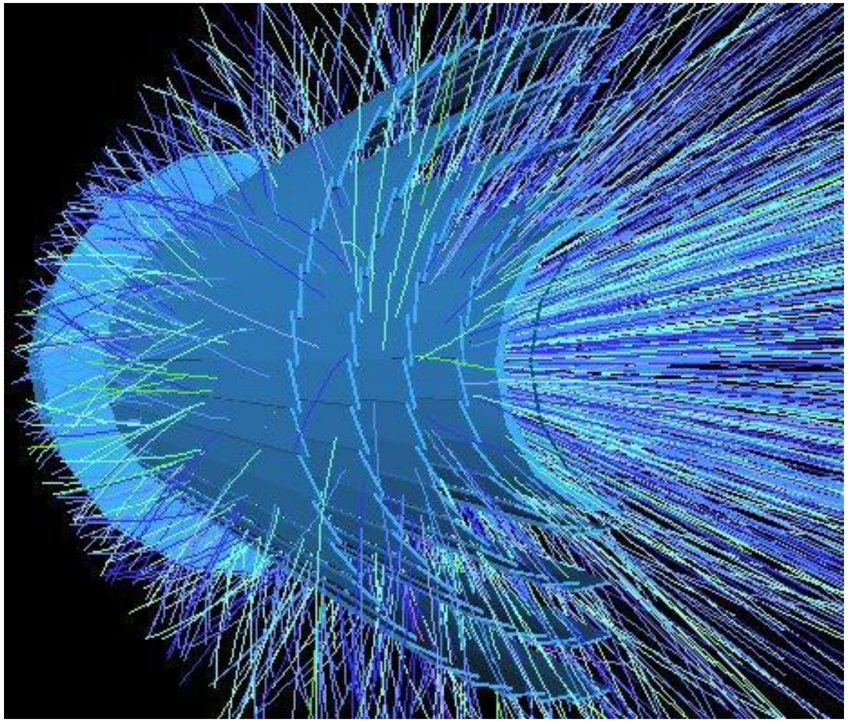
400 collisions per BX
(100 with luminosity levelling)

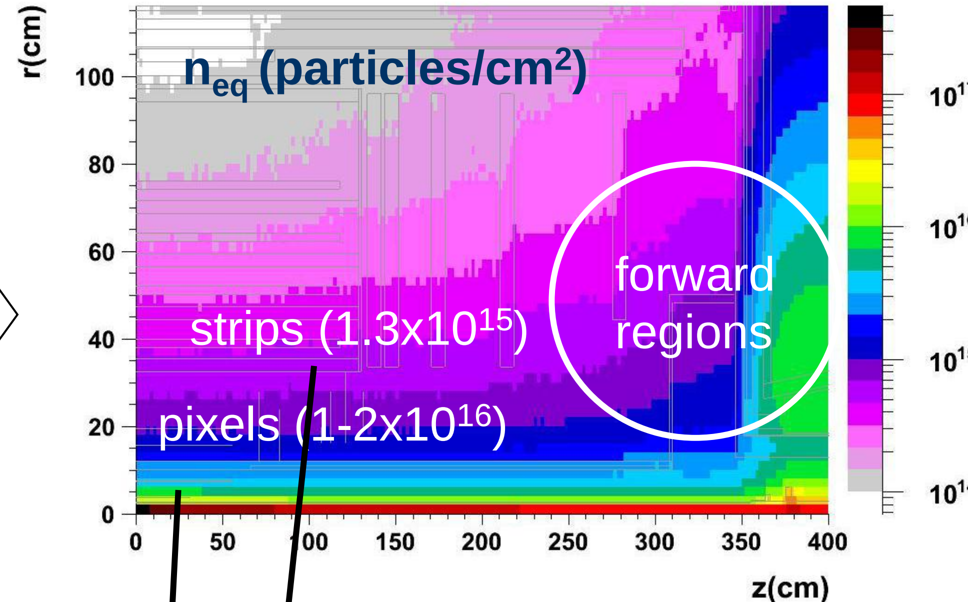
1. **event pile-up … hit rates … occupancies**
   → improve on … material, trigger, pattern recognition, data BW, data storage …
   i.e. granularity, speed, parallelism, eff. data reduction …

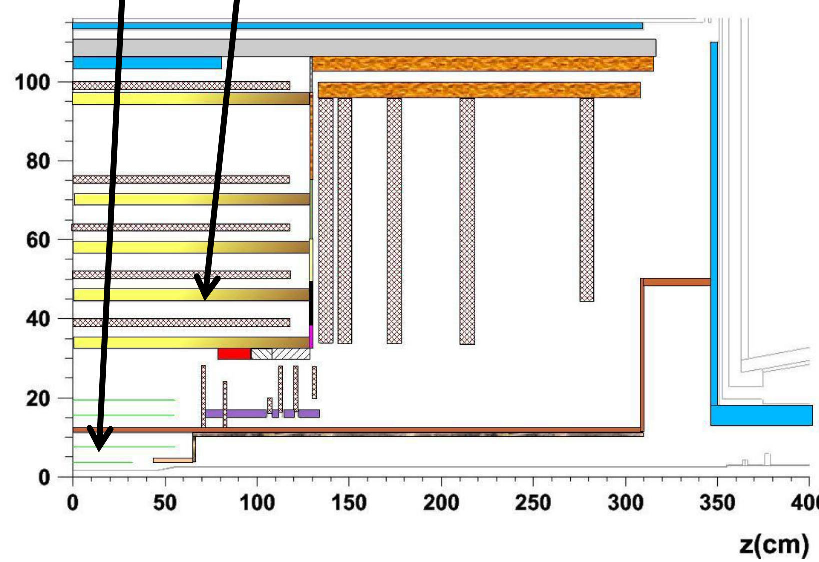
2. **radiation damage**
   → improve on … materials, electronics, links, ageing, …


2010/07/19 11.54
LHC 2010 RUN (3.5 TeV/beam)
delivered integrated luminosity (nb^{-1})
PRELIMINARY (±10% scale)
ATLAS / LHCf
ALICE *
CMS / TOTEM
LHCb
0
50
100
150
200
250
300
350
400
100
120
140
160
180
200
day of year 2010
* ALICE: low pile-up since 01.07.2010

Radiation levels at the sLHC (L = $10^{35}cm^{-2}s^{-1}$)







radiation levels

non-ionizing

10^{15} (r ≅ 20cm)

> 10^{16} (r ≅ 5 cm)

ionizing

5 kGy (r ≅ 2 m, ECAL)

> 10 MGy (r ≅ 5 cm)

German Specialities

- Large university groups (plus Desy, MPI) compared to other countries
  - contribute significantly to detector R&D and building
  - contributions in other countries more lab-based
    INFN (IT), CNRS/IN2P3 (FR), NatLabs (US), …

- Expertise especially in
  - micro pattern detectors (pixels, strips, gaseous)
  - muon detection systems
  - calorimetry (Liquid Argon)
  - trigger & DAQ

  - dedicated mechanical workshops (→ compound materials w. industry)
  - ASIC and FPGA electronics (→ interconnect technologies w. industry)

The plans in general

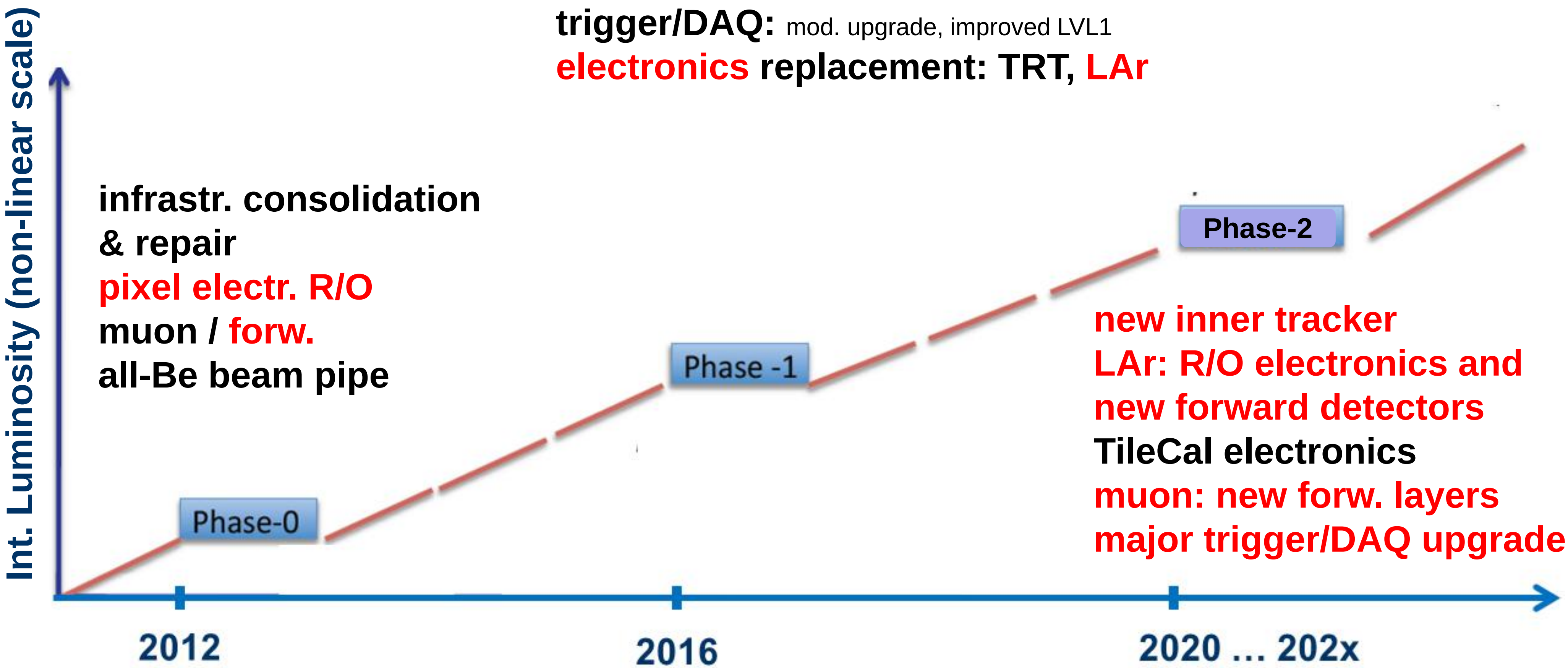
- LHC detector technology – although high tech – already old in HEP standards (1995)

- Replace detectors with new/better technology where ever possible and needed (high radiation areas)
  - inner tracking devices and forward regions

- For the very large detector components: calorimeters, muon systems
  - change/improve/refurbish: mostly readout electronics & trigger inputs as well as new parts

ATLAS plans

pixel IBL
muons: add. CSC layers, improved triggering
trigger/DAQ: mod. upgrade, improved LVL1
electronics replacement: TRT, LAr

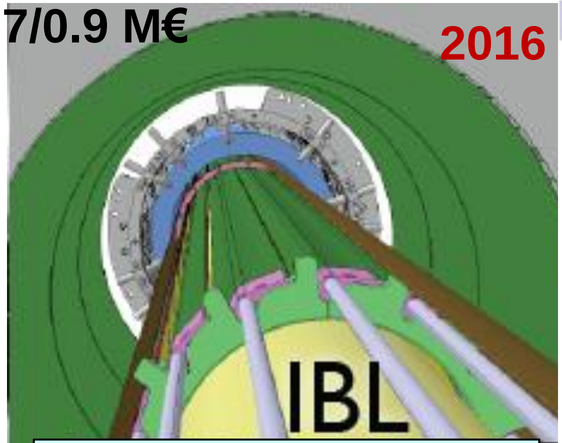


infrastr. consolidation & repair
pixel electr. R/O
muon / forw.
all-Be beam pipe

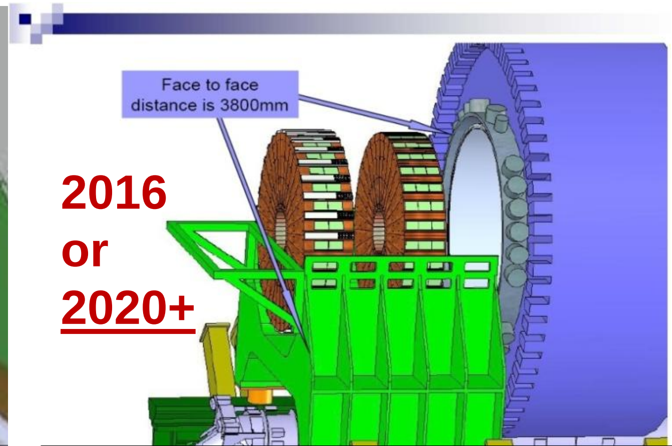
new inner tracker
LAr: R/O electronics and new forward detectors
TileCal electronics
muon: new forw. layers
major trigger/DAQ upgrade

contribution of german groups: ~ 10-15% (incl. Desy)

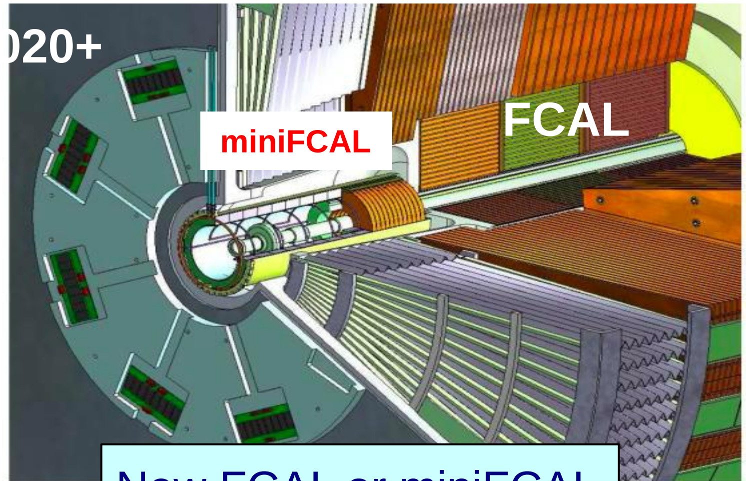
ATLAS: current major projects



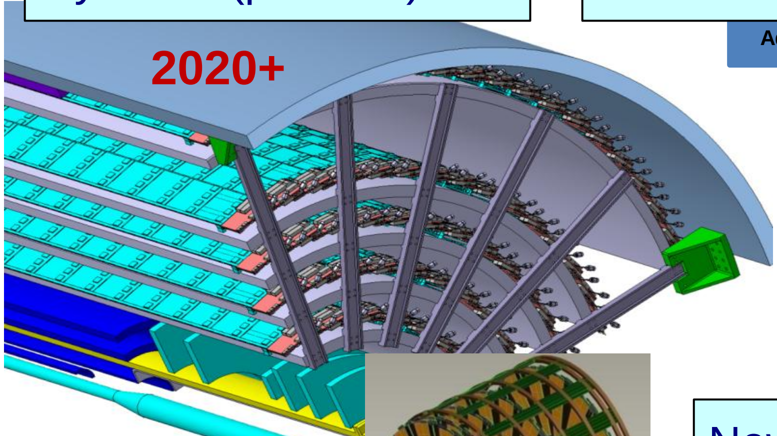
new innermost pixel layer IBL (phase 1)



new LAr and new HEC cold electronics (phase 1 or 2)

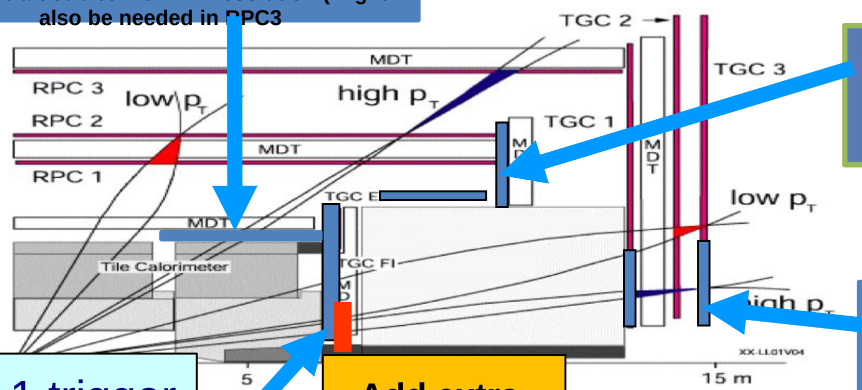


New FCAL or miniFCAL (phase 1 or 2)



new Inner Tracker & EC (phase 2)

Add extra doublet with mm resolution (might also be needed in RPC3



Might need to add a Doublet of Trigger ch. To improve L1 in low BdL region

Replace very forward chambers for higher resolution and rate capabilities

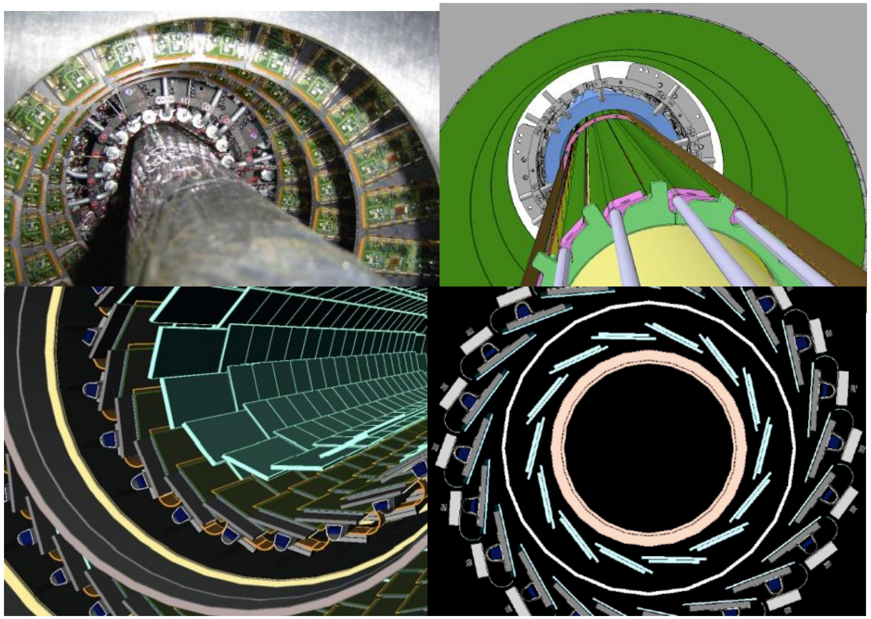
Add extra shielding for n

New L1 trigger components (phase 1 or 2)

...bers for ...ering ...g
Replacement extent depends on cavern background (large uncertainty)

Several new muon chambers and trigger ideas (μ + calo)

ATLAS: IBL (2016)

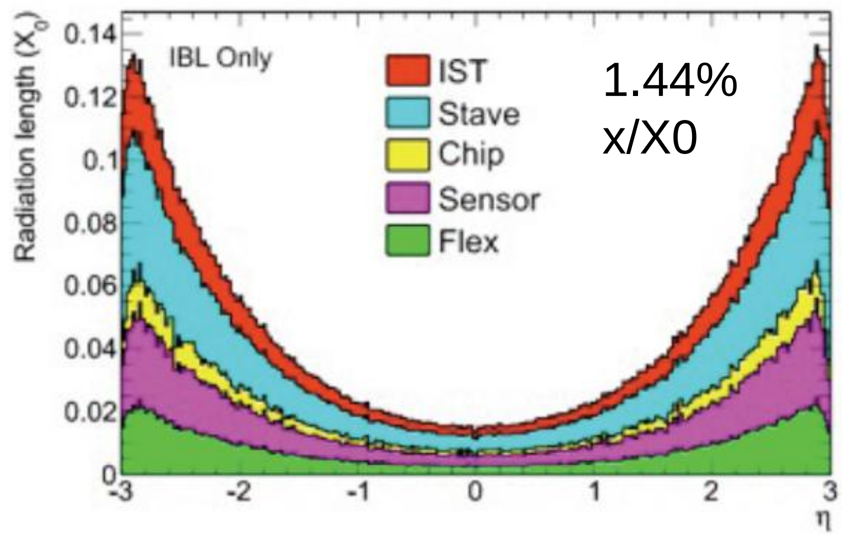


- smaller diameter beam pipe
- innermost pixel layer inserted into present pixel detector

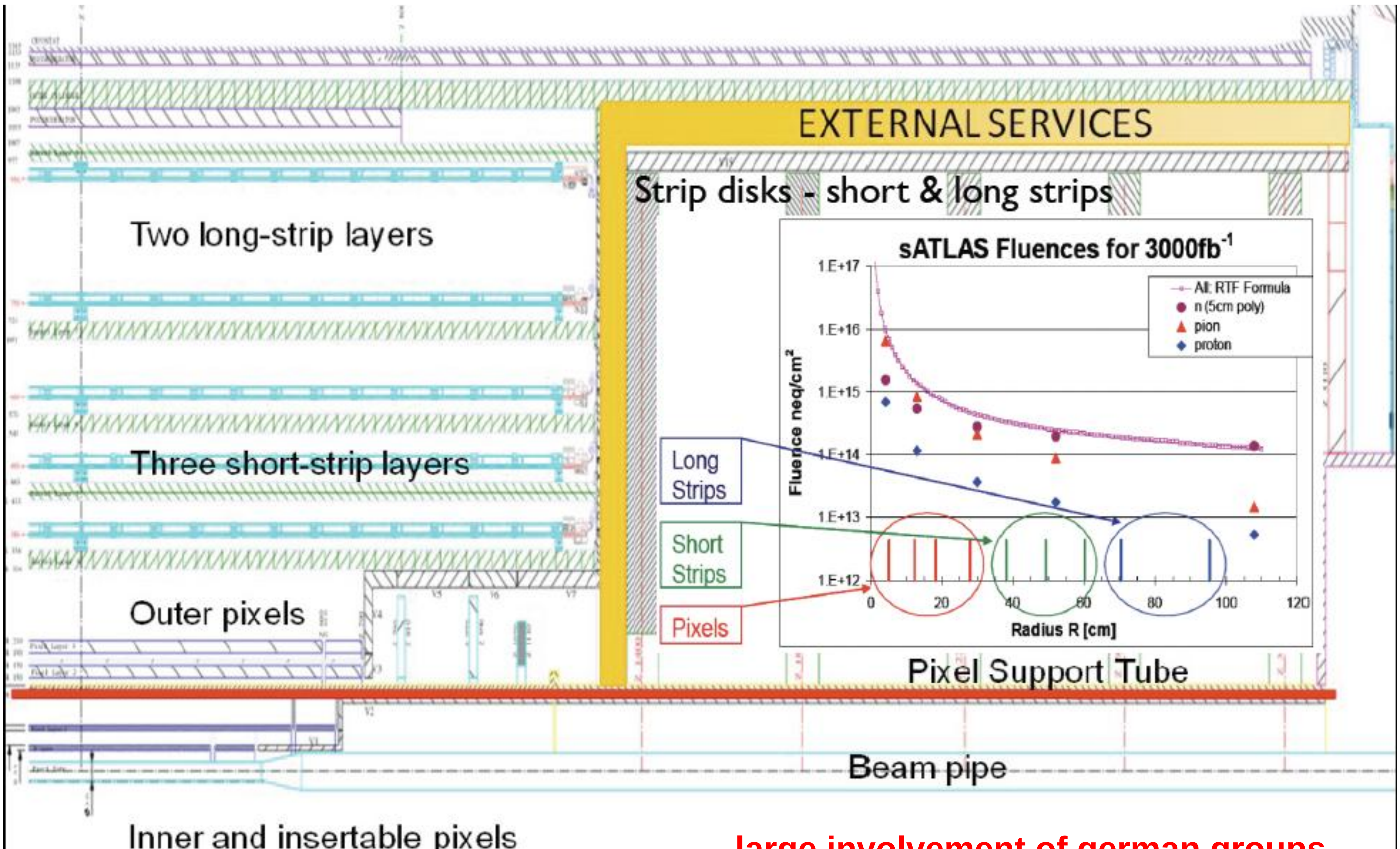
- new Si sensor materials
  planar Si, 3D-Si, diamond
- new FE chips (2 x more BW)
- new light weight support structures

- 3.5 $x/X_0 \rightarrow$ 1.44 % x/X_0

- project has started (TDR received)
- 9 MCHF → 1.2 MCHF (Germany)



ATLAS: New Inner Tracker (2020+)



large involvement of german groups

ATLAS: Calorimeter Upgrade

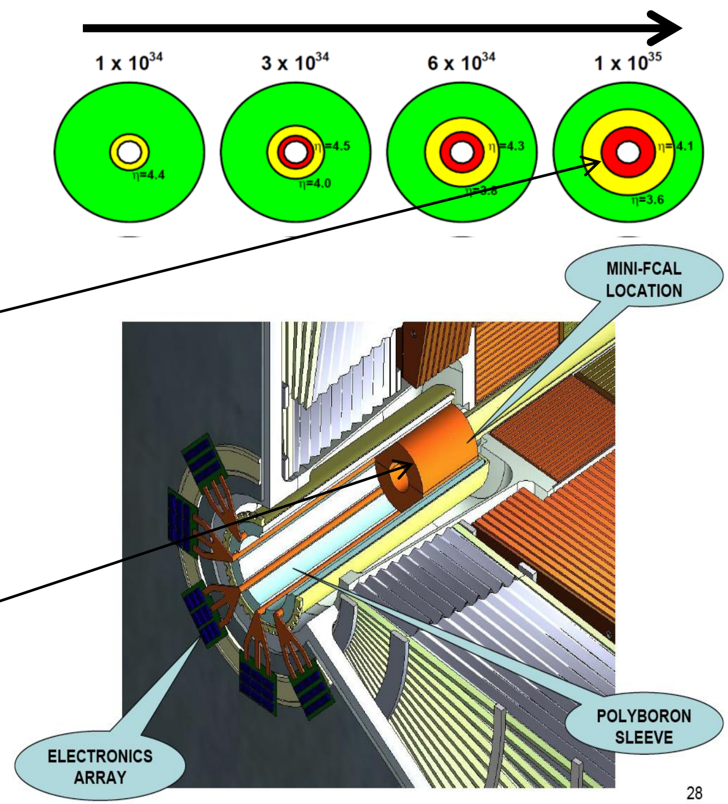
Calorimeters cannot (easily) be replaced and most parts will work fine at high lumi, but electronics improvements possible and needed (rad. damage and age ing)
→ also: finer granularity for LVL1 trigger input and better pile-up handling
In very forward areas: replacements needed.

- **2012 electronics consolidation/repair and access improvements**

- **new electronics (2016 or 2020+)**
  - **free-running R/O electronics for LAr and TileCal**
  - **new digital L1 calo trigger electronics**
  - **replacement of HEC cold electronics**

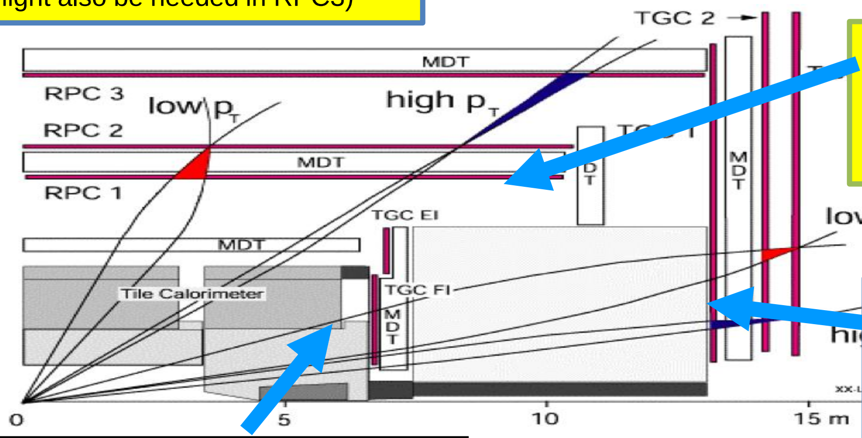
- **2020+ new Forward Calorimeters**
  FCAL will stop working above 3 x 10^{34} $cm^{-2}s^{-1}$
  - **ion build up between electrodes → voltage drop**
  - **even LAr heating and boiling**

  - **new FCALs & miniFCAL**
  - **smaller gaps, better cooling**
  - **and/or warm Cu/Diamond miniFCAL**



ATLAS: Muon Detectors

Add extra doublet with mm resolution (might also be needed in RPC3)



Might need to add a Doublet of Trigger ch. To improve L1 in low BdL region

Replace very forward chambers for higher resolution and rate capabilities

Replace Small-Wheel chambers for high rate tracking and triggering
Many R&D projects ongoing
Replacement extent depends on cavern background (large uncertainty)

- **New electronics for trigger improvements (2016)**
- **Consider bringing MDT into trigger (2016?)**
- **New small wheels, with new detector technologies (2016?)**
- **Improved shielding (2020+)**

ATLAS Plans Germany

IBL / New inner tracker:

New (forward) calorimeter elements:

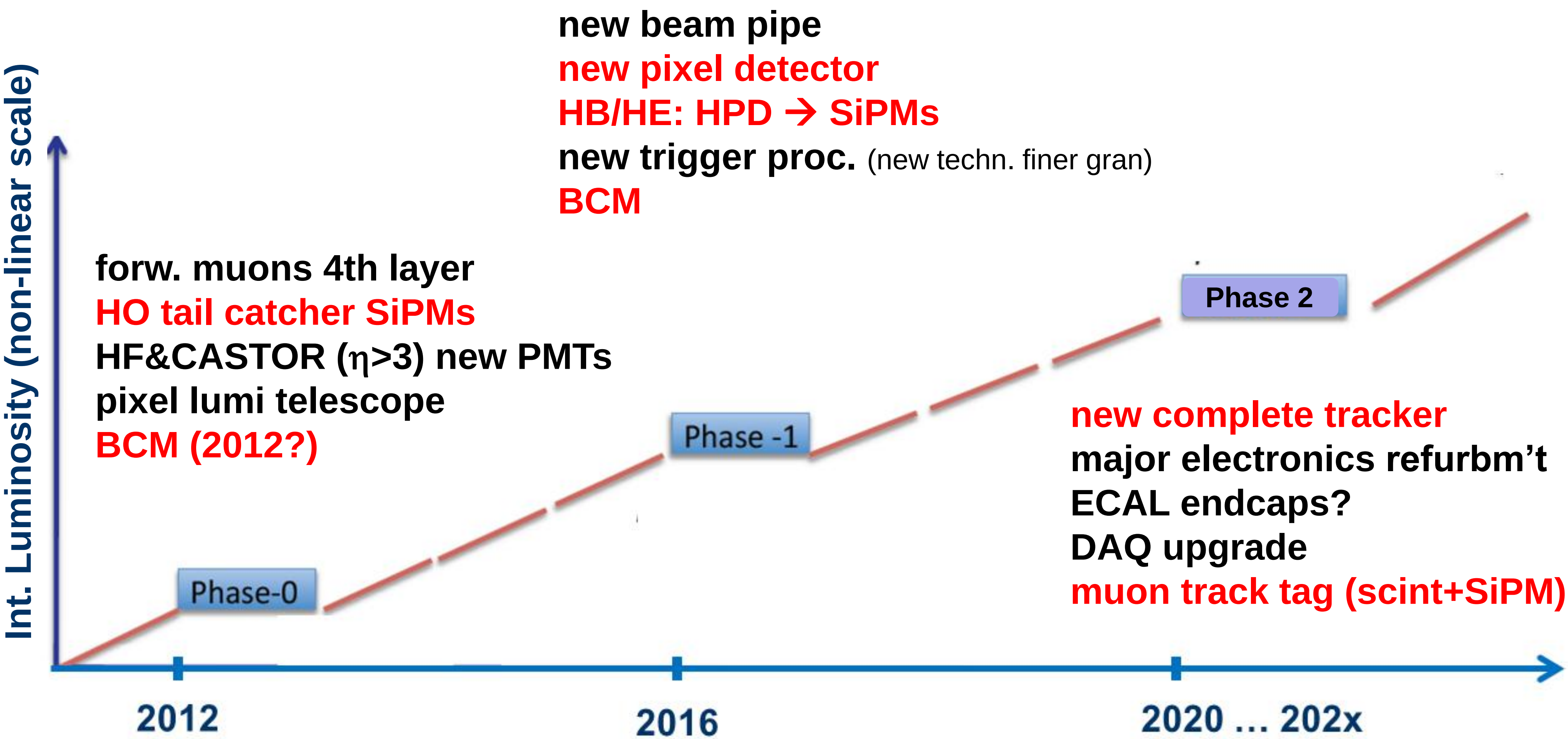
New muon chambers:

New trigger elements:

ATLAS Forw. Protons (AFP)

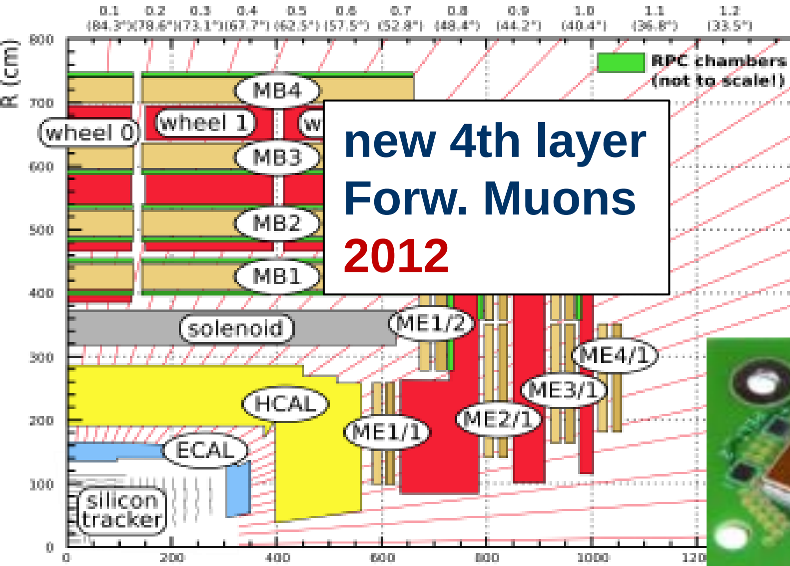
not mentioned

CMS Plans



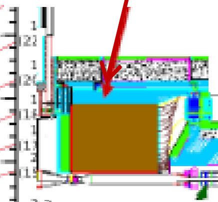
contribution of german groups: ~5-10% (incl. Desy)

CMS: current major projects

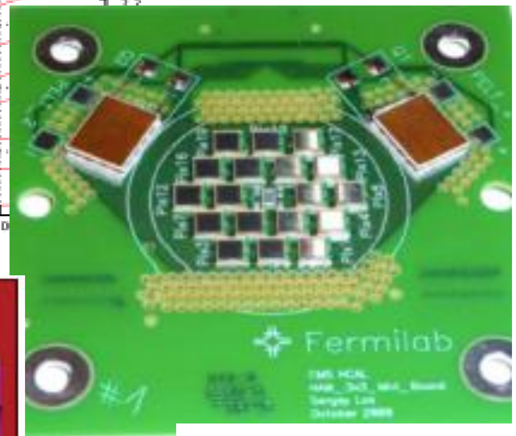


new 4th layer Forw. Muons
2012

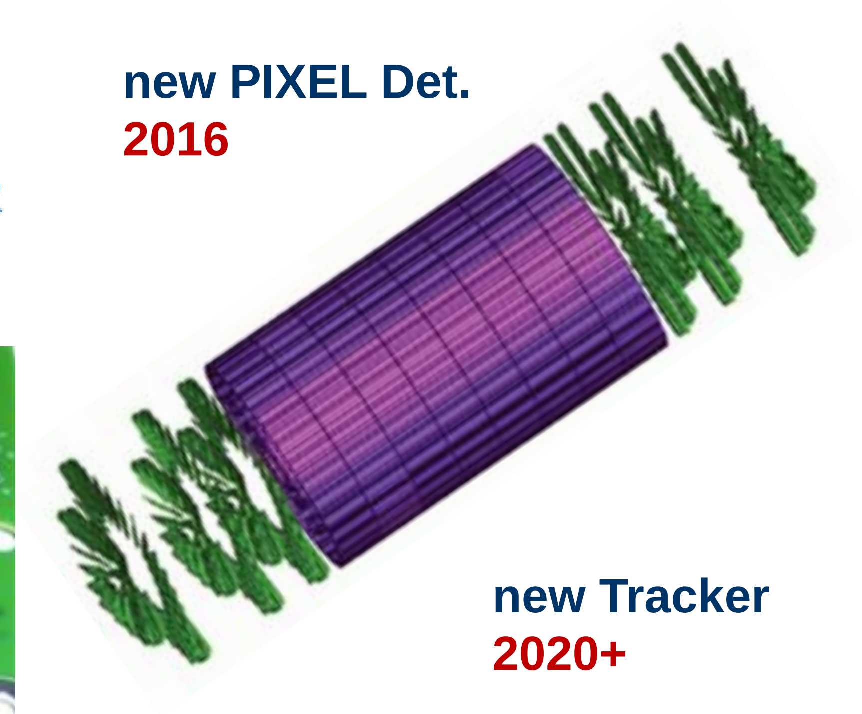
new HF PMTs
2012 or 2016



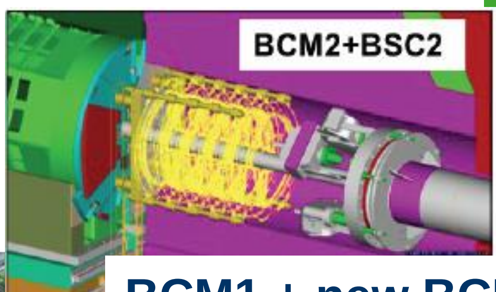
CASTOR



new PIXEL Det.
2016



new Tracker
2020+

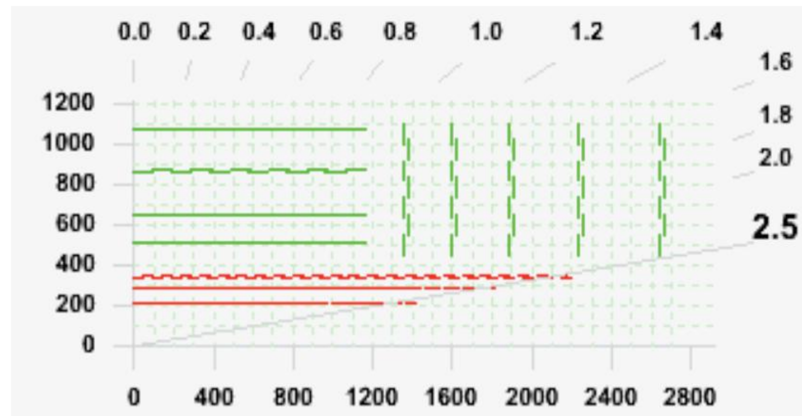


BCM1 + new BCM2
2012 2016

CASTOR (new PMTs)
2012

new PD R/O
→ SiPM
and backend el.
HO 2012
HCAL 2016

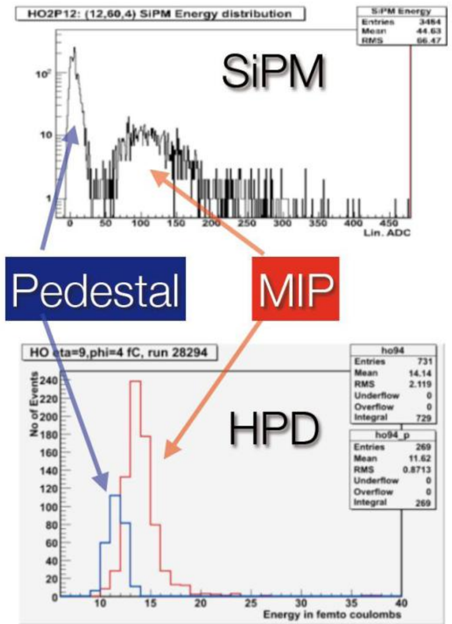
MTT 2020+

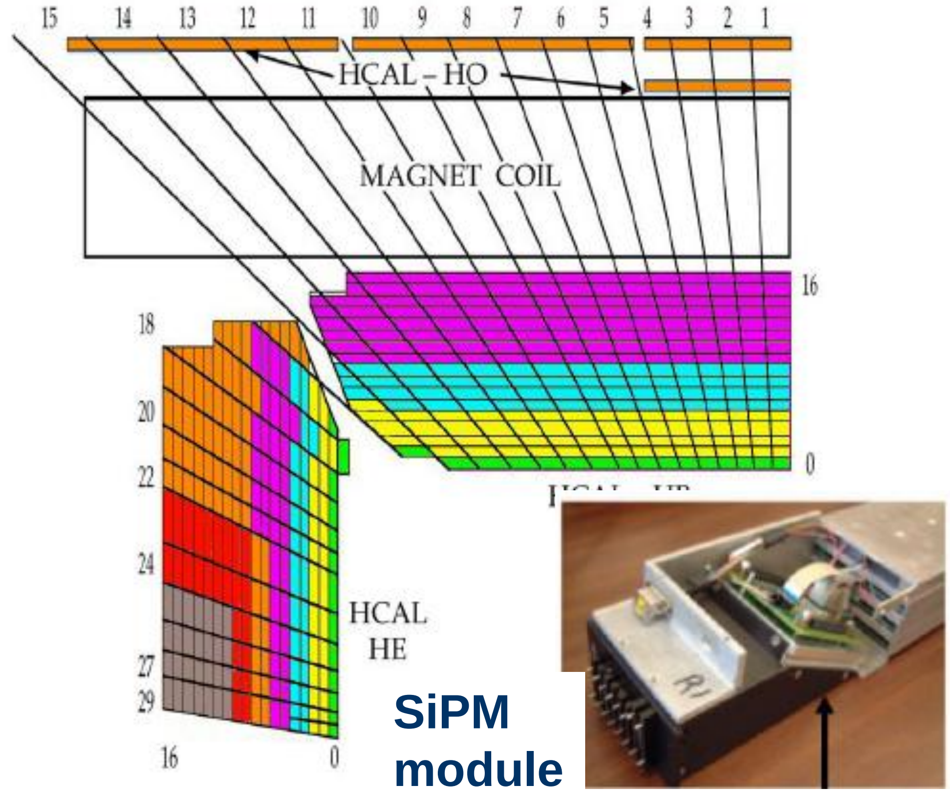


CMS: HCAL Upgrades & MTT

2009 - 2012

- **HO:** Replace HPD's with **SiPM**, better S/N





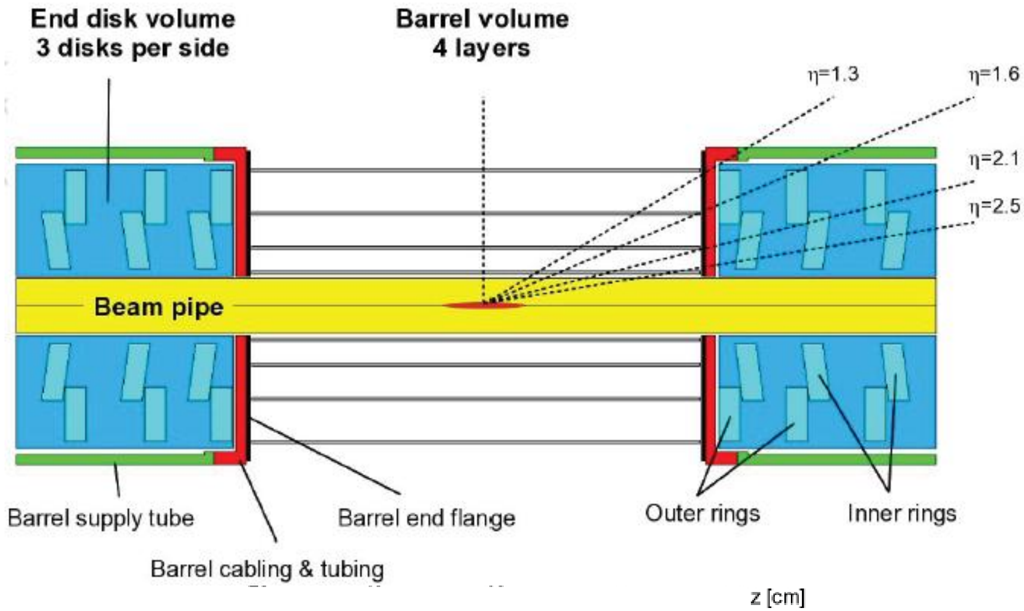
SiPM module

2016

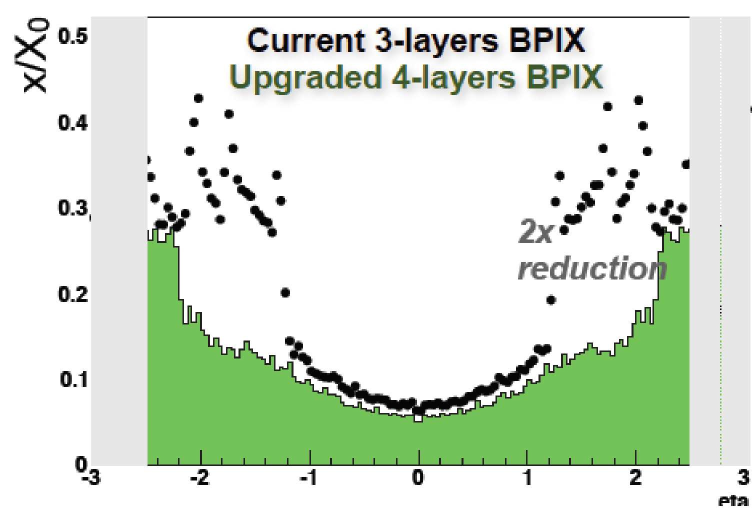
- **HB, HE**: Replace all HPD's with **SiPM, HF+CASTOR** with PMTs
- Increase longitudinal segmentation, timing and lepton ID
- Improvements in the readout electronics Front-End (new chips) and Back-end (μ-TCA)
- Consequences and improvement of trigger (new electronics, granularity x12)

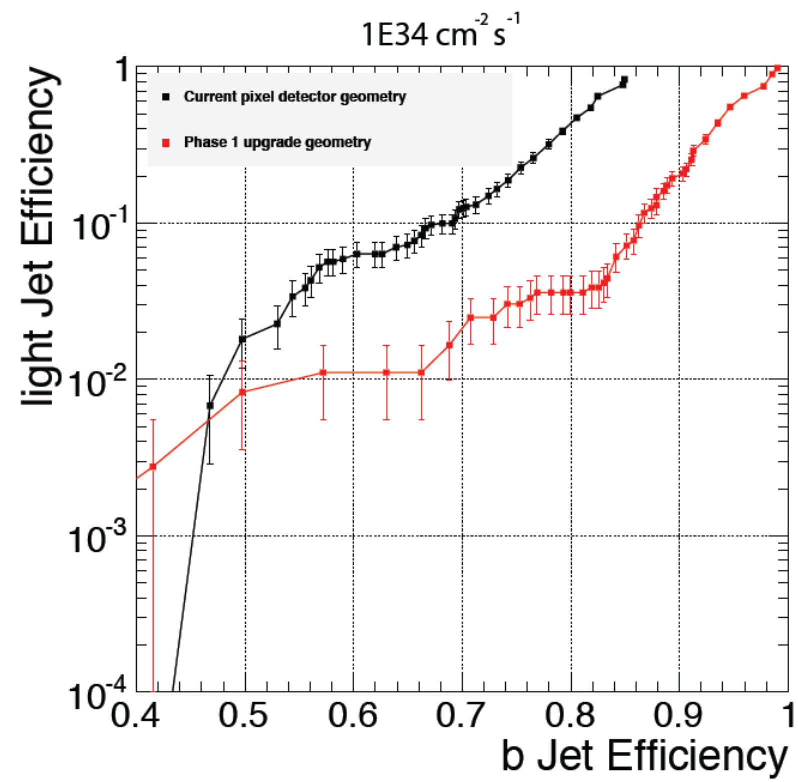
2020 MTT: new component: scint + **SiPM** in front of muon system

CMS: Pixel Upgrade (2016)



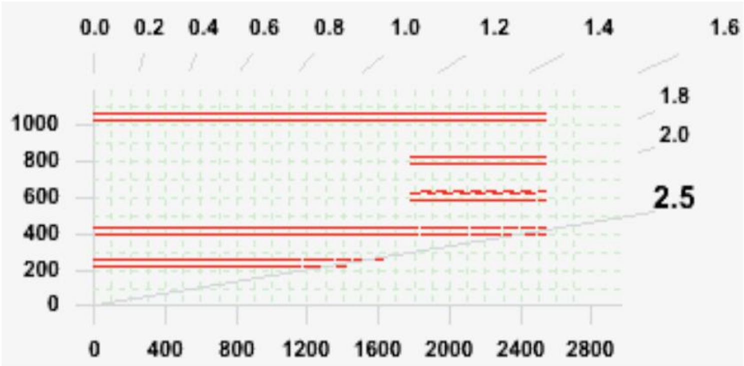
- **completely new pixel detector with 4 layers and 2x3 disks**
- **similar to present design**
- **better resolution and efficiency**
- **less material**

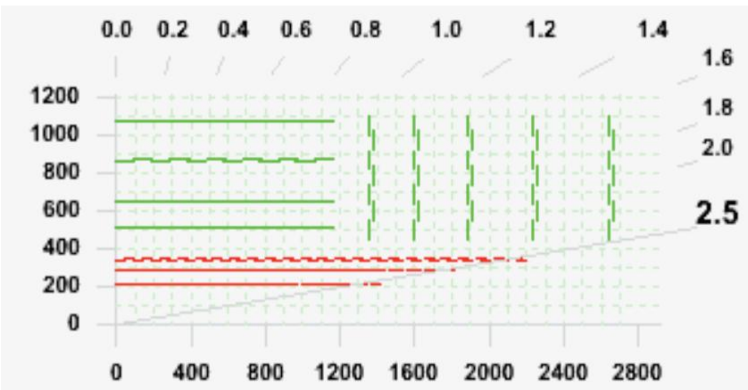


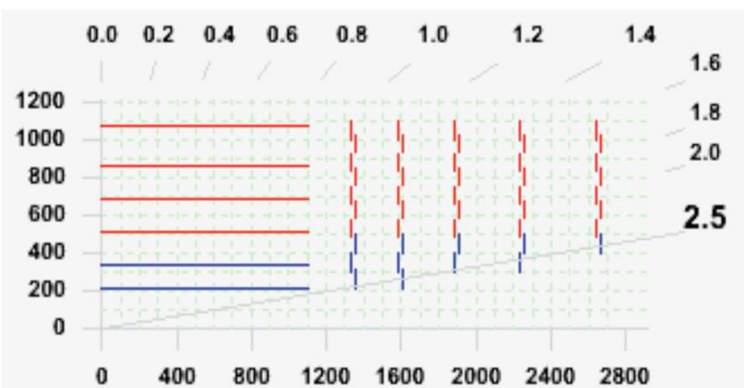


also new: major involment of german groups

CMS: Tracker Upgrade (2020)







- **layout options**
- **less layers, less material**
- **large involvement of German groups**

CMS plans Germany

Pixel detector → Inner Tracker

UHH DESY RWTH - I KIT Karlsruher Institut für Technologie

HCAL (HO & HB/HE & MTT)

DESY RWTH - III

BCM (Beam Conditions Monitor)

DESY KIT Karlsruher Institut für Technologie

CASTOR (Forw. Quartz/W Calorimeter)

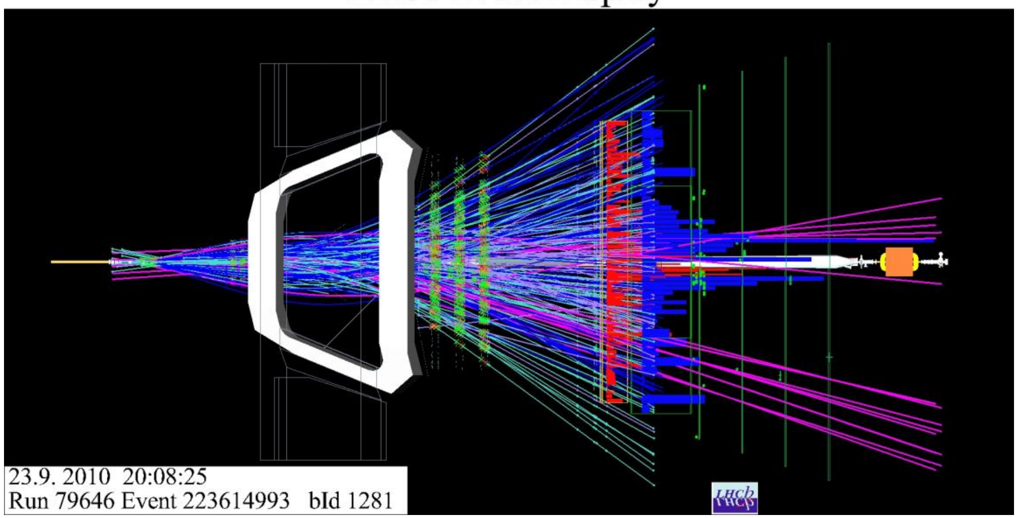
DESY KIT Karlsruher Institut für Technologie

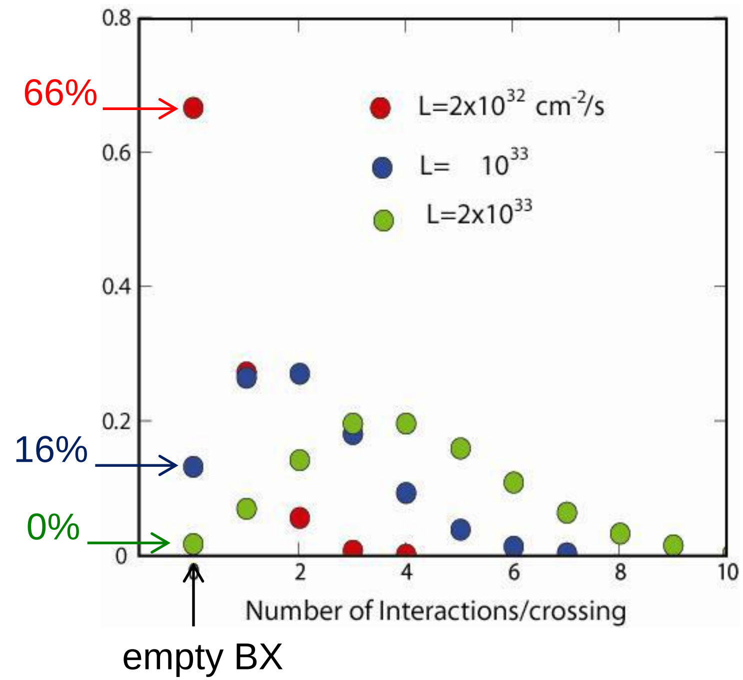
LHCb

- LHCb originally designed for $L = 2x10^{32}\ cm^{-2}s^{-1}$ with $\langle n_{ev} \rangle = 0.4$
- already now: $\langle n_{ev} \rangle = 2 - 2.3$ at run start $= 5 \times \langle n_{ev} \rangle_{design} \cong L_{effective\ per\ BX} = 10^{33} cm^{-2}s^{-1}$

(reason: low β*, no defocusing and unexpectedly small ε)

LHCb Event Display





i.e. upgrade conditions have already started !

and LHCb still works (congratulations!)

LHCb

- extrapolation by multiplying by no. of bunches is not correct , β^* can be tuned
- goal: make experiment capable of safe running at $L = 2 \times 10^{33}\ cm^{-2}s^{-1}$ (10 x design)
  - ❑ need to overcome current trigger (1 MHz) and bandwidth limitations
    - ➢ read out entire detector at 40 MHz (BX) and transfer data to CPU event filter farm where flexible full detector trigger algorithms are applied
    - ➢ replace detectors which suffer from radiation damage up to $n_{eq} = 0.8 \times 10^{16}\ cm^{-2}$ (e.g. VELO: strip → pixel)
    - ➢ LHCb upgrade in principle independent of the LHC machine‘s luminosity upgrade planning, but needs to be tuned to shut down plans
  - ❑ phase 1 (2016) replace (almost full) frontend electronics for 40 MHz R/O and replacement of critical subdetector parts (eg RICH HPDs)
  - ❑ phase 2 (2020) computer farm further replacement of detectors (main trackers)

Concluding Remarks and Funding Aspects

- CMS has an Upgrade Technical Proposal (270 pages, Oct. 2010) detailing the planning until 2016, total volume 67 MCHF.
- ATLAS and LHCb do not yet have such proposals (IBL = 9MCHF)

- The total cost for all phases should very likely amout to 30 – 40% of the initial cost of the detectors, i.e. 150-200 MCHF for ATLAS and CMS each, 25-30 MCHF for LHCb

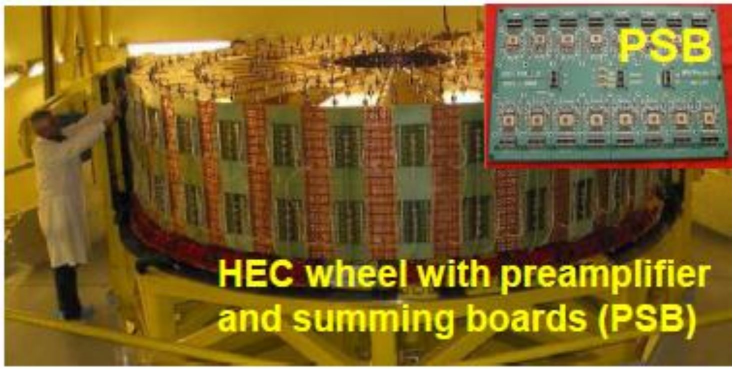
- The german groups would like to contribute to this enterprise corresponding to their fractional contribution to the collaboration: ATLAS (10-15%), CMS (5-10%), LHCb (5-7%), incl. DESY

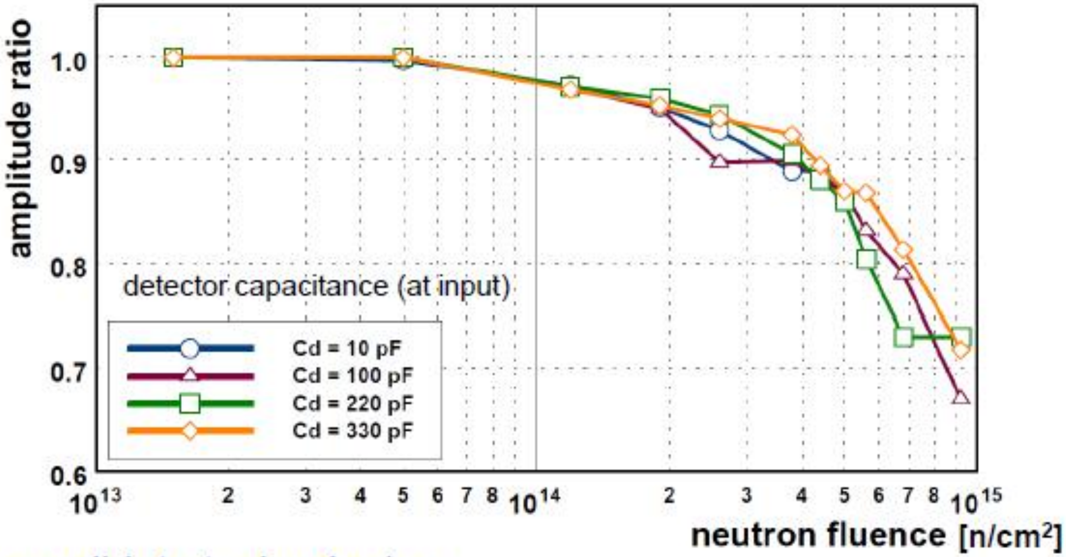
- As a spending timeline the years 2013 – 2025 may be assumed.

BACKUP SLIDES

ATLAS: HEC

- front-end electronics of ATLAS Hadronic Endcap (HEC) is mounted inside the cryostat
- ASIC for preamplifier and summing of trigger signals in GaAs 1µm technology
- 0.2 x 10^{14} n_{eq}/cm^2 expected for 10 years at nominal LHC luminosity (~1000 fb^{-1})
- signal amplitude degrades at ~3 x 10^{14} n_{eq}/cm^2
- could be at the margin for HL-LHC (+ageing !)





- if HEC electronics must be replaced
→ cryostat must be opened
→ very delicate and long operation

- new ASIC technologies tested (MPI Munich)
- must operate at room and LAr temperature (87 K) with equal performance
→ low power, low noise, stable signal amplitude, small gain variation between channels (<1%)

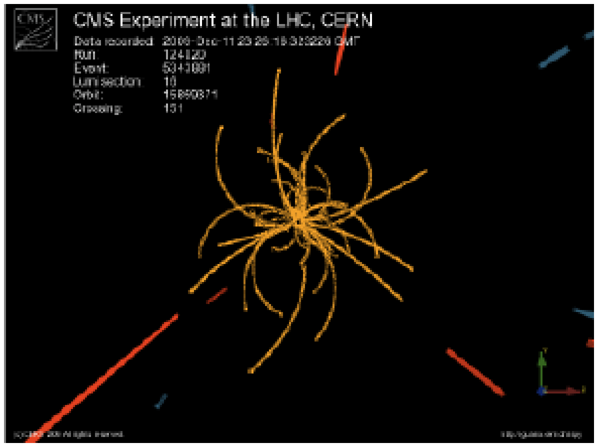
- candidate technologies:
  - SiGe Bipolar → radiation tolerant up to 2 x 10^{15} n_{eq}/cm^2 , but gain is temperature dependent
  - Si CMOS 250/350 nm and GaAs 250 nm
→ radiation tolerant and good temperature stability

CMS: Anomalous Signals in Calorimeters

- in collision data, CMS observes anomalous signals in ECAL and HCAL (now reproduced in simulation and taken into account/corrected in data analysis)

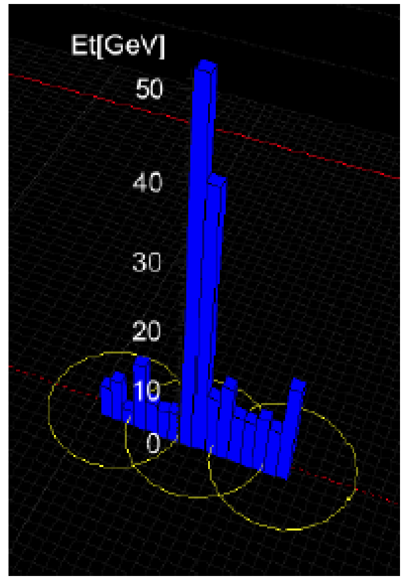
G. Tonelli ICHEP2010

ECAL



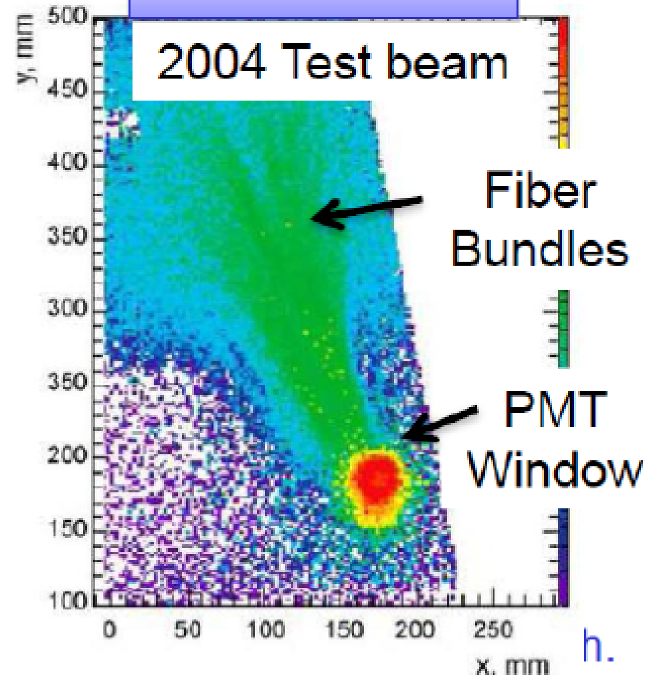
- Appear mostly in a single crystal
- In time with collisions but with wider time-spread (also occur in cosmics at a much lower rate)
- Caused mostly by deposits in APDs by highly ionising secondary particles.

HCAL: HB,HE



- Appear in 1-72 channels
- Random, low rate, ~ 10-20 Hz (E>20 GeV)
- Caused by ion feedback, noise & discharges in HPDs

HCAL: HF



h.

- In time with collisions
- Caused by C^v light by particles going through PMT glass

Upgrade-Pläne der deutschen CMS-Gruppen

Aktueller Stand der Planungen:

	2012	2016	2020
Aachen-I	-	Pixel	Tracker
Aachen-III	HO	-	MTT
DESY	HO, CASTOR, BCM	Pixel, HCAL, BCM	Tracker
Hamburg	-	Pixel	Tracker
Karlsruhe	-	Pixel, BCM	Tracker

Pixel: Bau der 4. Barrel-Lage (Modulbau, Integration, QA), DC-DC Stromversorgung

Tracker (Strips…Pixel): Sensorentwicklung, (Super-)Modul-Design, DC-DC Stromversorgung, CO_2-Kühlung, …

MTT (Muon Track Tag): Szintillator+SiPM Lage vor dem Myon-System als Beitrag zum Myon-Trigger

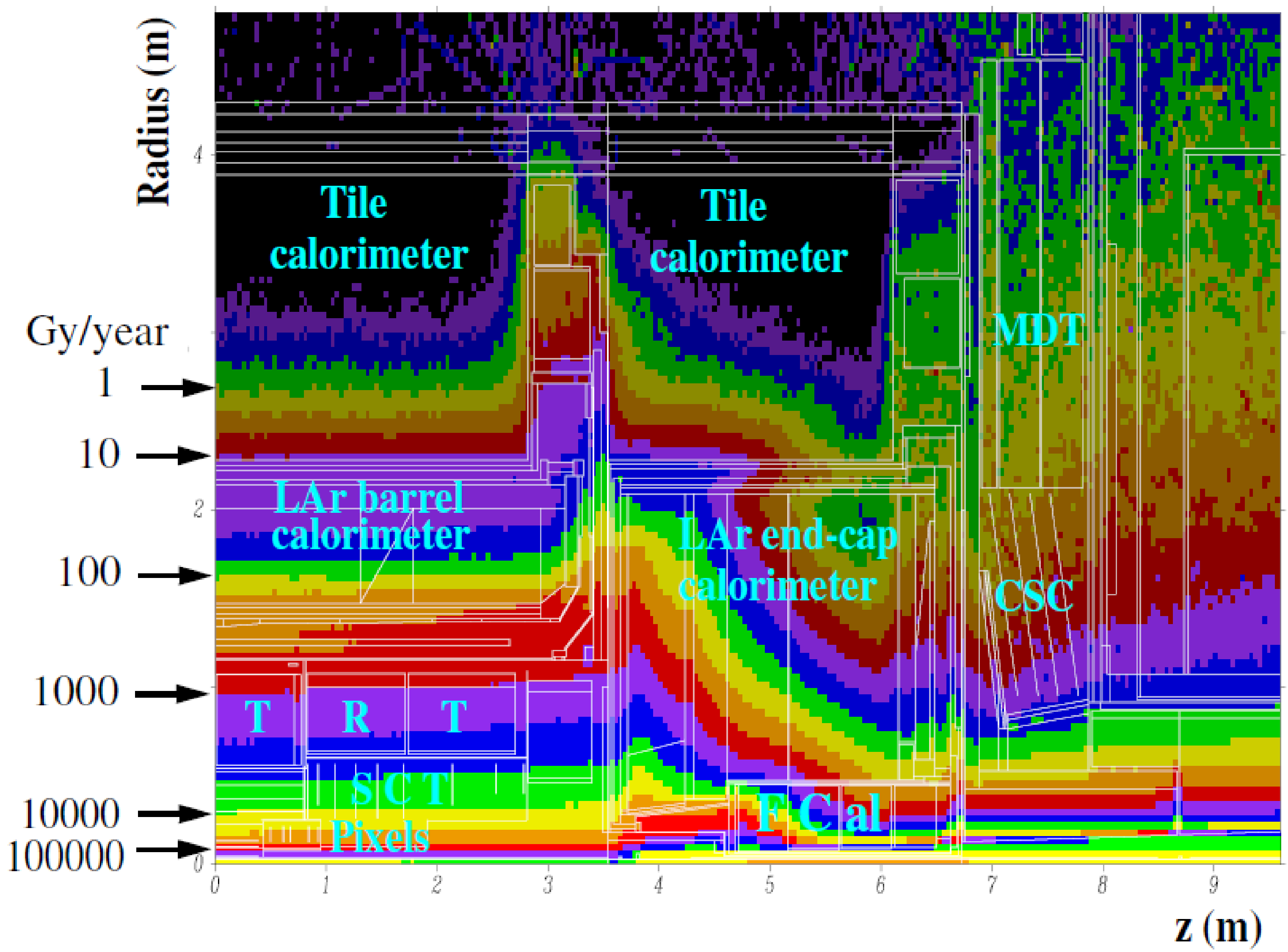
HO (HCAL Outer): Ersatz der HPDs durch SiPMs

HCAL: Ersatz der HPDs durch SiPMs, bessere longitudinale Segmentierung, Read-out + Trigger Upgrades

BCM (Beam Condition Monitor): neuer ASIC, neuer optischer Link, neue Sensoren

CASTOR: Ersatz der PMTs (Magnetfeld- und Strahlenhärte)

For 10**34


Radius (m)
Gy/year
1
10
100
1000
10000
100000
Tile calorimeter
Tile calorimeter
MDT
LAr barrel calorimeter
LAr end-cap calorimeter
CSC
T R T
SCT
Pixels
FCal
z (m)
0
1
2
3
4
5
6
7
8
9
0
2
4

Road to higher luminosities and sLHC

Several possible machine upgrades are being explored which may allow higher luminosities:

“Phase-I”

2014/15 Linac4

Final focus quadrupoles (NbTi)

“Phase-II”

2017? Crab cavities

2020? Final focus quadrupoles (NbSn)

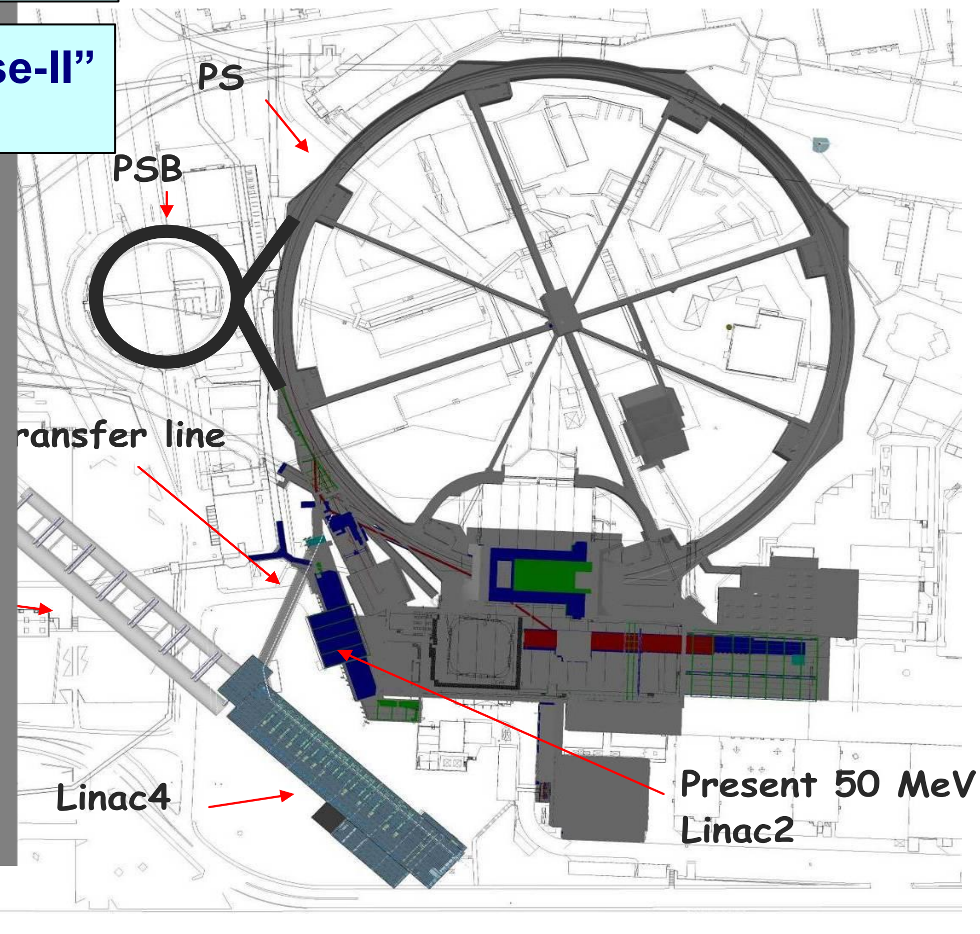
Later still, further injector upgrades possible:

SPL to replace PSB

New PS2 to replace PS

Improved SPS

...Will allow brighter beams, more reliability



Linac4

Goal is to increase the injection energy to PS Booster 50 -> 160 MeV

Allows twice the brightness (machine current/emittance)

Also use H- (previously p) and strip before injection; allows higher current densities

Also will increase reliability

Expected to be ready and tested end 2014

Will need 8 month shutdown to integrate into transfer tunnel

Will take time to tune PS to benefit from higher brightness

Linac4 construction well advanced (Aug 2009)

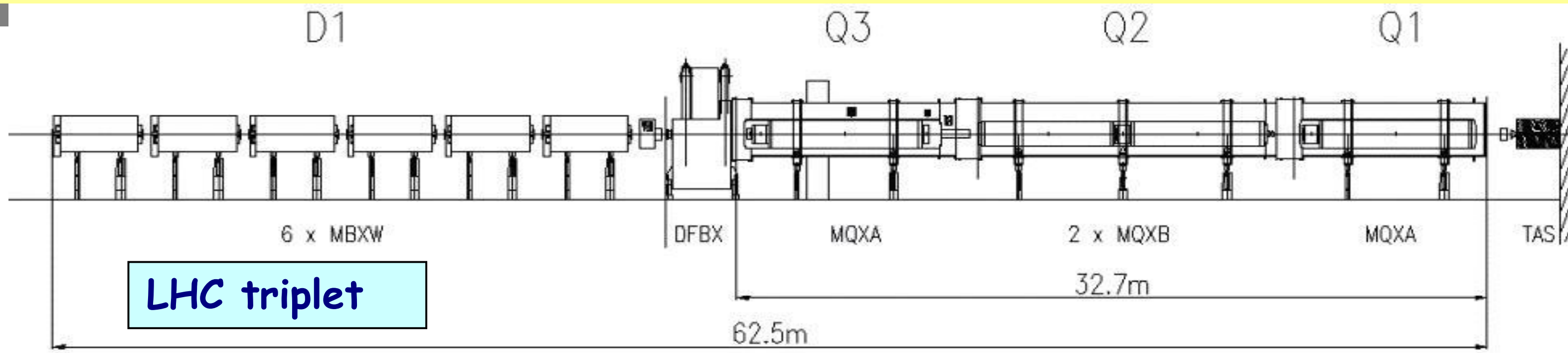
First Upgrade of final-focus quadrupoles

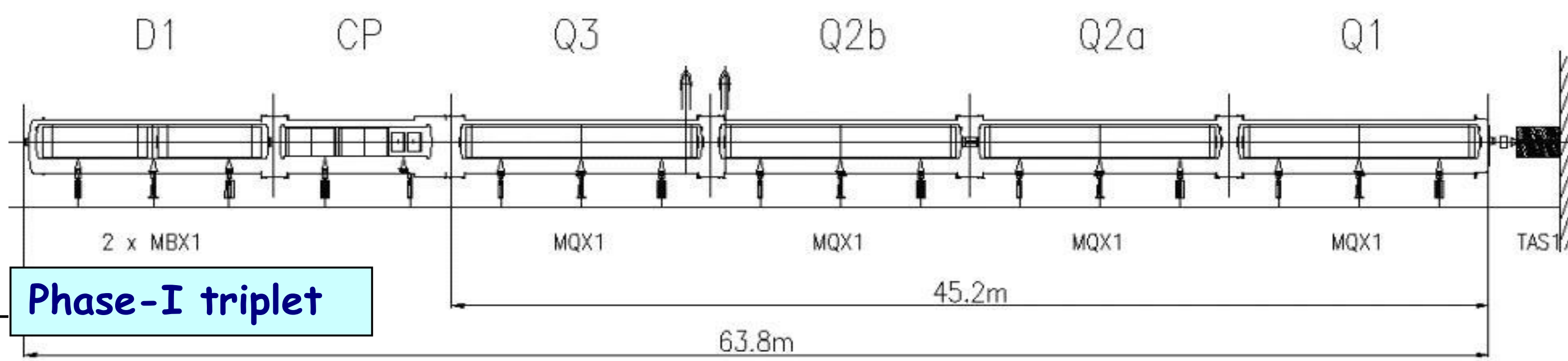
The new quadrupoles will use spare superconductor from the LHC programme (NbTi)

They will have wider aperture, allowing β* to reduce from 55 cm to ~30 cm

The current quadrupoles can safely cope thermally with up to nominal luminosity; the new ones will cope with at least 3 times nominal

Schedule less certain; hopefully same time as Linac4



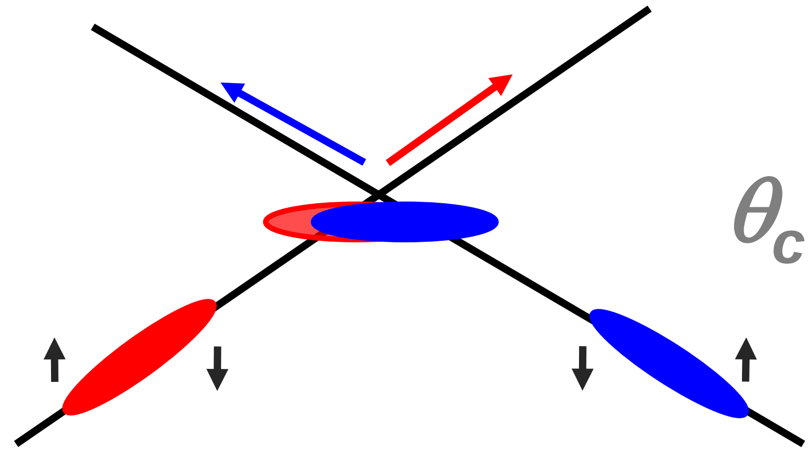


CRAB Cavities

Rotate the bunches so they move "sideways" (like a crab)

Allows a larger crossing angle, reducing beam-beam interactions, while ensuring each proton sees all those in the other bunch

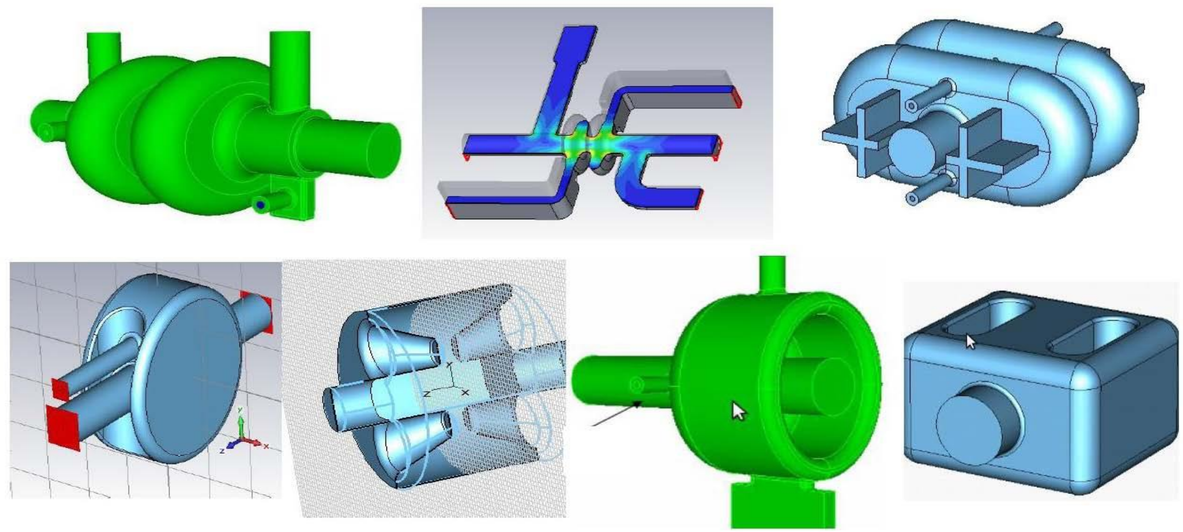
First proposed in 1988, now used in KEK to achieve record luminosity



Many designs under study

Propose to test in interaction region 4 of LHC, installation 2014/15?

Timescale for deployment ~2018?



Luminosity Levelling

Both the machine and the experiments have major challenges to cope with very high instantaneous luminosities

For example, in the machine, the heat-load on the focussing quadrupoles can cause quenches

The beam life-time becomes very short (a few hours) while the fill time remains 5 – 10 hours, so efficiency drops

For the experiments, it can mean trying to cope with 360 – 480 pile-up events per bunch crossing, deteriorating calorimetry performance and requiring very high granularity and data rates in the inner trackers, which in turn lead to more material

Luminosity Levelling

Several options are available for starting collisions "detuned" giving lower peak luminosity, and changing during the spill to maintain that luminosity:

reduce β^* in steps; increase CRAB voltage; slowly reduce the bunch length

These scenarios are much preferred and will be investigated

They could lead to peak pile-up of minimum bias events in the range 80 – 150 for the experiments – much easier to handle

Levelling can lead to higher integrated luminosity if you can have a high machine fill and peak luminosity is limited (e.g. by interaction region quadrupoles)

Further developments...

NbSn Quadrupoles

NbSn can stand higher fields at higher temperatures: allows large aperture, high field gradient quadrupoles, giving a further reduction in β^* (~11 cm) and coping with higher heat loads

Difficult material to work with; Fermilab leading the development

Should allow significant increase above 3 x nominal

Injector Chain

Further improvements will be much more costly, such as a new SPL, PS (PS2), and upgrades to the SPS

Possibly targetted after 2020

Summary Possible ATLAS/LHC Upgrades Timeline

2009 — **Start of LHC (Confirmed!)**

Ramp up luminosity to nominal (10^{34} cm^{-2} s^{-1}) and energy to 7 TeV per beam

2015 — **Bring in Linac4 and new quadrupoles – Phase-I Upgrade**

Ramp up luminosity to 2.5 x nominal

2018 — **CRAB Cavities**

Ramp up luminosity to peak 4.5 x nominal, and then start lumnosity levelling going to ~300 fb^{-1} per year

2020 — **Major ATLAS Upgrade: Phase-II with new inner tracker and forward calorimeter and muon chambers**

Collect data until > 3000 fb^{-1}. New machine injectors PS2, SPL, ...

2030 — **ILC ?**