LHC Upgrade: Detectors

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IFIC Valencia

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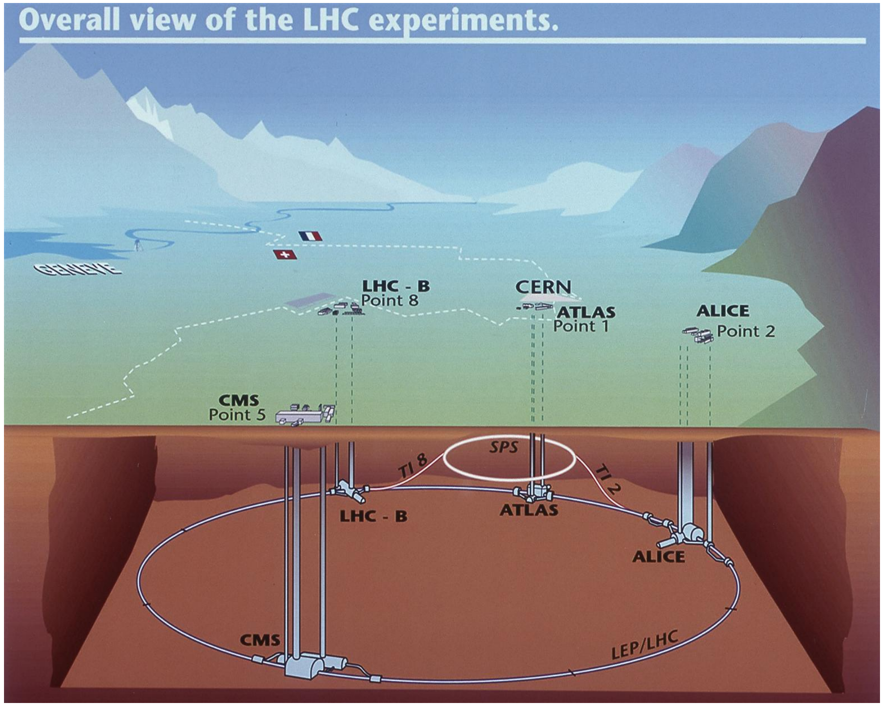
Overview

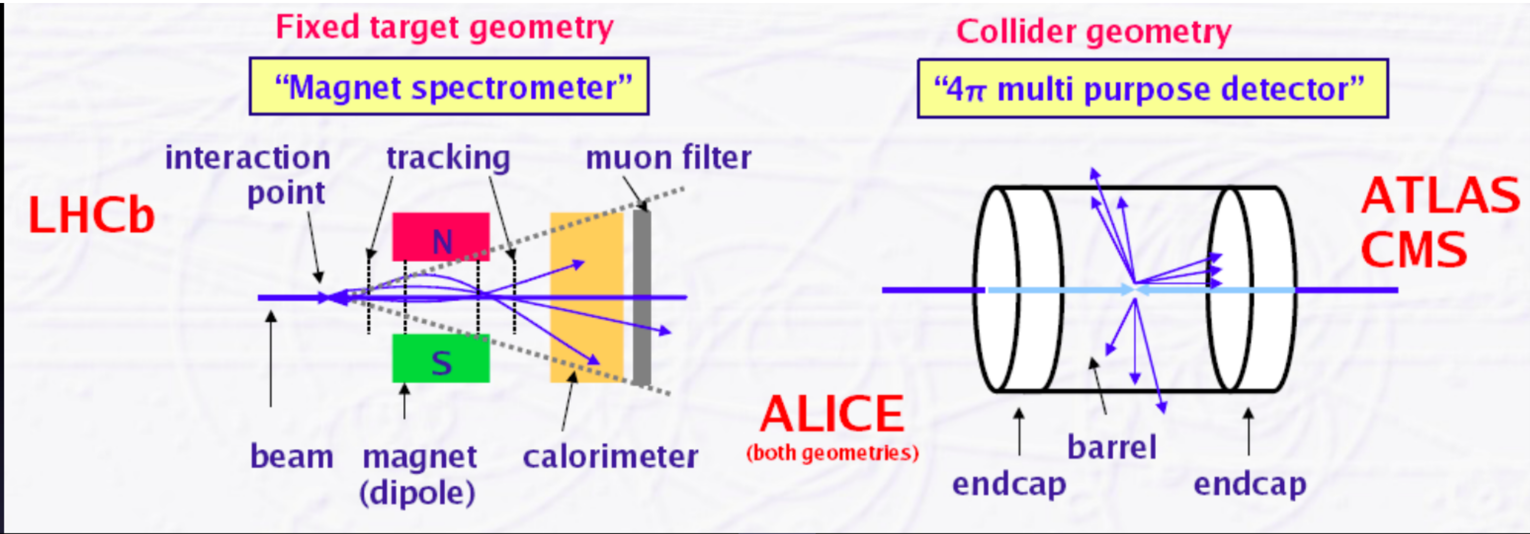
- Introduction to LHC detectors
- Upgrades of the LHC
- Detector upgrades of the experiments: ATLAS and CMS
  - Tracking detectors: silicon
  - Calorimeters
  - Muon detectors
- Detector upgrades of the LHCb and ALICE experiments
  - Silicon and Time Projection Chamber

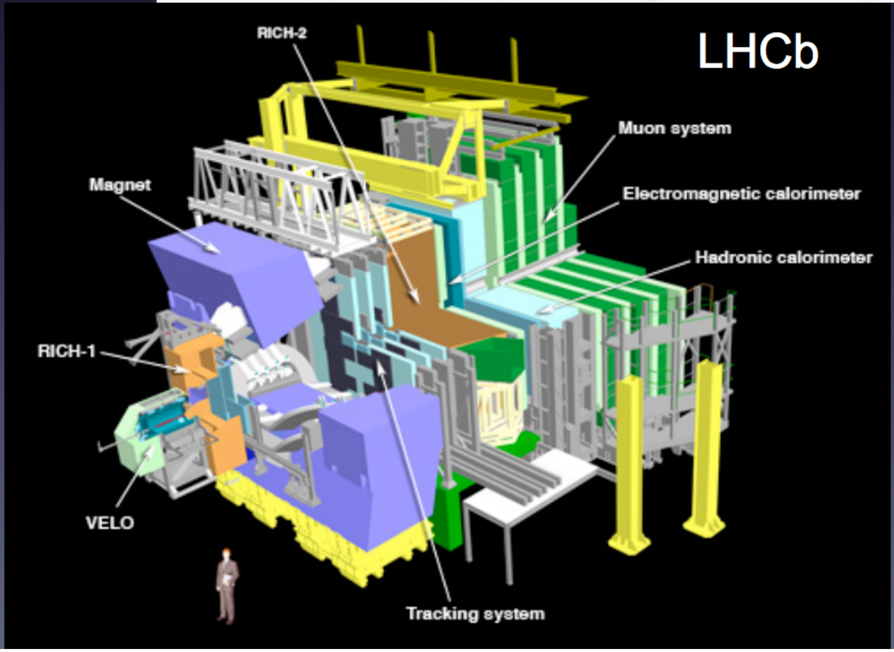
Large Hadron Collider

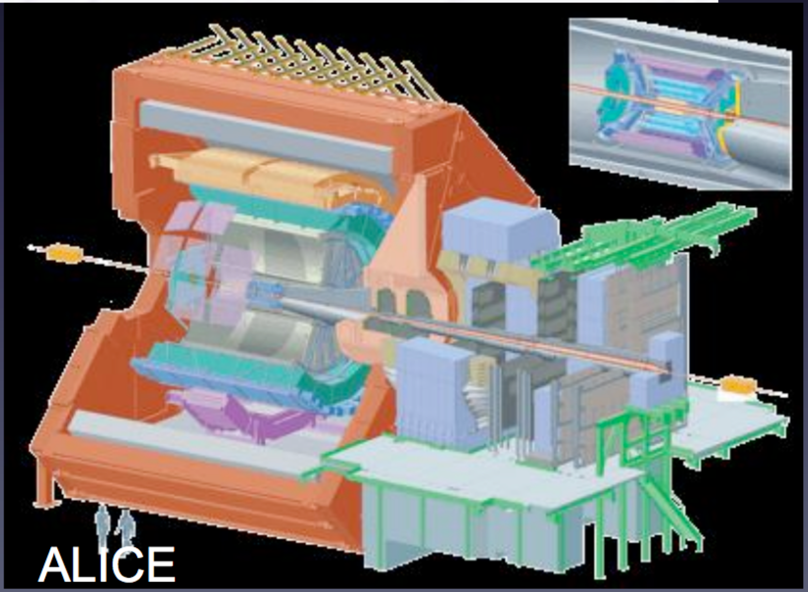
- p-p, p-HI, HI-HI collider
- up to 14 TeV p-p collisions



Configuration of HEP detectors

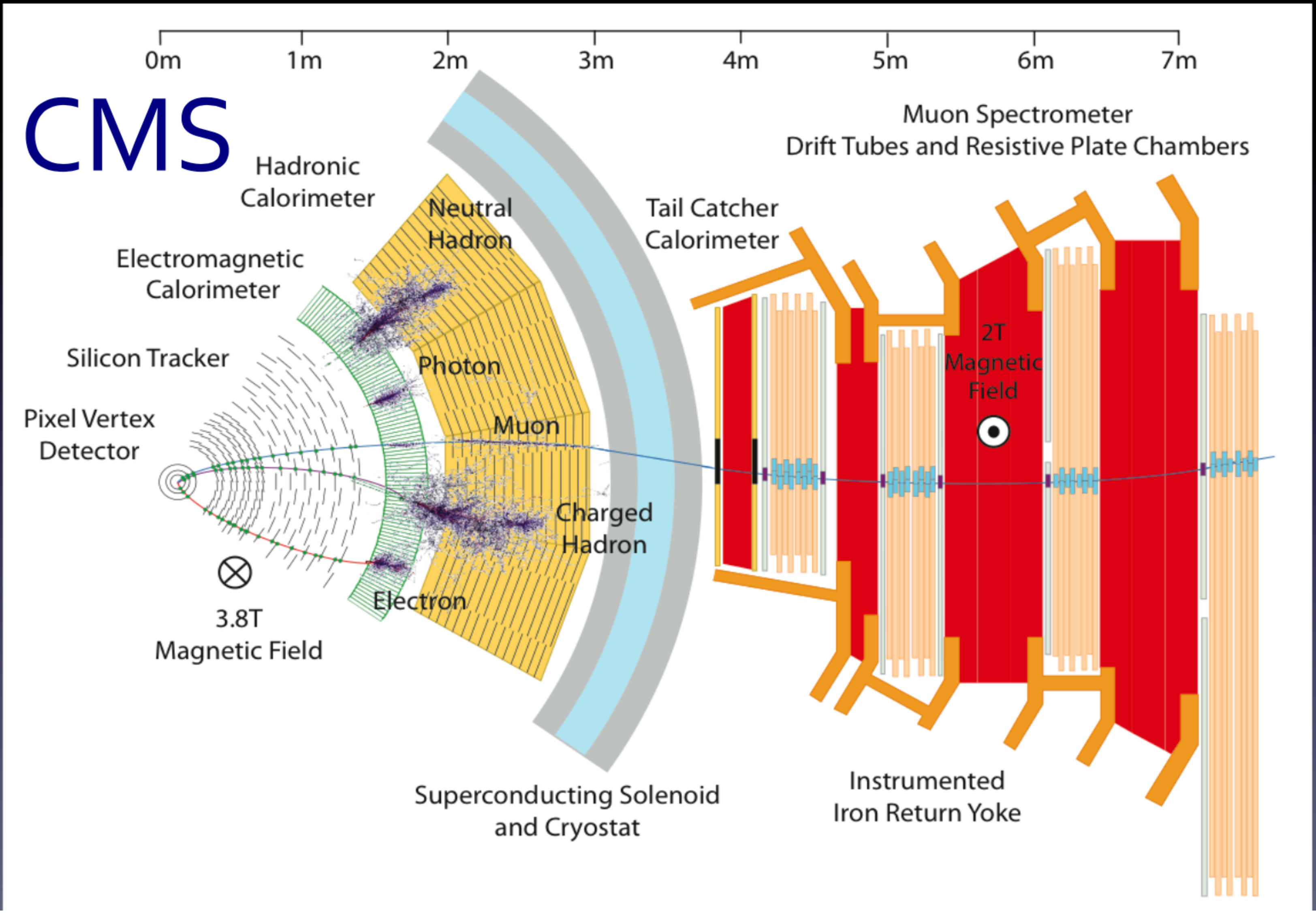






Configuration of multipurpose detectors

Particle flow reconstruction



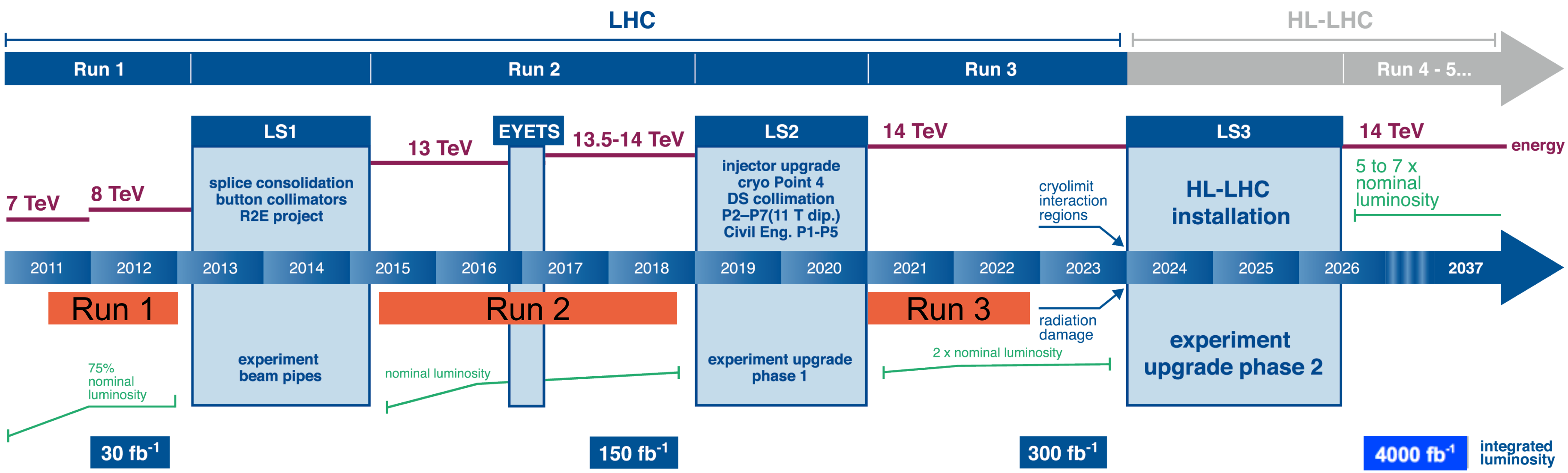
Results with LHC data

- Experiments at LHC have produced many interesting results
- LHC measurements have lead to the exclusion of some popular models
- Probing of Standard Model Higgs Sector and TeV-scale BSM requires more data

→ **High-Luminosity LHC**

Towards the High-Luminosity LHC

LHC / HL-LHC Plan



$L \sim 1 \cdot 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch spacing, pile up <μ>~40

$L \sim 2 \cdot 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch spacing, pile up <μ>~60

$L \sim 5\text{-}7 \cdot 10^{34}\ cm^{-2}s^{-1}$
Luminosity levelling, pile up of up to <μ>~140

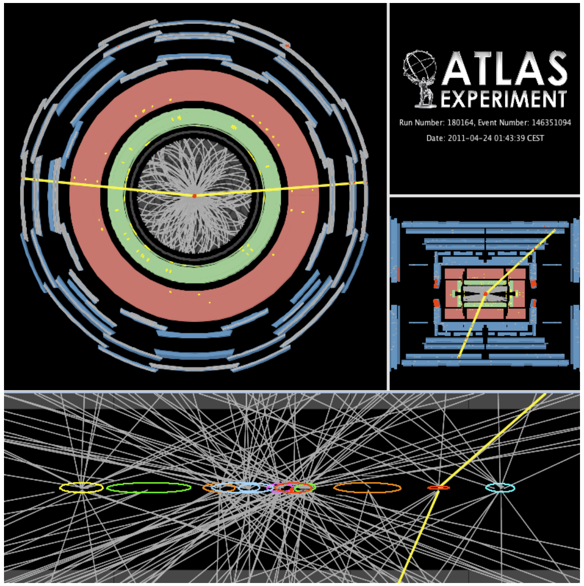
From LHC to HL-LHC

Instantaneous luminosity x5 (for ATLAS, CMS, LHCb) → Particle densities x5-10

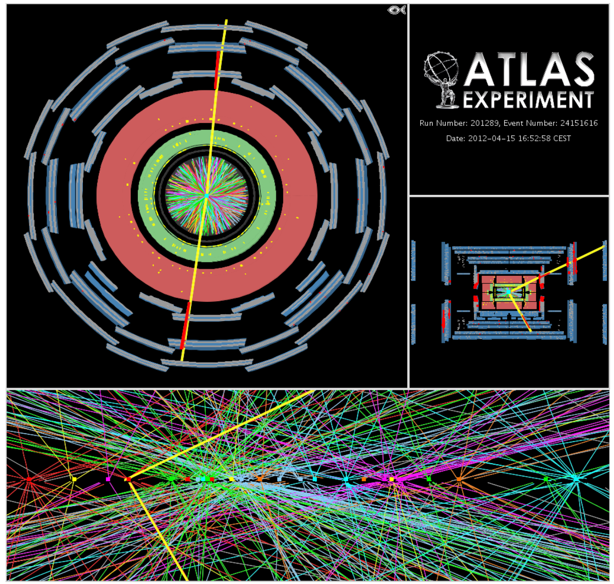
Integrated luminosity x10 (for ATLAS, CMS, LHCb) → Radiation damage x10

Increase of overlap of pp events (pile up x3-5)

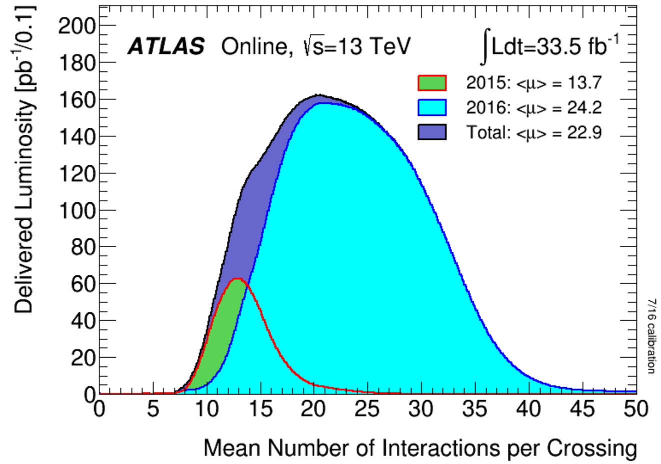
Collisions from LHC to HL-LHC



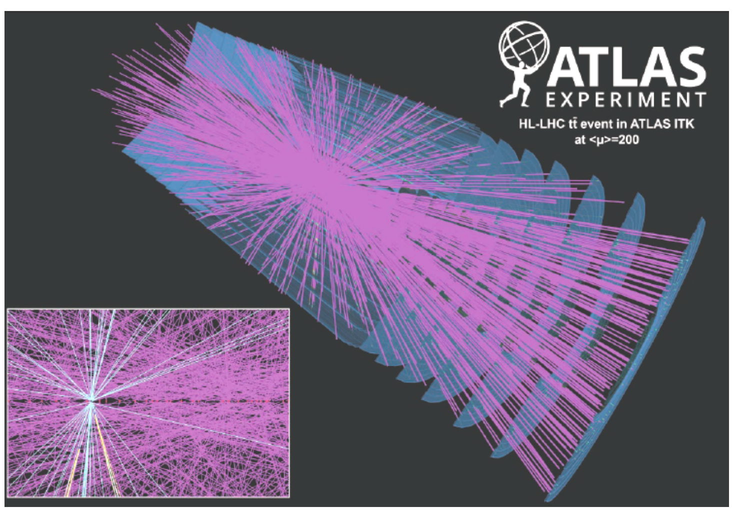
2011:
$\sqrt{s}$ = 7 TeV
L_{peak} = 2.1x10 ^{32} cm^{-2}s^{-1}
<μ> = 10 - 15



2012:
$\sqrt{s}$ = 8 TeV
L_{peak} = 4x10 ^{33} cm^{-2}s^{-1}
<μ> = 20



2016:
$\sqrt{s}$ = 13 TeV
L_{peak} = 1.4x10 ^{34} cm^{-2}s^{-1}
<μ> = 24

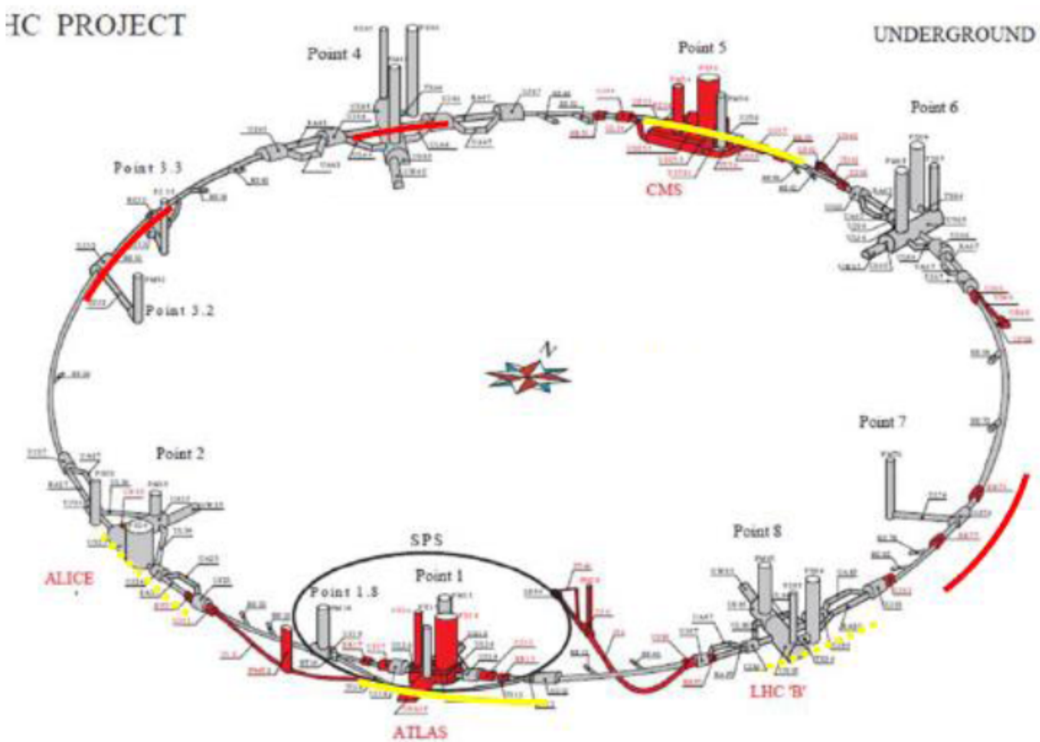


Simulated event with ttbar events and average pile-up of 200 collisions per bunch crossing

2026:
$\sqrt{s}$ = 14 TeV
L_{peak} > 10 ^{35} cm^{-2}s^{-1}
<μ> = 200

HL-LHC for Run 4+

- Shutdown of 30 months
- Aim for maximal luminosity of 4000 fb^{-1}

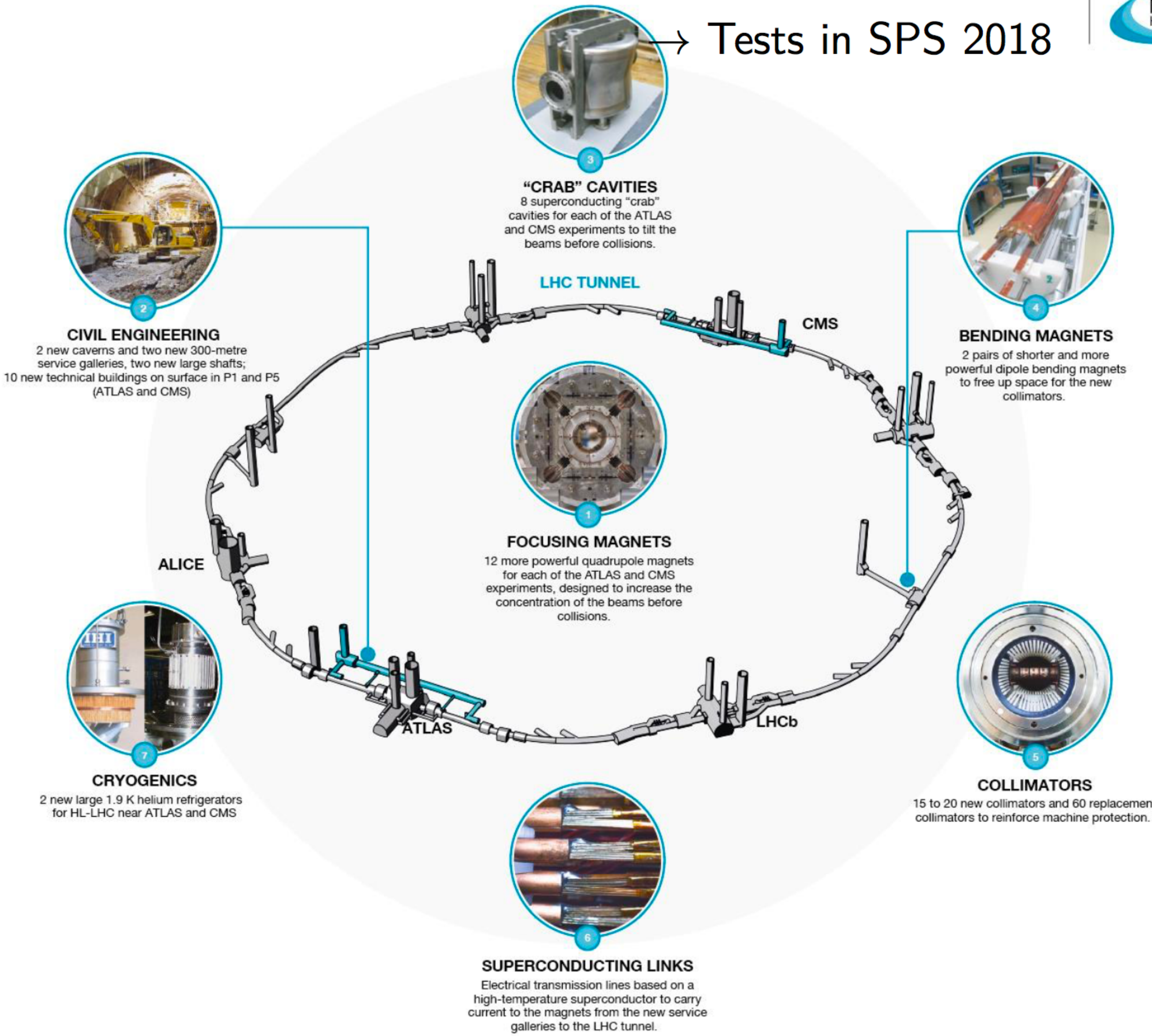


- Cryogenic system upgrade
- New large aperture triplet magnets (Nb_3Sn)
- New 11 T insertion magnets (NbTi)
- Crab Cavities
- Collimation upgrade
- Machine protection
- ...

Major intervention on more than 1.2 km of the LHC

HighLumi LHC landmarks

→ Tests in SPS 2018



How to get to HL-LHC

Lower beta* (~15 cm)

New inner triplet magnets - wide aperture Nb_3Sn
Large aperture NbTi separator magnets
Novel optics solutions

Dealing with the regime

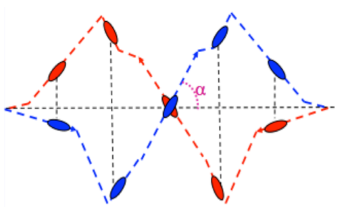
Collision debris, high radiation

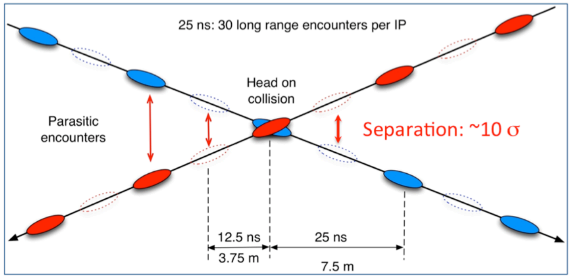
Beam from injectors

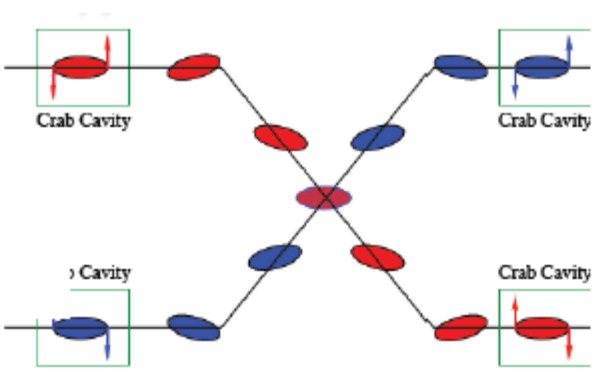
High bunch population, low emittance, 25 ns beam

Crossing angle compensation

Crab cavities

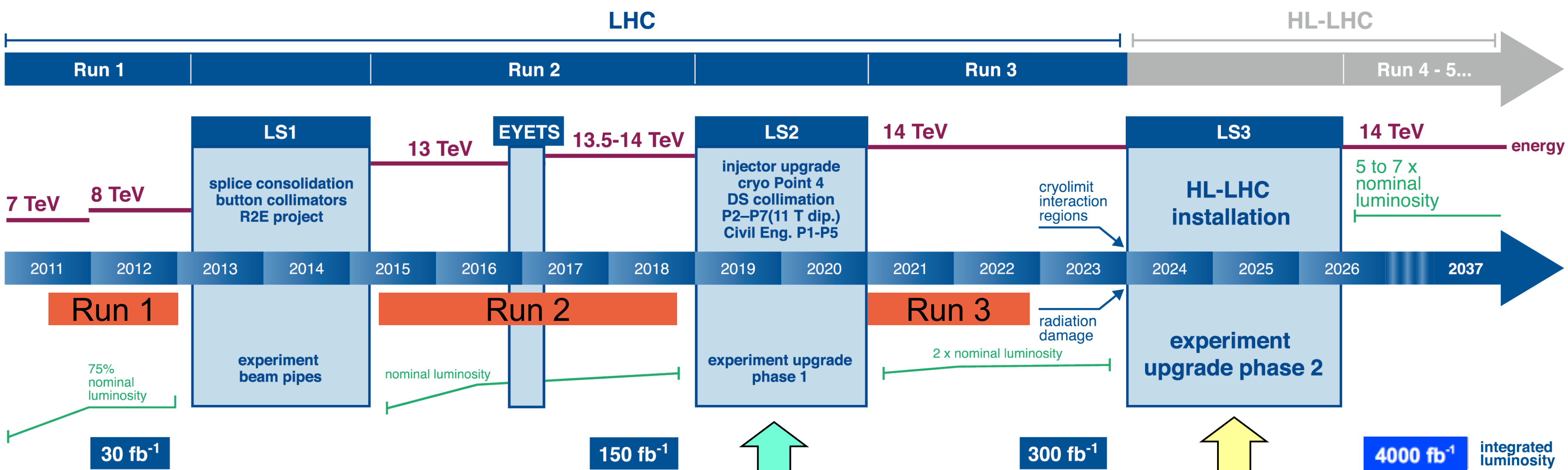






Towards the High-Luminosity LHC: Detectors

LHC / HL-LHC Plan



Phase "1"
CMS Pixel
Upgrade

Phase-1
Detector
Upgrade in
ATLAS and
CMS

Major Upgrade
in ALICE and
LHCb

Phase-2
Major Upgrade
in ATLAS and
CMS

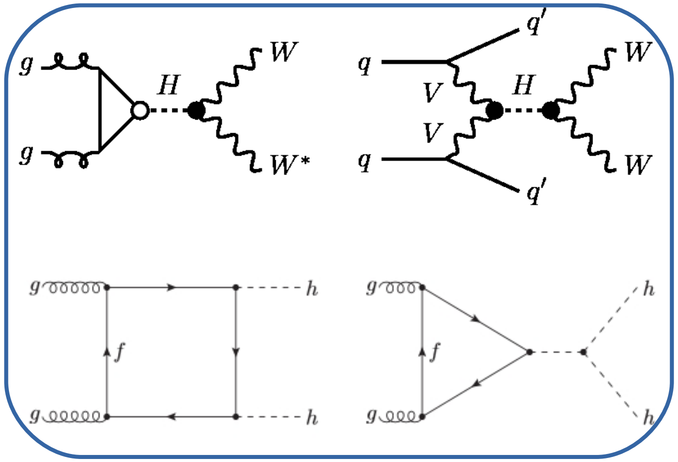
All experiments will modify or upgrade their detectors in LS2 and LS3.
Too much material to cover.
Focus on selected ones!

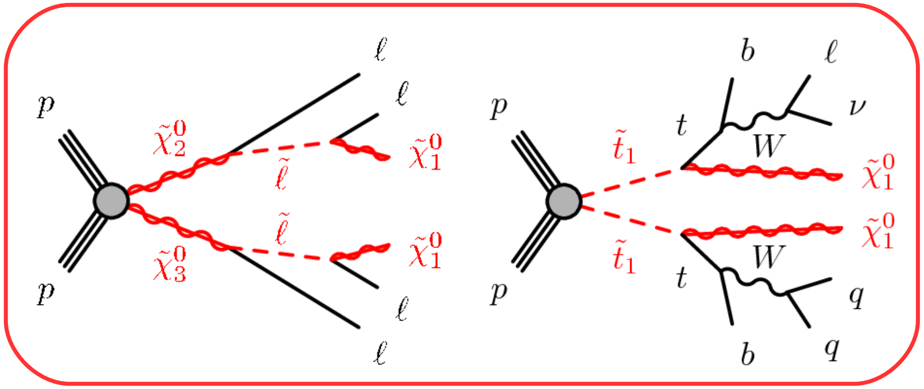
Lecture 2

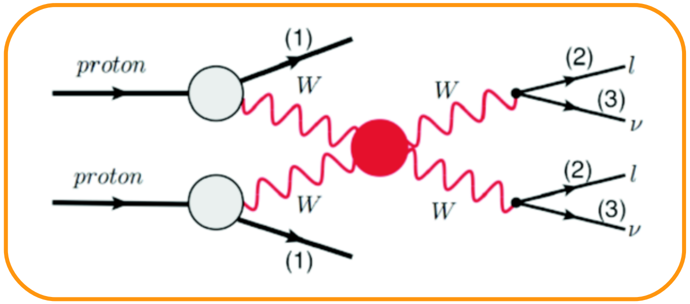
Lecture 1

Physics goals at the HL-LHC

- Higgs Precision Measurements
- Vector-Boson-Scattering Precision Measurements
- Searches for BSM Physics

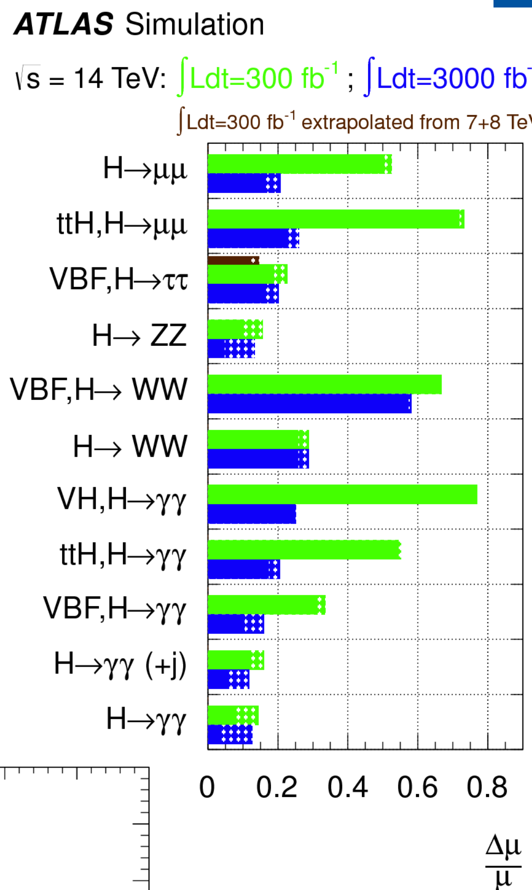


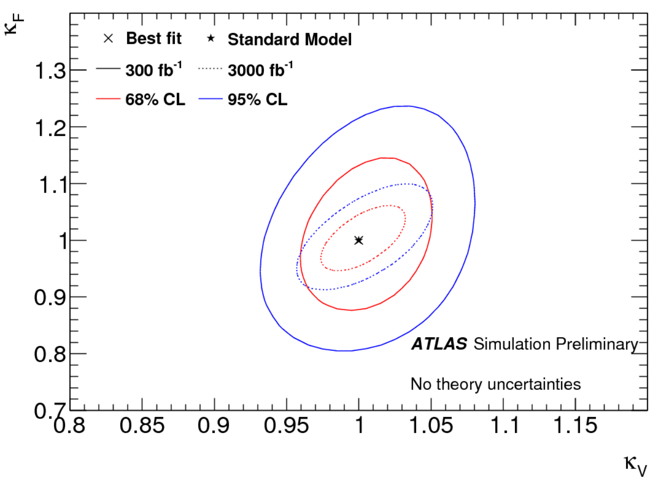




Higgs Couplings

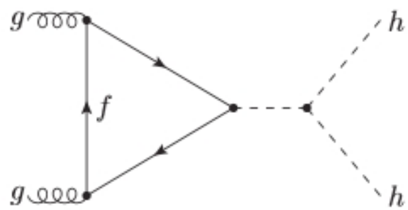
- Higgs couplings highly sensitive to BSM physics
- With HL-LHC dataset significant improvement in precision
- Study based on following channels
  - H → gg
  - H → ZZ* → 4l
  - H → WW* → lνlν
  - H → tt
  - ttH, H → gg and H → μμ
  - WH/ZH, H → gg
  - H → μμ



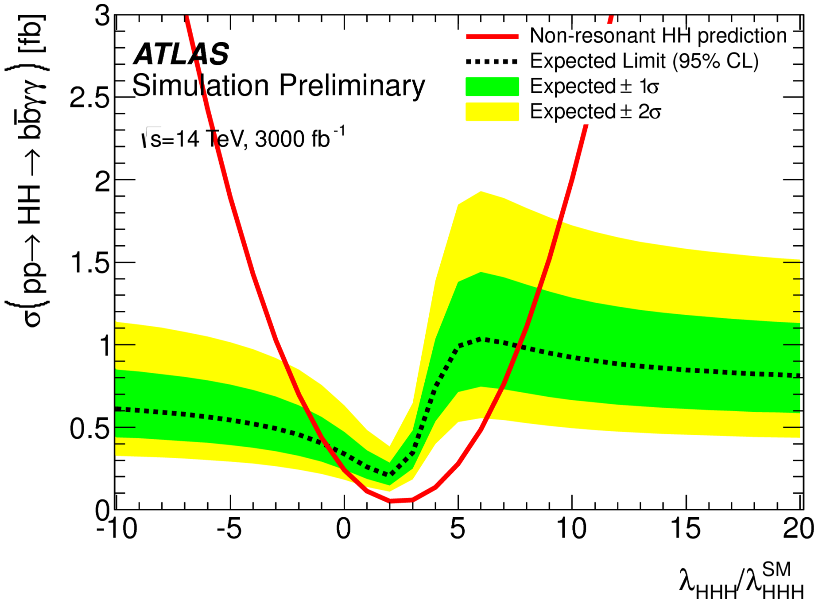


Higgs Self Coupling

- Double Higgs Production → direct handle on Higgs self coupling
- H (→ bb) H (→ gg) final state considered → clean final state und sufficiently large branching fraction



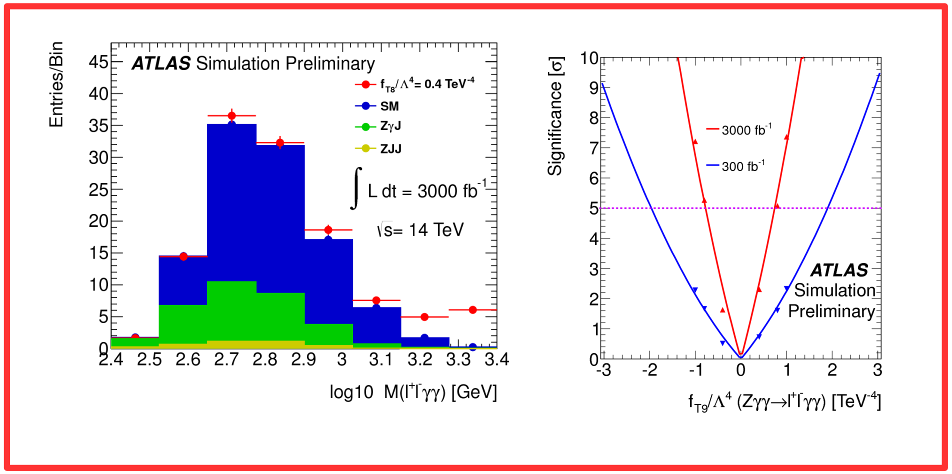
Event Selection Criteria
$\geq$ 2 isolated photons, with $p_T > 30$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$
$\geq$ 2 jets identified as b-jets with leading/subleading $p_T > 40/30$ GeV, $\lvert\eta\rvert<2.4$
< 6 jets with $p_T > 30$ GeV, $\lvert\eta\rvert < 2.5$
No isolated leptons with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
$0.4 < \Delta R_{b\bar{b}} < 2.0, 0.4 < \Delta R_{\gamma\gamma} < 2.0, 0.4 < \Delta R_{\gamma jet}$
$122 < m_{\gamma\gamma} < 128$ GeV, $100 < m_{b\bar{b}} < 150$ GeV
$p_T^{\gamma\gamma}, p_T^{b\bar{b}} > 80$ GeV

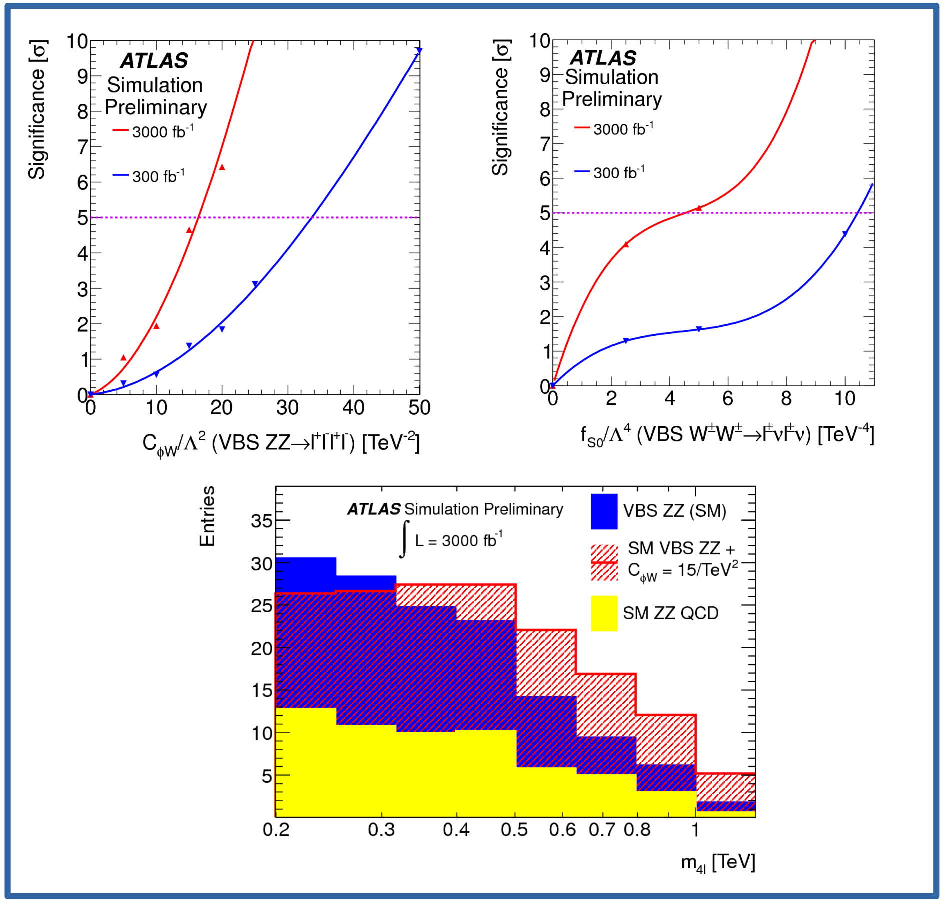


ATL-PHYS-PUB-2017-001

Vector Boson Scattering

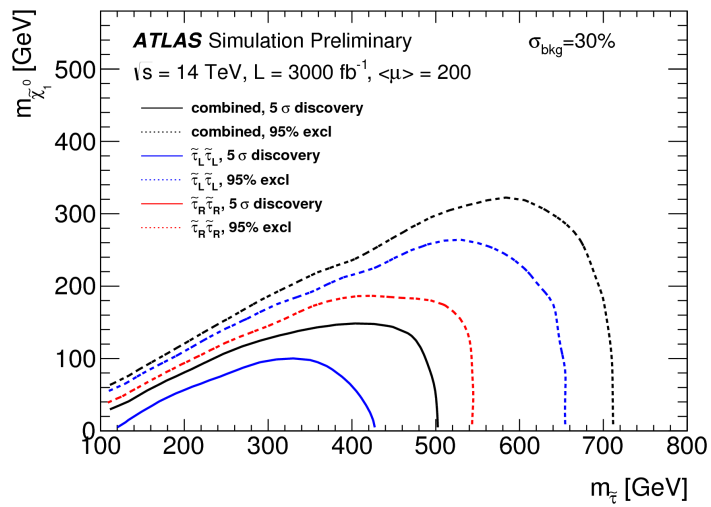
- Expected new physics at the TeV-Scale → VBS cross section
- Higgs discovery solves this problem → experimental confirmation? Contributions from BSM physics?

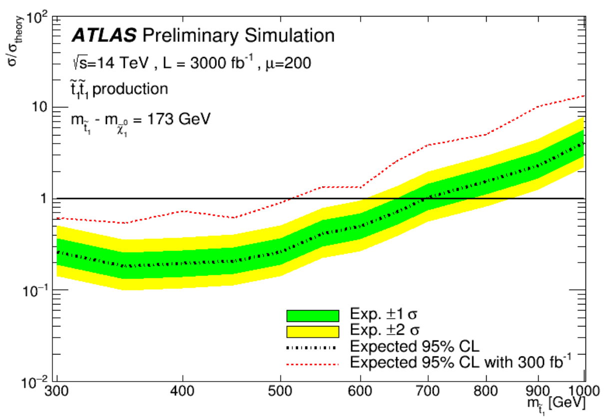


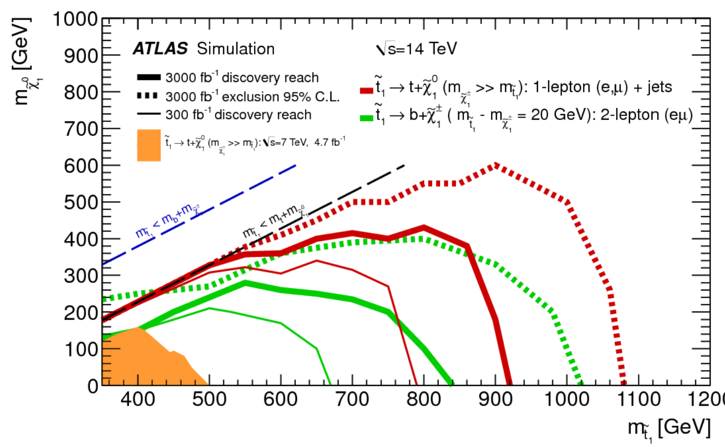


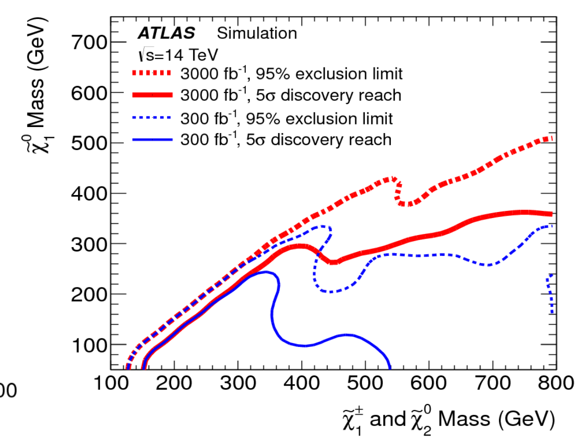
Searches for BSM Physics

- Mass range for SUSY searches largely enhanced
- Direct production of EW gauginos
- Direct production of staus
- Direct production of stops









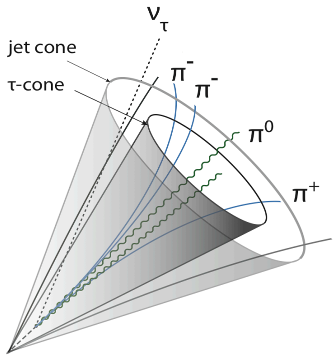
HL-LHC Physics Summary

- Rich physics programme at the HL-LHC
  - Higgs precision measurements: Precision tests of SM
  - Vector Boson Scattering: Probing BSM in the electroweak sector
  - Direct BSM searches: mass ranges extended and direct sensitivity to new processes

But: Measurements of final states extremely challenging

Requirements at the HL-LHC

- VBS/VBF: forward jets → forward tracking to reject pile-up by jet-vertex association
- SUSY cascades: triggering & reconstruction of low p_T leptons and identifying heavy flavour
- Resonances in top pairs, W, Z, H: reconstruction of leptons & b-quarks in boosted topologies
- High-mass gauge bosons: good lepton momentum resolution at high p_T
- Efficient tracking with small fake rates: radiation tolerance and high granularity tracking detector

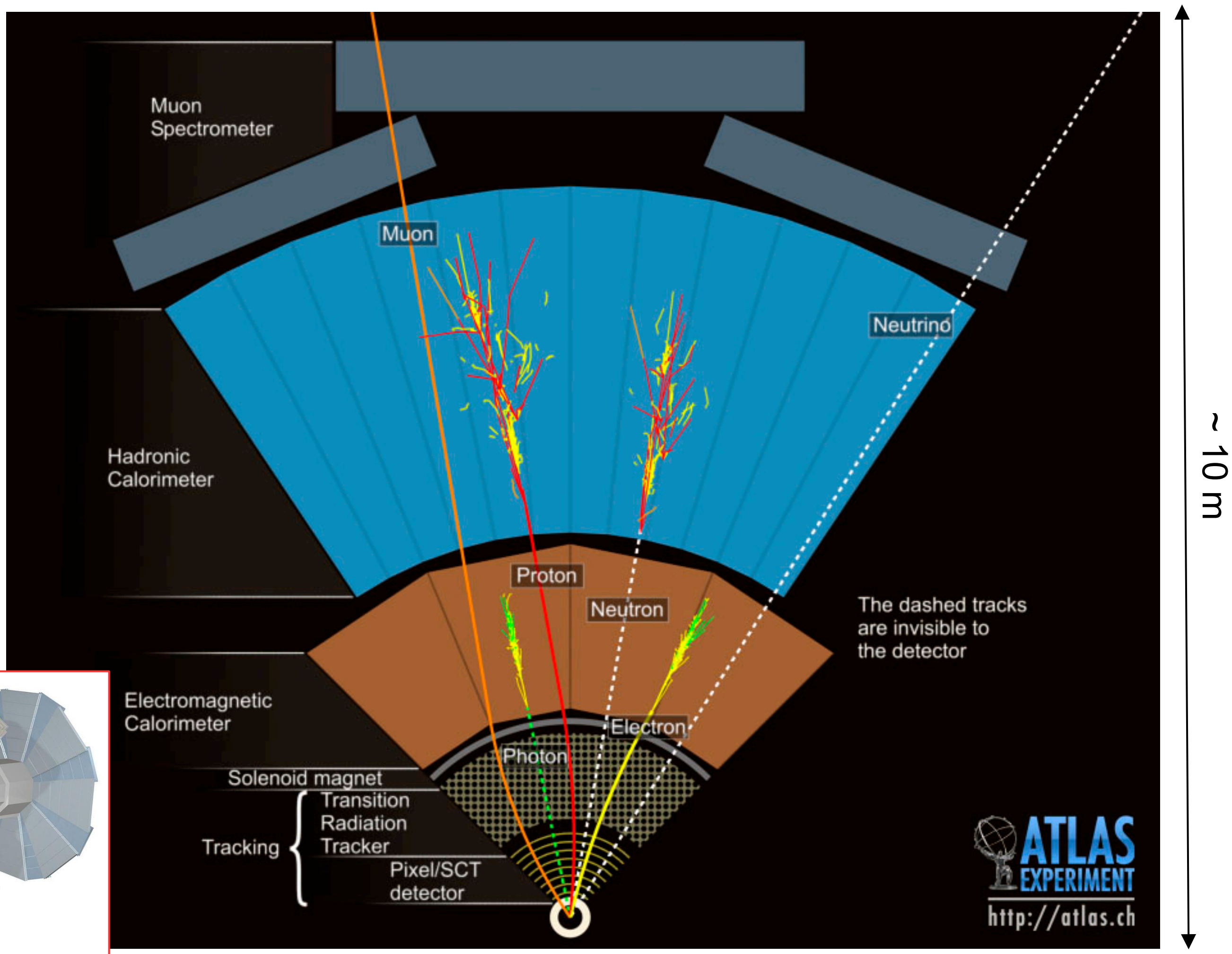


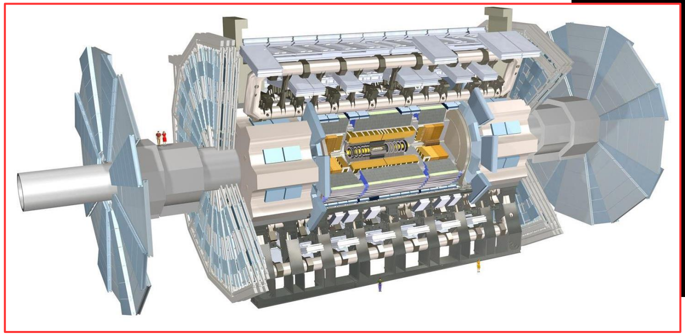
Challenging for detectors

Multipurpose detector in HEP

Layers of the ATLAS experiment at the LHC

- Different types of detectors to identify particles and measure their energy and momentum





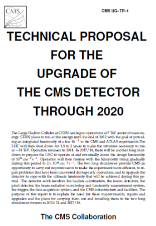
Phase-2 Detector Upgrade: ATLAS + CMS

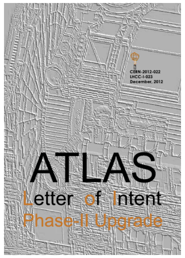
Trigger/DAQ:
Upgrades, add tracking at L1, partially new electronics

Tracking detector:
New all silicon tracking detectors for ATLAS and CMS with extended coverage to $|\eta| < 4$

Calorimetry:
ATLAS: New FE electronics for Tile and LAr calorimeter
CMS: Replace endcaps and replace electronics in electromagnetic calorimeter

Muon system:
ATLAS: New FE electronics and possible upgrade of muon spectrometer
CMS: Extend forward chambers and replace electronics



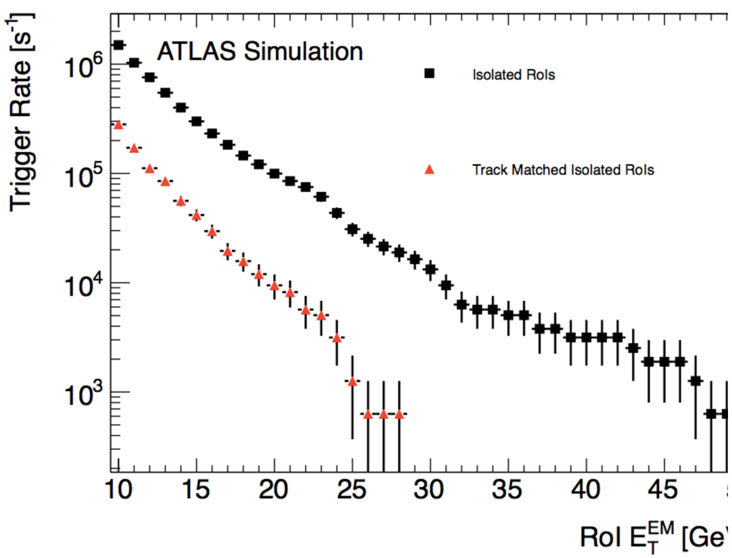


ATLAS: LHCC-I-023, CERN-LHCC-2012-022

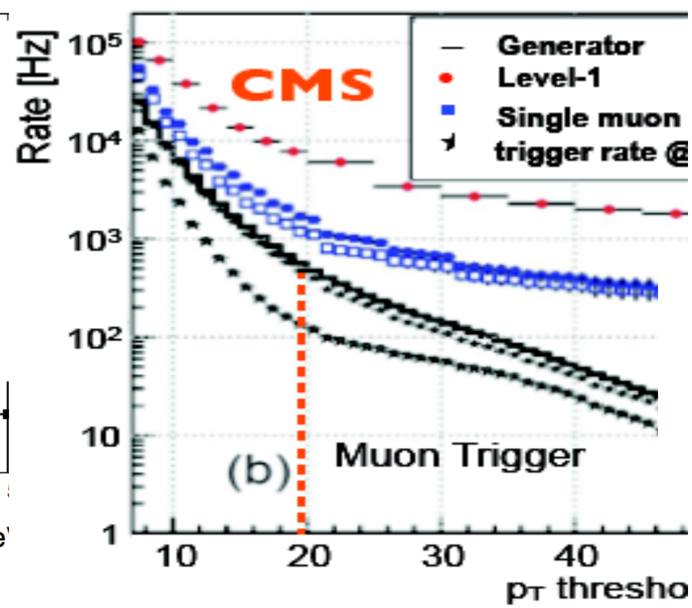
CMS: Technical preparation in preparation, LHCC-2011-006, LHCC-P-004

Triggering at the HL-LHC

- High luminosity → many interesting events
- High pile up (overlapping multiple interactions) and occupancy lead to decrease in resolution at trigger level
- Aim to keep low-p_T lepton triggers (~20-25 GeV)
  - → Matching tracking information to muon and calorimeter information
  - → Exploiting isolation for electron and tau identification and veto for photons



Single electron trigger rate @ 1E34 for <μ> ~ 140



Single muon trigger rate @ 1E34 for <μ> ~ 140

No track trigger

With track trigger

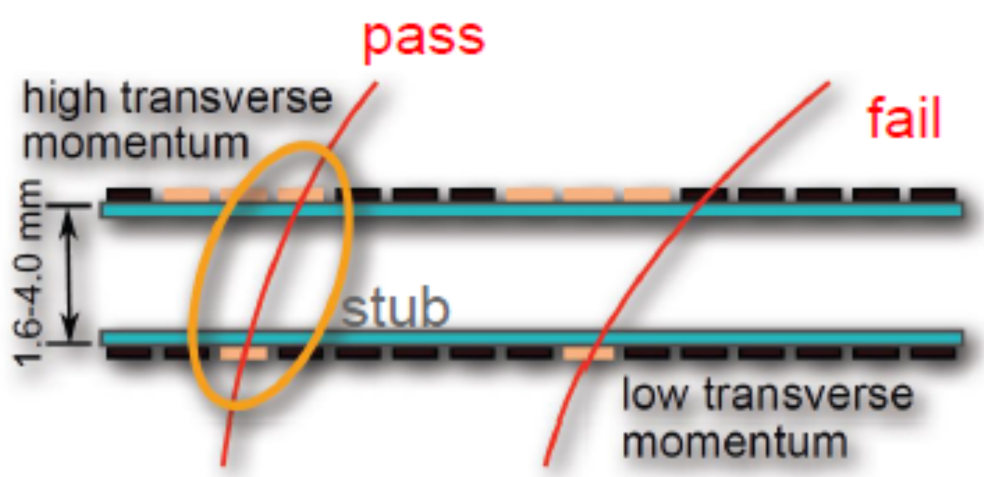
Upgrade Trigger Scheme in CMS

Key point: include tracking information with fast readout

Level 1	Rate ~ 1 MHz, muon + calo + tracks
HLT	Rate 10 kHz

Track trigger: silicon strip modules provide time and p_T discrimination → Rate reduction due to sharp thresholds (leptons) and isolation (multijet backround reduction)

p_T discrimination with stacked modules: exploit bending in magnetic field two closely spaced sensors read out by a single readout chip

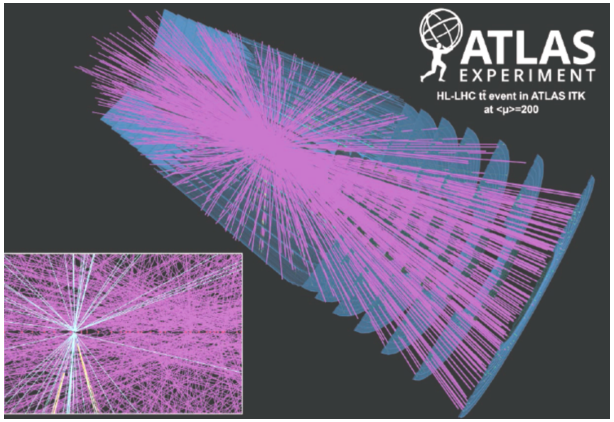


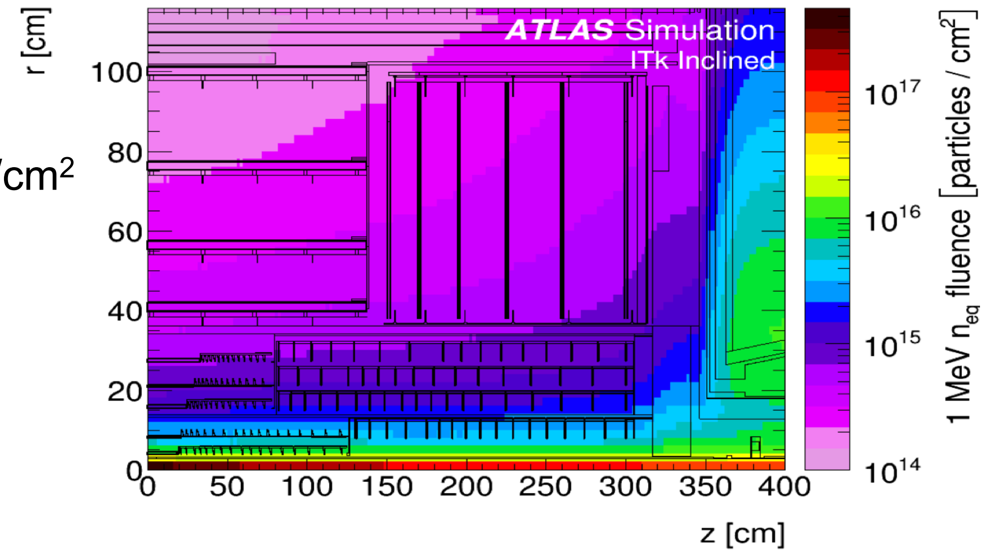
Sensor spacing optimized
Same geometrical cut corresponds to different p_T

→ Correlation on module level to form stubs is sent out if within p_T cut (down to 2 GeV)

Tracking detector challenges at the HL-LHC

- Luminosity of up to 7.5x10 ^{34} $cm^{-2}s^{-1}$
  - Triggering with high rate and large event sizes
- On average 200 interactions per bunch crossing
  - High occupancy → keep at 1% level by high granularity detector
- High particle fluences
  - Radiation hardness of up to 2×10^{15} n_{eq}/cm^2 for outer tracking layers, up to 2×10^{16} n_{eq}/cm^2 for inner tracking layers
- Low material budget advantageous

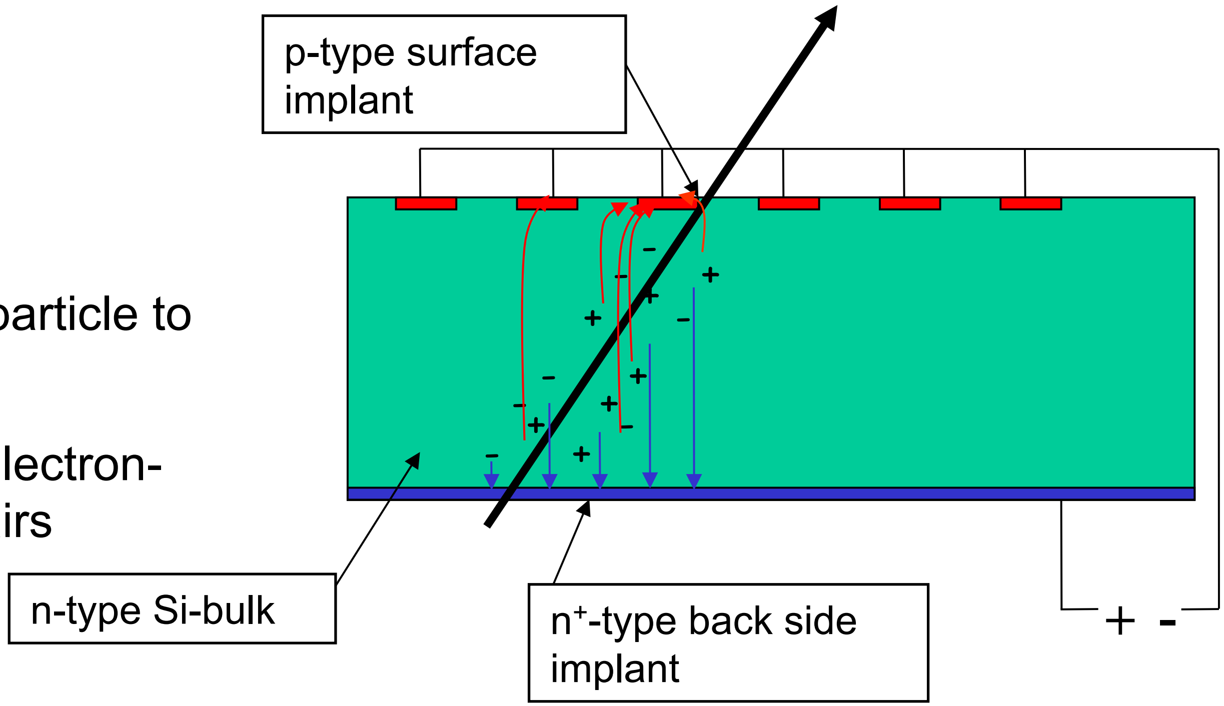




For ATLAS and CMS: new silicon tracking detector for Phase-2
Aim to keep performance of current detector under harsher conditions

Recap: Principle of a silicon detector: reverse biased depleted pn-diode

- Take a pn-diode
- Segment it
- Apply a bias voltage
- Wait for an ionising particle to deposit charge
  - Ionisation → Electron-hole (e^-, h^+) pairs

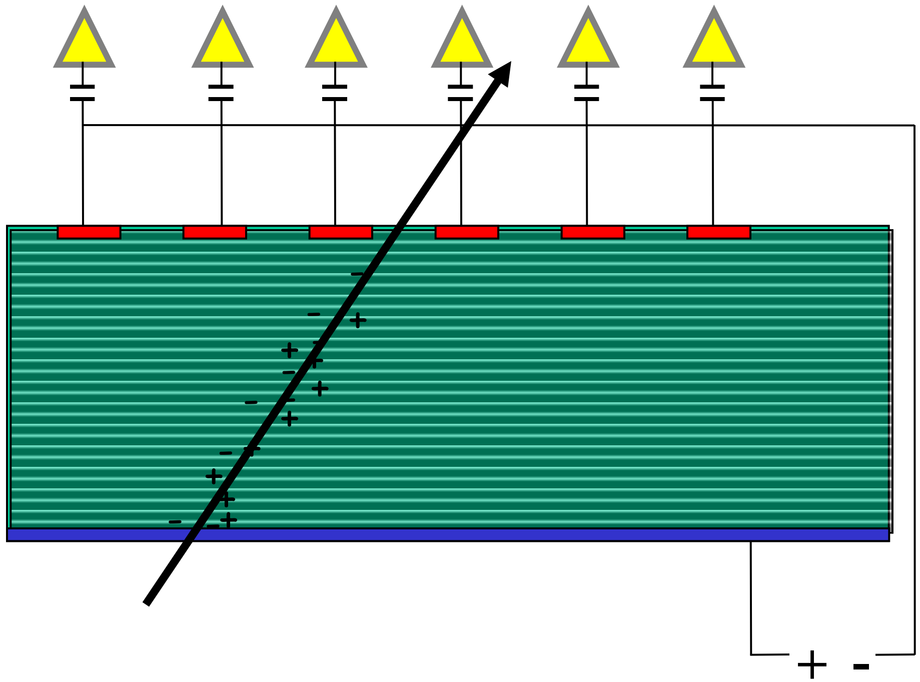


- Charges separate and drift in the electric field

Recap: Principle of a silicon detector: Signal

→ Segmented and depleted piece of silicon and an ionising particle generates electron-hole pairs

- e^-h^+-pairs separate in E-field, and drift to electrodes
- Moving charges → electric current pulse
- Small current signal is amplified, shaped and processed in integrated circuits ("chips") on read-out electronics

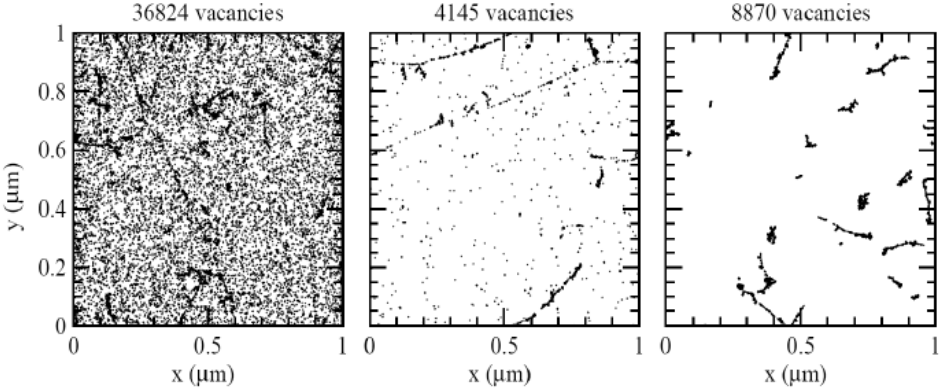


Typical drift velocity 50 µm/ns (drift time ~ 6 ns, in 300 µm)
With fast read-out electronics: signal collected in few ns

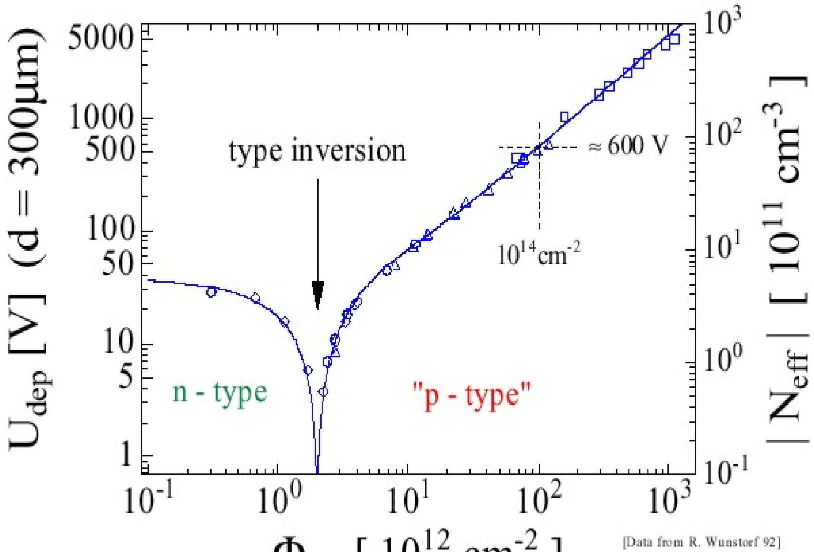
Recap: Radiation damage in silicon sensors

Radiation damage: non-ionising energy loss of charged and neutral particles → damage in silicon bulk (defects: recombination/generation centers)

- Increase of leakage current
- Generation of charged centers, which change effective doping concentration
  → Type inversion (n-doped material becomes p-doped, eventual loss of resolution)
- Increase of depletion voltage
- Centers act as trapping centers affecting the charge collection efficiency



Simulated defects in silicon after 10 MeV protons, 24 GeV protons and 1 MeV neutrons at $1 \cdot 10^{14}$ N_{eq}/cm^2



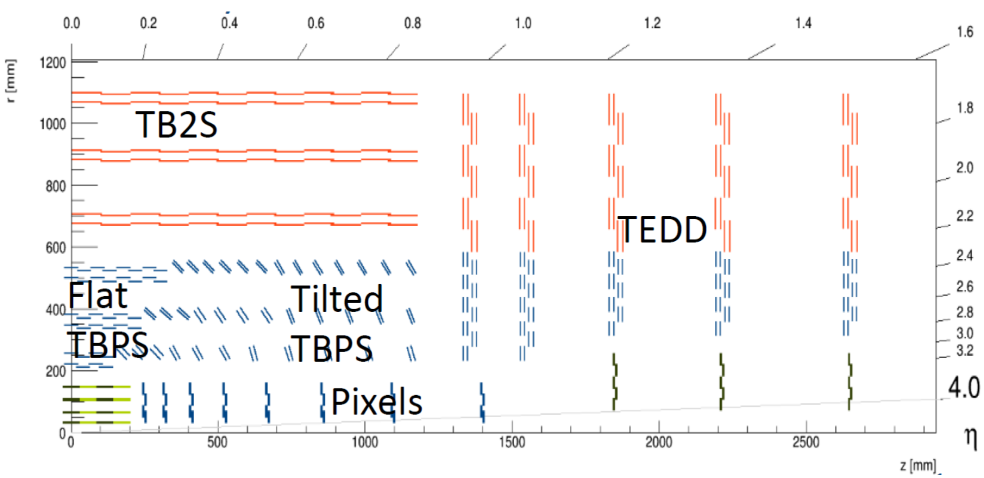
[M. Moll DESY-THESIS-1999-040]

➢ Radiation damage degrades detector performance and limits life time

Upgrade of ATLAS and CMS trackers

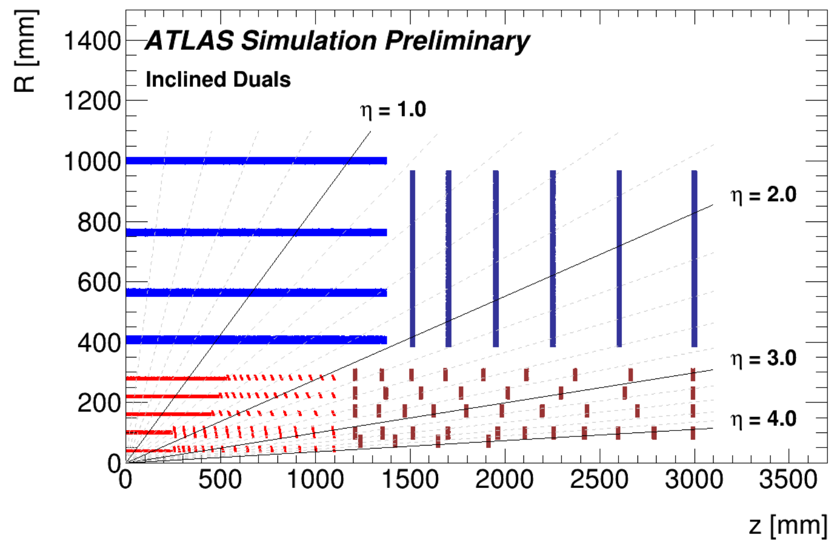
- Inner region: Pixel detector modules
- Outer region: Strip detector modules

CMS



Detector	Area [m^2]	Layers (B+EC)
CMS Pixel	4.9	4 + 11
CMS Outer	218	6 + 5

ATLAS

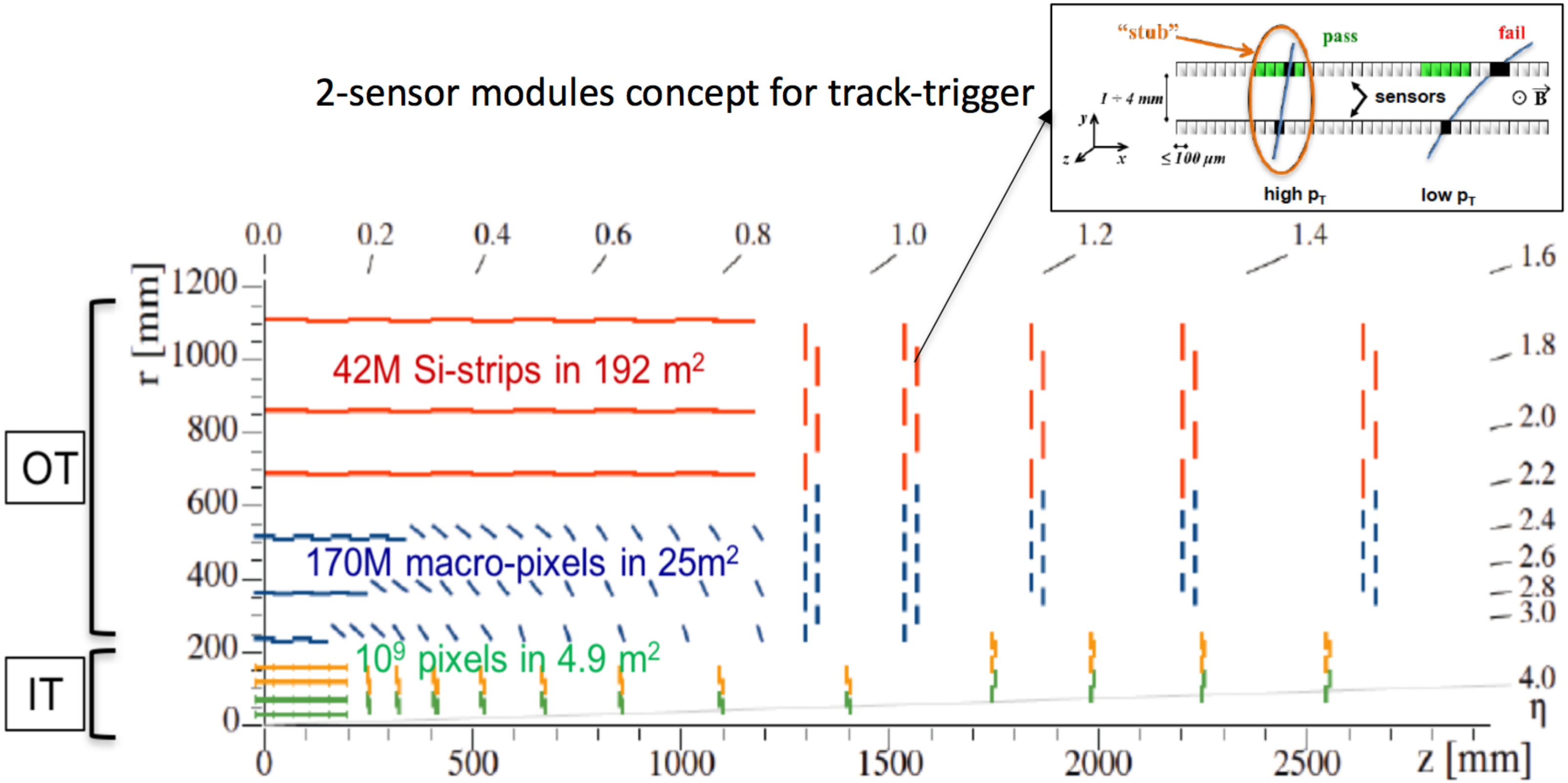


Detector	Area [m^2]	Layers (B+EC)
ATLAS Pixel	~13	5 + 6-8
ATLAS Strip	160	4 + 6

- Extended coverage to forward region
- Fast data transmission with low power giga-bit data transmission
- CO_2 cooling (thinner pipes)

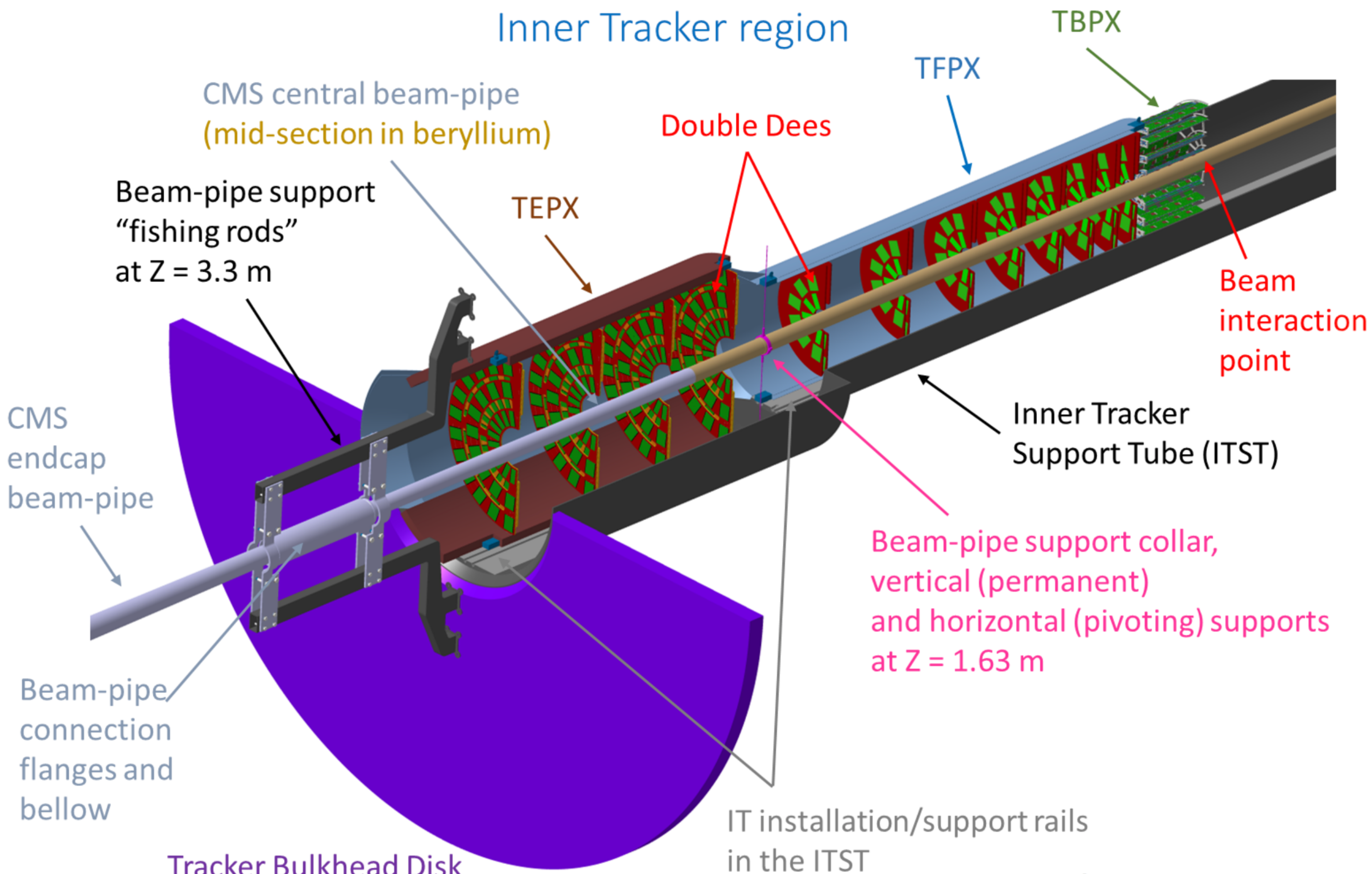
CMS Phase-2 tracking detector

- ❖ Outer Tracker design driven by ability to provide tracks at 40 MHz to L1-trigger
- ❖ Tilted modules in OT 3 inner layers
- ❖ Inner Tracker (pixel) design to extend coverage to η ≃ 3.8



- OT Si-sensors ≃ 200µm thick - 90/100µm pitch - 2.5/5cm strips - 1.5 mm macro-pixels in inner layers
- IT Si-silicon sensors ≤ 150µm thickness - 50x50 to 25x100µm² - large pixels in outer layers?

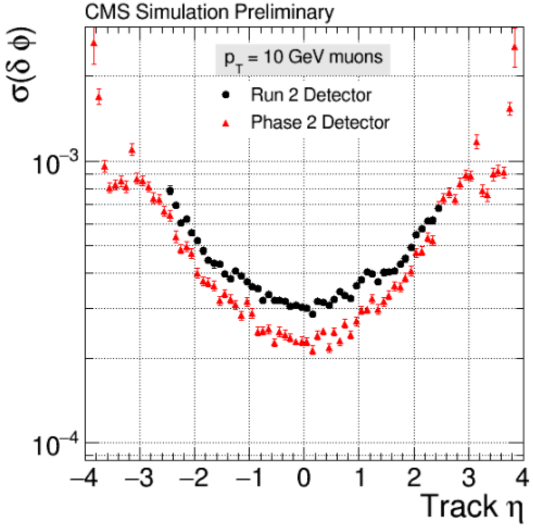
CMS Phase 2 Inner Tracker

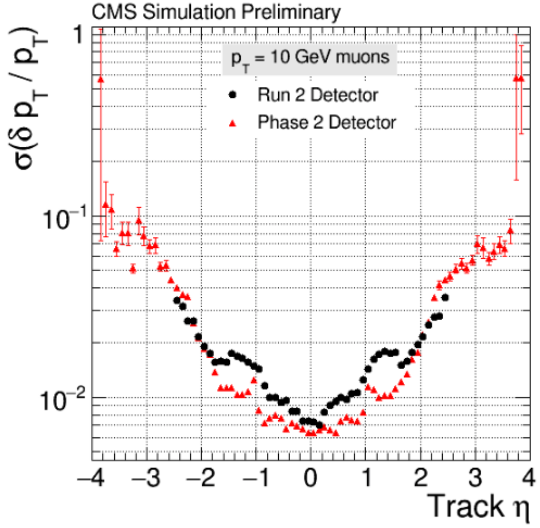


Outer Tracker not shown

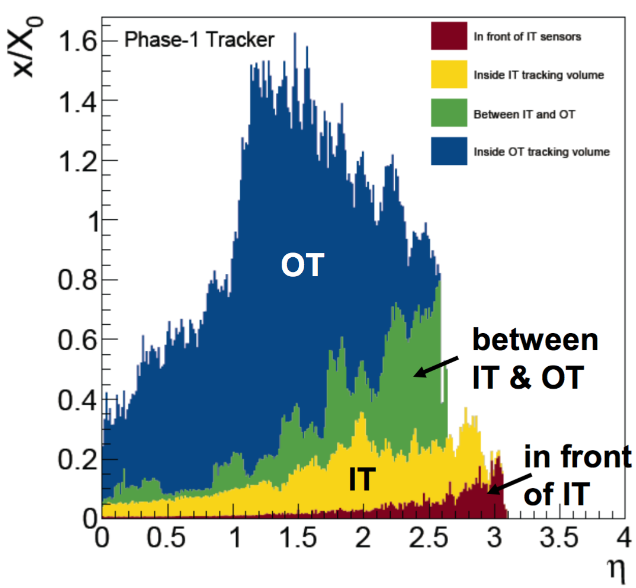
Performance

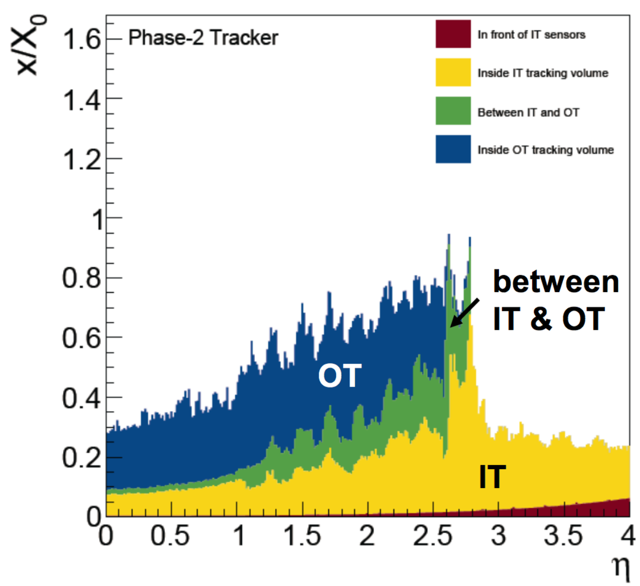
Tracking resolution





Material distribution

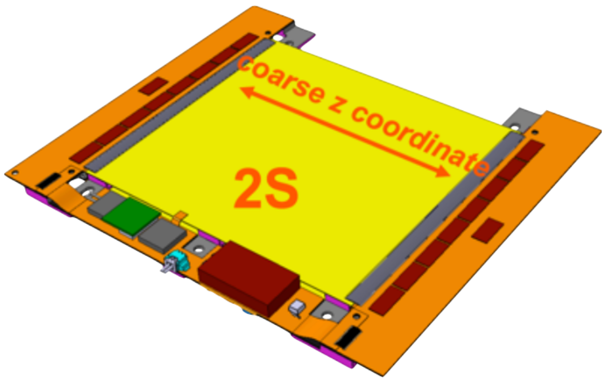


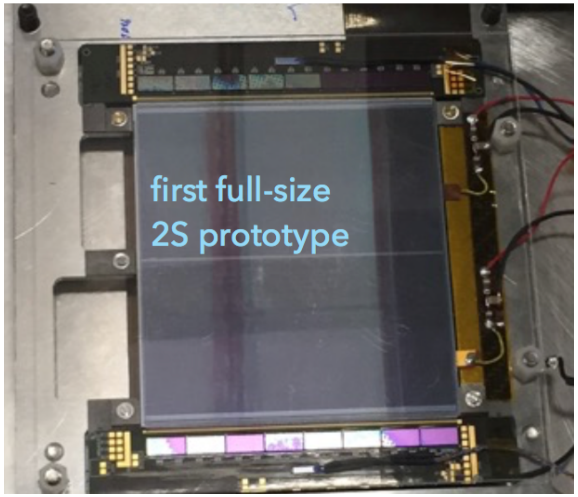


CMS Outer Tracker

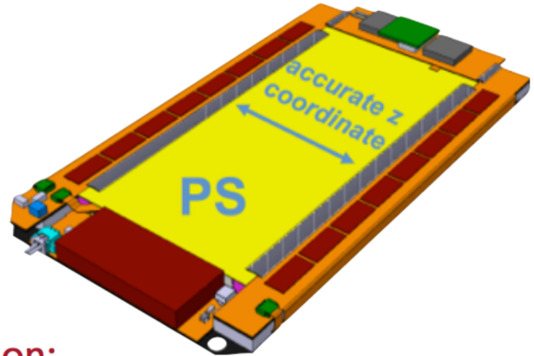
- 2 types of 200 µm thick n-in-p silicon modules, p_T-discriminating

2S modules
- 2 strip sensor mounted back-to-back
- Sensors wire-bonded to hybrid from top and bottom
- Strip dimensions: 5 cm x 90 µm





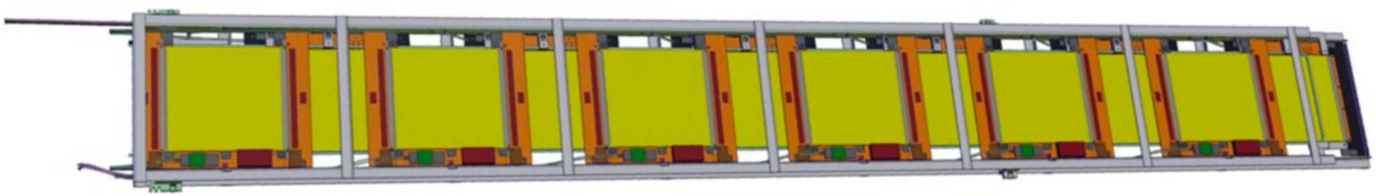
PS modules
- Measures z
- 1 strip sensor (2.5 cm x 100 µm) 1 pixel sensor (1.5 mm x 100 µm) mounted back-to-back with a separating bridge

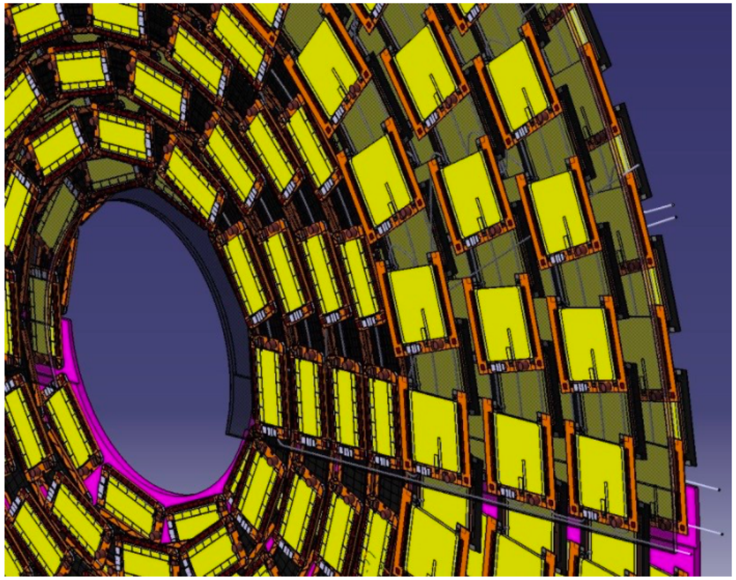


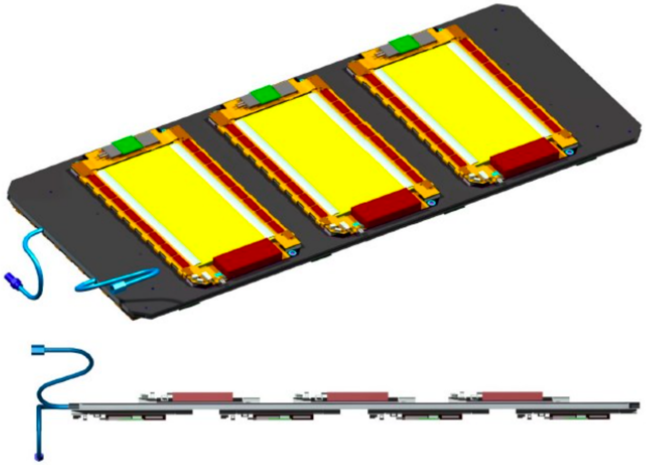
common:
on-module DC-DC converter
LpGBT for data transmission & control

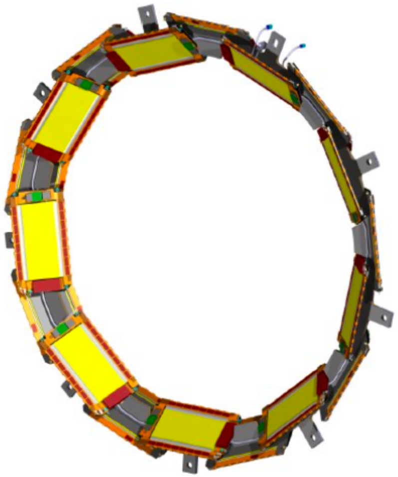
- Hybrid with binary readout electronics connecting data from two sides
- Module single entity, uses DC-DC powering
- Modules mounted on support structure

CMS Phase-2 tracking detector





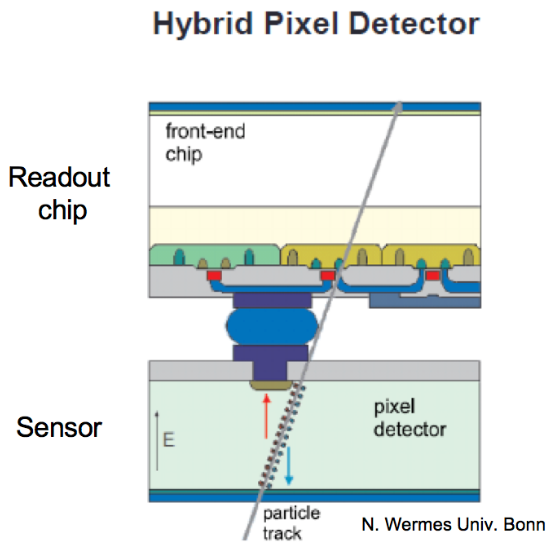


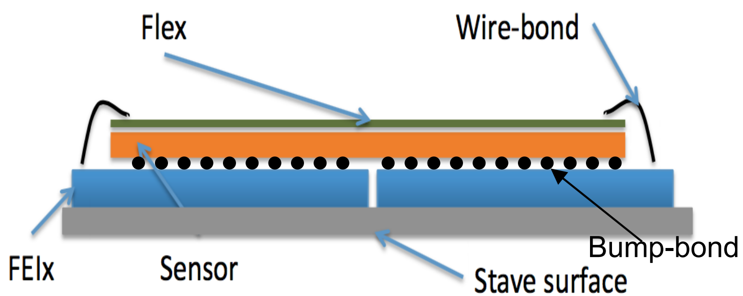


- 2S modules screwed to “ladders”
  - Each module has individual optical connection for communication and readout
- PS modules on “planks” and “rings”
- End-cap modules loaded on “double disk” structure

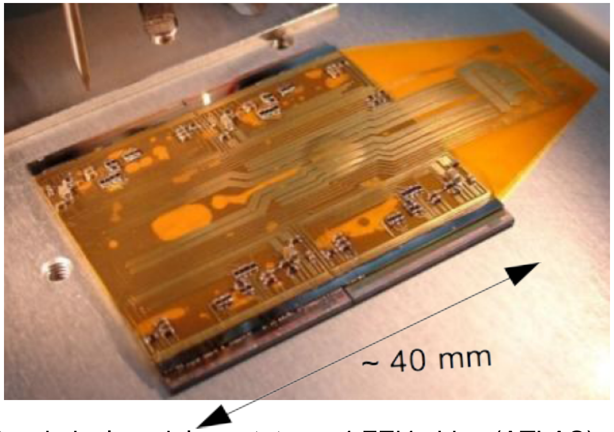
Pixel detector upgrades: Hybrid pixel modules

- Sensor and front-end electronics connected to module with high density bump bonding → bare module
- Flex glued on top of bare module (on sensor side)
- Flex and bare module connected via wire-bonds (data, LV, HV)
- Quad (4-chip) modules and single, double modules for inner most layers





~600k channels/module with 4 chips

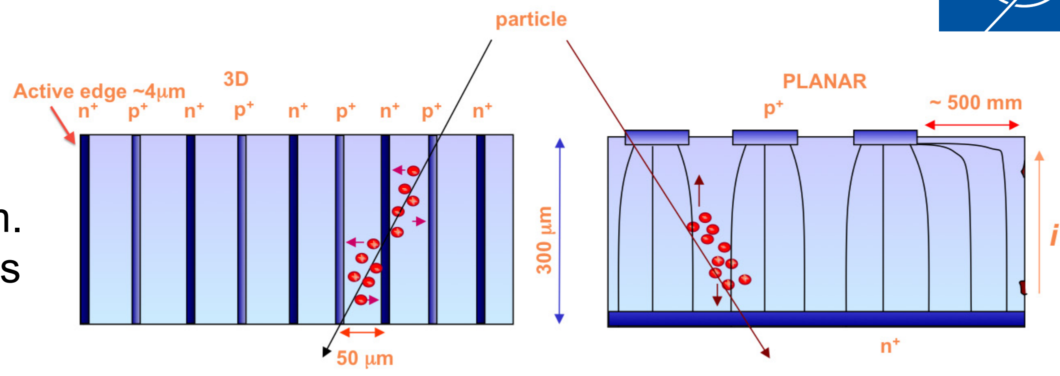


Quad pixel module prototype, 4 FEi4 chips (ATLAS)

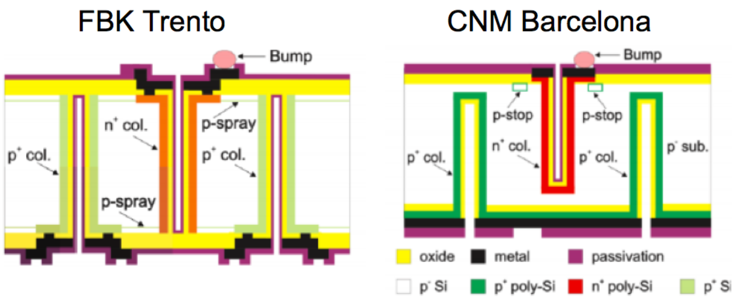
Alternative under investigation for ATLAS most outer pixel layer: CMOS modules (more in Lecture 2)

Pixel sensors

- **Sensor options**
  - Planar or 3D sensors
  - Small pixel sizes of 50 µm x 50 µm. (25 µm x 100 µm) 400 x 384 pixels



  - Features of 3D sensors:
    - lower bias voltage than planar sensors
    - Less power consumption
    - Smaller clusters at high track incident angle
    - But difficult processing



A. Zoboli et al., IEEE TNS 55(5) (2008) 2775
G. Giacomini, et al., IEEE TNS 60(3) (2013) 2357

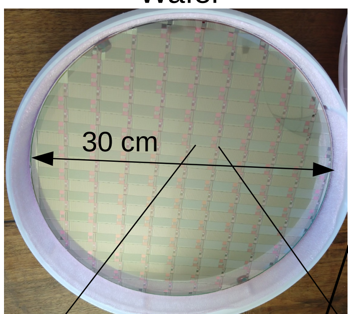
G. Pellegrini et al. NIMA 592(2008) 38
G. Pellegrini et al. NIMA 699(2013), 27

→ Many performance studies in laboratory and test beam before and after irradiation

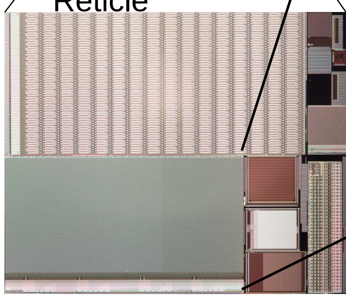
Pixel readout electronics

- **Fast readout chips required**
  - RD53 Collaboration is developing front-end chip in 65 nm technology
  - Output bandwidth 1.2 Gbit/s

Wafer

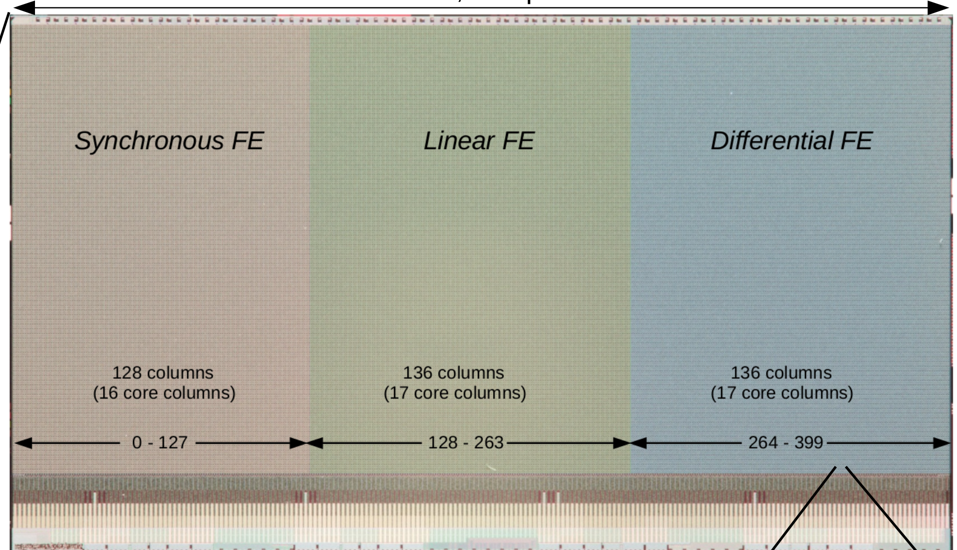


Reticle

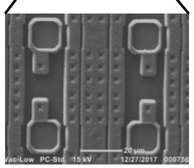


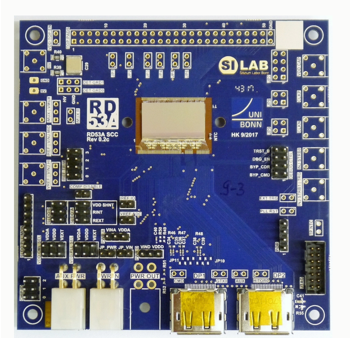
10 other chips sharing the run, including CMS MPA/SSA

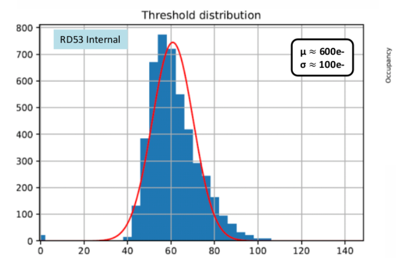
2 cm, 400 pixel columns



- Chip doc. on CDS: cds.cern.ch/record/2287593
- Paper getting started

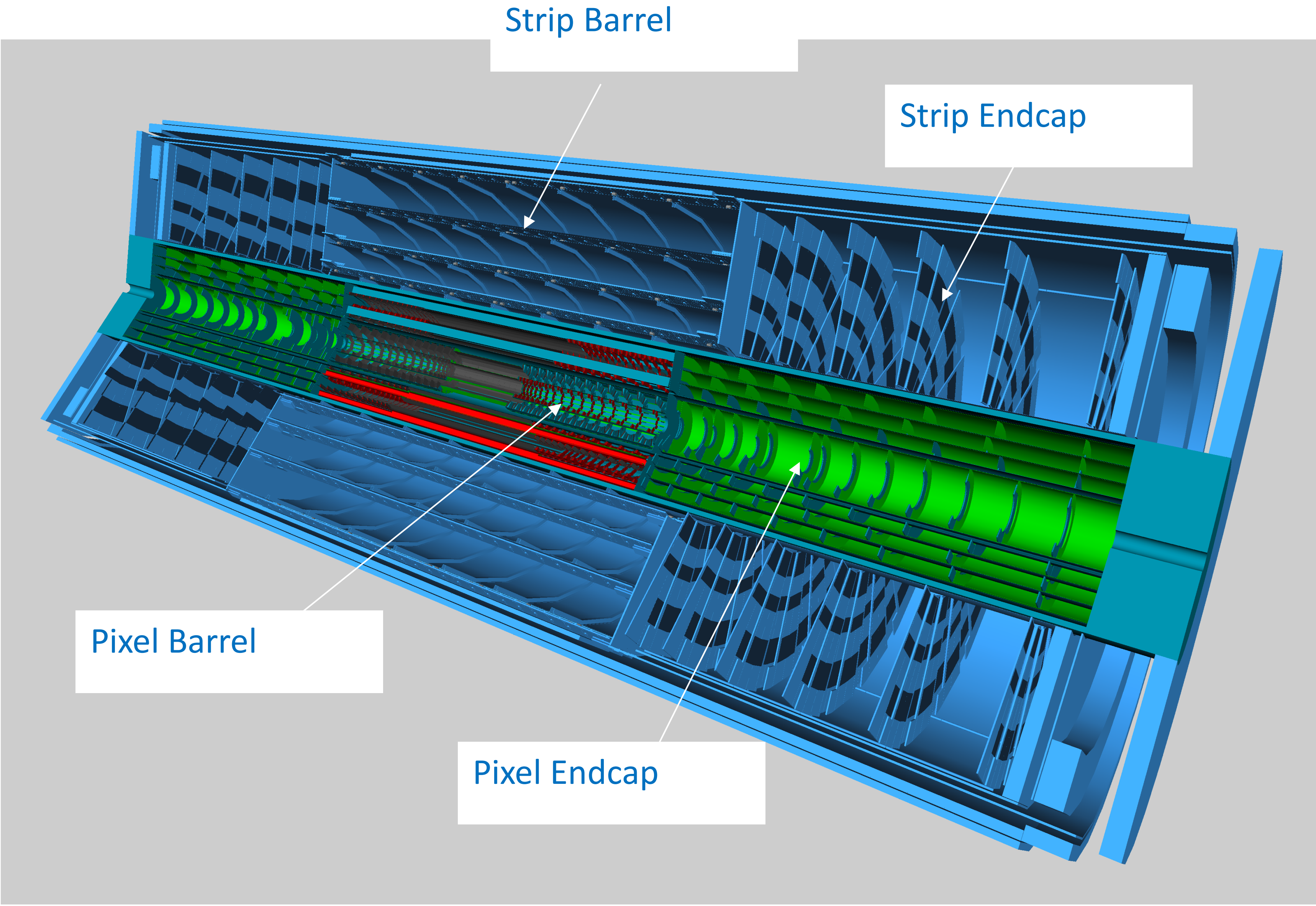




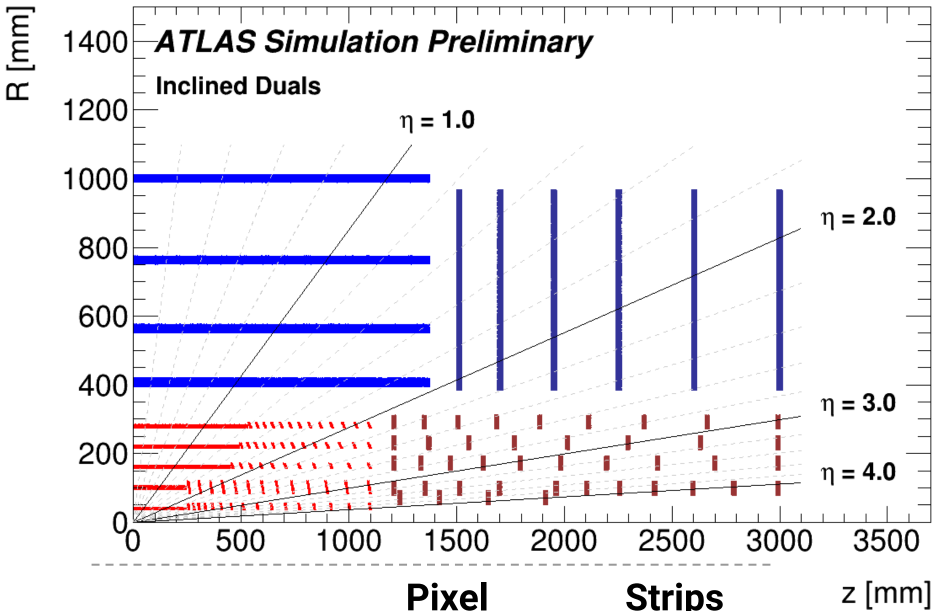


600e- tuned threshold
Same #pix as full FE-I4

ATLAS Inner Tracker Upgrade for Phase-2



Layout of new ATLAS Inner Tracker



	Pixel	**Strips**
Silicon area	13 m^2	160 m^2
Nb channels	580 millions	50 millions

Deploy
- Fast data transmission with low power giga-bit transmitter
- CO_2 cooling (thinner pipes)
- Triggering at L0 with 1 MHz and at L1 300/400 kHz
- Large area: aim for cheaper components

Pixel Detector:

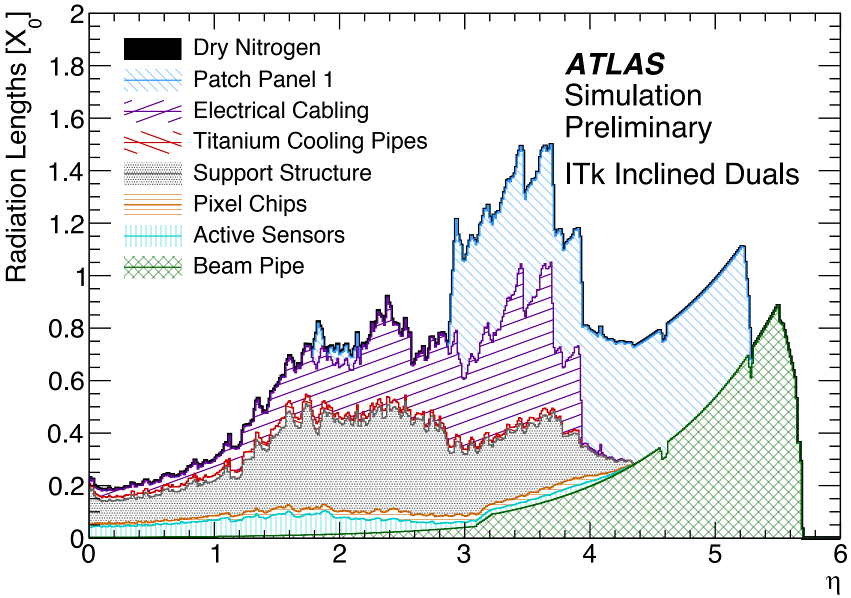
- >5G pixels
- 5 barrel layers + endcap structures
- 50x50 mm^2 or 25x100 mm^2
- >13 m^2 active silicon
- coverage up to $|\eta| < 4.0$

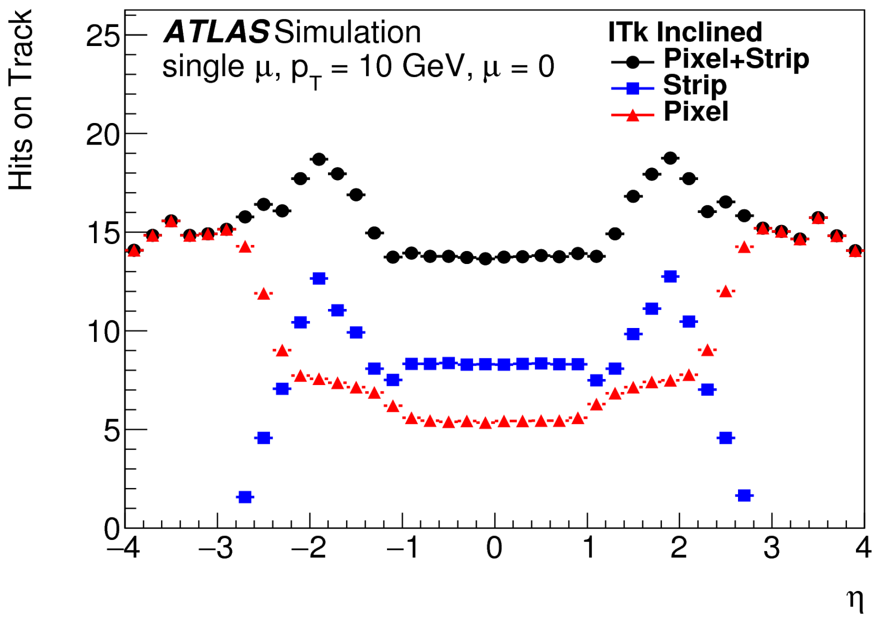
Strip Detector:

- 50M readout channels
- 4 barrel layers, 12 endcap discs
- barrel: 24mm/48mm strip-pairs
- endcaps: 19-60mm strip-pairs
- 75.5 mm pitch
- 160 m^2 active silicon

CERN-LHCC-2017-005

Expected Material and Performance of new ITk





reconstruction efficiency
> 90% in central region
> 80% in forward region

fake rate < 0.001

- > 13 clusters per track
- < 0.1 holes per track

Expected Performance new ITk: Tracking

clusters from hits

↓

space points

↓

track seeds

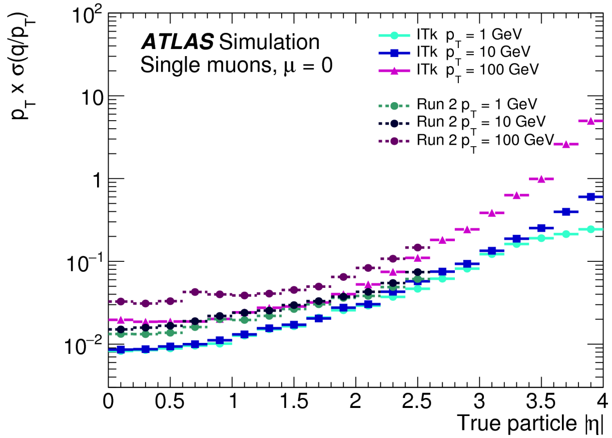
↓

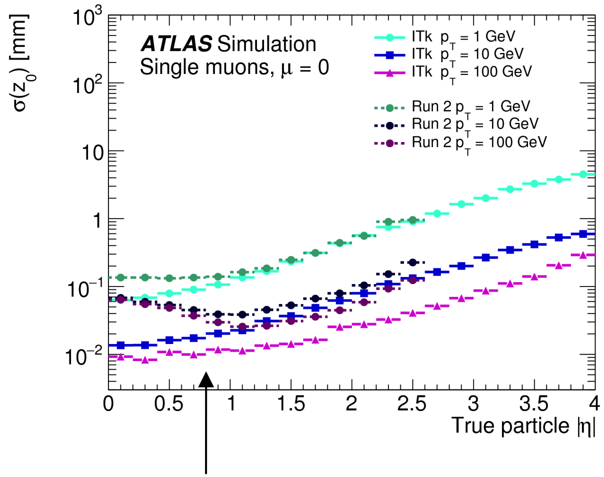
track “roads“

↓

ambiguity resolving

Conservative estimate for performance of ITk: algorithms not fully optimized



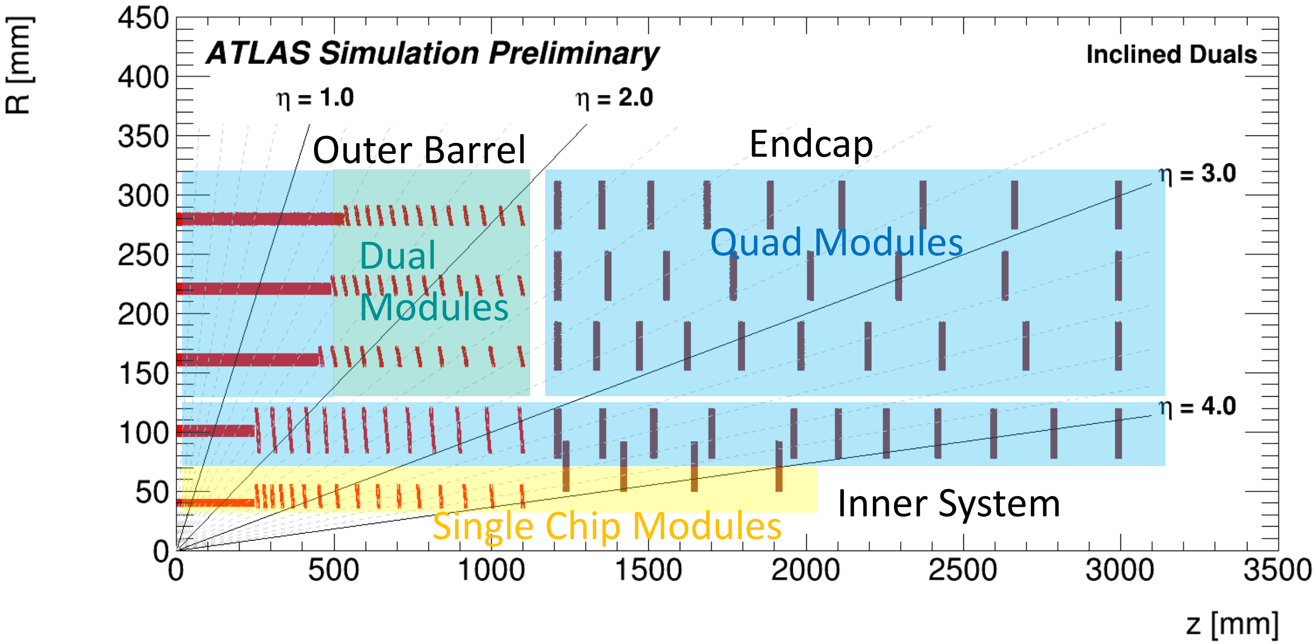


significant improvement wrt. current tracker:
→ reduced material
→ strip detector performs better than TRT

smaller pitch in ITk

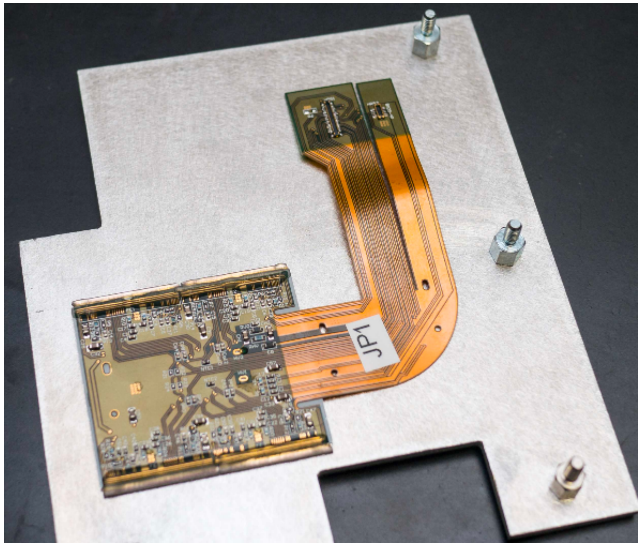
Impact Parameter Resolution
→ for low pT dominated by multiple scattering
→ for high pT dominated by intrinsic detector resolution

Layout of the ATLAS pixel detector



Active area: 12.7 m^2
Pixel size: 50x50 (or 25x100) μm^2
# of modules: 10276
# of FE chips: 33184
# of channels: ~5 10^9

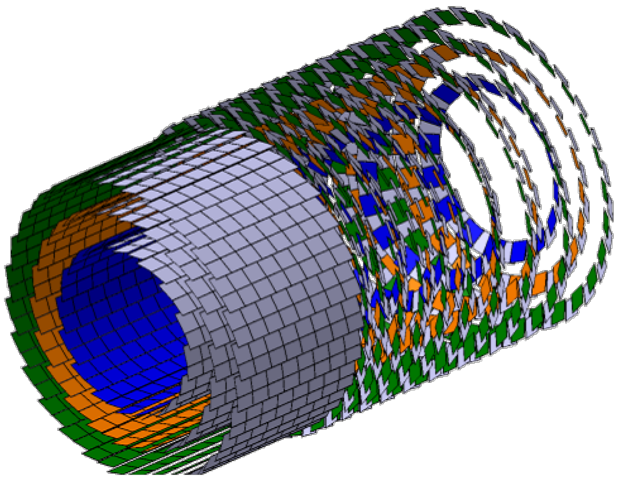
- Different sensors types and technologies depending on distance from interaction point
- Fast readout with max. 4 MHz trigger rate
- Up to $|\eta|$ of 4

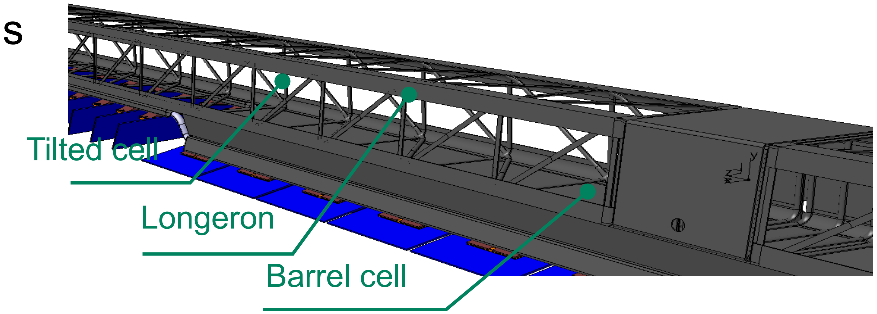


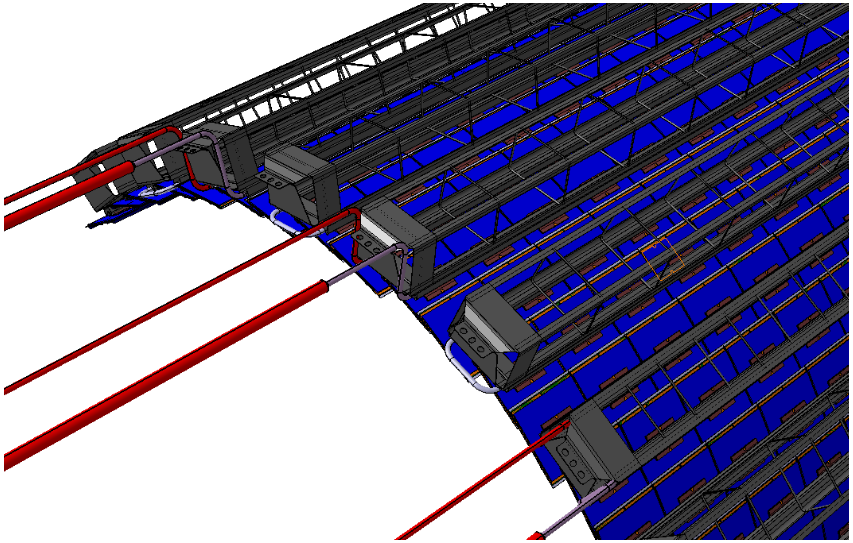
Quad module with 4 FEs

ATLAS Pixel Design

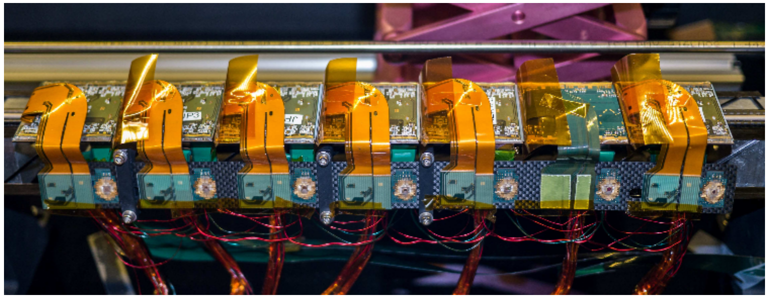
- Structure from carbon-fibre composites
  - Example for outer central region: longerons







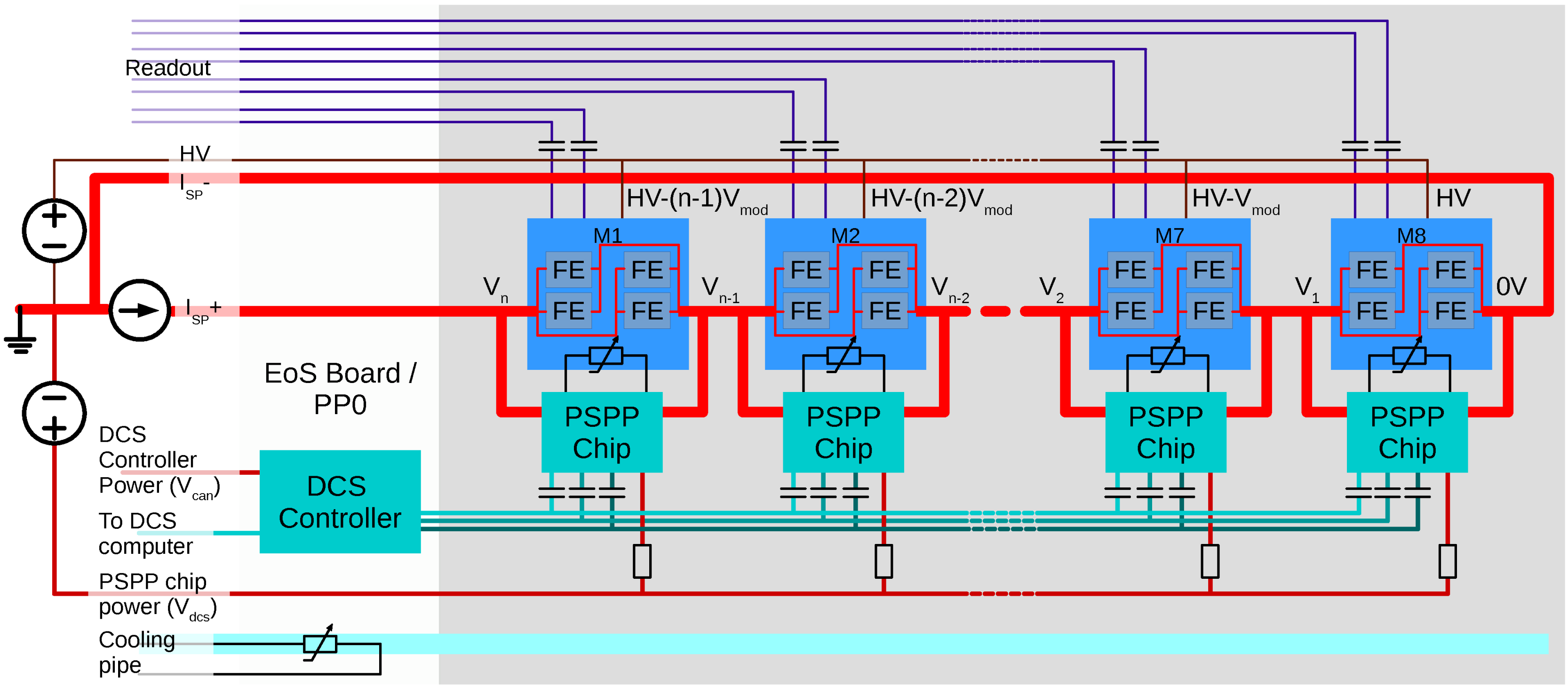
Electrical prototype with FE-i4 based modules



7 quad modules on carbon local support structure

Powering of Pixel Detector

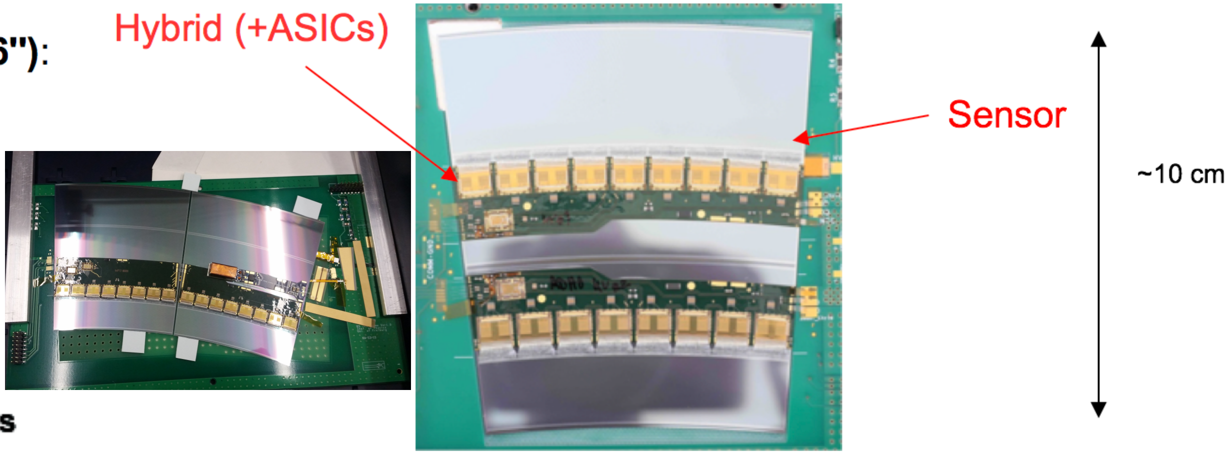
- Powering serially with chains of up to 14 modules
- Constant current to all modules in one chain



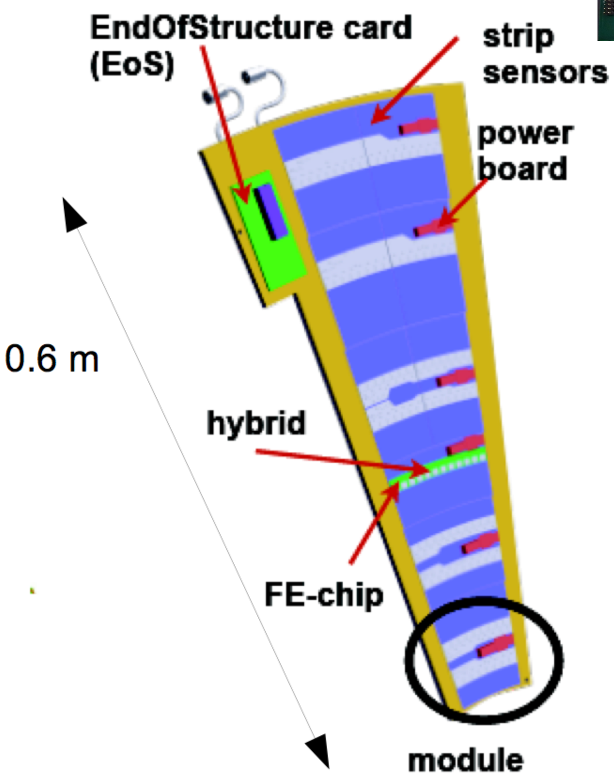
Concept of the upgrade strip tracker in ATLAS

- Modularity for easier final assembly, multiple site production, early system tests

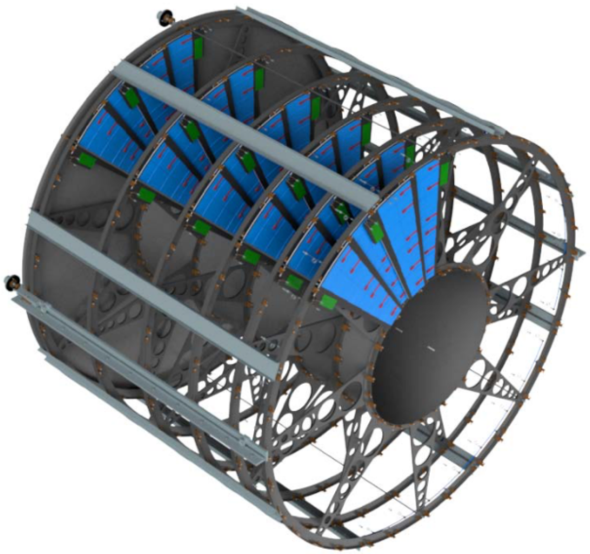
Module (6"):



Carbon core with double-sided modules (sketch: **petal**)

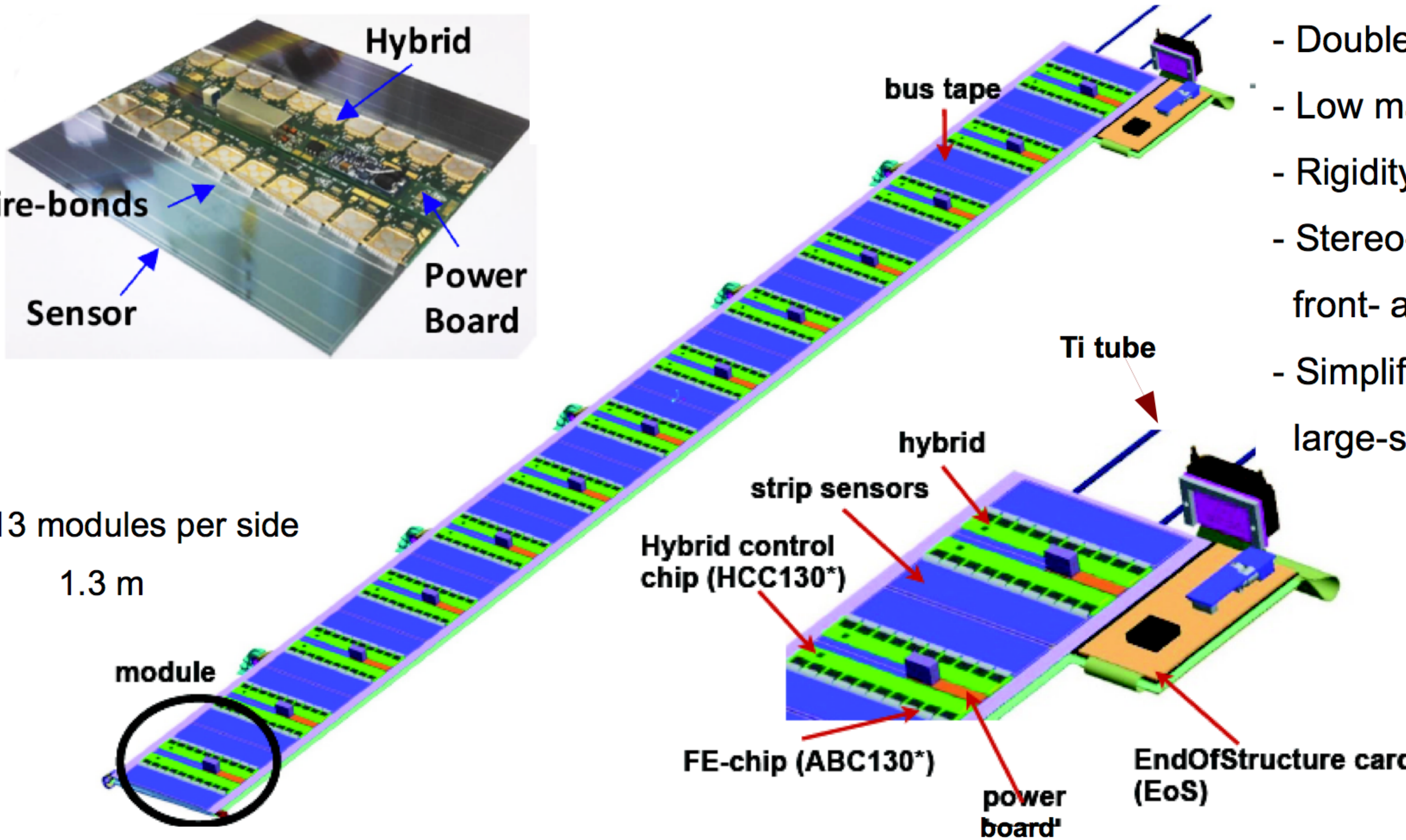


End cap with petals: radius ~ 1 m



Not to scale

Layout of structures for the central region

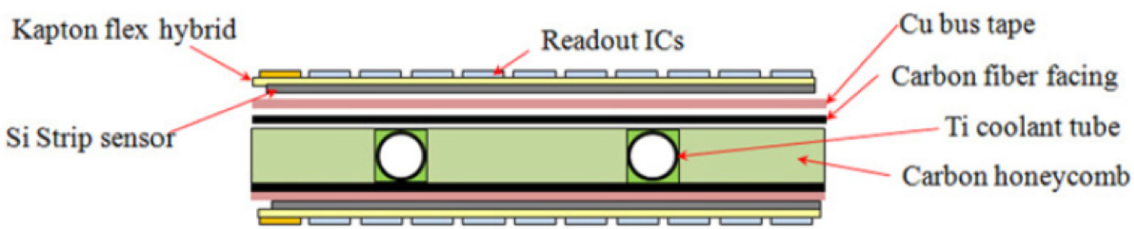


- Double-sided
- Low material
- Rigidity
- Stereo-angle between front- and backside
- Simplify assembly for large-scale production

13 modules per side

1.3 m

Stave cross section:



NIM A 699(2013)93–96

Sensor design and readout electronics

– Silicon sensors:
  – n-in-p float zone 320 µm thick
  – Strip length 8 – 58 mm
  – Covering in central region 97 x 97 mm

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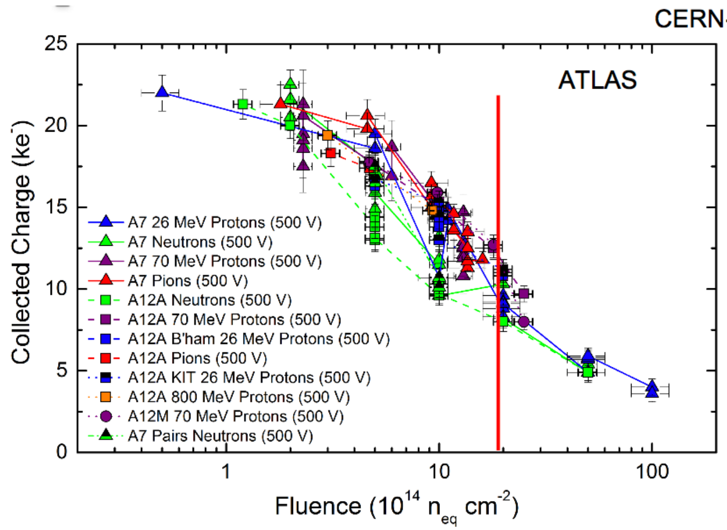
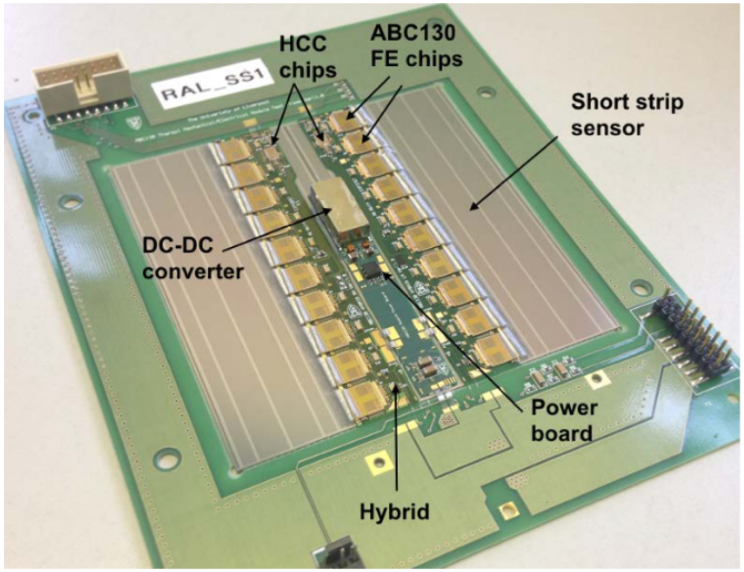


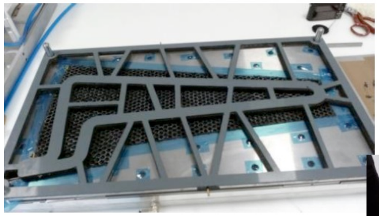
Collected charge after proton, neutron and gamma irradiation, β-source tests after 80 min annealing at 60°C

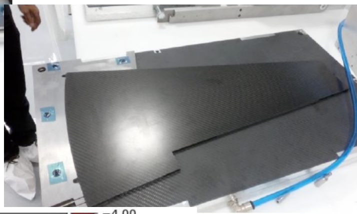
– Readout electronics
  – Binary chip in 130nm CMOS production
  – Plus controller chip and HV multiplexing on module
  – DC-DC powering for increased power efficiency



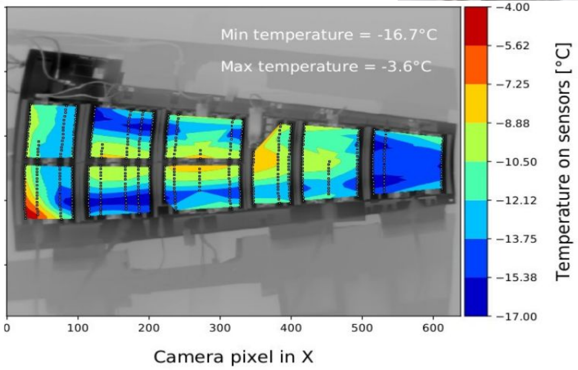
Prototyping of larger strip structures

- Development of industrial production of petal cores for endcap region ongoing

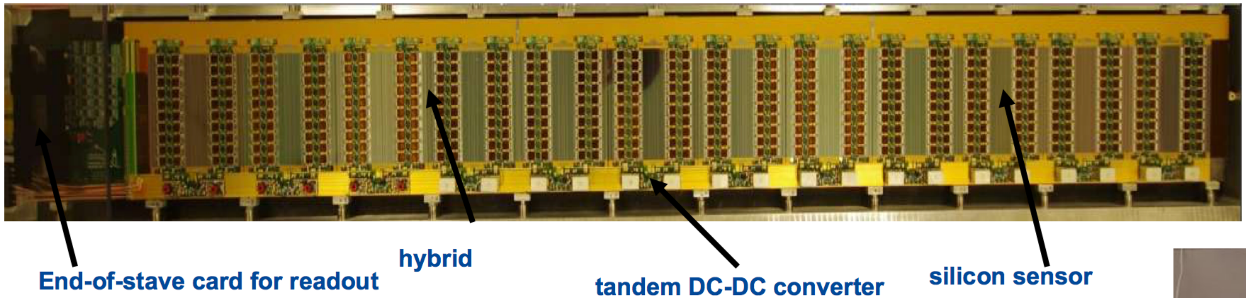




Petal Thermomechanical model



- Stave with 13 modules tested for central region
  - 1.3 m long with titanium cooling pipes
  - Successful test of construction, shielding, grounding, powering, readout, ..



- Test of global mechanics: services routing

Service tray mockup@Valencia

CMS Phase-2 Upgrade

L1-Trigger/HLT/DAQ

- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters

NEW READOUT

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

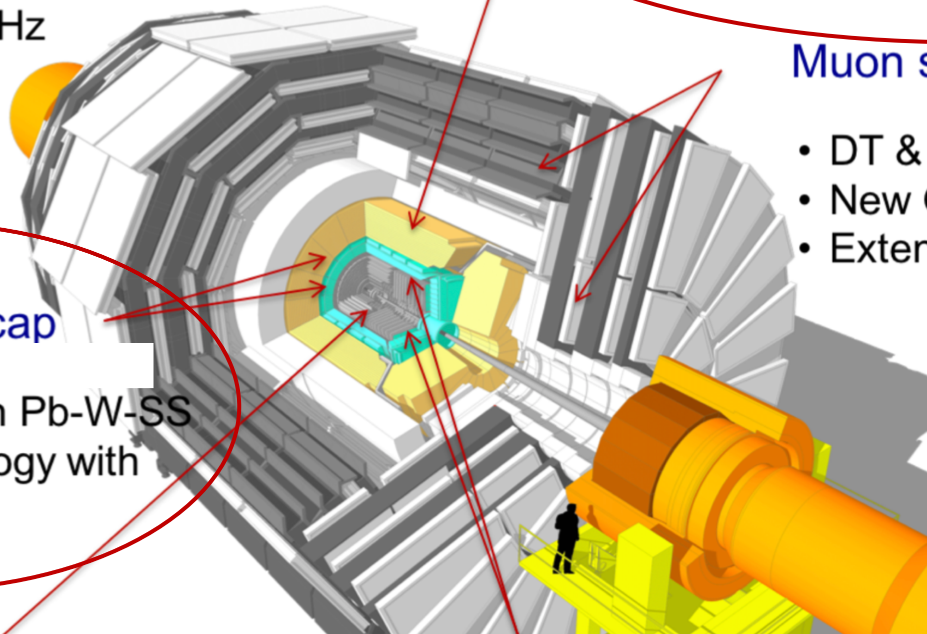
Muon systems

- DT & CSC new FE/BE readout
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3

NEW DETECTOR

Calorimeter Endcap

- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing



Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure

Tracker

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8

MIP Timing Detector

- ≃ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Recap: Electromagnetic Calorimeters

- Dominant processes at high energies (E > few MeV) :

- Photons: Pair production

$$\sigma_{pair} \approx \frac{7}{9}\left(4\alpha r_e^2 Z^2 \ln\frac{183}{Z^{1/3}}\right) = \frac{7}{9}\frac{A}{N_A X_0}$$

$$I(x) = I_0 e^{-\mu x} \qquad \mu = \frac{7}{9}\frac{\rho}{X_0}$$

μ= attenuation coefficient
X_0 = radiation length in [cm] or [g/cm²]

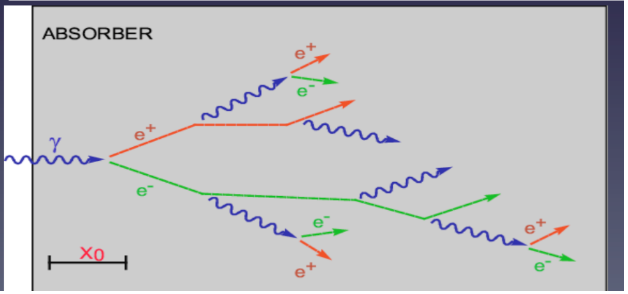
$$X_0 = \frac{A}{4\pi N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

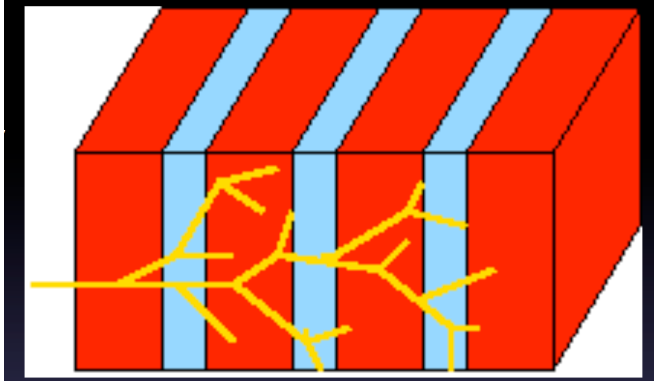
- Electrons: Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}} = \frac{E}{X_0}$$

$$E = E_0 e^{-x/X_0}$$

After traversing $x=X_0$ the electron has only 1/e=37% of its initial energy





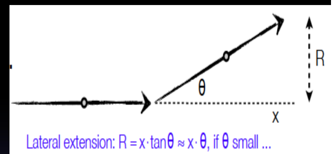
- Sampling fraction

Recap: EM Calorimeters – Shower development

Lateral development of EM shower

- Opening angle:
  - bremsstrahlung and pair production

$$\langle \theta^2 \rangle \approx \left(\frac{m_e c^2}{E_e}\right)^2 = \frac{1}{\gamma^2}$$



  - multiple coulomb scattering [**Molière** theory]

$$\langle \theta \rangle = \frac{E_s}{E_e}\sqrt{\frac{x}{X_0}} \quad \text{where} \quad E_s = \sqrt{\frac{4\pi}{\alpha}}\left(m_e c^2\right) = 21.2 MeV$$

- Main contribution from low energy e^- as $<\theta> \sim 1/E_e$, i.e. for e^- with $E < E_c$

- **Molière** Radius

$$R_M = \frac{E_s}{E_c} X_0 \approx \frac{21.2 MeV}{E_c} X_0$$

- Assuming the approximate range of electrons to be X_0 yields $<\theta> \approx 21.2$ MeV/E_e ➛ lateral extension: $R = <\theta> X_0$

Longitudinal shower containment

- EM calorimeter can be quite compact. Since $t_{max} \approx \ln(E)$ → calorimeter thickness must increase as ln(E)
- After shower max e^+/e^- will stop in ≈ $1X_0$
- To absorb 95% of photons after shower max ≈ $9X_0$ of material are needed
- The energy leakage is mainly due to photons
- A useful expression to indicate 95% shower containment is:

$$L(95\%) = t_{max} + 0.08\,Z + 9.6\,[X_0]$$

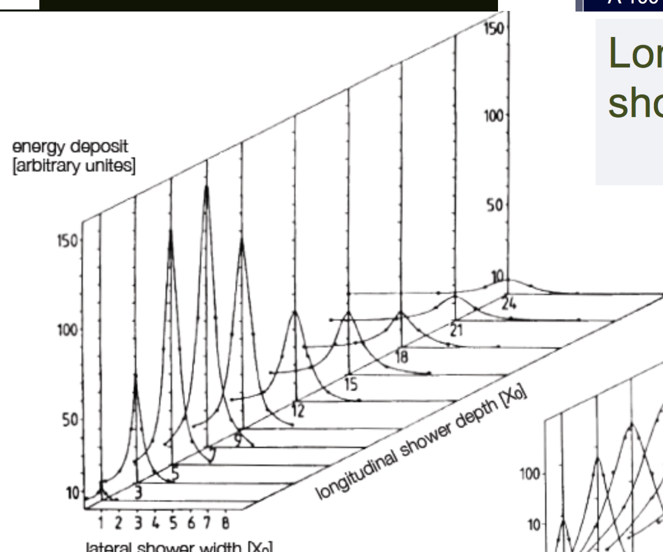
$$E_C \approx 10 MeV \quad E_0 = 1\,GeV \;\Rightarrow t_{max} = \ln 100/\ln 2 \approx 6.6 \quad N_{max} = 100$$

$$E_0 = 100\,GeV \;\Rightarrow t_{max} = \ln 10{,}000/\ln 2 \approx 9.9 \quad N_{max} = 10{,}000$$

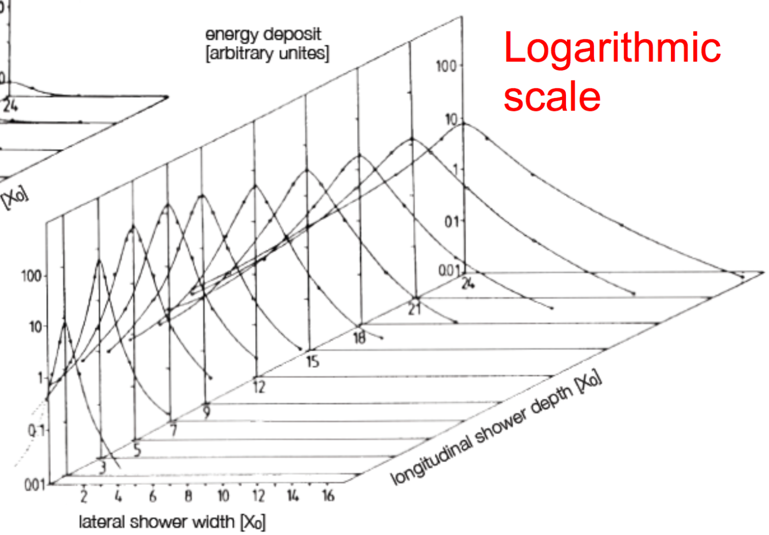
	Scint.	LAr	Fe	Pb	W
X_0(cm)	34	14	1.76	0.56	0.35

A 100 GeV e^- is contained in 17.5 cm Fe or 5.6 cm Pb

Longitudinal and transfer EM shower profile of 6 GeV e^- in Lead



Linear scale



Logarithmic scale

Recap: Hadronic Calorimeters

Hadronic shower

Hadronic interaction:

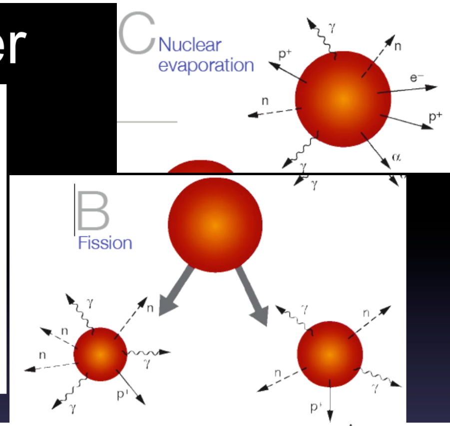
Elastic:

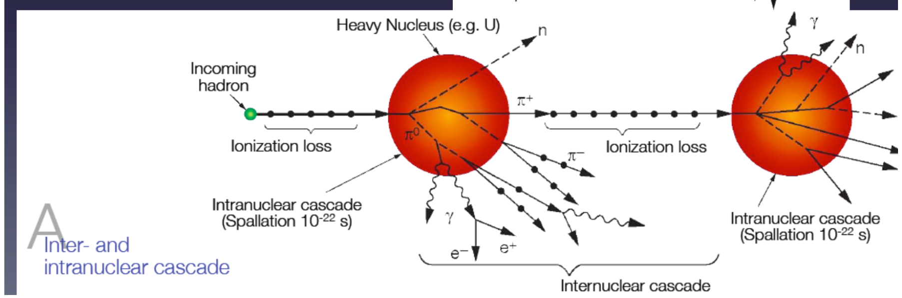
$$p + \text{Nucleus} \rightarrow p + \text{Nucleus}$$

Inelastic:

$$p + \text{Nucleus} \rightarrow$$
$$\pi^+ + \pi^- + \pi^0 + \ldots + \text{Nucleus}^*$$

$$\left[\begin{array}{l} \text{Nucleus}^* \rightarrow \text{Nucleus A} + n, p, \alpha, \ldots \\ \qquad\quad\ \rightarrow \text{Nucleus B} + 5p, n, \pi, \ldots \\ \qquad\quad\ \rightarrow \text{Nuclear fission} \end{array}\right.$$





Hadronic vs EM showers

Hadronic vs. electromagnetic interaction length:

$$\left.\begin{array}{l} X_0 \sim \dfrac{A}{Z^2} \\ \lambda_{\text{int}} \sim A^{1/3} \end{array}\right] \rightarrow \frac{\lambda_{\text{int}}}{X_0} \sim A^{4/3}$$

$$\lambda_{\text{int}} \gg X_0$$

[$\lambda_{int}/X_0 > 30$ possible; see below]

Typical
Longitudinal size: 6 ... 9 λ_{int} [95% containment] [EM: 15-20 X_0]

Typical
Transverse size: one λ_{int} [95% containment] [EM: 2 R_M; compact]

Hadronic calorimeter need more depth than electromagnetic calorimeter ...

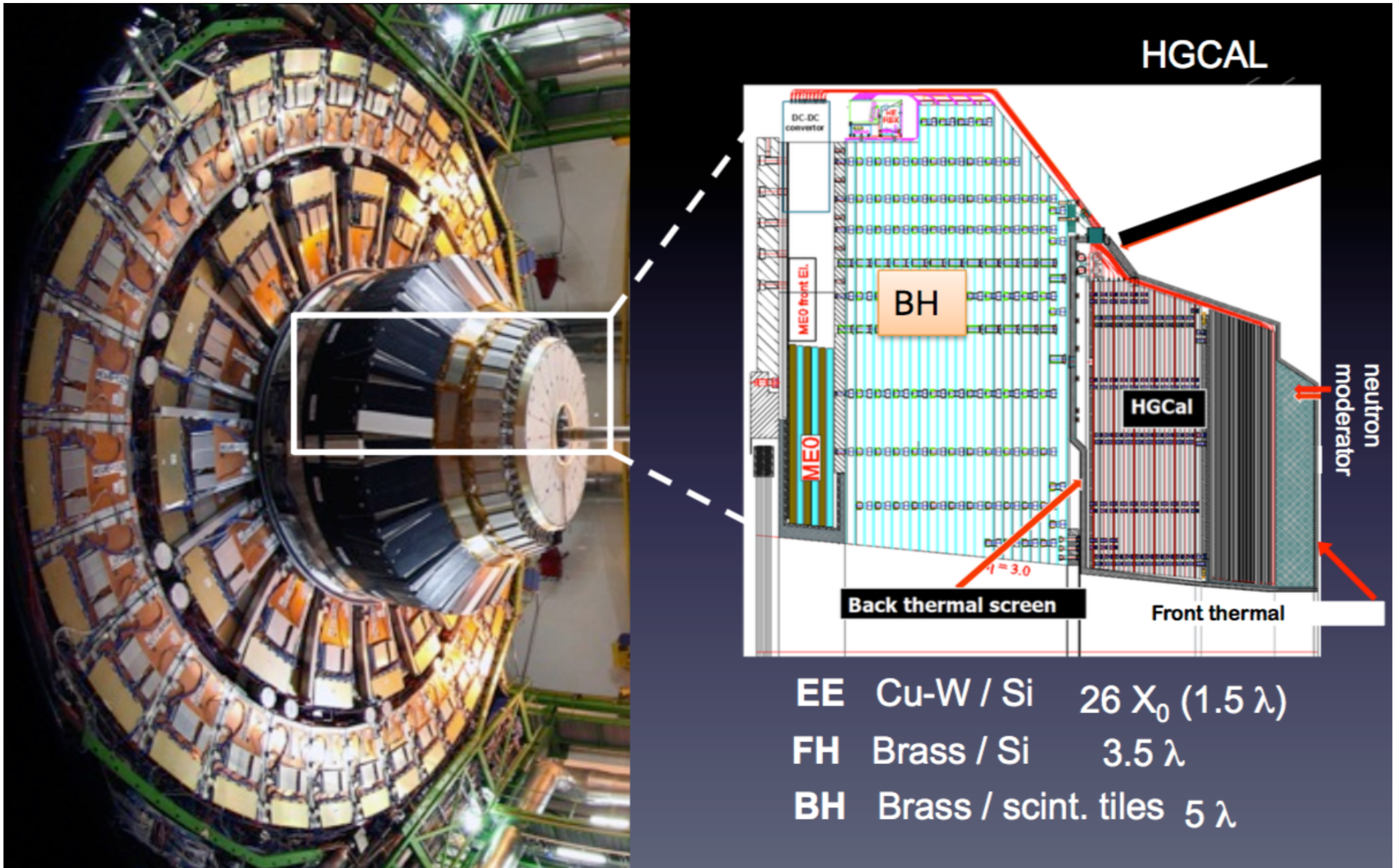
Some numerical values for materials typical used in hadron calorimeters

	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8

Courtesy of Daniela Bortoletto

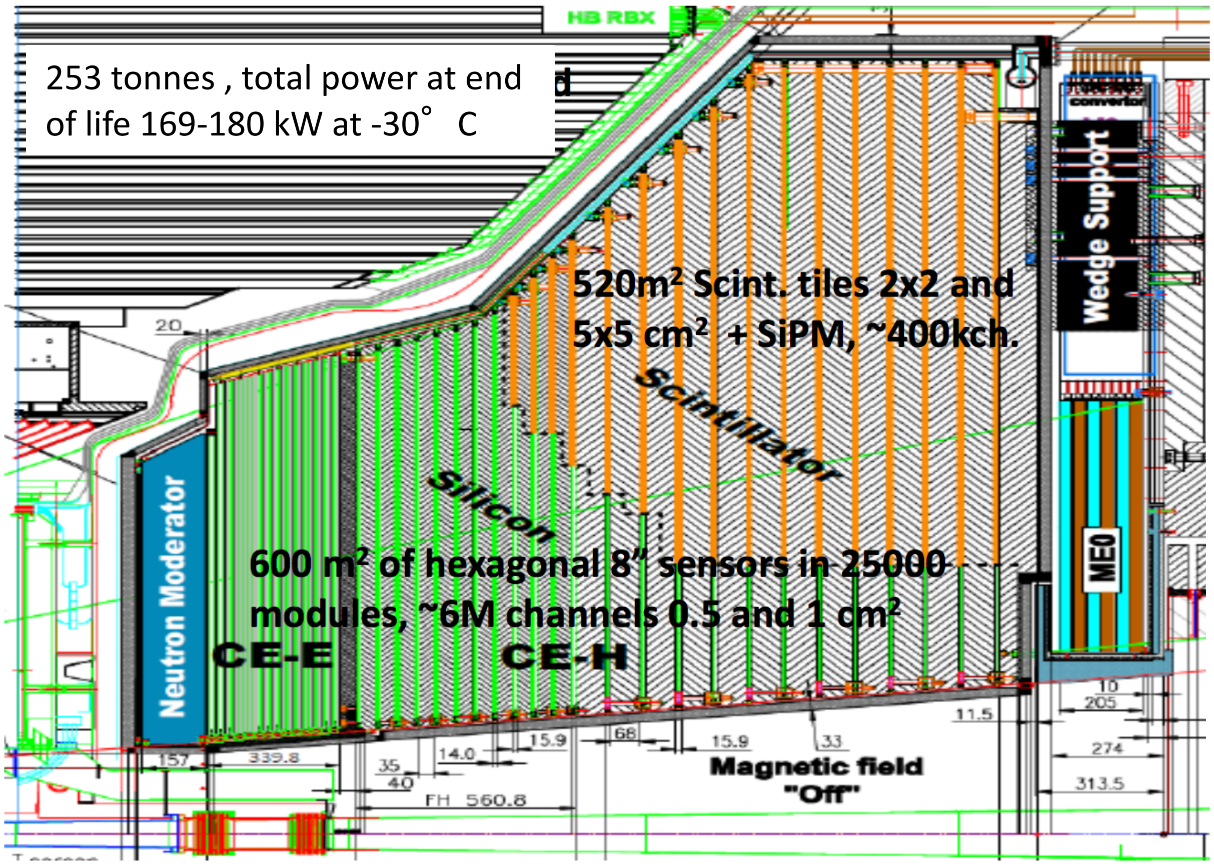
New Endcap calorimeter for CMS for Phase-2

- Complement tracker upgrade with extended coverage of calorimeter to $|\eta| < 4$ and high granularity (high energy resolution): HighGranularityCalorimeter
- Sampling calorimeter with silicon sensors and scintillators, share depending on radiation damage



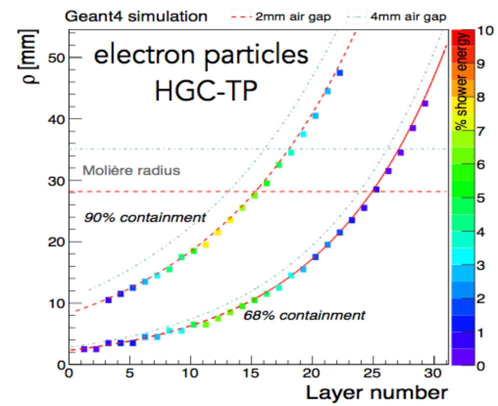
New Endcap calorimeter design

- 3D shower topology and time resolution of ~30 ps (p_T > few GeV)
- Electromagnetic: 28 layers of silicon sensors and W/Cu absorber (26 radiation lenghts, 1.5 interaction lengths)
- Hadronic: 24 layers of 8 silicon and 16 silicon PM/scintillator tiles in stainless steel absorber (8.5 interaction lengths)

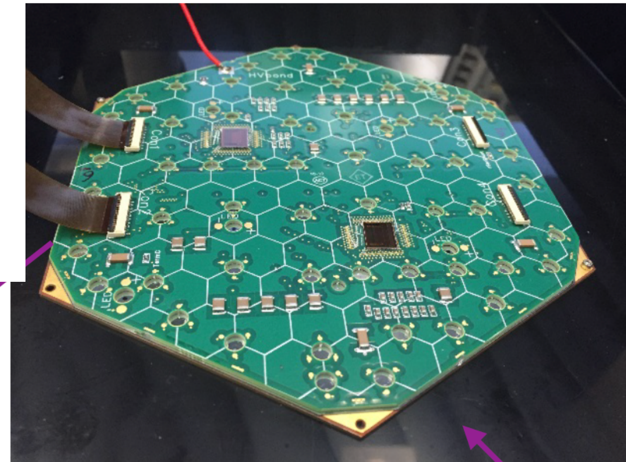


P-in-n sensors with 200 µm thickness

– Good energy resolution for EM showers
– Molière Radius: 90% contained in ~2cm

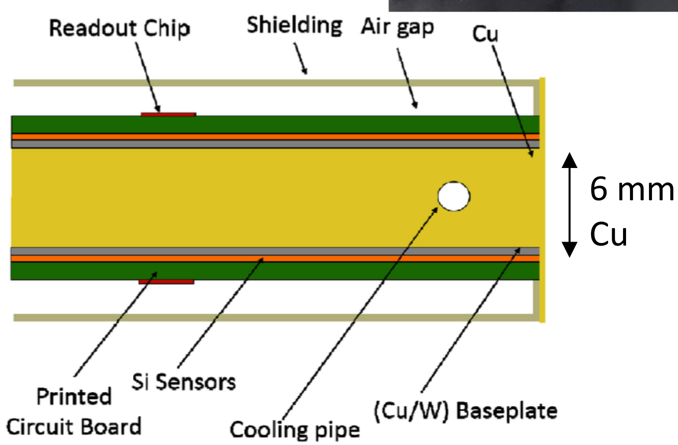


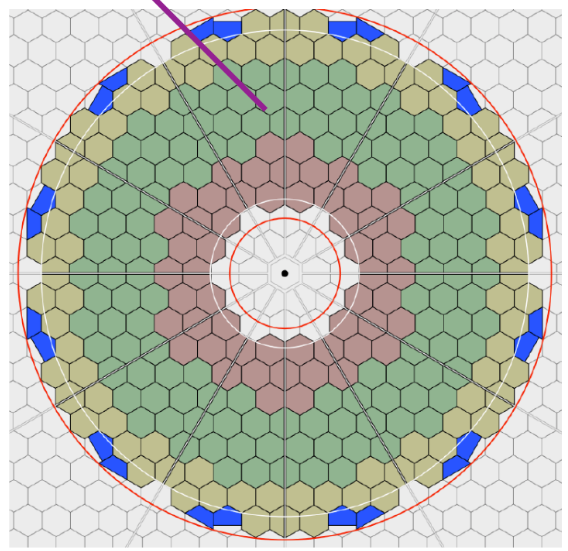
Thin and highly segmented parts

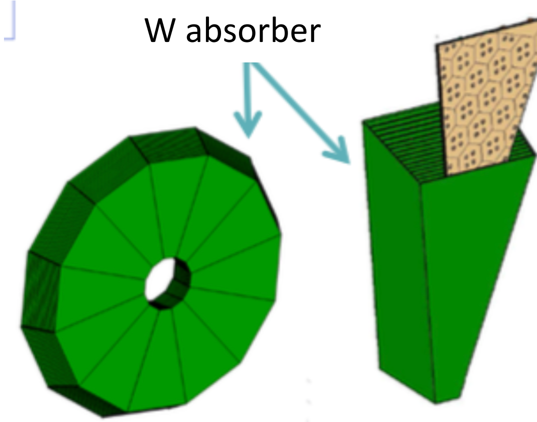


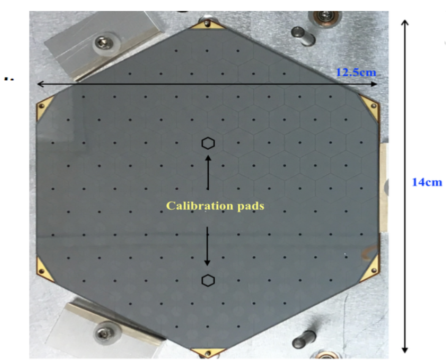
An assembled hexagonal module with hexagonal cells (1 or 0.5 cm² size, making a total 6 million channels)

Section view

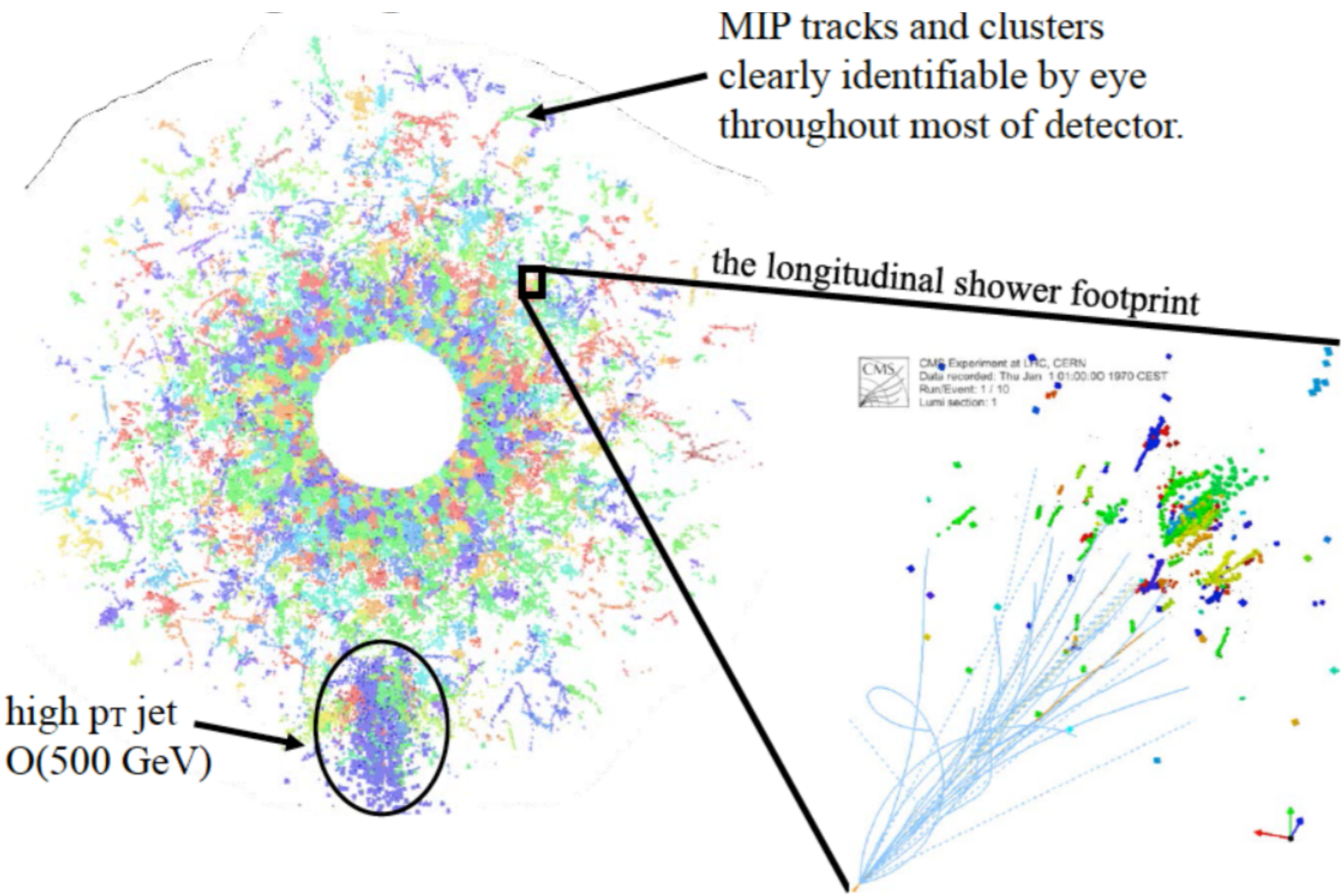






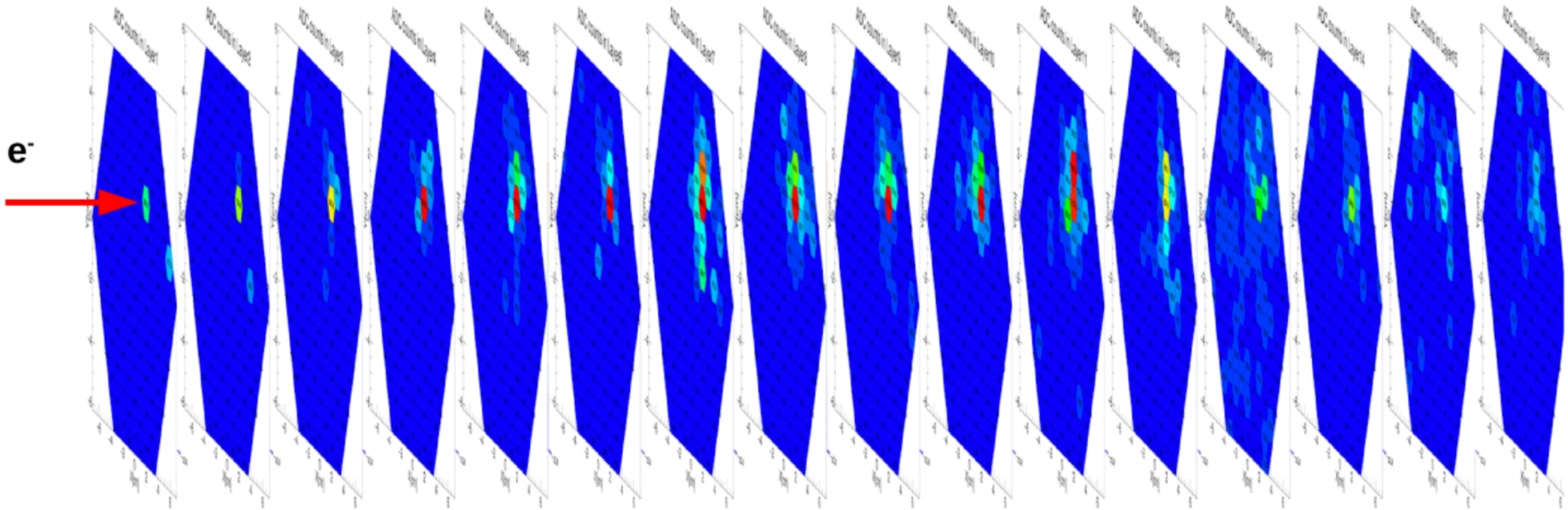


Imaging Calorimeter: Simulation



Imaging Calorimeter: Test beam measurement

Allows measurement of the 4D (space+time) topology of energy deposits in particle shower, to enhance particle ID, energy resolution and pile-up rejection

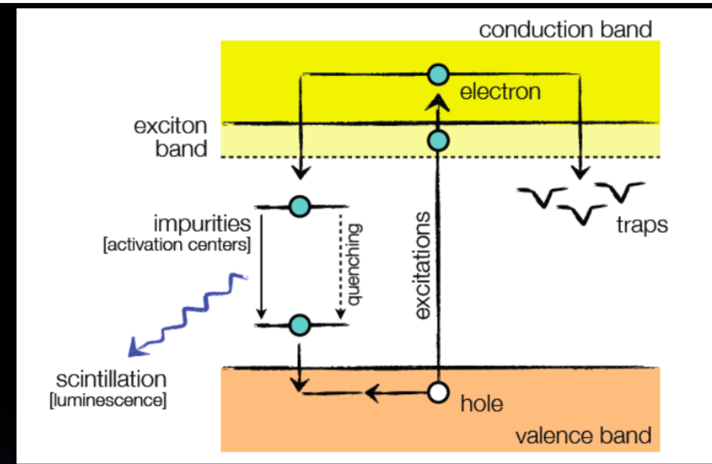


A 32 GeV electron event at Fermilab Test Beam Facility

Shower development clearly seen

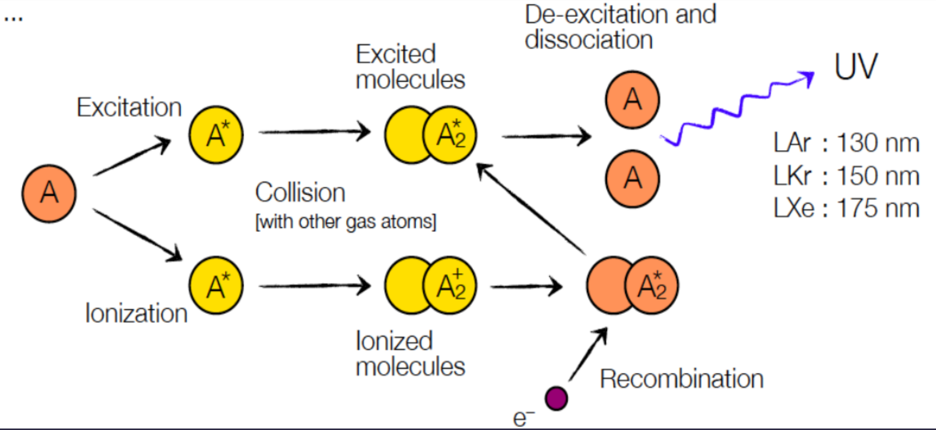
Silicon in use for Calorimetry

Recap: Scintillators

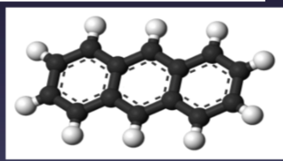


- Inorganic (Sodium iodide (NaI), Cesium iodide (CsI),…)

…

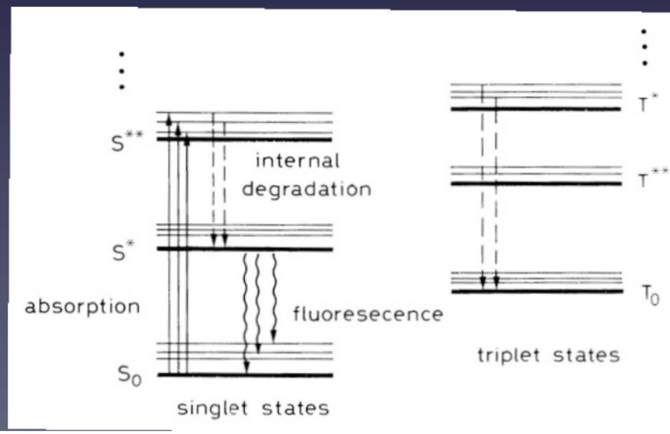


- Organic crystals
  - Aromatic hydrocarbon compounds with benzene rings such as Anthracene (C14H10), etc

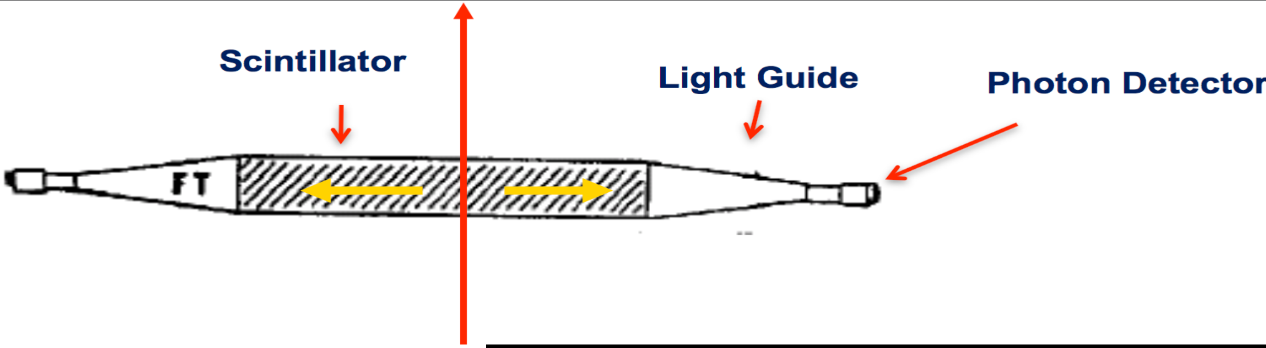


- Plastic scintillators
  - Organic scintillators suspended in the aromatic polymer (easy to mold and machine)
- Liquid scintillators

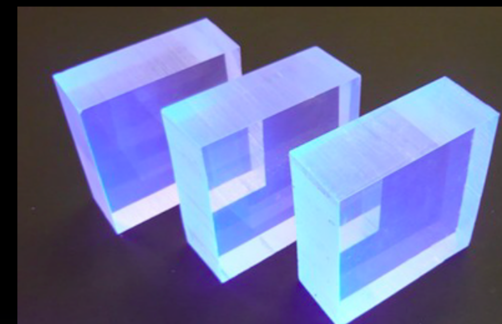
- Noble gasses (Liquid Argon, Liquid Xenon…)
- Molecule structure generates energy levels with transition λ=360-500 nm



Recap: Scintillators



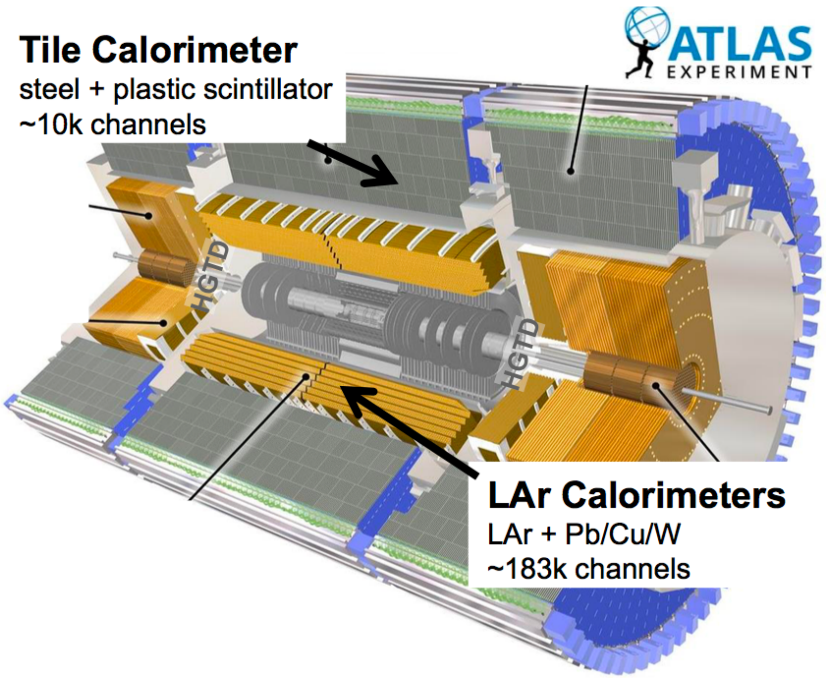
- dE/dx converted into light and then it is detected via photo-sensor (photomultipliers, SiPM,….)
- Main features
  - Sensitivity to energy
  - Fast time response
  - Pulse shape discrimination
- Requirements:
  - High efficiency for conversion of exciting energy to fluorescent radiation
  - Transparency to its fluorescent radiation to allow transmission of light
  - Emission of light in a spectral range detectable for photo-sensors
  - Short decay time to allow fast response

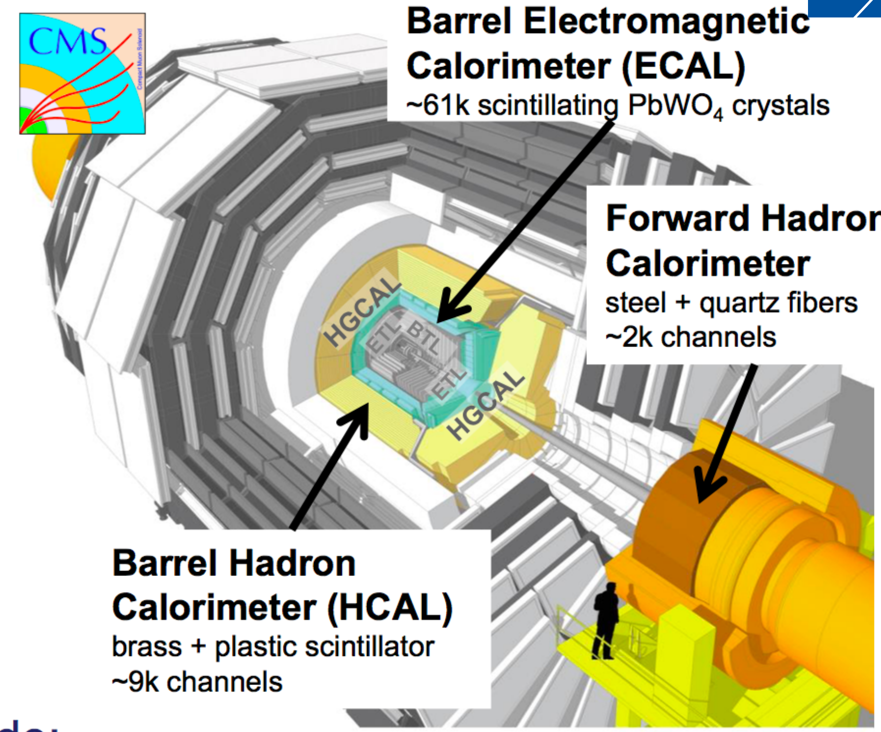


Plastic Scintillator BC412

CMS: PbWO4 75,848 crystals

Further Calorimeter Upgrades



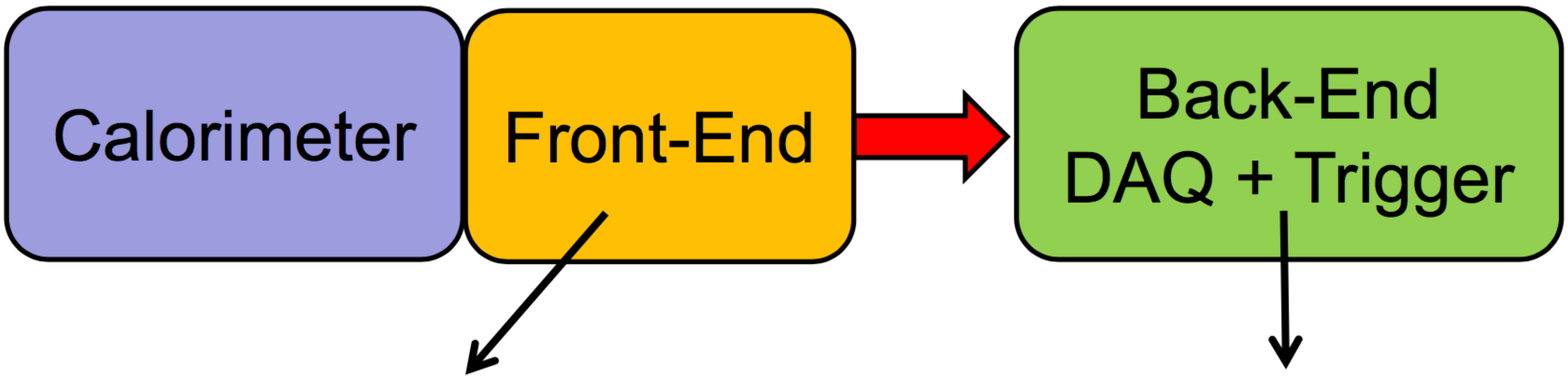


- Motivation for calorimeter electronics upgrade:
  - Higher trigger rate of 0.75 - 1 MHz and larger event buffers (> 10 μs)
    → improved trigger system for high pile-up
  - Improved radiation tolerance (2-10 kGy) and system longevity - where necessary
  - Improved timing measurement - where possible

- General concept: move buffers and pipelines off detector and read out at 40 MHz

New readout electronics

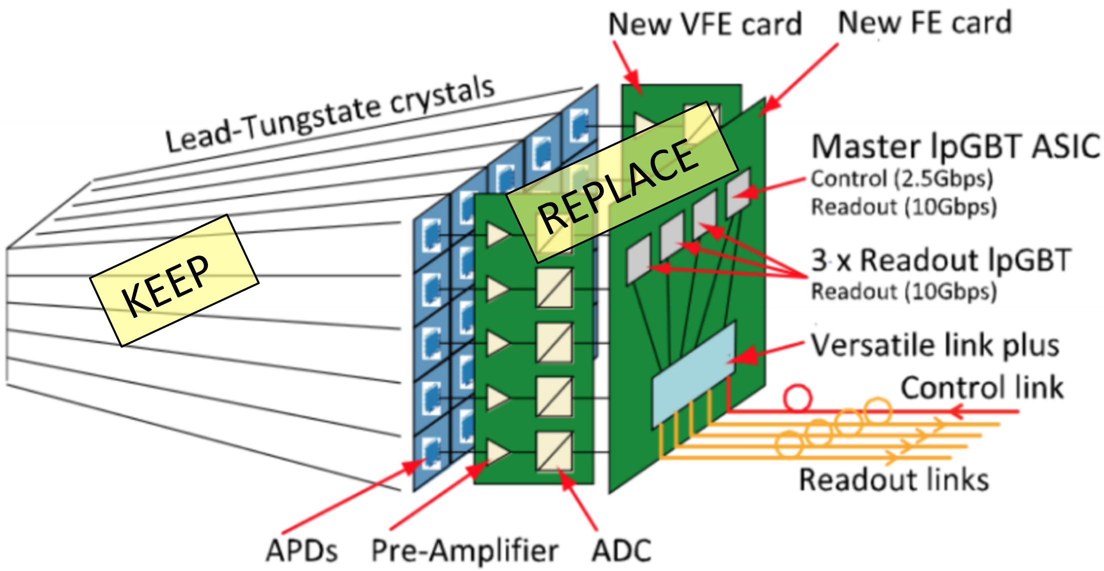
Further Calorimeter upgrades

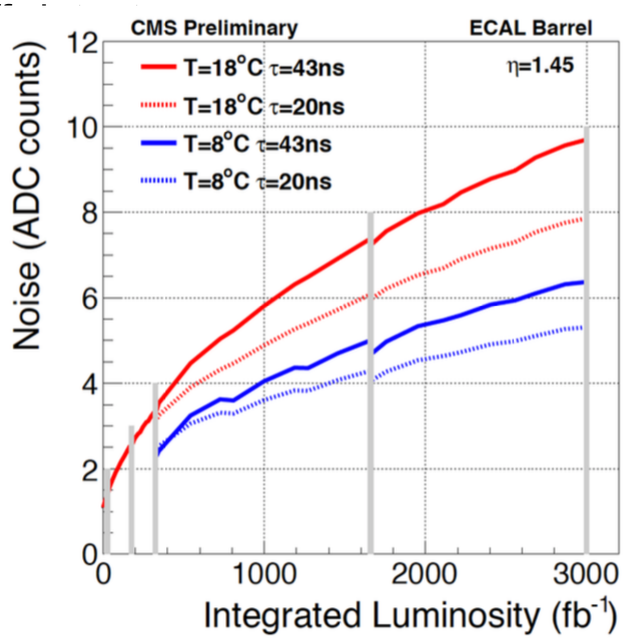


- Radiation tolerant ASICs and Commercial-Off-The-Shelf (COTS) components:
    - signal amplification and shaping
    - ADCs, TDCs
    - optical links with 5-10 Gbps
- Trigger, Timing and Control (TTC) distribution
- Power distribution for HV and LV

- High-bandwidth, low-latency signal processing with FPGAs
- Data buffering in FPGAs or on-board memory
- High-bandwidth interfaces to hardware trigger and to network based trigger/DAQ systems

New electronics for CMS Barrel Calorimeters





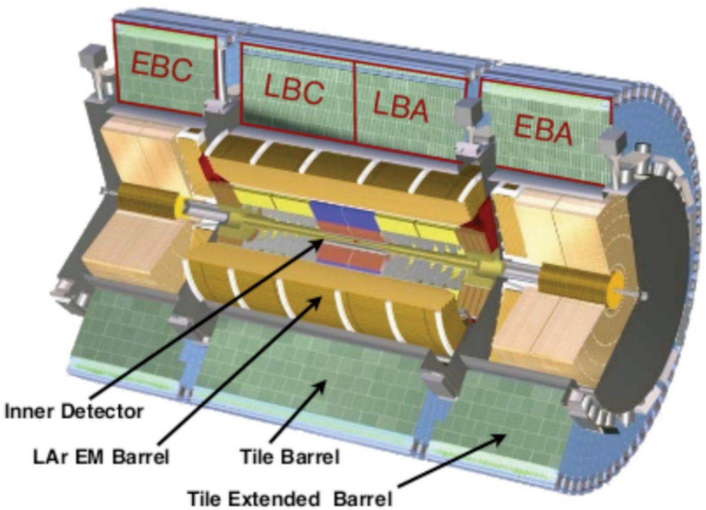
- Current lead tungstate crystals and avalanche photodiodes (APD) will be kept

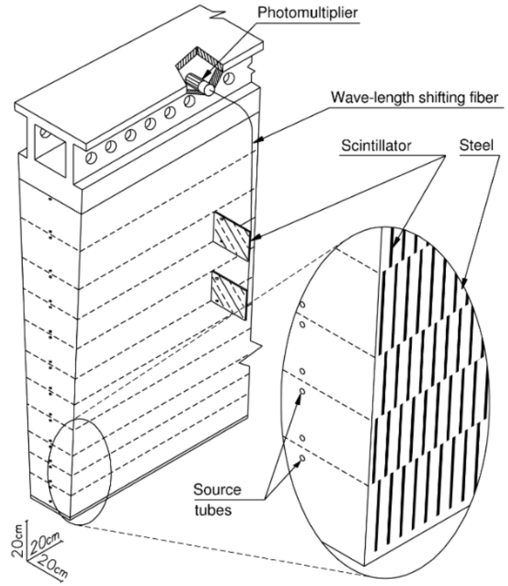
- **Electronics will be replaced to accommodate L1 trigger requirement**
  - Allows single-crystal readout (instead of 5x5 towers) at 40 MHz, providing maximum flexibility at trigger

Lower operating temperature and optimisation of electronics shaping time to mitigate APD noise

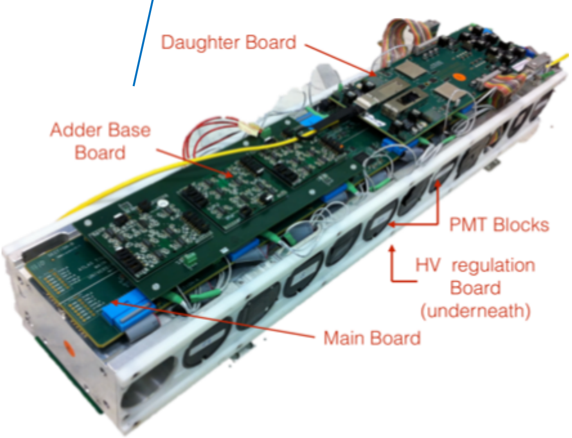
Upgrade of Hadronic Tile Calorimeter in ATLAS

- Major upgrade of on-detector mechanics and electronics





- On-detector electronics hosted inside girders at rear of TileCal.
- Today, includes LV/HV PS. Consider local vs remote HV.
- All data will be digitized on-detector at 40 MHz. Shielded location allows use of qualified COTS components.
- Shaper followed by dual 12-bit ADCs.
- Careful analysis of failures over last 10 years, improved redundancy and serviceability.



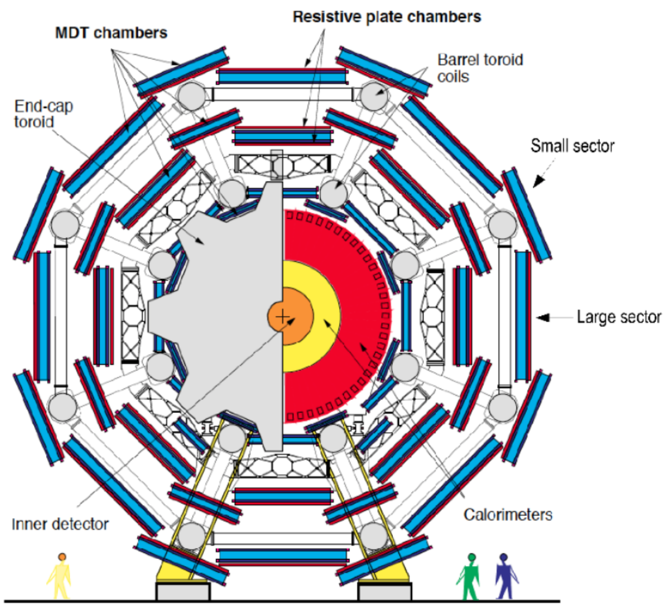
Dete

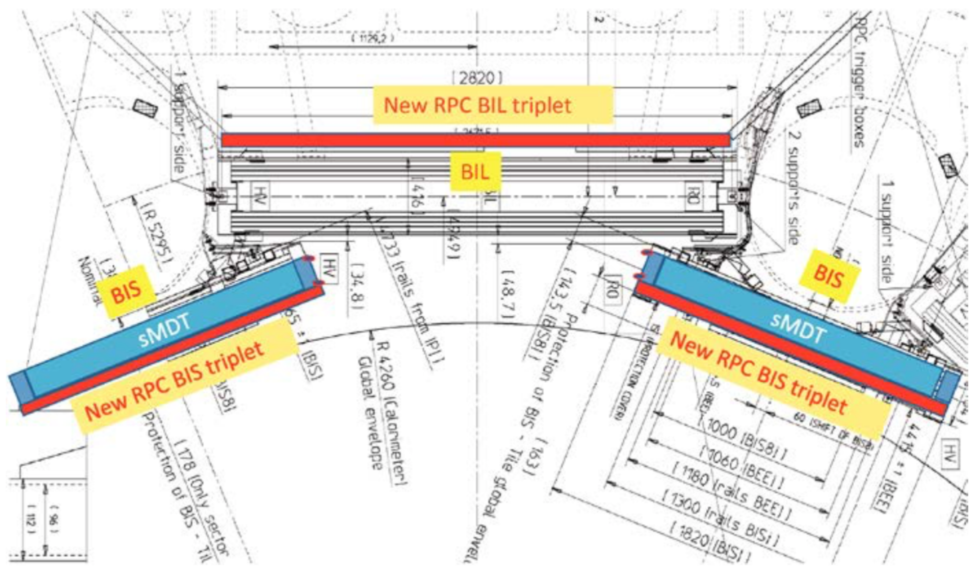
- Additionally:
New front-end and back-end boards for Liquid Argon Calorimeter (see spare slides)

Upgrade of Muon Detectors

- Additional stations will be included in ATLAS and CMS
  → increased coverage and timing
- Replacement of electronics with improved radiation hardness, higher bandwidth and better trigger capability

ATLAS Muon Chambers

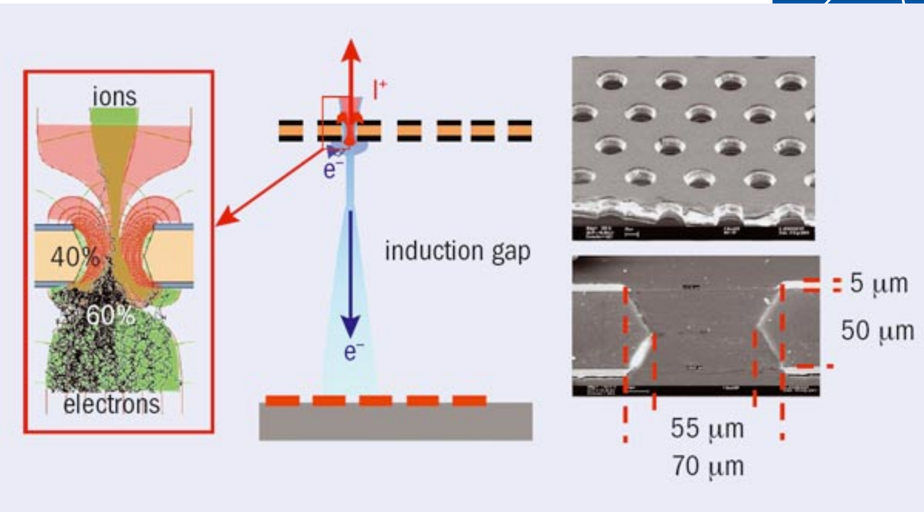




Recap: GEMs and RPCs

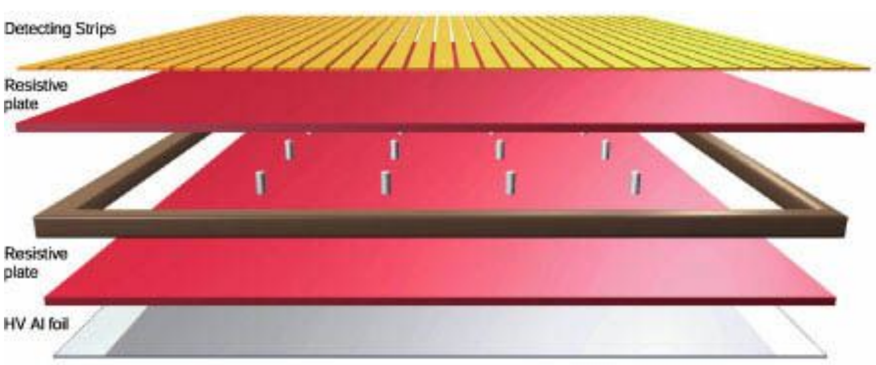
GEM – gas electron multiplier

- Thin kapton foil coated with metal film
- Chemically produced holes (diameter ~100 µm)
- Electrons guided by high drift field of GEM which generates avalanche
- Electric field strength of some 10 kV/cm
- Avalanche gain of 100 – 1000



RPC– resistive plate chambers

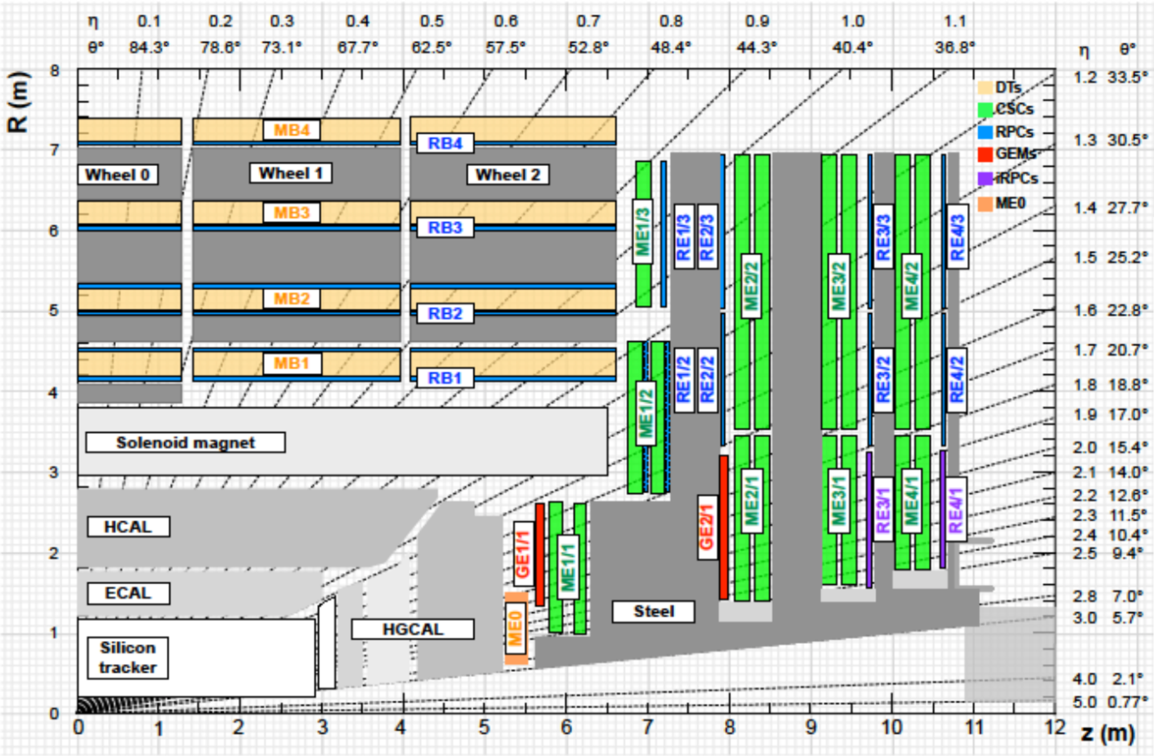
- Two parallel plates, a positively-charged anode and a negatively-charged cathode
- Plates of very high resistivity plastic material and separated by a gas volume
- Electrons created by ionization and multiplied picked up by external metallic strips
- Good spatial resolution
- Time resolution of one ns

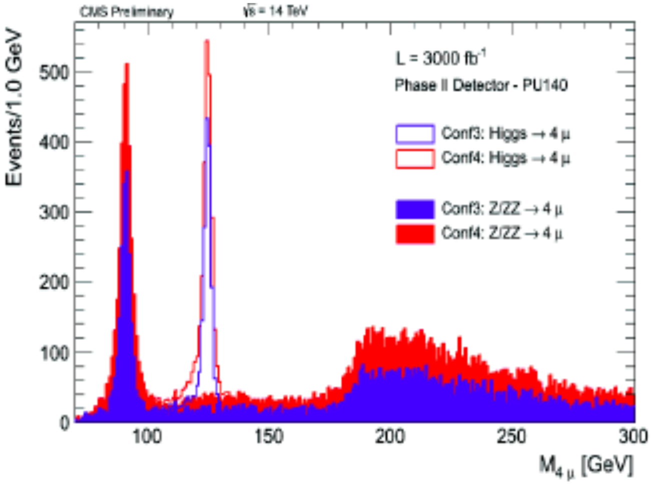


New Muon Detectors in CMS

- Complete muon stations to 1.6 < |η| < 2.4
  - GEMs in 2 first stations (improved p_T resolution)
  - RPCs in 2 last (timing resolution to reduce background)

- Replacement of readout electronics in Drift tube minicrates and Cathod Strip Chambers: improved timing precision





H→ZZ (4μ) without with MEo

(Short) Summary of Lecture 1

- **HL-LHC** will provide exciting physics from 2027 onwards
  - Enormous detector challenges, especially for inner layers
  - New domain of particle rates and radiation levels

- ATLAS and CMS will replace **inner detectors** with all-silicon tracking detector

- CMS will get new endcap **calorimeter**: silicon + W/Cu and scintillators + steel
- Upgrade of calorimeter readout electronics for ATLAS and CMS

- Upgrade of **Muon** detectors to increase coverage and timing

Acknowledgment

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Ingrid Maria Gregor, Karl Jakobs, Ulrich Parzefall, Didier Contardo

SPARE

More Calorimeter Upgrades in ATLAS

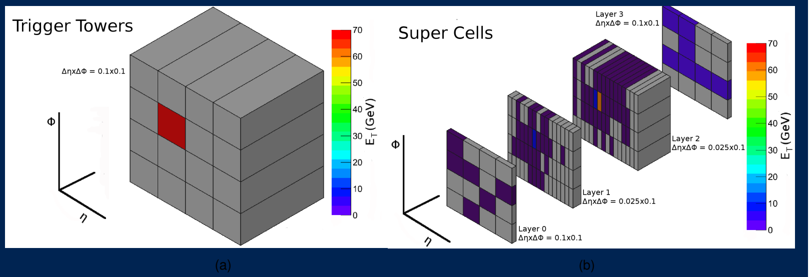
LAr calorimeter:

- new front-end (Trigger Digitiser Board LTDB) and back-end (Digital Processing System LDPB) boards
- increased trigger tower granularity ($\Delta\eta \times \Delta\varphi$ = 0.025x0.1)
- good trigger performances with the increasing luminosity and pile-up:
  - low trigger rate thanks to the background rejection
  - low thresholds and better turn-on curves thanks to the higher geometrical resolution

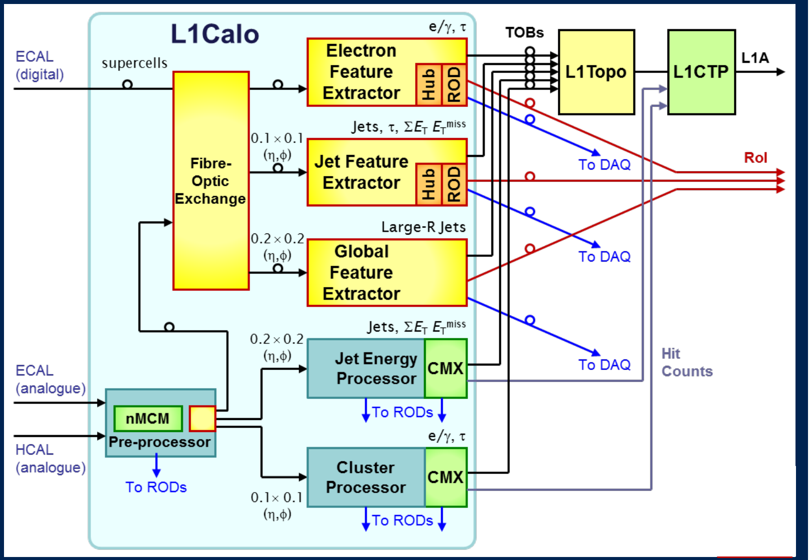
L1Calo:

- new Feature Extractor boards: eFEX, gFEX, jFex
- more refined processing of electromagnetic calorimeter information at higher granularity
- better discrimination between photons, electrons, taus and jets
- efficient single object triggers for electroweak-scale physics

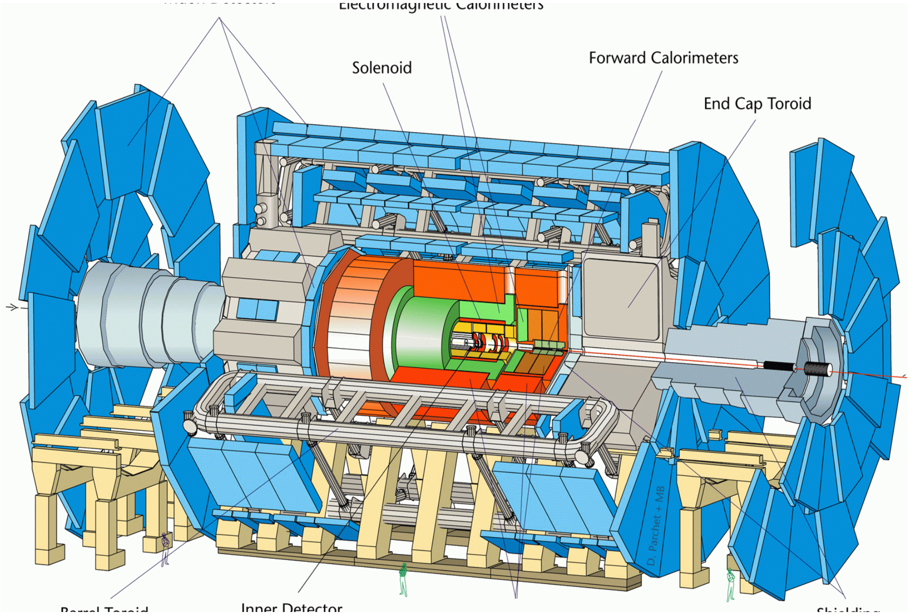
ATLAS-TDR-022-2013

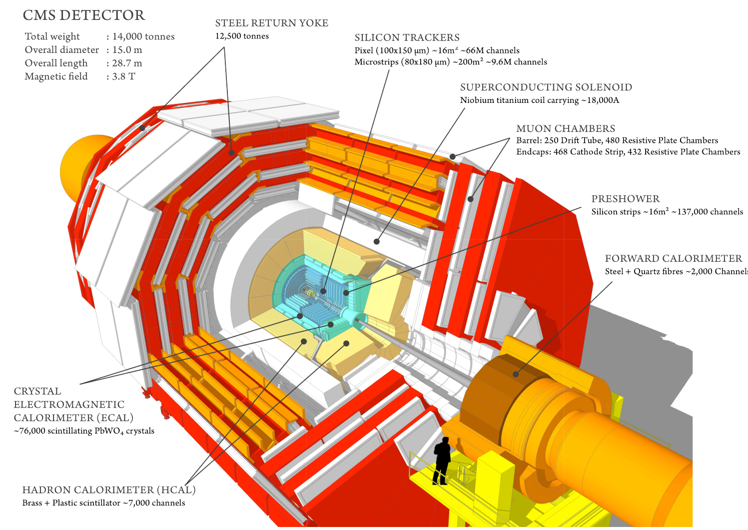


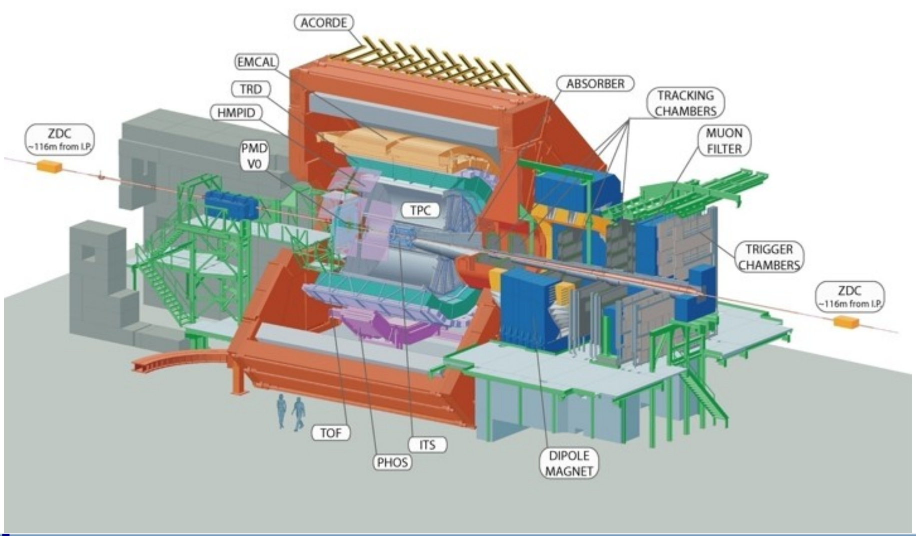
ATLAS-TDR-023-2013

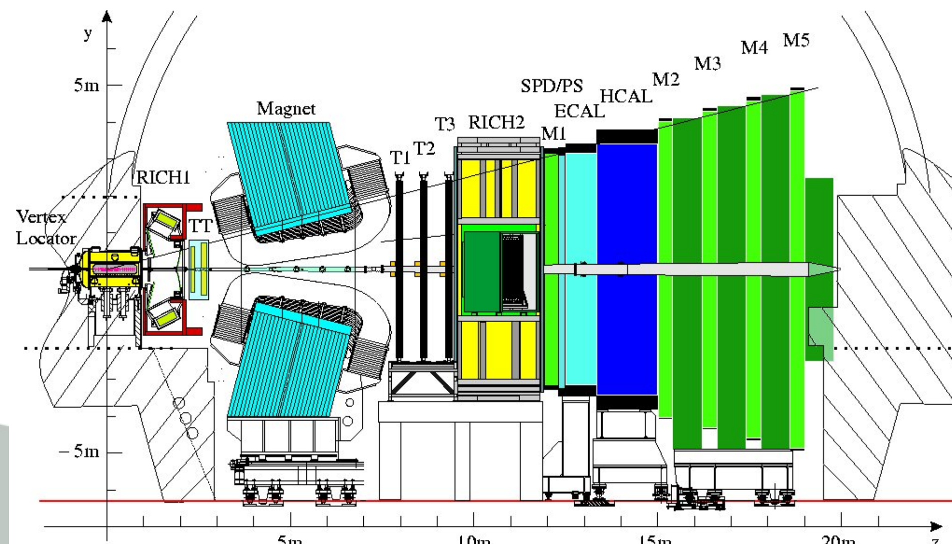


Experiments





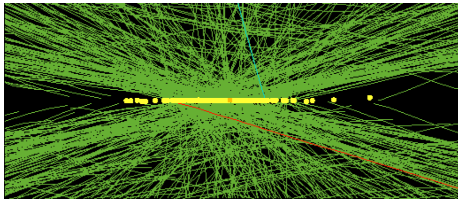




Pile up at the HL-LHC

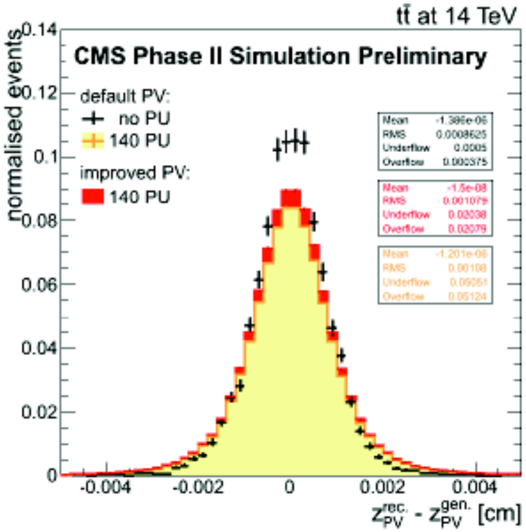
Capabilities to mitigate pile-up assessed in ATLAS and CMS

At L~ $5*10^{34}$ $cm^{-2}s^{-1}$ average pile-up of 140, in-time and out-of-time pile-up occuring

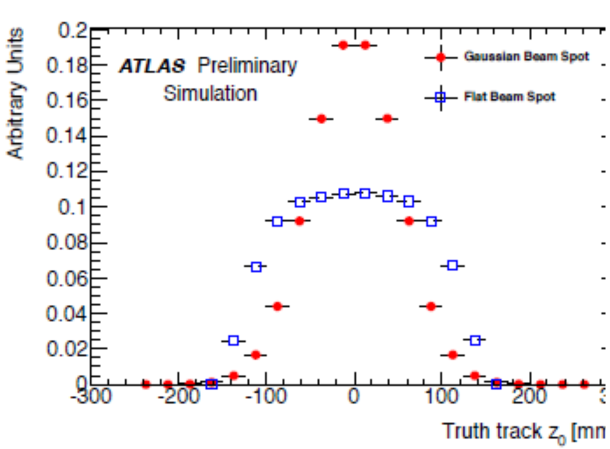


CMS-PHO-GEN-2012-002
78 reconstructed vertices in event from high pile-up

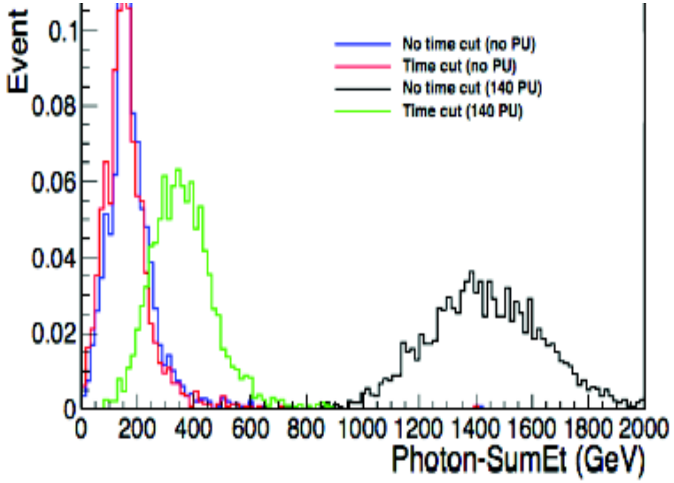
- Drives several detector developments (high eta tracking, muon tagging, timing) and algorithm optimization
- Impact of different beam configurations evaluated in ATLAS



Vertex finding in CMS Phase 2 tracker: new alg. 90% → 96% eff.



Longer beam spot ~flat +- 15cm compared gaussian sigma = 5 cm, ttbar events with 140 pile-up



Precise timing
Sum ET of photons in VBF H → γγ

HL-LHC baseline and ultimate goals

- **Baseline goal**: 250 fb^{-1}/year to reach 3000 fb^{-1}
  - Luminosity leveled with β^* at $5 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Pile-up $\approx$ 140
  - Machine efficiency = 50%
- **Ultimate goal**: 320 fb^{-1}/year to reach 4000 fb^{-1}
  - Luminosity leveled with β^* at $7.5 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Pile-up $\approx$ 200
  - Machine efficiency = 50%
- **Ultimate energy**: 7.5 TeV, under study

Squeezing

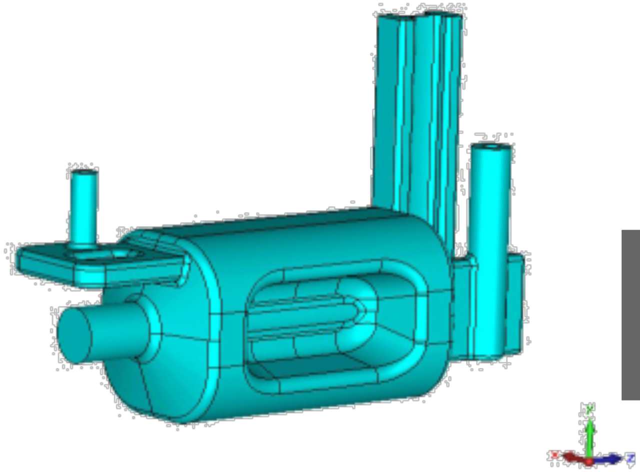
	2017	HL-LHC
β*	40 cm	15 cm
Beam size at IP (sigma)	12 um	7 um
β at triplet	~4.5 km	~20 km
Beam size at triplet	~1.5 mm	~2.6 mm
Crossing angle	370 urad	590 urad

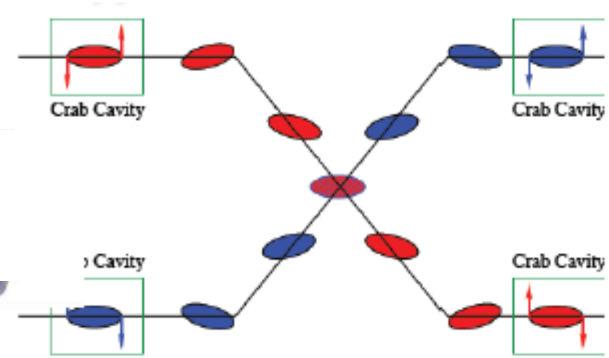
- Bigger beams in inner triplets
- Larger crossing angle
- Larger aperture in inner triplets

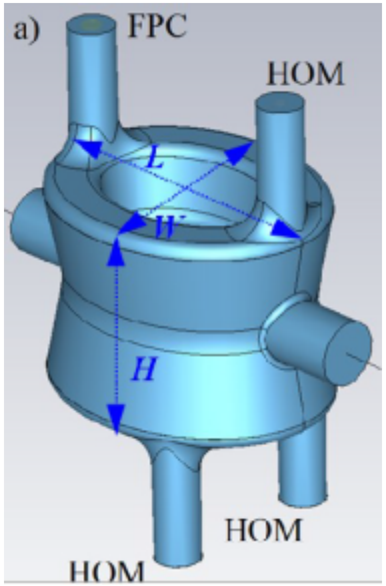
Development of Crab Cavities

Crab Cavities for compensation of geometrical reduction

Reduce effect of crossing angle

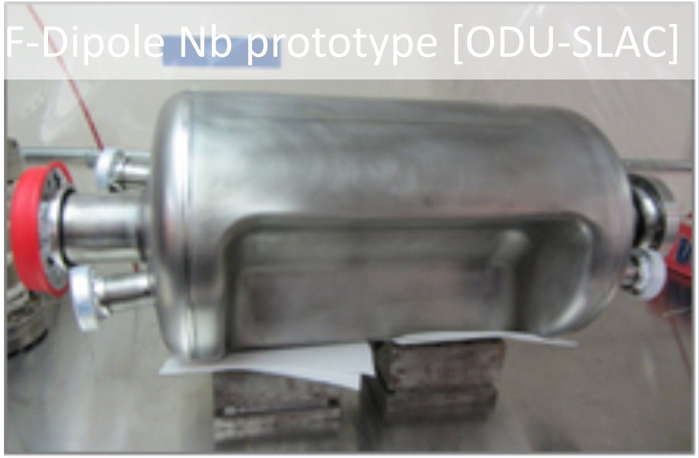






Major R&D program

Now concentrate on two designs in order for test installation in SPS



Development of Crab Cavities

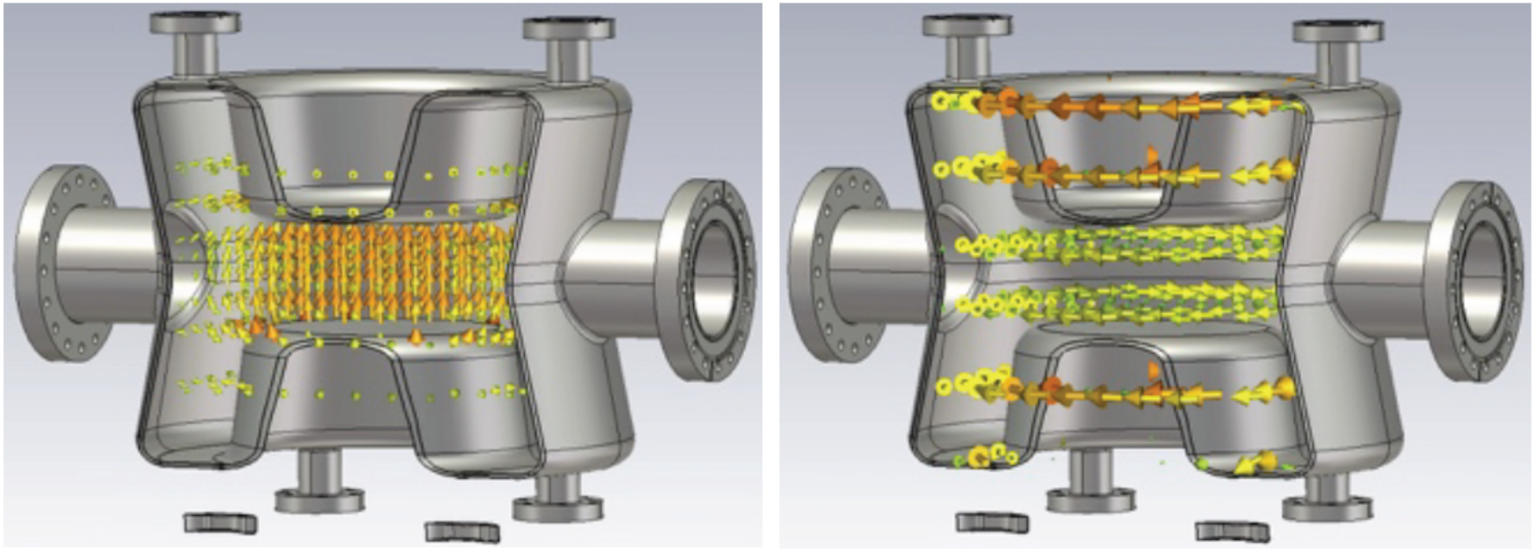
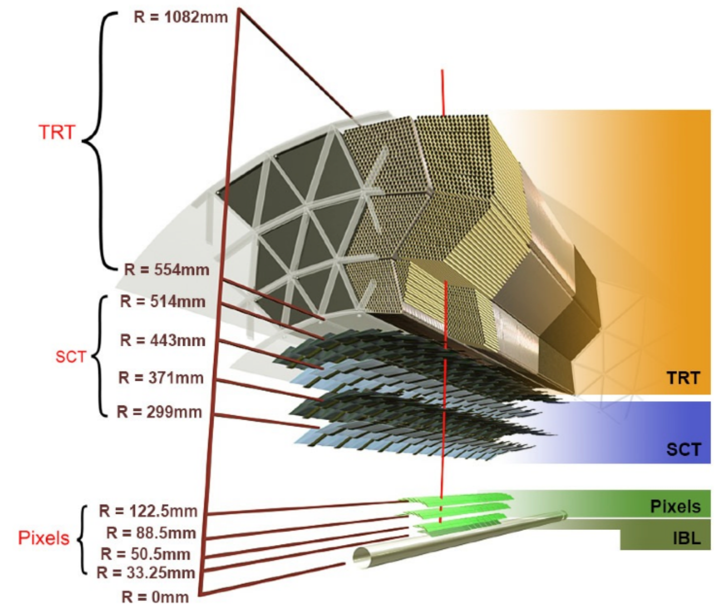
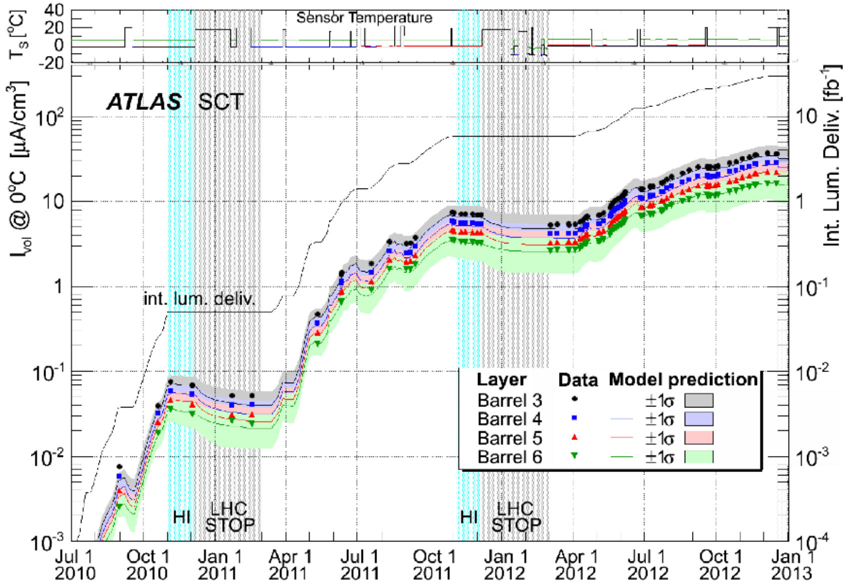


Figure 4. Electric (left) and magnetic (right) field distributions inside the DQWCC.

Inner detector of the ATLAS experiment

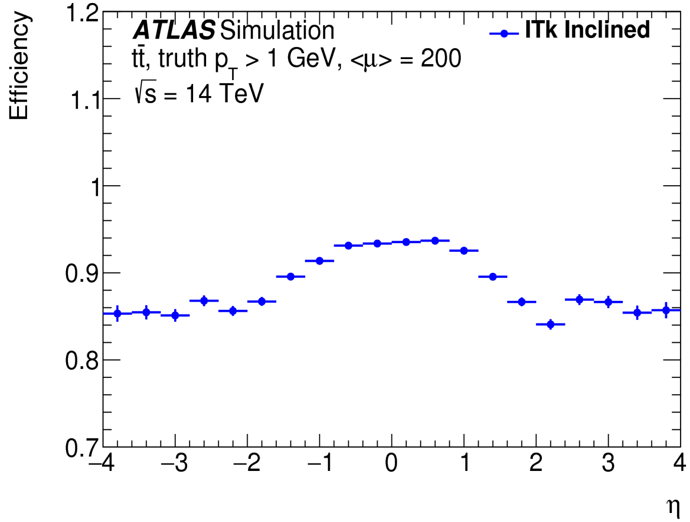
- Current inner tracker of ATLAS performing very well
- Transition radiation detector and silicon detectors for tracking
  - Planar strip sensors
  - Hybrid pixel with planar and 3D sensors
- However, cannot cope with radiation damage and high occupancy at HL-LHC operation



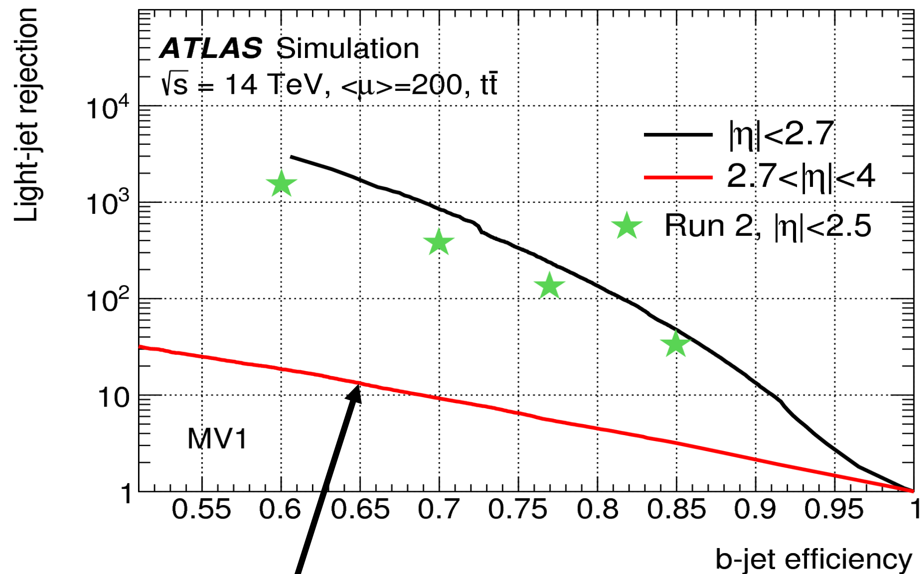


Detector	Area [m²]	Channels	Maximum dose [1MeV n_{eq}/cm²]
Pixel	1.8	92 M	up to $3*10^{15}$
Strip	60	6 M	up to $2*10^{14}$

Expected Performance of new ITk



Estimated using a tt sample with <μ>=200
→ primary, stable, charged particles with pT > 1 GeV, $|\eta|$ < 4

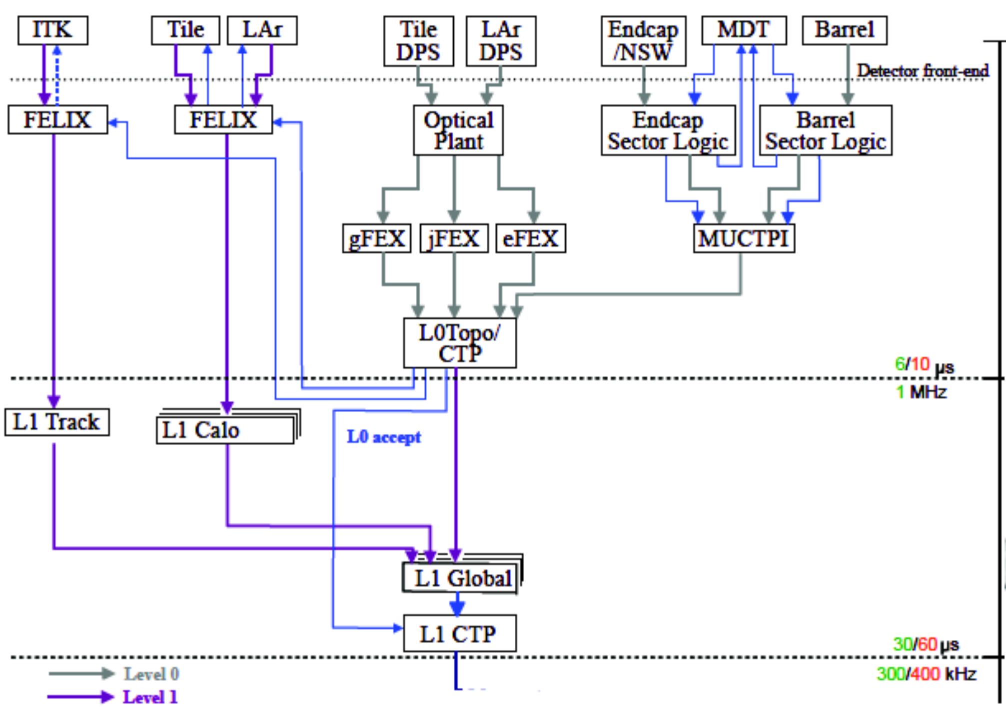


→ not optimised!
→ important to discriminate between VBF and tt in forward regions

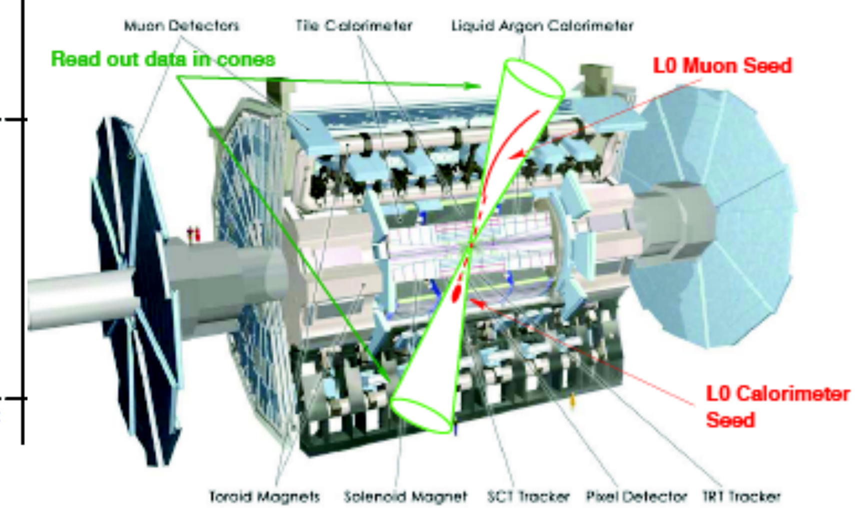
- b-tagging
→ evaluated using tt sample with parton-jet matching
→ Run-2 algorithms without dedicated tuning used

Upgrade Trigger Scheme in ATLAS

- New design foresees Phase1 Level 1 → in Phase2 Level 0
- Precision calorimeter, muon and inner tracker information in L1 (with new electronics)



Triggering sequence: L0 trigger (calo/muon) reduces rate within ~ 6 μs to 1 MHz and defines ROI → L1 track trigger extracts info in ROIs from readout electronics

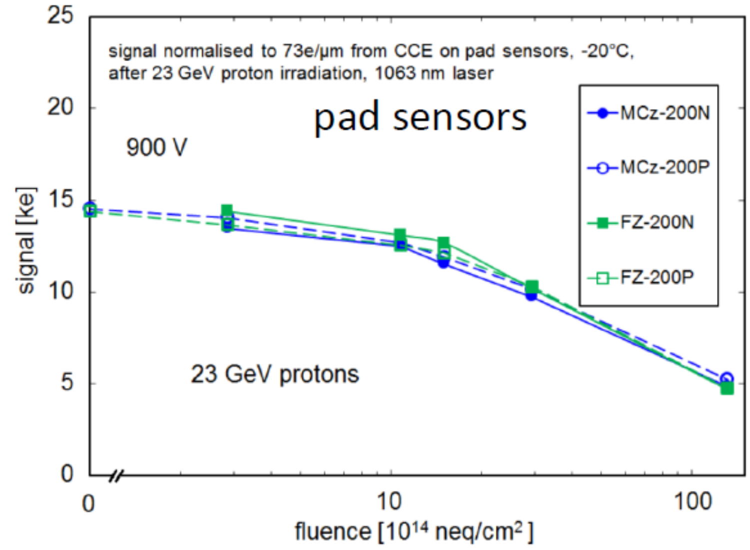


Level 0 Rate ~ 1 MHz, latency ≤ 6 μs, muon + calo
Level 1 Rate 300-400 kHz, latency ≤ 30 μs, muon + calo + tracks
HLT Rate 5-10 kHz

- Event building ROI driven

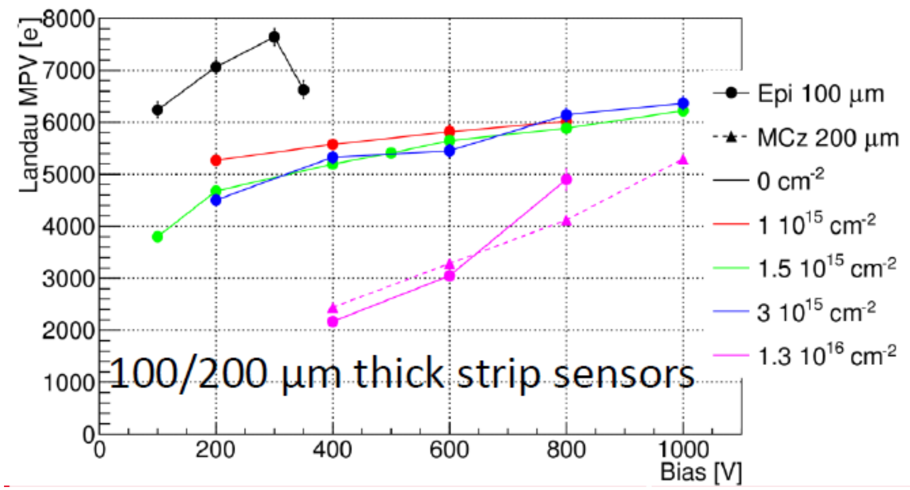
Planar sensor study in CMS

- Charge collection studied for irradiated 200 µm thick n-in-p pad diodes
  - 5k electrons after1x10^{16} neq/cm² (900 V bias)



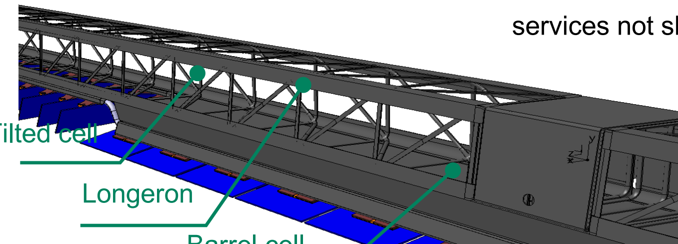
Thin sensors:

- Similar signal in 100 µm epi strip sensors as in 200 µm (MCz: 5 k electrons at ~800 V)
- However: Strong increase of current and noise with voltage, signs of soft breakdown/ charge multiplication
- Charge collection measurements repeated with pixel sensors: Weighting field



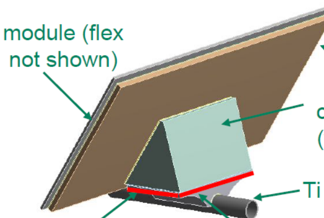
ITk Pixel Outer Barrel Demonstrator programme

- Programme to evaluate and validate the SLIM concept for outer barrel layers of ITk Pixel Detector: longeron with 2 cooling lines with flat and inclined modules based on FE-i4
- Several prototypes for thermo-fluidic, thermal and full electrical system test including serial powering, DCS and CO_2 cooling

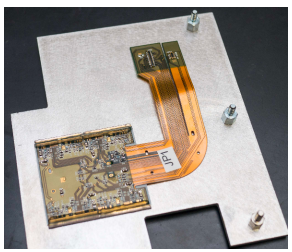


TRUSS longeron for layer 2 (1.6 m) with two cooling lines and 2x14 flat and 2x16 inclined modules

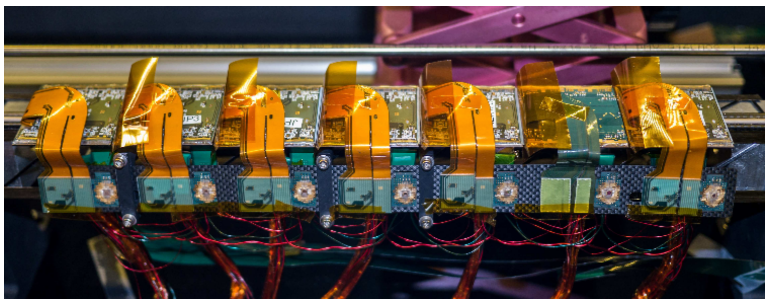
Inclined module on cell



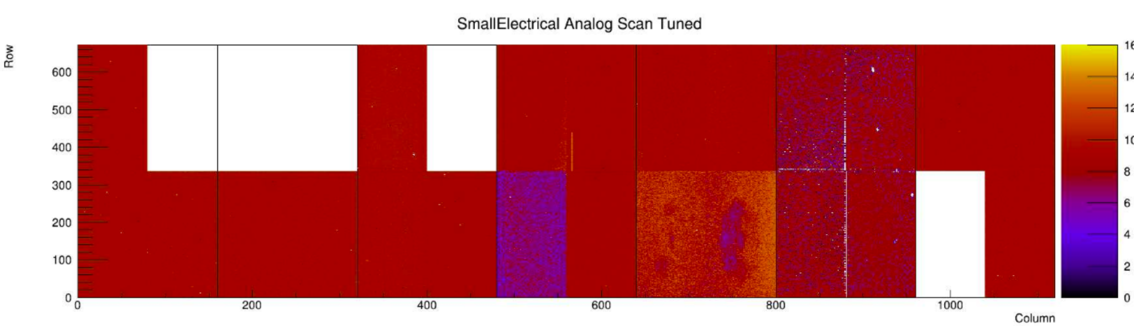
Electrical prototype with FE-i4 based modules



Quad module with 4 FEs

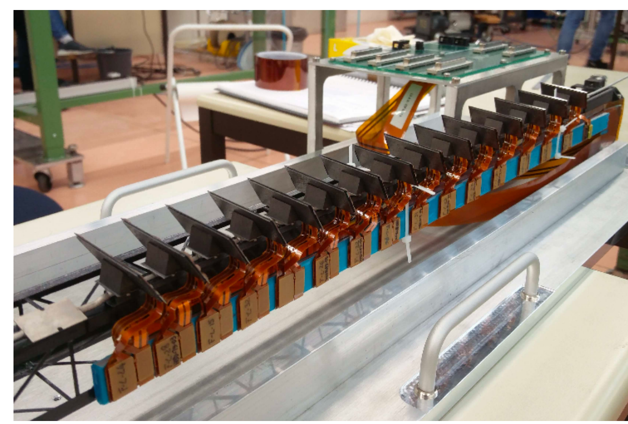


7 quad modules on carbon local support structure



All modules functional in one serial powering chain

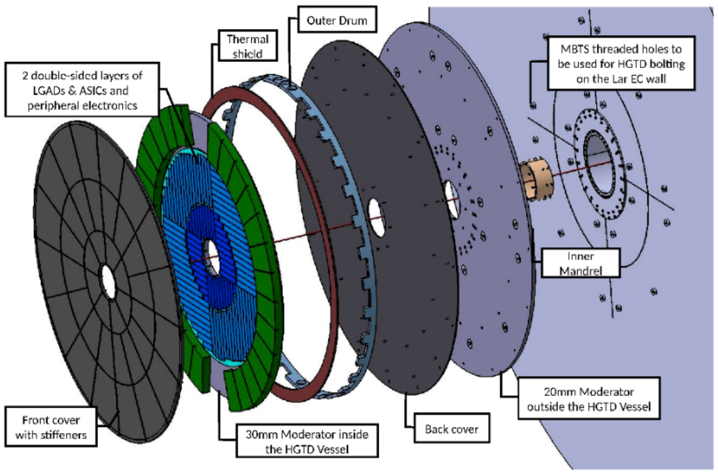
Thermal prototype with heater modules

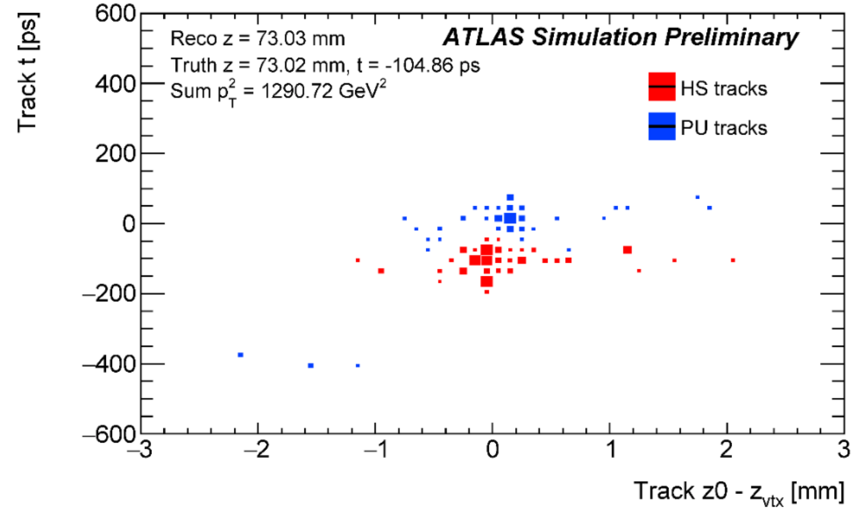


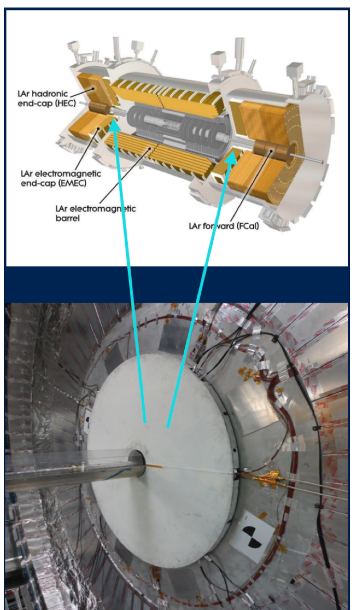
Values for required thermal figure of merit achieved

High Granularity Timing Detector for ATLAS Phase-2

- Disks covering 2.4 < η < 4.0 with 2(3) hits per track for R > 30 cm and R < 30 cm.







- MOTIVATION: PILE-UP MITIGATION, IMPROVE E/γ AND JET/ E_T^{MISS} PERFORMANCE
- LOWER TRIGGER THRESHOLDS AND INCREASED PHYSICS ACCEPTANCE; VALIDATE ISOLATION FOR E/γ
- SORT CHARGED TRACKS BY TIME TO REDUCE CONFUSION IN TRACKING AND PARTICLE FLOW