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The HL-LHC Upgrades of ATLAS and CMS

Georg Steinbrück, Hamburg University

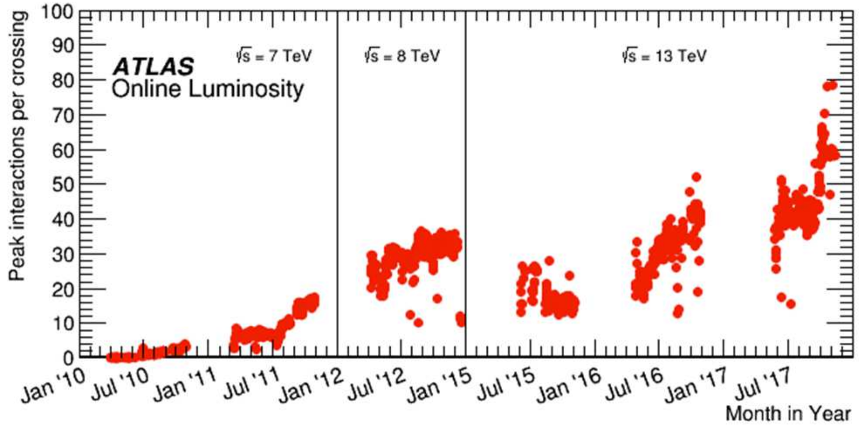
11th Annual Meeting of the Helmholtz Alliance
"Physics at the Terascale"
November 27-29, 2017
DESY, Hamburg

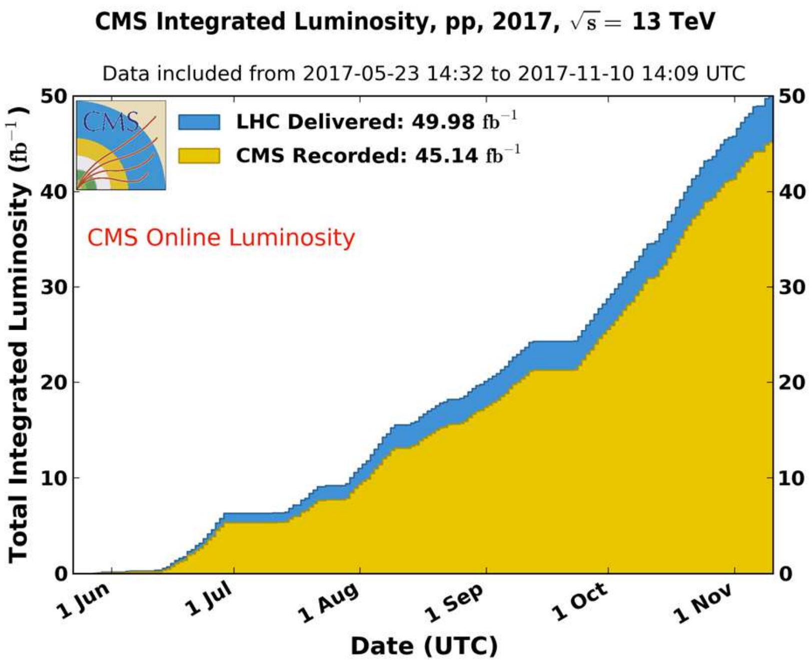
Outline

- **HL-LHC and Physics Motivation**
- Challenges for Detectors at the HL-LHC
- Detector Concepts: ATLAS and CMS
- Tracker
- L1 Track Trigger
- Calorimetry
- Timing Layer
- Muon Systems

LHC and its Experiments

- LHC is exceeding expectations in many ways.
- All four experiments in excellent shape.
  - ATLAS&CMS each ~700 publications
  - ALICE&LHCb each 200-300 publications

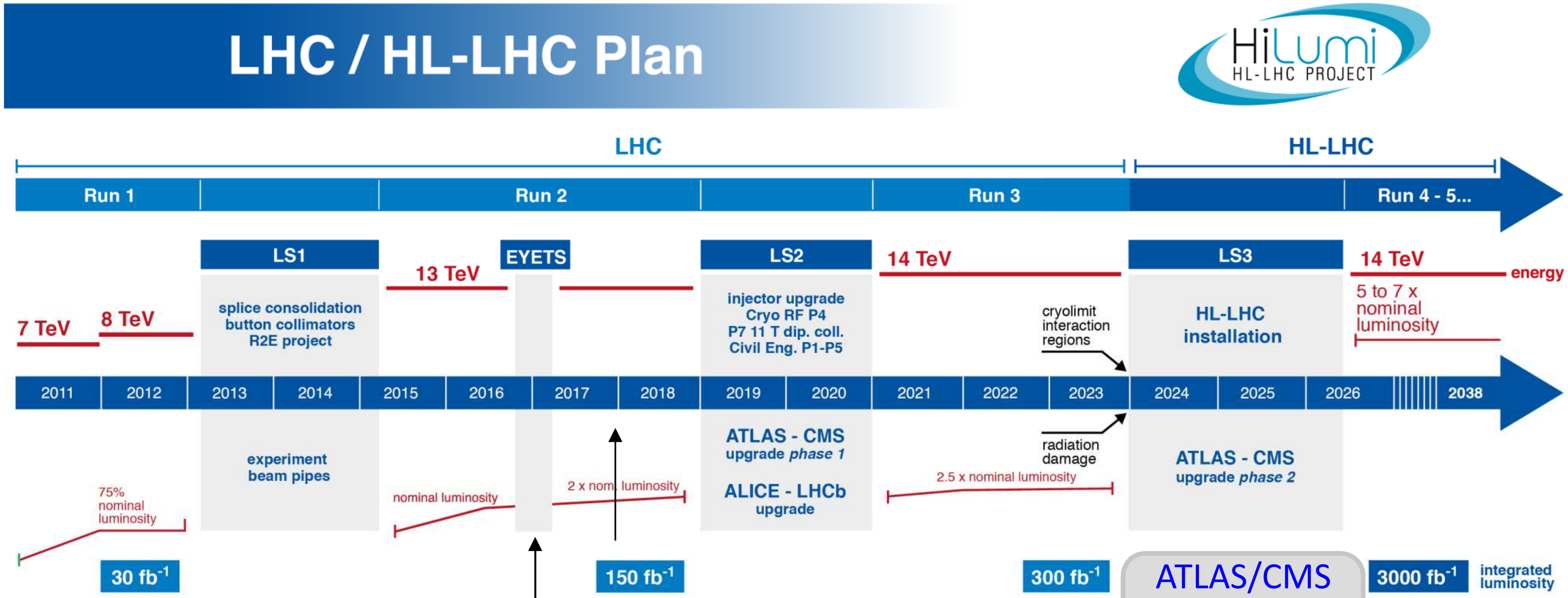




- European Strategy: exploitation of full potential of the LHC (up to 4000 fb^{-1}).
- Upgrades of machine and detectors are necessary to reach this goal.
  - Detectors are ageing and suffering from radiation damage.
  - Increase in luminosity will require detector improvements.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults#2017_proton_proton_13_TeV_collis

The High Luminosity LHC: Roadmap

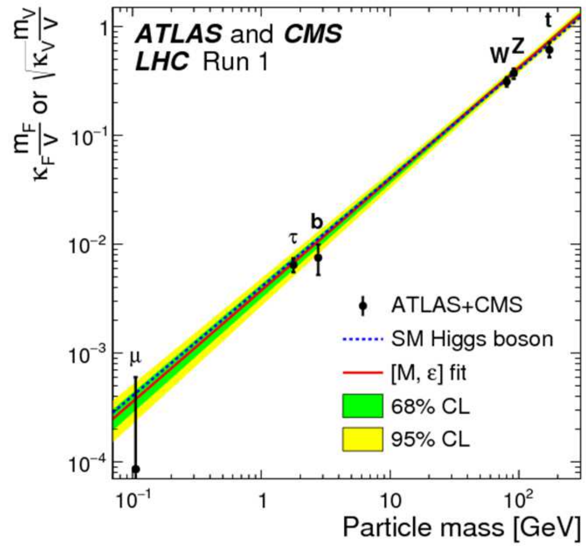


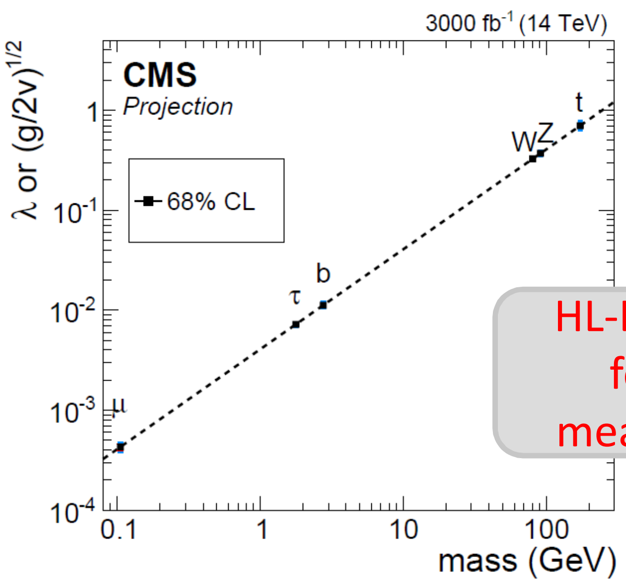
ATLAS/CMS
+LHCb
Upgrade

Installation of CMS phase-1 Pixels

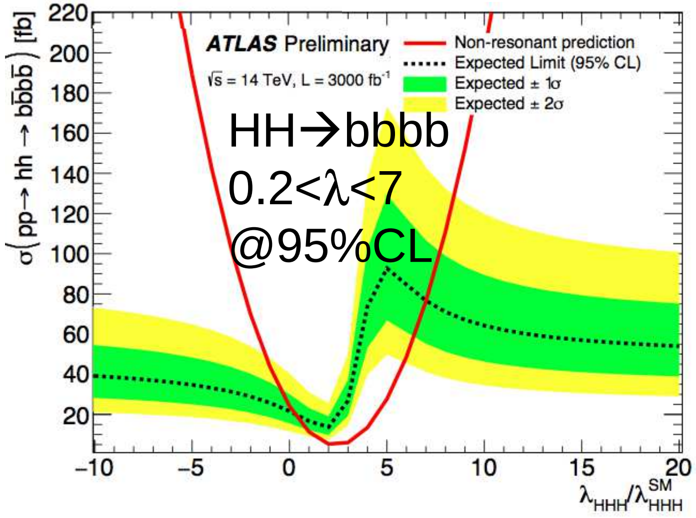
TDRs
CMS/ATLAS 2017/18

Physics Motivation HL-LHC: Higgs





HL-LHC: Higgs couplings to fermions and bosons measurable at the %-Level

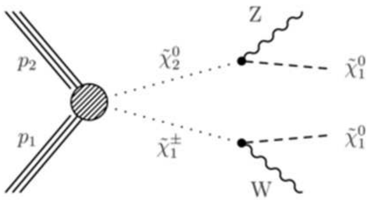


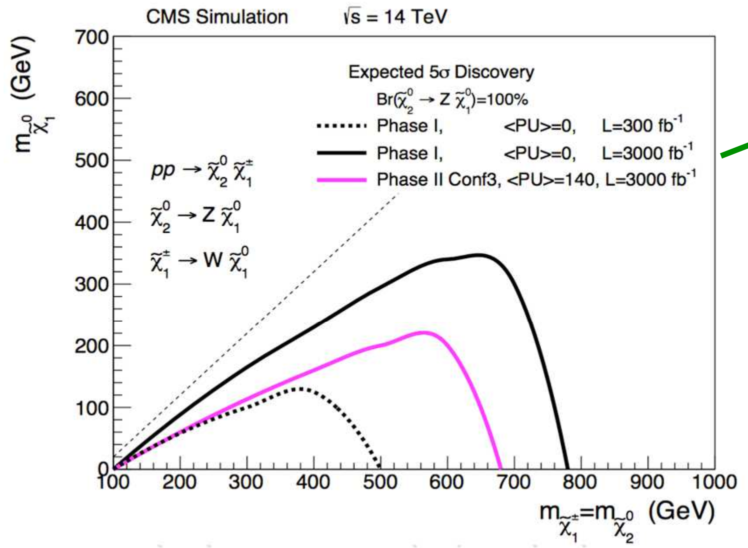
HH→bbbb
0.2<λ<7
@95%CL

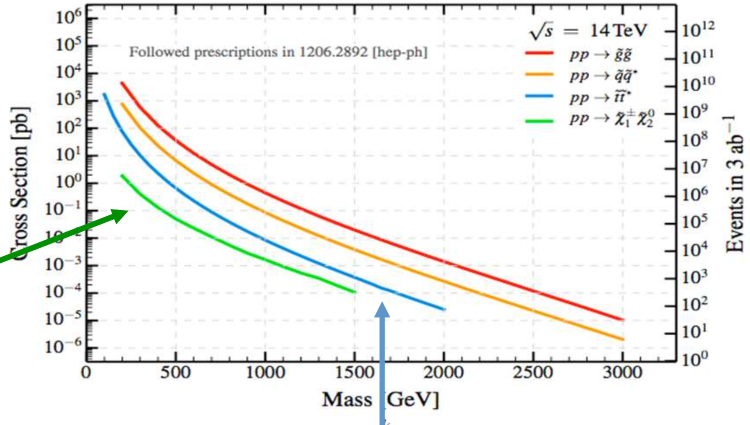
First measurement of Higgs self-couplings!

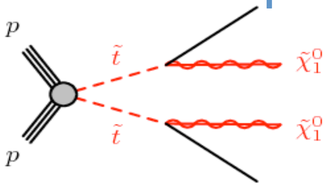
Physics Motivation HL-LHC: SUSY

Direct production of charginos/neutralinos

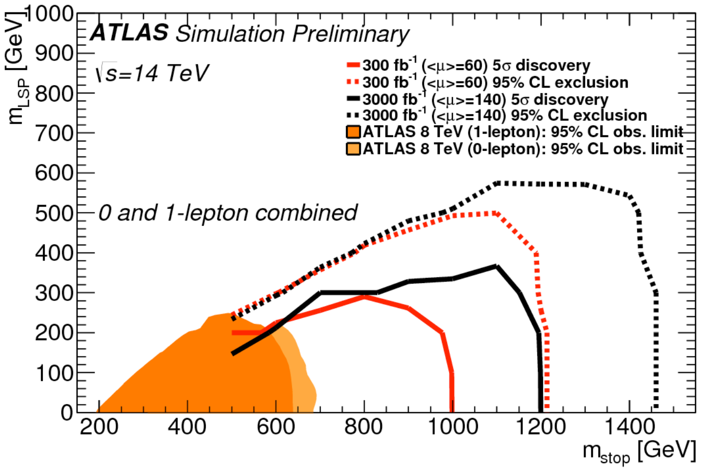






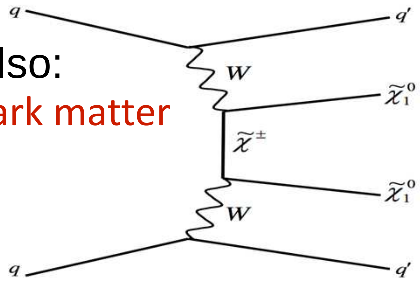


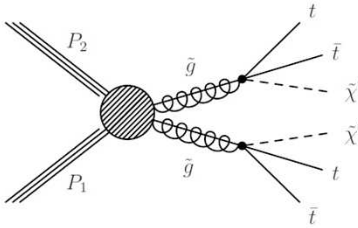
stop production



And also:

VBF Dark matter

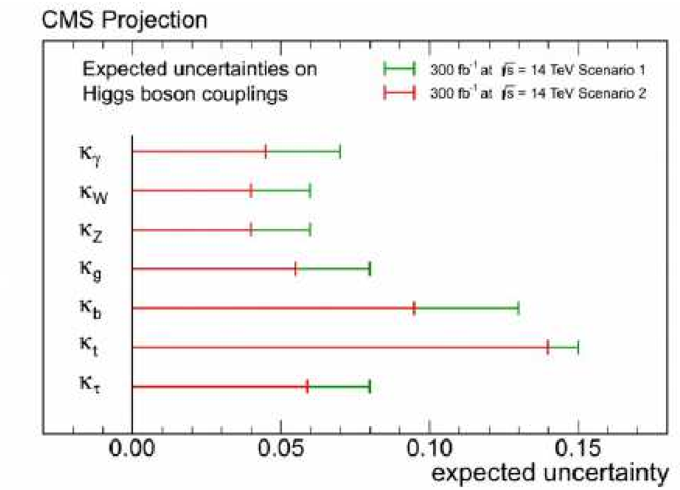


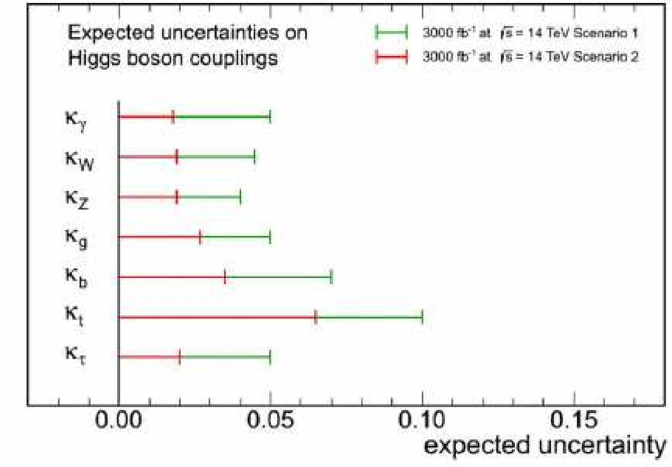


production of gluinos

Physics Motivation HL-LHC

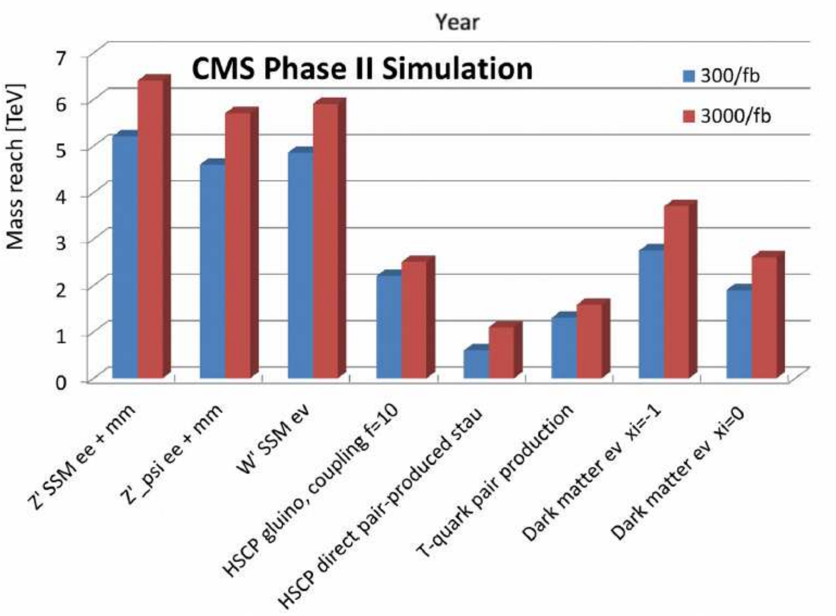
300 fb-1





3000 fb-1

Mass reach for heavy particles



Detector Challenges at the HL-LHC

Luminosity of up to 7.5x10^{34} cm^{-2}s^{-1},

up to 200 events/ 25 ns bunch crossing

ttbar event with 140 pile-up events (ATLAS simulation)

- Precision measurements & very rare decays
  - Maintain/improve current performance for all phys. objects
- Particle densities (radiation)
  - x10 (up to 3 GHz/cm^2) → x10 higher radiation damage
- Pile-up:
  - Increases combinatorial and rate of fake tracks
  - Adds extra energy (Calo)
  - Increases data volume / BX
- Pile-up mitigation:
  - High granularity detectors (tracker, calorimeters) with high efficiency
  - Precise timing to associate tracks and neutral clusters to each vertex

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- Tracker
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- Muon Systems

ATLAS and CMS Upgrades in a Nutshell

Tracker: ATLAS and CMS replace full tracker

Radiation tolerant - higher granularity

Extended coverage in forward region

Trigger/DAQ: both ATLAS and CMS add tracking at Level 1, new back-end electronics

Calorimeters:

ATLAS: new FE electronics for Tile and LAr (trigger) - replace FCAL if required

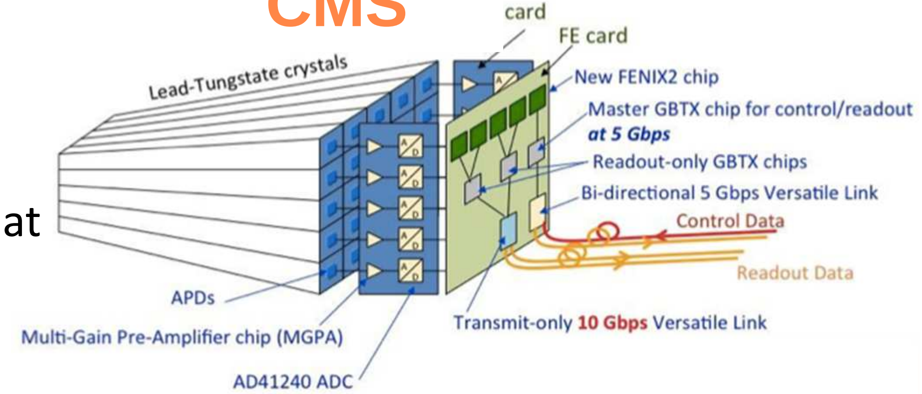
CMS: replace full endcaps (longevity), FE electronics in ECAL barrel for trigger

Muon systems:

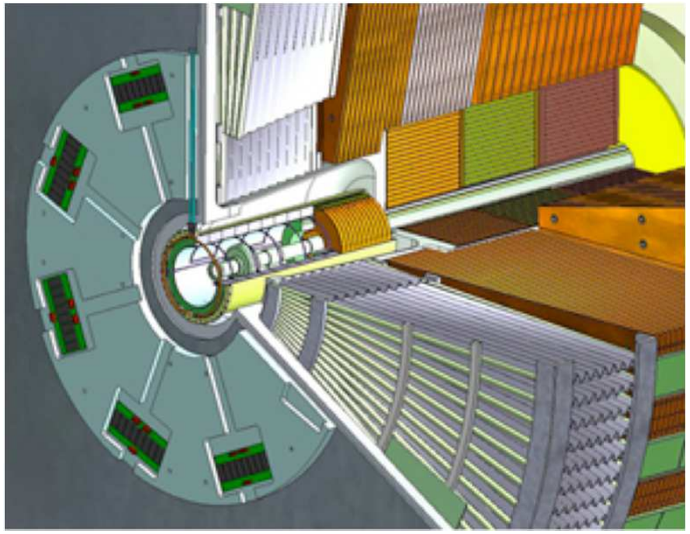
ATLAS: new FE electronics for trigger

CMS: additional forward chambers + GEM detectors - new FE electronics in DT chambers (longevity & trigger)

CMS



ATLAS



ATLAS and CMS Upgrades in a Nutshell

	ATLAS	CMS
Pixel Detector	New 🇩🇪 BN, DO, GÖ, HD, MPI, SI, W	New 🇩🇪 HH
Tracker	New, all silicon 🇩🇪 B, DESY, DO, FR High granularity timing detector MZ, GI 🇩🇪	New, all silicon 🇩🇪 AC, DESY, KA **MIP timing detector**
Calorimeters	Replace Electronics 🇩🇪 DD, MPI	Replace End-Caps 🇩🇪 Replace Electronics DESY (R&D)
Muon System	Replace electronics 🇩🇪 FR, MZ, M, MPI, WÜ	Extend End-Caps 🇩🇪 Replace Electronics AC
Trigger	Upgrade 🇩🇪 HD, MZ	Upgrade

Ingrid-Maria Gregor | LHC Detector Upgrades | November 11, 2017|

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Tracker-Specific Challenges at HL-LHC

Instantaneous Luminosity/Rate:

- Luminosity of up to 7.5x10^{34} cm-^{2}s^{-1} with lumi levelling, up to 200 events/ 25 ns bc

→Higher track density

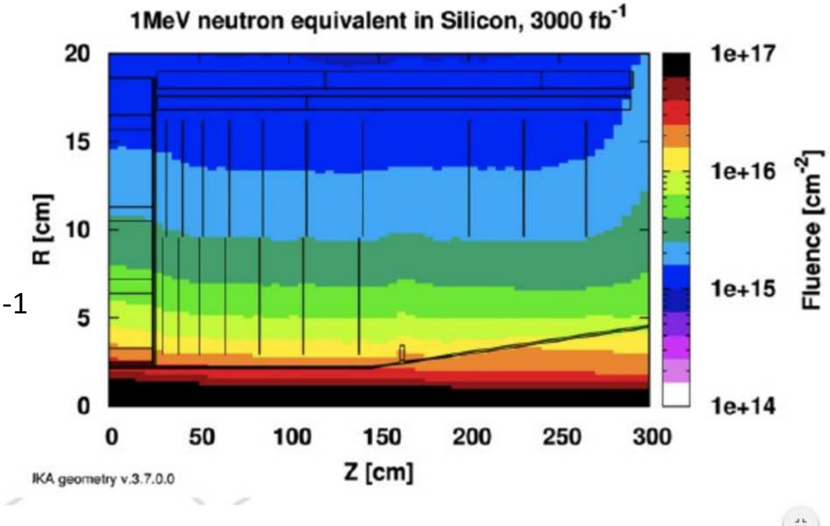
  - Goal: Maintain occupancy at ≈ % (strips) and ‰ level (pixel), and increase spatial resolution
  - Solution: **Shorter strips, Smaller pixel size** (**25(30)x100** or **50x50** μm^{2})
    (currently 100x150@CMS, 50x400/50x250@ATLAS/ATLAS IBL)

→Higher hit rate

  - New links

Integrated Luminosity:

- Radiation level for the 1st pixel layer after 3000 fb^{-1}
  - Non-ionizing energy loss (NIEL): **$\Phi_{eq} \approx 2.3\times10^{16}$ cm^{-2}**
  - Ionizing energy loss (IEL): **dose ≈ 12 MGy**
  - **Radiation hard sensors and ROCs**



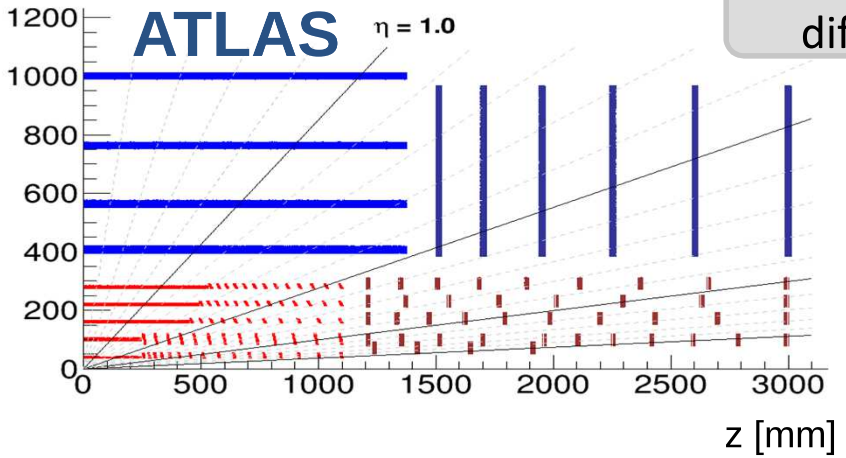
ATLAS/CMS Tracker for Phase-2

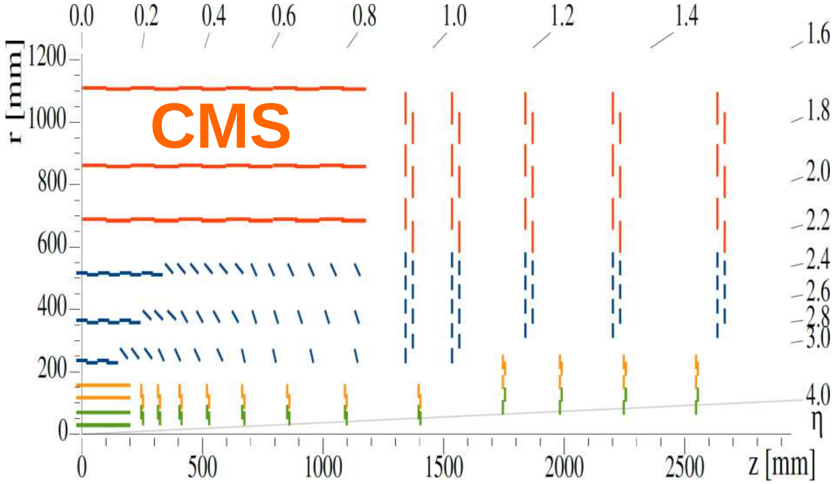
Both experiments:

- Finer granularity
  - Strip pitch ~ 60-90 µm & length ~ 2.5 – 5 cm
  - Pixel size 25(30) x 100/ 50 x 50 µm^2
- Reduced material in active volume
- Increased acceptance: |η| < 2.5 ➔ |η| < 4.0
  - VBF processes and improved association of tracks to jets for PU mitigation

Tracker		**ATLAS**	**CMS**
Inner (Pixels)	Layers (B+EC)	5 + 9	4 + 12
	Area	~13 m^2	4.9 m^2
Outer	Layers (B+EC)	4 + 6	6 + 5
	Area	163 m^2	192 m^2

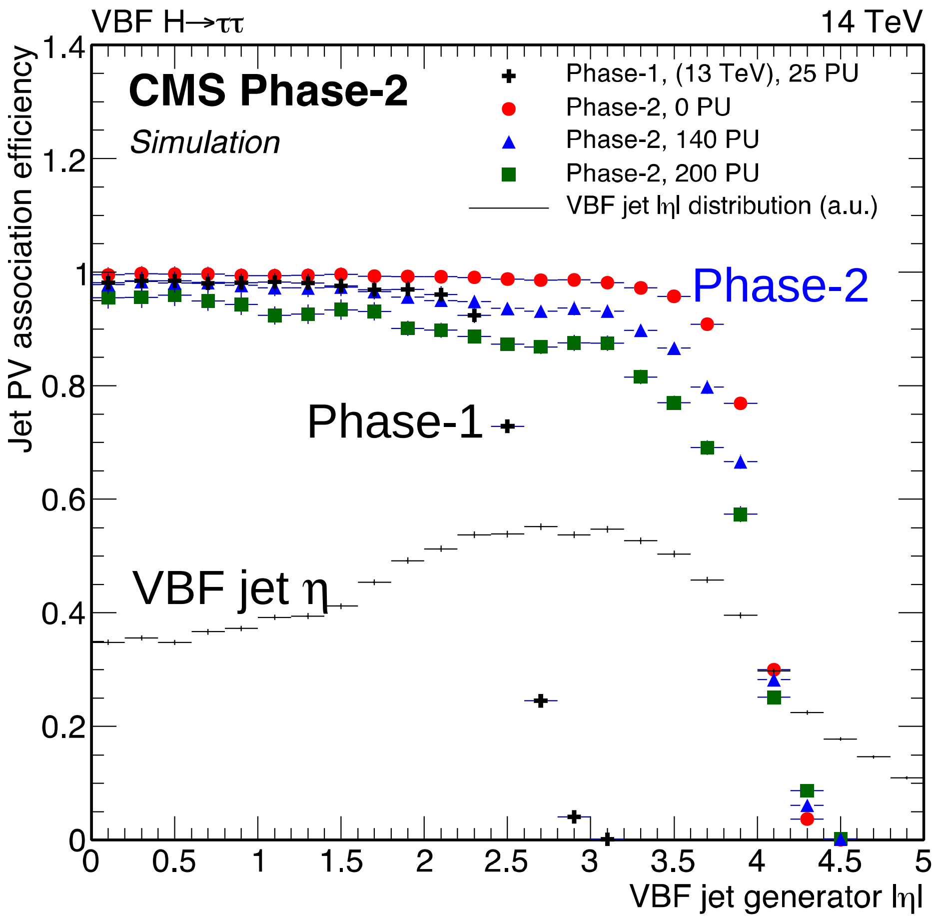
Solutions differ





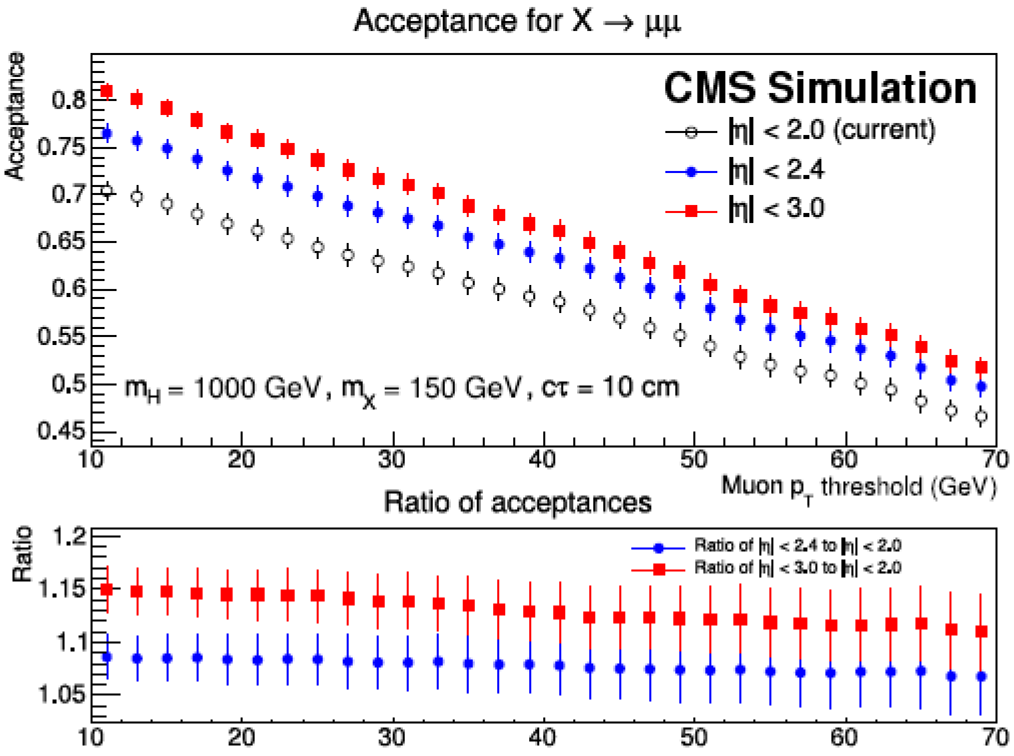
Why Move Forward?

- Improved sensitivity and acceptance in VBS, VBF Higgs studies, bbH, H→4l, etc.
- Improved IP and vertex resolution
  - pileup rejection, b tagging
- MET resolution: soft tracks
- Forward electron ID



Efficiency for associating a jet from VBF-process to a primary vertex.

Acceptance Gain for Exotica



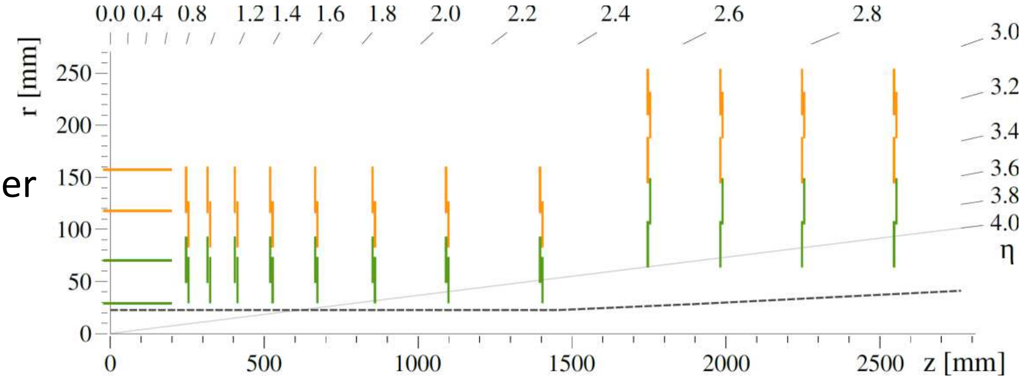
Gain in acceptance by going forward

- **Heavy exotic Higgs boson** in Hidden Valley models decays into long lived X bosons, which decay leptonically

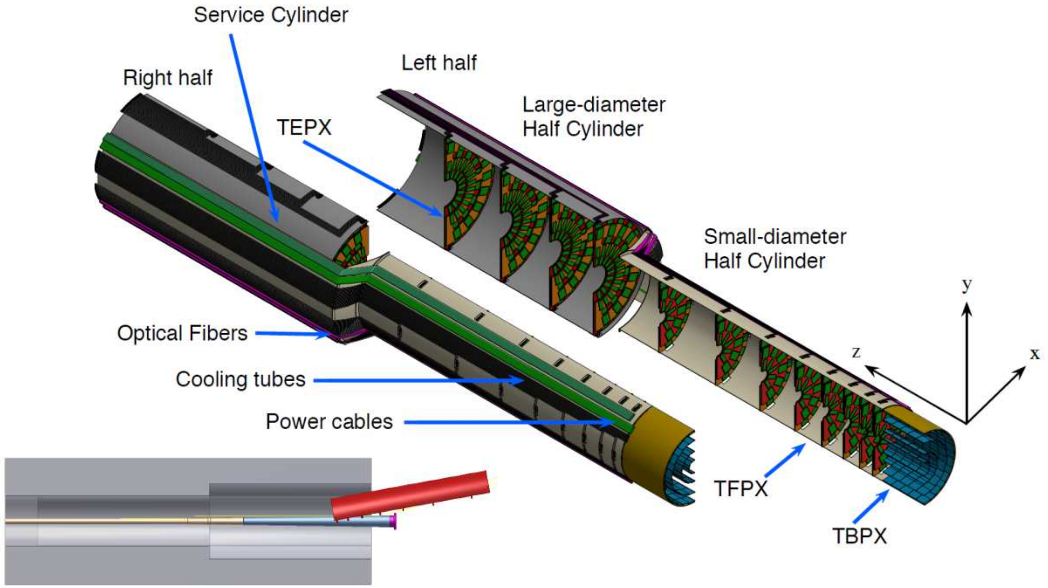
CMS Pixel Detector Layout, Phase-2

Coverage of geometrical acceptance:

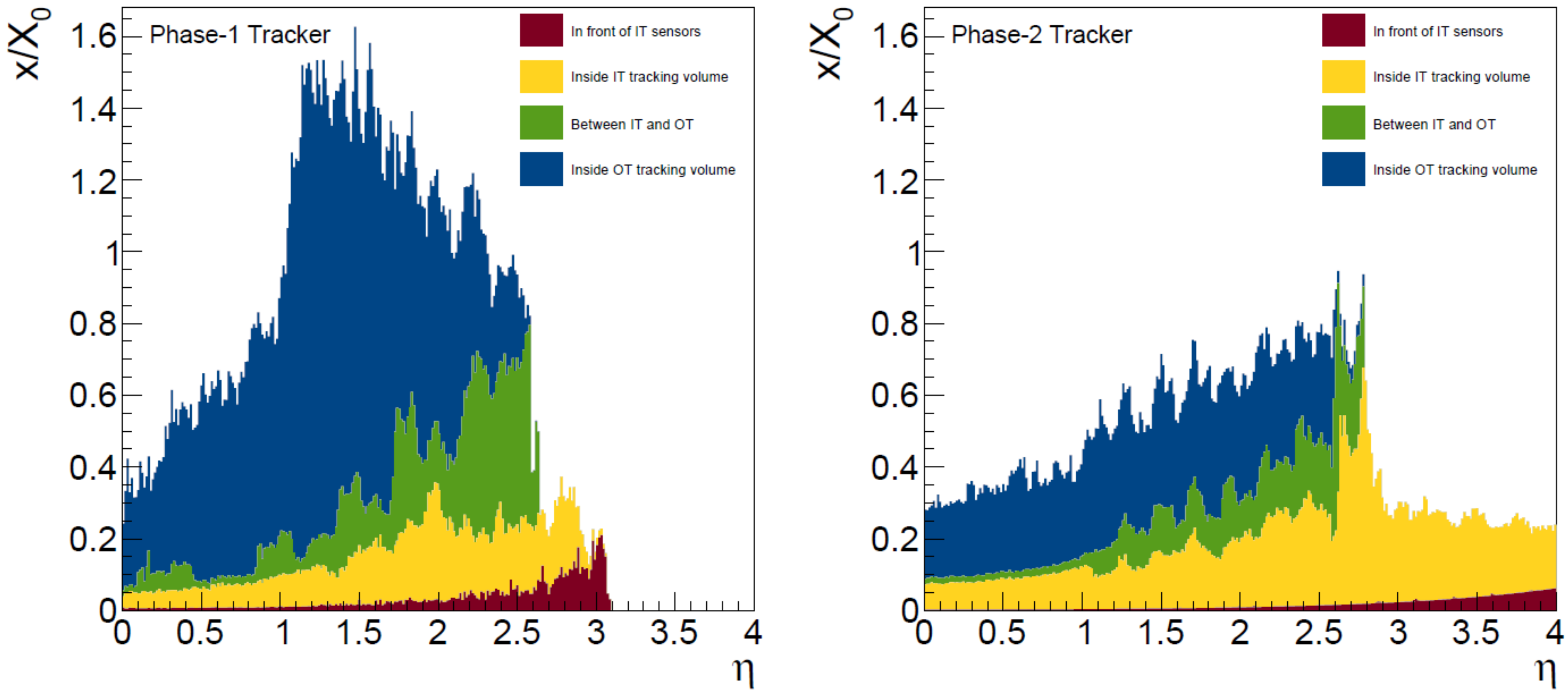
- Barrel:
  - 4 layers à la phase 1: 2.9-16.0 cm, but shorter
- Forward:
  - 12 disks on each side, coverage to |η|=4
- **Hybrid pixels, planar (3D option for inner layer)**
- **Total: ~4.9 m^2 of Si, >4300 modules**



- Simple mechanics:
  - no turbines/blades in the FPIX disks
- Only 2 modules types: 1x2, 2x2
- Step in the pixel envelope
  - to allow installation of central section with beam pipe in place



Material Budget CMS Tracker



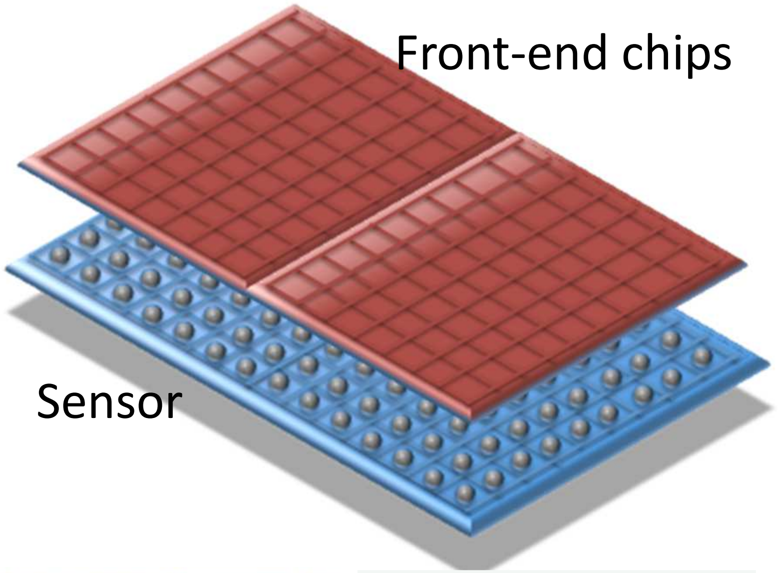
Clear reduction in the material budget in the forward region

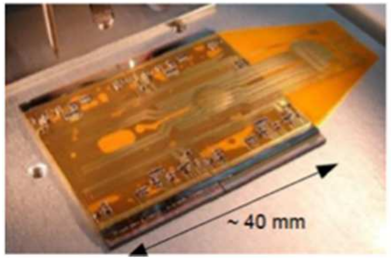
Pixel Modules for ATLAS and CMS

Hybrid pixel modules

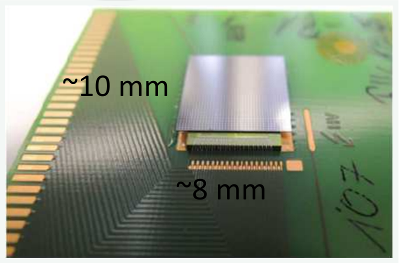
- Current technology in ATLAS and CMS
- Will be the choice for Phase-2 (one exception…)
- Planar or 3D sensors
- Technology challenges & solutions:
  - Smaller pixel size (down to 25x100 µm^2)
    - High density RO-chips →65nm CMOS (RD53 collaboration)
    - High-density bump-bonding
  - Radiation hardness
    - 65nm radiation hard, but exact dose limit depends on chip design details, extensive studies ongoing, first RD53A chips being tested
    - Radiation hard sensors under development: Thin planar n-in-p sensors or 3D sensors

Hybrid pixel detector





Examples: ATLAS quad FE-I4 modules



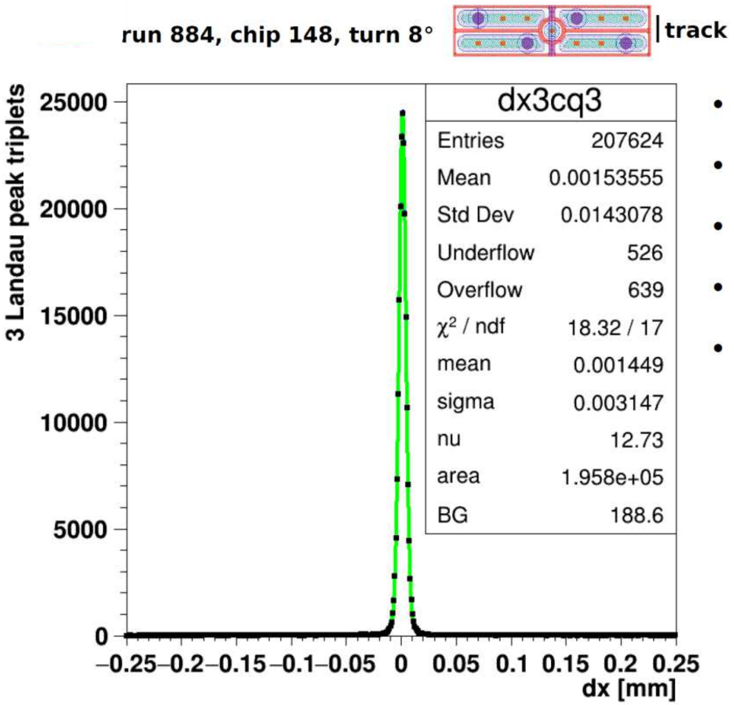
CMS sensor bump bonded to ROC4sens

Pixel Sensors: R&D at CMS

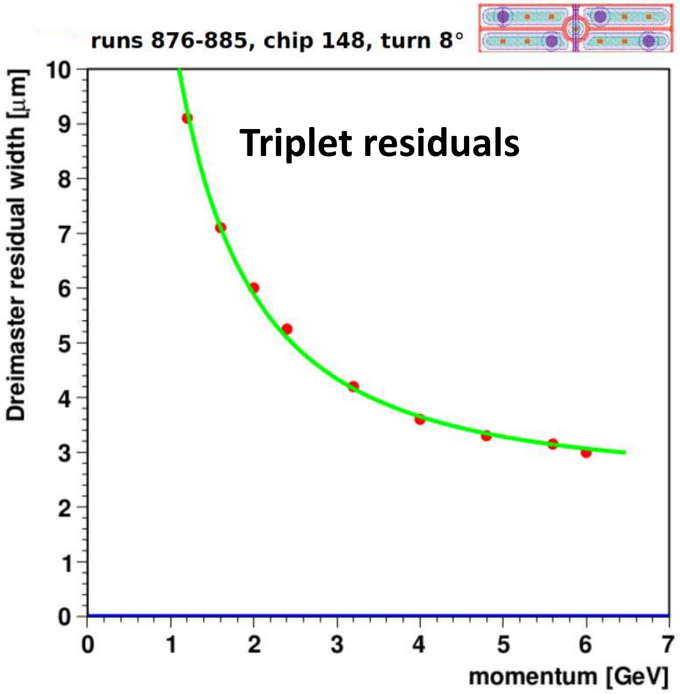
Resolution studies@DESY Testbeam (5.6 GeV e)

- Turn 8°, cluster pulse height cut around peak of Landau
- Triplet residuals, unfolding→ 2.0 µm resolution

triplet residuals

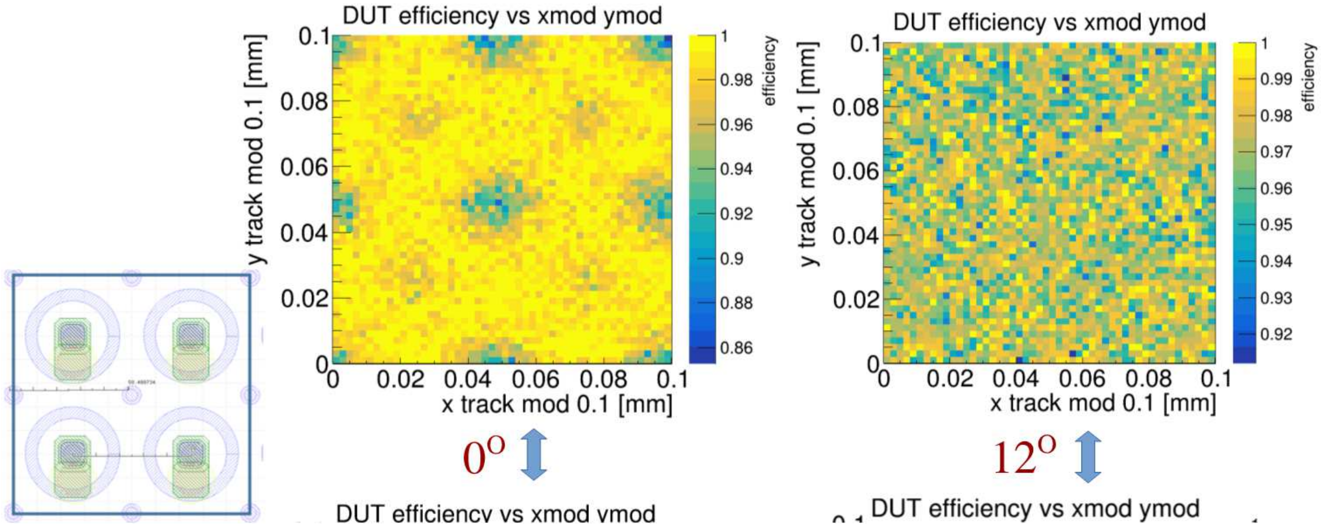


momentum scan



CMS 3D Pixel Sensors

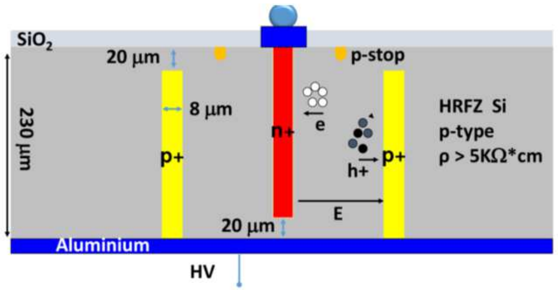
Resolution studies@DESY Testbeam (5.6 GeV e)

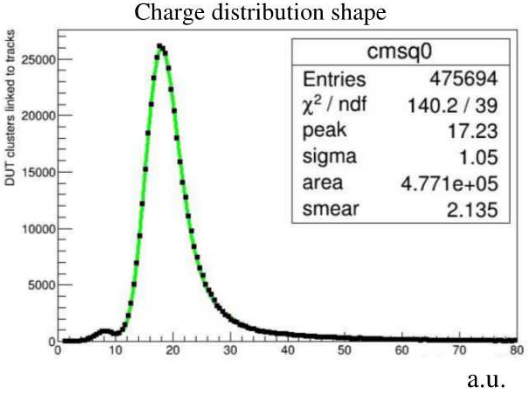


CNM, Barcelona

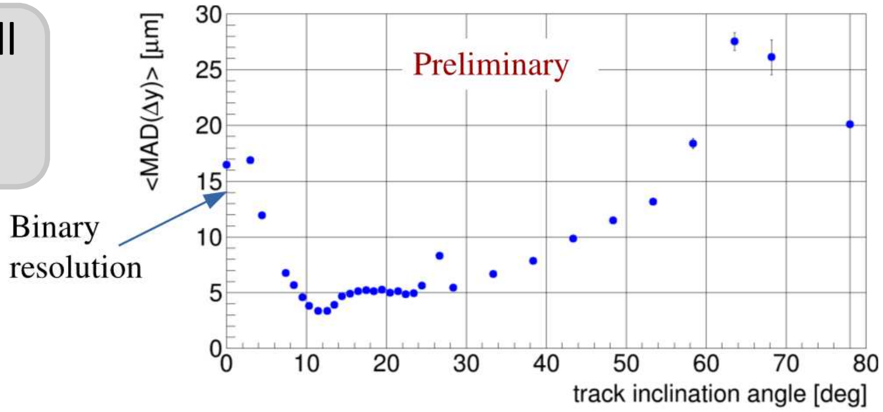
Double sided 3D process

50x50 µm





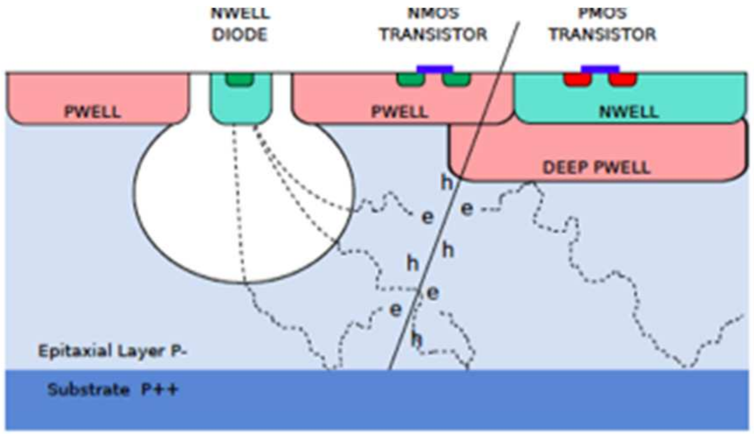
First small pixel 3D in CMS



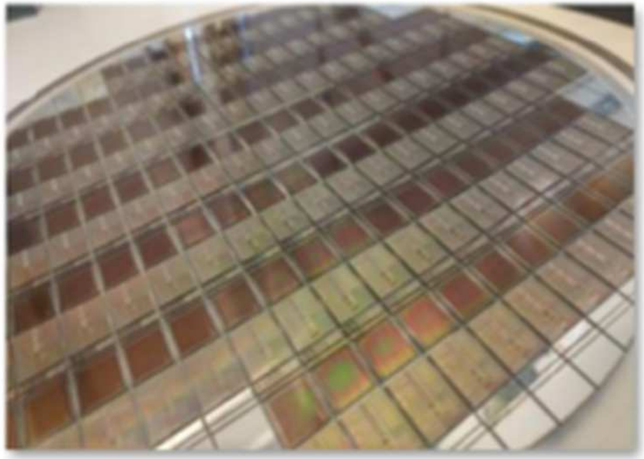
CMOS Pixels for ATLAS

ATLAS CMOS Collaboration:

- Development of radiation hard monolythic HV-CMOS sensors for ATLAS ITk
- HV-CMOS pixels good candidate for outer Itk pixel layers:
    - Low material budget, low power consumption
    - Reduced production and assembly costs
    - Several prototypes produced by different foundries (TowerJazz, Lfoundry, AMS) have been designed and tested or are in production.
    - Good performance demonstrated up to 5E15 cm^{-2}
- Technology foreseen for outer pixel layer
- Final decision one year before start of production

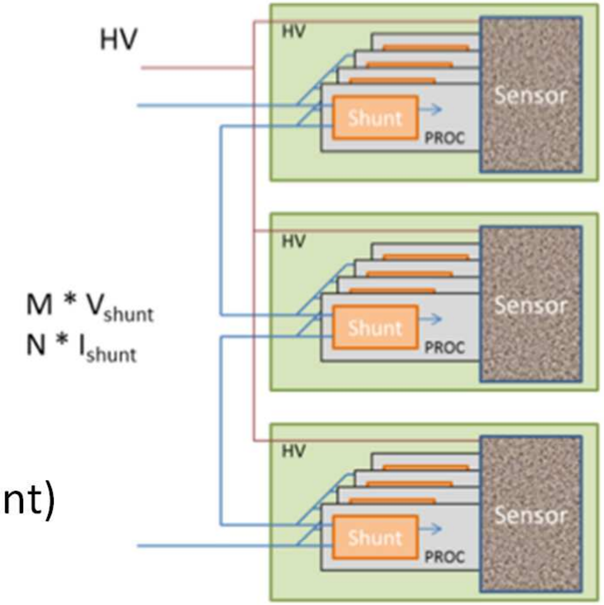


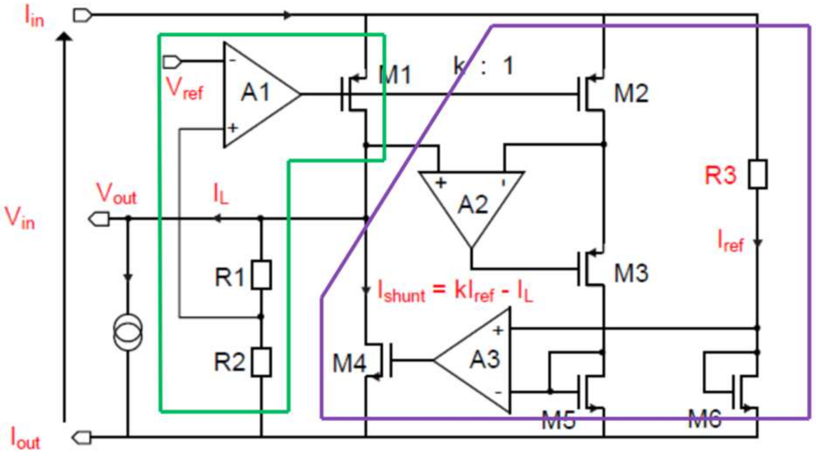
Schematic cross-section of CMOS pixel sensor (*ALICE ITS Upgrade TDR*)



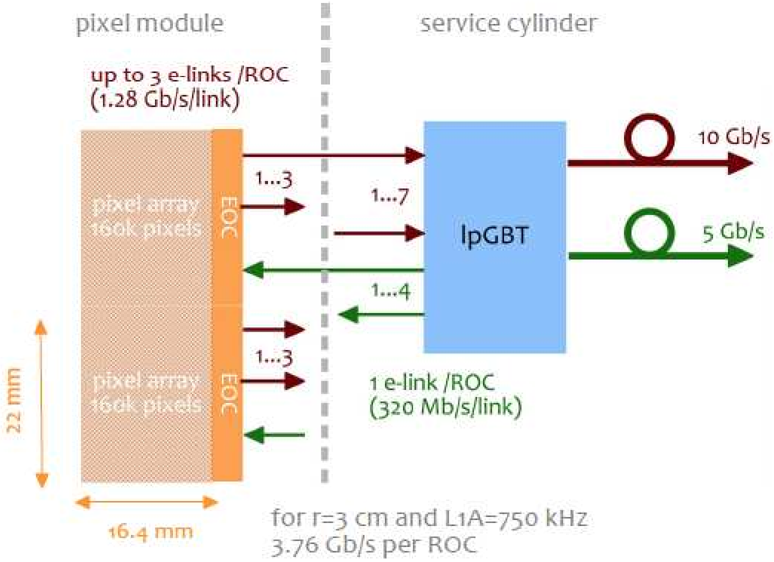
Serial Powering

- Required power (ROCs) ~1W/cm^2
  →O(50/100) kW CMS/ATLAS!
- ~~Traditional powering schemes (direct from PS, DC-DC)~~
  - Material and space issues, Radiation
- **Serial powering** across modules
  - Material gain factor given by # of modules in series
- Serial powering: current driven (voltage drops ~not relevant) and intrinsically low mass; not very efficient and failure modes needs to be carefully evaluated
- **Shunt-LDO*** circuit is the heart of SP approach
  - Developed for ATLAS FEI4 chip family, ported in RD53
  - Provides regulated voltage, shunts the excess current (*LDO: Low Dropout Regulator)

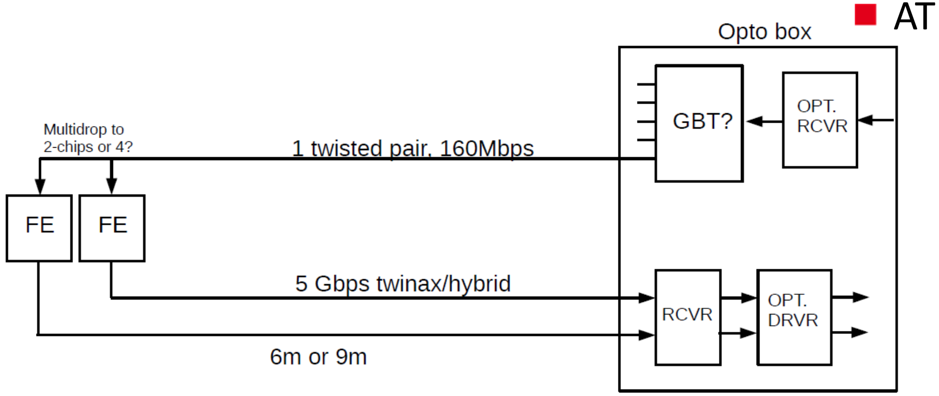




Getting the Pixel Data Out



- No opto-electronic device able to withstand the radiation environment of the inner layers.
- Solution: Fast electrical links to get the data out, followed by optical links.
- Common development for ATLAS/CMS: **lpGBT**
- CMS: “remote” lpGBT on pixel service cylinder and connected to the module (readout and control signals) via e-links cables: 1.28 Gbps
- ATLAS: twinax/hybrid cables: 5Gbps



6m 28 AWG twinax
+ 1m 36 AWG TWP

CMS Outer Tracker

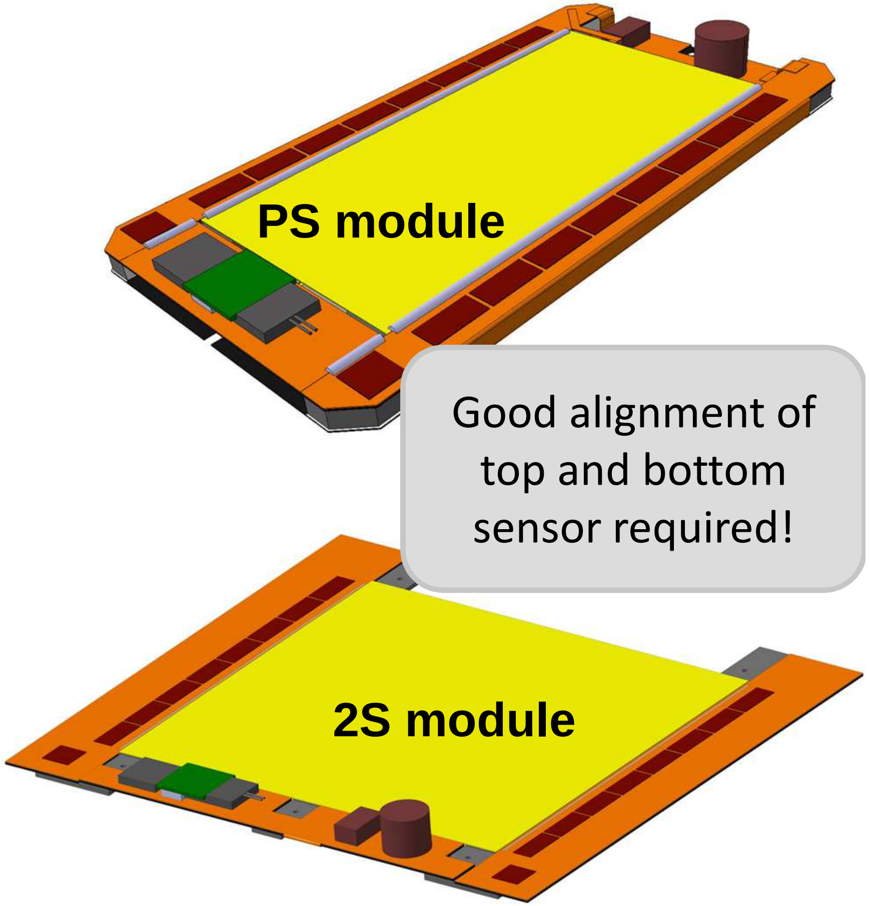
- On-module pT-discrimination
- Data sent out for track reconstruction at L1

PS-module for 3 inner layers

- Top sensor: strips 2x25 mm, 100 µm pitch
- Bottom sensor: long pixels 1.2 mm × 100 µm
- z-information from pixel sensor

2S-module for 3 outer layers

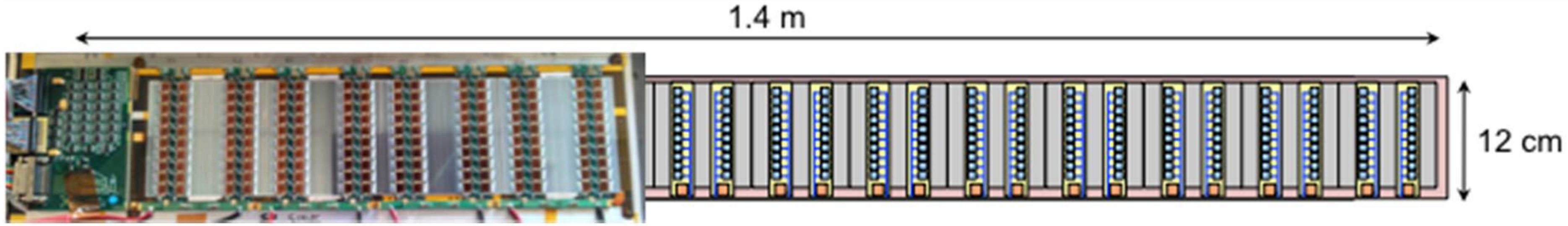
- Strip sensor 10x10 cm^2 with 2x5cm long strips, 90 µm pitch
- no z-information



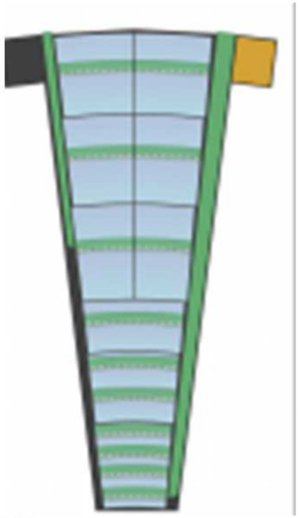
Good alignment of top and bottom sensor required!

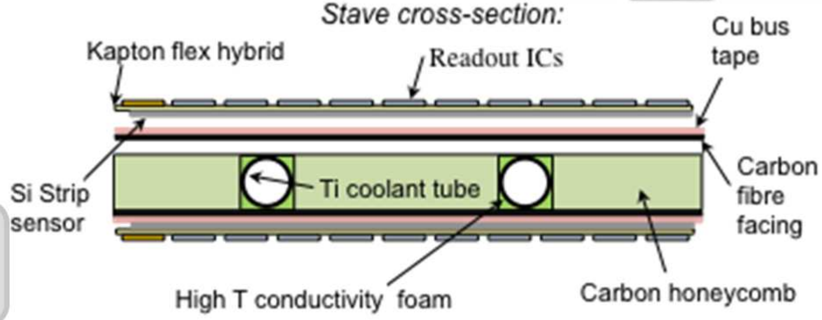
CMS Tracker TDR submitted (Katja Klein editor)
OT: Getting ready for pre-production (2019)

ATLAS Outer Silicon Strip Tracker



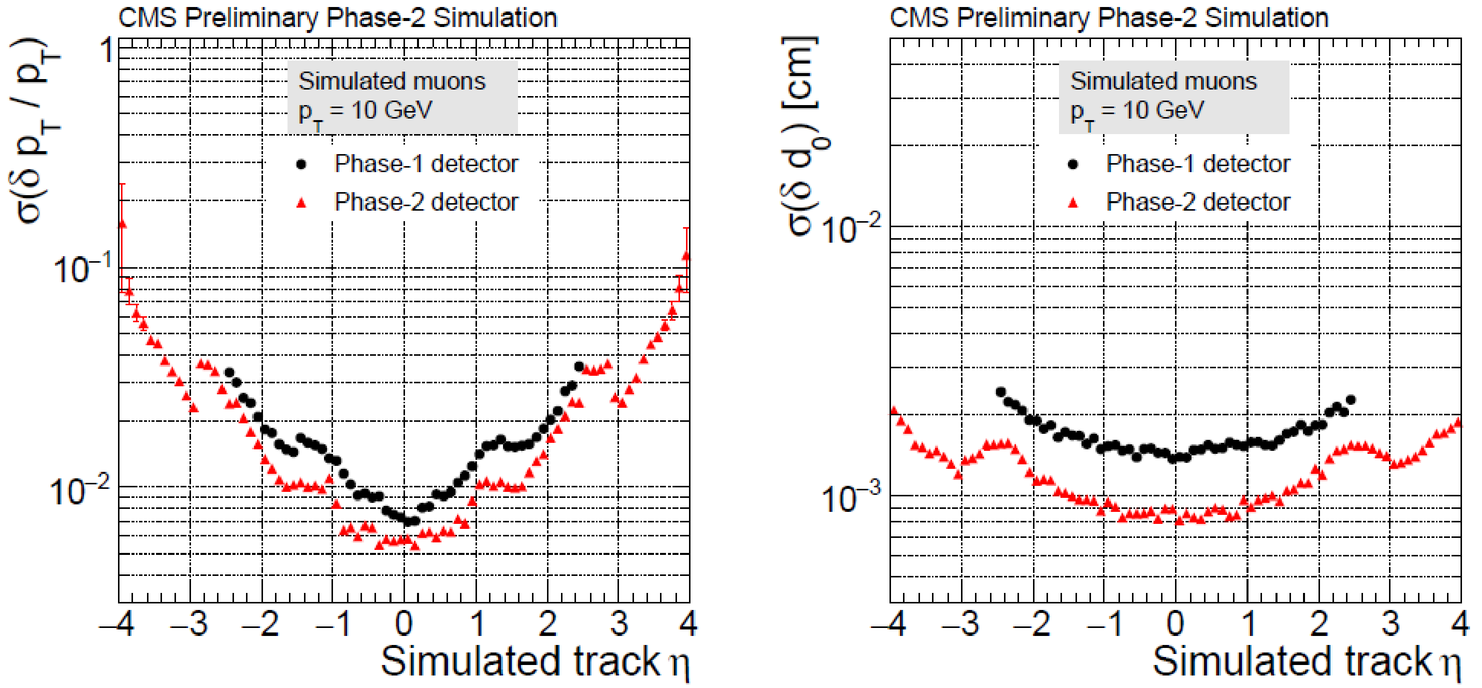
- Double-sided layers with stereo-angle, n-in-p sensors
- Barrel: Short (23.8 mm) and long strips (47.8 mm) with 74.5 µm pitch
- Endcaps: Radial strips of different pitch (6 different modules)
- Stave/petal one object; top and bottom side read out separately
  - Not suited for self-seeded trigger
- Silicon Modules directly bonded to a cooled carbon fiber plate.
- Services integrated into plate including power, control and data transmission.





ATLAS TDR approved June 2017, Ingrid Gregor editor
Getting ready for pre-production (2019)

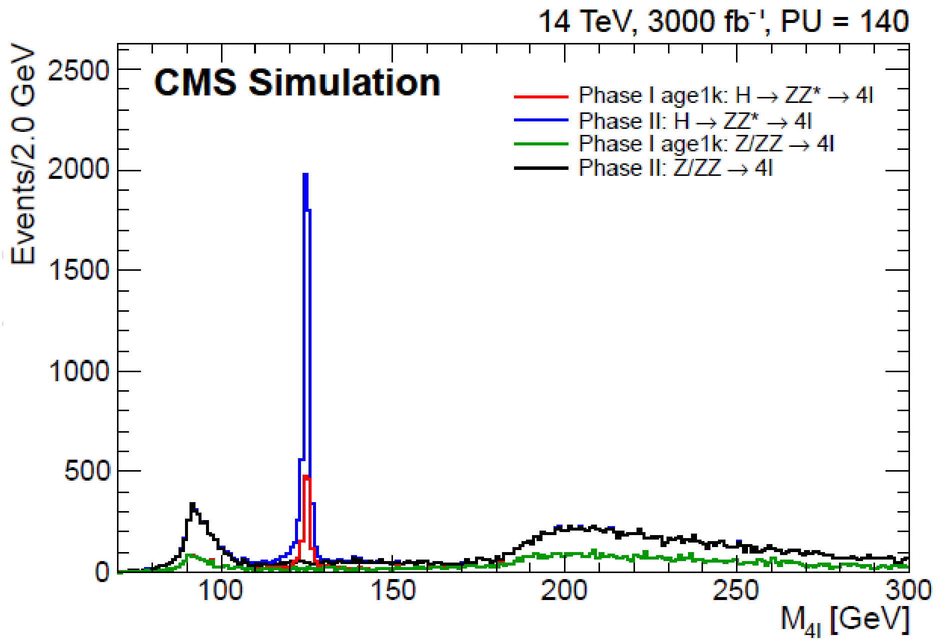
Performance Gain: pT and transverse impact parameter resolution (CMS)



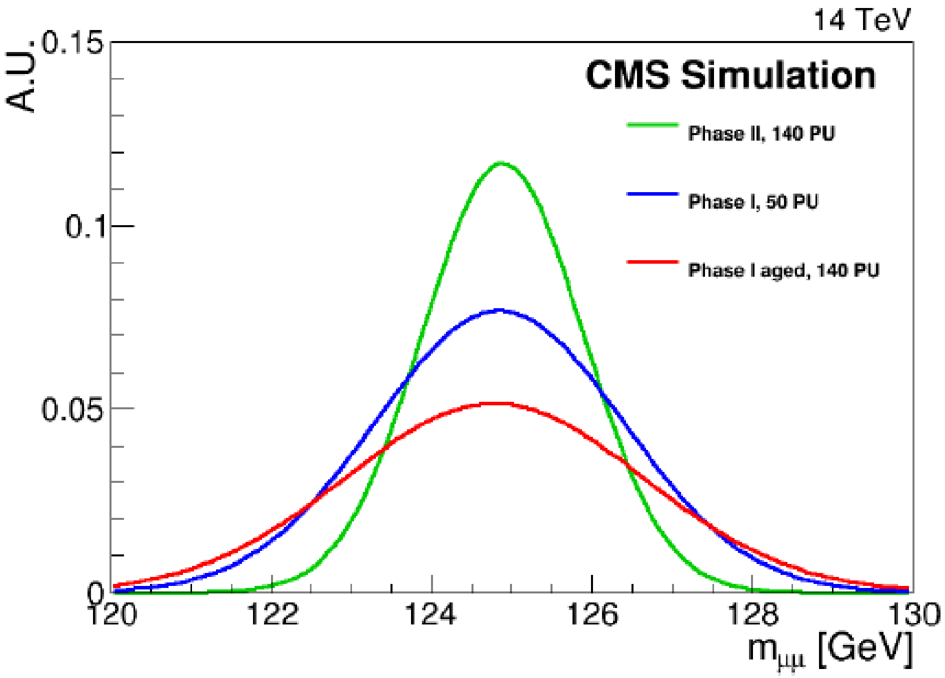
- Based on RD53 chip specs (1200 electrons threshold, 4 bits charge resolution)

Clear improvement wrt Phase 1
Extended coverage

Higgs Physics @ PU 140



- H→ZZ→4l



H→μμ mass resolution

Dramatic improvement for Higgs physics at large (140) PU

Plots based on fast simulation

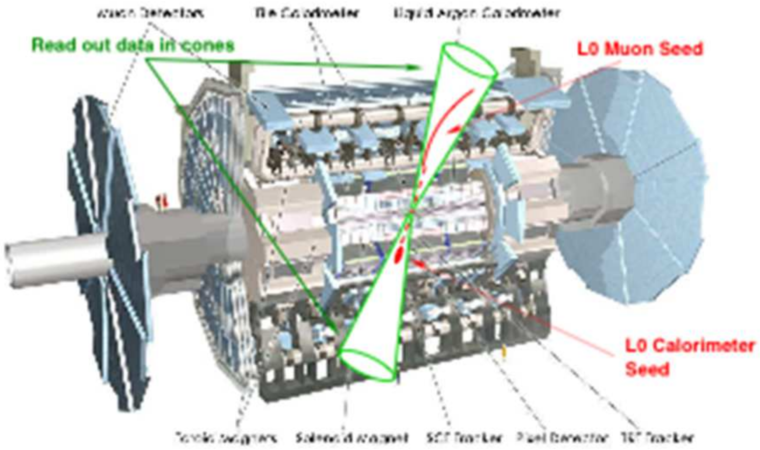
Outline

- HL-LHC and Physics Motivation
- Challenges for Detectors at the HL-LHC
- Detector Concepts: ATLAS and CMS
- Tracker
- **L1 Track Trigger**
- Calorimetry
- Timing Layer
- Muon Systems

Level 1 Track Trigger

ATLAS

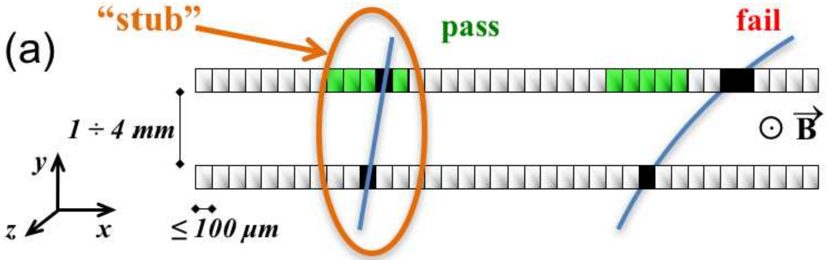
- Currently being installed: **FTK** Fast TracK Trigger: at L2, 25µs, pattern recognition with associative memories (AM), track fitting in FPGAs
- ‘Pull architecture’
- HL-LHC: L0 trigger (Calo/Muon) reduces rate within ~6 µs to ≳ 500 kHz and defines ‘regions of interest’ (RoIs)
- L1 track trigger extracts tracking info inside RoIs from detector FEs



CMS

‘Push architecture’ for outer tracker

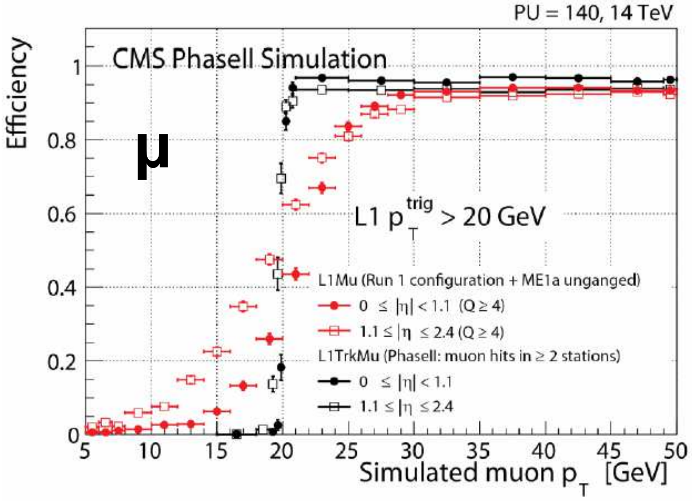
- Track segment selection at front-ends based on pt measurement (at 40 MHz)
- All tracks with pT > 2 GeV
- ~1mm primary vertex resolution
- Pattern recognition and track fit at L1 in off-detector electronics (FPGA-based)
- Explore ‘pull architecture’ for pixel b tags at L1

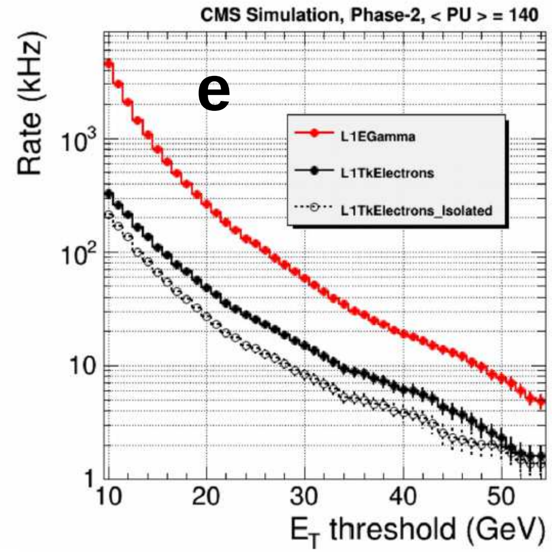


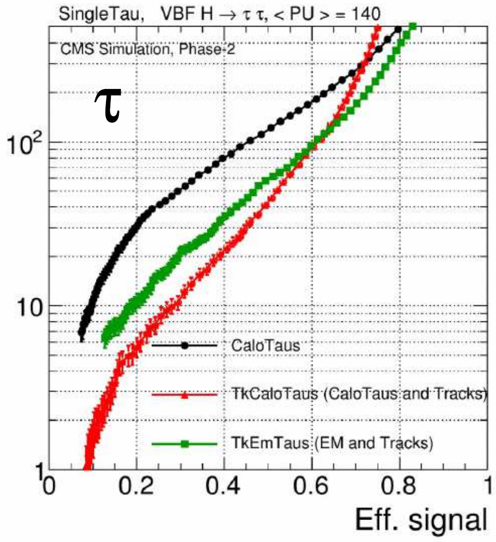
Level 1 Track Trigger: CMS Performance

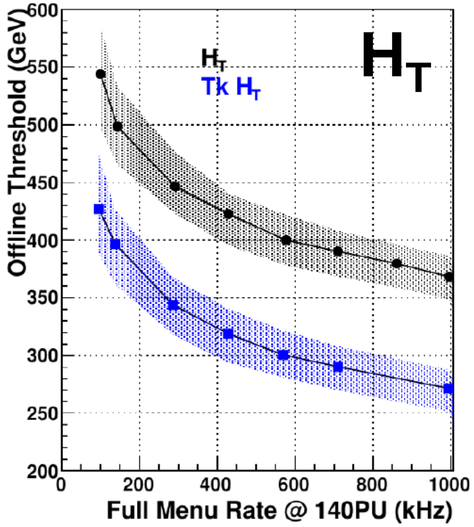
Goals:

- Validate calorimeter or muon trigger objects
  - Lower thresholds
- Improve muon trigger p_T measurement
- Check isolation of e, γ, μ or τ candidates
- Association to primary vertex









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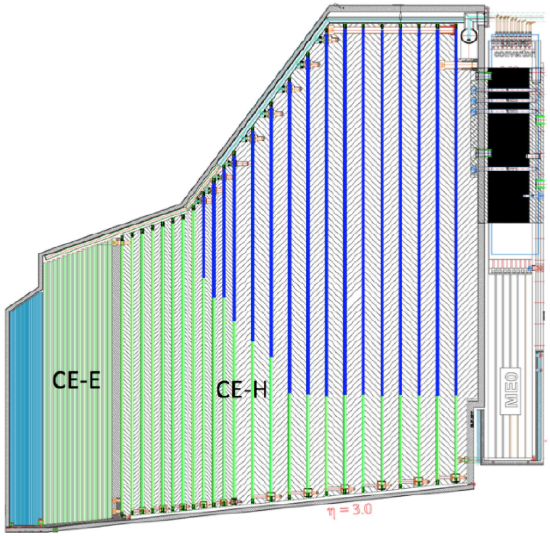
CMS HGCAL

CMS Endcap Calorimeter:

- Needs to be replaced
- High granularity calorimeter for particle flow
- Electromagnetic (CE-E): 26 X_0, 1.5λ: 28 layers **Si** - CuW + Cu/Pb/SS
- Hadronic (CE-H): 8.5λ, 24 layers of **Si&Scint** – steel



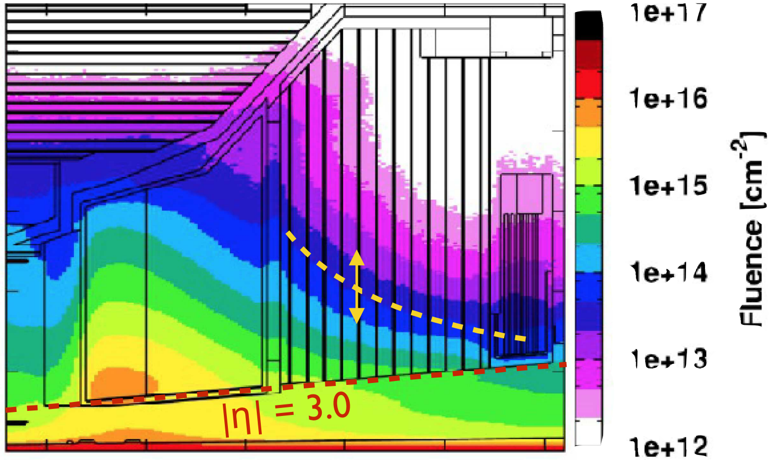
Physics motivation:

- VBF identification and hadr. tau-jets, PU rejection

Challenge:

- High fluence, especially at |η| > 3
- Φ>5E13 cm^{-2} →Silicon
- Φ<5E13 cm^{-2} →Scintillator + SiPM

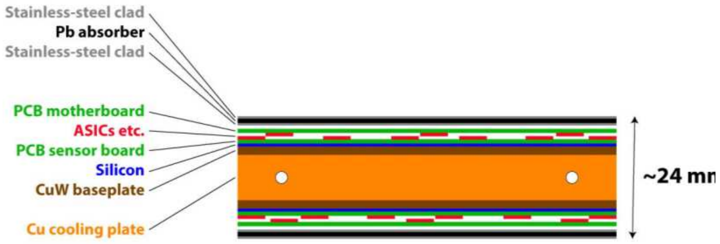
→Rad. hard Si + SiPMs needed!

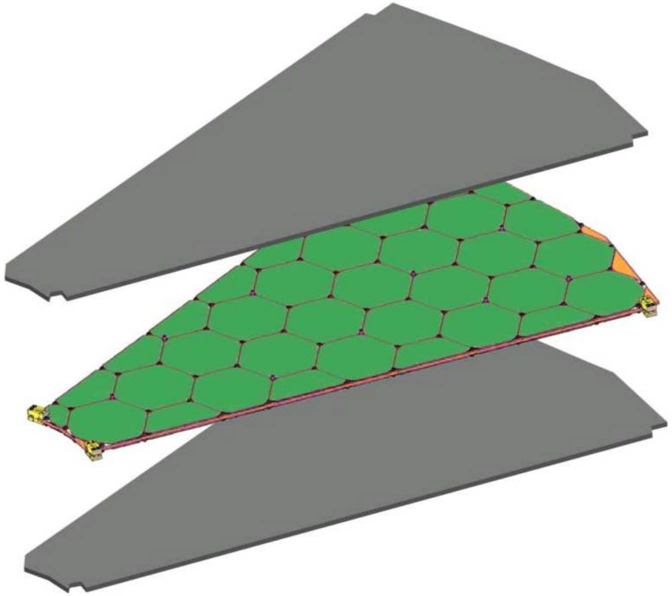


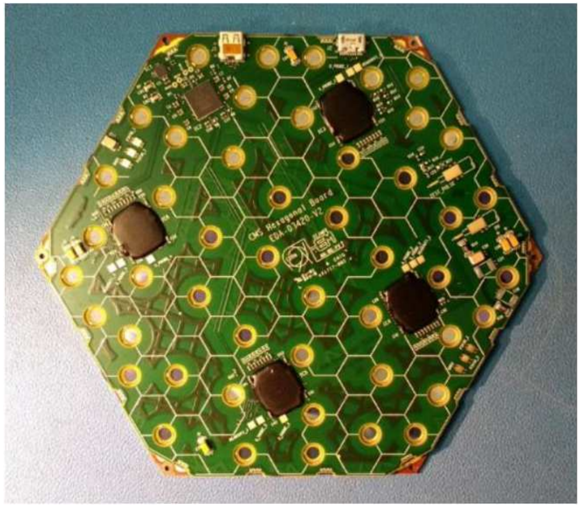
CE-E

CE-E

- 600 m^2 of Silicon!
- Fluence up to 1E16 cm^{-2}, 100 Mrad →Radiation hard sensors with HV-stability up to 1kV
- Hexagonal n-in-p sensors with 1/0.5 cm^2 cells: 8 in wafers
- Goal: Good S/N up to the end of the HL-LHC for MIP-calibration



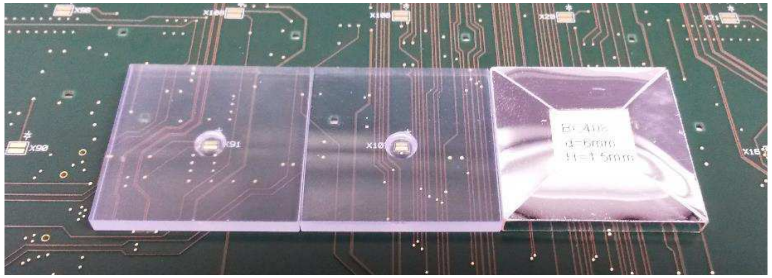




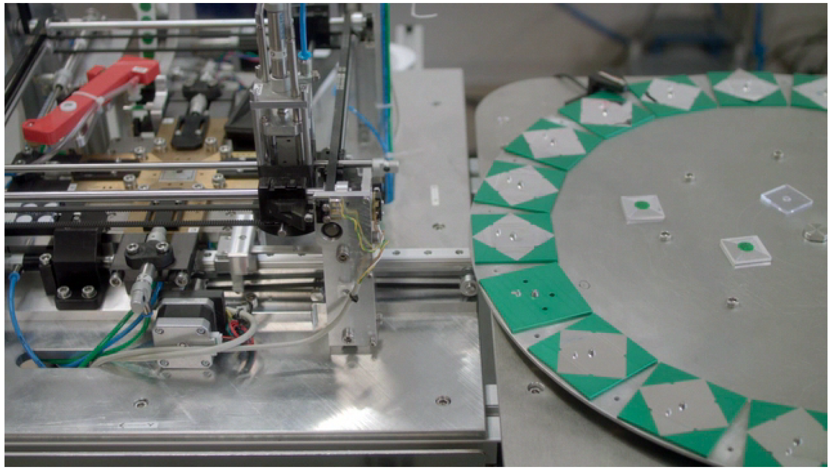
CE-H: Hadronic

CE-H

- Photosensors (SiPM) mounted directly on scintillator tiles
- Tiles wrapped with reflective cover
- Rad. Hardness studies of SiPMs at Hamburg University: 1E9-1E14 cm^{-2}
- Development of tile module (R&D phase) at DESY



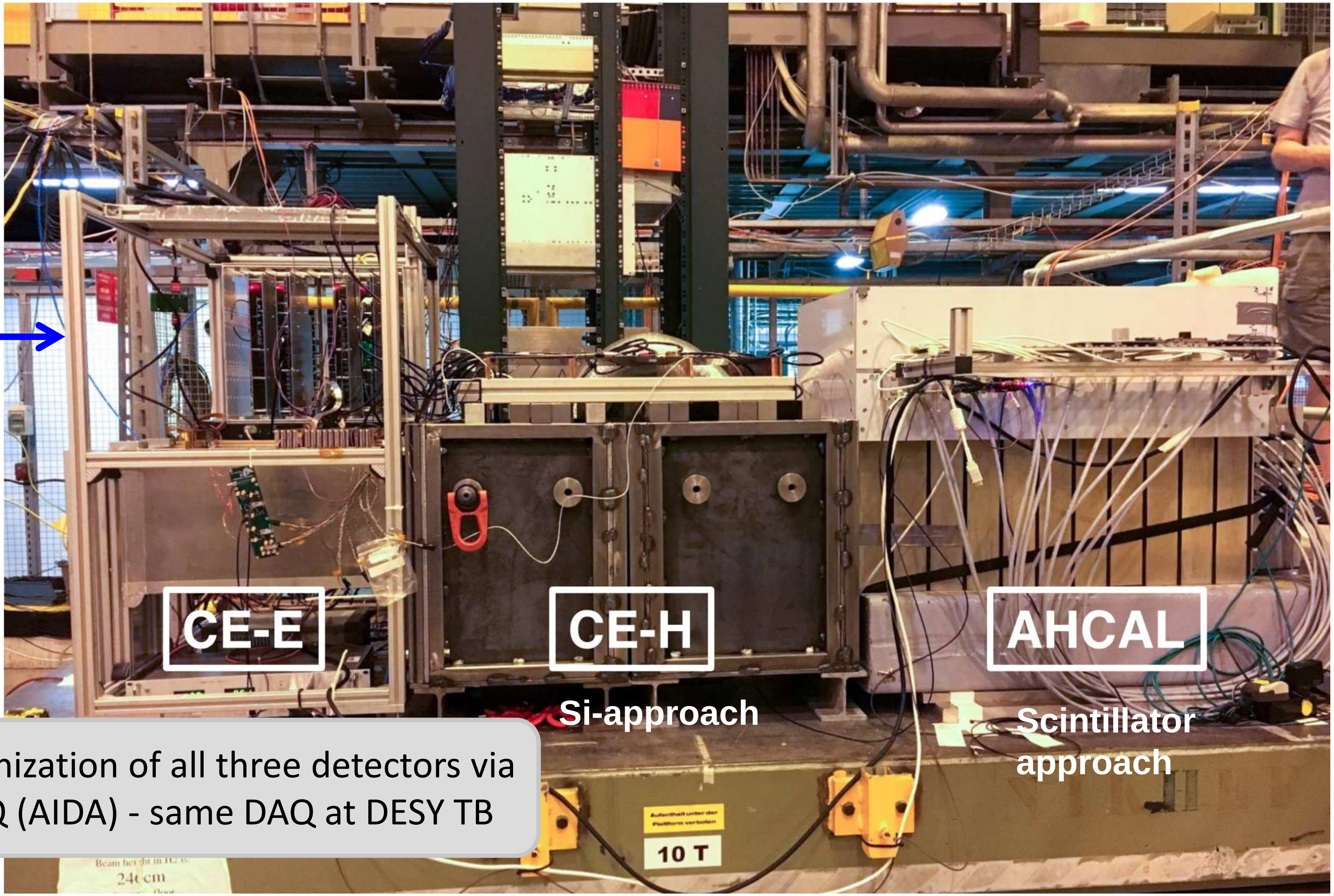
Automated tile wrapping machine at Hamburg University for CALICE



HGCAL at testbeam (CERN)

beam

High-E π
at SPS



synchronization of all three detectors via EUDAQ (AIDA) - same DAQ at DESY TB

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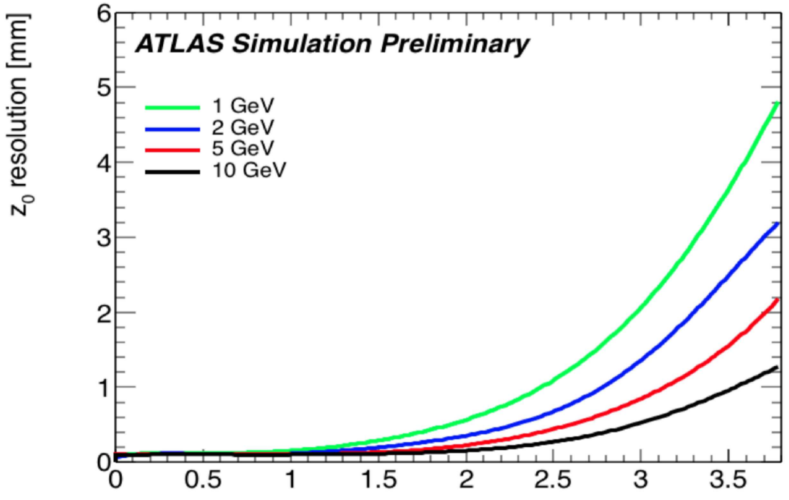
- Muon Systems

Timing Layers: ATLAS and CMS

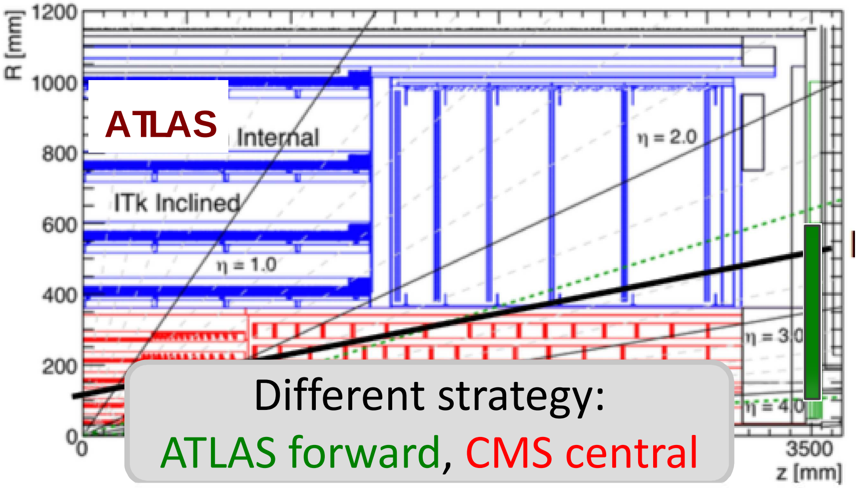
The problem:

- Track-to-vertex association is ambiguous when tracking z-resolution is larger than separation between vertices

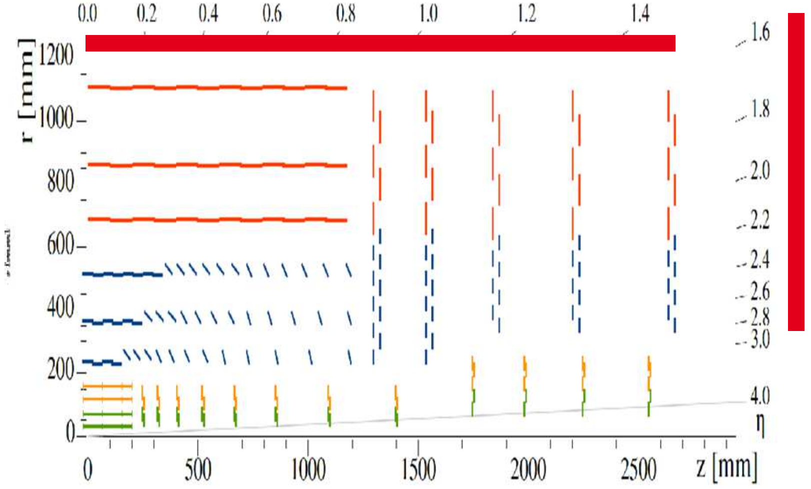


Z_0 resolution of ITK: For |η|>2.5 resolution above average distance between vertices of ~0.6 mm

Solution: Timing layer



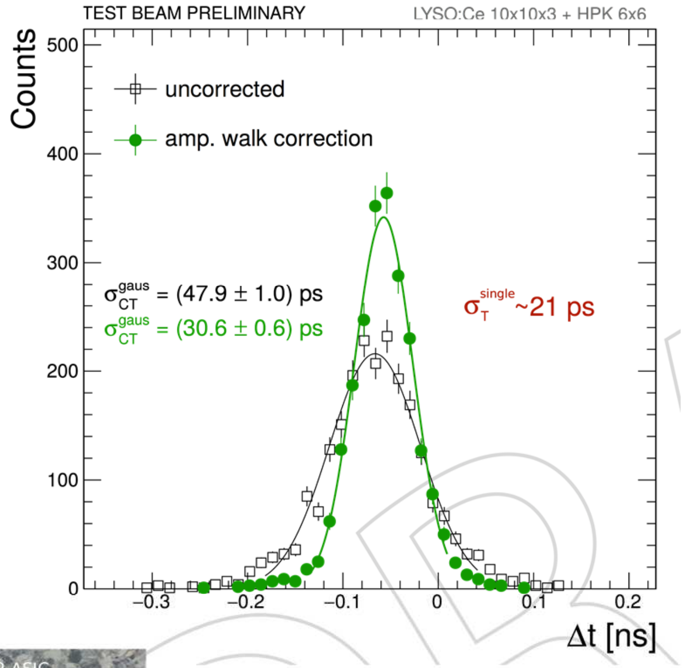
Different strategy:
ATLAS forward, CMS central

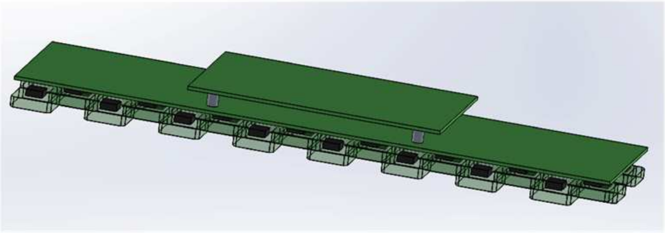


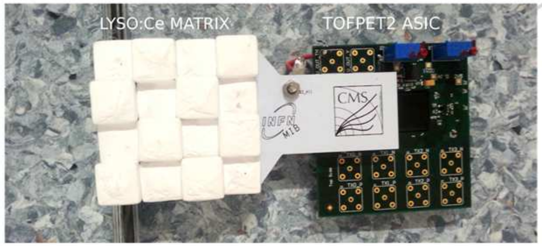
Timing Layers: ATLAS and CMS

Scintillators (LYSO:Ce) and SiPM for lower irradiation areas

- CMS barrel
- Fluences up to 2E14 cm^{-2} neq for 4000 fb^{-1}
- SiPMs: Increase of Dark Count Rate
  - Time resolution increases from 25 to 40 ps







Timing Layers: CMS Performance

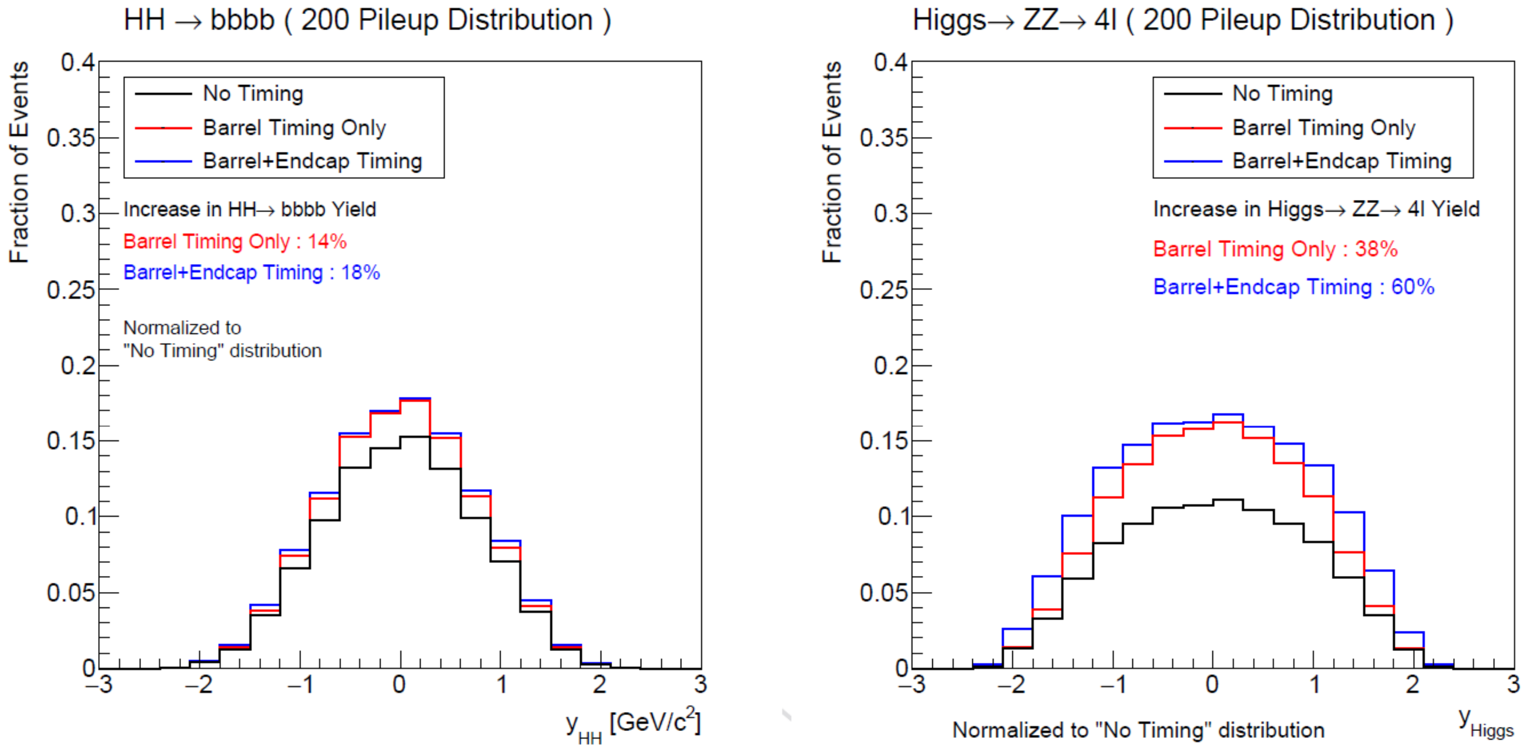
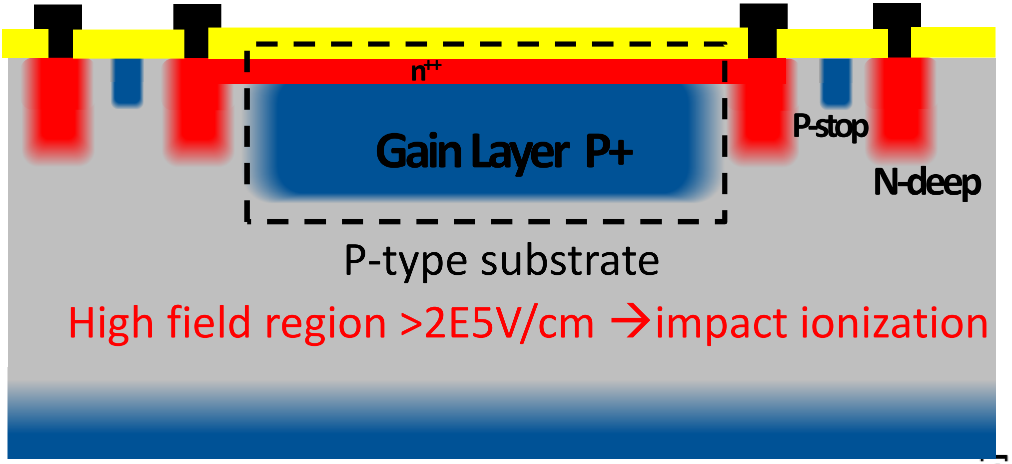


Figure 3.11: Projections for yield enhancement in HH → $b\bar{b}b\bar{b}$ (left) and H → ZZ → 4l (right) as a function of η.

Yield enhancement in H→bbbb and H→ZZ

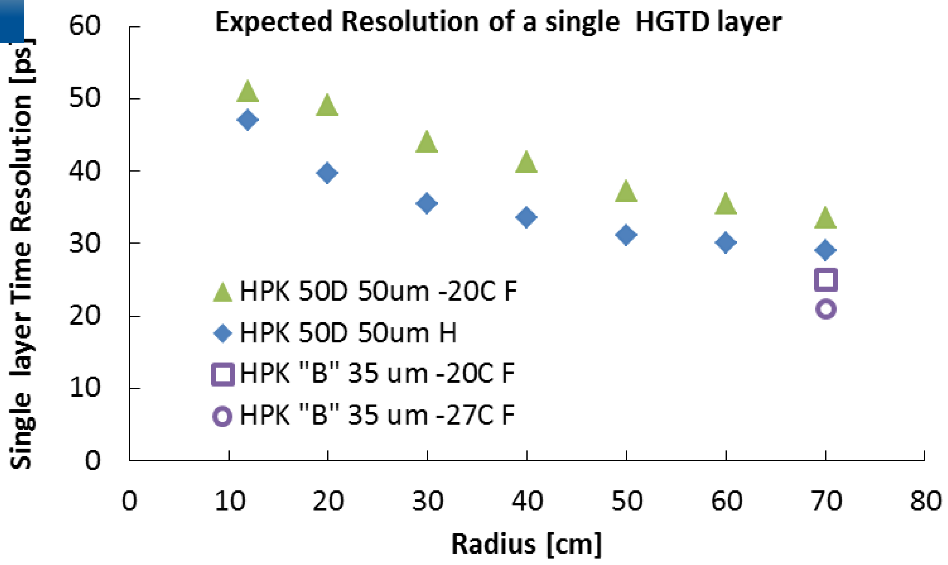
Timing Layers: ATLAS and CMS

Low Gain Avalanche Detectors (LGAD)



- Timing resolution degrades with irradiation
- Sensor size limited by non-uniformity of operation voltage as a function of fluence

- Excellent timing resolution 10-20 ps
- Challenge: Fill factor due to dead area between pads (junction termination)



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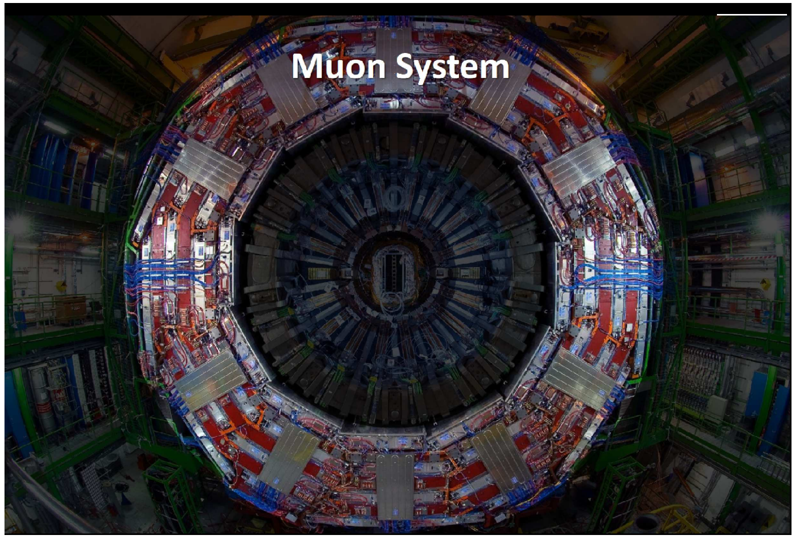
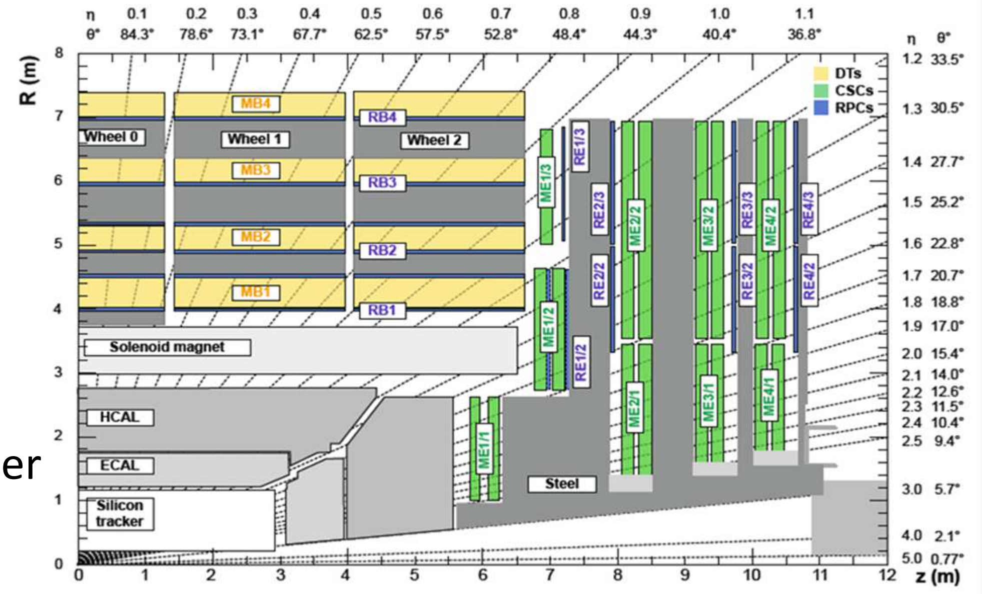


The Upgrade of the Muon System: CMS



Highly hermetic and redundant muon system

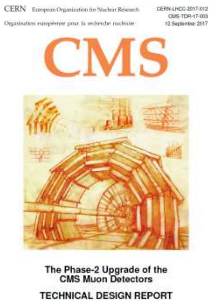
- Drift tubes (DT) to |η|~1.2
- CSC Endcaps 1.0<|η|<2.4
- RPCs for redundancy
- Trigger coverage to |η|<2.4,
  pT threshold 20-25 GeV for inclusive μ-trigger

Excellent performance

- $\Delta p_T/p_T$ global 1% (10 GeV) - 10% (1 TeV), stand-alone 10% - 40%
- Chambers show no signs of aging

Upgrade:

- No plans to rebuild large gaseous muon chambers
- Concentrate on add. detectors for weakly instrumented areas and trigger and r/o electronics


CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire
CERN-LHCC-2017-012
CMS-TDR-17-003
12 September 2017

CMS

The Phase-2 Upgrade of the CMS Muon Detectors

TECHNICAL DESIGN REPORT

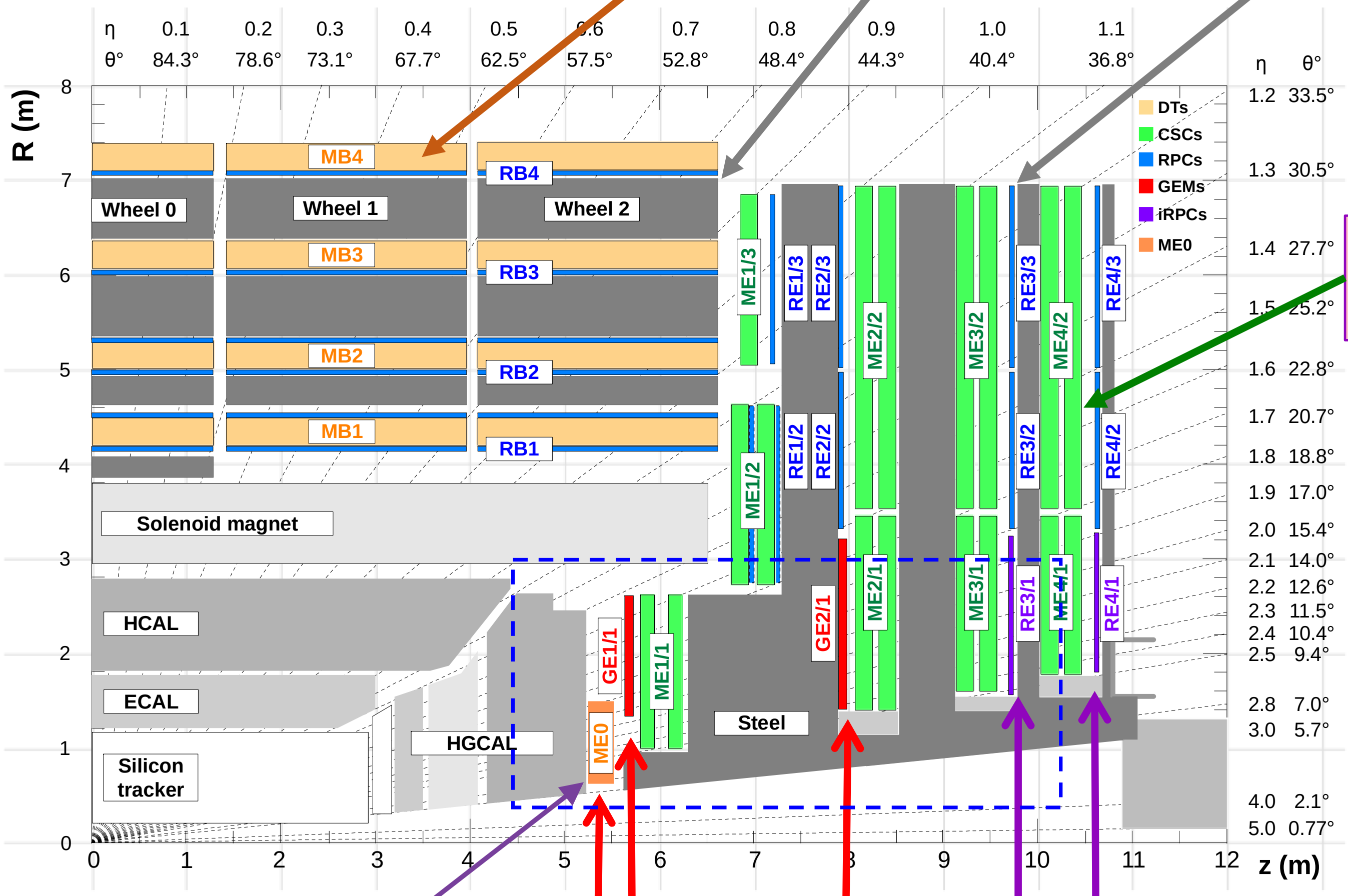
The Upgrade of the Muon System: CMS

DT: faster electronics

RPC: more precise timing


The Phase-2 Upgrade of the CMS Muon Detectors
TECHNICAL DESIGN REPORT

CMS-TDR-17-003
Editor: Th. Hebbeker
Danke!



CSC: faster electronics

Challenges in the **forward region** (trigger and offline):

- high rates
- small bending

2.4<|η|<3.0

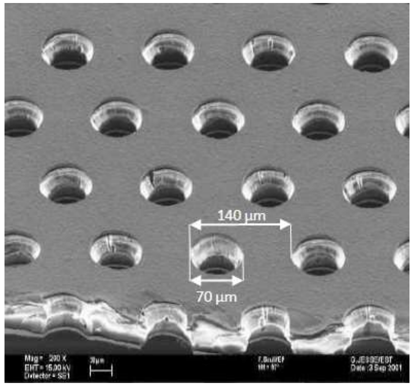
Plus: GEM detectors

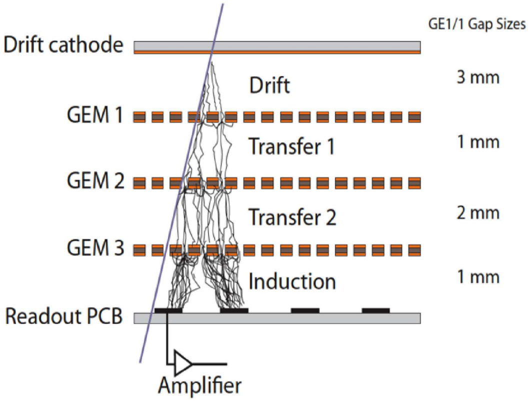
Plus: improved RPCs

Aachen 3A contribution: DT and GEM

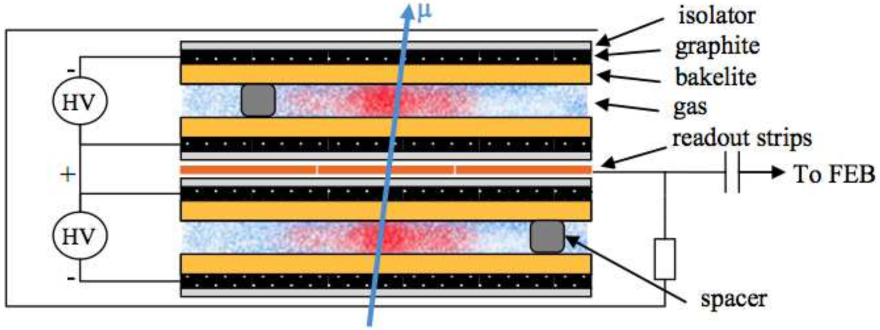
The Upgrade of the Muon System: CMS

GEM = Gas electron multiplier





iRPC = improved RPC



Avalanches in strong electric field in pin holes
CMS design: triplet GEMs (gas gain 10^4)

GE1/1, GE2/1: 2 layers of triplet GEMs

ME0: 6 layers of triplet-GEMs

Improvements:

- Higher rate capability
  (lower resistivity, smaller gas gain)
- Two-ended strip readout

RE3/1, RE4/1: double-layer RPC units

Erika Garutti

Very high rate capability, longevity in HL-LHC environment

Conclusion

- HL-LHC: 7.5x10^{34} cm-^{2}s^{-1}, 200 pileup, 3000 fb^{-1}
- Great physics potential, very challenging environment
- Comprehensive Upgrade programs for ATLAS and CMS
  - Currently TDRs are being published or have been published for the subsystems
- Busy and exciting years ahead of us!

- Thanks to Ingrid Gregor, Anna Macchiolo, Kerstin Höpfner, Erika Garutti, Daniel Pitzl for material, plots and useful comments!

BACKUP

AM+FPGA approach to L1 Tracking

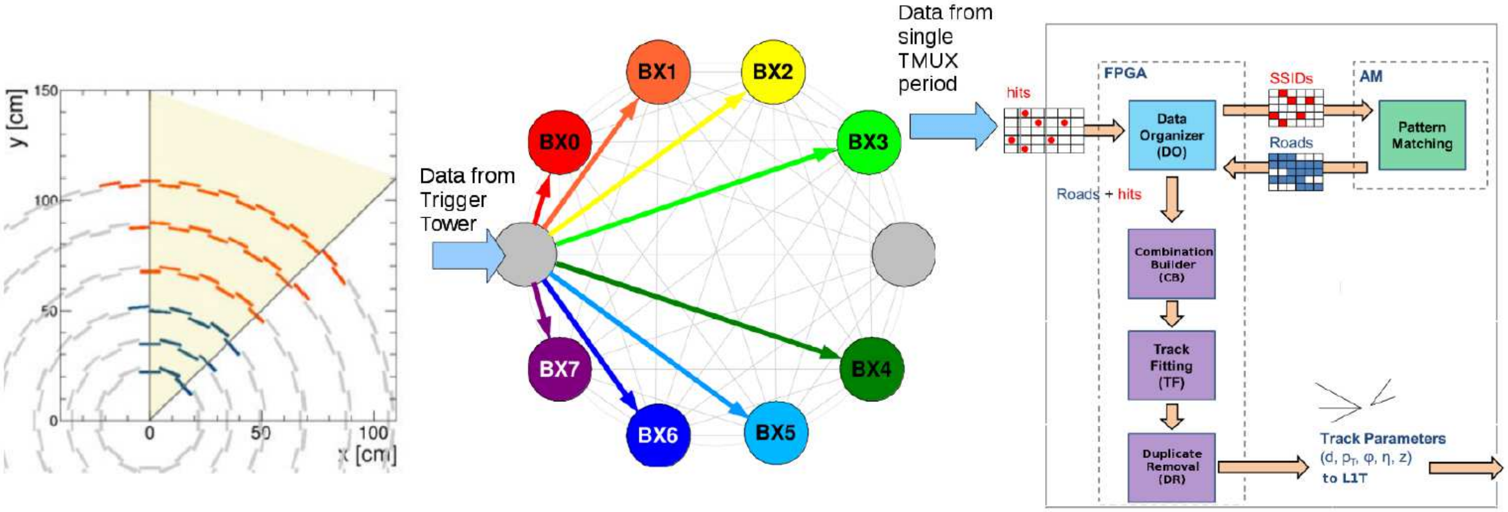
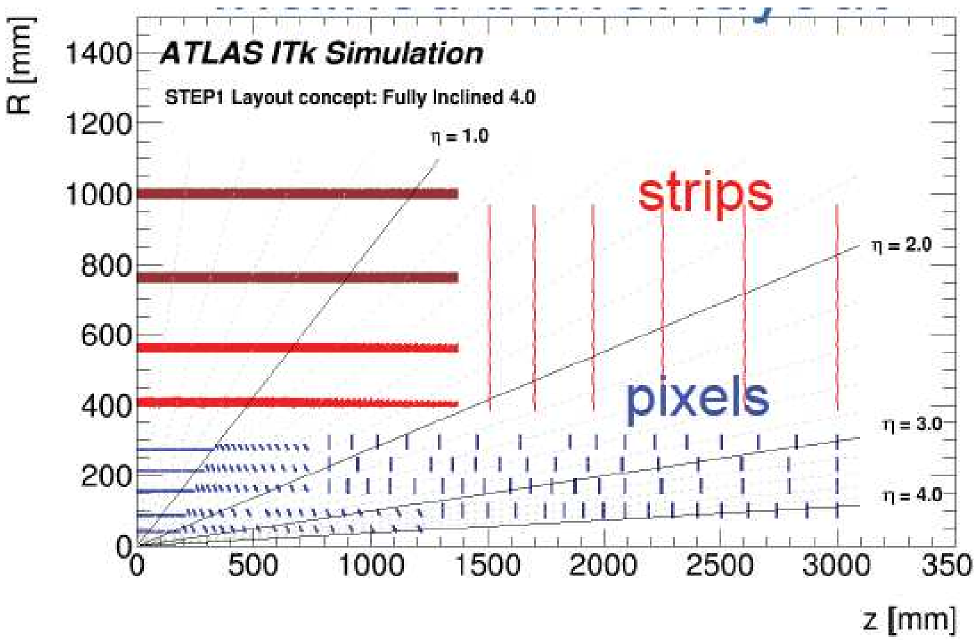


Figure 3.31: Data flow in the AM+FPGA L1 tracking approach. The detector is subdivided into trigger towers that span η, φ regions of the detector (left). Stubs from each trigger tower are organized according to the bunch crossing (BX) number (centre) and then routed to the appropriate set of AM and FPGA resources (right). Within the FPGA, a Data Organizer (DO) stores the full-resolution stubs and converts these into super-strips (SS). The SSs are used in pattern recognition in the AM chips, which return matched roads to the FPGA. Road-matched stubs are sent from the DO to track fitters (TF). Duplicate tracks are removed from the TF output, which is then sent to the downstream L1 trigger system.

Detector Layout: ATLAS ITk

- **5 pixel barrel layers** for tracking in dense environment
- **Forward rings**
  - Coverage to |η|~4
  - Special pattern: constant #hits vs. η @large η
  - Inclined layout: Less material crossed at large|
  - Mechanics more difficult

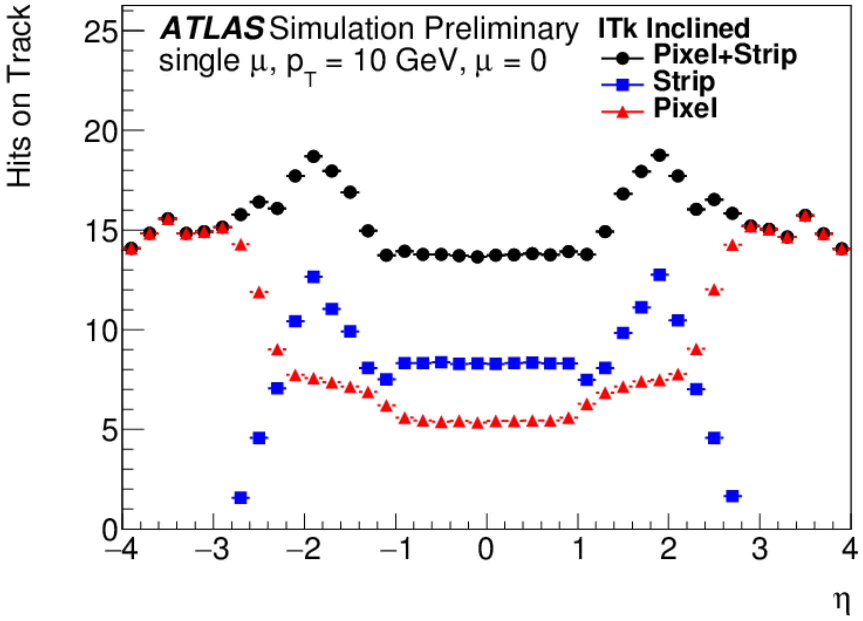
Total: ~13 m^2 of Si, 9000 modules!



- Baseline: **Hybrid modules with planar sensors, possibly 3D** for innermost layers
- Pixel size 50x50 or 25x100 µm^2
- **CMOS sensors** under investigation for outer layers

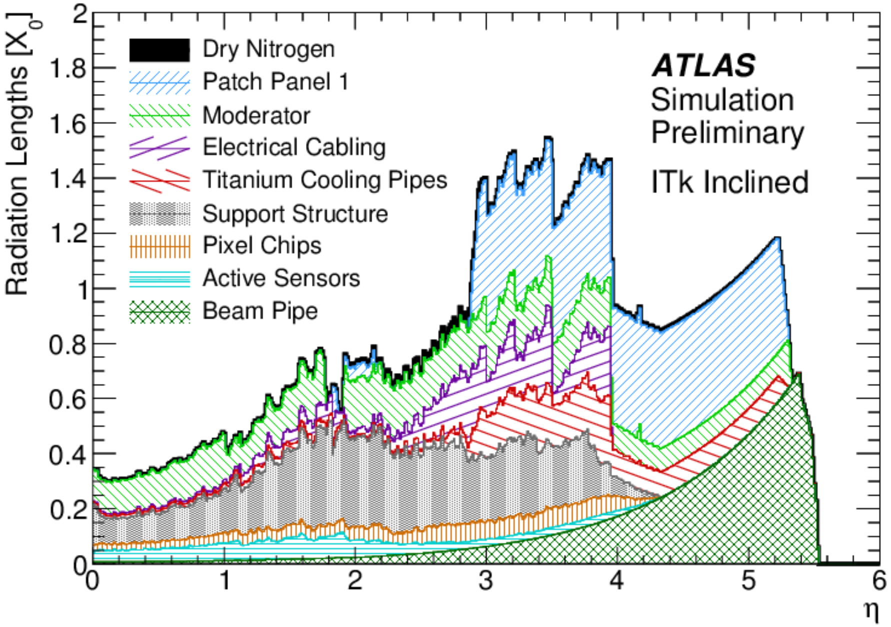
ATLAS ITk Inclined Layout Material and Hits

- **Mean number of hits per track for single muons above 10 GeV**

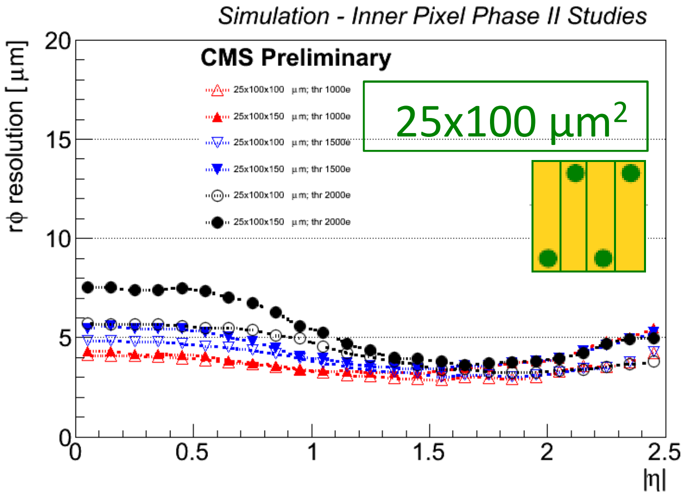


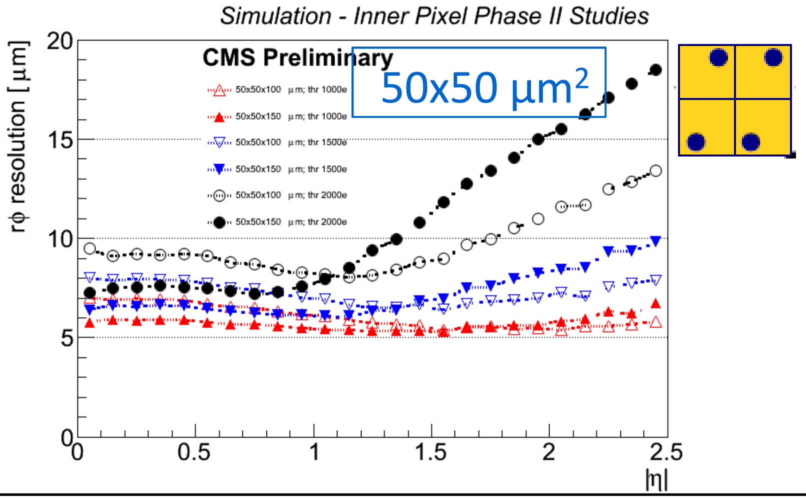
Many hits at large η close to beam spot

- **Material budget**

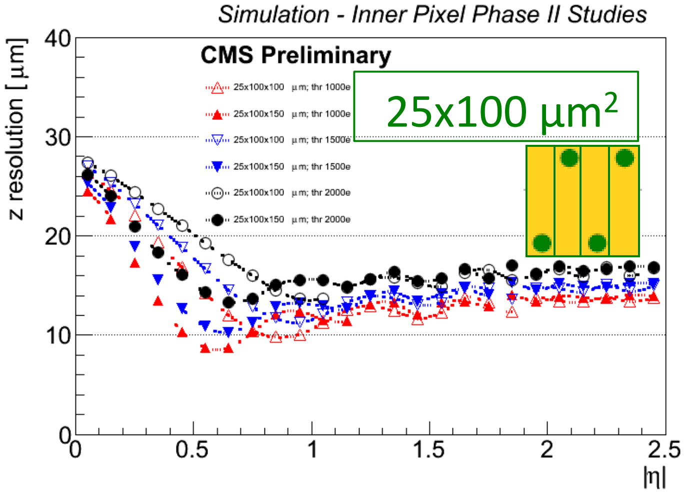


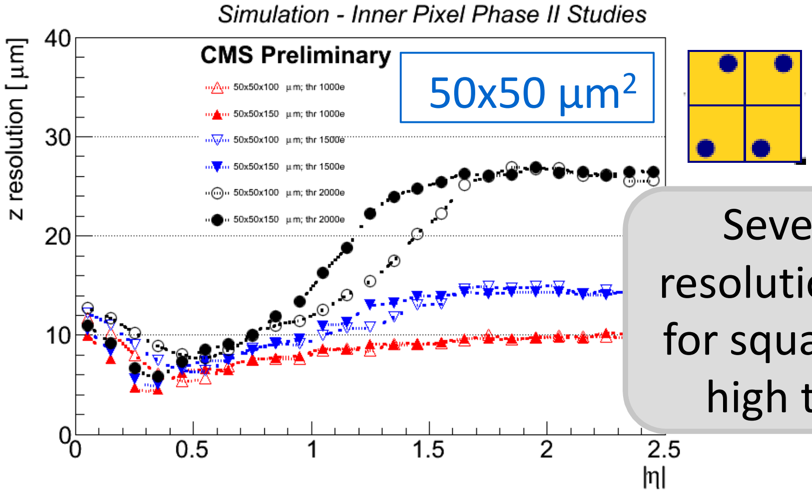
CMS: Pixel Pitches





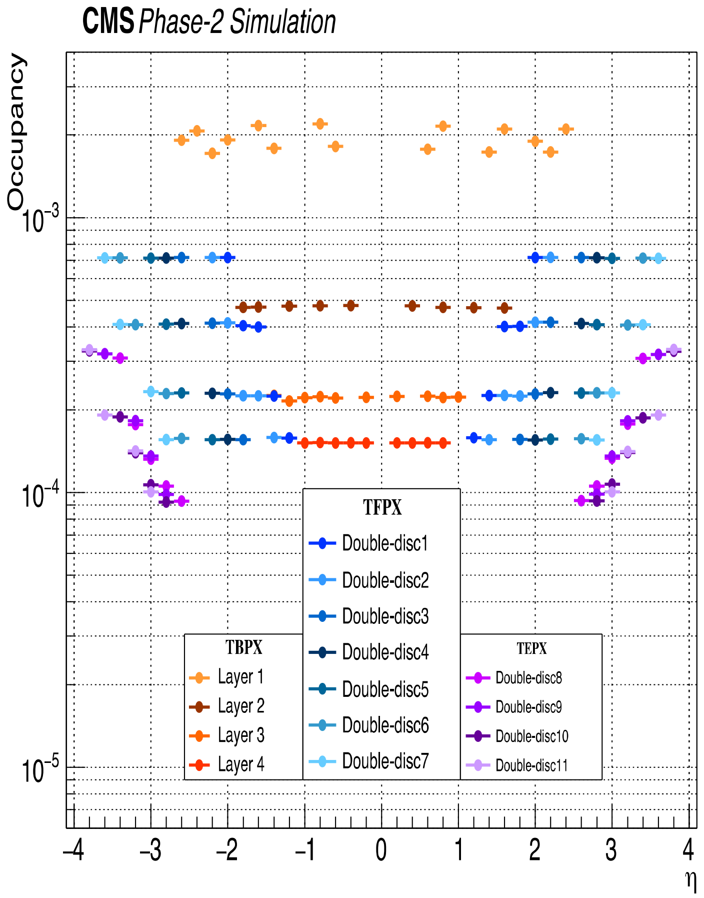
thickness open=100 µm/full=150 µm   threshold 1000e/1500e/2000e





Severe loss of resolution at large η for square pixels for high thresholds

CMS: Occupancy (Pixels) at 200 PU



~ 2 ‰ in layer 1,
< 1 ‰ everywhere else

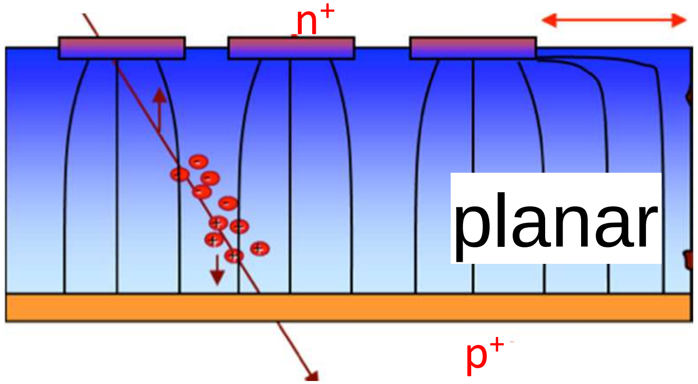
Based on RD53 chip specs (1200 electrons threshold, 4 bits charge resolution)

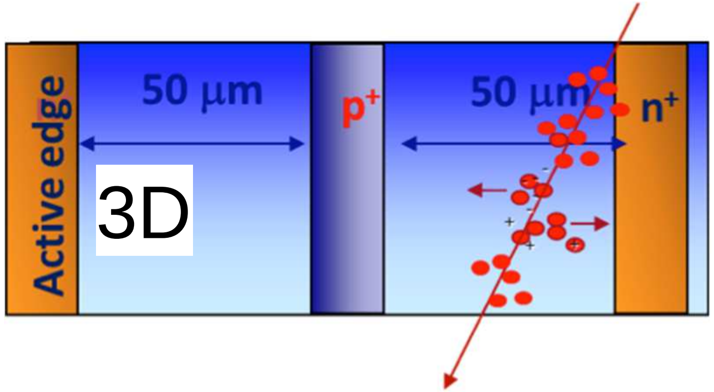
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Thin Planar or 3D Pixel Sensors

Promising candidates for layers with very high radiation damage are:

- 3D pixel sensors
- thin planar pixel sensors (active thickness 100 - 150 µm, currently O(300 µm))





Common advantage:

- Short drift path
- Higher field at same V_{bias}

➡ Lower operation voltage
➡ Less power consumption

Thin planar sensors (n-in-p):

- Lower total I_{leak} after irradiation
- Less material (multiple scattering)

Drawbacks:

- Smaller initial signal (76 e^-/µm)
- Thinning step required
- Sensor „bow“

3D sensors:

- Thicker sensors possible

Drawbacks:

- Higher capacitance
- Lower yield
- Higher cost