Future Detectors 3/3

CERN-FERMILAB
HADRON COLLIDER PHYSICS
Summer School 2015

Werner Riegler, CERN, werner.riegler@cern.ch

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Lecture 3

CMS upgrade

Silicon Detectors

ALICE upgrade

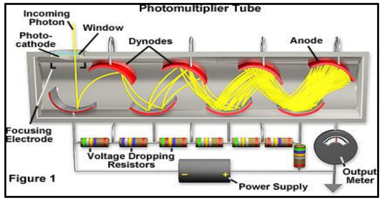
ATLAS upgrade

FCC Detectors

Photon Detectors at LHC

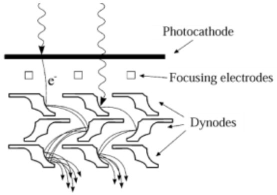
Photomultipliers (PMT):

- Used for ATLAS Barrel Hadron Calorimer scintillator readout
- Used for ALICE T0 cherenkov detector and V0 scintillator trigger detector
- Used for LHCb ECAL and HCAL scintillator readout
- Used for CMS Hadron Forward Calorimeter quartz fiber readout



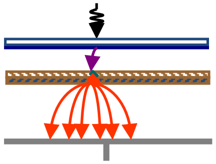
Multi Anode Photomultipliers (MA PMT):

- Planned for LHCb RICH upgrade to replace HPDs
- Planned for CMS Hadron Forward Calorimeter upgrade to replace PMTs



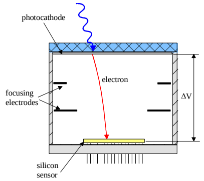
Micro Channel Plate Photomultipliers (MCP PMT):

- Planned for ALICE T0 cherenkov detector upgrade to replace PMTs



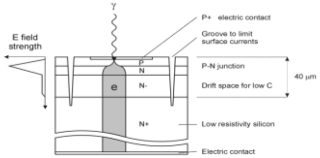
Hybrid Photon Detectors (HPD):

- Used for CMS Hadron Barrel and Hadron Endcap Calorimeter Scinitillator readout
- Used for LHCb RICH detector



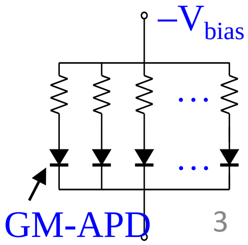
Avalanche Photo Diodes (APD):

- Used for CMS ECAL
- Used for ALICE PHOS and ECAL Calorimeters



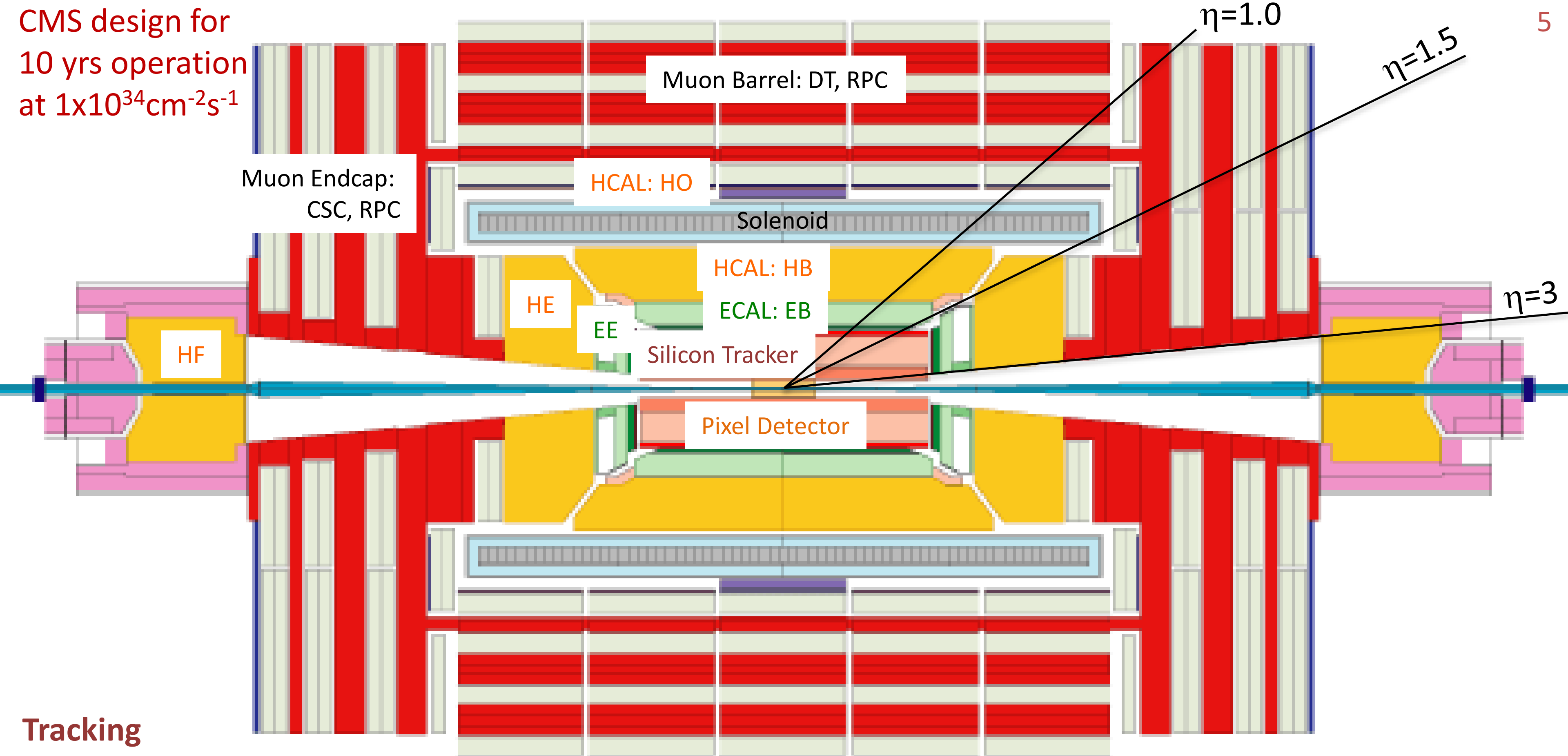
Geigermode APDs (GAPD) = Multi Pixel Photon Counters (MPPC) = Silicon Photo Multiplier (SiPM):

- Planned for CMS Hadron Barrel and Hadron Endcap Calorimeter to replace HPDs
- Planned for LHCb Fiber Tracker (operation around -40 degrees)



The CMS Experiment Upgrade

CMS design for 10 yrs operation at $1 \times 10^{34} cm^{-2}s^{-1}$



Tracking

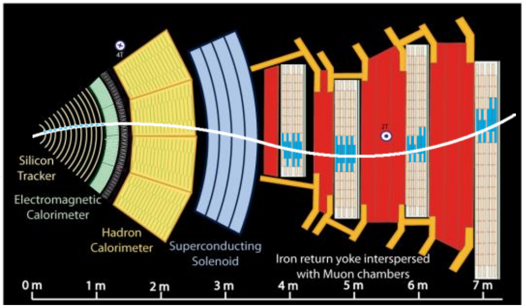
More than $220 m^2$ surface and
76M channels (pixels & strips)
6m long, ~2.2m diameter
Tracking to $|\eta|<2.4$

Muon System

Muon tracking in the return field
Barrel: Drift Tube & Resistive Plate Chambers
Endcap: Cathode Strip Chambers & RPCs

ECAL

Lead Tungstate ($PbWO_4$)
EB: 61K crystals, EE: 15K crystals



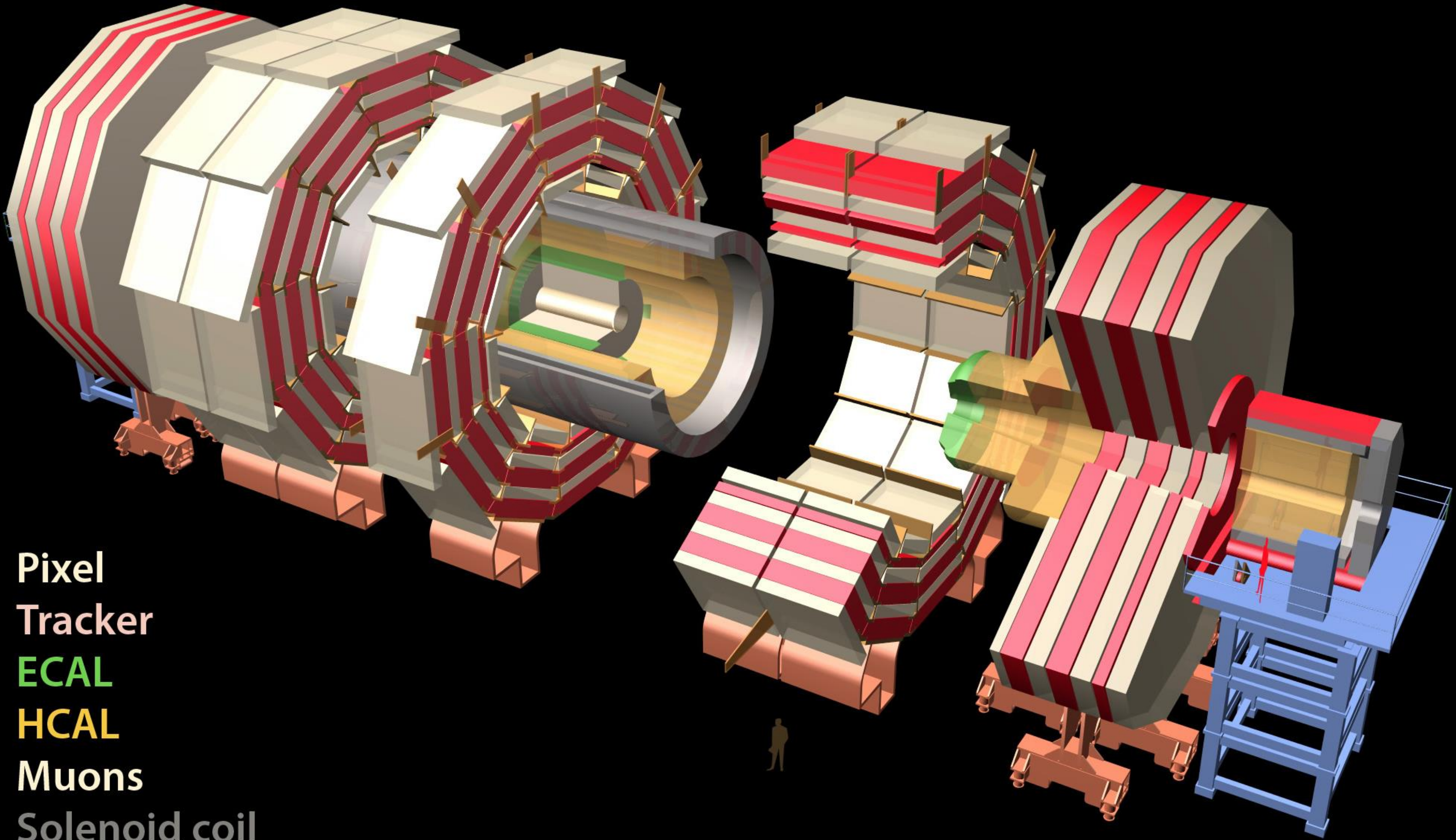
HCAL

HB and HE: Brass/Plastic scintillator
Sampling calorimeter. Tiles and WLS fiber
HF: Steel/Quartz fiber Cerenkov calo.
HO: Plastic scintillator “tail catcher”

Trigger

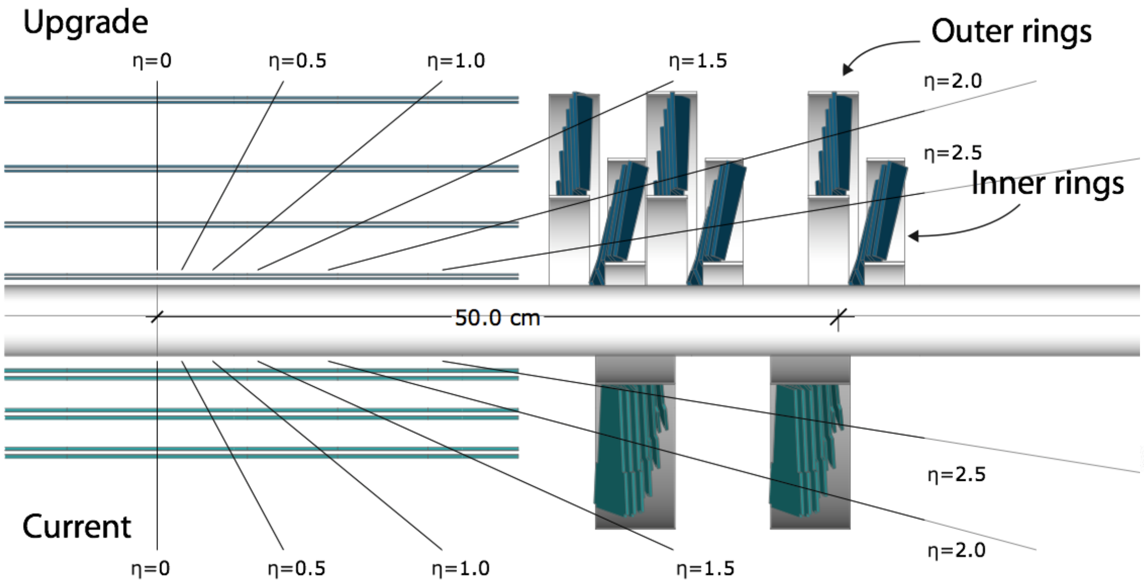
Level 1 in hardware, 3.2µs latency ,100 kHz
ECAL+HCAL+Muon
HLT Processor Farm,1 kHz: Tracking , Full reco

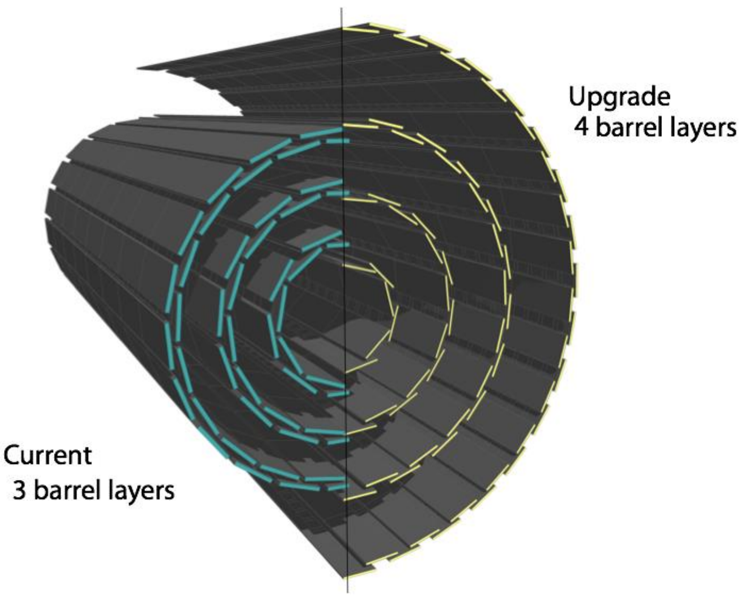
CMS



Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

Phase 1 Upgrades – Pixel Detector





- 4 layers / 3 disks
  - 1 more space point, 3 cm inner radius
  - Improved track resolution and efficiency
- New readout chip
  - Recovers inefficiency at high rate and PU
- Less material
  - CO2 cooling, new cabling and powering scheme (DC-DC)
- Longevity
  - Tolerate up to 100 PU and survive to 500 fb^{-1}, with exchange of innermost layer

Ready to install at end of 2016

Pilot blade (partial disk) in LS1

Phase 1 Upgrades – HCAL

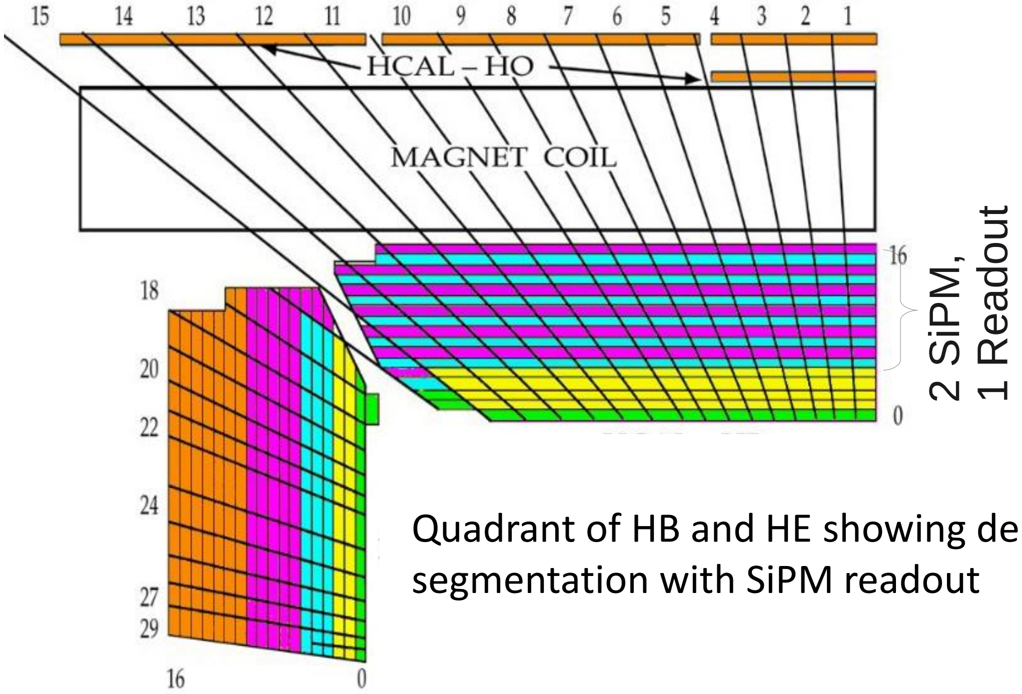
- ○ Backend electronics upgrade to μTCA
- ○ New readout chip (QIE10) with TDC

} HF BE upgrade in LS1, FE at end of 2015

  - Timing: improved rejection of beam-related backgrounds, particularly HF
- ○ Replace HPDs in HB and HE with SiPMs

HB/HE FE upgrade in LS2

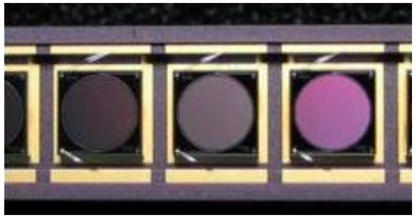
  - Small radiation tolerant package, stable in magnetic field
  - PDE improved x3, lower noise
  - Allows depth segmentation for improved measurement of hadronic clusters, rejection of backgrounds, and re-weighting for radiation damage

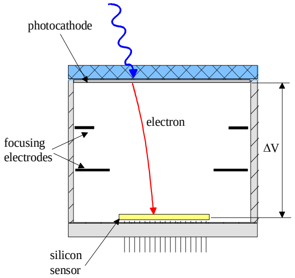


Quadrant of HB and HE showing depth segmentation with SiPM readout

SiPMs: successful R&D program

- Tested to 3000 fb-1
- Neutron sensitivity low





Driving Considerations for the Phase 2 Upgrade

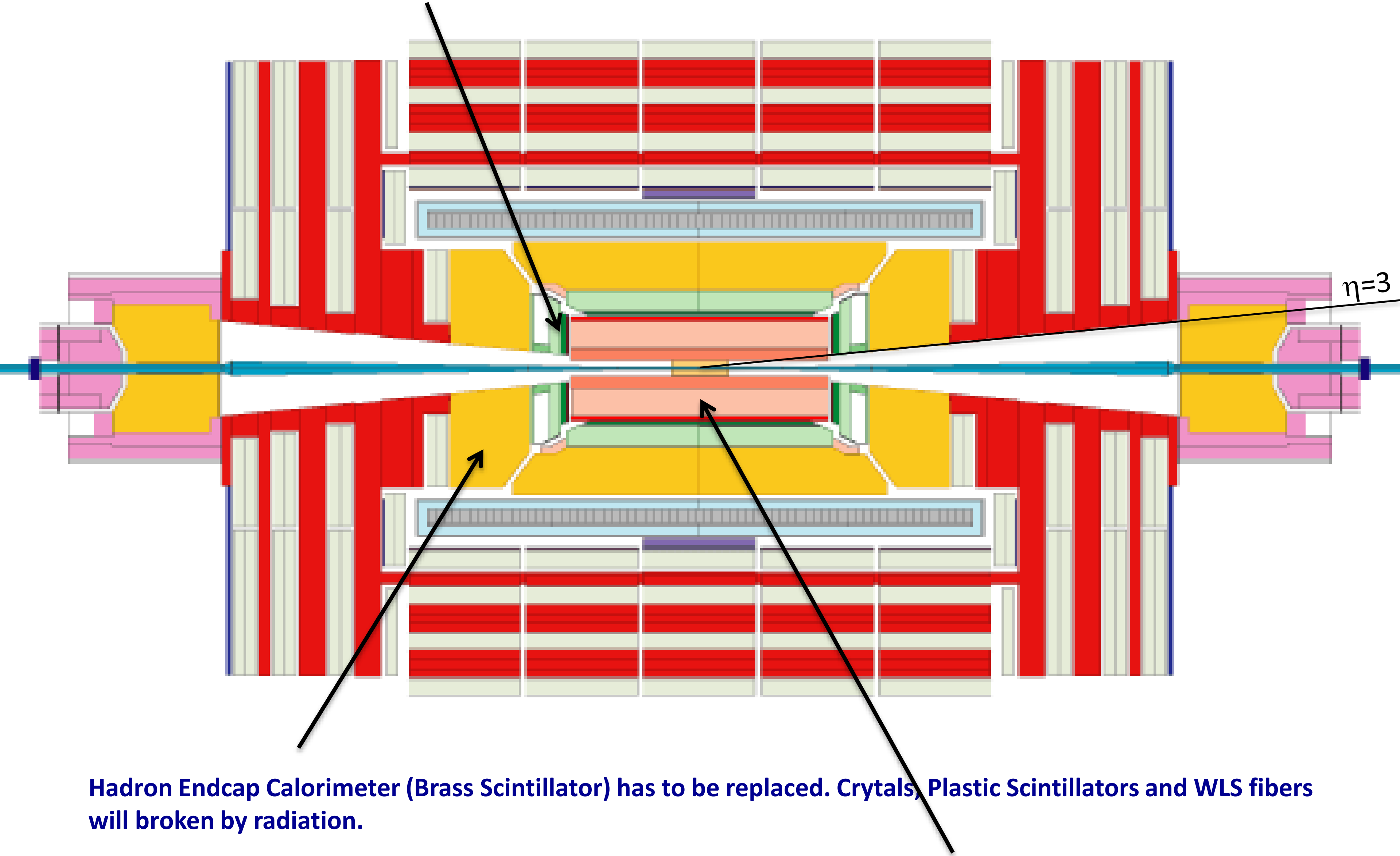
- ➢ By LS3 the integrated luminosity will exceed 300 fb^{-1} and may approach 500 fb^{-1} (use 500 for detector studies)
- ➢ CMS looks forward to over 5x more data beyond that, at significantly higher PU (and steady throughout the fill) and radiation
- ➢ HL-LHC with lumi-leveling at $5\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$ will deliver 250 fb^{-1} per year

- ○ Driving considerations in defining the scope for Phase 2
  - Performance longevity of the Phase 1 detector
  - Physics requirements for the HL-LHC program and beam conditions
  - Development of cost effective technical solutions and designs
  - Logistics and scope of work during LS3

- ○ The performance longevity is extensively studied and modeled, and the radiation damage models are included in full simulation

- ○ While the barrel calorimeters, forward calorimeter (HF) and muon chambers – will perform to 3000 fb^{-1}, it is clear that the tracking system and endcap calorimeters must be upgraded in LS3

Electromagnetic Endcap Calorimeter ($PbWO_4$ Crystals), light output will become too small due to radiation damage



Hadron Endcap Calorimeter (Brass Scintillator) has to be replaced. Crytals, Plastic Scintillators and WLS fibers will broken by radiation.

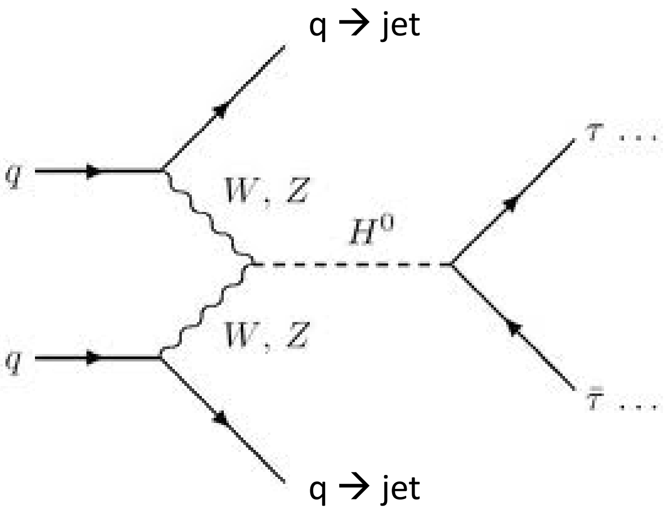
Entire silicon Tracker has to be replaced → radiation hardness and readout (track triggering)

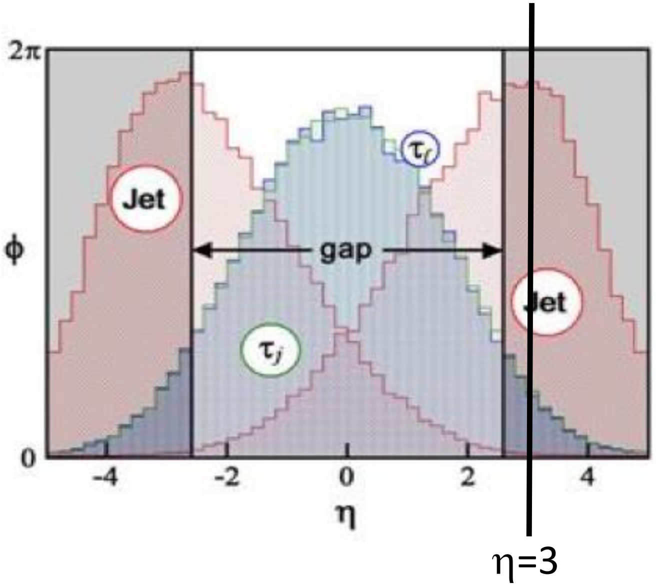
Performance Considerations

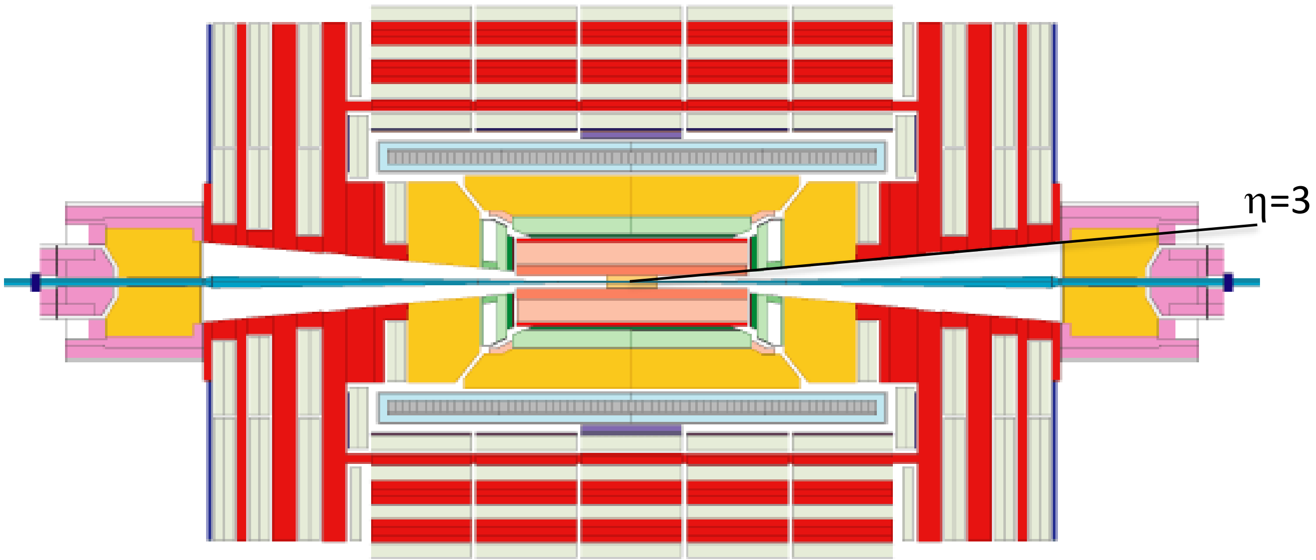
- Mitigation of the effects of high PU relies on particle flow reconstruction and excellent tracking performance.
  - The Phase 2 tracker design must maintain good performance at very high PU
  - We propose to extend the tracker coverage to higher η - the region of VBF jets
  - We are investigating precision timing in association with the calorimeters as a means to mitigate PU for neutral particles

- Endcap coverage
  - The present transition between the endcap and HF, at |η| = 3, is at the peak of the distribution of jets from VBF. We are studying the feasibility of extending the endcap coverage, and integrating a muon tagging station.
  - This has the potential for a significant improvement for VBF channels, but will have implications for radiation and background levels. Studies are ongoing.
  - Physics studies ongoing to optimize the requirements in resolution & granularity.

Vector Boson Fusion (VBF) -Jets







Very important channel to measure.

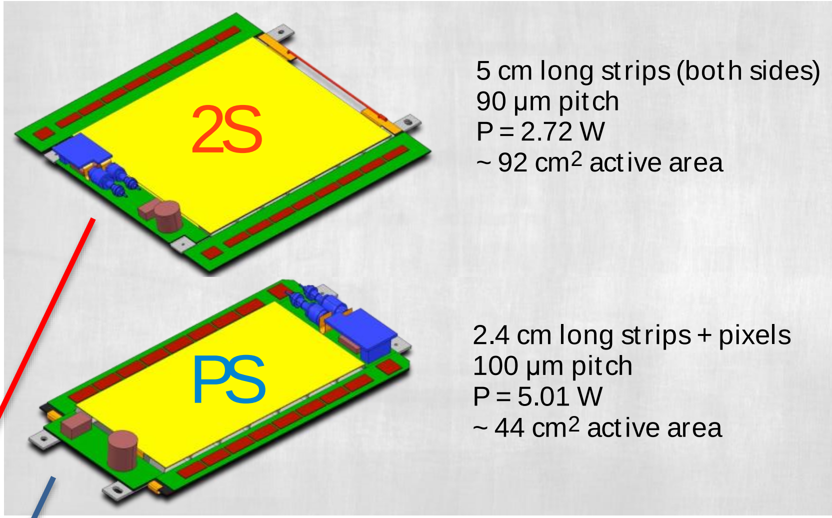
Quarks do not interact through color exchange i.e. the jets are peaked in forward direction at η=3.

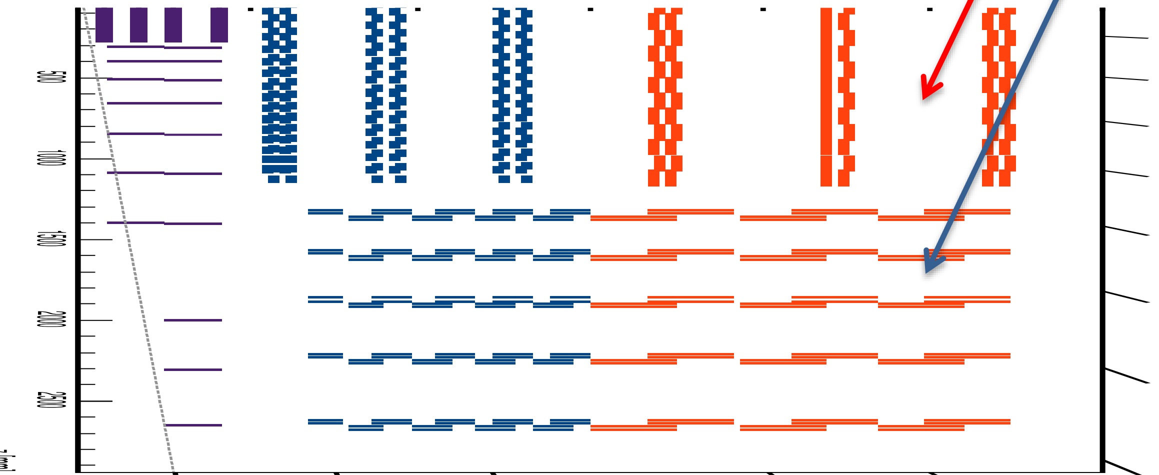
Signature: high jet activity in forward region, little hadronic activity in the barrel.

η = 3 is exactly in the transition region of the endcap calorimeters !

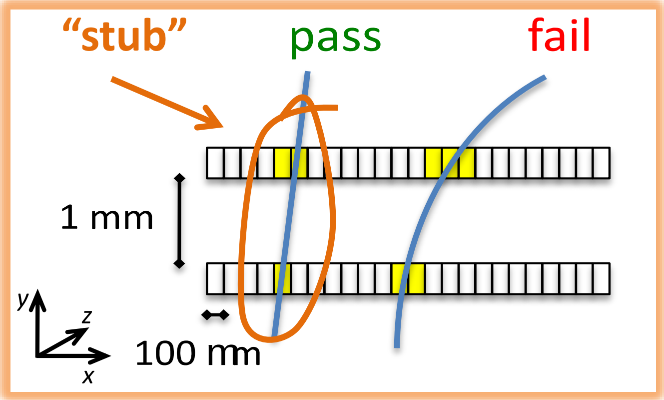
Phase 2 Tracker: conceptual design

- Outer tracker
  - High granularity for efficient track reconstruction beyond 140 PU
  - Two sensor “Pt-modules” to provide trigger information at 40 MHz for tracks with Pt≥2GeV
  - Improved material budget
- Pixel detector
  - Similar configuration as Phase 1 with 4 layers and 10 disks to cover up to |η|= 4
  - Thin sensors 100 µm; smaller pixels 30 x 100 µm
- R&D activities
  - In progress for all components - prototyping of 2S modules ongoing
  - BE track-trigger with Associative Memories





Trigger track selection in FE



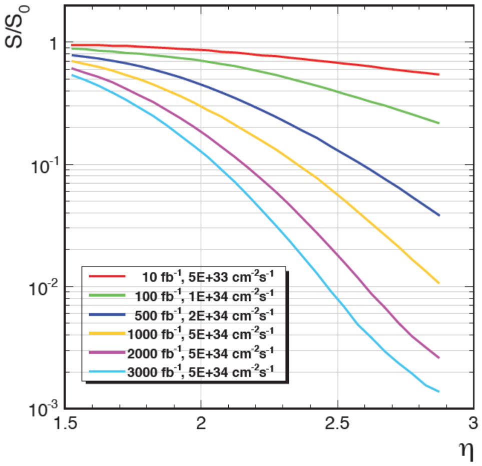


Figure 2. Simulated fraction of ECAL response to 50 GeV electrons under different operating conditions as a function of pseudorapidity.

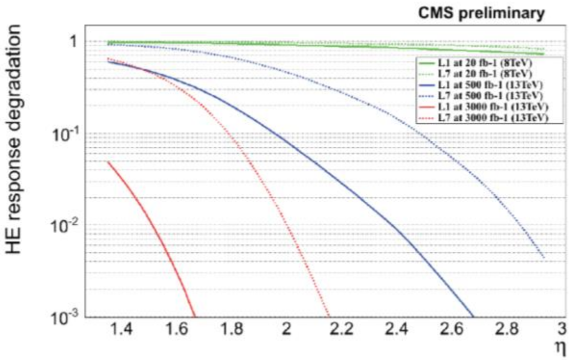
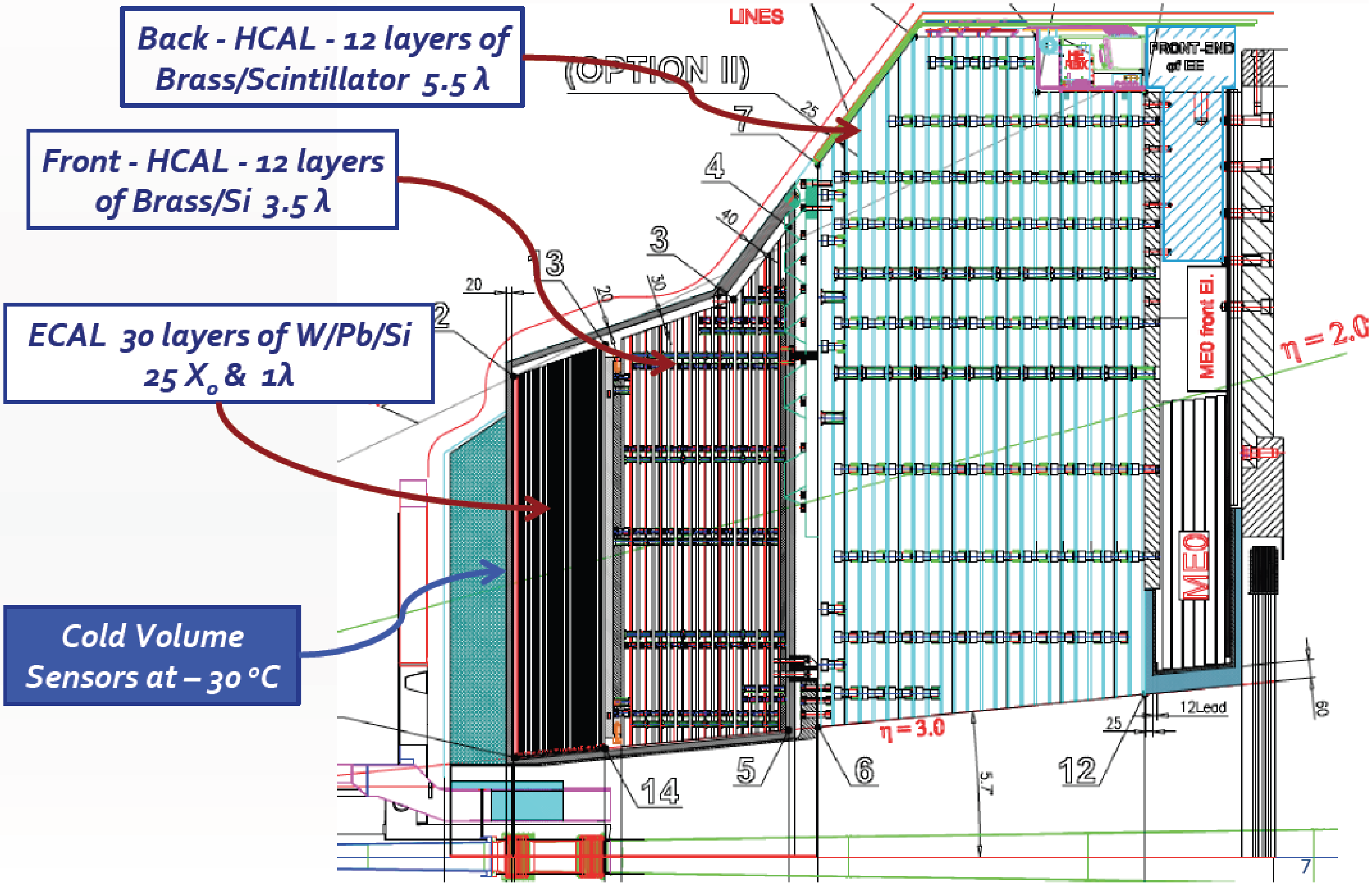


Figure 3. Response degradation of the Hadron Endcap calorimeters at different operating points for two different longitudinal segmentations in the calorimeter and as a function of pseudorapidity.

CMS Calorimeter Concept



Back - HCAL - 12 layers of Brass/Scintillator 5.5 λ

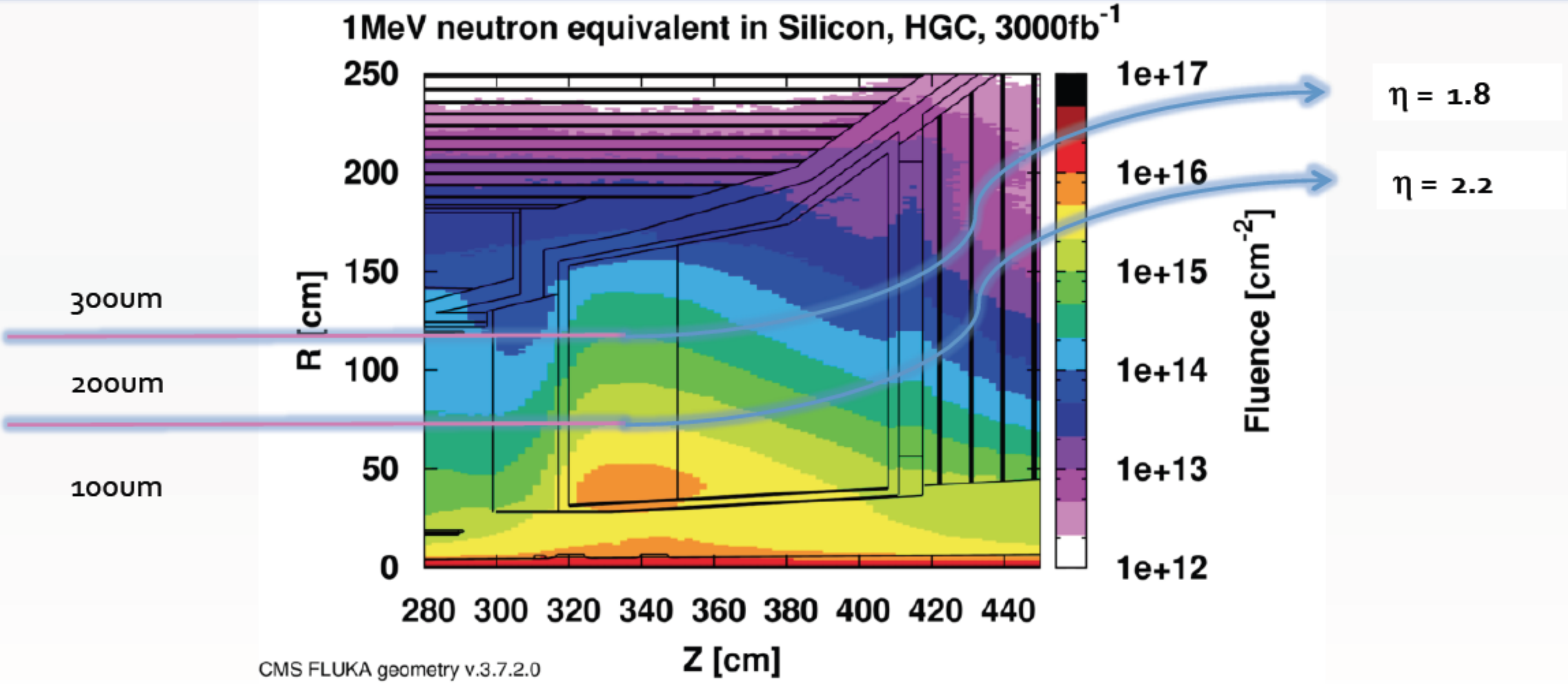
Front - HCAL - 12 layers of Brass/Si 3.5 λ

ECAL 30 layers of W/Pb/Si 25 X_o & 1λ

Cold Volume Sensors at – 30 °C

Sensor Parameters after 3,000 fb^{-1}

Si Thick	300	200	100	um
Max Fluence	$6*10^{14}$	$2.5*10^{15}$	$1*10^{16}$	n/cm^2
HGC EE Area	220	120	140	m^2
Vbias	600~900	600~900	600~900	V
Signal	15'000	7'500	6'000	e-
Ileak Power/Module	0.5~0.7	1.4~2.1	2.7~4.1	W/module
Ileak Power	5~7	7~11	16~25	kW



CMS FLUKA geometry v.3.7.2.0

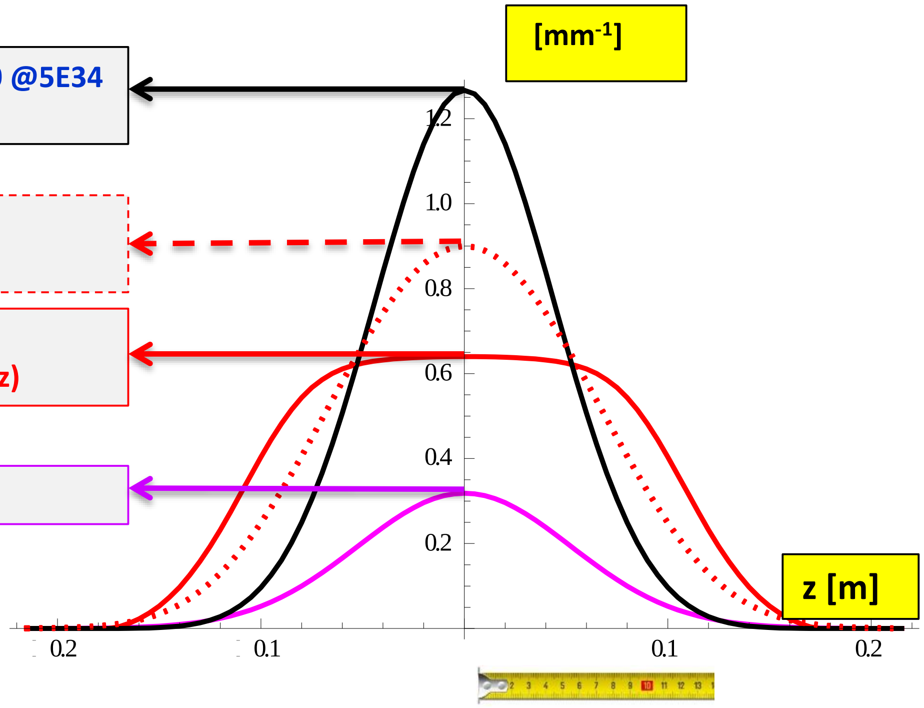
Pileup Density

HL-LHC baseline and backup (25 ns): 250 fb^{-1}/y , μ_{tot}= 140 @5E34
(BB wire .or. crab w/o CK scheme)

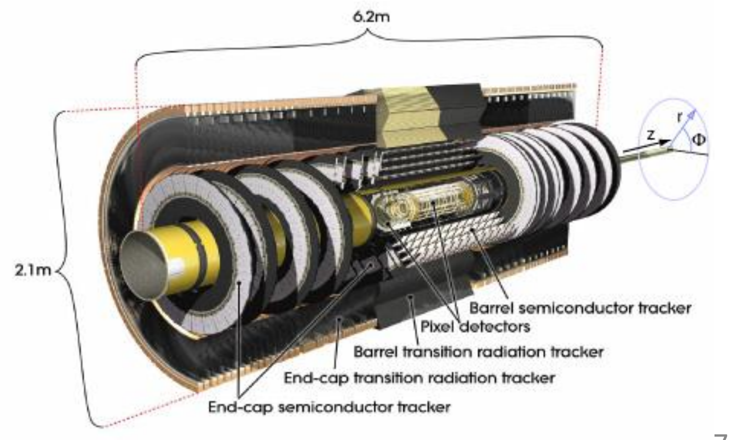
"HL-LHC+" (25ns): 250 fb^{-1}/y , μ_{tot}= 140 @5E34
(BB wire .and. crabs with CK scheme)

"HL-LHC++" (25ns): 250 fb^{-1}/y , μ_{tot}= 140 @5E34
(BB wire .and. crabs with CK scheme .and. 800 MHz)

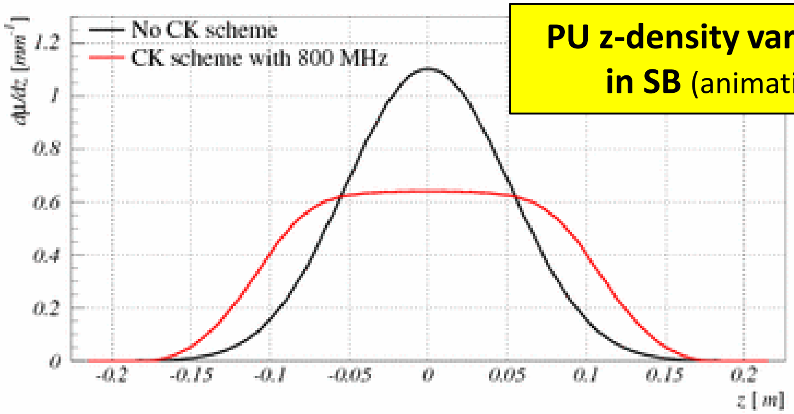
LHC2012 (50 ns): 25 fb^{-1}/y, μ_{tot}= 40 @7.5E33



Possibly reduce pileup density from 1.25/mm to 0.6/mm.
→ However – shape changes with time.



The ``crab-kissing'' (CK) scheme (5/5)



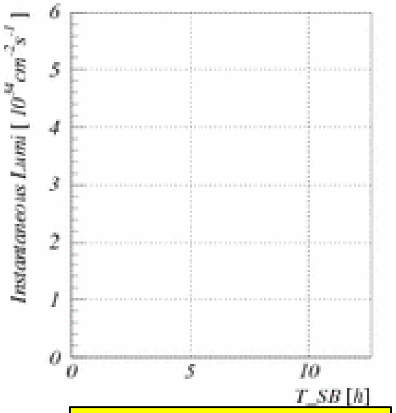
PU z-density variations in SB (animation)

→ The **density shape** is changing in stable beam

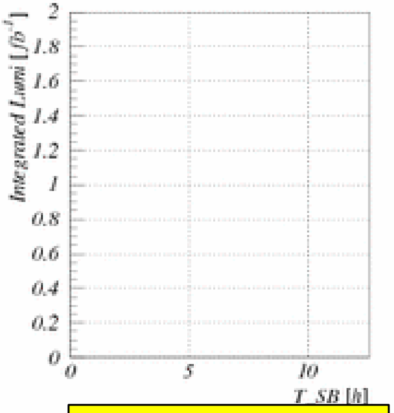
→ … but the **peak density** is halved and stays constant with the CK scheme.

Efforts are made to spread out the luminous region in order to be able to better distinguish the piled up vertices.
Order of 200 vertices in ± 5-10 cm
→ Pileup mitigation by tracking

The collisions are in a single bunch crossing have a spread in time. Independent of vertex position for Gaussian beams.
→ Pileup mitigation by timing ! Time resolutions in the order of 10-20ps are needed !



Lumi profile in SB

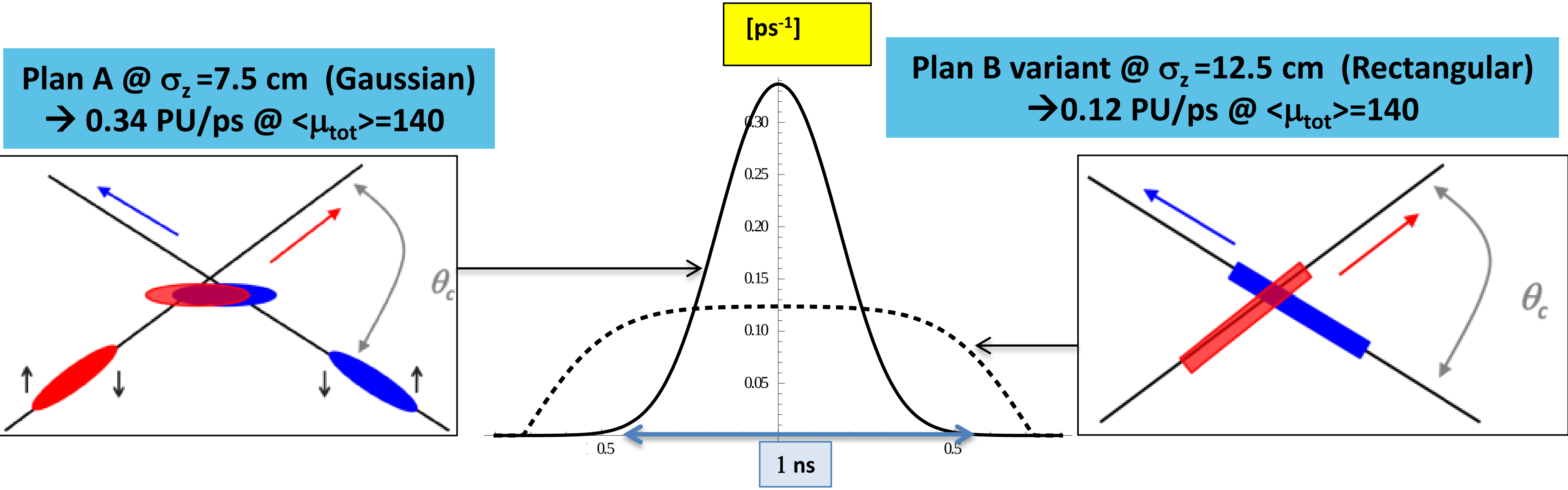


Perf. profile in SB

Sensitivity to bunch length & bunch shape (3/3)

→ Peak **time density** of vertices: **net gain**

- For longer r.m.s. bunch length
- Even more for rectangular bunches and Plan B (with non-zero Piwinsky angle)



Plan A @ σ_z=7.5 cm (Gaussian)
→ 0.34 PU/ps @ <μ_{tot}>=140

Plan B variant @ σ_z=12.5 cm (Rectangular)
→0.12 PU/ps @ <μ_{tot}>=140

In the best case, still 1.2 pile-up every 10 ps

(and loosing ~10% of integrated performance via the geometric loss factor)

Is it really usable??

Excursion to Silicon Detectors

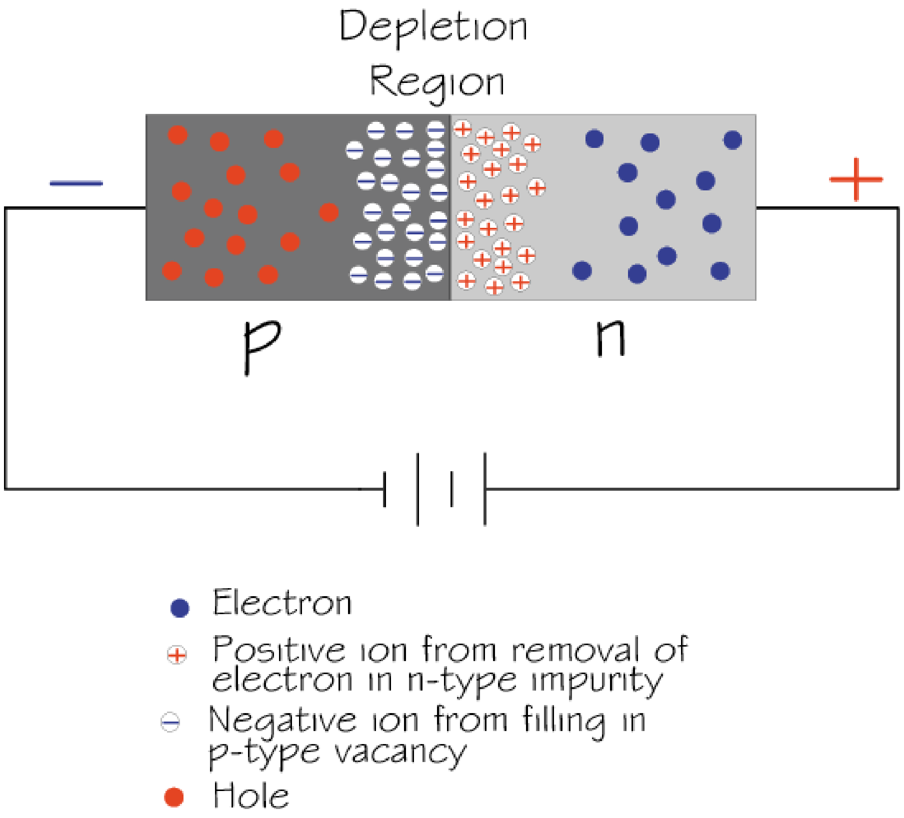
Si-Diode used as a Particle Detector

At the p-n junction the charges are depleted and a zone free of charge carriers is established.

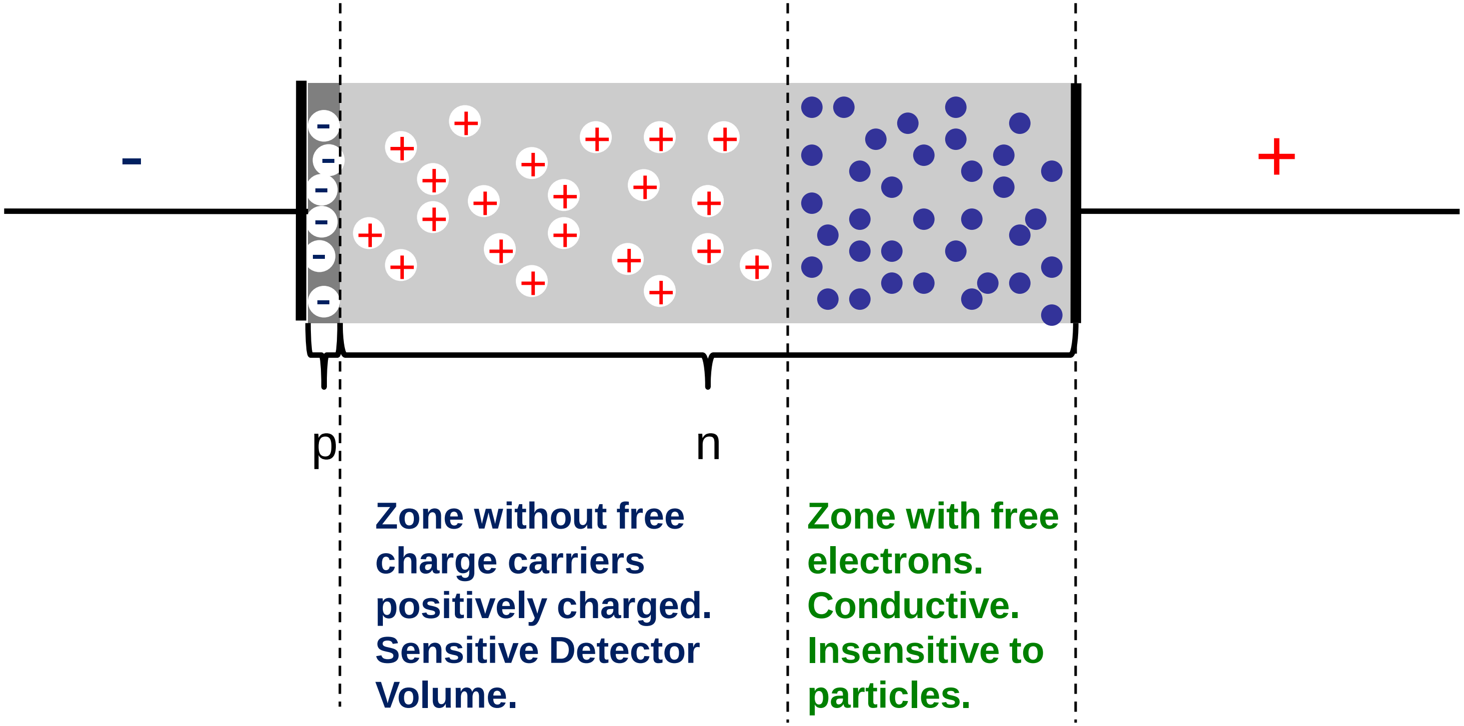
By applying a voltage, the depletion zone can be extended to the entire diode → highly insulating layer.

An ionizing particle produces free charge carriers in the diode, which drift in the electric field and induce an electrical signal on the metal electrodes.

As silicon is the most commonly used material in the electronics industry, it has one big advantage with respect to other materials, namely highly developed technology.

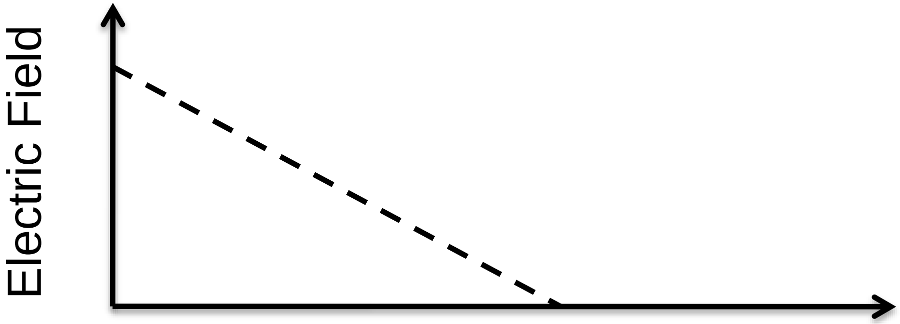


Under-Depleted Silicon Detector

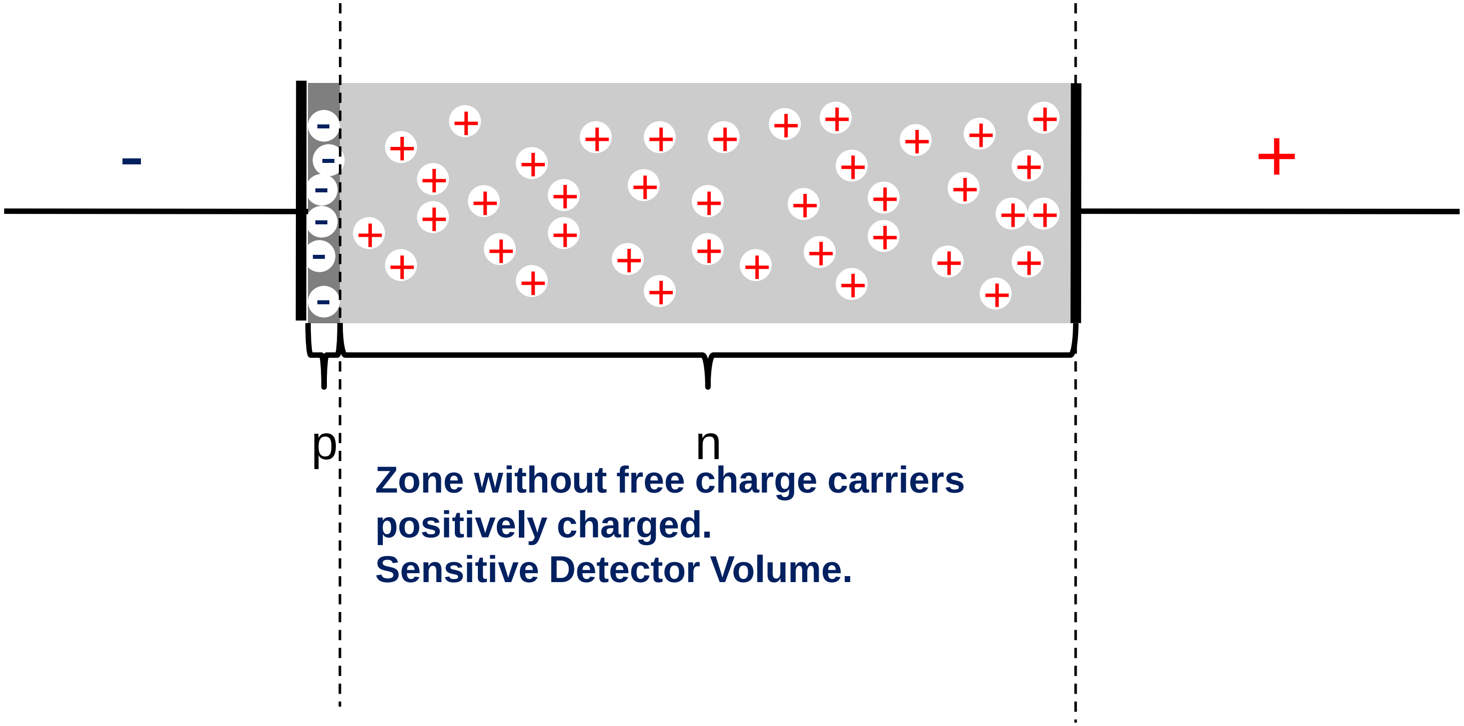


Zone without free charge carriers positively charged. Sensitive Detector Volume.

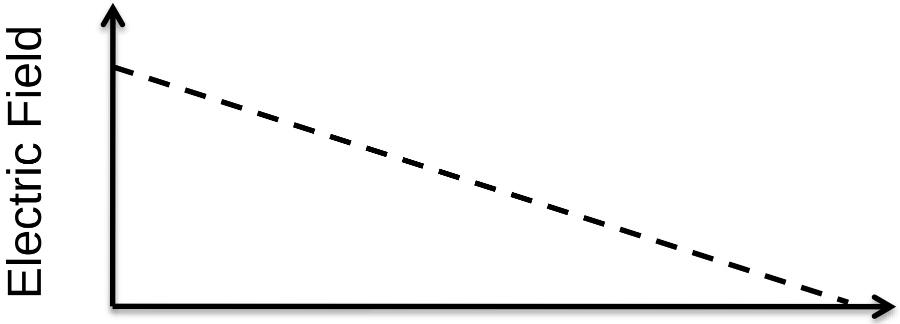
Zone with free electrons. Conductive. Insensitive to particles.



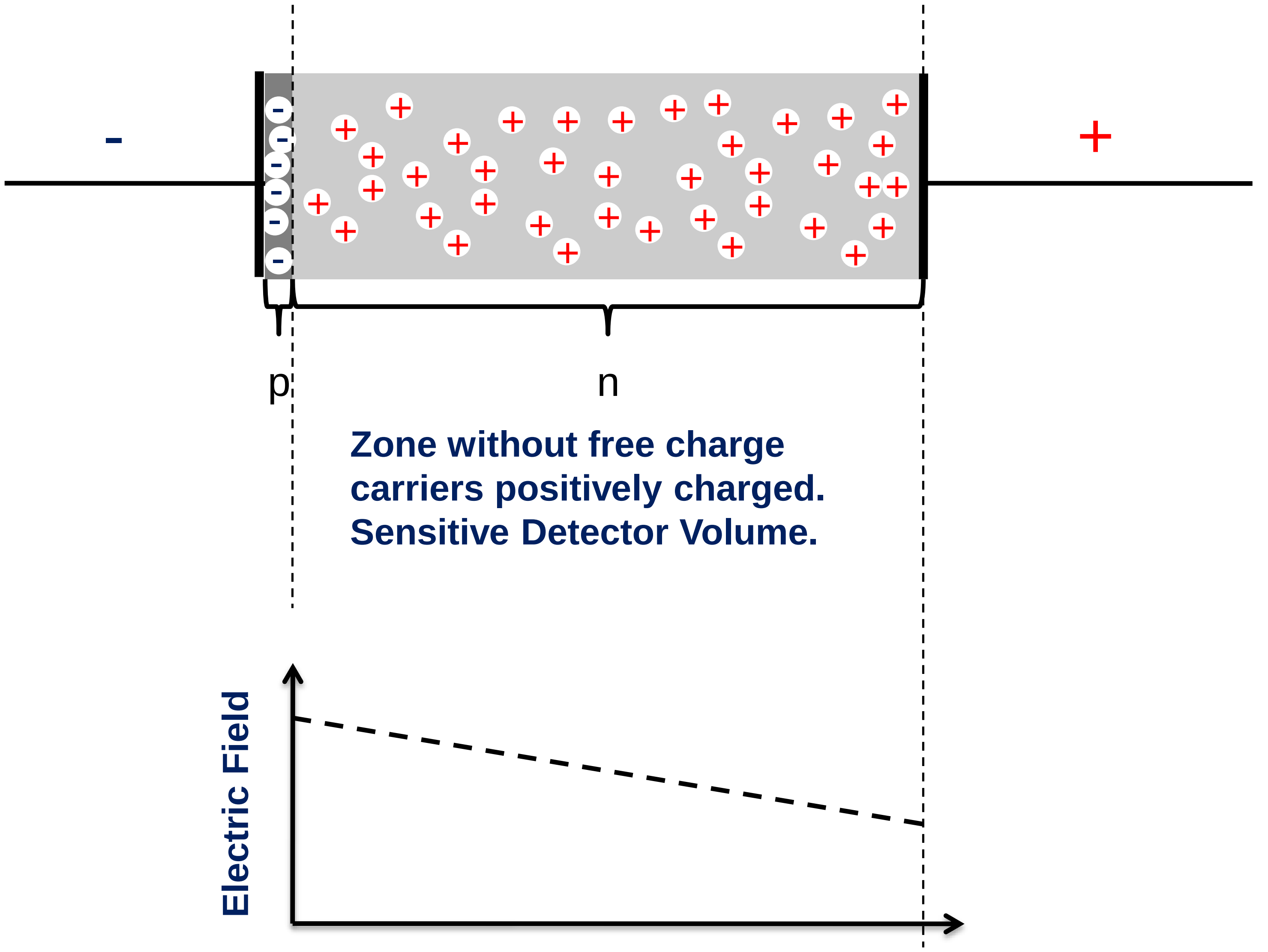
Fully-Depleted Silicon Detector



Zone without free charge carriers positively charged.
Sensitive Detector Volume.

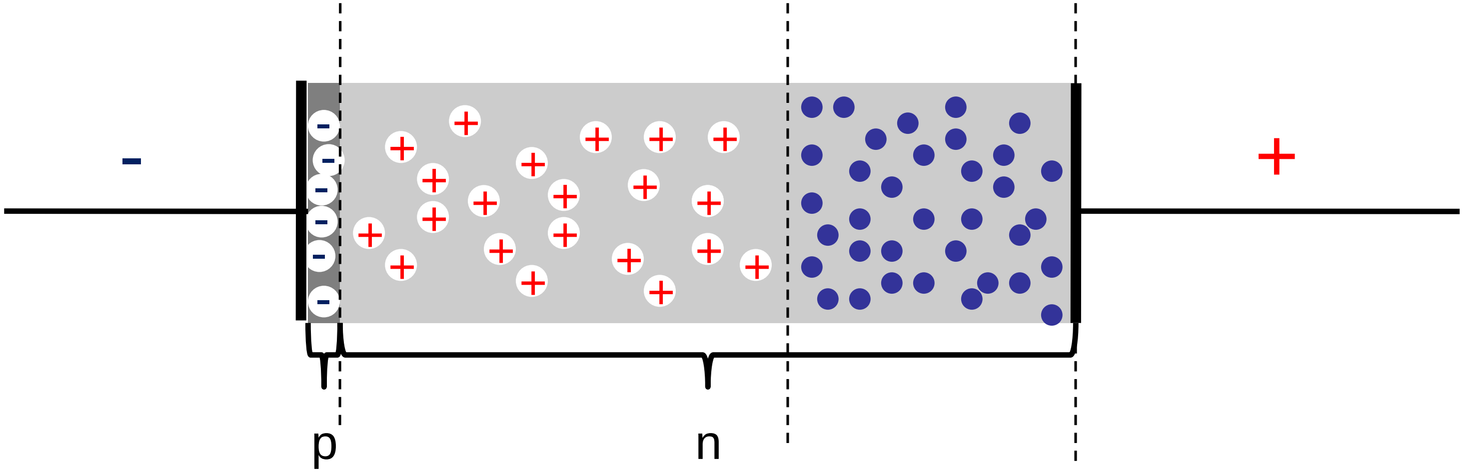


Over-Depleted Silicon Detector

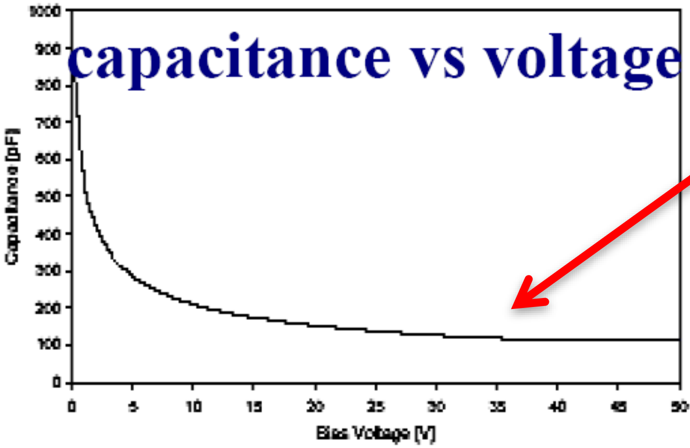


Zone without free charge carriers positively charged. Sensitive Detector Volume.

Depletion Voltage



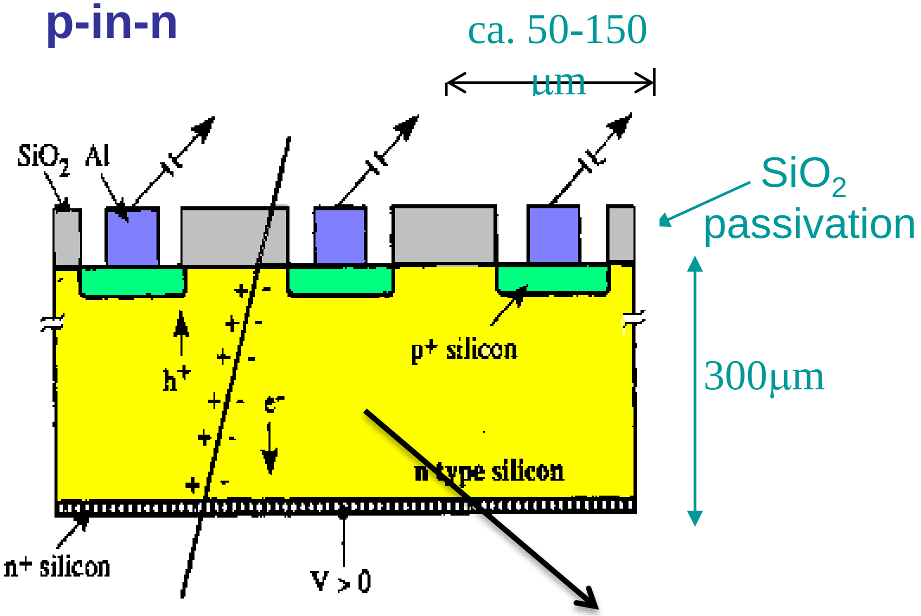
The capacitance of the detector decreases as the depletion zone increases.



Full depletion

Silicon Sensor

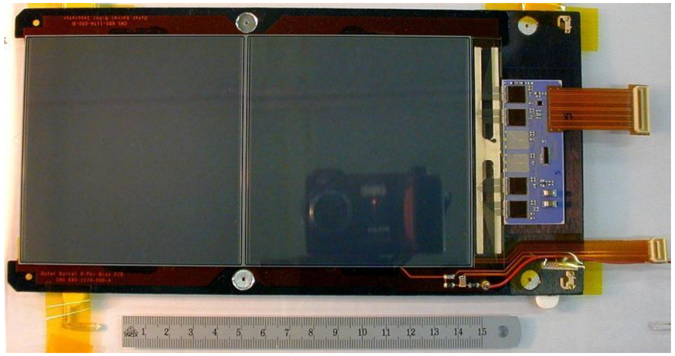
p-in-n

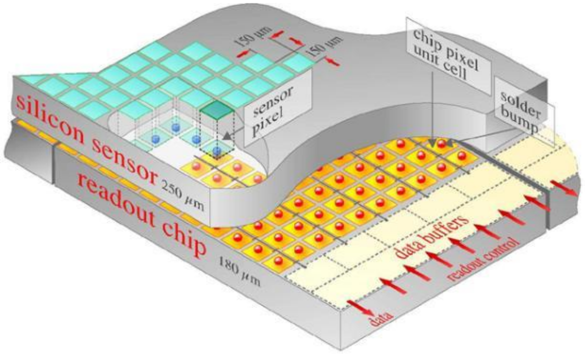


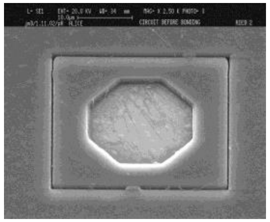
Fully depleted zone

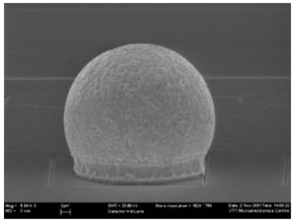
N (e-h) = 11 000/100µm

Position Resolution down to ~ 5µm !



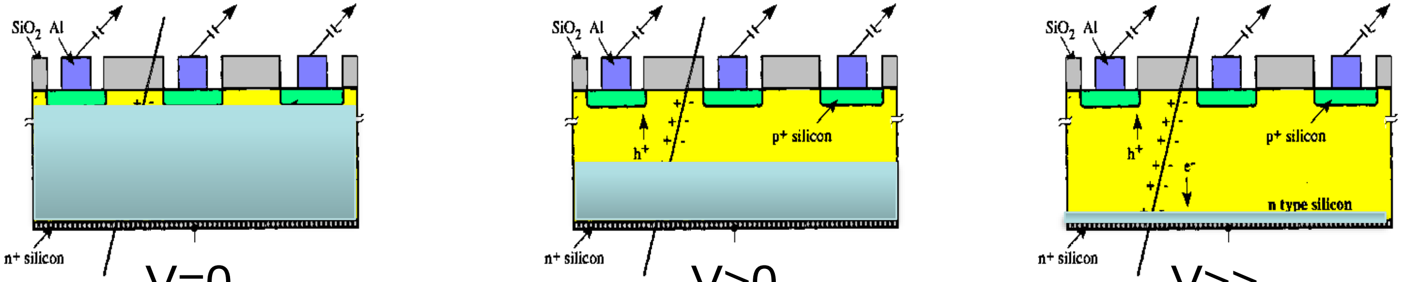






Silicon Sensor before Irradiation

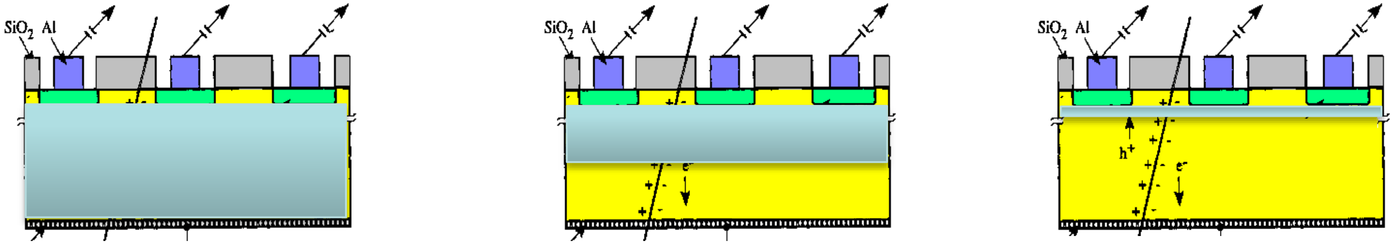
p(strips)-in-n



V=0 V>0 V>>0

→ depletion grows from the segmented side

n+(strips)-in-n



V=0 V<0 V<<0

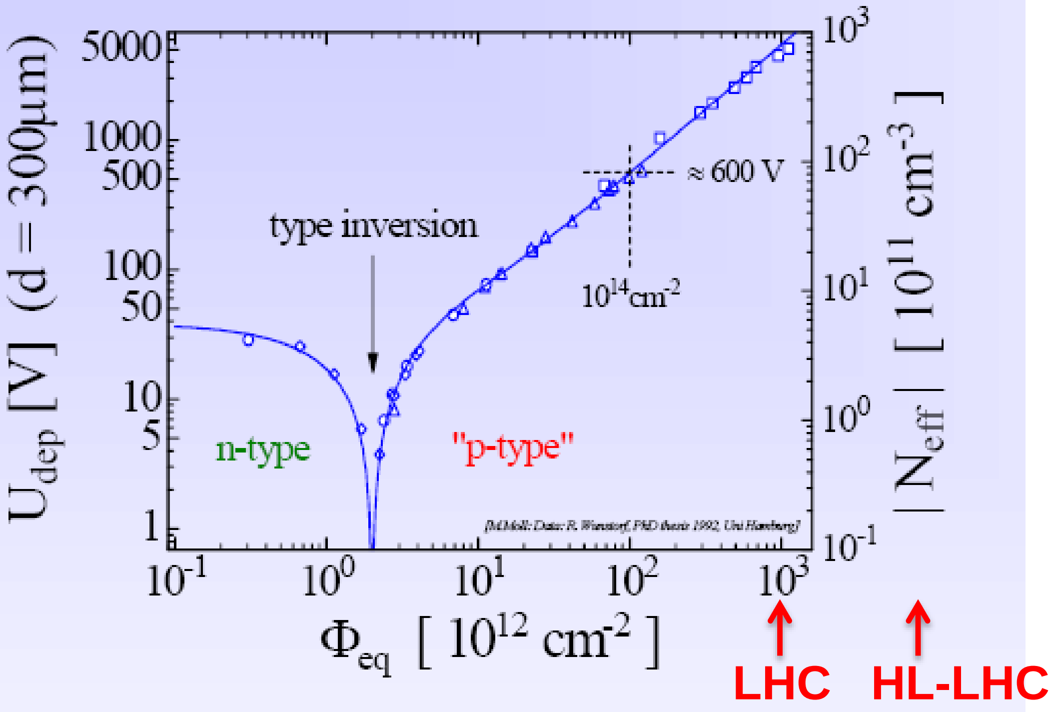
- → depletion grows from the un-segmented side
- → This detector does not work properly unless it is fully depleted.
- → For partial depletion the ‚charge collection‘ is very inefficient and the ‚cluster size‘ is increasing.

Radiation Effects, Type Inversion

Type inversion ! An n-type Si detector becomes a p-type Si detector !

More voltage is needed to fully deplete the detector.

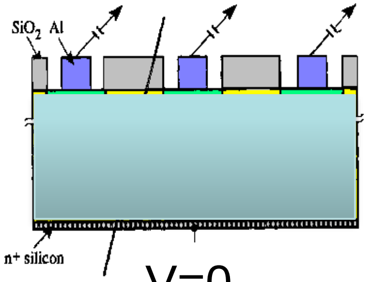
It might happen that the full depletion voltage becomes larger than the breakdown voltage → have to work in under depleted regime.



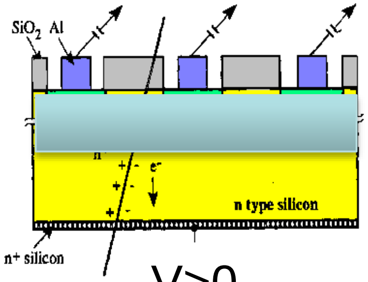
- "Type inversion": N_{eff} changes from positive to negative (Space Charge Sign Inversion)

Silicon Sensor after Irradiation and type inversion

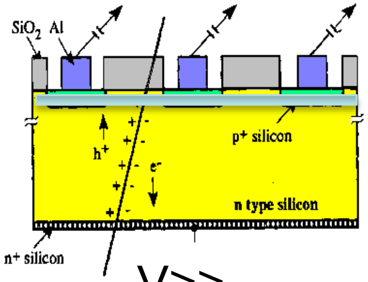
p(strips)-in-n



V=0

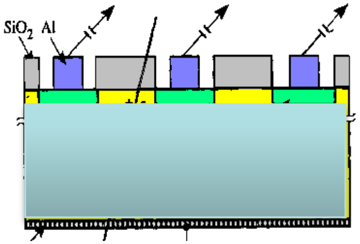


V>0

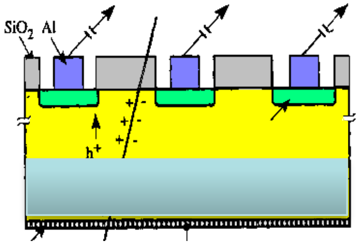


V>>0

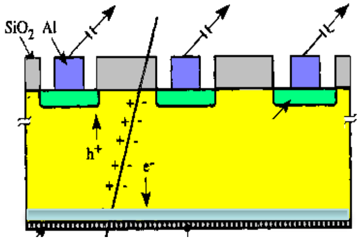
→ depletion grows now from the unsegmented side !



V=0



V<0



V<<0

- **→ depletion now grows from the segmented side**
- **→ can work in under-depleted mode**

For high radiation environment, where one might not reach full depletion after some time, n-in-p detectors are preferred.

p-in-n and n$^+$-in-n sensors

p-in-n single sided processing

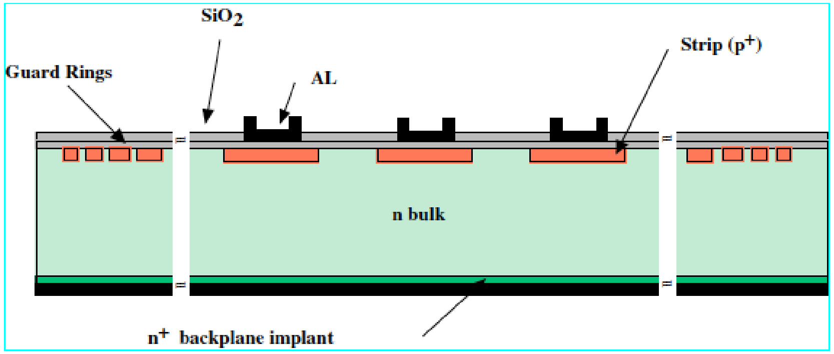


Figure 3.11: Schematic cross section of a p-in-n detector.

n-in-n double sided processing

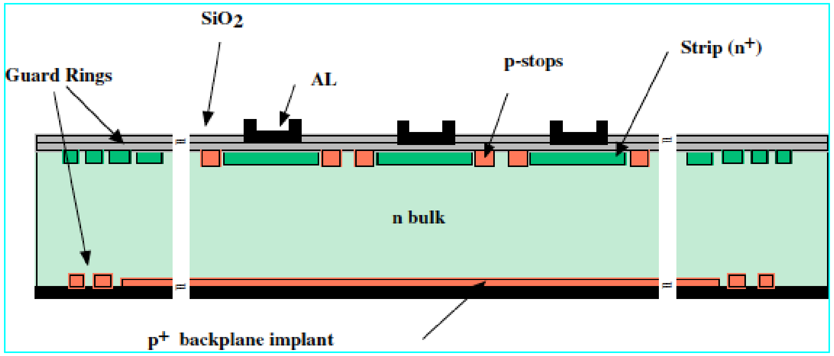


Figure 3.10: Schematic cross section of a n-in-n detector.

from P. Riedler

n-in-p Silicon Sensors

Since recently p-bulk material is available in a quality that is sufficient for these detectors. Baseline for large areas of HL-LHC trackers !

Advantage of n-in-p technology:

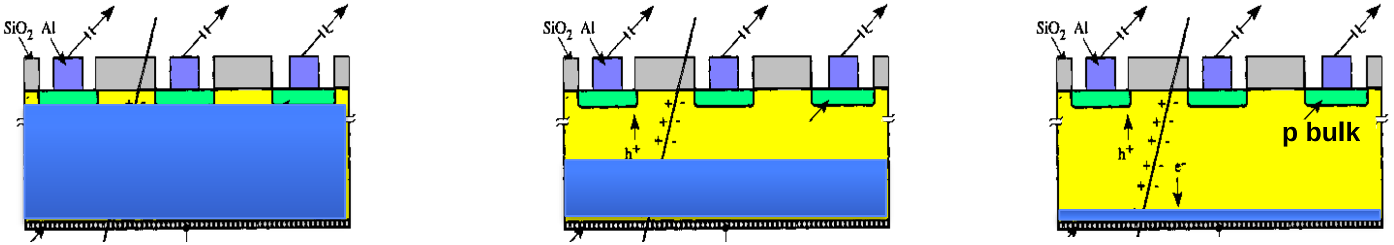
No type inversion

Depletion from the ‘correct’ side (i.e. from the readout side)

Single sided processing is possible

Electrons drift towards the readout side and are trapped less because electrons are faster → still good signal after irradiation.

n-in-p

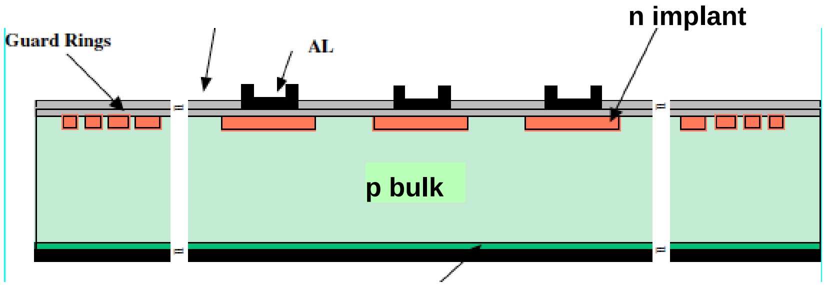


V=0

V<0

V<<0

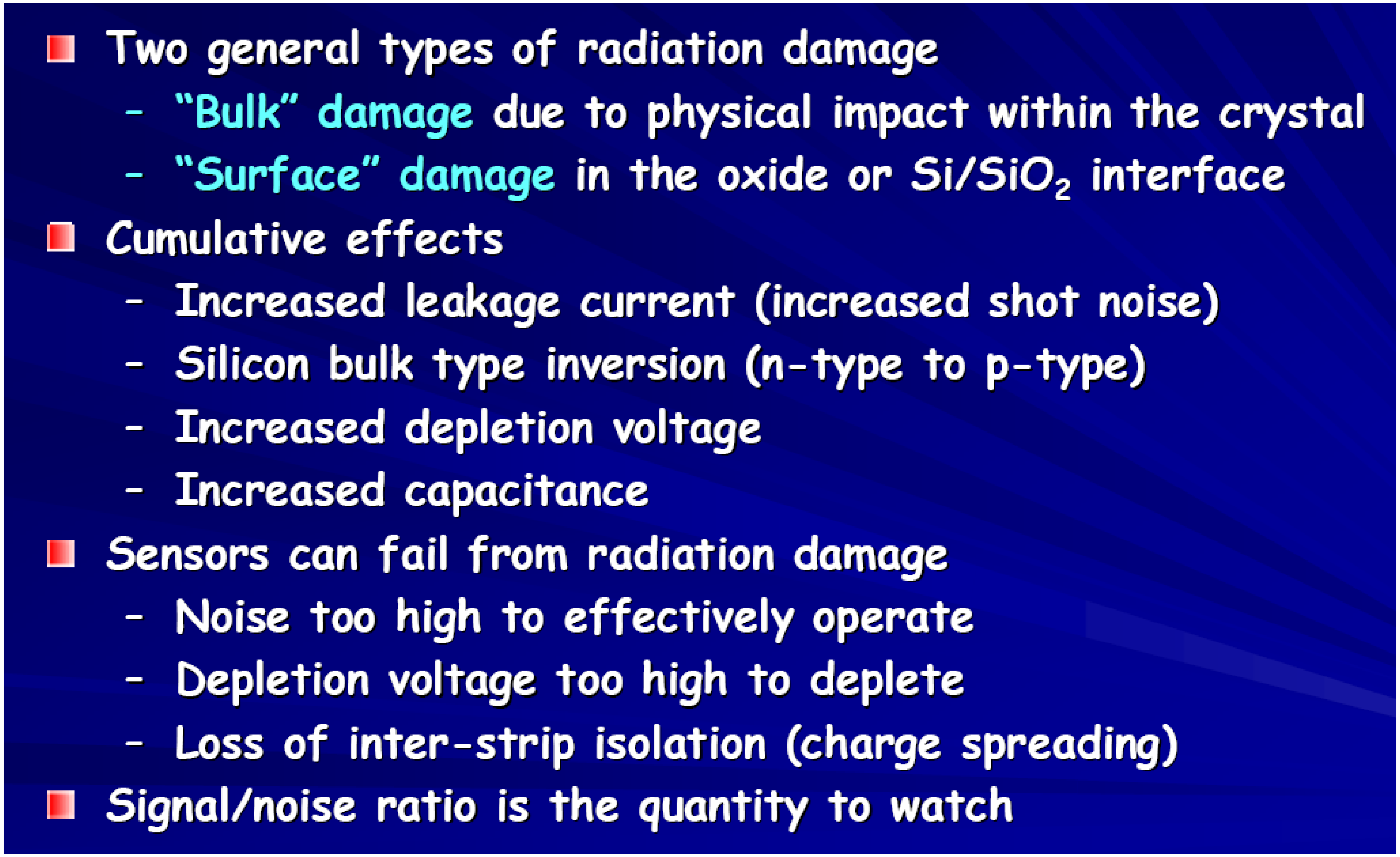
n implant



Radiation Effects ‘Aging’

LHC Pixels:	**10^{15} n/cm^2**	**14 TeV**	**300fb^{-1}**
HL-LHC Pixels:	**10^{16}n/cm^2**	**14TeV**	**3000fb^{-1}**
FCC-hh Pixels:	**2x10^{18}**	**100TeV**	**30 000fb^{-1}**

First Pixel layer only !! The rest of the tracker volume has significantly less radiation.



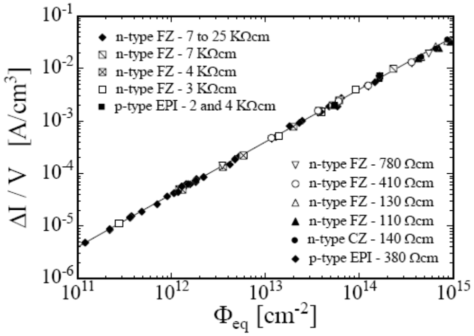
- Two general types of radiation damage
  - “Bulk” damage due to physical impact within the crystal
  - “Surface” damage in the oxide or Si/SiO$_2$ interface
- Cumulative effects
  - Increased leakage current (increased shot noise)
  - Silicon bulk type inversion (n-type to p-type)
  - Increased depletion voltage
  - Increased capacitance
- Sensors can fail from radiation damage
  - Noise too high to effectively operate
  - Depletion voltage too high to deplete
  - Loss of inter-strip isolation (charge spreading)
- Signal/noise ratio is the quantity to watch

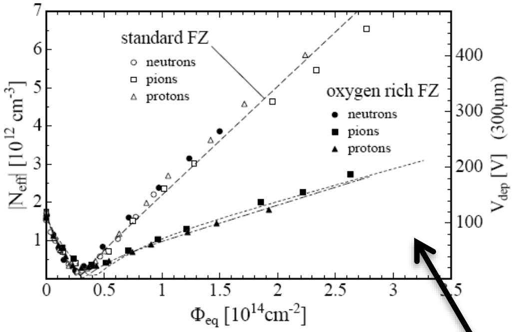
Radiation Effects ‘Aging’

Increase of leakage current

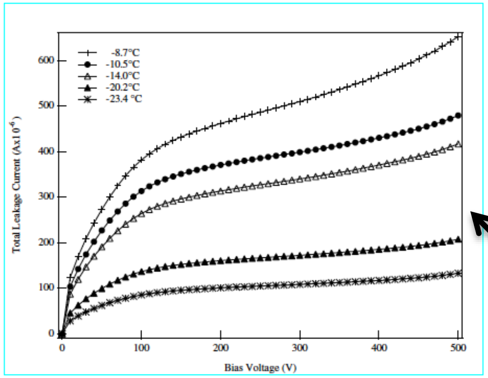
Increase of depletion voltage

Decrease of charge collection efficiency due to under-depletion and charge trapping.





Use silicon material engineering to limit radiation damage



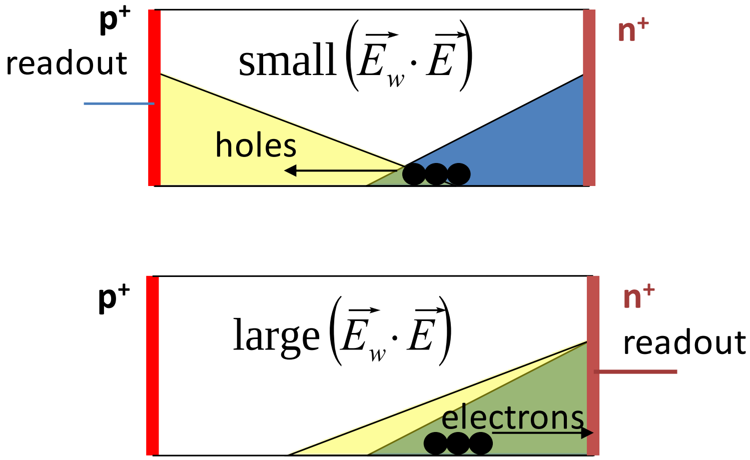
from P. Riedler

Figure 3.17: I-V curve of detector Wedge 12-1 at various temperatures after 12 days at 25 °C.

Use cooling to decrease leakage current (approx. factor two every 8 degrees)

Sensor Technology in Present Experiments

- p-in-n, n-in-p (**single sided process**)
- n-in-n (**double sided process**)
- Choice of sensor technology mainly driven by the **radiation environment**



G. Kramberger, Vertex 2012

	Fluence 1MeV n_{eq} [cm^{-2}]	**Sensor type**
ATLAS Pixel*	1 x 10^{15}	n-in-n
ATLAS Strips	2 x 10^{14}	p-in-n
CMS Pixels	3 x 10^{15}	n-in-n
CMS Strips	1.6 x 10^{14}	p-in-n
LHCb VELO	1.3 x 10^{14**}	n-in-n, n-in-p
ALICE Pixel	1 x 10^{13}	p-in-n
ALICE Drift	1.5 x 10^{12}	p-in-n
ALICE Strips	1.5 x 10^{12}	p-in-n

n-side readout (n-in-n, n-in-p):

- Depletion from segmented side (under-depleted operation possible)
- Electron collection
- Favorable combination of weighting field and
- Natural for p-type material

** per year

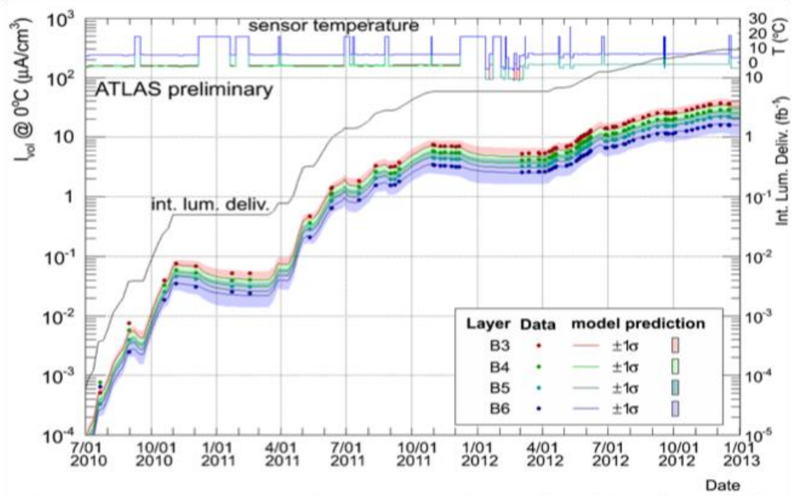
Radiation Damage Effects in Sensors

- Effects observed in ATLAS, CMS and LHCb (lower luminosity in ALICE)
- **Main challenge for the sensors is an increase in leakage current:**
  - Risk of thermal runaway -detector becomes inoperable
    - Operate sensors at low temperatures (see talk by B. Verlaat)
  - Increase in shot noise - degraded performance
- Leakage current increases with integrated luminosity in agreement with the predictions

- **Further effects:**
  - Sensor depletion voltage changes with radiation damage
  - Loss of signal due to radiation induced damage

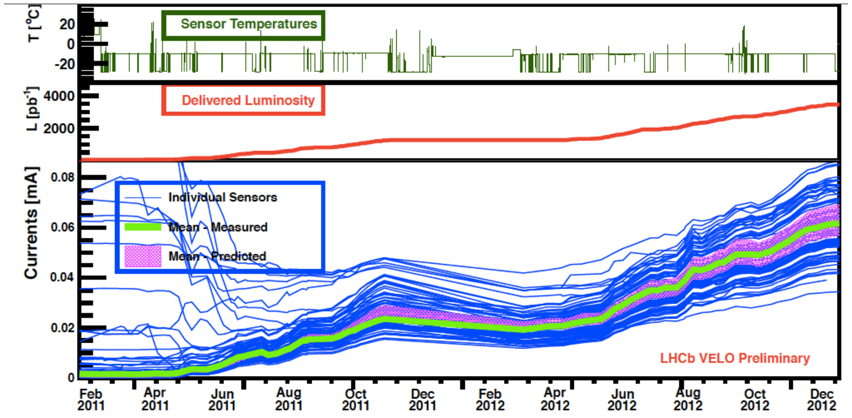
Effects will increase for HL-LHC

Leakage current vs. integrated luminosity (examples)



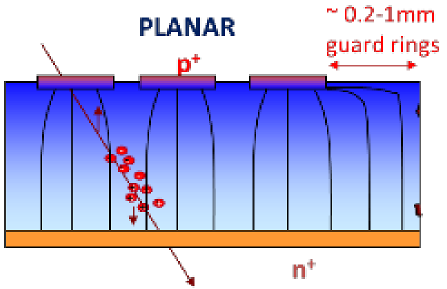
Excellent agreement over 4 orders of magnitude, need a good knowledge of inputs (L,flux,T).

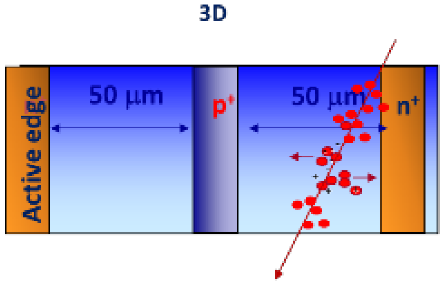
ATLAS SCT Barrel
H. Pernegger, LHCP 2013



LHCb VELO
H. Snoek, Hiroshima 2013

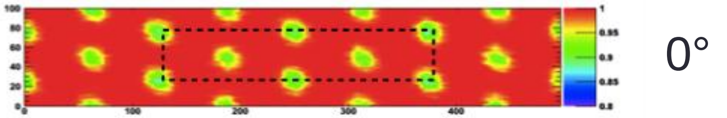
3D Sensors



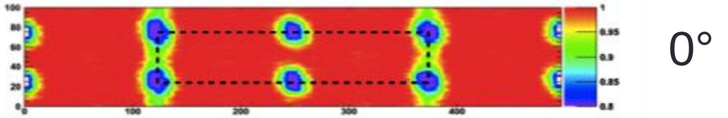


- **Both electrode types are processed inside the detector bulk**
- Max. drift and depletion distance set by electrode spacing **- reduced collection time and depletion voltage**
- **Very good performance at high fluences**
- Production time and complexity to be investigated for larger scale production
- Used in ATLAS IBL

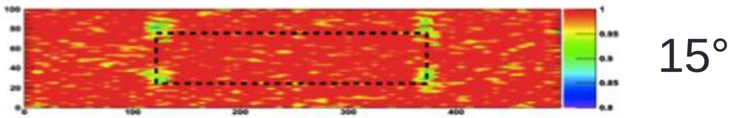
3D pixel sensors



SCC105 FBK-3D, un-irrad, HV=20V, Eff.=98.77%



SCC81 CNM-3D, n-irrad HV=160V, Eff.=97.46%



SCC34 CNM-3D, p-irrad, HV = 160V, Eff.=98.96%

ATLAS IBL Sensor (Threshold: 1600 e
proton-irrad: 5×10^{15} n_{eq}/cm^2 with 24 MeV protons
neutron-irrad: 5×10^{15} n_{eq}/cm^2 by nuclear reactor)

From: Prototype ATLAS IBL Modules using the FE-I4A Front-End Readout Chip" (JINST 7 (2012) P11010)

Key Sensor Issues for the Upgrades

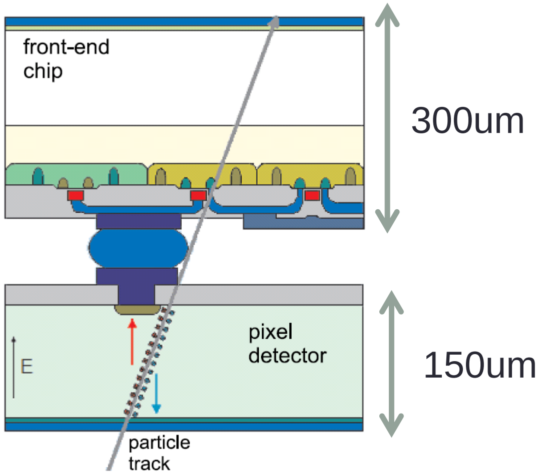
- **Radiation damage** will increase to several 10^{16} n_{eq} cm^{-2} for the inner regions in ATLAS and CMS
  - Example of common activities to develop radiation harder sensors within the RD50 collaboration
  - Operational requirements more demanding (low temperature and all related system aspects)
- **Increased performance:**
  - Higher granularity
  - Lower material budget
- **Control and minimize cost**
  - Large areas
  - Stable and timely production

Upgrades	**Area**	**Baseline sensor type**
ALICE ITS	10.3 m^2	CMOS
ATLAS Pixel	8.2 m^2	*tbd*
ATLAS Strips	193 m^2	n-in-p
CMS Pixel	4.6 m^2	*tbd*
CMS Strips	218 m^2	n-in-p
LHCb VELO	0.15 m^2	*tbd*
LHCb UT	5 m^2	n-in-p

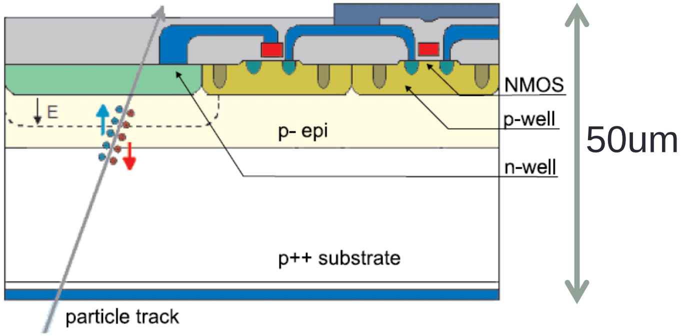
CMOS Sensors

- CMOS sensors **contain sensor and electronics combined in one chip**
  - No interconnection between sensor and chip needed
- Standard CMOS processing
  - Wafer diameter (8")
  - Many foundries available
  - Lower cost per area
  - Small cell size – high granularity
  - Possibility of stitching (combining reticles to larger areas)
- Very low material budget
- CMOS sensors installed in STAR experiment
- Baseline for ALICE ITS upgrade

Hybrid Pixel Detector



CMOS (Pixel) Detector



PIXEL Chip - technology

Monolithic PIXEL chip using Tower/Jazz 0.18 µm technology

- feature size 180 nm
- gate oxide < 4nm
- metal layers 6

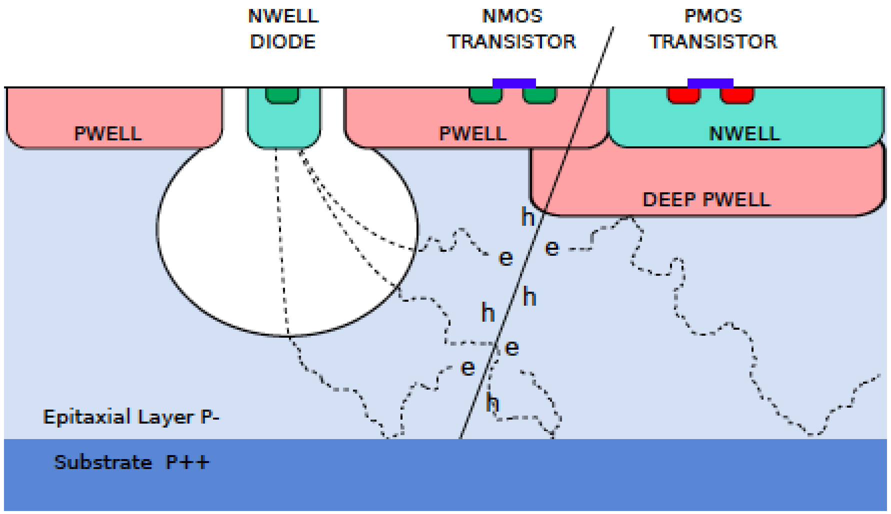
- high resistivity epi-layer
  - thickness 18-40 µm
  - resistivity 1-6 k Ω×cm

- “special” deep p-well layer to shield PMOS transistors (allows in-pixel truly CMOS circuitry)

- Possibility to build single-die circuit larger than reticle size

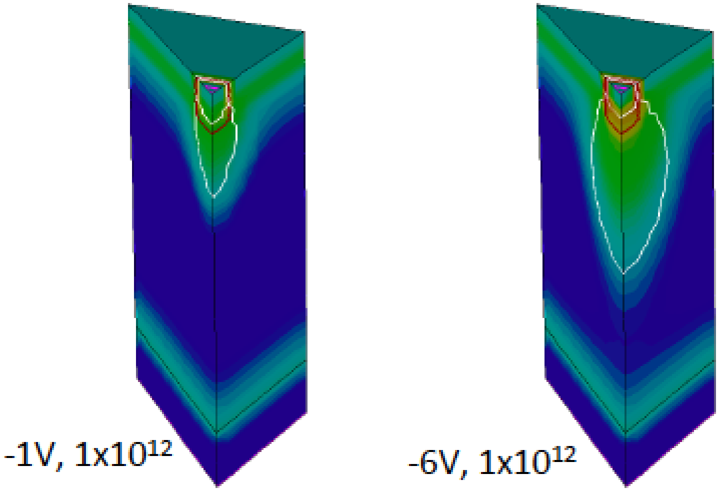
Radiation Resistance (<10^{13} neq/cm^{2}, <10kGy) and charge collection time (> ≈ microseconds) do for the moment not allow application in high rate environments of ATLAS, CMS, LHCb.

But ! Stay tuned for developments in the near future.



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

TCAD simulation of total diode reverse bias (*ALICE ITS Upgrade TDR*)



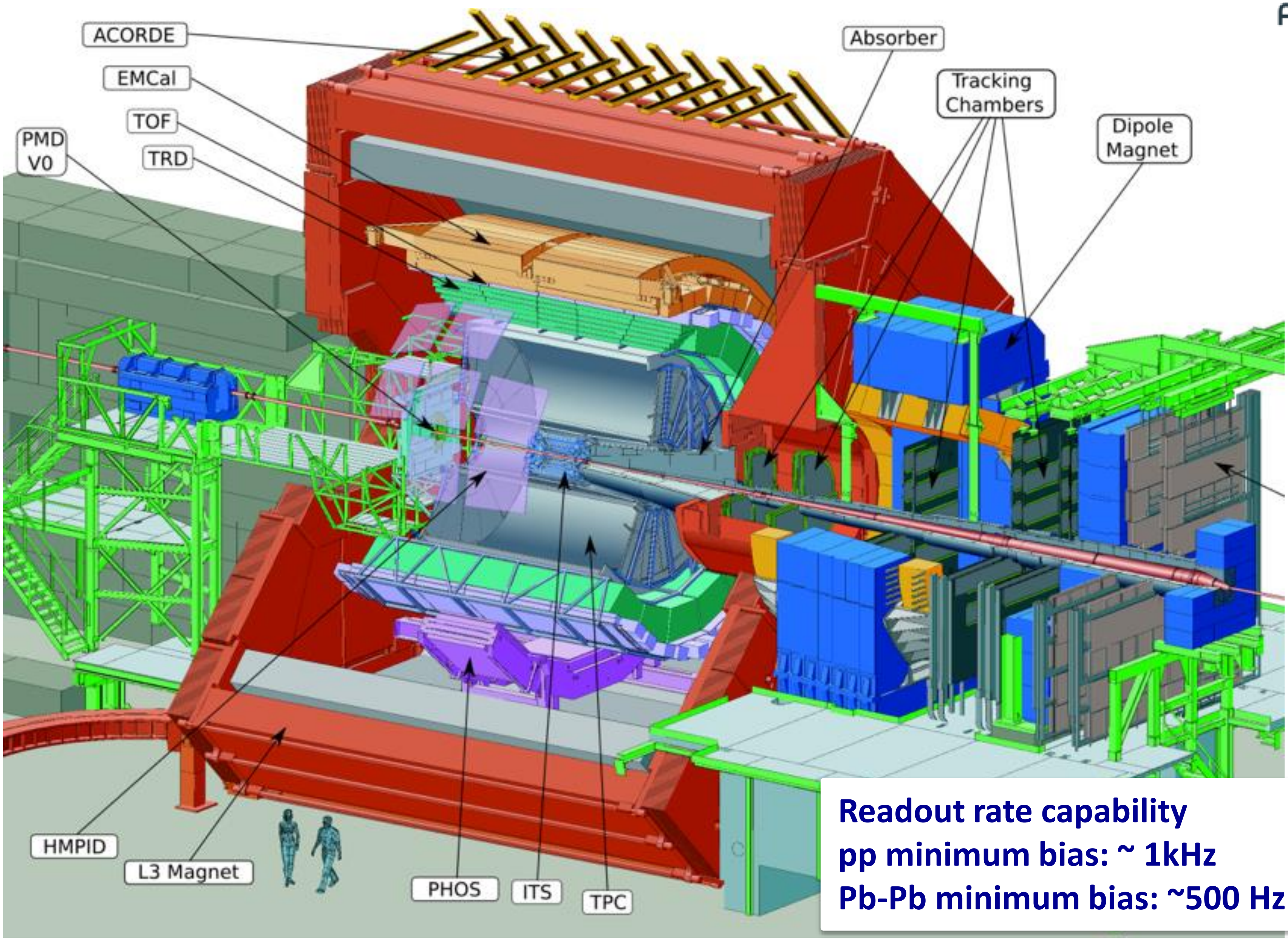
-1V, 1x10^{12}

-6V, 1x10^{12}

diode 3µm x 3µm square n-well with 0.5µm spacing to p-well white line: boundaries of depletion region

The ALICE Experiment upgrade

The Current ALICE Detector



Readout rate capability
pp minimum bias: ~ 1kHz
Pb-Pb minimum bias: ~500 Hz

New ITS Design goals

1. Improve impact parameter resolution by a factor of ~3

- Get closer to IP (position of first layer): 39mm ➡ 22mm
- Reduce material budget: X/X_0 /layer: ~1.14% ➡ ~ 0.3% (for inner layers)
- Reduce pixel size
    - currently 50μm x 425μm

      monolithic pixels ➡ O(20μm x 20μm),

2. Improve tracking efficiency and p_T resolution at low p_T

- Increase granularity: 6 layers ➡ 7 layers , reduce pixel size

3. Fast readout

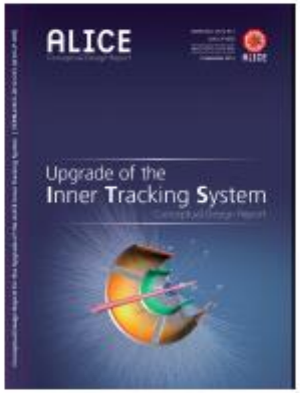
- readout of Pb-Pb interactions at > 50 kHz and pp interactions at ~ 1 MHz

4. Fast insertion/removal for yearly maintenance

- possibility to replace non functioning detector modules during yearly shutdown

New ITS Layout

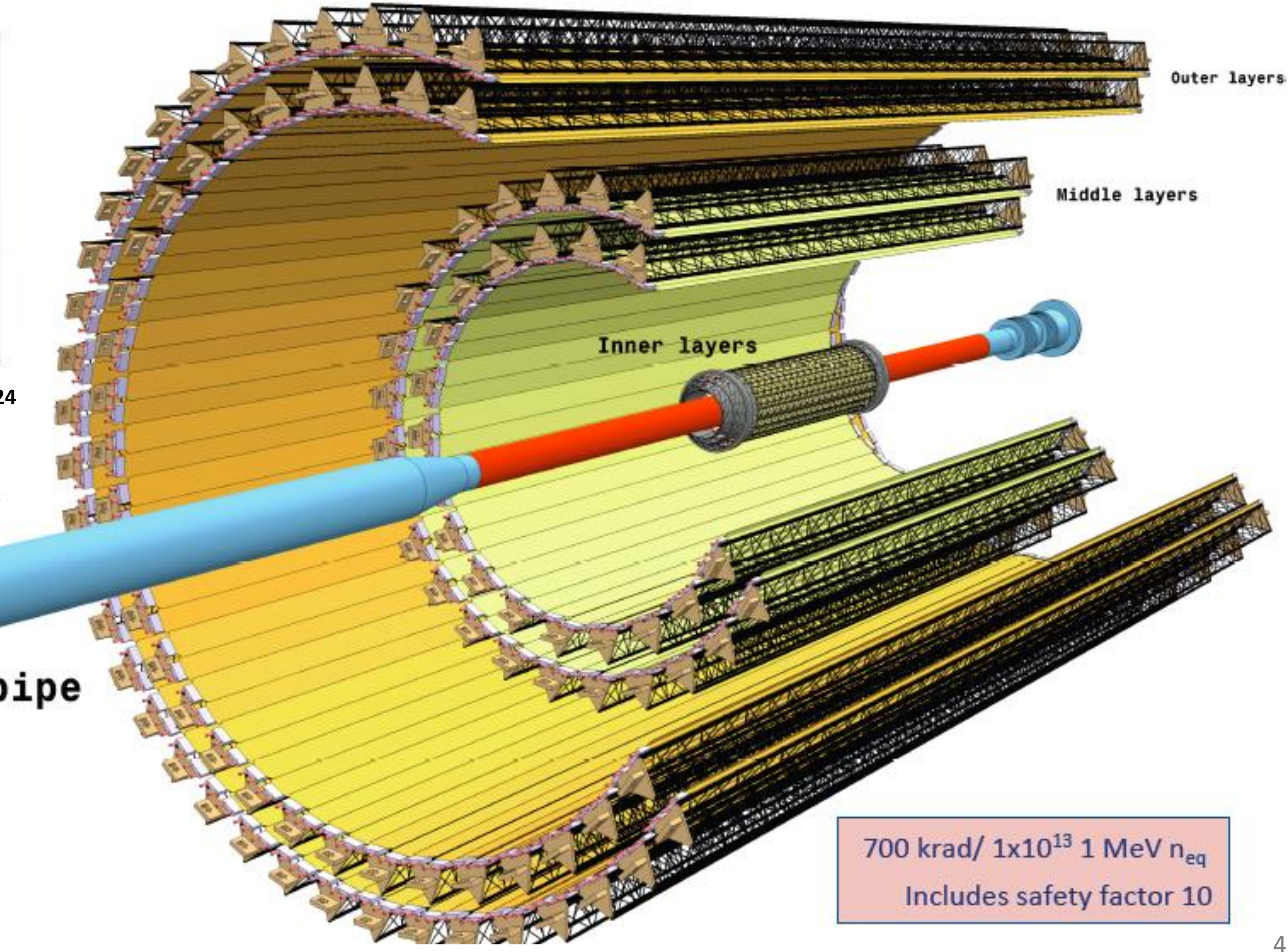
25 G-pixel camera
(10.3 m^2)


ALICE

Upgrade of the
Inner Tracking System

ITS TDR CERN-LHCC-2013-024

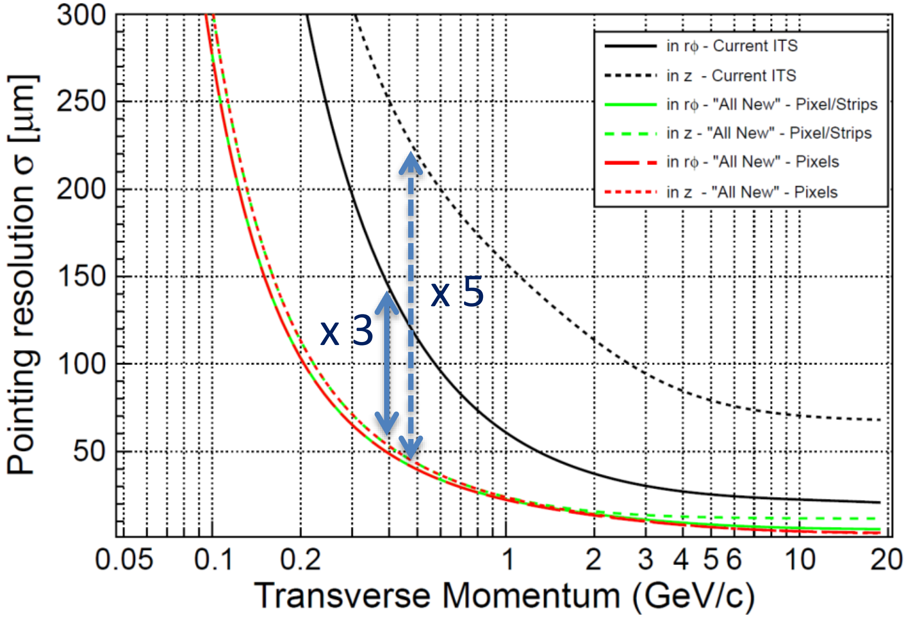
7 layers of MAPS

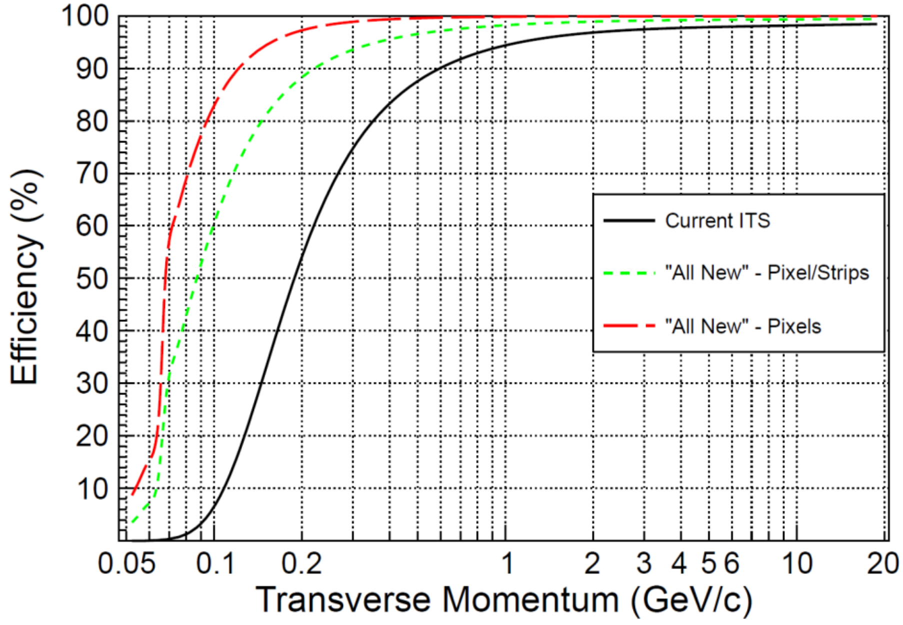


Radial coverage
22 – 406 mm

700 krad/ 1x10^{13} 1 MeV n_{eq}
Includes safety factor 10

Improvement of impact parameter resolution and tracking efficiency





Simulation layout

7 pixel layers

- Resolutions: $\sigma_{r\phi} = 4\ \mu m$, $\sigma_z = 4\ \mu m$ for all layers
- Material budget: $X/X_0 = 0.3\%$ for all layers

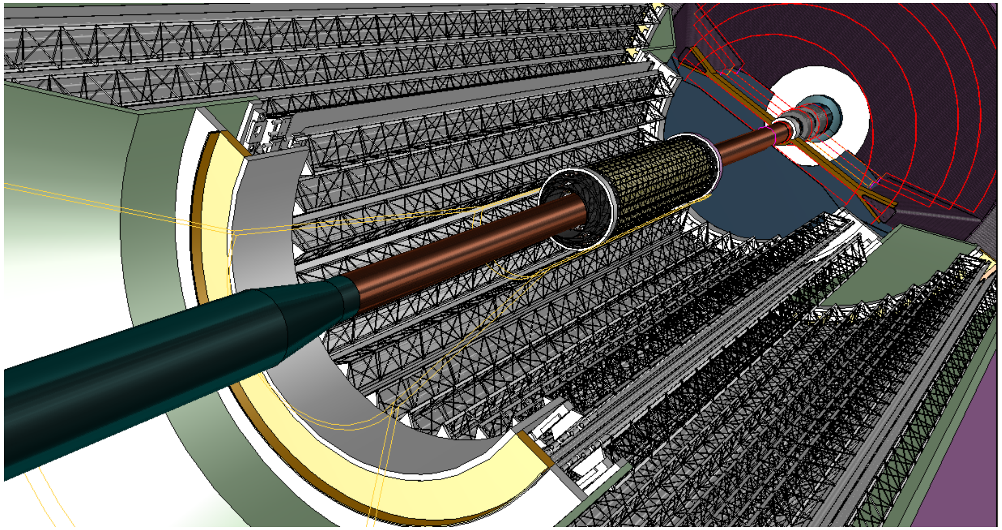
radial positions (cm):

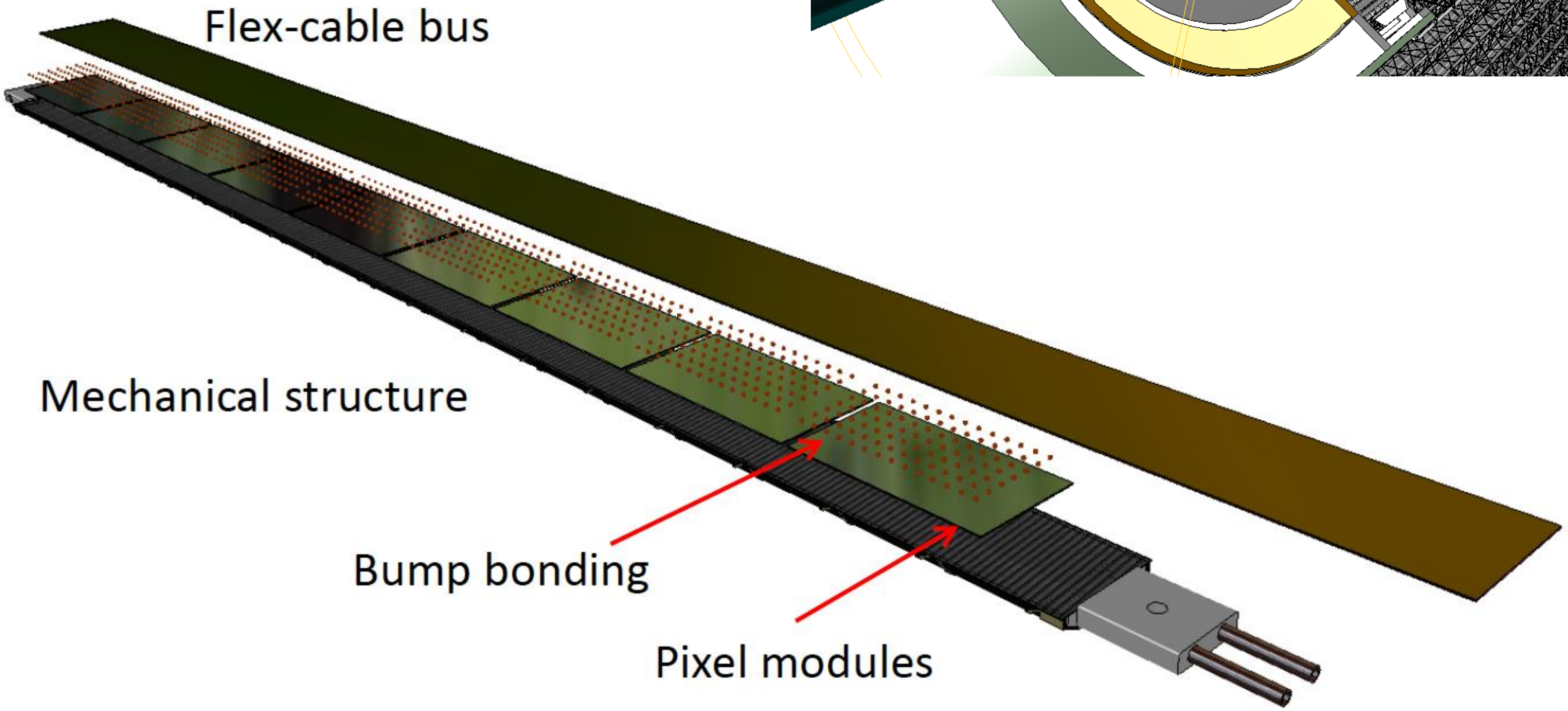
2.2, 2.8, 3.6, 20, 22, 41, 43

New ITS (baseline)

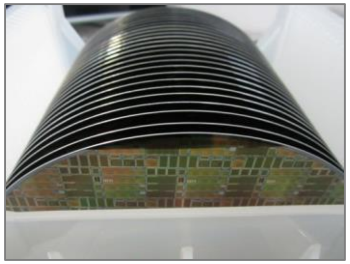
Inner Barrel: 3 layers
Outer Barrel: 4 layers

Detector module (Stave) consists of
- Carbon fiber mechanical support
- Cooling unit
- Polyimide printed circuit board
- Silicon chips (CMOS sensors)



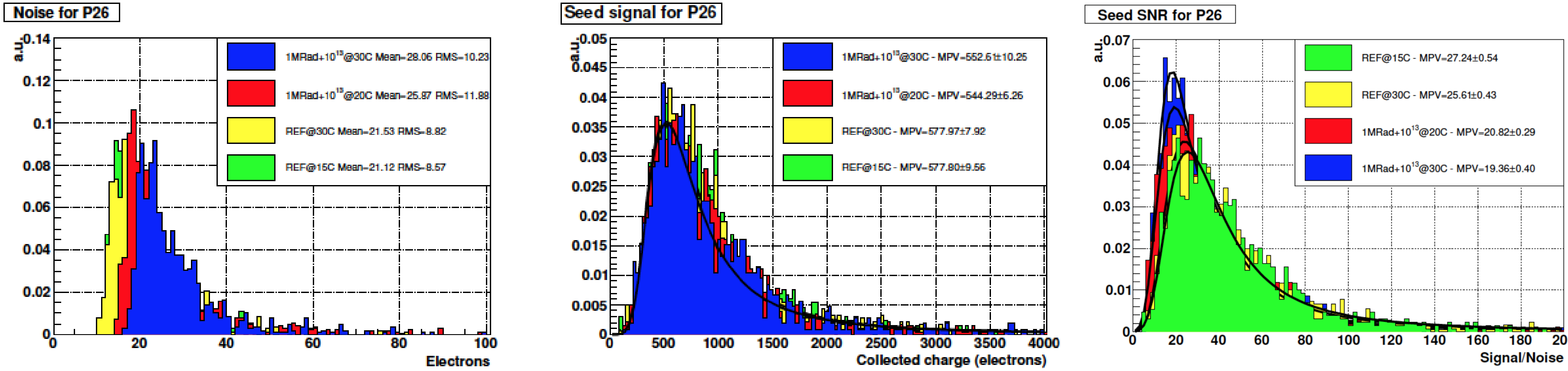


Pixel chip - R&D with TowerJazz technology



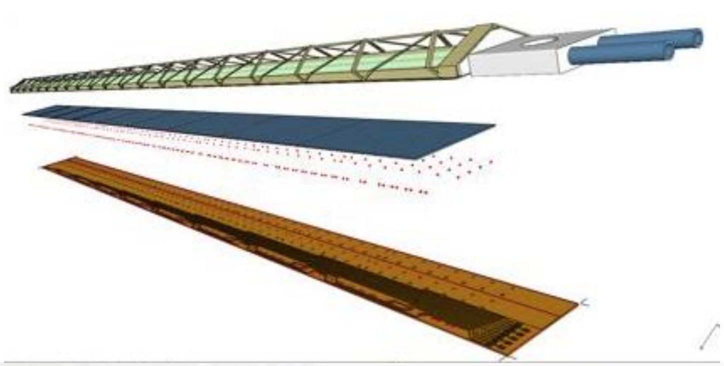
- R&D with TowerJazz CIS process in 2011-2013
- What has been established so far
  - Adequate radiation hardness
  - Excellent charge collection efficiency for pixel O(20-30)μm
  - Excellent detection efficiency
  - Prototypes of different readout architectures have being built and fully characterized

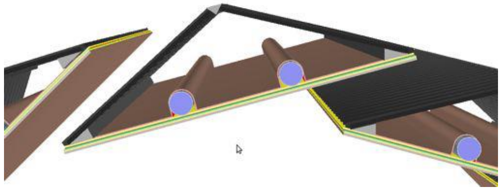
Example of experimental results

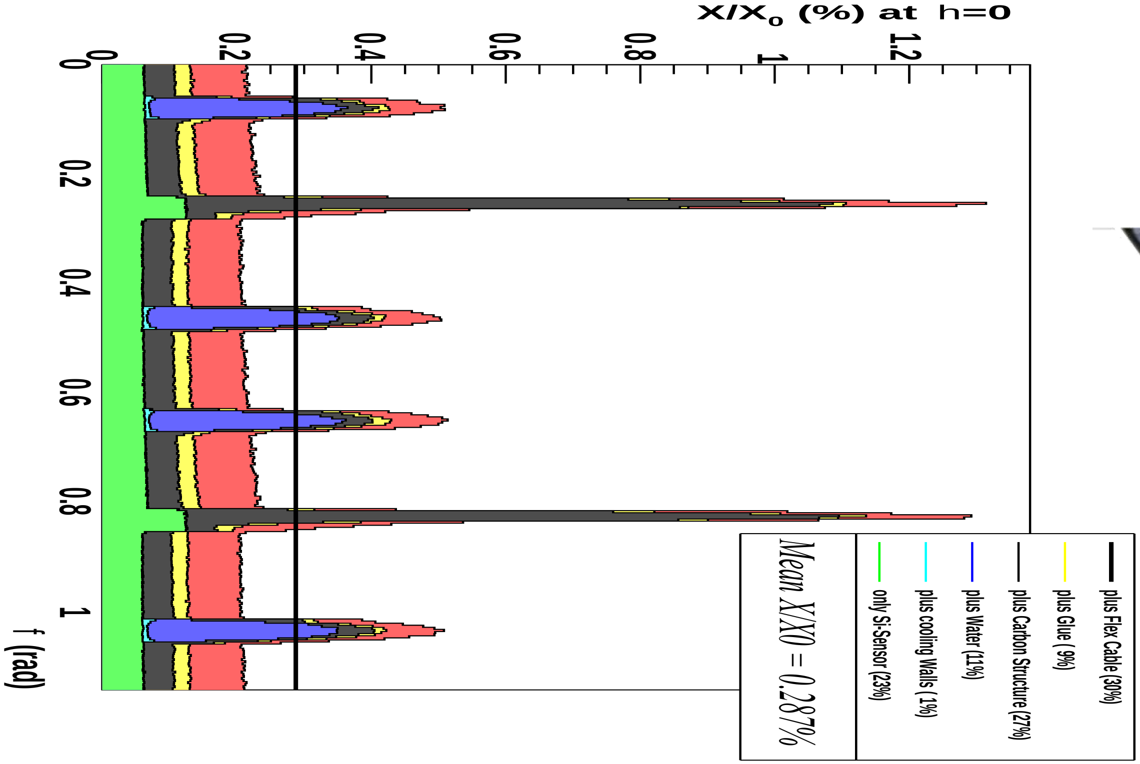


MIMOSA-32ter (IPHC), test-beam results

Inner Barrel Detector Stave







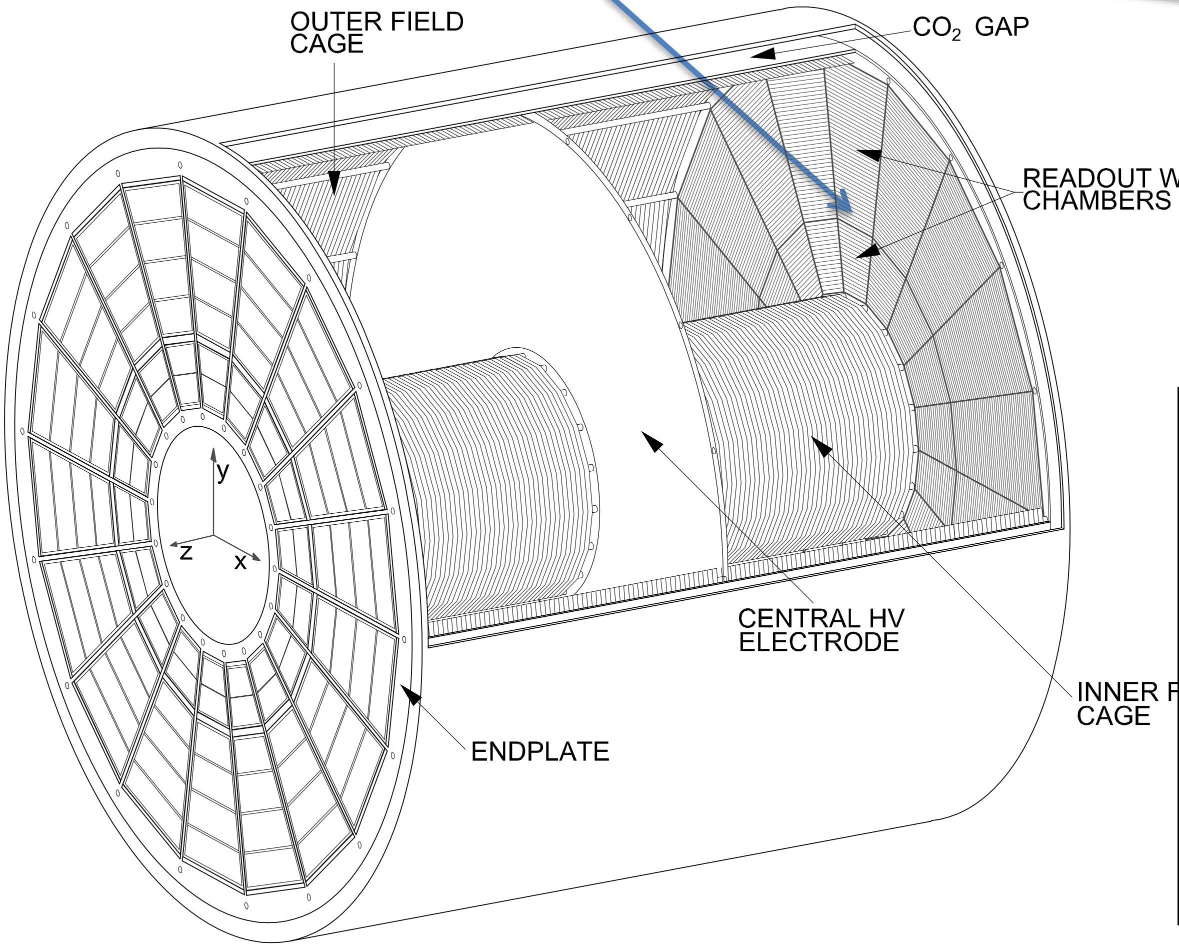
MECHANICS &COOLING

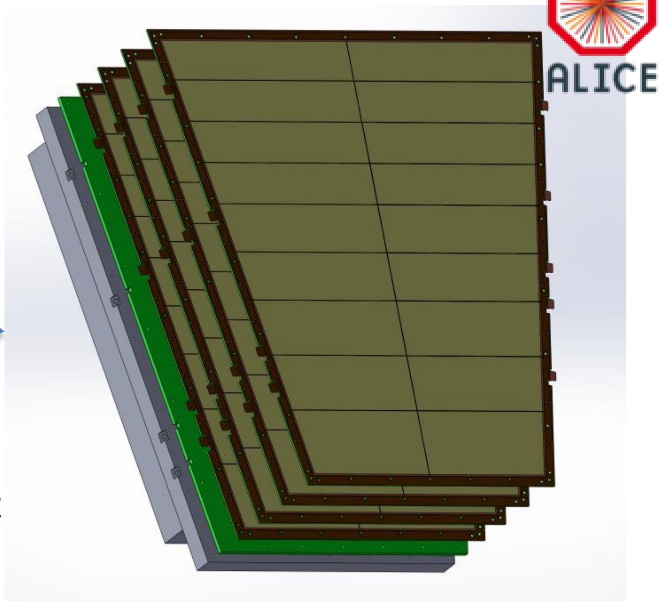
- ✓ Design optimization for material budget reduction

Total weight
1.4 grams

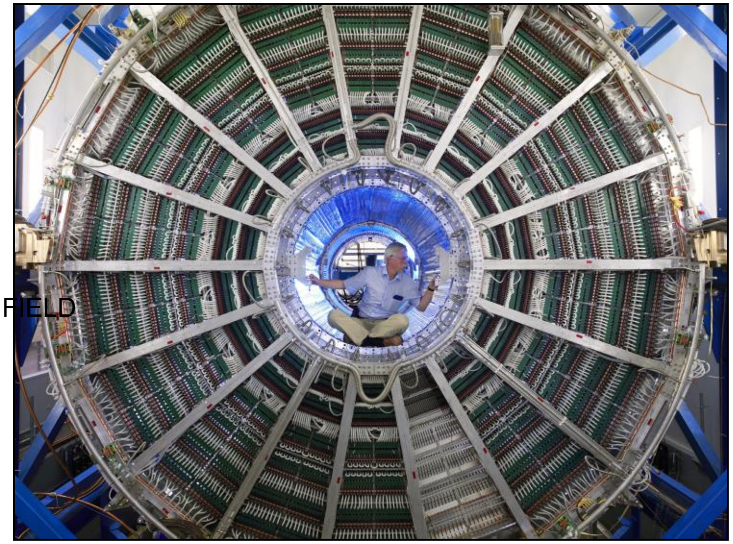
TPC Upgrade with GEMs

Replace wire chambers
With quadruple-GEM chambers



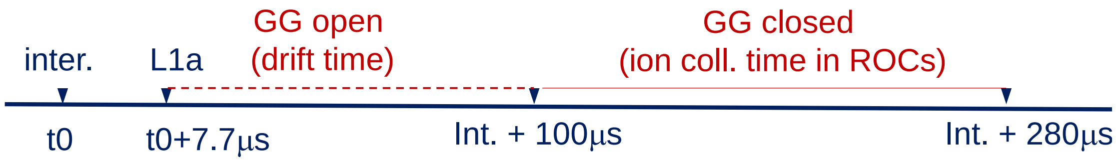


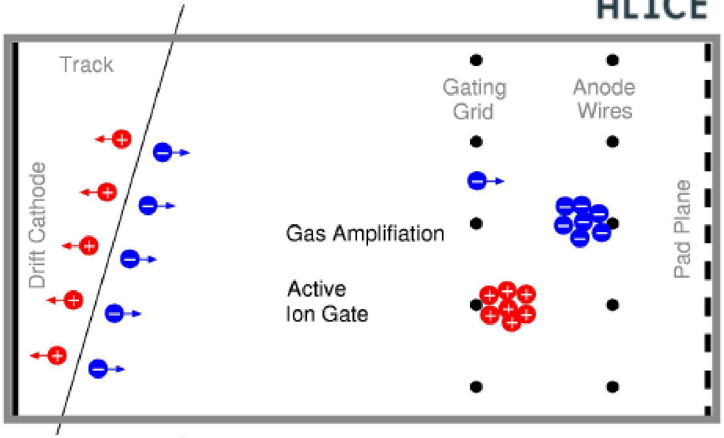
Exploded view of a GEM IROC



TPC upgrade – Why?

ROC ion feedback (λ_{int} and $\lambda_{readout}$ dependent)

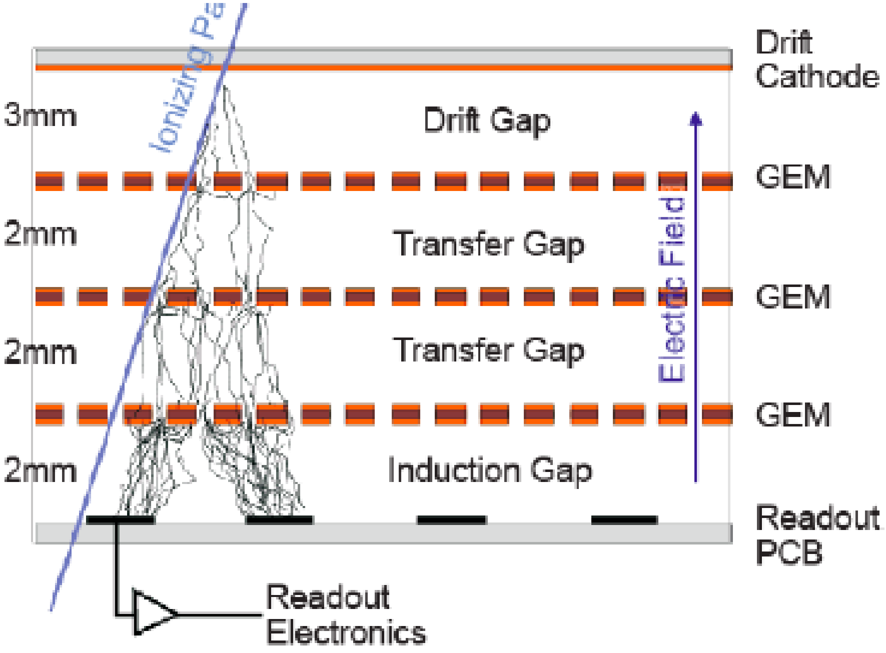




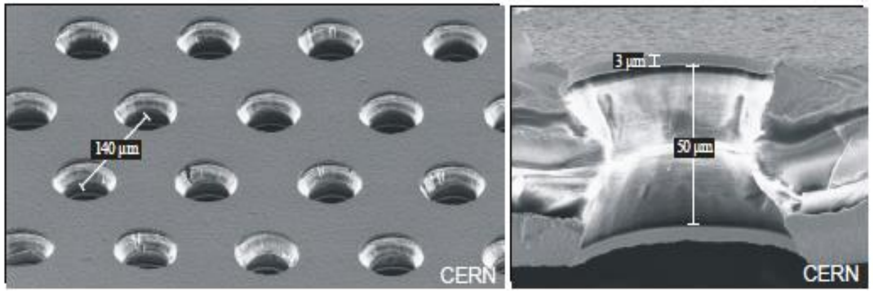
- Space charge (no ion feedback from triggering interaction)
  - GG open [t0, t0+100us], t0 ≡ interaction that triggers TPC
  - GG closed [t0+100us, t0+280us]
  - Effective dead time ~ 280us ➡ max readout rate ~3.5 kHz
  - Maximum distortions for λ_{int} =50kHz and L1=3.5kHz: Δr ~1.2mm (STAR TPC distorsions ~1cm)
- Space charge for continuous readout (GG always open)
  - gain ~6x10^3
  - 20% ion feedback if GG always open ➡ ion feedback ~10^3 x ions generated in drift volume
  - Max distortions for 50kHz ~100cm

MWPC not compatible with
50 kHZ operation

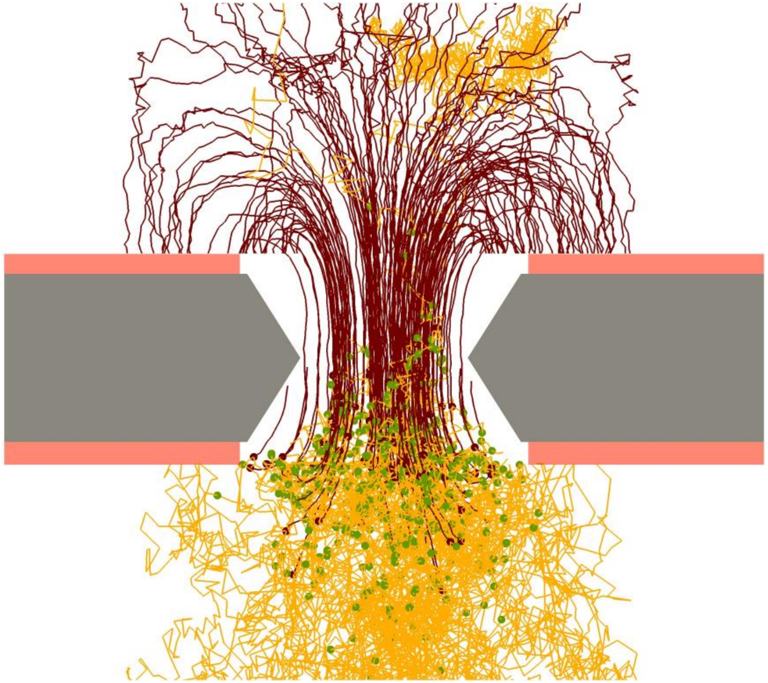
Triple-GEM principle of operation



GEMs are made of a copper-kapton-copper sandwich, with holes etched into it



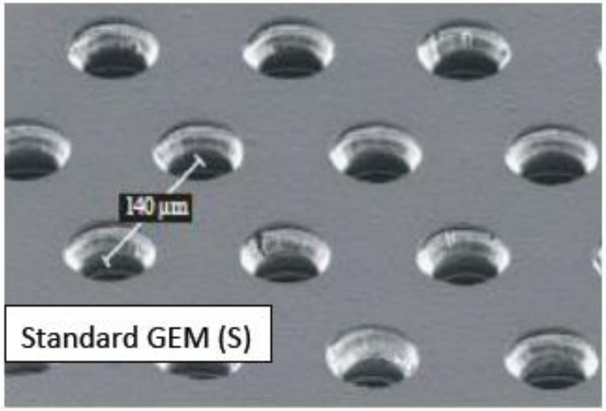
Electron microscope photograph of a GEM foil

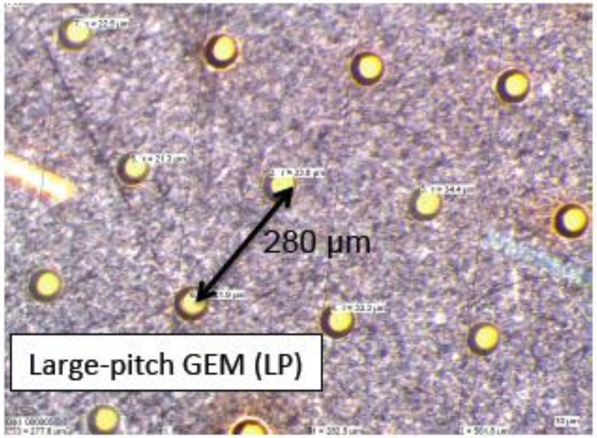


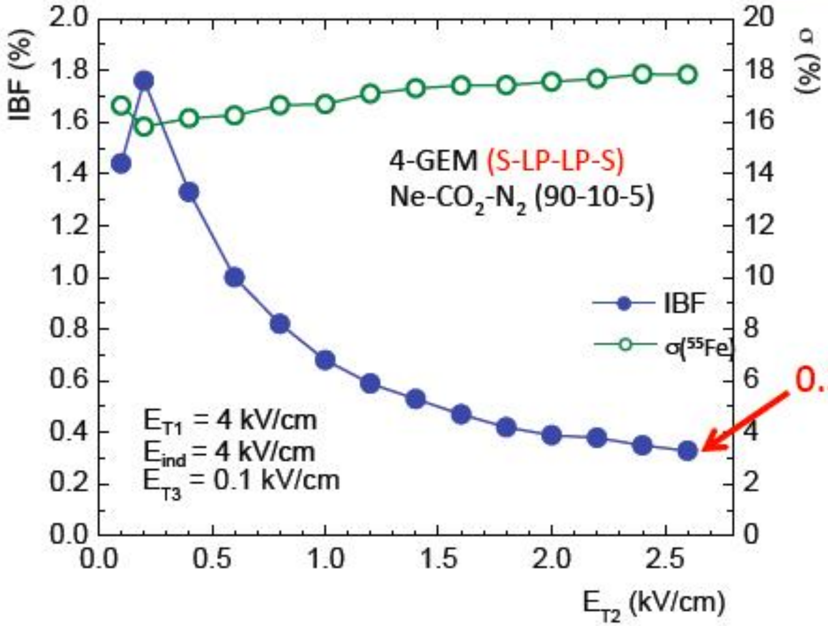
- Fast electron signal (polarity!)
- no “ion tail”
- No “coupling to other electrods”

➔ Gas gain about a factor 3 lower than in MWPC

R&D status with quadruple GEMs



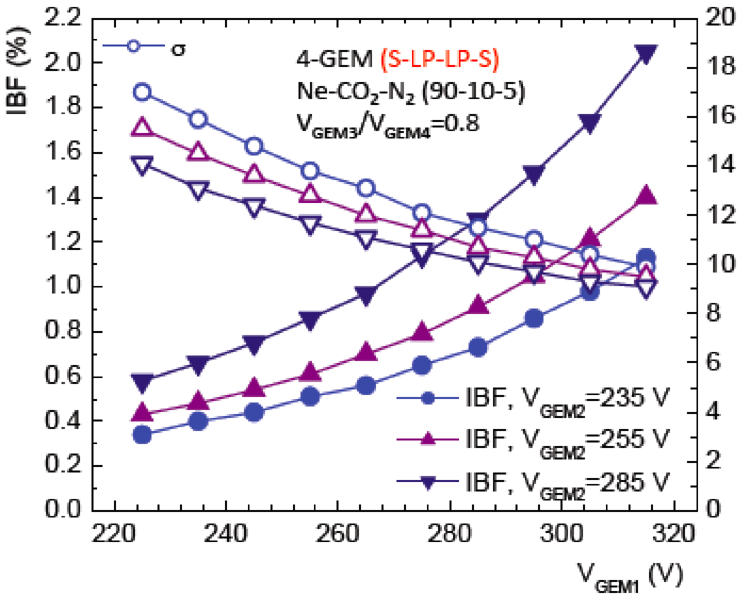


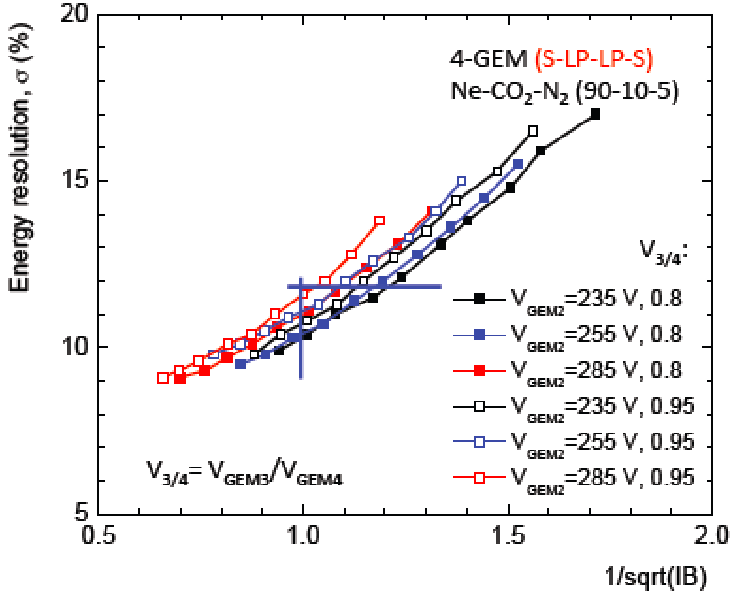


0.33%

- further reduction of IBF in 4-GEM system with large-pitch GEMs (S-LP-LP-S)
- consideration of energy resolution is important: dE/dx performance requires σ(^{55}Fe) ≤ 12%

further optimization: IBF vs. energy resolution

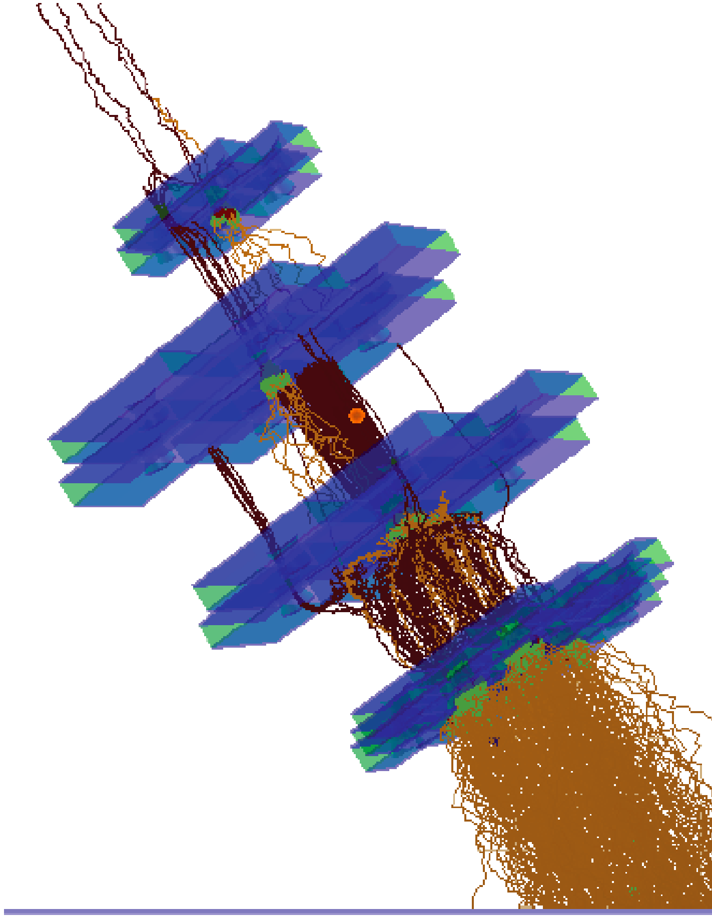


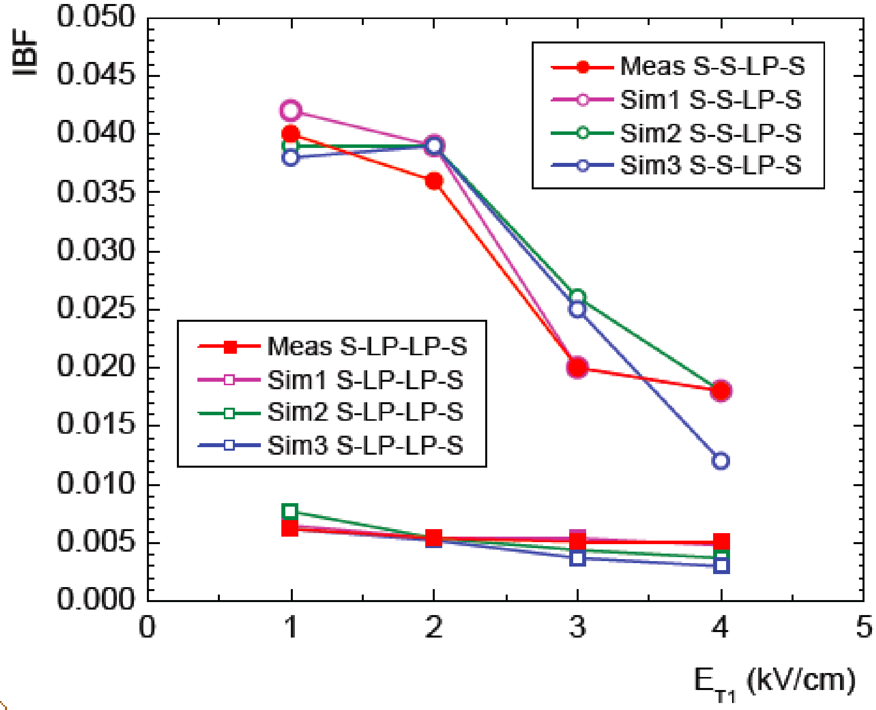


- Comprehensive voltage scan establishes operational point with IBF < 1% and energy resolution σ(^{55}Fe) < 12%

→ All performance studies are for IBF = 1% at gain = 2000, i.e. ε = 20

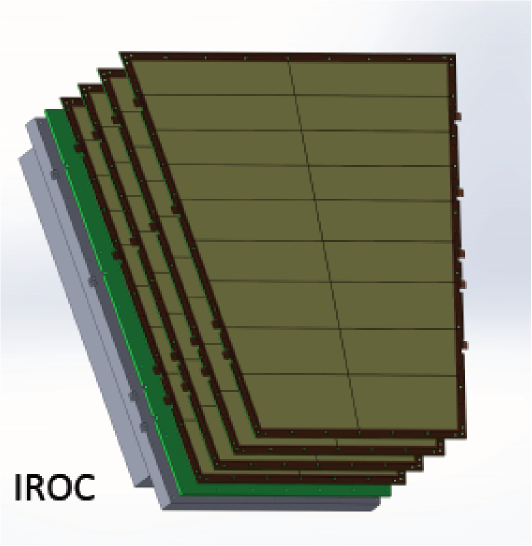
simulation: IBF in 4-GEM systems

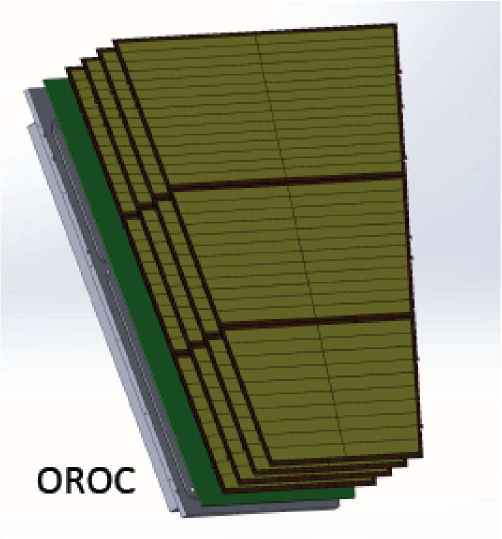




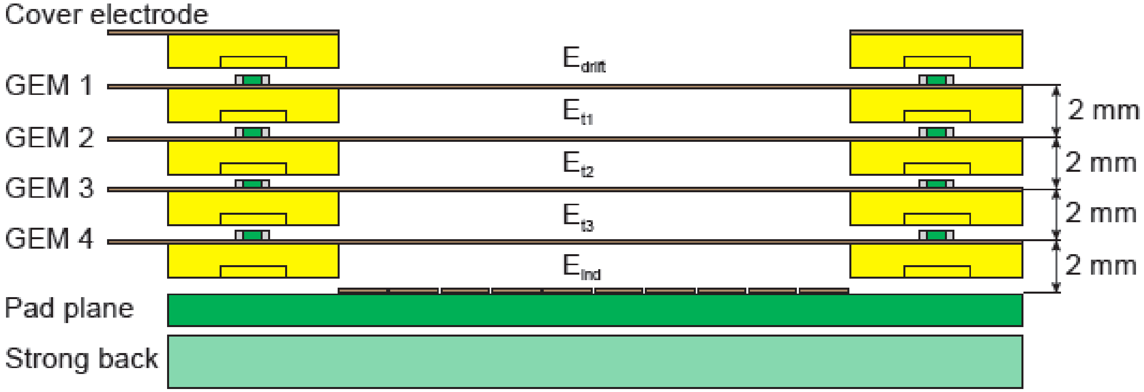
- IBF quantitatively well described by simulation based on Garfield++

TDR baseline solution: 4-GEM system



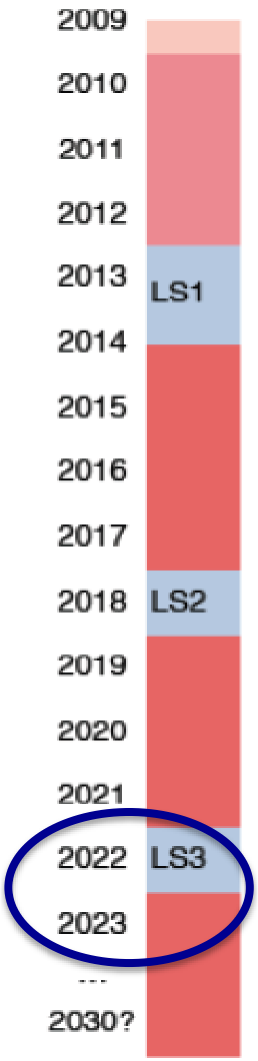


- large-size single-mask GEM foils
- one (three) per layer in IROC (OROC)



The ATLAS Experiment upgrade

ATLAS Upgrade Plan



$L_{inst} \simeq 5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ ($\mu \simeq 140$) w. level.
$\simeq 6\text{-}7 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ ($\mu \simeq 192$) no level.
$\int L_{inst} \simeq 3000\ \mathrm{fb^{-1}}$

- All new Tracking Detector
- Calorimeter electronics upgrades
- Upgrade muon trigger system
- Possible Level-1 track trigger
- Possible changes to the forward calorimeters

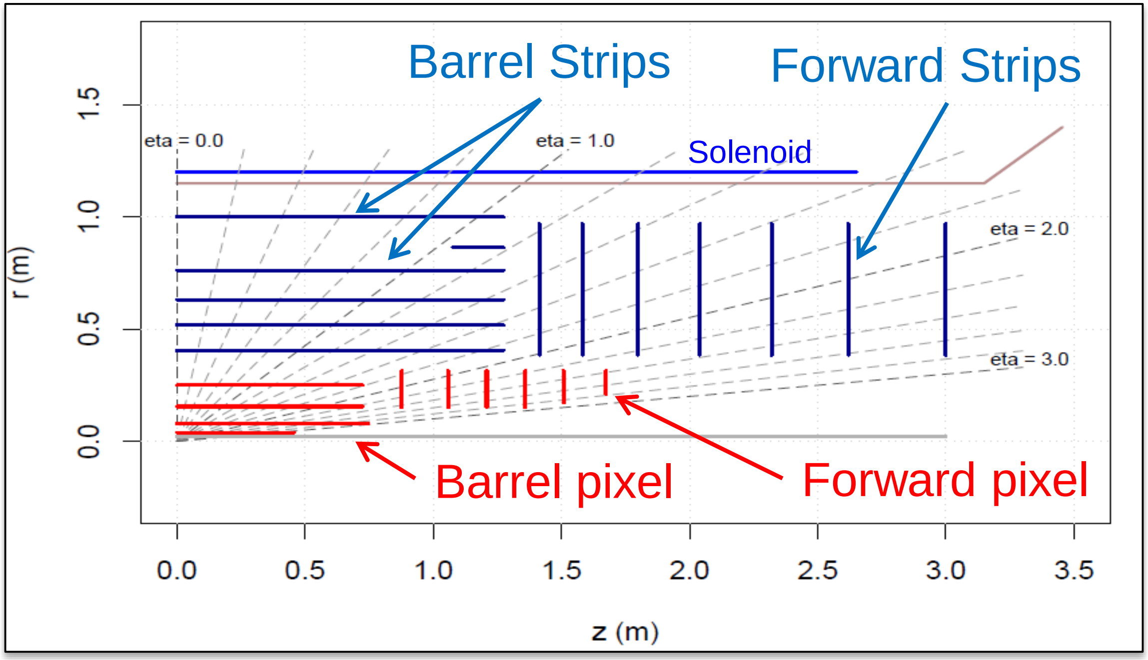
Phase-2

Prepare for $\langle\mu\rangle = 200$
Replace Inner Tracker
New L0/L1 trigger scheme
Upgrade muon/calorimeter electronics

New Tracking detector

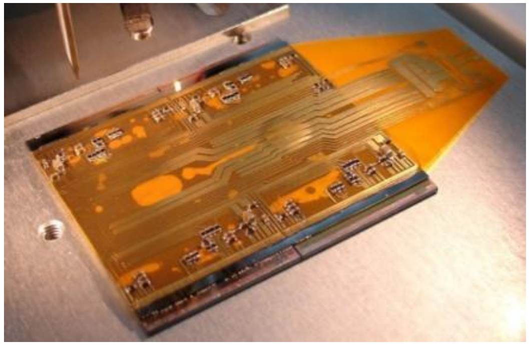
- Current Inner Detector (ID)
  - Designed to operate for 10 years at L=1x10^{34} cm^{-2}s^{-1} with <μ>=23, @25ns, L1=100kHz
- Limiting factors at HL-LHC
  - Bandwidth saturation (Pixels, SCT)
  - Too high occupancies (TRT, SCT)
  - Radiation damage (Pixels (SCT) designed for 400 (700) fb^{-1})

LoI layout new (all Si) ATLAS Inner Tracker for HL-LHC



Microstrip Stave Prototype

Quad Pixel Module Prototype



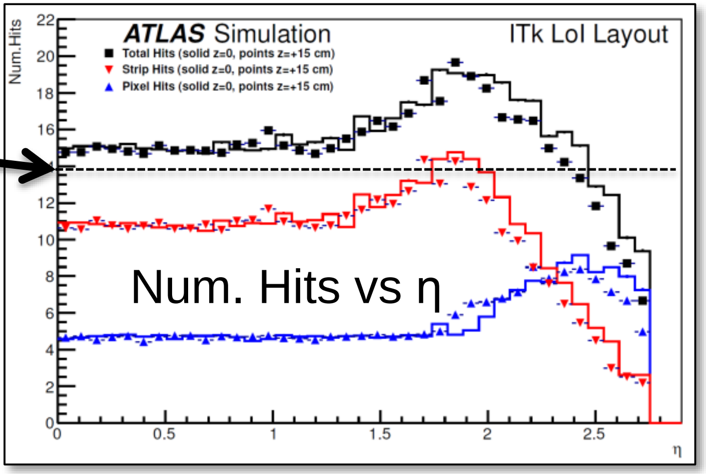
New 130nm prototype strip ASICs in production

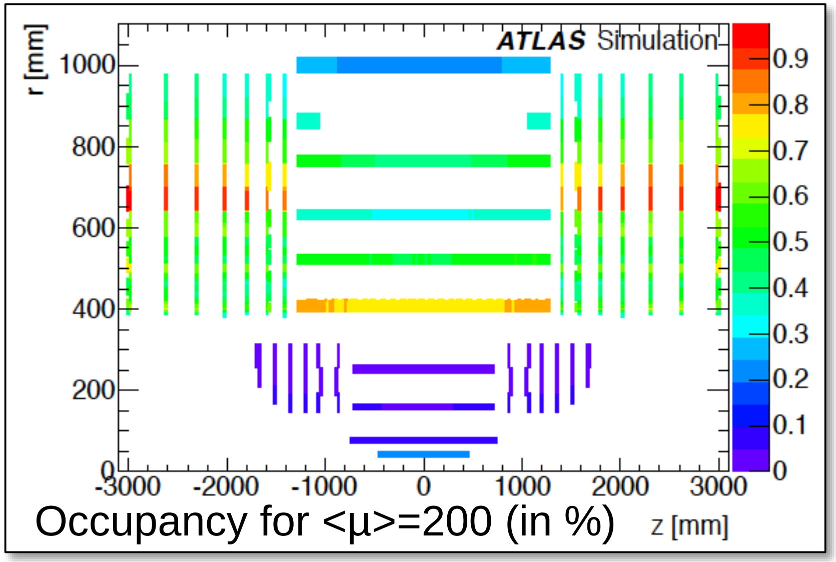
- incorporates L0/L1 logic

Sensors compatible with 256 channel ASIC being delivered

New Tracking detector cont.

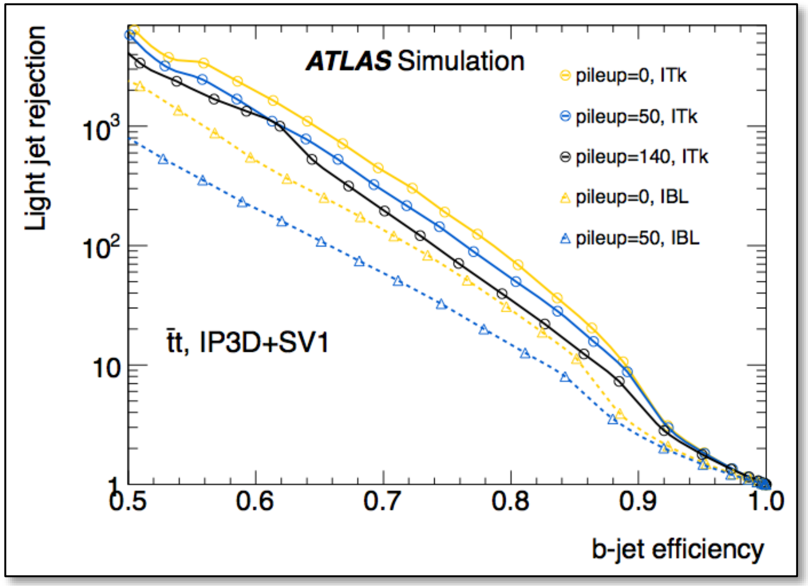
- Studies with LOI layout
  - Robust tracking (14 layers)
  - Occupancy <1% for <μ>=200
  - Reduced material wrt current ID
  - Comparable / better tracking performance at <μ>=200 as current ID at <μ>=0
- Prototypes tested to 2x HL-LHC flux
- Solid baseline design
  - working on optimisation





Occupancy for <μ>=200 (in %)

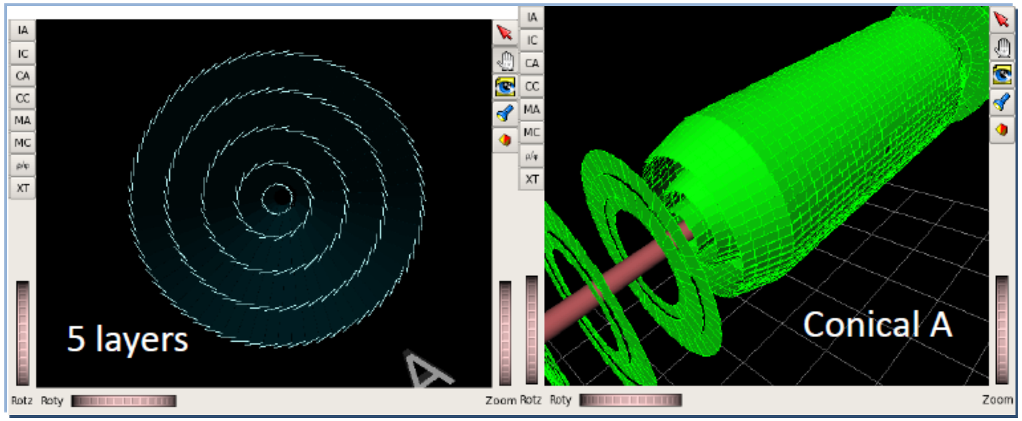
Light jet rejection, ID (w/IBL) and ITk



New Tracking detector cont.

- Many topics still to be addressed
  - How can the layout still be optimised?
  - Can all assemblies/components be qualified to the required radiation hardness?
  - How critical is the luminous beam-spot extent in z?
  - Are there physics reasons to significantly extent the coverage in η?
  - Cost / material optimisations with current technologies?
  - Alternative technologies?

- Addressing these questions now is very timely
  - note TDR of current ID was written in 1997 …

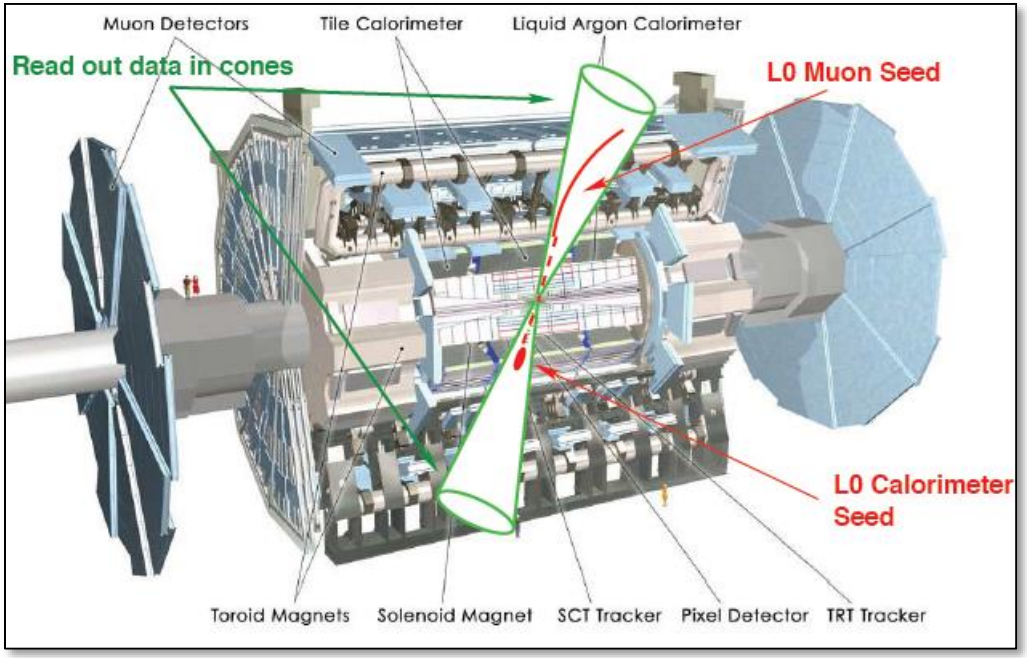


Alternative layouts being considered which include either a further pixel layer or inclined pixel

L1Track Trigger

- Adding tracking information at Level-1 (L1)
  - Move part of High Level Trigger (HLT) reconstruction into L1
  - Goal: keep thresholds on p_T of triggering leptons and L1 trigger rates low

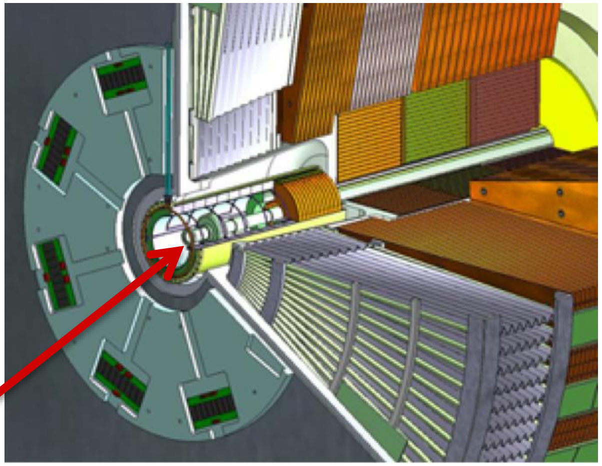
- Triggering sequence
  - L0 trigger (Calo/Muon) reduces rate within ~6 μs to $\gtrsim$ 500 kHz and defines RoIs
  - L1 track trigger extracts tracking info inside RoIs from detector FEs



- Challenge
  - Finish processing within the latency constraints

Calorimeter electronics

- Tile Calorimeters
  - No change to detector needed
  - Full replacement of FE and BE electronics
    - New read-out architecture: Full digitisation of data at 40MHz and transmission to off-detector system, digital information to L1/L0 trigger
- LAr Calorimeter
  - Replace FE and BE electronics
    - Aging, radiation limits
    - 40 MHz digitisation, inputs to L0/L1
    - Natural evolution of Phase-I trigger boards



  - Replace HEC cold preamps if required
    - i.e. if significant degradation in performance
  - Replace Forward calorimeter (FCal) if required
    - Install new sFCAL in cryostat or miniFCAL in front of cryostat if significant degradation in current FCAL

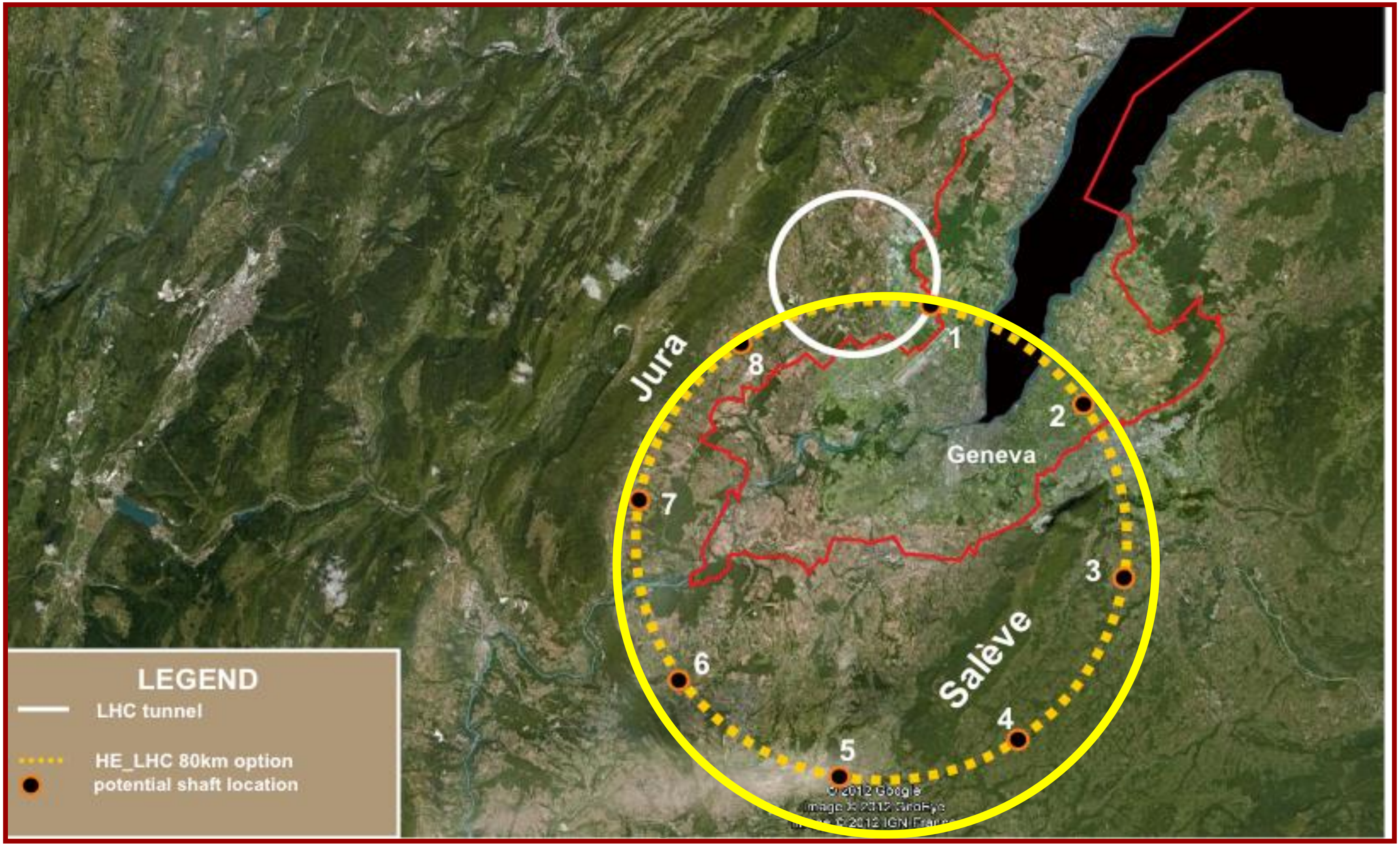
Physics at a 100 TeV Hadron Collider

Exploration + Higgs as a tool for discovery

What are the driving requirements for detector design ?

Future Circular Hadron Collider (FCC-hh)

LHC 14TeV 27km
FCC 100TeV 100km
→ Dipole Magnets from 8T to 16T



MDI Parameters

L* [25, 40]m or larger

(distance from IP to first magnet, space for experiment)

L_{peak} [$5x10^{34}$, $30x10^{34}$] $cm^{-2}s^{-1}$

→ **N_{pileup} [170, 1020] at 25ns**
→ **N_{pileup} [34, 204] at 5ns**

L_{int} [3, 30] ab^{-1}

Physics at a 100 TeV Hadron Collider

Exploration + Higgs as a tool for discovery

Numerous physics opportunities with a large number of possible measurements.

How to specify detectors for such a machine ?

ATLAS and CMS are general purpose detectors that were benchmarked with the ‘hypothetical’ Higgs in different mass regions with tracking up to η=2.5.

The Higgs is also key benchmark for the FCC detectors, with highly forward boosted features (100TeV, 125GeV Higgs)

FCC detectors must be ‘general general’ purpose detectors with very large η acceptance and extreme granularity.

Approximate Overall Needs

Tracking: Momentum resolution H15% at p_t=10TeV

Precision tracking (momentum spectroscopy) and Ecal up to η=4

Tracking and calorimetry for jets up to η=6.

12 λ_{in} calorimetry, 1-2% constant term.

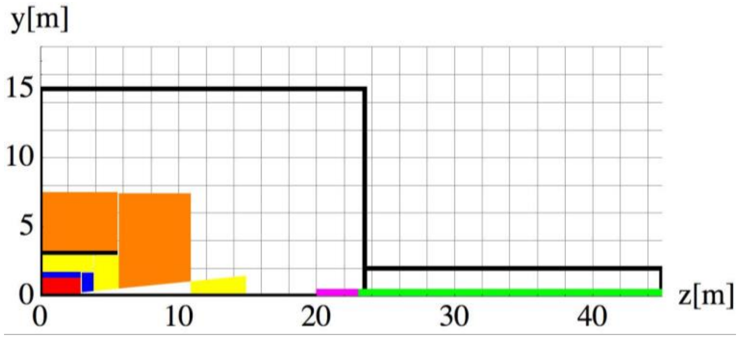
Calorimeter granularity of 0.05x0.05 or 0.025x0.025 to mitigate pileup and measure jet substructure and boosted objects.

B-tagging, timing for pileup rejection etc. …

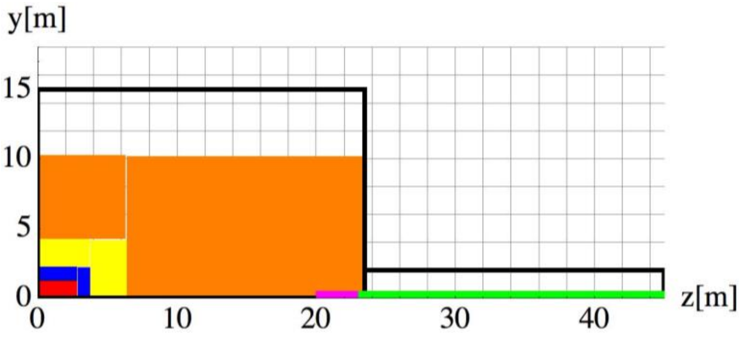
$$\frac{\Delta p_t}{p_t} \approx \frac{\sigma[m]\, p[\mathrm{GeV/c}]}{0.3\, B[T]\, L^2[m^2]} \sqrt{\frac{720}{N+4}}$$

Same momentum resolution for 7x Energy (14→ 100TeV):

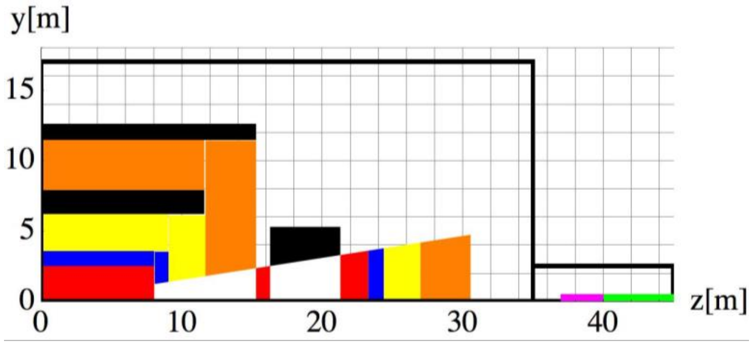
- 7x BL^2
- $\sigma/7$
- any combinations



CMS & ATLAS
@ LHC

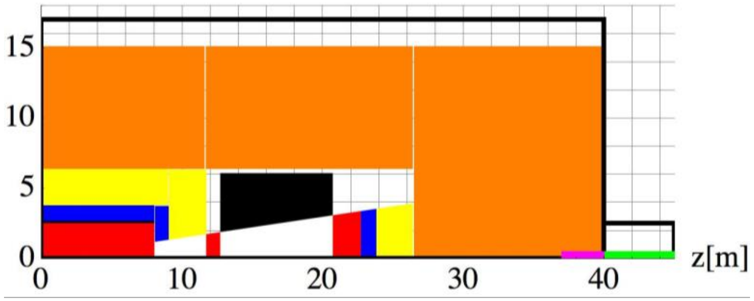


Future Circular Hadron Collider Detector Concepts



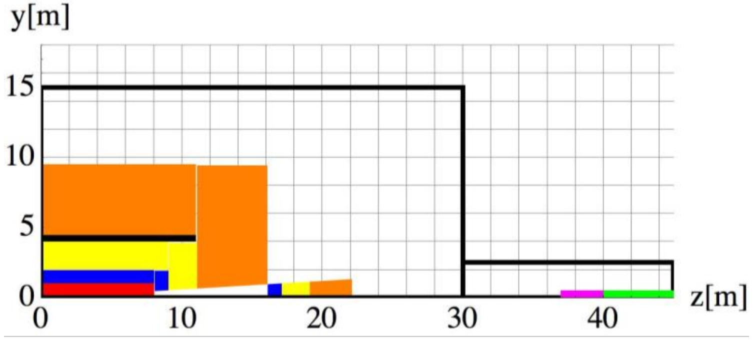
Twin Solenoid + Dipole, BL^2 scaled

Tracker r=2.5m p_t reso 15% at 10TeV
12 lambda ECAL+HCAL =1m+2.5m
Coil R=6m, 6T, Shielding Coil
Forward Dipole 10Tm



Toroid + Dipole, BL^2 scaled

Tracker r=2.5m p_t reso 15% at 10TeV
Thin Coil R= 2.5m, B= 4T
12 lambda ECAL+HCAL =1m+2.5m
Muon Toroid
Forward Dipole 10Tm



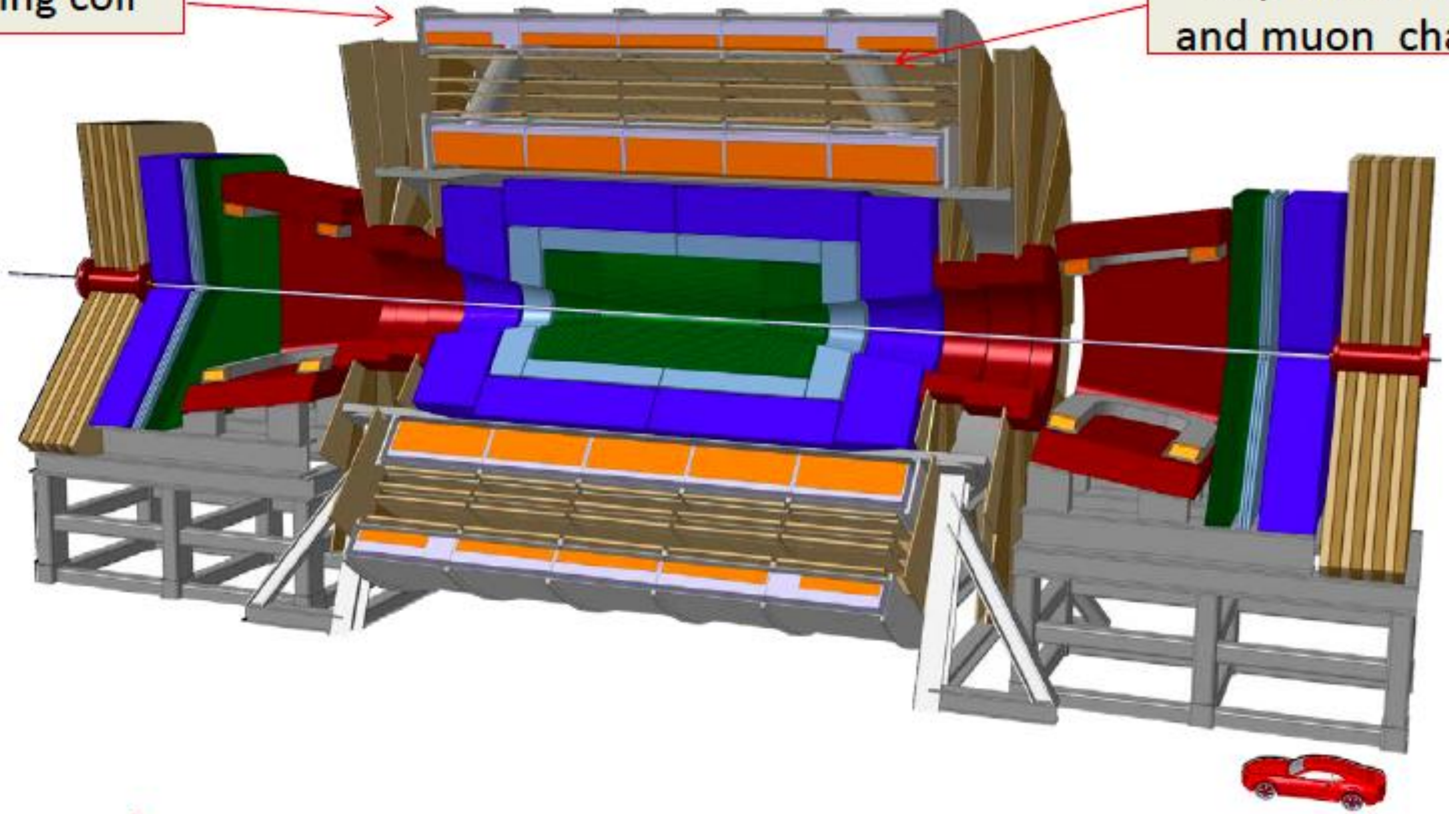
CMS+, resolution scaled

Tracker r=1.2m p_t reso 15% at 10TeV
12 lambda ECAL+HCAL =0.6m+2.2m
Coil R=4m
Iron Return Yoke
→ Extreme detector technology push

Tracker
Emcal
Hcal
Muon
Coil
TAS
Triplet

FCC 100TeV detectors

Future Circular Hadron Collider Detector Concepts



shielding coil

Gap filled with 3 T
and muon chambers

Twin Solenoid: 6 T, 12 m dia, 23 m long main solenoid + shielding coil

Important advantages:

- **Nice muon tracking space:** gap with ≈2-3 T for muon tracking in 4-5 layers.
- **Light:** shielding coil + structure ≈ 8 kt, much lighter than the iron yoke!

H. ten Kate et al.

Summary

Significant R&D is underway to develop detector technologies for the Phase I and Phase II upgrades of the LHC experiments.

Availability of 40MHz digitization on the frontend as well as large bandwidth data links and massive computing power allow to fully exploit HL-LHC luminosities of $5\text{x}10^{34}$ with up to 200 pileup events.

Radiation levels in excess of 10^{16} hadrons/cm^2 require novel silicon technologies.

High precision timing of the order of 10-20ps is investigated for pileup mitigation.

SiPMs are a game changer for readout of scintillators for calorimetry and tracking.

Monolithic silicon sensors are a game changer for low mass high precision tracking, presently adapted to radiation levels of 10^{13} hadrons/cm^2 and microsecond speed. Efforts to make them fast and radiation hard are ongoing.

In parallel, we (YOU !) have to start thinking about the next step on the energy frontier and related detector concepts !!