IMPACT OF THE INNOVATIONS IN SEMICONDUCTOR ADVANCED TECHNOLOGY ON THE TRACKING CONCEPTS IN FUNDAMENTAL RESEARCH

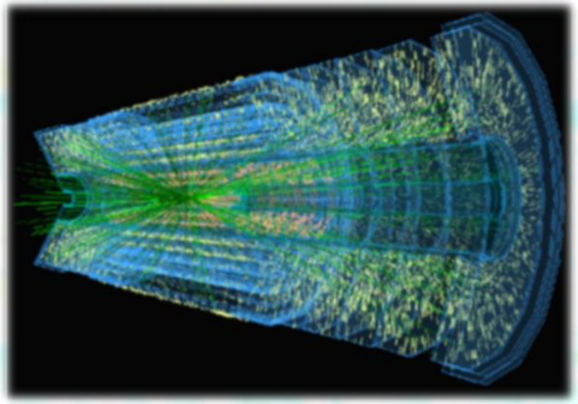
Birmingham Instrumentation Laboratory for Particle physics and Applications BILPA

UNIVERSITY OF BIRMINGHAM

Phil Allport

INFIERI Summer School, Huazhong University of Science and Technology

- **Introduction to Silicon Tracking Detectors**
- **Development of Silicon Detector Arrays in Particle Physics**
- **Overview of LHC Detector Upgrade Programme**
  - **Silicon Detectors for HL-LHC**
    - **Strip Detectors**
    - **Hybrid Pixel Detectors**
    - **Silicon Detectors for Calorimetry**
    - **Monolithic Active Pixel Sensors**
    - **Silicon Fast Timing Detectors**



- **Collider Physics Beyond the HL-LHC**
- **Example Applications of HL-LHC Technologies**
  - **Hadron Radiotherapy**
- **Conclusions**

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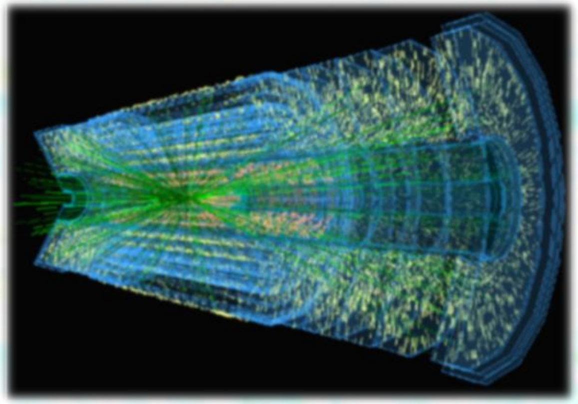
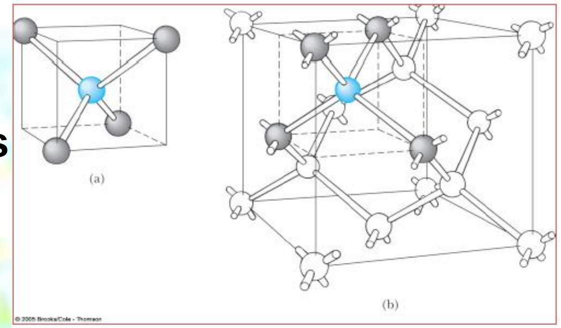


Silicon Tracking Detectors

- **The basic building block of all silicon detectors is the diode.**
- **p-type material (doped heavily with acceptor, trivalent atoms) is brought into contact with n-type material (doped with pentavalent atoms)**



- **In equilibrium, the excess carriers, holes and electrons, diffuse across the boundary leaving negative and positive fixed charge regions**
- **The induced field opposes further diffusion leaving a region depleted of free carriers**
- **Find the depletion region thickness from solving**

$$\frac{d^2\varphi}{dx^2} = -\frac{\rho}{\varepsilon_r \varepsilon_0} \quad \textbf{with } E(-\mathrm{d_p}) = E(+\mathrm{d_n}) = 0$$

- **Further depletion is achieved through an external voltage**

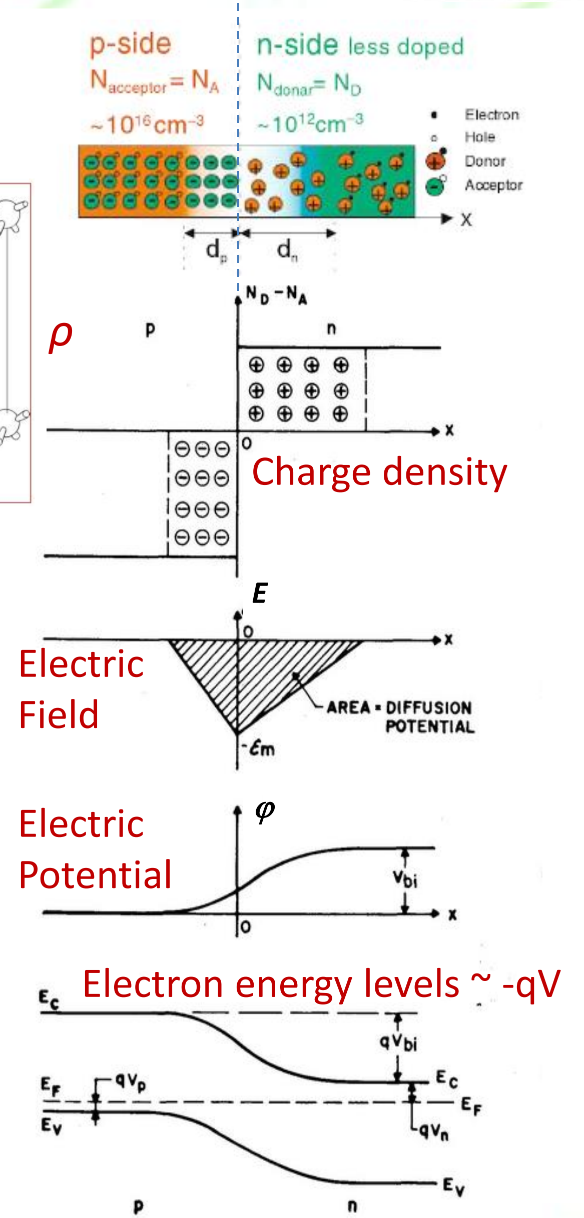
$$d(\boldsymbol{V}) = \sqrt{\frac{2\varepsilon_r \varepsilon_0 (N_A + N_D)}{q N_A N_D} (\boldsymbol{V} - V_{bi})}$$

- **Find when** $N_{A,D} \gg N_{D,A}$

$$d(\boldsymbol{V}) \approx \sqrt{2\varepsilon_r \varepsilon_0 \rho_{n,p} \mu_{e,h} (\boldsymbol{V} - V_{bi})}$$

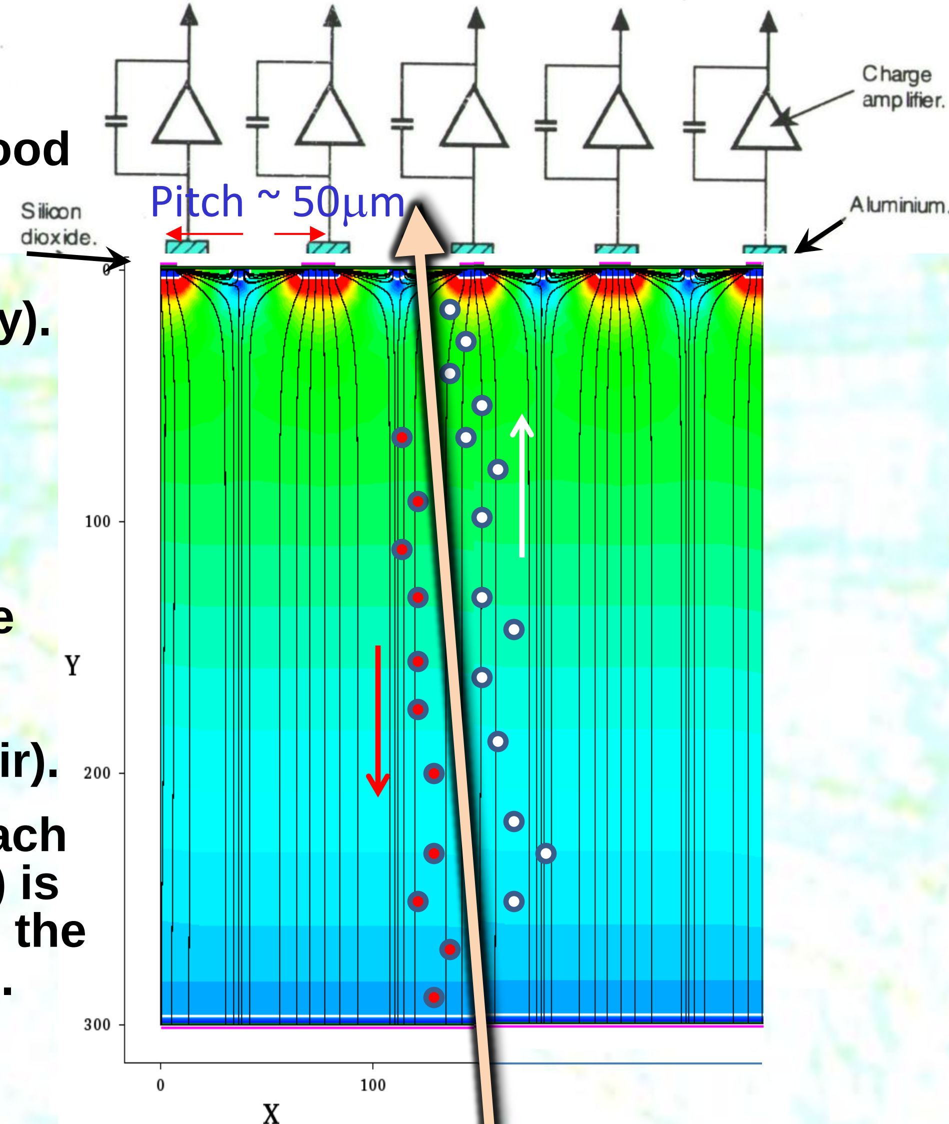
$\rho_{n,p}$ **resistivity**

$\mu_{e,h}$ **mobility**



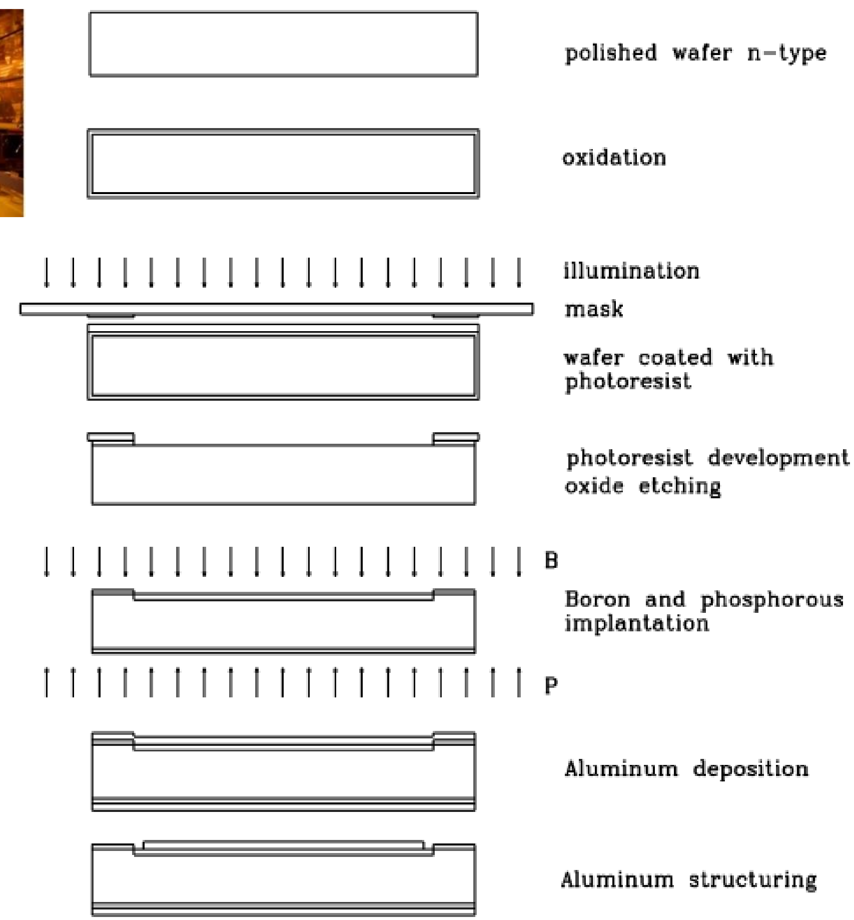
Silicon Tracking Detectors

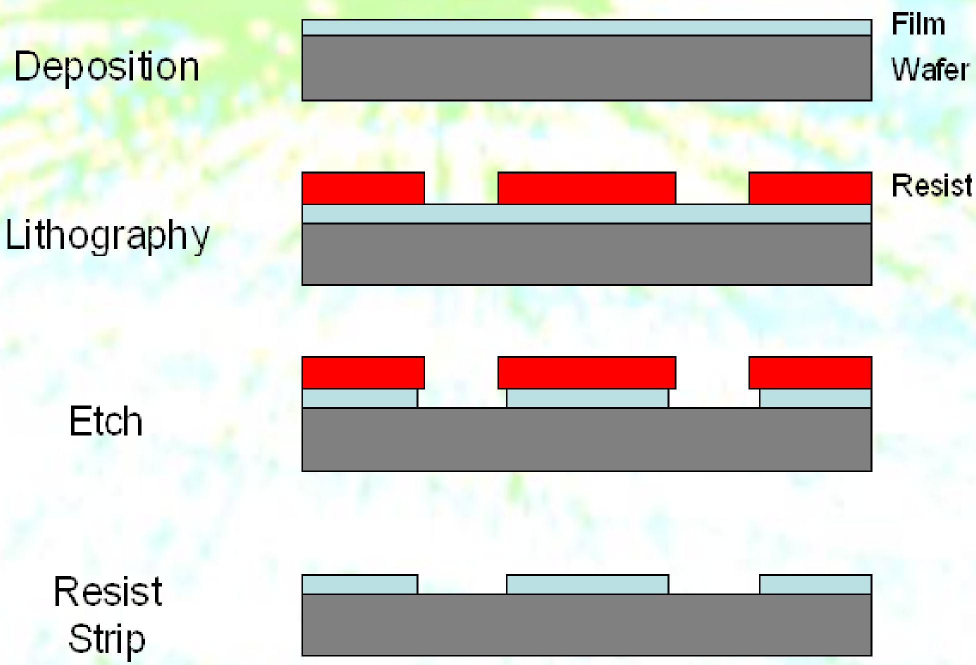
- Highly segmented silicon diodes have been used as detectors in high energy physics for well over 40 years
- The principle application has been to detect the passage of particles with good spatial resolution and high efficiency.
- Detectors are fast (~few ns), thin (few 100µm) and radiation-hard (up to ~MGy).
- Segmentation → position
- Thickness → signal size
  → efficiency
- Electron/hole pairs are liberated by the passage of charged particles as they traverse the depleted volume of the silicon (~80 e/h pairs/µm; 3.6eV per pair).
- Induced signal in electronics due to each e/h pair (for parallel electric field lines) is proportional to their separation due to the field divided by the detector thickness.



Silicon Tracking Detectors

- **Fabrication uses standard semiconductor processing techniques.**
- **Dopant ions implanted into surface using a potentials of ~ 10 kV.**
- **Surface can be patterned into strips, pads or pixels using photo-lithography.**
- **Allows exploitation of technologies that have driven the revolution in commercial silicon devices.**





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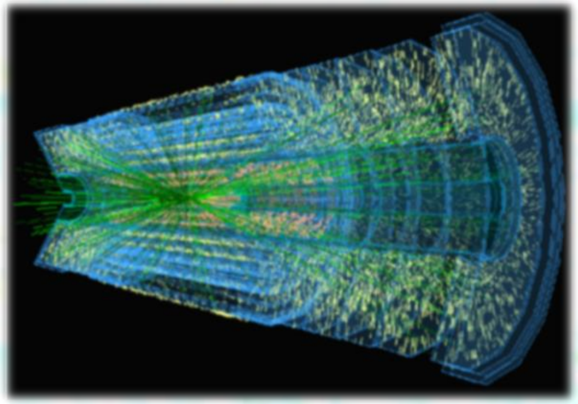

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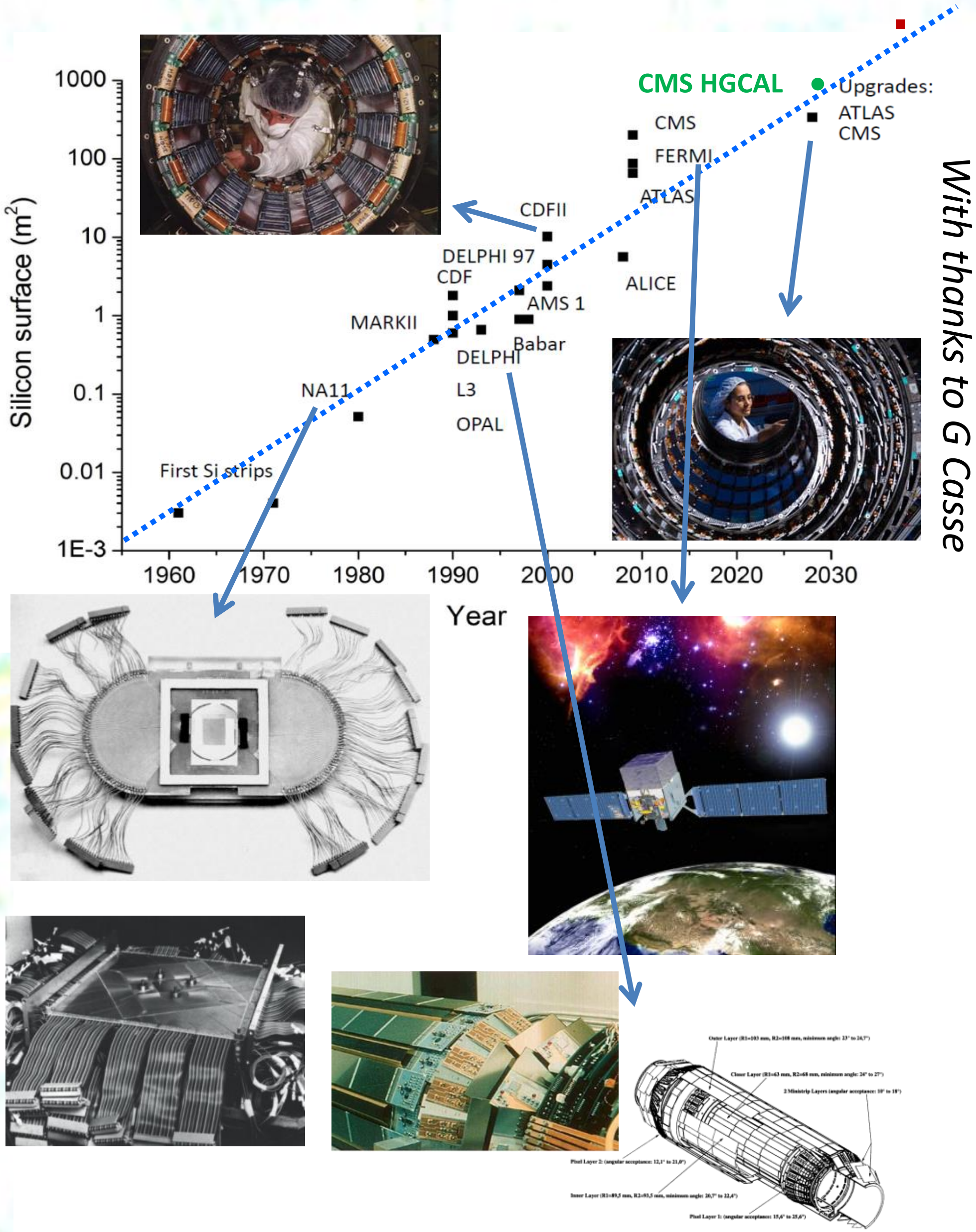
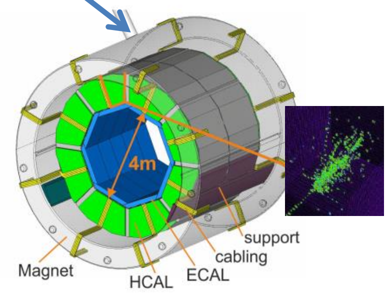
Development of Silicon Arrays



CALICE/(FCC)
SiW EM-Calorimeter



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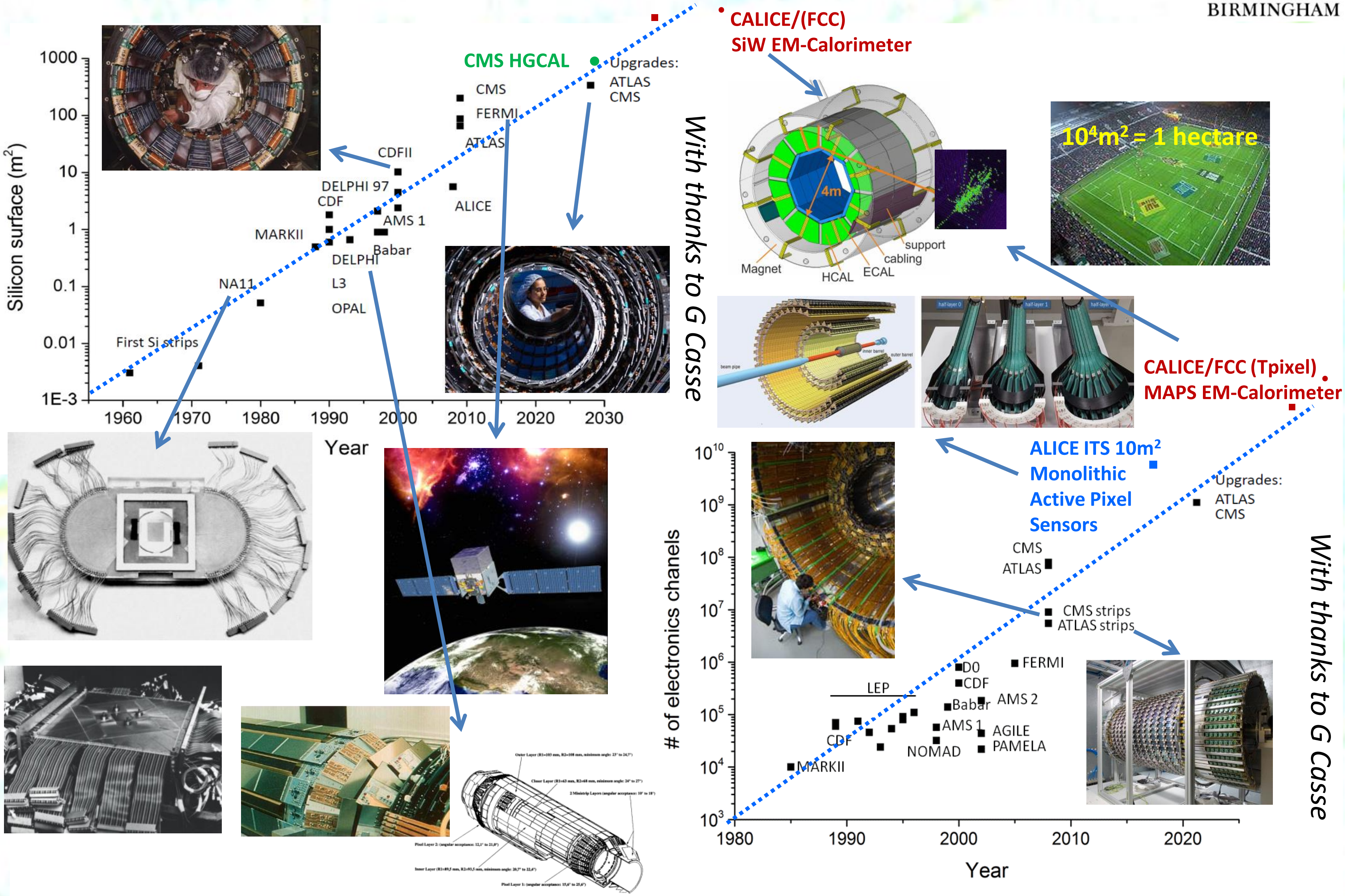

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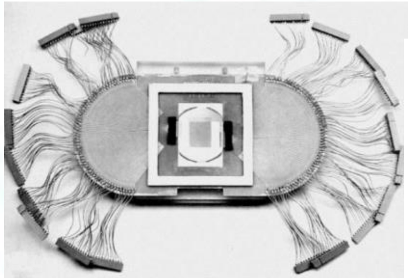
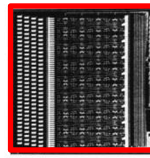
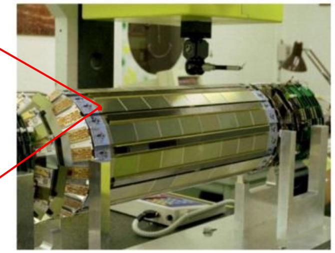
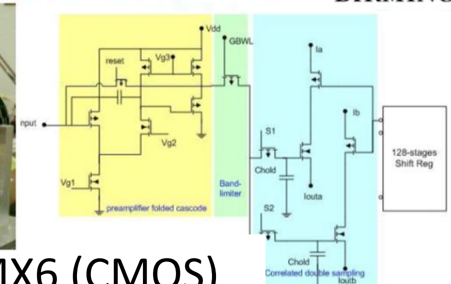


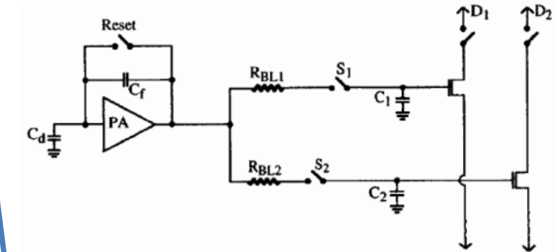
Application Specific Integrated Circuit (ASIC) development has been essential





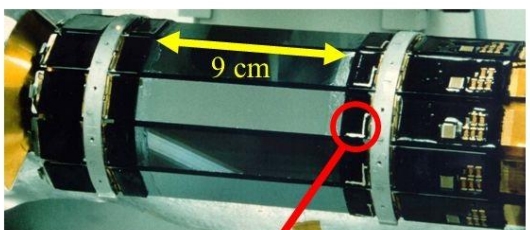


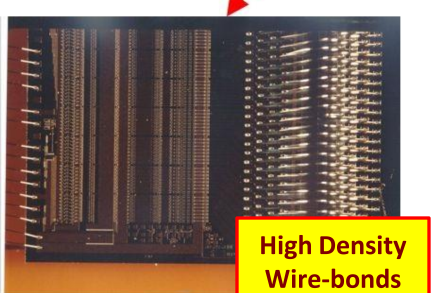
DELPHI (LEP) MX6 (CMOS)



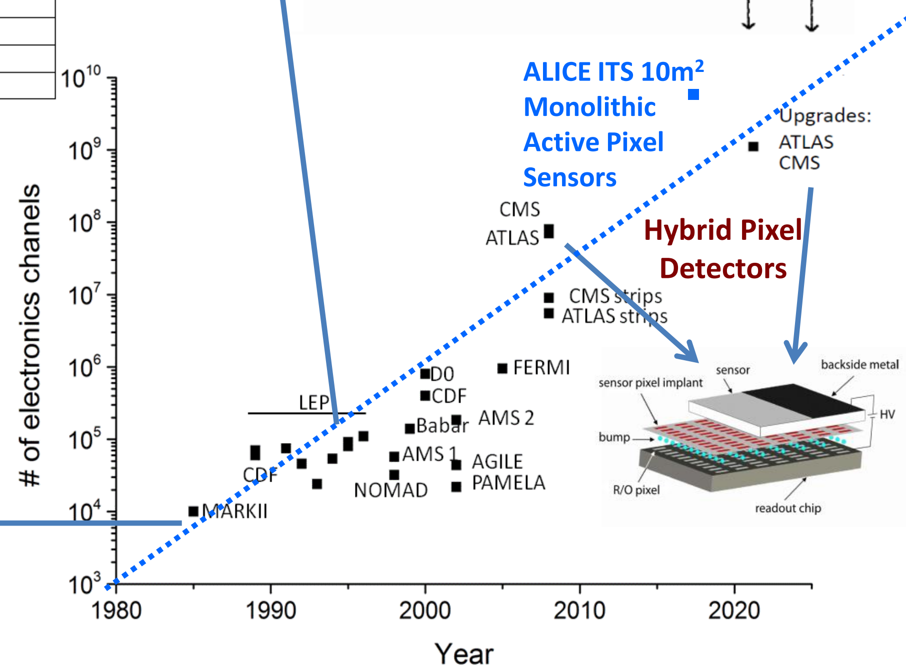
ASIC Series	Experiment	Peaking/Response Time (ns)	Noise ($a + bC_{Tot}$) a (enc), b (enc/pF)	Radiation Hardness (kGy)
Microplex	Mark-II	~10^3	280, 97	~0.5
CAMEX64A	ALEPH	~10^3	335, 35	~0.1
MX1, MX3, MX6	DELPHI	~10^3	340, 20	~0.1
MX5, MX7	OPAL	~10^3	325, 23	~0.4
SVX	L3	~10^3	350, 58	~0.2
SVXD, SVXH, SVX3	CDF, D0	132/396	600, 60	100
APC128	H1	100	700, 50	~1
HELIX	ZEUS, HERA-B	50	340, 40	5
AToM	BABar	100-400 (tunable)	300, 30	50
VA1	Belle	~10^3	200, 8	20
Beetle	LHCb	24	450, 50	300
ABCD3TA	ATLAS	20	400, 70	100
APV25	CMS	50 (peak)	270, 38	200

Strip Readout ASICs





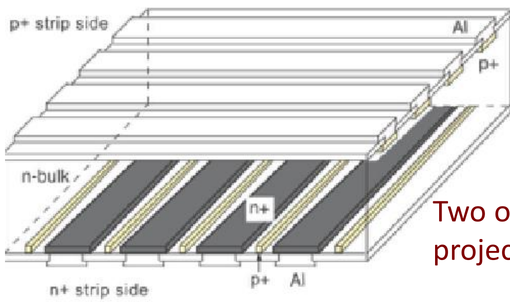
MARK II (SLAC) 128 Channel Microplex Chip (NMOS)



With thanks to G Casse

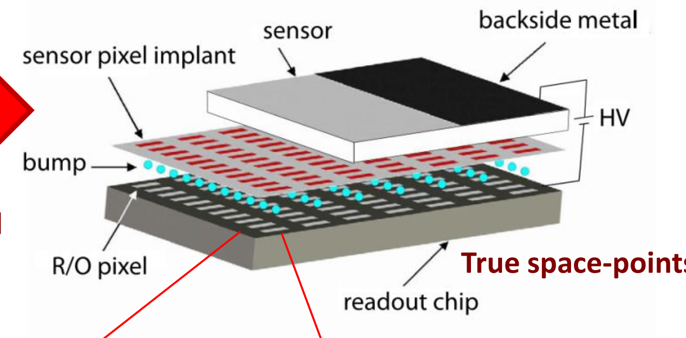
Development of Silicon Arrays

The highest channel count arrays are based on pixelated detectors. For **hybrid pixel sensors** connection to the electronics requires flip-chip technologies.



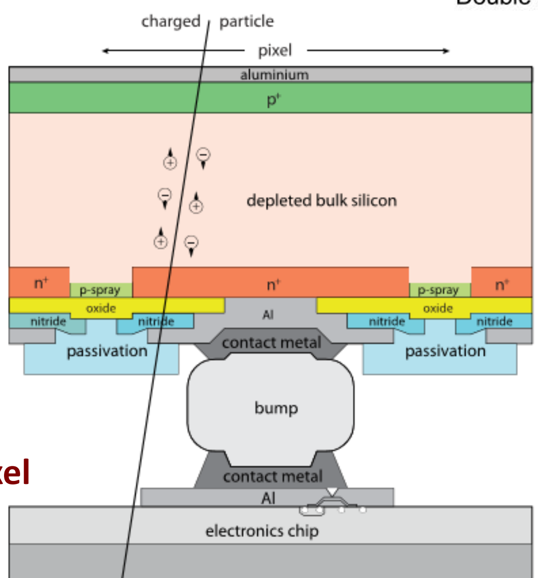
Double sided strip sensor

Two orthogonal projections



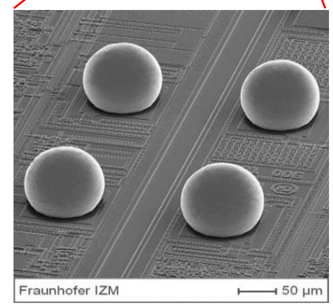
Hybrid pixel detector

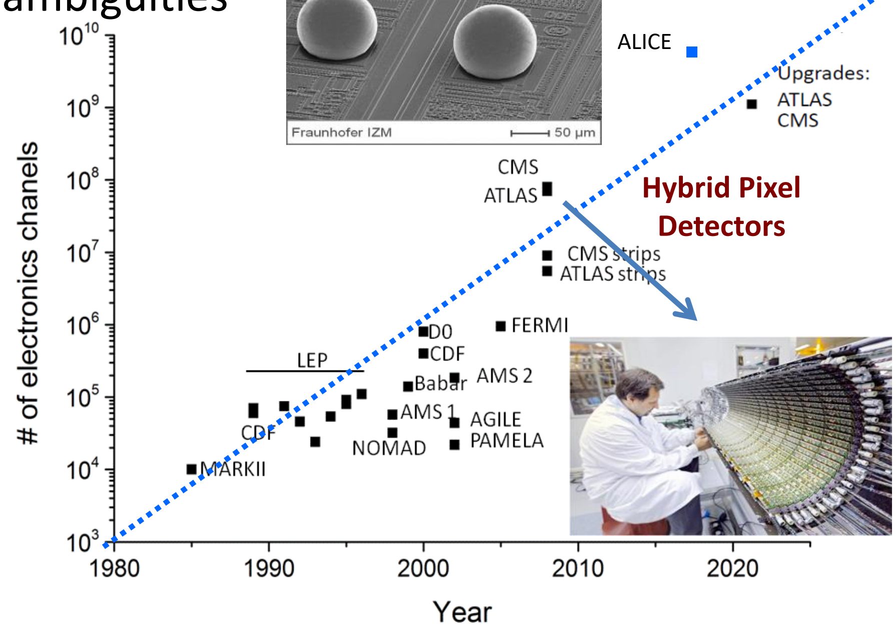
True space-points



Hybrid Pixel Readout ASICs

Required in high track density environments to avoid ambiguities



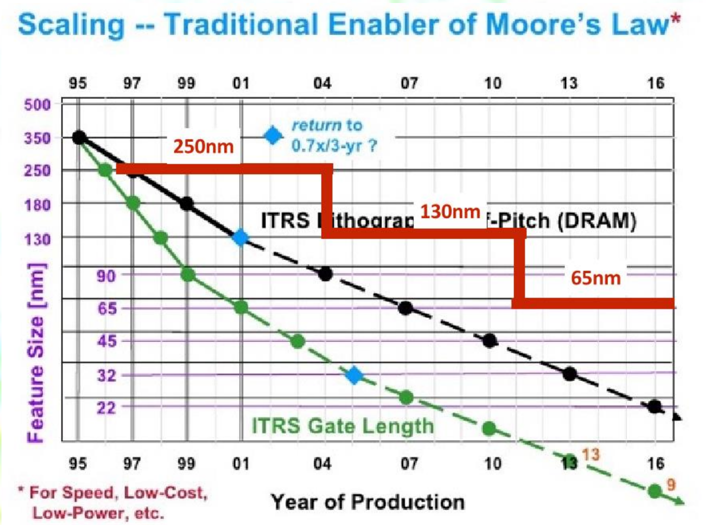


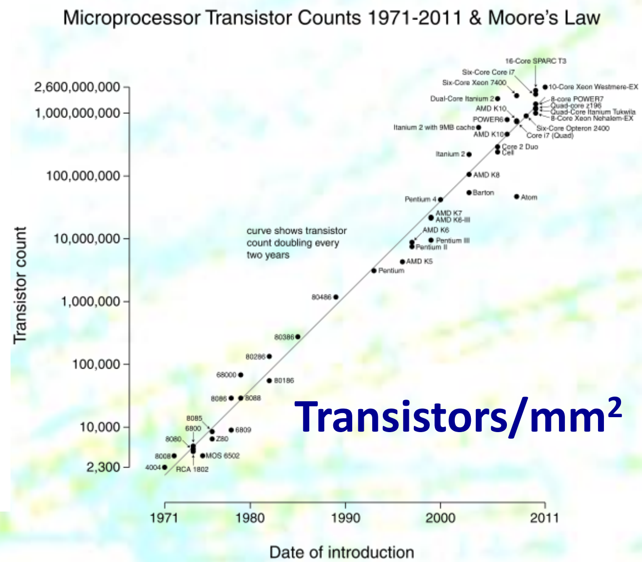
Hybrid Pixel Detectors

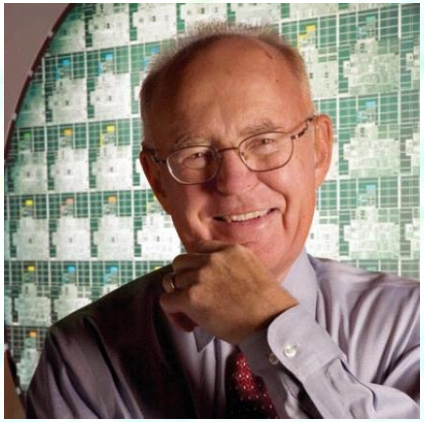
With thanks to G Casse

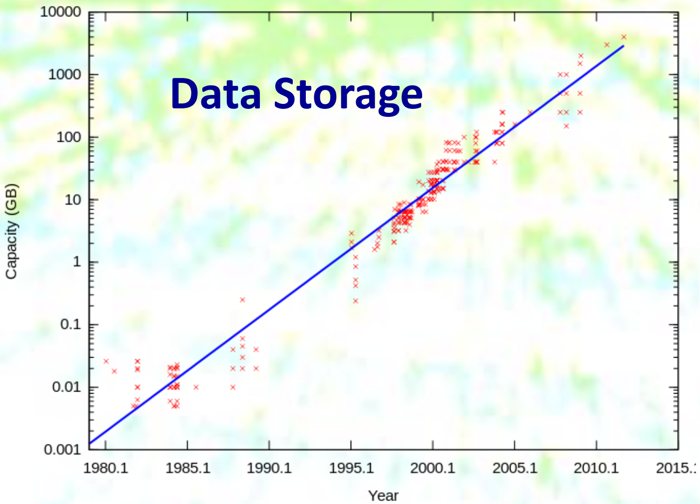
Minimum feature size	250nm	130nm	65nm
Example Read-out Hybrid Pixel Chips	ATLAS FE-I3 CMS Medipix	NA62 TDCPix ATLAS IBL FE-I4 LHCb VeloPix Medipix3RX TimePix3	CLICpix RD53A TimePix4
Typical hit data storage density capabilities	<1Gb/s/cm^2	~5Gbp/s/cm^2	40Gb/s/cm^2
Output Bandwidth	40-160 Mb/s	0.3-1.2 Gb/s	2-20 Gb/s

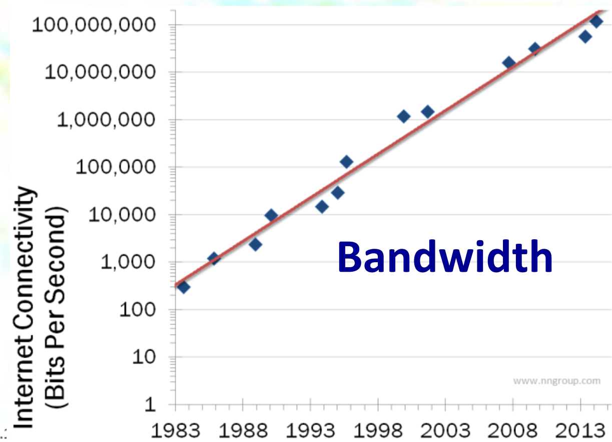
Commercial Microelectronics Evolution

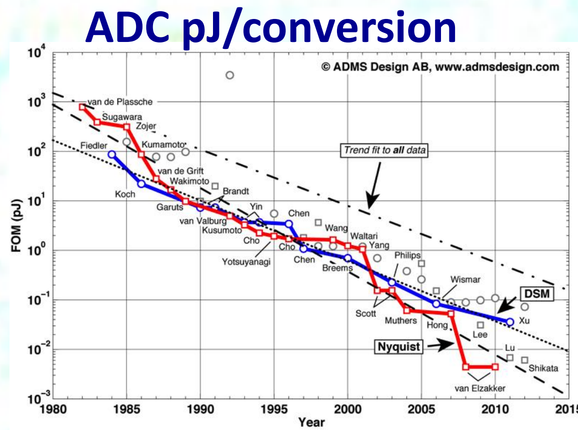










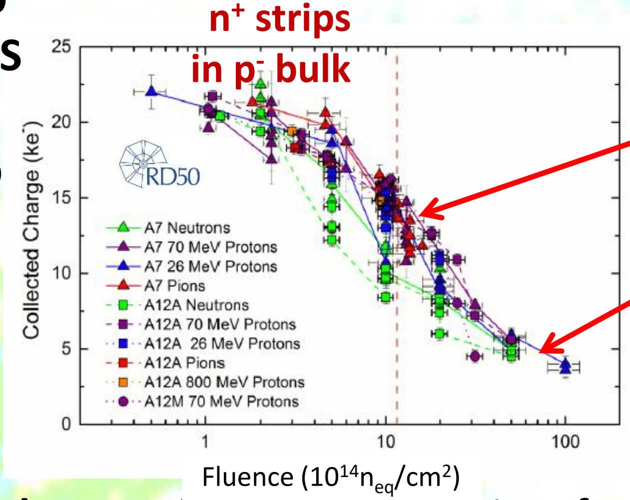


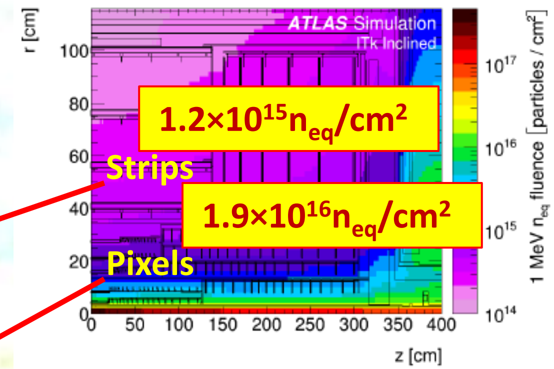
All these figures showed doubling times of < 2 years up to now. Some scalings will stop, but other improvements conceivable. Can still hope for major detector improvements and enhanced data aquisiiton plus computing capabilities. However, storage and CPU costs may not scale as fast as might be needed for future projects.

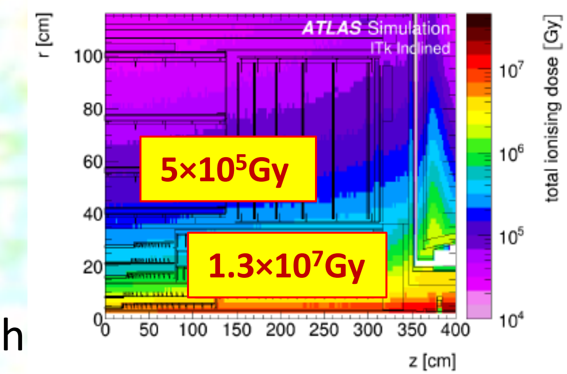
Radiation Implications for Electronics

- Hybrid silicon detectors (pixels/strips) **signal** output drops with irradiation to HL-LHC doses

RD50
ATLAS
CMS
LHCb



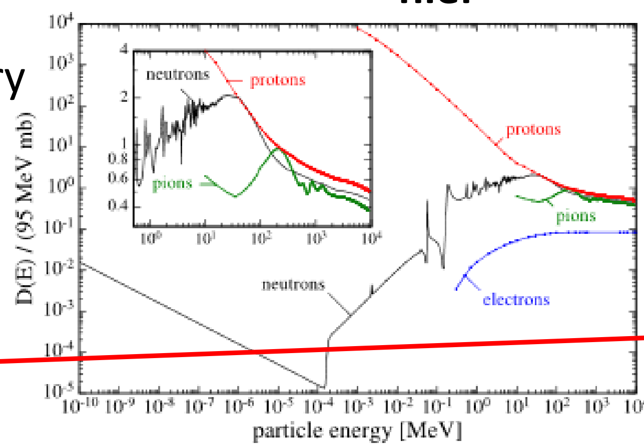




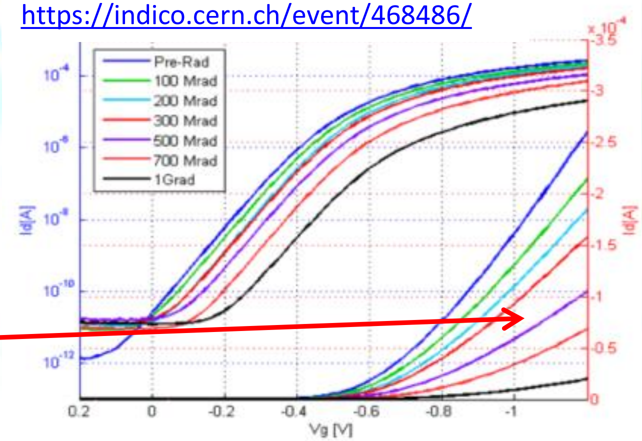
For Pixels: also need rad-hard data links with up to ~40 hits/cm^2 each 25ns

- **Bulk damage** (measured in units of 1MeV equivalent neutrons/cm^2 (assuming scaling with **n**on-**i**onising **e**nergy **l**oss) drives the deterioration of **sensors**. → **niel**
- For **microelectronics** worry about **t**otal **i**onising **d**ose.
- (65nm CMOS - **RD53**) can start to see significant deterioration above **500Mrad (5MGy)**

◊Many different effects◊



Federico Faccio: PMOS turn-on V_g
https://indico.cern.ch/event/468486/



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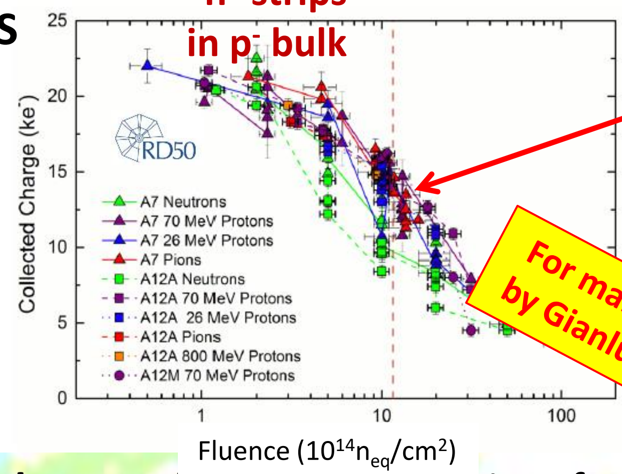

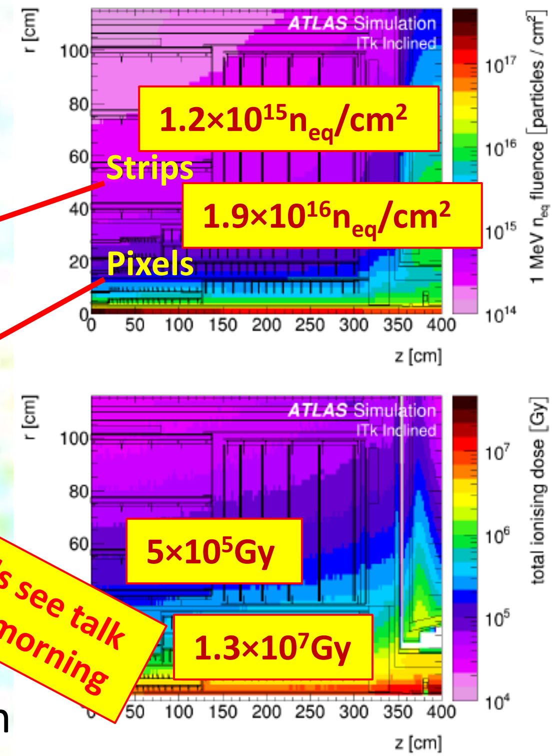

For many more details see talk by Gianluigi Casse this morning

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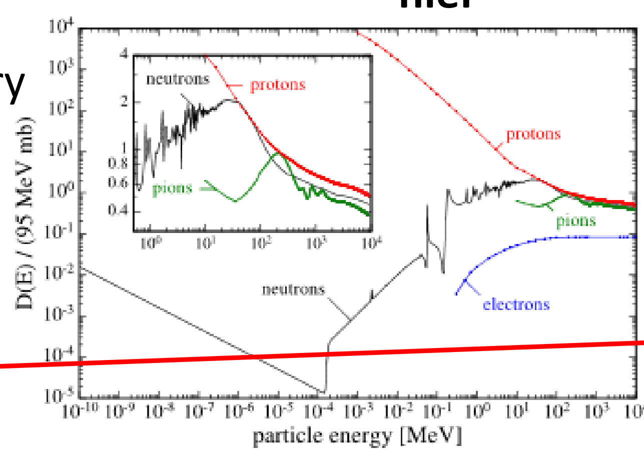

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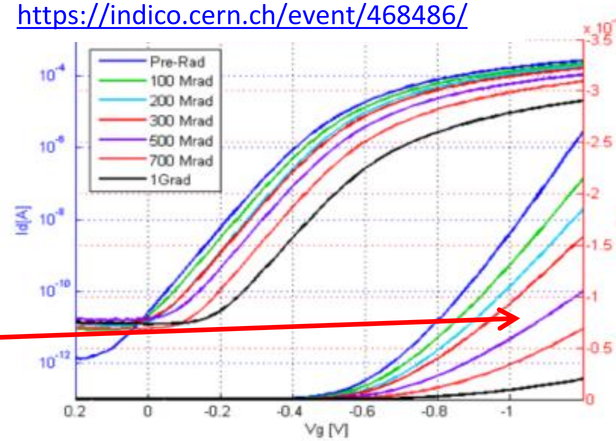
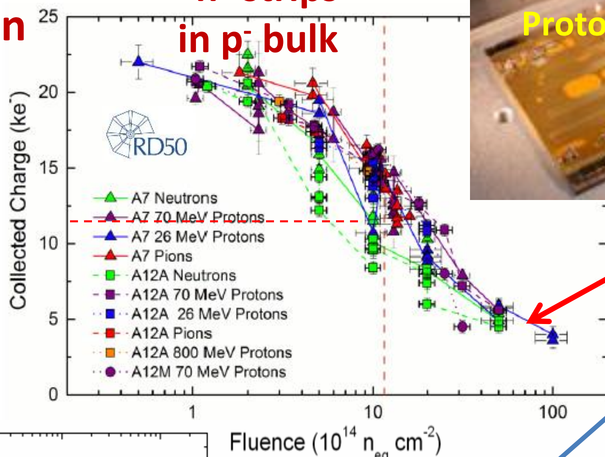


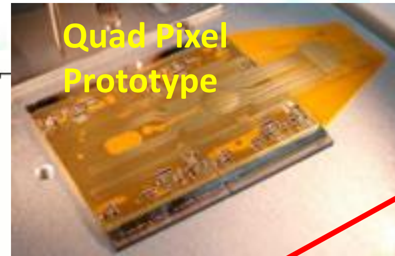
Thin and 3D Pixel Sensors

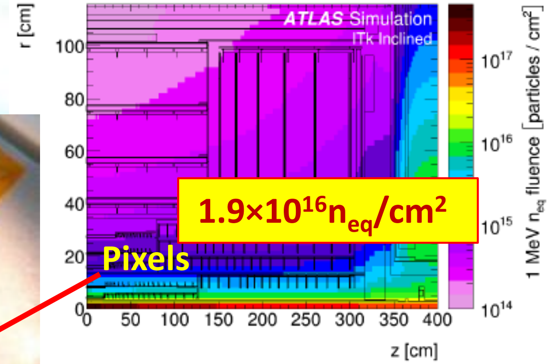
- At the highest doses, charge trapping becomes the most fundamental limitation

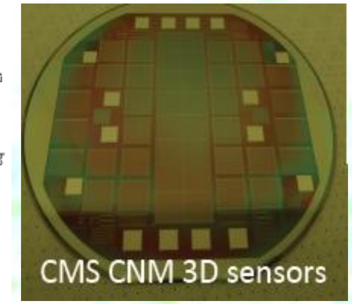
Need short collection distance

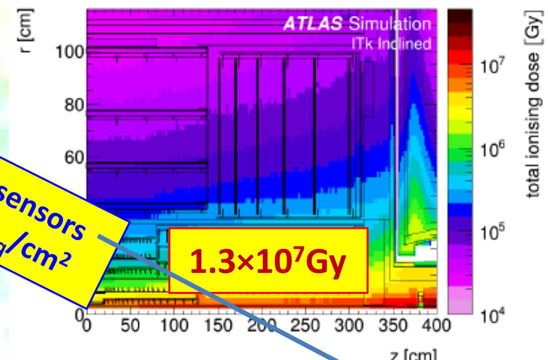
n+ strips in p- bulk



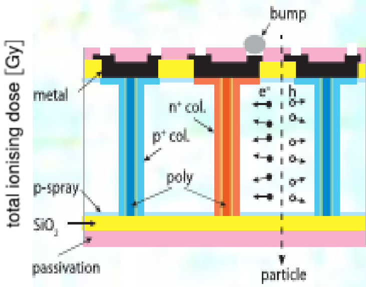


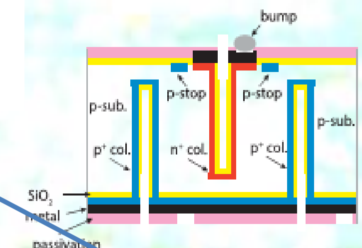


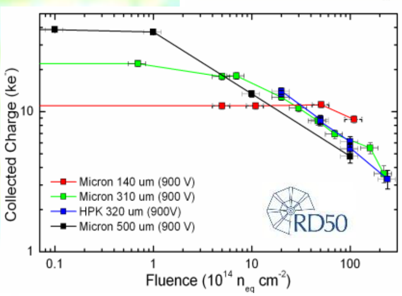


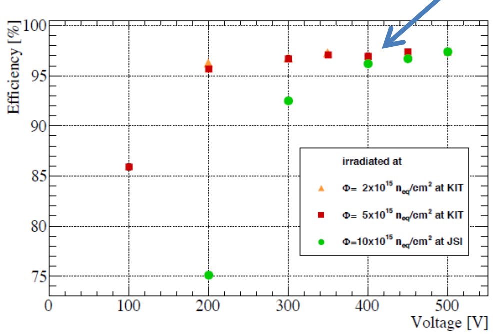


Thin and 3D sensors OK at $10^{16} n_{eq}/cm^2$

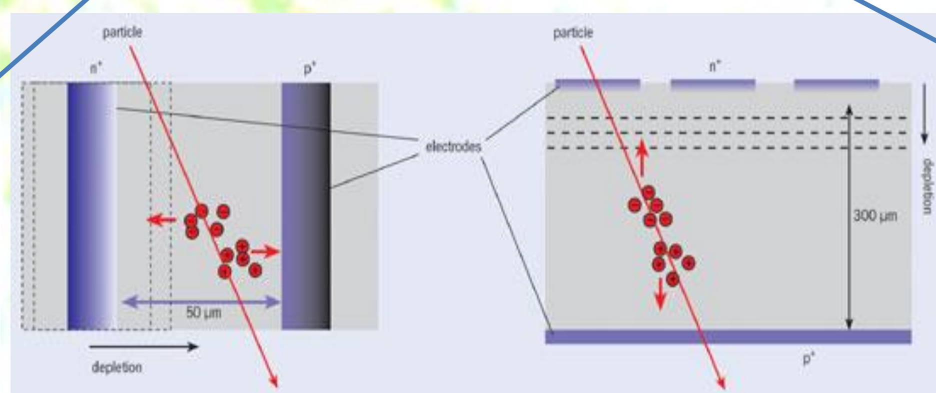






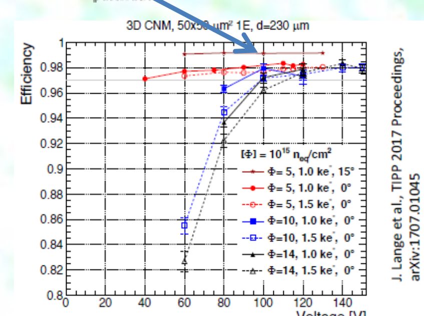


100µm thick planar n-in-p 50µm pixels



3D
lower V

Planar n-in-p
simpler = cheaper



CNM 3D 50µm pixels

Thin and 3D Pixel Sensors

Birmingham Instrumentation Laboratory for Particle physics and Applications (BILPA)

UNIVERSITY OF BIRMINGHAM

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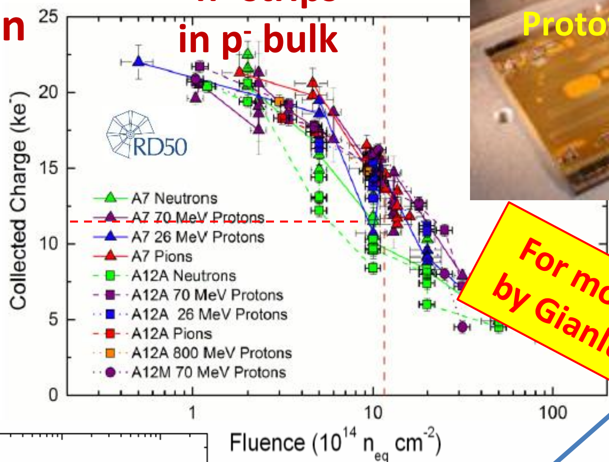
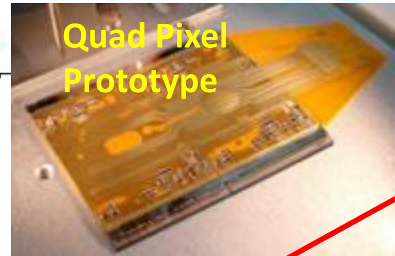
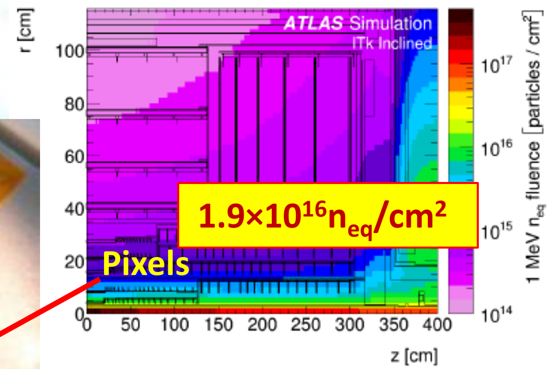
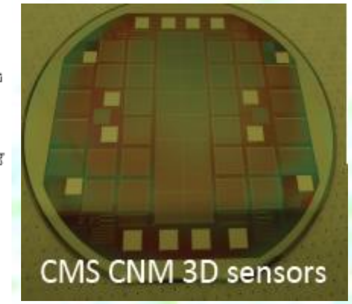
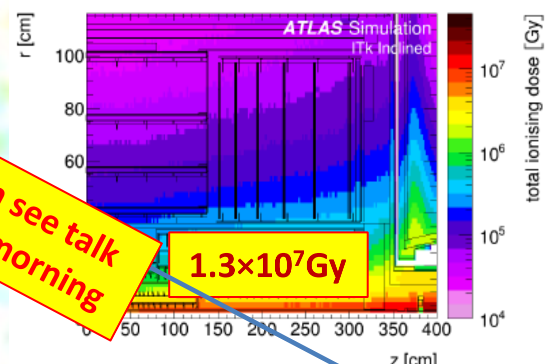


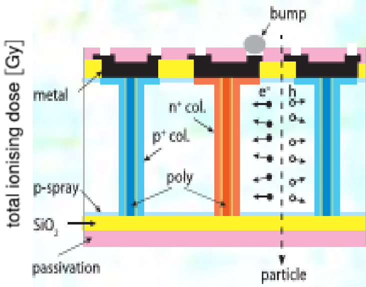


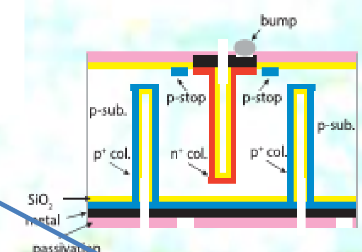


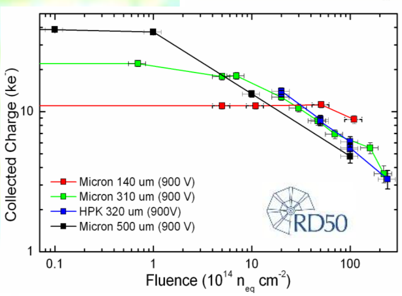


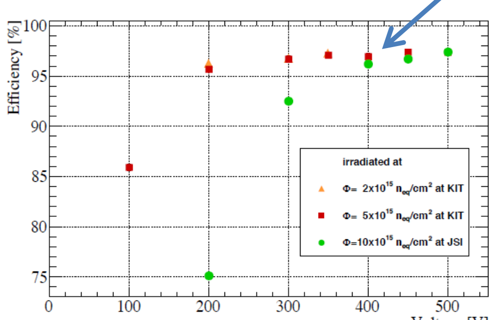
For more details again see talk by Gianluigi Casse this morning



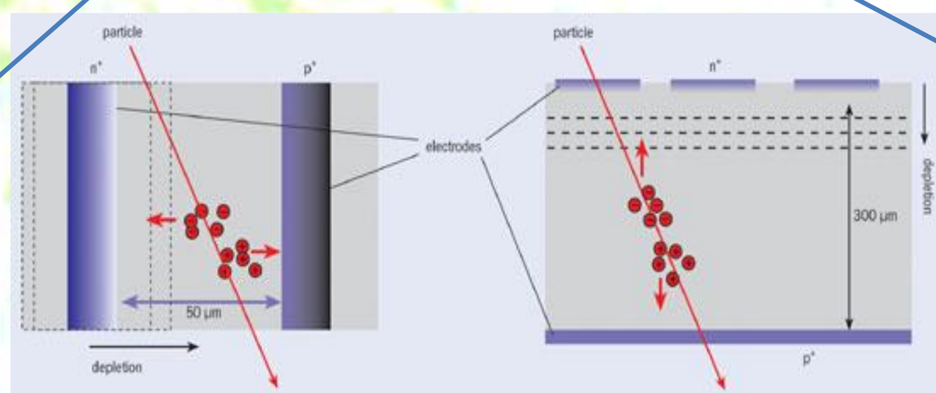






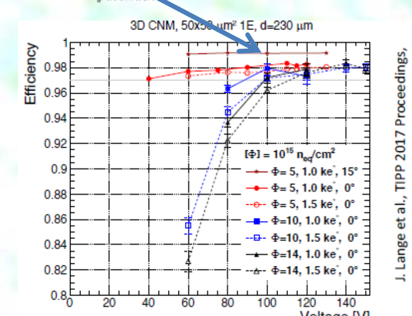


100µm thick planar n-in-p 50µm pixels



3D
lower V

Planar n-in-p
simpler = cheaper



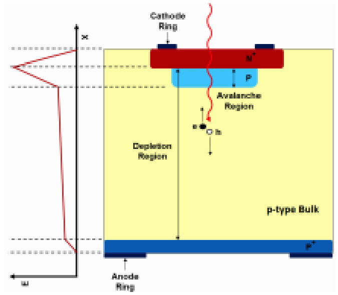
CNM 3D 50µm pixels

Birmingham Instrumentation Laboratory for Particle physics and Applications BILPA

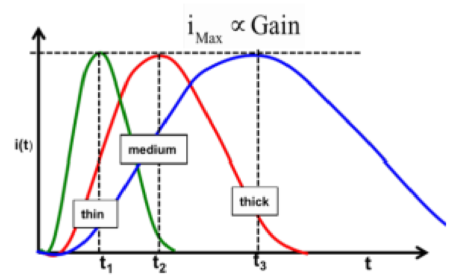
Fast Timing Detectors

UNIVERSITY OF BIRMINGHAM

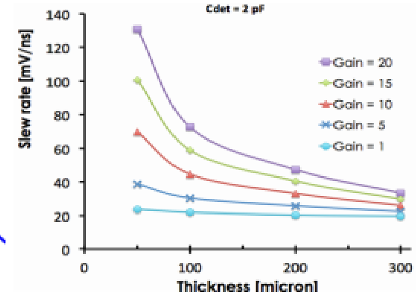
RD50, ATLAS, CMS: Low Gain Avalanche Detectors (LGAD)
(Radiation issues still under study for HL-LHC applications)



(a) Cross section of an LGAD diode.



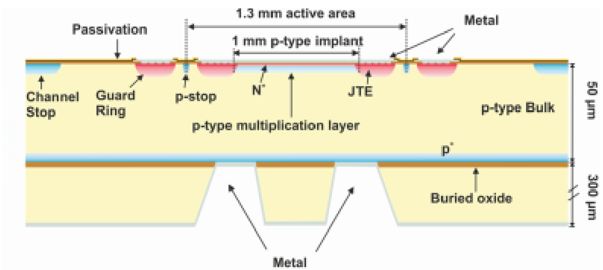
(b) Current signals for LGADs of different thicknesses.



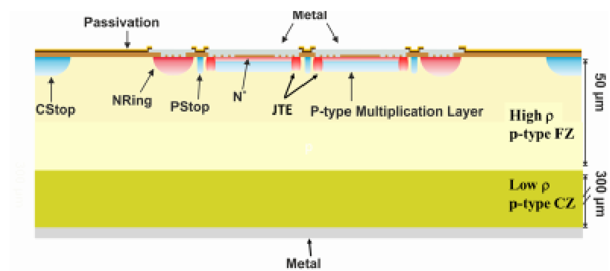
(c) Signal slope as function of LGAD thickness.

$$\sigma_{\text{TimeWalk}} = \left[\frac{V_{th}}{\frac{S}{t_{rise}}}\right]_{RMS} \propto \left[\frac{N}{\frac{dV}{dt}}\right]_{RMS},$$

$$\sigma_{\text{Jitter}} = \frac{N}{(dV/dt)} \simeq \frac{t_{rise}}{(S/N)}.$$

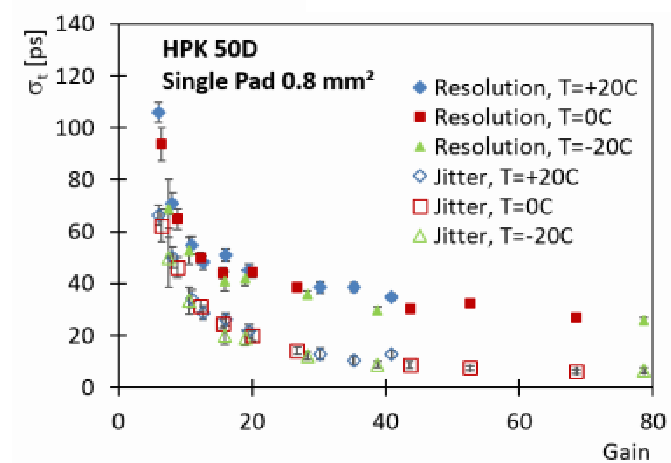


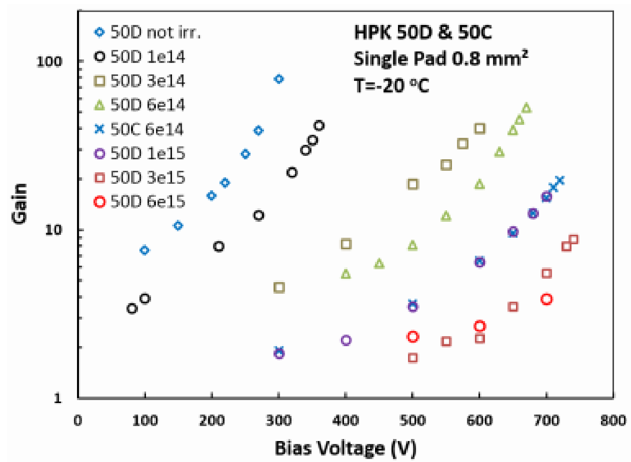
(a) LGA single-pad sensor.

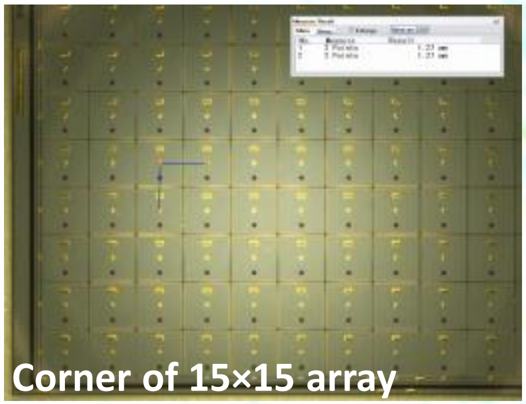


(b) Array sensor with 2 × 2 pads.

ATLAS EXPERIMENT







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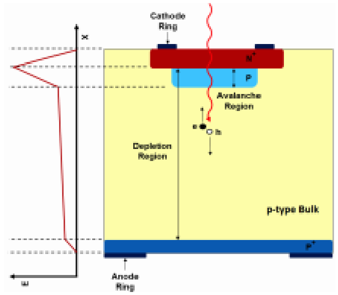

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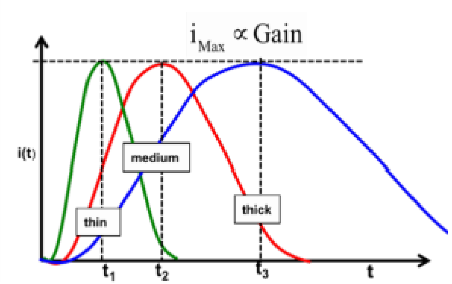

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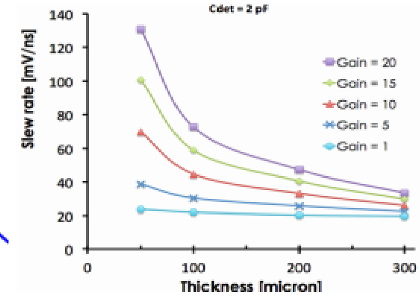

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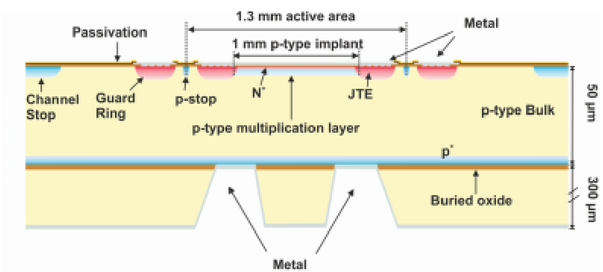

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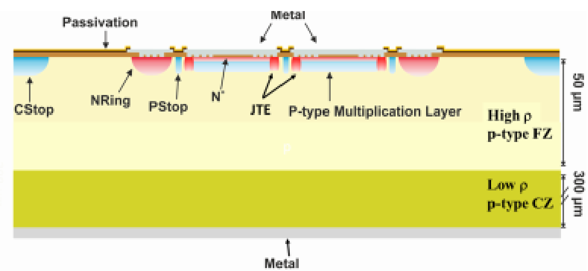

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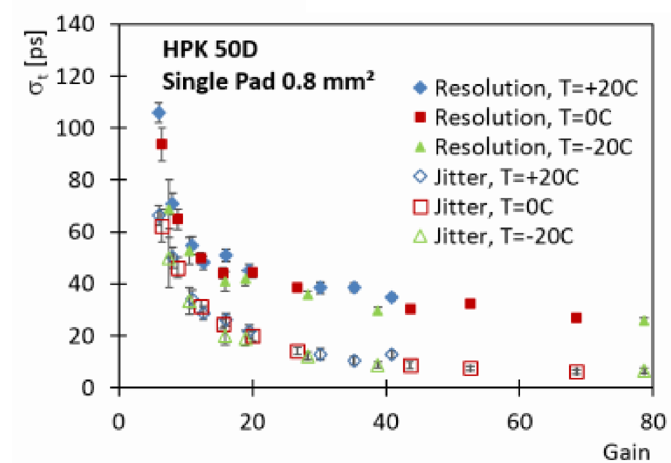
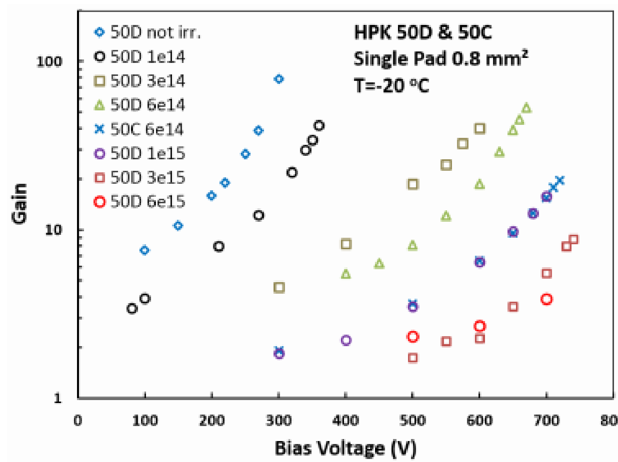
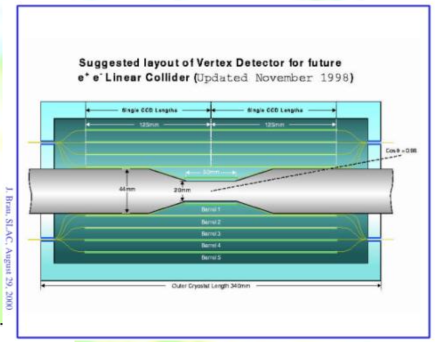
ATLAS EXPERIMENT

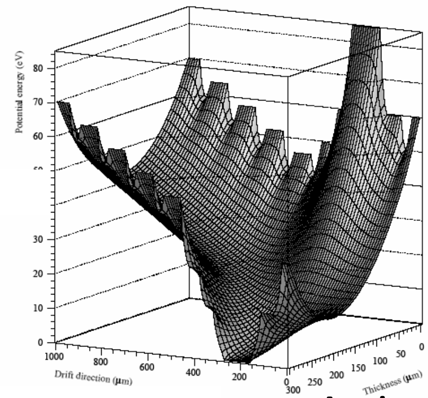


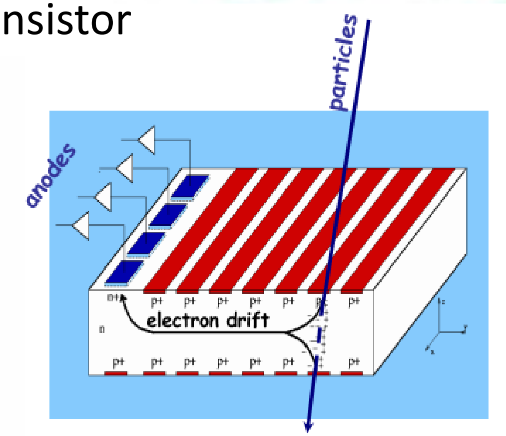


CCD, Drift and DEPFET

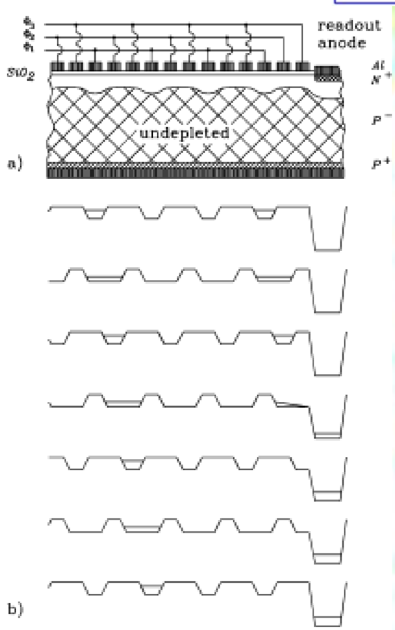
A number of technologies have been adopted and could be suitable for future facilities where the charge is moved through the silicon by clocking potentials (**CCD**), lateral field (**Drift**) or stored in the silicon beneath a transistor allowing non-destructive read-out (**DEPFET**)

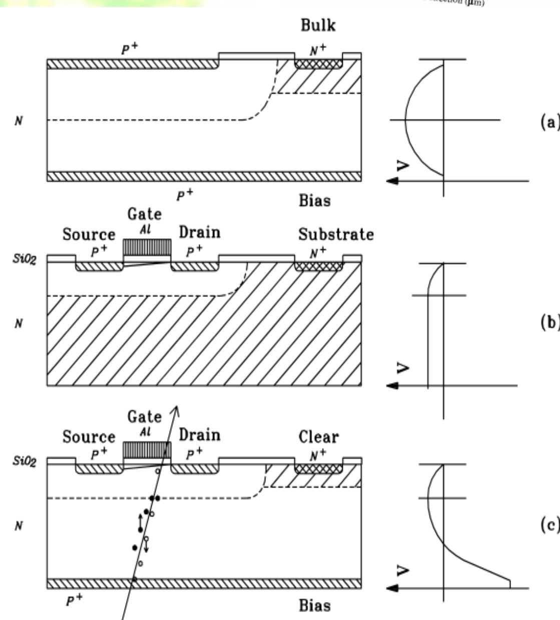




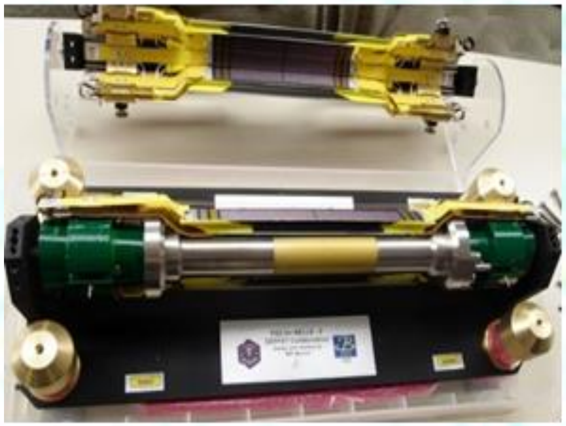


Arrival time gives lateral drift distance





Charge stored beneath gate can be read out as giving increased I_d for given V_g



BELLE II Vertex Detector at SuperKEKB

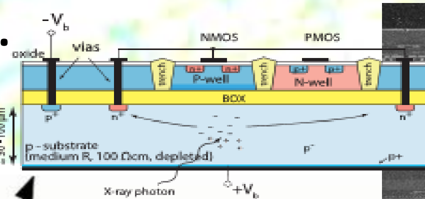
Monolithic: SoI and 3D Integration

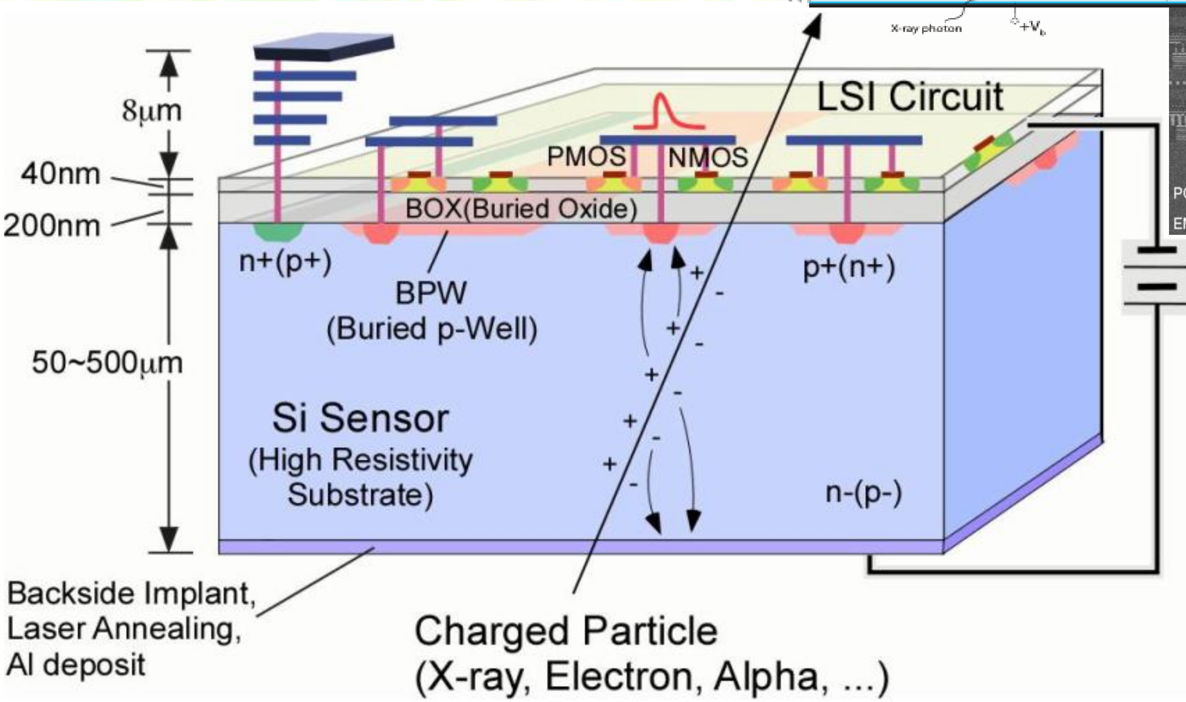
Monolithic pixel sensors combine the functionality of the microelectronics with the sensor substrate as part of a single silicon object.

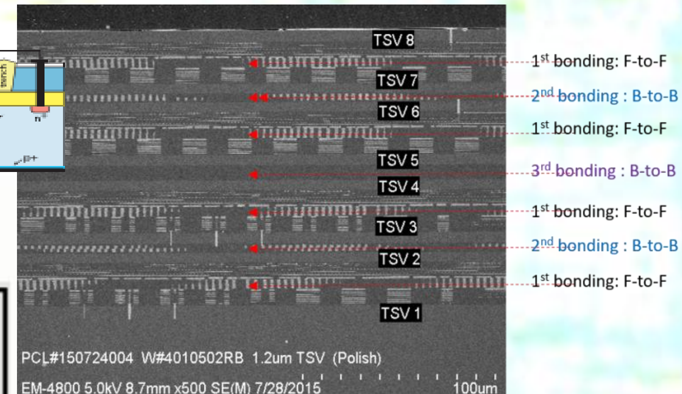
CCDs and DEPFETs already incorporate active circuit elements in the sensors which are therefore no longer simple passive devices.

However, these devices are potentially slow and prone to radiation damage.

Silicon on Insulator technology allows integration of full read-out circuitry above a buried oxide over the sensing substrate.







Wafer bonding, through silicon via (TSV) and back-thinning technologies allow circuits to be stacked in 3D.

Could imagine detector concept with stacked opto-electronics digital electronics, analogue electronics and sensor substrate

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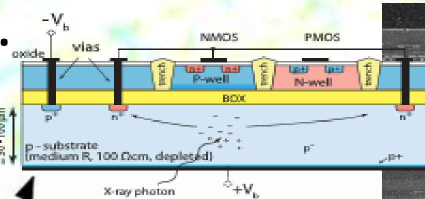

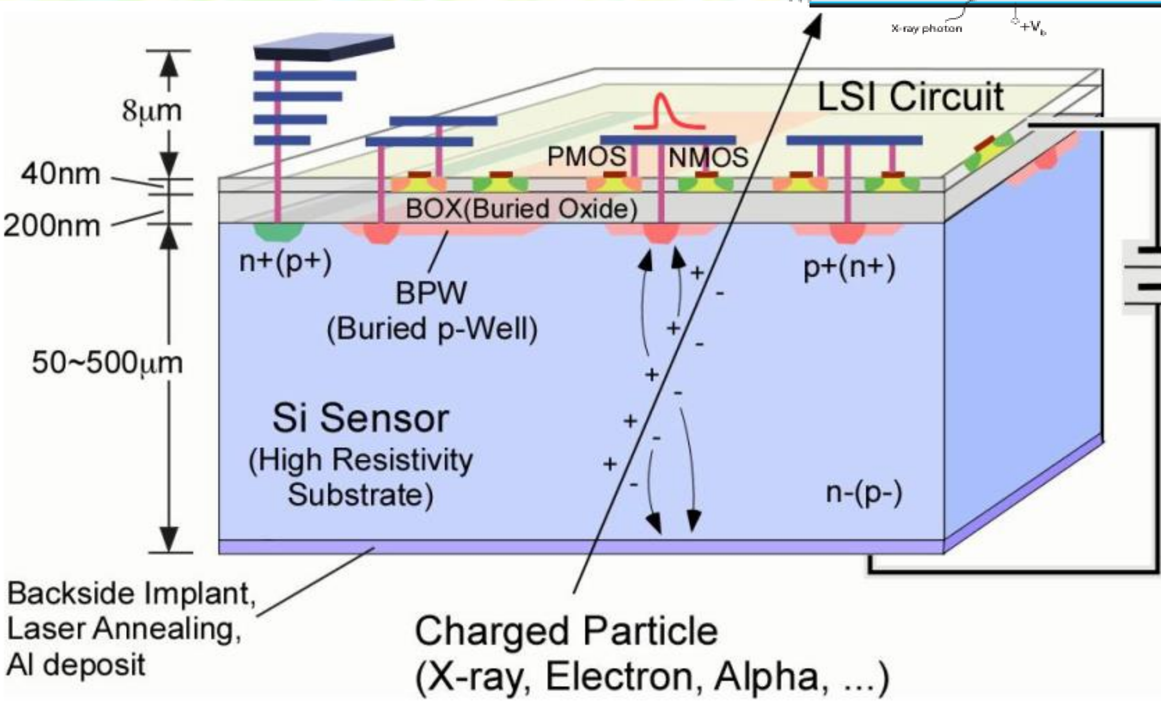

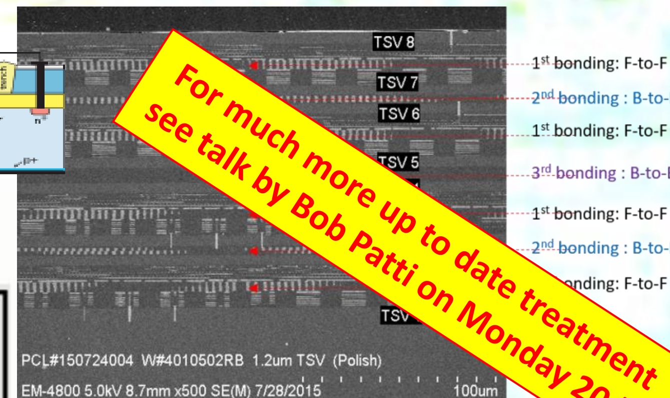

For much more up to date treatment see talk by Bob Patti on Monday 20/5

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MAPS: HV/HR-CMOS Detectors

- **Commercial CMOS Image Sensors offer possible dramatic decrease in costs (Monolithic Active Pixel Sensors)**
- **MAPS can deliver very low power consumption at low R/O speeds, possibly <100mW/cm^2 i.e. simple water cooling**
  - **Ultra low material budget (cf ALICE ITS upgrade: <0.5% for inner layers, <1% for outer layers)**
  - **But these devices limited in speed and radiation hardness**
  - **Current and near future MAPS for heavy ion experiments**
    - **integration time up to 4µs (noise, electron diffusion)**
    - **radiation resistance up to few 10^{13} $n_{eq}cm^{-2}$**
- **Major developments in HV/HR-CMOS → deep depletion region with charge collection by drift not diffusion → huge improvements in collection speed and radiation hardness**
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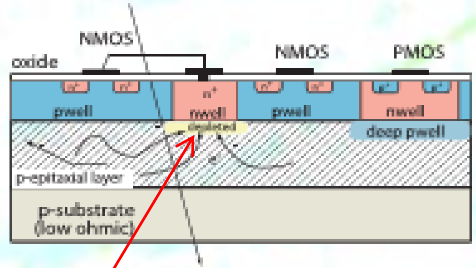

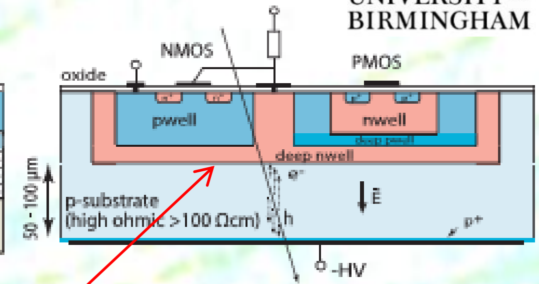

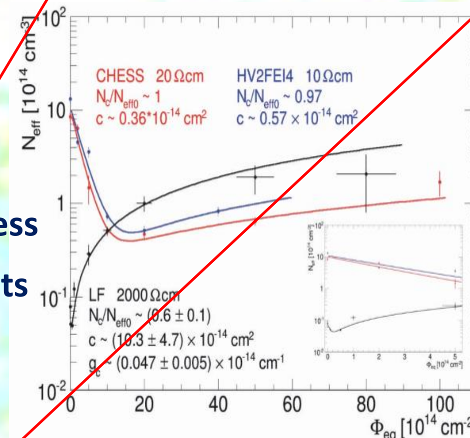

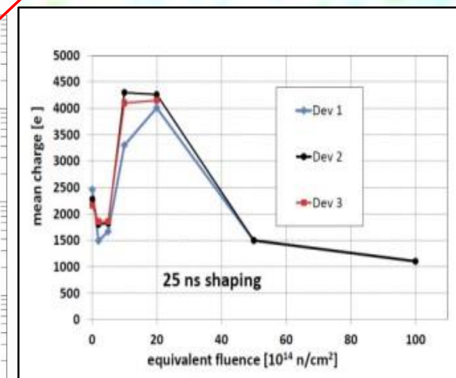

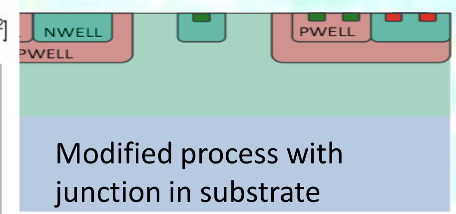

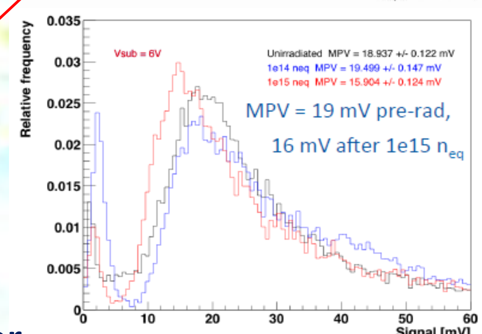

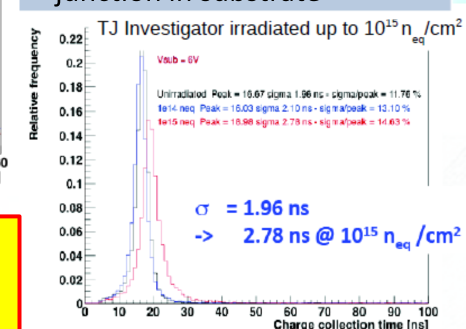

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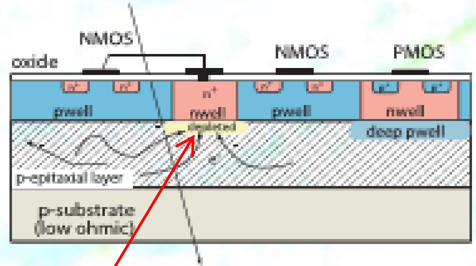

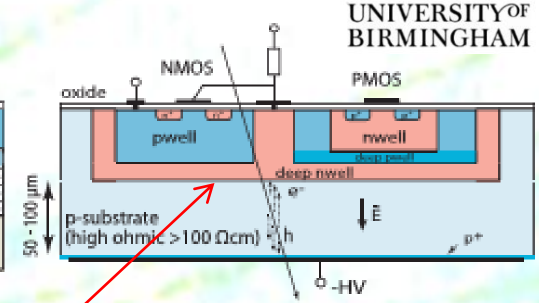

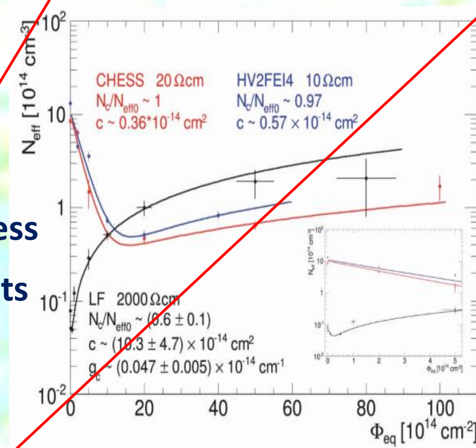

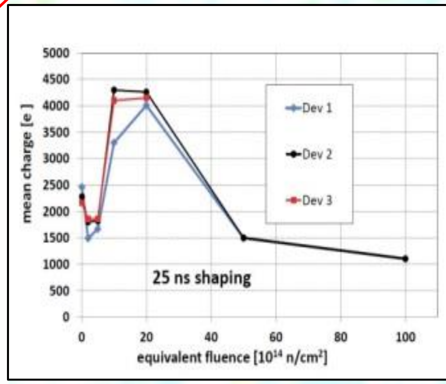

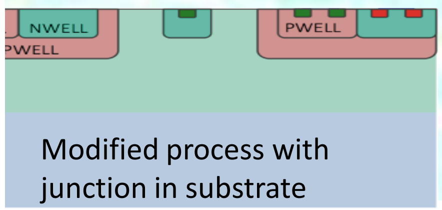

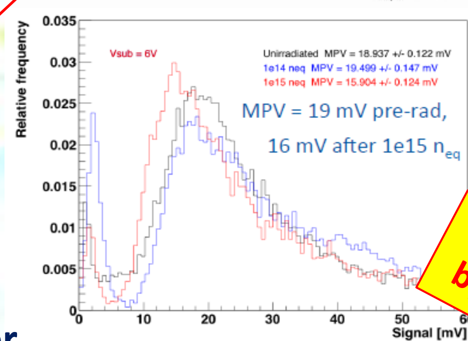

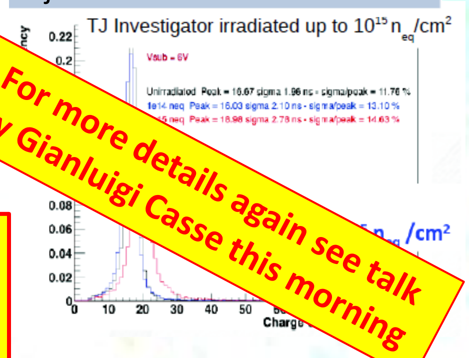

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IMPACT OF THE INNOVATIONS IN SEMICONDUCTOR ADVANCED TECHNOLOGY ON THE TRACKING CONCEPTS IN FUNDAMENTAL RESEARCH

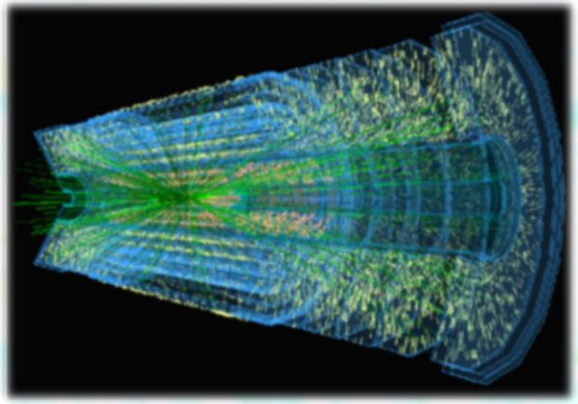
Birmingham Instrumentation Laboratory for Particle physics and Applications BILPA

UNIVERSITY OF BIRMINGHAM

Phil Allport

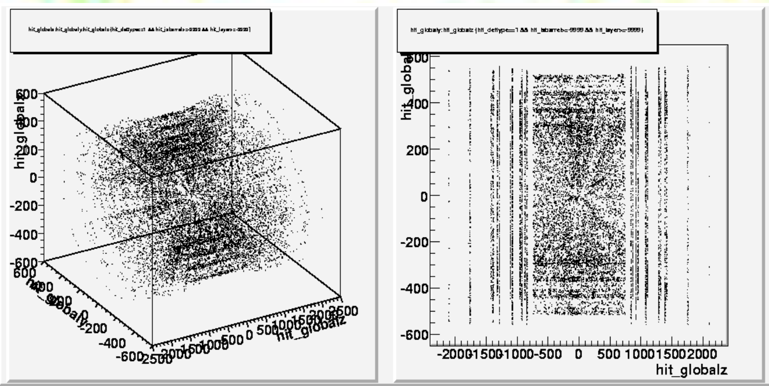
INFIERI Summer School, Huazhong University of Science and Technology

- Introduction to Silicon Tracking Detectors
- Development of Silicon Detector Arrays in Particle Physics
- **Overview of LHC Detector Upgrade Programme**
  - **Silicon Detectors for HL-LHC**
    - **Strip Detectors**
    - **Hybrid Pixel Detectors**
    - **Silicon Detectors for Calorimetry**
    - **Monolithic Active Pixel Sensors**
    - **Silicon Fast Timing Detectors**
- Collider Physics Beyond the HL-LHC
- Example Applications of HL-LHC Technologies
  - Hadron Radiotherapy
- Conclusions



Experimental Challenges: Detectors

- Tracking detectors focus on measuring the paths of all the charged particles to find their energies (E), momenta (p) and charge (±), derived from linking the hits for each particle combined with additional information from other detector layers (which often also can see the neutral particles)
- A very powerful technique to measure momentum is to track in a known magnetic field where the curvature is proportional to 1/p.



Join the dots and fit for curves (seen end-on) in a solenoid magnetic field

- As the particle traverses the full detector system (including the tracker) the pattern of energy loss in different materials provides information on the particle type (and therefore mass).
- Where massive detectors stop the particle entirely (electromagnetic and hadronic calorimeters) they directly provide E and also the energies and directions of the neutral particles. (In ATLAS ionization in liquid Ar with Pb, Cu or W absorbers is used for calorimetry except the for hadronic barrel based on steel and scintillator tiles)
- Muons (the main component of cosmic ray interactions at ground level) are very penetrating and, for these charged particles, identification is based on them getting all the way out

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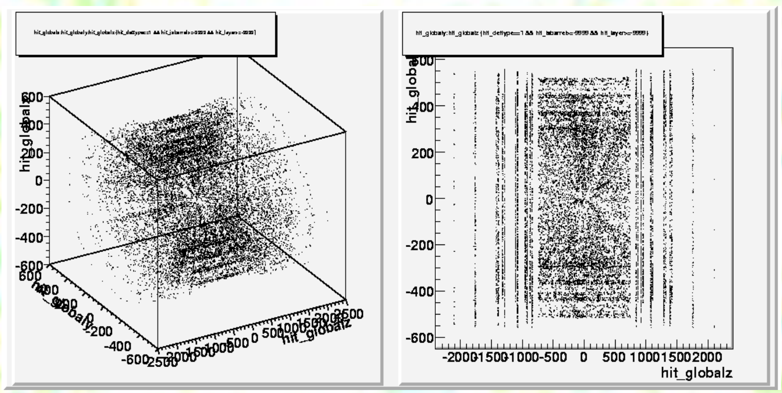

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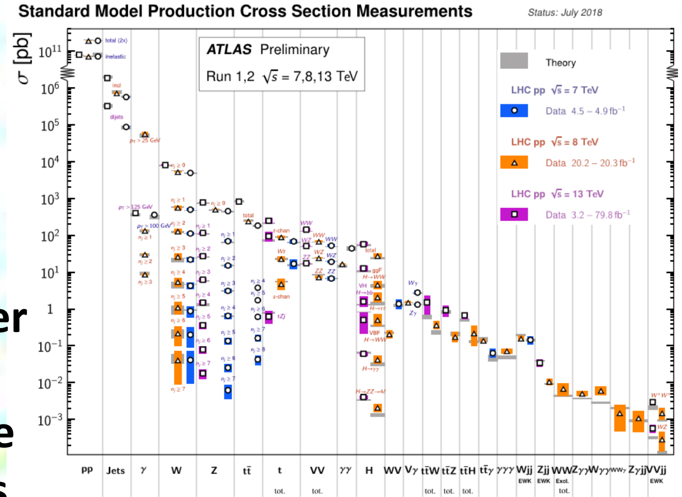
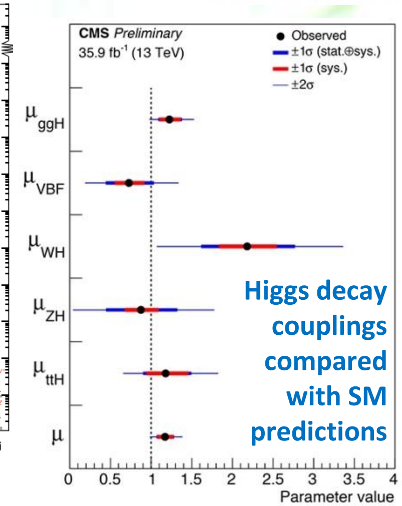
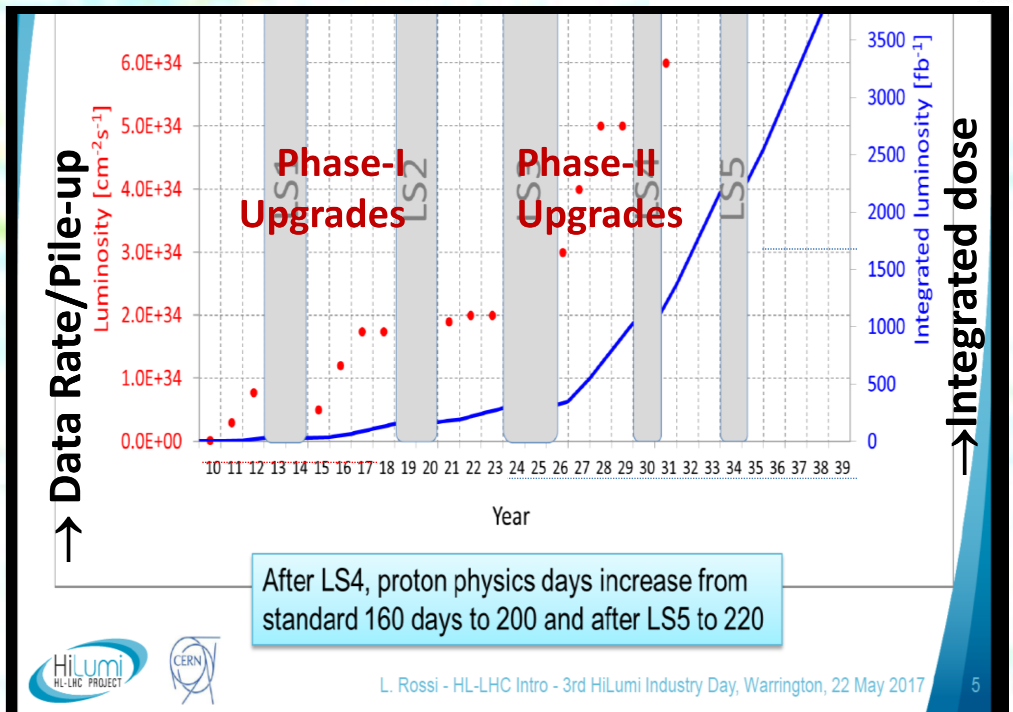
The High Luminosity LHC (HL-LHC)

- **The LHC has delivered a fantastic programme of precision physics measurements, discoveries and searches for new phenomena.**
- **At a hadron collider, the total number of collisions delivered ("integrated luminosity") not only determines the statistical accuracy of measurements, but also the sensitivity to rare phenomena and the mass reach in searches for new particles.**
- **The HL-LHC is a hugely ambitious programme to deliver over 10 times more data by the end of LHC running than the accelerators or experiments were originally designed for.**
- **It requires major upgrades of the CERN accelerator complex and of all the LHC experiments.**



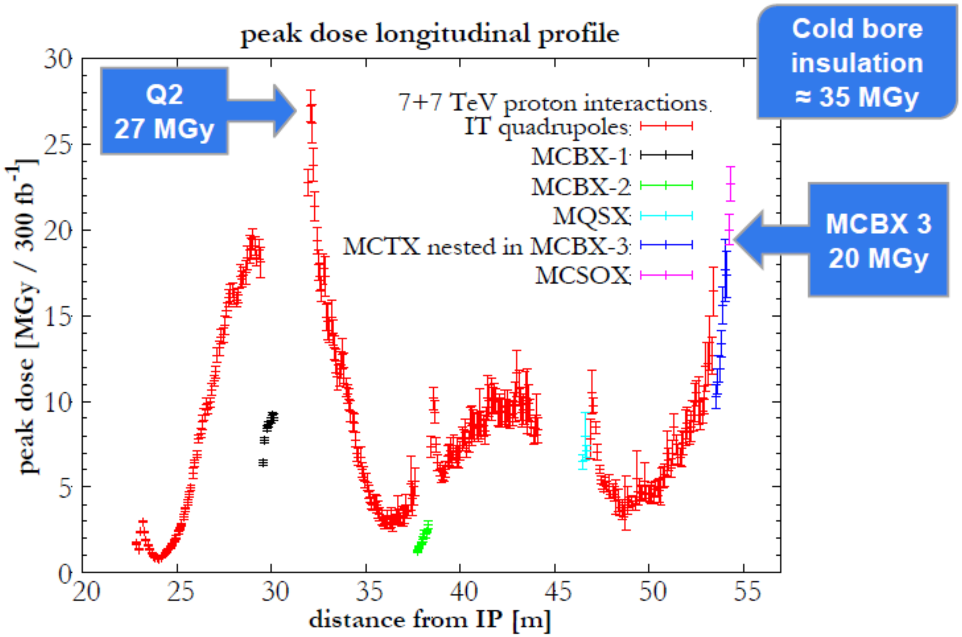


Higgs decay couplings compared with SM predictions



The High Luminosity LHC (HL-LHC)

Radiation damage to triplet magnets at 300 fb-1



LHC accelerator overviw
Frédérick Bordry
3rd ECFA High-luminosity LHC experiments workshop
3rd October 2016 – Aix-les-Bains
12

1983 : First studies for the LHC project
1988 : First magnet model (feasibility)
1994 : Approval of the LHC by the CERN Council
1996-1999 : Series production industrialisation
1998 : Declaration of Public Utility & Start of civil engineering
1998-2000 : Placement of the main production contracts
2004 : Start of the LHC installation
2005-2007 : Magnets Installation in the tunnel
2006-2008 : Hardware commissioning
2008-2009 : Beam commissioning and repair

2010-2035: Physics exploitation
2010 – 2012 : Run 1 ;7 and 8 TeV
2015 – 2018 : Run 2 ; 13 TeV
2021 – 2023 : Run 3
2024 – 2025 : HL-LHC installation

HiLumi HL-LHC PROJECT

Goal of HL-LHC project:

- 250 – 300 fb^{-1} per year
- **3000 fb^{-1} in about 10 years**

Around 300 fb^{-1} the present Inner Triplet magnets reach the end of their useful life (due to radiation damage) and must be replaced.

The High Luminosity LHC (HL-LHC)

Goal of High Luminosity LHC (HL-LHC):

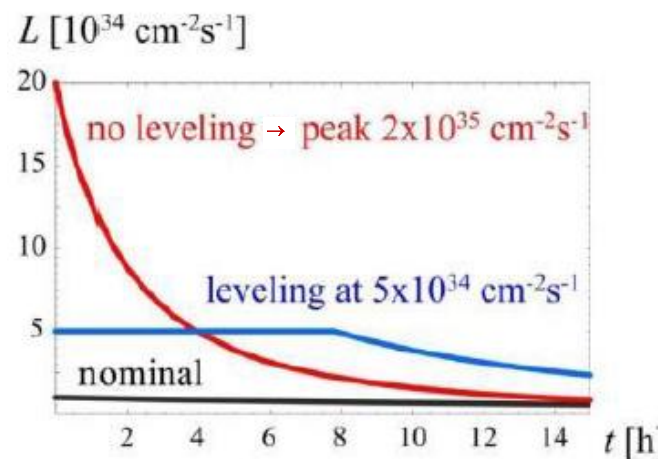
The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

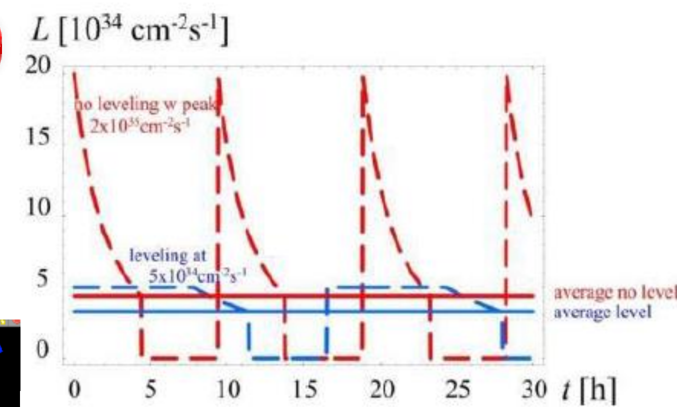
Prepare machine for operation **beyond 2025 and up to 2035-37**

Devise beam parameters and operation scenarios for:

- #enabling a total integrated luminosity of **3000 fb^{-1}**
- #implying an integrated luminosity of **250-300 fb^{-1} per year**,
- #design for μ ~ **140 (~ 200)** (➔ peak luminosity of **5 (7) 10^{34} cm^{-2} s^{-1}**)
  pile-up density (<1.3 events/mm)
- #design equipment for 'ultimate' performance of **7.5 10^{34} cm^{-2} s^{-1}** and **4000 fb^{-1}**

=> Ten times the luminosity reach of first 10 years of LHC operation





LHC accelerator overviw
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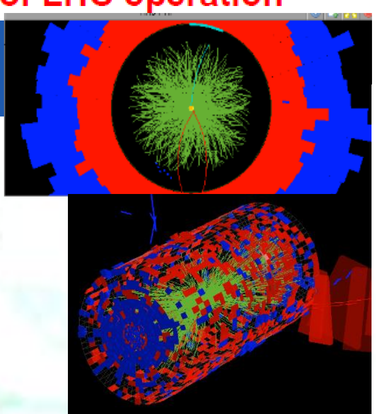
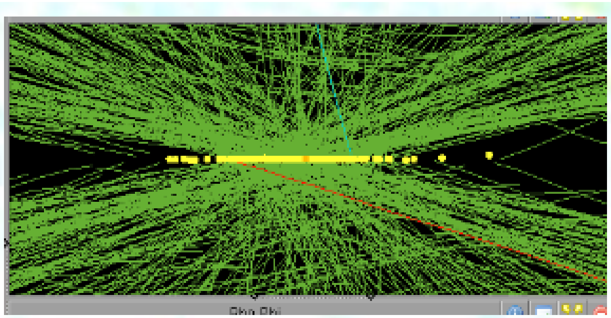
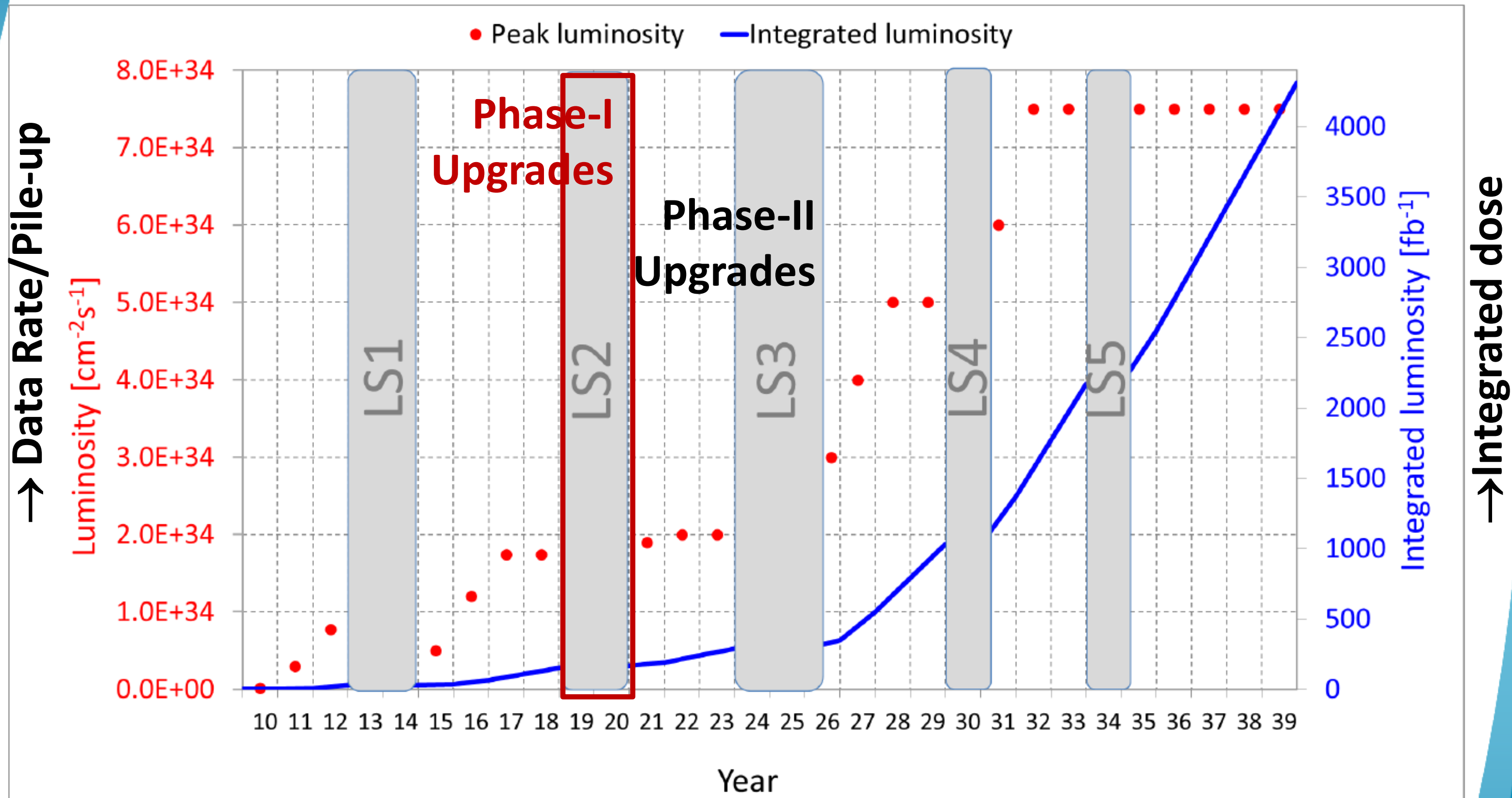




Even with "luminosity levelling", 200 superimposed collisions every 25ns is a huge challenge for the experiments

The High Luminosity LHC (HL-LHC)

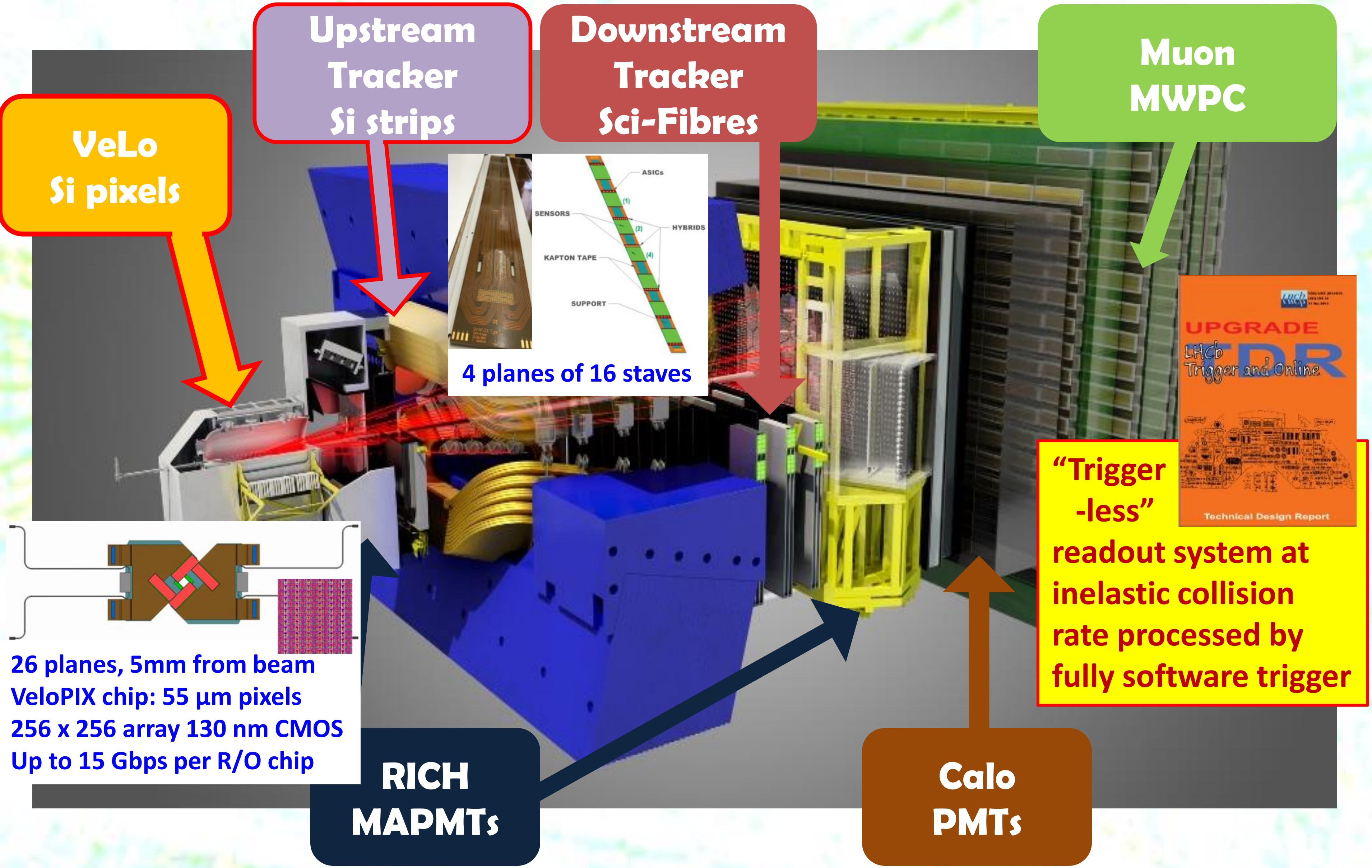
Luminosity profile: ULTIMATE



After LS4, proton physics days increase from standard 160 days to 200 and after LS5 to 220

L. Rossi - HL-LHC Intro - 3rd HiLumi Industry Day, Warrington, 22 May 2017 5

LHCb: Phase-I Upgrades



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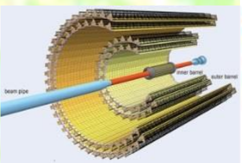
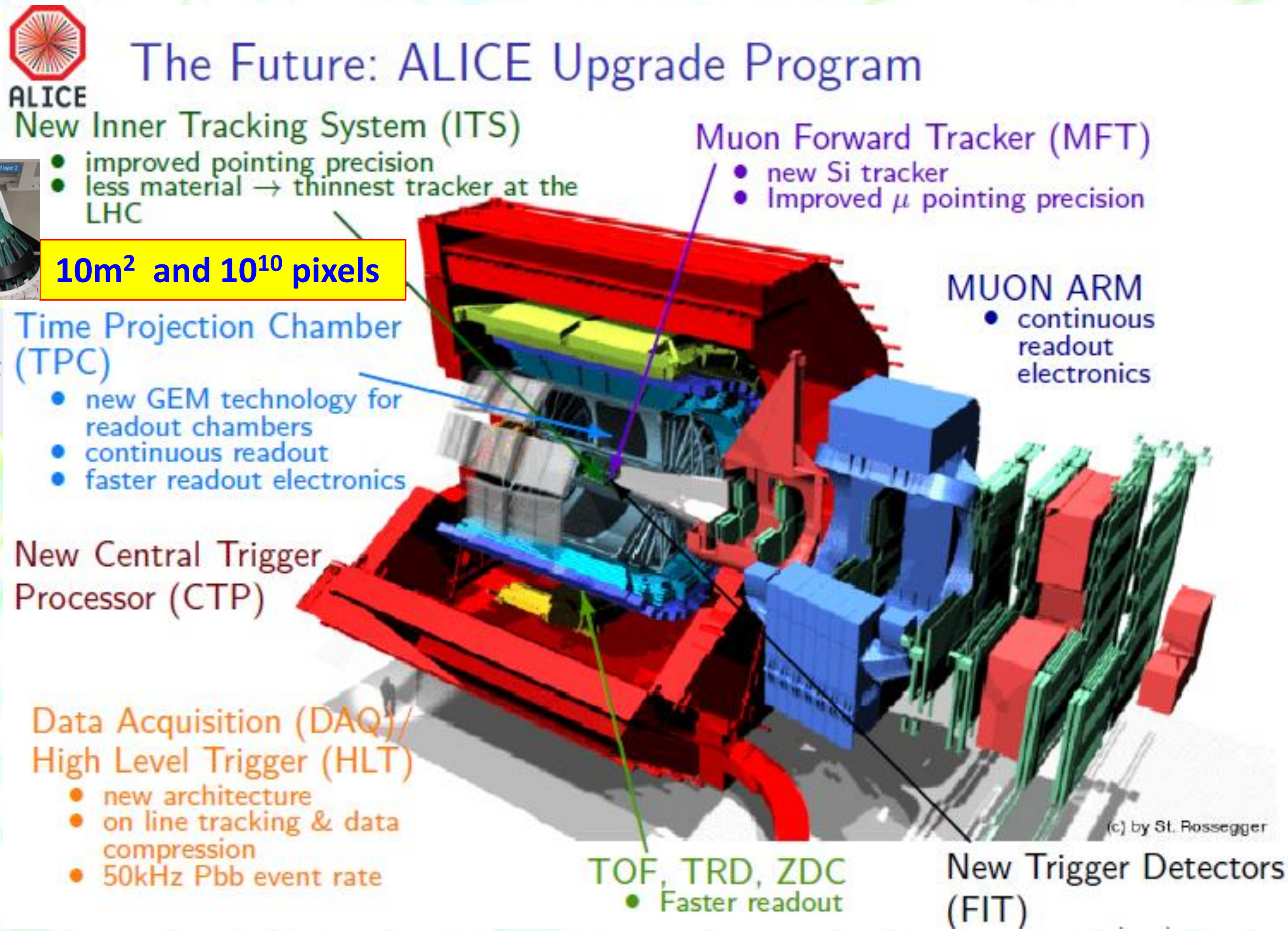
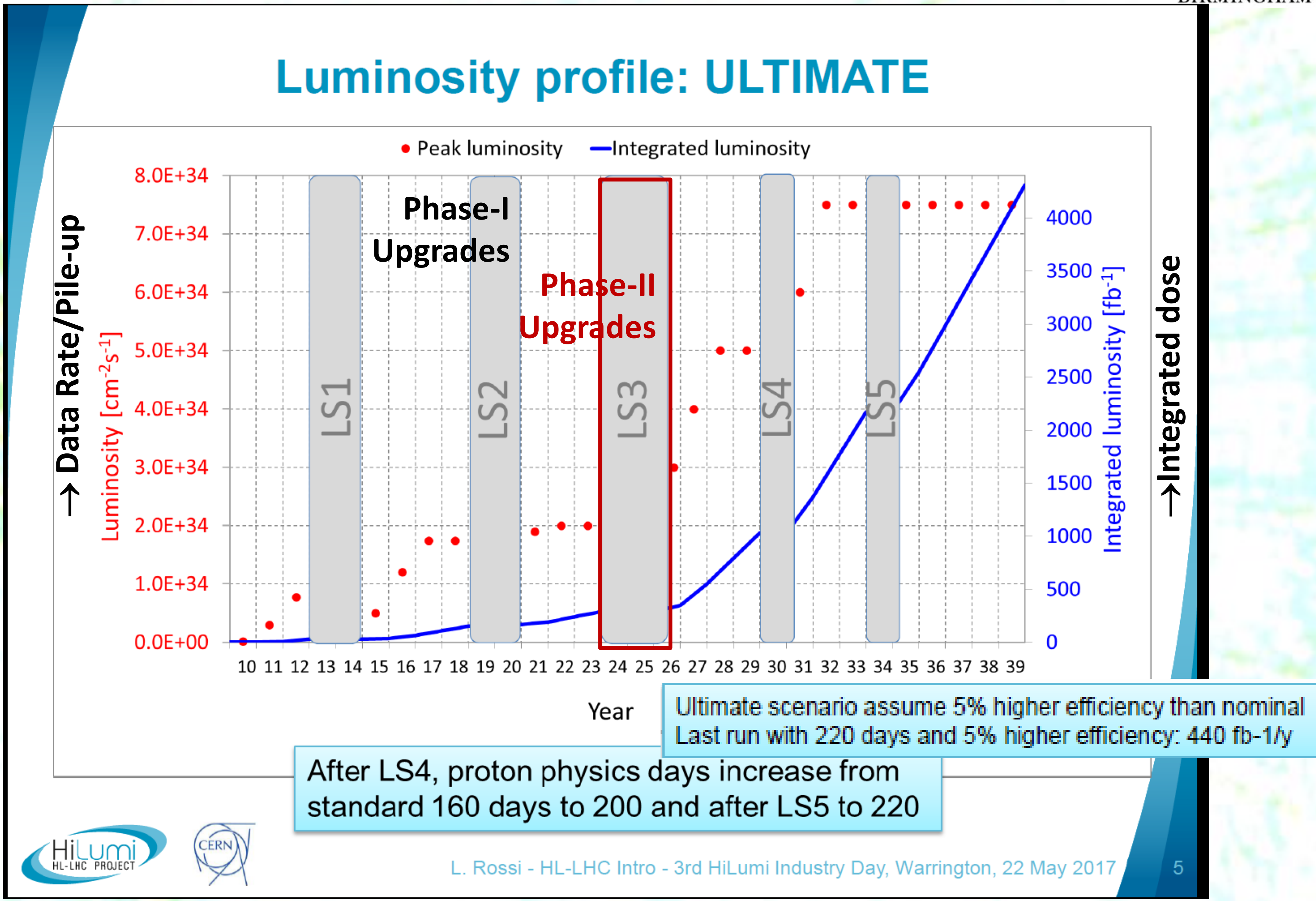
ALICE: Phase-I Upgrades



10m^2 and 10^{10} pixels



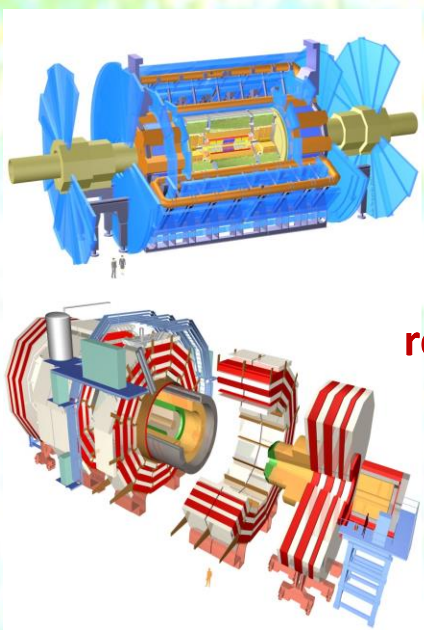
The High Luminosity LHC (HL-LHC)



Phase II Experiment Upgrades:
The Ship of Theseus

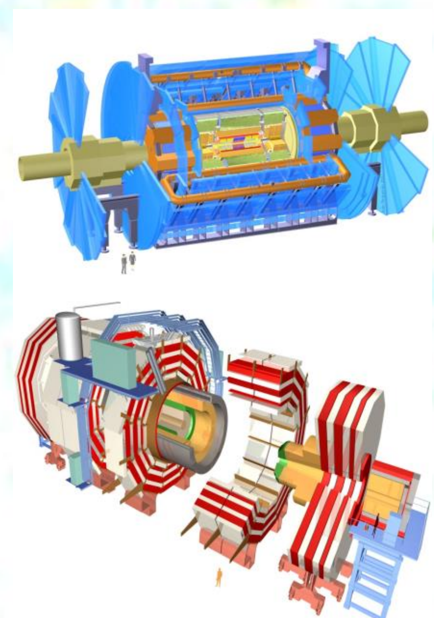
"The ship wherein Theseus and the youth of Athens returned from Crete had thirty oars, and was preserved by the Athenians down even to the time of Demetrius Phalereus, for they took away the old planks as they decayed, putting in new and stronger timber in their place, in so much that this ship became a standing example among the philosophers, for the logical question of things that develop; one side holding that the ship remained the same, and the other contending that it was not the same."

- Plutarch

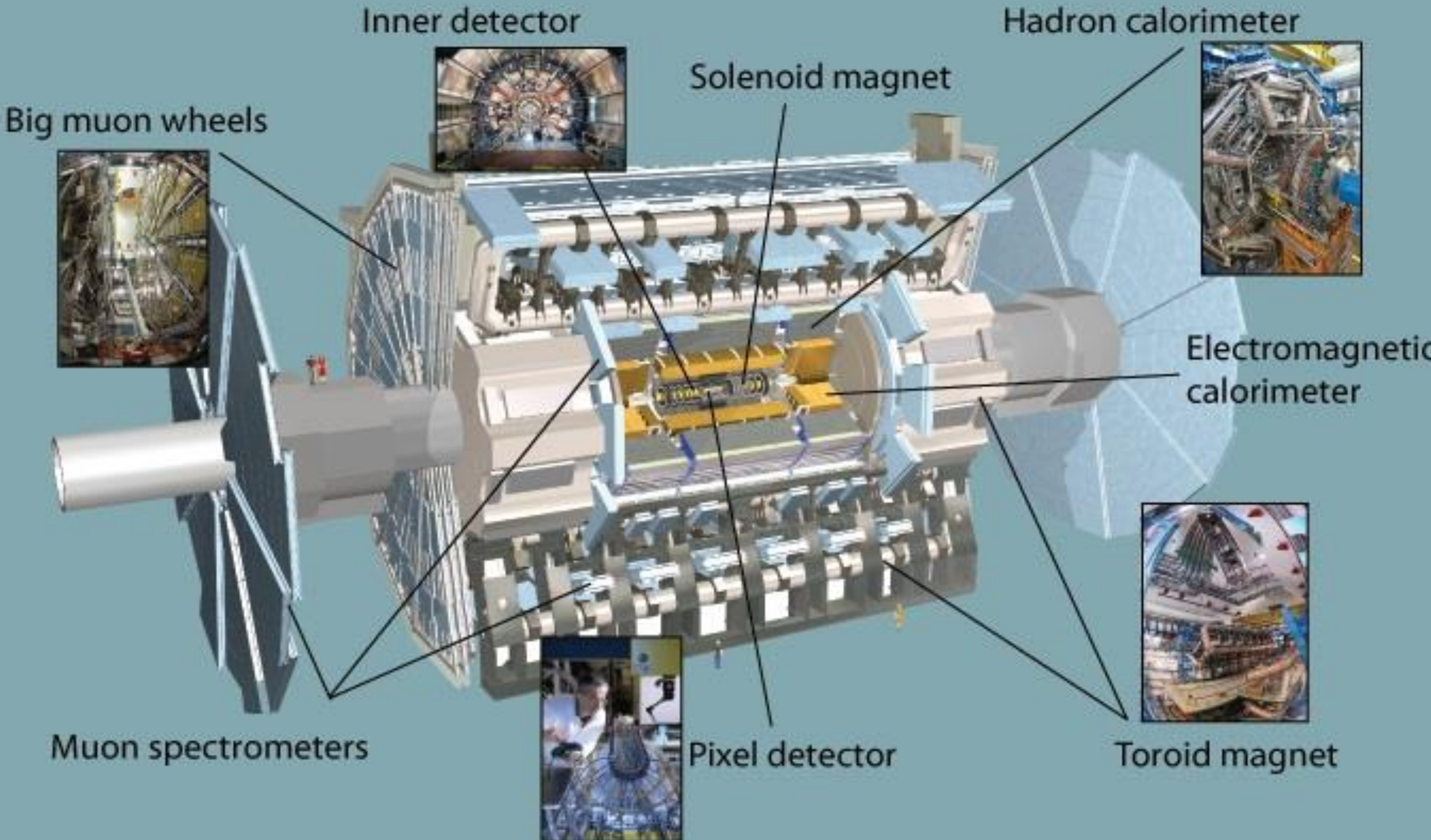


Phase-II

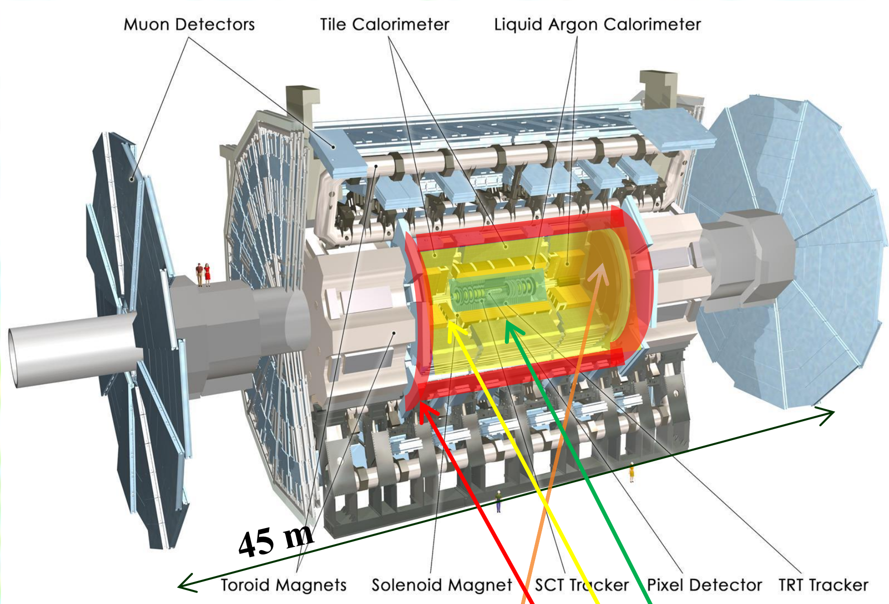
(In practice the task is more analogous to crews having to rebuild their ships while at sea)



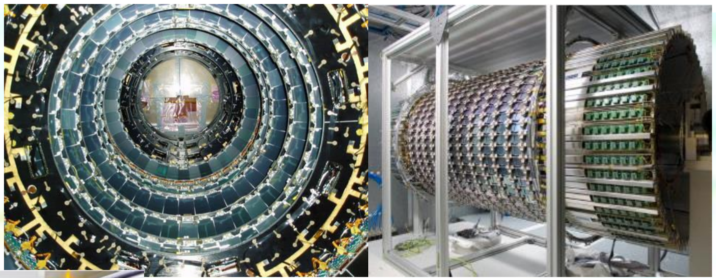
ATLAS is a collaboration of around 3000 scientific authors from 183 universities and laboratories in 38 countries including 12 from China and typically has ~1200 PhD students (see cern.ch/ATLAS)



ATLAS: Phase-II Upgrades

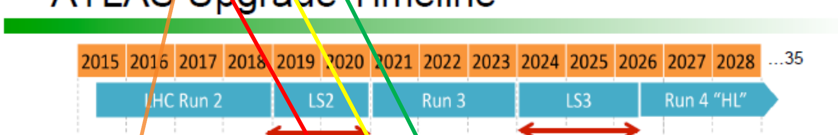


Current ATLAS Strip Tracker (SCT)

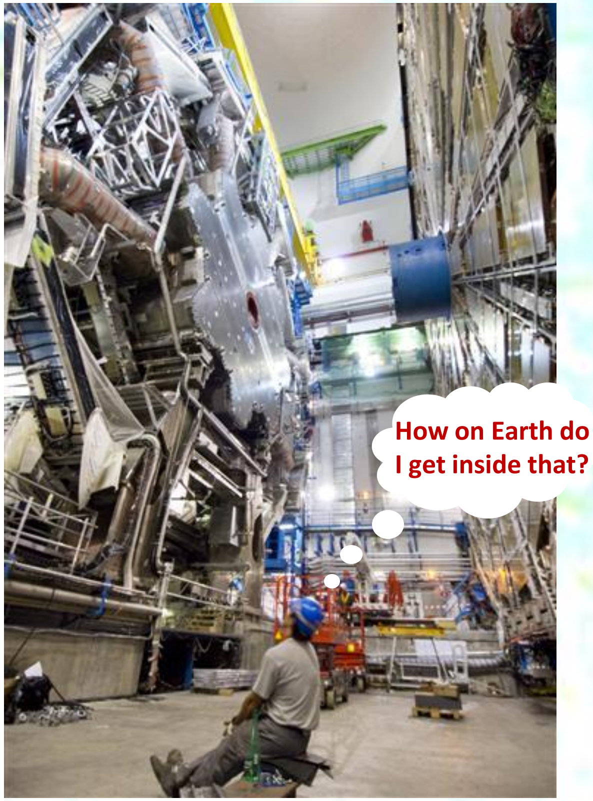


Current Outer Pixel

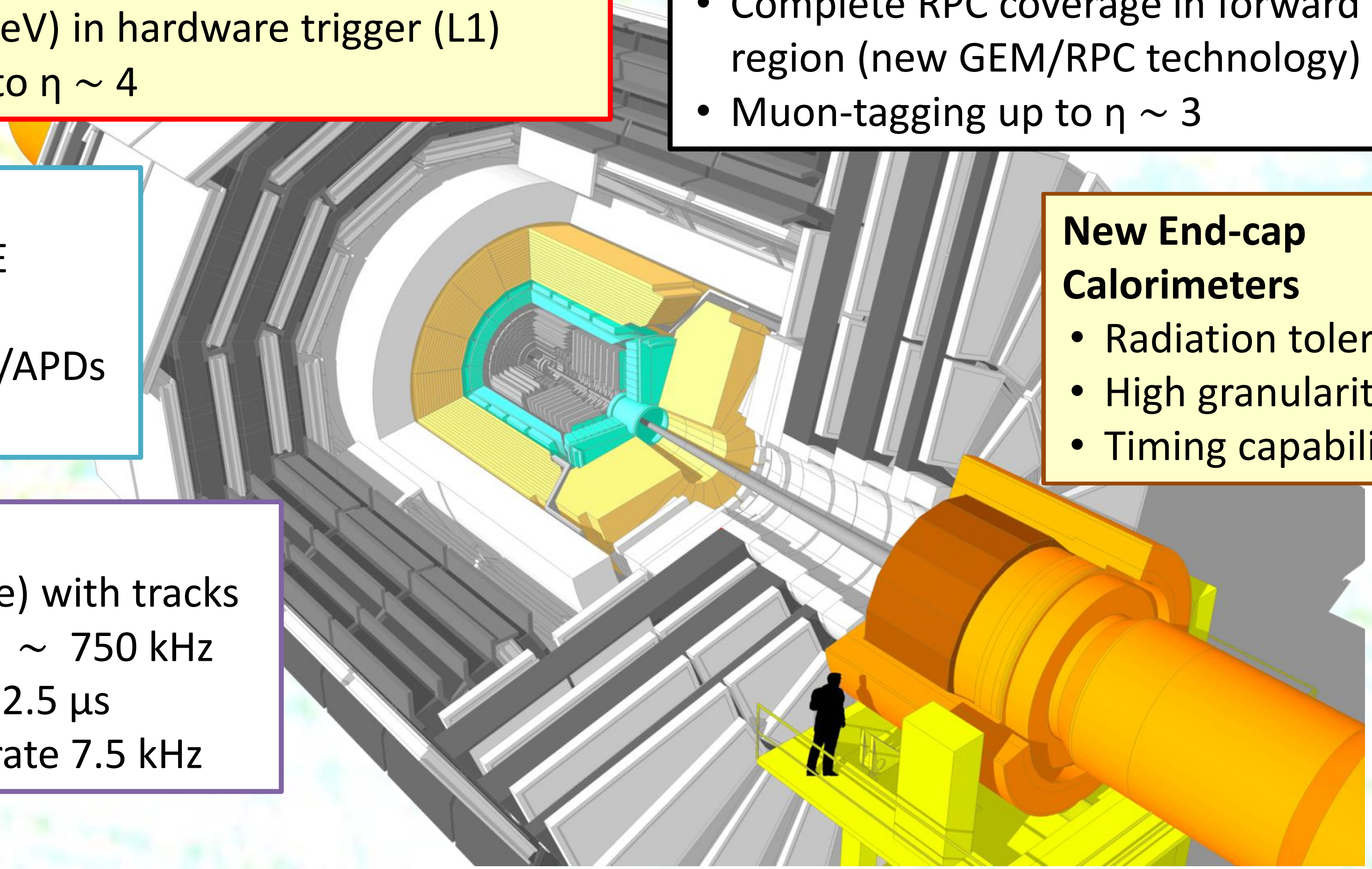
ATLAS Upgrade Timeline



Phase-1 Upgrade	Phase-2 Upgrade
L = 2e34 (μ~60) int L = 200 fb^{-1}	L = 7.5e34 (μ~200) int L = 3000 fb^{-1}
• New Muon Small Wheel (NSW) • Fast Track Trigger (FTK) • TDAQ Phase-1 • LAr Calorimeter Electronics • ATLAS Forward Protons (AFP)	• All new Tracking Inner Detector (ITk-Strip/Pixel) • Calorimeter Electronics Upgrade • New Forward Calorimeter • Muon System Upgrade • TDAQ Phase-2



CMS: Phase-II Upgrades



New Tracker
- Radiation tolerant - high granularity - less material
- Tracks (P_T>2GeV) in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT and CSC FE/BE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Muon-tagging up to η ~ 3

Barrel ECAL
- Replace FE/BE electronics
- Cool detector/APDs
- Timing layer

New End-cap Calorimeters
- Radiation tolerant
- High granularity
- Timing capability

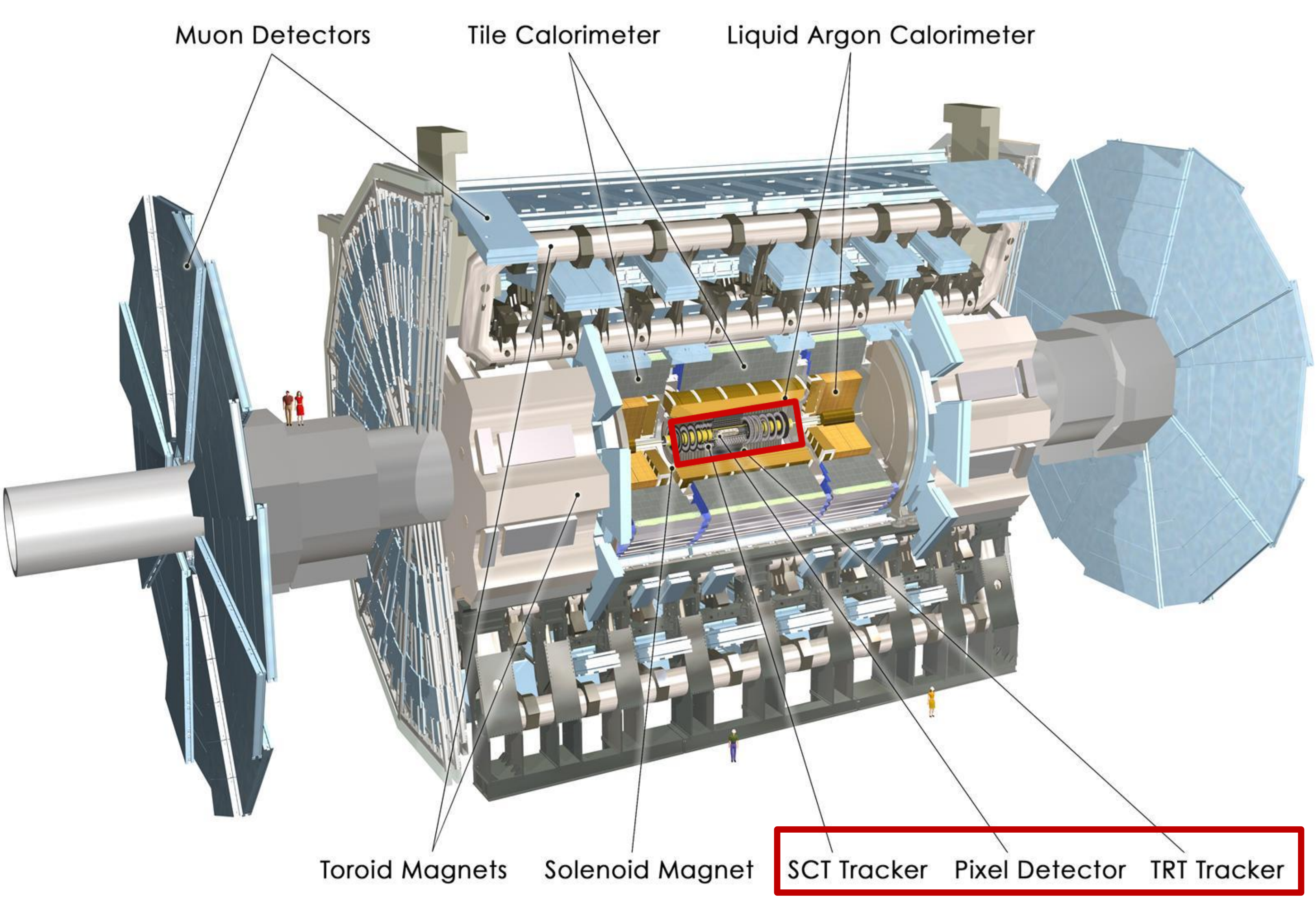
Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 µs
- HLT output rate 7.5 kHz

Strip and Pixel Technologies

- **For HL-LHC, fine granularity over large areas and minimal mass are targeted consistent with constraints of very high radiation environment, very high hit and data rates, cooling, plus complex event triggering capabilities.**
- **Vertex detectors target finest granularity (RD53: 50µm×50 µm pixels), minimal scattering material (ALICE: <0.5% X_0/layer) and the highest radiation tolerance (ATLAS and CMS: $2\times10^{16} n_{eq}/cm^2$ and 1Grad, RD50, RD53).**
- **Large area silicon coverage for high efficiency inner detector track finding (>99% for muons), precision momentum resolution (even 30% at 1 TeV), good extrapolation outwards and into pixel layers, excellent pattern recognition even in dense jets, low material, triggering capability and highly cost effective.**
- **Systems require low mass cooling and compact, radiation-hard, optical plus electrical links with HV/LV multiplexing (very large numbers of channels running at low voltages drawing high currents → power loss in cables).**

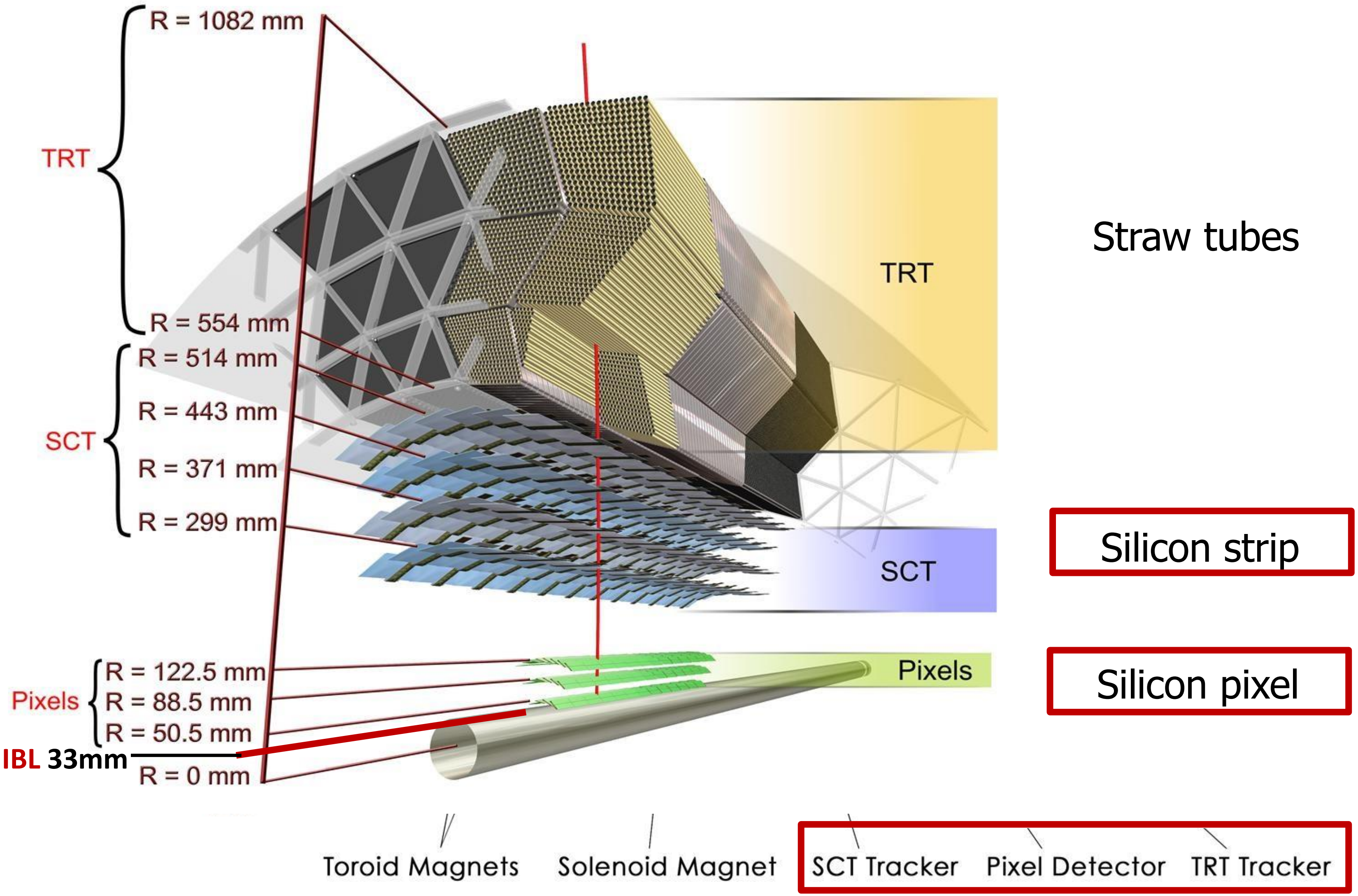
ATLAS Tracker Upgrade (ITk)

Current ATLAS Inner Detector (60m^2, 10^8 channels)



ATLAS Tracker Upgrade (ITk)

Current ATLAS Inner Detector ($60m^2$, 10^8 channels)



Straw tubes

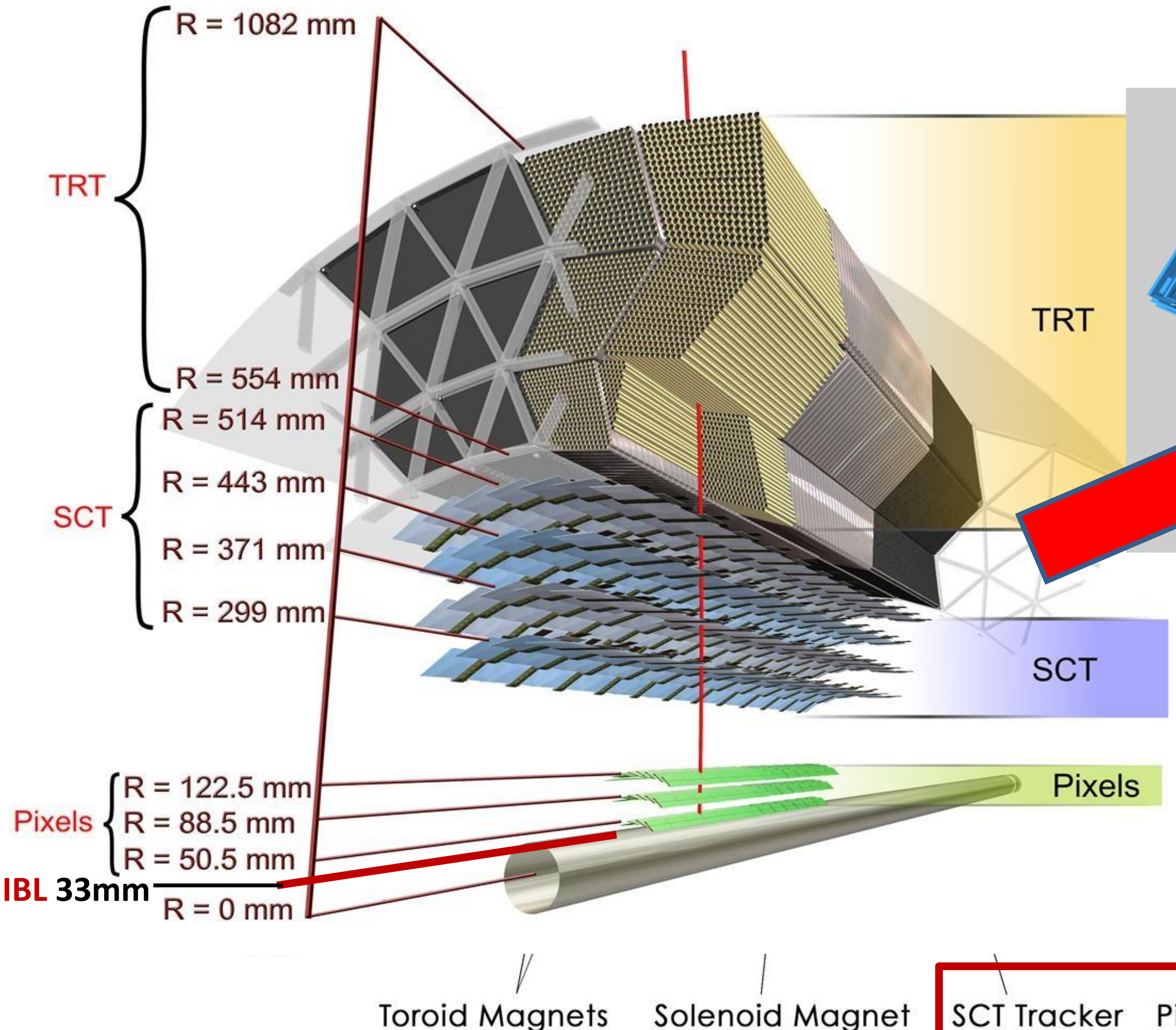
Silicon strip

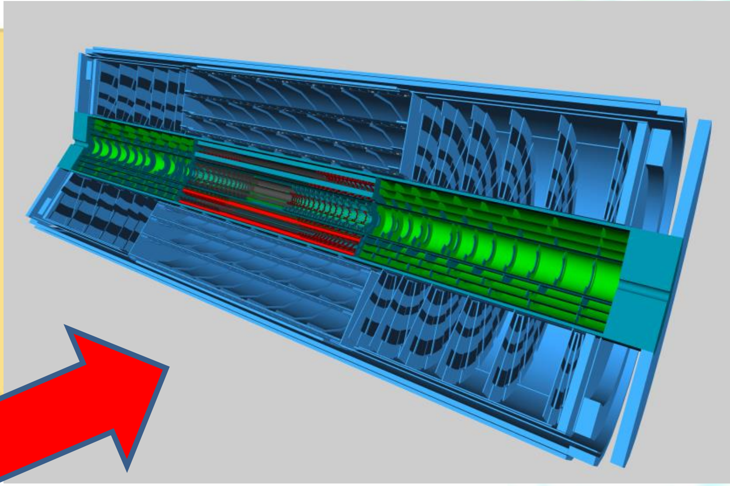
Silicon pixel

ATLAS Tracker Upgrade (ITk)

New All Silicon Inner Detector ($180m^2$, $\sim10^{10}$ channels)

Strip TDR: https://cds.cern.ch/record/2239048



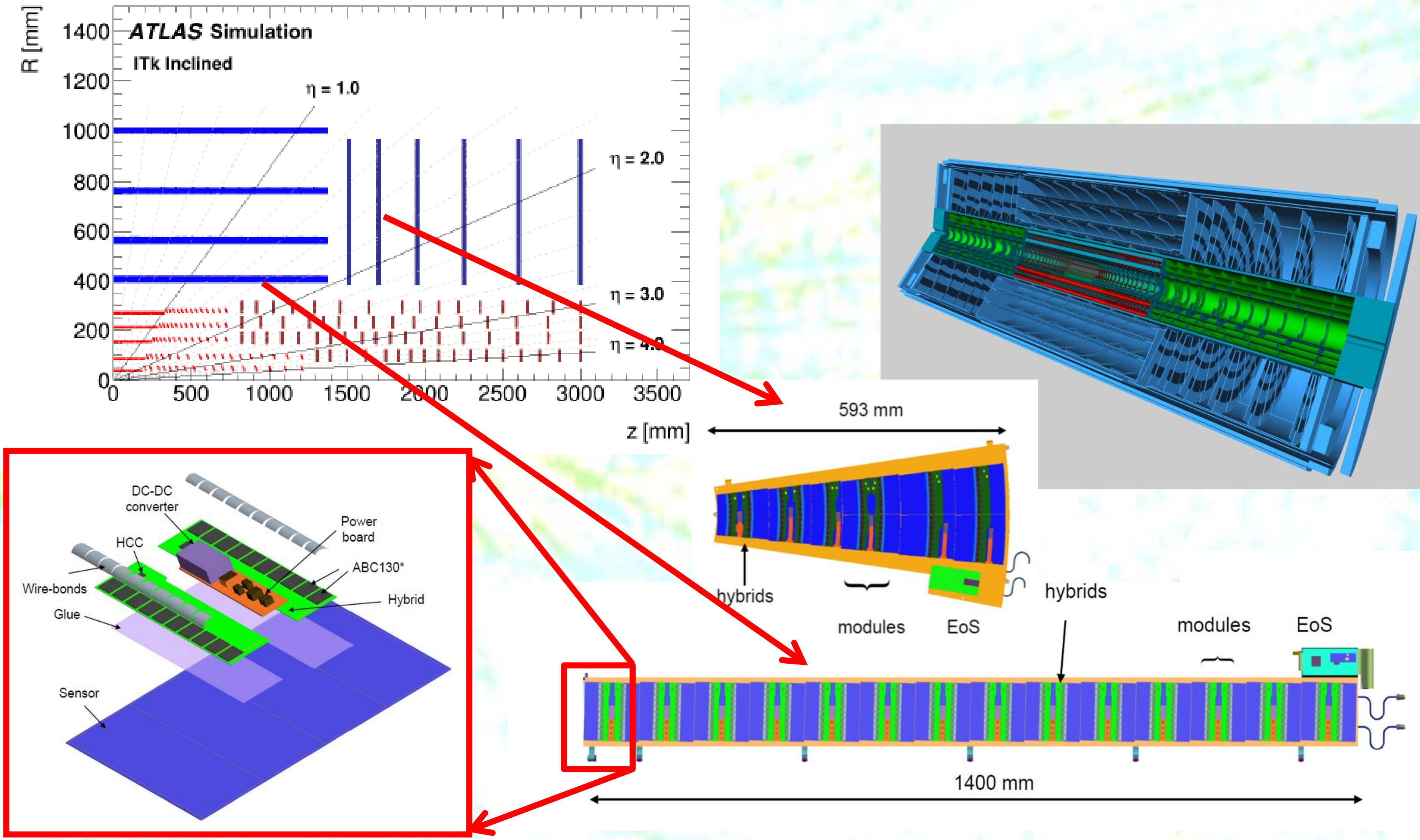


Silicon strip

Silicon pixel

ATLAS Tracker Upgrade (ITk)

New All Silicon Inner Detector (180m^2, ~10^{10} channels)



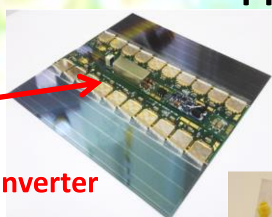
ATLAS Tracker Upgrade (ITk)

Single-sided modules sandwiched around low mass structures

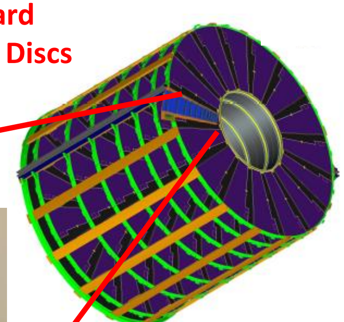
256 Channel ASICs (4 row wire bonding) in 130nm CMOS with L0/L1 functionality

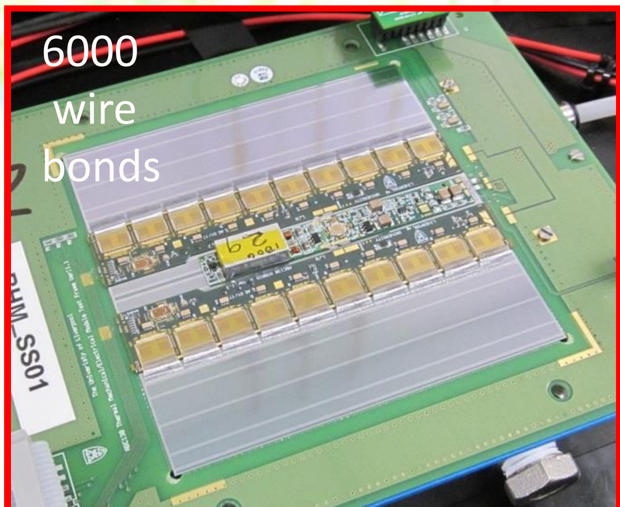
Powering (DC/DC strip Serial pixel), HV multiplexing, CO_2 embedded cooling, low mass modular supports & services

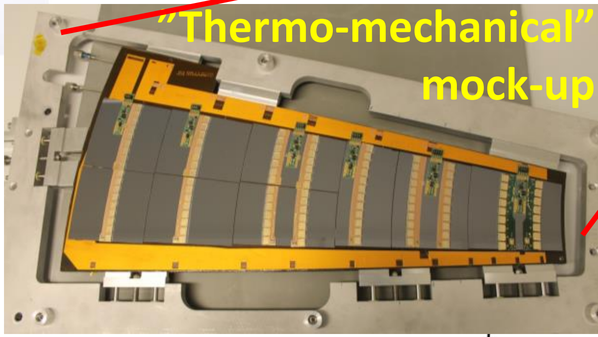
Module with on-board DC-DC converter

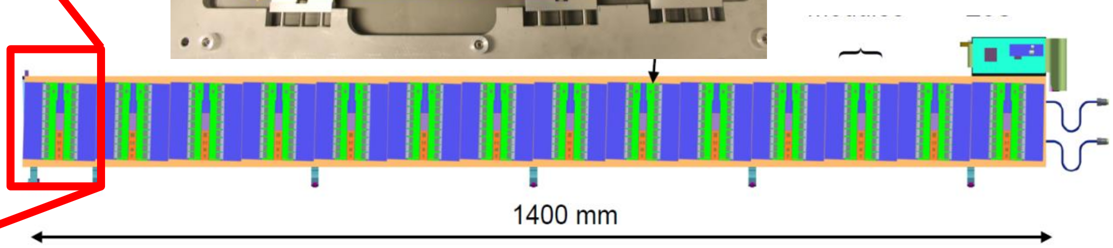


ATLAS Forward Wedges and Discs









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ATLAS Tracker Upgrade (ITk)

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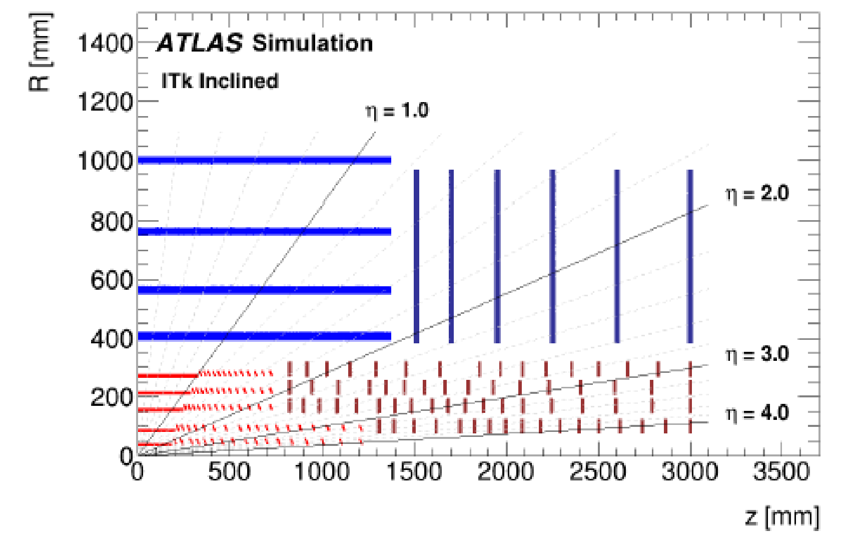
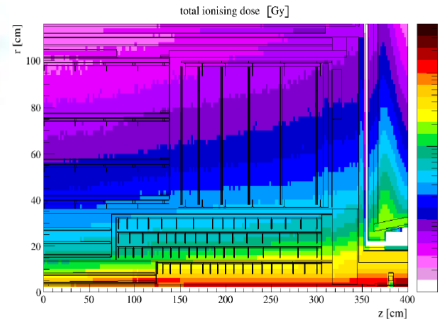
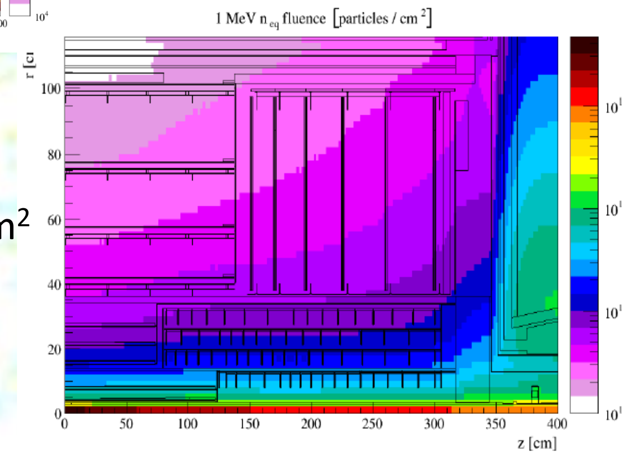
Strips: 165m^2, 6×10^7 channels



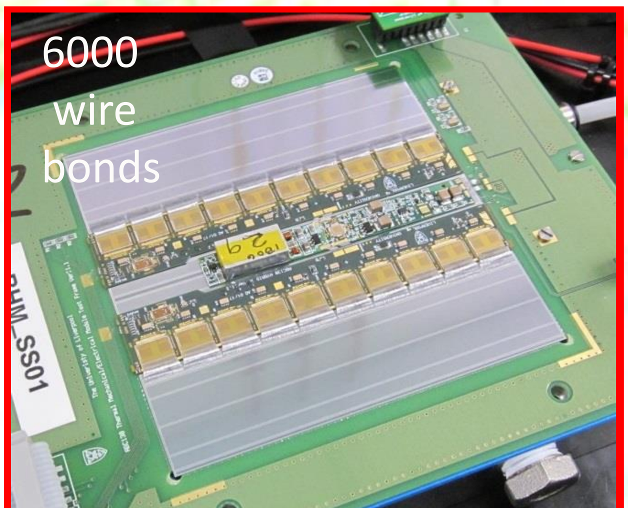


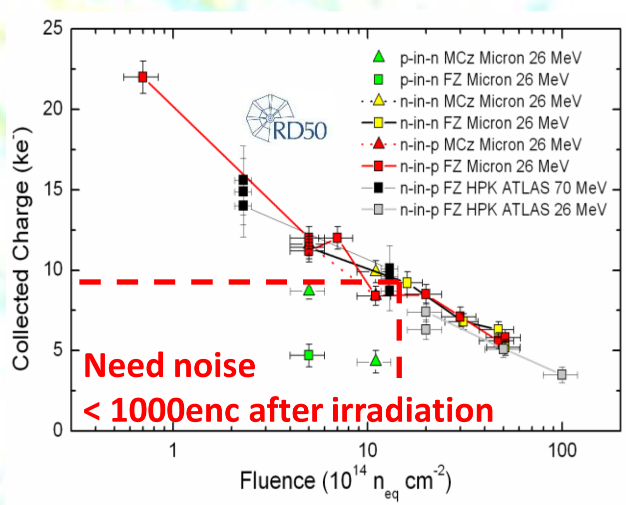
Unprecedented levels of radiation at HL-LHC

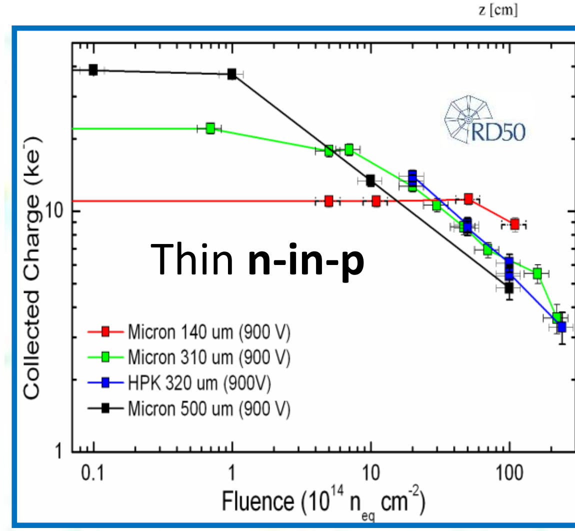


Strip detectors must survive damage to lattice equivalent to that from 1.2×10^{15}/cm^2 1 MeV neutrons and 0.5 MGy

(Pixels > ×10 this)







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Reliability of Modelling

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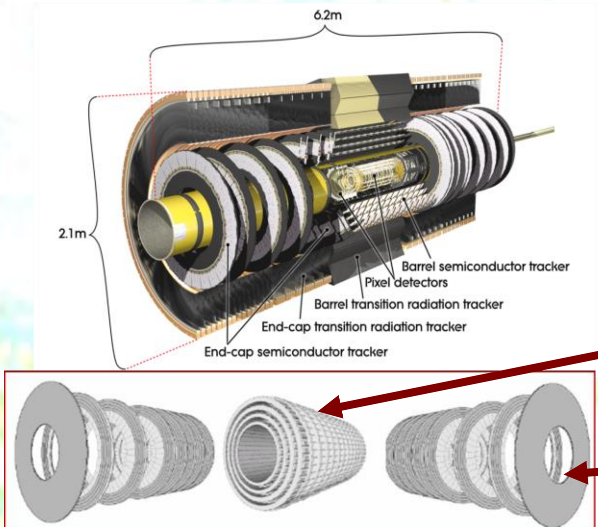
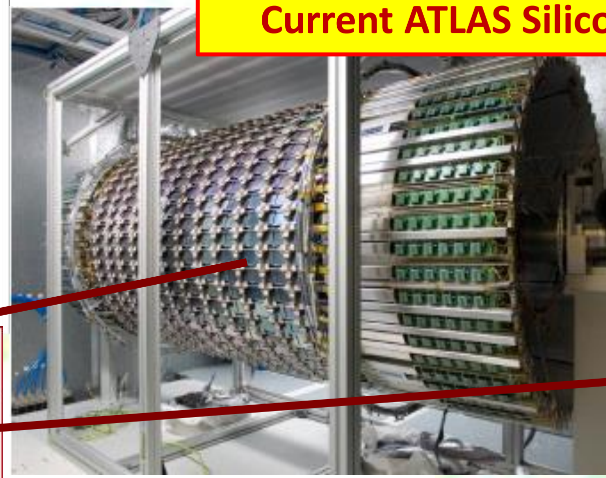
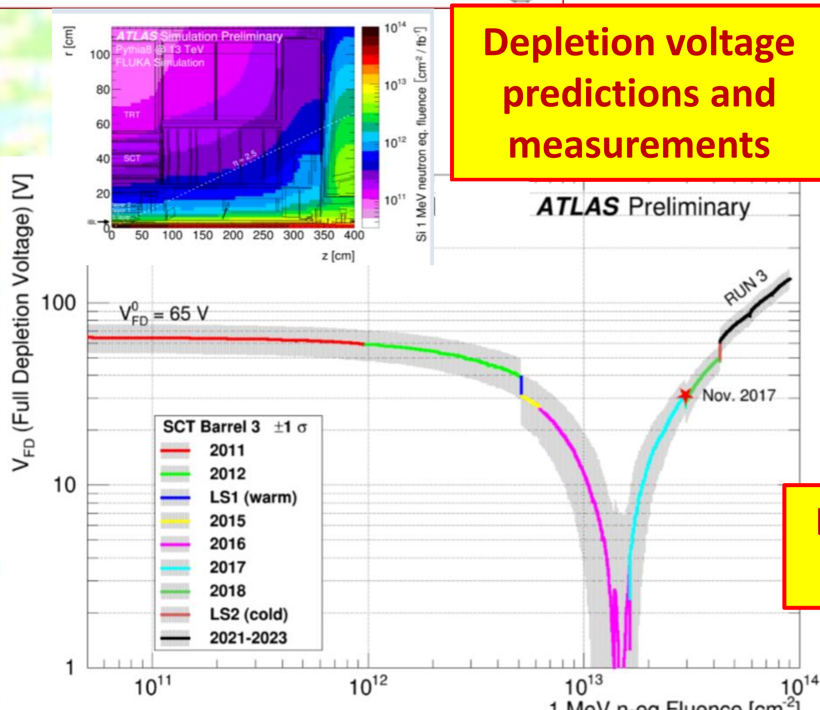
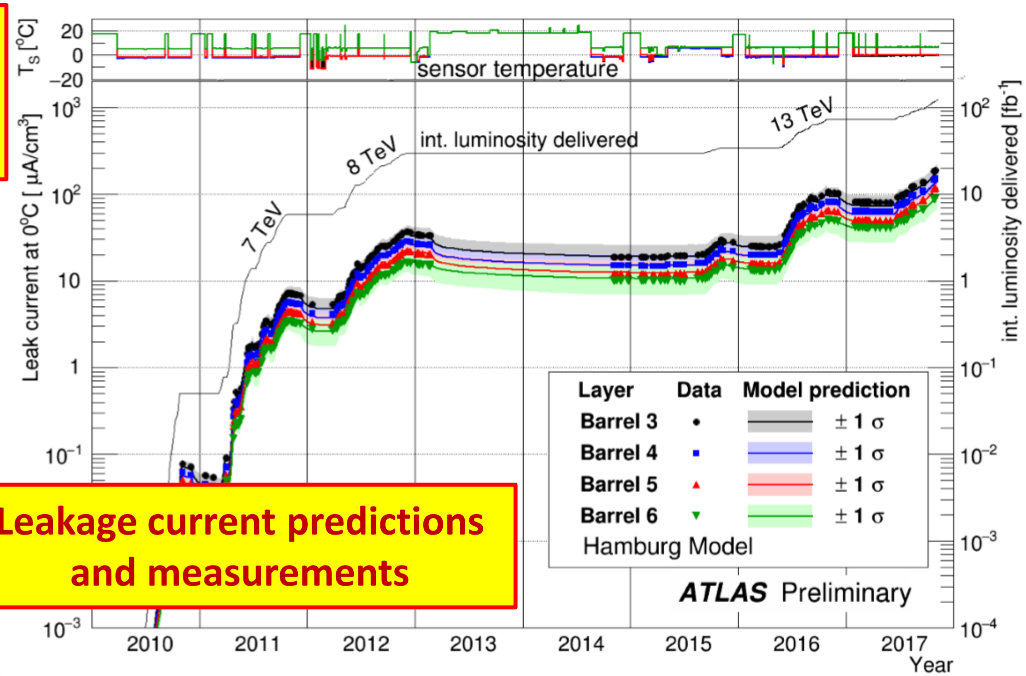


Current ATLAS Silicon Strip Tracker



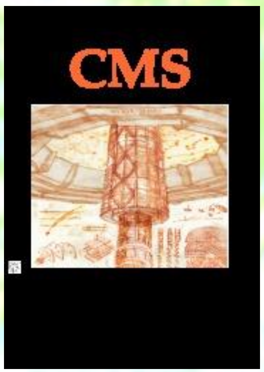
Depletion voltage predictions and measurements

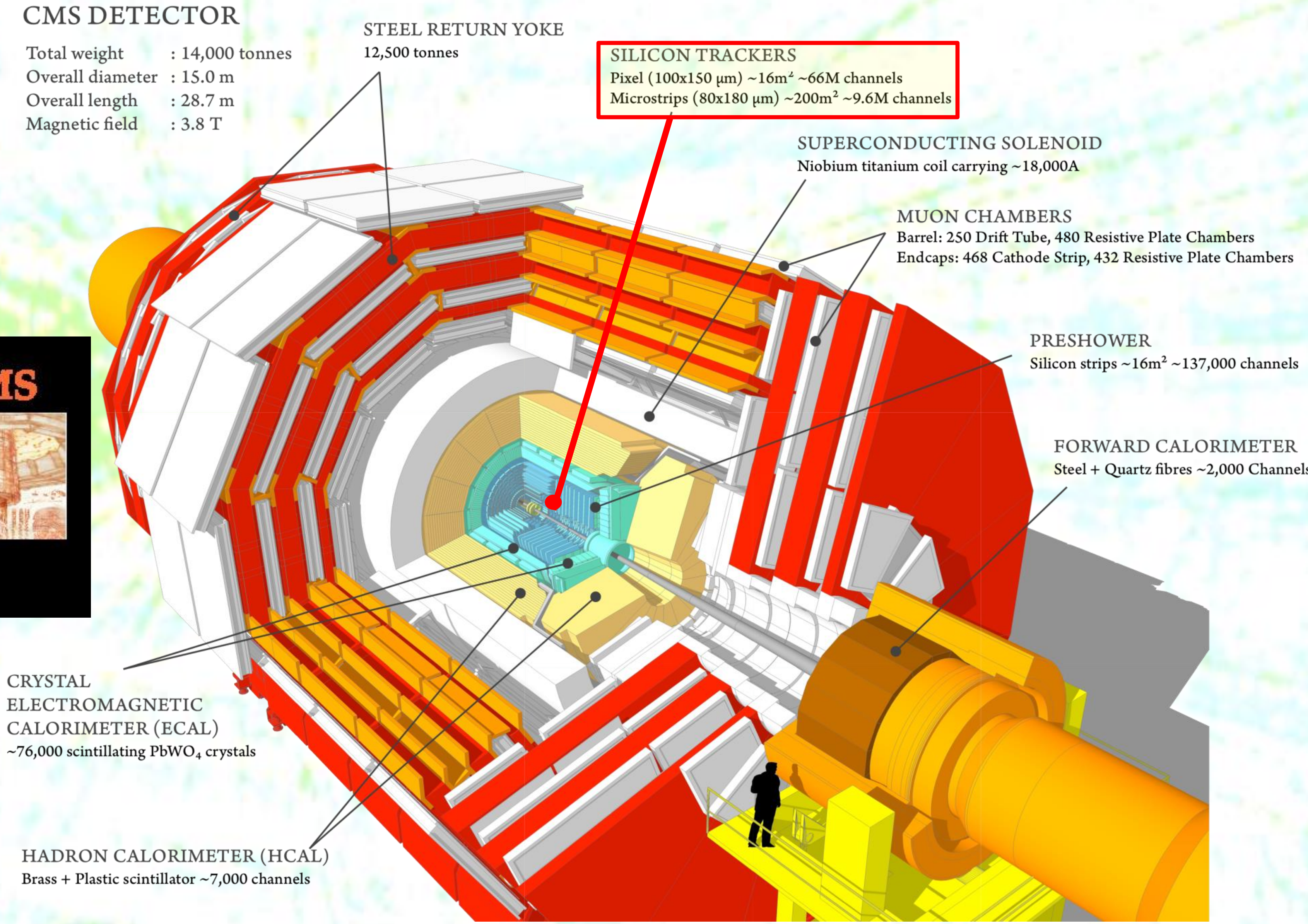




Leakage current predictions and measurements

CMS Tracker Upgrade





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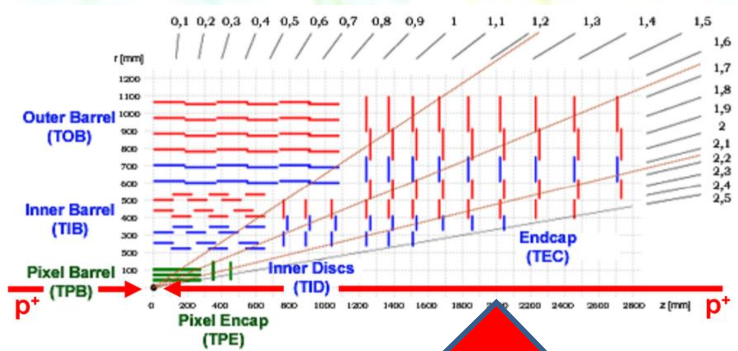
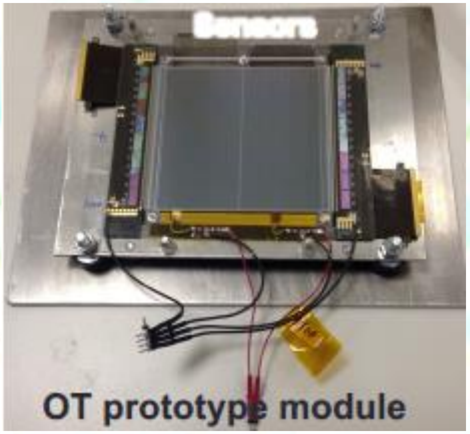
CMS Tracker Upgrade

Outer trackers need radiation hardness of current n-in-n pixel sensors at fraction of the cost

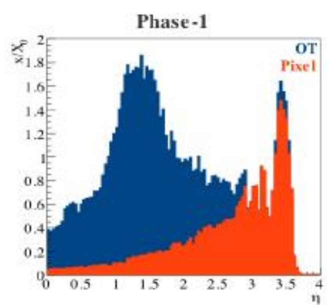
→ ATLAS/CMS: n-in-p strip technology



Many large area sensors produced for both ATLAS and CMS

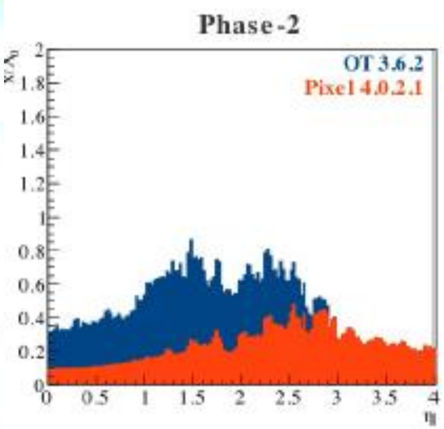


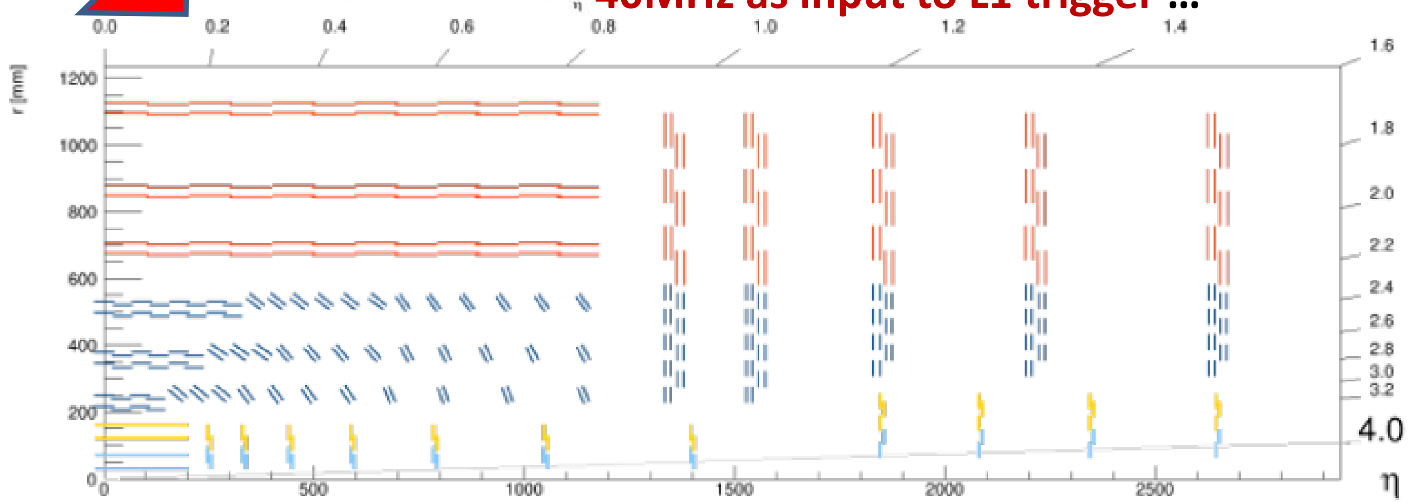
Interest in larger (8”) wafers particularly for forward regions (and HGCAL)



Greatly reduced material in tracking volume

In CMS design driven by requirement to identify all tracks with P_T>2GeV at 40MHz as input to L1 trigger …





CMS Tracker Upgrade

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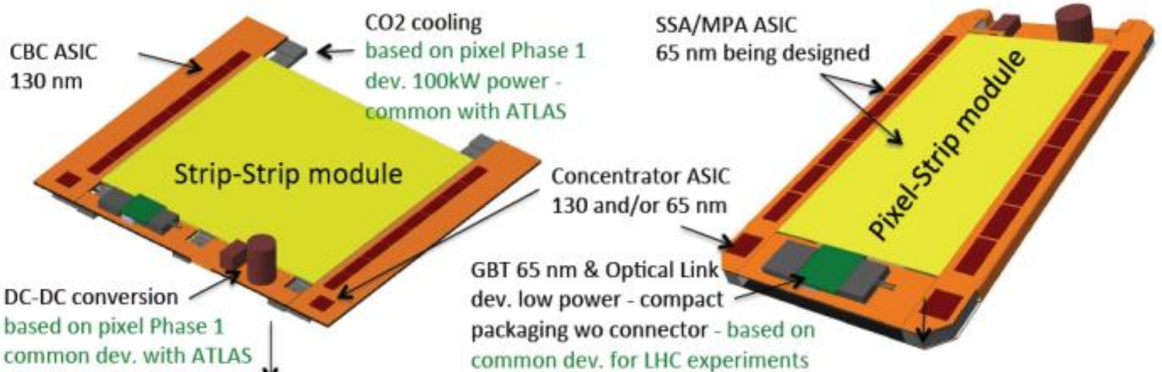
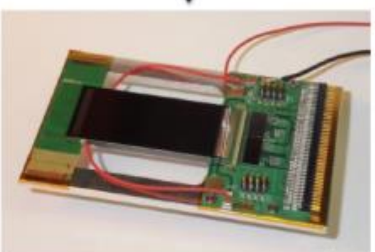
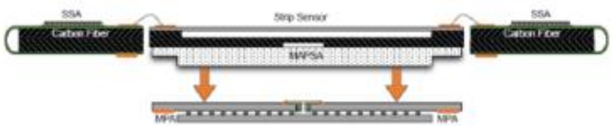
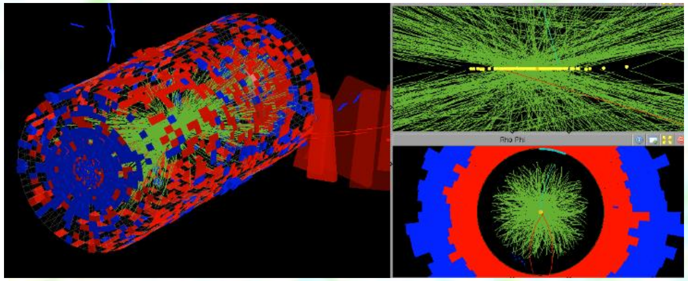
Paired layers with short strips (outer radii) and long pixels plus short strips (inner radii)

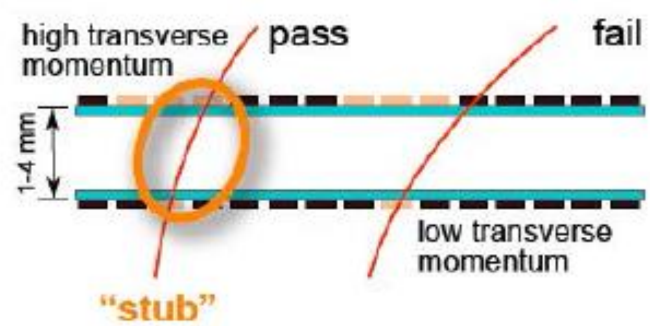






Flex hybrid - Flip-Chip assembly - possibly TSV for inter-chip connection



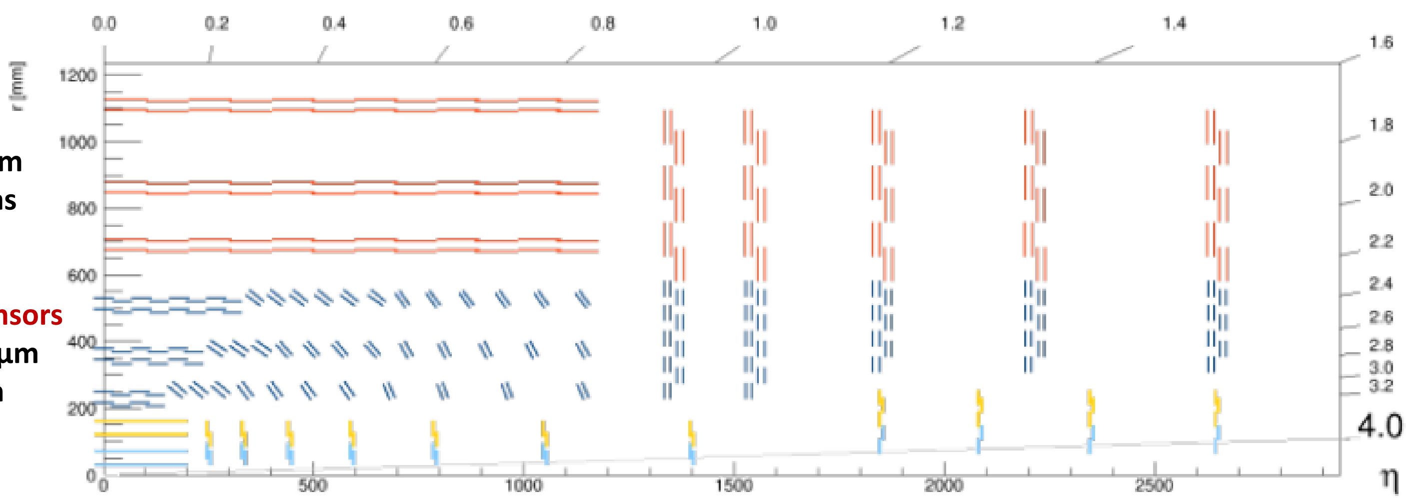


5cm x 10cm silicon strip sensors

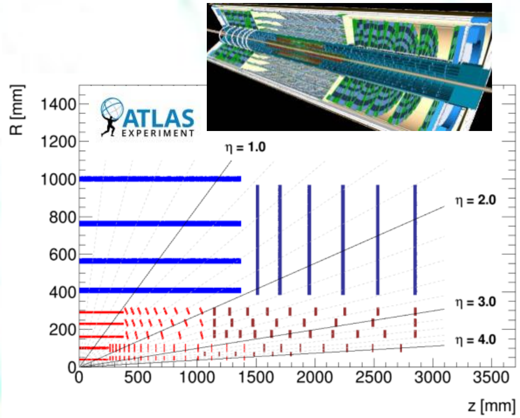
- strips: length 2.5cm, pitch 100µm
- AC coupled with poly-silicon bias resistors

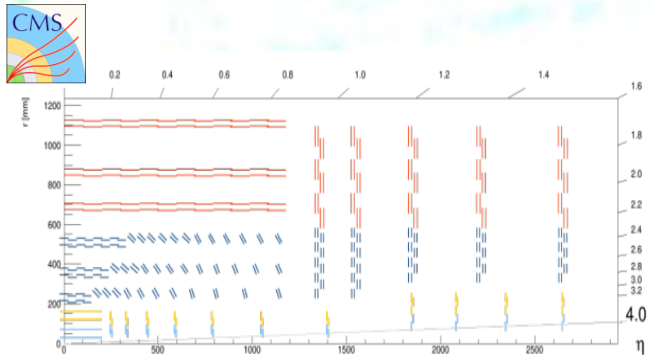
5cm x 10cm silicon macro-pixel sensors

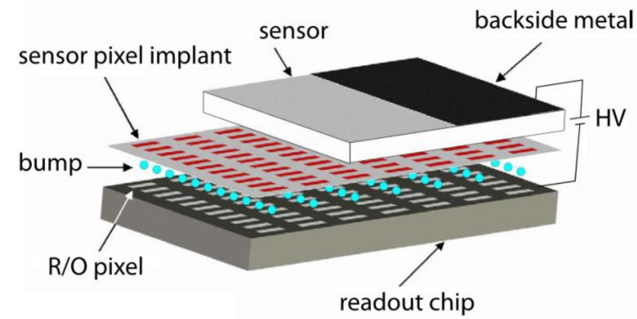
- pixels: length 1.5mm, pitch 100µm
- DC coupled with punch-through biasing



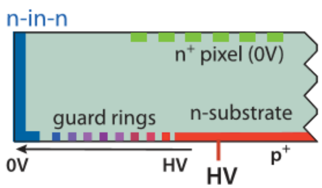
Hybrid Pixels at HL-LHC

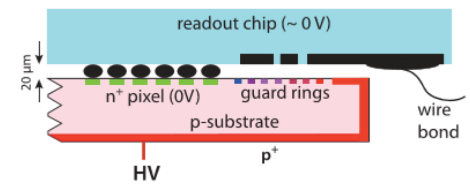


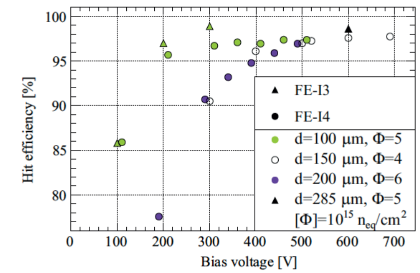


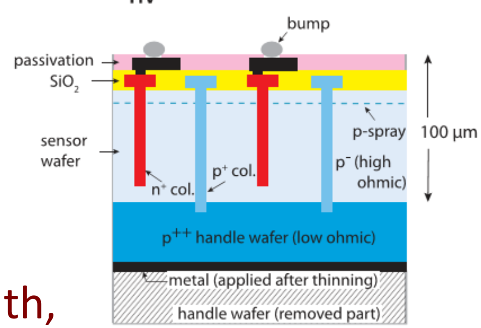


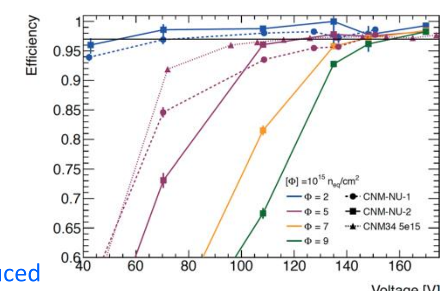
Radiation hardness to $\sim 10^{16} n_{eq}/cm^2$ and 10MGy achievable using either **thin sensors** or (at lower voltage operation) **3D sensors** with columns through substrate.







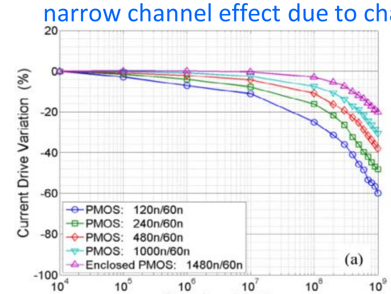


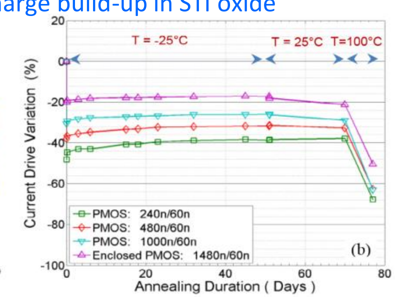


The problem is that **Grad** radiation hardness is **not** guaranteed with commercial **65nm CMOS** and depends on transistor (PMOS) channel width, temperature history, vendor and even batch to batch

Minimum feature size	250nm	130nm	65nm
Example Read-out Hybrid Pixel Chips	ATLAS FE-I3 CMS Medipix	NA62 TDCPix ATLAS IBL FE-I4 LHCb VeloPix Medipix3RX TimePix3	~~CLICpix~~ RD53A ~~TimePix4~~
Typical hit data storage density capabilities	<1Gb/s/cm^2	~5Gbp/s/cm^2	40Gb/s/cm^2
Output Bandwidth	40-160 Mb/s	0.3-1.2 Gb/s	2-20 Gb/s

Federico Faccio: Radiation induced narrow channel effect due to charge build-up in STI oxide





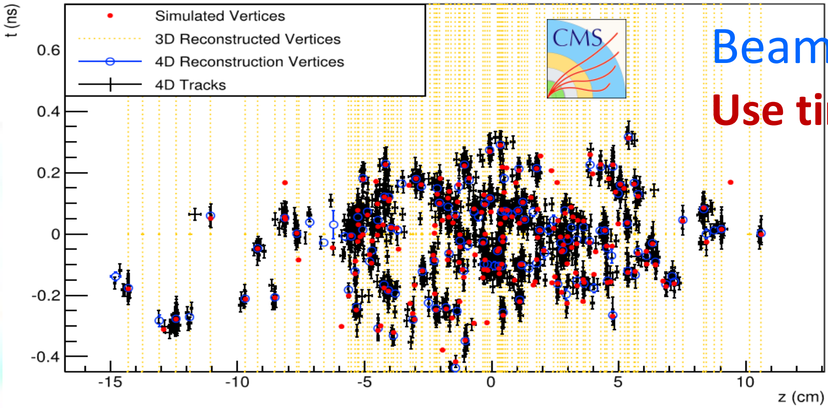
HL-LHC Timing Detectors

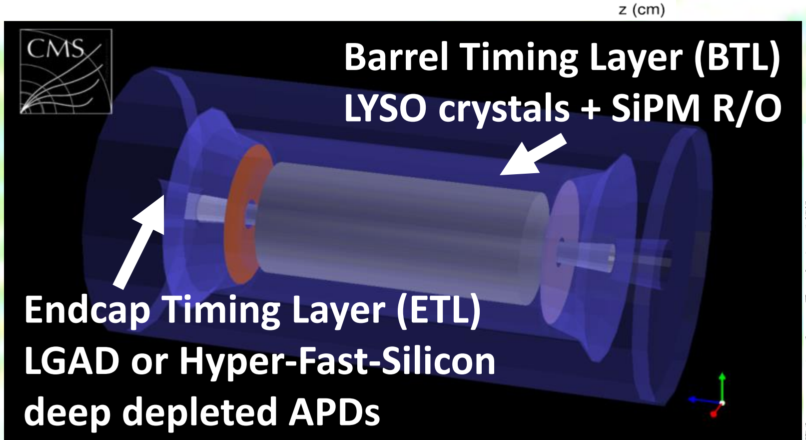
Birmingham Instrumentation Laboratory for Particle physics and Applications
BILPA

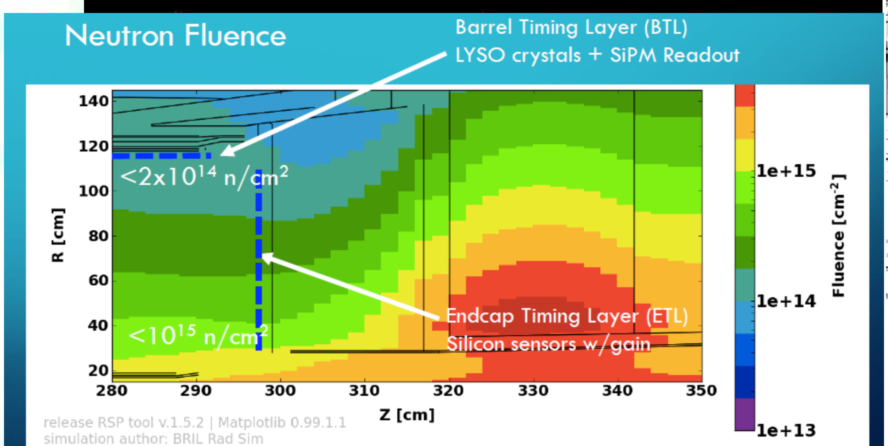
UNIVERSITY OF BIRMINGHAM

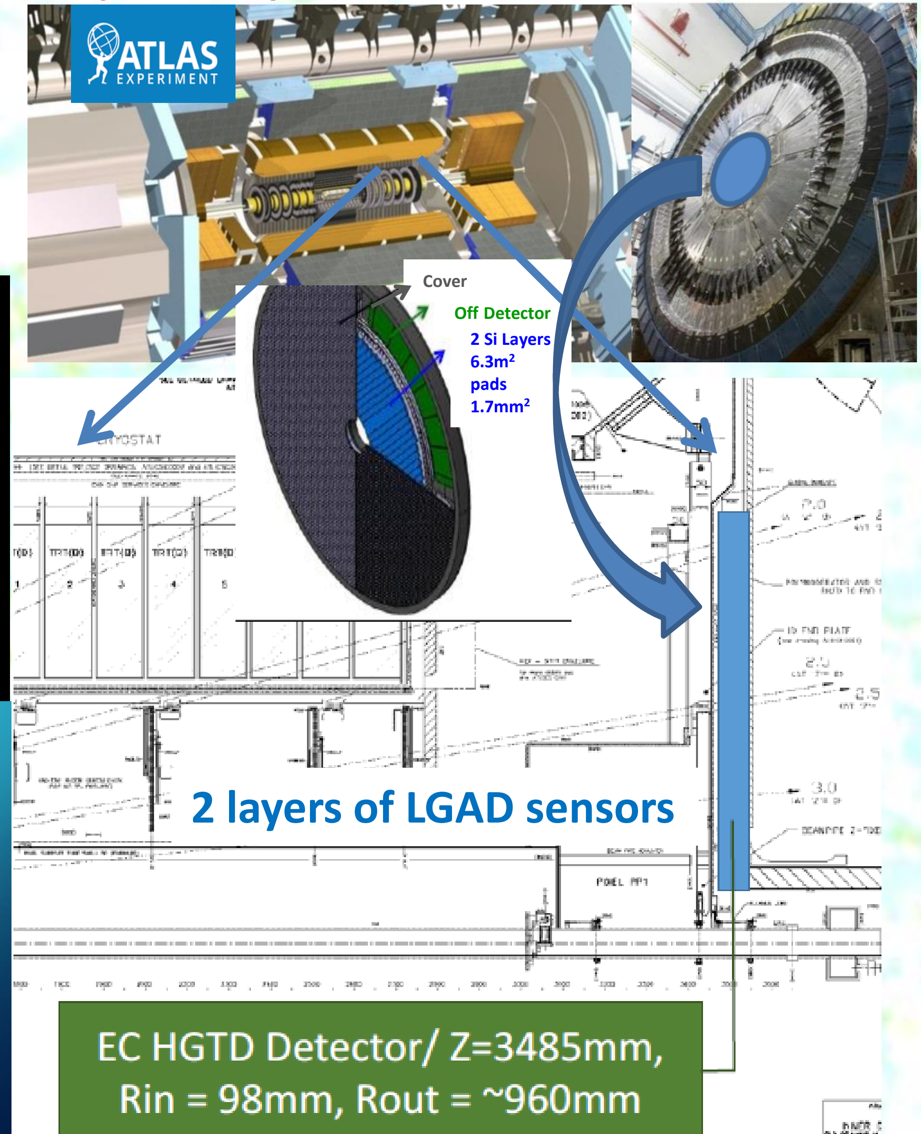
Beamspot: σ_z ~ 9 cm; σ_t ~ 0.2ns 200 pile-up

Use timing to help identify tracks with correct vertices









2 layers of LGAD sensors

EC HGTD Detector/ Z=3485mm,
Rin = 98mm, Rout = ~960mm

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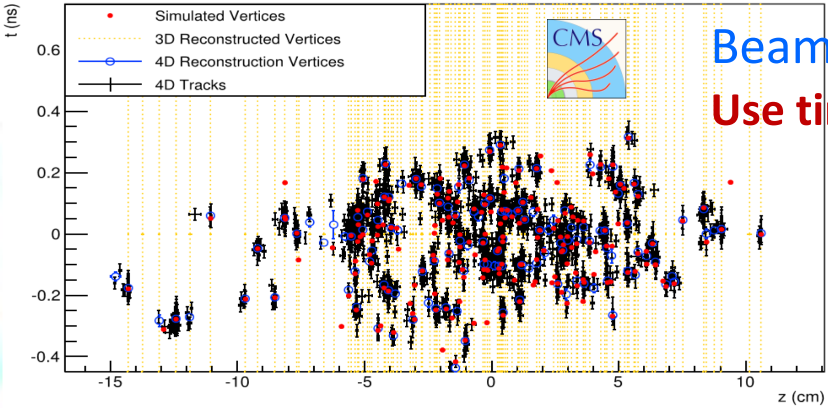

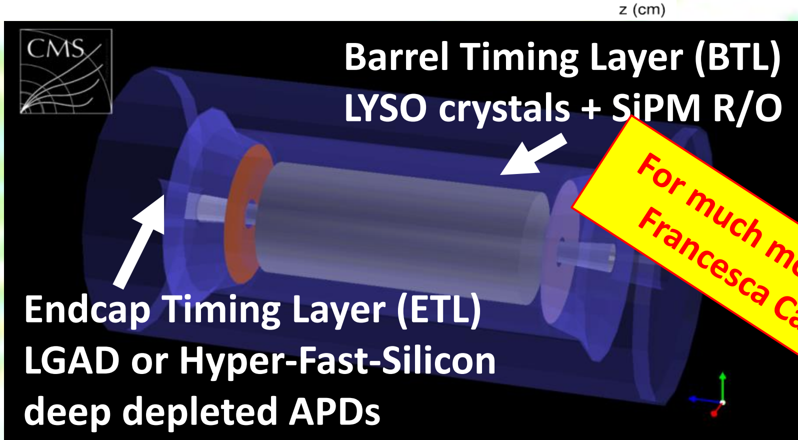

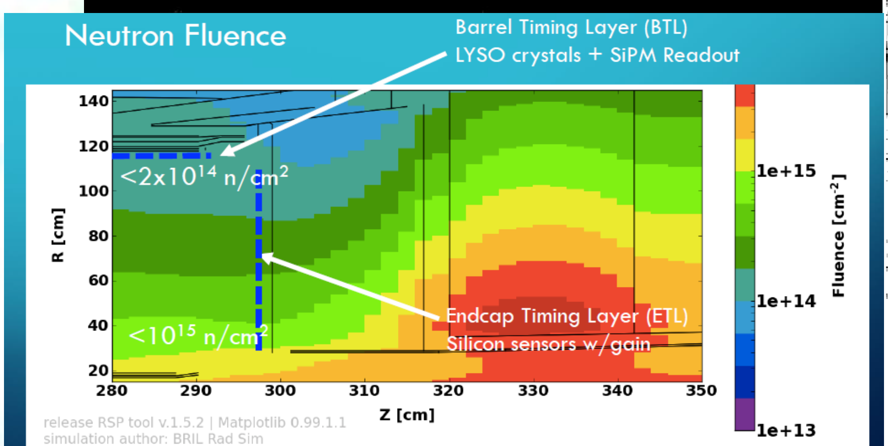

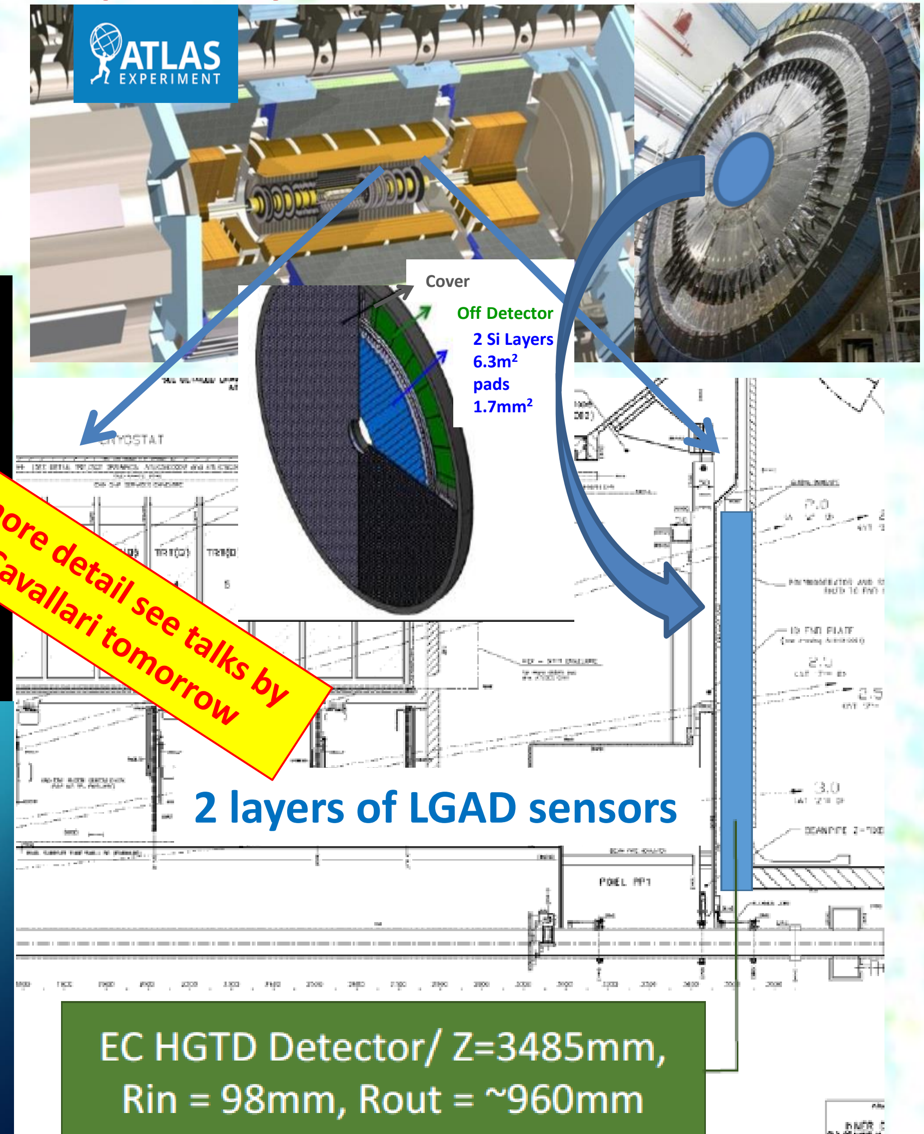

For much more detail see talks by Francesca Cavallari tomorrow

2 layers of LGAD sensors

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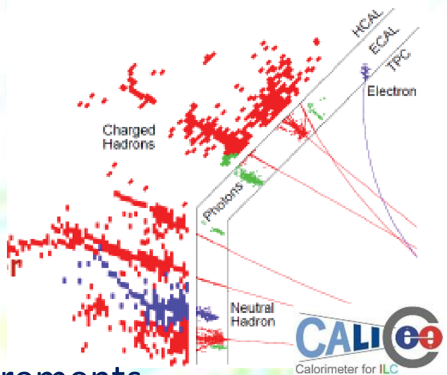
Birmingham Instrumentation Laboratory for Particle physics and Applications (BILPA)

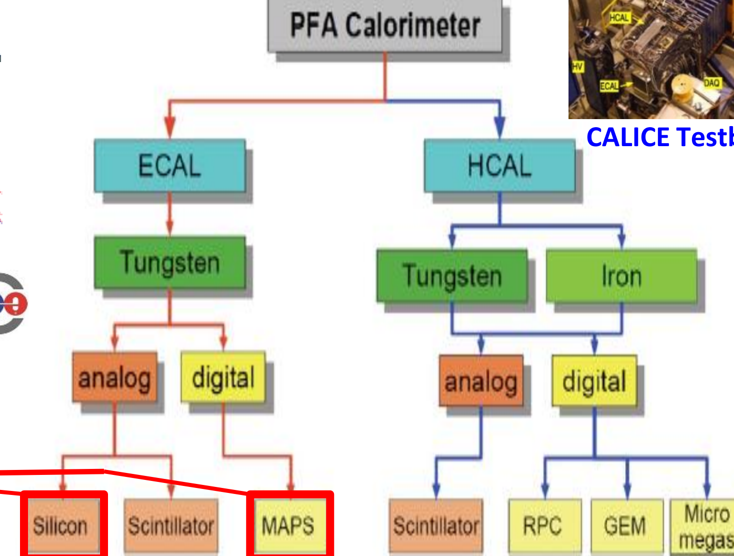
Calorimetry and Particle Flow

UNIVERSITY OF BIRMINGHAM

CALICE Testbeam

- **CALICE** (Calorimeter for *ILC*)
  - Fundamental concept:
    - Particle flow
    - Associate energy deposits with charged particles
    - → Drives granularity requirements
    - Allows "tracking" of neutrals

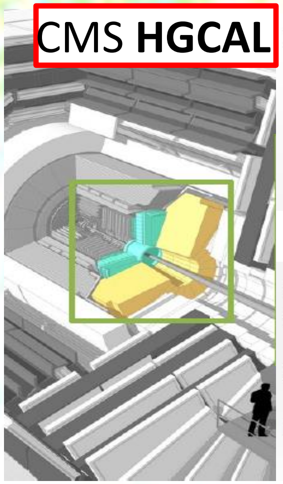




- ALICE **FoCAL**
  - Tungsten-Silicon sampling EM Calorimeter

FCC-hh?

- CMS **HGCAL**



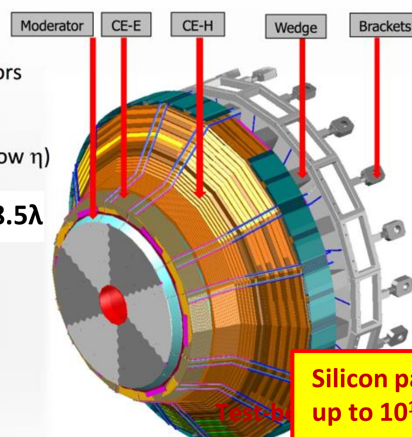
Main characteristics:

EC-E - 28 active layers, silicon sensors
EC-H - 24 active layers
8 silicon sensor
16 silicon (high η) + scint (low η)

ECAL: 25 X_0, ~1.3λ; HCAL: 8.5λ

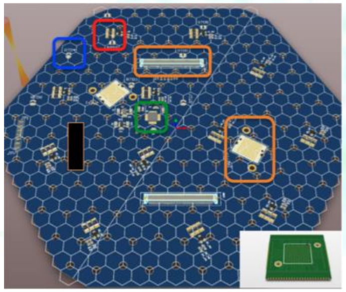
EC-E total weight =18.5t
EC-H Absorbers material:
St.Steel, weight = 170t
Front Shielding weight = 0.8t

Total weight of Endcap = 253t

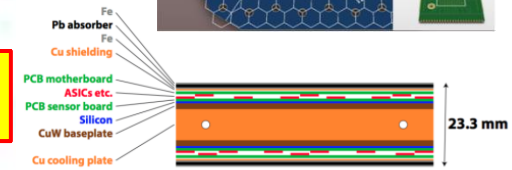


Key Parameters:

- EC covers 1.5 < η < 3.0
- Full system maintained at -30°C
- ~600m² of silicon sensors
- ~500m² of scintillators
- 6M si channels, 0.5 or 1 cm² cell size
- ~22000 si modules
- Power at end of HL-LHC: ~60 kW per endcap



Silicon pads to withstand doses up to 10^{16}n/cm² and several MGy



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Birmingham Instrumentation Laboratory for Particle physics and Applications BILPA

UNIVERSITY OF BIRMINGHAM

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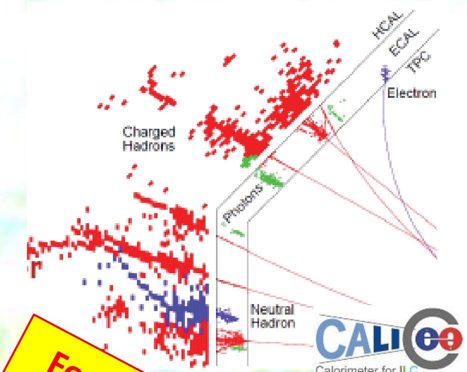

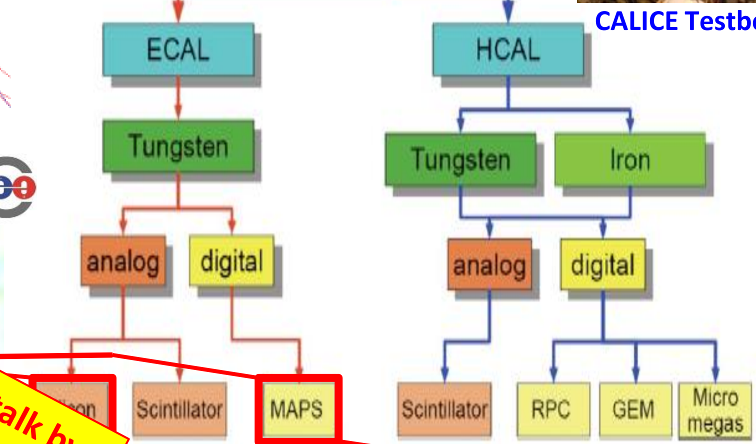

CALICE Testbeam

For many more details see talk by Dave Barney tomorrow morning

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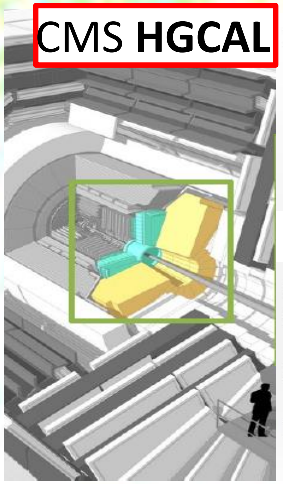
  - Tungsten-Silicon sampling EM Calorimeter

FCC-hh?

- CMS **HGCAL**



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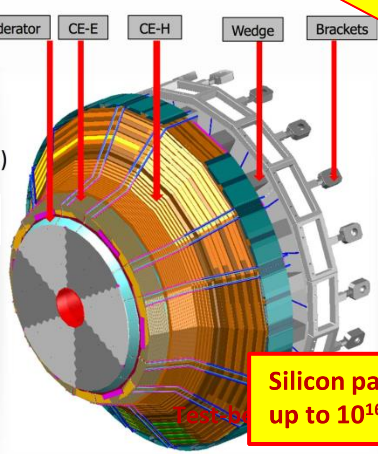

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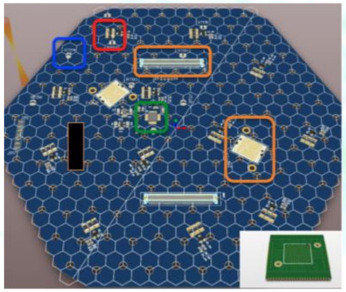

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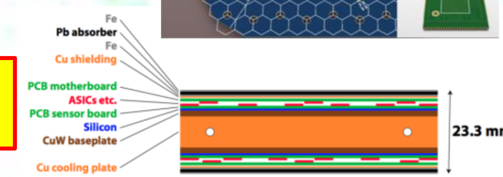
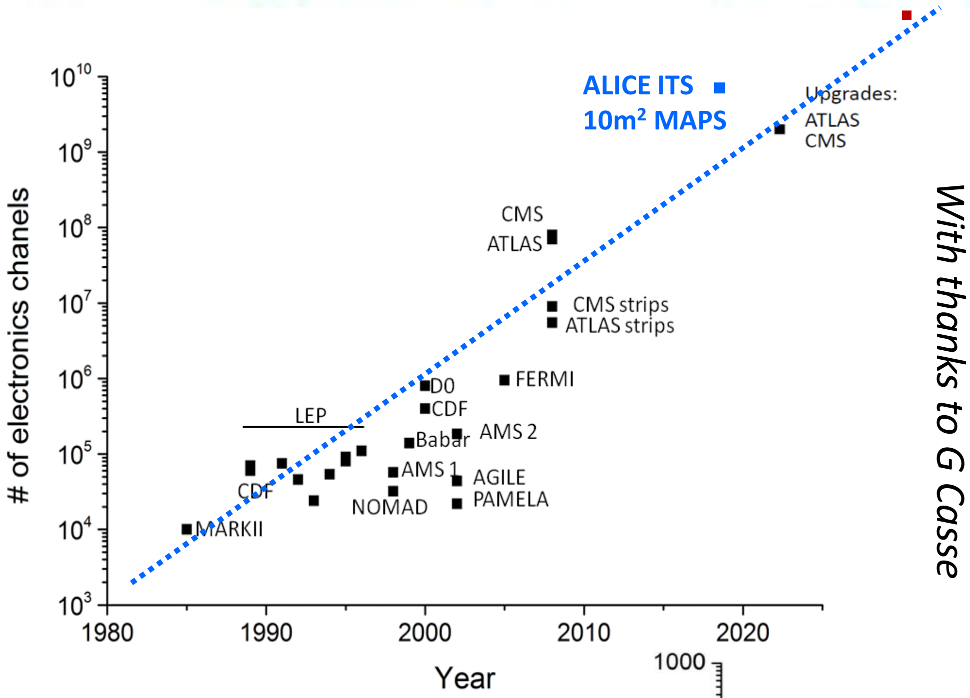
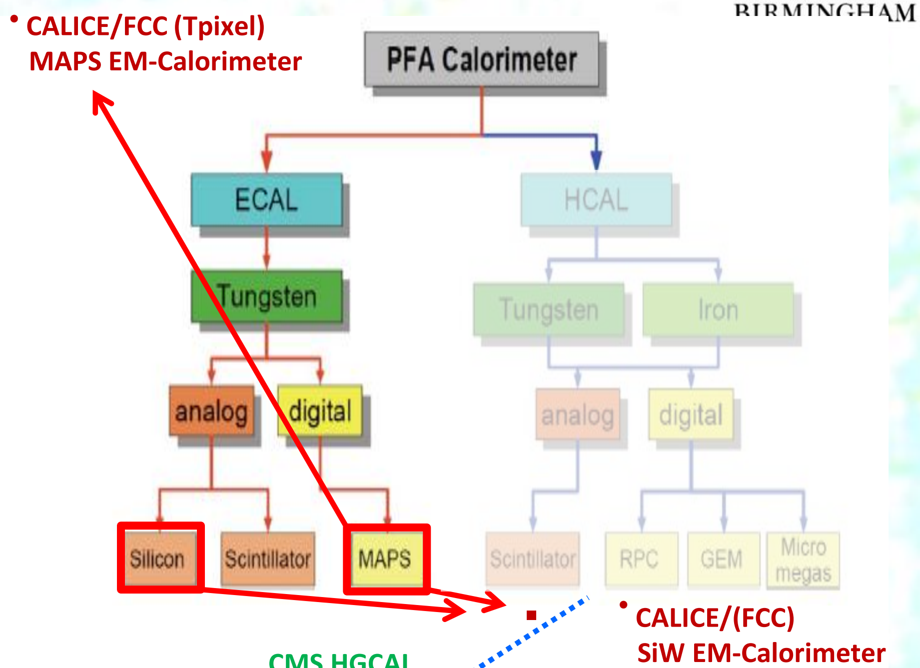
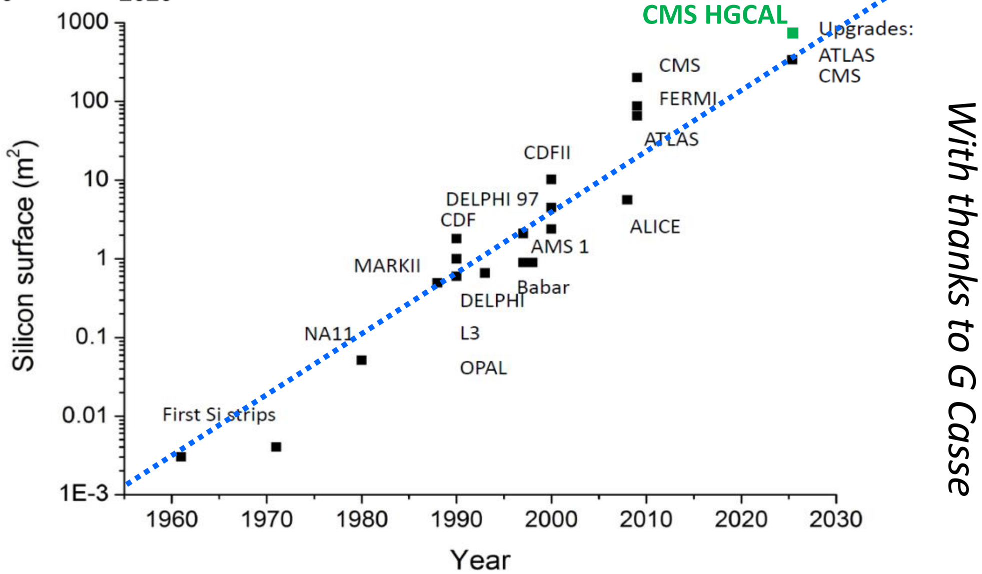


Silicon Based Detector Evolution



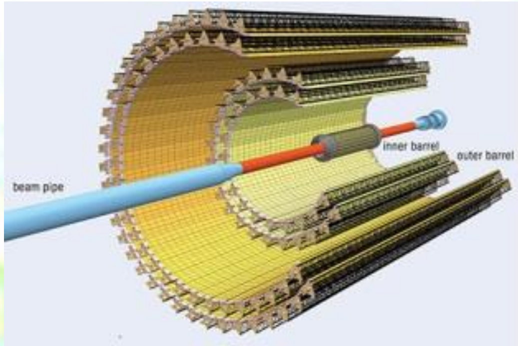


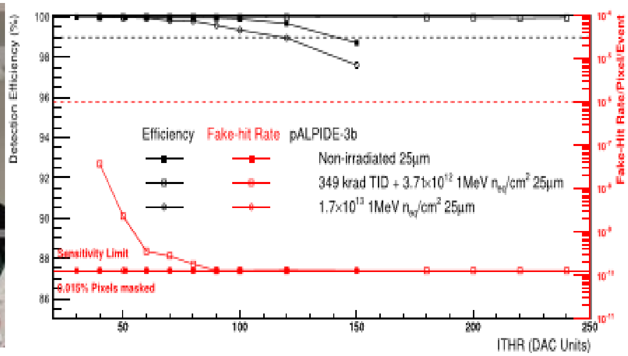
Need detector costs to scale with Moore's law.
For sensors, more likely with fully commercial processes such as CMOS Imaging Sensors (MAPS) as used in mobile phones, cameras etc.
(Need « $/cm²)



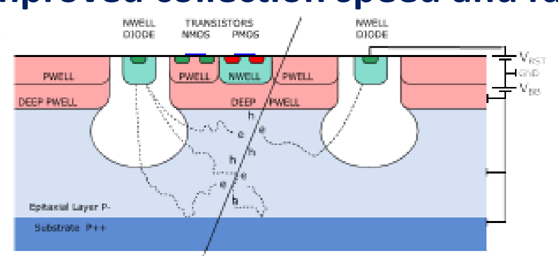
MAPS for LHC Upgrades

- **Low power consumption (<100mW/cm^2) at upgraded ALICE ITS (4µs integration time) allows very low material budget (<0.5% for inner layers, <1% for outer layers) and is radiation resistant up to few 10^{13} $n_{eq}cm^{-2}$**

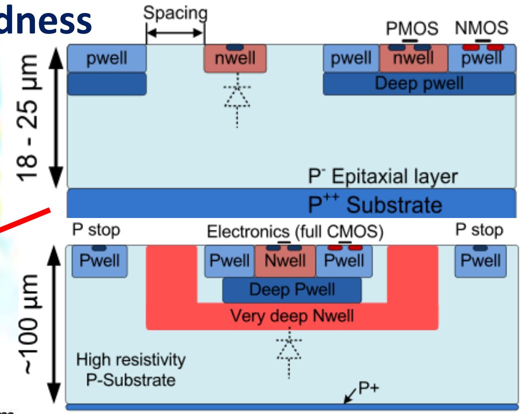


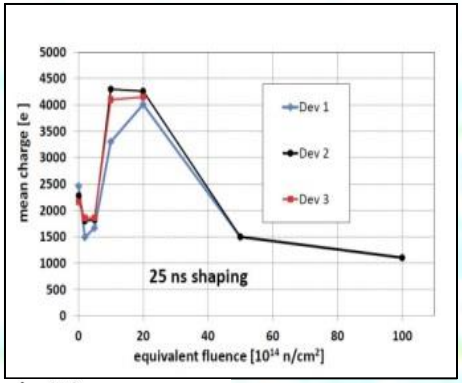


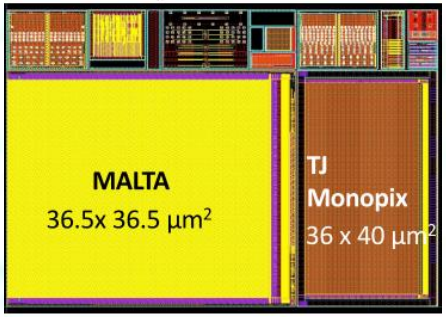
- **Developments of HV/HR-CMOS → deep depletion region with charge collection by drift not diffusion → improved collection speed and radiation hardness**



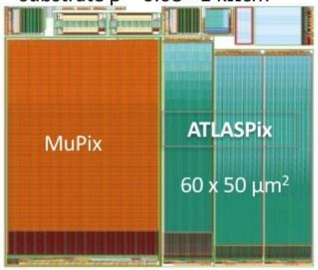
TowerJazz 180 nm epitaxial (25 µm)
substrate ρ > kΩ cm







ams 180 nm
substrate ρ ~ 0.08 - 1 kΩcm



~2cm×2cm prototypes developed for ATLAS

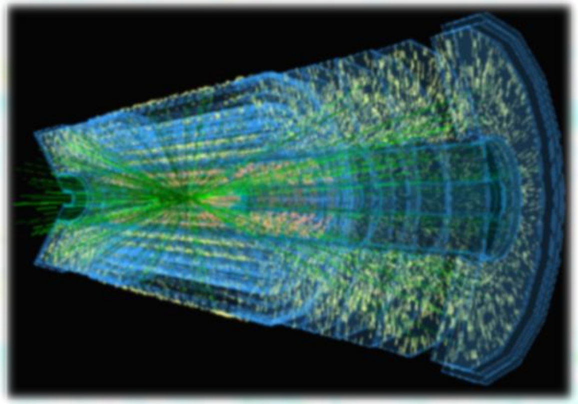
LFoundry 150 nm
substrate ρ > 2 kΩcm

IMPACT OF THE INNOVATIONS IN SEMICONDUCTOR ADVANCED TECHNOLOGY ON THE TRACKING CONCEPTS IN FUNDAMENTAL RESEARCH

Phil Allport

INFIERI Summer School, Huazhong University of Science and Technology

- Introduction to Silicon Tracking Detectors
- Development of Silicon Detector Arrays in Particle Physics
- Overview of LHC Detector Upgrade Programme
  - Silicon Detectors for HL-LHC
    - Strip Detectors
    - Hybrid Pixel Detectors
    - Silicon Detectors for Calorimetry
    - Monolithic Active Pixel Sensors
    - Silicon Fast Timing Detectors
- **Collider Physics Beyond the HL-LHC**
- Example Applications of HL-LHC Technologies
  - Hadron Radiotherapy
- Conclusions



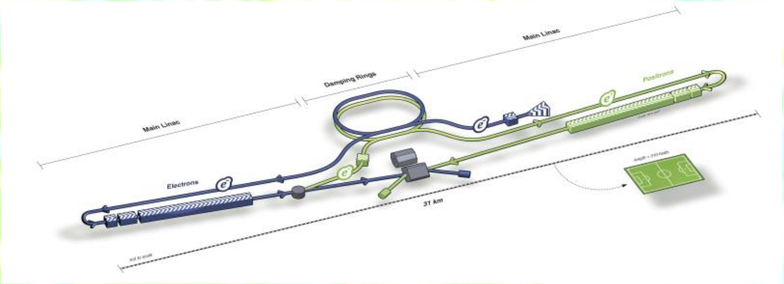
Future Collider Options

- **Easier access and lack of the need to instrument large area means novel detector technologies often first find application at smaller or fixed target experiments (for example the TDCpix 75ps hybrid pixel ASIC for the NA62 Gigatracker or the MuPix monolithic CMOS sensor for the μ3e experiment).**
- **Nevertheless, for conciseness, only future collider experiments will be considered here.**
- **The main flavours of planned major future collider facilities are:**
  - **e^+e^- (or even possibly eventually $\mu^+\mu^-$) colliders**
  - **proton-proton and heavy ion colliders**
  - **electron-proton and electron-ion colliders**
- **The highly important developments for future fixed target, neutrino and non-accelerator experiments will also not be covered here but are discussed in other presentations.**

Proposed e+e- Colliders

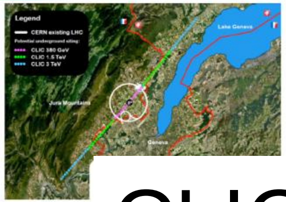
CepC-ee: 2030

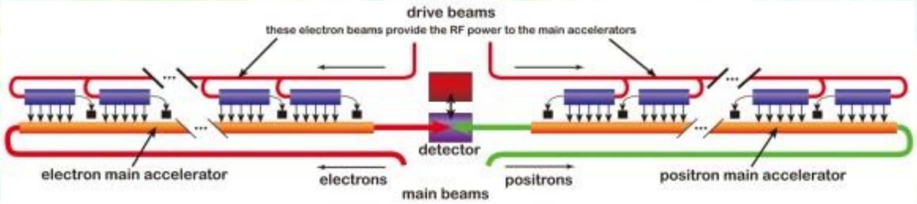
(Follow with SppC: similar parameters to FCC-hh)



ILC 250: 2032

(May be possible to upgrade to 500GeV or even beyond)



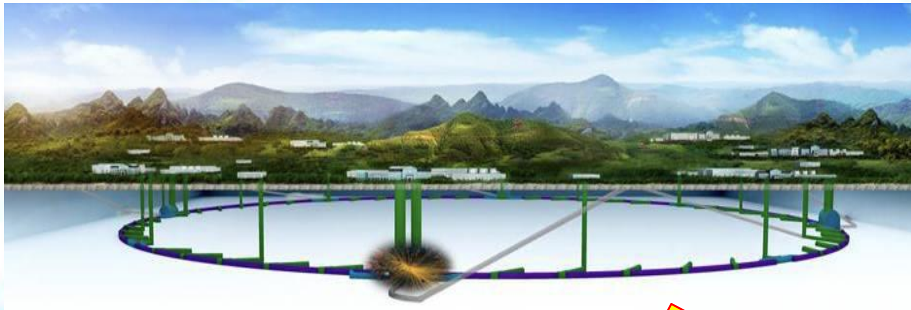


CLIC 350: 2035

(Designed to offer potential 3TeV final energy upgrade)

FCC-ee: 2039

Proposed e+e- Colliders



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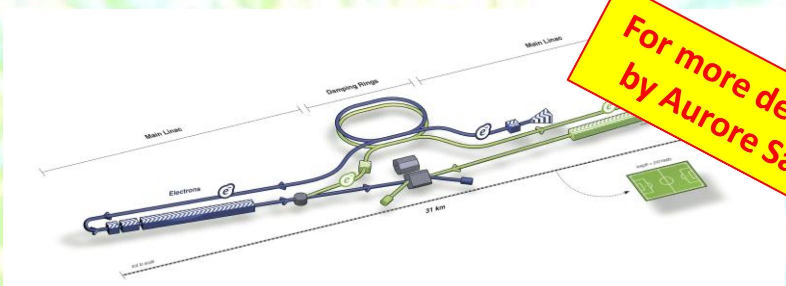

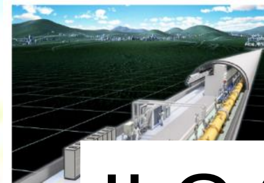

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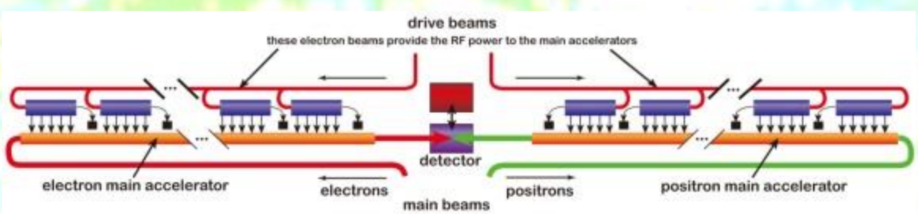
(May be possible to upgrade to 500GeV or even beyond)

For more detailed discussion see talks by Aurore Savoy-Navarro yesterday



CLIC 350: 2035

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FCC-ee: 2039

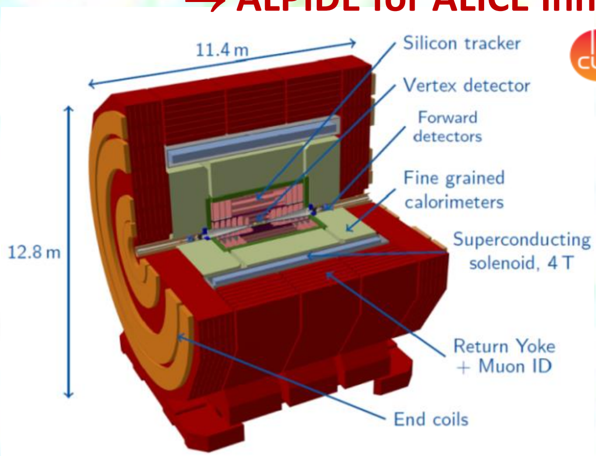
ILC/CLIC Proposed Pixel Technologies

- Demands of ultra-low mass, highest resolution, low power and fast time-stamp
- Can exploit time structure of bunch trains separated by up to 200ms for readout and power cycling
- A wide range of technologies with many years of development:
  - DEPFET (see also BELLE-II)
  - FinePixel CCD
  - Thin Planar sensor or HV-CMOS Hybrid (C3PD)+CLICpix
  - Monolithic CMOS
    - Vertical integration with TSVs (FNAL 3D)
    - SoI for Fine Space and Time (SOFIST)
    - Monolithic Active Pixel Sensors (MAPS)
      - Chronopix (time stamp, sparse readout)
      - MIMOSA (developments since 2000 for ILC)

        → STAR Heavy Flavour Tracker

    → ALPIDE for ALICE Inner Tracker System Upgrade

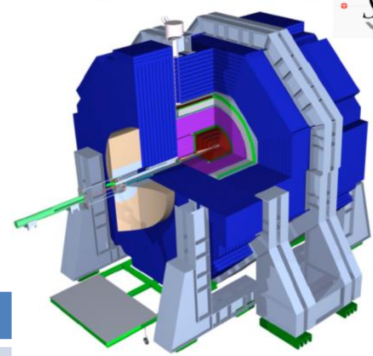
Spatial resolution: highly granular sensor:
$\sigma_{R\phi}$ ~ 3 µm (pitch ~ 20 µm)
multiple scattering : very low material budget:
$O(0.1\% X_0/\text{layer})$
Single bunch time resolution
→ 1st layer: ~ 5 part/cm²/BX → few % occupancy
Power dissipation ↔ preferably gas cooling
→ <130µW/mm² (Power cycling, ~3% duty cycle)

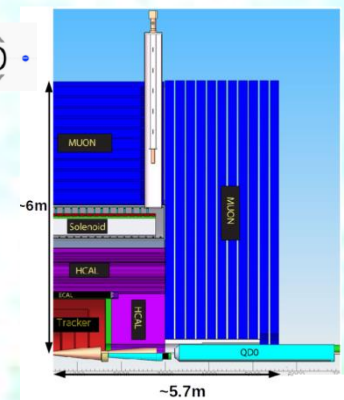


Compact Linear Collider

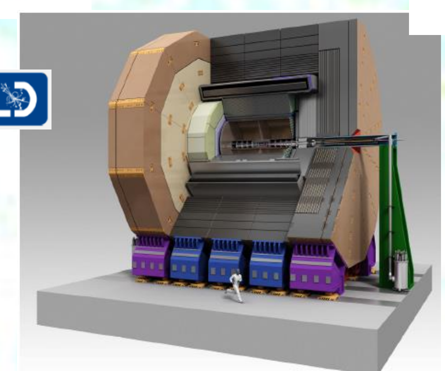
	ILC	CLIC
Bunches/train	1312	312
Bunch separation	544ns	0.5ns
Repetition rate	5Hz	50Hz
Ionising dose Gy/year	~1000	~50
Fluence 10^9 n_{eq}/cm^2/year	100	4

SiD



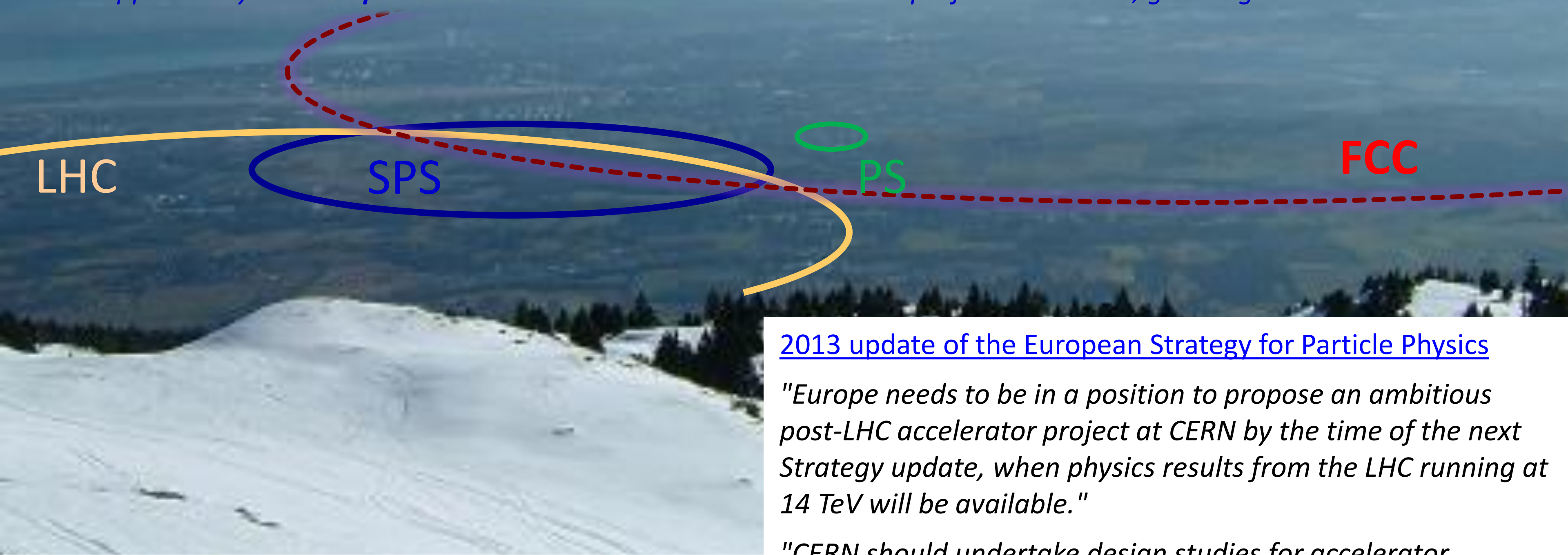


ILD



Future Circular Collider

*Work supported by the **European Commission** under the HORIZON 2020 project EuroCirCol, grant agreement 654305*



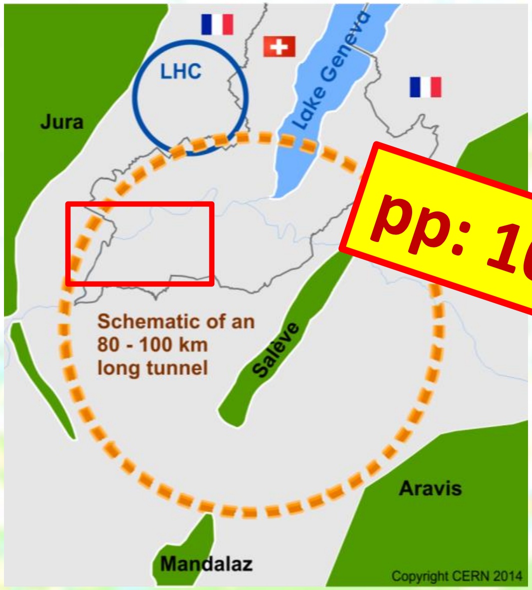
[2013 update of the European Strategy for Particle Physics]()

"Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available."

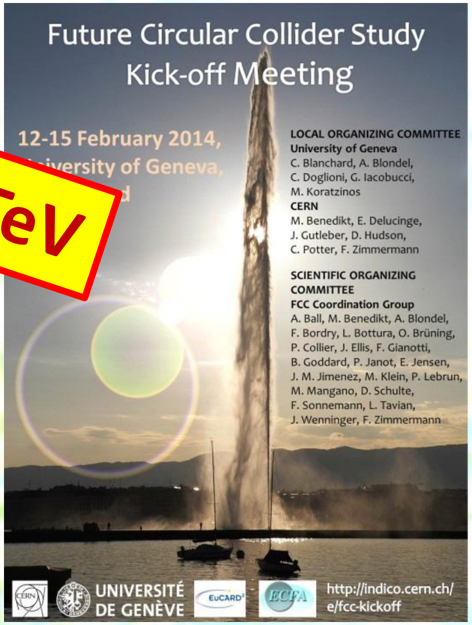
"CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide."

[http://cern.ch/fcc]()

FCC Programme



pp: 100 TeV



hh: pp and AA
e^+e^-: Higgs factory
eh: ep/eA options

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FCC Programme

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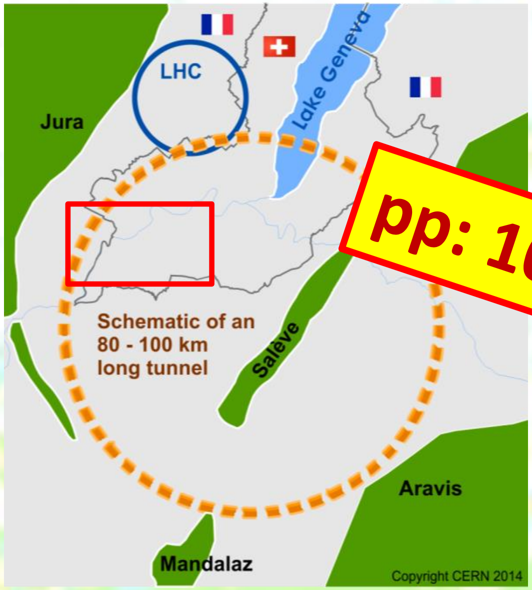

pp: 100 TeV

For more details again see talks by Aurore Savoy-Navarro yesterday

hh: pp and AA
e^+e^-: Higgs factory
eh: ep/eA options

FCC-hh Parameters

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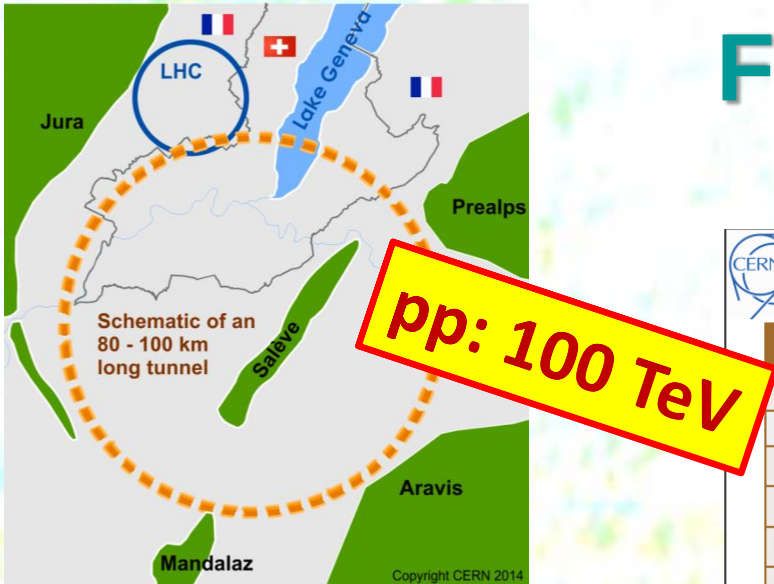
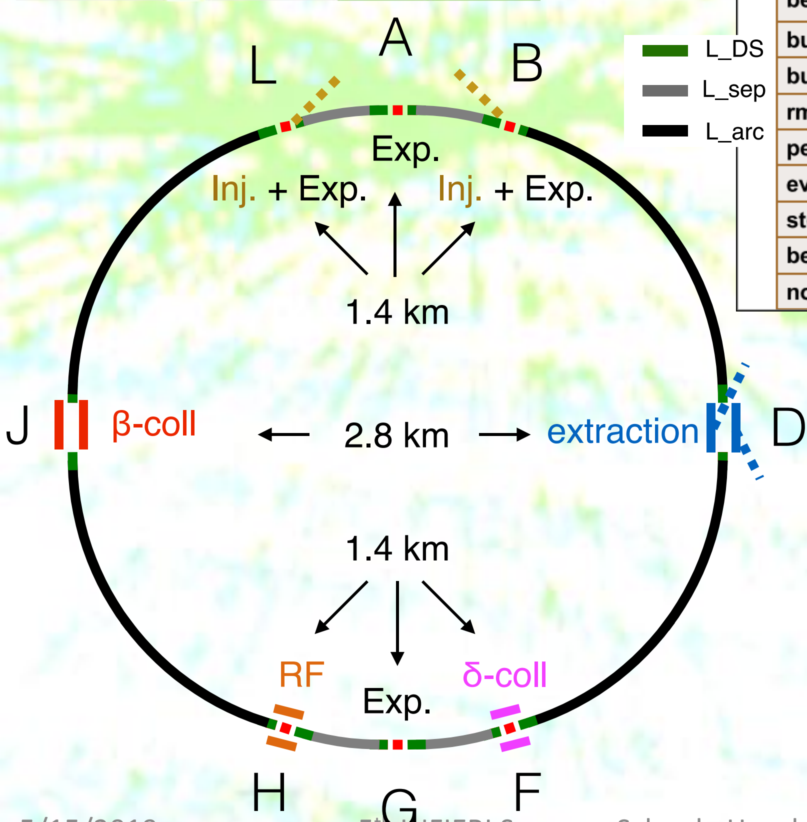
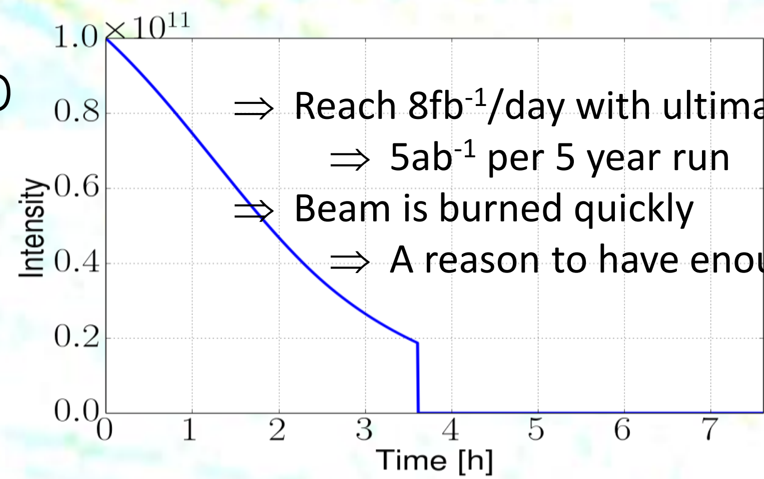


hadron collider parameters - 1

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	100		27	27
straight section length [m]	1400		528	528
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25
rms bunch length [cm]	7.55		7.55	(8.1) 7.55
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	25	(5) 1
events/bunch crossing	170	1k (200)	~800 (160)	(135) 27
stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
beta* [m]	1.1-0.3		0.25	(0.20) 0.55
norm. emittance [μm]	2.2 (0.4)		2.5 (0.5)	(2.5) 3.75





⇒ Reach 8fb^{-1}/day with ultimate for 25ns spacing

⇒ 5ab^{-1} per 5 year run

⇒ Beam is burned quickly

⇒ A reason to have enough charge stored

FCC-hh Detector Concept

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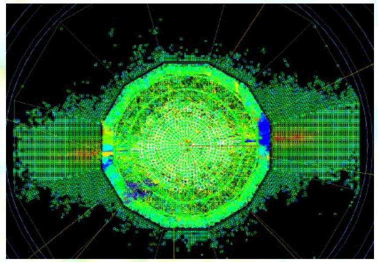
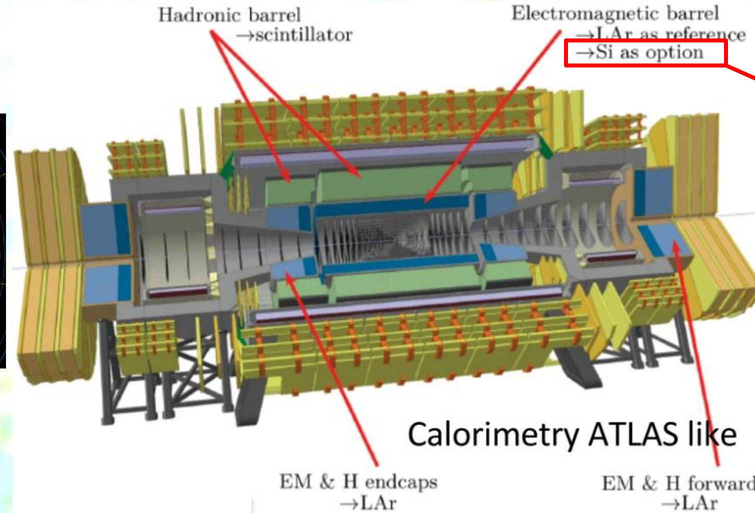
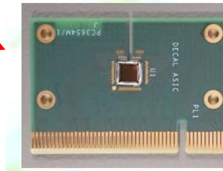
Baseline for Conceptual Design Review
https://fcc-cdr.web.cern.ch/
4T 10m solenoid
- Forward solenoids
- **Silicon** tracker
- Barrel ECAL **LAr/Si-W**
- Barrel HCAL Fe/**Sci**
- Endcap HCAL/ECAL **LAr**
- Forward HCAL/ECAL **LAr**

Other options explored

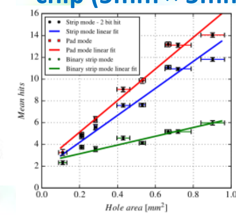


$Z'(40TeV)\rightarrow q\bar{q}$

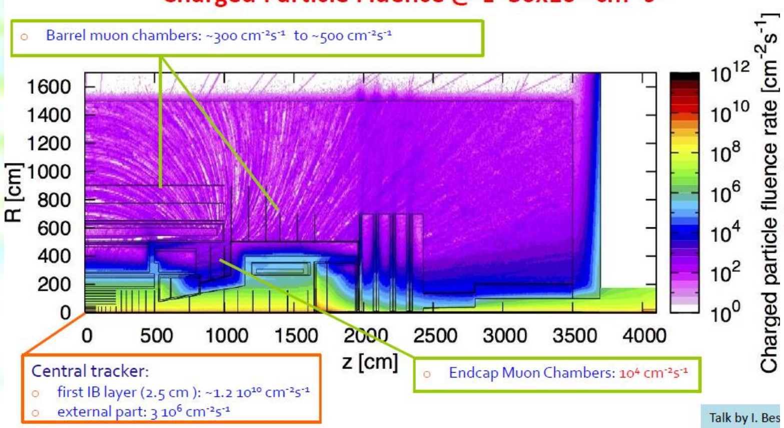




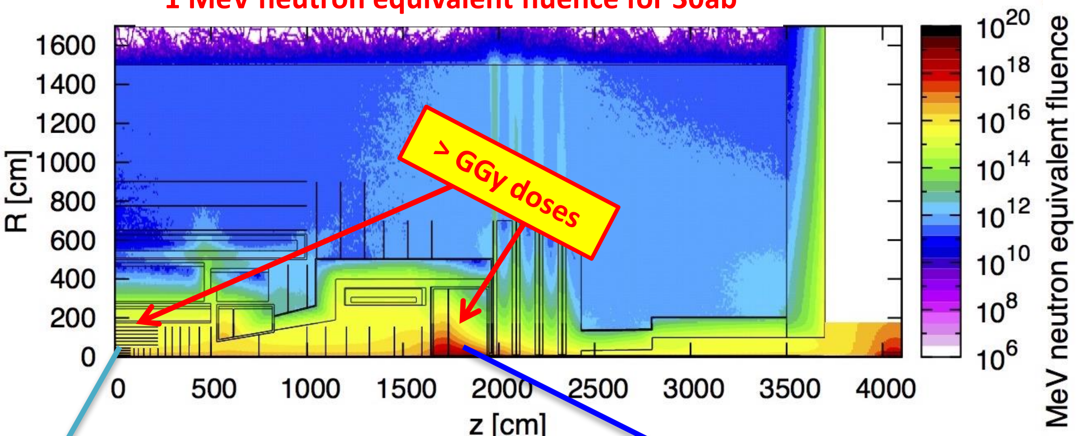
Reconfigurable CMOS Digital ECAL and Outer Tracker chip (5mm × 5mm)

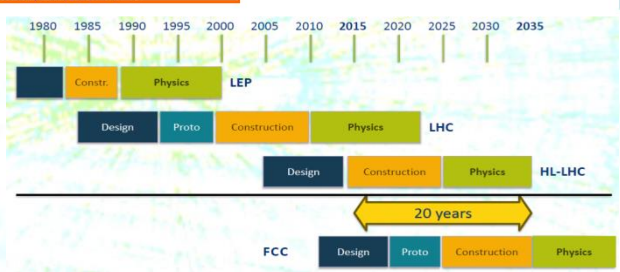


Charged Particle Fluence @ L=30x10^{34}cm^{-2}s^{-1}



1 MeV neutron equivalent fluence for 30ab^{-1}



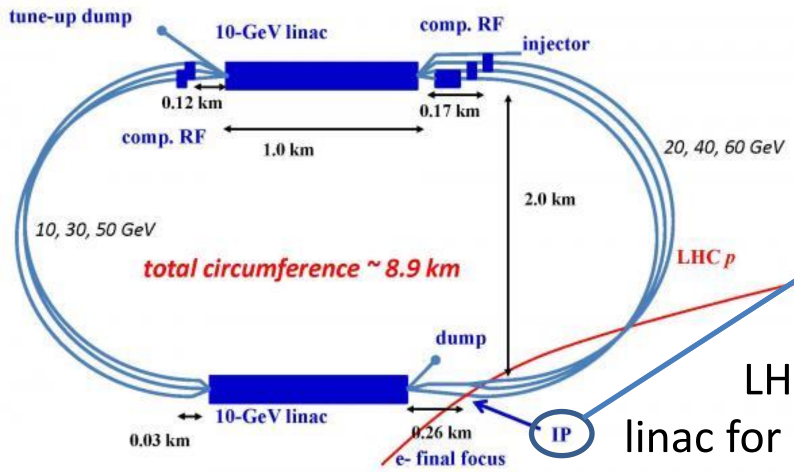


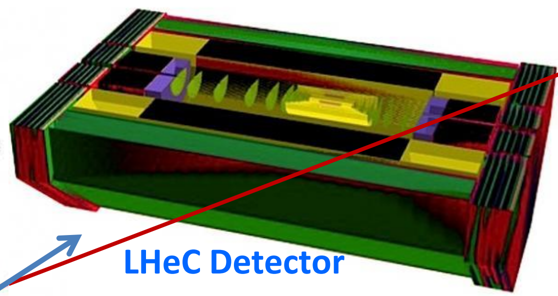
Central tracker:
- first IB layer (2.5 cm): ~5-6 10^{17} cm^{-2}
- external part: ~5 10^{15} cm^{-2}

Forward calorimeters:
- maximum at ~5 10^{18} cm^{-2} for both the EM and the HAD-calo
- 10^{16} cm^{-2} at R=2 m

➢ **20 year R&D lead-times (concept → large arrays)**

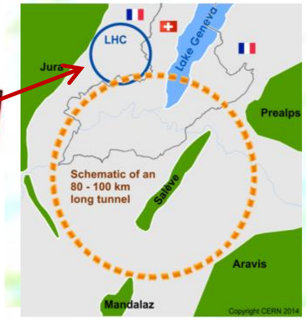
Electron-Hadron Colliders



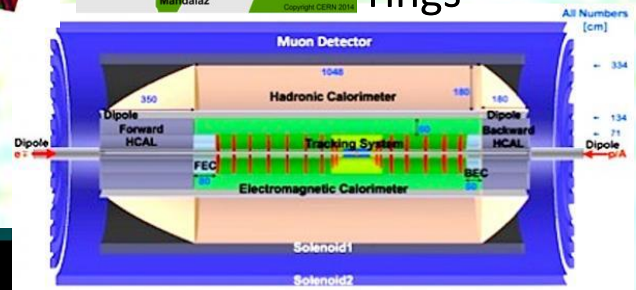


LHeC Detector

LHeC: energy recovery linac for e-h collisions at LHC

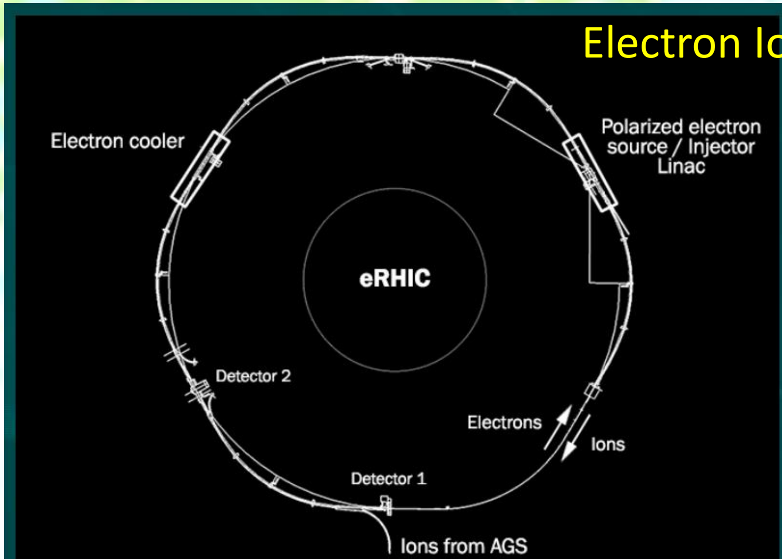


FCC-eh: use both hadron and electron rings

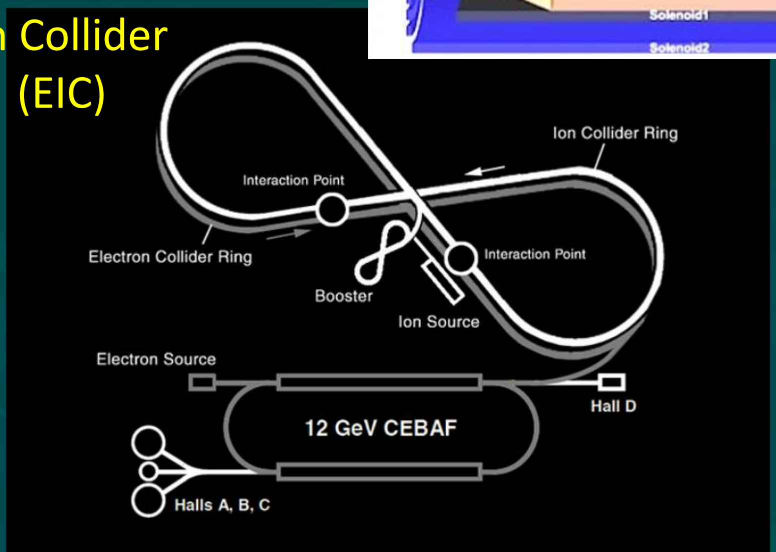


FCC-eh Detector

Electron Ion Collider (EIC)



Schematic of proposed eRHIC at Brookhaven National Laboratory. This design would make use of the existing ion sources, pre-accelerator chain, superconducting magnet ion storage ring, and other infrastructure of the Relativistic Heavy Ion Collider (RHIC). A new electron source and electron accelerator and storage rings would be added inside the RHIC tunnel so that interactions (collisions) can take place at points where the stored ion and electron beams cross (up to three detectors).

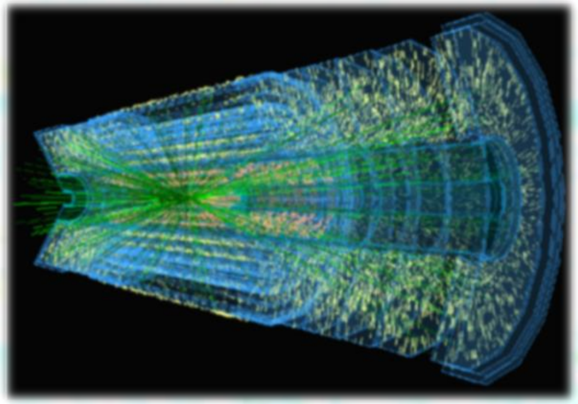


Schematic of proposed JLab Electron-Ion Collider (JLEIC) at Thomas Jefferson National Accelerator Laboratory. This design would make use of the Continuous Electron Beam Accelerator Facility (CEBAF), which would steer accelerated electrons into two interaction points (IP) of a newly constructed figure-eight shaped ion accelerator, fed by a new ion source and associated pre-accelerator components.

IMPACT OF THE INNOVATIONS IN SEMICONDUCTOR ADVANCED TECHNOLOGY ON THE TRACKING CONCEPTS IN FUNDAMENTAL RESEARCH

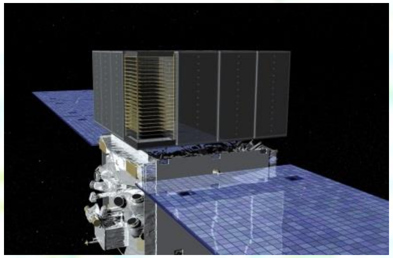
Phil Allport
INFIERI Summer School, Huazhong University of Science and Technology

- Introduction to Silicon Tracking Detectors
- Development of Silicon Detector Arrays in Particle Physics
- Overview of LHC Detector Upgrade Programme
  - Silicon Detectors for HL-LHC
    - Strip Detectors
    - Hybrid Pixel Detectors
    - Silicon Detectors for Calorimetry
    - Monolithic Active Pixel Sensors
    - Silicon Fast Timing Detectors
- Collider Physics Beyond the HL-LHC
- **Example Applications of HL-LHC Technologies**
  - **Hadron Radiotherapy**
- Conclusions

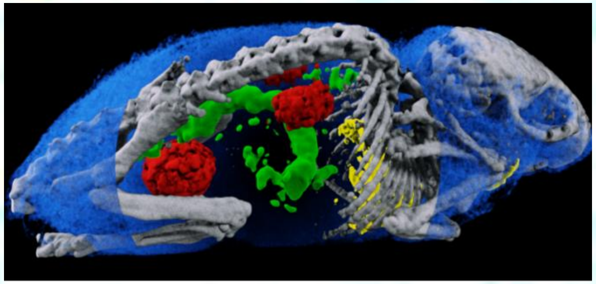


Particle Tracking Applications

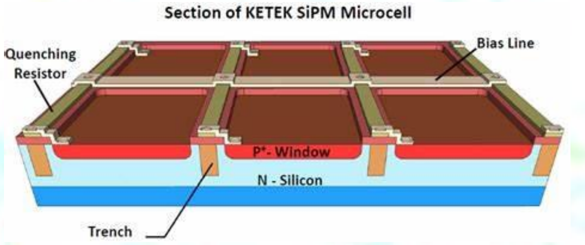
- Charged particle tracking plays an important role in several other science areas, for example in anti-hydrogen physics (eg ALPHA), nuclear physics (eg R3B at FAIR), the heavy ion programme at RHIC or CERN and in astrophysics (eg AMS and FERMI).



- Important application areas are also represented by the Medipix and Timepix hybrid pixel ASIC series (, X-ray diffractometry, radiation dosimetry, material separation and mass spectrometry imaging, … see https://medipix.web.cern.ch/).



- There are many areas where photo-detectors exploit similar technologies which both contribute to and benefit from developments in particle physics.

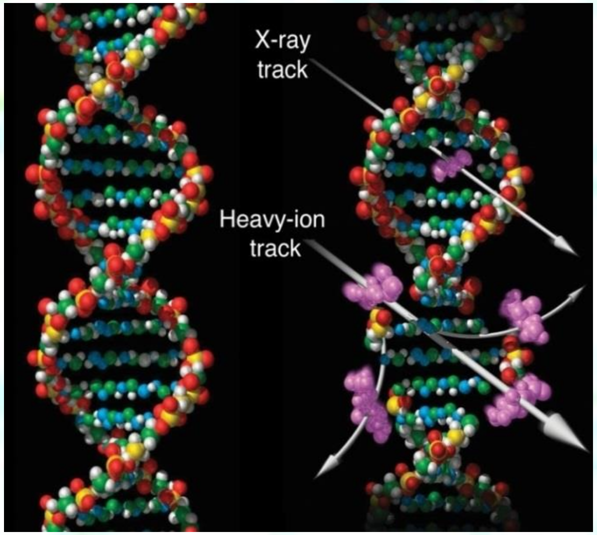


- However, the focus of this final section will be the use of accelerator derived particle beam for hadron radiotherapy and the possible improvements to treatment outcomes from using particle tracking technologies.

Hadron Radiotherapy

- Cancer is responsible for 1 in 8 deaths worldwide
- Typically 1 in 2 people will be affected by cancer at some point in their lives
- Most common cancers are Lung (22%), Colorectal (10%), Breast (8%), Prostate (6%)
- Overall survival rate can be above 50%
- Typically, radiotherapy is used in 40% of all cancer treatment

- Radiotherapy uses radiation to kill the cancer cells
- Energy is deposited in the cells which damages the DNA and stops the cells from replicating
- Surrounding healthy cells are also damaged so need to plan treatment to minimise the dose to the healthy tissue and maximise that to the cancer



- High energy x-rays from linear accelerators used to treat cancers deep within a patient
- Low energy x-rays and electrons used to treat skin cancers
- Protons/Ions used to give highly localised dose distributions beams mostly from cyclotrons or synchrocyclotrons
- Ions heavier than protons cause even more ionisation and more complex forms of damage, resulting in less repair and a more lethal effect on the tumour
- See http://enlight.web.cern.ch/, http://www.pprig.co.uk/ , https://www.advanced-radiotherapy.ac.uk/ and talks at https://indico.cern.ch/event/456299/

Hadron Radiotherapy

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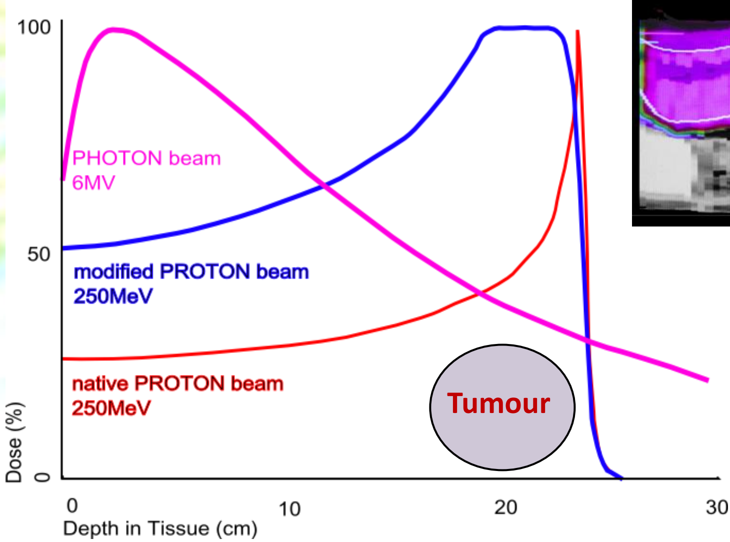
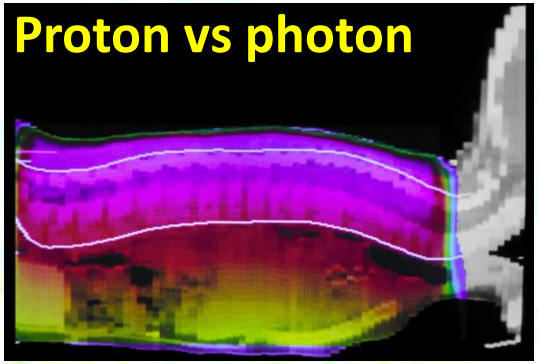
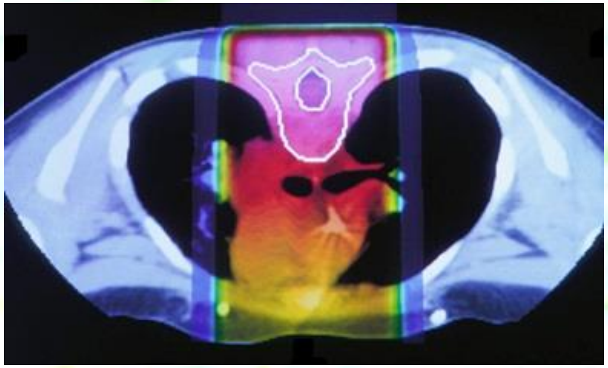
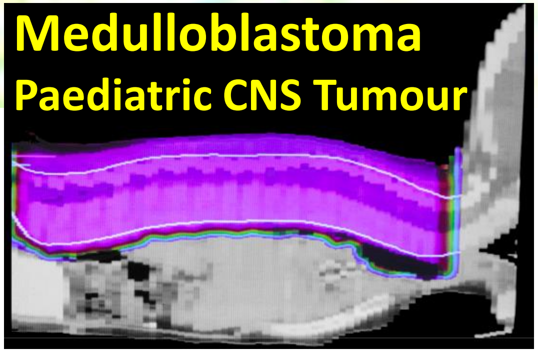
Proton and Ion therapy

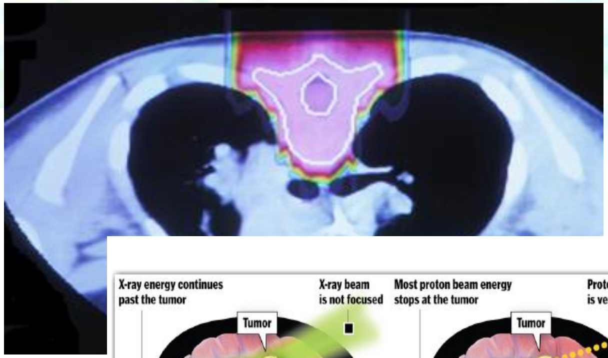
- Tumours in the head and neck region
- Tumours near the spine or other critical organs
- Some types of brain tumours
- Some childhood cancers so the risk of second cancers later in life is greatly reduced
- Shorter treatment lengths
- Less side-effects
- Faster recovery

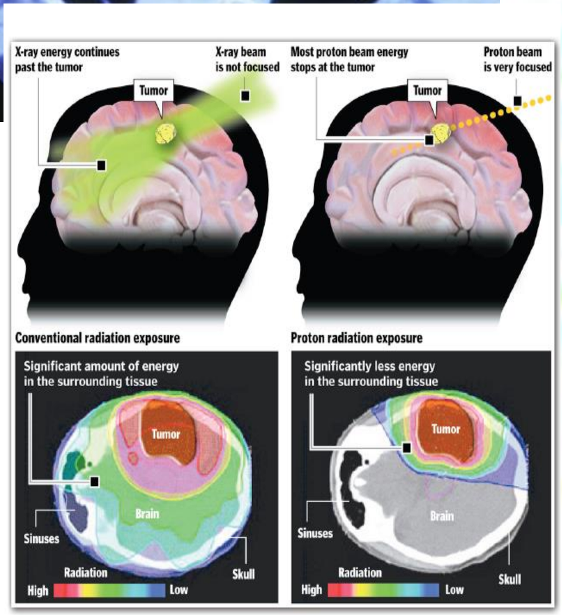












https://www.ptcog.ch/index.php/

Lists 94(5) facilities in operation, 45(8) "in construction" and 21(4) in planning stage (in China)

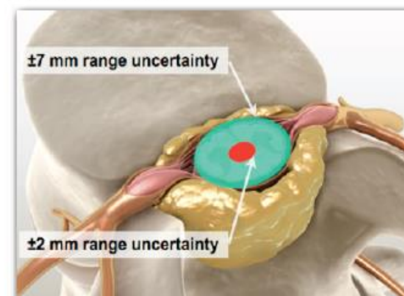
Hadron Radiotherapy

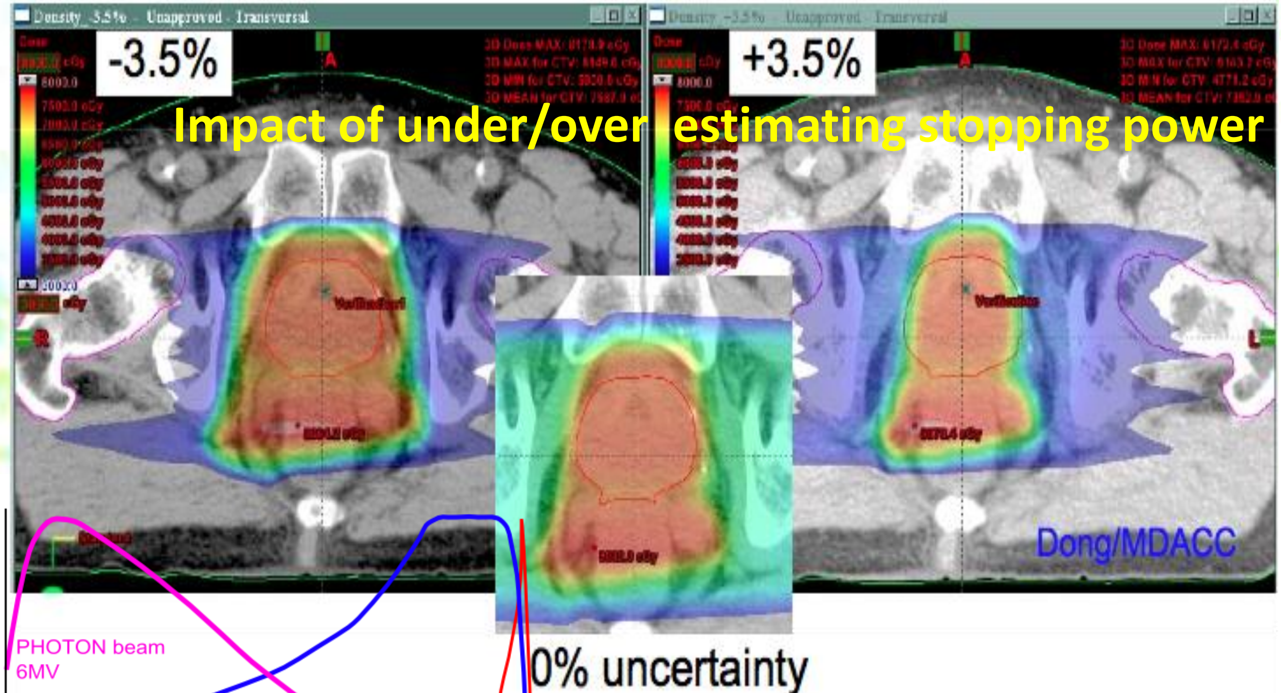
Advantage
Intense dose in small targeted volume

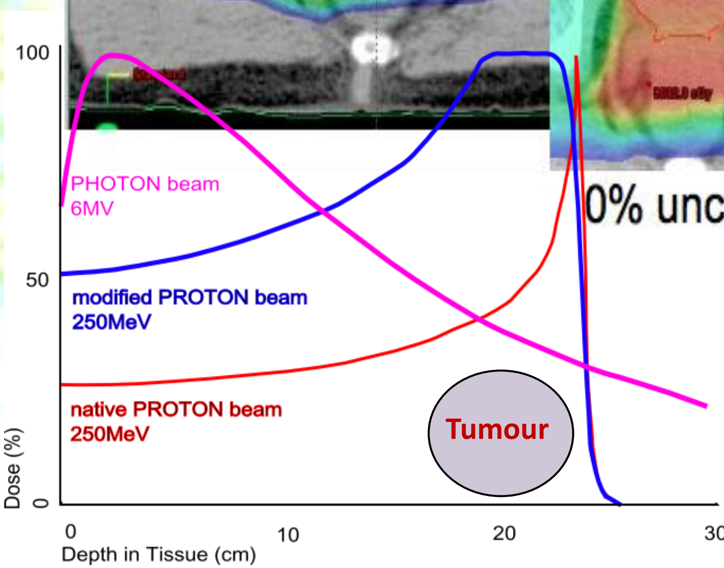
Potential Problem
Intense dose in small healthy volume

Patient planning
- Perform x-ray CT
- Translate from diagnostic x-rays to treatment protons
- Prone to errors - 1 - 2 cm in soft tissue, greater in bone

- **Need to see the patient using the "same" protons as used in treatment**





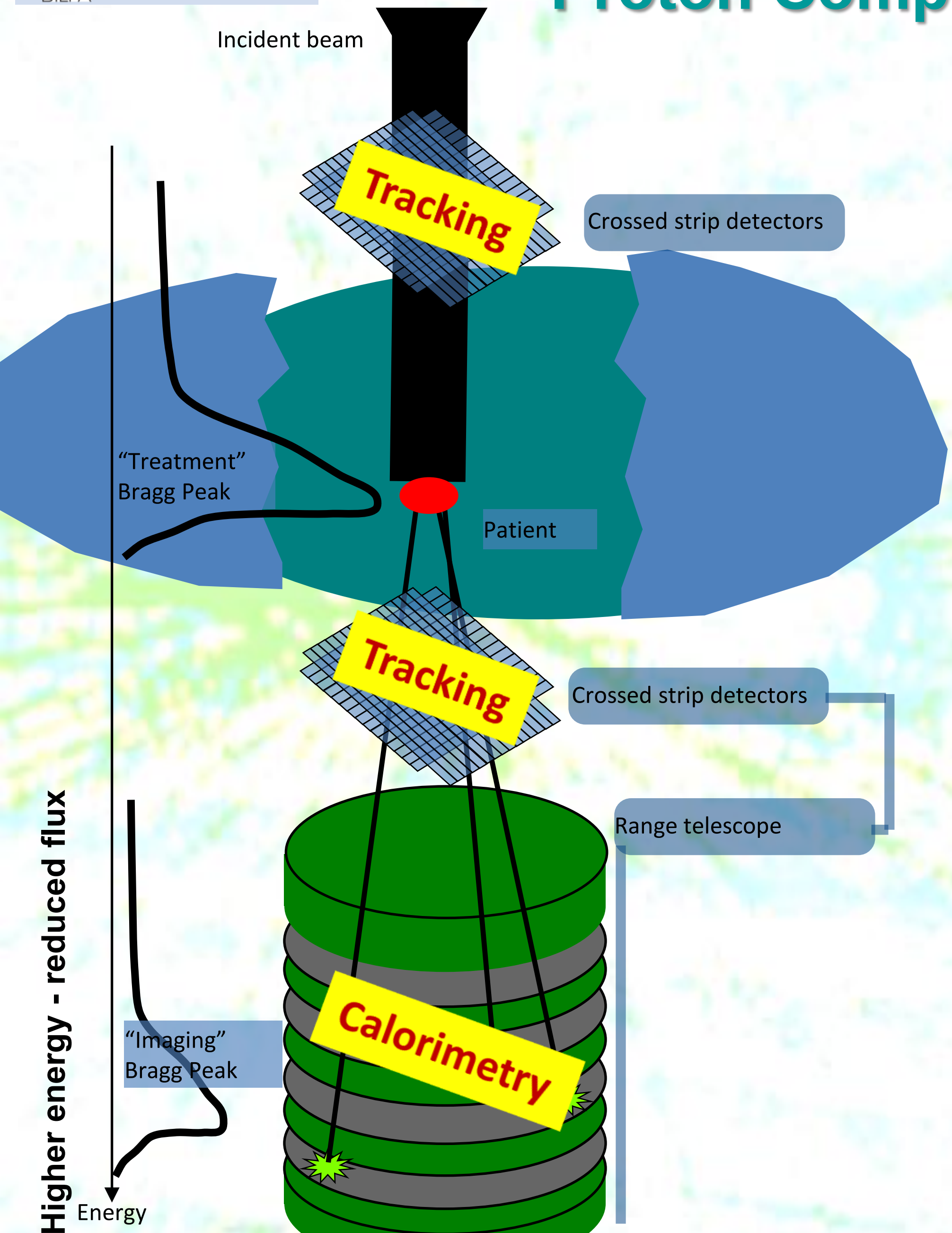


Proton Computed Tomography (pCT) hoped to be the key

https://www.ptcog.ch/index.php/

Lists 94(5) facilities in operation, 45(8) "in construction" and 21(4) in planning stage (in China)

Proton Computed Tomography



Records beam position and profile in real-time to correct beam steering

Beam profile, particle flux for a given current and energy distribution can be routinely determined to cross-check delivery system calibration

With gantry movement permit full proton-Computed Tomography (pCT) scan using same particle type as for treatment.

Current uncertainty in proton range is ~3.5%. If beam passes through 20cm of tissue, then Bragg peak could be anywhere within +/- 7 mm

Aim to reduce proton range uncertainties to a ~1% – variation of +/- 2mm.

Simplified treatment plans – fewer beams; reduced probability of secondary cancers induced; and treatments will be shorter

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Proton Computed Tomography

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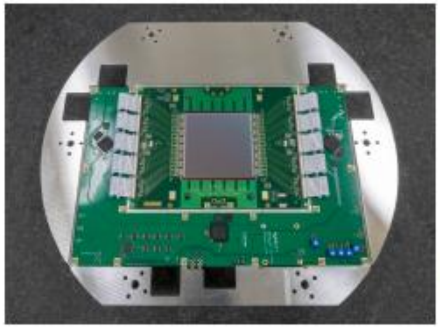
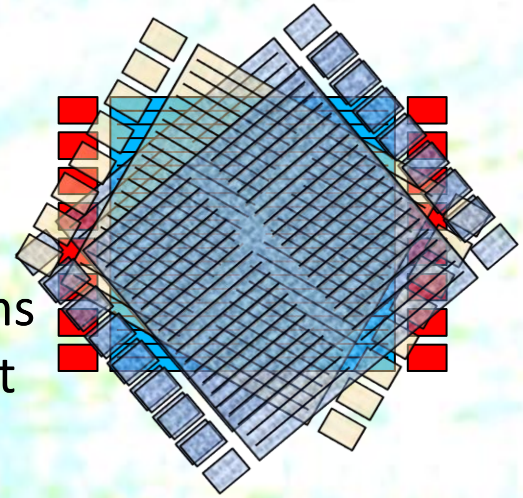
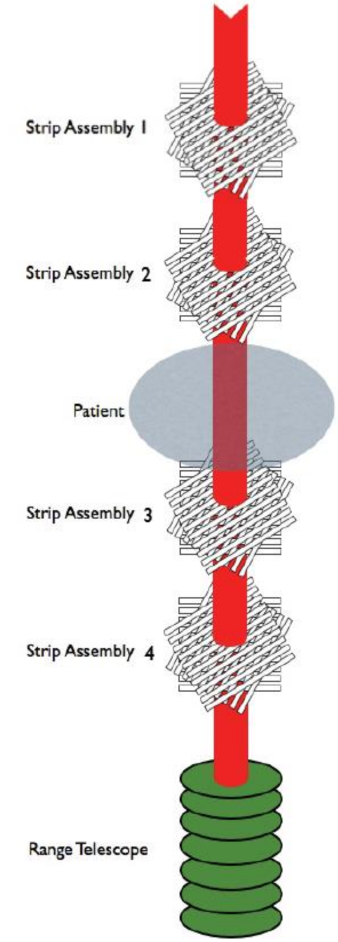
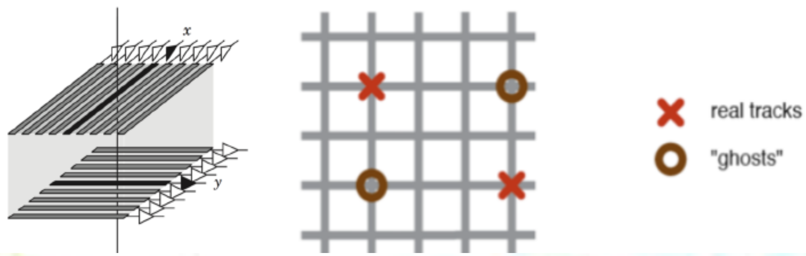






- **x-u-v:** A disadvantage of other systems with crossed strips is that they cannot cope with two or more protons per frame without ambiguities.

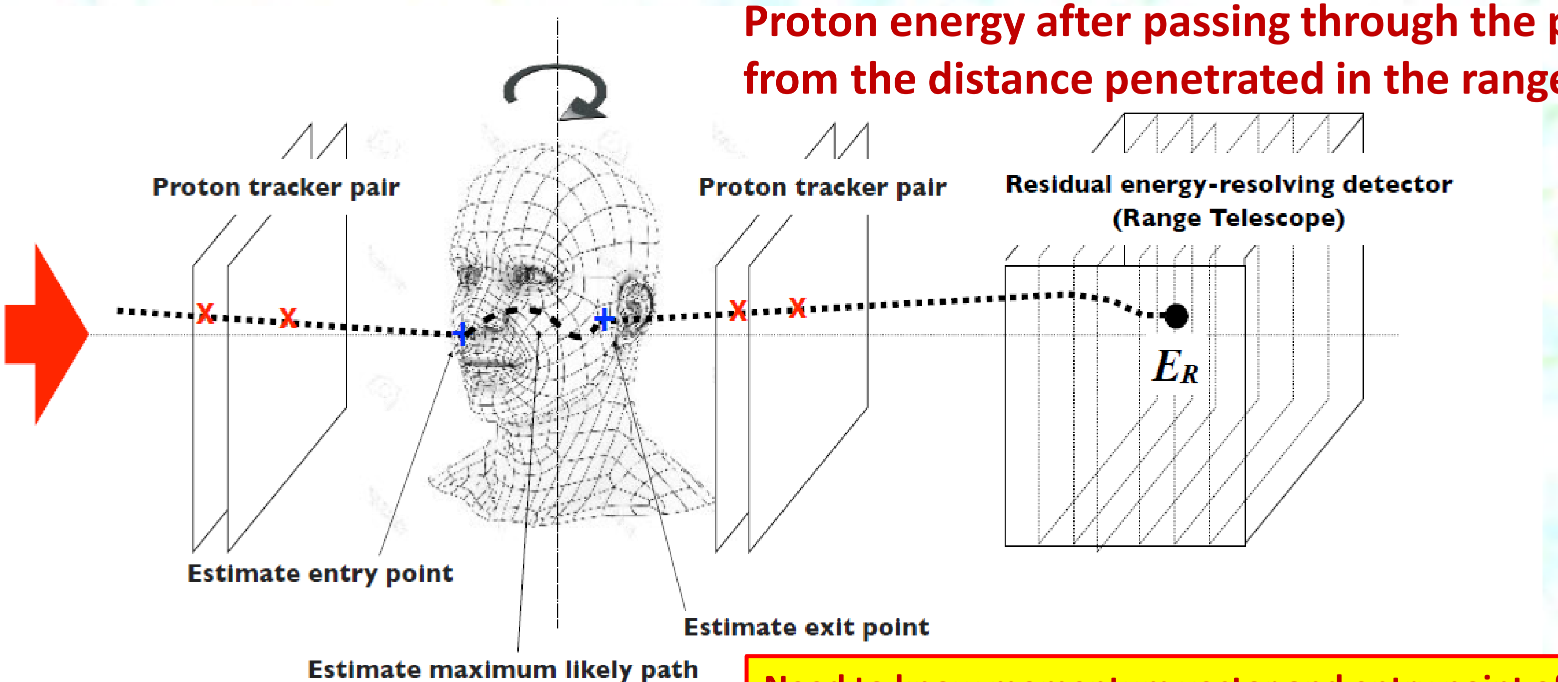
For a strip detector with orthogonal strips and N hits, there are: $N^2 - N$ 'Ghost-hits' or ambiguities generated



- The usual way round this with strips is to have a third layer **(3N Channels)**
- Depending on strip pitch, still problems above few 10s hits / frame
- Then need truly pixelated sensor, but needs to be fast **(N^2 Channels)**

Proton Computed Tomography

Proton energy after passing through the patient found from the distance penetrated in the range telescope

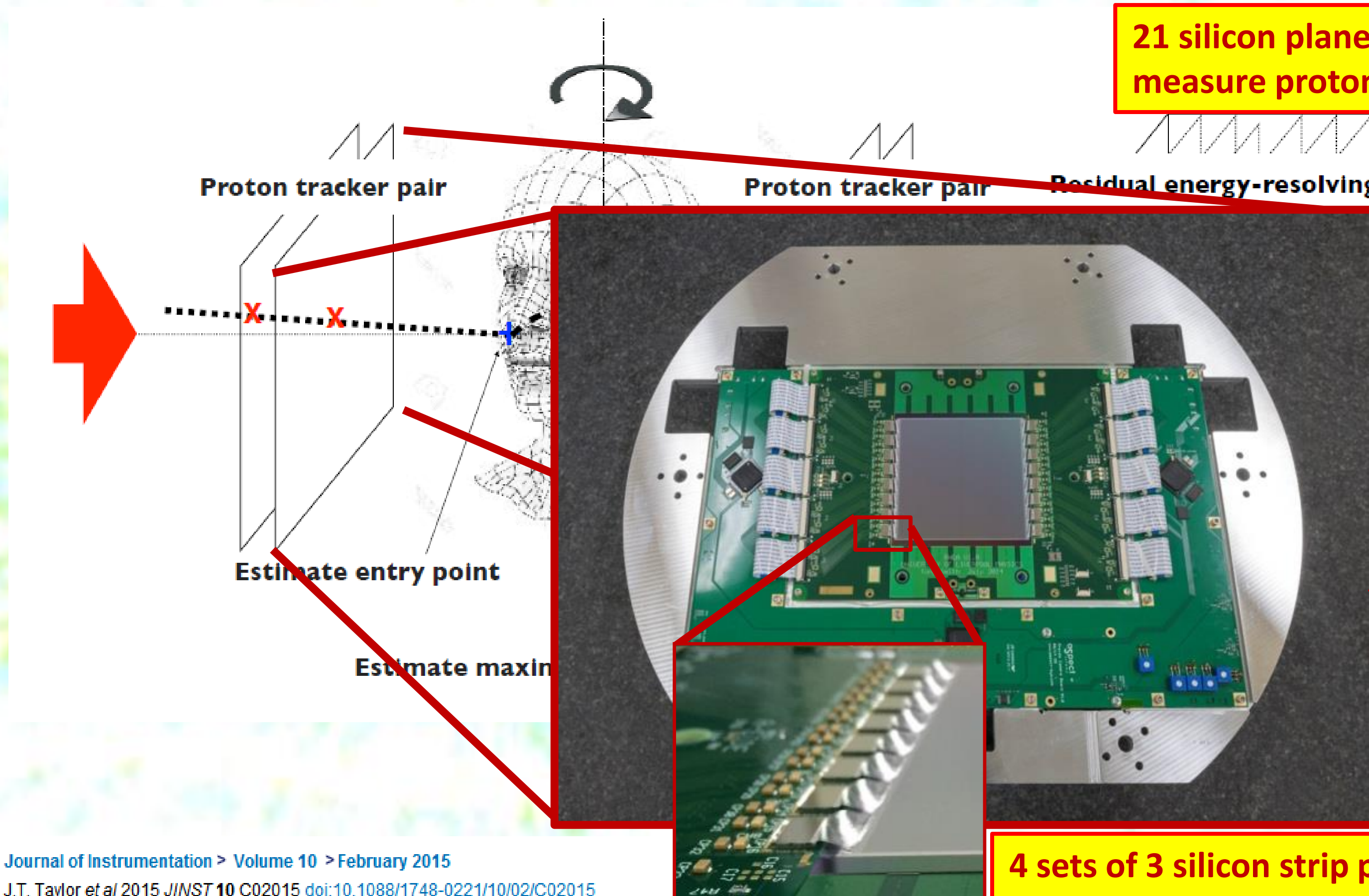


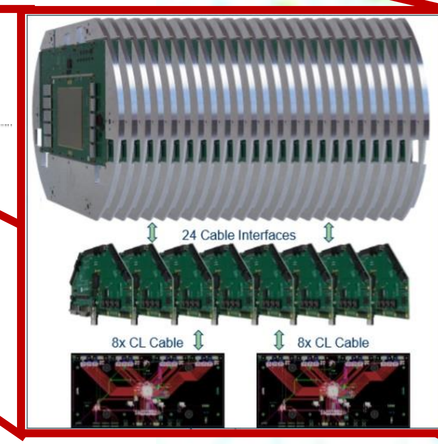
Need to know momentum vector and entry point of each proton going into the patient and also momentum vector and exit point coming out.
Need tracks plus incoming and outgoing energies

www.pravda.uk.com

Proton Computed Tomography

21 silicon planes interspersed with absorber to measure proton stopping distance





In final realisation, range telescope and tracker used common (n-in-p) strip technology

4 sets of 3 silicon strip planes reading out at the duty cycle of the cyclotron

Journal of Instrumentation > Volume 10 > February 2015
J.T. Taylor *et al* 2015 *JINST* **10** C02015 doi:10.1088/1748-0221/10/02/C02015

Proton tracking for medical imaging and dosimetry

10TH INTERNATIONAL CONFERENCE ON POSITION SENSITIVE DETECTORS

J.T. Taylor[a], P.P. Allport[a], G.L. Casse[a], N.A. Smith[a], I. Tsurin[a], N.M. Allinson[b], M. Esposito[b], A. Kacperek[c], J. Nieto-Camero and C. Waltham[b]
Show affiliations

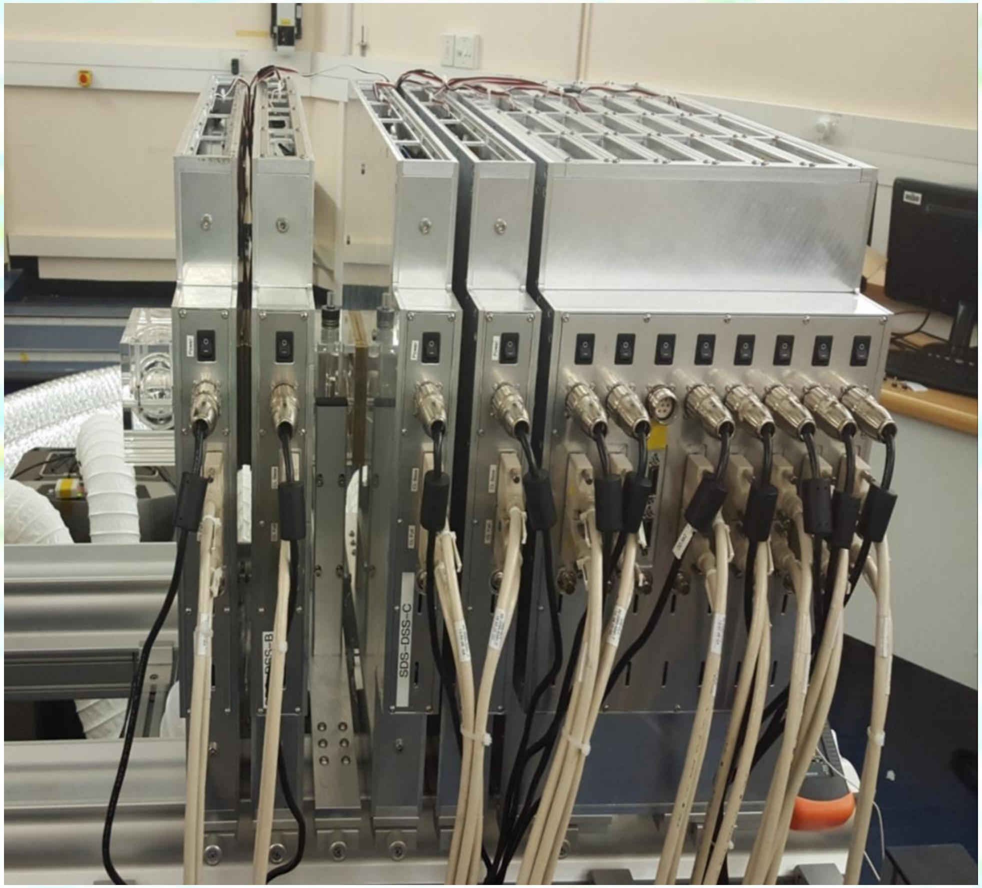
Br J Radiol. 2015 Sep;88(1053):20150134. doi: 10.1259/bjr.20150134. Epub 2015 Jun 4.

Proton radiography and tomography with application to proton therapy.

Poludniowski G[1,2], Allinson NM[3], Evans PM[1].

Proton Radiotherapy Verification and Dosimetry Applications

- Installed at iThemba for first tests May 2016 (125 MeV degraded beam).
- Compensator in place.
- 180 rotations at 1^{o} steps.
- Over 1M protons / rotation.
- Second run November 2016.
- 280 M proton histories recorded.
- Reconstructed using novel Back-Projection-Filtering algorithm specifically developed for proton CT.
- Stopping power for all inserts (except lung) agree within 1.6% of expected values.
- Still need optimal way to combine scattering and stopping power.



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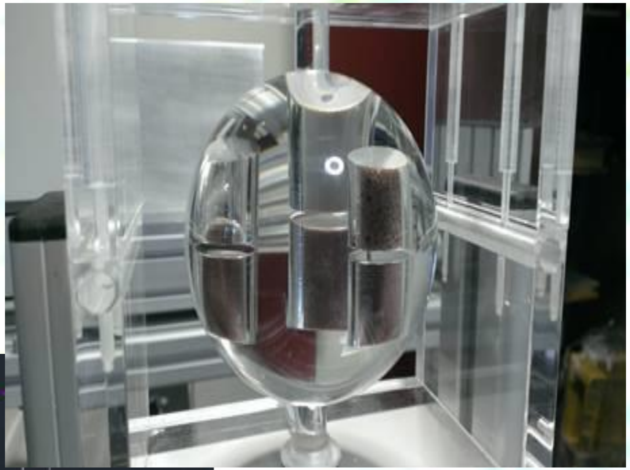

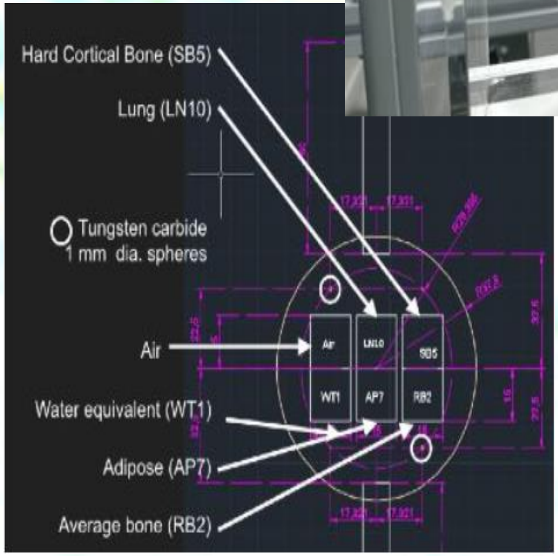

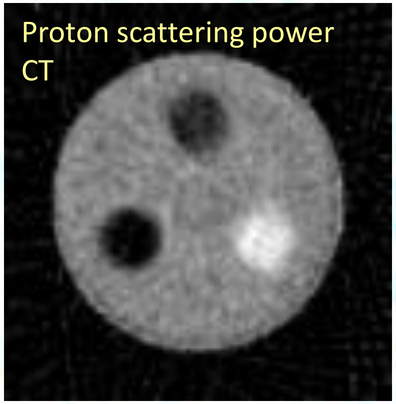

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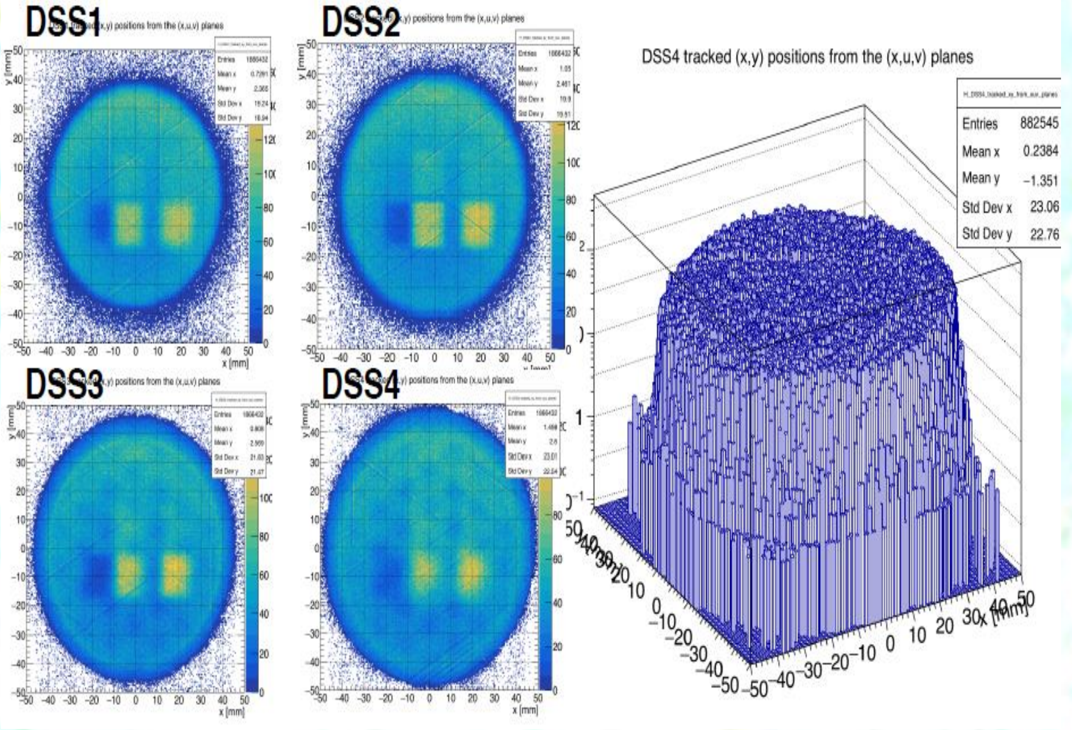
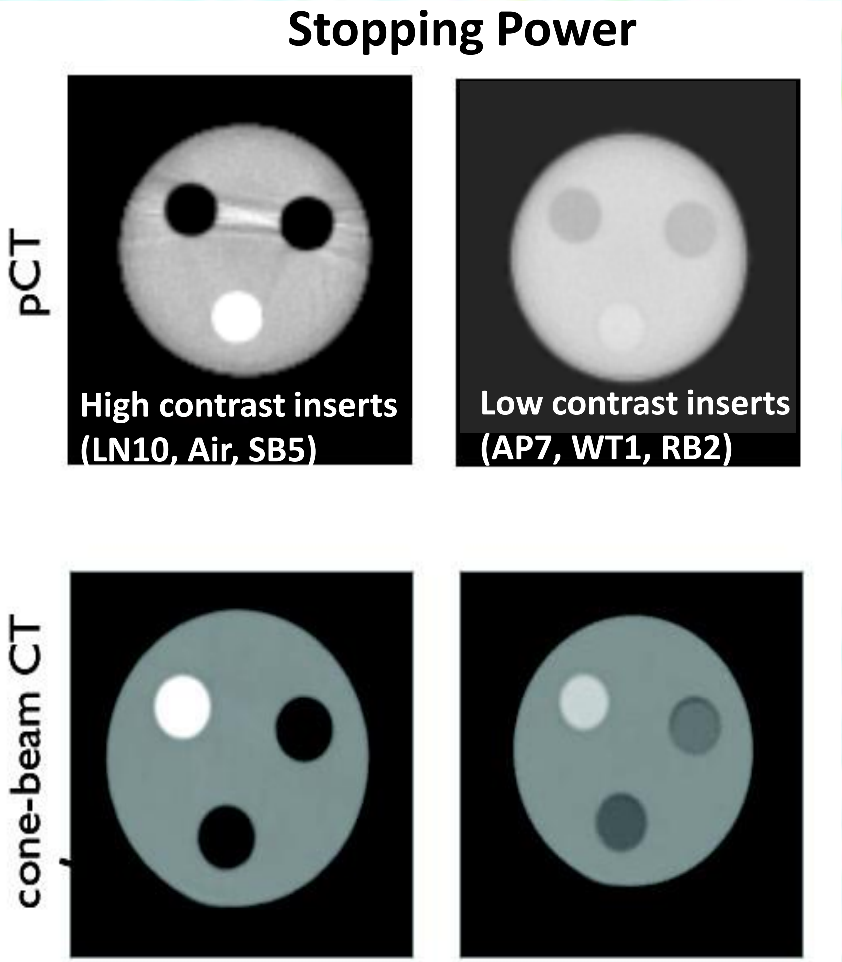
- Still need optimal way to combine scattering and stopping power.

Raw data rate ~ 360 Gbit/s



Proton Radiotherapy Verification and Dosimetry Applications

- Installed at iThemba for first tests May 2016 (125 MeV degraded beam).
- Compensator in place.
- 180 rotations at 1° steps.
- Over 1M protons / rotation.
- Second run November 2016.
- 280 M proton histories recorded.
- Reconstructed using novel Back-Projection-Filtering algorithm specifically developed for proton CT.
- Stopping power for all inserts (except lung) agree within 1.6% of expected values.
- Still need optimal way to combine scattering and stopping power.



Proton Radiotherapy Verification and Dosimetry Applications

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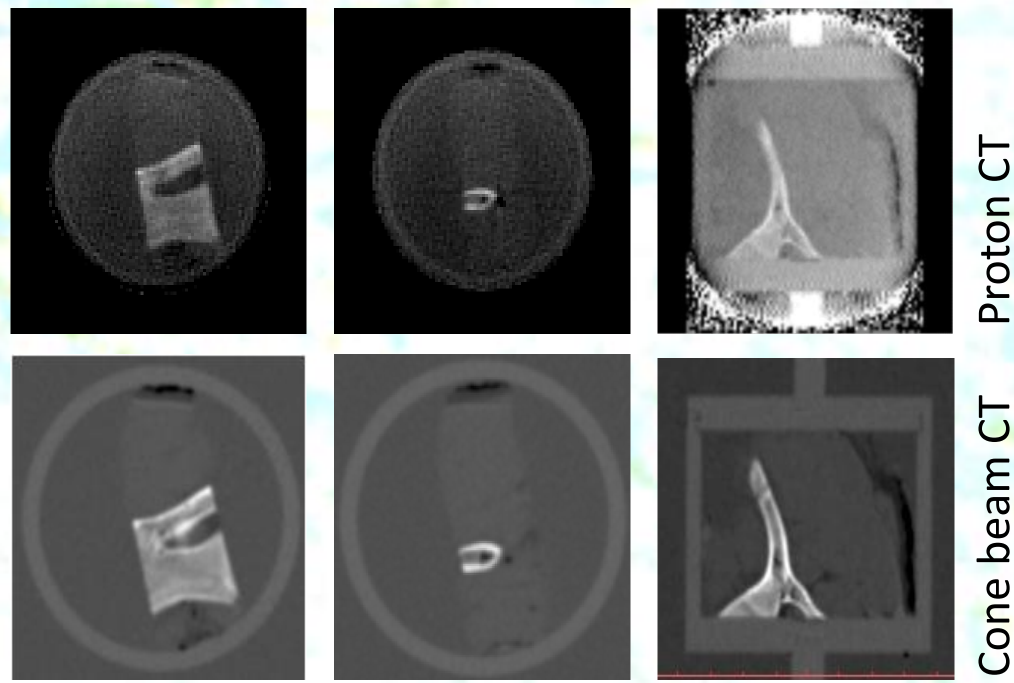
- Stopping power for all inserts (except lung) agree within 1.6% of expected values.
- Still need optimal way to combine scattering and stopping power.

Lamb chop chosen as first test of proton CT on real tissue due to regions of bone, soft tissue and fat

Same parameters as for imaging phantom, but with 2^{o} rotation steps

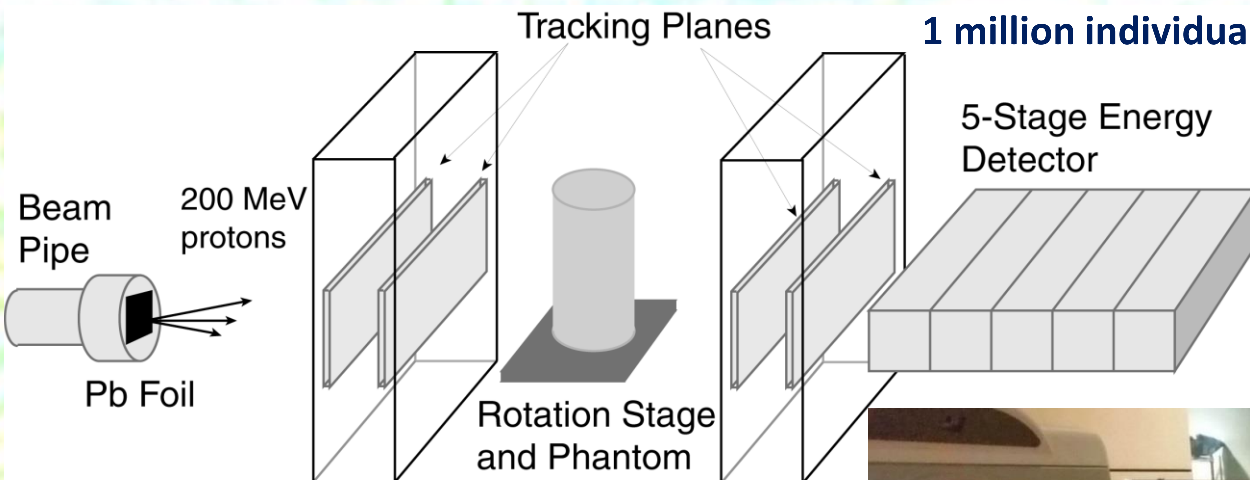


The pCT Collaboration

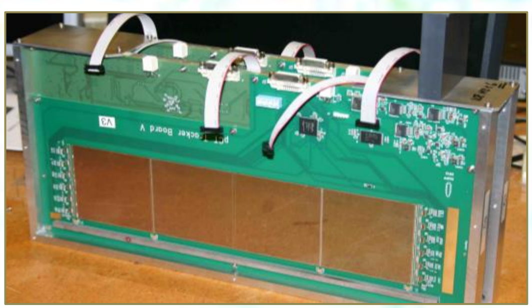
R. P. Johnson, Tia Plautz, Hartmut F.-W. Sadrozinski, A. Zatserklyaniy: *SCIPP, U.C. Santa Cruz, Santa Cruz, CA , USA*
V. Bashkirov, V. Giacometti, F. Hurley, P. Piersimoni, R. Schulte: *Division of Radiation Research, Loma Linda University, CA, USA*
P. Karbasi, K. Schubert, B.Schultze: *Baylor University, Waco, TX, USA*

Loma Linde with SCIPP (UCSC) see for example Robert P Johnson *et al* 2017 "*Review of medical radiography and tomography with proton beams*" https://doi.org/10.1088/1361-6633/aa8b1d

1 million individual protons reconstructed per second

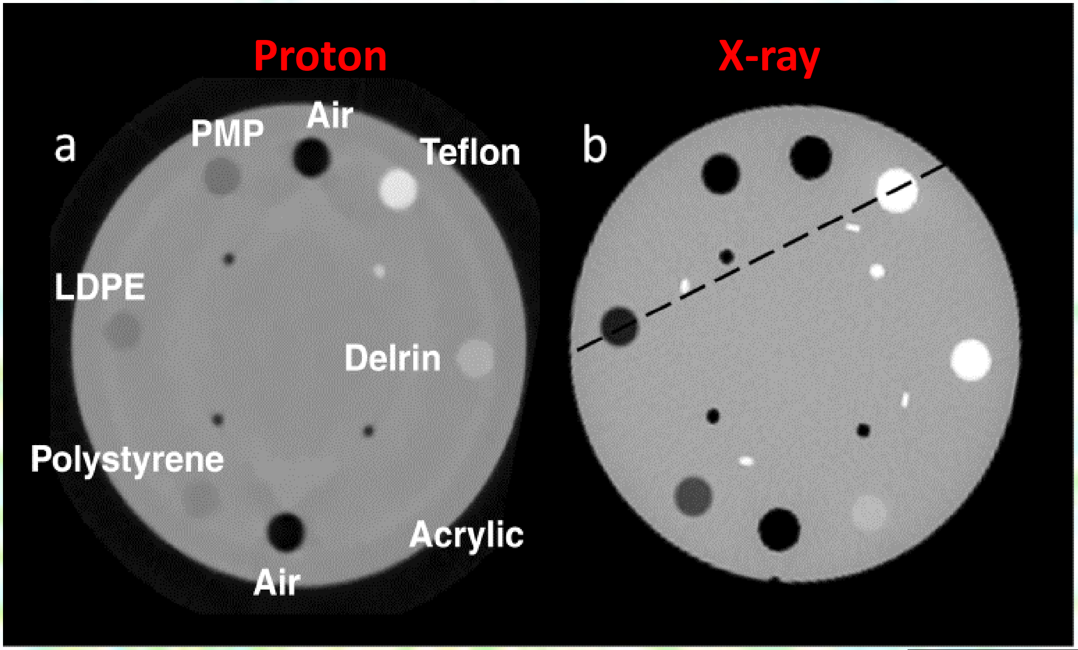


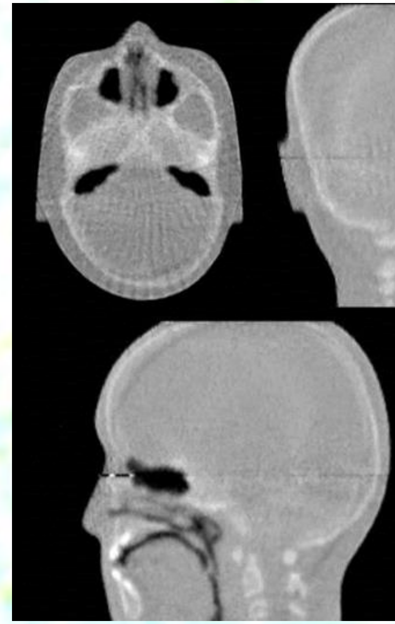
H.F.-W. Sadrozinski, et al, *Development of a Head Scanner for Proton CT*, Nucl. Instr. Meth. A 699 (2013) 205.



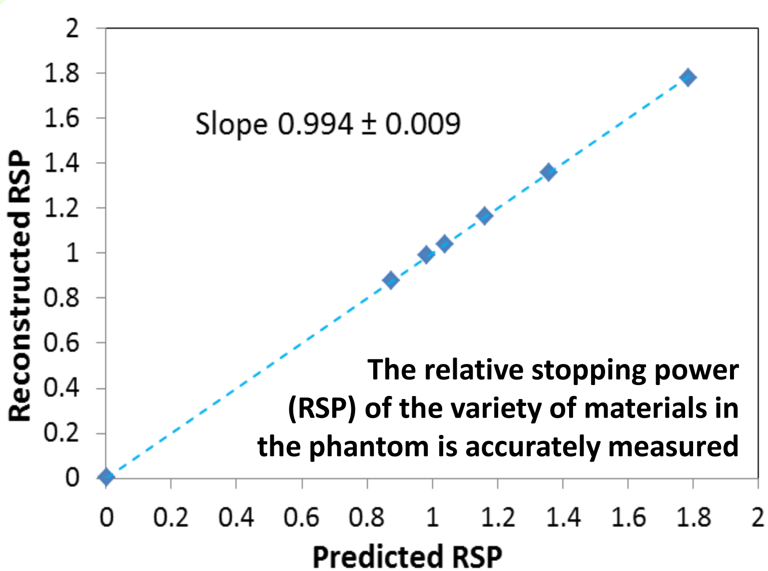
Four 9cm*9cm silicon strip sensors with thin-edge technology in x-y configuration

The pCT Collaboration

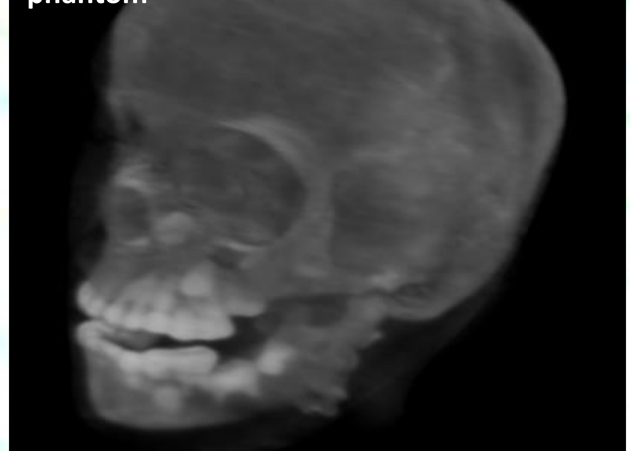




Three cardinal planes of 3D RSP images obtained with Phase II scans of the anthropomorphic head phantom.

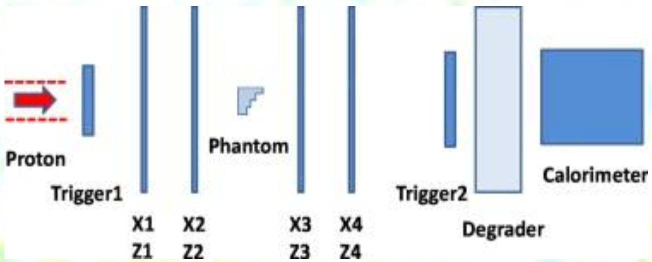


3D rendering of the pCT-reconstructed RSP map of a pediatric anthropomorphic head phantom

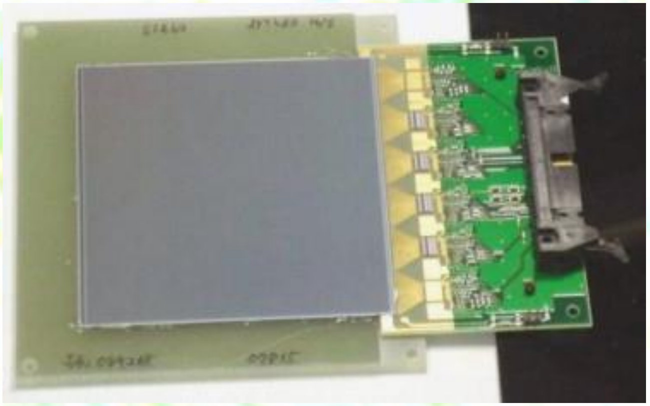


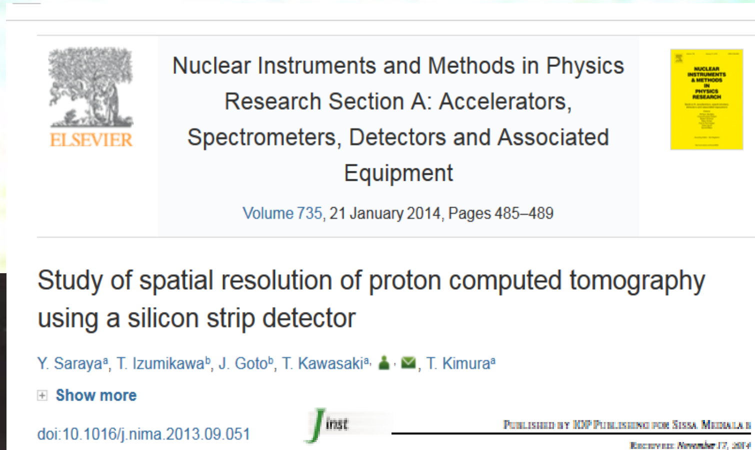
Other Silicon Trackers

- Another group using similar sensors to the pCT Collaboration is based at Niigata University



Item	Specifications
Outer dimensions	89.5×89.5 mm²
Active area	87.6×87.6 mm²
Substrate thickness	410±10µm
Strip pitch	228µm
Readout pitch	456µm
Number of strips	384
Full depletion voltage	<120 V




Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

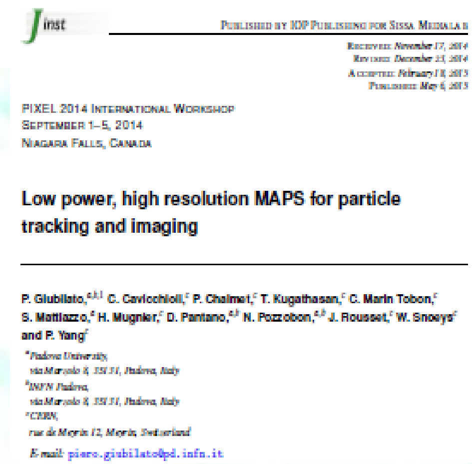
Volume 735, 21 January 2014, Pages 485–489

Study of spatial resolution of proton computed tomography using a silicon strip detector

Y. Saraya[a], T. Izumikawa[b], J. Goto[b], T. Kawasaki[a], T. Kimura[a]

Show more

doi:10.1016/j.nima.2013.09.051


JINST

Published by IOP Publishing for Sissa Medialab

PIXEL 2014 International Workshop
September 1–5, 2014
Niagara Falls, Canada

Low power, high resolution MAPS for particle tracking and imaging

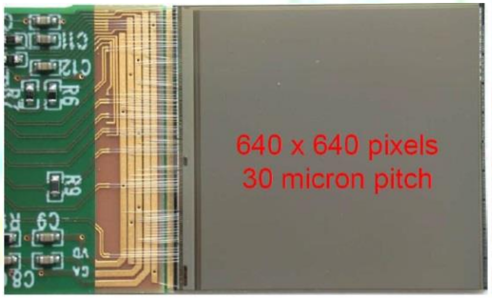
P. Giubilato, C. Cavicchioli, P. Chalmet, T. Kugathasan, C. Marin Tobon, S. Mattiazzo, H. Mugnier, D. Pantano, N. Pozzobon, J. Rousset, W. Snoeys and P. Yang

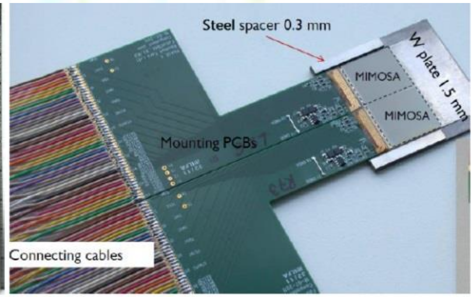
E-mail: piero.giubilato@pd.infn.it

- A very promising approach being followed by Padua with CERN is the use of MAPS technologies for the tracking but with intelligent on-chip data sparsification to deliver faster, low power readout
- However, the approach does not yet address the radiation tolerance challenges. Although these are being addressed for particle physics applications, these are yet to be demonstrated in a wafer-scale sensor, which is ideally what is needed for pCT.

CMOS Sensors and BGO

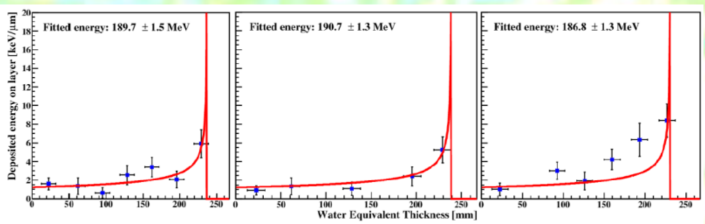
- MAPS (Mimosa) are also being looked at by groups in the Netherlands and Norway

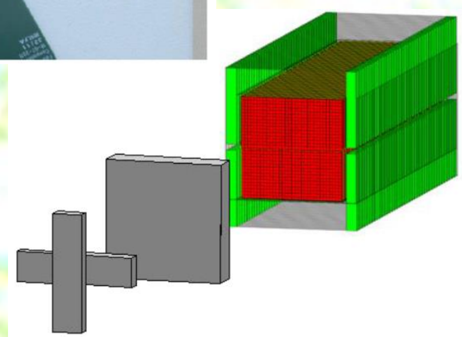


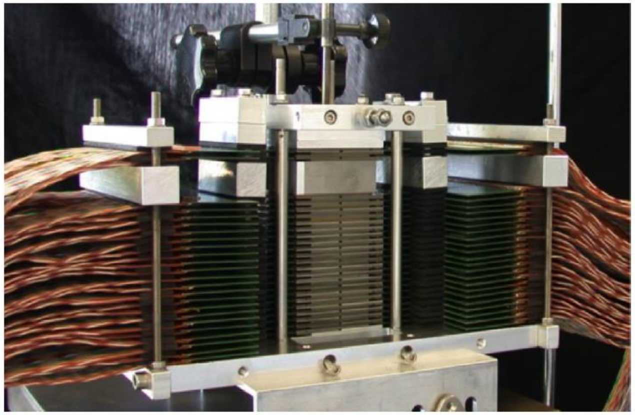


Proton tracking in a high-granularity Digital Tracking Calorimeter for proton CT purposes

H. E. S. Pettersen*[a, b], J. Alme[b], A. Biegun[c], A. van den Brink[c], M. Chaar[b], D. Fehlker[b], I. Meric[d], O. H. Odland[a], T. Peitzmann[c], E. Rocco[c], K. Ullaland[b], H. Wang[c], S. Yang[b], C. Zhang[c], D. Röhrich[b]



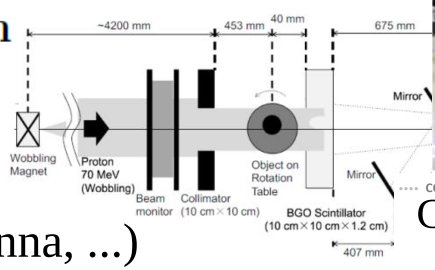




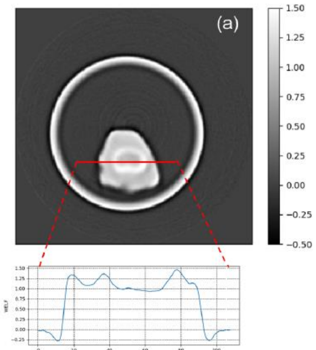
- There are a number of other initiatives using different tracking/calorimeter technologies, scintillating fibres, multi-wire proportional chambers, … all of which have potential advantages and disadvantages when compared with silicon detectors

Improved Proton CT Imaging using a Bismuth Germanium Oxide Scintillator

Sodai Tanaka *et al* 2018 *Phys. Med. Biol.* in press
https://doi.org/10.1088/1361-6560/aaa515



Chicken leg



- Also Micro-Pattern Gas Detectors (CERN, Vienna, ...)

Scintillator Tracking

Fermilab, Delhi and Northern Illinois system uses scintillating fibre tracker
Area 20x24 cm^2 (4 planes upstream) and 24x30 cm^2 (4 planes downstream) with 15 cm separation between planes.
96 plastic scintillating tiles with dimensions of 27cm width, 36 cm height, and 3.2mm thickness were used in the range stack.

Fermi Lab

FERMILAB-TM-2617-AD-CD-E

At the proton beam at the Central DuPage Hospital in Warrenville, IL

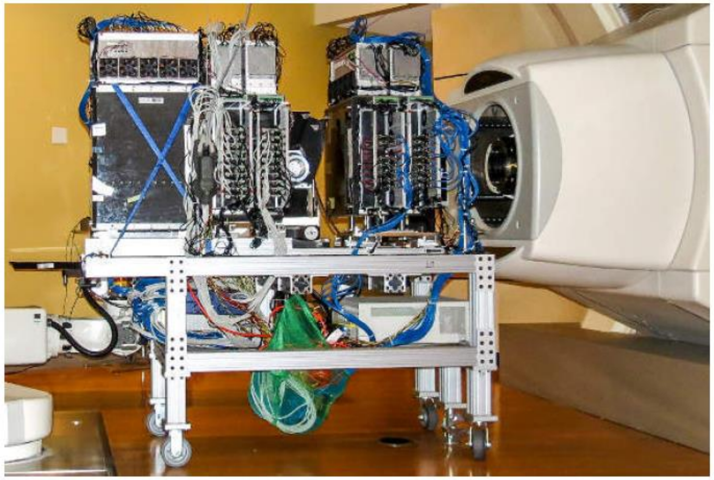


Figure 3: Fully assembled proton CT scanner at CDH Proton center. From right to left, beam enters the upstream tracker planes followed by the downstream tracker planes and finally the range stack. The gap in the middle is the position of the rotation stage for the head phantom in the horizontal plane.

Birmingham Instrumentation Laboratory for Particle physics and Applications BILPA

Conclusions

UNIVERSITY OF BIRMINGHAM

- **The particle physics community has over 40 years of experience of operating finely segmented silicon sensors for precision tracking of charged particles in high rate, high radiation environments.**
- **A number of different techniques have been developed towards high spatial resolution, fast timing, low mass, high granularity, large area and low cost per unit area arrays.**
- **Over time this has allowed a rough increase by a factor of ten each decade in the area which can be instrumented with silicon sensors.**
- **Linked with the advances in commercial microelectronics and new generations of application specific integrated circuits (ASICs) with complexity now approaching that of microprocessors, the channel count of the arrays has grown even faster, as have the corresponding rates of data that can be handled.**
- **New technologies are just emerging that could be expected to be game-changers for the design of future particle tracking systems.**
- **As current techniques find applications in a range of other fields, so these new technologies can be expected to bring even greater benefits in the future.**

→ **It is currently a very exciting time to be a detector physicist.**

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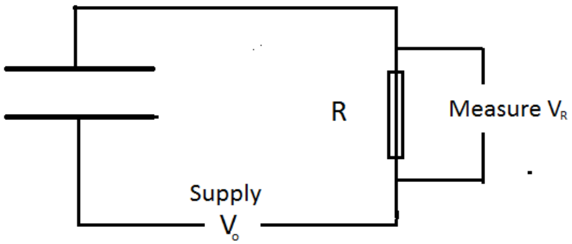
THANK YOU

Any Questions?

BACK UP



The magnitude V_R of the voltage drop can be determined from conservation of energy,

remembering that the energy stored in a capacitor is given by $\frac{1}{2}CV^2$, where *V* is the voltage across it.

Initially $V = V_0$.   Subsequently $V = V_0 - V_R$

The difference in energy is equal to the work done by the electrons and holes moving through the electric field, which is given by $q\mathcal{E}d$, where *d* is the distance moved by charge *q*

So $\frac{1}{2}CV_0^2 = \frac{1}{2}C(V_0 - V_R)^2 + q\mathcal{E}d_+ + q\mathcal{E}d_-$

Rearranging this, $CV_0V_R - \frac{1}{2}CV_R^2 = q\mathcal{E}(d_+ + d_-)$

Since $V_R \ll V_0$ the second term can be neglected,

and so $V_R = \frac{q\mathcal{E}}{CV_0}(d_+ + d_-) = \frac{q}{Cd}(d_+ + d_-)$ **(since $\mathcal{E} = \frac{V_0}{d}$)**

When both sets of charges reach the electrodes, $d_+ + d_- = d$ so $V_R = \frac{q}{C}$

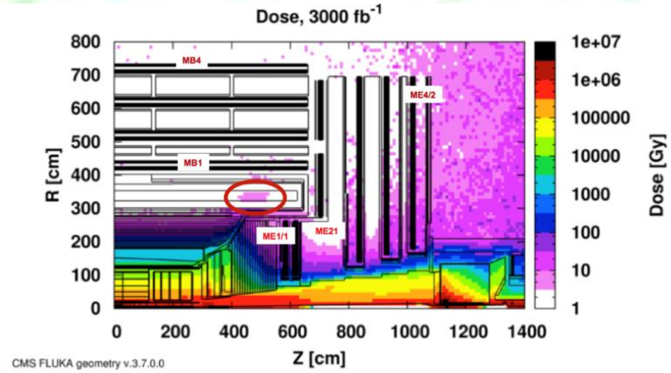
The final pulse size is as expected.

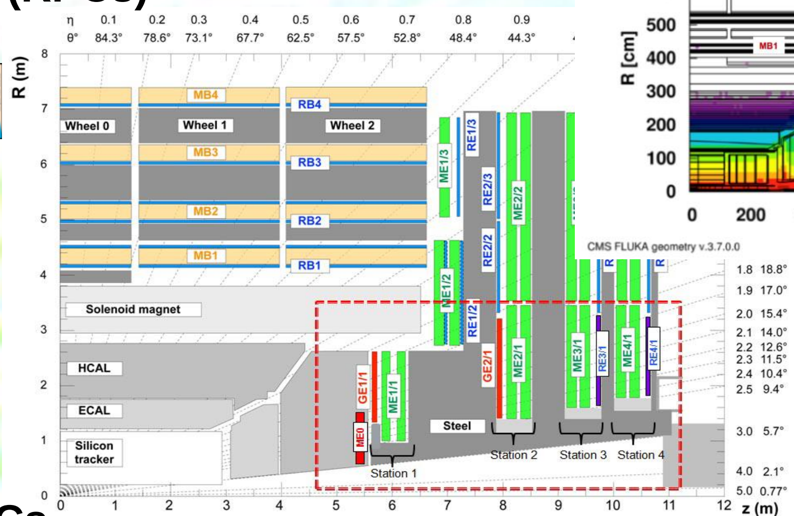
Other Tracking Technologies

- Muon detectors need improved spatial resolution and enhanced rate capability → advanced micro-pattern gas detectors
- Large area detector construction necessitates very close links with industry to develop designs and processes for mass production
- Other technologies being used for tracking in high rate environments include scintillating fibres (LHCb) and straws (NA62, Mu2e)
- Several technologies (see back-up) can also provide « ns time resolution ("4D detectors") which with bunch time structure and beam spot spread in z, can help correctly assign tracks to primary vertices
  - Fast timing also allows time of flight measurements which give velocity at low momentum and hence can help with particle ID

Gaseous Tracking Detectors

- CMS new forward muons for improved triggering and directional measurements
  - Gas Electron Multiplier (GEMs)
  - Resistive Plate Chambers (RPCs)

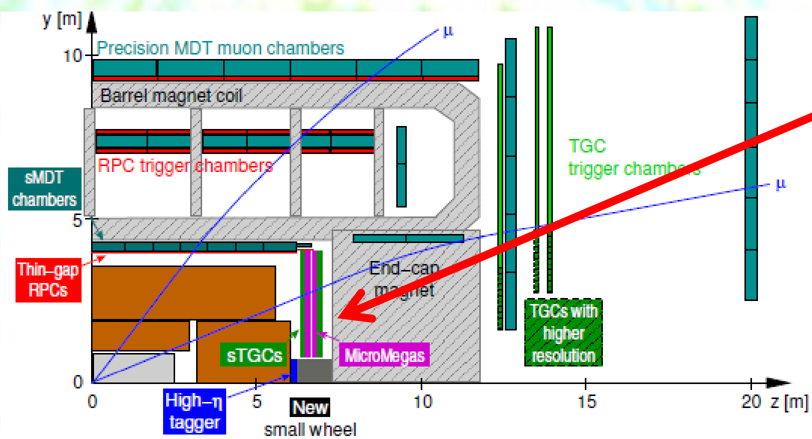




HL-LHC background
5x rates and
6x total doses
with respect to LHC

- ATLAS barrel muon trigger
  - 276 additional RPCs
  - small tube diameter Monitored Drift Tubes sMDTs

  (make space for the new RPCs and increase tracking rate capability)



- ATLAS: improve endcap muon tracking and trigger
- New Small Wheels
  - small-strip thin Gap trigger chambers (sTGCs)
  - MicroMegas tracking detectors (MM)

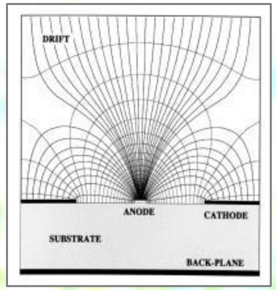
Gaseous Tracking Detectors

Birmingham Instrumentation Laboratory for Particle physics and Applications (BILPA)

UNIVERSITY OF BIRMINGHAM

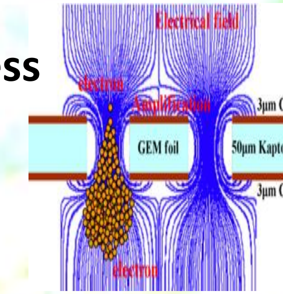
Main R&D activities for ATLAS and CMS are for new muon chambers in the forward directions.

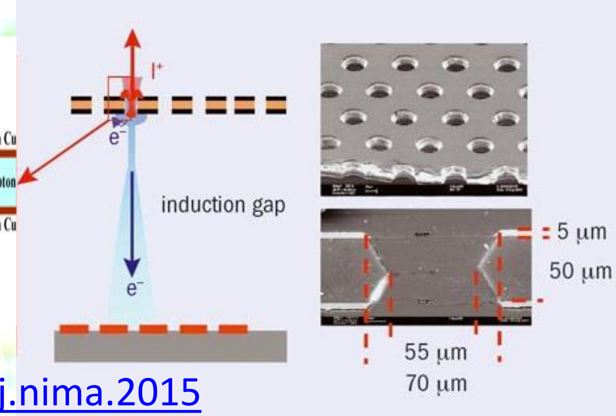
- **Increase rate capabilities and radiation hardness**
- **Improved resolution (online trigger and offline analyses)**
- **Improved timing precision (background rejection)**



Technologies

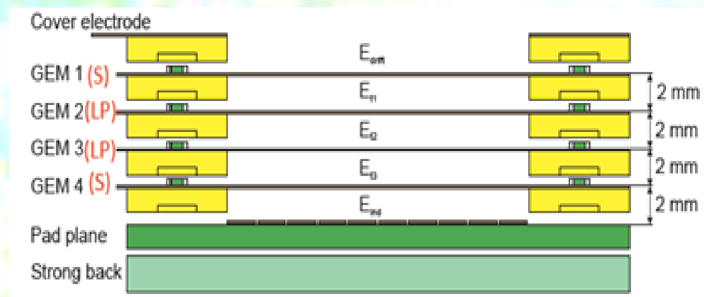
- **Gas Electron Multiplier (CMS forward chambers, ALICE TPC and current LHCb)**
- **MicroMegas and Thin Gap Chambers (TGCs) (ATLAS forward chambers)**
- **Resistive Plate Chambers (RPCs) - low resistivity glass for rate capability - multi-gap precision timing (ATLAS/CMS)**

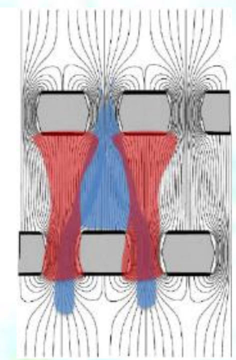




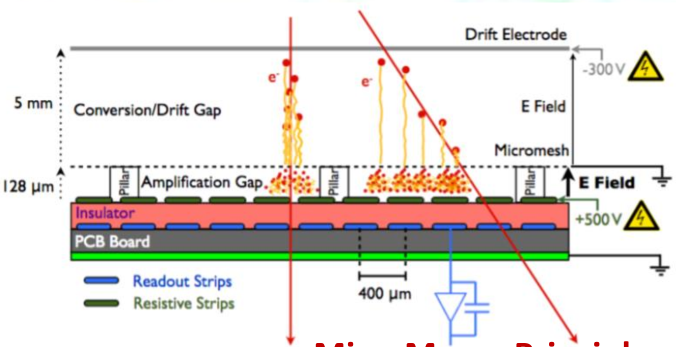
Fabio Sauli
doi:10.1016/j.nima.2015

GEM stack for ALICE TPC R/O.





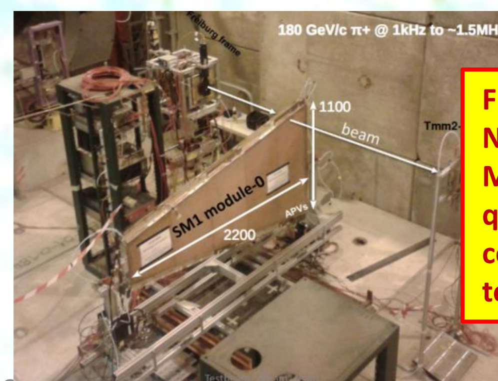
4 layer stack to target Ion backflow < 1% given continuous readout at 50kHz



MicroMegas Principle

CERN RD51 common micro-pattern gas detector R&D

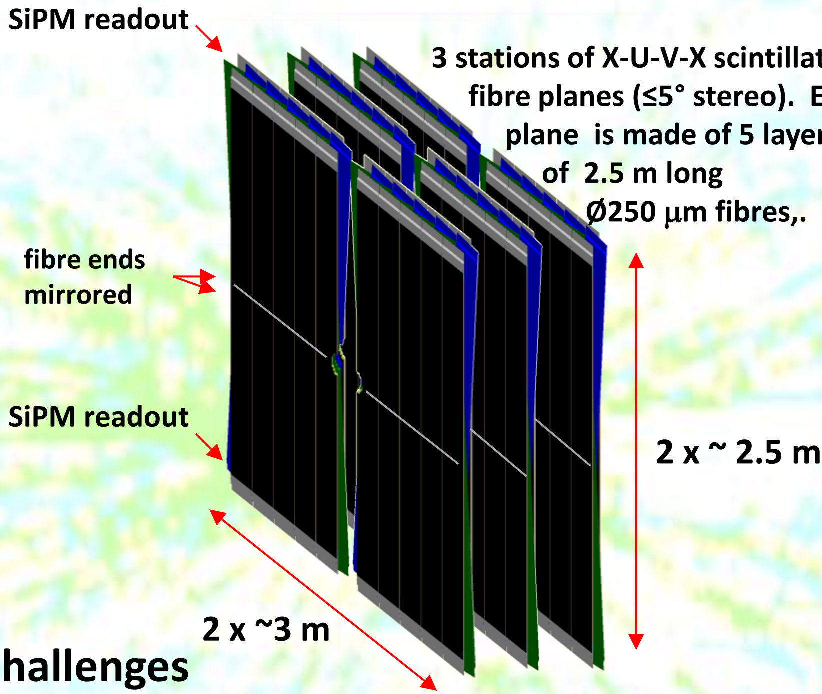
Need to develop commercial large-scale production capabilities



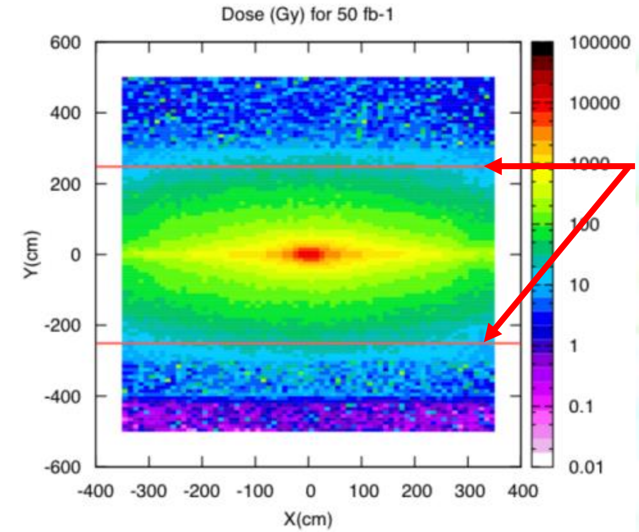
Full scale ATLAS New Small Wheel MicroMegas quadruplet completed and tested at CERN

Scintillating Fibre Tracking

Large scale SciFi tracker for LHCb

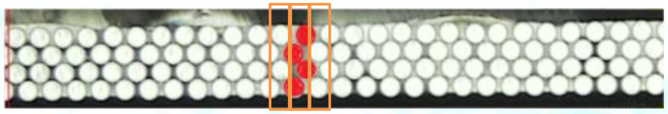


3 stations of X-U-V-X scintillating fibre planes (≤5° stereo). Every plane is made of 5 layers of 2.5 m long Ø250 μm fibres,.

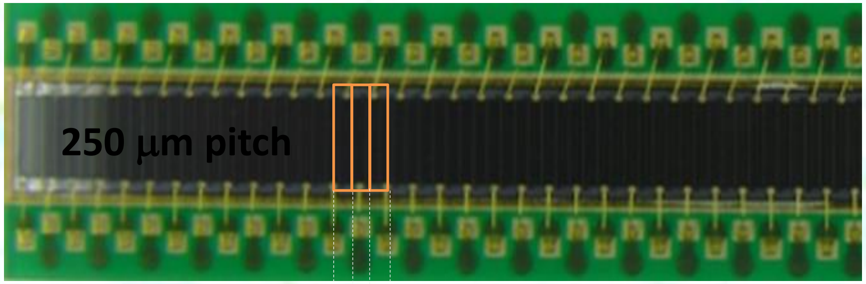


SiPM location

$F_n = 6 \cdot 10^{11}$ cm^{-2}



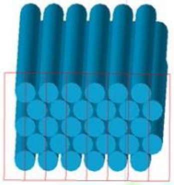
4 layer proto mat



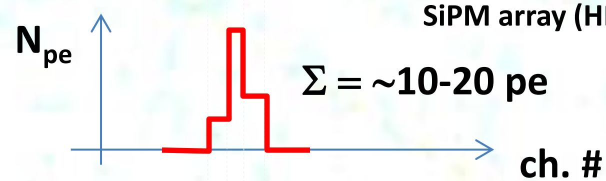
SiPM array (HPK)

Challenges

- Large size – high precision
- O(10,000 km) of fibres
- Operation of SiPM at -40°C



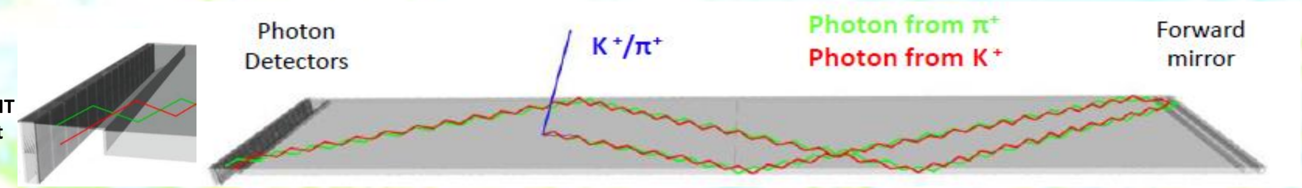
3 million (SCSF-78MJ TDR baseline) scintillating fibres with up to 30kGy non-uniform exposure (CERN/LHCC 2014-001)



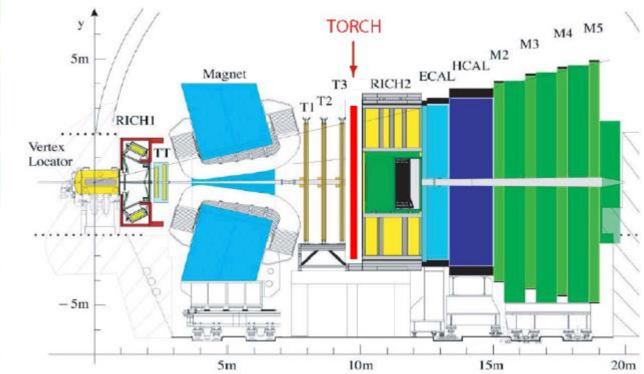
Timing Detectors (c=30cm/ns; 1/c= 33ps/cm)

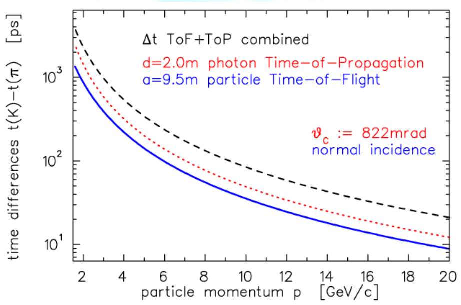
- **Many applications call for precision timing for particle ID (incl Time of Flight)**
  - ***eg* BELLE-II TOP (Time of Propagation) σ = 35ps: 2.5m x 0.45m x 2cm Quartz bars**

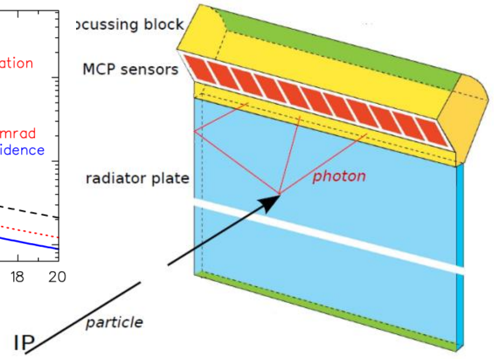
MCP PMT Readout

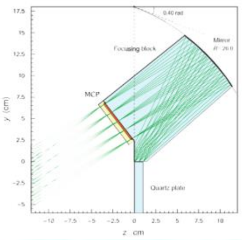


  - ***eg* LHCb TORCH** (Time Of internally Reflected CHerenkov light) **15ps ToF (30 pe/track)**

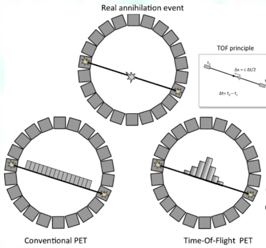






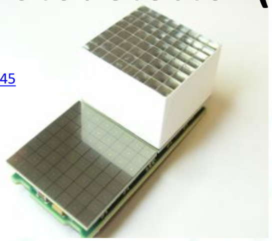


- **PET Scanner technologies: ToF fast scintillator and photodetector (eg LYSO+SiPM)**



25ps time bins

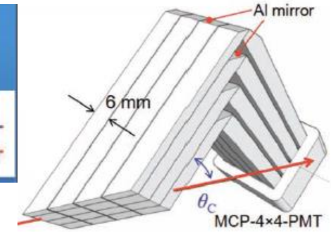
https://doi.org/10.1016/j.nima.2017.02.045

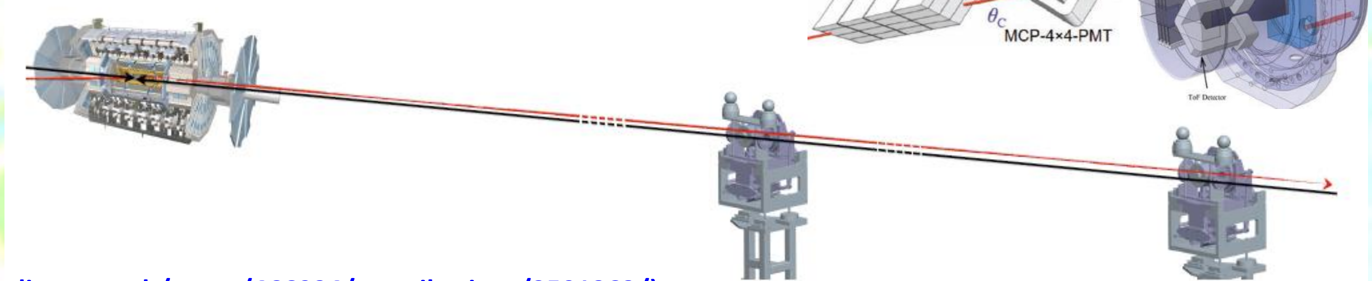


Also CMS Barrel Timing Layer (30ps pile-up mitigation)

Timing Detectors (c=30cm/ns; 1/c= 33ps/cm)

- **Charged particle detection with quartz/scintillator plus fast photodetectors *eg* ATLAS Forward Physics, or direct detection also possible with fast gas or semiconductor detectors**



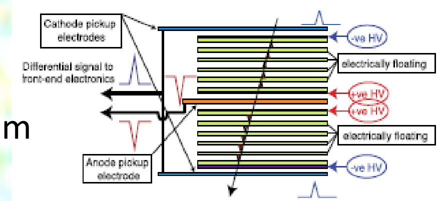


ATLAS AFP: <15ps James Pinfold (https://indico.cern.ch/event/466934/contributions/2591363/)

ALiCE ToF

140 m² of Multigap RPCs at 3.7 m from the IP

- Rate capability ~100 Hz/cm² (glass resistivity)
- **Fast readout electronics**
- Leading edge disc. with time-over-thresh correction (NINO)



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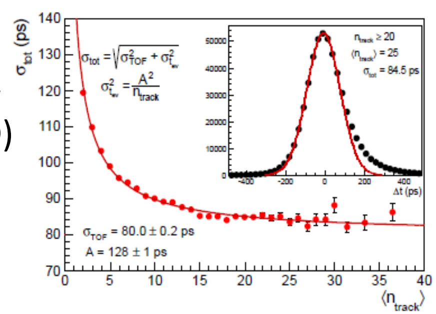
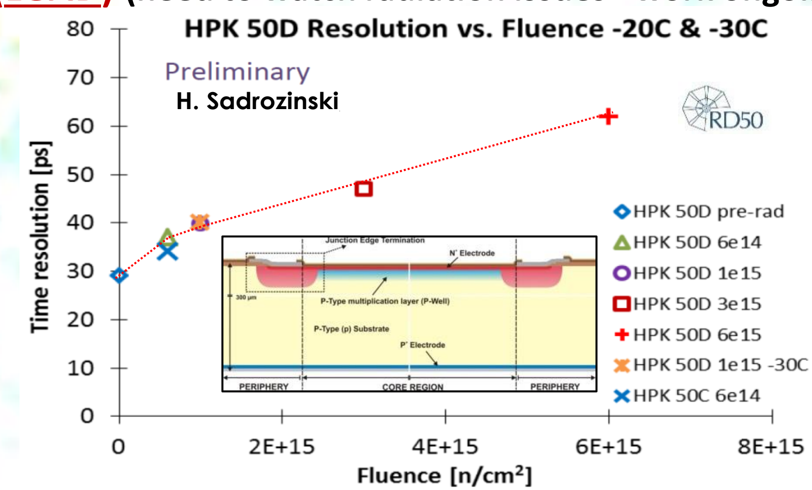


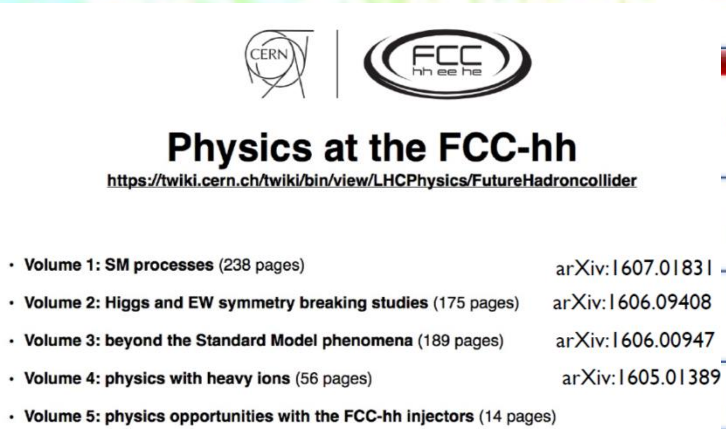
- **Single particle resolution *in situ*: down to 80 ps**

RD50, ATLAS, CMS: Low Gain Avalanche Detectors (LGAD) (need to watch radiation issues - work ongoing)



FCC Planning and Status

- Fastest "*technically feasible*" schedule
- Very/hopelessly optimistic schedule; scenario with no cash-flow limitations
- Not even consistent with HL-LHC schedule, but shows what could be achieved
- Physics and performance simulations prepared for Rome FCC Week


Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- **Volume 1: SM processes** (238 pages) arXiv:1607.01831
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages) arXiv:1606.09408
- **Volume 3: beyond the Standard Model phenomena** (189 pages) arXiv:1606.00947
- **Volume 4: physics with heavy ions** (56 pages) arXiv:1605.01389
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)

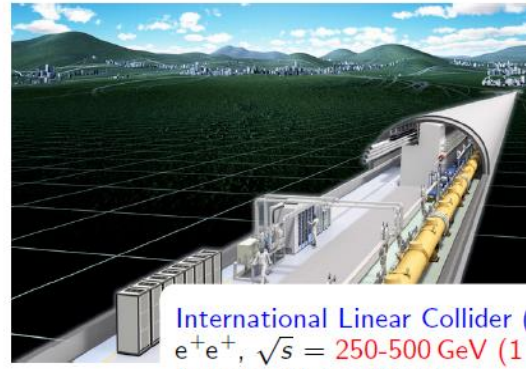
- Full Conceptual Design Review (CDR) driven by **European Strategy update in 2020**
- FCC-hh summary volume (100-200 pages) as well as the extensive FCC-hh comprehensive CDR volume "Experiment and Detectors" (>1000 pages)
- November 22nd 2018: Publication

Energy Frontier e^+e^- Facilities

2013 update of the European Strategy for Particle Physics

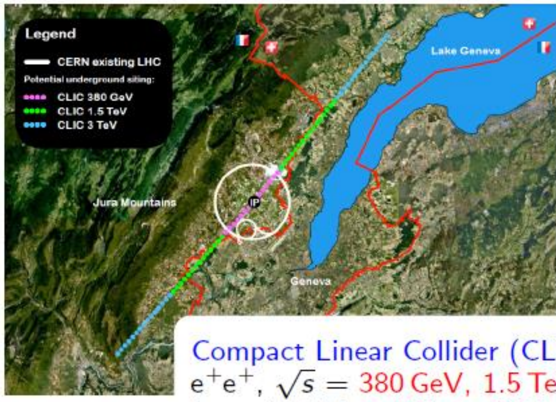
"There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded …. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation"

Circular Electron Positron Collider (CEPC)
e^+e^-, $\sqrt{s} =$ 240-250 GeV; SPPC pp,
Circumference: 54-100 km

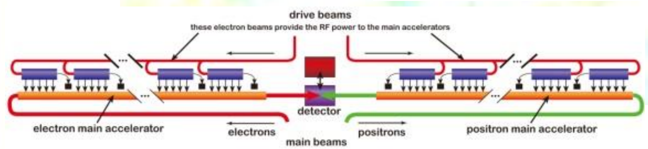


Future Circular Collider (FCC)
e^+e^+, $\sqrt{s} =$ 90-350 GeV;
pp, $\sqrt{s}$:~100 TeV
Circumference: 90-100 km

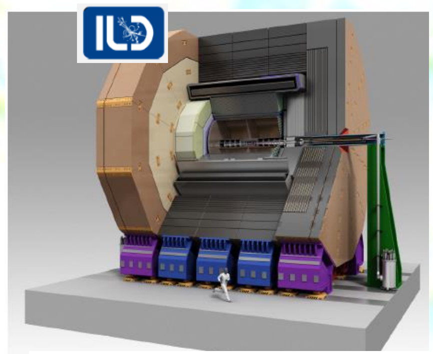
International Linear Collider (ILC)
e^+e^+, $\sqrt{s} =$ 250-500 GeV (1 TeV)
Length: 31 km (50 km)

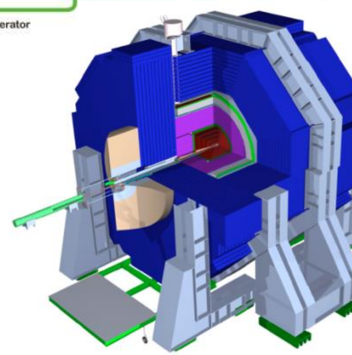


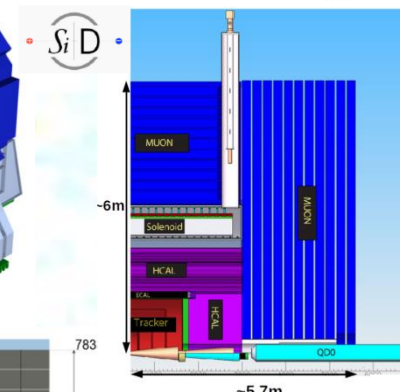
Compact Linear Collider

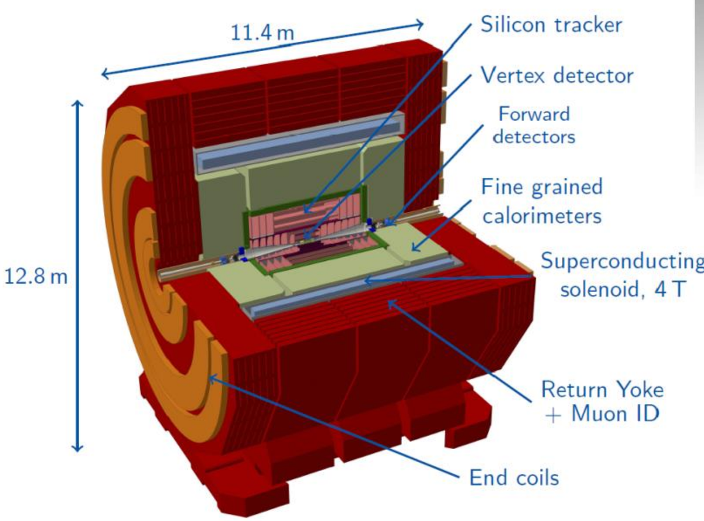


Compact Linear Collider (CLIC)
e^+e^+, $\sqrt{s} =$ 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km

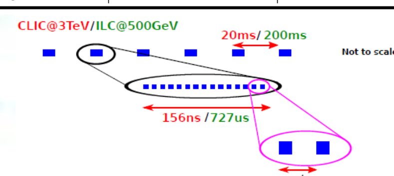


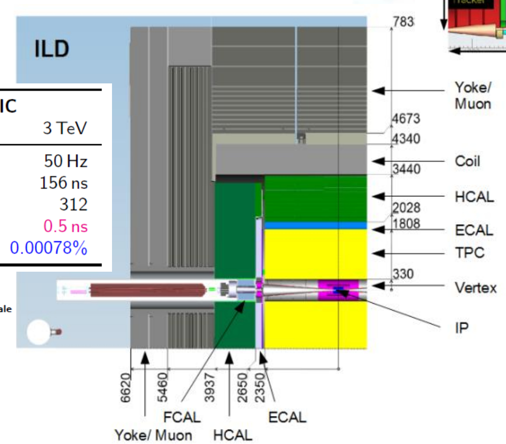




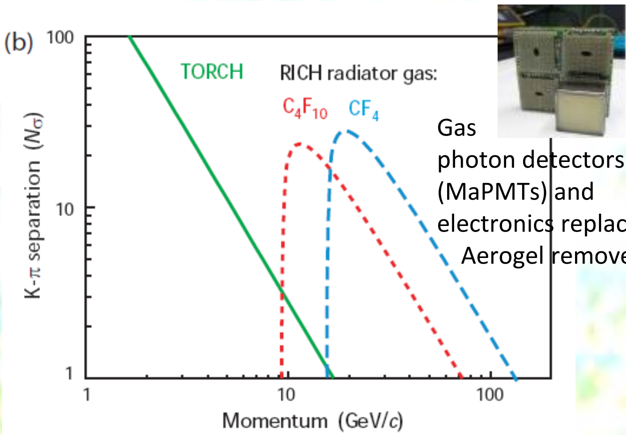


Property	ILC		CLIC	
$\sqrt{s}$	500 GeV	1 TeV	380 GeV	3 TeV
Repetition rate	5 Hz	4 Hz	50 Hz	50 Hz
Train duration	727 µs	897 µs	178 ns	156 ns
BX / train	1312	2450	356	312
Bunch separation	554 ns	366 ns	0.5 ns	0.5 ns
Duty cycle	0.36%	0.36%	0.00089%	0.00078%



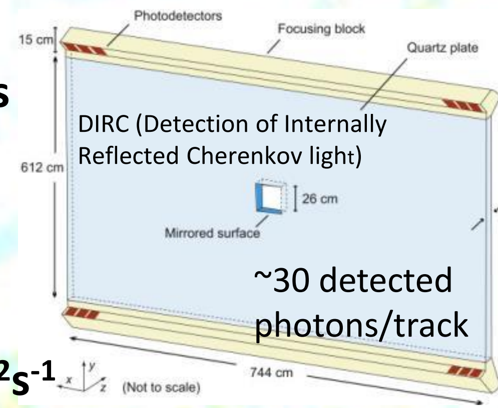


Particle ID and Timing



Gas photon detectors (MaPMTs) and electronics replaced. Aerogel removed.

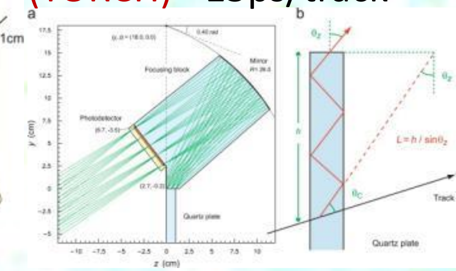
LHCb RICH system needs upgrades for triggerless operation at higher rates: $\mathcal{L}=2\times10^{33}cm^{-2}s^{-1}$



DIRC (Detection of Internally Reflected Cherenkov light)

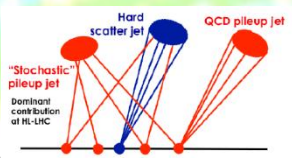
~30 detected photons/track

LHCb Time Of internally Reflected CHerenkov (TORCH) ~15ps/track

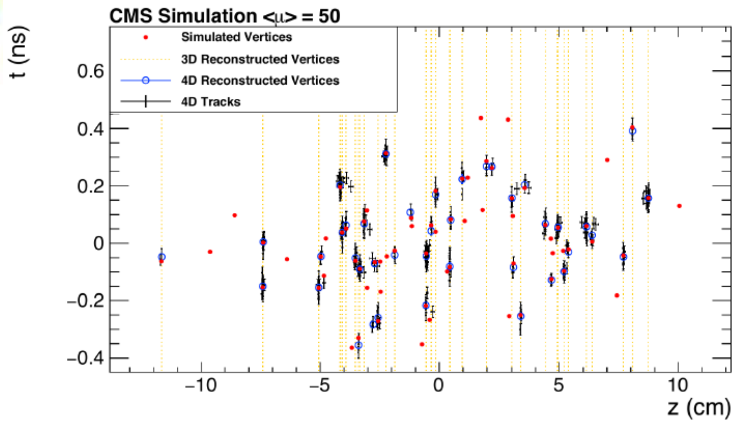


For 200 PU, depending on crossing scheme, HL-LHC can deliver down to an event/mm and up to 1.45ns bunch crossing duration

→ Use 20-30ps timing to better associate high p_T objects to vertices

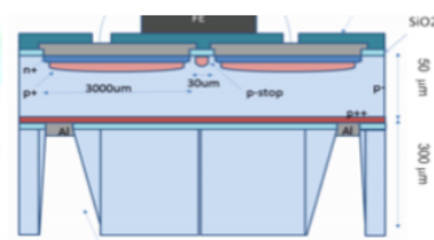


20 ps resolution assumed for charged particles with $p_T > 1$ GeV



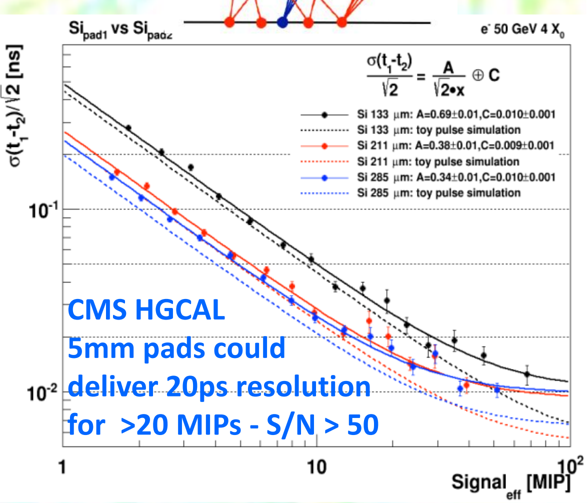
Requirements:

- time resolution =30-50 ps/mip
- Radiation tolerance to 10^{15}-10^{16}n/cm^2



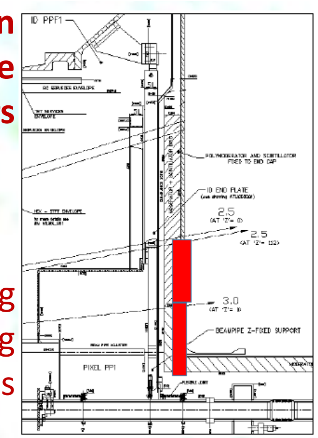
RD50

Low Gain Avalanche Detectors



CMS HGCAL 5mm pads could deliver 20ps resolution for >20 MIPs - S/N > 50

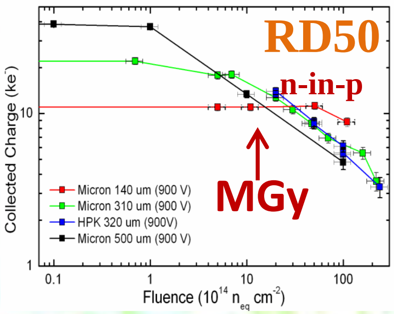
ATLAS propose dedicated **H**igh **G**ranularity SiW **T**iming **D**etector in front of end-cap at z=3500mm, covering 2.4<η<4.2 (650mm>r>110mm) 50µm thick few mm^2 pads

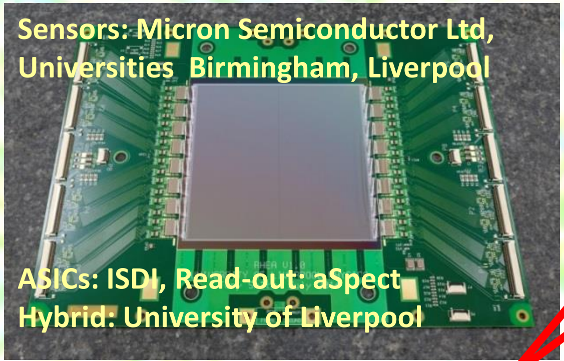


Birmingham Instrumentation Laboratory for Particle physics and Applications (BILPA)

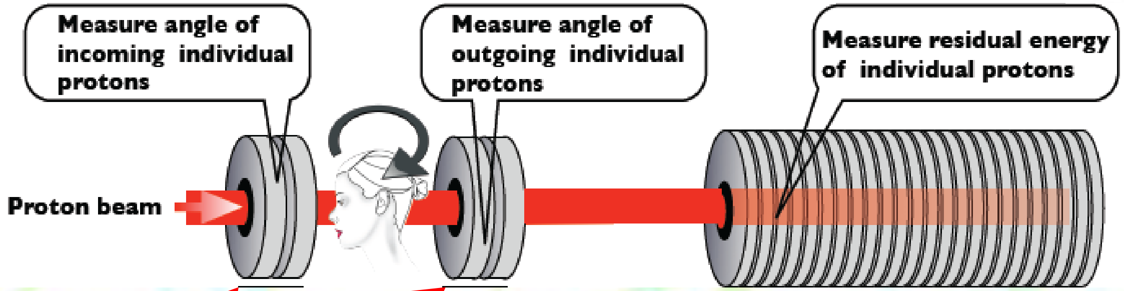
Proton Computed Tomography

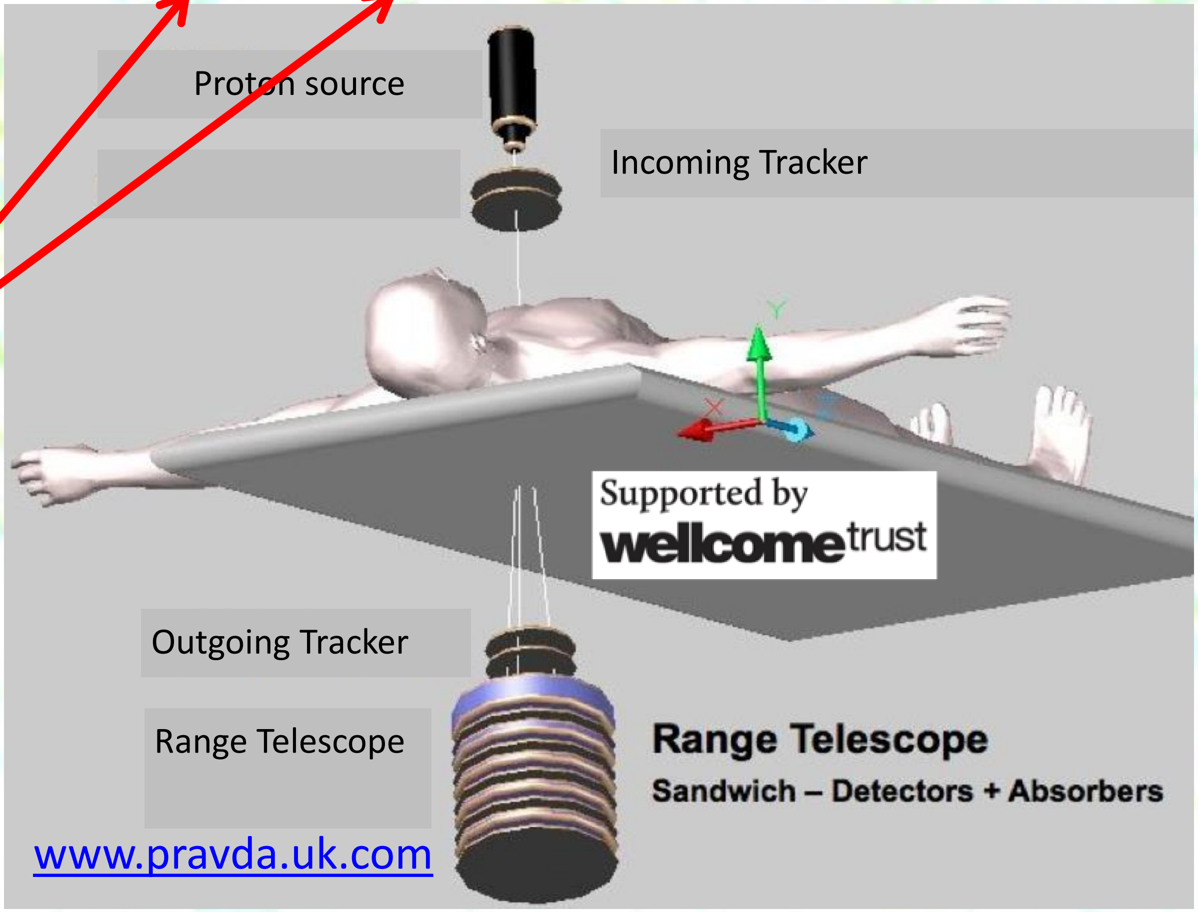
UNIVERSITY OF BIRMINGHAM





PRaVDA micro-strip detector





Silicon sensors with 2048 strips at 91µm pitch using 150µm thick n-in-p radiation-hard technology developed for High Luminosity LHC

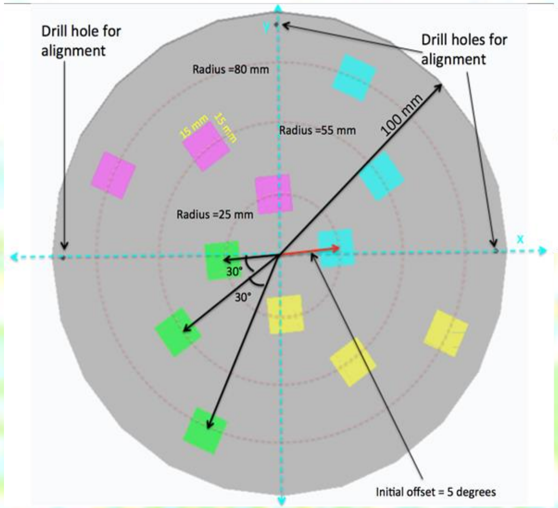
12 planes of strips used to make 4 tracking modules, 2 before and 2 after the patient

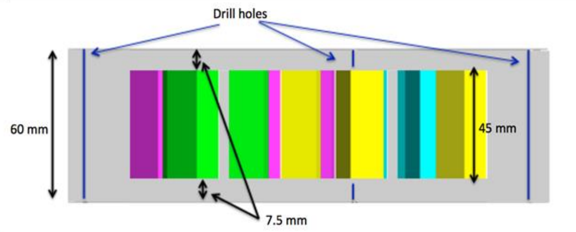
Each module of strips has three planes crossed at 60º in an (x,u,v) configuration to allow high particle rate

The pCT Collaboration

Spatial Resolution Studies: Edge Phantom

A phantom was designed and fabricated for the purpose of measuring a **modulation transfer**





Left: Top down view of the Edge Phantom.
Right: Side view of the Edge Phantom

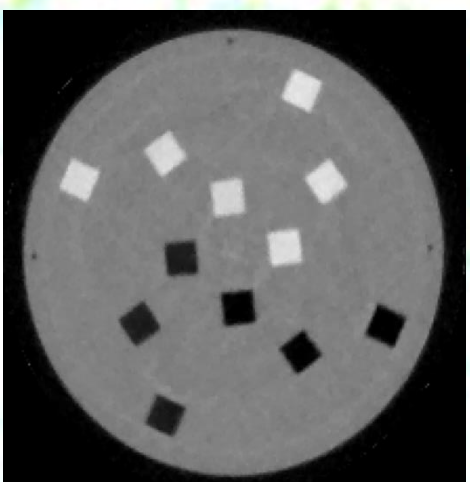
Cyan: Tooth Enamel
ρ = 2.04 g/cm^3; RSP = 1.784
Magenta: Cortical Bone
ρ ~ 1.91 g/cm^3; RSP = 1.699

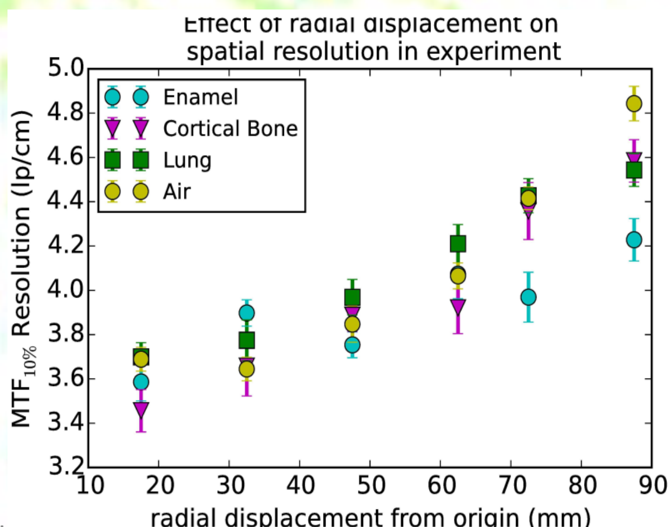
Green: Lung
ρ ~ 0.205 g/cm^3; RSP = 0.203
Yellow: Air
ρ = 0.0012 g/cm^3; RSP = 1.06e-03

MTF is the function of relative modulation with respect to spatial frequency (lp/cm) that characterizes the resolution of an imaging system.

Water Equivalent Path Lengths measured using stepped pyramids of polystyrene blocks show each proton can be reconstructed to an rms precision of ~3 mm

7 min continuous scan (1 rev/min), 150 Million histories, 1 mm x 1 mm x 1 mm voxel size, 1 deg angular bin size.





Spatial Resolution

is close to maximum (for 1mm pixels the Nyquist frequency is 5 lp/cm).

MTF varies as a function of radius by± 10-20%.

T. Plautz, IUPESM World Congress 2015, Toronto, ON