Vertex 2017

Workshop Summary

T. Bergauer

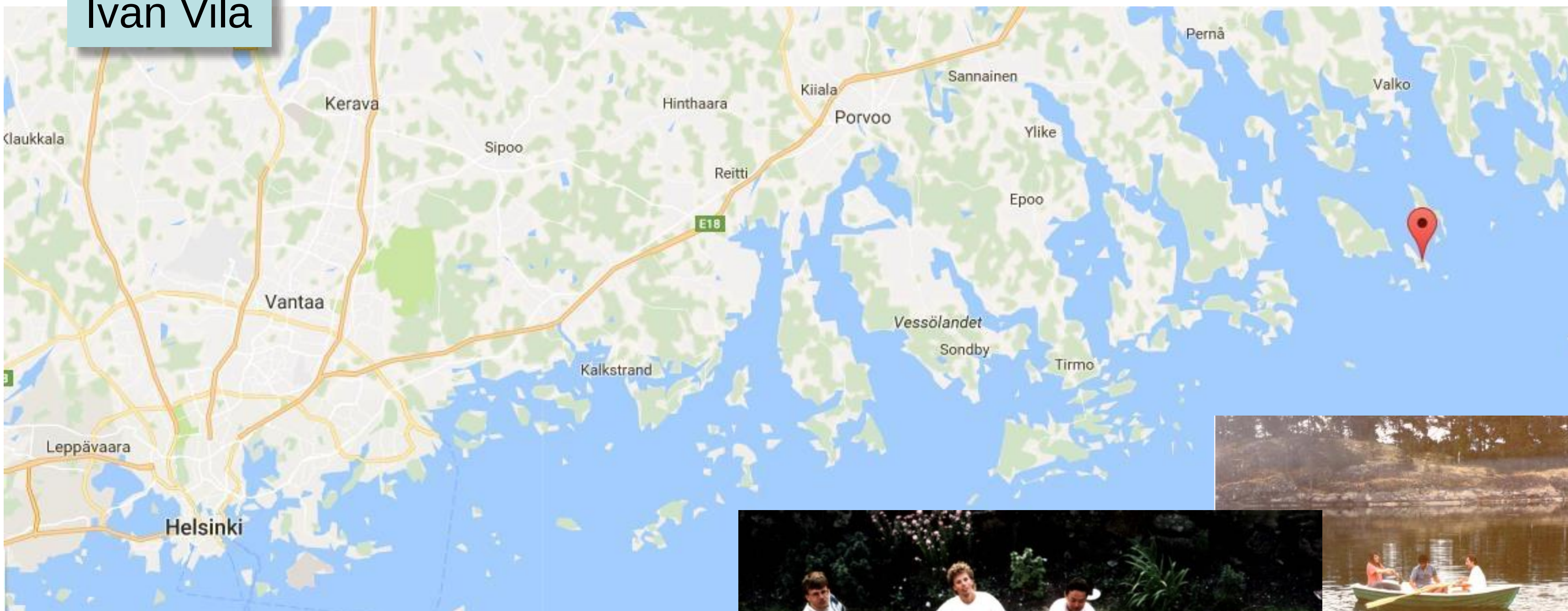
15 Sept 2017

Past Vertex Conferences

- 2017 Las Caldas, Asturias, **Spain**
- 2016 Isola d'Elba, Italy
- 2015 Santa Fe, New Mexico, USA
- 2014 Mácha Lake, Czech Republic
- 2013 Lake Starnberg, Germany
- 2012 Jeju, Korea
- 2011 Rust, Austria
- 2010 Loch Lomond, Scotland, UK
- 2009 Mooi Veluwe, Putten, The Netherlands
- 2008 Uto Island, Sweden
- 2007 Lake Placid, New York, USA
- 2006 Perugia, Italy
- 2005 Chuzenji Lake, Nikko, Japan
- 2004 Menaggio Como, Italy
- 2003 Low Wood, Lake Windermere, Cambria, UK
- 2002 Kailua-Kona Hawaii, USA2001 Brunnen, Switzerland
- 2000 Sleeping Bear Dunes, Lake Michigan, USA
- 1999 Texel, The Netherlands
- 1998 Santorini, Greece
- 1997 Mangaratiba, Rio de Janeiro, Brazil
- 1996 Chia, Sardignia, Italy
- 1995 Ein Gedi, Dead Sea, Israel
- 1994 Lake Monroe, Indiana, USA
- 1993 Lake Bohinj, Slovenia
- 1992 Basto Island, Finland

1992: Basto Island

Ivan Vila



Let us know by mail to BRENNER@VXCERN before friday 15.5.1992 if you are interested. Because of limited space a maximum of 30 persons can attend this workshop.

Everybody is welcome to suggest topics for the meeting and prepare a talk. A big paper screen and colour pens will be available for explanations.

We remind you of the primitive circumstances on the island and kindly ask you to bring your own sleepingbag.

2017: Las Caldas

Thanks the local organizing committee as everything was perfectly organized:

Ivan Vila, Marcos Fernandez, Abraham Gallas, Gervasio Gomez, Sebastian Grinstein, Giulio Pellegrini, Marcel Vos

2018: India

Earlier History: 1980

NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 499-502, © NORTH HOLLAND PUBLISHING CO

FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

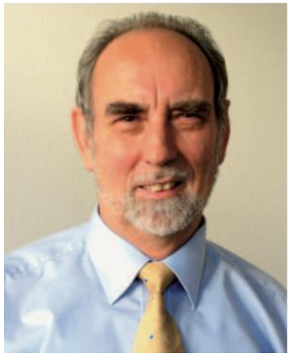
J KEMMER

Fachbereich Physik der Technischen Universitat Munchen, 8046 Garching, Germany

Received 30 July 1979 and in revised form 22 October 1979

Dedicated to Prof Dr H -J Born on the occasion of his 70th birthday

By applying the well known techniques of the planar process oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than 1 nA cm^{-2}/100 μm at room temperature Best values for the energy resolution were 10 0 keV for the 5 486 MeV alphas of ^{241}Am at 22 °C using 5 × 5 mm^2 detector chips



1938-2007

History 1982

SILICON DETECTORS WITH 5 μm SPATIAL RESOLUTION FOR HIGH ENERGY PARTICLES

E. BELAU [1], J. KEMMER [2], R. KLANNER [1], U. KÖTZ [3], G. LUTZ [1], W. MÄNNER [1], E. NEUGEBAUER [1], H.J. SEEBRUNNER [1] and A. WYLIE [1]

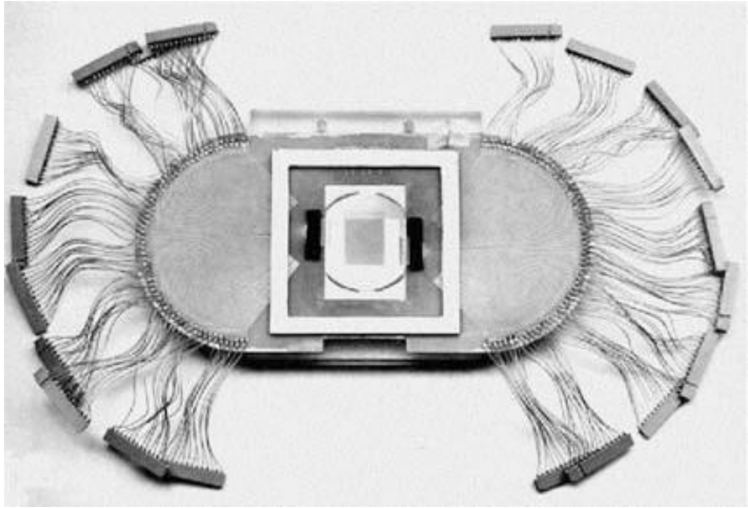
[1] *Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, München, Fed. Rep. Germany*
[2] *Physik Department der Technischen Universität München, München, Fed. Rep. Germany*
[3] *Deutsches Elektronen Synchrotron DESY, Hamburg, Fed. Rep. Germany*

Nuclear Instruments and Methods 217 (1983) 224-228
North-Holland Publishing Company

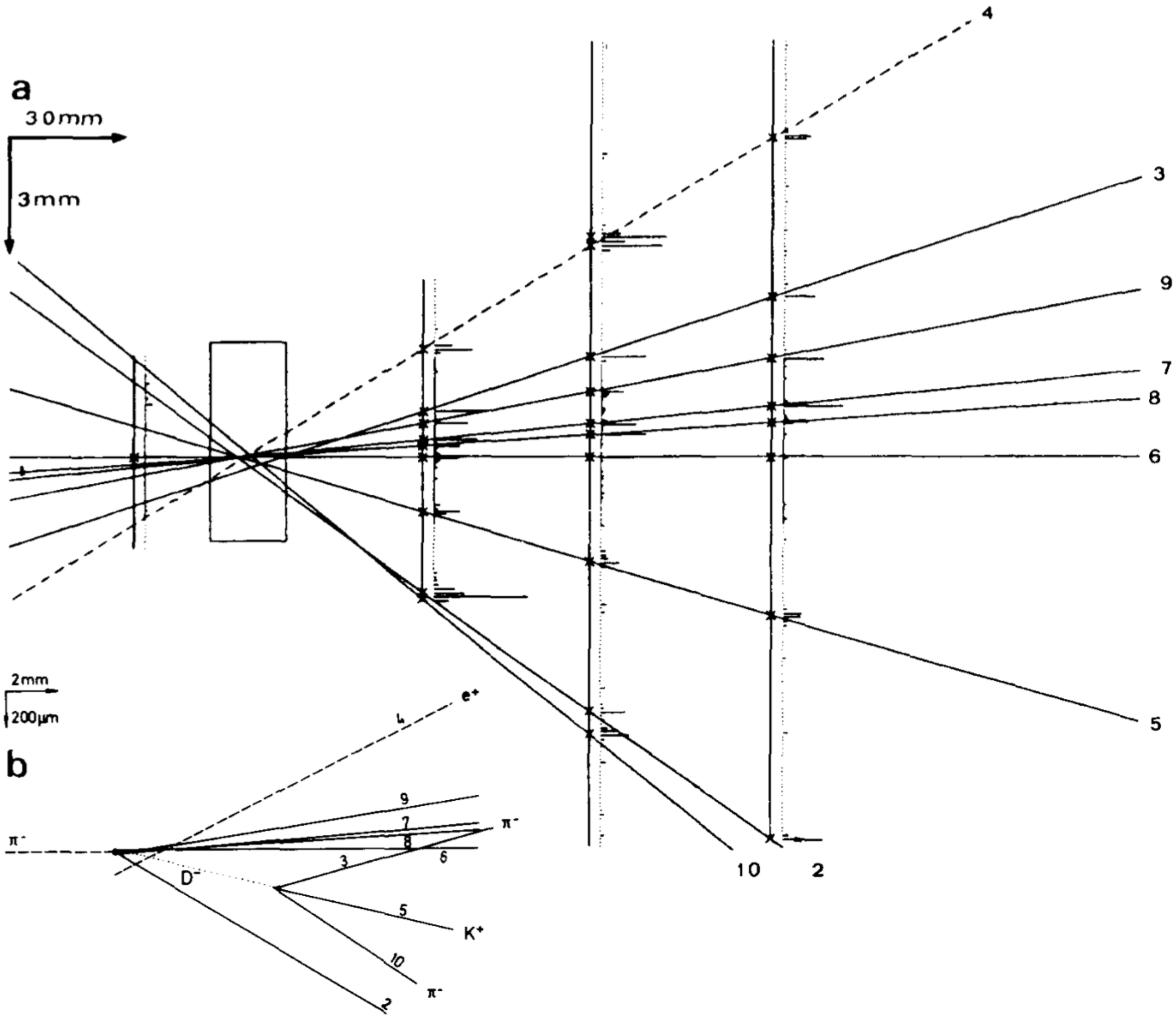
NA11 Detector:

- First proof of principle to use a position sensitive silicon detector in HEP experiment
- Aim: measure lifetime of charm quarks ($c\tau$=30 μm) $\Rightarrow$ high resolution required

- 1200 diode strips on 2436mm^2 active area
- **Resolution of 4.5 μm**
- 250-500 μm thick bulk material



History 1982

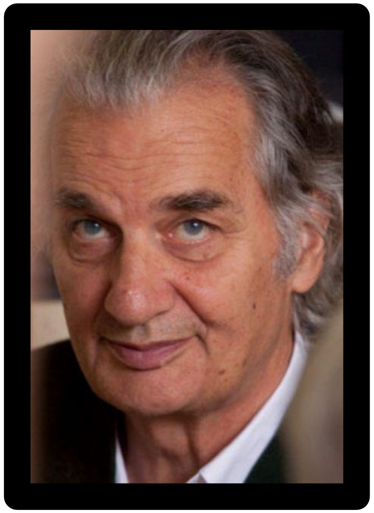


Computer reconstruction of the production and decay of a D^- into $K^+ \pi^- \pi^-$ as measured in the NA11 experiment in 200 GeV/c π^- Be interactions.

(a) 4 planes of one view.
(b) Enlargement of the vertex region.

2017: Honor and obituary

The 2017 HEP Prize of the EPS has been awarded to **Erik H.M. Heijne, Robert Klanner, and Gerhard Lutz** “for their pioneering contributions to the development of silicon microstrip detectors that revolutionised high-precision tracking and vertexing in high energy physics experiments”.



Gerhard Lutz (1939-2017)

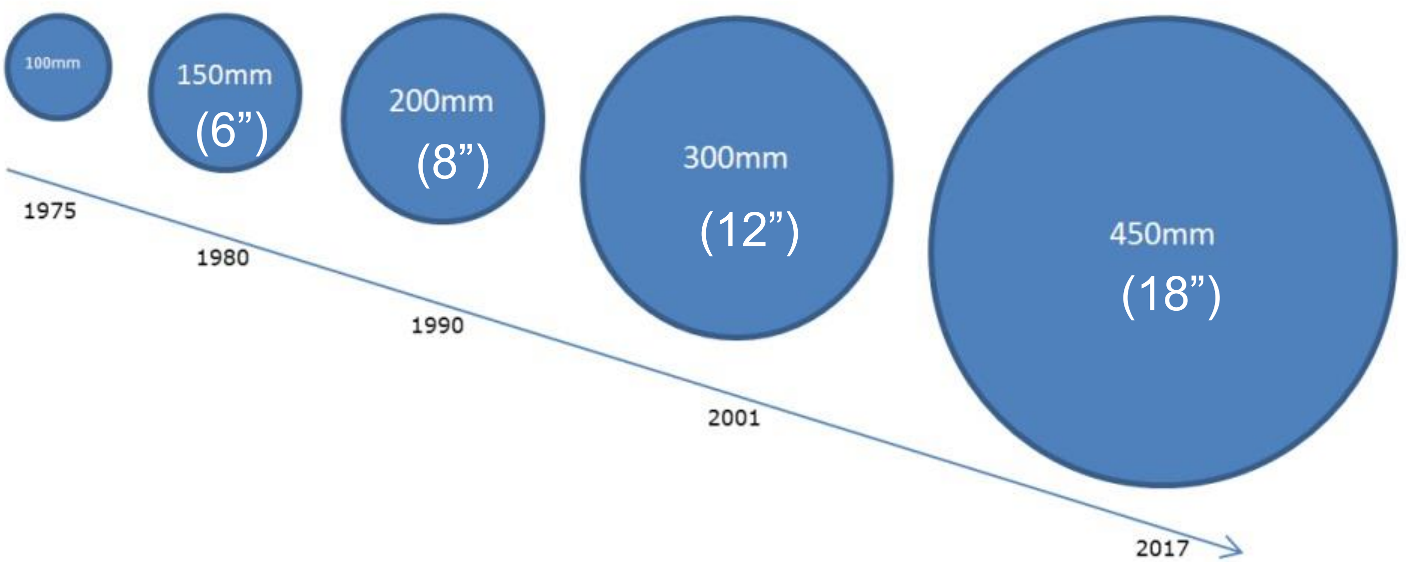
Wafer Areas now and then

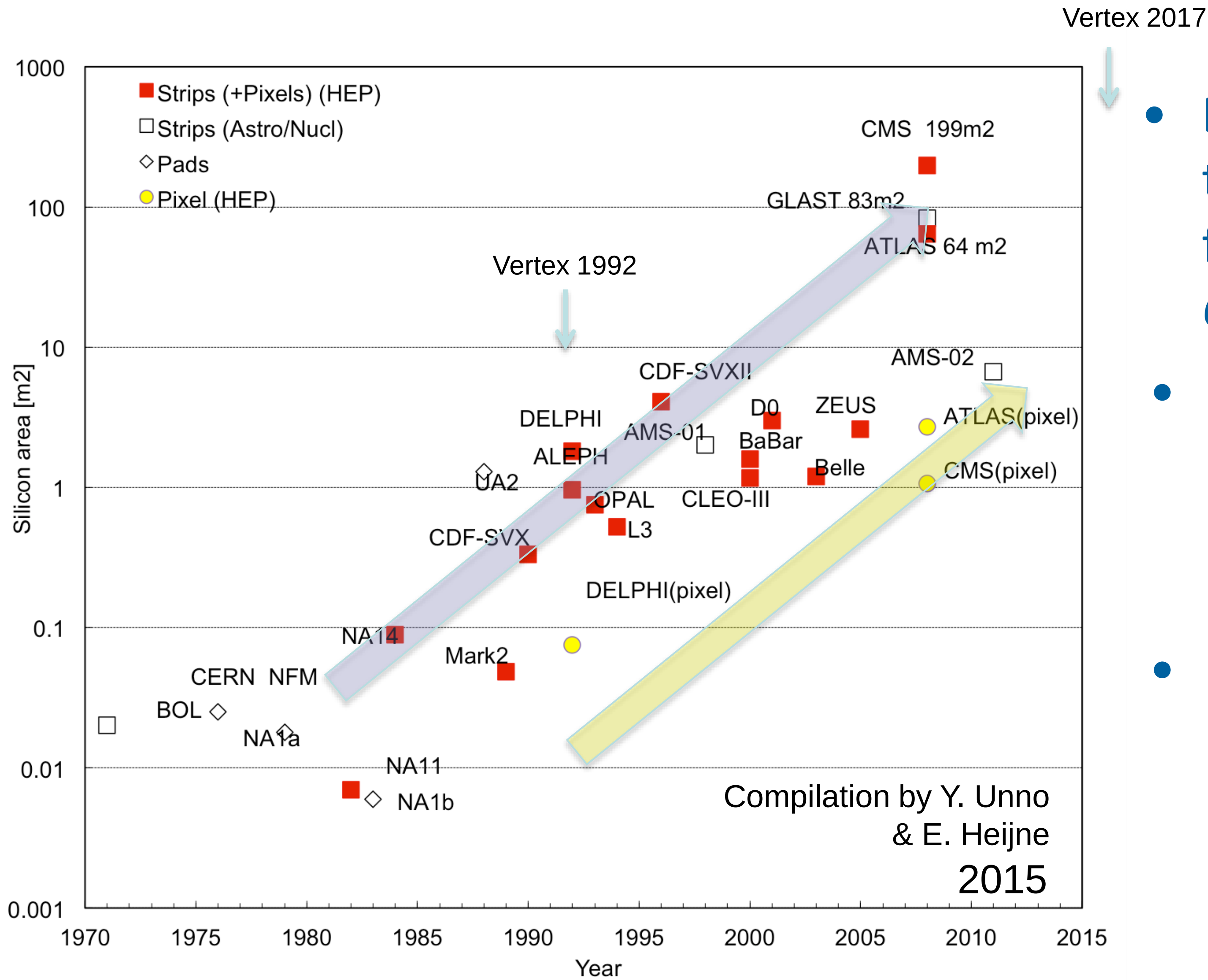
SILICON DETECTORS WITH 5 µm SPATIAL RESOLUTION FOR HIGH ENERGY PARTICLES

The detectors [2] are made of high-ohmic n-doped silicon single crystal wafers of 2″ diameter and 280 µm thickness (fig. 1). Using the planar process [1], p-doped strip diodes, covered by aluminium contacts, are implanted into one side of the wafer. On the other side a

1983!

Wafer Areas in Chip industries:



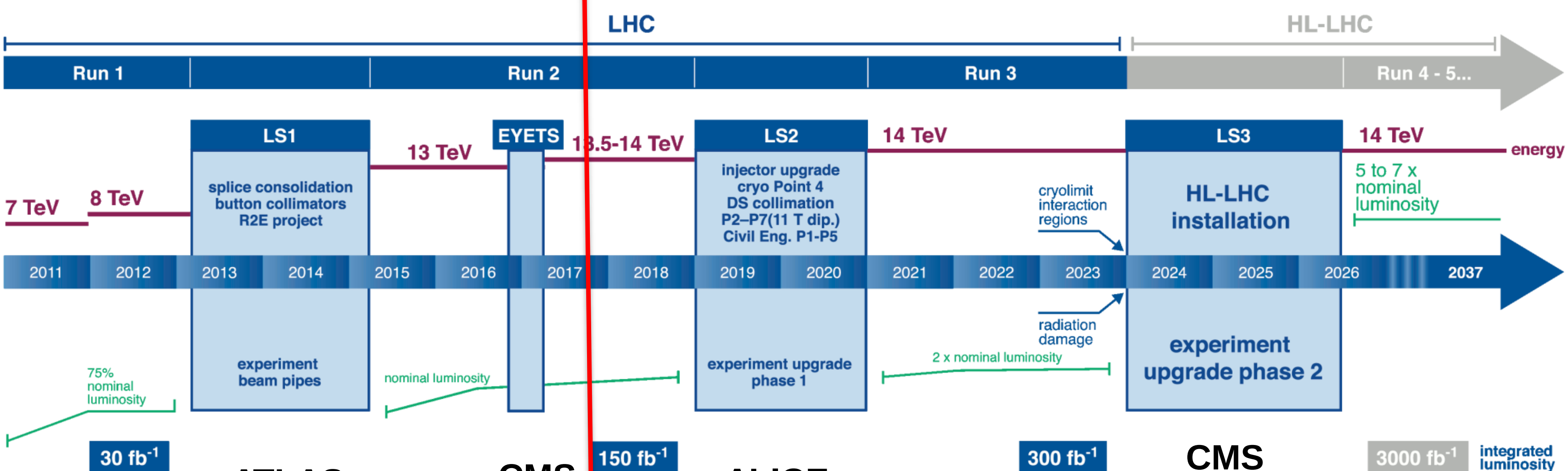


- Evolution of the silicon area from $O(1\ m^2)$ to $O(100\ m^2)$
- The front of the 1st "wave" has been "Strip" detectors.
- We may see the 2nd "wave" of the "pixel-like" detectors now...

Current and Future

EXPERIMENTS

LHC Roadmap



ATLAS IBL

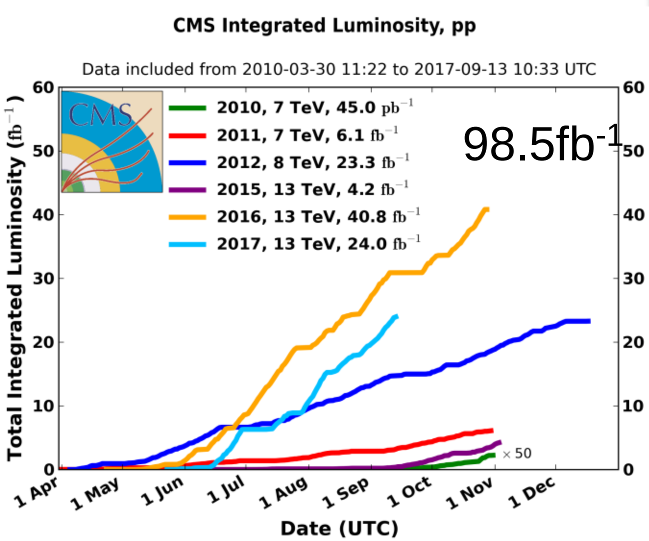
CMS Ph-I Pixel

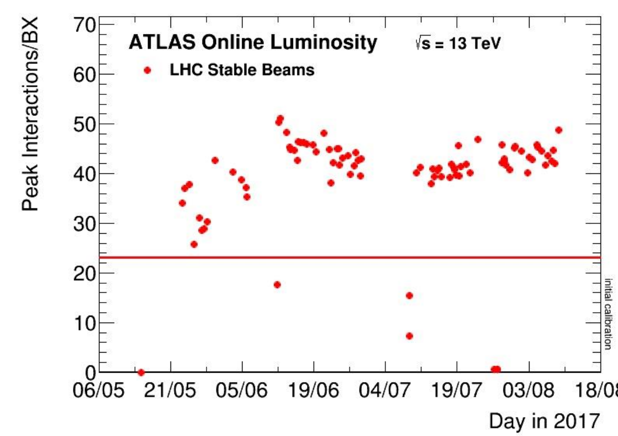
ALICE ITS+MFT

LHC-b (VELO, TT, IT+OT)

CMS Ph-II Strips

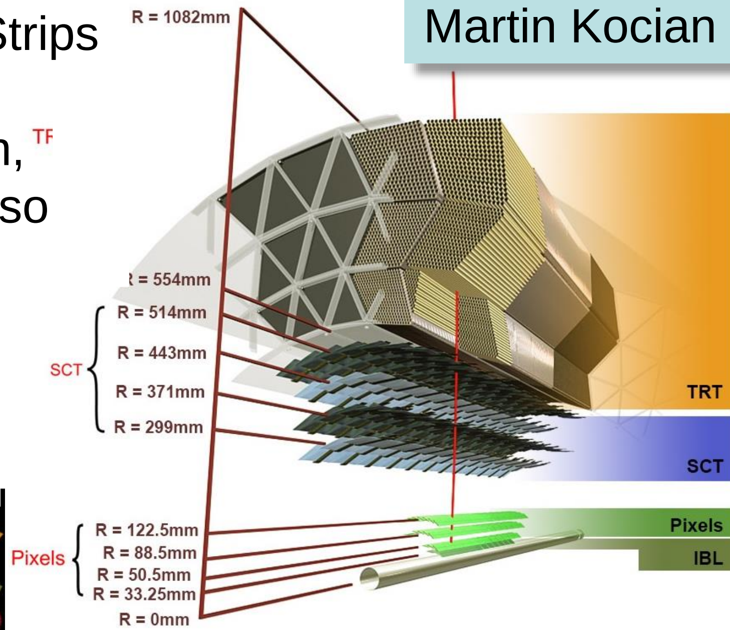
ATLAS ITK





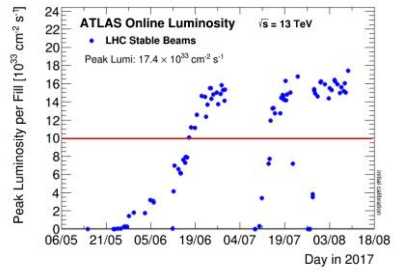
ATLAS Performance

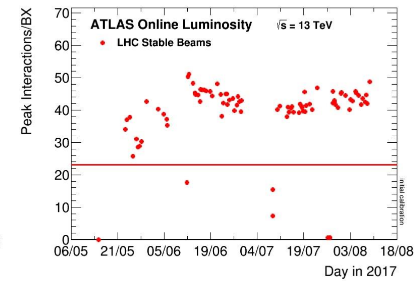
SCT: 60m² Strips (4+2x9)
Pixels: n-in-n, FEI3, IBL: also 3D



Martin Kocian

LHC delivers almost twice of design luminosity:



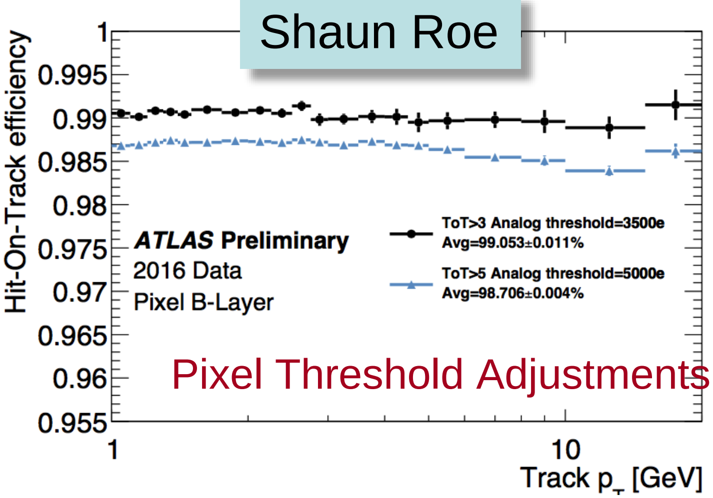


Pixel Readout Hardware Upgrade:

Module Link Occupancy at 100kHz L1					
	μ	B-Layer 160Mbps	Layer-1 160Mbps	Layer-2 80Mbps	Disks 80Mbps
25ns 13 TeV (Estimation based on Run2)	30	50%	33%	49%	62%
	50	71%	92%* → 46%	139%* → 69%	86%
	80	101%	125%* → 63%	188%* → 94%	115%

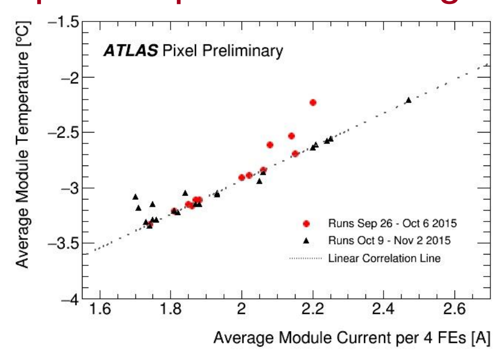
* Assuming bandwidths before the upgrade

Shaun Roe

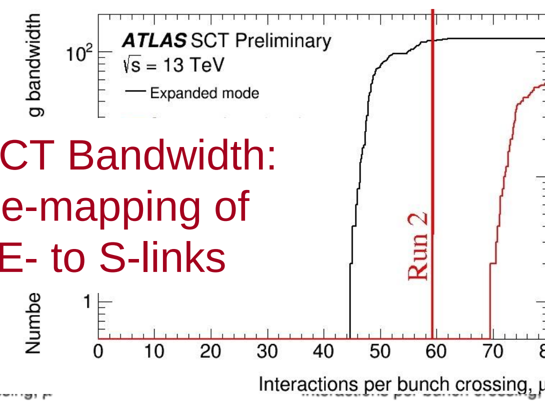


Pixel Threshold Adjustments

Frequent alignment due to rapid temperature changes



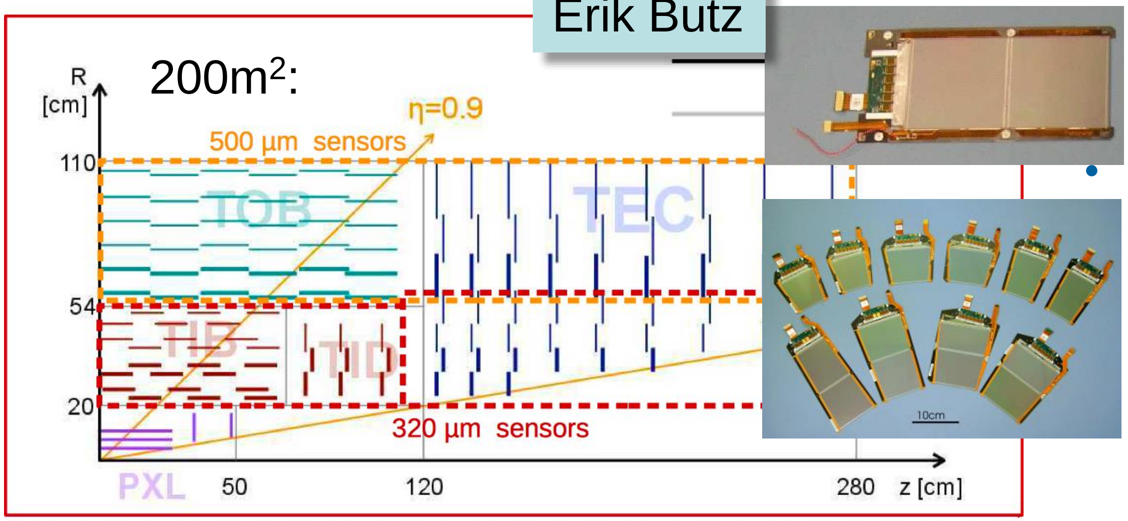
SCT Bandwidth: Re-mapping of FE- to S-links



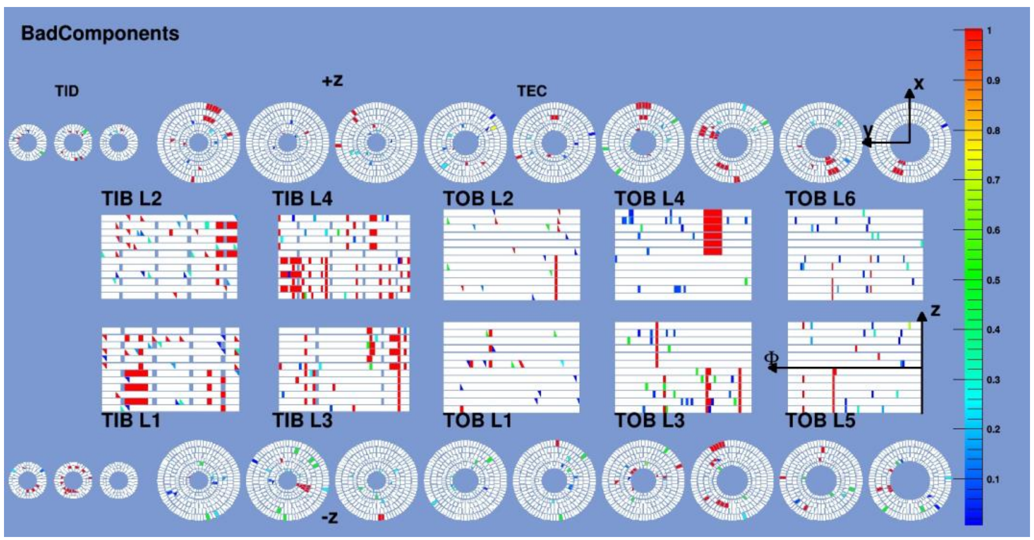
SCT is fine at a L1 trigger rate of 100 kHz and a pile-up of 60.

CMS Strip Tracker Operation

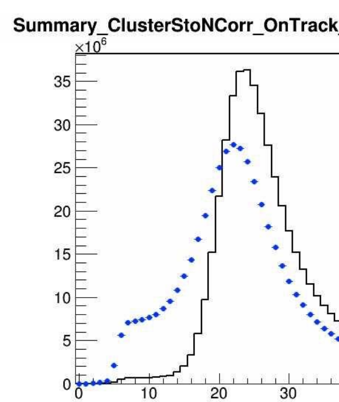
Erik Butz

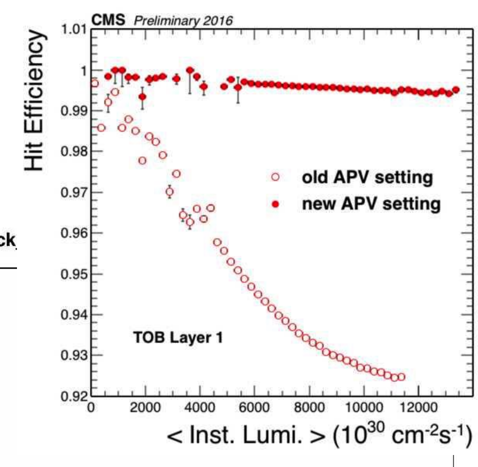


- 2015/2016: decrease in signal to noise, loss of hits on tracks
- traced to saturation effects in the pre-amplifier of the APV25 readout chip
- 2017 fully recovered after tuning of APV parameters
  - **Thanks to Erik who actually found the solution!**



Channels active in readout: ~96.5% → ~stable since 2016

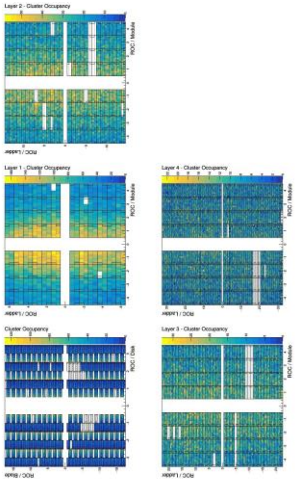


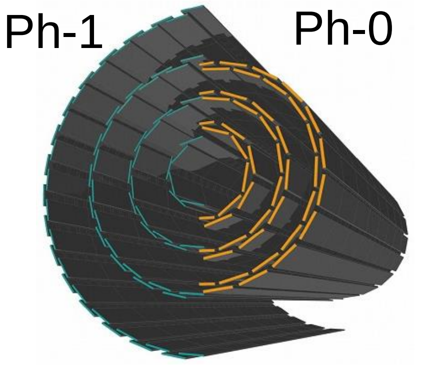


CMS Ph-I Pixel Upgrade

Jory Sonneveld

- New pixel detector installed in EYETS 2016/17
- 2 months from installation to data taking!!
- twice number of channels and active area ($2m^2$)
- Innermost layer moved closer to beam pipe (4.4cm → 2.9cm)
- New readout chips: PSI46dig (Layer 2-4+Fpix) and barrel layer 1 (higher rates, PROC600)
- DC-DC conversion powering system
- CO_2 cooling system
- New µTCA DAQ system
- Significantly reduced amount of material

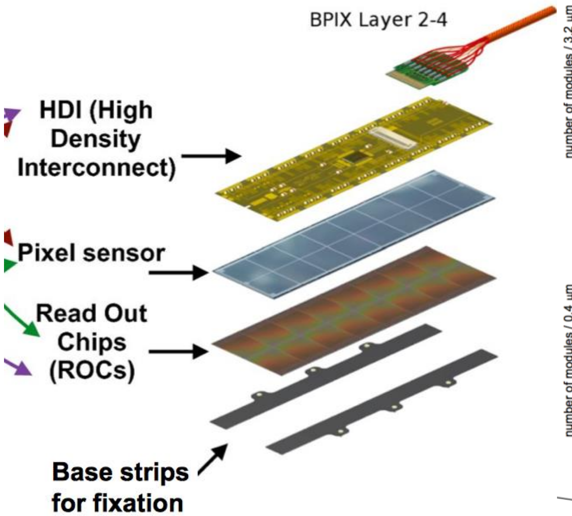


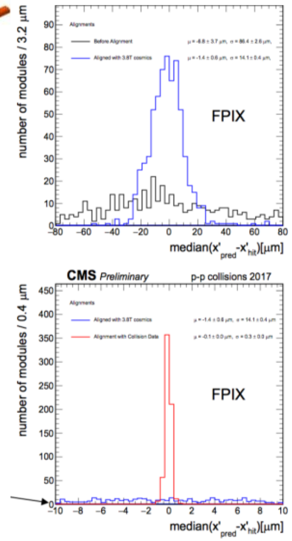


Layer 1: PROC600
Layer 2-4: PSI46dig

Viktor Veszpremi

Alignment with cosmics and tracks

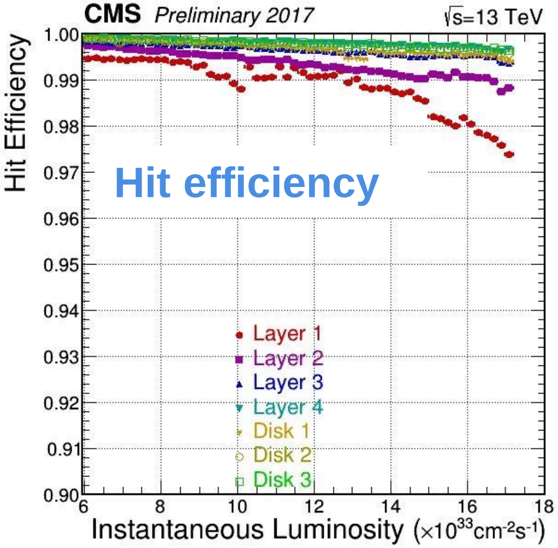




Layer 1 resolution limited by

- **timing of different chips**
- **Radiation damage**

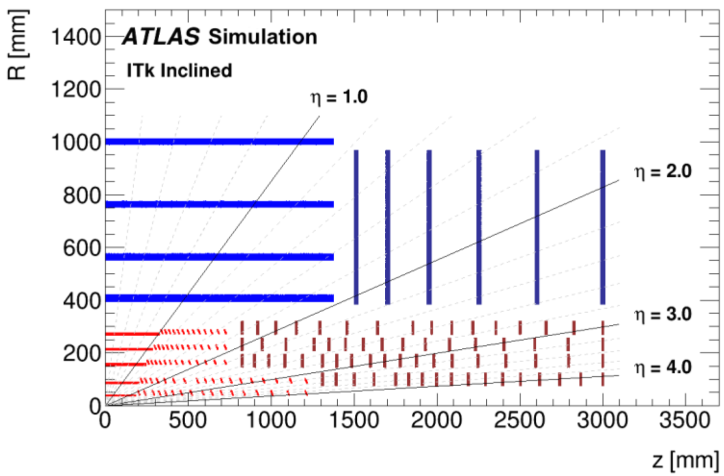
- **SEU in TBM**



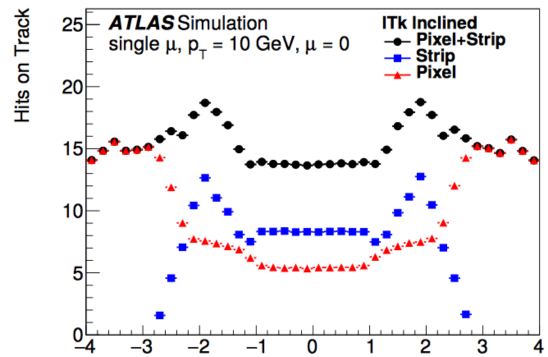
ATLAS Ph-II Upgrades

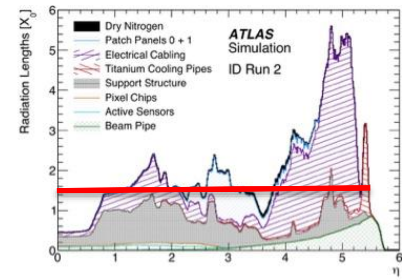
ATLAS

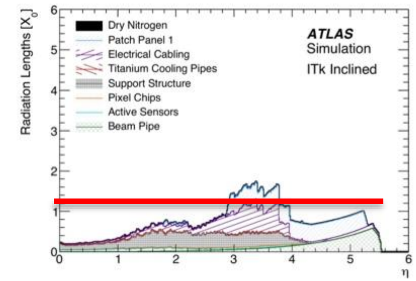
Inclined pixels



Extension to η=4

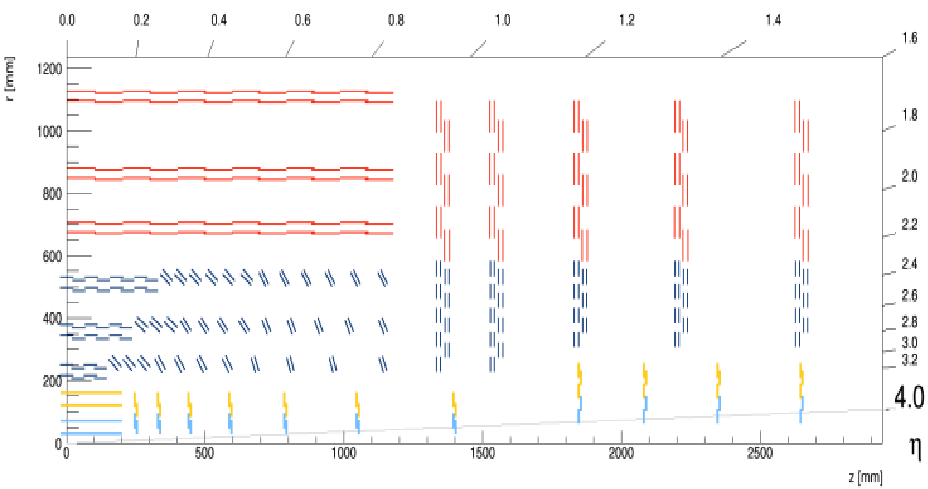




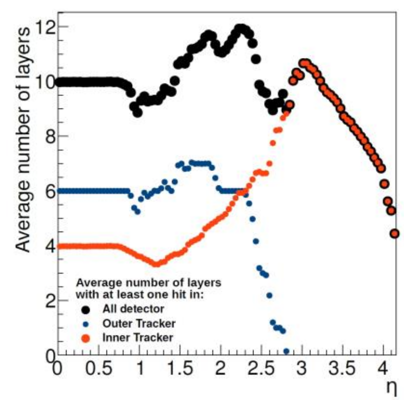


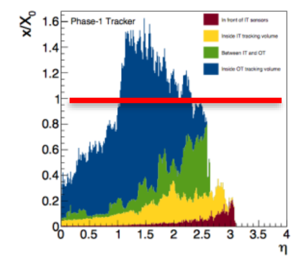
FTK: Tracking joins the trigger on software level

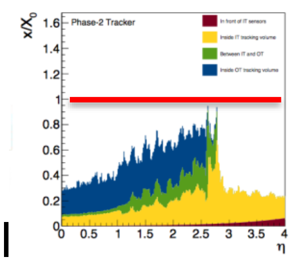
CMS



Extension to η=4







Inclined strips beneficial for p_T concept (Trigger on hardware level

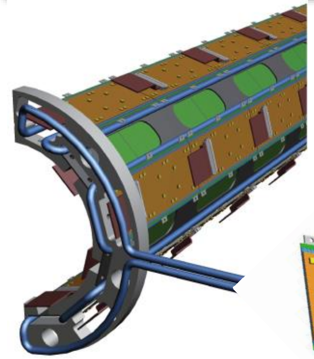
Ph-II Upgrade: Pixels

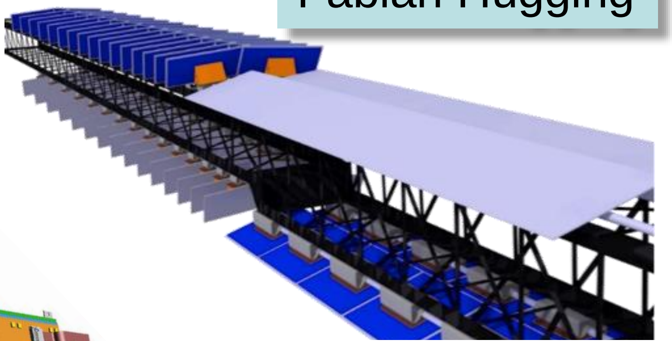
Lorenzo Viliani

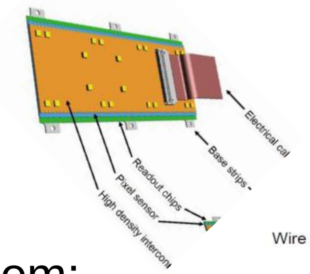
Fabian Hügging

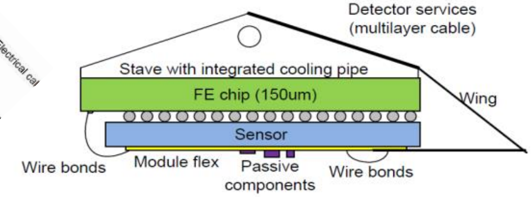
Similar approach of ATLAS and CMS

- "classical" hybrid pixel detectors with bump-bonding
  - Planar n-on-p or 3D detectors
  - Prototypes using FEI4 chip, later RD53A
- ATLAS: 10k modules arranged on staves, inclined
  → up to 14m² detector area
- CMS: ~4.9 m²
- Different pixel layouts being tested → 50 x 50 µm preferred by ATLAS, 25x100 µm preferred by CMS
  - Both need some coating to prevent sparking
- Serial Powering being tested using FEI4

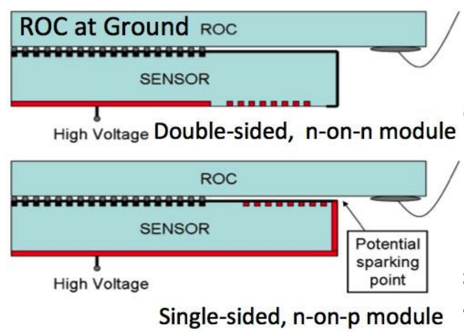


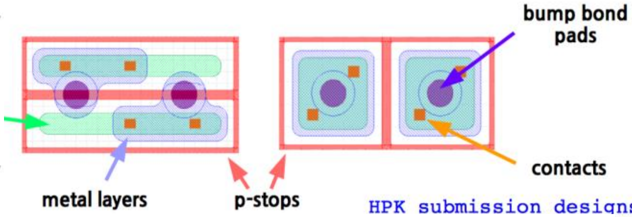


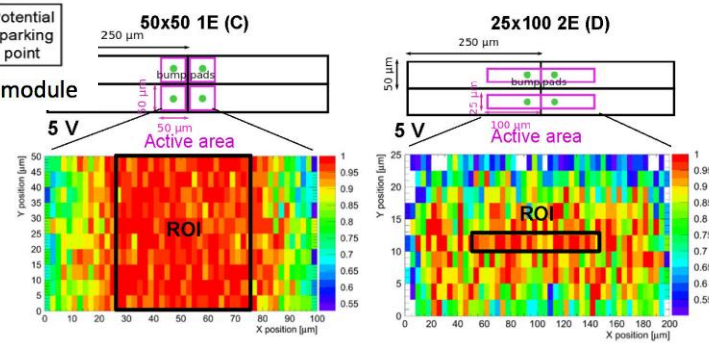


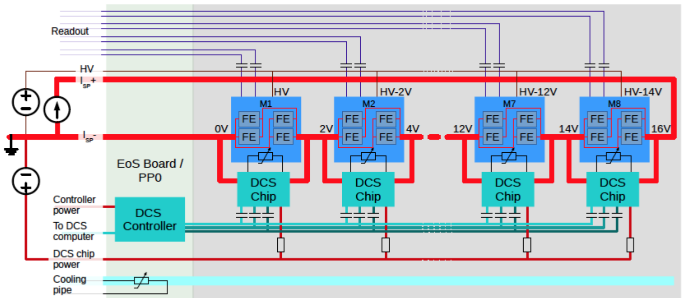


Sparking problem:



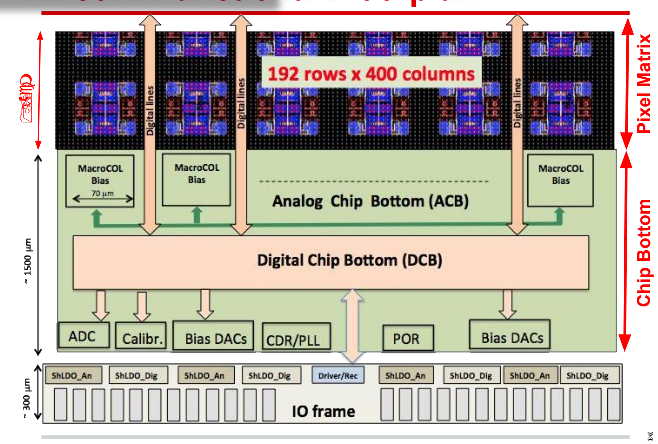






RD53: HL-LHC readout

Roberto Beccherle

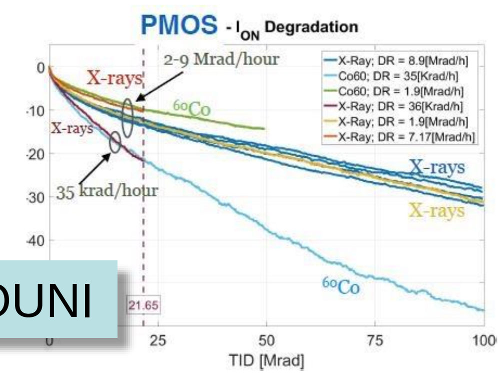


- RD53: collaboration of18 institutes focused on pixel chips for ATLAS/CMS phase2 upgrades.
- Features:
  - TSMC 65nm Process
  - Serial powering
  - Aurora Xilinx output protocol
  - SEU protection
  - Radiation hardness: 1 Grad, $2x10^{16}$ n_{eq}/cm^2 over 10 years
- Radiation Hardness studies performed
  - Edge leakage current, temperature effect, bias effect, annealing effect, low dose rate effect
  - Standard IP block library used, but some modifications (resized cells for better radiation hardness)

- Small pixels: 50x50 um^2 (25x100um^2)
- Large chips: ~2 cm x 2 cm (~10^9 transistors)
- Hit rates: 3 GHz/cm^2
- Trigger: 1MHz, 10us (~100x buffering and readout)

- RD53A chip submitted end of August
  - Several months of intense face-2-face work of both ATLAS and CMS designers before tape-out
  - Expected to be back by the end of the year

Dose-rate Effect:



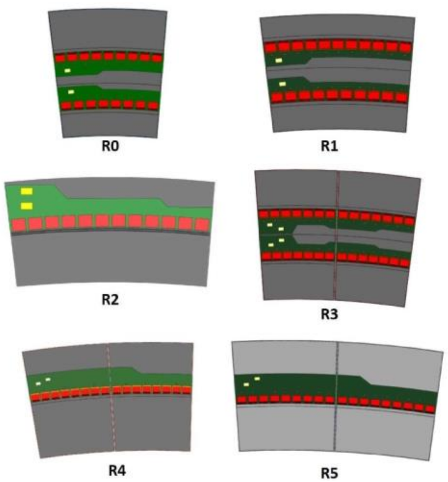
Mohsine MENOUNI

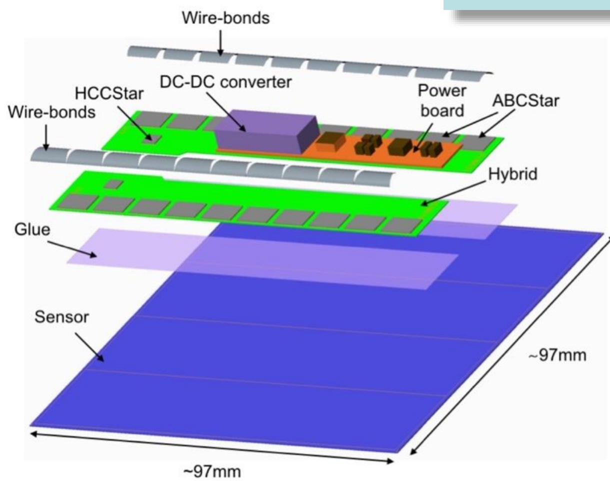
HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

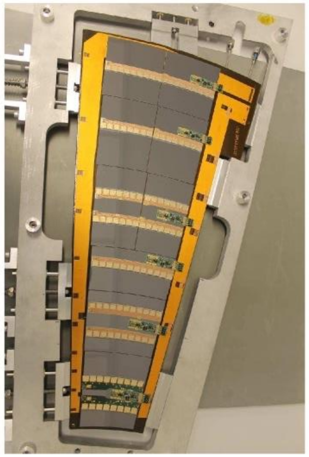
ATLAS Ph-II Upgrade: ITK

ÖAW AUSTRIAN ACADEMY OF SCIENCES

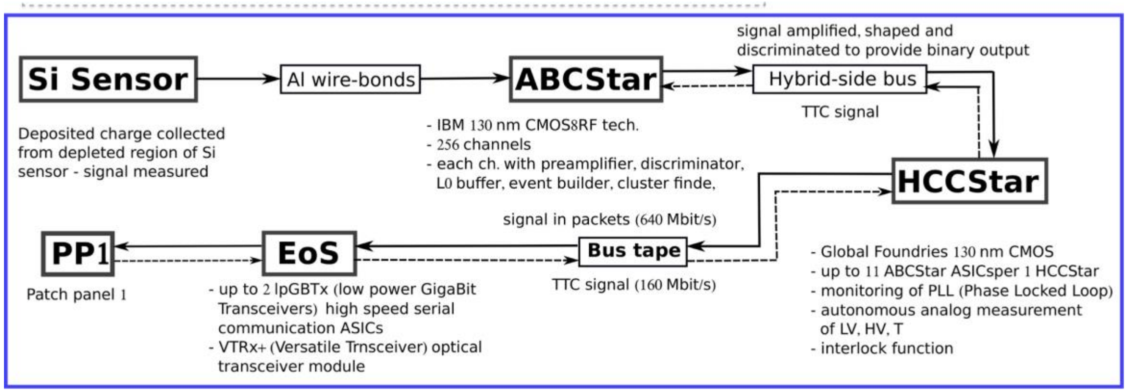
Jiri Kroll







- Stereo angle **directly implemented in sensor geometry**
- **Wedge-shaped sensors** in petals (similar what CMS Tracker uses now!)



Numbers:
Petals: 392
Staves: 384

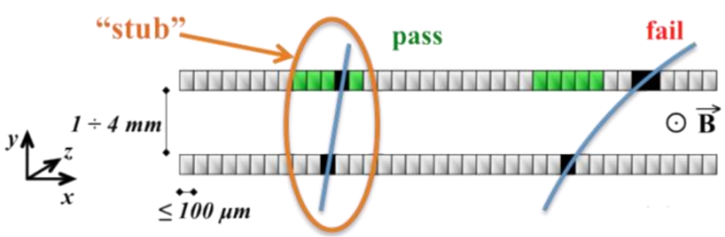
Modules: 17888
Active area: 165m²
(from 65m² as it is now)

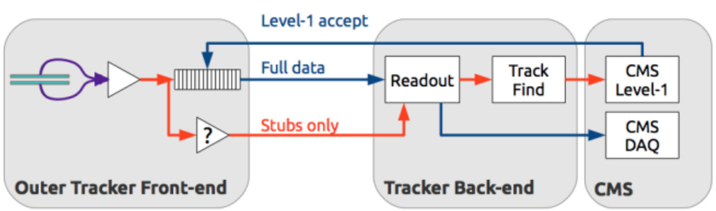
CMS Ph-II Upgrade

Jelena Luetic

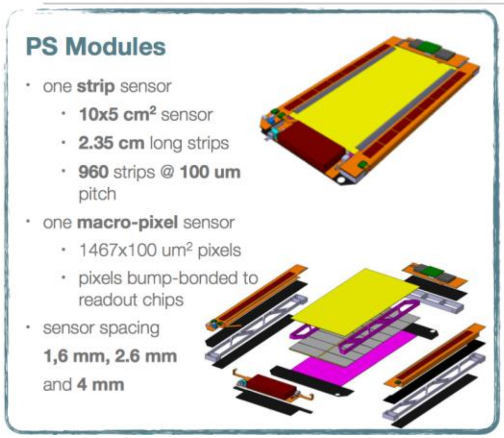
Track Trigger:

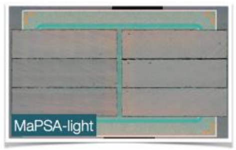
- Local p_T discrimination will give input to L1 trigger at BC frequency
- Tunable window, different sensor spacings
- Three approaches for back-end

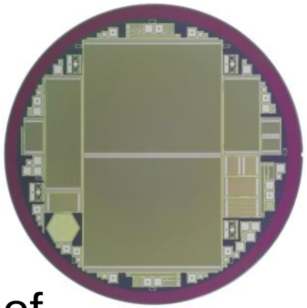




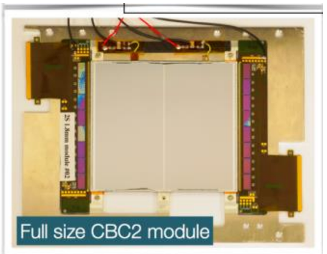
Associative memory	specially designed ASICs perform fast pattern recognition, full selection done by the FPGA
Hough transform	FPGA based, two stage track finding (Hough transform for coarse stub grouping+ Kalman filter for precision fitting)
Tracklet	FPGA based, road search algorithm, stubs in neighbouring layers form seed, linearised χ^2 fit for final parameters







Qualification of Infineon as new supplier for sensors

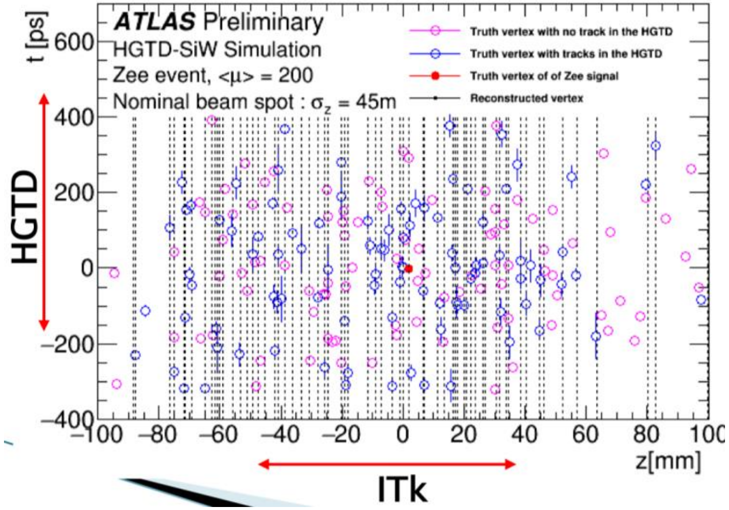


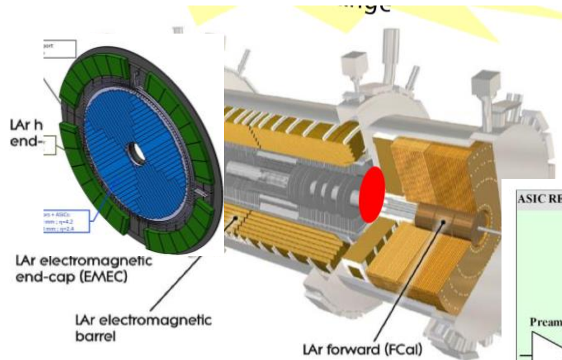
Ph-II Timing Layers

Gregor Kramberger

Initially also L0 trigger capabilities → not considered anymore
→ But Luminosity monitor (40MHz)

ATLAS

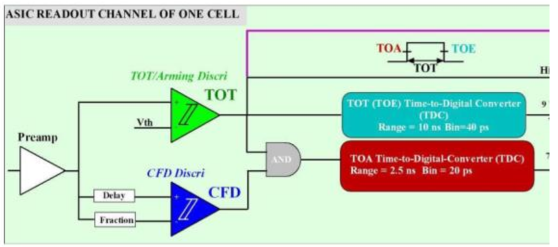




11m² of LGADs

$\Phi_{eq,max}$=6·10^{15} cm^{-2}
TID_{max}=4 MGy

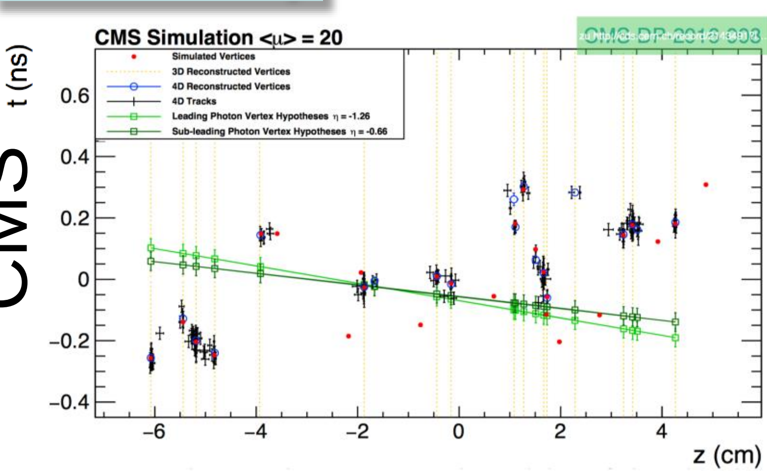
20 (60)ps time resolution

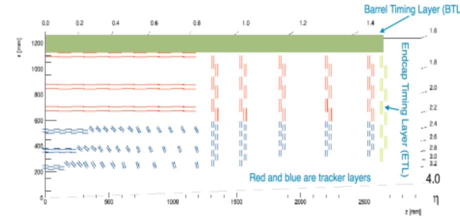


Atlas LgadTiming Integrated ReadOutChip (ALTIROC)

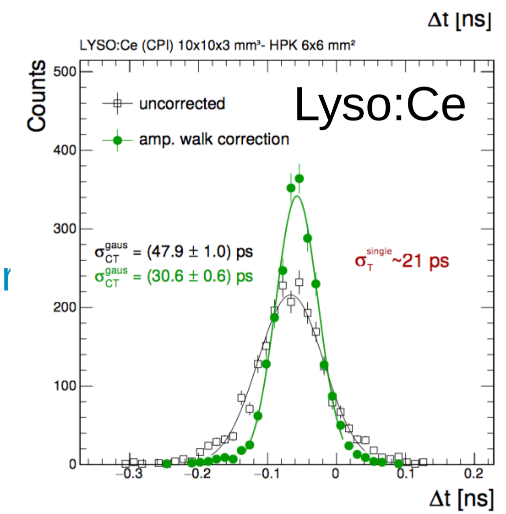
Rachel Yohay

CMS



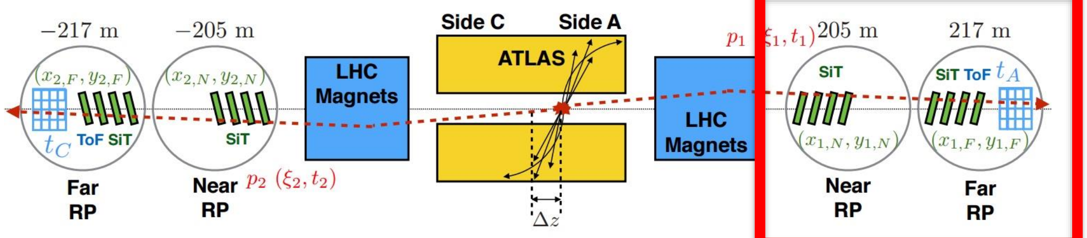


Barrel: LYSO:Ce scintillator with SiPM readout
Endcap: LGADs with custom ASIC with CO_2 cooling a.s.o.



Very Forward Experiments

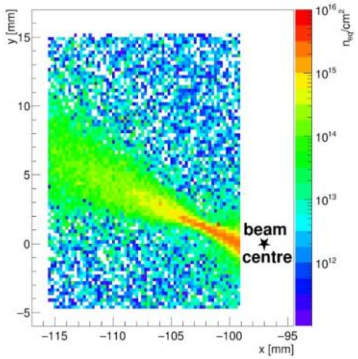
- ATLAS: AFP
- CMS: CT-PPS

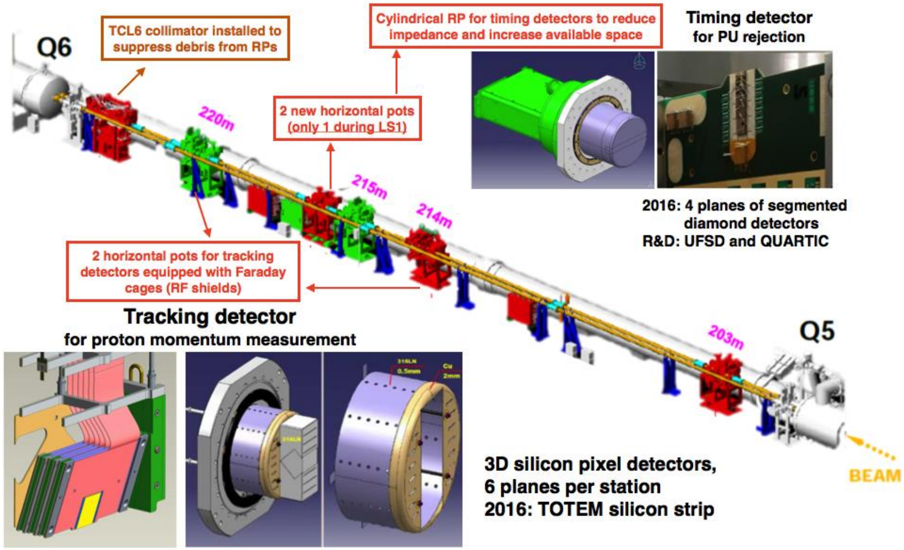


Since YETS 2015/16

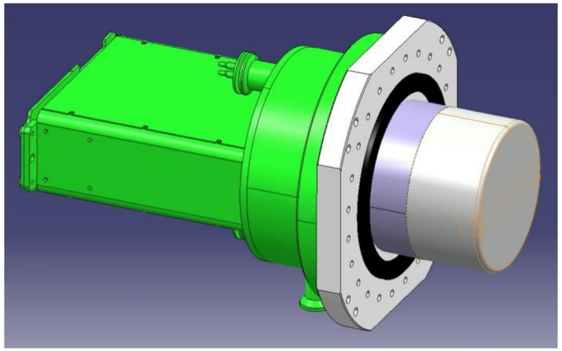
Since EYETS 2016/17

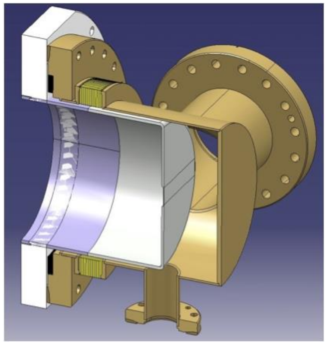
Non- uniform irradiation:



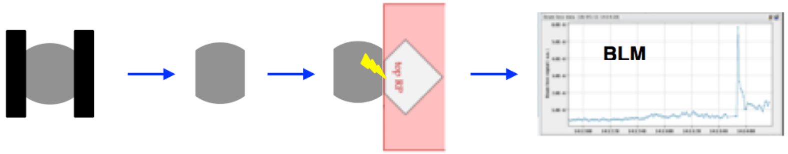


Roman Pots System with movable devices:



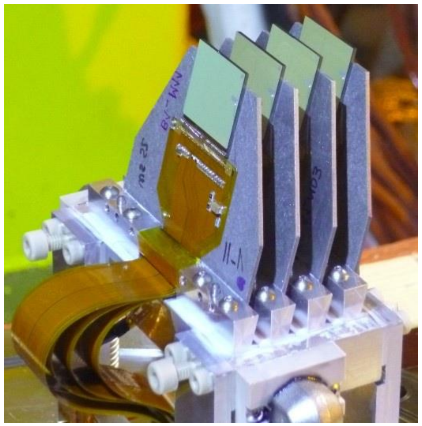


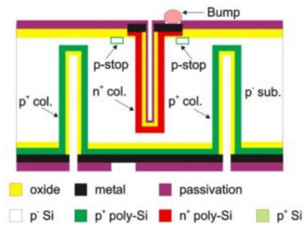
Alignment procedure at stable beams:

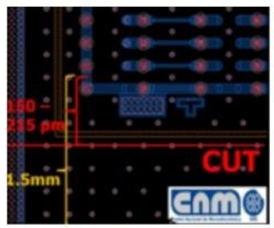


Fabian Forster

Tracking Stations

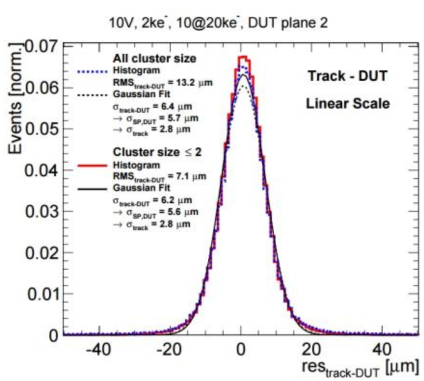






- 3D sensors (50x250 µm² pixel size, 336x80 pixels) with slim edge
- FE-I4 readout chip

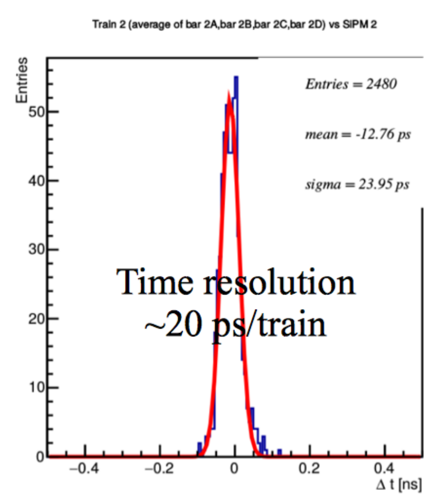
Testbeam result: 6 µm resolution per plane → 3 µm per station



Timing Stations

Cherenkov Quartz bars placed at Cherenkov angle

Readout with Micro-Channel-Plate Photomultiplier (MCP-PMT) at the end of the bars



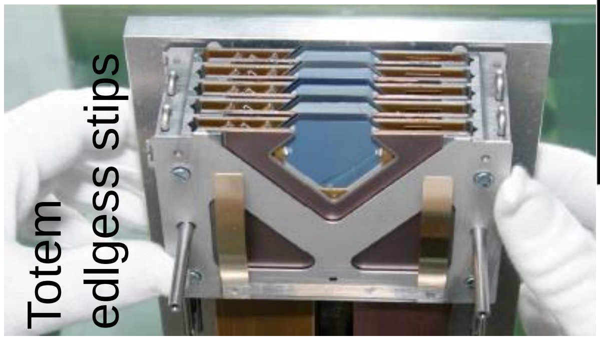
time resolution: ~20 ps

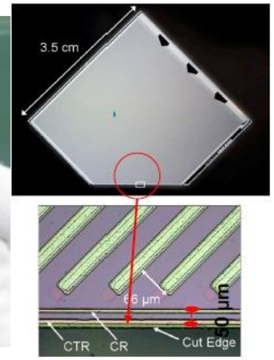
→ ~4 mm z-resolution of the primary vertex in the central detector

TOTEM / CT-PPS

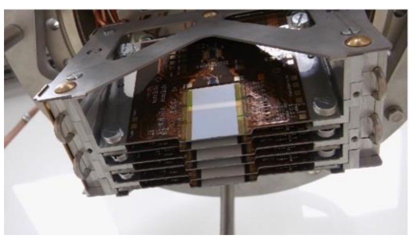
Fabio Ravera

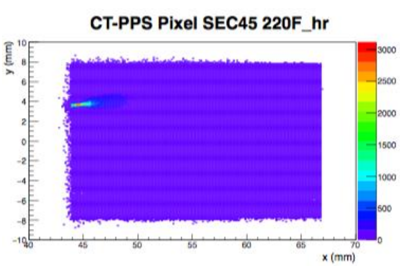
Tracking Stations

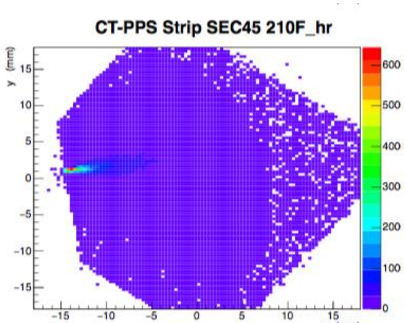




- Upgrade: CNM 3D Sensors+PSI46dig chip
- Installed March this year

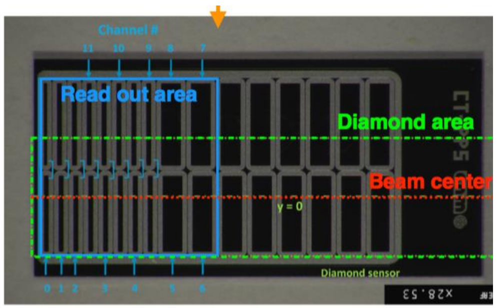


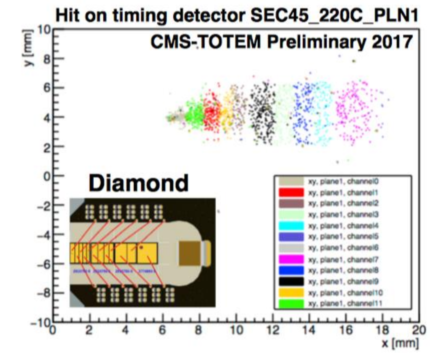




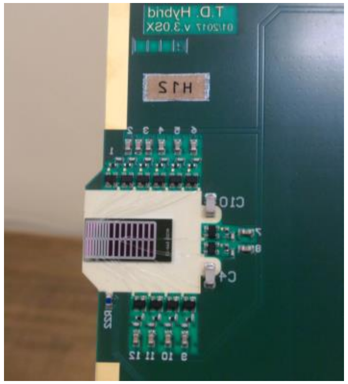
Timing Stations

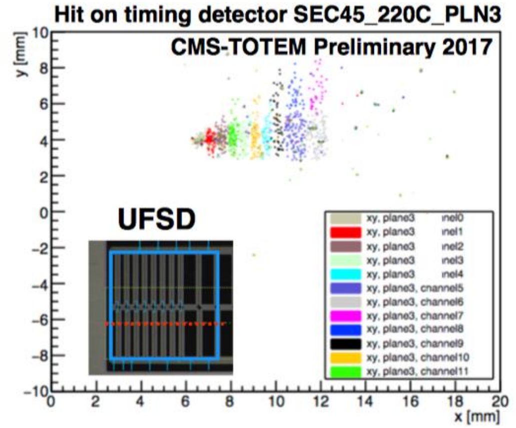
A resolution of ~ 10 ps on the proton arrival time allows to determine the vertex z position with σ z ~ 2 mm





plane of UFSD/LGAD (**first installation in HEP**):



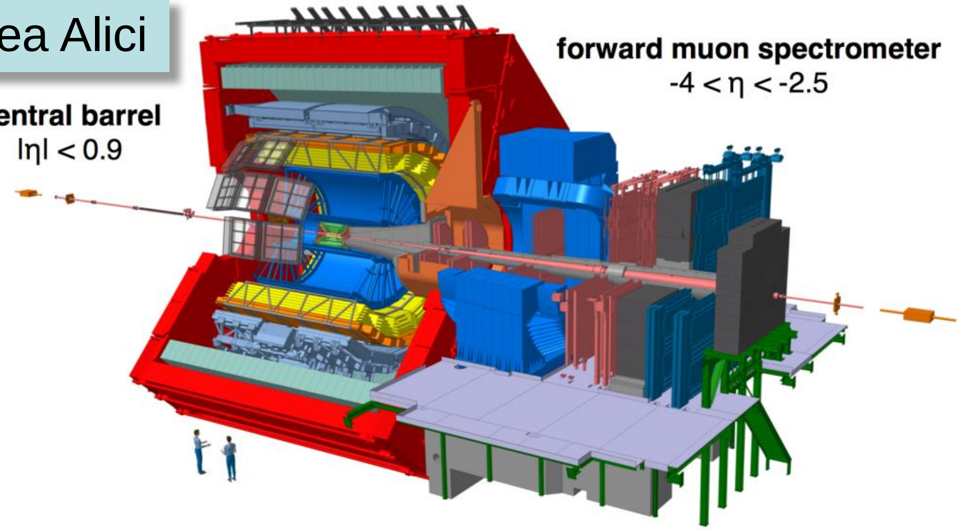


ALICE Operation

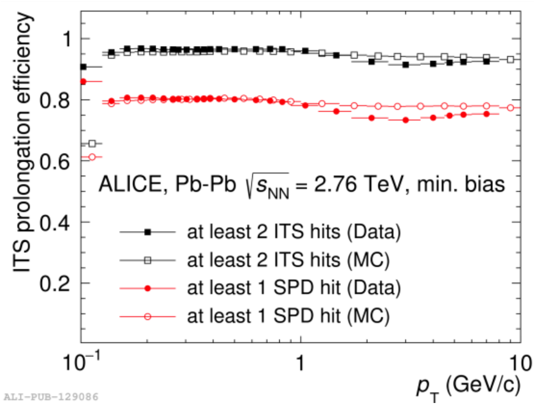
Andrea Alici

Three independent subdetector systems:

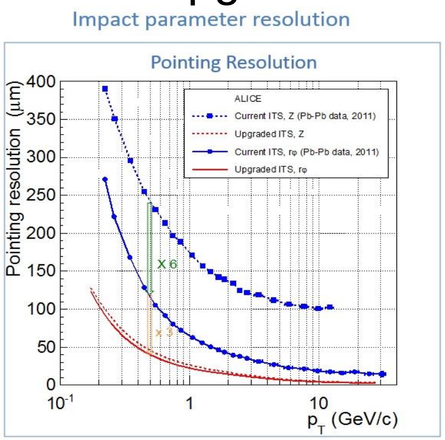
- 2 layers of Silicon Pixels
  - 3.3 + 6.5 M pixels
  - 240 p^+n sensors (0.21m^2)
- 2 layers of Silicon Drift Detector (260 modules)
- 2 layers of Silicon Strips (1698 modules)
- Surrounded by big TPC

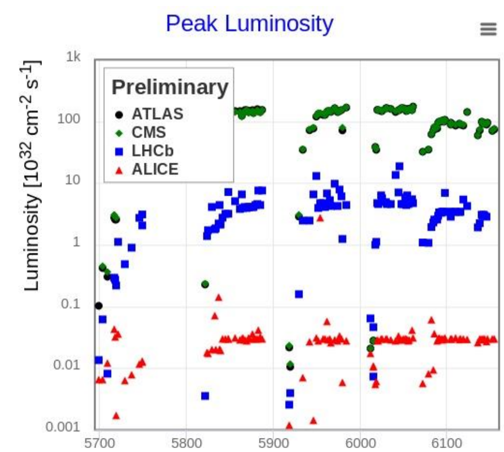


- No increasing leakage current due to radiation, but at some SSD modules due to increasing humidity of the air coming from ventilation
  - 2016: new ventilation machine installed
  - EYETS 2017: new cooling unit to cool down the dry air



Upgrade:





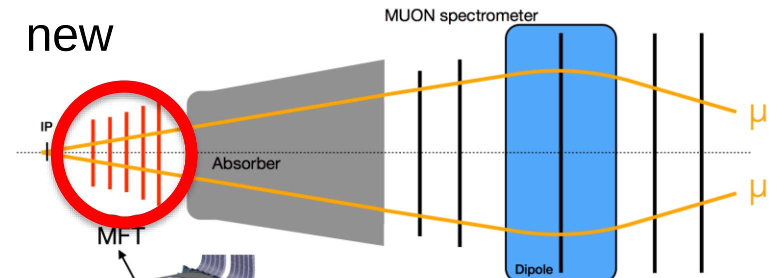
expected integrated dose since LHC startup

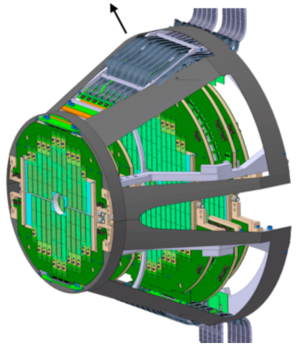
Detector (inner radius)	TID (krad)	1 MeV neq (cm^{-2})
SPD (r = 3.9 cm)	94	1.6 10^{12}
SDD (r = 15 cm)	7.8	2.1 10^{11}
SSD (r = 38 cm)	1.72	9.2 10^{10}

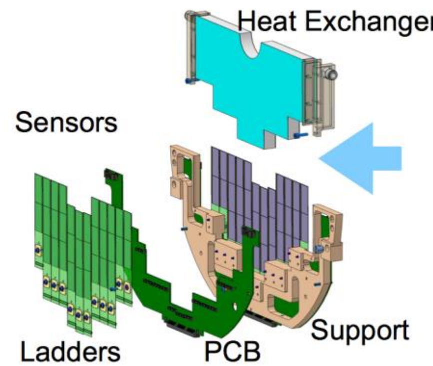
The present ITS will be completely replaced in the ALICE upgrade in LS2 (ALPIDE MAPS)

ALICE MFT Upgrade

Raphael Tieulent



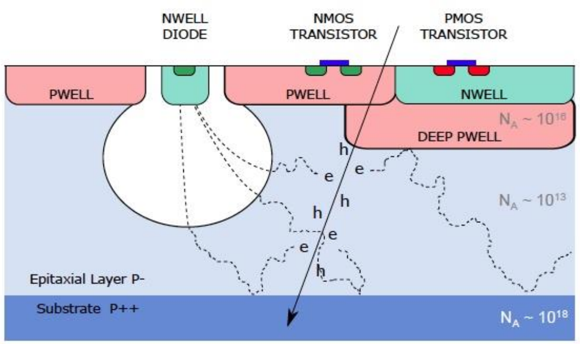


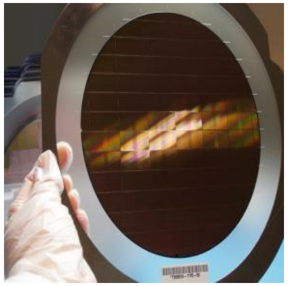


Present muon spectrometer suffering from uncertainties extrapolating tracks through absorber

→ **Muon Forward Tracker**

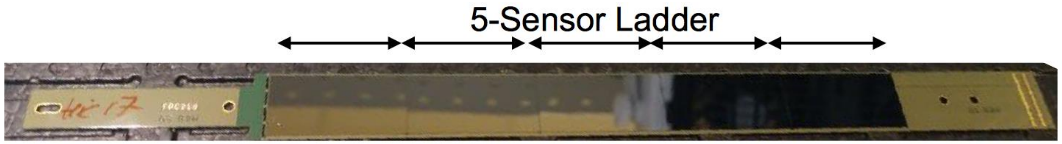
920 silicon pixel sensors (0.4 m^2) on 280 ladders of 2 to 5 sensors each





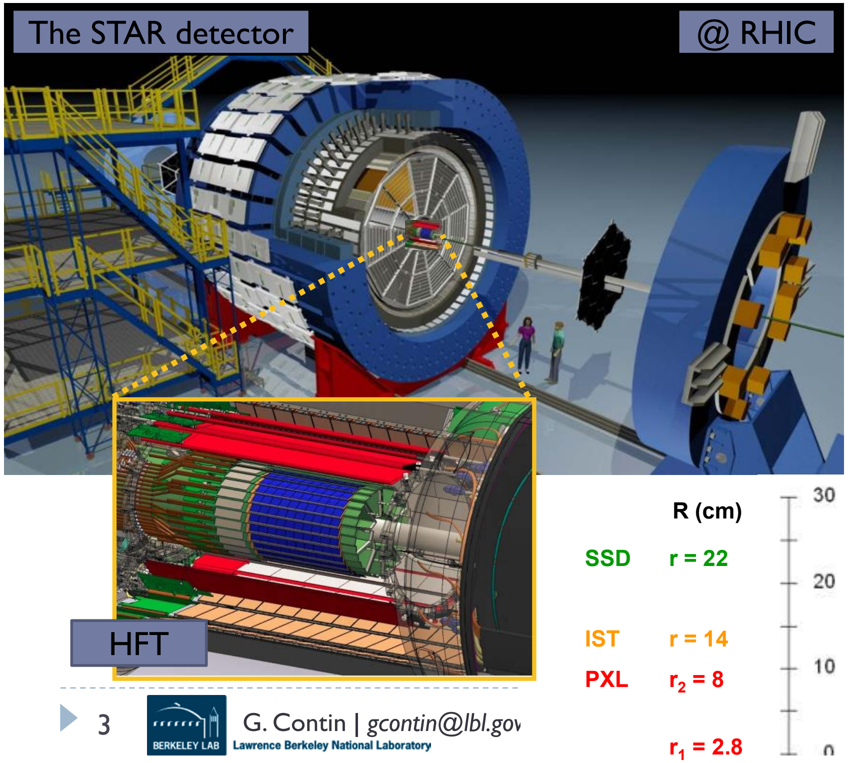
ALPIDE pixel sensor (CMOS MAPS, TowerJazz 0.18 µm technology)

- Sensor Thickness 50 µm
- Sensor Size 15 mm x 30 mm. Pixel pitch 29 µm x 27 µm
- Spatial Resolution 5-6 µm
- High-resistivity (> 1kΩ cm) p-type epitaxial layer (25µm) on p-type substrate
- Also being used for ITS upgrade



STAR PXL @ RHIC

Giacomo Contin



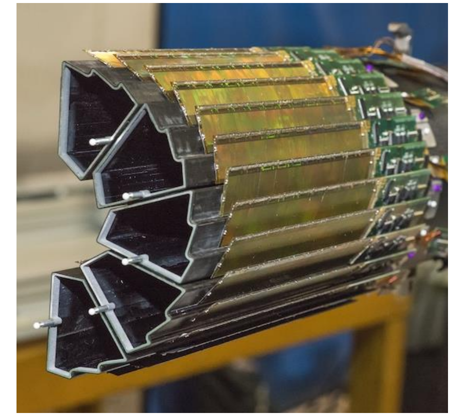
Need to resolve displaced vertices in high multiplicity environment

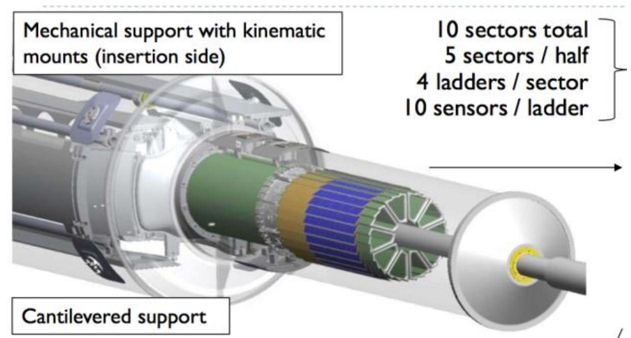
TPC – Time Projection Chamber (main tracking detector in STAR)

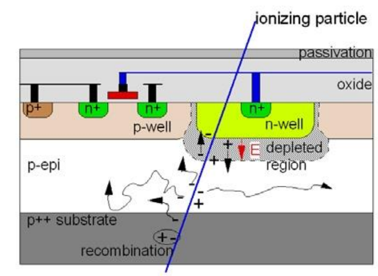
HFT – Heavy Flavor Tracker

- **SSD – Silicon Strip Detector**
- **IST – Intermediate Silicon Tracker**
- **PXL – Pixel Detector**

Tracking inwards with gradually improved resolution:

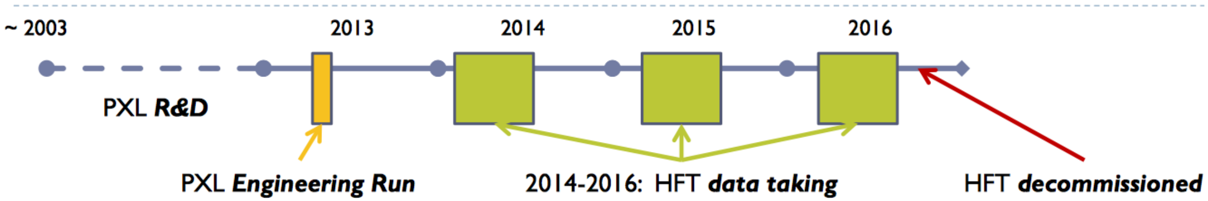






Ultimate-2: third **MIMOSA-family** sensor version developed at IPHC, Strasbourg

Integration time: **186 µs**



Success!

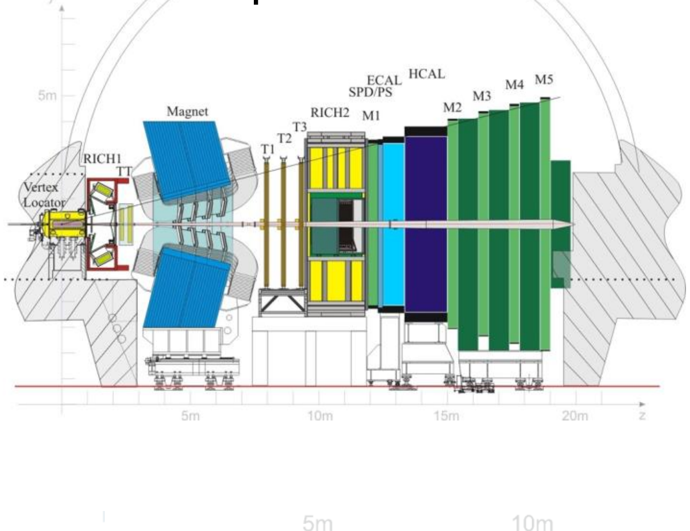
Performance exceeded expectations

Weaknesses

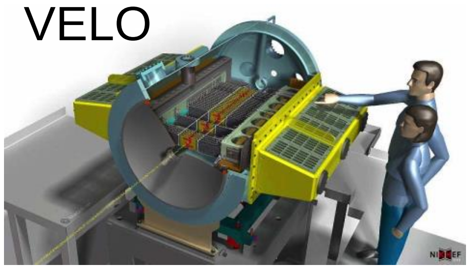
- The technology was new for a collider environment
- Short (3-years) physics program

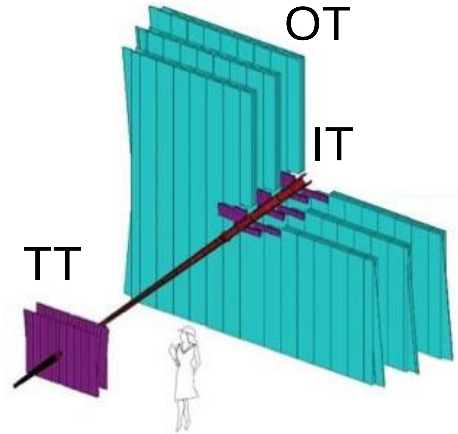
LHC-b

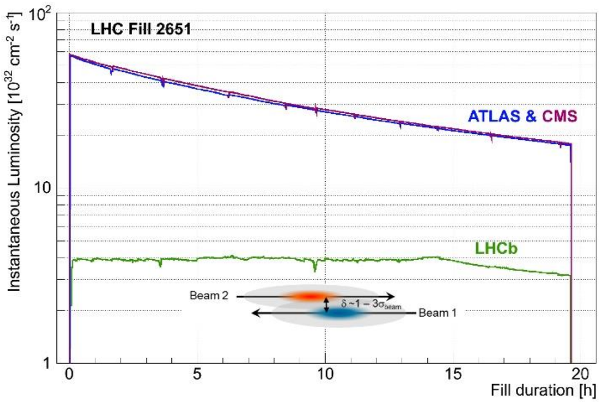
Forward spectrometer:



VELO

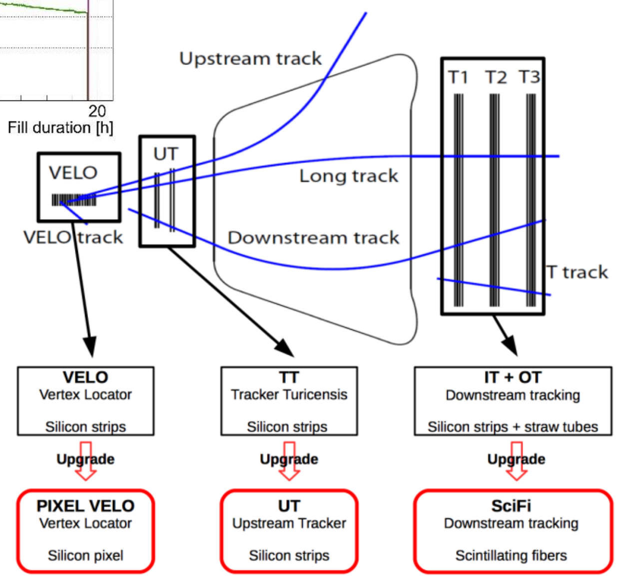






Run I → 3 fb^{-1} collected
Run II → **6 fb^{-1} collected**
→ 8 fb^{-1} expected by the end of 2018

Precision of many physics measurements at LHCb will be statistically limited at the end of Run II

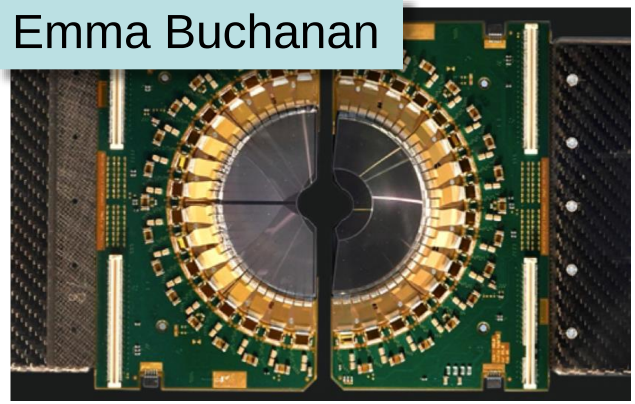


LHCb Upgrade - Run III

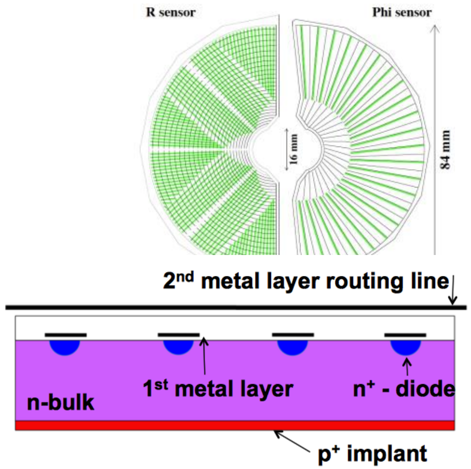
- 5x luminosity→ L= 2*10^{33}cm^{-2}s^{-1}
- 5 fb^{-1} / year
- Trigger upgrade
- Sub-detectors upgrade

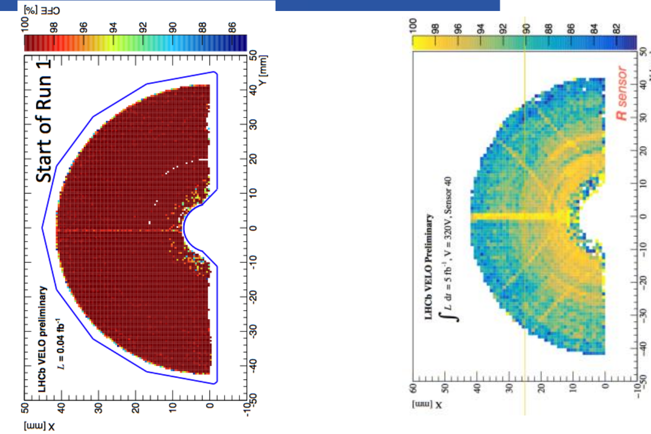
LHC-b Trackers Operation

Emma Buchanan



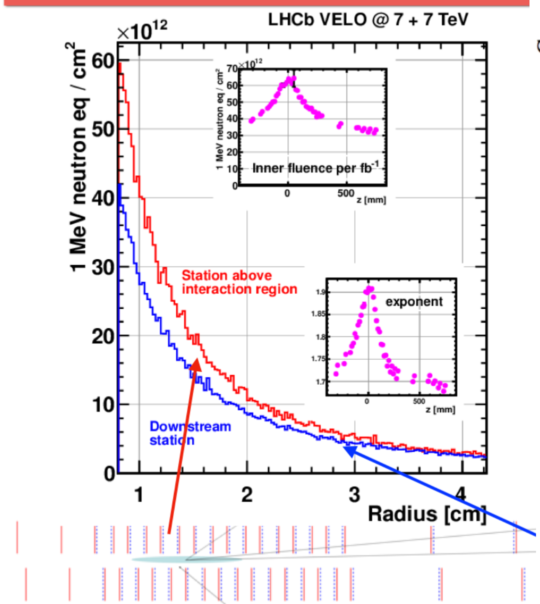
Evaporative CO_2 cooling (first in HEP!)

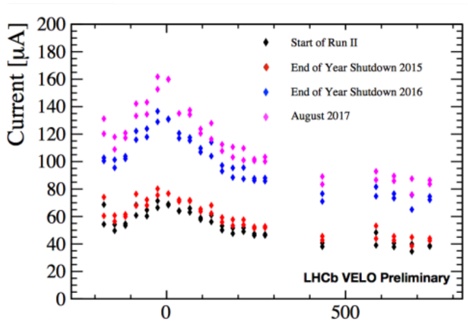


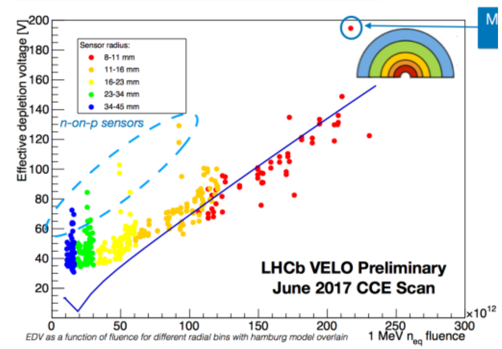


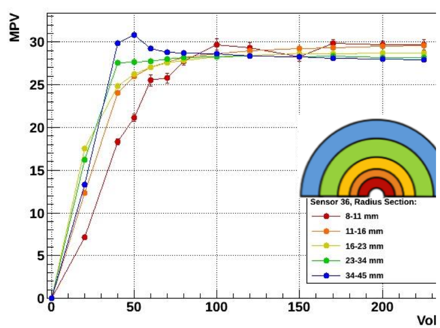
R sensors suffering from inefficiencies

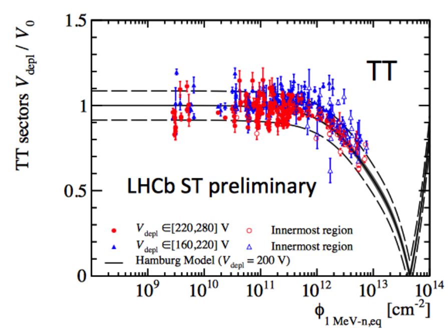
Fluence per fb^{-1} expected in Run II

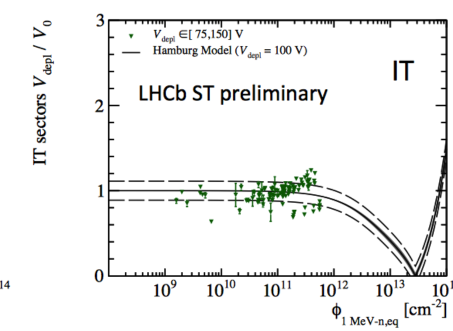










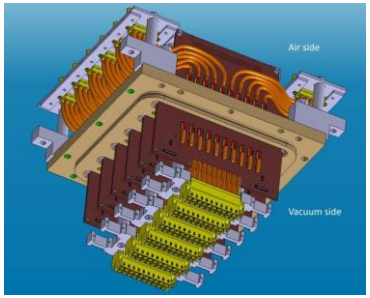


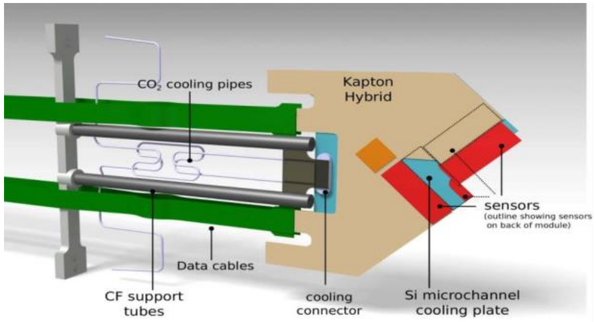
LHC-b VELO upgrade

Moving from Silicon Strips to Pixels:

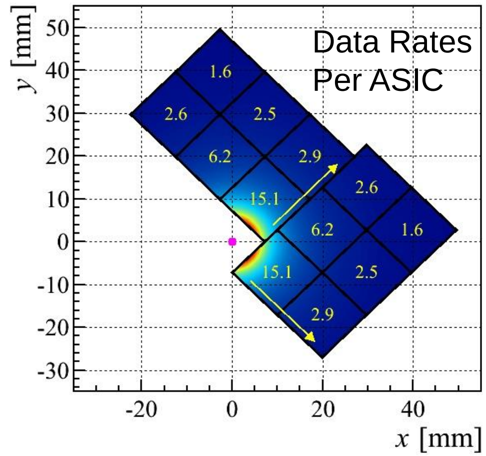
Edgar Lemos Cid

- Higher radiation tolerance
- Increased Readout Rate (1 MHz to 40 MHz).
- Closer to Beam
- Microchannel CO_2 cooling
- VeloPix derived from Timepix3:

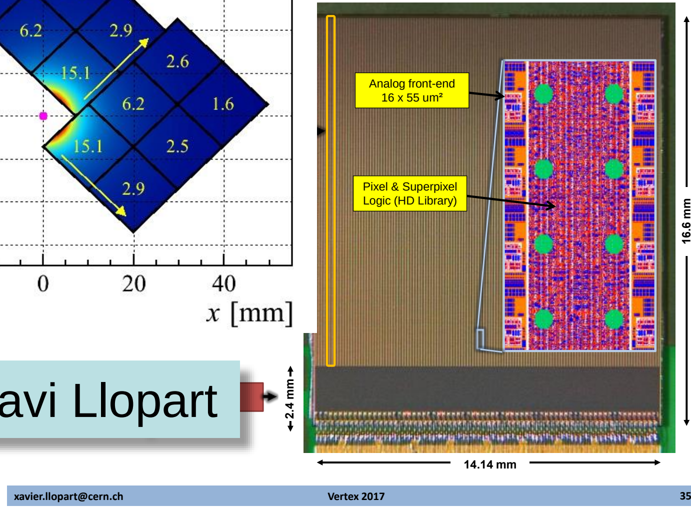




	Timepix3 (2013)	VeloPix (2016)
Pixel arrangement	256 x 256	
Pixel size	55 x 55 μm²	
Peak hit rate	80 Mhits/s/ASIC	800 Mhits/s/ASIC 50 khits/s/pixel
Readout type	Continuous, trigger-less, TOT	Continuous, trigger-less, binary
Timing resolution/range	1.5625 ns, 18 bits	25 ns, 9 bits
Total Power consumption	<1.5 W	< 2 W
Radiation hardness		400 Mrad, SEU tolerant
Sensor type	Various, e- and h+ collection	Planar silicon, e- collection
Max. data rate	5.12 Gbps	20.48 Gbps
Technology	130 nm CMOS	

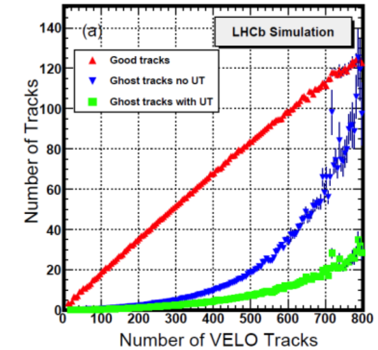


Xavi Llopart

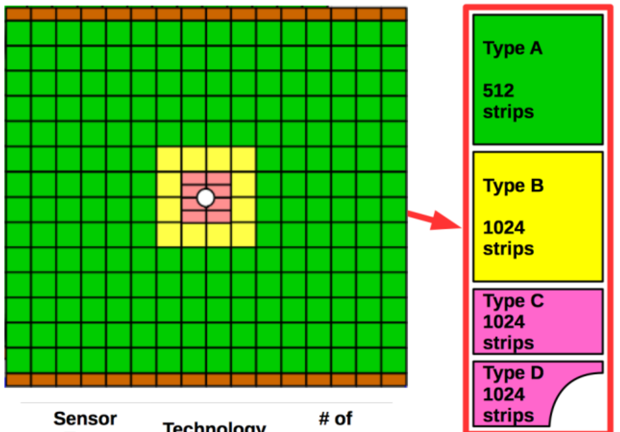


Marco Petruzzo

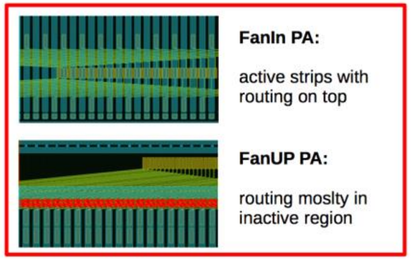
Upgrade:
- Full software trigger
- Readout and event reconstruction at 40 MHz
- Tracking system replacement



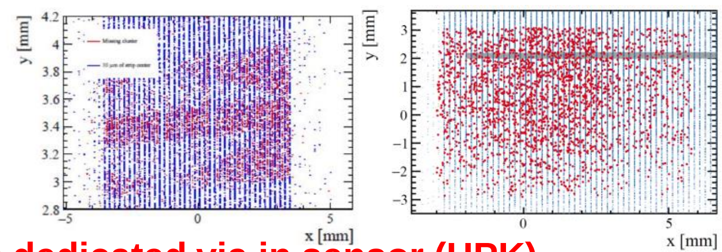
Four Layers of single-sided sensors on vertical double-sided staves:



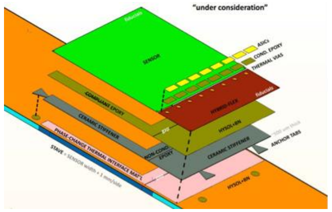
Sensor Type	Technology	# of sensors
A	p-in-n	728
A	n-in-p	160
B	n-in-p	48
C	n-in-p	16
D	n-in-p	16

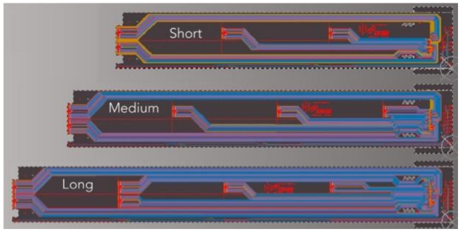


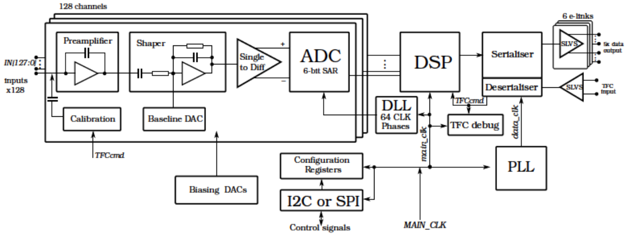
Double-metal inefficiencies, solved by thicker SiO_2



Front-side biasing with dedicated via in sensor (HPK)



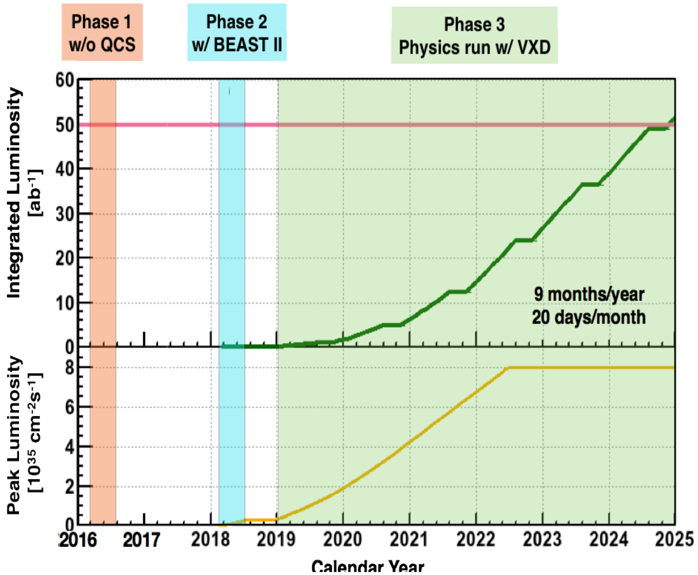


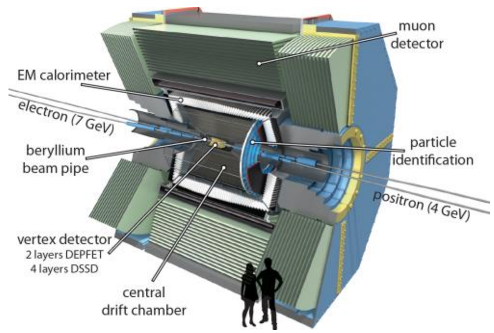


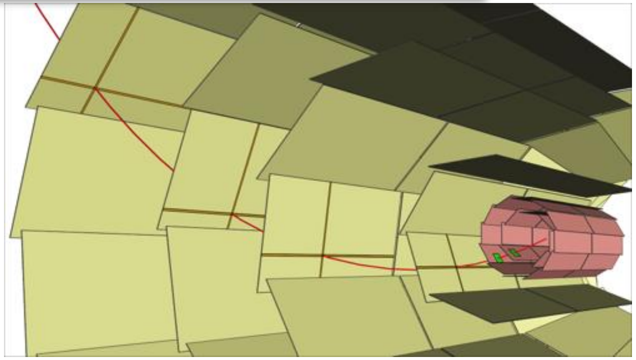
SALT ASIC: TSMC CMOS 130 nm technology 128 channels, wirebonded to sensors Input pitch 80μm

Belle II at KEK

Jochen Dingfelder, Gagan Mohanty







Belle I (until 2010): SVD only

Belle II (starting 2018): PXD+ new SVD

Challenges for vertex reconstruction:

- Higher backgrounds (lumi. increase, nano-beams) ⇒ higher occupancy
- Boost reduced from $\beta\gamma$ = 0.42 to 0.28 ⇒ B-meson flight length of 125 μm

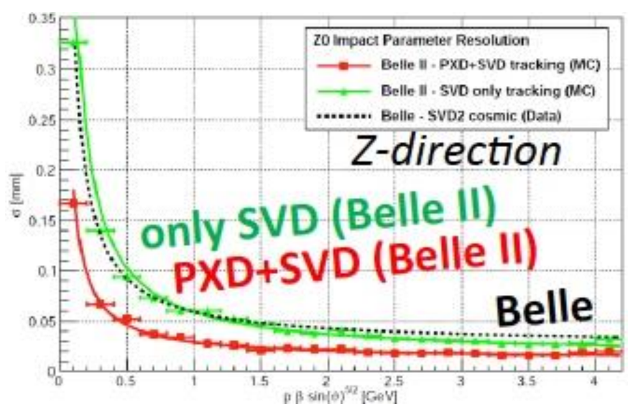
SuperKEKB accelerator

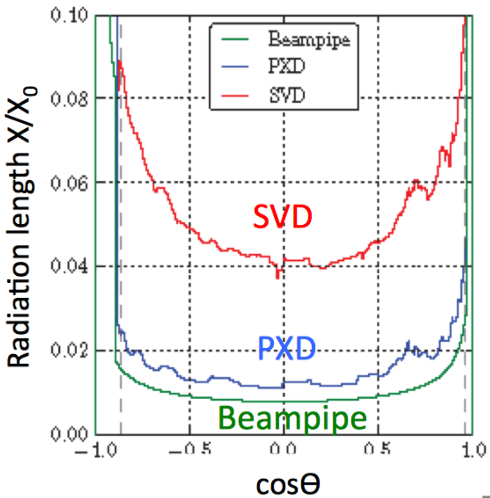
E_{cm}=10.58 GeV @ Υ(4s)

Peak Lumi 8x10^{35} $cm^{-2}s^{-1}$

Integrated lumi: 50 ab^{-1}

→ **15 times higher as HL-LHC**

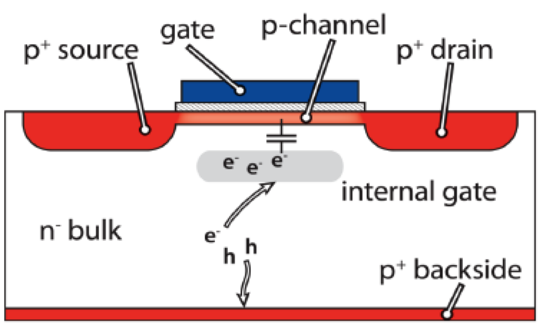


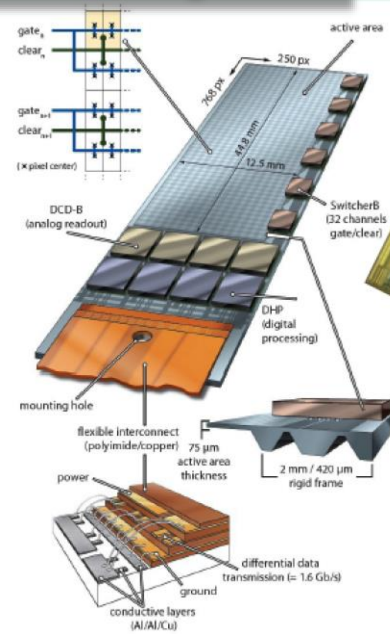


Belle II PXD

Jochen Dingfelder

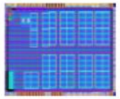
- DEPFET concept developed by late Gerhard Lutz
  - First use in HEP experiment here
- Pixel is FET transistor
  - amplification in sensor
  - “clearing” of signal necessary

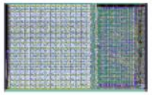




Low mass vertex detectors with highest possible integration!
- Thin sensor area
- EOS for r/o ASICs
- Thin (perforated) frame with steering ASICS

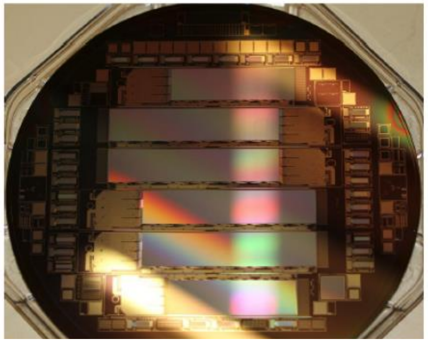
SwitcherB - Row Control
- AMS/IBM HVCMOS 180 nm
- Size 3.6 x 1.5 mm²
- Gate and Clear signal
- Fast HV ramp for Clear
- Rad. hard proved (36 Mrad)



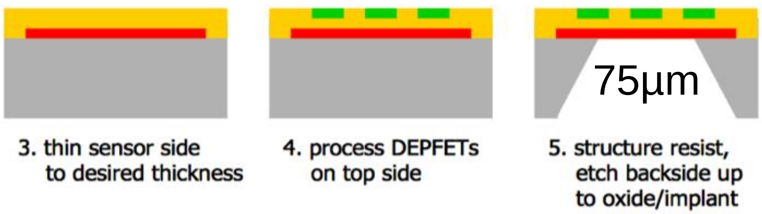


DCDB - Drain Current Digitizer
Amplification and digitization of DEPFET signals.
- UMC 180 nm
- 256 input channels
- 8-bit ADC per channel
- 92 ns sampling time
- Rad. hard proved (10 Mrad)

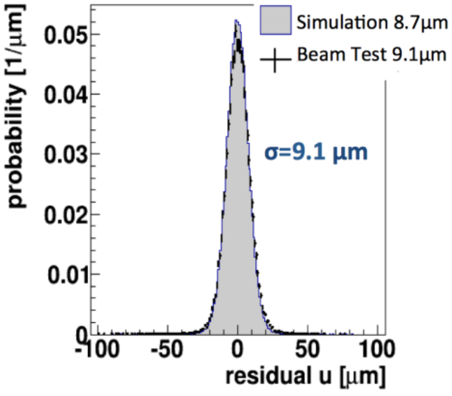
DHP - Data Handling Processor
- TSMC 65 nm
- Size 4.0 x 3.2 mm²
- Stores raw data and pedestals
- Common mode and pedestal correction
- Data reduction (zero suppression)
- Timing and trigger control
- Rad. Hard proved (100 Mrad)



DEPFET Production



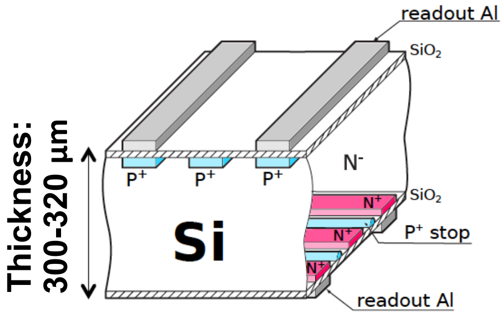
30° tilt: many 2 pixel clusters



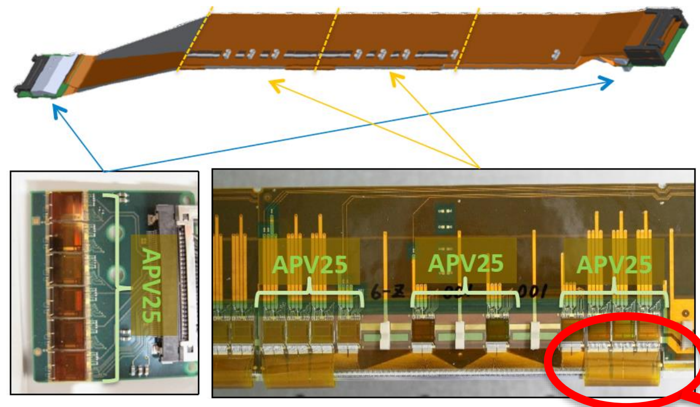
21 final production wafers → processing finished

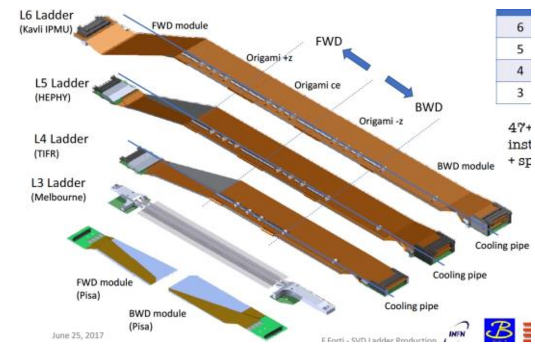
Gagan Mohanty

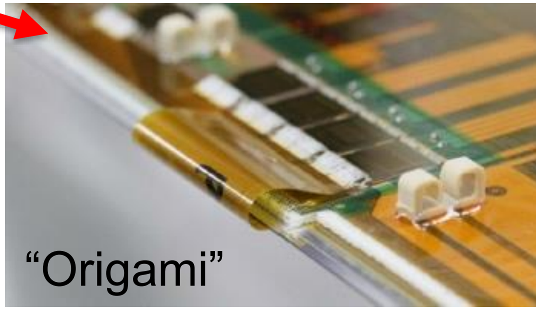
➡ Double-sided silicon micro-strip detector (DSSD): p-in-n 6′ wafer



➡ APV25 chip: originally developed for CMS

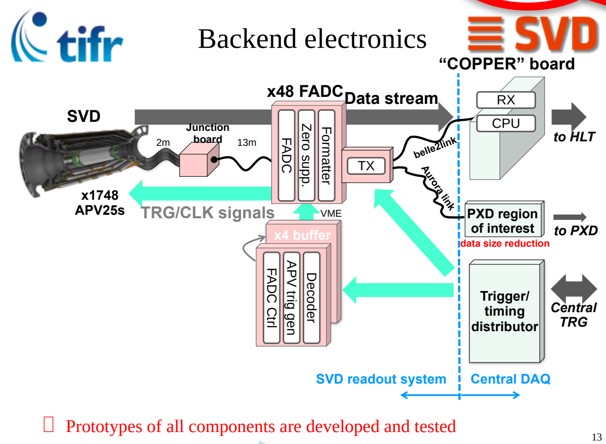






Sensors	Rectangular (Large)	Rectangular (Small)	Trapezoidal
# of *p*-strips	768	768	768
p-strip pitch	75µm	50µm	50…75µm
# of *n*-strips	512	768	512
n-strip pitch	240µm	160µm	240µm

HPK (Rectangular) — Micron (Trapezoidal)



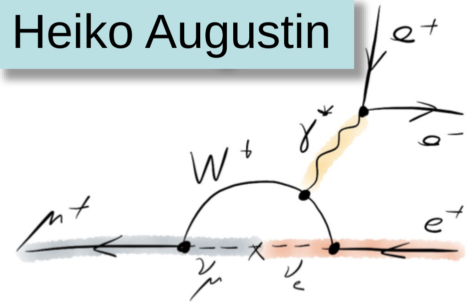
Ladder Assembly status:

- L3: 100% completed
- L4: 7 out of 12 done (60%)
- L5: Just finished
- L6: 12 out of 20 done (60%)

Shifting now to ladder mount on support structure

Mu3e at PSI

Heiko Augustin

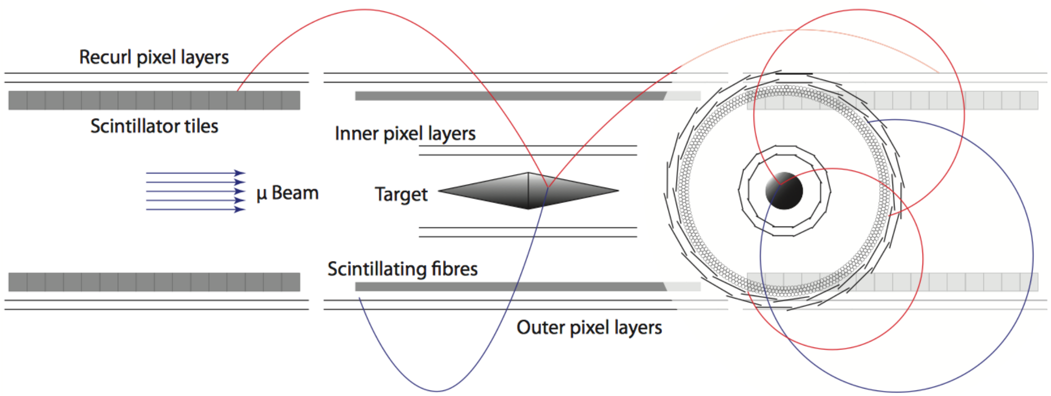


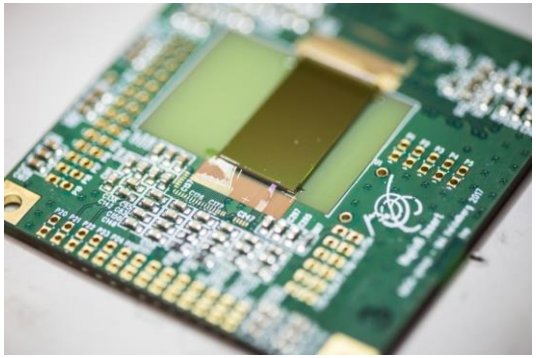
- LFV decay $\mu^+ \to e^+e^-e^+$ suppressed in the SM (BR < 10^{-54})
- current limit BR < 10^{-12} (SINDRUM)
- aiming for sensitivity of 1 in 10^{16} decays
- any observed signal is a sign for new physics

- irreducible background from internal conversion: $\mu^+ \to e^+e^+e^-\bar{\nu}_\mu\nu_e$

10^9 decays/s

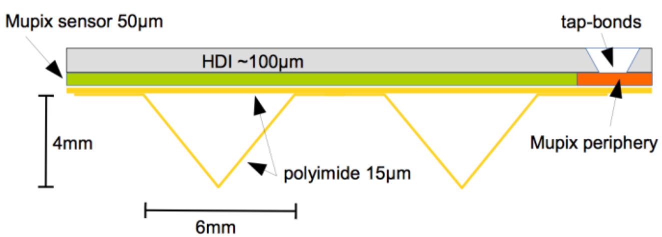
1 T field, continuous µ-Beam:



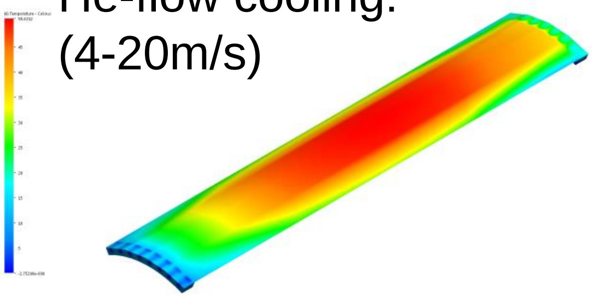


MuPix8: HV/HR-CMOS very advanced, 128x200 pixels, 81x80µm, 50µm thick

1.16 ‰ X_0 / layer



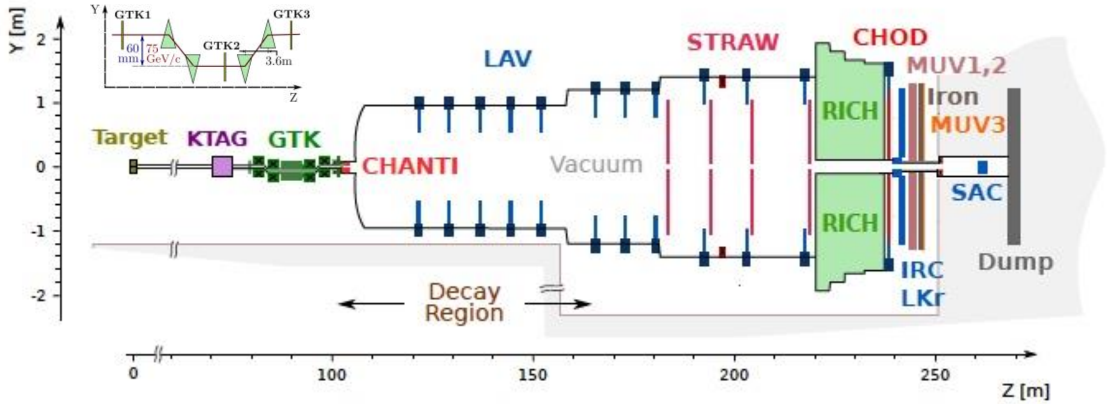
He-flow cooling: (4-20m/s)

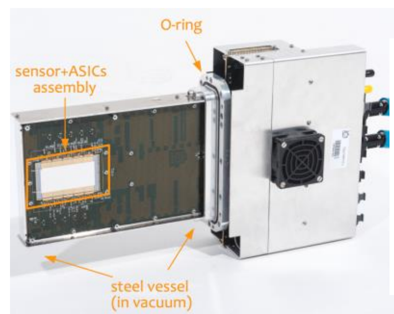


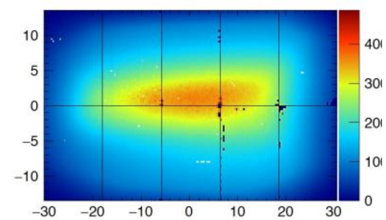
start data taking in 2020

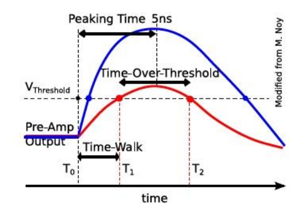
NA62 Gigatracker

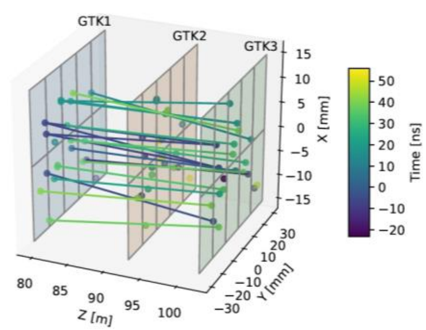
- Fixed target at SPS to measure BR of K+ decay "in flight": $K^+ \to \pi^+ \nu \bar{\nu}$
  - Installed 2016
  - 75 GeV/c continuous hadron beam
- GTK sensors in direct beam
  - 6x3cm^2 size
  - 300x300µm^2 pixels
  - Exchanged every 100 days
- ~20 hits per plane
- High Timing precision
  - Time walk correction in chip
  - Time offset (online)
  - Time resolution 130ps
  - Time resolution per track 74ps
- High radiation levels,
- CO_2 microchannel cooling

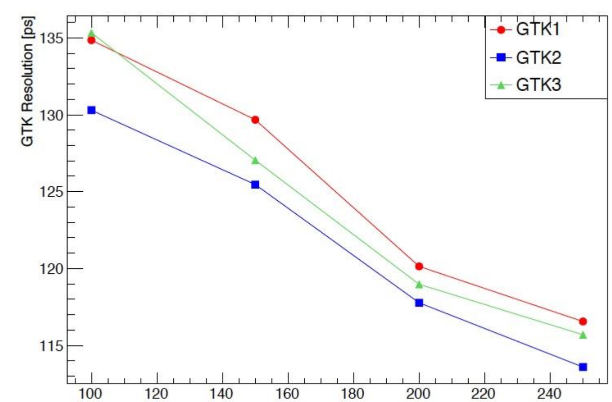










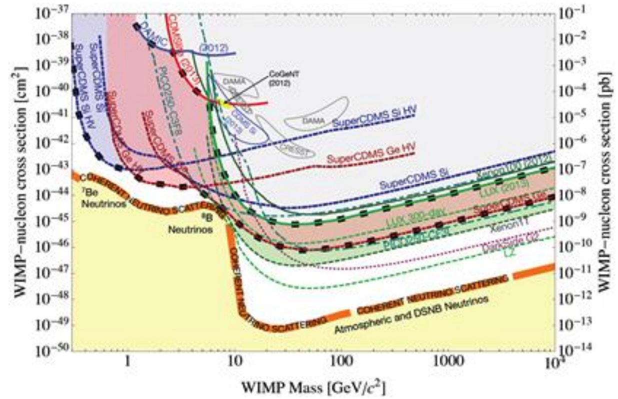


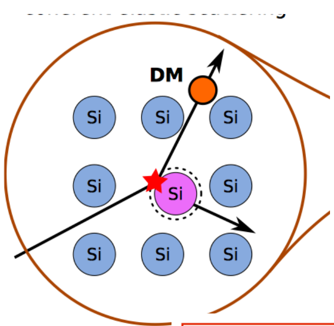
Dark Matter Detection

Ben Kilminster

Dark Matter Detector usually 100t of Water/lAr/Xr/Crystals

- Exclusion plot on low-mass scale limited by energy threshold
- Neutral particle scatters off Si atom
- recoils energy produce ionization
- coherent neutrino scattering
- Can be accessed by low-noise CCD
- DAMIC (SNOLAB) & CONNIE (Reactor)





3.62 eV per e & hole

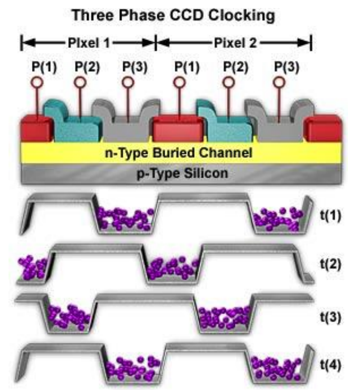
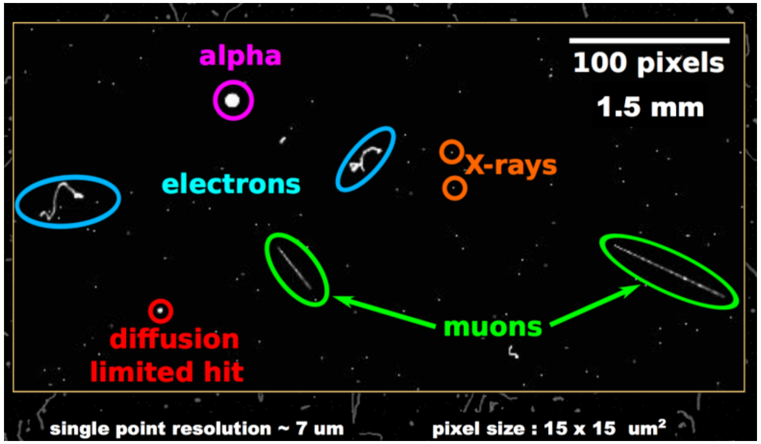
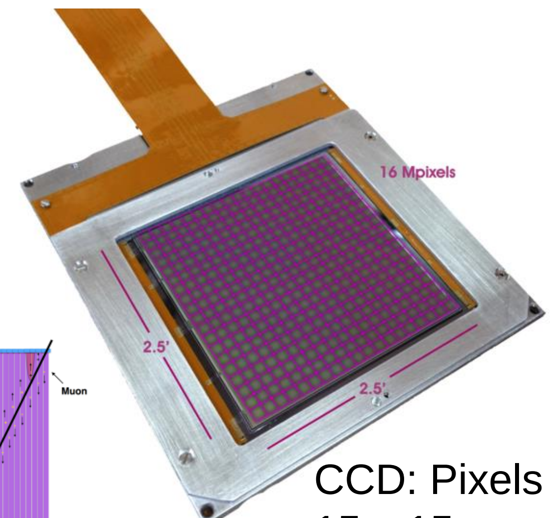
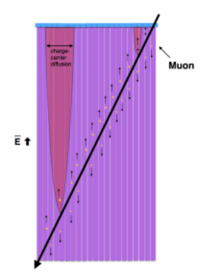


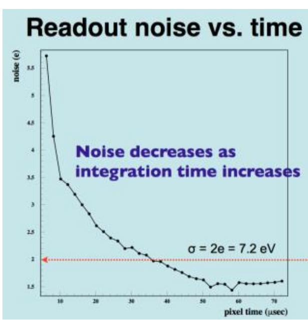
Figure 1







CCD: Pixels 15 x 15 µm 650 µm thick

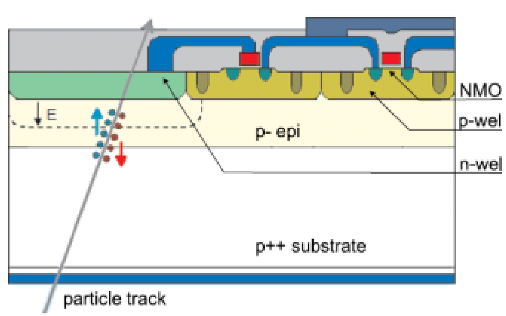


DETECTOR TECHNOLOGIES

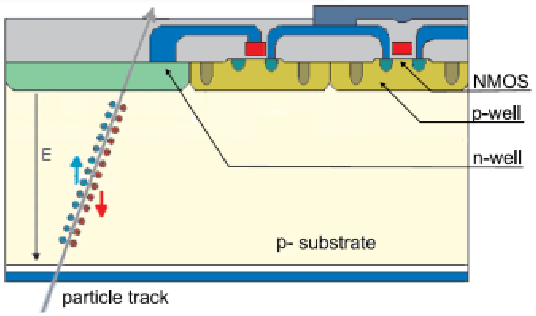
MAPS & HV-CMOS technology

Tomasz Hemperek, Hara-san

- Move from classical Monolithic CMOS detector to HV-CMOS
- Different processes
  - AMS (MuPix, CCPD, ATLAS)
  - Lfoundry (e.g. Passive LFCMOS)
  - TowerJazz (e.g. ALPIDE)
  - Xfab HV-SOI (up to 7 metal layers) reduces threshold shift
  - Lapis: 0.20um FD-SOI process (SOIPIX → Japanese grant)
- Many groups working on it: Bonn, CERN, Geneva, JSI, UK, US, Japan → mostly ATLAS **(where is CMS?)**
- **Biggest improvement recently**: high resistivity material to create thicker depletion zones (20Ωcm (standard) → 2kΩcm)
- **Next Steps:** radiation hardness – >10^{16} hadrons, stitching

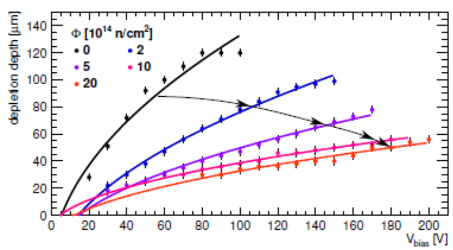


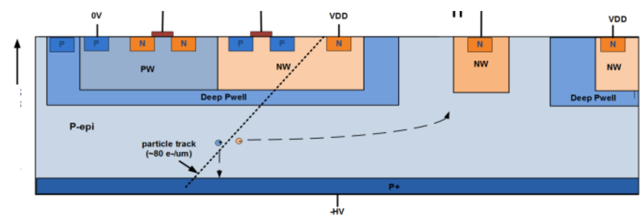
MAPS: Charge collection in intrinsic depletion zone and by diffusion



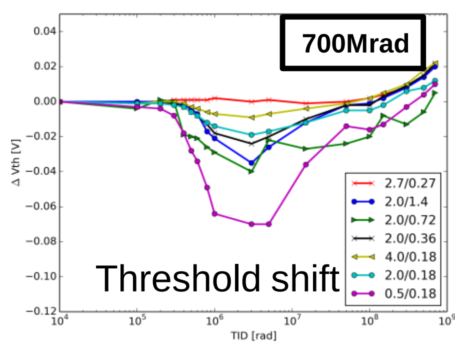
Charge collection drift in E-field → HV-CMOS

Edge-TCT:



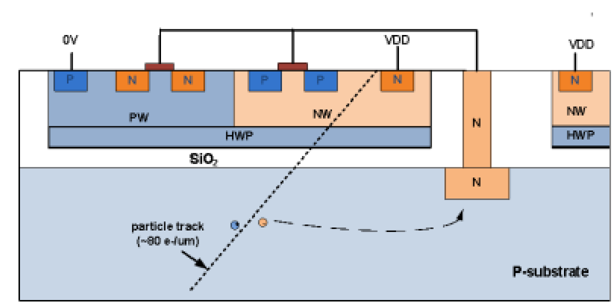


Minimize collection electrode to lower capacitance (noise)



Threshold shift

Xfab HV-SOI



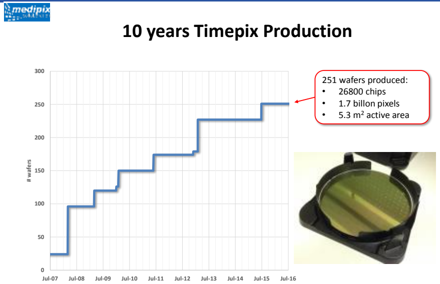
Timepix Detectors

Xavi Llopart

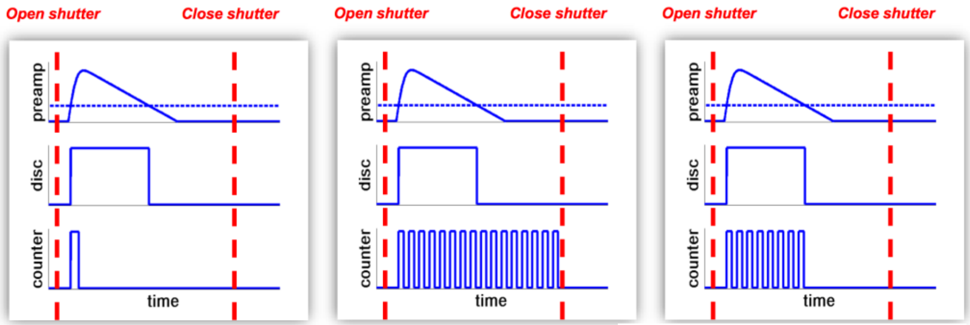
History:

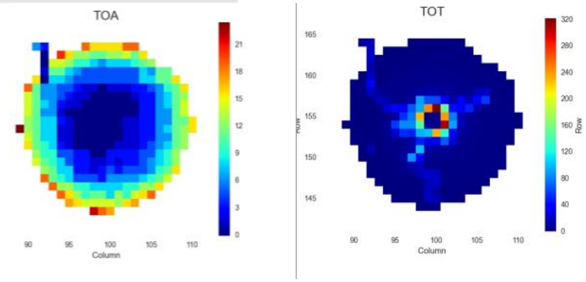
- Medipix2 (1999)
- Timepix 2006 (EUDET/AIDA funded)
- Medipix 3
- Timepix3, Clicpix (2013)
- Velopix, Clicpix2 (2016)
- **Timepix 4 (2018/2019)**
  - 4-side buttable
  - 6.94 cm^2 (3.5x more)
  - 200ps time resolution

- 10 years ago: Timepix for TPCs
- Now: Applications everywhere
  - LHC-b VELO, Clicpix



- Particle counting
- Arrival Time
- Time over threshold

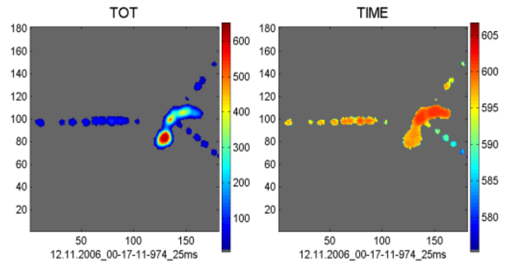




Ar 150 GeV/c
[p-on-n 500 µm sensor]

Timepix with 3-GEM detector

- DESY pion testbeam in November 2006 (A.Bamberger, U. Renz, M.Titov, X. Llopart)
- Triple GEM gas detector
- Checked-board pattern (TOT and TIME)



Timepix Applications

UFSD/LGAD

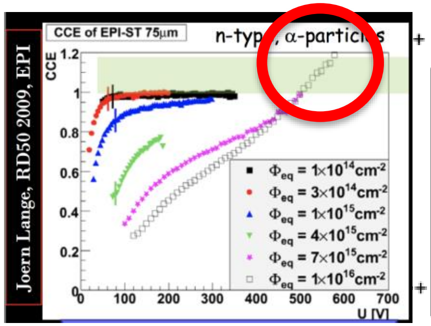
Ultra Fast Si Detectors / Low gain avalance detectors

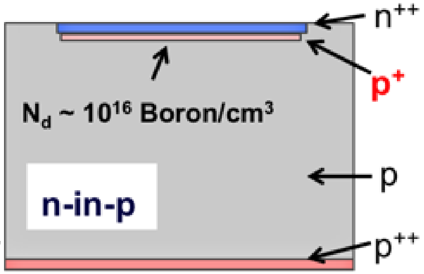
Maria Obertino, (Marcos, Gregor, Sophia)

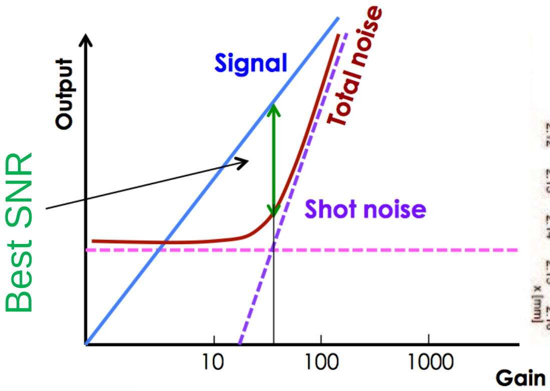
Amplification found "accidentally" as the sensors were getting thinner and higher voltages are being applied

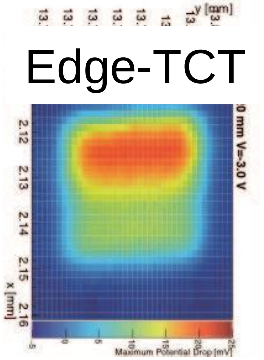
Now being exploited by highly doped, thin layer of p-implant underneath p-n junction –> high electric field accelerates electrons enough to start multiplication

- "Low" Gain since shot noise rises more than signal
- Gain sensitive to doping profile → irradiation reduces gain → time resolution goes worse
  - Irradiation sensitivity mitigated by Gallium dopant (less probabilities for intersticials) and/or carbon
  - LGAD gain prone to annealing effects
- Already 4 suppliers: **CNM**, FBK, HPK, Micron
- Variant of "Inverted-LGAD" with strips on top

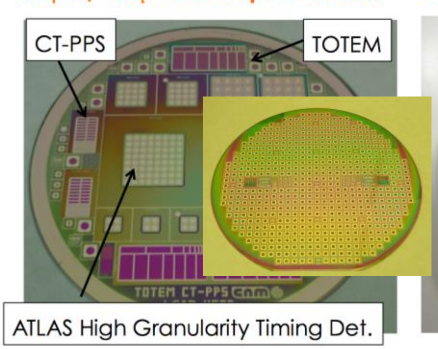




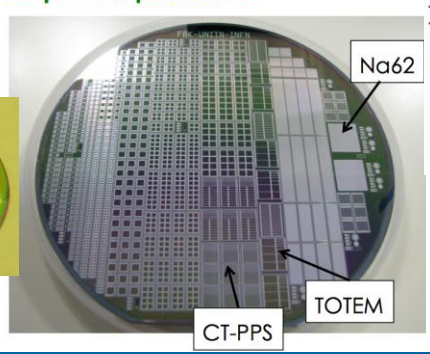


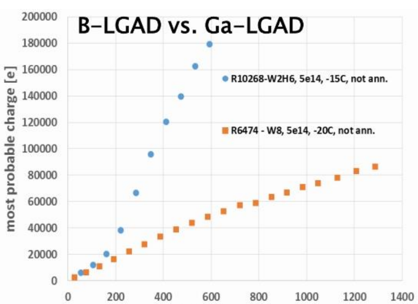


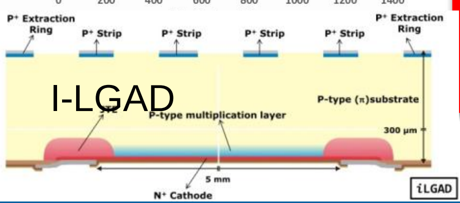
75 µm/ 50 µm CNM production

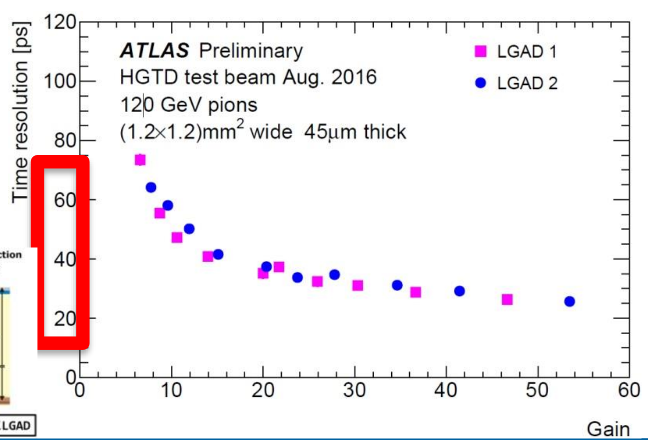


50 µm FBK production









Flip chip and 3D Integration

Sami Vähänen, Ron Lipton

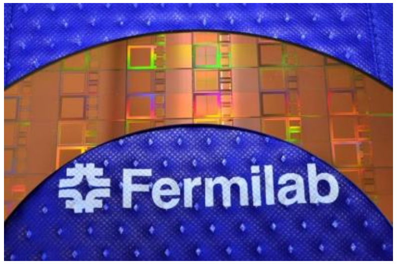
Direct Bond Interconnect (DBI) Process

Wafer-to-Wafer bonding

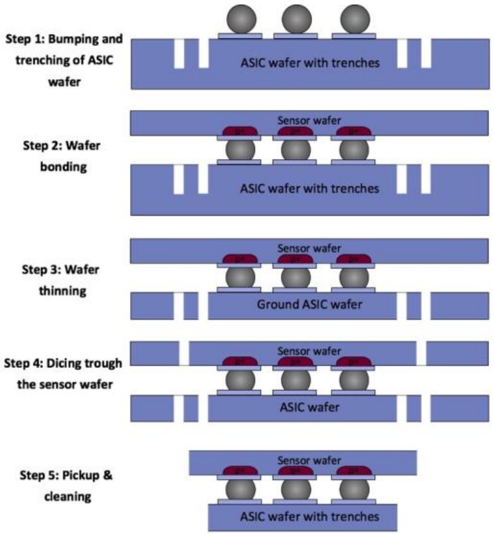
- Sensor diameter must match
- (chips 8-12”, sensor 6-8”)
- Chip and sensor layout must match
- Intrinsically „edge-less“

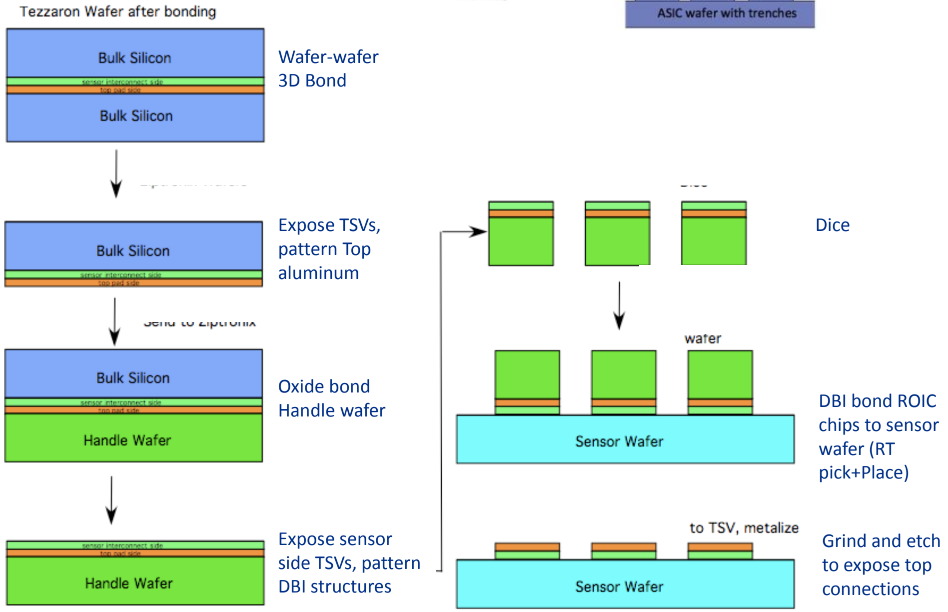
Die-to-Wafer bonding

- Possible to select good dies (new metallization necessary after probing)
- Application for timing by lowering noise (capacitance)



Ring leftover when matching larger chip to smaller sensor wafer

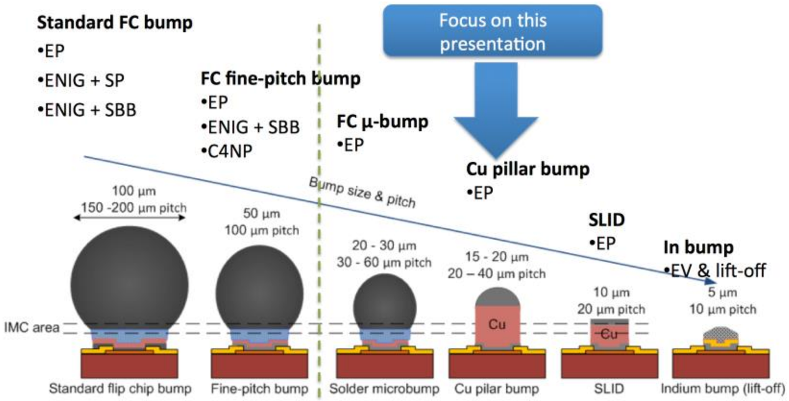


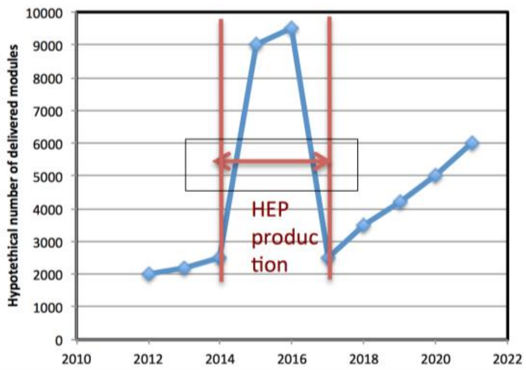


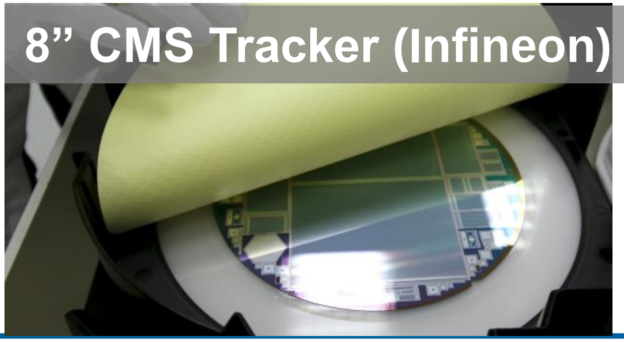
Commercialization

Sami Vähänen

- Commercial vs. R&D paths
  - e.g. bump-bonding
- Costly, time consuming "commercialization"
  - Demand of technology in HEP is not constant in time
  - Thus companies usually not so interested in us
- Examples:
  - Small detector area → "home made", e.g. DEPFET@HLL (10 working wafers)
  - CMS/ATLAS Trackers ~50k wafers
    Example: 6-8" sensors for CMS Tracker/HGCal Phase-II Upgrade @ Infineon
- Future: Pixels in huge quantities
  - Will only work if commercial processes are used as far as possible, e.g. HV/HR-CMOS







CO_2 Cooling

Paolo Petagna, Alessandro Mapelli, Oscar Augusto

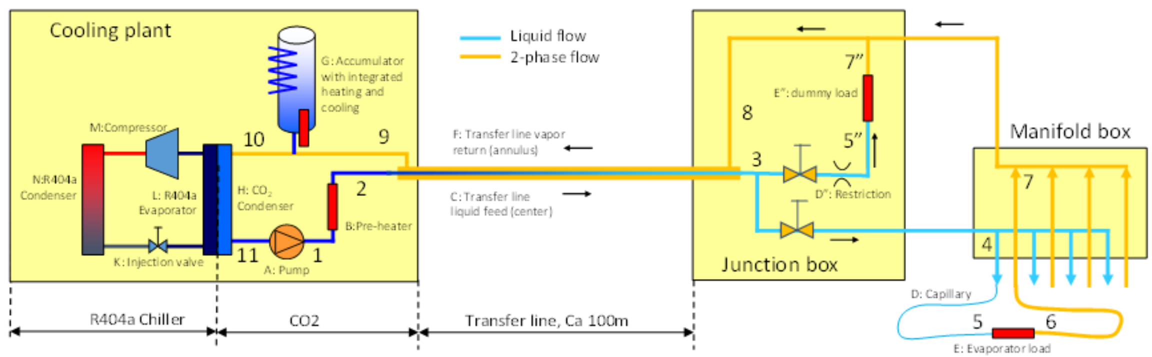
10 years ago: experimental, high pressure, hard to control

- developed for the AMS TRD and for the LHVb Velo
- specific two-phase pumped loop (2-PACL)

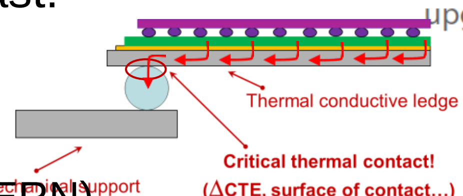
Now: established technique for all HEP experiment upgrades

- Thanks to Bart Verlaat, Paolo Petagna et al.

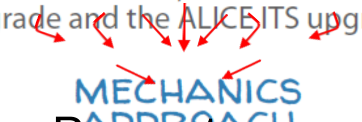
AIDA 2020 CO_2 test facility (CERN)
Airflow facility (Oxford)



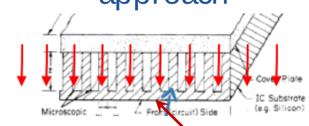
Past: "Traditional" approach: fair enough for STRIPS



Present (Upgrades): "Integrated" approach for the NA62 GTK, the LHCb VeLo upgrade and the ALICE ITS upgrade

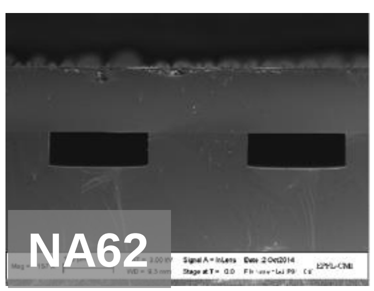


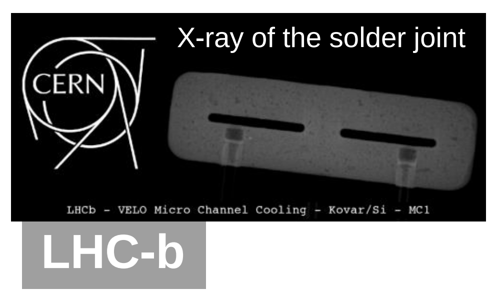
Future: same CTE — Silicon microchannel approach

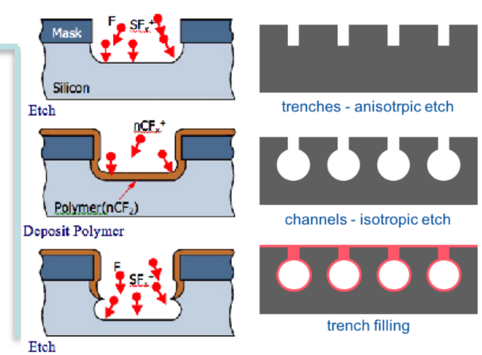


Thin silicon substrate with embedded ∝-channels

Microchannels etched in silicon
60 µm x 60 µm (40 mm long)







Diamond Detectors

Marko Mikuz for Harris Kagan

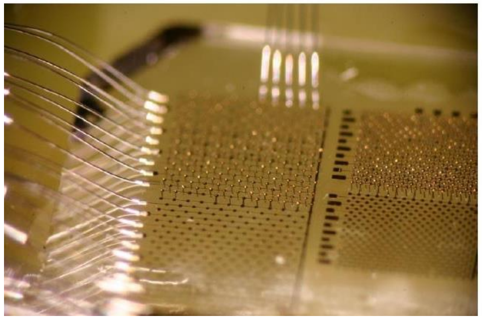
- RD42 collaboration: 32 institutes, 130 people (founded 1994)
- Diamond: no pn-junction, just (segemented) metallization
- Single crystal vs. poly crystalline (grains)
- Application (so far): Beam Conditions Monitors/Beam Loss Monitors

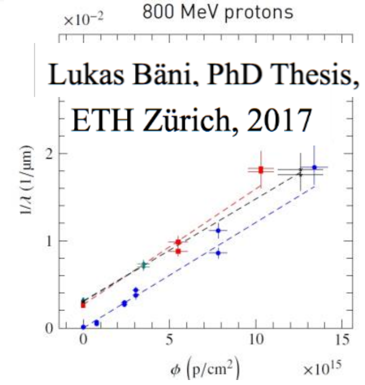
New efforts:

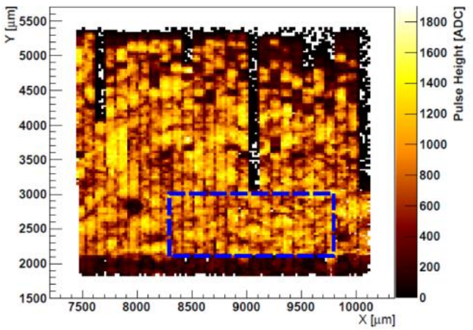
- Radiation tolerance normalized for single and poly-crystal and particle species
- 3D Diamond by laser "drilling of holes" (UK effort) → acts like "single crystal" if grain size > CCD
  - First try 2015 (99 "columns")
  - Full 3D device 2016 (1188 "columns", 2µm hole diameter
  - 2017: 3500 cell pixel prototype w/50x50µm

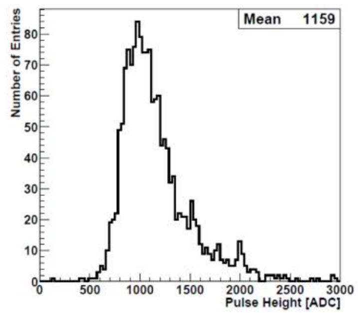
Readout with CMS pixel readout:

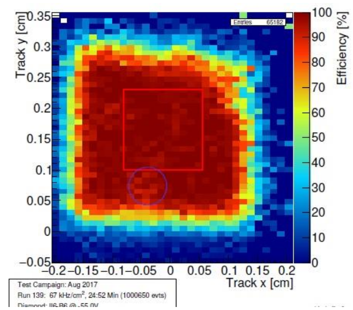
- Preliminary efficiency 99.2%
- Collect >90% of charge!



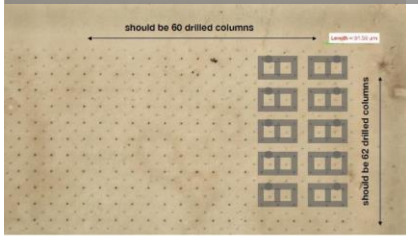








CMS pixel readout



RD50 & TCT

Marcos Fernandez Garcia

WG1: defect/material characterization

- Thermally Stimulated Current (TSC)
- Deep Level Transient Spectroscopy (DLTS)
- Red/IR front/back TCT
- Edge-TCT
- **New: Two-Photon-Absorption-TCT**: very powerful technique!

Using these to understand:

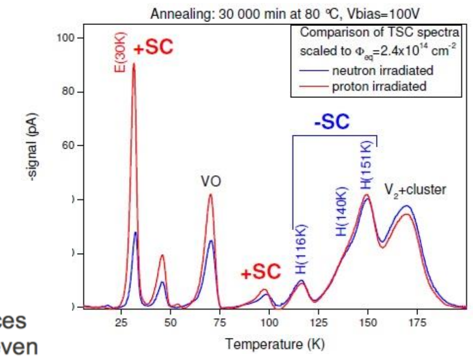
- N-Bulk: Donor Removal
- P-bulk: acceptor removal: CiS study, HVCMOS CCE study

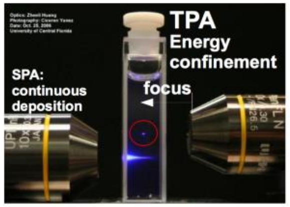
Study of irradiated LGAD sensors:

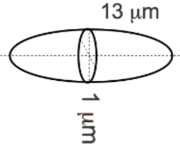
- Onset at low bias voltages

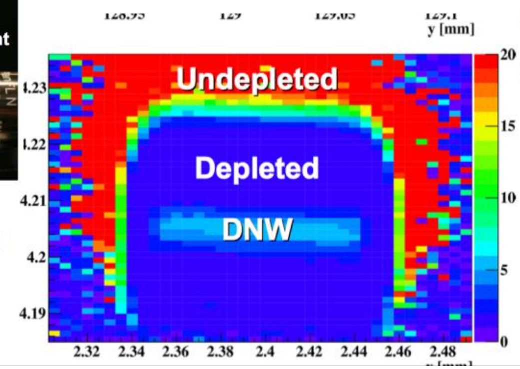
RD50

- H(116K,140K,151K) defects introduce **negative space charge** (-SC) and are responsible for type inversion of n-type material..
- In **Oxygenated** materials **E(30K)** introduces +SC and thus reduces increase of V_{dep} or even avoids type inversion.







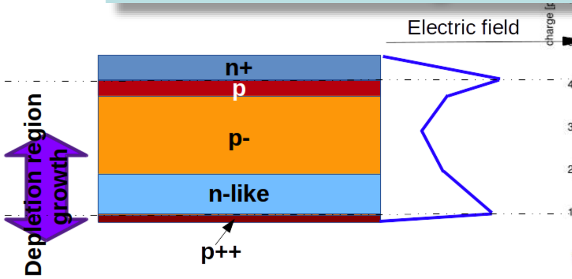


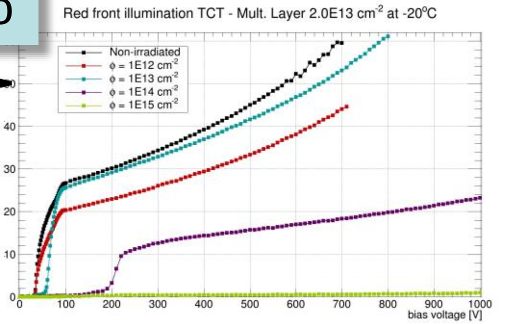
HVCMOS (CCPDv3) Showing: Collection time map

TPA-TCT

λ=1300 nm, σ=1 µm, **200 fs**-pulsed laser

Sofía Otero Ugobono

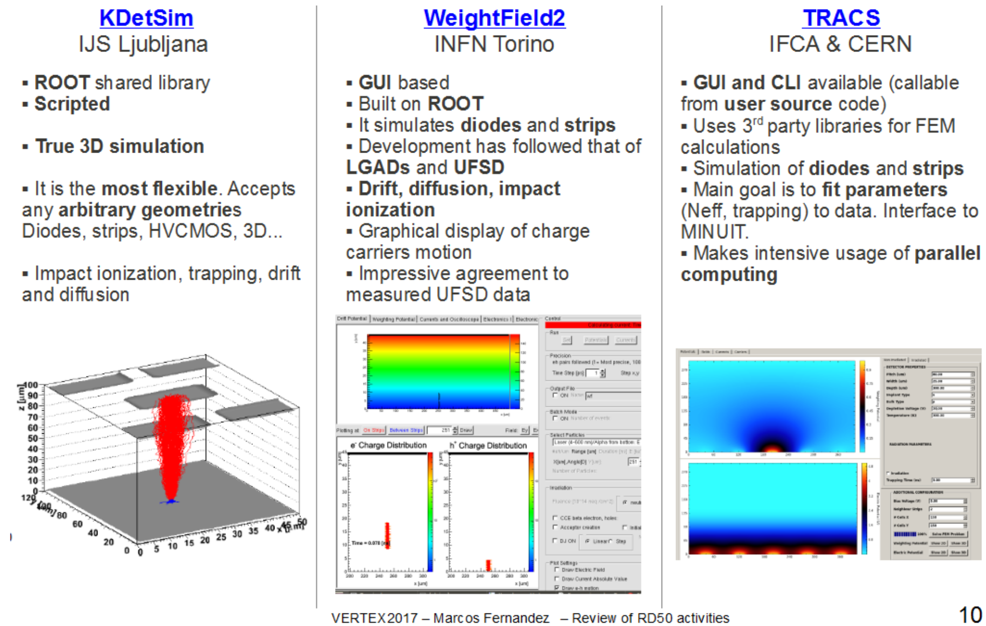




Silicon Sensor Simulation

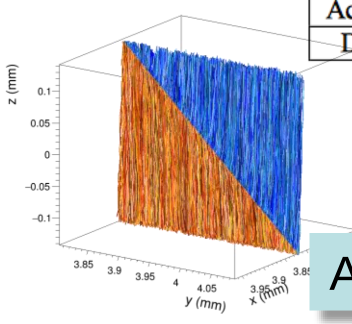
- **RD50 WG2: fast simulators:** KDetSim (Lublijana), Weightfield2 (Torino), TRACS (IFCA&CERN)
- **Perugia TCAD Irradiation model**
  - Commercial Synopsys Sentaurus
  - >20 publications
  - Parametrization of experimental results of both bulk and surface damage
  - New version up to 2.2E16 n_{eq}/cm^2
  - “Modelling radiation damage effects is a hard task!”
- **Allpix² - Generic Pixel Detector Sim. Framework**
  - Modular easy-to-use
  - Charge generation sim Geant4
  - import electric fields in the TCAD DF-ISE format

Marcos Fernandez Garcia



Daniele Passieri

Type	E (eV)	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	Ec-0.42	1.0×10^{-15}	1.0×10^{-14}	1.6
Acceptor	Ec-0.46	1.5×10^{-15}	1.5×10^{-14}	0.9
Donor	Ev+0.36	3.2×10^{-13}	3.2×10^{-14}	0.9



Andreas Nürnberg

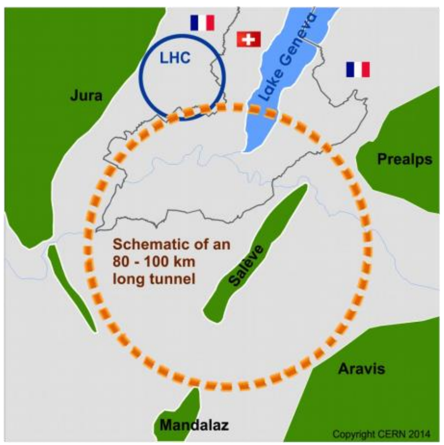
FUTURE EXPERIMENTS

Future Circular Collider

Zbynek Drasal

FCC-ee, FCC-eh, FCC-hh

- ~16T magnets → 100TeV pp collider in 97.75km tunnel

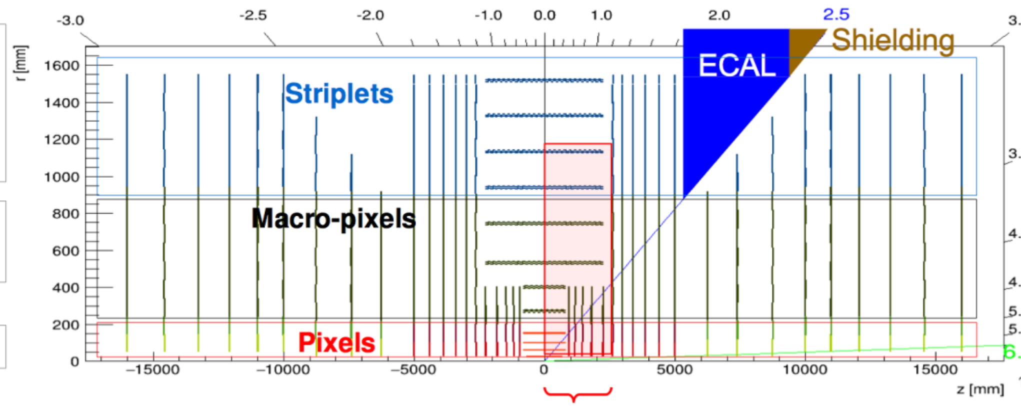


Forward detectors up to η<6

Surface: ~430m²
#Channels: 489.4M
9964.4M
5460.9M

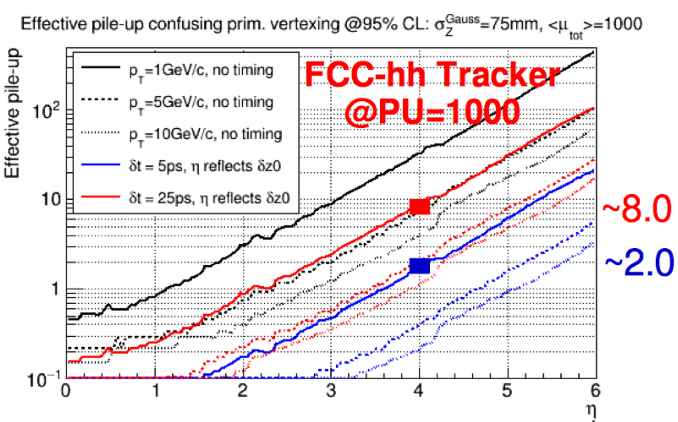
Pixel R↗0.9 m
due to occupancy

4 (seed) BRL layers

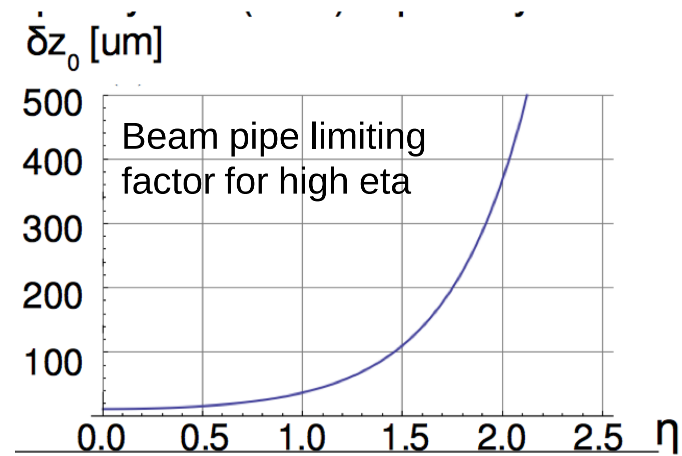


→ 1MeV n_{eq} fluence ~6x10^{17} cm^{-2} & TID ~0.4GGy

→ data rates (766 TB/s untriggered, 19 TB/s triggered @1MHz)



Mitigation against pileup:
Timing, Timing, timing

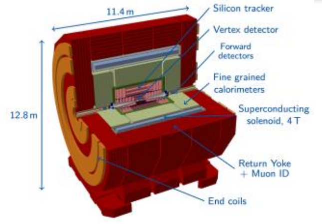


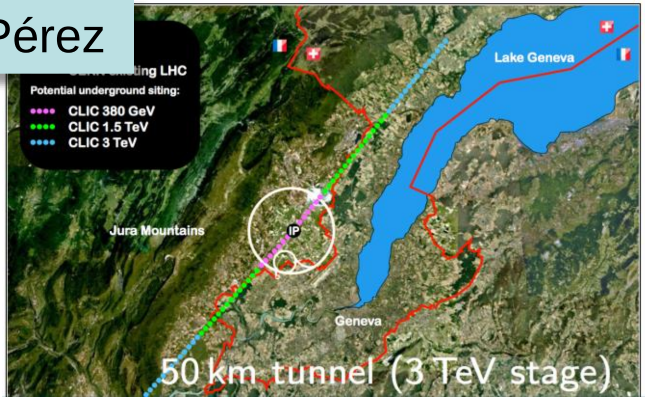
CLIC / ILC

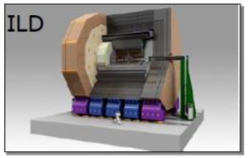
Andreas Nürnberg, Alejandro Pérez Pérez

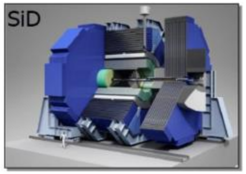
e^+/e^- Colliders: Well known initial state, no QCD background, fully reconstructable final states

- **CLIC@CERN:** Up to 50km length@3TeV (100MV/m gradient), beam size 45 x 1 nm
- **ILC@Japan:** Up to 50km length@1TeV, 31.5 MV/m gradient. Two detector concepts (ILD, SiD)



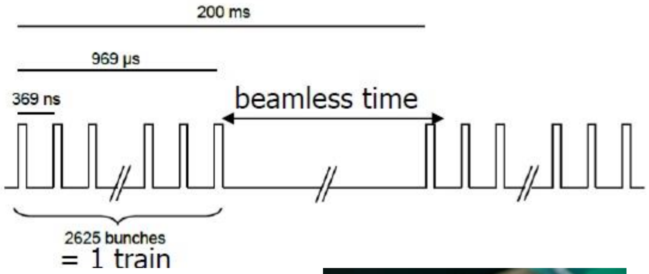






Detectors:

- Pixels inside, strips outside
  - ILC: additional TPC with "Silicon external tracker" around it
- Lower radiation w.r.t. LHC
- Bunch train beam allows power pulsing
- Airflow cooling (FEA ongoing)
- Low occupancy
- Very low material budget

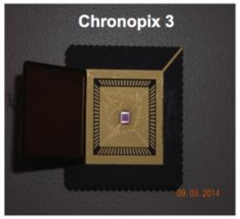


See K. Hara Talk for SOI recent developments

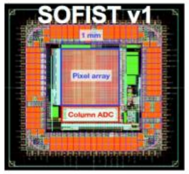
Detector technologies: HV/HR-CMOS, SOI

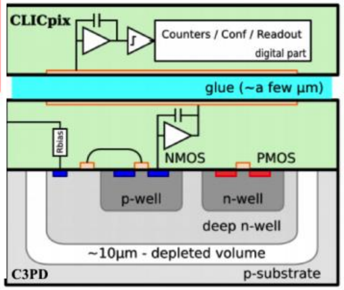
- CliCpix2, C3PD (glued), **CLICTD**
- **Chronopix, SOI, FPCCD**, DEPFET, CMOS

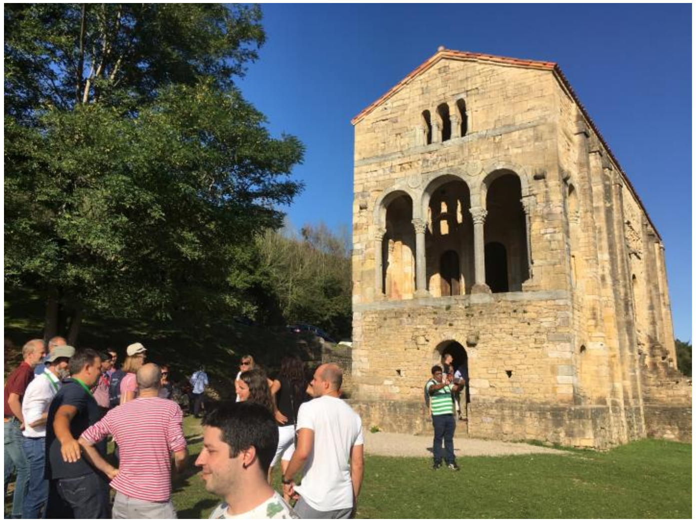
Oregon University
Yale University



Osaka University,
Tsukuba University,
Tohoku University, KEK







Summary of the

SUMMARY

Summary of Summary

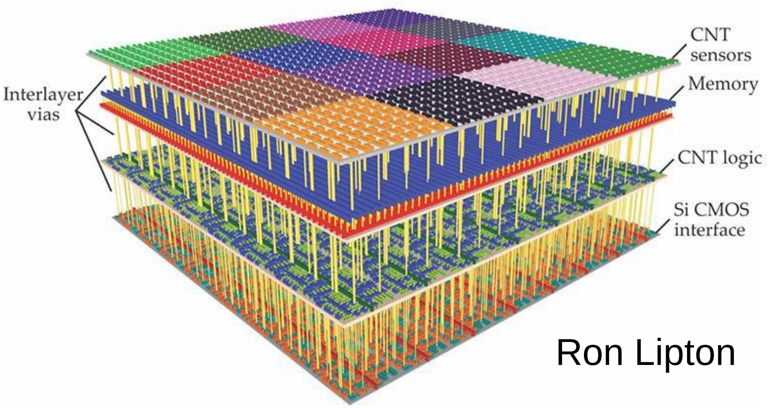
- 5 Days with 46 excellent talks, 11 posters, great food and wine

- **LHC Detectors performing extremely well**, but getting older and older….
  - Automatic procedures being implemented to cope with SEU, de-sync,….
  - CMS Pixel replacement happened during winter shutdown 2016/2017
  - Upgrade programs everywhere. (LS2: ALICE, LHC-b)
  - new situation we are facing now: parallel work of operation of existing detectors and R&D, prototypes (**manpower!, funding!)**
- **Most recent detectors:** NA62 GTK, Forward experiments of ATLAS and CMS
- **Upcoming Experiments:** Belle II, Mu3e (FCC very actively investigated)
- **New Application of Silicon:** Dark Matter detection

- CO_2 cooling is everywhere
- Timing, Timing, Timing,…..
- Much progress on recent developments:
  - LGAD, HV/HR-CMOS, Timepix4/Velopix
  - 4-side buttable/stichting sensors to achieve large areas (TSV/Vertical integration)
  - “The future is just monolithic” (K. Hara)

Summary of Summary

Let's look into a monolithic, precisely timed and amplified future



A three-dimensional integrated circuit, made possible with carbon nanotubes (CNTs). *Physics Today 70, 9, 14 (2017)*

Thank you for your attention!