Karlsruhe Institute of Technology

Disclaimer – fine print:

- You have to live with my selection
- Impossible to represent everybody correctly - apologies
- No posters – talks only
- I try to be bit entertaining

Summary
or better, You tell me later if this is a summary!

Frank Hartmann

Institut für Experimentelle Teilchenphysik (ETP)

27th Vertex Conference – and we still love it

The beginning 1992 – people told me about it

Basto Island, 1992

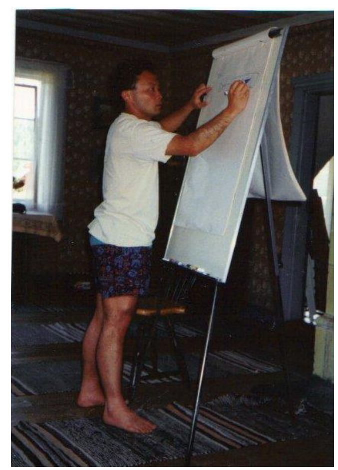
Richard, 8057

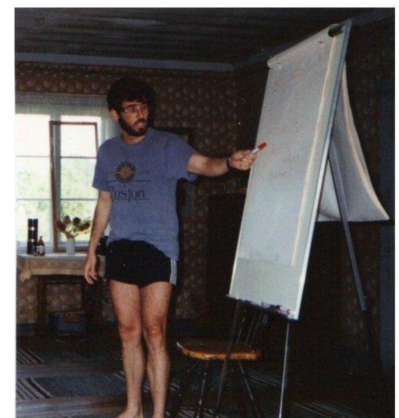
Let us know by mail to BRENNER@VXCERN before friday 15.5.1992 if you are interested. Because of limited space a maximum of 30 persons can attend this workshop.

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.

Basto Island:
cooked by the participants





Share your experience fully and freely

The Intermediate Silicon Layers Detector

My Beginning:

Frank Hartmann

Institut für Experimentelle Kernphysik - Karlsruhe

for the CDF ISL Group

VERTEX '98

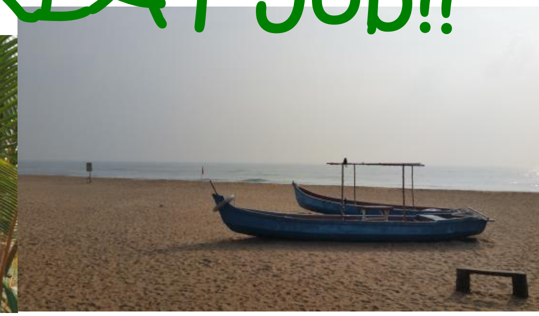
28 September - 4 October 1998,
Santorini Island, Greece

UNIVERSITY OF KARLSRUHE

The Laws of Vertex conferences

- **It must be at the water (lake, island or the sea)** GREAT Job!!



Gulf of Bengal

- It must be remote, that people are forced to have frank discussions – no escape Check!
- Plenary only! You must stay the whole length!
- **Excursion must be AT LEAST ½ day long**



Good Job

A+ for location
B for duration

Hm??

- My personal VERTEX law: Confess all problems that we all can learn
- **My personal 2nd VERTEX law: Food must be excellent!** A++++

Vertex conferences

2018 Chennai, India

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, USA

2001 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

Lessons Learned:

- This is my 20th Vertex anniversary
- I should go more often

Other vertex places <u>and it’s waters</u>

Conference dinner in Nikko 2005
Legs are still hurting

Elba 2016
I am sure the water was **<u>awesome</u>**

WOW - Ein Gedi
swimming, muddy but **<u>warm</u>**

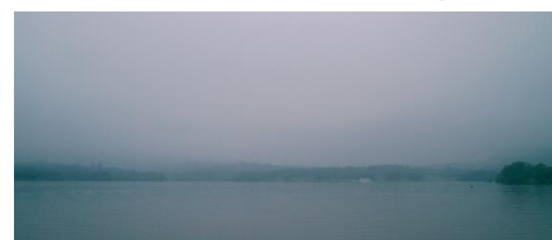
Japanese Onsen are **<u>hot</u>**
Nikko 2005

Water was **<u>OK</u>**

2011 RUST Colin Wilbur
CEO of Micron electronics

Best **<u>Mix</u>** regatta team
ATLAS, LHCB, CMS

2003 Lake Windermere was freezing **<u>cold</u>**



I was told, Loch Lomond was as **<u>cold</u>**

I '*summarize*'

- Operational Experience – 10
- Radiation Hardness – 7
- Application of Silicon Detectors in high/low backgrounds environment – *not sure what this means* - 2
  - But it is: pnCCDS & CMS HGCAL
- Detector Design and Construction – *UPGRADE* – 9
- Fast Timing - 4
- Future Collider experiments - 3
- Tracking and Vertexing - 5
- Electronics and System Integration - 8
- Social Activity

Intro + social activity + 48 talks in 60 min
You do the math how many seconds I spend on your contribution!

First Silicon Strip Sensor (I found)

NUCLEAR INSTRUMENTS AND METHODS 97 (1971) 465-469;

Institut für Experimentelle Kernphysik der Universität and the Kernforschungszentrums Karlsruhe, Germany

The counters are large area ion-implanted detectors with a common aluminium contact and a front contact consisting of five or twelve gold strips separated by 0.2 mm.

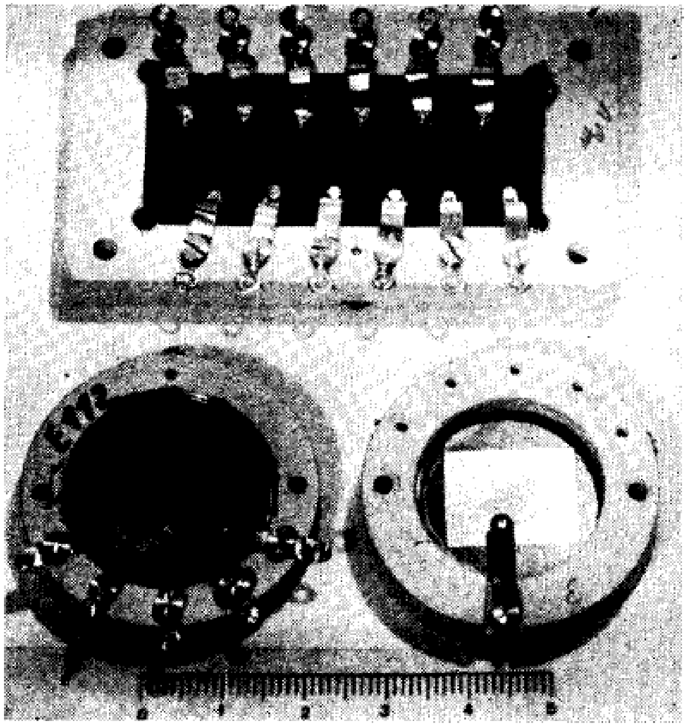


Fig. 1. Ion-implanted semiconductor detectors with subdivided front-contact and common back-contact.

Today, I simply try to continue the good old tradition.

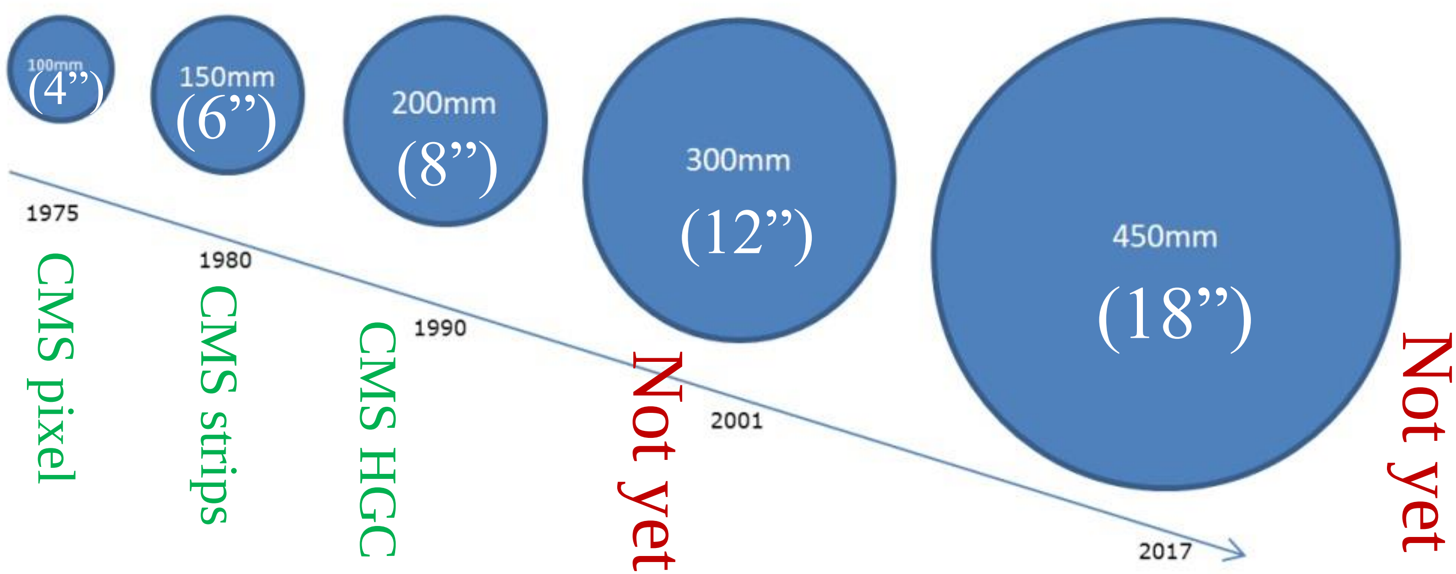
Wafer sizes now and then

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!

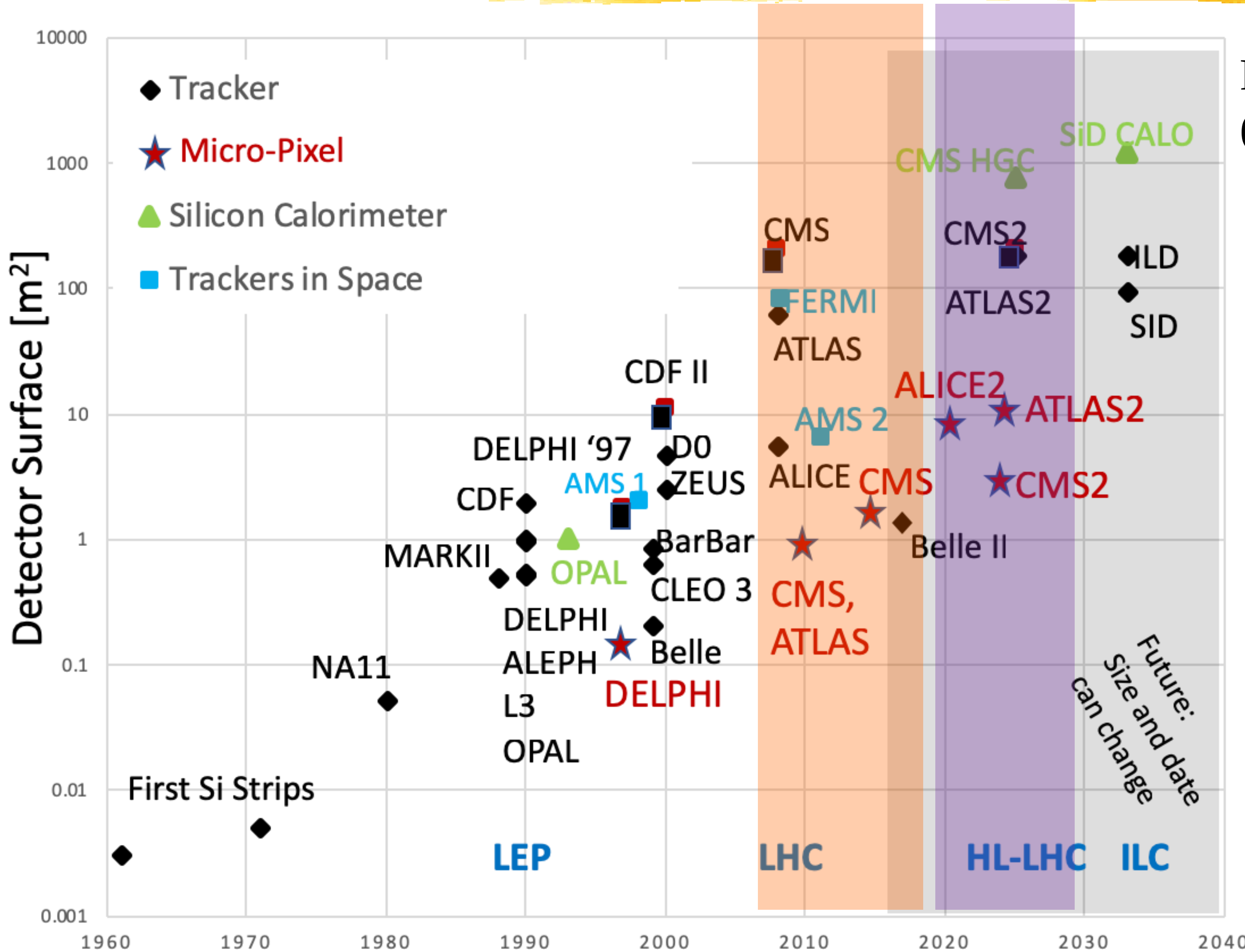
Wafer Areas in Chip industries:



We are stuck in the 90’

Size matter!
Does it?

Monday Tuesday Wednesday



FCC-h
(no number)

You can never have enough acronyms, right? Anyhow, now they have been introduced ☺

- TOT, TOA, MIP, HIP, TPC, PID, TOF, TRD, DEPFET, SNR,CCE, MAPS, PU, DCS, DSSD, DEPFET, QE, ENC, ESA, PCB, ASIC, FE, CMOS, ADC, DAQ, BX, TDR, LHC, IP, SMD, DAC, SEU, I/O, PLL, CLK, CSA, TID, IR, FADC, ECL, HCAL, RICH, FEA, PIN, DUT, RAM, QCD, CPU, HEP, NWELL, PWELL
- STAR, HFT, EEMC, BEMC, MTD, SST, PXL, DCA, IST, ATLAS, SCT, TRT, IBL MCC, TMT, MDT, TGC, FE4, S-Link, CMS, LS1, LS2, ROC, TBM, PROC, FPIX, BPIX, FEAST, TIB, TOB, TEC, TID, AOH, APV25, PP1, LHCb, VELO, EDV, R-CLUSTER, ALICE, ITS, SPD, SDD, SSD, HMPID, HS, HM, ECS, FEROM, BELLE2, HER, LER, PXD, SVD, DHP, SWD, DCDB, BEAST2, FANGS, PLUME, CLAWS, CDC, AFP, SiT, BSM, LQBars, MCP-PMT, PID (not the PID above), FE-I4, TCL, PPS, CT-PPS, CEP, RP, UFSD, VFAT2, FED, FEC, scCVD, pCVD, NINO, HPTDC, pnCCD, CCD, XMM, EPIC, eRosita, ATHENA, WFI, CAMP, FLASH, LCLS, FEL, SSJFET, RNDR, VERITAS, CoG, Mpix, HGCal, SM, VBF, SiPMs, CE-E, CE-H, OGP, QC, CALICE-AHCAL, GBT, L1, TV1, TV2, HGVROC, SKIROC, lpGBT, VU9P, EM, PF, PV, ONSEN, DHH, SOI, SW, LMU, RD53A, RD53B, ACB, DCB, FE65P2, CHIPIX, DRAD, VDDA, VDDD, LDO, IV, CV, TCT, EPI, CZ, MCZ, NIEL, DLTS, TSC, SIMS, SR, HVCMOS, DEMAPS, MAPS, DOFZ, PITS, FTIR, MW-PC, TPA, iLGAD, CCD (not the CCD above), MFP, BCM, BLM, Aurora, DBA, CBA, AFE, TMR, HiRadMat, ARIES, FLUKA, TCT(not the TCT above), TNC, SPS, SSDC, 1E, 2E, TCAD, PKA, CC, DCS (not the DCS above), b/w, EDR, TBPX, TFPX, TEPX, VL+, OT, IT, OPB, CTE, RF, HSLB, basf2, TT, UT, SciFi, TDR (not the TDR above), PRR, SALT, PEPI, GBT-SCA, CIS, ALPIDE, FCP, OL, CYSS, COSS, HIC, ABC, HCC, ABCstar, TTC, TA, FCC, FCChh, micron, JTE, DMAPS, HR-MAPS, HV-MAPS, ATLASpix, Monopix, CHESS, H35DEMO, CCPD, CACTUS, MALTA, TWCC, ADDR, ENGRUN1, CLIC, CLICpix, C3PD, ELAD, Allpix2, GEANT4, BRIL, MVA, LCFIPlus, ILD, SiD, ECAL, FPCCD, VTX, GFX, ID, ACTS, CTF, LSM, CA, GPU, EMCal, HMPID, ZDC, T0A, V0A, PHOS, MCH, MTR, FMD, PCA, DOF, FLP, EPN, TF, MWPC, GEM, TBA, ASD, ECD UBM, IMC, MET, TLPB, MEDIPIX, SLID, CMP, DBI, W2W, D2W, RDL, LTC, PACL, CMB STS, AMS, HGDT, HTC, VCR, STREAM, MSC ITN, TJ180nm, DPW, CMD, TSV, AIDA, SPAD, RDL, ISSCC, APSEL, VIPIC, HI-PVD, LCSL, ULITIMA, XIMOS, SOIPIX, SOFIST, BOX, PDD, INTPIX, FORCE, XRPIX, STREAM, UTIMATE, CBC, MPA, SSA, CIC, CKF, CDC

I almost overlooked PU - it is a word in the common dictionary, right?

From this one, you can figure out that I read all talks completely

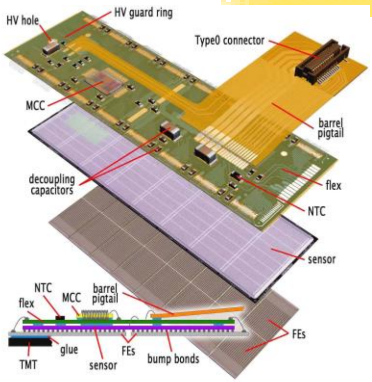
No company or institute abbreviations

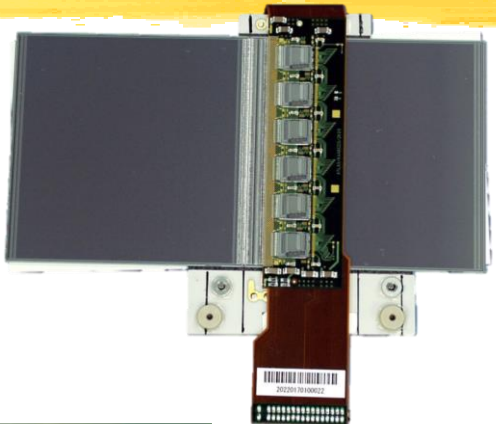
AKA some individuals working in hero mode whereas detectors live happily

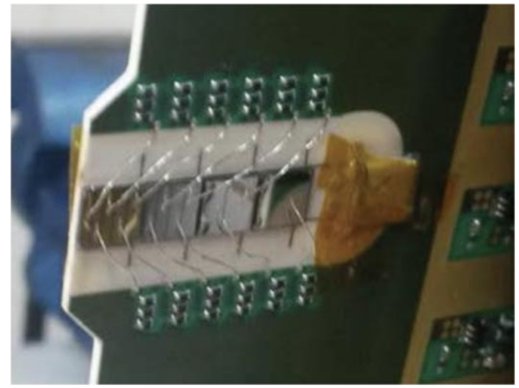
Operations

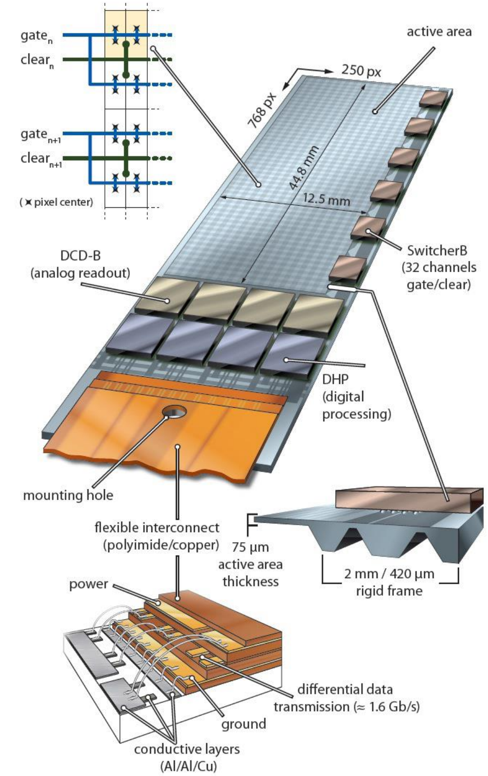
Nice picture of an action hero

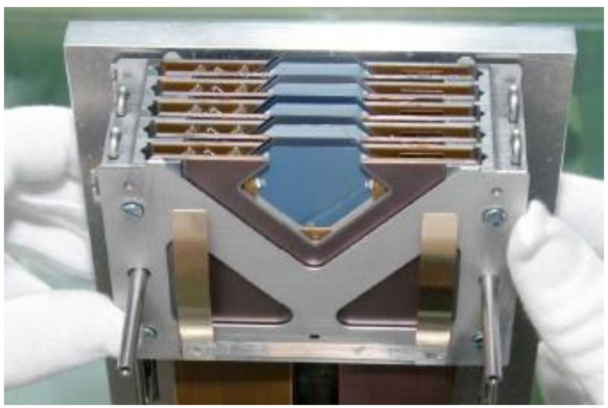
All modules are equal, aren't they? Can you identify yours?



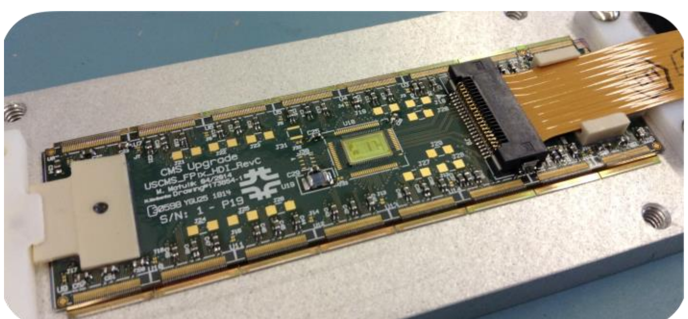


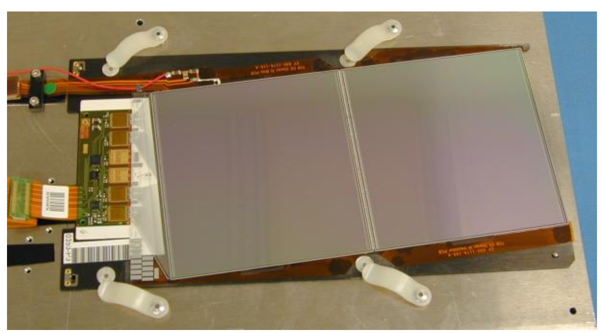


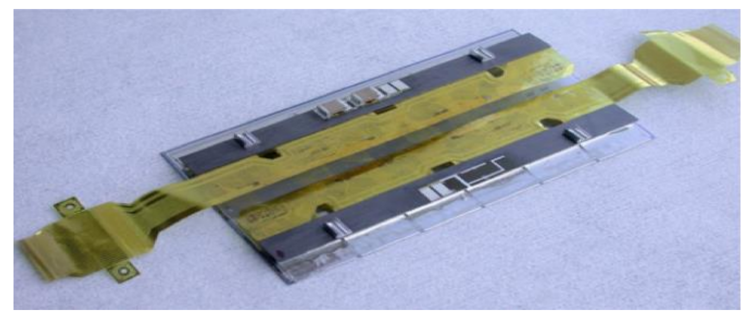




Homework
– who is who?

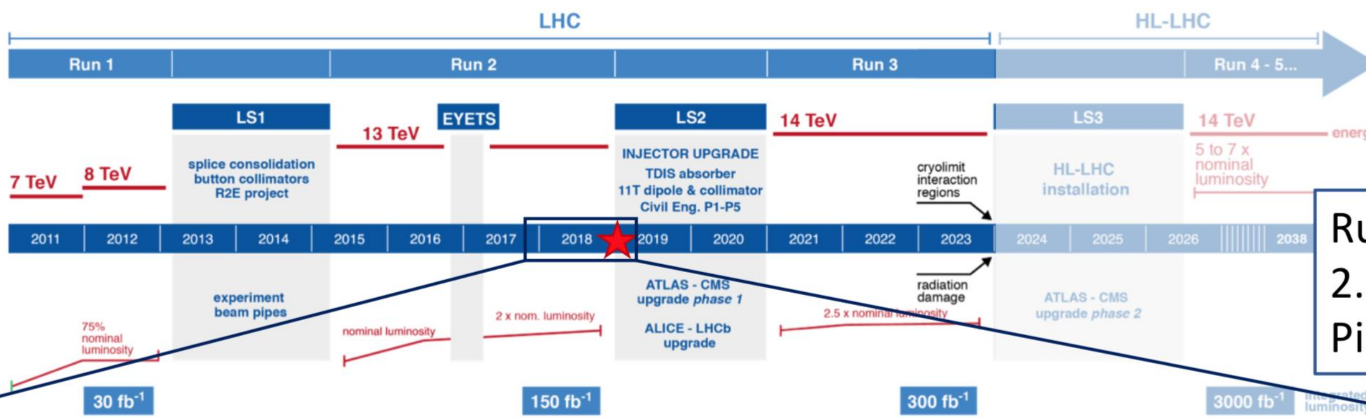




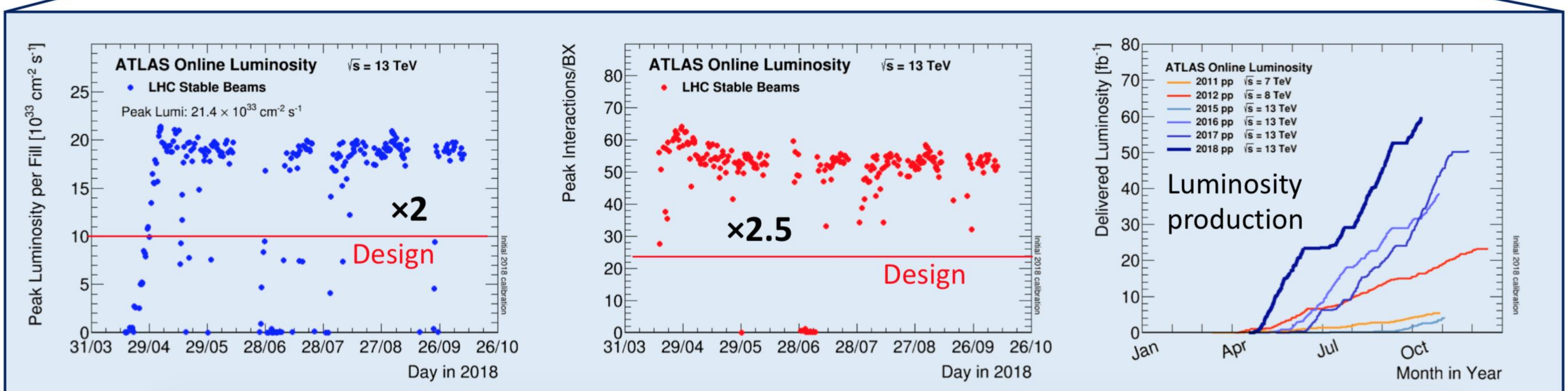


The new normal

LHC Roadmap and Performance in 2018

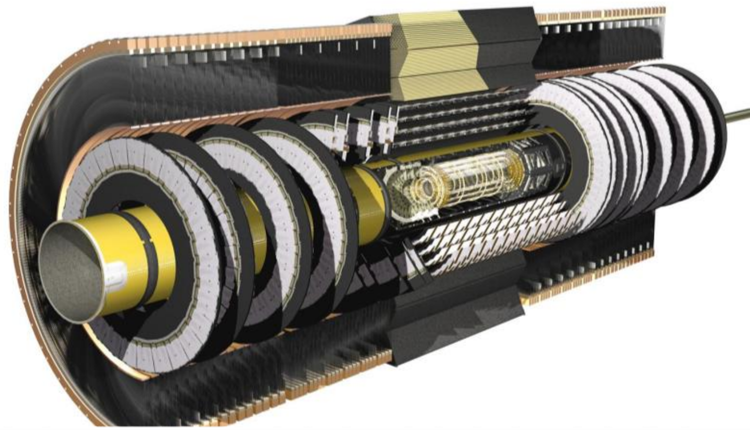


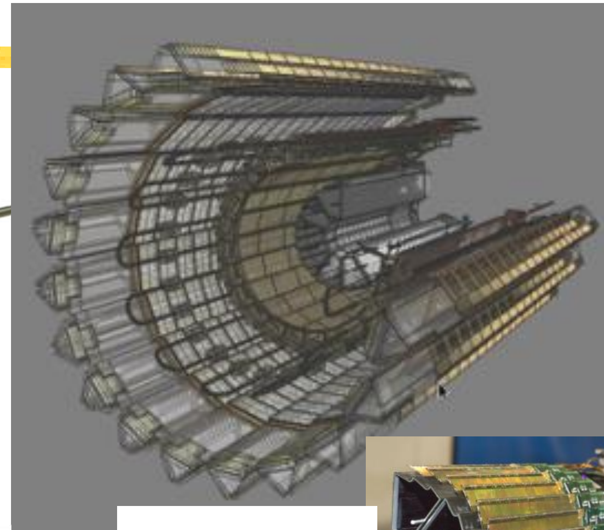
Run 3 prediction:
$2.5 \times 10^{34}\ cm^{-2}\ s^{-1}$
Pile-up: $\mu = 61.5$

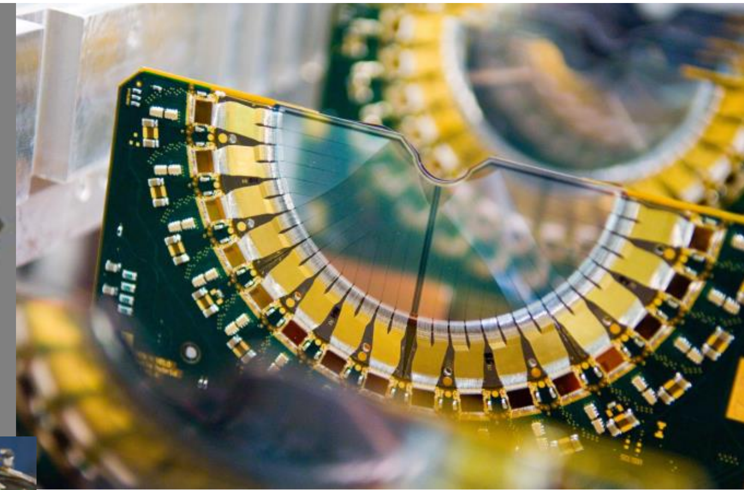


Presented by Kathrin Becker, Satoshi Hasegawa, Ivan Shvetsov,
David Hutchcroft, Luca Bariogli, Benjamin Schwenker

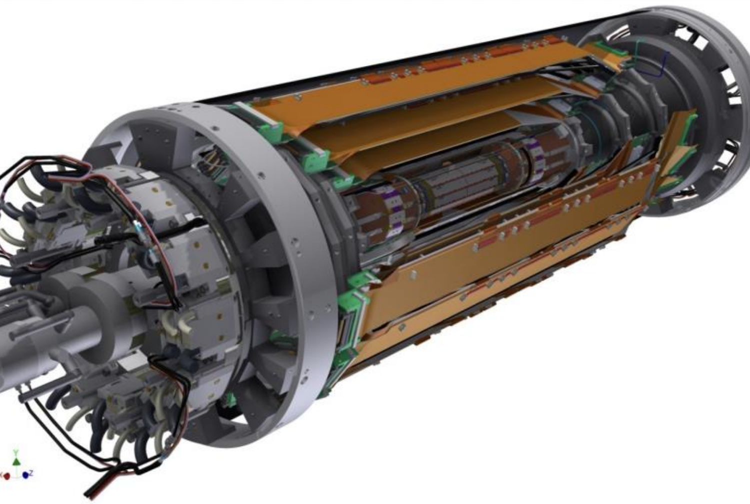
Who is who?

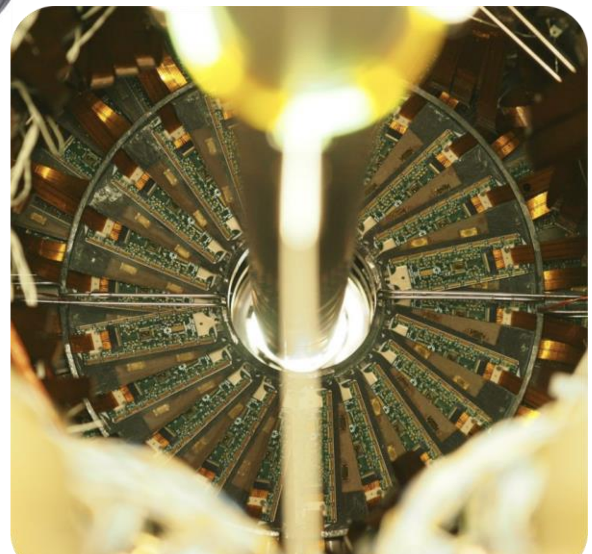






Air flow





Problems are not authorized by the management!

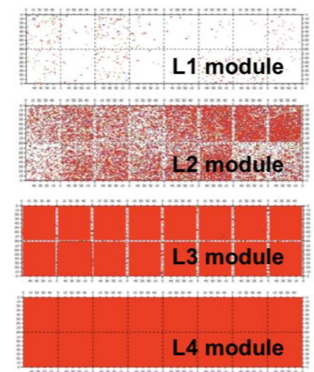
- They exist nevertheless! **Have you confessed all???** Hm??
  - **Basically Everybody: SEU – recovery automated** Good Job
  - ATLAS:
    - Pixel VCSELs on opto-boards die – exchange during LS2
    - Upgrade and unification of readout system – increase bandwidth
    - Mask pixel chips, where redundancy is neede due to bandwidth at high PU (small issue)
  - ALICE:
    - Damage due Beam Loss - the only one at LHC detectors AFAIK
    - Humidity leads to increase of leakage currents up to permanent damage
  - BELLE2 – not a real problem, since according to plan
    - 1/10 equipped and good use of remaining volume by installing BEAST2 sensors (more later)
    - Lost optical connection to ~1/4 of one PXD module

BTW: despite all this – EVERYBODY took fantastic data
No. of working channels despite age good everywhere. Availability is awesome!

Problems are <u>not</u> authorized by the management!

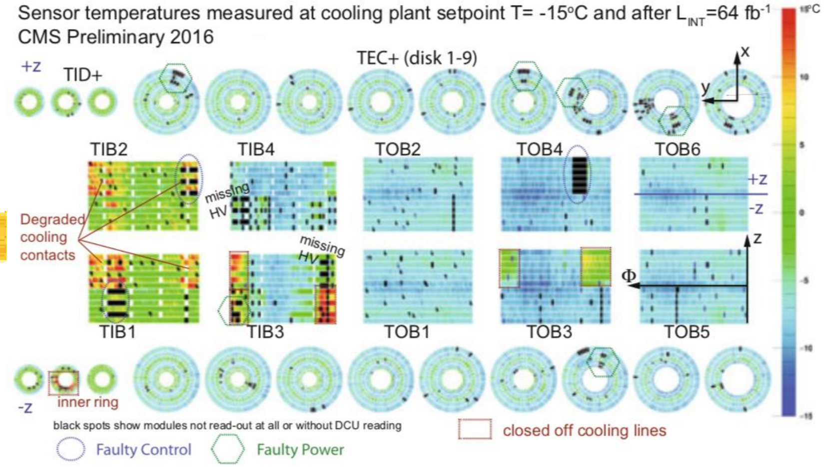
They exist nevertheless! **Have you confessed all???** Hm??

- CMS – interesting year:
  - Dying DC-DC converter during disable cycle – UNDERSTOOD, fix underway
  - Modules with broken DC-DC broke due to HV=ON & LV=OFF
  - SEU in TBM – only recoverable with power cycle (reset line missing)
  - Remaining inefficiencies in Layer 1
    - new L1 with new ROC and TBM during LS2; damaged modules to be replaced
  - CMS Strips fine (minus the well-known uncooled 3%)
    - HIP effect in the permille regime
- LHCb:
  - Beware THE DOUBLE METAL
  - LHCb: "We are fine. Btw. We built a full spare VELO - just in case"
- CT-PPS:
  - Missing cooling for LGADs as UFSD timing detector



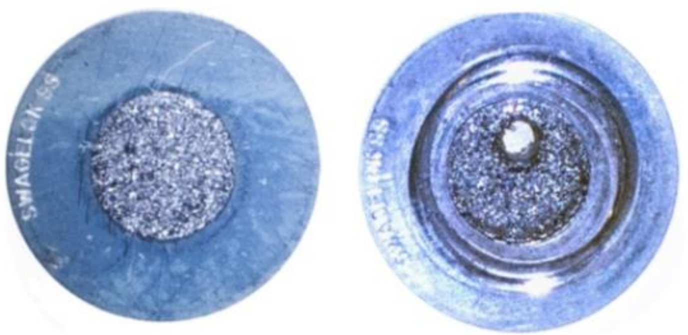
Did I mention? – EVERYBODY took fantastic data

Close to no problems with cooling

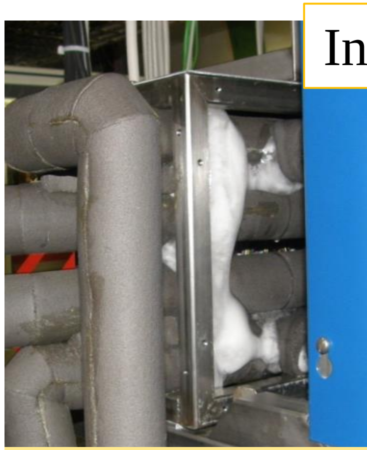


- ATLAS (RUN II):
  - IBL inlet **temperature instabilities, causing problems for the alignment**:
    - too much flow! After flow reduction (orifices added to the pipework) **problem solved**
- CMS TK– over-pressure incident (RUN I)
  - close both sides of loops and warm up
    - HV shorts, leaks, strongly degraded cooling contacts
- CMS (start of RUN II)
  - Ice clogged air pressure valve lines
    - Pipe not impervious to RH from outside air
- ALICE clogged filters (RUN I)
  - Filters 'inside' detector

Before After



Insulation ?!?!



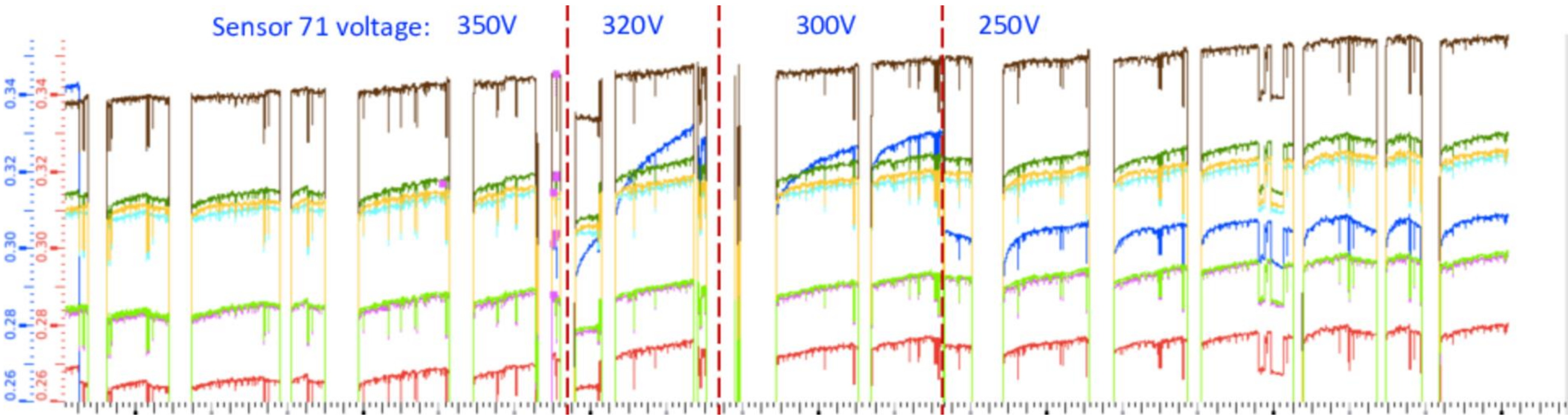
LHCb-Velo system

CMS Tracker system

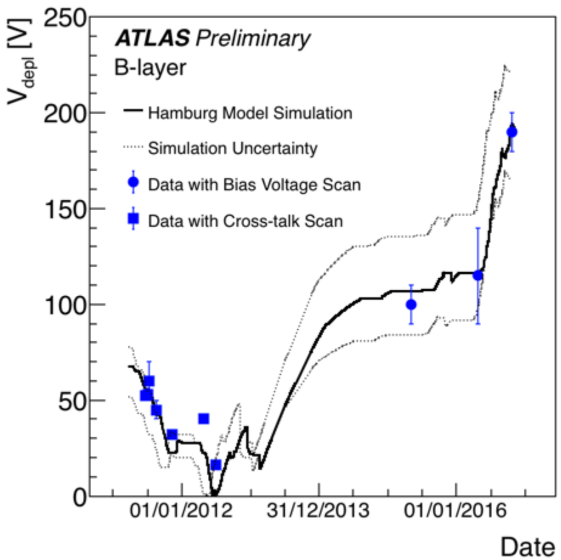
https://indico.cern.ch/event/41288/

Monitoring is crucial

- VELO



Radiation damage exists
We are not inventing it to get new toys!

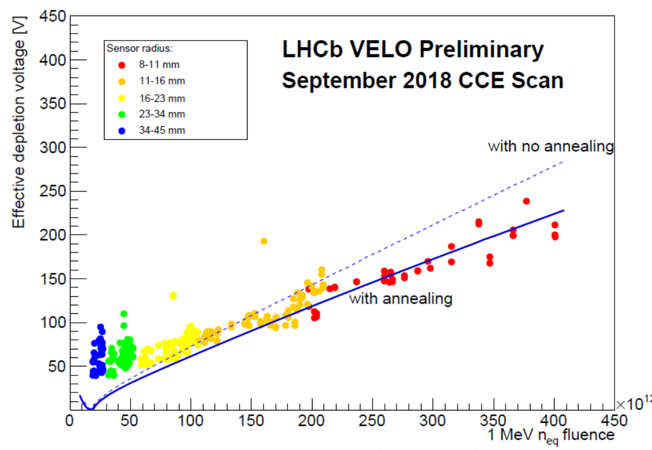


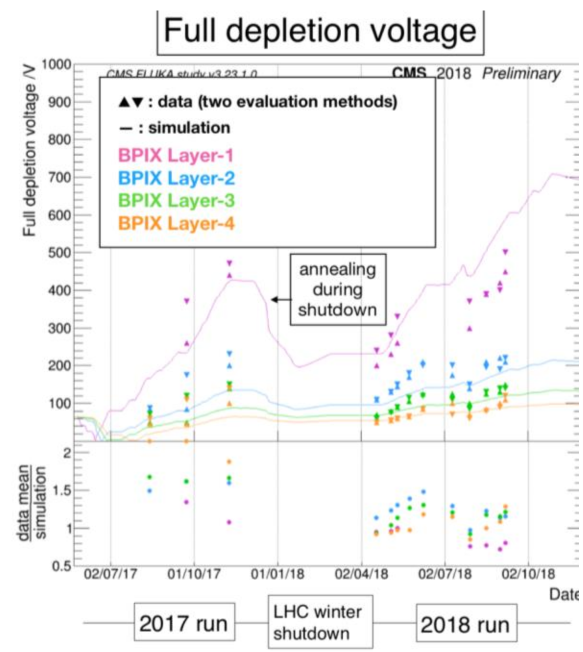
The Hamburg Model rocks

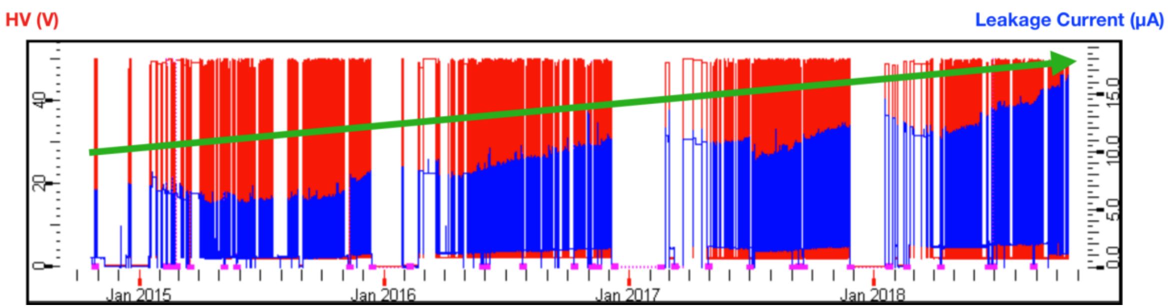
- Good recipe when to increase bias voltages

And even better, GianLuigi promised for PH2

- Parametric description of operation parameters (signal, trapping, current) as a function of fluence and temperature.



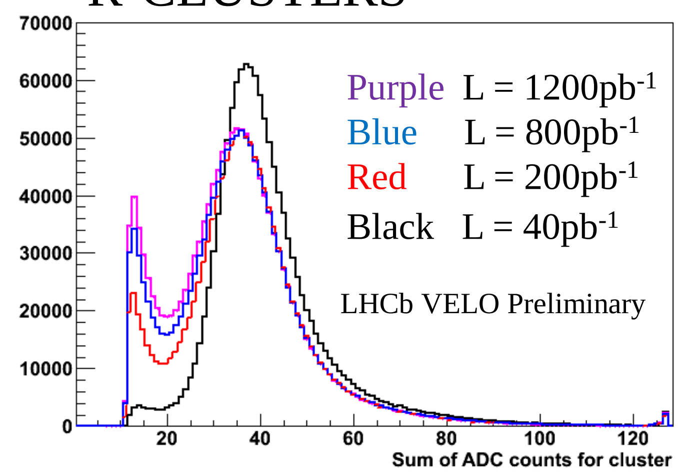


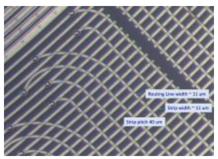


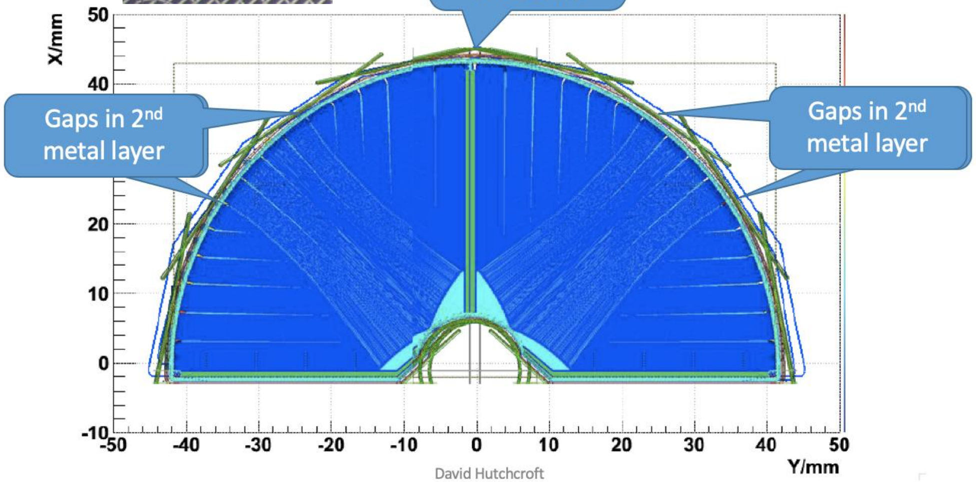
Presented by David Hutchcroft

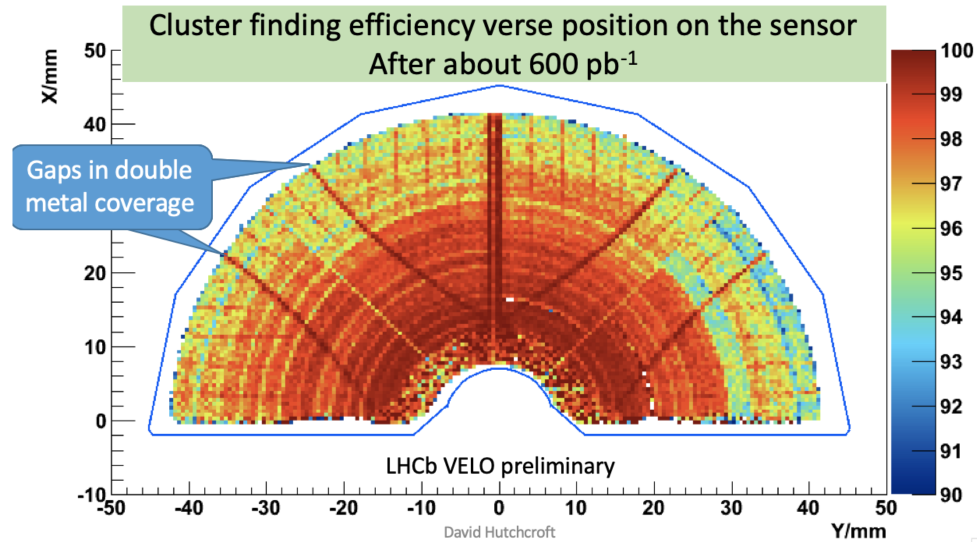
LHCB – be wary about double metal

- One day of David's life in the control room
  - David: "What is this?"
  - The collaboration: "Oh, we don't know. -- Please investigate!"
    - And add the effect to the data simulation!
  - Use fake R-clusters to tune SIM.









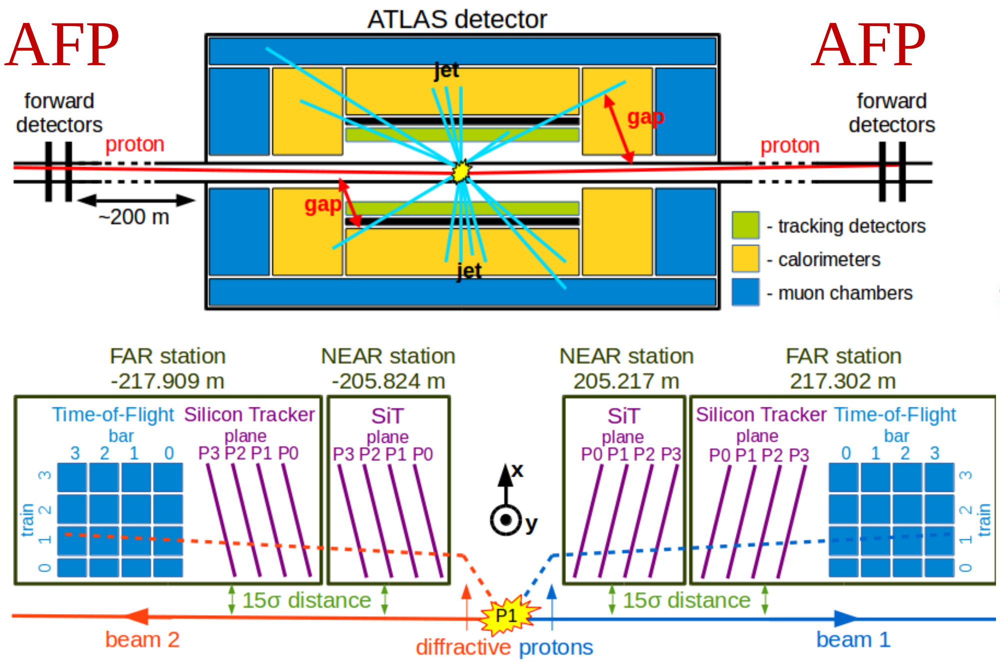
AFP & CT-PPS – do you remember what this stands for?

Paula Agnieszka Erland & Maria Obertino

- ATLAS Forward Proton Detectors
- CMS-TOTEM Precision Proton Spectrometer
- Both in Roman pots ~ 200m away from main experiment
- Both: timing & tracking stations

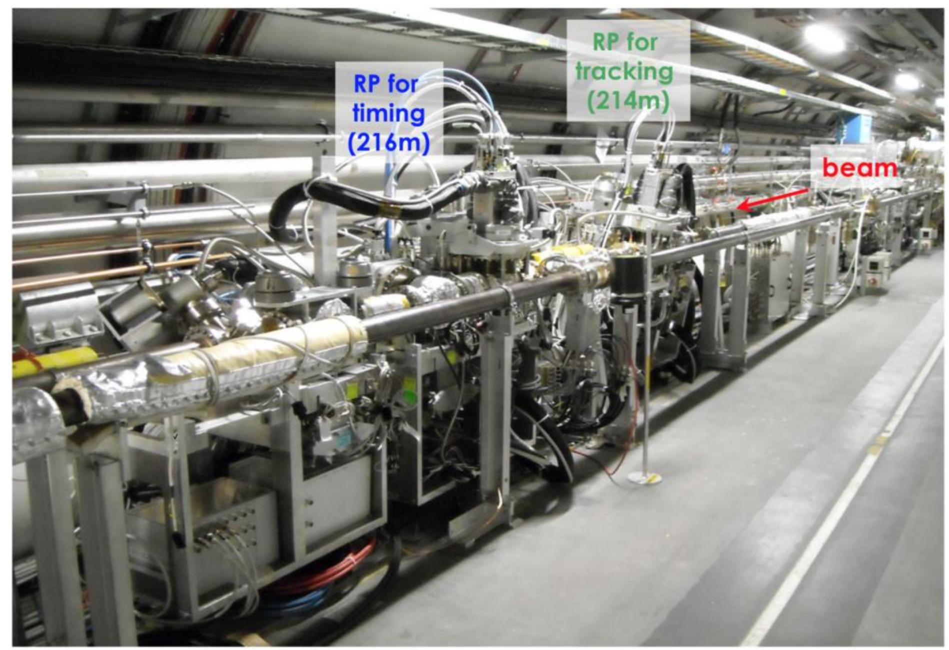
And both run stable and continuous

AFP



CMS-TOTEM

RP for tracking (220m)



Paula Agnieszka Erland & Maria Obertino

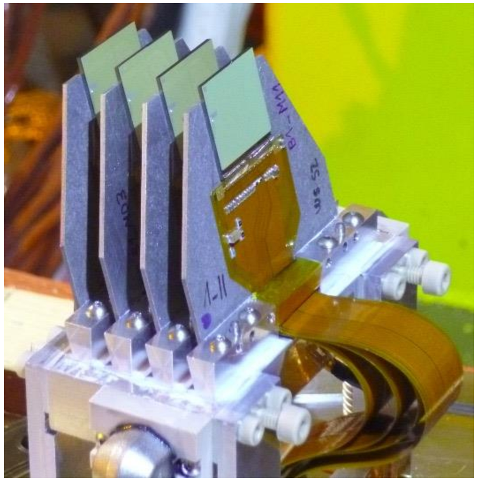
AFP & CT-PPS

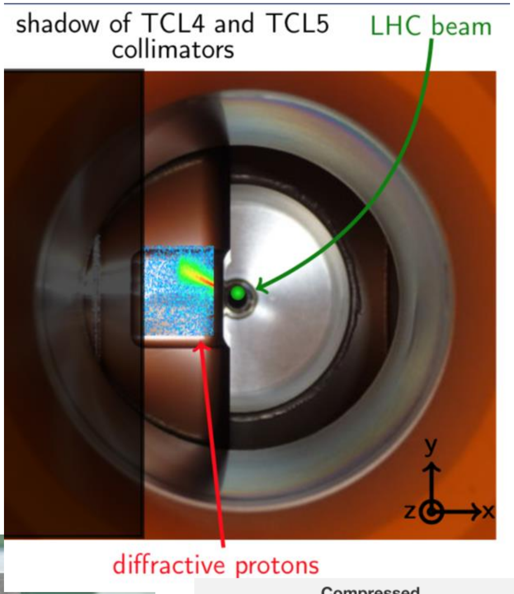
Tracking station

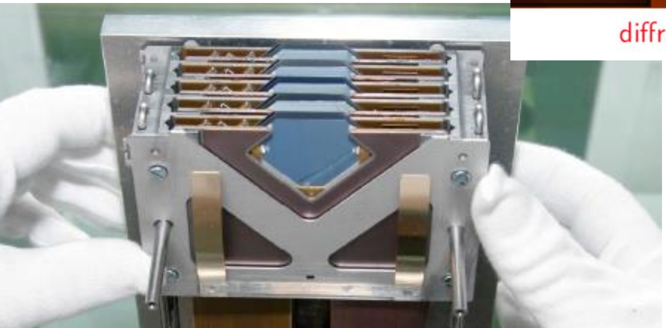
- Highly non-uniform irradiation
- 3 D silicon sensor
- Edgeless
- Standard ATLAS or CMS pixel ROCs

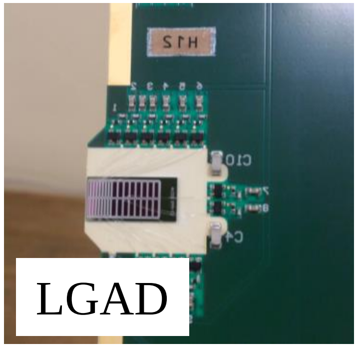
Timing Station TOF

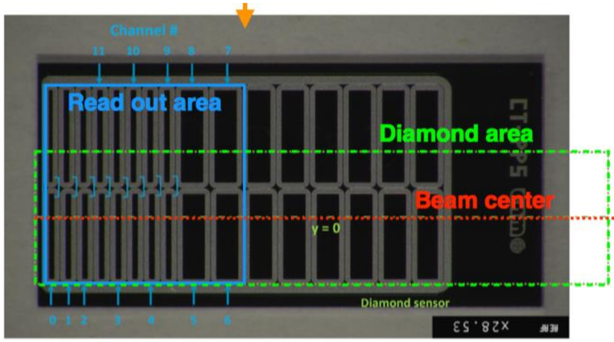
- To reduce background
- AFP: Quartz, Cherenkov, MCP-PM
- CMS: sc diamonds (double diamond – same amplifier)
- CMS: LGADs (1[ST] in HEP) but not cooled ☹

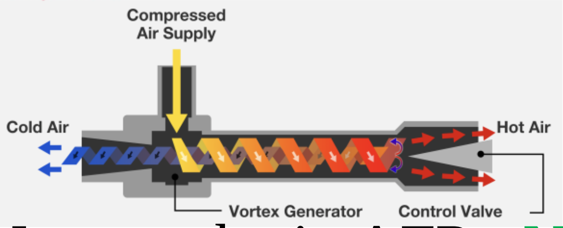




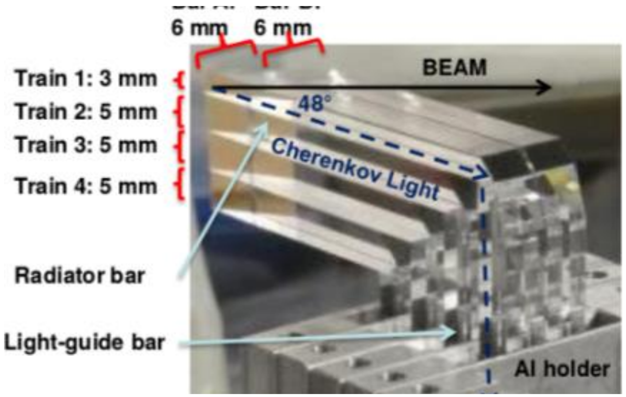








Vortex tube in AFP - NEW



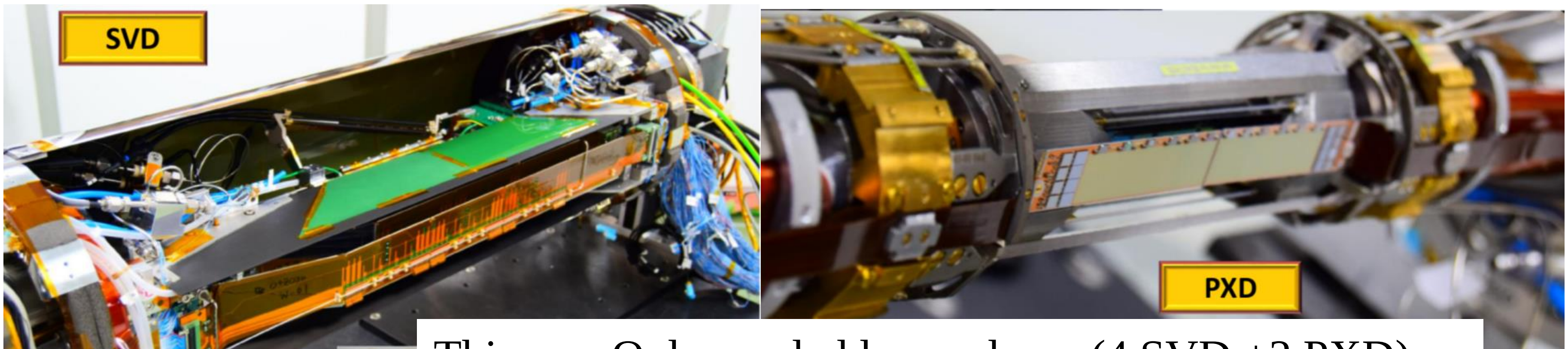
Micro-channel plate photomultiplier

NEW

Brought to you by Benjamin Schwenker

BELLE 2 – pilot - First deployed DEPFET

- PXD and SVD fully integrated in Belle 2 DAQ, run control and HV control
- SVD key operation features like S/N and cluster timing are within or exceeding TDR expectation
- PXD stable operation of 4 large, thinned sensors at low threshold (<1000e-), excellent S/N ratio

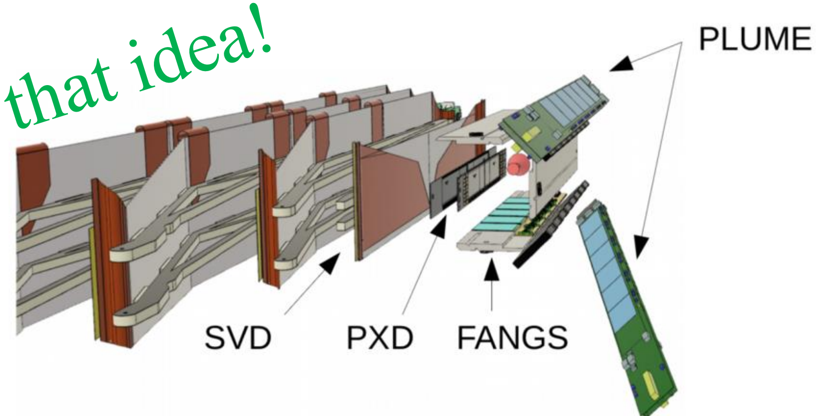


This run: Only one ladder per layer (4 SVD +2 PXD)

BEAST2 sensors **to understand the environment** :

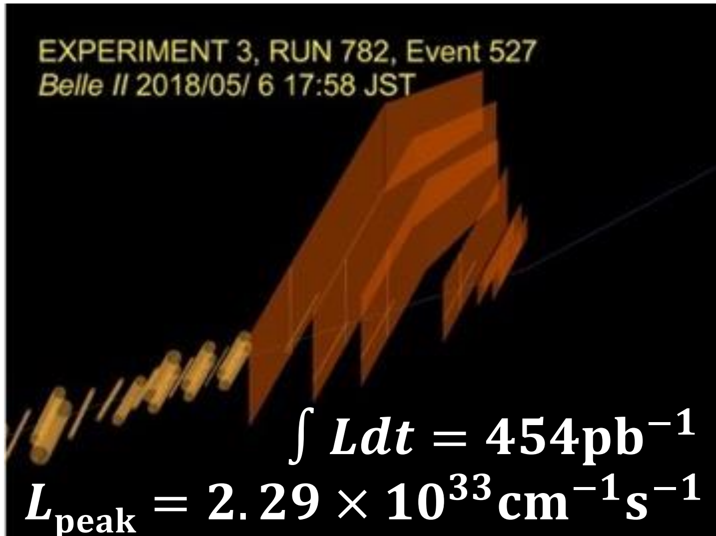
- FANGS: Hybrid silicon pixel detector with FE-I4 front end (ATLAS)
- CLAWS: Plastic scintillators with SiPM readout (ILC)
- PLUME: Double sided CMOS pixel detector (STAR)
- Diamond sensors for total ionizing dose measurement and for beam abort system (not shown)
- 3He detector for thermal neutron flux measurement (not shown)
- TPC for fast neutron flux measurement (not shown)

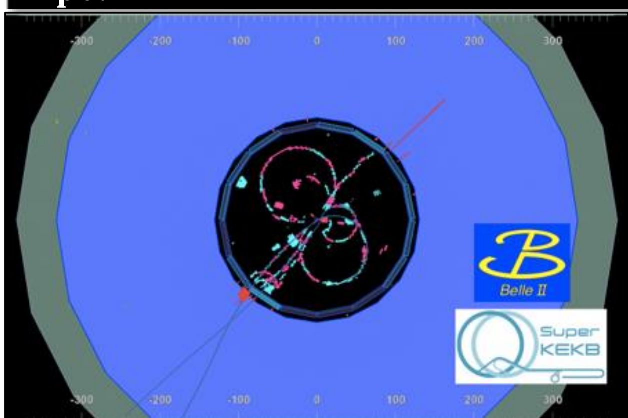
I like that idea!

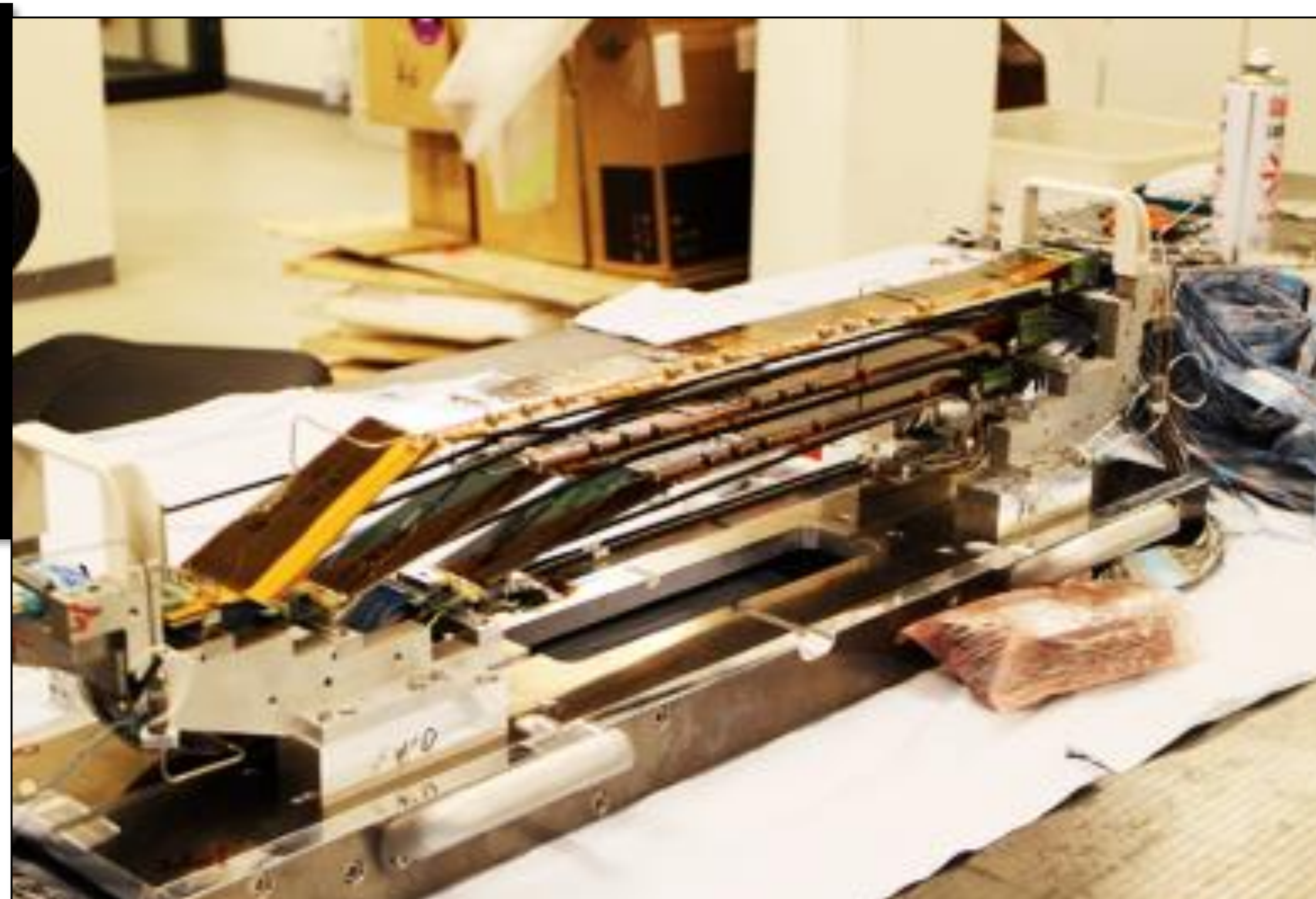


One more on Belle2 pilot

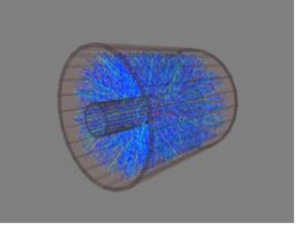
Insertion into Belle II in mid. Nov 2017



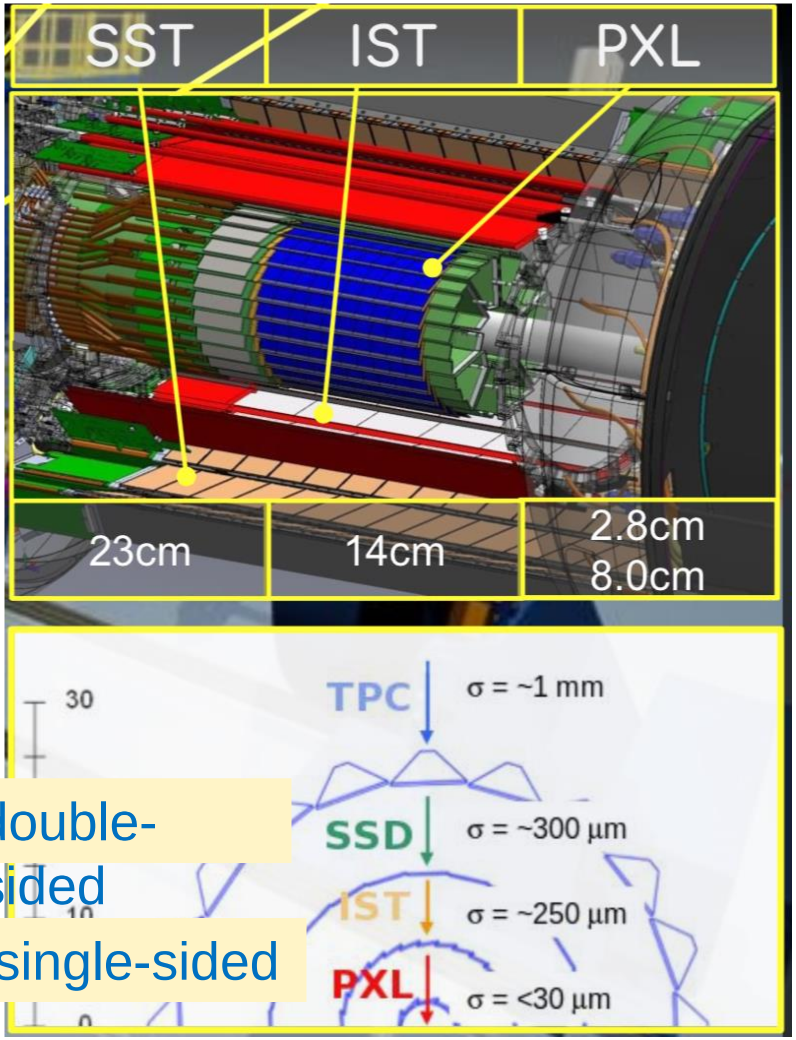




Brought to you by Jason Webb



STAR – Heavy Flavor Tracker

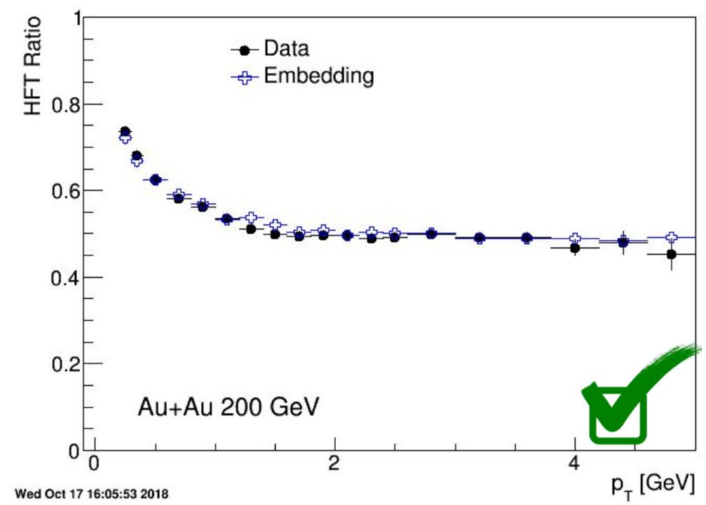


double-sided

single-sided

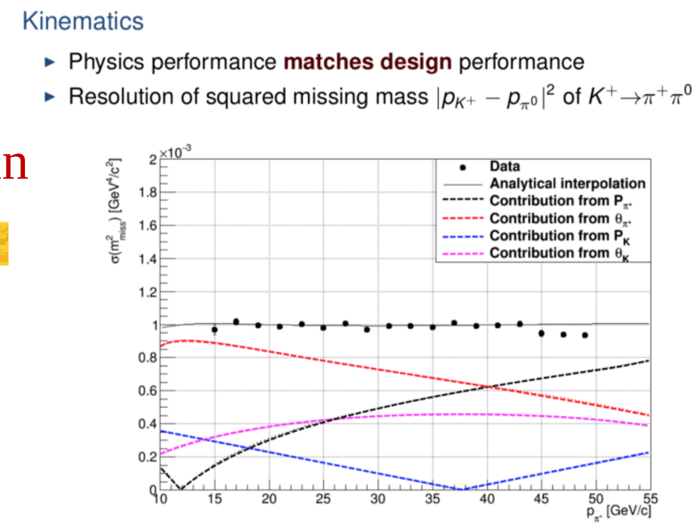
PXL: Two layers of MAPS- ULTIMATE

- Charm Physics
- Very lively walk-through to understand that tracking efficiencies requires
  - detailed simulations,
  - accounting for the sources of pileup background,
  - the misalignments of the detectors,
  - understanding of the uncertainties in our calibrations



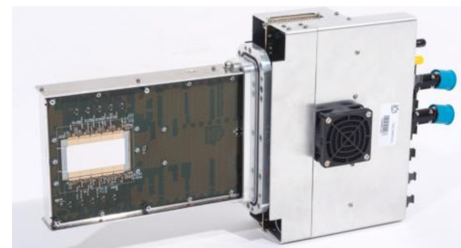
Something special
NA62-Gigatracker

By Matthieu Perrin-Terrin

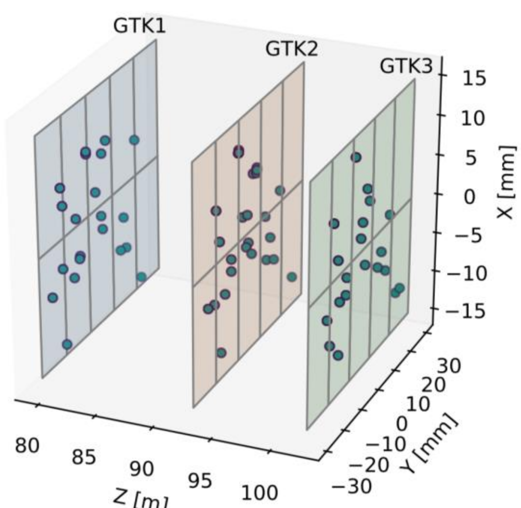


- B($K^+ \to \pi^+ \nu \bar{\nu}$) with 10% precision
- N62: decay in flight technique at CERN-SPS
  - Requires beam spectrometer
- Beam Rate 0.8-1GHz – **GIGA**
- Self-triggered
- Time res <200ps
- Peaking time 5ns
- In beam pipe (vacuum)
- On micro-channel cooling

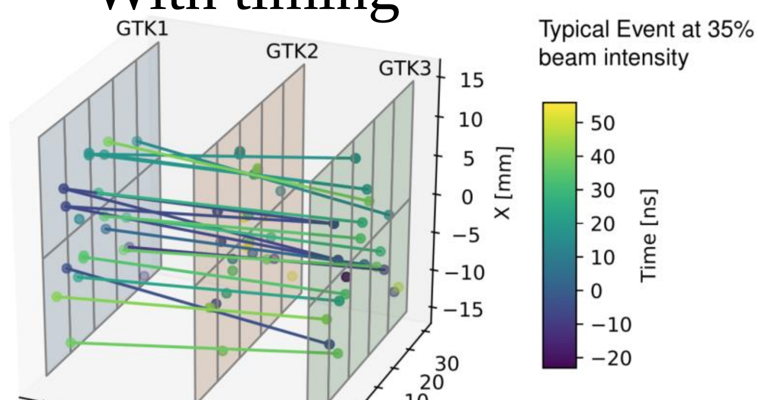
- Few noisy/dead pixels (< 100 per station)
- Hit res 130 ps
- Track res 75 ps



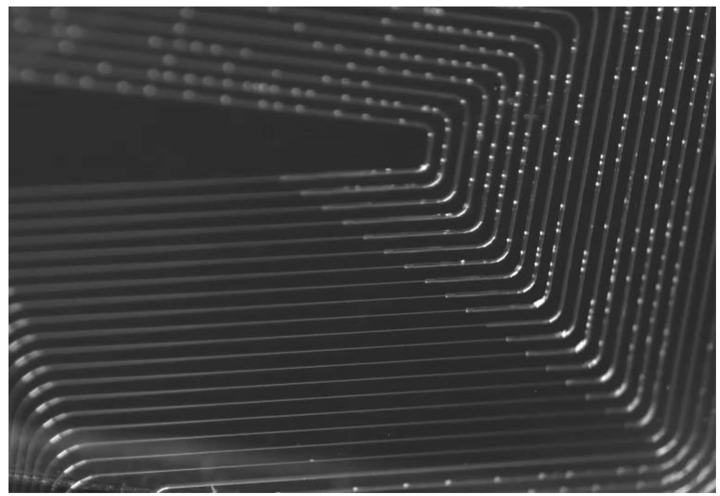
Without timing



With timing



Is it 4D or 5D tracking?



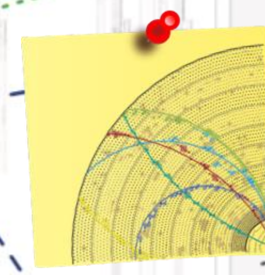
Nicola de Filipis - CMS

Goetz Gayken - ATLAS

Iouri Belikov - ALICE

Renata Kopecna - LHCb

Bianca Scavino – BELLE II



Tracking Highlights

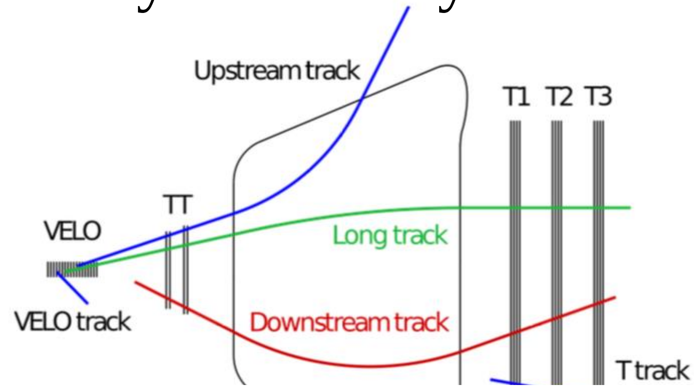
CMS, ATLAS, ALICE, LHCB, BELLE II

Very simplified, therefore probably wrong and clearly incomplete

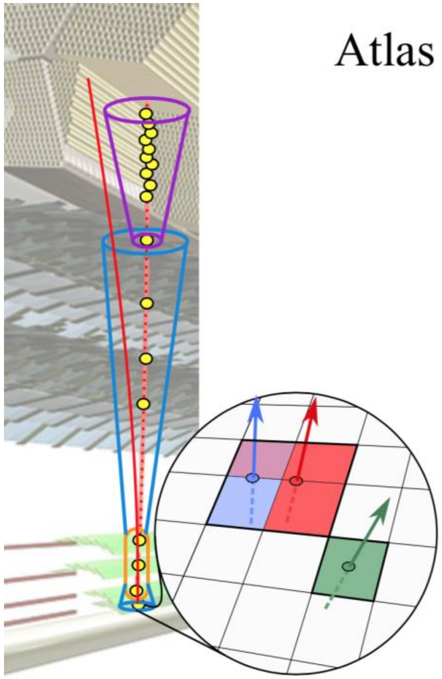
- We align and calibrate
- Hits, Cluster
- We do tracking in a sequence
  - Maybe iterative
  1. Track Finding
     - Pattern recognition
     - Kalman
     - Cellular Automaton
     - Legendre
     - Use constraints:
       - Geometry, beam spot
       - Kinematic, Mass
  2. Track Fitting
     - Kalman
     - Gaussian sum
     - Deterministic annealing
     - Elastic arm algo
  3. Vertex and 2nd vertex identification

- We can go
  - Inside → Out
  - Outside → In
  - Both
- Seeding
- We clean in between
- Neural network can help
- GPUs seem to help
  - ALICE GPU:
    - 2.5 – 5 times faster
    - **1 GPU** replaces **~40 CPU** cores
- Silicon only, +TPC+TRD, +Drift, +TRT
- Different environment
- ~PU=5 Pb Pb; 60 pp; 200 pp
- b-tagging
- Long lived particles (*Ks*, Λ)

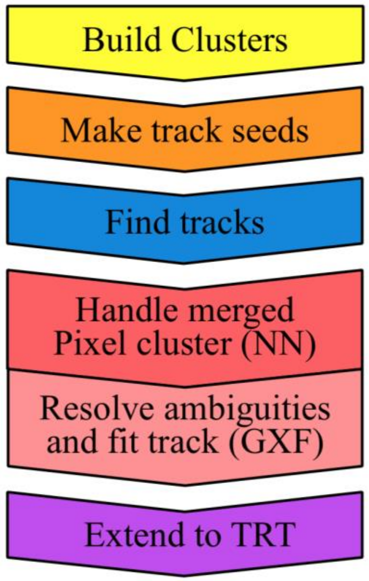
LHCb actively finds everywhere



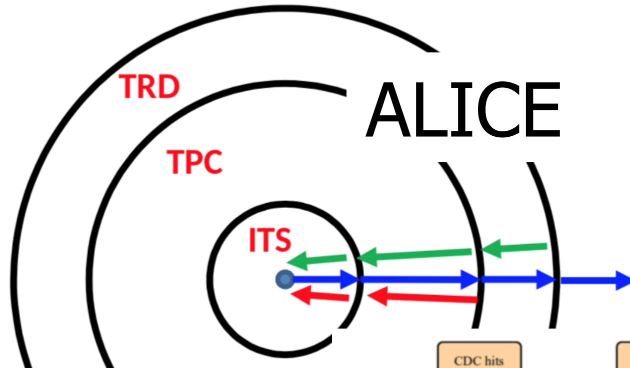
e.g. Downstream track for long lived particles (Ks, Λ)

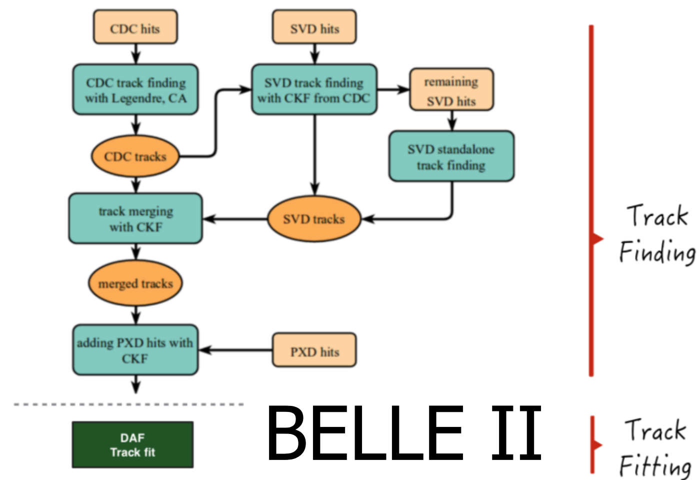


Atlas ID track reconstruction:



ATLAS, CMS

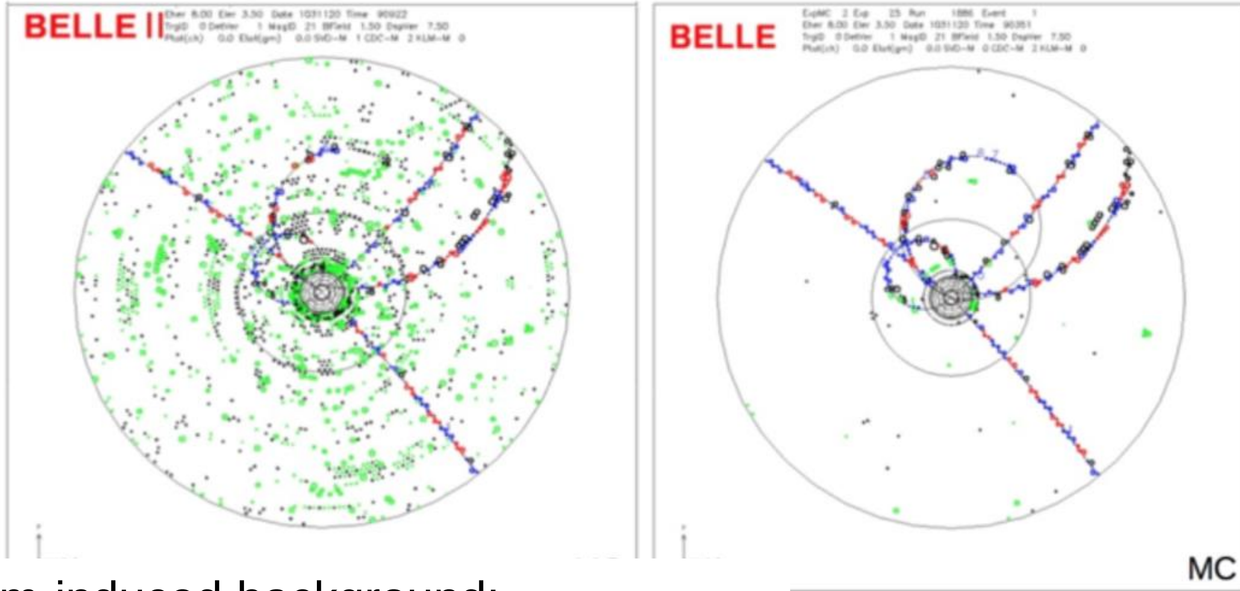




BELLE II

With the ALICE upgrade (**after LS2**) and continuous readout, z position of tracks in TPC not fixed anymore.
➔ New ALICE ITS will then seed inside out

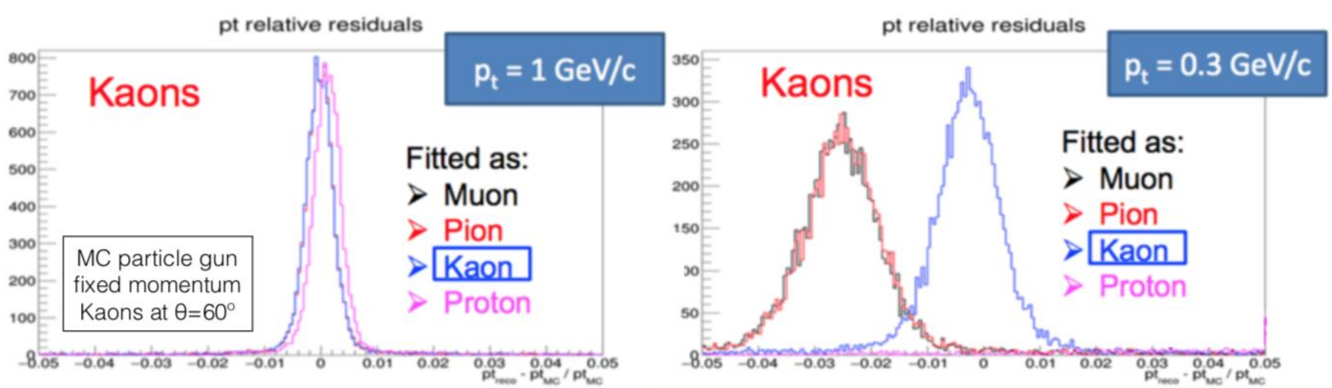
Belle II



High occupancy of the beam-induced background:
11 tracks ➔ few **hundreds** signal hits vs. **10^4 background** hits

- Deterministic Annealing Filter with 3 different mass hypotheses in parallel (π, K, p)

Always uses all mass hypotheses



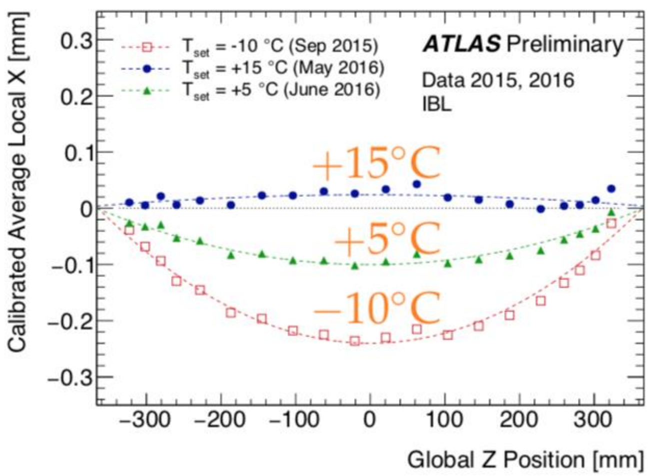
Alignment - ATLAS

Alignment

Every 10 minutes

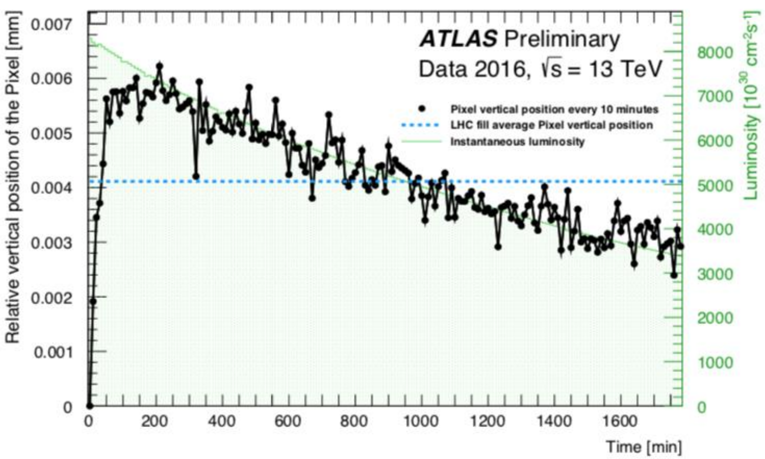
- based on global χ^2 minimisation of hit-to-track residuals,
- performed at different levels:
  sub-detector $\rightarrow$ layers $\rightarrow$ modules.
- Since run 2, alignment updates ($\sim$ every 10 min):

IBL bowing correction



$\mathcal{O}(100\,\mu m)$

Pixel y-position

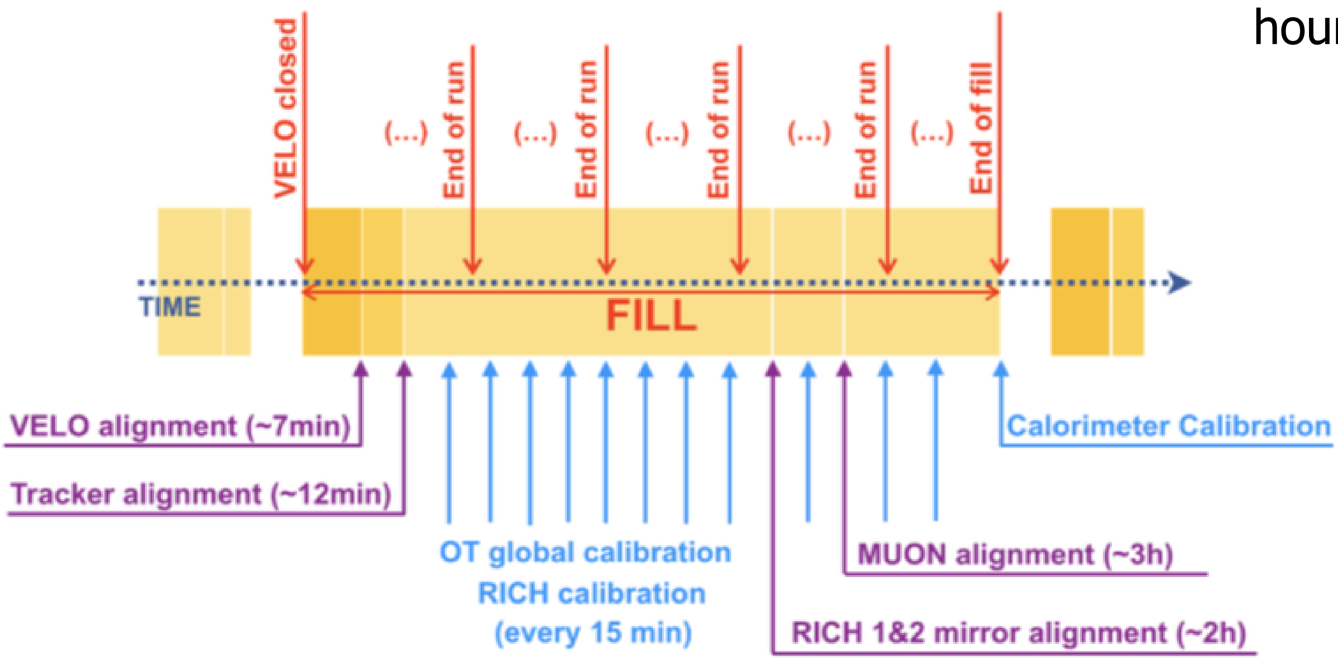


$\mathcal{O}(5\,\mu m)$

Alignment and calibration – example LHCb

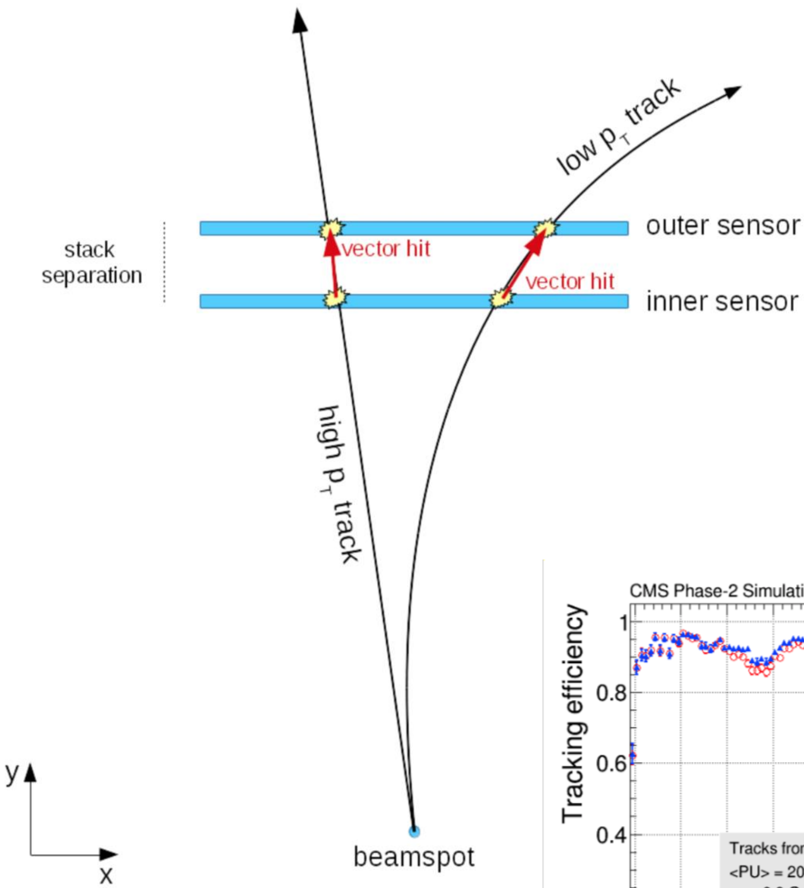
- Timely, iterative and automatic
- Real time alignment
- Same conditions online and offline ensured

⌘ Without any performance loss, analyses can start already 24 hours after data-taking

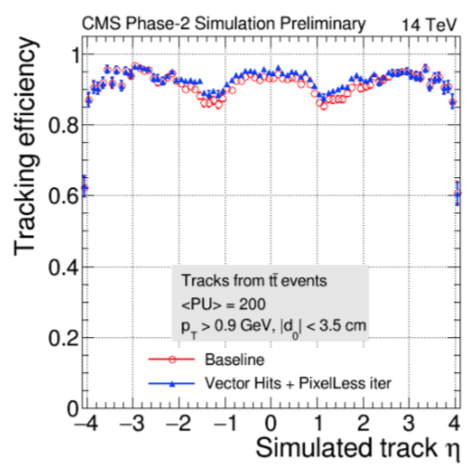


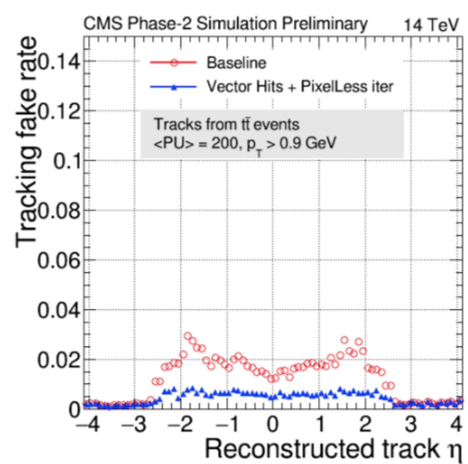
(...) - time needed for both a data accumulation and running the task

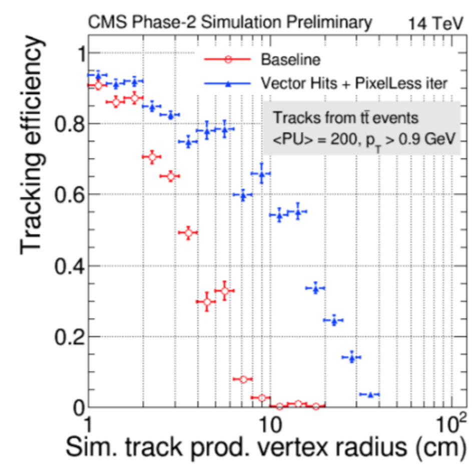
Example CMS – Phase II



- Closely spaced modules (~mm)
- ➔ vector hits in each layer
- Reduces combinatorics
  - DIRECTION
- First very crude algo trial
  - Reduced fake rate significantly
  - Extends production radius







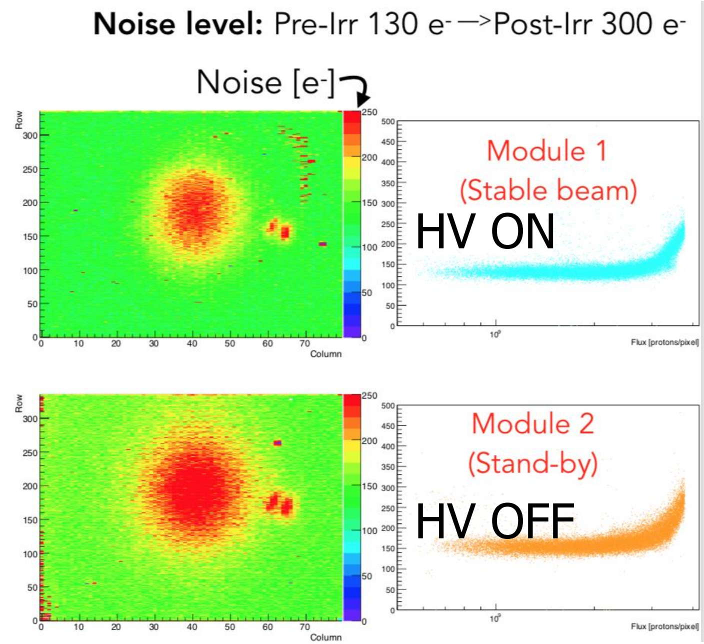
Nice picture of a radiation worker figure

We withstand anything

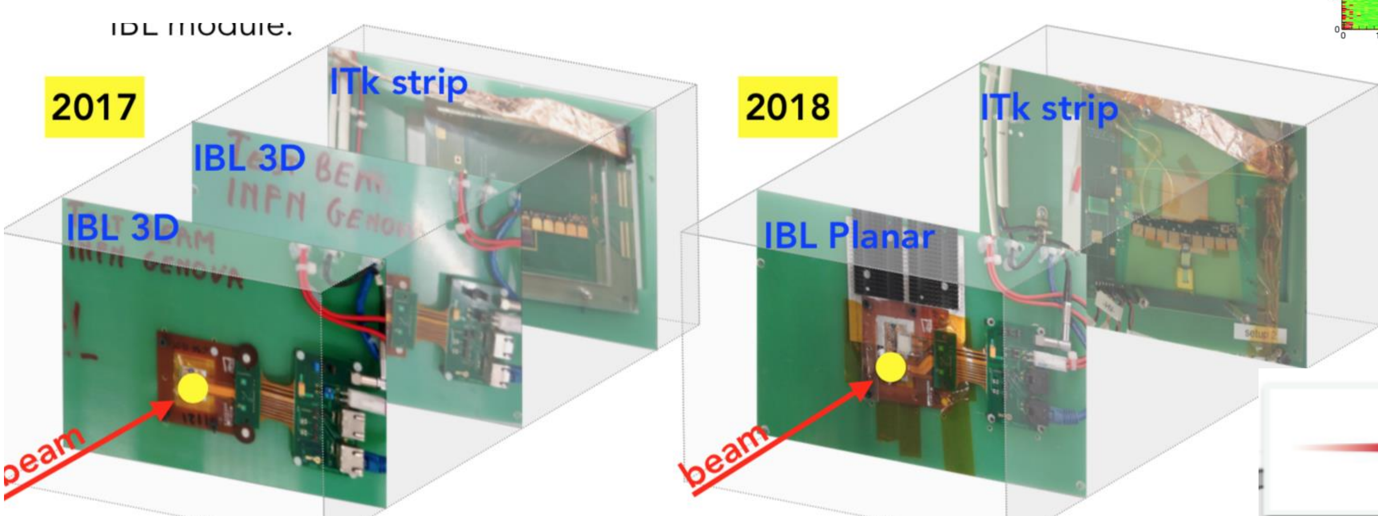
Radiation hardness

CMS, please learn from ATLAS

- **Applause, ATLAS started beam loss tests**
  - 3D pixel, planar pixel, strips
    - not yet with RD53A
- At HiRadMat: High intensity pulsed 440GeV proton beam from SPS
  - 10^{11} protons; beam spot $\leq$2mm
- My personal 2 cents: You must do this with a homogenous coverage, as you expect in reality
  - You clearly show the worst case & damage



Noise increase



HiRadMat
High-Radiation to Materials

On Monday, I heard RD50 and RD42 are dividing the world

RD50

RD50 does silicon

Looks like, you are sharing quite a bit

RD42

RD50 does diamond

And where can I order sapphire detectors??

RD50 & RD42 – one simple slide

- **These RD collaborations are invaluable!**
  - THANK YOU
  - for providing unbiased results on many many fronts!
  - for providing test benches and facilities!

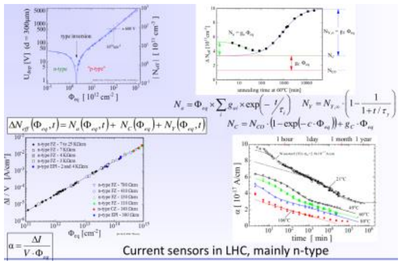
- Too many things - **I give up** to summarize!
  - Whenever you see a slide about a rad tolerant detector, mind either RD50 or RD42 provided the initial recipe

RD50 –

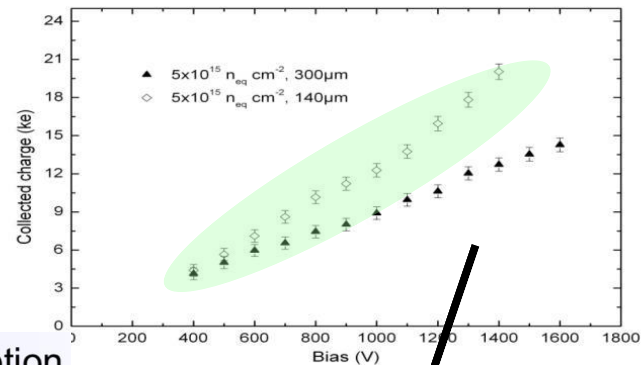
Summarizes and brought to you by Gianluigi Casse
Obviously, large overlap with work inside experiment collab.

on a second thought, I do not like to give up ☺

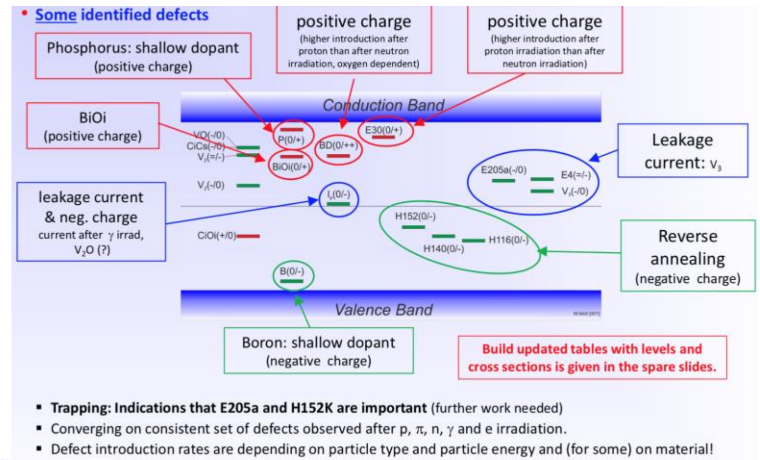
we all know it



amplification

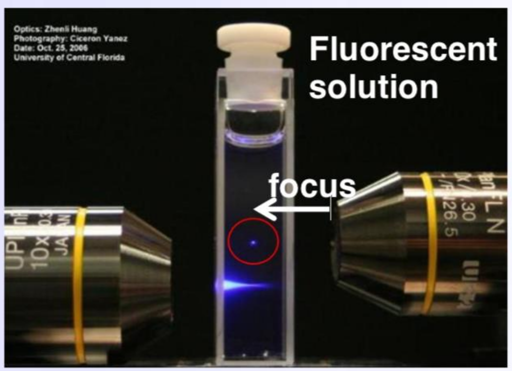


Map all defects

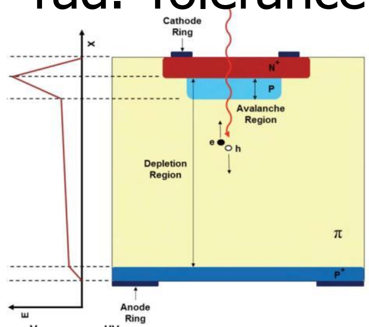


Interesting

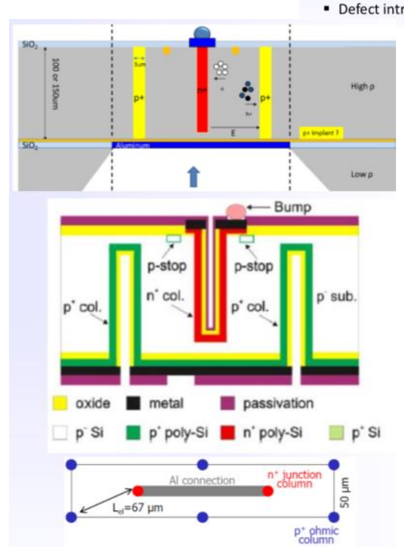
TPA: Two Photon Absorption



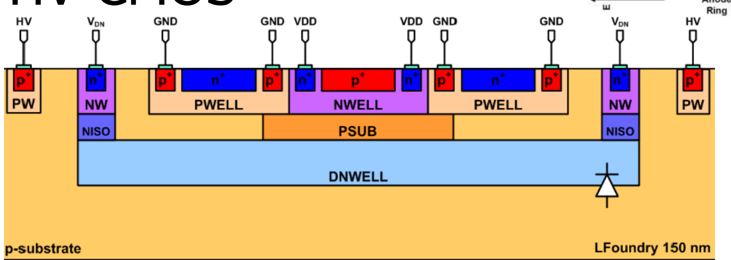
LGAD and its rad. Tolerance



Heard of 3D sensors?



HV-CMOS

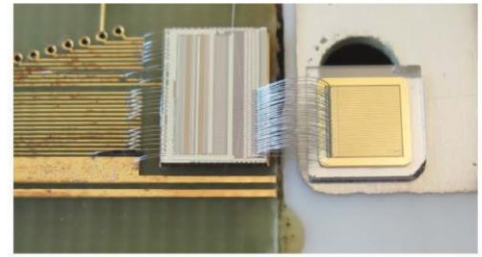


Now, up to rad tolerance studies to 10^{17} n_{eq}/cm^2

Interesting news/ideas about LGAD - later

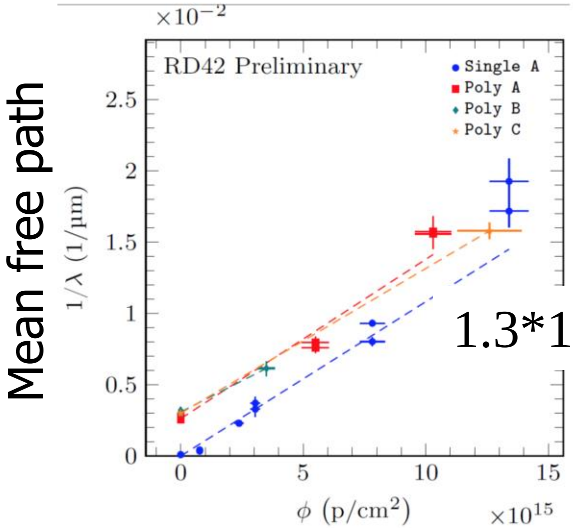
Diamonds are Harris Kagan's best friends

And … RD42 in one slide

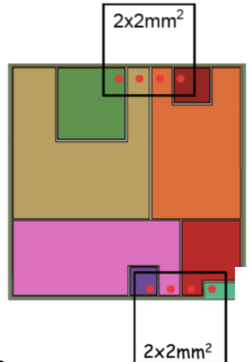


sCVD diamond with strip metalisation and amplifier

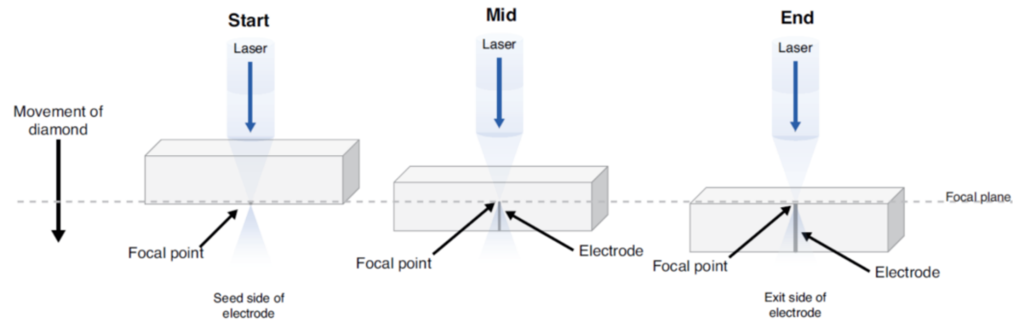
Diamonds are radiation hard



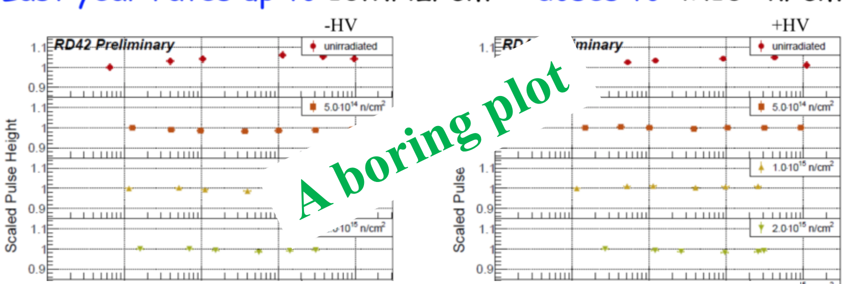
$1.3*10^{16}$ p/cm²



For BCM:
some dynamic range into sensor design
- pad sizes from 1mm² -32mm² work well



Last year rates up to 10MHz/cm² + doses to $4x10^{15}$n/cm²

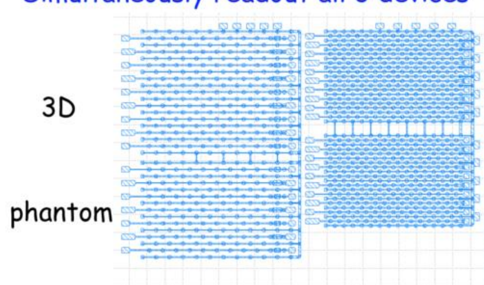


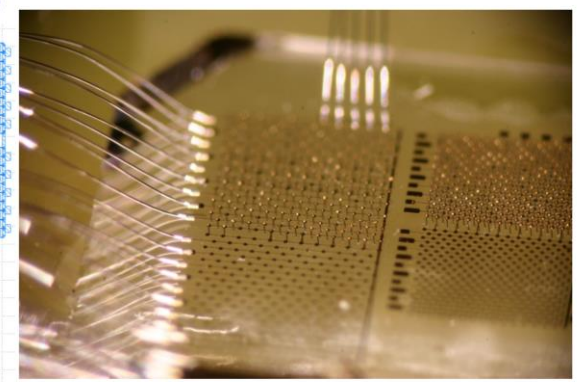
No rate dependence seen
-- Polarization was only at surface

Going 3D

All work as expected; just tested after irrad@3.5x10¹⁵ p/cm²

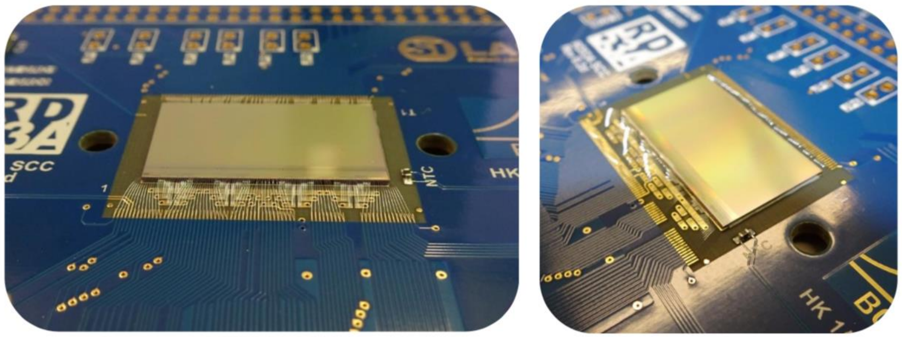
Simultaneously readout all 3 devices





Next - irradiation up to 10^{17} p/cm²

I'm from CMS and say, also in the name of ATLAS, THANK YOU RD53



The RD53A chip

- Size: 20 x 11.8mm^2 (half size of production chip)
- 400 columns x 192 rows (50x50 μm^2 pixels)

First 12" wafers at CERN with RD53A 4

- 65nm pixel ROC for ATLAS and CMS Phase 2
- RD53A test chip in hand
  - WORKS
  - Unlocks sensor R&D
- rad tolerance up to 0.5GRad
  - Probably higher

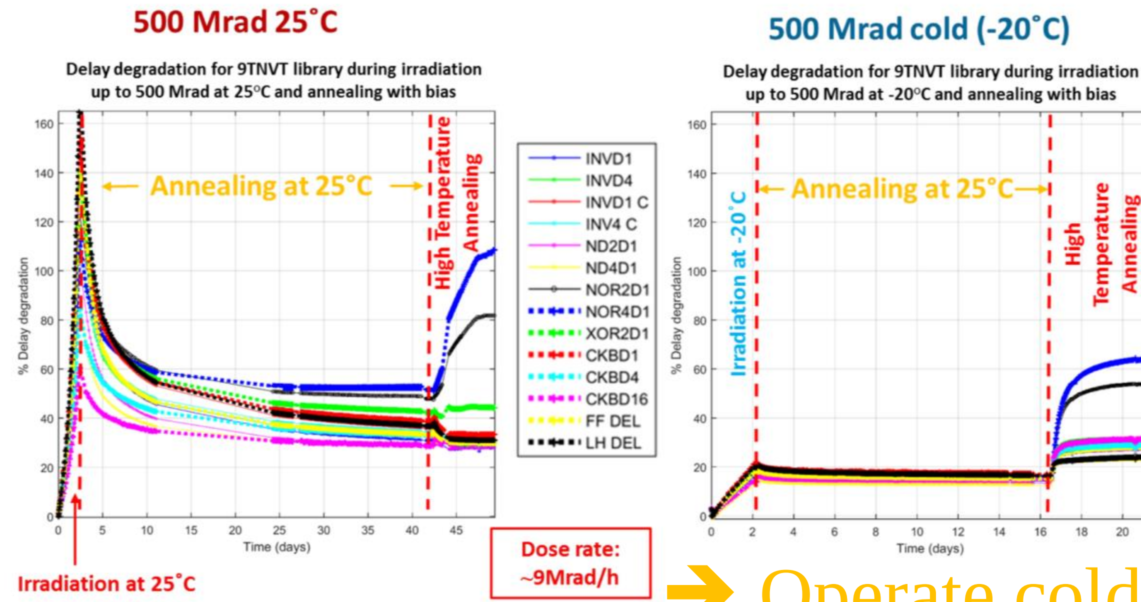
Excellent JOB!

RD53 – radiation tolerance

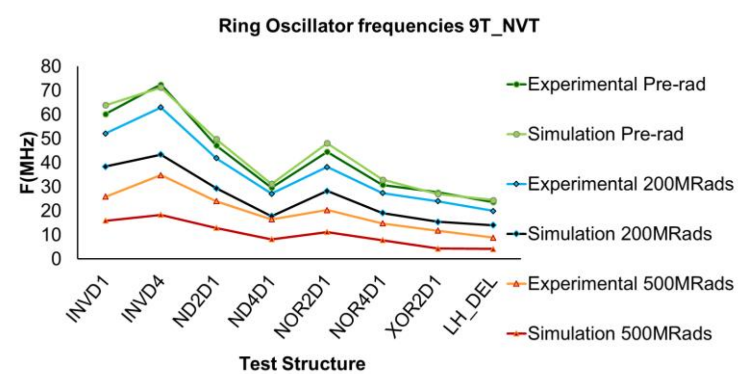
- Radiation damage above 100Mrad
  - Analog: transconductance, Vt shift:
    - Do not use the smallest possible transistors
  - Digital: speed degradation.
- Radiate **cold** reduces damage
- Anneal at RT helps
  - Higher T is detrimental
- Simulation of rad damage works
- No significant change of serial power part after irrad.
- Interesting
  - Trickle configuration might make Tripple Module Redundancy TMR obsolete
  - SEU studies – next step

500 Mrad cold vs room T

Room temperature and high temperature annealing with BIAS



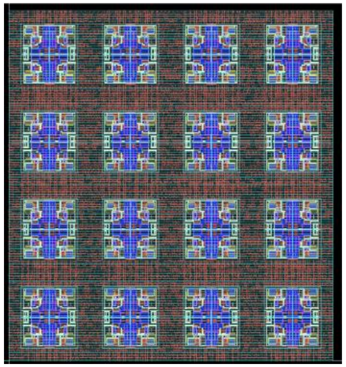
➔ Operate cold

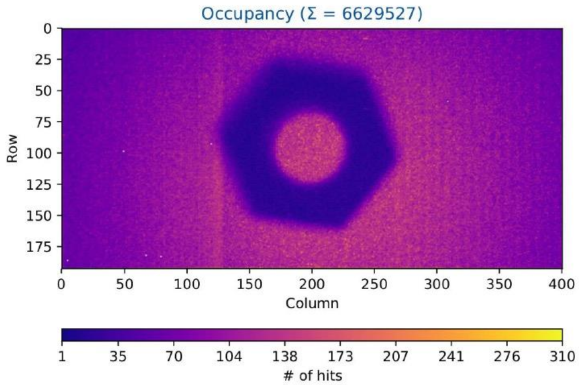


Since we are talking about RD53 already ...

- **RD53:**
  - ~150 members of which ~40% ASIC designers, 24 Institutes from Europe and USA, both from CMS and ATLAS experiments
- **65nm technology** allows to design a smaller pixel capable to sustain extreme particle fluxes and long latencies
  - ~**2500** transistors/pix (50x50 μm^2)
    - Same as in 50x250 μm^2 in 130nm
  - ~2 trans/um2
  - RD53 chip - 50% of area to digital
- RD53A chip has 3 FE
  - '*Unfortunately*' all 3 work well; meaning the management has no easy choice
- Several test-beam DONE (AIDA-2020, ATLAS, CMS) by the sensor community to study planar and 3D silicon sensors. Currently - also irradiated modules being studied.
  - Low thresholds (~800e- to 1200e-) are normally achieved
- Further reading – specs/features:

8x8 pixel core





- Pixel size 50x50um^2; threshold 600e, intime threshold 1200 e, hit loss@ max rate <1%; trigger rate 1MHz, 12.5 us latency; >4 bits Time over Threshold; 1-4 links @ 1.28Gbits/s; 500 Mrad at -15C; Good SEU behaviour; <1W/cm2; T range -40C to +40C;Bias of edge and top "long" pixels; 6-to-4 bit dual slope ToT mapping; 80 MHz ToT counting; ATLAS 2-level trigger scheme TMR for SEU hardening; Power saving ~20%; Design for test scan chains; Optimal data formating and compression Date aggregation between pixel chips (CMS)

Sorry
– out of space

Can we have a better name?

RD53, on the path to the final chip RD53B

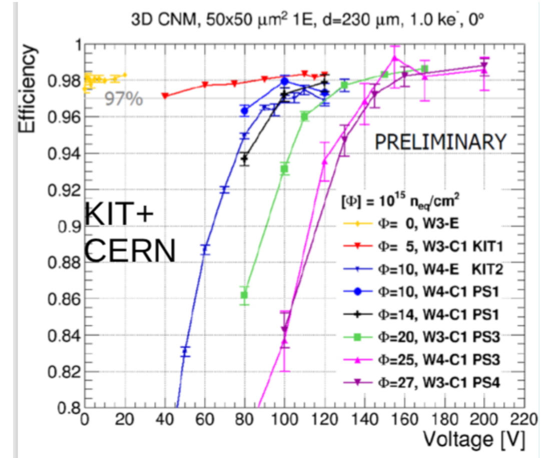
- Common design team
- CMS and ATLAS will get different chips
  - Simply different sizes/geometries – cell matrices
  - This is factorizable – GREAT
  - Both will have all functions - choseable

	ATLAS	CMS
Size	**20x19.2 mm² (400 x 384)**	**22x16.4 mm² (440 x 328)**
Trigger	1 level: 1MHz, 10us 2 level: L0: 4MHz, 10us, L1: 600KHz, 25us	1 level: 750 kHz, 12 us
Distance to the beam → Hit rate	r = 4 cm	r =3 cm
		CMS data aggregation between chips on pixel module
Readout	ATLAS aggregator chip	LpGBT
Serial powering protection	Passive protection PSPP (TBC)	Passive protection

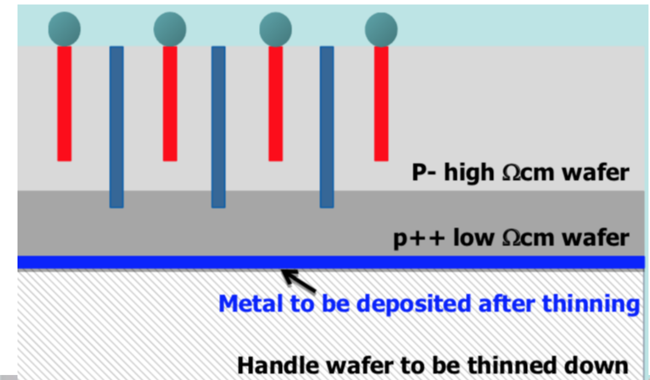
Shown by Guilio Tiziano Forcolin

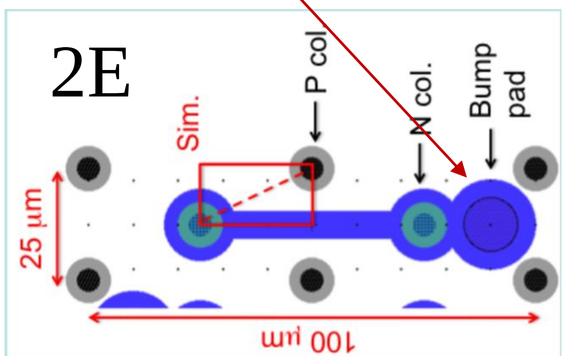
3D – we all know how it works, right?

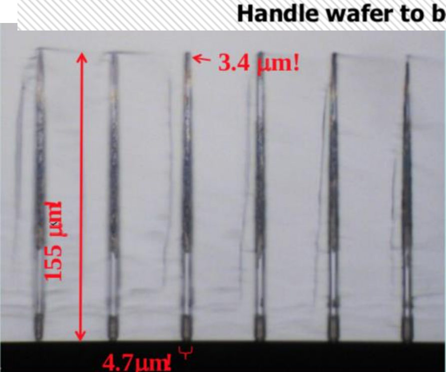
- No 3D zoo anymore. This is what we get:
- Thin **Single Sided Double Column SSDC** on low Ωcm wafer
- Ratio 30:1!
- Edgeless edge possible
- 25x100μm² 2E difficult to manufacture due to constraints on position of bump
- Large sensors challenging

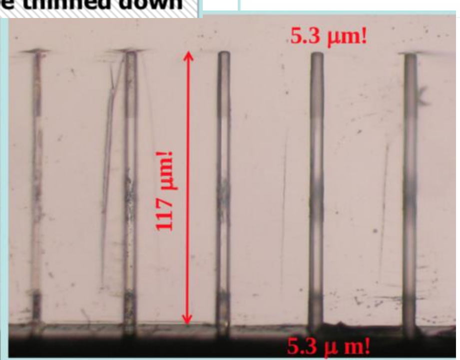


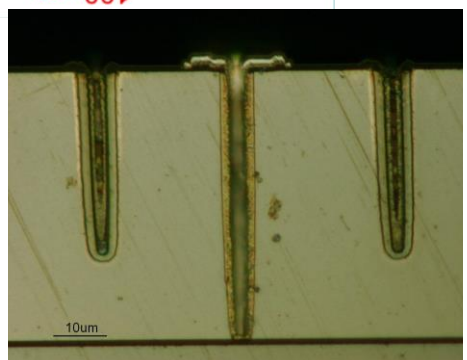
Unbelievable,
They work after $3*10^{16}$ n_{eq}/cm^2

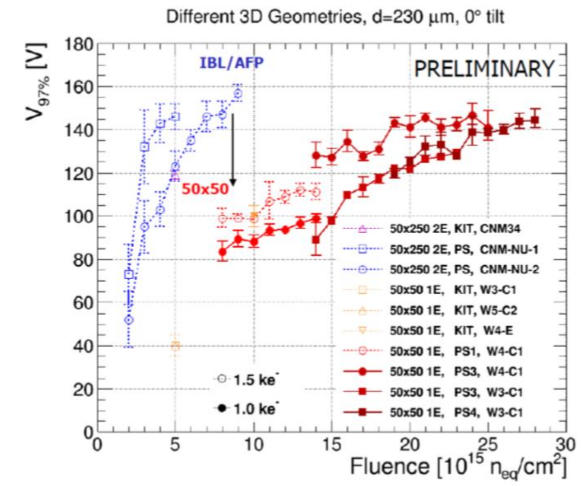








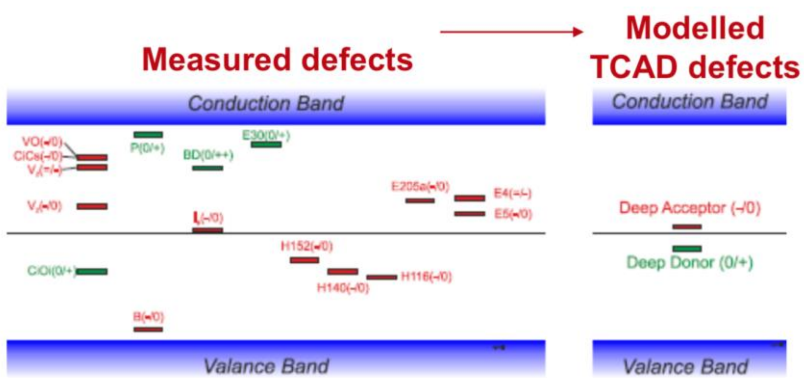


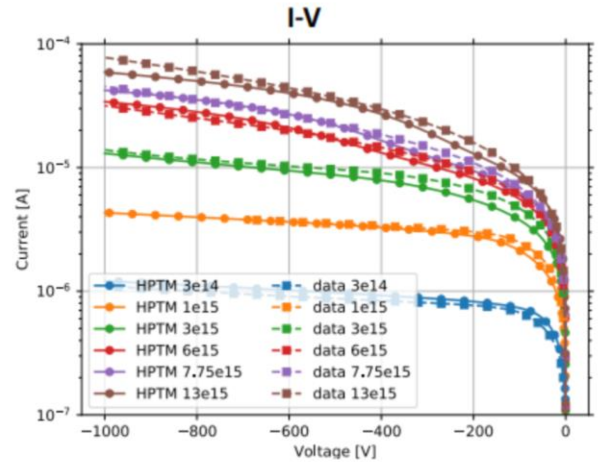


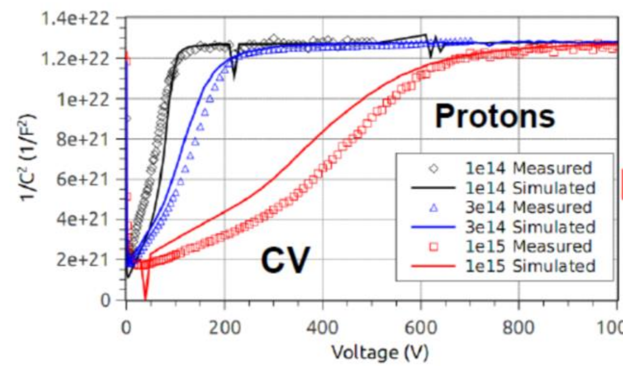
By Geetika Jain

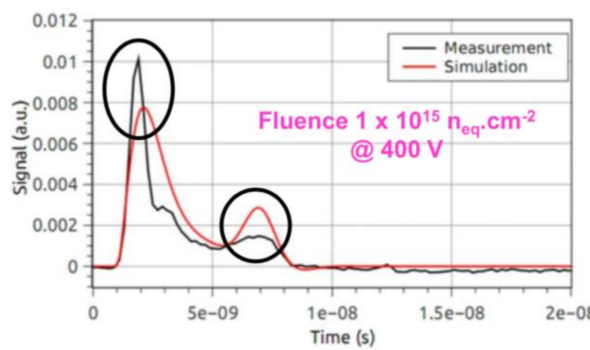
Radiation modelling gets better and better

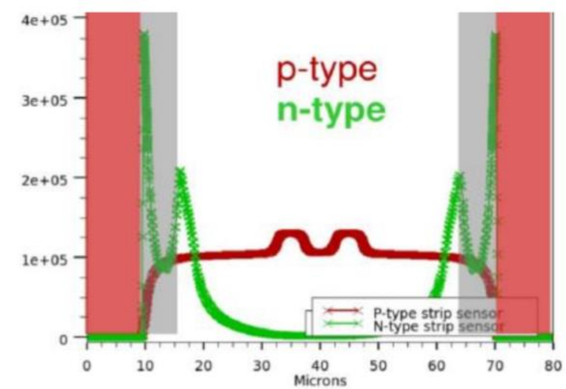
- Iterate
  - Feed measurements into simulation
- Model a representative number of defects – not all
  - Allows good prediction to beyond 10^{15} n_{eq}/cm^2
- Also surface simulated
- Good to understand fields
- Works also for e.g. LGADs











- Predict the future
- Optimize your detector

Now, everything is radiation tolerant.

Let’s build some detectors

Radiation, please come in,
we developed a tolerance

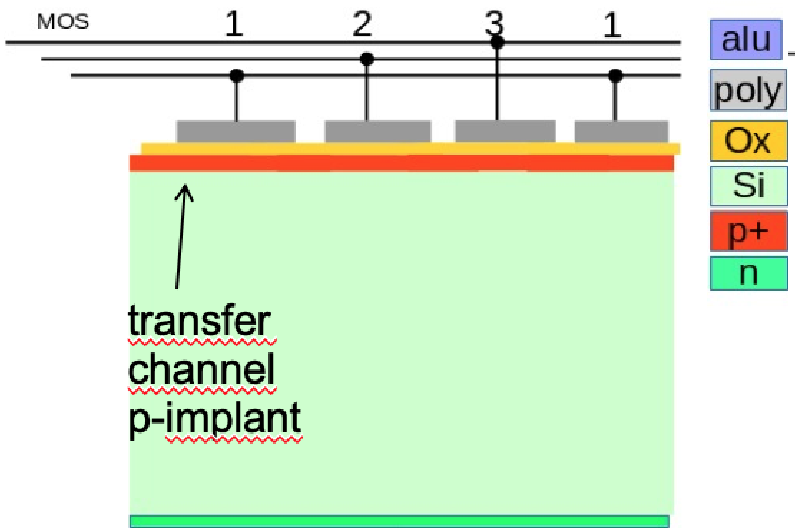
Application of Silicon Detectors in high/low backgrounds environment

Still no idea what this means

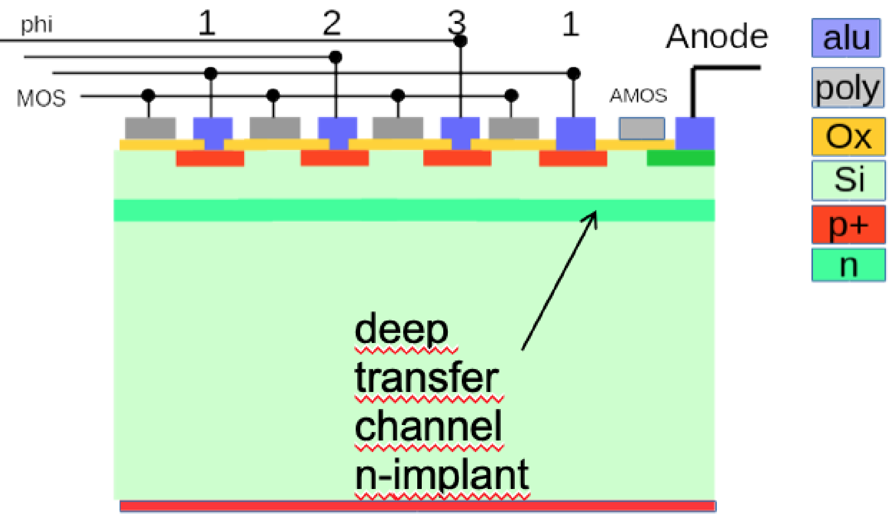
BUT the talk pnCCD was very interesting

Florian Schopper
proudly presents

pnCCD



fully depleted MOS-CCD
is derived from a Diode structure
and collects holes.
(LBNL, Dalsa)



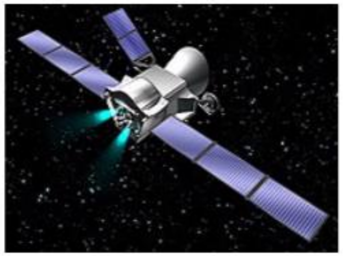
fully depleted pn-CCD
is derived from a Driftsensor structure
and collects electrons.
(HLL, pnSensor)

Improve speed:
readout/line: 20µs → 4µs frame
transfer/line: 300ns → 60ns

Vbias up to 600V

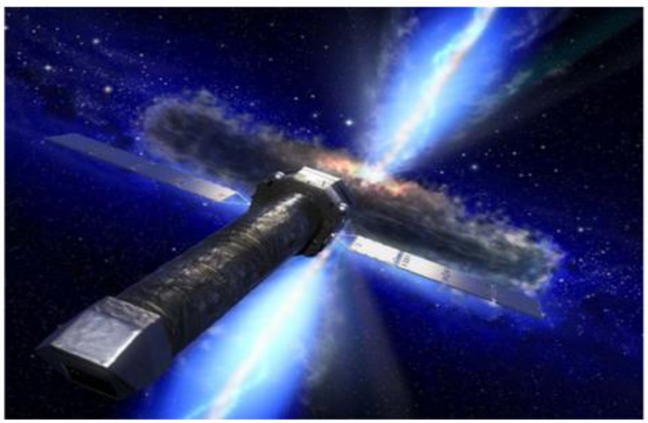
Florian Schopper
proudly presents

Applications I: Astronomy

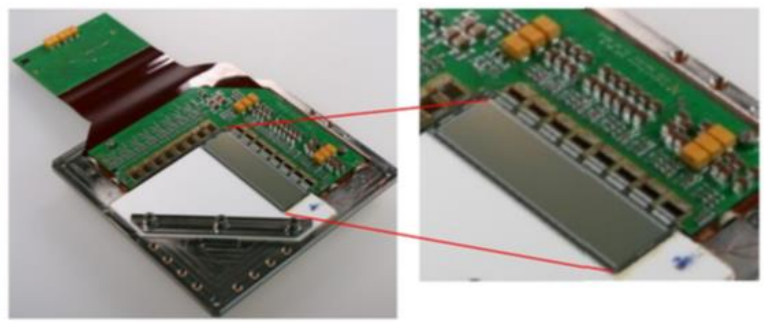


BepiColombo,ESA, launched only X 4days ago, on its way to mercury

The MIXS instrument contains an array of SDDs (300x300 μm²) with DEPFET readout nodes



ATHENA, launch 2028

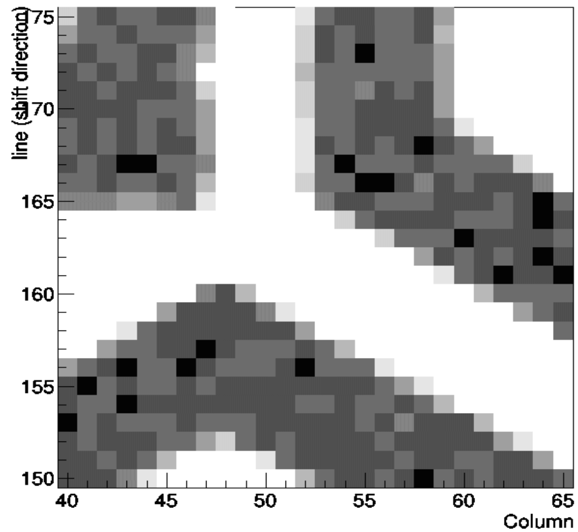


Wide Field Imager (WFI) DepFet array.
1 MPix with 120x120 μm² pixel

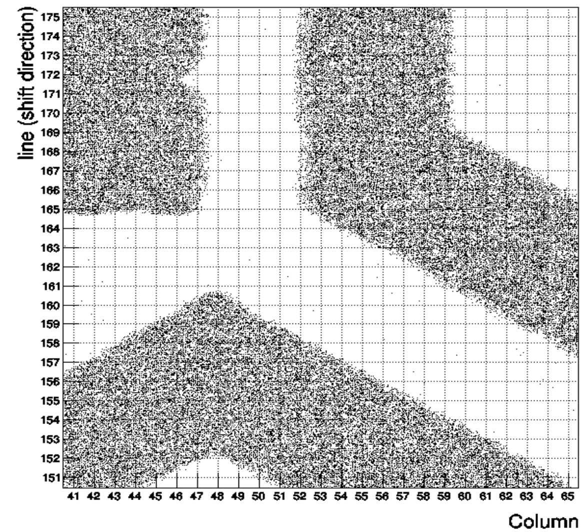
Florian: Launched! We test it when it arrives – in 5 years
Frank to my fellow HEP friends: Don’t do that!

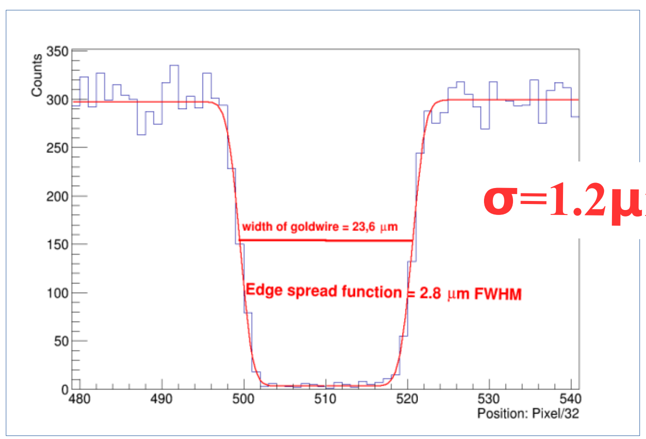
Applications Ib: high resolution spectroscopic imaging

CCD pixels



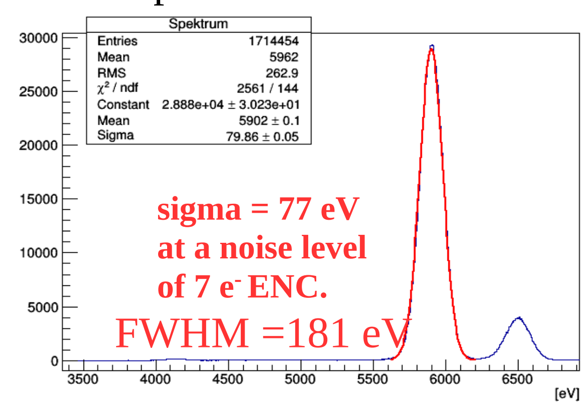
hit positions placed on 32x32 Subgrid

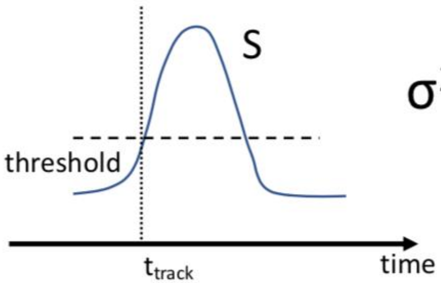




σ=1.2μm

2x2 pixels are summed





$$\sigma^2_t = \sigma^2_{\text{Jitter}} + \sigma^2_{\text{Time Walk}} + \sigma^2_{\text{Landau Noise}} + \sigma^2_{\text{Distortion}} + \sigma^2_{\text{TDC}}$$

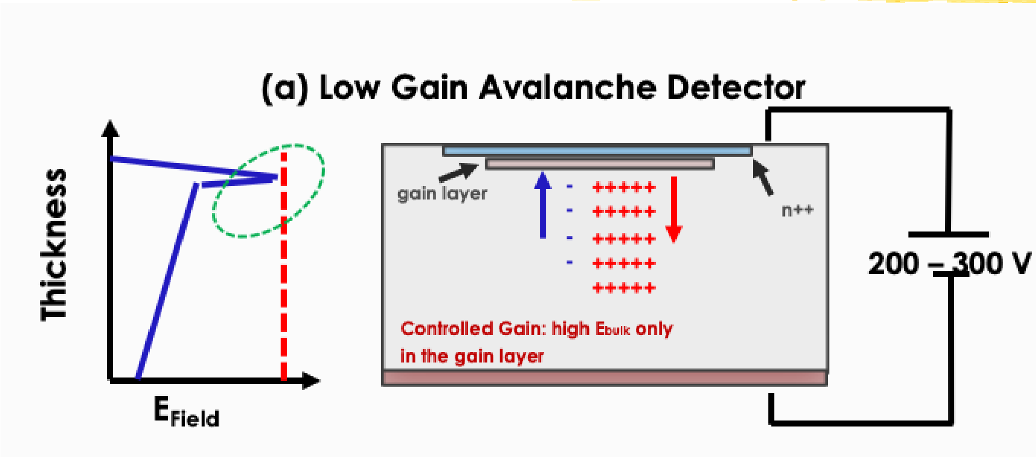
Negligible
Optimize FE electronics

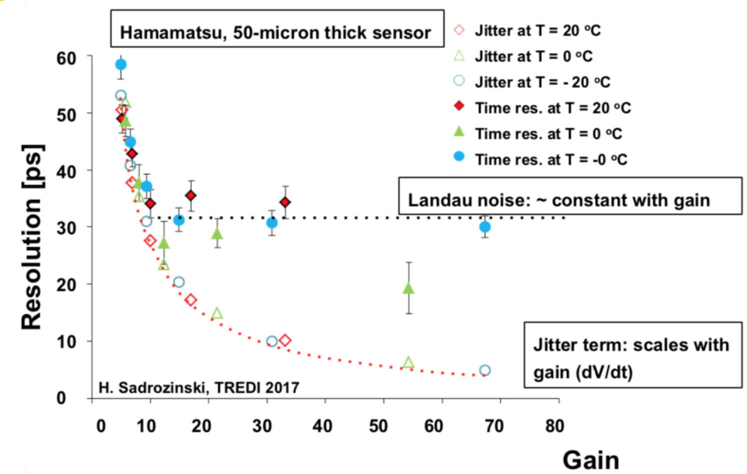
Negligible
Optimize RO electronics

THINGS with TIMING

Presented with some technical difficulties by Amedeo Staiano

UFSD - the most intriguing news

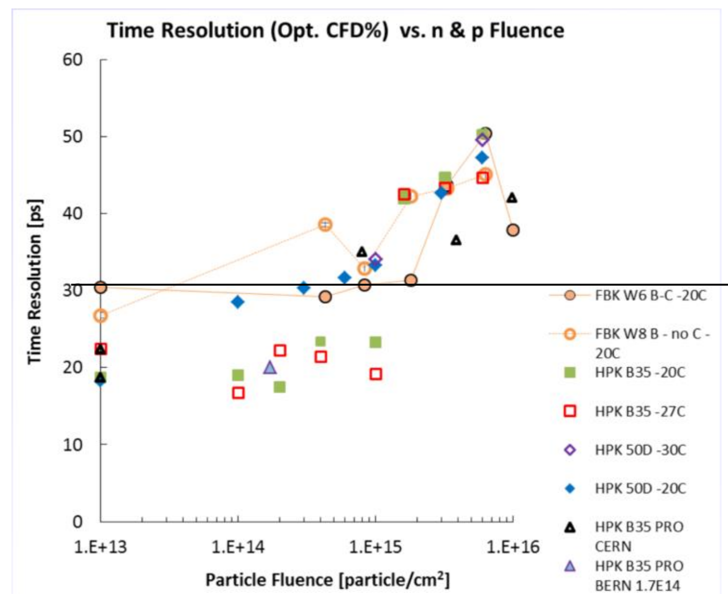




- High gain – low jitter – good time resolution
- Gain layer in early LGADs lost with radiation due to donor removal (B displacement)

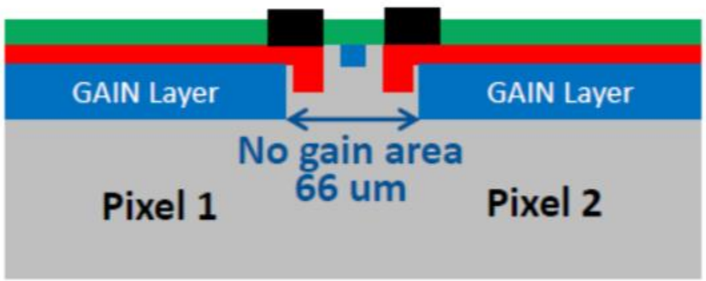
- **Boron+Carbon diffused helps up to $3*10^{15}$ n_{eq}/cm^2**
  - **hurray, the goal was $1*10^{15}$ n_{eq}/cm^2**
  - Carbon occupies interstitials – Carbon is good
  - Mind, 20 years ago, Carbon was evil

  - Gallium instead of Boron didn't help

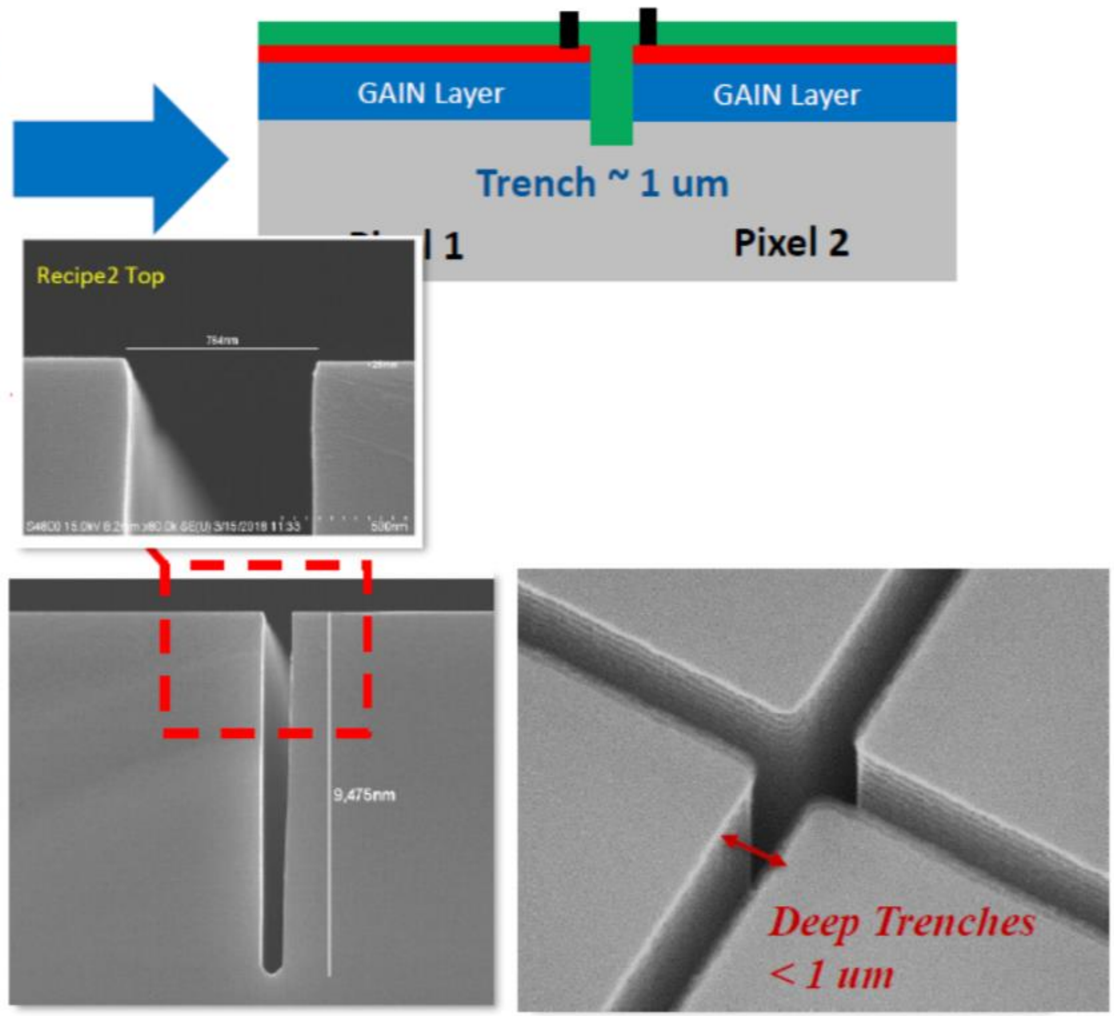


UFSD/LGAD – fill factor 66μm → 1μm

Standard JTE + p-stop isolation



Trench Isolation



Trench isolation could drastically reduce the inter-pixel border region down to few microns

Trench isolation technology

- Typical trench width < 1 um
- Max Aspect ratio: 1:20
- Trench filling with: SiO_2, Si_3N_4, PolySi

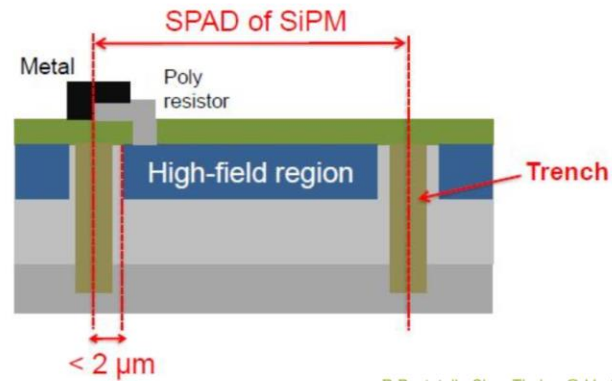
CMM
CENTRE FOR MATERIALS AND MICROSYSTEMS

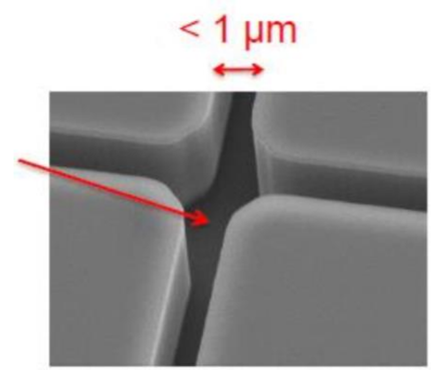
150 ps timing brought to you by Rok Pestotnik

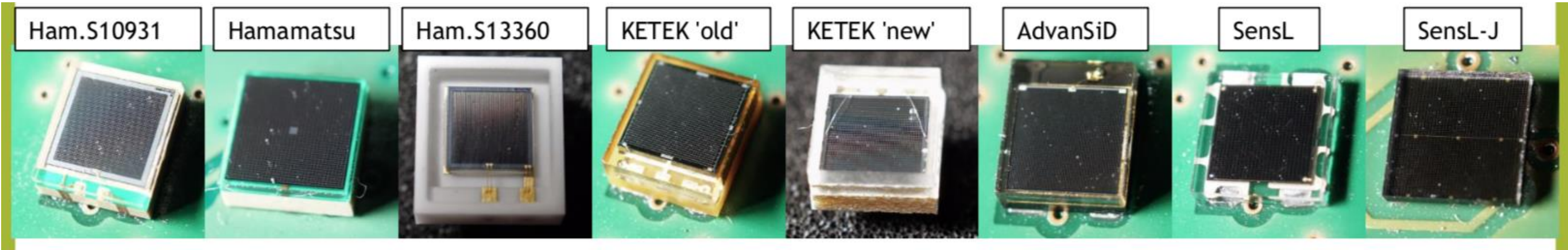
UF-SIPMs

- SiPMs are attractive photosensors (also single photon)
- **150 – 300 ps** FWHM are achieved in test samples with only one cell hits - more cells hits - full system (300 ps TOF.PET)

  timing is degraded by delayed contribution in multi-cell events
  - First improvement – time-walk correction
    - ~200 ps FWHM single photon level timing was achieved
  - Further improvements
    - separating the contributions by multi-threshold measurement/waveform sampling







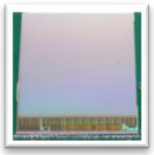
Ingredients for later talks

MAPS, depleted MAPS, HVCMOS

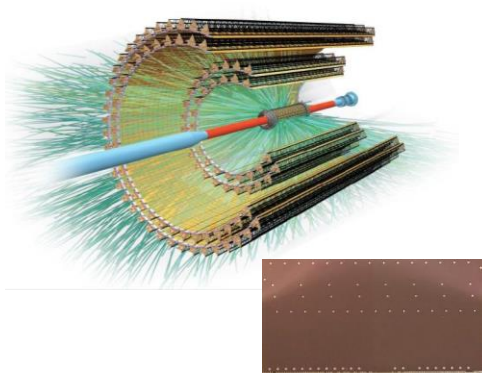
Special mix of contributions from

- Abishek Sharma,
- Eva Vilella Figueras,
- Thanushan Kugathasan,
- Heinz Pernegger

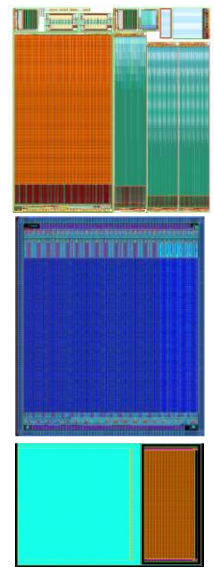
MAPS evolution

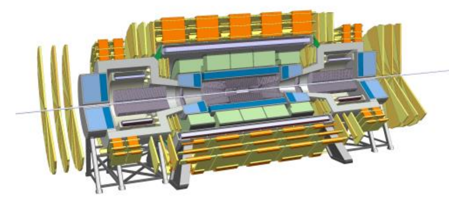
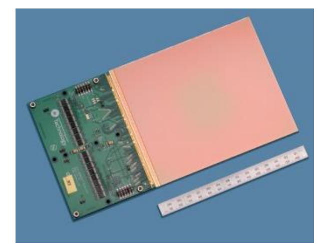
ULTIMATE in STAR
IPHC Strasbourg
First HEP MAPS system



ALPIDE in ALICE
First MAPS with sparse readout similar to hybrid sensors
Chip-to-chip communication for data aggregation



ATLAS CMOS
Depleted radiation hard MAPS with:
Sparse readout
Chip-to-chip communication
Serial power
…

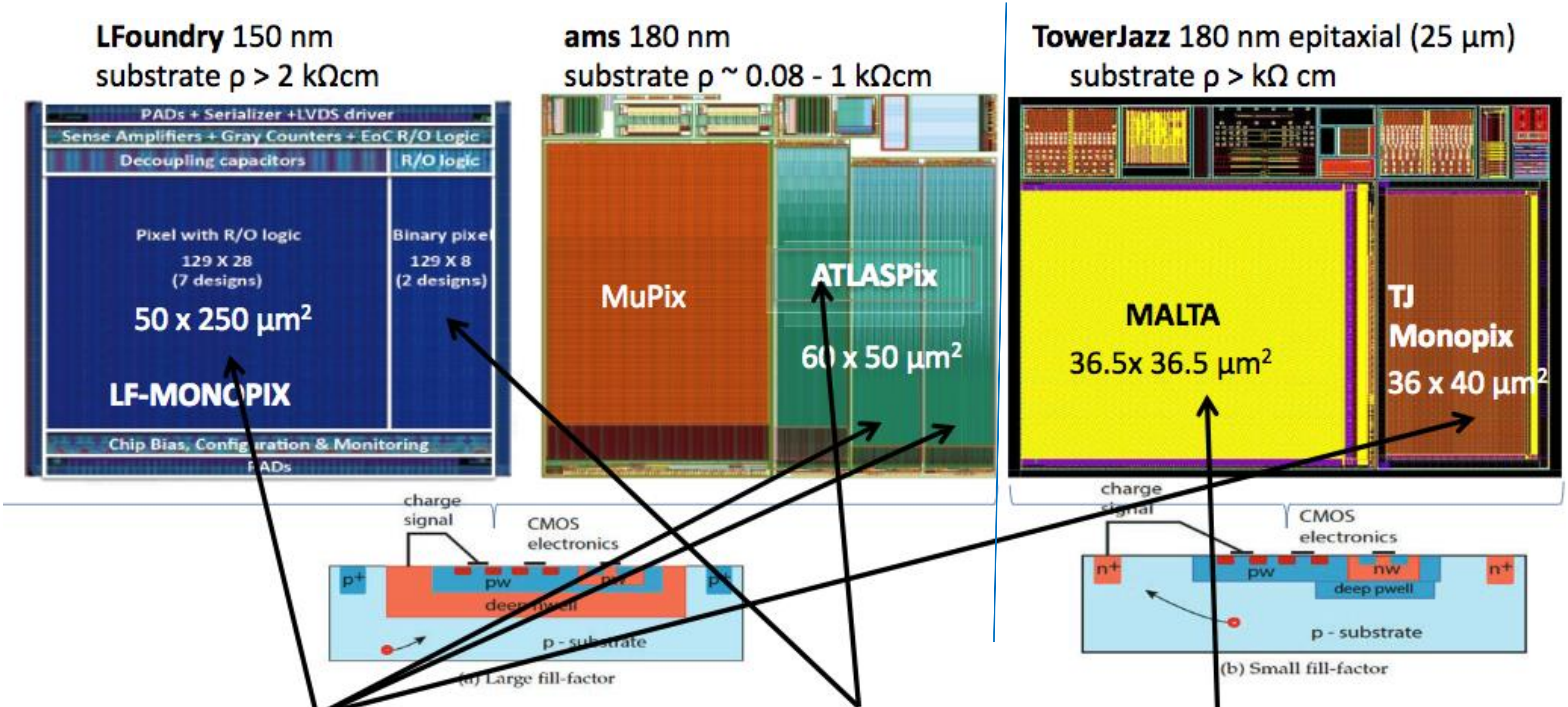



FCC, CLIC, …
Large stitched fast radiation hard MAPS with:
Sparse readout
Chip-to-chip communication
Serial power
…

Important steps in every iteration

Radiation hard CMOS sensor developments for ATLAS

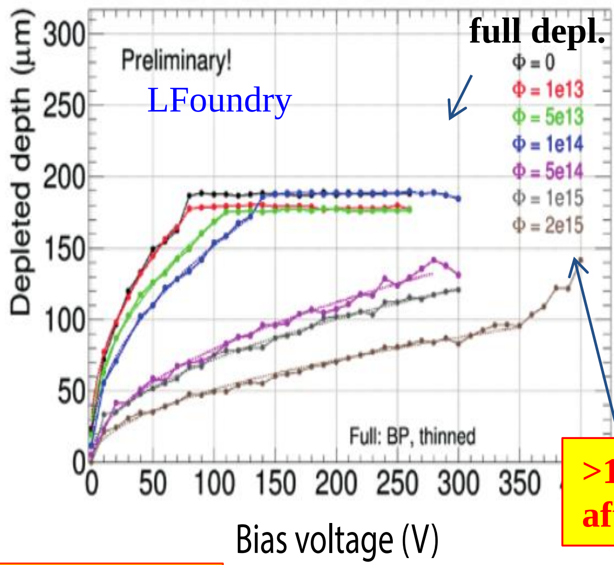
- Targeted towards outermost ITK pixel layer
- Pursue designs with large and small electrodes



column drain (conservative) - parallel pixel to buffer - asynchronous

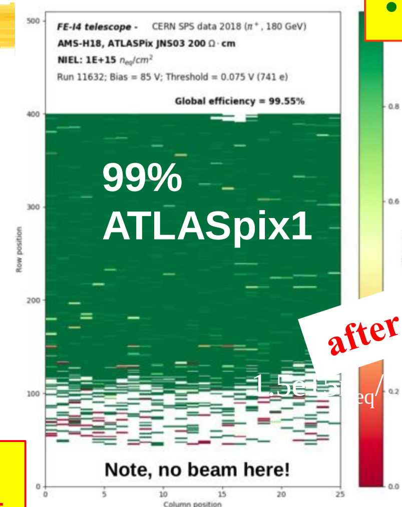
Preliminary results with large electrodes

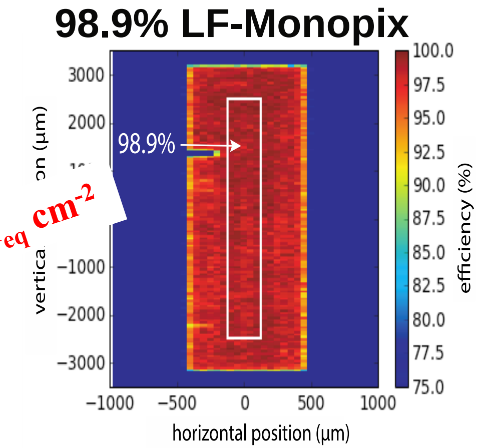
- radiation hardness ✓



>100 μm after 2×10^{15}

- efficiency ✓





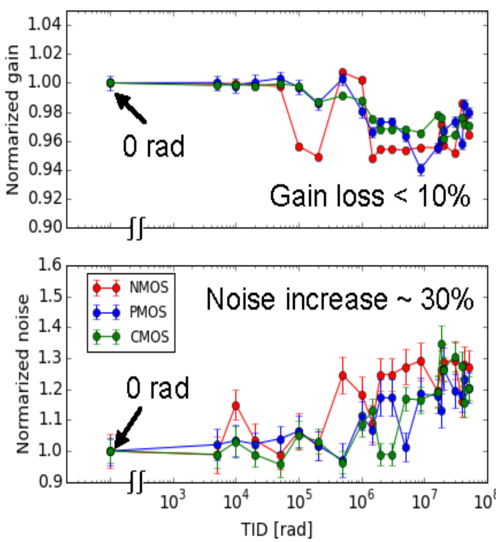
after 10^{15} n_{eq} cm^{-2}

- TID 1 MGy ✓

LFoundry

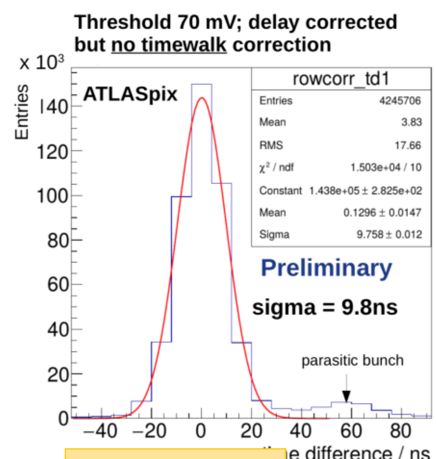
gain

noise

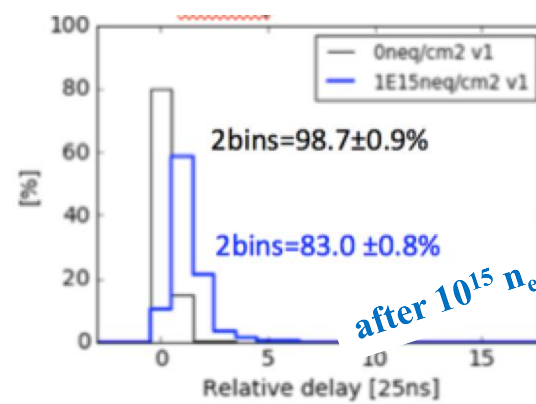


- Timing optimization ongoing

AtlasPix



LFMonoPix

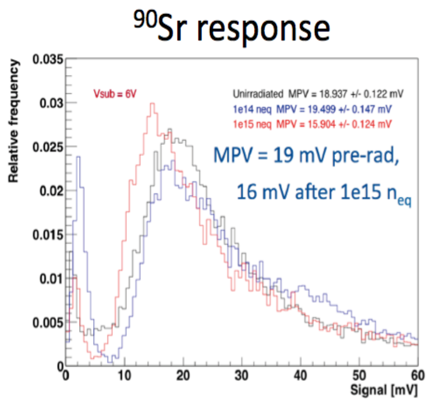


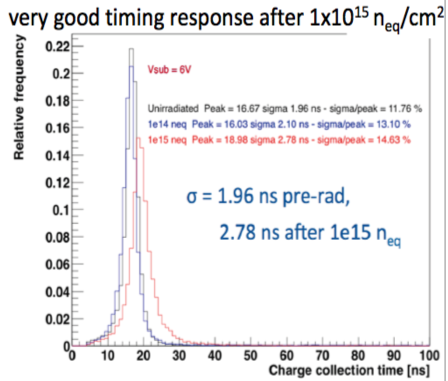
after 10^{15} n_{eq} cm^{-2}

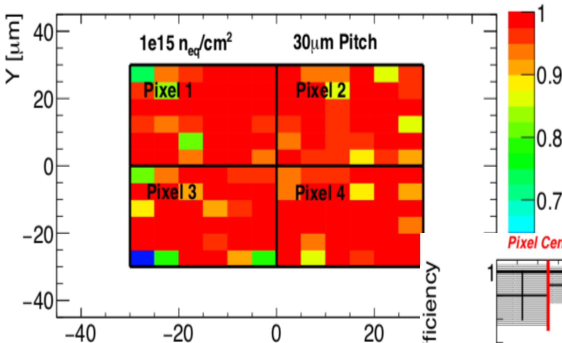
More later

Preliminary results with small electrodes

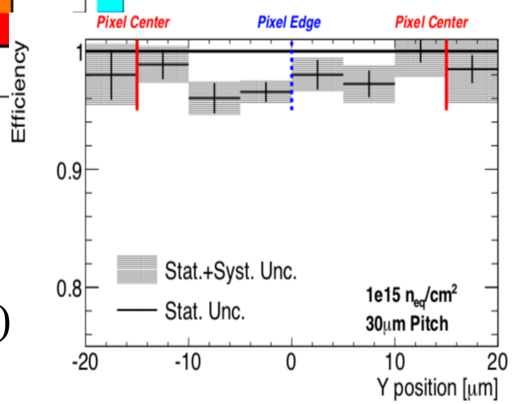
2017 Investigator measurements







Irradiated Investigator



Efficiency 97.4%

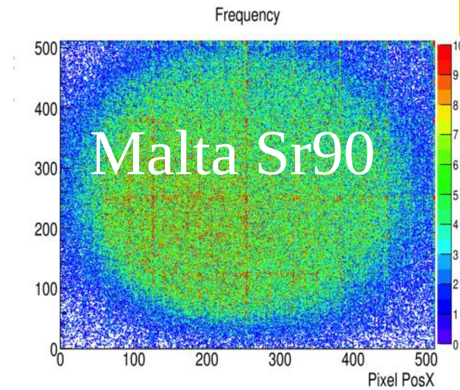
After 10^{15} n_{eq}/cm^2

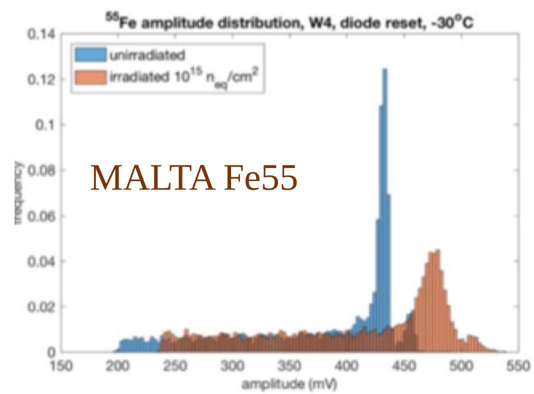
at low threshold (<100e-)

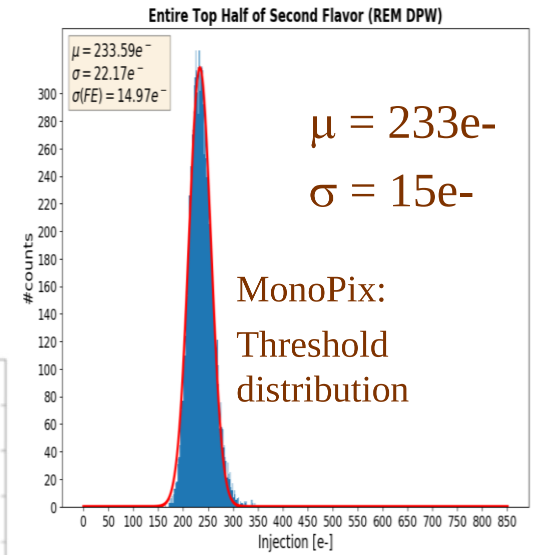
2018 MALTA & TJMonoPix work

- same FE design, different readout architecture
- Tests ongoing (lab, beam tests, irradiations) show excellent ENC ~ 10-20e-; good timing after irradiation
- Efficiency problem in corners after irradiation to fix with implant change

More later







μ = 233e-

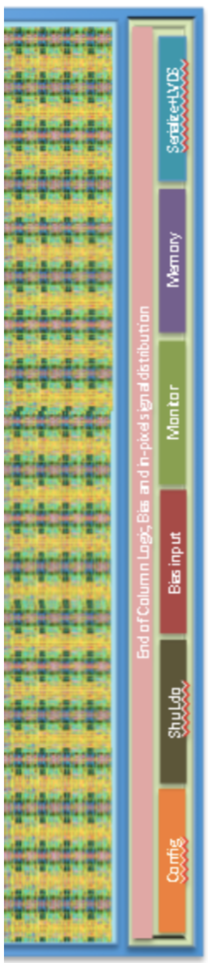
σ = 15e-

MonoPix: Threshold distribution

Life/work beyond the pixel cell

ATLAS CMOS-1 Periphery

STREAM



Key focus now is the realization of an ATLAS-ready ASIC: include essential RD53 functionality in monolithic sensor

Key topics : Hit data Memory and Trigger
- Analysing memory design in order to efficiently use bandwidth, distribute power and use little space
- Memory: efficient storage concept : local EoC hit memory plus global memory for trigger latency

Key topics : Serializer and output
- Data out after trigger is serialized with 1280 Mbps to go to aggregator with RD53 protocol
- Clock recovery from Clk/CMD 160MHz to receive from PP0

Key topics : Power and bias, configuration
- Submitted designs of blocks for serial power: use on CMOS sensor shunt regulators for serial powering
- Implement configuration with RD53 protocol

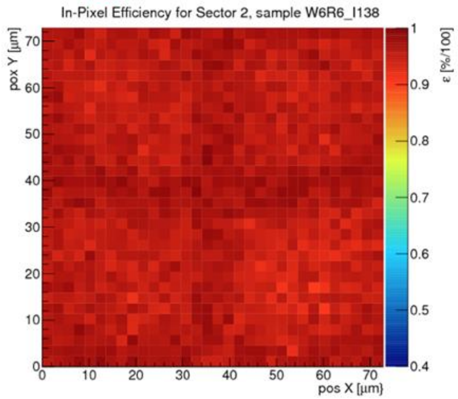
GREAT

CMOS, how to ‘solve’ the corners

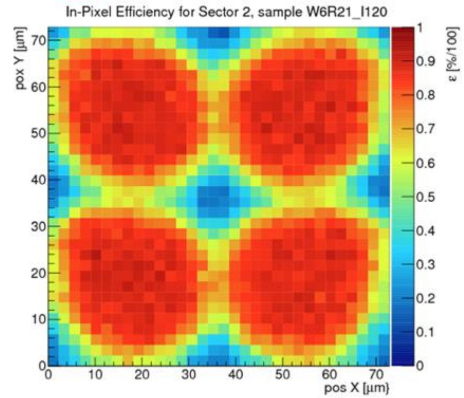
Small collection electrode radiation tolerance

2x2 pixels
36.4 μm²

Unirradiated
Q_{th} = 250 e⁻

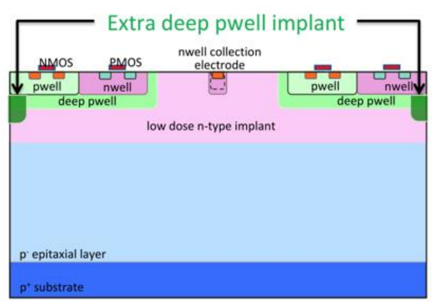


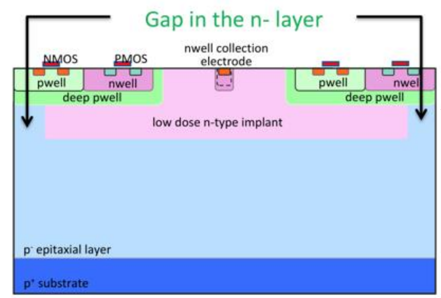
Irradiated 5x10^{14} n_{eq}/cm^2
Q_{th} = 350 e⁻



Issue: Detection efficiency loss in the pixel corners

Solution
Increase lateral electric field in critical sensor regions (corners)





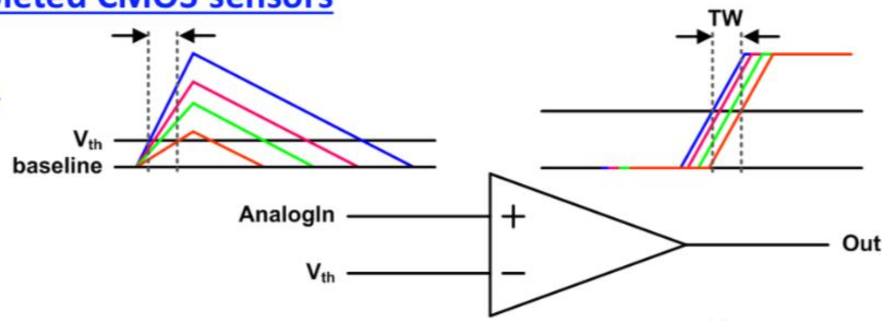
State of the Art

Eva Vilella Figueras says: "CMOS hurry!"

Time resolution of depleted CMOS sensors

Sources of time uncertainty in depleted CMOS sensors

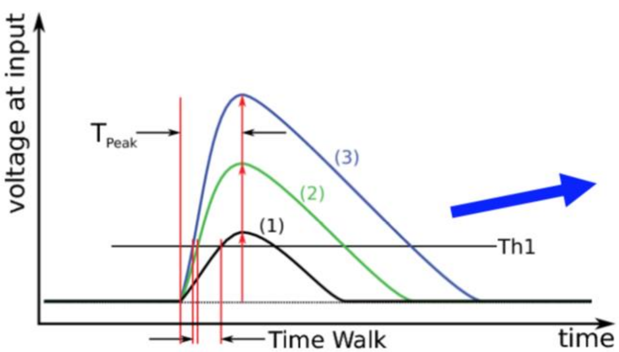
- Charge collection time
- Delay RO electronics
- Time-walk



TW

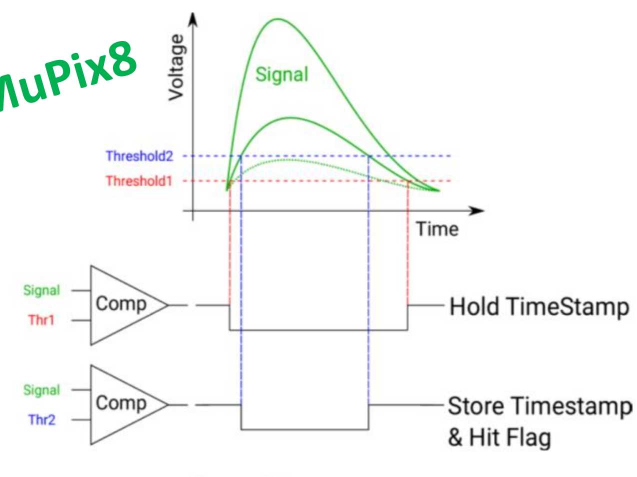
- **MuPix8 – 13 ns**
- **MuPix8 corrected – 7ns**
- MALTA – 25 ns
- CACTUS – 100 ps (sim, very large pixels, large power)

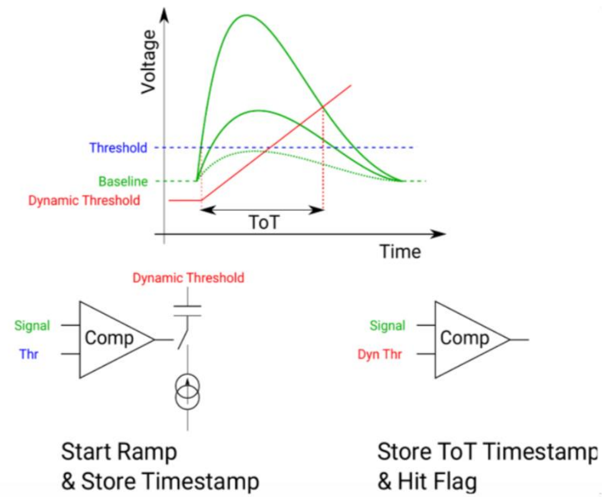
⌘ Address TW



Ref.: R. Schimassek, IEEE NSS/MIC/RTSD, 2017

MuPix8





Time-walk compensated comparator

Threshold 1 triggers delay circuit
Signal height controls delay

2 threshold method
Th1 at noise level –min TW
Th2 confirms signal

Ramp method
Constant Th &
Linear dynamic Th

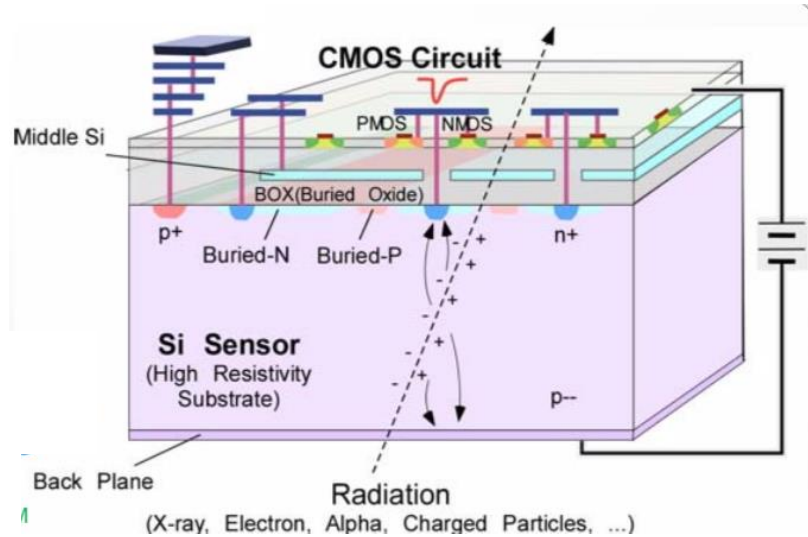
Very clearly presented by Kazuhiko Hara

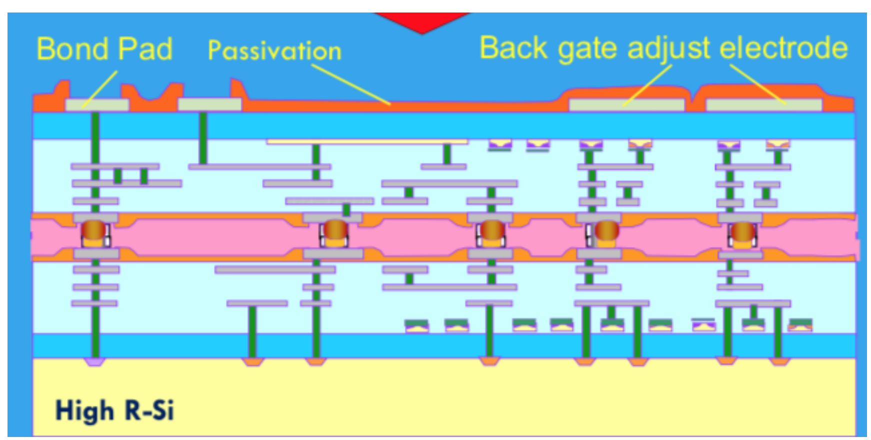
SOI

- Candidate for ILC
- Lots of interesting material - here an excerpt:
  - Pixel 30x30 μm^2
  - Incredible space resolution $\leq 1.4\mu m$
  - Time resolution ~ $1\mu s$
  - S/N 120 for $67\mu m$ thickness

- And 3D is coming

LAPIS 0.2μm FD-SOI





BELLE II – PXD & SVD

ALICE

LHBC VELO & Tracker

ATLAS Pixel & ITK

CMS IT & OT

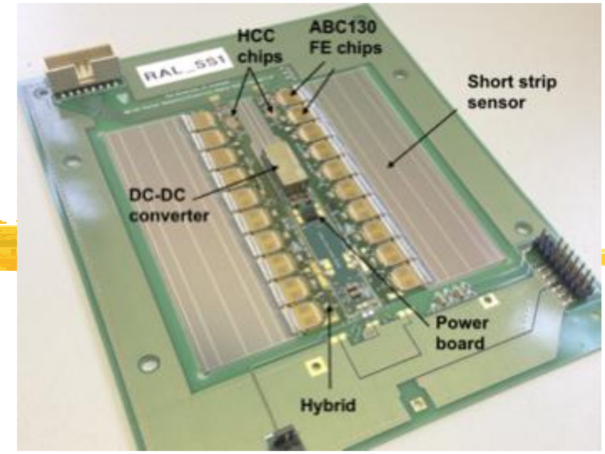
These detectors will be awesome

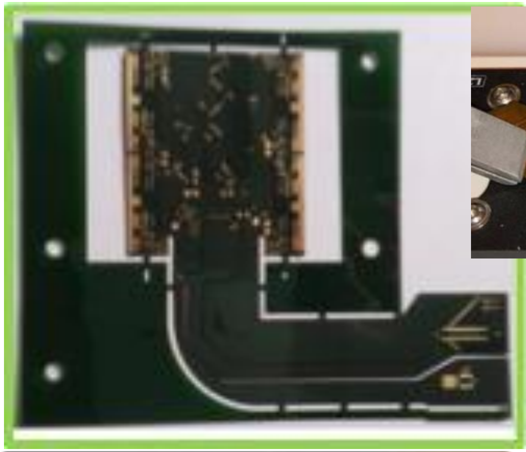
Upgrades

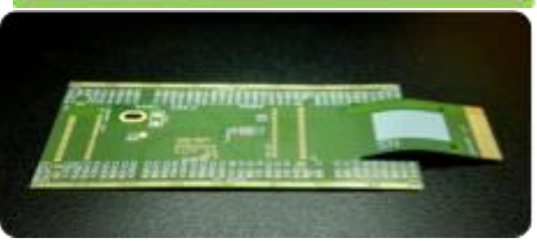
And, I have to say it:
Share more problems!!
<u>I</u> want to learn from you!

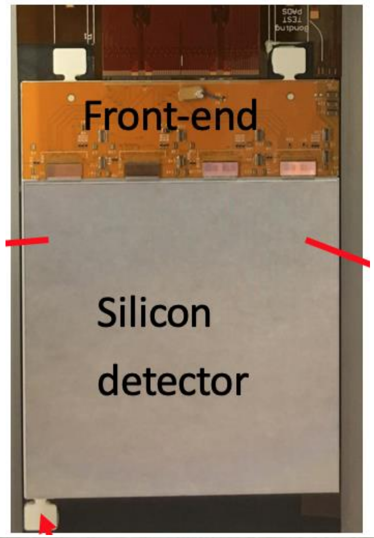
Modules
We use the same as today, *right?*

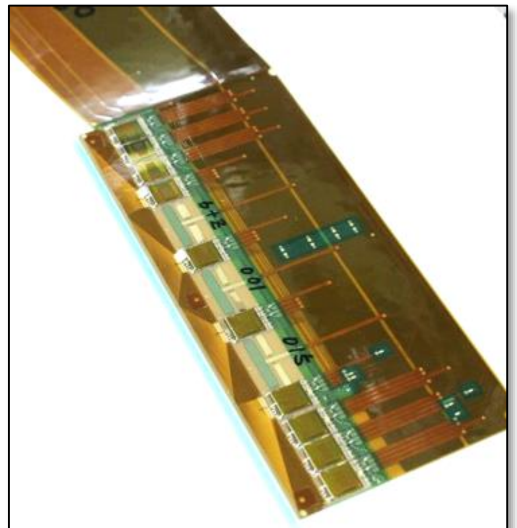
More homework – who is who?

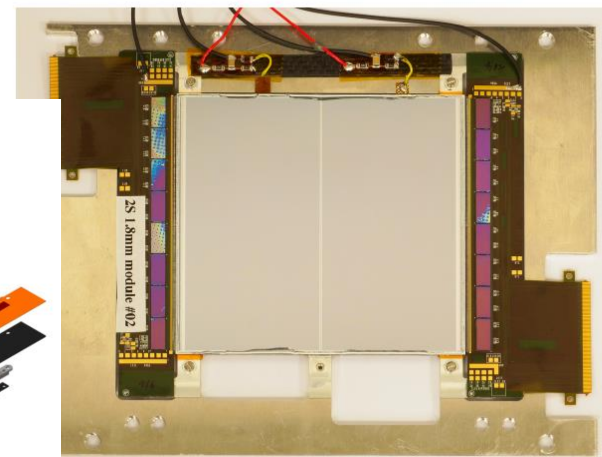


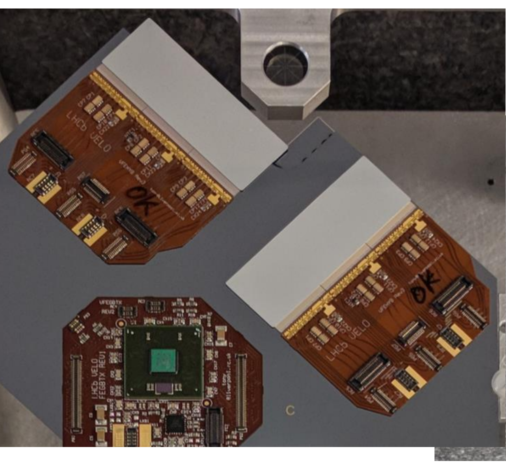


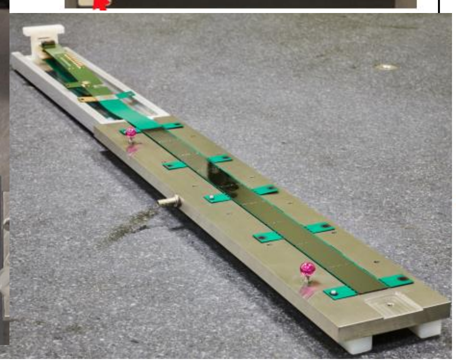


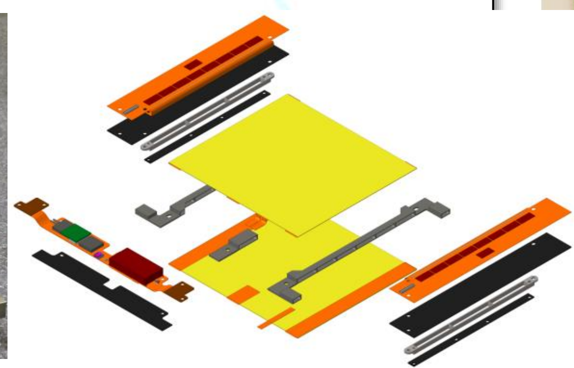






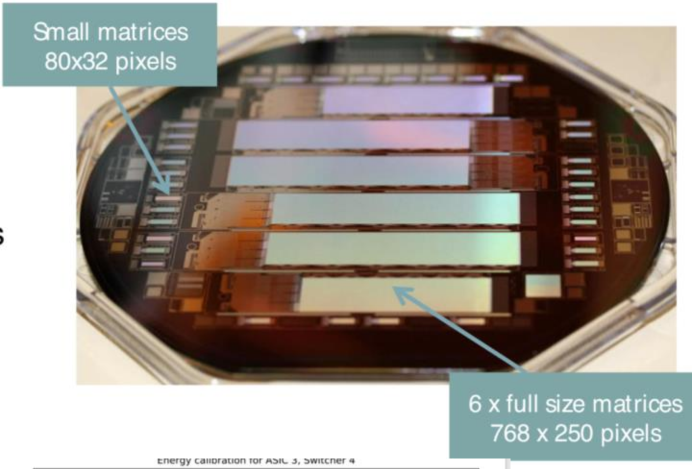


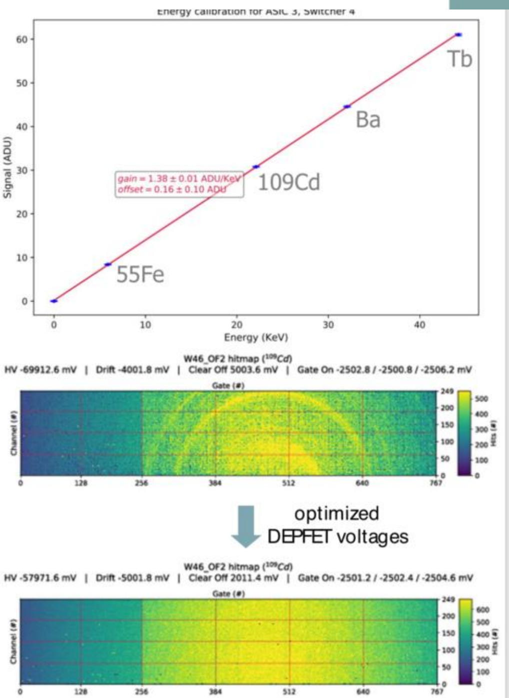




Christian Koffmane proudly presents

Belle II – PXD – THANK YOU for doing the best possible



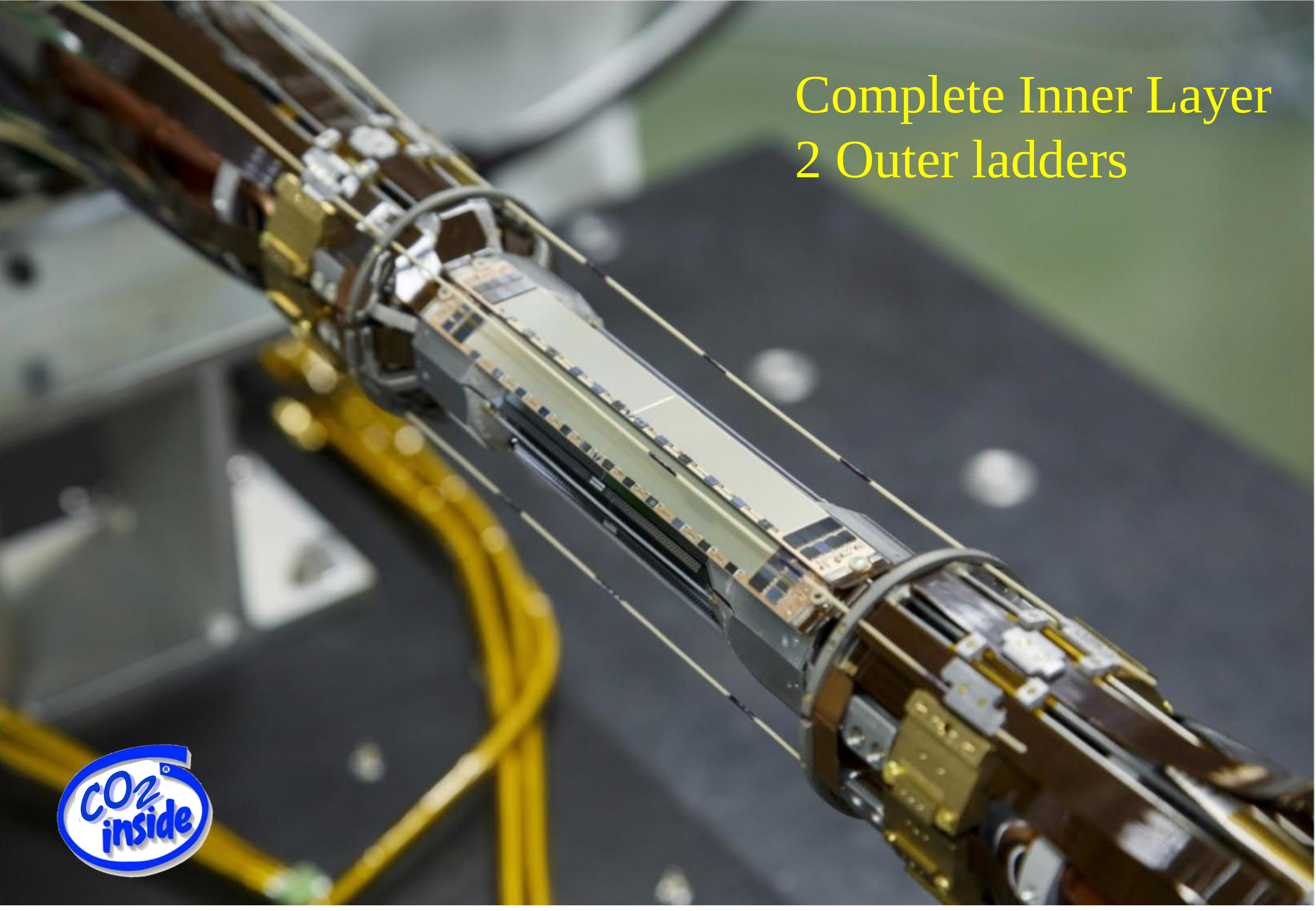


Module Type	FC+SMD	probe card test	kapton	characterization	ladders assembled	final test
L1 BWD	14	14 passed	14	13 passed 1 rework ok	13	9 passed 1 b-grade 3 lost
L1 FWD	15	15 passed	15	11 passed 1 rework ok 2 b- grade, 1 lost		
L2 BWD	20	19 passed 1 rework ok	20	17 passed 1 rework ok 2 still to be tested	4	2 passed 2 lost
L2 FWD	22	18 passed 2 rework ok 2 lost	20	13 passed 2 rework ok, 1 lost 4 still to be tested		

- 17 ladders glued (plus 10 dummy ladders during the qualification of the gluing

Ladders damaged during installation on cooling block due to particles
Production stopped for further investigation – TEMP descope

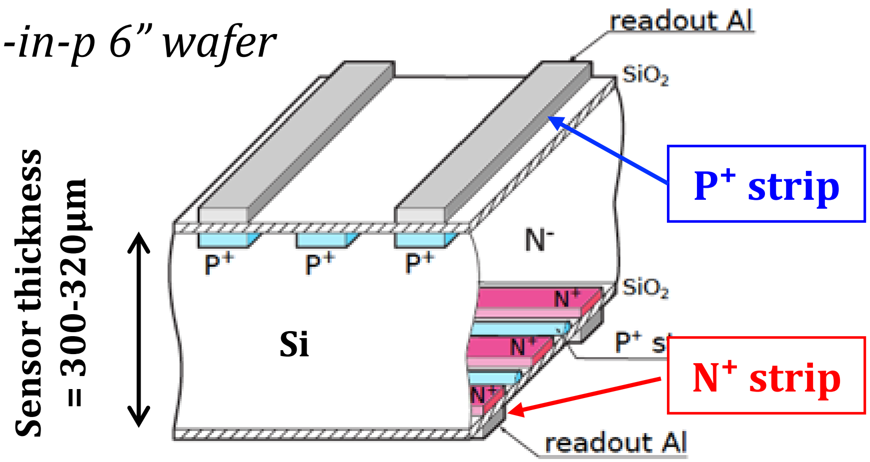
→ in order to keep Belle II schedule a de-scoped PXD (complete inner layer + 2 outer ladders) is installed for the start of phase 3, installation of the full PXD scheduled for 2020

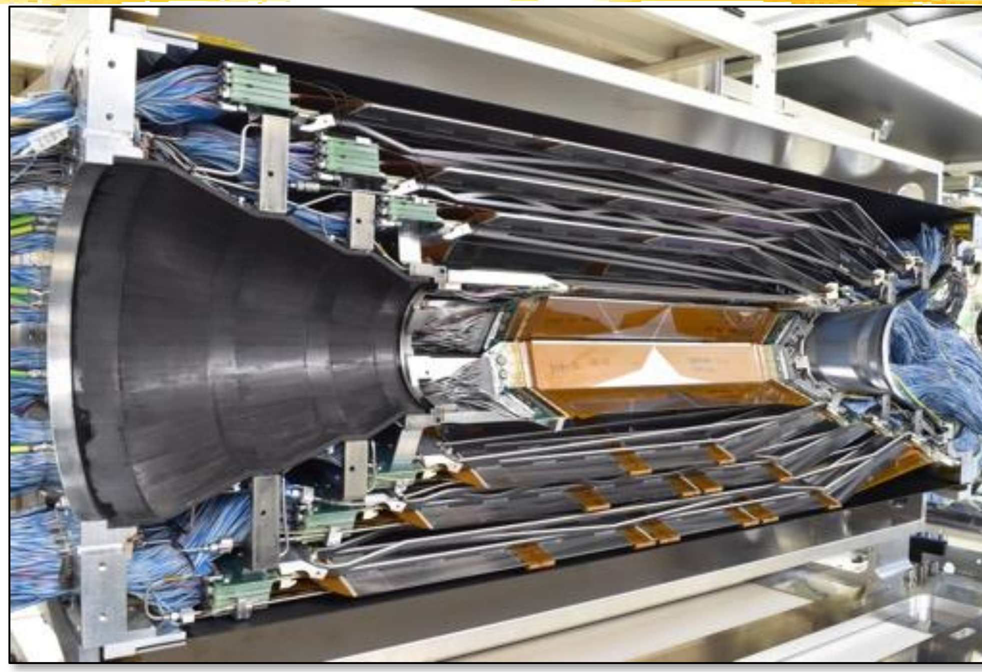

Complete Inner Layer
2 Outer ladders
CO2 inside

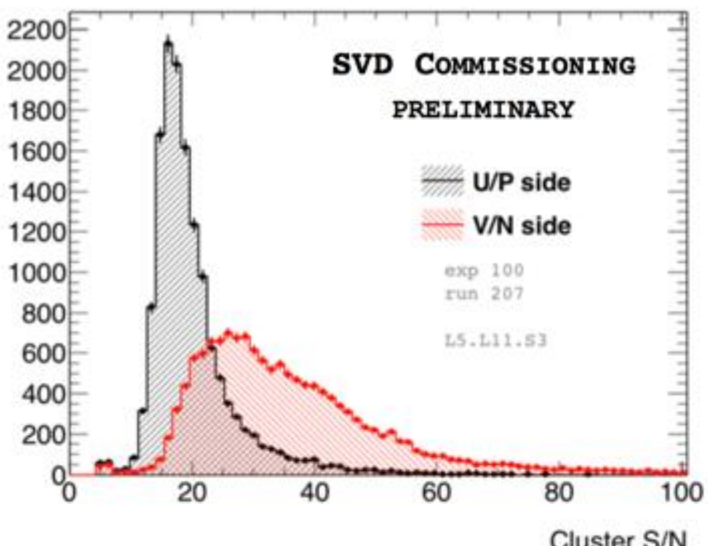
Belle II – SVD

Double-sided Si Strip Detector

p-in-p 6" wafer

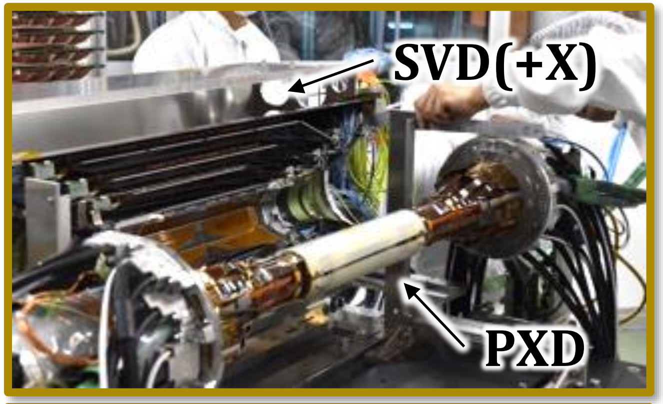


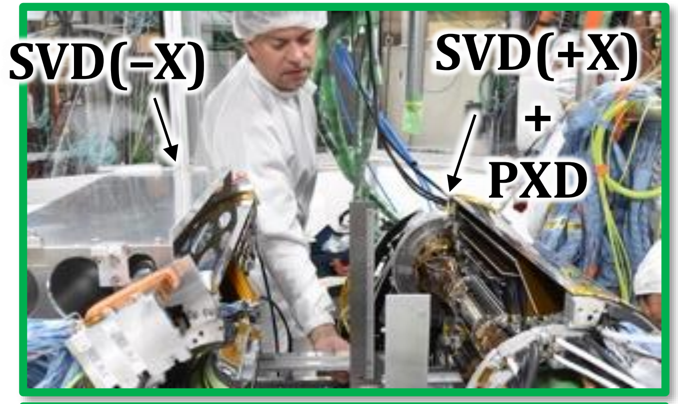


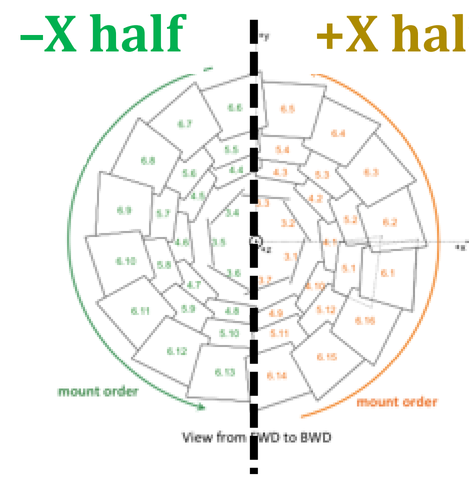


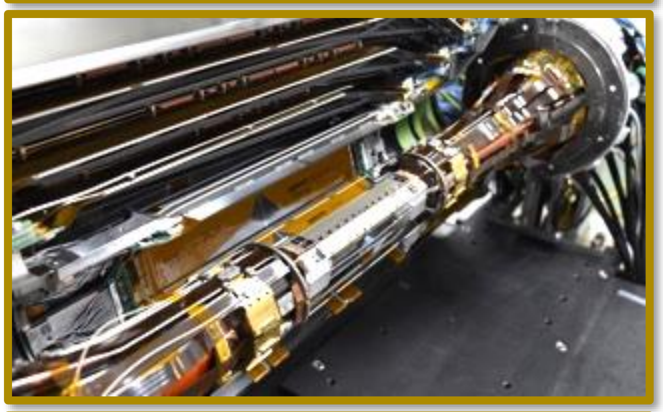
- SVD has run stably since July to mid Sept, collecting 30×10⁶ cosmic events.
- Efficiency >99% for most of the sensors

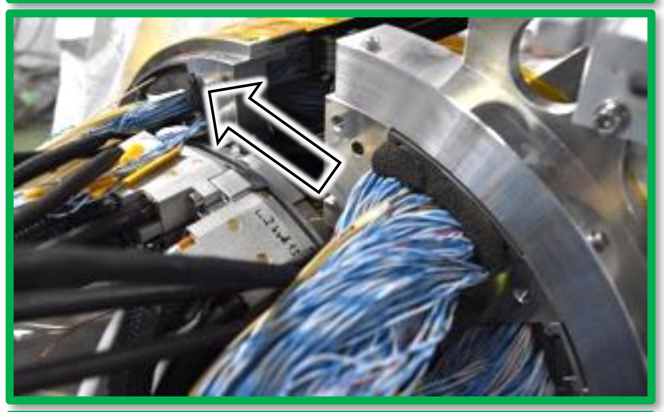
PXD + SVD “Marriage”







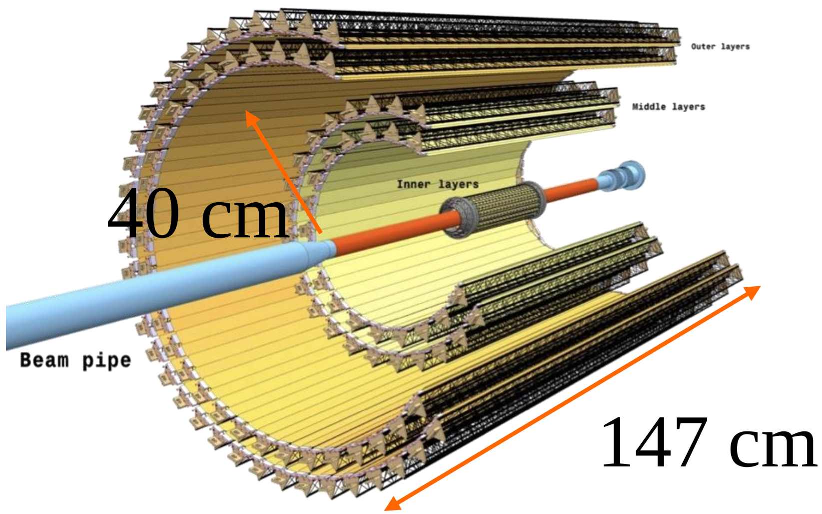


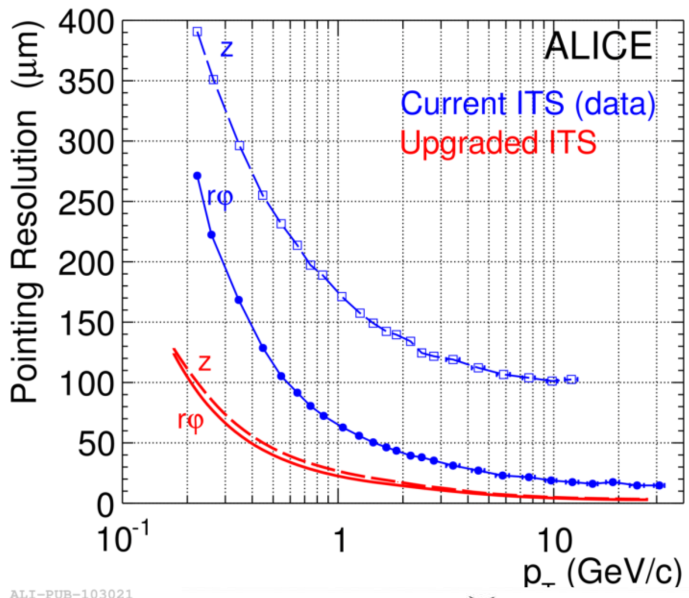


The combined VXD will be commissioned for one month before the installation to the Belle II detector by the end of 2018.

Serhiy Senyukov presents

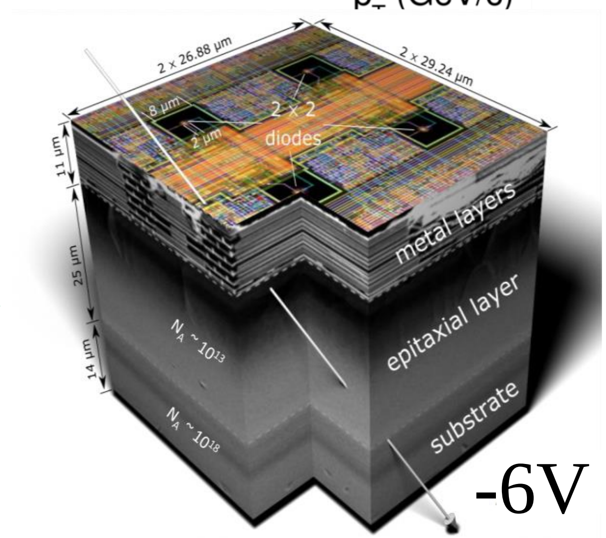
The ALICE Tracker Upgrade - Install LS2 (2020)





- **3+4 layers of MAPS (CMOS) ~10m²**
  - 27x29 μm² pixels
  - MAPS thinned to 50 μm
    - ~0.3 % X_0 per layer
  - **12.5 G-pixels**
- Radial coverage ***21*** - 400 mm
- Increase of readout speed
  1 kHz → 50 kHz (pp) and 400 kHz (PbPb)

I call it – perfect fit for ALICE



ALICE ITS Upgrade TDR CERN-LHCC-2013-024

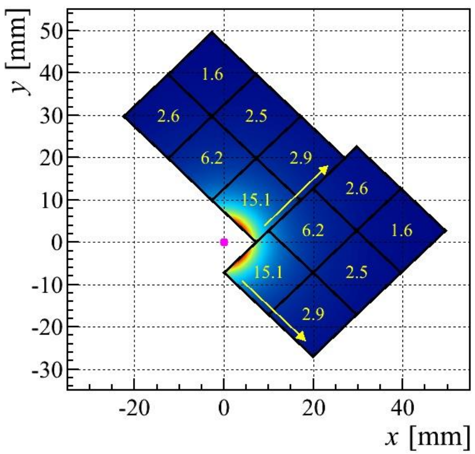
The ALICE Tracker Upgrade - Install LS2 (2020

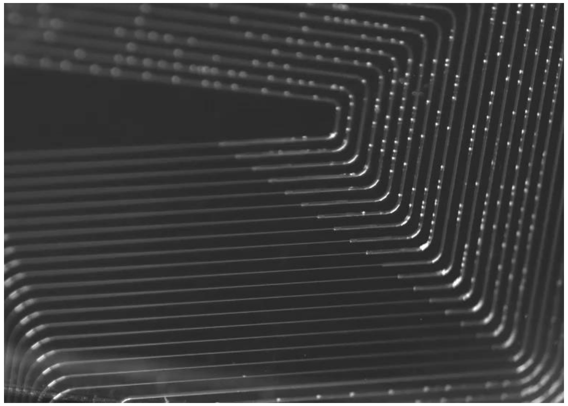
Manufacturing sites:
Bari, Liverpool, Pusan, Strasbourg, Wuhan
Daresbury, Frascati, LBNL, NIKHEF, Turin

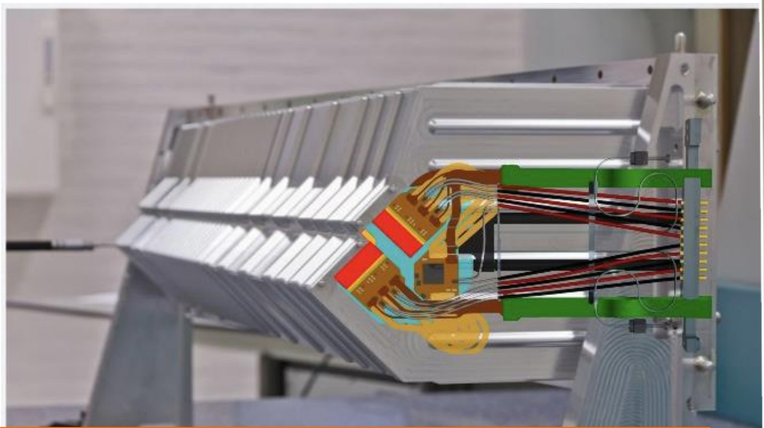
Assembly of the first inner half-barrel completed in June 2018

LHCb VELO – LS2 – strips2pixel

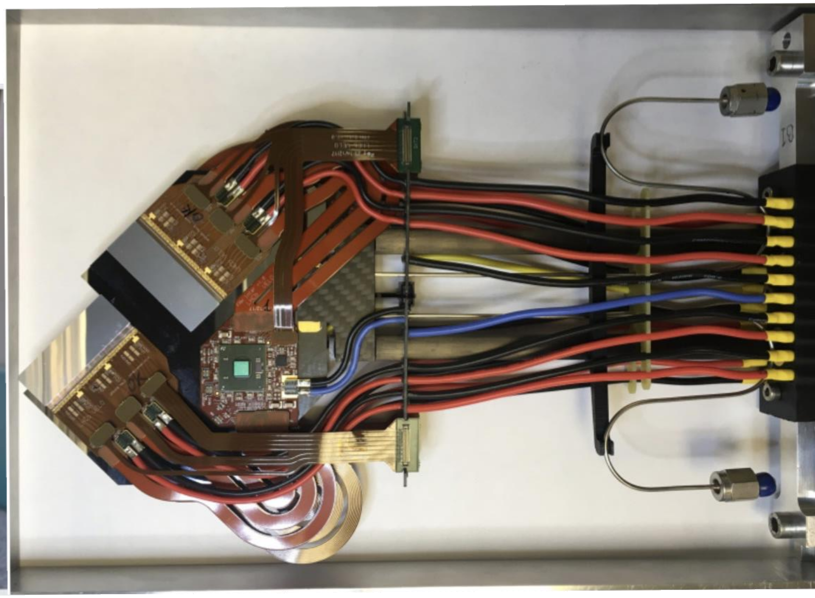
- All-pixel detector 55x55 μm^2 n-in-p 200 μm thick pixels sensor, bias up to 1000V, readout with VELOPIX
  - Very high rad ($8x10^{15}$ n_{eq}/cm^2 for 50 fb^{-1}until LS4) & non-uniform irradiation (~ $r^{-2.1}$)
- Go closer: distance to beam 51 mm instead of 8.2 mm
- Sensors on CO_2 micro-channel cooling
- No hardware trigger
  - **Full 40 MHz readout** – software HLT
  - 20 Gbit/s for central ASICs



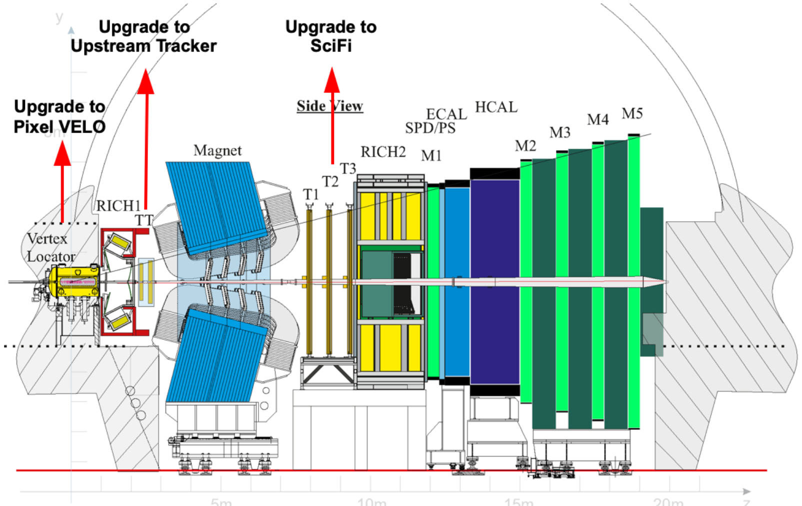




Each sensor (43mm x 15mm) bump-bonded to three VELOPIX ASICs

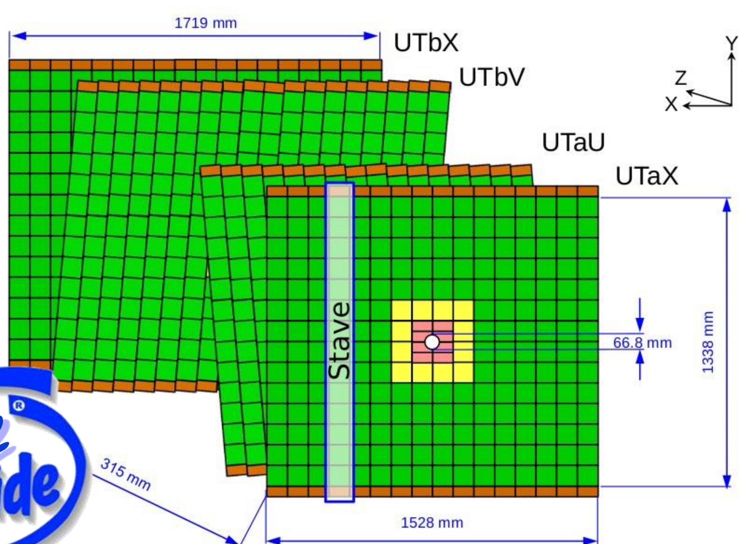


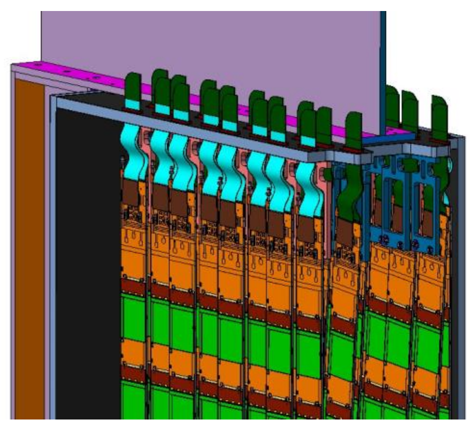
LHCb – Upstream Tracker



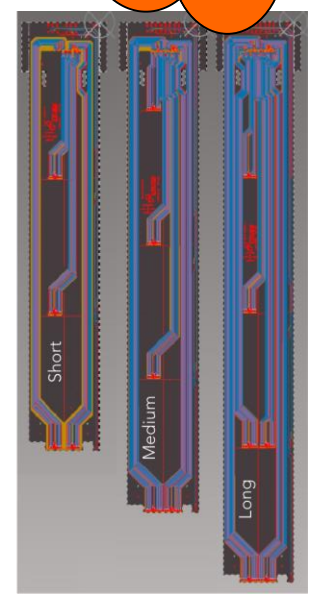
- **ALL OK,** but
- Problems with FE ASIC
  - Silicon ASIC for LHCb Tracking – SALT
  - Mainly in pre-amp
- Obviously final design evaluation not yet done
- 4th SALT iteration submitted
  - This must work

Fingers crossed





Long flex



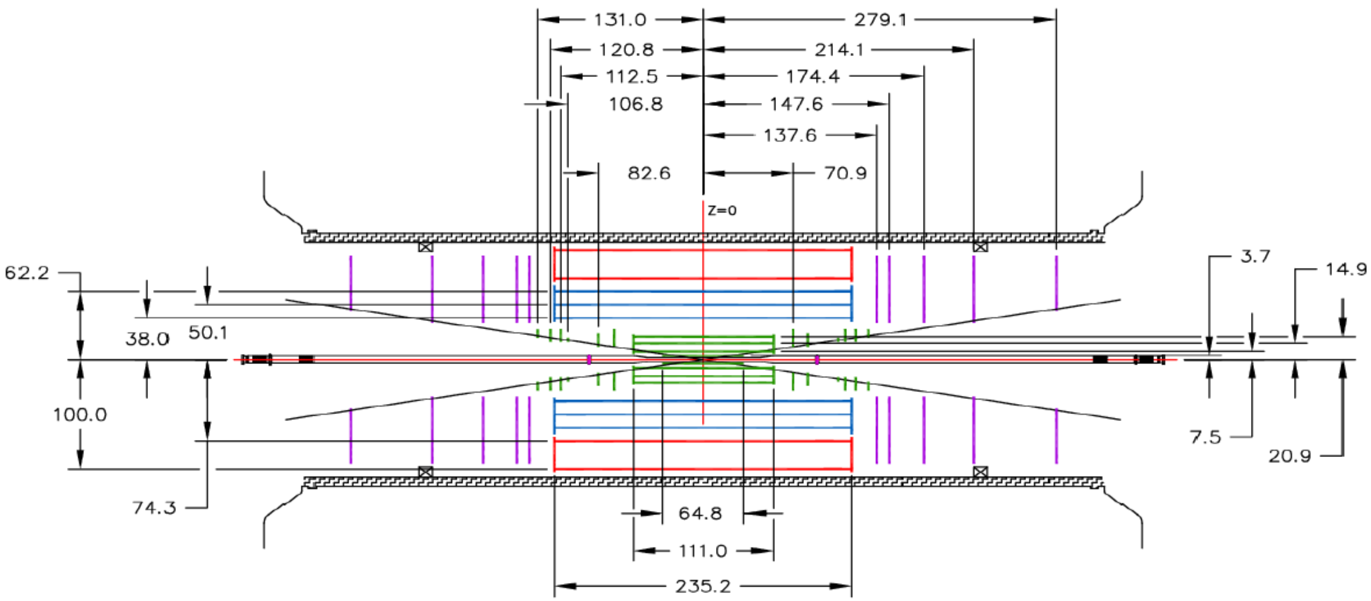
ATLAS and CMS

Nicely presented by

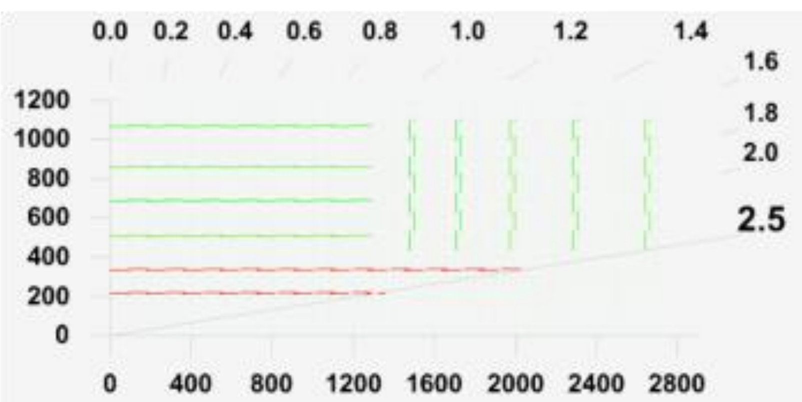
Matthias Hammer,
Stella Orfanelli,
Serhiy Senyukov,
Anirban Saha

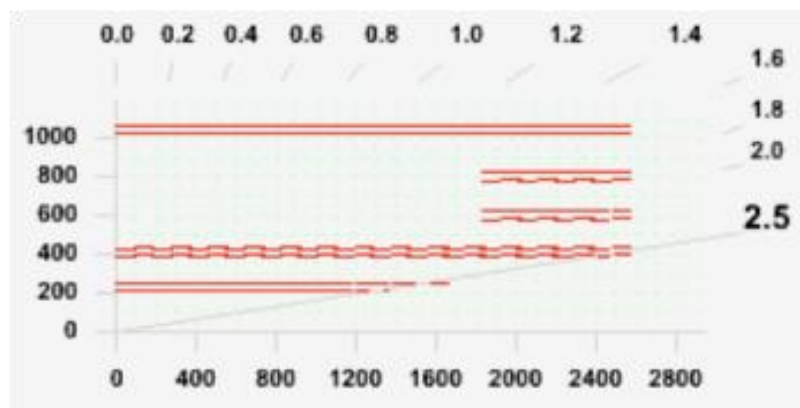
Mixed by Frank Hartmann

ATLAS & CMS Phase II -- ideas in 2010



- Pixels
- Short strips
- Long Strips
- End-Cap





- Strip PT
- Pixel-Strip PT

Technologies

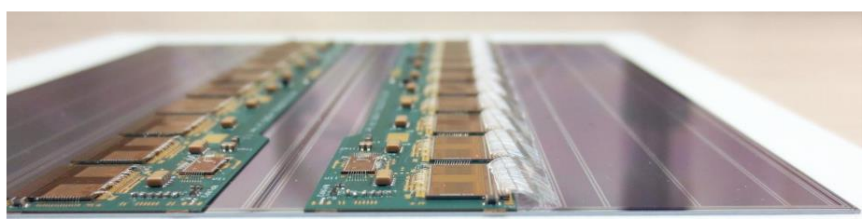
Pixels

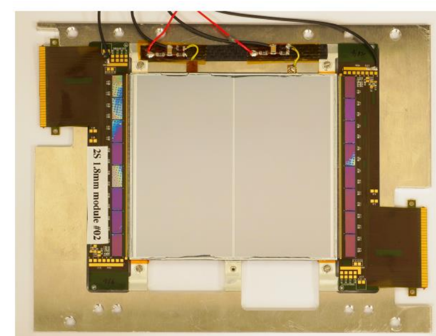
- Light weight mech.
- Serial power
- CO_2
- n-in-p sensors
- RD53B (see earlier)

Outer Tracker

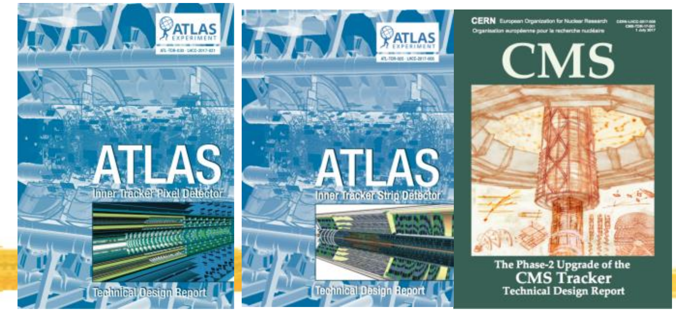
- Light weight mech.
- DCDC
- CO_2
- n-in-p sensors & 3D
- ABC / CBC
- Modules quite different
  - More later
- CMS Track Trigger

Good ingredients to be light





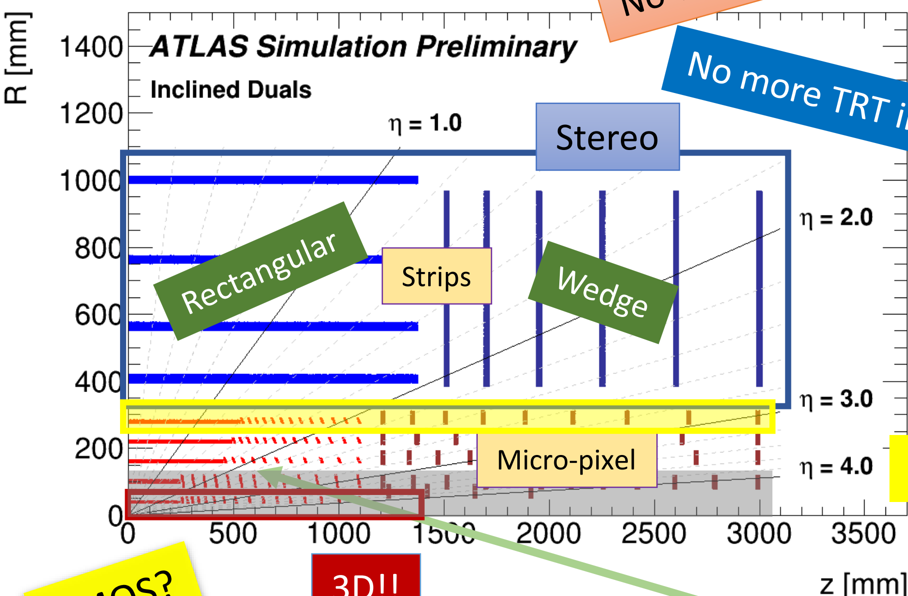
The two beasts for LS3



Sensor active thickness 100 - 300 μm

No Trigger inside

No more TRT inside



Stereo

Rectangular

Strips

Wedge

Micro-pixel

η<4

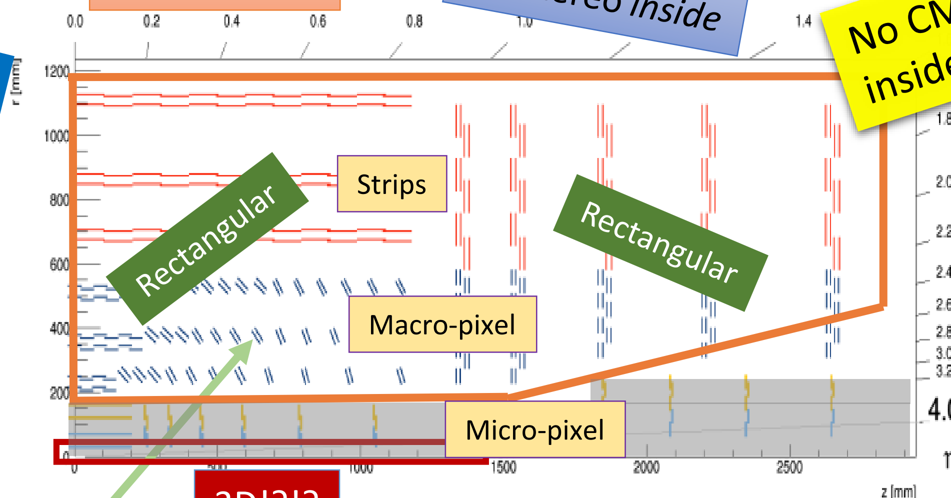
3D!!

CMOS? inside

Trigger inside

No Stereo inside

No CMOS inside



Rectangular

Strips

Rectangular

Macro-pixel

Micro-pixel

η<4

3D!?!?

Sensor active thickness 100? - ~240(300) μm

Easy Extraction

Inclined

All n-in-p *inside* with different thicknesses

Homework:
Why does CMS has 2 more OT layers than ATLAS?
Why has CMS one pixel layer less?

Presented by CMS

Who triggered this triggering idea?

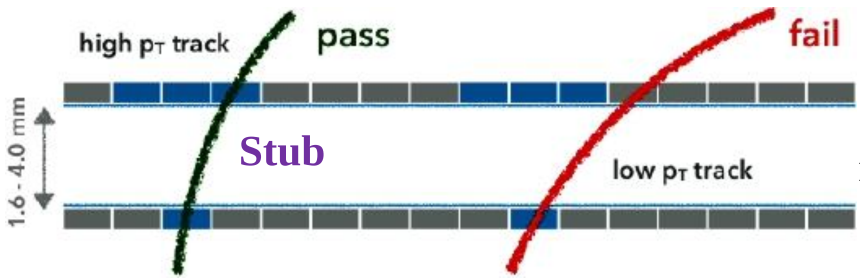
@ full 40 MHz readout all hits/*stubs* compatible with p_T>2 GeV

@L1 fully reconstructed tracks (p_T>2 GeV) with ~ 1 mm vertex res.

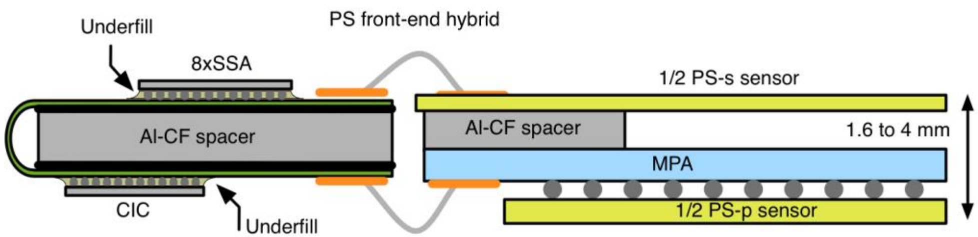
➔ **The need to have Tracking in L1 defines largely the CMS Tracker design!**

Fun fact: ~80% of data rate is trigger data

Thanks to CMS 3.8 T magnetic feld!

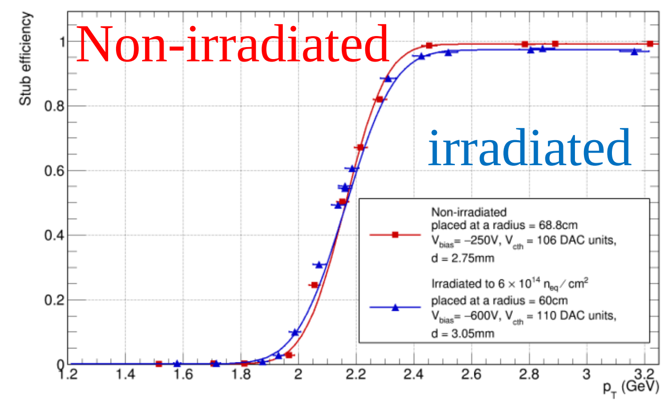


Same electronics reads two sensors



Stub correlation MPA

Stub efficiency



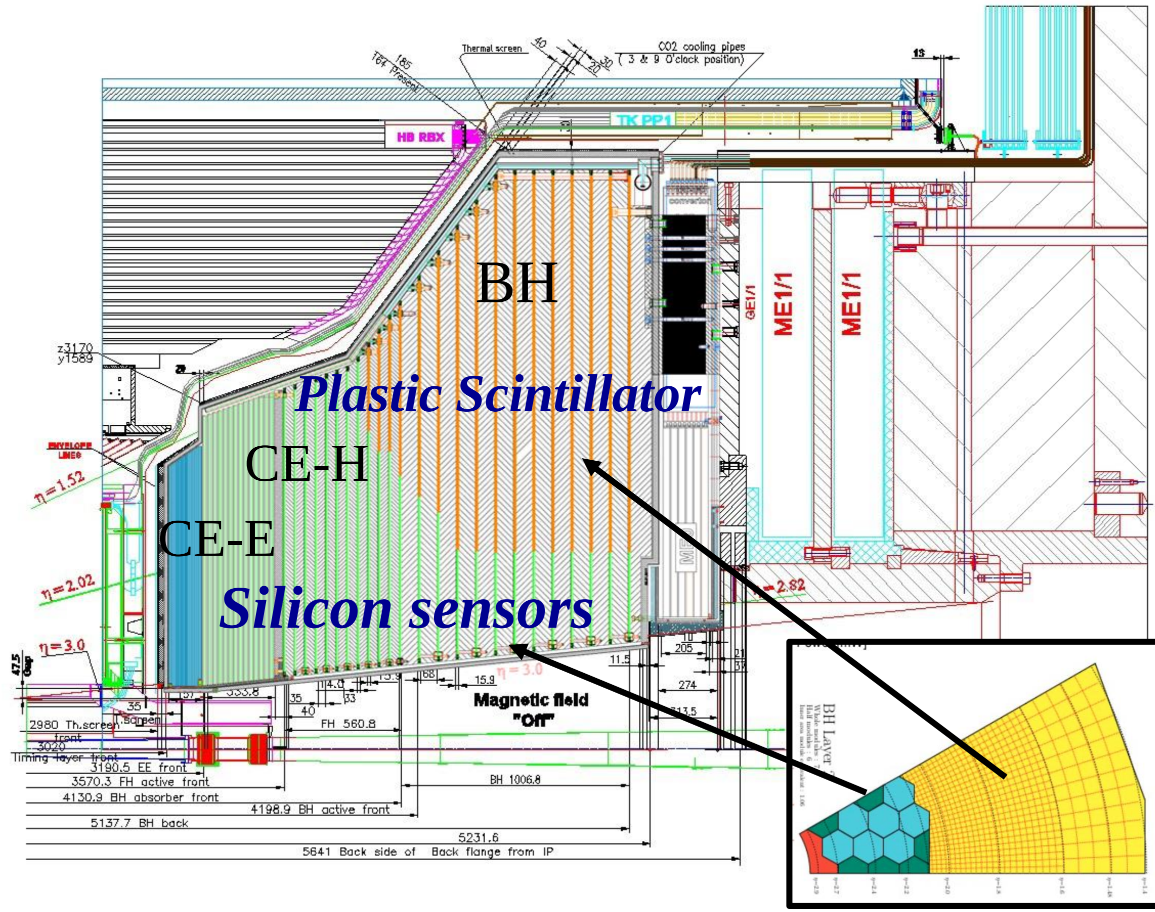
➔ Rate reduction - factor 10-100

Welcome calorimetry

5D Calorimeter (X, Y, Z, t, ΔE)

Proudly presented by
Shashi Dugad

- CMS endcap calorimeter **fka** High Granularity Calorimeter HGCAL will operate at T=-30°C
- The silicon part
  - ~600 m² of silicon
  - ~6M channels, 0.5 or 1 cm² cells
  - ~25000 modules (8” sensors)
- + Plastic scintillators
  - 500m² plastic scintillators
  - 400k SiPMs on tile
- Timing, trigger



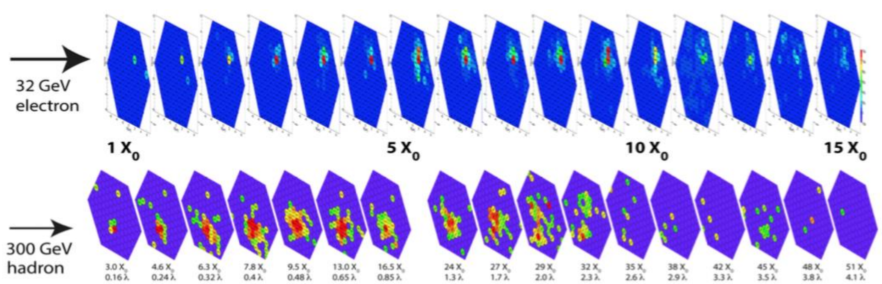
Tungsten/Pb

*CE-E: **28** sampling layers – 25 X_o + ~1.3 λ*

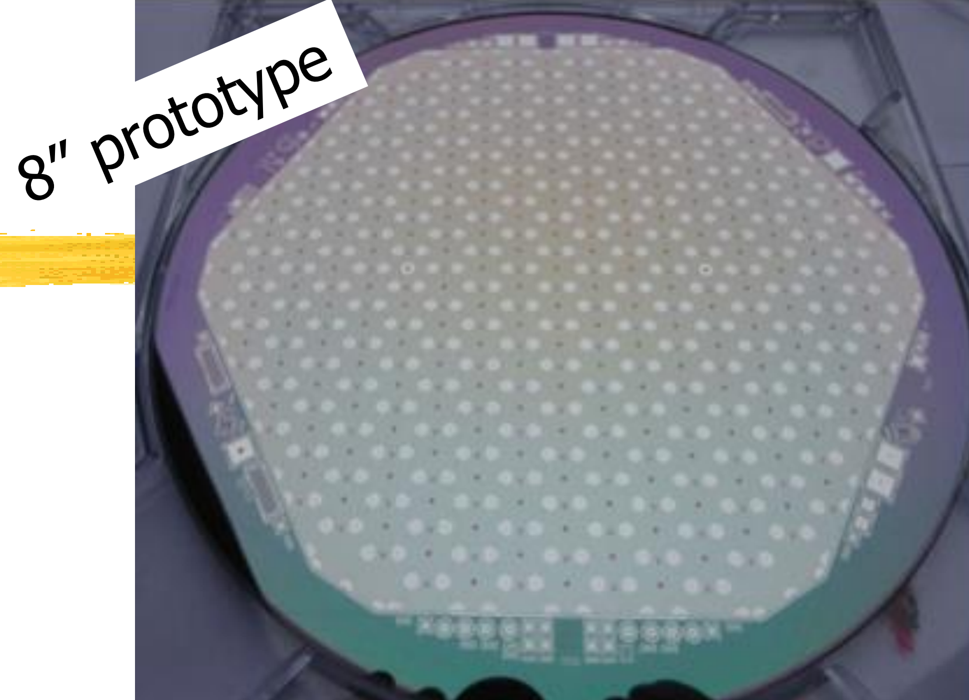
stainless steel

***24** sampling layers – 9 λ*

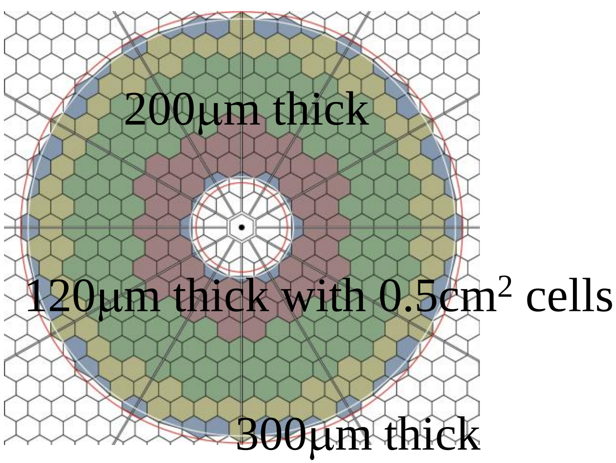
Testbeam

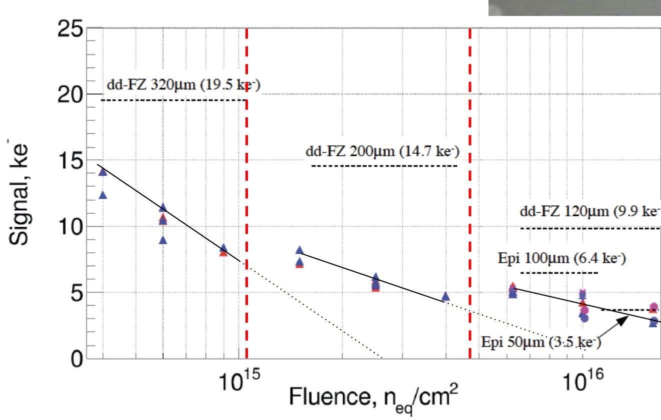


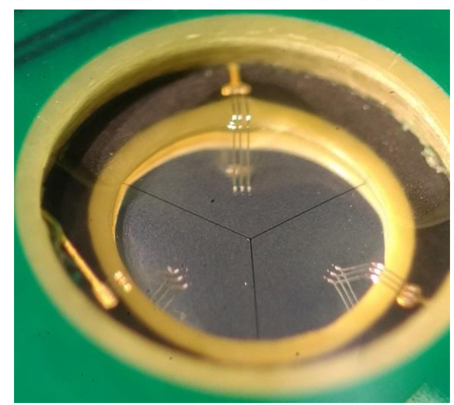
HGCAL sensors



- 8″ wafers are baseline
- Hexagonal to maximize use of area
- 120, 200, 300 μm thick n-in-p pad sensors
  - No biasing scheme
- Cell size ~0.5 or ~1 cm^2
  - Smaller cell size in central region
    - Due to occupancy and noise
- Tested *OK* at $1.5x10^{16}$ n_{eq}/cm^2 neutron only
- Cells are wire-bonded to a PCB on top with holes







Potential Future

3D integration

FCC

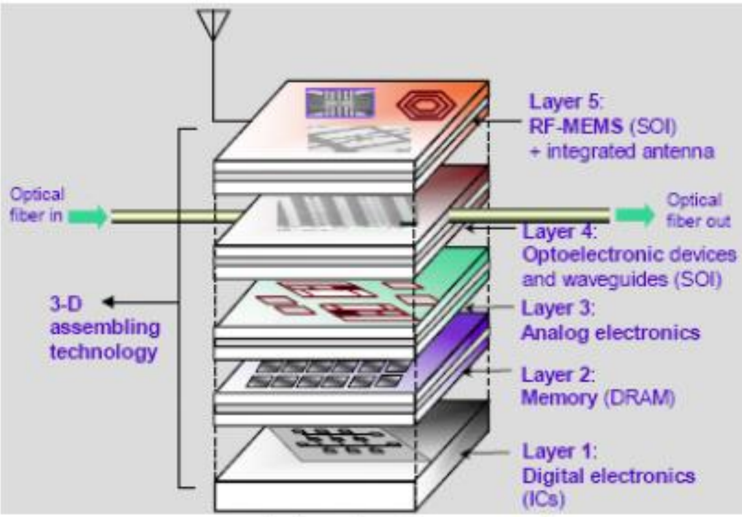
ILC

CLIC

Nice picture of a person looking in a crystal ball

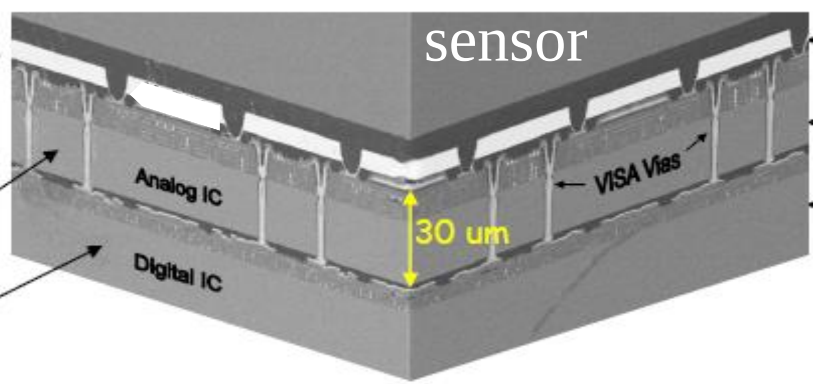
3D vertical integration
– one dimension too much for me

By Valerio Re



The industry dream
J. Joly, LETI

Possible HEP dream (schematic)



- Denser (smaller form factor)
- Faster (reduced delay because of shorter interconnects)
- Lower power (smaller interconnect capacitance)
- Lower cost (sizably less expensive than aggressive CMOS scaling)
  - In CMOS electrode and digital must fit into cell
- Integration of dissimilar technologies
  - sensor, analog, digital, optical
  - Monolithic

➔

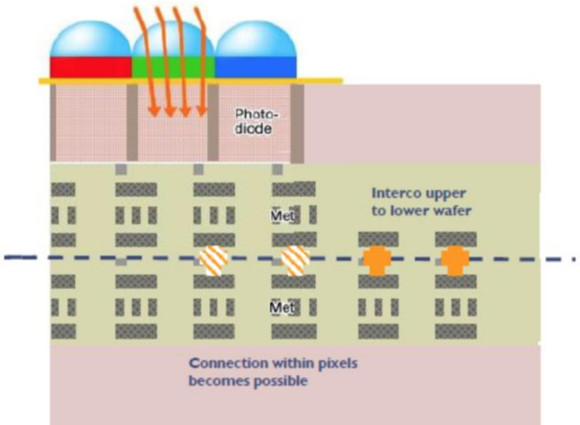
- **Improve resolution**
  - **shrink pixel size and pitch**, down to 20 μm or even less
- **Preserve or even increase pixel-level electronic functions**
  - handling of high data rates, large dynamic range, high resolution analog-to digital conversion and timing, sparsification, large memory capacity, intelligent data processing...: presently this also contributes to limiting the minimum size of pixel readout cells
- **Decrease amount of material**
  - **thin sensor and electronics** (50 -100 μm total thickness)

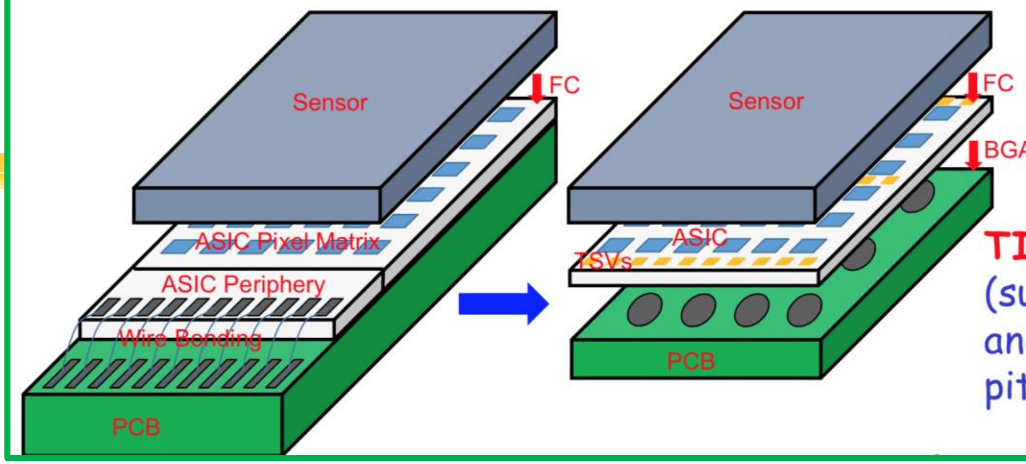
For ILC??

3D II

LFoundry

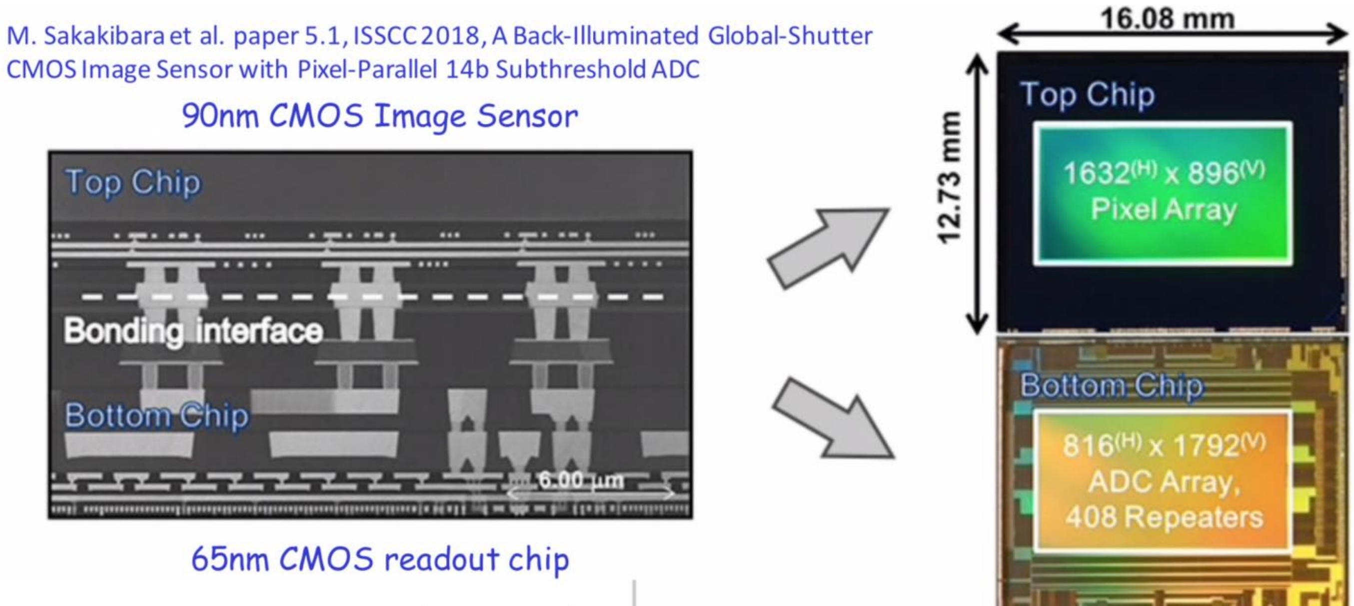
- now Hybrid / Stacking is developed to improve fill factor, speed, low power, …





TIMEPIX4 chip (sub-ns time stamping and reduced pixel pitch):

M. Sakakibara et al. paper 5.1, ISSCC 2018, A Back-Illuminated Global-Shutter CMOS Image Sensor with Pixel-Parallel 14b Subthreshold ADC



SONY:
Pixel size 6.9 x6.9 μm^2 & 14-it ADC

Which is for us?
Which for industry?

Ok, 10^{16} n_{eq}/cm^2 works. Let's go to 10^{17} n_{eq}/cm^2.

From the OFF: but we need 10^{18} n_{eq}/cm^2

- Physicist: **Ok**, thin is good, → let's go thinner 50μm
- Engineer: Sorry, **NO**, signal is not enough and amplification via very high voltage does not work
- Physicist: **But** it will be amplified after several 10^{15} n_{eq}/cm^2 and then it stands the voltage – change of doping by rad.!
- Engineer: Sorry, **NO**, what do I do until then?
- Physicist: **OK**, then we build an amplification layer a la LGAD
- Engineer: **But** LGAD works only until several 10^{15} n_{eq}/cm^2
  - donor removal
- Physicst: Haha, and then …
- Engineer: **OK might work.**
  - Please solve the LAGD fill factor issue allowing small pixels otherwise the S/N is probably still too low.

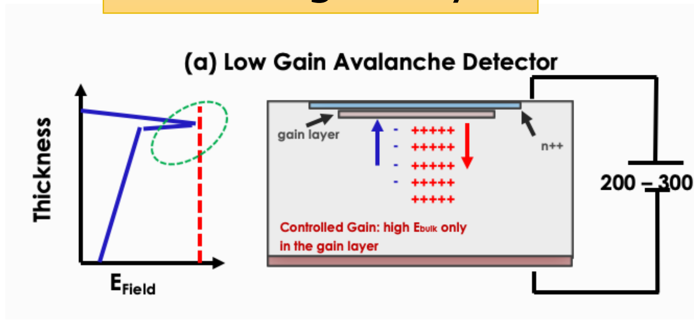
→ **Use different amplification mechanism for different fluence levels**

→ **Control the gain (bias voltage)**

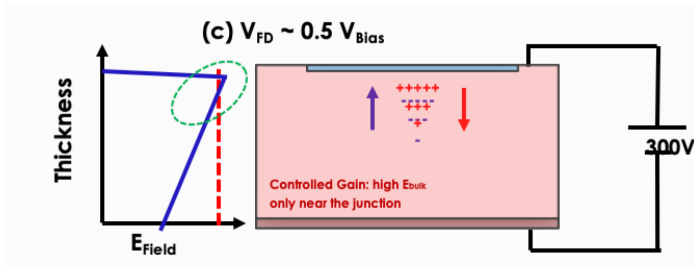
Physicist = Nicolo Cartiglia

Good Luck

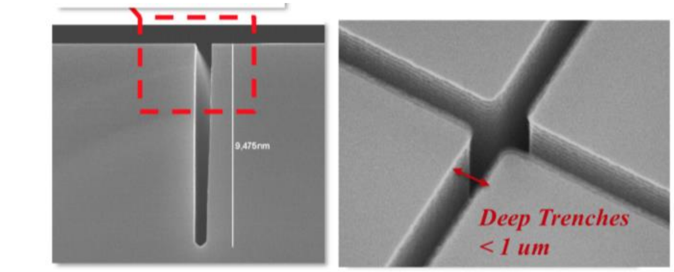
Gain via gain layer



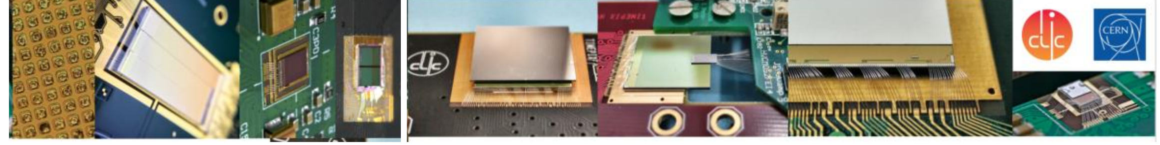
Gain via Vbias and bulk doping



Physicst answer:



CLIC

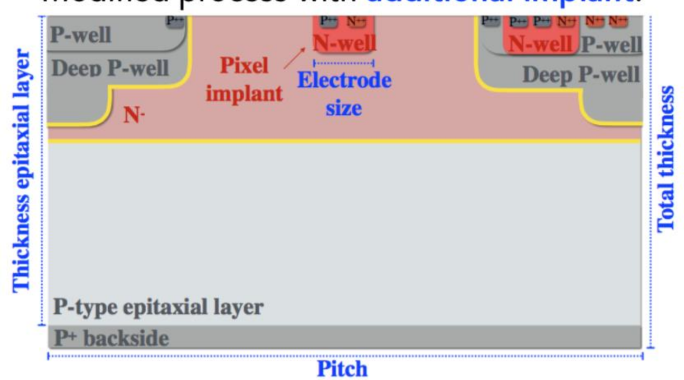


A=140 m^2 silicon

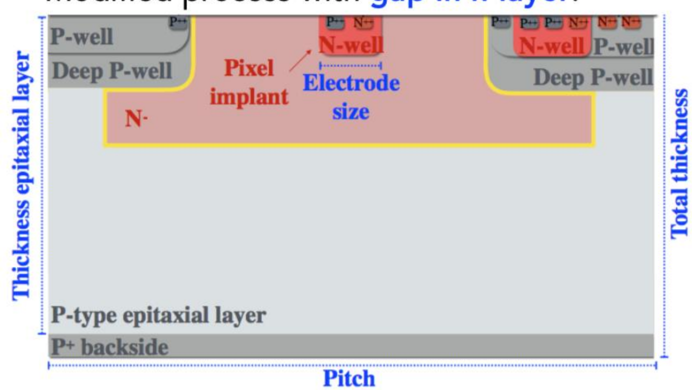
Studied by Ruth Magdalene Munker

- Tracker
  - Spatial res. 7 μm
  - Material 1-2 % X_0/layer
  - Timing res O(ns)
- Vertex
  - Spatial res. 3 μm
    - 25x25 μm pixels
  - Material 0.2 % X_0/layer
  - Timing res O(ns)
- Technologies under investigation:
  - Hybrid to CLICPIX
    - BB + passive sensor
    - Glued (capacitively coupled) + active CMOS
  - Monolithic:
    - SOI
    - HR CMOS
    - Next generation of HR CMOS
- Large number of studies shown

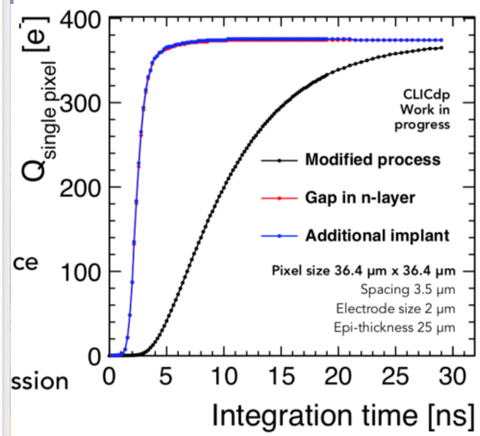
Modified process with additional implant:



Modified process with gap in n-layer:



Simulated



Submitted - MALTA

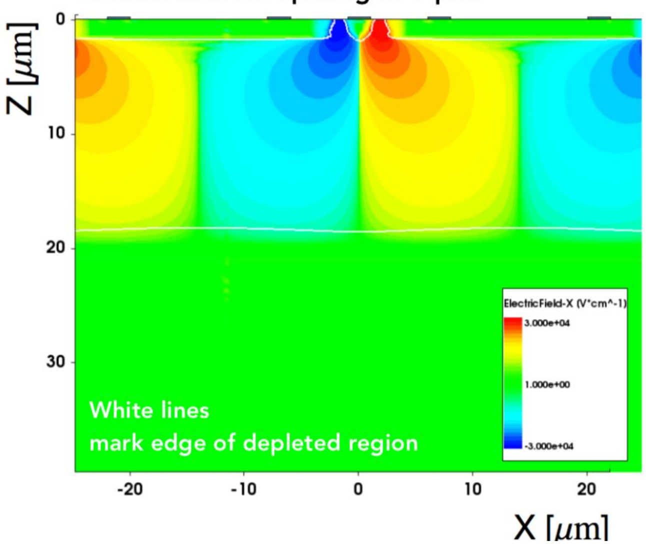
Shape field - helps with timing and corners

CLIC, one representative study

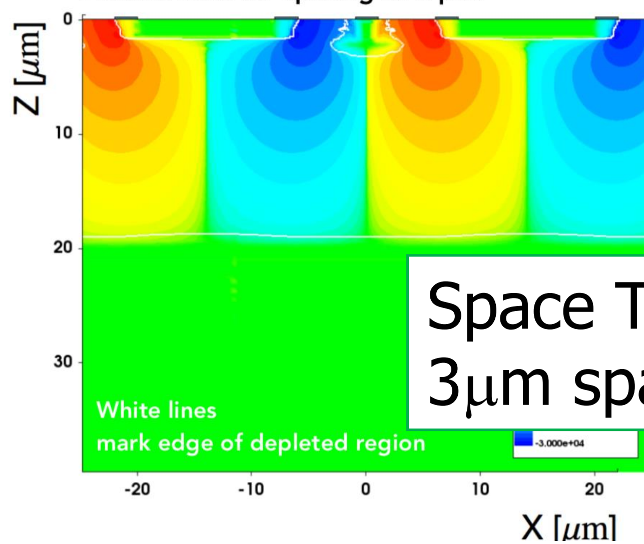
Results of 2D TCAD simulations for different spacings for the modified process:

PhD Thesis M. Munker CERN-THESIS-2018-202

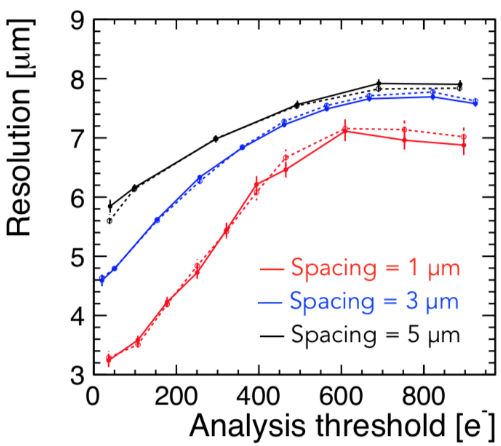
Electric field for spacing of 1 µm:

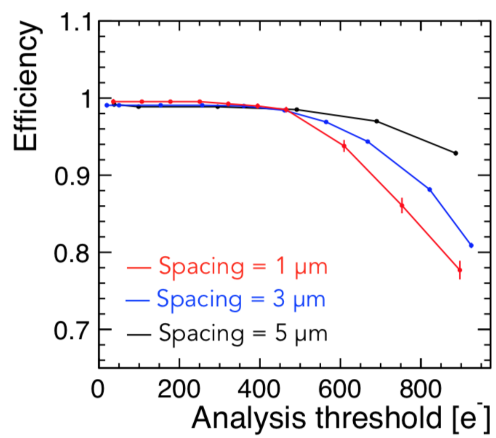


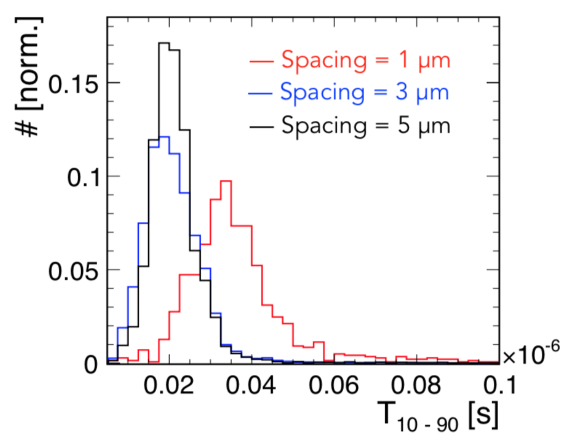
Electric field for spacing of 5 µm:



Space Time compromise:
3µm spacing

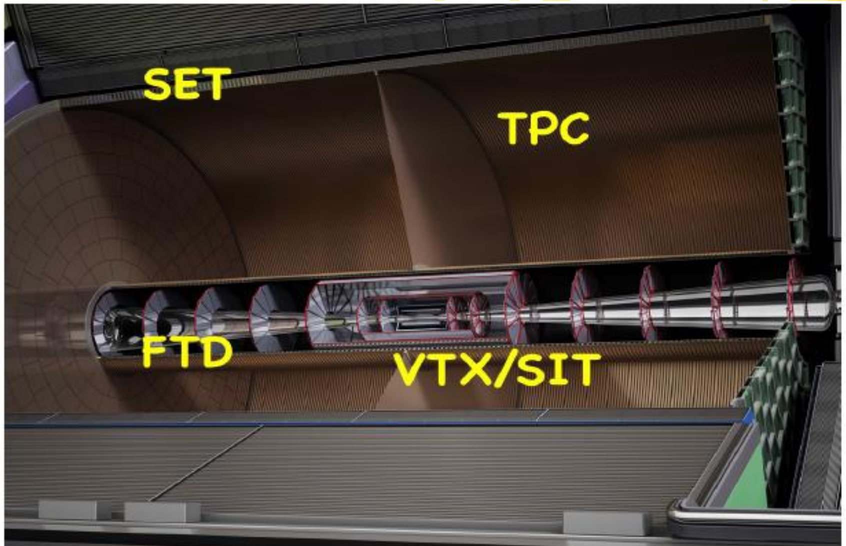


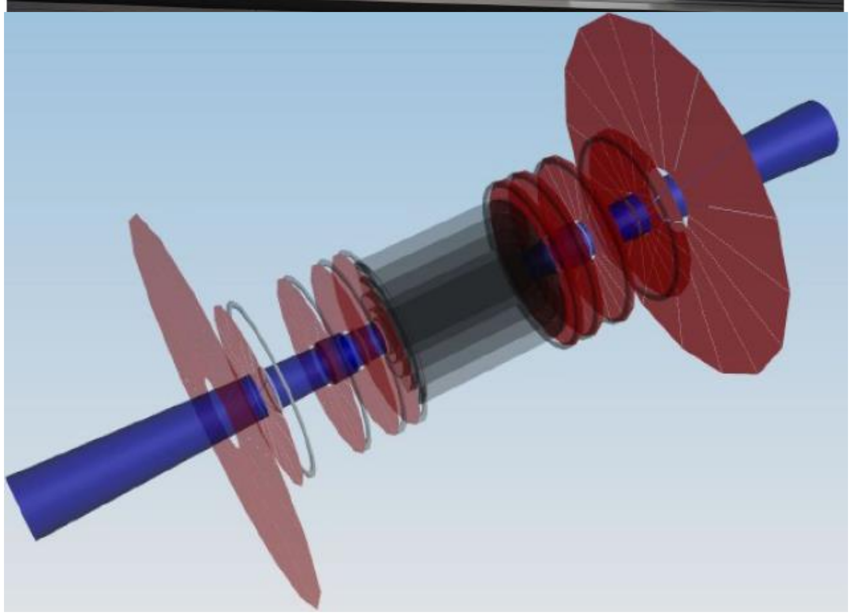




By Gagan Mohanty for the SiD and ILS collaboration

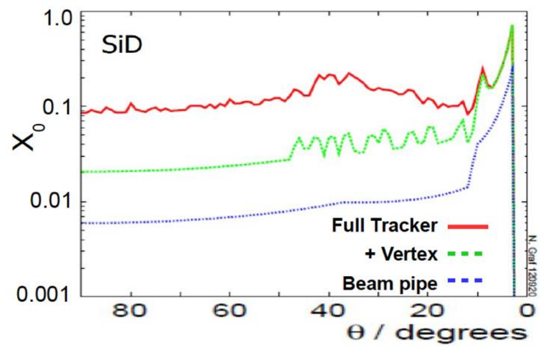
ILD and SiD @ ILC usual question: which is which

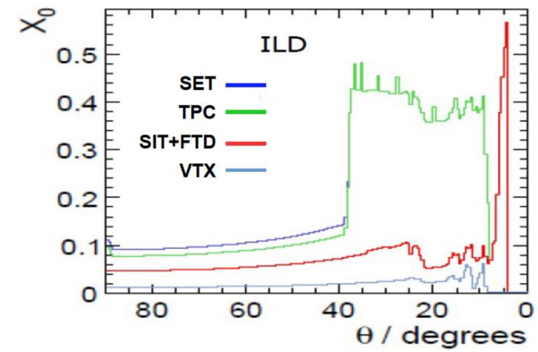




100MeV track reconstruction

Super low material budget





Current sensor R&D:

- 20x20 (16x16) μm^2 pixel
- DEPFET, FPCCD, SOI and CMOS and **3D vertical integration**

☞ What is the need of hour?
Political decision in Japan and rest-of-the world

Explained to you by Estel Perez Codina

FCChh aka I need another crystal ball

- **FCC-hh (pp-collider)**
  - **100 km long tunnel (Geneva area)**
  - **~16T magnets**
  - **√s=100TeV**
- **How do we build a detector suitable for 100 TeV pp collisions?**

Parameter	(HL) LHC	FCC-hh	
		"Baseline" (10 years)	"Ultimate" (15 years)
Collision √s energy [TeV]	14	100	
Dipole field [T]	8.33	16	
Circumference [km]	26.7	97.75	
# IP	2 & 2	2 & 2	
Bunch spacing [ns]	25	25	25 (5)
Luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	(5) 1	**5**	**30**
# Events/bunch crossing	(135) 27	170	**~1000** (200)

O(20) ab^{-1} per experiment in **25 years** of operation

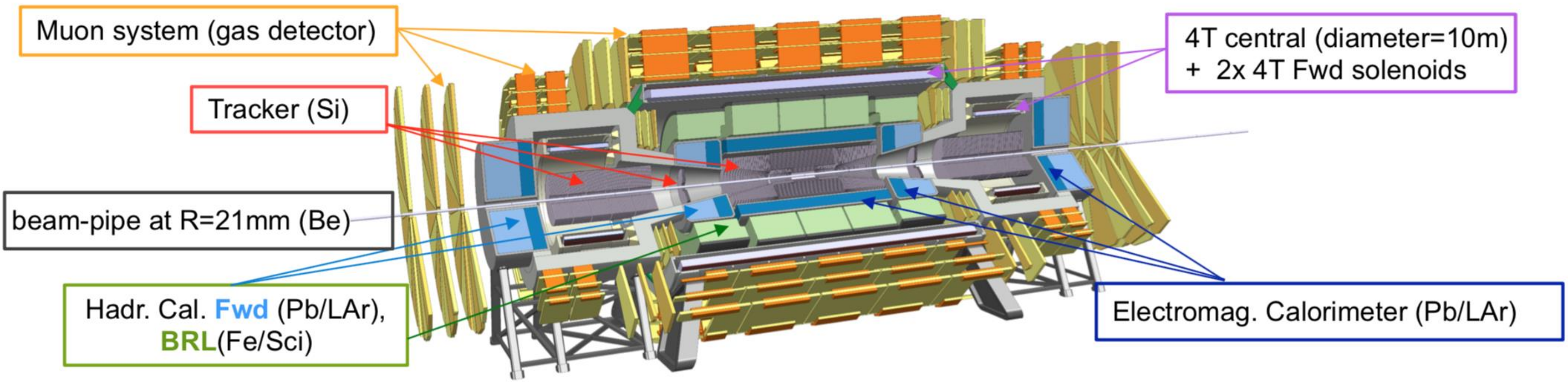
- High precision **tracking up to |η|~4** (is 2.5 at LHC)
- **~10-20% for 10 TeV tracks** (10% at 1TeV at LHC)
- Reconstruct tracks in the **dense environments** created by boosted jets.
- Provide efficient **b, c, τ-tagging**
- Etc.

- Sensor $10^{18} n_{eq}/cm^2$
- Spatial resolution 10μm everywhere

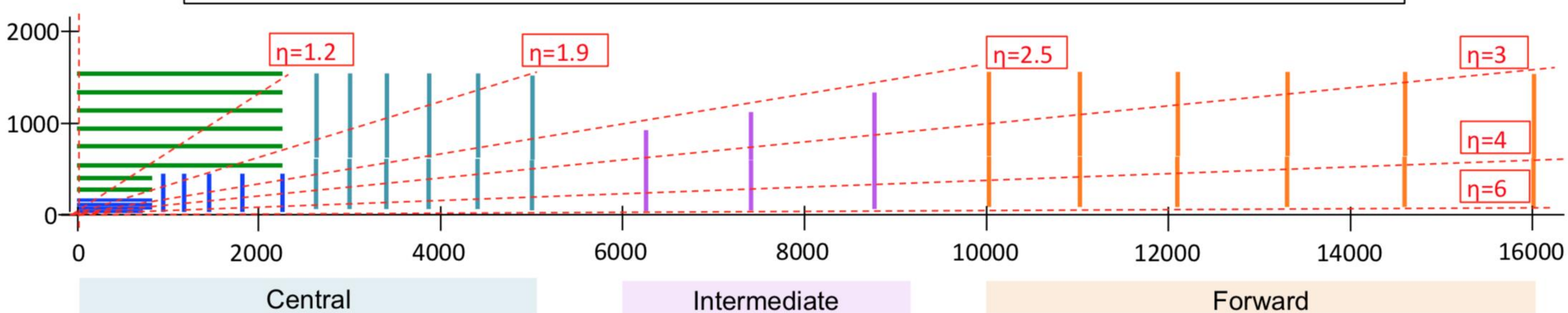
We have a new challenge!

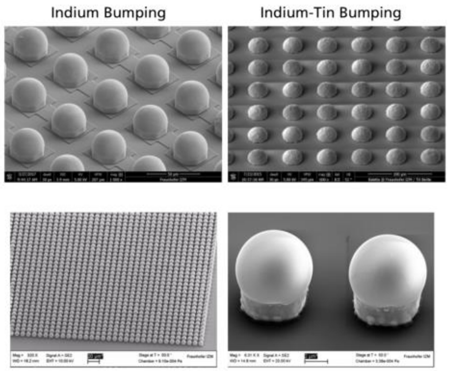
NEXT: FCC Conceptual Design Report by the end of **2018**

Reference detector layout

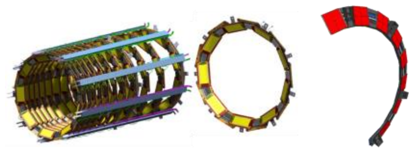


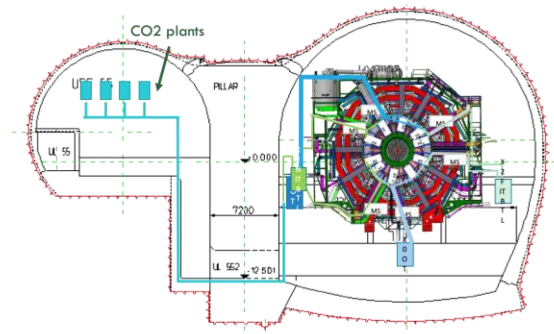
Tracker radius: 1.6m , half-length: 16m , 4T solenoidal B-field





Indium Bumping 10 µm Pitch for IR image sensors





Cooling

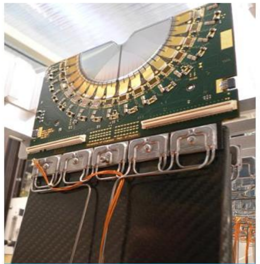
Mechanics

Interconnection

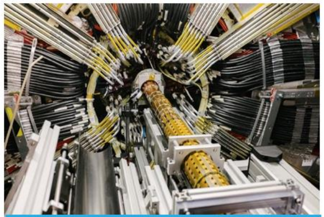
This morning

WHERE?

So far…

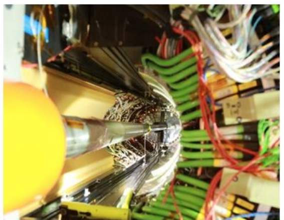


LHCb Velo 1.6 kW @ -25 C



ATLAS IBL 1.5 kW @ -35 C

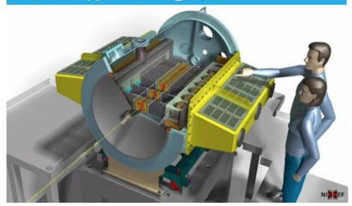
AMS Tracker 150 W @ -20 C



CMS Pix Phase I upgrade 7 kW @ -25 C

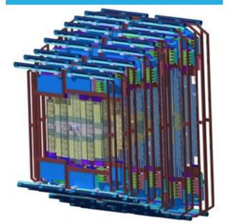
In the near future …

LHCb Velo Upgrade - 2 kW @ -35 C



Source: The LHCb Collaboration, LHCb VELO Upgrade Technical Design Report, CERN/LHCC 2013-021, Nov 2013

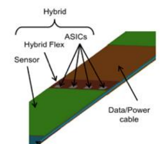
CBM STS



Source: A. Lymanets et al, "The Silicon Tracking System of the CBM at FAIR: detector development and system integration" TIPP 2014

BELLE II Vertex Detector

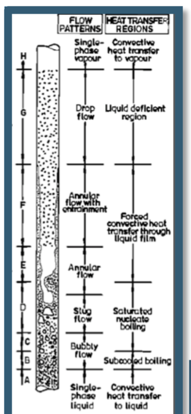
Source: H. Ye" Thermal Test and Monitoring of the Belle II Vertex Detector" Forum on Tracking Detector Mechanics 2016, Bonn



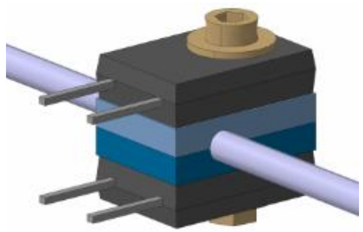
LHCb UT 5 kW @ -35 C

CO_2 probably also inside Paola Tropea

Then there are the details



Vertical pipe



Pre-heater concept tested (2x10W resistors clamped to pipe)

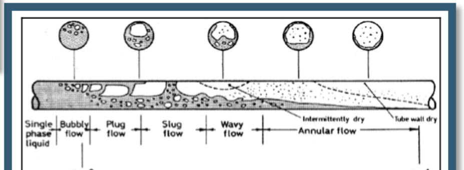
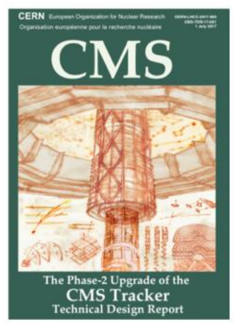


Figure 10.5. Flow patterns during evaporation in a horizontal tube from Collier and Thome (1994).

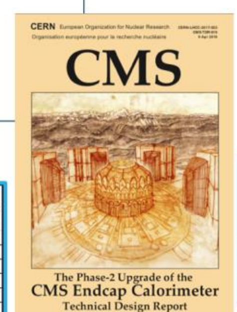
Horizontal pipe

AND THEN? AT HL-LHC…

CMS

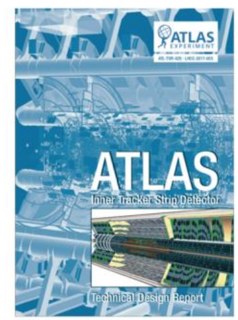


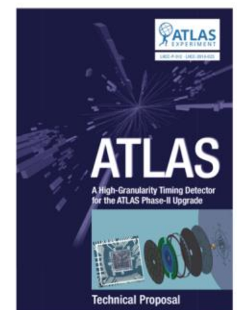
TECHNICAL PROPOSAL FOR A MIP TIMING DETECTOR IN THE CMS EXPERIMENT PHASE 2 UPGRADE

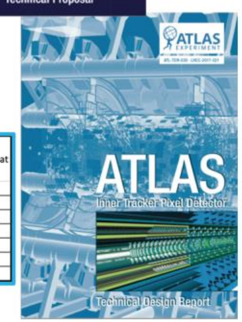


CMS	Evaporation T at the detector exit	Heat load of detector	Ambient pick up	Total heat
	ºC	kW	kW	kW
Outer Tracker	-35	102	11	113
Inner Tracker	-35	50	5	55
Barrel Timing Layer	-35	45	6.5	52
Calorimeter Endcap	-35	240	7	247
Endcap Timing Layer	-35	80	8.0	88
		517	37.5	555

ATLAS







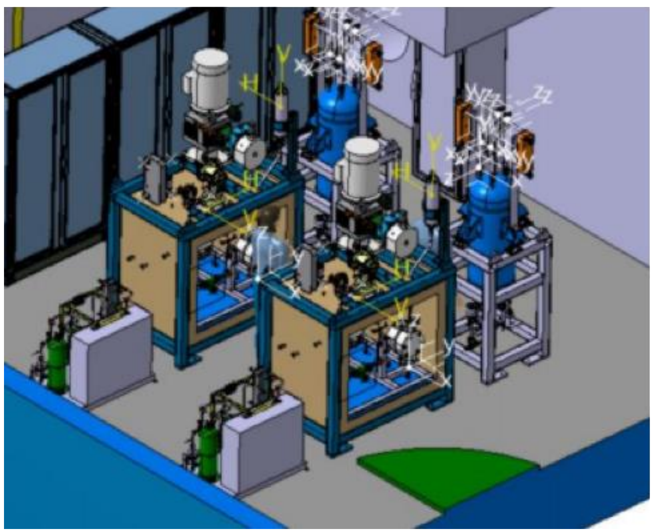
ATLAS	Evaporation T at the detector exit	Heat load of detector	Ambient pick up	Total heat
	ºC	kW	kW	kW
Pixel Endcap	-30	26.2	2.6	113
Pixel Barrel	-35	55.1	5.5	60.61
Pixel Insertable	-45	20.6	2.1	23
Strip	-30	122.7	12.3	135
HGDT	-30	25	2.5	28
		249.6	24.96	359

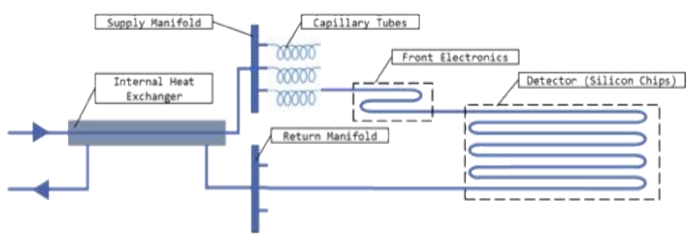
A good order of magnitude bigger & more complex than ever….

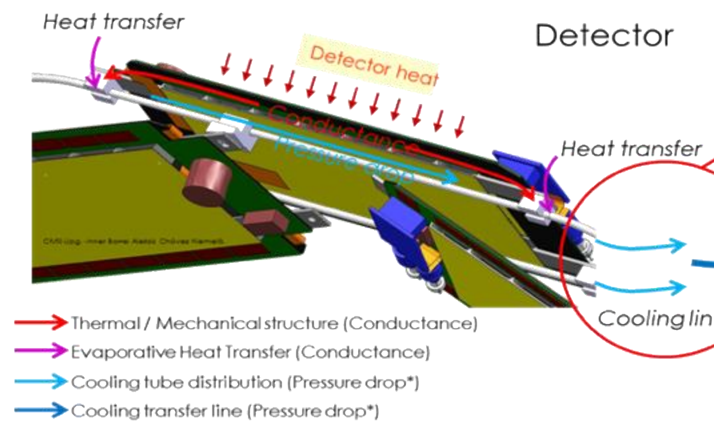
CO_2 systems - The design chain

- The complexity of an evaporative system: each design modification on a components would influence the behaviour of the full system: how?

site integration	experiment integration	detector design	electronics and module design
⇅	⇅	⇅	⇅
cooling plant ⇄	transfer lines ⇄	distribution ⇄	heat sink







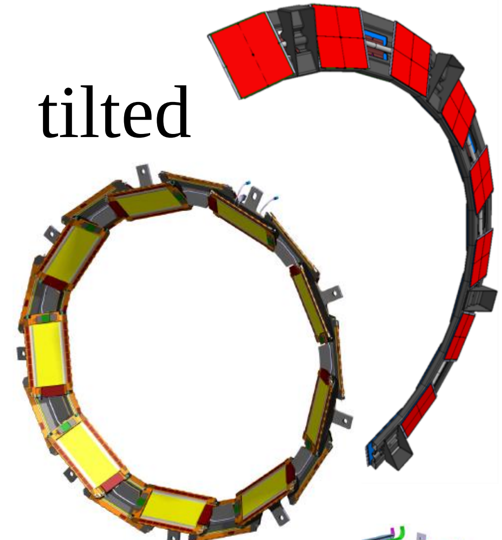
Need a lot of chats & coffee

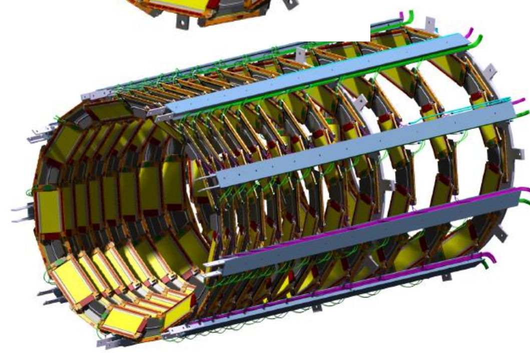
Kindly presented by Georg Viehhauser

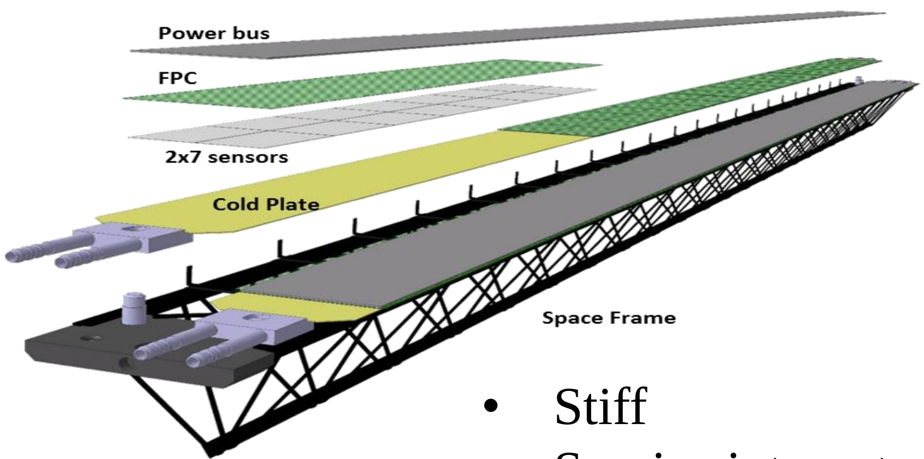
Advanced mechanics for silicon tracker

- Mechanical properties are driven by needs of Track Based Alignment (TBA)
  - **The key requirement is stability not initial position**
- Thermal properties are driven by radiation damage issue
  - bring cooling as close to heat sources as possible
- Future experiments require $0.1X_0/1X_0$ per layer
  - Material-optimized layouts do require tilted module geometries
  - Services must be tightly integrated into structures
  - Stiffness optimization and material optimization

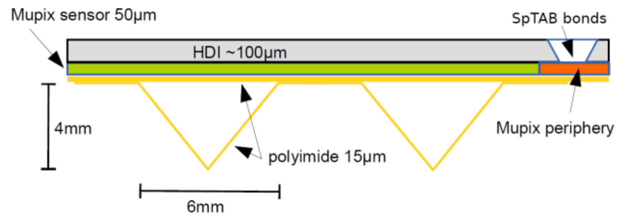
tilted







- Stiff
- Service integrated



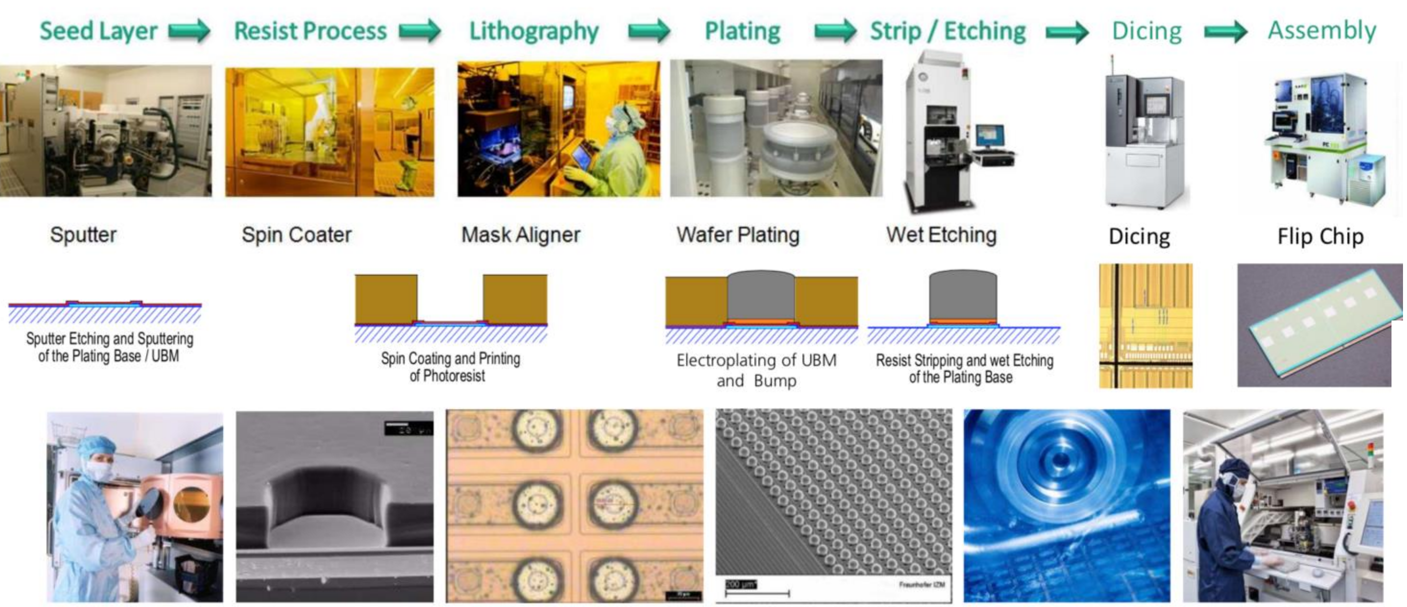
Ultra low mass

I do not like mechanics and services – <u>too heavy</u>

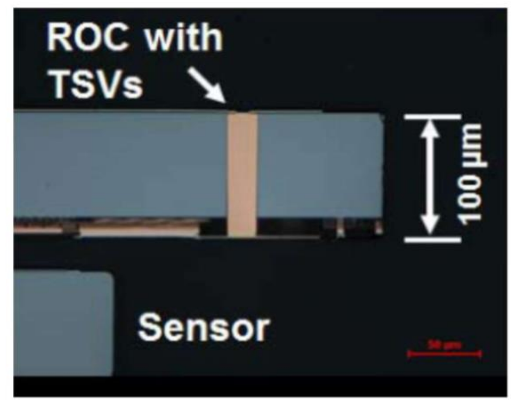
Thanks IZM and Thomas Fritzsch

Hybridization techniques

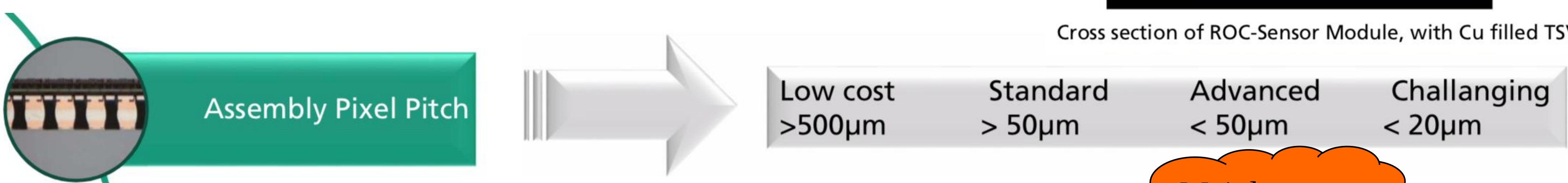
Wafer Level Packaging: Micro Bumping and Hybridization Process



- ⌘ For the immediate future, we go with **BB** and **TSV**
- ⌘ Later (see 3D), we want **<u>more</u>**



Cross section of ROC-Sensor Module, with Cu filled TSV



Mainly Just lucky

@ IZM – thank you always being patient with us

Organisers Thank You

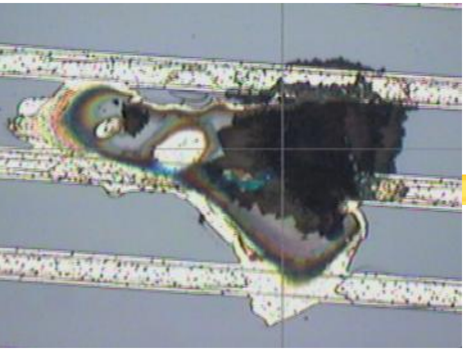
GREAT Job!!

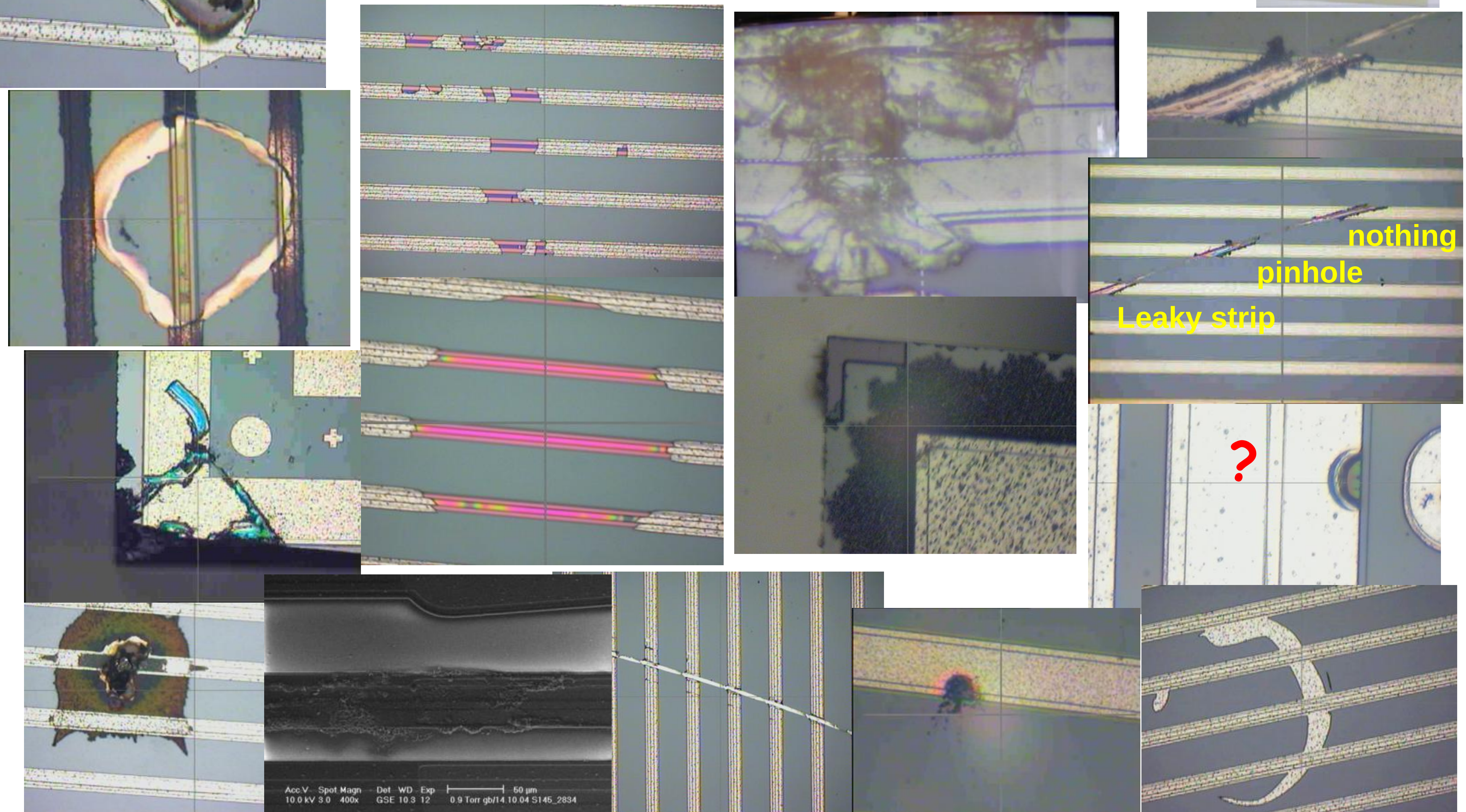
A+++++

Nice Dinner on Tuesday

Backup

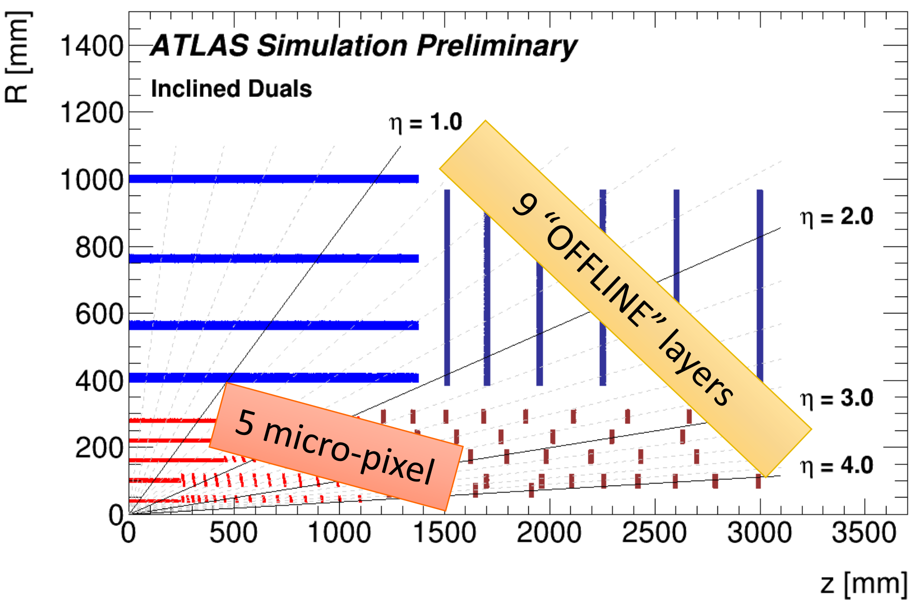
The ART of sensor defects

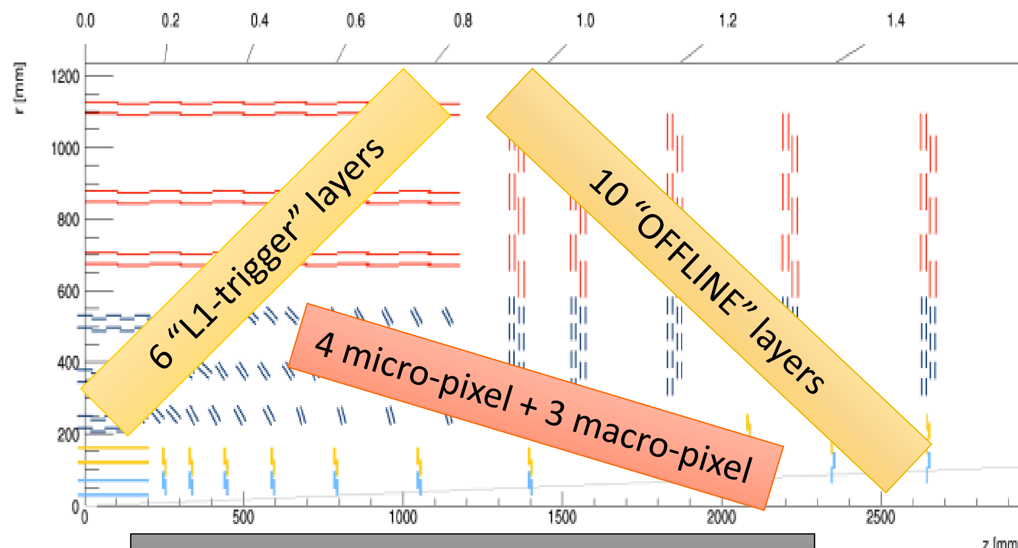




Please, explain the numbers of layers

- Why has CMS 6 and ATLAS *only* 4 outer layers?
  - You need to count "**OFFLINE**" and "**L1-trigger**" layers separately!
  - With a fine granular pixel, only ***few*** outer layers are needed to measure p_T
    - ***Few*** = enough + redundancy
      -- 4 seems a perfect number even for an inner 4-layer pixel detector
- Why ATLAS has 5 pixel layers and CMS *only* 4?
  - CMS has in fact 7 "pixel" layers, counting the 3 PS-layer with 1.5mm macro-pixels



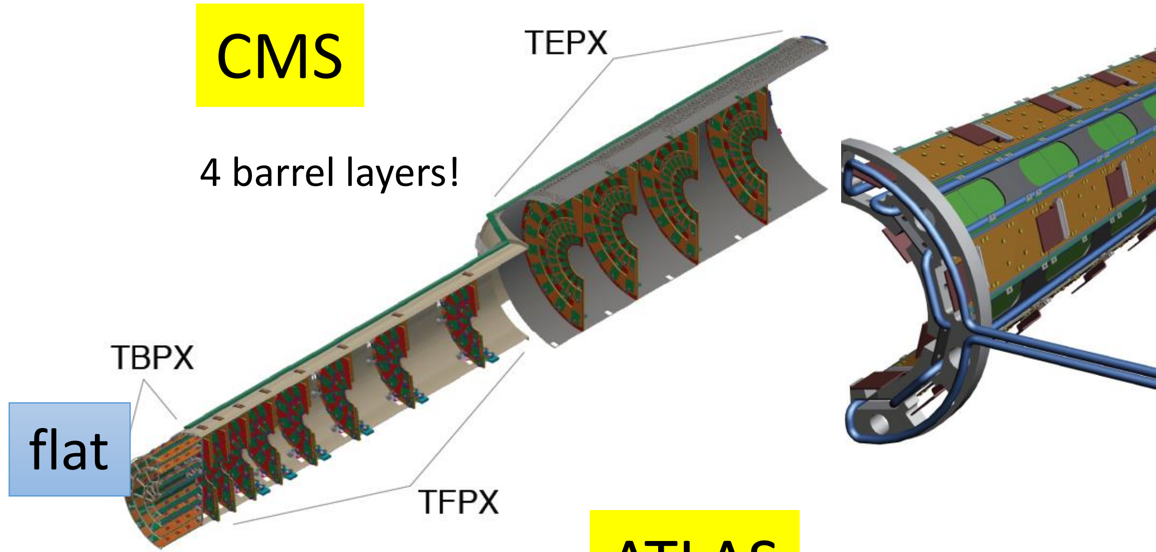


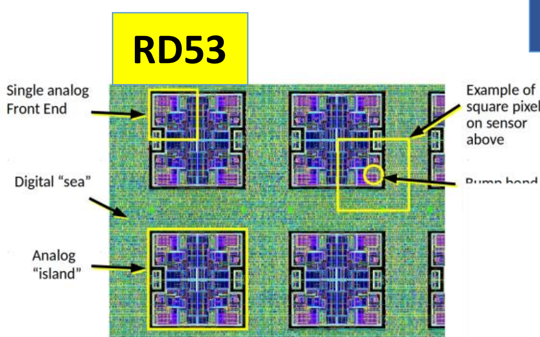
Fun fact: tilting helps track trigger a lot – rf. TK talk.

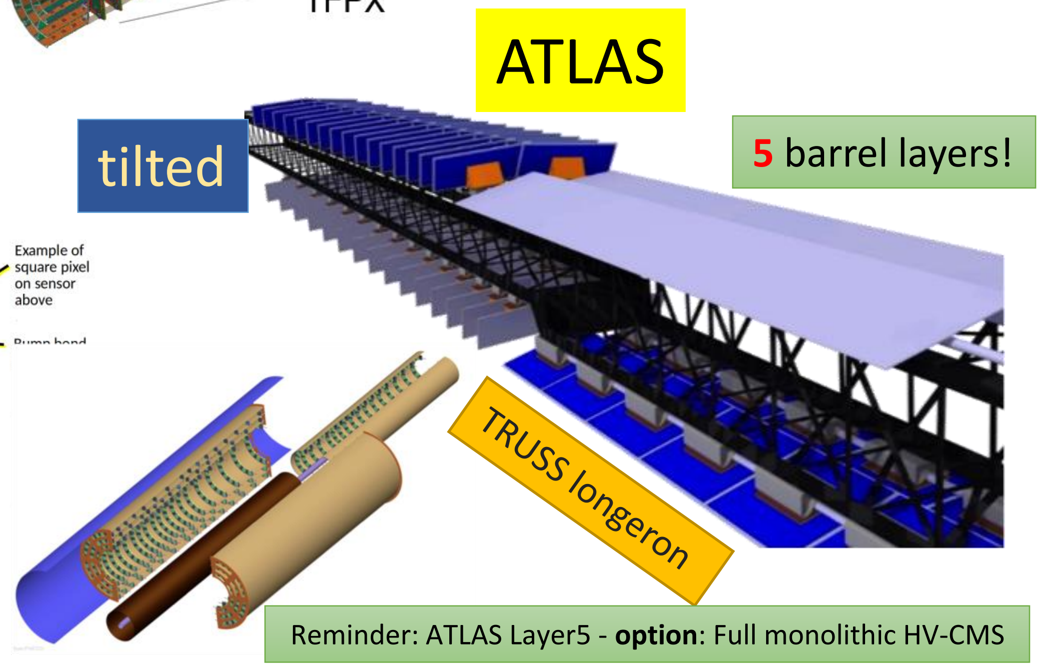
Next to the beam pipe

Many commonalities:

- "Classical" hybrid pixel detectors with bump-bonding
  - **THIN** Planar n-on-p or 3D detectors (inner layers)
    - Both need coating to prevent sparking
  - Common R&D on chip **RD53**A – 65nm TSMC
  - Modules: Doublets, Quads chip of singlets (ATLAS only)
- Different pixel cell layouts being tested:
  - 50 x 50 µm preferred by ATLAS
  - 25x100 µm preferred by CMS
- Serial Powering (part of **RD53**)
- Both detectors up to η=4
- Both easily extractable (half-shells)
- **Surface: 2*CMS < 1*ATLAS**



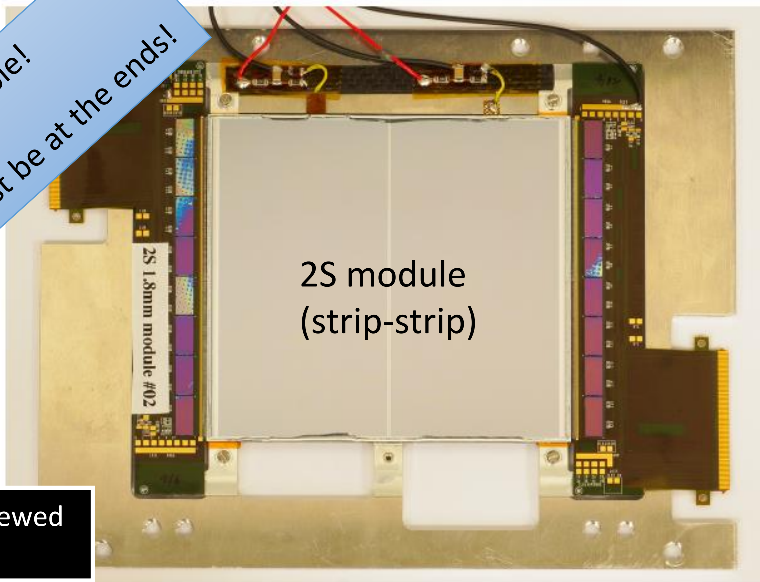




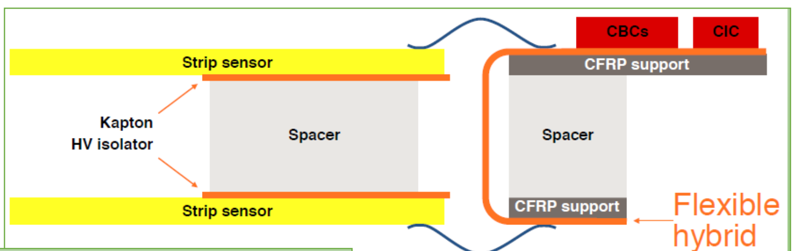
Away from the beam pipe

CMS

Stereo NOT possible!
Strips parallel
All chips must be at the ends!



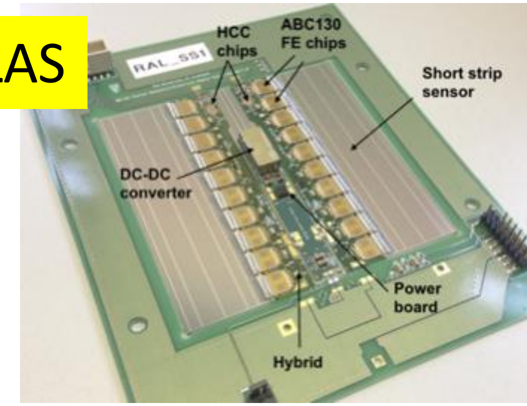
Mostly screwed to cooling



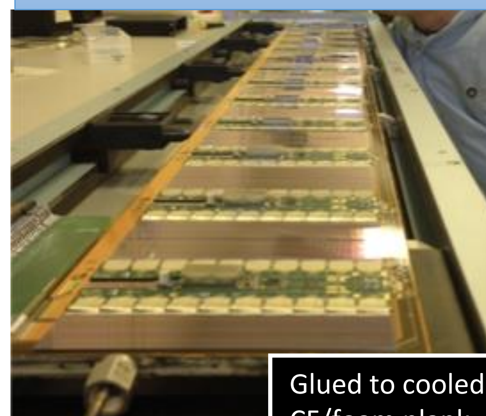
Interesting feature:
The module is the system!
No other electronics!

No full-size PS prototype yet

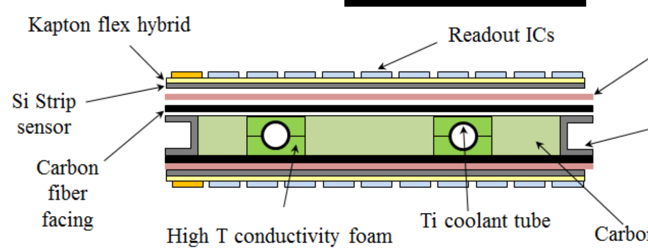
ATLAS

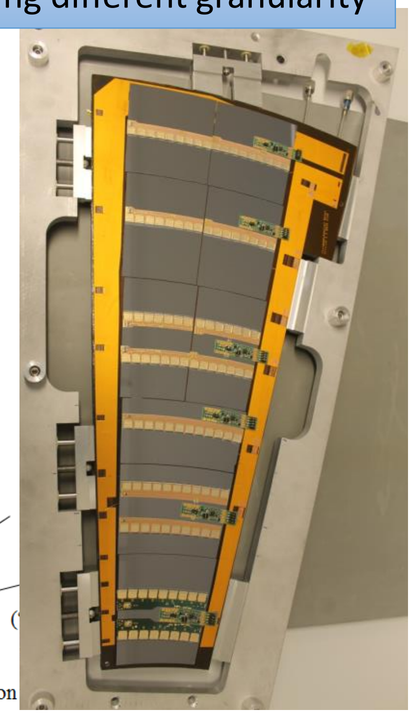


All Stereo – chips **on** sensor allowing different granularity



Glued to cooled CF/foam plank



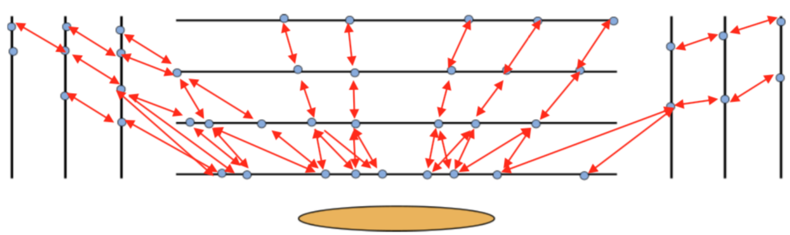


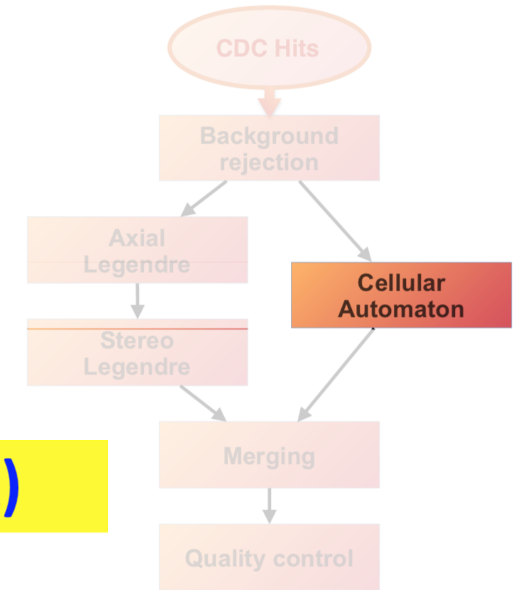
CA

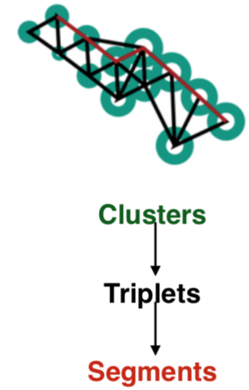
What is Cellular automaton (CA)

The CA is a track seeding algorithm designed for parallel architectures:

- In a CA, a network of cells evolves in discrete time steps from an initial state according to predefined rules, depending only on the values of the cells in the local neighborhood.
- A graph of all the possible connections between layers is created
- Doublets are created for each pair of layers (compatible with a region hypothesis)
- A cell is defined as a segment linking three hits.
- Neighborhood rules : pair of hits in common and similar eta
- Evolution rules: At each time step a cell increases its state if on its left it has a neighbor with the same state.
- The neighbor fit triples are joint in a longer seed
- Fast computation of the compatibility between two connected cells
- No knowledge of the world outside adjacent neighboring cells required, making it easy to parallelize







- MVA filters or hand crafted features
- Hit connection through bridging

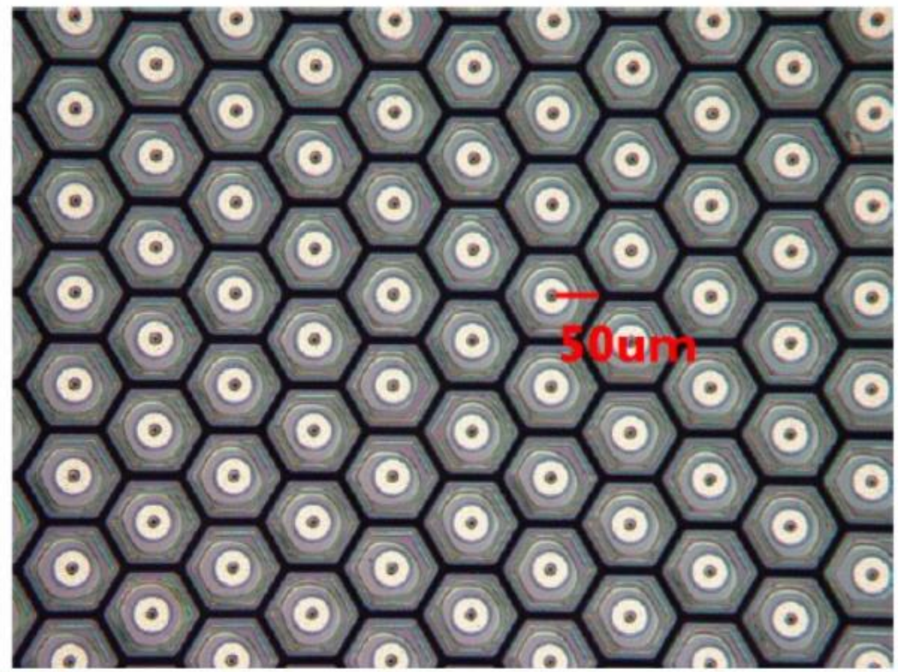
- Build segments from individual hits in each super layer
- Build tracks from segments

CMS

- **seed generation:** it provides initial trajectory candidates
  - internal to the tracking detector (inner tracker or muon system)
  - external by using input from other detectors (calorimeters).
- **building trajectories starting from seeds:** it is based on the Kalman filter formalism and consists of:
  - layer navigation provides a list of reachable layers from the current layer in a given direction.
  - propagator: each reachable layer provides measurements (rec hits) compatible with a trajectory candidate
  - updator: each compatible measurement is combined with the corresponding predicted trajectory state

And then we have 3D trenches for timing

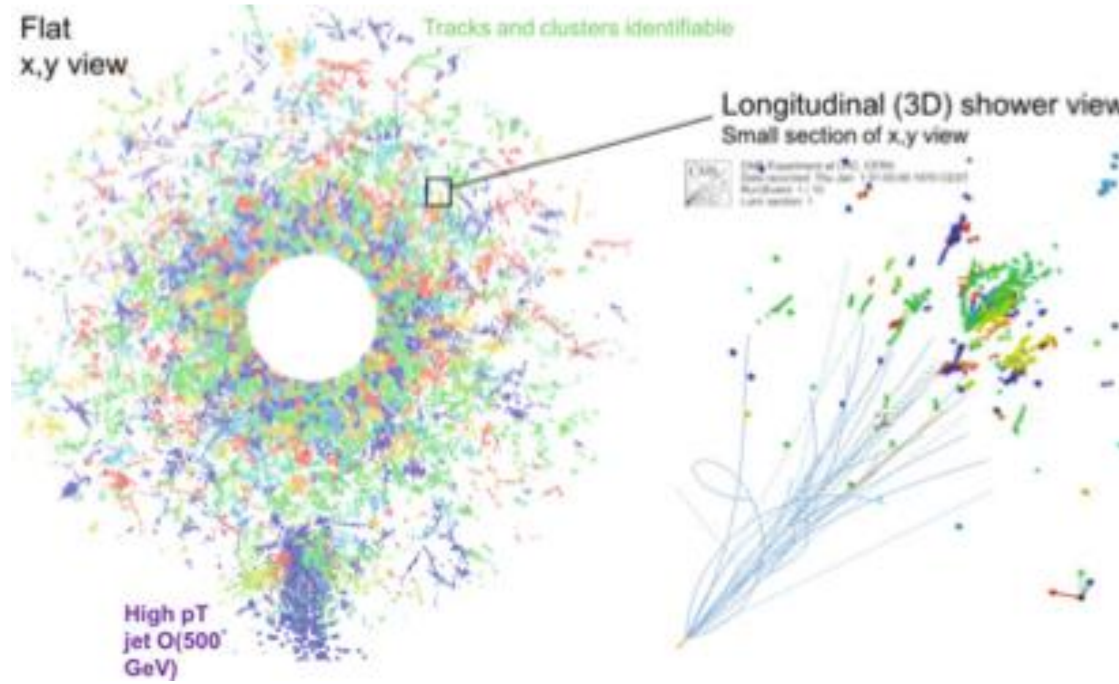
- Advantages:
  - High average field
  - Uniform weighting field
  - Initial pulse (largely) independent of position
  - Very Radiation Hard
- Drawbacks:
  - Possible fabrication problems
  - High electrode capacitance



A. Montalbano et. al.
NIMA 765 (2014), 23

CMS HGCAL

- Not a MIP detector
  - Some smaller calibration cells
  - **Allows for MIP tagging – ‘following’ a ‘track’**
- Very high dynamic range 1-5000 MIPS
  - CSA **C**harge **a**mplifier/**s**haper plus a TOT **T**ime- **o**ver-**T**hreshold circuit. This allows to span the necessary huge dynamic range.
- Intrinsic timing resolution of
  - <50 ps for S/N>10
  - ~20 ps for S>20 MIPS
  - For charged and neutral particles
- L1 Trigger



Concept works, see test beam