Vertexing and Tracking Summary and Outlook

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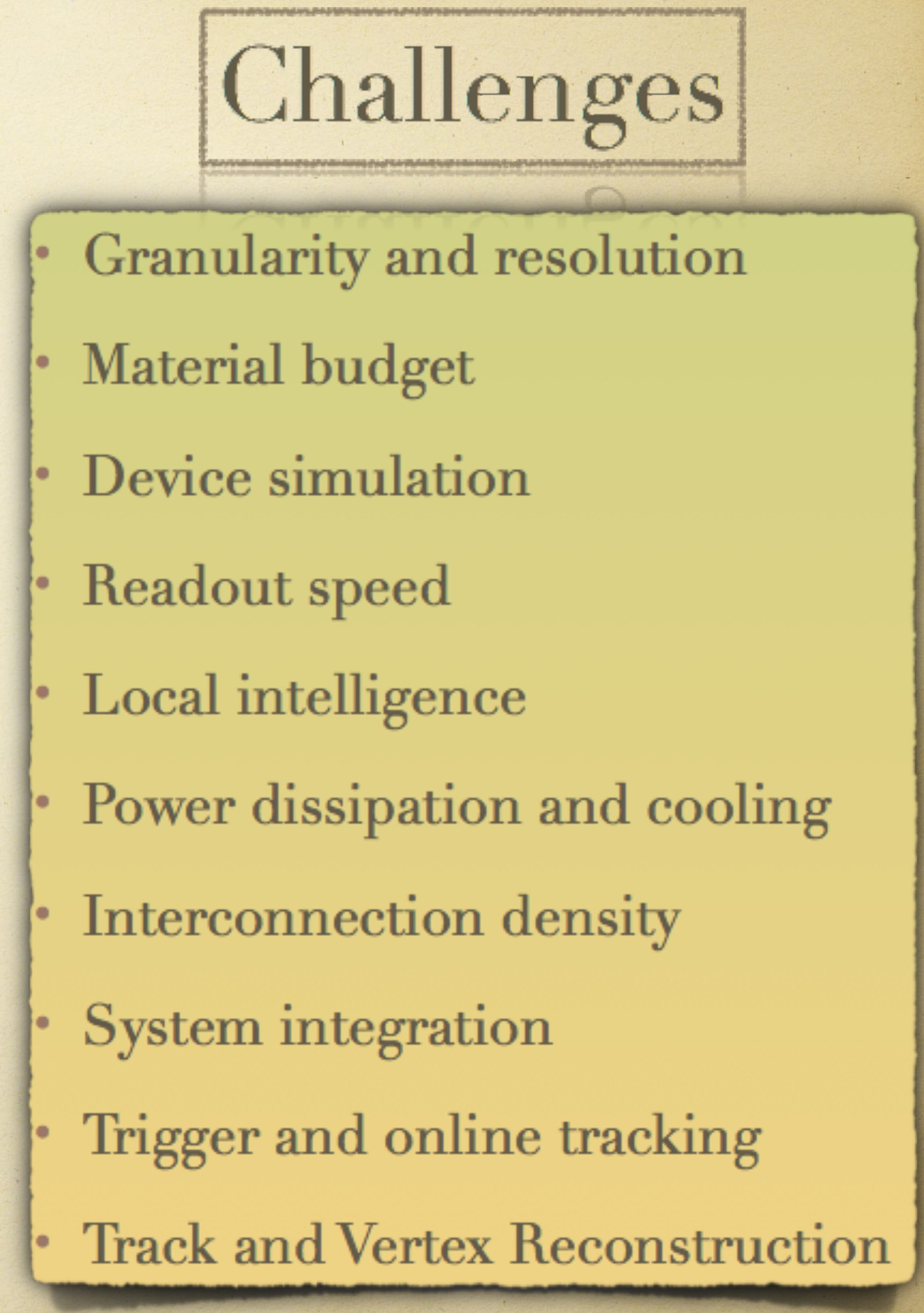
Disclaimer and apologies

- Vertex detectors are a very active and vibrant field
- Impossible to represent everyone and everything: personal taste in choice of topics
    - Please don't get mad at me.
- Could not attend most of the conference
    - I regret not enjoying this beautiful place
    - Busy building Belle-II vertex detector !

Outline

- Yesterday and Today
- Tomorrow
- Day After Tomorrow
- The Future



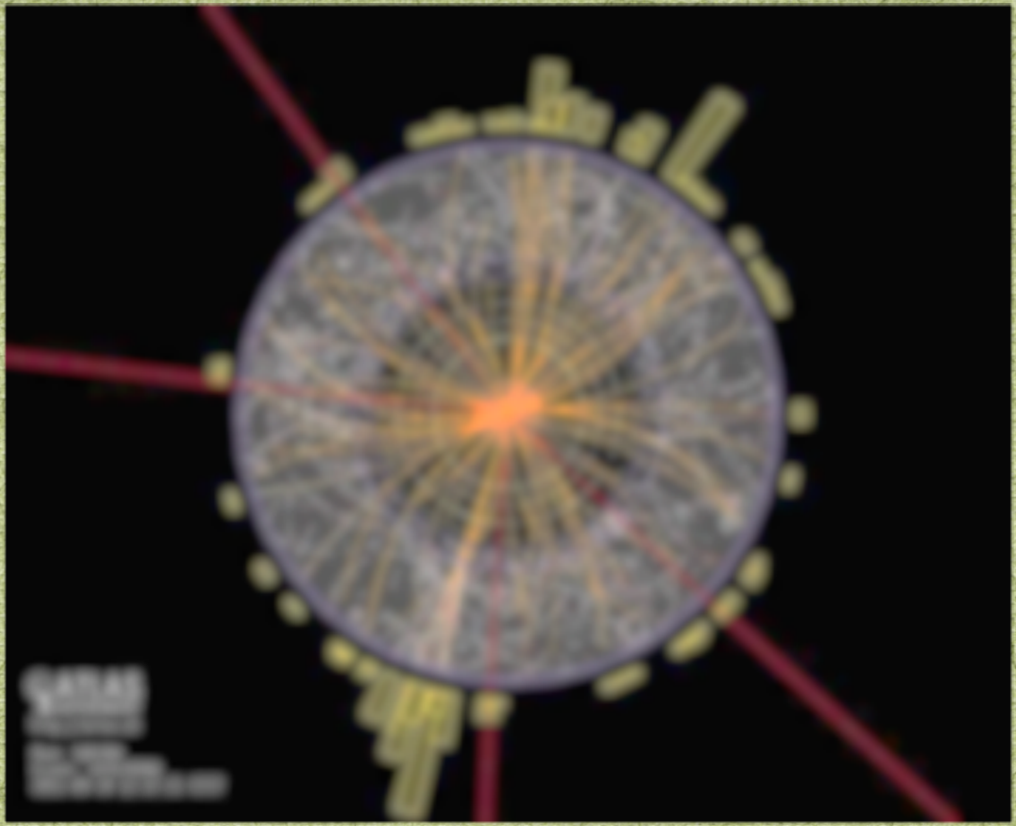
Challenges

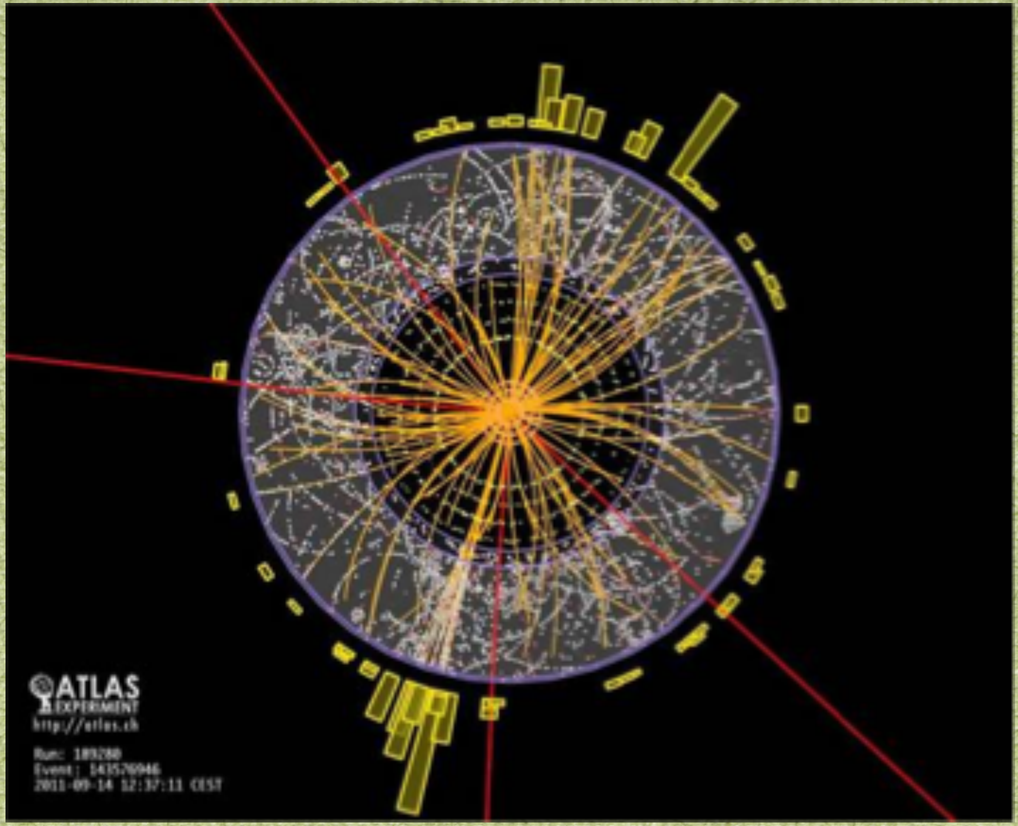
- Granularity and resolution
- Material budget
- Device simulation
- Readout speed
- Local intelligence
- Power dissipation and cooling
- Interconnection density
- System integration
- Trigger and online tracking
- Track and Vertex Reconstruction

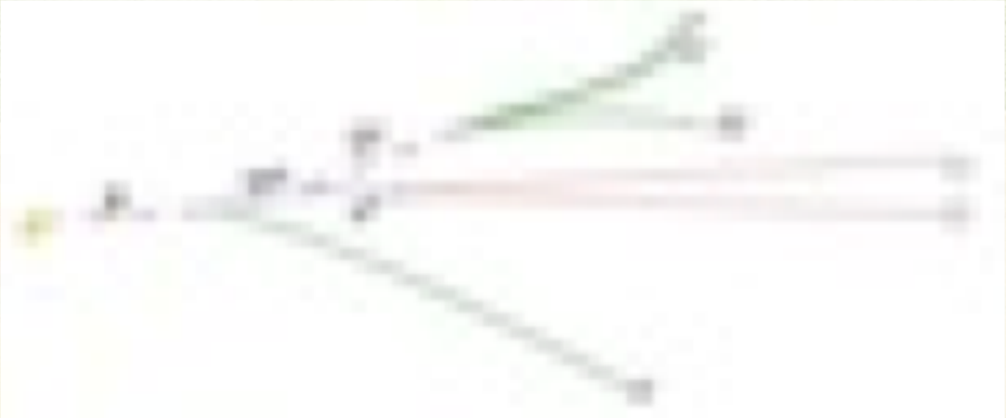
The Vertex conference series

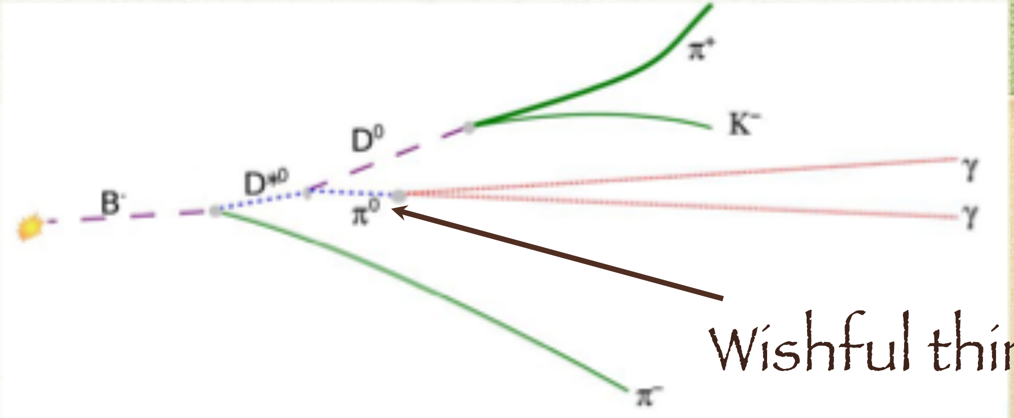
2015		2014	Macha Lake, The Czech Republic
2013	Lake Starnberg, Germany	2012	Jeju, Korea
2011	Rust, Austria	2010	Loch Lomond, Scotland, UK
2009	Mooi Veluwe, Putten, The Netherlands	2008	Uto Island, Sweden
2007	Lake Placid, New York, USA	2006	Perugia, Italy
2005	Chuzenji Lake, Nikko, Japan	2004	Menaggio, 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, Sardinia, Italy
1995	Ein Gedi, Dead Sea, Israel	1994	Lake Monroe, Indiana, USA
1993	Lake Bohinj, Slovenia	1992	Basto Island, Finland


Capitol Records
YESTERDAY · DR. ROBERT
I'M ONLY SLEEPING · AND YOUR BIRD CAN SING
WE CAN WORK IT OUT · DAY TRIPPER
NOWHERE MAN · WHAT GOES ON?
DRIVE MY CAR · IF I NEEDED SOMEONE
ACT NATURALLY
The Beatles
Yesterday And Today







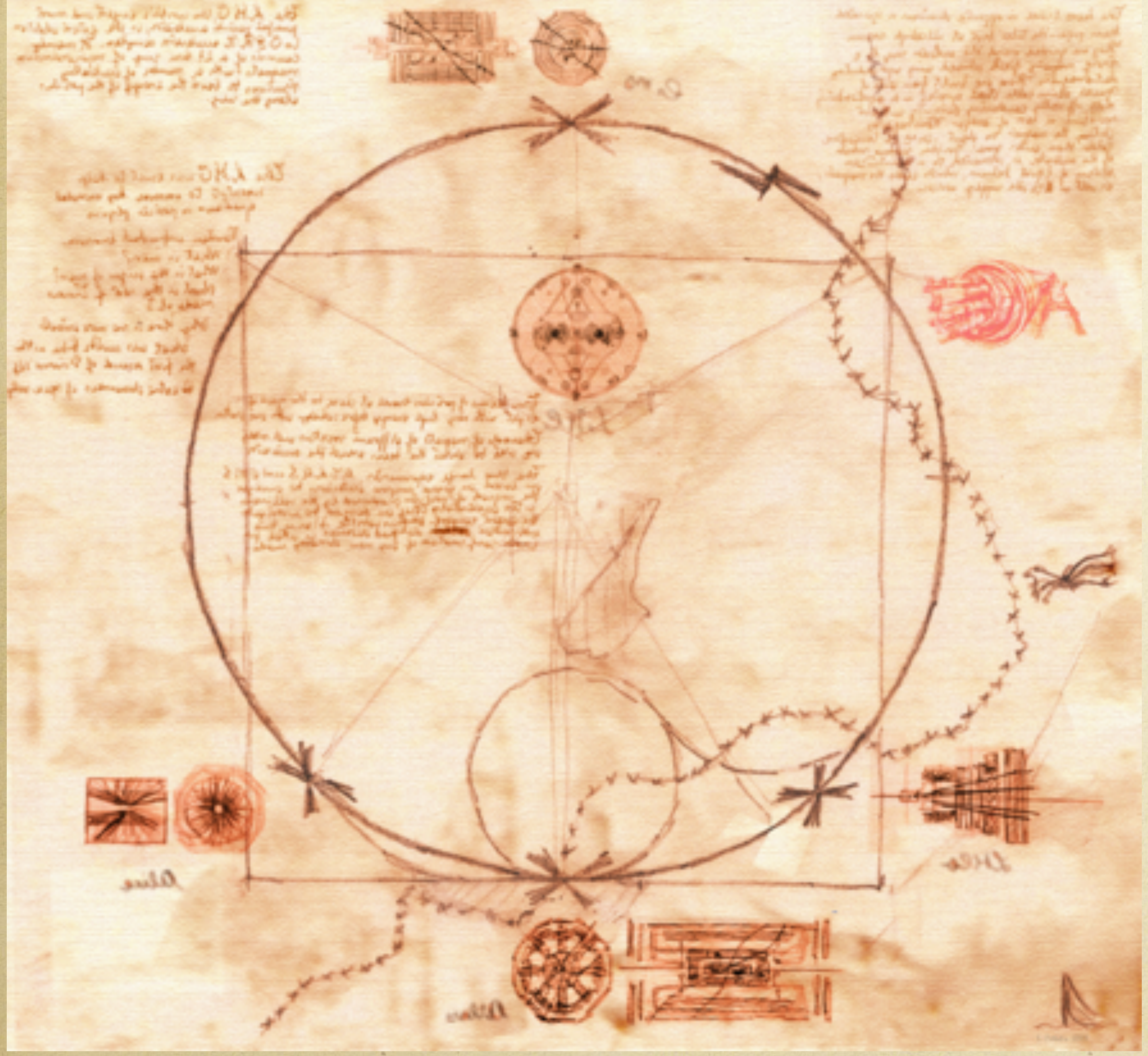


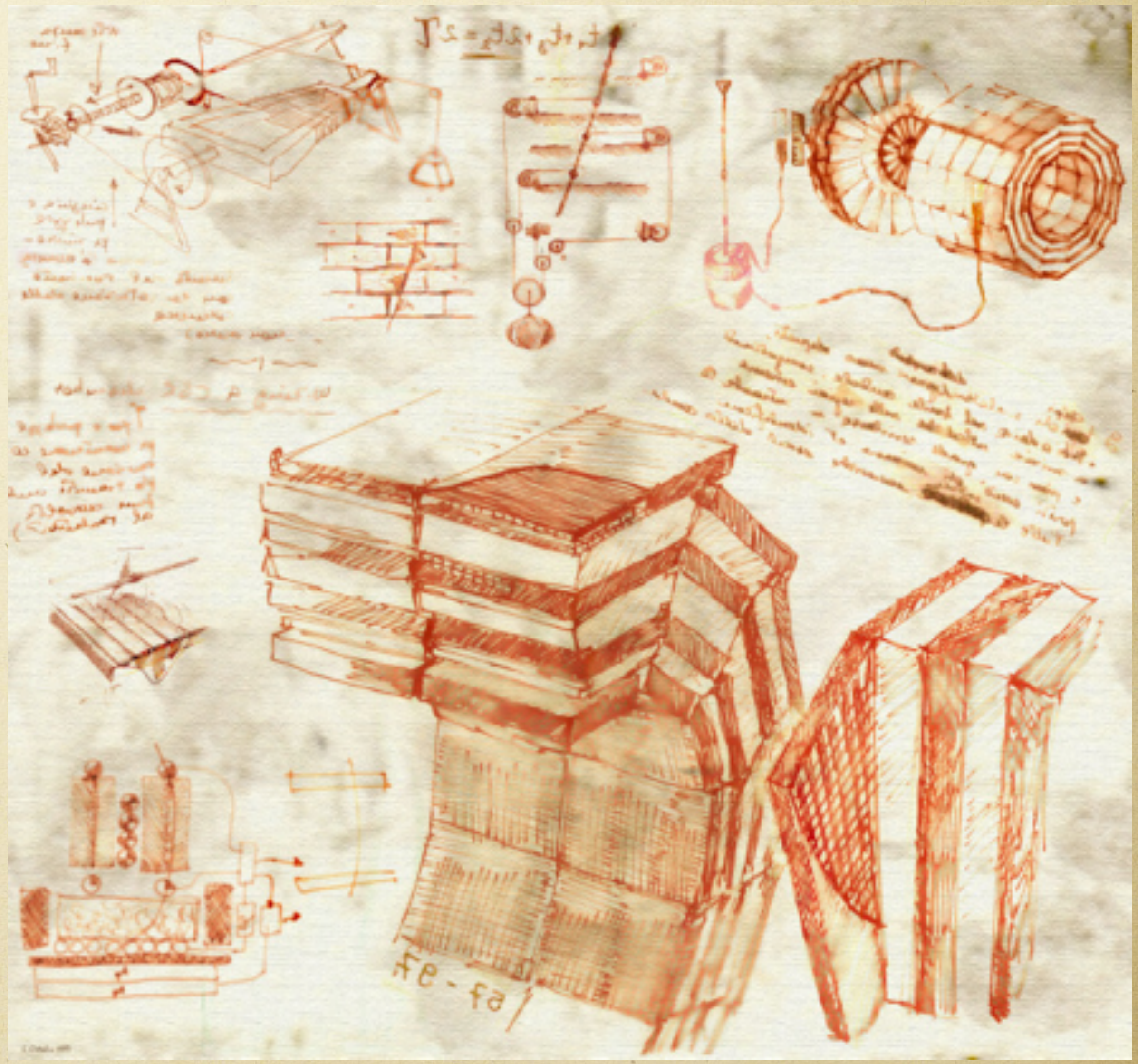
Wishful thinking

We need eyes to see

Long R&D process

LHC ca. 1515 A.D.



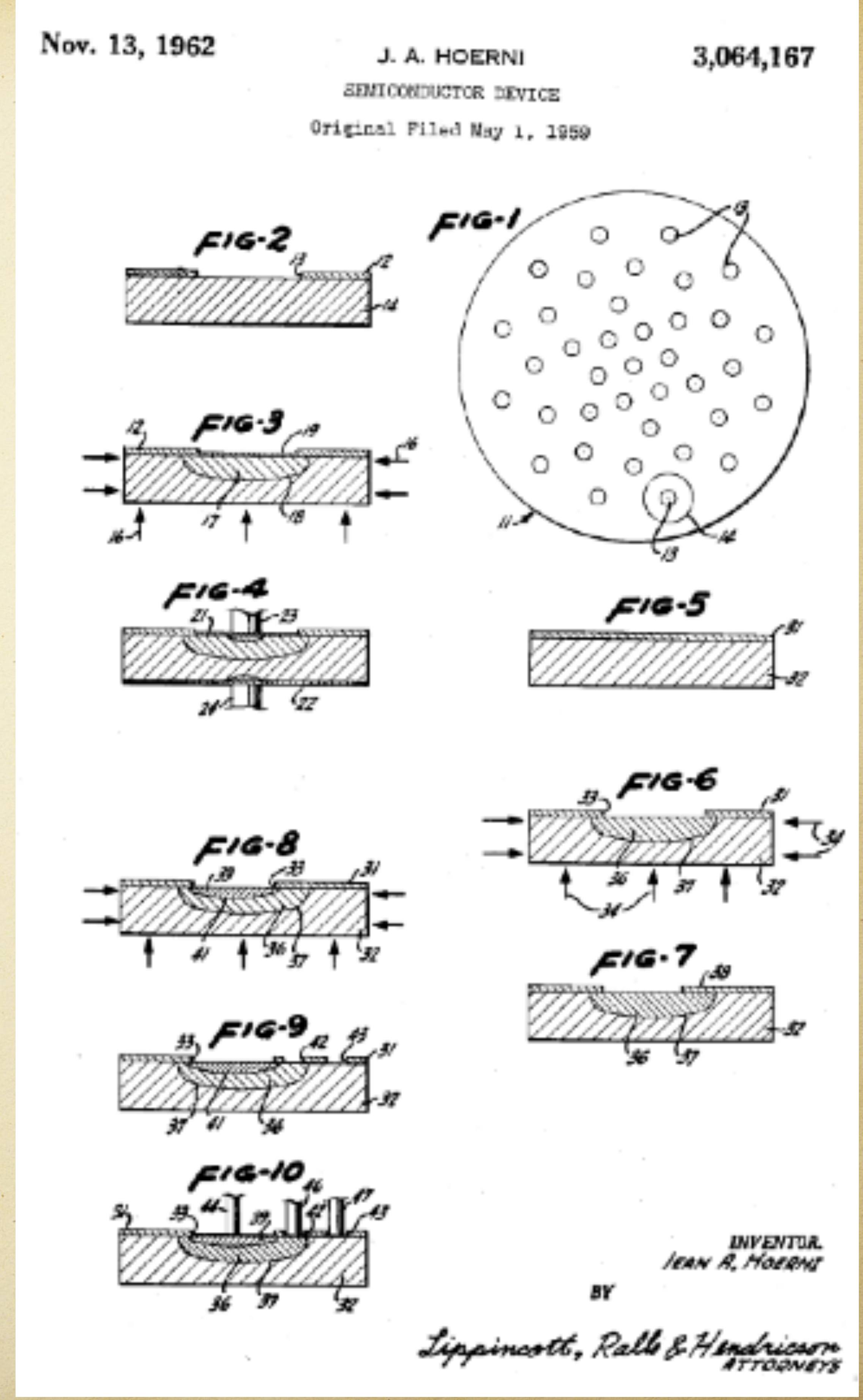


S. Cittolin

The Planar Process

or the birth of semiconductor technology.

In solid state sensors, more than in other fields, detector development is heavily driven by the available (affordable) technology.



Nov. 13, 1962 J. A. HOERNI 3,064,167

SEMICONDUCTOR DEVICE

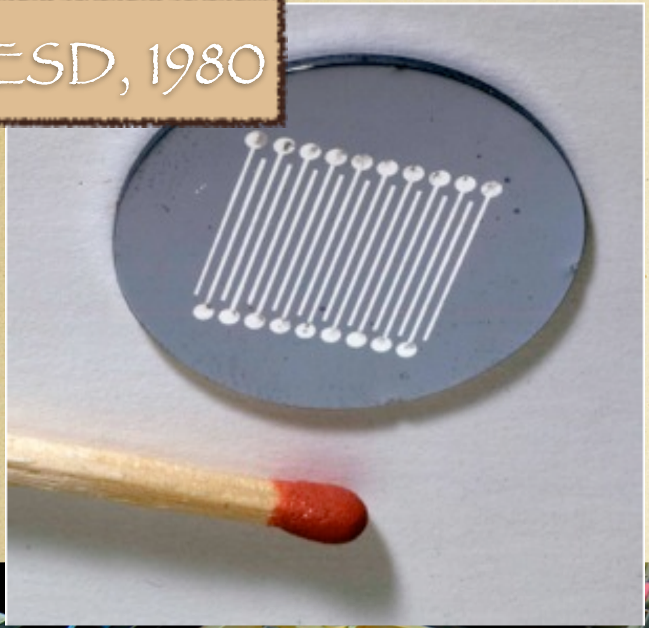
Original Filed May 1, 1959

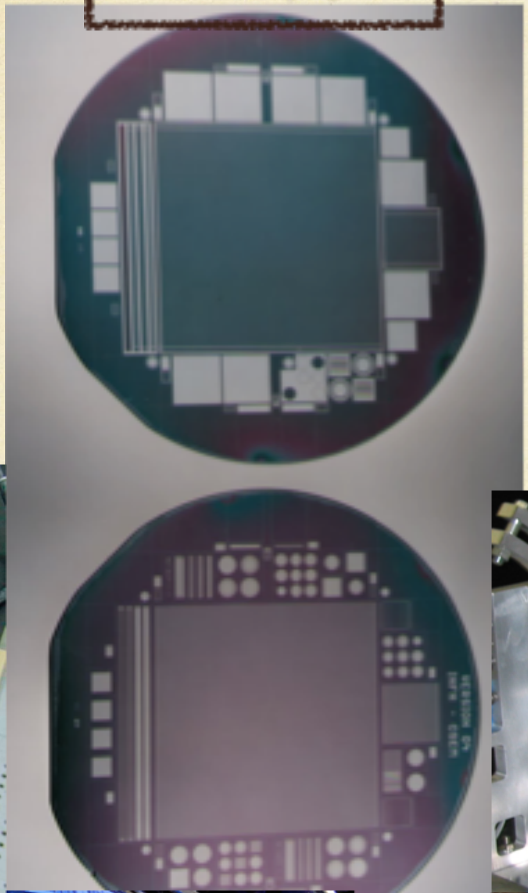
INVENTOR.
JEAN A. HOERNI

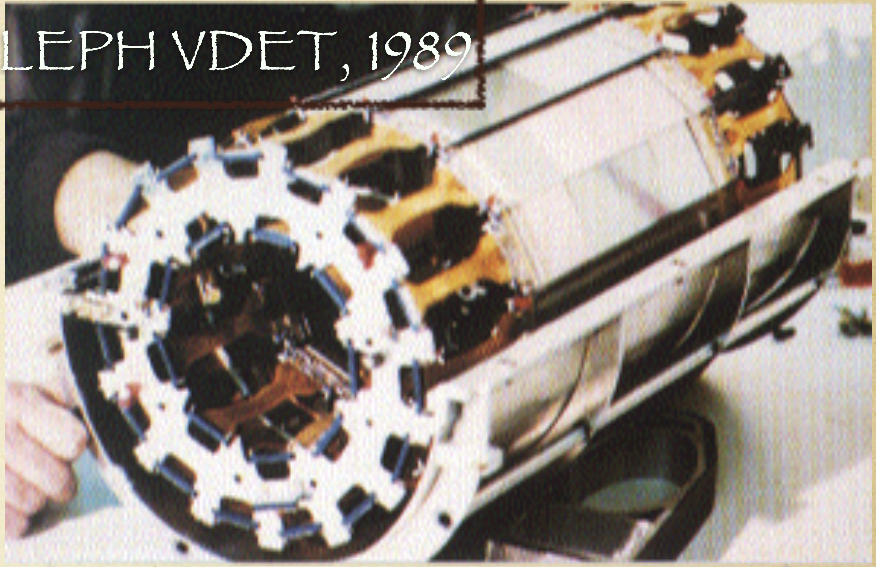
BY

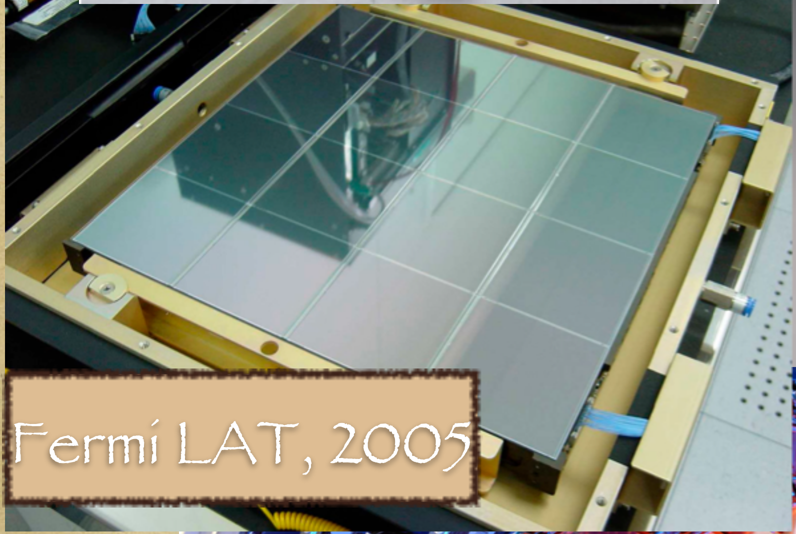
Lippincott, Ralls & Hendricson
ATTORNEYS

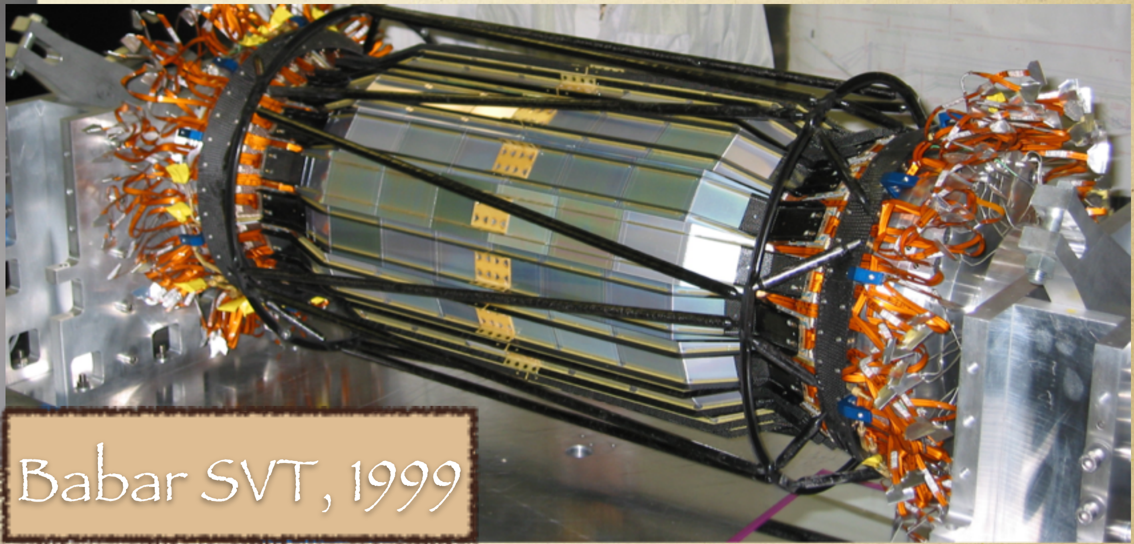
A long history: Semiconductor Strip Detectors


MESD, 1980

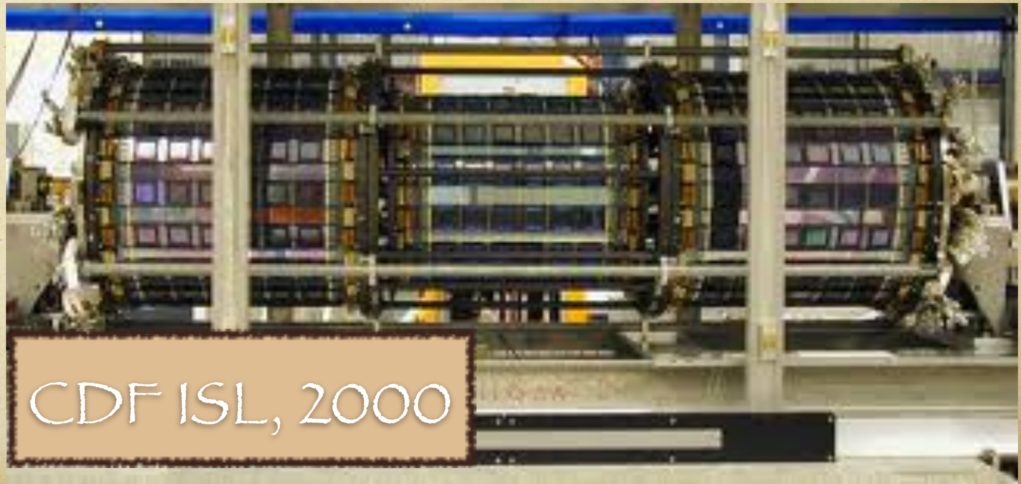

DSSD, 1986


ALEPH VDET, 1989


Fermi LAT, 2005

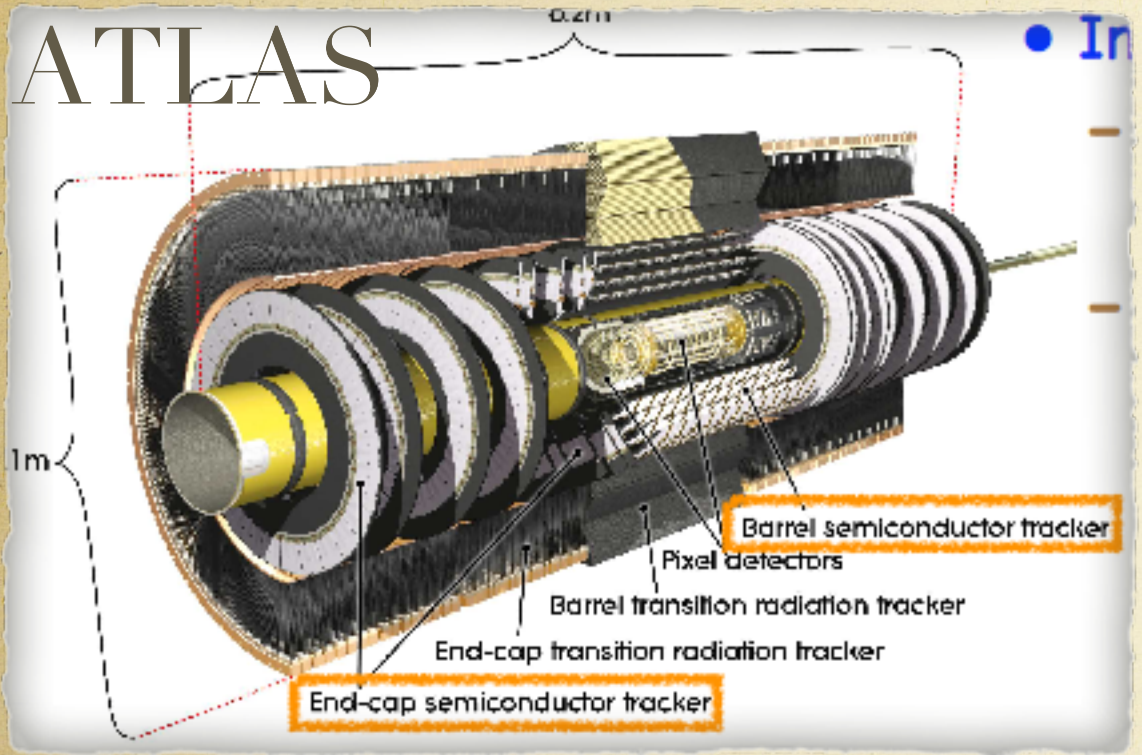

Babar SVT, 1999


CMS Tracker, 2007

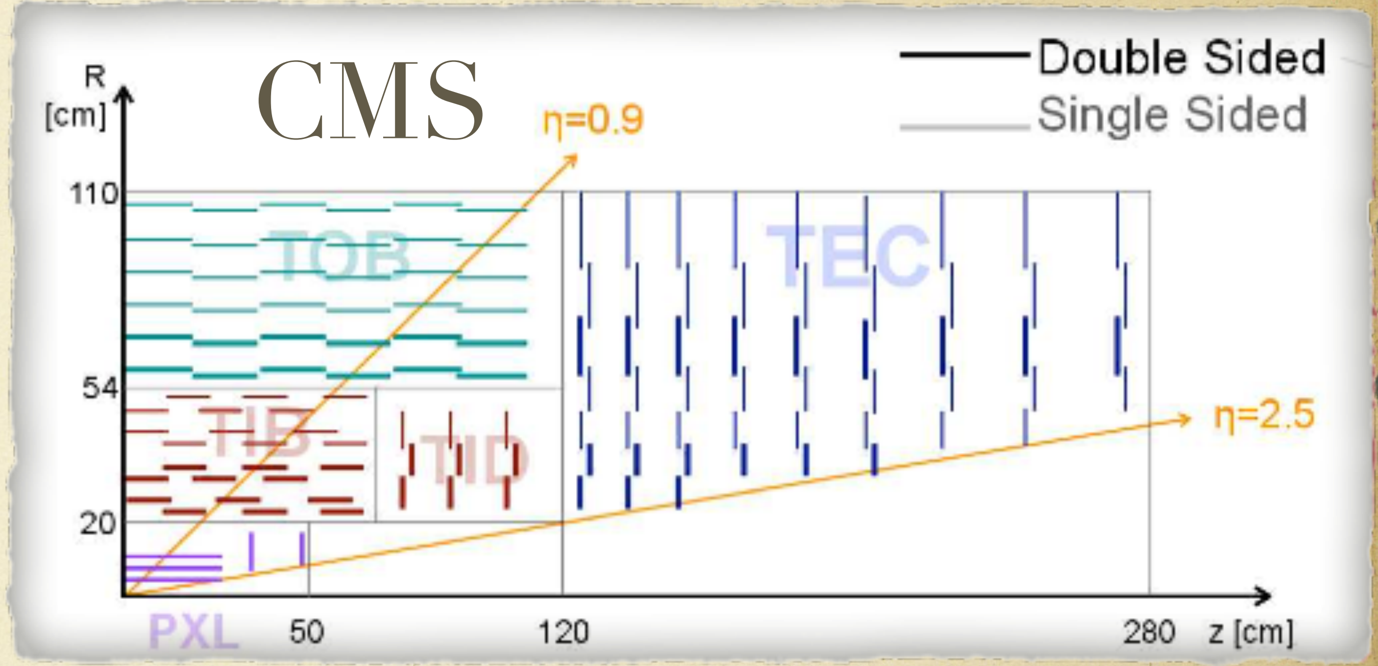

CDF ISL, 2000

Today’s marvels

ATLAS

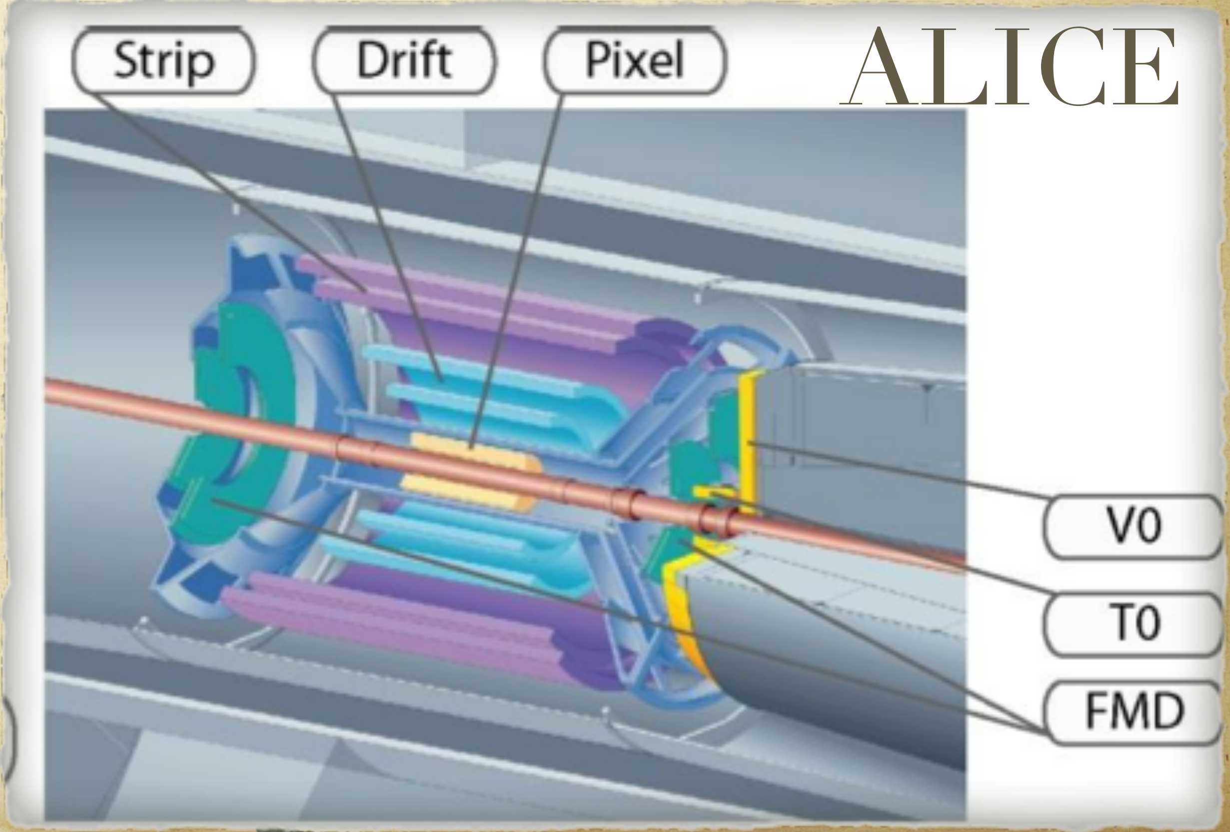


CMS

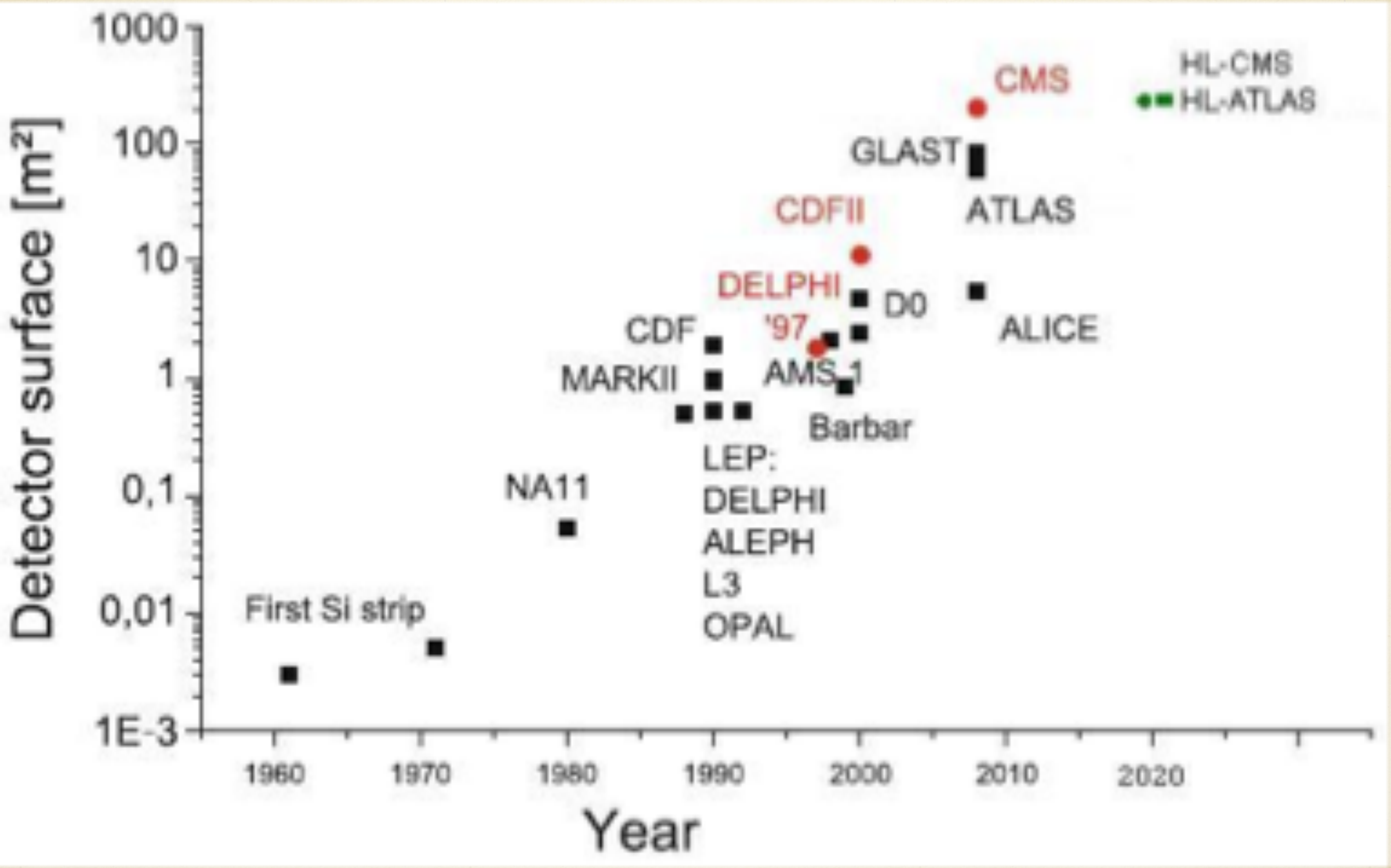


LHCb

ALICE



Silicon Detectors

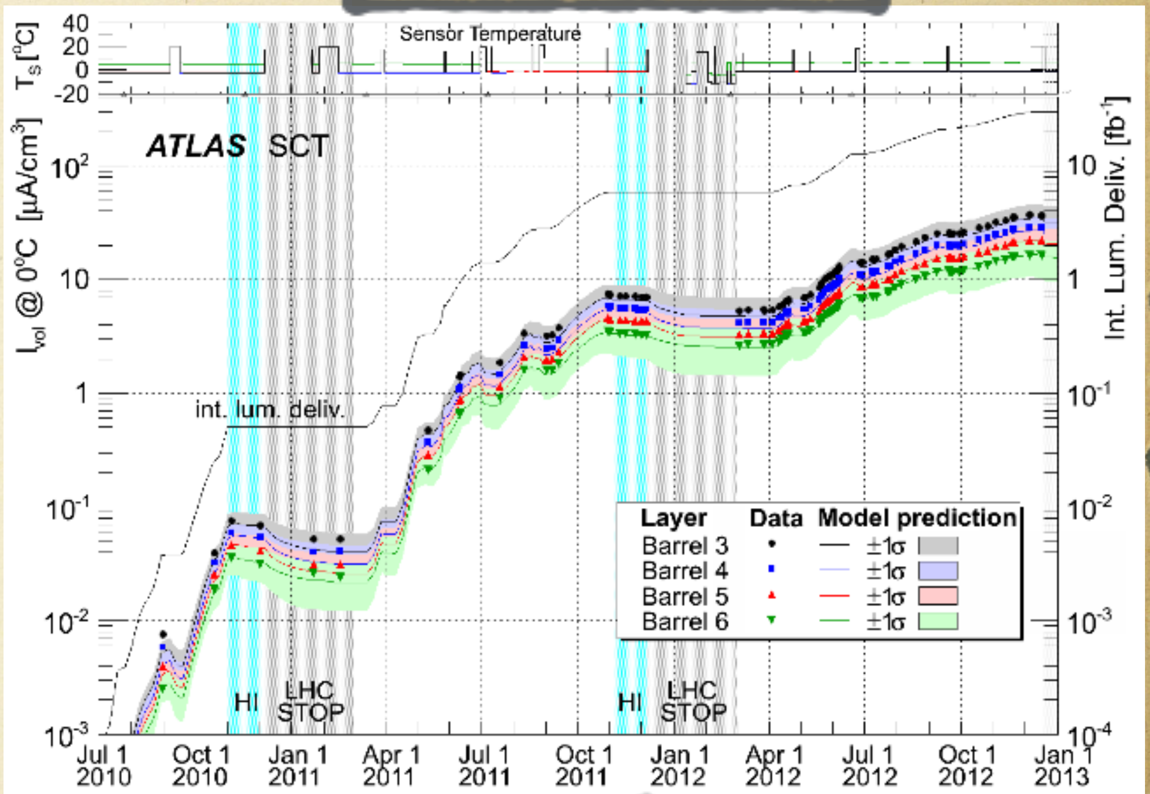


G. Casse, VCI 2013

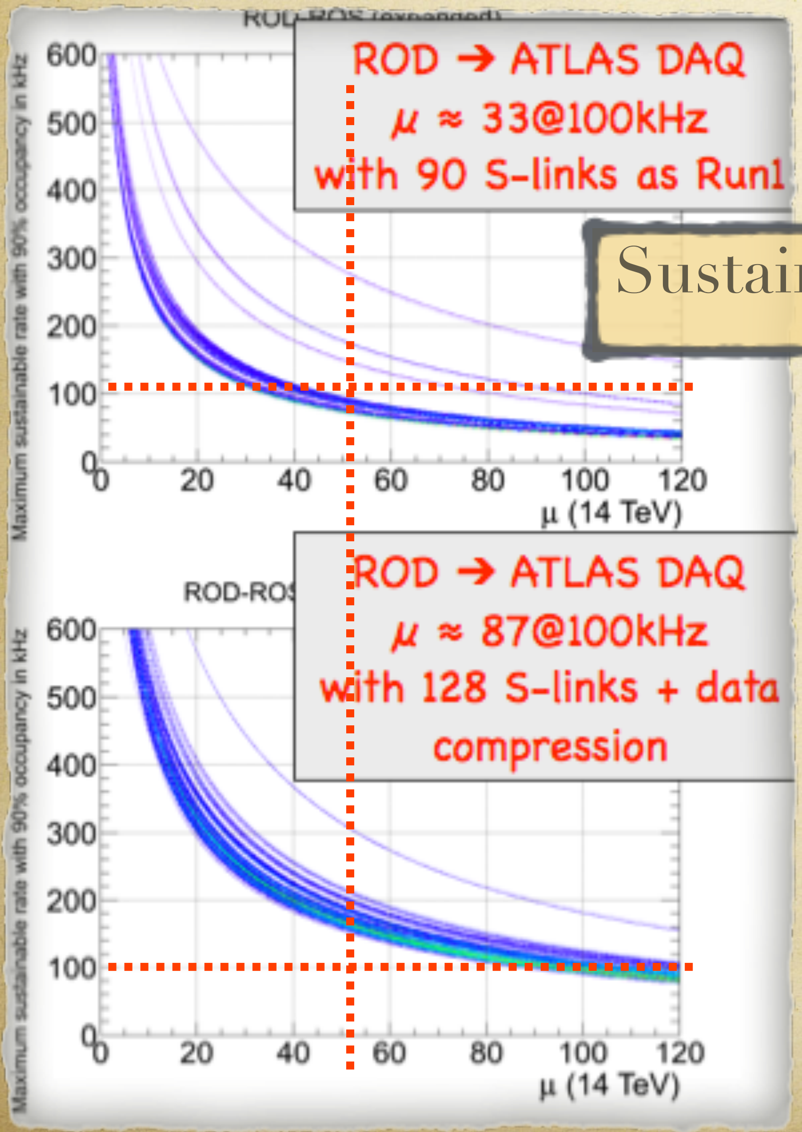
ATLAS - SCT

- Very good performance and stability over Run1. CO2 evaporative cooling. Well understood detector
- Improved bandwidth to cope with larger pile-ups in Run 2

Leakage Current



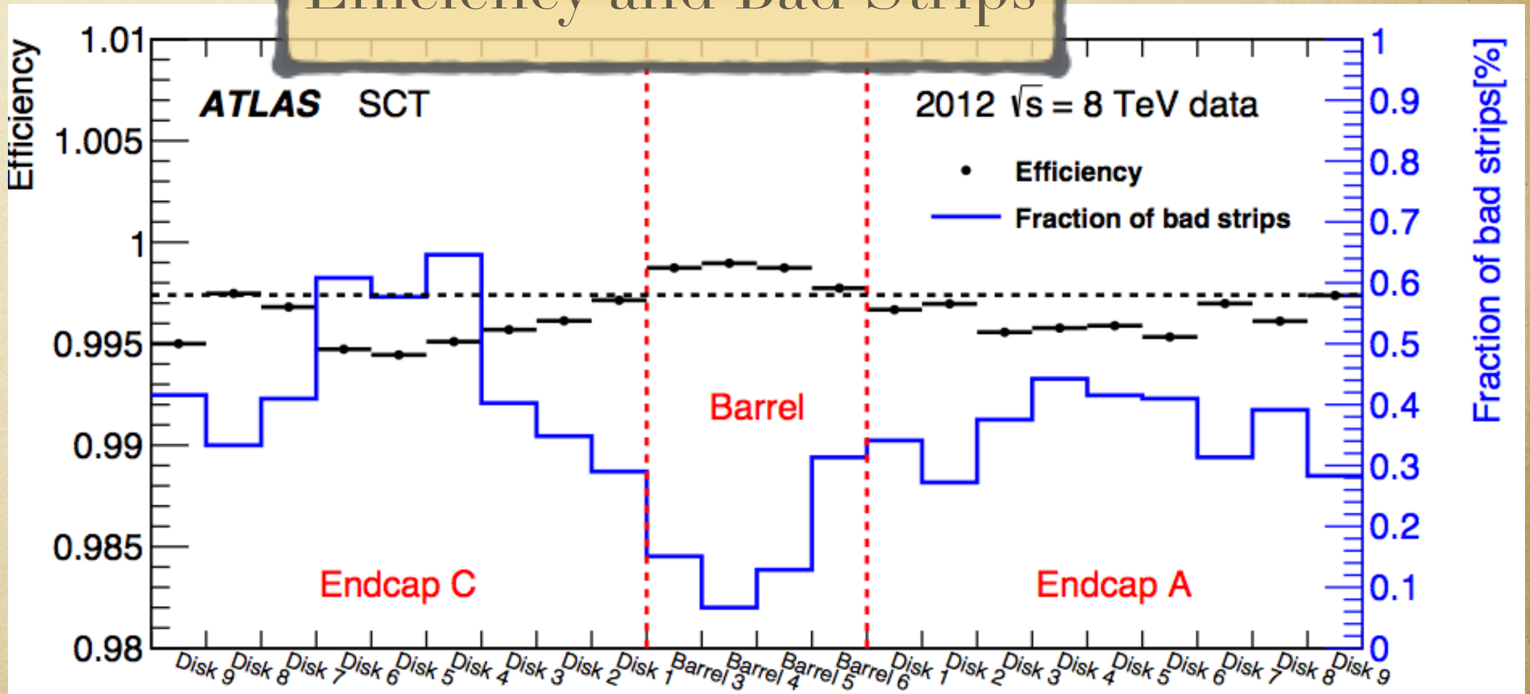
Sustainable Rate



ROD → ATLAS DAQ
μ ≈ 33@100kHz
with 90 S-links as Run1

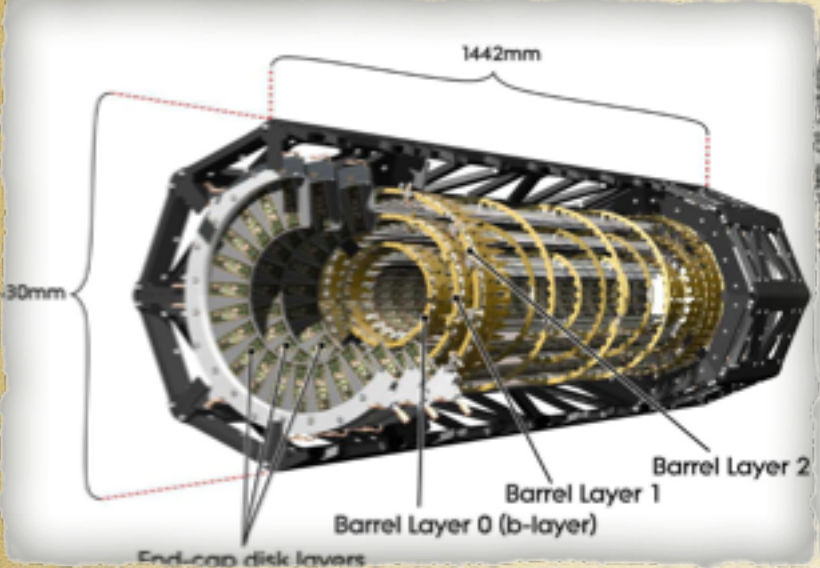
ROD → ATLAS DAQ
μ ≈ 87@100kHz
with 128 S-links + data compression

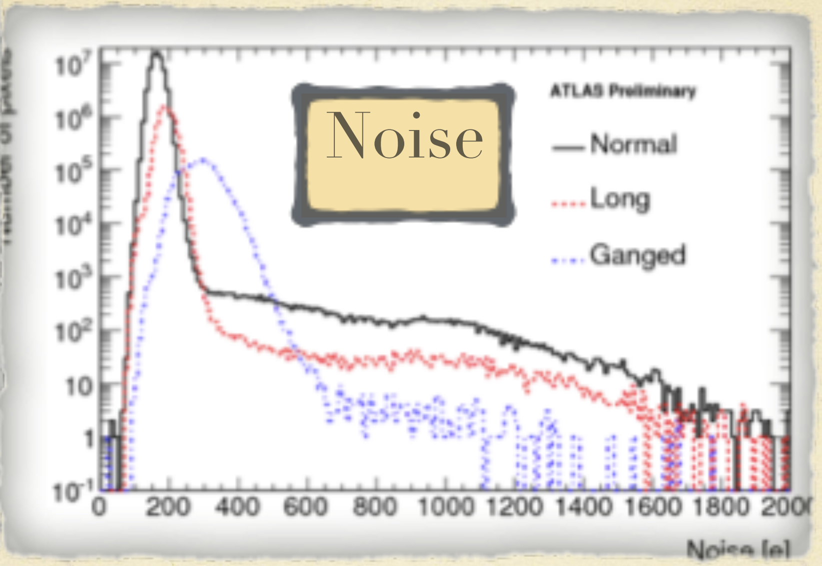
Efficiency and Bad Strips

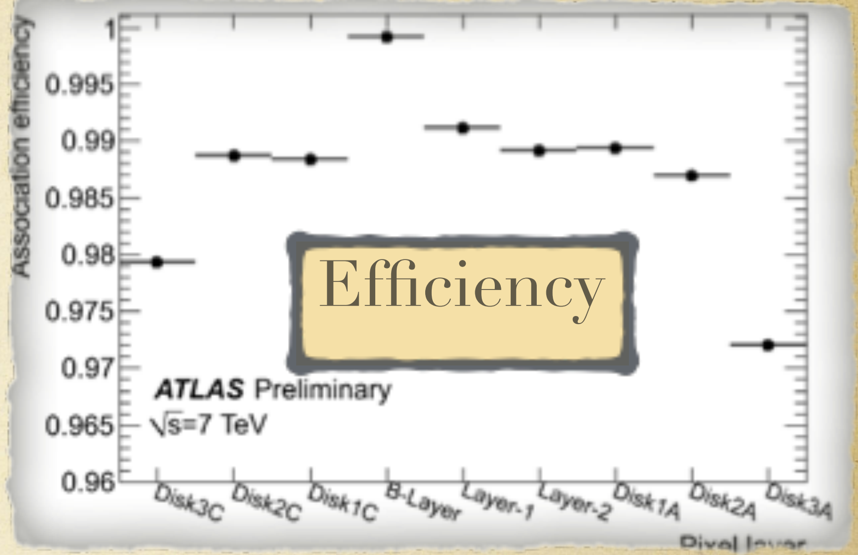


K.Nagai: VTX2014

ATLAS - PIXELS

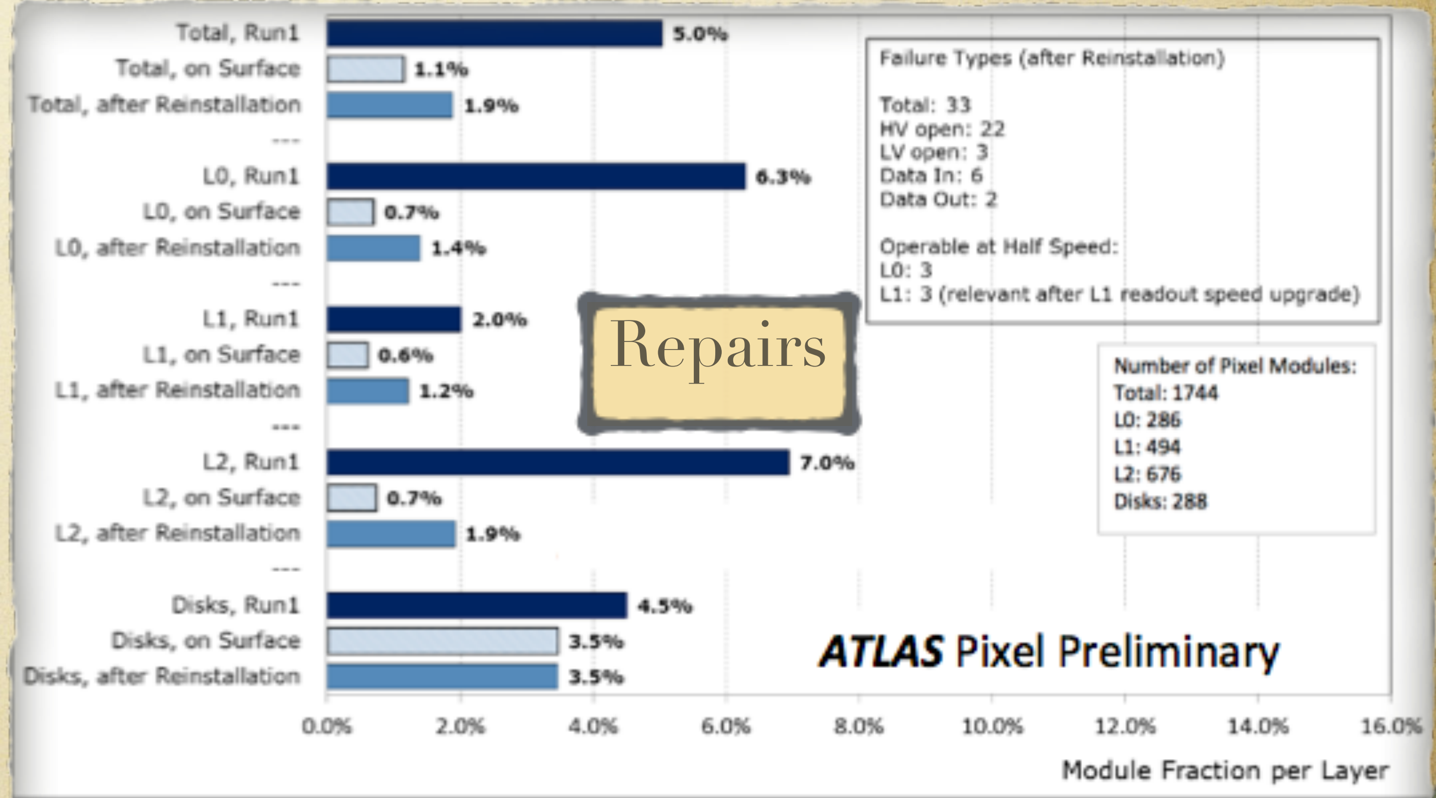






A. La Rosa: VTX2014

- Pixel size 50x400(600)um
- 80M pixels system, 1744 modules
- Significant (5%) number of disabled modules
- Extraction - repair and reinsert done in LS1
- Services are fragile

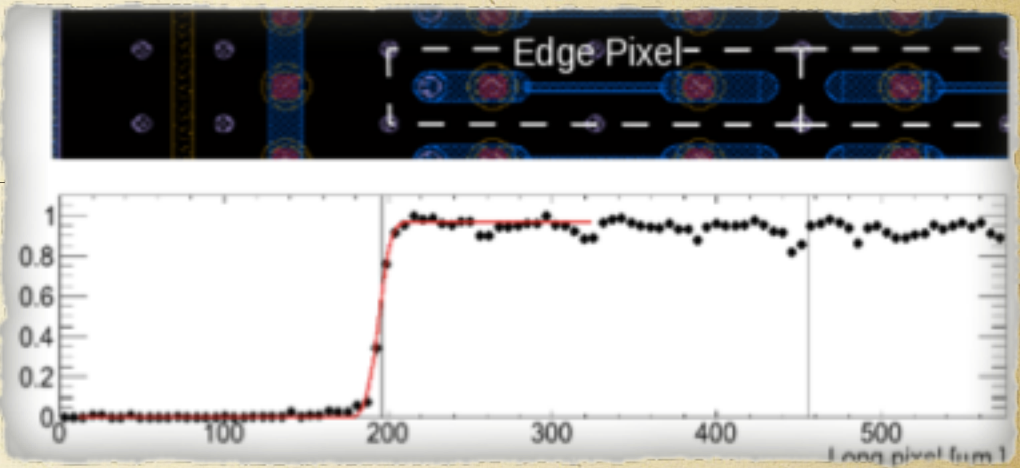


To be mentioned that few modules have been lost when the Detector was reinstalled in ATLAS, so the services are still mechanical fragile

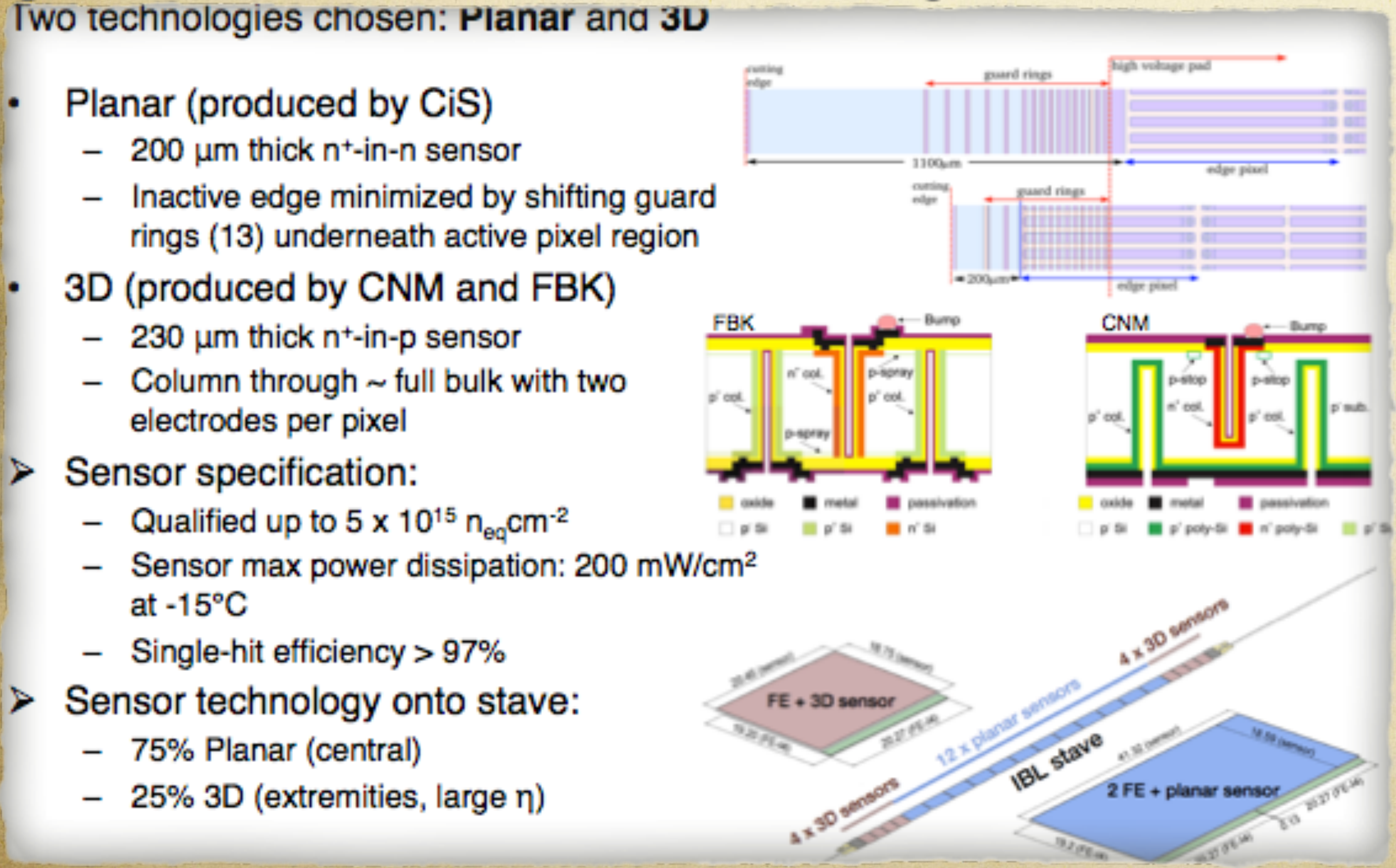
ATLAS - IBL

- 4th pixel layer (IBL) Installed in LS1
  - Improve pattern recognition, redundancy, resolution
- New sensor technology, new chip: 50x250um
  - First time of 3D sensor

Edge efficiency

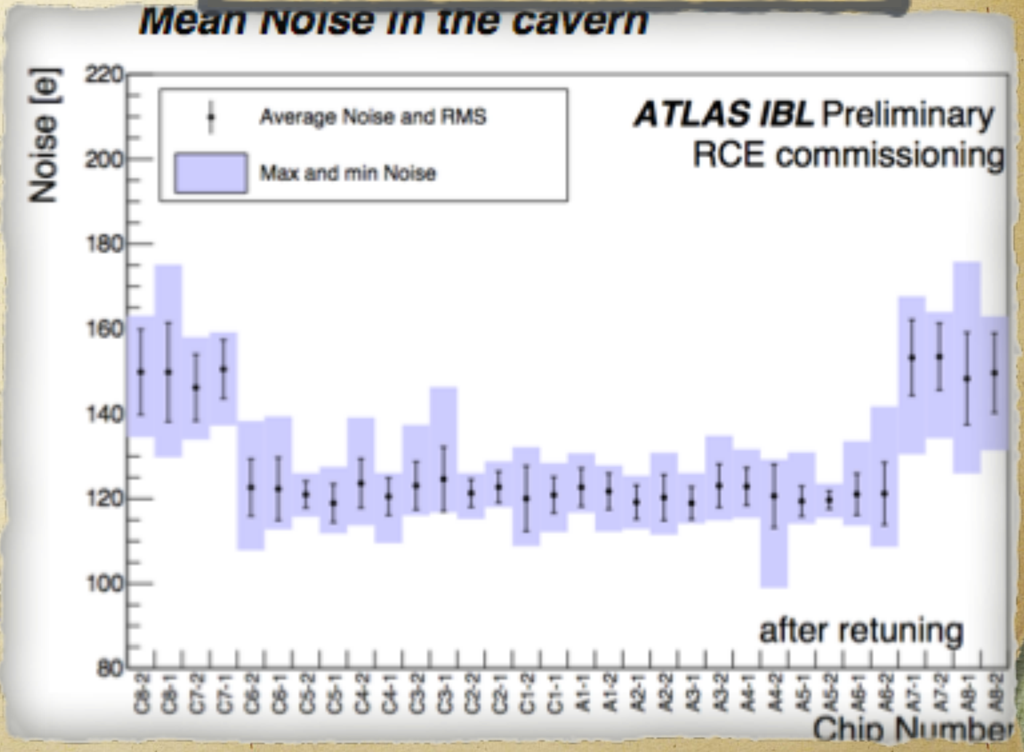


Two technologies: planar and 3D


Two technologies chosen: **Planar** and **3D**

- Planar (produced by CiS)
  - 200 µm thick n⁺-in-n sensor
  - Inactive edge minimized by shifting guard rings (13) underneath active pixel region
- 3D (produced by CNM and FBK)
  - 230 µm thick n⁺-in-p sensor
  - Column through ~ full bulk with two electrodes per pixel
- Sensor specification:
  - Qualified up to 5 x 10^{15} $n_{eq}cm^{-2}$
  - Sensor max power dissipation: 200 mW/cm^2 at -15°C
  - Single-hit efficiency > 97%
- Sensor technology onto stave:
  - 75% Planar (central)
  - 25% 3D (extremities, large η)

Noise after installation

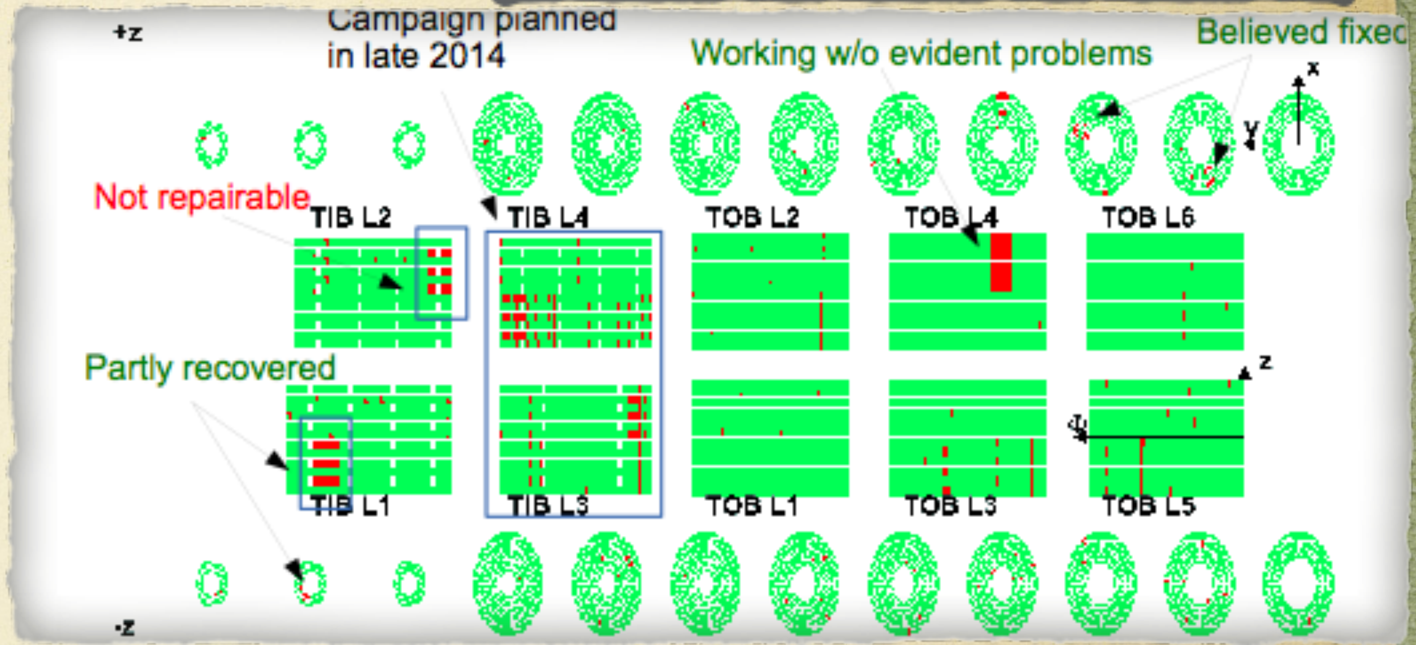


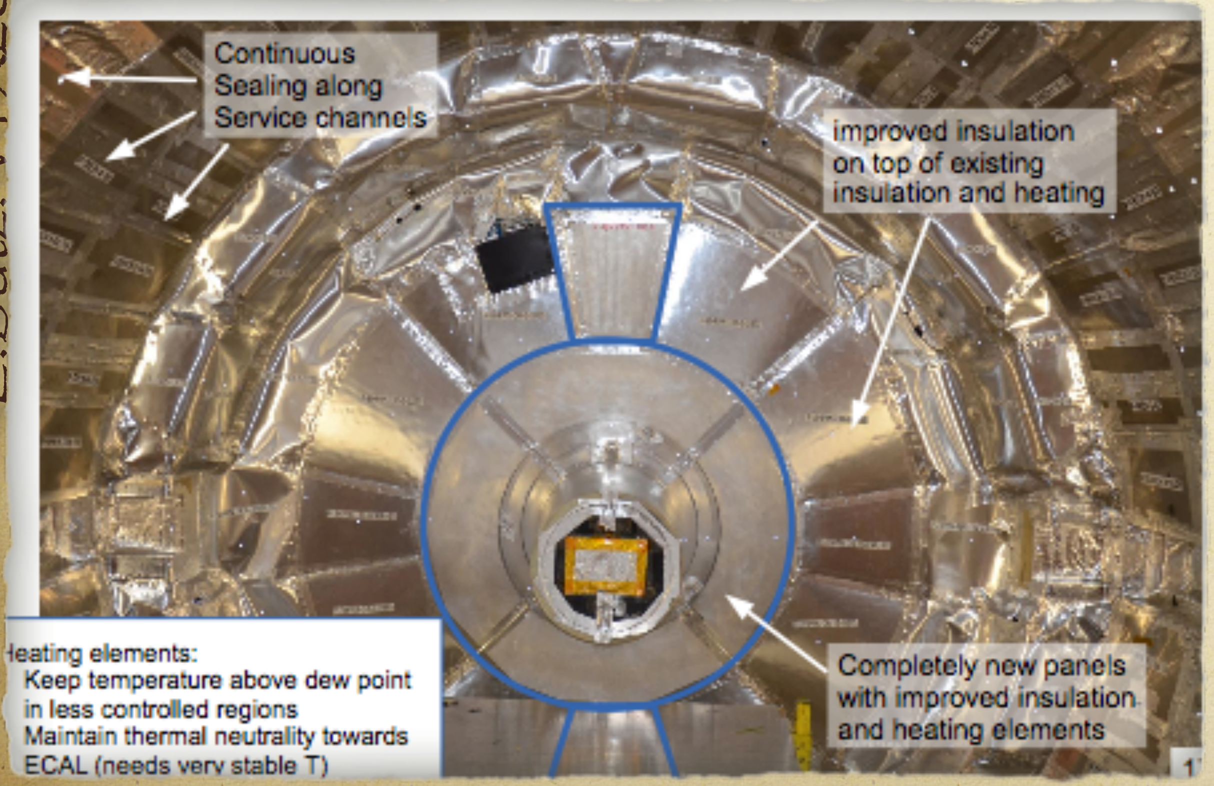
A. La Rosa: VTX2014

CMS - SST

- Largest silicon tracker ever built: active area 200m^2, 5 m long, 2.5 m diameter
- Very good performance in Run1(warm). S6F14 cooling
- Extensive activity to allow cold (-15°C) operation in Run2
  - Needed to cope with radiation damage of sensors

Detector status after repairs





Continuous Sealing along Service channels

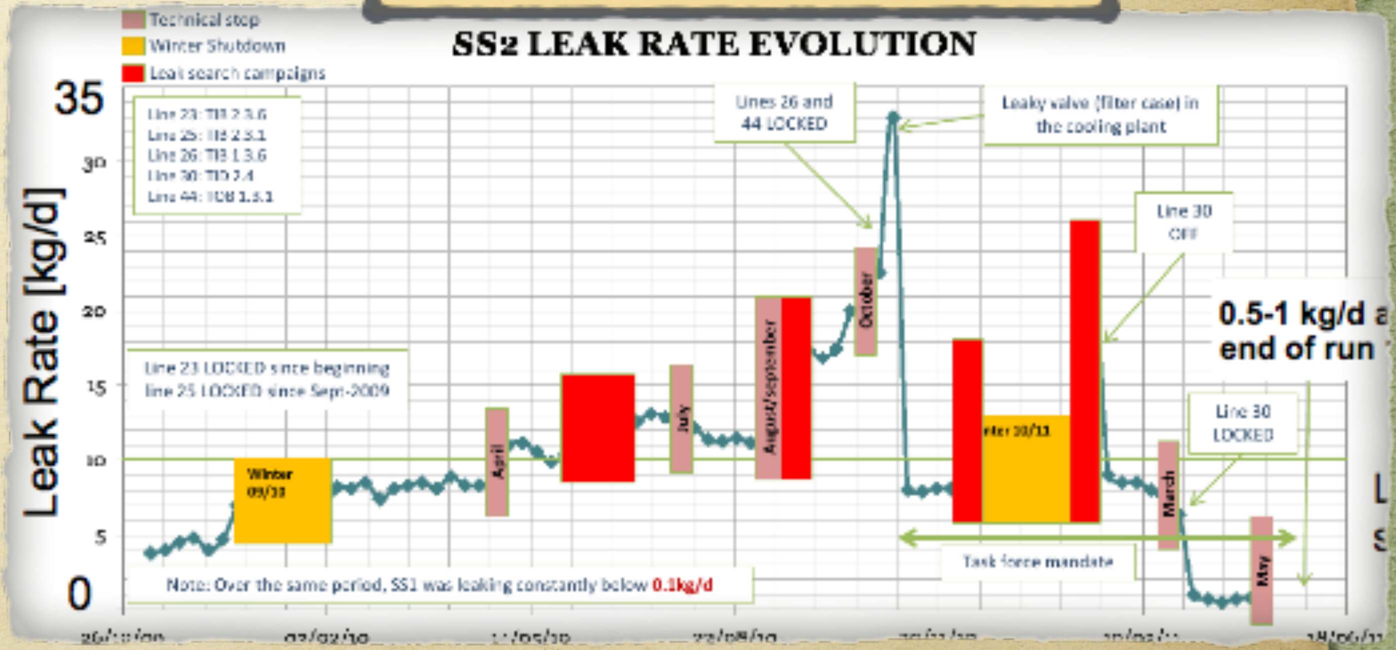
improved insulation on top of existing insulation and heating

Heating elements:
Keep temperature above dew point in less controlled regions
Maintain thermal neutrality towards ECAL (needs very stable T)

Completely new panels with improved insulation and heating elements

E.Butz: VTX2014

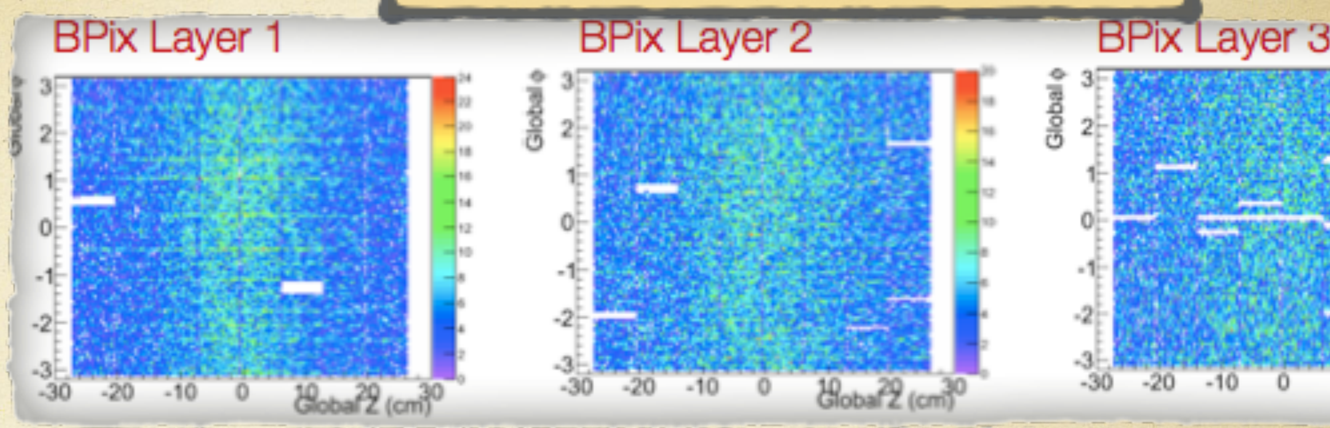
Cooling circuit leak rate

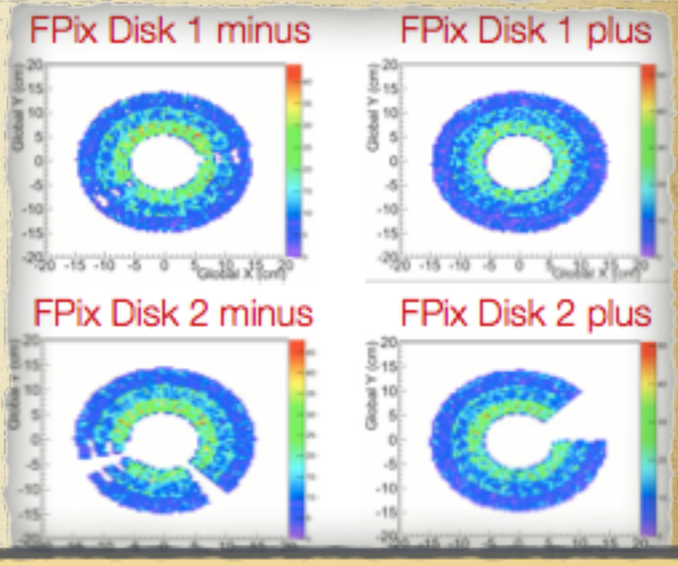


Closed lines to keep leak rate low

CMS - PIXELS

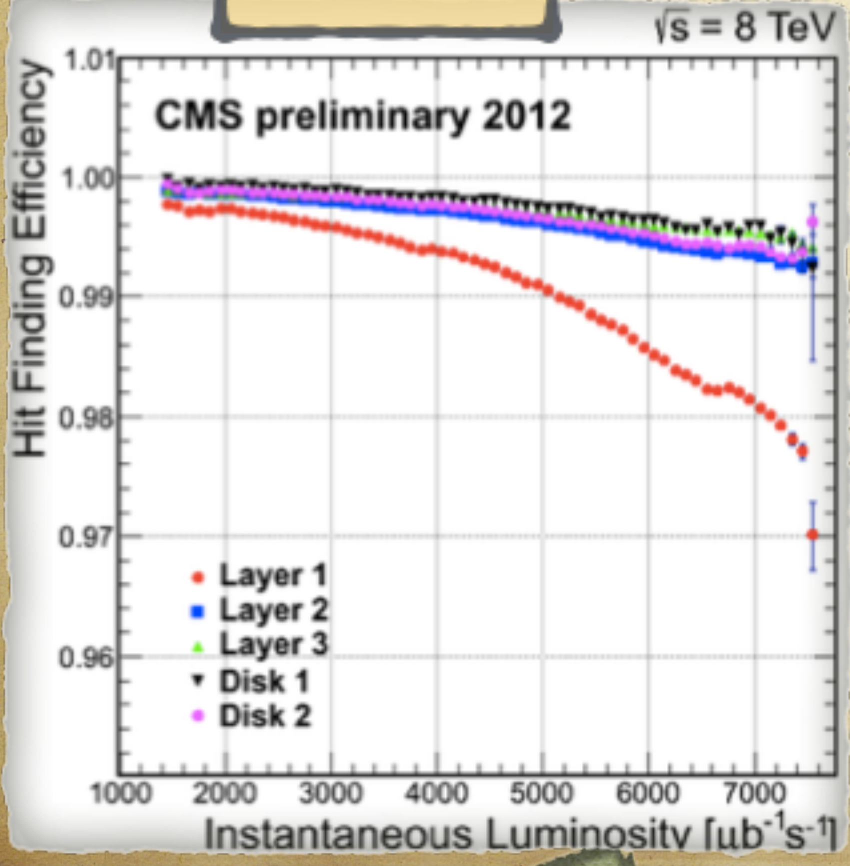
Detector status after Run1





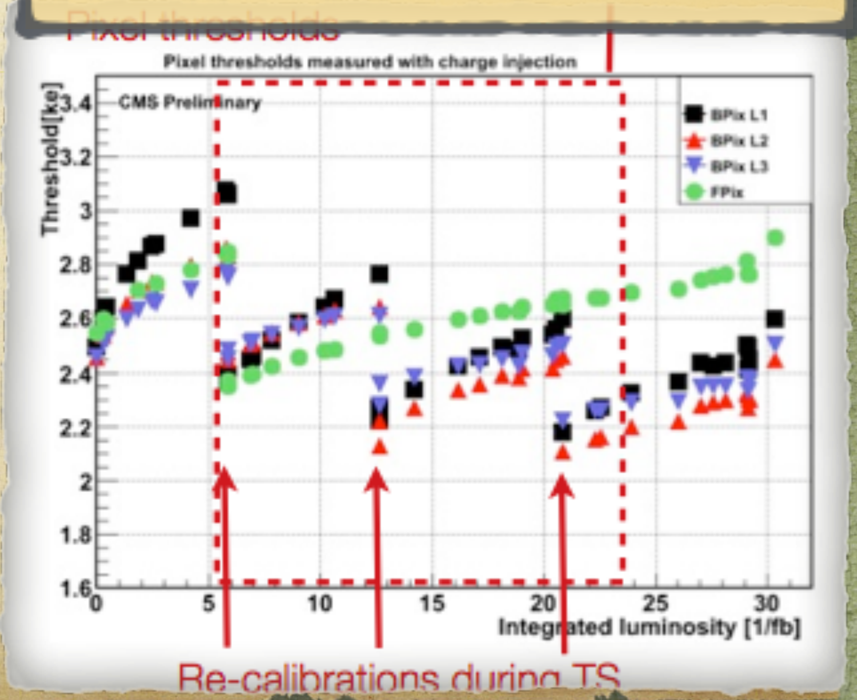
- 66 M Pixels (100x250um)
- Faults at the end Run1:
  - 2.3% in BPix, 7.8% in FPix
  - Repaired (99.9%) in LS1.

Efficiency



- Several radiation effects:
  - Current, voltage
- Threshold recalibration needed with increased current: not expected
- Automatic SEU detection and recovery essential for high efficiency

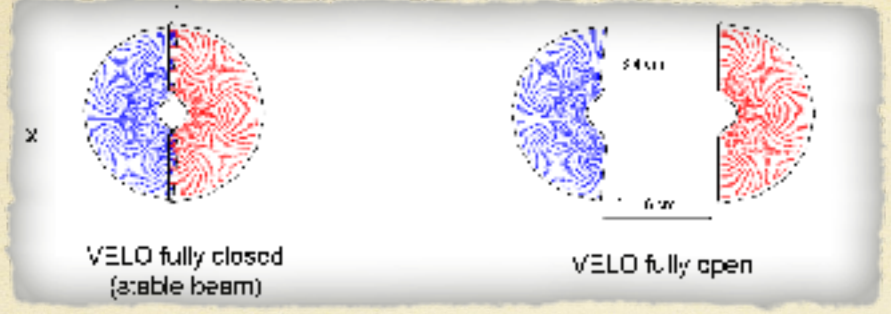
Threshold drift and recalib

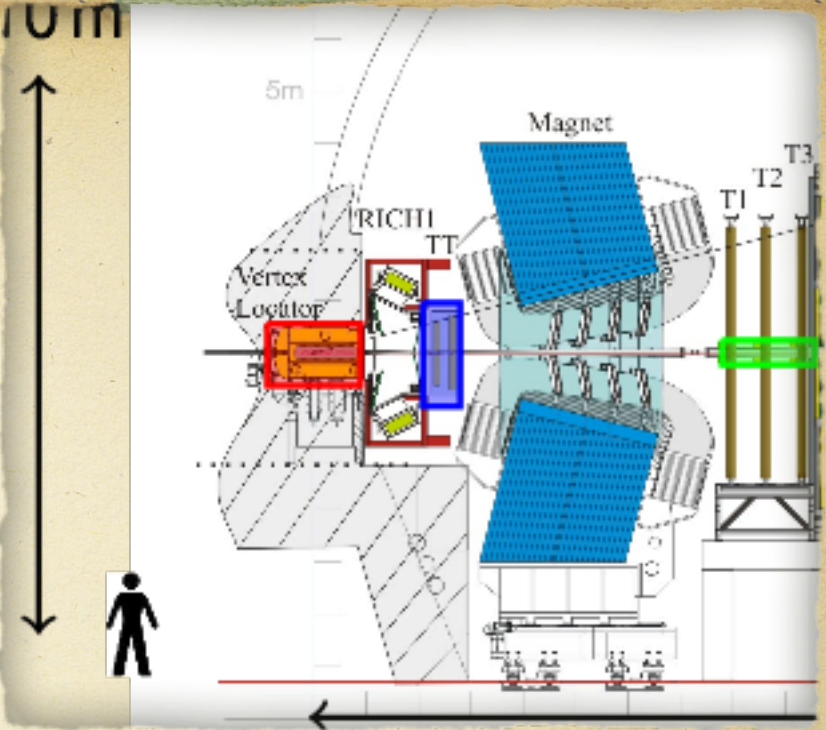


A. de Cosa: VTX2014

LHC-b : VELO, TT, IT

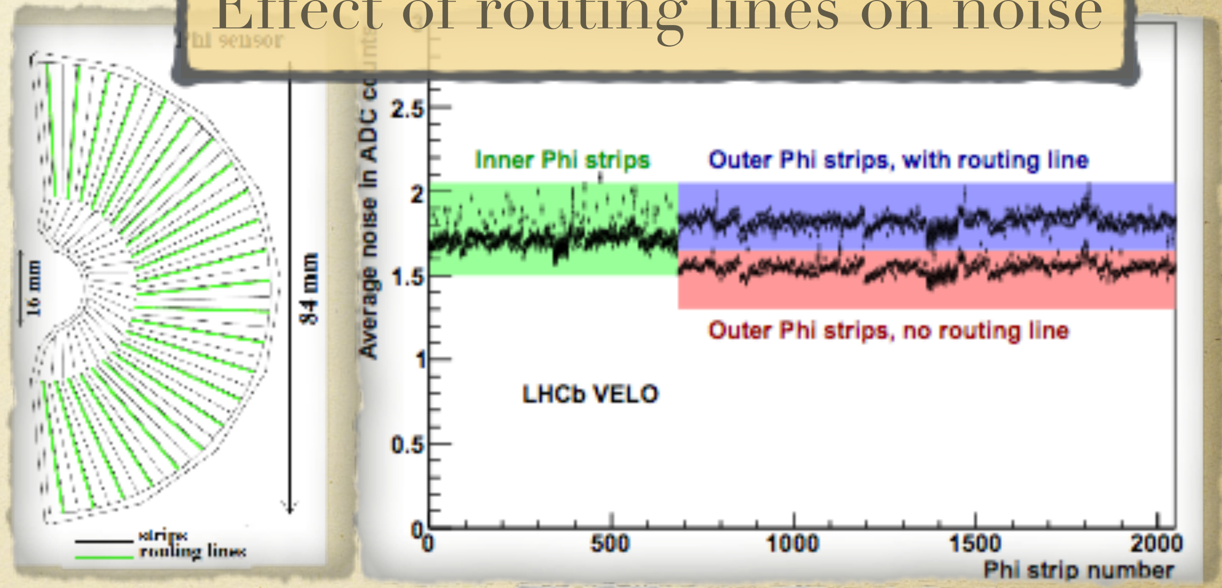
- Strip detectors, working well
- VELO has delicate moving mechanism



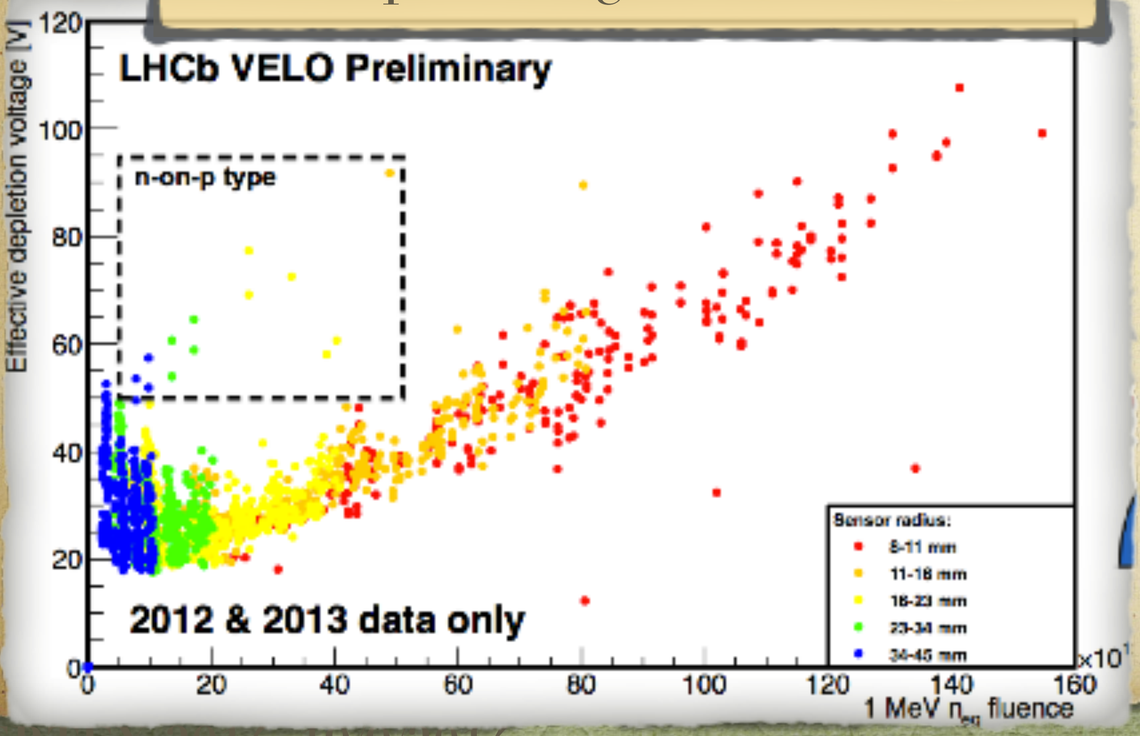


- Careful monitoring of detector changes due to radiation
  - Currents, depl voltage, temperature scans, CCE scans

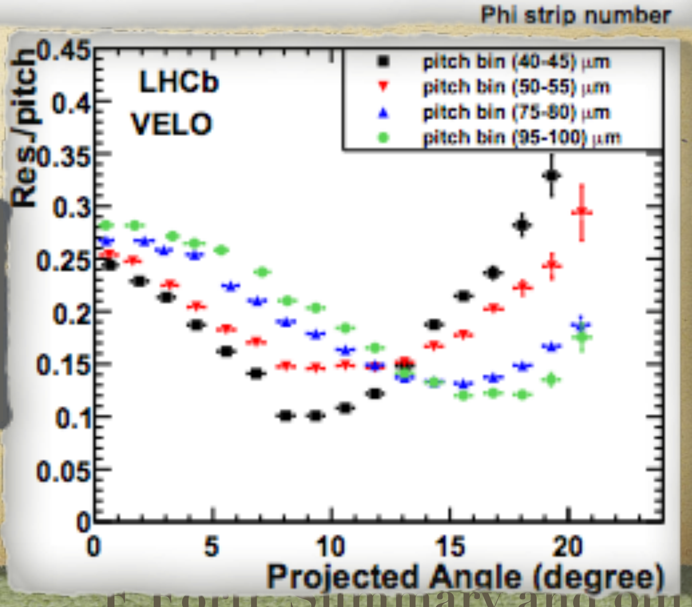
Effect of routing lines on noise



Depl voltage vs fluence



Resolution/pitch vs. angle



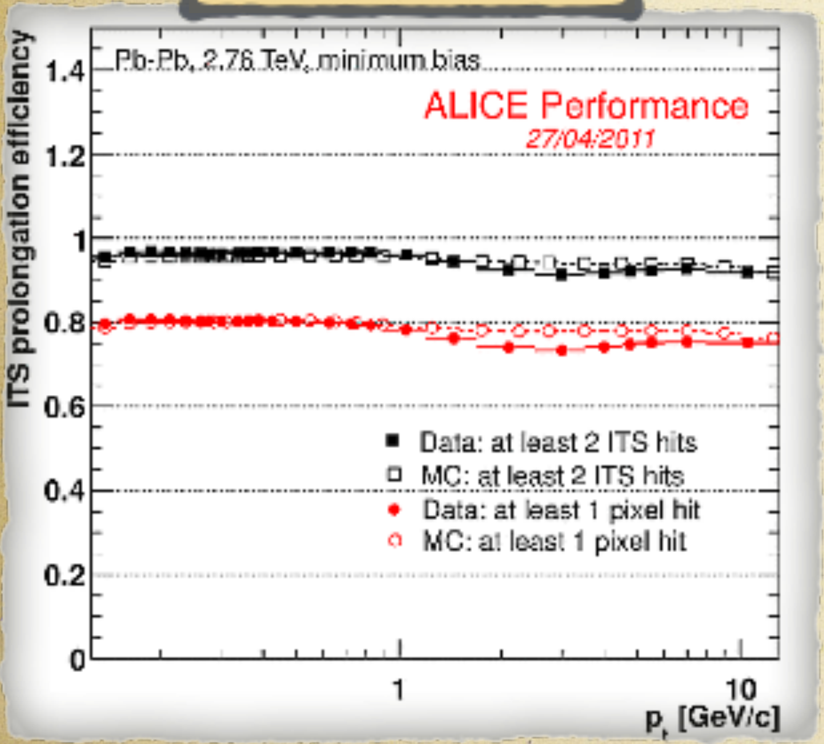
C. Elsasser: VTX2014

ALICE ITS: SPD, SDD, SSD

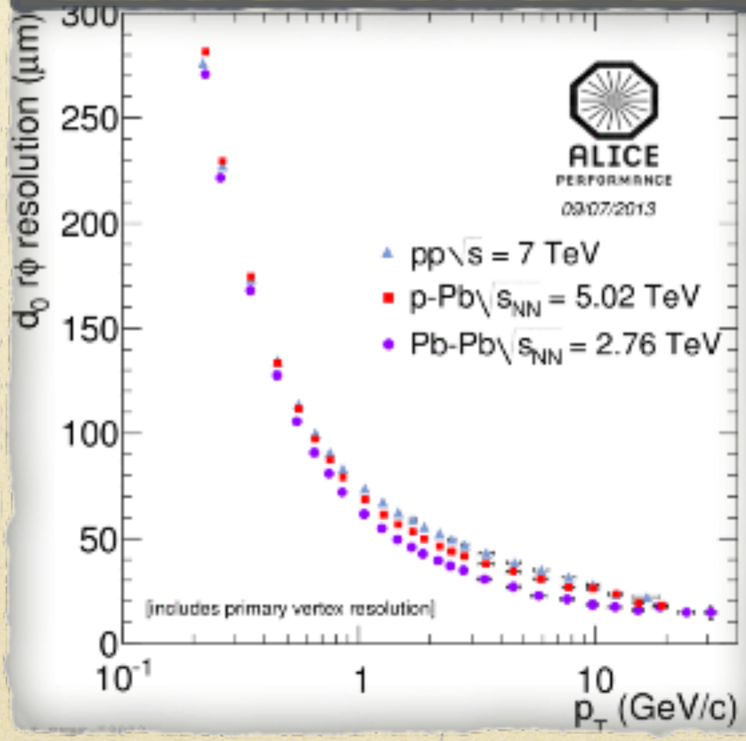
- Pixel, Drift and Strip technologies working together.
- Good efficiency and performance over Run1

S. Senyukov: VTX2014

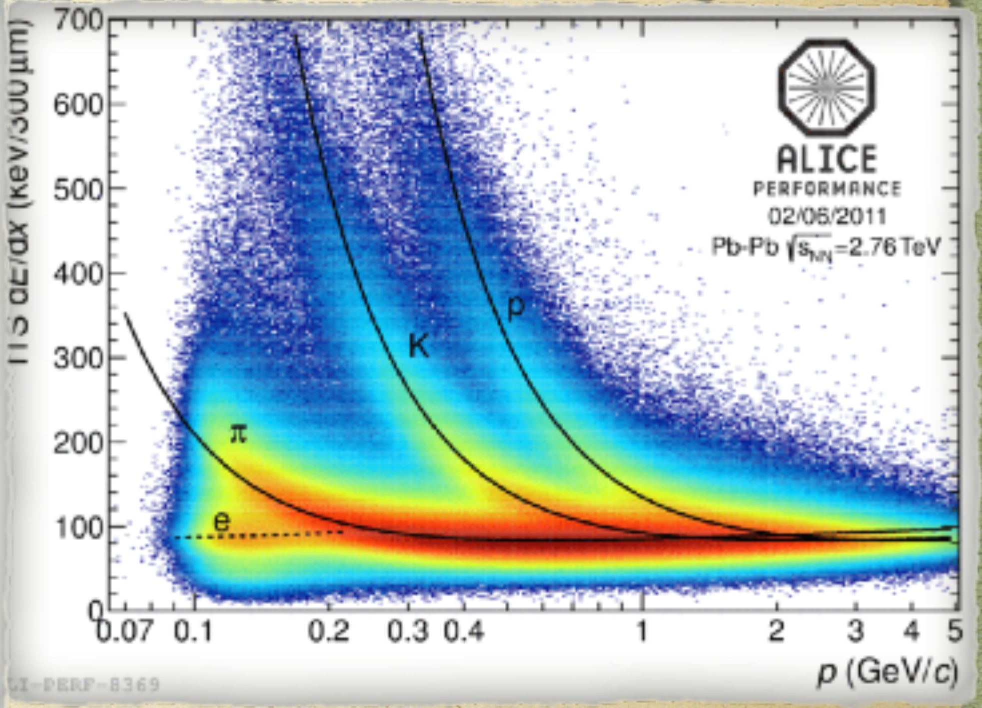
Efficiency



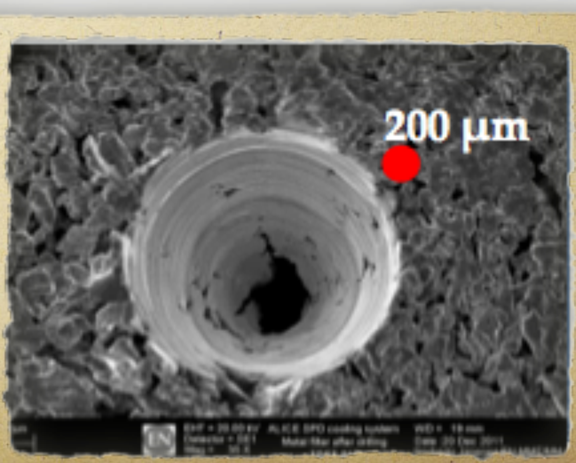
Impact par resolution



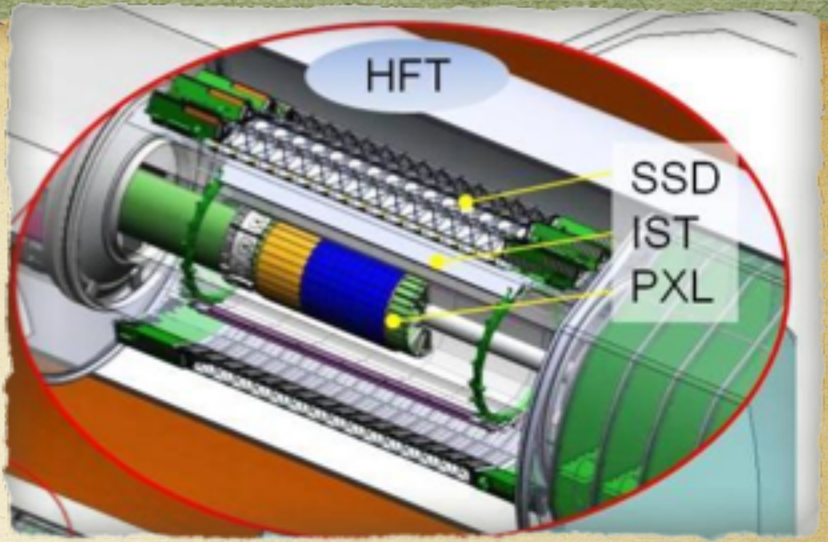
PID



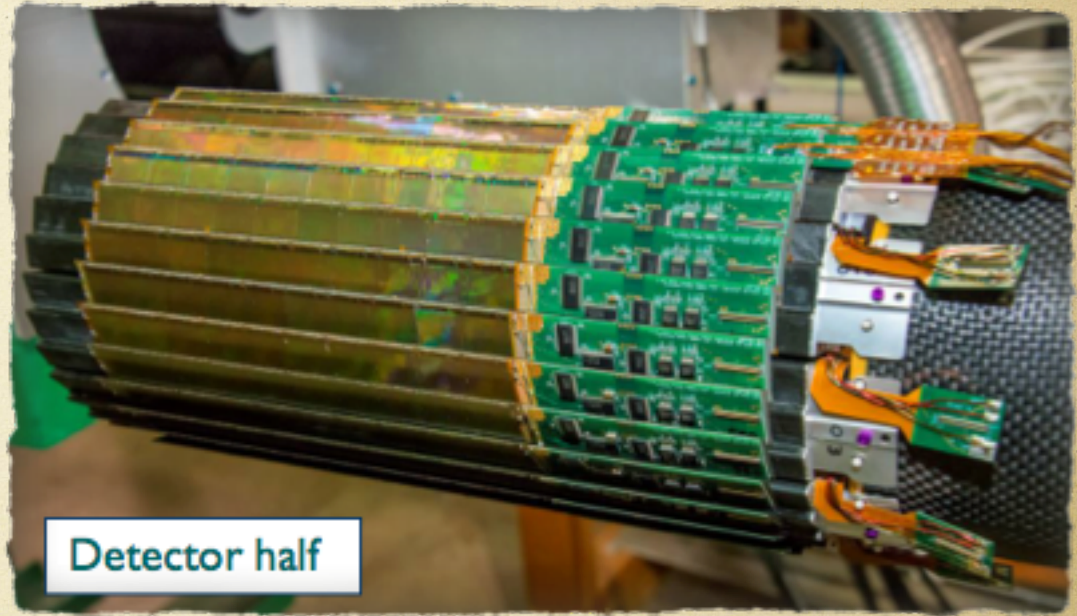
- Issues with clogged filters (SPD) and SEU (SSD) improved in LS1

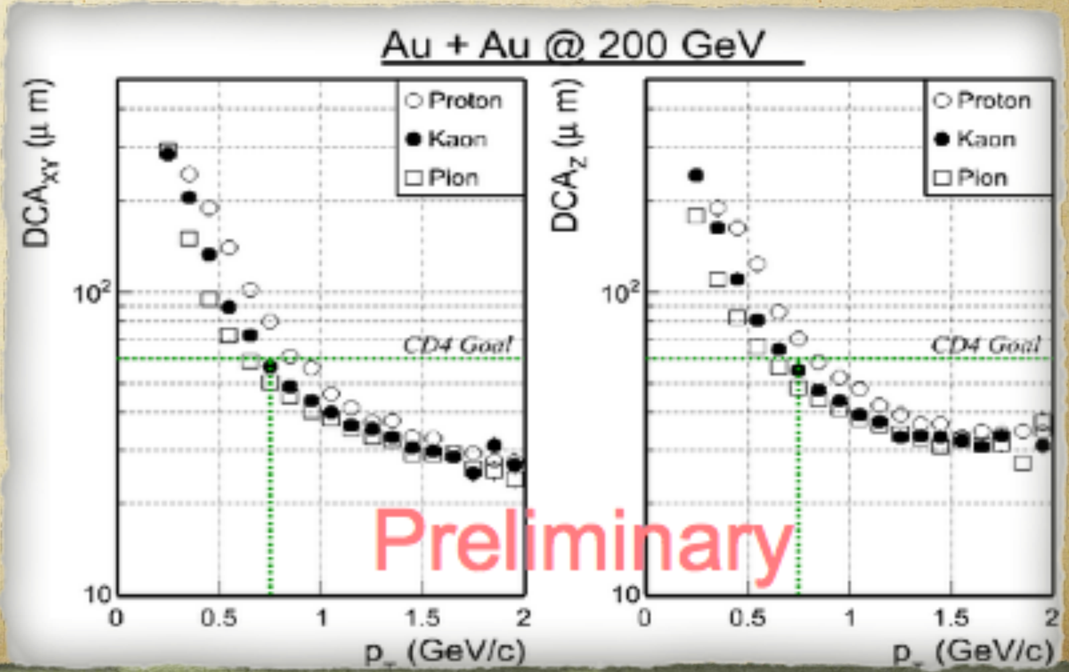


STAR HFT: PXL, IST, SSD



- SSD, IST: conventional strips and pads
- PXL: First MAPS detector at collider (Ultimate-2, from Mimosa series)
- Installed in Jan 2014, run March-July 2014
- 356M Pixels 20.7x20.7 um
- Chips thinned down to 50um
- Integration time: 185.6us
- Many lessons learned - mostly rom system issues:
  - Al cable production delays
  - Issues in ladder assembly
  - Mechanical inteference
  - Shorts between lines
- Radiation resistance under study

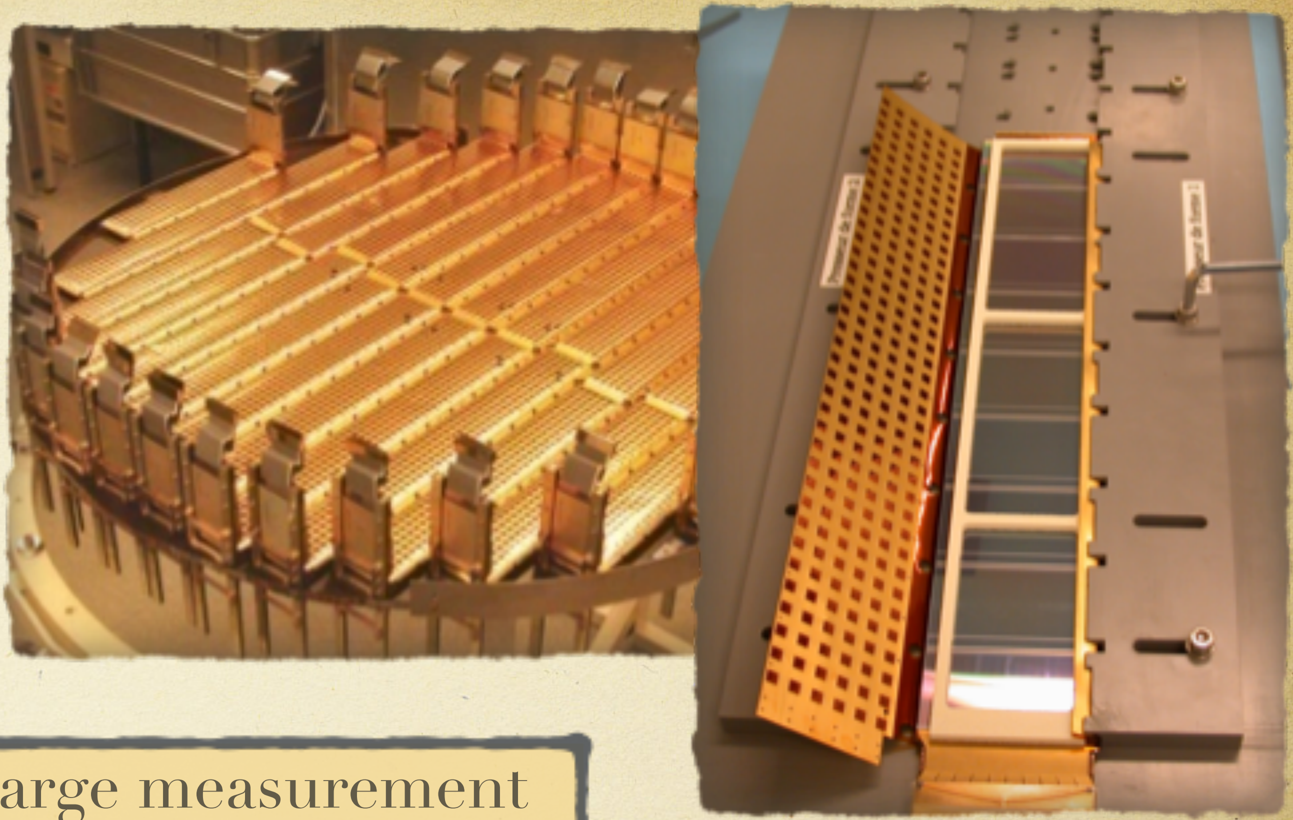




M. Szelezniak: VTX2014

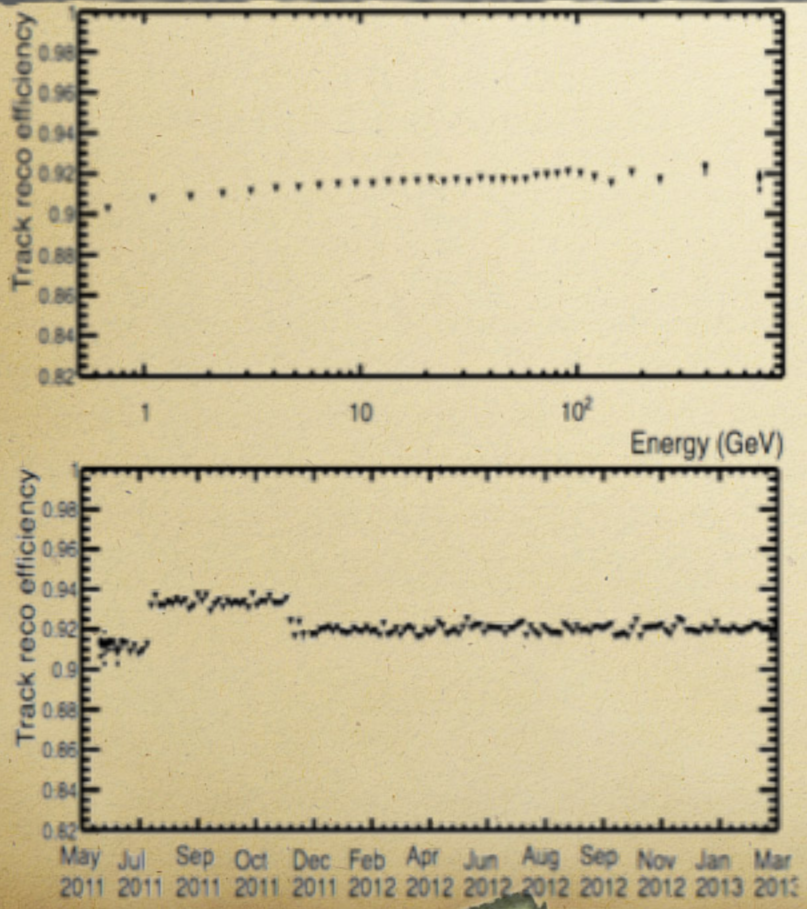
AMS02

- Space operation poses a completely different set of challenges and requirements
- Very long strips, slow shaping, low power (192 W total)
- Continuous thermal variations
  - Dynamic alignment
- Charge measurement
  - Difficult calibration up to 100MIP



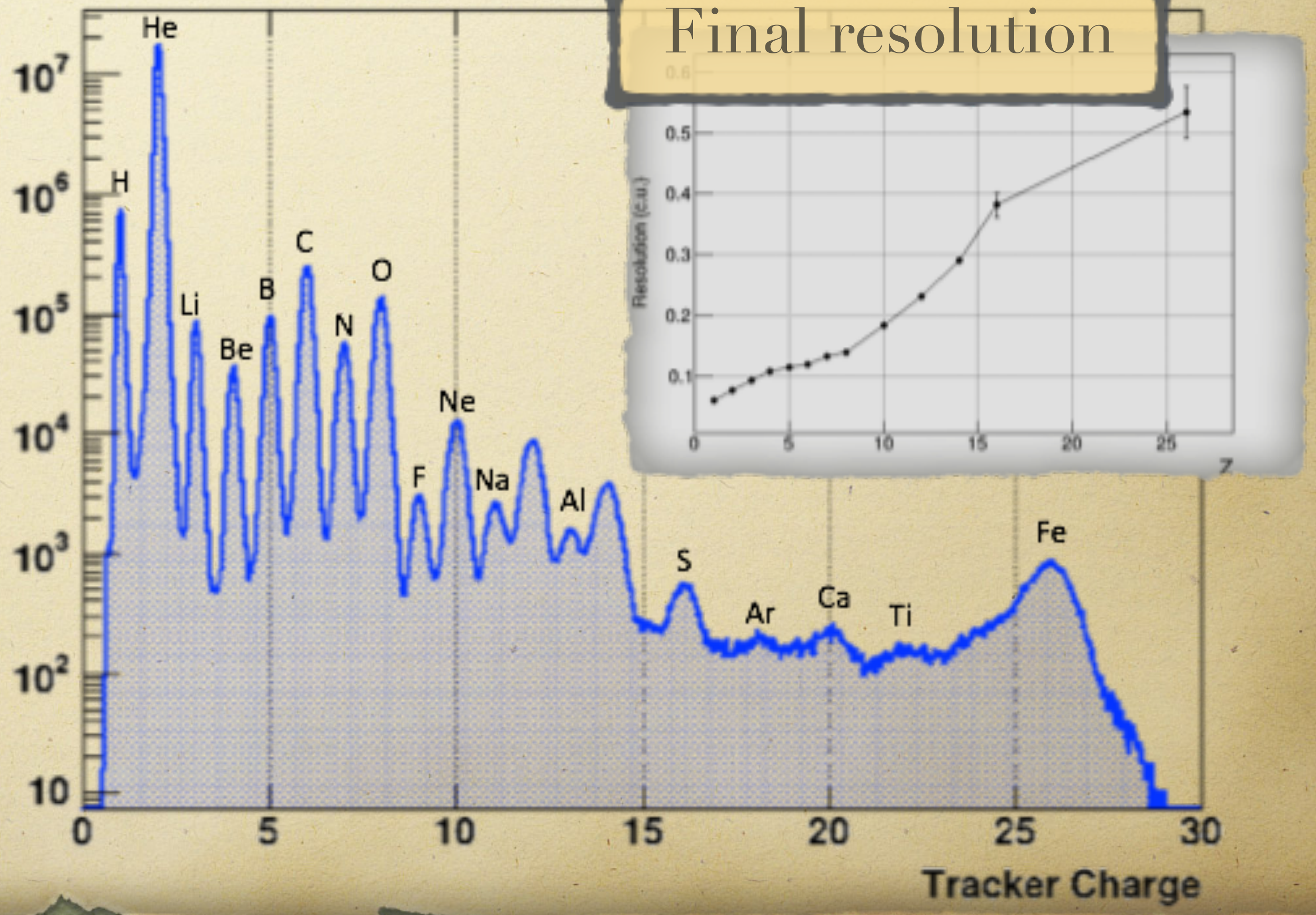
P. Saouter: VTX2014

Efficiency vs energy and time



Charge measurement

Final resolution



System and services lessons

- A lot (most?) of the development work is concentrated on sensors and electronics.

Right, but…

- System engineering is never enough
  - Sometimes improvised without good engineering practices
  - Essential for operating a large detector
  - Retrofitting is a terrible pain
- Knowledge is power
  - Detailed monitoring of everything and handles for adjustment are essential
  - Essential to allow time for detailed analysis and investigation of detector performance and changes
- Plan for the unexpected
  - Redundancy, extra control handles, extra monitoring


KEEP
CALM
AND LOVE THE
TOMORROW
PEOPLE

Detectors in preparation

LHC phase 1 upgrades (2018-19)

- ALICE: ITS MAPS on hi-res epi
- CMS: Pixels: mainly system integration improvements
- LHCb:
  - VELO: pixel, 40MHz, sw trigger (or FPGA ?), microchannel evaporative cooling
  - Upstream Tracker: large single-sided strips, SALT ASIC

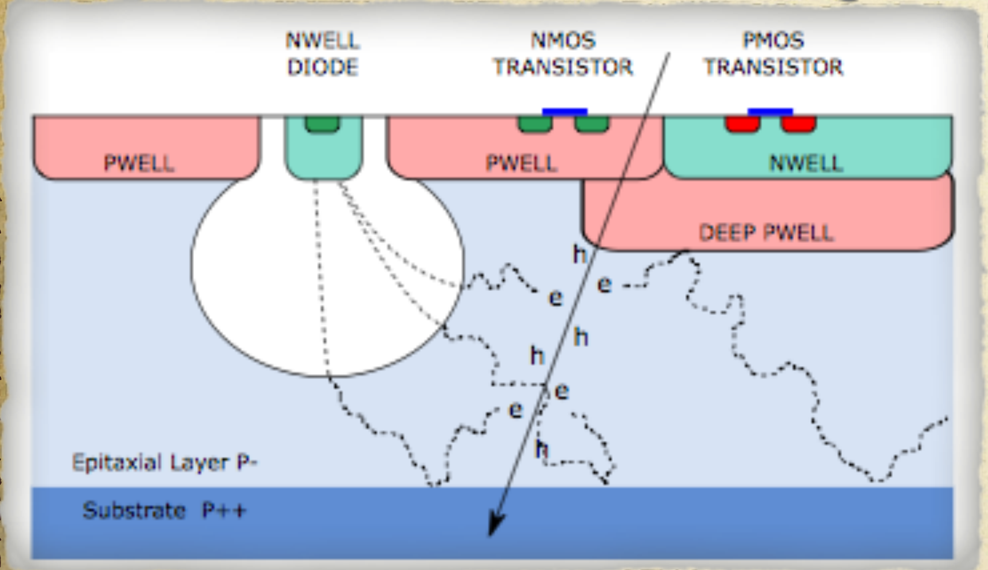
NON-LHC in preparation

- BELLE-II:
  - PXD: first DEPFET application, ROI
  - SVD: DSSD Origami module concept
- NA62: GIGATRACKER: extremely fast, micro channel cooling

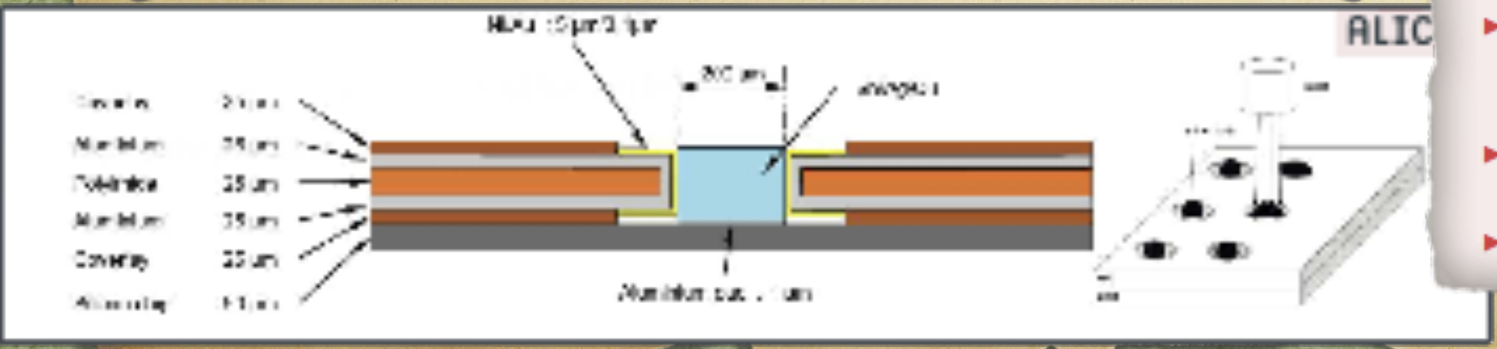
ALICE ITS

- MAPS on hi-resistivity epi
- TowerJazz 0.18um with deep pwell

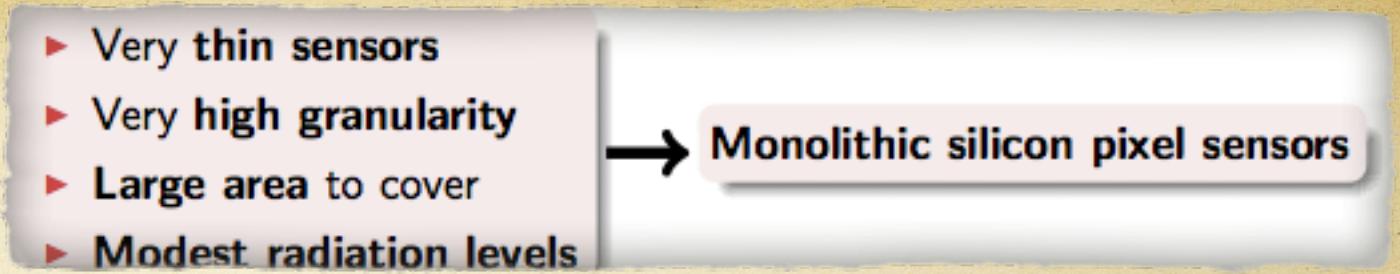
MAPS schematic



Chip-to-flex connections: laser soldering

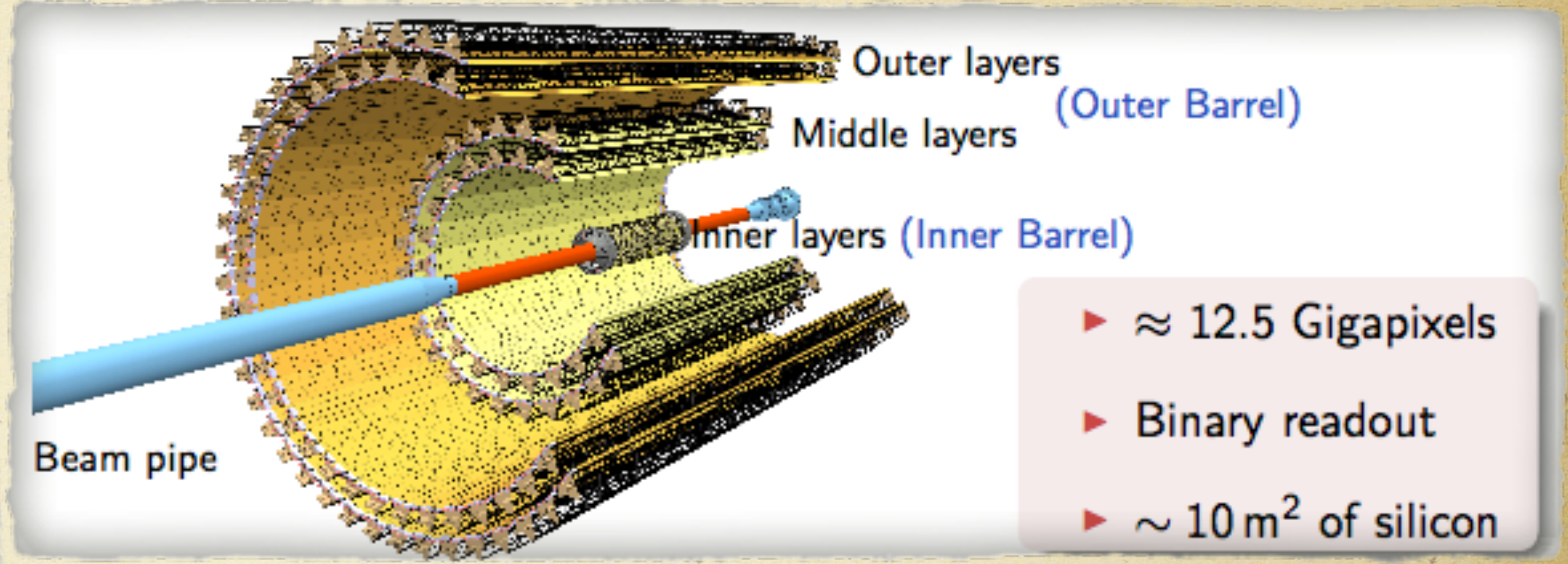


F. Reidt: VTX2014



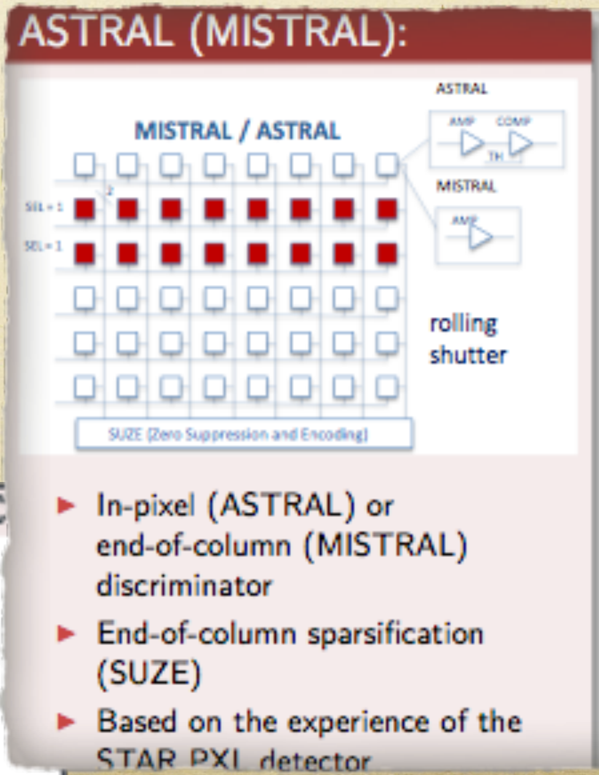
- Very thin sensors
- Very high granularity
- Large area to cover
- Modest radiation levels

→ **Monolithic silicon pixel sensors**



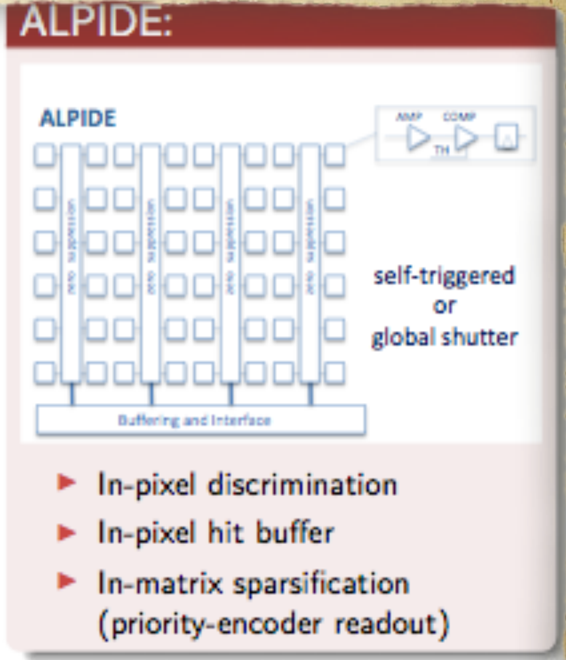
- ≈ 12.5 Gigapixels
- Binary readout
- $\sim 10\,\mathrm{m}^2$ of silicon

Readout architectures under study



ASTRAL (MISTRAL):

- In-pixel (ASTRAL) or end-of-column (MISTRAL) discriminator
- End-of-column sparsification (SUZE)
- Based on the experience of the STAR PXL detector



ALPIDE:

- In-pixel discrimination
- In-pixel hit buffer
- In-matrix sparsification (priority-encoder readout)

CMS PIXELS

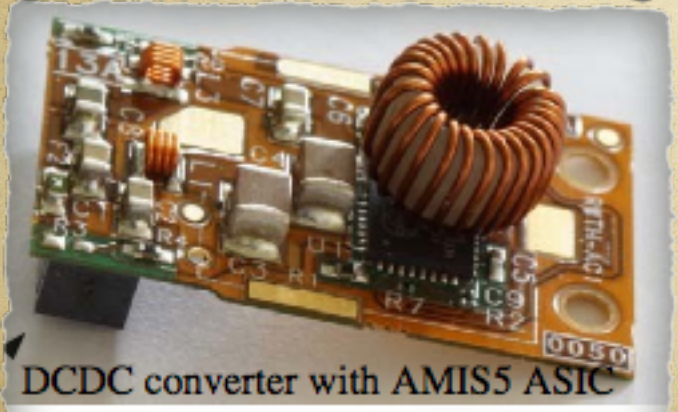
- Maintain performance at higher luminosity
- Evolutionary upgrade of existing pixels

- C6F14 cooling → evaporative CO2
  - higher load, less material
  - T= -20 C with option to go lower (radiation)

- detector core unchanged:
  - pixel size, sensor
  - readout architecture
  - analog front-end (minor cha
- Minimal disruption of data taking
- performance improvements
  - higher rate capability of ROC and data transmission
  - additional tracking layer
  - optimized material budget

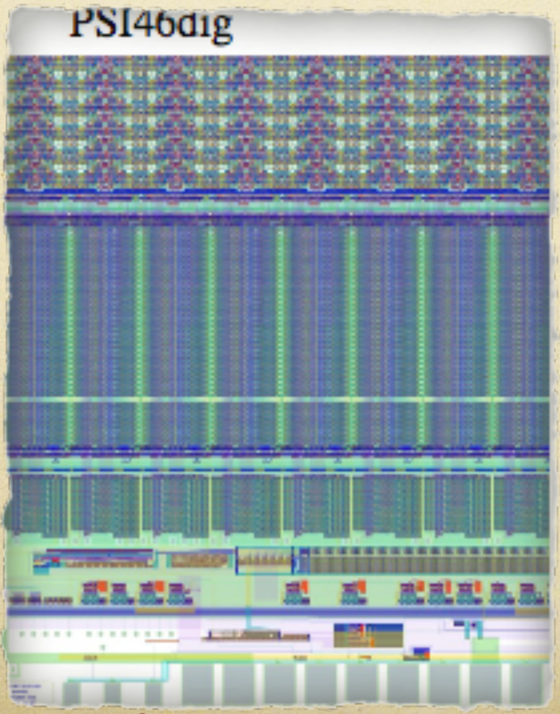
W. Erdmann : VTX2014

DCDC Converters

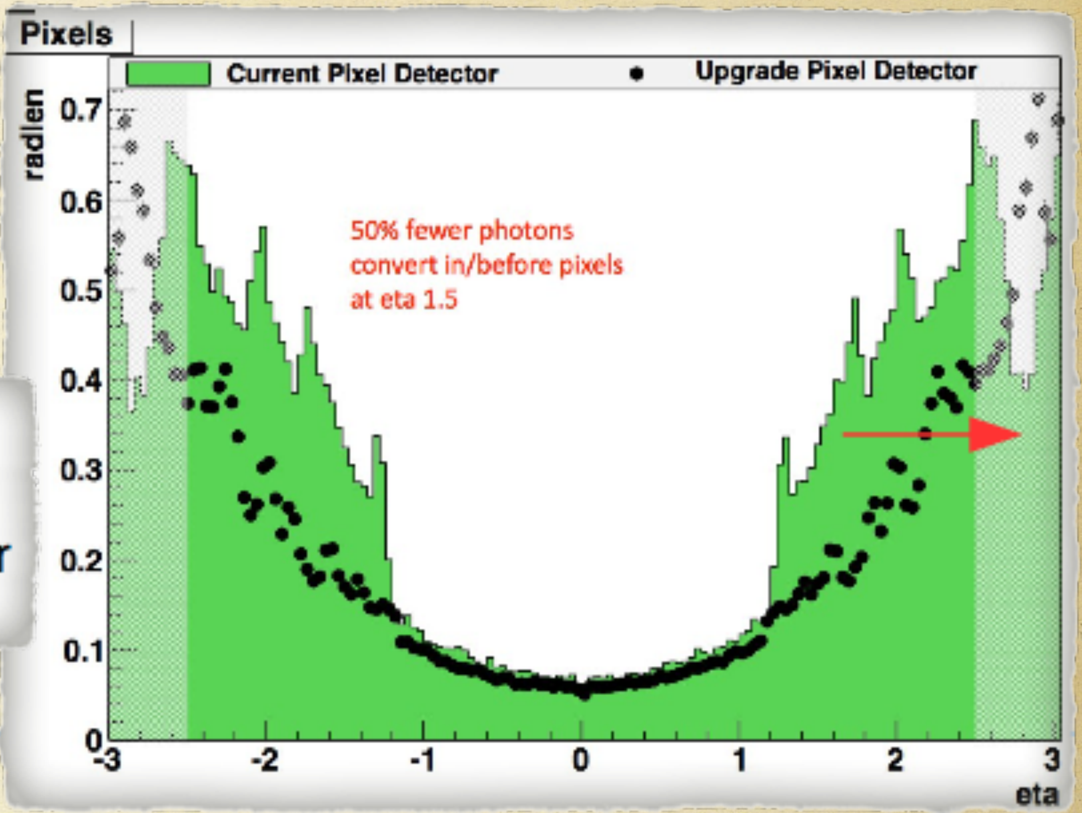


DCDC converter with AMIS5 ASIC
(RF shield not mounted)

Readout IC

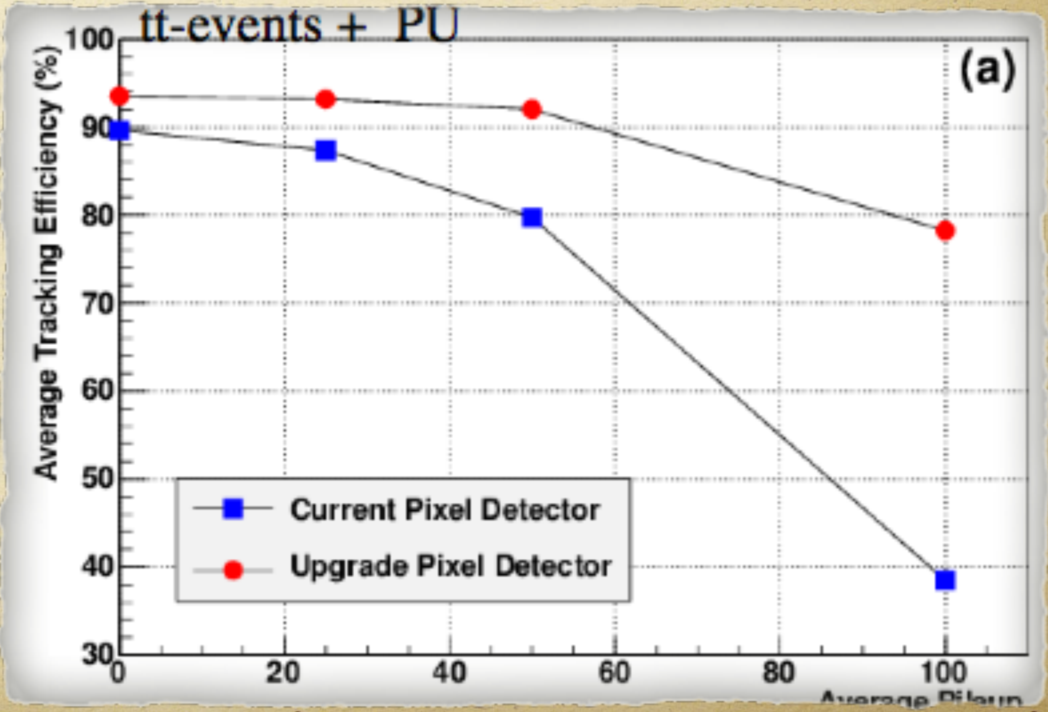


Improved material budget



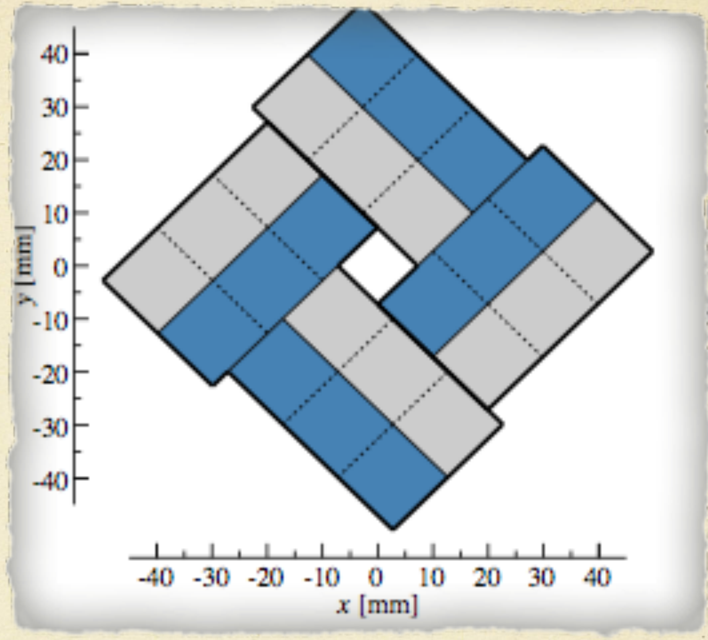
50% fewer photons convert in/before pixels at eta 1.5

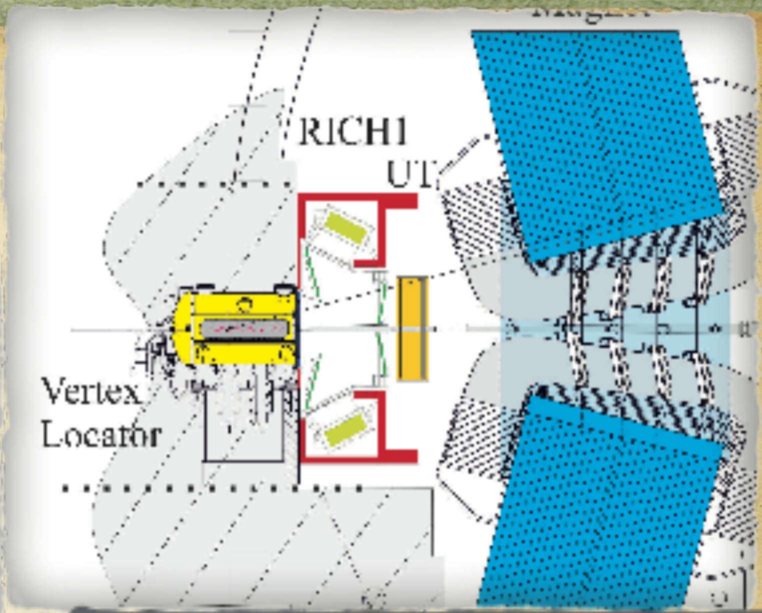
Improved efficiency



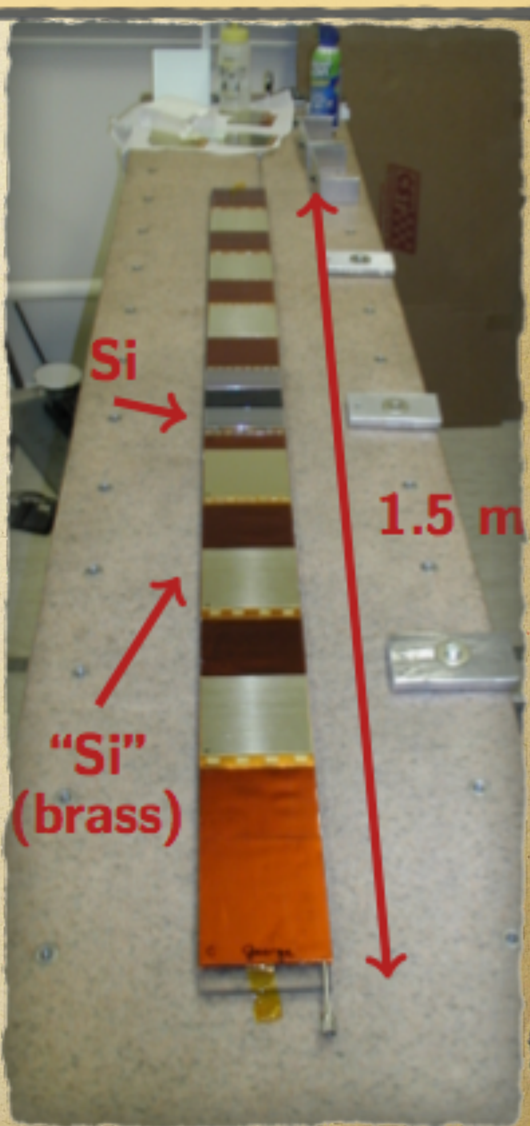
LHCb VELO + UT

- Triggerless 40MHz readout
- VELO: Pixel 55x55um , VeloPix readout chip
  - Microchannel CO2 evaporative cooling at -20C
  - Closer to beam
- UT: Strips, SALT chip readout, long staves





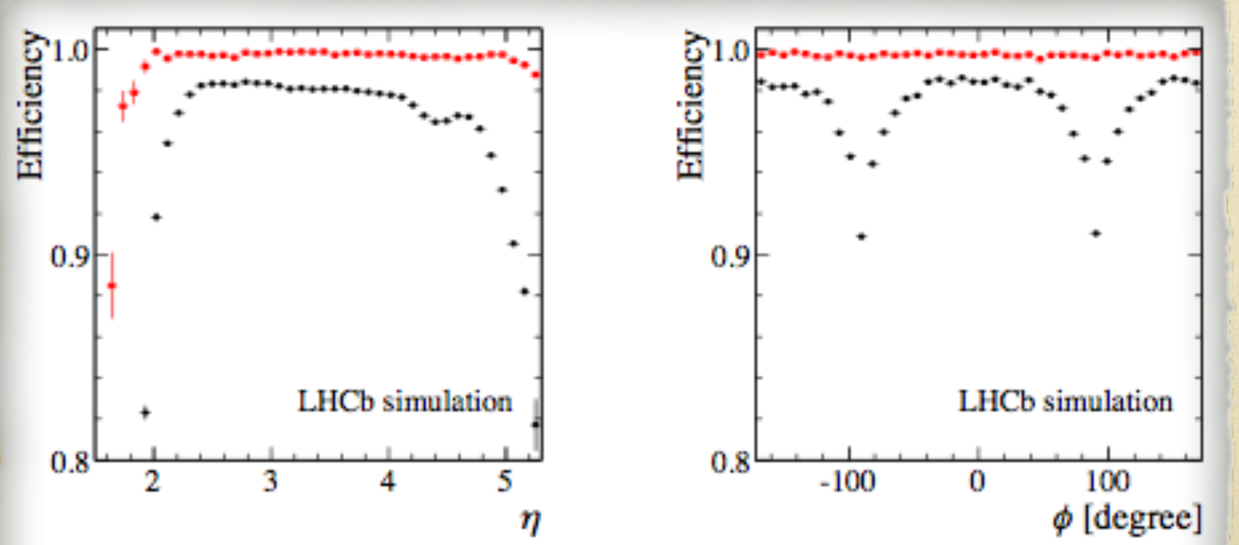
UT Stave prototype



F. Lionetto : VTX2014

H. Schindler: VTX2014

Significant improvements

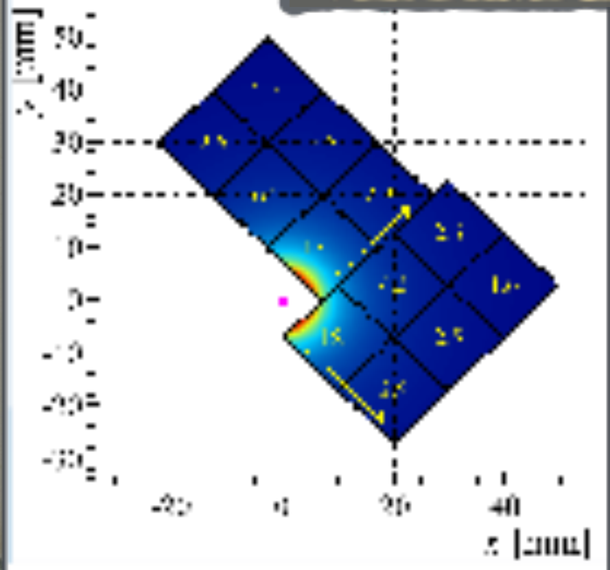


Reconstruction efficiency of existing (black) and upgraded (red) VELO at upgrade luminosity ($\mathcal{L} = 2 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$).

Requirements

- Tip of hottest sensor accumulates fluence of 8×10^{15} 1 MeV $n_{eq}\,\mathrm{cm}^{-2}$ after 50 fb^{-1}.
- Outer region of the same sensor will see by factor 10 – 20 lower fluence.
- Sensors must be able to withstand 1000 V bias without breakdown.

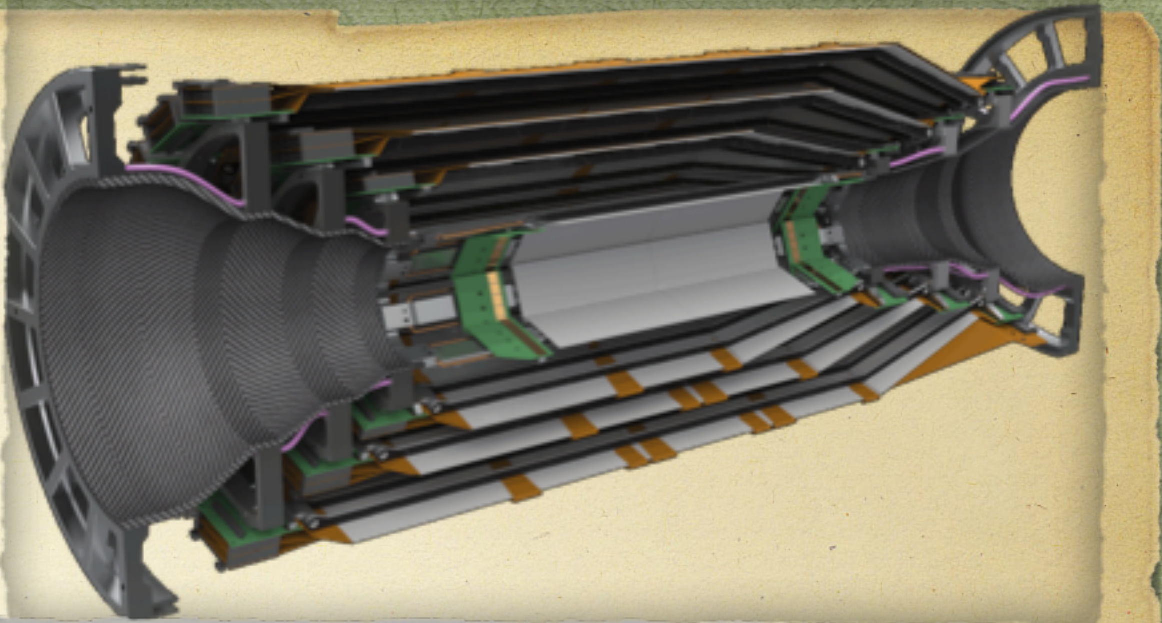
Data rate



Data rate [Gbit/s] for hottest module.

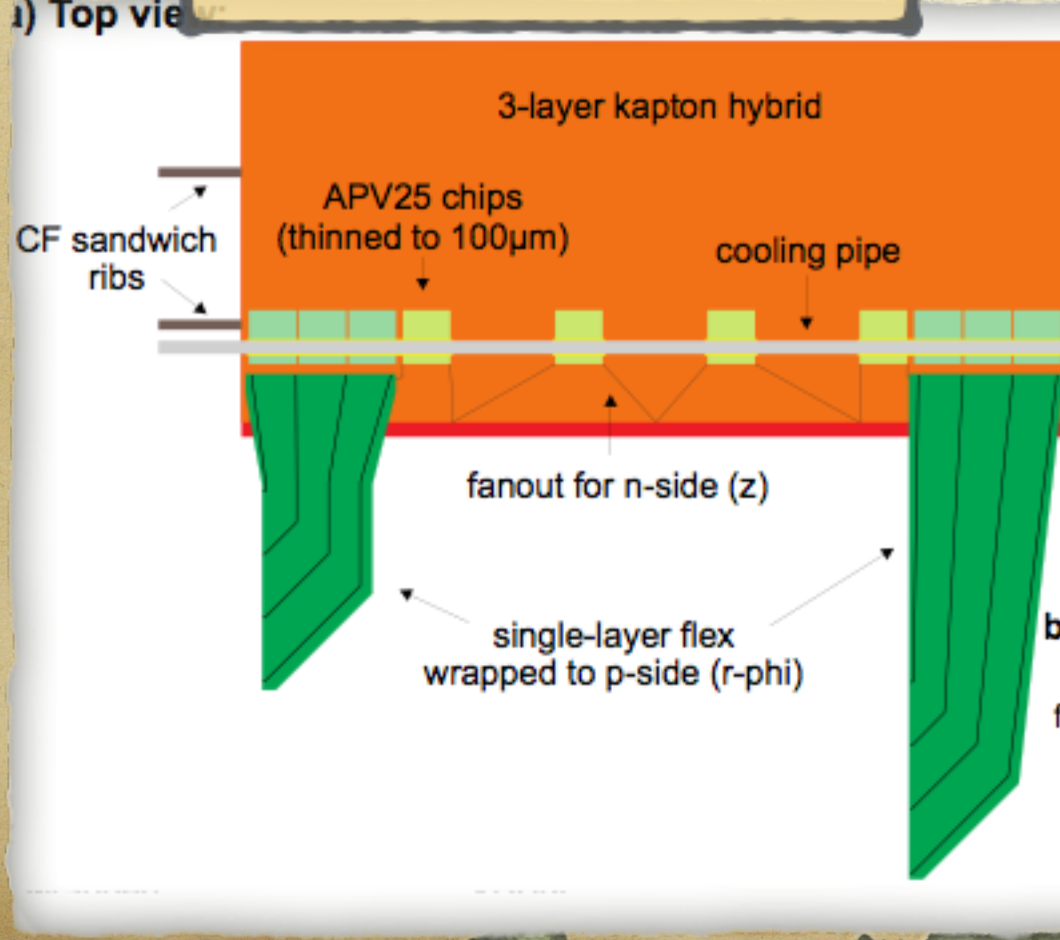
BELLE II SVD

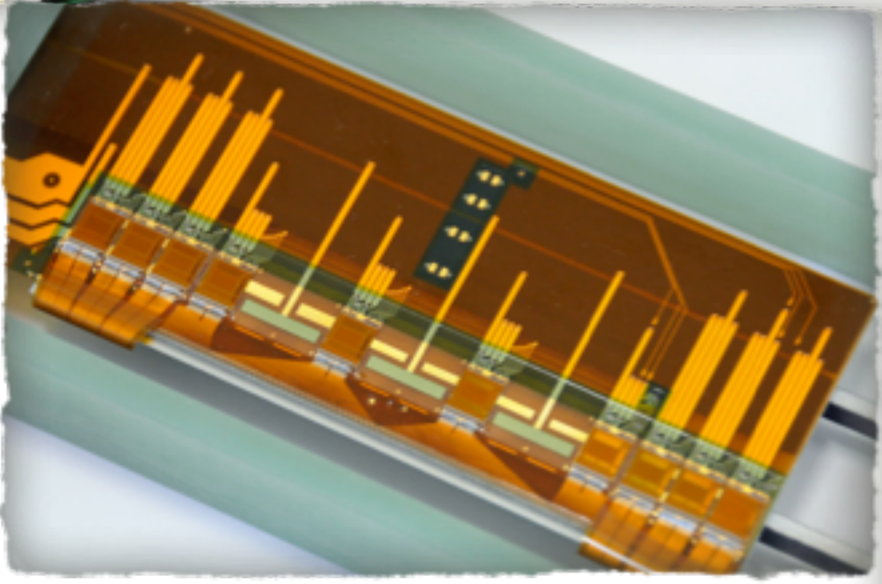
- 4 layers of double-sided strip sensors
- APV25 readout
- Origami concept
- CO2 evaporative cooling
- Install in 2016

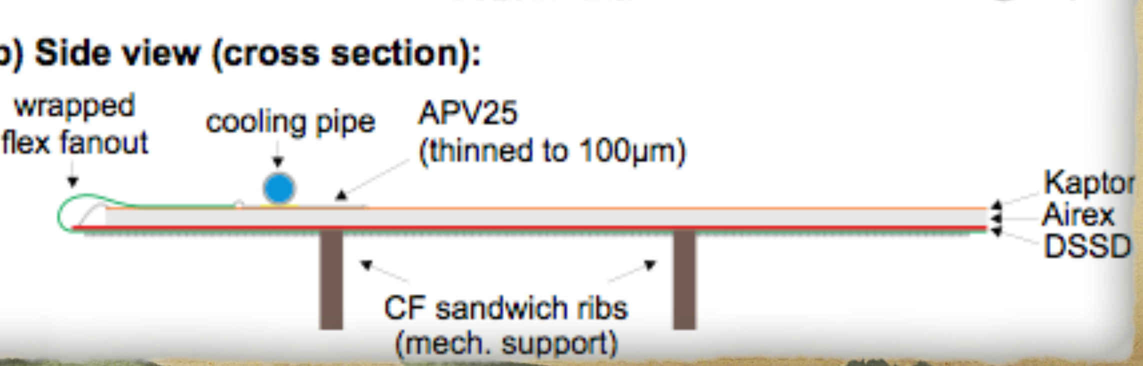


Layer 5 module

Origami Concept





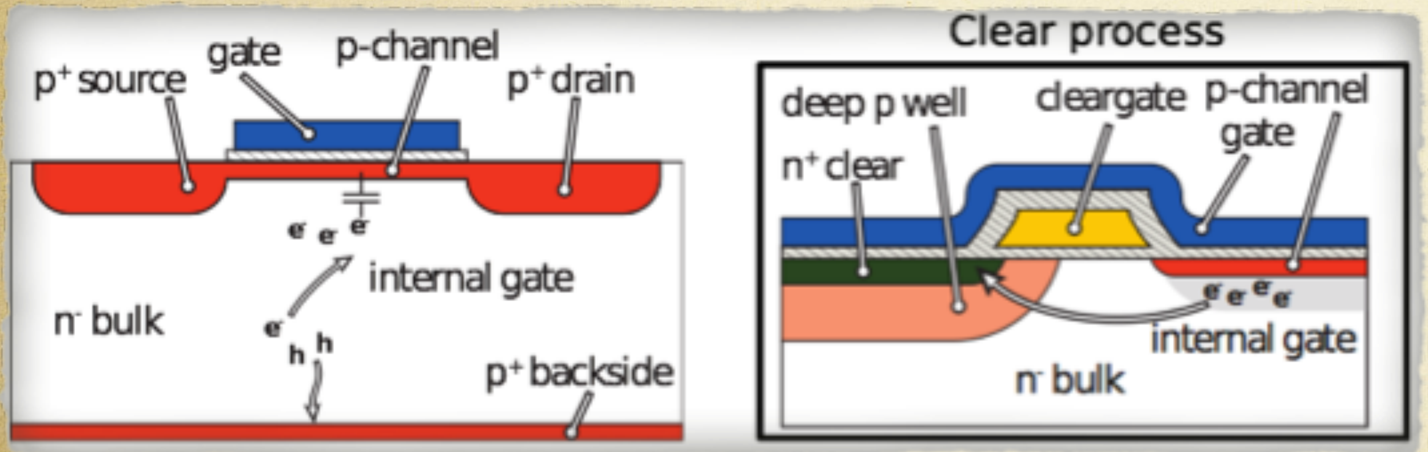


L. Vitale: VTX2014

BELLE II PXD

- 2 layers DEPFET Pixel Detector (PXD) with 8 Mpixels at 1.4 and 2.2 cm radii.
- First DEPFET application at colliders

DEPFET Concept



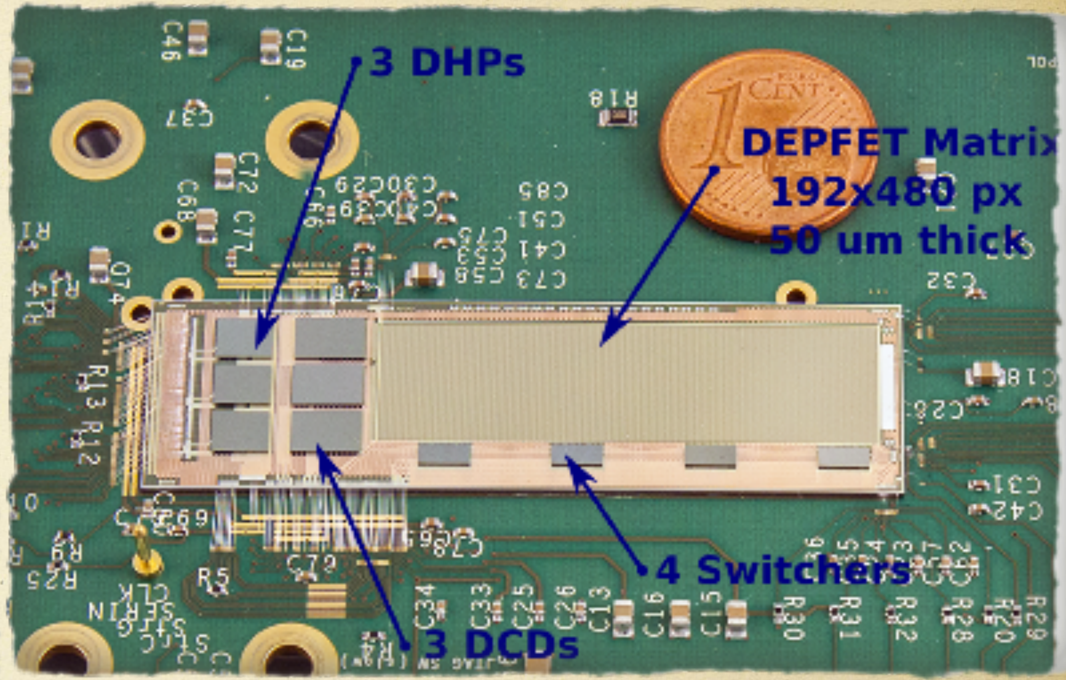
M.Schnell: VTX2014

Issues:

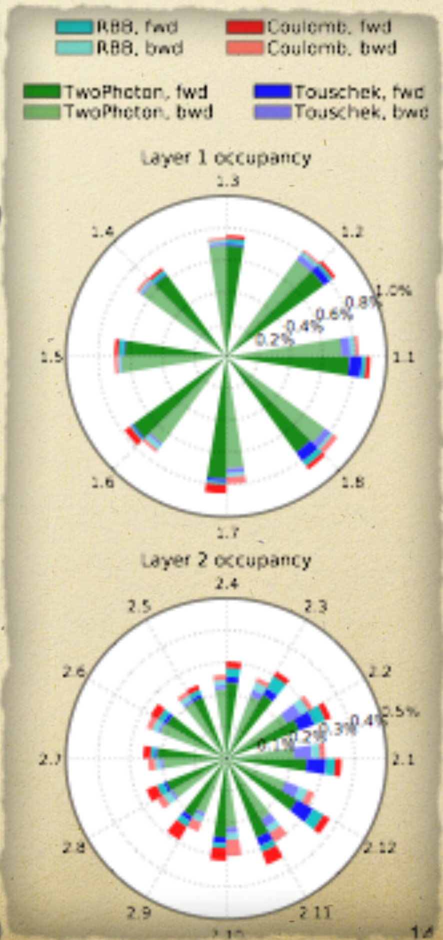
- Occupancy due to background
- Data reduction through ROI readout
- Very sophisticated technology

Installation in 2016

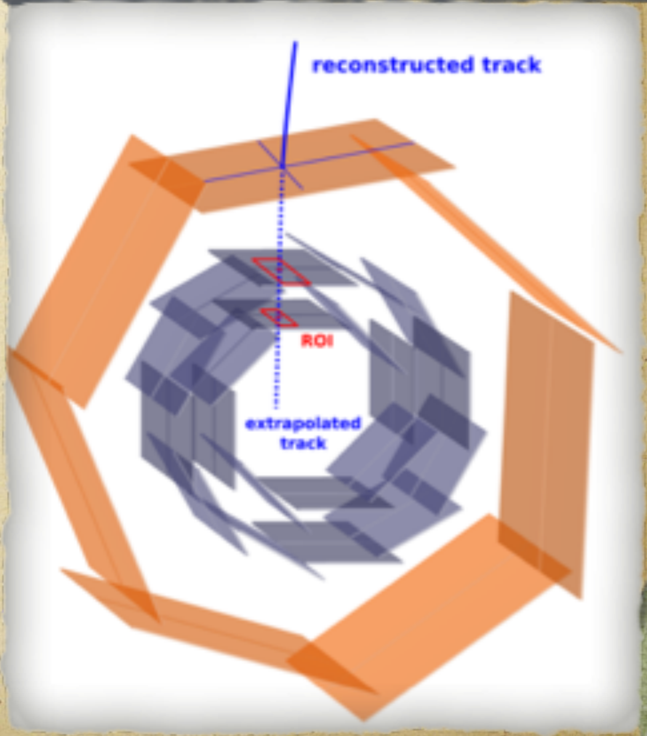
Very complex module and readout



Background by source



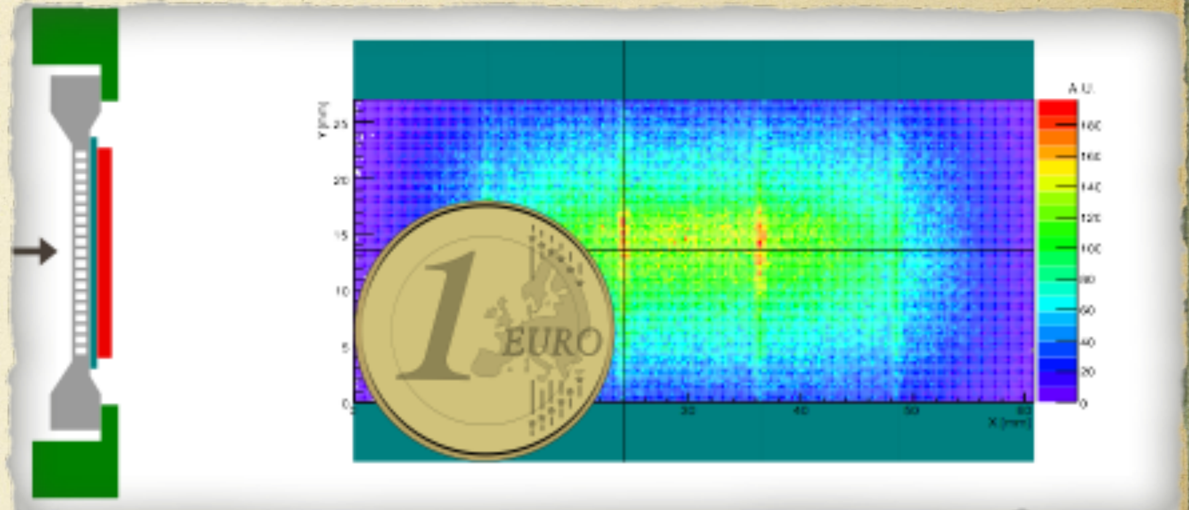
ROI from SVD Track



NA62 GIGATRACKER

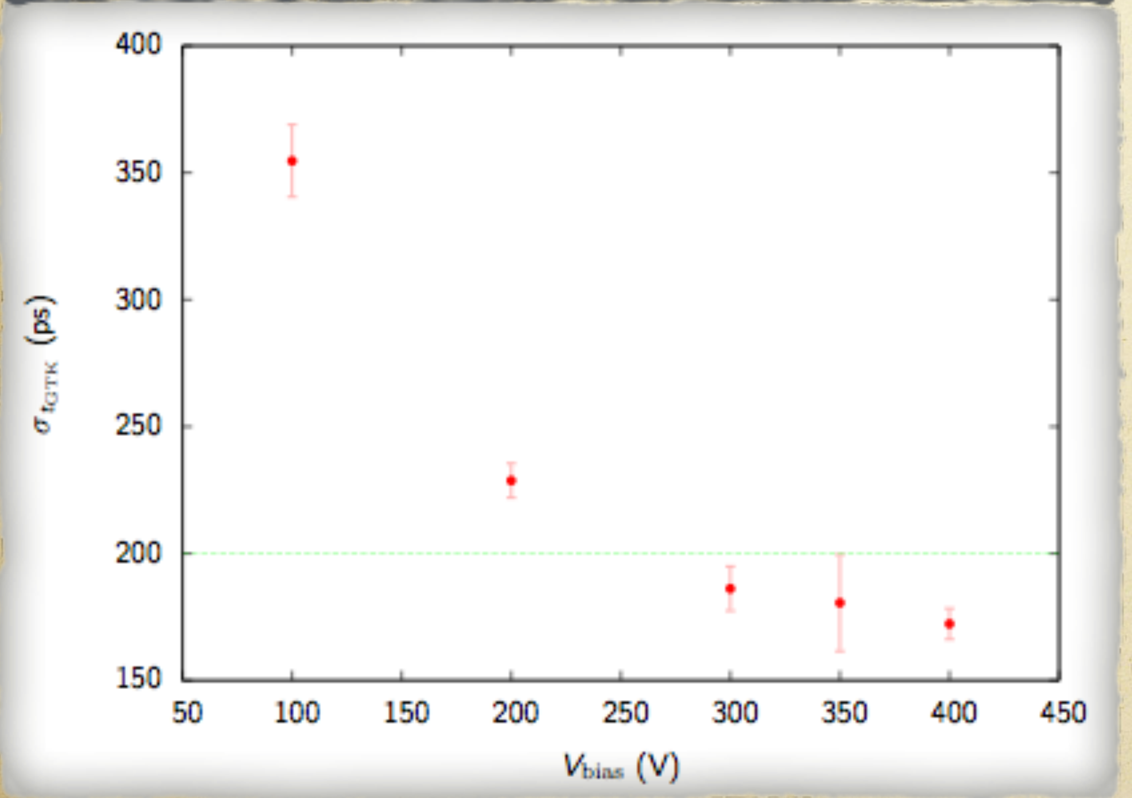
- Very fast pixel detector on small area
- TDCPix readout IC with time walk correction
- First micro cooling application

Track the beam

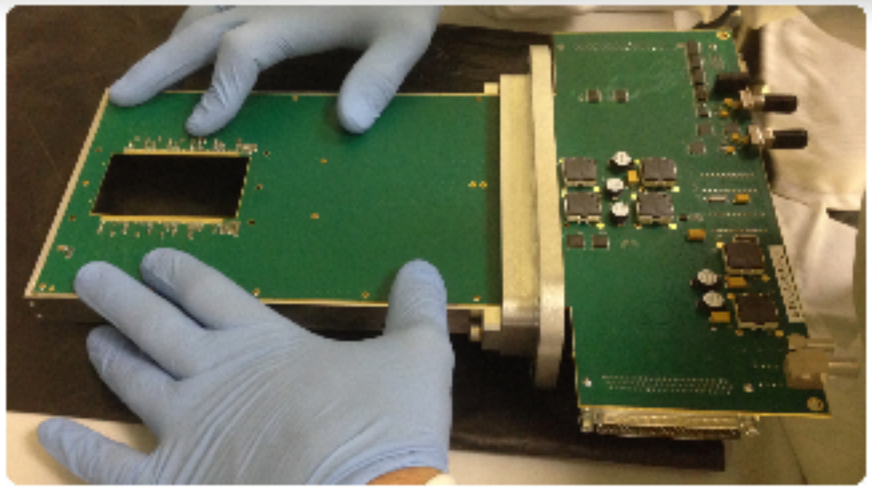


Test beam results on time resolution

B.Velghe: VTX2014



On beam soon

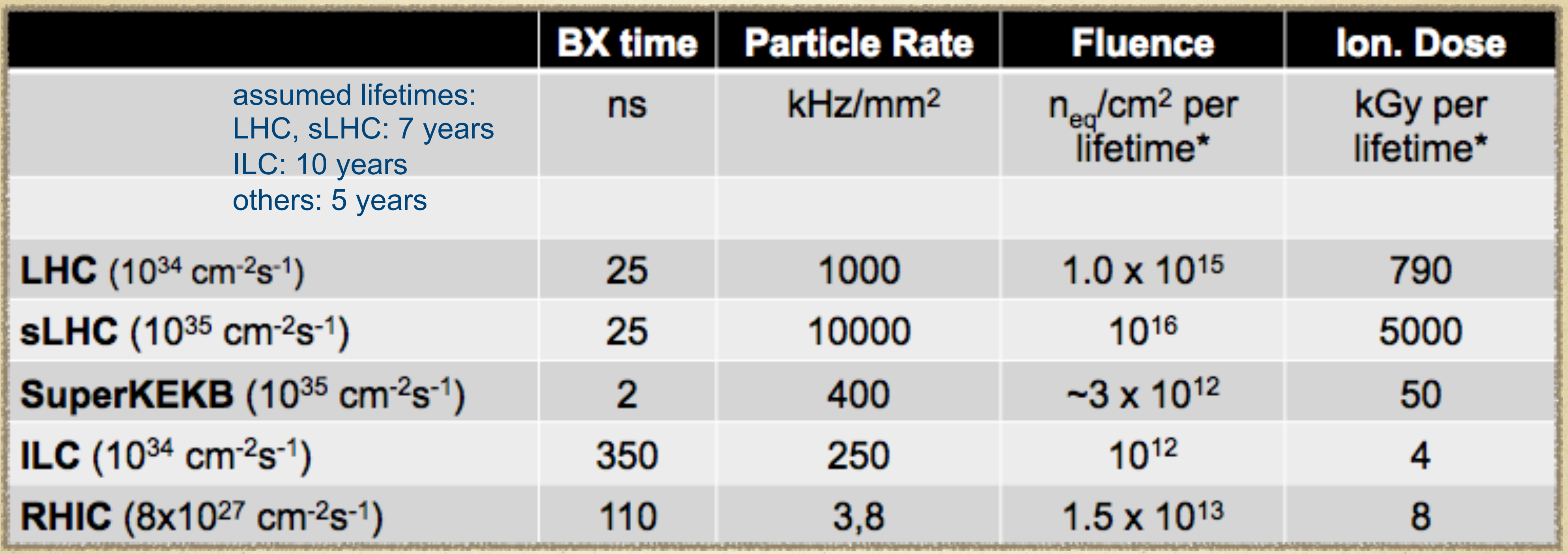


- Sustains **750 MHz** hit rate with $\leq$ **200 ps** hit time resolution,
- First micro cooling application in HEP, station thickness $\approx$ **450 μm**,
- Final integration is ongoing. All sub-systems tests are going well.

First beams in three weeks !

Present detectors

Detectors at future accelerators

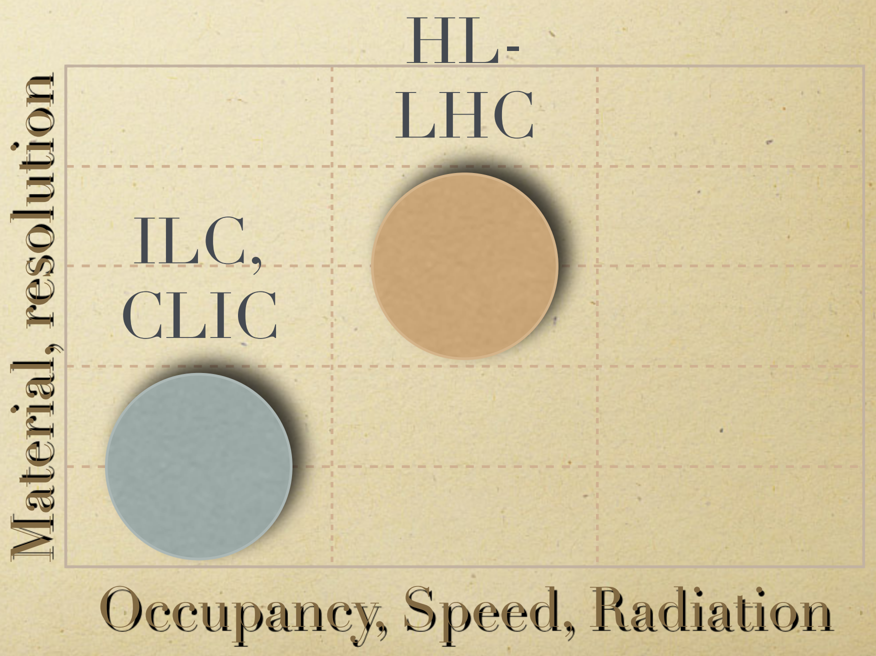


	BX time	Particle Rate	Fluence	Ion. Dose
assumed lifetimes: LHC, sLHC: 7 years ILC: 10 years others: 5 years	ns	kHz/mm^2	n_{eq}/cm^2 per lifetime*	kGy per lifetime*
LHC (10^{34} cm^{-2}s^{-1})	25	1000	1.0×10^{15}	790
sLHC (10^{35} cm^{-2}s^{-1})	25	10000	10^{16}	5000
SuperKEKB (10^{35} cm^{-2}s^{-1})	2	400	$\sim 3 \times 10^{12}$	50
ILC (10^{34} cm^{-2}s^{-1})	350	250	10^{12}	4
RHIC (8×10^{27} cm^{-2}s^{-1})	110	3,8	1.5×10^{13}	8

N. Wermes VTX2013

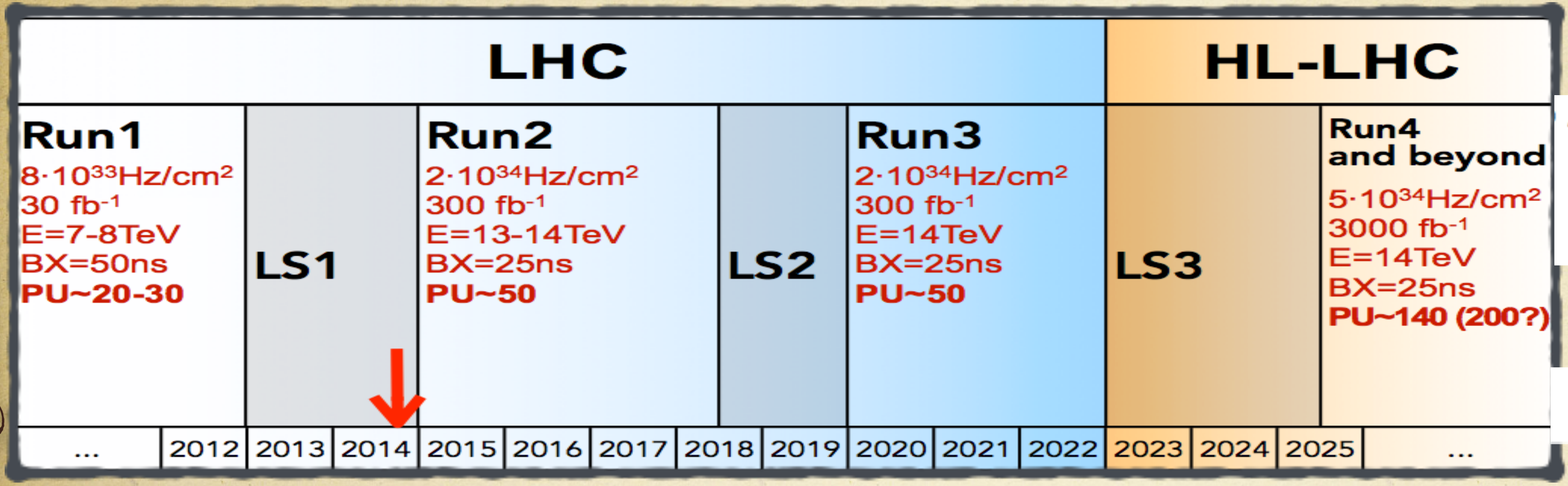
- Wide range of requirements
- Different development directions

Two extremes



HL-LHC (Phase 2 upgrades)

G. Sguazzoni: VTX2014



LHC					HL-LHC	
Run1 $8 \cdot 10^{33}$Hz/cm^2 30 fb^{-1} E=7-8TeV BX=50ns **PU~20-30**	**LS1**	**Run2** $2 \cdot 10^{34}$Hz/cm^2 300 fb^{-1} E=13-14TeV BX=25ns **PU~50**	**LS2**	**Run3** $2 \cdot 10^{34}$Hz/cm^2 300 fb^{-1} E=14TeV BX=25ns **PU~50**	**LS3**	**Run4 and beyond** $5 \cdot 10^{34}$Hz/cm^2 3000 fb^{-1} E=14TeV BX=25ns **PU~140 (200?)**

… 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 …

Average N_{vertex} ~ <140>
up to 230 multiple interactions,
1000 tracks per $\Delta\eta = 1.0$

fluence of $2 \times 10^{15}\, n_{eq}/\text{cm}^2$

K. Lohwasser: VTX2014

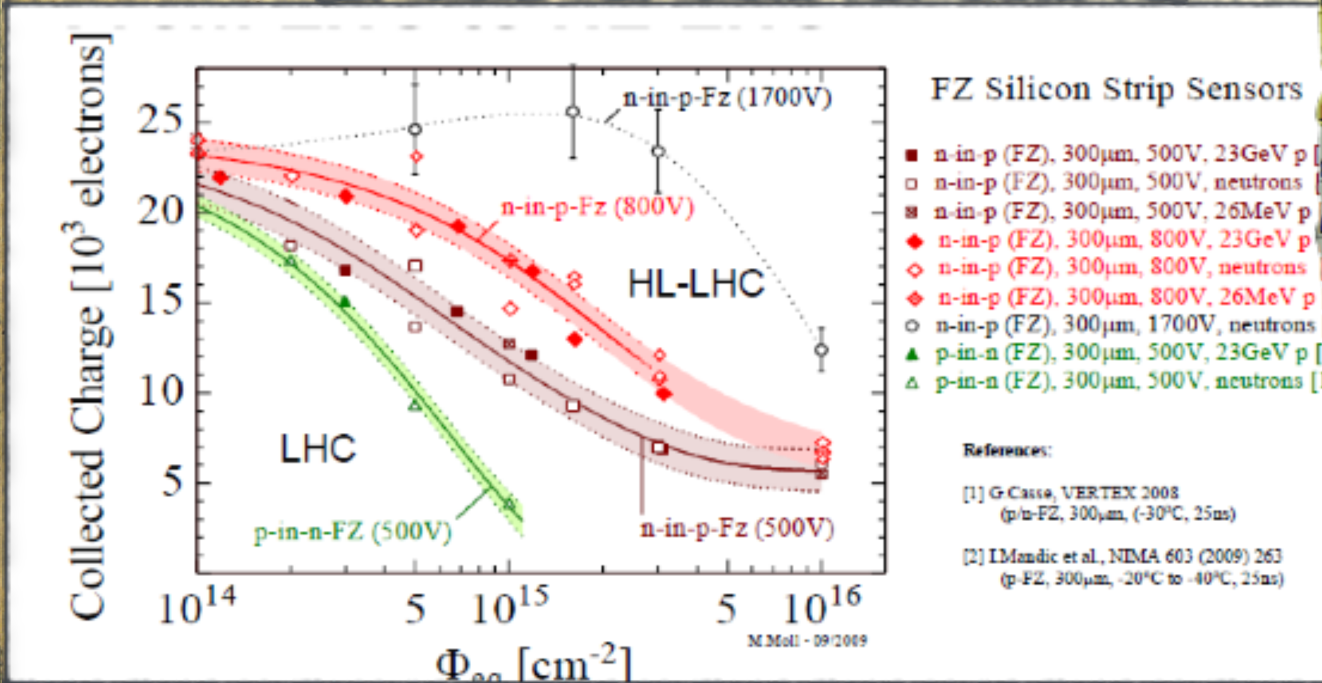
- Current devices will **not** survive
- Main technical challenges:
  - Radiation hardness
  - Occupancy
- Cost *is* an issue

- Common R&D is essential
  - Example of RD50, RD53 collaborations
- Design optimization
  - At all levels (sensors, modules, system)
  - Robustness
- Exploit common solutions
  - Scale economy, modularity

Radiation Hardness

- Choice of sensor material

Charge Collection



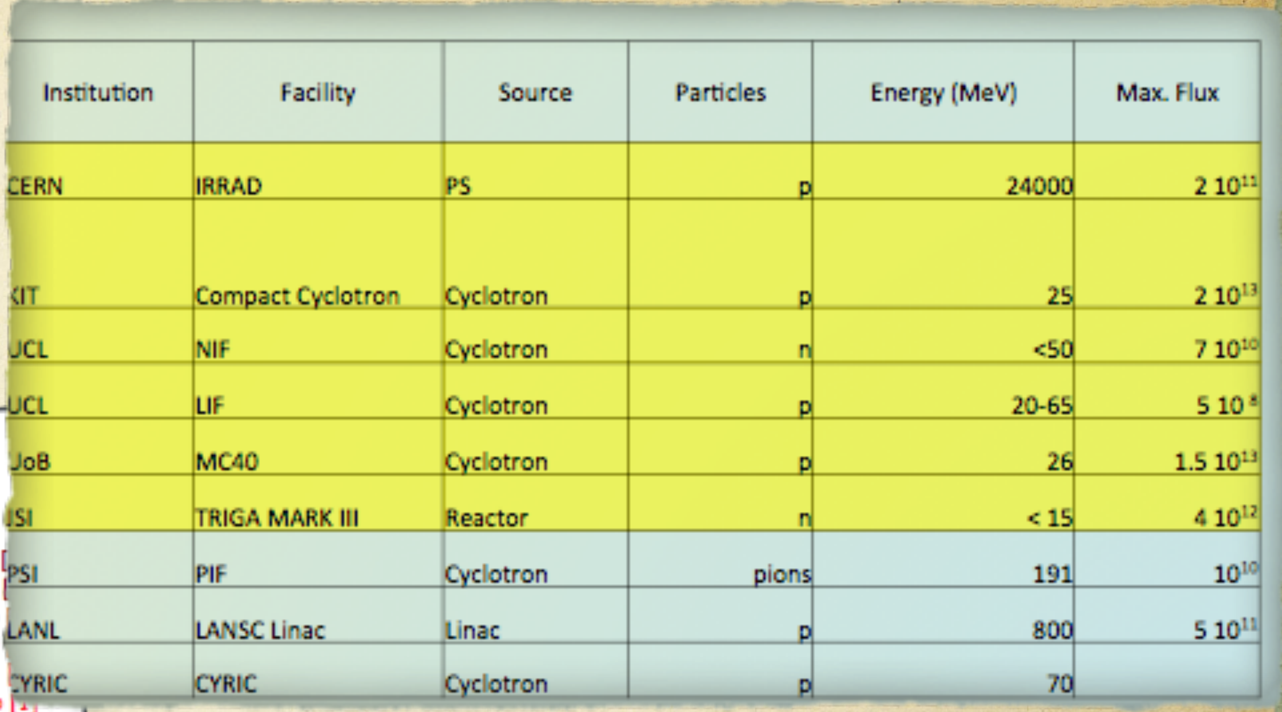
References:

[1] G.Casse, VERTEX 2008 (p/n-FZ, 300µm, (-30°C, 25ns)

[2] I.Mandic et al., NIMA 603 (2009) 263 (p-FZ, 300µm, -20°C to -40°C, 25ns)

M. Fernandez: VTX2014

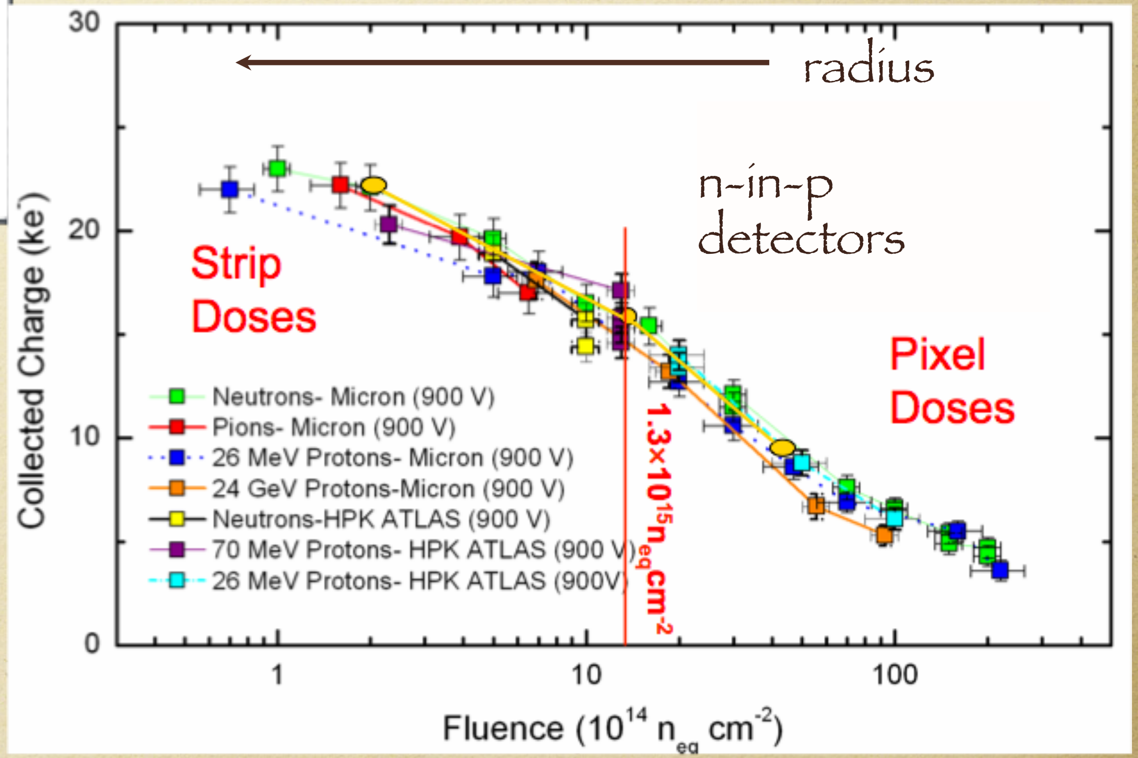
Overview of irradiation facilities



Institution	Facility	Source	Particles	Energy (MeV)	Max. Flux
CERN	IRRAD	PS	p	24000	$2\ 10^{11}$
KIT	Compact Cyclotron	Cyclotron	p	25	$2\ 10^{13}$
UCL	NIF	Cyclotron	n	<50	$7\ 10^{10}$
UCL	LIF	Cyclotron	p	20-65	$5\ 10^{8}$
UoB	MC40	Cyclotron	p	26	$1.5\ 10^{13}$
JSI	TRIGA MARK III	Reactor	n	< 15	$4\ 10^{12}$
PSI	PIF	Cyclotron	pions	191	10^{10}
LANL	LANSC Linac	Linac	p	800	$5\ 10^{11}$
CYRIC	CYRIC	Cyclotron	p	70	

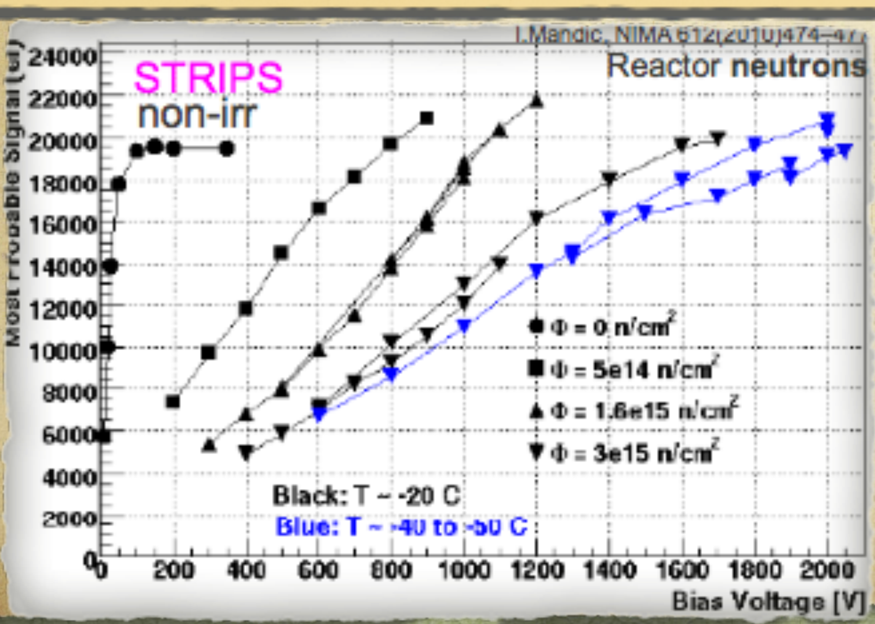
V. Cindro: VTX2014

n-in-p material

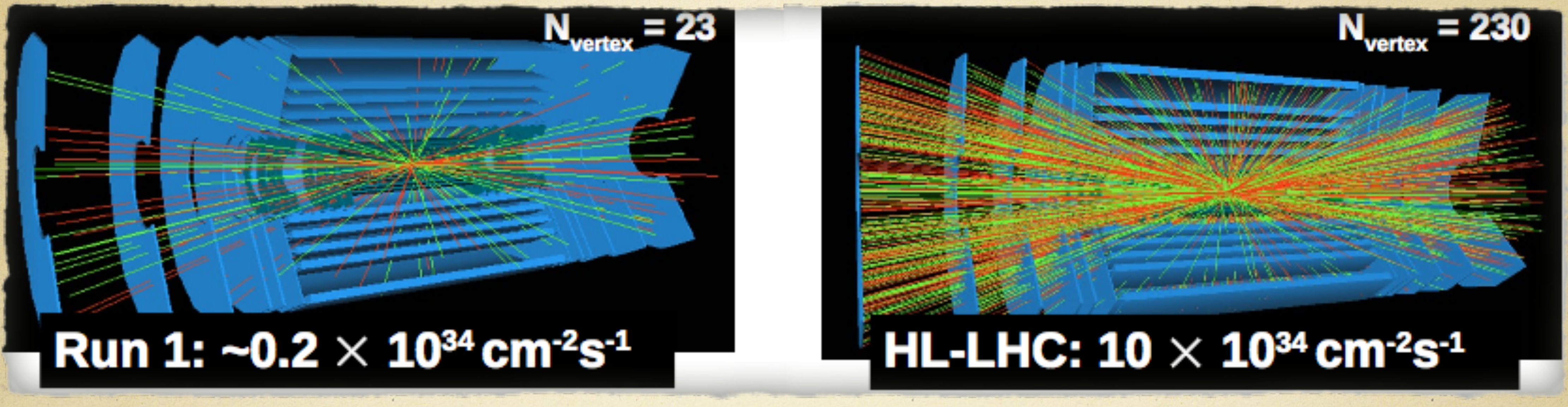


G. Casse: VCI 2013

Charge multiplication in irradiated sensors



Occupancy

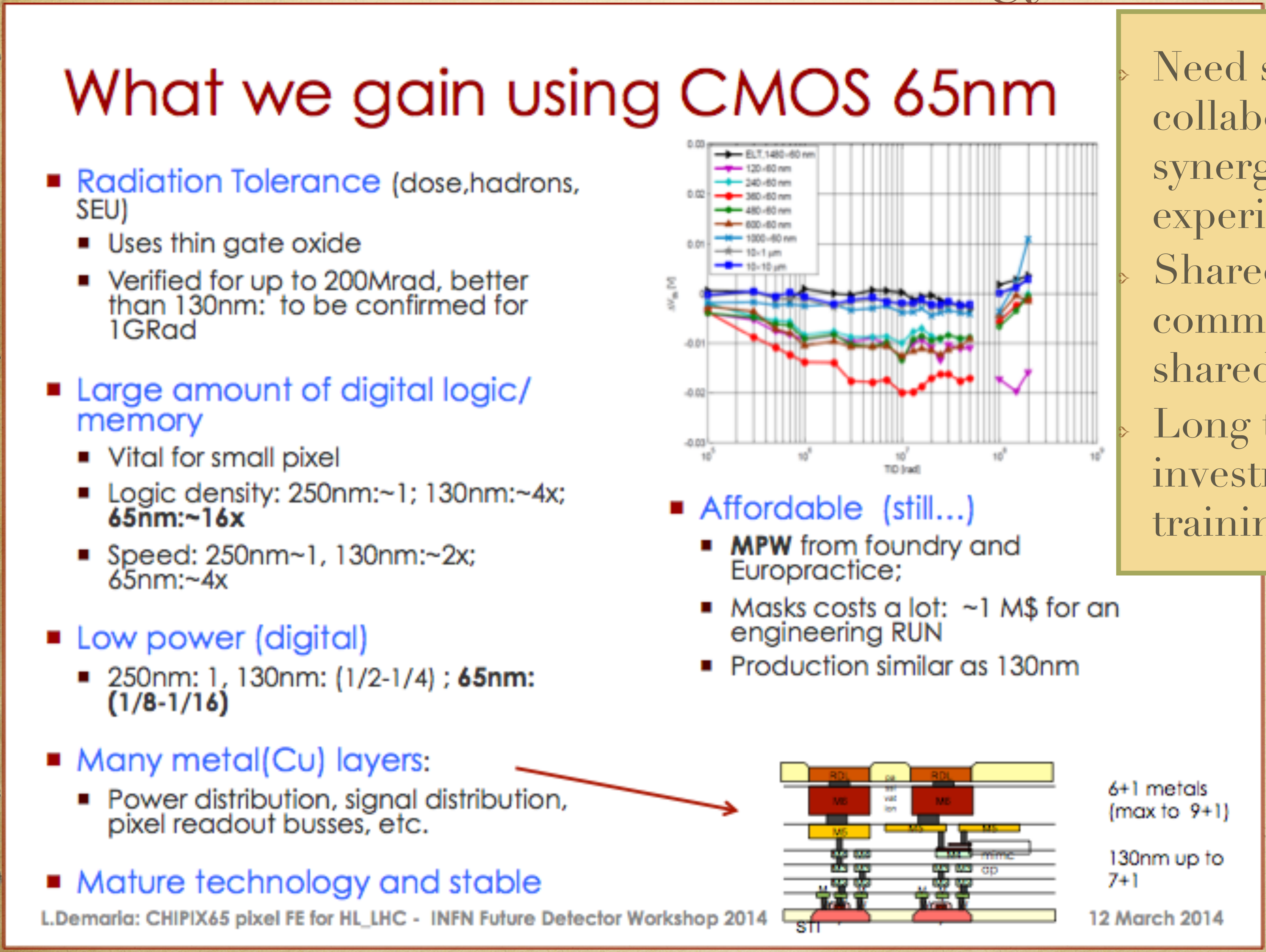


K. Lohwasser: VTX2014

- Improve layout
- Increase granularity
- Faster readout
- Smarter readout

- Read all analog signals
- Read only above threshold
- Read Region of Interest
- Make a local track stub
- Make track parameters

Electronics technology node



What we gain using CMOS 65nm

- Radiation Tolerance (dose,hadrons, SEU)
  - Uses thin gate oxide
  - Verified for up to 200Mrad, better than 130nm: to be confirmed for 1GRad
- Large amount of digital logic/ memory
  - Vital for small pixel
  - Logic density: 250nm:~1; 130nm:~4x; **65nm:~16x**
  - Speed: 250nm~1, 130nm:~2x; 65nm:~4x
- Low power (digital)
  - 250nm: 1, 130nm: (1/2-1/4) ; **65nm: (1/8-1/16)**
- Many metal(Cu) layers:
  - Power distribution, signal distribution, pixel readout busses, etc.
- Mature technology and stable
- Affordable (still...)
  - **MPW** from foundry and Europractice;
  - Masks costs a lot: ~1 M$ for an engineering RUN
  - Production similar as 130nm

6+1 metals (max to 9+1)

130nm up to 7+1

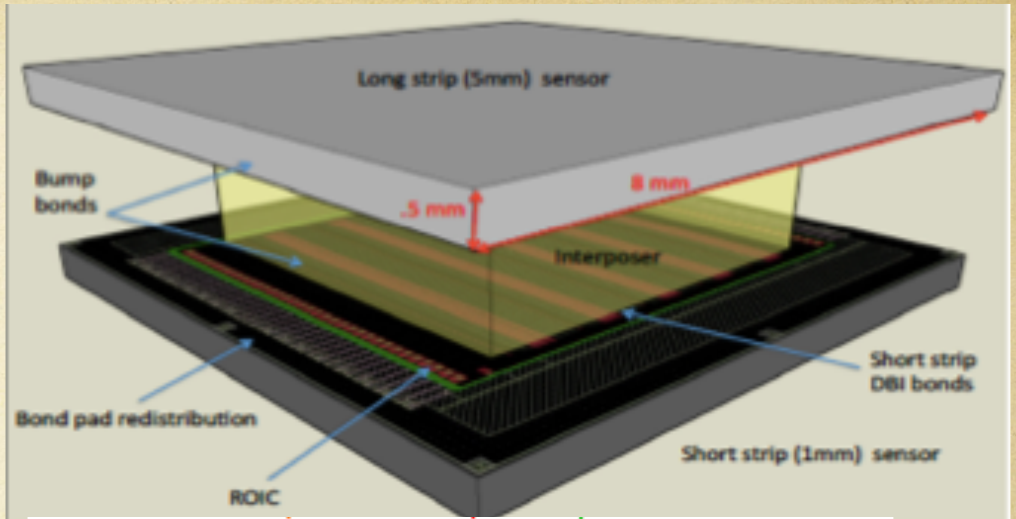
L.Demaria: CHIPIX65 pixel FE for HL_LHC - INFN Future Detector Workshop 2014 12 March 2014

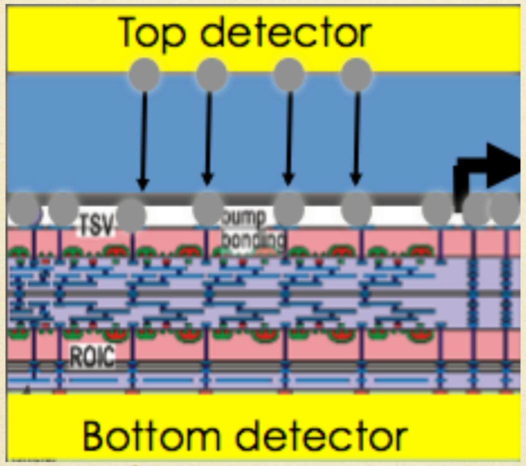
- Need strong collaboration and synergy between experiments
- Shared runs, common IP locks, shared knowledge
- Long term investment in training people

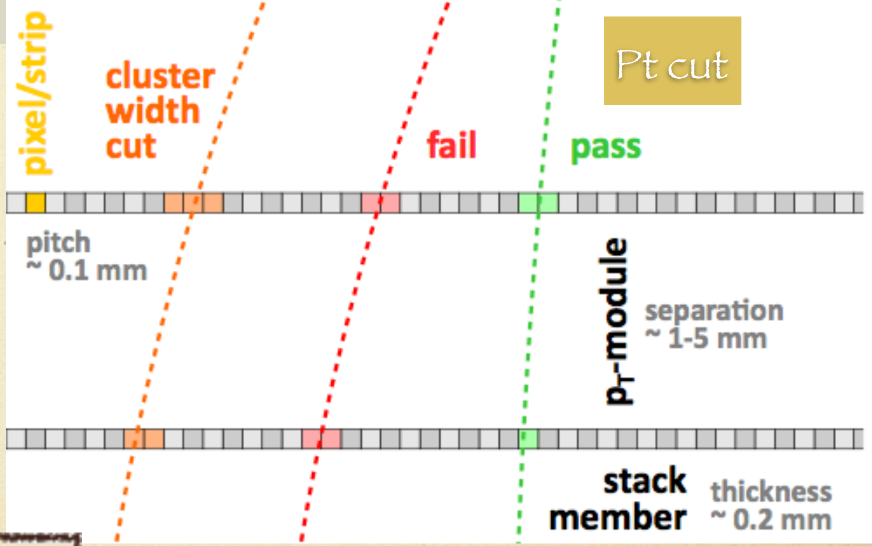
L .Demaria: IFD14

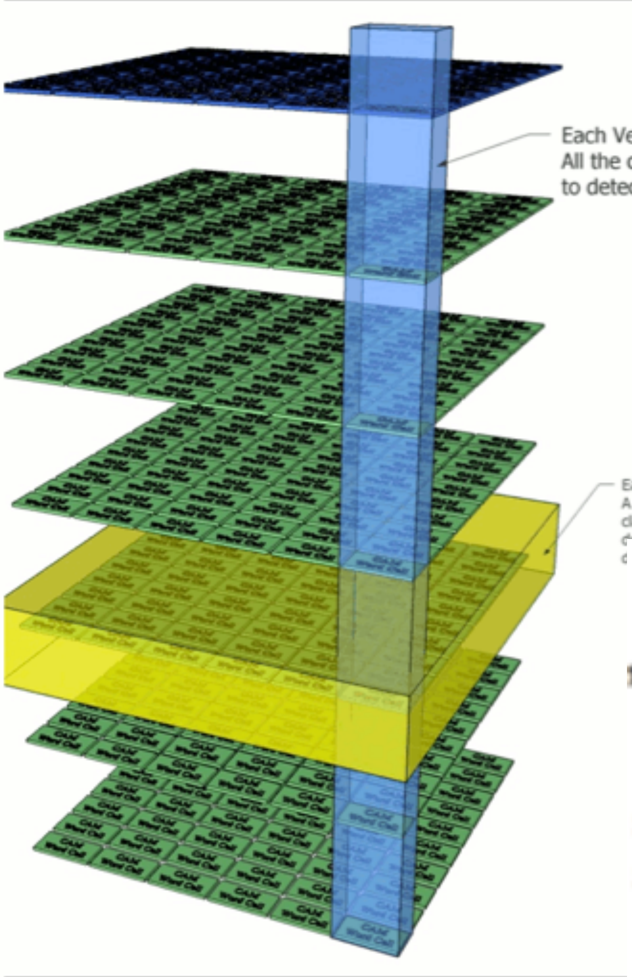
Smart detectors

- Granularity is not enough for high rates
- LHC @ 10^{34} cm-2s-1: 200 events overlapping
- Build track segments or measure pt at sensor levels and use track in LVL1-2 Trigger
- Use 3D chip technology

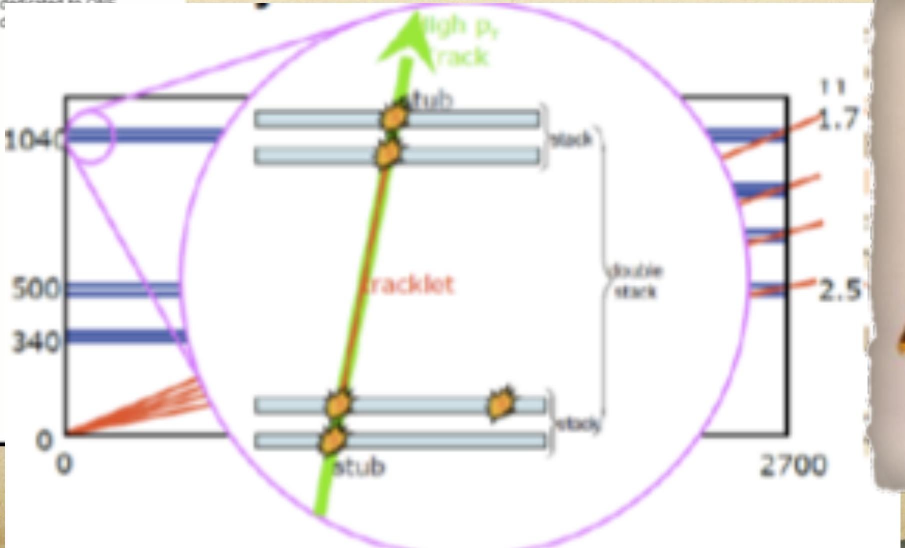


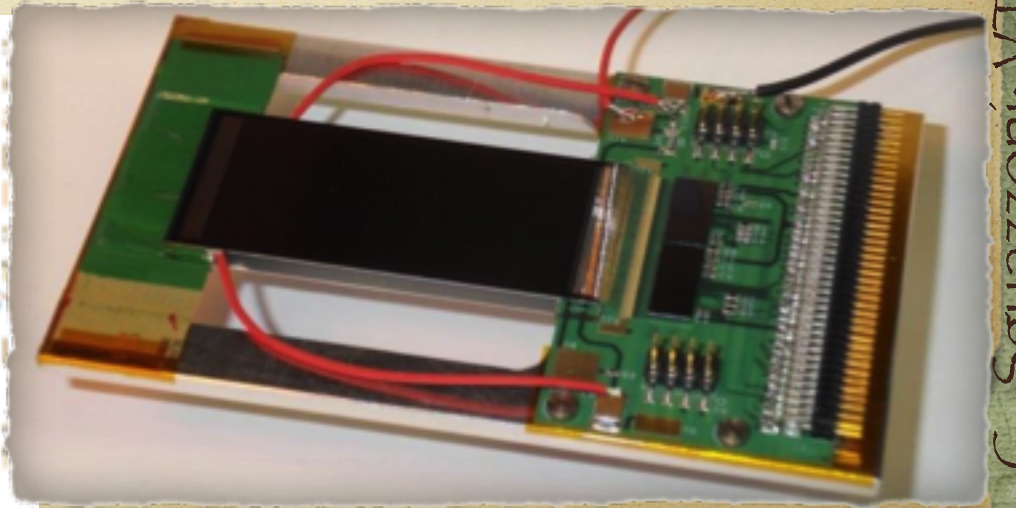






Content addressable memory in each layer

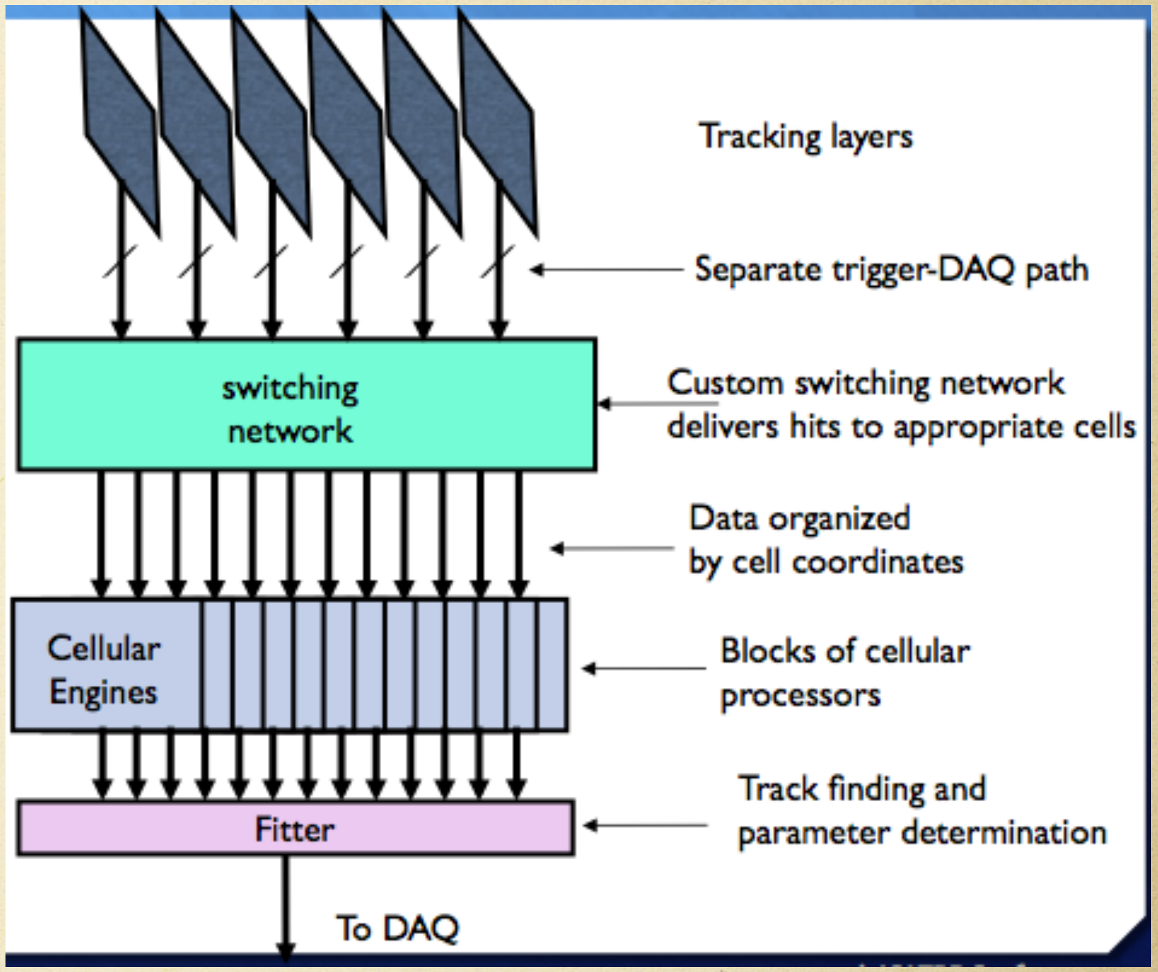


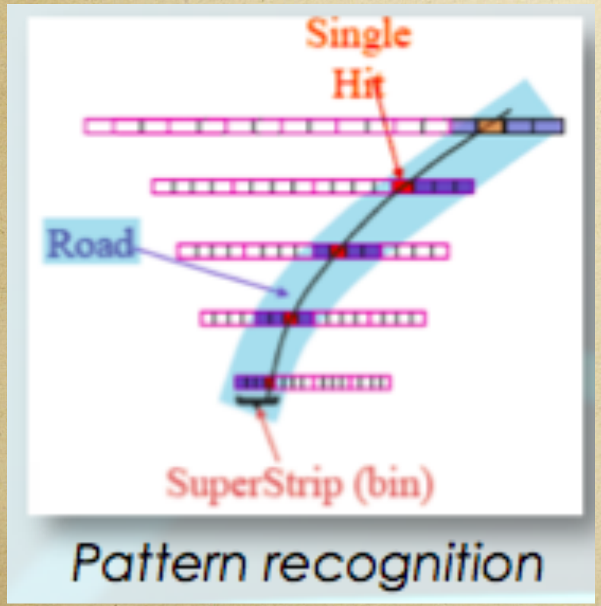


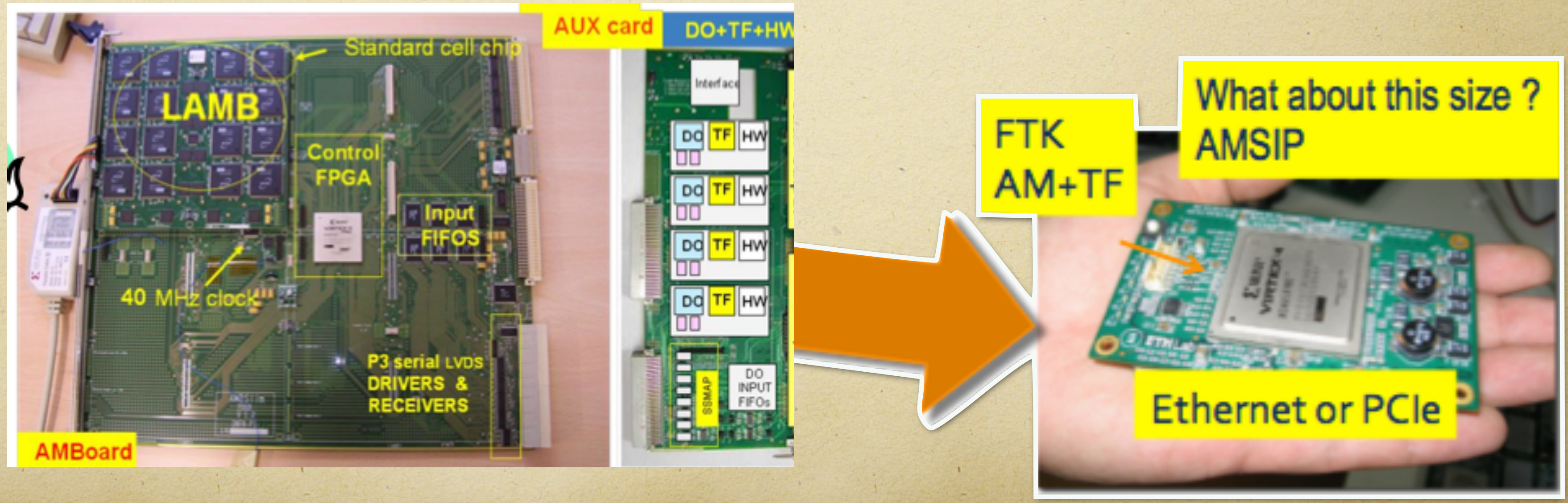
G. Sguazzoni: VTX2014 E. Ramberg, VCI 2013

Track triggers

- Associative memory based trigger proven in CDF, proposed in Atlas, CMS
- LHC-b proposes a vision-based FPGA implemented track trigger
- Enormous potential
  - Can change the way experiments are designed
  - Can make increased luminosity fully useful for physics



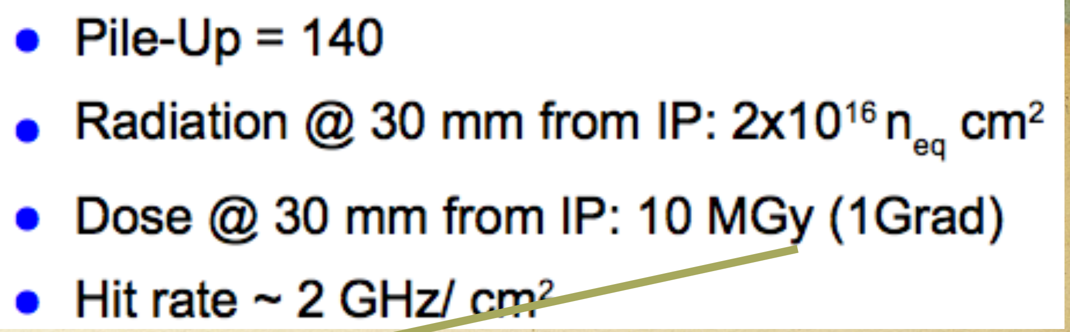




T. Iizawa: VTX14

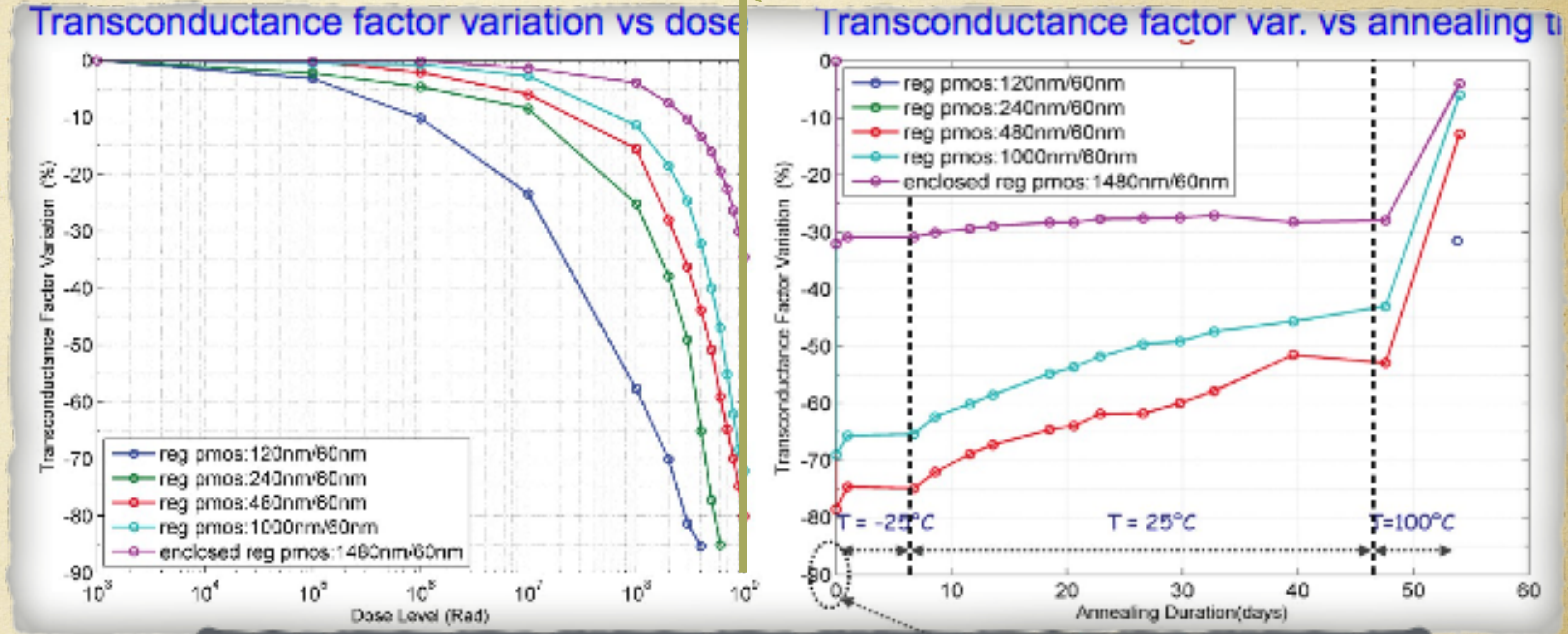
A.Annovi: IFD14

HL-LHC Pixels



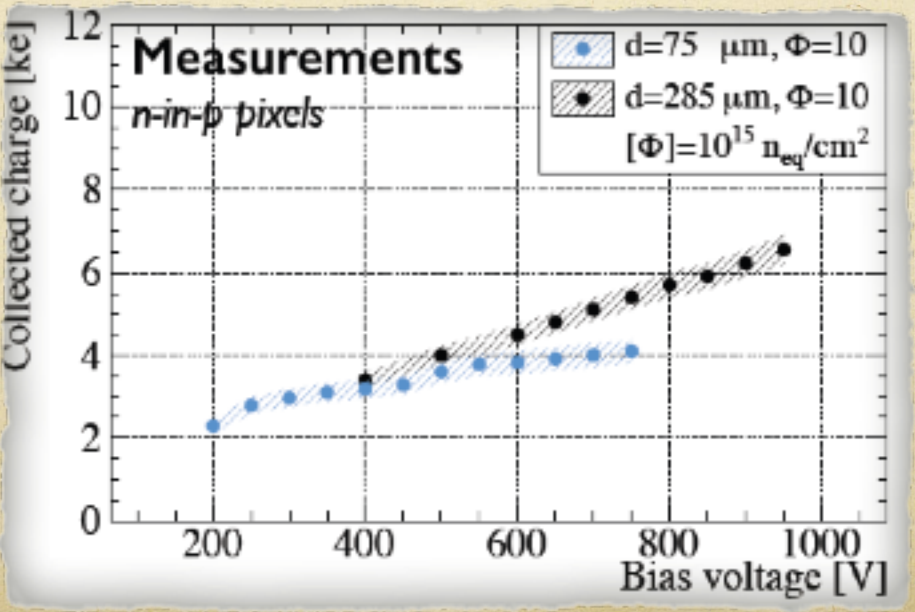
- Pile-Up = 140
- Radiation @ 30 mm from IP: 2×10^{16} n_{eq} cm^2
- Dose @ 30 mm from IP: 10 MGy (1Grad)
- Hit rate ~ 2 GHz/ cm^2

- Very high radiation and occupancy
- Aim at small pixels size: 50x50 um^2
- Hybrid pixel scheme
- Radiation effects can be dramatic



65 nm PMOS radiation effect and annealing

- Sensor choice ?
- Very little charge (thick and thin sensors give same amount)



Other technology ?

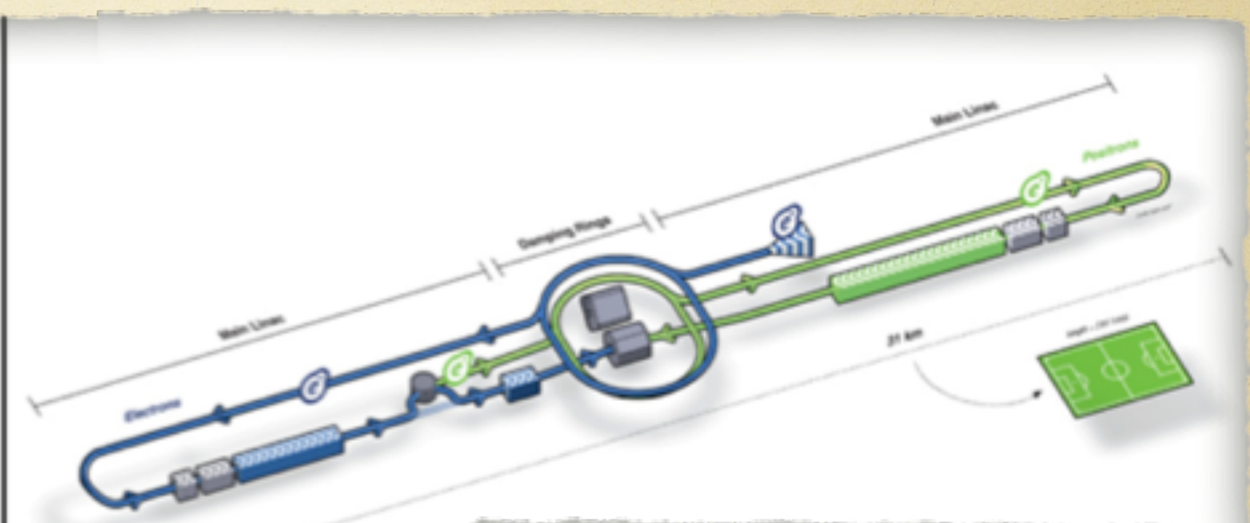
- 3D Sensors
- HV-CMOS
- Active edge
- Diamonds

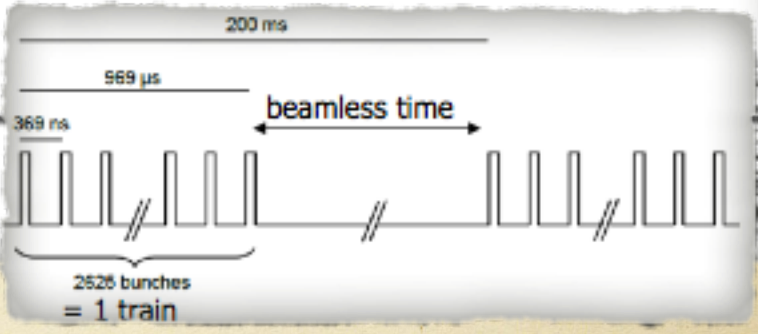
Active R&D

P. Valerio: VTX2014 M. Musich: VTX2014

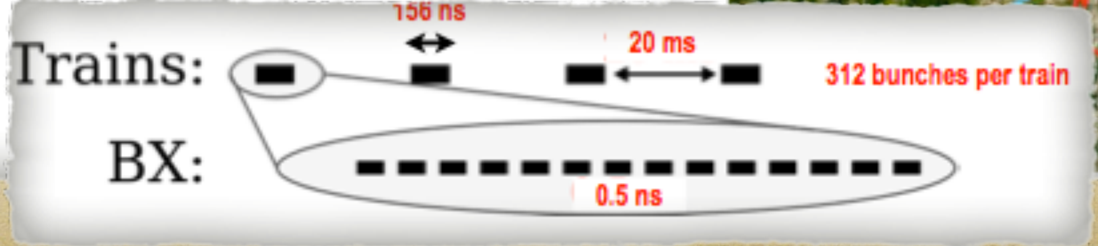
ILC and CLIC

- ILC:
  - e^+e^- linear collider
  - 31 km linear tunnel
  - Baseline: √s = 500 GeV
    - Phase @ 250 GeV (Higgs factory)
    - Options : 90 GeV(GigaZ), e^-e^-, γγ, $e^-\gamma$
    - Upgrade: 1 TeV
  - 2 detectors in « push pull »
    - only one collision point
    - ILD and SiD
  - Luminosity:
    - 1.8 x 10^{34} cm^{-2} s^{-1}
    - 500 fb^{-1} (4 years)
  - Polarisation: e^- = 80% ; e^+ = 30% (upgrade 60%)



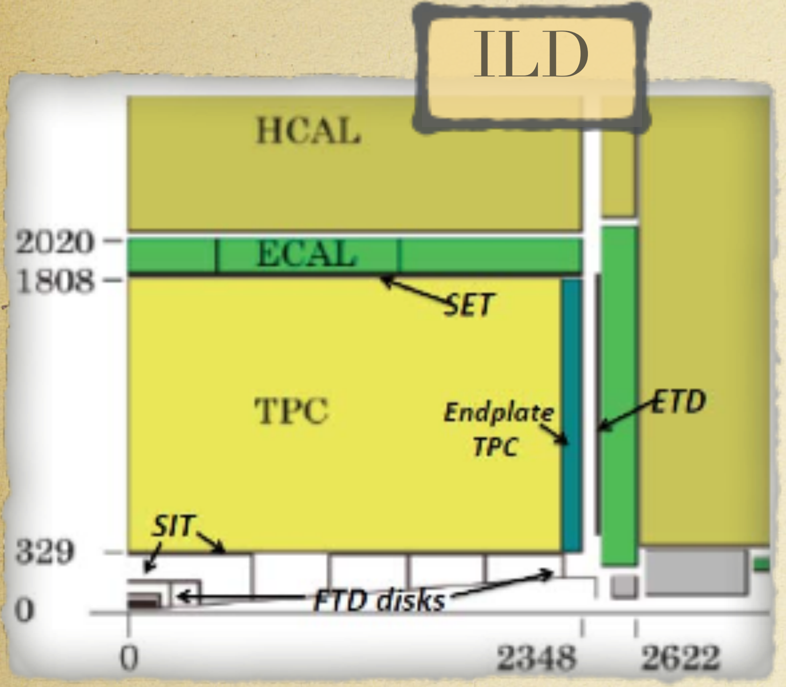


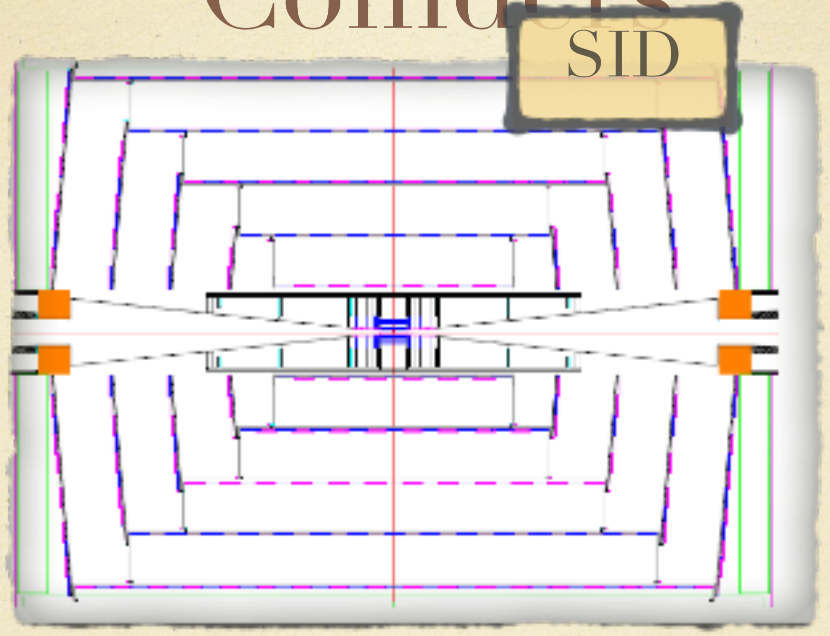
- **Linear electron-positron collider**
- **√s = 3 TeV (staged construction)**
- **High luminosity: few x 10^{34} $cm^{-2}s^{-1}$**
- **Small bunch size: σ_{xyz}(40 nm, 1 nm, 44 µm)**
- **Beam structure:**



Tracking and Vertexing at Linear Colliders

A. Besson: VTX2014





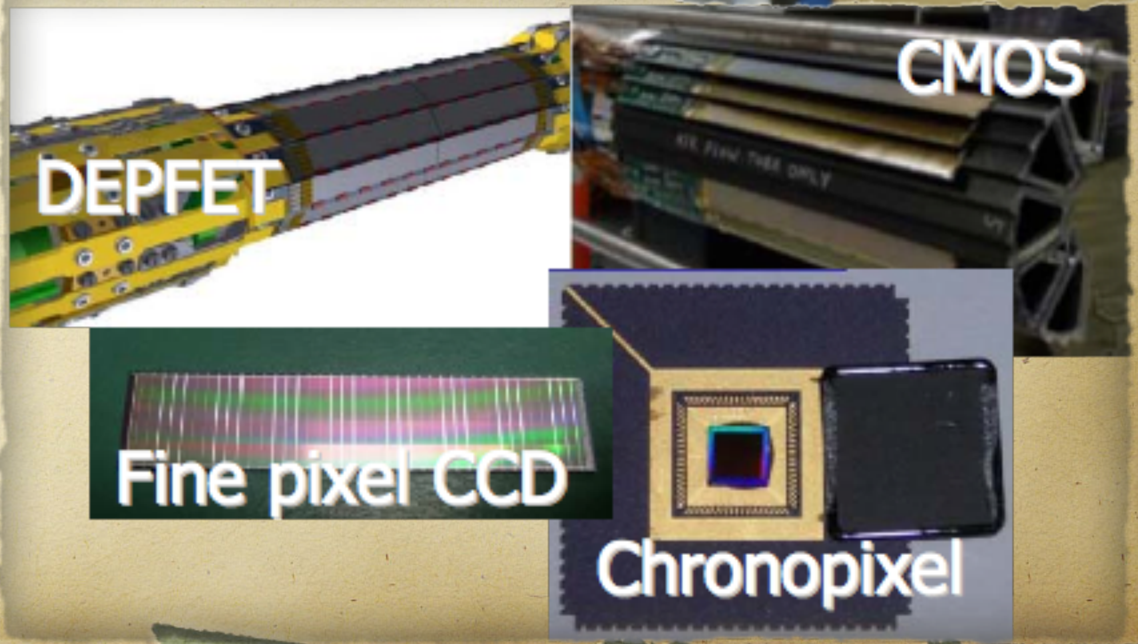
S. Redford: VTX2014


50 μm thick silicon wafer

- Large low-material tracker (silicon or TPC)
- Super-thin vertex detector

System and services design determines material budget

- Mechanical support
- Cooling
- Power distribution

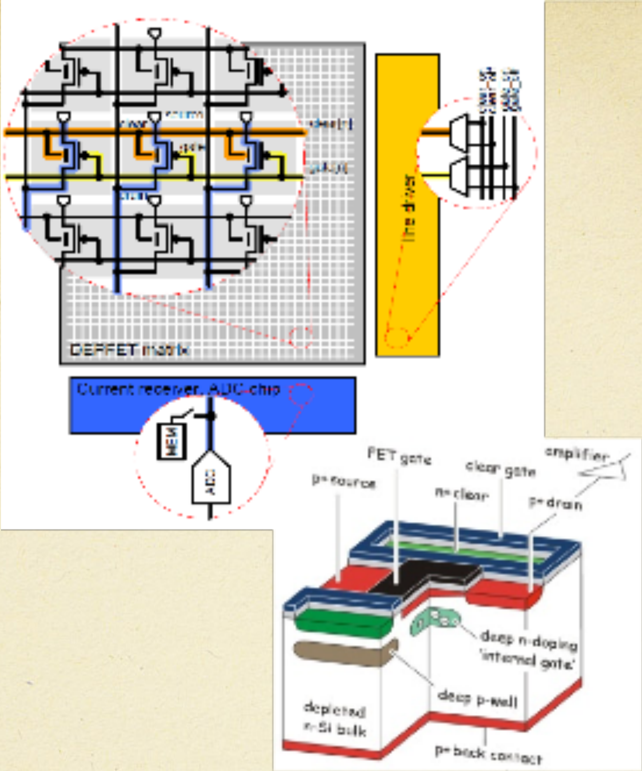


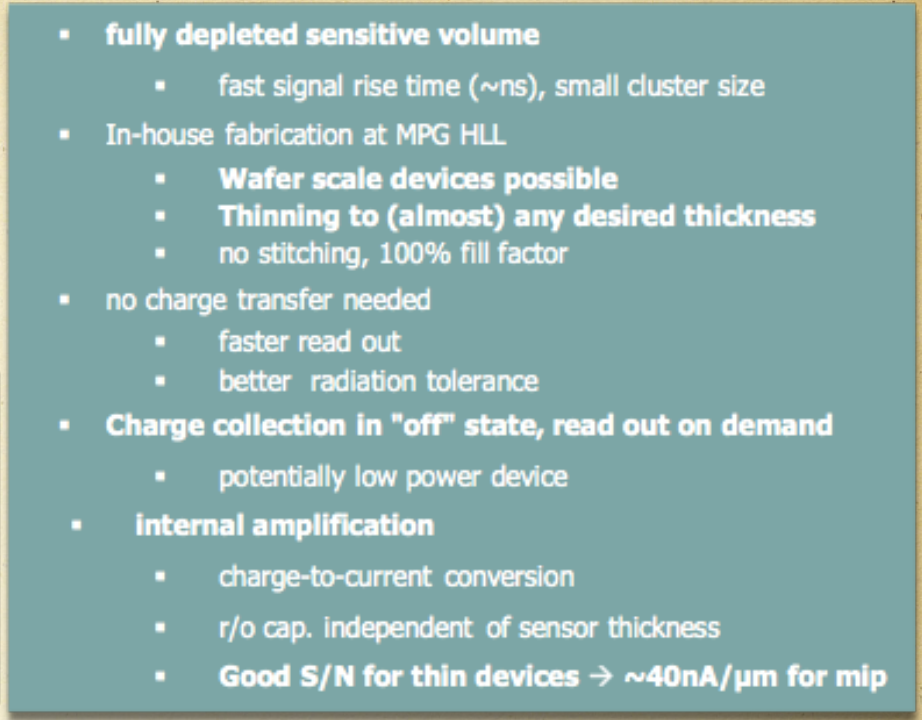
FUTURE R&D

- SOI
- DEPFET
- CMOS MAPS
- HV-CMOS
- Vertical integration
- Diamonds
- Internal amplification
- Neutron PSD
- Sensor edge management
- 3D Sensors
- Smart trackers
- Advanced materials

DEPFETs

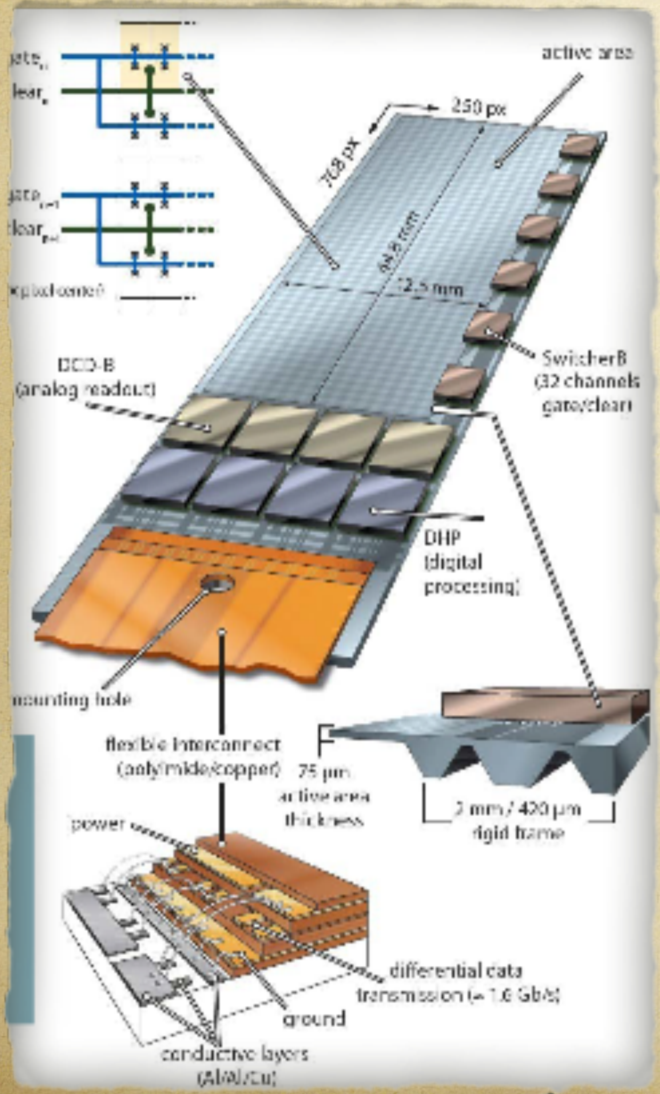
- Complex and expensive technology
- Can be extremely thin
- Difficult to get speed and extreme radiation hardness

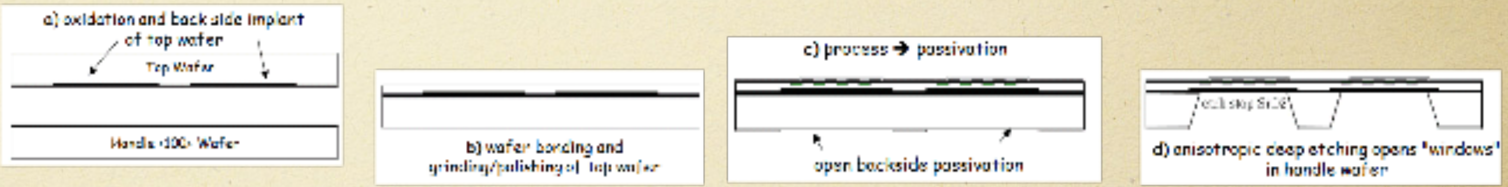




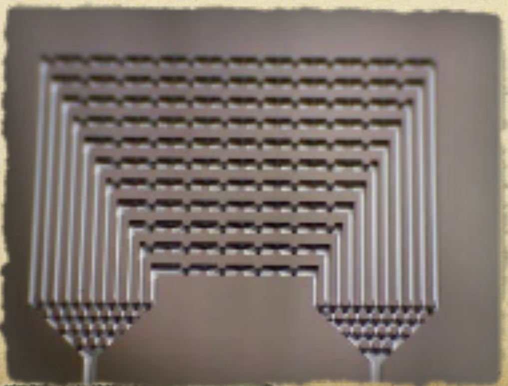
- **fully depleted sensitive volume**
  - fast signal rise time (~ns), small cluster size
- In-house fabrication at MPG HLL
  - **Wafer scale devices possible**
  - **Thinning to (almost) any desired thickness**
  - no stitching, 100% fill factor
- no charge transfer needed
  - faster read out
  - better radiation tolerance
- **Charge collection in "off" state, read out on demand**
  - potentially low power device
- **internal amplification**
  - charge-to-current conversion
  - r/o cap. independent of sensor thickness
  - **Good S/N for thin devices → ~40nA/μm for mip**

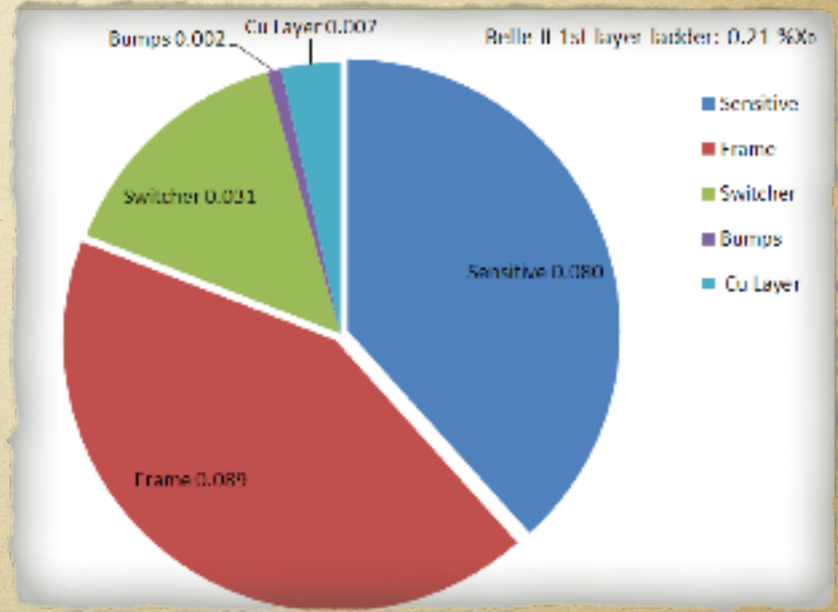
C. Koffmane, VTX14





- Established: to be installed in Belle-II
- Possible for ILC
- Investigate integrated microcooling

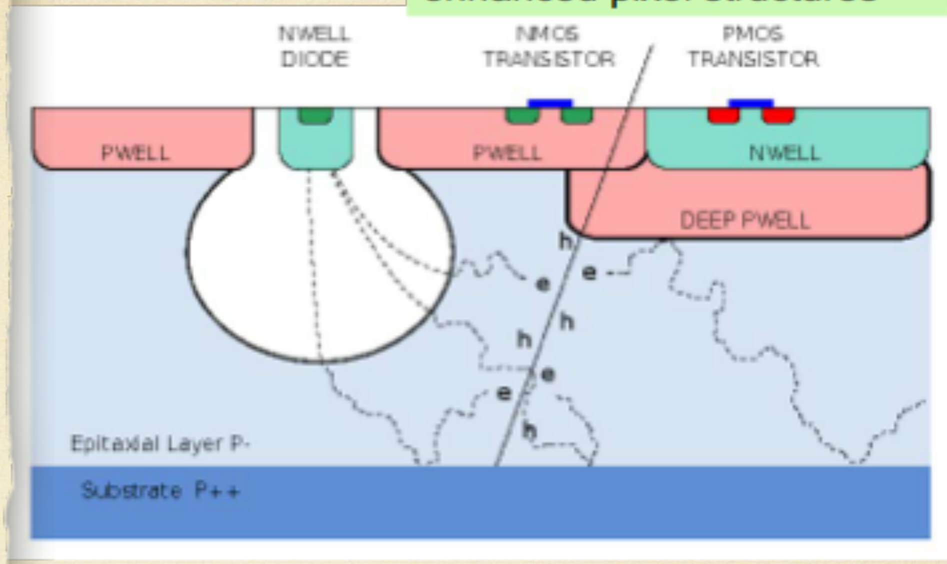




CMOS MAPS

- Exploit commercial CMOS technology to produce cheap and performant sensors
- Already used in various fields
- Used/Planned in several experiments: STAR, MU3E, ALICE, ATLAS ?

- Growing complexity in electronics processing in the pixel
- Still issues to be solved for very high radiation, very high speed readout
- Traditional MAPS have very little charge collected —> HV and HR CMOS



Deep p-well: enhances charge collection, allows enhanced pixel structures

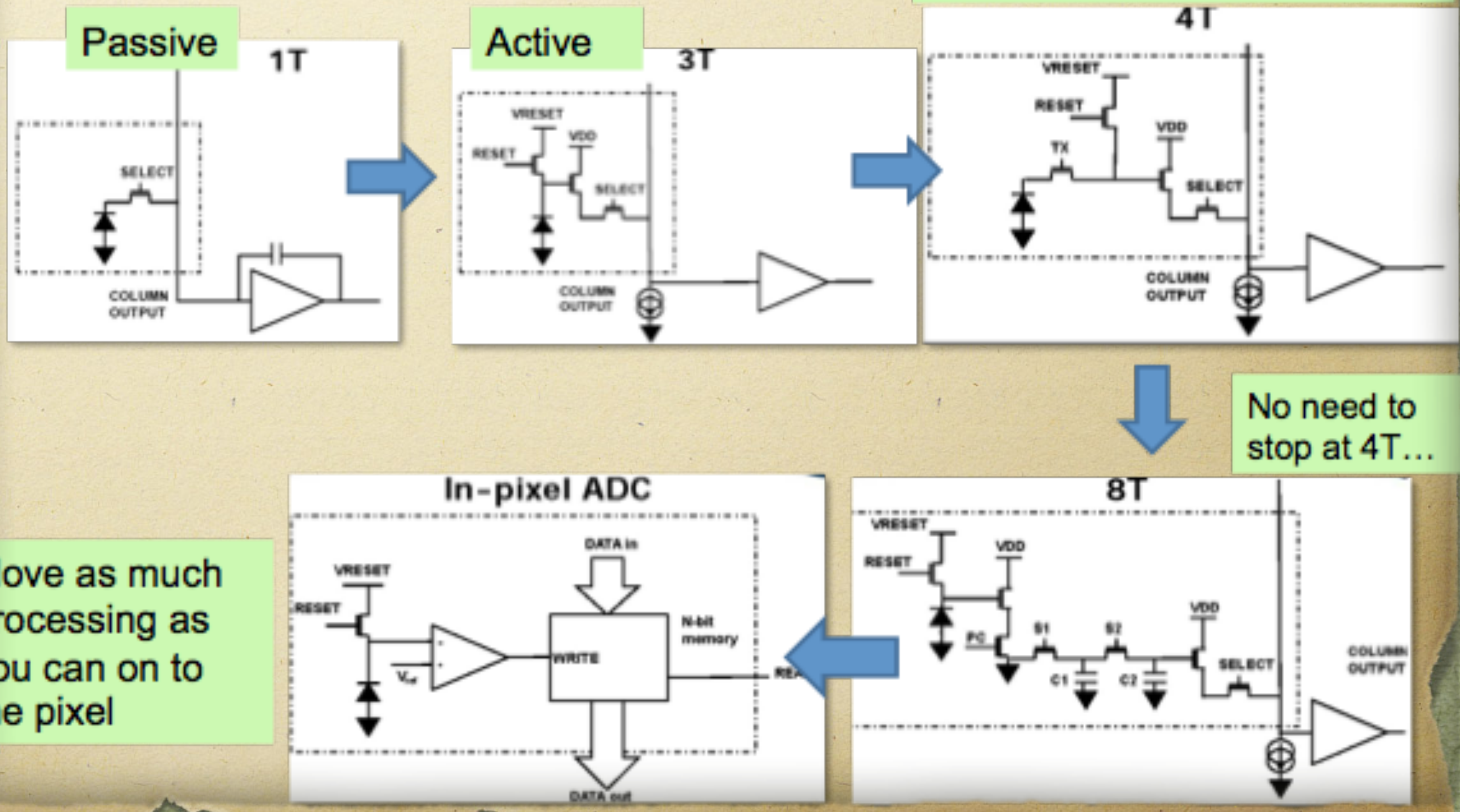
Thin epitaxial layer: shorter collection times, less multiple scattering, less chance of charge capture

High-resistivity epitaxial layer: improved signal to noise.

Guard rings: improve resistance to radiation damage.

High-resistivity epitaxial layer + low voltage bias (HR-CMOS): charge collection by drift, faster, radiation hardness

High voltage bias (HV-CMOS): charge collection by drift, faster, radiation hardness



Correlated Double Sampling (CDS), reduced noise

No need to stop at 4T…

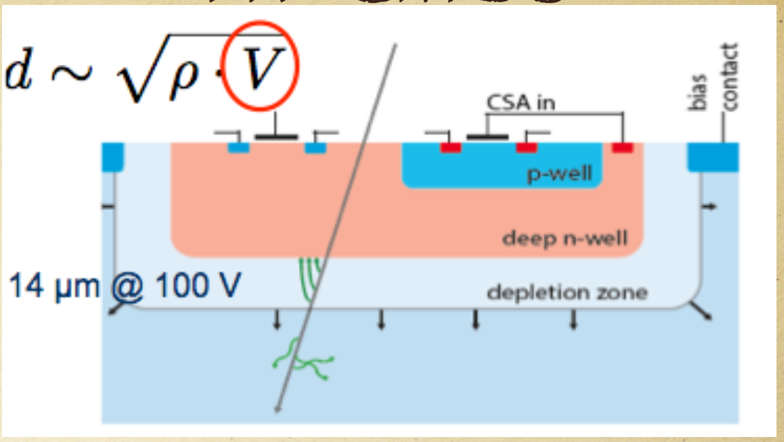
Move as much processing as you can on to the pixel

F. Wilson: VTX2014

HV-HR CMOS MAPS

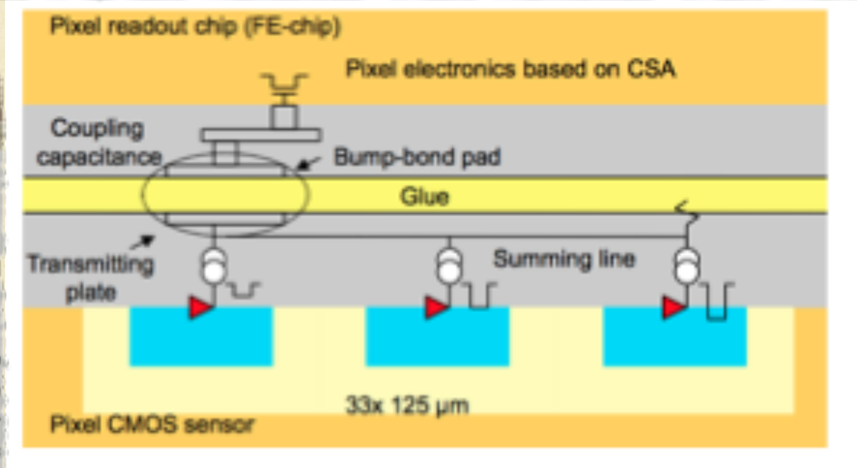
- Introduce a depletion layer in CMOS MAPS
- HV/HR-CMOS could be a solution to offer rad-hard and cheap pixel sensors
- Could be used in conjunction with standard readout ICs to increase readout speed and compatibility with experiments

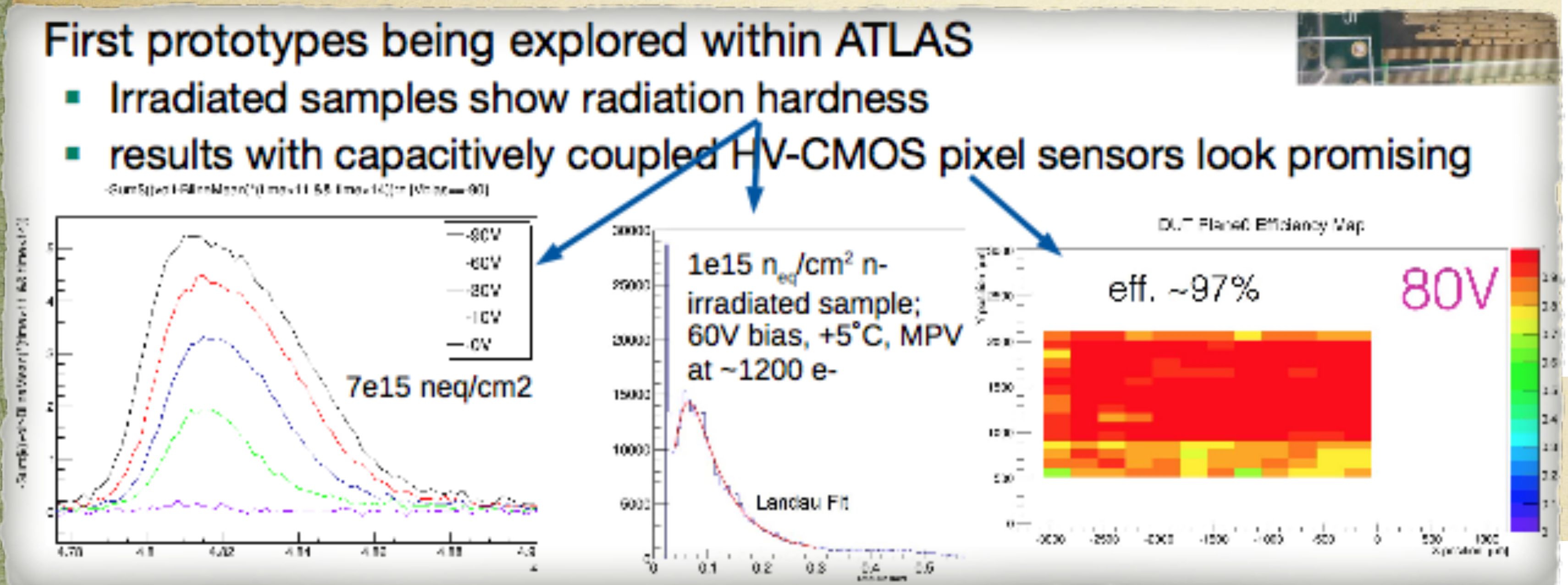
HV-CMOS



G.Usai, IFD14

Capacitively coupled pixel detector

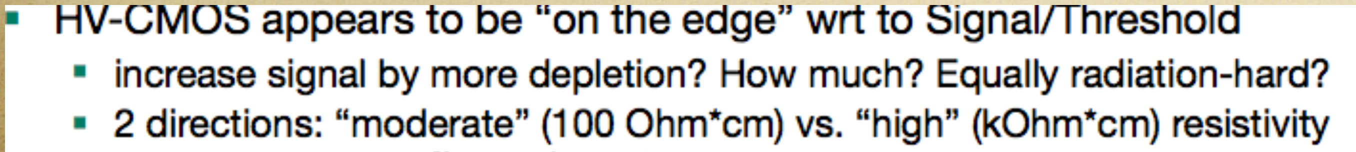




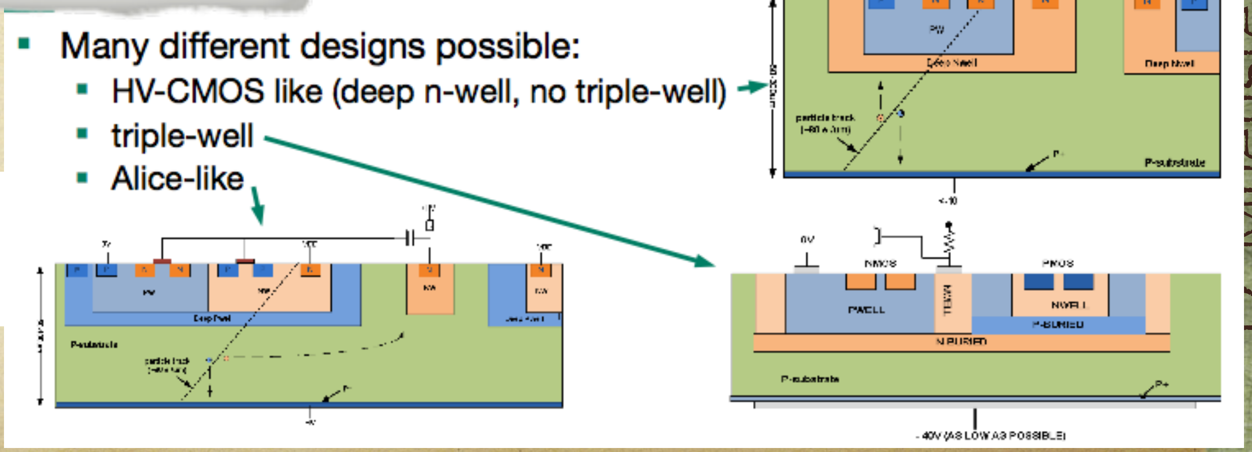
First prototypes being explored within ATLAS

- Irradiated samples show radiation hardness
- results with capacitively coupled HV-CMOS pixel sensors look promising

HR-CMOS



- HV-CMOS appears to be "on the edge" wrt to Signal/Threshold
  - increase signal by more depletion? How much? Equally radiation-hard?
  - 2 directions: "moderate" (100 Ohm*cm) vs. "high" (kOhm*cm) resistivity



- Many different designs possible:
  - HV-CMOS like (deep n-well, no triple-well)
  - triple-well
  - Alice-like

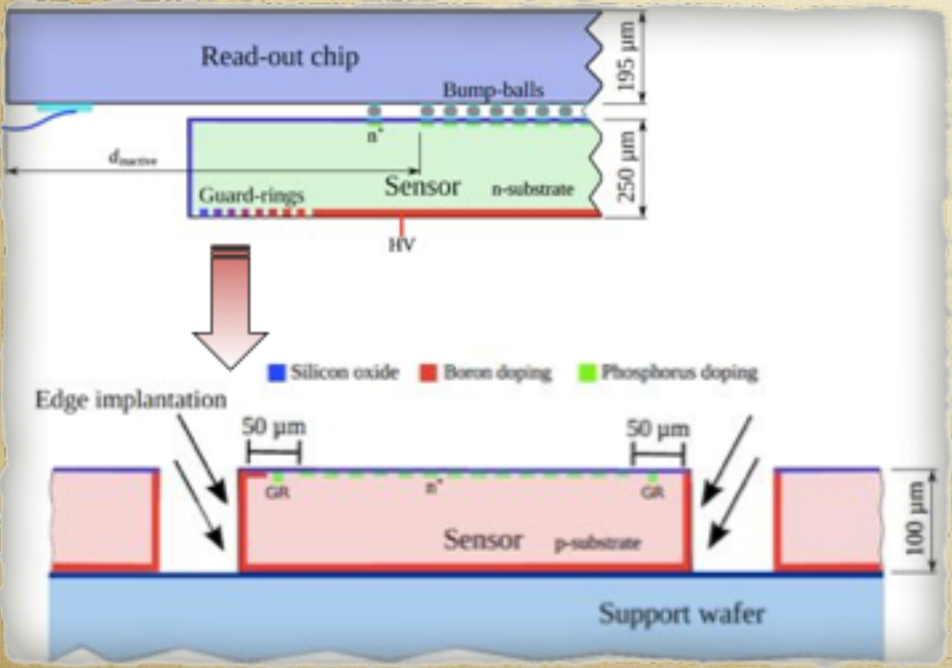
D. Muenstermann: VTX2014

Sensor Edge Management

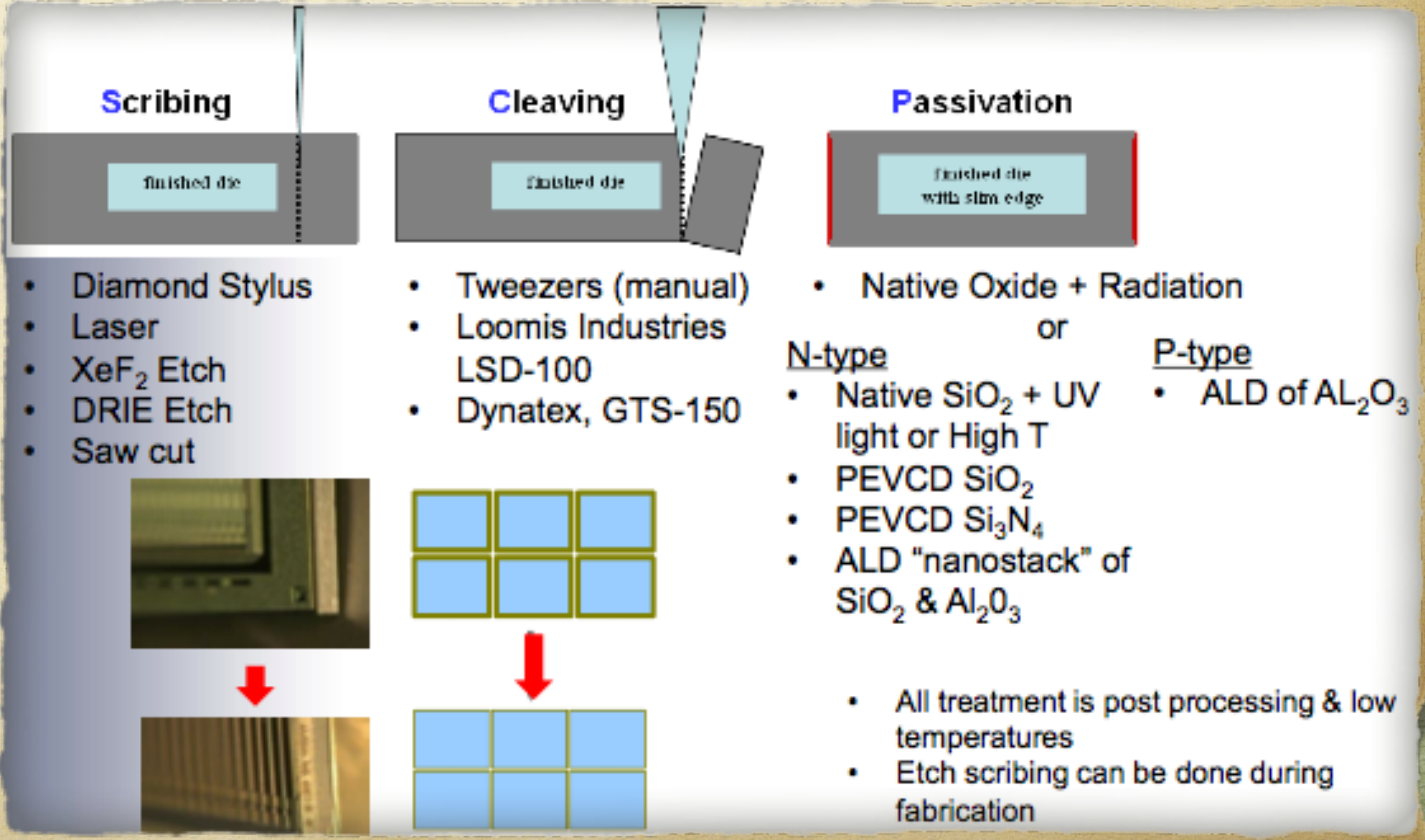
Reduction of dead area at the sensor edge

1. Slim edge: reduce the guard rings and protection to the mininum
2. Active edge: turn the physical edge into a junction (implant +passivation) allowing depletion to reach the edge
3. Scribe, Cleave & Passivate (SCP): post processing

- Reduction of material and dead zones
- In conjunction with through silicon vias: buttable modules



M.Meschini, IFD14



Scribing

- Diamond Stylus
- Laser
- XeF_2 Etch
- DRIE Etch
- Saw cut

Cleaving

- Tweezers (manual)
- Loomis Industries LSD-100
- Dynatex, GTS-150

Passivation

- Native Oxide + Radiation

or

N-type

- Native SiO_2 + UV light or High T
- PEVCD SiO_2
- PEVCD Si_3N_4
- ALD "nanostack" of SiO_2 & Al_20_3

P-type

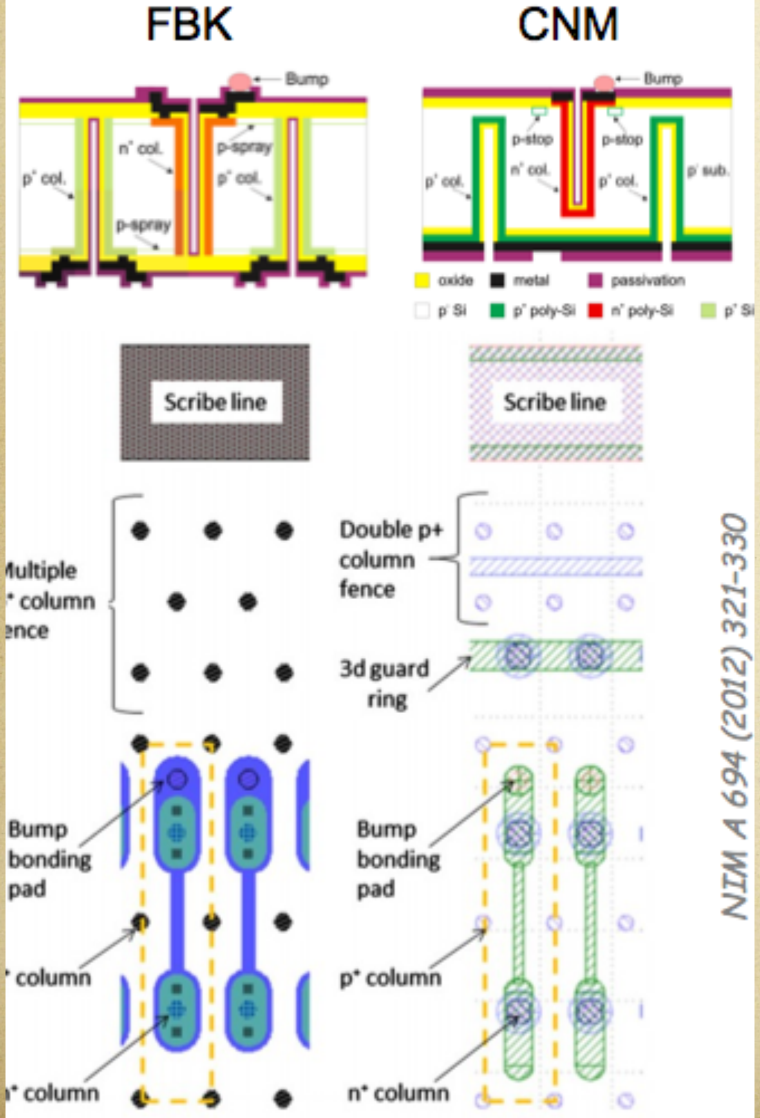
- ALD of AL_2O_3

- All treatment is post processing & low temperatures
- Etch scribing can be done during fabrication

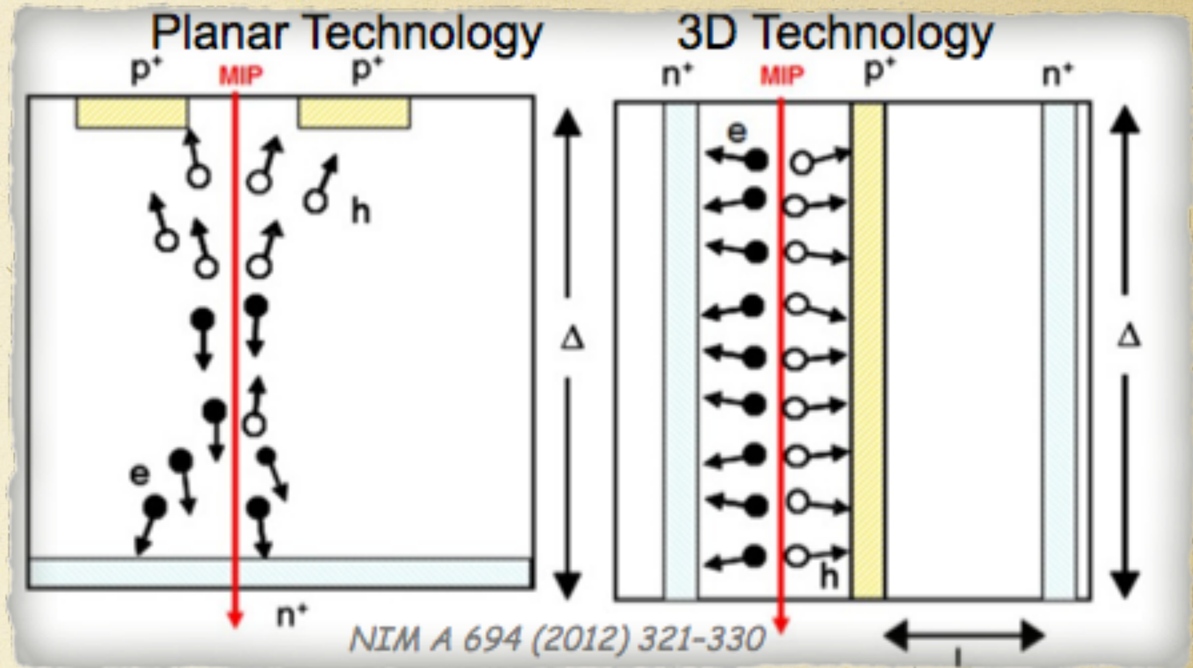
A. Blue, VTX14

3D sensors

- Proposed in 1997 (Parker, Kenney, Segal)
- Two types installed in ATLAS IBL

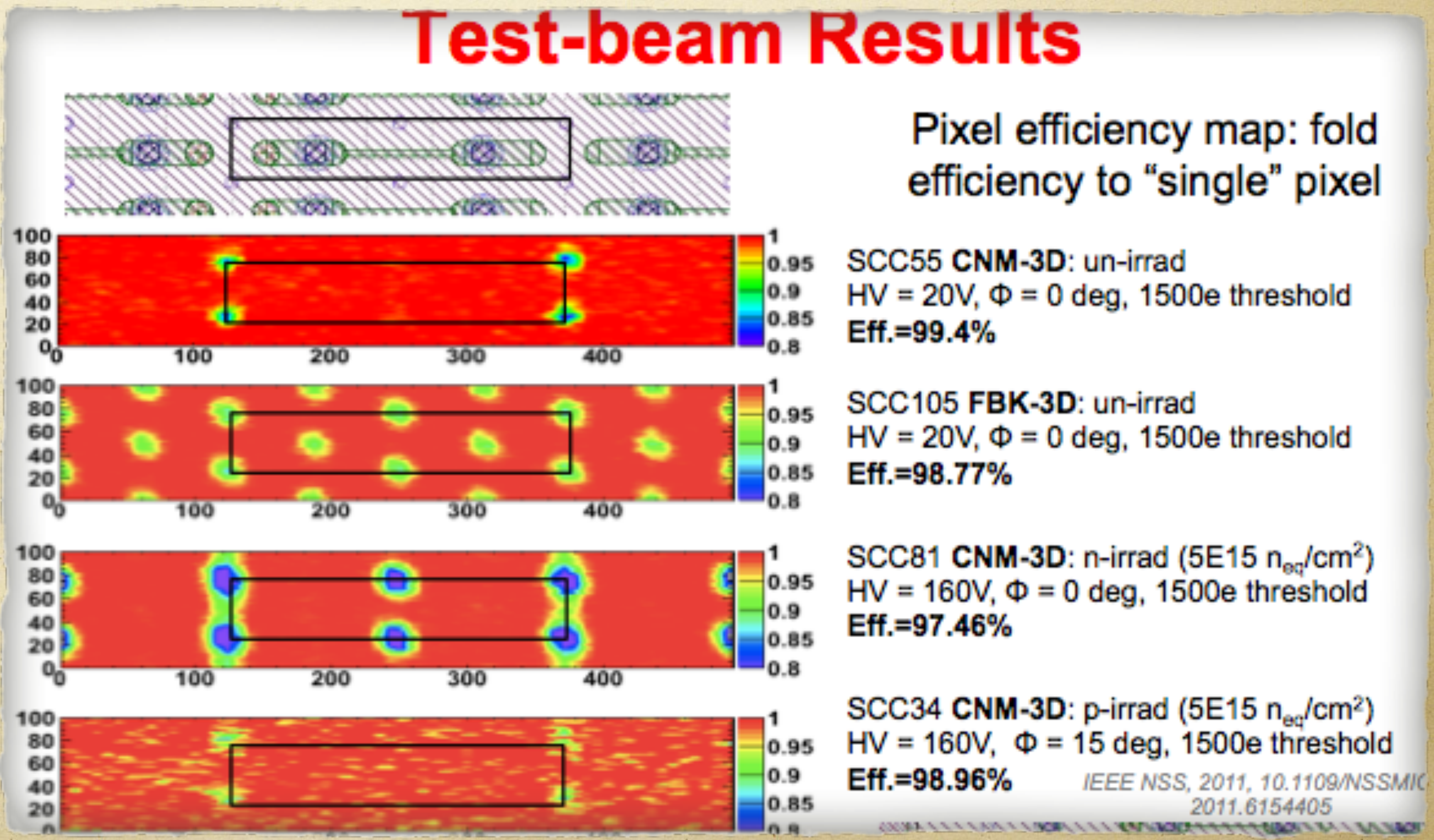


NIM A 694 (2012) 321-330



NIM A 694 (2012) 321-330

S. Grinstein, VTX14



Test-beam Results

Pixel efficiency map: fold efficiency to "single" pixel

SCC55 **CNM-3D**: un-irrad
HV = 20V, Φ = 0 deg, 1500e threshold
Eff.=99.4%

SCC105 **FBK-3D**: un-irrad
HV = 20V, Φ = 0 deg, 1500e threshold
Eff.=98.77%

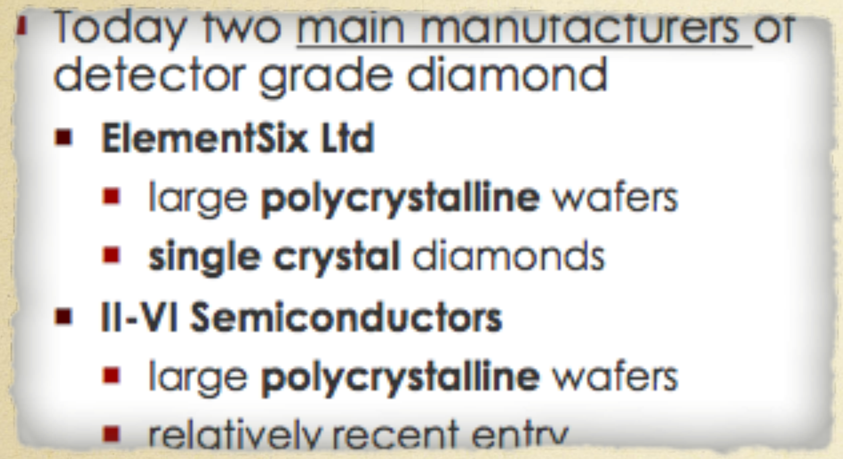
SCC81 **CNM-3D**: n-irrad (5E15 n_{eq}/cm^2)
HV = 160V, Φ = 0 deg, 1500e threshold
Eff.=97.46%

SCC34 **CNM-3D**: p-irrad (5E15 n_{eq}/cm^2)
HV = 160V, Φ = 15 deg, 1500e threshold
Eff.=98.96%

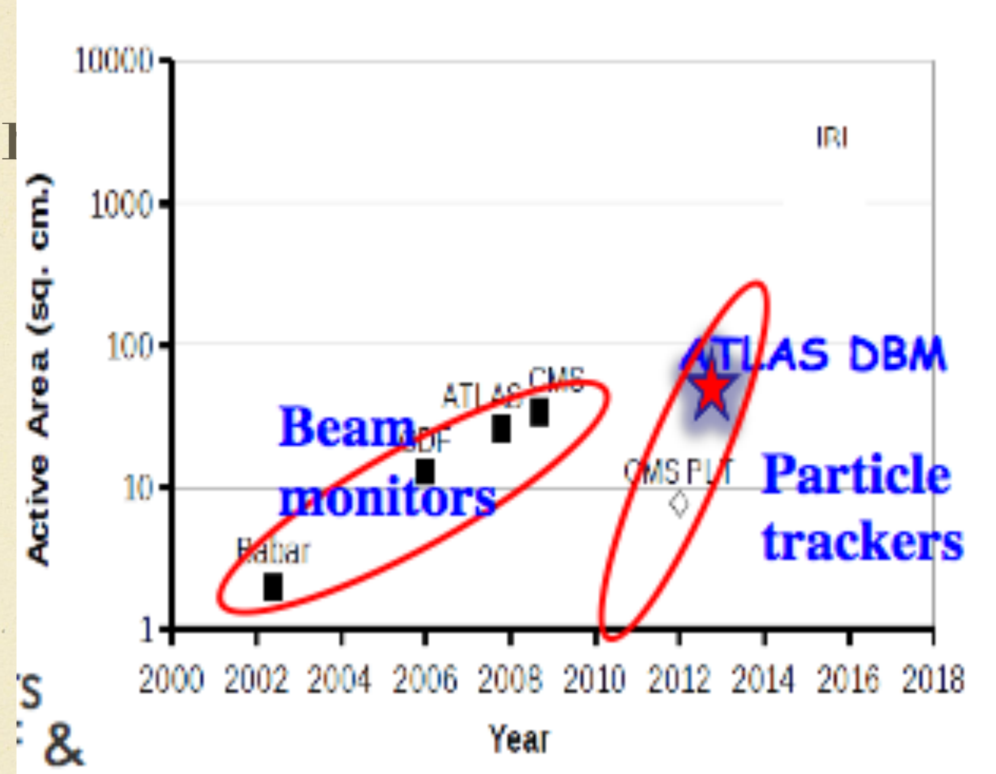
IEEE NSS, 2011, 10.1109/NSSMIC.2011.6154405

Diamonds

- Diamonds established for beam ar
radiation monitoring

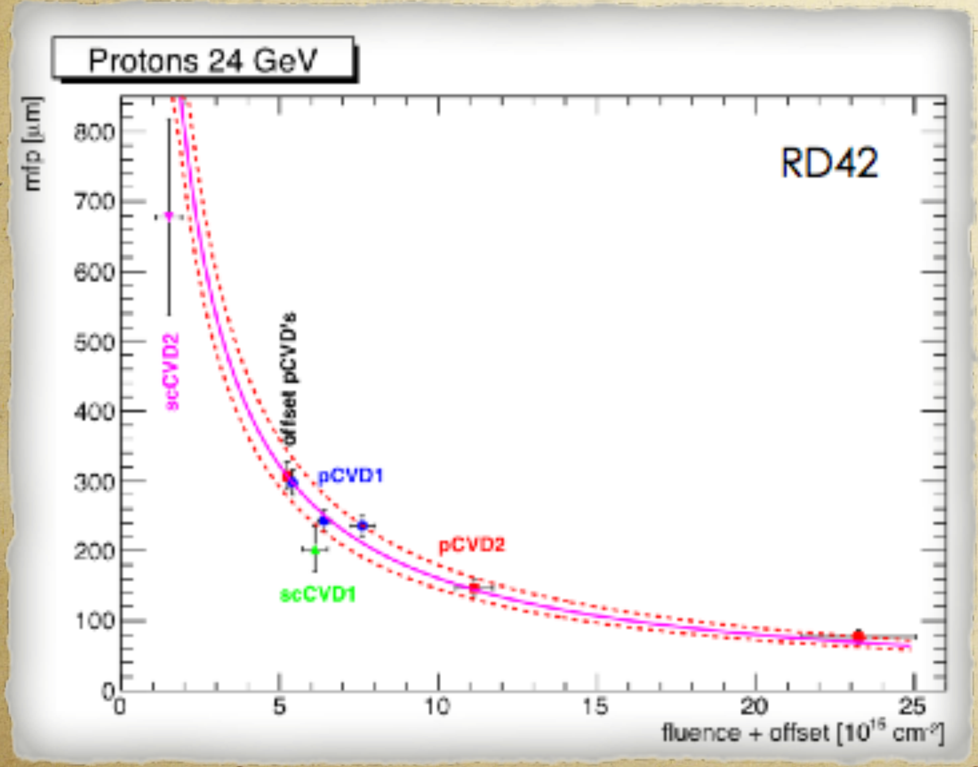


Today two main manufacturers of detector grade diamond
- ElementSix Ltd
  - large polycrystalline wafers
  - single crystal diamonds
- II-VI Semiconductors
  - large polycrystalline wafers
  - relatively recent entry

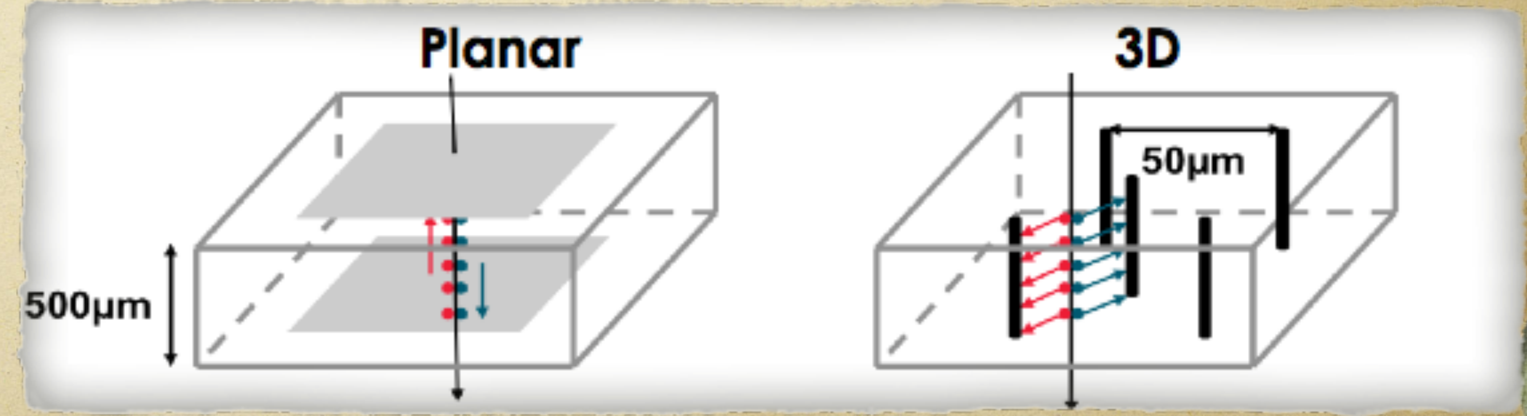


A. Oh,VTX14

- Consistent radiation hardness constants



- 3D technology tested to reduce collection length and improve performance

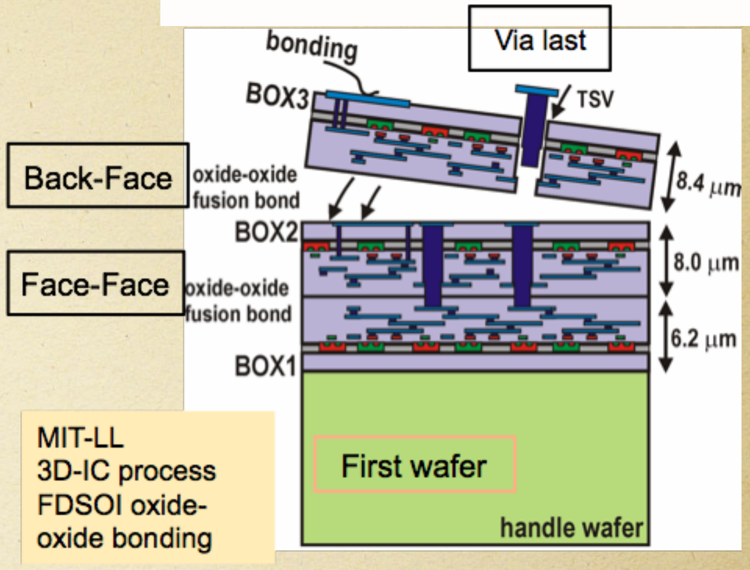


Systems

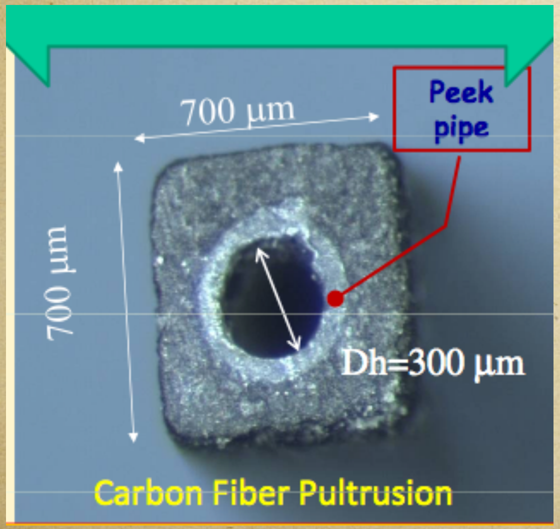
Detector system design is much more than sensors. Many technologies can change qualitatively and quantitatively the way systems are built. The future will tell.

- Vertical integration through-silicon vias
- Advanced interconnections technologies
- Advanced materials
- Innovative powering schemes
- Micro cooling / integrated cooling

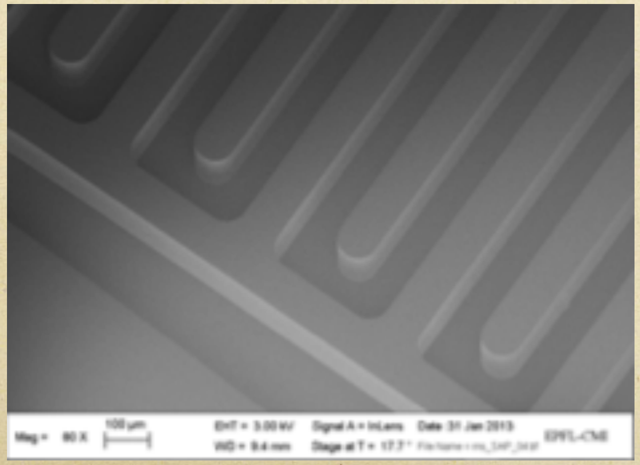
Vertical Integration: a new view on interconnections



E. Ramberg: VCI 2013



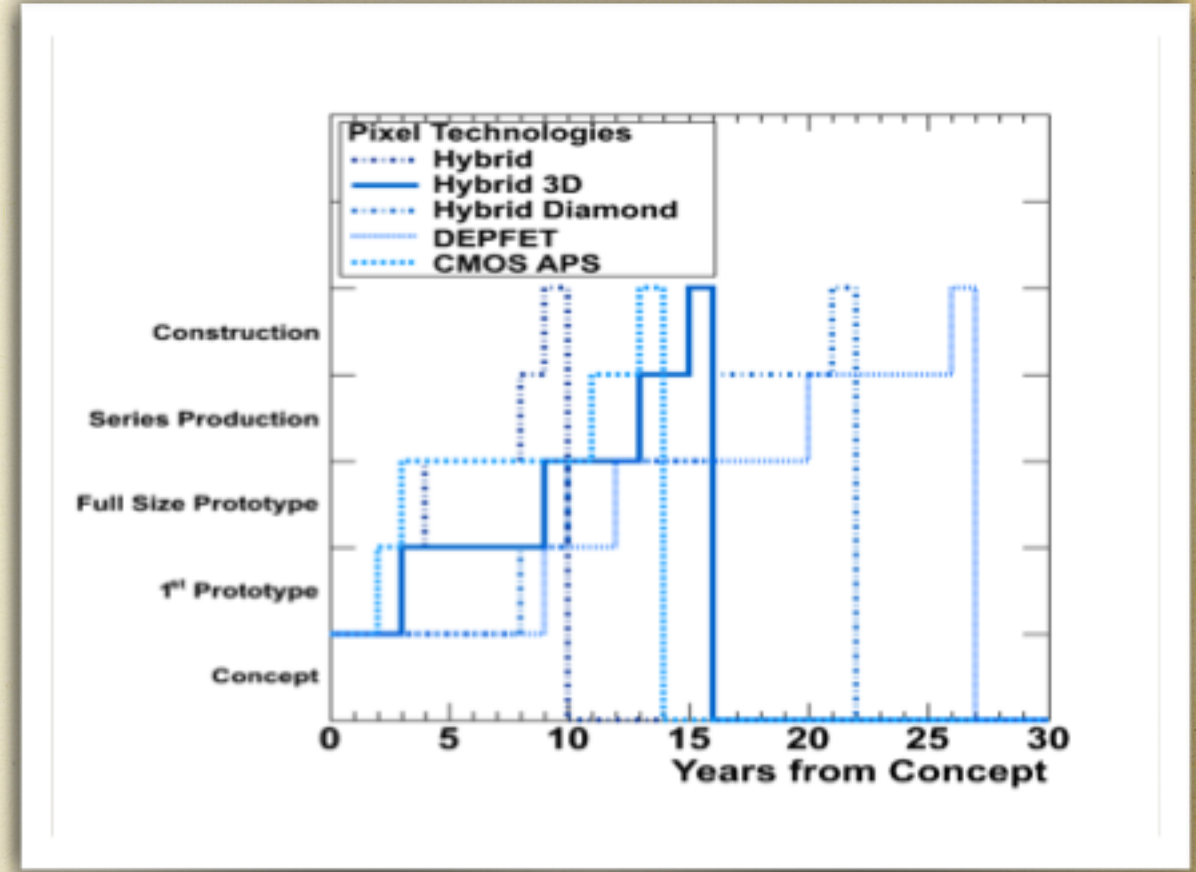
F. Bosi: PM 2012



N. Berger, VCI 2013

Outlook

- Solid state sensors R&D make best use of advanced technological process and push technology towards new limits.
- The road from idea to running detector is long and winding.
- Many interesting and promising techniques exist, but large costs require coordinated action
- It is essential that expert work in synergy and collaboration to produce performant and affordable detectors for tomorrow's experiments



- A great Thank you ! to the organizers for this opportunity and the perfect organization

Sources

- In the slides it is indicated the presenter at the meeting (not necessarily the original author of the work)
- 2014 International Workshop on Vertex Detectors, VTX14 https://indico.cern.ch/event/300851/other-view?view=standard
- 2014 Americas Workshop on Linear Colliders 2014, AWLC14: http://agenda.linearcollider.org/conferenceOtherViews.py?view=standard&confId=6301
- 2014 INFN Workshop on Future Detectors for HL-LHC, IFD14: https://agenda.infn.it/conferenceOtherViews.py?view=standardshort&confId=7261
- 2014 9th "Trento" Workshop on Advanced Silicon Radiation Detectors, TNW14: http://indico.cern.ch/event/273880/
- 2013 International Workshop on Vertex Detectors, VTX13
- 2013 Lepton-Photon Symposium, LP 2013: http://www-conf.slac.stanford.edu/lp13/
- 2013 Vienna conference on instrumentation, VCI 2013: http://vci.hephy.at/
- 2012 Crakow European Strategy Meeting: http://indico.cern.ch/conferenceDisplay.py?confId=175067
- 2012 Pisa Meeting on Advanced Detectors, PM 2012: http://www.pi.infn.it/pm/2012/
- 2011 Technology and Instrumention in Part. Phys., TIPP 2011 http://conferences.fnal.gov/tipp11/
- 2010 FNAL Detector R&D Workshop: https://indico.fnal.gov/conferenceDisplay.py?confId=3356