PAUL SCHERRER INSTITUT

Detector R&D

Europhysics Conference on High-Energy Physics 2011

Grenoble, 26. July 2011

Roland Horisberger
Paul Scherrer Institute

Enormous world wide activity in particle detector R&D by:

- particle physics
- nuclear physics
- astro-particle science
- X-ray photon scattering science
- neutron scattering science
- medical/biological sciences

Almost impossible to keep overview and summarize all.
June/July 2011 (TIPP2011, VERTEX2011) ~ 500 contributions.
EPS-HEP2011 "Detector R&D" Session ~ 30 contributions

Please excuse personal selection based on ignorance and interest.

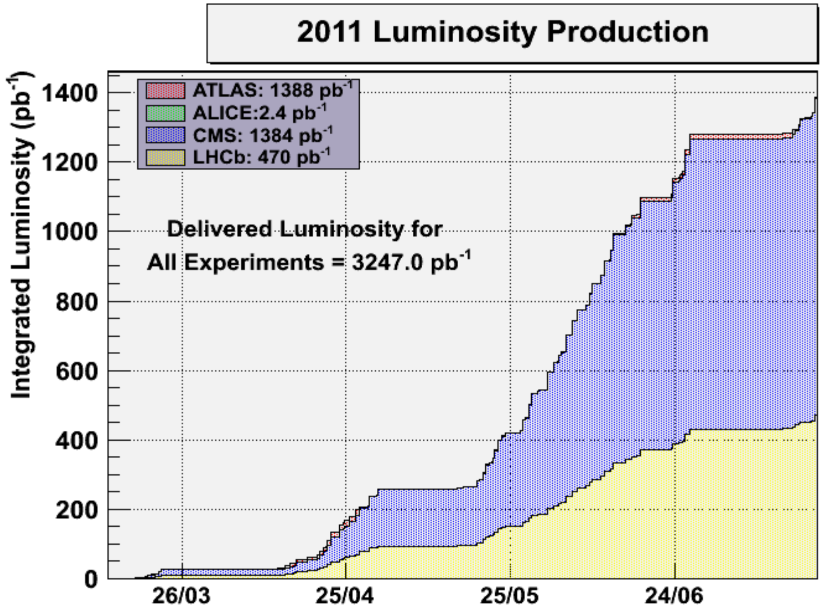
- **Detector Performance of LHC experiments**
- **Improvements and Upgrades**
- **Challenges to Tackle**
- **Insights, Technologies & "driving" Developments**
- **Cute Ideas & Well Done**

Apologies to those a) who do great work, but are not mentioned in my talk.
b) who's work is mentioned, but may not be correctly referenced.

Detector performance of LHC experiments

• Enormous growth (~10^5) of LHC luminosity since startup

• Experiments constantly adapting
  - algorithms
  - FPGA firmware
  - DAQ software



• Problems showed up with rates !

• Low lumi periods allowed debugging

• Overall things have worked as planned !

→ **great success !**

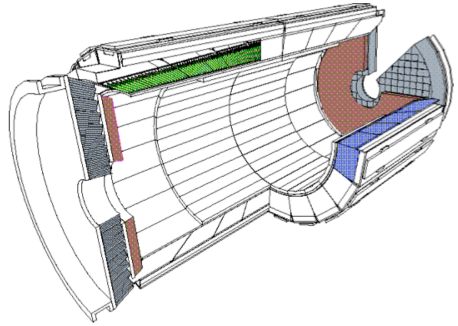
• High channel segmentation of experiments has paid off (so far)
  - operational channels (typ > 98% or better) & well calibrated

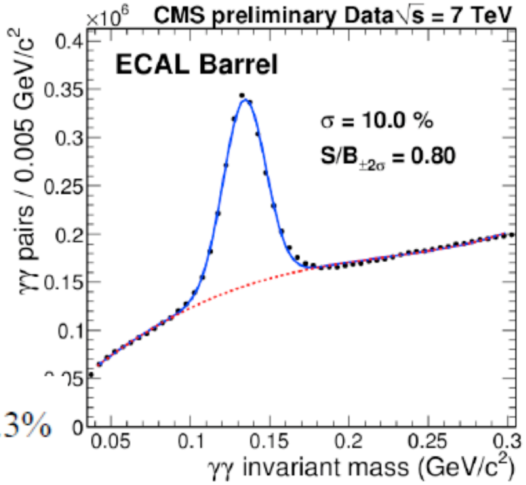
• Flexibility in detector specific, low level digital data manipulation by FPGA's has been crucial to this success story. → lesson for HL-LHC and other ambitions projects

CMS

- all sub-detectors in good shape
- well calibrated & aligned
- Trigger & DAQ runs ~100KHz
- Data taking efficiency ~93%

CMS ECAL

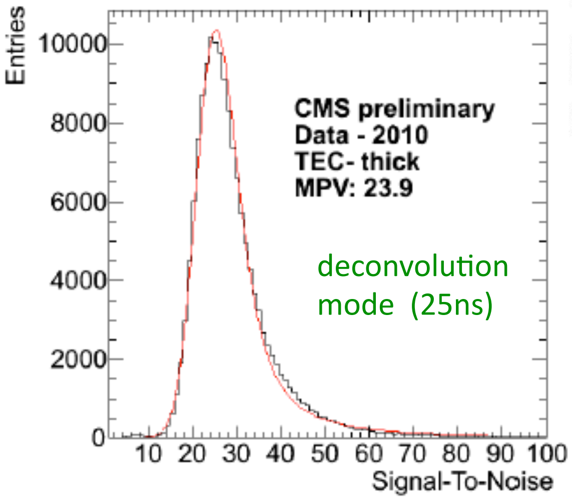


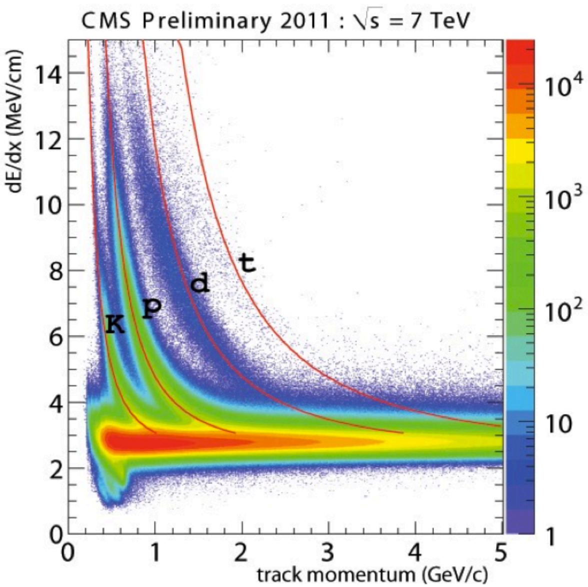


$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(GeV)}} \oplus \frac{12\%}{E(GeV)} \oplus 0.3\%$$

Silicon Strips ~200m²

alive channels : 98%





Pixels pixel size = 100μ x150μ

- alive pixel channels : 97%
- Pixel threshold = 2500 e
- in-time threshold ~3200 e
- analog pulse height readout

measured position resolution:

rφ = 12.7μ +/- 2.3μ

z = 28.2μ +/- 1.9μ

measured impact parameter (10GeV)

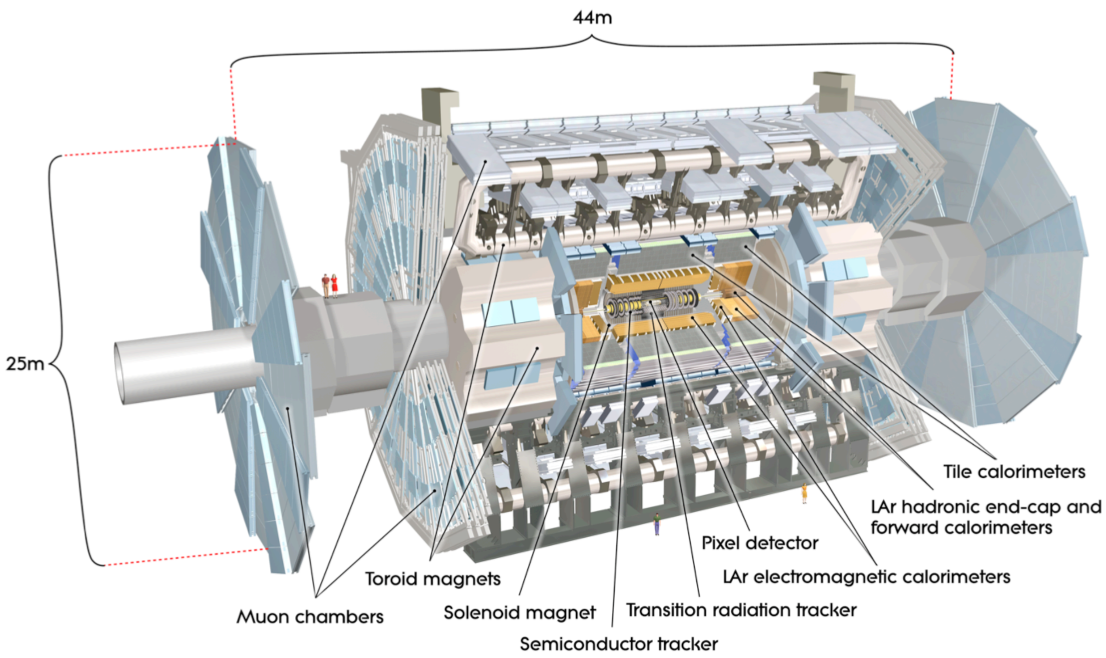
δ (rφ) = 25μ

δ (z) = 45μ

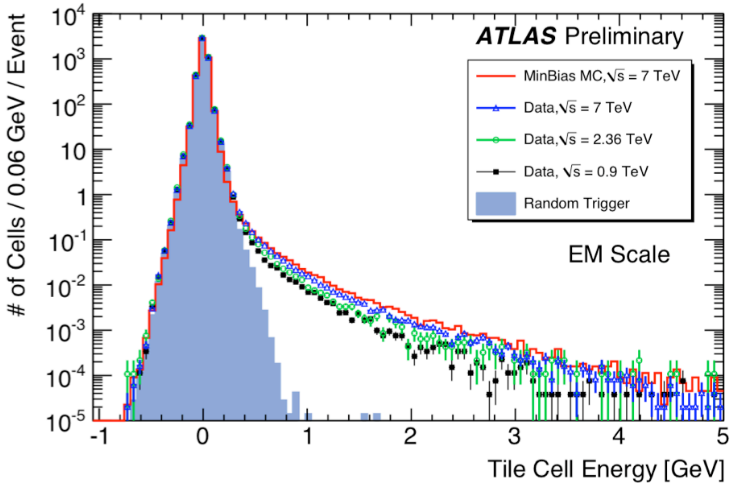
ATLAS

- work very well
- run efficiency 95.3% !

General Comment:
remarkable agreement
between Data – MC



e.g. Tile Calorimeter

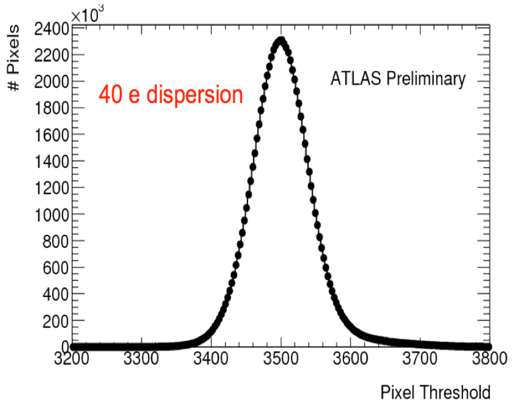


Pixels pixel size = 50μ 400μ

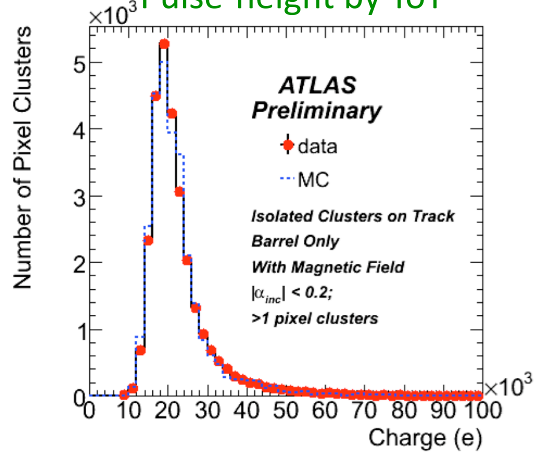
alive pixel channels : 97%

meas. resolution: rφ = 19μ z =115μ

Well adjusted pixel tresholds

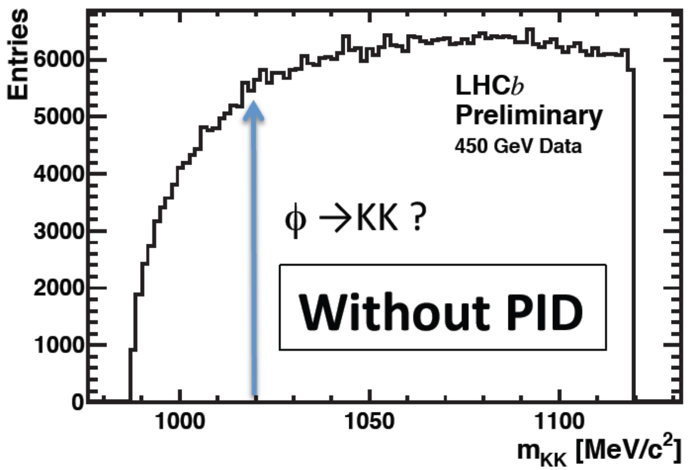


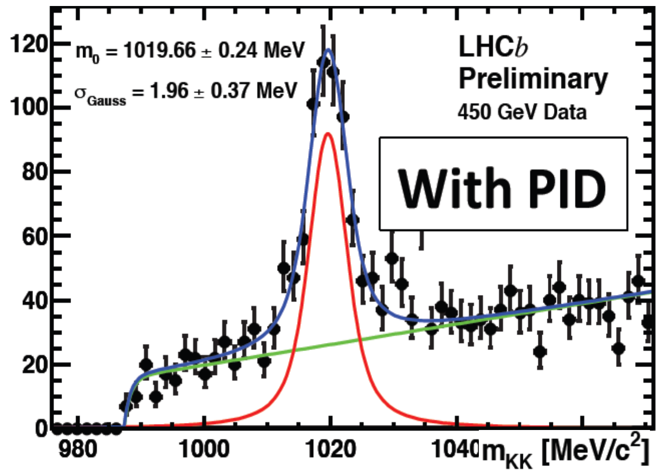
Pulse-height by ToT

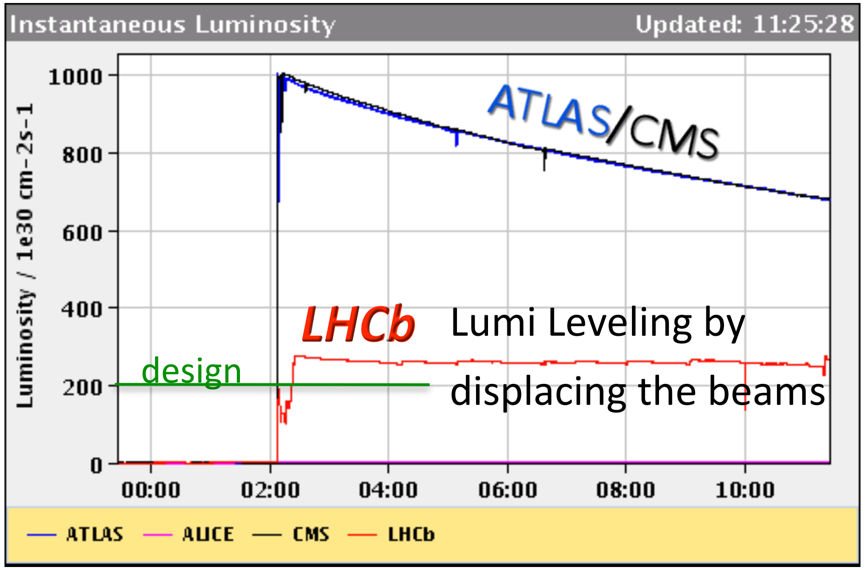


LHCb

- Luminosity leveling → $L \sim 3 \cdot 10^{32}$ cm^{-2}s^{-1}
- Experiment operates well (at 50ns) with $\mu \sim 1.5$ beyond design of $\mu \sim 0.6$
- RICH works very well in complex events !



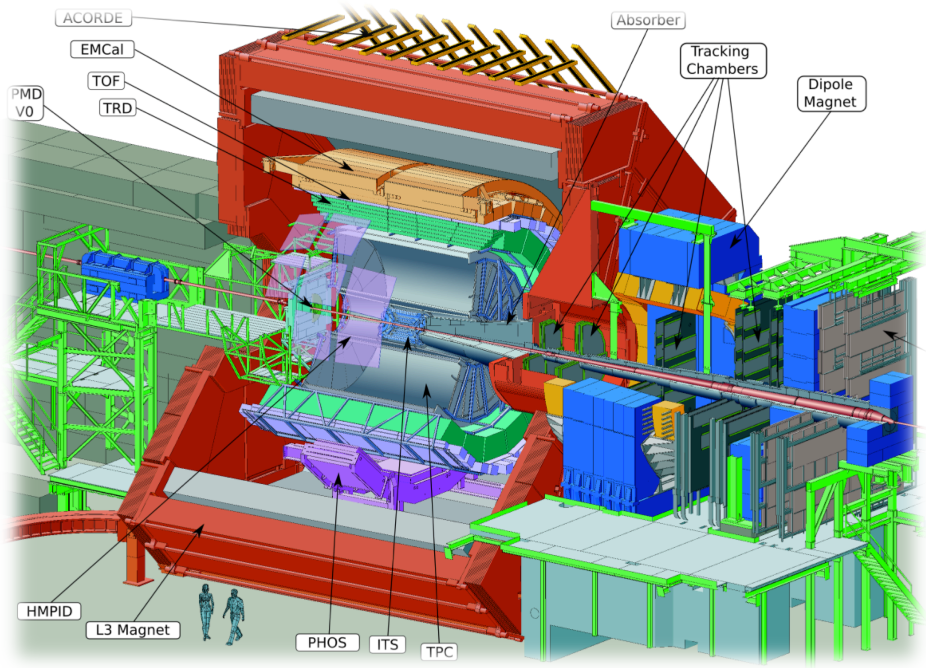


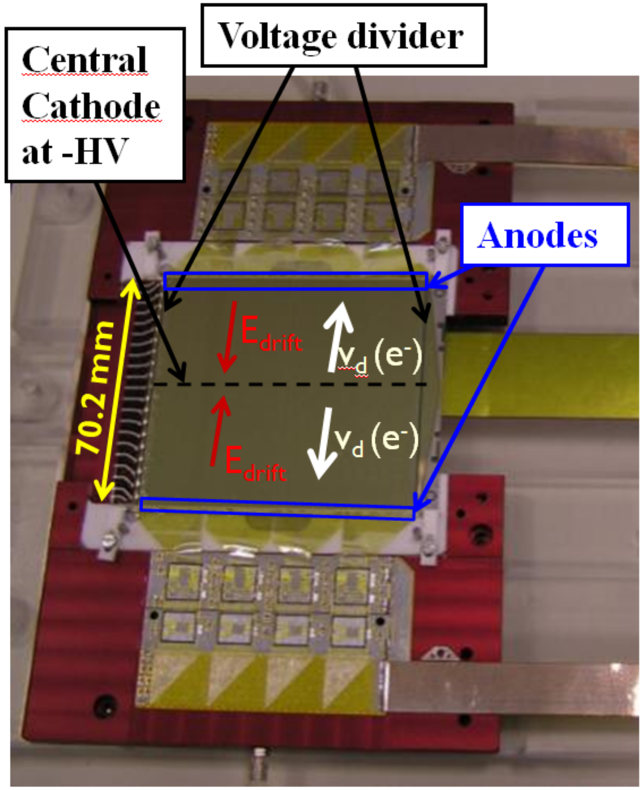


Remarkable little running inefficiency 1.4% due to VELO closing/opening to beam

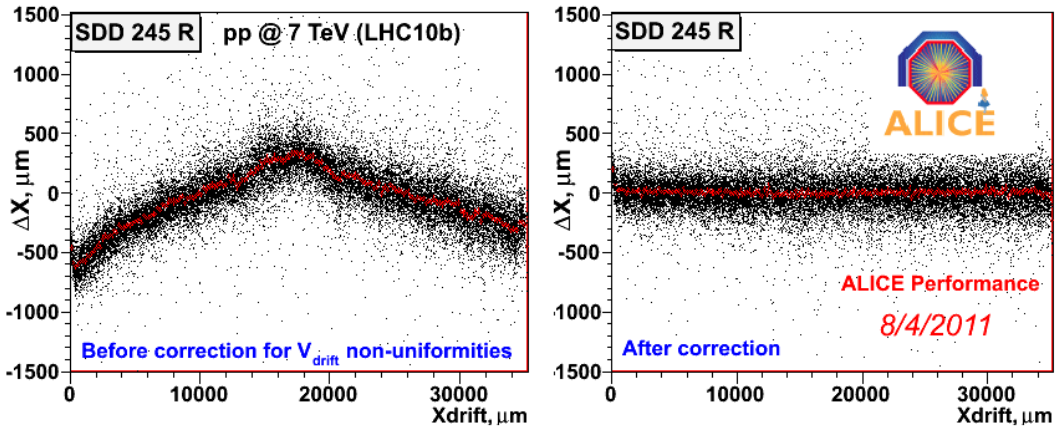
ALICE

- Specialized on HI running but can do some things in pp
- 3 different silicon technologies
- **Silicon Drift Detector** unique !





Calibration / Alignment of Silicon Drift Detectors



Impact parameter at 1GeV measured δ ($r\varphi$) ~ 60μ !

ALICE

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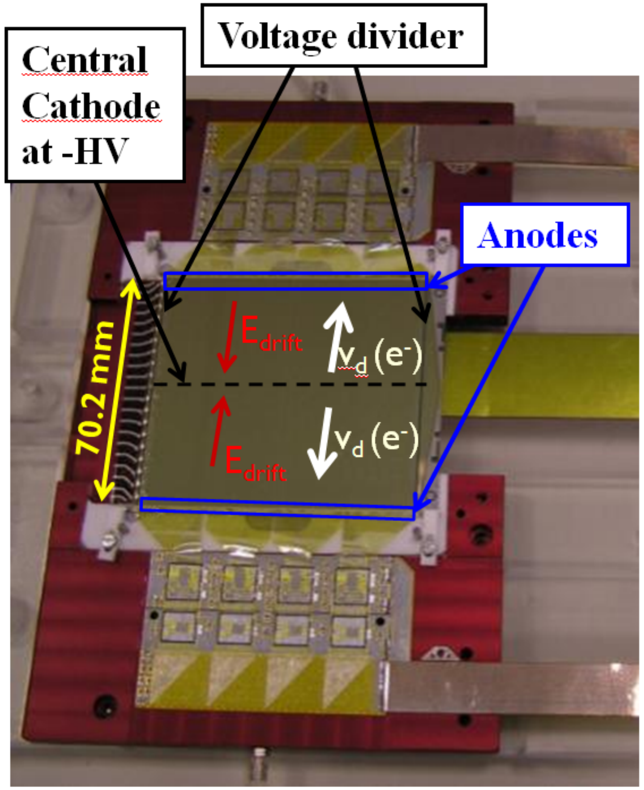

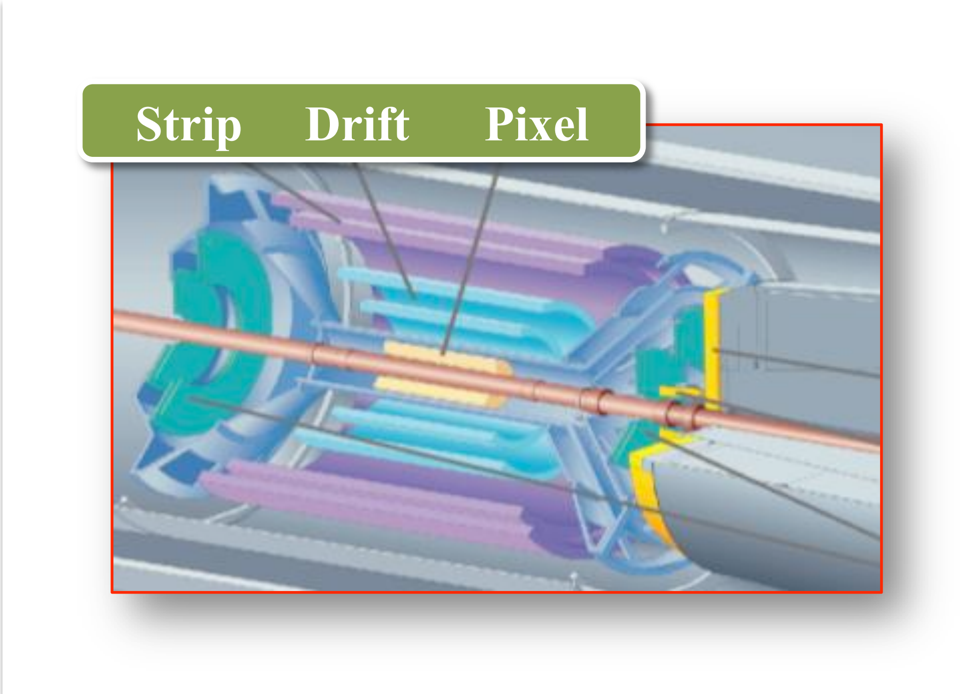

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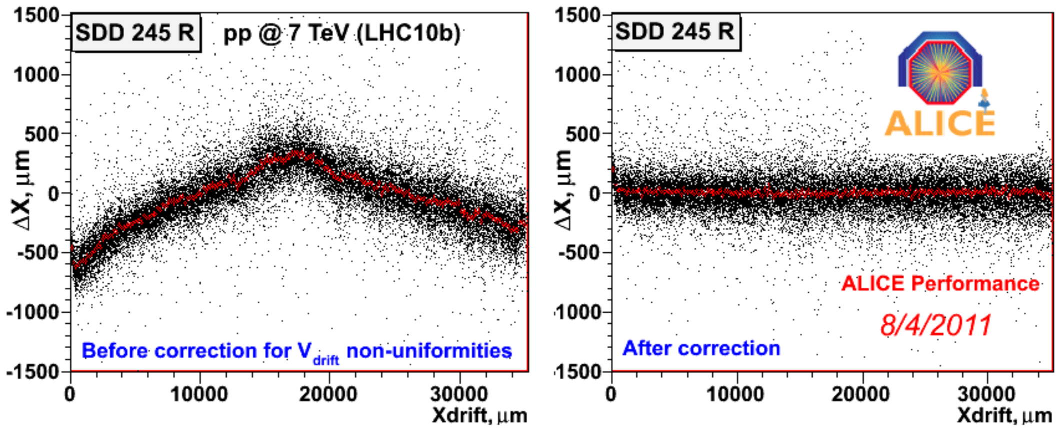


Impact parameter at 1GeV measured δ (rφ) ~ 60μ !

Improvements and Upgrades

- Data taking & physics analysis demonstrates shortcomings of experiments
- Upgrade decision are often problem driven. Many collaborators can convince themselves
- When it comes to the fix them, proposals quite often diverge again.

A few proposed upgrades with their solution are presented:

ATLAS Insertable B-Layer (IBL)

CMS Pixel Upgrade

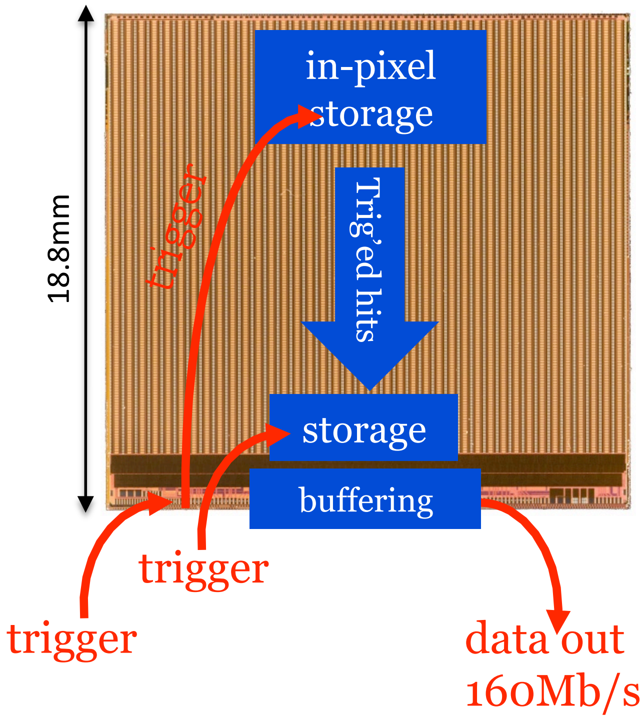
LHCb & VELO Upgrades

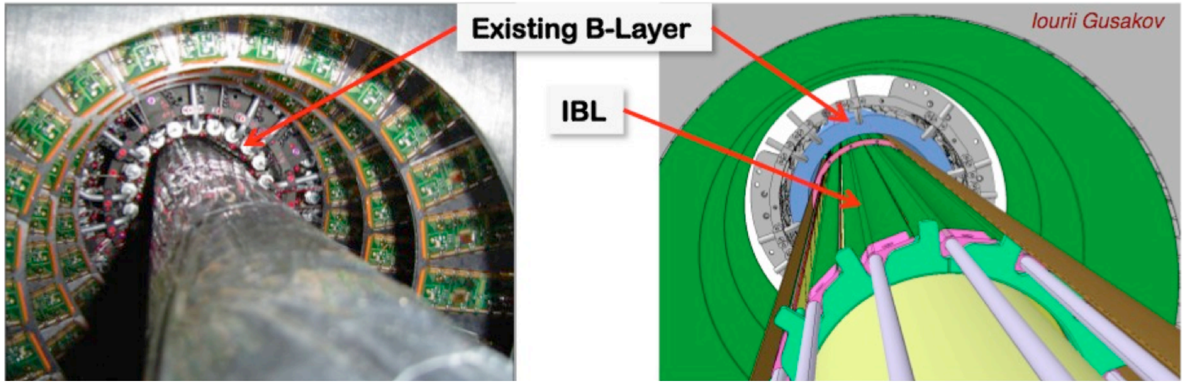
Resistive MicroMega for ATLAS μ-Chambers

CMOS Pixel Sensors for STAR

ATLAS IBL Upgrade

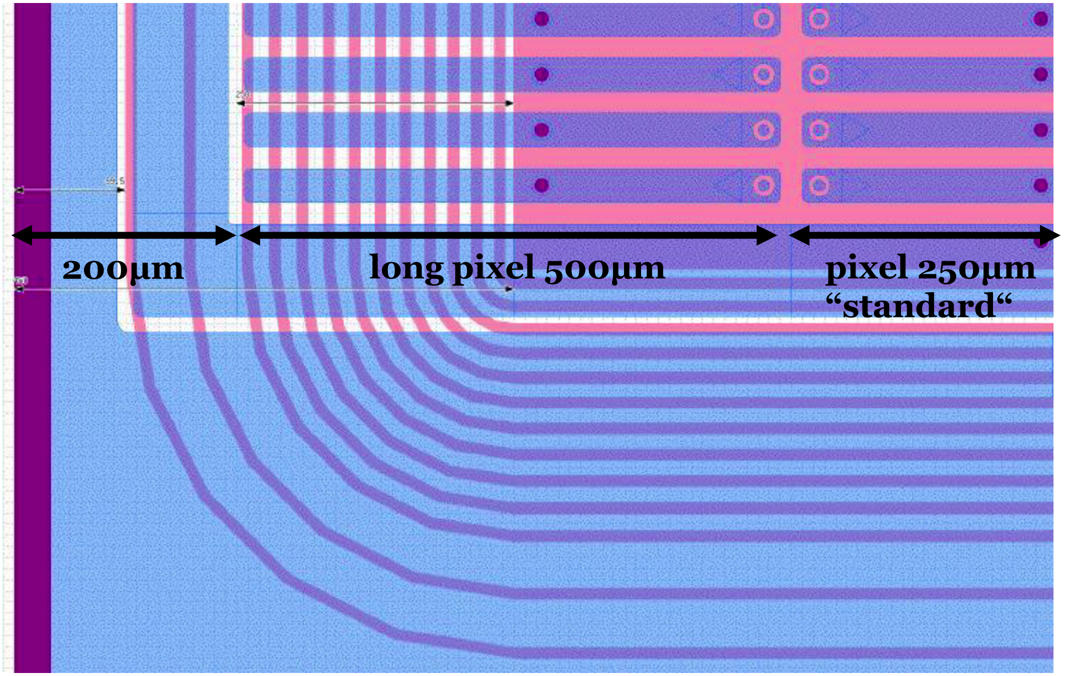
- FE-13 gets inefficient at HL-LHC
- new FE-14 ROC in 0.13µ CMOS
- new pixel size 50µ x 250µ
- chip shows excellent behavior
  - low pixel threshold ~1600 e
  - very rad. tolerant
  - low power (22µW/pixel)





Sensor options: planar n-in-n   or 3D

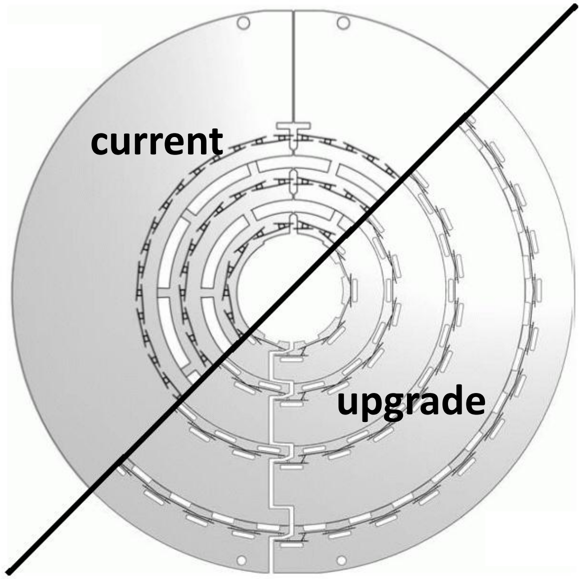
Remarkable: planar sensor with ~200µ pixel to edge



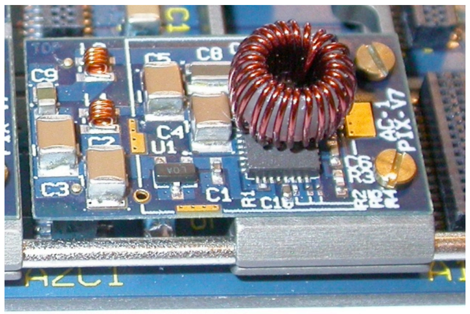
CMS Pixel Upgrade

Minimal changes to get a pin-compatible system

- Improve pixel vertexing in large PU events
  → 3 layers to 4 layers !!
- Shift material budget to high η and use CO_2 cooling
  → smaller impact parameter & less γ conversion
- Modify ROC to operate at 2×10^{34} efficiently
  → reduce data loss as go beyond LHC luminosities

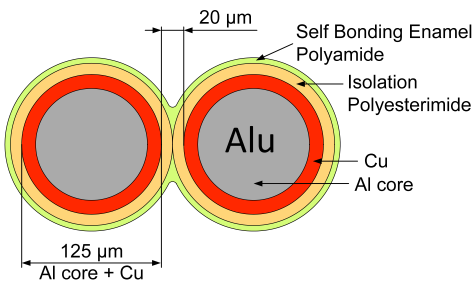


DC-DC converters

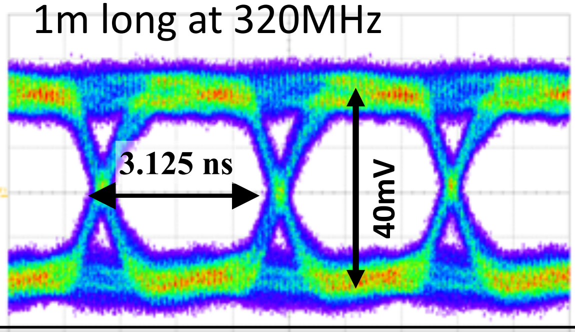


Buck Converter
V_{in} ~12V
V_{out} ~2.5V, I_{out} <2.8A
efficiciency ~80%

μ-twisted CCA pair

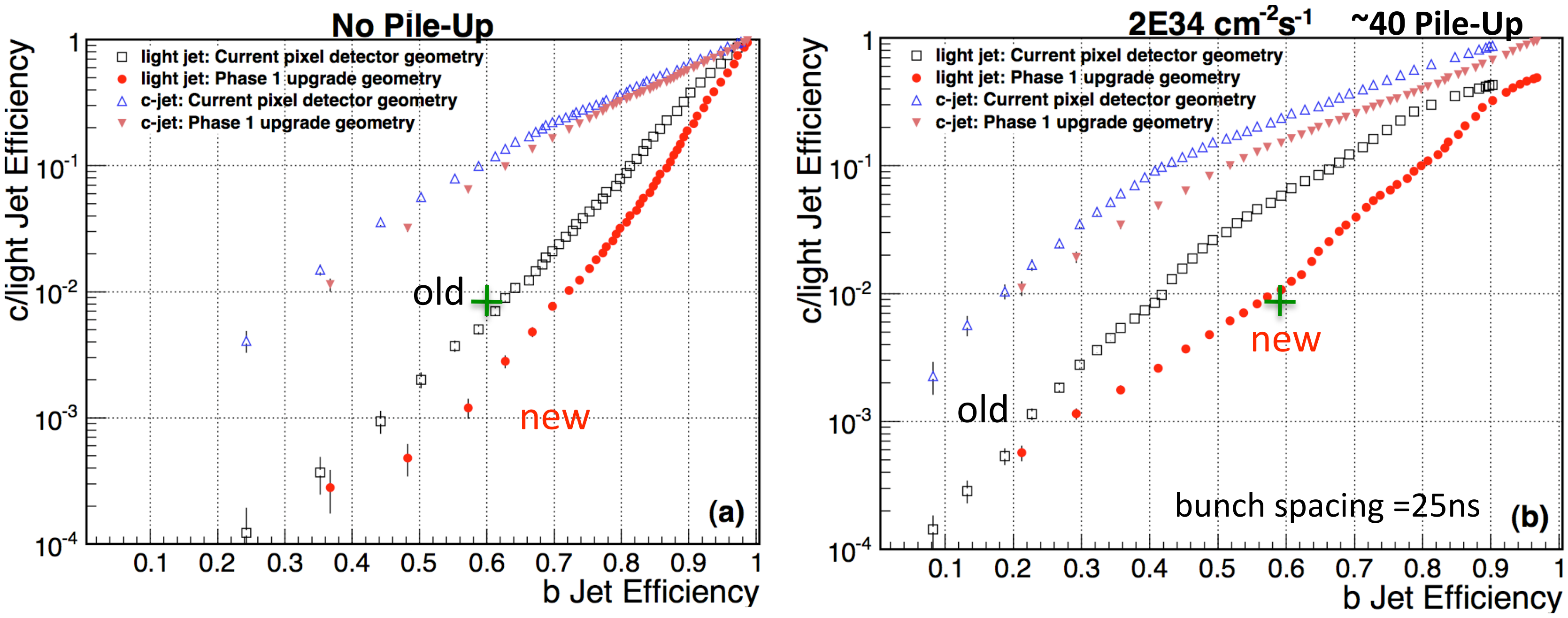


1m long at 320MHz



Changes to ROC for 2×10^{34}

- 40MHz analog → 160MHz digital
- 0.25μ CMOS, 5Metals → 6Metals
- increase depth of
  - data buffer 32 → 96
  - timestamps 12 → 24
- add readout buffer (64)
- add 8 bit ADC for pulse height
- lower pixel thresholds
- PKAM events → DAQ resync

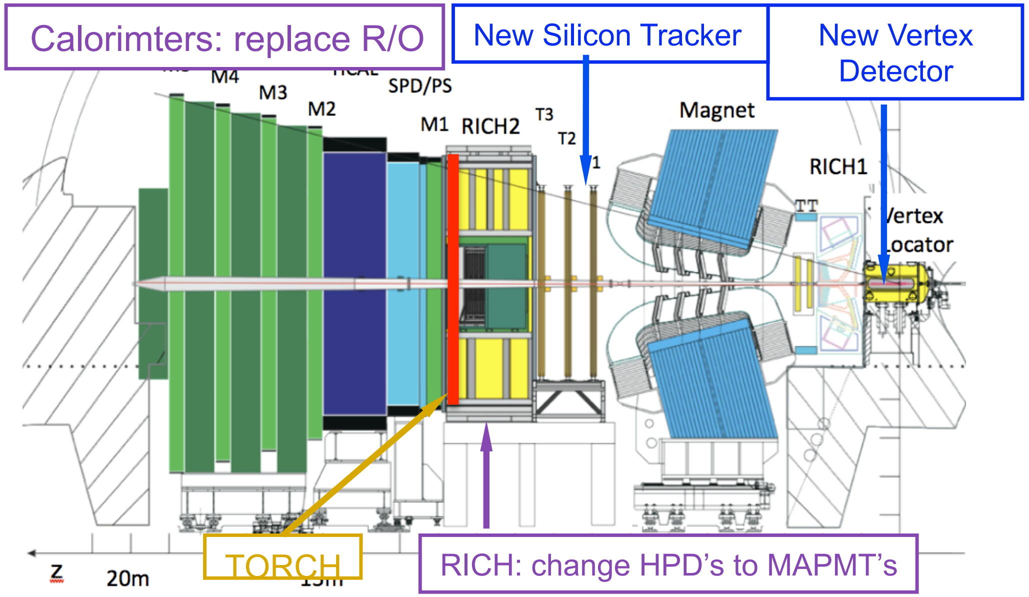


3 layer pixel (old) with no PU <u>same performance</u> as 4 layer pixel (new) with ~40 PU

More pixel hits is essential for large number of PU events.

LHCb & Velo Upgrade

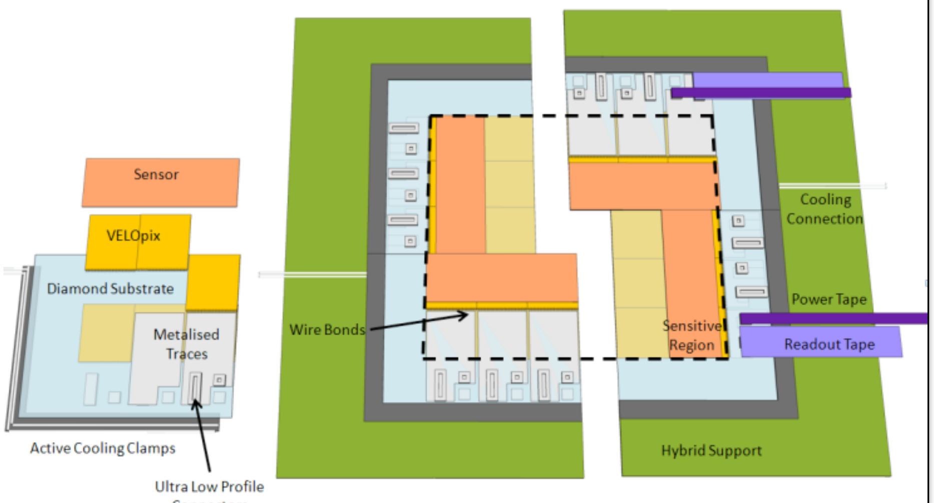
- $5fb^{-1}$/year → $50fb^{-1}$/year
- open access allows simpler change
- trigger limitations 1MHz → 40MHz
- software trigger with 20KHz output
- should deal with int. rate μ ~2.1



VELO Upgrade Options:

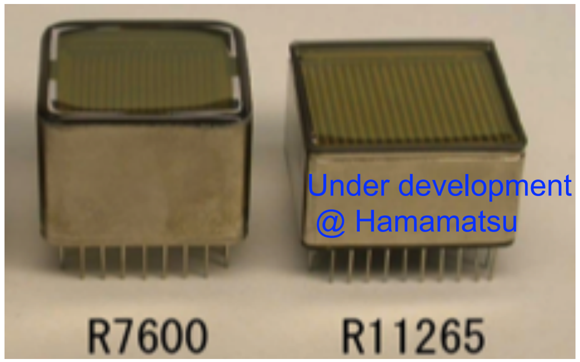
a) Strip detector: strip pitch 30μ

b) VELOPIX , Timepix based 55μx55μ pixel ROC, large data rates output



PID Upgrade (keep RICH-1 & RICH-2)

HPD's with 1MHz ROC → MAPMT's 40MHz

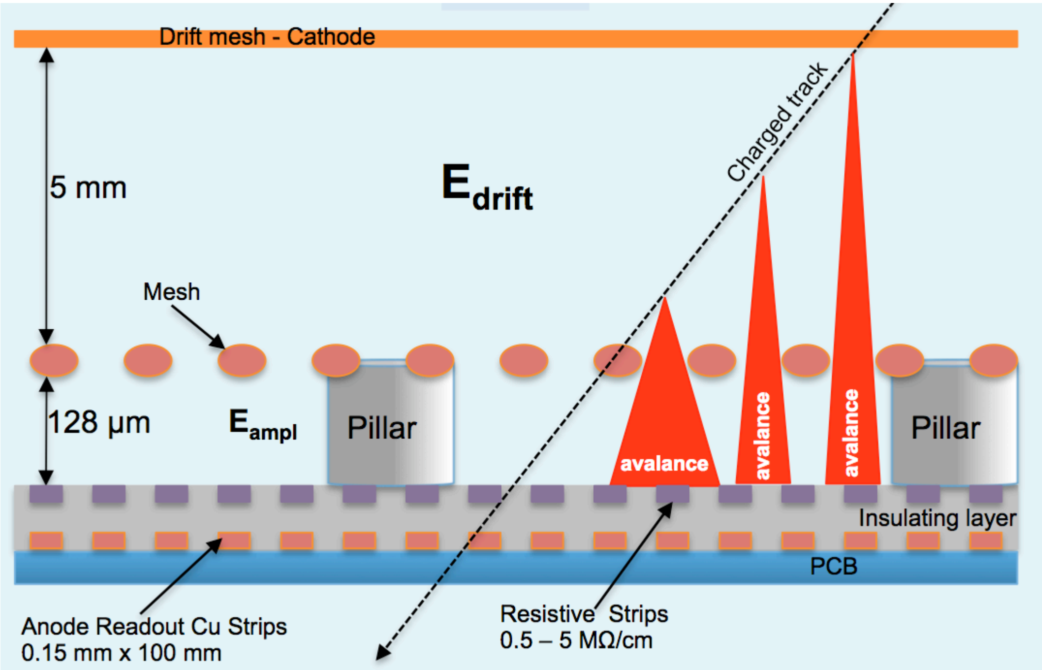


ATLAS μ-Chamber Upgrade

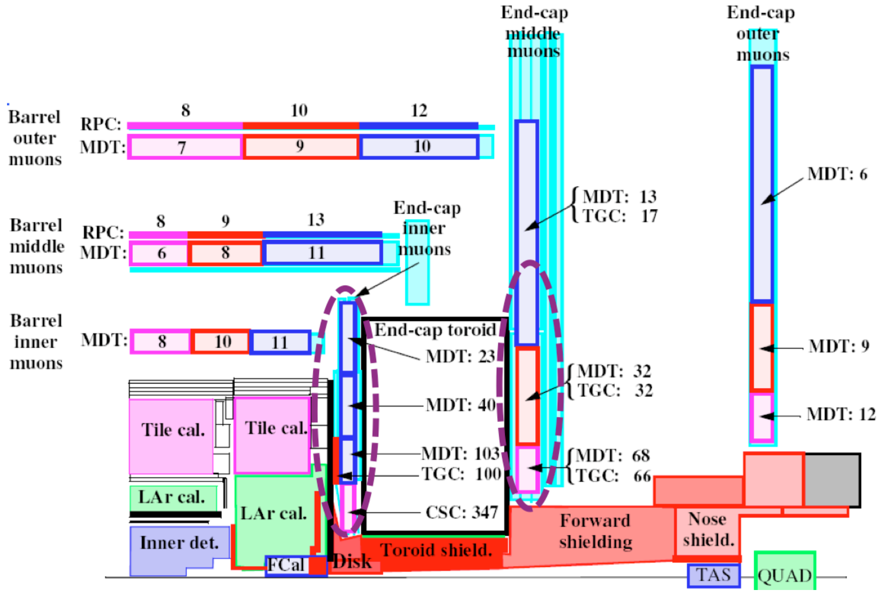
- Reduce forward muon fake rate
- several technologies considered, present:

Resistive MicroMegas

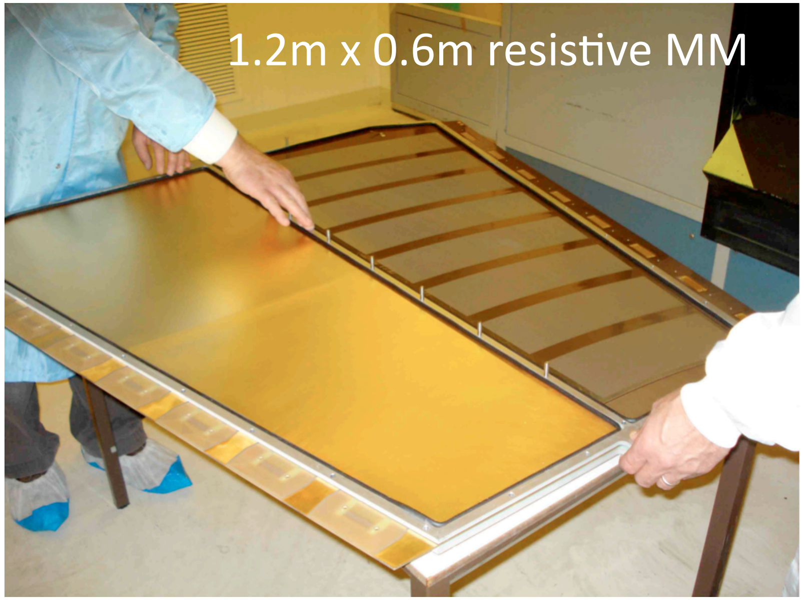
- designed for tolerating sparkes
- resistive strip parallel to readout strip



Prototype (9cmx8cm) tested with neutrons ~10^6/cm^2 .
Shows no sparking compared to normal MM!



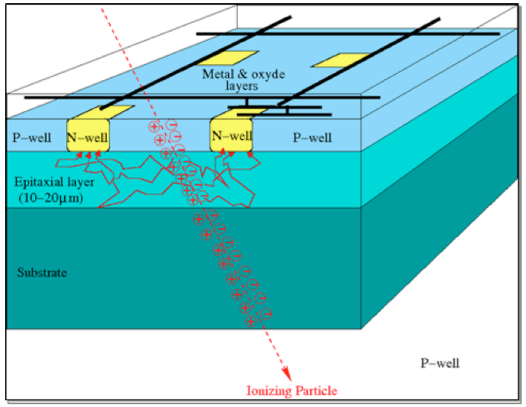
Technology is cheap → 200m^2

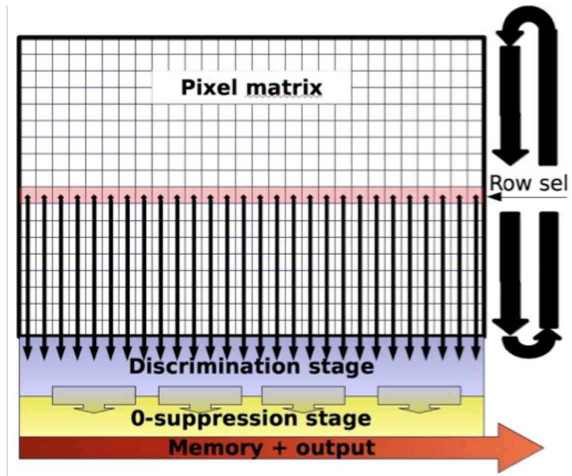


CMOS particle sensors

Use signal from ionizing particles in CMOS bulk.

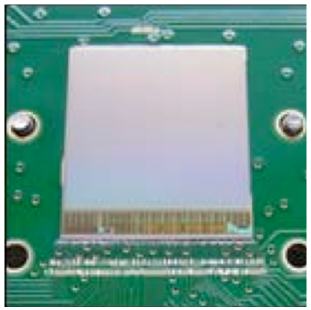
- commercial standard CMOS process --> low cost
- signal collection by diffusion only → speed, spread
- typical signal ~ 1000 electrons on n-wells contacts
- typically few unipolar pixel transistors in p-well
- very small pixels with very low noise ~20electrons
- rolling shutter to avoid random chip internal X-talk
- well suited for high precision & low rates
- 0-suppression in CMOS periphery → digital readout



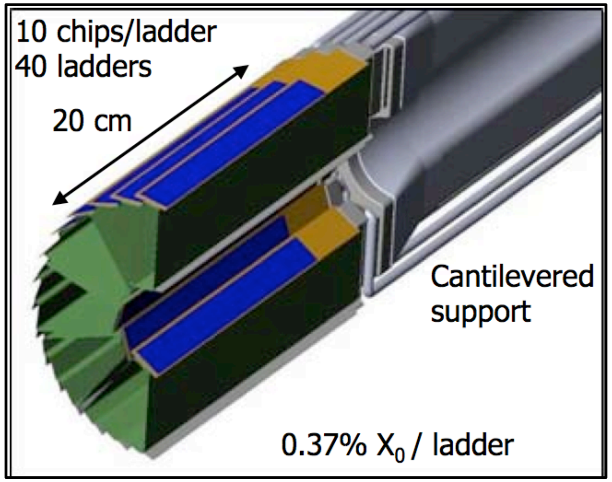


STAR Pixel Upgrade (planned for 2014)

- 2 layers at 2.5cm / 8cm
- Mimosa 28 chip ("Ultimate") in AMS-0.35μ CMOS



- pixel size 20.7μ
- chip size 20mm x 23mm
-position resolution ~10μ
- 200nsec per row scan



Challenges to Tackle

HL-LHC Performance Estimates (min. β* =15cm , CRAB cavities)

Parameter	nominal	25ns	50ns
N	1.15E+11	2.0E+11	3.3E+11
n_b	2808	2808	1404
Peak Luminosity	**1 10^{34}**	**7.4 10^{34}**	**6.8 10^{34}**
Events/crossing	**19**	**141**	**257** ← **worry !**

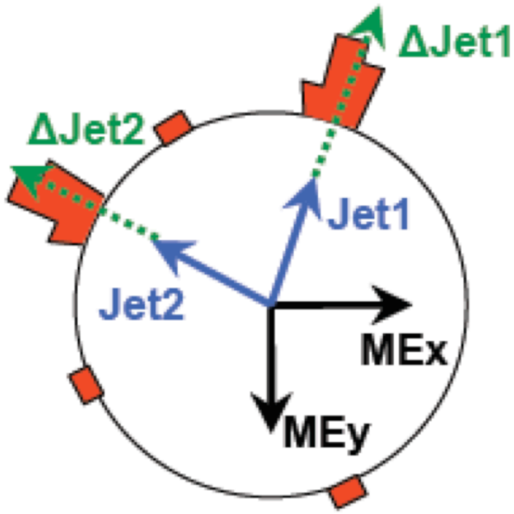
Physics analysis with many overlapping PU events is likely to suffer from

- **MET resolution**
- **jet energy resolution**
- **jet-jet separation**
- **Triggering problems** → fast readout links are useful

Missing Transverse Energy with CMS

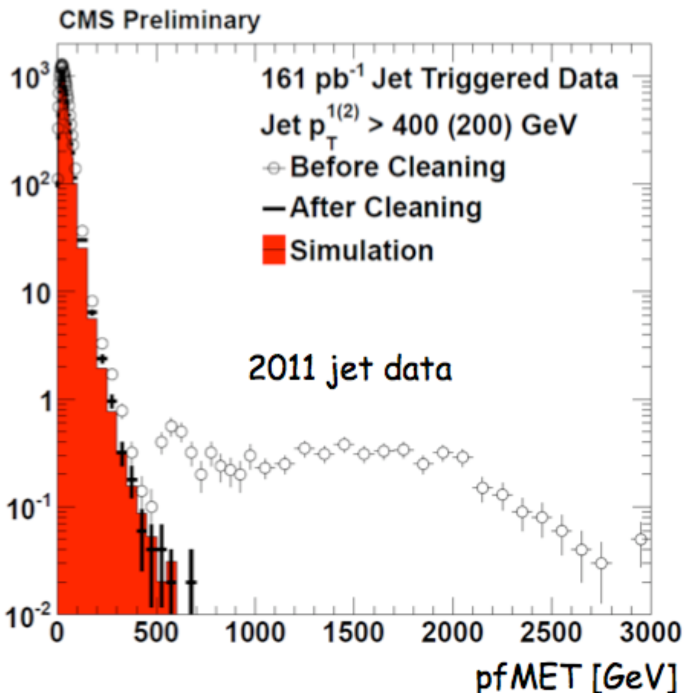
In CMS different methods to calculate Missing Transverse Energy (MET) :

a) Calorimeter MET
b) Track-corrected MET
c) Particle flow MET (pfMET) → best results

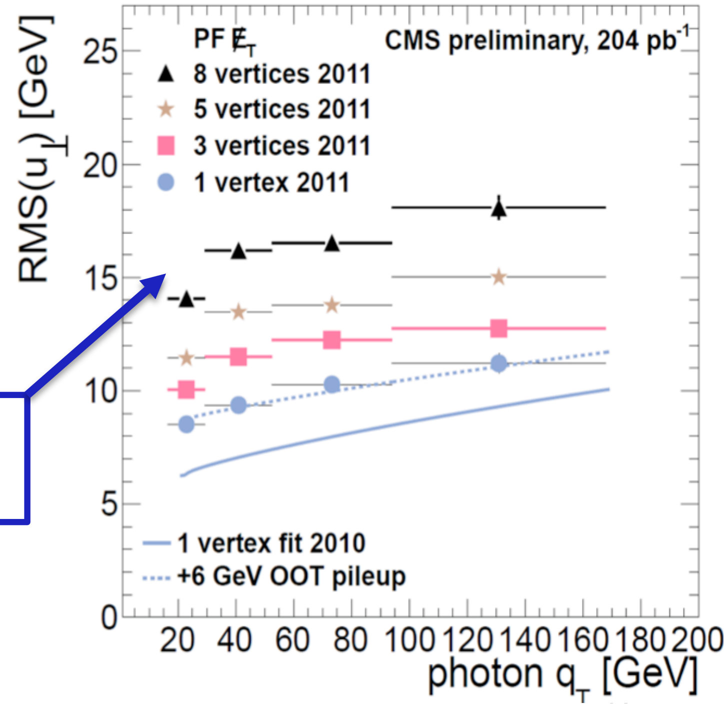


F. Lacroix (U. Chicago / FNAL)

Missing Transverse Energy can be faked by e.g. discharges or particle hits in photo-sensors ! Was dealt with careful algorithms !



MET degradation .vs. # PU events



How about 90 PU ($2x10^{34}$, 50ns)

High Granularity Particle Flow Calorimetry

M. Danilov, (ITEP), CALICE

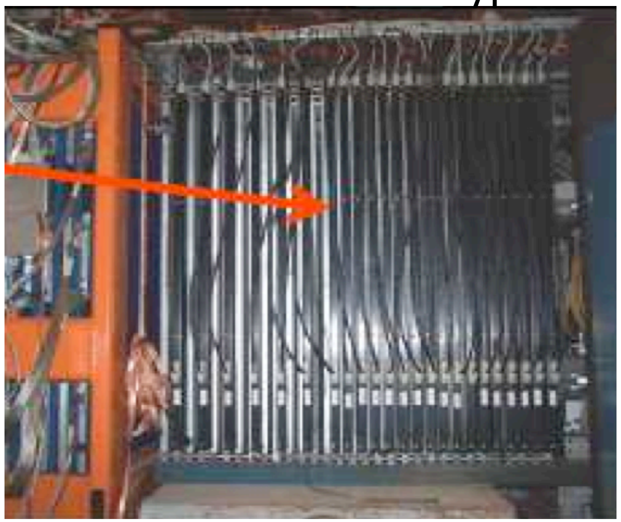
Particle Flow Calorimetry has good chance to function even in with many PU events.

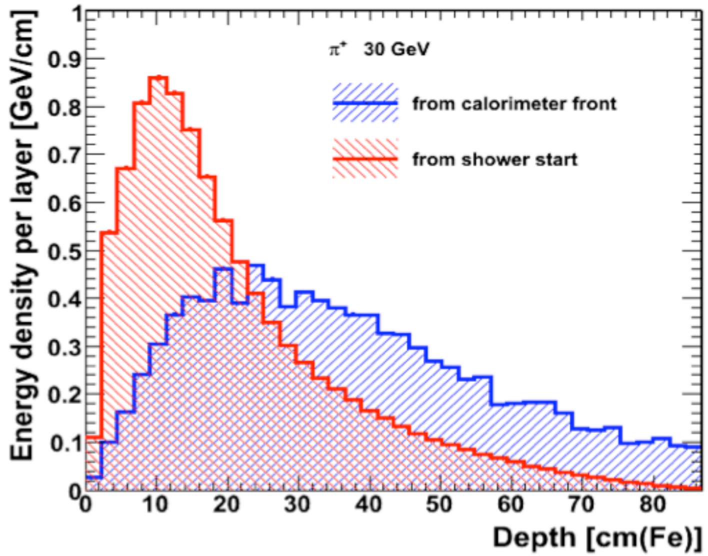
Basic Particle Flow Algorithm:

- Charged energy (65% in jet) – measure by tracking → **separate multiple PU-events**
- Photon (25% in jet) – precisely measured in ECAL
- neutrons / K_L (only 10% in jet) – measured in HCAL with moderate resolution
- Have to subtract away the charged energy in observed HCAL showers
- Confusion error in separation of showers is dominant
- Need a highly segmented HCAL detector → depth segmentation is crucial

CALICE AHCAL Prototype

calorimeter plane 90cm x 90cm





- 38 layers with 2cm Fe (W since 2011)
- Scint. tiles with SiPM readout

PF-Calos scaling like $\Delta E/E$ ~ 3%

Insights, Technologies & “driving” Developments

Silicon sensors (basic material properties studies by RD-50) (U. Parzefall, U. Freiburg)

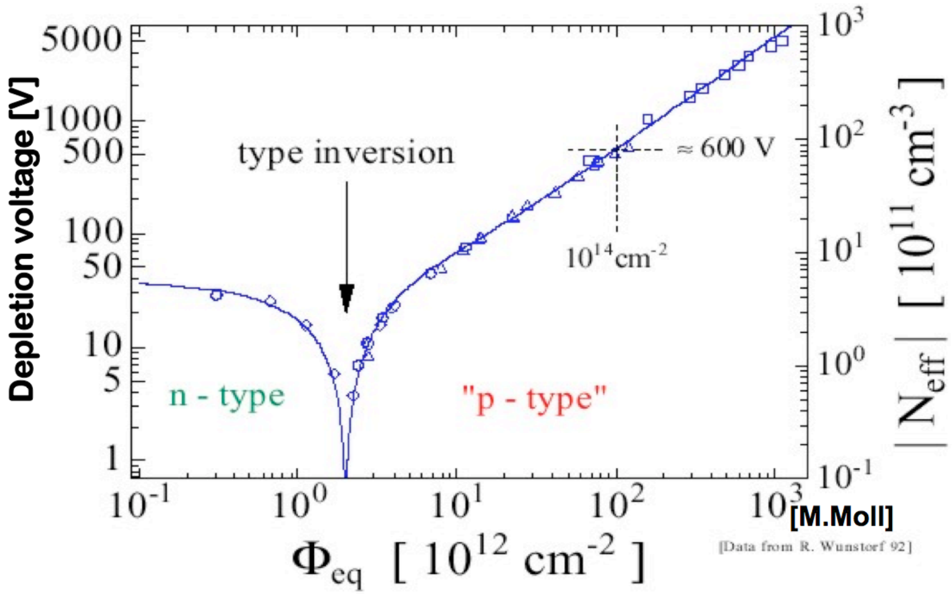
Irradiation in silicon sensors gives :

- Surface damage from Ionizing Energy Loss (IEL) → surface charges (SiO_2)
- Crystal damage from Non-Ionizing Energy Loss (NIEL) → energy levels in bandgap

the latter leading to leakage current, trapping centers and doping effects.

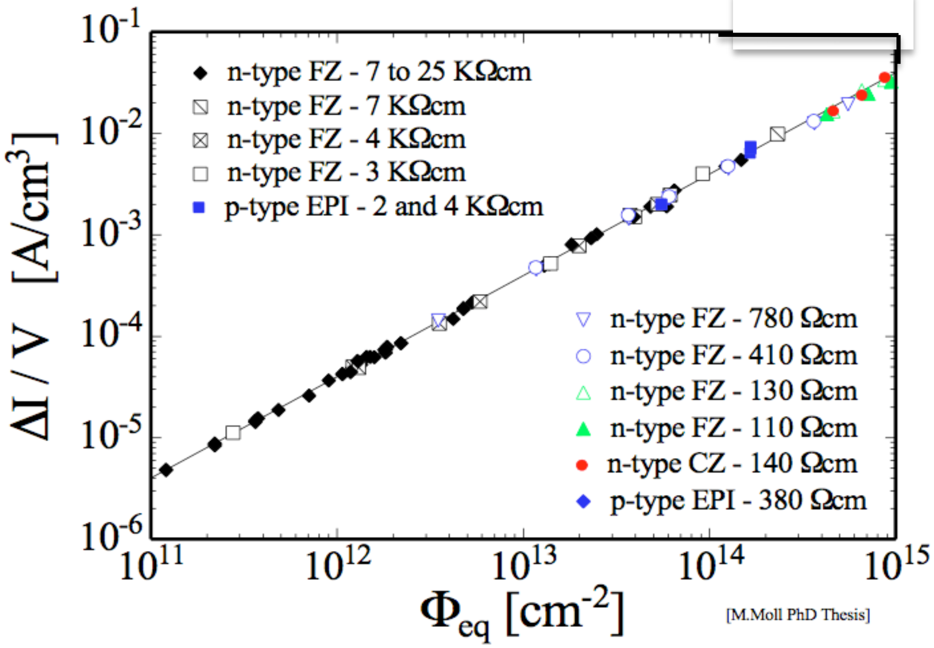
→Type Inversion (doping)

Normalise dose Φ_{eq} to damage of 1-MeV-neutrons

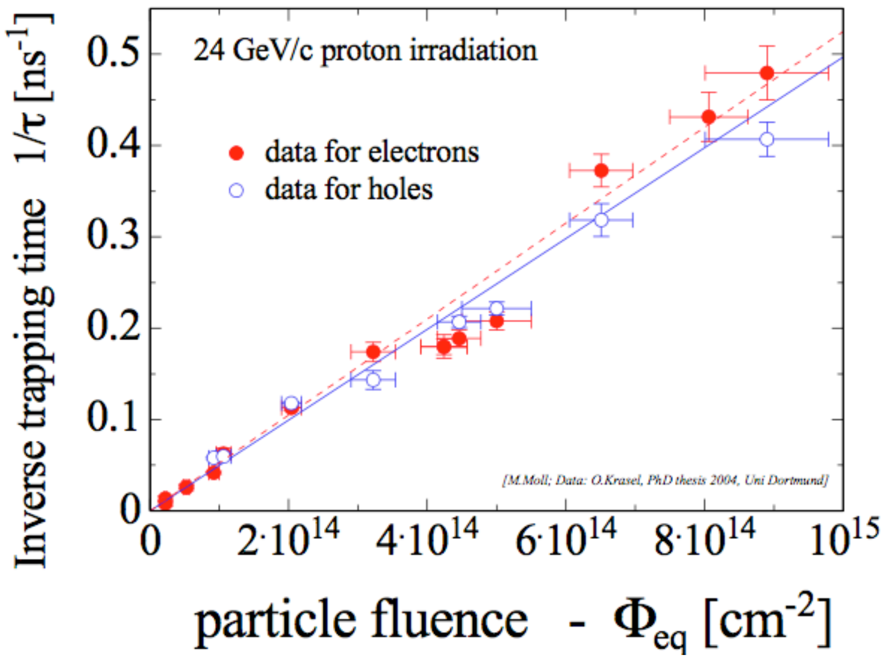


Observe the generation of universal, device doping independent

leakage currents



charge trapping times



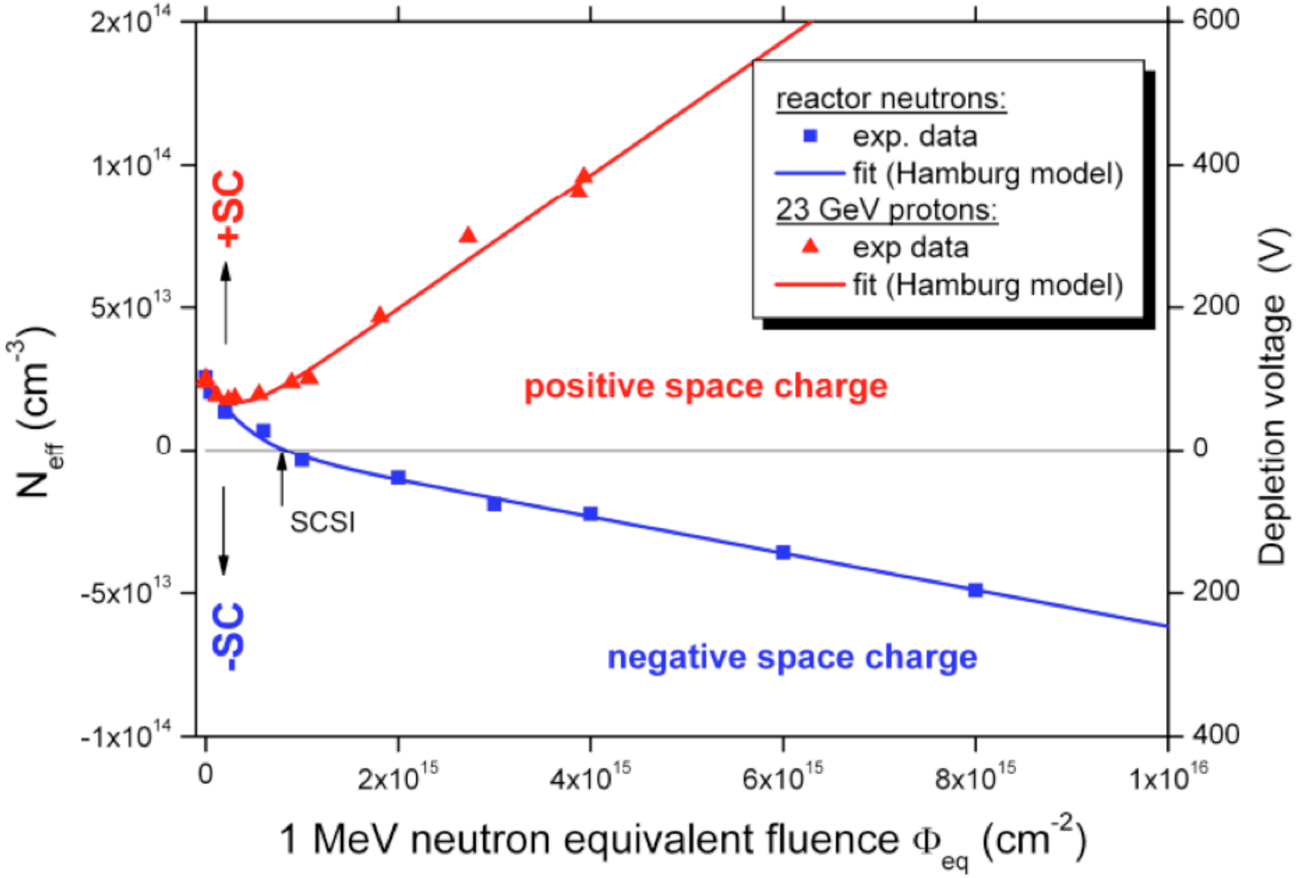
Signal charge trapping is **dominant** radiation effect at $10^{15} n_{eq}$ and above !

$$\tau_{eff}(10^{15} n_{eq}) = 2ns \qquad w = v_{sat}\tau_{eff} = 200\mu m$$

$$\tau_{eff}(10^{16} n_{eq}) = 0.2ns \qquad w = v_{sat}\tau_{eff} = 20\mu m$$

charge collection distance

Effective doping concentration N_{eff} depends on radiation activated defects:



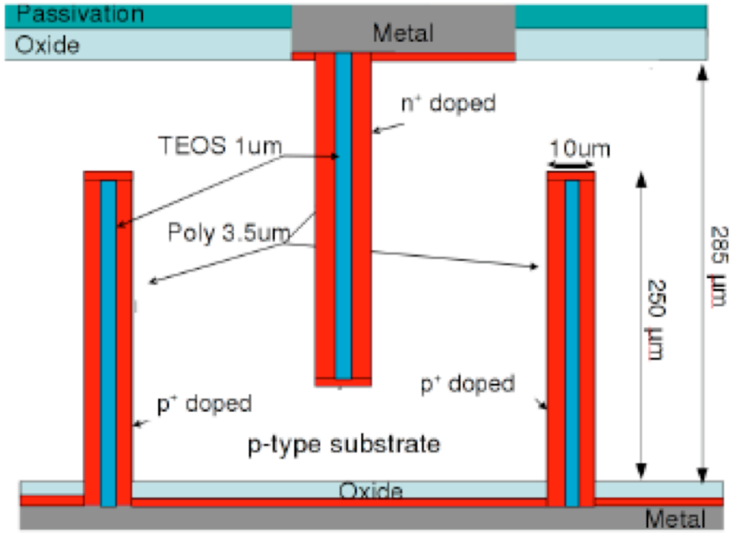
Epitaxial silicon diodes irradiated with:

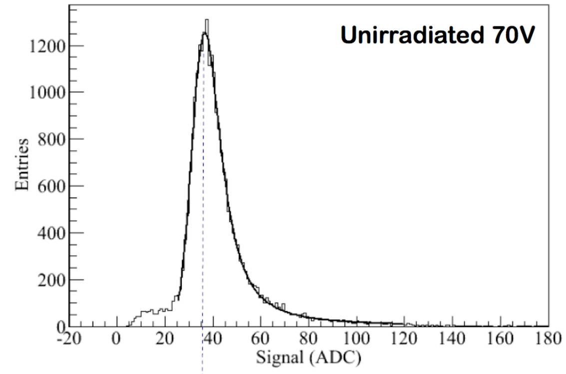
23 GeV protons

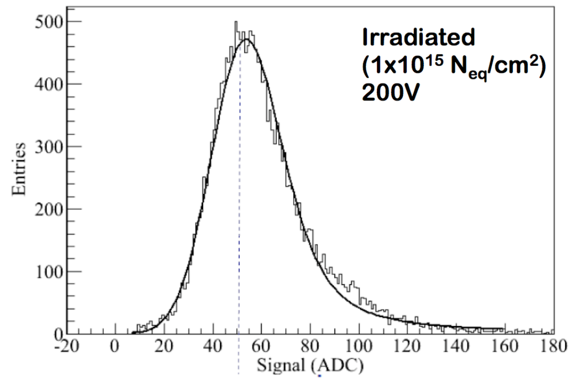
reactor neutrons

Depending an radii, HL-LHC experiments will expose their silicon sensors more to charged hadrons or neutrons → pixels (more hadrons) & strips (more neutrons)

Charge Collection in 3D Detectors

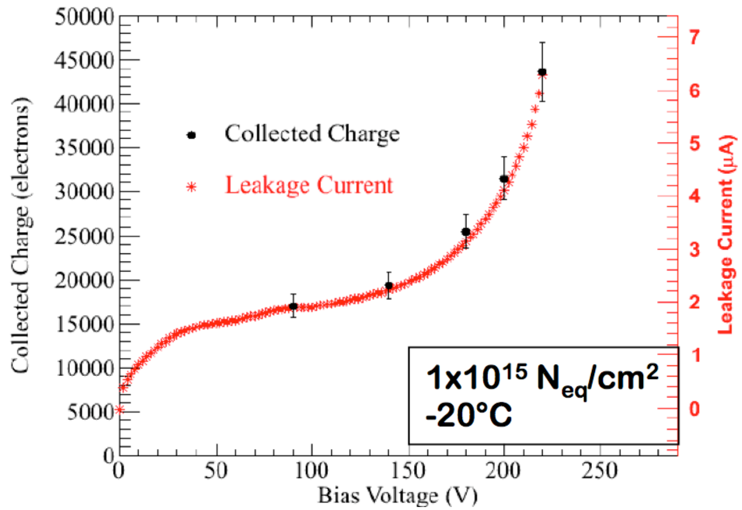






- short charge collection distance
- insensitive regions for tracks passing through electrode pillars. e.g. 90^0 tracks
- interleaved electrode pillars → capacitance!
- 3D sensors show avalanche charge <u>multiplication</u> after irradiation. (seen also in planar)

  → non gaussian noise in electronics

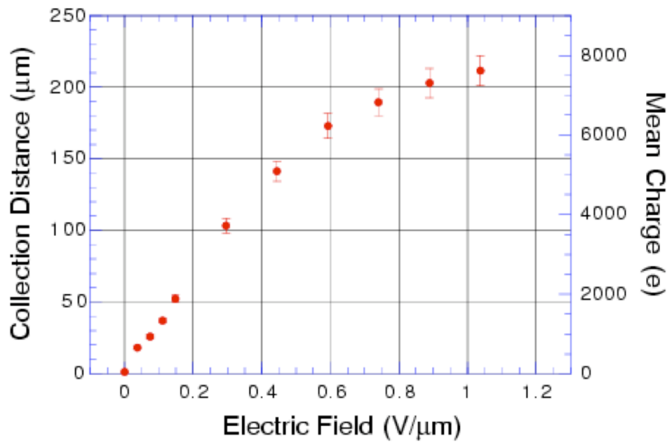


(RD42, W. Trischuk, U.Toronto)

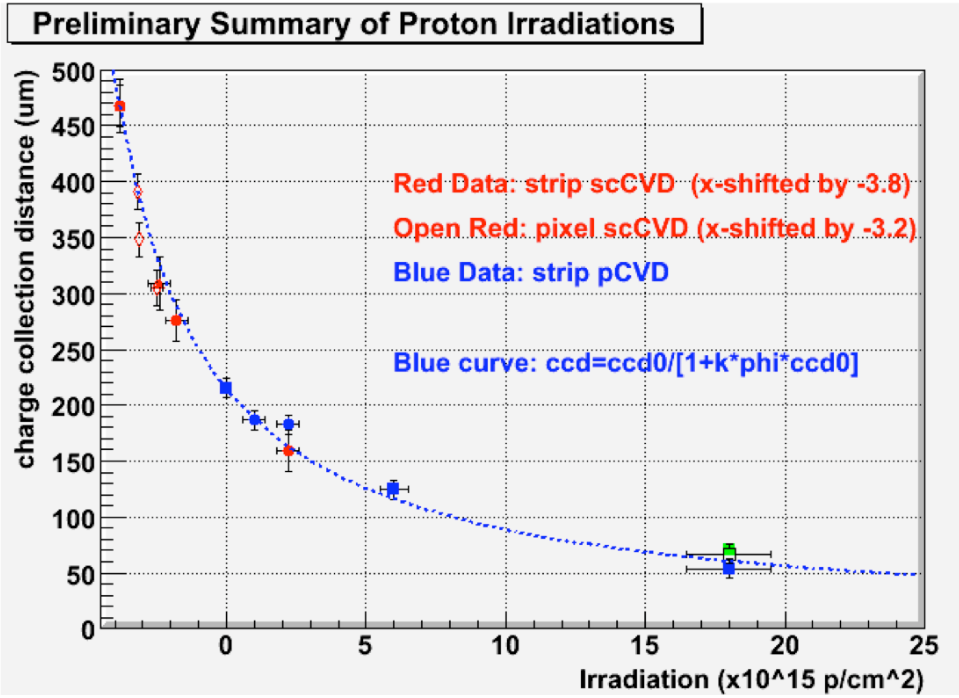
Diamand Sensors

Particle detectors from Chemical Vapor Deposited (CVD) Diamond are trapping defect dominated.

Mono-crystalline diamonds show much better charge collection distances !



Mono- / Poly-crystalline Comparison



Poly-crystalline material shifted by ≈ 3.8 × 10^{15} p/cm^2 to mono-crystalline material

Running construction projects:

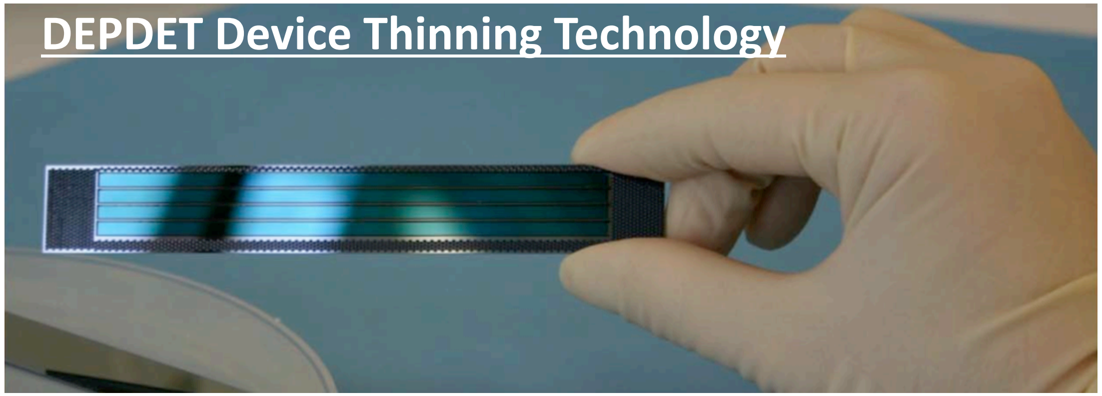
- ATLAS Beam Conditions Monitor
- CMS Pixel Luminosity Telescope
- ATLAS Diamond Beam Monitor

Cute Ideas & Well Done

DEPFET Vertex Detector for BELLE II

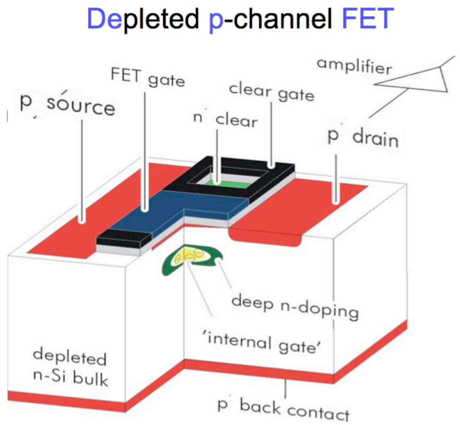
Belle II pixel vertex detector

- 2 layers at radii = 1.4, 2.2 cm
- monolithic sensor thickness 75µm
- pixel size ~50 x 50 µm^2
- rolling shutter mode , 100nsec → S/N=17/1

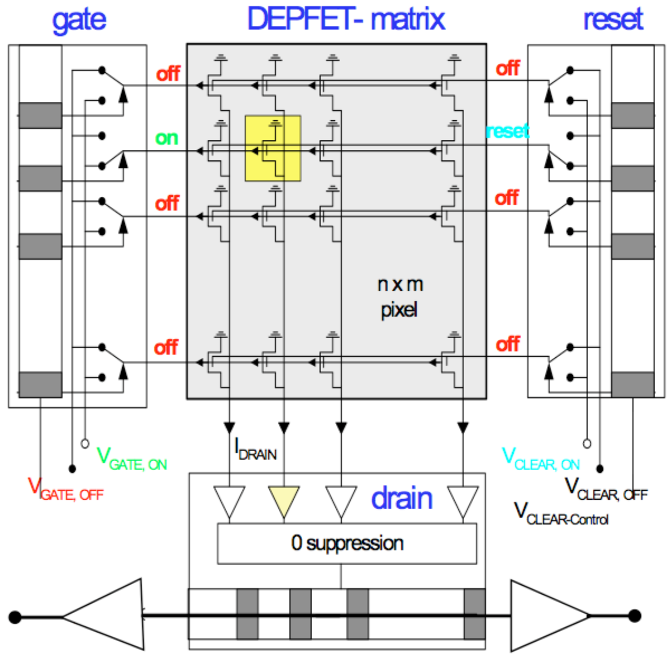


Final device 75um thick → X/X_0 = 0.18% !!

(self supporting, no extra mechanics in sensitive region)



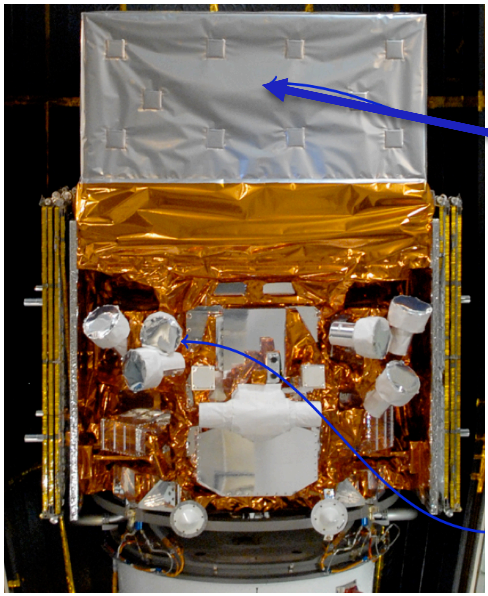
Ch. Kiesling (MPI, Munich)

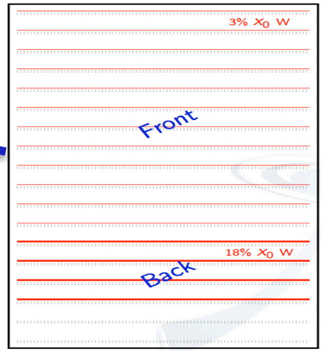


Si-Strip Tracker of the Fermi Large Area Telescope

J. Bregeon (INFN,Pisa)

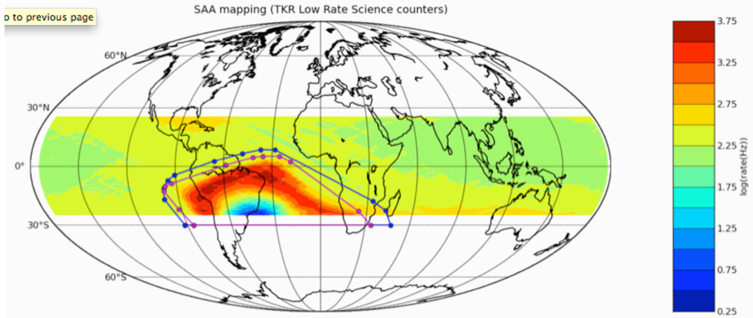
Fermi Obervatory with Large Area Telescope (LAT), Pair conversion 20MeV → 300GeV

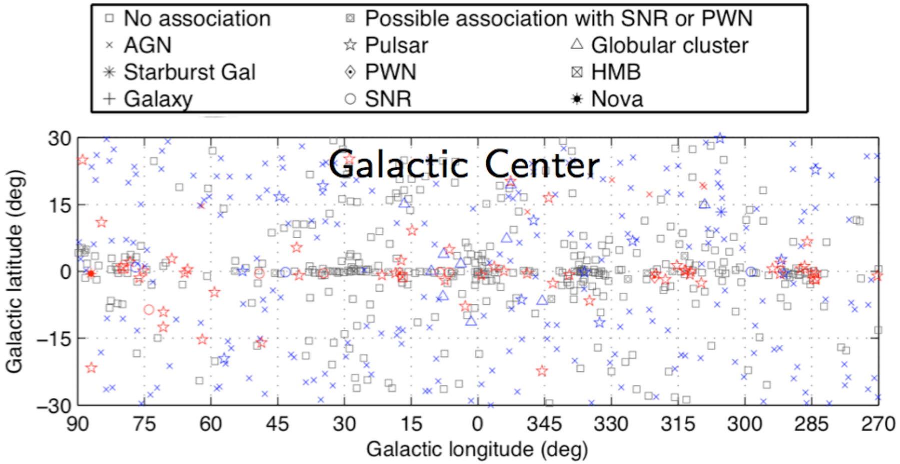




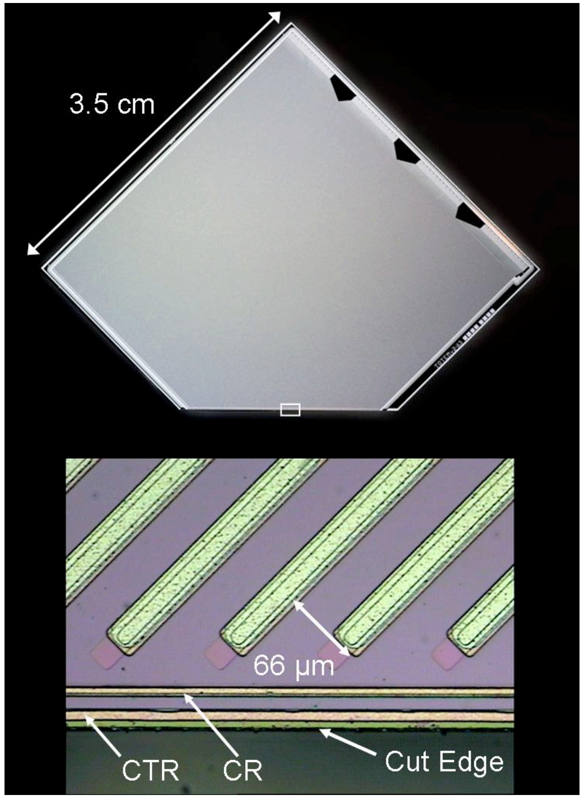
- Si-strip/W pair conv. telescope, 1.5 X_0
- 75m^2 Si-detectors in 18 planes
- very stable operation observed
- almost industrial production **(9month)**
- **160W power consumption ! → 2W/m^2**
- launched 2008, lots of data take

South Atlantic Anomaly (no data taking)





Edgeless Silicon Strip Sensors for TOTEM



- Very High Res. Si n-type <111>
- 300um thick, V_{dep} ~20V
- Standard planar technology
- Diamond saw dicing
- AC coupled strip

Sensitive strips 50µ close to edge ! !

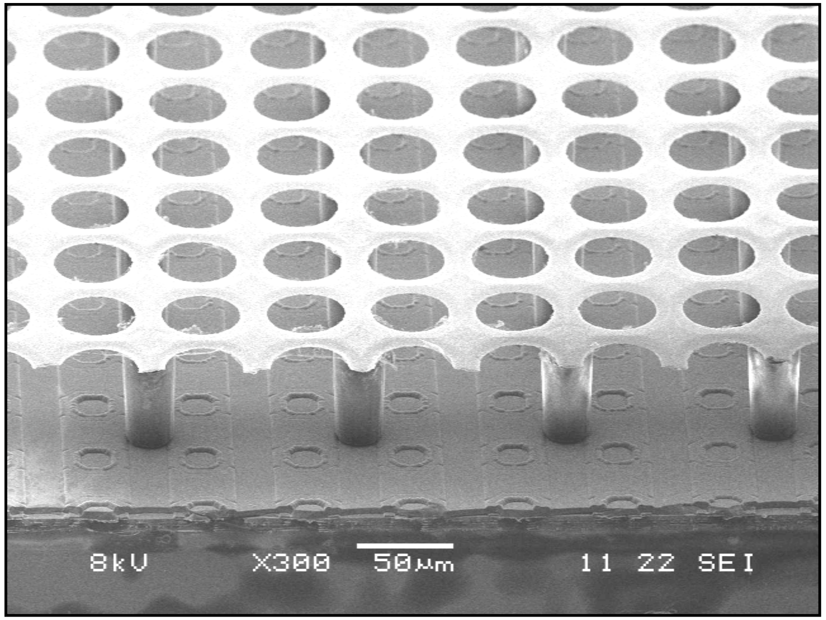
move very close to beam within Roman Pot.

G. Ruggiero (CERN), VERTEX2011

Gaseous Pixel Detector

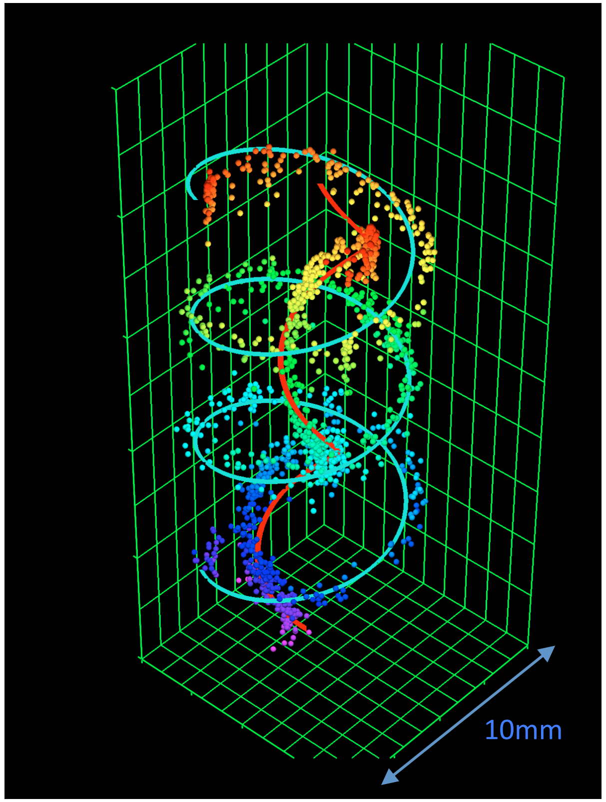
H. van der Graaf (Nikhef) TIPP2011

Gaseous Pixel detector (GridPix) is a MEMS made Micromegas like structure on a CMOS readout chip



Performance :

- position resolution:15 µm
-single electron efficiency: > 90 %
- track detection efficiency: 99.6 %;

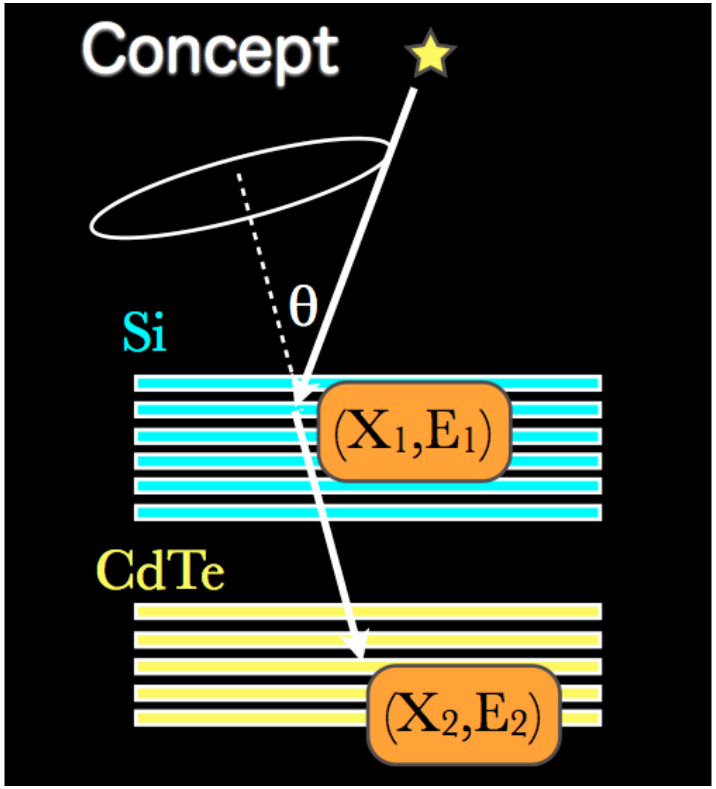


^{90}Sr electrons in 0.2 T B-field

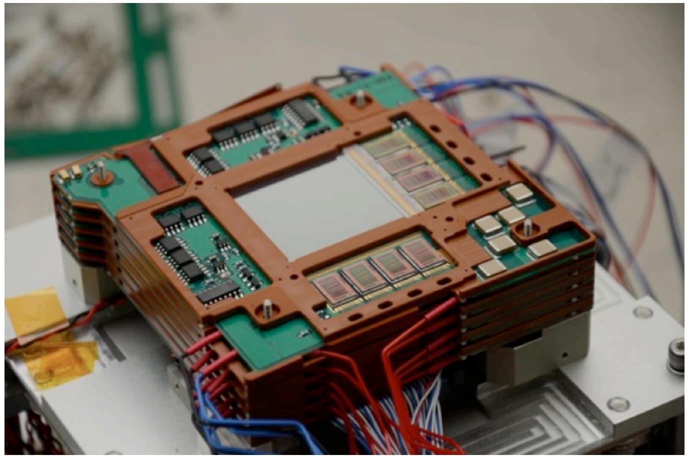
µ-TPC operation with TimePix chip

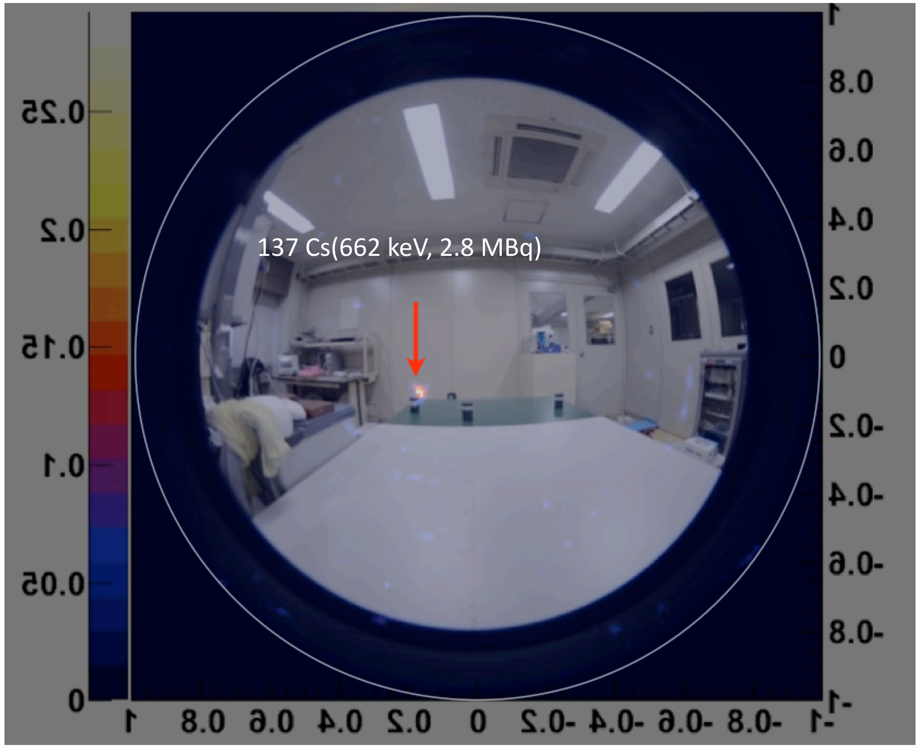
Si-CdTe Compton γ-ray Camera

S. Takeda (ISAS/JAXA) , TIPP2011



$$cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$



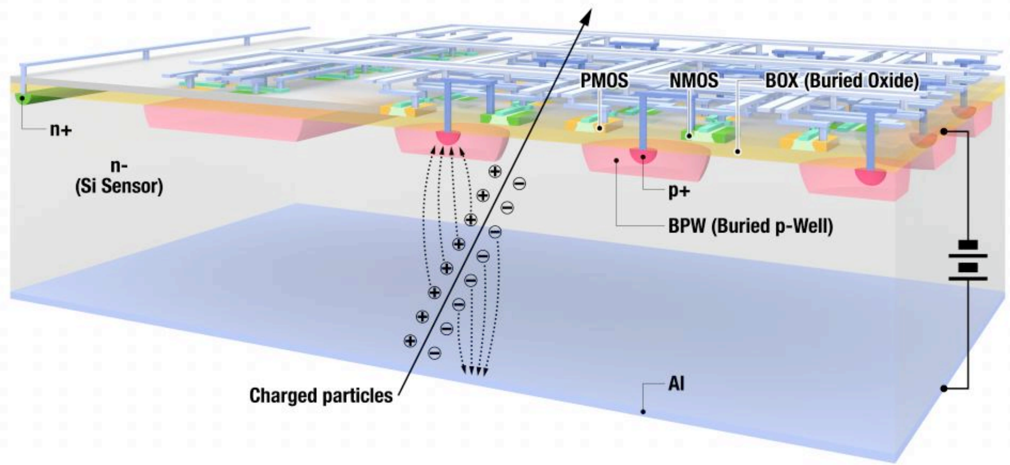


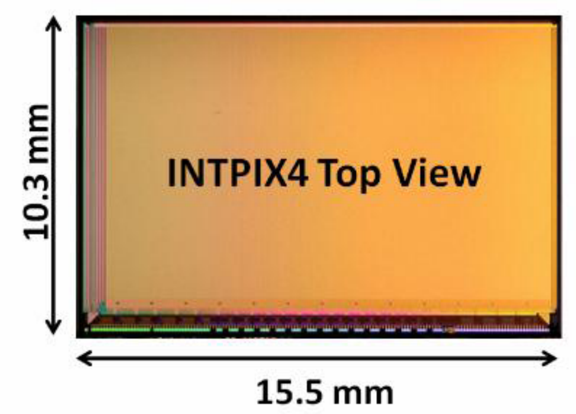
Y. Onuki (Tohoku Univ.), VERTEX2011

SOI-CMOS Pixel Sensors

Silicon On Insulator (SOI) technology with 0.2μm CMOS process on Hi-R(Cz 700Ω・cm) / Low-R(Cz 18Ω・cm

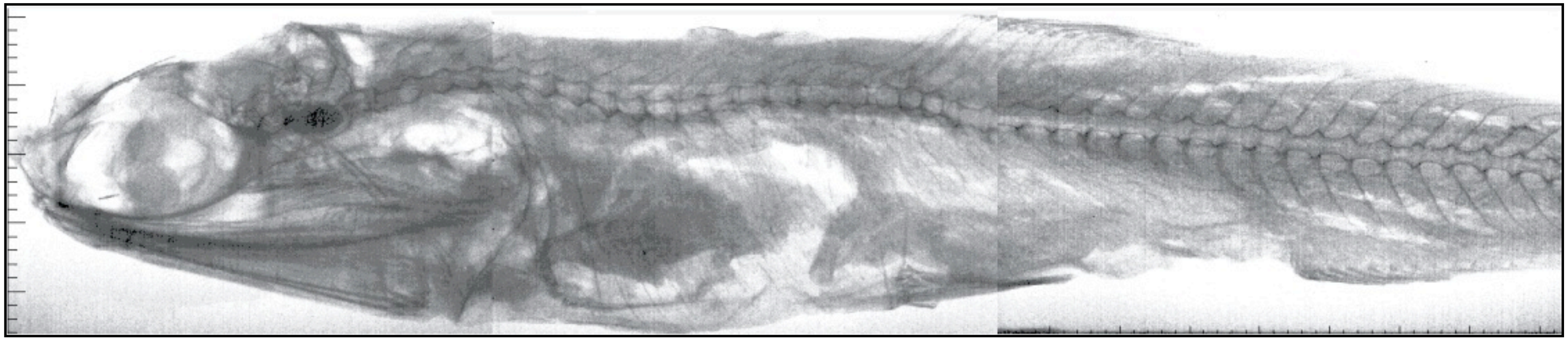
Buried P-Well(BPW) successfully solves back gate effect.





X-ray picture of a dry sardine

X-ray tube: Mo, 20kV, 5mA



Summary & Conclusions

- Detector Development is a fascinating and highly active field
- New detectors technologies offer new experimental opportunities
- Smaller experiments are quite often first system testers
- Role of micro-electronics is crucial
  - reduce costs of highly segmented systems
  - fast data links
  - fast timing in highly segmented systems
  - waveform sampling and digitization
  - flexible detector specific digital data manipulations (FPGA)
- Beam tests are vital to our community
- Detectors must be tested under equivalent conditions
- HL-LHC detectors need extensive high rate beam tests
- HL-LHC with many Pile-Up events will challenge calorimeter based physics analysis
- Tracker will bee crucial in this task → particle flow

→ **combined tracker-calorimeter design**

Thank you for your attention !