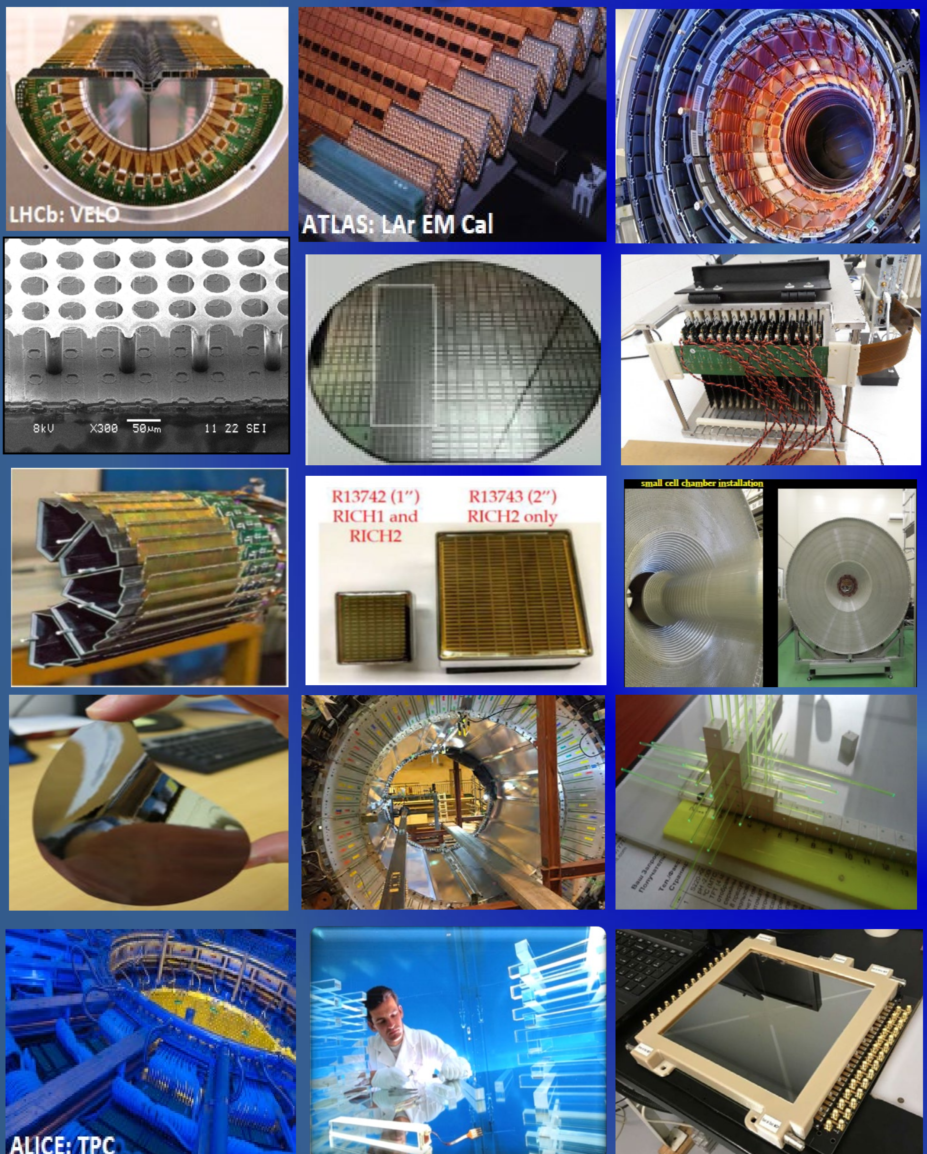
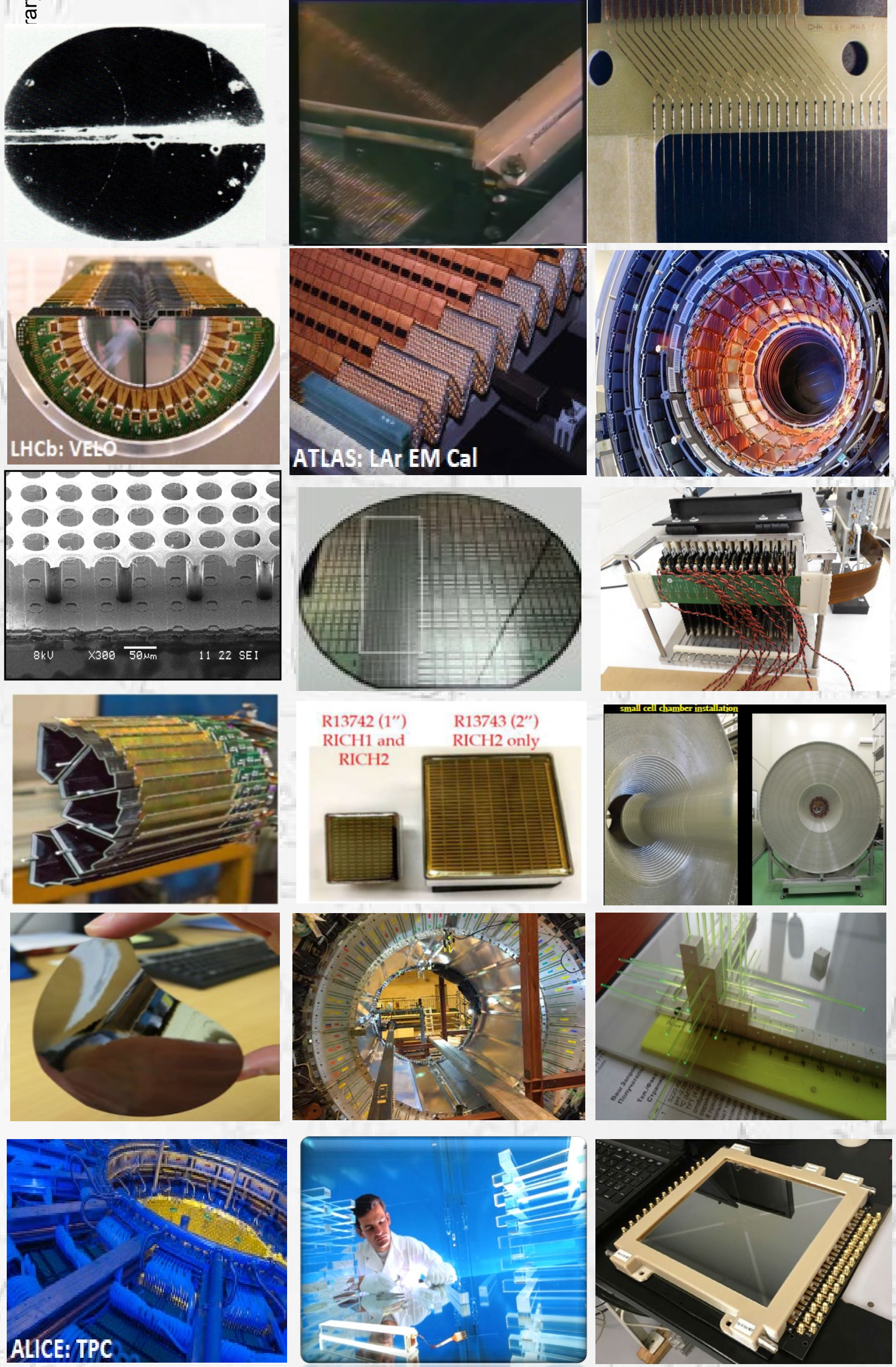
Particle Detectors Physics(III)

Maxim Titov,
CEA Saclay, Irfu, France



Asia-Europe-Pacific School of HEP (AEPSHEP2024), Nakhon Pathom, Thailand, Jun. 12 – 25, 2024



- Particle Interactions with Matter
- "Classic" Detectors (historical touch...)
- Advancing Concepts Tracking Detectors: Gaseous Detectors
- Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors
- Advancing Concepts in Picosecond-Timing Detectors
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing

Ultra Radiation Hard 3D Detectors: Concept

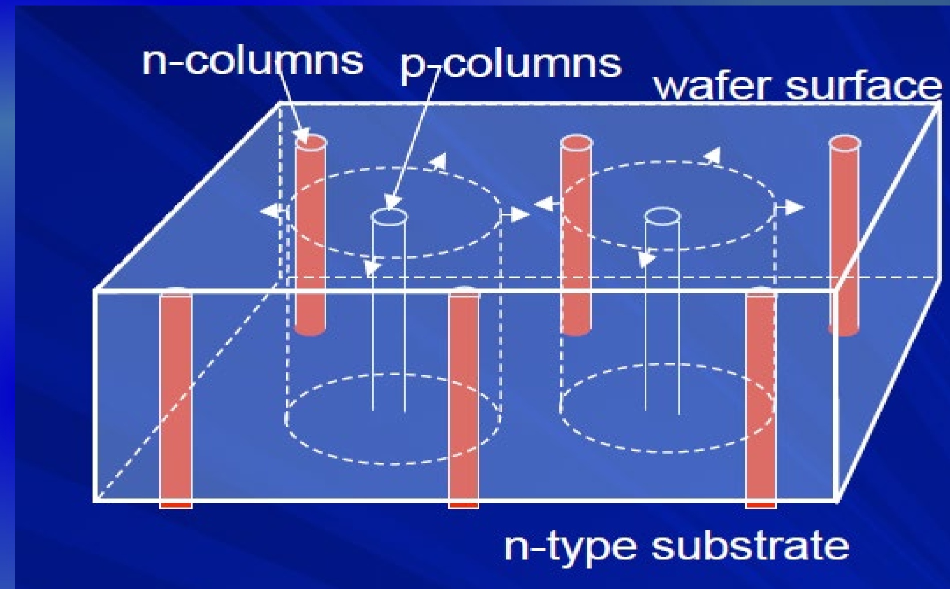
Maximum drift and depletion distance set by electrode spacing:

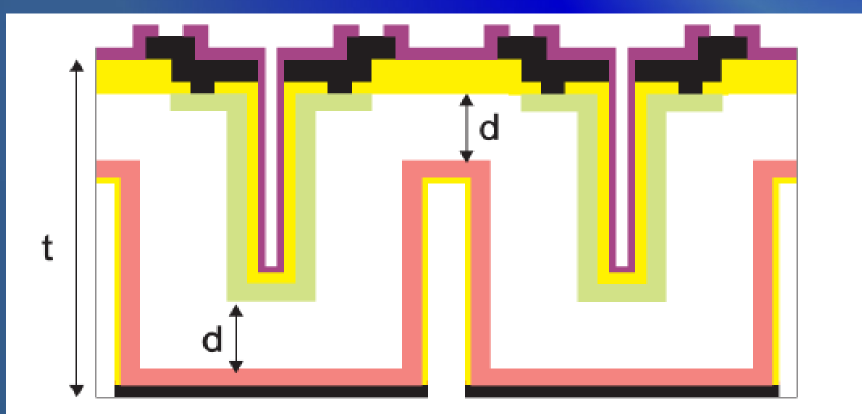
- *Lower depletion voltages*
- *Faster/more efficient charge collection*
- *Small leakage currents*
- *Very good performance at high fluences*
- *Narrow dead regions at the edges*

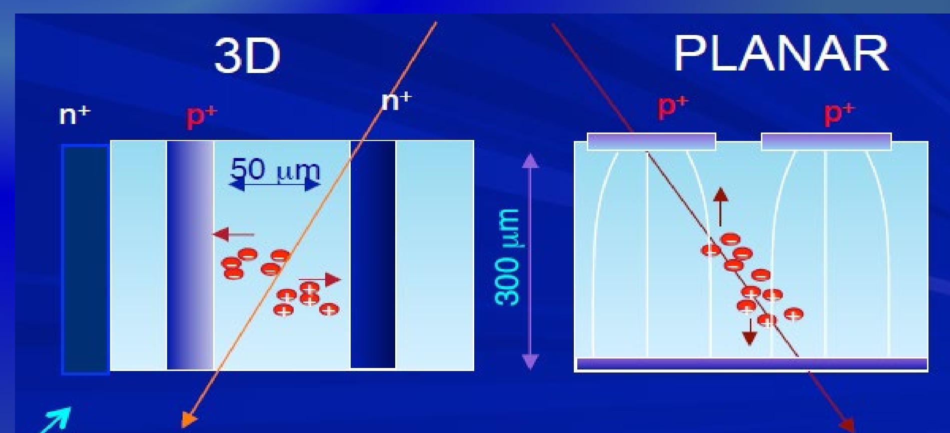
Production time and complexity for larger scale production

Used in ATLAS IBL

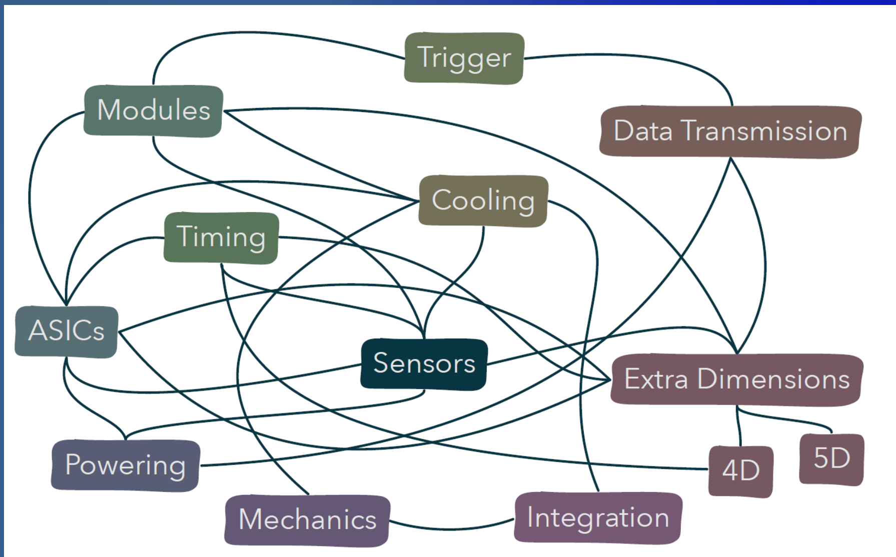
Both electrodes types are processed inside detector bulk
hole diameter: 10 mm; distance ~20-50 mm







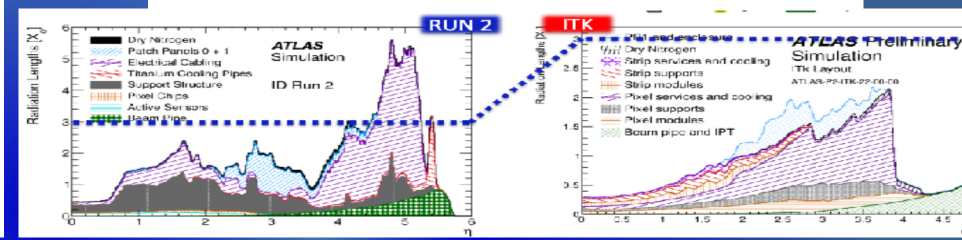
MORE than ASICs and Sensors, we have to take care of all aspects – Mechanics and Cooling, Powering Schemes, Optical Links, Integration …



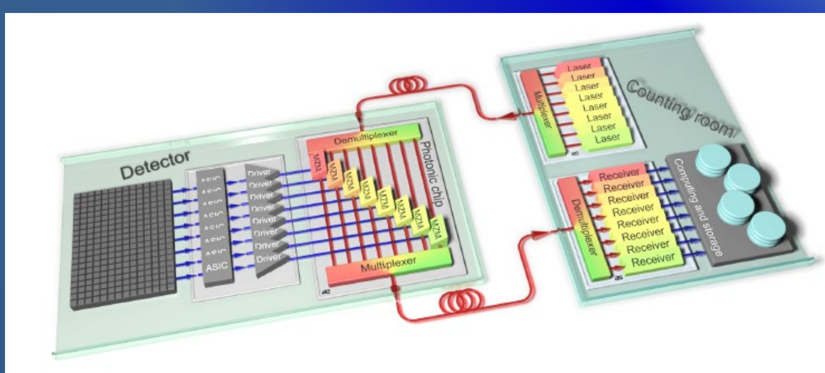
Keeping the radiation budget under control needs efforts in all areas:

- Advanced serial powering schemes
- Ultra-light structural materials and integration
- Heat management (CO_2 cooling) integrated in the detector design

Significant budget reduction for ATLAS ITK:



- ✓ Current link implementation based on vertical cavity surface emitting lasers (VCSEL)
- ✓ Higher bandwidth requirements could be addressed by silicon photonics and Wavelength Division Multiplexing (WDM)

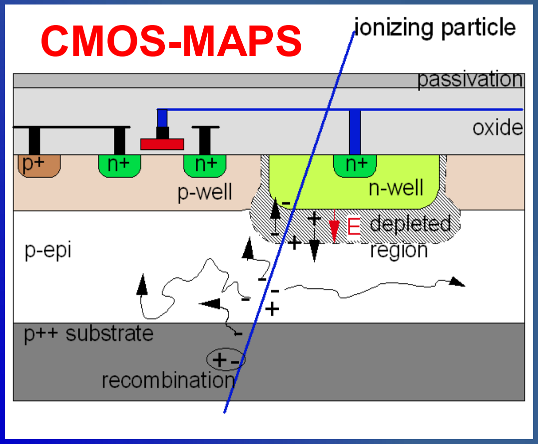


Experiment	Sub-detector	What	How	Where
CMS	Outer Tracker	Strip modules, LpGBT, VTRx+	DC-DC	Front-end
	Phase-1 pixel	Pixel modules	DC-DC	Patch panel
	Phase-2 pixel	LpGBT, VTRx+	DC-DC	Patch panel
		Pixel modules	Serial	
	Endcap calorimeter	Silicon modules, LpGBT, VTRx+	DC-DC	Patch panel or front-end
	Barrel calorimeter	Crystal ADC	DC-DC	Front-end
	Muon system (GEM)	Chambers	DC-DC	Front-end
	Timing detector	Readout, LpGBt, VTRx+	DC-DC	Front-end
ATLAS	Strips	Strip modules, LpGBT, VTRx	DC-DC	Front-end
	Phase-2 pixel	LpGBT, VTRx+	DC-DC	Patch panel
		Pixel modules	Serial	
	Tile calorimeter	Electronics	DC-DC	Patch panel
	Liquid argon calorimeter	Electronics	DC-DC	Front-end
	Muon micromegas	GBTx, VTRx	DC-DC	Front-end
LHCb	Velo	Pixel modules, GBTx	DC-DC	Patch panel
	Fiber tracker	Fiber modules, GBTx, FPGA	DC-DC	Front-end
ALICE	Pixels	Pixel modules	DC-DC	Front-end
Belle 2	SVD	Silicon modules	DC-DC	Patch panel

Emergence Of Monolithic Detectors: CMOS MAPS

Monolithic Active Pixel Sensors (MAPS):

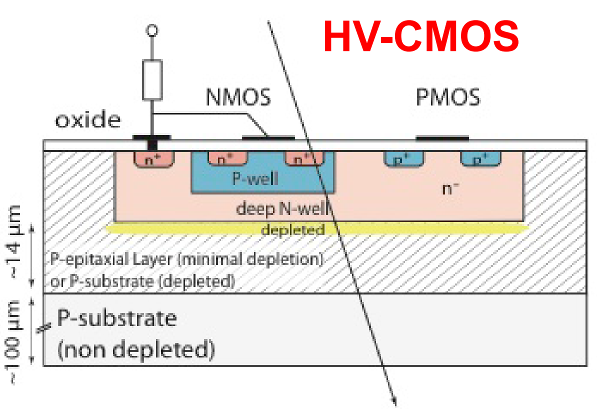
- *Commercial standard CMOS industrial process - low cost;*
- *Small pixels sizes ≃ 25 x 25 μm^2 ; thin sensors ~ 50 - 100 μm;*
- *Typical signal ~ 1000e on n-well contacts, low noise ~ 20e;*
- *Charge generation volume integrated into the ASIC*
  → no chip bump-bonding;
- *Charge collection mainly by diffusion → spread;*
  timing limited by rolling-shutter r/o (ms);



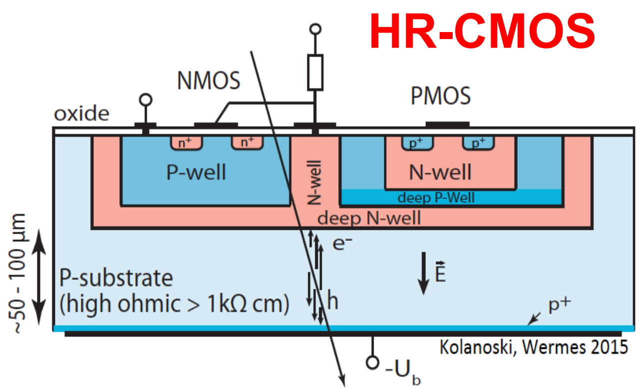
Charge generation volume is integrated into the ASIC

Monolithic Active Pixel Sensors (MAPS) with depletion

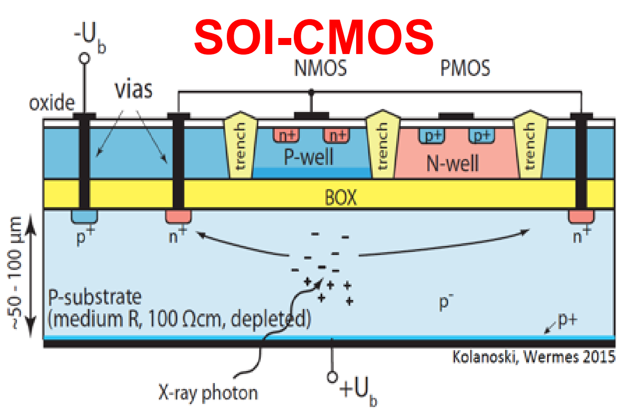
- *HV/HR-CMOS process electronics in deep n-well to allow bias for partial/full depletion or SOI process (vias through insulator to isolate bias from electronics)*



HV process, 10 - 15 um depletion region under deep N-well



HR process - can be fully depleted

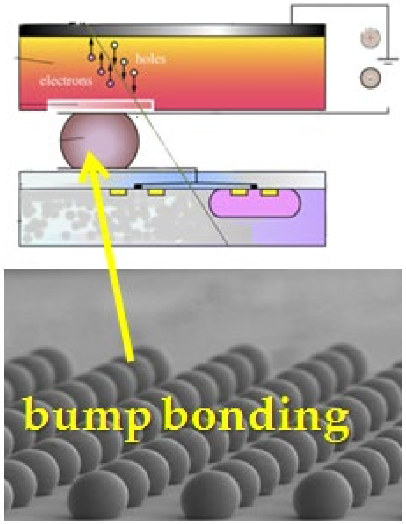


SOI process fully depleted or HV process

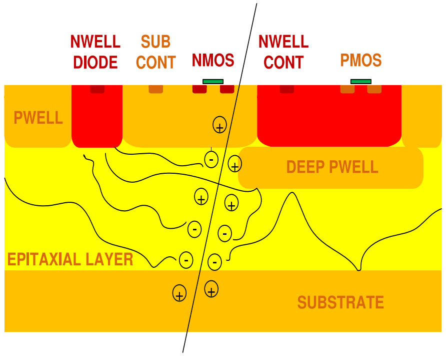
Solid State Tracking: Detector – Electronics Integration Trends

- ✓ *Radiation hardness improvements demand newer technologies*
- ✓ *Improved functionality can only be achieved with higher integration*
- ✓ *Power dissipation and material budget must be reduced*

TODAY: Pixels 50 – 100s μm

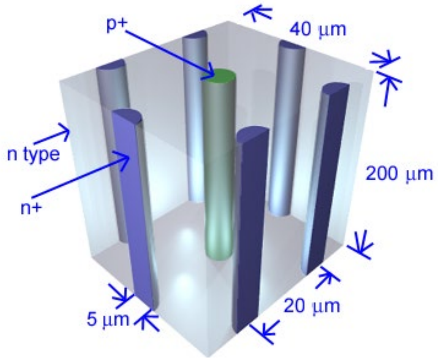


TODAY: Monolithic 25 – 50 μm



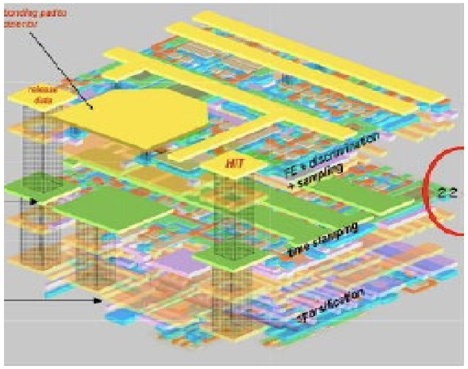
Integrated sensor & electronics: Less X0, no bonding, low noise

TODAY: 3D Detectors (25–50 μm)



Lower V_{dep} (power)
Faster charge collection

Day After Tomorrow: 3D TSV (< 20 μm)



3D vertical Integration (TSV)

Motivation to develop new Pixel Detectors:

- Decrease fabrication cost
- Develop thinner pixel systems
- Easy fabrication of large area devices
- Integrate More (= denser) Intelligence

Trends and Perspectives:

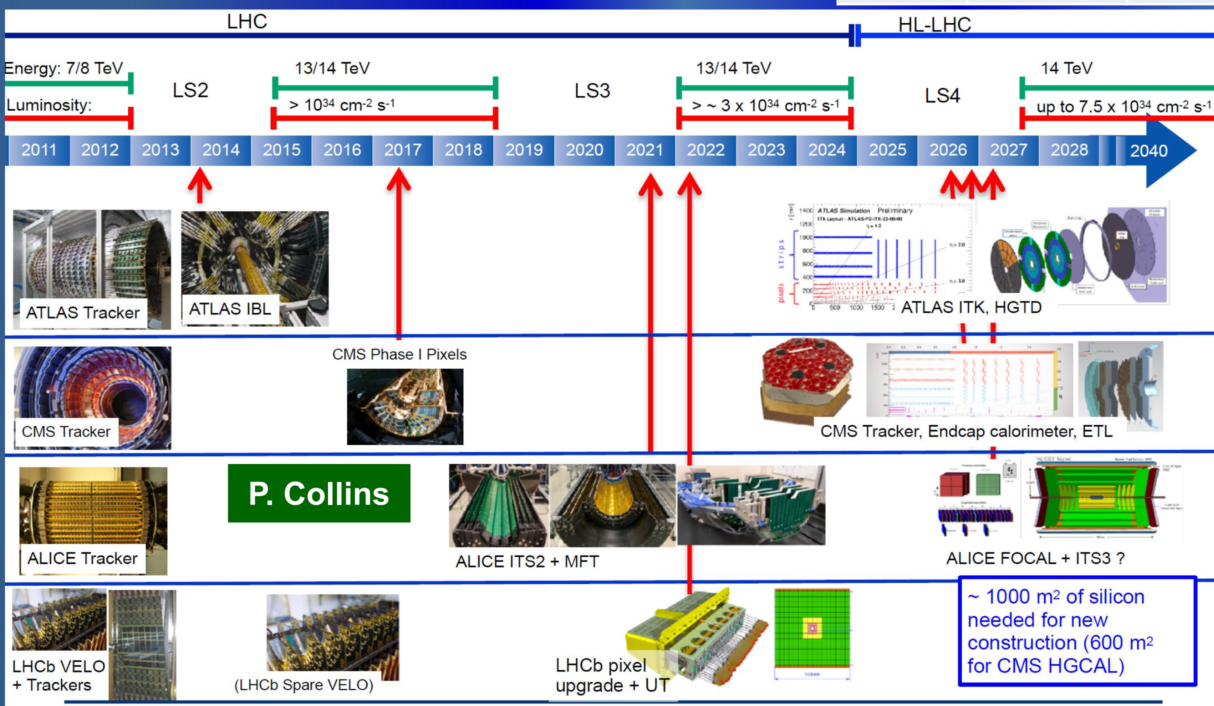
- Improve rad. hardness (p-type bulk)
- Reduce the thickness to 50 mm
- From 6” to 8” and 12” wafers
- R&D on SLID/TSV interconnect.

Silicon @ LHC: State-of-the-Art & Upgrades

Lots of common developments for ATLAS, CMS Pixel Upgrades @ HL-LHC (2026):

- ✓ Pixel chips based on common 65 nm CMOS RD53 development
- ✓ Planar n-in-p sensors → cost-effective single sided processing
- ✓ 3D sensors for innermost layers;
- ✓ Option of MAPS for outer pixel layer (ATLAS)
- ✓ CO_2 cooling, Serial powering , LpGBT

Exp. / Timescale	Application Domain	Tech.	Detector size / Module size / Channel count	Radiation Environment	Special Req. / Remarks
ATLAS ITK Upgrade CERN LS3	Hadron Collider (Vertex / Tracking)	Si hybrid pixels (n-in-p), 3D innermost, Si-Strips	**Total area:** pixel – 12.7 m^2 ; strips - 165 m^2 **Single unit:** pixel- 50x50 (25x100) μm^2 strip len./pitch: ~24 – 80 mm / ~70 μm **Channels count :** pixels – 5 G ; strips – 60 M	**Fluences up to 2×10^{16} n_{eq}/cm^2**	Option for outermost pixel layer: MAPS RD53 ASIC 65 nm CMOS
CMS Tracker Upgrade CERN LS3	Hadron Collider (Vertex / Tracking)	Si hybrid pixels (n-in-p), 3D innermost, Si-Strips	**Total area:** pixel - 4.9 m^2 ; strips - 200 m^2 **Single unit:** pixel- 25x100 (50x50) μm^2 strip len./pitch: 50-24-1.5 mm /~100 μm **Channels count :** pixels – 3 G ; strips – 175 M	**Fluences up to 2.3×10^{16} n_{eq}/cm^2**	Special p_T-modules in outer strip layers RD53 ASIC 65 nm CMOS
ALICE ITS Upgrade CERN LS2	Heavy Ion Physics (Tracking)	CMOS MAPS, 7 barrel layers	**Total area:** 10 m^2 ; **Single unit:** pixel size 30x30 μm^2 **Channels count :** 12.5 G	**Fluences up to 1.7×10^{13} n_{eq}/cm^2**	0.3% X_0 per layer (inner barrel) ASIC: 180 nm TowerJazz
LHCb VELO Upgrade CERN LS2	Hadron Collider (B Physics)	Si hybrid pixels (n-in-p)	**Total area:** 0.12 m^2 ; **Single unit:** pixel size 55x55 μm^2 **Channels count :** 41 M	**Fluences up to 8×10^{15} n_{eq}/cm^2**	130 nm CMOS, 40 MHz VELOPIX readout, rates up to 20 Gb/s
LHCb Upstream Tracker Upg. CERN LS2	Hadron Collider (B Physics)	Si strips (n-in-p & p-in-n)	**Total area:** 9 m^2 ; **Single unit:** strip length/pitch: 50 -100 mm / 100 – 200 μm^2 **Channels count :** ~ 500k	**Fluences up to 5×10^{14} n_{eq}/cm^2**	
BELLE II PXD / SVD	e+e- Collider (B Physics)	DEPFET / Si-strips (p-in-n)	**Total area:** 0;03 m^2 / 1.2 m^2 ; **PXD unit:** pixel size ~50x50 μm^2 **SVD unit: strip-** 120 mm / 50–240 μm^2 **Channels count :** 7.7 M / 245 k	**Fluences up to 10^{13} n_{eq}/cm^2**	0.15 X_0 per layer



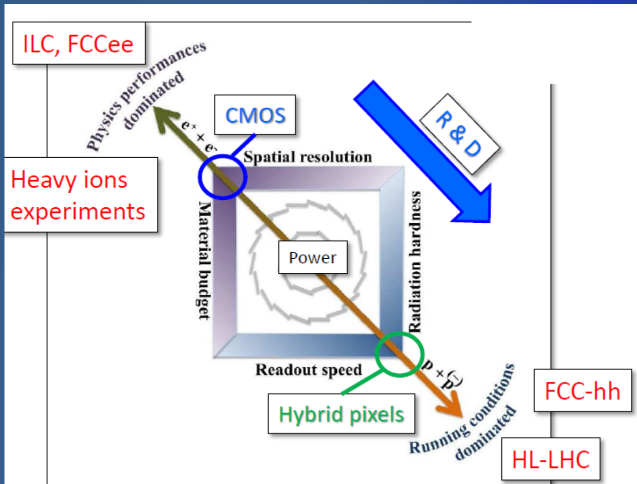
Pixel Systems will enlarge dramatically:

- Surface: ATLAS by factor of ~15
- Channel count : ALICE will reach 12.5 billion pixels with CMOS MAPS
- Cell size: LHCb by ~1000 (strips → pixels)

✓ The Si-strip sensors will consist of (n-in-p) and replace (p-in-n) → radiation hardness consideration,

✓ 3D sensors develop. (FBK, CNM) has been focused on ATLAS-IBL pixels plus several joint MPW production runs with CMS / LHCb.

Vertex and Tracking Systems: State-of-the-Art



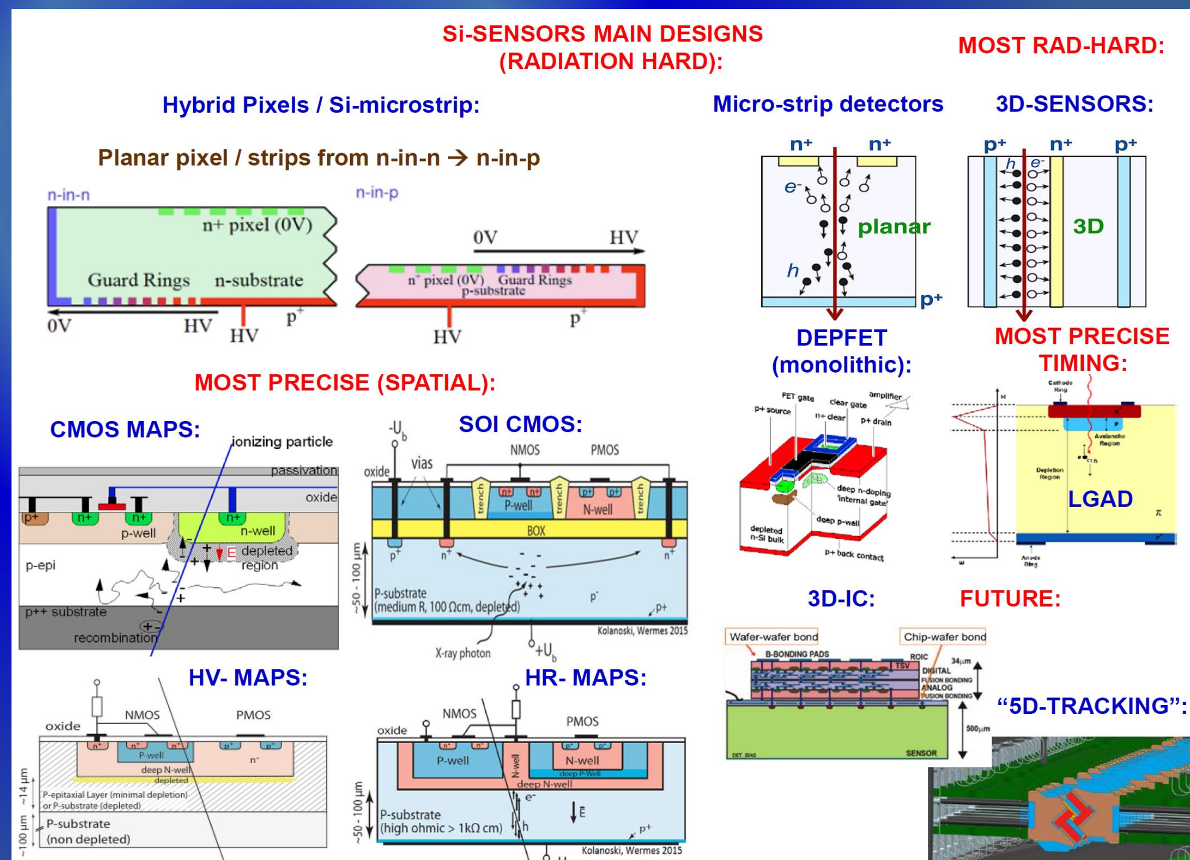
- ✓ Basic applications are optimized for two different realms of interest : electron and hadron colliders → different optimizations/requirements (pp: radiation hardness, speed; e+e-: granularity, material budget)
- ✓ Design problems include: granularity vs the power (particularly for precision timing) and the inactive material to service power and data readout etc. for both accelerator types. Radiation hardness and a strong emphasis on data reduction / feature extraction for the on-detector electronics are particular issues for hadron colliders.

Hadron Colliders:

- ✓ Hybrid pixel detectors (planar & 3D)
- ✓ HV/HR-CMOS for outer pixel layers for HL-LHC upgrades;
- ✓ LGADs for ps-timing

Lepton Colliders:

- ✓ CMOS (STAR HFT, ALICE ITS)
- ✓ DEPFET (Belle II)
- ✓ Chronopix
- ✓ SoI
- ✓ FPCCD
- ✓ 3D-IC (Global Foundries, LAPIX, TJas,…industries)



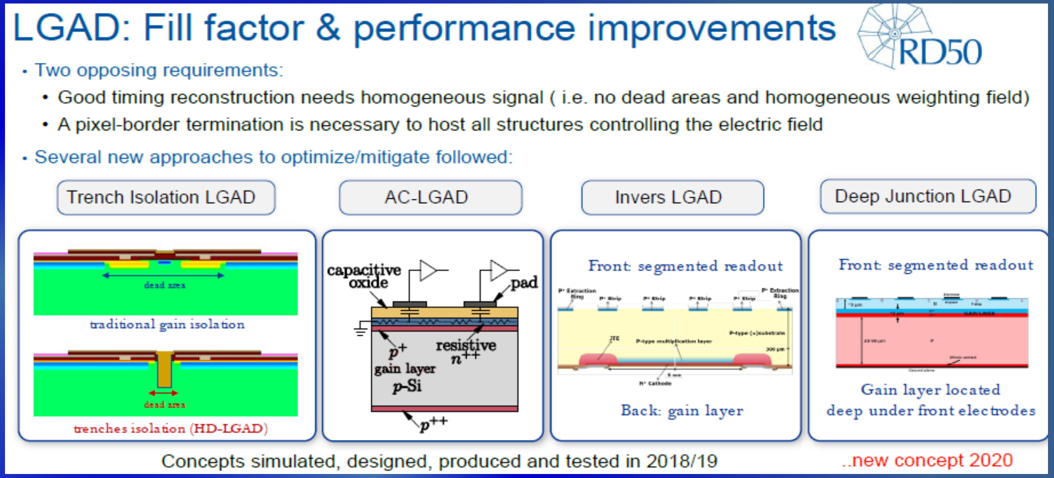
RD50 Collaboration: Radiation Hard Semiconductor Devices

Sensors for 4D Tracking: Development of Radiation Hard Timing Detectors (LGAD)

Incredible success story → pioneered by RD50 and CNM since 2010 (> 50 production runs)

Areas of LGAD developments within RD50:

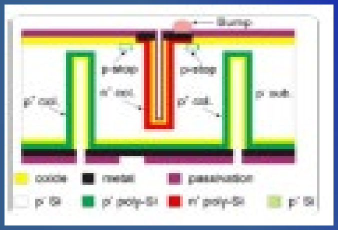
- Timing performance (~ 25 ps for 50 um sensors)
- Fill factor and signal homogeneity
- Radiation Hardness (~$2x10^{15}$ n_{eq}/cm^2)
- Performance Parameterisation Model

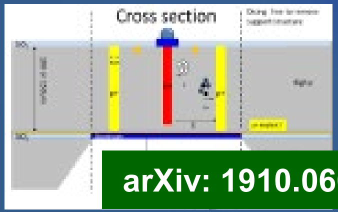


One of the biggest riddles remains the understanding of the radiation damage microscopic mechanisms that lead to the degradation of the gain layer in the LGAD devices.

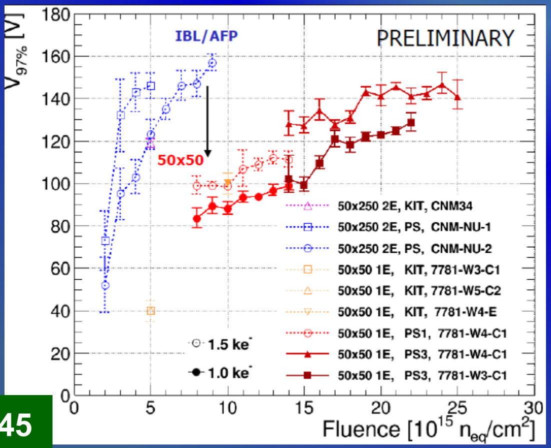
Optimization of 3D sensors for HL-LHC Upgrades:

Good efficiency even up to ~ $3x10^{16}$ n_{eq}/cm^2 & time resolution: 30 ps at V_{bias} > 100V and T = -20C

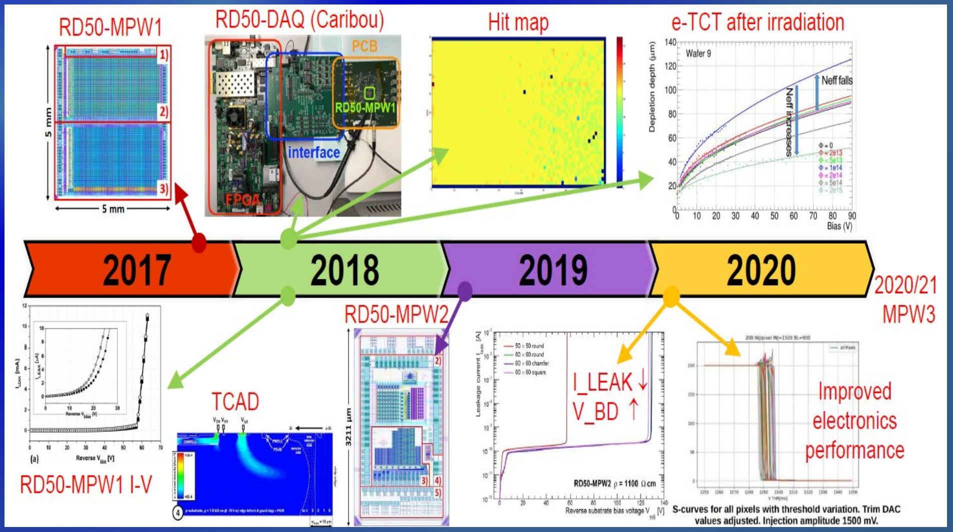




arXiv: 1910.06045



Development of Radiation-Hard (HV-CMOS) sensors:

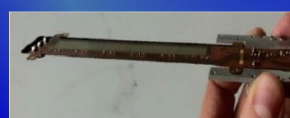


Monolithic Sensors (MAPS): State-of-the-Art

CMOS MAPS for charged particle tracking was initiated for ILC in 1998

	ULTIMATE STAR-PXL	ALPIDE ALICE-ITS	MIMOSIS CBM-MVD	PSIRA proposal ILD-VXD
Data taking	2014-2016	>2021-2022	>2021	>2030
Technology	AMS-opto 0.35 μm	**0.18 μm**	0.18 μm	0.18 μm (conservative) < 0.18 μm ?
	4M	HR, V_{bias} ~-6V Deep P-well	HR, Deep P-well	?
Architecture	Rolling shutter + sparsification + binary output	**Asynchronous r.o. In pixel discri.**	Asynchronous r.o. In pixel discri.	Asynchronous r.o. (conservative)
Pitch (μm^2) / Sp. Res.	20.7 x 20.7 / 3.7	27 x 29 / 5	22 x 33 / <5	~ 22 / ~ 4
Time resolution (μs)	~185	**5-10**	5	**1 – 4**
Data Flow		~10^6 part/cm²/s Peak data rate ~ 0.9 Gbits/s	peak hit rate @ 7 x 10^5 /mm²/s **>2 Gbits/s output (20 inside chip)**	~375 Gbits/s (instantaneous) ~1166Mbits / s (average)
Radiation	O(50 kRad)/year	$2x10^{12}$ n_{eq}/cm² 300 kRad	$3x10^{13}$ n_{eq}/cm²/yr & 3 MRad/yr	O(100 kRad)/year & O($1x10^{11}$ n_{eq}(1MeV)) /yr
Power (mW/cm²)	< 150 mW/cm²	**< 35 mW/cm²**	< 200 mW/cm²	~ 50-100 mW/cm² + Power Pulsing
Surface	2 layers, 400 sensors, $360x10^6$ pixels 0.15 m²	7 layers, $25x10^3$ sensors **> 10 m²**	4 stations Fixed target	3 double layers 10^3 sensors (4cm²) 10^9 pixels ~0.33 m²
Mat. Budget	~ 0.39 % X_0 (1st layer)	~ 0.3% X_0 / layer		~ 0.15-0.2 % X_0 / layer
Remarks	1st CPS in colliding exp.	(with CERN)	Vacuum operation Elastic buffer	Evolving requirements

MIMOSA @ EUDET BT Telescope
→ 3 um track resolution achieved

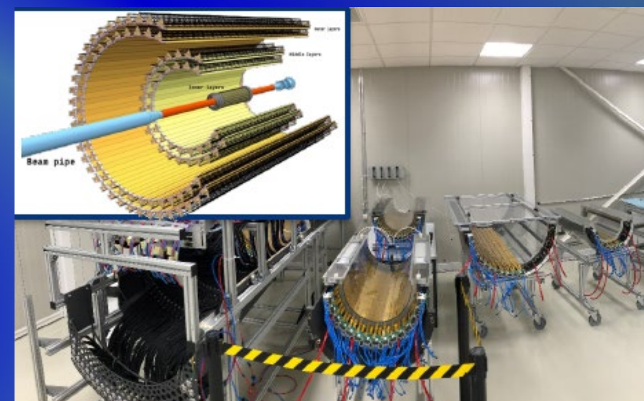


STAR Heavy Flavour Tracker (2014):

Ladder with 10 MAPS sensors (~2x2 cm each) mounted on carbon fiber sectors: 356M pixels on ~0.16 m²(Si);
50 um thin sensors;
20 to 90 kRad/year

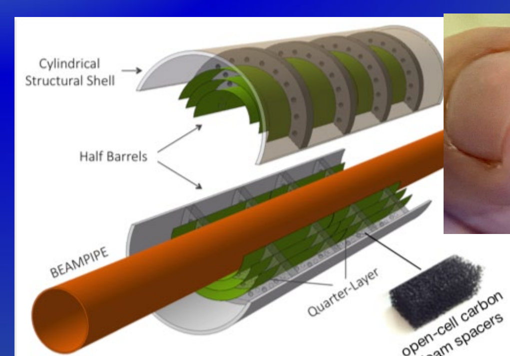
CMOS MAPS for ALICE ITS2 (Run 3):

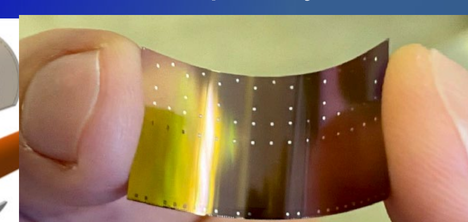
- TowerJazz 180 nm technology; on-chip digital readout architecture → rad-hard to >TID 2.7 Mrad
- 7 layers of MAPS ≃ 10 m² with 12.5 Gpix
- High resistivity eps layer → rad hard to TID 2.7 Mrad;



CMOS MAPS for ALICE ITS3 (Run 4):
(LOI: CERN-LHCC-2019-018)

- ✓ Three fully cylindrical, wafer-sized layers based on curved ultra-thin sensors (20-40 μm), air flow cooling
- ✓ Almost massless (IB), < 0.02-0.04% per layer





Beyond ALICE ITS3
→exploit stiching

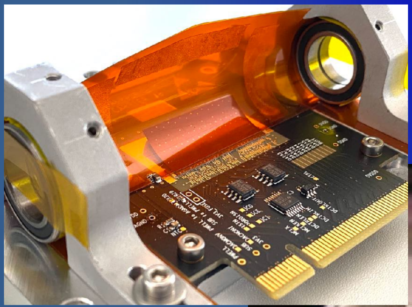
Vertex Technologies for Future Linear Colliders (ILC)

- **Sensor's contribution to the total X_0 is 15-30% (majority cables + cooling + support)**
- **Readout strategies exploiting the ILC low duty cycle 0(10^{-3}): triggerless readout, power-pulsing**
  - → continuous during the train with power cycling → mechanic. stress from Lorentz forces in B-field
  - → delayed after the train → either ~5µm pitch for occupancy or in-pixel time-stamping

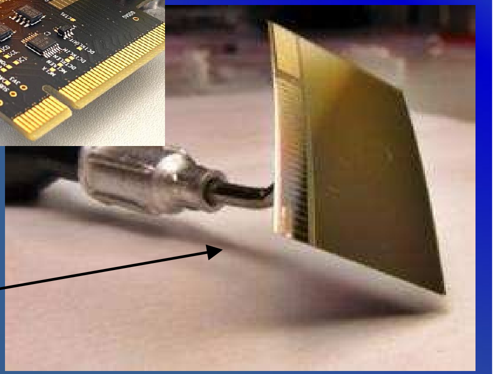
Physics driven requirements	Running constraints	Sensor specifications	
$\sigma_{s.p.}$ 2.8um		Small pixel	~16 µm
Material budget 0.15% X_0/layer		Thinning to	50 µm
	Air cooling	low power	50 mW/cm²
r of Inner most layer 16mm	beam-related background	fast readout	~1 µs
	radiation damage	radiation tolerance	≤3.4 Mrad/ year ≤$6.2\times10^{12} n_{eq}$/ (cm² year)

Technology	FPCCD	DEPFET	SOI	CMOS	iLGAD
Added value (example)	Very granular	Low material budget	2 tier process (high density µcircuits)	Industry evolution	PID

180 nm CMOS technology: VALIDATED

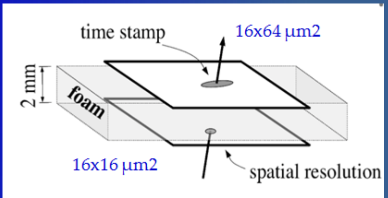


ALPIDE@ ALICE ITS-3 (bending 50 um sensor)



MIMOSIS @ CBM-MVD

CMOS (MAPS): 2-sided ladders: « mini-vectors » concept for ILC with high spatial resolution & time stamping



ALICE-ITS3 upgrade drives the R&D:

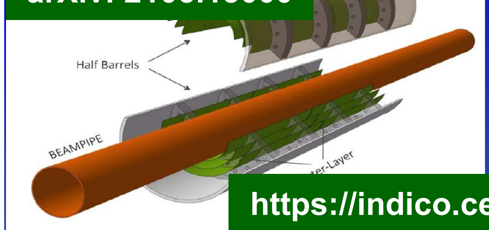
Bending thin Si-layers (MAPS):

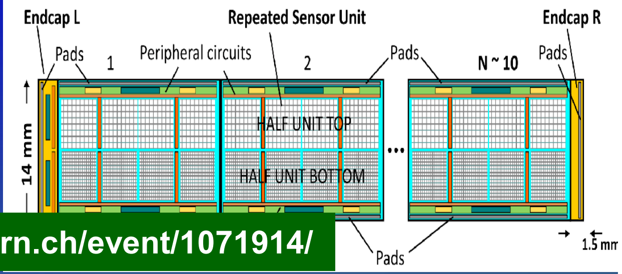
Truly cylindrical, supportless CPS for ALICE-ITS3 upgrade (65 nm)

Industrial stitching & large surfaces for low-mass detect.:

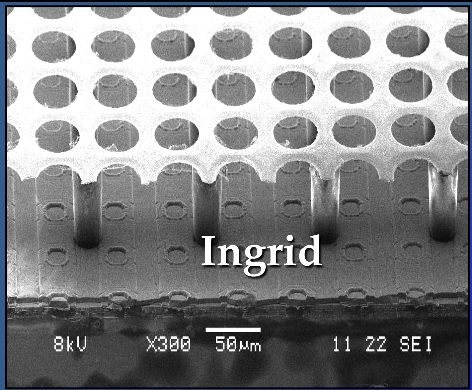
using several reticles from the same wafer (possible with both 180 and 65 nm)

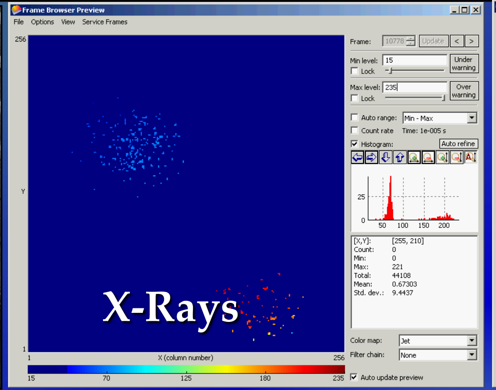
arXiv: 2105.13000

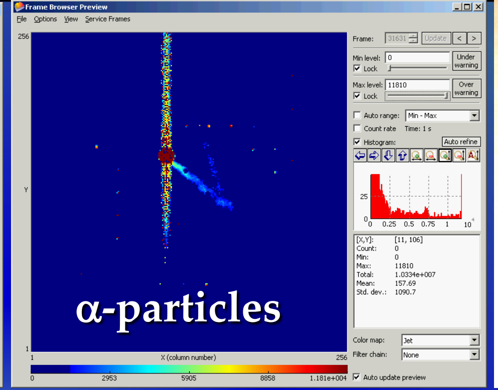


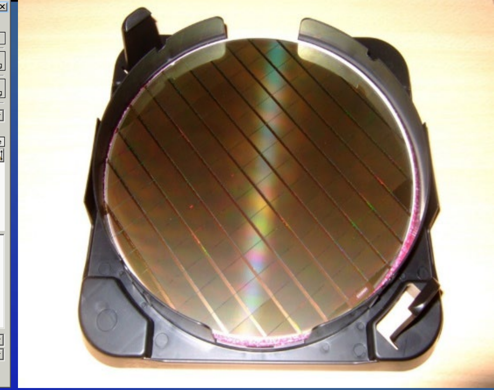


https://indico.cern.ch/event/1071914/

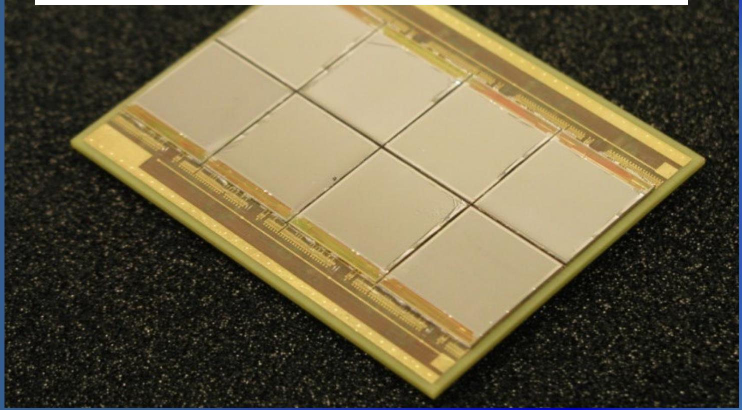






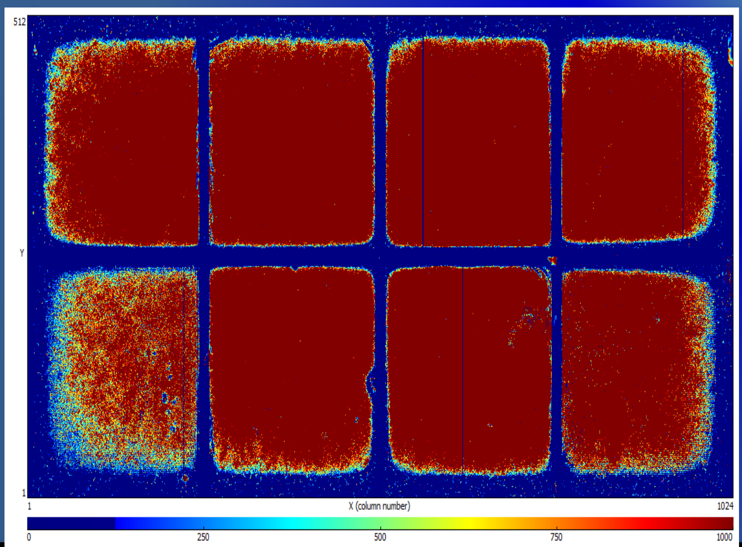


“Octopuce” (8 Timepix ASICs):

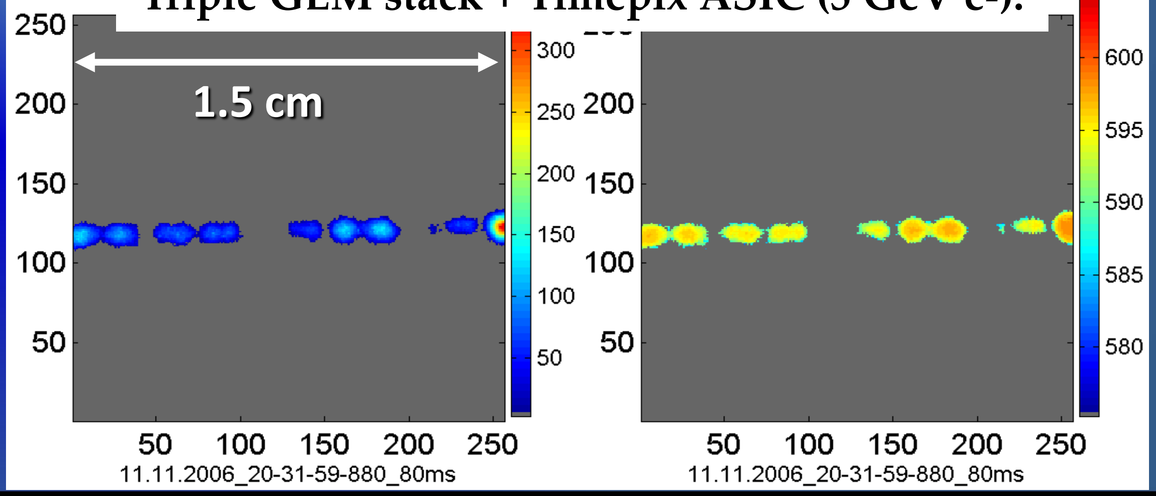


ULTIMATE « MARRIAGE » OF GASEOUS and SIICON DETECTORS –

PIXEL READOUT of MICRO-PATTERN GASEOUS DETECTORS



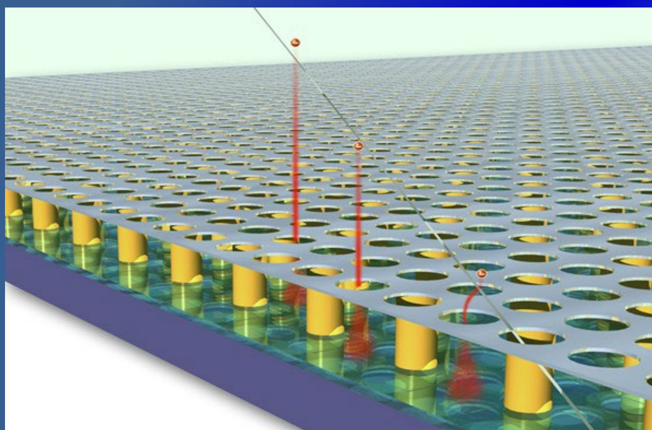
Triple GEM stack + Timepix ASIC (5 GeV e-):

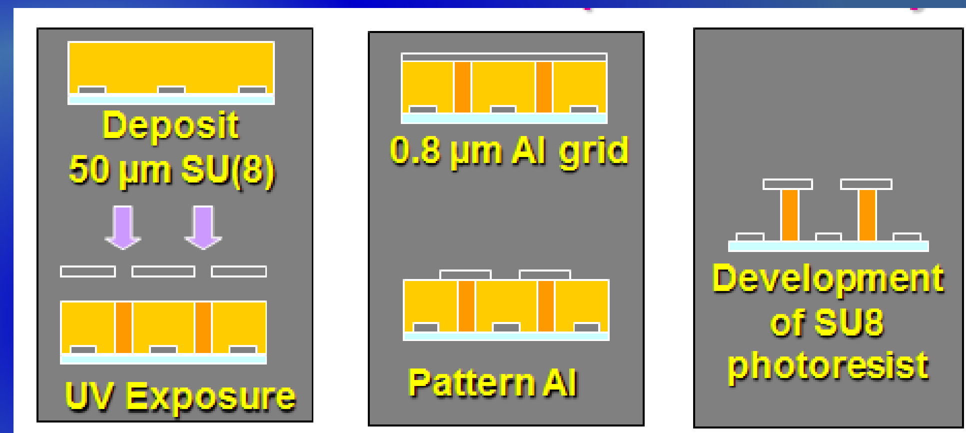


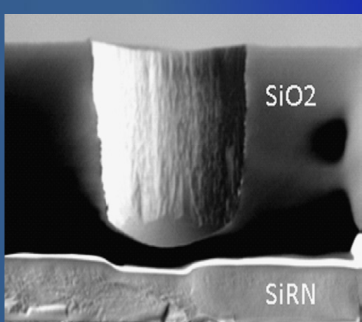
Pixel Readout of MPGDs: "GridPix" Concept

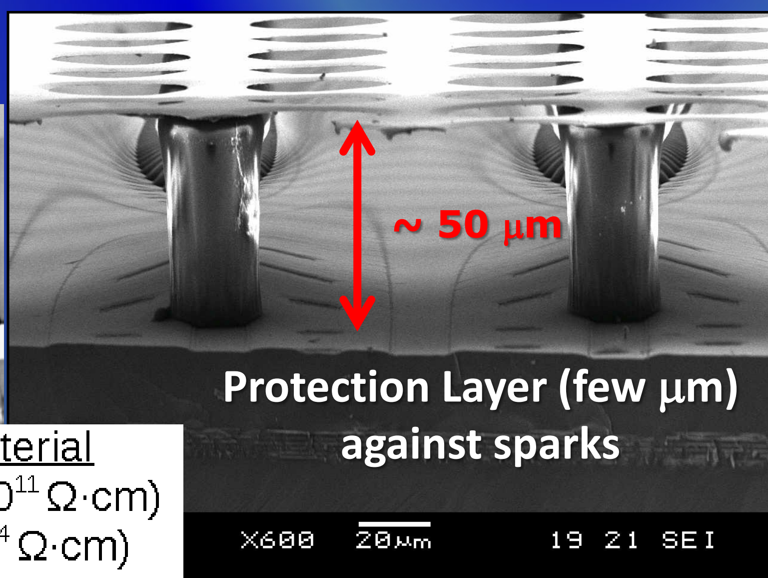
"InGrid" Concept: By means of advanced wafer processing-technology INTEGRATE MICROMEGAS amplification grid directly on top of CMOS ("Timepix") ASIC

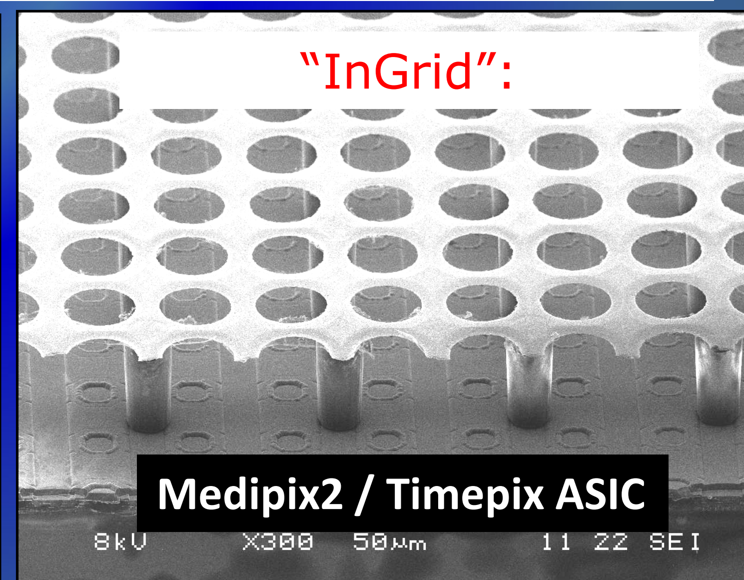
3D Gaseous Pixel Detector → 2D (pixel dimensions) x 1D (drift time)











high resistive material

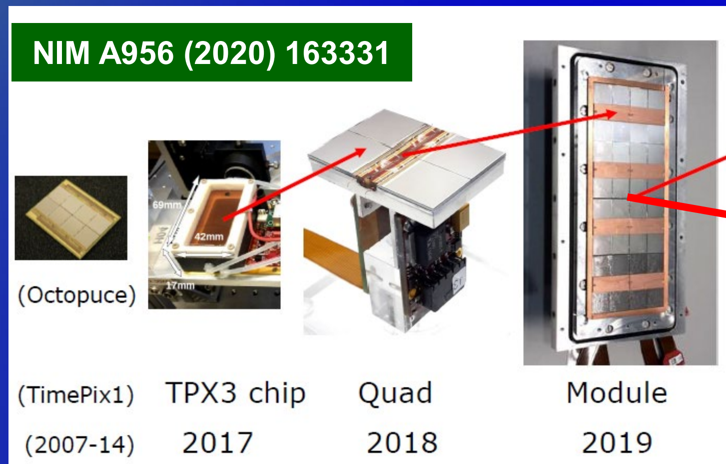
15 μm aSi:H (~10^{11} Ω·cm)

8 μm Si_XN_Y (~10^{14} Ω·cm)

Towards Large-Scale Pixel "GridPix" TPC

Testbeams with GridPixes:
160 GridPixes (Timepix) & 32 GridPixes (Timepix3)

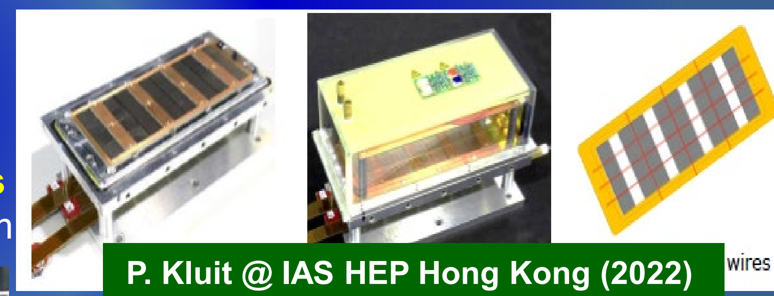
A PIXEL TPC IS REALISTIC!

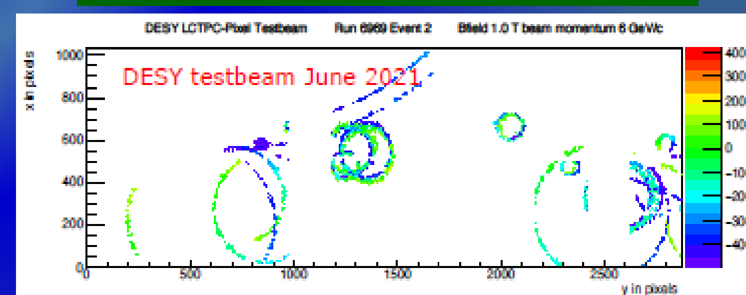


Physics properties of pixel TPC:

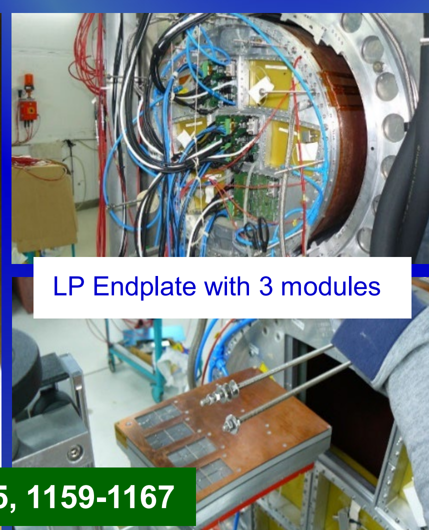
- Improved dE/dx by cluster counting
- Improved meas.of low angle tracks
- Excellent double track seperation
- Lower occupancy @ high rates
- Fully digital read out (TOT)

Quad board (Timepix3) as a building block
→ 8-quad detector (32 GridpPixs) with a field cage at test-beam @DESY in June 2021:

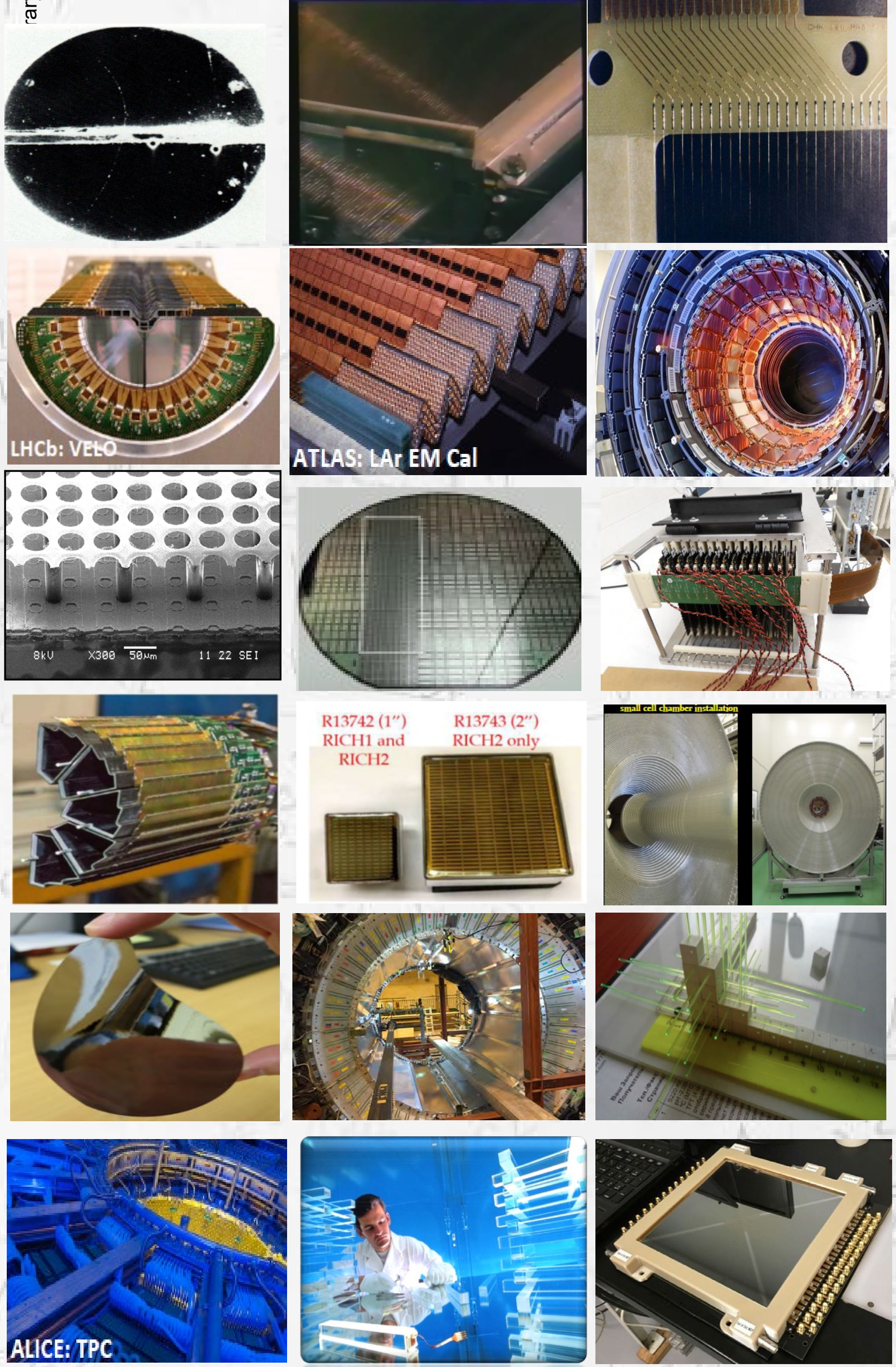




3 modules for LP TPC @ DESY: 160 (1 x 96 & 2 x 32) GridPixs
320 cm² active area, 10,5 M. channels, new SRS Readout system



- ✓ ion back flow can be further reduced by applying a double grid.
- ✓ Protection layer resistivity to be reduced
- ✓ New Timepix4 developments



- Particle Interactions with Matter
- "Classic" Detectors (historical touch...)
- Advancing Concepts Tracking Detectors: Gaseous Detectors
- Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors
- Advancing Concepts in Picosecond-Timing Detectors
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing

Advanced Concepts in PARTICLE IDENTIFICATION (PID)

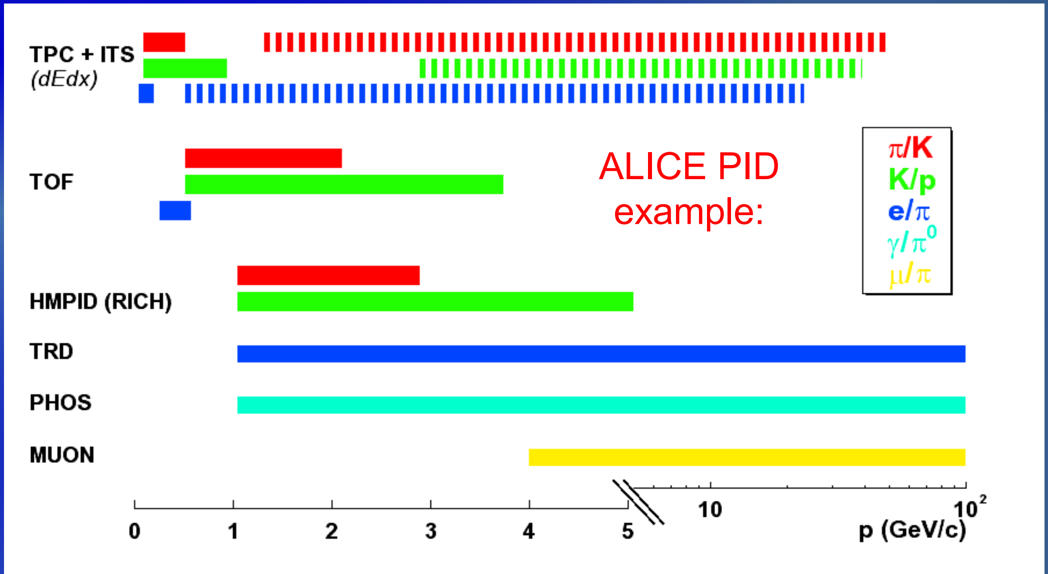
Essential to identify decays when heavy flavour are present: everywhere

Three legs: dE/dx, Time-of-Flight, Cherenkov radiation

Admirable workmanship in radiators and light transport:

- ✓ **Vacuum Photon Detectors**
  - – PMT, MaPMT, MCP - PMT
  - – Hybrid Tubes (APD, HAPD)
  - - LAPPD
- ✓ **Solid State Photon Detectors**
  - – Silicon-based (VLPC, CCD, SiPM)
- ✓ **Gas-based Photon Detectors**
  - - Photosensitive (TMAE/TEA in gas)
  - - MWPC / MPGD + CsI
- ✓ **Superconducting Photon Detectors**
  - – Transition Edge Detectors
  - – Kinetic Inductance detectors
  - - Quantum dots, carbon nanotubes

Excellent PID capabilities by combining different techniques over a large momentum range



- ➢ Threshold Cherenkov Counters – photon counting (Aerogel + PMT)
- ➢ RICH Detectors (particle momentum and velocity → Cherenkov angle and/or yield):
  - - TOP principle: 1-time of propagation + Cherenkov angle (instead of 2D imaging)
  - - RICH + TOF: Measure timing of Cherenkov light
  - - ALICE MRPC: Gaseous timing
  - - TRD: Cluster Counting method (dN/dx)

Imaging Cherenkov Detectors

$$\cos\theta = \frac{1}{\beta n}$$

$$m = \frac{p}{\beta\gamma}$$

$$\Rightarrow \quad m = \frac{p}{\beta\gamma} = p\sqrt{n^2\cos^2\theta_c - 1}$$

$$\frac{\Delta m}{m} = \sqrt{\left(\frac{\Delta p}{p}\right)^2 + \left(\gamma^2 \cdot tg\theta \cdot \Delta\theta\right)^2}$$

$$\sigma_\theta^2 = \sum_i \Delta\theta_i^2 \Rightarrow \sigma_{\theta_c} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$

➔ minimize s_q
➔ maximize $N_{p.e.}$

⇒ **low chromaticity**
high granularity
high packing density

⇒ **Goal**: detect the maximum **number of photons** with the best **angular resolution**

Separation power :

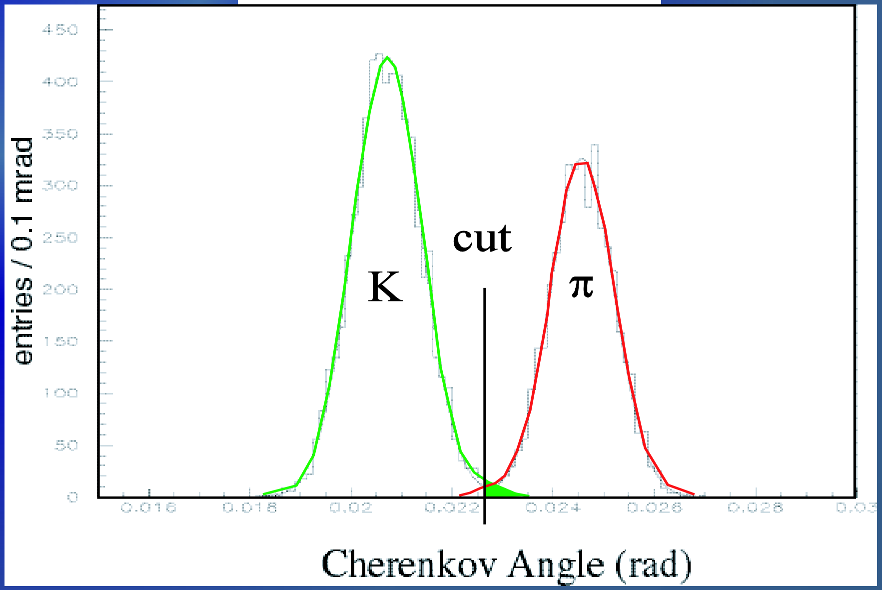
$$\theta_2 - \theta_1 = n\sigma_{\theta_c}$$

- Separating two particle types using the signal from a RICH detector is illustrated for K and π from a test beam

~ Gaussian response, $\sigma_\theta \sim 0.7$ mrad
Peaks are separated by 4 mrad = 6 σ_θ

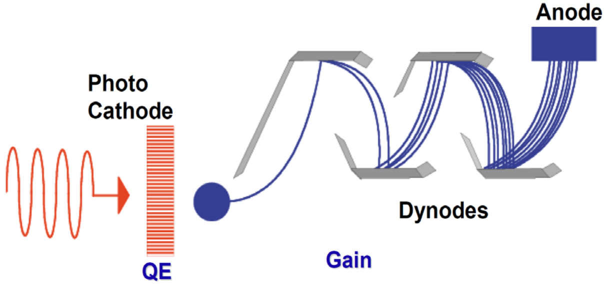
Generally: $N_\sigma = \dfrac{|m_1^2 - m_2^2|}{2\, p^2\, \sigma_\theta \sqrt{n^2-1}}$

- Adjusting the position of the cut placed between the two peaks to identify a ring as belonging to a K or p gives a trade-off between *efficiency* and *misidentification*

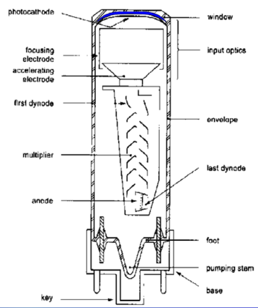


Several Key Photon Detector Technologies

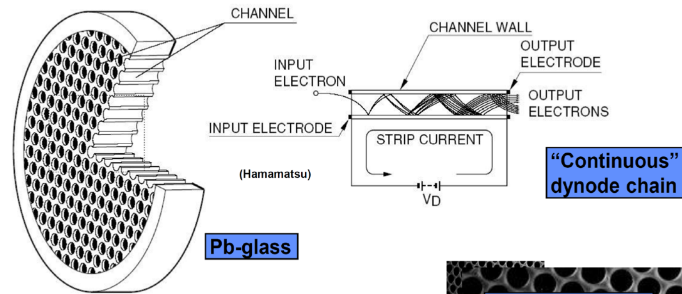
Vacuum photon detectors: Photo Multiplier Tube



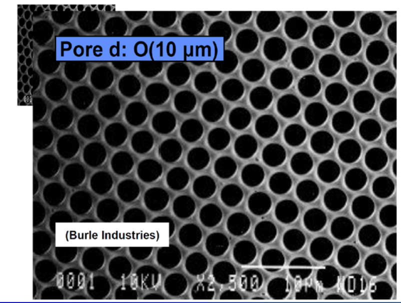
- Photon-to-Electron Converting Photo-Cathode
- Dynodes with secondary electron emission
- Typical gain ~10^6.
  Transient time spread ~200 ps
- Sensitive to magnetic field
- Choice of Photo-Cathode: high QE *for the wavelength of incoming light*
- Concerns: dynamic range, time dependence of response, rate capability



Vacuum photon detectors: Micro Channel Plate



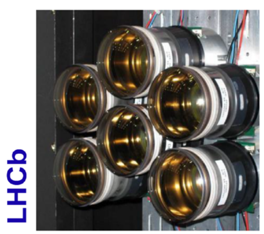
- **Gain fluctuations** can be minimized by operating in the saturation mode
- Kind of **2D PMT**:
  + high gain up to 5 x 10^4;
  + fast signal (transit time spread ~20 ps);
  + less sensitive to B-field (0.1 T);
  - limited lifetime (0.5 C/cm^2);
  - limited rate capability (mA/cm^2)

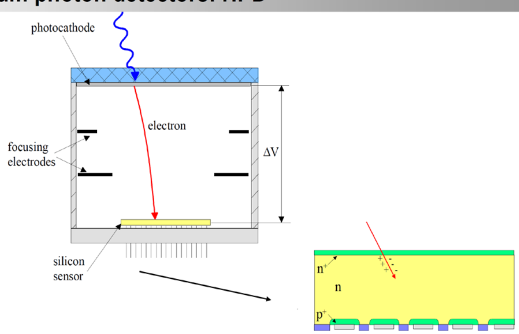


Vacuum photon detectors: HPD

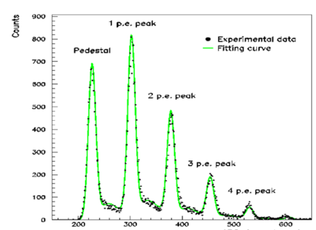
Photo Multiplier Tube
- dynodes and anode
+ silicon sensor

Hybrid Photo Detector





- It takes 3.6 eV to create an electron-hole pair in silicon. Using an accelerating voltage 20 kV → **~ 5000 electron-hole pairs, amplification in 1 step** → Good energy resolution
- But : High voltage, ion feedback → requires good vacuum



Solid-state photon detectors

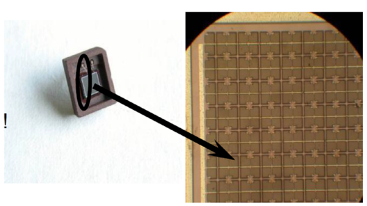
- **More compact, lightweight, tolerant to MF, cheaper, allow fine pixelization, ...**

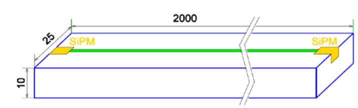
E.g.: **Silicium Photon Multiplier (SiPM)**

- Fully solid state photon detector, large array of tiny avalanche photodiods
- p-n junction under large reverse-bias voltage, packed over a small area and operated in a limited Geiger mode above breakdown voltage → detectable electrical response from low-intensity optical signals, down to single photons
- Binary output, linearity achieved by summing cell outputs

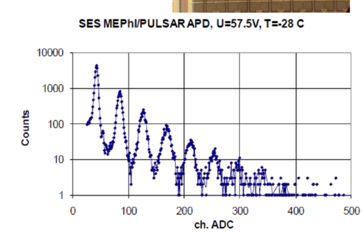
SiPM 3x3 mm^2 attached directly to BICRON-418 scintillator 3x3x40 mm^3

Signal is readout directly from SiPM w/o preamp and shaper !





- Sensitive area: 3x3 mm2 # of pixels: 5625
- Pixel size: 30 μm x 30 μm
- Depletion region: ~1 μm
- SiPM noise (FWHM): room temperature 5-8 electrons
  -50 C 0.4 electrons



Photon Detection for PID: State-of-the-Art

- RICHes with focalisation
  (SELEX, OMEGA, DELPHI, SLD-CRID, HeraB, HERMES, COMPASS, LHCB, NA62, EIC dRICH)

✓ Extended radiator (gas)
✓ Mandatory for high momenta

- RICHes with Proximity focusing
  (STAR, ALICE HMPID, HERMES, CLEO III, CLAS12, EIC mRICH, Belle ARICH, FARICH (Panda, ALICE, Super Charm-Tau)

✓ Thin radiator (liquid, solid, aerogel)
✓ Low momenta

- DIRC and its derivatives (Detector of Internally Reflected Cherenkov light)
  Babar DIRC,BELLE II TOP, Panda Barrel/Endcap & EIC (focusing DIRCs), LHCb TORCH, FDIRC GLUEX

✓ Quartz as radiator and light guide
✓ Low momenta

- Time-Of-Flight (TOF) detectors
  (ALICE, BES III)

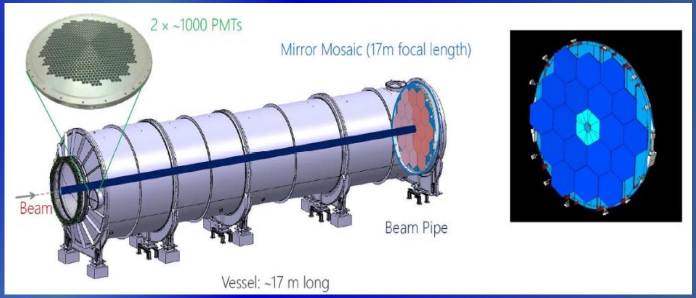
✓ Use prompt Cherenkov light
✓ Fast gas detector

LHCb RICH I and II Upgrade for Run-III:

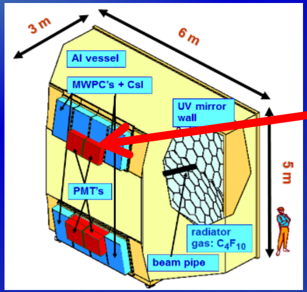
✓ New electronics @ 40 MHz
✓ New optics layout for RICH 1
✓ MaPMTs sill replace HPDs for RICH 1 and RICH2

NA62 RICH with 2000 PMTs :

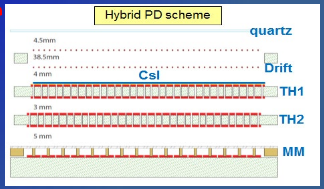
✓ Good test for GPU-based online selection (RICH participates in the low level trigger)



COMPASS RICH Upgrade:



Replace 8 MWPC's/CsI with hybrid (THGEM /Micromgas) with CsI



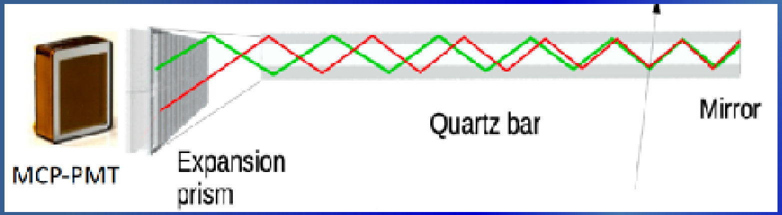
✓ Exploring a possibility to use more robust PC: hydrogenated nano-diamond crystals
✓ R&D towards compact RICH for the future EIC

Many Clever Techniques for Ultra-Fast TOF and TOP

Fast progress in the new DIRC-derived concepts, including time-of-propagation counters - exceptional time-resolution of O(10ps), based on MCP-PMTs

Belle II Time of Propagation RICH (TOP)

Based on a DIRC concept: instead of 2D-imaging → 1D + Time Of Propagation (TOP, path length)

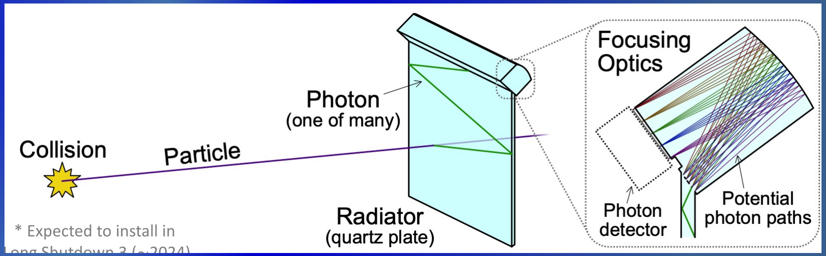


Installed between drift chamber and calorimeter

- ✓ Single photon efficiency; < 100 ps SPTR
- ✓ few mm spatial res.; operation in 1.5T B field

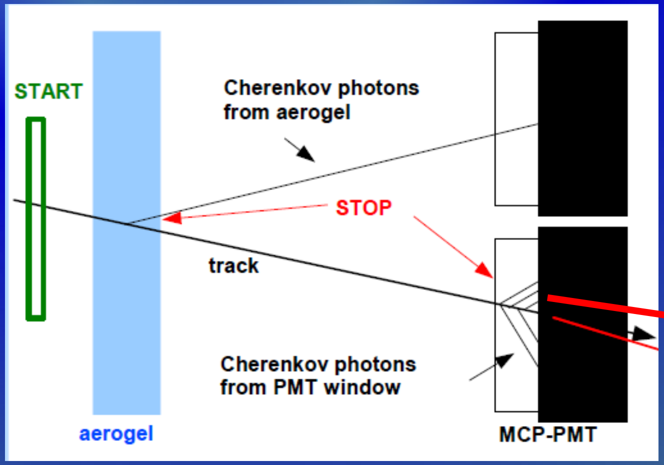
LHCb TORCH (Time Of internally Reflected CHerenkov light) for Run 4/5:

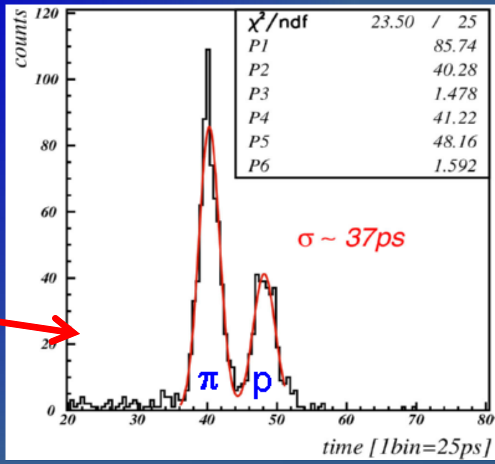
- ✓ Prompt production of cherenkov light in quartz bars
- ✓ Cherenkov photons travel to detector plane via total internal reflection and cylindrical focusing block
- ✓ 70 ps per photon →15 ps per track
- ✓ Photons detected by square micro channel plate PMTs; resolution improved by charge sharing



Generic R&D: combination of proximity focusing RICH + TOF with fastphoto sensors (MCP-PMT or SiPM) using Cherenkov photons from PMT window

Cherenkov photons from PMT window can be used to positively identify particlesbelow threshold in aerogel





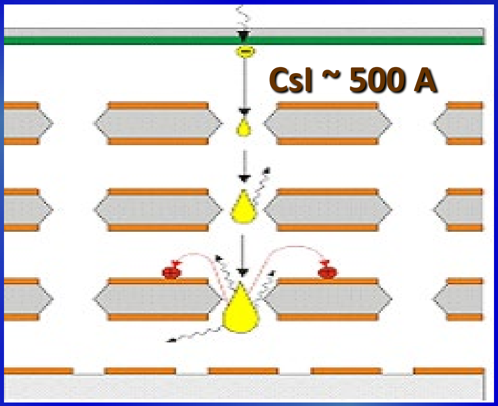
MPGD-Based Gaseous Photomultipliers

GEM or THGEM Gaseous Photomultipliers (CsI -PC) to detect single photoelectrons

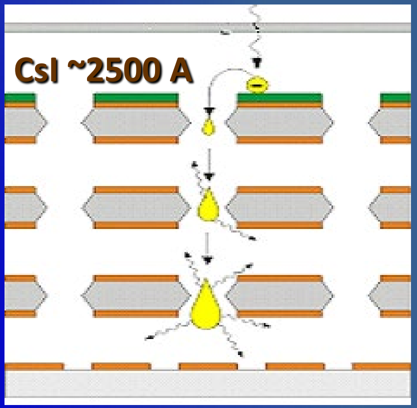
Multi-GEM (THGEM) Gaseous Photomultipliers:

- ✓ *Largely reduced photon feedback (can operate in pure noble gas & CF_4)*
- ✓ *Fast signals [ns] → good timing*
- ✓ *Excellent localization response*
- ✓ *Able to operate at cryogenic T*

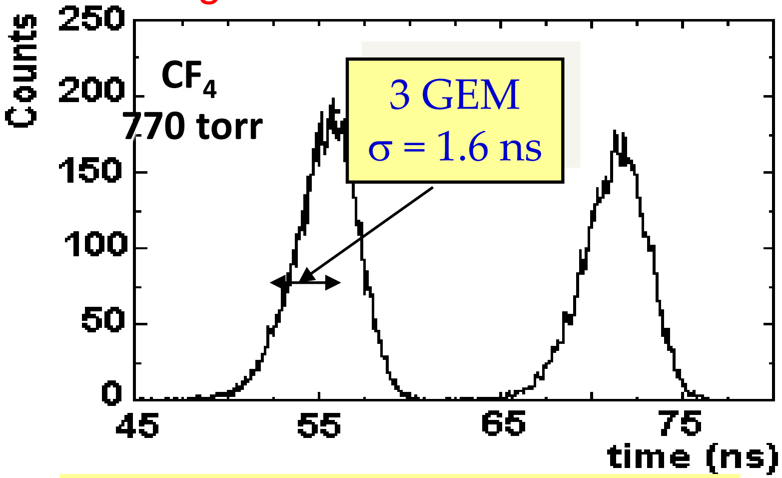
Semitransparent Photocathode (PC)



Reflective Photocathode (PC)

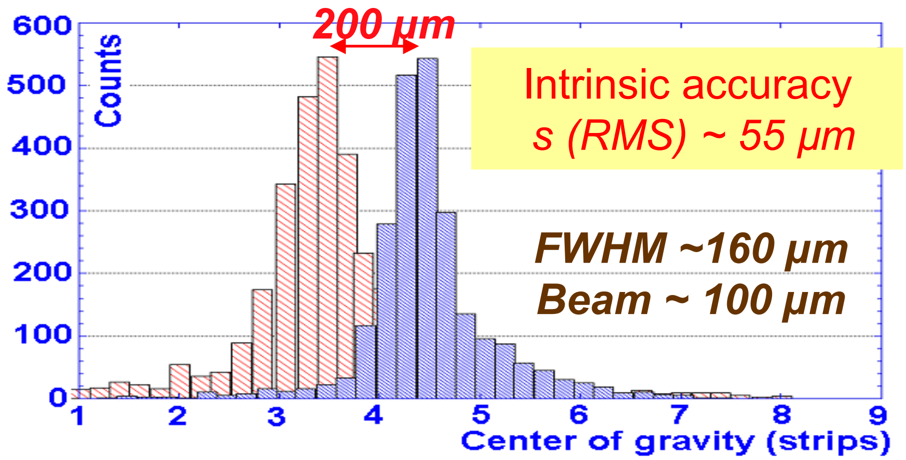


Single Photon Time Resolution:



Micromegas: s ~ 0.7 ns with MIPs

Single Photon Position Accuracy:



Intrinsic accuracy s (RMS) ~ 55 μm

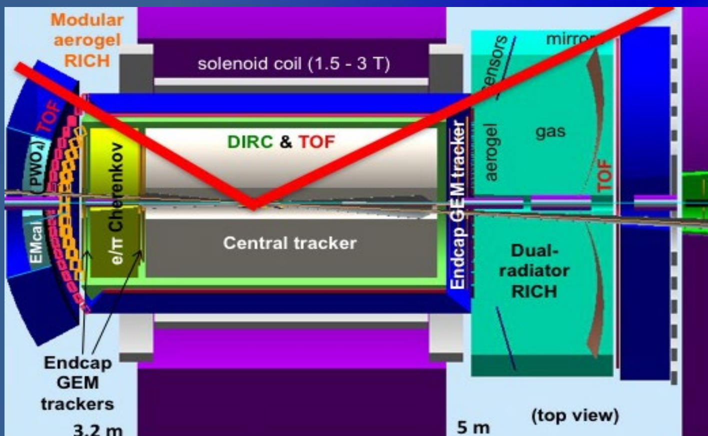
E.Nappi, NIMA471 (2001) 18; T. Meinschad et al, NIM A535 (2004) 324; D.Mormann et al., NIMA504 (2003) 93

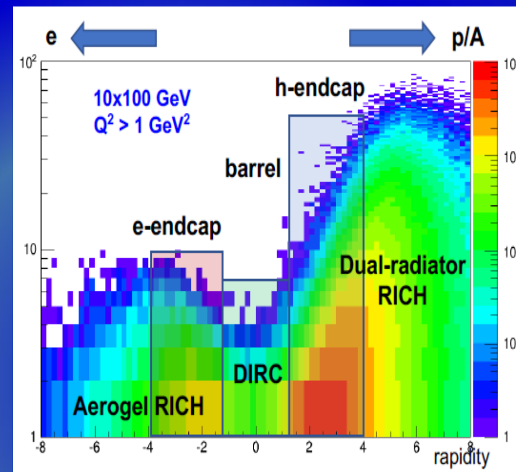
Particle Identification (PID) for Electron-Ion Collider

RICH Detectors for Particle Identification @EiC

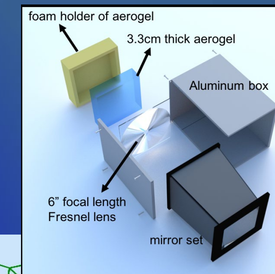
- ✓ **dRICH: dual-radiator (aerogel & C2F6) RICH**
- ✓ **mRICH: lens-focusing modular aerogel RICH**
- ✓ **hpDIRC: compact fast focusing DIRC**

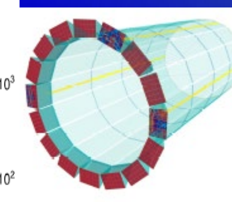
TOF (and/or dE/dx in TPC): can cover lower momenta



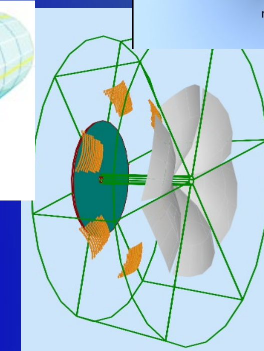


mRICH:





hpDIRC:



dRICH:

General Challenges for Photodetectors:

- ➢ Photodetectors: Big challenge is to provide a realiable highly-pixelated photodetector working at 1.5 – 3 T field
- ➢ SiPMs: high dark count rate and moderate radiation hardness prevented their use in RICH detector, where single photon detector required at low noise
- ✓ MCP-PMTs: very expensive, not tolerant to magnetic fields;
- ✓ Large-Area Picosecond Timing Detector (LAPPD): promising, still not fully applicable for EIR yet → need pixellation, efforts underway, control of cost;

Particle Identification Summary

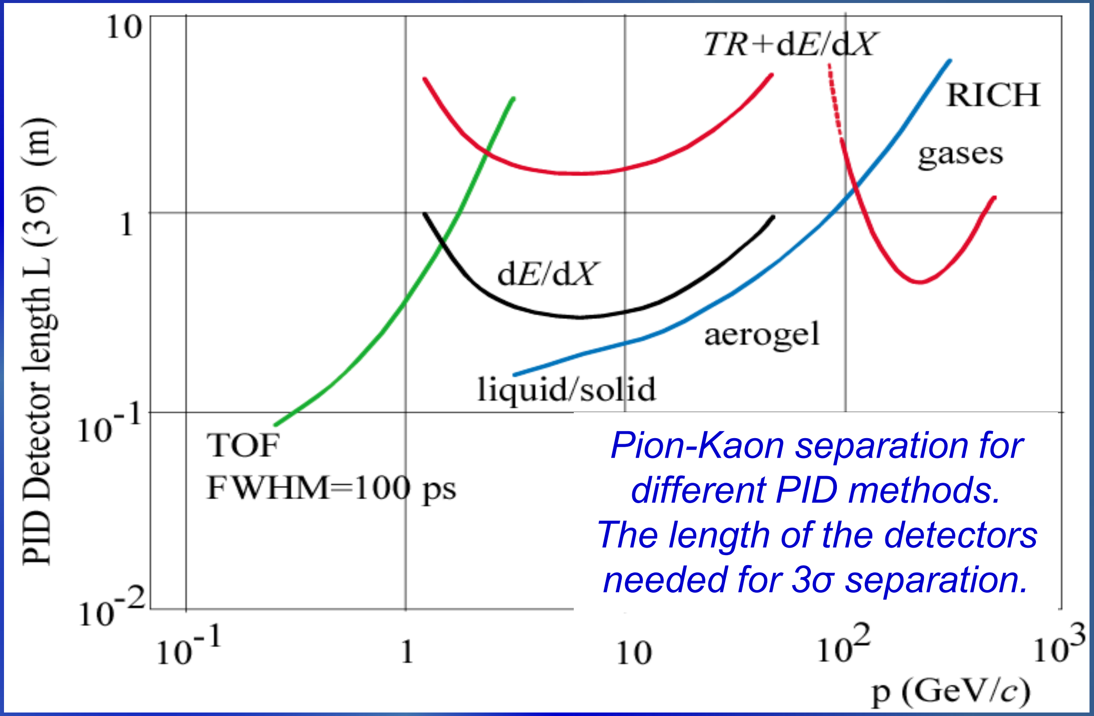
There is a wide variety of techniques for identifying charged particles:

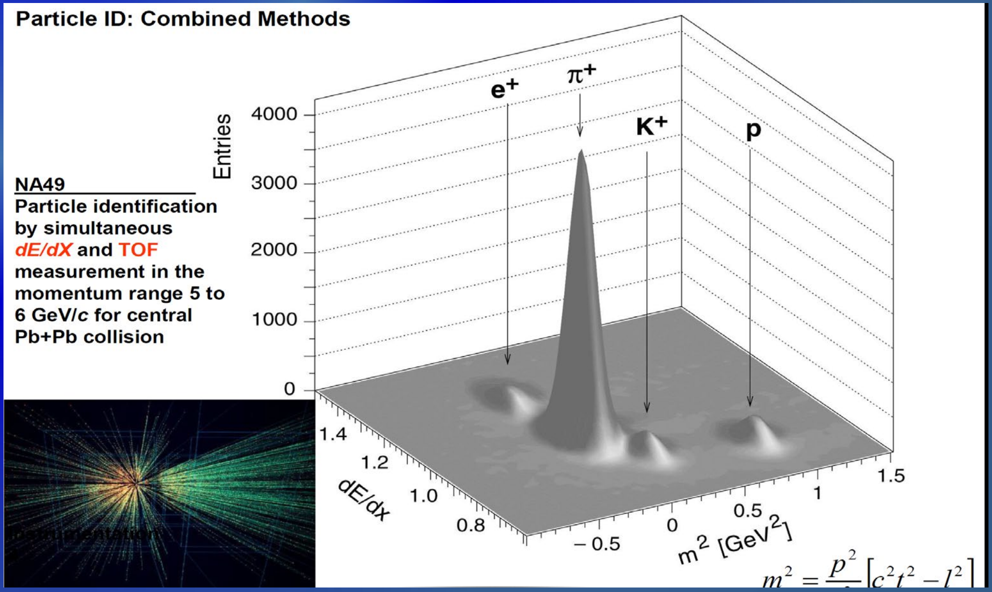
- **Transition radiation** is useful in particular for electron identification

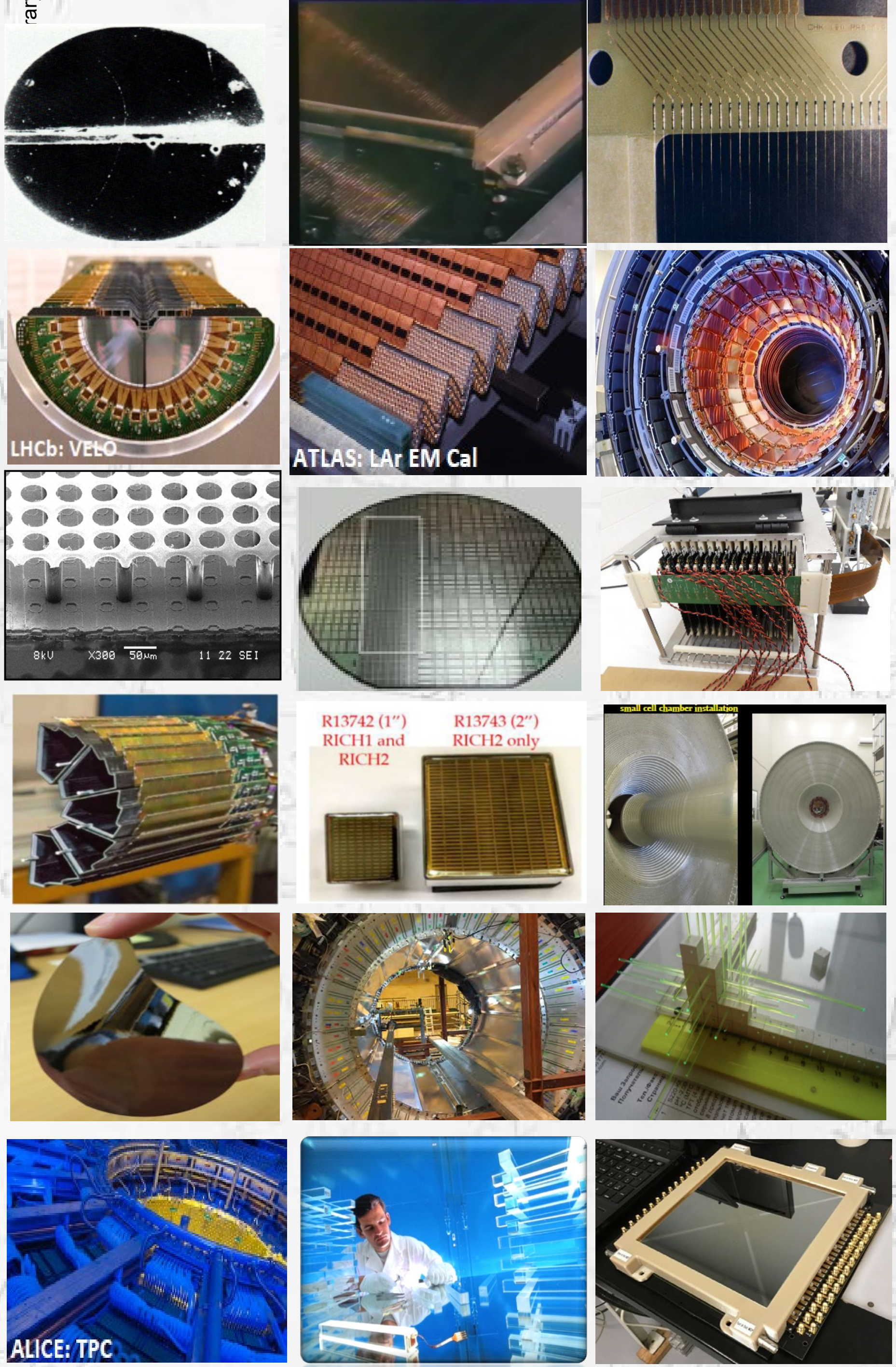
- **Cherenkov** detectors are in widespread use. Very powerful, tuning the choice of radiator

- **Ionization** energy loss is provided by existing tracking detectors but usually gives limited separation, at low *p*

- **Time Of Flight** provides excellent performance at low momentum
  With the development of faster photon detectors, the range of TOF momentum coverage should increase







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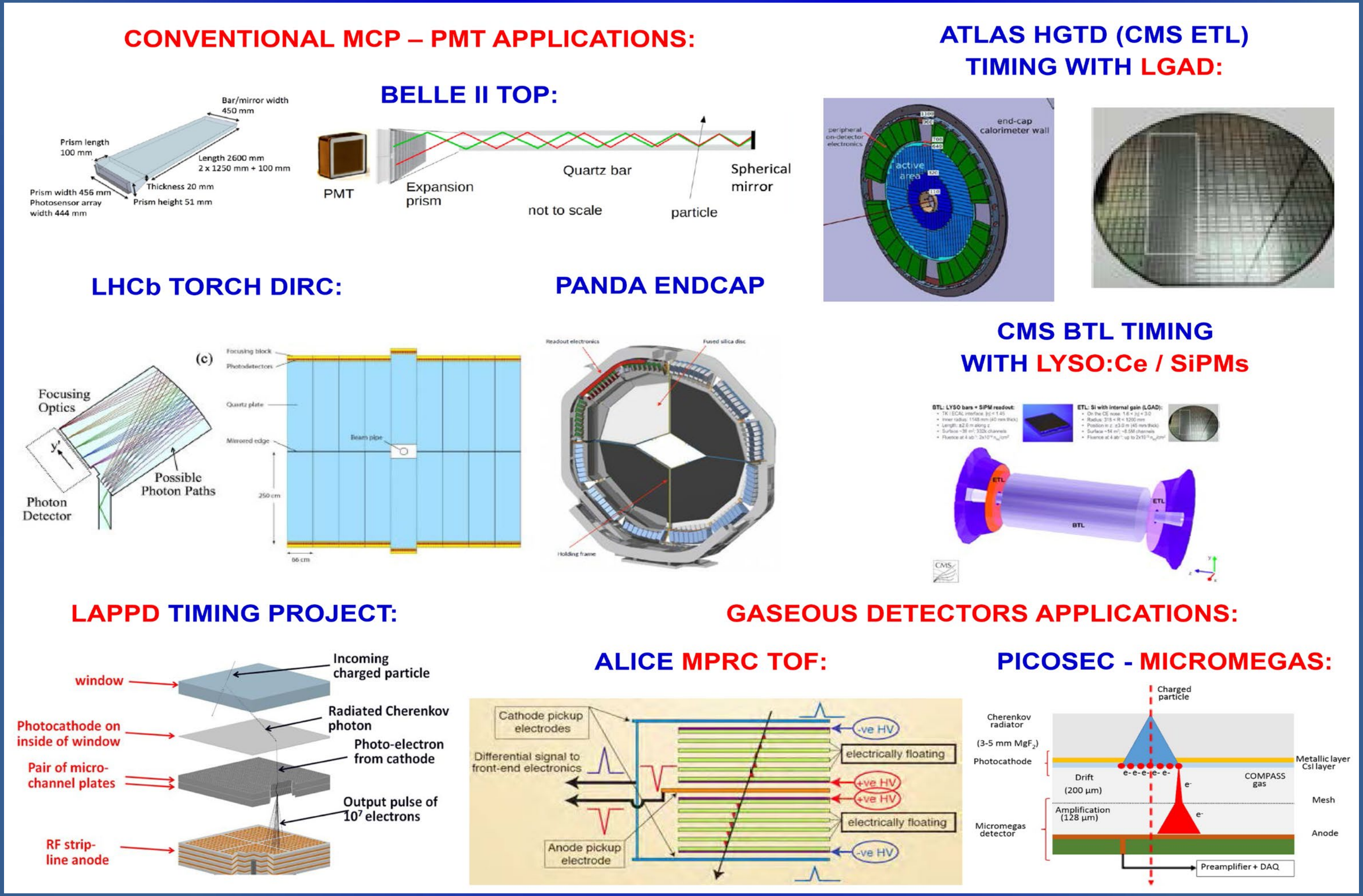
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing

Advanced Concepts Picosecond (a few 10's) Timing Detectors

Several types of technologies are considered for "Picosecond-Timing Frontier":

- Ionization detectors (silicon detectors or gas-based devices)
- Light-based devices (scintillating crystals coupled to SiPMs, Cherenkov absorbers coupled to photodetectors with amplification, or vacuum devices)



Examples of timing detectors at a level of~ 30 ps for MIPs and ~ 100 ps for single photons

TIMING Detectors with a few 10's of picosecond resolution

Picosecond-level timing was not the part of initial HL-LHC detector requirements:

Became available through pioneering R&D on LGAD / crystals / precise timing with Si:

Fast development of precise timing sensors:

- ✓ 4D pattern recognition for HL-LHC pile-up rejection: tracking ~O(10's) μm & timing detectors ~O(10's) ps
  → ATLAS HGTD, CMS ETL (LGAD)
  → CMS BTL (LYSO +SiPM)
- ✓ ps-timing reconstruction in calorimetry (resolve develop. of hadron showers, triangulate H → γγ prim. vertices)
  → CMS HGCAL (Si & Sci.+ SiPMs)
- ✓ TOF and TOP (RICH DIRC) PID → new DIRC applications (~ 10's of ps & 10's of μm per MIP/pixel)
  → both at hadron / lepton colliders
- ✓ General push for higher luminosity at LHC, Belle-II, Panda, Electron-Ion Collid.
  → Fast timing is needed at colliders, fixed target, and neutrino experiments

- ➢ Regular PMTs → large area, … but slow
- ➢ MCP-PMT → fast, but small, and not available in quantities to over large areas:
  → ultimate time resolution ~ 3.8 ps (single-pixel devices)
  → radiation hardness up to ~ 20 C/cm (HPK, ALD-coated MCP-PMT°

Detector	Experiment or beam test	Maximum rate	Maximum anode charge dose	Timing resolution	Ref.
MRPC presently	ALICE	~500 Hz/cm^2 *** (tracks)	-	~60 ps/track (present)***	[4]
MRPC after upgrade	ALICE	Plan: ~50 kHz/cm^2 ** (tracks)	-	Plan: ~20 ps/track	[4]
MCP-PMT	Beam test	-	-	< 10 ps/track *	[7,8,9]
MCP-PMT	Laser test	-	-	~27 ps/photon *	[14]
MCP-PMT	PANDA Barrel test	10 MHz/cm^2 * (laser)	~20 C/cm^2 *	-	[11]
MCP-PMT	Panda Endcap	~1 MHz/cm^2 ** (photons)	-	-	[28]
MCP-PMT	TORCH test	-	3-4 C/cm^2 *	~90 ps/photon *	[27]
MCP-PMT	TORCH	10-40 MHz/cm^2 ** (photons)	5 C/cm^2 **	~70 ps/photon **	[24-27]
MCP-PMT	Belle-II	< 4MHz/MCP *** (photons)	-	80-120 ps/photon***	[23]
Low gain AD	ATLAS test	~40 MHz/cm^2 ** (tracks)	-	~ 34 ps/track/single sensor *	[34,35]
Medium gain AD	Beam test	-		< 18 ps/track *	[39]
Si PIN diode (no gain)	Beam test (electrons)	-		~23 ps/32 GeV e^-	[8]
SiPMT (high gain)	Beam test – quartz rad.	-	< 10^{10} neutrons/cm^2	~ 13 ps/track *	[8]
SiPMT (high gain)	Beam test - scint. tiles	-	< 10^{10} neutrons/cm^2	< 75 ps/track *	[41]
Diamond (no gain)	TOTEM	~3 MHz/cm^2 * (tracks)	-	~ 90 ps/track/single sensor *	[36]
Micromegas	Beam test	~100 Hz/cm^2 * (tracks)	-	~24 ps/track *	[31,32,40]
Micromegas	Laser test	~50 kHz/cm^2 * (laser test)	-	~76 ps/photon *	[31,32,40]

* Measured in a test
** Expect in the final experiment
*** Status of the present experiment

J. Va'vra, arXiv: 1906. 11322

Challenges:

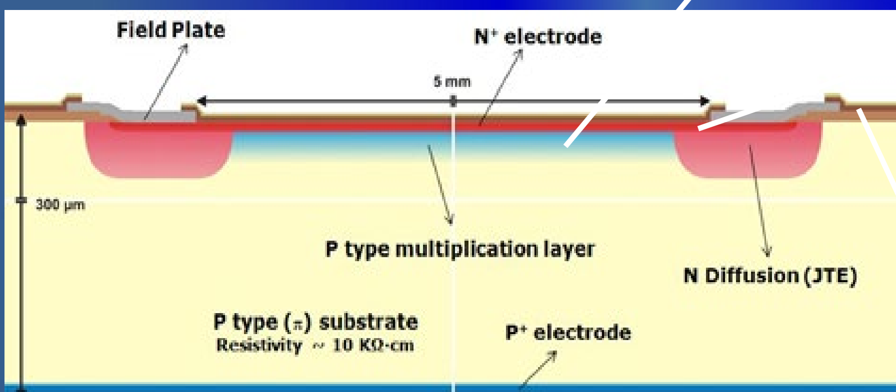
- ✓ Radiation hardness: LGAD-sensors, 3D-trench Si sensors, …
- ✓ Large scale applications : system aspects of timing detectors
- ✓ "5D reconstruction": space-points / ps-timing are available at each point along the track → LHCb EoI for LS4 is of general interest across experiments;
- ✓ LAPPD → large-area ps- PID/TOF for hadron/lepton colliders
  Incom Inc. company started to produce LAPPDs → cost still has to be controlled

Basic Principles: Low-Gain Avalanche Detectors (LGAD)

LGADs exploit the avalanche phenomenon of a reverse-biased p-n junction: ***Internal gain (~10) is optimized for high bias (fast collection, reduced trapping), low noise, high rate***

LGAD Structure:

- Highly resistive *p*-type substrate
- ***n*+ and p+ diffusions** for the electrodes
- ***p* diffusion** under the cathode → enhanced electric field → **multiplication**



Electric field profile is critical since the charge multiplication depends **exponentially** on it.

$$N(x) = N_o\, e^{(\alpha x)}$$

$$\alpha_{e,h}(E) = \alpha^{\infty}_{e,h}\, e^{-\left(\frac{E_o}{E}\right)}$$

Critical regions of the LGAD design:

- **Central area (gain region, multiplication layer)**
  Uniform electric field, sufficiently high to activate mechanism of impact ionization (multiplication)

- **N - Implant Edge Termination**
  - Lightly-doped N-type deep diffusion (JTE) and addition of a field plate
  - Allows high electric field in the central r region since breakdown voltage VBD(Edge) >> VBD (Central)

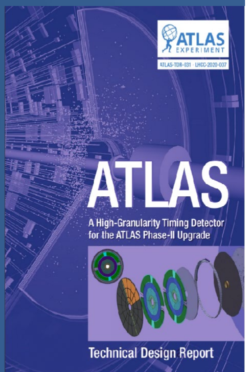
- **Periphery**
  - P-spray/stop: counteracts inversion and cuts off current path
  - Biased guard ring around the detection region collects the surface component of the current

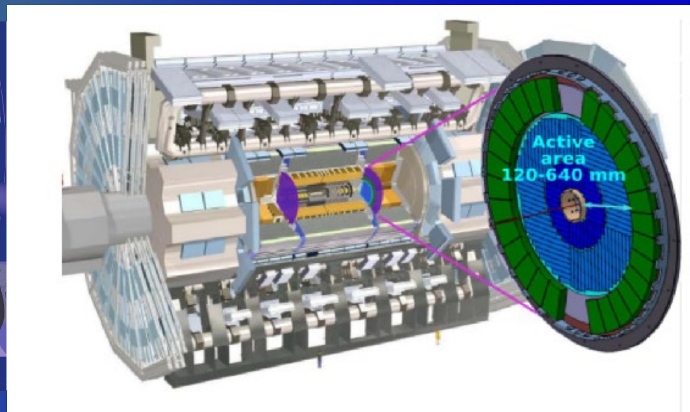
TIMING DETECTORS for ATLAS / CMS Phase-II Upgrade

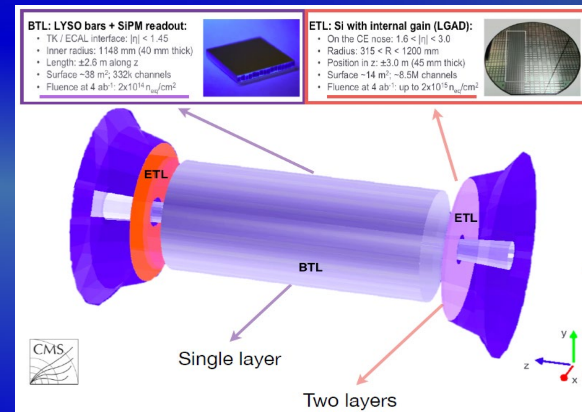
ATLAS High Granularity Timing Detector:

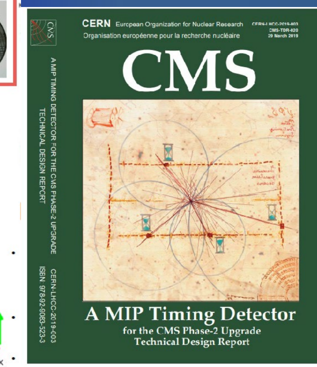
CMS Endcap Timing Detectors:

Equipped with LGADs (1.3 x 1.3 mm^2 pads) targetting > 50 ps resolution (rad-hard only viable solution)





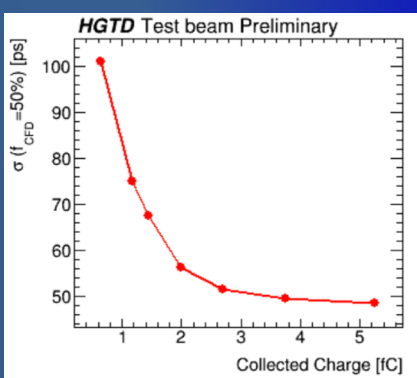


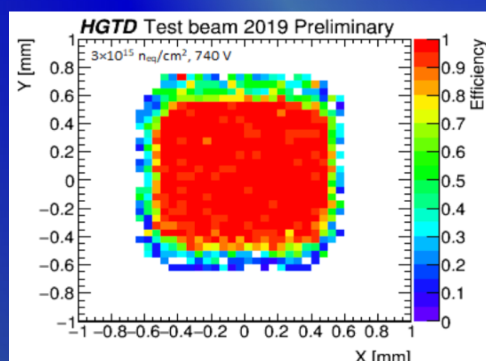


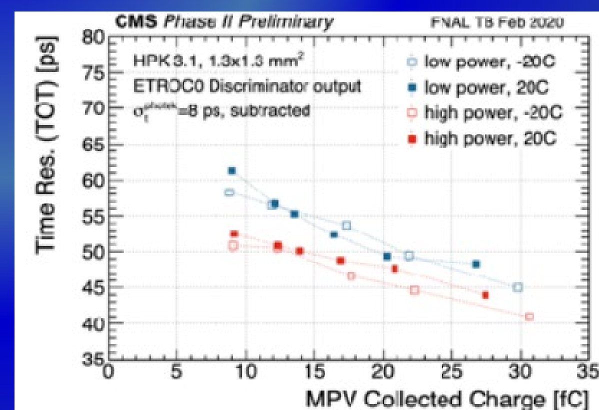
Two double sided layers in front of Calorimeter endcaps:
Fluence < 2.5 x 1015 neq/cm2
Coverage: 2.4 < η < 4.0 with 12 cm < R < 64 cm @ z = 3.5 m

Two double sided layers in front of Calorimeter endcaps:
fluence < 1.7 x 1015 neq/cm2
Coverage: 1.6 < η < 3.0 with 0.31 < R < 1.2 @ z = 3 m

Post irradiation: 4 fC and 50 ps achieved (high/uniform efficiency)







P. Collins @ ICHEP2020

Pre irradiation 40-50 ps after discriminator with full efficiency

- LGAD are currently produced by 3 foundries (CNM, FBK, HPK)
- LHCb is developing a time-tracking device O(100 ps) device, based on 3D trench Si-sensors with a more uniform field/charge collection, and a goal to withstand fluence of 10^{16} - 10^{17} n_{eq}/cm2

Towards Large Area in Fast Timing GASEOUS DETECTORS

Multi-Gap Resistive Plate Chambers (MRPC):

- ✓ ALICE TOF detector (160m^2) achieved time res. ~ 60 ps
- ✓ New studies with MRPC with 20 gas gaps using a low-resistivity 400 μm-thick glass → down to 20 ps time resolution

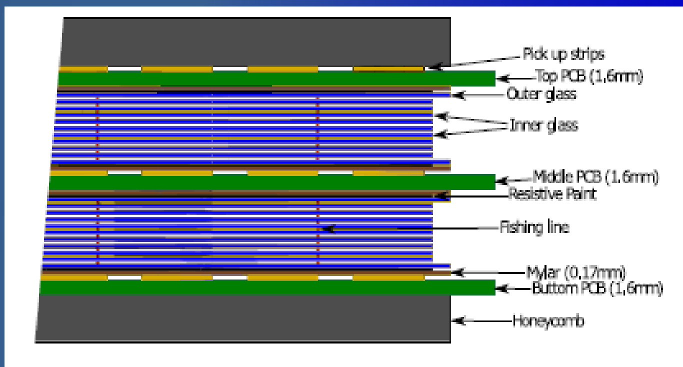
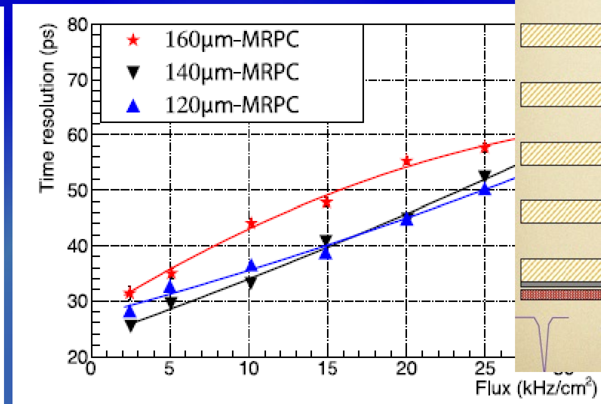
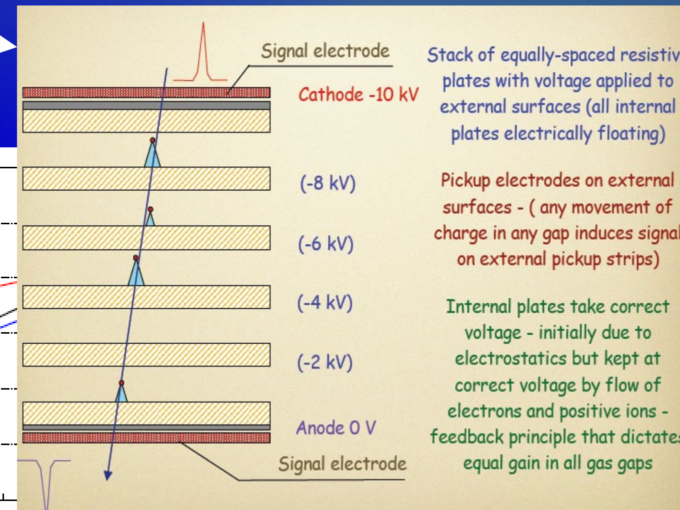


Fig. 1. Cross section of the double stack 20-gap MRPC.



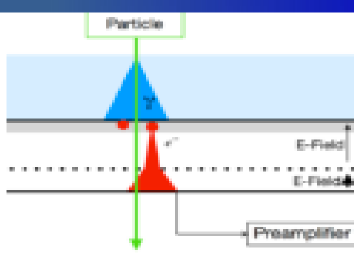


Gaseous Detectors: Micromegas with Timing (RD51 Picosec Collaboration)

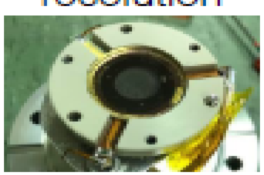
PICOSEC Micromegas

σ ~ 25 ps timing resolution (per track)

Cherenkov radiator + Photocathode + Micromegas



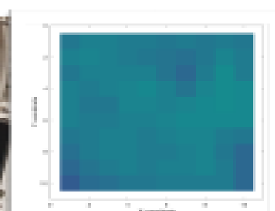
24ps timing resolution



Single pad (2016)
⌀1 cm

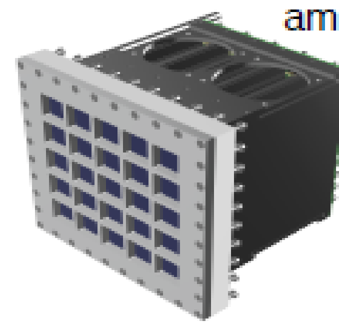
Tested in RD51 testbeam July 2021

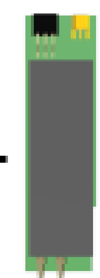
10x10 module
□ 1 cm



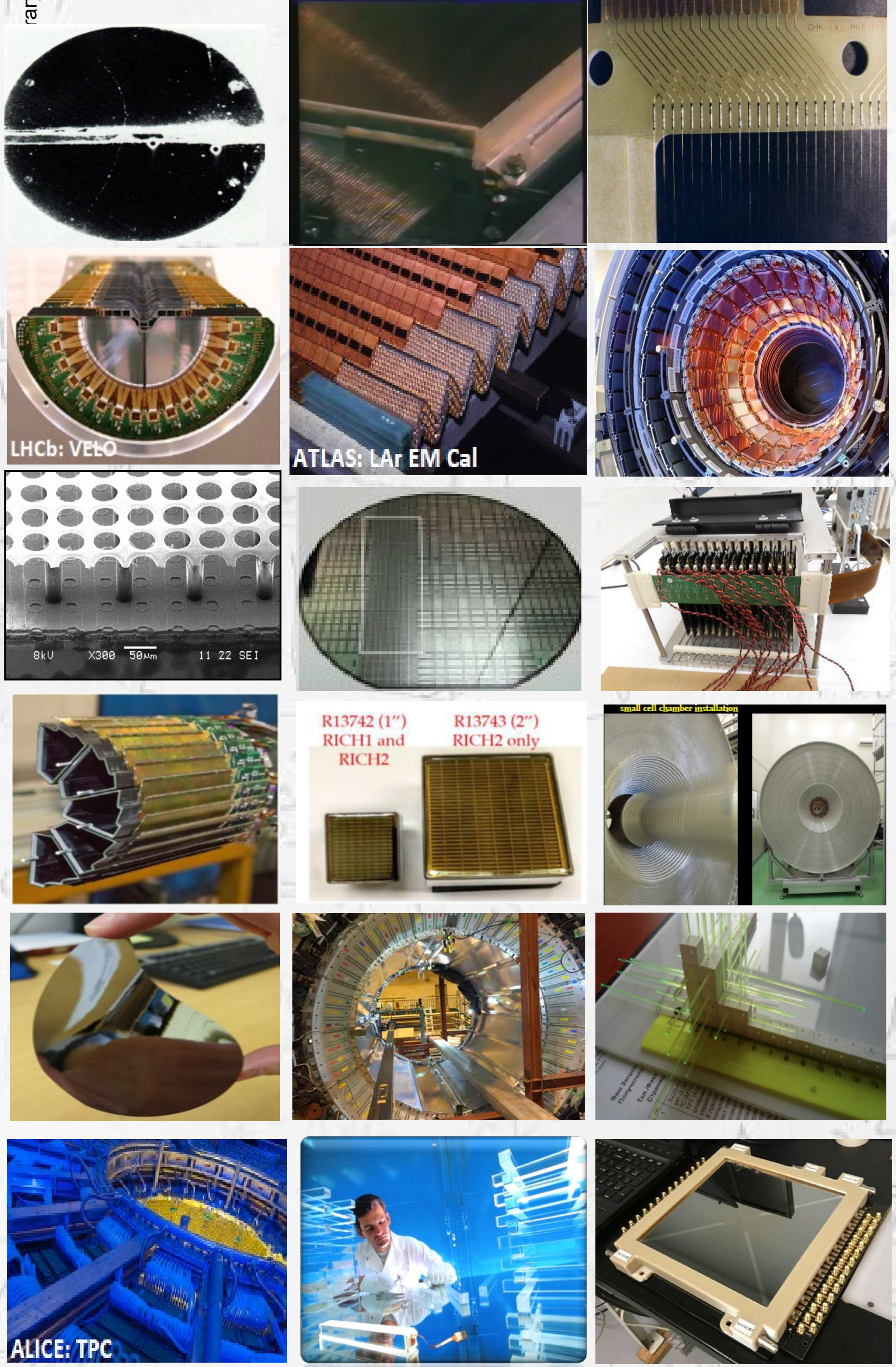
Planarity < 10μm

Custom pre-amp cards



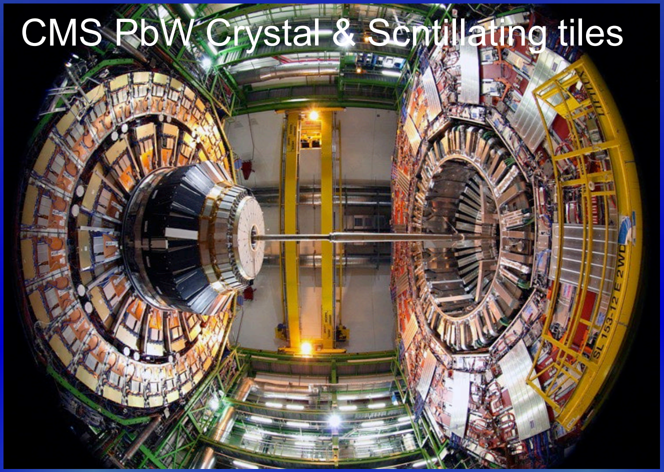


https://indico.cern.ch/event/1040996/contributions/4398412/attachments/2265036/3845651/PICOSEC-update-final.pdf

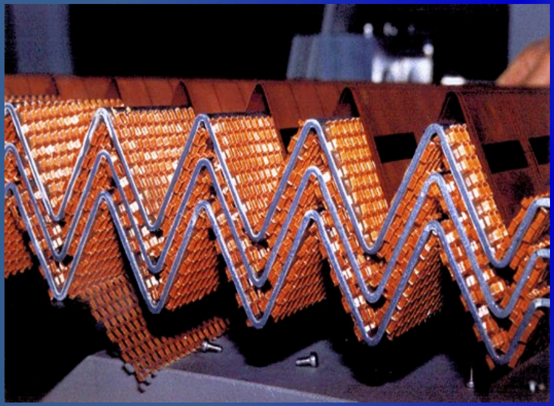


- Particle Interactions with Matter
- "Classic" Detectors (historical touch...)
- Advancing Concepts Tracking Detectors: Gaseous Detectors
- Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors
- Advancing Concepts in Picosecond-
  Timing Detectors
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing

Advanced Concepts in CALORIMETRY



4 main technologies: LAr, Scintillators, Crystals (tiles or fibers), Silicon sensors



Two main concepts:

Homogeneous crystals (CsI, LYSO):
- Best possible resolution
- Application to PET

Sampling:
- Imaging: Particle Flow Algorithm
- Dream: Dual readout
- Sampling with Crystals, shashlik-type

Two main approaches for improving jet energy resolution:

Dual (or triple) readout, e.g. DREAM (FCC-ee, CePC) improvement of the energy resolution of hadronic calorimeters for single hadrons:

Cherenkov light for relativistic (EM) component
Scintillation light for non-relativistic (hadronic)

Particle flow algorithm and imaging calorimeters (CALICE detectors for ILC, CLIC, CMS HGCAL):
→ Precise reconstruction of each particle within the jet (reduction of HCAL resolution impact)

Calorimeter Concepts: Basic Principles

Two types calorimeter concepts: Homogeneous and Sampling (both EM and HAD)

Homogeneous calorimeter

It uses **a high-density material** where the shower is generated **and produces the signal**

Some typical materials

BGO, PbWO… → Scintillation
Lead Glass → Cherenkov light

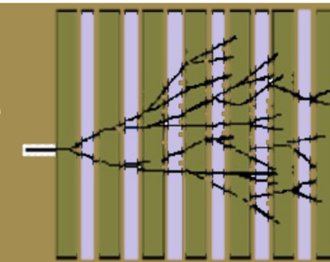
Advantages: Best energy resolution

Disadvantages: Expensive

Used only for electromagnetic calorimeters

Sampling calorimeter

It alternates **layers of high-densitity material (passive absorber)** where the shower is generated **and detectors (active planes) to produce the signal**



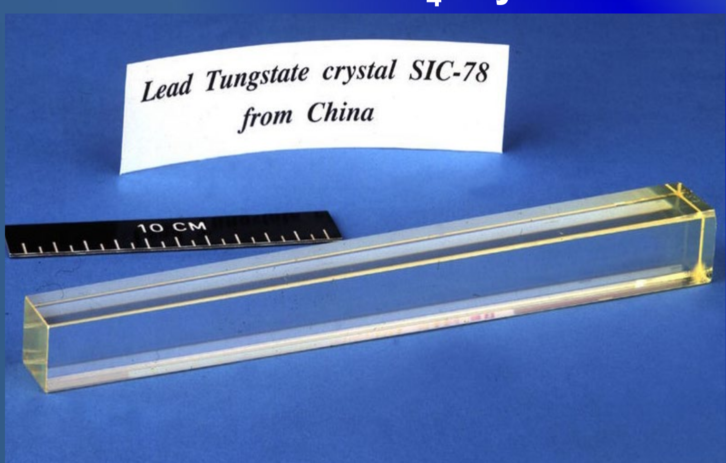
Typical absorbers: Fe, Pb, U

Typical detectors: Gaseous detectors, plastic scintillators, quartz fibers, silicon detectors noble liquid ionization chambers…

Advantages: Cheap absorber
Optimization of absorber/sensor
Compactness

Disadvantages: Worse energy resolution due to lower energy deposition and sampling fluctuations

CMS $PbWO_4$ crystal



- EM interaction : X_o ranges from 13.8 g/cm2 for Fe to 6.0 g/cm2 for U
- H interaction : λ_I ranges from 132.1 g/cm2 for Fe to 209 g/cm2 for U
- EM Calorimeters: MANY (15-30) Xo deep
- H Calorimeters: many (5-8) λI deep

ATLAS Liquid Ar

Energy Resolution of Electromagnetic Calorimeters

Usually parameterized by (valid both for homogeneous & sampling calorimeters & for both electromagnetic and hadronic calorimeters) :

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

$a = intrinsic\ term$

$b = constant\ term$

$c = noise\ term$

a : intrinsic resolution or term

Simplified model :
- Number of produced ions/e $^-$ pairs (or photon) N=E/w
- Detectable signal (→E) is ∝ N (N quite large)

$$\frac{\sigma}{E} = \frac{\sigma_N}{N} = \frac{1}{\sqrt{N}} \approx \frac{a}{\sqrt{E}}$$

In a hadronic calorimeter there are two components

$$Signal = S_{em} + S_{had} = \mathbf{e} f_{em} E + h f_{had} E$$

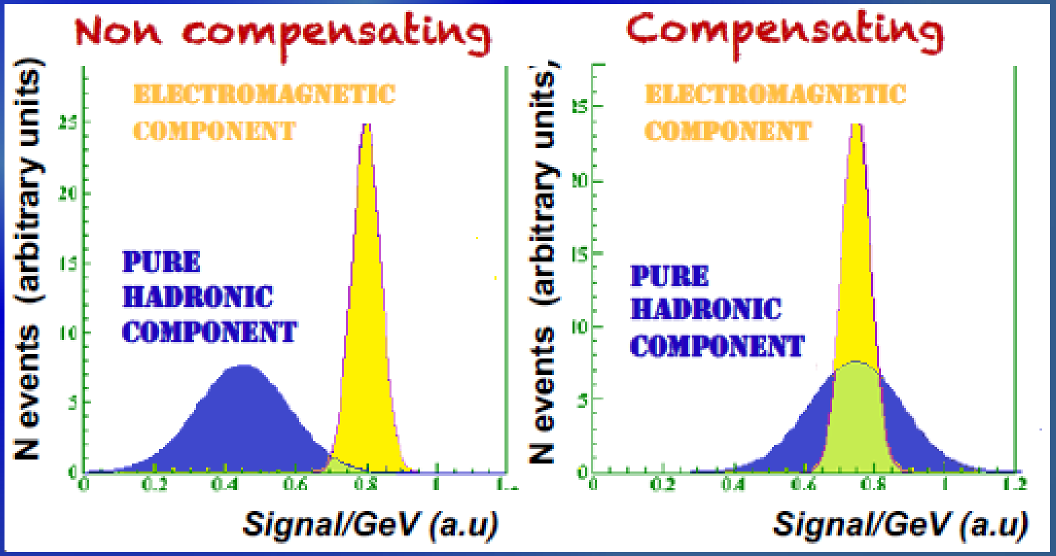
f_{em}, f_{had} = Fractions of each component

$f_{had} = 1 - f_{em}$

$\mathbf{e}, h$ = Calibration constants for each part

$$\frac{e}{h} = 1$$

→ Compensanting Calorimeter

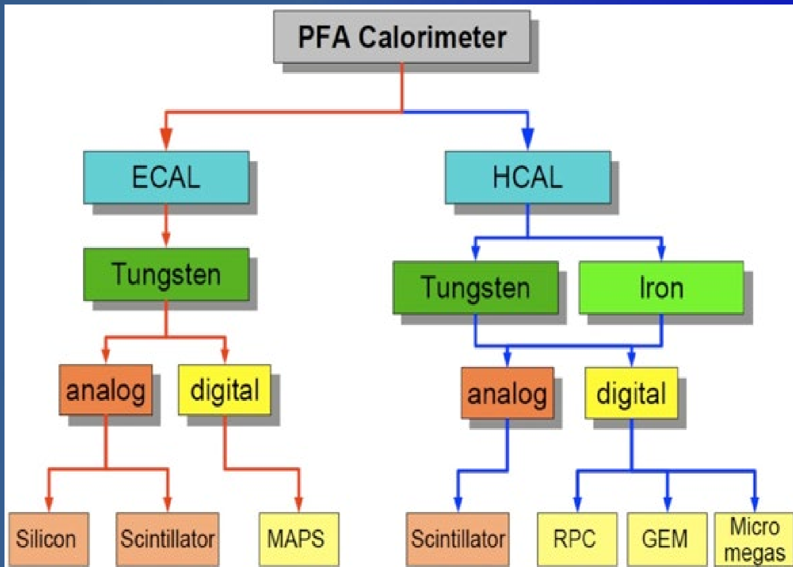


c : contribution of electronics noise
+ at LHC pile up noise…

b : constant term
contains all the imperfection: dead spaces, response variation versus position (uniformity), time (stability), temperature, mis-calibration, radiation damage, ….

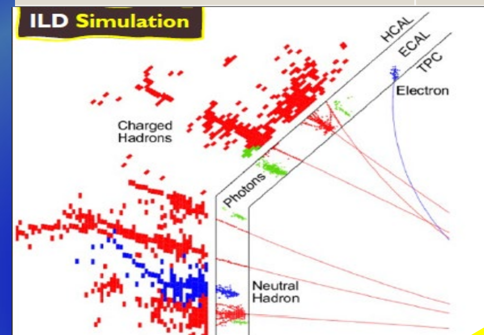
Particle Flow Calorimeters: CALICE Collaboration

Development and study of finely segmented / imaging calorimeters (PFA): initially focused on the ILC



PFA Calorimetry → reconstruct every single particle in the event

Average jet composition	PFA reconstruction
60% charged	Measured on the tracker, negligible resolution
30% photons (from π^0 decay)	Measured at ECAL ~10-20% /√(E)
10% neutral hadrons (n, K_L)	Measured at HCAL ~60-100% /√(E)



PFA reconstruction Issues:
- overlap between showers
- complicated topology
- separate "physics event" from beam-induced bkg.

Example: **ILD detector for ILC**, proposing **CALICE** collaboration technologies

	ECAL option	ECAL option	HCAL option	HCAL option
Active layer	silicon	scint+SiPM	scint+SiPM	glass RPC
Absorber	tungsten	tungsten	steel	steel
Cell size (cm×cm)	0.5×0.5	0.5×4.5	3×3	1×1
# layers	30	30	48	48
Readout	analog	analog	analog	Semi-dig (2 bits)
Depth # (X_0/Λ_{int})	24 X_0	24 X_0	5.5 Λ_{int}	5.5 Λ_{int}
# channels [10^6]	100	10	8	70
Total surface	2500	2500	7000	7000

MATURED (CALICE):
- **SiW-ECAL**
- **SciW-ECAL**
- **AHCAL**
- **DHCAL (sDHCAL)**

→ (Almost) ready for large-scale prototype
→ Prepare for quick realization of 4-5 years to real detector

ADVANCED (beyond CALICE):
- **MAPS ECAL**
- **Dual-readout ECAL**
- **LGAD ECAL (CALICE)**

→ Evaluate additional physics impact to ILC experiment
→ Needs intensive R&D effort to realize as real detector

Calorimeter Technologies at Glance (Developed for ILC)

SILICON BASED SANDWICH CALORIMETERS
SI-W ECAL

Absorber: Tungsten
Sensor: Silicon
Readout: Pads 5x5 mm^2
Higgs Factories / Luxe

Narrow showers

- Better separation of particles in the transverse direction
- Compact design

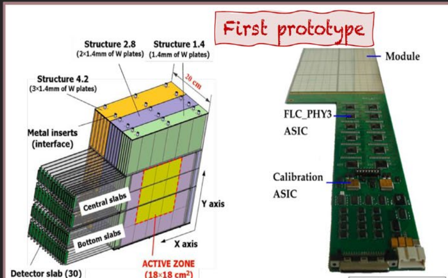
Tungsten: $X_0 = 3.5$ mm, $\rho_M = 9$ mm, $\lambda_I = 95$ mm

OPTIMIZED FOR PFA

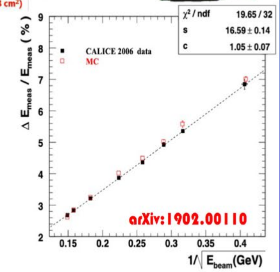
Mature technology developed by CALICE since years
Adapted also for the CMS HGCAL upgrade calorimeter

Timing information or ToF capabilities in the first layers could be achieve by replacing (part) with LGADs ~10 ps

First prototype

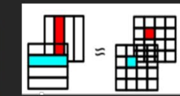


30 Layers
10K Channels
External readout



OPTICAL BASED SANDWICH CALORIMETERS: SCW-ECAL

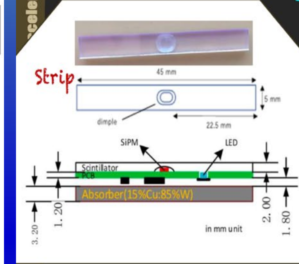
Absorber: Tungsten
Sensor: Plastic scintillator
Readout: Strips (5 x 45 mm^2)
- SiPM
Higgs Factories



(5x45 mm^2) → (5x5 mm^2)

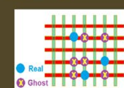
Less readout channels than SiW-ECAL

Possibility of introducing dedicated timing layer(s)



Cheaper 👍 (plastic and electronics)

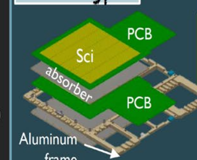
Ghosts 👎



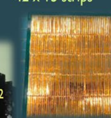
Should be eliminated by double SiPM readout

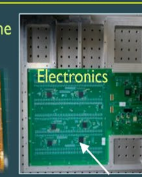
Prototype

ECAL Basic Unit (EBU)
- Scintillator strips + Hamamatsu SiPMs + SPIROC2E chips
- Tungsten-copper alloy (85:15)

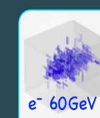


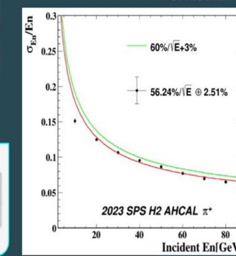
Scintillator plane
42 x 15 strips





32 EBU layers ~23 X_0
6720 readout channels
192 SPIROC2E chips





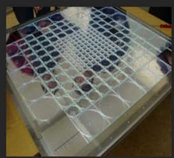
OPTICAL BASED SANDWICH CALORIMETERS: AHCAL

Absorber: Stainless steel (*)
Sensor: Plastic scintillator
Readout: Tiles (3 x 3 cm^2)
- SiPM
Higgs Factories

(*) Tungsten also tested for CLIC

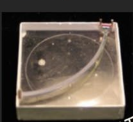
Mature technology developed by CALICE since years
Adapted also for the CMS HGCAL upgrade calorimeter

Many technical developments after the first prototype used as a probe of concept

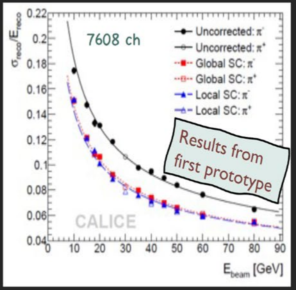


First prototype

1 plane.
Diferent sizes:
3x3cm2 (30x30 cm2 core)
6x6cm2 12x12 cm2 (external)



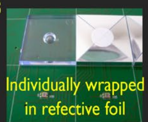
Old Tile design



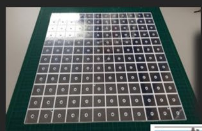
SC= Software Compensation

New Developments

Single Tile design



Glued one by one
Light Tightness 👍
Dead areas between tiles 👎



Megatile design

Large scintillator plate with optically separated trenches filled with reflective TiO2

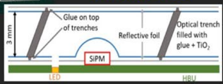


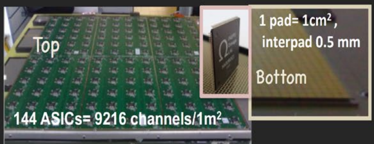
Plate wrapped in reflective foil

Easier assembly and no dead areas 👍
Not fully light tight 👎

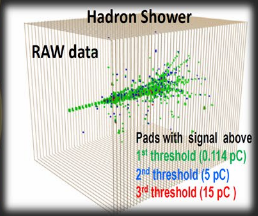
GAS BASED SANDWICH CALORIMETERS
SDHCAL

M.C. Fouz

Absorber: Stainless steel
Sensor: RPC
Readout: PADS 1x1cm^2
Semi-digital Readout
Higgs Factories



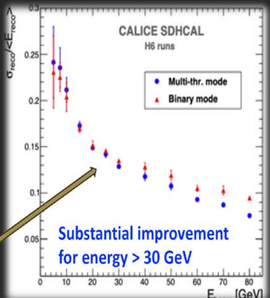
SDHCAL ~1.3m^3 prototype
At Test Beam @ CERN



- 48 layers (~6λ_I)
- 1 cm x 1 cm granularity 3-threshold, 500000 channels
- Power-Pulsed
- Triggerless DAQ system
- Self-supporting mechanical structure (<500 μm deformation)

Technology under development by CALICE since more than 10 years

Advantage of semi-digital vs digital
→ Multi-threshold improves resolution



CMS High Granularity Calorimeter for Phase II Endcap Upgrade

CMS endcap region:

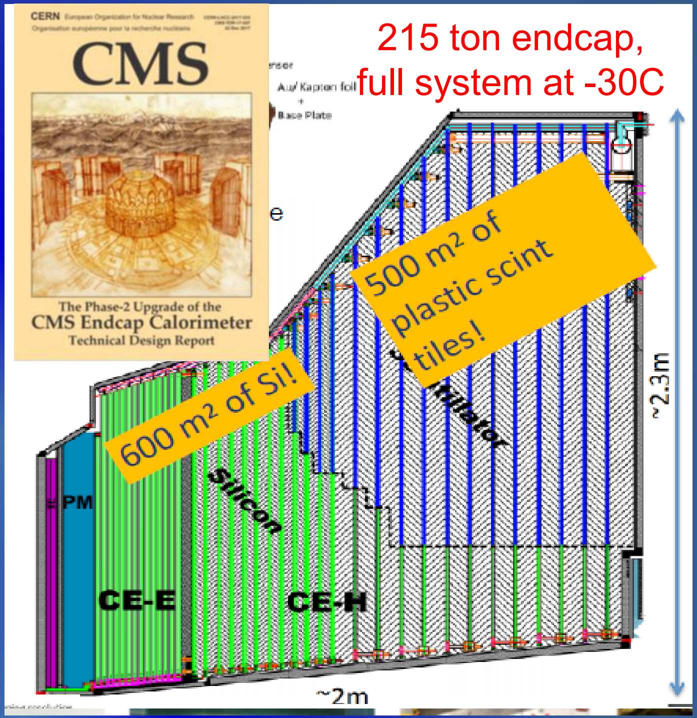
- PbWO4 crystal transmission loss due to radiation damage
- Worsening energy resolution due to increased pileup

✓ Build a fine segmented 'particle flow' calorimeter, ECAL + HCAL combined.

✓ Use Si sensors as long as radiation and particle flow requires, then switch to cheaper scintillator tiles + SiPM (à la CALICE). (27000 Si-modules, 6M Si-channels, 400000 SiPMs)

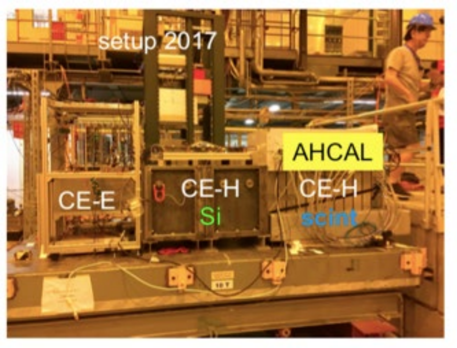
- CE-E: Si, Cu, CuW,Pb absorbers, 28 layers, 25 X0 & ~1.3λ
- CE-H: steel absorbers, 24 layers, ~8.5λ

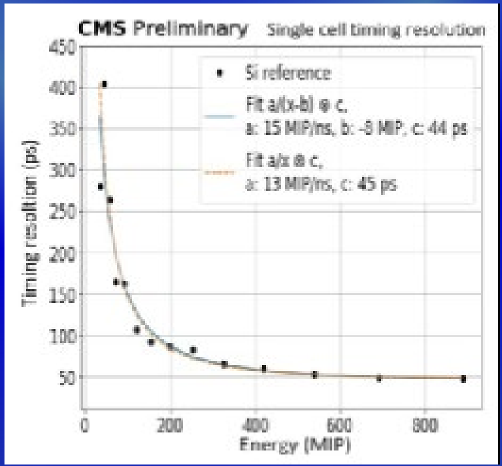
✓ Si pad sensors from 8" wafers. Different sensor geometries and thicknesses (300,200,120 μm); fluences $2x10^{14}$ - 10^{16} n_{eq}/cm^2

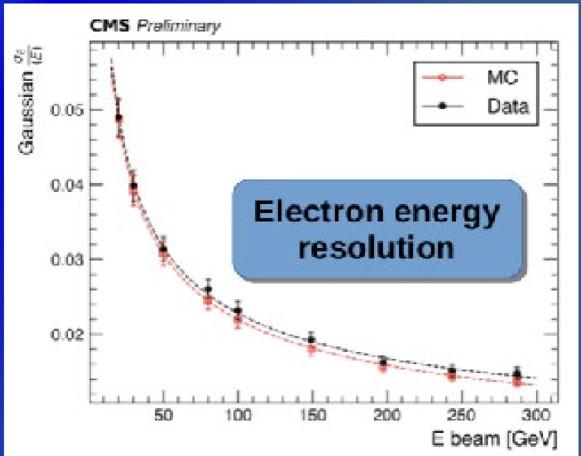


New (combined) CMS HGCAL + ILC AHCAL test-beam results:

- 28 EM layers, 12 Si-HAD layers,
- 39 Sci-layers from CALICE AHCAL

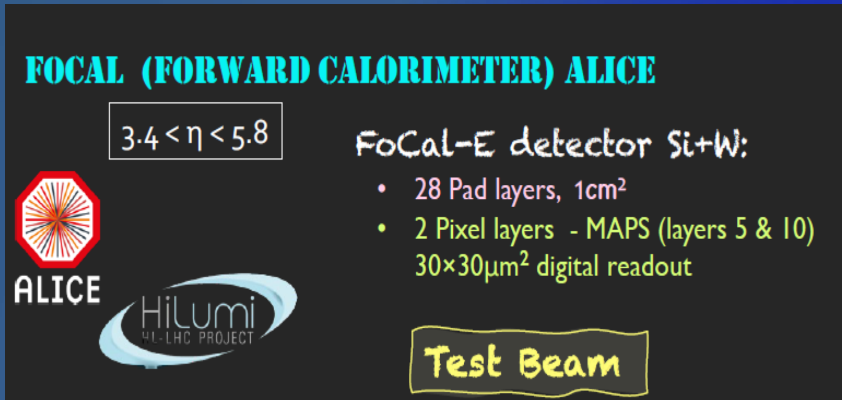


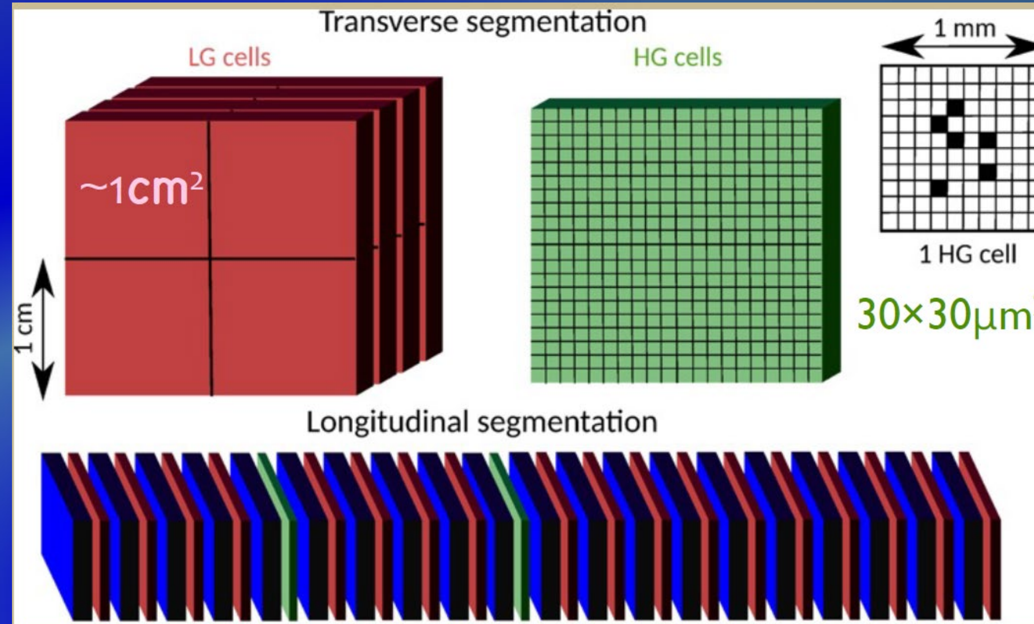




Multi-layer measurements of shower signal allows precise ToF estimate of e/γ/h0 : ~ 50 ps has been achived in Si for S/N >20

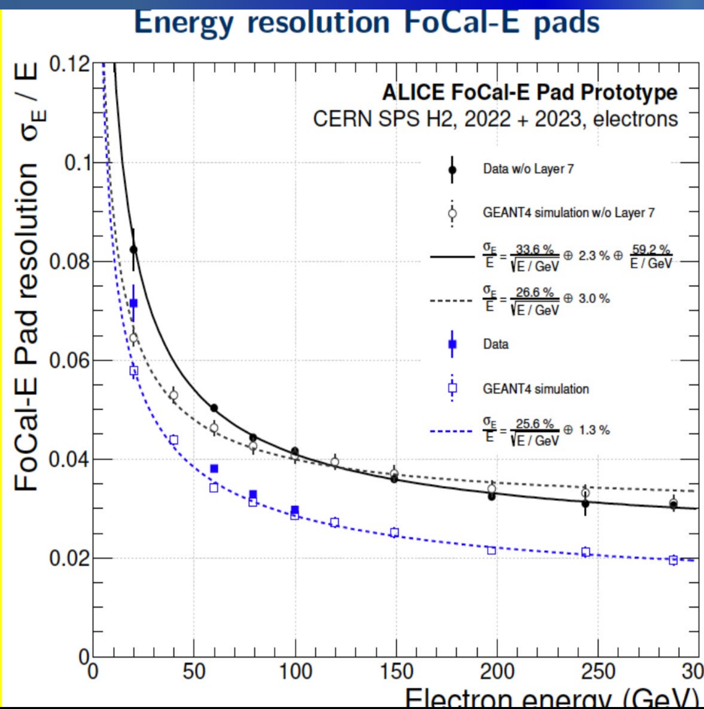
R&D for ALICE FOCAL – MAPS based SiW ECAL

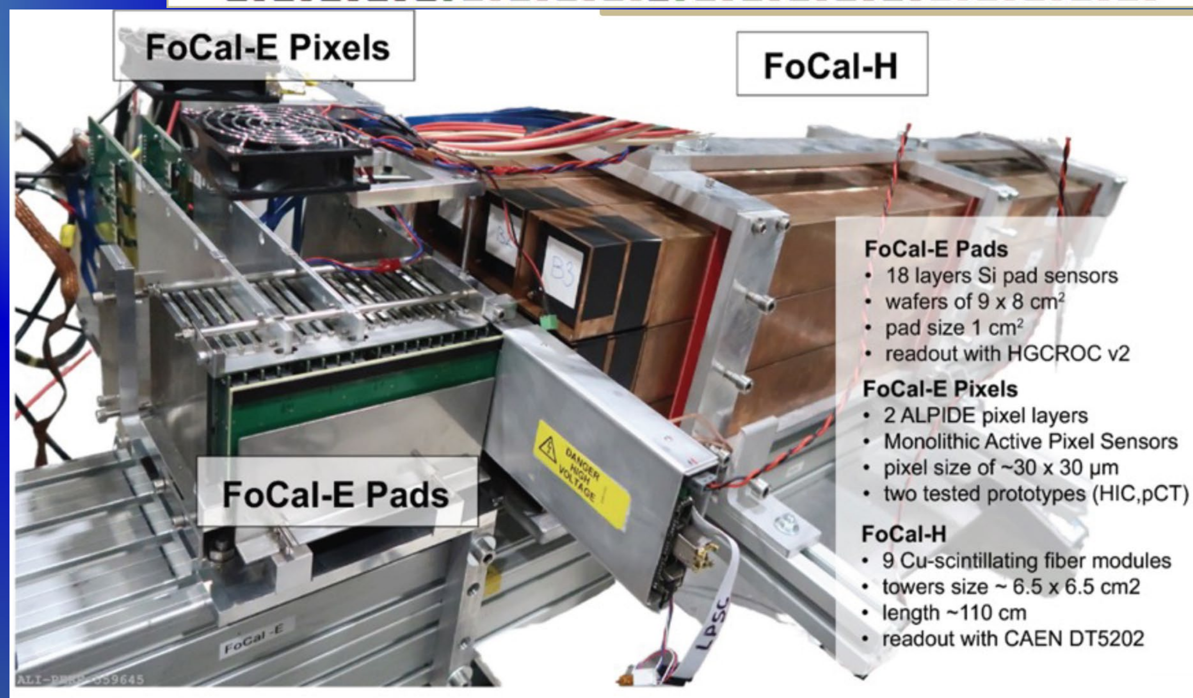




Monolithic Active Pixel Sensors (MAPS) with digital readout:

Fine granularity of pixels (better separation of showers)





DREAM (Dual REAdout Module): High Resolution HCAL

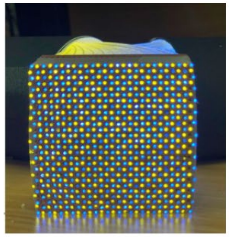
Cherenkov fibres

Scintillating fibres

Fast signals for relativistic (EM) component

Slow signals for non-relativistic (hadronic)

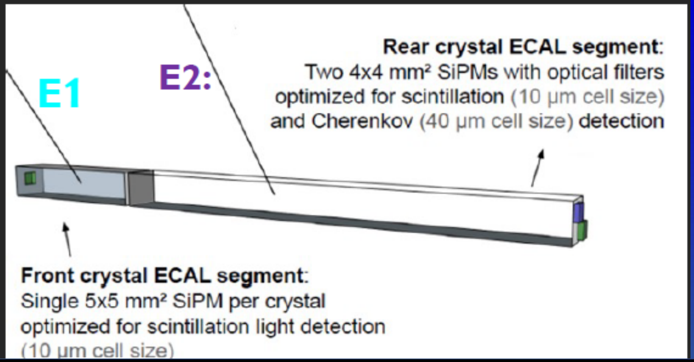
Building Blocks:



SiPM for much Better separation of Cherenkov &. scintillation light

Dual readout to capture Electromagnetic and hadronic components of shower

Scintillator and Cherenkov from the same active medium, disentangle using optical filters

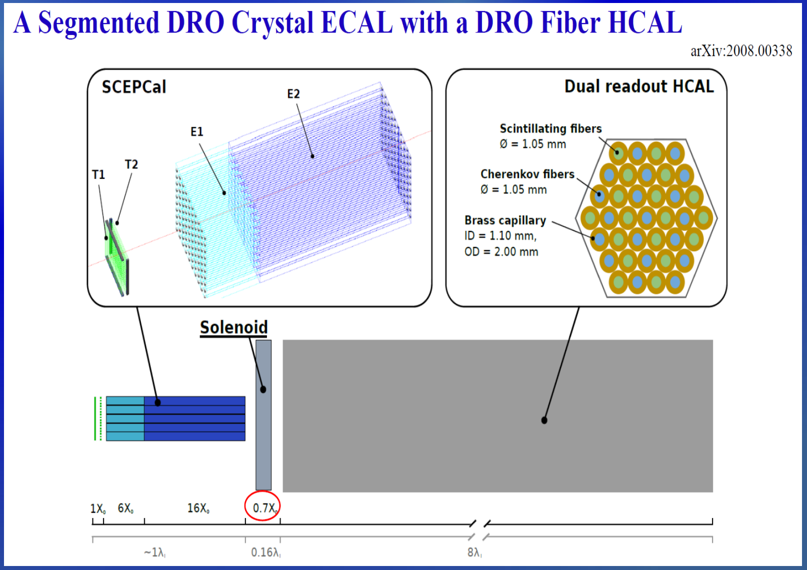


Simultaneous Detection of Cherenkov & Scintil. light:

Hadron showers :
- EM component (π^o s)
- Non-EM component (mainly soft π)

Response is different (e/h ≠ 1)

- *Cherenkov light almost exclusively produced by electromagnetic component (80% of hadronic component is non relativistic)*
- ***RECIPE:* determine electromagnetic component event by event by *comparing Č and dE/dx signals* → correct response**
- ***e/h ratio is very different for Quartz and Scintillator measurements of energy:***
  → Use Quartz fibers to sample EM component (~only!), in combination with Scintillating fibers



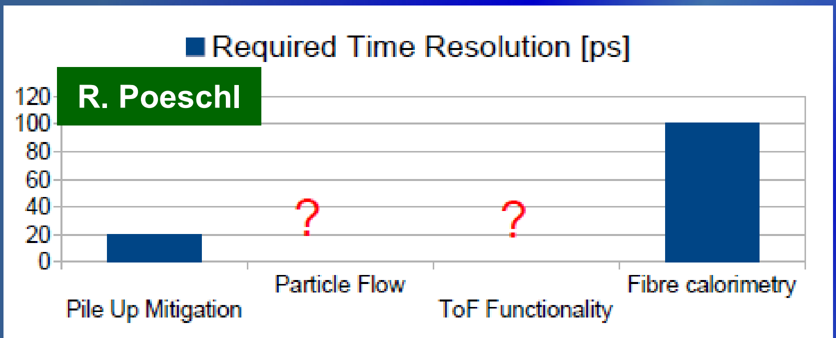
R&D Focus :
Optimize readout technologies for scintillation and Cherenkov signals – includes minimization of material between crystals to maximize sampling (-> homogeneous calorimeter)

Particle Flow (Imaging) Calorimeters: The 5th Dimension ?

Impact of 5D calorimetry (x,y,z, E, time) needs to be evaluated more deeply to undertand optimal time acc.

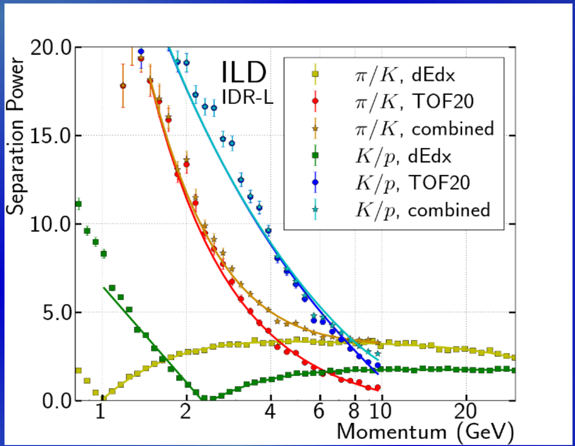
What are the real goals (physics wise)?

- *Mitigation of pile-up (basically all high rates)*
- *Support for full 5D PFA → unchartered territory*
- *Calorimeters with ToF functionality in first layers?*
- *Longitudinally unsegmented fibre calorimeters*

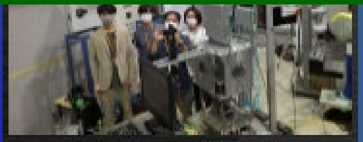


Replace (part of) ECAL with LGAD for O(10 ps) timing measurement

20 ps TOF per hit can separate π/k/p up to 5-10 GeV



T. Suehara @ILCX2021



Test beam at Tohoku October 2021

Timing resolution
Is affected by noise

Sensor	Amp. th.	Time reso.
S8664-50K (inverse)	20 mV	123 psec
	40 mV	63 psec
S2385 (normal)	20 mV	178 psec
	40 mV	89 psec

✓ **The added value of ps-timing information is well recognized:**

→ *Gain in scientific return to be quantified (Tracking PID, CaLO PID, Shower development)*

✓ **Trade-off between power consumption & timing capabilities (maybe higher noise level)**

→ *Timing in calorimeters / energetic showers?*

→ *Intelligent reconstruction using O(100) hits & NN can improve “poor” single cell timing*

→ *can help to distinguish particle types: usable for flavour tagging (b/c/s), long-lived searches (decaying to neutrals), enhance s(E) / E …*

Other Calorimetry R&D: Crystals, Scintillating/Cherenkov Fibers

Main Calorimetry concepts & techniques:

✓ **Noble Liquid** (intrinsic radiation hard, 3D imaging, good timing resolution, finely segmented readout)
→ reference design for FCC-hh, also for FCC-ee

✓ **Homogeneous crystals** (ultimate resolution)
→ CMS CALO based on $PbWO_4$

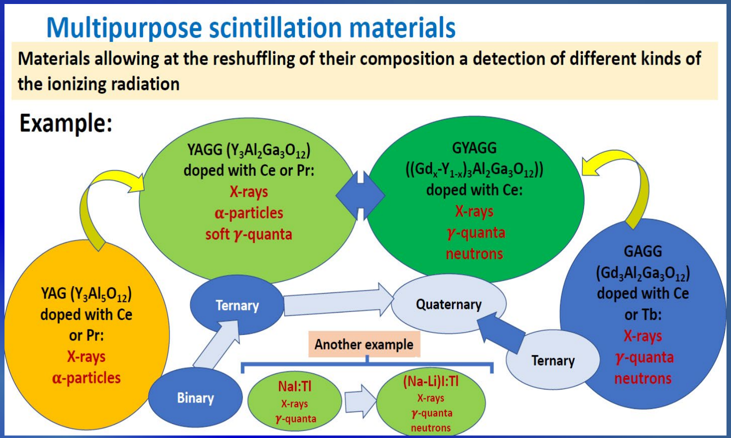
✓ **Particle Flow Calorimetry** (5D imaging)
→ ILC/CLIC concepts, CMS HGCAL

✓ **Scintillator-based** (cost-effective, mod. rad.-hard)
→ rad-hard crystals (LYSO, BaF_2 crystal scintillators, YAG, GAGG);
→ LHCb ECAL upgrade (shashlyk, spagetti-type);
→ FCC-hh hadronic barrel similar to ATLAS Tile Calo;

✓ **Dual-readout calorimetry**
→ Dual-fibre readout calorimeter for FCC-ee, CePC

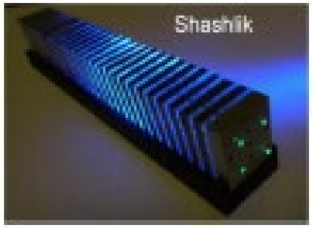
SiPMs are mostly used in HEP Calorimetry:

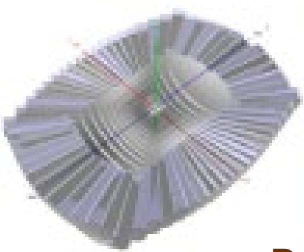
→ SiPMs readout of plastic scintillators, crystals, dual-readout calorimeters;
→ Challenge: cold operation at -30C to keep radiation damage under control



LHCb Phase-2 upgrade sampling electromagnetic crystal calorimeter

- ≃ 300 Mrad, ≃ 50 ps



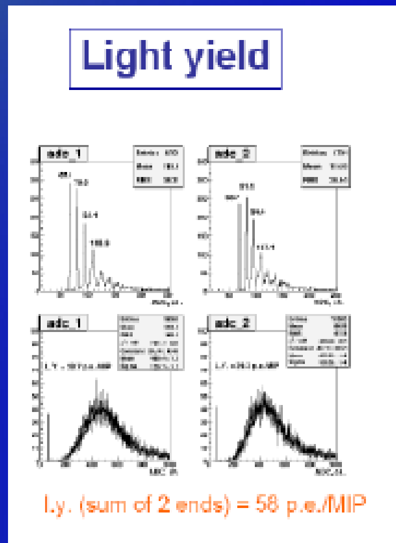


Dual-readout R&D:
32 + 32 scint./cerenkov fibers protoype
σ(E)/E≃ 10(30)%/√E + 1% for e/γ(π)

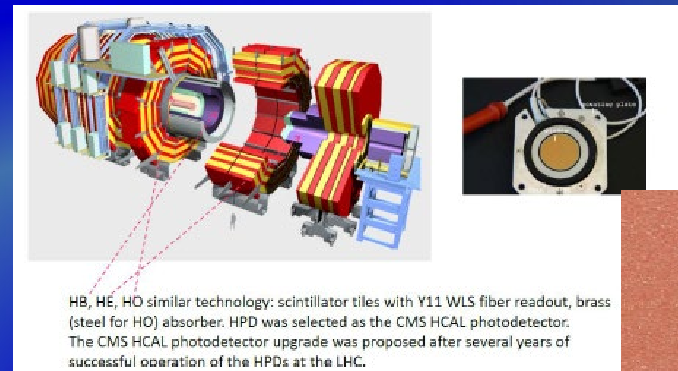
Examples of SiPM Applications in Experiments

T2K Near Detector: Large scale (~60 000) use of SiPMs: Sci-detector with WLS fibers

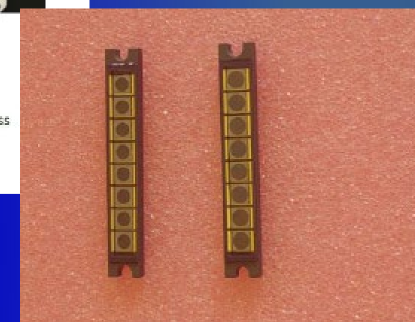
Hamamatsu MPPC:
Active area:
1.3 x 1.3 mm2



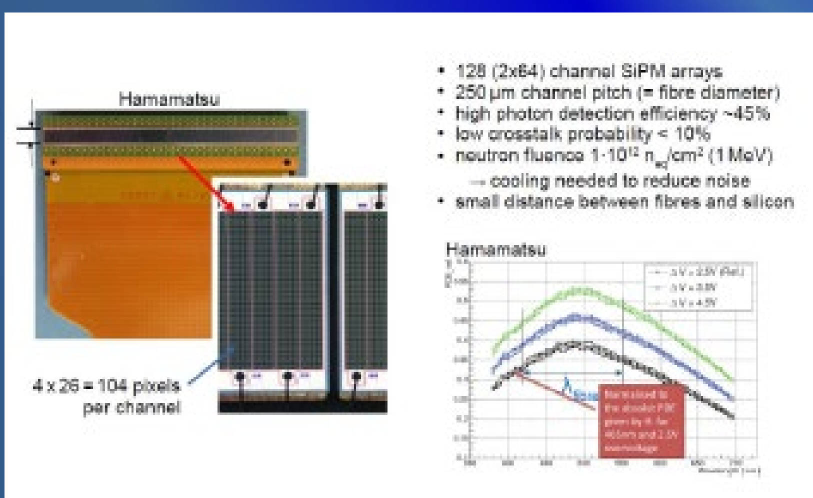
CMS HCAL Phase I Upgrade: replacement of HPDs with 20 000 SiPMs – higher QE, better immunity to magnetic fields, depth segmentation, timing (kill bkg)



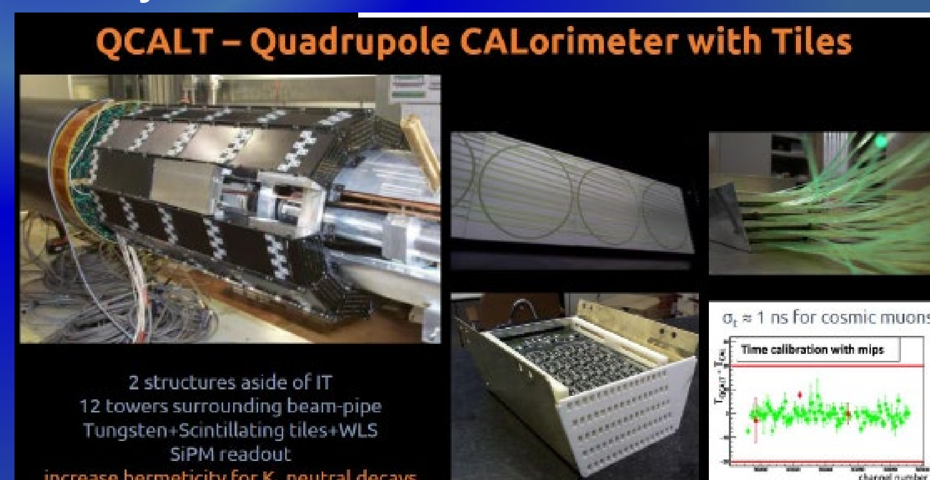
SiPM:
2.8-3.3 mm diameter

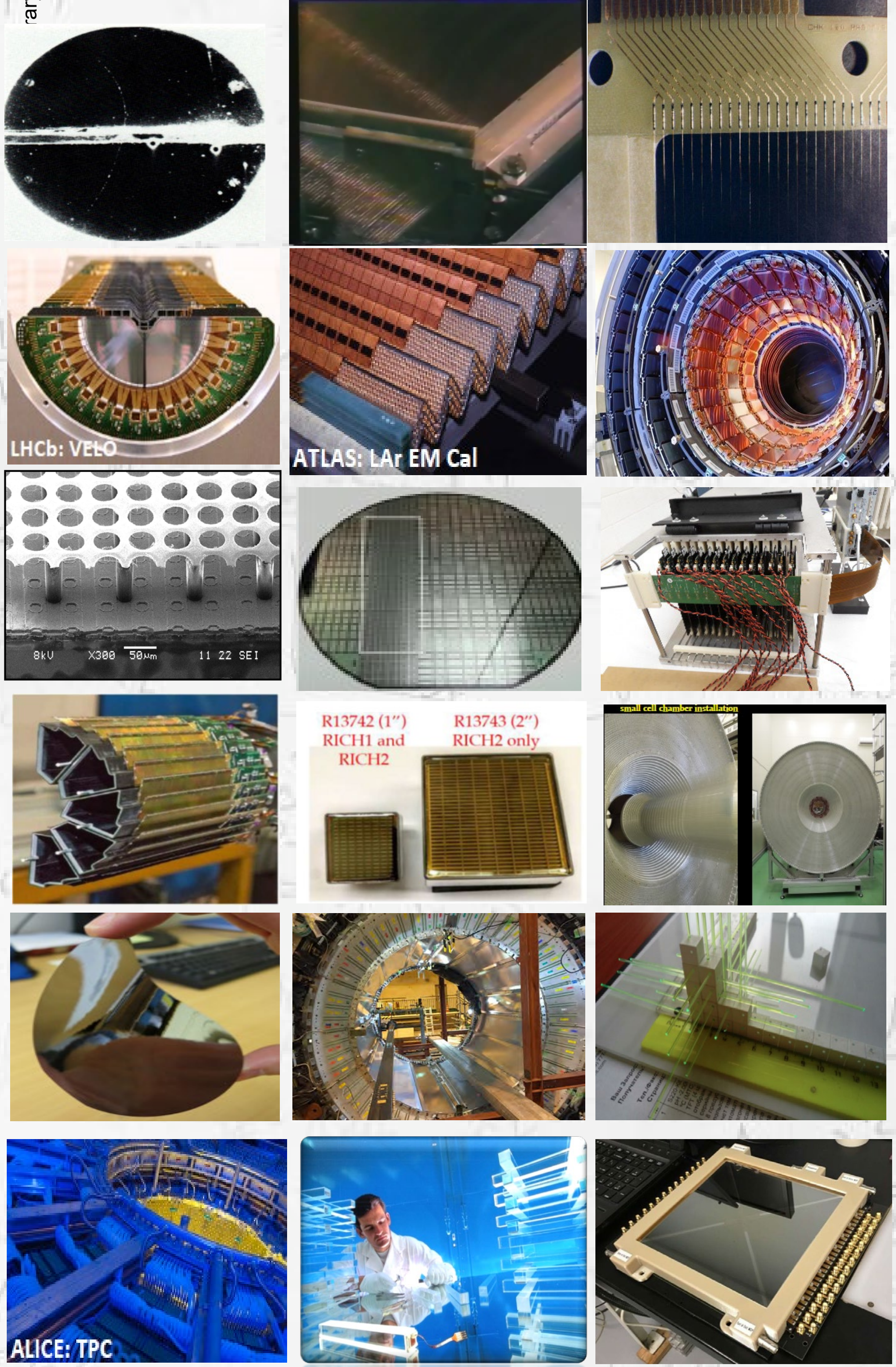


SciFi Tracker @LHCb: 6 layers of 2.5 m long Sci-fibers readout by 128 SiPM array



KLOE2 Calorimeter: SiPM will be used to read-out LYSO crystals and W/Sci tiles with WLS fibers

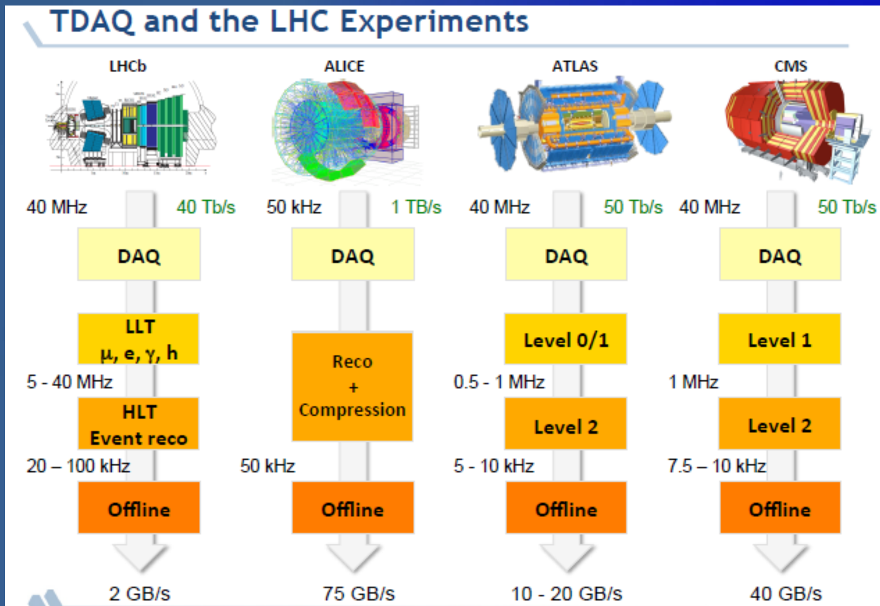


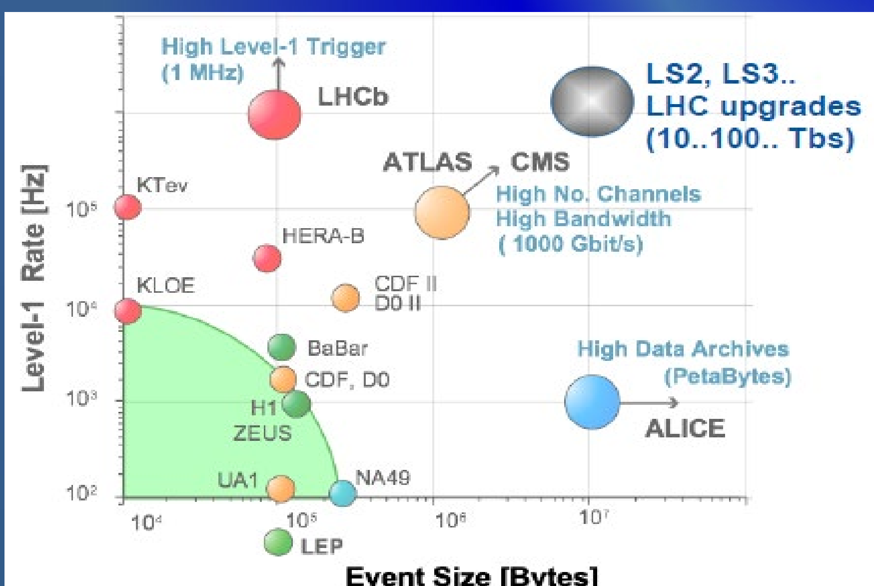


- Particle Interactions with Matter
- “Classic” Detectors (historical touch...)
- Advancing Concepts Tracking Detectors: Gaseous Detectors
- Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors
- Advancing Concepts in Picosecond-Timing Detectors
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing

Advanced Concepts in TRIGGER and DAQ (TDAQ)

Massive amounts of data coming of upgraded and next generation experiments





- Optical data transmission is key in readout modern HEP detectors:
- ✓ Current links at 10 Gb/s, and limited to 5 x 10^{15} n_{eq}/cm^2, 100 Mrad in radiation tolerance;
  → current state-of-the art – VCSEL;
- ✓ Silicon photonics for optical conversion and multiple amplitude modulation can provide high bandwidth;
- Wireless transmission (60 GHz), could allow on-detector data reduction (e. g. for trigger readout of trackers) → promising upcoming alternative

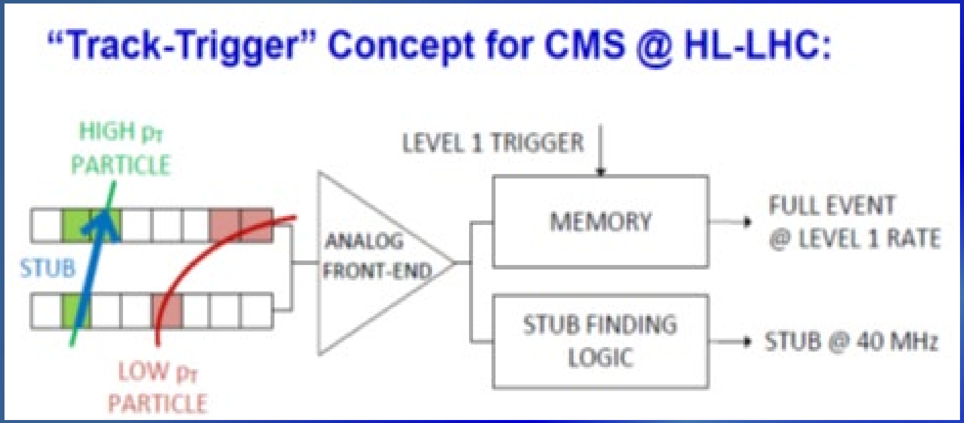
Trigger Architecture:
→ multi-layered (event building, event processing); triggerless, multi-level trigger;
Trigger Tools:
→ ASICs, ATCA, FPGA, CPU, GPU

- General trend: progressive replacement of the complex multi-stage trigger system with a single level trigger system and a large farm of Linux computers for the final online selection:

➢ ATLAS TDAQ → single-level hardware trigger (max. rate 1 MHz and 1 um latency);
➢ ALICE and LHCb will be triggerless (no hardware trigger) after LHC Phase I upgrade

"Intelligent Trackers": Frontier Application for HEP ?

"Track-Trigger" Concept for CMS @ HL-LHC:



- ✓ Cannot send all hits to trigger at 40 MHz → local "intelligence" is based on recognition of high-p_T tracks using hit correlation in 2 closely-spaced layers:

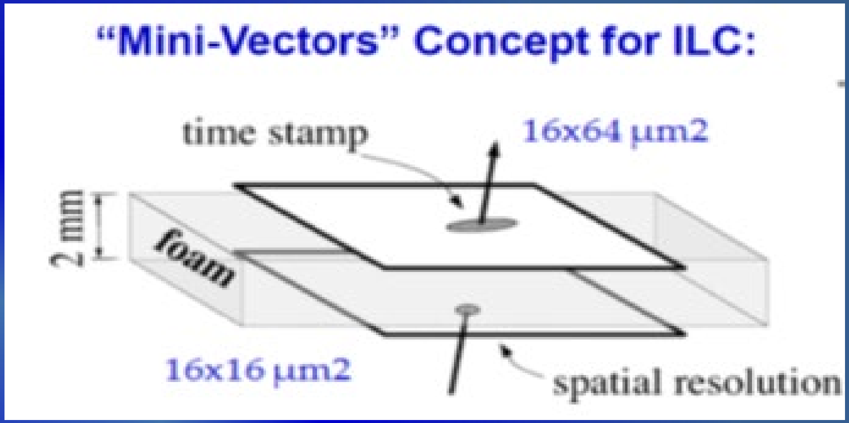
  - Store billion(s) of patterns in dedicated associated memory for L1 Track-Trigger;
  - Region of Interest Builders;
  - Advanced FPGS for data processing/transmission;

- ✓ 65 nm CMOS ASIC allows to satisfy power requirem. Despite of large amount of necessary logic @ 40 Mhz

- ✓ Particle Flow" approach now possible at L1 trigger – use information from all detectors:
  - trigger on secondary vertices using NN
  - "anomaly detection" by machine learning)

- ✓ Issues: L1 latency, backhround

"Mini-Vectors" Concept for ILC:



- ✓ ILC will run without trigger

- ✓ Develop concept of 2-sided ladders using 50 µm thin CPS → "mini-vectors" providing high spatial resolution & time stamping

- ✓ Realization of double-sided ultra-light ladders (PLUME) equipped with two complementary types of CPS

- ✓ Introduce NN in CPS to mitigate data flow from beam-related background

- ✓ Issues: high precision alignment & power cycling in high magnetic field (ILC)

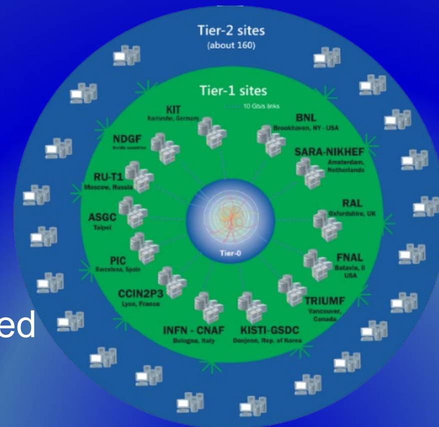
M. Winter,
R. Zhao, Dev. of CMOS sensors with on-chip artificial NN, PhD, Univ. Strasbourg, 2019

Worldwide LHC Computing Grid (WLCG) Collaboration

Initiated in 2001, an International collaboration was launched to distribute/analyse LHC data (Belle II, LBNF/DUNE and Linear colliders)

Challenges on HL-LHC computing:

- ✓ HEP computing much more capacity is needed
- ✓ New computing models and more efficient software have to be developed



WLCG Grid & Computing power:

- ✓ ~170 sites, 42 countries
- ✓ 2 million jobs / day
- ✓ CPUs: 6.500.000 of today's fastest cores

- ➢ **Additional resources are needed – Cloud computing, High-Performance Computing (HPC)**

  - Cloud resources are much more competitive in terms of cost than in the past
  - Increasing usage of HPC resources in the mid-term to long term future

- ➢ **HPC often employ GPU architectures to achieve record breaking results (towards exa-scale) - this will requite a fundamental re-write/optimization of the LHC software**

- ➢ **Modern tools and methods are used – Big-data, Machine Learning - Deep learning** (monitoring, analysis optimization, particle classification)

2018 HEP Software Fondation White paper: https://cerncourier.com/a/time-to-adapt-for-big-data/

LHC Computing - Towards a Change of Paradigm …

Machine Learning algorithms (NN, BDT, …) in particle physics has a long history:

1992:

Courtesy of J.-L. Faure


M^r FAURE

C.R. 92/13

DSM

Département d'Astrophysique, physique des Particules, physique Nucléaire et d'Instrumentation Associée

SÉMINAIRES TECHNIQUES DU DAPNIA

Le Mardi 19 Mai 1992 à 11 heures

RÉSEAUX DE NEURONES
EN PHYSIQUE
DES HAUTES ÉNERGIES

par Jean-Louis FAURE
du
Service de Physique des Particules
DSM - DAPNIA - Saclay

Ce séminaire,
fait par un non-spécialiste pour des non-spécialistes,
a pour but :

1) - D'introduire la terminologie et les méthodes utilisées par les Réseaux Neuronaux Artificiels (RNA), pour résoudre des problèmes de classification, clustering, identification, contrôle, analyse du signal ou des images, en essayant de montrer l'originalité des RNA par rapport aux méthodes plus classiques.

2) - De présenter les applications actuelles et les espoirs pour le traitement de certains problèmes de physique, en particulier en Hautes Énergies.

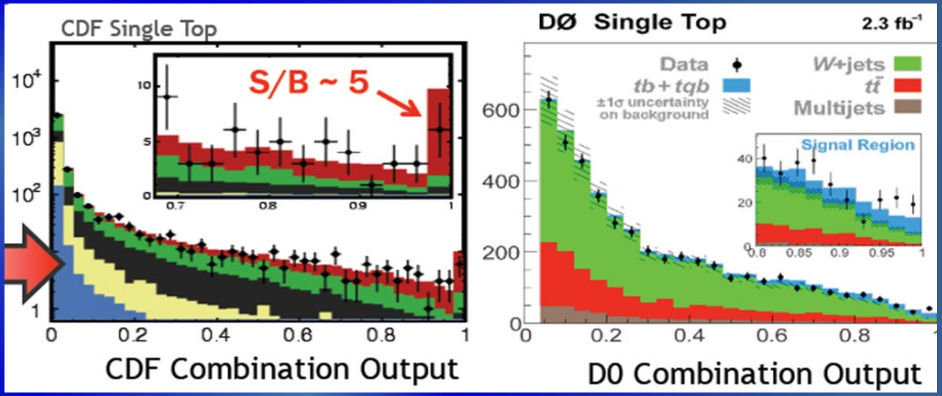
Salle «André BERTHELOT» - Bâtiment 141, pièce 143

Les séminaires techniques s'adressent à tout le personnel du DAPNIA.

DAPNIA communication

Discovery of single top quark at FNAL (before the LHC)

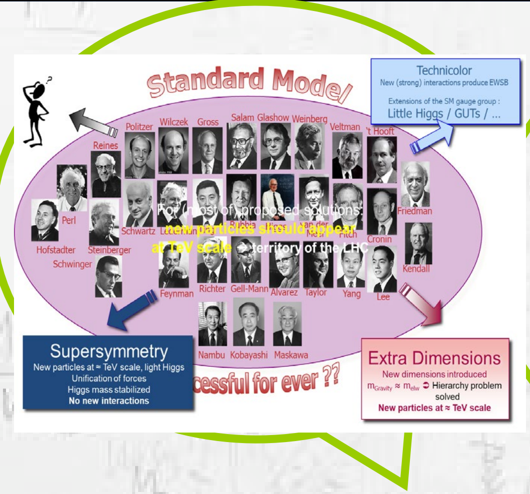
2009:



Bringing modern advances in machine learning from offline to online/trigger is a major challenge:
Machine Learning in High Energy Physics Community Paper: arXiv: 1807.02876

Computing infrastructure so far has been largely based exclusively on X86 architecture using CPUs. GPUs are gaining a lot of popularity as co-processors due to the success of Machine Learning and „Artificial Intelligence“:

- ✓ ALICE will employ a GPU based Online/Offline system (O2)
- ✓ CMS is porting part of their trigger software to run on GPU processors
- ✓ LHCb is exploring GPUs for their online data reduction
- ✓ ATLAS is developing algorithms to run on GPUs



Wide Choice of Detector Technologies to Reveal the SM Secrets

- Advancing Concepts Tracking Detectors: Gaseous Detectors
- Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors
- Advancing Concepts in Picosecond-Timing Detectors
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing

Summary of Particle Detector Physics Lectures

The progress in experimental particle physics was driven by the advances and breakthrough in instrumentation, leading to the development of new, cutting-edge technologies:

- ✓ The detrimental effect of the material budget and power consumption represents a very serious concern for a high-precision silicon vertex and tracking detectors;
- ✓ CMOS sensors offers low mass and (potentially) radiation-hard technology for future proton-proton and electron-positron colliders;
- ✓ MPGDs have become a well-established technique in the fertile field of gaseous detectors;
- ✓ Several novel concepts of picosecond-timing detectors (LGAD, LAPPD) will have numerous powerful applications in particle identification, pile-up rejection and event reconstruction;
- ✓ The story of modern calorimetry is a textbook example of physics research driving the development of an experimental method;
- ✓ The integration of advanced electronics and data transmission functionalities plays an increasingly important role and needs to be addressed;
- ✓ Bringing the modern algorithmic advances from the field of machine learning from offline applications to online operations and trigger systems is another major challenge;
- ✓ The timescales spanned by future projects in HEP, ranging from few years to many decades, constitute a challenge in itself, in addition to the complexity and diversity of the required R&D.

Replacing OUTLOOK …
A FEW WORDS OF INSPIRATION …

If, in some cataclysm, all scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis that *all things are made of atoms —little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.*
In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.

– Richard Feynman

5* Scientific Discoveries of the Last Decade In Fundamental Physics

- ✓ *Higgs Boson*
- ✓ *Gravitational Waves*
- ✓ *Black Hole Event Horizon*

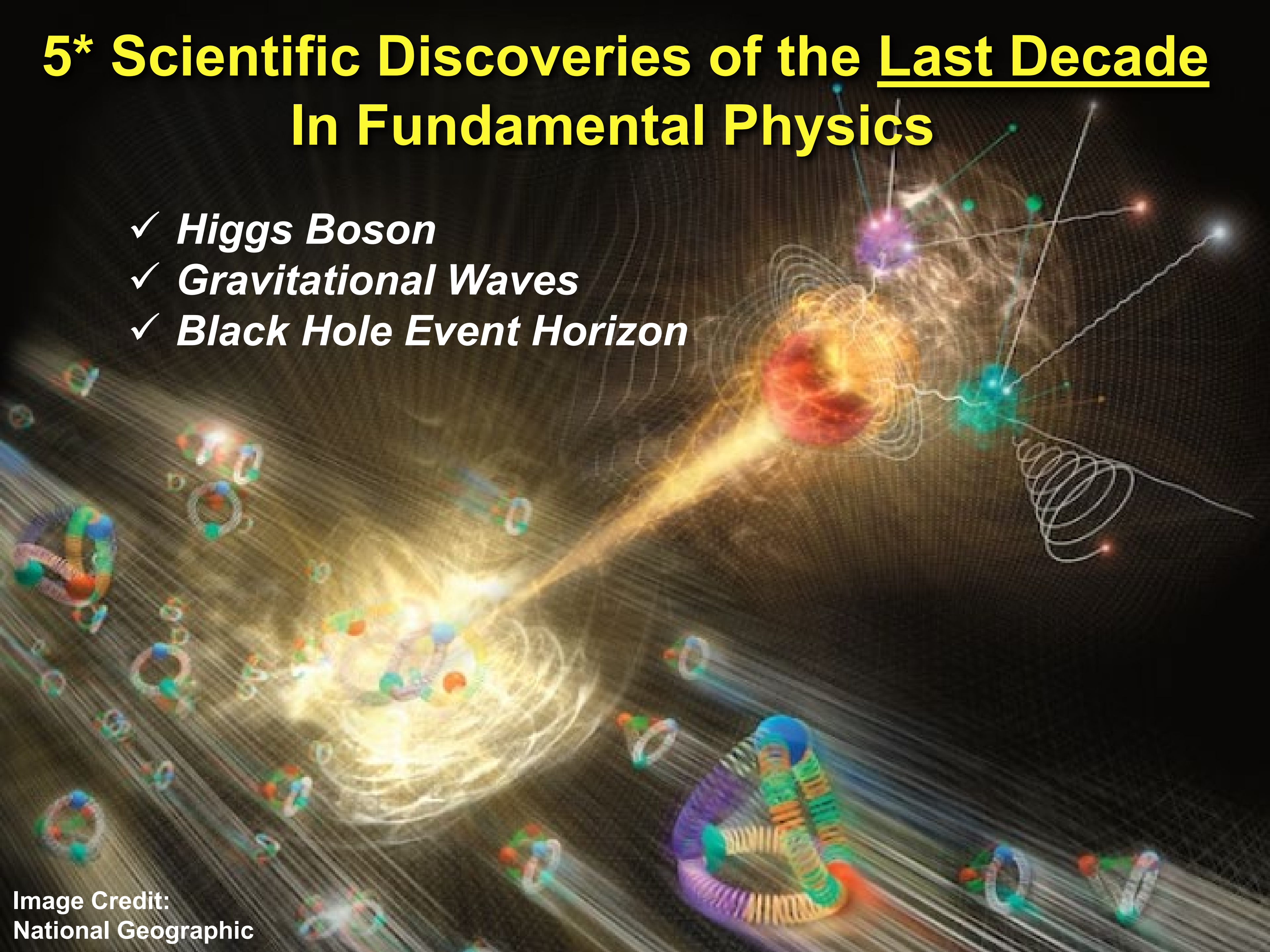


Image Credit:
National Geographic

5* Scientific Discoveries of the <u>Last Decade</u> In Fundamental Physics

- ✓ ***Higgs Boson***
- ✓ ***Gravitational Waves***
- ✓ ***Black Hole Event Horizon***

We have a "virtuous cycle", which must remain strong and un-broken: from fundamental science comes applied research and technological breakthrough, enabling novel detector concepts and techniques, which in turn lead to a greater physics discoveries and better understanding of our Universe.

Image Credit: National Geographic

Higgs Discovery at Large Hadron Collider @ CERN (2012)

"As a layman I would now say… I think we have it – It is a Discovery" (Rolf-Dieter Heuer, CERN DG)

The unique organizational structure and culture of particle physics contributed to this scientific breakthrough

Both ATLAS and CMS Collaborations have reported observation of a narrow resonance ~ 125 GeV consistent with long-sought Higgs boson

The HIGGS BOSON is part of our "origin".

We did not know on that day and still have to establish if it is – "THE HIGGS BOSON" of the SM or comes from one of the SM extensions

Gravitational Waves – LIGO Observatory (2016)

Detection by the LIGO detector of gravitational waves, or ripples in space and time, after they traveled more than a billion of light years. This confirmed a key prediction of Einstein's theory of general relativity and provided the first direct evidence that black holes merge.

M87 Black Hole – Event Horizon Telescope (2019)

What Are We Seeing in This image ?

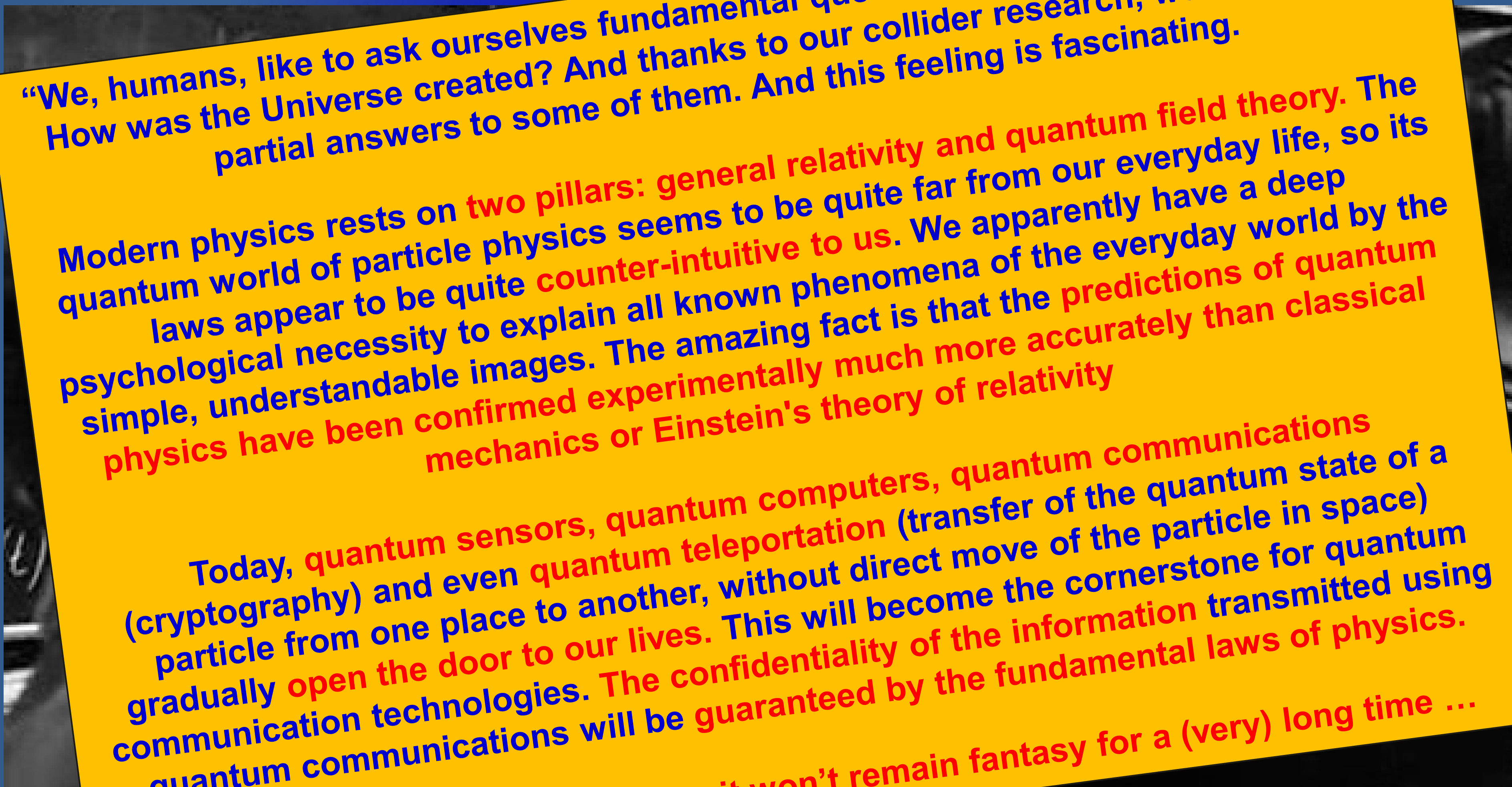
Black Holes are "Where God Divided by Zero!"

- The first **DIRECT** evidence for black holes !!!
- Black holes are **REALLY BLACK**, consistent with GR predictions
- The bright ring comes from emission of the accretion materials

Richard Feymann – The Quantum World of Particle Physics - There’s Plenty of Room at the Bottom(1959)

“The principles of quantum physics do not speak against the possibility of maneuvering things atom by atom.”

Richard Feymann – The Quantum World of Particle Physics - There’s Plenty of Room at th… 59)



“We, humans, like to ask ourselves fundamental questions. Where did we come from? How was the Universe created? And thanks to our collider research, we can provide partial answers to some of them. And this feeling is fascinating.

Modern physics rests on two pillars: general relativity and quantum field theory. The quantum world of particle physics seems to be quite far from our everyday life, so its laws appear to be quite counter-intuitive to us. We apparently have a deep psychological necessity to explain all known phenomena of the everyday world by the simple, understandable images. The amazing fact is that the predictions of quantum physics have been confirmed experimentally much more accurately than classical mechanics or Einstein's theory of relativity

Today, quantum sensors, quantum computers, quantum communications (cryptography) and even quantum teleportation (transfer of the quantum state of a particle from one place to another, without direct move of the particle in space) gradually open the door to our lives. This will become the cornerstone for quantum communication technologies. The confidentiality of the information transmitted using quantum communications will be guaranteed by the fundamental laws of physics.

For now, it’s a fantasy... Hopefully, it won’t remain fantasy for a (very) long time …

… quantum physics do not speak against the possibility of maneuvering things atom by atom.”

One Day at CERN in 2050 …

THE DAILY TELEGRAPH Monday.

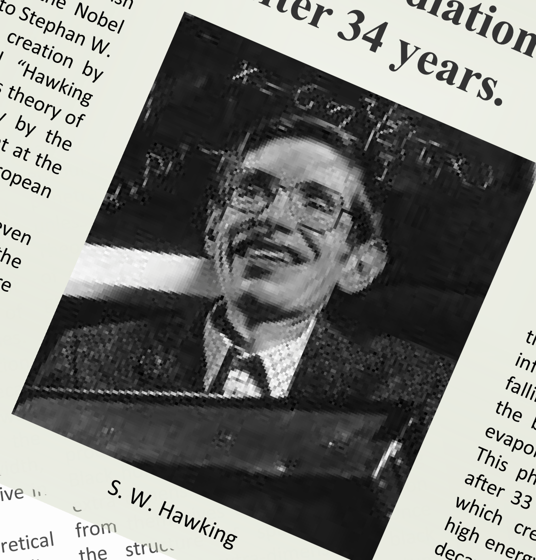
The Daily Telegraph

News 9

Hawking's "luminous" victory!

Stephen Hawking's black hole radiation theory is proven experimentally at CERN after 34 years.

CAMBRIDGE, 17 November: The Sweedish Royal Academy has announced that the Nobel Price in Physics for this year will go to Stephan W. Hawking for his theory of particle creation by black holes, which is also named "Hawking radiation" after its founder. Hawking's theory of black hole decay was proved recently by the famous black hole production experiment at the LArge Hadron Collider (LHC) of CERN (European Center for Nuclear REsearch.
Black holes are such objects from which even light cannot escape. Since lightspeed is the ultimate speed in universe, black holes are objects from which no escape is possible. However this idea was completely changed by a revolutionary paper by Hawking published in 1975 which suggested that black holes could emit radiation via a



S. W. Hawking

complicated quantum mechanical process. Briefly this idea states that spacetime near a black hole is not a classical vacuum. Energy fluctuations near a black hole creates particle-antiparticle pairs among which the antiparticle with negative energy enters the black hole while the particle with positive energy flies off to infinity. Negative energy of the antiparticle falling into the black hole reduces the mass of the black hole, therefore black hole seems to evaporate and emit particles.
This phenomena was finaly observed in CERN after 33 years of its proposal in an experiment which created miniature black holes through high energy proton collisions. These black holes decayed immediately after their production, emitting a spectrum of high multiplicity of particle species.

Late Edition
New York: Today, partly sunny then a few clouds, high 41. Tonight, increasing clouds, low 33. Tomorrow, increasing wind, high 40. Yesterday, high 40, low 29. Details, Page 38.
THREE DOLLARS

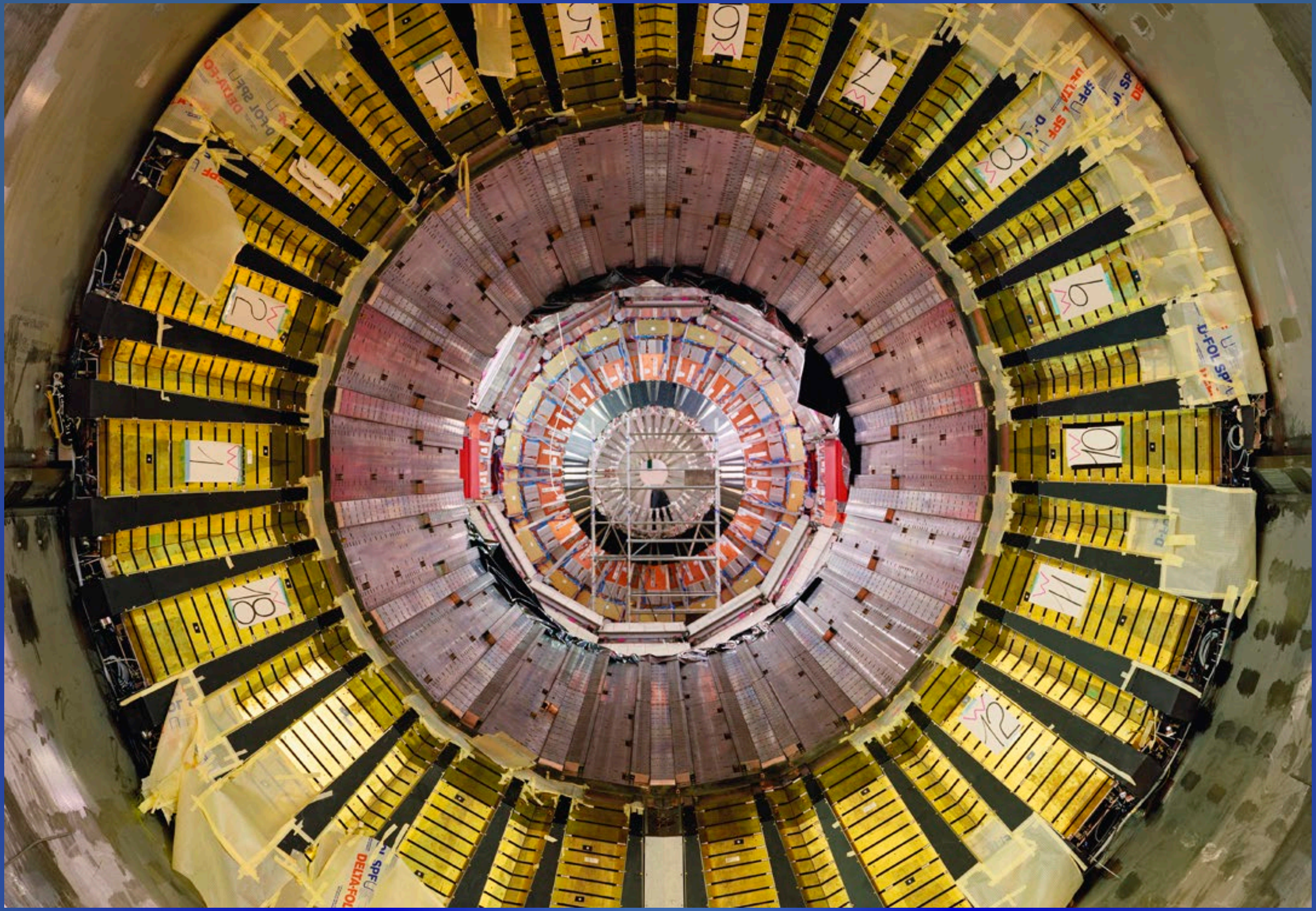
…imes

live in … quantum m… spectrum. As… decay product… among the dat… properties to da…

fac… spaceti… Direct exp… coming from th… temperature of black… that spacetime has more… four dimensions (length, … height and time) that we perceive in … everyday life.
In recent years, many theoretical assumptions predicted the possibility for the existence of extra dimensions in spacetime, but till now these extra dimensions were not observed since firstly they open up at only very small distance scales and secondly, the

from … the struc… formed, the … holes decay thr… mechanical process … radiation abd the decay prod… be studied

Who Knows …



Knowledge is limited. Whereas the Imagination embraces the entire world… Albert Einstein

Bridge the gap between science and society …

The Role of Big High Energy Physics Laboratories, like CERN – innovate, discover, publish, share

… in order to bring the world (a little bit) closer together