Requirements, emerging technologies and challenges for detectors at future colliders

LHCP, 09/06/2021

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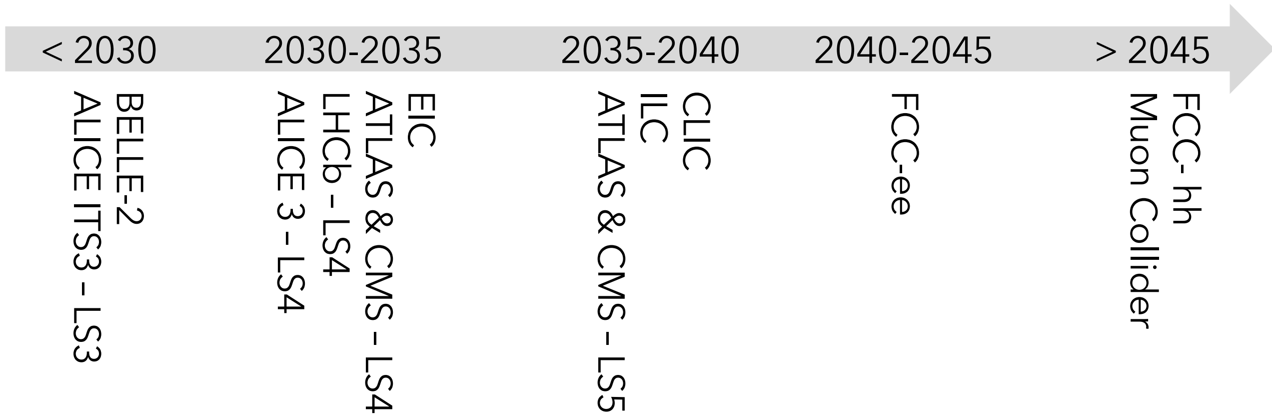
Upgrades and new collider projects timeline



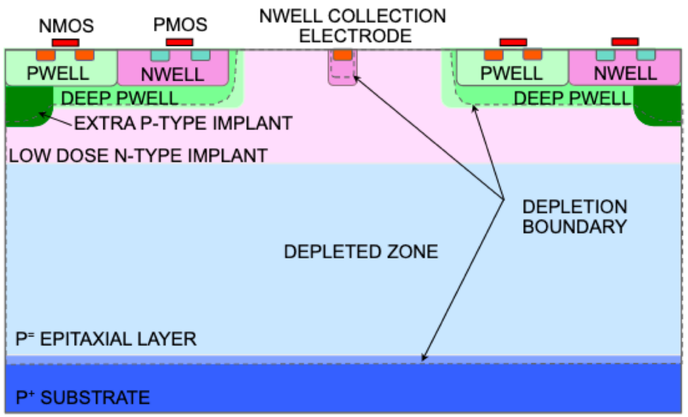
Walk through new experimental paradigms and a (limited) selection of R&D topics

- Representative of other program needs, QCD, rare decays/phenomena, Neutrino, Dark Matter…
- Main resource:
  - ECFA R&D roadmap process: https://indico.cern.ch/event/957057/
  - Input from future facilities: https://indico.cern.ch/event/957057/page/21634-input-from-future-facilities
  - Task force's symposia: https://indico.cern.ch/event/957057/program

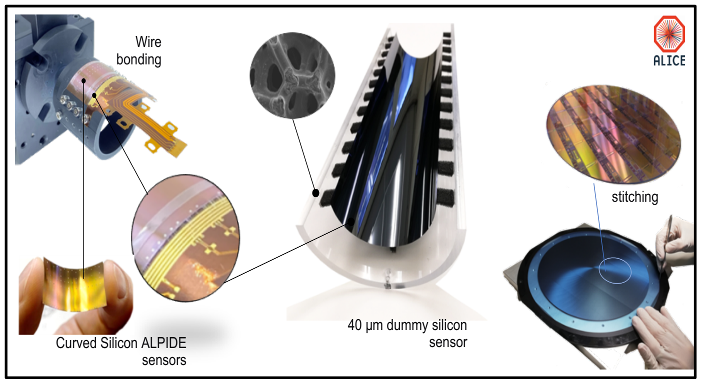
Note: glossary of acronyms at the end of the presentation

Ultimate position precision for Vertex Detectors (σ_{IP})

- ALICE ITS3 in LS3 (2025) target $\sigma_{hit} \simeq 3$ µm, $X/X_0^* \simeq 0.05\%$ / layer
  - ➢ MAPS 65 nm node (10-20 µm pitch), 12″ wafer with stitching (no PCB), ultra low power ≃ 20 mW/cm^2 (gas flow cooling), thickness down to 20 µm (bending) and ultra-light mechanics
- Further project needs
  - Up to O(100) MHz/cm^2, CLIC up to 6 GHz/cm^2, FCC-hh up to 30 GHz/cm^2
  - Also benefit with BC identification O(ns) time stamp for BIB rejection, possibly ultrafast timing
  - ➢ Step(s) to ≲ 28 nm and/or 3D integration while maintaining ultralow power and X/X_0



A recent design optimized for rad. tol. and timing



ALICE ITS3 upgrade proposal

* *X/X_0 could become the limiting factor to precision - low X/X_0 beam pipe, layers inside, also for low radius benefit, being considered*

Ultimate position precision for Tracking (σ_{Pt})

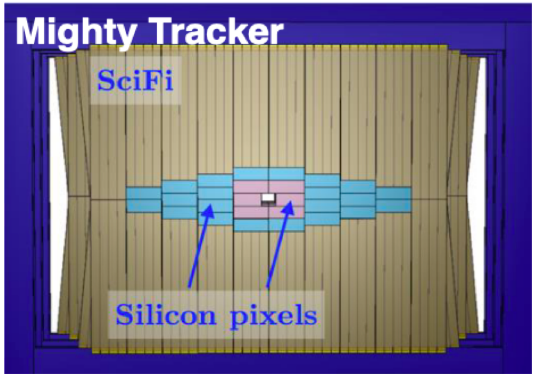
- FCC-ee at Z-peak is the most demanding, BES limit is $\sigma(p_T)/p_T \simeq 10^{-3}$*
  - ➢ MAPS with granularity tuning, possibly larger size or grouped pixels for power optimization**
    - X/X_0 in tracker typically larger due to detector area O(x20) VD
- First occurrence in LHCb & ALICE-3 LS4, EIC (2031)

LHCb post LS4: first large scale application 30 m^2

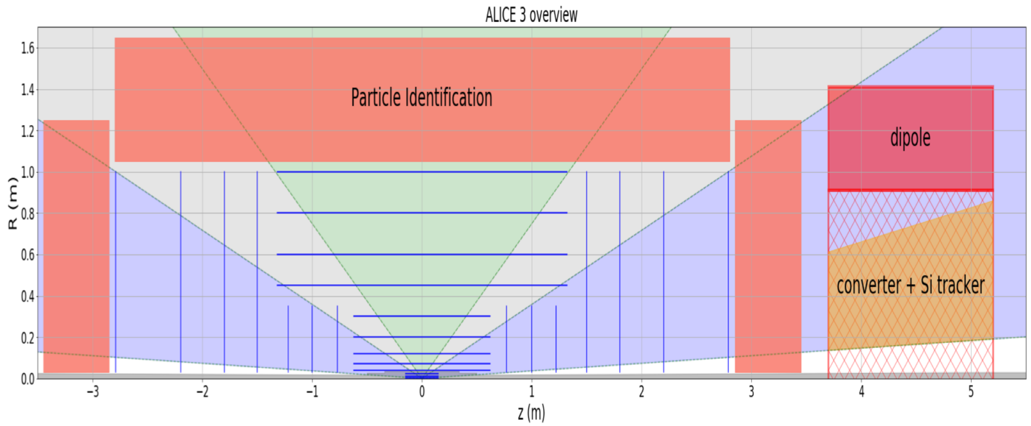
UT upstream magnet 6 m^2

MT at low r within SciFi 20 m^2

- 50 x 150 – 100 x 300 pitch
- $\lesssim 5 \times 10^{14}$ neq/cm^2



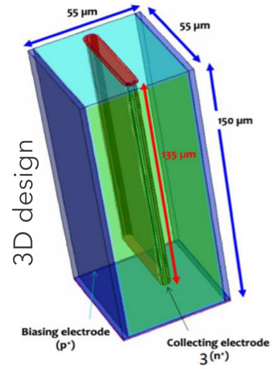
Alice-3 (LS4) – MAPS 20 µm pitch - BC timing 25 ns - 10^{13} neq/cm^2

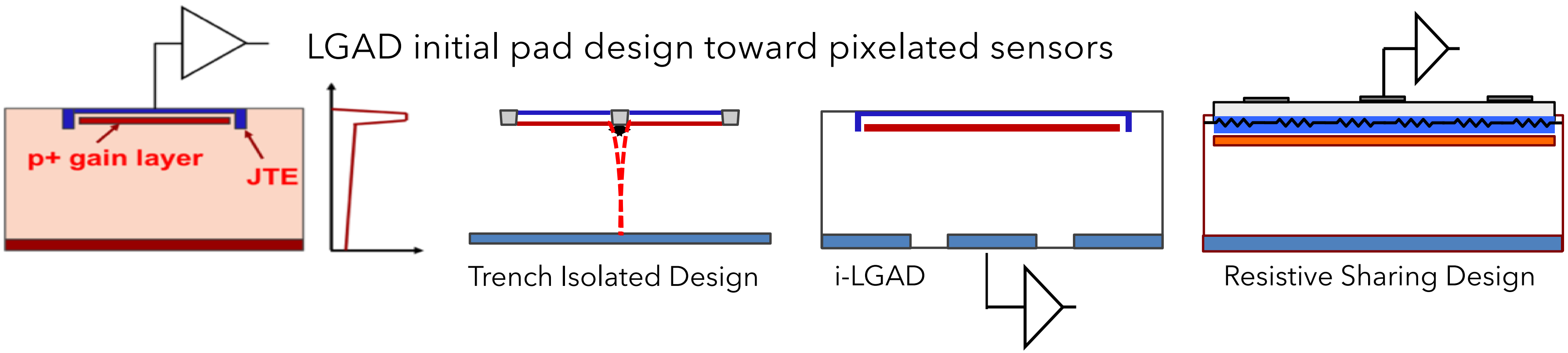


* *Requirements are usually less demanding but still targeting unprecedented* $\sigma_{hit} \simeq$ 7 µm at low $X/X_0 \lesssim 1\%$ / layer
** *TPC and DCs are low X/X_0 alternative at relatively low rates e-e colliders - see slide 11*

4D tracking with ultrafast timing (σ_t)

- Hit & track-vertex time association provides ultimate BIB/PU rejection at e-e/hh colliders, could enable correction of time-dependent parameters within BCs*
  - ➢ MAPS, planar/3D/passive CMOS exploiting timing capabilities w/o amplification
    - Targeting σ_t O(≲100) ps with specific designs – by geometry 3D should be best
  - ➢ LGADs w/ amplification, at 100 % fill factor, VD pitch, large area, monolithic design
    - Targeting σ_t O(≲10) ps **
  - ➢ Ultrafast FE, rise time ≃ to signal O(100's) ps, @ low power consumption
  - ➢ Detector configuration optimized for X/X_0, eg all/dedicated layers, preferably tracking than VD…





* ex. BES within BC correction at FCC-ee would ideally require O(5) ps precision

** Also relevant for ToF PID layers, see slide 10

Extreme radiation tolerance

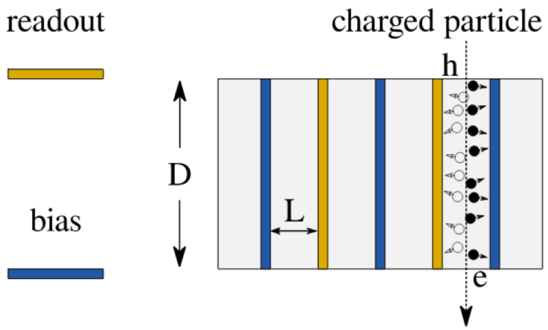
- Major challenge for FCC-hh no current technologies can survive below 30 cm*
    - Both sensors and ASICs

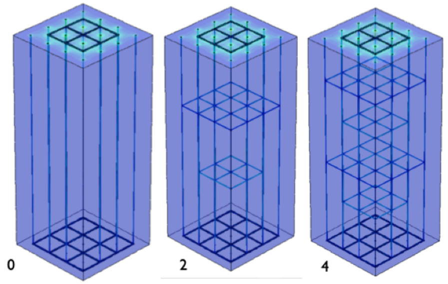
➢ Behavior beyond neq $10^{17}/cm^2$ not really known, models may be too pessimistic
- 3D, thin & planar … may approach needs Diamond is a good candidate
- Other WBG semiconductors GaInP, GaAs, GaN, SiC WBG now commercially used to be evaluated
- New materials 2D graphene and metamaterials are also options to consider

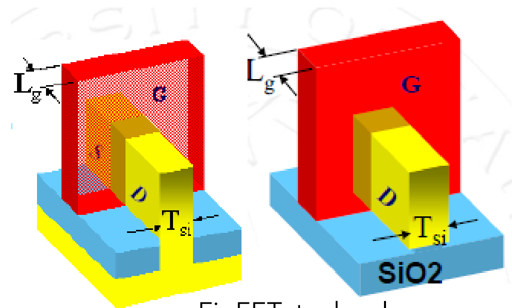
➢ Qualification at NIEL $\gtrsim 10^{17}$ neq/cm^2 is an issue in itself

- ex. CVD-diamond semiconductor pixel sensors
    - New 3D design with laser graphitization process for thin low ρ electrodes
    - In depth field optimization readout structures
    - Need scaling for production of large areas

- ex. ASICs
    - Deeper nodes in 3D do not guaranty rad. tol.
    - Higher dielectric thick oxide (multiple) gates
    - Carbon based process beyond CMOS, nanotube, graphene







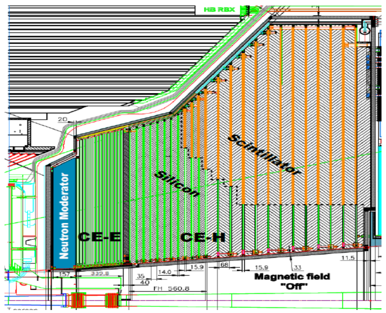
ex. FinFET technology

** But also several current technologies would not fulfill needs at relatively large radii, limits already hit at HL-LHC for: ASICs, Si, Scint., SiPMs… increased rad. tol. highly desirable for LHCb upgrade-2 VD, replacement of ATLAS/CMS VD and Timing LGADs*

Calorimetry Particle Flow & Dual EM/Had. in all concepts

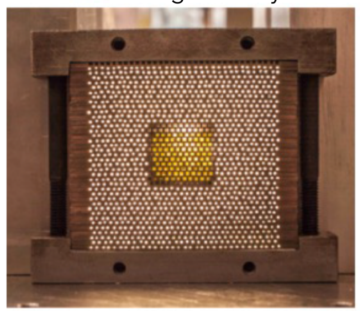
- PFlow to profit of det. with best precision (eg. tracker for charged particles)
  - Mostly driven by ⊥ & // granularity or shower containment
- Dual EM & Had. shower component measurements for e/γ – π ID and energy compensation
  - Mostly driven by // segmentation or physical dual signal readout (Cerenkov/Scintillating light)

High ⊥ & // granularity
Si-pads/Scint tiles

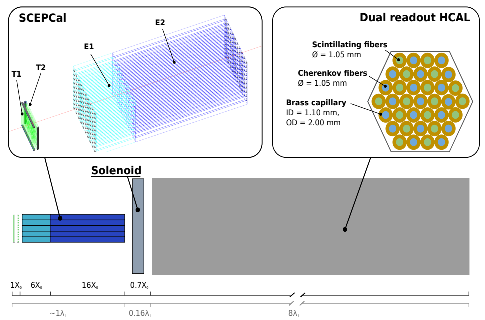


Shashlik EM concept with
fine ⊥ granularity

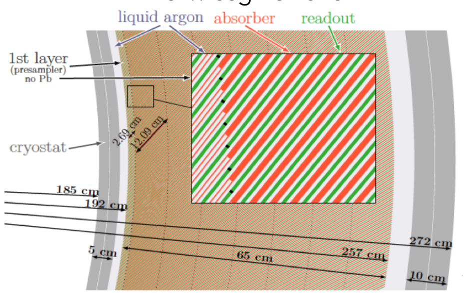
Spaghetti concept
fine ⊥ granularity



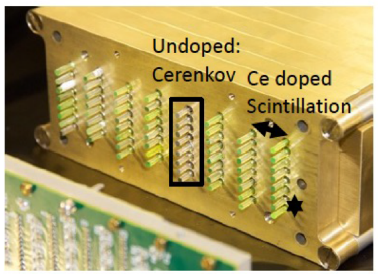
Homogenous DR EM + DR Hadronic



LAr multilayer electrode design
for // segmentation



Shashlik EM concept
extended to DR



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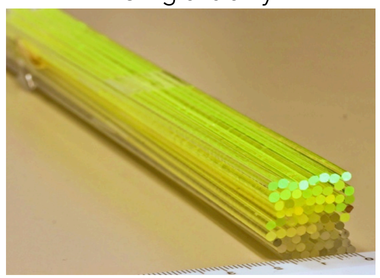
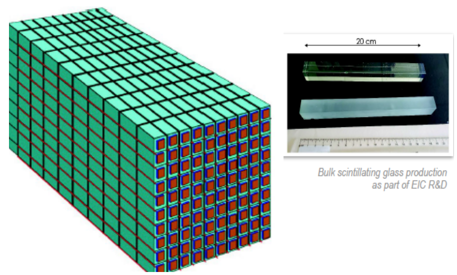


Homogenous hadronic
⊥ & // granularity

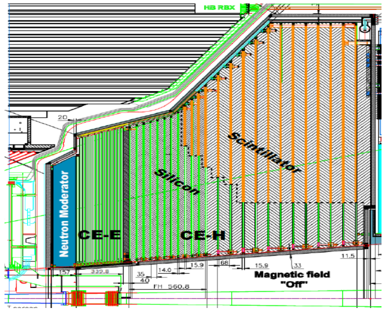


Calorimetry Particle Flow & Dual EM/Had. in all concepts

- Different sampling concept are reaching similar ballpark performance, while homogenous design can provide ultimate energy resolution, especially for γs

➢ Novel designs, heterogenous, can drive experimental choices toward specific environment (background, PU) & physics focus e/γ, jets, momentum range…

High ⊥ & // granularity
Si-pads/Scint tiles



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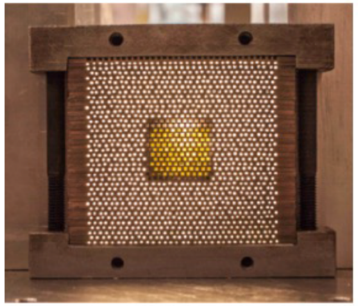
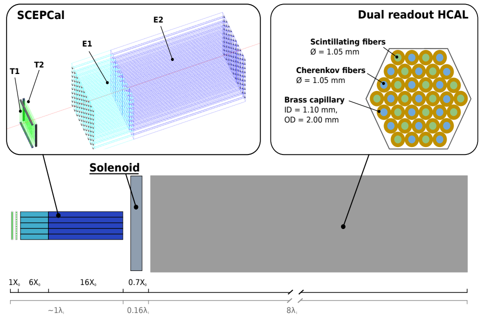
Spaghetti concept
fine ⊥ granularity



Homogenous DR EM + DR Hadronic



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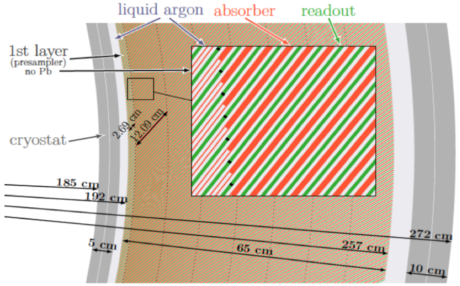
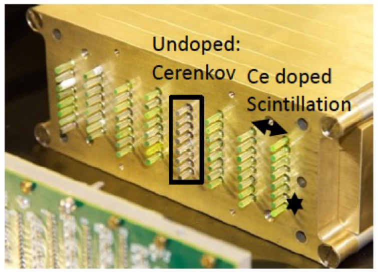
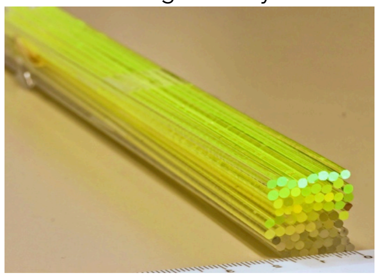


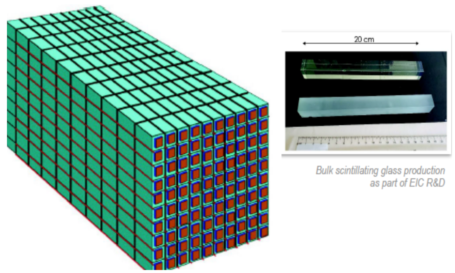
Shashlik EM concept
extended to DR



Homogenous DR EM with
fine ⊥ granularity



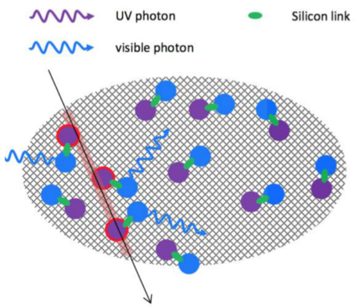
Homogenous hadronic
⊥ & // granularity



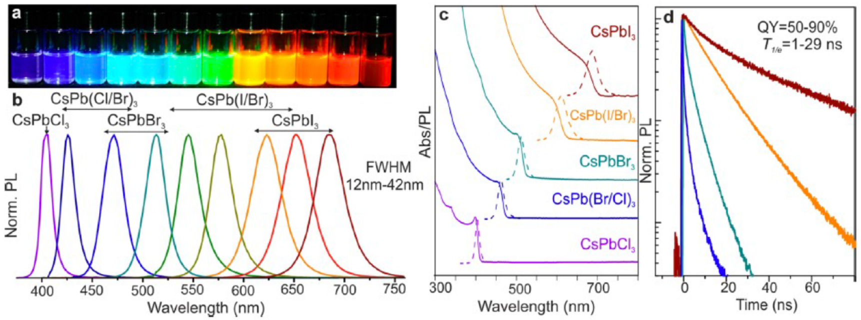
5D calorimetry with ultrafast timing*

- Several use cases, PU mitigation, 2γ-vertexing, shower origin (DR), separation of Ceren./Scint. in single material (O(10) GHz sampling) – shower reconstruction precision with ML techniques
  - ➢ Silicon option, see slides 5 (LAPPD could be an option, see slide 15)
  - ➢ Scintillating/Cerenkov light devices**
    - New materials and doping: ex. SiO_2:Ce_3 provide both Cerenkov and Scintillation light
    - Nano materials: luminophore higher light yield, faster, more rad. tol. - quantum dots embedded in solution, polymer or on passive material surface, faster, possible tuning of λ-emission with dot size
    - Heterogenous materials, exploiting 3D printing for unconventional shapes
  - ➢ Ultrafast analog or digital photoconverters SiPM(SPAD) adapted to new materials, see slide 15

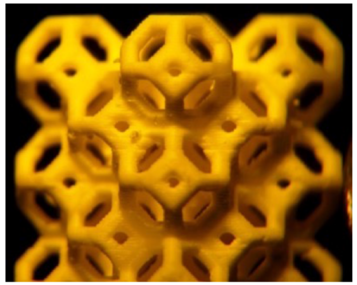
Nano materials luminophore



Quantum dot ex. perovskite embedded in polymer



YAG 3D printing in ≃ 30 nm layers

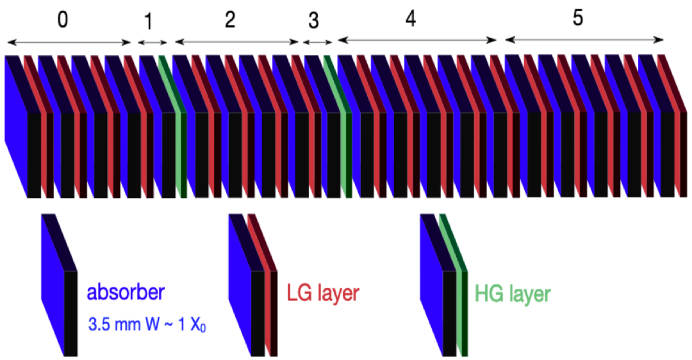


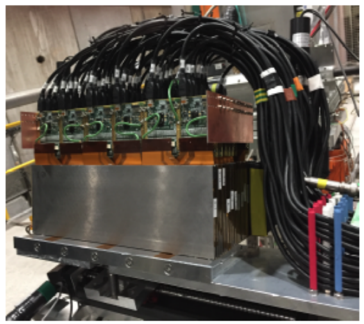
* First implementation @ $\sigma_t \simeq 50$ ps per cell in CMS HGC – overall precision depends on # cells (energy), 80 MHz sampling in CMS Crystal ECAL
Next step LHCb Upgrade-2 SPACAL, Shashlik design with σ_t O(10) ps

** Also relevant for ToF PID layers, see slide 10, ex. CMS LYSO crystal layer MTD

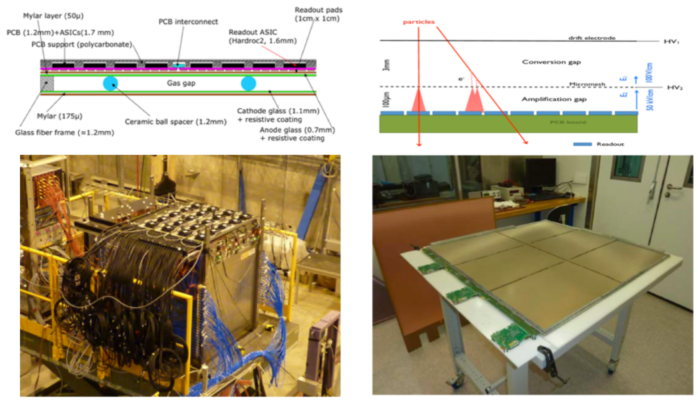
Digital high granularity calorimetry

- Measure energy by hit counting
  - MAPS for EM section**
    - Granularity versus performance & power dissipation, compactness - sampling fraction
  - Scintillating tiles, RPCs, MPGDs for Had. section
    - Granularity versus performance & power dissipation, compactness - sampling fraction
    - New resistive designs for MPGDs RPWell – MicroMegas (see slide 12 and 16)





ALICE LS3 2025 FOrwardCALorimeter heterogenous design and prototype



RPC & MicroMegas 2 bits (3 thresh.) semi-digital in 1m^3 prototype (GEM layers in preparation)

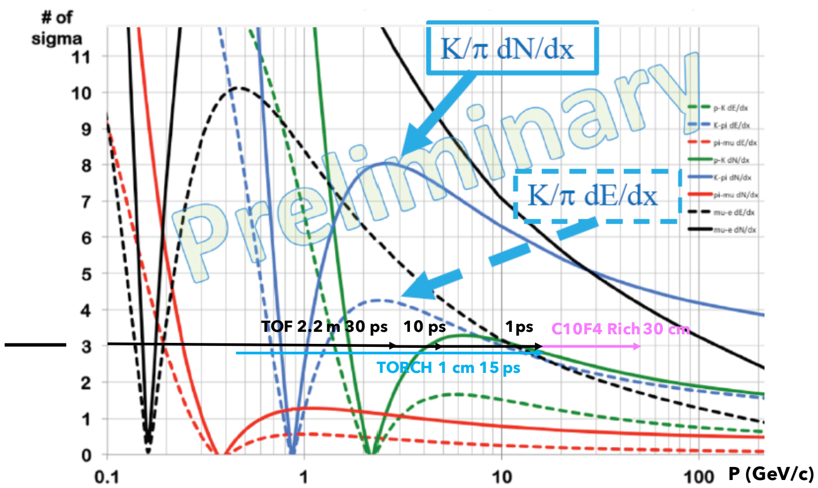
** Monolithic and/or 3D integration CMOS sensors with pads can also be considered for analog calorimetry for compactness*

Particle Identification, extending p_T coverage

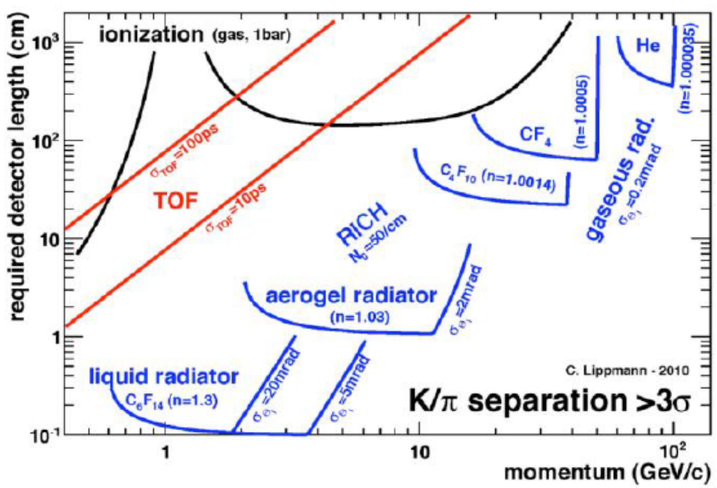
- TPC or Drift Chambers (DC), dE/dx and/or dN_{cl}/dx
  - Crossing at 1 -2 GeV requires another measurement – well adapted to barrel also provides tracking
- RICH, β through Cerenkov angle
  - Different refractive index and expansion volumes needed to cover p-range - adapted to forward regions
- DIRC, combining Cerenkov angle (reflection) and ToP - ToF
  - Thin quartz radiators w/ or w/o expansion for intermediate p-range both in barrel and forward regions
- ToF, direct β measurement
  - Si/Scint./MPGD thin layer(s) adapted to cover low-intermediate p-range both in barrel & forward regions

IDEA DC PID simulation - - - dE/dx —— dN_{cl}/dx

3σ π/K separation with typical ToF (@2m), Torch (DIRC) & Rich

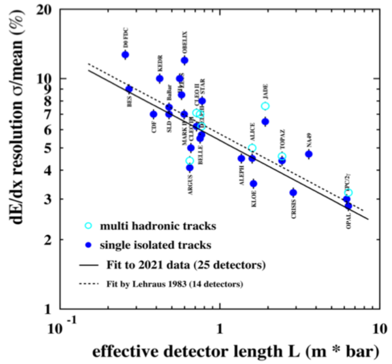


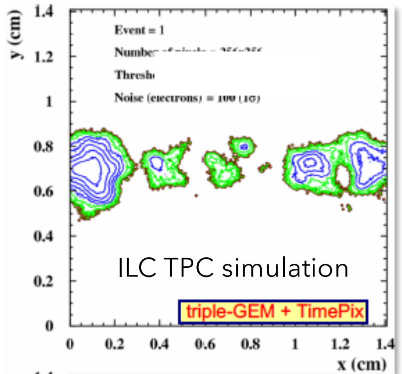
RICH radiators

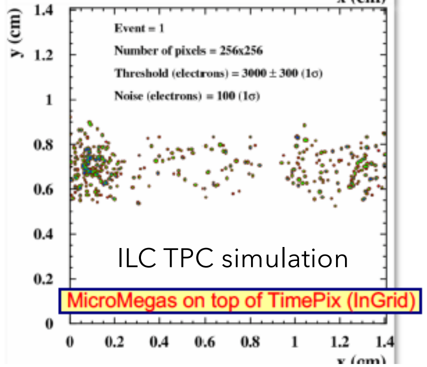


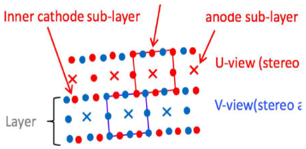
TPC – DC with dE/dx and dN_{cl}/dx

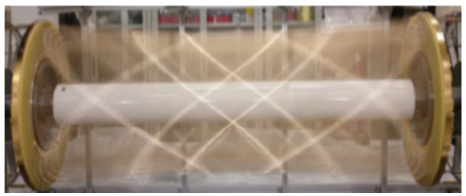
- dE/dx, typical resolution 5% for 1 m.bar
  - High pressure can improve PID (and p-range)
- ➢ dN_{cl}/dx, ≳ x2 better resolution at same depth
  - In x-y space in TPCs (diffusion may be a limiting factor)
    - High granularity MPGD RO, possibly 3D with σ_t O(1) ns
  - In time in DC
    - Signal sampling @ ≳ 1 GHz
- ➢ Combination could be optimal at p relativistic rise
- For tracking TPC & DC provide O(100) x $\sigma_{hit} \simeq$ 100 µm & low X/X_0
  - ➢ ex. IDEA DC @ FCC-ee 1.6 (5%) X/X_0 barrel(endcap), $\sigma(p_T)/p_T \simeq 3 \times 10^{-3}$*
    - Carbon wires - new assembly techniques
  - ➢ ex. TPC GEM and MicroMegas RO
    - Pixel pitch O(50) µm, resistive DLC layer (AC coupling) to tune ρ, monolithic design





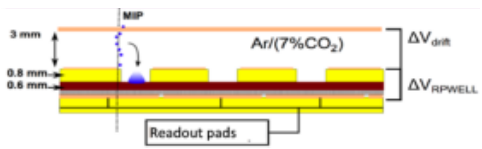


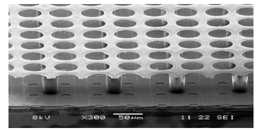




MEG-2 He Drift Chamber

GEM and MicroMegas new RO designs



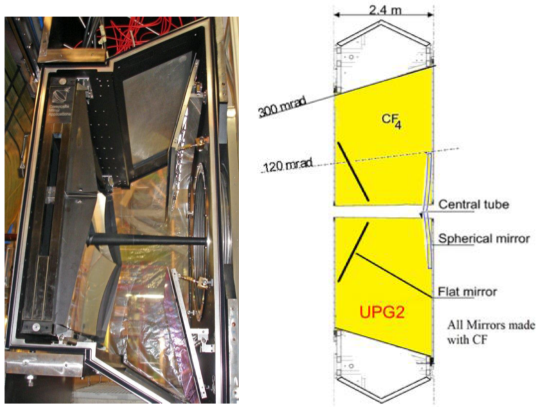


High granularity resistive AC designs RPWELL (left) & MM middle, InGrid CMOS on timepix monolithic (right) - eco-friendly gas Ar:CO2 - high rate sparkles capability for muon detection

* *With a Si wrapping layer at outer radius*

RICH with new designs and radiator materials

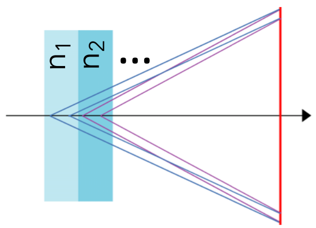
- ex. LHCb (gas) up to p ≃ 100 GeV, $\sigma_\Theta \simeq 0.2$ mrad
  - ➢ Light optical elements in acceptance - higher granularity with longer lever arm and/or smaller pixel size, photosensors with high QE in green to enhance signal for timing
    - Light mirrors, high reflection coating
    - MPPC with 5 mm pitch, high rad. tol.

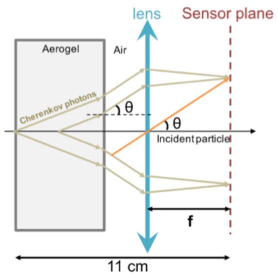


LHCb current and LS4 upgrades

- ex. EIC (gas) up to p ≃ 50 GeV
  - ➢ Option for High Pressure RICH with Ar at 3.5(2) bar (≃ C_4F_{10}/CF_4 1 bar)

- ex. ALICE-3 & EIC (aerogel) down to p ≃ 10 MeV/c
  - ➢ Multiple-refractive index (left) or lens focusing (right) radiators
  - ➢ Tunable refractive index within new materials
    - Photonic crystals in 1D/2D/3D very thin layers O(100) nm
    - Metamaterials metallic wire or nanomaterials with layer thickness < λ creating an effective medium

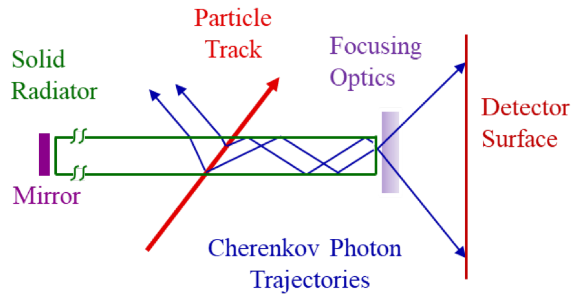


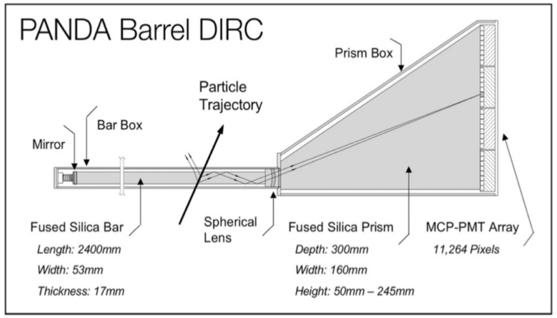


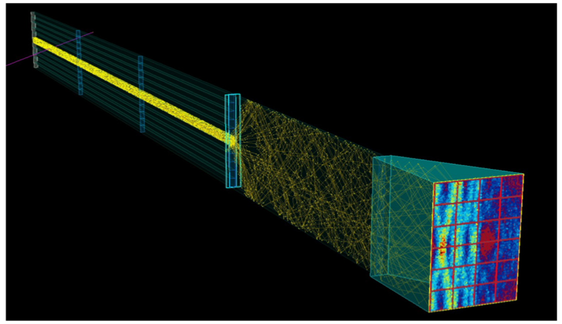
➢ Ultrafast timing σ_t O(≲ 50) ps to exploit same γ-Cerenkov arrival time for bgk rejection
- SiPM/LAPPD see slide 15

DIRC with focusing and ultrafast timing for 3D (x-y-t)

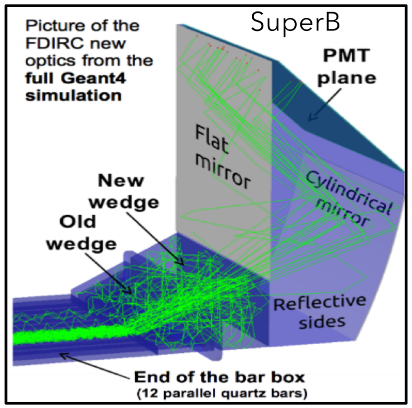
- Fused Silica Quartz radiator O(1) cm thick, up to p ≃ 10 GeV
  - ➢ σ_Θ down to 0.5 mrad, with high granularity MCP-PMTs and/or expansion lever arm
  - ➢ $\sigma_t \simeq$ 10-15 ps with MCP-PMT (SiPM) O(≲50) ps SPTR (30 γ / track in LHCb TORCH)
- Lens focusing designs, ex. Panda, IEC new hybrid bars & expansion design (right)







- Reflection focusing designs, ex. SuperB, LHCb upgrade-2
  - In LHCb ToF alone at 10 m & $\sigma_t \simeq$ 10 ps cover up to p ≃ 10 GeV



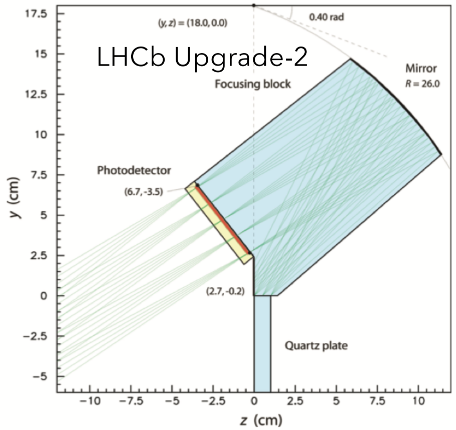
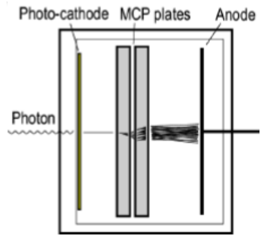
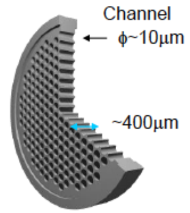


Photo Detectors high QE, ultrafast for single-γ, rad. tol.

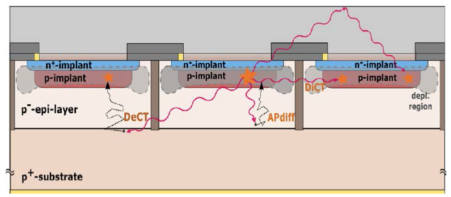
- MCPM-PMT
  - 2 " square, 64 x 64 pixels LHCb TORCH
  - LAPPD* large area 20 cm^2
    - Cheaper materials ex. borosilicate glass, 20 μm pores
  - SPTR (HPK) down to $\sigma_t \simeq 34$ ps



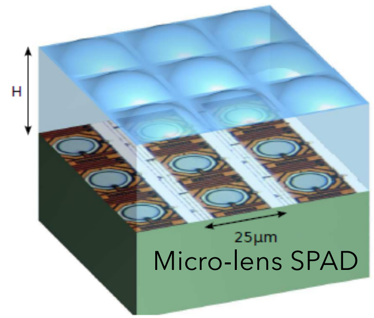


➢ ALD coating to improve CE and rad. tol.
➢ Al layer to protect photocathode for improved rad. tol.
➢ Hybrid design with pixel ASIC integration in vacuum tube, $\sigma_{hit} \simeq 10$ μm, $\sigma_t \simeq 10$ ps, 2.5 Ghit/s LHCb-2

- SiPM
  - Analog design, integrating charge on pixels
  - ➢ SPAD digital, counting pixel hits, in CMOS process / 3D integ. design
    - Improved σ_{hit} and σ_t^*, but higher DCR & lower fill factor
    - Micro-lens array design to compensate fill factor effect



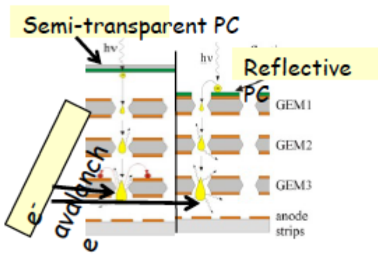
➢ New materials (WBG), ex. GaInP, GaAs, SiC, GaN - smaller pixels
  - Improve rad. tol. (low DCR)
  - Improve QE , particularly in UV for noble liq./ultrafast devices (Cerenkov)*

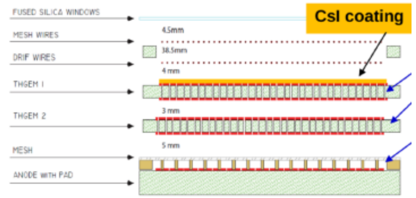


* *SPAD 50* μm pitch $\sigma_t \simeq 20$ ps compared to ≃ 30(80) ps with 1(3x3) mm^2 SiPMs
** *Also relevant to TPC/Cerenkov vessels for neutrino & DM experiments*

Gas detectors for photo-detection and ultrafast ToF

- Multi-GEM, MM, or hybrid with recent RO (see slide 12)
  - Minimize IBF ≲ 3%
  - ➢ Improve photocathode QE and rad. tol.
    - ex. Hydrogenated diamond films in spray techniques
      Nano-diamond (gold) grains (UV-sensitive)

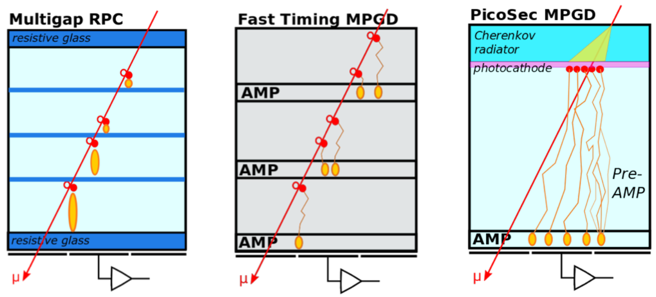




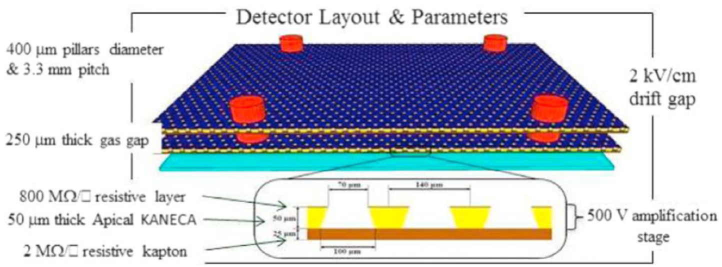
Compass RICH

- Ultrafast timing layers
  - ➢ Multigap RPCs, 24 x 160 μm gaps for $\sigma_t \simeq$ 10-20 ps in O(5) mm
    - Materials for low ρ, mechanical challenges
  - ➢ Fast Timing MPGD
    - Multiple thin amplification gaps
  - ➢ MM with Cerenkov radiator and photocathode
    - New materials for photocathode, ex DLC coating for rad. tol.

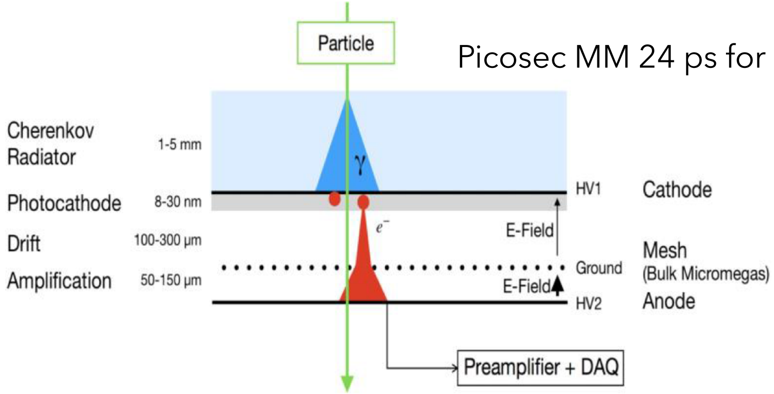
Intrinsic multilayer concept

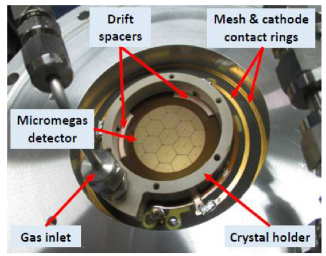


FTM with μ-rwell readout



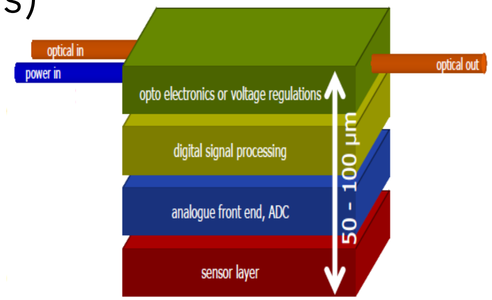
Picosec MM 24 ps for 10 pe (≃ 1 mip)





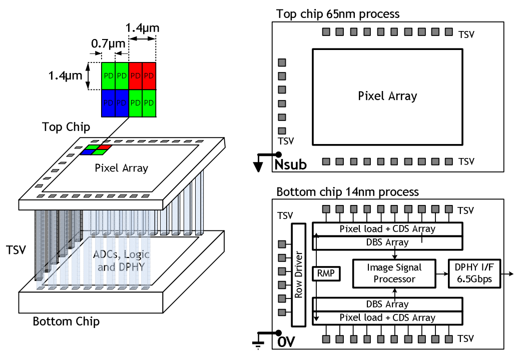
3D integration and deep node technologies

- Sensitive layer + ASICs + Silicon photonics transceiver (for ≳100 Gbps)
  - Optimize layer technologies to functionalities

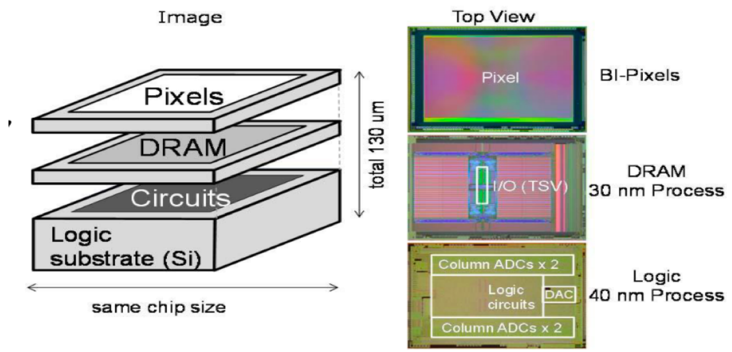


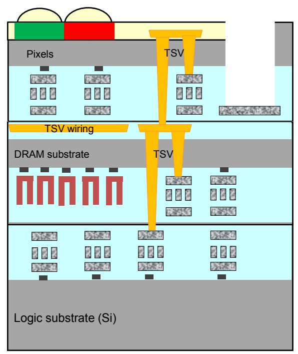
➢ Stacking with high density bonding
  - Flip chip bumps, liq. phase, metal-metal diffusion, nano-porous gold bumps ≲ 10 µm pitch, anisotropic conductive films…

➢ Stacking with Trough Silicon Via
  - Enable ultralow pixel pitch*, more RO functions, lower dead areas & X/X_0 with thinning
  - ex. CMOS image sensor 3D integration exist at Samsung and Sony in deep nodes



Samsung: 1.4 µm pixels in 65 nm & 14 nm FIN-FET (3D transistors) readout , wafer level stacking





3D layer thinned to 3 µm design for 960 fps Sony(left) layers thinned to 3 µm Samsung (right) 1.2 µm pixel pitch, 2.5 TSV 6.3 µm in 28 nm logic 20 nm DRAM

* *Ultralow pitch could have interest for inclined tracks*

Outlook

- Tremendous technology opportunities and new ideas exist to prepare unprecedented performance for next generation of detectors, keys to this new era:
  - 3D nano-scale new materials & process
  - 4th dimension, time measurement
  - Heterogenous designs
  - ML reconstruction techniques
- System, production, operation aspects and costs need to be considered
- Collaborative effort and joint budgets are more than ever crucial to access expensive technologies and allow efficient top-up of developments addressing several project needs

Glossary of acronyms

1) ALD – Atomic Layer Deposition
2) BC – bunch crossing
3) BES - Beam Energy Spread
4) BIB – Beam Induced Background
5) Bgd – Background
6) DIRC – Detection of Internal Reflected Cerenkov light
7) DLC - Diamond Like Carbon
8) DR – Dual Readout
9) LGADS – Low Gain Avalanche Photodiodes
10) MAPS – Monolithic Active Pixel Sensors
11) MPPC- Micro Pixels Photo Converters (SipMs, MCP-PMT)
12) PU – Pile-Up
13) RO readout
14) SPTR – Single Photon Time Resolution
15) ToP – Time of Propagation
16) ToF time of Flight
17) WBG Wide Band Gap