Requirements for future solid state devices at accelerator experiments

ECFA roadmap detector R&D, TF3 solid state devices symposia

D. Contardo, 23/04/2021

Outline

More than 20 projects presented in session of "input from future facilities": https://indico.cern.ch/event/957057/page/21634-input-from-future-facilities

Here a snapshot of most demanding requirements, timescales and technology approach

- Future collider experiments are representative of needs, hence the focus of this talk

Project timescales for new solid sate devices

Projects	Timescale	Vertex Det.	Tracker	Calorimeter	Time of Flight
Panda (Fair/GSI)	2025	✓			
CBM (Fair/GSI)	2025	✓			
NA62/KLEVER	2025	✓			
ALICE	2026-27 (LS3) – 2031 (LS4)	✓	✓	✓	✓
Belle-II*	2026	✓			✓
LHCb	2031 (LS4)	✓	✓		
ATLAS-CMS	2031 (LS4) - 2035 (LS5)	✓			✓
EIC	2031	✓	✓	✓	✓
ILC	2035	✓	✓	✓	✓
CLIC	2035	✓	✓	✓	✓
FCC-ee	2040	✓	✓	✓	✓
Muon-collider	> 2045	✓	✓	✓	✓
FCC-hh	> 2050	✓	✓	✓	✓

Projects representative of most demanding requirements, timescales reflect target for installation/start of operation – progress in specifications and state of approval can be at different stages**

- R&D completion typically ≃ - 5 years for construction, and including typically ≃ 5 years system engineering on top or in // to technology demonstration***
- Upgrade programs earlier than future colliders provide opportunities to iterate technologies and mature systems in real operation environments

** Belle-2 may have another upgrade in 2030*

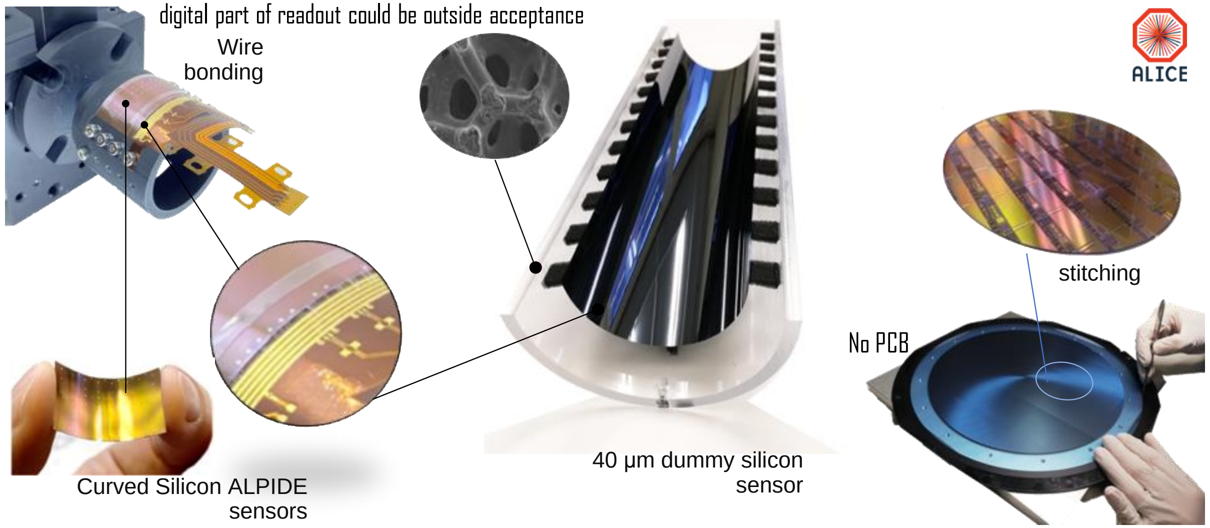
*** Alternative technology options are also considered for calorimetry and time of flight*

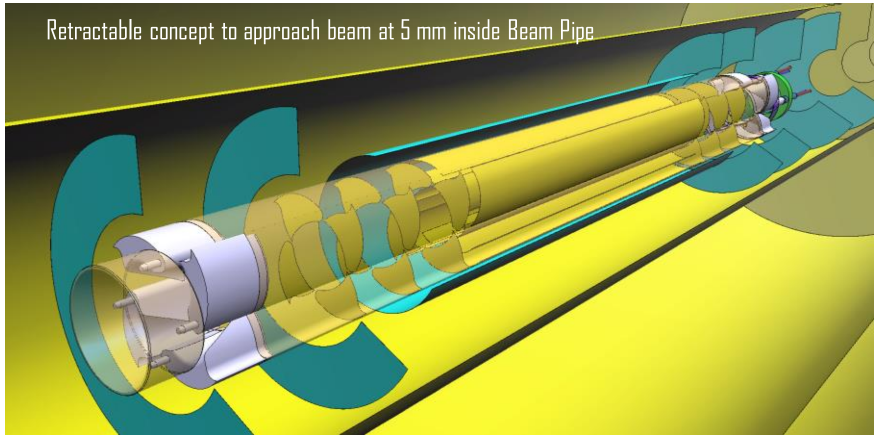
**** To minimize time and cost* several parameters need to be tested at once in few prototype iterations

Vertex Detectors high position precision

- Most demanding are ALICE and ILC, CLIC, FCC-ee colliders
  - FCC-ee target: $\sigma(d_0)/d_0 \simeq 2(20)$ μm at 100(1) GeV (90°), flavor physics benefit with higher precision
- Drivers are hit position precision (σ_{hit}), multiple scattering (X/X_0), layer configuration*
  - ALICE ITS3 target: $\sigma_{hit} \simeq$ 3 μm, $X/X_0 \simeq$ 0.05% / layer
    - 10-20 μm pixel pitch, thickness down to 20 μm**
    - 12" wafers (10 x 28 cm sensors), power ≃ 20 mW/cm² for gas flow cooling (TF7 and TF8)

➢ MAPs with stitching process in 65 nm node (TowerJazz)





From C. Gargiulo TF8 Sympasia

ALICE ITS2: ALPIDE 30 μm pitch, 50 μm thick, $\sigma_{hit} \simeq$ 5 μm, $X/X_0 \simeq$ 0.3% / layer (of which only < 20 % from sensors, 16 mm bending test encouraging

** Beam pipe X/X_0 can depend on operating condition, ex x 2 thicker for FCC-ee compared to ILC for beam background reduction*

*** Charge sharing is an optimization of pitch, active thickness, pixel design and process, track angle, B-field*

Vertex Detector medium rate & timing* requirements

- ALICE, CBM** (Fair), Belle-2***, EIC, ILC, FCC-ee Colliders rates $\lesssim$ 100 MHz/cm^2****
  - Achieved in MAPS demonstrators with different power: ex. ALPIDE $\simeq$ 40 mW/cm^2 at $\simeq$ 10 MHz/cm^2, MIMOSIS (CBM) $\simeq$ 60 mW/cm^2 at $\simeq$ 70 MHz/cm^2…
- ALICE Run-4, CBM, EIC, ILC, FCC-ee timing precision $\simeq$ 1 – 10 μs
  - Existing systems, consistent with power consumption of above examples
- Belle-2, ALICE-run-5 timing precision $\simeq$ 100 ns, Panda (Fair) $\simeq$ 10 ns
  - Achieved in MAPS demonstrators, but more challenging for power consumption

Power consumption is a challenge to go down to $\lesssim$ 0.1 % X/X_0 per layer *****

- ➢ Technology node, power distribution and readout architecture (see also TF7)
  - Large size sensors is a new territory

** "Medium" range is relatively large, exact specifications are driven by background rates defining number of integrated bunch crossing, options exist to go down (or closer) to BC timestamps: ILC 0.5 μs, ALICE 25 ns, FCC-ee 20 ns (at Z), Belle-2 4ns*
Also driving readout architecture: ALICE, CBM, ee-colliders w/o trigger, options w/ for ALICE and FCC-ee; Belle-2 w/ trigger

*** CBM also considering stitching, 180 and 65 nm*

**** Belle-2 considering current 180 nm TJ technology at this stage (eg $\sigma_{hit} \simeq$ 5 μm, $X/X_0 \simeq$ 0.1%)*

***** Ballpark value, each experiment is different and architecture for power dissipation can be different*

****** Power pulsing to lowering consumption possible at ILC and CLIC*

Vertex Detector high rates & medium/high timing requirements

- NA62, LHCb, ATLAS, CMS, CLIC rates $\simeq$ 1 to 5 GHz/cm^2, timing precision 25 ns to resolve BC at LHC, 5 ns for beam background CLIC*, NA62 & LHCb $\lesssim$ 50 ps**
  - ATLAS - CMS replacing inner layers (for radiation tolerance) can benefit from precision improvement for physics precision and pile-up mitigation

Challenge to reach GHz with current MAPS node (> 100 nm), also to reduce pitch below 50 μm at these rates in hybrid technology ($\simeq$ limit with RD53 65 nm technology) and/or to implement high time resolution (TF7)

- ➢ 28 nm node technology MAPS (for high rates) and ASICs (to reduce hybrid pitch)
- ➢ 3D integration also an option for both technologies, hybridization at low pitch

** Bunch Crossings at CLIC every 0.5 ns*

*** Consider 2D/3D/LGAD hybrid sensors with 65-28 nm technology, LGADs not in small pitch yet and not yet rad. tol. at level of LHCb*

Vertex Detector radiation tolerance

- ALICE, CBM, BELLE-2, EIC, ILC, CLIC, FCC-ee: NIEL $\lesssim 10^{15}$ neq/cm^2 and TID $\lesssim$ 100 MRad
  - Well within HV-CMOS radiation tolerance*
- LHCb, ATLAS, CMS: NIEL $\simeq$ 2-5 10^{16} neq/cm^2 and TID $\simeq$ 1 Grad
  - Marginally compatible with current hybrid technology requiring - inner layer replacement(s)
  - Limiting ability for low radius and forward η coverage

Challenge to enable MAPs to these levels (ex to be considered in ATLAS/CMS inner layer replac.)

➢ Lower technology nodes (65 nm – 28 nm)… process-design developments

Improvements of hybrid technology (would benefit LHCb)

➢ Smaller pitch and thinner planar/3D sensors, improved process and design
➢ Lower ASIC node 28 nm

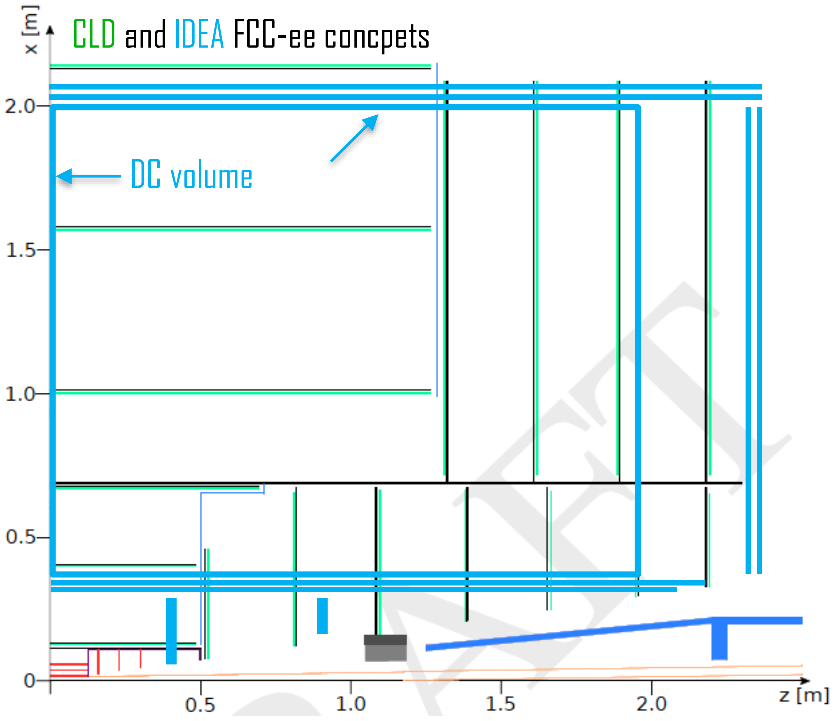
** Even consistent for ILC, CLIC and FCC-ee with standard process rad. tol. $\simeq 10^{13}$ MeV neq/cm^2 and TID $\simeq$ 3 MRad*

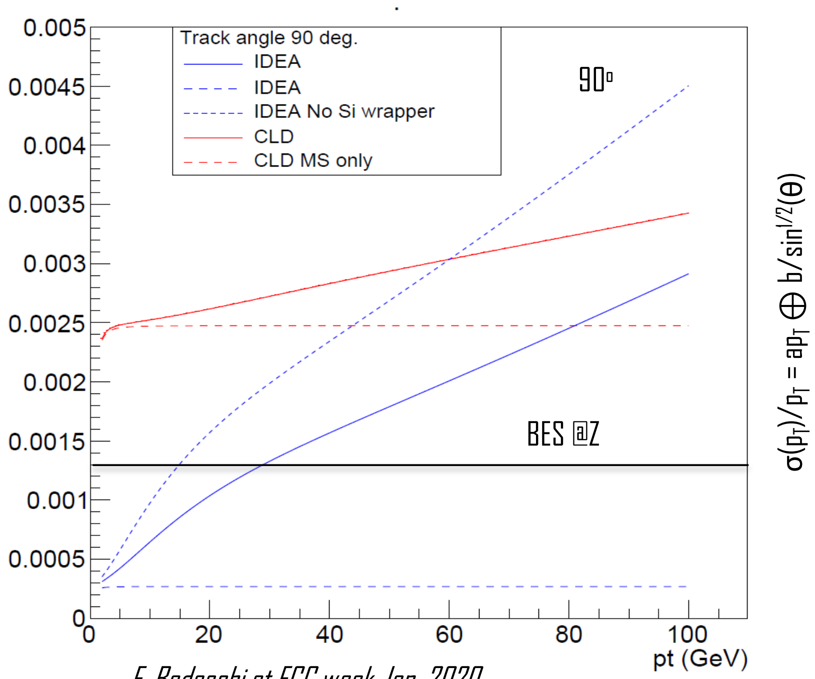
Tracker transverse momentum (p_T) precision

- Most demanding are ILC, CLIC, FCC-ee
  - Initial FCC-ee target: $\sigma(p_T)/p_T^2 \lesssim 5 \times 10^{-5}\ \mathrm{GeV}^{-1}$ $p_T \gtrsim 100$ GeV (90°), not yet Beam Energy Spread limit at Z-peak energy
- Drivers are: number of measured hits & position precision (σ_{hit}), B-Field* and lever arm, multiple scattering (X/X_0)

Different detector concepts

- Full Si, O(10) hits high σ_{hit}
- TPC/DC, O(100) hits low σ_{hit} with Si wrap-up layer at r_{out} (for high σ_{hit} at large lever arm)





F. Bedeschi at FCC week Jan. 2020

** FCC-ee B-field limited to 2T at Z-peak, can be higher at other energies; ILC -CLIC at 3T*

Tracker sensor requirements

- Ballpark optimization target: $\sigma_{hit} \simeq 7$ µm at $\simeq 1\%$ X/X_0 per layer
  - Longitudinal granularity and coordinate precision is not constraining
    - eg strip-sensor are well suited (so far with hybrid technology)
  - Large area layers require powerful cooling & relatively strong mechanical supports (TF8)
    - X/X_0 (limiting factor to σ_{hit} benefit) is more difficult to minimize than in VD

MAPS large area trackers can be a new paradigm to improve σ_{hit} and X/X_0

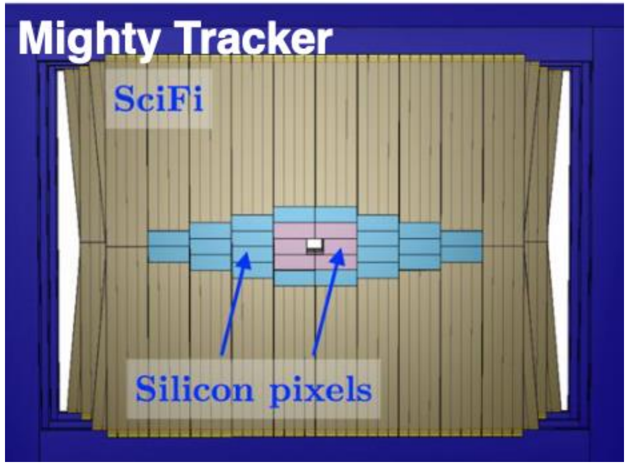
- Present radiation tolerance of HV-CMOS is sufficient for inner radii in LHCb tracker layers
- ➢ Stitching for sensor size, longer pixels and/or grouping of pixels preserving low power

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

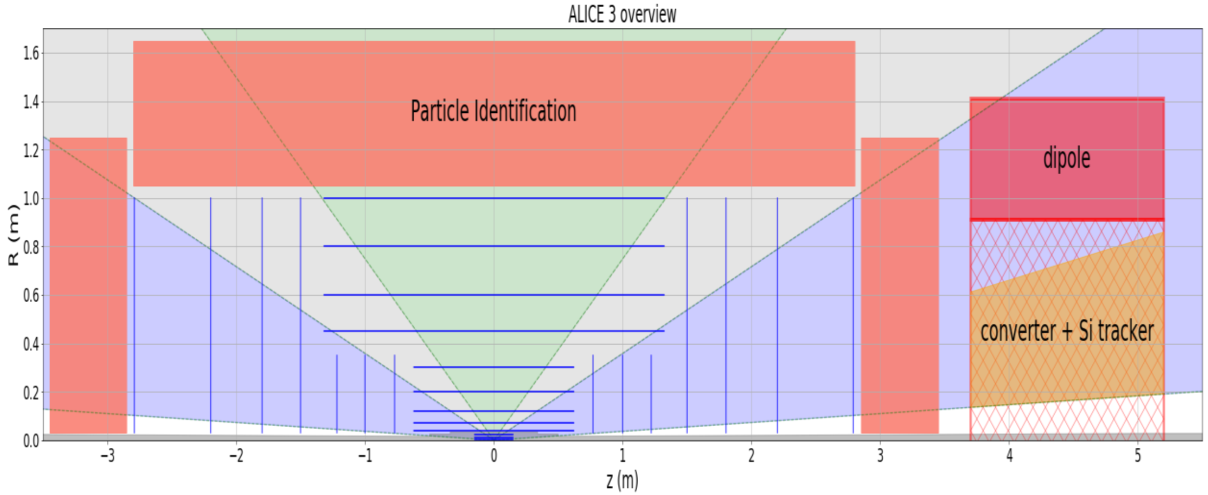
UT upstream magnet 6 m^2

MT at low r within SciFi 20 m^2

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

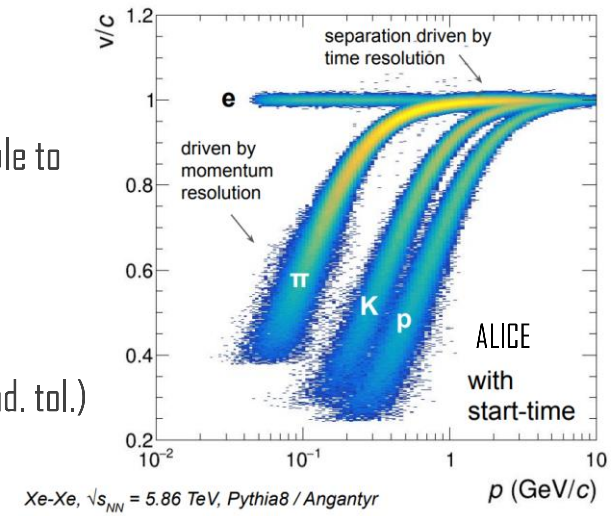


Alice 3 (LS4) – MAPS 20 µm pitch - BC timing 25 ns - 10^{13} neq/cm^2



Time of Flight precision requirements

- Particle Identification (PID) dedicated layer(s)
  - ALICE 3 (post LS4), targeting $\sigma_t \simeq 20$ ps for 3σ π/K up to 5 GeV/c
  - Belle-2, FCC-ee similar requirement to cover dE/dx crossing at low P, better resolution highly desirable to extend PID potential to higher P
- 4D tracking for track collision time association
  - Dedicated layer(s) or implementation in VD and/or tracking layers*
  - ATLAS/CMS HGTD/MTD $\sigma_t \lesssim 30$ ps (pile-up mitigation) desirable for high η LGADS replacement in LS4-LS5 (for rad. tol.)
  - LHCb pile-up mitigation for vertex precision
  - Options for e-e colliders to reduce beam backgrounds and improve 1st, 2nd, 3rd vertices identification, to be balanced with impact on X/X_0
  - FCC-ee at $\sigma_t \simeq 6$ ps can allow to correct $\sqrt{s}$ variation within bunches

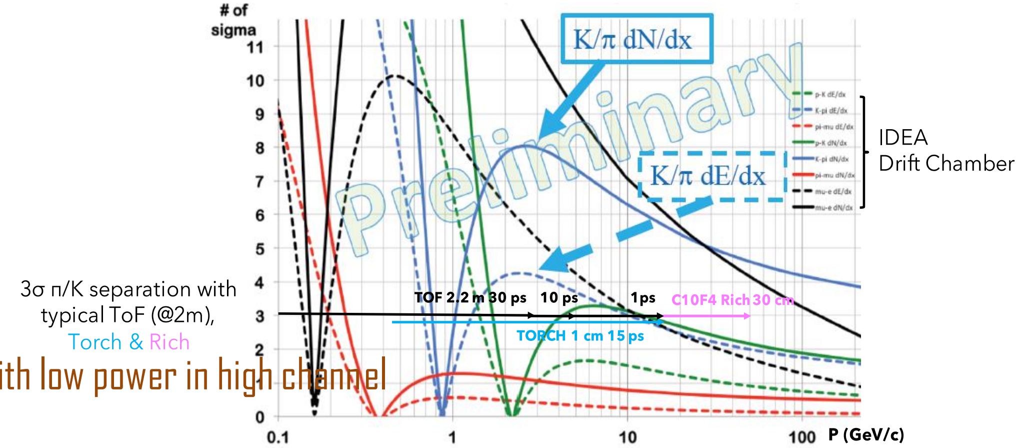


Develop designs with fast signal collection, small stochastic fluctuation

- ➢ w/o amplification (MAPS, Hybrids 2D/3D)**, w/ ampl. LGADS***, SPADS (TF4)
- ➢ Improve radiation tolerance, develop LGADs with pixel pitch,

Develop fast FE (TF7)

- ➢ Pre-amp with similar rise time as signal, high resolution TDC and clock distribution, with low power in high channel density (technology nodes 65 – 28 nm)



** Number of layers in tracking systems would improve track time resolution, also for PID*

*** NA62 VD achieved $\sigma_t \simeq 100$ ps and CMS HGC $\sigma_t \simeq 50$ ps with current 2D hybrid sensor technology*

**** Currently $\sigma_t \simeq 25$ ps limited by Landau fluctuation*

Calorimetry requirements

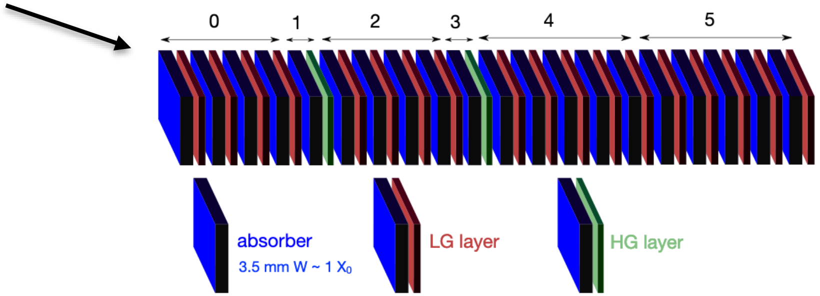
- ILC, FCC-ee EM calorimeter sections*
  - PFlow concept: energy of charged particles from tracker, minimize overlaps of sho granularity, allow dynamic em/had compensation & calibration corrections with high longitudinal granularity
  - CALICE (ILC) 2500 m^2 of Si-sensors in 30 layers embedded in W absorber, hybr pads, high dynamic range analog readout, energy resolution measured with r
    - $\sigma E(EM)/\sqrt{E} \simeq 16\%/\sqrt{E} \oplus 1\%$ - $\sigma E(had)/\sqrt{E} \simeq 44\%/\sqrt{E} \oplus 2\%$ - $\sigma E/E$ Jets $\simeq 3.5\ \%$ (50 GeV) jets
  - High time resolution potential not yet exploited to consider shower time development**

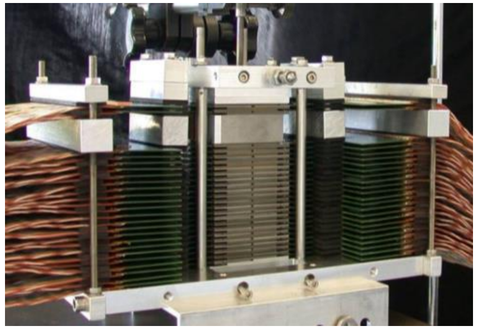
Challenge to improve sampling fraction for EM energy resolution (TF6)

- Monolithic pad design, 3D integration, new power distribution, photonics could help (TF7)

MAPS digital layers for particle counting*** could be a new paradigm

- ALICE (LS3) FOCAL foresees a heterogenous design





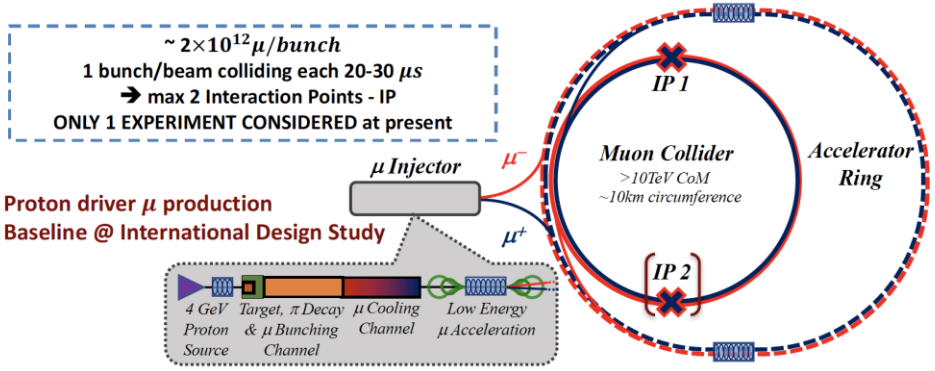
MIMOSA MAPs prototype
20 layers, 4 x 4 cm^2

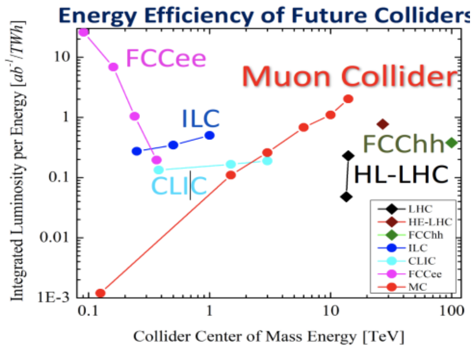
*also small size beam/lumi. calorimeters in very forward regions **$\sigma_t \simeq 50\ ps$ demonstrated for CMS HGC
*** Could also allow improving shower simulation parameters

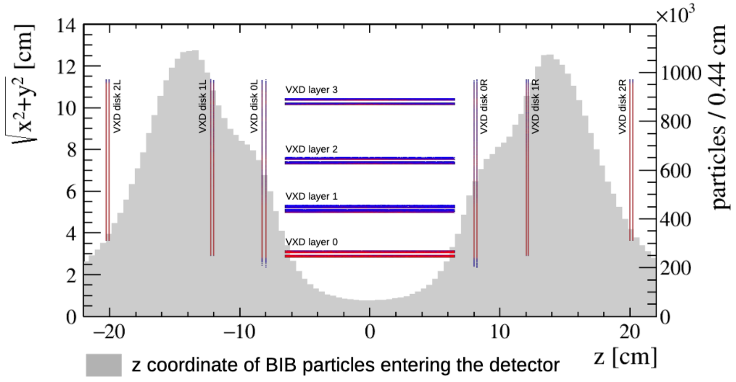
Muon collider

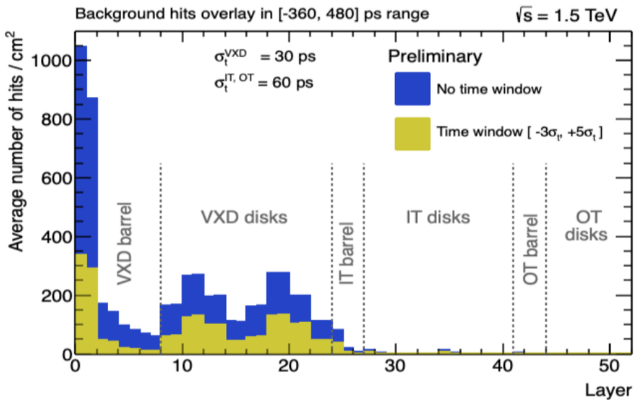
Luminosity 2 x 10^{35} $cm^{-2}s^{-1}$ at 10 TeV

Challenge in high rate continuous Beam Induced Background from muon decays interacting in machine elements









- General requirement for VD and tracker at ILC, CLIC, FCC-ee apply, with special configuration for background rejection
  - Barrel length - doublet sensor concept (CMS-p_T like modules) to reject non IP pointing tracks
  - $\sigma_t \simeq 10$ ps to eliminate out of time hits
- Fluence preliminary estimates indicate that NIEL could be beyond current HV-CMOS MAPS capability
- High granularity and timing performance also required in calorimeters for background rejection

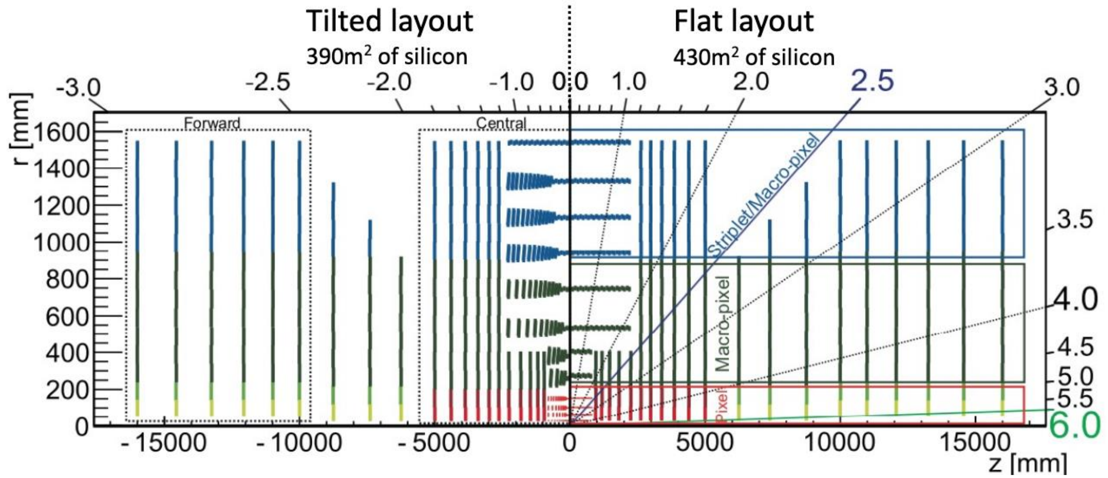
FCC-hh requirements

New territory of operation conditions

- $L = 30 \times 10^{34}$ $cm^{-2} s^{-1}$ – 30 GHz of collisions - 1000 per BC - 30 ab^{-1} integrated
- Physics coverage up to $\eta = 6$

Tracking requirements

- <0.4> ps vertex separation and <130> μm
  $\simeq$ BP MS resolution limit for 1 GeV/c p_T at $\eta = 2$
- Track rates 30 GHz/cm^2 (r = 2.5 cm)
- Granularity close to FC-ee with pitch $\simeq$ 25 μm
- Precision will be limited by ability to minimize X/X_0
- $\sigma_t \simeq 5$ ps would be required to recover HL-LHC like effective pile-up
- Fluence 10^{18} neq/cm^2 and TID 30 GRad at 2.5 cm*



New paradigms needed for radiation tolerance**

- R < 30 cm out of reach of currently used hybrid sensor technologies
- Current MAPS and LGADS marginally at level of rad. tol. for outermost layers

New paradigms needed for rates (TF7)**

** Forward calorimetry requires up to x 2-5 higher rad. tol. – timing at similar level as for tracking could also be needed to mitigate pile-up*
*** HE-LHC @ 2 HL-LHC would also need new technologies*

Summary

- More detailed summary of requirements and timescales for new features can be prepared
  - Current requirements are not in asymptotes of physics performance
  - They can top-up from one project to another according to combined technical progress
    - Ex. improvement of IP - p_T precision is typically a compromise of hit position precision, and X/X_0, low power consumption at high rates and/or high timing resolution can further enable measurement precision and background rejection
- Candidate technologies and developments in following talks of this symposia

Some projects not discussed but presented at input session

- Amber (successor of COMPASS): new paradigm to operate at cryogenic target, timeline 2026 – MAPS candidate, challenge for cooling and electronics (TF7 – TF8)
- NA60+ 2025 (LS3) VD interest in large size MAPS (stitching) of similar performance as for other projects
- TauFV at CERN: VD very similar to LHCb upgrade-2, possibly shorter timescale 2026-2027
- Mu3e PSI: VD with MAPS possible upgrade on timescale 2026