Tracking at FCC experiments

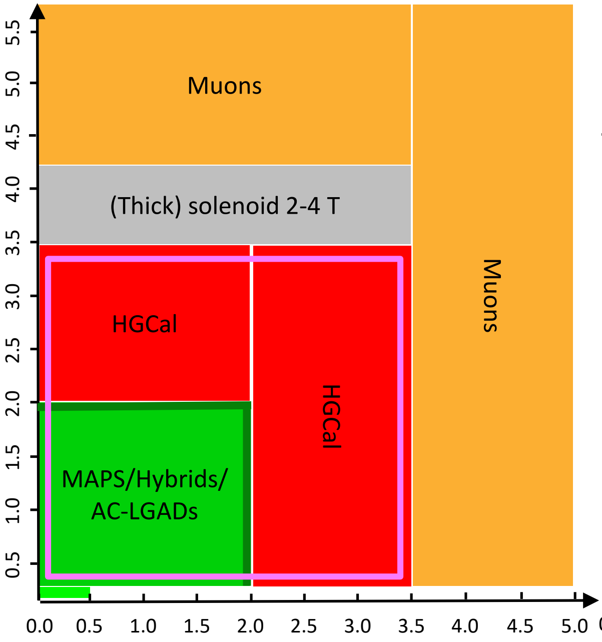
- FCC-ee conceptual design proposals
- Technology R&D for precision, further challenges at FCC-hh
- ➢ French contribution’s prospect

FCC meeting at IRFU, April 20/2022

D. Contardo, IP2I

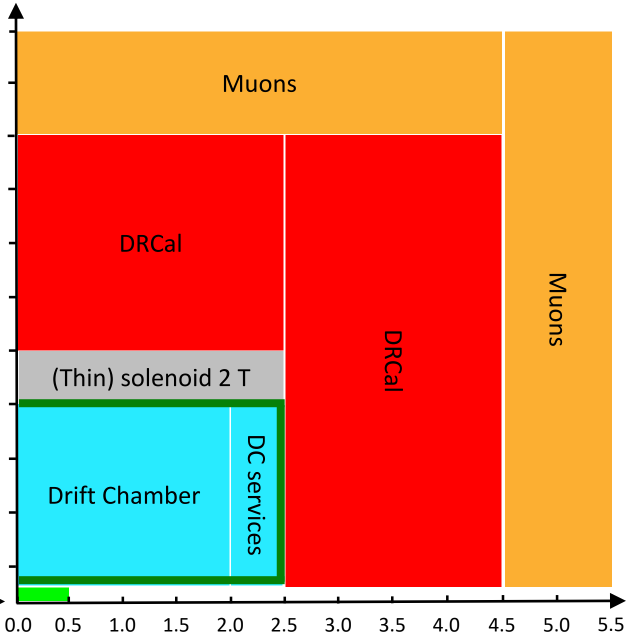
FCC-ee conceptual designs today

CLD
- B-field ability for 3 – 4 T
- 3D High Gran. PFlow (jets)
- Med. track IP & p_T precision
- Med.(-) γ-energy precision
- Low p PID



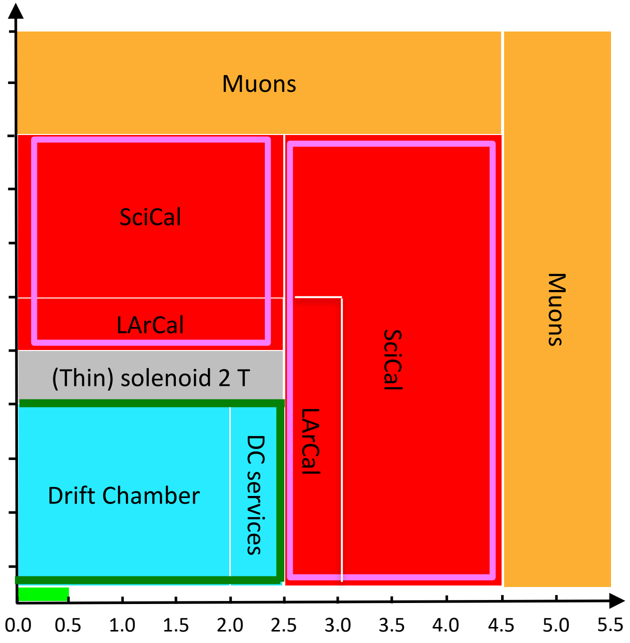
- PID RICH before HGCAL

IDEA
- B-field limited by X/X_0
- 2D Medium Gran. PFlow
- High track IP & p_T precision
- Med.(+) γ-energy precision
- High p PID



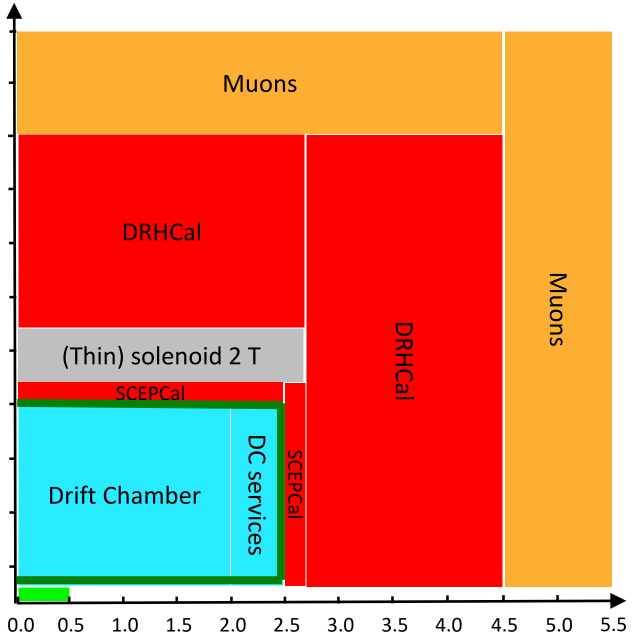
- TPC instead of DT

LArDet
- B-field limited by X/X_0
- 3D Medium Gran. PFlow
- High track IP & p_T precision
- Med.(+) γ-energy precision
- High p PID



- TPC instead of DT

IDEA+ (SCEPCal)
- B-field ability for > 2T ?
- 2D Medium Gran. PFlow
- High track IP & p_T precision
- High γ-energy precision
- High p PID



- TPC instead of DT
- LKr instead of SCEPCal
- SciCAL instead of DRHCAL

Options & Variants

- Tracking systems can be exchanged in different conceptual designs above

Also recent discussions for possible French contribution to new scintillating materials in DRCal/SCEPCal

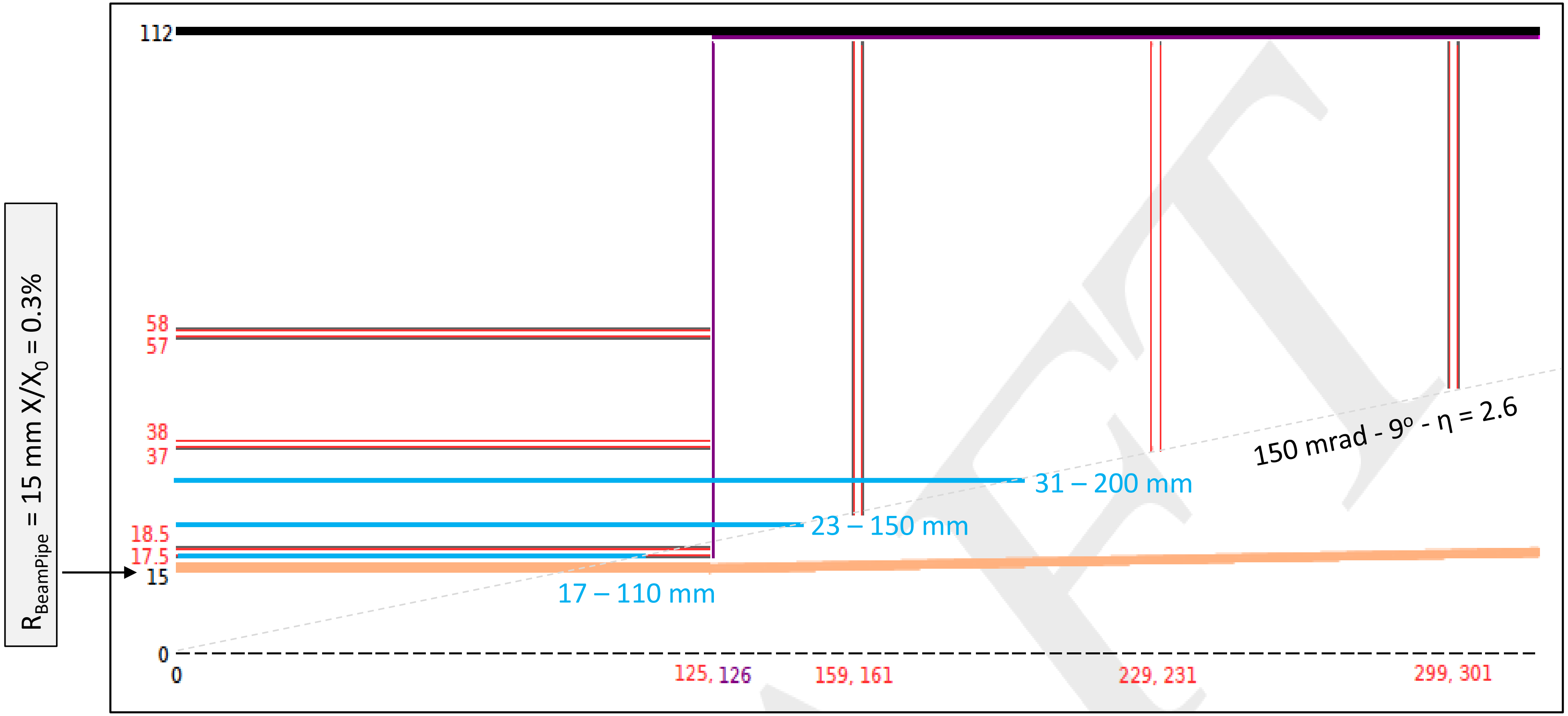
Vertex Detector: MAPS

Wrap-up/Timing Layer: MAPS/Hybrids/AC-LGADs/SPADs/MicroMegas/μ-Rwell…

CLD and IDEA Vertex Detectors designs (superimposed)

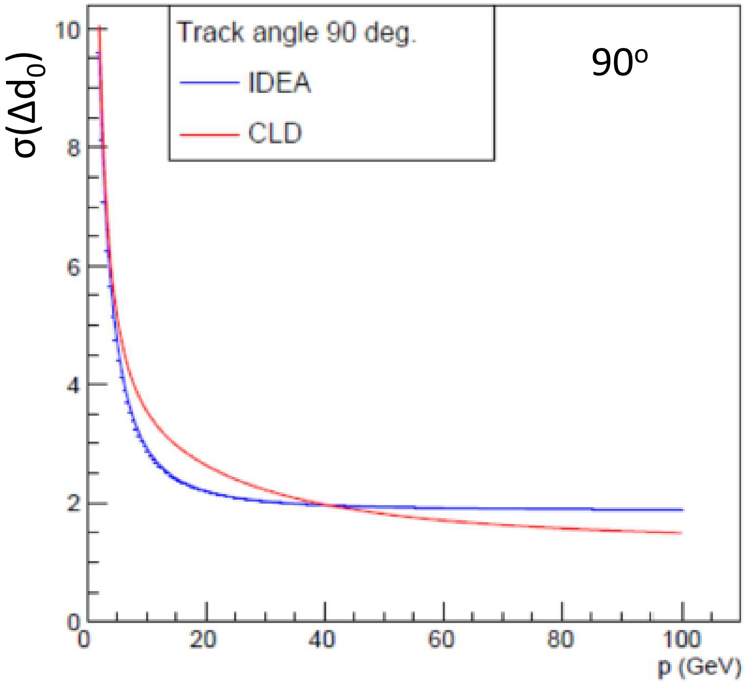
MAPS with $\sigma_{hit} \simeq 3\ \mu m$ and $X/X_0 \simeq 0.3\%$ / layer of Si

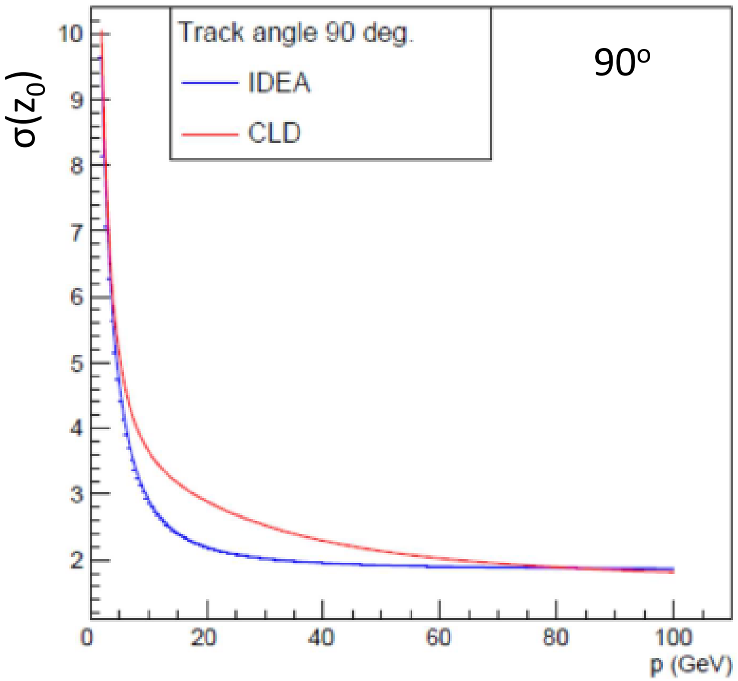
- CLD concept: double layers in Barrel/Endcap configuration
- IDEA concept: single closer layers in Long Barrel configuration



CLD and IDEA Vertex Detector, d_0 and z_0 precision

- Initial performance target is achieved with relatively close precision despite design differences
  - At first glance IDEA wins for precision at low p_T (at small η) with less layers of Silicon
  - ➢ Are these configurations two different asymptotes of σ_{hit} versus X/X_0, is there room for better hit precision?
  - ➢ Do differences (over η/p_T range) matter for physics, motivate different configurations / sensor optimizations ?





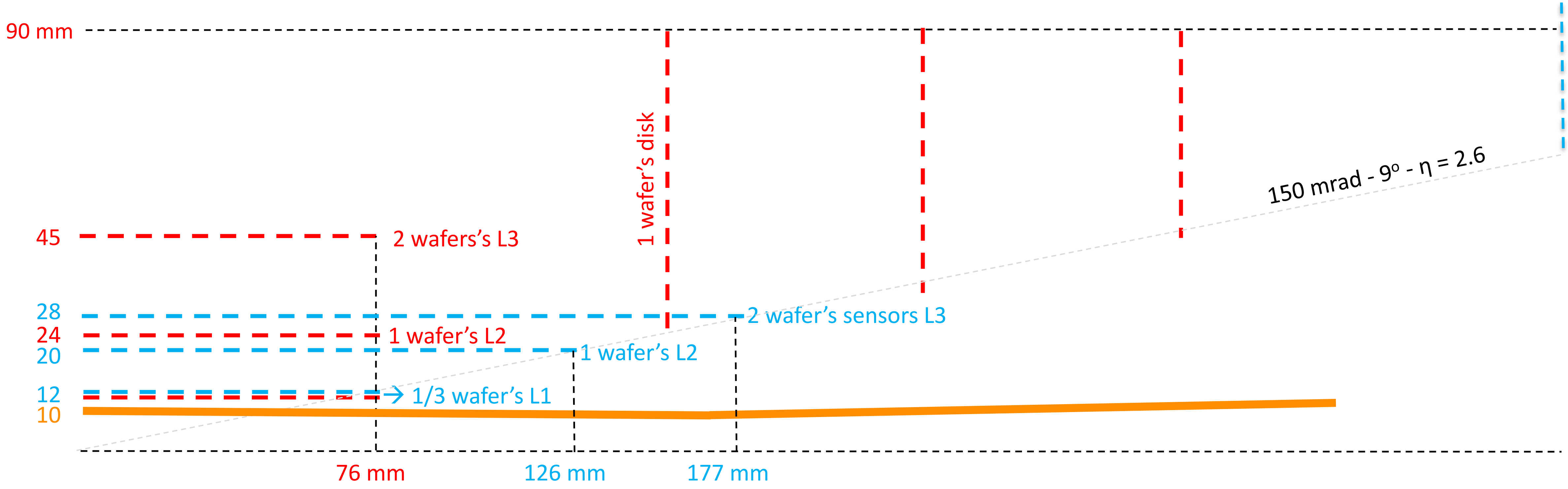
F. Bedeschi https://indico.cern.ch/event/838435/contributions/3658345/attachments/1968063/3273039/Bedeschi_IDEA.pdf

* $\sigma(\Delta d_0) \simeq 5 \oplus 15 / p\sin^{3/2}\Theta \simeq 2/5/20\ \mu m$ *(100/10/1 GeV at 90°)*

More aggressive Vertex Detector designs ?

ex. CLD & IDEA like designs (superimposed)

- 12” wafers with bent geometry and low X/X_0* (<10 sensors)
- 1st layer at 10-12 mm coupled to cooled beam pipe seems feasible
  - Could enable new features, ex. finer pitch, precision timing ?
- Layer(s) within the beam pipe could be an option ?



* ALICE ITS3 targets: 12” wafers - 20 µm thick – 0.05% X/X_0 with gas flow cooling & cylindrical design

Vertex Detector readout architecture

- Incoherent pair production background dominates
  - Up to x40 hits/BC at 365 vs 91 GeV
  - But ≃ /4 <rates> due to much larger BC spacing
- Ballpark requirements
  - O(1-10) µs integration window*
  - O(50) MHz/cm^2 hit throughput

CLD studies

91 GeV
bunch spacing 17.5 ns

365 GeV
bunch spacing 3.4 µs

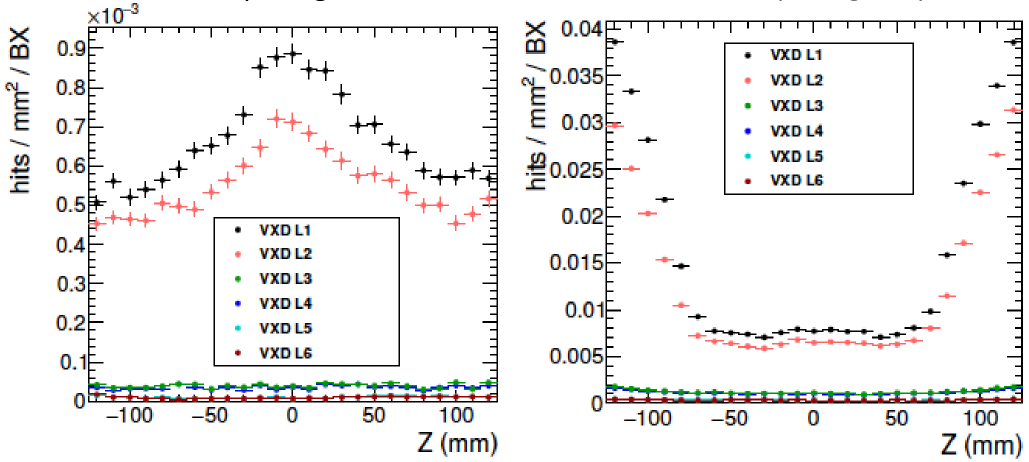


Figure of merit is the power consumption in the pixel matrix and at periphery vs impact on X/X_0

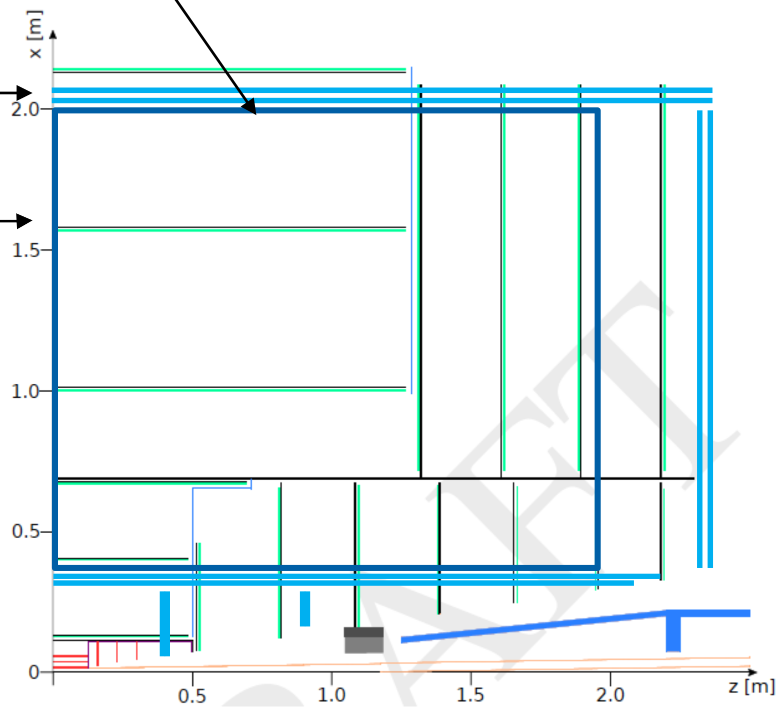
- ➢ GEANT + digitization + reconstruction simulation to provide
  - Hit rates to simulate power consumption of architecture options
  - Tracking efficiency & fake rates to set time integration window
    - RO w/o trigger appears possible wrt rates, impact on power and X/X_0 to be checked?
- Possibly different specifications/features according to radius/beam conditions ?

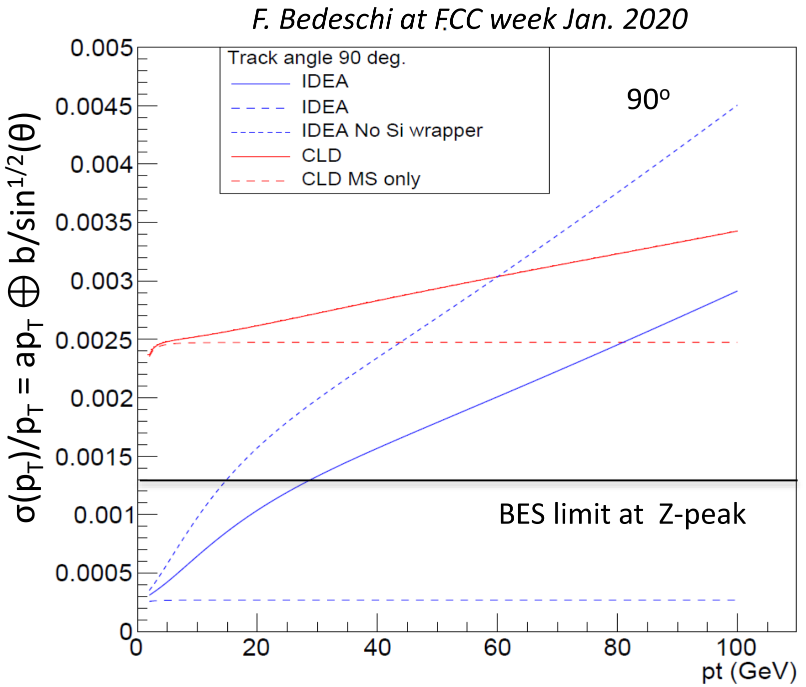
** Windows down to BC clock, O(20) ns at Z-peak, can be achieved with fast shaping, but benefit is not demonstrated:*

- *ex. further BIB rejection in VD to approach beam line and/or improve multiple vertices ID ?*
- *ex. 0.1 Z Pile-Up at Z-peak in 1 µs window, should be identified by total energy and reconstructed through vertex precision ?*

CLD and IDEA Central Tracker designs (superimposed)

Si-sensors 200 µm thick, 50 µm x 1 mm, 5-7 µm precision, 1– 2 % X/X_0 from inside to outside
IDEA Drift CHamber 120 hits, 100(1000) µm rΦ(z) precision, 0.016(0.05) % X/X_0 barrel(endcap)



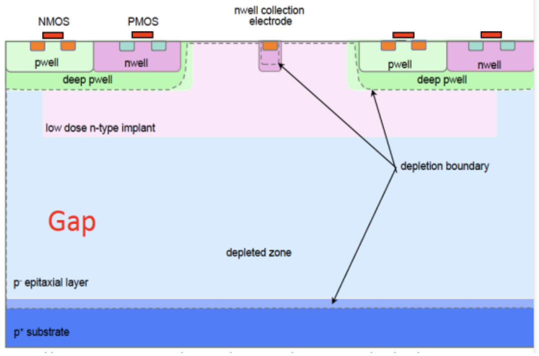


- Initial performance target achieved ($\sigma(p_T)/p_T^2 \lesssim 2 \times 10^{-5}$ GeV^{-1})
  - At first glance IDEA winning over full p_T range (low X/X_0 in DCH more critical than better hit precision in Si)
  - ➢ Full Si Central Tracker needs optimization, number of layers, σ_{hit} vs X/X_0*

** Also possibly optimization of wrapping layers around DCH*

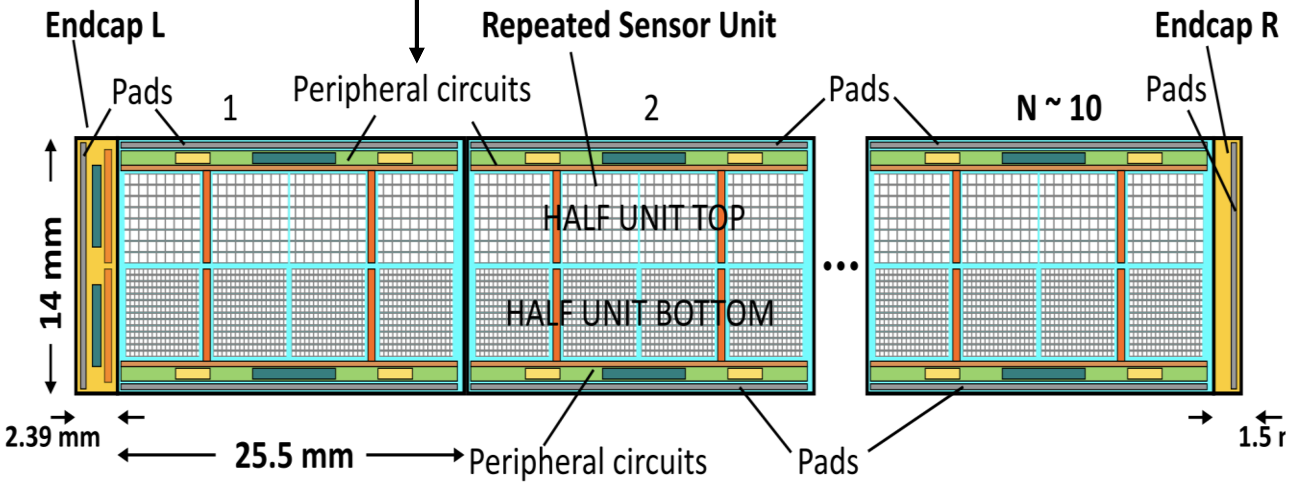
R&D Vertex Detector: MAPS for position precision at low X/X_0

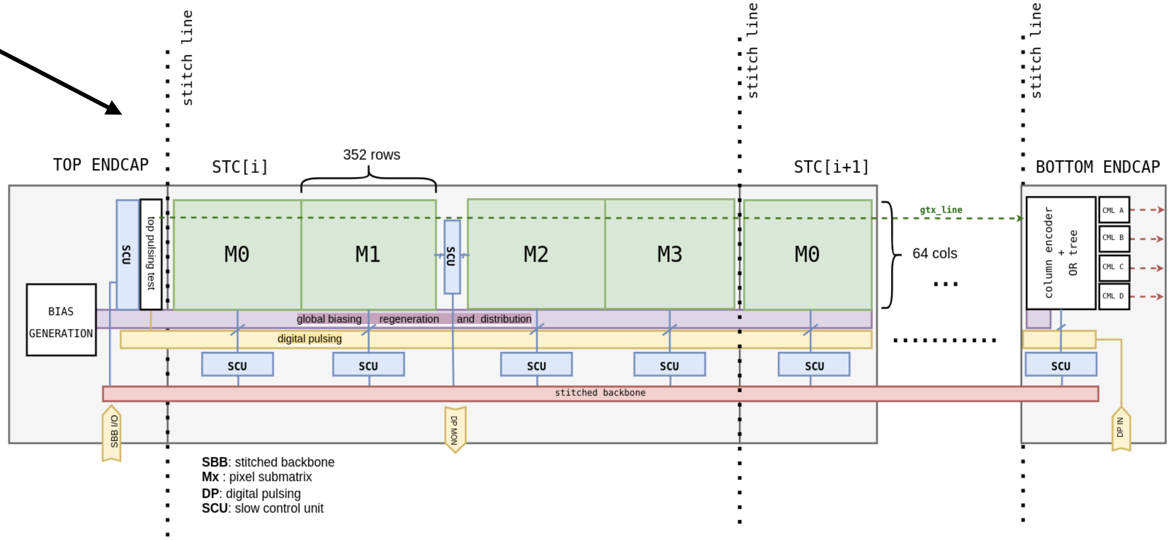
- CERN EP WP1.2 R&D in TJ 65nm stitched process on 12” wafers – targeting ALICE ITS3
  - 1st Multi-Layer-Reticle end 2020, different designs and splits (process parameters)
    - Evaluation so far so good, depleted design preferred for less charge sharing higher/faster signal, not mandatory for NIEL $O(10^{12})$ neq/cm^2 (TID O(1) MRad)
  - 2nd submission Engineering Run 1 May 2022, stitched process for yield
  - 3rd submission Engineering Run 2 Oct. 2023, full ALICE sensor ≃ 10 x 28 cm^2 ?



- Toward FCC-ee: smaller pitch ? higher rates O(50) MHz
  - ➢ Architecture optimization to minimize power consumption

ER1: MOSS (ALPIDE/MIMOSIS*) architecture and MOST (MALTA**) w/o clock in matrix for lower power & high rates





* MIMOSIS IPHC see talk A. Besson, ** CPPM/IRFU see talk of M. Barbero

R&D Silicon Central Tracker

- MAPS option for position and precision at low X/X_0
  - Transverse precision achieved for VD, can be released depending on X/X_0 achievements
  - Pixels can be grouped in longitudinal direction to minimize power consumption
  - Low X/X_0 is the challenge
  - ➢ Proposal for 1st MAPS Central Tracking in ALICE-3 and LHCb-2 UT/MT in LS4 (2034-2035)*

- Low cost hybrid CMOS is a plausible alternative
  - Less favorable for low pitch and low X/X_0 ?

- Mechanics and services, X/X_0, mostly a system aspect*
  - ➢ Design and prototyping of light systems with sensors built in 12” wafers
  - ➢ Study interfaces to beam pipes, and other systems

** See additional information slide 23*

*** See ex. of ALCIE additional information slide 24*

R&D for Central Tracker: Drift CHamber & TPC

- Drift Chambers*
  - Build large size detector with ultra-light wires
- TPC*
  - Control ion backflow distortion, ex. with pixel – double MM meshes designs, low gain. High P
  - R&D studies driven by CEPC: H. Qi https://indico.fnal.gov/event/46746/contributions/210382/
  - IRFU contributions on MM readout, LCTPC (ILD/ILC), CLAS12 (JLAB) TPC
  - ➢ Simulation study of mixed CT configuration with Si and TPC at increased radii (inner/outer) ?
- DCH and TPC: demonstrate PID performance with dE/dx and dN/dx
  - Potential to improve rΦ hit precision in DC exploiting cluster counting not yet investigated ?

** See additional information slide 25*

4D-tracking at FCC-ee

- Scale from sub-BC clock O(<20) ns down to intra-BC precision O(<10) ps*
  - Requires ToA and ToT implementation in the readout
  - 4D-tracking means timing measurement in several (all) layers
- Motivation
  - PID with ToF, ex. 1 hit with 10 ps precision at 2 m provides 3σ π/K separation up to 5 GeV**
  - Enabling mass measurement of LLPs decaying in charged particles
  - Ultra-pure track reconstruction (would need measurement in VD) ?
  - Energy spread correction in head-head, middle-middle, tail-tail collisions, O(6) ps vertex precision

➢ Simulations

- Demonstrate benefit for physics
- Define where the measurements should be implemented and with which precision per hit
- Define readout architecture & estimate power impact compatibility with low X/X_0 constraint

** Collision time spread in BC at Z-peak is O(40) ps*

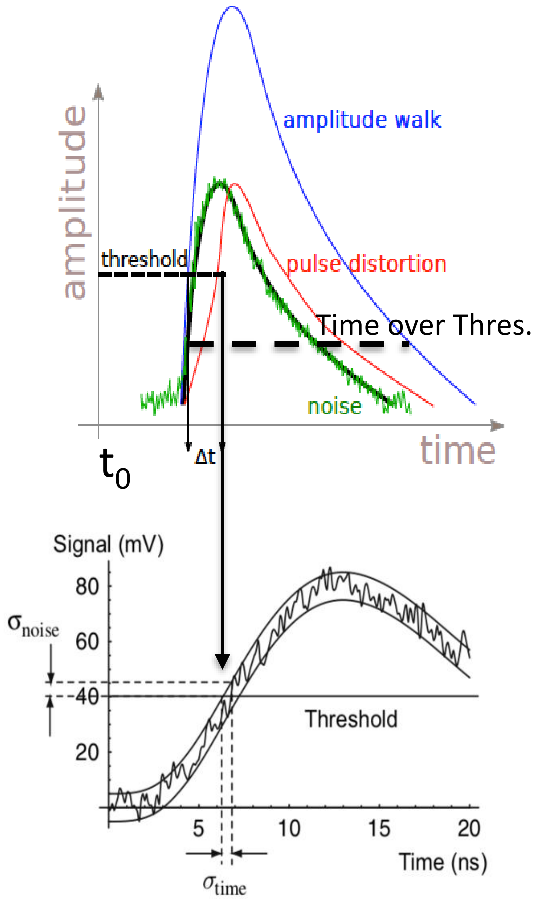
*** See additional information slide 26, multiple scattering limit to be evaluated*

Timing precision, technology considerations

$$\sigma_t = \sigma_{sign} \oplus \sigma_{elec} = \sigma_{sign} \oplus \sigma_{jitter} \oplus \sigma_{time\text{-}walk} \oplus \sigma_{TDC} \oplus \sigma_{clock}$$

- Sensors w/o amplification
  - Planar large electrodes, precision limited by S/N
  - Planar small electrodes, precision limited by spread hit-electrode distance
  - 3D limited by S/N (but no effect of Landau fluctuation on charge collection time)
- Sensors w/ low amplification
  - LGADs limited by Landau fluctuation, but high S/N
- Sensors w/ avalanche amplification
  - SPADs minimal Landau fluctuation and high S/N (ultimate precision?)

➢ Simulation to assess limits
  - Differently depending on parameters, active thickness, pitch, electrode size, that compete in performance for different technologies
  - No obvious path to reach O(≲10) ps, (while maintaining sufficient rad. tol.) ?



CERN EP seminar W. Riegler: https://indico.cern.ch/event/1083146/

R&D for $\lesssim$ 100 ps (1)

- Hybrid designs could be an alternative to MAPS for Central Tracker
  - Planar sensor
    - CMS diode tests show ≤ 70 ps for S/N ≥ 10 (asymptote ≃ 10 ps)
    - NA62 VD achieved ≃ 115 ps
    - ➢ Improvement with thicker sensors and/or lower noise electronics ?
  - Hybrid 3D sensors
    - TimeSpot TSMC 28 nm achieved ≃ 20 ps at 150 µm thickness and 50 µm pitch
    - ➢ Improvement with finer pitch and lower noise electronics ?
  - LGADS
    - ATLAS/CMS achieved ≃ 30 ps at 50 µm thickness 1.3 mm^2 pads
    - ➢ AC-LGADs, TI-LGAD to enable pixel pitch with thinner sensors ?

R&D for ≲ 100 ps (2)

- MAPS large electrodes
  - ex. Cactus IRFU* LFoundry 150 nm, 1mm^2 pads, target ≃ 60 ps @ 100 µm thickness
  - ➢ Improvement with thicker sensors and/or lower noise electronics ?
- MAPS small electrodes
  - ex. FASTPIX TJ 180 nm, 20(10) µm pitch, hexa. geo., adv. dop. prof., epi. ≤ 30 µm, achieved $\sigma_t \simeq 120(140)$ ps
  - ➢ Optimize design in deeper node ex. TJ 65 nm
  - ➢ Consider imaging technologies with even lower nodes and 3D integration*
    - Ultra small pitch and ultra thin epi layer for ultimate hit, timing precision and low X/X_0
      - Issue can be radiation tolerance (although constraint is relatively low at FC-ee)
    - Commercial application (ex. for automotive…) now at high speed and high rates

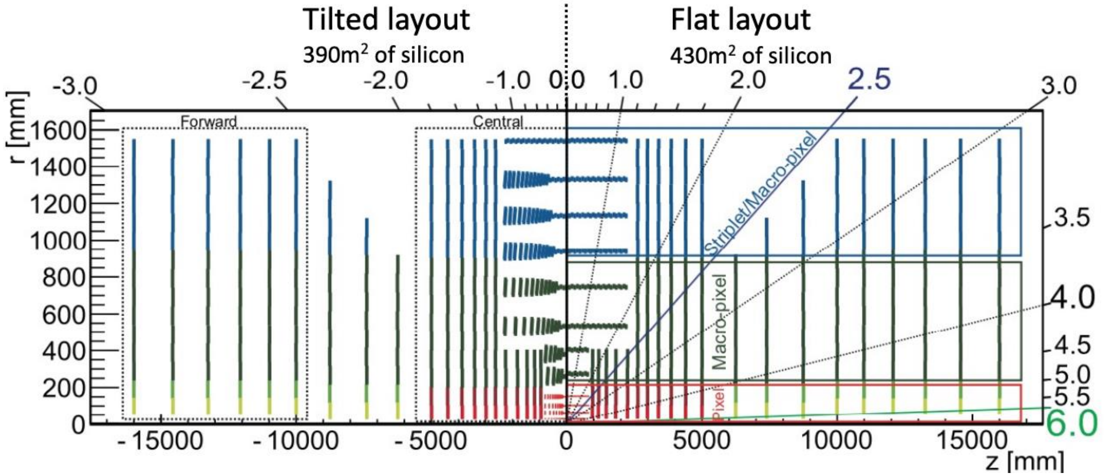
➢ MAPS also candidates for 4D-shower tracking
  - HGCal with pads, UltraHGcal with pixels (possibly particle counting with charge from ToT)
  - ➢ Compactness to improve sampling fraction, no X/X_0 constraint, but power issue

*, Y Degerli presentation, ** See ex. in additional information slide 27

FCC-hh tracking requirements

- New territory of operation conditions
  - 30×10^{34} cm^{-2} s^{-1} – Collisions 30 GHz,1000 per BC - 30 ab^{-1} integrated, coverage up to $\eta = 6$
- Tracking requirements
  - <0.4> ps & <130> µm between vertices
  - Track rates 30 GHz/cm^2 (r = 2.5 cm)
  - ➢ 4D-tracking for pile-up mitigation and reco. power
    - Granularity close to FC-ee
    - O(5) ps precision to recover HL-LHC like PU
  - Fluence 10^{18} neq/cm^2 and TID 30 GRad at 2.5 cm

FCC-hh tracker concept (≃ x5 scale of FCC-ee)



➢ New paradigm needed for radiation tolerance
  - No present technologies can survive below R < 30 cm
    - ex. current MAPS and LGADS are marginally at level of radiation tolerance for outermost layers

➢ New paradigm needed for rates and data transfer
  - Deep technology node, 3D integration, photonics and/or wireless data transmission*

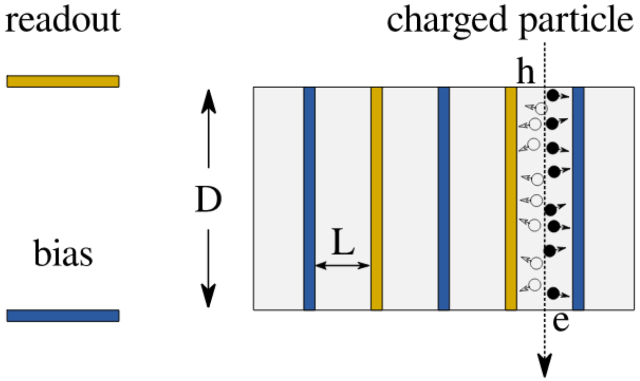
** WADAPT project at IFRU/LETI on wireless transmission, could also reduce X/X_0 at FCC-ee?*

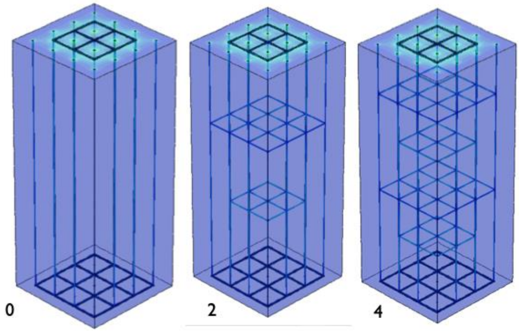
R&D for FCC-hh tracking

- Si-sensor NIEL tolerance
  - Unknown beyond $10^{17}/cm^2$ neq, models maybe too pessimistic, qualification itself is an issue
    - 3D & thin planar may approach needs
    - Other WBG semiconductors Diamond*, GaInP, GaAs, GaN, SiC** to be evaluated
- ASIC TID tolerance
  - ➢ Not clear if finer technology nodes alone would provide substantial improvements

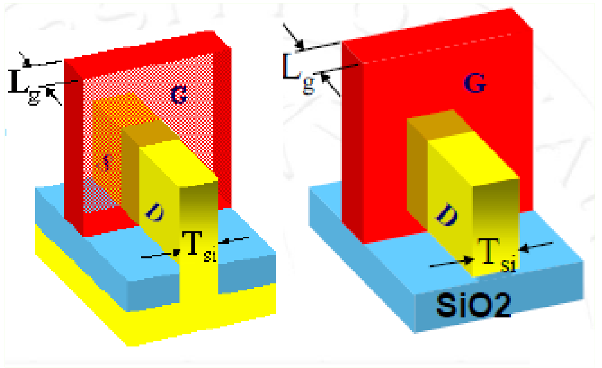
➢ New materials and 3D process could be a solution
  - Graphene, Carbon-based metamaterials, nanotubes…

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





ex. ASICs
- Higher dielectric thick oxide (multiple) gates
- Carbon based beyond CMOS, nanotube, graphene



ex. FinFET technology

** IN2P3 MP DIAMTEC - DIAMASIC in a different context of beam monitoring, ** CEA-IM2NP*

Outlook on potential French contributions (personal view)

- Conceptual design simulations
  - CLD-like with MAPS and HGCal technologies
    - Needs to solve PID issue without spoiling the PFLow benefit (ex. 4D-tracking – TPC - large radii)
    - Difficult to reconcile with high EM energy resolution
  - IDEA and IDEA+EM with Noble Liquid or Scintillating mat., DCH or TPC
    - Best performance “on paper” so far based on DCH, Crystal Cal and DR Cal
  - ➢ Need to clarify sub-BC timing benefits and requirements
- MAPS R&D for MIP and EM-shower tracking
  - TJ 65 nm with stitching best candidate today to provide fine pitch, at low power & X/X_0
    - ➢ Architecture for low power and higher rates (than ALICE ITS3) to be developed
    - ➢ Exploitation of timing to be developed (current sensor designs target O(100) ps precision)
  - Longer term, but could start now
    - ➢ Deeper nodes & process used for commercial imagers
      - Ultimate precision position & timing with ultra-fine pitch and 3D teers – rad. tol. ?
  - ➢ Access to technology difficult and expensive
    - ~~➢ PEPR could be an opportunity to federate efforts and resources (with some autonomy wre CERN)~~
- TPC R&D for low backflow & improved PID
- Possible contributions to intermediate projects: ITS3 (LS3), ALICE-3 & LHC-b (LS4)
- ➢ FCC-hh would need parallel dedicated investigations of new materials for radiation tolerance

Summary of french R&D areas in additional information slides 19 to 22 (may not be exhaustive)

Additional information

R&D topics in French community

- MAPS for Vertex Detector - O(12) sensors in 12’’ wafers times number of experiments

Track IP precision ALICE ITS3 in LS3 fulfil current FCC-ee requirements

- ➢ MP CMOS: IPHC , CBM, Belle2, ILC TJ 180 nm
- ➢ MP DICE: CPPM, IPHC, IP2I proposal for approval to join

TJ 65 nm in framework of WP1.2 CERN

Timing O(100) ps expected with current devices, compatibility with IP precision & benefit undefined yet

- ➢ MP Quartet: IPHC TJ 180 nm,
- ➢ IRFU Lfoundry: 150 nm
- ➢ May need deeper node, possibly 3D integration (2D tier attempts at IPHC) for real estate

- MAPS for Central Tracking – Medium production O(100) m^2

Improve X/X_0 for p_T precision ALICE-3, LHCb UT & MT in LS4

- ➢ No dedicated R&D: grouped pixels in strips slightly released ⊥ pitch

Timing implementation may not affect signigicanly X/X_0, benefit undefined yet

- ➢ R&D similar as for pixels
- ➢ Alternative technologies: CMOS, 3D, LGAD hybrid designs*

- MAPS for Wrap-up/Timing Layer:

Wrap-up - p_T precision w/ DC/TPC

- ➢ Same as MAPS layer in a Central Tracker

Timing Layer to provide low p PID** can be integrated in a Si-CT

- ➢ Need specific R&D, possibly new node and 3D integration, to reach $\lesssim$ 30 ps requirements
- ➢ IRFU: Micromegas + cerenkov radiator + photocathod
- ➢ Other alternative technologies 3D, LGAD, SPADs

** Today: CMOS hybrid same order of timing precision 100 ps as MAPS, 3D and LGADS O(30) ps*

*** 10 ps precision covers only $p < 5$ GeV, $1/\sqrt{n}$ for n layers, also increased radius option; impact of MS to be estimated for ultimate requirements*

R&D topics in French community

- MAPS for High Granularity Calorimetry - large production O(1000) m^2

Improve sampling fraction	➢ No dedicated R&D: group pixels in pads
Digital calorimetry	➢ No dedicated R&D: pixels granularity
4D within shower w/ timing <10 ps	➢ No dedicated R&D: similar as for TL

- Summary MAPS (more phase space in CLD-like design, maybe limited to VD in other designs)
  - Current effort addressing mostly impact precision and low X/X_0
  - First attempts at exploiting timing properties with current technologies O(100) ps
  - Strong justification to develop designs that could provide $\lesssim$ 30 ps
  - System aspects (mechanics, cooling…) important for X/X_0
  - ➢ Large community with an IN2P3 platform C4PI at IPHC
    - Intermediate project interests ex. ALICE ITS3, BELLE 2, ALICE 3, LHCB 2
  - ➢ Proper time to define common orientations beyond current R&D activities
    - Should consider technology aspects but also detector target, Vertex/Central Tracking, HGCalorimetry
  - ➢ PEPR proposal (J. Baudot) opportunity to open R&D perimeter and structure common effort
    - Large consortium: CPPM, IJCLab, IPHC, IP2I, IRFU, LLR, LP2I, LPNHE, LPSC, Subatech
  - ➢ Opportunity of synergies with electronics R&D MP, ex. for timing implementation (including 3D integration)
    - MP Fastime ASIC < 10 ps precision, MP Lojic130 clock precision (IP2I + …) in 130 nm TSMC
  - ➢ Requires substancial resources both funding and RH, also competitive international environment
    - Technology access complex for sensors (so far driven by CERN) no identified path towrd 3D integration

R&D topics in French community

- Noble Liquid Calorimeter

Improve granularity for PFlow ability High density feedthrough Low noise electronics in cold Improve EM-energy resolution w/ LKr

- ➢ R&D at IJCLab dedicated to FCC-ee
- ➢ Large community in ATLAS

- High Granularity Calorimeter

ECAL section electronics and system integration	➢ MP CALICE/ILC, IJClab, LLR, LPNHE, LPSC, and CMS at LLR, OMEGA for electronics
ECAL section Si-sensors	➢ Possible synergy with MAPS developments
HCAL section	➢ MP CALICE, SemiDigital HCal with RPCs IP2I or with MicroMegas IRFU

- Scintillating – Cerenkov in DRCal and SCEPCal

Material	➢ R&D at ILM (UCBL1), CPPM in CERN Crystal Clear (LHCb 2 - LS4), interest at IP2I and LPCC ➢ New powder-O concept R&D at IJCLab
Electronics	➢ R&D at LPCC: 65 nm electronics for LHCb 2 LS4

- Summary Calorimeters (fully Conceptual Design correlated)
  - ➢ Large community for HGC and Noble Liquid
    - HGC R&D still oriented toward ILC? possible synergy with MAPS R&D; Noble liquid fully dedicated to FCC
  - ➢ Interest to follow-up other options for contribution in a high E-γ resolution and/or DRCAL Conceptual Design
  - ➢ PEPR proposal* related to scinti.- cerenkov “Chronography” (C. Morel) timing oriented (including medical application) – CPPM, ILM, IJClab, IP2I, IRFU, LPCC, LPSC, Omega
  - ➢ Requires substancial resources both funding and RH, when reaching system design level

** No dedicated PEPR proposals for calorimetry, other that could be related to FCC R&D?*

R&D topics in French community

- Drift Chamber

Light wires Assembly technics

  - ➢ R&D MP Change at IJCLab - not in FCC-ee IDEA framework

- TPC

Ability to operate at Z-peak luminosity (ion-backflow) Ability for dN/dx

  - ➢ R&D TPC/MicroMegas at IRFU, option for TPC readout

- PID

Timing Layer

  - ➢ R&D at IRFU Micromegas with Cerenkov radiator and photocathode
  - ➢ R&D at IJCLab AC-LGAD

RICH

  - ➢ R&D MP Cerenkov Lab (DIRC with ToF design) at IJCLab - not in FCC-ee framework

- Interest to follow-up these developments and connect them to FCC-ee
  - ➢ Resource needs relatively limited at this stages

- General conclusion: maybe a good time to form dedicated FCC-ee MPs acknowledged by IN2P3 & IRFU
  - Common with ILC existing progams where relevant
  - Will need to consider implementation of DRD proposals under ECFA

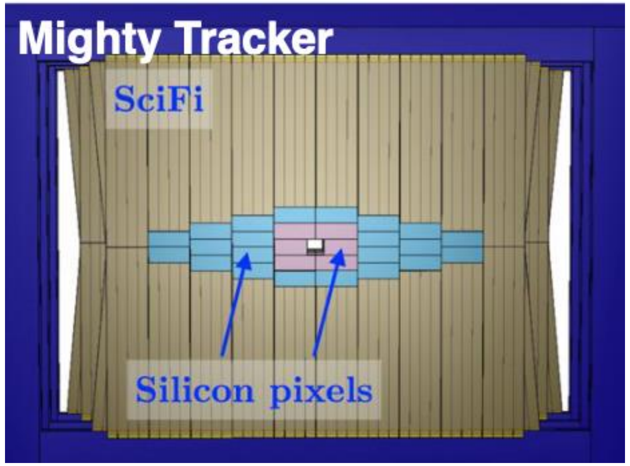
R&D Silicon Central Tracker

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

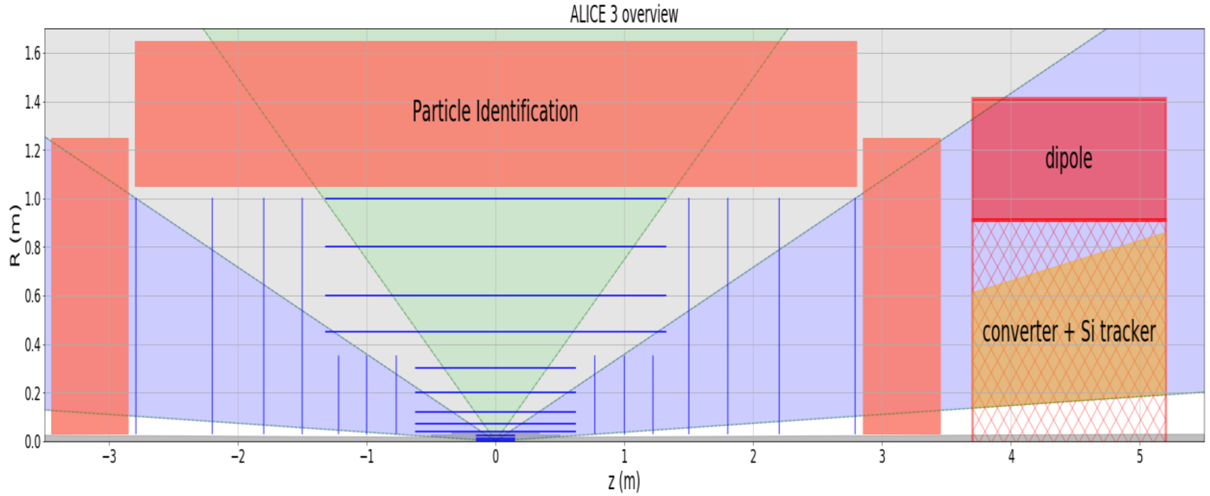
UT upstream magnet 6 m^2

MT at low r within SciFi 20 m^2

- 50 x 150 – 100 x 300 pitch
- ≲ 5 x 10^{14} neq/cm^2



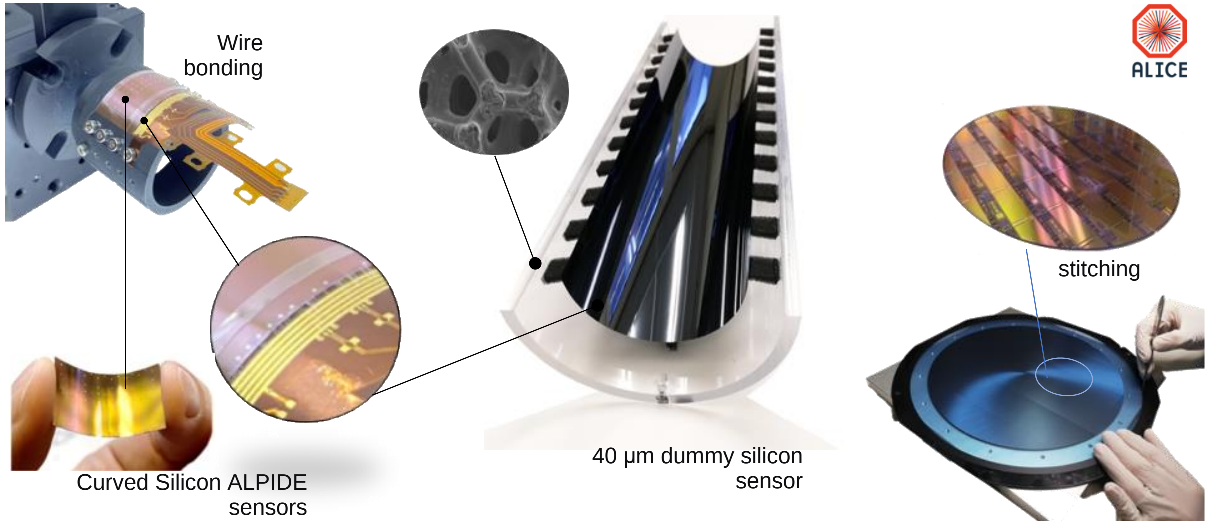
Alice 3 (LS4) – MAPS 20 µm pitch - BC timing 25 ns - 10^{13} neq/cm^2



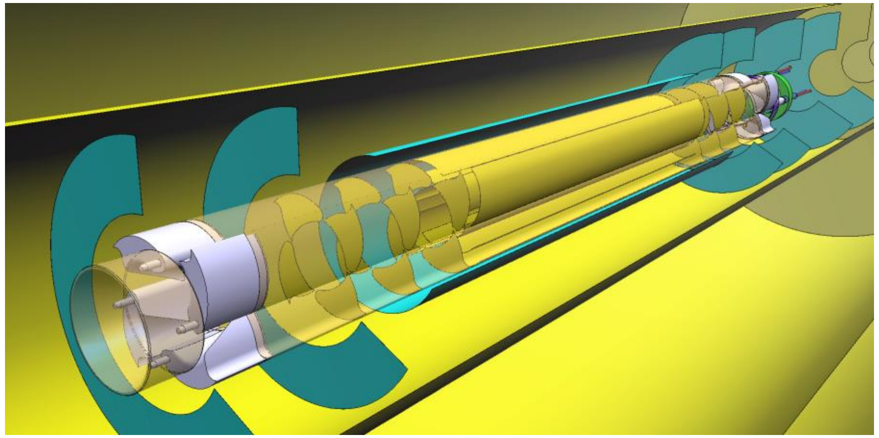
VD and Si Central Tracker: mechanical design and integration

ex. ALICE ITS3

digital part of readout could be outside acceptance



Retractable concept to approach beam at 5 mm inside Beam Pipe

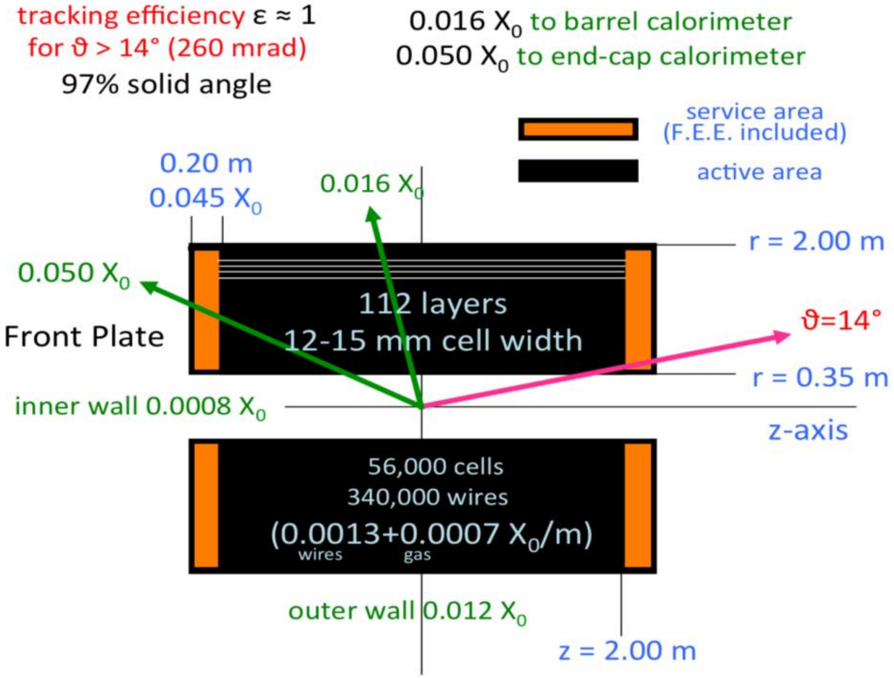


From C. Gargiulo ECFA R&D TF8 Symposia

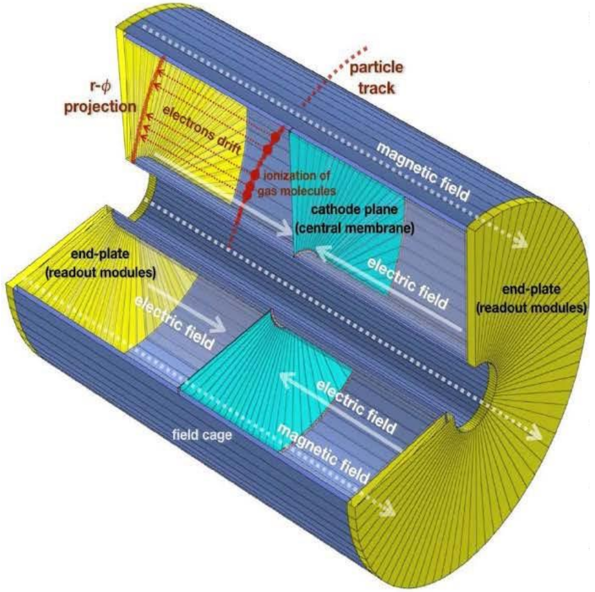
In ALICE ITS2 0.36 % X/X_0 /layer of which: 15% Sensors, 50% Printed Circuit, 20% Cooling Circuit, 15% Support Structures

Central Tracker: Drift CHamber & TPC

IDEA Drift Chamber concept



CEPC TPC

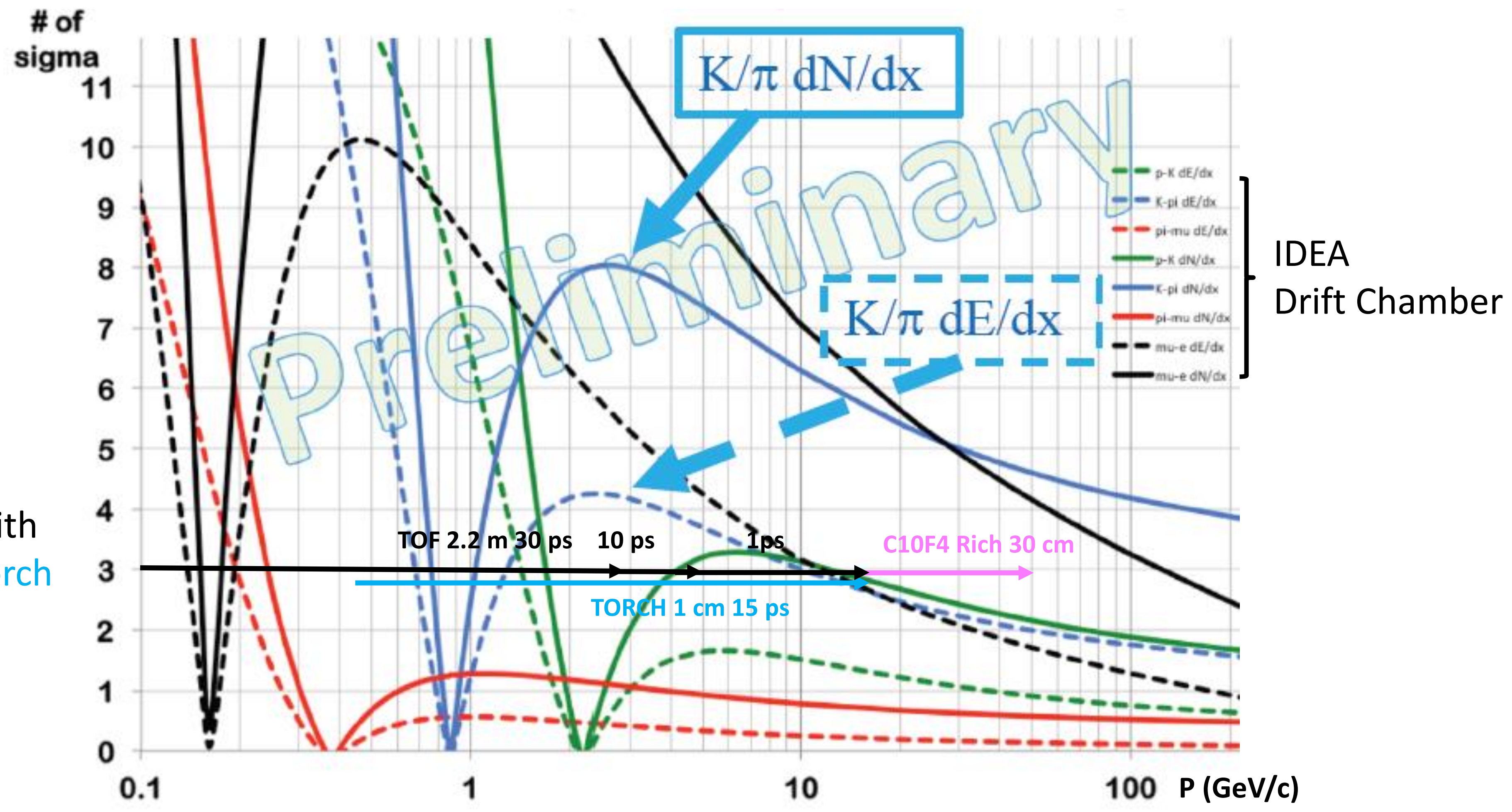


Momentum resolution (B=3.5T)	$\delta(1/p_t \approx 10^{-4}/GeV/c)$
δ_{point} in $r\Phi$	<100 μm
δ_{point} in rz	0.4-1.4 mm
Inner radius	329 mm
Outer radius	1800 mm
Drift length	2350 mm
TPC material budget	$\approx 0.05X_0$ incl. field cage $< 0.25X_0$ for readout endcap
Pad pitch/no. padrows	≈ 1 mm × (4~10mm) /≈ 200
2-hit resolution	≈ 2 mm
Efficiency	>97% for TPC only ($p_t > 1GeV$) >99% all tracking ($p_t > 1GeV$)

Pixel TPC with double meshes	Triple or double GEMs	Resistive Micromegas	GEM+ Micromegas	Double meshes Micromegas
IHEP, Nikehf	KEK, DESY	Saclay	IHEP	USTC
Pad size: 55um-150um square	Pad size: 1mm×6mm	Pad size: 1mm×6mm	Pad size: 1mm×6mm	Pad size: 1mm×6mm (If resistive layer)
Advantage for TPC: Low gain: 2000 IBF×Gain: -1	Advantage for TPC: Gain: 5000-6000 IBF×Gain: <10	Advantage for TPC: Gain: 5000-6000 IBF×Gain: <10	Advantage for TPC: Gain:5000-6000 IBF×Gain: <5	Advantage for TPC: High gain: 10^4 Gain: 5000-6000 IBF×Gain: 1-2
Electrons cluster size for FEE: About Ø200um	Electrons cluster size for FEE: About Ø5mm	Electrons cluster size for FEE: About Ø8mm	Electrons cluster size for FEE: About Ø6mm	Electrons cluster size for FEE: About Ø8mm
Integrated FEE in readout board Detector Gain: 2000	FEE gain: 20mV/fC Detector Gain: 5000-6000	FEE gain: 20mV/fC Detector Gain: 5000-6000	FEE gain: 20mV/fC Detector Gain: 5000-6000	FEE gain: 20mV/fC Detector Gain: 5000-6000

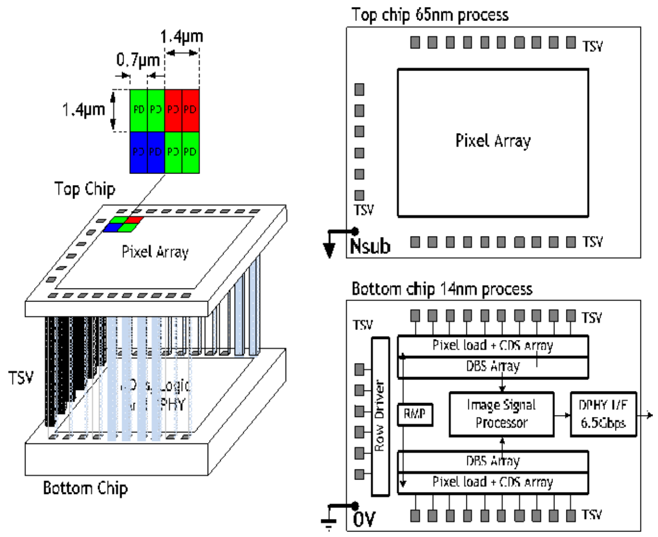
Particle ID, broad-brush coverage of technology options

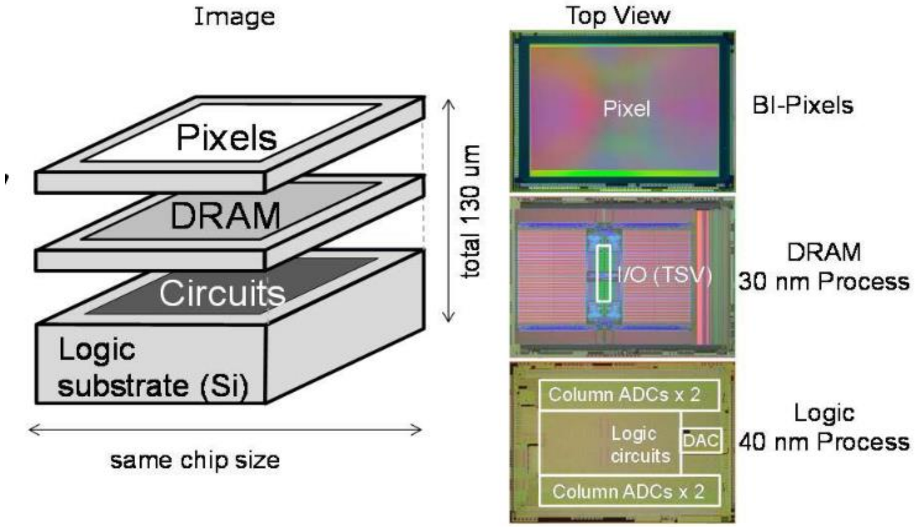
3σ π/K separation with typical ToF* at 2m, Torch & Rich

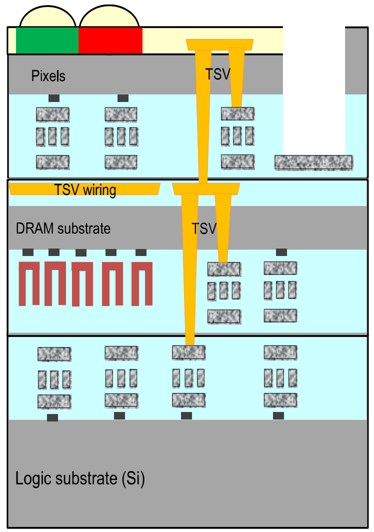


* *Not considering multiple scattering effect*

Commercial imager technologies







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

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

** V. Re: https://indico.cern.ch/event/999816/*

Comparison of e-e collider beam parameters

Update to 100 - 5 x 10^{34} cm^{-2} s^{-1} ?

Beam parameters	ILC		CLIC			FCC-ee			CepC	
Energy (TeV)	0.25	0.5	0.38	1.5	3	0.091	0. 24	0.36	0.091	0.24
Luminosity (x 10^{34} cm^{-2} s^{-1})	1.35	1.8	1.5	3.7	5.9	230	8.5	1.7	32	2.93
Bunch train frequency (Hz)	5		50							
Bunch separation (ns)	554		0.5			20	994	3000	25	680
Number of bunches / train - beam	1312		352	312		16640	393	48	12000	242
Integrated luminosity (ab^{-1})/years	2/+11	4/+22	1/8	2.5/8	5/8	150/4	15/5	1.7/5	16/2	5.6/8
Main SM process	ZH	tt, ttH	tt			Z	WW, ZH	tt	Z	WW,ZH
Beam size at IP σx/σy/σz (µm)	515/7.7/300	474/5.9/300	150/2.9/70	60/1.5/44	40/1/44					