Conceptual design studies for FCC-ee experiments
Detector performance perspective

FCC-France workshop, January 20-21/2021

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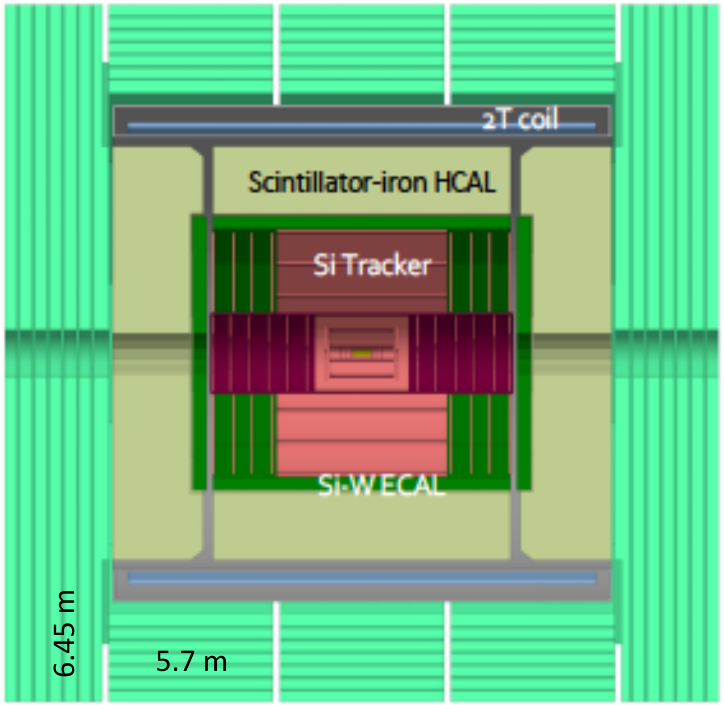
Conceptual Design studies

- Physics benchmarks simulations (see E. Perez)
  - Assess relative effect of various detector performance variables in given configurations
  - Tell if, and when, the statistical uncertainty or a performance asymptote are reach
- Detector inputs and studies - Focus of this presentation
  - Needed to factorize the effect of the technology parameters and of the configuration
    - To guide R&D toward critical parameters (possibly best compromise)
    - To iterate configurations for optimization
- Eventually the process informs choices for technical design of multiple experiments
  - Optimized mix of technologies within one experiment
  - Potential complementarity in the context of the overall physics reach of the program

CLD and IDEA Conceptual Designs

- Representative of configuration alternatives and of possible technology mix*
- CLD scaled from CLICdet; Other technology options proposed for ILC and for CEPC (see M. Ruan)
- Initial physics requirements are fulfilled, now exploring PID, γ energy resolution… flavor, LLP, Z-pole



No dE/dx, no ToF

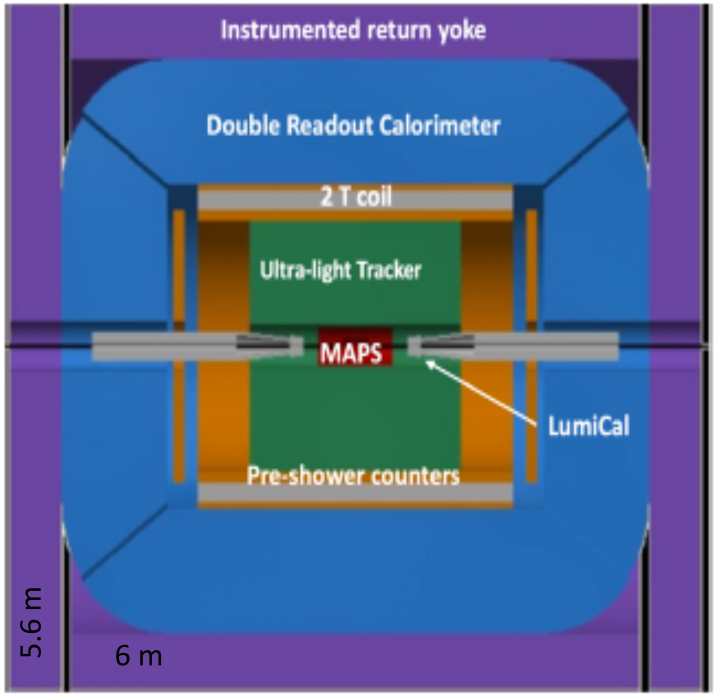
← CLD - IDEA →

← Solenoid magnet 2T →

Sampling Calorimeters
← HGC inside mag.
Pre-shower + Dual readout outside mag. →
/Lar(Xe)/EM-Crystals

Outer Tracker
← MAPs - Drift Chamber →
Si-Hybrid / TPC

← MAPs Vertex Detectors →



dE/dx (DC), no ToF

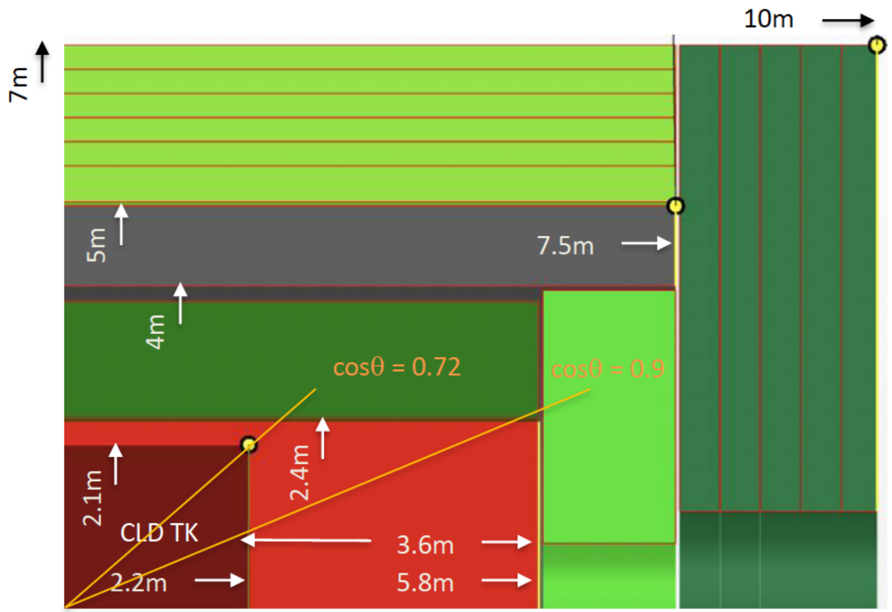
* F. Grancagnolo https://indico.in2p3.fr/event/20792/contributions/81817/attachments/58694/78898/FCC-ee_France.pdf

Note : several muons chamber technology options but not driving Conceptual Design; dedicated LLP extension, ex HADES, neither addressed here
https://indico.cern.ch/event/932973/contributions/4099681/attachments/2141446/3609338/HADES_A_long_lived_particle_detector_concept_for_the_FCC-ee_or_CEPC.pdf

Magnet configuration

2T solenoids to achieve luminosity at the Z-pole

- CMS-like solenoid after calorimetry in CLD
  - 0.7 λ_i , 70 cm thick
- Thin solenoid before calorimetry in IDEA
  - $X/X_0 \simeq 0.46$ coil + 0.28 cold mass, 0.16 λ_i, 30 cm thick
- ALPHA proposal for FCC-ee/ep/hh*
  - Same 4T magnets used in ee and hh experiments
  - Larger size, improved performance (acceptance, resolution), offer option to run at higher field at 240 GeV
  - ➢ No studies yet, 3T magnet option could be considered in a calorimeter outside design**, longer magnet can also be considered w/o increasing radius
- Magnet cost scales linearly with stored energy
  - Overall cost to consider calorimeter volume
  - Re-use of magnets in an ALPHA configuration should compensate increase in volumes

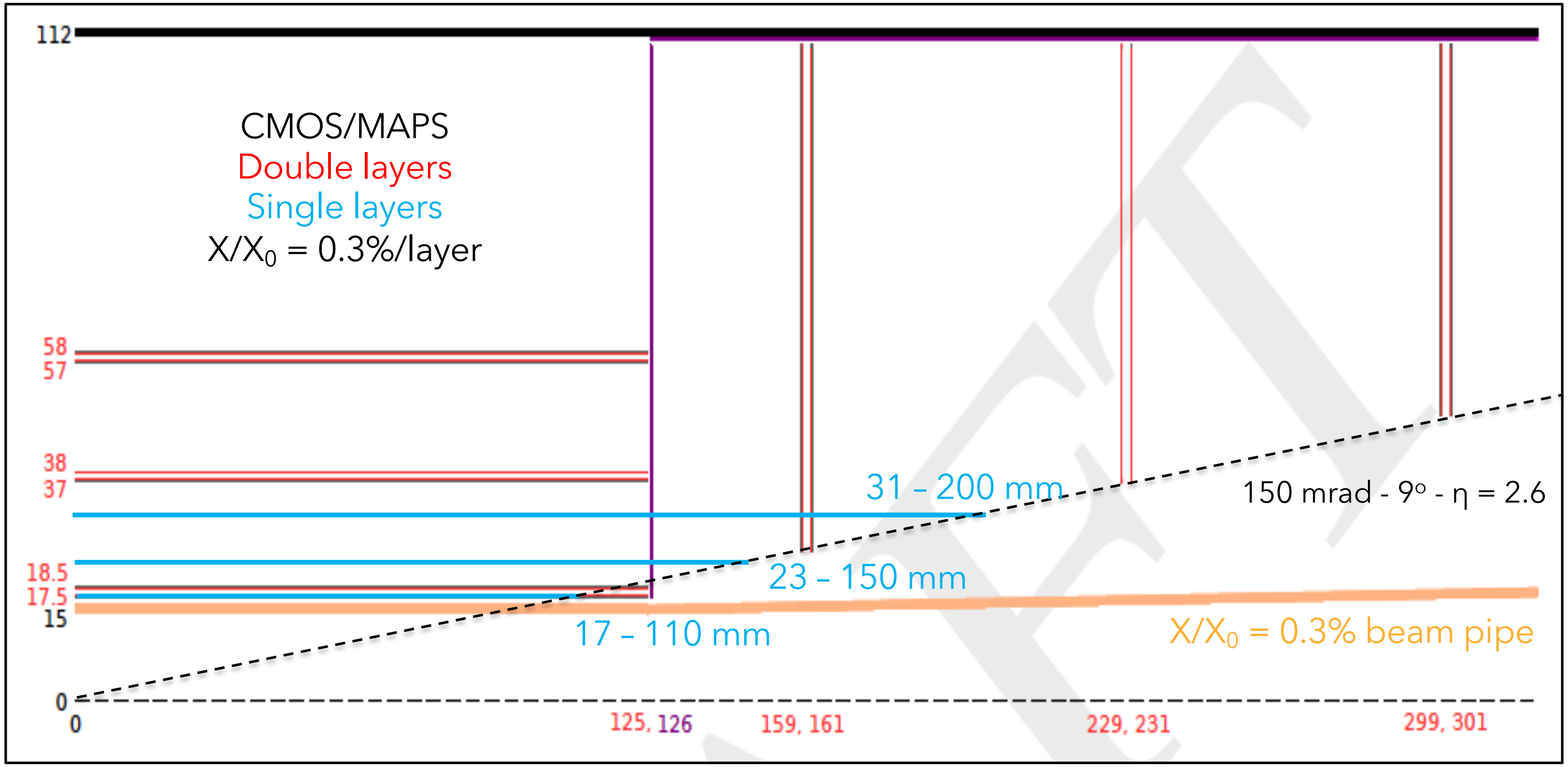


Advanced **L**epton **P**hoton **H**adron **A**pparatus
15 x 4 m inner radius 4T solenoid
would allow operation at 3 T at 240 GeV

* *M.Mannelli* https://indico.cern.ch/event/932973/contributions/4066713/attachments/2142269/3610001/ALPHA%20Common%20Magnet%20Platform%2020%2011%2012%20V1.pd
* * 3T is a CEPC option

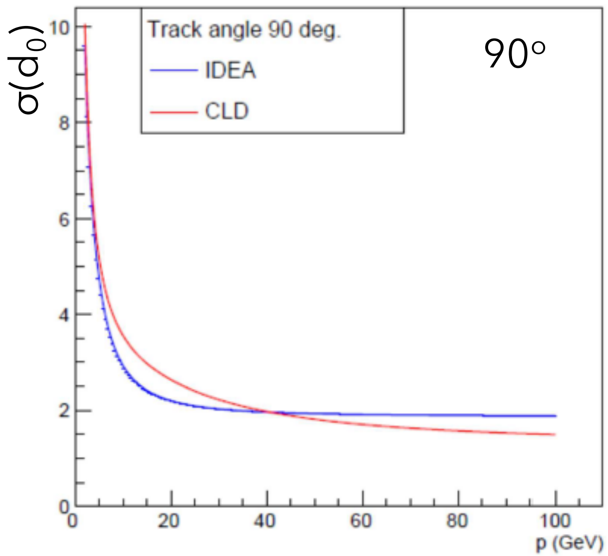
CLD and IDEA Vertex Detectors

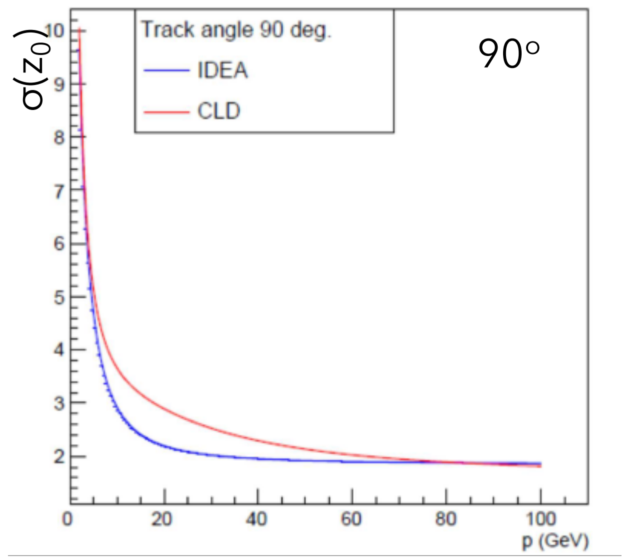
Followed by inner tracker in CLD ≃ last vertex layers in IDEA
Then Outer Si-tracker in CLD and DC + Si-wrapper in IDEA



CLD and IDEA Vertex Detector, d_0 and z_0 precision

- Different number of layers, grouping/radii & length provide similar precision
  - With less layers of silicon in IDEA

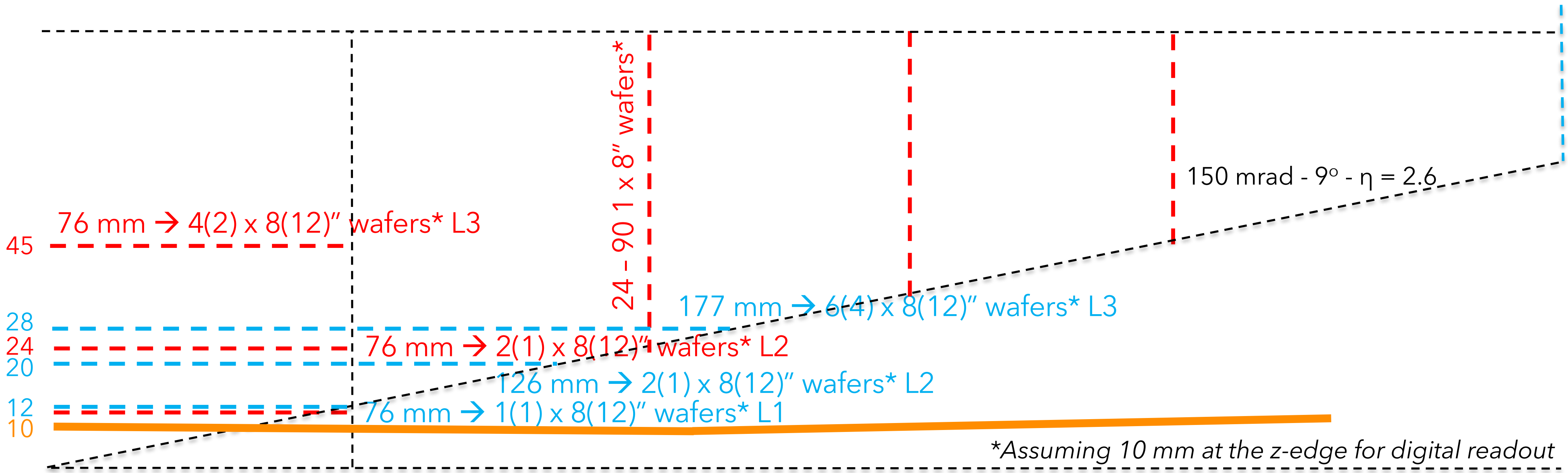




- ➢ Stand alone studies can factorize the origin of the differences for optimization
- ➢ Object reconstruction of vertices (1^{st}, 2^{nd},3^{rd})* & physics studies to say if small variations matter
- ➢ MAPS design will likely be very similar (apart if hit resolution versus X/X_0 need compromise)

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

CLD and IDEA VD scaled to a 10 mm radius beam pipe*



- Alice target 12" wafers - 20 μm thick – 0.05% X/X_0 with gas flow cooling and cylindrical design**
- ➢ Standalone simulations can assess improvements with lower radius and X/X_0
  - Services could be outside acceptance in IDEA design (although x 6 X/X_0 at 9° compared to CLD design)
- ➢ More performant design could be considered in physics simulation
- ➢ Mechanical coupling of 1st layer to (cooled) beam pipe could be investigated, & also layers housed in BP

* M. Boscolo https://indico.cern.ch/event/923801/contributions/4044051/attachments/2139973/3605610/MDI_mboscolo_FCCISworkshopNov20.pdf

** 16 mm bending radius with 50 μm Alpide, M. Mager https://indico.cern.ch/event/932973/contributions/4073514/attachments/2141373/3608219/2020-11-12_FCC_ALICE_MAPS.pdf

Vertex Detector rates

Incoherent pair production background dominates, with highest rate/bandwidth/occupancy at 91GeV

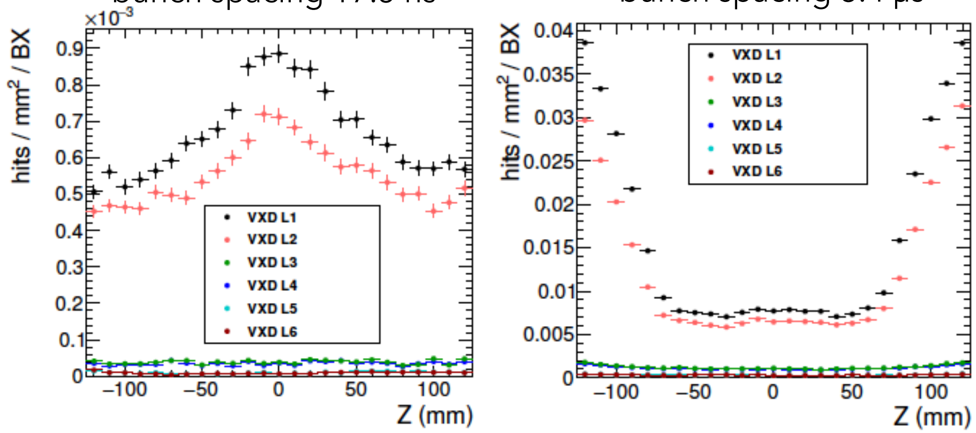
- /3.8 at 365 GeV due to bunch spacing, despite x10 bgd

- 10 μs window, <3> hits, 25x25 μm^2 pixels, 32 bit word
  - 13.5 MHz/cm^2 – 400 Mbps/cm^2 - 0.09 %
- 10 μs window, <2> hits, 15x15 μm^2 pixels*, 32 bit word
  - 9 MHz/cm^2 – 300 Mbps/cm^2 - 0.02 %

CLD studies

91 GeV
bunch spacing 17.5 ns

365 GeV
bunch spacing 3.4 μs



Values depend substantially on assumptions but remain well within present MAPS demonstrator abilities

- 12 mm inner radius is likely acceptable (x3 rate increase?)
- Issue is in power consumption: longer integration time, binary continuous readout favor low power, potentially enabling gas-flow cooling, best implementation may depend on exact occupancies

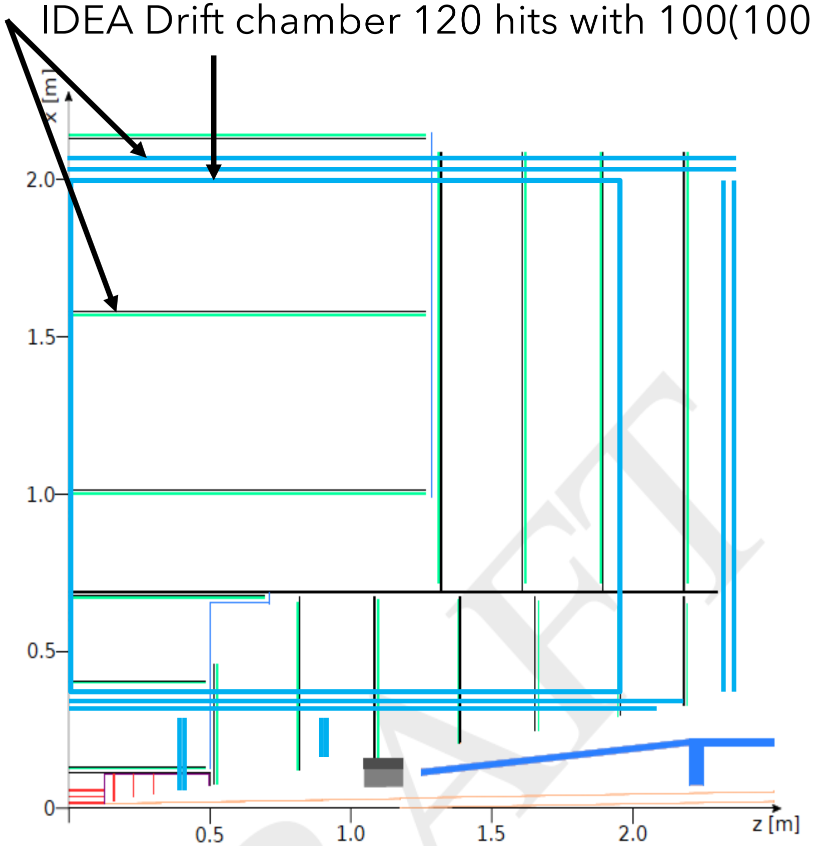
→ Need for an O(1) μs (or smaller) time window to be clarified - a time stamp can be provided by outer tracker layers and/or a ToF dedicated detector

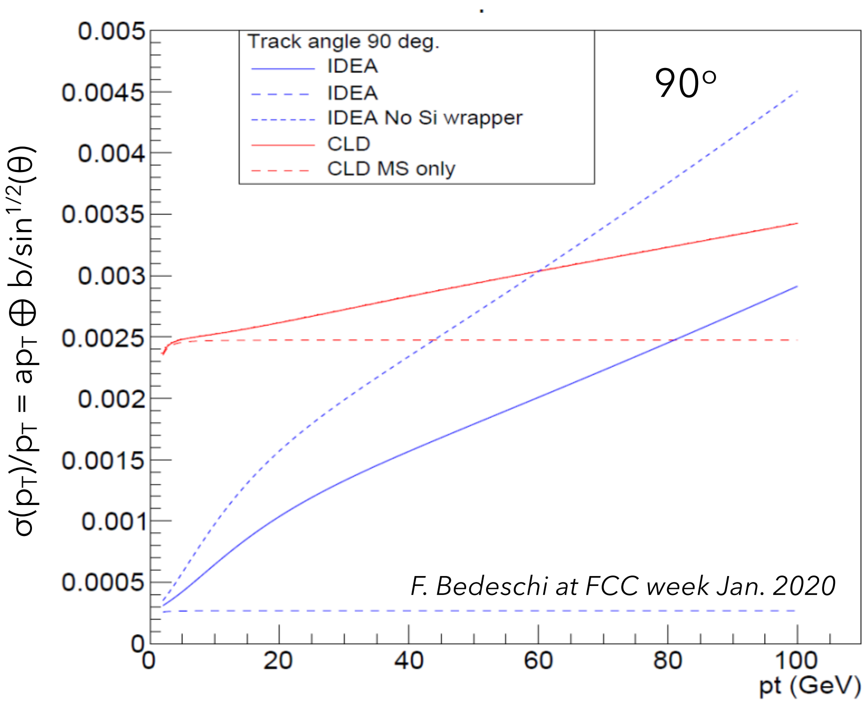
** Likely a better match to 3 μm hit resolution with binary readout allowing lower power consumption*

CLD and IDEA Outer Tracker configurations

200 μm thick Si-sensors 50 μm x 1 mm pitch, 5-7 μm hit resolution 1 – 2 % X/X_0 from inside to outside

IDEA Drift chamber 120 hits with 100(1000) μm rΦ(z) resolution, 0.016(0.05) % X/X_0 barrel(endcap)





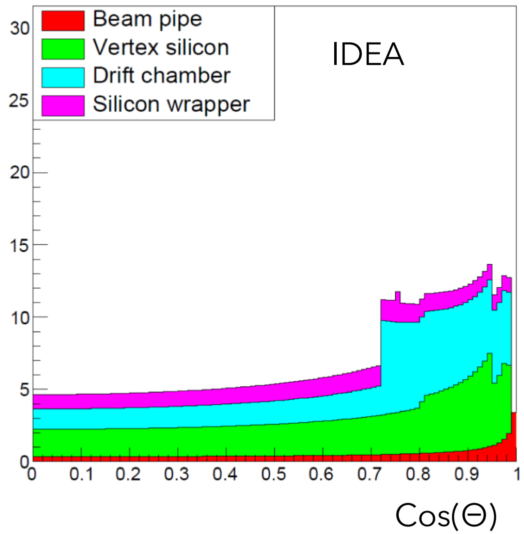
The limit set by beam energy spread is not yet reached*

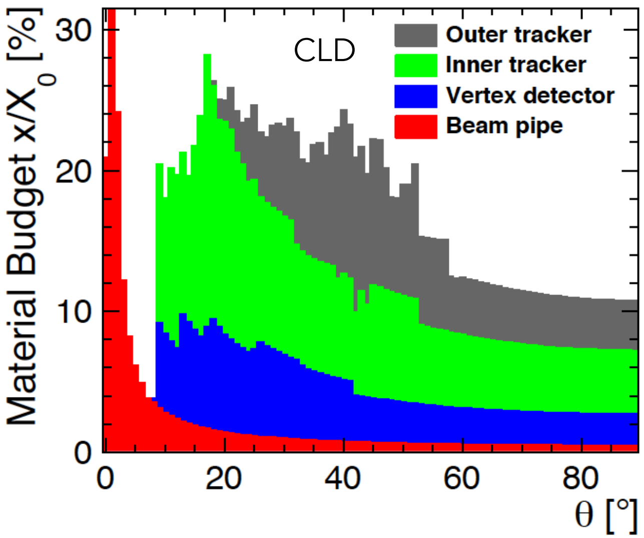
* *E. Perez* https://indico.cern.ch/event/932973/contributions/4076717/attachments/2139667/3604876/2020_11_10_detector_requirements.pdf

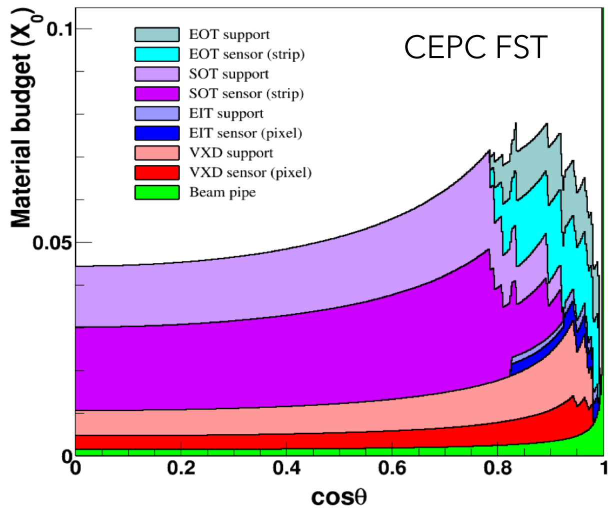
CLD and IDEA Outer Tracker configurations

- CLD MS can likely be substantially reduced
  - ex. with 5 first layers as in IDEA, inner tracker X/X_0 should mostly disappear (green in middle plot)
  - X/X_0 is likely too conservative for an outer tracker with MAPS – CEPC considers much lower X/X_0
- IDEA shows that improved hit resolution in the last layer could still be beneficial

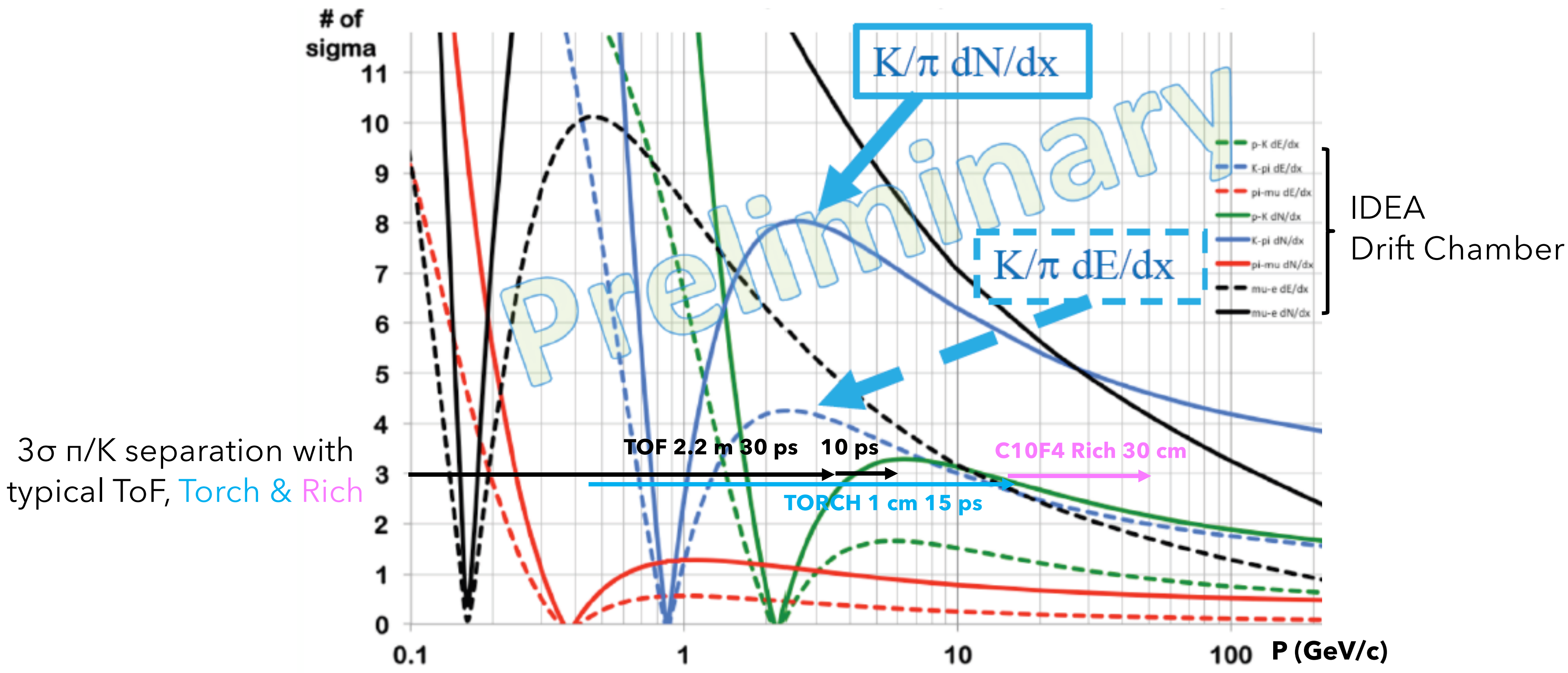
➢ Standalone studies can provide optimization of number of layers versus hit precision and X/X_0
➢ Full simulation to study tracking efficiency, including for far vertices, and effect of alignment & field
➢ DC potential to improve rΦ hit resolution exploiting cluster counting should be investigate







Particle ID, broad-brush coverage of technology options



ToF can cover the deep at crossing of dE/dx - larger momentum are more difficult to cover

Particle ID configurations

- DC + ToF attractive and compact to cover largest momentum while integrating tracking
  - DC (see M. Primavera) & TPC* target similar dE/dx resp. ≃ 4(2) % & ≃ 5(3) % w/o w/ cluster counting
    - ➢ R&D to demonstrate cluster counting – maybe less effective in TPC due to long drift
  - 20 ns ToF resolution could be implemented in the 2 Si-wrapper layers (if compatible with tracking needs) or in dedicated LGAD or Scint./Crystal layer(s) of lower granularity in front of the calorimeter; a micromegas design could also be considered (see T. Papaevangelou)
- In a Silicon Tracker design TORCH – RICH – TORCH/ToF + RICH would be needed**
  - TORCH target a ToF resolution of 15 ps – it would need space at barrel/endcap transition
    - ➢ R&D on photosensors to improve single photon time resolution
  - A RICH would likely need a substantial depth ≃ 30 cm (to reach ≃ 40 GeV for 3σ π/K separation)
    - ➢ R&D to evaluate radiator material (w or w/o focusing) (also considering eco-friendly gas)

➢ Physics studies will provide requirements for relevant nσ separation and range
➢ Requirements for segmentation and impact on calorimetry performance

* U. Einhaus ILD extrapolation 3.26% w/ https://indico.cern.ch/event/932973/contributions/4059402/attachments/2141475/3608471/2020_11_12_FCC_WS.pdf
*** Mix depending on momentum range specs & technology progress, some past experience of focusing RICH in DELPHI and SLD experiments*

Other benefits of ToF and tracking technology options

- ToF benefits* to be further investigated to understand interest to integrate tracking
  - LLP, HSCP secondary vertices ID and mass reconstruction
  - 6 ps interaction timing precision to discriminate √s within bunch crossings at Higgs pole
  - ➢ 4 layers with 20 ps resolution would provide 10 ps per track - inner layers could provide time of low P_T tracks if of interest
  - ➢ An additional timing layer at larger radius after ECAL could provide LLP ID independent of vertex**
- Pixelated LGADs – Si-Hybrids w/o ampl. - MAPS w or w/o ampl. could be considered
  - ➢ R&D needed to assess ultimate resolution of the different options
    - Pixels with small sensor thickness may provide resolution w/o amplification
  - ➢ Power consumption and effect on cooling (X/X_0) to be estimated
    - Preamplification stage depends on channel capacitance and number of channels
    - TDC depends on occupancy and technology node*** (channels activated if signal)
    - Digital part depends on occupancy (buffering) and bandwidth (including data size)

* E. Perez https://indico.cern.ch/event/932973/contributions/4080458/attachments/2140587/3607516/2020_11_11_Timing.pdf
** Chih-Hsiang Yeh https://indico.cern.ch/event/932973/contributions/4059399/attachments/2139871/3606257/Slides.pdf
*** 28 nm technology of interest

CLD, IDEA and LAr calorimeter concepts

Representative of the 3 major sampling calorimeter concepts now all targeting:

- PFlow reconstruction, originally proposed and specific optimization of CALICE design
- A certain level of compensation in EM-Had. energy components of hadron showers
- ➢ Technologies differ in ⊥ and // segmentation, sampling fraction, timing capability…

- CLD CALICE-like design, Si-W EM + Scint. Tiles+SiPM/RPC-Steel AHCAL/DHCAL (see V. Boudry)
  - High transverse granularity (25 mm^2 pads in EM section followed by 9(1) cm^2 pads AHCAL/DHCAL
  - High longitudinal 23/48 sampling in EM/HCAL for event by event energy corrections including compensation and leakage
  - Timing capability $\lesssim$ 50 ps per cell (ex. CMS HGC)
- IDEA Dual Readout calorimeter, Cerenkov & Scint. fibers + SiPM (see G. Gaudio)
  - Concept for intrinsic EM/Had compensation
  - High transverse segmentation 7 mm^2
  - Timing can provide some equivalent to longitudinal segmentation
- LAr sampling calorimeter (proposal with similar concept as for FCC-hh)
  - High transverse granularity $\Delta\eta \times \Delta\varphi \approx 0.01 \times 0.01$; first layer $\Delta\eta \times \Delta\varphi \approx 0.0025 \times 0.02$ and 8 (or more) depths segmentation, good sampling fraction, uniformity and linearity
  - Timing capability 60(100) ps for 50(100) GeV showers

CLD, IDEA and LAr calorimeter performance

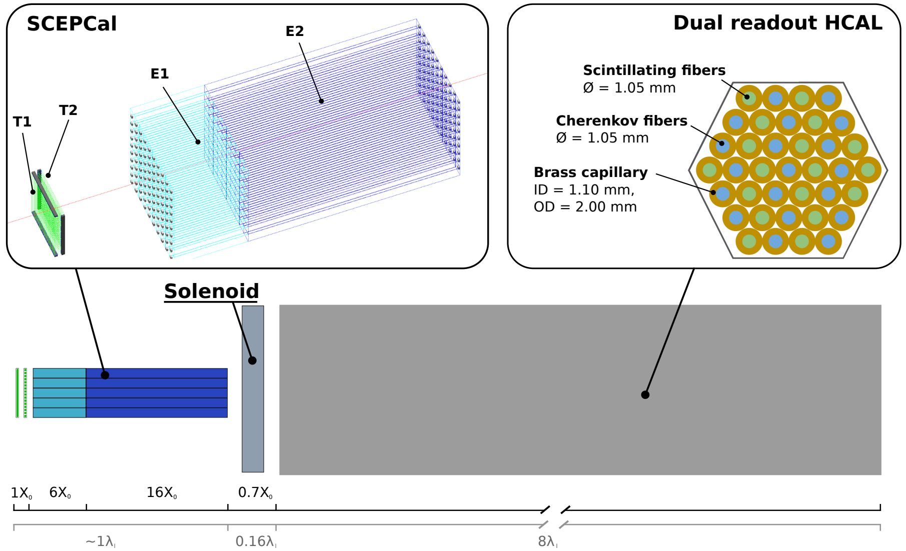
- Primary goal for Z–W separation of 3% resolution for 50 GeV jets appears well-fulfilled; with PFlow reconstruction techniques it should require $\sigma E(\gamma)/\sqrt{E} \lesssim 20\%$ and $\sigma E(K_0)/\sqrt{E} \lesssim 45\%$*
  - $\sigma E(EM)/\sqrt{E} \simeq 16\%/\sqrt{E} \oplus 1\%$** - $11\%/\sqrt{E} \oplus 0.8\%$*** - $\lesssim 10\%/\sqrt{E}$****
  - $\sigma E(had)/\sqrt{E} \simeq 44\%/\sqrt{E} \oplus 2\%$** - $30\text{-}40\%/\sqrt{E} \oplus 1\%$*** - $37\%/\sqrt{E} \oplus 1\%$****
  - $\sigma E/E$ Jets $\simeq$ 3.5 % (50 GeV) jets w/ PFlow - 5.4(5.2)% 45 GeV jets w/(w/o) 1 X/X_0, w/o PFlow
- Other performance variables e/π ID, π_0/γ ID, angular resolution can vary with technology
  - ➢ Thorough studies are needed to assess impact of variables & relatively small performance differences with physics benchmarks
  - Performance is likely going to further improve with R&D and reconstruction techniques progress
    - Example of new technical options
      - ➢ Si-W ECAL with MAPS (digital calorimetry including timing)
      - ➢ Dual readout with single fibers for Cerenkov and Scintillation with pulse shape analyses from front and rear readout (see E. Auffray)
    - Further exploitation of multivariate and deep learning reconstruction technics
      - ➢ Including timing measurement

** M. Lucchini* https://indico.cern.ch/event/932973/contributions/4062153/attachments/2141122/3607756/20_11_12_SCEPCal_in_IDEA_%40FCC_workshop.pdf
*** Measured with realistic prototypes D. Heuchel w/ software compensation for HCAL energy resolution* https://indico.cern.ch/event/932973/contributions/4062111/attachments/2140851/3607495/DH_FCC_Workshop_CALICE_Results_final.pdf
*** From simulation L. Pezzotti* https://indico.cern.ch/event/838435/contributions/3658384/attachments/1970595/3277775/FCCWS2020.pdf
***** From simulations M. Alexa* https://indico.cern.ch/event/727555/contributions/3456388/attachments/1869198/3075062/20190626-FCC-Week-FCC-ee-Calorimetry.pdf

Segmented Crystal Electromagnetic Precision Calorimeter

See R. Alexsan "ideally" $3\%/\sqrt{E} \oplus 0.3\%$

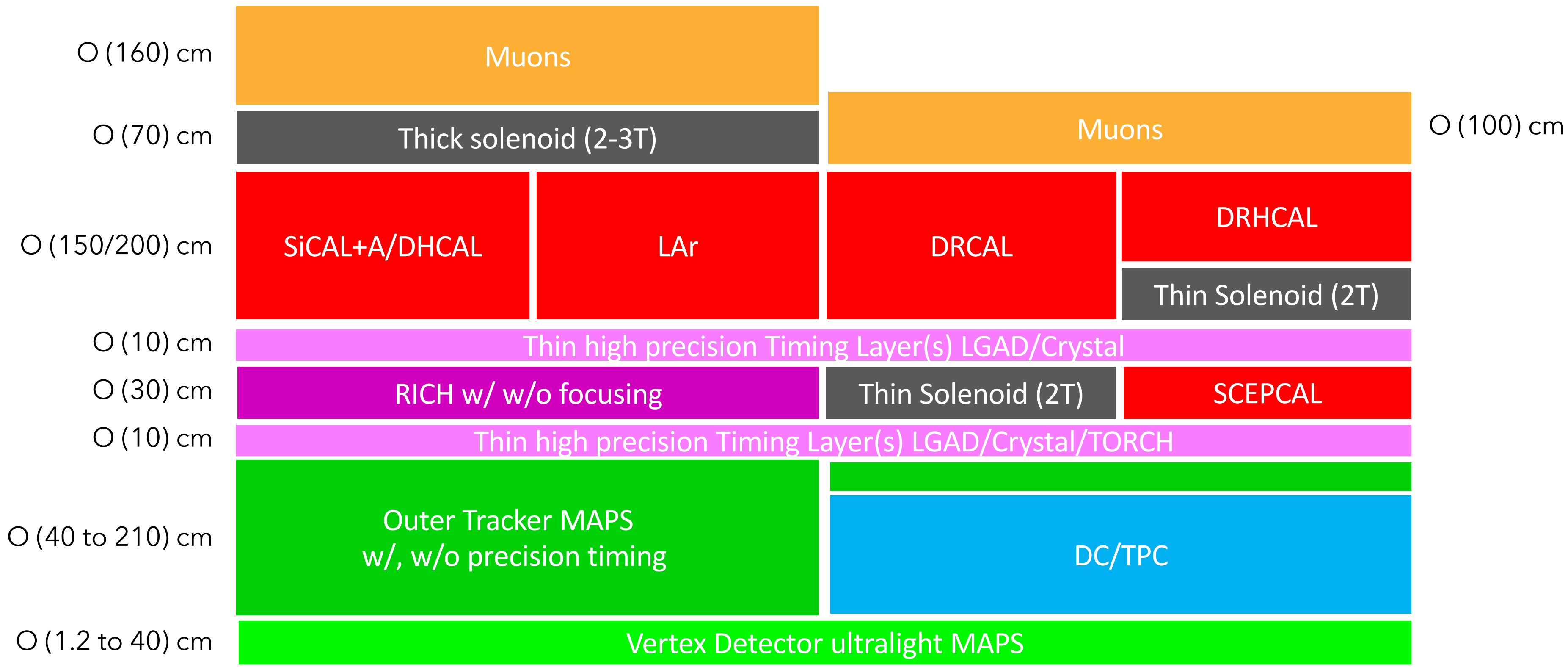
- SCEPCal homogenous crystal*
  - 2 timing layers 3 x 3 mm^2 followed by 2 depths 1 x 1 cm^2 (½ R_M) ⊥ granularity
  - New concept of dual readout for neutral hadrons pre-showering EM/Had. Compensation
  - $\sigma E(EM)/\sqrt{E} \simeq 3\%/\sqrt{E} \oplus 0.5\%$
  - $\sigma E(had)/\sqrt{E} \simeq 27\%/\sqrt{E} \oplus 2\%$
  - ➢ Ongoing implementation in simulation with IDEA dual readout HCAL after solenoid



- Technical alternatives
  - ➢ Crystal fibers for higher ⊥ granularity (see E. Auffray)
  - ➢ More // segmentation with readout between layers or timing at both ends (CEPC see M. Ruan)
  - ➢ AHCAL/DHCAL/LArHCAL

* *M. Lucchini* https://indico.cern.ch/event/932973/contributions/4062153/attachments/2141122/3607756/20_11_12_SCEPCal_in_IDEA_%40FCC_workshop.pdf

Conceptual Design summary exercise



- Precision Timing layer(s) may become part of Outer Tracker functionality
- Some other dedicated layers/functionalities also optional
- Technologies can be exchanged in left/right CLD/IDEA-like solenoid configurations

Outlook

- Several mix of configurations and technologies are possible for multiple FCC-ee experiments
  - Likely there will be a certain level of performance compromise targeting dedicated physics areas
- The physics benchmarks are well established
  - A vast simulation work is needed to factorize effect of technology & of configurations in object reconstruction performance & to assess benefit of relatively small variations in specific physics reach
  - Fast and full simulations can be used as relevant, and development of accurate detector description is anyway needed (see C. Helsen)
- R&D is crucial to anticipate and establish performance projections to be used for simulation
- The process to build conceptual design must consider cost scales