# Detector Concepts for Future Colliders

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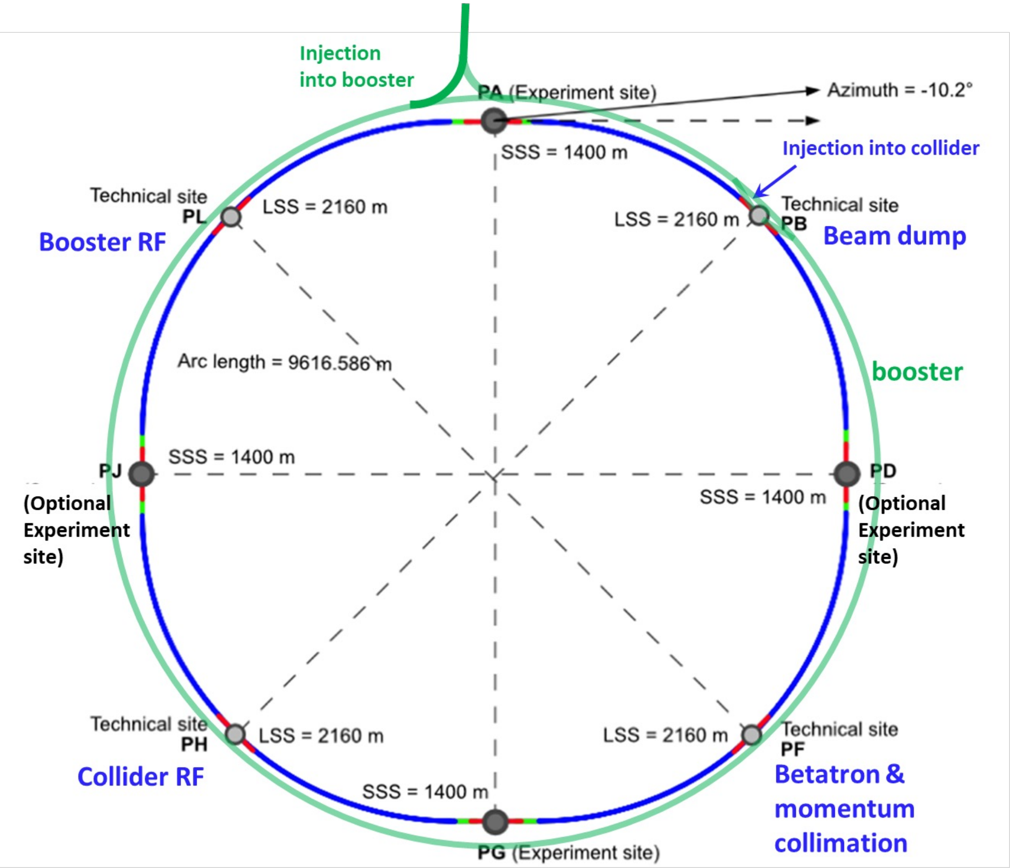
DPF-PHENO 2024, Pittsburgh

I will focus primarily on FCC-ee

# Reveal the Secrets of the Higgs Boson

- One of the primary science drivers identified in the P5 report.
  - Increased Higgs Production rate during the HL-LHC era will certainly facilitate the precision studies of the Higgs properties.
  - "Construct a Higgs factory [using e+e- beams], which would allow precision measurements of the Higgs boson properties and searches for exotic decays, possibly into dark matter."
  - "Precision studies of the Higgs self-interaction and searches for possible new spinless particles related to the Higgs require much larger energies per fundamental particle (parton) interaction: on the order of 10 TeV or more."
- The physics at e+e- colliders allow a broad, multi-faceted exploration:
  - Measure a comprehensive set of electroweak and Higgs observables with high precision
  - Tightly constrain a large number of SM parameters,
  - Unveil, if any, small but significant deviations from SM predictions,
  - Evidence for rare processes/particles beyond SM expectations.

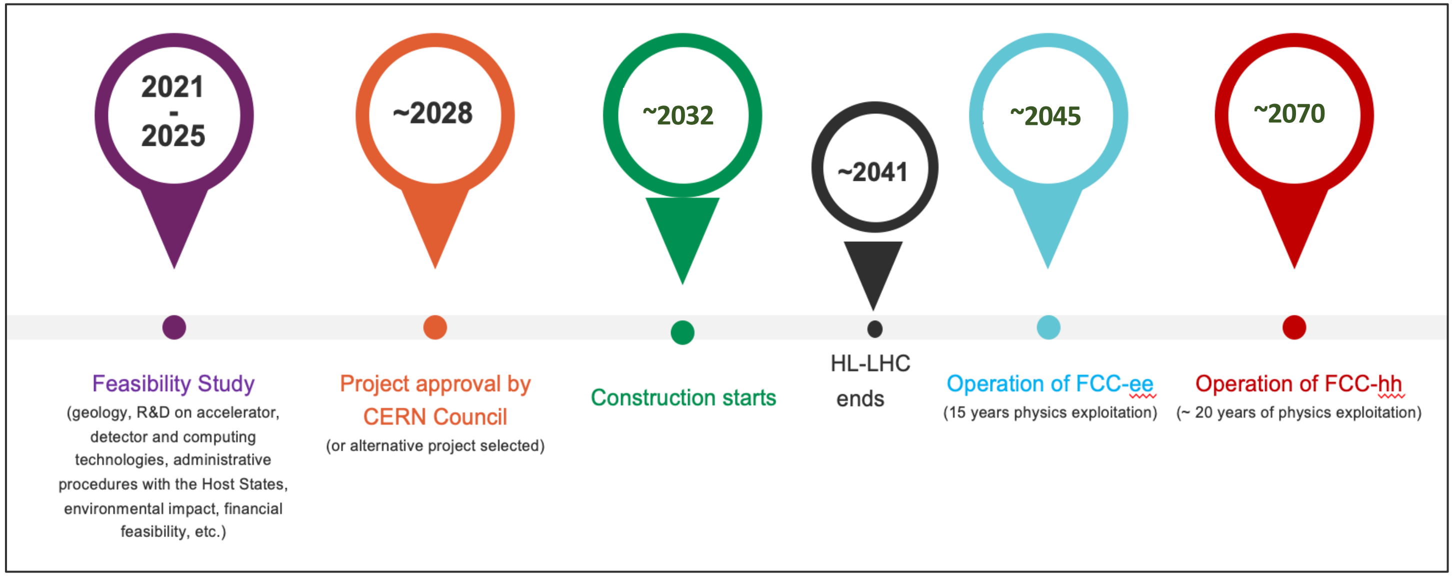
# FCC Program



**90.7 km ring, 4 Interaction Points**

Two stage operation:

- FCC-ee (2045-2060) as Higgs, EW and top factory
- FCC-hh (2070-) continuation with pp, AA collisions



Feasibility Study
(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

Project approval by CERN Council
(or alternative project selected)

Construction starts

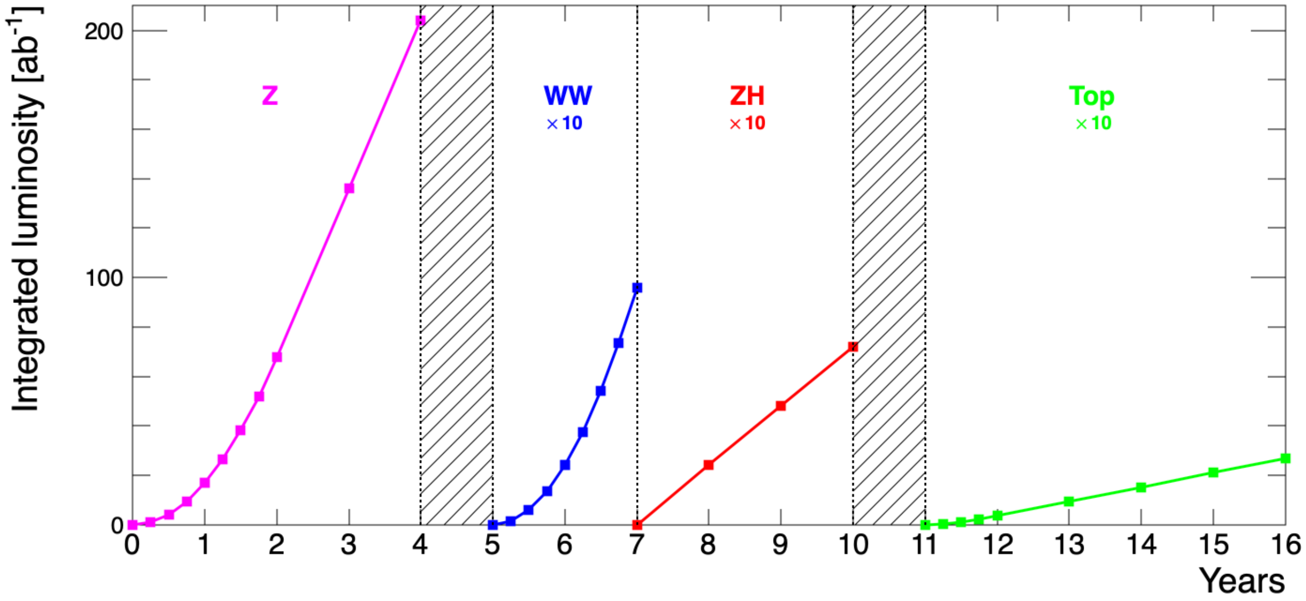
HL-LHC ends

Operation of FCC-ee
(15 years physics exploitation)

Operation of FCC-hh
(~ 20 years of physics exploitation)

Details in M. Benedikt presentation

# FCC-ee (proposes a 4-stage operation)



Z-pole: 4 –years (5 x $10^{12}$ Zs

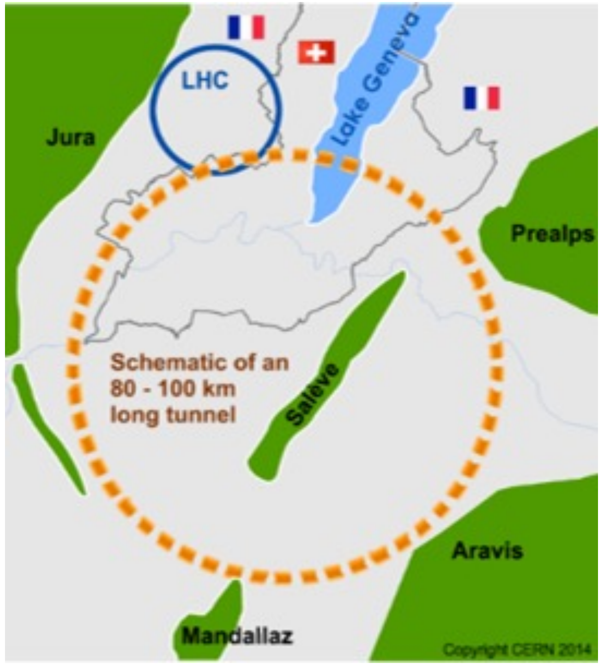
- (ref: LEP $10^7$)

WW: 2 years (> $10^8$ WW)

ZH: 3 years (2 x $10^6$ H)

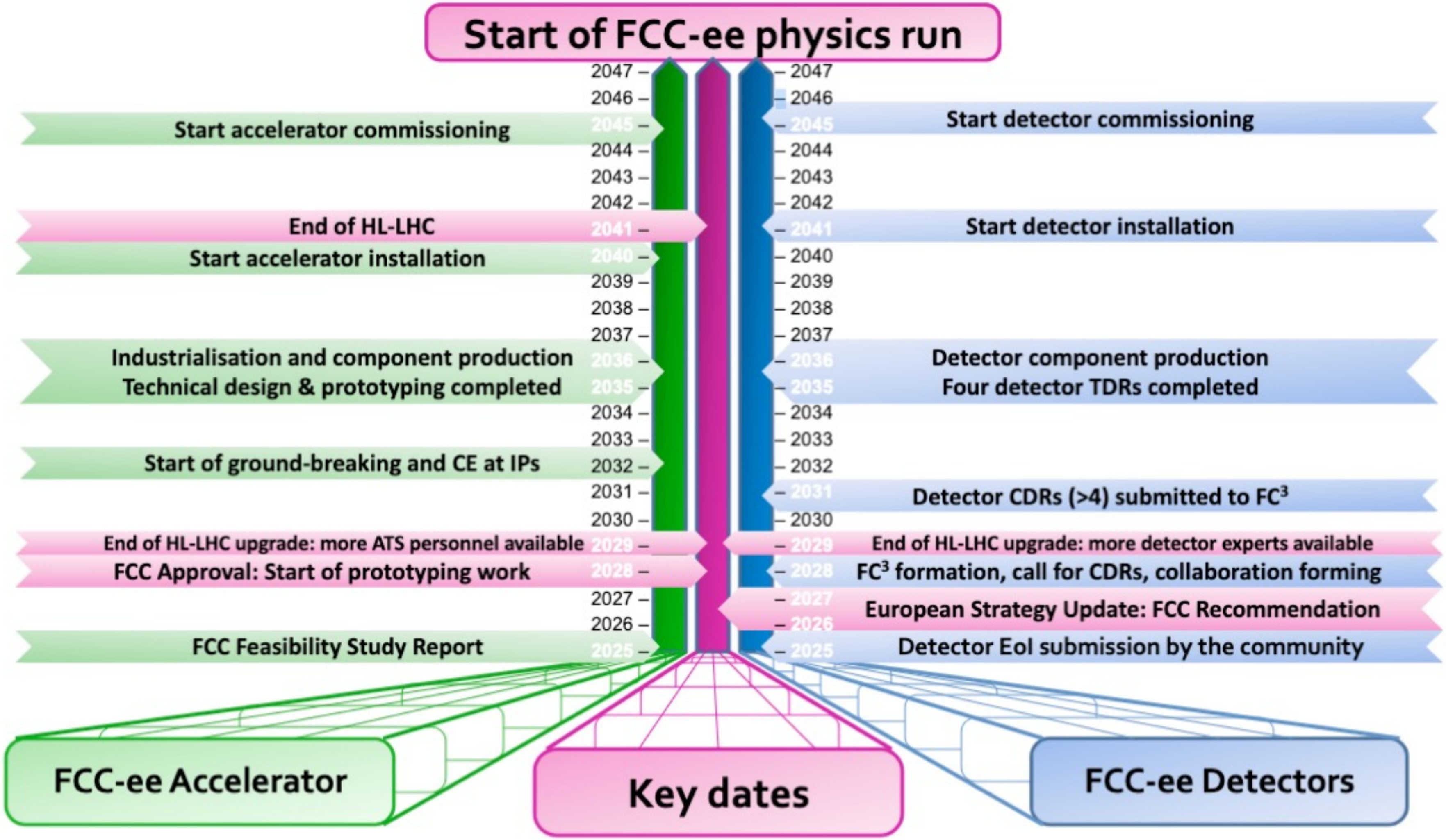
tt: 5 years (2 x $10^6$ $t\bar{t}$ pairs)

| FCC-ee parameters | | Z | $W^+W^-$ | ZH | ttbar |
|---|---|---|---|---|---|
| √s | GeV | 91.2 | 160 | 240 | 350-365 |
| Luminosity / IP | $10^{34}$ cm$^{-2}$ s$^{-1}$ | 140 | 20 | 5.0 | 1.25 |
| Bunch spacing | ns | 25 | 160 | 680 | 5000 |
| ”Physics” cross section | pb | 35,000 | 10 | 0.2 | 0.5 |
| Total cross section | pb | 70,000 | 30 | 10 | 8 |
| Event rate | Hz | 100,000 | 6 | 0.5 | 0.1 |
| ”Pile up” parameter [$\mu$] | $10^{-6}$ | 2,500 | 1 | 1 | 1 |



# Timeline

Defines the timescale for completing the R&D and selecting the technologies for detector production



**Start of FCC-ee physics run**

| | | |
|---|---|---|
| | 2047 | |
| | 2046 | |
| Start accelerator commissioning | 2045 | Start detector commissioning |
| | 2044 | |
| | 2043 | |
| | 2042 | |
| End of HL-LHC | 2041 | Start detector installation |
| Start accelerator installation | 2040 | |
| | 2039 | |
| | 2038 | |
| | 2037 | |
| Industrialisation and component production | 2036 | Detector component production |
| Technical design & prototyping completed | 2035 | Four detector TDRs completed |
| | 2034 | |
| | 2033 | |
| Start of ground-breaking and CE at IPs | 2032 | |
| | 2031 | Detector CDRs (>4) submitted to FC$^3$ |
| | 2030 | |
| End of HL-LHC upgrade: more ATS personnel available | 2029 | End of HL-LHC upgrade: more detector experts available |
| FCC Approval: Start of prototyping work | 2028 | FC$^3$ formation, call for CDRs, collaboration forming |
| | 2027 | European Strategy Update: FCC Recommendation |
| | 2026 | |
| FCC Feasibility Study Report | 2025 | Detector EoI submission by the community |

**FCC-ee Accelerator**

**Key dates**

**FCC-ee Detectors**

# Challenges at FCC-ee

- At the Z pole, high beam currents with bunch spacing 20 ns
  - Almost continuous beam has implications on power management/cooling, density, readout,…
- Extremely high luminosities L ~ 1.8 x $10^{36}/cm^2s$ at Z-pole
  - Require absolute luminosity measurements to $10^{-4}$ to achieve desired physics sensitivity
  - Online/Offline handling of high data rates/total volume.
- Physics interaction rate at Z pole ~ 100 kHz
  - Implications on detector response time, event size, FE electronics and timing
- Beam dynamics
  - 30 mrad crossing angle sets constraints on the solenoid field to 2 T → larger tracker volume
  - Backgrounds from incoherent pair production (IPC) and synchrotron radiation (SR) to a lesser extent (tungsten masks significantly reduces SR toward IP)
- High Luminosities
  - High statistical precision: Requires control of systematics down to $10^{-6}$ – $10^{-5}$ level.
  - Online and Offline data handling O($10^{13}$) events
  - Physics events up to 100 kHz imposes requirements on detector response time, FE electronics and DAQ.

# Detector Requirements

**Higgs Factor Program**

- 1.2M ZH events at $\sqrt{s}$ = 240 GeV
- 75k WW → H events at $\sqrt{s}$ = 365 GeV
- Higgs Couplings to fermions
- Higgs self-couplings (2-4 $\sigma$) via loop diagrams
- Unique possibility to measure electron self-coupling in s-channel e+e- → H at $\sqrt{s}$ = 125 GeV.

- Momentum Resolution $^{\sigma_{pT}}/_{p_T} \simeq 10^{-3}$ $at\ p_T \sim 50$ GeV.
- Jet energy resolution of 30%/$\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for *b, c* tagging

**Precision EW and QCD Program**

- 5 x $10^{12}$ Z and $10^8$ WW events
  - $m_Z$, $\Gamma_Z$, $\Gamma_{inv}$, $\sin^2\theta_W$, $m_W$, $\Gamma_W$, …
- $10^6$ tt events
  - $m_{top}$, $\Gamma_{top}$, EW couplings
- Indirect sensitivity to new physics

- Absolute normalization of luminosity to $10^{-4}$.
- Relative normalization to $10^{-5}$ (eg $\Gamma_{had}/\Gamma_l$)
- superior momentum resolution, limited by multiple scattering → minimize material.
- Track angular resolution < 0.1 mrad
- Stability of B-field to $10^{-6}$

# Detector Requirements

**Heavy Flavor Program**

- $10^{12}$ bb, cc; 1.7 x $10^{11}$ $\tau\tau$ produced in a clean environment.
  - CKM matrix, CP measurements, flavor anomaly studies eg $b \to s\tau\tau$, rare decays, CLFV searches, lepton universality, PNMS matrix unitarity.

- Superior impact parameter resolution
  - Precisely tag and identify secondary vertices and measure lifetimes.
- ECAL resolution at few $\%/\sqrt{E}$
- Excellent $\pi^0/\gamma$ separation for tau identification
- Particle ID: $K/\pi$ separation over a wide momentum range → precision timing.

**Feebly coupled particles Beyond SM**

- Opportunity to directly observe new feebly interacting particles with masses below $m_Z$.
- Axion-like particles, dark photons, Heavy neutral leptons,
- Long lifetimes LLPs.

- Benchmark study: $Z \to \nu N$ with N decaying late
- Sensitivity to far detached vertices
  - Tracking: more layer, continuous tracking
  - Calorimeter: granularity, tracking capability
- Large decay length → extended decay volume
- Precise timing
- Hermeticity

# Detector Requirements

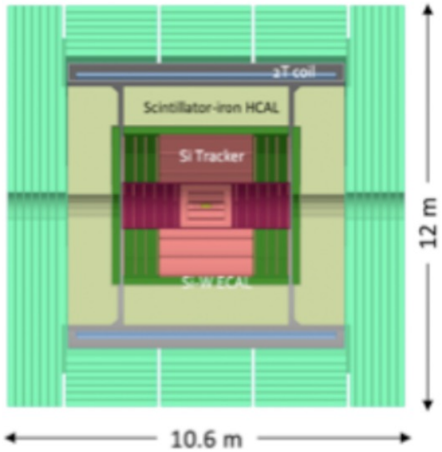
❖ In summary, we require:

- Ultra-lightweight material
- Precision momentum ($\sigma(1/p_T) < 3 \times 10^{-5}$ GeV$^{-1}$) and angular res. (< 0.1 mrad)
- Excellent EM resolution with low constant term
- Unprecedented low jet energy resolution to distinguish W/Z/H to dijets.
- Micron-precision b- and c- tagging capability
- Particle ID in a broad momentum range, incl. pico-second timing capability

# Several Strawman FCC-ee Detector Benchmarks

(2 – 4 detectors planned)

## CLD

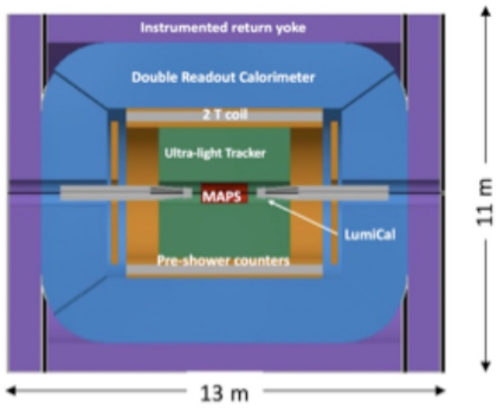


Design (ILC/CLIC/Calice)

- All silicon tracker (pixels + strips)
- Si-W EM calorimeter
  - ○ $22X_0$, 40 long. layers.
- Steel-Scintillator hadronic calo.
  - ○ SiPM readout
- Solenoid outside calorimeter
- RPC based Muon system

https://arxiv.org/pdf/1911.12230.pdf

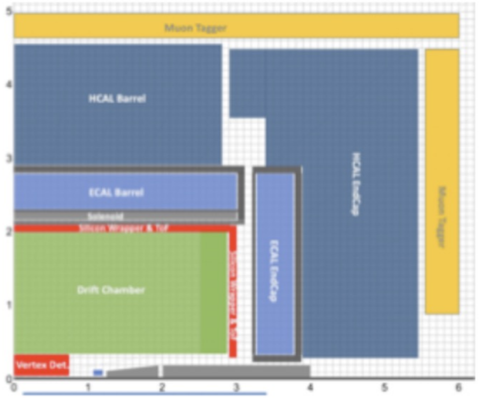
## IDEA



- MAPS based vertex detector (1% $X_0$)
- High-precision low-mass drift chamber with surrounding Si microstrip ($t_d < 400$ ns).
- pre-shower with MPGD readout
- Lead-Fiber dual readout calorimeter
- Sensitive to both Sci/Cerenkov
  - ○ Hybrid with crystal EM?
- large $\mu$-Rwell muon chambers

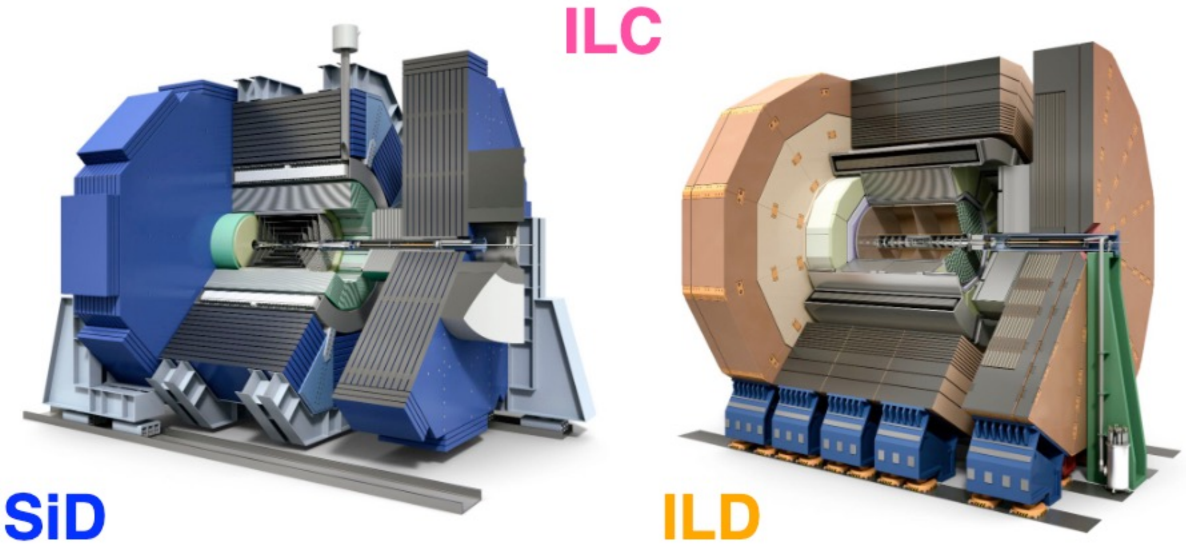
[https://inspirehep.net/files/49ec726758c422bc454e270a71f6e59f](https://inspirehep.net/files/49ec726758c422bc454e270a71f6e59f)

## Allegro



- Includes a highly granular noble liquid calorimeter
- Possible design being explored are lead/steel absorbers (RM ~4 cm), stacked azimuthally inclined at 50° wrt radial axis with LAr as the active medium.
- Other considerations include Tungsten absorbers and/or Liquid Krypton.
- https://arxiv.org/pdf/2109.00391.pdf

# Detector Concepts (ILC)

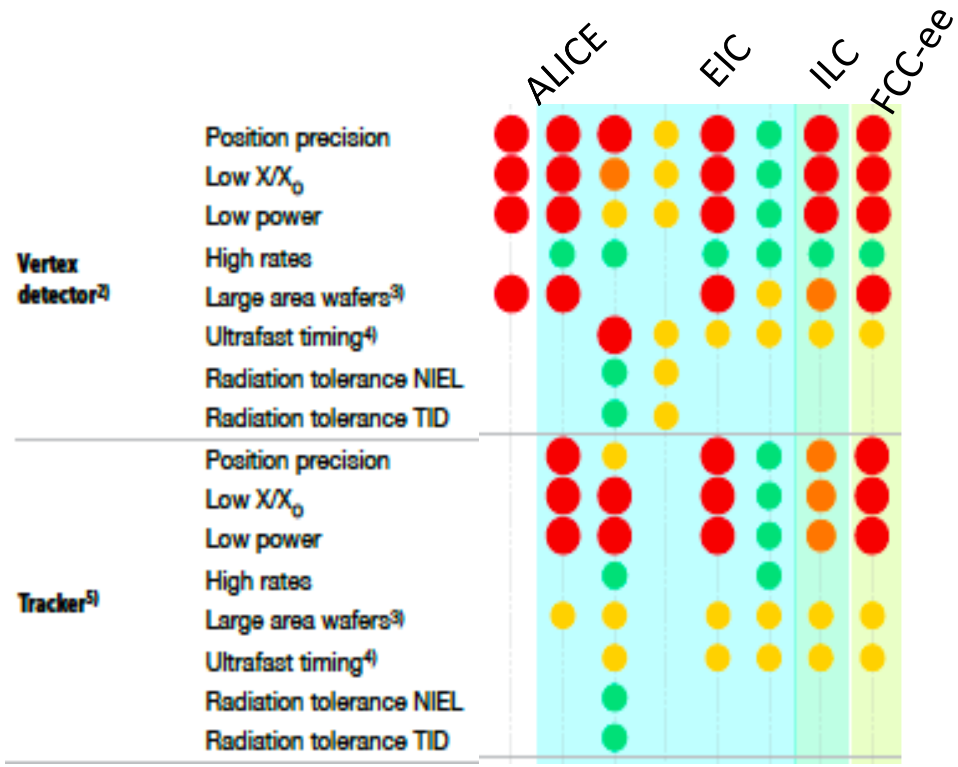


SiD : Compact all-silicon tracking systems with highly granular calorimeters optimized for PFA

ILD: Large detector with PFA calorimeters

- Large B field enables particle separation and consequently helps with Particle Flow Analysis together with a fine granularity calorimeter. ILC detectors well suited for PFA.
  - FCC detectors constrained in B field, therefore must rely more larger tracker volume and highly segmented calorimeters for PFA.
- Non-continuous beam structure allows for pulsed powering and therefore has the potential to reduce cooling requirements (less material!)

# Tracking Requirements



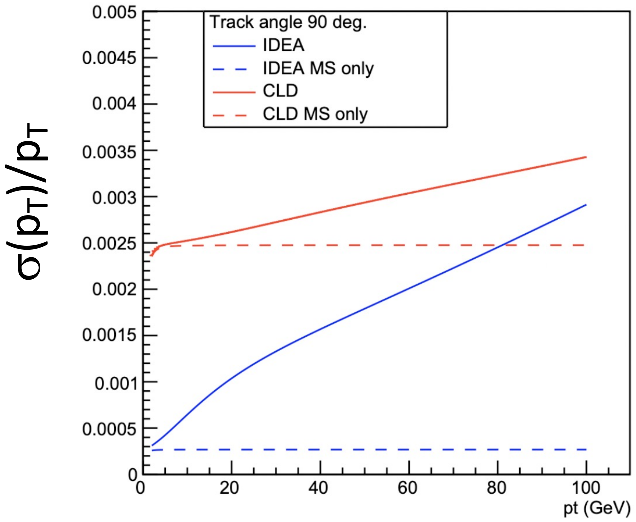
Ref: ECFA Detector R&D roadmap
https://indico.cern.ch/event/957057/

| Detector | Characteristic | FCC-ee/ILC | EIC |
|---|---|---|---|
| Vertex | Position (μm) | < 3 | < 3 |
| | X/Xo (%/layer) | ~ 0.05 | ~ 0.05 |
| | Power mW/cm$^2$ | ~ 20 | ~ 20 |
| | Rates (GHz/cm$^2$) | ~ 0.05 | ~ 0.05 |
| | Wafer size (") | 12 | 12 |
| | Timing precision σ(ns) | 25 | 25 |
| Tracker | Position (μm) | ~ 6 | ~ 6 |
| | X/Xo (%/layer) | ~ 1 | ~ 1 |
| | Power mW/cm$^2$ | < 100 | < 100 |
| | Wafer size (") | 12 | 12 |
| | Timing precision σ(ns) | < 0.1 | < 0.1 |
| TOF | Timing precision σ(ns) | < 0.01 | < 0.01 |

EIC/ALICE inner tracker development is a prototype for the FCC inner silicon tracker option!

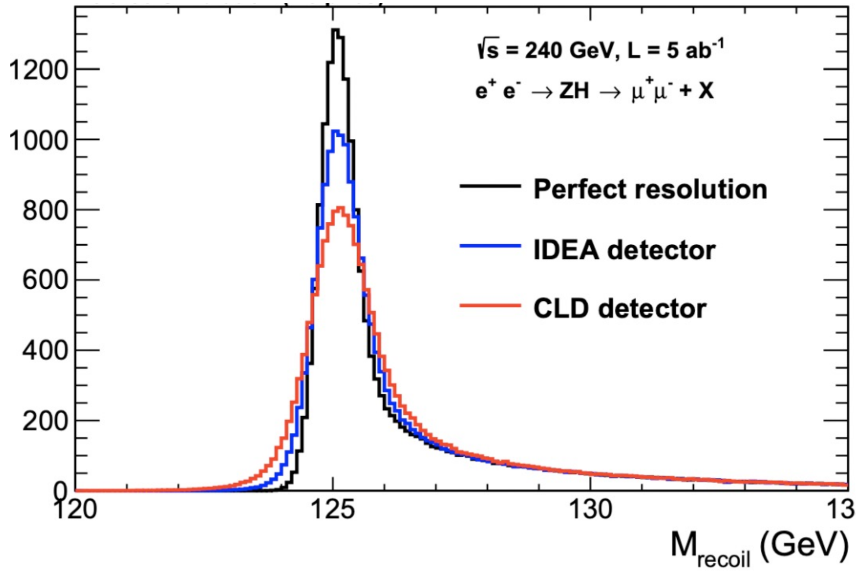
# Tracker Options

- All Silicon tracker : proposed concept for CLID
  - Monolithic CMOS 65 nm technology, an extension of the proposed concept for EIC : which itself replicates the current development for ALICE ITS3.
  - 65 nm TJZ, 12” wafers, 20 mW/cm$^2$, 0.05% $X_0$/layer, 3$\mu$m hit precision
- High-precision low-mass drift chamber (IDEA/ALLEGRO)
  - Transparent! Reduced material → minimal multiple interaction → better momentum resl.
  - Particle separation through dE/dx or dN/dx, Continuous tracking.



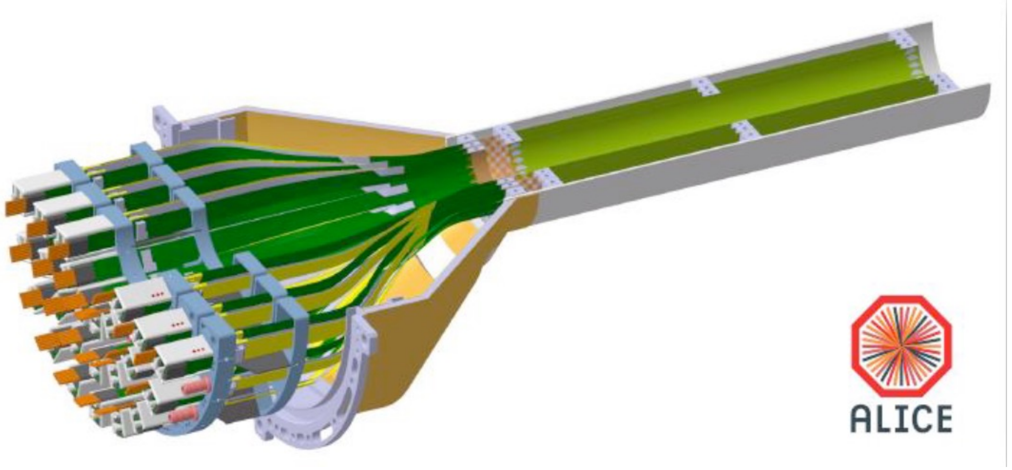
CLID
- All Si Tracker
- total material budget 11%

IDEA
- Drift Chamber
- Material budget is < 2%



# Synergy with ITS3/EIC

- Large stitched monolithic CMOS sensors (TPSCo 65 nm) developed for ITS3/EIC
- Thinned down to 50 μm, curved sensors to reach < 0.1% X0/layer!!
- Position resolution ~ 5μm
- Cooling by airflow
- Radii : 18/24/30 mm, Length 27 cm
- Promising results (M. Winter)



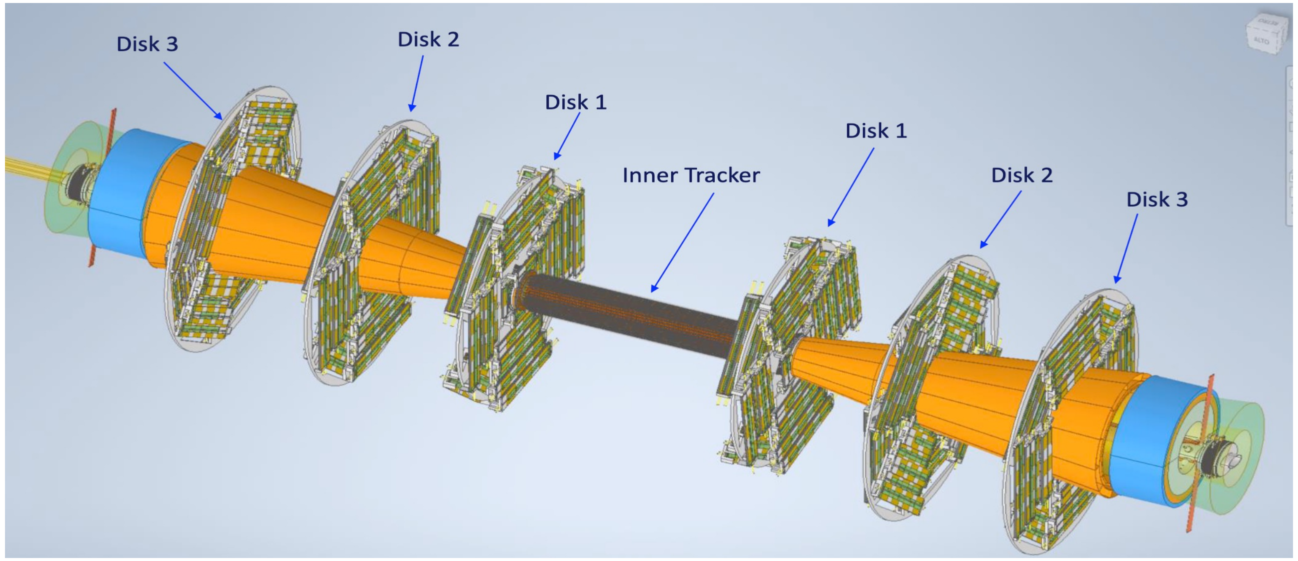
Relative challenges for FCC

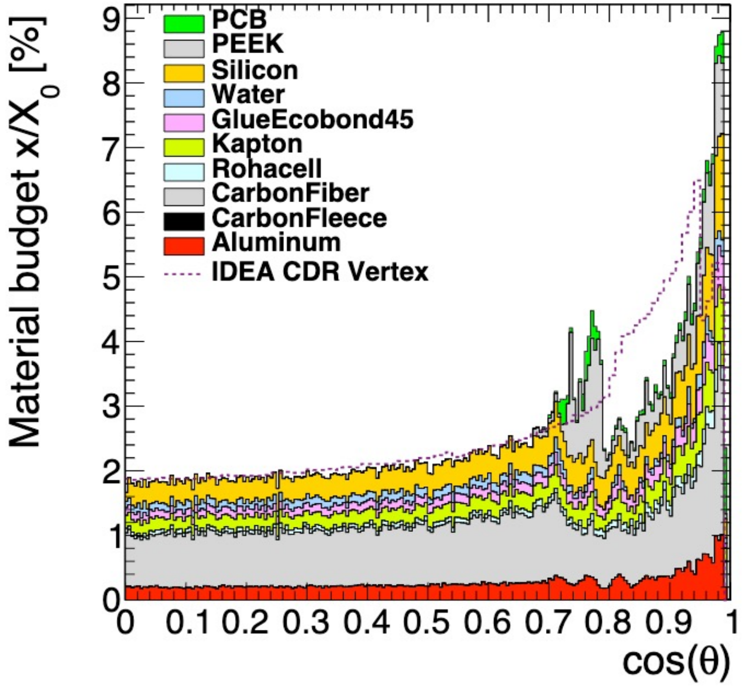
- Minimize X/Xo
- Optimize resolution vs X/Xo
- Stitched sensors yield
- Readout architecture design
- System integration

(see ALICE-3/FCC comparison by D. Contadro)

# Vertex detector, possible integrated design

- Layout of a vertex detector for FCC has recently been engineered (F. Palla)
  - Integration inspired by ALICE ITS3 experience → but several challenges identified due to different FCC configuration. Material budget kept at 0.3% X/Xo per layer
  - Inner Layer: (ARCADIA), 110nm Lfoundry, 50 μm thick,, 50mW/cm$^2$.
  - Outer Layer and disks: (ATLASPIX3), TSI 180 nm, 50 μm thick, 100 mW/cm$^2$
  - Service cones provide mechanism for air cooling and cable routing
  - Lightweight carbon fiber, honeycomb structures, Al reinforcements support structures
- Plan for lighter design using curved and stitched MAPS

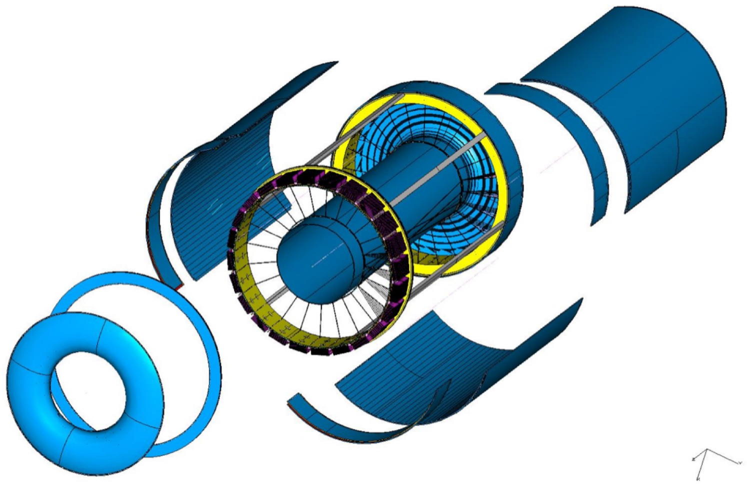


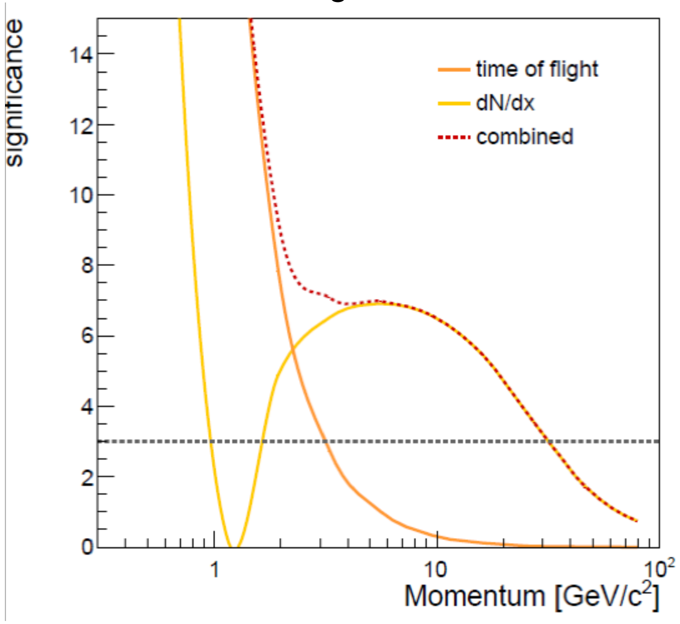


# Gaseous Tracking

❖Drift Chamber tracker proposed in for FCC detector benchmarks (IDEA/ALLEGRO)

- R = 0.35 m – 2.00 m
- 90% He, 10% $iC_4H_{10}$
- 112 layers per 15° azimuth (~350k wires)
- Max drift time 350 ns
- 1.6% $X_o$ at 90°

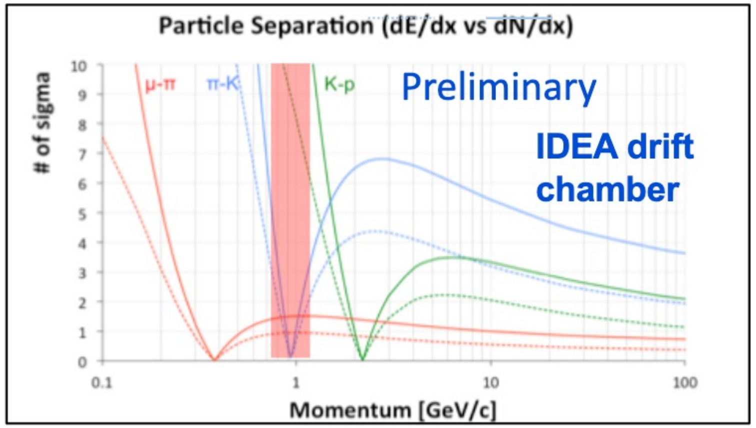


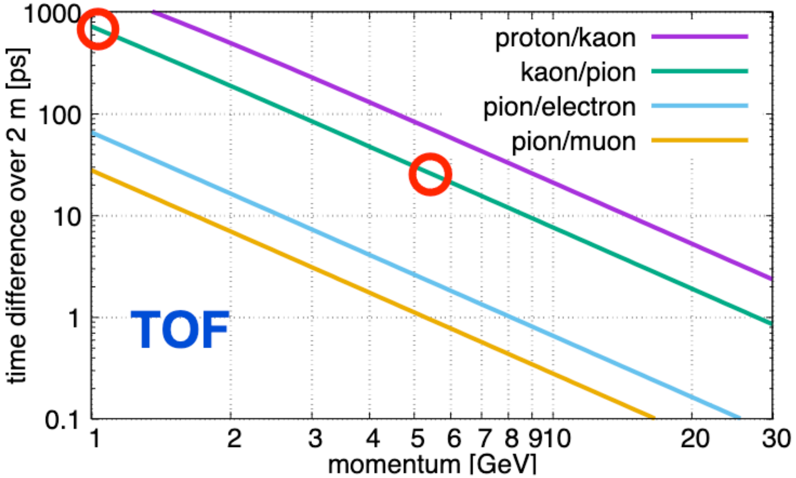


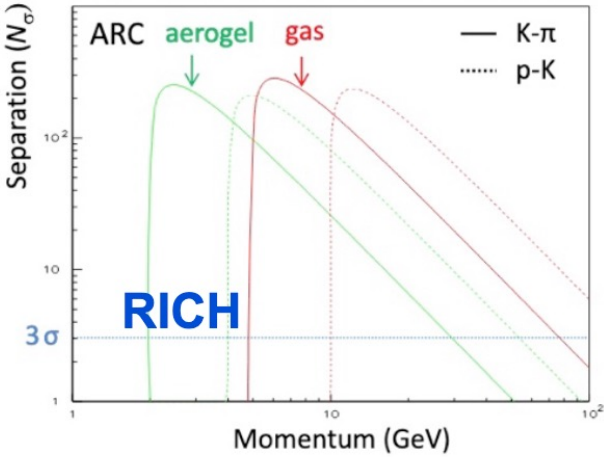
- Large scale mechanical structures and full-size prototypes planned to demonstrate the feasibility of gaseous tracking
- Fast readout electronics to exploit cluster counting techniques
- TPC and other trackers considered, but need to mitigate distortions due to primary ion effects
  - 2 x $10^{12}$ primary ions at any time in TPC (> x2500 ILC)

# Particle ID

- Particle ID using time of flight, dE/dx, cluster counting is essential for flavor physics studies. (see FCC-ee analysis, CEPC analysis)
- dE/dx in drift chamber can provide >3$\sigma$ $\pi$/K separation up to 50-100 GeV.
  - Non-differentiable for p~1 GeV. Mitigated with dedicated TOF systems surrounding tracking volume
- LGAD based timing layer can provide high precision (~10 ps) timing resolution.
  - For a 2m path length (outer radius), $\sigma_t$ ~ 10 ps can achieve a 3$\sigma$ p/K separation for p < 5 GeV/c.
- Pressurized RICH detectors being investigated, can potentially offer 3$\sigma$ $\pi$/K separation 5-80 GeV.





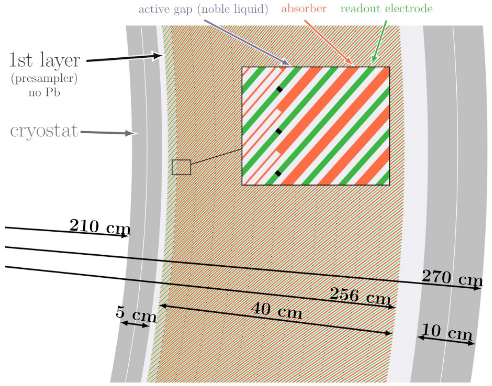


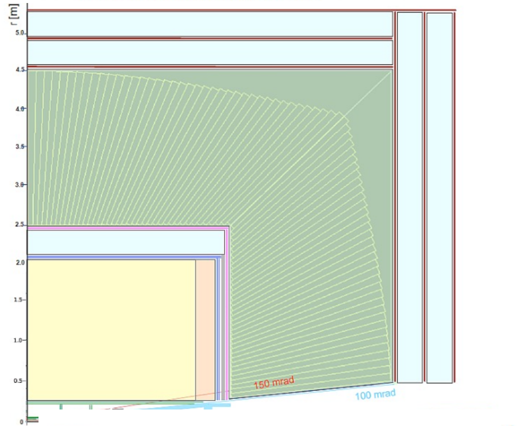
# Calorimeter

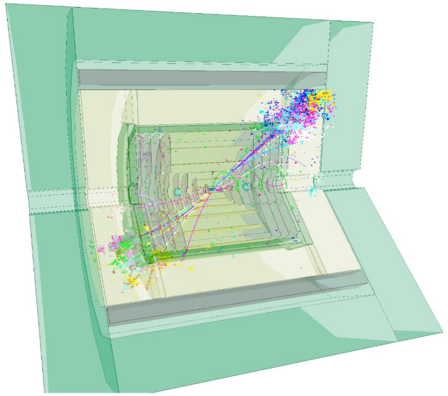
Reference: M. Aleksa et. al.

- The three detector concepts for FCC-ee have been proposed largely around unique calorimeter designs:

1. ALLEGRO: LAr calorimeter
    - 2 mm Pb/Steel absorber oriented 50$^o$ wrt radial direction and multi-layer readout electrode to offer high granularity readout.
    - Finer longitudinal (12 vs. 4 in ATLAS) segmentation and superior (~5x) SNR with cold electronics, 22 Xo, $R_M$ ~ 4 cm (with LAr)
2. Dual Readout Fiber calorimeter:
    - Copper absorbers with embedded Scintillation and Cerenkov fibers
    - 75 towers to ~0.1 radian, no physical longitudinal segmentation.
    - Dual readout with EM crystal calorimeters offer superior performance
3. Si-W EM calorimeters and Tile-Scintillator hadronic calorimeter with SiPM readout.
    - CALICE style proposed for both CLD and ILC.

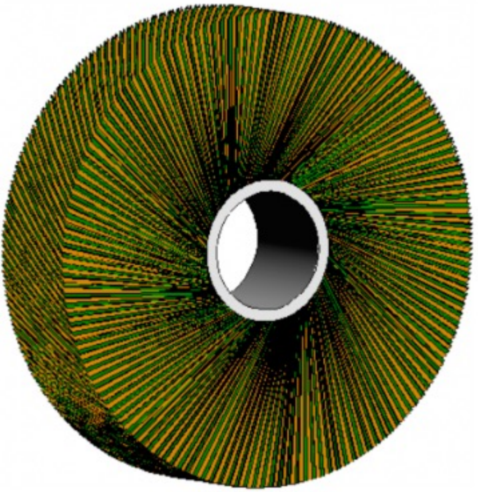




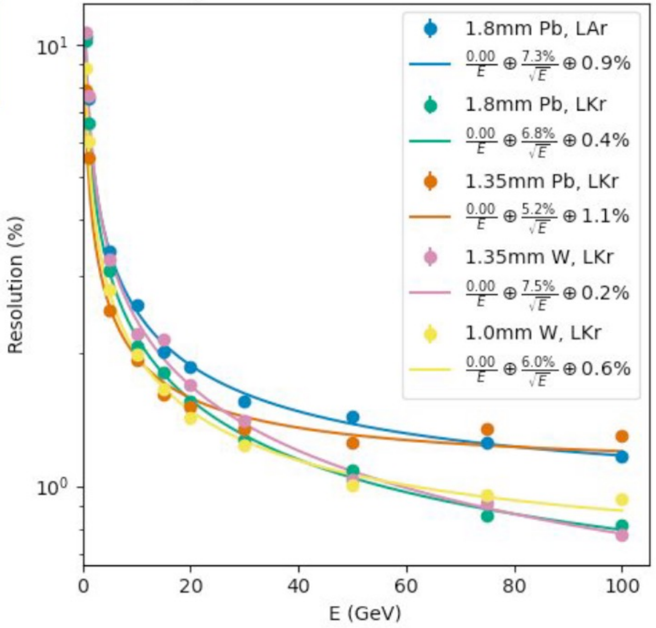


# Nobel Liquid calorimeters

- LAr calorimeters have been well demonstrated in a number of HEP experiments.
  - Also a proposed design concept for FCC-ee:
  - Pb/Steel absorbers with 7-layer readout electrode positioned 50$^o$ wrt radial direction.
  - Possible turbine design option being explored for forward region
- High granularity (x10 ATLAS) for better PFA
  - Prototype with two absorbers and one electrode constructed.
  - Plans to build additional prototypes and test in realistic conditions.
- Cold digital electronics
  - Evolving from what is being used for DUNE Vertical Drift Potential to offer superior x5 S/N performance

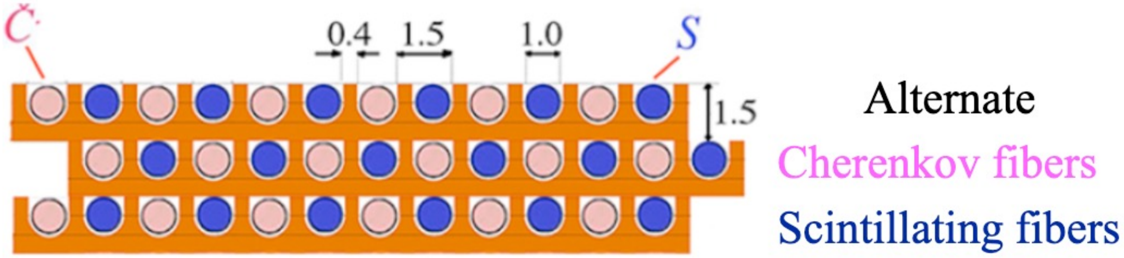


Turbine structure proposed for forward calorimeters



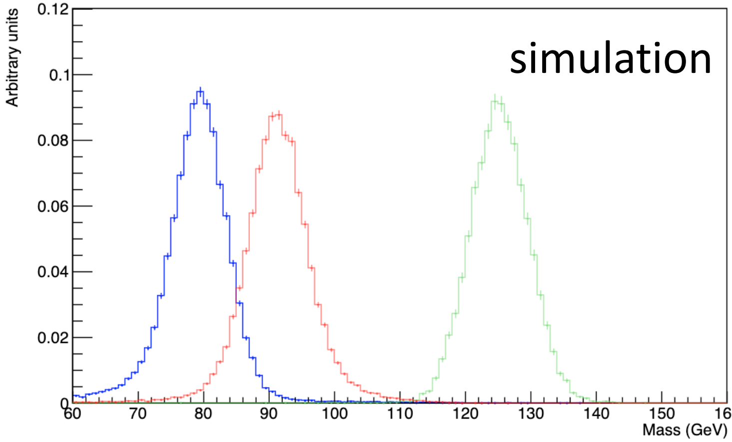
Resolution studies for different active/passive mediums

# Dual Readout Fiber

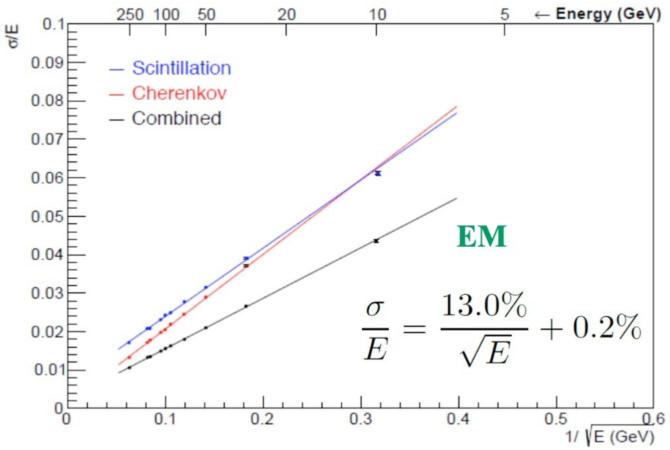


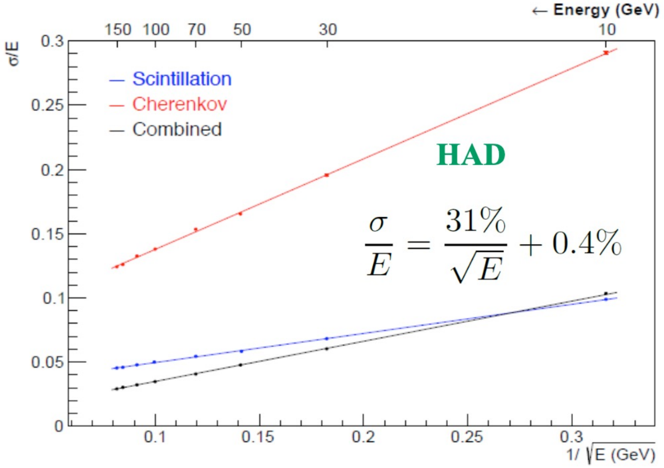
Reference: Snowmass submission

- ❖Promising results matching earlier simulation studies.
- ❖ Need large scale prototypes with TB verification to demonstrate capabilities.
- ❖Possibility to use longitudinal segmentation using timing information



W,Z,H → jj using DR





A front face EM crystal calorimeter with a DR will provide both a superior EM resolution (~3%/$\sqrt{E}$) and a hadronic energy resolution.

# Comparison in performance

https://link.springer.com/article/10.1140/epjp/s13360-021-02034-2

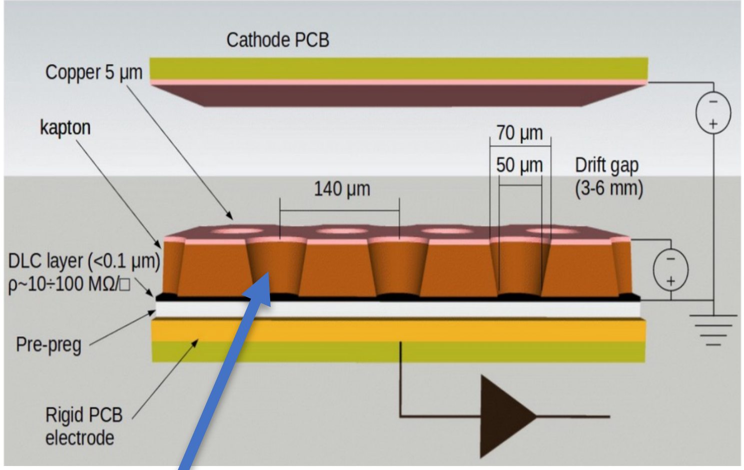
| **Detector Technology** | **EM Energy Resolution** | | **Hadronic Energy Resolution** | | |
|---|---|---|---|---|---|
| | stochastic | constant | stochastic (single hadrons) | 50 GeV jets | 50 GeV jets (inc. PFA) |
| High granularity Si/W (EM) and Tile/Scintillator Had. | 15-17% | 1% | 40-50% | ~6%* | 4% |
| High Granularity LAr (EM) and Tile Scintillator (Had) | 8-10% | < 1% | 40% | ~6%* | 3-4%* |
| Dual Readout (DR) Fiber | 11% | < 1% | 30% | 4-5% | 3-4%* |
| DR with EM crystal | 3% | < 1% | 26% | 5-6% | 3-4% |

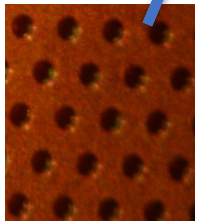
* = estimated, no data or simulation exists.

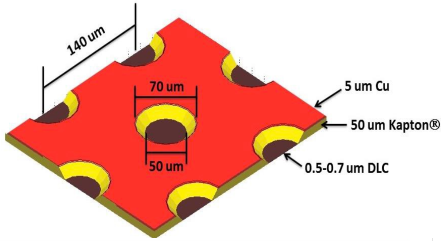
# Muon Detectors

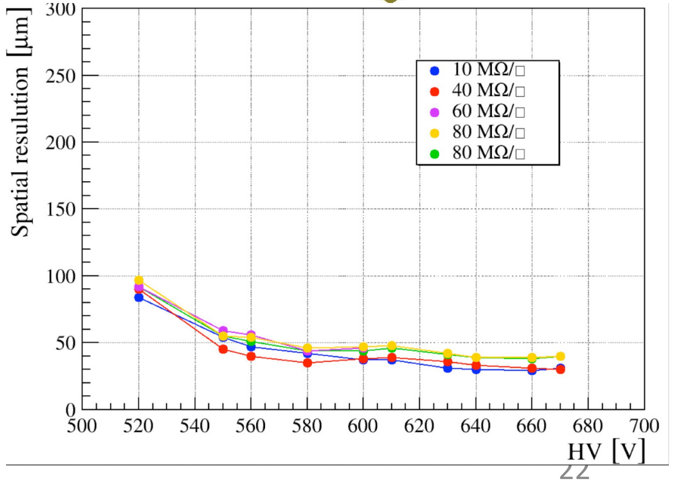
- ❖Several options being considered to provide robust, large-area muon detectors with fast timing and high spatial resolution: Identify muons and search for LLPs
  - Significant experience from ongoing LHC experiments
- ❖Large area precision drift tube chambers using eco-friendly gases capable of 3D tracking with precision position and timing information.
- ❖μRwell detector technology proposed for IDEA: combines advantages of MPGD and RPC with amplification stage + resistive stage + readout PCB.
  - Early test beam results appear promising offering >90% efficiency and < 100 μm spatial
- ❖RPC technology, proposed for CLD, can also be well suited offering fast signals (~ns) and good spatial resolution.
- ❖These technologies must be further developed and demonstrated at large scales.

References: NIM, EuroPhys









# Summary

- Significant R&D efforts ongoing toward realizing a detector for future e+e- collider.
  - From individual detector systems to integrated designs
  - Several prototyping efforts already under way in a number of areas
  - Many of the technological concepts being proposed already exist but needs to be demonstrated scaled-up.
  - Inner tracker has significant synergies with ongoing efforts in ALICE/ITS3 and EIC.
- Large synergy between detector requirements for ILC and FCC.
- Newly organized Detector R&D (DRD) collaborations at CERN offer a vehicle for collaboration and efforts.
- Targeted detector R&D efforts in U.S. beginning to take shape.
- Resources to pursue such R&D efforts remain minimal, largely due to other ongoing efforts in HL-LHC upgrades.
- While challenges remain, there is good progress toward realizing the fundamental concepts that will lead to defining integrated detector concepts for future colliders.