Tracking requirements and detector technologies @ FCC-ee

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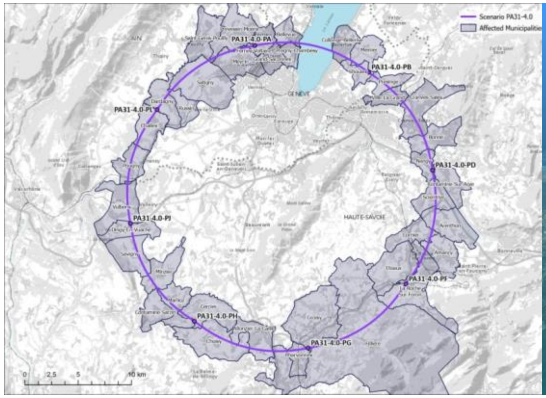
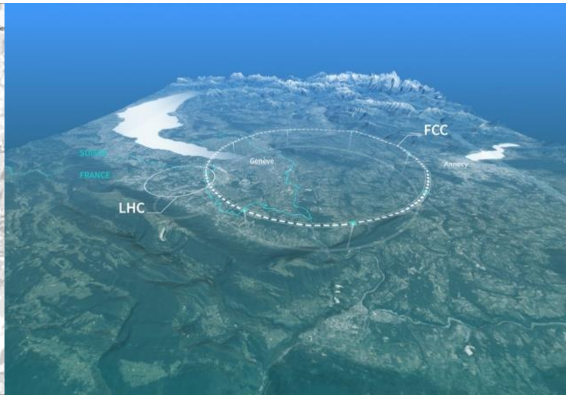



Seminar @ IHEP
Beijing, September 3, 2026

European Strategy 2020

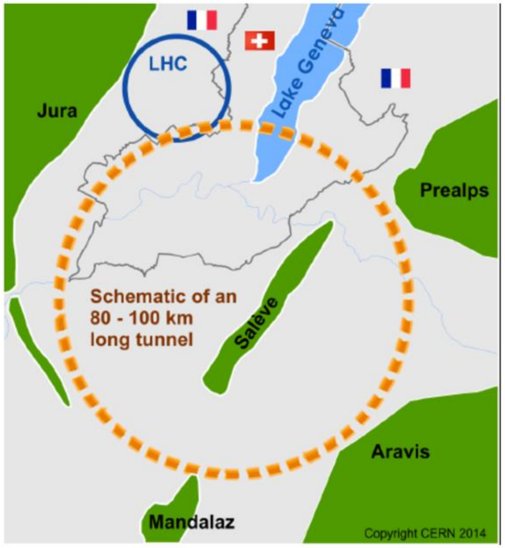
*"**An electron-positron Higgs factory is the highest priority next collider**. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."*

"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

FCC project @ CERN: a new 100 km tunnel in the Geneva region, for two complementary machines covering the largest phase space in the high energy frontier:

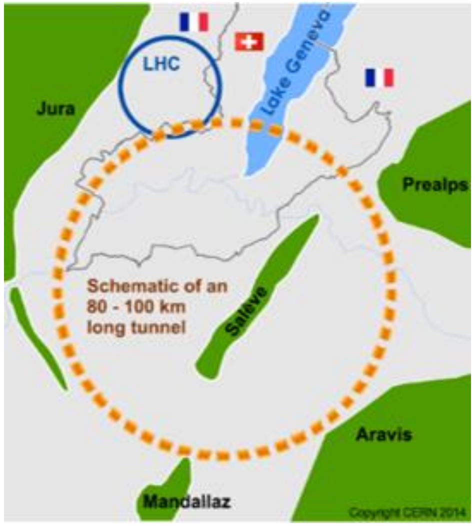
- **extreme precision circular e+e-collider (FCC-ee) with** variable collision energy from 90-360 GeV
- **highest energy reach in pp collisions** (**FCC-hh**): 100 TeV

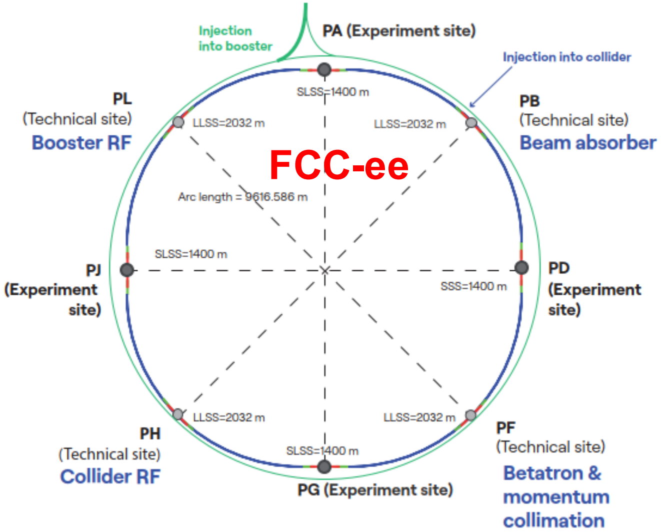
FCC Feasibility Study (FS) launched in 2021:
- To be carried out in 2021-2025
- Mid-term review in Autumn 2023
- March 2025: documentation submitted to ES committe

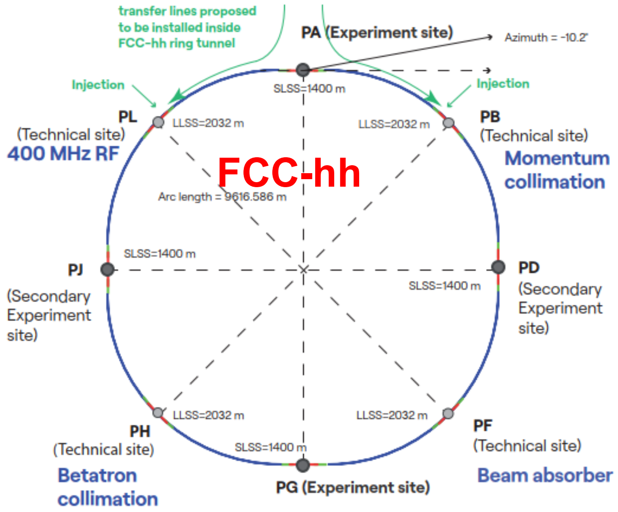


European Strategy 2025 + FCC Week 2026

FCC integrated program - timeline





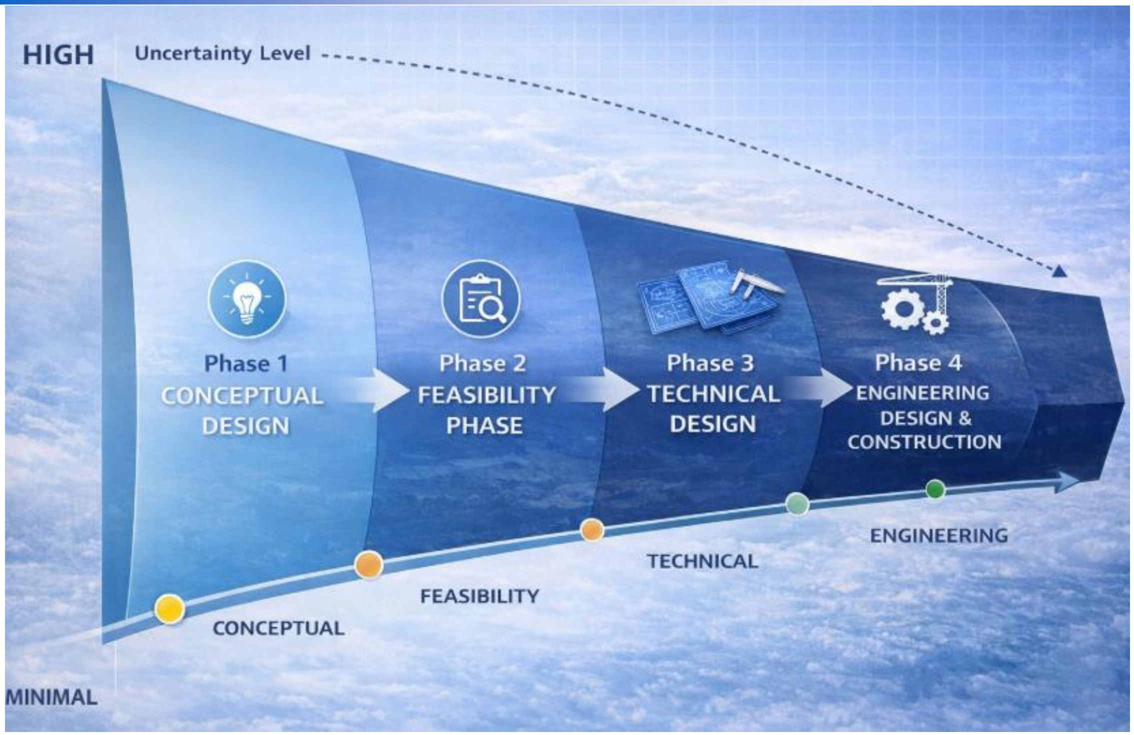


2020 - 2045 | **2048 - 2062** | **2075?**

- **focus on implementation of FCC-ee as first step ; possible pathway to FCC-hh to be decided later**
- **common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure**
- **highly synergetic and complementary physics programme maximising the physics opportunities**
- **FCC-ee project would allow the start of a new, major facility at CERN within a few years of the end of HL-LHC**

Total cost for FCC-ee over ~15 years of about 15 BCHF…

From feasibility study to project realization



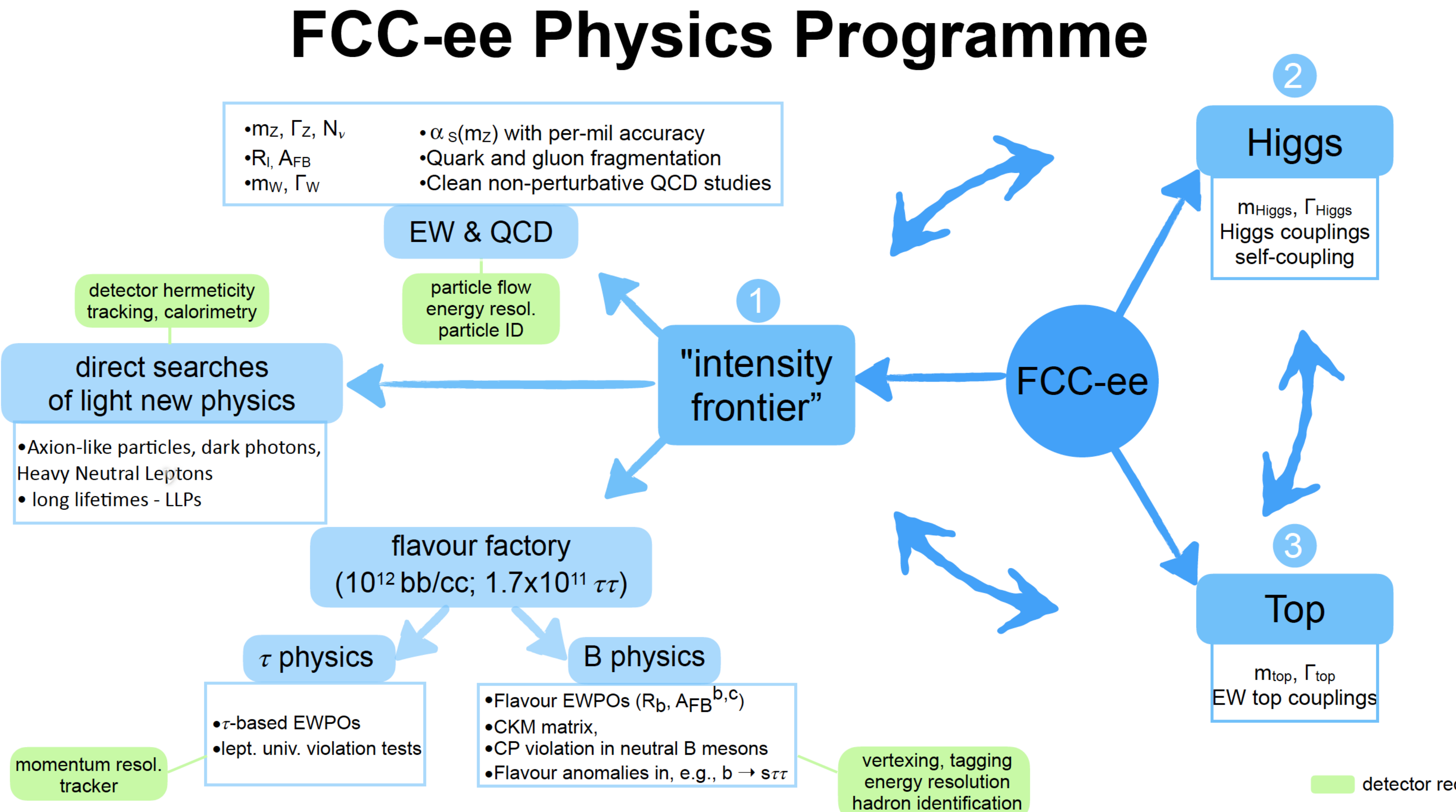
- Following the positive assessment of the Feasibility Study and Council approving the continuation, the FCC moves towards technical design.
- Expertise across CERN and from collaboration partners is required to be able to deliver an integrated technical design, with cost estimate and schedule, taking into account project authorisation processes, societal acceptance, procurement strategy.
- 2026-2028 Reference Design Phase
- 2029-2032 Technical Design Phase

Reference Design Phase (RDP) objectives:

- Increase maturity of technical design (incl. recommendations from feasibility study reviews)
- Overall project integration and requirements on civil engineering sufficiently detailed to enable subsequent launch of civil engineering tender design
- Overall project design sufficiently detailed to allow advancing with environmental impact and evaluation as core parts of project authorisation processes i
- Reducing project risks via:
  - Integrated planning across all domains and interface management
  - Prototyping of critical systems
  - Build up cost / performance contingency by design optimization
  - Civil engineering refinement
  - Close coordination with Host States on territorial implementation aspects
  - Reinforcing collaboration as basis for global support for the project

Aiming for project decision by CERN Council after the Reference Design Phase in 2028

A broad physics program



Physics requirements: Higgs, EWK and Heavy Flavour

- **Tracking:**
  - Momentum resolution for Z recoil (and $H \rightarrow \mu\mu$)
    - Comparatively low momenta involved → transparency is important
  - Vertex resolution/transparency to separate g, c, b, τ final states
- **Calorimetry:**
  - Jet-jet invariant mass resolution to separate W, Z, H in 2 jets
  - Good π^0 ID for τ and HF reconstruction

Higgs boson sector

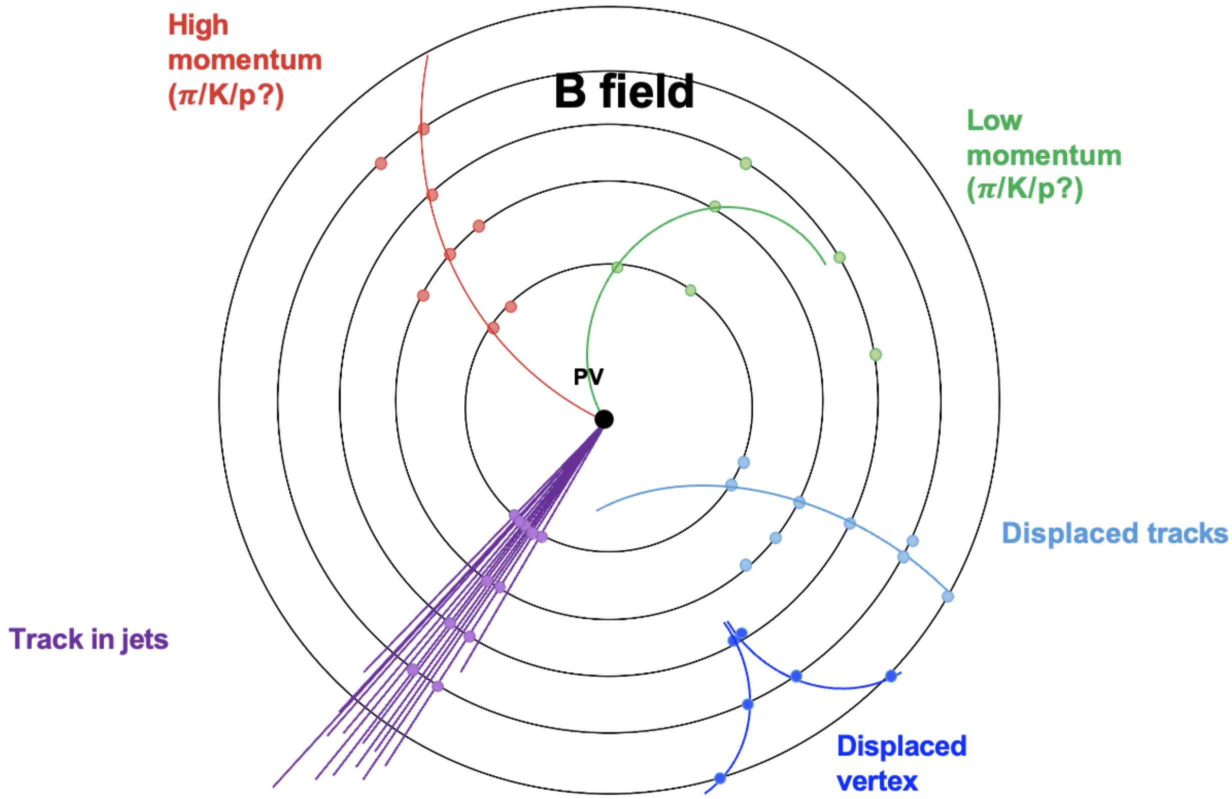
- **EWK:**
  - Extreme definition of detector acceptance
  - Extreme EM resolution (crystals) under study
    - Improved π^0 reconstruction
    - Physics with radiative return
- **Heavy Flavour:**
  - PID to accurately classify final states and flavor tagging

EWK and Heavy Flavour

Tracking and particle identification

- Tracks and vertices are the building blocks of collider physics events.
- Identifying from which particle they originate is key for new physics studies

→ Demanding requirements on tracking systems from physics benchmarks

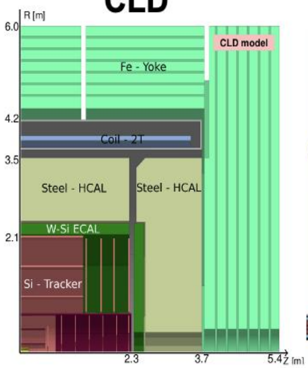


Trackers designed to cope with requirements
Tracking algorithms to fully exploit their capabilities

FCC-ee detector concepts: tracking systems

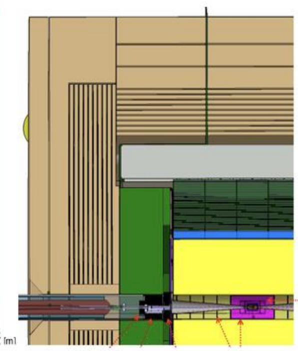
Legend: Inner Tracker, Outer Tracker, Wrappers

CLD



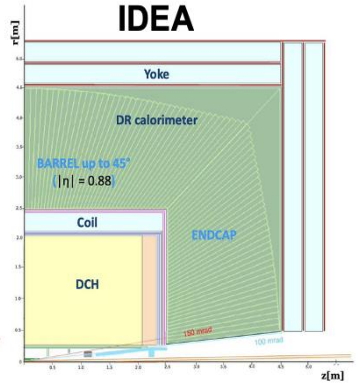
- Evolved from CLIC detector
- Silicon vertex with 25µm pixels
  - Geometry with ALICE ITS approximation → FCC-SEED
- Silicon tracker with 50µm strips
  - Sensors plus ASICs or monolithic structure or MAPS
- ARC (Array of RICH Cells) Lightweight with 20cm radial depth
  - Two radiators (gas + aerogel)

ILD



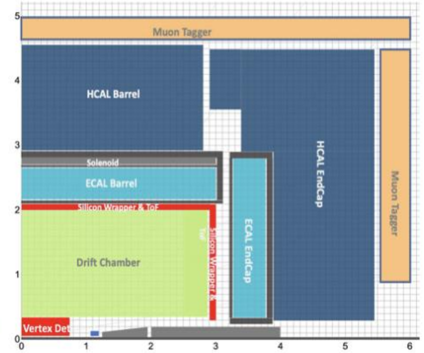
- Initial design for ILC
  - Significant changes for FCC-ee
- Silicon Vertex
  - Currently borrowed from CLD for simulations
- TPC as outer tracker
  - Studying different layouts varying the inner Radii
- Silicon External Tracker for ToF + momentum resolution

IDEA



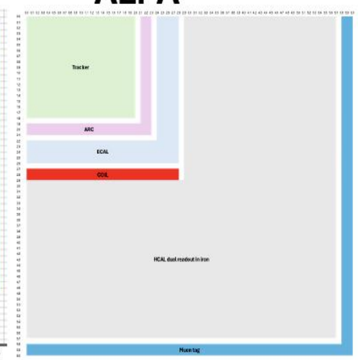
- Conceived for FCC-ee
- Silicon vertex tracker
  - Outer based on ATLASPix3 with 50x150µm² pixels
  - Inner ARCADIA based 25x25 µm² pixels
- Outer tracker based on low mass Drift Chamber
  - 112 layers
  - 4m Long
  - R = 35-200cm
- Silicon wrapper
  - either with MAPS with with ~10^{11} channels!
  - or CMOS-LGADS ~40ps

ALLEGRO



- Conceived for FCC-ee, started with a noble-liquid calorimeter
- Tracking system taken from IDEA
- Silicon Vertex with curved or straight sensors
- Outer tracker with
  - Extended Drift Chamber
  - Straw tubes
  - Scintillating Fiber Tracker (SciFi)
    - 5m Long
    - R = 35-200cm
- Silicon wrapper
  - Monolithic pixel or AC-LGADs

ALFA

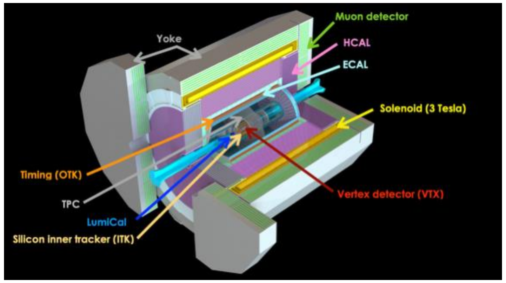


- Newly Conceived project for FCC-ee
- MAPS tracker following ALICE ITS3 developments
  - Vertex curved MAPS 65 nm CMOS TPSCo 10x10 µm² pixels
  - Outer tracker Reticle-size MAPS,
    - 25x32 mm² to 50x128 mm² module
- ARC (Array of RICH Cells) Lightweight with 20cm radial depth
  - Two radiators (gas + aerogel)

\+

AGORA

ADVANCED GLASS OPTIMIZED RESEARCH APPARATUS



AGORA experiment at (CEPC/FCC)

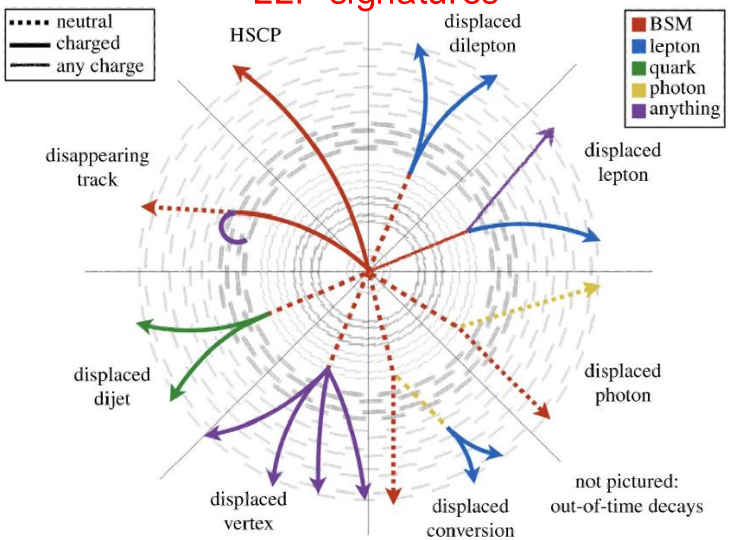
Vertex	Si Pixels: CMOS MAPS+stitching
Inner tracker (ITK)	Si Pixels: CMOS MAPS 55-nm
Gas detector	TPC with high granularity
Outer tracker (OTK)	AC-LGAD → TOF

Strategy for detector requirement studies

Some **benchmark analyses** are chosen to study
- the dependence of their sensitivity on some aspects of the detector performance

  - Higgs mass from recoil in $Z\rightarrow\mu\mu$
  - LFV $Z\rightarrow\tau\mu$
  - $e^+e^- \rightarrow\mu\mu(\gamma)$ at the Z and above
  - Exotic Higgs to LLP pairs
  - $K_s\rightarrow\pi^+\pi^-$
  - $B\rightarrow k^*\tau\tau$
  - Flavor tagging and $H\rightarrow cc$
  - τ lifetime
  - Higgs couplings to heavy flavour: bottom and charm

LLP signatures



So far:
- rely on **Delphes** with baseline card on the IDEA detector performance
- analysis tools able to provide variations of resolutions to study dependence or precision or sensitivity

N. B. Some studies done for the FS could be obsolete and not updated with recent progress on detector concepts

Strategy for detector requirement studies

High precision in detection and measurements of charged particles demands:

- the precise measurement of the track momentum and of the track angles
- the reconstruction of far displaced vertices
  - properties mostly related to the large volume, main tracker

- the determination of the track impact parameters
  - mostly related to the vertex detector

N.B. Need of a superb control of the systematic uncertainties → put considerable demands on the acceptance, construction quality and stability of the detectors

Requirement from momentum measurement

Outer tracker: Drift Chamber (IDEA)

For the purpose of tracking and ID at low and medium momenta mostly for heavy flavour and Higgs decays, the IDEA drift chamber is designed to cope with:

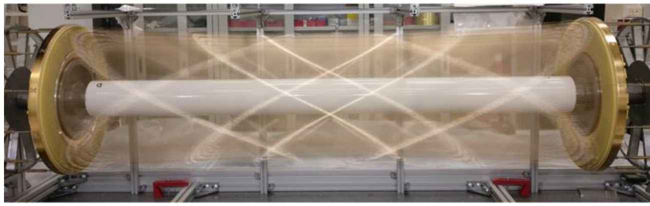
- transparency against multiple scattering, more relevant than asymptotic resolution
- a high precision momentum measurement
- an excellent particle identification and separation

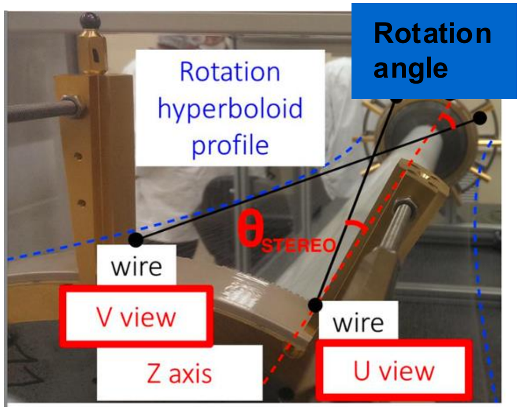
The IDEA DCH (inspired by MEG2 DCH) is:

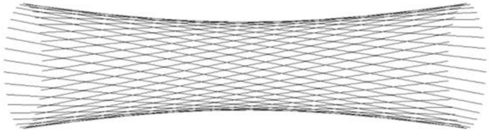
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - iC_4H_{10} 10%
- inner radius R_{in} = 0.35m, outer radius R_{out} = 2m
- length L = 4m
- drift length ~1 cm, drift time up to 400ns
- σ_{xy} < 100 μm, σ_z < 1 mm
- 12÷14.5 mm wide square cells, 5 : 1 field to sense wires ratio
- 112 co-axial layers (grouped in 14 superlayers of 8 layers), at alternating-sign stereo angles, in 24 azimuthal sectors

343968 wires in total:
sense vires: 20 μm diameter W(Au) => 56448 wires
field wires: 40 μm diameter Al(Ag) => 229056 wires
f. and g. wires: 50 μm diameter Al(Ag) => 58464 wires

MEG2 DCH







Inner+Outer tracker (CLD)

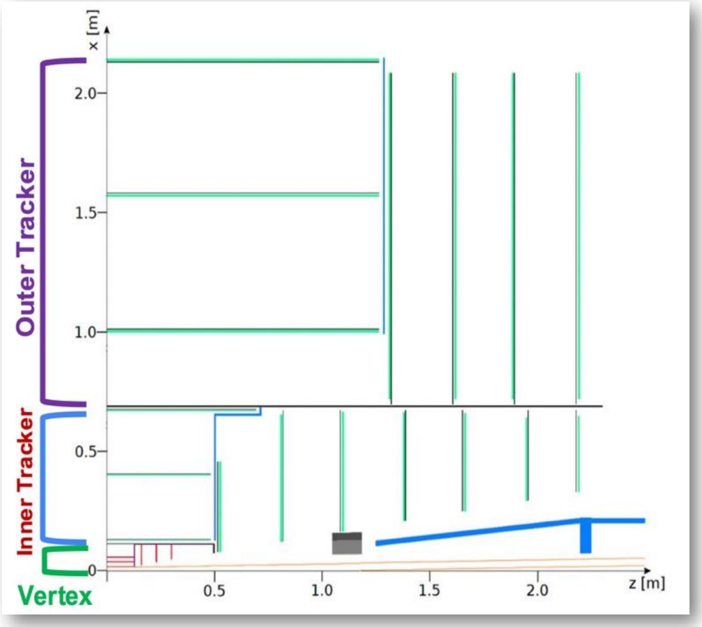
Full silicon tracker:

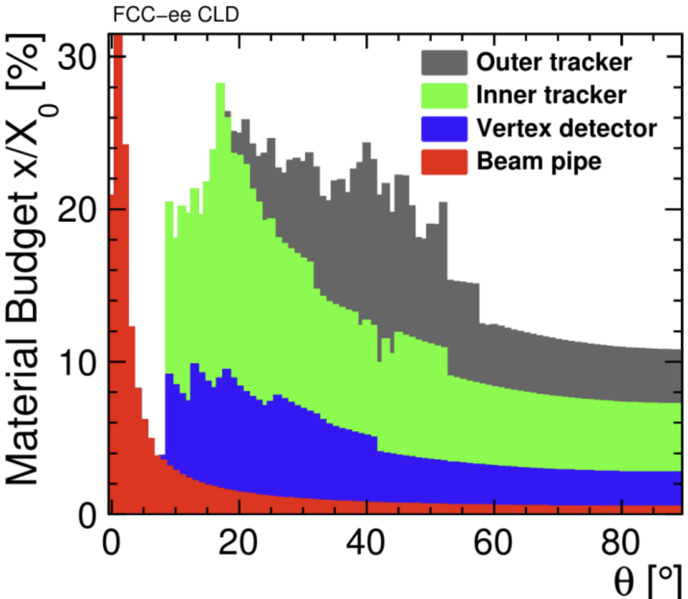
- geometry compatible with ALICE ITS technology, but could be either sensors plus ASICs or monolithic structure, will benefit from the very active R&Ds (in DRD3 and others)

Consisting of:

- Inner Tracker: 3 short layers and 7 inner disks
- **Outer tracker**: 3 long layers and 4 outer disks
- 200 µm Silicon thickness
  - 50 µm x 0.3 mm cell size
- Material budget: 1.1 % – 2.1 % X_0 per layer (including overlaps)
- 7 µm x 90 µm single point resolution (except first inner tracker discs, 5 µm x5 µm)
- at least 8 hits for θ > 8.5°

Details in **Zhang talk**

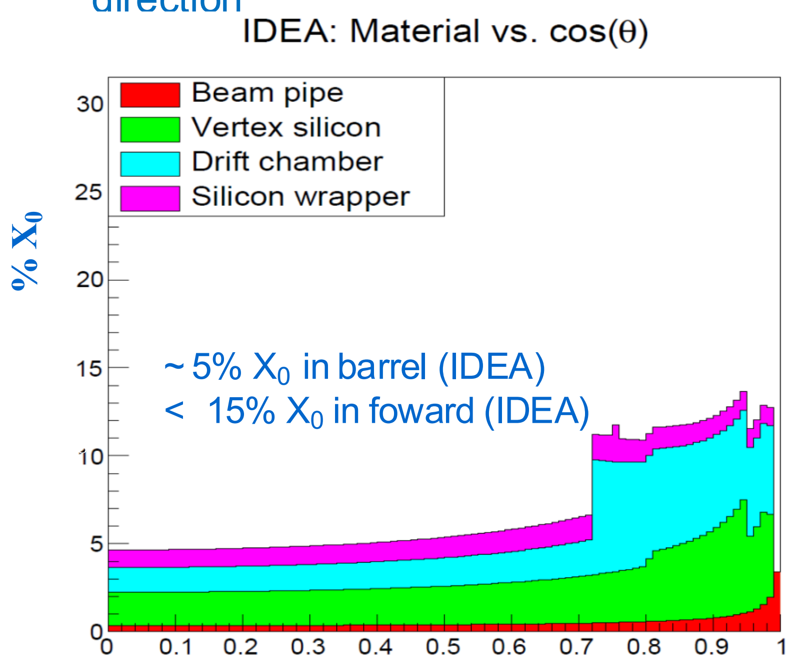




IDEA vs CLD: momentum measurement

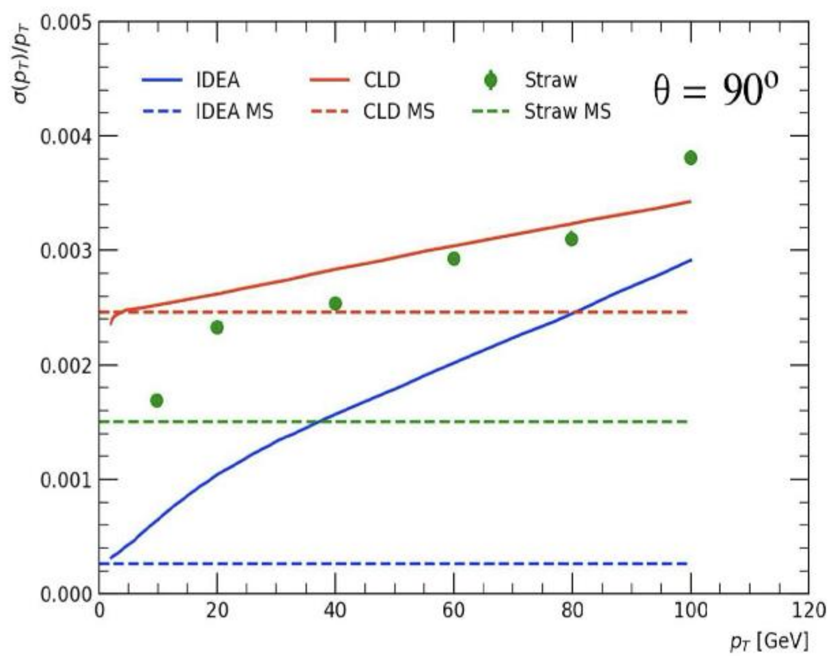
The IDEA Drift Chamber is quite transparent:

- gas: He 90% - iC_4H_{10} 10%
- thin and light wires
- New mechanical assembly procedure by separating the gas containment from the wire support functions
- New concepts for wire tension compensation resulting in endcaps with a 5% X_0 (including front end electronics/cables) and 1.6% X_0 in the radial direction



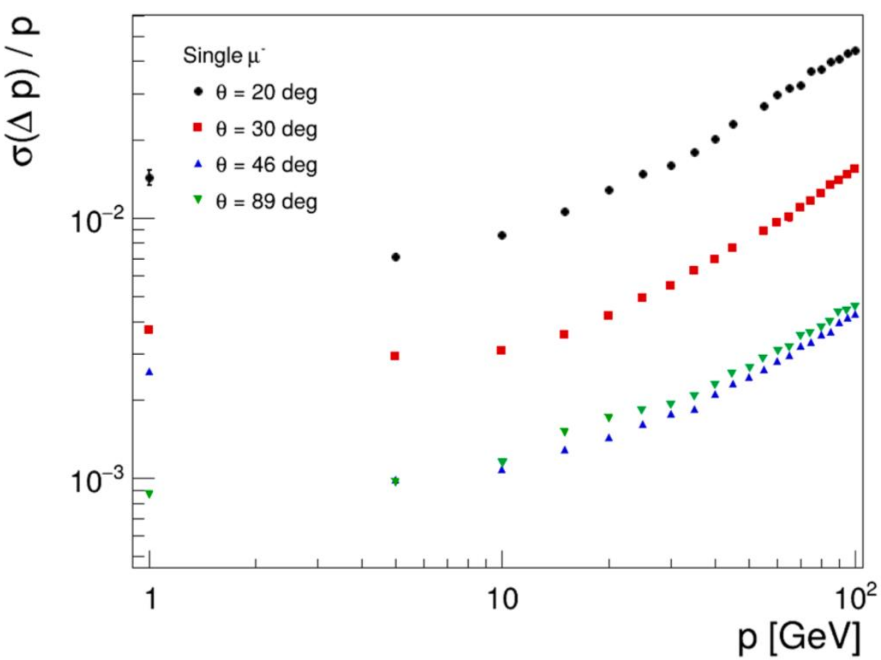
The CLD silicon tracker is made of:

- six barrel layers, at radii ranging between 12.7 cm and 2.1 m, and of eleven disks.
- the material budget for the tracker modules strongly affects momentum resolution

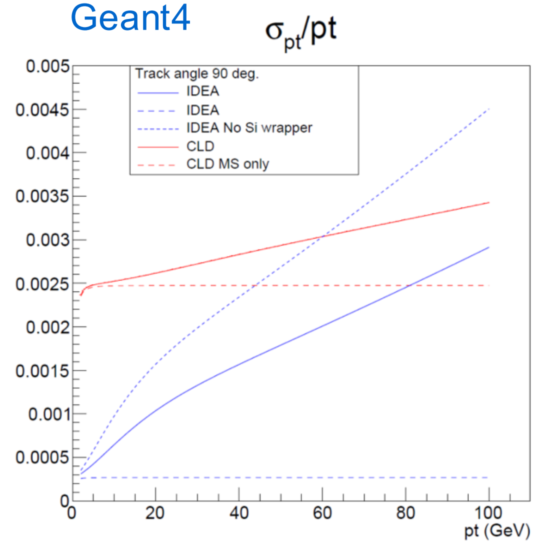


Outer tracker: Drift Chamber (IDEA) performance

- **DCH used in conjuction with vertex and silicon medium tracker and/or silicon wrapper**
- NEW FULL simulation based on key4HEP/DD4HEP/Geant4
  - momentum resolution as a function of momentum p, for single muons at different θ
  - below 0.7 GeV/c, particles begin to loop in the magnetic field (2T option), leading to a transition between two distinct regions in the p_T spectrum.



Old simulation based on Geant4



Analytic formula

Particle momentum range far from the asymptotic limit where MS is negligible

$$\frac{\Delta p_T}{p_T}\Big|_{res.} \approx \frac{12\,\sigma_{r\phi}\,p_T}{0.3\,B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\,B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

Drasal, Riegler, https://doi.org/10.1016/j.nima.2018.08.078

For 10 GeV (**50 GeV**) μ emitted at an angle of 90° w.r.t the detector axis, the p_T resolution is

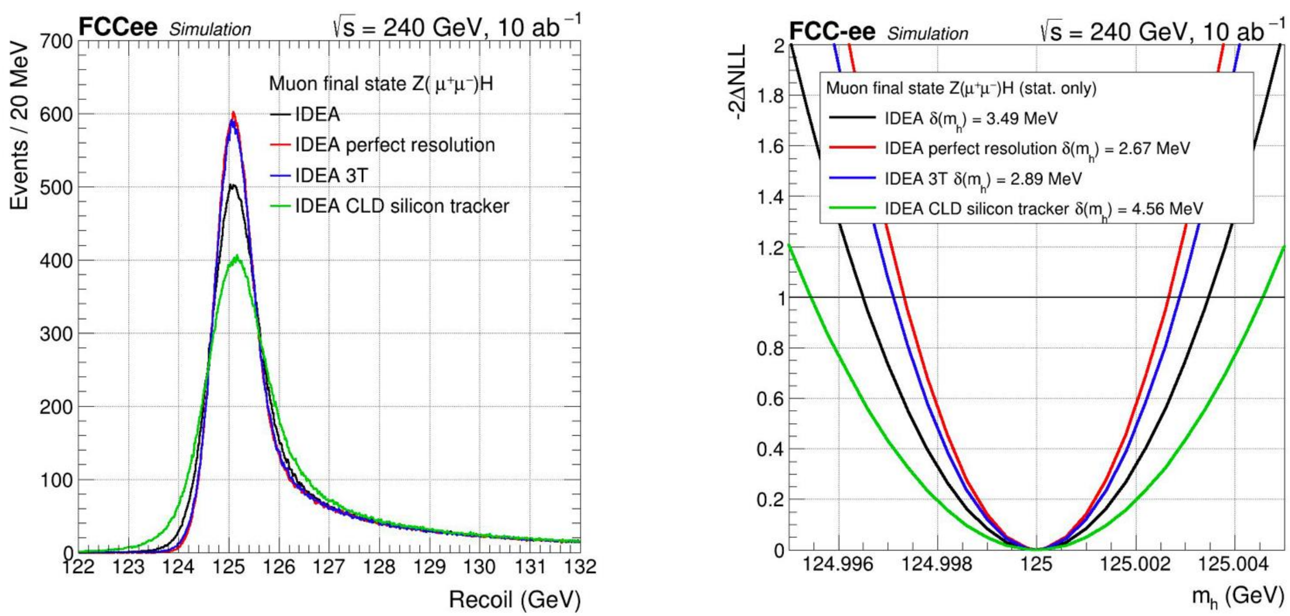
- about 0.05 % (**0.15%**) with the very light IDEA DCH → impact on Higgs mass measurement

Constraint from Higgs Mass measurement

Higgs boson mass to be measured with a precision better than its natural width (4MeV), in view of a potential run at the Higgs resonance

Higgs mass reconstructed as the recoil mass against the Z, M_{recoil} , and solely from the Z

$$M^2_{recoil} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$



μ from Z, with p of O(50) GeV, to be measured with a p_T resolution smaller than the BES in order for the p_T measurement not to limit the mass resolution → $\sigma_{p_T}/p_T \sim 0.15/0.2\%$ @ $\mathcal{O}(50)$GeV

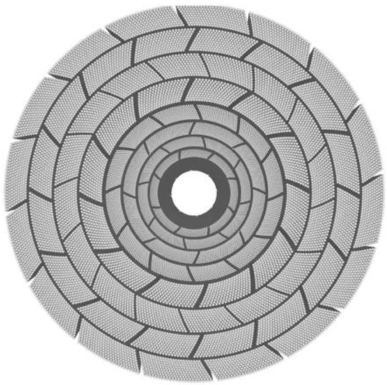
- achieved with the baseline IDEA detector → uncertainty of 4.27 MeV with 10 ab^{-1}
- CLD performs less well because of the larger amount of material → larger effects of MS

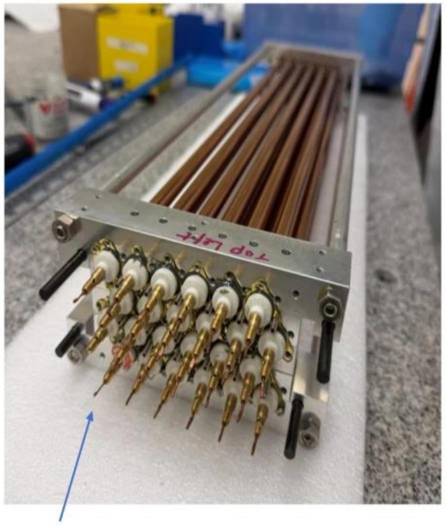
If the B increased from 2T to 3T → 50% improvement of the momentum resolution
14% improvement on the total mass uncertainty

Outer tracker: Straw tracker (ALLEGRO)

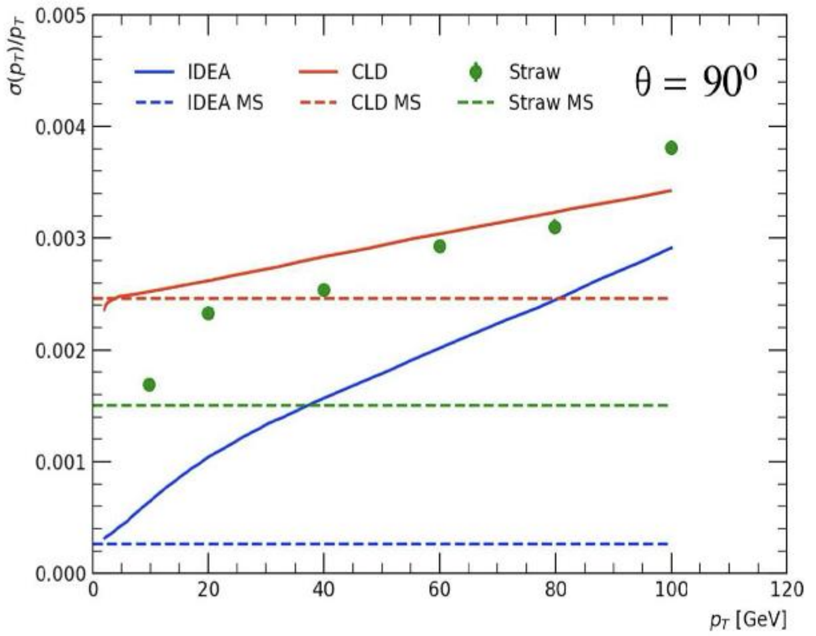
Straw tracker R&D is pursued:

- Implemented the **geometry** inside the FCC-ee simulation framework for ALLEGRO
- Targeting **Al + Mylar** (~15µm mylar, 0.05µm Al) and 25µm tungsten wires →~1.2% X_0 (structural support not included)
- Building several **prototypes**, 24 straw prototype using ultrasonic soldering straw tubes from NA62
  - 0.02µm nm Au, 0.05µm Cu, 36 µm PET
  - length = 0.5 m, diameter = 1 cm, wire diameter = 50 µm
- **Compared to drift tubes/chambers** :
  - a marginal 3.5% better transverse momentum resolution for very high momentum tracks but a 4 times worse resolution for low momentum tracks
  - in terms of particle identification, more than 17% worse resolution w.r.t a drift chamber of the same dimensions
- **Test beams** assessing working points, cluster counting, performance with different gases





bad tubes all on one side

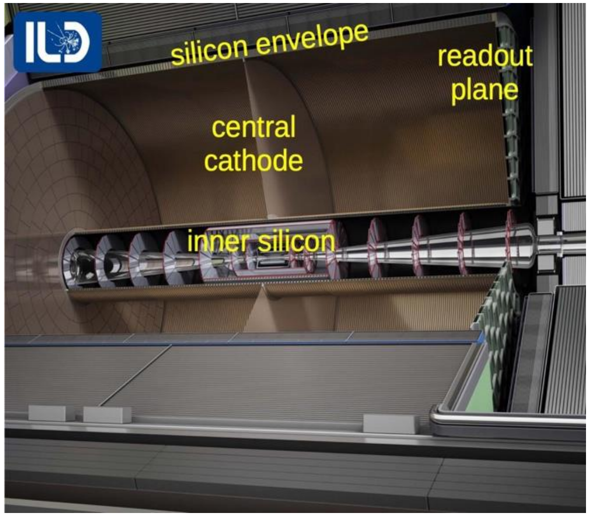


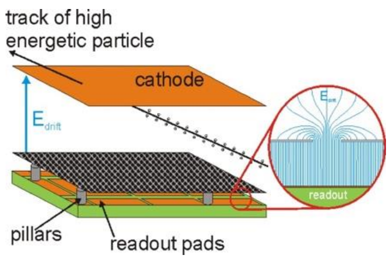
N. De Filippis

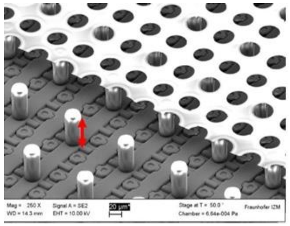
Outer tracker: Time Projection Chamber (ILD → AGORA)

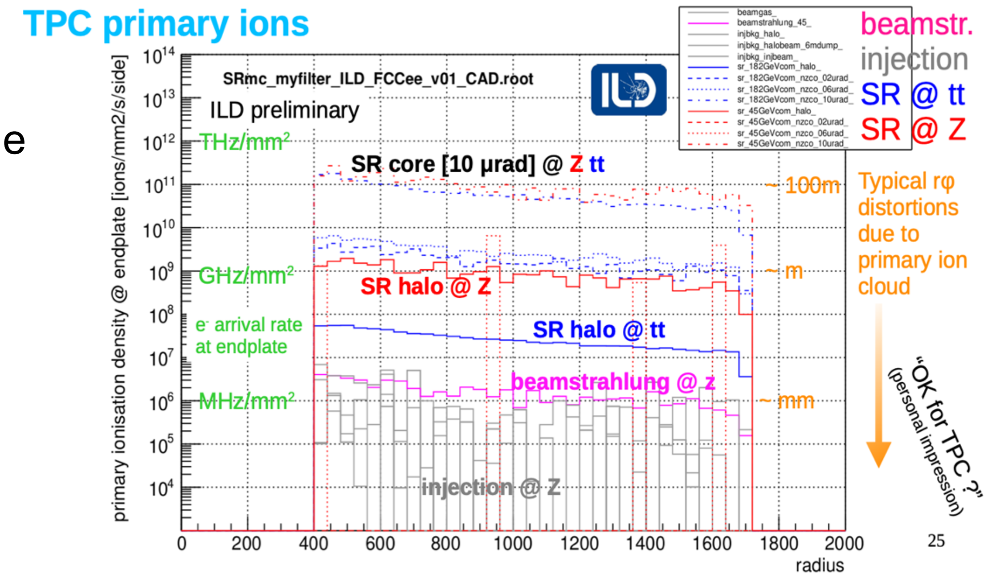
- TPC as part of ILD's hybrid tracking system
- Readout plane: gas amplification GEM, micromegas, readout by pads/pixels
  - GridPix based on Timepix3 with $55x55 \mu m^2$ pixels can detect one primary electron
- ~3% X_0 in barrel, higher in endcap
- Operation challenges at Z-pole due to space charge distortions and SR backgrounds are being simulated
  - Gas choices still to be evaluated
  - Backgrounds are a concern for stable operation
  - Ways of reducing ion backflow, handle distortions is needed.

- **A very complete work made for the CEPC TDR**









Details in D. Jeans talk

Requirements from reconstruction of displaced vertices

Reconstruction of LLP and very displaced vertices

The reconstruction of:

- long-lived particles (LLP) that decay into charged particles within the tracker volume, but after having crossed the (first) layers of the vertex detector
- decays that involve K_s or Λ's.

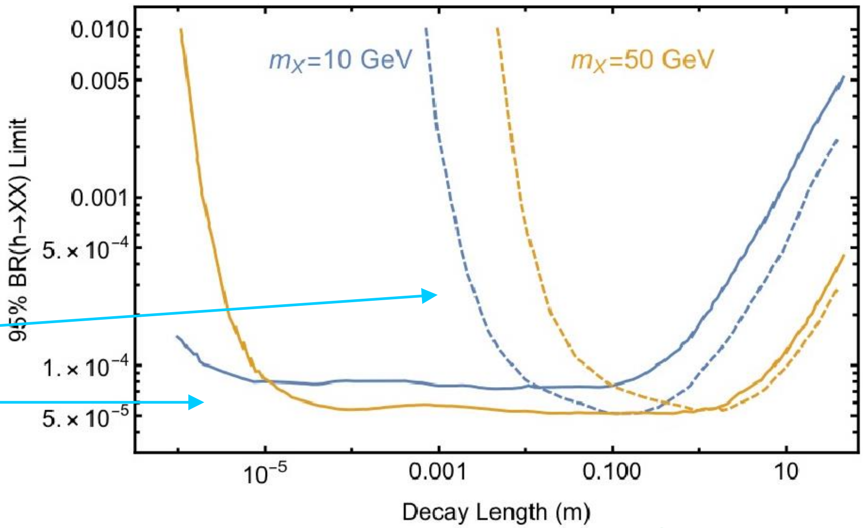
requires **very displaced vertices** to be identified efficiently (primarily) by the **main tracker**

Example: Higgs boson into pairs of long-lived particles (LLPs) which travel a macroscopic distance before decaying to quark pairs → jets containing candidate secondary/displaced vertices (exotic Higgs decays with decay lengths $c\tau$ ranging from microns to meters)

$$e^+e^- \rightarrow hZ \rightarrow XX + \ell\bar{\ell} \text{ at } \sqrt{s} = 240 \text{ GeV}$$

Tracker-based searches optimal for decay lengths below 1 meter, with sensitivity to shorter LLP decay lengths down to the tracker resolution (impact parameter res. 2-3 μm)

- 'long lifetime': m_x < 10 GeV and $c\tau \gtrsim$ 1cm
- 'large mass': $m_x \gtrsim$10 GeV and $c\tau \gtrsim 1\mu$m



Improvement of the vertex resolution → better sensitivity to LLPs with relatively short lifetimes

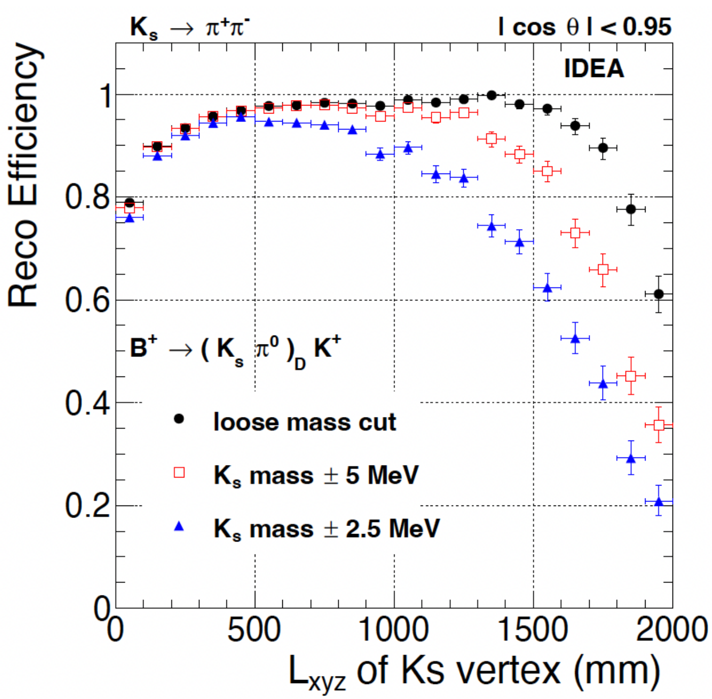
Constraint from $B^+ \rightarrow D^0K^+ \rightarrow (K_s\pi^0)_DK^+$

The reconstruction of $K_s \to \pi^+\pi^-$ from pairs of opposite charge tracks

- that do not come from the primary vertex,
- that can be fitted to a common vertex
- with a vertex mass that is close to the nominal K_s mass

The efficiency for K_s reconstruction defined:

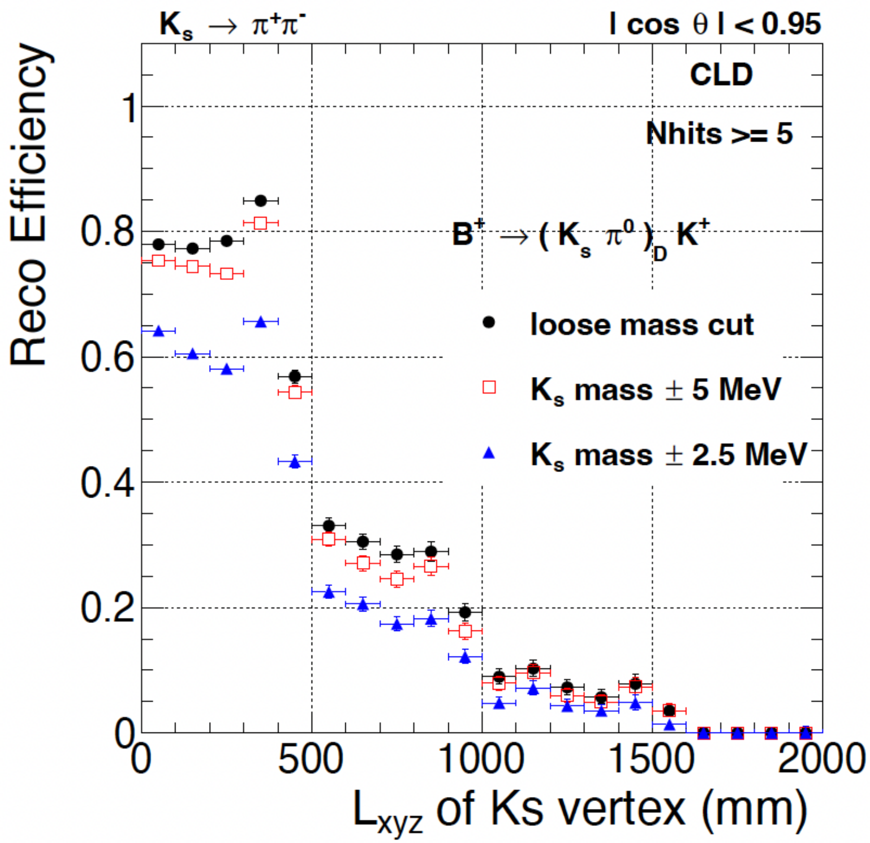
- for the K_s that come from the $B^+ \to (K_s\,\pi^0)_D K^+$ decay, for which the generated daughter pions satisfy the acceptance requirement $|\cos\theta| < 0.95$
- as a function of the distance L_{xyz} between the decay vertex of the K_s and the interaction point



IDEA detector:

- with a mass cut of +/-5 MeV, the efficiency **remains above 80% as long as the K_s decays within 1.5 m** from the interaction point.
- at larger distances, the efficiency drops since the π tracks only go through a small distance in the tracker.

Constraint from $B^+ \to D^0K^+ \to (K_s\pi^0)_D K^+$



The performance of **CLD detector** significantly worsens compared to IDEA:

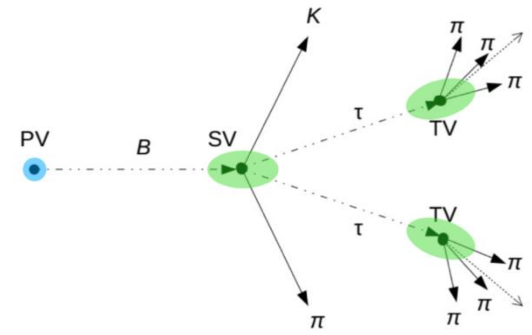
- visible the steps corresponding to the positions of the tracker layers
- the efficiency for selecting 5-hits tracks displaced by more than 40 cm vanishes in the central region
- due to the large amount of material of the full silicon tracker that leads to much larger effects from MS
  - worse resolutions on the K_s vertex and on the K_s mass

An efficient reconstruction of $K_s \to \pi^+\pi^-$, and, more generally, of LLP that lead to late appearing tracks, calls for

- a highly transparent tracker
- a large tracking volume
- a considerable number of measurement layers

Constraint from $B \rightarrow K^{*}\tau\tau$ reconstruction

The search for the rare $B \rightarrow K^{*}\tau\tau$ decay (BR ~ $O(10^{-7})$ in the SM) has set some requirements on the track efficiencies



- demanding that both taus decay into three prongs → a final state with 6 soft pion tracks

- a momentum acceptance down to 100−150MeV is necessary to maintain a good signal efficiency

- a minimum number of e.g. 5 hits to reconstruct a track implies that there be at least 5 measurement layers at a radius below 33 cm (50 cm) to reconstruct a track with a transverse momentum of 100MeV (150 MeV)

- this requirement on the position of the layers of the vertex detector and of the innermost layers of the main tracker, is **fulfilled** by both the IDEA and the CLD tracker designs

Requirements from the measurement of the track impact parameter

Impact parameters and vertex detector

Measurement of the impact parameters driven by the **vertex detector** key for:

- for reconstructing vertices
- for efficient identification of heavy quarks and τ
- for a powerful measurement of lifetimes

The radial distance of the first layer of the vertex detector is also crucial

Resolution on impact parameters

$$\sigma(d_0) = a \oplus \frac{b}{p \sin^{3/2} \theta}$$

a ~ 5 μm, b ~ 15 μm·GeV (FCC-ee)
a ~ 25 μm, b ~ 70 μm·GeV (LEP)
a ~ 12 μm, b ~ 70 μm·GeV (LHC)

a, is driven by the single hit resolution

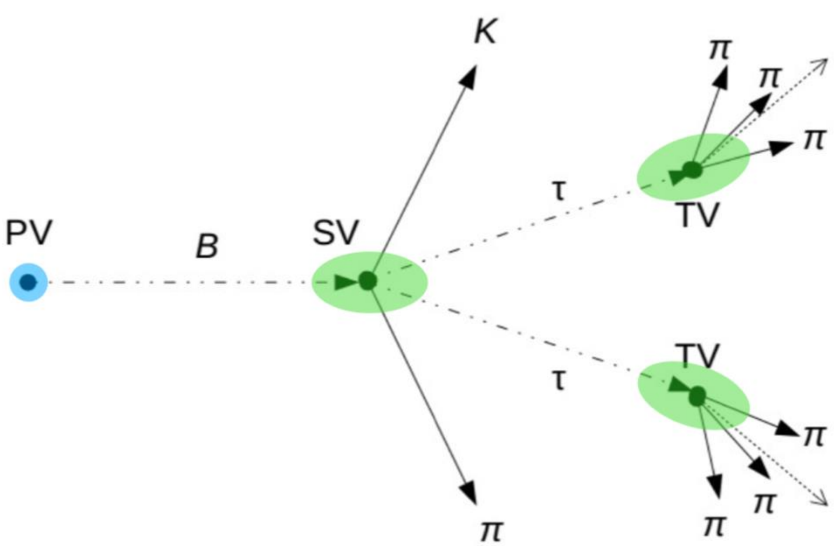
- represents the contribution of multiple scattering
- depends on the material budget of the vertex detector layers and of the beam-pipe

Assumptions used for next studies:

- the radius of the beam pipe is 1 cm
- the radius of the innermost layer of the vertex detector is 1.2 cm
- the material crossed by a particle emitte at a polar angle θ before the first VXD measurement amounts to 0.67%/sinθ of a radiation length

Constraint from the measurement of BR($B \rightarrow K^*\tau\tau$)

The BR($B \rightarrow K^*\tau\tau$) ~ O($10^{-7}$) in the SM and the current experimental upper limit is larger than this prediction by three orders of magnitude. New physics contribution would enhance the BR.



→ stringent requirements on the performance of the vertex detector come from the measurement of the BR($B \rightarrow K^*\tau\tau$)

Both τ leptons decay into three charged pions and a neutrino

The secondary vertex (SV) is given by the kaon and pion tracks that come from the K^* decay

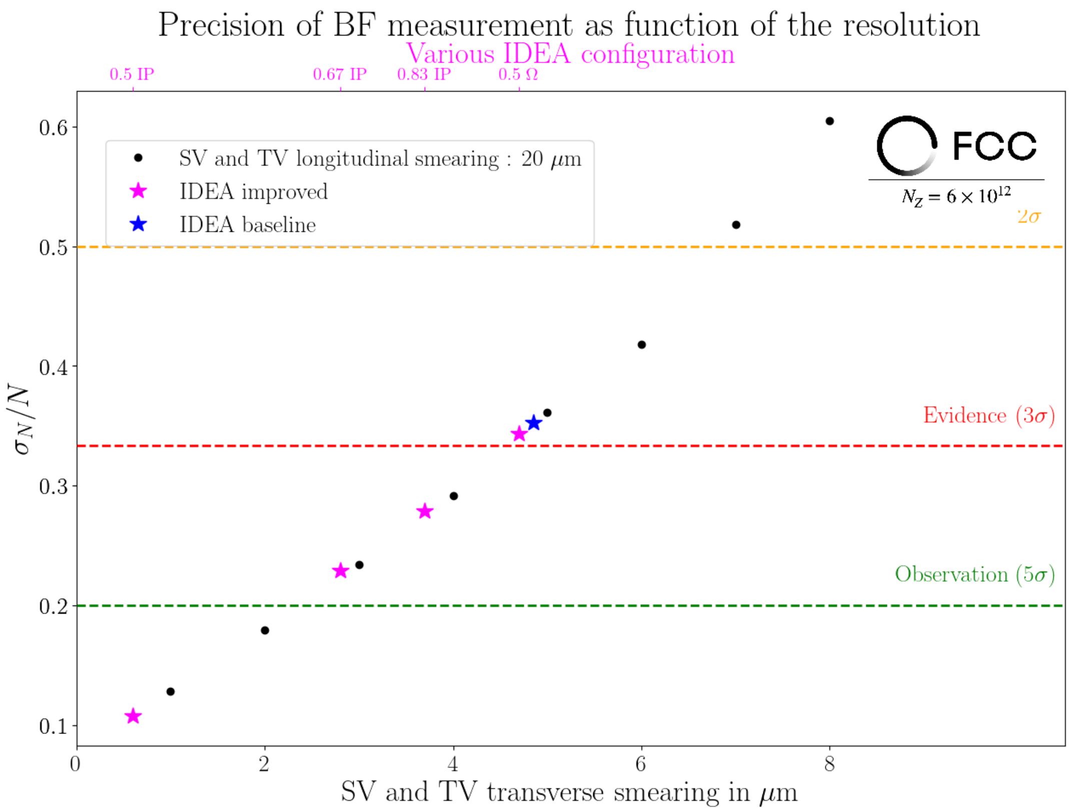
The reconstruction of $B \rightarrow K^*\tau\tau$ critically relies on the precise reconstruction of the secondary and tertiary vertices

For displaced vertices, the resolution depends very much:

- on the track multiplicity of the vertex
- on the track momenta and angles
- on the angular separation of the tracks

Constraint from the measurement of BR($B \rightarrow K^* \tau\tau$)

The precision of the measurement shows a very strong dependence on the resolution of the position of the secondary and tertiary vertices in the transverse direction



With a statistics of 6×10^{12} Z bosons:

- a resolution better than ~ **4.3 μm** is needed to reach a 3σ evidence of the decay mode
- it should be better than about **2.2 μm** for a 5σ observation of this decay
- For IDEA simulation this resolution is of **5 μm** only

- A better resolution on the track IP by about 10% (about 40%) would allow 3σ (5σ)
- A reduction of the overall VXD material by 35% + with an improvement of the single hit resolution in the VXD layers by 30% (i.e. from 3 μm to 2 μm in the barrel layers) brings the sensitivity beyond 3.7σ

Constraint from Heavy flavour tagging and H→cc

Studies based on a graph neural network:

ParticleNet

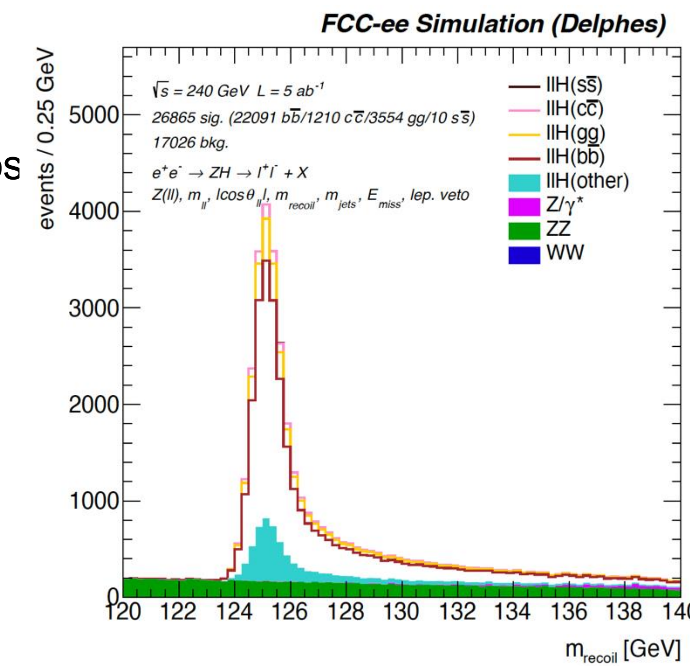
H. Qu, L. Gouskos, ParticleNet: Jet Tagging via Particle Clouds. Phys. Rev. D 101(5), 056019 (2020)

Features:

- the identification of jets induced by gluons or even strange quarks contemplated
- the tagging efficiency of bottom and charm quarks is much larger than what was achieved with algorithms from the previous generation for the same mistag rate

ParticleNet key for measurement of the **Higgs couplings to bottom, charm and strange quarks, and to gluons**

- HZ events at √s = 240 GeV
- Z decays into an electron or a muon pair, or into neutrinos



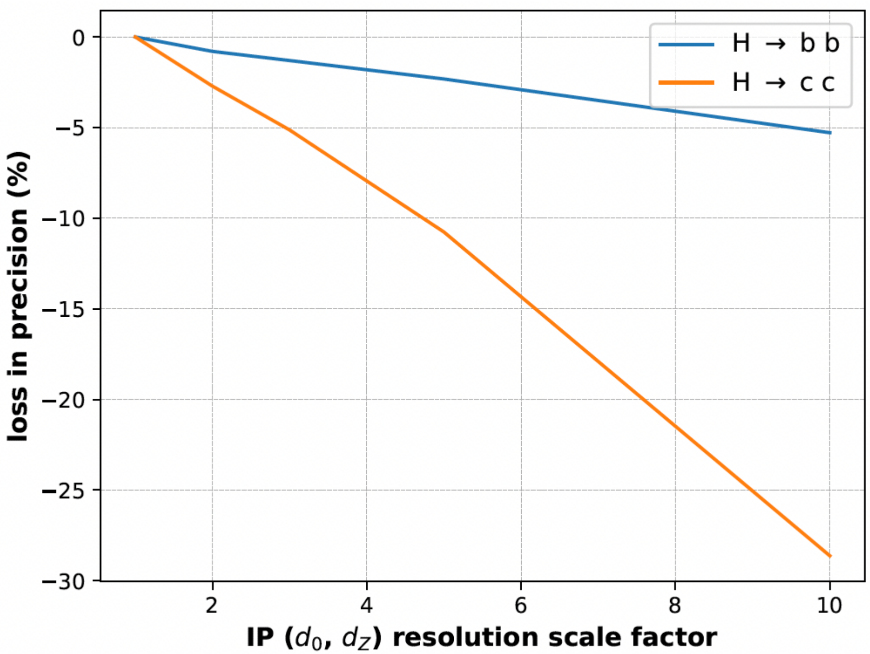
A simultaneous fit to the recoil mass distributions (and, for the Z(vv) channel, to the visible mass distributions) measured in all categories allows the Higgs couplings to bb, cc, ss and gg pairs to be extracted

Heavy flavour tagging and H→cc coupling

For an integrated luminosity of 10 ab^{-1}, the **H → bb** signal strength can be measured with **0.28% uncertainty**, and the one for **H → cc** with **2.1%**

Studied **the dependence of this precision with the track impact parameters resolution**

- by degrading the resolution by a factor ranging between 2 and 10



- the measurement of the Higgs coupling to bottom quarks is only **marginally** degraded when this resolution is worsened
- the uncertainty on the Higgs coupling to charm quarks depends **significantly** on the resolution on the track parameters

due

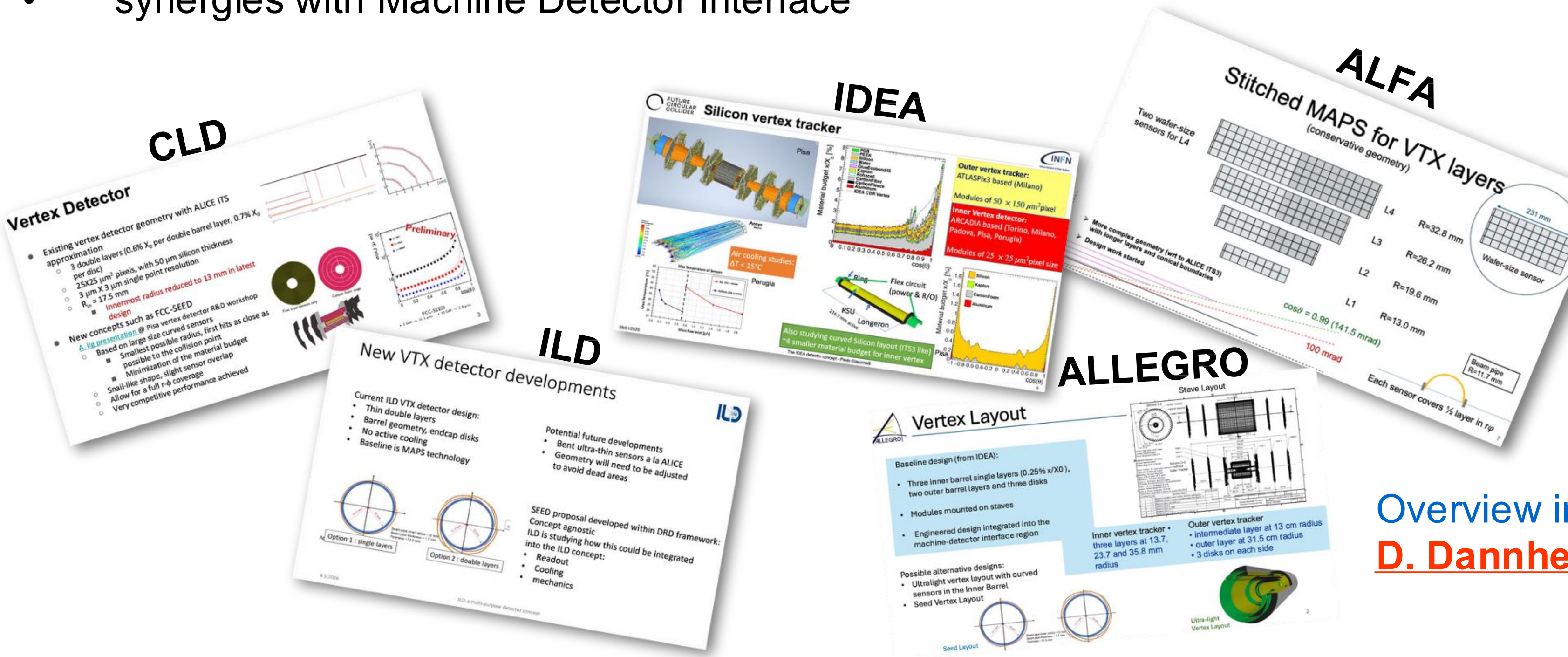
- to the much worse signal-to-background ratio in this channel
- to the smaller displacement of c quarks compared to b quarks

A degradation by a factor of 2 of the impact parameter resolutions → degradation of the H→cc coupling measurement by about 3%.

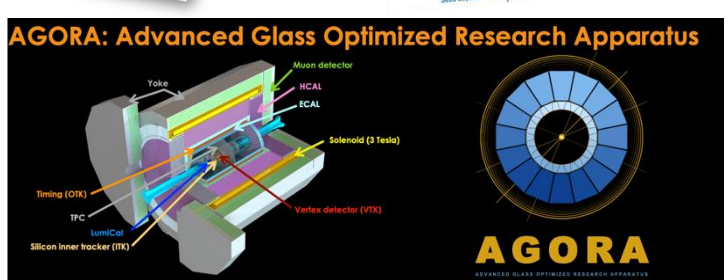
Inner tracker: Vertex detector

Silicon vertex systems currently largely shared among detector concepts

- highly segmented layers (4-5), close to interaction point, low material budget → maximise flavour tagging capabilities
- leverage ALICE developments for lightweight **MAPS** (Monolithic Active Pixel Sensors)
- synergies with Machine Detector Interface



Overview in
D. Dannheim talk

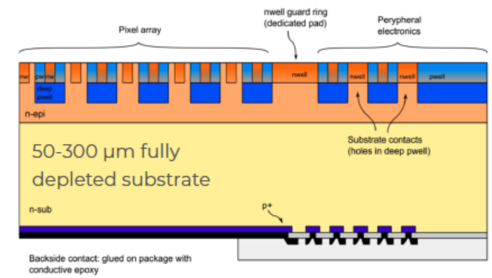


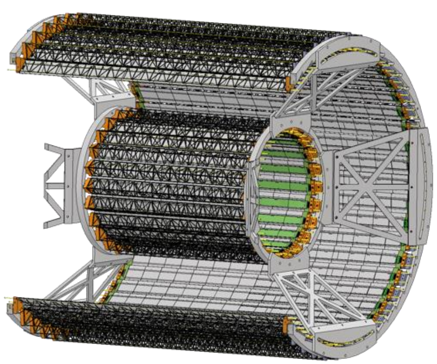
Inner tracker: Vertex detector (IDEA)

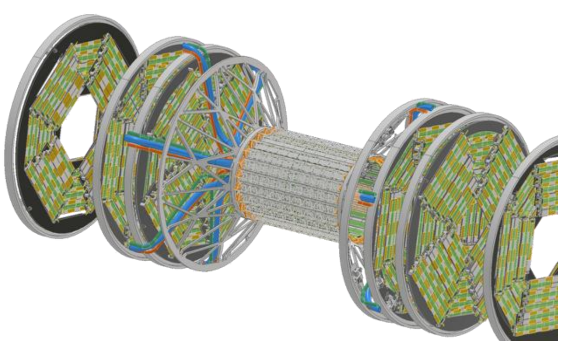
Technology: Depleted Monolithic Active Pixel Sensors (DMAPS):

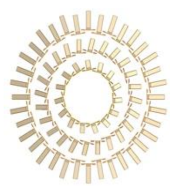
Two layouts:

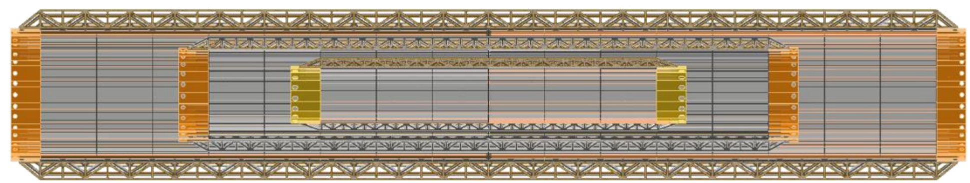
- 3 flat barrel layers: ARCADIA based 25 x 25mm^2 pixel size for hit resolution ~ 3 μm
- 4 curved barrel layers: 5 μm ALICE ITS3 inspired (30 μm pixels)
- low power consumption (< 20 mW/cm^2)

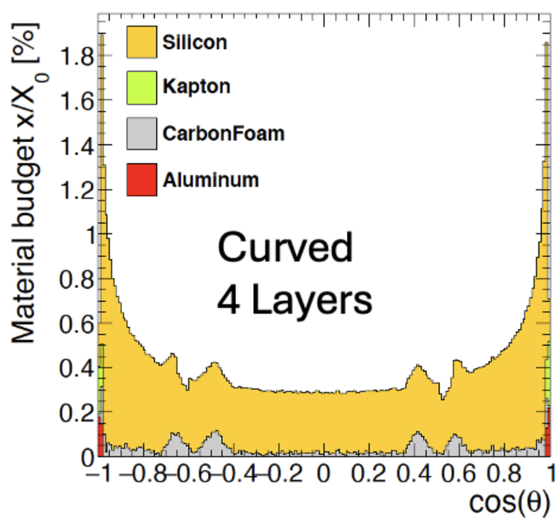


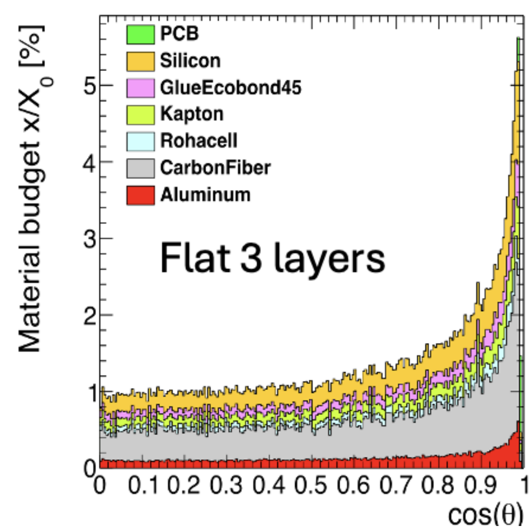




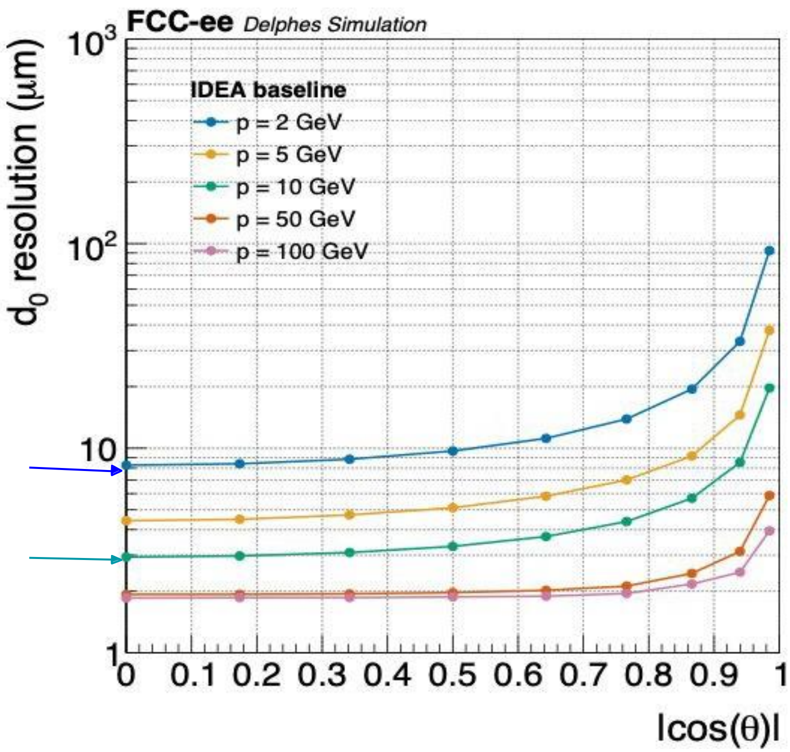




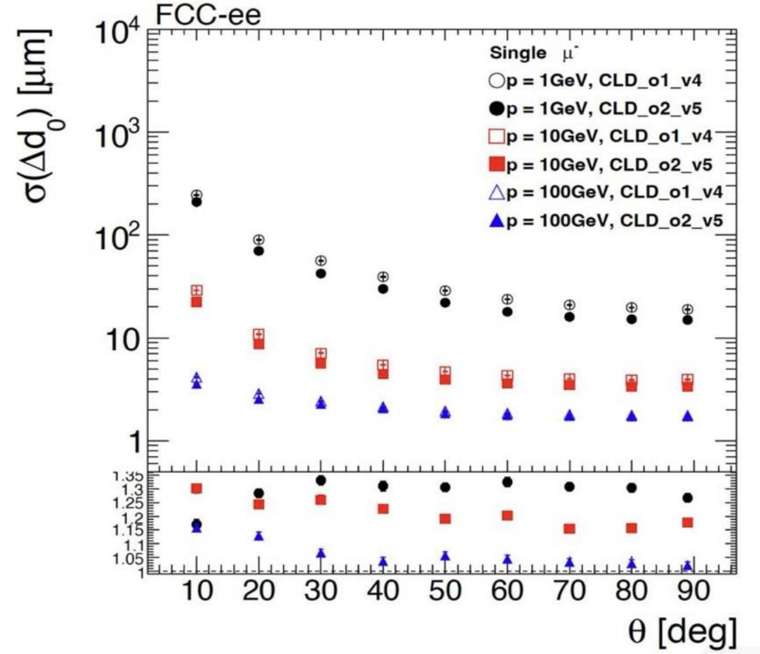


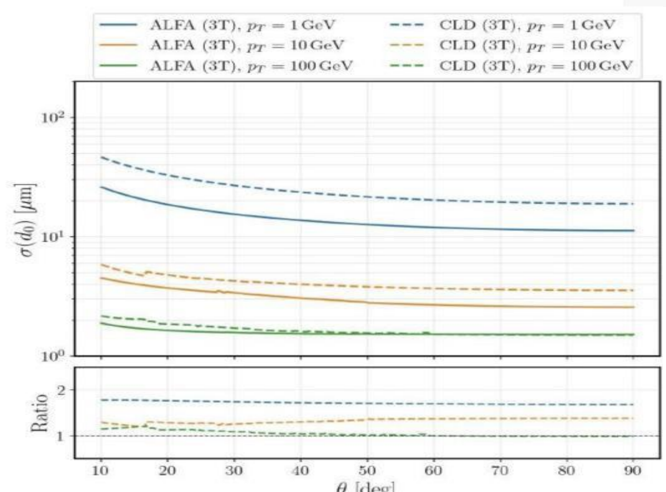


IDEA vs CLD/ALFA



	Vertex Barrel [mm]	R_1	R_2	R_3	L
O1_v4	CLD baseline geometry	17.5	37	57	125
O2_v5	**CLD with new beam pipe**	**13.0**	**35**	**57**	**109**





Resolutions at low p_T dominated by multiple scattering and material effects.

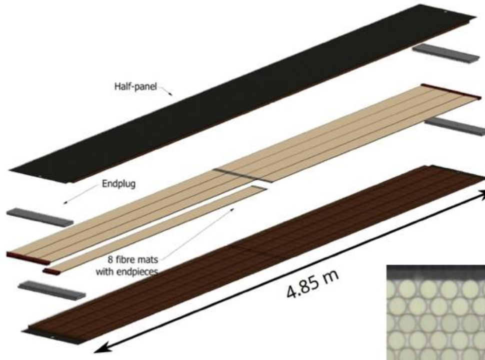
$\sigma(d_0)$: 2 GeV ~ 8 μm ; 10 GeV ~ 3 μm

$\sigma(d_z)$: 2 GeV ~ 8 μm ; 10 GeV ~ 2.5 μm

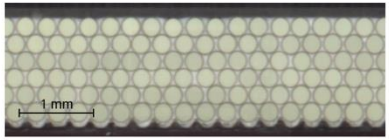
https://repository.cern/records/4qhzh-e4s53

Scintillating Fiber Tracker (SciFi, ALLEGRO)

- A full-barrel SciFi tracker as the outer tracker is proposed for ALLEGRO
  - Simulations under IDEA geometry for comparison
- Development driven by the LHCb upgrade

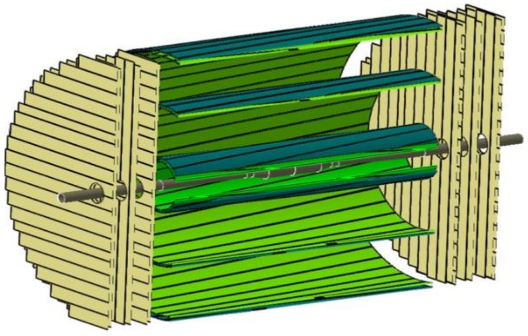


SciFi «Mat»



- **Main components** are
  - **Scintillating fibers** for detection,
  - **SiPMs** as sensitive detectors to re scintillation

	For 6 Layer Mats with 10° stereo angle
Fiber Diameter	250µm
Mat Thickness	1.5mm
X Resolution Per Mat	30µm
Phi Resolution Per Station	21µm/R
Z Resolution Per Station	300µm
Time Resolution Per Mat	300ps
Material Budget Per Station With Supports X/X_0	1%
Material Budget Per Station Without Supports X/X_0	0.41%



Ongoing R&D and simulations:

- SciFi stations with a stereo angle
- Dual-sided readout to add timing and reduce background
- New Fibers for Radiation Hard(er) SciFi

Details in E. De Santis talk

Constraint from the measurement of τ lifetime

Precise measurements of the mass, the lifetime and the leptonic branching fraction of the τ offer a crucial test of lepton flavour universality (LFU)

$$\left(\frac{g_\tau}{g_\mu}\right)^2 \simeq \frac{\tau_\mu}{\tau_\tau} \mathrm{BF}(\tau \to e\nu_\tau\bar{\nu}_e) \left(\frac{m_\mu}{m_\tau}\right)^5$$

currently limited by the precision on

- the τ lifetime (290+/- 0.5 fs)
- BR ($\tau \rightarrow e\nu_\tau\nu_e$) (17.82+/- 0.04%)

With about 2×10^{11} τ pair events expected at Tera-Z, FCC-ee has the potential to test LFU at an unprecedented level thanks to a much improved determination of the 3 key ingredients

- statistical uncertainty on the τ lifetime is expected to be 10 ppm or better
- the alignment of the vertex detector was the dominant source of systematic uncertainty (Belle and DELPHI) but not the case according to more advanced studies
- expected systematic uncertainty due to misalignment, scaled from the systematics quoted by DELPHI according to the luminosity increase, is below 10 ppm
- one source of uncertainty comes from the knowledge of the overall length scale of the vertex detector. For this uncertainty to be smaller than one half of the statistical uncertainty on the τ lifetime, this scale should be known to better than 5 ppm

Conclusions

- Tracking (and PID) fundamental for many physics cases eg. Higgs, Flavor physics, QCD-EWK, BSM

- Ambitious physics programs demand advanced tracking detectors:
  - precise measurement of the track momentum and track angles, reconstruction of displaced vertices, determination of the track impact parameters → constraints on detector technologies and performance

- Excellent momentum resolution → at the level $\sigma_{p_\mathrm{T}}/p_\mathrm{T} \sim 0.2\%$ at $\mathcal{O}(50)$GeV for
  - measuring the Higgs mass measured at its intrinsic width (4 MeV) with sensitivity driven by m_recoil for $Z(\mu^+\mu^-)$ and determined by BES

- Transparency of the tracker crucial

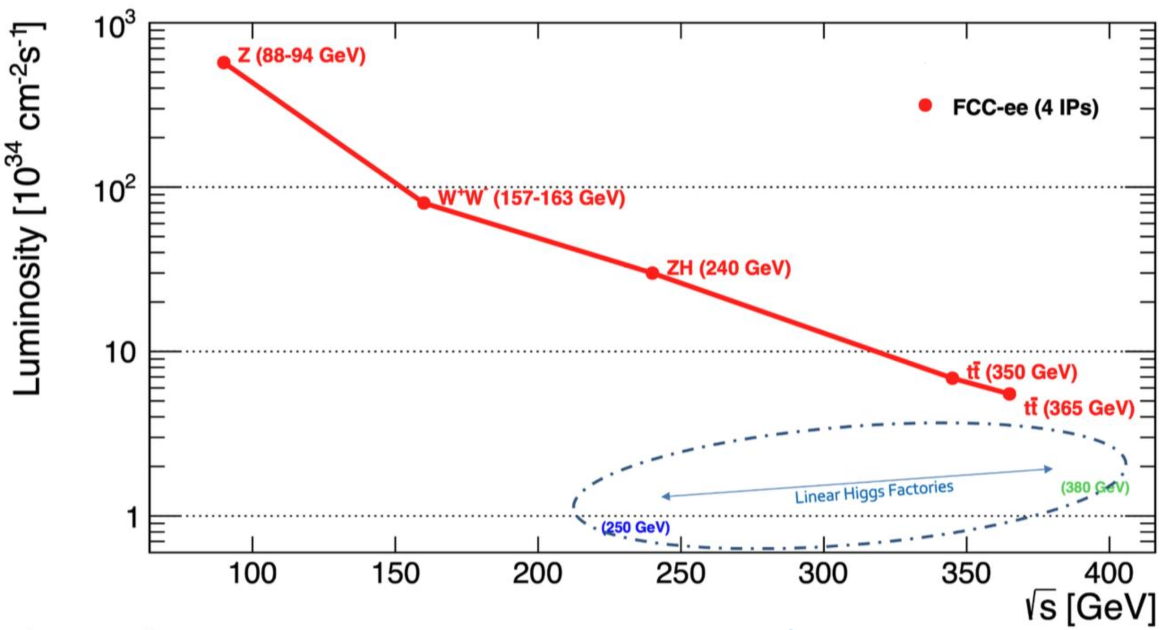
- Several detector concepts in place profiting from multiple technologies and expertise at LHC
  - active R&D in silicon and gaseous tracking, but new ideas coming in

Join the team !

Backup

P.S. Workshop on FCC-ee Tracking and PID at CERN, November 16-20, 2026:
https://indico.cern.ch/event/1660971/

Machine luminosity for physics @ FCC-ee



- Higgs factory:
  - 2.2×10^6 $e^+e^- \rightarrow$ HZ
- EW & Top factory:
  - 6×10^{12} $e^+e^- \rightarrow$ Z (LEPx10^5)
  - 2.4×10^8 e+e$^- \rightarrow W^+W^-$
  - 2×10^6 $e^+e^- \rightarrow$ tt
- Flavor factory:
  - 5×10^{12} $e^+e^- \rightarrow$ bb, cc
  - 10^{11} $e^+e^- \rightarrow \tau^+\tau^-$

~100 kHz of physics data at the Z pole

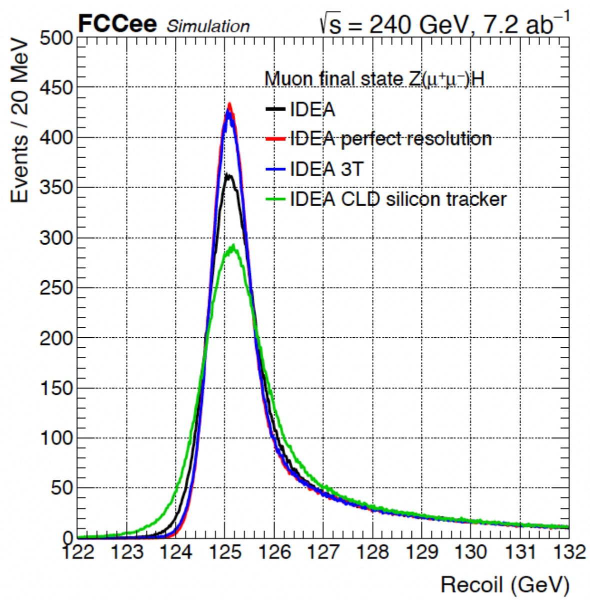
Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^8 WW	2.2×10^6 ZH + 65k WW $\rightarrow$ H	2×10^6 $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

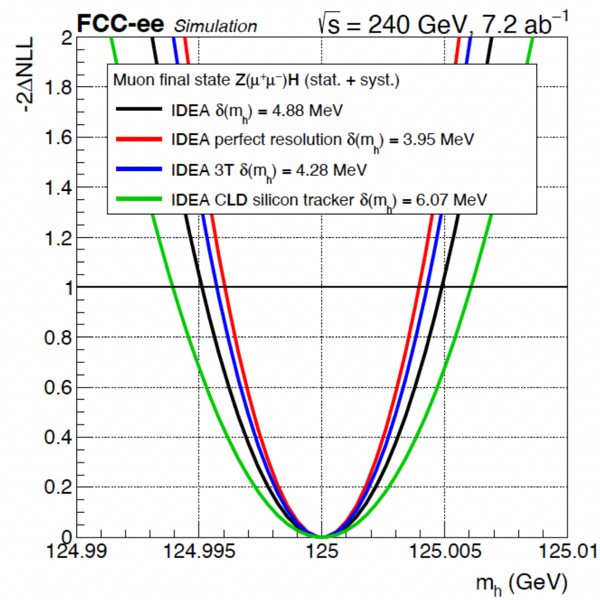
Constraint from Higgs Mass measurement

Higgs boson mass to be measured with a precision better than its natural width (4MeV), in view of a potential run at the Higgs resonance

Higgs mass reconstructed as the recoil mass against the Z, M_{recoil} , and solely from the Z

$$M_{recoil}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$





With a perfect measurement of the muon momentum:

- the width of the M_{recoil} peak determined by BES ~ 0.185% of the beam energy at $\sqrt{s}$ = 240 GeV
- uncertainty on M_H of 4.0 MeV with an int. lumi of 7.2 ab−1 (including the contribution of all systematic unc.)

μ from Z, with momentum of O(50) GeV, to be measured with a p_T resolution smaller than the BES in order for the momentum measurement not to limit the mass resolution

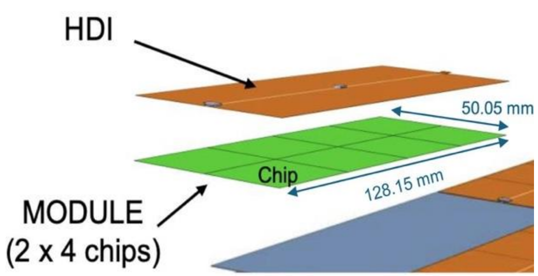
- achieved with the baseline IDEA detector → uncertainty of 4.9 MeV with 7.2 ab^{-1}
- CLD performs less well because of the larger amount of material → larger effects of MS

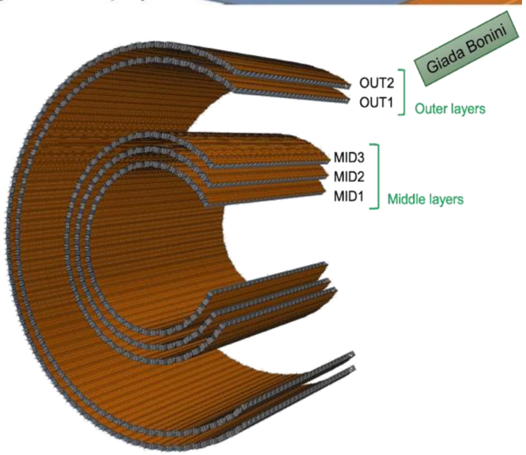
If the B increased from 2T to 3T → 50% improvement of the momentum resolution
14% improvement on the total mass uncertainty

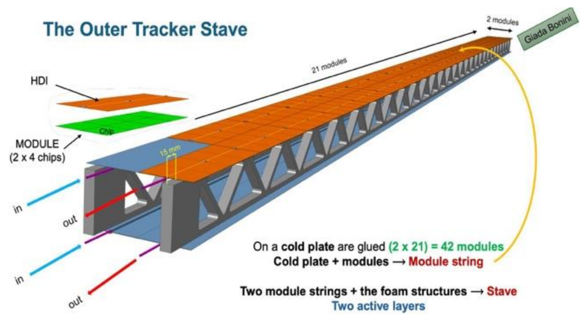
Outer tracker: Silicon MAPS (ALFA)

- High-performance all-MAPS (10µm everywhere), from Vertex to Outer Tracker detector, including luminometers, very robust. Challenges: keep sufficiently light, reasonable size and costs. **Lower rates thus slower front-end in outer layers, and eco-friendly cooling fluid.**
- Small collection electrodes are ideal: minimal capacity, minimal power density, minimal pixel size

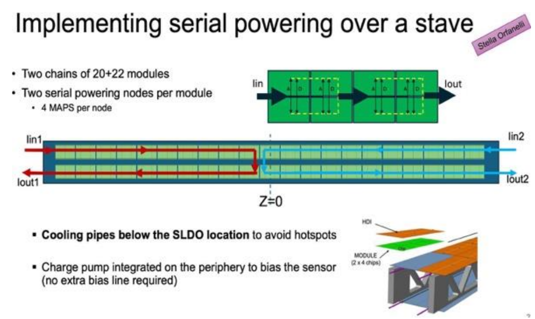
Building block for barrel stave



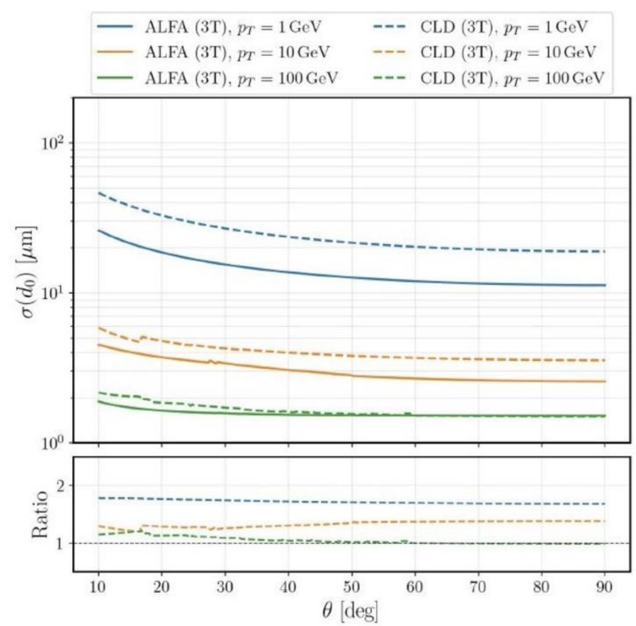




Serial powering is fundamental



Performance compared to CLD



Details in D. Abbaneo talk

Silicon wrapper (IDEA)

Instrumented surface:

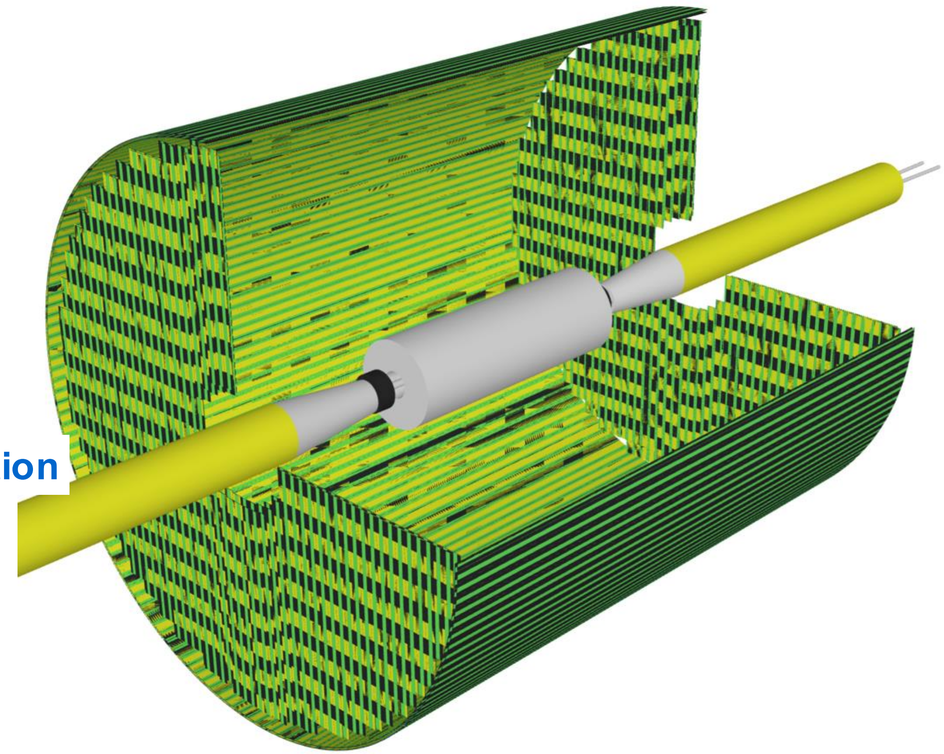
- r = 2m:
- $|z| < 2.4$ m;
- $|\eta| < 2.6$

$\Longrightarrow$ Total area for a single layer: ~90 m^2

Baseline design uses same MAPS detectors as original vertex detector design:

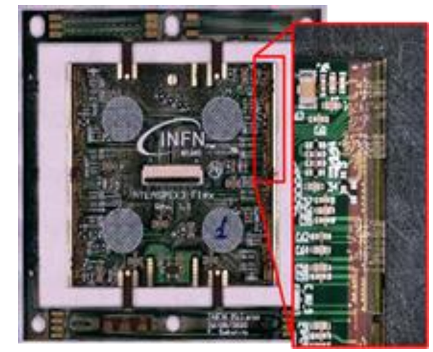
- **50 µm x 150 µm** pixel size → **7 µm x 45 µm resolution**

$\Longrightarrow$ Total number of channels: ~ 150×10^9



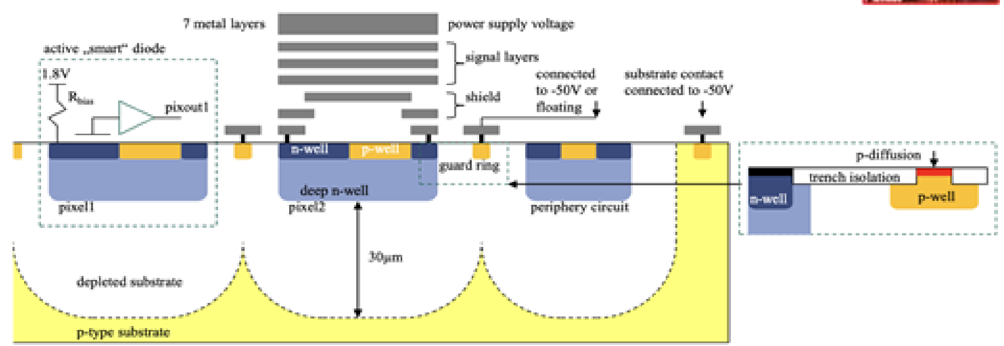
Silicon medium and outer tracker KIT+UK+IHEP+INFN

ATLASPIX3 modules: a full-size system on chip, targeting the outer tracker



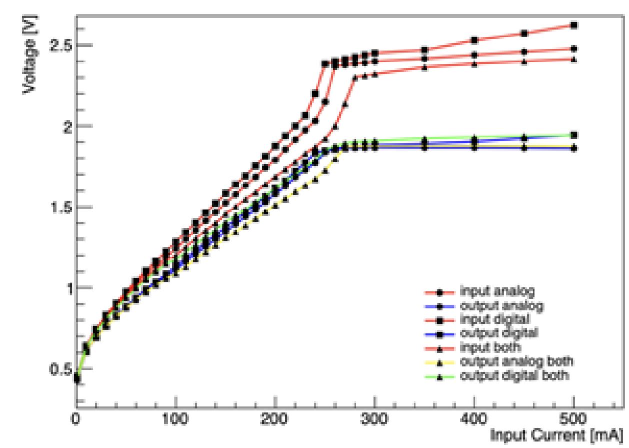
- Intermediate barrel at 15 cm radius
- Outer barrel at 31.5 cm radius

- quad module, inspired by ATLAS ITk pixels
- pixel size 50×150 μm^2
- TSI 180 nm process on 200 Ωcm substrate
- 132 columns of 372 pixels



Power consumption:

- ATLASPIX3 power consumption 100-150 mW/cm^2



Complete system consists of 900'000 cm^2 area / 4 cm^2 chip = 225k chips (56k quad-modules)

Data rate constrained by the inner tracker:

- average rate 10^{-4} - 10^{-3} particles cm^{-2} event^{-1} at Z peak
- assuming 2 hits/particle, 96 bits/hit for ATLASPIX3
- 640 Mbps link/quad-module provides ample operational margin
- 16 modules can be arranged into 10 Gbps fast links: 3.5k links
- can also assume 100 Gbps links will be available: 350 links

Silicon wrapper (IDEA) based on RSD

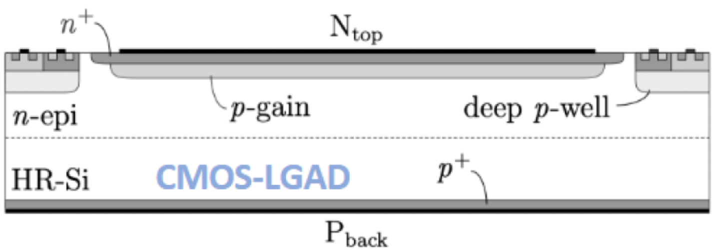
M. Mandurrino
FCC-ee Tracking WS

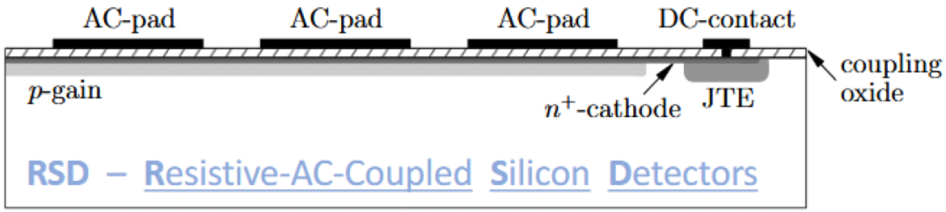
Torino

CMOS integration of the **LGAD technology** already demonstrated (in LF11is)

Spatial resolution **~3% of sensor pitch** (allowing to relax the channel density)

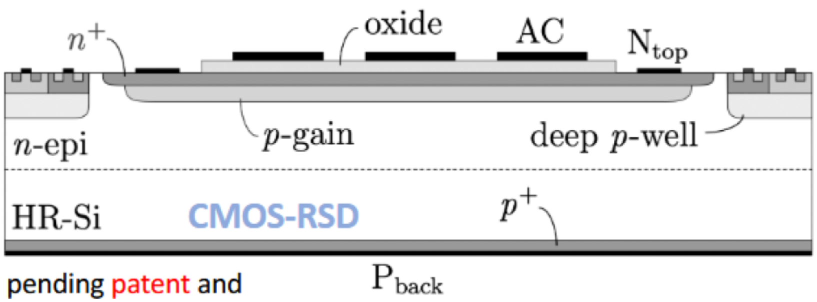
Time resolution similar to standard LGADs: **30-40 ps**





Plausible concurrent targets:

- σ_t = 10-20 ps
- µm-level σ_x
- 100% FF



pending patent and extent of protection

Detector layout and process flow design activities are ongoing

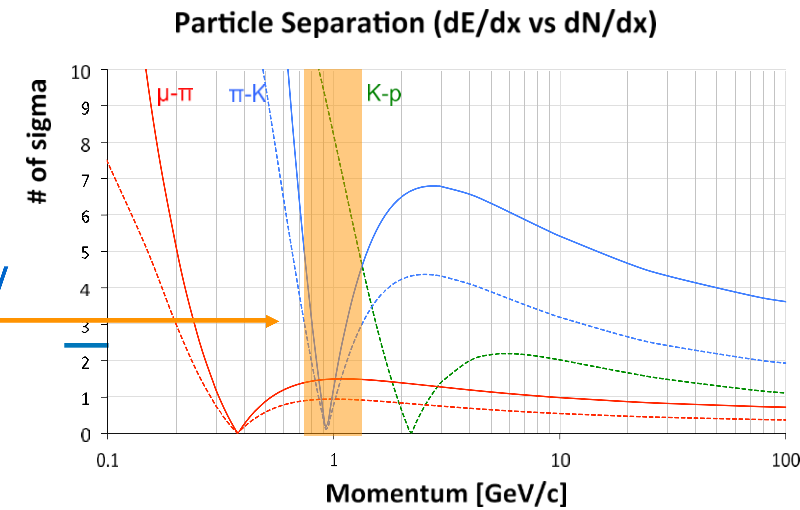
First prototypes in next silicon production runs (std. CMOS process)

Silicon wrapper

INFN Genova

In IDEA concept, tracking and PID provided by the DCH (+ VTX + outer Tracker)

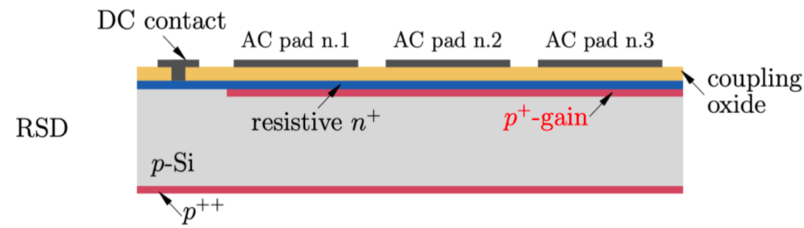
- Silicon wrapper for precise polar angle measurement
- Good K-π separation from dE/dx except for p ~ 1 GeV

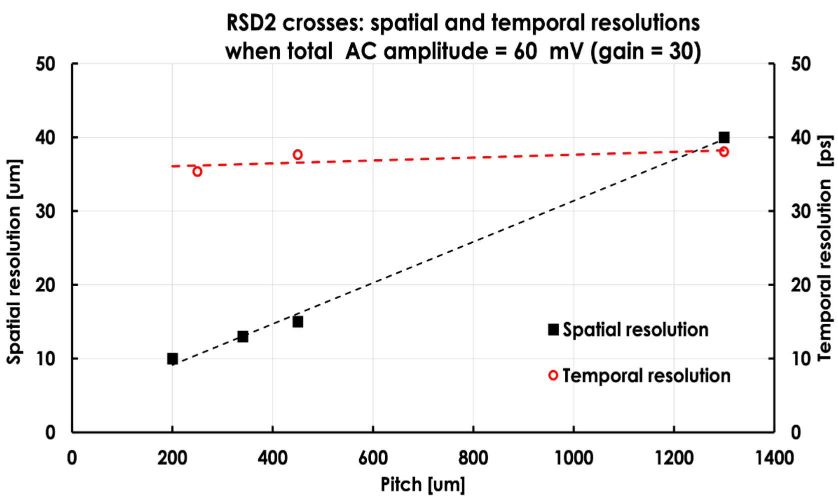


Baseline: ATLASPIX3 modules **BUT**

LGAD (Low-Gain Avalanche Diodes) with RSD (Resistive Silicon Detectors) technology are a possible option:

- TOF with excellent time resolution
- in resistive readout the signal is naturally shared among pads without the need of B field or floating pads





Reconstruction of the position from the signal distribution between contiguous electrodes

Need to show that LGAD could be produced with acceptable cost

- Technology developed by INFN Turin group, production by FBK
- External funding also (ERC, PRIN)

N. De Filippis

Requirements on track angles

Requirements on angular resolution

The polar and azimuthal angles of the momentum of a prompt, charged particle, at production vertex measured as

- the angles of the corresponding track at its distance of closest approach to the detector axis

The corresponding angular resolutions in IDEA and CLD vary between

- about 20 μrad for high momentum particles produced in the central region of the detector
- a few mrad for soft, forward particles

N.B .The contribution of these angular resolutions to the precision of the recoil mass is negligible compared to that of the momentum resolution.

For the reconstruction of the **mass of heavy-flavoured mesons**, the momenta of the daughter particles must be taken at the decay vertex of the meson, and the resolution of the azimuthal angle crucially relies on the reconstruction of this decay vertex.

- N.B: for all examples considered involving B-mesons, the mass resolution remains completely dominated by the momentum resolution

The reconstruction of:

- long-lived particles (LLP) that decay into charged particles within the tracker volume, but after having crossed the (first) layers of the vertex detector
- decays that involve K_s or Λ's.

requires **displaced vertices** to be identified efficiently (primarily) by the main tracker

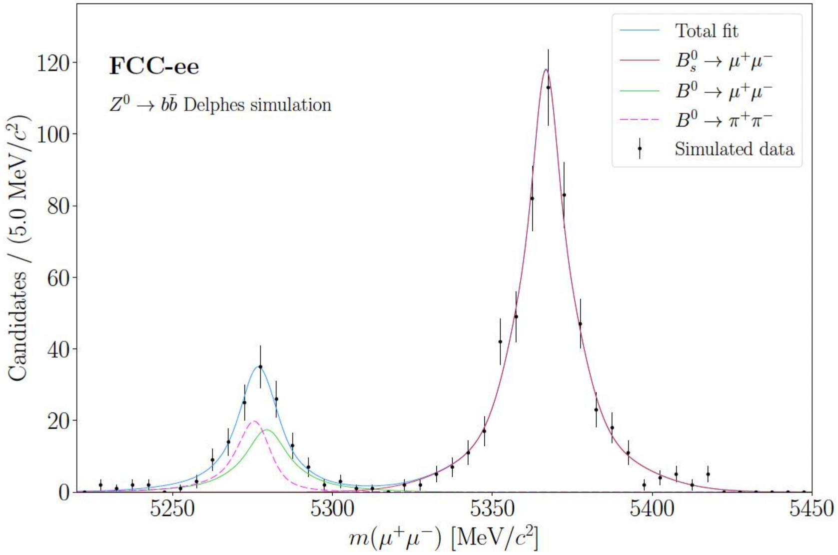
Requirements for standalone muon reconstruction

Requirements on Muon detector

The muon detector has to identify muons with a very high efficiency and to serve as 'tail-catcher' for the hadron showers that may not be fully contained in the calorimeter.

- an important figure of merit is the $\pi \rightarrow \mu$ misidentification probability

Example: control of the π contamination via $B^0 \rightarrow \mu^+\mu^-$ decay



excellent mass resolution IDEA → a very good separation of the B^0 and B_s peaks

A significant background coming from $B^0 \rightarrow \pi^+\pi^-$ is however present under the B peak.

Assuming a double $\pi \rightarrow \mu$ mis-identification probability of 2×10^{-5} → background contribution would be as large as the signal itself

A good standalone resolution will be

- useful to reduce the π contamination and to identify π decays in flight that happen before the muon detector
- important for searches for long-lived particles that decay outside the tracker volume → the requirements on the standalone momentum resolution need to be quantified

Additional requirement

The measurement of the luminosity from $e^+e^- \rightarrow \gamma\gamma$ events to a precision of about 10^{-5}, requires the large background from $e^+e^- \rightarrow e^+e^-$ events to be known very precisely

- the targeted precision will set some requirement on the e/γ separation, which, in turn, will constrain the tracker inefficiency and the level at which this inefficiency is known

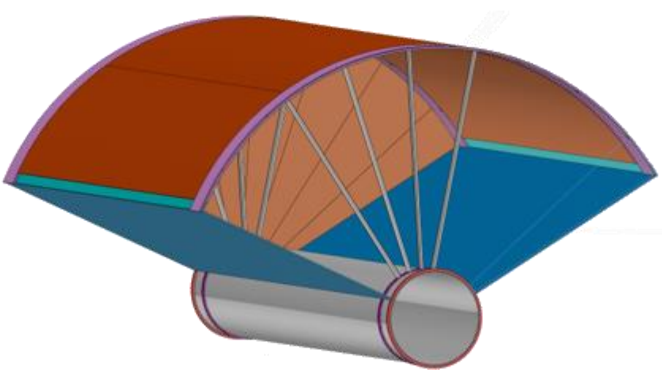
The ratio of the partial width of the Z boson into hadrons to that into muons, R_μ, will be measured with a statistical precision of about 5×10^{-6} at Tera-Z. Counting the number of $\mu^+\mu^-$ events to a similar level of systematic precision sets a very hard requirement on the knowledge of the tracking (and muon chamber) efficiency

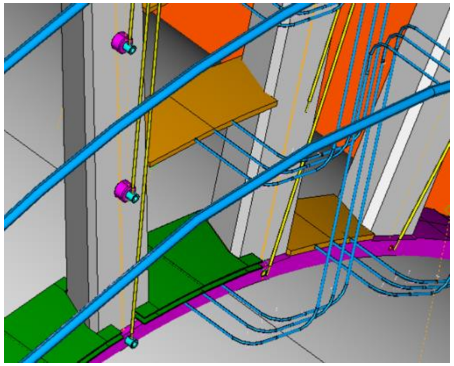
Impact of **beam induced backgrounds;**

- for the CLD tracker, these studies relied on full simulations and concluded that backgrounds should not be an issue
- for the IDEA tracker, the results presented in the CDR will have to be verified with a full simulation
- moreover, these backgrounds should be revisited in view of the updated machine parameters and machine-detector interface.

Drift chamber (IDEA): full-length prototype

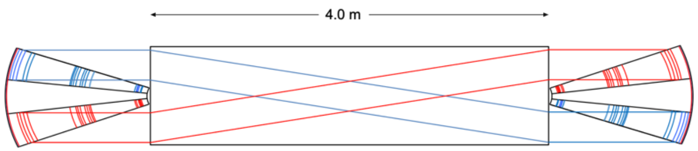
Target: a full length DCH prototype with 3 sectors per endcap

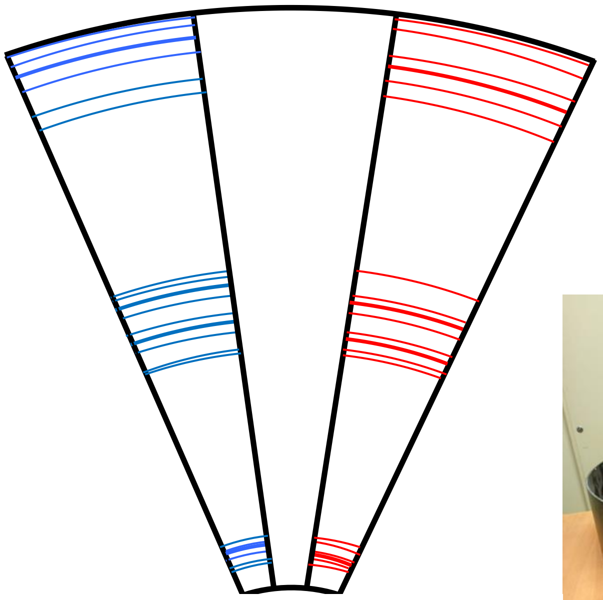




- 8 spokes (4 per endcap)
- Internal ring
- part of the outer ring
- part of the cylindrical panel

MAX COVERAGE





TOTAL LAYERS: 8
Sense wires: 168
Field wires: 965
Guard wires: 264

PCBoards wire layers: 42
Sense wire boards: 8
Field wire boards: 22
Guard wire boards: 12
HV values: 14

Readout channels: 8+8 +16+16+16+16 + 16+16 = 112

Internal ring and a spoke delivered recently → mechanical test will start soon

Drift chamber (IDEA): goals of the full-length prototype

- **Check the limits of the wires' electrostatic stability at full length and at nominal stereo angles**

- **Test different wires**: uncoated Al, C monofilaments, Mo sense wires, …, of different diameters
  - Test different wire anchoring procedures (soldering, welding, gluing, crimping, …) to the wire PCBs
  - Test different materials and production procedures for spokes, stays, support structures and spacers
  - Test compatibility of proposed materials with drift chamber operation (outgassing, aging, creeping, …)

- Validate the **concept of the wire tension recovery scheme** with respect to the tolerances on the wire positions
  - Optimize the layout of the wires' PCBs (sense, field and guard), according to the wire anchoring procedures, with aim at minimizing the end-plate total material budget

- Starting from the new concepts implemented in the MEG2 DCH robot, **optimize the wiring strategy**, by taking into account the 4m long wires arranged in multi-wire layers

- Define and validate **the assembly scheme** (with respect to mechanical tolerances) of the multi-wire layers on the end plates
  - Define the front-end cards channel multiplicity and their location (cooling system necessary?)

- **Optimize the High Voltage and signal distribution** (cables and connectors)

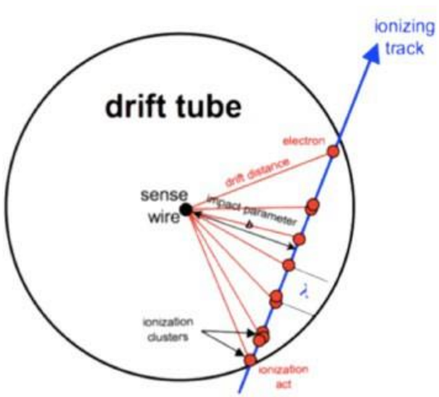
- Test performance of **different versions of front-end, digitization and acquisition chain**

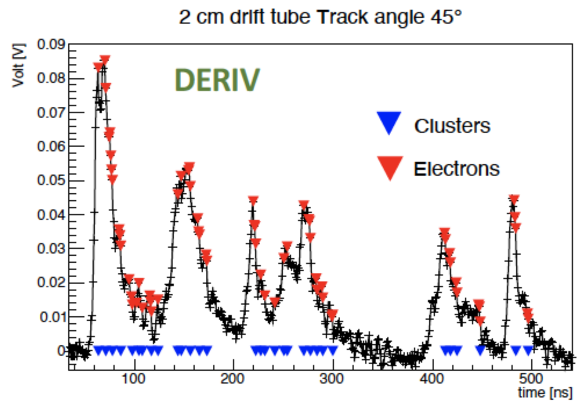
▸ ***Full-length prototype necessary*** ○ ***Can be done in parallel on small prototypes***

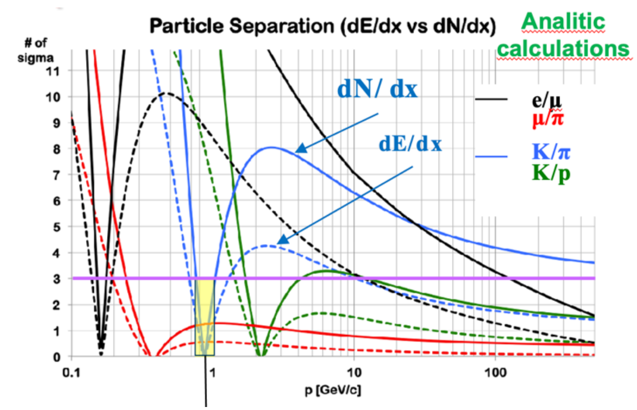
Drift Chamber (IDEA): performance of PID

Principle: In He based gas mixtures the signals from each ionization act can be spread in time to few ns.

- By counting the number of ionization acts per unit length (dN/dx), it is possible to identify the particles (P.Id.) with a better resolution w.r.t the dE/dx method.

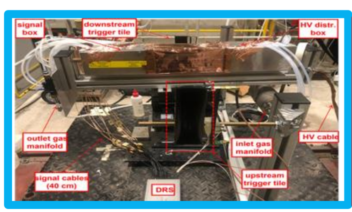


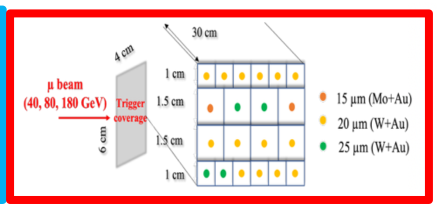


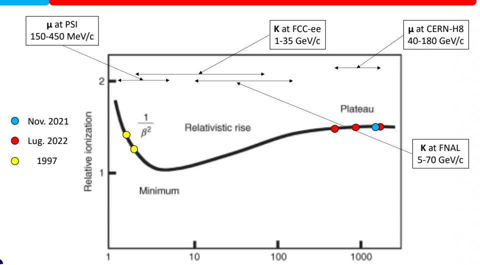


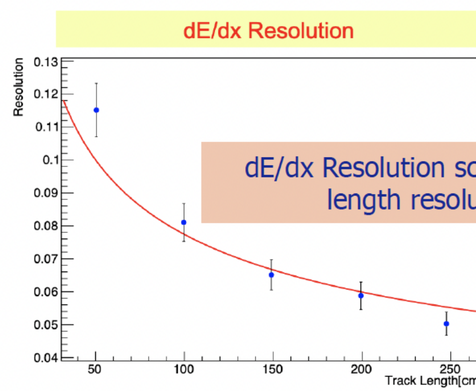
Beam tests to experimentally asses and optimize the **performance of the cluster counting/timing:**

- to muon beam tests at CERN ($\beta\gamma$ > 400) in Nov. 2021+July 2022 (p_T =165/180 GeV)

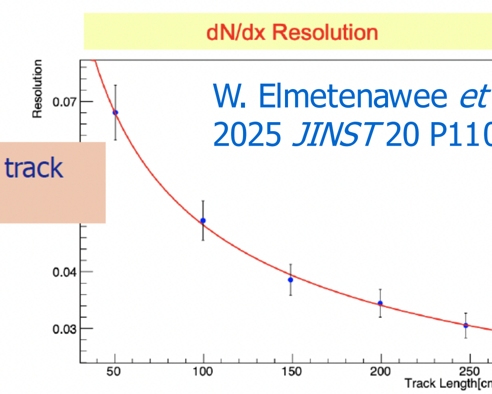








dE/dx Resolution scan vs track length resolution



W. Elmetenawee *et al.* 2025 *JINST* 20 P11019

dE/dx resolution dependence on the track length $L^{-0.37}$

dN/dx resolution dependence on the track length $L^{-0.5}$

~ 2 times improvement in the resolution using dN/dx method

N. De Filippis

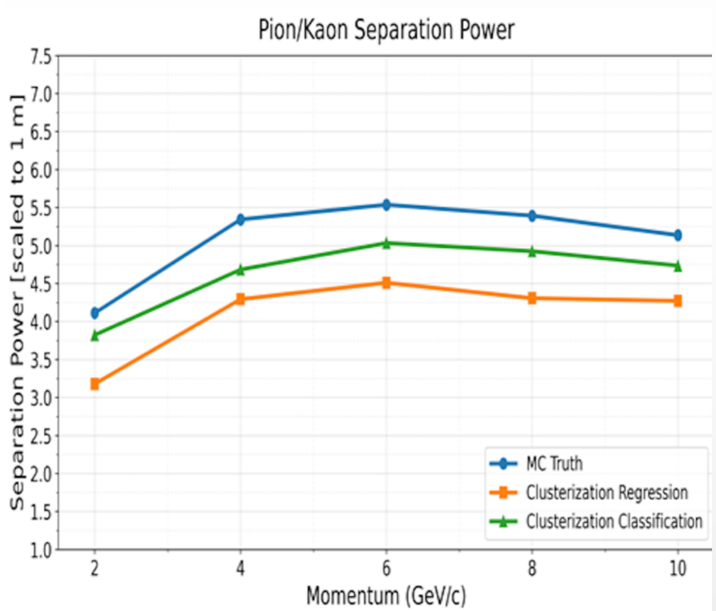
Drift Chamber (IDEA) performance of PID with Deep Learning

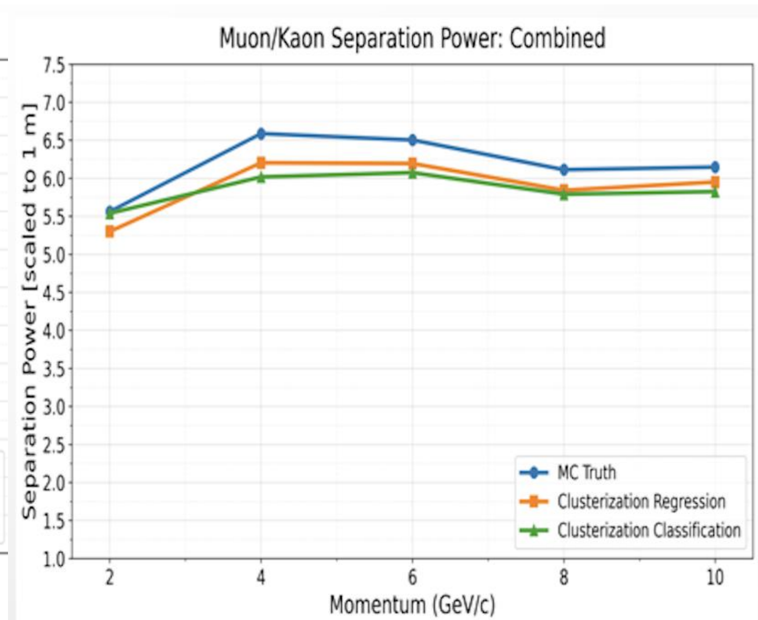
G. Zhao (IHEP) + M. Anwar/A. Alì /N. De Filippis (Bari Poliba)

Kaons

Momentum	Monte Carlo Mean / Std	Peak Finding Mean / Std	Clusterization Regression Mean / Std	Clusterization Classification Mean / Std
10 GeV	15.25/3.88	14.17/3.61	14.46/3.30	14.37/3.63
8 GeV	14.86/3.89	13.82/3.62	14.21/3.32	14.13/3.60
6 GeV	14.41/3.76	13.52/3.55	13.98/3.32	13.94/3.62
4 GeV	13.79/3.70	12.99/3.51	13.55‘/3.29	13.58/3.61
2 GeV	13.08/3.62	12.35/3.43	12.92/3.26	13.05/3.57

$$S = \frac{|\mu_A - \mu_B|}{(\sigma_A + \sigma_B)/2}$$





Recent studies (DELPHES based) with IDEA

Goal: investigate inner barrel layers configuration

- figure of merit: **i.e. transverse impact parameter and z coordinate of the track at the point of minimum approach of the track helix**

Investigated configurations:

1. **Short Barrel Geometry (aiming to use bent stitched MAPS)**
   a. **Reduced barrel length (~10 cm).**
2. **First Layer on Top of Beam Pipe**
   a. **Moves first layer closer to IP (without entering the beam pipe).**
3. **First Layer Inside the Beam Pipe**
   a. **More aggressive layout, innermost radius moved to 8–10 mm.**
   b. **Requires re-engineering of beam pipe and cooling strategy.**

Details in **M. D'Alfonso talk**

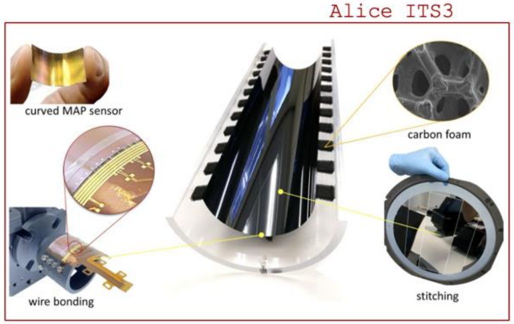
Recent studies (DELPHES based) with IDEA

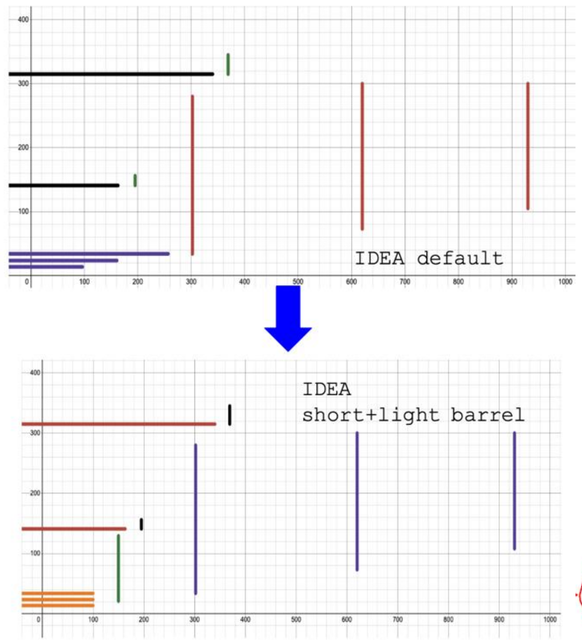
Short + Light barrel

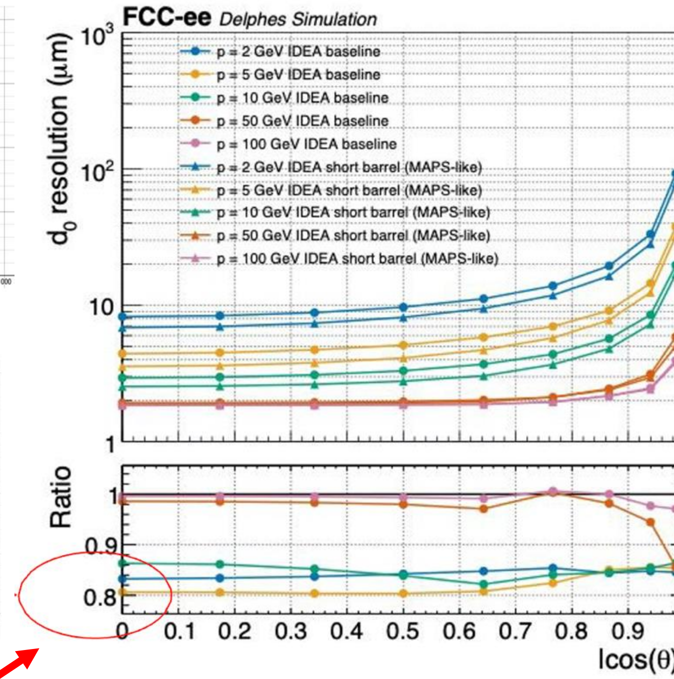
Design changes inspired by ITS3 Alice:

- Barrel shortened to **~10 cm**.
- Material budget of the first 3 barrel layers reduced from 100% X/X₀ to 40% V/X₀

Alice ITS3





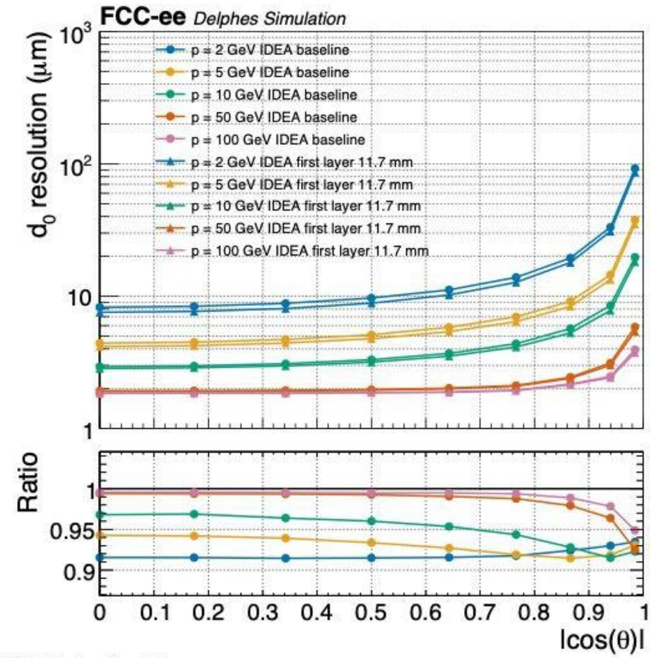


reduced material budget results in better d_0 and d_z resolutions at low p

Recent studies (DELPHES based) with IDEA

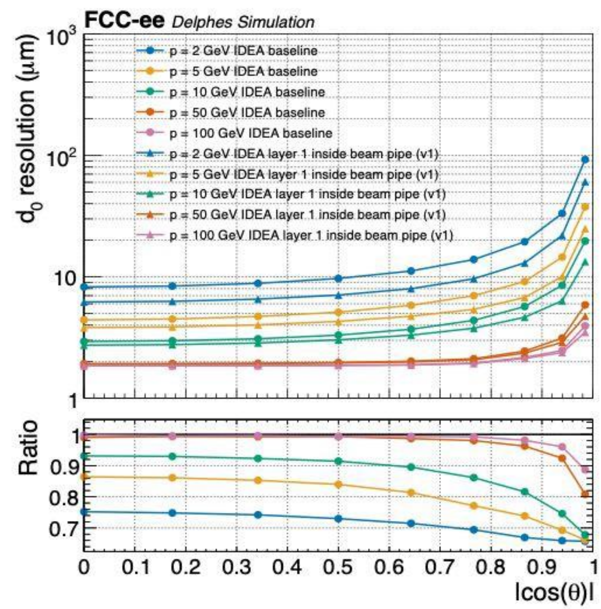
First Layer on Top of Beam Pipe

→ **gain up to 10% in d_0,z_0 positioning the first layer on top of the beam pipe (13.7 mm → 11.7 mm)**



First Layer Inside the Beam Pipe

d0 (15%) gain of 5% at p=5GeV for first layer at 8mm
up to 25% for p= 2GeV



N. De Filippis