Muon systems in FCC-ee detector concepts

Riccardo Farinelli

September 14th, 2026

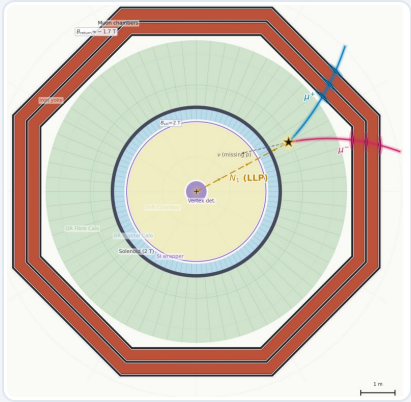
Muon system requirements

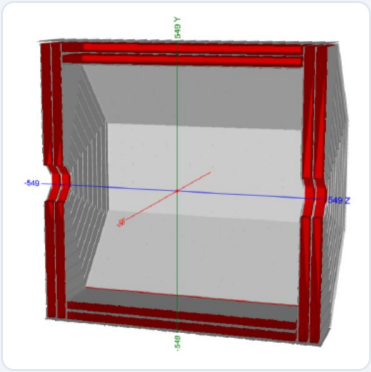
Basic Assumption

- Triggerless / software-based event selection
- Z peak: 40 MHz bunch crossing, ~100 kHz interaction rate

Expected rate in the barrel << 1kHz/cm^2

Expected rate in the endcap < 10 kHz/cm^2





Complementary System Role

Complements the tracker and calorimeters by providing robust muon identification, background suppression, sensitivity to long-lived particles (LLP), and calorimeter leakage recovery.

Primary Muon System Tasks

- High-efficiency **muon ID** at large radius with low fake rate
- Rejection of hadron **punch-through** from the calorimeter
- Calorimeter leakage recovery support (**tail catcher** role)
- Sensitivity to long-lived particle decays outside the central tracker
- **High-precision tracking capability** for long-lived particle signatures



Muon system requirements: Precision EW & Higgs physics

Physics Case

- Beam Energy Spread (BES) measurement
- Rare decays (e.g. B → K*μ⁺μ⁻, Bs → μ⁺μ⁻)
- Higgs recoil-mass measurement ($e^+e^- \to ZH$, $Z \to \mu^+\mu^-$)

Typical signatures

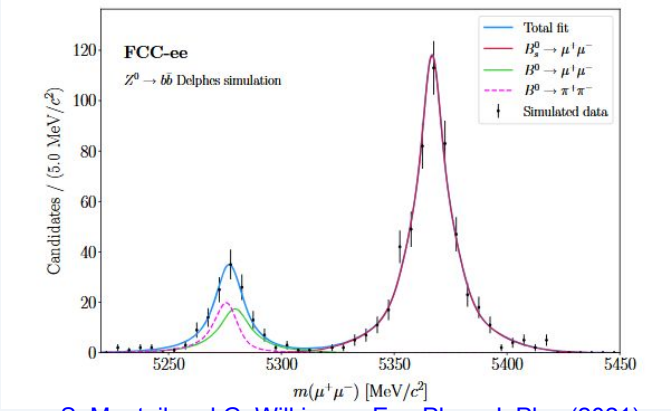
- Isolated prompt muons
- Clean dimuon final states

Event reconstruction

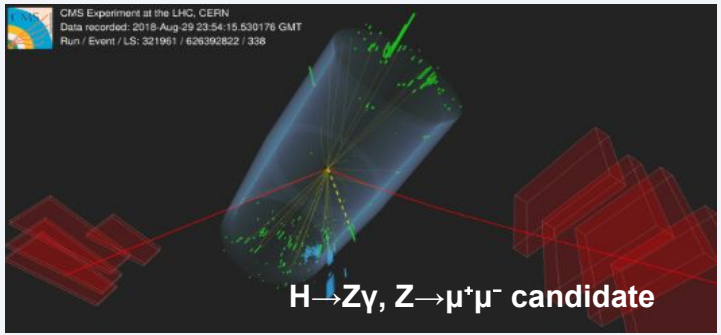
- **Tracking/PID system**
  - Precise muon momentum reconstruction
  - Reconstruction of the Z invariant mass and Higgs recoil mass
- **Muon system**
  - Muon identification confirmation
  - Rejection of hadron punch-through

Muon-system requirements

- High muon-identification efficiency
- Very low π/K/p misidentification probability
- Low fake rate



S. Monteil and G. Wilkinson, Eur. Phys. J. Plus (2021) 136:837



https://cds.cern.ch/record/2807943

Muon system requirements: Long-lived particle searches

Physics Case

- Heavy neutral leptons
- Dark-sector particles

Typical signatures

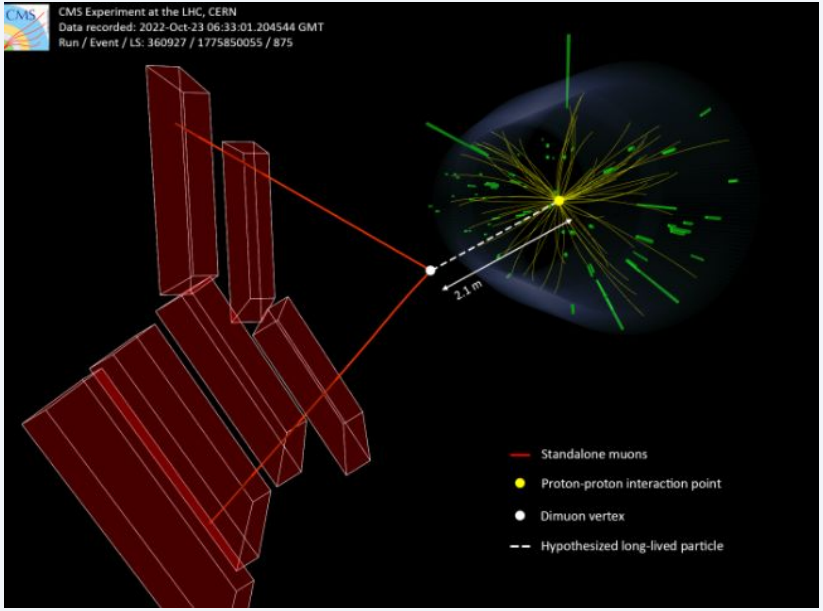
- Displaced decay vertices far from the interaction point
- Disappearing tracks
- Delayed energy deposits / anomalous time-of-flight

Event reconstruction

- **Tracking/PID system + calorimeters**
  - Particle-flow reconstruction
  - Displaced-vertex reconstruction
- **Muon system**
  - Confirmation of displaced signatures
  - Veto of late calorimeter decays and disappearing tracks
  - Independent momentum measurement
  - Cosmic-muon rejection

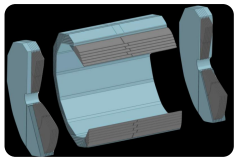
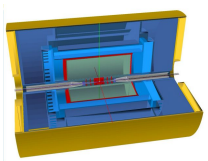
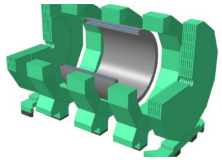
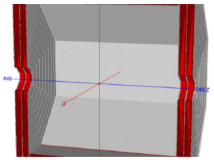
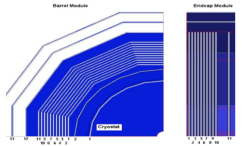
Muon-system requirements

- Large-radius tracking capability
- High detection efficiency
- Robust pattern recognition



Candidate for a long-lived neutral particle that decays into a pair of muons

Overview of the FCC detector concepts

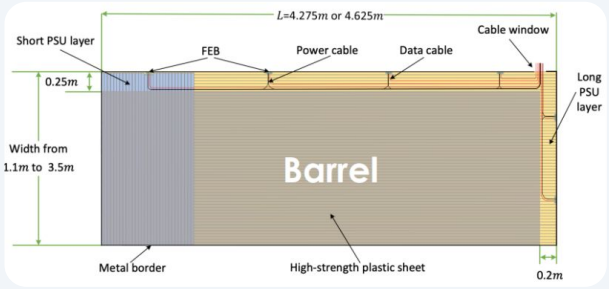
	AGORA	ALFA	ALLEGRO	CLD	IDEA	ILD
						
Vertex	Si	Si	MAPS	Si	MAPS	Si
Tracker	TPC	Full Si	DHC / Straw / SciFi	Full Si	Drift Chamber	Si+TPC
ECAL	Crystal	Si-W	Liquid Argon	Si-W	Crystals	Si-W
HCAL	Scint. sampling	Scint. / RPC	Scint. sampling	Scint. sampling	Fibre DR	Scint. / RPC
Muon	Scint.	Scint. / RPC	Scint. /MM / DT / RPC	RPC	μ-RWELL	Scint. / RPC
PID	tracker	ARC (?)	tracker	ARC (?)	tracker	tracker
B-field	2 T	2 T	2 T	2 T	2 T (3 T)	2 T

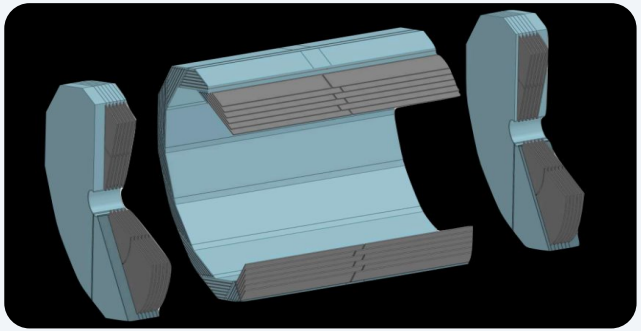
AGORA muon system

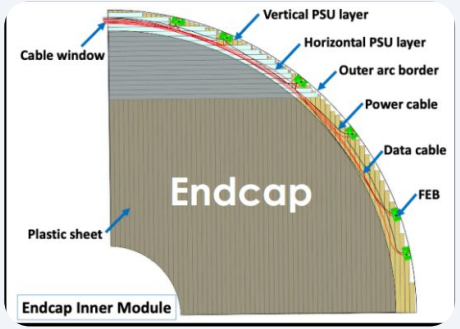
João Guimarães da Costa

The Muon Detector Design

- **Simulation**: design optimization ongoing
- **Structure**: 6 layers of plastic scintillator strips embedded in the iron Yoke.
- **Efficiency:** μ identification efficiency > 95% with π→μ fake rate < 1%.
- **Resolution:** Spatial resolution ~1 cm and Time resolution ~1 ns.
- **Capability:** Rate capability of 50 Hz/cm²





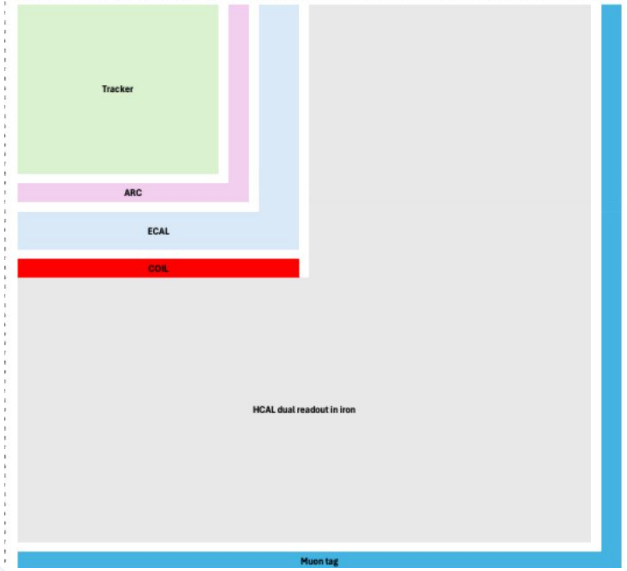


ALFA muon system

Duccio Abbaneo

The Muon Detector Design

- **Simulation:** just started
- **Structure:** robust and redundant with multiple layers
- **Purpose:** no compelling case for precise muon tracking; simple and cost-effective design is highly prioritized
- **Technologies**: Evaluating a sampling calorimeter based on the SiPM-on-tile design. Active layers are made of plastic scintillator. Same technology can be extended to the muon system. RPC also could be used. Proposal and EoI are welcome

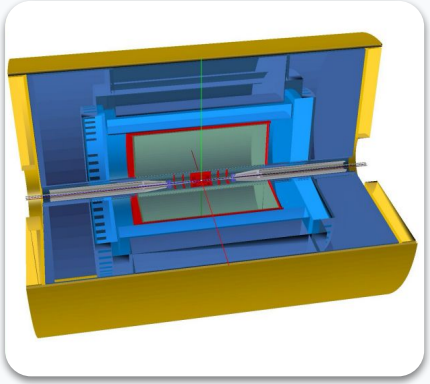


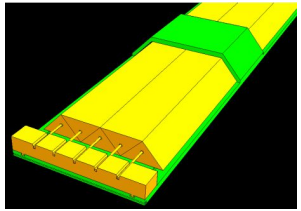
ALLEGRO muon system

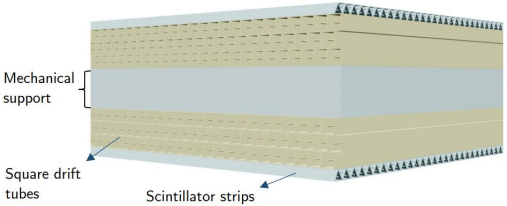
Hunchen Chen

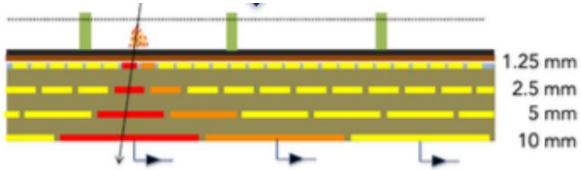
The Muon Detector Design

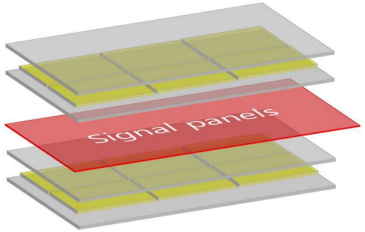
- **Simulation:** only a sensitive cylinder/disk placeholder in the layout
- **Purpose:** both tagging muon system and tracking muon system are considered at the current stage
- **Technologies**: several groups are actively exploring several solution for different region of the muon system:
  - ➢ **Scintillator bars:** Equipped with WLS fibers and SiPM readout
  - ➢ **Bigap RPC:** Utilizing environmental gas mixtures
  - ➢ **Squared drift tubes:** Combined with scintillator strips
  - ➢ **DLC-based resistive Micromegas:** Featuring pad readout and capacitive charge sharing

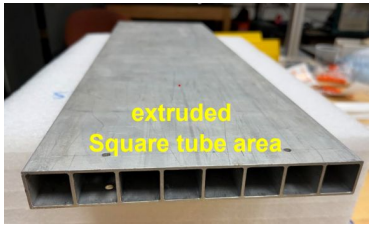










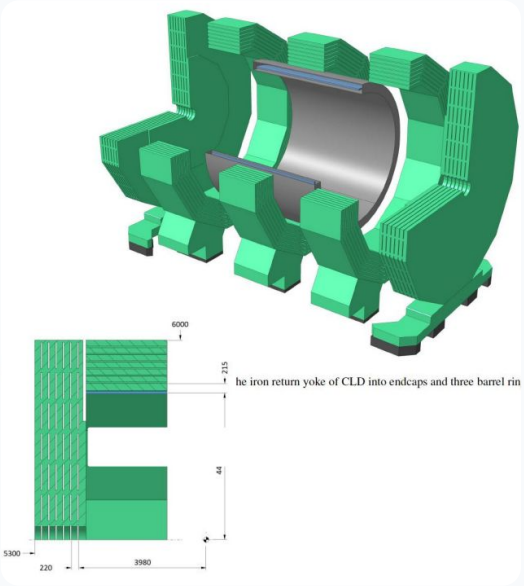


CLD muon system

Jinlong Zhang

The Muon Detector Design

- **Simulation:** design optimization ongoing
- **Structure:** 6 equidistant layers to guarantee optimal detection coverage
- **Purpose:** tagging muon system with an additional layer placed after the solenoid for hadronic shower tail-catcher
- **Technologies**: RPCs with compact cells of 30x30 mm²

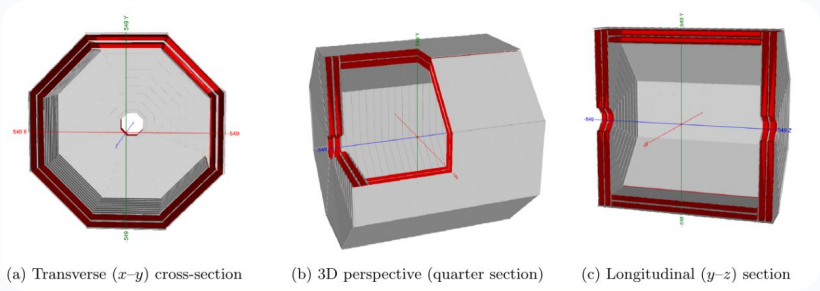


IDEA muon system

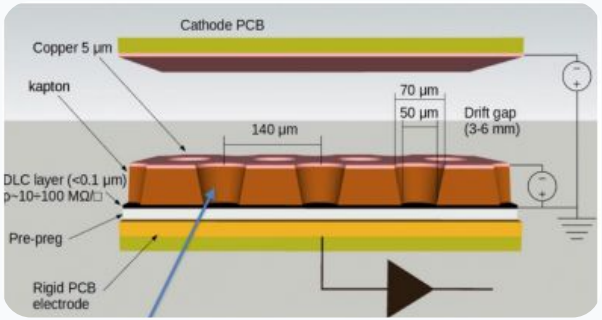
Paolo Giacomelli

The Muon Detector Design

- **Simulation:** optimization ongoing for standalone tracking muon system
- **Purpose:** tracking muon system
- **Structure:** 4 layers embedded in the iron Yoke
- **Technologies**: μRWELL chamber (50 x 50 cm²) with $\sigma_{hit} \approx 200$ μm with 1.2 mm strip pitch.



(a) Transverse (x–y) cross-section (b) 3D perspective (quarter section) (c) Longitudinal (y–z) section

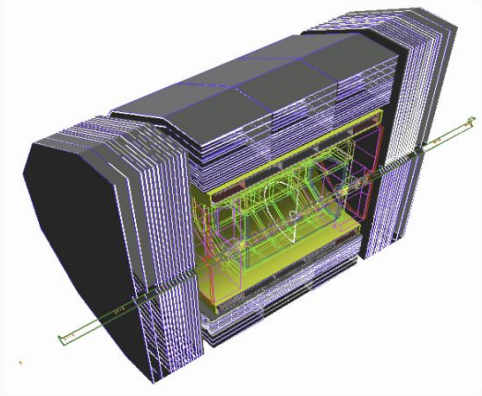


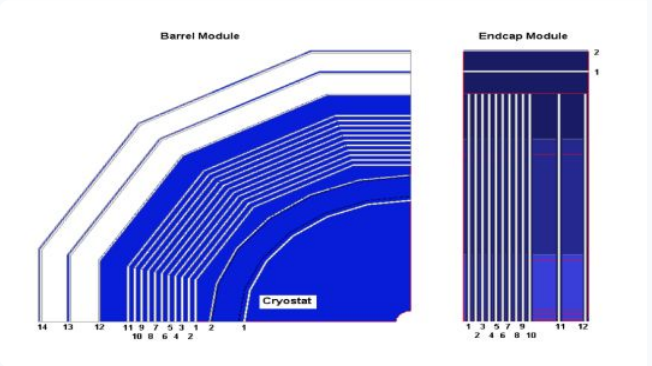
ILD muon system

Taikan Suehara

The Muon Detector Design

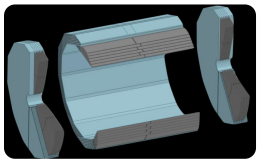
- **Simulation:** advanced and validated via detailed geometry software
- **Purpose:** tagging muon system with very low π→μ fake rate
- **Structure:** 14 (12) active layers for the barrel (endcap) region, interleaved with iron slabs of return yoke
- **Technologies**: Scintillator strips read out by SiPM through WLS or RPC (X&Y) with a width of 3 cm. Same technologies are considered for the highly granular HCAL





Overview of the muon systems at FCC-ee

AGORA

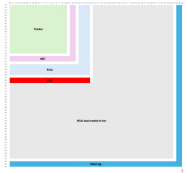


Tech: plastic scintillator strips

Layout: 6 layers in iron yoke

Purpose: tagging muon system

ALFA

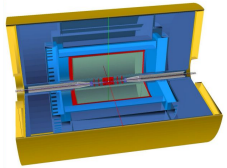


Tech: RPC or Scint. under discussion, possibly same HCAL

Layout: under discussion

Purpose: tagging muon system

ALLEGRO

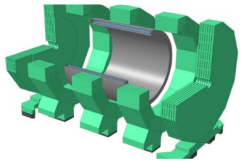


Tech: Squared drift tubes and Scintillator strips or Micromegas or Bigap RPCs

Layout: under discussion

Purpose: both tagging muon system and tracking muon system are considered

CLD

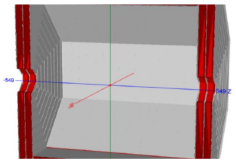


Tech: RPCs with 30x30 mm² cells.

Layout: 6 equidistant layers embedded in yoke slots. and 1 extra layer behind solenoid as tail-catcher.

Purpose: high granularity tagging and calorimetry support.

IDEA

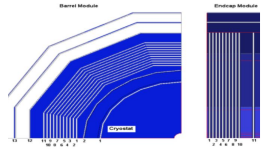


Tech: 50x50 cm^2 μ-RWELL chambers with 1.2 mm strip pitch

Layout: 4 stations interleaved with 30/50 cm iron yoke

Purpose: standalone tracking muon system for LLP

ILD



Tech: Scintillators (SiPM/WLS) or X-Y RPCs, possibly same HCAL

Layout: 14 active layers in barrel, 12 layers in endcap in iron yoke

Purpose: Robust tagging and 2D reconstruction

Performance: over 95% efficiency, under 1% π→μ fake rate
Coverage: over 98% solid angle
Resolution: 1 ns time resolution and 1 cm spatial for tagging muon system or 200 μm spatial for tracking muon system
Rate: 50 Hz/cm^2 in the barrel and 10 kHz/cm^2 in the endcap

Optimization of the muon system

IDEA Muon System for standalone track reconstruction

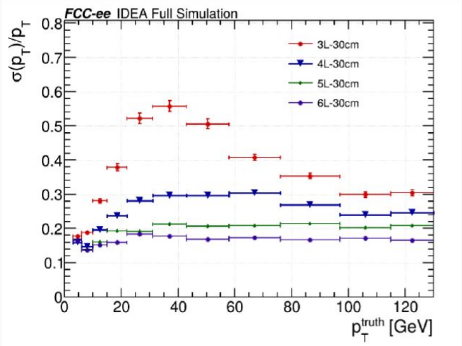
Mahmoud Althakeel

Three physics realities to fight

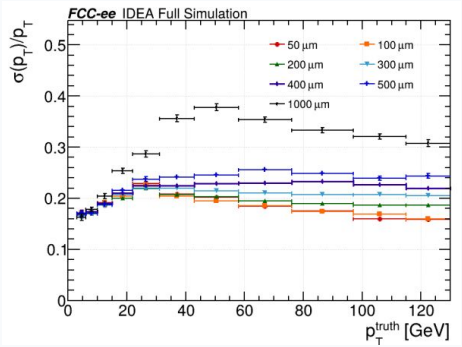
- **Secondary-hit contamination:** δ rays and hadronic secondaries deposit hits indistinguishable from MIPs
- **Limited hit multiplicity:** three hits give an exact circle fit with zero degrees of freedom, adding layers adds DoF and suppresses combinatorial fakes
- **Multiple scattering in Iron:** MCS dominates momentum resolution for p < 20 GeV/c

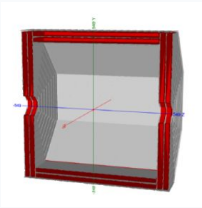
Performance evaluation

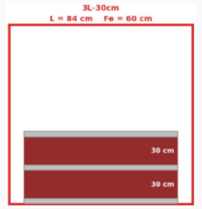
- **Standalone tracking algorithms:** Pre-processing, Hit clustering, Combinatorial search, Outlier rejection and Propagation
- **Momentum resolution:** a 20% resolution can be achieved with an optimized layering of the muon system, i.e. 4L-50cm or 6L-30cm together with a spatial resolution on the hit of ~ 200 µm

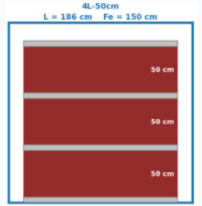


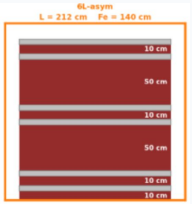
(a) $\sigma(p_T)/p_T$ vs p_T











ILD for π→μ fake rate and tail catcher

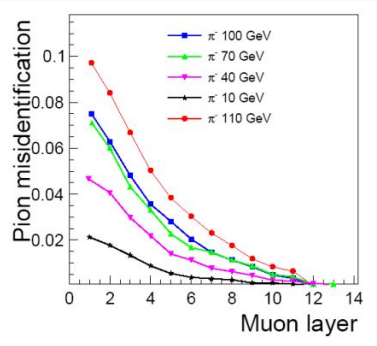
Imad Laktineh

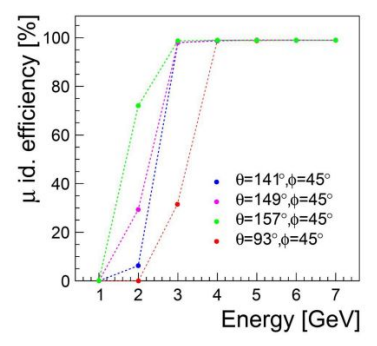
μ Identification

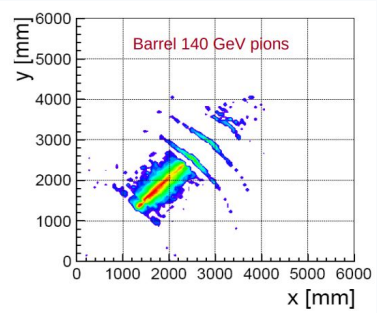
- **Muon energy:** excellent separation power at energies only above 4 GeV
- **Granularity:** π→μ + ***ν*** can be misidentify if granularity is low
- **Multiple layers:** pion misidentification is strongly reduced with a large number of layers, depending on the pion energy

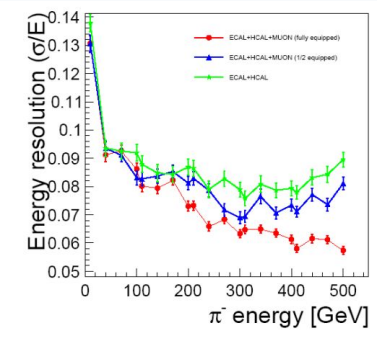
Tail Catcher

- **Energy resolution:** improvement can be introduced for high pion energies, smaller effect for the FCC-ee operation region
- **Granularity:** high segmentation can improve the energy reconstruction









Technologies

RPC for muon systems

Detector Architecture

Plates: Constructed from two parallel high-resistivity plates (typically Bakelite or glass).

Gas Gap: Separated by a perfectly uniform gas gap (usually 1 to 2 mm).

Operating Principle (Avalanche Mode)

Electric Field: Operates under a strong, uniform electric field (typically 4-5 kV/mm).

Resistive Quenching: High bulk resistivity ($\rho \sim 5x10^{10}$ - $5x10^{12}$ $\Omega \cdot cm$) limits charge delivery, naturally preventing full spark and localizing dead-time.

Signal Readout

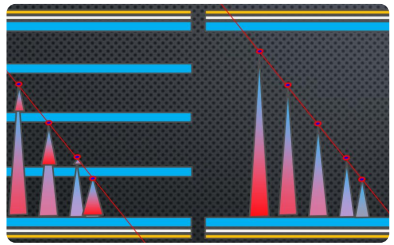
Induction: Fast electron movement induces capacitive signals on external metallic electrodes (strips/pads) separated by insulating PET film.

Reconstruction: Orthogonal layers (X and Y) or propagated time provide efficient 2D spatial reconstruction.

Key Performance Advantages

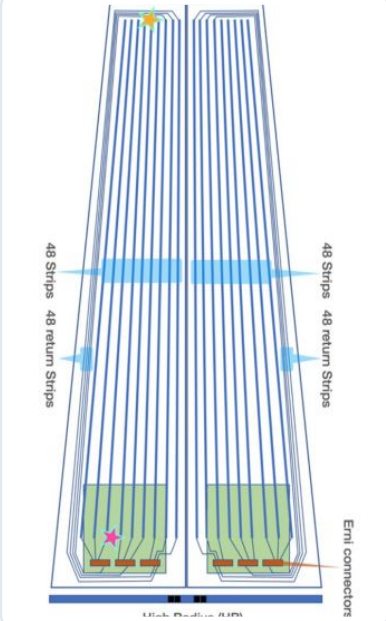
Outstanding Timing: Standard RPCs achieve around 200 ps resolution, making them ideal for fast triggering and bunch-crossing ID.

Scalability: Extremely cost-effective design, allowing for the massive large-area coverage required by modern outer muon spectrometers.



Operating Principle

Standard RPCs operate in avalanche mode to maintain extremely fast and localized signals, avoiding spark transitions via resistive protection layers.



RPC for muon systems

Hardware and Geometry Innovations

Advanced Materials: R&D is shifting towards glass electrodes. Glass provides exceptional surface flatness and perfect gas tightness, eliminating linseed oil coatings.

Gap Reduction: Shrinking the physical width of the gas gap improves timing performance, reduced avalanche charge, and lowers operating high voltages.

The Eco-Gas Challenge (Global Warming Potential)

Environmental Impact: Standard gas mixtures rely heavily on fluorinated greenhouse gases (e.g., R-134a and SF6) which have an unacceptably high GWP.

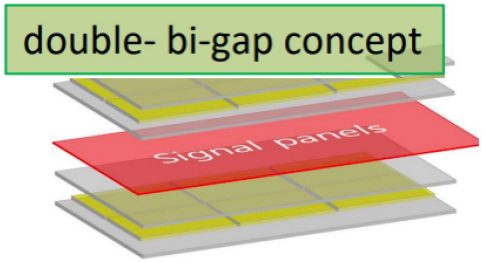
Alternative Mixtures: The community is aggressively testing low-GWP replacements, primarily relying on HFO-based gas molecules.

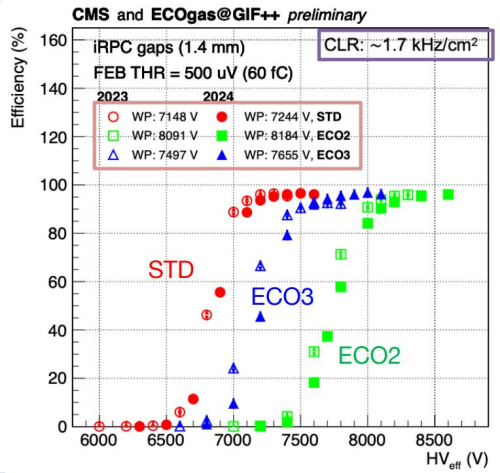
Current Limitations: Eco-friendly alternatives generally require higher operating voltages. Chemical stability and long-term aging under irradiation are still under investigation.

Zero emission

Reduce GHG: gas recirculation and recuperation systems are the first way to reduce emissions

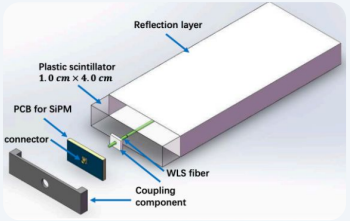
Sealing: RPC with no gas losses reduce significantly the emission and the recirculation power





Scintillating bars

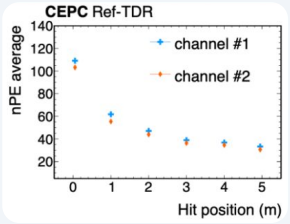
João Guimarães da Costa

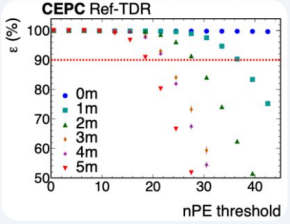


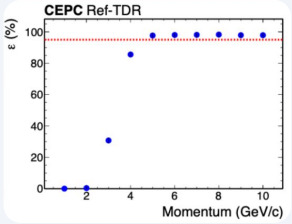


AGORA R&D & Performance

- **SiPM & Scintillators:** Extensive testing on SiPM and long plastic scintillator strips with WLS fibers.
- **Strip Performance:** 5 meter strips demonstrate >90% detection efficiency.
- **Reconstruction:** Standalone muon detector efficiency reaches ~98% for muons above 4.5 GeV/c.

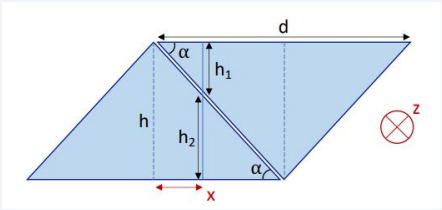


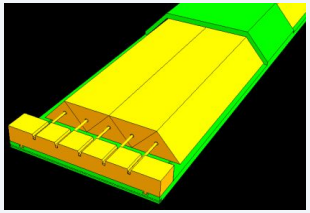




ALLEGRO R&D & Performance

- **Strip Performance:** position resolution 2.5 − 3.3 mm if digital readout or 1 mm if averaged on the light; time resolution 250 - 500 ns
- **Attenuation length:** λ ~ 3-4 m
- **Light yield:**~ 90 PE/cm per path length within the strip





Can Suslu

LEMUR

DT for muon tracking

DT

A Proven Technology

Robust, mature solution for high-precision muon track reconstruction.

Reliability: 99.7% functional rate after 15 years, with TDAQ efficiency ~100%.

Performance: Momentum scale accurate to 0.1%, resolution ~80 μm.

Detector Parameters and Geometry

Dimensions: Length up to 6000 mm with outer diameter of 30.0 mm.

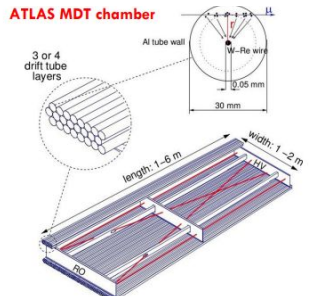
Materials: 0.4 mm Aluminum cathode wall, 35 μm Tungsten anode wire.

Configuration: Superlayers (72 tubes/layer, 6 layers/module) for redundancy.

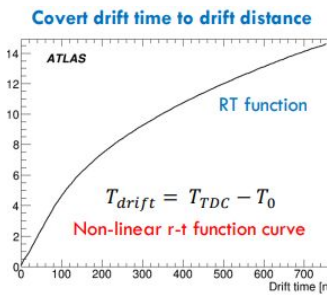
Operating Conditions

Gas Mixture: Ar/CO2 (93/7) optimized for stable drift properties.

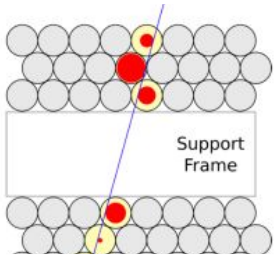
Pressurization & Field: Operated at 3 bar absolute with High Voltage of 3080 V.



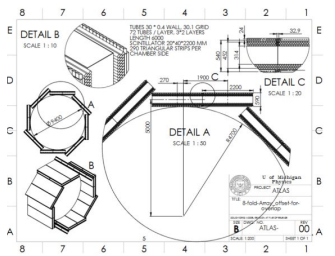
ATLAS MDT chamber



Non-linear r-t curve



Track fitting setup



Detector blueprint

DT for muon tracking

The Extrusion Squared Drift Tube Concept

Cost Reduction: Shifting to extruded multi-cell squared drift tubes reduces manufacturing costs by a factor of 5.

Simplicity: The squared extrusion severely simplifies chamber construction and alignment processes.

Performance: Squared tubes maintain drift properties and spatial resolutions comparable to classic round tubes.

Current R&D and Engineering Goals

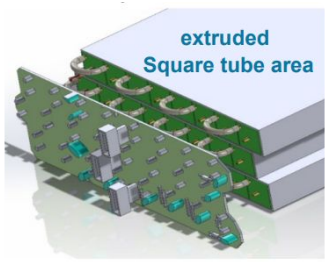
Readout Electronics: Developing highly cost-effective, high-performance front-end electronics for massive channel counts.

Full-Scale Prototyping: Investigating optimal configurations, full-size detector construction, and modular integration.

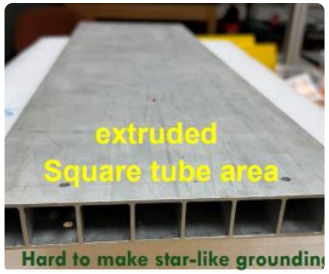
System-Level Integration (ALLEGRO Concept)

Magnetic Synergy: Studying muon detector layout in combination with specific magnet configurations.

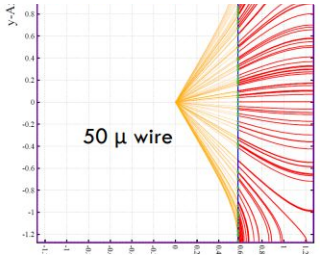
Global Architecture: Ensuring seamless mechanical and data integration with inner tracker and calorimeter systems.



Extruded square tube area



Extruded profile prototype



E-field lines simulation

MPGD for Muon Tracking

Deployment Strategy at FCC-ee

Heritage: MPGDs are successfully used in highest-intensity LHC regions.

Advantage: High spatial resolution & scalable industrial manufacturing.

Baseline Technologies

Architecture: Single-amplification-stage MPGD designs.

Spark Quenching: Resistive layer passively suppresses discharges for safety.

PCB Design: Advanced techniques allow highly customized internal structure.

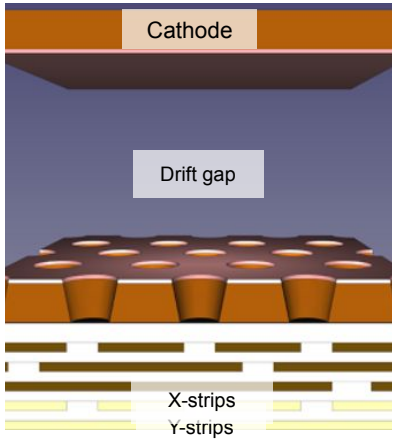
Current R&D & Cost Optimization

Challenge: Covering massive muon end-caps requires managing huge active areas.

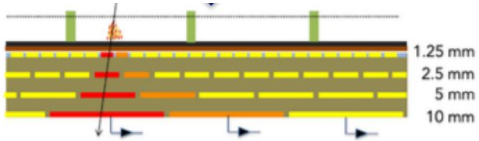
R&D Focus: Direct optimization of the readout plane geometry.

The Goal: Minimize readout channels to drastically reduce electronics costs.

μ-RWELL



MicroMegas



MPGD Performance and Large-Area R&D

Intrinsic Performance vs. System Requirements

Intrinsic: Spatial res 50-100 µm, rates >1 MHz/cm², single-chamber time res ~10 ns.

System Goal: Cover massive muon areas; relax resolution target to 100-200 µm to reduce channels.

Engineering the Readout: Charge Sharing

Charge Sharing: conductive layer spreads charge over larger area using complex pad layering.

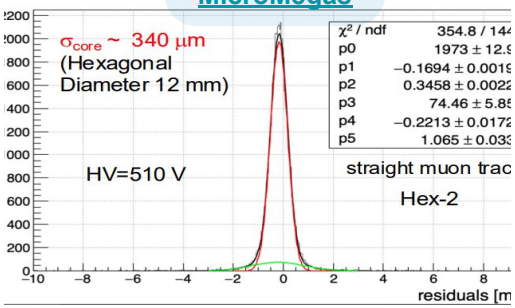
Segmentation: Strips pitch increased up to 1.2 mm; Pads area increased up to few cm².

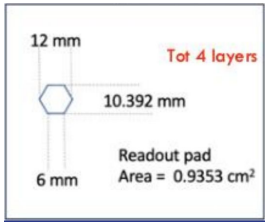
The Physics Driver: Long-Lived Particles (LLPs)

Simulation Target: Full apparatus simulations target the 100-200 µm spatial resolution range.

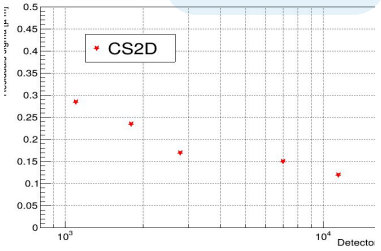
Requirement: Better than 200 µm is strictly required to maintain a 20% momentum resolution.

MicroMegas

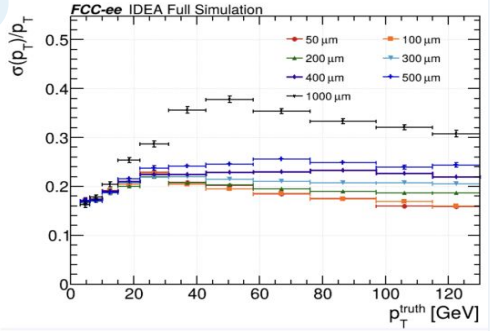




µ-RWELL



straight muon tracks
1.2 mm strip pitch



Thin Gap Chambers (TGC) for Muon Systems

Detector Architecture and Geometry

Thin Gap Principle: Distance between anode wires and cathode planes (1.4 mm) is strictly smaller than wire pitch (1.8 mm).

Components: 50 µm gold-plated tungsten wires (anodes) sandwiched between graphite-coated FR4 cathode planes.

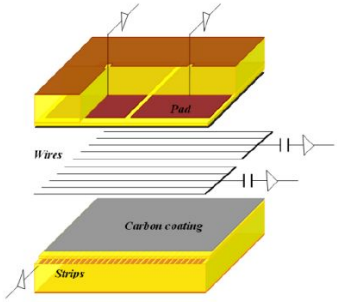
Operating Principle and Performance

Spatial Tracking: 2D coordinate readout is achieved via wire readout and orthogonal copper strips or pads behind the cathode.
Resolution: about 300 µm depending on the readout segmentation and better than 10 ns

Current Challenges and R&D for Future Colliders

Eco-friendly & Safe Gases: Replacing highly flammable n-pentane with non-flammable, eco-friendly gas alternatives.

Large-Area Scalability: Designing lightweight, rigid support structures to scale TGC production for outer envelopes of future colliders.



sTGC schematics: 1.8mm wire pitch, 1.4mm wires to cathodes

TGC

sTGC Schematics

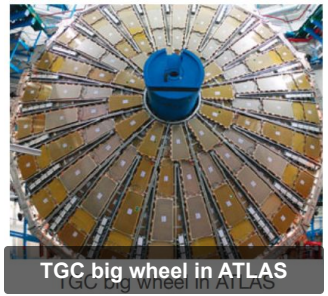
Detailed visual architecture showing wire and strip layout.

- 1.8 mm wire pitch
- 1.4 mm wires to cathodes



50 µm tungsten wires gold coated

50 µm gold-coated tungsten wires used as anodes.



TGC big wheel in ATLAS

What next

FCC-ee organization and timeline

Clickable link at pag 4

Get involved

FCC Detector concept: regular monthly meeting

FCC-PED subgroups: signup and follow the indico agenda for news and updates

Detector concepts: email to the contact person if you are interested, some concept needs the technological support

EoI: only one Expression of Interest from RPC community has submitted

Group name	Email	Signup	Indico
Calorimetry	FCC-PED-DetectorConcepts-Calorimetry@cern.ch	click	click
Luminometry	FCC-PED-DetectorConcepts-Luminometry@cern.ch	click	click
Magnet	FCC-PED-DetectorConcepts-Magnet@cern.ch	click	click
Muon	FCC-PED-DetectorConcepts-Muon@cern.ch	click	click
TDAQ	FCC-PED-DetectorConcepts-TDAQ@cern.ch	click	click
Tracker & PID	FCC-PED-DetectorConcepts-Tracker@cern.ch	click	click
AGORA	FCC-PED-DetectorConcepts-AGORA@cern.ch	click	click
ALFA	FCC-PED-DetectorConcepts-ALFA@cern.ch	click	click
ALLEGRO	FCC-PED-DetectorConcepts-ALLEGRO@cern.ch	click	click
CLD	FCC-PED-DetectorConcepts-CLD@cern.ch	click	click
IDEA	FCC-PED-DetectorConcepts-IDEA@cern.ch	click	click
ILD	FCC-PED-DetectorConcepts-ILD@cern.ch	click	click

Signing up to any of the above e-groups adds you to the overall "FCC-PED-DetectorConcepts@cern.ch" e-group as well

Concept Studies

AGORA
ALFA
ALLEGRO
CLD
IDEA
ILD

Detector Subsystems

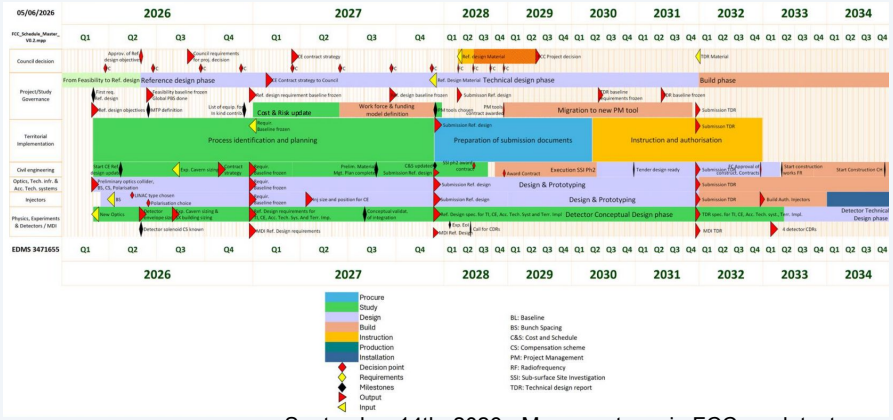
Calorimetry
Luminometry
Magnet
Muon
TDAQ
Tracker & PID

Timeline

Present and Future: FCC-ee is scheduled for the future but the activity is now

Reference design: material has to be submitted within the end of 2027

Technologies: potential, limitations, and technological readiness levels will be considered together with cost and operabilities



List of workshops of interest for FCC-PED muon

EoIs for the Development of Sub-Detectors and Detector Concepts for the FCC
https://indico.cern.ch/event/1529896/#b-611792-muons-muons

FCC week
https://indico.cern.ch/event/1552126

IDEA Study Group
https://agenda.infn.it/event/49076/

ALLEGRO Detector Concept Meeting - Muon Detector Working Group
https://indico.cern.ch/event/1671835/

DRD1 WG1+WG2 workshop on FCC-ee
https://indico.cern.ch/event/1675383

Expressions of Interest for the Development of Sub-Detectors and Detector Concepts for the FCC

Link to the list of EoI here

ID 0076: Development of **micro-RWELL** technology for the Muon system

ID 0084: Resistive **Micromegas** detectors for Muon systems at FCC-ee

ID 0049: Detector development and production, **MPGDs** or **MWPC**

IDs 0016 & 0078: Timing **RPCs** for muon system

ID 0037 & 0060: A Muon System with **Square Drift Tubes** and **Scintillator Strips**

All the technologies included in the detector proposal are developed by at least one group

Conclusion

FCC-ee community

Six detector concepts: RPC are mentioned in 4/6 concepts for calorimeter or muon systems

Join: some of them needs a technological support

Technologies

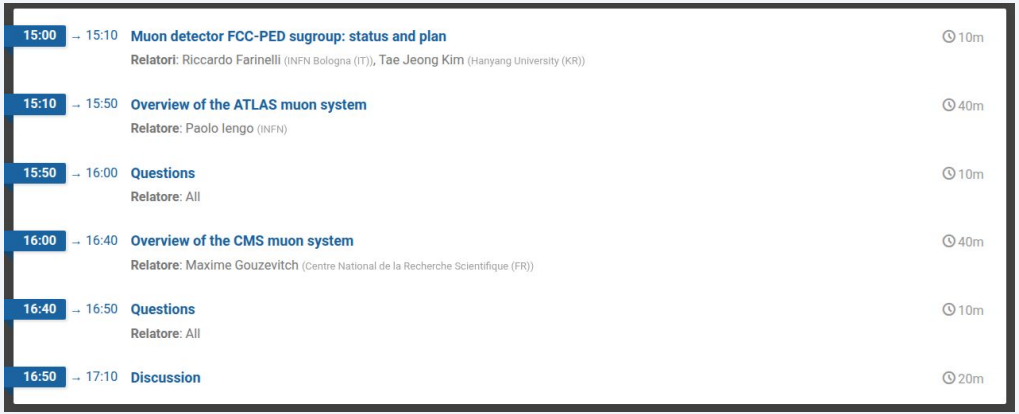
RPC: a spatial resolution of 1-10 mm and a time resolution of 0.1-1 ns are suitable

Competitors: the main competitor are the scintillating strips with SiPM with performance better than 2 mm and 0.5 ns

Challenges: GHG emission has to be reduced to zero with sealed RPC and recirculating and recuperating systems; eco-gas reduces the impact on the environment if it is not possible to recycle 100% of the gas due to needs for fresh gas

Backup

Forth group meeting



- **Day and time:**
  September 30th at 15.00
  (CEST - CERN time)

- **Indico page:**
  https://indico.cern.ch/event/1696830/

Zoom room:
https://cern.zoom.us/j/62724546127?pwd=U0NIZXx9r8dCccgyXN8FgWQUhbaTaO.1

If you are interested to share your activities, please contact us at:
fcc-ped-detectorconcepts-muon@cern.ch

Gaseous Calorimetry and muon tagging

The Sampling Calorimeter Concept

Built as a dense sandwich structure: alternating layers of heavy passive absorbers (e.g., Lead, Steel, Tungsten) to induce particle showers, and active gaseous layers (RPCs or MPGDs) to sample the shower energy.

The Particle Flow Paradigm

Traditional Calorimeters: Simply integrate the total analog energy.

Particle Flow Algorithms (PFA): Track and measure every single particle in a jet (charged/neutral hadrons, photons).

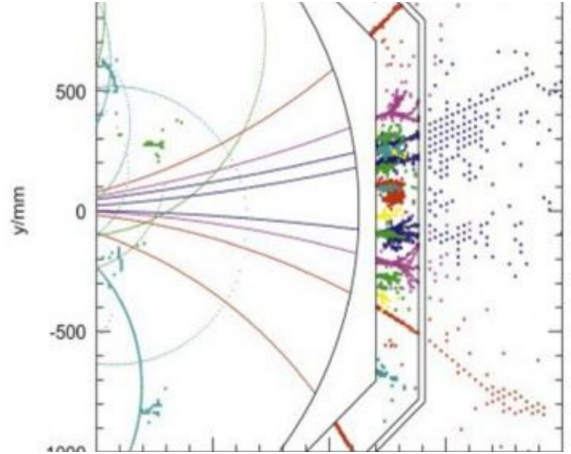
Granularity: PFA requires ultra-high 3D spatial granularity to disentangle overlapping showers.

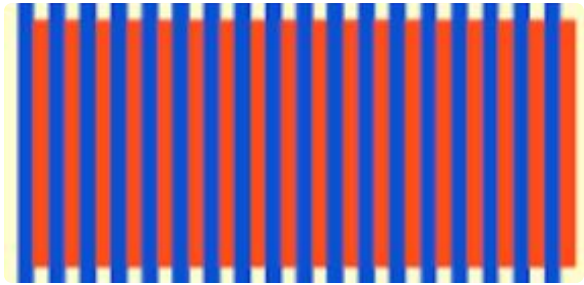
Why Choose Gaseous Technologies?

Cost-Effective Segmentation: Gaseous detectors segment easily into tiny readout pads (e.g. 1x1 cm) over massive areas, avoiding high crystal costs.

Digital/Semi-Digital Readout: Operates in 1-bit or 2-bit/3-bit modes. Counting hit pads provides an excellent hadronic shower energy estimator.

4D Capabilities: Excellent timing (especially RPCs) adds time-of-flight info, identifying delayed neutrons.





RPC for calorimetry

The SDHCAL Architecture and Readout

Structure: Built as a dense sampling calorimeter. Features 8 layers of 2 cm thick stainless steel absorbers interleaved with active Glass RPC (GRPC) planes.

Embedded Electronics: Front-end electronics completely embedded on the back of the readout boards to minimize dead space.

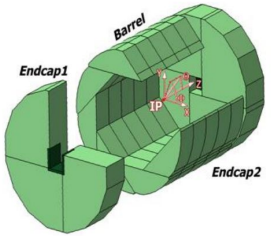
Semi-Digital Segmentation: Fine lateral segmentation of 1 cm². Uses a 2-bit readout (3 charge thresholds) to avoid signal saturation in hadronic shower cores.

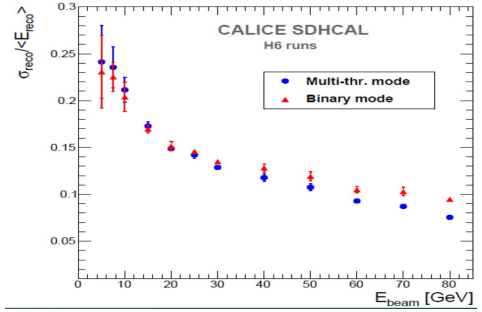
The 48-Layer Technological Prototype

A massive, full-scale technological prototype consisting of 48 active GRPC layers built and tested in beam campaigns, fulfilling all ILD requirements:

- **Mechanics:** Extreme compactness and a fully self-supporting mechanical structure.
- **Data Acquisition:** Capable of operating in both traditional trigger mode and advanced triggerless mode.
- **Thermal Management:** Validated for both power-pulsing mode and continuous readout mode.

RPC

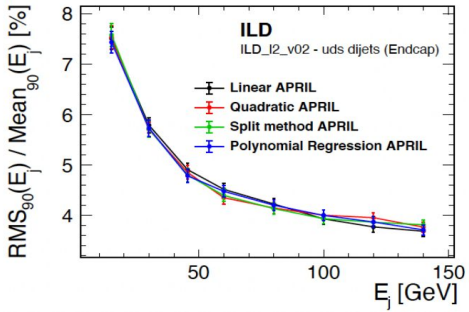




Single Particle

Energy resolution of CALICE SDHCAL.

Single particle



Jet Performance

Reconstructed jet energy resolution curves.

Jet

RPC for calorimetry

RPC

The Timing Revolution: 4D Particle Flow

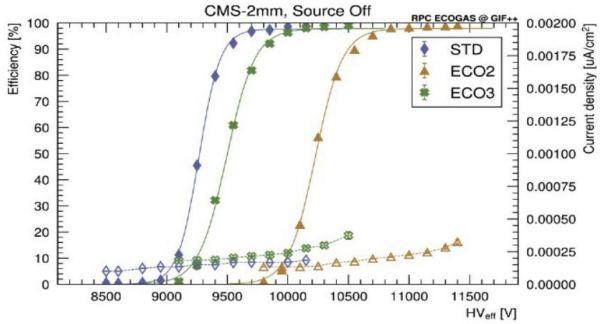
- **PFA Support:** Precise timing improves separation of overlapping hadronic showers.
- **MRPC Transition:** Shifting to Multi-gap RPCs for 50-70 ps resolution and high-rate capability.
- **Manufacturing:** A novel, cost-effective production method developed in Lyon.

Electronics & Eco-friendly Gases

- **ASIC Evolution:** Upgrading from HR2 to Petiroc, and ultimately to Caloroc (full timing, TDC, and continuous readout).
- **Green Gases:** Eco-friendly gas alternatives (HFO1234, NOVEC) to replace R134a and SF6.

Advanced High-Rate Materials

- **Low-resistivity Glass:** Excellent rate capabilities, currently facing engineering challenges in thickness and scale (Tsinghua U.).
- **Low-resistive PEEK:** Innovative polymer reaching optimal resistivity (10^9 Ohm.cm) with R&D on homogeneity (IP2I-Lyon).



Efficiency vs Effective High Voltage

ECO-gas mixtures performance comparison.

Mixture	$C_2H_2F_4$ [%]	HFO [%]	CO_2 [%]	iC_4H_{10} [%]	SF_6 [%]	tCO_2e
STD	95.2	0	0	4.5	0.3	3384
ECO3	0	25	69	5	1	762
ECO2	0	35	60	4	1	763

Eco-friendly Gas Mixtures

Reduction of CO2 equivalents using alternative mixtures.

MPGD for calorimetry

The High-Rate Calorimetry Solution

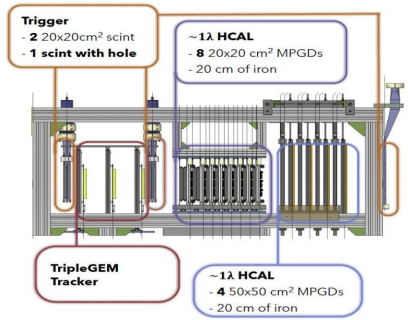
- **Endcap Suitability:** MPGDs (Micromegas) are crucial for high-flux Endcap regions.
- **Performance:** Stable operation at extreme particle rates (> 1 MHz/cm²) with excellent spatial resolution.

Technological Evolution (Micromegas)

- **First Generation:** LAPP developments with standard MM and HR ASIC achieved a very low charge threshold (few fC).
- **Second Generation:** Current detectors incorporate resistive anodes for robust spark protection.

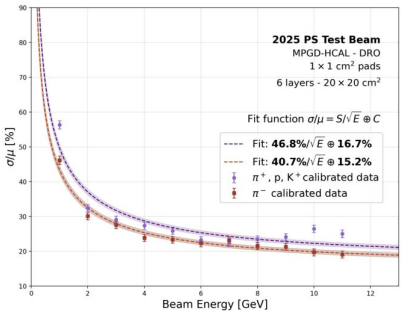
Energy Resolution: Digital vs. Semi-Digital

- **Digital Read-Out:** Suffers from saturation, plateauing at ~20% resolution for hadron energies > 40 GeV.
- **Semi-Digital (SRDO):** Multi-threshold SRDO overcomes saturation, delivering superior performance.
- **SRDO Resolution:** σ/E = 46% / √E ⊕ 12%



Test Beam Setup

Active detector elements and trigger configuration.



Energy Resolution Curve

Resolution as a function of beam energy.

Bunch spacing regime

Proposed Technologies & Current Capabilities
The current candidate technologies for the muon sub-systems are μ-RWELL, MicroMegas, TGC, drift tubes, RPC, and scintillator strips

- **Tagging systems:** Rely mainly on RPC and scintillator strips, which can provide a time resolution of approximately 300 ps
- **Tracking systems:** Rely on the remaining technologies, which achieve a time resolution of about 10 ns

Feedback on Bunch Spacing Regimes

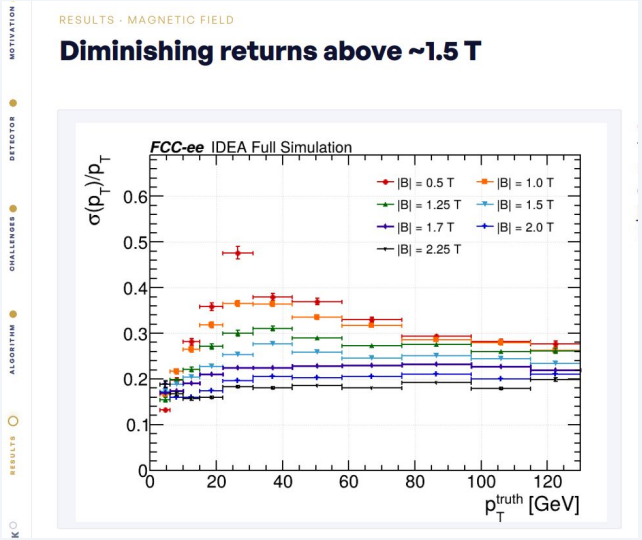
- **Fully compatible regime (> 10 ns):** A bunch spacing in this range is fully compatible with all current detector concepts, allowing both tagging and standalone tracking muon systems to operate effectively.
- **Regime necessitating additional instrumentation (1.25 ns to 10 ns):** If a bunch crossing of 1.25 ns is proposed, concepts pointing to a standalone tracking muon system (such as ALLEGRO and IDEA) will be forced to include a dedicated timing layer. It will be mandatory to pair the tracking detectors (e.g., μ-RWELL, MicroMegas, drift tubes) with RPCs or scintillator strips. This will be highly demanding in terms of budget and detector integration, as these concepts will need to implement both tracking and timing sub-systems
- **Very challenging regime (< 1.0 ns):** Spacings significantly below 1.0 ns would make bunch-crossing assignment really demanding and this has to be proven. RPC and scintillator strips could provide a time resolution around 300 ps.

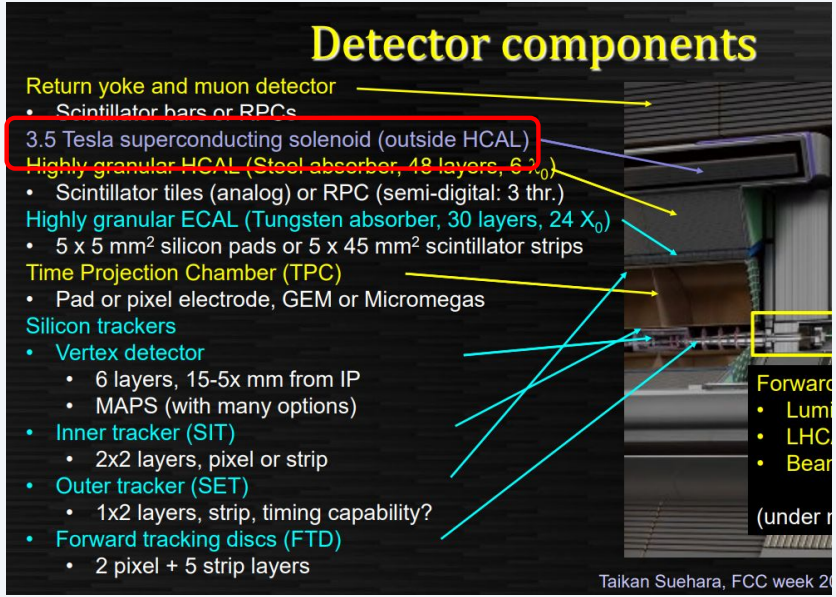
Even with “perfect” timing, how do we know from which bunch crossing signal came in otherwise empty event?

Trackers mainly for LLPs. How would we anyway be able to assign to BX for otherwise empty event?

It has to be considered cluster time resolution and not single station time resolution. This values should be updated. i.e. in CMS 8 layers of drift tube can achieve 5ns time resolution even with Ar:CO2 gas mixture.

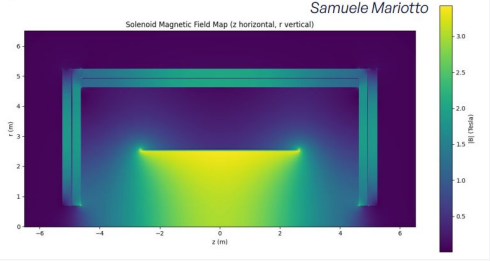
Magnetic field





The magnetic field inside the solenoid will be 2 or 3 Tesla, but the reversed field outside will be less (where the muon system lives). In this study we use a fixed value of -1.7 Tesla in the muon system.

Samuele Mariotto



- IDEA optimization studies shown an improvement from 22% dpt/pt (2T) to 18% (3T)
- ILD reports a 3.5T solenoid (to be clarified)

LLPs/HNLs/ALPs and other BSM searches

Rebeca Gonzalez Suarez

Existing HNL results



Notes in CDS - For the Feasibility study

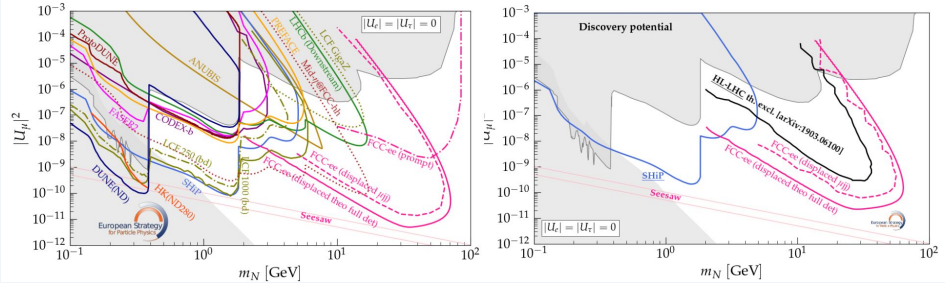
- Searching for type I seesaw mechanism in a two Heavy Neutral Leptons scenario at FCC-ee
  - https://repository.cern/records/xxdz5-1kg14 arXiv:2410.03615 — llν, displaced and prompt (realistic HNL)
- Updated studies on the sensitivity of FCC-ee to heavy neutral leptons coupling to electrons at the Z-pole run
  - https://doi.org/10.17181/jcwpj-nsk15 — eeν, displaced
- Measuring the parameters of an HNL model at FCC-ee
  - https://doi.org/10.17181/xee7v-h4y88 — μνjj, displaced (properties)
- Searches for Heavy Neutral Leptons at FCC-ee in final states including a muon
  - https://doi.org/10.17181/x50tr-mft25 arXiv:2503.19464 — μ+μ−νν and μνjj, displaced and prompt
- Search for HNL at FCCee, and comparisons between Fast and Full Simulation
  - https://doi.org/10.17181/69wjb-k4y74 — llν, displaced and prompt (full simulation!)
- Probing Heavy Neutral Leptons in the semi-leptonic channel with evjj final state at the FCC-ee using Machine Learning Techniques
  - https://doi.org/10.17181/k1enk-ezg43 — evjj, displaced (ML)
- Timing-based mass measurement of exotic long-lived particles at the FCC-ee
  - https://repository.cern/records/7gmk9-hay55 arXiv:2406.05102 — μνjj, displaced (timing)
- Sensitivity of the FCC-ee to HNLs decaying to muon pairs and neutrinos
  - https://repository.cern/records/krn1s-h6w79 — μ+μ−νν, displaced

Looking at discovery

The potential of FCC-ee goes beyond exclusion

How much lumi for exclusion? How much for observation?

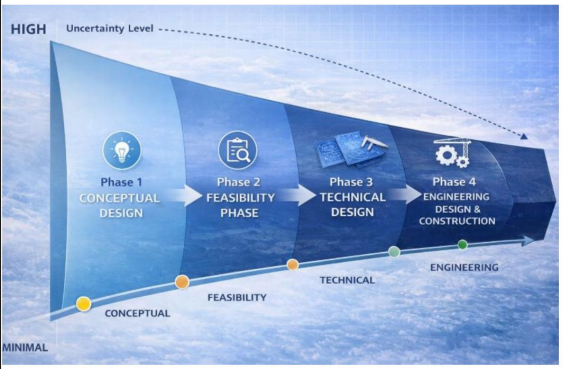
- Stats and clean environment → more than enough to think about observation and measurements of properties if HNLs exist in the accessible phase space



FCC Status & Plans for Reference Design Phase

[Michael Benedikt and Frank Zimmermann]

From Feasibility Study to Project Realisation

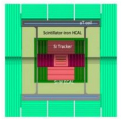


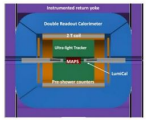
- Following the positive assessment of the Feasibility Study and Council approving the continuation, the FCC moves towards technical design.
- Expertise across CERN and from collaboration partners is required to be able to deliver an integrated technical design, with cost estimate and schedule, taking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

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

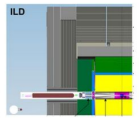
Physics, Experiments, Detectors - objectives

- Continue developing the **international high-energy physics community**
- Consolidation of the **interaction region layout, detector integration,** and **beam-background** mitigation
- Optimised **procedures for √s calibration** & possible **monochromatic operation at √s = 125 GeV**
- Finalising common **software/analysis framework** and developing **common computing architecture**
- Realistic studies of **experimental systematic uncertainties** for some **EW precision** measurements and consolidation of the **pertaining requirements** on collider, detectors, and theory
- **Engagement of theory community** to address theory challenge and nurture the young generation
- Proposal for staging implementation and improvements of the **staged/descoped FCC-ee**
- **Prepare** to answer call for (at least 4) **documented EoI's for FCC-ee experiments end 2028**


CLD


IDEA


ALLEGRO



ILD

ALFA

etc.

Priorities for the next phase

PED priority items in the pre-TDR phase

1. Lay the foundations for the conceptual design studies of four (or more) detectors
2. Consolidate IR layout, detector integration, and related background mitigation
3. Complete the software & analysis toolkit to ease detector performance evaluation
4. Collaborate with IT to develop a computing architecture model for experiments
5. Confirm, with full analyses, the current uncertainty estimates on EWPOs (Z and W)
6. Gather the worldwide theory community to address the theoretical challenges
7. Streamline and optimise the procedure for centre-of-mass energy calibration
8. Develop an efficient PED Education/Communication/OutReach/InReach strategy
9. Ascertain the detector cost estimate
10. Articulate the physics case, feasibility, and schedule implications of other $\sqrt{s}$ stages

FCC Master Schedule

