# The μ-RWELL technology for the IDEA Muon System




**R. Farinelli**
on behalf of INFN – MUON IDEA group

# Muon system tasks at IDEA

The most important physics measurements will be performed by the central tracker.

**Basic assumption (not yet decided):*** triggerless / software-based event selection
→ All relevant physics events stored for offline analysis with ~100% efficiency
(Z peak: 40 MHz bunch crossing rate, ~100 kHz interaction rate)

The **muon system complements the tracker and calorimeters** by providing muon identification, background suppression, sensitivity to long-lived particles, and calorimeter leakage recovery.

**Muon system tasks:**
- High-efficiency identification of penetrating muons at large radius with low fake rate
- Support for particle-flow reconstruction and calorimeter leakage recovery (tail catcher role)
- Rejection of hadron punch-through from the calorimeter
- Sensitivity to long-lived particle decays outside the central tracker
- Good tracking capability for Long-lived particle signature

(*) https://indico.cern.ch/event/1408515/contributions/6521330/attachments/3073372/5437820/jb_FCCee_TDAQ_22may25.pdf

# Muon system tasks at IDEA (Physics drivers)

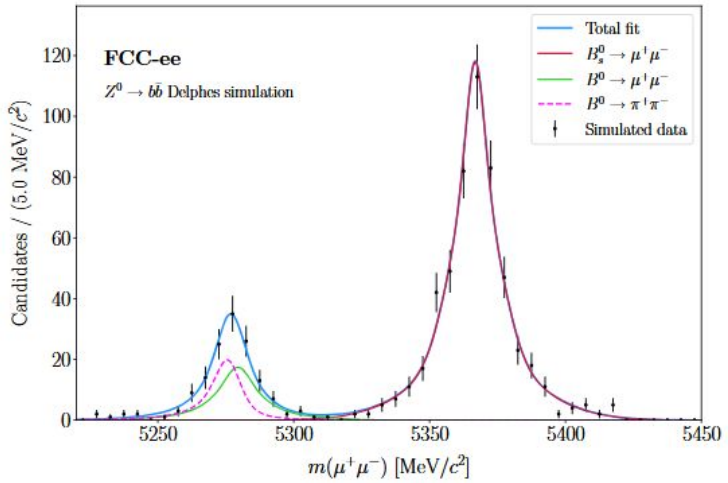
## Precision electroweak & Higgs physics

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

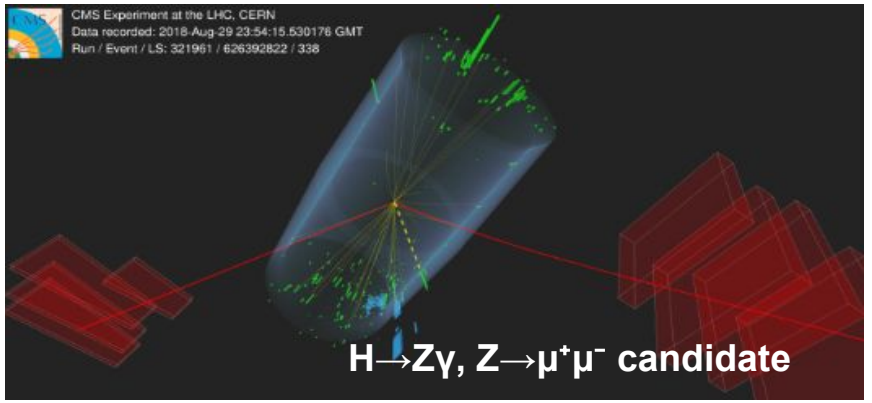
**Typical signatures**
- Isolated prompt muons
- Clean dimuon final states

**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 tasks at IDEA (Physics drivers)

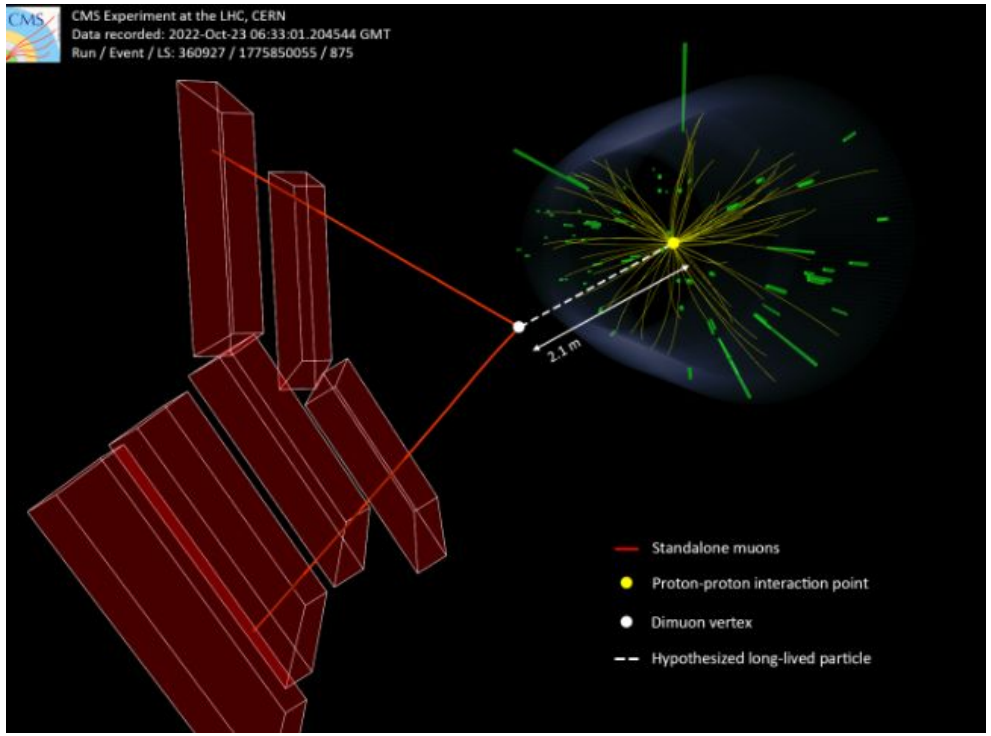
## Long-lived particle searches

**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

# The IDEA Muon System: Simulation

# Simulation campaign for standalone muon reconstruction

Over the past year, a comprehensive simulation campaign has been carried out to optimize the IDEA muon system for standalone track reconstruction(*)

## Simulation campaign

- **12 detector layouts evaluated**
  - Number of Layers $N_{lay}$: 3, 4, 5, 6
  - Yoke thickness: 10–50 cm per gap
  - Magnetic field $B$: −0.5 to −2.25 T
  - Hit resolution $\sigma_{hit}$: 50–1000 µm
- **Reference configuration:** $B = 1.7$ T & $\sigma_{hit} = 400$ µm & $\varepsilon_{\text{layer}} = 98\%$

All detector layouts are reconstructed using the same standalone tracking algorithm.

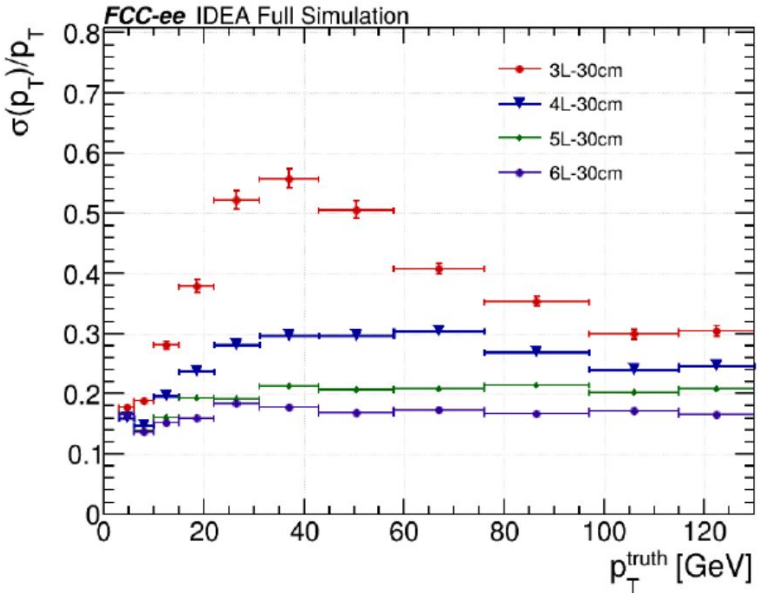


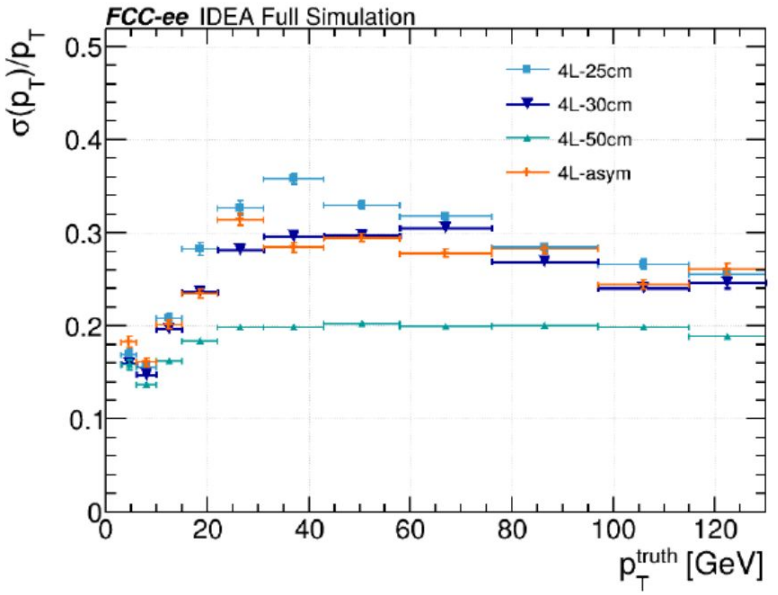

**Gray:** µRWELL stations; **Red:** iron yoke; **Frame color:** detector family (3L, 4L, 5L, 6L, asymmetric)

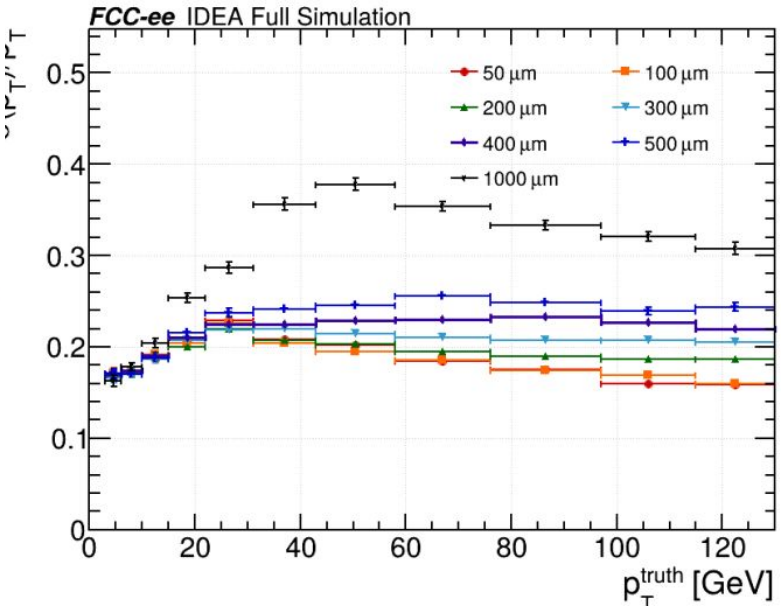
A full simulation and reconstruction framework has been developed to quantify the impact of detector geometry and detector performance on standalone muon reconstruction

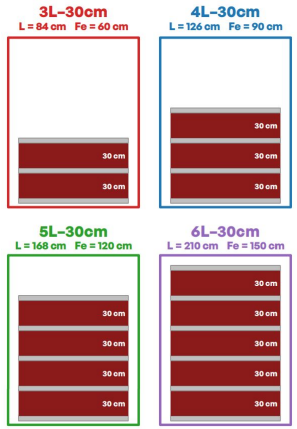
[*] Optimization of the IDEA Muon System for standalone track reconstruction at FCC-ee

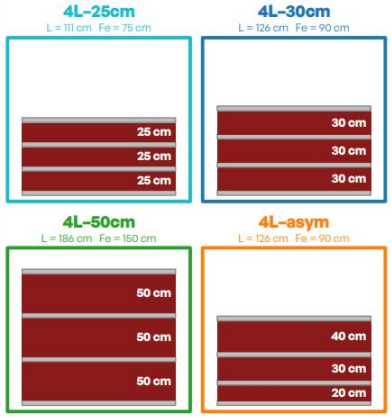
# Simulation campaign for standalone muon reconstruction

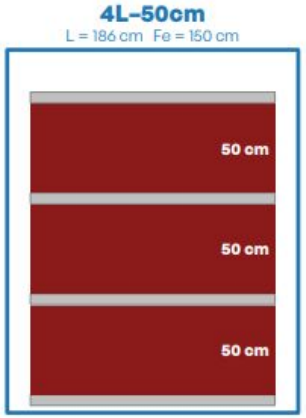



[*] Optimization of the IDEA Muon System for standalone track reconstruction at FCC-ee

# Current status of the standalone muon-system optimization

The simulation framework is now mature enough to identify the main detector-performance drivers. Further optimization is ongoing, but the current studies already provide clear design indications.

| Parameter | Current conclusion |
|---|---|
| Spatial resolution | Achieving $\sigma_{x'y}$ < 200 μm provides a more precise determination of the track sagitta ; multiple scattering dominates below 20 GeV. |
| Iron yoke thickness | Thicker iron increases multiple scattering and degrades momentum resolution. An optimal balance with the magnetic lever arm is required. |
| Number of layers | More layers improve momentum resolution and reconstruction redundancy. Current studies indicate that **4 layers** already provide most of the performance. |
| Magnetic field | Stronger magnetic field improves momentum resolution, especially at high momentum. |

🟢 **Status**
✔ Simulation framework validated
✔ Main detector parameters scanned
✔ Preliminary detector optimization achieved
🔄 Reconstruction algorithm under optimization
🔄 Full detector integration studies ongoing

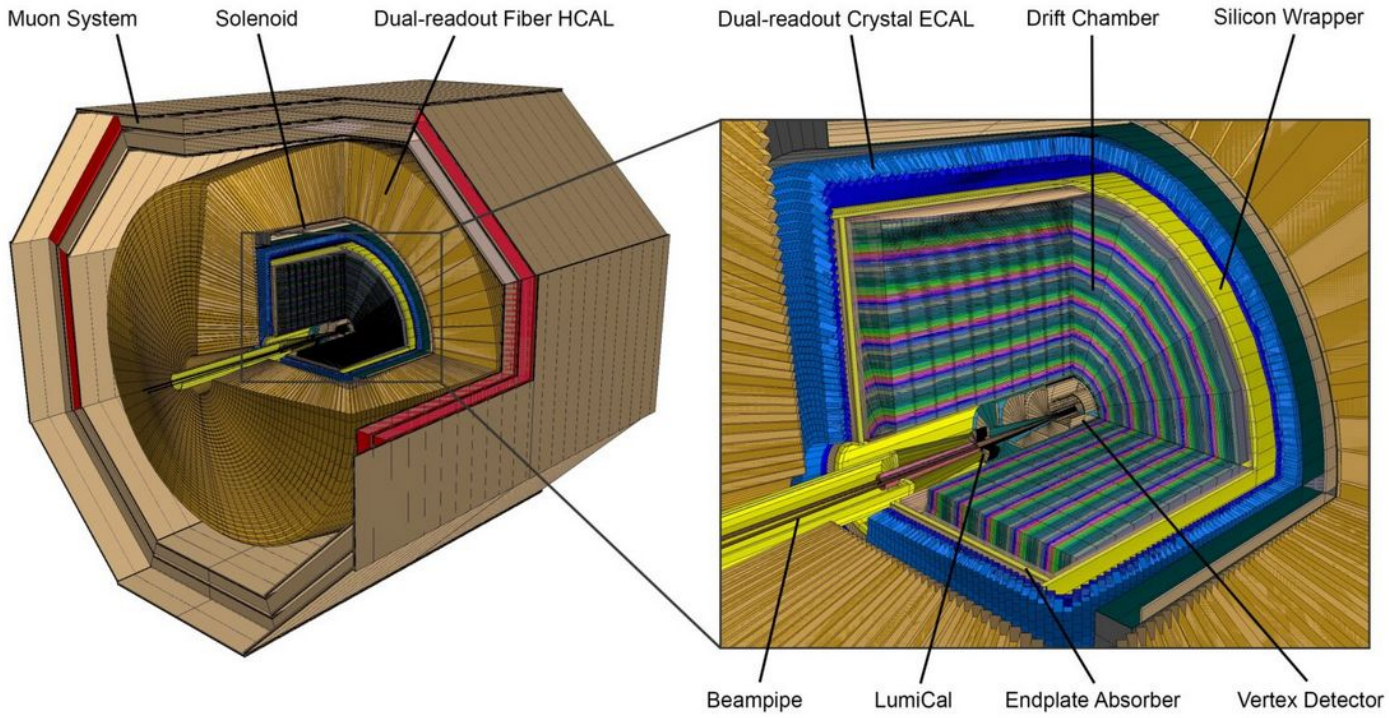
**The present studies indicate that a μRWELL-based muon system with <200 μm spatial resolution and 4 detector layers can already satisfy the standalone reconstruction requirements. Further optimization of the detector layout and reconstruction algorithm is in progress.**

# Muon system (detector drivers)

**Muon system in IDEA** are designed to be instrumented with **μ-RWELL technology(*)**

**Detector requirements:**

- Efficiency ≥ 98%
- **Space resolution ≤ 200 μm**
- Particle Flux < 1kHz/cm$^2$
- **Instrumented Surface/FEE: 2900 m$^2$ (11600 det.),**
  **~5×10$^6$ ch. (<1000 ch/detector)**
- **Mass production -> Technology Transfer to Industry**
- FEE Cost reduction -> custom made ASIC
  (based on TIGER[**] or the new TORA CHIP[***])




**Key parameters for next-generation muon detectors: high spatial resolution, minimized FFE channels, scalable mass production.**

[*] "The IDEA detector concept for FCC-ee", arXiv:2502.21223 [physics.ins-det]
[**] The CGEM-IT readout chain . 2021 JINST 16 P08065
[***] Development of new large area micromegas detector and its tora ASIC-based readout electronics for AMBER experiment at CERN

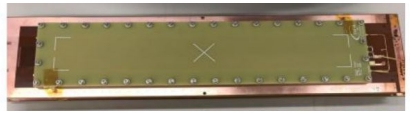
# The IDEA Muon System: Detector & Transfer to Industry

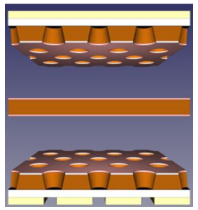
# u-RWELL R&D History

1D Layout optimization | 2D layouts optimization | ACD μ-RWELL

New u-RWELL ideas (in collaboration with RD51)

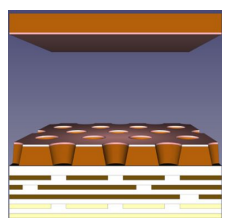


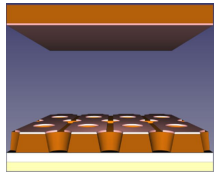




2x1D layout

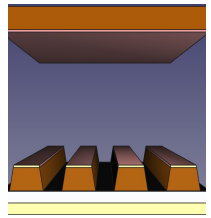
Cap.Sharing layout

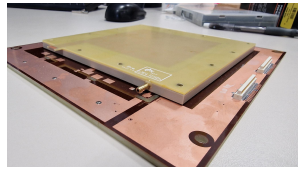




TOP layout

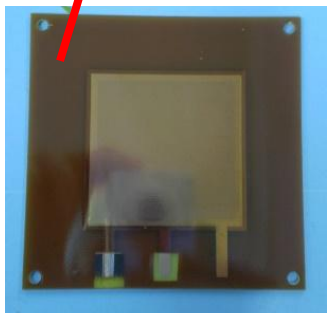
μ-RGroove layout





R&D for FCC start

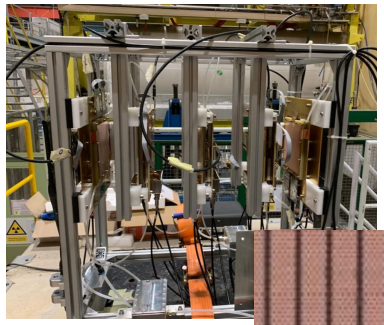
2009 2020 2021 2022 2023 2024 2025 2026

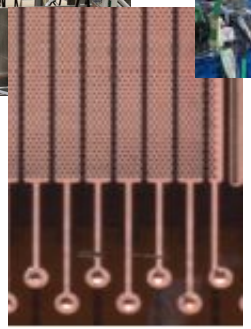


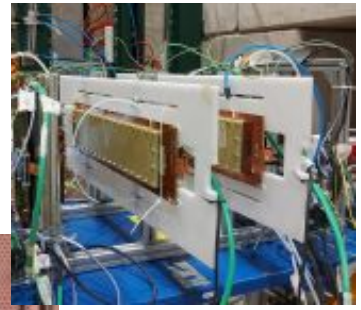
IDEA slice test: DC + pre-shower + dual_calo + muon





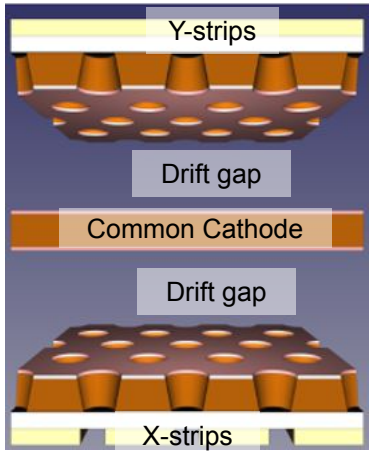







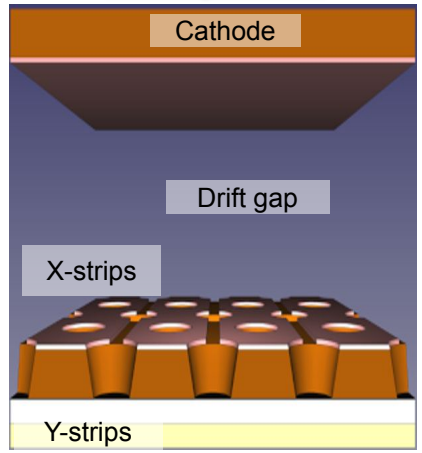
# Overview of Tested 2D Detector Layouts

**2×1D Layout**



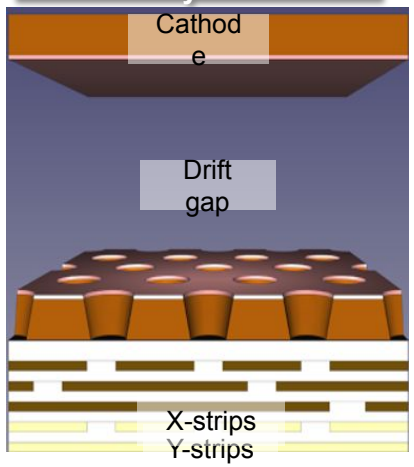

Lower gas gain w.r.t. the "COMPASS R/O" (X / Y are not sharing any charge)
Pitch strip: 0.8 mm

**Top R/O Layout**



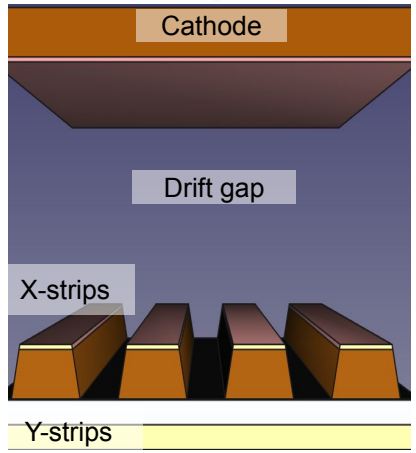

Lower gas gain w.r.t. the "COMPASS R/O" (X / Y are not sharing any charge)
The "Top" coordinate introduces dead zone in the active area
Pitch strip: 0.4 mm

**Capacitive Sharing [*] Layout**




Reduce the FEE channels
The charge is divided between X and Y → Higher gas gain required w.r.t. 1D
Pitch strip: 1.2 mm

**μ-RGRoove (**) Layout**

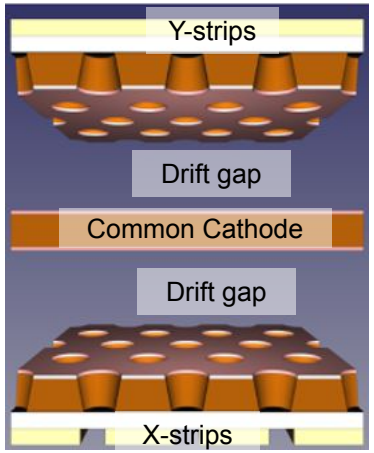



Lower gas gain w.r.t. the "COMPASS R/O" (X / Y are not sharing any charge)
No dead zone w.r.t the Top R/O layout
Pitch strip: 0.4 mm

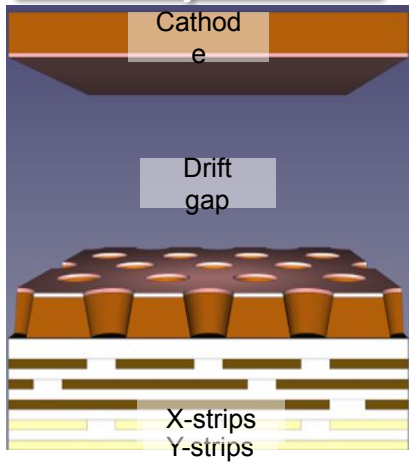

[*] K. Gnanvo et al., NIM A 1047 (2023) 167782
[**] T. Xiangqi et al., 2024 *JINST* 19 P07031
R. Farinelli *et al* 2025 *JINST* **20** C06064

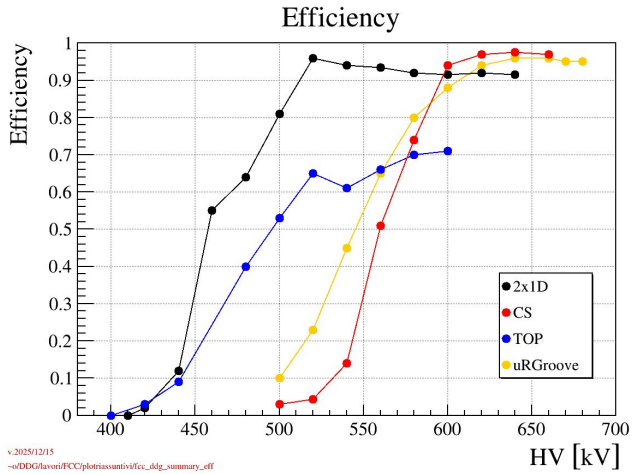
# Overview of Tested 2D Detector Layouts

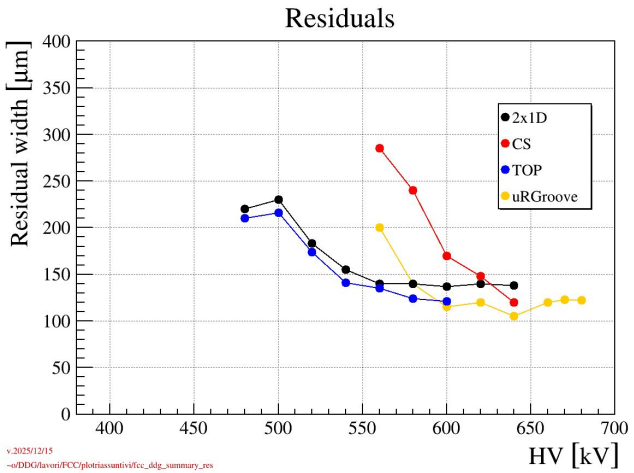
**2×1D Layout**




**Capacitive Sharing [*] Layout**

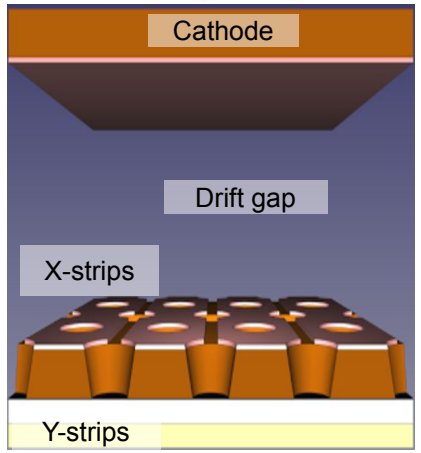


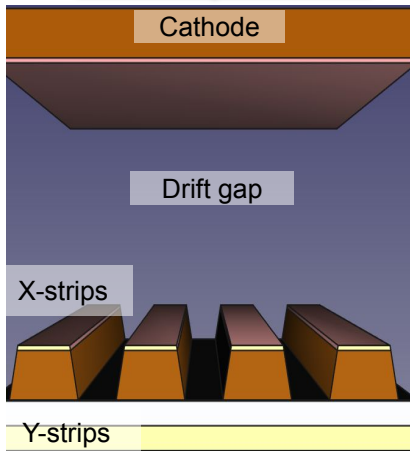




Results evaluated with APV25/SRS

**Top R/O Layout**




**µ-RGRoove (**) Layout**





[*] K. Gnanvo et al., NIM A 1047 (2023) 167782
[**] T. Xianggi et al., 2024 *JINST* 19 P07031
R. Farinelli *et al* 2025 *JINST* **20** C06064

# Readout segmentation drives the FEE channel count

**Detector Size: 50 x 50 cm2 – Muon system 4 layers total surface: 2900 m2**

| Readout | Pitch [cm] | Spatial Resolution | FEE channels/tile | Tot channels | Tested |
|---|---|---|---|---|---|
| PAD | 0.5 | ~200 μm | 10000 | **115 M** | Tested by other group |
| PAD | 1 | ~350 μm | 2500 | **30 M** | Tested by other group |
| 2D STRIP | 0.04 | ~100 μm | 2500 | **30 M** | Tested by us |
| 2D STRIP | 0.12 | <150 μm | 840 | **10 M** | Tested by us |
| 2D STRIP | 0.2 | <150 μm | 500 | **6 M** | **New Layout** |

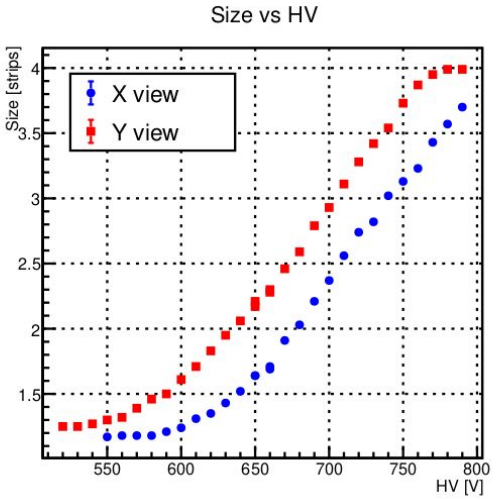
For the same detector area, **2D STRIP R/O** provide a much more favorable scaling of the channel count than **PAD R/O**

**2D STRIP readout can reduce the total FEE channel count from ~30 M to ~6 M while maintaining ~100–150 μm spatial resolution.**

# Proposed 2D Detector Layout

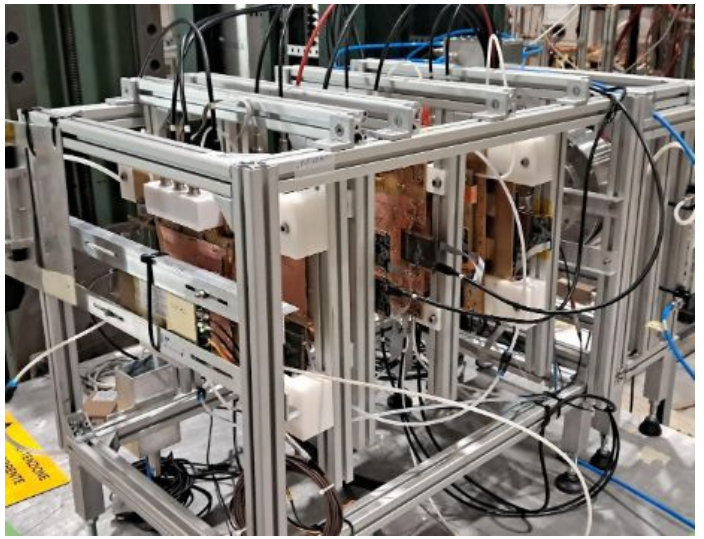
**ACD µ-RWELL**: µ-RWELL with improved **A**dvanced **C**harge **D**ispersion

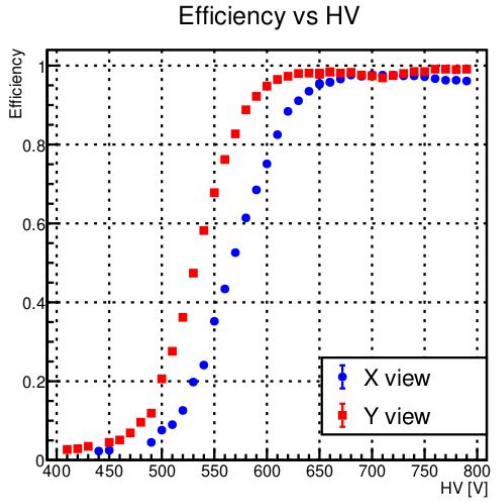
- **First DLC layer** with high resistivity (ρ=100 MΩ/•) for **higher spark quenching, detector stability**
- **Second DLC layer** with low resistivity (ρ< 1 MΩ/•) for **signal spreading**




**ACD µ-RWELL – First 2D prototype test (May '26)**

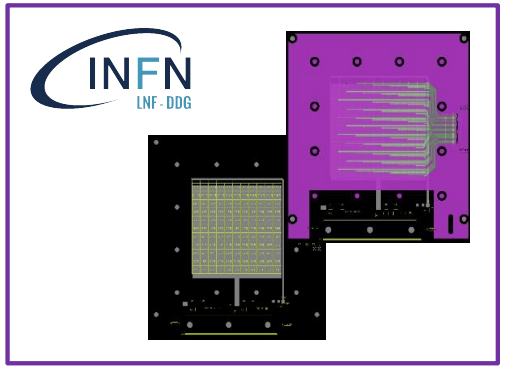
- First A**CD µ-RWELL prototypes** with 2D readout successfully built and tested at SPS-H8 beamline
- Production issue: second foil **resistivity ≈ 20 MΩ/□** (non-optimal condition)
- Despite this, the **Charge Dispersion mechanism was clearly confirmed** with TIGER/GEMROC and APV/SRS
  → results consistent with expectations
- Overall performance was very encouraging
  → **strong support for further R&D development**





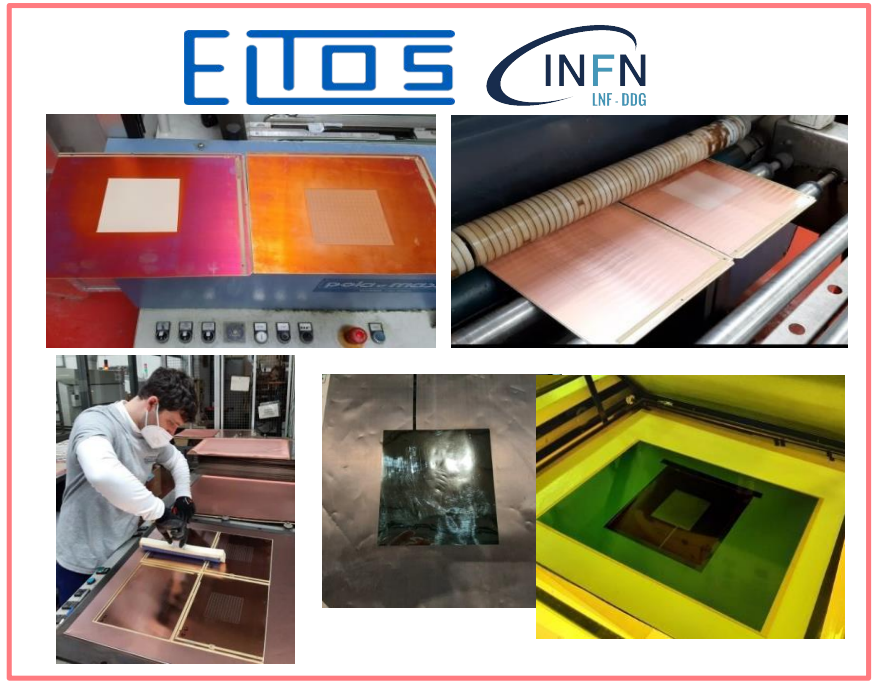
# Technology Transfer

**LAYOUT design**

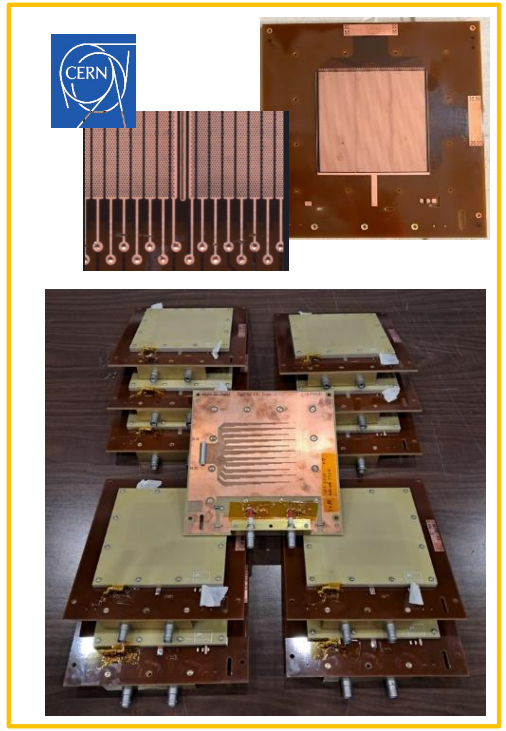



**Feedback from tests**

**PCB production**




**Final detector manufacturing**




**DLC foil production[*]**




**[*] DLC Magnetron Sputtering machine co-funded by INFN- CSN1**

**The TT project, originally part of the EU Horizon 2020 program under AIDAInnova, is now moving forward under the new European initiative, OTELLO, taking its next steps towards innovation**

G. Bencivenni et al., "Milestone Report WP7.3.2", AIDAinnova- MS27

# Summary & Outlook

## 1. Physics Motivation & Detector Requirements

- **Precision Physics & LLP:** Excellent performance required for EW precision measurements and Long-Lived Particle searches at future colliders.
- **Simulation Guidance:** Detailed simulation studies optimized key detector parameters:
  - **Number of Layers:** Standardized to **4 layers**.
  - **Iron Absorber:** Optimized thickness for tracking between **30-50 cm**
  - **Spatial Resolution:** Target range set to **~200 µm**.

## 2. Technology Choice: 2D Strip Readout

- **Channel Scaling:** 2D Strip readout drastically reduces Front-End Electronics (FEE) channels compared to Pad readout:
  - Scaled down from **~30M (Pad)** to **~6M channels (2D Strip)** for a 2900 m² surface.
- **Cost & Complexity:** Cost-effective solution without compromising spatial resolution (**<150 µm** achieved).
- **Tested Layouts:** Validated across multiple 2D layouts (2x1D, CS, Top R/O, µ-RGroove, ACD).

## 3. ACD µ-RWELL Prototype Results

- **Advanced Charge Dispersion (ACD):** Double-DLC architecture for enhanced spark quenching & signal spreading.
- **Beam Test Validation (May '26):** First 2D ACD µ-RWELL prototypes tested at SPS-H8 beamline.
- **Key Outcome:** Confirmed Charge Dispersion mechanism even with non-optimal foil resistivity (~20 MΩ/□).
- **Outlook:** Performance provides strong support for further R&D.

## 4. Technology Transfer & Future Steps

- **Industrial Synergy:** Complete production chain established covering DLC sputtering, PCB manufacturing, and final detector assembly.
- **European Framework:** Transitioned from EU Horizon 2020 (AIDAinnova) to the new European initiative **OTELLO**.
- **Next Milestones:** Scale up manufacturing for large-area detectors and optimize DLC foil uniformity for full-system integration.

The working group:

M. **A**li, G. **B**encivenni, D. **C**abiati,
F. **C**hiapponi, C. **C**ibinetto, E. **D**e Lucia,
E. **D**i Fiore, D. **F**alchieri, **R. Farinelli**,
M. **G**atta, P. **G**iacomelli, M. **G**iovannetti,
G. **F**elici, M. **G**reco, F. M. **M**elendi,
G. **M**ezzadri, G. **M**orello, M. **P**oli Lener,
M. **S**codeggio



# BACKUP

RESULTS · COST & SCALE

# µRWELL chamber count per configuration

| CONFIGURATION | BARREL | ENDCAP (+Z) | Simulation & optimization | TOTAL |
|---|---|---|---|---|
| 3L–30cm baseline | 4 424 | 1 392 | 1 392 | **7 208** |
| 3L–50cm | 4 504 | 1 608 | 1 608 | **7 720** |
| 4L–25cm | 5 872 | 1 952 | 1 952 | **9 776** |
| 4L–30cm | 6 024 | 2 144 | 2 144 | **10 312** |
| 4L–50cm Good Candidate | 6 480 | 2 560 | 2 560 | **11 600** |
| 5L–30cm | 7 912 | 3 040 | 3 040 | **13 992** |
| 6L–25cm | 9 520 | 3 840 | 3 840 | **17 200** |
| 6L–30cm low fakes | 9 984 | 4 032 | 4 032 | **18 048** |
| 4L–asym | 5 872 | 2 144 | 2 144 | **10 160** |
| 6L–asym | 9 780 | 3 936 | 3 936 | **17 652** |
| 6L–paired | 8 608 | 3 120 | 3 120 | **14 848** |
| 6L–paired–50cm | 9 280 | 3 456 | 3 456 | **16 192** |



Placed µRWELL chambers per configuration, split into barrel and the two endcaps. Total chamber count (and readout channels) scales with the number of stations and the layer radii. **4L-50cm** vs **6L-30cm** : similar resolution, very different chamber/channel counts — the engineering cost axis.

ALGORITHM

# StandaloneMuonTracking — seven steps

**1 · Pre-processing** — crowded layers trimmed to top-N MIP-like hits; optional pair-coincidence filter for doublet geometries.

**2 · Hit clustering** — Union-Find groups spatially connected hits by $\Delta\varphi$ and 3D distance; one-gap bridging tolerates a single inefficient layer.

**3 · Iterative N-hit combinatorial search** — ten pre-filters (layer span, $\Delta\varphi$ window, monotonic z–r, pair distance, isolation, tan $\lambda$, $\chi^2$/NDF…) then a combined score $S_k = \chi^2/\mathrm{NDF} + w\cdot\langle\Delta E_{dep}\rangle/\sigma_E$.

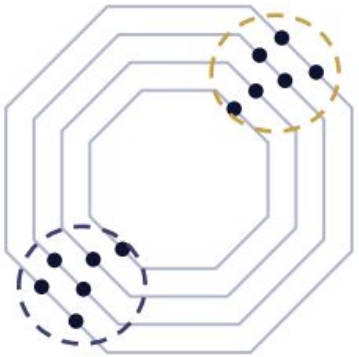
**4 · Outlier rejection** — highest-residual hit iteratively dropped, circle refit, down to the minimum hit count.

**5 · Neighbour-track quality gate** — candidates sharing space with an accepted track face stricter $\chi^2$ & hit requirements; kills ghosts in busy regions.

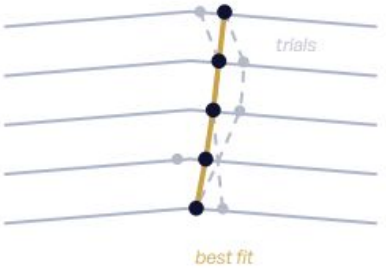
**6 · Track-state computation** — Eigen LSQ circle fit gives ($d_0$, $\varphi_0$, $\omega$); linear z-vs-arclength gives ($z_0$, tan $\lambda$); charge from bend cross-products.

**7 · Inner propagation** — analytical two-segment helix to the perigee, accounting for the B-field sign reversal at the solenoid boundary (Runge–Kutta available for non-uniform maps).

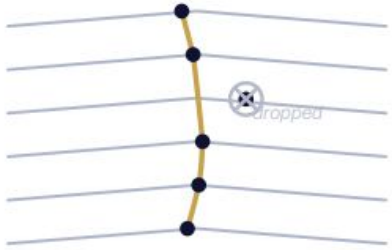
2 · Hit clustering



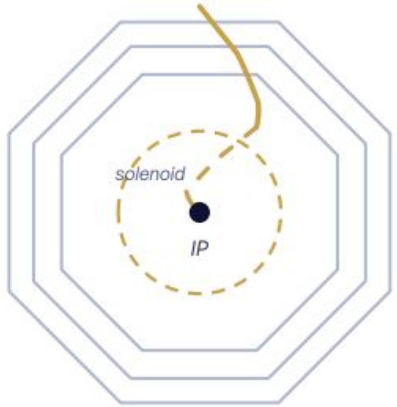
3 · Combinatorial search




4 · Outlier rejection

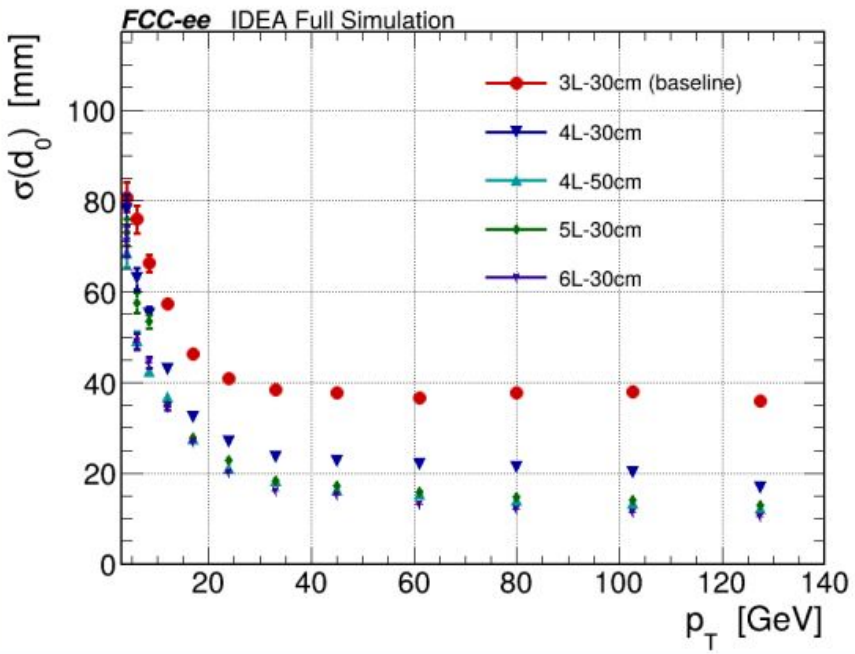


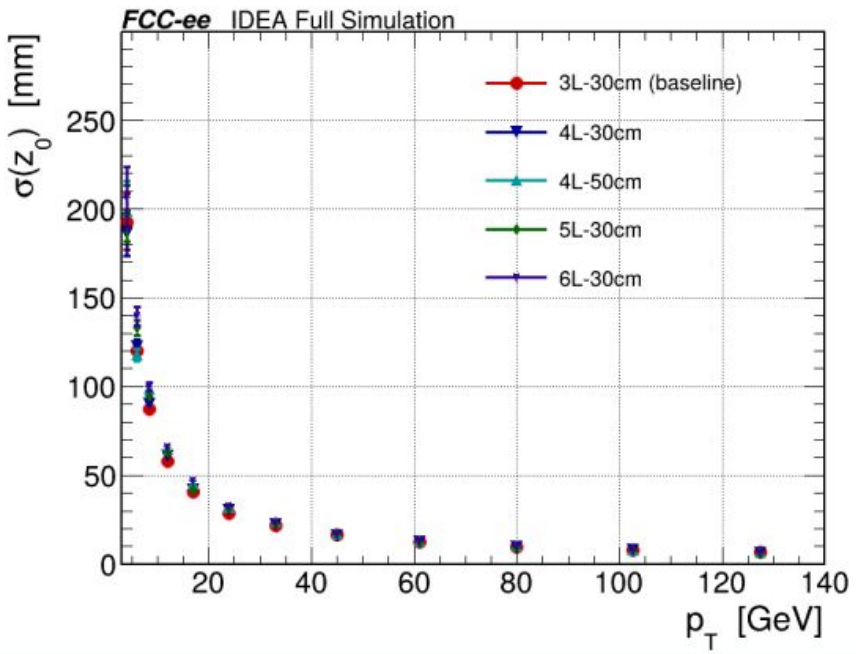

7 · Inner propagation



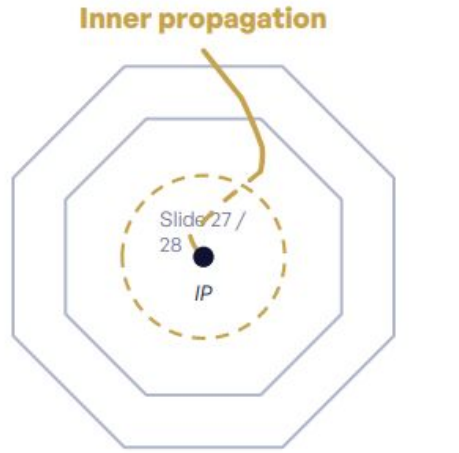
RESULTS · IMPACT PARAMETERS

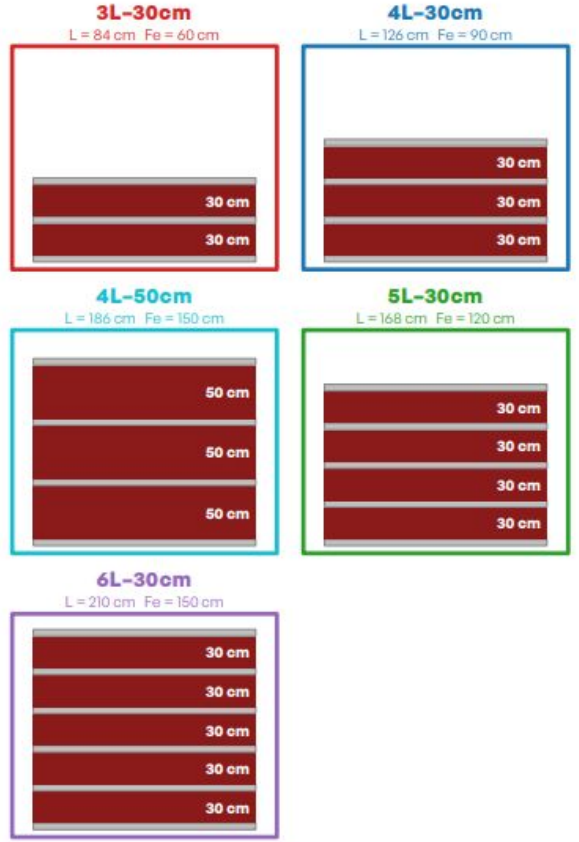
# $d_0$ resolution scales with the lever arm




Gaussian-core $\sigma(d_0)$ (left) and $\sigma(z_0)$ (right) vs truth $p_T$ for 3L-30cm baseline, 4L-30cm, 4L-50cm, 5L-30cm, 6L-30cm, from the 100 k muon-gun sample. $\sigma(d_0)$ ranges **~36 mm (3L)** down to **~13 mm (6L-30cm)**. MCS-limited at low $p_T$; sagitta-limited above ~20 GeV. $\sigma(z_0)$ is largely insensitive to layer count — driven by single-station resolution and dip-angle propagation.



# FCC_ee in pills

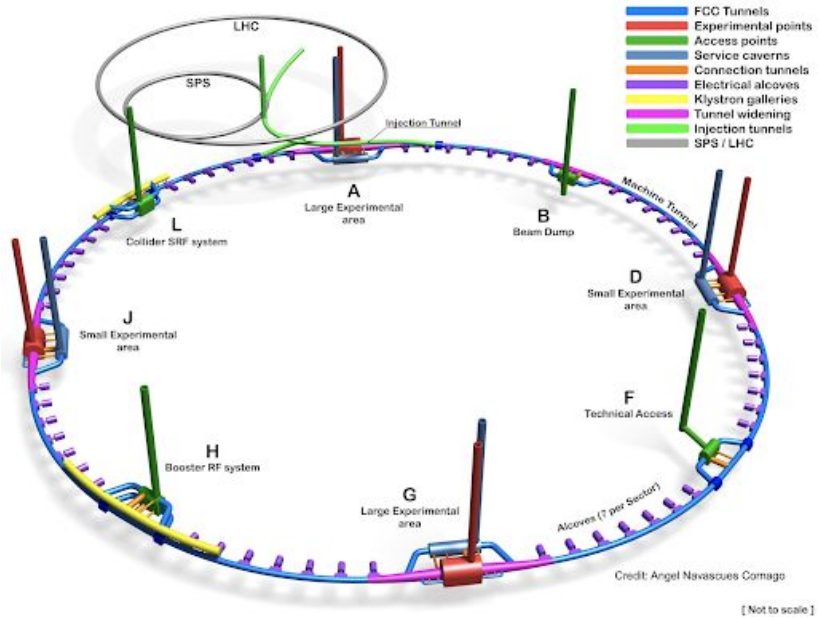
- FCC_ee will operate at 4 different center-of-mass energies:
  - Z pole (90 GeV)
  - WW pole(160 GeV)
  - HZ pole (240 GeV)
  - $\bar{t}t$ pair pole (360 GeV)

- Higher Luminosity (~ **$10^{34} \div 10^{36}$ cm$^{-2}$s$^{-1}$**) and lower rate environment than HL-LHC

- **Precision studies** of Higgs, EW bosons and top quark:
  Detection of isolated muons is similar to that in LEP. Identifying non-isolated muons from hadron decays within jets requires stricter measurements to achieve precision in flavor physics.

- **Exploration** of physics **beyond the Standard Model**:
  High statistics of inelastic electron-positron collisions enable the production of rare processes involving feebly interacting and slow particles.

| 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 | $6 \times 10^{12}$ Z | $2.4 \times 10^8$ WW | $2.2 \times 10^6$ ZH + 65k WW $\rightarrow$ H | $2 \times 10^6$ $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H | |




[1] Future Circular Collider Feasibility Study Report Volume 1 : Physics and Experiments

# Muon physics - Tagging

**Flavour and rare decays**

**The abundant production of beauty and charm hadrons at $Z^0$ pole offers outstanding opportunities in flavour physics that in general exceed those available at Belle II and are complementary or more sensitive to the heavy-flavour programme of the LHC.**

**Rare flavour-changing neutral currents sensitive to new physics**

**Mass resolution and muon identification → crucial for separating close-in-mass states like**

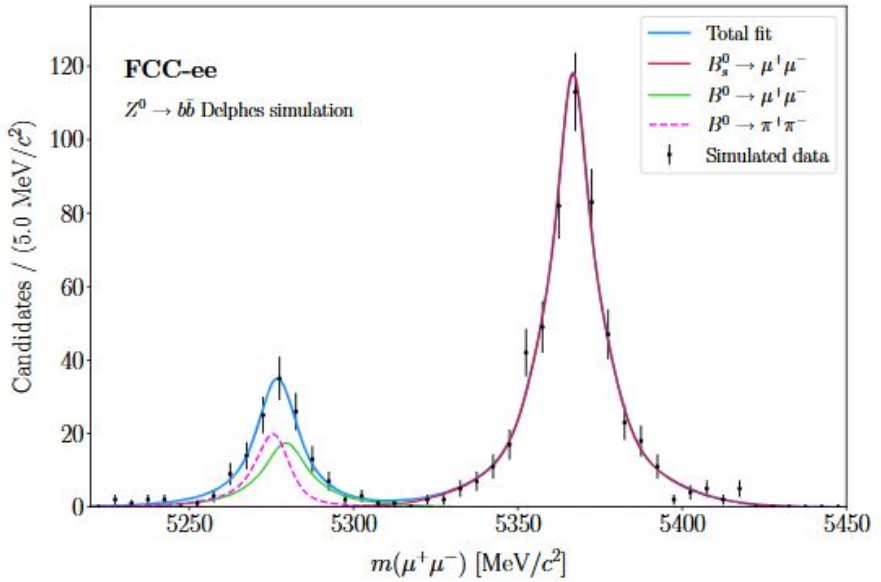
**$B^0$s → $\mu^+ \mu^-$ (5366 MeV/c2)**

**$B^0 \rightarrow \mu^+ \mu^-$(5279 MeV/c2)**

**with their branching fractions □ powerful test of minimal flavour violation**

Advantageous attributes for flavour physics studies at Belle II ($\Upsilon(4S)$), the LHC (pp) and at $Z^0$ pole

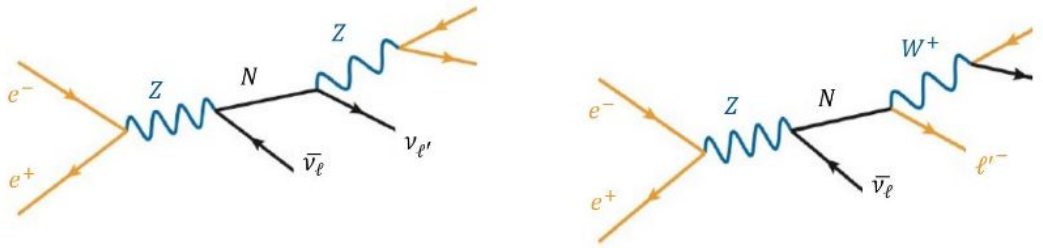
| Attribute | $\Upsilon(4S)$ | $pp$ | $Z^0$ |
|---|---|---|---|
| All hadron species | | ✓ | ✓ |
| High boost | | ✓ | ✓ |
| Enormous production cross section | | ✓ | |
| Negligible trigger losses | ✓ | | ✓ |
| Low backgrounds | ✓ | | ✓ |
| Initial energy constraint | ✓ | | (✓) |





[2] LHCb collaboration, Phys. Rev. Lett. 118, 191801 (2017) [1703.05747]
[3] ATLAS collaboration, JHEP 04, 098 (2019) [1812.03017]
[4] CMS collaboration, JHEP 04, 188 (2020) [1910.12127]
[5] M. Beneke, C. Bobeth, R. Szafron, JHEP 10, 232 (2019)
[6] S. Monteil and G. Wilkinson, Eur. Phys. J. Plus (2021) 136:837

# Muon physics- Tracking

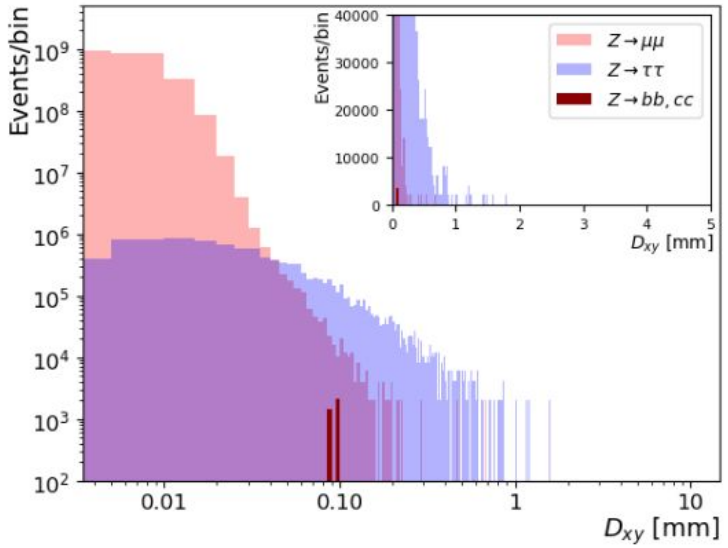



## Heavy Neutral Lepton searches

### Detecting HNLs

- **LLP signature** discrimination due a **clean background**
- **Reconstruction displaced** decays with **precise tracking/ vertixing**
- Sensitive to **low-mass HNLs** (5 ÷ 85 GeV) via rare Z or W decays
  - **Fully leptonic** decay **μ μ $\nu_\mu$**
  - **Semi-leptonic** decay into **μj j'** where j and j' are jets from q q′ pairs coming from the charged vector boson coupling with HNL and muon

Reconstructed transverse distance Dxy between the displaced vertex and the interaction point.




**Background** from heavy-quark **production is strongly suppressed** by the exclusive requirement of **two final-state muons**, while **the τ -induced background** exhibits a tail extending up to **a few millimeters**

[7] L. Bellagamba et al., arXiv:2503.19464 [hep-ex]

# Muon detector challenges

**The requirements (still at a preliminary stage) for the muon system include:**

- **Instrumenting the return yoke outside the coil**
- **High efficiency muon identification > 98% (momentum measured by tracking system)**
- **Serving as tail-catcher for the hadron showers not fully contained in the calorimeter (discr./sep. efficiency lower than 1%)**
- **Standalone momentum measurement for long-lived particles (space res. O(100 $\mu$m))**
- **Rate capability << 1kHz/cm2**
- **Mass production and cost effectiveness**

**Gaseous detectors have historically been favoured for muon detection at colliders like LEP and LHC due to their cost-effectiveness for large areas, high time and position resolution and robustness (RPC, drift-tube, etc).**

**Decades have passed since the last muon apparatus were built, during which significant advancements have been made in detector technologies, particularly in Micro-Pattern Gaseous Detectors (MPGDs):**

- **Micro-Megas and GEM are used for ATLAS and CMS muon detector upgrade in the endcap region to handle the LHC rate**
- **μ-RWELL, an innovative type of gaseous detector, expected to have significantly improved capabilities in high-rate intensity environments such as in LHCb Phase II.**

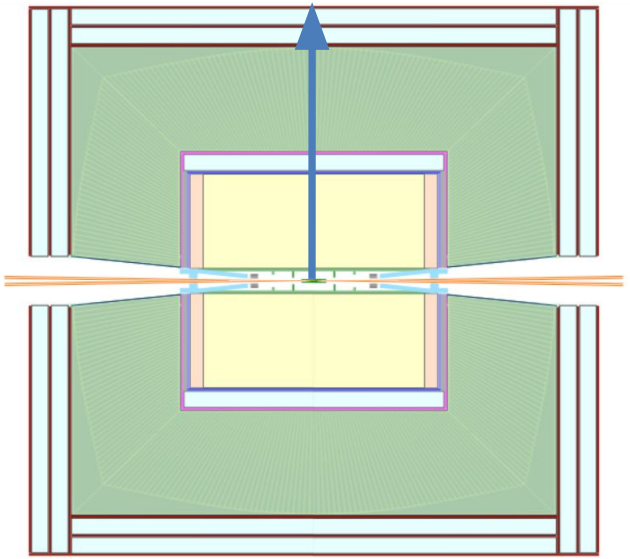
[8] “ATLAS New Small Wheel TDR”, CERN-LHCC-2013-006; ATLAS TDR-020
[9] “CMS Technical Design Report for the Muon Endcap GEM Upgrade”, CERN-LHCC-2015-012 ; CMS-TDR-013
[10] “LHCb Upgrade II Scoping Document”, CERN-LHCC-2024-010 ; LHCB-TDR-026

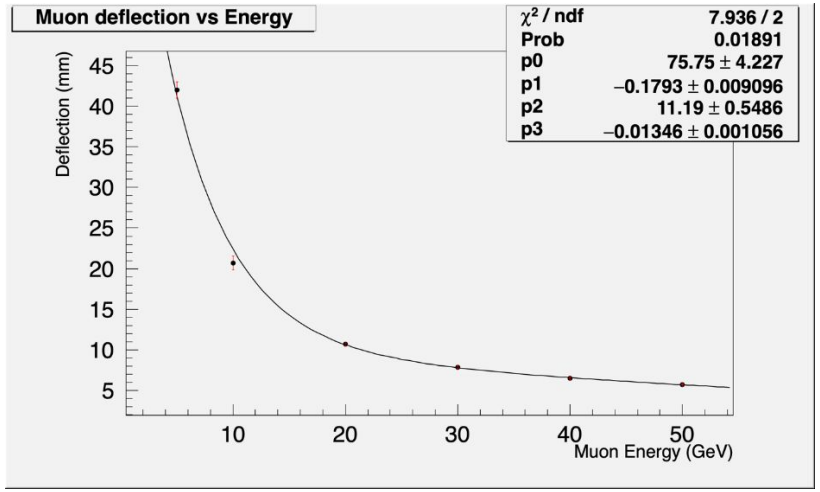
# WP5 2024 -simulation

Study Multiple scattering effect on muon tracks at IDEA Detector environment within DD4hep:

There are several ways to do the study, but the simplest way is:

- Shoot muons from the interaction point in the X-axis perpendicular to the beam-pipe. Direction (1, 0, 0), and monitor the hits in 2D (Y & Z) at the muon first barrel station.



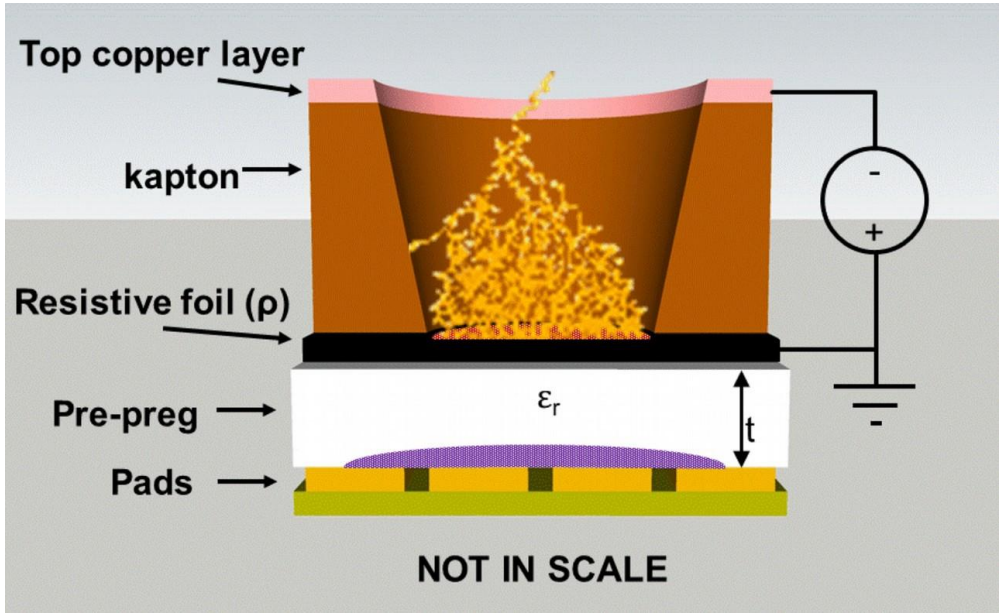



Overall, the energy function against the standard deviation of the track deflection for the first Muon layer.

**Similar study is on going for Long-Lived Particles**

# The μ-RWELL: principle of operation

Applying a suitable voltage between the **top Cu-layer and the DLC** the WELL acts as a **multiplication channell for the ionization** produced in the conversion/drift gas gap.



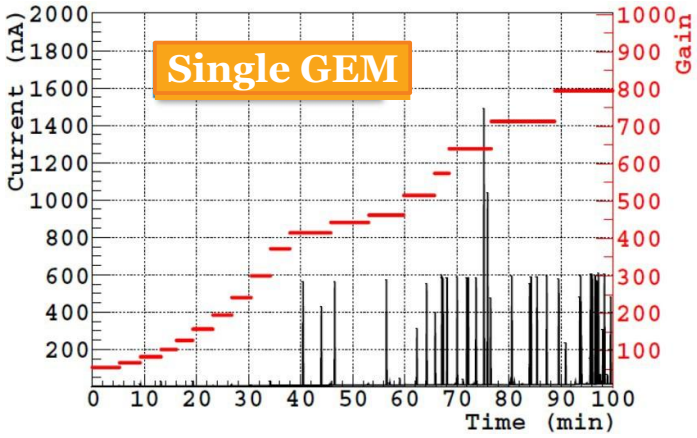

Introduction of the **resistive stage:**

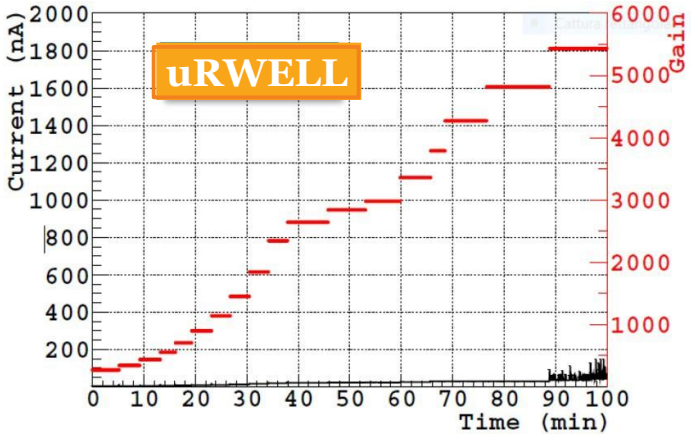
**Pros: suppression of the transition from streamer to spark**

→ Spark amplitude reduction

**Cons:** reduction of the capability to stand high particle fluxes.

But an **appropriate grounding schemes** of the resistive layer solves this problem




Comparison between the **current** drawn by a single GEM and a μ-RWELL at various **gas gain**.

The black spikes are the sparks in the detectors, clearly dumped in the μ-RWELL for higher gains