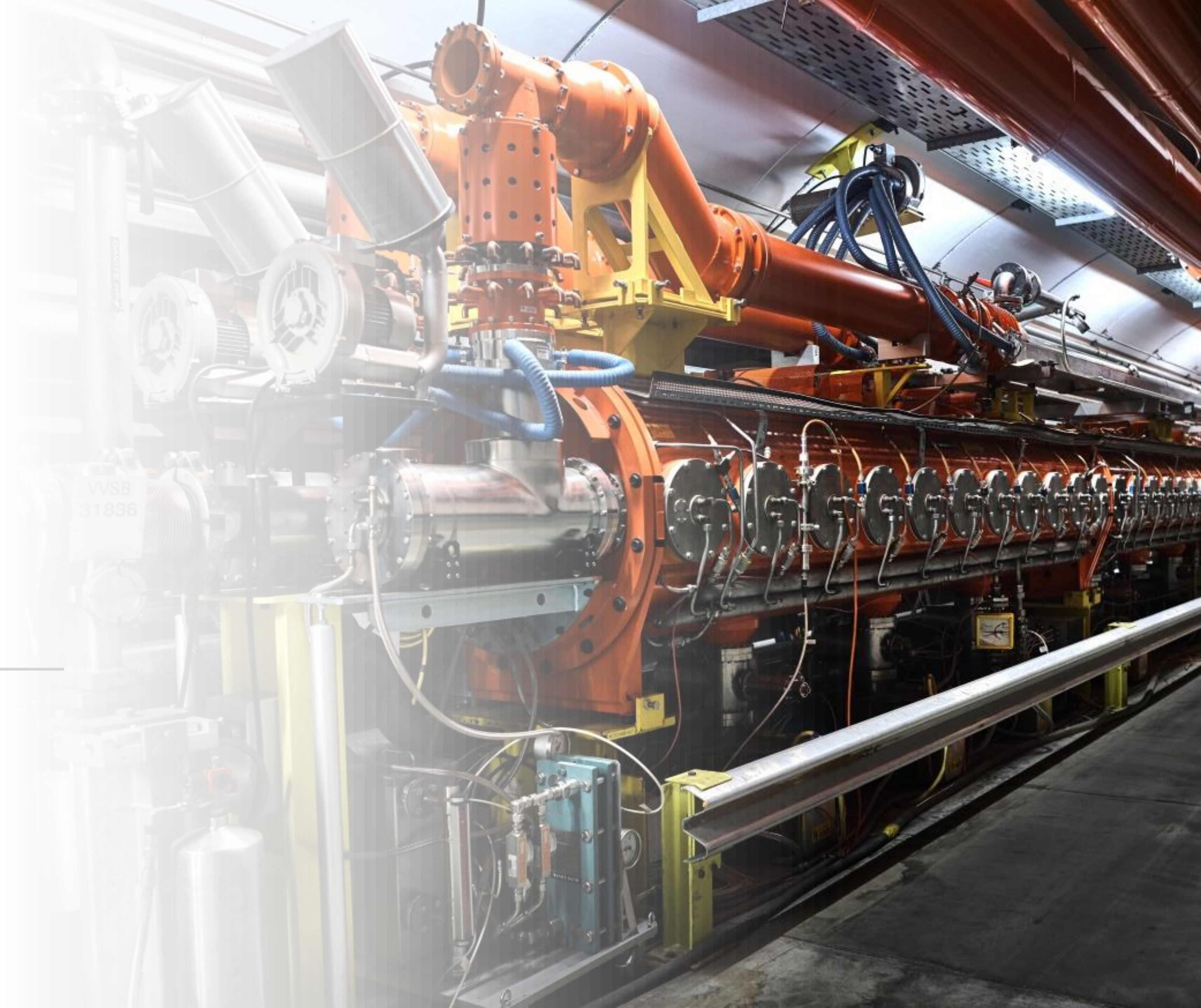
Non-collider Physics in Belgium

E. Cortina Gil

UCLouvain



Non-collider Physics in Belgium

- Small fraction of the HEP community involved.
  - Smaller teams
  - Smaller budgets and resources available
  - Less global visibility

- Excellent training experience
  - All aspects should be covered: Simulation, Operation, Construction, Analysis.
  - Excellent local visibility

- Three experiments:
  - NA62
  - SHiP
  - milliQan

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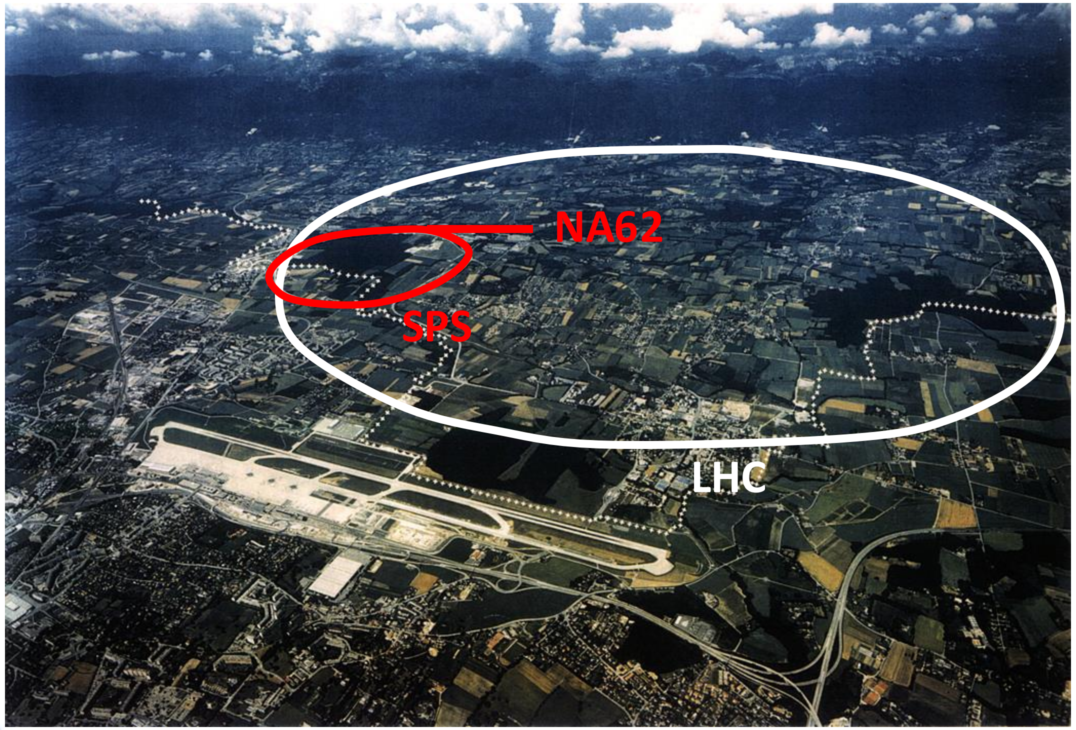
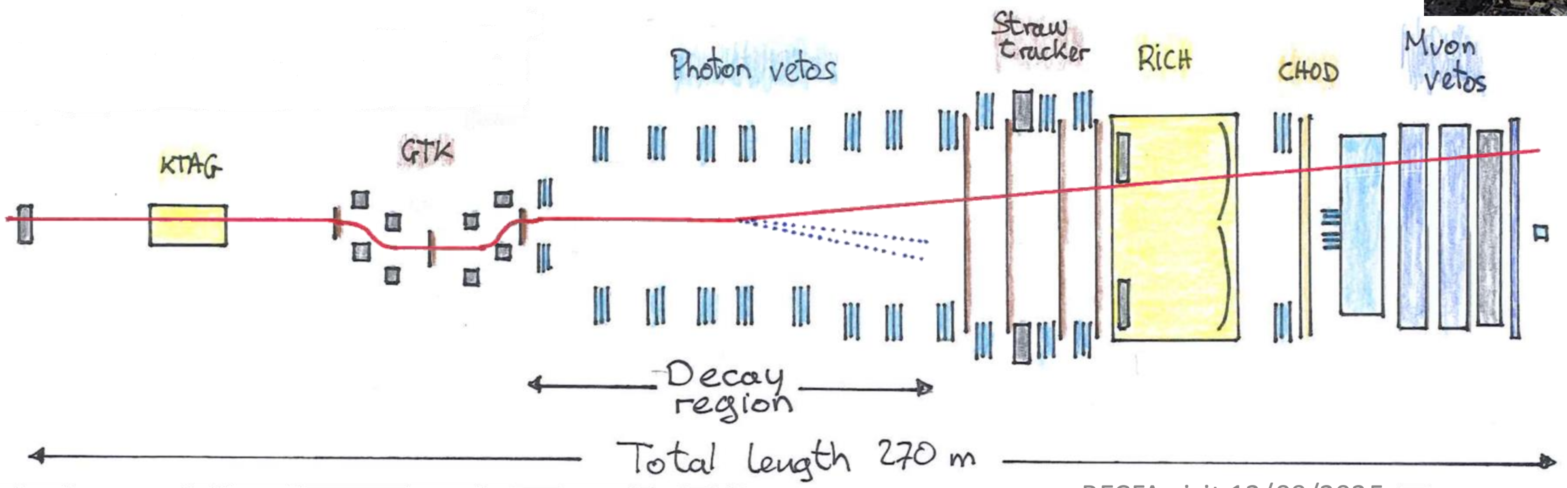
NA62

NA62 experiment

- Kaon experiment at CERN SPS
  - Main goal: Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$
  - Broader physics program
    - LFV/LNV in K^+ decays
    - Hidden sector particle searches
  - Two operation modes:
    - Kaon mode
    - Dump mode





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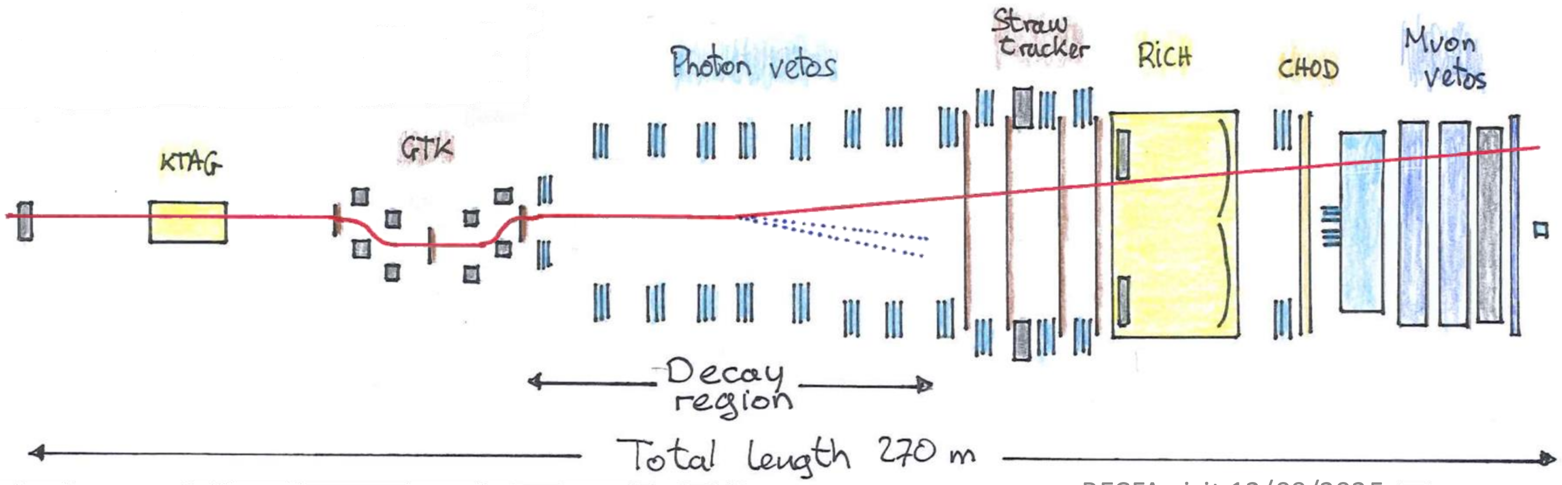
- Kinematic reconstruction
- PID
- Photon hermiticity
- Sub-ns timing



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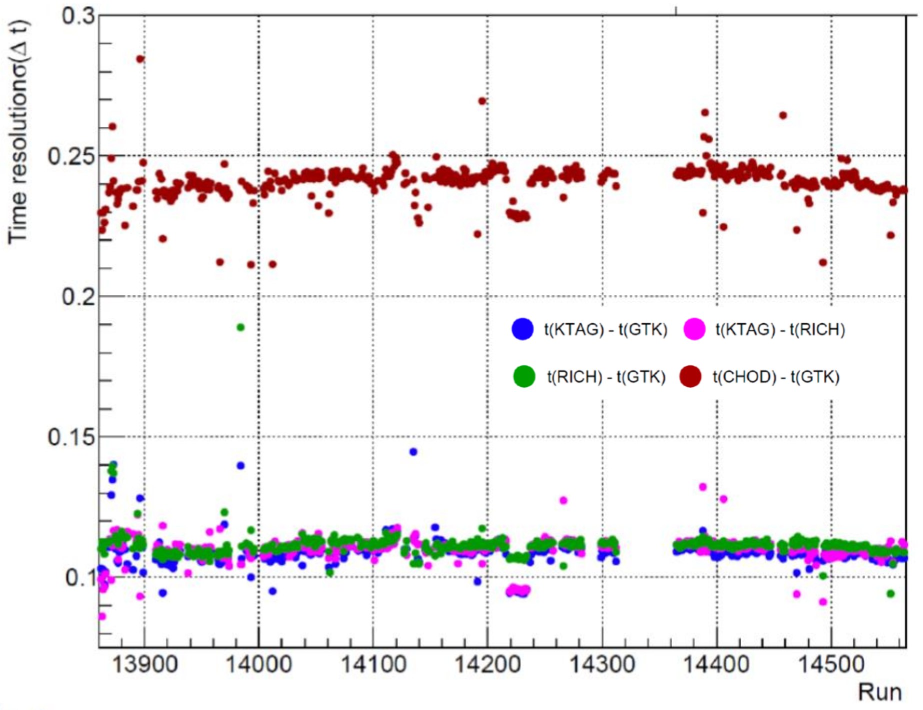

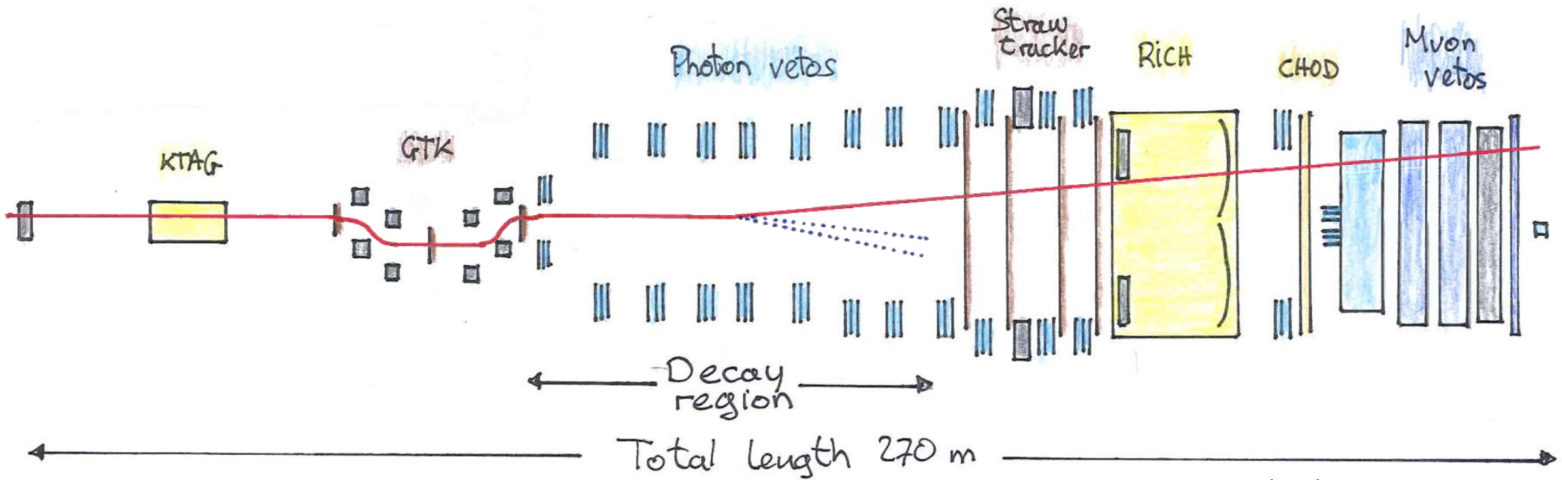

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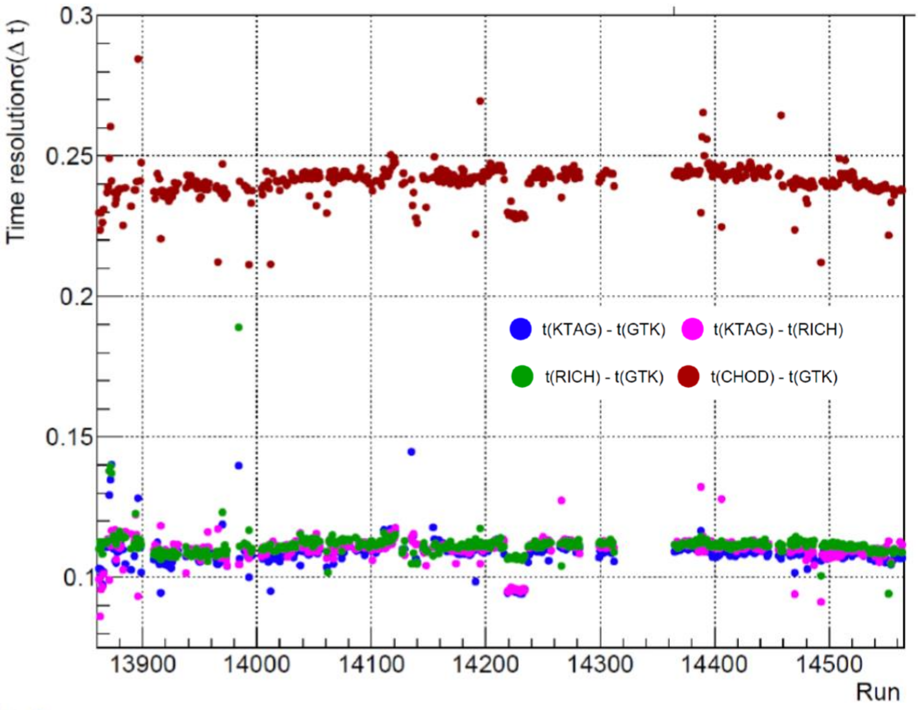

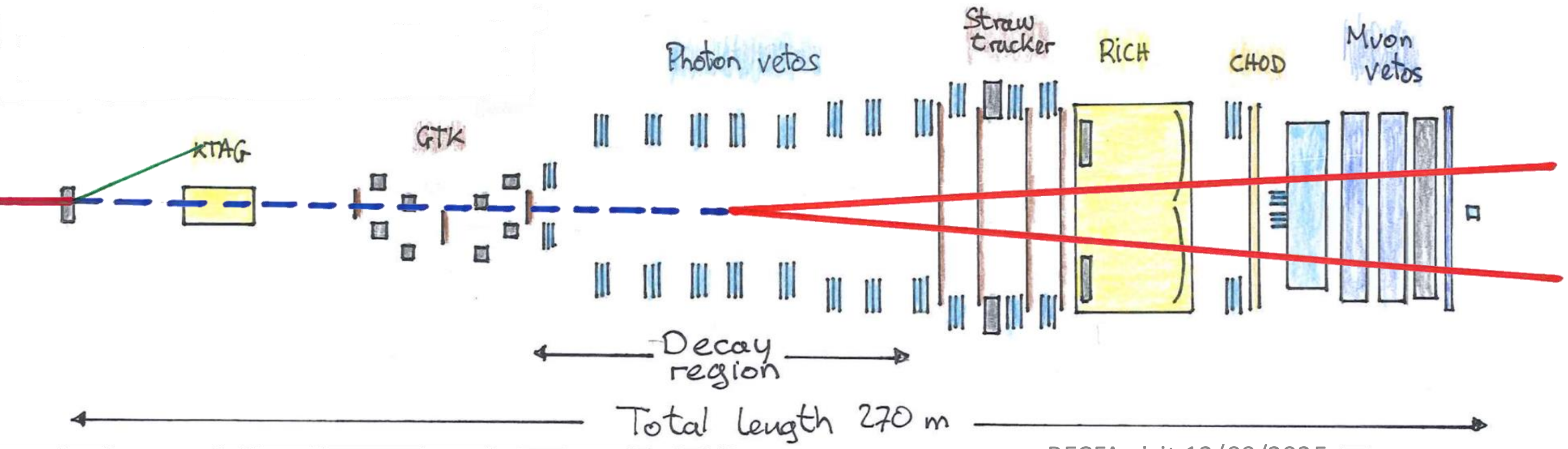

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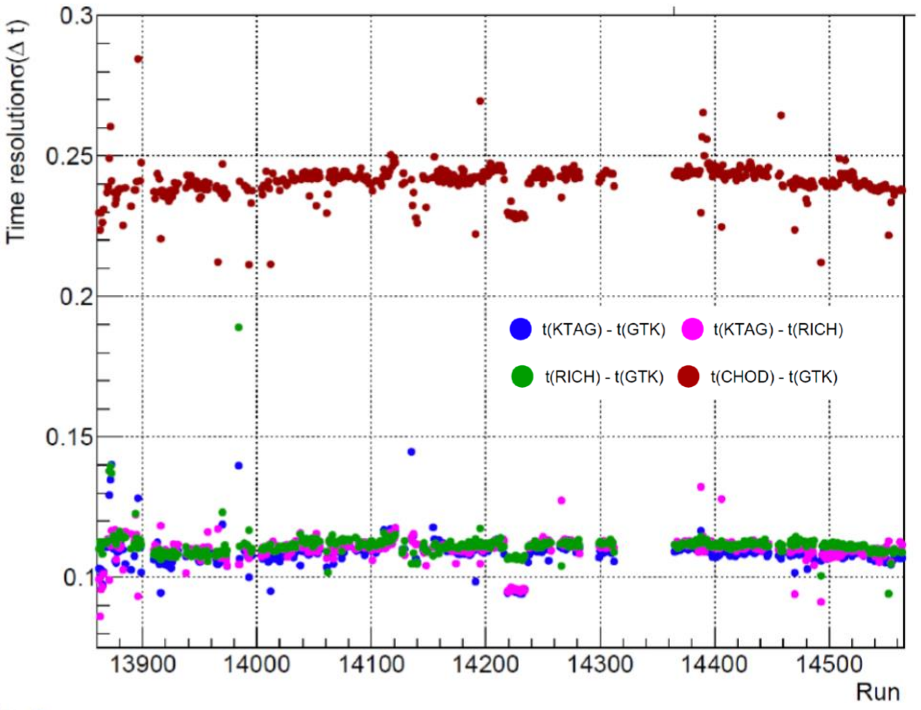

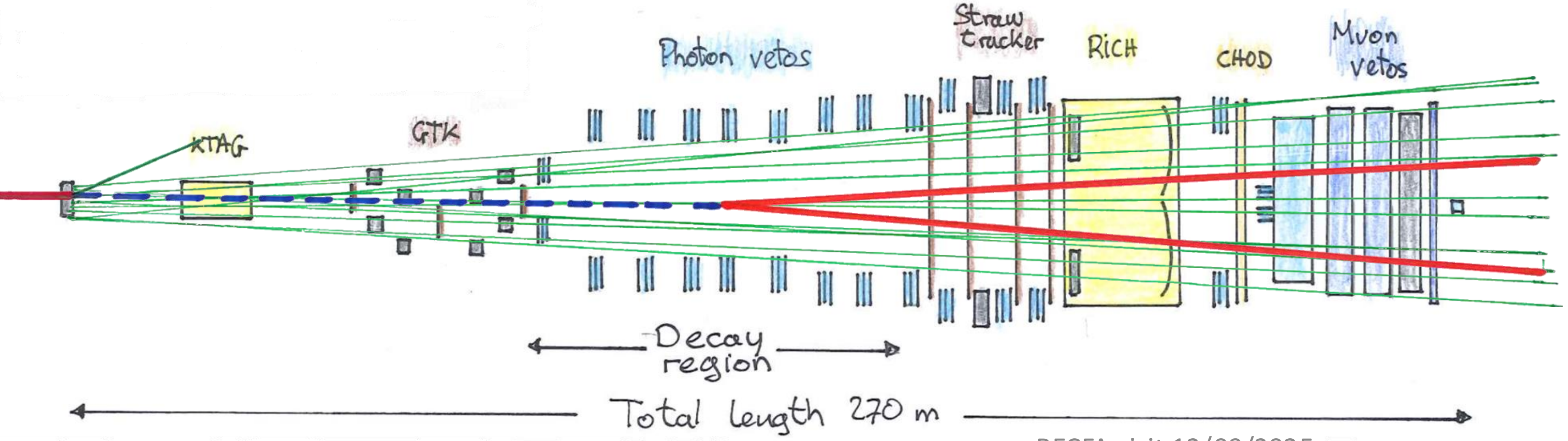

Timeline

Proposal

Technical Design

First beam

Upgrade:

- 4th GTK station
- Rainbow collimator
- Veto counter
- ANTI0
- HASC2

End of data taking

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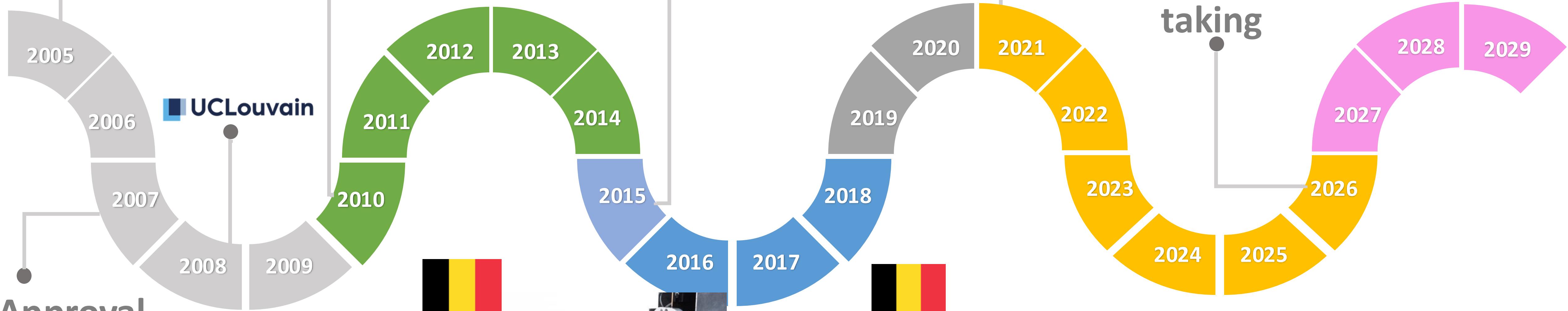
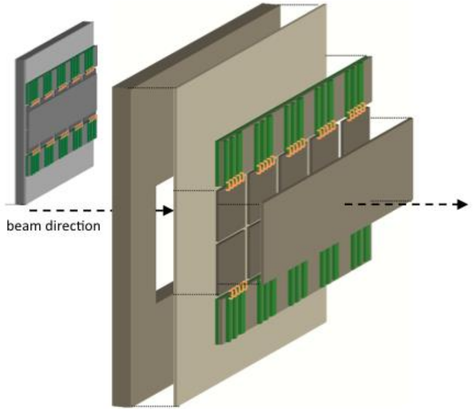
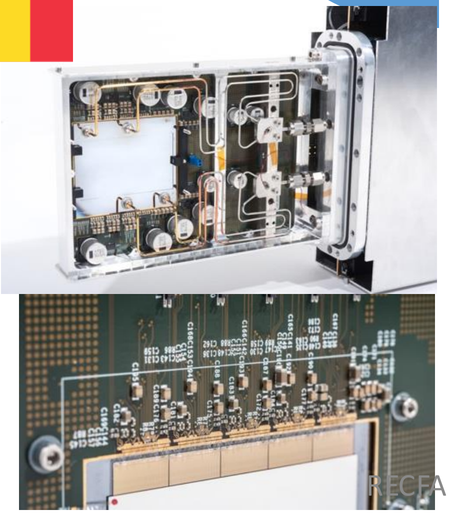
Approval







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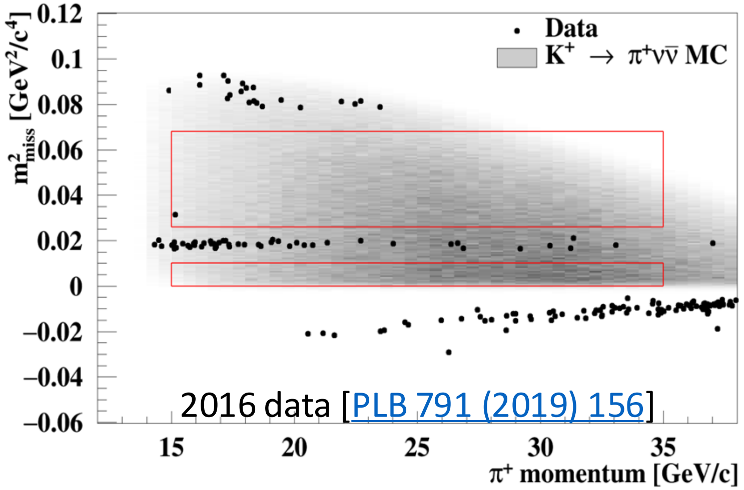

2016 data [PLB 791 (2019) 156]

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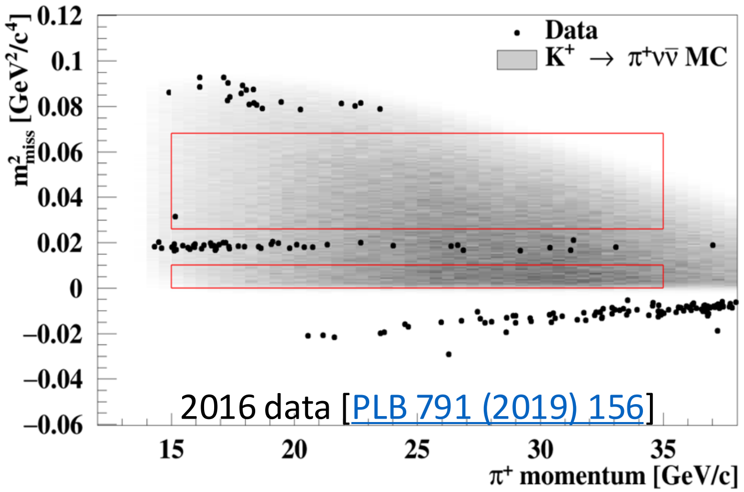

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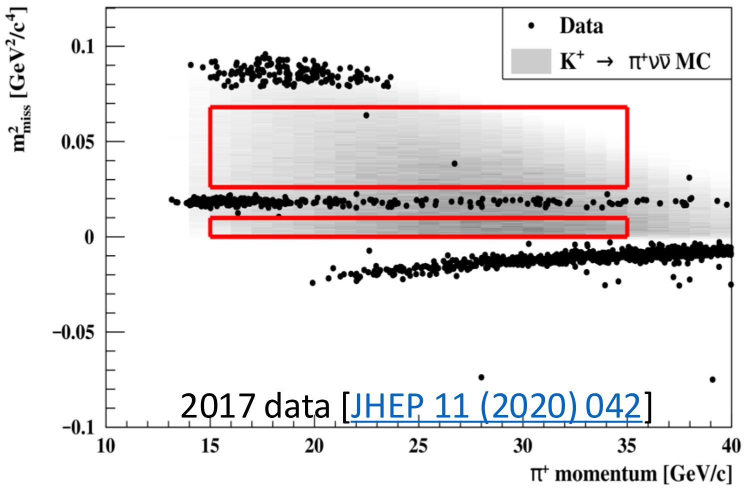

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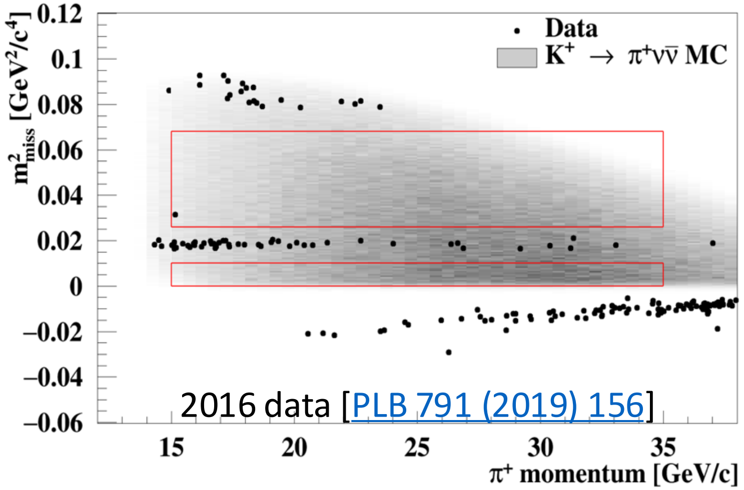

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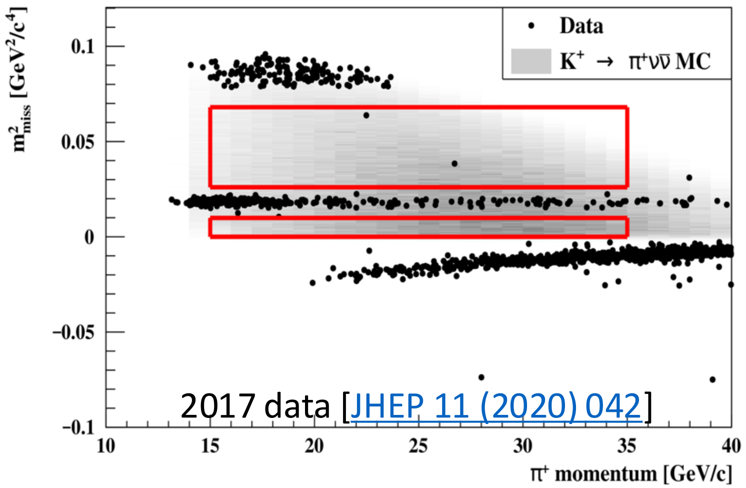

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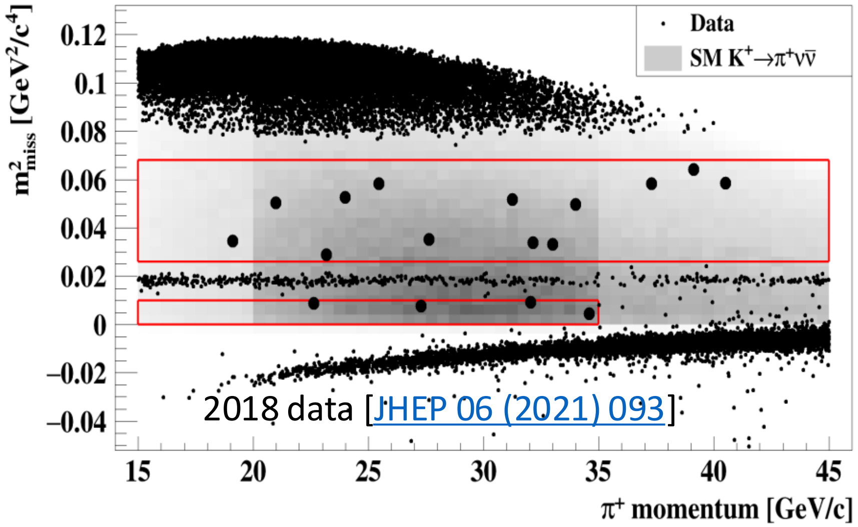

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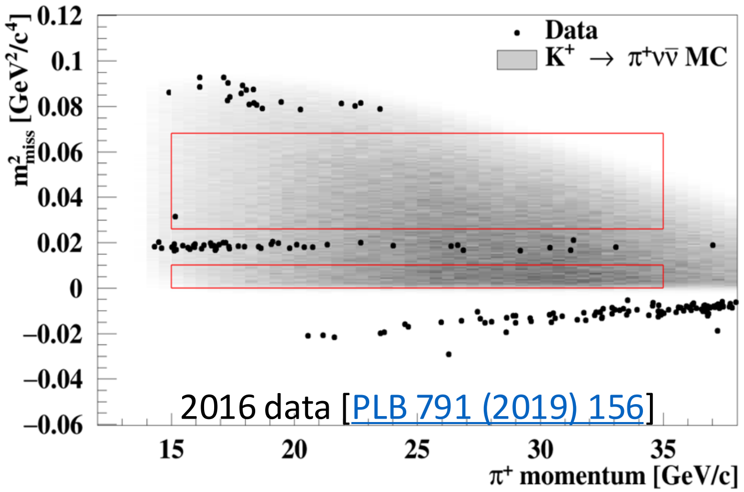

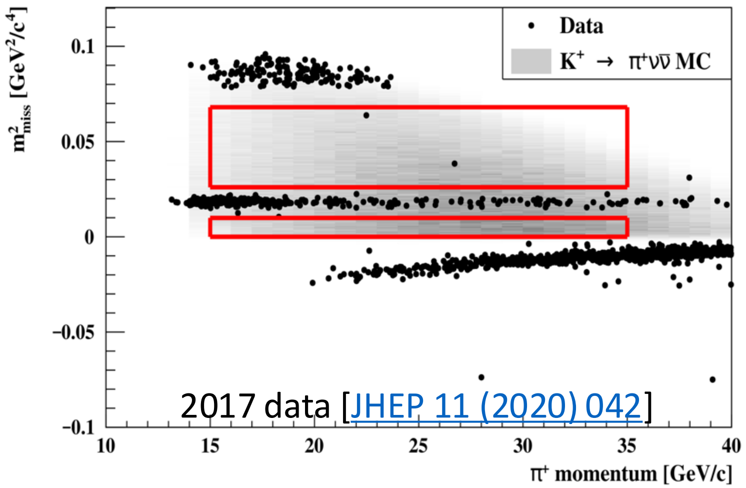

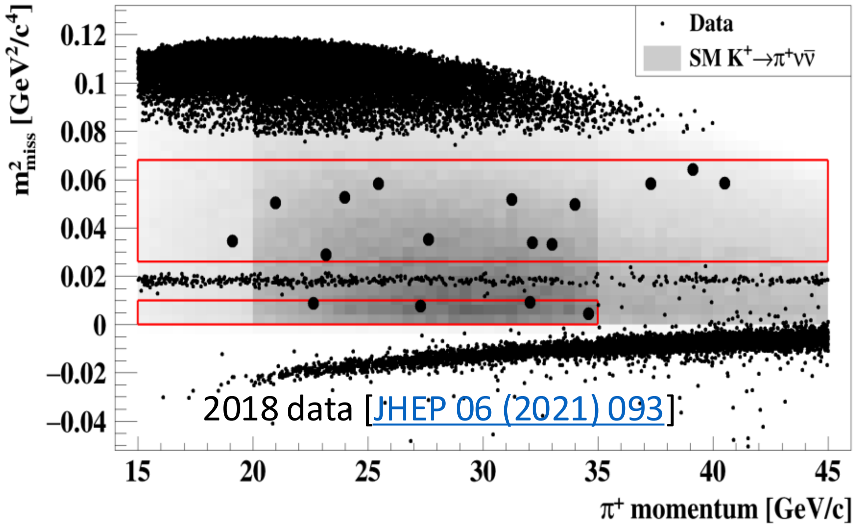

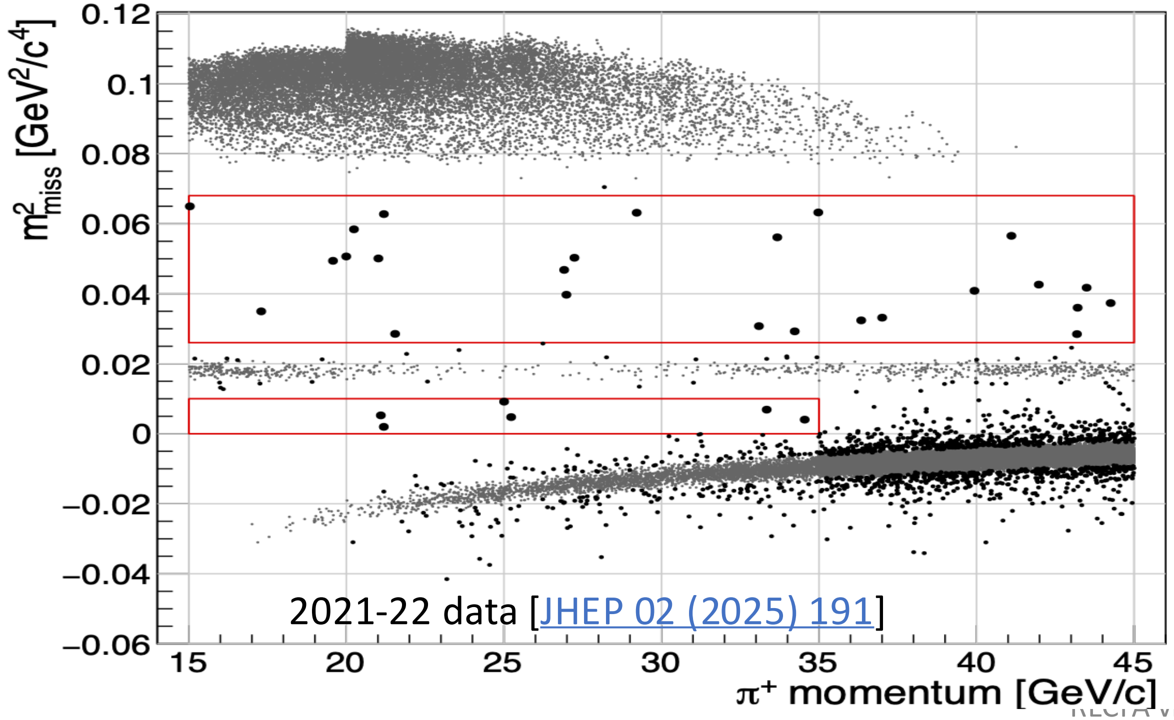

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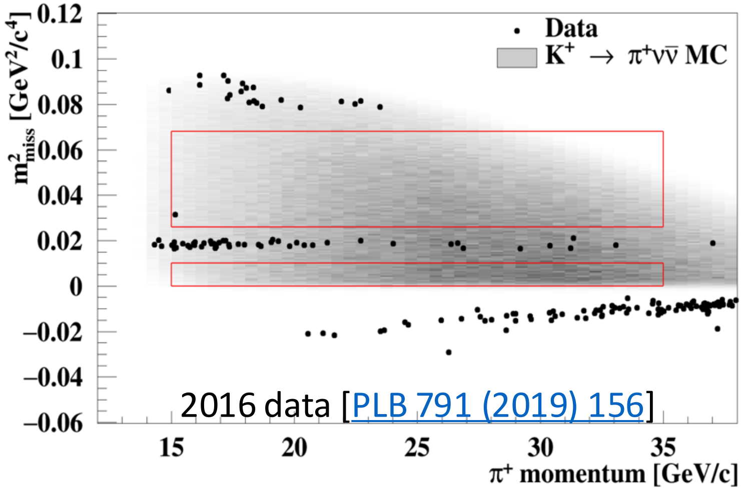

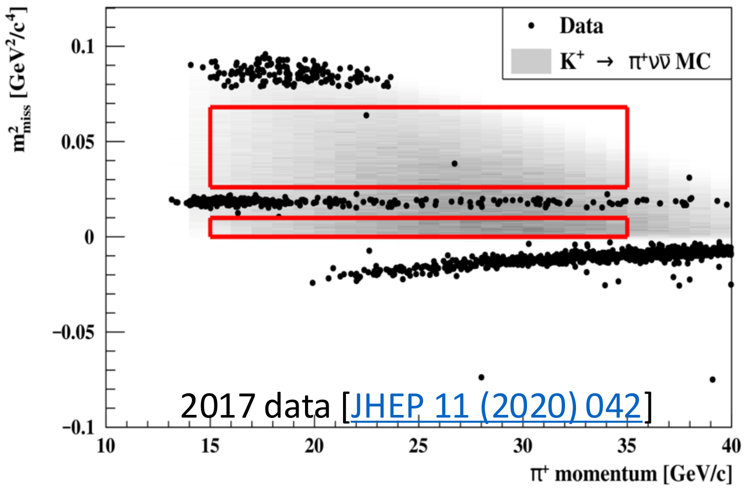

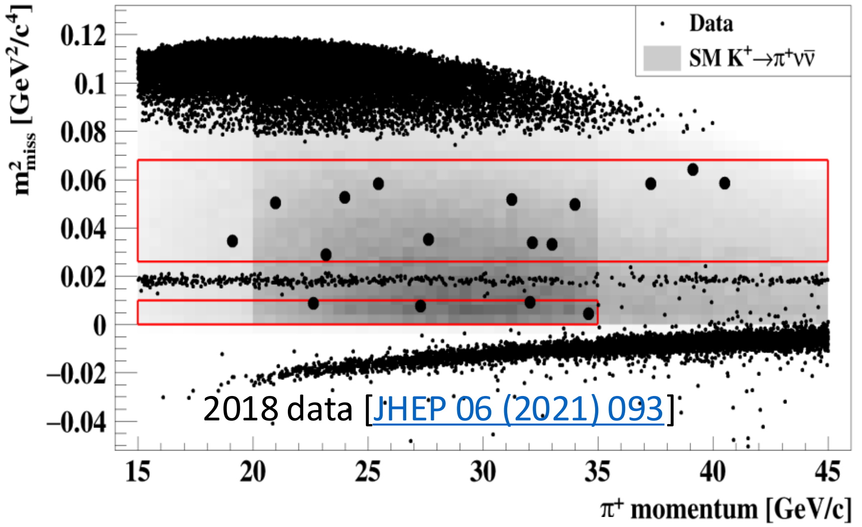

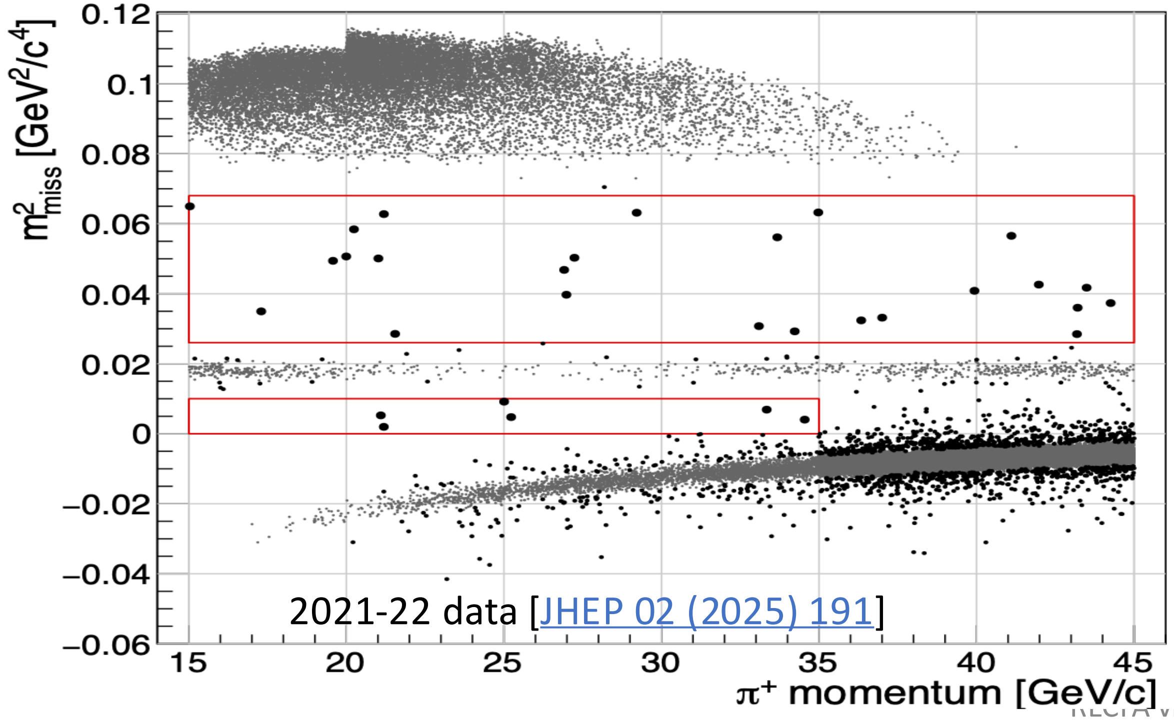

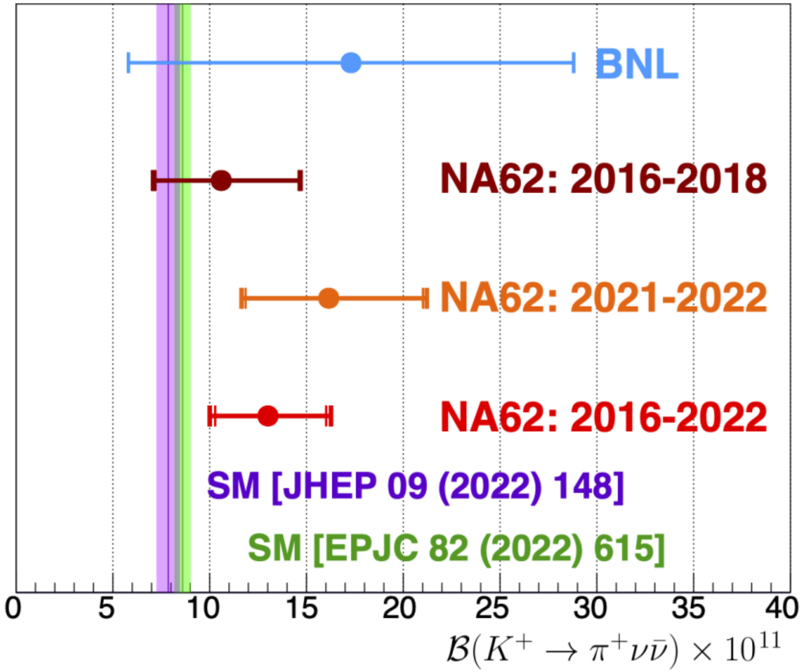

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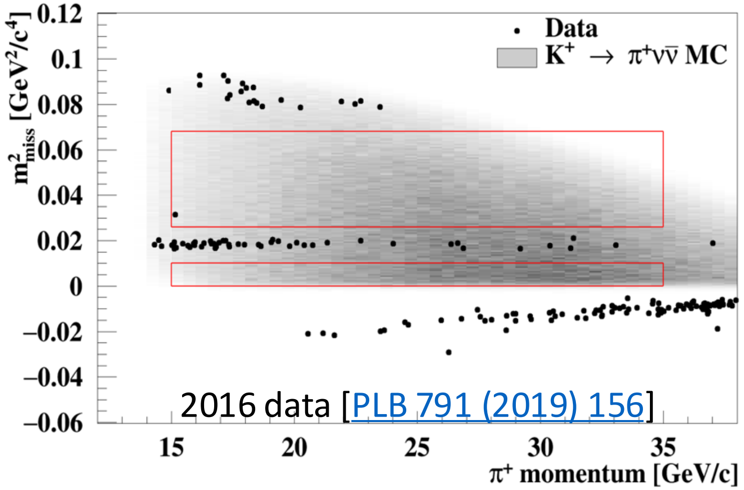

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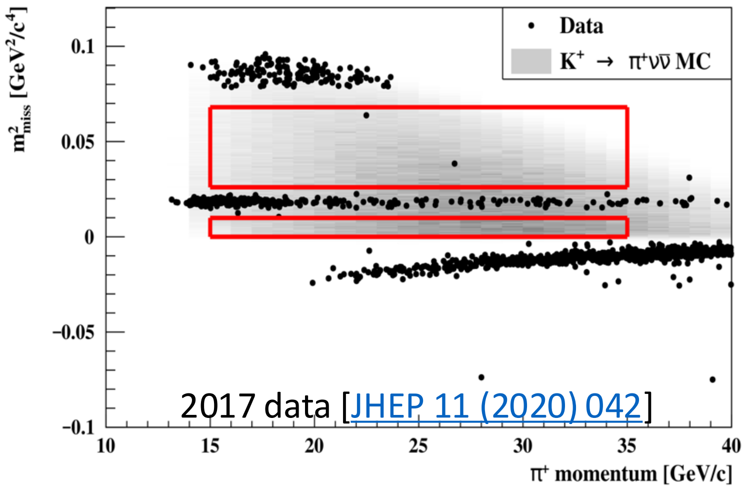

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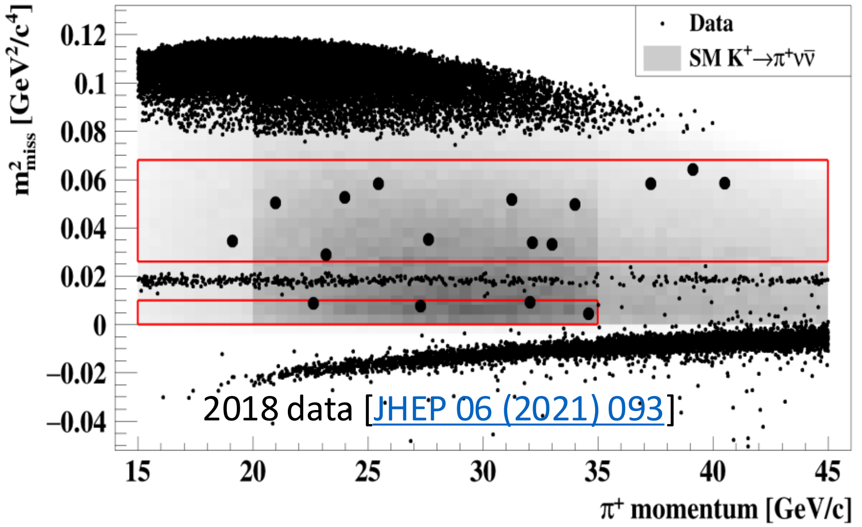

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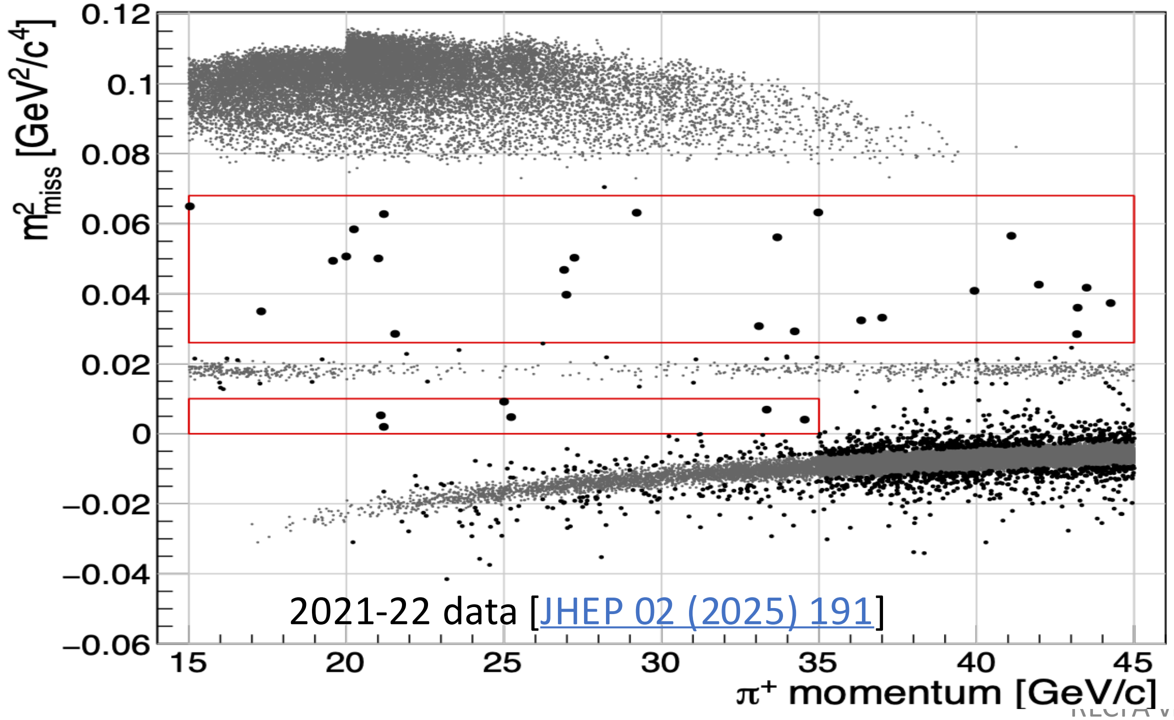
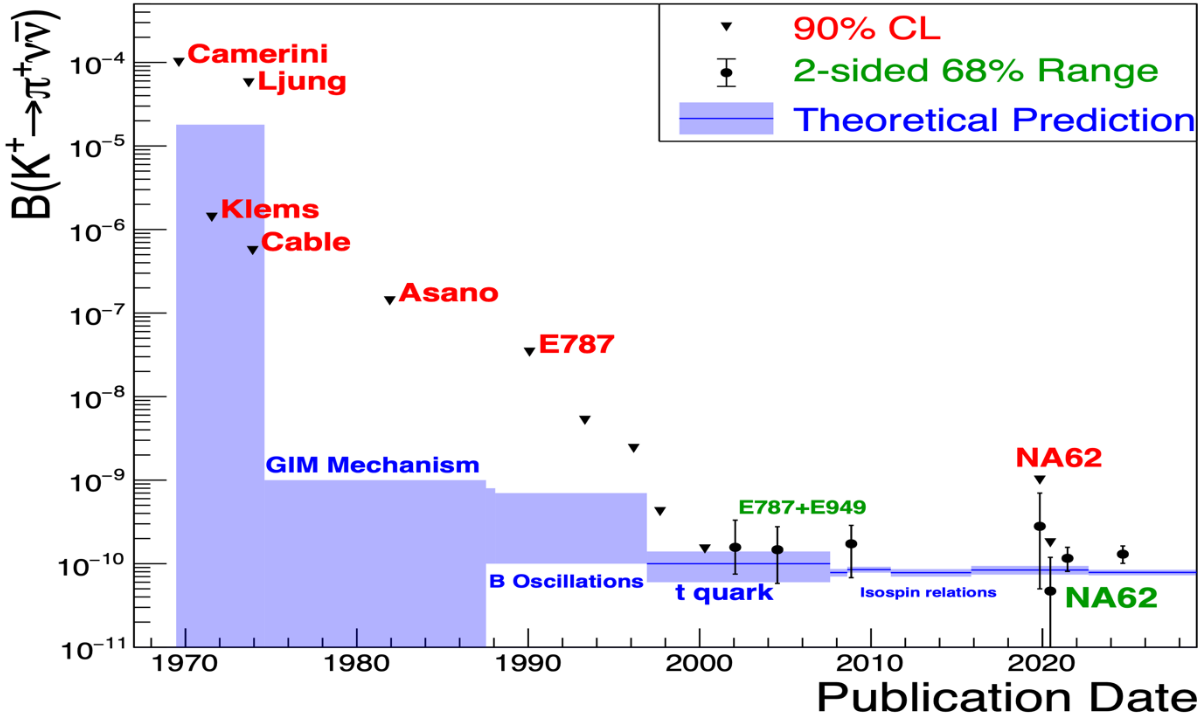


2021-22 data [JHEP 02 (2025) 191]



Results: LFV/LNV in $K^+ \to \pi^\pm \ell_1^\mp \ell_2^+$

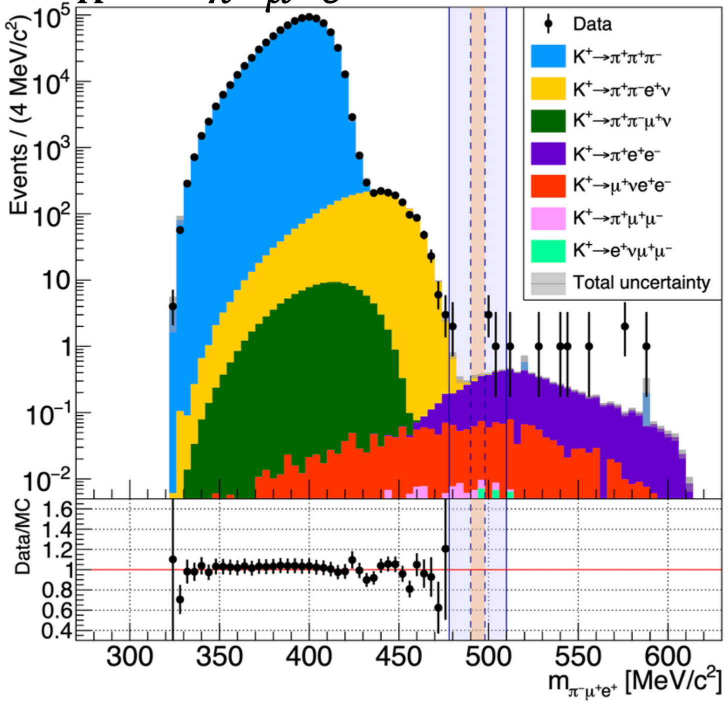
Situation in 2018

	Limit at 90% C.L.
$K^+ \to \pi^-\mu^+\mu^+$	$< 4.2 \times 10^{-11}$ (NA62 at CERN [11])
$K^+ \to \pi^-e^+e^+$	$< 2.2 \times 10^{-10}$ (NA62 at CERN [11])
$K^+ \to \pi^-\mu^+e^+$	$< 5.0 \times 10^{-10}$ (E865 at BNL [12])
$K^+ \to \pi^+\mu^-e^+$	$< 5.2 \times 10^{-10}$ (E865 at BNL [12])
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$ (E865 at BNL [13])
$\pi^0 \to \mu^-e^+$	$< 3.4 \times 10^{-9}$ (E865 at BNL [12])
$\pi^0 \to \mu^+e^-$	$< 3.8 \times 10^{-10}$ (E865 at BNL [14])
$\pi^0 \to \mu^\pm e^\mp$	$< 3.6 \times 10^{-10}$ (KTeV at FNAL [15])

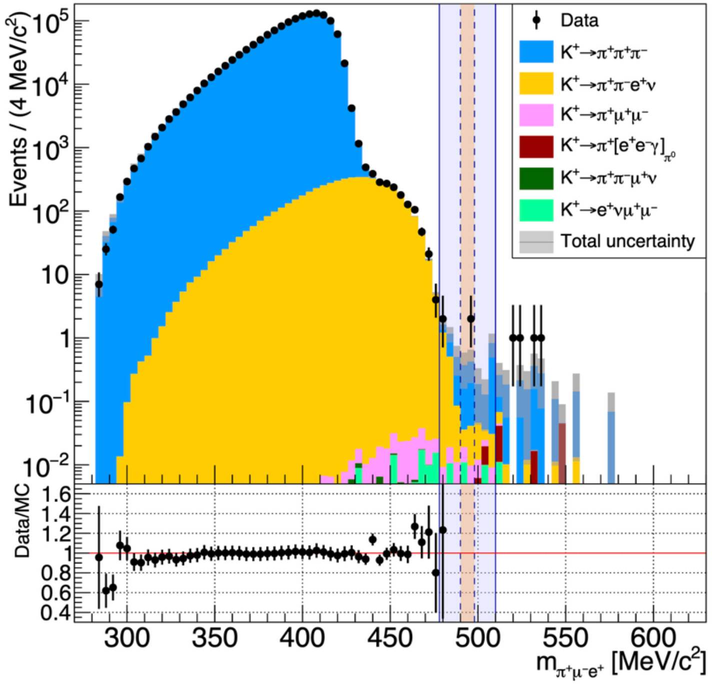
PRL 127, 131802 (2021)

$$\mathcal{B}(K^+ \to \pi^-\mu^+e^+) < 4.2 \times 10^{-11};$$
$$\mathcal{B}(K^+ \to \pi^+\mu^-e^+) < 6.6 \times 10^{-11};$$
$$\mathcal{B}(\pi^0 \to \mu^-e^+) < 3.2 \times 10^{-10}.$$

$K^+ \to \pi^-\mu^+e^+$ 2017-2018 run

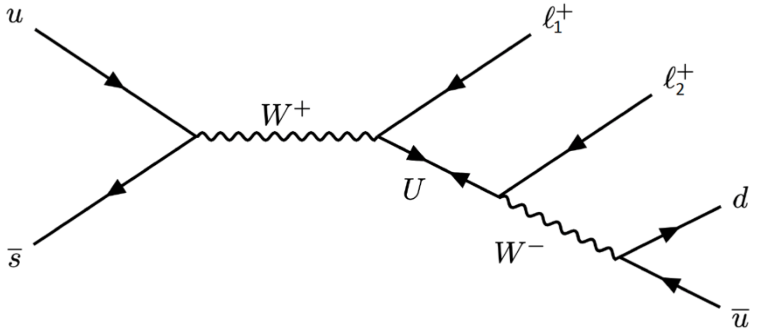


$K^+ \to \pi^+\mu^-e^+$



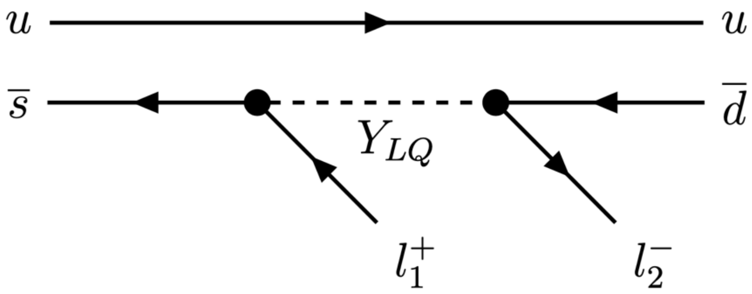
$K^+ \to \pi^-\ell_1^+\ell_2^+$

ΔL = 2 via Majorana neutrinos U



$K^+ \to \pi^\pm\mu^\mp e^+$ *decays*

ΔL = 2 = mediated by a leptoquark



Results: Beam Dump

- 1.4 10^{17} POT taken in 2021
- Runs in 2023, 2024, 2025
  - Improved trigger and beam setup
  - ~10^{18} POT … analysis ongoing
- Solid analysis technique

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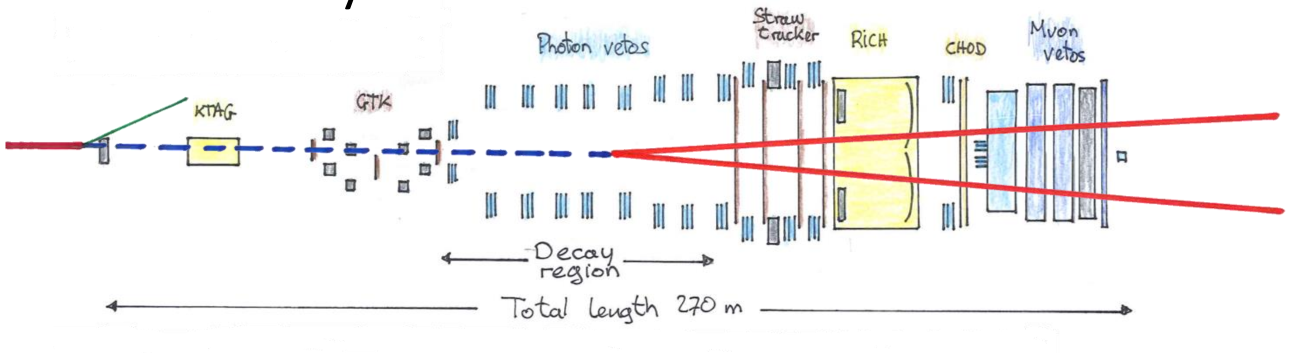

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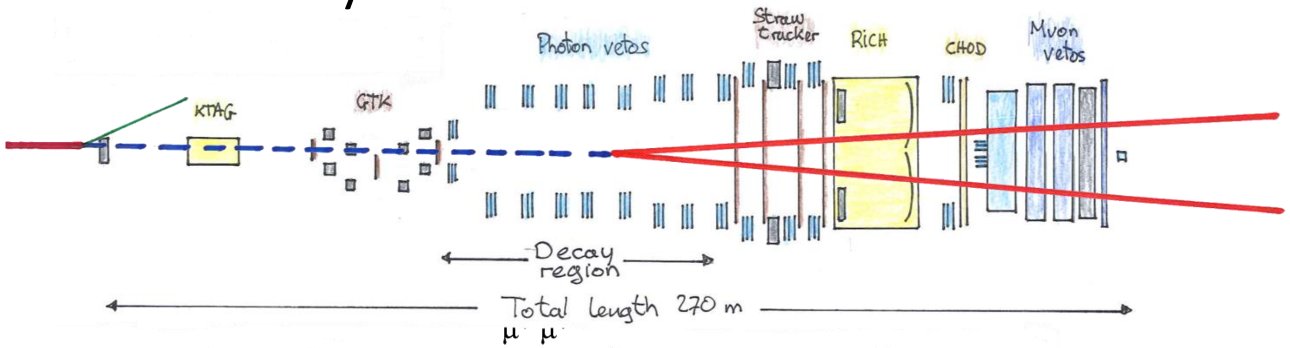

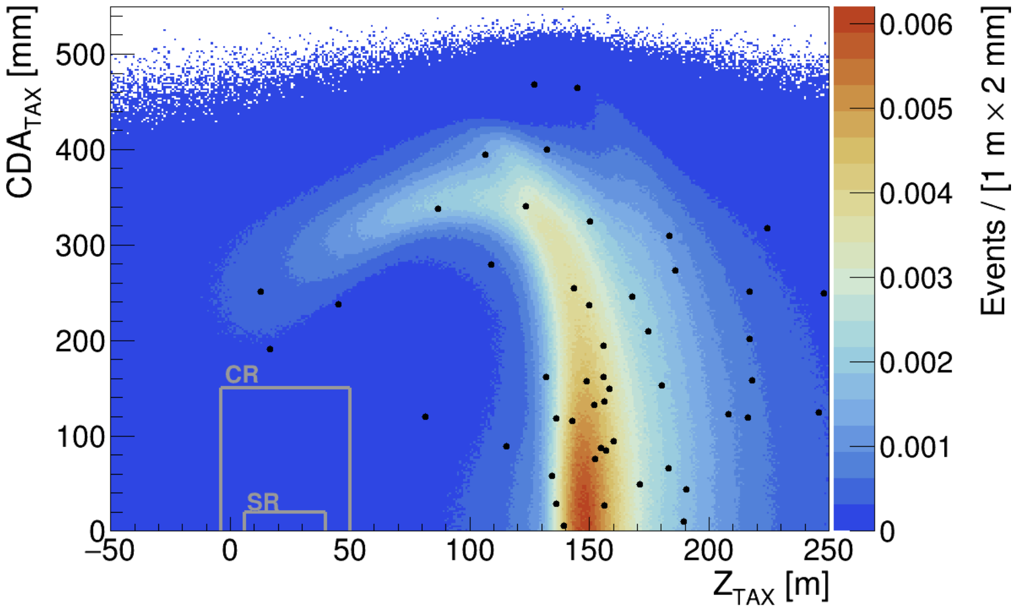

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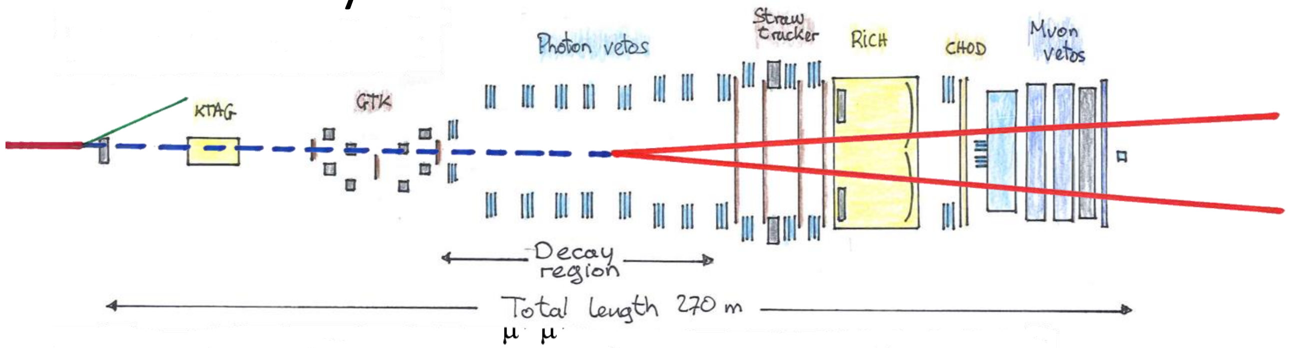

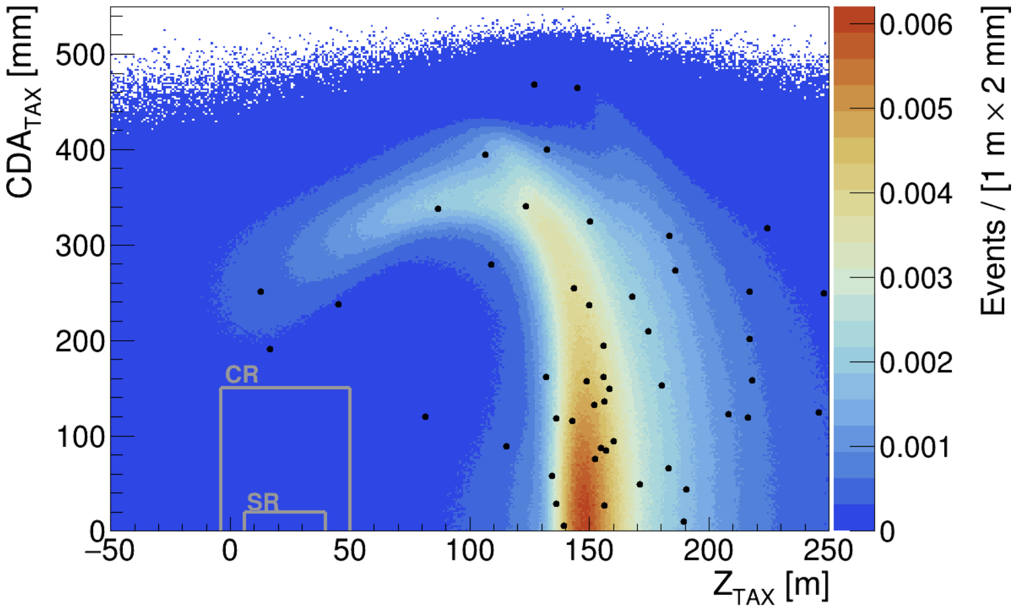

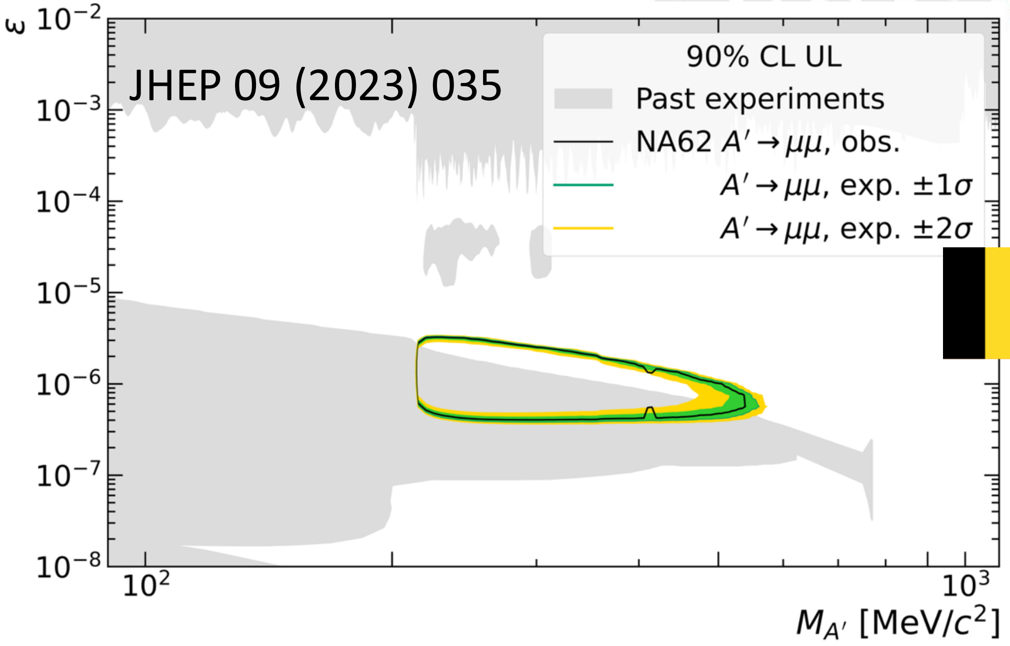

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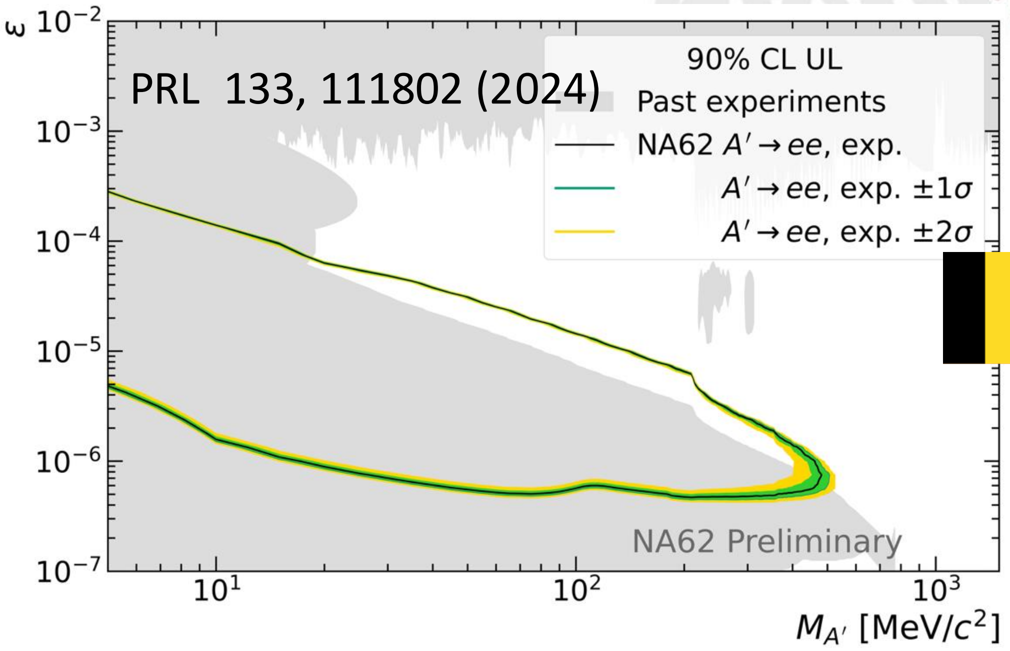

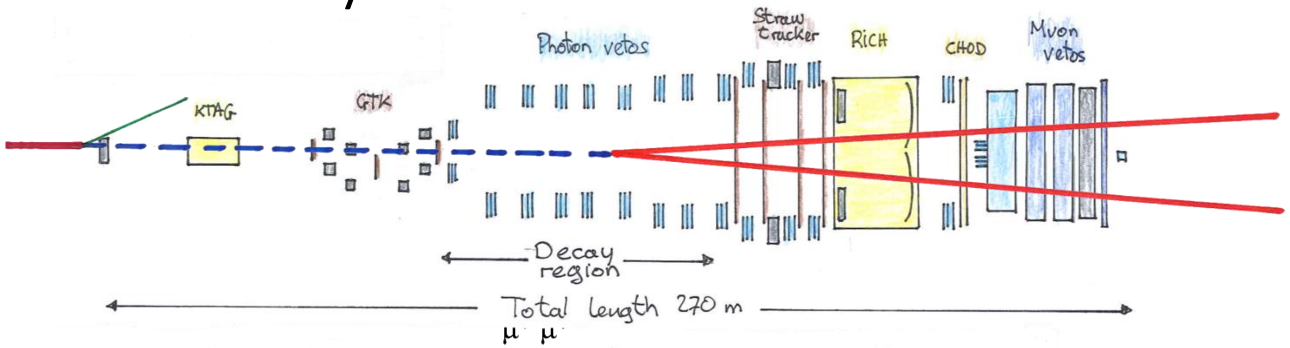

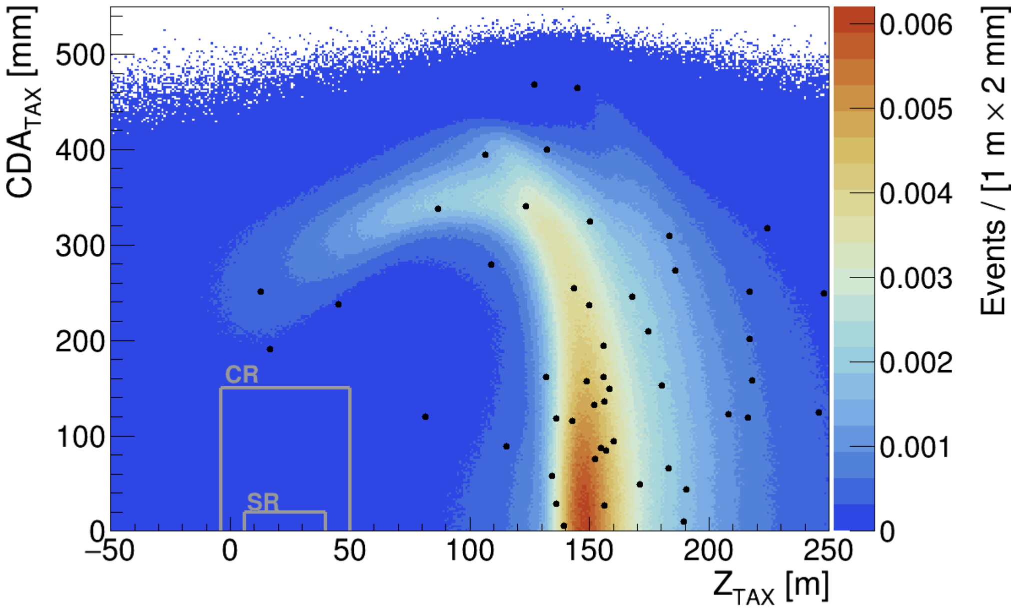

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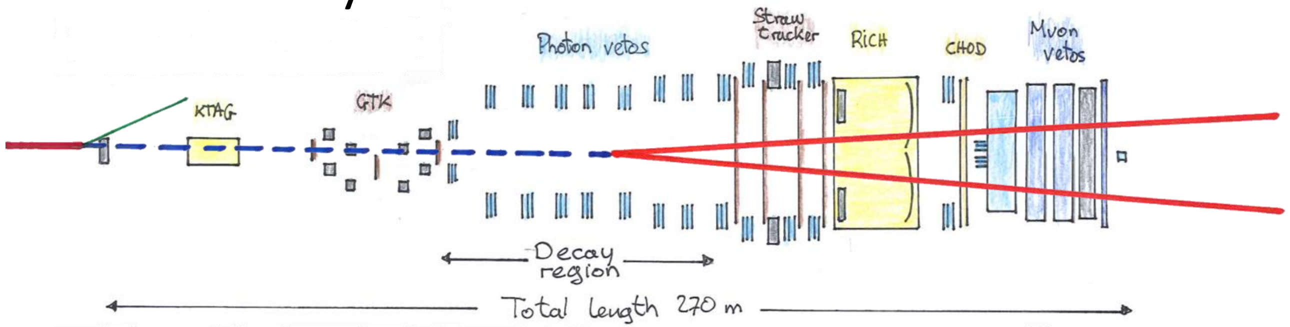

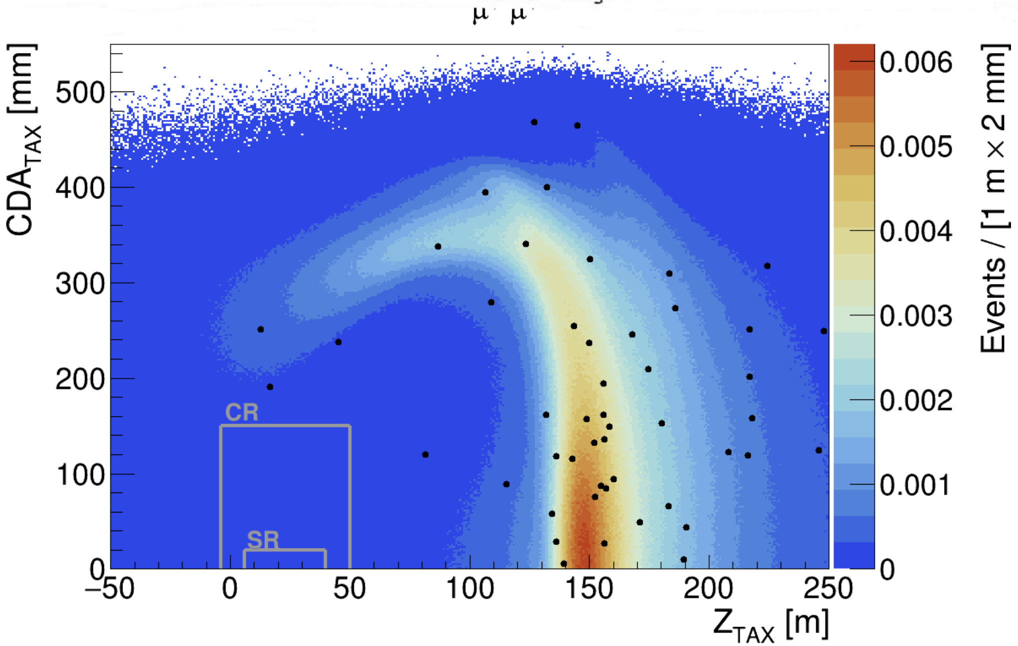

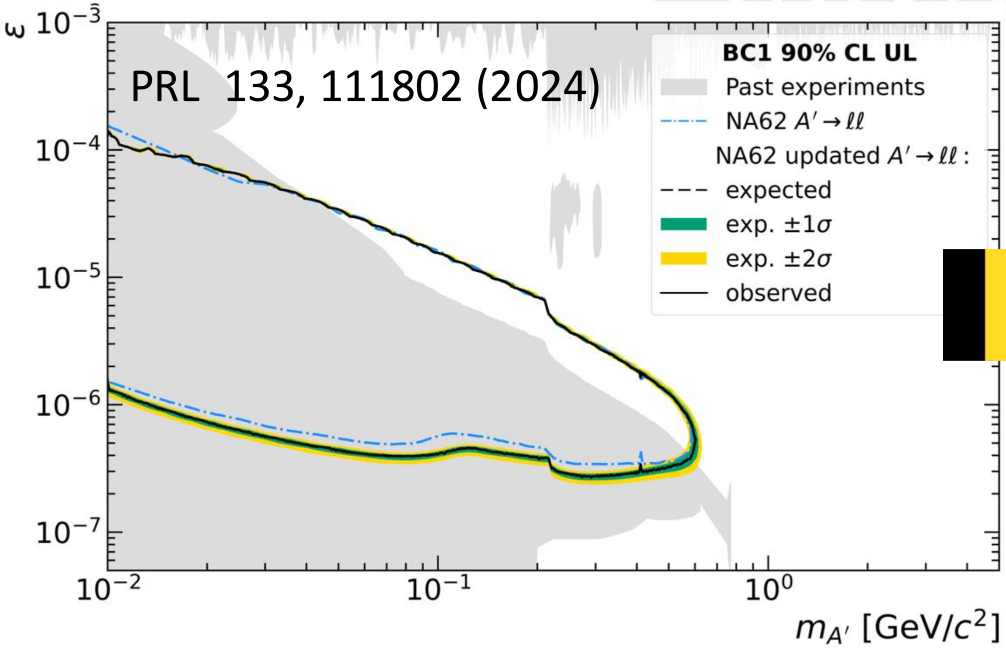

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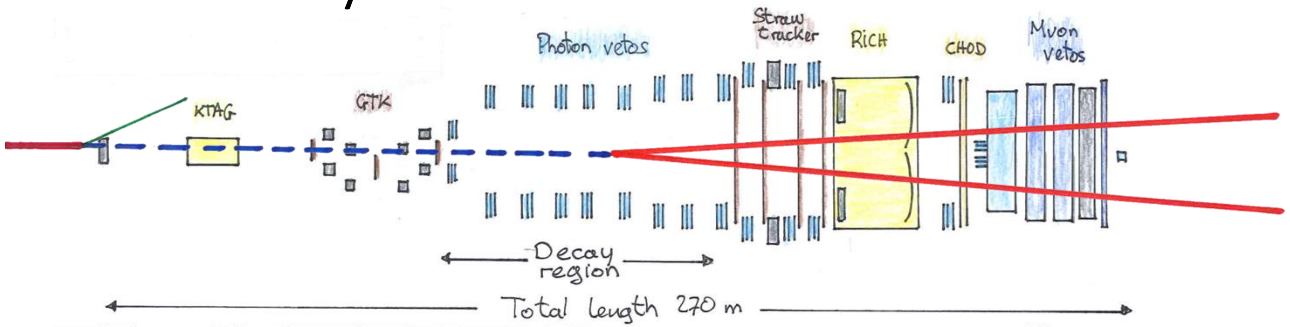
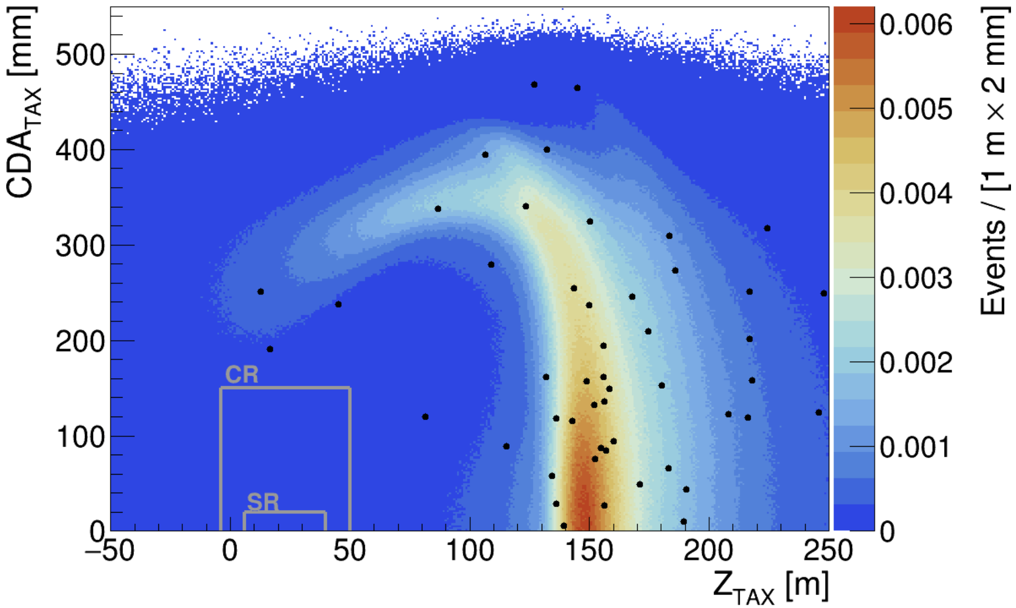
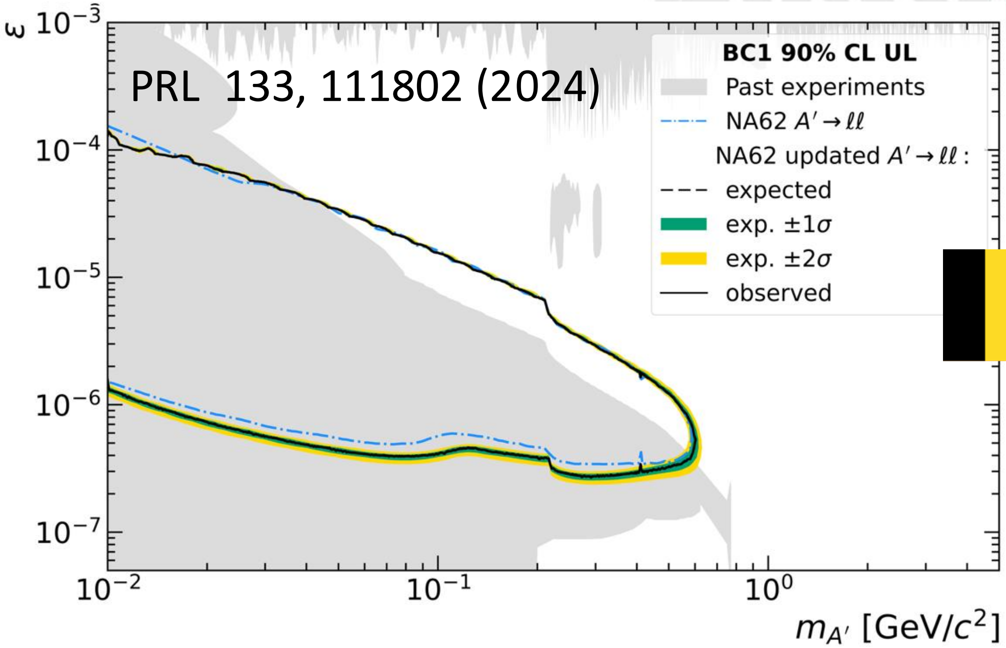
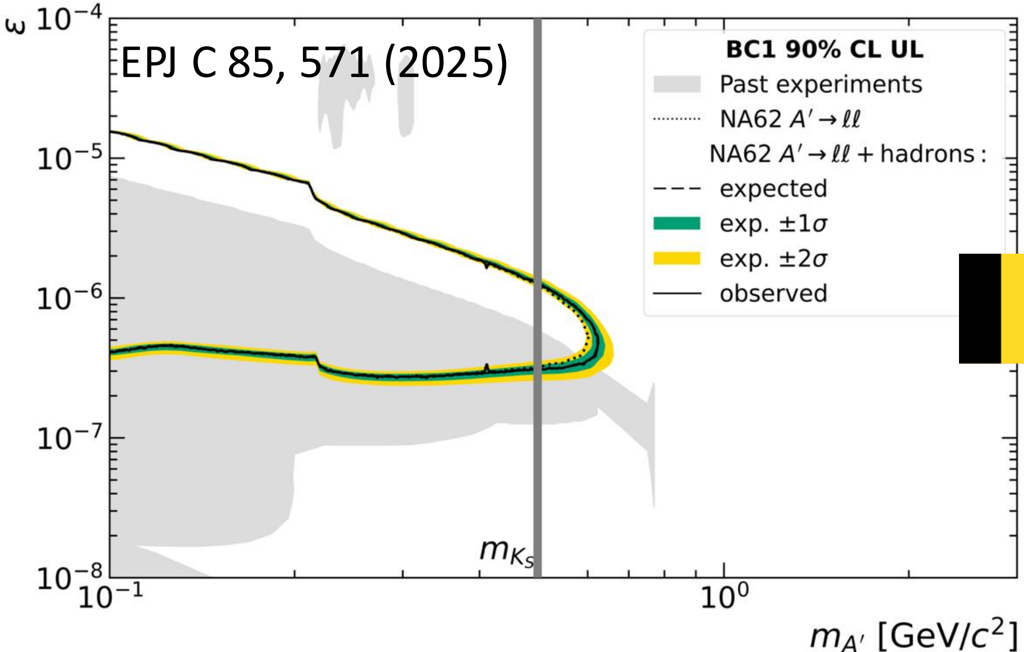








Summary

Successful experimental program over 20 years

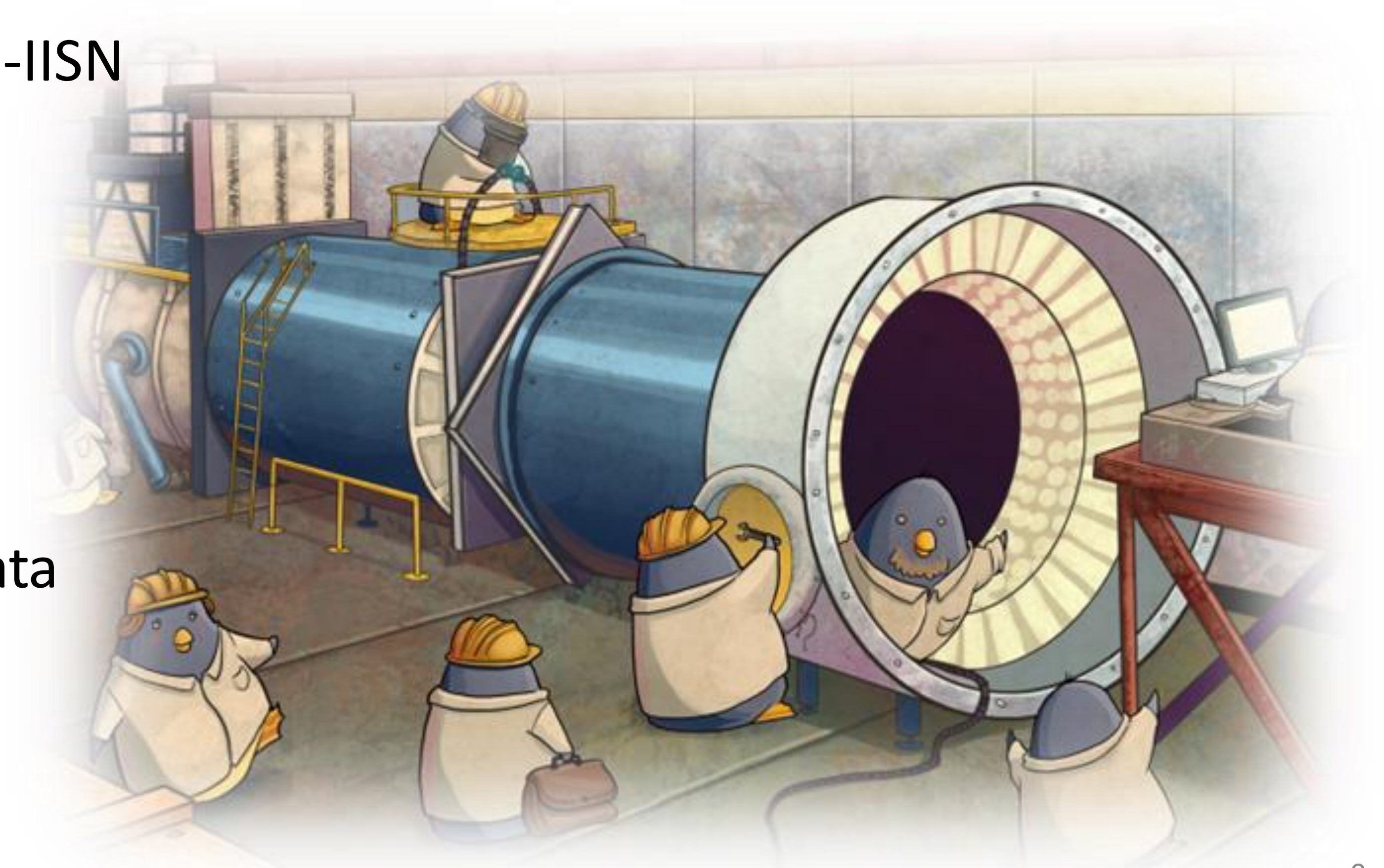
- 1 Staff, 5 PhD students, 11 Postdocs
- > 30 papers (JHEP, PLB,PRL)

Excellent and sustained support from FNRS-IISN

- Personnel :1 phD student, 4 Postdocs
- Equipment, Running Budget and M&O

Future:

- End of data taking (June 2026)
- Still several years to fully analyze all data
- Excellent data quality with the world largest sample of K^+ decays

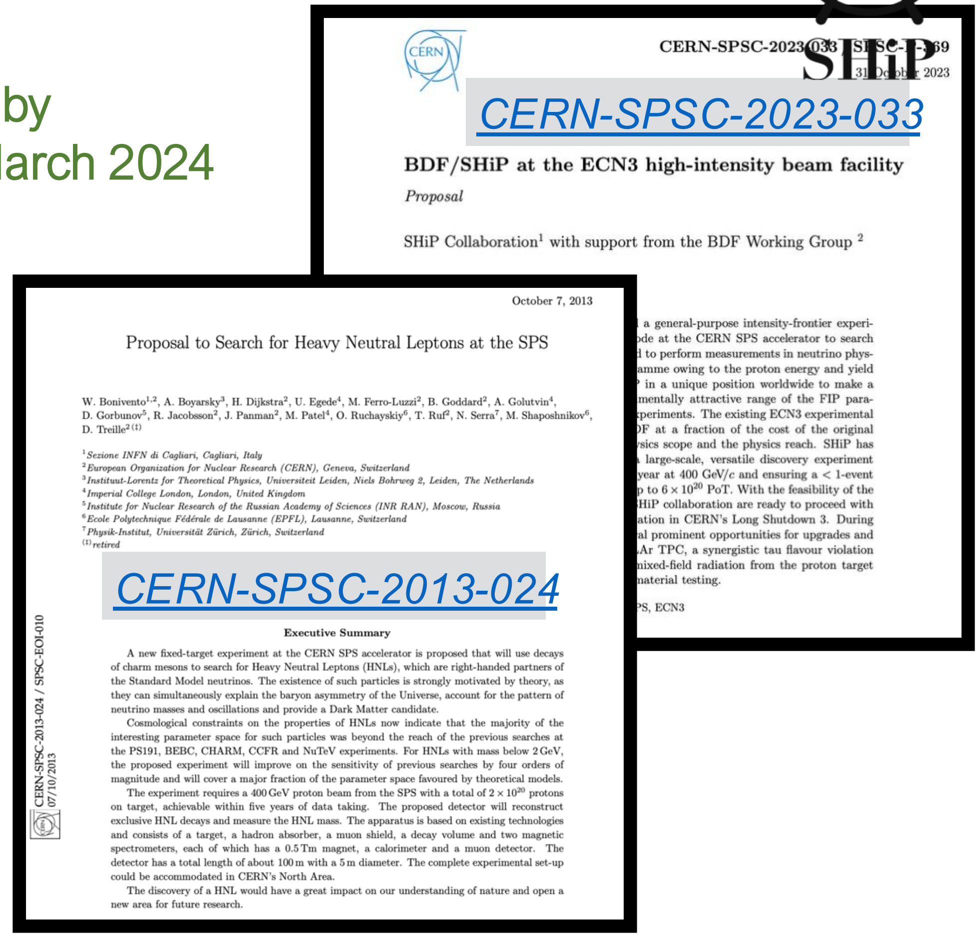


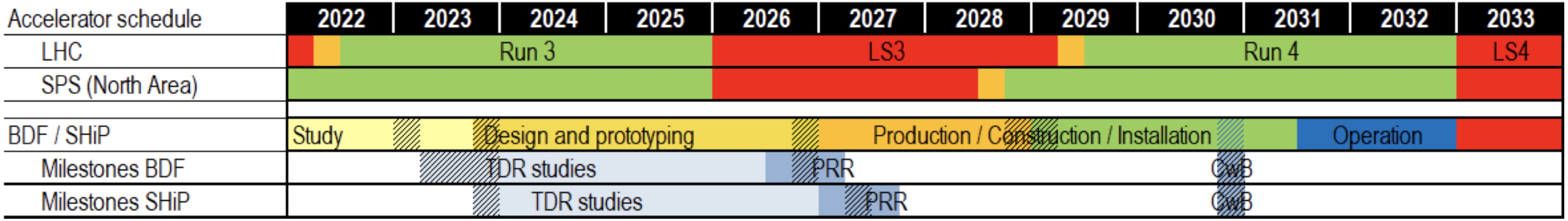
SHiP

The SHiP experiment

- The initial proposal for a new fixed-target experiment at SPS was submitted in 2013
- A search for long-lived feebly-interacting particles (FIP) in charmed meson decays
- Go beyond the (past and future) collider reach for displaced signatures
- A discovery experiment capable of characterizing new physics
- A technical design study for a new high-intensity physics program launched by CERN Council

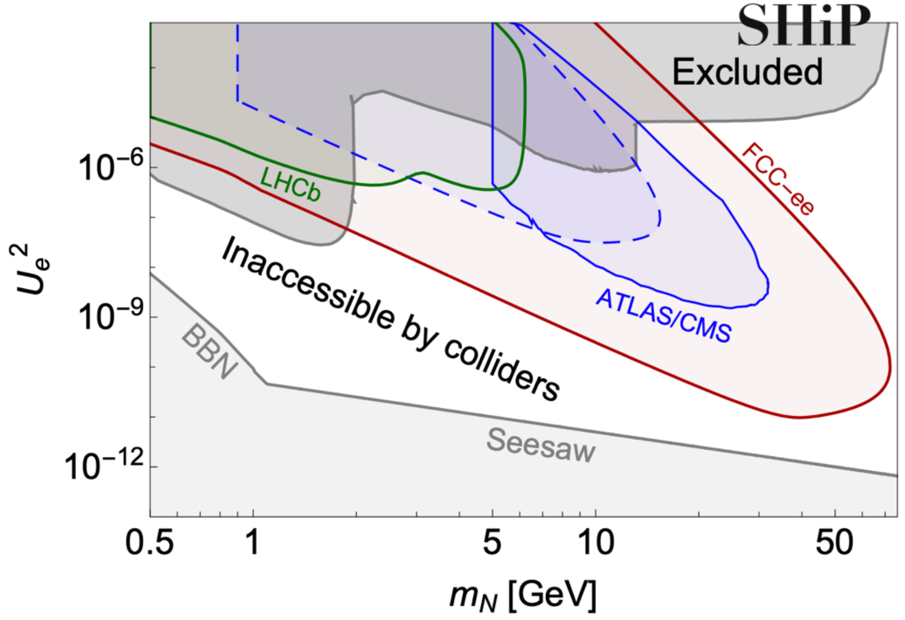
The project was **approved** by CERN Research Board in March 2024

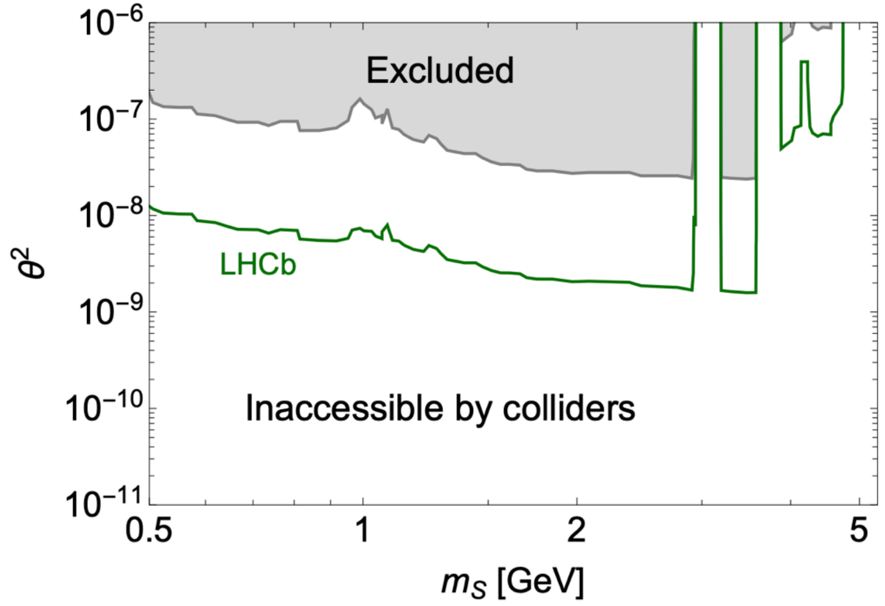




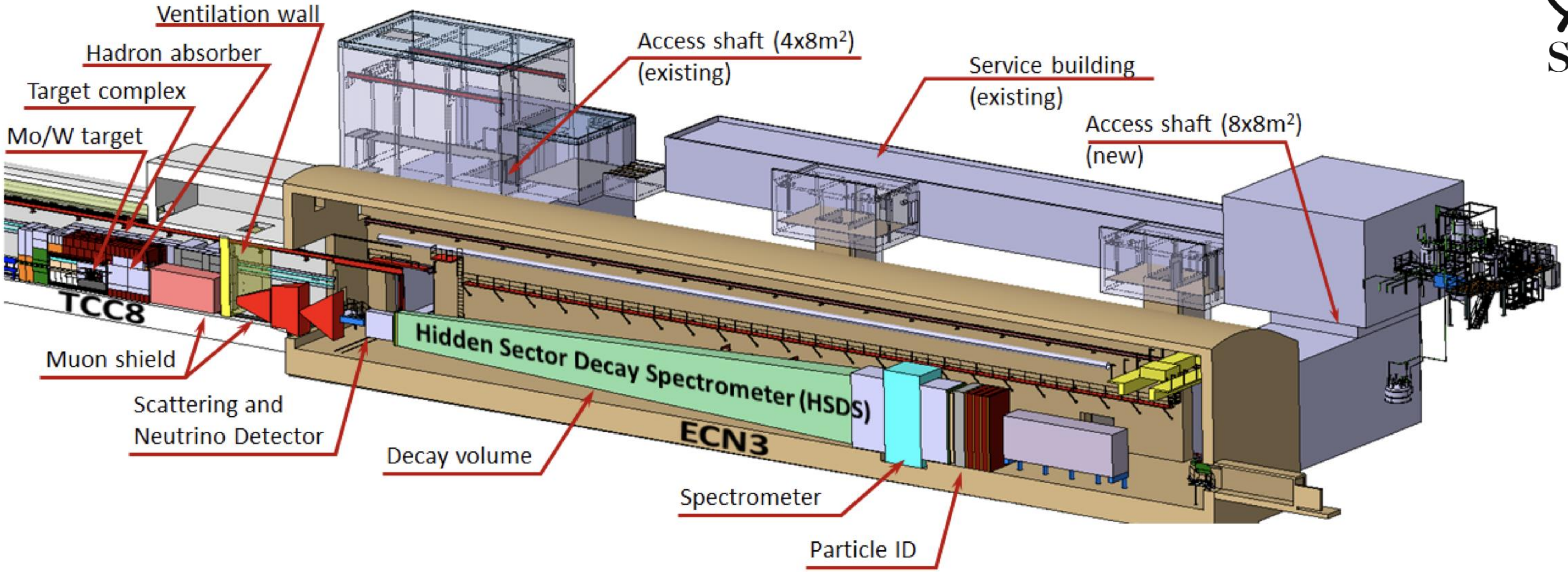
SHiP: Physics program

- Search for new physics:
  - Light dark matter (LDM)
  - Portals to hidden sector (HNLs, ALPs, etc.)
  - Capable of reaching the «physical floor» in the phase space of a much larger lifetime acceptance that can not be probed at colliders
- Unique access to SM neutrinos:
  - Rich neutrino physics program with sensitivity to NC and CC production channels for all types of neutrino
  - Several orders of magnitude more statistics to measure tau neutrino and antineutrino deep inelastic scattering cross sections
  - Study tau neutrino magnetic moment, neutrino-induced charm production, PDFs





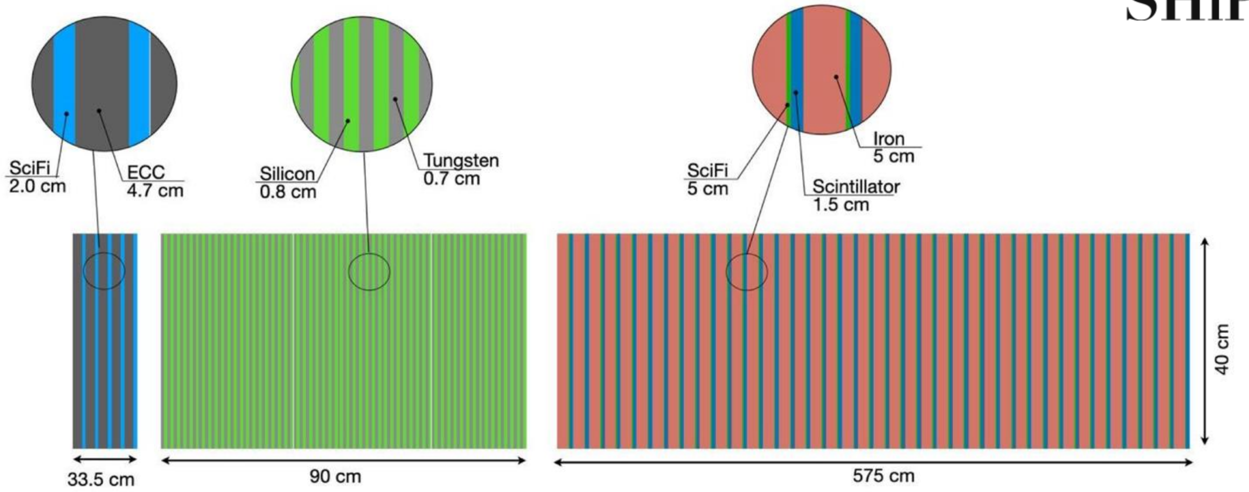
SHiP: Detector systems

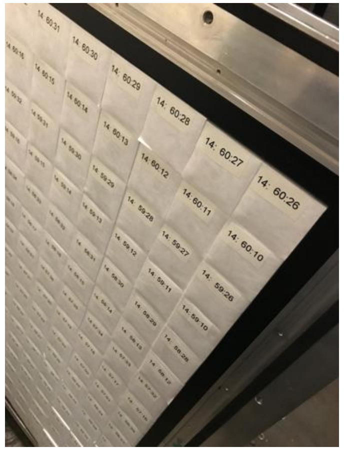


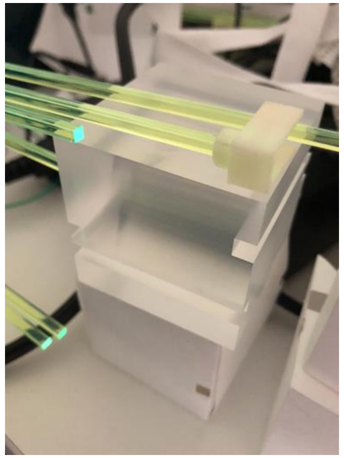
- A beam-dump experiment: a high-density tungsten target followed by a hadron absorber
- An active muon shield to deflect $2x10^{10}$ energetic muons escaping the target per spill
- The upstream Scattering and Neutrino Detector (SND) to study light dark matter scattering and SM neutrinos
- The downstream Hidden Sector Decay Spectrometer (HSDS) to reconstruct the decay vertices of FIPs and perform particle identification

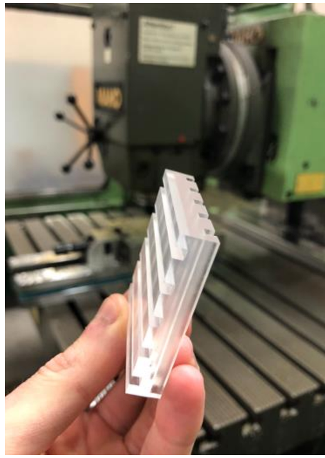
SHiP: A new calorimeter design

- **Give a new life to the scintillation material from the SoLid experiment in Belgium!**
- **Composition**: EJ-200 plastic scintillator detector with 40x40x1 cm^3 layers made of 5x5x1 cm^3 tiles
- Each detector layer optically isolated with XY optical fiber readout (BCF-91A) fed through grooves at 1 cm pitch
- Design options:
  - Veto: a charge particle upstream veto system (similar to SND@LHC); a few active layers with high detection efficiency
  - TileCal: a sampling calorimeter with active and 5 cm-thick passive (iron) layers



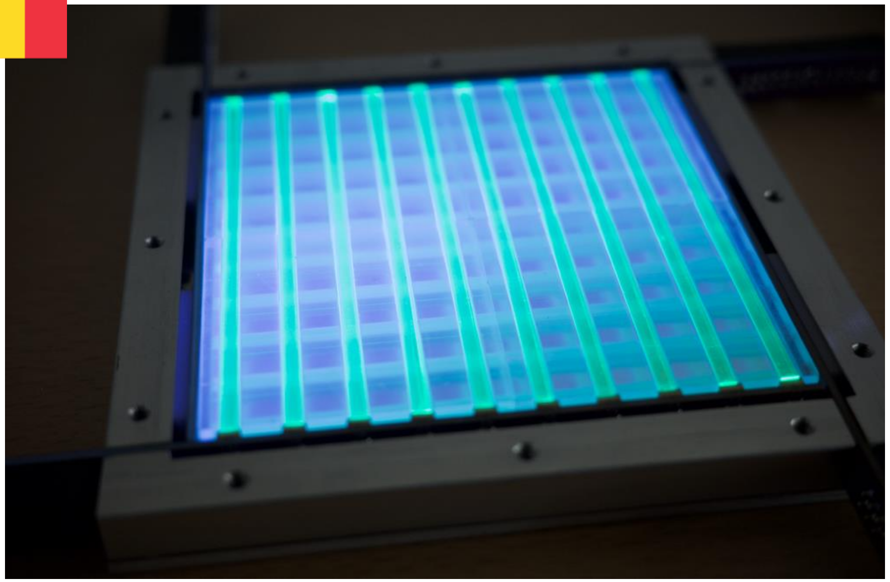


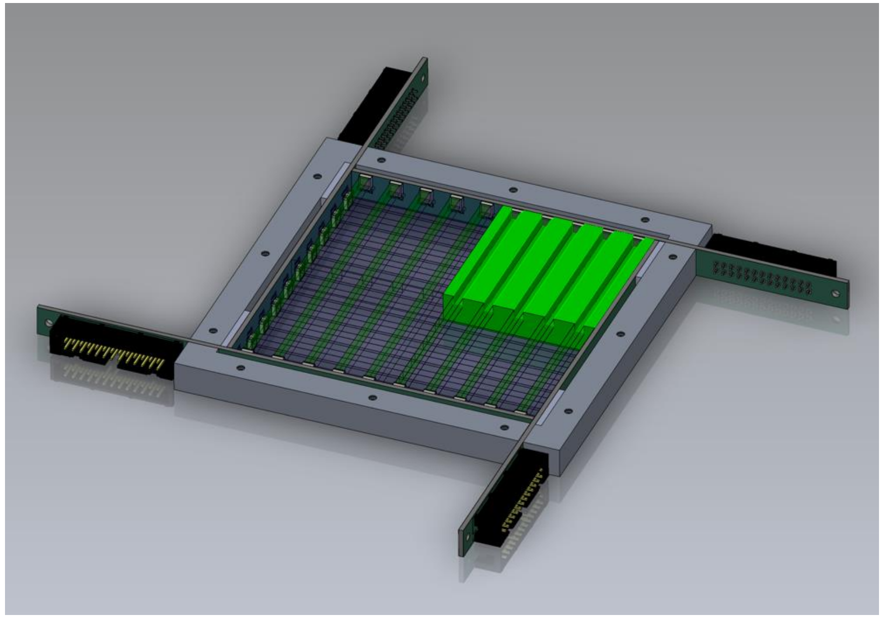


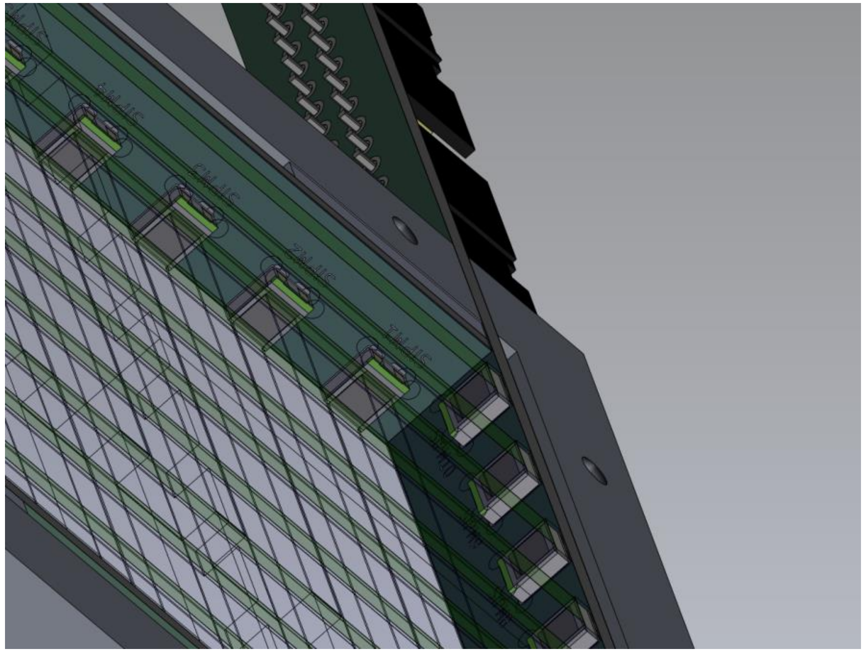


SHiP: Calorimeter prototype

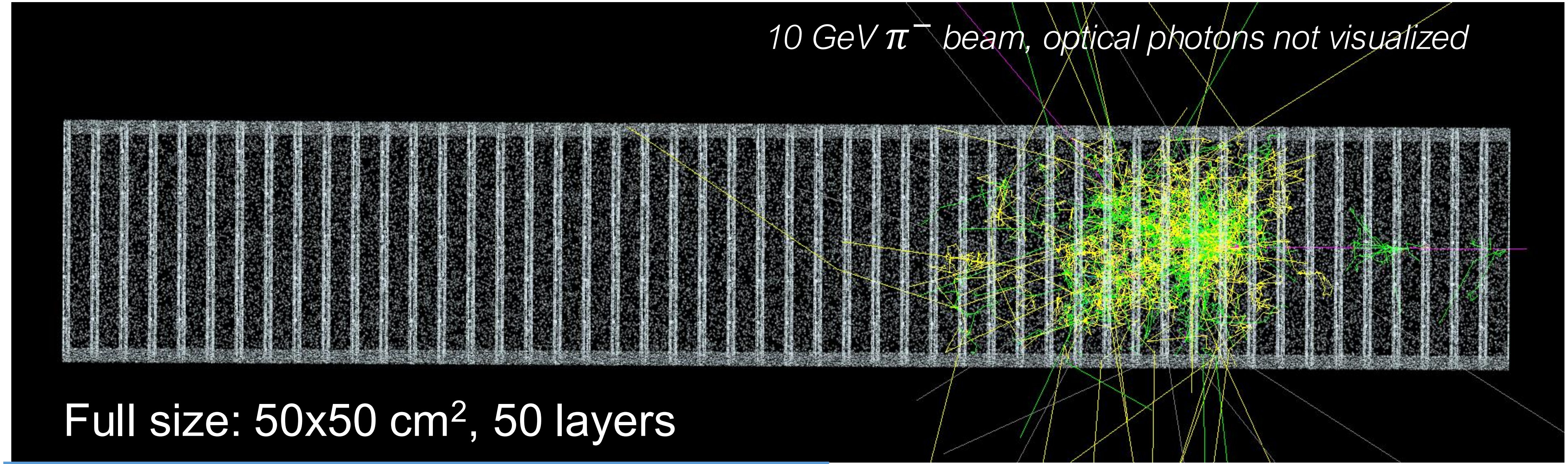
- At UGent, we built the first prototype this year
- Double-sided SiPM readout in X and Y
- The full detector will contain 6 planes and will be used in upcoming test beams at CERN later this year

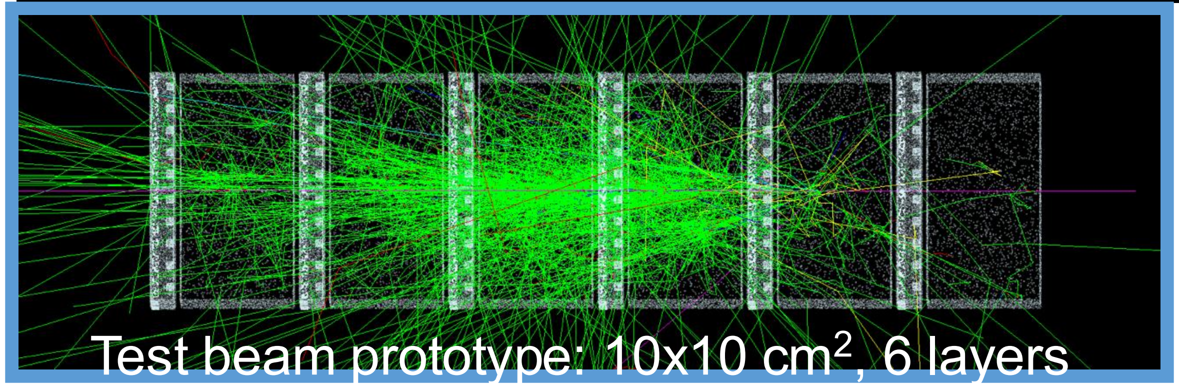






SHiP: Simulation model





Dimensions: 10x10x36 cm^3

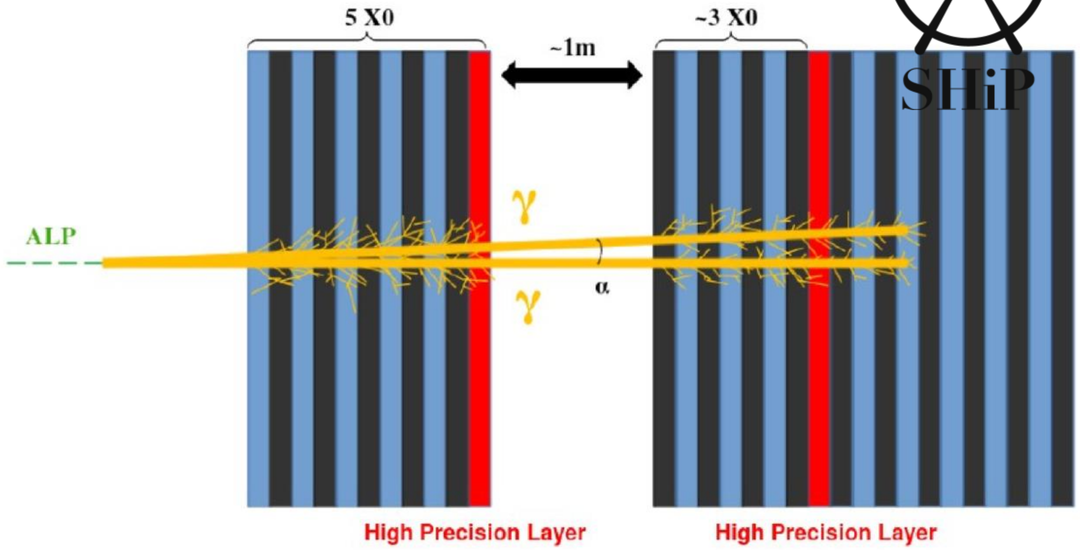
Weight: ≈ 30 kg

Readout channels: 120

- Developed a dedicated simulated calorimeter design with extruded plastic scintillators, optical fibers, and iron absorbers
- A test beam prototype with 6 layers of 10x10 cm^2 modules
- Single SiPM readout per fiber
- Granularity mainly defined by the availability of readout electronic channels

SHiP: High-precision layers

- Designing high-precision layers ($4x6m^2$) based on GEM technology for PID system
- Allow for precise tracking in hadronic showers
- Better particle identification with improved shower directionality reconstruction
- The first test beam is foreseen later this year



SHiP: Future and funding

- UGent became an official member of SHiP in 2024
- Already well-established collaborations with SND and PID detector groups of SHiP
- Engaged in a substantial R&D program with detector design and test beam studies
- UGent was successful in getting one FWO postdoctoral fellowship researcher this year (2025-2028) for this project

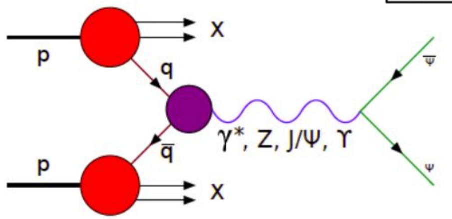
- Several test beams at CERN are scheduled this year
- UGent will study its first detector prototypes for calorimeter and high-precision detector systems

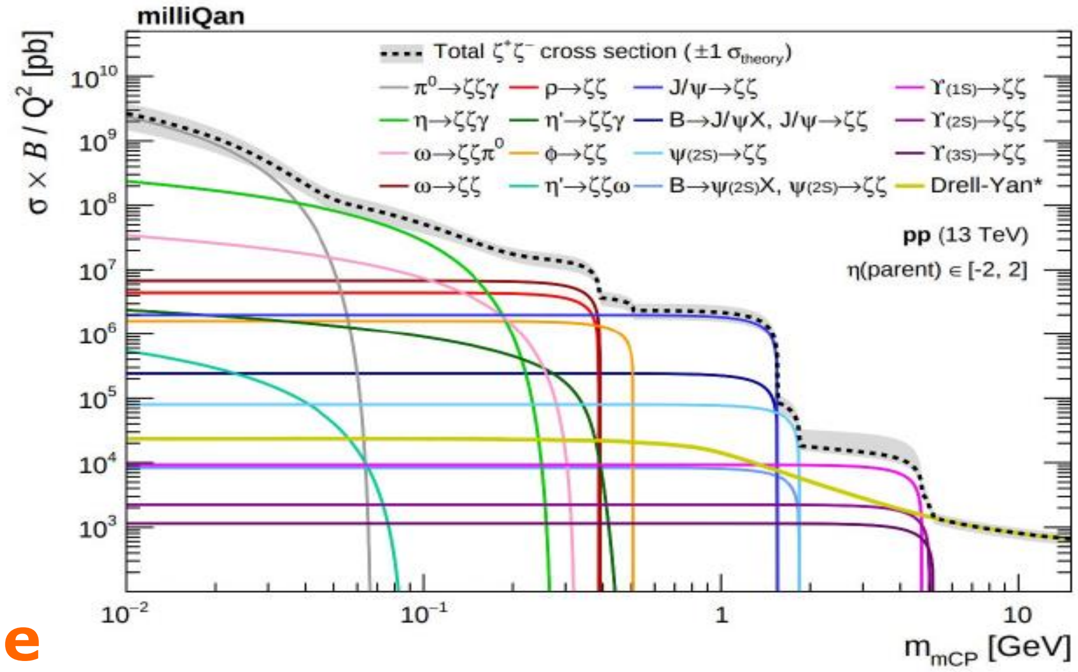
milliQan

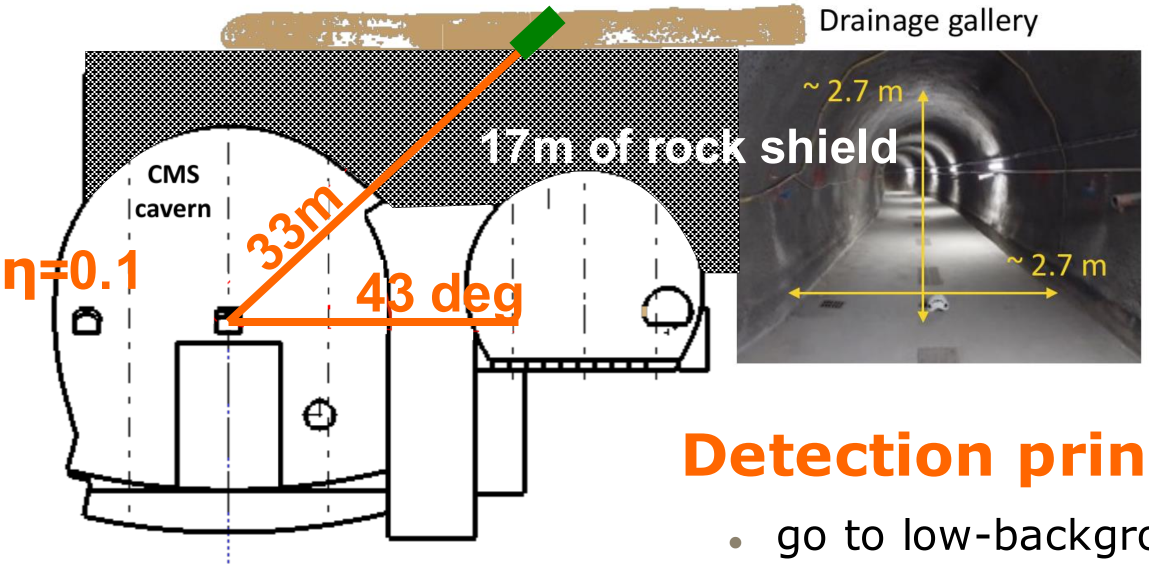
milliQan experiment

Millicharges particles? (mCPs)

- assume dark sector fermion coupled with extra U(1)
- appears as fermion with arbitrary small charge from kinetic mixing with hypercharge
- any process with electrons, produces mCPs!







Detection principle

- go to low-background area close to LHC collisions
- drainage gallery above CMS!
- require 4 coincident scintillation detections of single photo-electrons

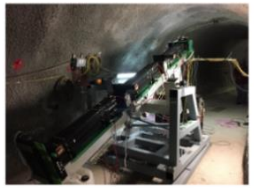
Timeline and funding

milliQan history

- technically part of CMS, but in practise independent collaboration of ~35 people

milliQan proposal

(2014)



milliQan Demonstrator Commissioned

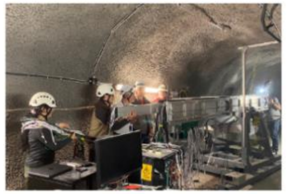
(2018)

milliQan demonstrator search

(2020)

Run 3 projections

(2021)



Bar Detector Construction Begins

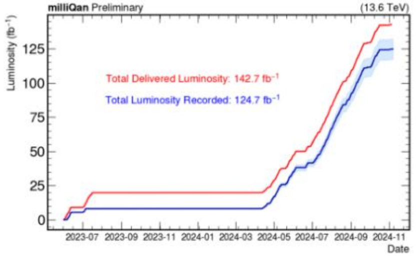
(2022)

Bar Detector Commissioned

(June 2023)

Slab Detector Commissioned

(July 2024)



Collected $124.7\ fb^{-1}$ data

(Dec 2024)

Bar detector search

(May 2025)

Paper submitted in June 2025:
arXiv:2506.02251 [hep-ex]

Paper accepted by PRL
on August 20, 2025.
https://doi.org/10.1103/rtp1-679h

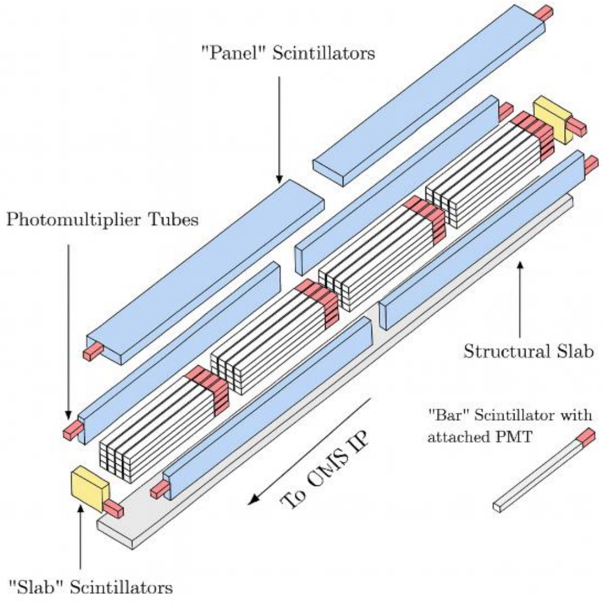
Belgium in milliQan

- VUB joined in 2019 
- financed participation with small university funds, contributed to commissioning
- one FWO CMS postdoc with small milliQan contribution ('21-’24)
- 50% parttime PhD student from FWO-FNRS WEAVE on mCPs from cosmic ray interactions ('24-'27)
- joint 25% parttime PhD student with UCLouvain from milliQan institute in Lebanon ('25-'26)

milliQan experiment

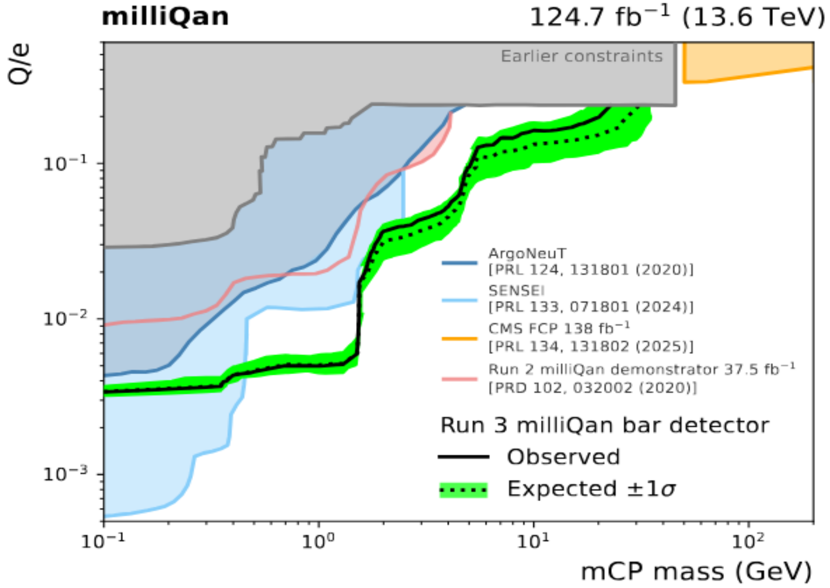
Bar detector

- 4 layers of 4x4 “bars”
- each bar a 5x5x60cm scintillator + PMT
- mCP signal is single photoelectron in 4 bars in straight line, within 15ns
- side, front and back panels veto cosmics and beam muons
- constructed in ‘23
- collected 125fb^{-1} in '23-'24, >56fb^{-1} in '25



First results this Summer

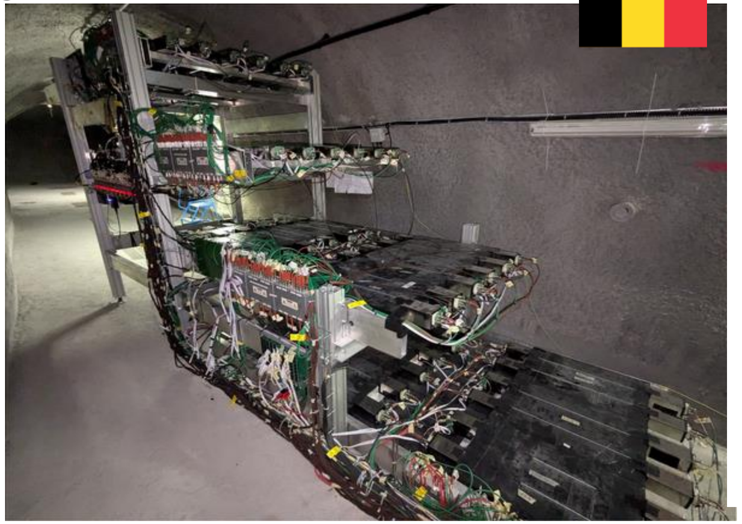
- unique sensitivity below ~20 GeV
- [arXiv:2506.02251](https://arxiv.org/abs/2506.02251), accepted by PRL
- 37 authors, 3 from VUB
- our contribution: fine timing calibration (“time-walk”)

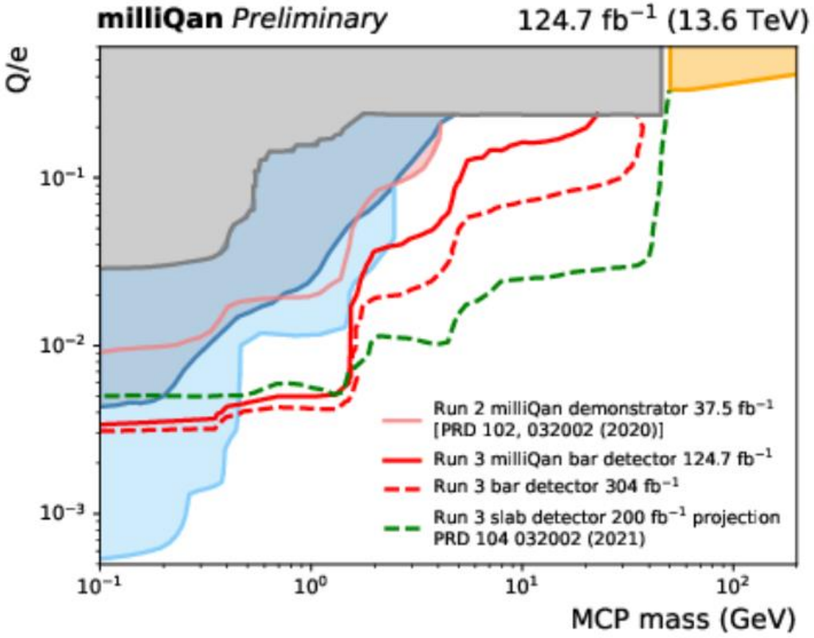


milliQan experiment

Slab detector

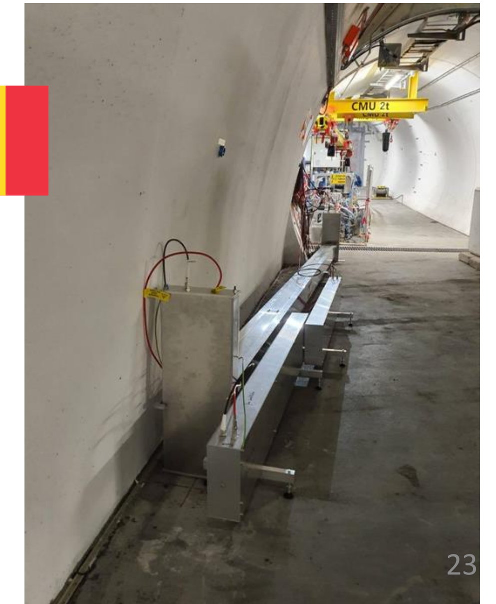
- larger surface, less scintillator depth
- increase acceptance at high mass
- construction finished Fall ‘24
- data analysis forthcoming
- 1 VUB student, new shared student with UCLouvain
- also started search for production from atmosphere
- joint FWO-FNRS WEAVE project with IceCube colleagues ULB





Future? FORMOSA

- much higher production rate forward
- 2025: demonstrator operational next to FASER
- 480m downstream of ATLAS
- new challenge from beam backgrounds
- full detector aiming for FPF



Summary

Summary

- Small but very active community
  - Participating in three experiments in different phases.
  - All three experiments are CERN based with focus in the search of new physics.
  - Exploring regions not accessible by large colliders
- Excellent « school » for experimental physics
  - For PhD students , but also for the more senior members.
- Man power
  - Atractiveness: difficult to compete with big experiments
  - Reduced funding
- Some projects are not well funded
  - Requiring « imaginative » solutions
  - Several subdetectors are inherited or recovered

UCLouvain

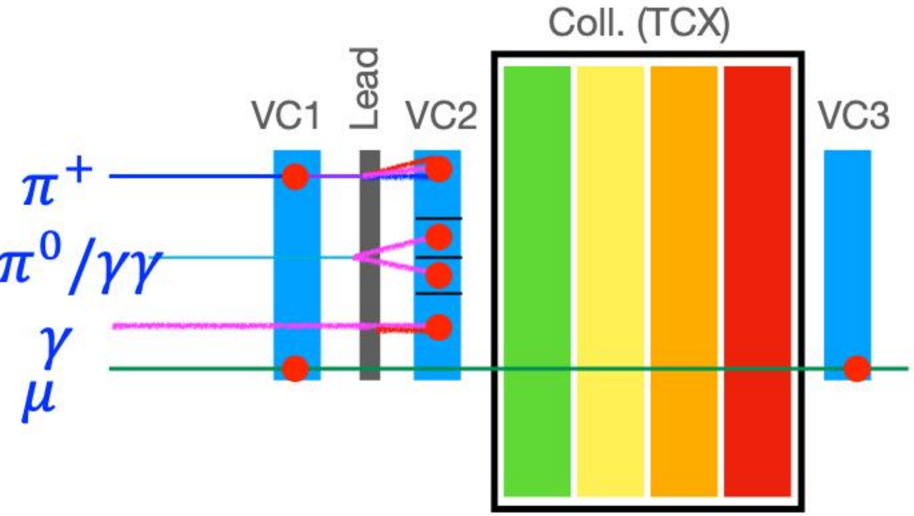
UNIVERSITEIT GENT

VUB VRIJE UNIVERSITEIT BRUSSEL

BACKUP

New upstream vetos: VetoCounter & ANTI0

[FELIX readout: Streaming Readout Workshop talk 2021]



VetoCounter

- Detect particles from decays upstream of final collimator.
- **Factor ~3 rejection** with ~2% accidental veto.

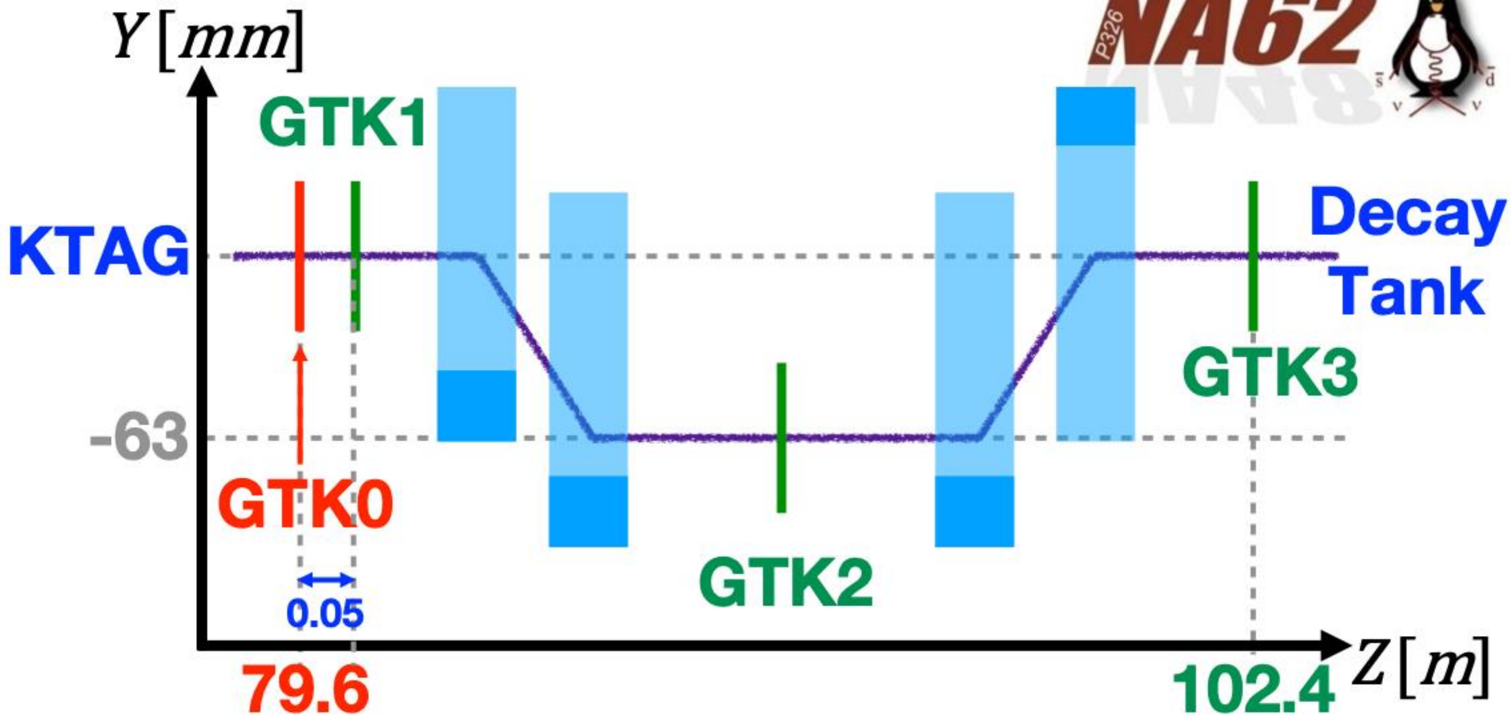
ANTI0

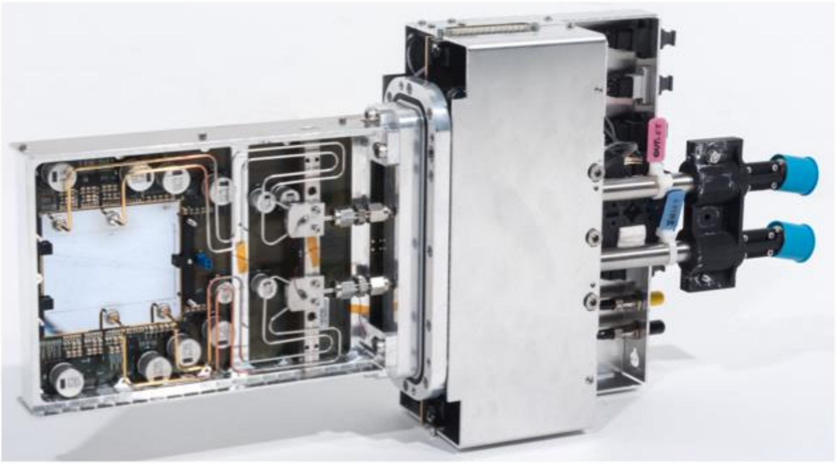
- Detect particles up to ~1 m from beam line.
- **Reject ~20% of upstream background** with <1% signal loss.

[SPSC report 2023][EP Newsletter, Dec21]

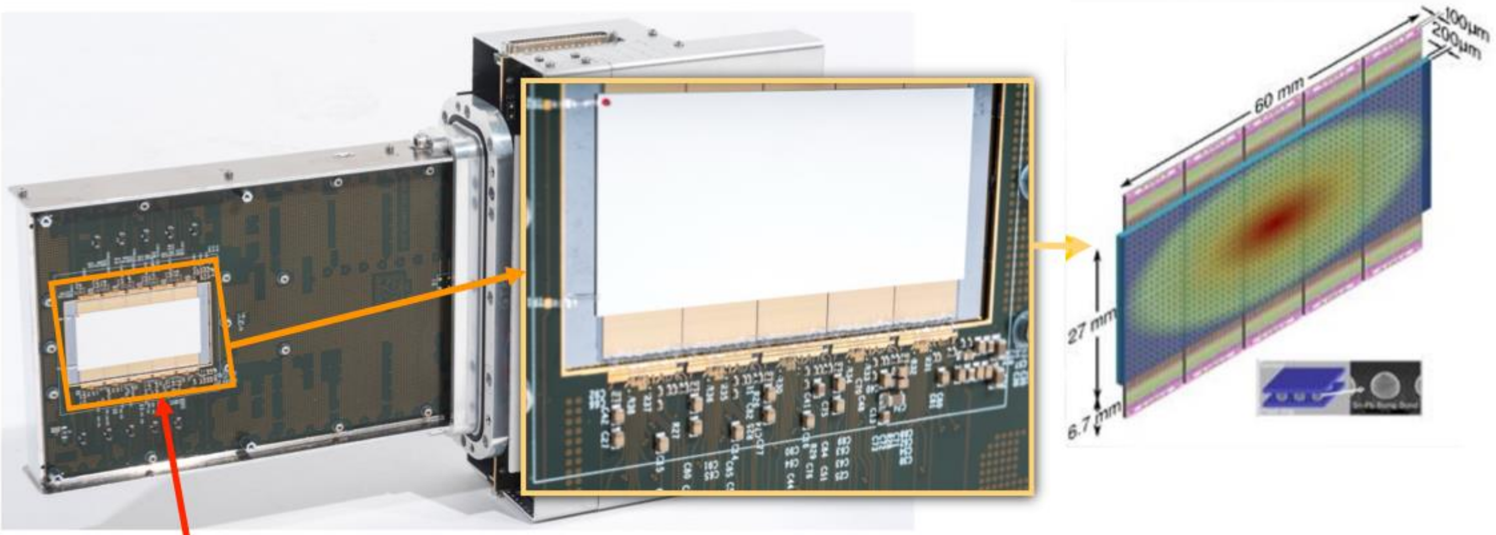
4th GTK station

- Si Pixel detector exposed to ~1GHz beam.
- Essential for $K^+ - \pi^+$ matching.
  - Measures K^+ 3-mom. & time
- 4th GTK station improves efficiency & pileup resilience.



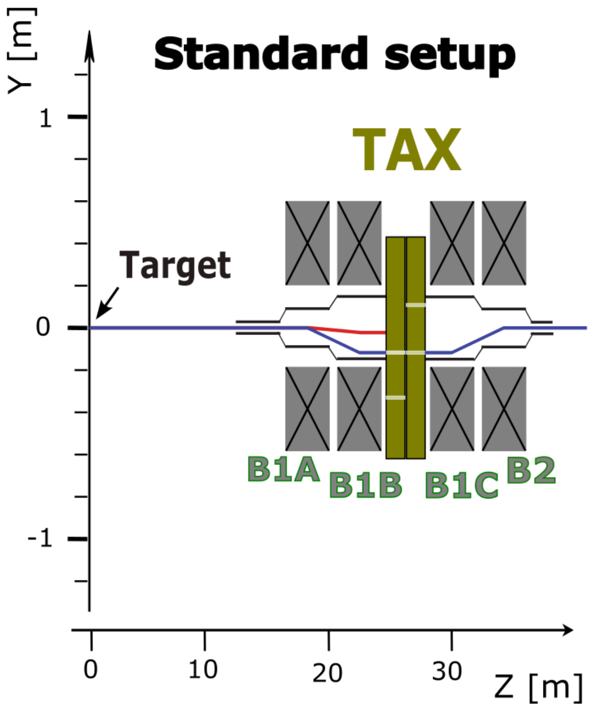


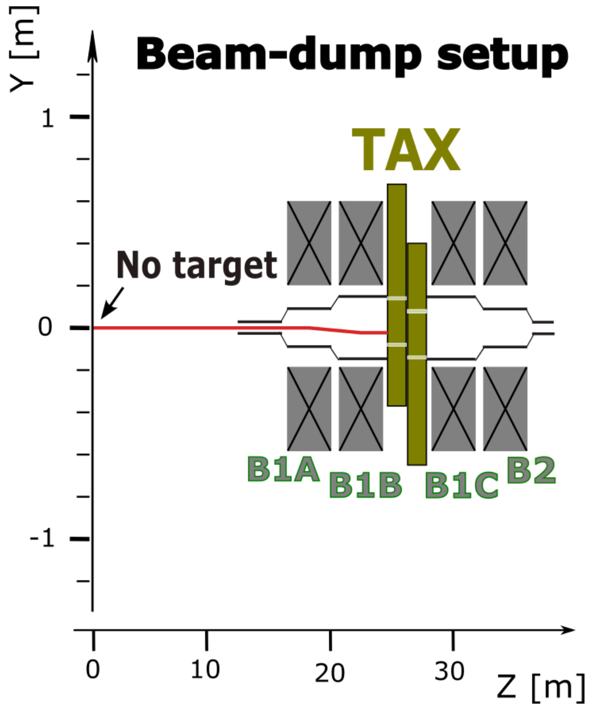
Cooling plate

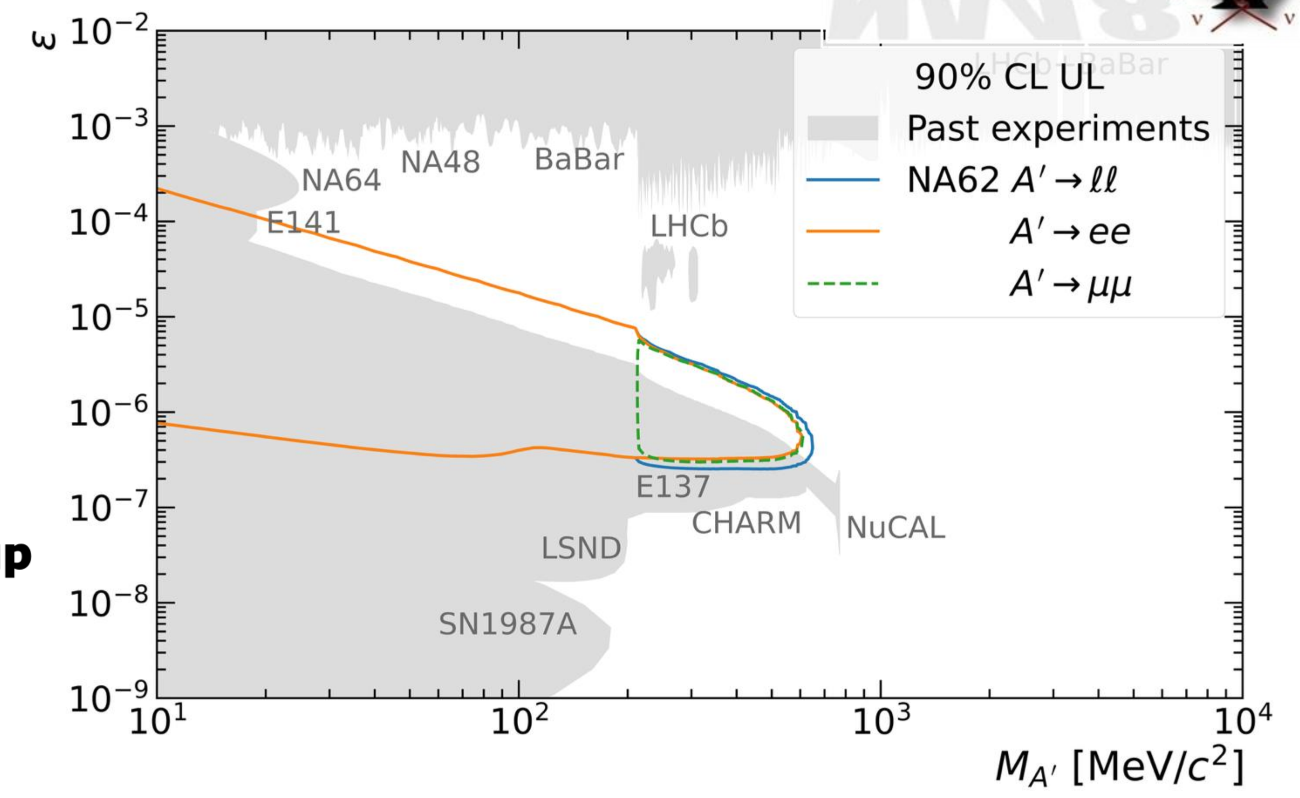


Si Pixels ~(30x60 mm active area)

NA62: Beam Dump

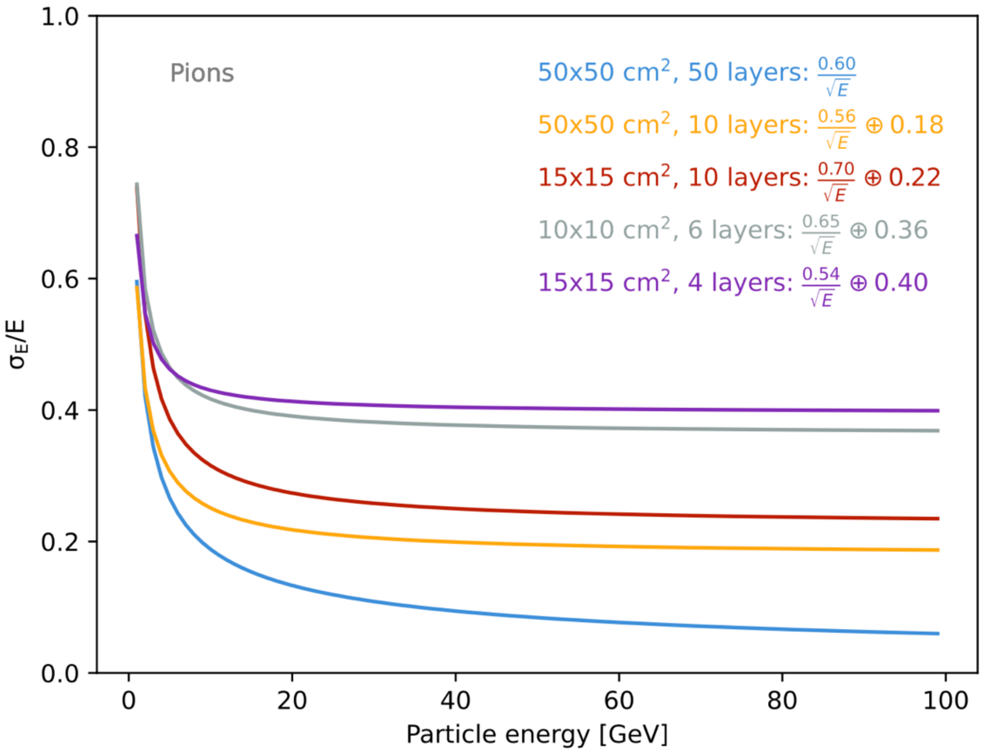


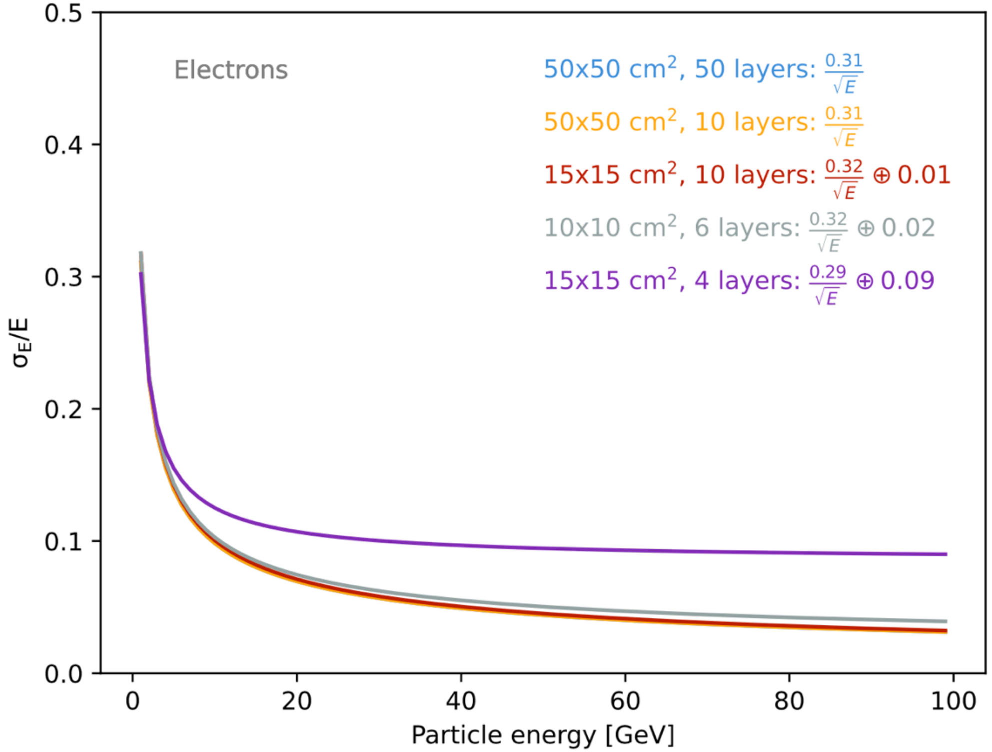




SHiP: Energy resolution

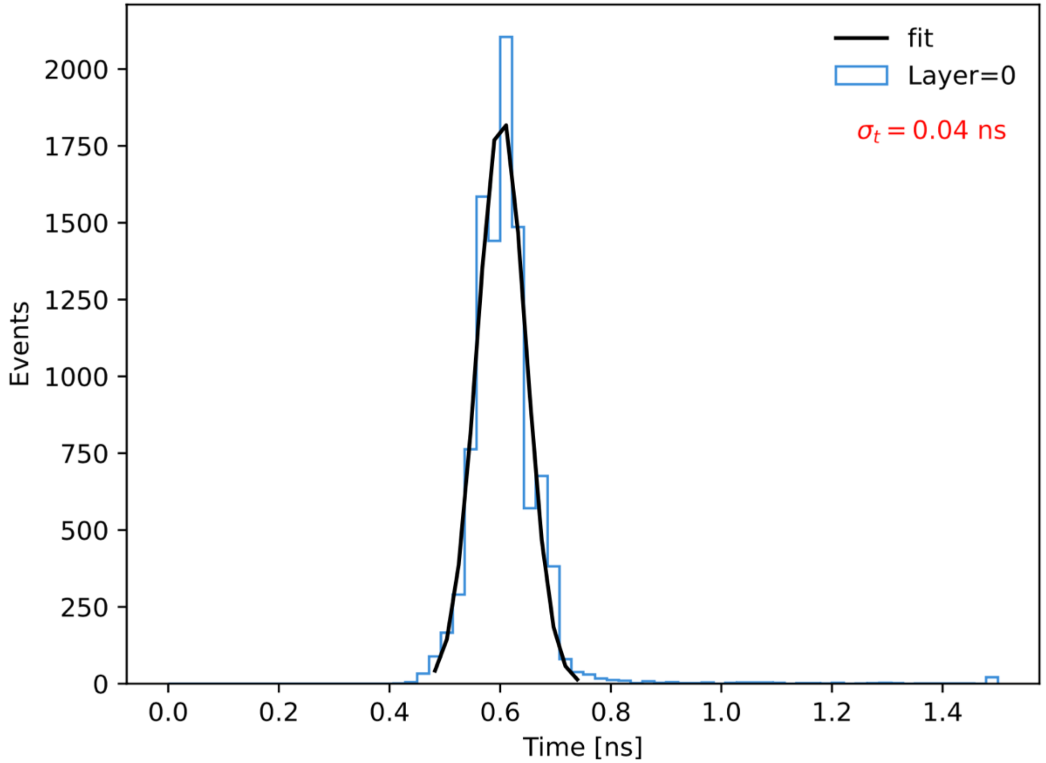
- Full-sized detector: expect $0.60/\sqrt{E}$ (pions) and $0.31/\sqrt{E}$ (electrons), dominated by statistical fluctuation
- Test beam prototype:
  - Require 10 MeV of deposited energy in the first scintillator layer
  - Pions: resolution is limited by the constant term due to significant shower leakage (lateral and longitudinal)
  - Electrons: sufficient containment of EM showers over the full energy range

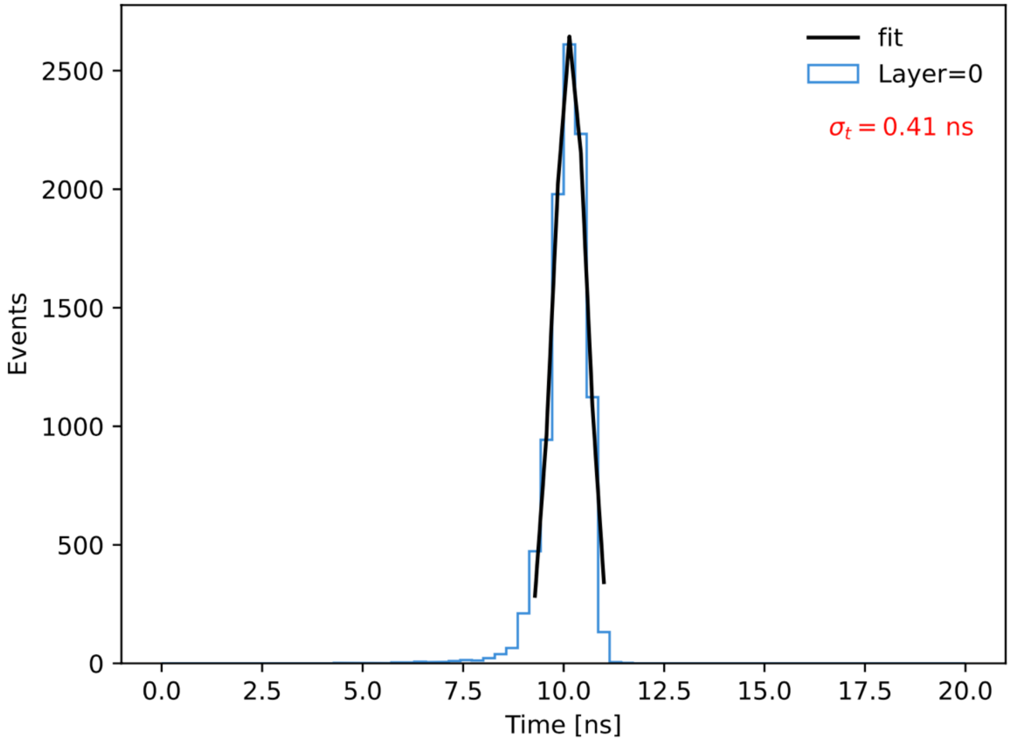




SHiP: Time resolution

- The ‘slow’ BCF-91A WLS fibers are used (decay time of ≈ 12 ns)
- Trigger on the 10th photoelectron or the average photon arrival time





- The intrinsic detector time resolution is below 1 ns
- Expect it to be further worsened (and mainly driven) by the electronic noise