L'esperimento NA62 al CERN

M. Mirra per il gruppo NA62-Napoli

Riunione Gruppo 1, Napoli 16/01/2025

Breaking news

CERN press release

NA62 experiment at CERN observes ultra-rare particle decay

In the Standard Model of particle physics, the odds of this decay occurring are less than one in 10 billion

25 SEPTEMBER, 2024

25 SETTEMBRE 2024

CERN: L'ESPERIMENTO NA62 OSSERVA UN PROCESSO RARISSIMO

INFN press release

UKRI press release

UK Research and Innovation

CERN reports first observation of ultra-rare particle decay

OCTOBER 1, 2024 | 5 MIN READ

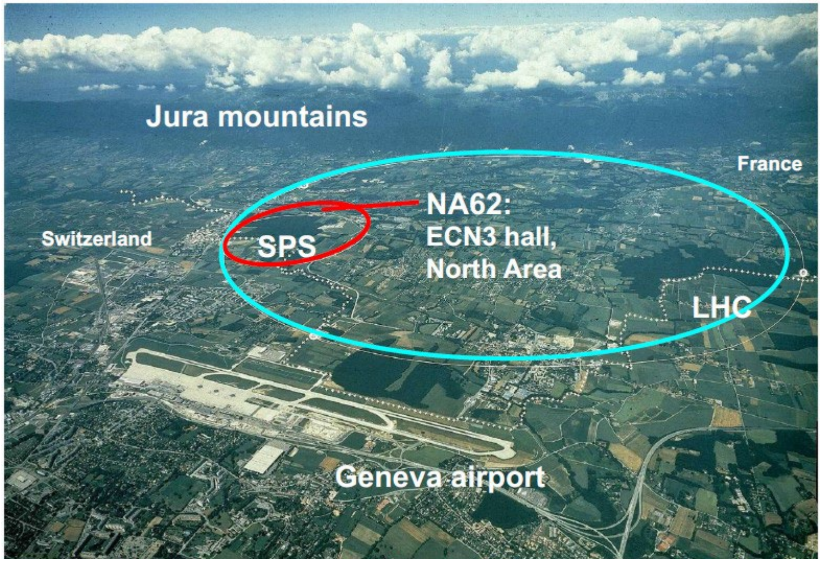
A One-in-10-Billion Particle Decay Hints at Hidden Physics

Physicists have detected a long-sought particle process that may suggest new forces and particles exist in the universe

Scientific American

Kaon experiments at CERN

Kaons have been fundamental in the development of the SM flavor sector
SPS experiments have been at the forefront of kaon physics for decades



- ✓ Fixed target experiment at CERN SPS.
- ✓ Main NA62 goal: BR($K^+ \to \pi^+ \nu\bar{\nu}$) measurement to 15% precision with a novel decay-in-flight technique.
- ✓ Officially approved to run up to LS3.
- ✓ Currently ~300 participants from 31 institutions.

NA31: K_S /K_L (1984-1990)
CPV

NA48, NA48/1: K_S/K_L(1997-2002)
Discovery of direct CPV, Re(ε'/ε), rare K_S and hyperon decays

NA48/2: K^+/ K^-(2003-2004)
Direct CPV, rare $K^\pm$ decays

NA62: K^+/ K^-(2007-2008)
$R_K = \Gamma(K_{e2}) / \Gamma(K_{\mu 2})$

NA62: K^+ (2016-2018)
Physics Run1

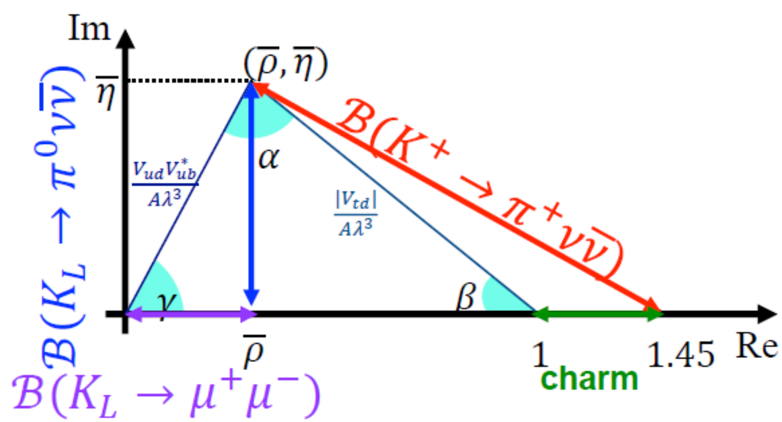
NA62: K^+ (2021-now)
Physics Run2

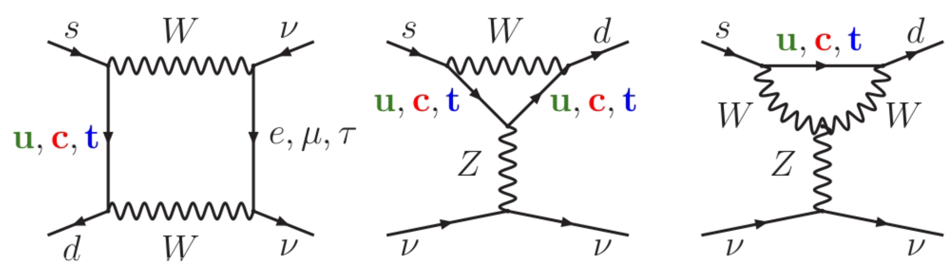
Seeking new physics through kaon decays

New physics at TeV scale not found (so far): explore higher mass scale via virtual production (ultrarare processes). Over-constraining unitary triangle via kaon decays is a crucial compatibility test of the SM

$K \to \pi\nu\bar{\nu}$ are extremely rare decays with rates very precisely predicted in SM:

- FCNC processes, no tree-level SM contribution
- $\sin^5\theta_C$ suppression (top loop dominance)
- Hadronic part from K_{e3} via isospin rotation





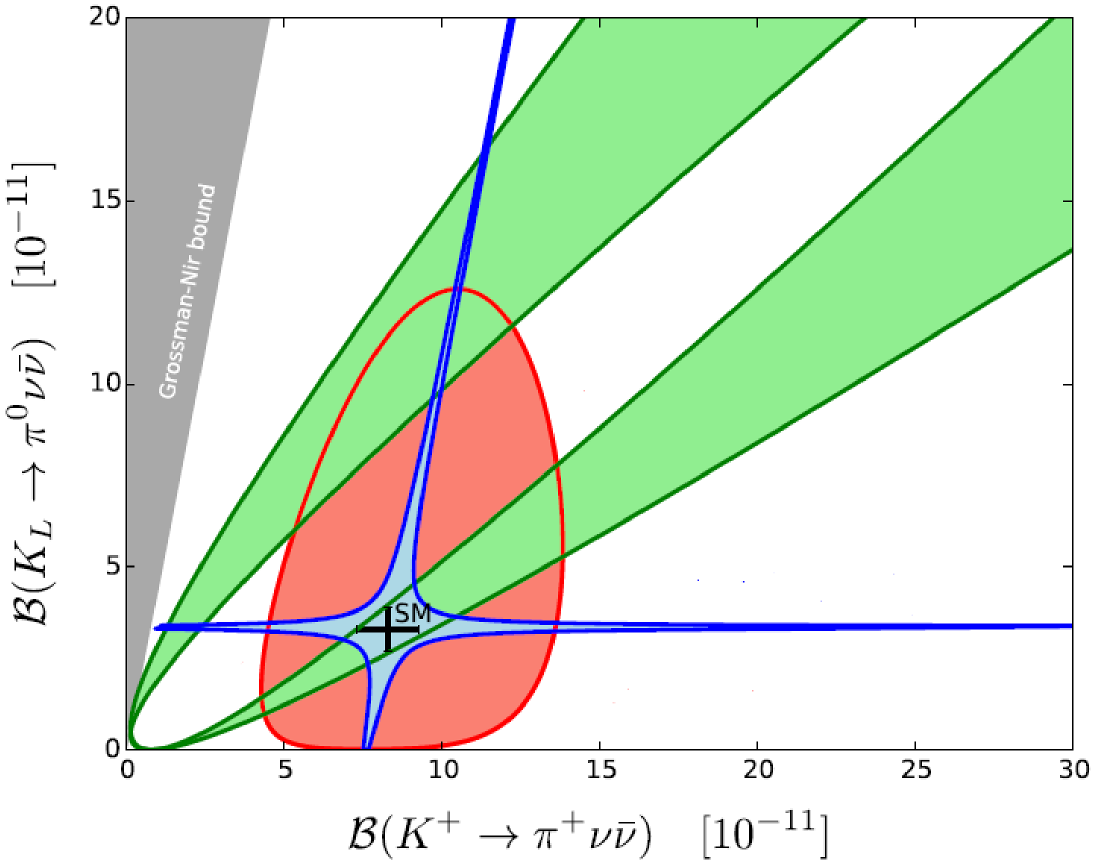
Decay Mode BR	SM [Buras et al. EPJC 82 (2022) 7, 615]	SM [D'Ambrosio et al. JHEP 09 (2022) 148]	Experimental Status
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.1}_{-3.5}) \times 10^{-11}$ (NA62)
$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 2 \times 10^{-9}$ (KOTO)

NA62 (2016–18 data): [JHEP 06 (2021) 093]

KOTO (2021 data): [Eur.Phys.J.C 84 (2024) 4, 377]

Correlations between BSM contributions to BRs of K^+ and K_L modes.

- **Must measure both to discriminate between BSM scenarios.**



JHEP 11 (2015) 166

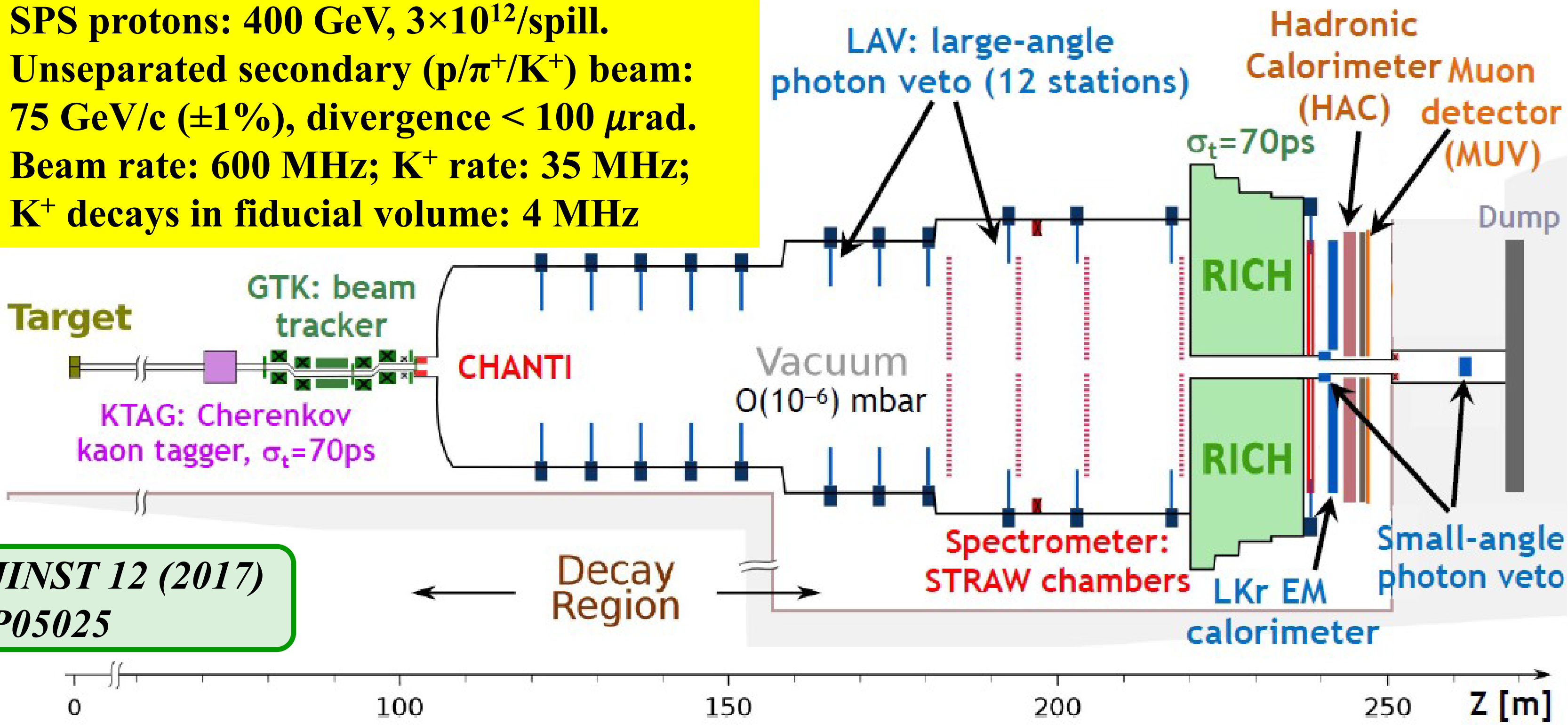
- **Models with a CKM-like structure of flavour interactions (e.g. MFV)**
- **Models with new flavour and CP-violating interactions in which either left or right handed currents fully dominate (e.g. Z or Z' FCNC scenarios)**
- **Models like Randall-Sundrum**
- **Grossman-Nir Bound:** model-independent relation

$$\frac{\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})}{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})}\frac{\tau_{K^+}}{\tau_{K_L}} \lesssim 1$$

$$\Rightarrow \mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \lesssim 4.3 \cdot \mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$$

Beamline and detector

SPS protons: 400 GeV, 3×10^{12}/spill.
Unseparated secondary ($p/\pi^+/K^+$) beam:
75 GeV/c (±1%), divergence < 100 μrad.
Beam rate: 600 MHz; K^+ rate: 35 MHz;
K^+ decays in fiducial volume: 4 MHz

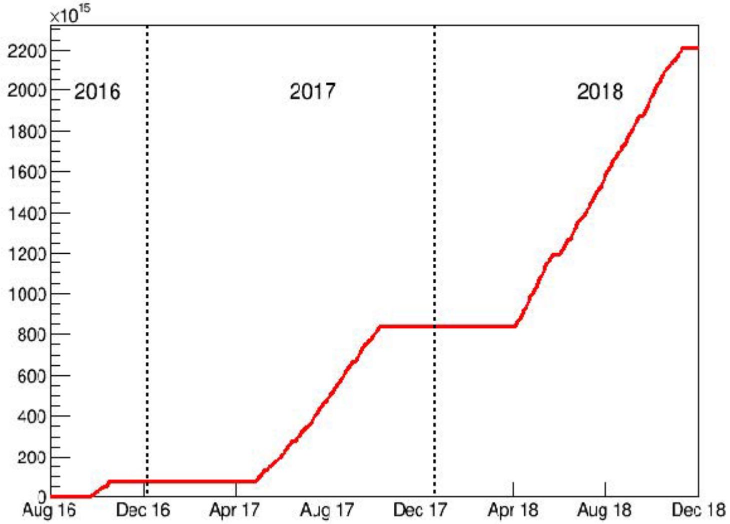


JINST 12 (2017) P05025

- ✓ **Excellent time resolution:** $\mathcal{O}$(100 ps) to match beam and daughter particle information
- ✓ **Kinematics:** rejection of main *K* modes 10^{-4} via kinematics reconstruction
- ✓ **PID capability (RICH+LKr+MUV):** $\mathcal{O}(10^{-7})$ muon suppression for 15GeV < p < 35 GeV
- ✓ **High-efficiency photon veto:** 10^{-7} rejection of π^0 for $E(\pi^0)$ > 40 GeV

NA62 timeline and dataset

Run 1 (2016-2018) integrated luminosity: 2.2×10^{18} POT collected

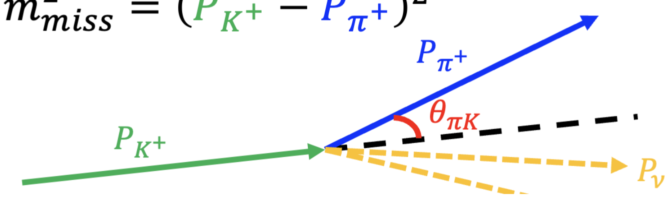


- **Commissioning run 2015: minimum bias data ($\sim3\times10^{10}$ protons/pulse).**
- **Physics run 2016 (30 days, $\sim1.3\times10^{12}$ ppp): 2×10^{11} useful K^+ decays.**
- **Physics run 2017 (160 days, $\sim1.9\times10^{12}$ ppp): 2×10^{12} useful K^+ decays.**
- **Physics run 2018 (217 days, $\sim2.3\times10^{12}$ ppp): 4×10^{12} useful K^+ decays.**
- **Run 2 in progress: June 2021 till LS3 ($\sim3\times10^{12}$ ppp + upgraded detector).**

The story so far: $K^+ \to \pi^+ \nu\bar{\nu}$ with 2016-2018 data

Signal: BR = $(8.60 \pm 0.42) \times 10^{-11}$

$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$



K track in
π track out
No other particles
in final state

Main backgrounds

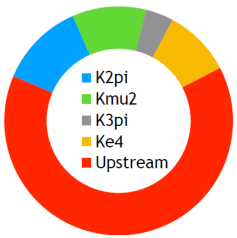
Upstream beam background

$K^+ \to \mu^+ \nu(\gamma)$	BR = 63.5%
$K^+ \to \pi^+ \pi^0(\gamma)$	BR = 20.7%
$K^+ \to \pi^+ \pi^+ \pi^-$	BR = 5.58%

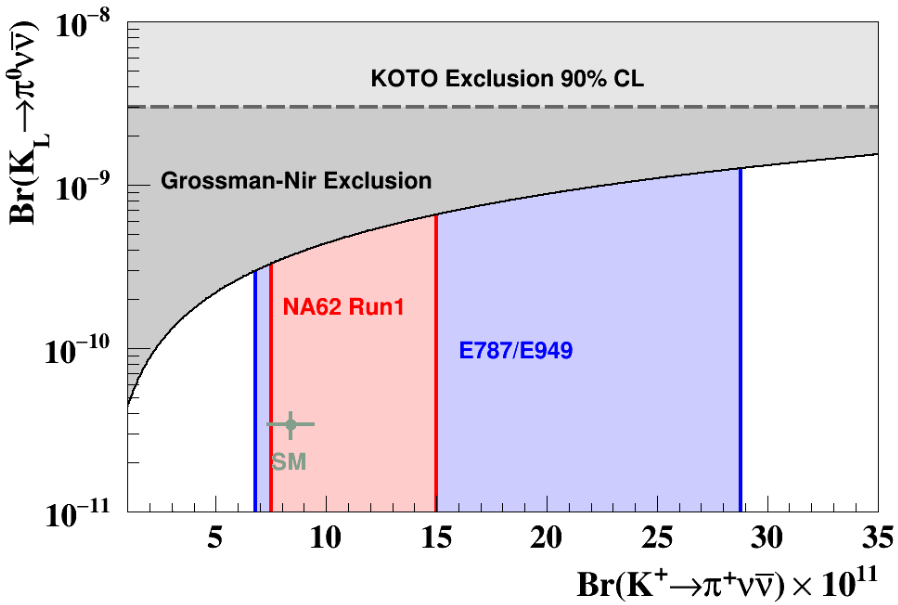
Summary of NA62 Run 1:

NA62 2016-2018 data :

- Expected SM sig: $10.01 \pm 0.42_{sys} \pm 1.19_{ext}$
- Expected bkg: $7.03^{+1.05}_{-0.82}$ evts
- Upstream largest background



- 20 events observed



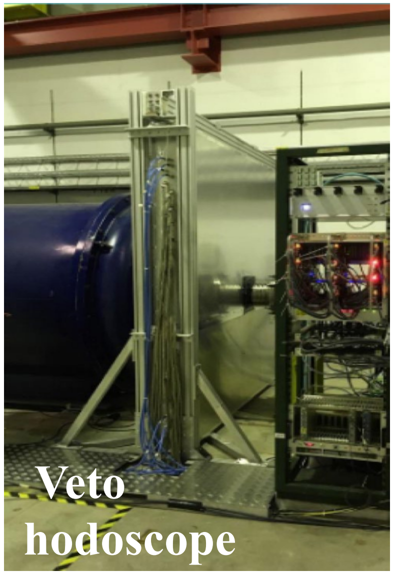
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.4}\,|_{stat} \pm 0.9_{sys}\right) \times 10^{-11}$$ (3.4σ significance)

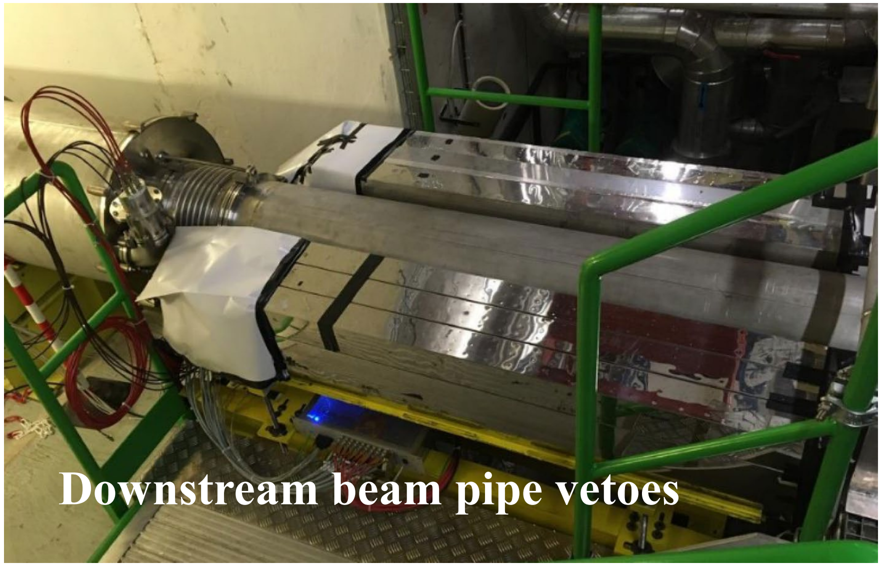
JHEP 06 (2021) 093

NA62 Run 2

Key modifications during LS2 to reduce background from upstream decays and interactions:

- **4th GTK (Kaon beam tracker) & rearrange GTK achromat (GTK2 upstream of scraper). New veto hodoscope upstream of decay volume and additional veto counters around downstream beam pipe**
- **New downstream veto for photon conversion in the beampipe**
- **Intensity increased by~ 35% with respect to 2018 [450 → 600 MHz].**
- **Improvements to the trigger configuration**





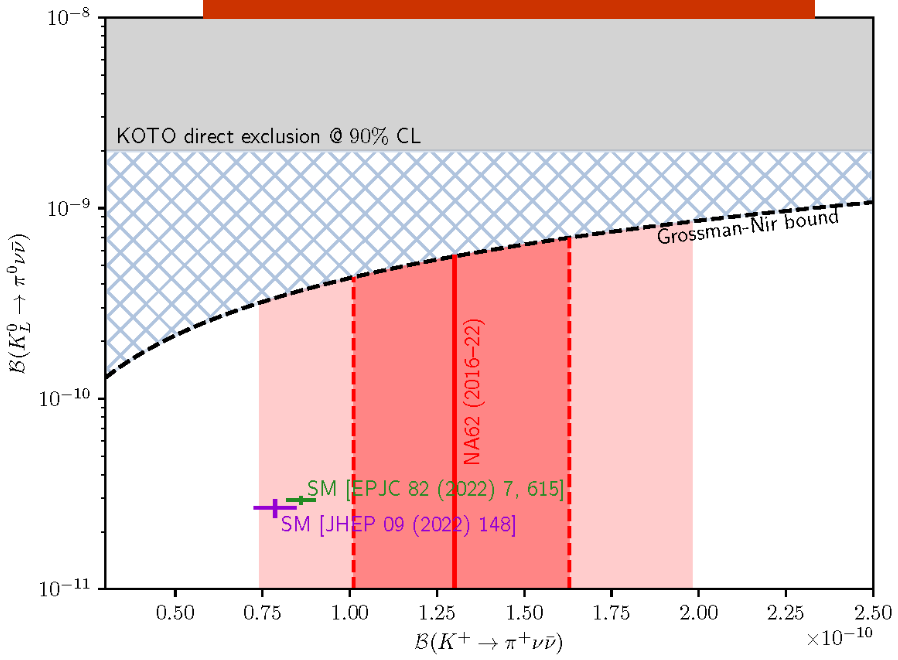
Results in context

- ✓ New NA62 result with 2021-2022 data (see R. Fiorenza's talk)

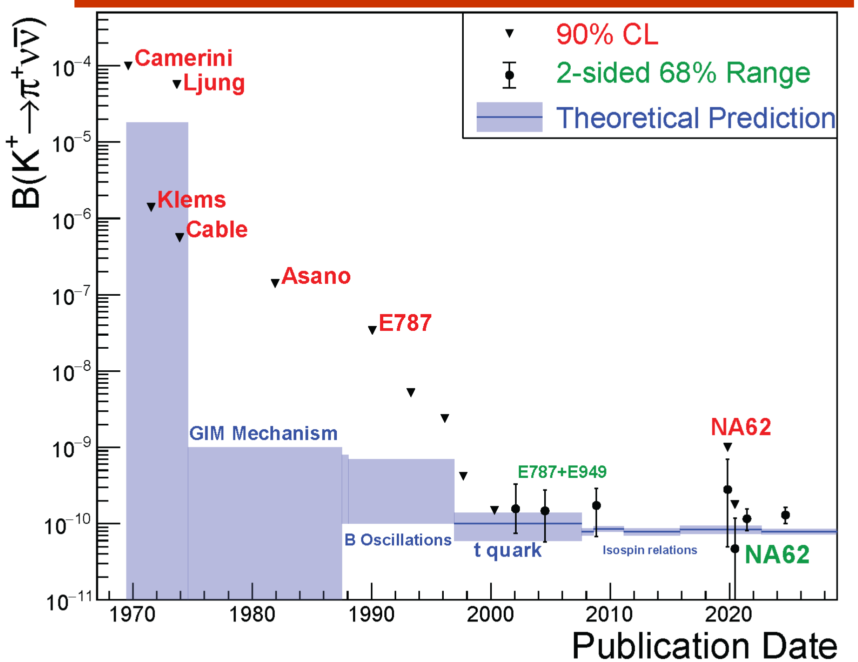
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(13.0^{+3.0}_{-2.7}\,|_{stat} \pm 1.3_{sys}\right) \times 10^{-11} \quad \text{[arXiv:2412.12015]}$$

- ✓ Central value moved up; the combined NA62 result is consistent with the SM expectation within 1.7σ.
- ✓ Fractional uncertainty decreased: 40% to 25%
- ✓ Bkg-only hypothesis rejected with significance Z>5
- ✓ The full NA62 dataset will clarify the agreement or tension with the SM expectation.

Global $K \to \pi\nu\bar{\nu}$ status



Time evolution of $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$



A general purpose experiment in kaon sector

NA62 P326

Flavour Physics with kaons

Hidden sector Physics

Search for New Physics at the EW scale with sizeable coupling to SM particles via indirect effects in loops:

Experiment main goal:
BR($K^+ \to \pi^+ \nu\nu$)

Search for lepton flavour and number violation, rare and forbidden decays:

$K^+ \to \pi^- e^+ e^+ (\gamma)$
$K^+ \to \pi^- \mu^+ \mu^+ (\gamma)$
$K^+ \to \gamma l^+ \nu$
$K^+ \to \pi^+ \mu^\pm e^\mp (\gamma)$
$K^+ \to \pi^- \mu^+ e^+ (\gamma)$
$\pi^0 \to e^+ e^-$

Search for New Physics below the EW scale (MeV-GeV) feebly-coupled to SM particles via direct detection of long-lived particles:

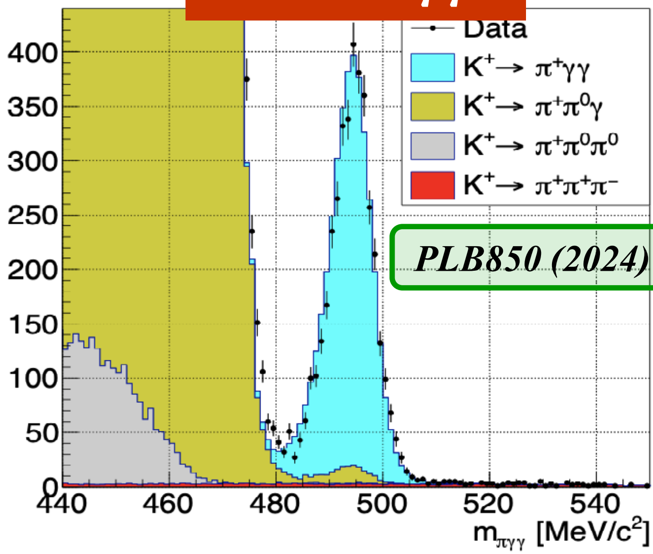
Heavy neutral Lepton(H)
Dark Photon(A'), Axion Like Particle (ALPs), Dark Scalar (S) in K decays:
$K^+ \to \mu^+ H$, $K^+ \to e^+ H$
$K^+ \to \pi^+ \pi^0$ with $\pi^0 \to A'\gamma$

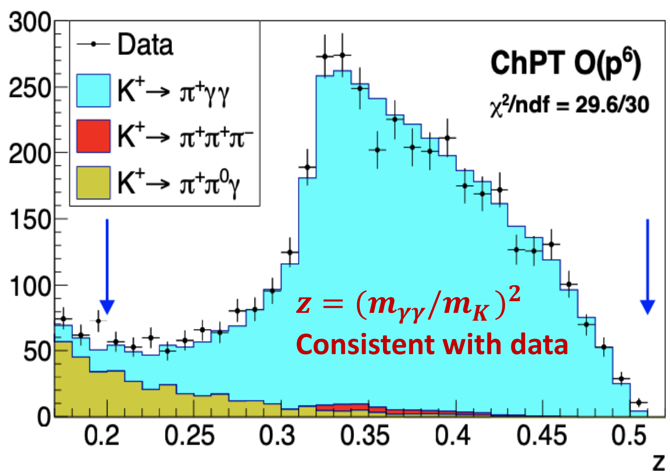
A general purpose experiment in kaon sector

Selected rare decays

$K^+ \to \pi^+\gamma\gamma$

PLB850 (2024) 138513





$z = (m_{\gamma\gamma}/m_K)^2$

Consistent with data

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

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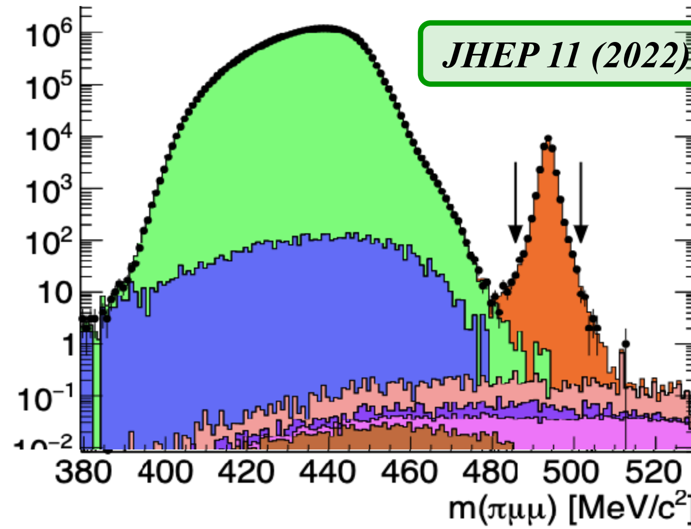
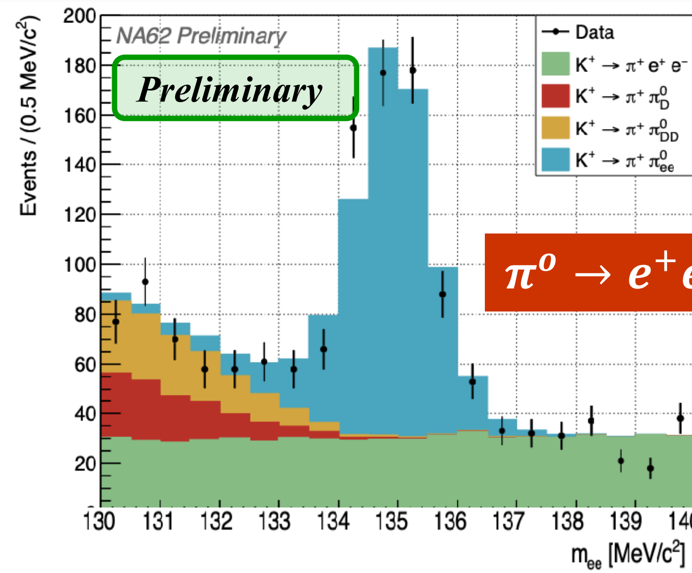


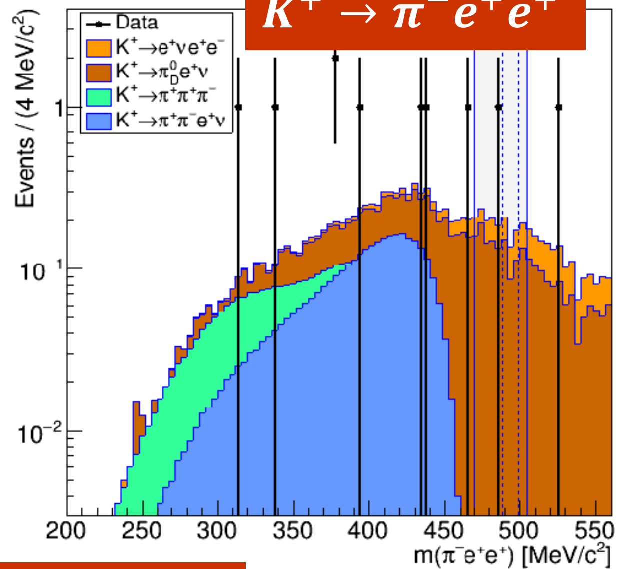
Preliminary

$\pi^0 \to e^+e^-$

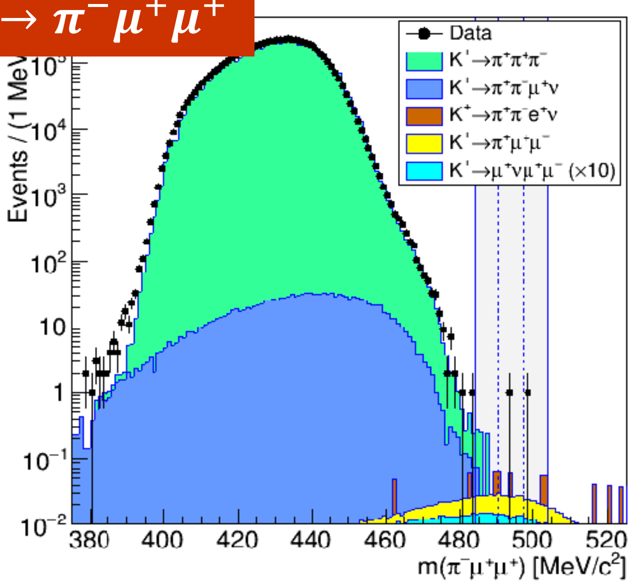


A general purpose experiment in kaon sector

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

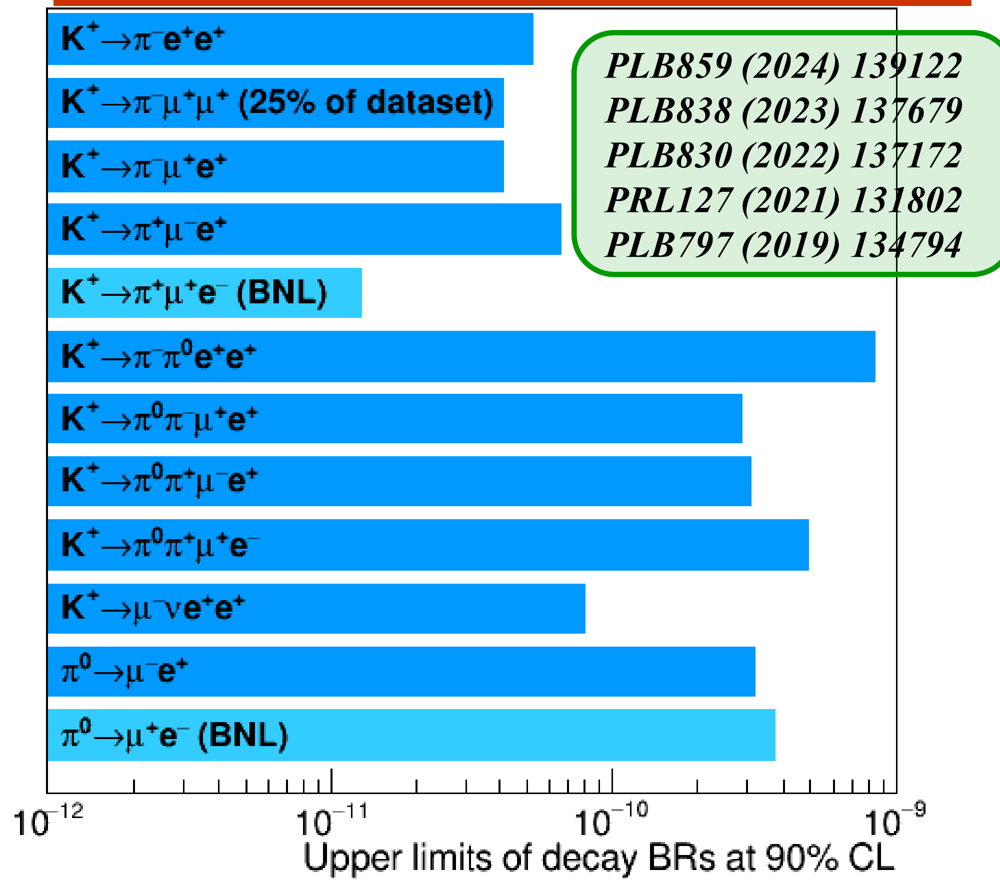


$K^+ \to \pi^- \mu^+ \mu^+$



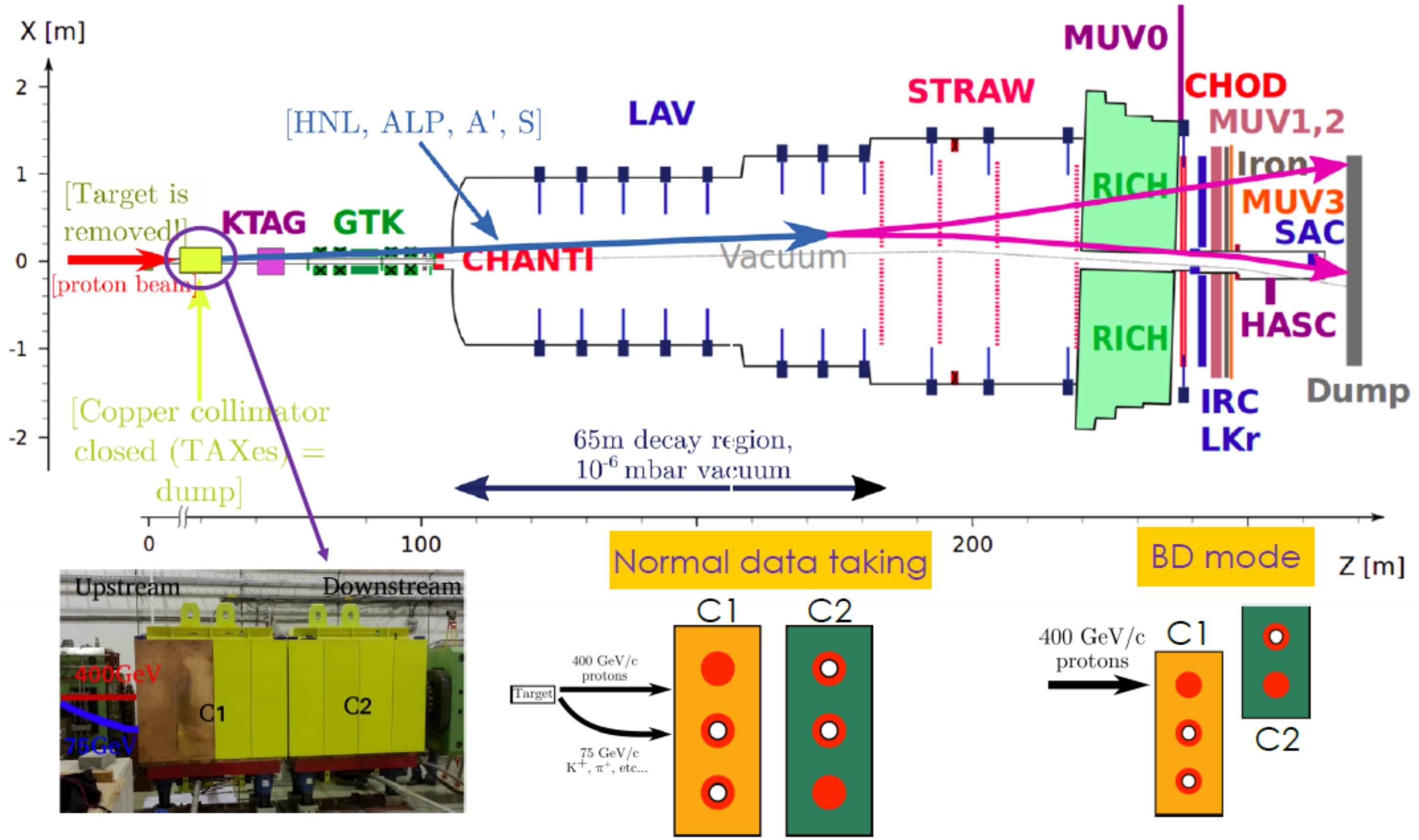
A comprehensive programme of searches for LFV/LNV kaon and pion decays: 10 decay modes addressed so far.

LNV/LFV K+ and π^0 decays, NA62 Run 1



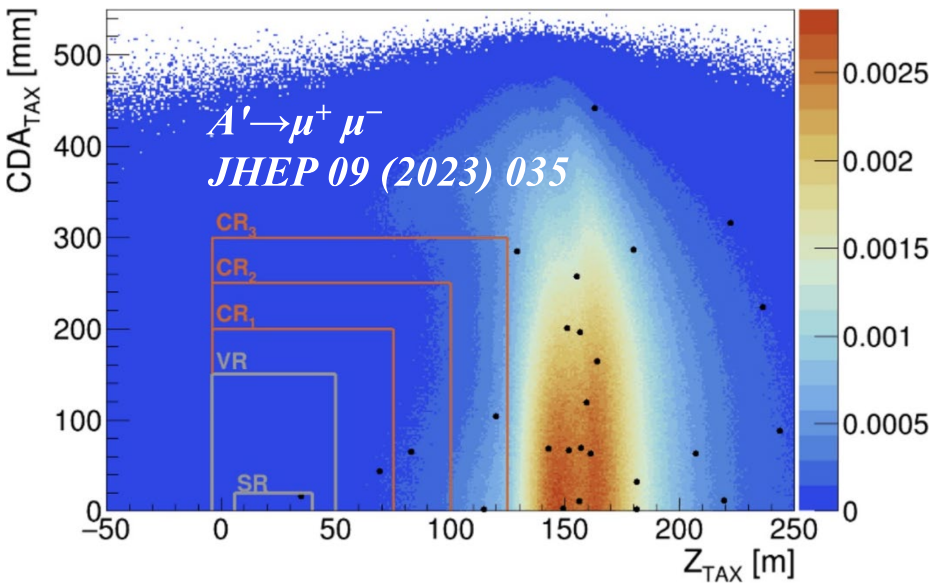
NA62 in dump mode

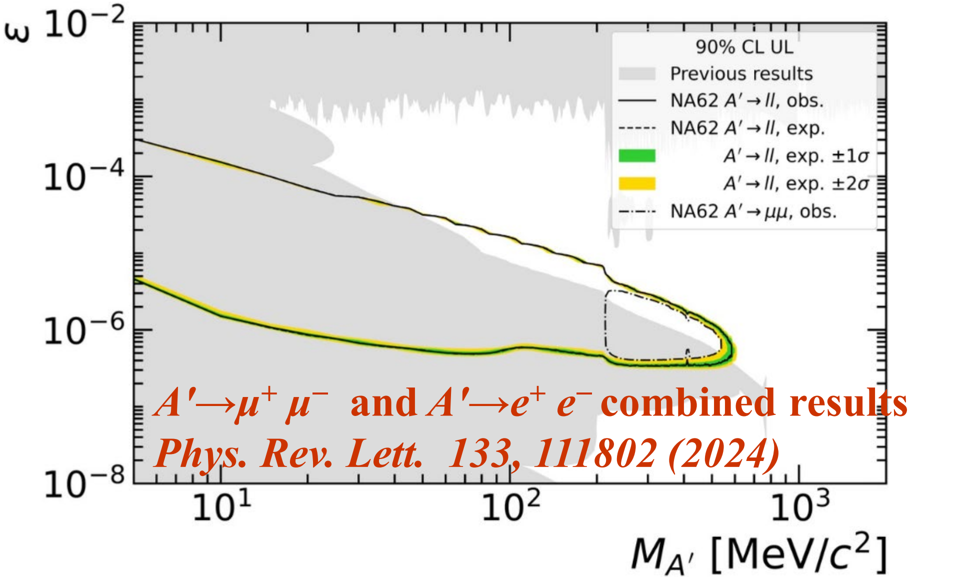
Beam dump mode: 22 λ_{int} Cu-Fe collimators (TAX) used as target removing the Be target
Search for dark sector particles production in interaction with TAXs decaying into visible final states in the NA62 experimental apparatus
Beam-dump dataset: so far, 6×10^{17} pot collected in 30 days; 10^{18} pot to be collected by end of NA62 (LS3)



NA62 in dump mode: dark photon search $A' \to \ell^+ \ell^-$

- **Dark photon A′:**
  - **extra U(1) massive gauge singlet**
  - **mixing with SM hypercharge**
  - **ε and $M_{A'}$ are free parameters**
- **Require $\ell^+\ell^-$ vertex in FV and pointing back to beam interaction point in TAX (CDA vs Z_{TAX})**
- **Backgrounds:**
  - **Prompt: interactions of single halo μ with material upstream of/inside FV**
  - **Combinatorial: accidental coincidence of single halo μ**





Naples working group

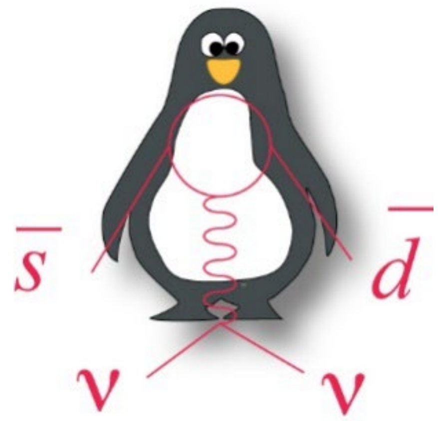
F. Ambrosino(PO) - Deputy Spokesperson	60%
V. Bottiglieri (Borsa)	80%
C. Di Donato (PA)	20%
R. Fiorenza (AdR)	100%
M. Francesconi (Ric. INFN)	30%
R. Giordano(PA)	30%

P. Massarotti(PA)	25%
M. Mirra (Ric. INFN) - Responsabile Locale	40%
M. Napolitano(senior)	
I. Rosa(PhD–end 2026)	100%
G. Saracino(PA)	60%
Tariq Junaid (AdR)	20%

5.65 FTE

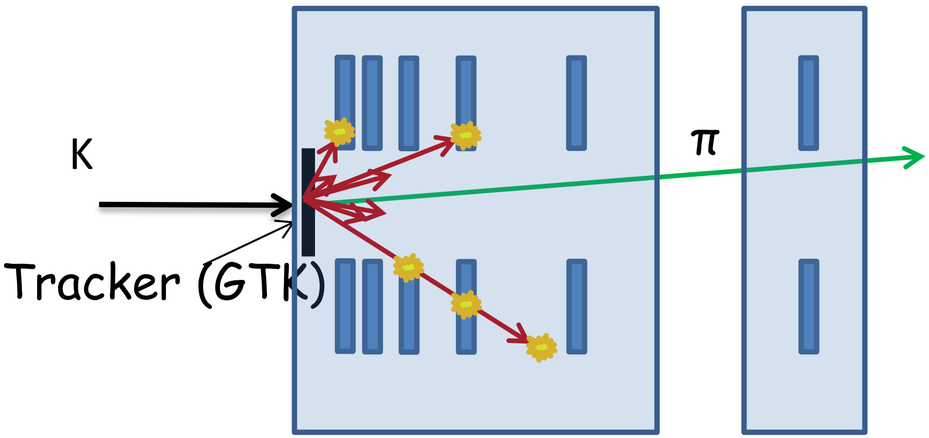
Activities in NA62

- **Full responsabily of the CHANTI detector: hw/sw maintanece, data quality analysis**
- **Involved in the main channel analysis ($K^+ \to \pi^+ \nu\bar{\nu}$), in lepton flavor universality measurements and dark sector**

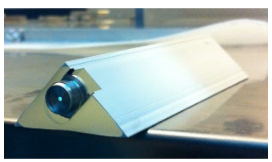


CHANTI postcard

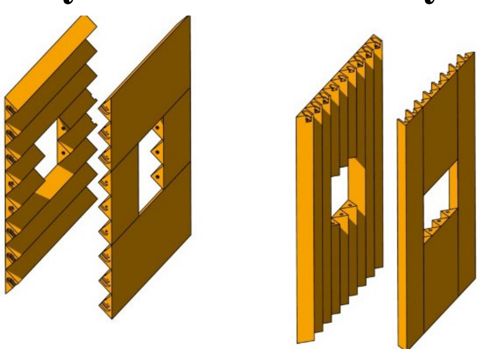
Detector proposed and built entirely in Naples, thanks to the INFN mechanical design and workhop service.
Six guard rings to veto kaon inelastic interaction on GTK3 and beam background.
Staggered scintillator bars with triangular section read via WLS fibers and SiPM forming 6 xy sensitive planes



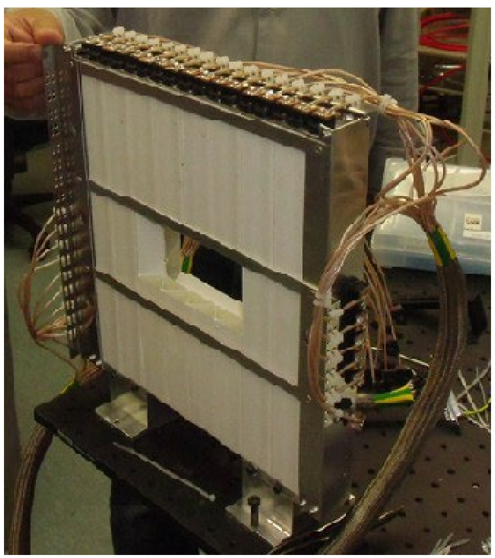
Scintillator bar



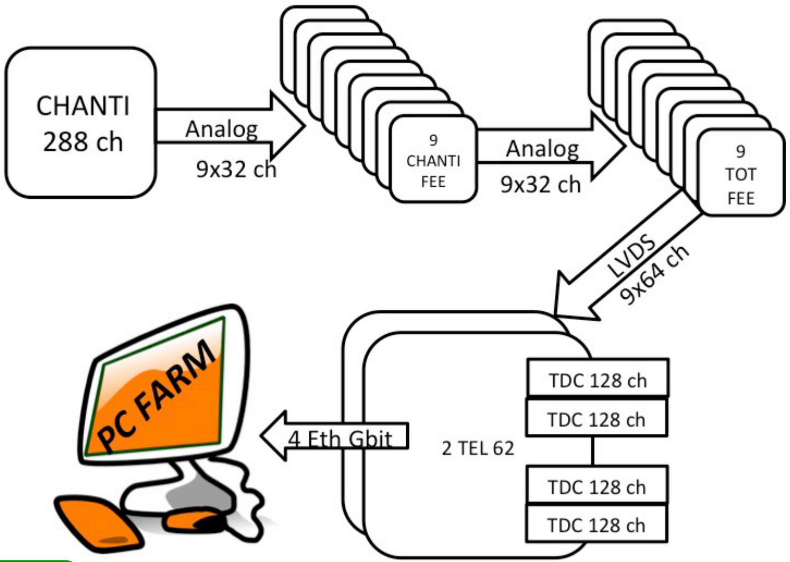
Layout of the X/Y layers



Fully cabled station



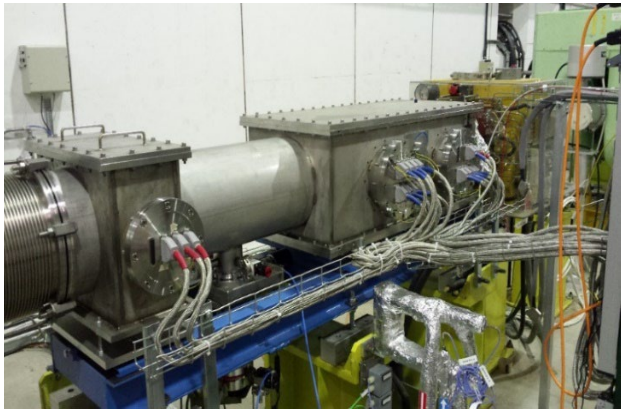
Front end electronics



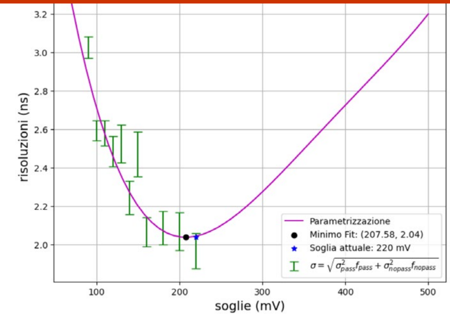
JINST 11 (2016) P03029

CHANTI in 2024 run

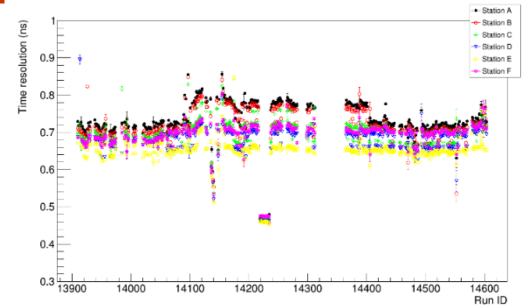
- New FE boards installed to cope with the higher intensity reached in 2021 run
- In 2024 a new FPGA-based TDC FELIX readout board has replaced the TEL62 board to readout the CHANTI detector.
- Successful and smooth RUN2 data taking for CHANTI

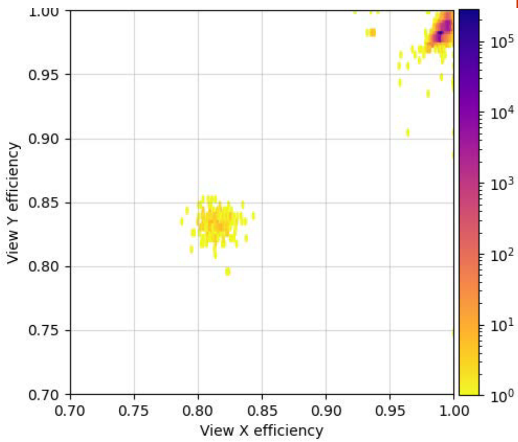


Single hit time resultion studies by bachelor student Valeria Spasiano in Naples

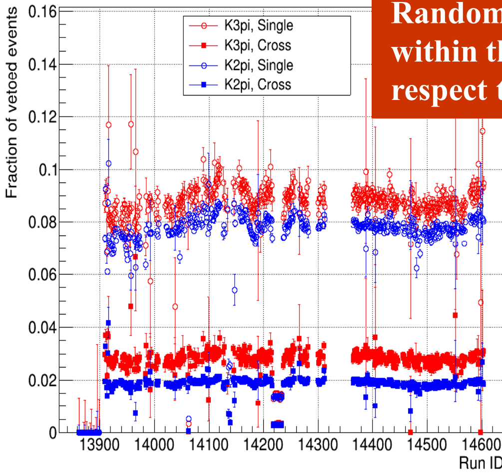


Time resolution: overall stable, well below target of 1 ns (veto in pnn analysis: ±3 ns window)





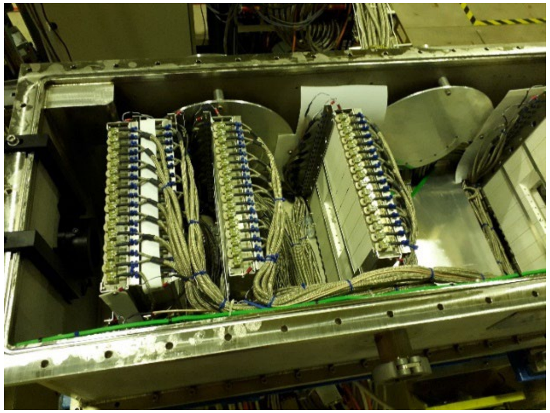
Efficiency of each view with "halo muons" by checking the in-time and in-space coincidence with other CHANTI stations



Random veto: stable within the year and with respect to previous years

CHANTI 2025 run preparation

- **SiPMs currents are monitored during the whole data taking: a replacement before 2025 run is mandatory to prevent any aging effect due to radiation damages.**
- **This work was already done before 2023 run and it required a big effort from L. Roscilli, F. Cassese, C. Cassese and B. De Fazio.**



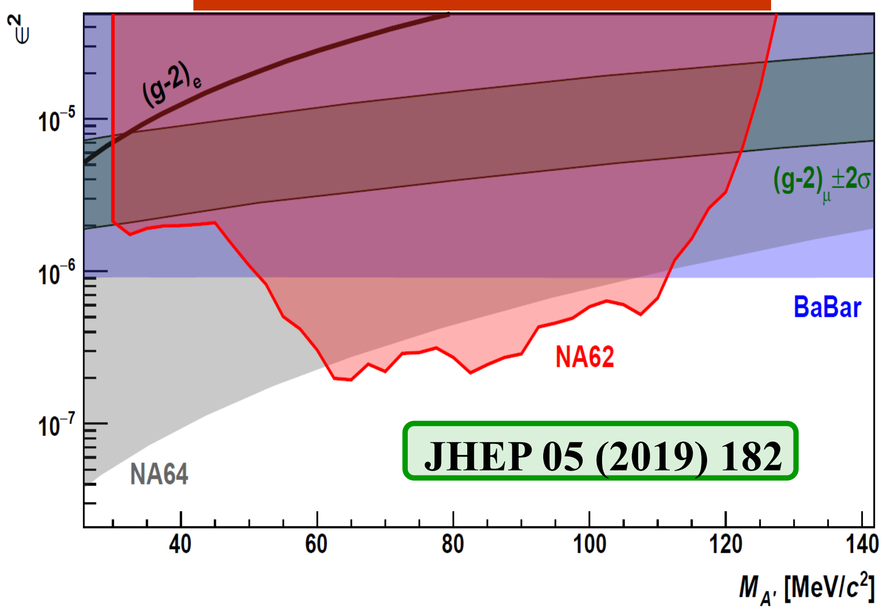
- **Several tools built to keep the CHANTI stations alignment.**

Analysis activities

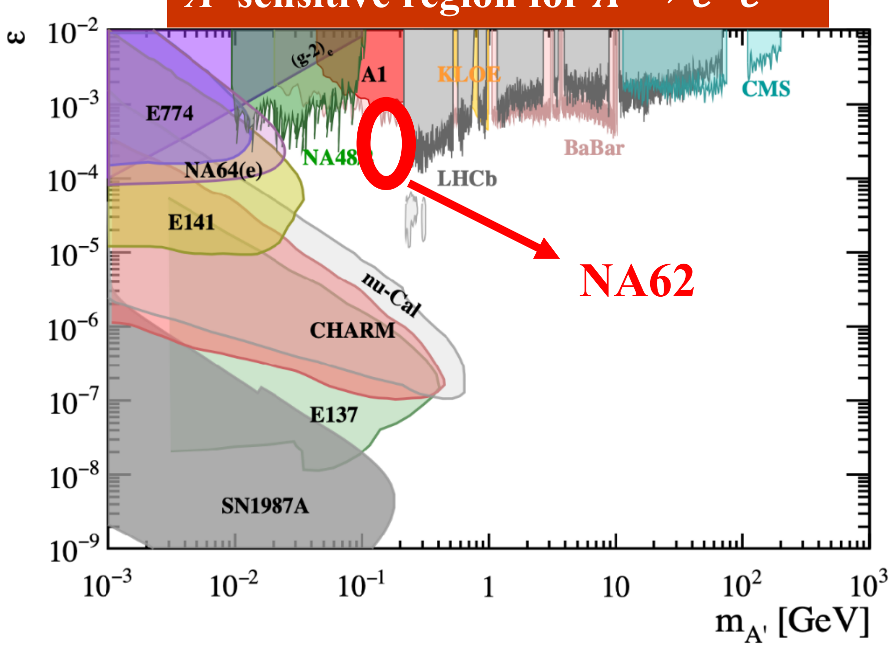
- Improvements in $K^+ - \pi^+$ matching and random veto studies for the main analysis $K^+ \to \pi^+ \nu\bar{\nu}$ (see R. Fiorenza's talk)

- Dark sector:
  - Search for an invisible dark photon in π^0 decays:
    $K^+ \to \pi^+\pi^0, \pi^0 \to A'\gamma,\ A' \to inv$
  - Study of the $K^+ \to \mu^+\nu_\mu A',\ A' \to e^+e^-$ (see I. Rosa's talk)

A' exclusion limit - 2016 data



A' sensitive region for $A' \to e^+e^-$



The HIKE saga

Original plan:

HIKE to succeed NA62 in ECN3 hall at CERN SPS after LS3 and to extend the NA62 physics program into the HL-LHC era and beyond

15-year program with start of data taking around 2030

Phase 1: K^+ beam, 4x NA62 primary intensity

$K^+ \to \pi^+ \nu\nu$ to 5%, LFV/LNV & other rare decays, precision measurements

Time sharing with SHADOWS, HIKE in beam-dump mode

Phase 2: K_L beam, 6x NA62 primary intensity

$K_L \to \pi^0 \ell\ell$ to 12-18%, LFV/LNV & rare decays, precision measurements

HIKE proposal SPSC-P-368 (2311.02831) made public October 2023

Decision of CERN Directorate at Research Board, 06 Mar 2024:

SHiP experiment approved to run in ECN3 after LS3

HIKE physics case judged excellent but decision made on "strategic" grounds

NA62 experiment will conclude for decommissioning at start of LS3

- No dedicated kaon experiment at CERN for the first time in many decades
- No experiment capable of carrying out the HIKE suite of measurements at any facility in the world

PRIN 2022 HetCal

Development of high performance heterostructured calorimeter for future intensity frontier experiments (HetCal)

Main goals

- Establish a technological solution to be adopted for electromagnetic calorimeters for the next generation high intensity experiments.
- Obtain energy resolution and efficiency comparable to that for homogenous detectors based on inorganic crystals, with sub ns time resolution
- Two alternative solutions proposed:
  - ✓ Shashlyk, based on the KOPIO calorimeter design, with spy tiles
  - ✓ Heterostructures with quantum confined nanocrystals in combination with standard scintillators

Research team

INFN NAPOLI

F. Ambrosino,
M. Francesconi
P. Massarotti
M. Mirra (PI)
R. Fiorenza
I. Rosa

- Prototype construction
- Test beams

Università degli Studi di Napoli Federico II

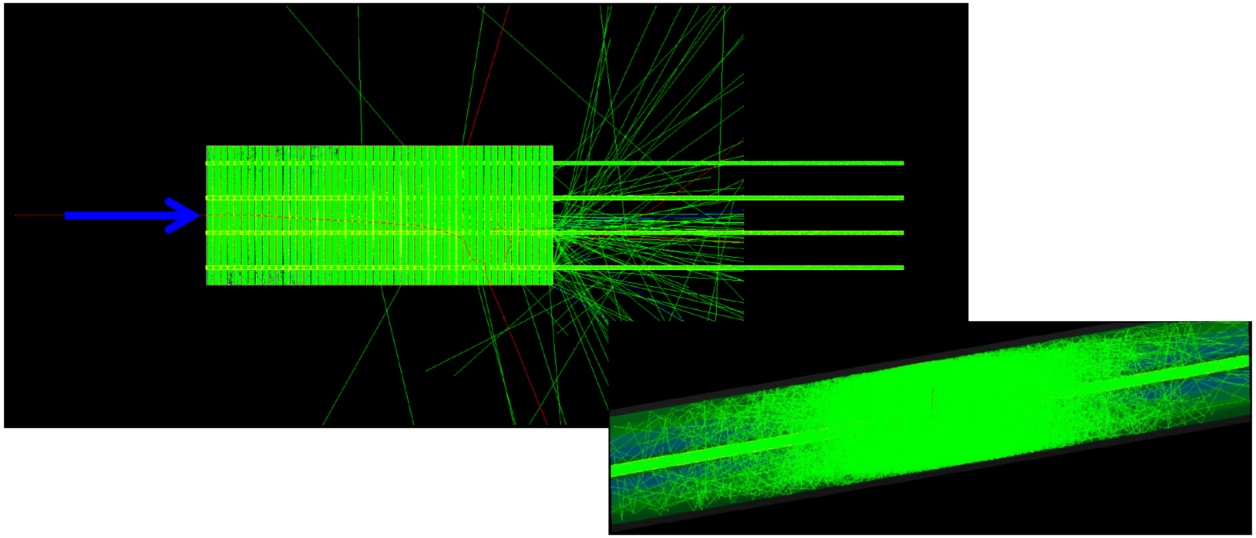
G. de Nardo,
M. Merola (coPI)
M. Campajola

- Prototype simulation
- Prototype design

Shashlyk simulation

Geant4 simulation developed to drive the Shashlyk prototype design:

- 500 layers of PS+PTP+POPOP scintillator (1.6mm) and lead (0.3mm)
- Transverse module size: 40 x 40 mm2, length ~27X_0
- TiO_2 coating for the scintillator
- WLS fibers with tunable absorption-emission spectrum
- Optical photons tracking and sensitive detector for photon counting

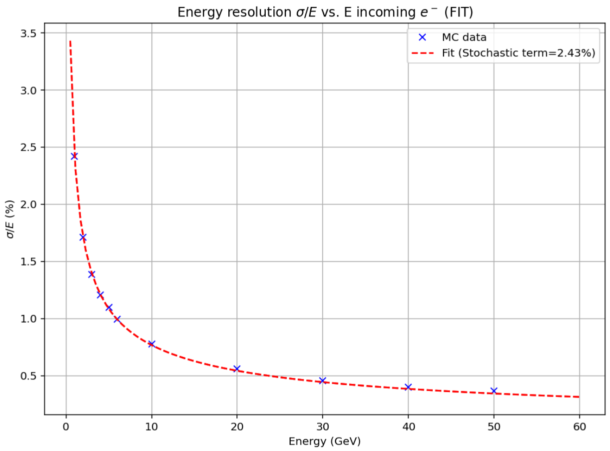


I. Rosa

Shashlyk simulation

Several performance checked and different materials/configurations tested with the Geant4 tool

- **Energy resolution**



Stochastic + constant

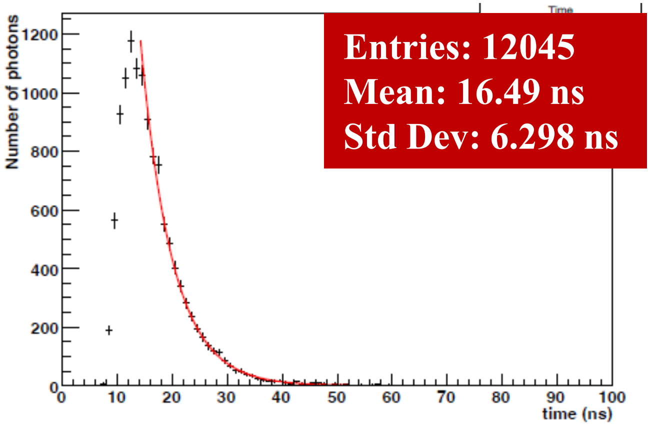
$$\frac{\sigma(E)}{E} = \frac{2.41}{\sqrt{E\ (\mathrm{GeV})}} \oplus 0.12\ [\%]$$

Stochastic only

$$\frac{\sigma(E)}{E} = \frac{2.42\,\%}{\sqrt{E\ (\mathrm{GeV})}}$$

σ_E/E defined as RMS/E_{mean}

- **Photon arrival time distribution**



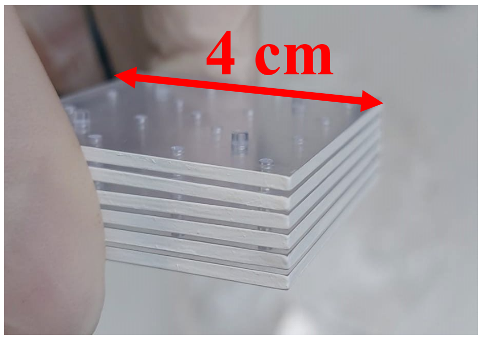
- **1GeV incident photon with mirrored fibers**
- **Photon spectrum compatible with WLS emission one**
- **Black paint fibers option: 50% less light, but 15% narrower distribution**

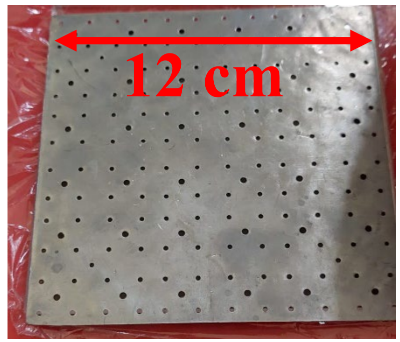
I. Rosa

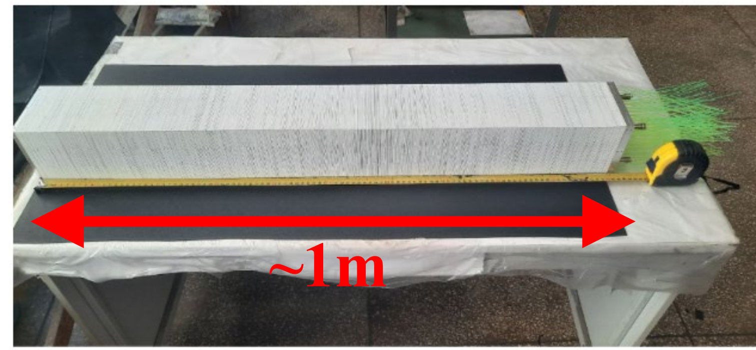
Shashlyk prototype construction

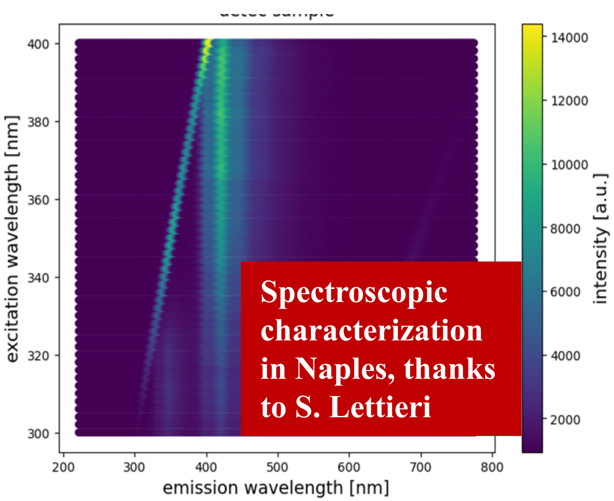
Shashlyk prototype design assembled in Kharkiv:

- 3x3 channel matrix with cell size 4x4 cm
- 500 layers of scintillator (polystyrene + 0.05% POPOP + 2% PTP) + lead
- All edges tiles and both lead tiles sides coated with reflective paint.
- WLS fibers BCF-92XL with 1.2mm diameter, mirrored at one side







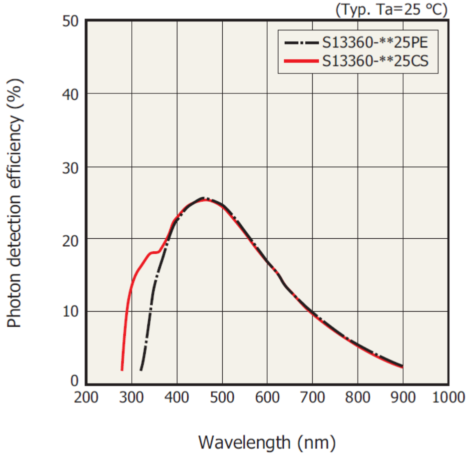


Shashlyk prototype construction

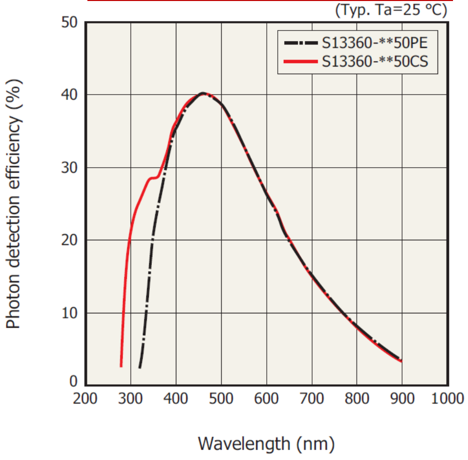
Switch between two possible photosensors

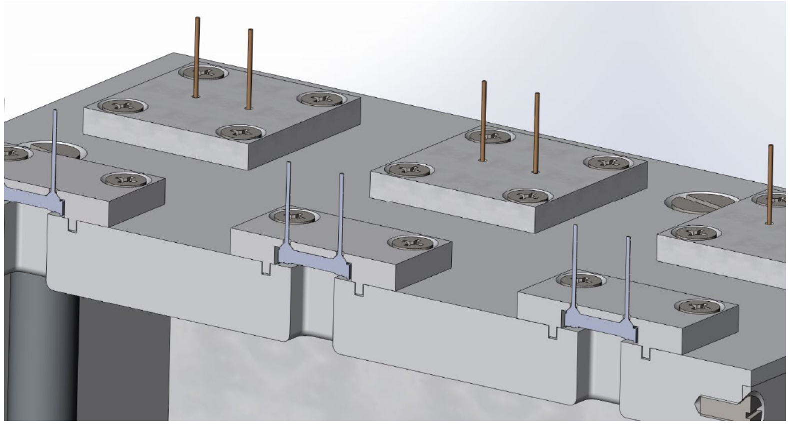
- **SiPM solution: Hamamatsu S13360-6050/25CS**

Pixel pitch: 25 μm

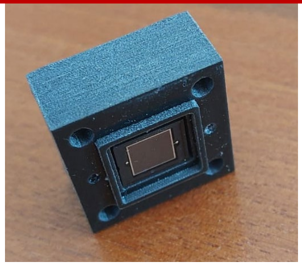


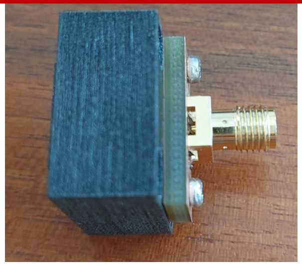
Pixel pitch: 50 μm

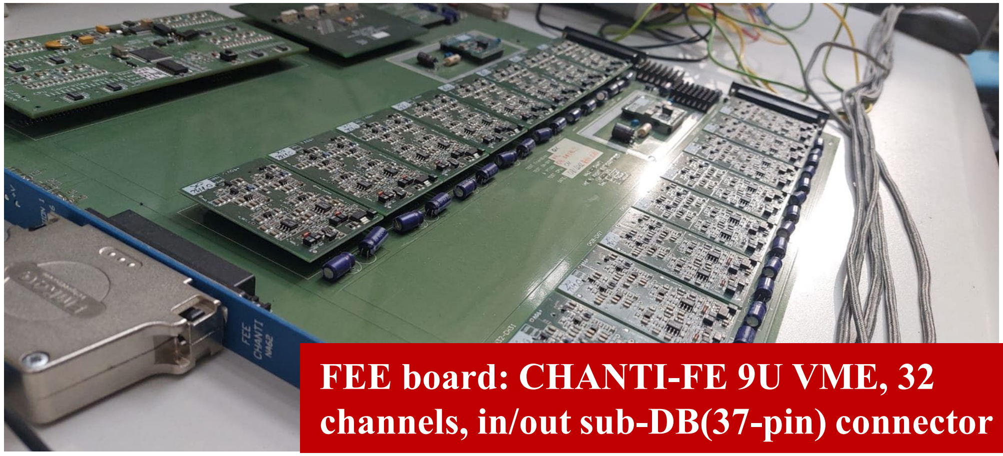




SiPM connector - SER (A. Di Meno)+progettazione (G. Passeggio) a Napoli



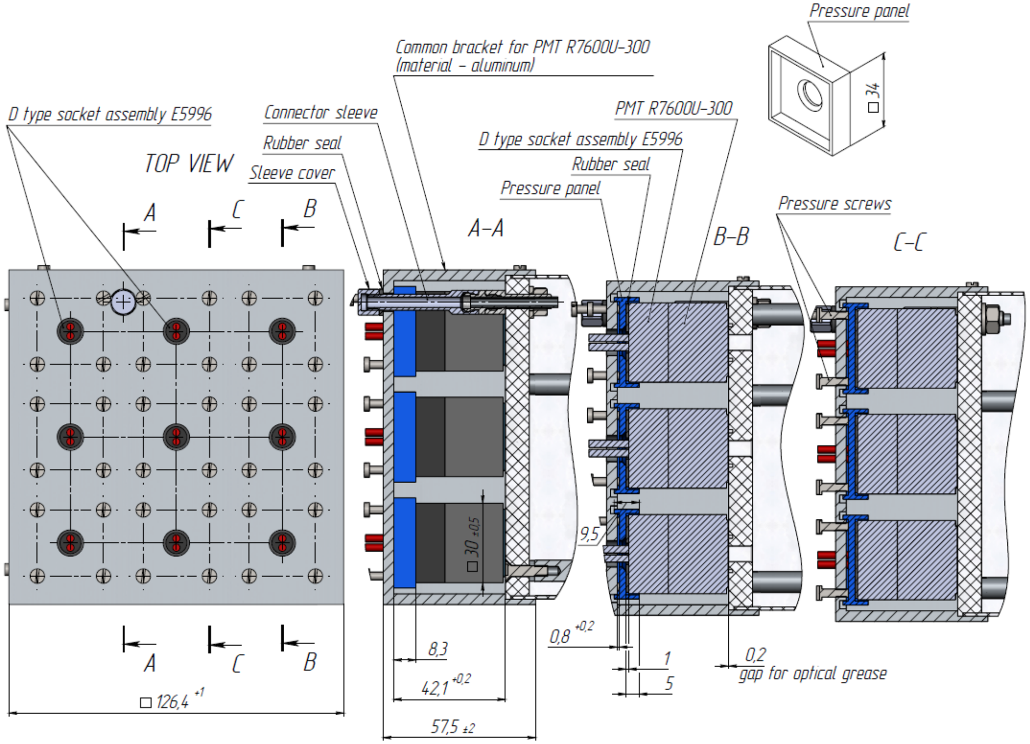


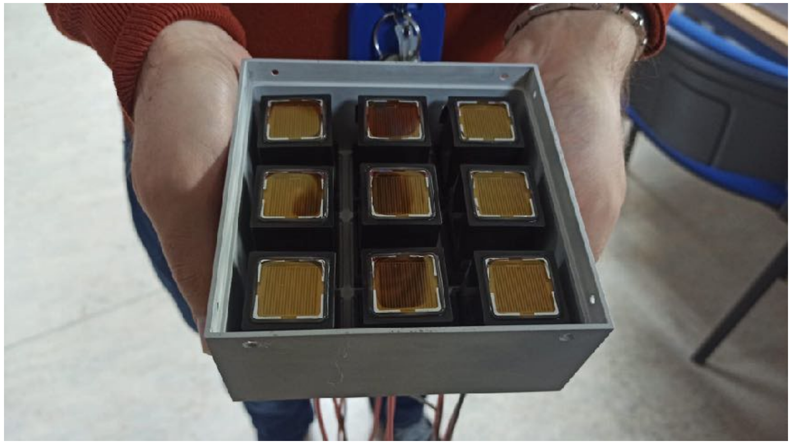


FEE board: CHANTI-FE 9U VME, 32 channels, in/out sub-DB(37-pin) connector

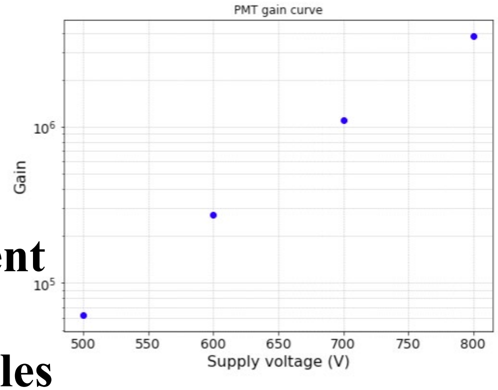
Switch between two possible photosensors

- **PMT solution: Hamamtsu R7600U-300 extended green**





Preliminary checks by bachelor student Francesco Milano in Naples



2024 beam test of shashlyk prototype

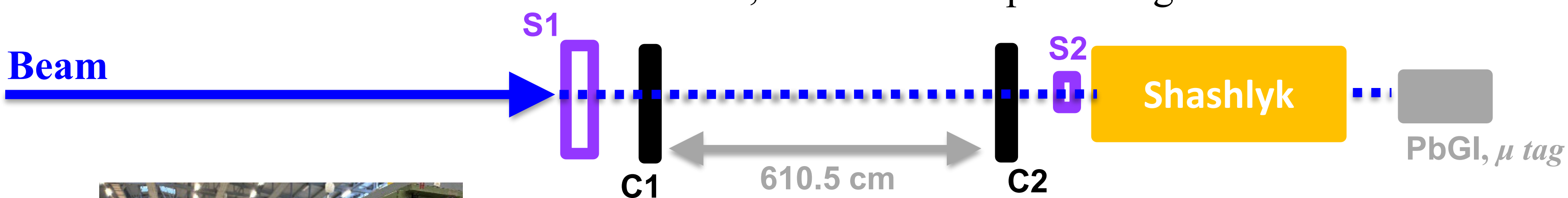
Test at T9 CERN beamline, October 2024:

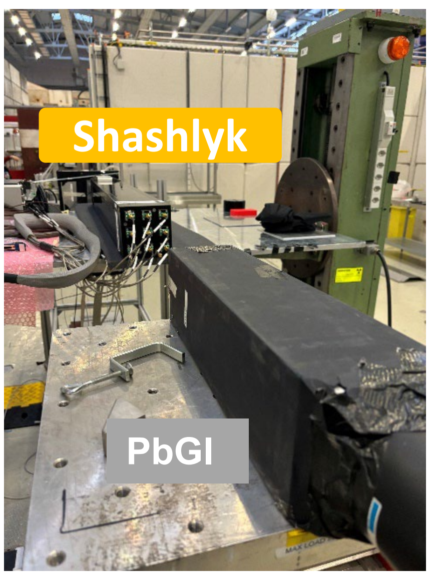
Electron beam, 1-6 GeV

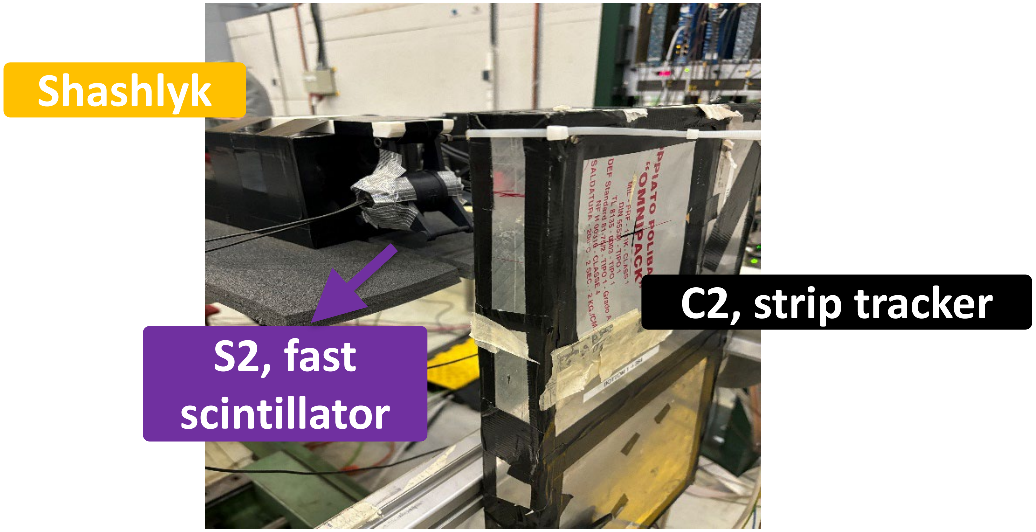
MIP beam (μ^- or π^-), ~4 GeV

Beamline with Cherenkov detectors to allow verification of beam ID $e/\mu\pi/p$

S1	Large upstream plastic scintillator for wide illumination
S2	Ultra-fast plastic scintillator to trigger on particles hitting center of the Shashlyk, timing
C1, C2	Si strip tracking chambers

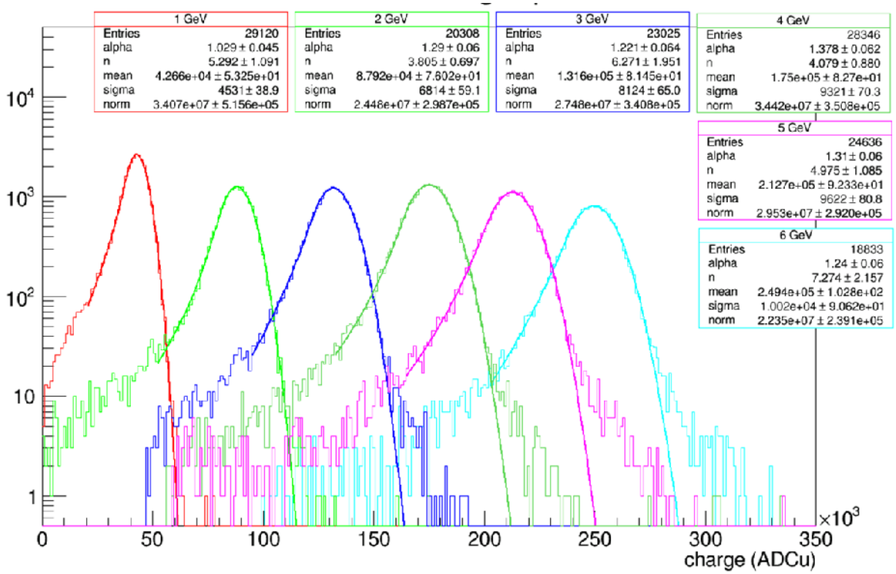


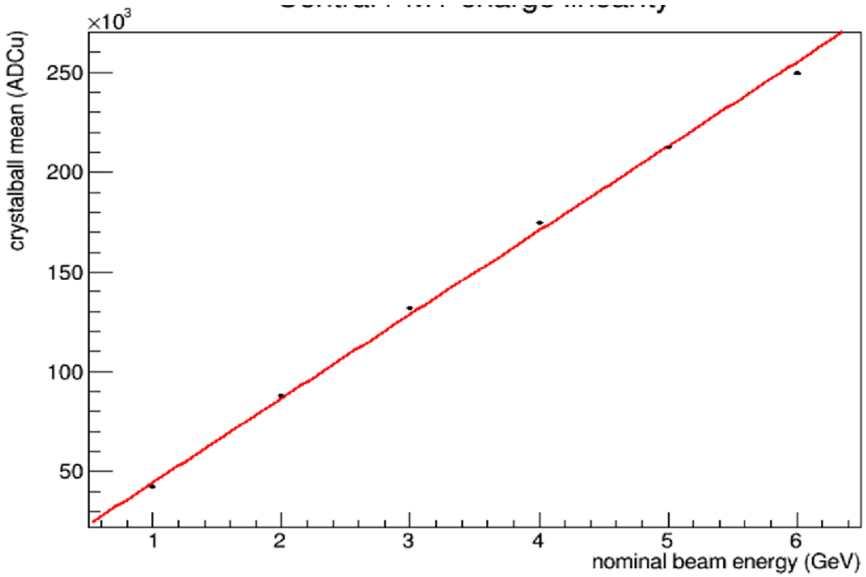


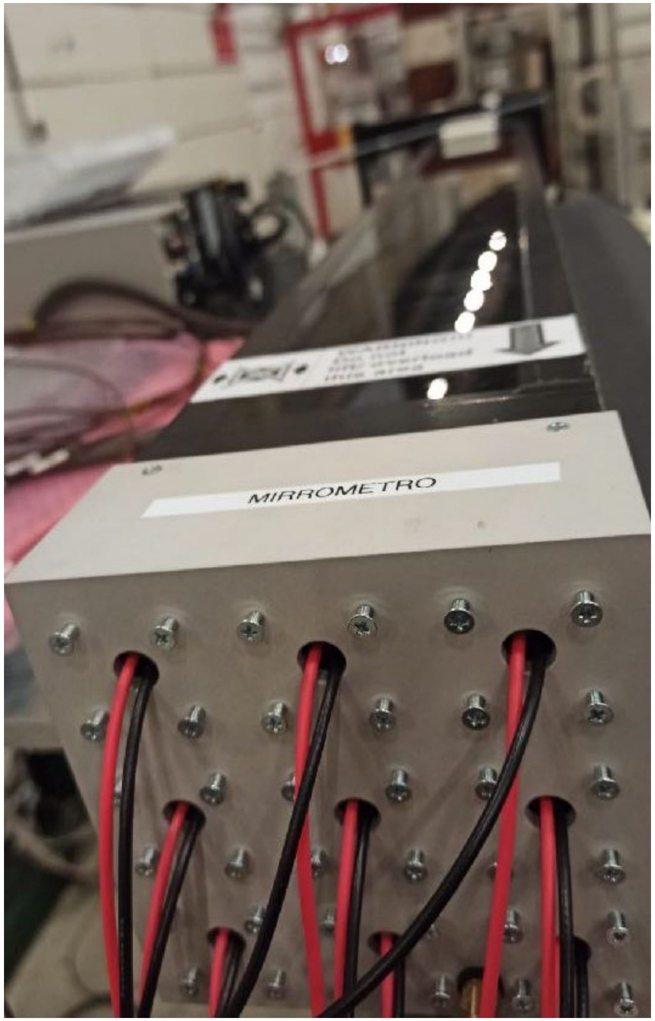


2024 beam test of shashlyk prototype

Charge spectra with central PMT





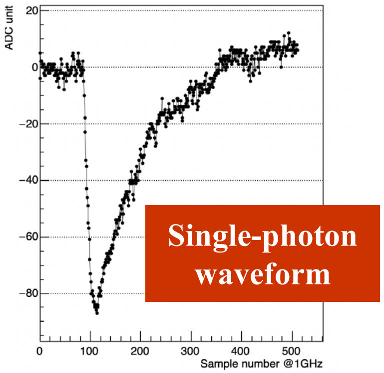


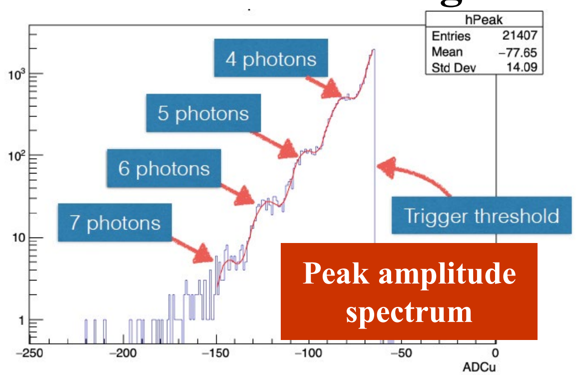
M. Francesconi

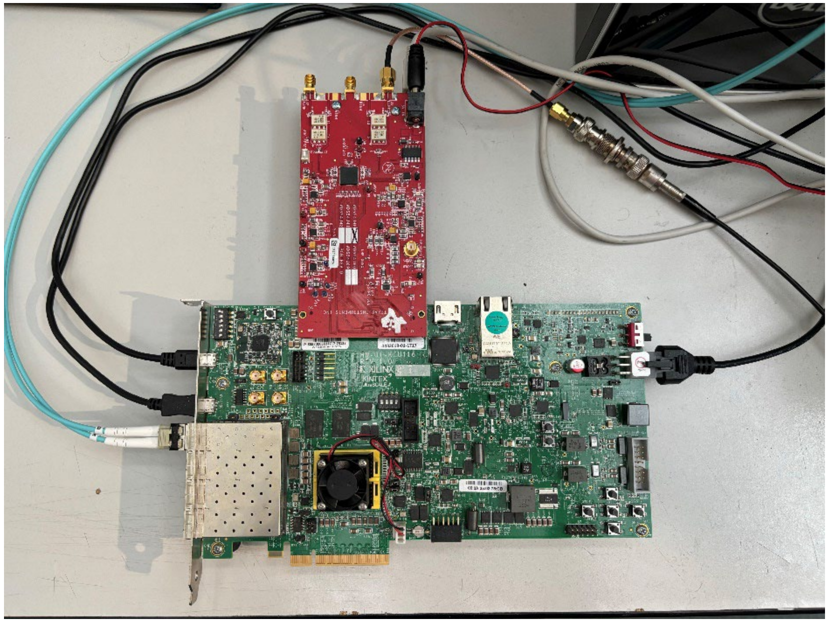
Shashlyk prototype readout

Preliminary Geant4 simulation of the detector shows photon arrival time with ~6ns spread and $\sigma_E/\sqrt{E} \sim 3\% / \sqrt{E}$ (GeV), motivating the requirements of GHz sampling of analog signals with 14 bit , not to spoil the detector perfomances.

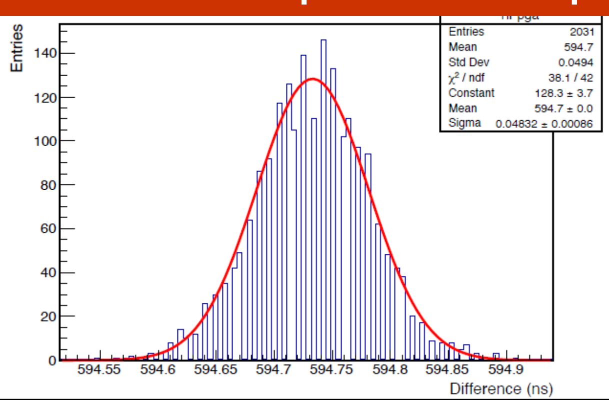
- **Full chain implemented with the TI ADS54J40 and Xilinx Kintex Ultrascale+ : successful read out of SiPM dark noise signals**







CFD resolution of 49 ps with double pulse



- **Pole-zero filter used to remove the tail and improve pileup identification**

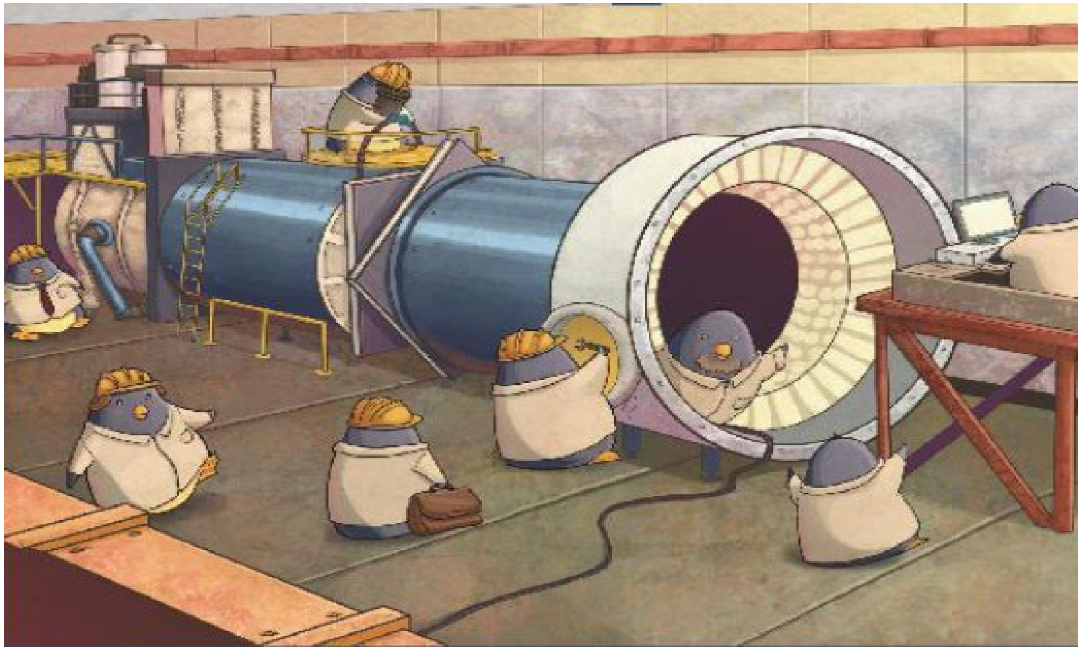
Francesconi et al., NIMA 1067 (2024) 169679

M. Francesconi & R. Giordano

Conclusions

- ✓ **The CERN Kaon factory has a vast and unique physics program for the search of NP, complementary to what can be done at LHC and B-factories**
- ✓ **First observation of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay with a significance >5σ, using the NA62 2016−2022 dataset: the smallest particle decay BR measured with a significance >5σ. O(15%) precision on BR($K^+ \to \pi^+ \nu\bar{\nu}$) will be reached by LS3 with optimization of the analysis.**
- ✓ **High quality physics results are being published by the collaboration. The current run(2021-2025) will allow to fully exploit the physics reach with the current NA62 setup. It will collect data both in «kaon mode» and in «dump mode»**
- ✓ **Naples working group involved both in detector side (full responsibility of CHANTI) and in physics analysis for the main channel $K^+ \to \pi^+ \nu\bar{\nu}$ and dark sector**
- ✓ **HW activities started in Naples to study electromagnetic calorimeters for the next generation of high intensity experiments**

Backup



NA48 LKr calorimeter in HIKE

Quasi-homogeneous ionization calorimeter: 27 X_0 f LKr

Photon efficiency likely adequate even for K_L program
- NA48-era studies for NA62: $1 - \varepsilon < 10^{-5}$ for $E\gamma > 10$ GeV
- High-energy efficiency confirmed with NA62 data

Time resolution
- $\sigma_t \sim 500$ ps for π^0 with $E\gamma\gamma > 20$ GeV
- Would require 4x improvement in K^+ phase to hold accidental veto rate to current levels
- Critical for KLEVER: Accidental rate ~140 MHz!

Consolidation work necessary
Investigating upgrade possibilities
- Increase operating voltage to increase drift velocity
- Faster digitizers and signal shaping

For K_L phase, LKr inner bore limits beam solid angle

LKr resolution:

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\%$$

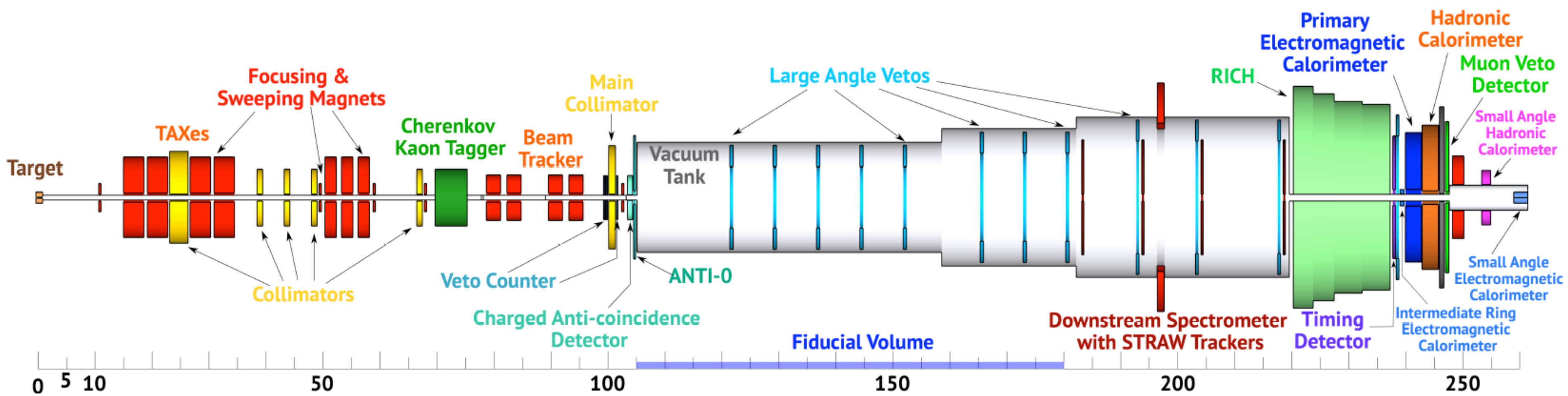
$$\sigma_t = \frac{2.5 \text{ ns}}{\sqrt{E}}$$

HIKE phase 1: $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at high-statistics

Goal: Measure BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) to within ~5%

Requires **4x** increase in intensity

Basic design of NA62 will work at high intensity



1.2×10^{13} ppp = 4x NA62

Key challenges:

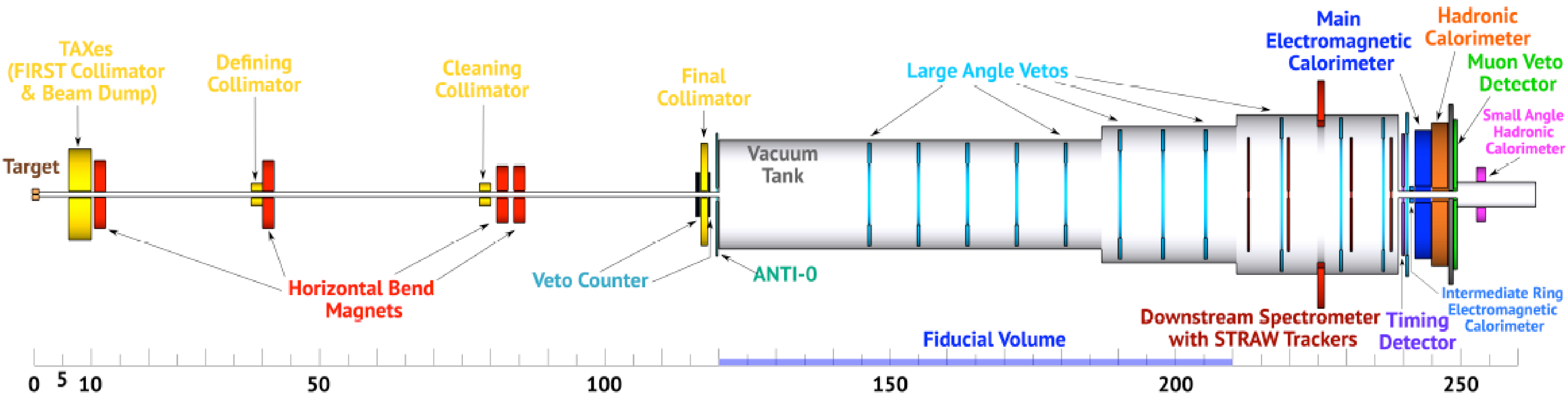
- Require **4x** better time resolution to keep random veto rate under control
- Must maintain other key performance specifications at high-rate:
- Space-time reconstruction, material budget, single photon efficiencies, etc.

These characteristics are necessary for rare K_L decays as well

- Calorimeter, photon vetoes, and readout reused for K_L experiments

HIKE phase 2: rare K_L decays

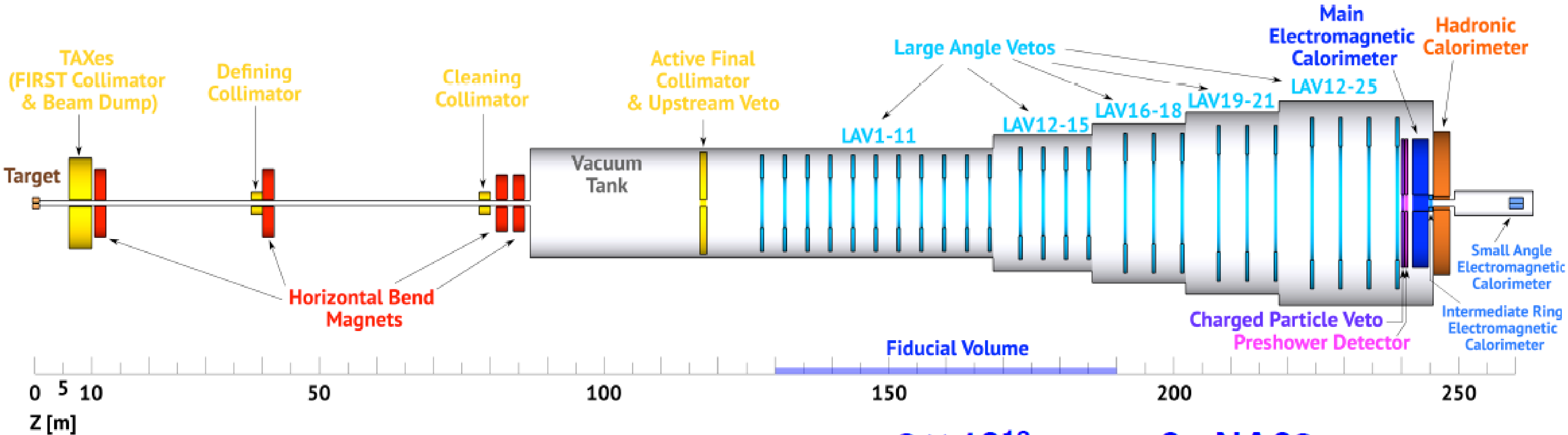
K_L beamline, tracking and PID for secondary particles



2×10^{13} ppp = 6x NA62

- Statistical power: 3.8 10^{13} Kaon decays in decay volume per year (1.2 10^{19} POT/year)
- 120 m long neutral beamline, secondary beam opening angle = 0.4 mrad
- Using detectors of previous phase, with some detectors removed
- Minor modifications to make left/right symmetric and optimize geometrical acceptance.
- Will provide valuable information to characterize neutral beam: measurement of K_L, n, and Λ fluxes and halo

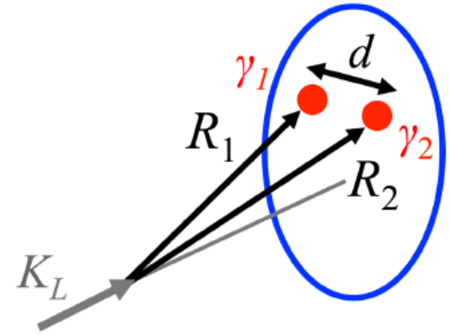
HIKE phase 3: $K_L \to \pi^0 \nu\bar{\nu}$



2×10^{13} ppp = 6x NA62

Studied in context of Physics Beyond Colliders

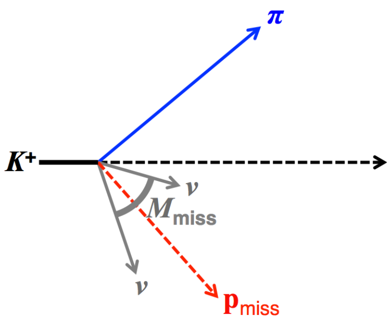
- **Essential signature: 2γ with unbalanced $p_\perp$ + nothing else**
  All other K_L decays have ≥ 2 extra γs or ≥ 2 tracks to veto
  Exception: $K_L \to \gamma\gamma$, but not a big problem since $p_\perp = 0$
- **$M(\gamma\gamma) = m(\pi^0)$ is the only sharp kinematic constraint**
- **Target sensitivity: 6×10^{19} pot in 5 years**
- **~60 SM $K_L \to \pi^0\nu\nu$, $S/B \sim 1$, δBR/BR($\pi^0\nu\nu$) ~ 20%**
- **High-energy experiment complementary to KOTO**



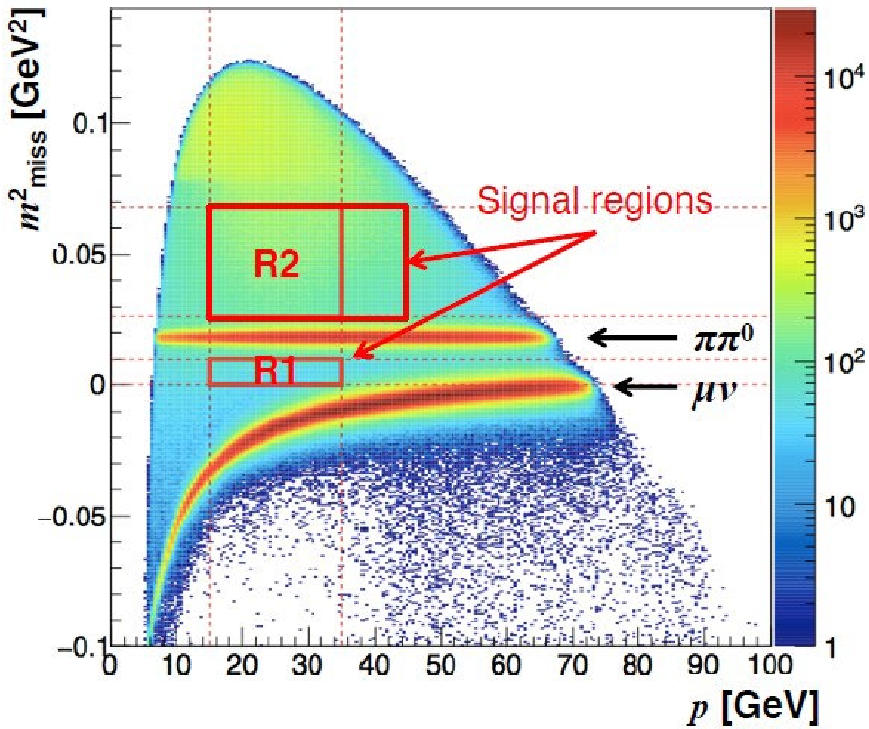
$$m_{\pi^0}^2 = 2E_1E_2(1-\cos\theta)$$

$$R_1 \approx R_2 \equiv R = \frac{d\sqrt{E_1E_2}}{m_{\pi^0}}$$

Signal: BR = $(8.4 \pm 1.0) \times 10^{-11}$



K track in
π track out
No other particles in final state
$m^2_{miss} = (P_K - P_\pi)^2$



Main backgrounds

$K^+ \to \mu^+\nu(\gamma)$	BR = 63.5%
$K^+ \to \pi^+\pi^0(\gamma)$	BR = 20.7%
$K^+ \to \pi^+\pi^+\pi^-$	BR = 5.58%

Upstream beam background

Selection criteria

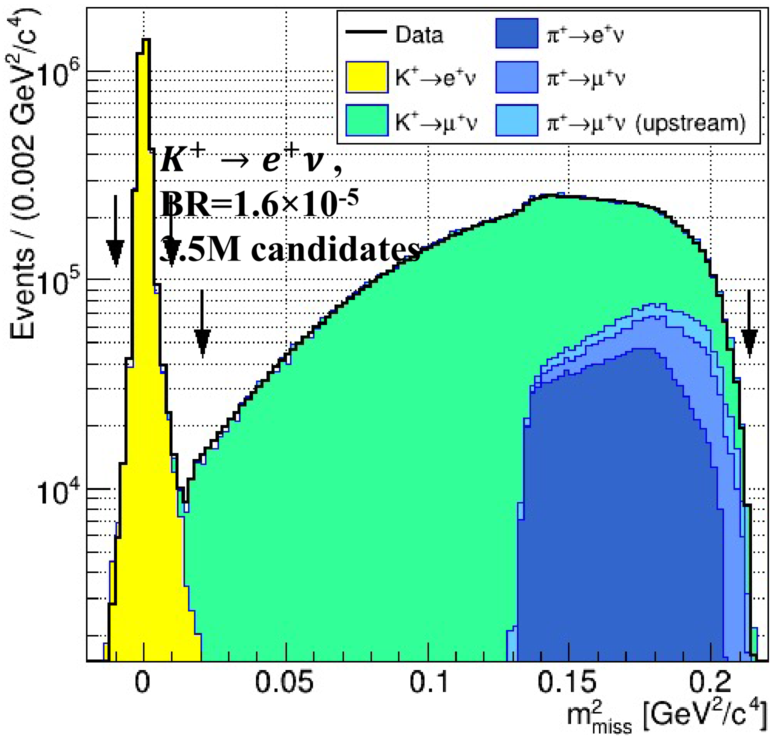
K^+ beam identification
Single track in final state
π^+ identification (μ^+/e^+ event rejection)
γ rejection

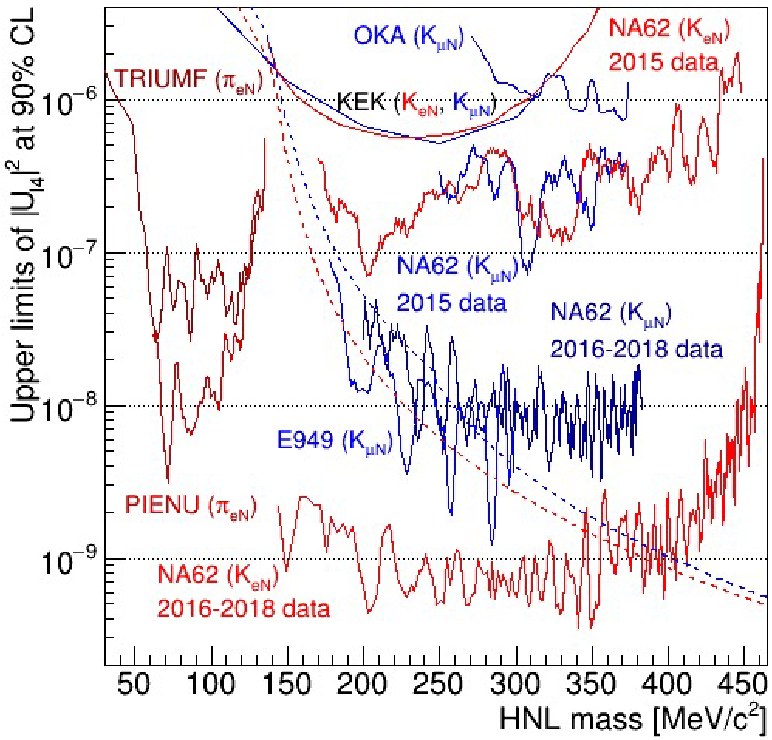
A general purpose experiment in kaon sector

Recent results on hidden-sector mediator production and other BSM physics in kaon decays:

- **searches for heavy neutral leptons from $K^+ \to l^+\nu$ decays**

Events with a K^+ in the initial state and a lepton (e^+ or μ^+) in the final state; squared missing mass $m^2_{miss} = (P_k - P_l)^2$ using STRAW and GTK trackers; HNL production signal: a spike above continuous missing mass spectrum.



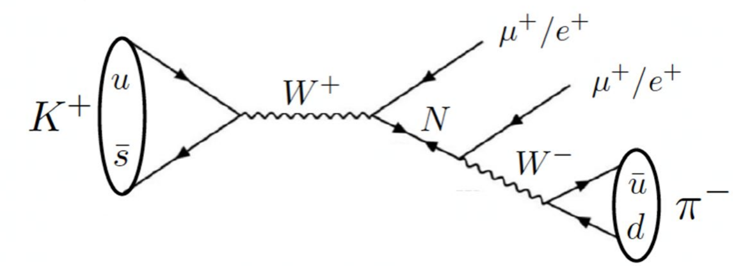


PLB 807 (2020) 135599, PLB 816 (2021) 136259

A general purpose experiment in kaon sector

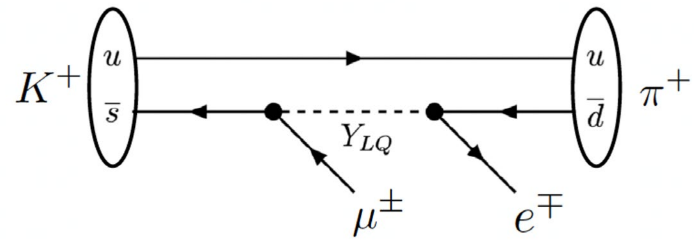
Recent results on hidden-sector mediator production and other BSM physics in kaon decays:

- **Lepton number violation:**



Same sign leptons mediated by Majorana neutrinos

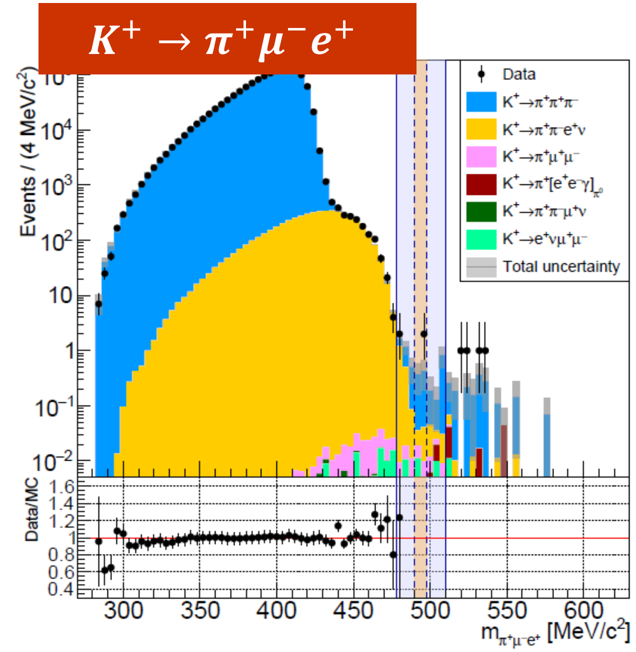
- **Lepton flavour violation:**



Opposite sign – different family leptons mediated by Leptoquarks

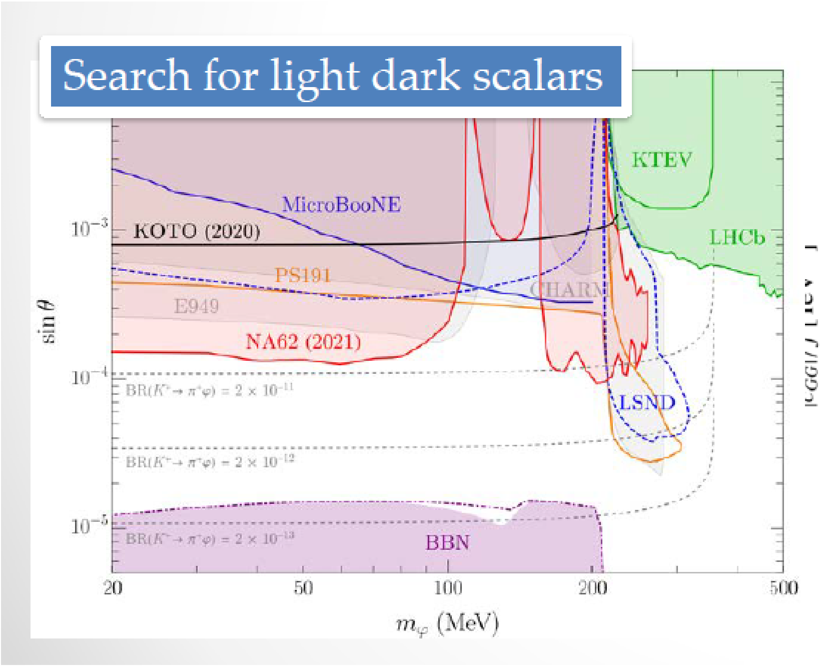
- **Experimental signature: 3 charged tracks with $\pi^{\pm}\mu^{\mp}e^{+}$**
- **Consistent with closed kinematics K^+ decay**
- **The invariant mass $M_{\pi\nu e}$ used to distinguish between signal and background**
- **Main bkg π mis-ID and decay in flight measured with data**
- **Normalized with $K^+ \to \pi^+\pi^+\pi^-$**

PRL 127 (2021) 131802

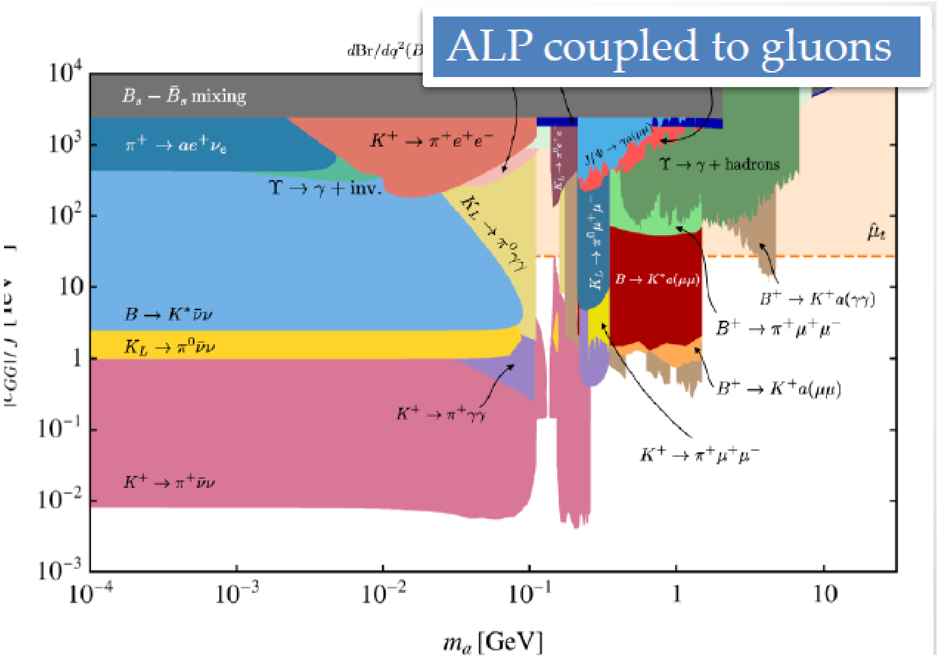


Run1 result on $K^+ \to \pi^+ X$

Limits on $K^+ \to \pi^+ X$ translate in strong limits on ALPs or scalars in the usual mass / coupling plane



PBC workshop report, *Eur.Phys.J.C* 81 (2021) 11, 1015



M. Bauer, M. Neubert, S. Renner, M.Schnubel and A. Thamm JHEP 09 (2022) 056

HIKE program

Observable	Target	Motivation
K^+ phase		
$K^+ \to \pi^+ \nu\nu$	BR to ~5%	New physics in FCNC decays
$K^+ \to \pi^+ \ell\ell$	Form factors at ~1% level	LFUV
$K^+ \to \pi\mu e,\ \pi^- \ell^+ \ell^+$	$O(10^{-12})$ sensitivity	LFV, LNV
$R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$	R_K to ~0.1%	LFUV
$K^+ \to \pi^+\gamma\gamma,\ \pi^+\pi^0\gamma,\ \pi^+\pi^0 ee$	As best as possible	Chiral parameters (LECs)
Hybrid phase		
$K_L \to \pi^0 \ell\ell$	Observation	New physics in FCNC decays
$K_L \to \mu\mu$	BR to < 1%	New physics in FCNC decays
$K_L \to \mu e,\ \pi^0 \mu e$	$O(10^{-12})$ sensitivity	LFV
$K_L \to \gamma\gamma,\ \pi^0\gamma\gamma$	As best at possible	Ancillary to $K_L \to \mu\mu$, LECs
K_L phase (KLEVER)		
$K_L \to \pi^0 \nu\nu$	BR to ~20%	New physics in FCNC decays

Plus periodic runs with dumped beam to accumulate at least 10^{19} pot to search for exotic, long-lived particles

Shashlyk calorimeter with spy tiles

Main electromagnetic calorimeter (MEC):

Fine-sampling shashlyk based on PANDA forward EM calorimeter produced at Protvino

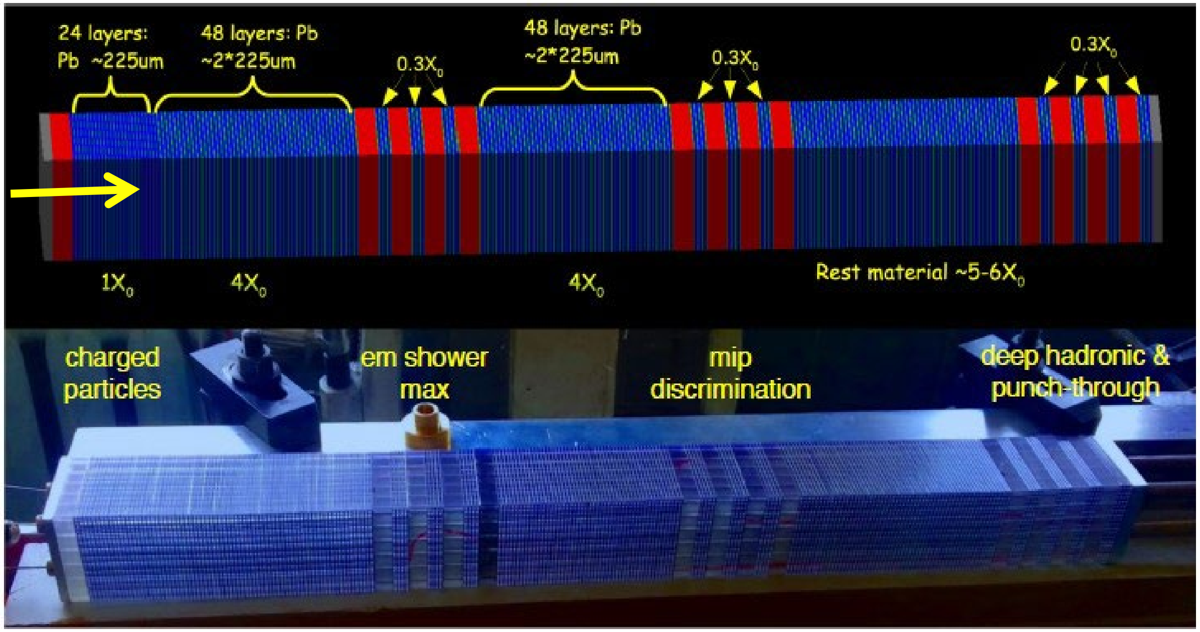
0.275 mm Pb + 1.5 mm scintillator

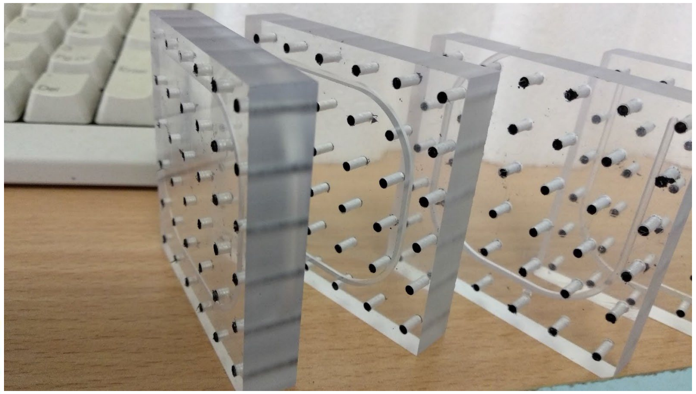
PANDA/KOPIO prototypes:

- $\sigma_E/\sqrt{E} \sim 3\% / \sqrt{E}$ (GeV)
- $\sigma_t \sim 72$ ps $/\sqrt{E}$ (GeV)
- $\sigma_x \sim 13$ mm $/\sqrt{E}$ (GeV)

New for HIKE: longitudinal shower information from spy tiles

- **PID information: identification of μ, γ, n interactions**
- **Shower depth information: improved time resolution for EM showers**

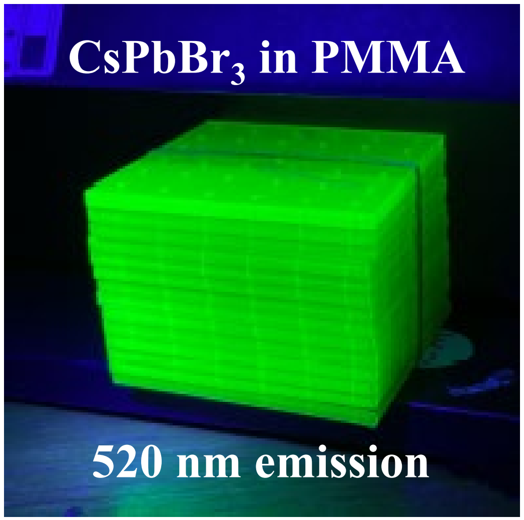


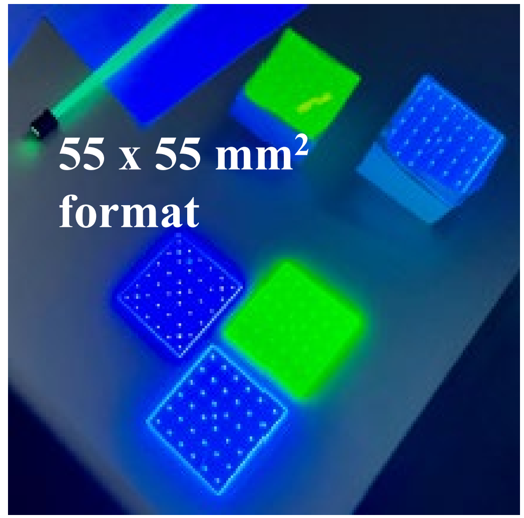


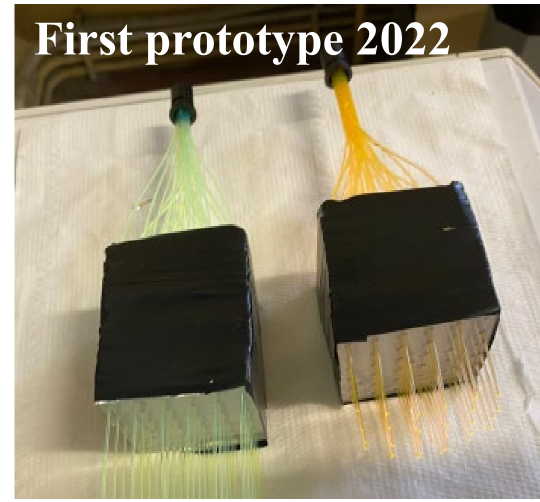
1[st] prototype assembled in Protvino and tested at OKA in April 2018 and DESY in Nov 2019

Innovative scintillators for shashlyk

R&D in synergy with NanoCal project: perovskite nanostructures in a polymer matrix can be used as sensitizers/emitters for ultrafast, robust scintillators







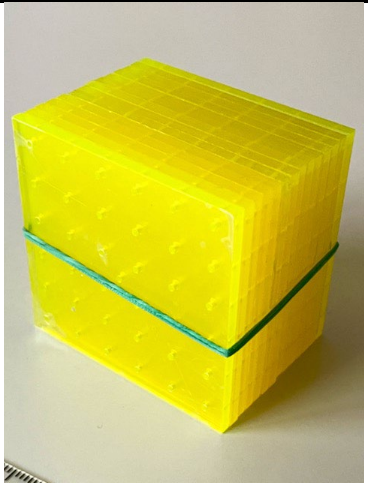
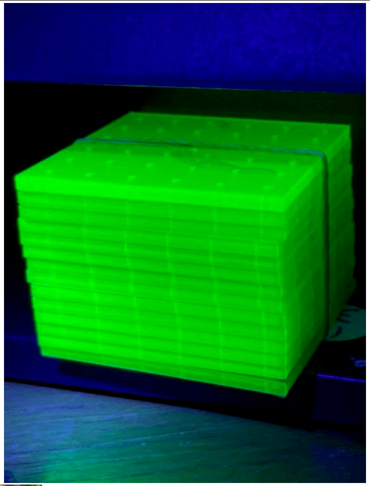
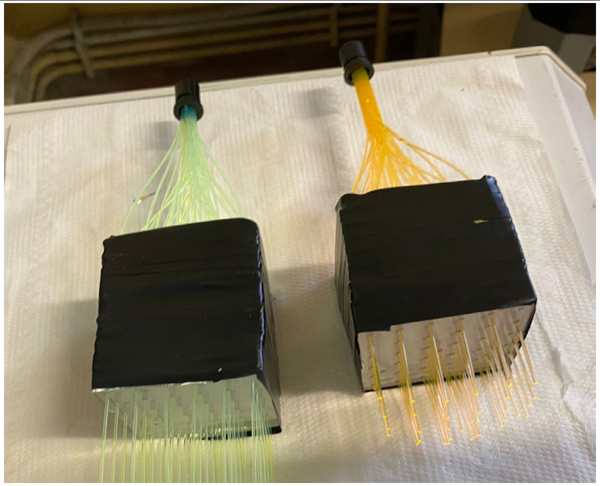
Quick-start using CsPbBr3, 0.2% w/w in UV-cured PMMA

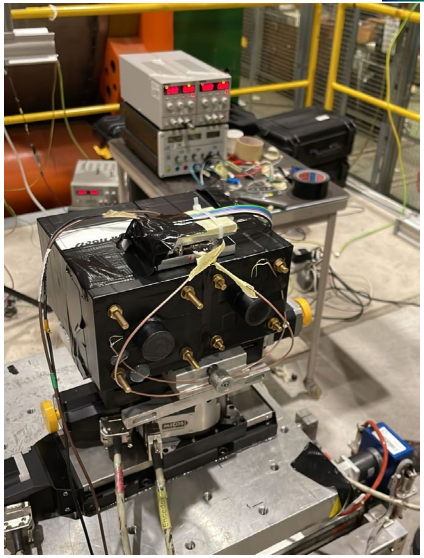
- Light yield O(few k) photons/MeV deposit
- 50% of light emitted in components with $\tau < 0.5$ ns
- Radiation hard to O(1 MGy)

Progress:

- **Oct 2022: First component test at CERN: fibers/tiles/SiPMs**
- **2023**: Further iterations to improve performance of NC scintillator prototype
- **2024:** Construction of full-scale prototype modules; performance comparison

2022 early prototypes

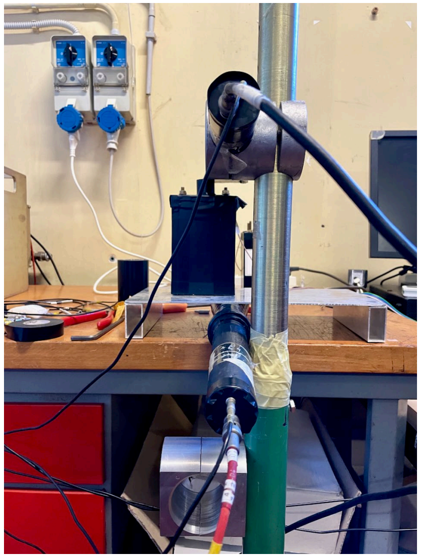




First test of NanoCal prototype at H2 CERN beamline with 80 GeV e^{-} and 150 GeV π^{+} (MIPs) in Oct 2022, followed by laboratory studies with cosmic rays spring 2023

Comparison of light yield from conventional (Protvino) shashlyk with NanoCal ($CsPbBr_3$/PMMA) prototype

LY_{mip}(NanoCal/Protvino) ~ 5%



Possible issues:

1. Nanoparticles exhibit too much self-absorption?
2. Inefficient excitation of nanoparticles: concentration too low, no contribution from matrix?

2023 beam test of shashlyk prototypes

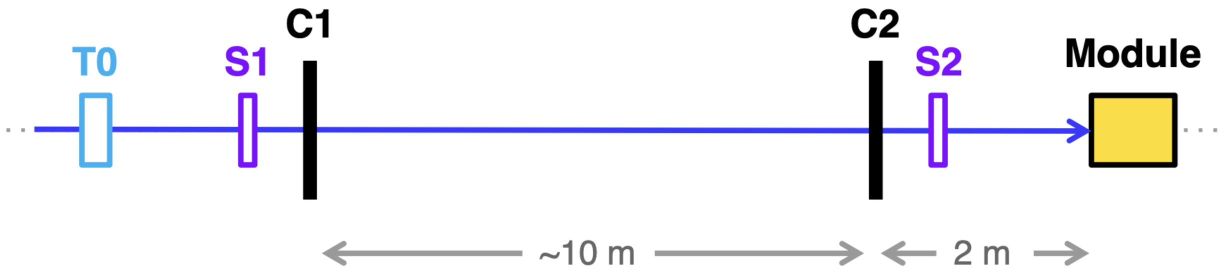
Test at T9 CERN beamline, June 2023:

Electron beam, 1-10 GeV

MIP beam (μ^- or π^-), ~4 GeV

Cerenkov detectors to allow verification of beam ID $e/\mu\pi/p$

T0	Time reference detector
S1, S2	Trigger scintillator paddles
C1, C2	Si strip tracking chambers, 10×10 cm^2



For each prototype:

- MIP efficiency map
- *e*− response
- Time resolution

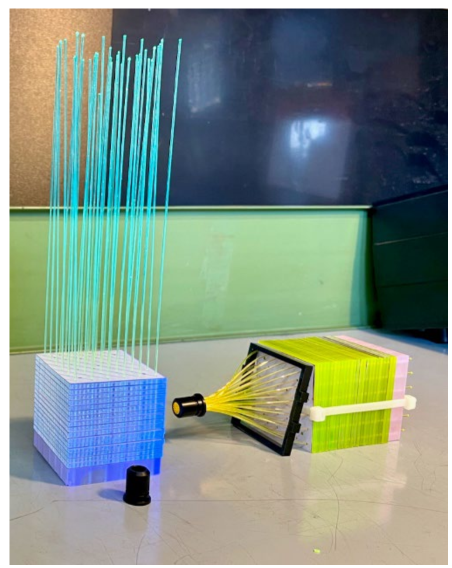
Tested prototypes:

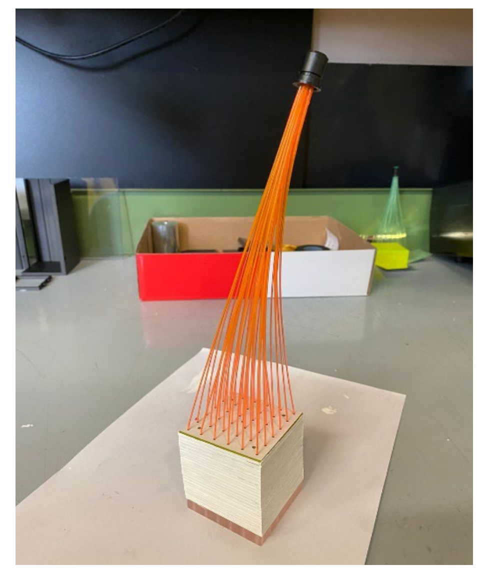
✓ Protvino scintillator + Y-11 with new mechanincs

✓ CsPbBr3 + NCA-1

✓ CsPb(BrCl)3 + NCA-1

✓ PVT + Y-11





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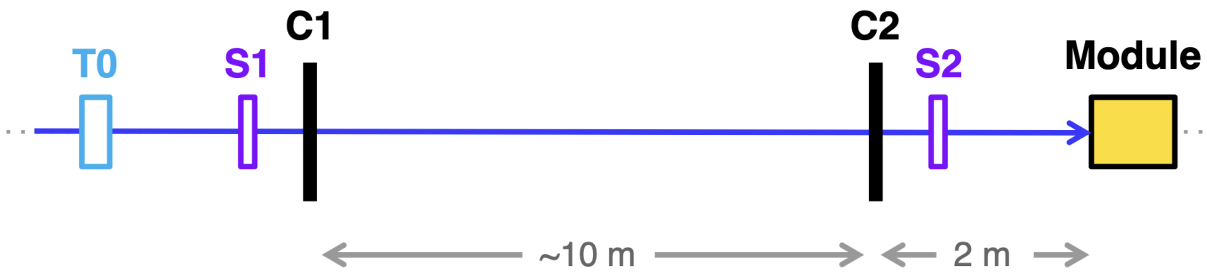
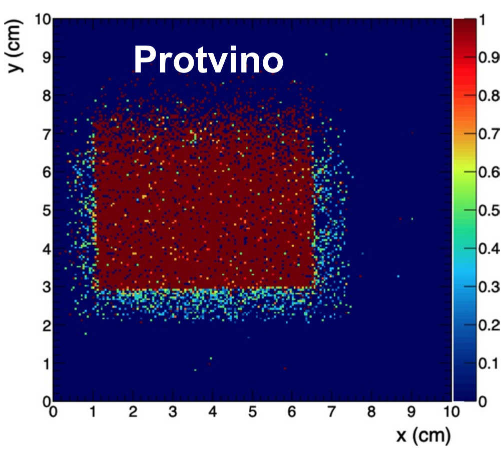


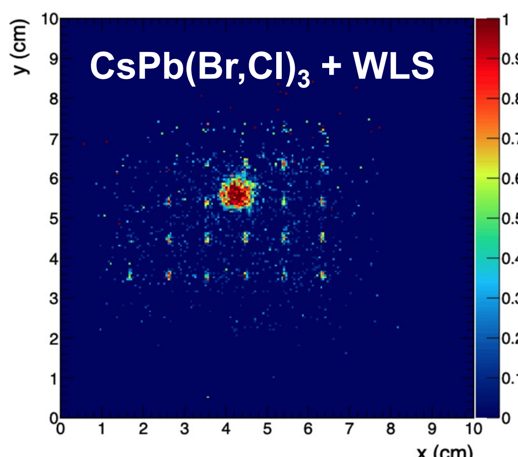
For each prototype:

- MIP efficiency map
- *e*− response
- Time resolution

Efficiency maps with 10 GeV μ, threshold = 5σ_{noise}

Disappointing result from new nanocomposite: only light is from readout fibers!

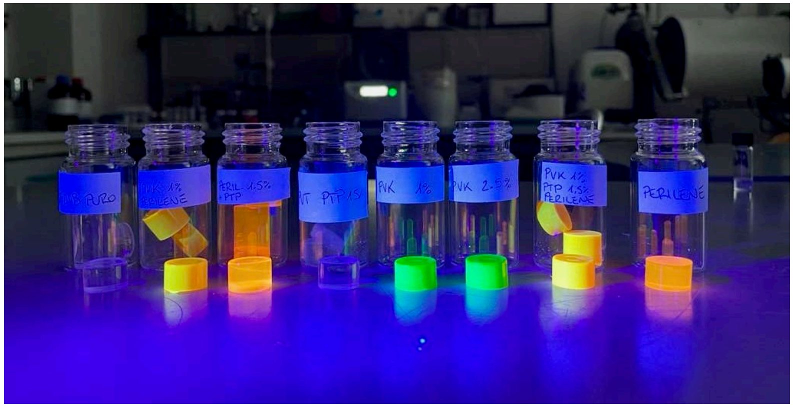




2024 beam test of nanocomposite scintillator

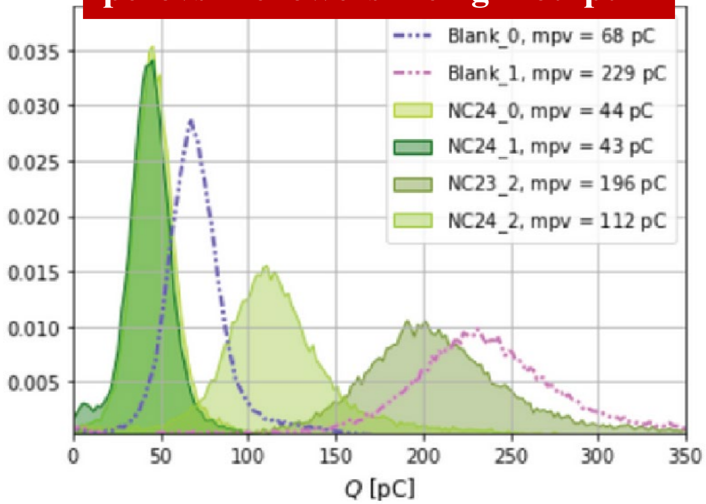
New samples with 1-2.5% nc in PVT with/without additional dyes tested at BTF in Apr '24

16th Pisa Meeting on Advanced Detectors, arXiv:2407.10915



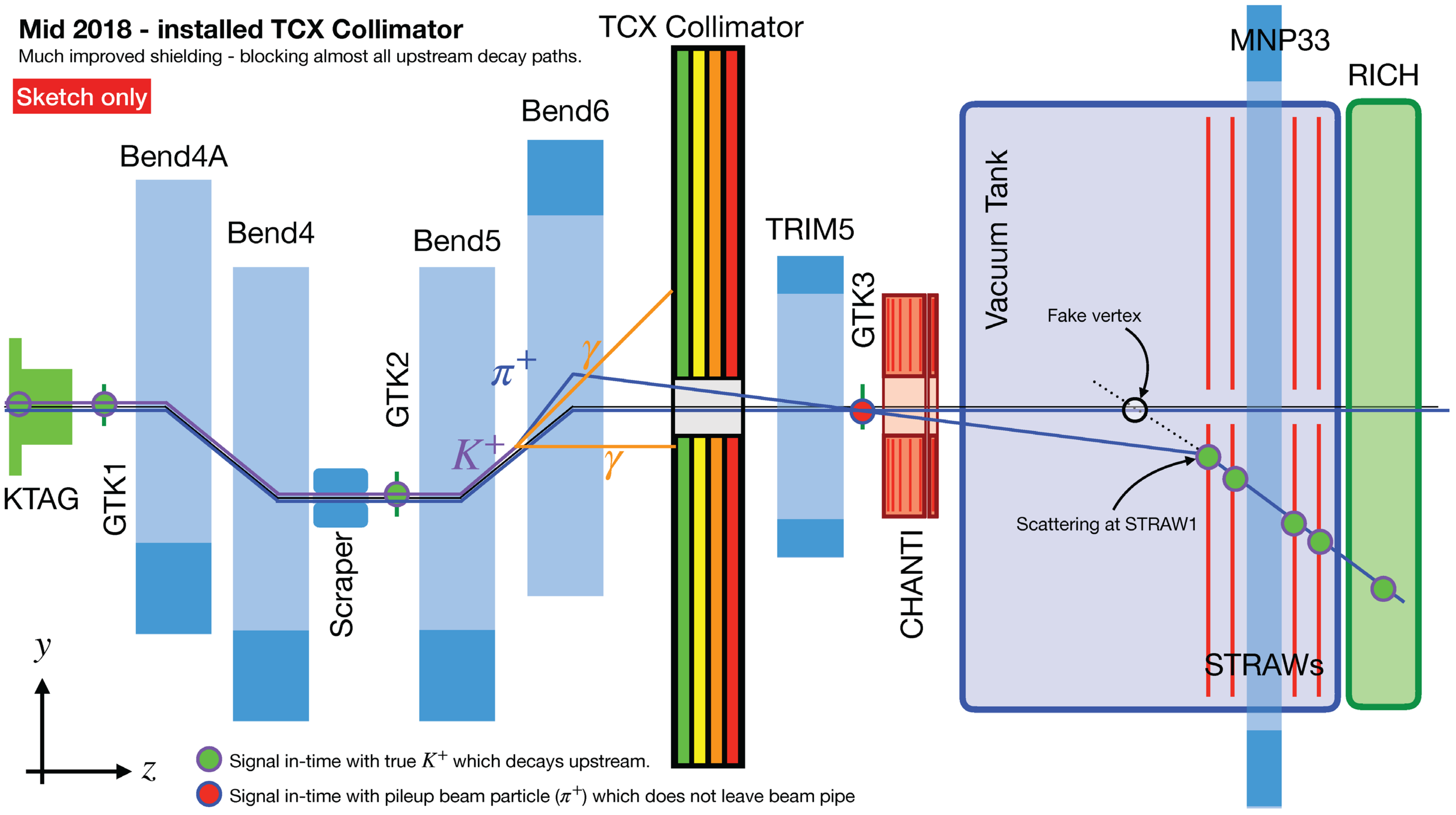
Blank_0	Only matrix (control for NC24_0, 1)
Blank_1	1.5% PTP (control for NC24_2)
Blank_2	Perylene dyad (control for NC24_3)
Blank_3	1.5% PTP + perylene dyad (control for NC24_4)
NC24_0	1% $CsPbBr_3$:F
NC24_1	2.5% $CsPbBr_3$:F
NC24_2	1.5% PTP + 1% $CsPbBr_3$:F
NC24_3	1% $CsPbBr_3$:F + perylene
NC24_4	1.5% PTP + 1% $CsPbBr_3$:F + perylene

Because of self-absorption, the perovskite lowers the light output

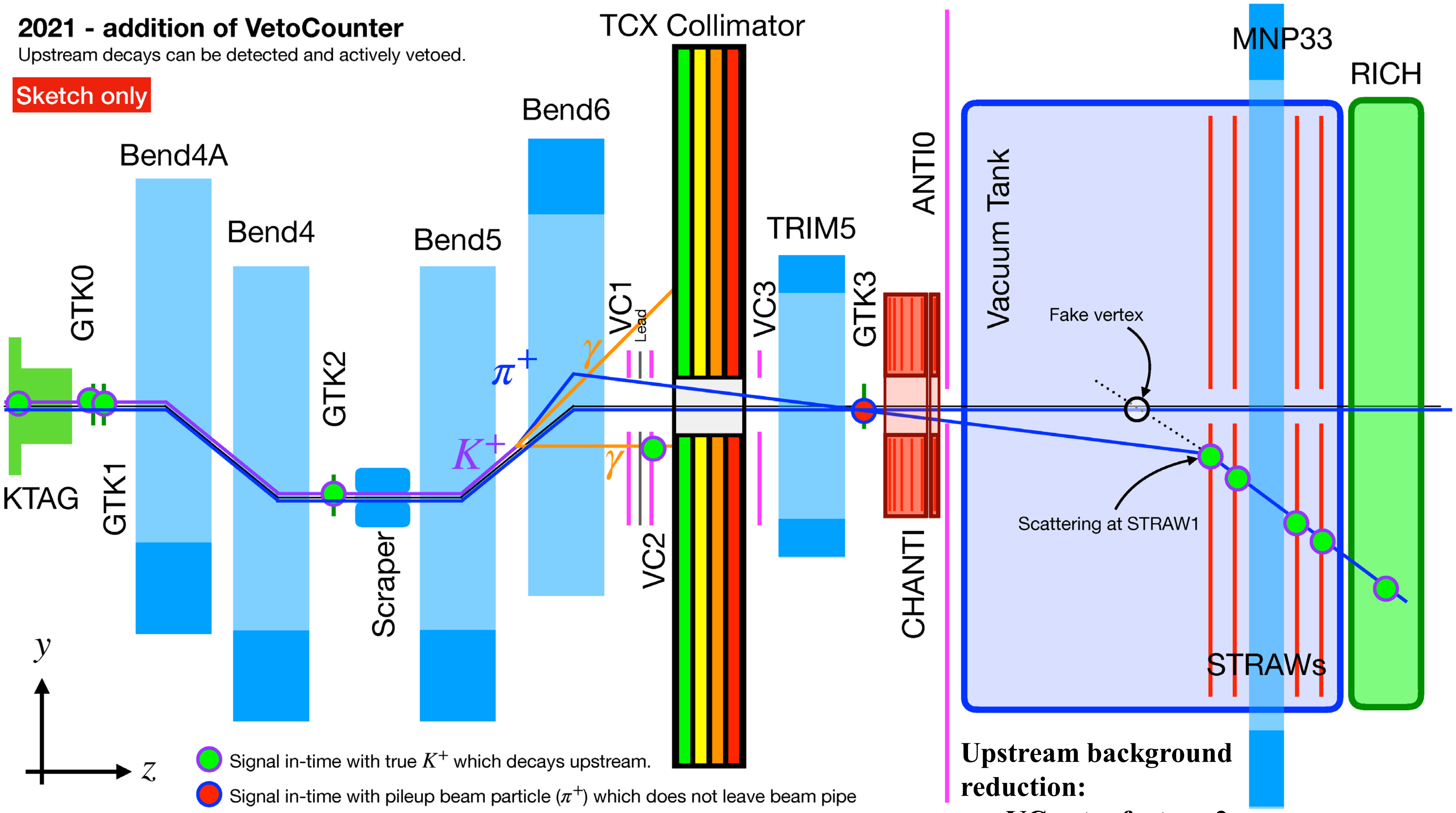


From all of the measurements performed, the use of perovskite quantum dots in scintillator for HEP is not straightforward, but it will require significant additional optimization effort.

Run 1 beamline layout



Run 2 beamline layout



Upstream background reduction:

- **VC veto: factor ~2**
- **ANTI0 veto: further 20%**

KOTO-II cost and timescale

Item	Cost M$
Calorimeter	10.1
CV	0.1
Barrel	7.7
BHPV	0.3
BHCV	0.1
Readout	2.4
Other items	3.1
Total	23.4

Total cost: $23.1M

- Calorimeter in CsI: $10.1M
  Reduced to $1.4M for shashlyk option
- Barrel veto $7.7M

Year	Main object
1	Beam line survey
2	Construction of the rest of the detector
3-6	Phase I: Physics run for mainly $K_L \to \pi^0 \nu \bar{\nu}$
7	Single event sensitivity will reach 8.5×10^{-13} for the $K_L \to \pi^0 \nu \bar{\nu}$ search
8	Detector upgrade
9-12	Phase II: Physics run mainly for $K_L \to \pi^0 \ell^+ \ell^-$ with an optimized setup
13	End of Phase II

Year 1 not well defined:

End of construction of Hadron Hall Extension (2033?)