Experimental proof of principle of the Neutrino Tagging technique at NA62

Radoslav Marchevski on behalf of the NA62 Collaboration

EPFL

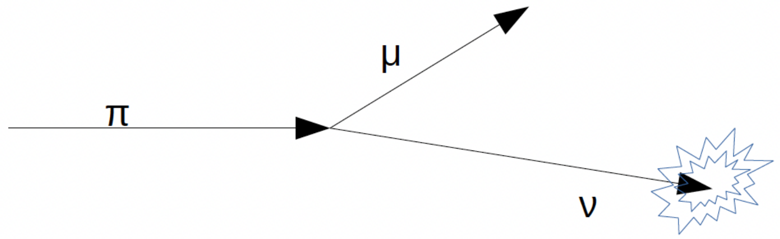
NuFact 2025 Conference
Liverpool, UK, September 1-6, 2025

Outline

- Neutrino tagging
- The NA62 experiment
- Proof of principle of Neutrino tagging
  - analysis strategy
  - offline selection
  - signal and background event yields
  - final result

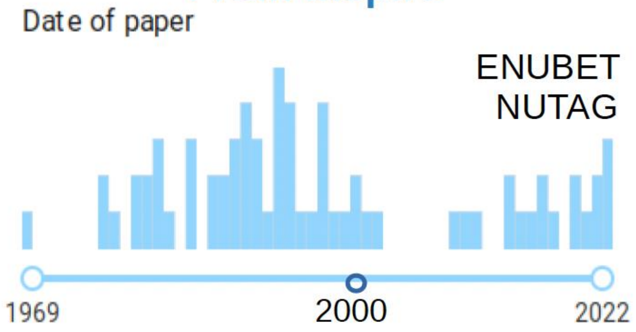
Neutrino tagging

- Concept introduced in the 70-80's
- Associate **individually** each neutrino interaction with its production mechanism



- Many variations of this idea were discussed in the 80-90's

From Inspire



LETTERE AL NUOVO CIMENTO VOL. 25, N. 9 30 Giugno 1979

Tagging Direct Neutrinos. A First Step to Neutrino Tagging.

B. Pontecorvo

Laboratory of Nuclear Problems, Joint Institute for Nuclear Research - Dubna, USSR

(ricevuto l'1 Giugno 1979)

As it is well known, high-energy neutrino investigations are performed by using neutrino beams from π and K decays ($\pi \to \mu\nu$, $K \to \mu\nu$), that is by letting the pions and the kaons decay over a large distance (the so-called decay length).

The possibility of using tagged-neutrino beams in high-energy experiments must have occurred to many people. In tagged-neutrino experiments it should be required that the observed event due to the interaction of the neutrino in the neutrino detector would properly coincide in time with the act of neutrino creation ($\pi \to \mu\nu$, $K \to \mu\nu$, $K \to e\nu\pi$, ...). Of course, in tagged-neutrino experiments the properties of neutrino beams (type, direction and energy) will be much better known than in the experiments performed so far. The main difficulty in designing such a facility is that the effective

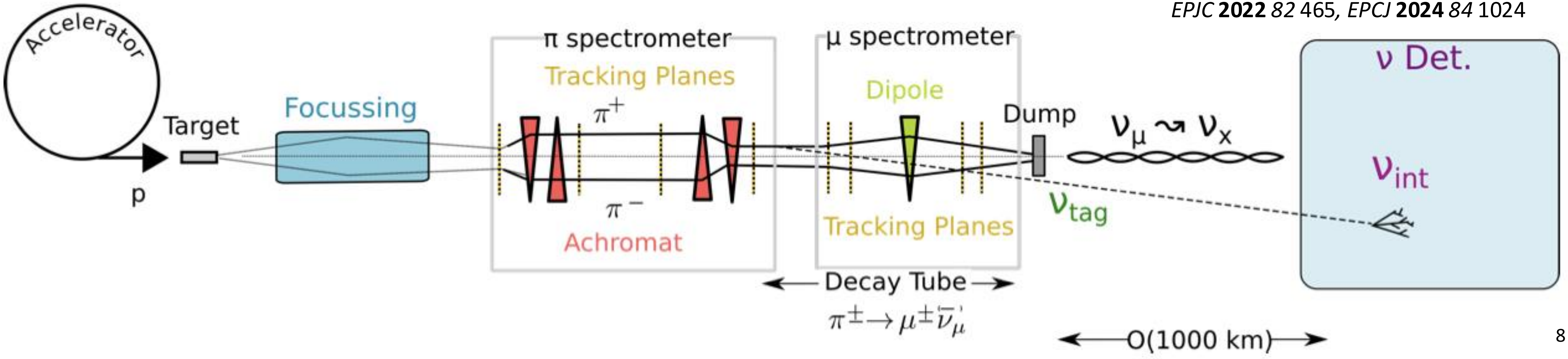
Neutrino tagging

- Instrument the beam line with spectrometers
- Each neutrino can be **fully & precisely characterized by its decay partners** (π, μ) at production
- Associate interacting neutrino at the far detector to the tagged neutrino at production
- Advantages:
  - knowledge of the beam flux
  - exceptional energy resolution: $\sigma_E/E < 1\%$

Ideal for studies of arXiv:2503.21589

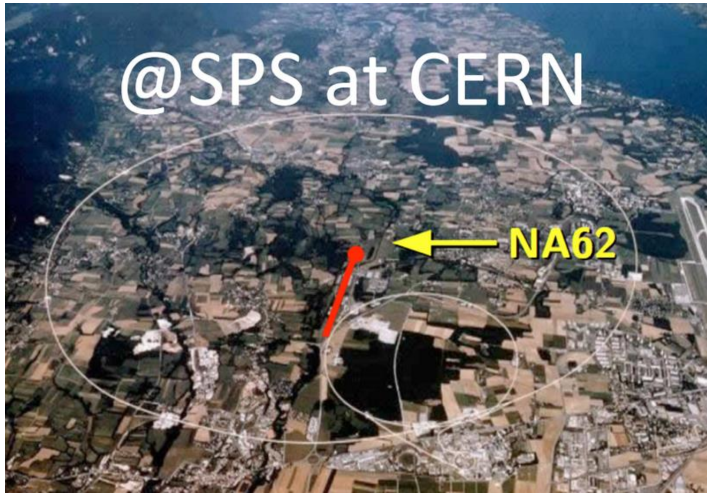
- cross-sections (short baseline)
- neutrino oscillations (long baseline)

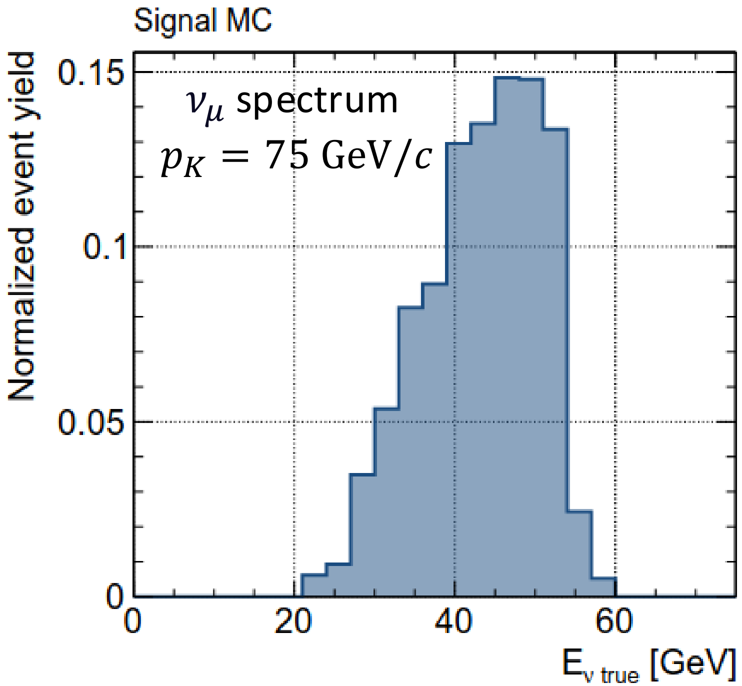
EPJC **2022** *82* 465, *EPCJ* **2024** *84* 1024



Proof of principle with NA62

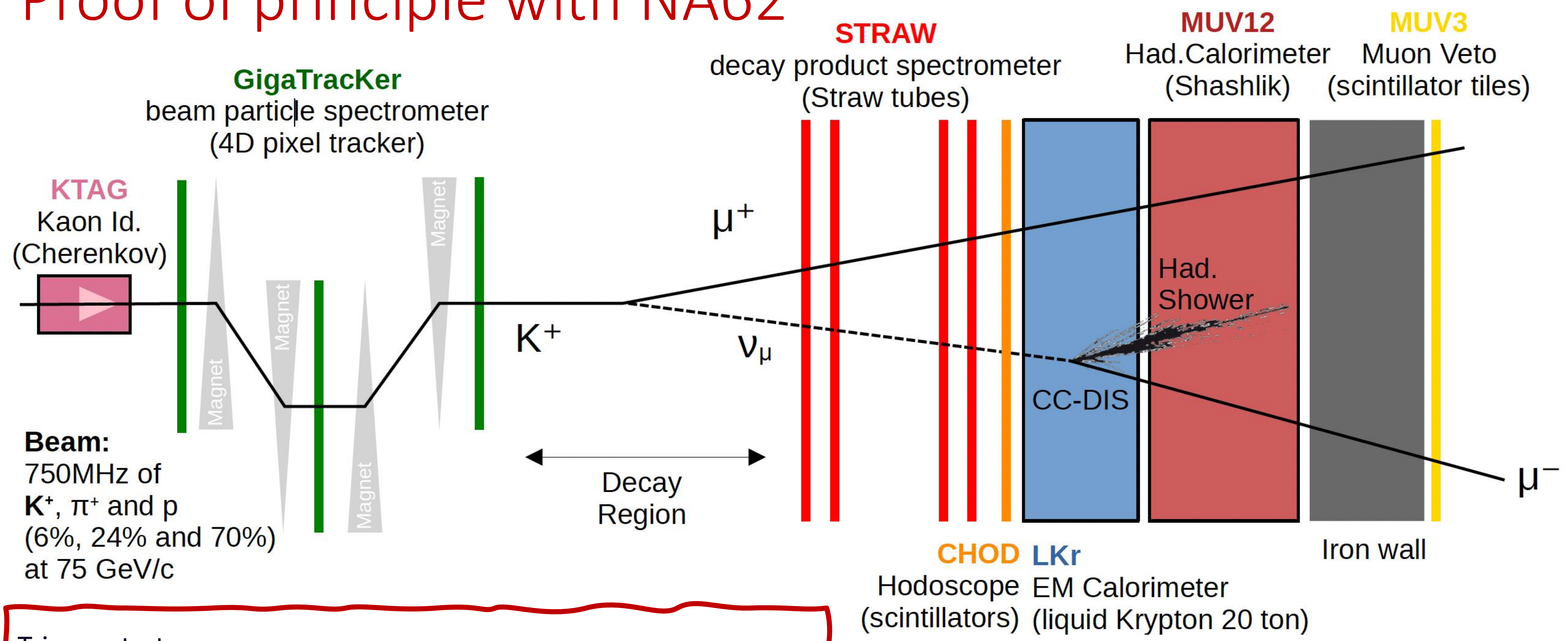
[JINST 12 (2017) 05, P05025]





- Fixed target Kaon experiment at CERN SPS (2015-present)
- **Goal:** measurement of $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ – $(7.86 \pm 0.61) \times 10^{-11}$ in the SM
- $\sim 10^{12}$ kaon decays per year, **mostly $K^+ \to \mu^+ \nu_\mu$**
- **All instrumentation available to detect the K^+, μ^+ and ν_μ!**

Proof of principle with NA62

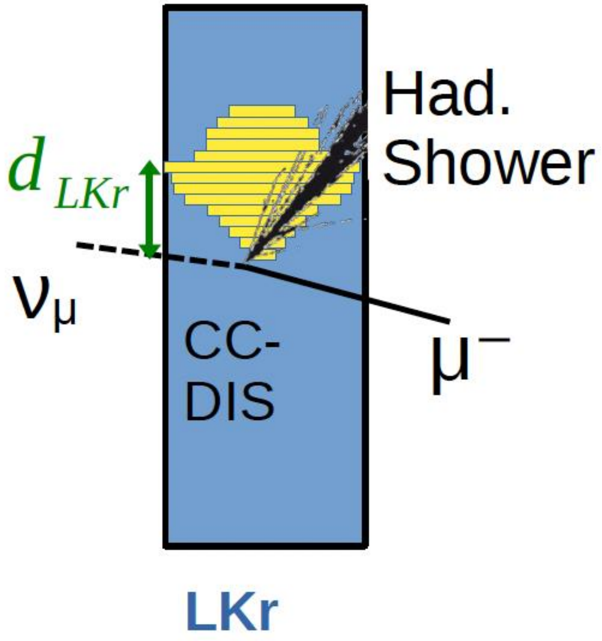


Trigger strategy

- One charged particle in **CHOD**
- Energy deposit in the **LKr**
- Two charged particles in opposite quadrants of the **MUV3**

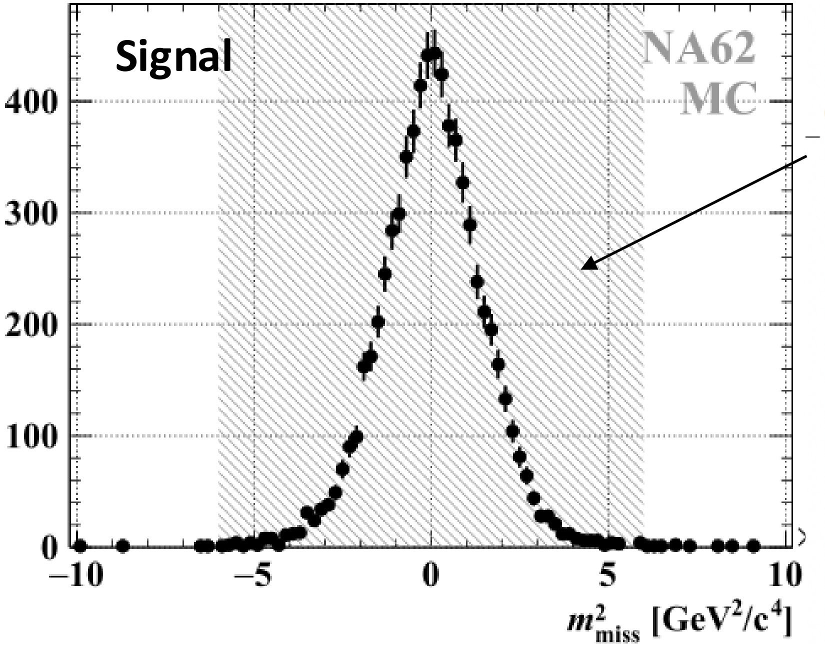
Analysis strategy

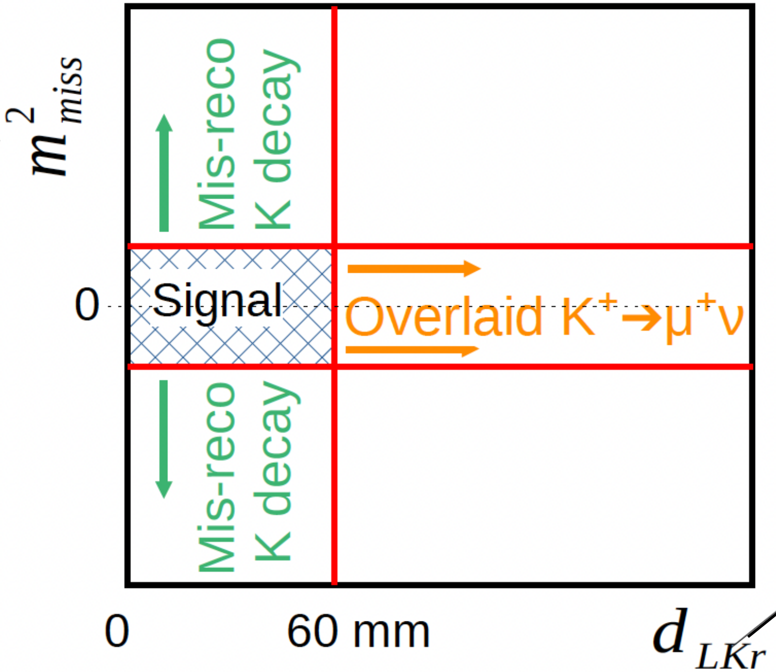
Main kinematic variable:
squared missing mass
$m^2_{miss} = (P_K - P_\mu)^2$

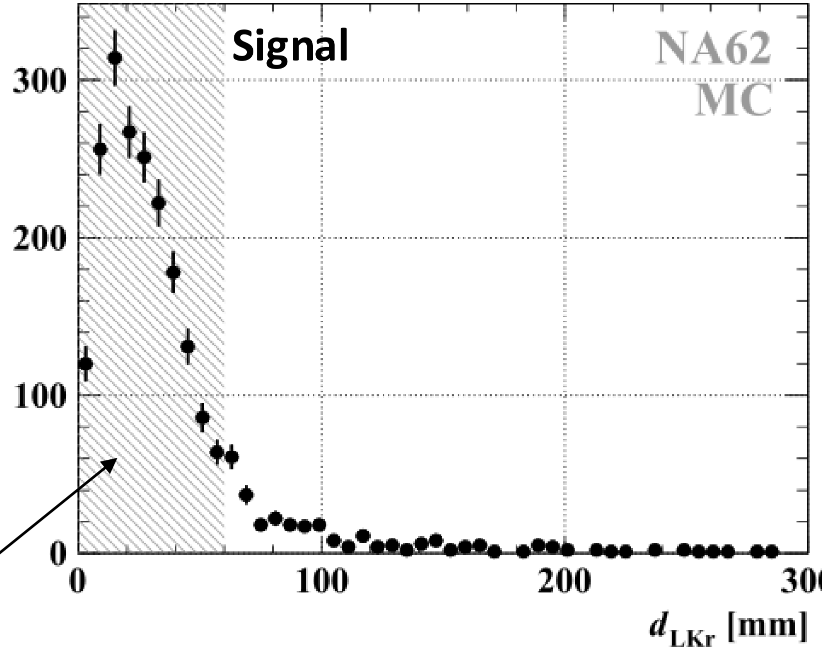


- Data sample: $\sim 5 \times 10^{12}$ K^+ decays collected in 2022
- Blind analysis, with a signal region defined in the m^2_{miss}, d_{LKr} plane
- Two leading background sources
  - **Overlaid $K^+ \to \mu^+\nu_\mu$**: $K^+ \to \mu^+\nu_\mu$ decay with extra activity in the LKr
  - **Mis-reconstructed K^+ decay**

PLB 863 (2025) 139345





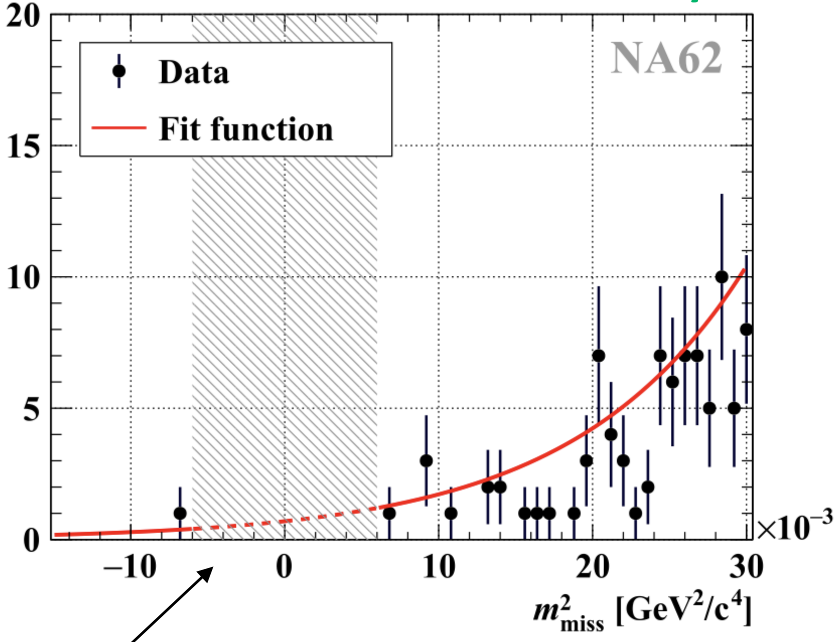


Analysis strategy

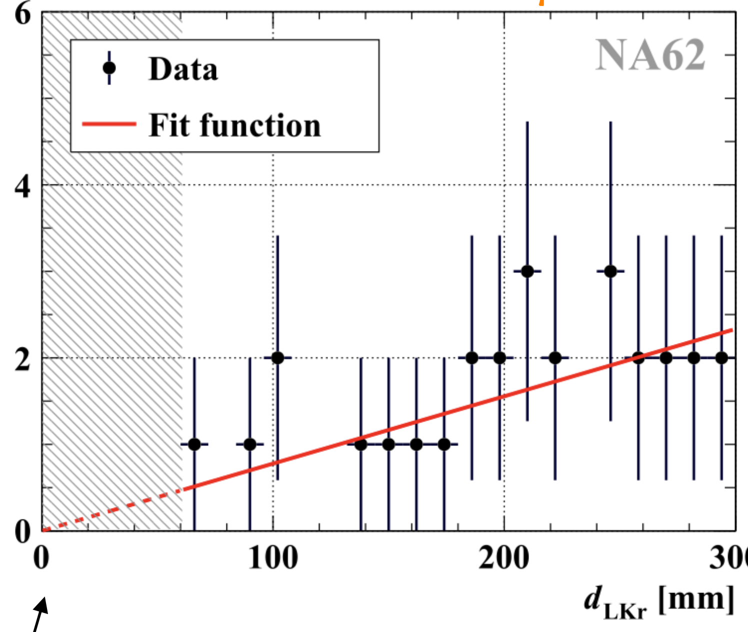
- **Background** extrapolated from signal side-bands with a relaxed selection
- **Expected signal** yield normalised to $K^+ \to \mu^+\nu_\mu$

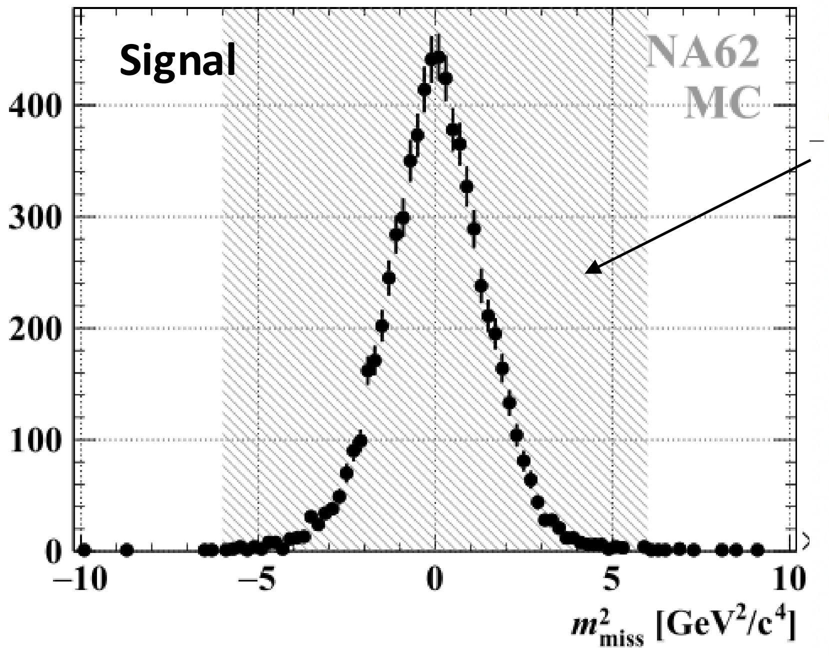
PLB 863 (2025) 139345

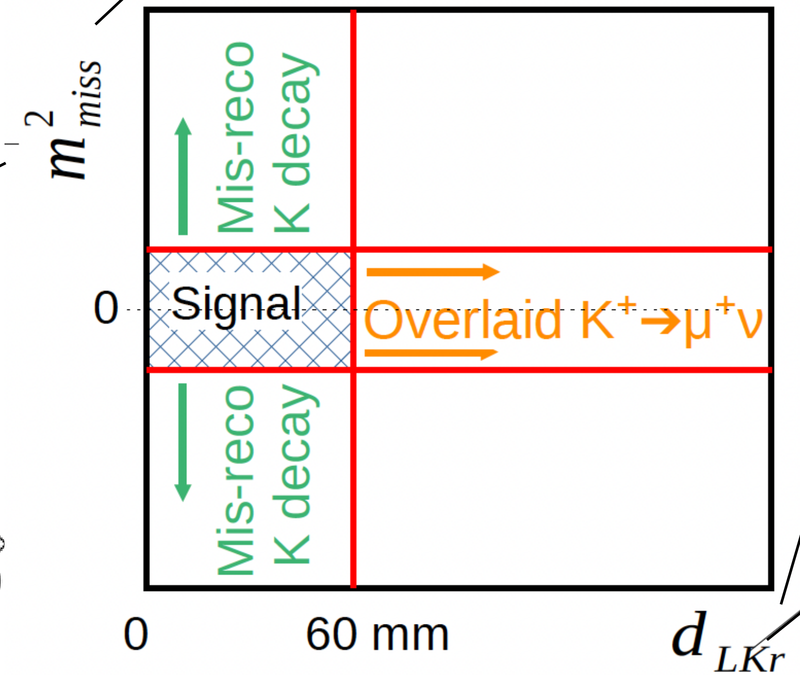
Mis-reconstructed K^+ decay

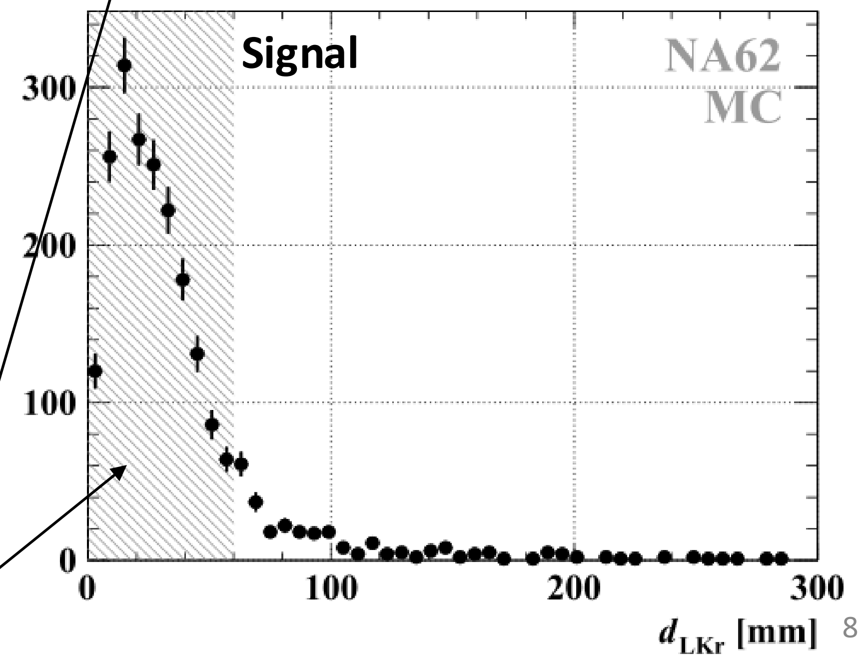


Overlaid $K^+ \to \mu^+\nu_\mu$









Expected signal and background events

- **Background** extrapolated from signal side-bands with a relaxed selection
- **Expected signal** yield normalised to $K^+ \to \mu^+ \nu_\mu$

$$N_{\mathrm{sig}} = 0.208 \pm 0.013_{\mathrm{stat}} \pm 0.009_{\mathrm{syst}}$$

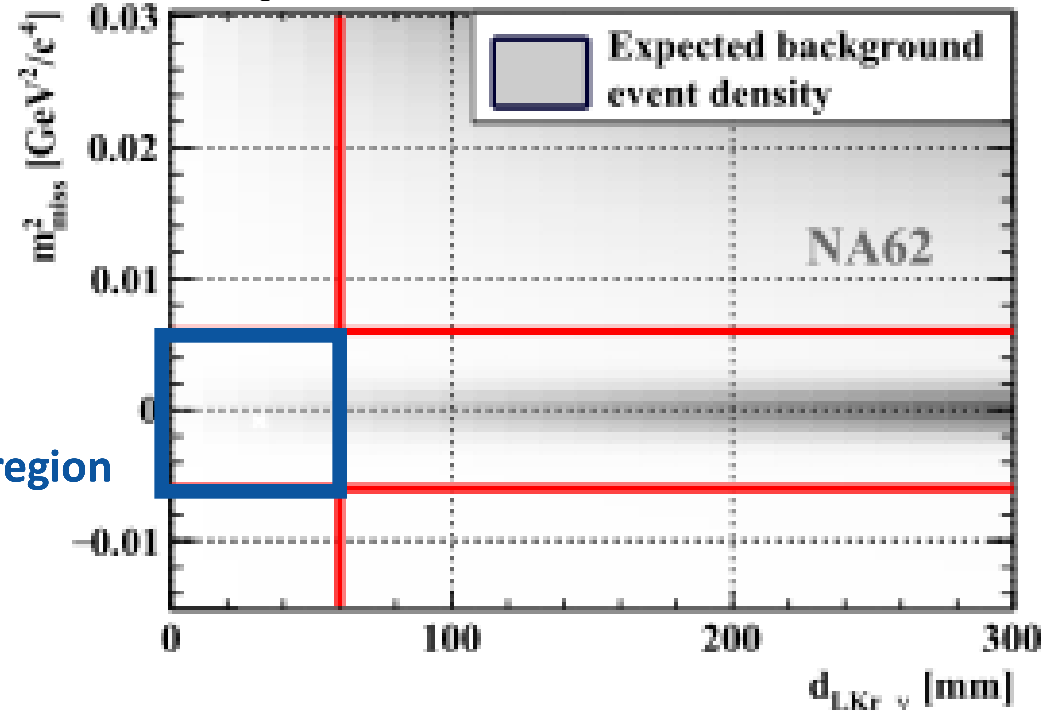
$$N^{bg}_{\mathrm{overlaid}\,K_{\mu 2}} = 0.030^{+0.041}_{-0.023}|_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}}$$

$$N^{bg}_{\mathrm{mis-reco}\,K_{\mu 2}} = 0.004^{+0.006}_{-0.003}|_{\mathrm{stat}} \pm 0.001_{\mathrm{syst}}$$

PLB 863 (2025) 139345

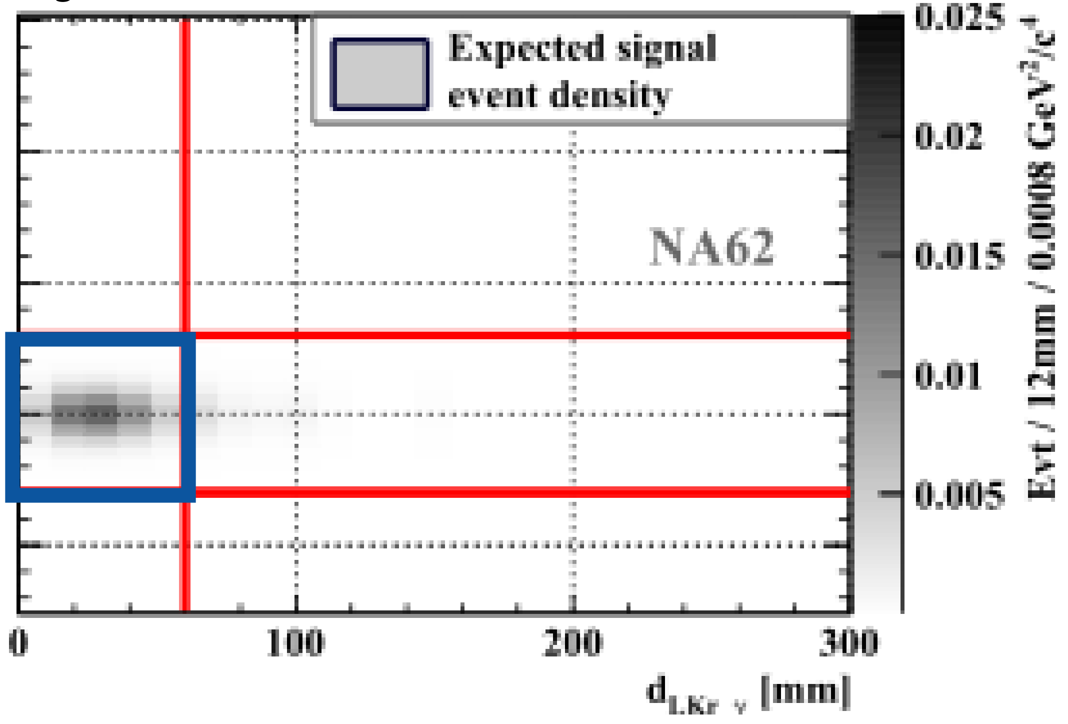
$S/B \sim 6$

Backgrounds



Signal region

Signal



Expected signal and background events

- **Background** extrapolated from signal side-bands with a relaxed selection
- **Expected signal** yield normalised to $K^+ \to \mu^+ \nu_\mu$

$$N_{\mathrm{sig}} = 0.208 \pm 0.013_{\mathrm{stat}} \pm 0.009_{\mathrm{syst}}$$

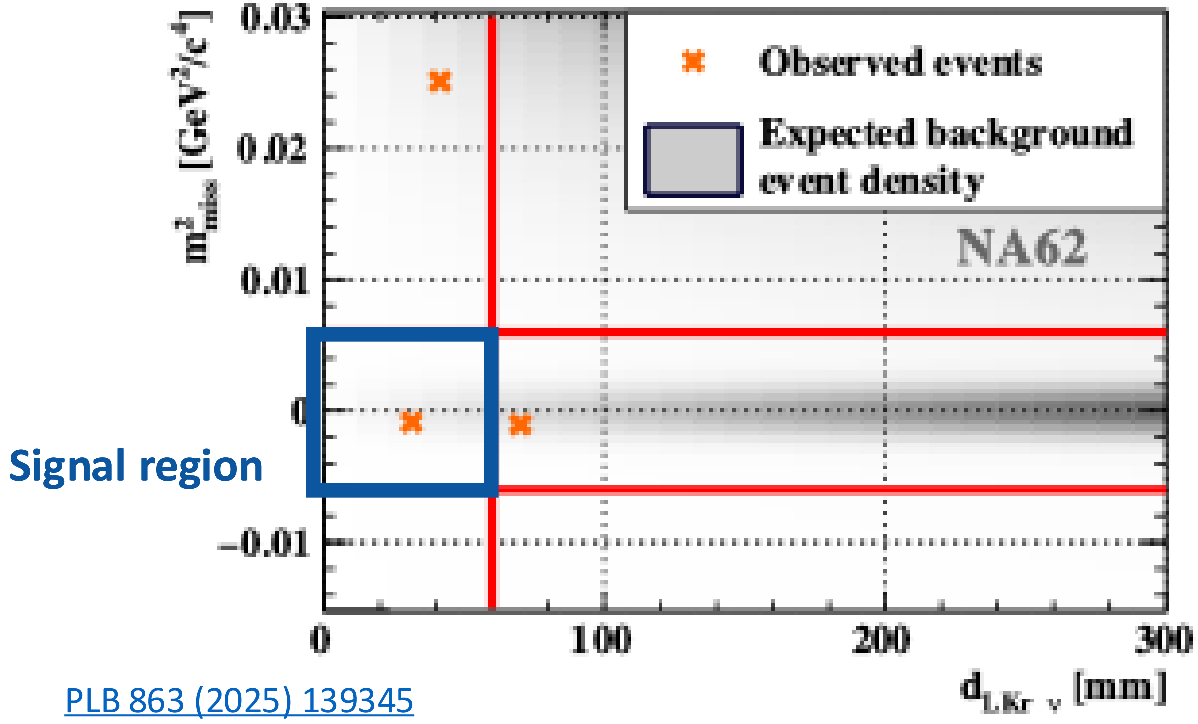
$$N^{bg}_{\mathrm{overlaid}\,K_{\mu2}} = 0.030^{+0.041}_{-0.023}|_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}}$$

$$N^{bg}_{\mathrm{mis-reco}\,K_{\mu2}} = 0.004^{+0.006}_{-0.003}|_{\mathrm{stat}} \pm 0.001_{\mathrm{syst}}$$

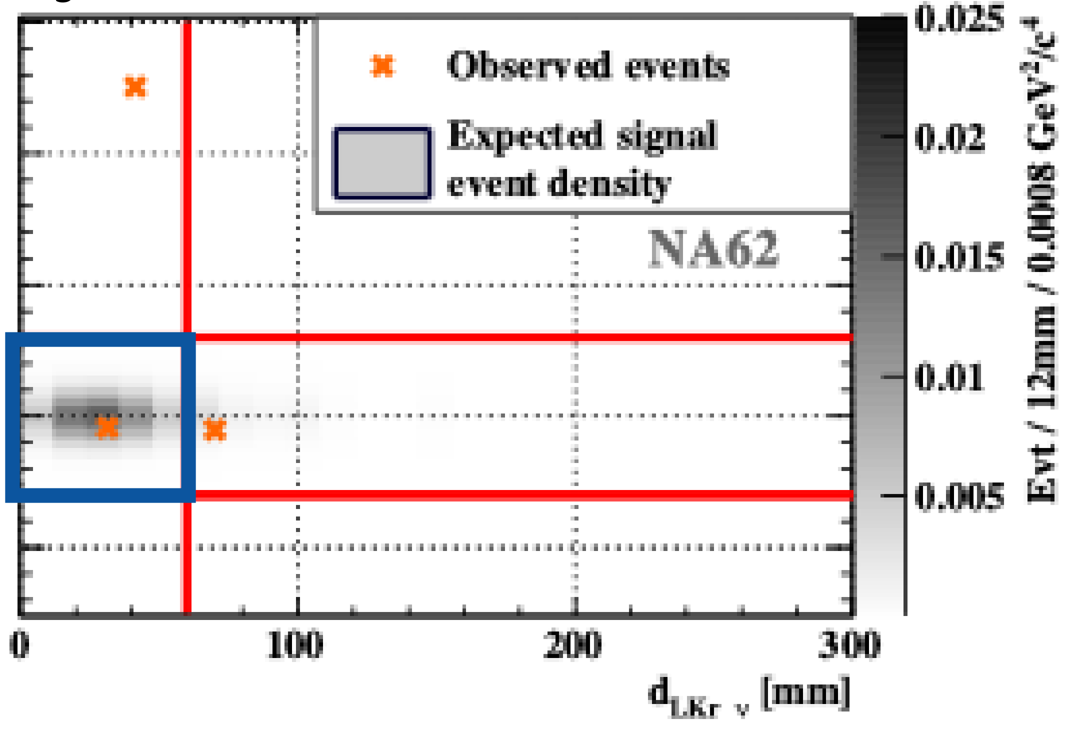
$S/B \sim 6$

One event observed in signal region!

Backgrounds



Signal



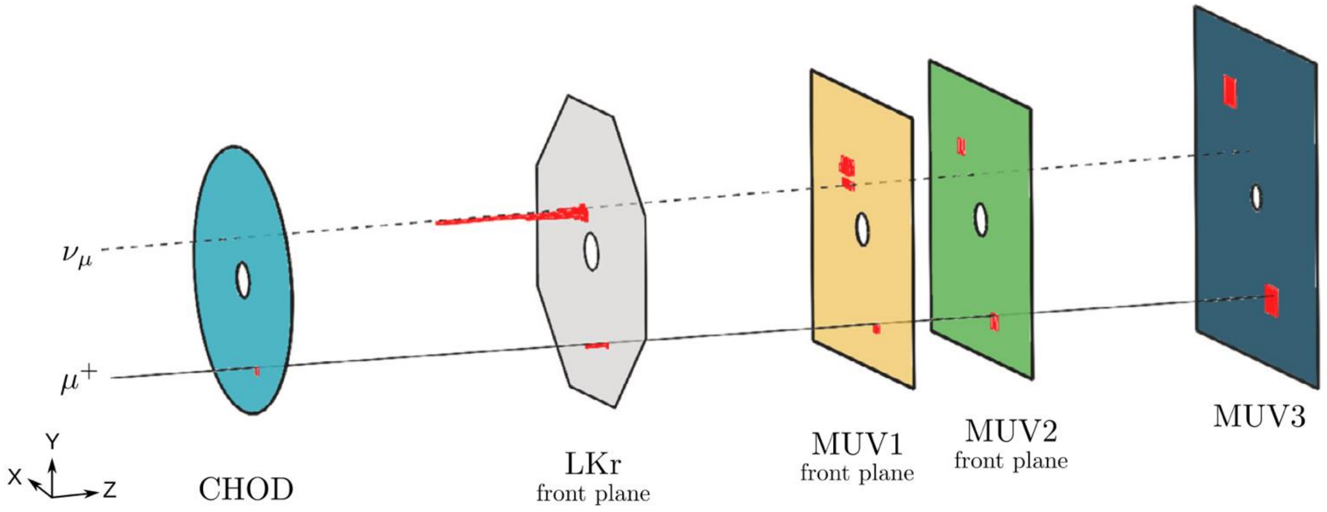
PLB 863 (2025) 139345

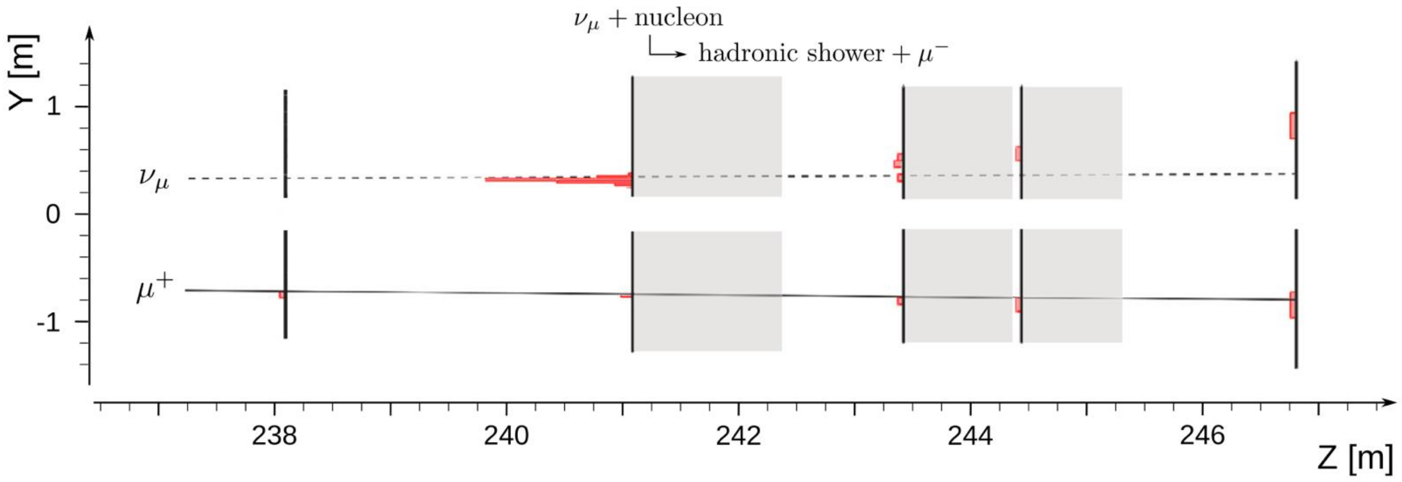
Results: first tagged neutrino candidate observed at NA62

- **One event observed in signal region**
- **First tagged neutrino candidate observed**
  - prob. of observing one event in signal region: **19%**
  - prob. of observing one background event: **3%**

PLB 863 (2025) 139345

Property	Value
K^+ momentum	77.34 GeV/c
μ^+ momentum	25.26 GeV/c
Decay vertex position z_{vtx}	161.2 m
Neutrino energy $E_\nu = E_{K^+} - E_{\mu^+}$	52.09 GeV
Distance of the LKr signal to the Z axis	334.9 mm
LKr energy associated with the neutrino E_{LKr}	12.54 GeV
MUV1 energy associated with the neutrino E_{MUV1}	13.75 GeV
MUV2 energy associated with the neutrino E_{MUV2}	10.74 GeV
Inelasticity y	0.69
Azimuthal angle between the LKr and MUV3 signals φ	3.28 rad
d_{LKr}	31.4 mm
d_{MUV3}	567.9 mm
m^2_{miss}	-0.00086 GeV$^2/c^4$





Summary and prospects

- Neutrino tagging technique could provide an ideal setup to study ν interactions (short term) and ν oscillations (long term)
- NA62 experiment has been used as a tagged neutrino experiment to demonstrate the feasibility of neutrino tagging
- Complete $K^+ \to \mu^+ \nu_\mu$ decay reconstruction with all particles in the event detected
- **First fully tagged neutrino candidate detected at NA62!** [PLB 863 (2025) 139345]
- A crucial step towards demonstrating that neutrino tagging in feasible
- Results to be confirmed with more data: *at least three times larger data set already available at NA62*