Neutrino Tagging feasibility study with NA62 data

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Bianca De Martino

CNRS/IN2P3, CPPM

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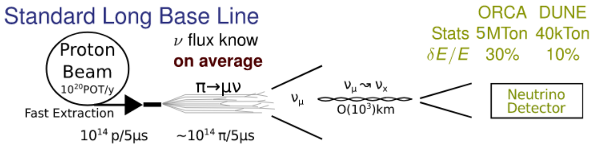
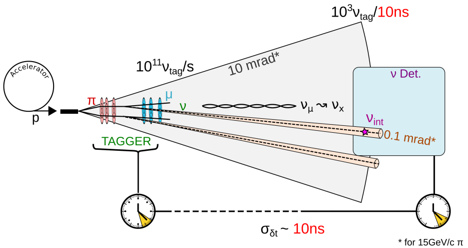
Context: accelerator based neutrinos experiments

- Many fundamental parameters of neutrino physics not yet measured: mass ordering, oscillations parameters and Charge-Parity violation
- A very convenient way to do neutrino physics is at accelerator based neutrino experiments
- Set-up: near detector (initial energy spectrum and composition of neutrino beam) + neutrino detector (neutrino beam properties after oscillations).
- These experiments typically have many systematics

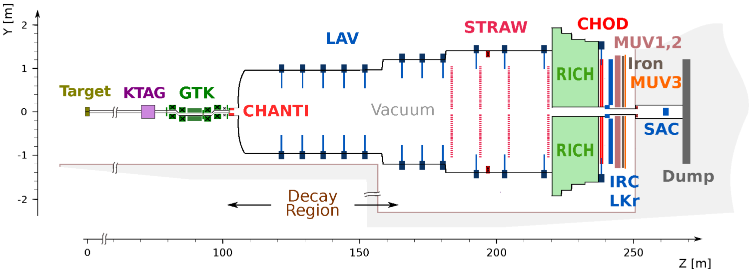


Context: neutrino tagging

- Neutrino Tagging: method for **accelerator based neutrino experiments** that consists in instrumenting a beam line with silicon trackers
- Each neutrino originating from a $\pi^+ \rightarrow \mu^+ \nu$ decay can be reconstructed based on simple kinematic relations from the decay incoming and outgoing charged particles
- The neutrinos interacting in the neutrino detector can be unambiguously matched with one neutrino reconstructed by the tracker based on time and angular associations
- Main advantages:
  - improved energy resolution: one order of magnitude better than with standard neutrinos detectors
  - improved beam knowledge
- $\rightarrow$ reduce the systematic uncertainties in neutrino oscillation studies

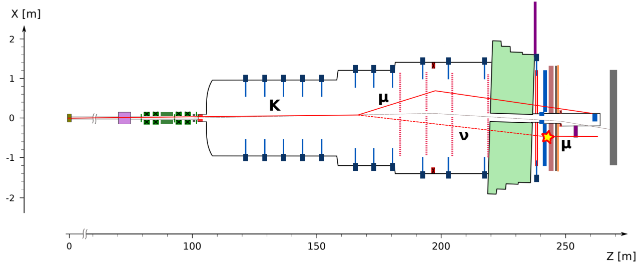


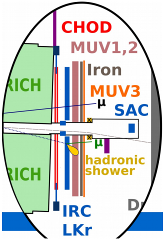
Feasibility study at NA62 - 1



- NA62 offers the possibility to perform a feasibility study on the neutrino tagging technique
- NA62 is a fixed-target particle physics experiment in the North Area of the SPS accelerator at CERN
- NA62's main purpose is the measurement of the branching ratio of the $K^+ \to \pi^+ \nu\overline{\nu}$ rare decay (SM signal Br $\sim 10^{-10}$)

Feasibility study at NA62 - 2

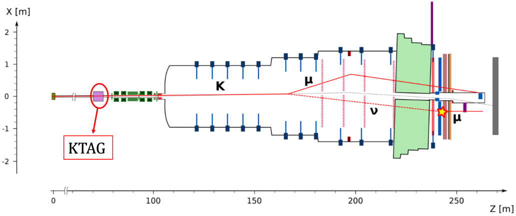




- The main decay mode $K^+ \to \mu^+ \nu_\mu$ (Br $\sim$ 63%) can be exploited for the purpose of this project:
    - Exploit tracker for charged particles
    - Reconstruct K+ and μ+ and look for neutrino associated activity in calorimeters
    - The neutrino interacts via a Charged Current interaction, that creates a second muon and an hadronic shower
- The ν interaction probability in the calorimeter is very small ($\sim 10^{-11}$) $\to$ need very intense beam to collect just a bunch of events
- NA62's high intensity kaon beam at 75 GeV/c delivers a nominal rate of $10^{12} K^+$ decays per year

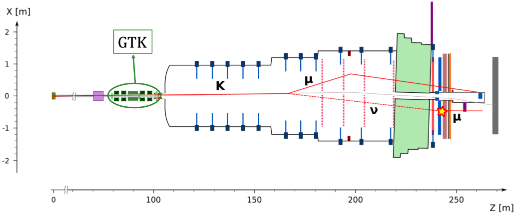
The detectors we need

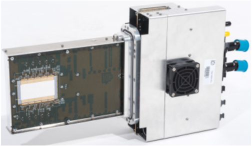
- KTAG: differential Cherenkov counter equipped with 8 arrays of photodetectors, identifies the K + in the beam



The detectors we need

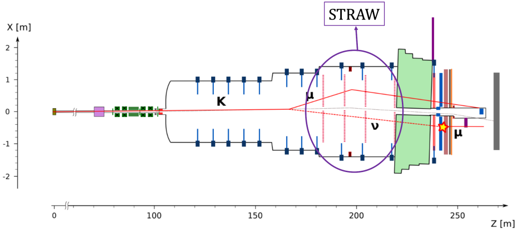
- GigaTracker: silicon pixel spectrometer with very good time resolution, reconstructs properties of incoming beam particles (K+)





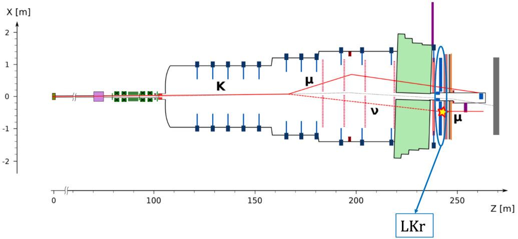
The detectors we need

- STRAW: straw tube spectrometer that reconstructs the properties of charged particles produced in K decays



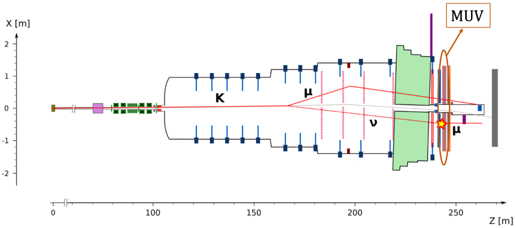
The detectors we need

- LKr: electromagnetic calorimeter filled with about 9000 l of liquid Krypton at 120 K



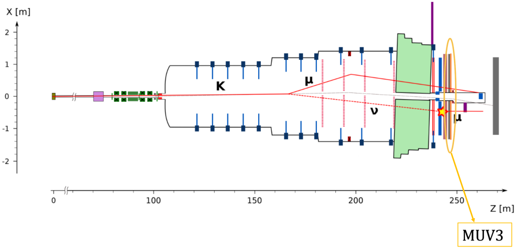
The detectors we need

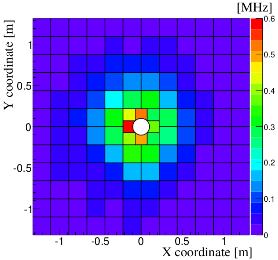
- MUV: 66 ton Shashlik (hadron) calorimeter used to discriminate between μ and π



The detectors we need

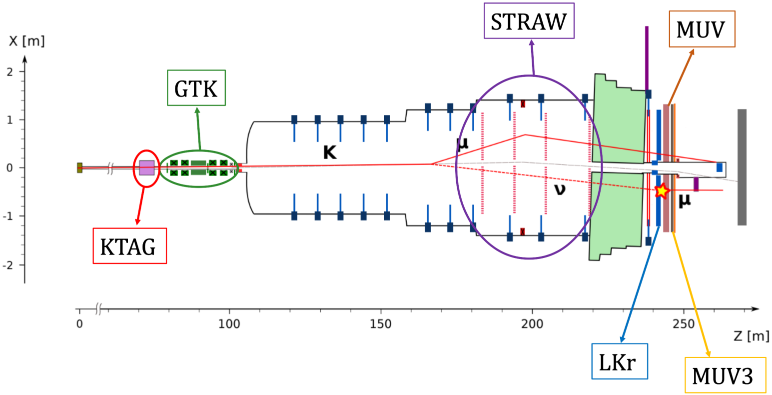
- MUV3: 50 mm thick scintillator tiles, placed behind an EM calorimeter, and hadronic calorimeter and an iron wall, used for muon identification





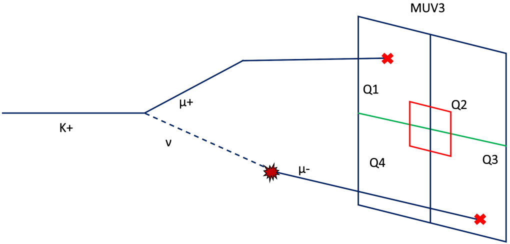
Trigger line: the signature of the signal

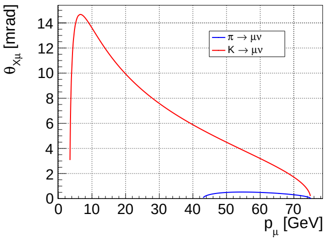
- Dedicated trigger line deployed in 2021
- ν_μ produced in the decay can interact via a CC interaction in the LKr calorimeter depositing energy in LKr and in the MUV, producing a second μ
- Trigger line selection: single downstream track before LKr with two muons at MUV3 with total energy deposit > 5GeV in LKr



MUV3 condition

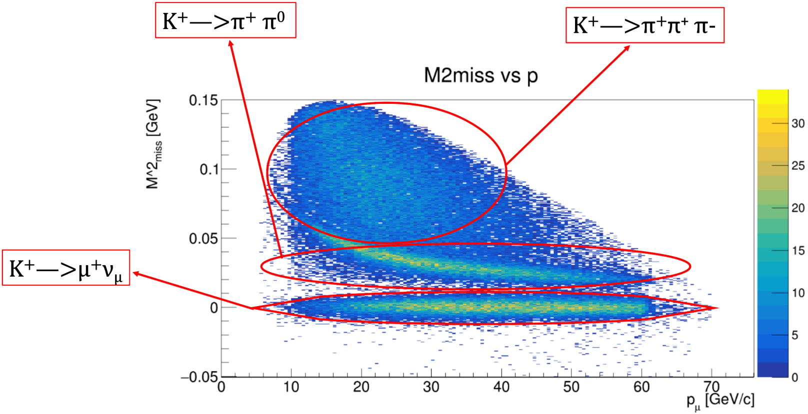
- The MUV3 trigger condition was made especially for the neutrino trigger line
- It selects events in a time window of 5 ns with respect to the trigger time that fall in **opposite outer quadrants** of MUV3
- Inner region closest to beam pipe excluded in order to avoid background of π^+
- Beam made of 70% of π^+, 24% of protons and 6% of K+





Data quality: squared missing mass

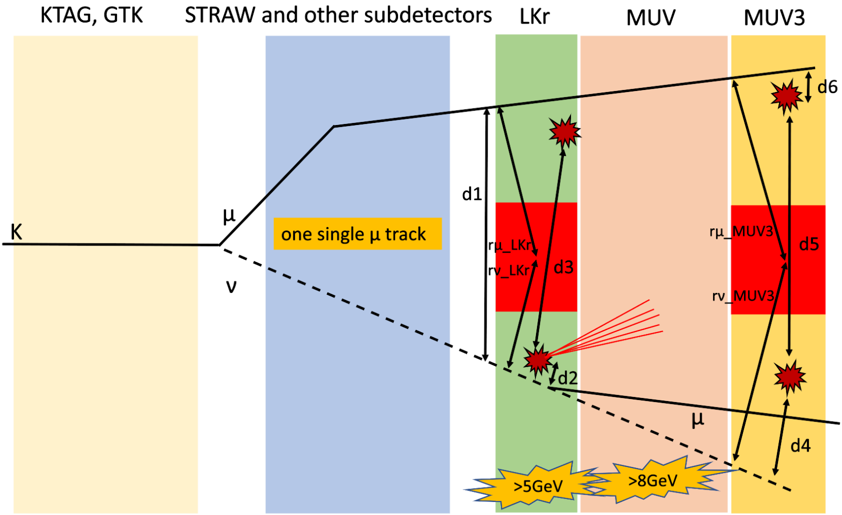
- What background can we expect?
- $M^2_{miss} = (P_K - P_\mu)^2$ computed assuming the mass of μ and using the nominal K momentum on 2022 data that passed our trigger



unavoidable background: an accidental μ from a π decay will fire the trigger

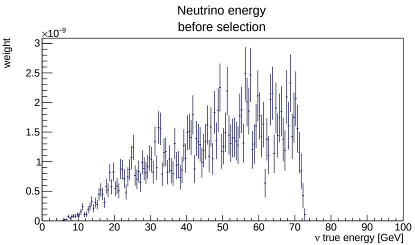
Selection of $K\mu\nu*$

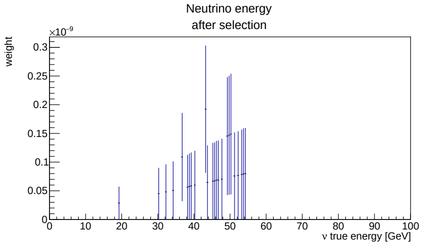
Signal at 10^{-11} → very strict selection to avoid background



Signal efficiency

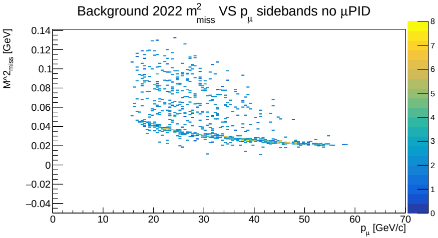
- Signal efficiency has to be estimated on MC sample
- 3k K^+ produced, forced to decay in μ^+ and ν_μ
- ν_μ forced to interact in LKr, only CC interactions are simulated
- Every event gets assigned a weight that corresponds to interaction probability in LKr → the average of the weight is the interaction probability in the LKr
- Signal efficiency: $\epsilon_{signal}^{selection} = \frac{\sum p_i^{pass}}{\sum p_i} = 1.8\%$

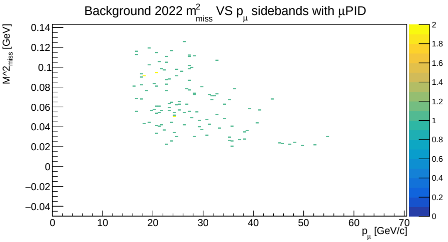




Background rejection

- In this analysis we want to be as close as possible to zero background
- Background studies used to optimise the selection
- Study background events that pass the selection in sidebands of signal region on data
- Extrapolate expected background in signal region
- Adding μ PID done with a Ring Cherenkov detector significantly lowers expected background





Number of expected tagged events in 2022

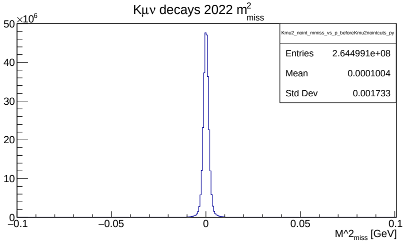
- $K\mu\nu* = K^+ \rightarrow \mu^+\nu_\mu$ with neutrino interaction in the LKr calorimeter (signal)

$$N^{exp}_{K\mu\nu*} = N_K \times Br(K \rightarrow \mu\nu) \times \epsilon^{sel}_{K\mu\nu*} \times \epsilon^{trig/sel}_{K\mu\nu*} \times P_{int,LKr} \quad (1)$$

- Normalize with respect to the total number of $K^+ \rightarrow \mu^+\nu_\mu$ (no interacting neutrino)

$$N^{exp}_{K\mu\nu*} = N_{K\mu\nu} \times \frac{\epsilon^{common}_{K\mu\nu} \times \epsilon^{sel}_{\nu*} \times \epsilon^{trig/sel}_{K\mu\nu*}}{\epsilon^{common}_{K\mu\nu} \times \epsilon^{trig/sel}_{K\mu\nu}} \times P_{int,LKr} \quad (2)$$

- $P_{int,LKr} = 5 \cdot 10^{-11}$
- $N_{K\mu\nu} = 1.6 \cdot 10^{11}$ obtained from data from 2022 run until beginning of October
- $\epsilon^{sel}_{\nu*} = 7.6\%$
- The offline selection enforces the trigger selection $\rightarrow \epsilon^{trig/sel}_{K\mu\nu*}$ assumed to be 100%

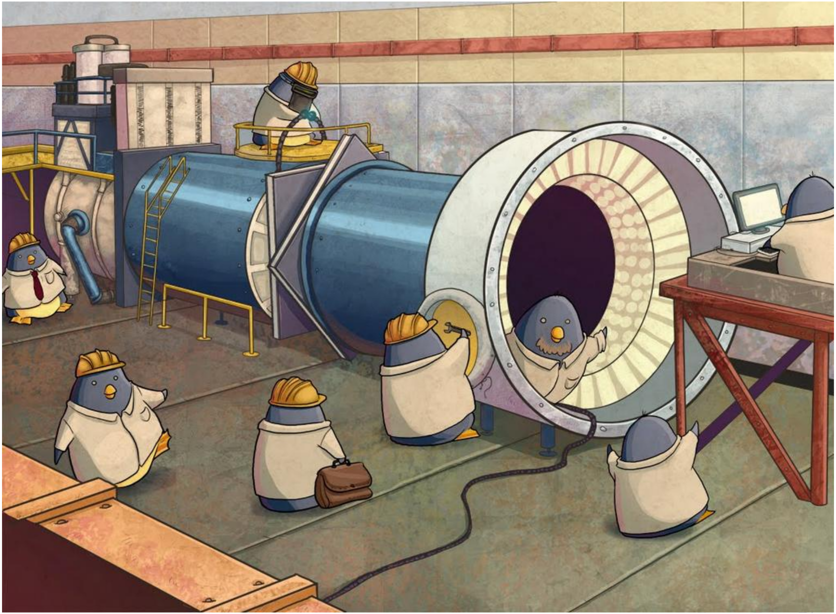


$$N^{exp}_{K\mu\nu*} = N_{K\mu\nu} \times \frac{\epsilon^{sel}_{K\mu\nu*} \times \epsilon^{trig/sel}_{K\mu\nu*}}{\epsilon^{trig/sel}_{K\mu\nu}} \times P_{int,LKr} = 0.6$$

Conclusions and next steps

- First feasibility study of neutrino tagging on data
- Trigger line has been optimised and commissioned
- Data quality is good, data taking ongoing until 15 November
- The selection has been optimised (1.8% acceptance)
- Background studies are being finalized (background free!)
- Expected event yield for 2022: 0.6 → 1.5 months of data taking until the end of the run, we might see 1 event in 2022 data
- Analysis on $K^+ \to \pi^0 \mu^+ \nu_\mu$ decay channel starting, expect same yield as $K\mu\nu$
- Next steps: study systematic uncertainties, get approval for analysis to unblind

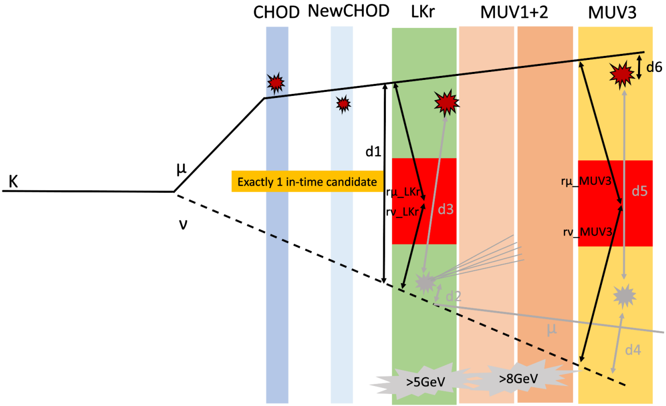
Thank you for your attention!



Backup

Selection of $K\mu\nu$

- The number of expected events can be normalized with respect to the number of "regular" $K\mu\nu$ from 2022 data
- The $K\mu\nu$ are selected using the same selection used for the signal selection up to the neutrino interaction selection
- This way many items will cancel out in the estimate of $N^{exp}_{K\mu\nu*}$



Data quality: MUV3 condition efficiency

- Select events that contain $K^+ \to \pi^+\pi^+(\mu^+\nu)\pi^-(\mu^-\nu)$ decays
- Propagate the muon tracks to the MUV3 detector
- Check that the third π^+ does not decay into a μ
- See if the two tracks fall in opposite outer quadrants
- Check if the event fired the trigger condition
- Efficiency = evts that did fire the trigger / evts that should have fired the trigger
- Run on full 2021 data
- efficiency $\sim 97\%$