First evidence for neutrino tagging

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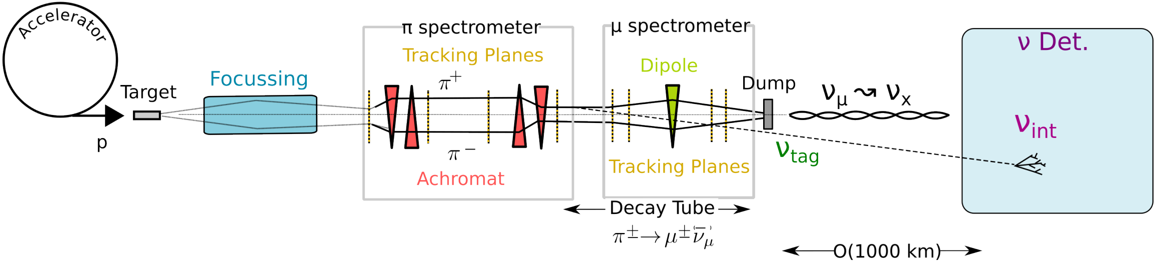
Outline

1. Neutrino Tagging
2. The NA62 experiment
3. Proof of principle of Neutrino Tagging
   - Analysis strategy
   - Offline selection
   - Event yield - background and signal
   - Revealing signal region content

Outline

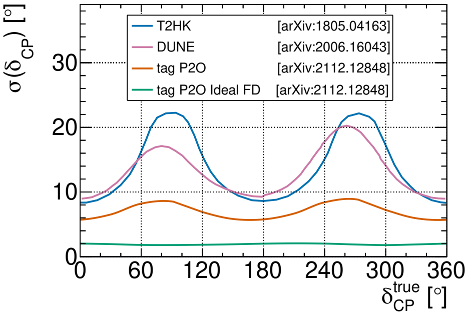
Neutrino Tagging

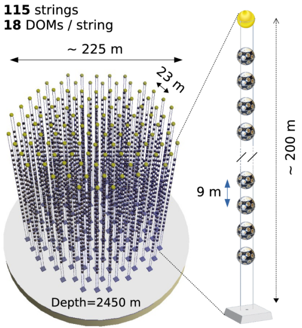
- Neutrino Tagging: new paradigm for accelerator based neutrino experiments
- Instrument a beam line with spectrometers
- **Kinematically reconstruct each** ν originating from a $\pi^+ \to \mu^+\nu_\mu$ decay $\to$ *tagged* ν
- **Associate** *interacting* ν at Far Detector to its tagged ν
- Main advantages:
  - energy resolution < 1% (VS 15% when measured with interaction), no energy scale
  - improved beam knowledge



Physics potential

- At a tagged Short Baseline Experiment:
  - precise flux knowledge → measure at 1% level ν_e x-sec and ν_μ differential x-sec
  - tagged ν energy determined independently of its interaction → refine interaction models
- These measurements would strongly improve the physics potential of upcoming LBE:
- At a tagged Long Baseline Experiment:
  - setup with a natural water Cherenkov detector (like KM3NeT/ORCA) would allow to **measure δ_{CP} with unprecedented precision**.
  - case study: P2O (Protvino to KM3NeT/ORCA)

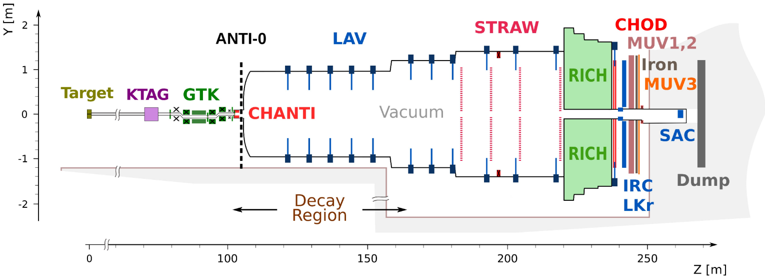




Outline

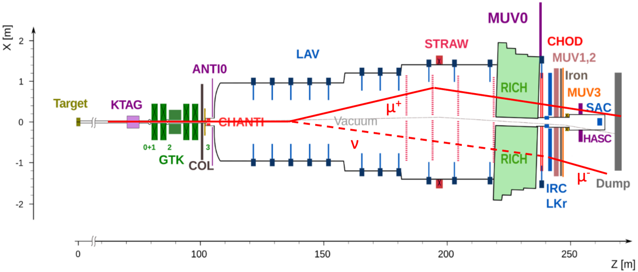
The NA62 experiment

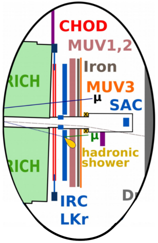
NA62 features



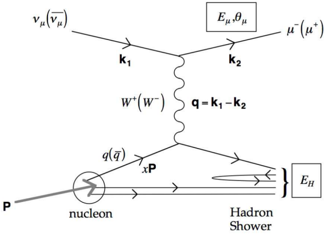
- NA62 is a fixed-target experiment in the North Area of the SPS at CERN
- NA62's main purpose is the measurement of $\mathscr{B}r(K^+ \to \pi^+ \nu\bar{\nu})$ (SM signal $\mathscr{B}r = (8.4 \pm 1.0) \cdot 10^{-11}$)
- NA62's high intensity kaon beam at 75 GeV/c delivers a nominal rate of $\mathscr{O}(10^{12}) K^+$ decays per year
- Beam composition: **6%** K^+, 70% π^+, 23% p, 750MHz over **3s spills**
- **Can be exploited as miniature tagged experiment**

Tagging proof of principle at NA62



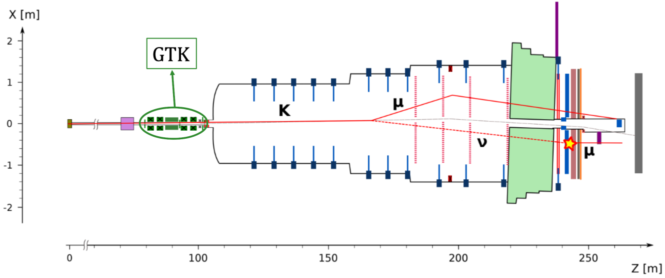


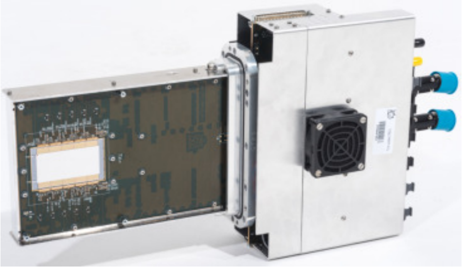
- Exploit K^+ main decay channel: $K^+ \to \mu^+ + \nu_\mu$
- **Goal: search for $K^+ \to \mu^+ + \nu_\mu$ ($K\mu\nu$) with all particles reconstructed**:
  - K^+ reconstructed by beam spectrometer
  - μ^+ reconstructed by downstream spectrometer
  - ν interacting in the EM calorimeter (20ton LKr)
- Interaction channel: CC-DIS: $\nu \to$ shower + μ^-
- Exploit μ^+, shower and μ^- for triggering strategy



Main subdetectors involved

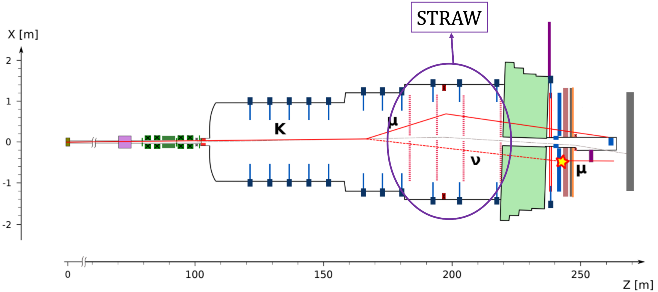
- GigaTracKer (GTK): silicon pixel spectrometer, reconstructs time and 4-momentum of incoming beam particles
- 130 ps hit time resolution
- $\sigma_p/p = 0.2\%$, $\sigma_\theta = 16$ mrad
- 60.8×27 mm silicon sensor





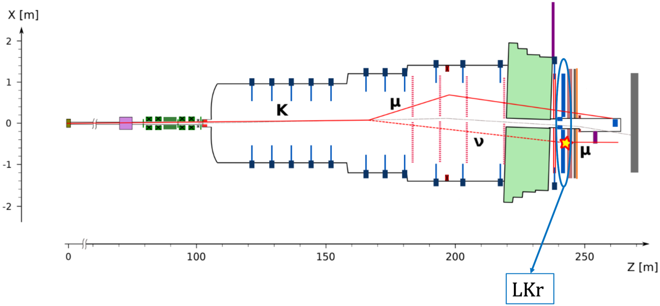
Main subdetectors involved

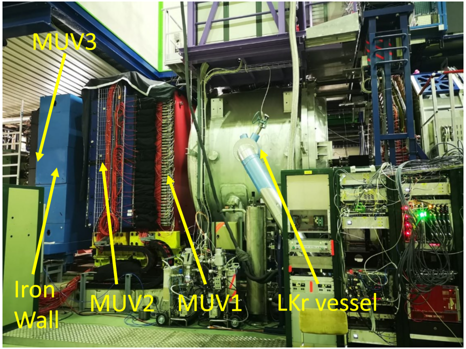
- STRAW: straw tube spectrometer that reconstructs the properties of charged particles produced in K decays



Main subdetectors involved

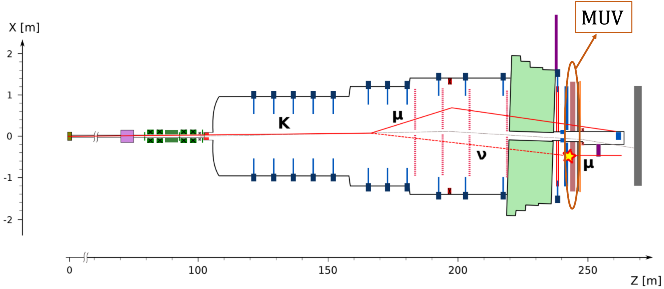
- Liquid Krypton calorimeter (LKr): electromagnetic calorimeter filled with about 9000 l of liquid Krypton at 120K

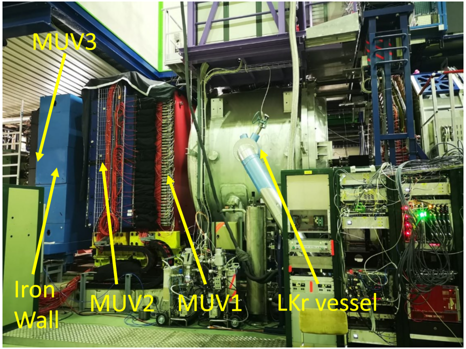




Main subdetectors involved

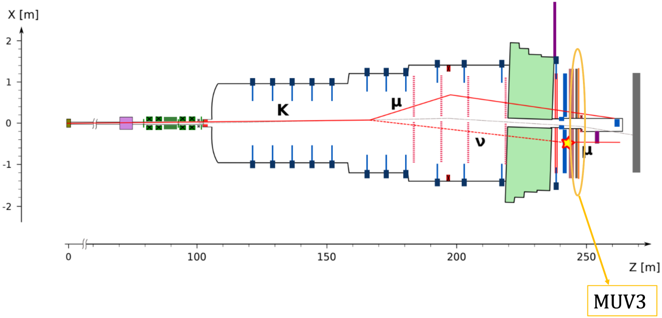
- MUon Veto (MUV) 1 and 2: 66 ton hadron calorimeter

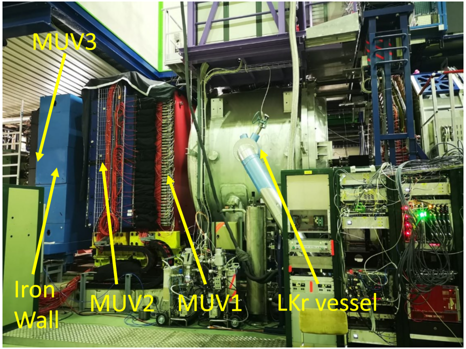




Main subdetectors involved

- MUon Veto 3 (MUV3): 50 mm thick scintillator tiles, placed behind LKr, MUV1 and 2, and an iron wall, used for muon identification

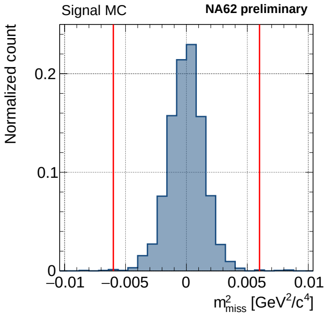


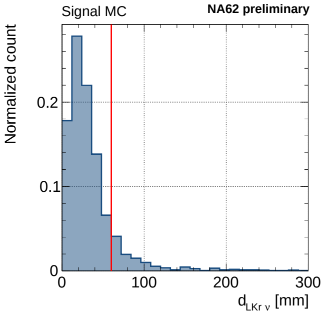


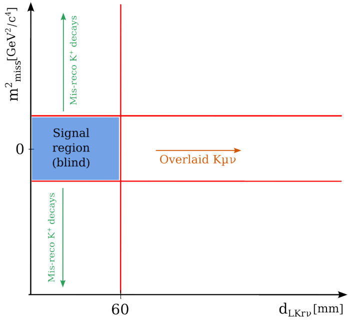
Outline

Analysis strategy

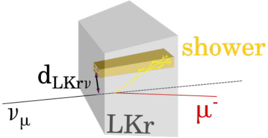
Analysis strategy







- Blind analysis
- Signal region defined as:
  - $|m^2_{miss}| = |(P_{K^+} - P_{\mu^+})^2| < 0.006\,\text{GeV}^2/\text{c}^4$
  - $|d_{LKr\nu}| < 60\,\text{mm}$



- Backgrounds assessed with data driven method on side bands; 2 background sources:
  - Overlaid $K\mu\nu$: $K \to \mu\nu$ with extra in-time activity → studied in side bands of $|d_{LKr\nu}|$
  - Mis-reconstructed kaon decays → studied in side bands of m^2_{miss}.

Analysis strategy

- Data sample: $5 \cdot 10^{12}$ effective K^+ decays, collected in 2022
- Expected event rate:

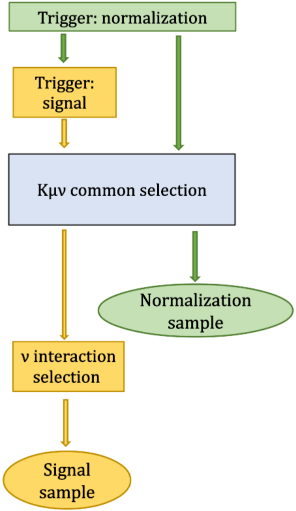
$$N^{exp}_{\text{signal}} = N_{K^+} \cdot \mathcal{B}(K^+ \to \mu^+ \nu_\mu) \cdot P_{\text{int,LKr}} \cdot \epsilon_{\text{signal}}$$

- Use $K^+ \to \mu^+ \nu_\mu$ (no ν interaction) decays as normalization sample:

$$N_{K^+} = \frac{N_{\text{norm}}}{\epsilon_{\text{norm}} \cdot \mathcal{B}(K^+ \to \mu^+ \nu_\mu)}$$

$$N^{exp}_{\text{signal}} = N_{\text{norm}} \cdot \frac{\epsilon_{\text{signal}}}{\epsilon_{\text{norm}}} \cdot P_{\text{int,LKr}}$$

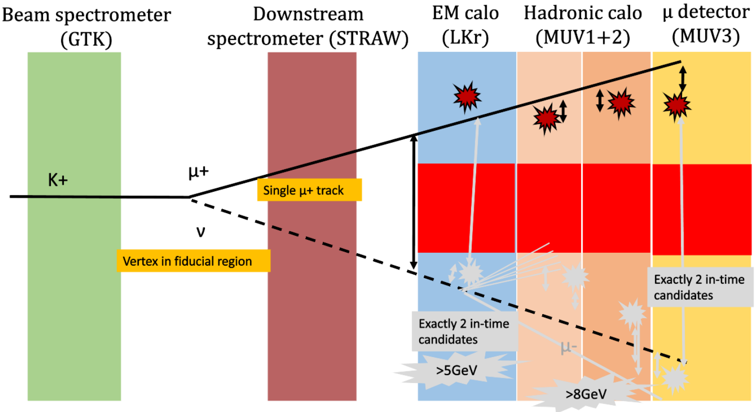
- As many common selection and trigger criteria as possible to signal and normalization
- Signal and normalization common efficiency terms cancel in the ratio
- Signal efficiency estimated thanks to a MC sample (GENIE)



Offline selection

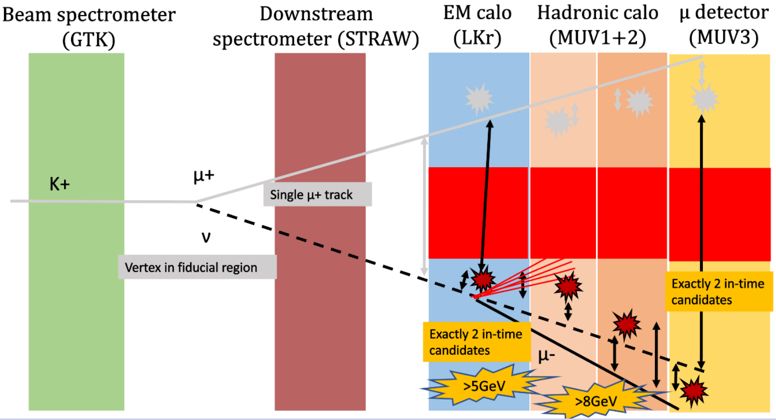
Common selection - signal and normalization

- Single positively charged track matched to LKr, MUV1, MUV2 and MUV3 candidates
- μ^+ particle identification
- photon rejection
- ν extrapolated position inside LKr acceptance

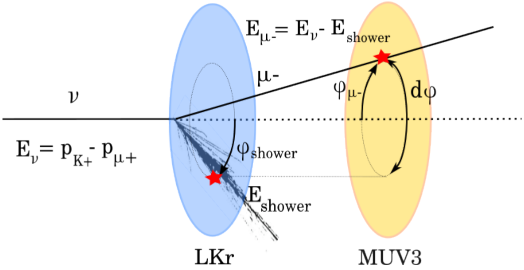


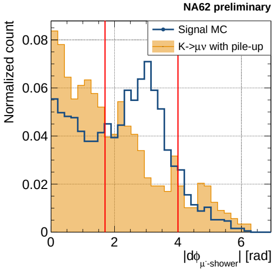
ν interaction offline selection

- Step 1: ν interaction associated to activity in LKr, MUV1, MUV2, MUV3 in time and space
- Step 2: Extra activity rejection
- Step 3: Energy requirements
- Step 4: Interaction topology

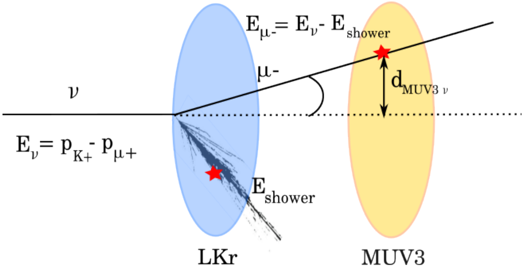


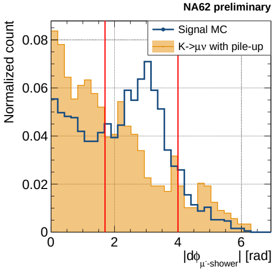
Interaction topology

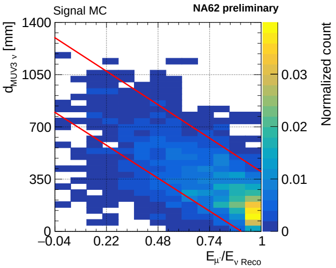


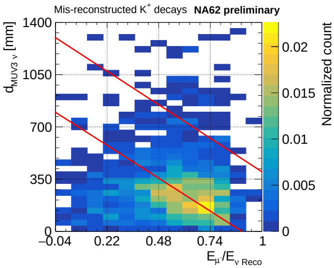


Interaction topology





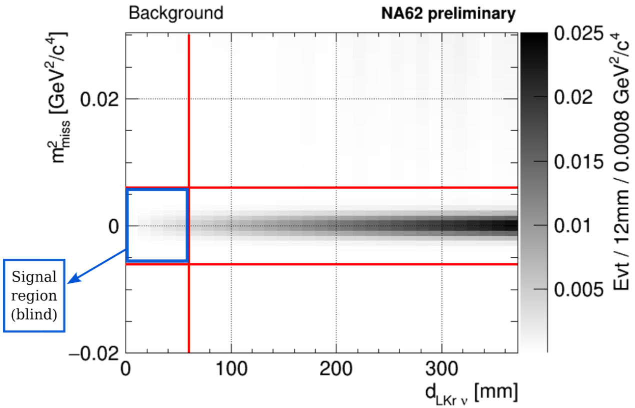




Signal and background yields

Background yield

Background pollution estimated with data-driven method, in side bands of SR



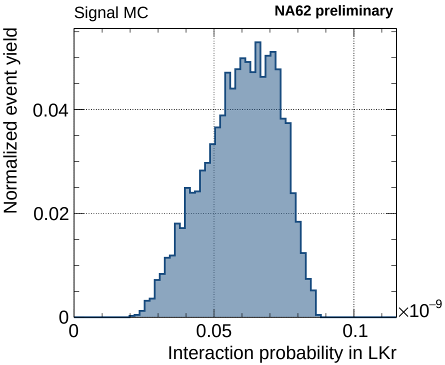
$$N^{exp}_{bkg}(\text{Mis} - \text{reco } K^+) = 0.0014 \pm 0.0007_{stat} \pm 0.0002_{syst}.$$

$$N^{exp}_{bkg}(\text{OV } K\mu\nu) = 0.04 \pm 0.02_{stat} \pm 0.01_{syst}.$$

Variables for signal yield computation

$$N^{exp}_{\text{signal}} = N_{\text{norm}} \cdot \frac{\epsilon_{\text{signal}}}{\epsilon_{\text{norm}}} \cdot P_{\text{int,LKr}}$$

- $P_{int,LKr} = (6.0 \pm 0.1_{syst}) \cdot 10^{-11}$
- $N_{norm} = (1.49 \pm 0.02_{syst}) \cdot 10^{11}$ from $K\mu\nu$ event yield
- $\frac{\epsilon_{signal}}{\epsilon_{norm}} = \epsilon^{\text{trig}}_{\text{signal only}} \cdot \epsilon^{\text{interaction}}_{\text{signal only}} = (2.55 \pm 0.15_{stat} \pm 0.04_{syst})\%$



$$\mathbf{N^{exp}_{signal} = 0.228 \pm 0.014_{stat} \pm 0.011_{syst}}$$

Summary

- In 2022 data sample ($5 \cdot 10^{12}$ K^+ decays):

$$N^{exp}_{\text{signal}} = 0.228 \pm 0.014_{stat} \pm 0.011_{syst},$$

$$N^{exp}_{bkg}(Mis-recoK^+) = 0.0014 \pm 0.0007_{stat} \pm 0.0002_{syst},$$

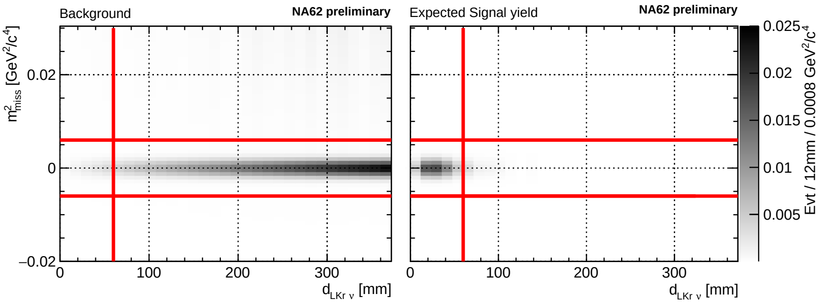
$$N^{exp}_{bkg}(OV\,K\mu\nu) = 0.04 \pm 0.02_{stat} \pm 0.01_{syst}.$$

- Signal-to-noise: 5.5

Probability for total expected event yield $\mathbf{N^{exp}_{events}} = \mathbf{0.2694}$

- for 0 data events p = 0.7638
- for 1 data event p = 0.2058
- for 2 data events p = 0.0277.

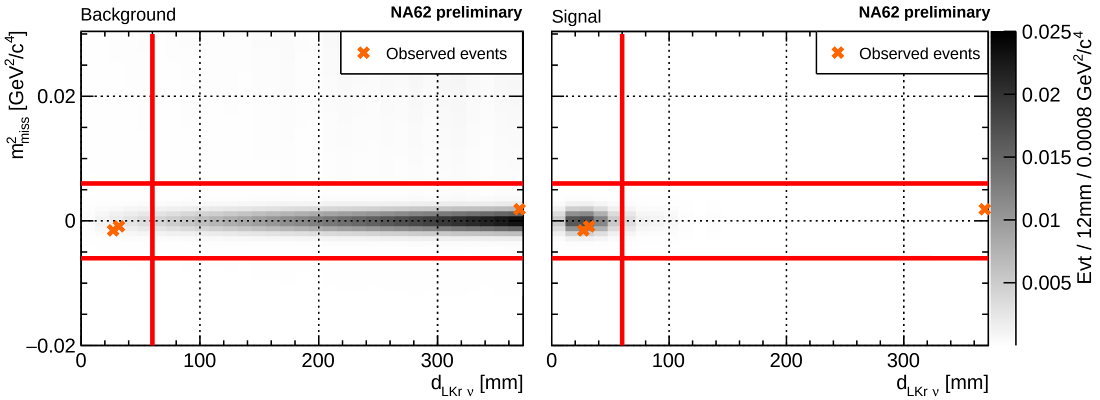
Results approved for unblinding by the NA62 collaboration



Revealing signal region content

Opening the box of signal region

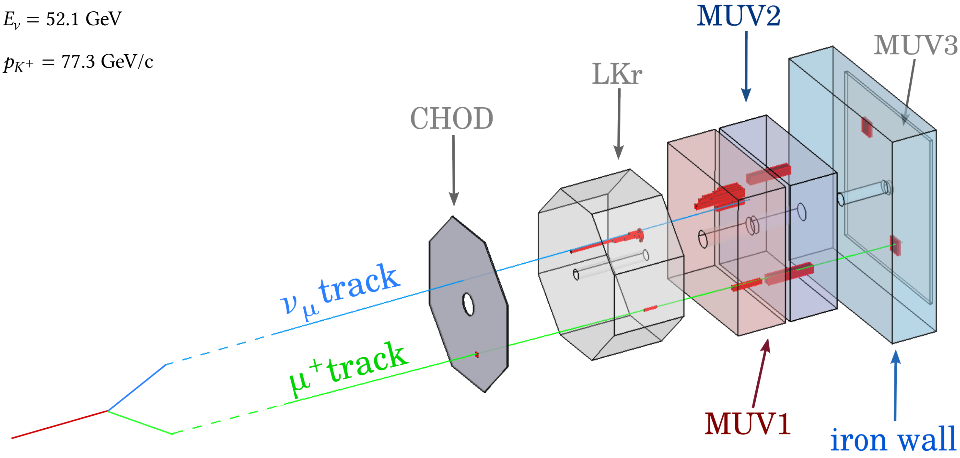
Two events are found in signal region‼



Corresponds to probability p = 0.0277 for total expected event yield $\mathbf{N^{exp}_{events}} = \mathbf{0.2694}$

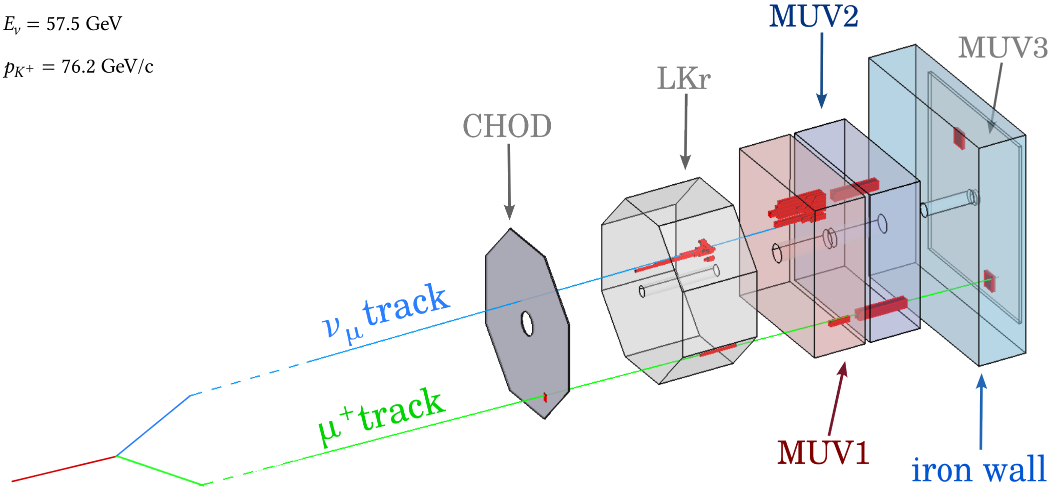
Event Display - Event A

- $p_{\mu^+} = 25.25$ GeV/c
- $E_\nu = 52.1$ GeV
- $p_{K^+} = 77.3$ GeV/c



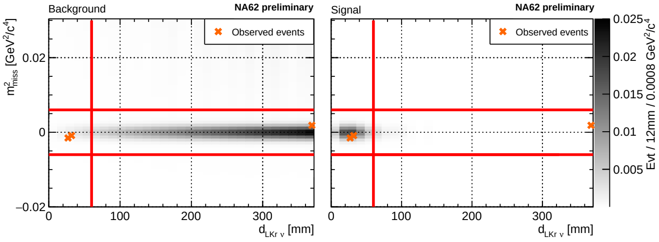
Event Display - Event B

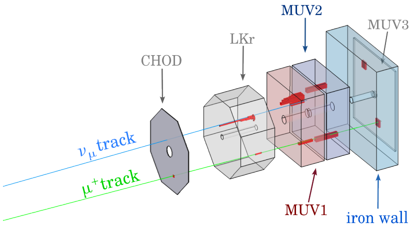
- $p_{\mu^+} = 18.74$ GeV/c
- $E_\nu = 57.5$ GeV
- $p_{K^+} = 76.2$ GeV/c



Conclusions

- NA62 experiment has been exploited as a miniature tagged experiment to perform proof of principle of the neutrino tagging technique
- Reconstruct $K^+ \to \mu^+ \nu_\mu$ decay with all particles detected
- Blind analysis performed, expected $N^{exp}_{signal} = 0.228 \pm 0.014_{stat} \pm 0.011_{syst}$ signal events
- Signal-to-noise ratio 5.5
- 2 events found in signal region upon opening the box
- **First tagged neutrino candidates in history!**
- Achieved crucial first step towards establishment of tagging as effective paradigm





Thank you for your attention!

Outline

Signal yield

$$N^{exp}_{\text{signal}} = N_{K\mu\nu} \cdot A^{int}_{K\mu\nu*} \cdot \epsilon^{RV} \cdot \epsilon^{sel}_{E5} \cdot \epsilon^{sel}_{MOQX} \cdot \epsilon^{sel}_{HLT} \cdot P_{int,LKr}$$
$$= \mathbf{0.228 \pm 0.014_{stat} \pm 0.011_{syst}} \qquad (1)$$

Contribution	**Value and uncertainty**
$P_{int,LKr}$	$(6.0 \pm 0.1_{syst}) \cdot 10^{-11}$
$N_{K\mu\nu}$	$(1.49 \pm 0.02_{syst}) \cdot 10^{11}$
$A^{int}_{K\mu\nu*}$	$0.0421 \pm 0.0025_{stat} \pm 0.0015_{syst}$
ϵ^{RV}	$0.816 \pm 0.014_{syst}$
$\epsilon^{MOQX}_{K\mu\nu*}$	$0.976 \pm 0.007_{stat} \pm 0.001_{syst}$
$\epsilon^{E5}_{K\mu\nu*}$	$0.82 \pm 0.01_{stat} \pm 0.01_{syst}$
$\epsilon^{HLT/sel}_{K\mu\nu*}$	$0.932 \pm 0.002_{stat}$

Signal candidates properties

Variable	Event A	Event B
d_{LKrv}	31.9 mm	27.0 mm
m^2_{miss}	$-0.000\,88\ \mathrm{GeV}^2/\mathrm{c}^4$	$-0.0015\ \mathrm{GeV}^2/\mathrm{c}^4$
$d\phi_{LKr-MUV3}$	3.29 rad	3.24 rad
E_ν	52.1 GeV	57.5 GeV
p_{μ^+}	25.25 GeV/c	18.74 GeV/c
p_{K^+}	77.3 GeV/c	76.2107 GeV/c
$E_{LKr\,in\,time}$	13.36 GeV	7.67 GeV
$E_{MUV1\,in\,time}$	9.85 GeV	10.90 GeV
$E_{MUV2\,in\,time}$	2.48 GeV	2.80 GeV
E_{μ^-}/E_ν	0.68	0.78
n_{KTAG}	28	17
z_{vtx}	161.2 m	157.7 m
x, y at MUV3 μ^-	(550, 770) mm	(330, 770) mm
x, y at MUV3 μ^+	(-330, -770) mm	(-550, -990) mm

Table: Features of the two signal candidates found in the signal region.

LBNE limitations: systematic uncertainties

- Oscillation parameters inferred from event spectra as a function of reconstructed neutrino energy:

$$N^{FD}_{\nu_\beta}(E^{reco}_\nu) = \Phi^{FD}_{\nu_\beta}(E^{true}_\nu) \times \epsilon^{FD}(E^{true}_\nu) \times \sigma^{FD}_{\nu_\beta}(E^{true}_\nu) \times S(E^{reco}_\nu, E^{true}_\nu) \times P(\nu_\alpha \to \nu_\beta)(E^{true}_\nu)$$

- Constrain systematic with ND that measures initial flux
- Heavily relay on models to predict near-to-far detector extrapolation: they see different fluxes due to
  - Oscillations
  - Acceptance
  - Solid angle coverage
- Heavily rely on $\sigma(E^{true}_\nu)$ models and measurements
- Near and far detectors have energy scale uncertainty

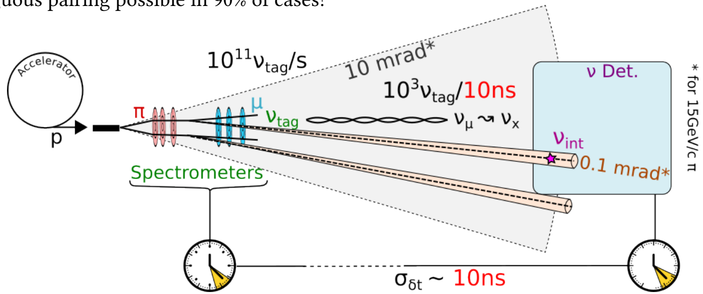
Unambiguous matching of ν-tag to ν–int

- Time coincidence:
  - Next generation Si trackers will have $\sigma_t \sim 10$ ps
  - Typically ν detectors have $\sigma_t \sim 10$ ns

$\rightarrow$ 1000 ν_{tag} per ν_{int}

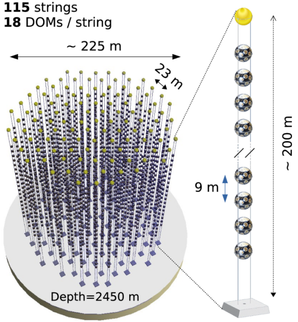
- Angular coincidence:
  - Dominant contribution: resolution on ν_{tag} is $\mathcal{O}(0.1)$ mrad for thickness of 0.5% X_0
  - ν beam divergence $\sim \frac{1}{\gamma} \rightarrow \sim 10$ mrad for 15 GeV $\pi^{\pm}$
  - $\rightarrow$ accidental matches reduced by a factor 10^4

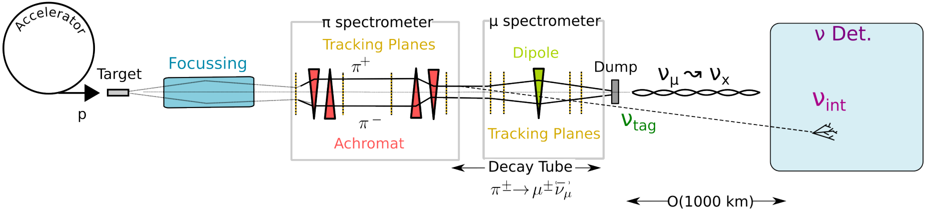
$\rightarrow$ 0.1 ν_{tag} per ν_{int} $\rightarrow$ unambiguous pairing possible in 90% of cases!



Adapted beamline for Tagging

- Main challenge: intense particle flux in neutrino beam line $\mathcal{O}(10^{18})$ particles/s
- Upcoming tracker capabilities: $\mathcal{O}(10^{12})$ particles/s
- Handles to **limit particle flux**:
  - slow extraction (few seconds instead of μs)
  - narrow band (π momentum selection)
  - increase beam transverse size (around $0.1m^2$)
- Limitation: low ν flux → **compensate with large FD** e.g. KM3NeT/ORCA (6.8 Mton)
- Win-win: tagging compensates for FD granularity, FD compensates for low ν flux
- Case study: Tagged P2O (Protvino to KM3NeT/ORCA), L = 2595km, E_ν = 5 GeV





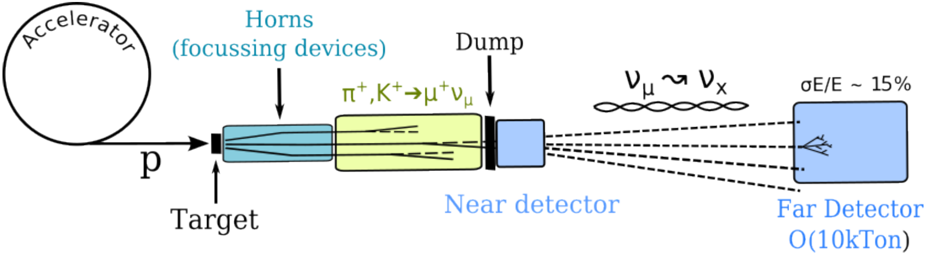
Perspectives overview

- A lot is left to do before implementing the Tagging at a tagged experiment
  - Beamline simulation and design (narrow-band, slowly extracted beam)
  - Development in field of silicon trackers ongoing
- Building a full scale tagged experiment involves operating Silicon trackers in neutrino beamline
- Very harsh environment, particle rate $\sim 10^{12}$ particles/s
- Need performing detectors, specs similar to HL-LHC
- Time resolution is a crucial element: need to be able to separate the beam particles
- → study the timing performances of Silicon detectors and understand the elements that affect their time resolution.

Feature	**NA62 GTK**	**HL-LHC**	**Nu Tagging**
Flux [MHz/mm^2]	2	$\mathcal{O}(10-100)$	$\mathcal{O}(\mathbf{10}-\mathbf{100})$
Hit Time Reso [ps]	130	<50	**<20**
Efficiency (%)	>99	>99	>99
Thickness (% of X_0)	< 0.5	<0.9	<0.5

Long Baseline Experiments (LBE)

- LBE suited to search for CP violation in the lepton sector and study oscillations
- Very intense hadron beams ($\pi^{\pm} \to \mu^{\pm} \overleftrightarrow{\nu}_{\mu}$) produced by impinging protons on target for ν beams production
- νs oscillate over $\mathcal{O}(10^3)$ km in matter
- Near detector: characterize initial ν flux
- Far detector: very large neutrino detectors, characterize ν flux after oscillation



LBE limitations

- Oscillation studies limited by systematic uncertainties stemming from:
  - interaction models and x-section measurements
  - energy scale uncertainties
  - near-to-far detector extrapolation models
- Need a new method to refine our knowledge!