Experimental proof of principle of the Neutrino Tagging technique at NA62

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PhD thesis defense

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Outline

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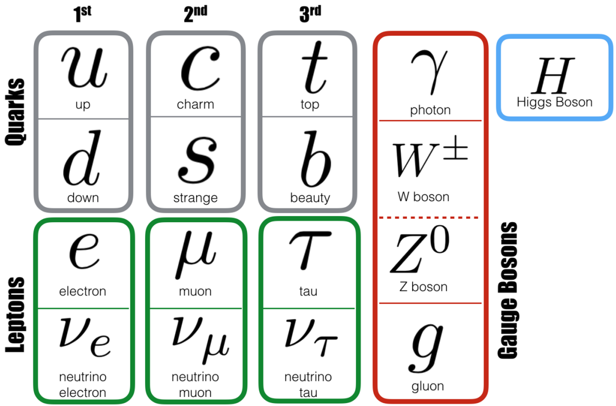
What are neutrinos?

Very elusive particle, existence first hypothetized in 1930, first detection in the 50s



- Neutral leptons, no color charge
- 3 species: e, μ, τ
- Massless within SM theory
- Only interact via weak interaction

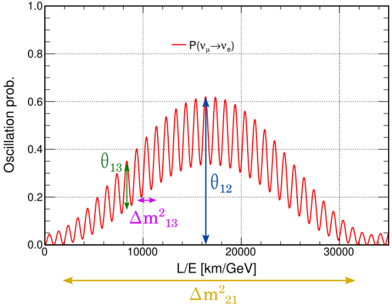
Neutrino oscillations

- 90s: νs became very fascinating due to discovery of ν oscillations
- ν change flavour → flavour eigenstates ≠ mass eigenstates:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

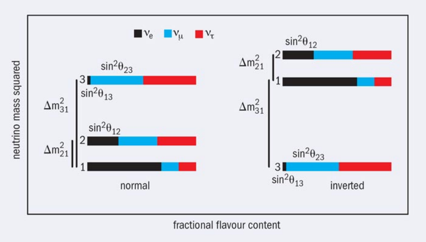
$$P(\nu_\alpha \to \nu_\beta) = \sum_i \sum_j U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}e^{\frac{\Delta m^2_{ij}L}{2E}}$$

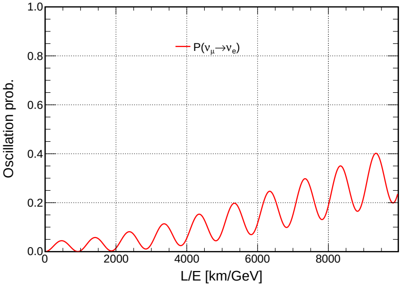
- $P(\nu_\alpha \to \nu_\beta)$ *oscillates* depending on the distance from the ν production point (L) and on the ν energy (E)
- U_{PMNS} parametrized by:
  - 3 mixing angles θ_{ij}
  - Squared missing mass differences: $\Delta m^2_{ji} = m^2_j - m^2_i$; $\Delta m^2_{21} = 7.5\cdot 10^{-5}$ eV^2, $\Delta m^2_{31} \sim \Delta m^2_{32} = 2.46\cdot 10^{-3}$ eV^2
  - CP-violating phase δ_{CP}
- Direct consequence: neutrinos have non-null, different masses
- **One of the most compelling proof of beyond SM physics**



Unknown parameters, current experiments

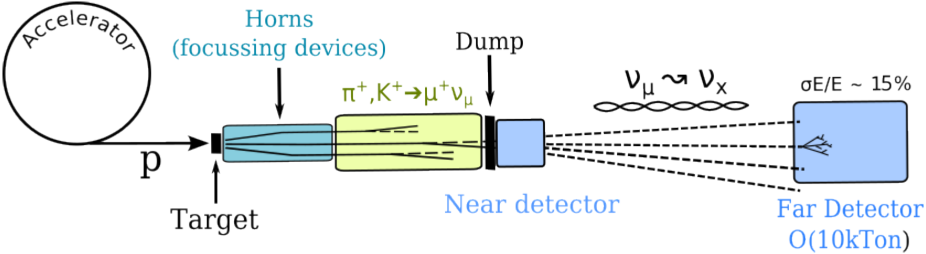
- Unknown oscillation parameters:
  - Mass ordering: $m_3 > m_2 > m_1$ or $m_2 > m_1 > m_3$?
  - Octant of θ_{23}
  - CP violating phase $\delta_{CP} \rightarrow$ key measurement
- Measuring $\delta_{CP} \neq 0, \pi$ means CP violation in lepton sector → one of the three Sakharov conditions to explain matter-antimatter asymmetry in universe!
- ν properties can be studied in many facilities → focus on accelerators facilities
- Produce ν_μ beam from $\pi^+ \rightarrow \mu^+ \nu_\mu$ to study oscillations → Long Baseline Experiments (LBE): L $\mathcal{O}(100 - 1000)$km





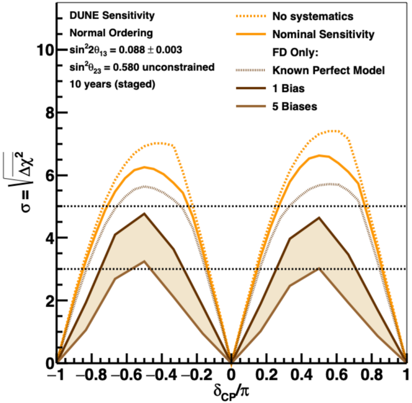
Long Baseline Experiments (LBE)

- LBE suited to search for CP violation in the lepton sector and study oscillations
- Very intense hadron beams ($\pi^{\pm} \to \mu^{\pm} \overset{\leftrightarrow}{\nu}_{\mu}$) 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

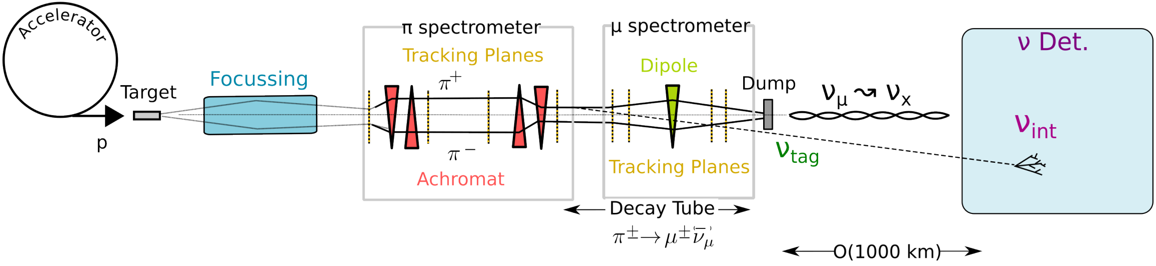
- Oscillation studies limited by systematic uncertainties stemming from:
  - interaction models and x-section measurements
  - energy scale uncertainties
  - near-to-far detector extrapolation models
- Need a new method to refine our knowledge!



Outline

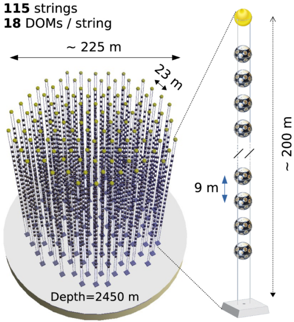
Neutrino Tagging

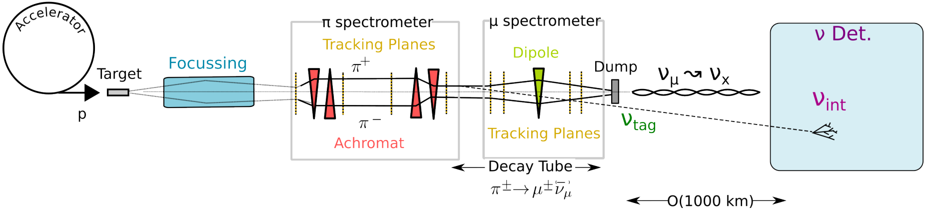
- Neutrino Tagging: new paradigm for accelerator based neutrino experiments
- Instrument a beam line with spectrometers
- **Kinematically reconstruct each** ν originating from a $\pi^+ \to \mu^+ \nu_\mu$ decay $\to$ *tagged* ν
- **Associate** *interacting* ν at Far Detector to its tagged ν
- Main advantages: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



Adapted beamline for Tagging

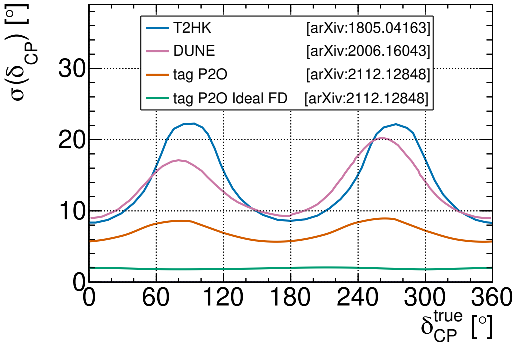
- Main challenge: intense particle flux in neutrino beam line $\mathcal{O}(10^{18})$ particles/s
- Upcoming tracker capabilities: $\mathcal{O}(10^{12})$ particles/s
- Handles to **limit particle flux**:
  - slow extraction (few seconds instead of μs)
  - narrow band (π momentum selection)
  - increase beam transverse size (around $0.1 m^2$)
- 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), $L = 2595$km, $E_\nu = 5$ GeV

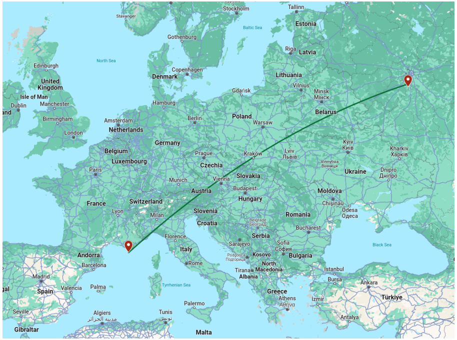




Physics potential

- At a tagged SBE:
    - 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 LBE:
    - **measure δ_{CP} with unprecedented precision**

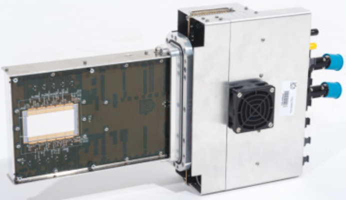




Summary: ν tagging, new paradigm for SBE and LBE

- Neutrino tagging can be used at Short and Long baseline experiments
- Neutrino tagging has the potential to drastically improve physics analysis of 3-flavor oscillations
- Need performing trackers with specs similar to those of HL-LHC
- Development ongoing for new technologies for Si trackers
- **Proof of principle** performed with state-of-the-art Si tracker: NA62's GigaTracKer

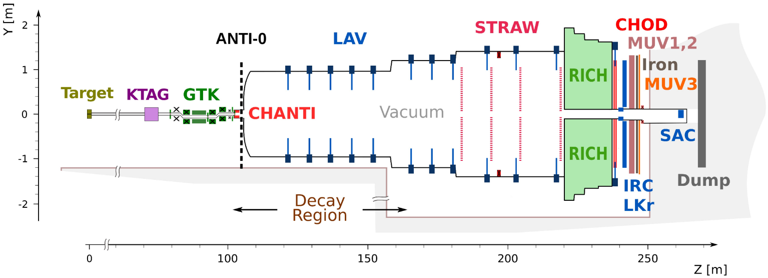
Feature	NA62 GTK (2014)	HL-LHC (2026)	Nu Tagging (2030)
Flux [MHz/mm^2]	2	$\mathcal{O}(10-100)$	$\mathcal{O}(\mathbf{10-100})$
Hit Time Reso [ps]	130	<50	**<20**
Efficiency (%)	>99	>99	>99
Thickness (% of X_0)	< 0.5	<0.9	<0.5



Outline

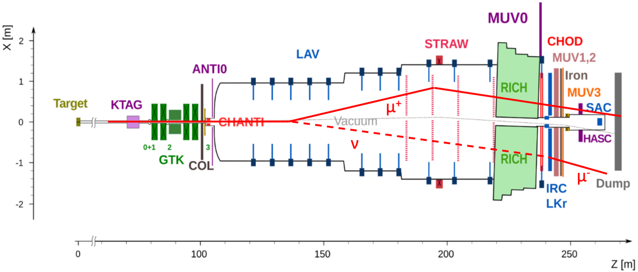
The NA62 experiment

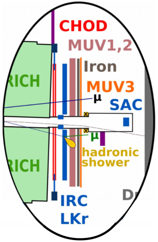
NA62 features



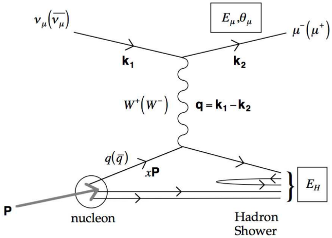
- NA62 is a fixed-target experiment in the North Area of the SPS at CERN
- NA62's main purpose is the measurement of $\mathscr{B}r(K^+ \to \pi^+ \nu\bar{\nu})$ (SM signal $\mathscr{B}r = (8.4 \pm 1.0) \cdot 10^{-11}$)
- NA62's high intensity kaon beam at 75 GeV/c delivers a nominal rate of $\mathscr{O}(10^{12}) K^+$ 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



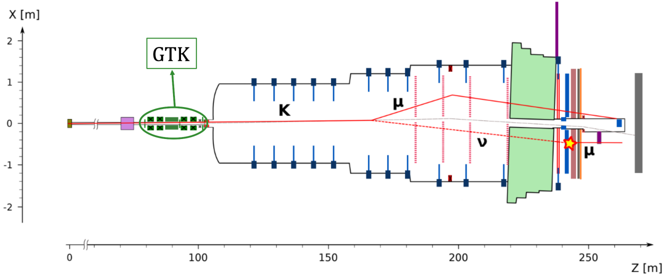


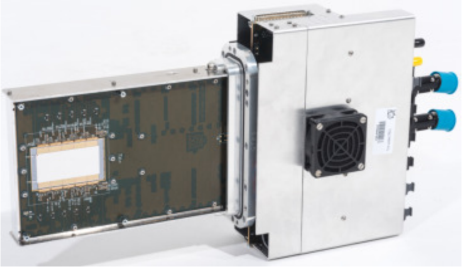
- K^+ main decay channel: $K^+ \rightarrow \mu^+ + \nu_\mu$
- Goal: search for $K^+ \rightarrow \mu^+ + \nu_\mu$ ($K\mu\nu$) with all particles reconstructed:
  - K^+ reconstructed by beam spectrometer
  - μ^+ reconstructed by downstream spectrometer
  - ν interacting in the EM calorimeter (20ton LKr)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



Main subdetectors involved

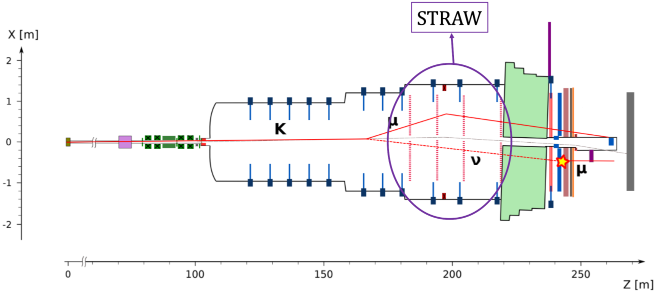
- GigaTracKer (GTK): silicon pixel spectrometer, reconstructs time and 4-momentum of incoming beam particles
- 130 ps hit time resolution
- $\sigma_p/p = 0.2\%$, $\sigma_\theta = 16$ mrad
- 60.8×27 mm silicon sensor





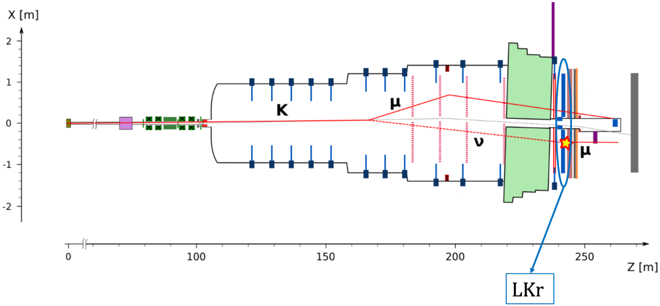
Main subdetectors involved

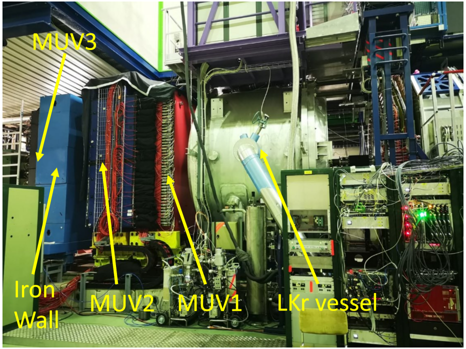
- STRAW: straw tube spectrometer that reconstructs the properties of charged particles produced in K decays



Main subdetectors involved

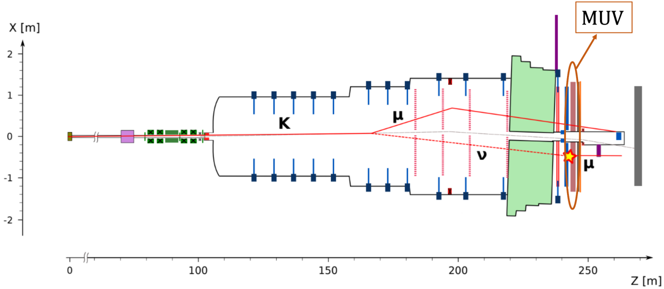
- Liquid Krypton calorimeter (LKr): electromagnetic calorimeter filled with about 9000 l of liquid Krypton at 120K

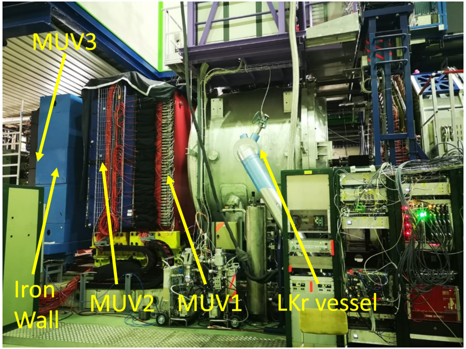




Main subdetectors involved

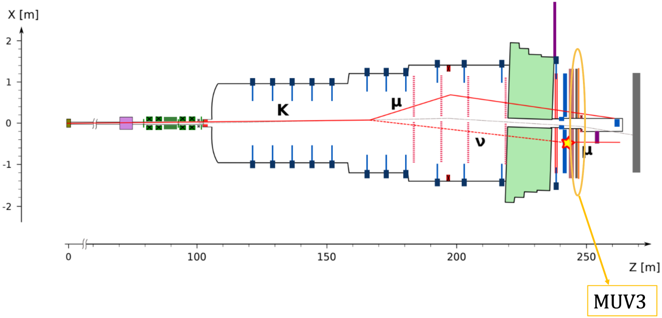
- MUon Veto (MUV) 1 and 2: 66 ton hadron calorimeter

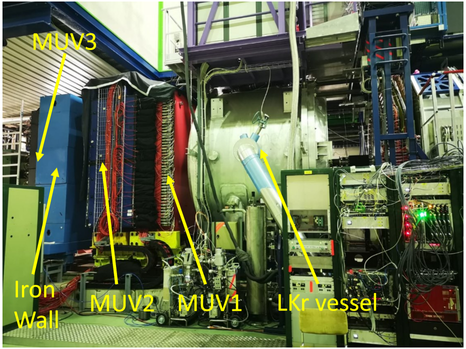




Main subdetectors involved

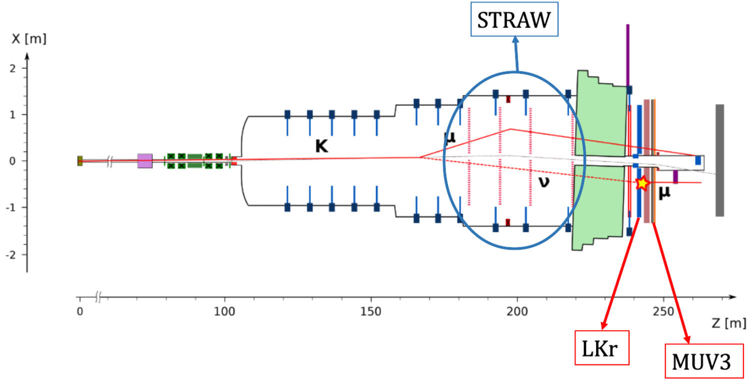
- MUon Veto 3 (MUV3): 50 mm thick scintillator tiles, placed behind LKr, MUV1 and 2, and an iron wall, used for muon identification





Trigger and Data Acquisition at NA62

- NA62 data taking system involves 2 trigger levels
- L0 trigger: hardware level trigger, 10x rate reduction factor (10 MHz → 1 MHz)
  - packets of information regarding pre-defined conditions
  - *masks:* predefined set of conditions to accept an event
- HLT (High Level Trigger): software level trigger, 100x rate reduction factor (1 MHz → 20 kHz)



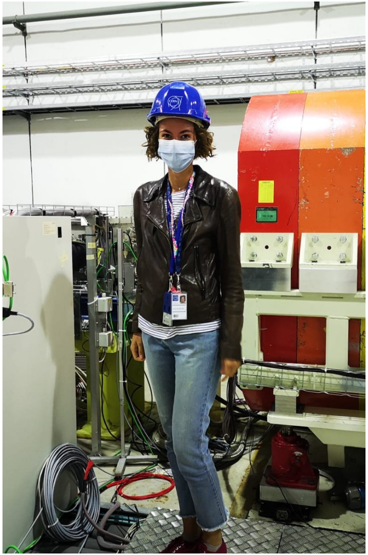
Outline

Analysis strategy

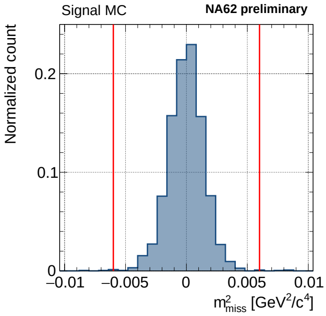
Analysis overview

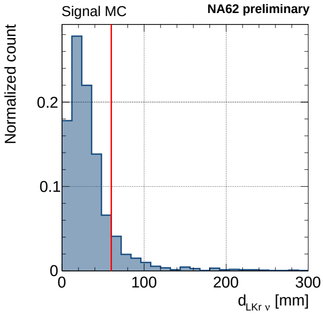
Analysis unfolded through some challenging steps:

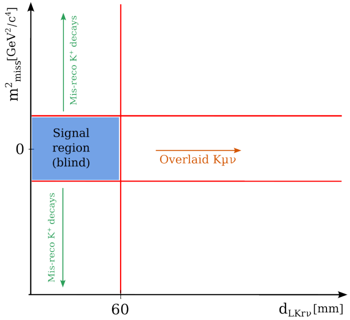
- Dedicated trigger line design:
  - Dedicated MUV3 L0-trigger condition to exploit decay topology
  - Stay within available bandwidth
  - Compromise between reducing trigger rate and minimizing signal suppression
- Trigger maintenance and improvements during data taking
- Offline selection building:
  - **very small ν interaction probability in LKr** $\sim 6 \cdot 10^{-11}$
  - possible background even from very rare sources
- Statistical data analysis:
  - trigger and offline selection efficiencies to estimate signal yield
  - estimate background pollution with almost no surviving data events after offline selection



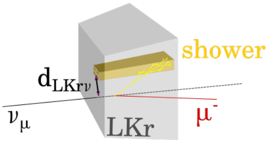
Analysis strategy







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



- 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:

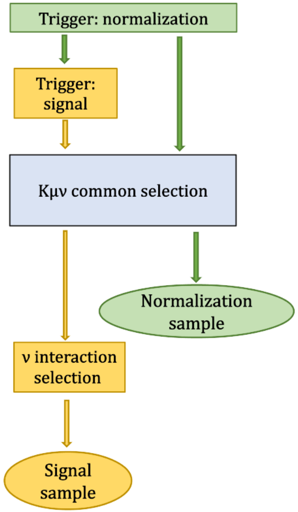
$$N_{\text{signal}}^{exp} = N_{K^+} \cdot \mathscr{B}(K^+ \to \mu^+ \nu_\mu) \cdot P_{\text{int,LKr}} \cdot \epsilon_{\text{signal}}$$

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

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

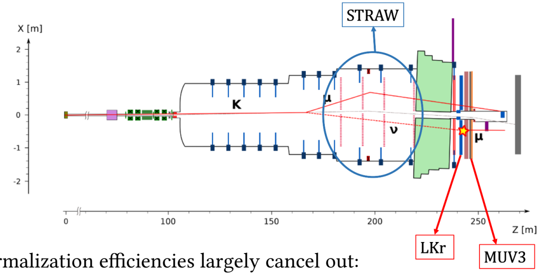
$$N_{\text{signal}}^{exp} = N_{\text{norm}} \cdot \frac{\epsilon_{\text{signal}}}{\epsilon_{\text{norm}}} \cdot P_{\text{int,LKr}}$$

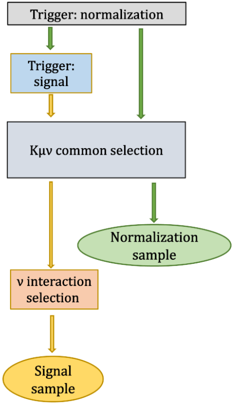
- As many common selection and trigger criteria as possible to signal and normalization
- Signal and normalization common efficiency terms cancel in the ratio



Triggering signal-like events

- Build trigger line to select signal-like events at trigger level
- Single μ^+ track before LKr
- μ^+ and μ^- (from interaction) in opposite quadrants at MUV3
- Total energy deposit > 5 GeV in LKr to reduce rate
- Normalization trigger selection included in signal trigger



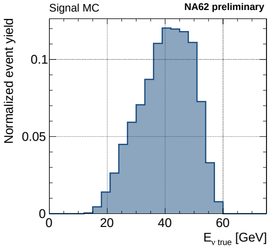


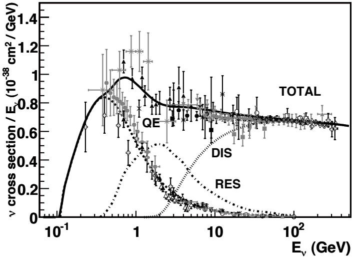
Signal and normalization efficiencies largely cancel out:

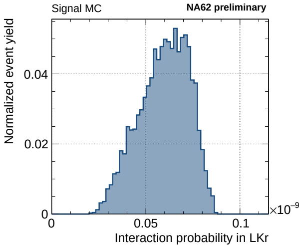
$$N^{exp}_{\text{signal}} = N_{norm} \cdot \epsilon^{int}_{K\mu\nu*} \cdot \epsilon^{LKr}_{K\mu\nu*} \cdot \epsilon^{MUV3}_{K\mu\nu*} \cdot \epsilon^{HLT}_{K\mu\nu*} \cdot P_{int,LKr}$$

MC sample

- MC sample used to estimate signal efficiencies
- K^+ forced to decay in $\mu^+\nu_\mu$
- ν forced to interact in the LKr active volume
- ν interaction simulated with GENIE using CC-QE, RES, DIS
- Average interaction probability: $6 \cdot 10^{-11}$
- To account for final state modeling uncertainties, two extra samples are produced with the ν energy used to generate the final state biased by $\pm10\%$.



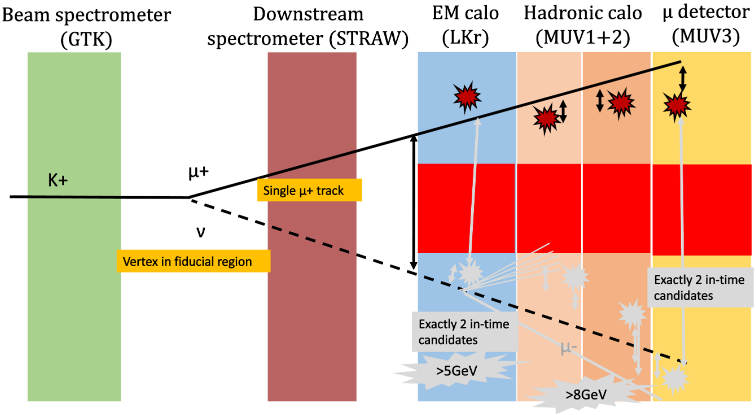




Offline selection

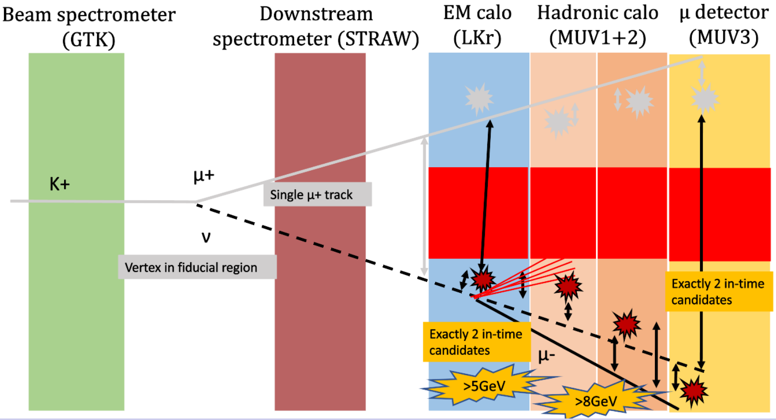
Common selection - signal and normalization

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

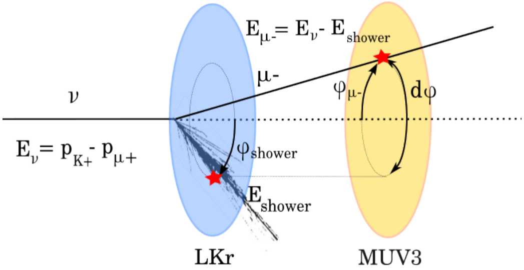


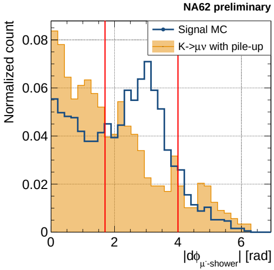
ν interaction offline selection

- 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

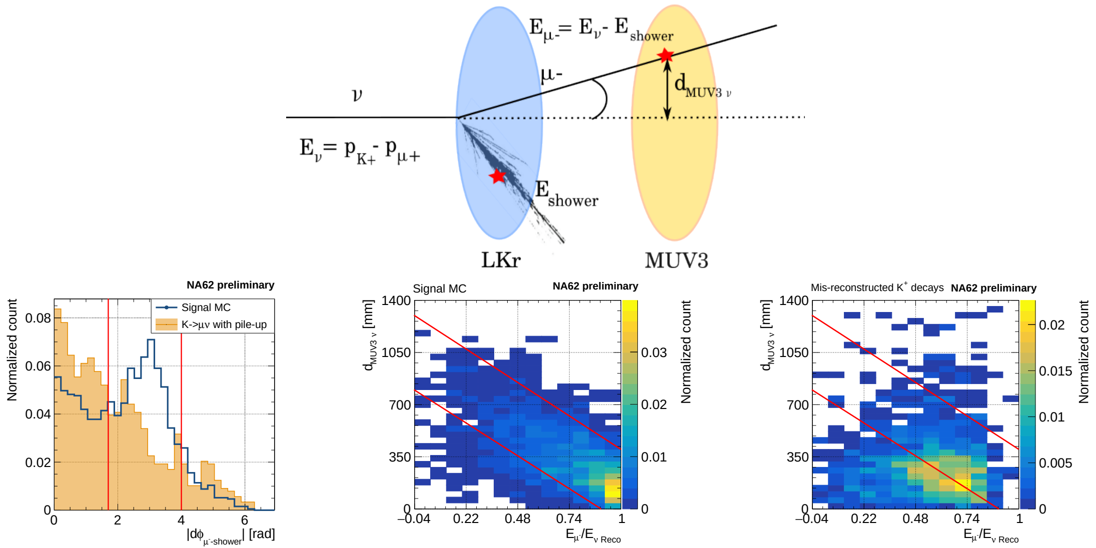


Interaction topology

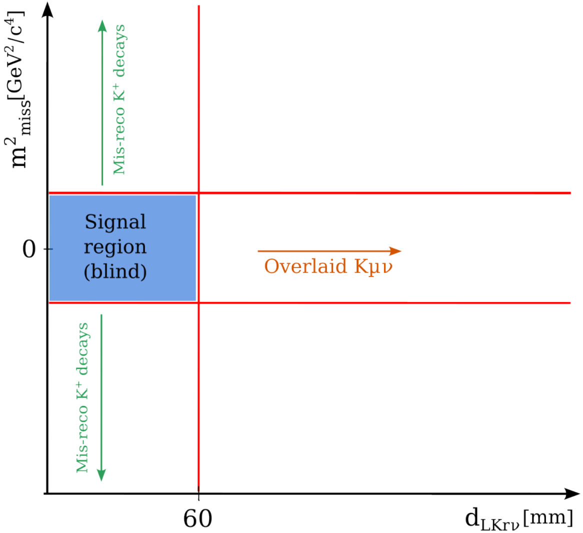




Interaction topology



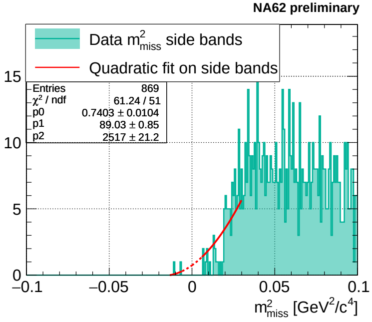
Background yield



Mis-reconstructed K^+ decays

- No data events in m^2_{miss} SB after full selection
- Estimate background with partial selection on full $d_{\text{LKr}\nu}$ range
  - Fit SB of m^2_{miss} with quadratic
- Scale integral from fit by acceptance of $d_{\text{LKr}\nu}$ cut and of missing cuts
- Syst obtained by estimating number of bkg events on two $d_{\text{LKr}\nu}$ ranges

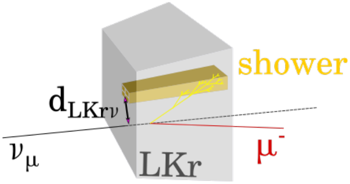
$$\mathbf{N^{exp}_{bkg}(Mis - reco\ K^+) = 0.0014 \pm 0.0007_{stat} \pm 0.0002_{syst}}.$$

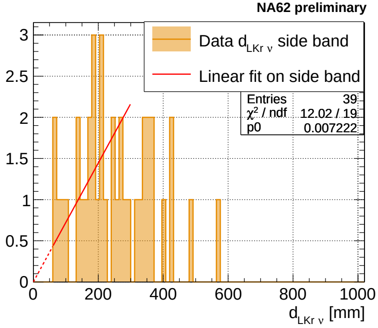


Overlaid $K\mu\nu$

- Only 1 background entry found, outside of control region [60,300] mm
- Use $d_{\mathrm{LKr}\nu}$ obtained with partial selection
- Each $d_{\mathrm{LKr}\nu}$ bin corresponds to a ring of area proportional to $d_{\mathrm{LKr}\nu}$
- Assuming constant event density, $d_{\mathrm{LKr}\nu}$ distribution grows linearly with $d_{\mathrm{LKr}\nu}$ → linear fit
- Scale integral by acceptances of missing cuts
- Systematics obtained by changing fit range

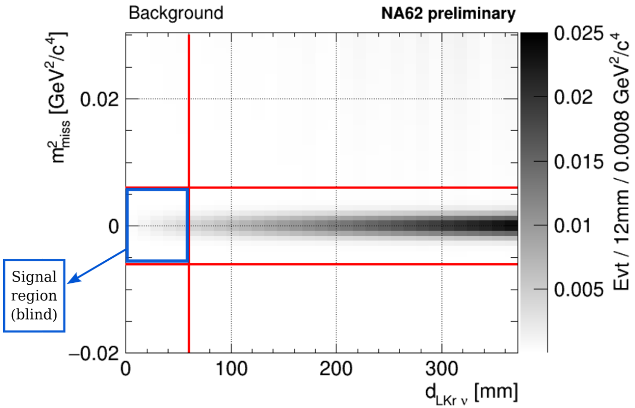
$$\mathbf{N^{exp}_{bkg}(OV\,K\mu\nu) = 0.04 \pm 0.02_{stat} \pm 0.01_{syst}}.$$





Background yield

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



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

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

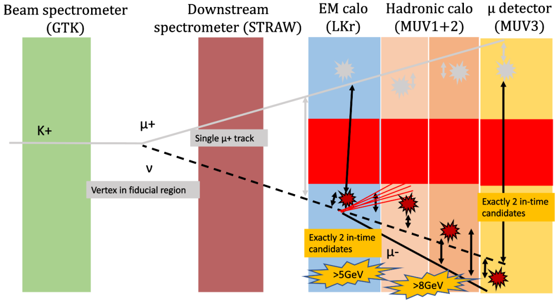
Signal yield

$$N_{signal}^{exp} = N_{norm} \cdot \epsilon_{K\mu\nu*}^{int} \cdot \epsilon_{K\mu\nu*}^{LKr} \cdot \epsilon_{K\mu\nu*}^{MUV3} \cdot \epsilon_{K\mu\nu*}^{HLT} \cdot P_{int,LKr}$$

ν interaction selection efficiency

$$\epsilon^{int}_{K\mu\nu*} = A^{int}_{K\mu\nu*} \cdot \epsilon^{RV}$$

- $A^{int}_{K\mu\nu*} = \frac{\sum^{selected} p_i}{\sum^{CS} p_i} = (4.21 \pm 0.25_{stat} \pm 0.15_{syst})\%$
- Systematic obtained from the two biased MC samples
- Have to account for Random Veto:
  - signal event rejection due to pile-up activity
- $\epsilon^{RV} = (81.6 \pm 1.4_{syst})\%$ estimated on standard $K\mu\nu$

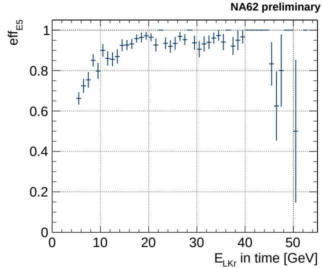


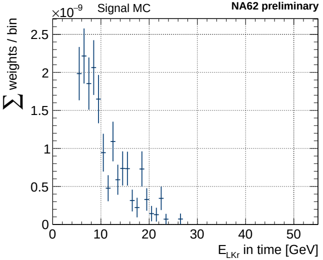
Trigger efficiencies

$$N_{\text{signal}}^{exp} = N_{norm} \cdot \epsilon_{K\mu\nu*}^{int} \cdot \epsilon_{K\mu\nu*}^{LKr} \cdot \epsilon_{K\mu\nu*}^{MUV3} \cdot \epsilon_{K\mu\nu*}^{HLT} \cdot P_{int,LKr}$$

- Need to estimate trigger efficiencies that do not cancel out
- Trigger efficiencies estimated on data
- Example: LKr trigger condition efficiency
  - Trigger condition: energy deposit $\geq$ 5 GeV
  - Use samples of $K^+ \to \pi^+\pi^0$
  - Build signal-like LKr selection
  - Plot efficiency VS total in-time energy
  - Weight distribution by E_{LKr} distribution from MC
  - Systematics from the two biased MC samples

Detector	Condition	Efficiency (%)
MUV3	$\mu^\pm$ in opposite quadrants	$97.6 \pm 0.7_{stat} \pm 0.1_{syst}$
LKr	Energy deposit $\geq$ 5 GeV	$82 \pm 1_{stat} \pm 2_{syst}$
HLT	single μ^+ track from K^+	$93.2 \pm 0.2_{stat}$



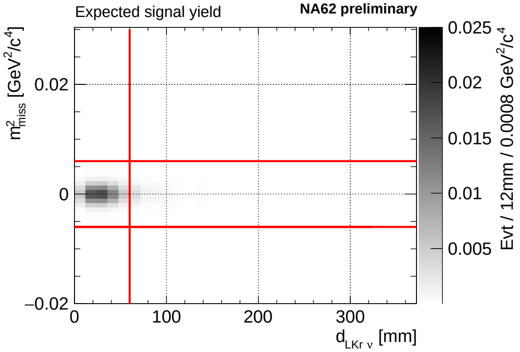


Expected signal yield

$$N^{exp}_{\text{signal}} = N_{norm} \cdot \epsilon^{int}_{K\mu\nu*} \cdot \epsilon^{sel}_{LKr} \cdot \epsilon^{sel}_{MUV3} \cdot \epsilon^{sel}_{HLT} \cdot P_{int,LKr}$$
$$= N_{norm} \cdot \frac{\epsilon_{signal}}{\epsilon_{norm}} \cdot P_{int,LKr}$$

- Now we have all items to compute $N^{exp}_{K\mu\nu*}$
- $P_{int,LKr} = (6.0 \pm 0.1_{syst}) \cdot 10^{-11}$
- $N_{norm} = (1.49 \pm 0.02_{syst}) \cdot 10^{11}$ from $K\mu\nu$ event yield
- $\frac{\epsilon_{signal}}{\epsilon_{norm}} = (2.55 \pm 0.15_{stat} \pm 0.04_{syst})\%$

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



Summary

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

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

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

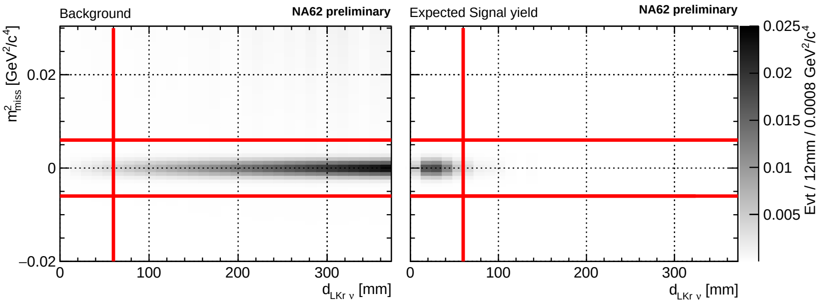
$$N^{exp}_{bkg}(OV\,K\mu\nu) = 0.04 \pm 0.02_{stat} \pm 0.01_{syst}.$$

- Signal-to-noise: 5.5

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

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

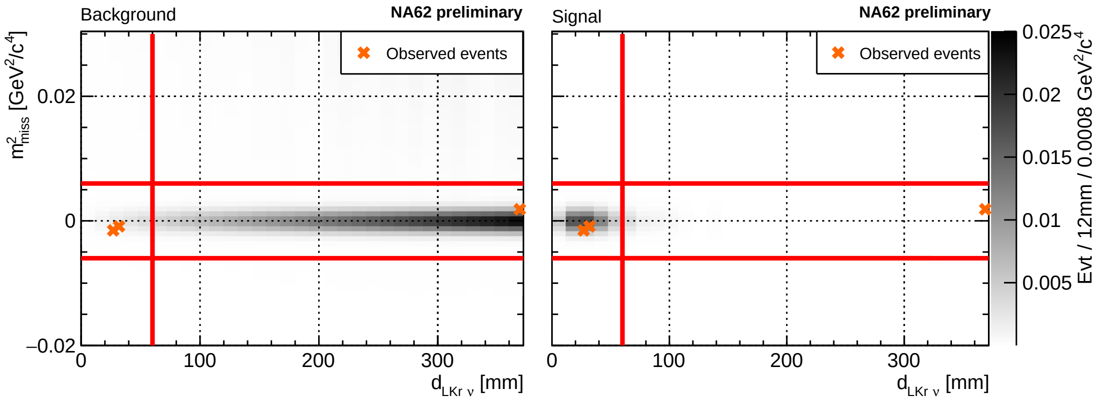
Results approved for unblinding by the NA62 collaboration



Revealing signal region content

Opening the box of signal region

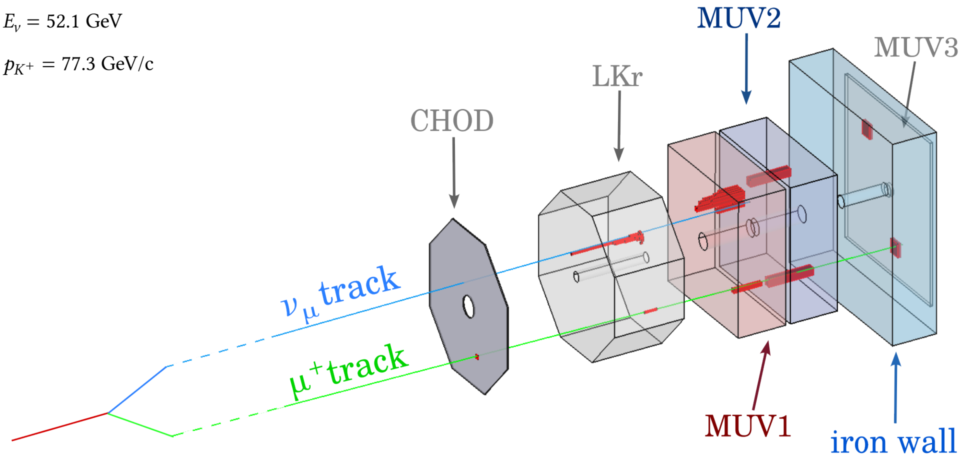
Two events are found in signal region!!



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

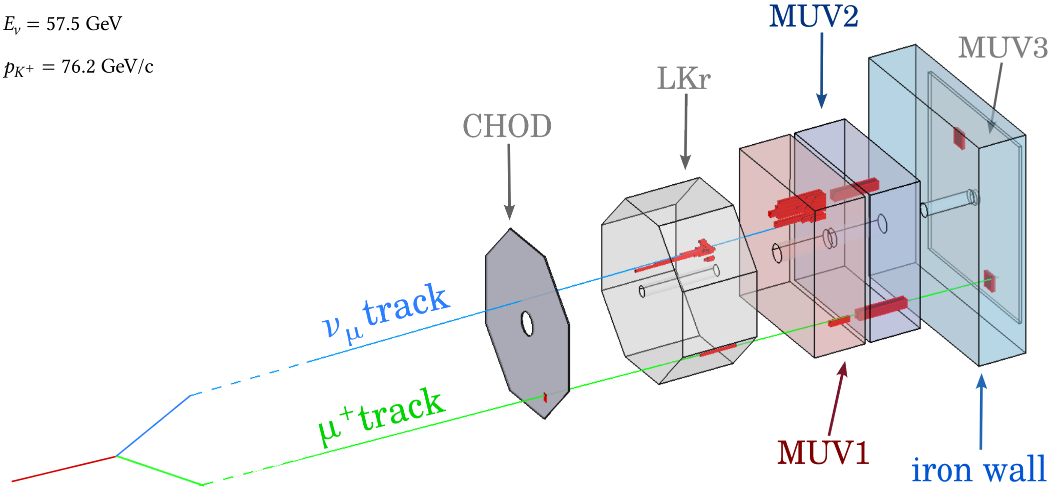
Event Display - Event A

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



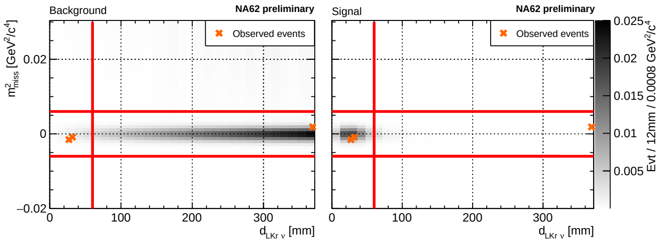
Event Display - Event B

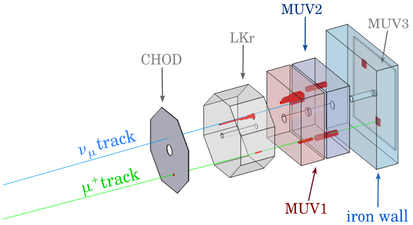
- $p_{\mu^+} = 18.74$ GeV/c
- $E_\nu = 57.5$ GeV
- $p_{K^+} = 76.2$ GeV/c



Summary: proof of principle with miniature tagged experiment

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





Outline

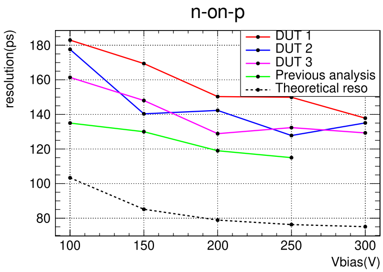
Perspectives overview

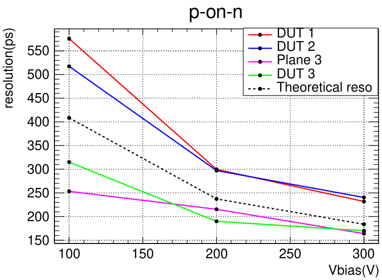
- A lot is left to do before implementing the Tagging at a tagged experiment
  - Beamline simulation and design (narrow-band, slowly extracted beam)
  - Development in field of silicon trackers ongoing
- Building a full scale tagged experiment involves operating Silicon trackers in neutrino beamline
- 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
- $\rightarrow$ 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	$\mathcal{O}(10-100)$	$\mathcal{O}(\mathbf{10-100})$
Hit Time Reso [ps]	130	<50	**<20**
Efficiency (%)	>99	>99	>99
Thickness (% of X_0)	< 0.5	<0.9	<0.5

Time resolution of state-of-the-art devices

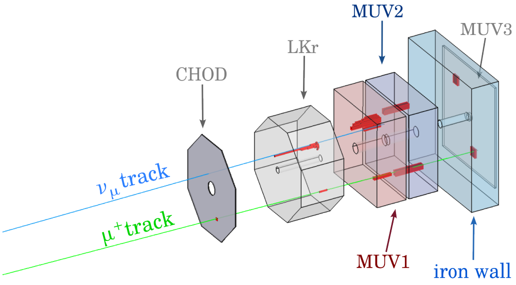
- An attempt has been made to investigate the limits of sensors of state-of-the-art device
- Data analysis of beam test taken at CERN SPS with π^+ at 180 GeV/c
- Device Under Test: 3 stations of single chips of NA62 GigaTracKer
- Difference in performance of n-on-p and of p-on-n sensor types demonstrated
- σ_t contributions remain to be quantified (e.g. Weighting Field effect)
- Results call for further testing of state-of-the-art devices and devices exploiting new technologies (such as TimeSpot)

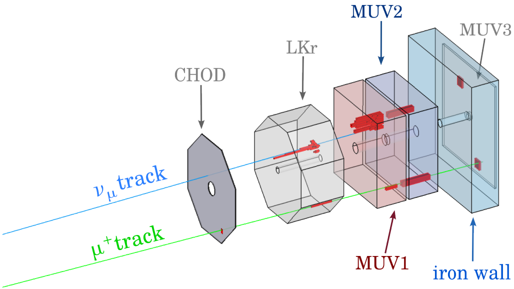




Conclusions and outlook

- Neutrino tagging: new paradigm for accelerator based neutrinos experiments
- Proof of principle with NA62, existing experiment exploitable as miniature tagged experiment
- **Two tagged neutrino candidates found in signal region**
- There is much left to do before implementing the tagging at a LBE
- **Achieved crucial first step towards establishment of tagging as effective paradigm**





Thank you for your attention!

Outline

Signal yield

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

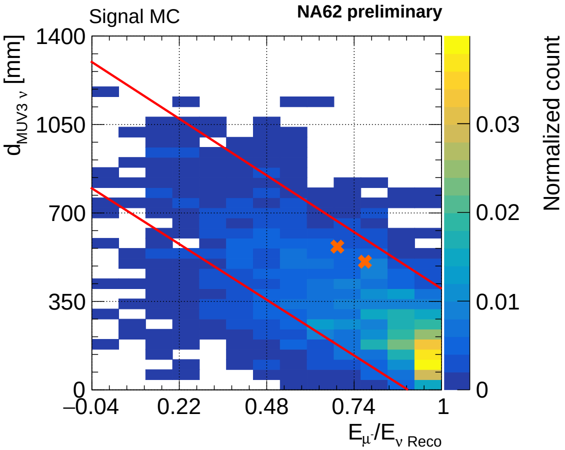
Contribution	**Value and uncertainty**
$P_{int,LKr}$	$(6.0 \pm 0.1_{syst}) \cdot 10^{-11}$
$N_{K\mu\nu}$	$(1.49 \pm 0.02_{syst}) \cdot 10^{11}$
$A^{int}_{K\mu\nu*}$	$0.0421 \pm 0.0025_{stat} \pm 0.0015_{syst}$
ϵ^{RV}	$0.816 \pm 0.014_{syst}$
$\epsilon^{MOQX}_{K\mu\nu*}$	$0.976 \pm 0.007_{stat} \pm 0.001_{syst}$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

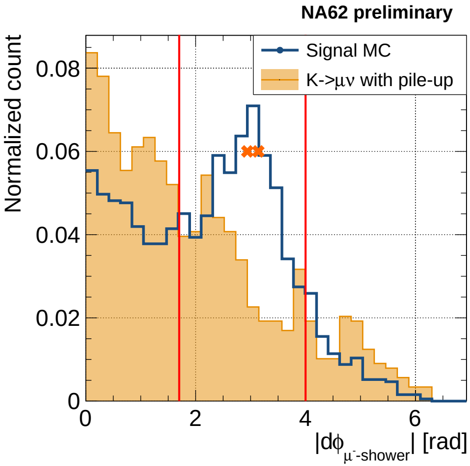
Signal candidates properties

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

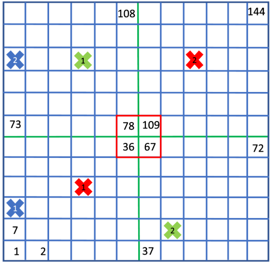
Table: Features of the two signal candidates found in the signal region.

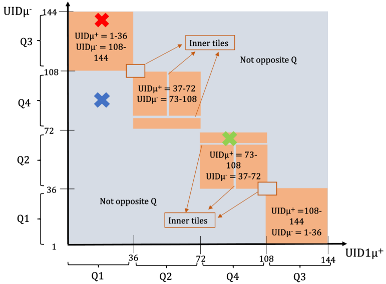
Signal candidates properties

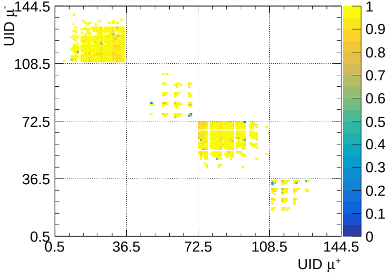




MUV3 efficiency







- Use sample of $K^+ \to \pi^+\pi^+(\mu^+\nu)\pi^-(\mu^-\nu)$
- $\epsilon^{MUV3} = 0.976 \pm 0.007_{stat} \pm 0.001_{syst}$
- Systematics obtained by weighting with the two biased MC samples

HLT efficiency mask10

- HLT trigger involves KTAG and STRAW information, with a Photon Veto condition
- HLT trigger efficiency computed with data
- $\epsilon^{HLT}_{mask10} = \epsilon^{KTAG} \cdot \epsilon^{nLAV} \cdot \epsilon^{STRAW\_1TRK} = 0.932 \pm 0.002_{stat}$.

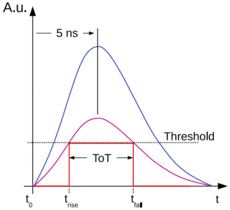
HLT algo	**Efficiency**
`KTAG` | ($K\mu\nu$ sel)	0.998 ± 0.001
`nLAV` | ($K\mu\nu$ sel) & `KTAG`	0.996 ± 0.001
`STRAW_1TRK` | ($K\mu\nu$ sel) & `nLAV` & `KTAG`	0.938 ± 0.001

TDCPix and previous test campaigns

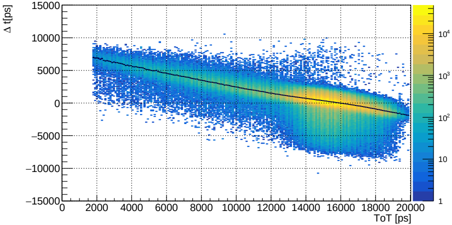
- TDCPix: time resolved readout chip of Silicon tracker of NA62 experiment (GigaTracker)
- 200μm thick planar sensors, p-in-n or n-in-p, 40×45 pixels of $300 \times 300 \mu m^2$
- From previous test campaign have been experimentally measured
    - electronics contribution from laser test with TDCPix demonstrator: ~ 80 ps
    - WF contribution with laser tests with TDCPix: ~ 85 ps
- Simulation of charge straggling contribution $\rightarrow \sim 100$ ps
- Missing:
    - experimental measures of charge straggling
    - experimental confirmation of WF effect with MIPs
    - systematic study on performances of n-on-p and p-on-n sensors

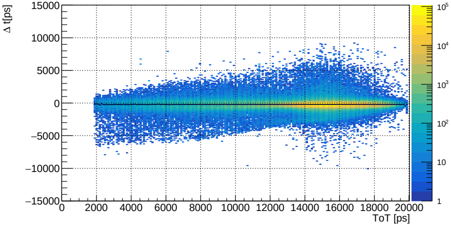
$$\sigma_t = \sqrt{\sigma^2_{electronics+TDC} + \sigma^2_{weighting\,field} + \sigma^2_{straggling}} = \sqrt{80^2 + 85^2 + 100^2} = 150 ps.$$

Time Walk Correction



- Procedure to be done on plane couples in absence of time reference
- Both planes are to be corrected → iterative procedure
- Use Time over Threshold ($ToT = t_{fall} - t_{rise}$) as a proxy to the signal amplitude
- Derive delay of detection at threshold as function of ToT thanks to $\Delta t = t_2 - t_1$ VS ToT distributions
- Effect of correction: flatten and shrink Δt VS ToT distribution





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

Sakharov's conditions for baryogenesis

- Baryon number violation:
  - B is a quantum number: for baryons it is +1, for antibaryons it is -1, for mesons and leptons it is 0.
  - it is conserved in all known interactions
  - $B \neq 0$ means $\#q - \#\overline{q} \neq 0$; if the baryon number is not conserved, then $\#q - \#\overline{q} \neq$ const
- CP violation:
  - Baryon number violation means that properties of particles and antiparticles must be different.
  - This is equivalent to both CP and C-symmetry violation.
  - CP symmetry means that a process in which all particles are exchanged with their antiparticles is equivalent to the mirror image of the original process.
- Departure from thermal equilibrium:
  - the processes that produce an excess of particles over antiparticles must be out of thermal equilibrium: the reverse process must have been suppressed.

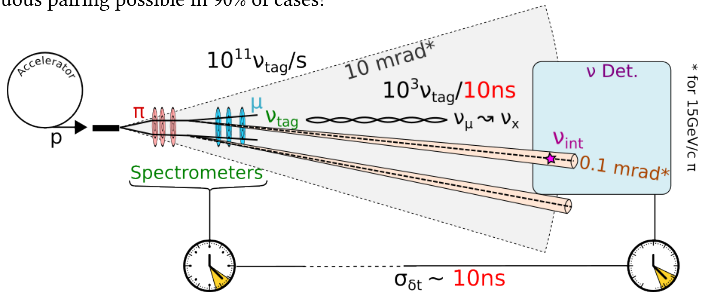
Unambiguous matching of ν-tag to ν–int

- 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}

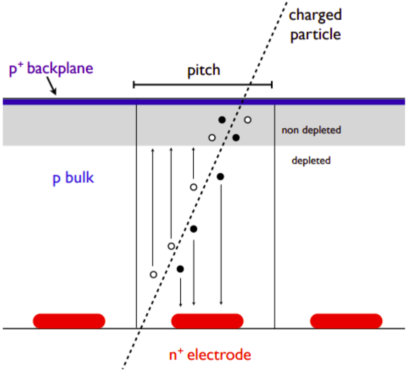
- Angular coincidence:
  - Dominant contribution: resolution on ν_{tag} is $\mathcal{O}(0.1)$ mrad for thickness of 0.5% X_0
  - ν beam divergence $\sim \frac{1}{\gamma} \rightarrow \sim 10$ mrad for 15 GeV $\pi^{\pm}$
  - $\rightarrow$ accidental matches reduced by a factor 10^4

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



Time Resolved Silicon Detectors

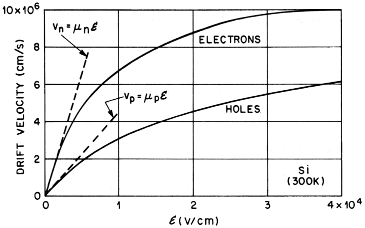
- Silicon pixel detector functioning principle is based on p-n junction
- e^- near p-n interface drift in p region, holes drift towards n region → depletion region
- Reverse V_{bias} applied → depletion region grows: $w_{depl} \propto \sqrt{V_{bias}}$
- Different sensor types depending on the doping of bulk and strips: n-on-p and p-on-n



Signal formation and detection

- Signal induced by motion of e^- and holes produced by crossing ionizing particle
- V_b affects the drift velocity of the charge carriers:

$$v_n = -\mu_n E = -\mu_n \frac{V_b}{d}$$
$$v_p = \mu_p E = \mu_p \frac{V_b}{d}.$$



- Current induced on an electrode by a moving charge described by the Ramo-Shockley theorem:

$$i(t) = -q\vec{v}(t) \cdot \vec{E}_W$$

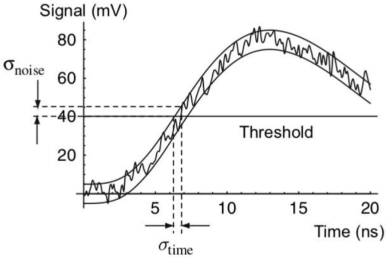
- Weighting field $\vec{E}_W$ describes coupling between the charge and the electrodes
- In parallel plate geometry:

$$i_c = e\vec{E}_W \cdot \vec{v}_c = \mu_c e\vec{E}_W \cdot \vec{E} = e\mu_c \frac{V_b}{d^2}$$

Time resolution budget in Silicon Pixel Detectors

$$\sigma_t^2 = \sigma_{\text{jitter}}^2 + \sigma_{\text{straggling}}^2 + \sigma_{\text{distortion}}^2 + \sigma_{\text{Time Walk}}^2$$

- σ_{jitter}: induced by the early or late firing of the comparator, due to the presence of noise ($\sigma_{\text{noise}} \propto \frac{1}{dV/dt}$)
- $\sigma_{\text{straggling}}$: variation of charge deposit in the sensor
- $\sigma_{\text{distortion}}$: due to non-uniformity of the weighting potential
- $\sigma_{\text{Time Walk}}$: delay of detection that depends on the signal amplitude



$$\sigma_{time} = \frac{\sigma_{noise}}{k} \qquad k = \frac{\Delta v}{\Delta t}$$

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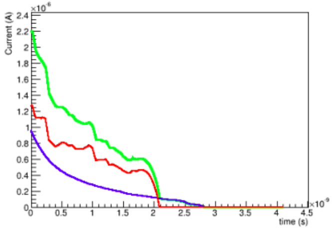

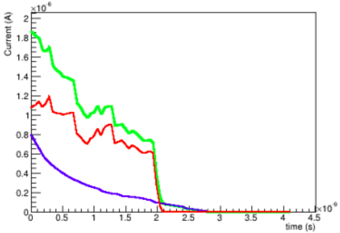

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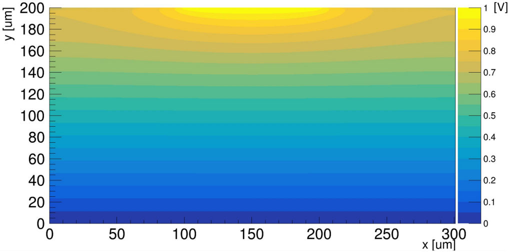
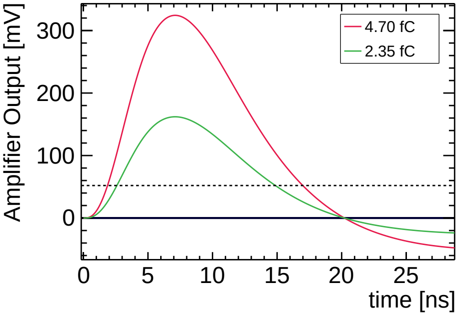
- $\sigma_{\text{distortion}}$: due to non-uniformity of the weighting potential
- $\sigma_{\text{Time Walk}}$: delay of detection that depends on the signal amplitude



Time resolution budget in Silicon Pixel Detectors

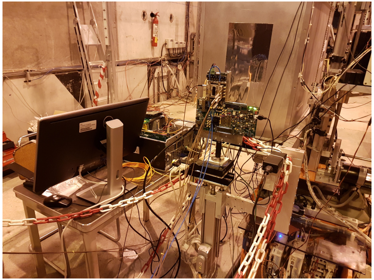
$$\sigma_t^2 = \sigma_{\text{jitter}}^2 + \sigma_{\text{straggling}}^2 + \sigma_{\text{distortion}}^2 + \sigma_{\text{Time Walk}}^2$$

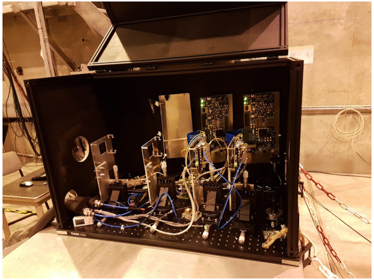
- σ_{jitter}: induced by the early or late firing of the comparator, due to the presence of noise ($\sigma_{\text{noise}} \propto \frac{1}{dV/dt}$)
- $\sigma_{\text{straggling}}$: variation of charge deposit in the sensor
- $\sigma_{\text{distortion}}$: due to non-uniformity of the weighting potential
- $\sigma_{\text{Time Walk}}$: delay of detection that depends on the signal amplitude



Beam Test Setup

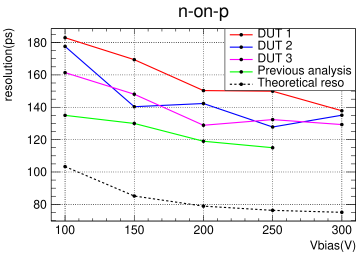
- Beam test data analysed aiming to study of time resolution contributions with MIPs crossing the sensor.
- Beam test taken at CERN SPS in 2017 with π^+ at 180 GeV/c
- Device Under Test (DUT): TDCPix, readout ASIC of the NA62 GigaTracKer
- 3 planes of TDCPix + 8 planes of TimePix3
- No external time reference
- TPX telescope has very small pixels (55μm) → can resolve the position inside the TDCPix pixel (300μm)

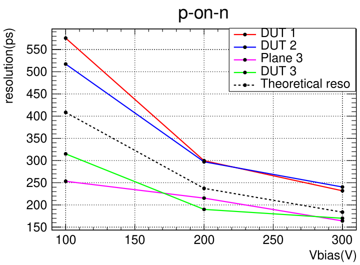


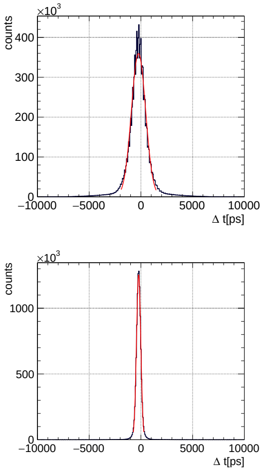


Time Resolution for the two sensor types

- Use Time over Threshold ($ToT = t_{fall} - t_{rise}$) as a proxy to the signal amplitude
- Perform Time Walk correction on hits from plane pairs
- Access resolution thanks to corrected Δt distributions
- Resolution of a plane: $\sigma_i = \sqrt{\frac{1}{2}(\sigma^2_{i-j} + \sigma^2_{i-k} - \sigma^2_{j-k})}$



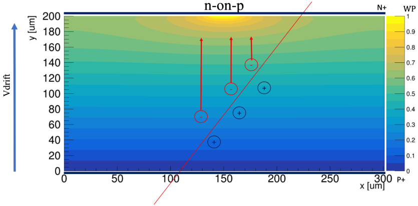


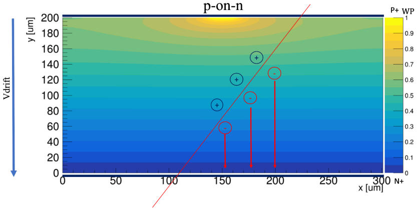


- Time resolution worse than expected → dominated by noise, maybe additional jitter contribution?

Observations

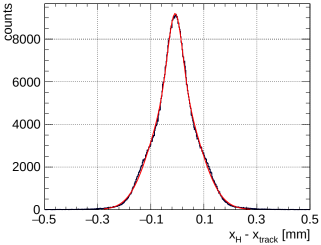
- Faster and more intense signal correspond to a better time resolution:
  - Signal composed by $h-$induced and $e-$induced part
  - Ramo theorem: $i_c = e\vec{E_W} \cdot \vec{v_c} = \mu_c e \vec{E_W} \cdot \vec{E} = e\mu_c \frac{V_b}{d^2}$
  - i_c larger for large $E_W \rightarrow$ larger for charges collected by the pixel electrode, where E_W is larger
  - $\sigma_{\text{noise}} \propto \frac{1}{dV/dt}$
- $\rightarrow$ Time resolution in n-on-p sensors better than in p-on-n:
  - $\mu_h < \mu_e \rightarrow v_e \sim 3v_h$
  - h induce a slower signal $\rightarrow$ more affected by noise
  - h collected in pixel electrode in p-on-n and in backplane electrode in n-on-p

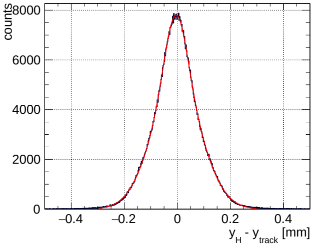




Time resolution and position inside the pixel

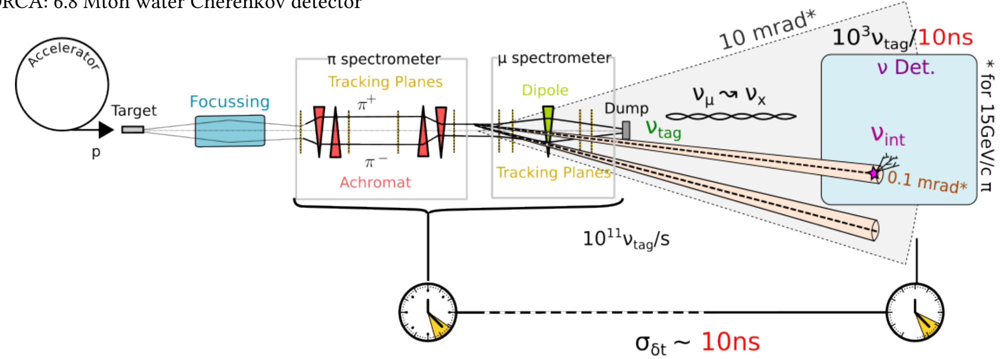
- Goal: see how the time resolution changes in different regions of the pixels
- Use tracks from TPX telescope to resolve position inside the TDCPix pixel
- Associate in space and time the track intercept and the hits of the TDCPix
- Time resolution studied in central and lateral pixel portions
- No significant variation in the time resolution is measured
- Calls for new testing campaigns to measure the WF contribution



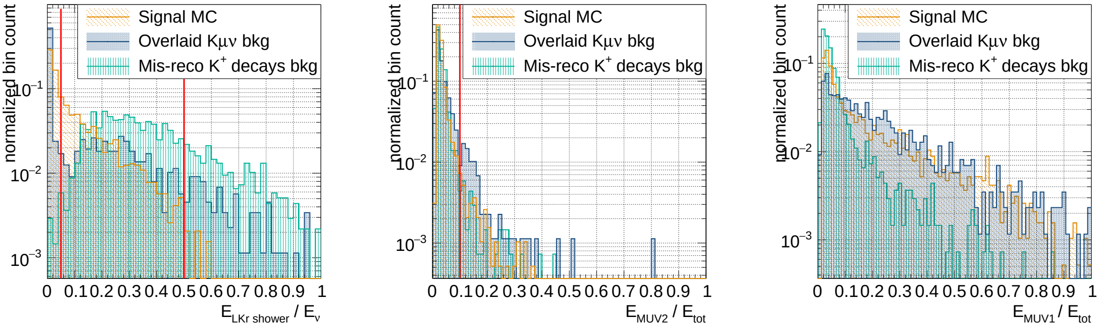


Unambiguous matching of ν-tag to ν-int

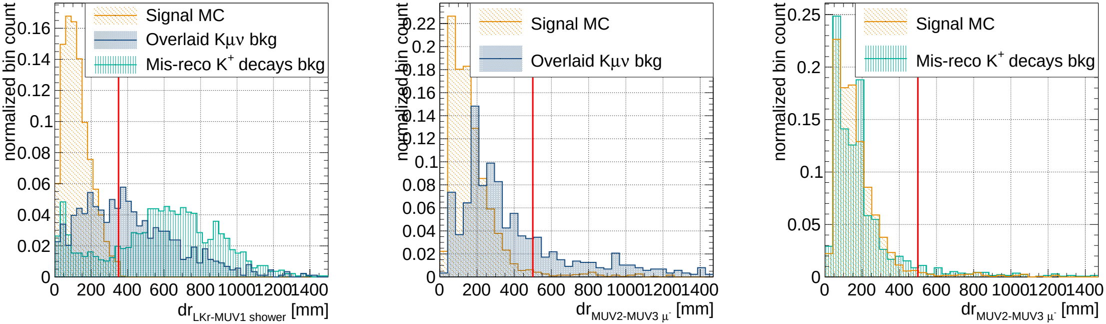
- Tagging relies on unambiguous matching between ν_{tag} and ν_{int}
- 3 key elements:
  - state-of-the-art silicon trackers
  - adapted beamline
  - large Far Detector
- Case study: Tagged P2O (Protvino to KM3NeT/ORCA), $L = 2595$km, $E_\nu = 5$ GeV
- ORCA: 6.8 Mton water Cherenkov detector



Energy requirement plots



DR plots


Signal MC
Overlaid Kμν bkg
Mis-reco K+ decays bkg
normalized bin count
dr LKr-MUV1 shower [mm]
dr MUV2-MUV3 μ- [mm]
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.05
0.15
0.25
200
400
600
800
1000
1200
1400

hit maps at LKr