King's College 18-21 Dec 2023

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Neutrino Tagging

Mathieu PERRIN-TERRIN

on behalf of the **NA62 Collaboration** and **NuTAG proto-Collaboration**

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Outline

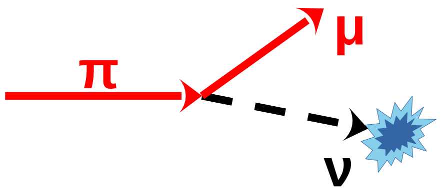
1. The neutrino tagging principles and physics potential
2. Proof-of-principle of the Neutrino Tagging at NA62
3. Towards full scale tagged neutrino experiments

Eur. Phys. J. C, 2022, 82, 465

Neutrino Tagging with Modern Technology

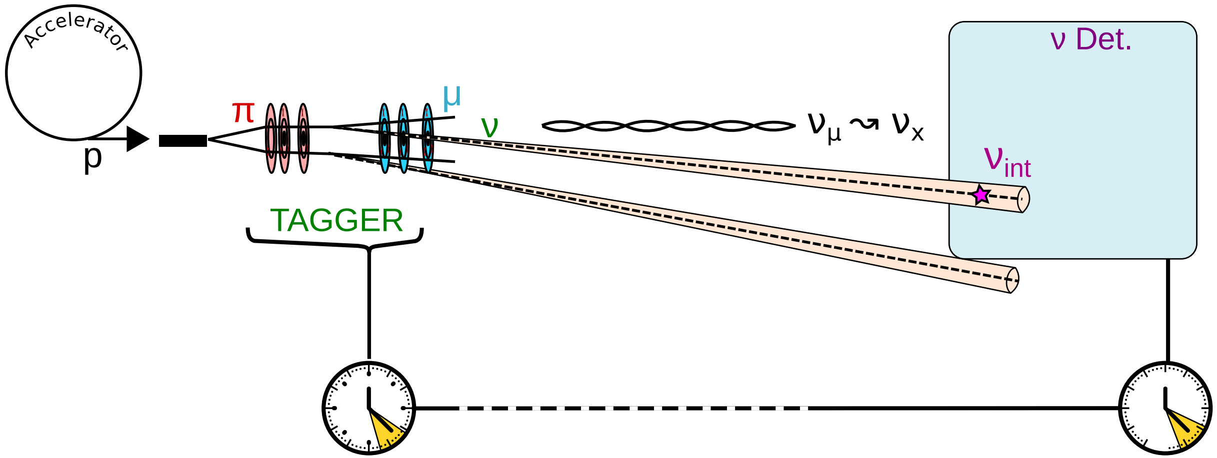
Associate individually each neutrino interaction with its production mechanism

- Pixel detectors (**TAGGER**) to track π's and μ's
- **ν kinematically reconstructed**



$$p_\nu = p_\pi - p_\mu$$

- Access to the **pristine ν flux**
- Unmatched **energy resolution:**
  <1% w/o energy scale vs 10-30% w/ energy scales syst. using ν interaction



Neutrino Tagging with Modern Technology

Beam particle rate is the main experimental **challenge.** Handles are:

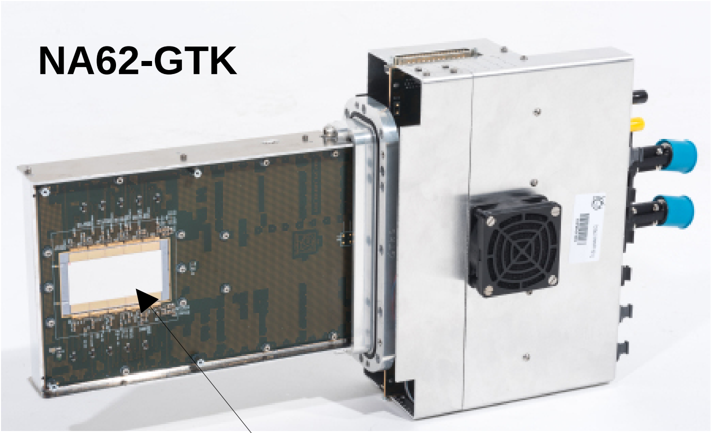
- **slow extraction** from proton driver
- **high intensity pixel 4D trackers**

4D trackers: state-of-the-art and beyond:

	Available	Radiation $[n_{eq}/cm^2]$	Flux [MHz/mm²]	Time Reso [ps]
NA62-GTK	>2015	10^{14}	2	130
HL-LHC	>2028	10^{16-17}	10-100	20

~10^{12} π/s with tracking planes of about 0.1m²

JINST, 2019, 14, P07010



sensor area: 3x6cm²

Eur. Phys. J. C, 2022, 82, 465

Physics @ Tagged Short Baseline Experiments

ν_μ cross-section and differential cross-section

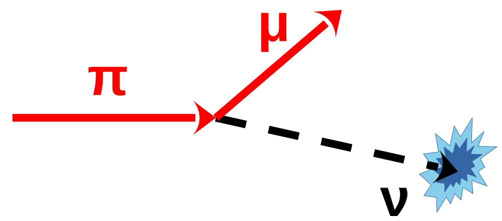
- **ν_μ flux** from $\pi \rightarrow \mu\nu$ and $K \rightarrow \mu\nu$ precisely determined by the tagger
- **ν_μ energy measured evt-by-evt at <1% precision**

ν_e cross-section

- **ν_e flux** determined as $N(\nu_e) = N(\text{Ke3}) = N(\text{K}\mu 2)\cdot\frac{B(\text{Ke3})}{B(\text{K}\mu 2)}$
- ν_e cross section precision limited by **statistics** and by ***B*(Ke3) precision (0.8%)**

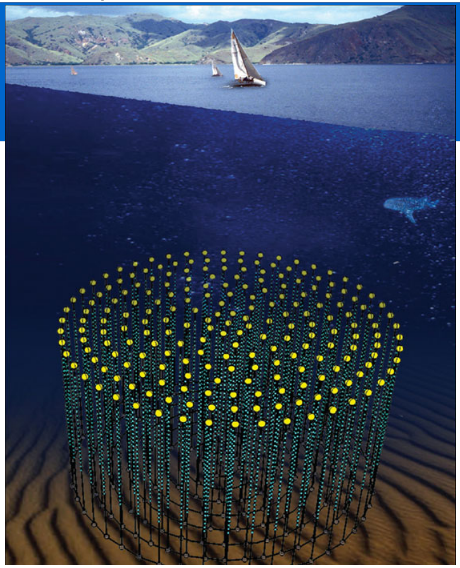
Ideal setup to study **interaction models**

- **ν energy measured independently of interaction**



Eur. Phys. J. C, 2022, 82, 465

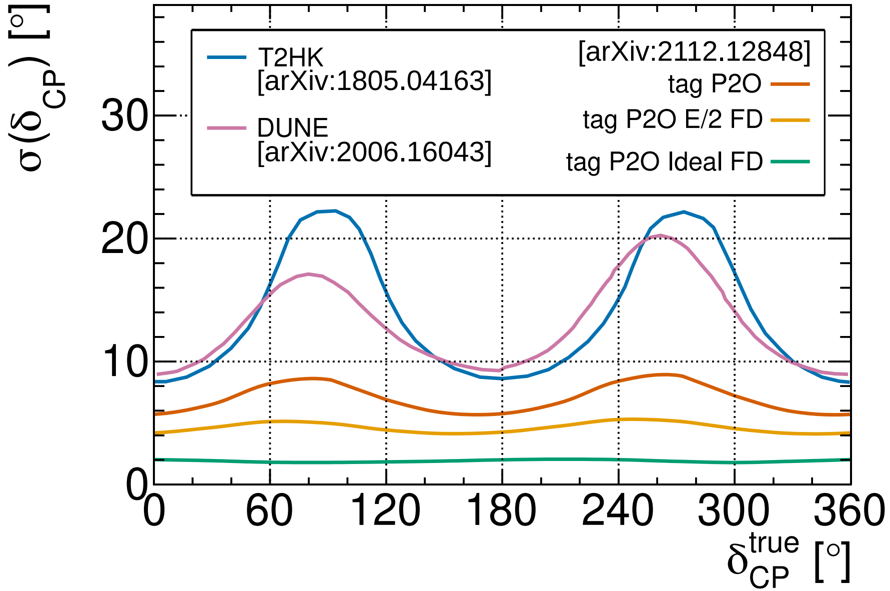
Physics @ Tagged LBL



More on ORCA in P.Coyle Talk at NuPhys2023

- Neutrino **flux is limited by tagger capability**
- Use XXL ν-detectors
  ➔ **O(Mton) natural water Cherenkov Detector** as KM3NeT/ORCA
- Lower detector precision compensated by **tagging precision**
- Very good **control of systematic** (flux, energy)

- **Case study:** Protvino to ORCA (P2O)
  First oscillation max at 5GeV (2600km)
- Tagged LBL: a new path to continue studying ν oscillation **after DUNE/HK** (w/o multi MW beam, w/o excavation)

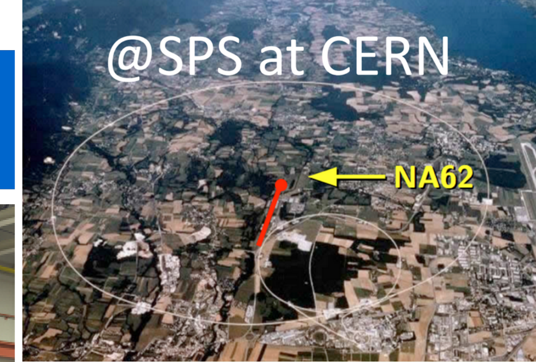


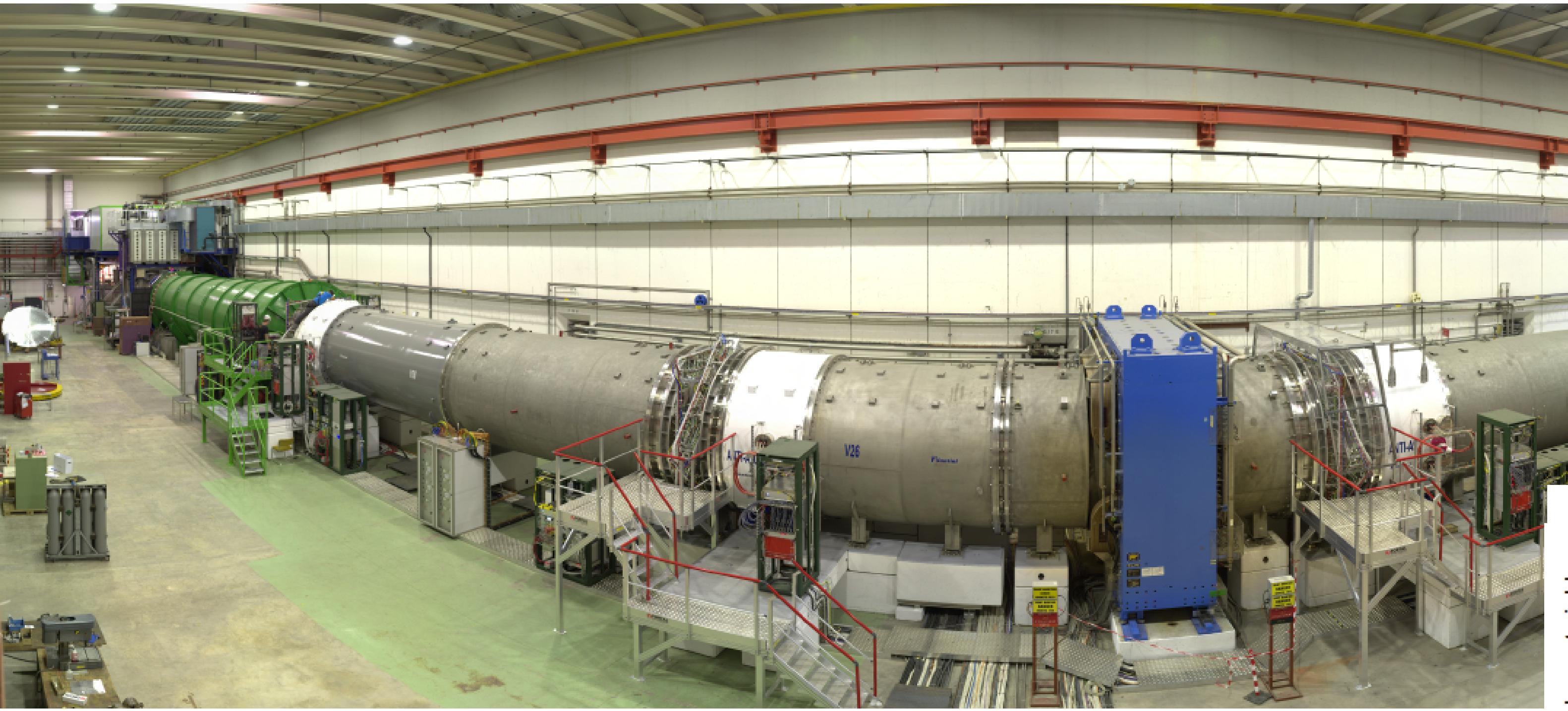
Outline

1. The neutrino tagging principles and physics potential
2. **Proof-of-principle of the Neutrino Tagging at NA62**
   For a more complete presentation on this topic see:
   B. De Martino's Talk at NuFact 2023
3. Towards full scale tagged neutrino experiments

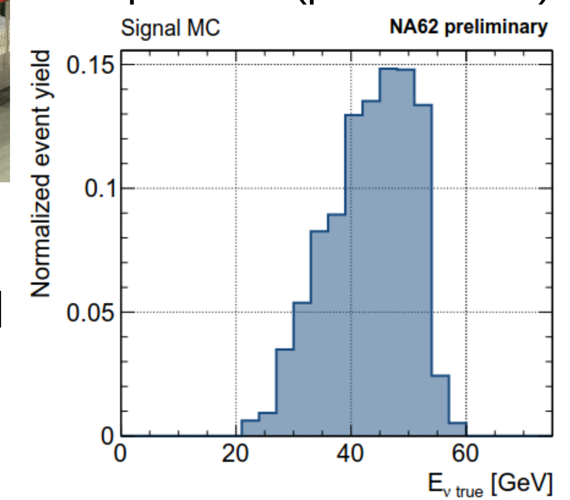
JINST, 2017, 12, P05025

Proof of Principle with NA62



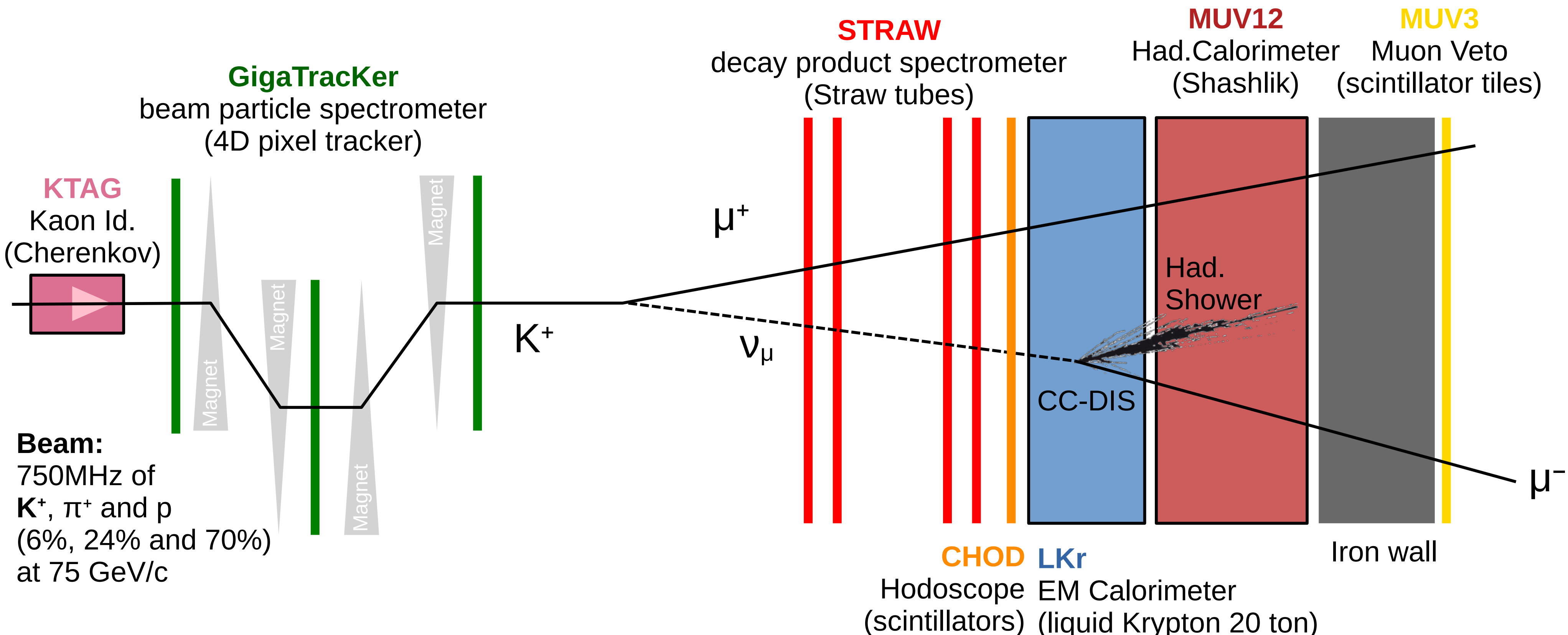


ν spectrum (p_K=75GeV/c)



- **Fixed target Kaon** experiment at CERN/SPS (2015 ➔2025)
- Goal: branching ratio of the rare K➔πνν: $(8.4\pm1.0)\cdot10^{-11}$ in SM
- ~10^{12} K decays per year, **mostly Kμ2.**
- All instrumentation to **detect the K, the μ and the neutrino !**

Simplified Experimental Setup for ν Tagging



Beam:
750MHz of
K^+, π^+ and p
(6%, 24% and 70%)
at 75 GeV/c

Trigger Strategy:

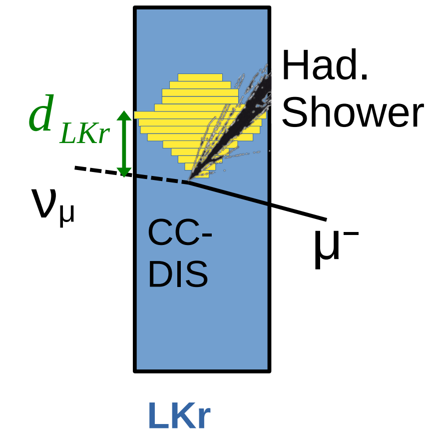
- One charged particle in **CHOD**
- Energy deposit in **LKr**
- Two charged particles in opposite quadrant of **MUV3**

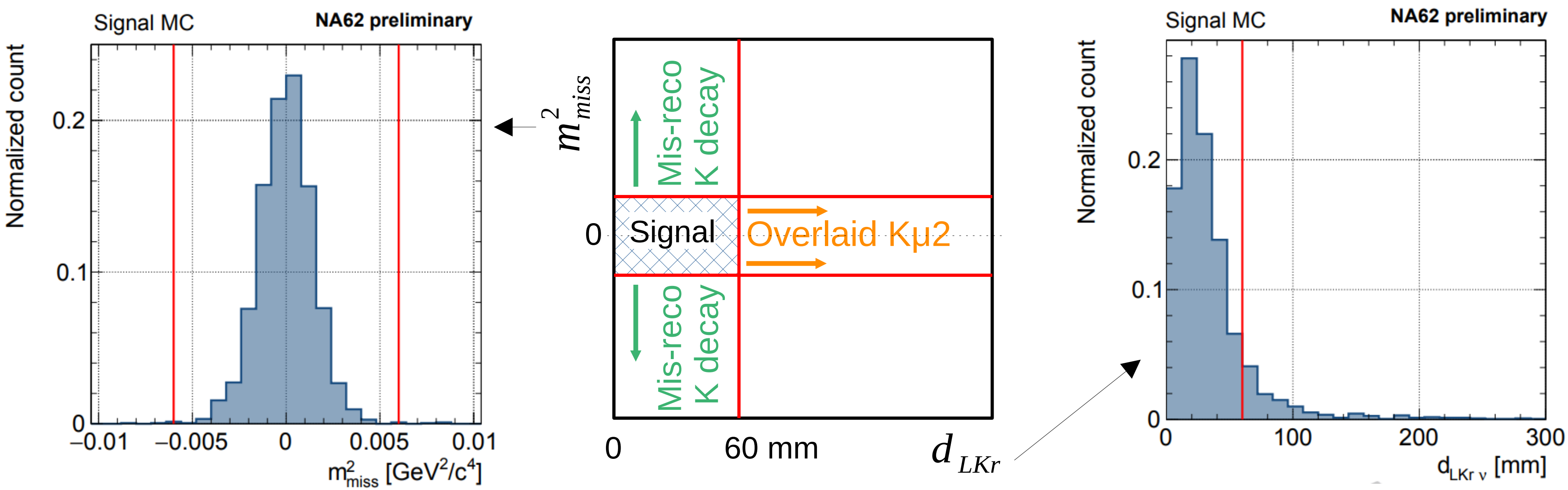
Data Analysis Strategy

- **Data Sample:** $5 \cdot 10^{12}$ effective K decay collected in 2022
- **Blind Analysis**, with a signal region defined as

$$|m^2_{miss}| = |(p_K - p_\pi)^2| < 0.6\,\mathrm{GeV}^2/\mathrm{c}^4 \qquad |d_{LKr}| < 60 \ \ \mathrm{mm}$$

- Two **background sources**
  - Overlaid Kμ2: K➔μν with extra activity in LKr
  - Mis-reconstrcted K decay





Signal and Background Expectations

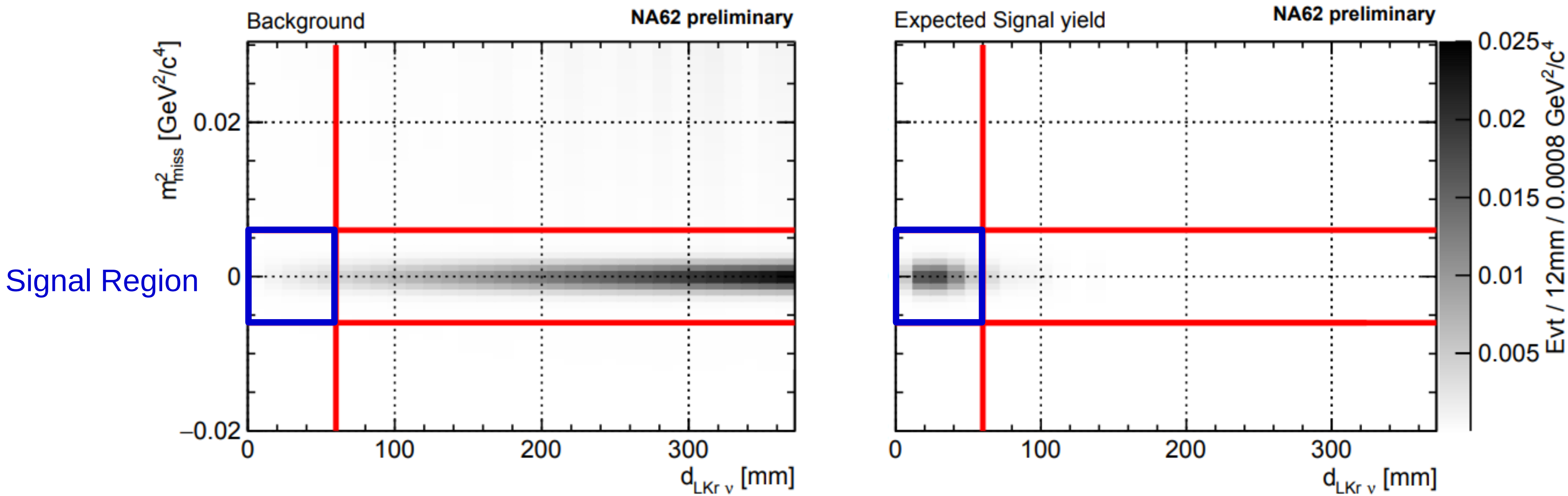
- **Background** extrapolated from signal side-bands with a relaxed selection

$$N^{exp}_{\text{mis-reco-K}} = \mathbf{0.0014} \pm 0.0007_{stat} \pm 0.0002_{syst}$$
$$N^{exp}_{\text{overlaid-K}\mu 2} = \mathbf{0.04} \pm 0.02_{stat} \pm 0.01_{syst}$$

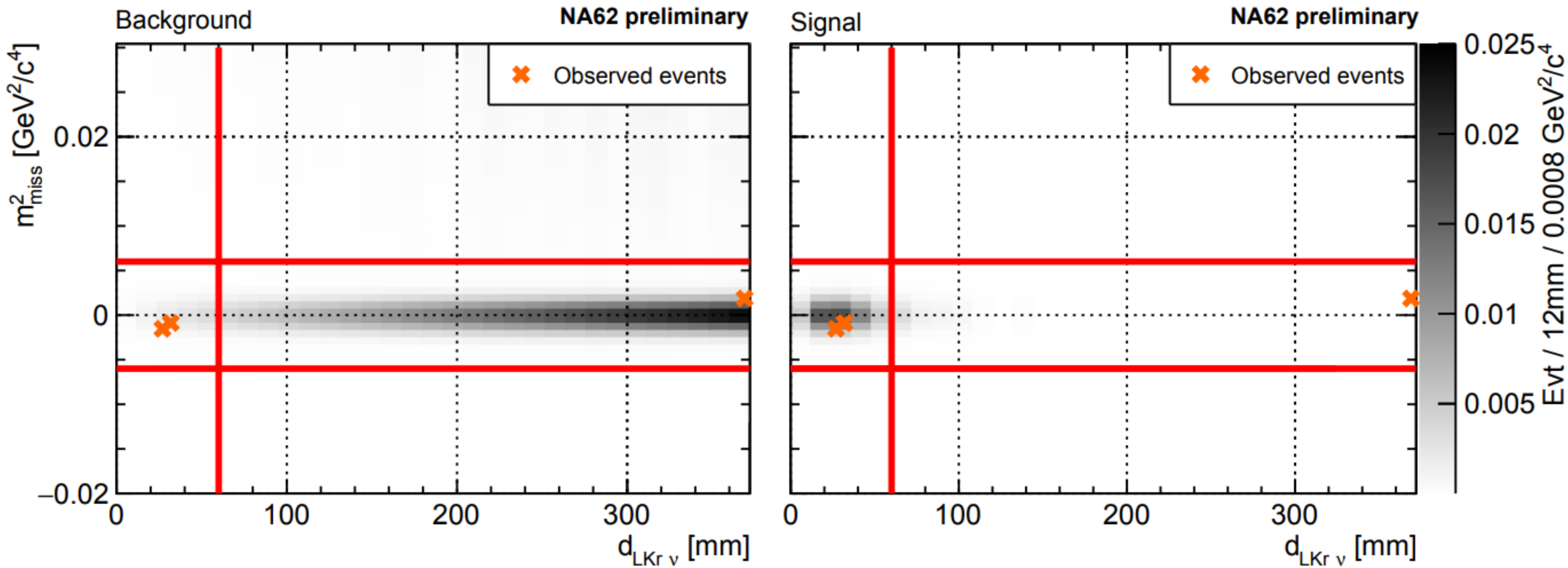
- **Signal** expect yield (normalized to Kμ2)

$$N^{exp}_{sig} = \underbrace{N_{K\mu 2}}_{(1.49 \pm 0.2_{syst.}) \cdot 10^{11}} \cdot \frac{\epsilon_{sig}}{\epsilon_{K\mu 2}} \cdot \underbrace{P_{int,LKr}}_{(6.0 \pm 0.1_{syst.}) \cdot 10^{-11}}$$
$$= \mathbf{0.228} \pm 0.014_{stat} \pm 0.011_{syst}$$

Sig / Bkg = 5.5



Signal Region Content



- Two events observed in signal region:
  the first two tagged neutrino candidates!

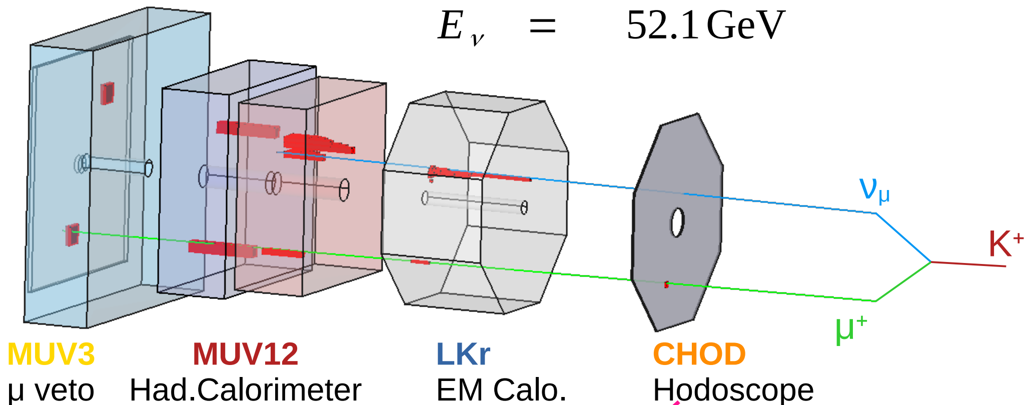
- First background event far from the signal region

Nb. Obs. Evt.	Probability when expecting 0.27
0	76%
1	20%
2	2.7%

Event Displays

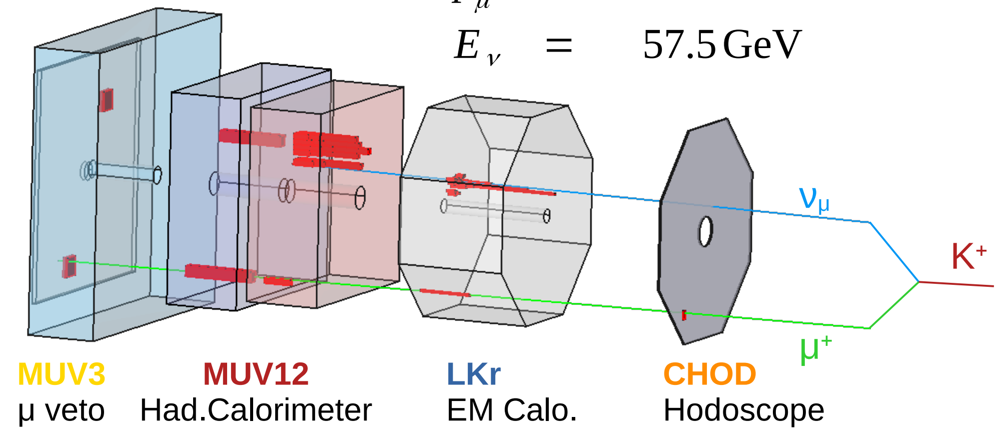
Event A

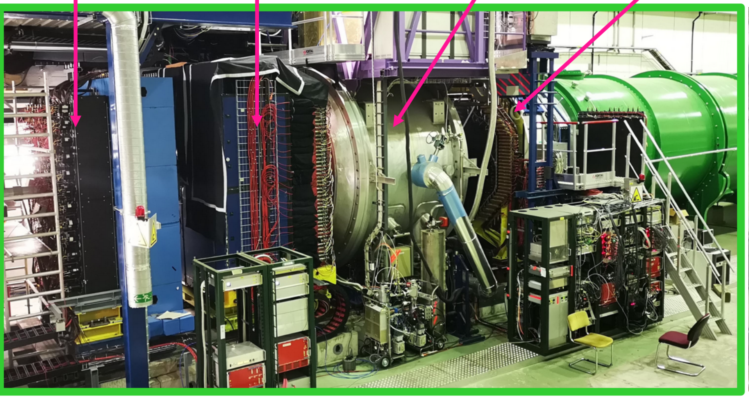
$$p_{K^+} = 77.3\,\text{GeV/c}$$
$$p_{\mu^+} = 25.25\,\text{GeV/c}$$
$$E_{\nu} = 52.1\,\text{GeV}$$

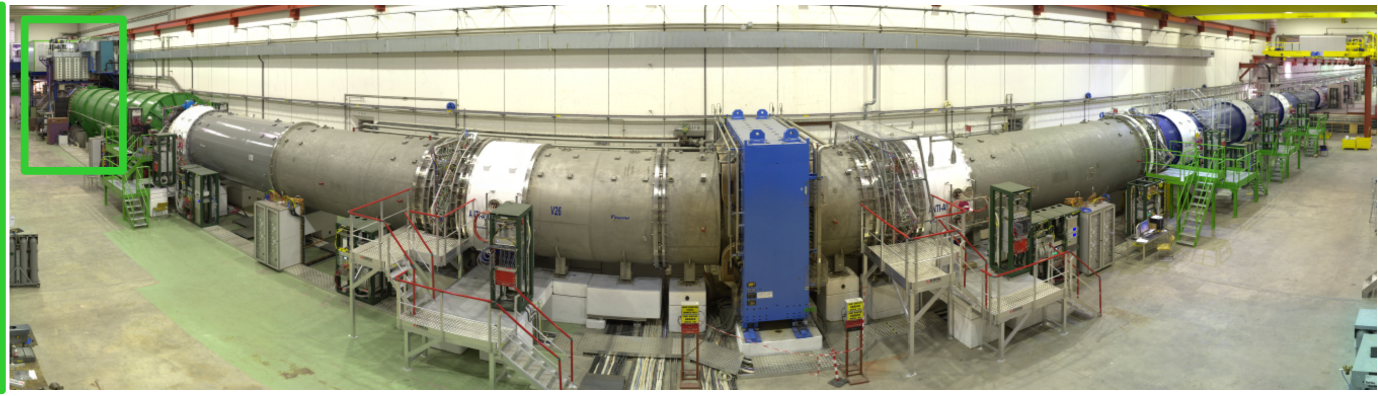


Event B

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







Outline

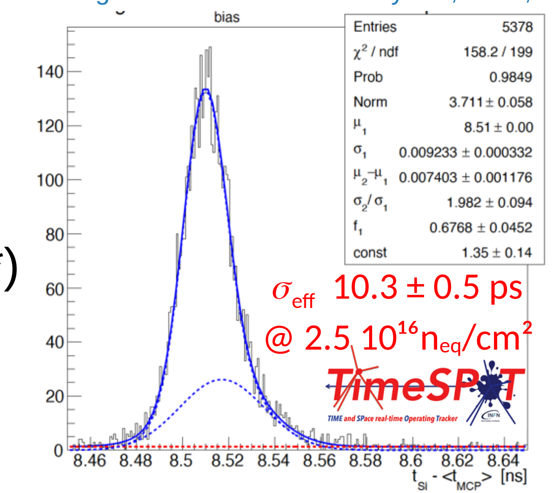
1. The neutrino tagging principles and physics potential
2. Proof-of-principle of the Neutrino Tagging at NA62
3. **Towards full scale tagged neutrino experiments**

Towards a full scale tagged ν experiment

Large **ν rate increase** to go from **NA62 to a proper tagged ν exp.**

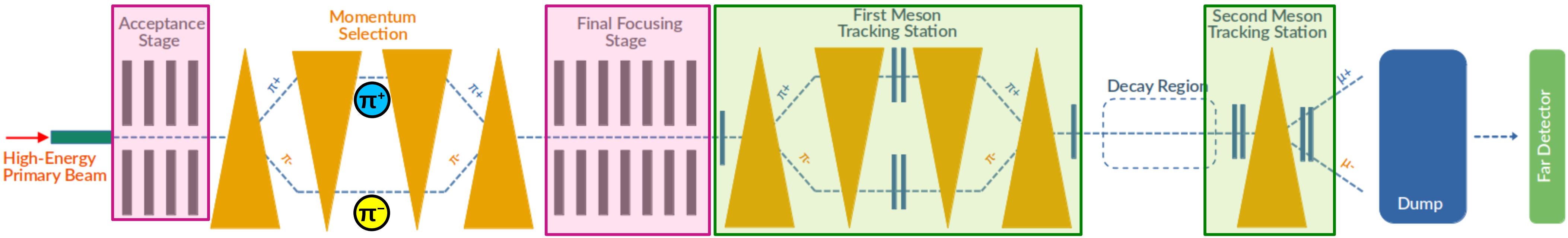
- Replace NA62-GTK with a **new pixel technology**: TimeSPOT
- Design dedicated **beam lines**: NuTAG project @ CERN-PBC*

Borgato et al. Frontiers in Physics, 2023, 11



Proof-of-concept study for a tagged LBL ν beam line (CERN-PBC*)

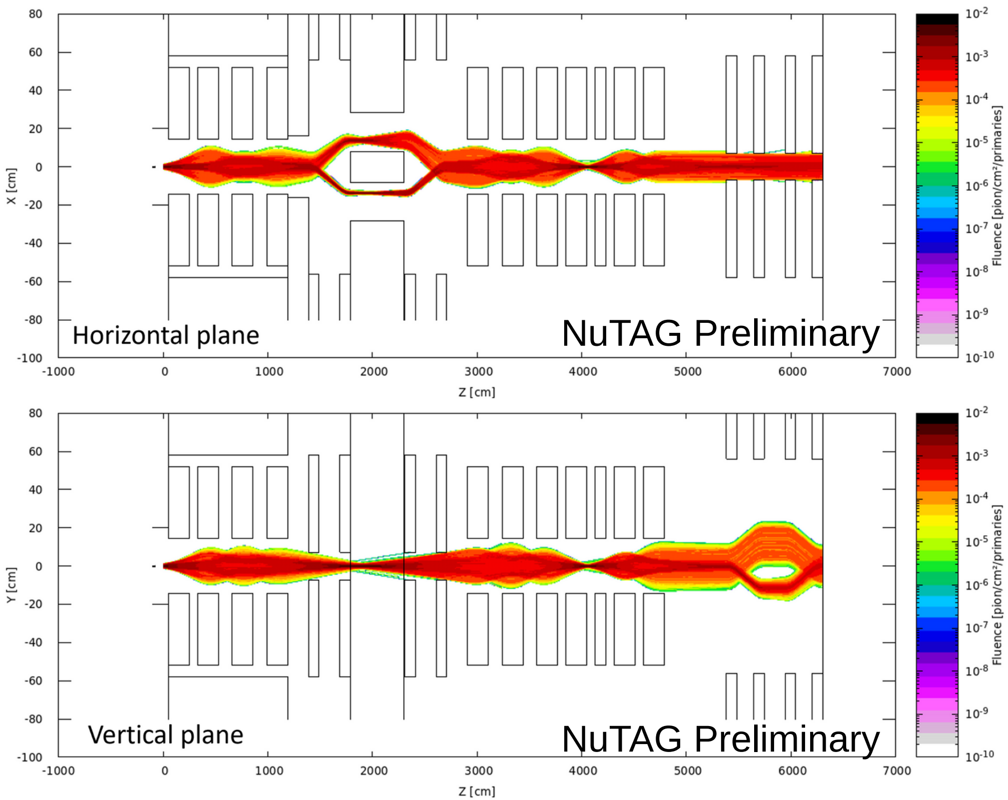
- **Slow extracted 400 GeV/c proton beam**, $2.5 \cdot 10^{13}$ p per 4.8s pulse
- Pion focusing using **large aperture quadrupoles**
- Both **π+** and **π-** transported together (ν & anti-ν collected together)
- **Two spectrometers** (for $\pi^{\pm}$'s and for μ±'s)



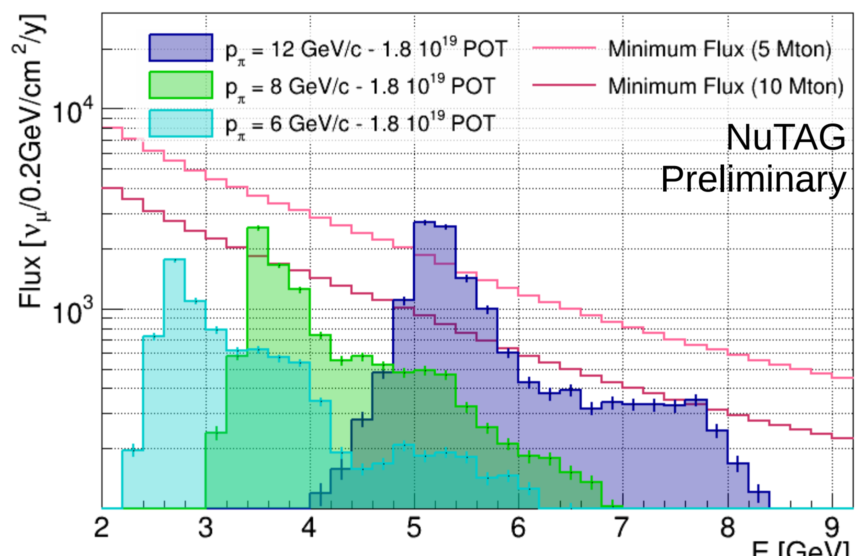
*A. Baratto-Roldan, E. Parozzi, M. Jebramcik, N. Charitonidis

Towards a full scale tagged ν experiment

- **Beam line modeled** up to π spectrometer with FLUKA



- Performance of an **LBL exp. using this tagged beam line** derived assuming:
  - $1.8 \cdot 10^{19}$ proton on target per year
  - detector mass of 5 or 10 Mton
- Flux sufficient to collect **ν_e samples size comparable to** DUNE/HK but **with lower systematics** (tagging)
- Room for improvement, beam **particle flux at tagger is** ~15 MHz/mm² << 100MHz/mm²

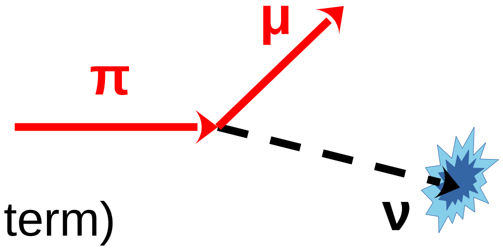


Summary and Conclusions

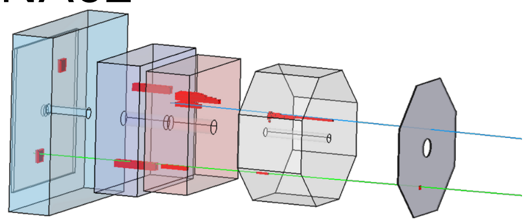
- **Neutrino tagging technique:**

  1. measure the ν properties from the prod. mechanism (π➔μν)
  2. associate each ν interacting in the ν-detector with a tag-ν

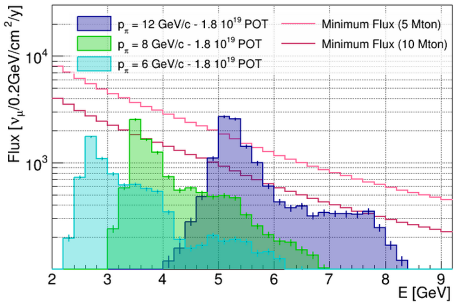
  Ideal setup to study **ν interaction (short term)**, ν oscillations (longer term)



- **The first two fully tagged neutrino candidate** detected at NA62
  - A crucial step to demonstrate that neutrino tagging is experimentally feasible
  - Results to be confirm with more data



- Proof-of-concept studies for **tagged beam line on-going at CERN**
  - first results show that a tagged **LBL** with Mton scale detector could work (tbc)
  - studies for a tagged **SBL @ CERN using ENUBET+NuTAG** techniques are starting



Thank you for your attention!

Questions?

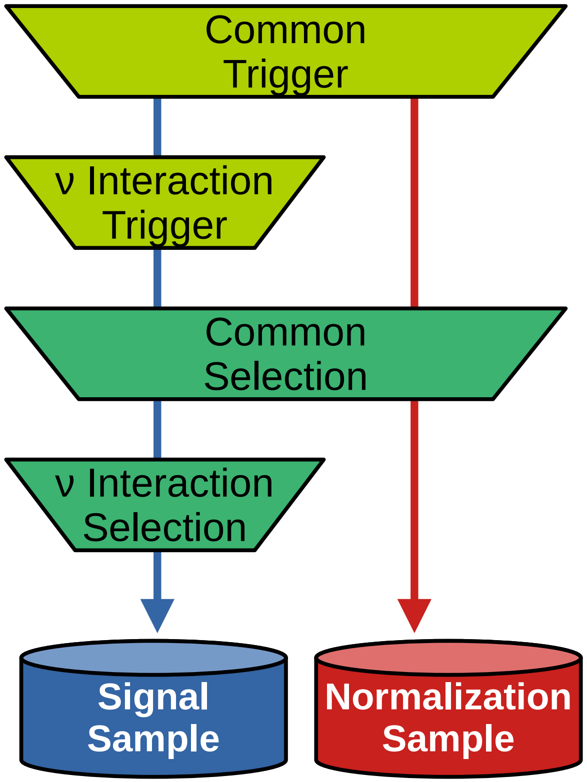
Data Analysis Strategy (2/2)

- **Data Sample:** $5 \cdot 10^{12}$ effective K decay collected in 2022
- **Expected event rate** derived with a normalization **sample** (Kμ2 w/o ν interaction)

$$N_{\mathrm{sig}}^{\mathrm{exp}} = N_K \cdot B(K^+ \to \mu^+ \nu_\mu) \cdot P_{\mathrm{int,LKr}} \cdot \epsilon_{sig}$$

with $$N_K = \frac{N_{\mathrm{K\mu2}}}{\epsilon_{\mathrm{K\mu2}} \cdot B(K^+ \to \mu^+ \nu_\mu)}$$

$$N_{\mathrm{sig}}^{\mathrm{exp}} = N_{\mathrm{K\mu2}} \cdot \frac{\epsilon_{sig}}{\epsilon_{\mathrm{K\mu2}}} \cdot P_{\mathrm{int,LKr}}$$

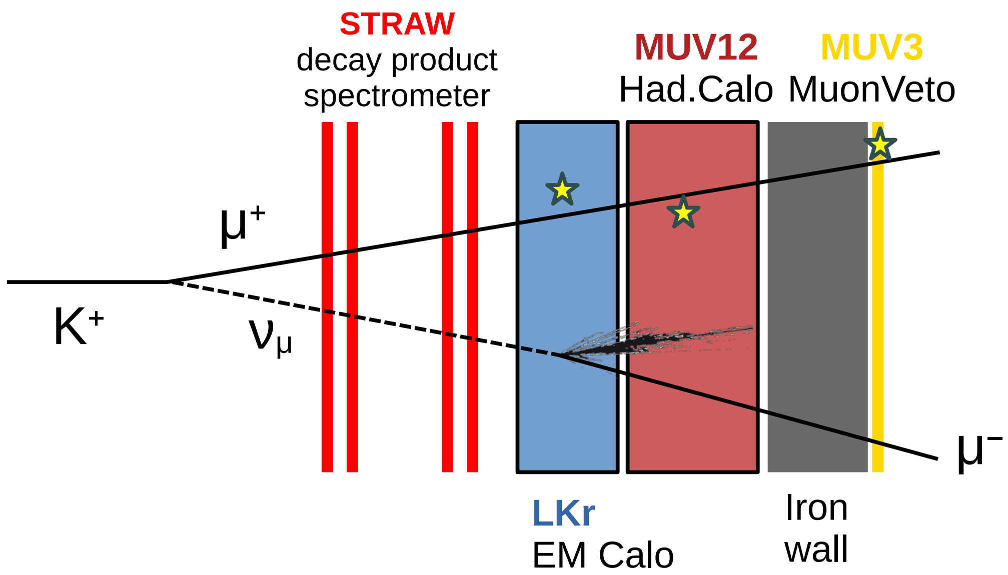


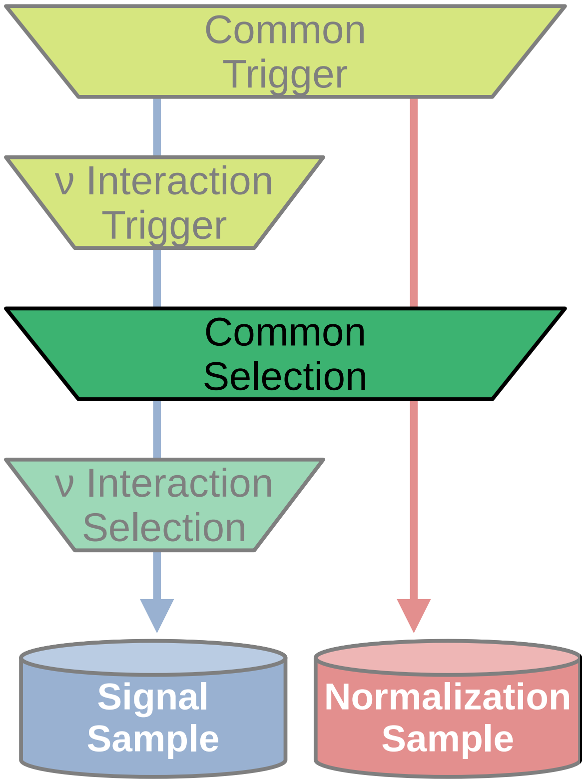
- Common efficiency terms cancel in ratio

- **Efficiency for ν interaction** and **interaction probability estimated with MC** sample (Geant4 + GENIE)

Selection

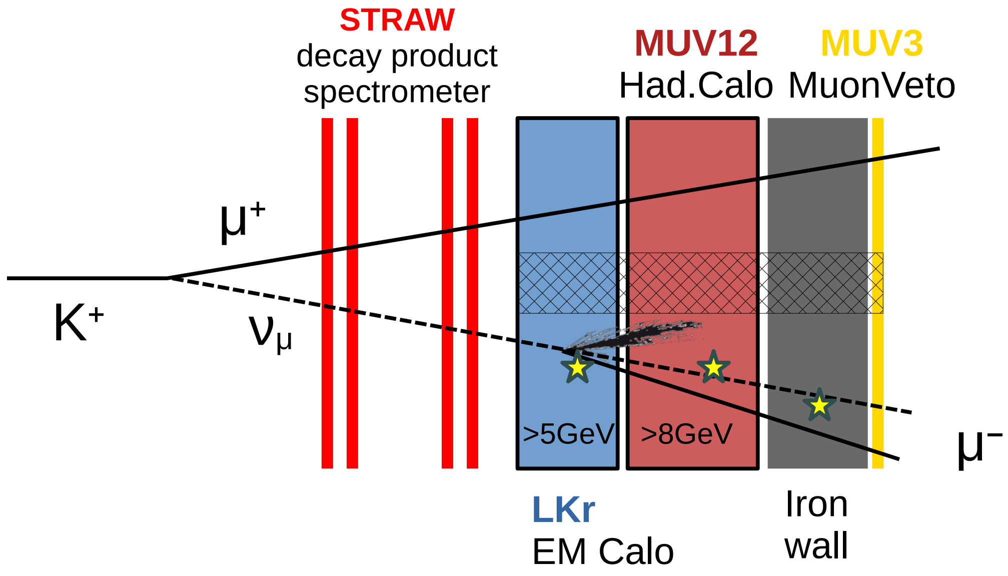
- Vertex in fiducial region
- Single track identified as μ+ and matched to activity in all detectors
- Photon rejection

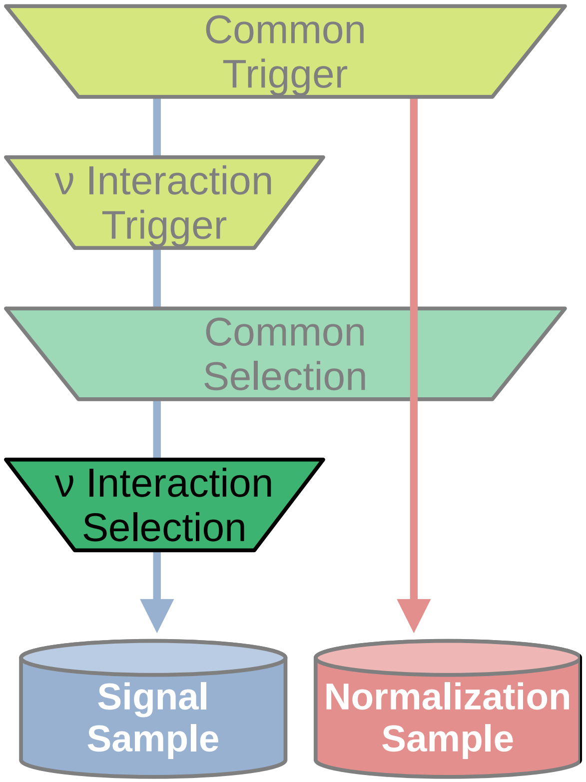




Selection

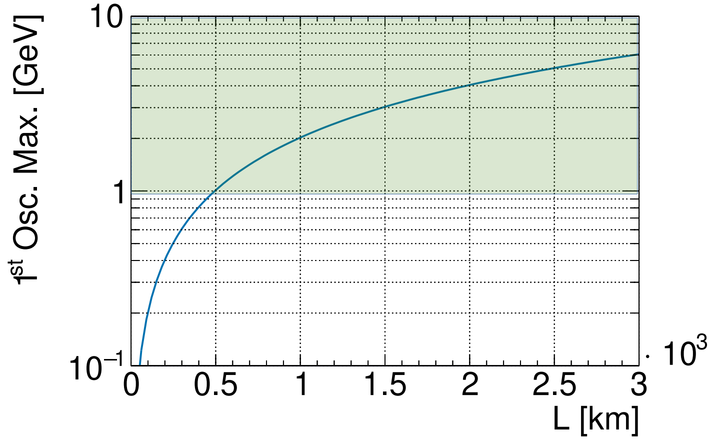
- ν associated to activity in all detector
- Extra activity rejection (close to beam pipe)
- Energy requirement
- Interaction topology
  - ν, had. shower and μ- in the same plane
  - Opening angle (shower to μ-) proportional to Bjorken y

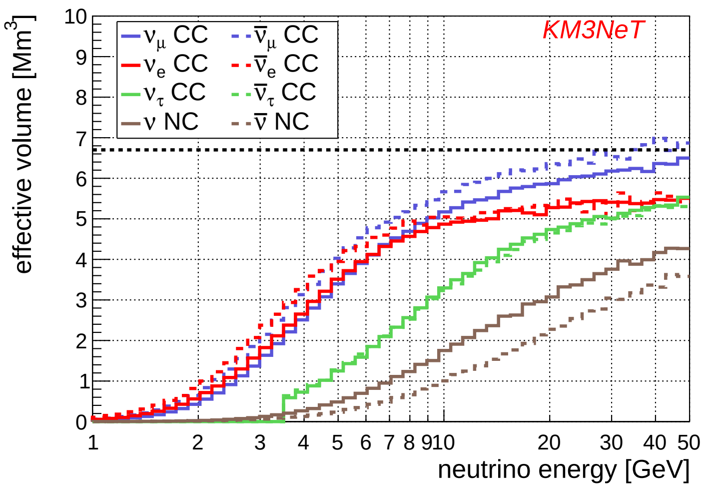


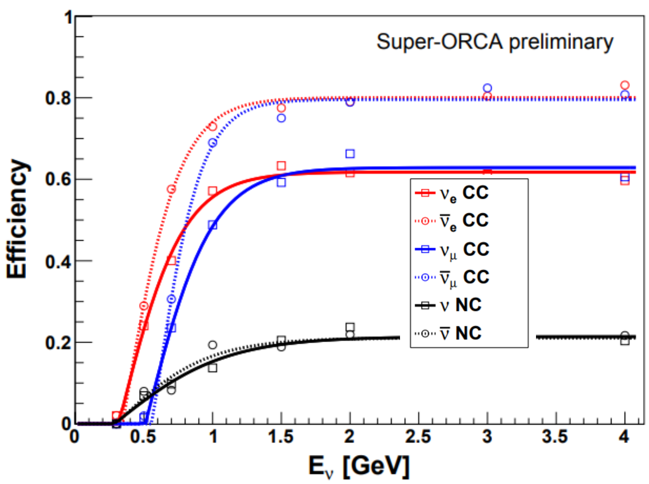


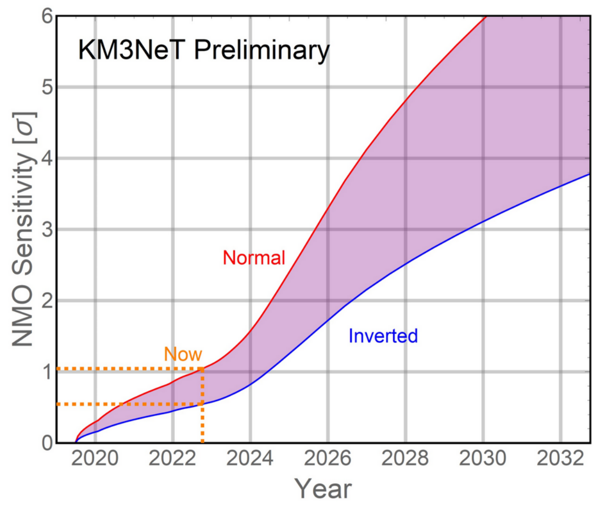
KM3NeT/ORCA for a LBL

- ORCA main purpose is the **Neutrino Mass Ordering** for which an **energy threshold** <5 GeV is needed
- Configuration **ten times more dense** (superORCA) were simulated and allow to have a **threshold <1GeV**
- KM3NeT technology allows to **recover and redeploy line**
- Depending on the baseline, **ORCA lines could be reconfigured ~2030**



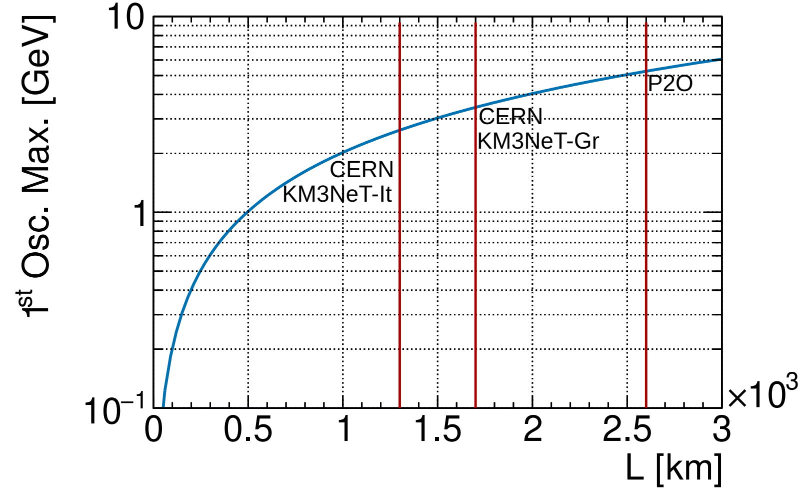






Possible Long Baseline in Europe

- From **U70-Protvino** (Russia) **to KM3NeT-ORCA**
  - P2O, letter of Interest published in 2019
- From **CERN** to **Greek** or **Italian** site of **KM3NeT**
  - Idea already explored in the past
  - CERN, Gran-Sasso and Greek site aligned
  - GNGS transfer line could be re-used
  - ORCA could be redeployed in Greece or Italy



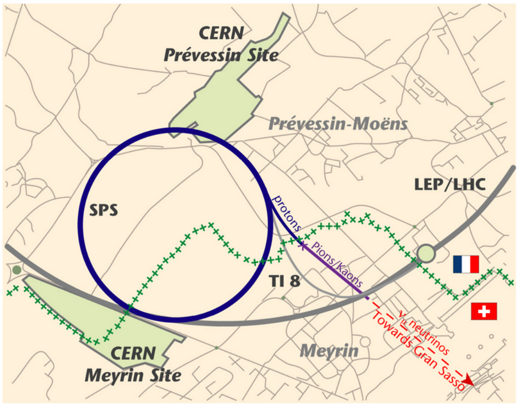
Nuclear Instruments and Methods in Physics Research A 383 (1996) 277–290

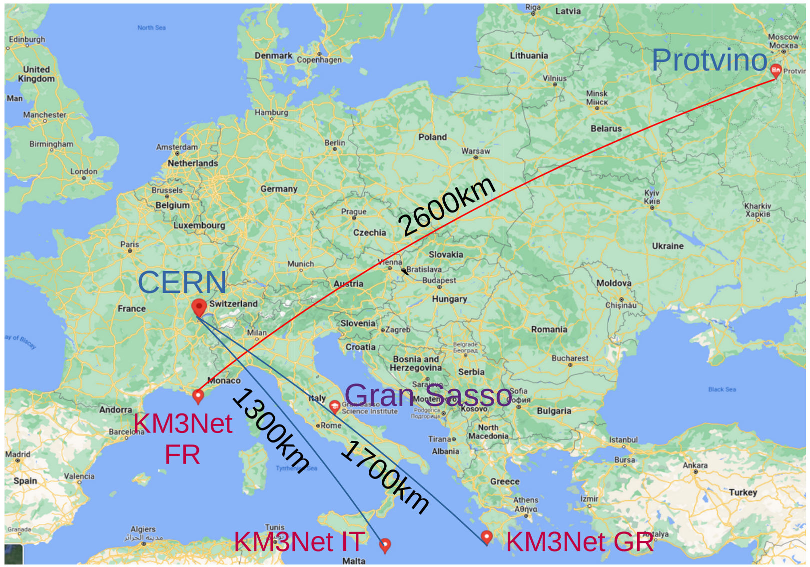
Design studies for a long base-line neutrino beam

A.E. Ball[a,*], S. Katsanevas[b], N. Vassilopoulos[b,1]

Place	λ	ϕ	A_z	α	Distance
CERN	6.0732	46.2442	-	-	-
Gran Sasso	13.5744	42.4525	122.502	3.283	731 km
Nestor	21.3500	36.3500	124.1775	8.526	1676 km

Table 1: Absolute coordinates (λ, ϕ) and azimuth and declination angles (A_z, α) in degrees, of Gran Sasso and Nestor w.r.t CERN



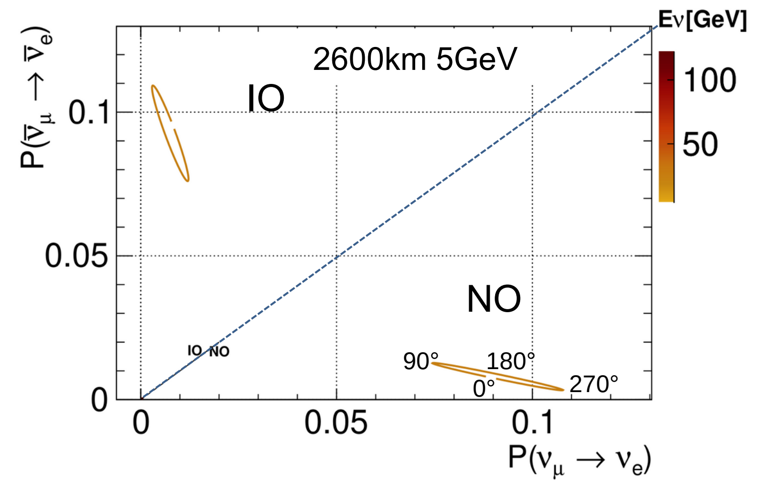


δCP measurements with a tag-LBL

- **TagP2O** used as case study
  - 1st oscillation max at 5GeV
  - Excellent energy resolution
- **Multiple ellipses** can be accessed:
  - some are more **circular**
  - **apsides** not always reached at 90 or 270°

➔ **Better** and **more stable** resolution

- With ORCA:
  14-25 ° precision in 1 year (i.e. DUNE/HK)
  6-8° precision in 10 years
- With a detector twice as dense
  4-5° in 10 years
- **2°** if e/μ identification is perfect (10 years)



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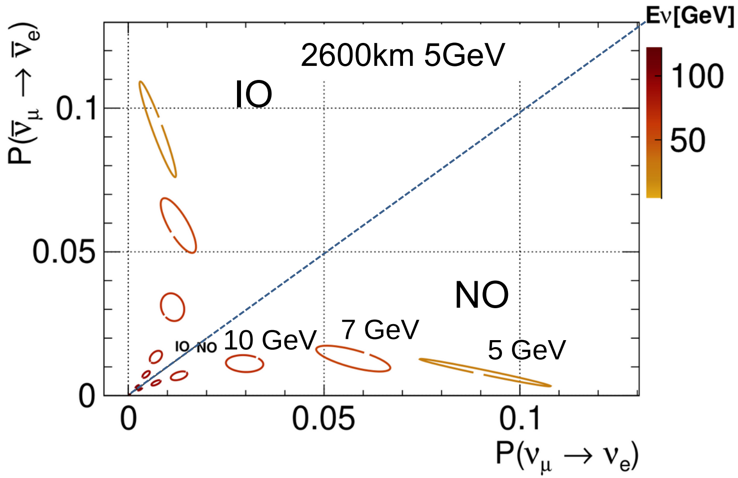

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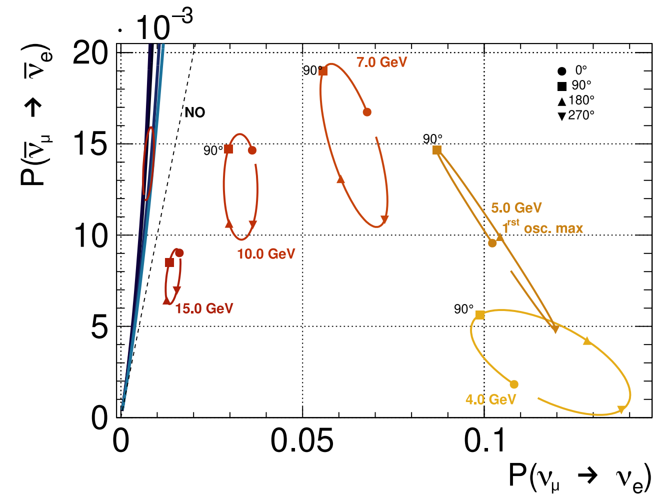
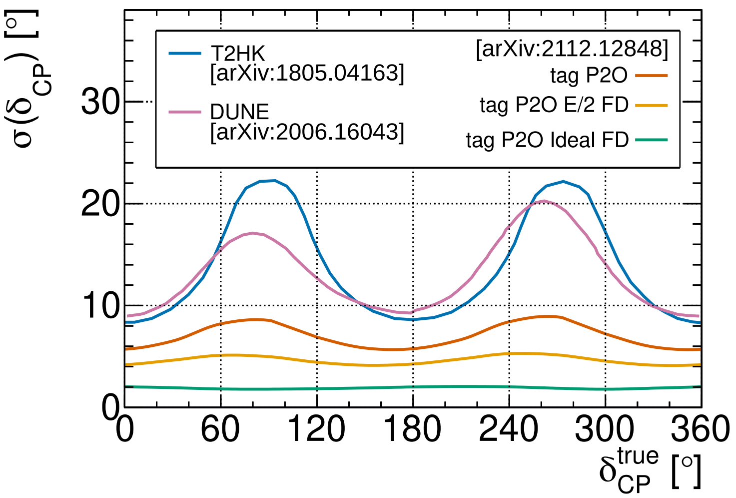
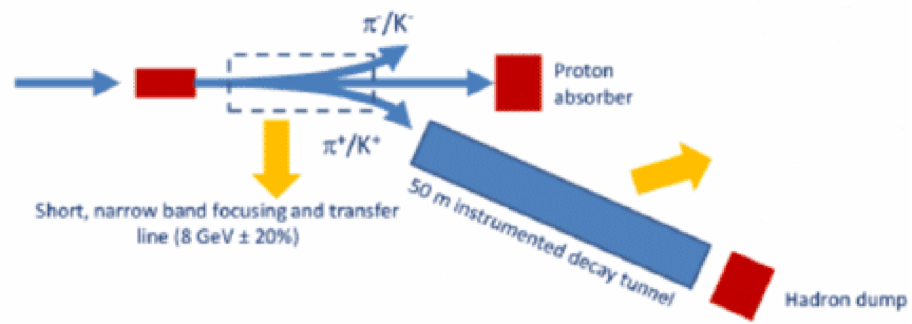




νe cross-section at SBL

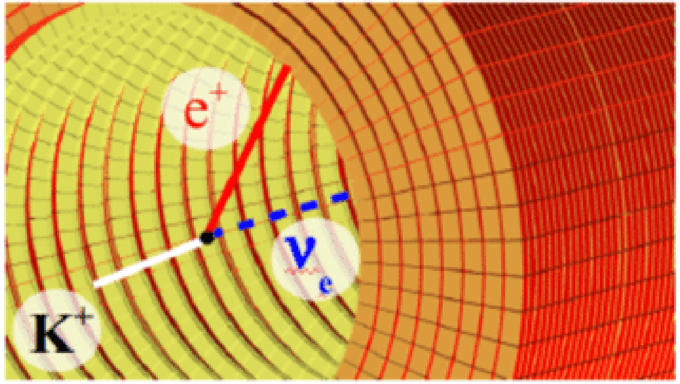
Mode	BR
$K^+\to\mu^+\nu_\mu$	63.56± 0.11
$K^+\to\pi^0 e^+\nu_e$	5.07 ± 0.04
$K^+\to\pi^0\mu^+\nu_\mu$	3.352 ± 0.033
$K^+\to\pi^+\pi^0$	20.67 ± 0.08
$K^+\to\pi^+\pi^+\pi^-$	5.583 ± 0.024
$K^+\to\pi^+\pi^0\pi^0$	1.760 ± 0.023

- The technique proposed by ENUBET
  - slow extraction beam line to collect K (and π) decays
  - count the positrons as **$N(e^+) = N(K^+\to\pi^0 e^+\nu_e) = N(\nu_e)$**
  - ν_e energy spread constrained with a narrow band beam (NBB)
  - 10^{20} POT needed (NBB!) to get the 10^4 ν_e and a 1% precision on x-sec



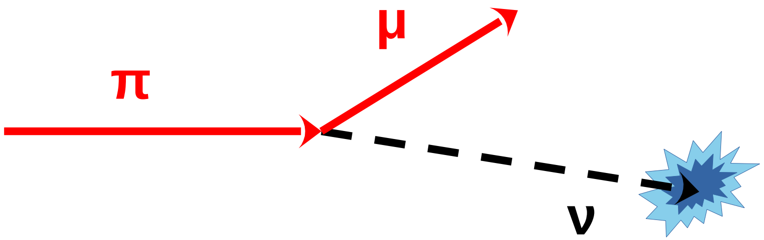
https://www.pd.infn.it/eng/enubet/

protoDUNE
500 tonne
@ 50m

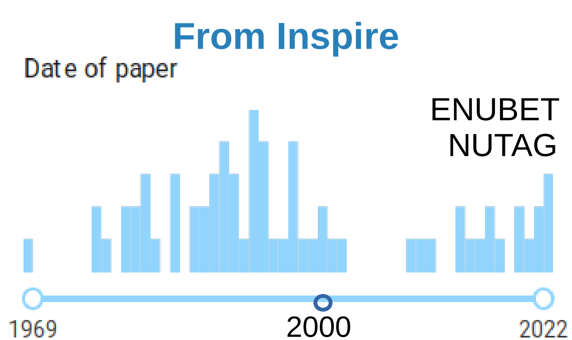


Neutrino Tagging

- 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



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

Tagging Direct Neutrinos. A First Step to Neutrino Tagging.

B. PONTECORVO

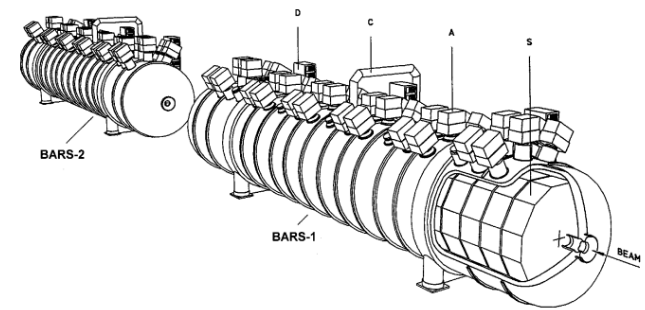
Laboratory of Nuclear Problems, Joint Institute for Nuclear Research - Dubna, USSR

(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

Experimental Demonstration



- Tagged Neutrino Facility (TNF) in Serpukhov
  Stopped in the 90's.
- Instruments to reconstruct the K **decay products**

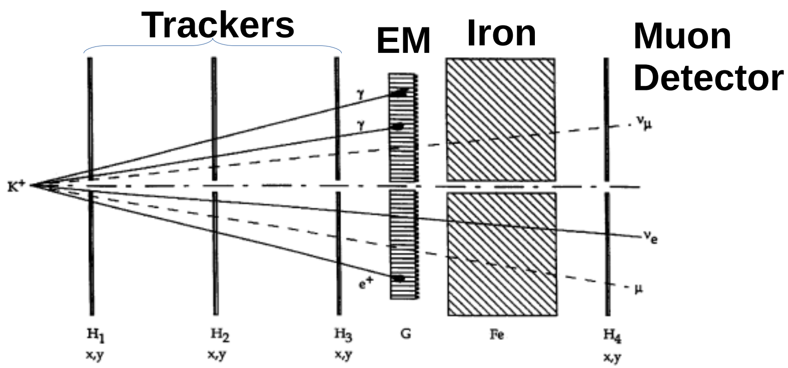
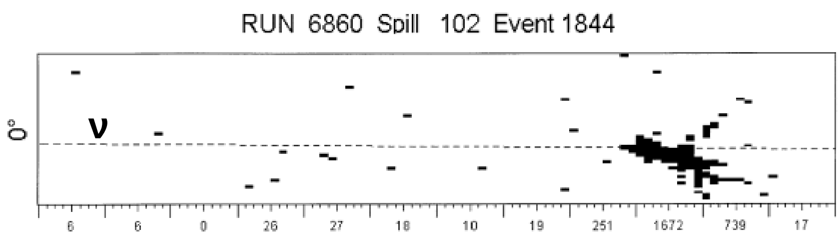


Рис. 2. Станция мечения. H1, H2, H3, H4 — двухкоординатные сцинтилляционные годоскопы (x, y); G — электромагнитный калориметр ГЕПАРД; Fe — 3-метровый железный поглотитель адронов.

http://web.ihep.su/library/pubs/prep1997/ps/97-32.pdf



"The dotted line shows the ν_μ trajectory calculated for a Kμν decay detected in the tagging station."

Fig. 4. 0°-projection of the neutral current tagged ν_μ interaction in the BARS. The dotted line shows the ν_μ trajectory calculated for a $K_{\mu 2}$-decay detected in the tagging station.

https://doi.org/10.1016/S0168-9002(98)00837-7