Project-ANR-19-CE31-0009

# Neutrino Tagging
# (NuTAG)

## — An new approach to accelerator based neutrino experiments —

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Seminar in Marseille

# Outline

- Scientific Landscape
- The concept of Neutrino Tagging
- Experimental Demonstration of the Neutrino Tagging
- Towards a Full Scale Tagged Neutrino Experiment
- Physics Case of Short and Long Base Line Tagged Neutrino Experiments

# Scientific Landscape

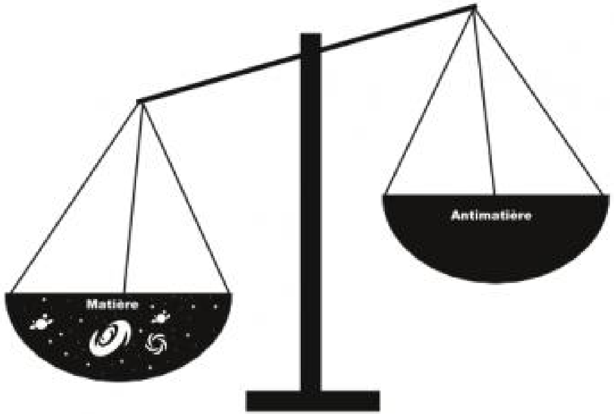
- **Neutrino physics**:
  - one of the **least explored** fields in particle physics
  - many **open questions** (neutrino mass ordering*, PMNS unitarity, **CP violation**)
  - a **portal to dark matter**
- The challenge for the **next decade**: the leptonic CP violation
  - fundamental to understand the **origin of matter** (on of the Sakharov conditions)
  - the main purpose of the next Long Baseline neutrinos experiments (**DUNE** and **T2HK**)

* NMO:

$$m_{\nu_1} < m_{\nu_2} < m_{\nu_3}$$

or

$$m_{\nu_3} < m_{\nu_1} < m_{\nu_2}$$

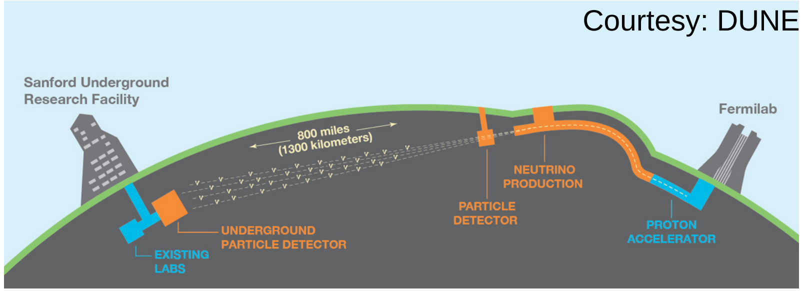


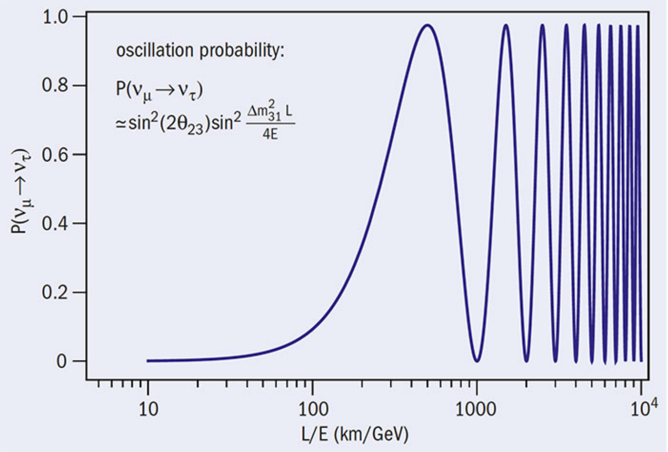
# Neutrino Experiments @ Accelerators

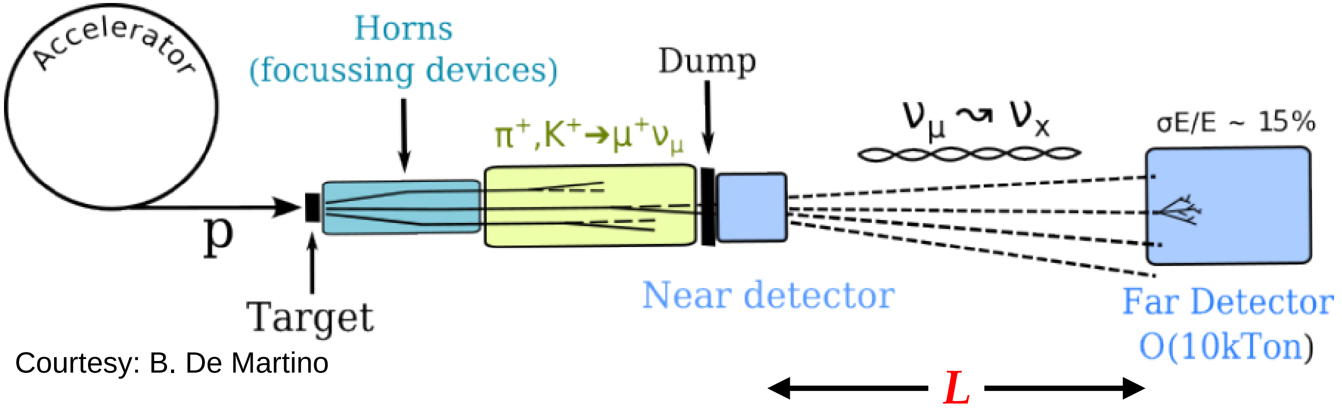
- Neutrinos produced with proton drivers
  - protons sent on **target** to produce **$\pi^+$** that decay as **$\pi^+ \rightarrow \mu^+ \nu_\mu$**
  - ν beam caracterised by a **near detector**
  - ν beam sent, through Earth crust, to **far detector**
  - **oscillations: ν** change flavour when propagating

$$P(\nu_\alpha \rightarrow \nu_\beta) \propto \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \quad \text{with } \Delta m^2 = m_i^2 - m_j^2$$

- Oscillation parameters obtained by **comparing the neutrino rate before and after propagation**


Courtesy: DUNE

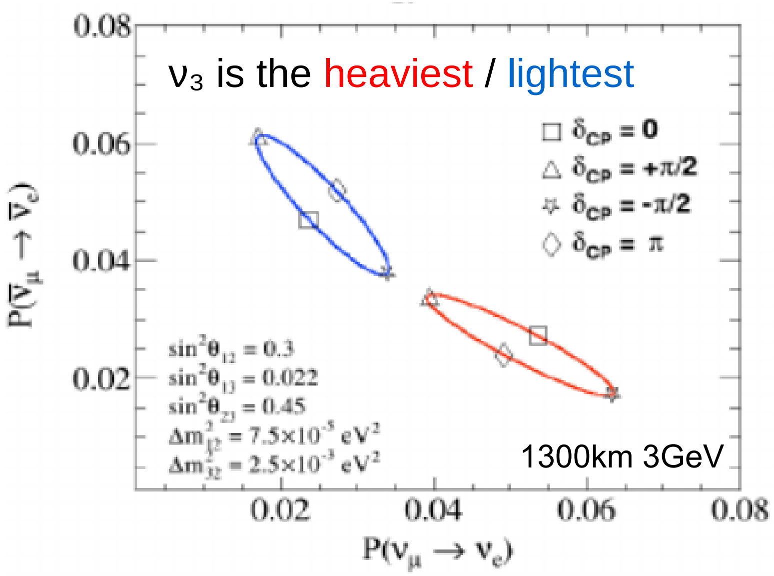
CERN Courrier 07/2016




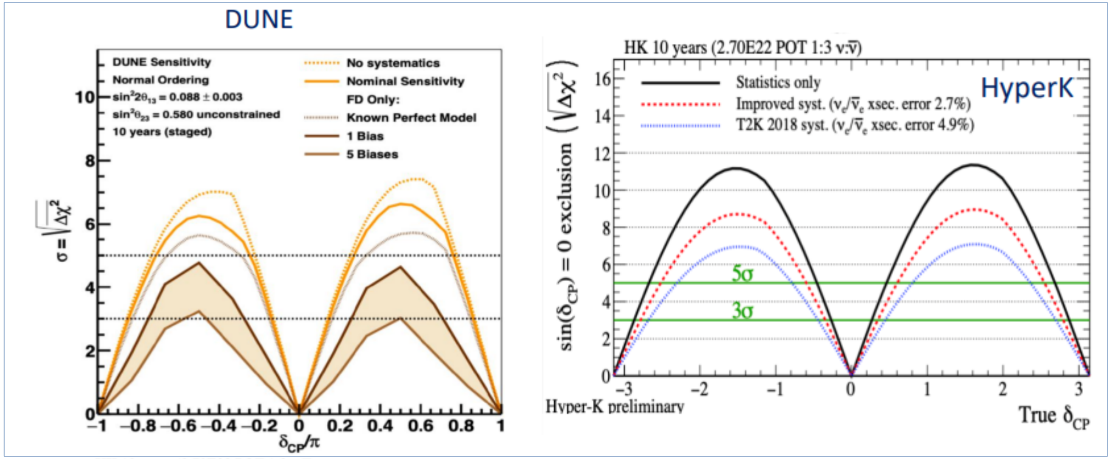
Courtesy: B. De Martino

# CP violation experimental studies

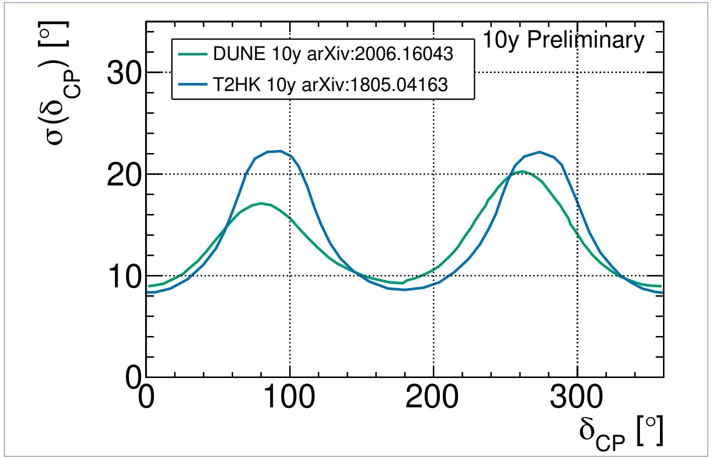
- ν and anti-ν can oscillate differently because of a parameter called: leptonic CP violating phase **$\delta_{CP}$**
  - Ranges for 0 to 360°
  - CP conserved if $\delta_{CP}$ = 0° or 180°
  - CP maximally violated at 90° and 270°
- Measurement principle:
  compare $P(\nu_\mu \rightarrow \nu_e)$ and P(**anti**-$\nu_\mu$➔**anti**-$\nu_e$)
- Expected status **at the end of DUNE & T2HK**



Discovery Potential

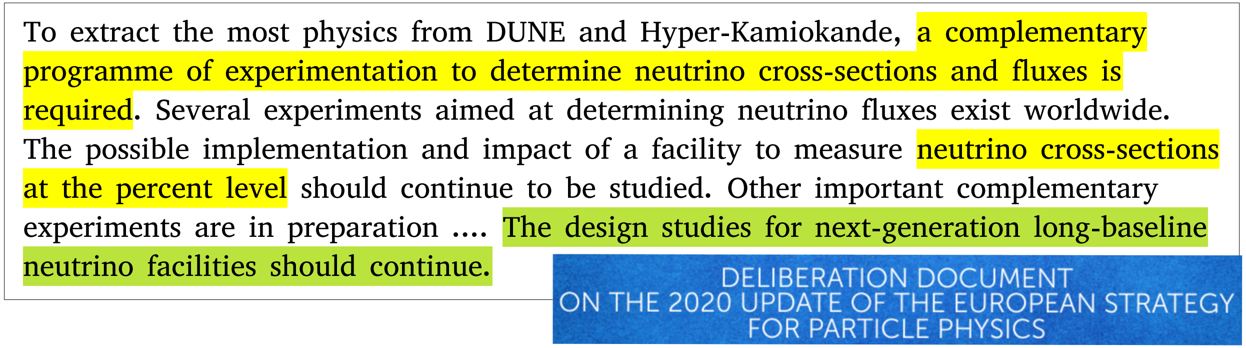


Measurement Precision



# DUNE and T2HK limitations

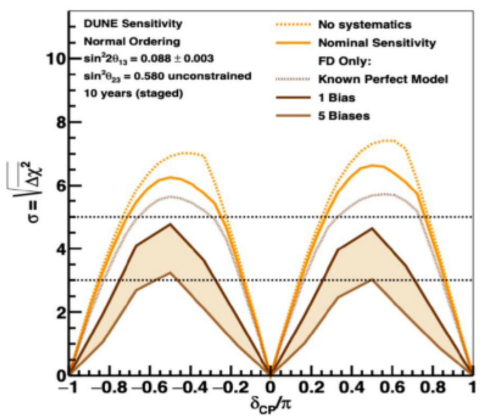
- Strong impact of the **systematic uncertainties** on
  - neutrino **cross section**
  - neutrino **flux**
  - **detector response** (e.g. energy scale)
- **Statistics** is also limited:
  ~250 $\nu_e$/year and 150 anti-$\nu_e$/year
- Two recommendations from **European Strategy for Particle Physics**:

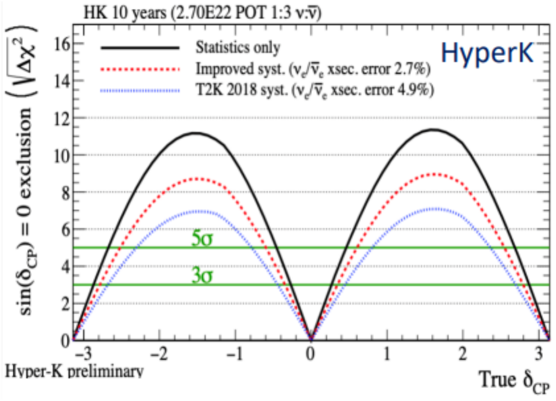


To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied. Other important complementary experiments are in preparation …. The design studies for next-generation long-baseline neutrino facilities should continue.

DELIBERATION DOCUMENT
ON THE 2020 UPDATE OF THE EUROPEAN STRATEGY
FOR PARTICLE PHYSICS

DUNE





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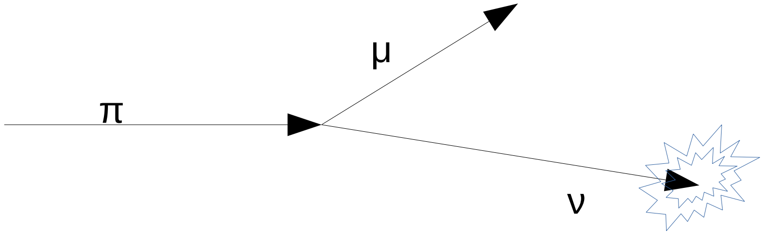
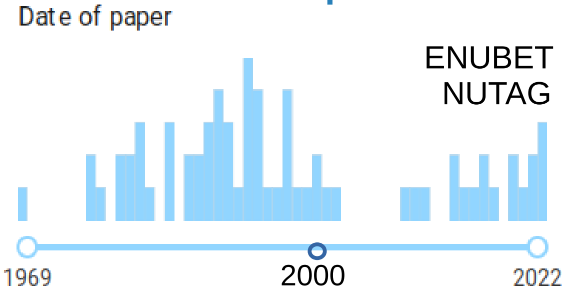
# Neutrino Tagging

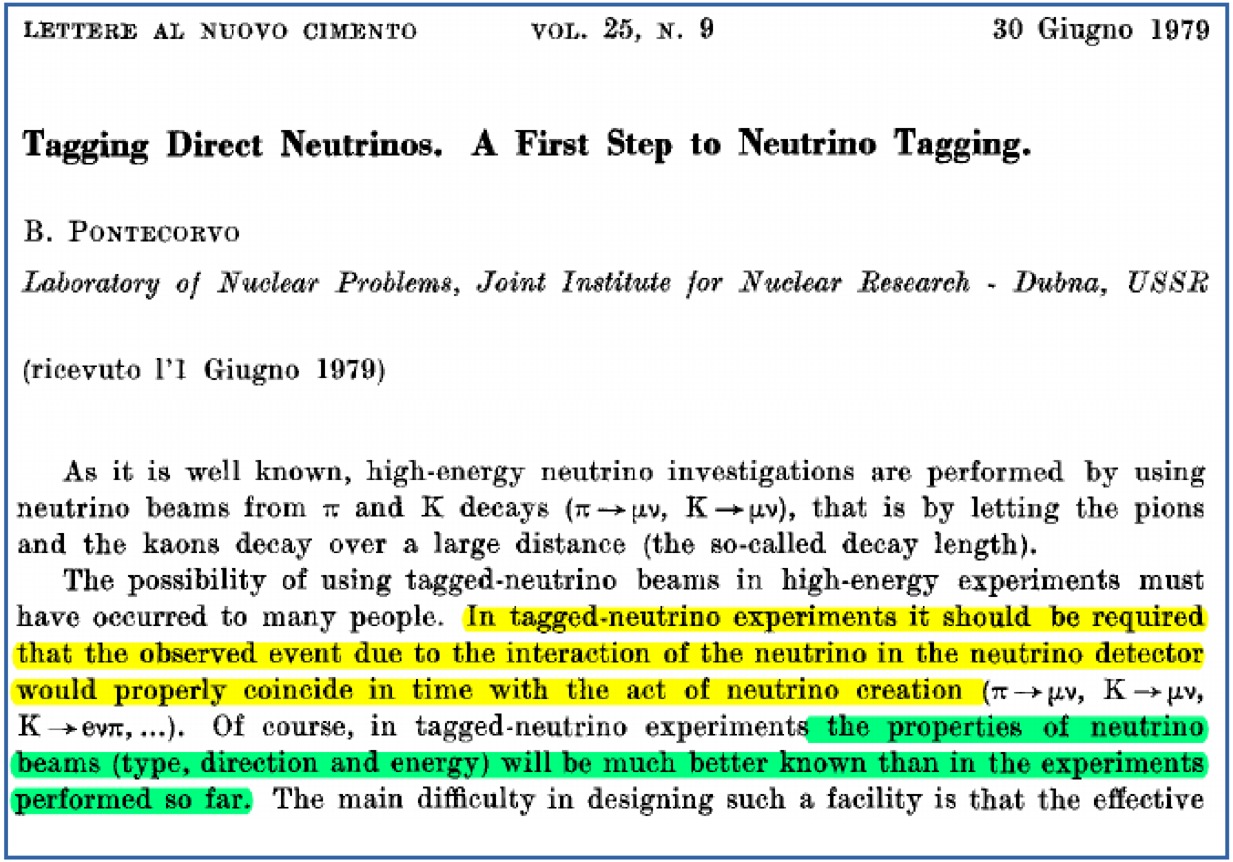
- Concept introduced in the 70-80’s
- Associate **individually** each neutrino interaction with its production mechanism



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

From Inspire





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

**Tagging Direct Neutrinos. A First Step to Neutrino Tagging.**

B. Pontecorvo

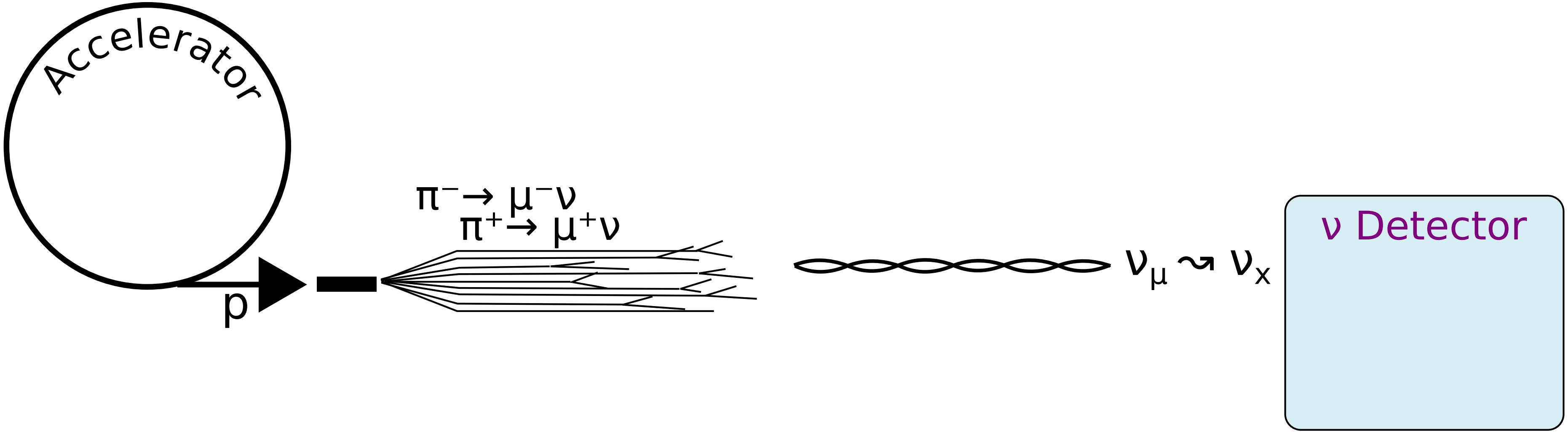
*Laboratory of Nuclear Problems, Joint Institute for Nuclear Research - Dubna, USSR*

(ricevuto l’1 Giugno 1979)

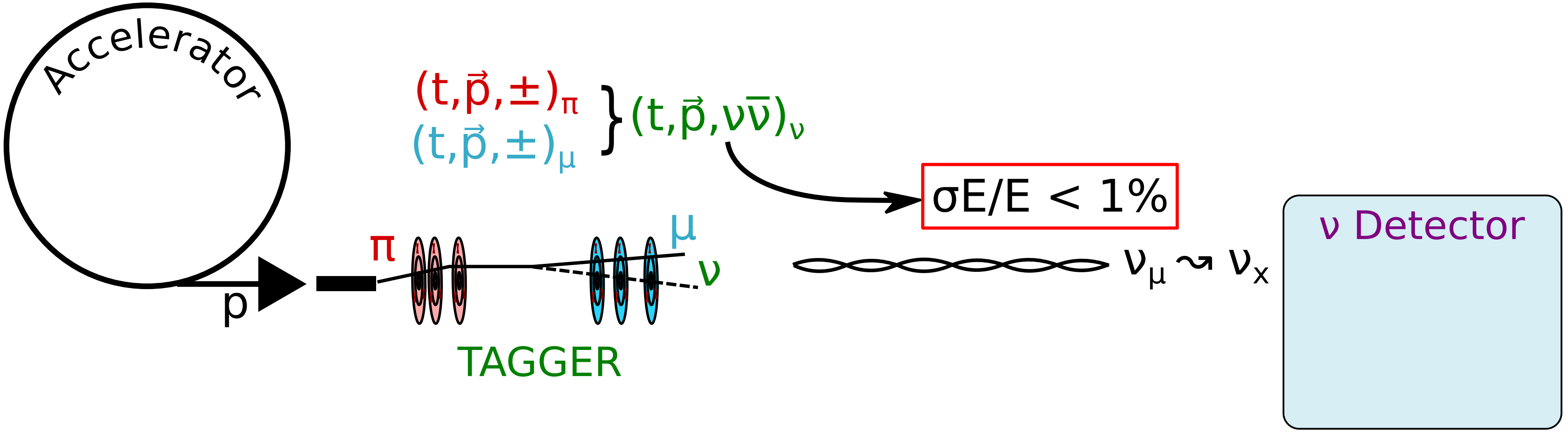
As it is well known, high-energy neutrino investigations are performed by using neutrino beams from $\pi$ and K decays ($\pi \to \mu\nu$, $K \to \mu\nu$), that is by letting the pions and the kaons decay over a large distance (the so-called decay length).

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

# Neutrino Tagging

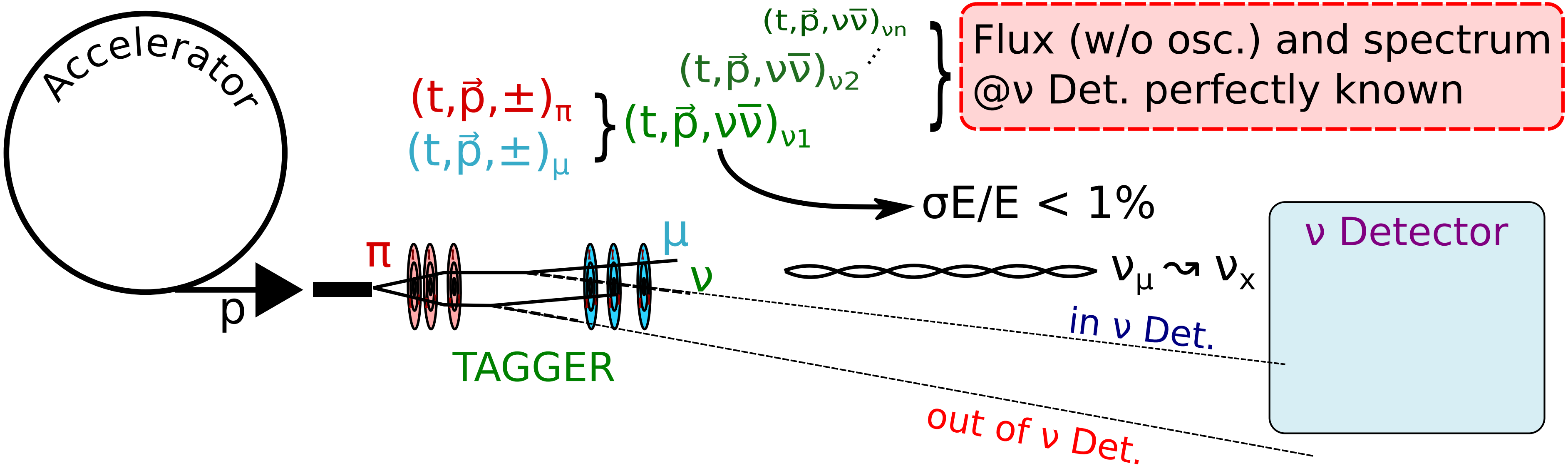


# ν tagging – Beam Instrumentation



- Each neutrino is fully & precisely **characterised from its decay partners (π,μ)**

# ν tagging – 1. Flux Determination



Accelerator

p

π

μ

ν

TAGGER

$(t,\vec{p},\pm)_\pi$

$(t,\vec{p},\pm)_\mu$

$\Big\}(t,\vec{p},\nu\bar{\nu})_{\nu 1}$

$(t,\vec{p},\nu\bar{\nu})_{\nu 2}$

$\cdots$

$(t,\vec{p},\nu\bar{\nu})_{\nu n}$

Flux (w/o osc.) and spectrum
@ν Det. perfectly known

σE/E < 1%

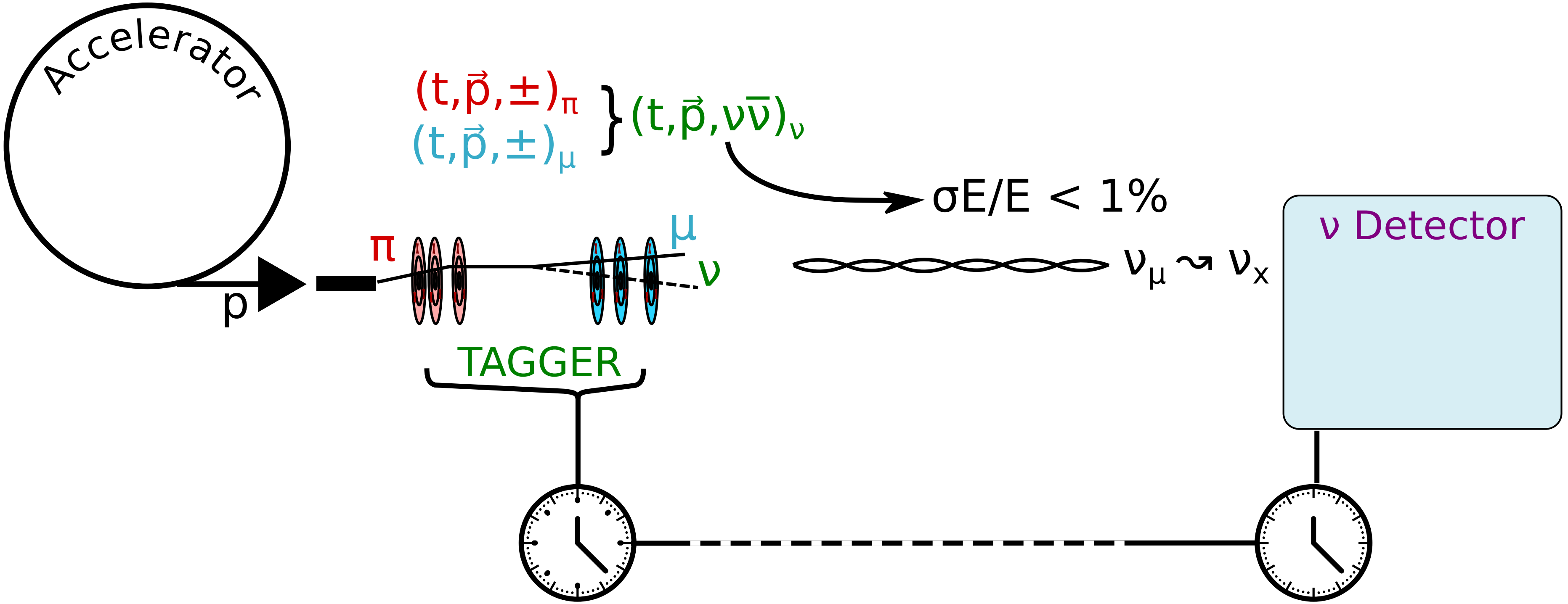
$\nu_\mu \rightsquigarrow \nu_x$

ν Detector

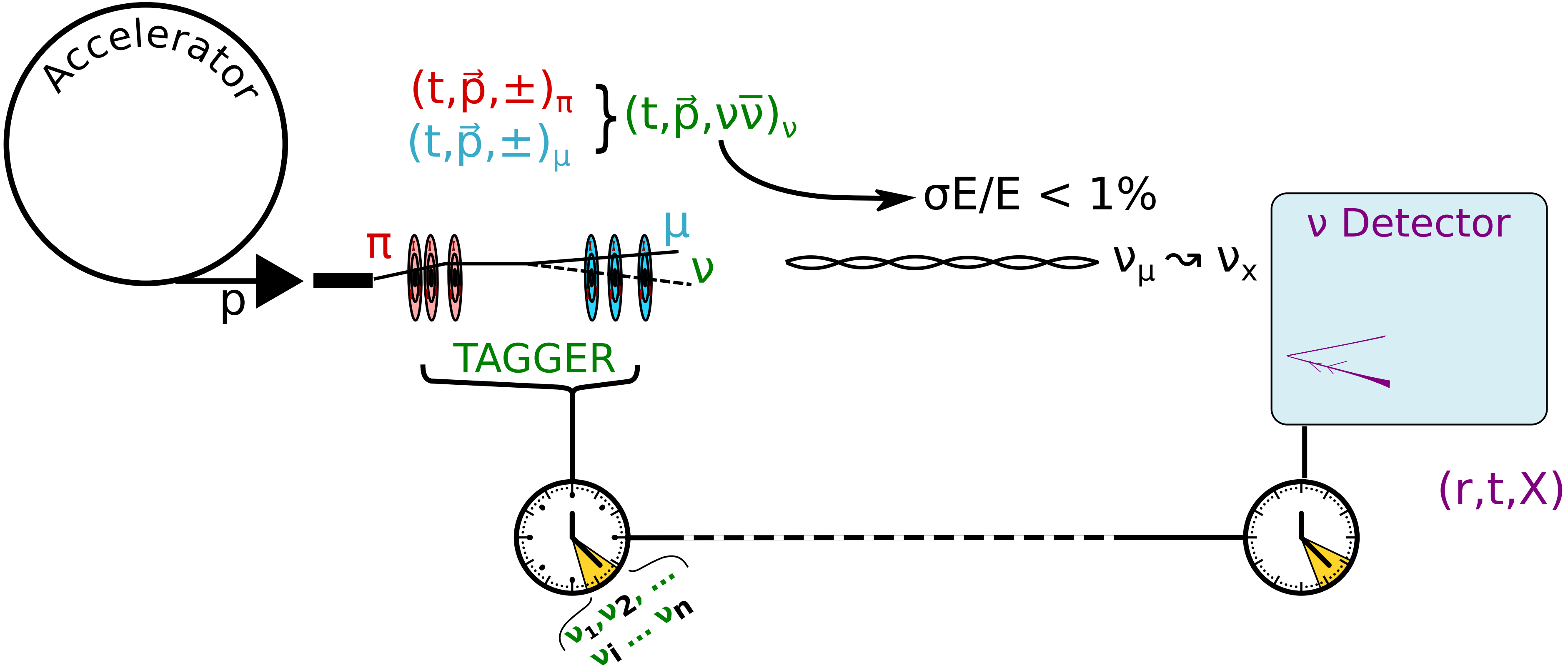
in ν Det.

out of ν Det.

# ν tagging – 2. Reco. Improvement



# ν tagging – 2. Reco. Improvement



Accelerator

p

π

μ

ν

$\left.\begin{array}{l}(t,\vec{p},\pm)_\pi \\ (t,\vec{p},\pm)_\mu\end{array}\right\}(t,\vec{p},\nu\bar{\nu})_\nu$

$\sigma E/E < 1\%$

$\nu_\mu \rightsquigarrow \nu_x$

ν Detector

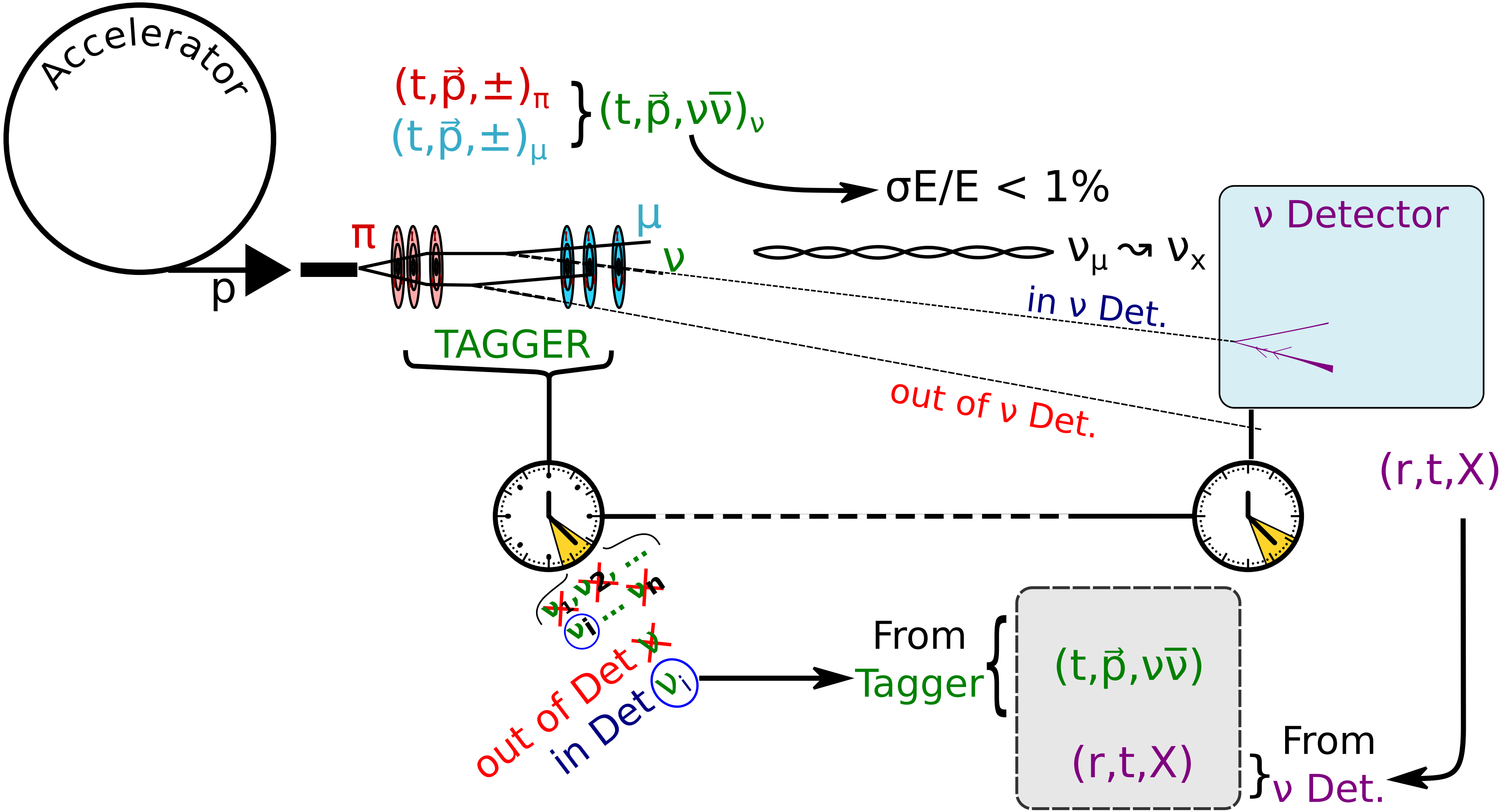
TAGGER

(r,t,X)

$\nu_1, \nu_2, \ldots$

$\nu_i \ldots \nu_n$

# ν tagging – 2. Reco. Improvement



Accelerator

p

π

μ

ν

$(t,\vec{p},\pm)_\pi$

$(t,\vec{p},\pm)_\mu$

$\}(t,\vec{p},\nu\bar{\nu})_\nu$

σE/E < 1%

ν Detector

$\nu_\mu \rightsquigarrow \nu_x$

in ν Det.

out of ν Det.

TAGGER

(r,t,X)

$\cancel{\nu_1}, \cancel{\nu_2}, \ldots \boxed{\nu_i} \ldots \cancel{\nu_n}$

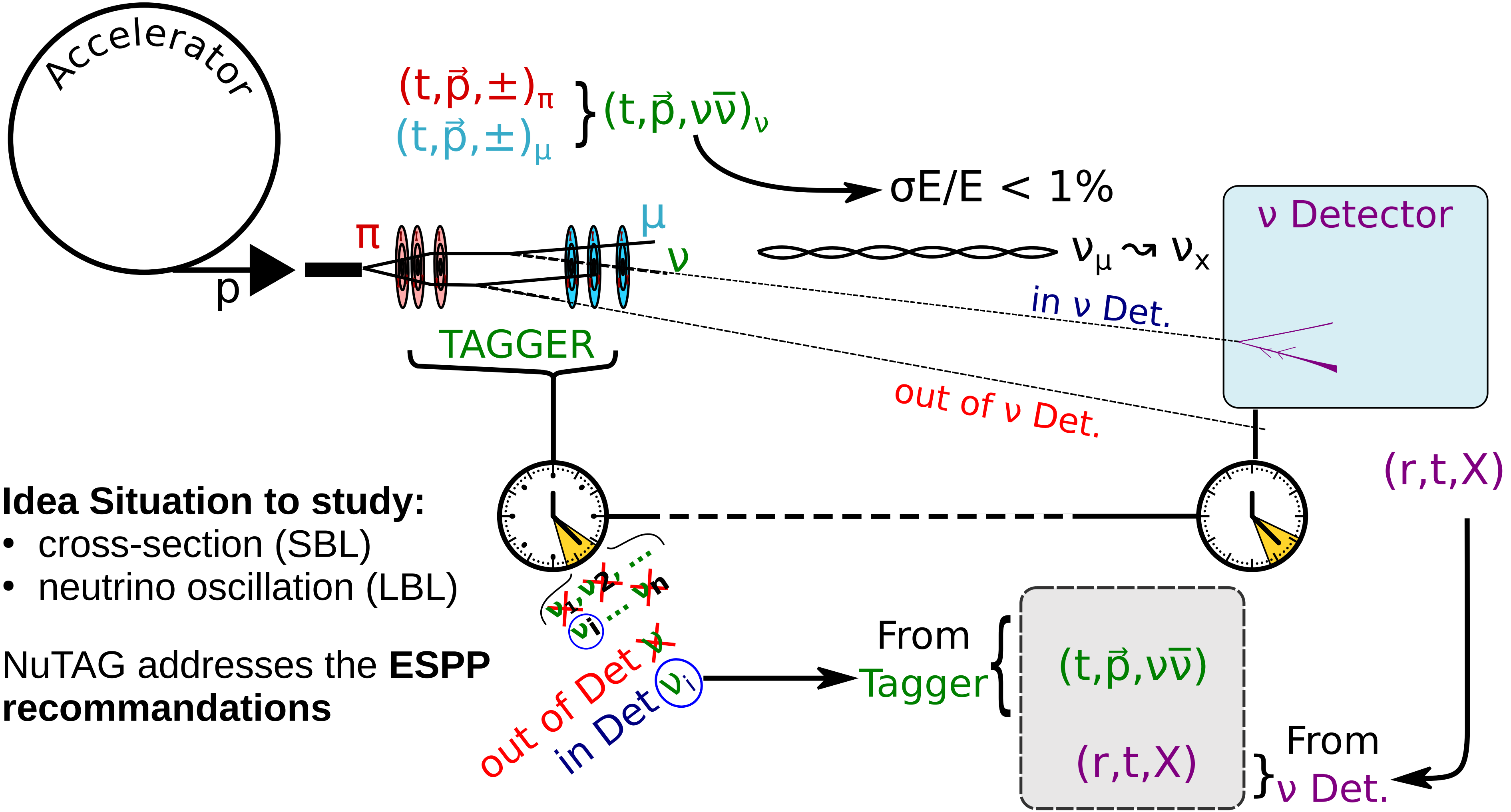
out of Det $\cancel{\nu}$

in Det $\nu_i$

From Tagger $\{$ $(t,\vec{p},\nu\bar{\nu})$

$(r,t,X)$ $\}$ From ν Det.

# ν tagging – 2. Reco. Improvement



**Idea Situation to study:**

- cross-section (SBL)
- neutrino oscillation (LBL)

NuTAG addresses the **ESPP recommandations**

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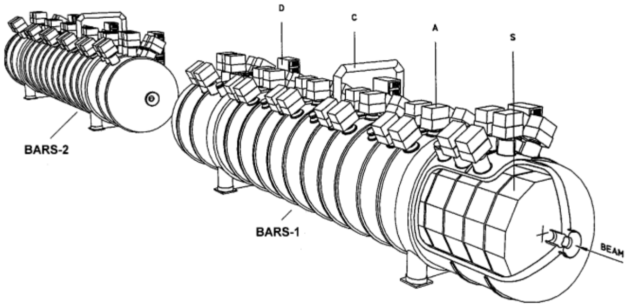
# Experimental Demonstration



- Implementation attempted at Protvino with Tagged Neutrino Facility (TNF) using the BARS
- Stopped in the 90’s

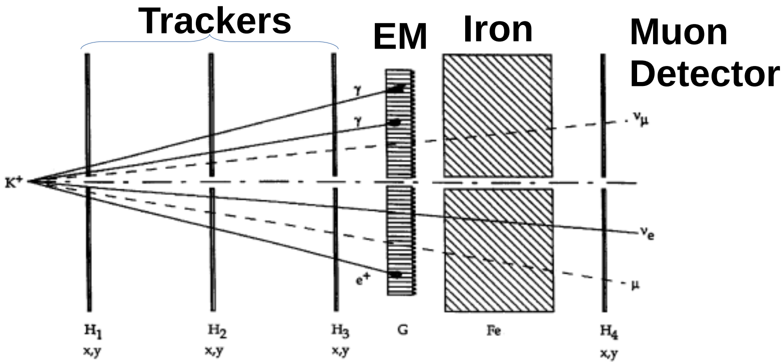
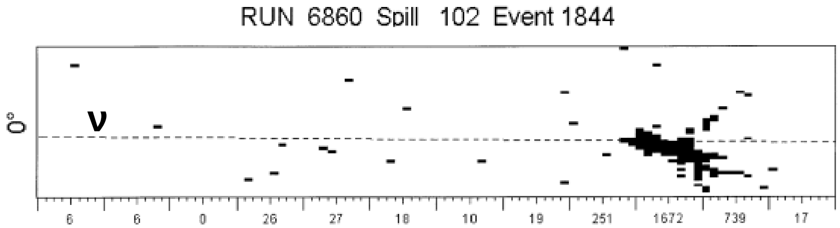


Рис. 2. Станция мечения. H1, H2, H3, H4 — двухкоординатные сцинтилляционные годоскопы (x, y); G — электромагнитный калориметр ГЕПАРД; Fe — 3-метровый железный поглотитель адронов.

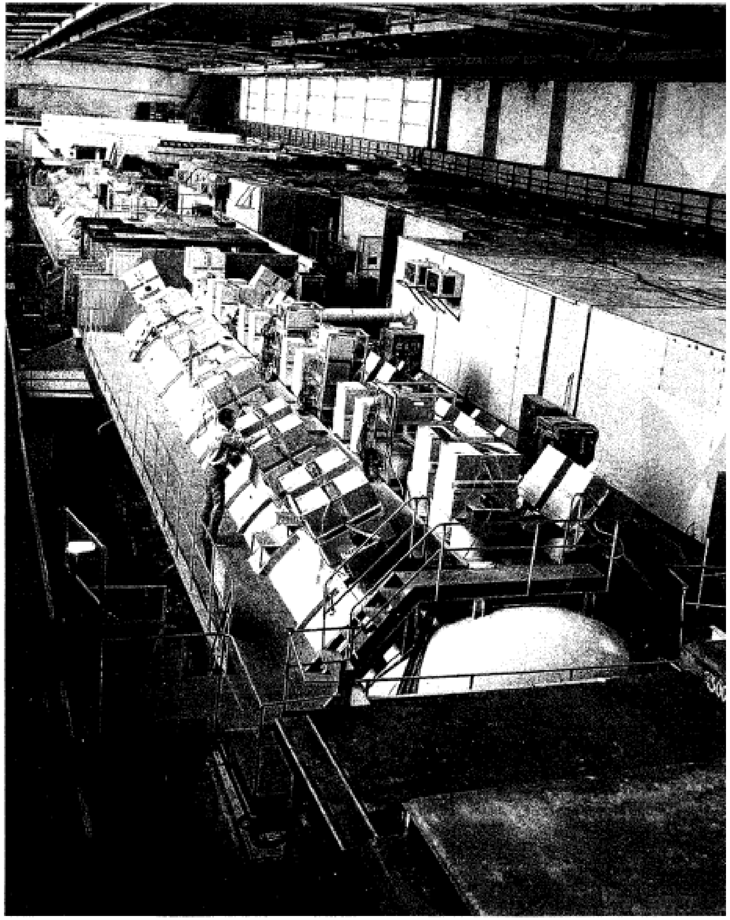
**http://web.ihep.su/library/pubs/prep1997/ps/97-32.pdf**



*“The dotted line shows the $\nu_e$ trajectory calculated for a Kμν decay detected in the tagging station.”*

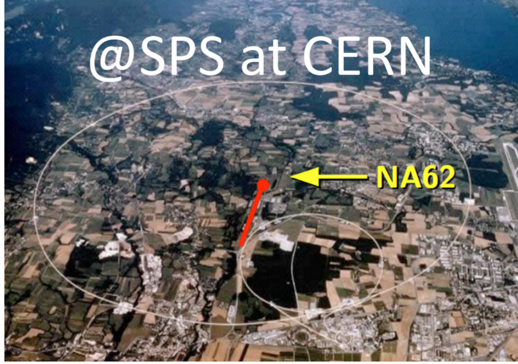
Fig. 4. 0°-projection of the neutral current tagged $\nu_\mu$ interaction in the BARS. The dotted line shows the $\nu_\mu$ trajectory calculated for a $K_{\mu2}$-decay detected in the tagging station.

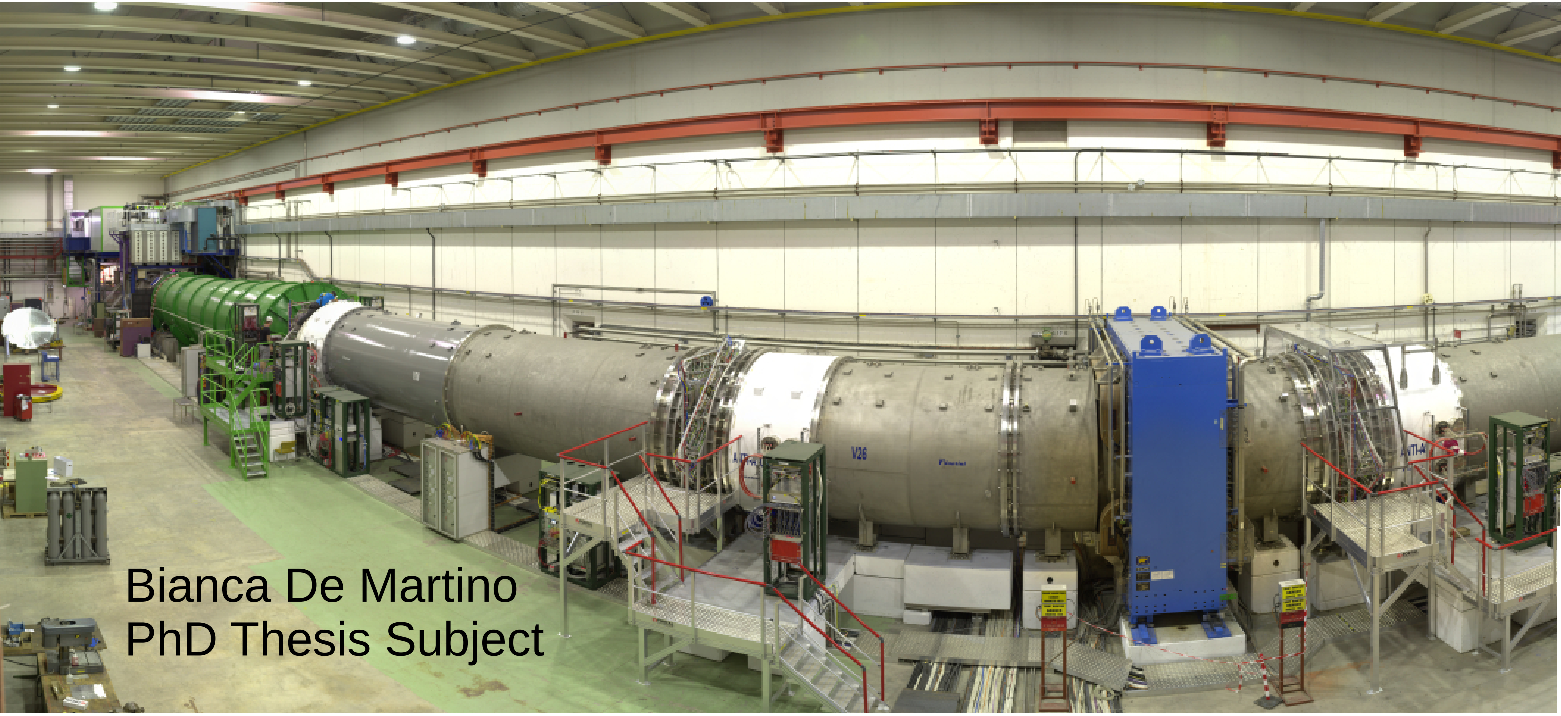
**https://doi.org/10.1016/S0168-9002(98)00837-7**



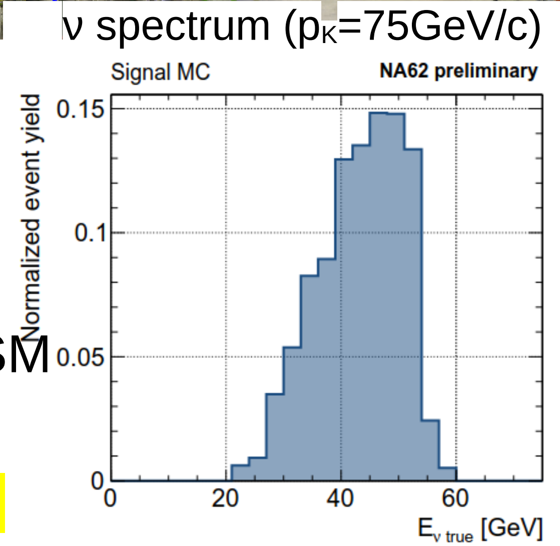
JINST, 2017, 12, P05025

# Proof of Principle with NA62





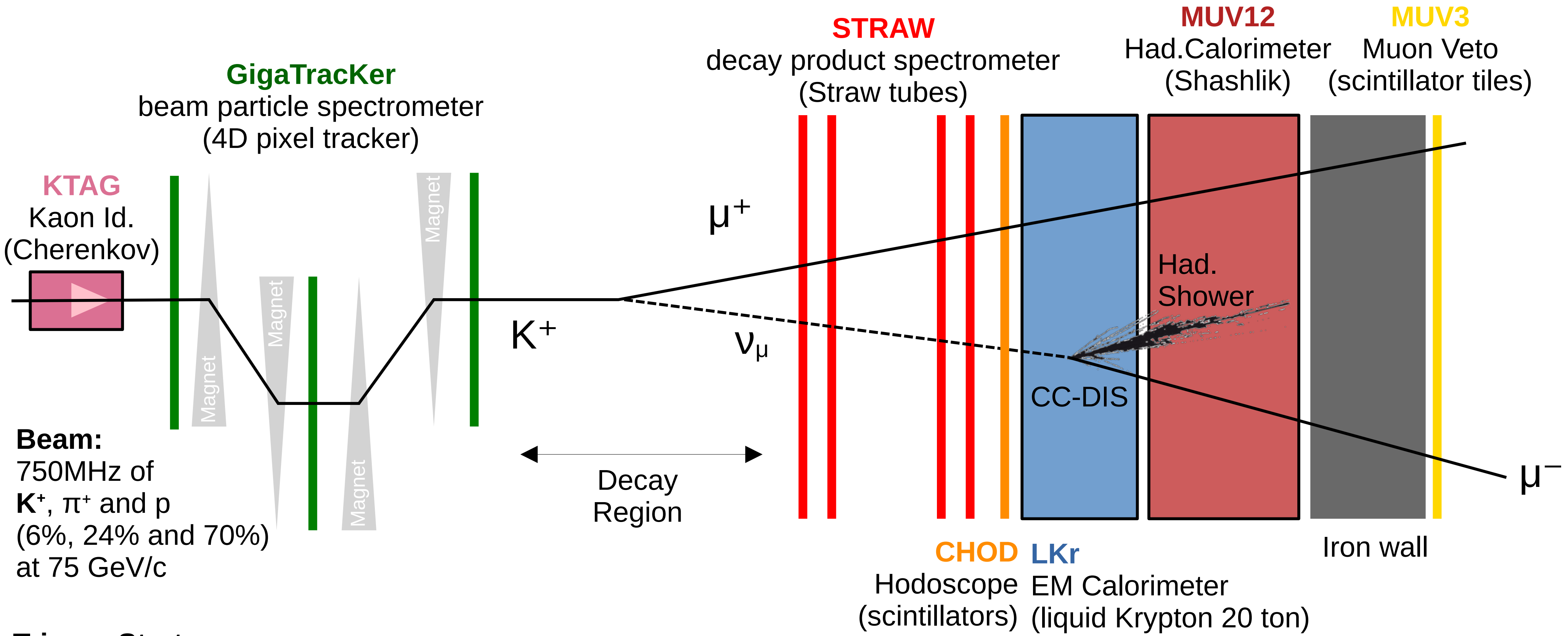
Bianca De Martino
PhD Thesis Subject



$\nu$ spectrum ($p_K$=75GeV/c)

- **Fixed target Kaon** experiment at CERN/SPS (2015 ➔2025)
- Goal: branching ratio of the rare $K^+ \rightarrow \pi^+ \nu\nu$: $(8.4 \pm 1.0) \cdot 10^{-11}$ in SM
- ~$10^{12}$ K decays per year, **mostly $K^+ \rightarrow \mu^+ \nu$.**
- All instrumentation to **detect the $K^+$, the $\mu^+$ 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:**

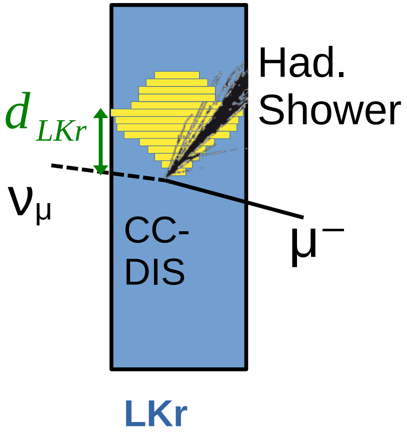
- One charged particle in **CHOD**
- Energy deposit in **LKr**
- Two charged particles in opposite quadrant of **MUV3**

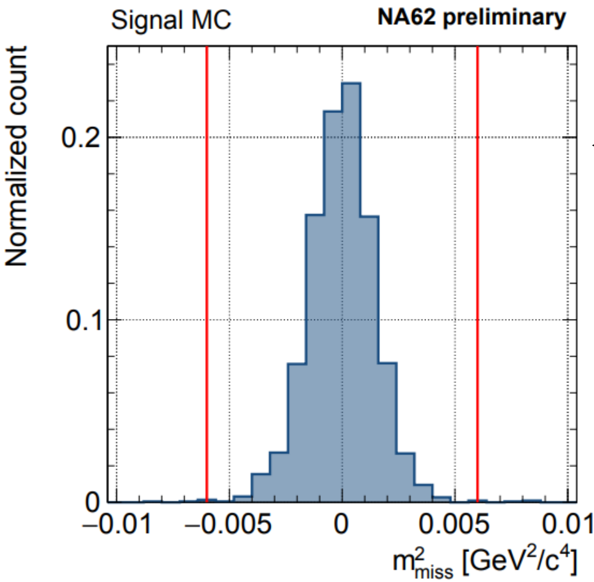
# Data Analysis Strategy

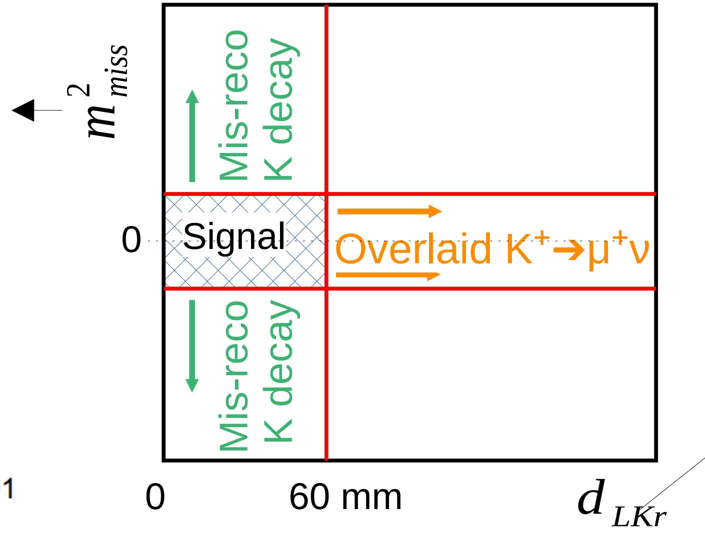
- **Data Sample:** $5 \cdot 10^{12}$ effective $K^+$ decay collected in 2022
- **Blind Analysis**, with a signal region defined as

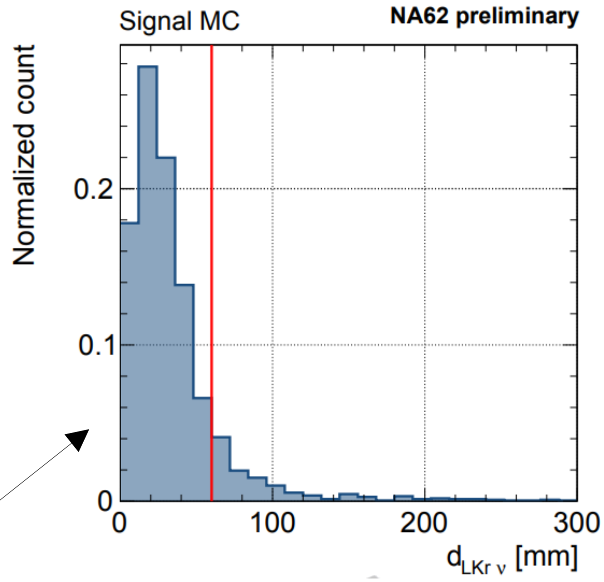
$$|m^2_{miss}| = |(p_K - p_\pi)^2| < 0.6\,\mathrm{GeV}^2/c^4 \qquad |d_{LKr}| < 60\ \mathrm{mm}$$

- Two **background sources**
  - Overlaid $K^+ \rightarrow \mu^+ \nu$: $K^+ \rightarrow \mu^+ \nu$ with extra activity in LKr
  - Mis-reconstrcted K decay









# Signal and Background Expectations

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

$$N^{\mathrm{exp}}_{\text{mis-reco-K}} = \mathbf{0.0014} \pm 0.0007_{\mathrm{stat}} \pm 0.0002_{\mathrm{syst}}$$

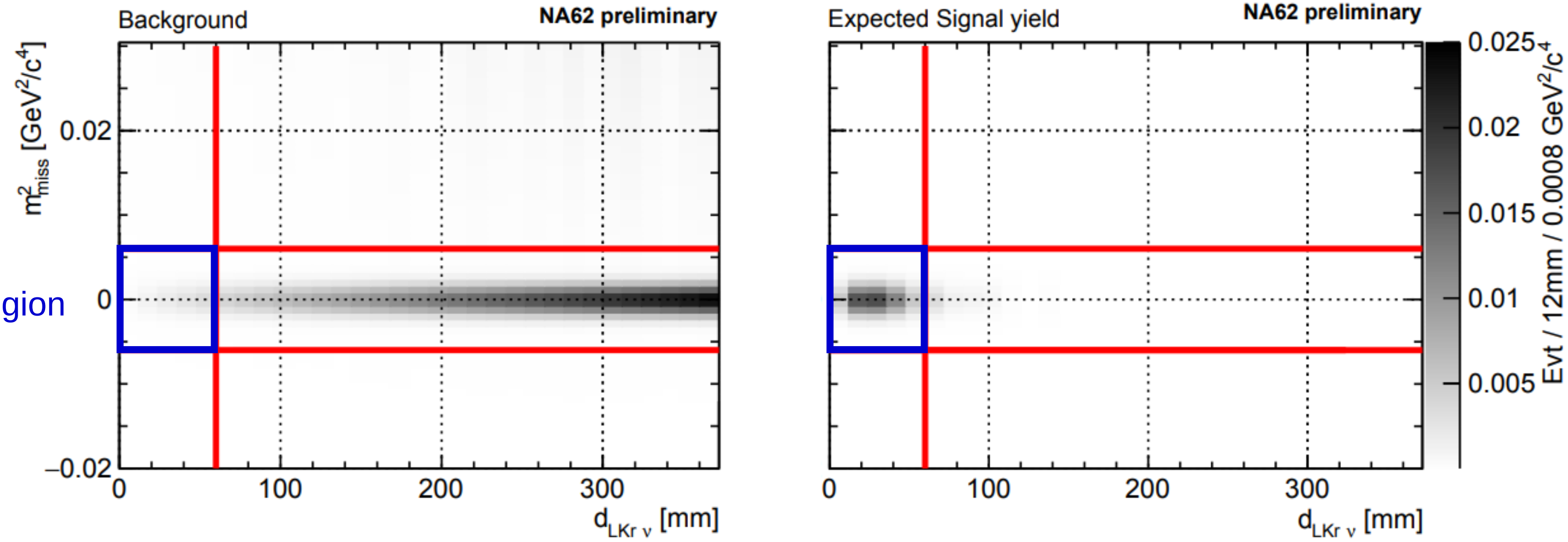
$$N^{\mathrm{exp}}_{\text{overlaid-K}\mu 2} = \mathbf{0.04} \pm 0.02_{\mathrm{stat}} \pm 0.01_{\mathrm{syst}}$$

- **Signal** expect yield (normalized to K⁺→μ⁺ν)

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

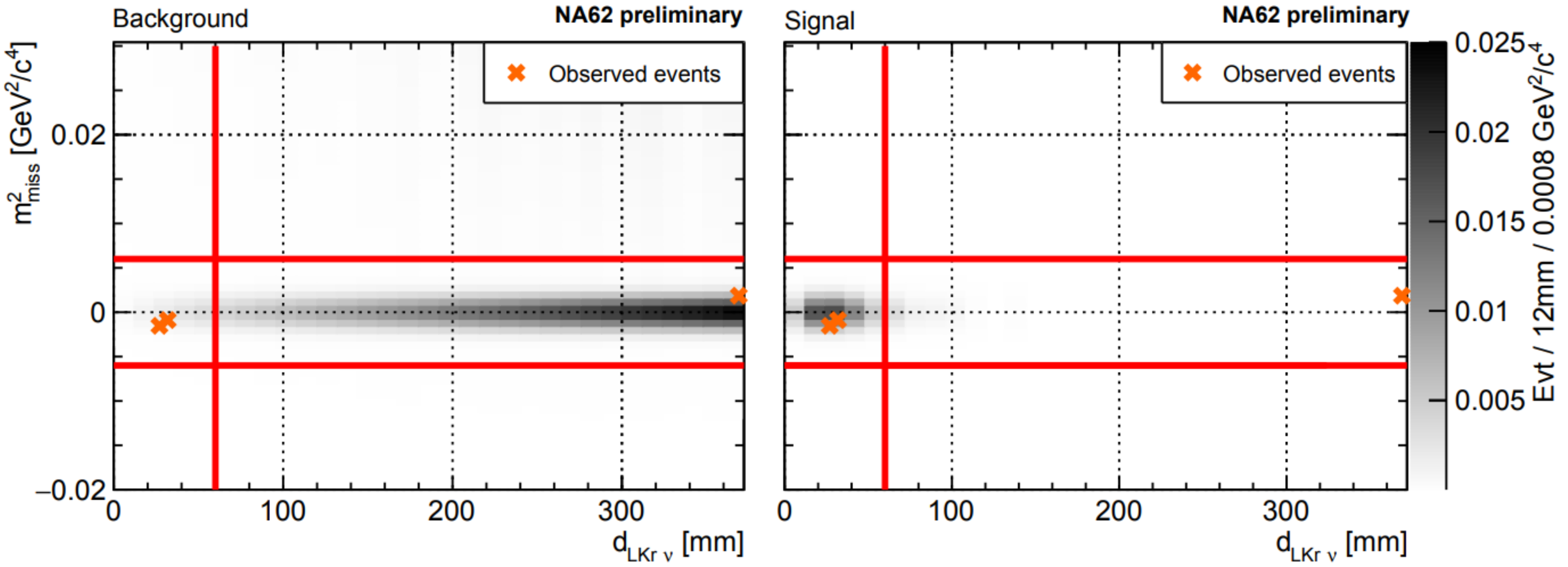
$$= \mathbf{0.228} \pm 0.014_{\mathrm{stat}} \pm 0.011_{\mathrm{syst}}$$

Sig / Bkg = 5.5



Signal Region

# Signal Region Content



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

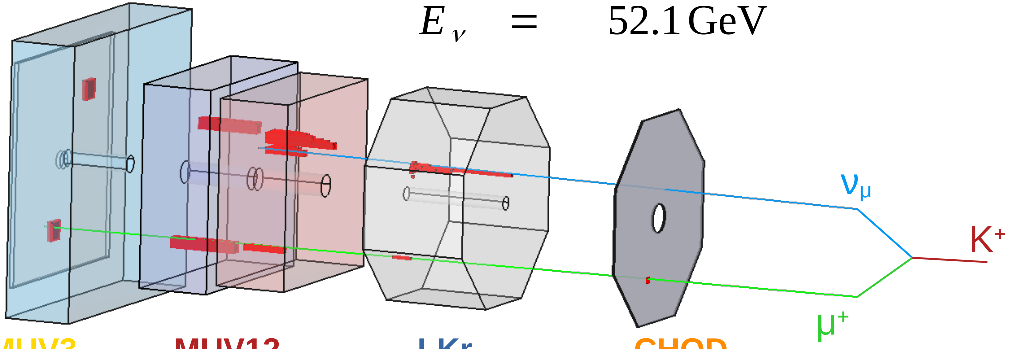
- First background event far from the signal region

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

# Event Displays

**Event A**

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



**MUV3**
μ veto

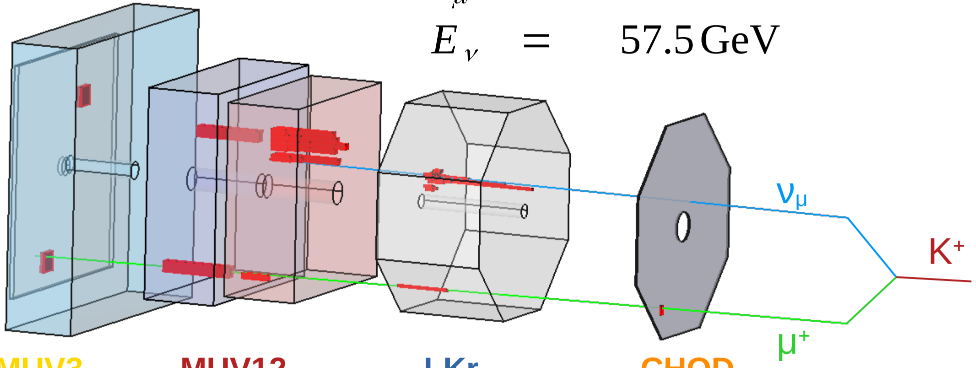
**MUV12**
Had.Calorimeter

**LKr**
EM Calo.

**CHOD**
Hodoscope

**Event B**

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



**MUV3**
μ veto

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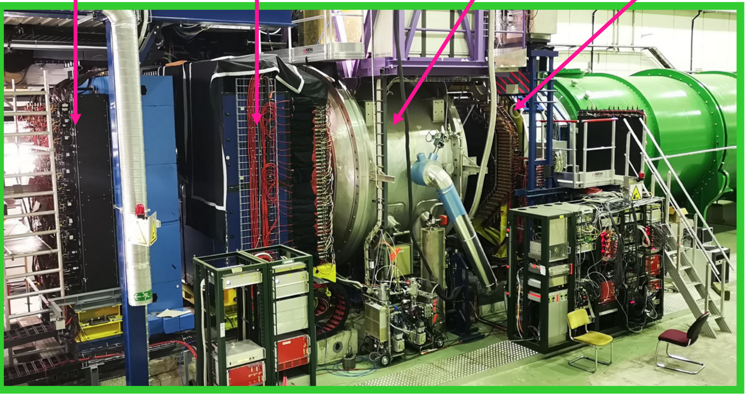
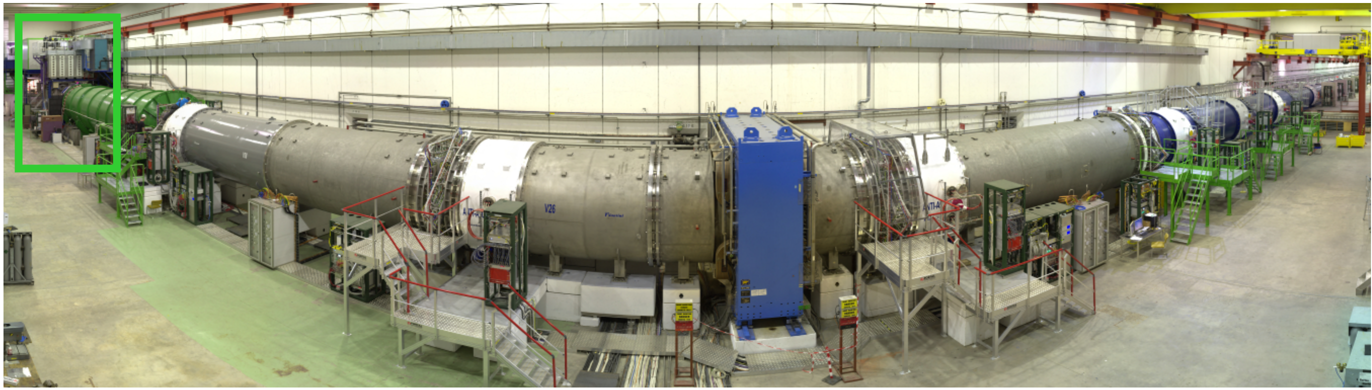
Hodoscope





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  - Beam particle rate
  - Beam line
  - Tracking technology
- Physics Case of Short and Long Base Line Tagged Neutrino Experiments

# Towards full scale ν-tagged experiments

- The main challenge is the **high particle rate** in the neutrino beam line ($>10^{18}$part/s)
- Rate is limited by **trackers irradiation and occupancy**

| | **Available** | **Max. Radiation** | **Max. Flux** |
|---|---|---|---|
| **NA62-GTK** | since 2015 | $10^{14}$ $n_{eq}/cm^2$ | 2 MHz/mm² |
| **HL-LHC** | before 2028 | $10^{16-17}$ $n_{eq}/cm^2$ | 10-100 MHz/mm² |

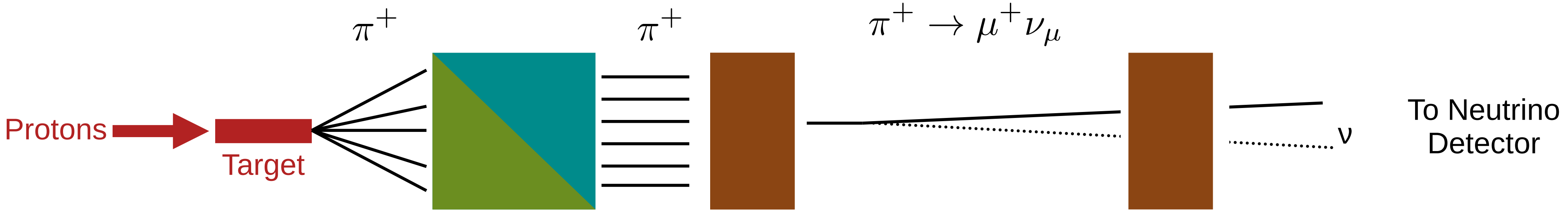
**Sets the specifications for the beam line**

arXiv:1904.12837

- Handles to **limit particle flux**:
  - spread particles in **time:** use slow extraction (few sec) instead of fast extraction (μs)
  - spread particles in **space:** use large beam transverse size
  - select only relevant π **momentum range**

# Tagged beam line conceptual design

- **Slow extraction (few sec.)**
- **Beam cleaning** (to reduce π rate) + **Static Pion Focusing Devices** (see next)
- **Beam size** around **0.1 m²**
- **Spectrometers** (one for the pion, one for the muon)



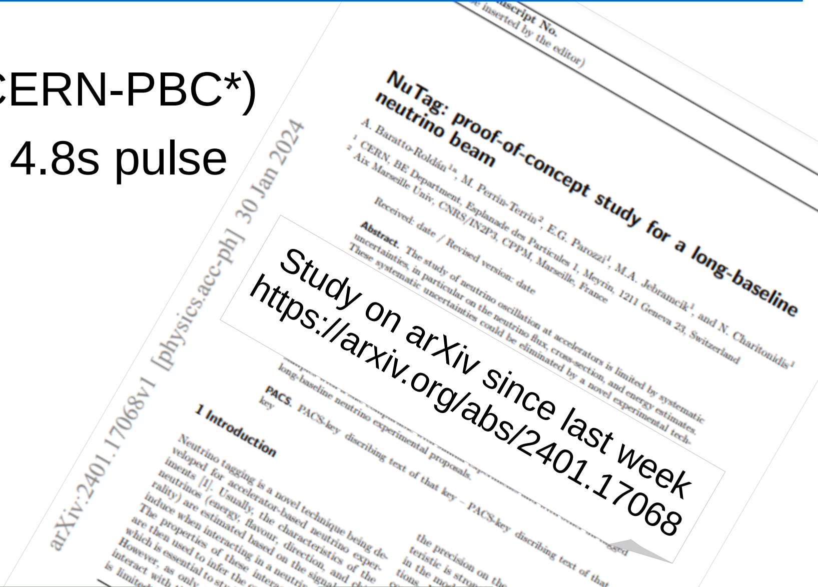
**$10^{12}$ part/s over $0.1 m^2$**
Maximum flux for
10y operation
with HL-LHC trackers

# Beam Line for a Long Baseline Setup

**NEW**

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

- **Slow extracted 400 GeV/c proton beam**, $2.5\cdot10^{13}$ 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)



arXiv:2401.17068v1 [physics.acc-ph] 30 Jan 2024

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**NuTag: proof-of-concept study for a long-baseline neutrino beam**

A. Baratto-Roldán[1a], M. Perrin-Terrin[2], E.G. Parozzi[1], M.A. Jebramcik[1], and N. Charitonidis[1]

[1] CERN, BE Department, Esplanade des Particules 1, Meyrin, 1211 Geneva 23, Switzerland
[2] Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

Received: date / Revised version: date

**Abstract.** The study of neutrino oscillation at accelerators is limited by systematic uncertainties, in particular on the neutrino flux, cross-section, and energy estimates. These systematic uncertainties could be eliminated by a novel experimental tech-

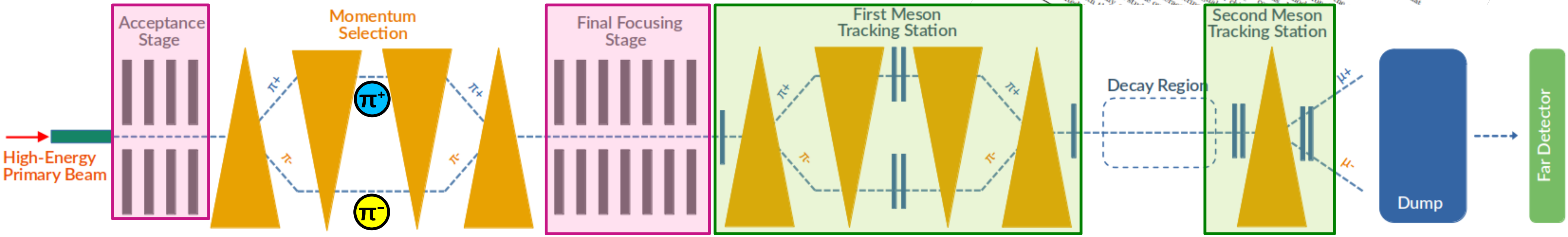
long-baseline neutrino experimental proposals.

**PACS.** PACS-key discribing text of that key – PACS-key discribing text of that key

**1 Introduction**

Neutrino tagging is a novel technique being developed for accelerator-based neutrino experiments [1]. Usually, the characteristics of the neutrinos (energy, flavour, direction, and chirality) are estimated based on the signal they induce when interacting in a neutrino

Study on arXiv since last week
https://arxiv.org/abs/2401.17068

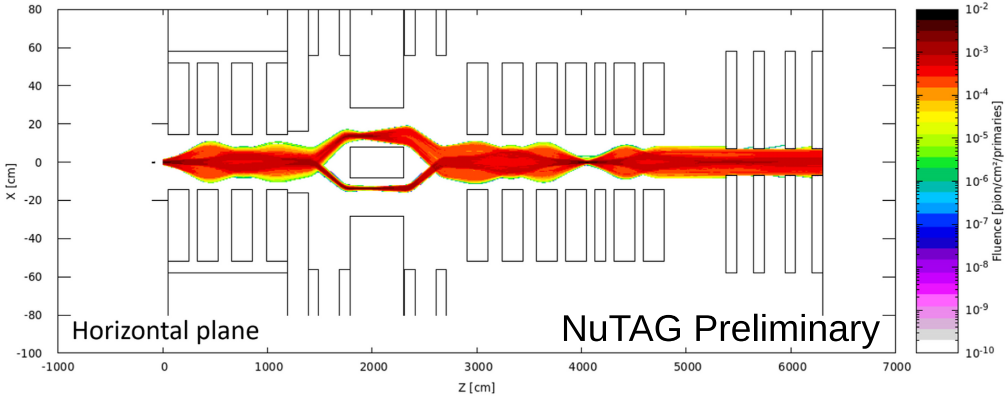


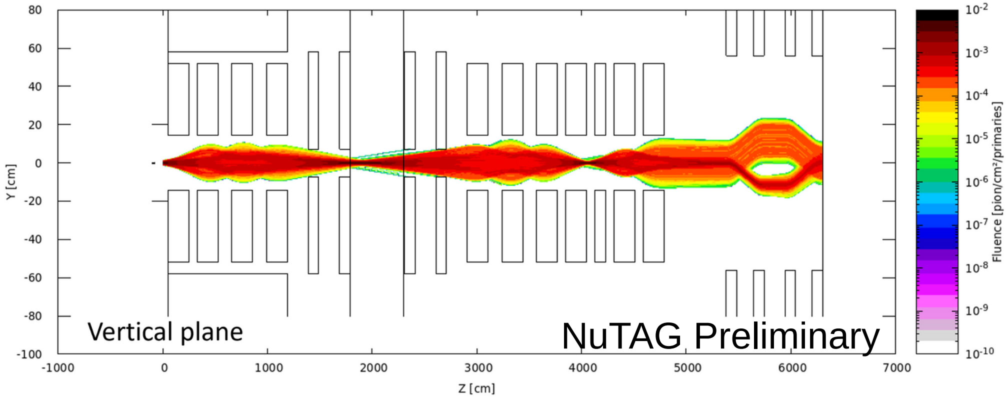
*A. Baratto-Roldan, E. Parozzi, M. Jebramcik, N. Charitonidis

# Beam Line for a Long Baseline Setup

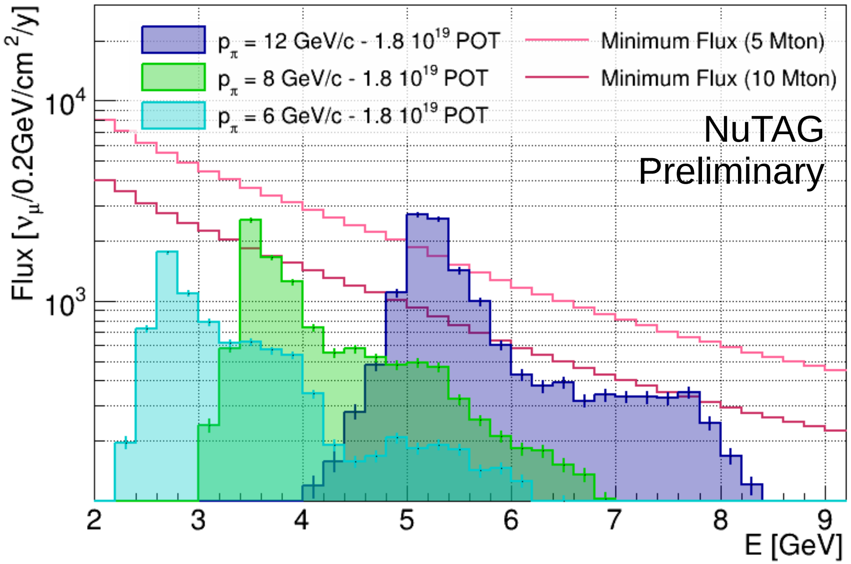
**NEW**

- **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 (<<100kW beam)
  - detector effective mass of 5 or 10 Mton
- Flux sufficient to collect **$\nu_e$ 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

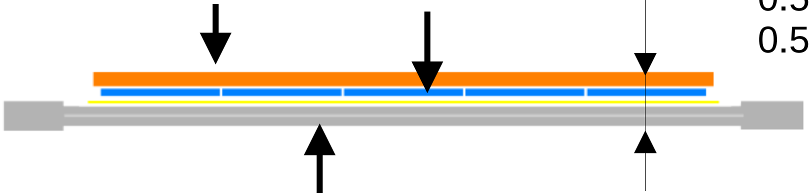


# Pixel Detector Technology for NuTag

**Beam tracker composed of**

- sensor (time reso, radiation)
- ASIC (time reso, hit rate, radiation)
- high cooling power (>1.5W/cm²)

with the lowest material budget



Sensor

Readout ASIC

Micro Channel Cooling Plate

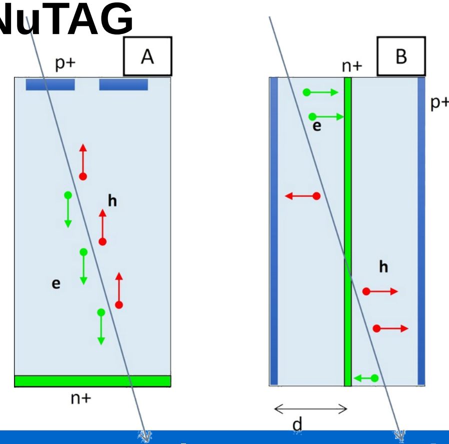
Total Thickness:
0.5 mm of Silicon
0.5% $X_0$

**NA62-GTK:** planar n-in-p sensor (200µm) readout with TDCPix ASIC (130nm CMOS)

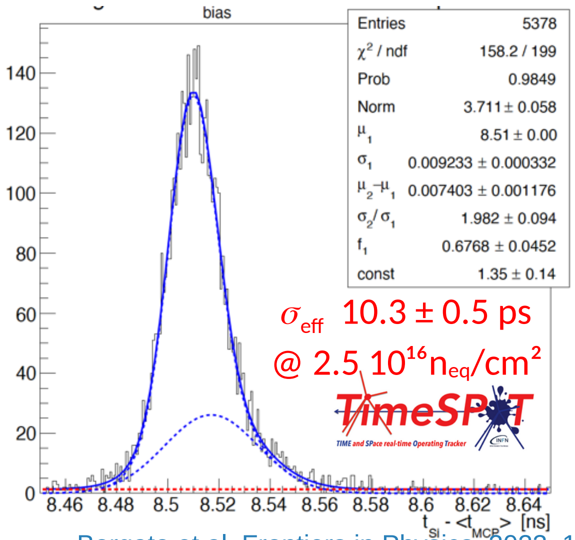
▶130 ps per hit ▶2 MHz/mm² ▶$4.5 \cdot 10^{14}$ $n_{eq}/cm^2$ ▶0.5%X_0

**TimeSpot/IGNITE developments suitable for NuTAG**

- 3D trench sensors:
  - ▶**10ps hit time resolution** after
  - ▶large irradiation: **>10¹⁶ neq/cm²**
- Readout ASIC is being developed using **28nm CMOS**



A. Lampis et al 2023 JINST 18 C01051



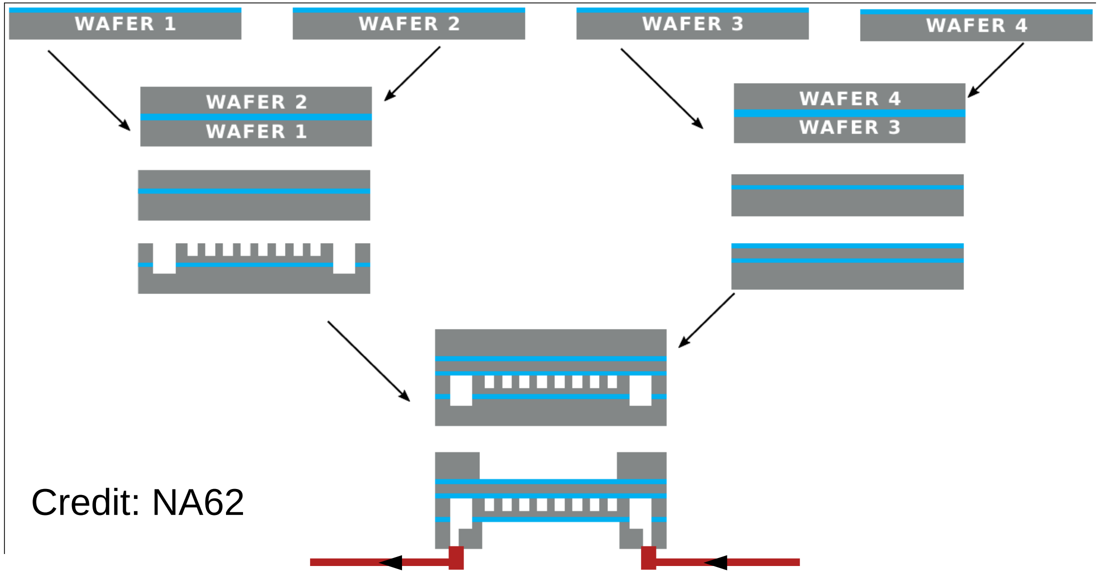
$\sigma_{eff}$ 10.3 ± 0.5 ps
@ 2.5 $10^{16} n_{eq}/cm^2$

TimeSPOT
TIME and SPace real-time Operating Tracker

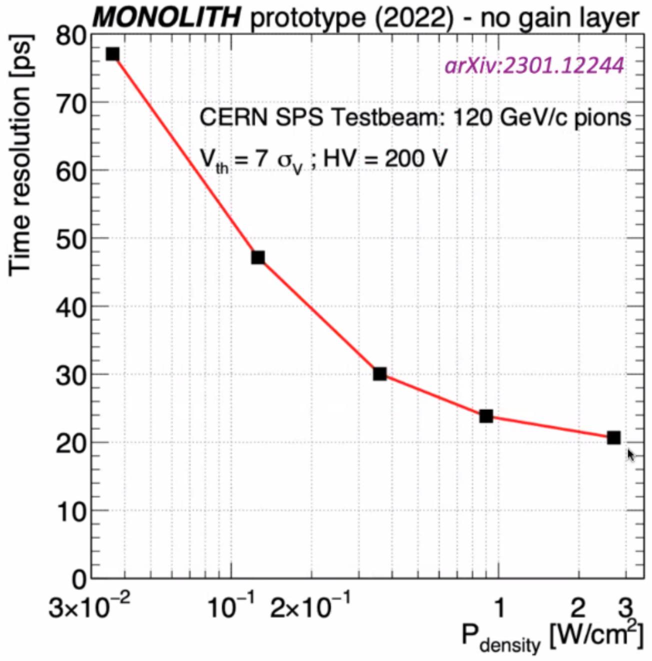
Borgato et al. Frontiers in Physics, 2023, 11

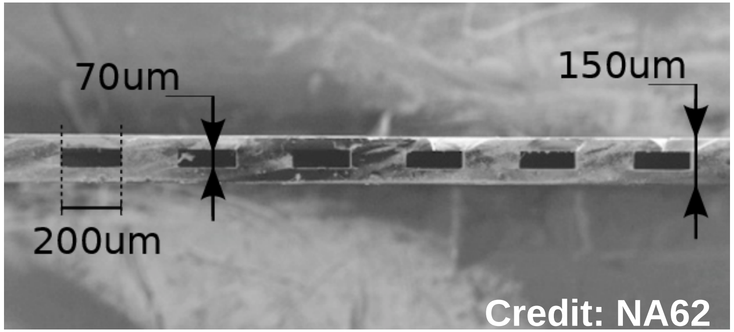
# The importance of cooling

- The performance of the cooling system sets the power of the ASIC and so its **time resolution**
- **Micro-channel** cooling is highly performant: thermal **FOM** of **~3°/(W/cm²)** vs 20°/(W/cm²) for ITK
- Technology was pionneered by NA62 and LHCb: major **difficulty to produce** the devices (wafer bonding and capillary/plate connection)



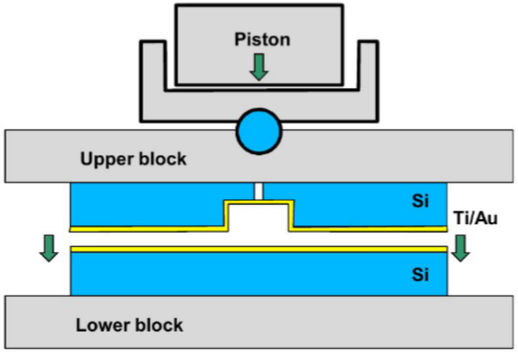
Credit: NA62



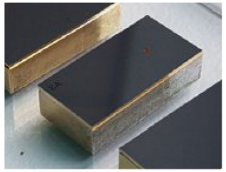


Credit: NA62

# The importance of cooling



R&T in CPPM to develop a new fabrication process
(see J. Cogan’s talk at Prospective CPPM, 13/03/2023)



- **Step1:** Investigate new bonding technique
  ➔ Gold thermocompression:
    - wide spread technology
    - working for Si/Si ——▶ Micromachines 2023, 14(7), 1297
    - working for Si/Metalic Alloy (i.e. connectors)

- **Step2:** Replace mechanical press with hyperbaric chamber
  ➔ larger devices can be bonded
  ➔ bonding can be done in batch
  ➔ devices planarity requirement are lower

Technique is Patented

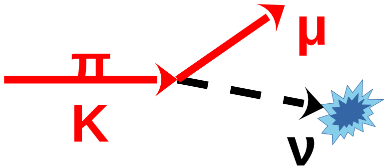
# Outline

- Scientific Landscape
- The concept of Neutrino Tagging
- Experimental Demonstration of the Neutrino Tagging
- Towards a Full Scale Tagged Neutrino Experiment
- Physics Case for Tagged Neutrino Experiments
  - Short Baseline Experiments
  - Long Baseline Experiments

# Physics @ Tagged Short Baseline Experiments

Ideal setup to study **interaction models**

- **ν energy measured independently of interaction**



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

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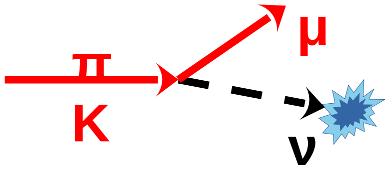

**$\nu_\mu$ cross-section and differential cross-section**

- **$\nu_\mu$ flux** from π,K➔μν precisely determined by the tagger
- **$\nu_\mu$ energy measured evt-by-evt at <1% precision**

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

# Physics @ Tagged Short Baseline Experiments

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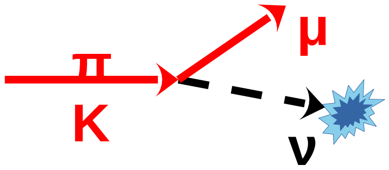

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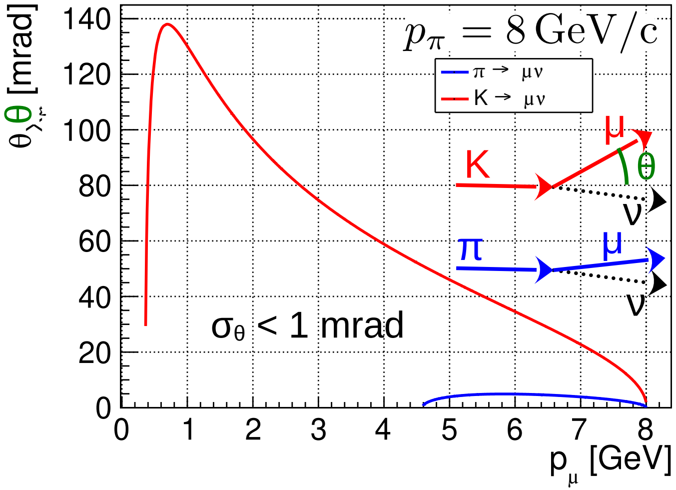
- **$\nu_\mu$ energy measured evt-by-evt at <1% precision**

**$\nu_e$ cross-section**

- K➔μν and π➔μν can be identified by **kinematics** ⟶
- **$\nu_e$ flux** determined from K➔μν rate corrected for branching ratios and acceptances :

$$\mathrm{N}(\nu_\mathrm{e}) = \mathrm{N}(\mathrm{K}^+ \to \pi^0 \mathrm{e}^+ \nu_\mathrm{e}) = \mathrm{N}(\mathrm{K}^+ \to \mu^+ \nu_\mu) \cdot \frac{\mathcal{B}(\mathrm{K}^+ \to \pi^0 \mathrm{e}^+ \nu_\mathrm{e})}{\mathcal{B}(\mathrm{K}^+ \to \mu^+ \nu_\mu)}$$

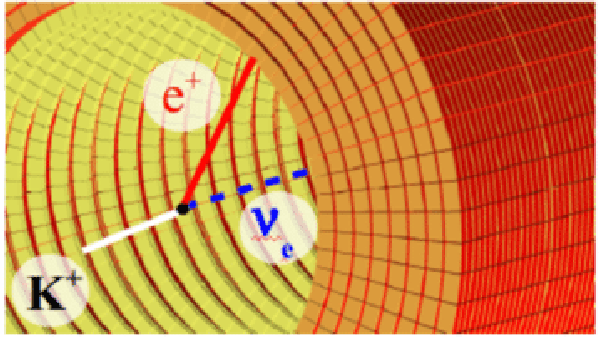
- $\nu_e$ cross section precision limited by **statistics** and by the uncertainties on **$B(K^+ \to \pi^0 e^+ \nu_e)$: 0.8%**



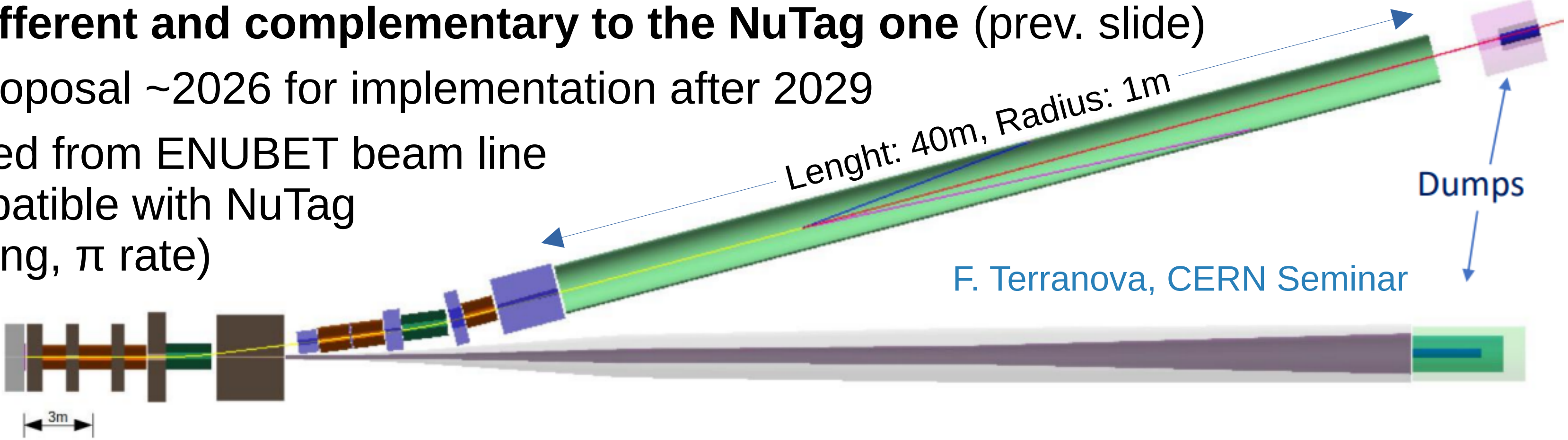
# Project for a Short Baseline at CERN

NEW

- Study started within ***CERN*** *Physics Beyond Collider* for a **SBL using proto-DUNE** and **implementing the NuTag and ENUBET techniques** to measure ν cross-sections
- **ENUBET** collaboration



- **ENUBET Method**
  **rate of $e^+$ gives rate of $\nu_e$ as** $\mathrm{N}(\nu_\mathrm{e}) = \mathrm{N}(\mathrm{K}^+ \to \pi^0 \mathrm{e}^+ \nu_\mathrm{e})$
  **$e^+$** can be **detected outside the beamline** (3-body decay)
- Method is **different and complementary to the NuTag one** (prev. slide)
- **Timeline:** proposal ~2026 for implementation after 2029
- Design started from ENUBET beam line
  a-priori compatible with NuTag
  (static focusing, π rate)



F. Terranova, CERN Seminar

# Outline

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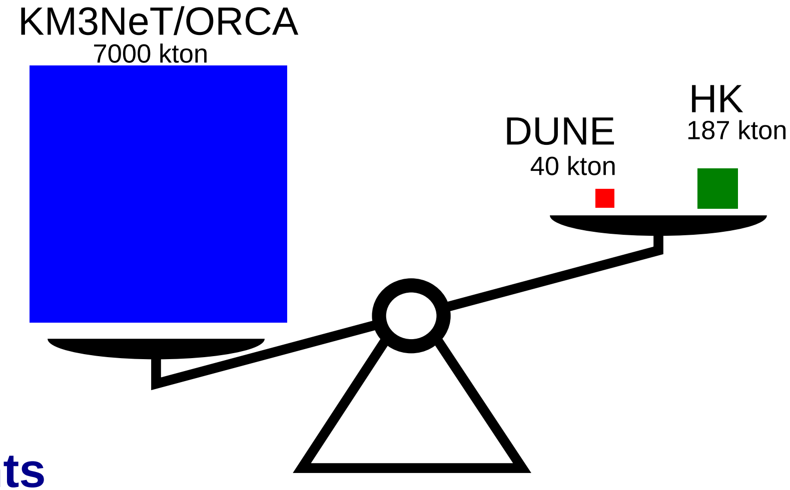
  - Long Baseline Experiments

# NuTag for $\delta_{CP}$ Precison Measurement



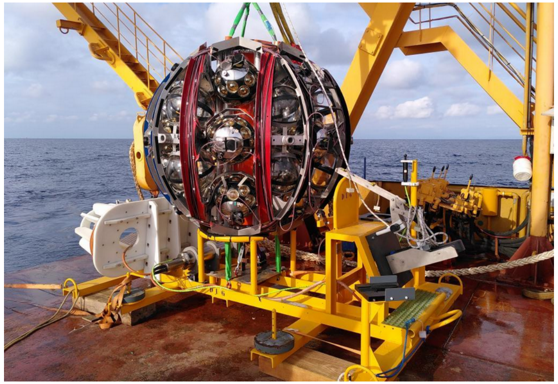
- **Future** measurements require **high statistics** and **low systematics**
- Very challenging for **conventional LBLNE**:
  - higher **power** beams
  - **larger** underground high granularity **far detectors**
  - more **precise near detector + dedicated experiments**

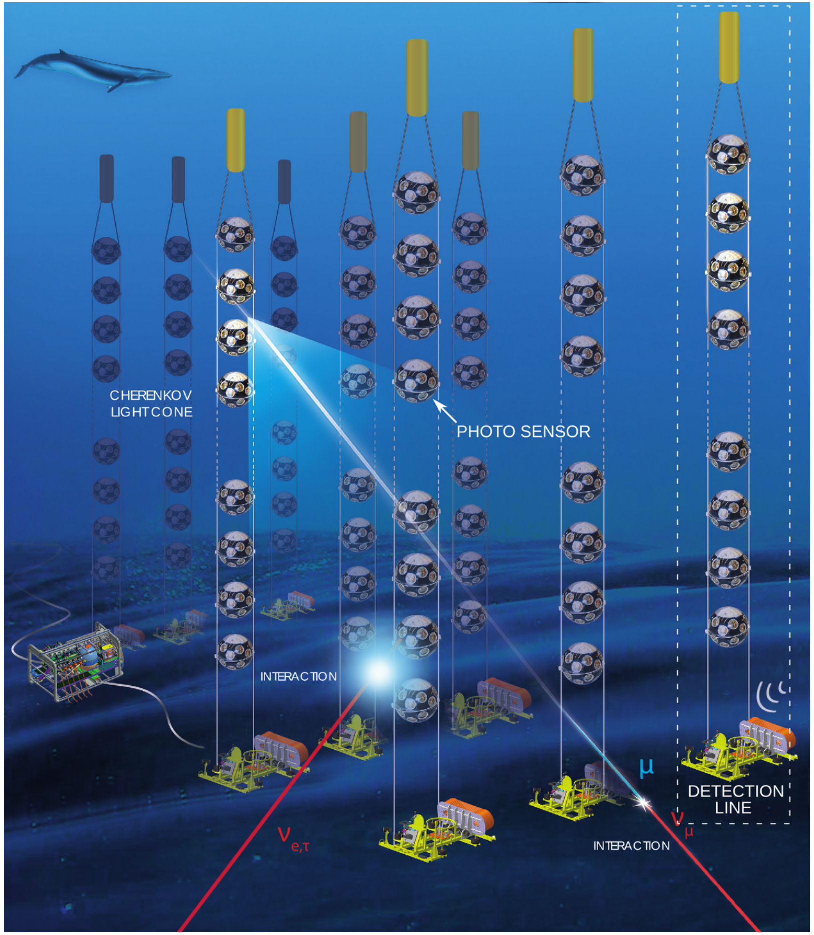
- **Alternative**:
  **« *low* » power tagged-beams + huge (>Mton) natural water Cerenkov detectors**
  - natural water detectors **size has virtually no limits**
  - detectors **poor granularity** (more than) **compensated by tagging**, (δE/E<1%)
  - **reduced systematical uncertainties** thanks to the tagging

Letter of intent for KM3NeT, J. Phys., 2016, G43, 084001, arXiv:1601.07459

# Natural Water Cerenkov detection [KM3Net]

- A versatile water Cerenkov detection technology:
  - the **multi-PMT DOM**
  - the **deployment tool (LOM)**
- DOM and line spacing determines the **energy threshold** of the detector



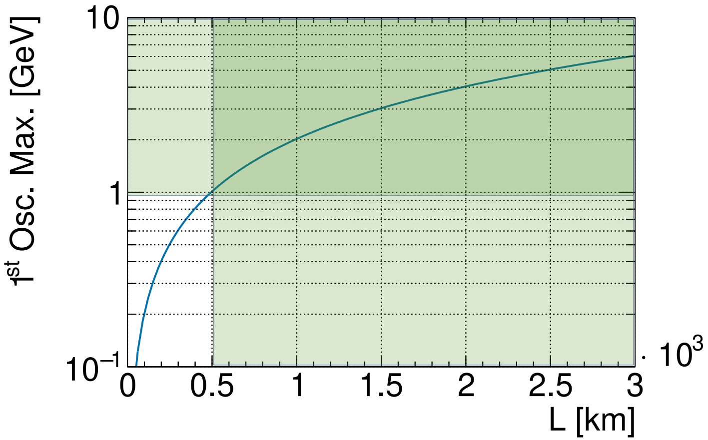


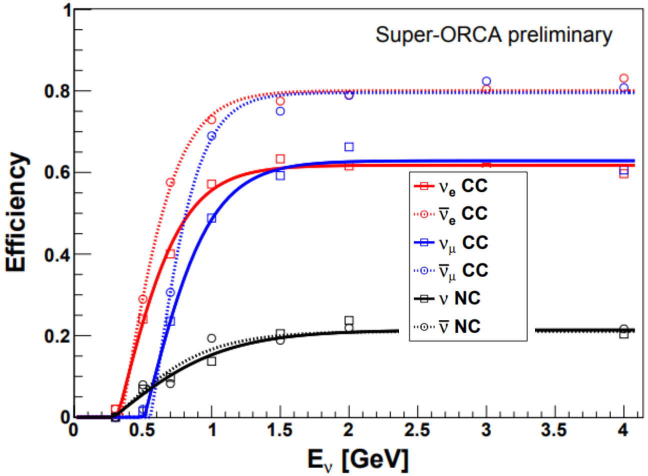
SuperORCA PoS, 2020, ICRC2019, 911, arXiv:1907.12983

# KM3NeT/ORCA for a Long Baseline Exp.

- ORCA main purpose is the **Neutrino Mass Ordering** for which an **energy threshold** <5 GeV is needed

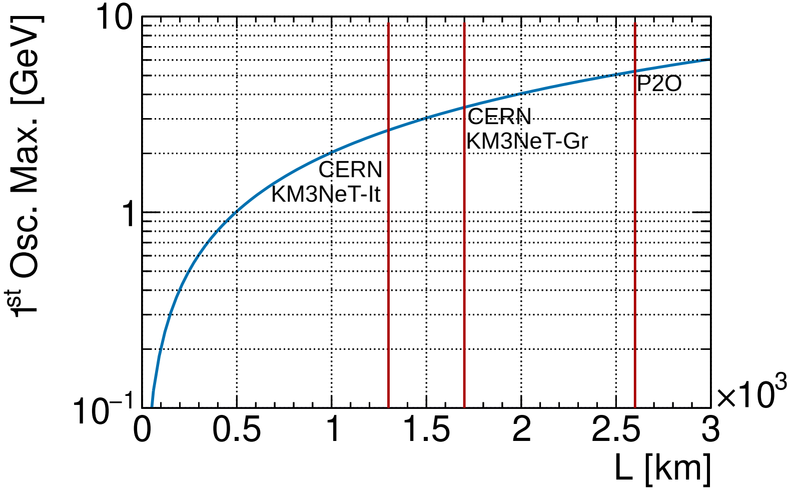
- Configuration **ten times more dense** (superORCA) were simulated and allow to have a **threshold ~1GeV**

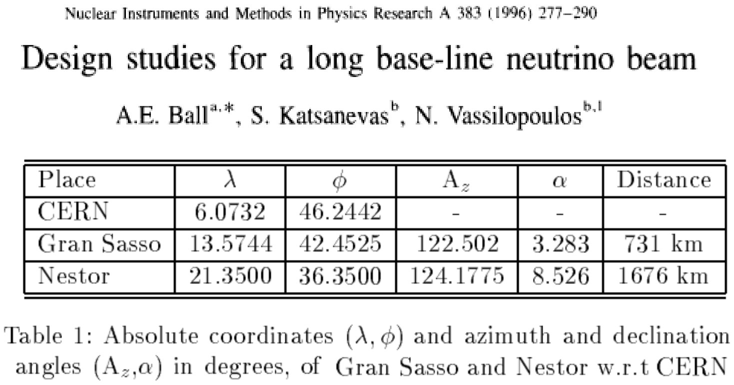




# Possible Long Baseline Exp. in Europe

- 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 (?)
  - Italian sea infrastructure could be re-used (?)





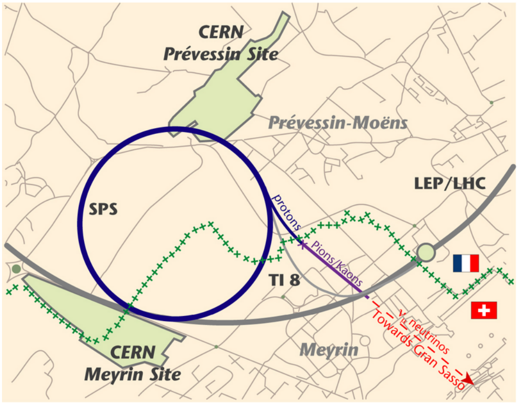
Nuclear Instruments and Methods in Physics Research A 383 (1996) 277–290

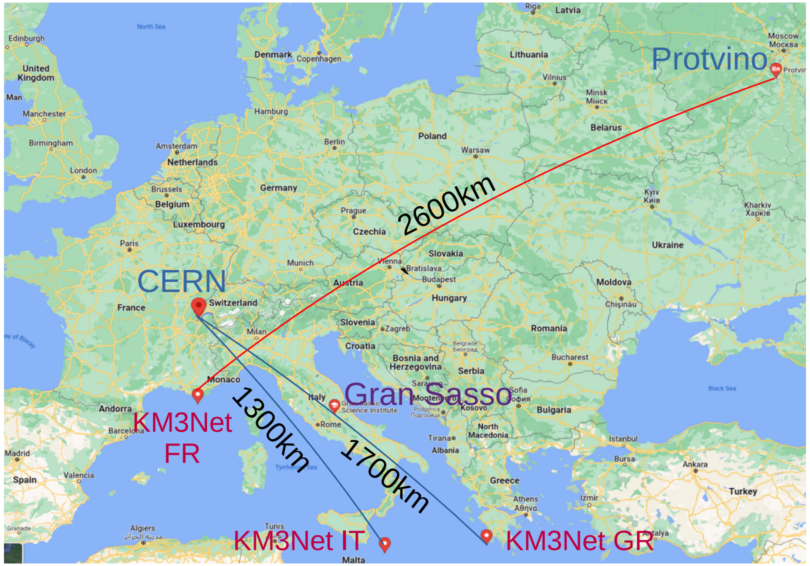
Design studies for a long base-line neutrino beam

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

| Place | $\lambda$ | $\phi$ | $A_z$ | $\alpha$ | 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 $(\lambda, \phi)$ and azimuth and declination angles $(A_z,\alpha)$ in degrees, of Gran Sasso and Nestor w.r.t CERN

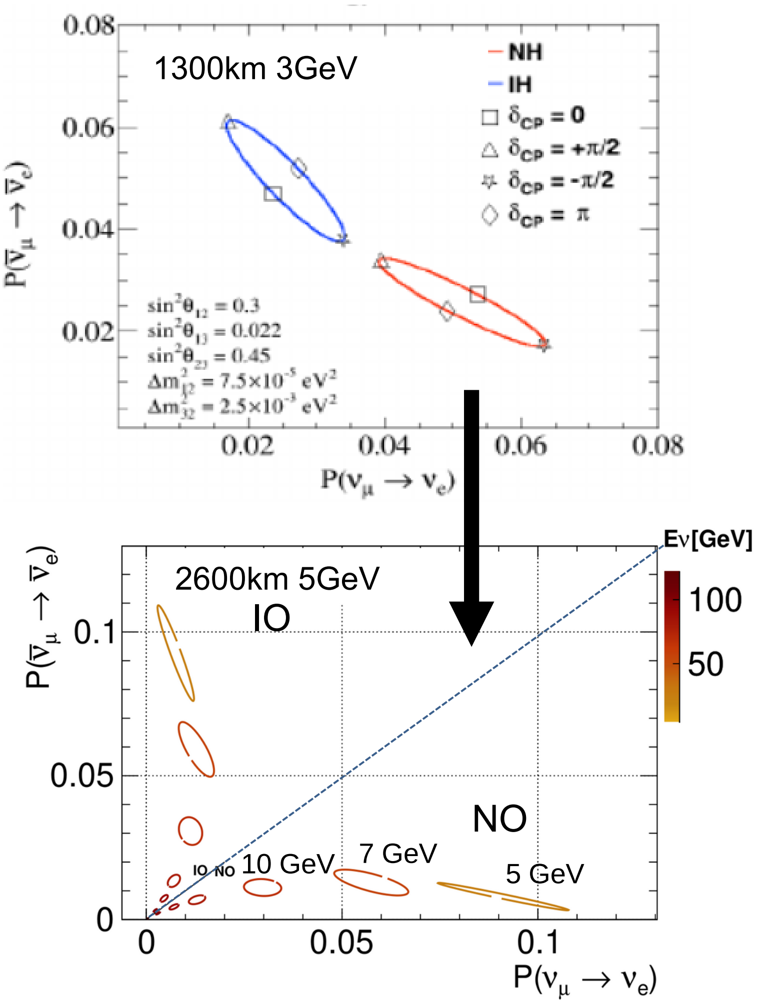




Neutrino tagging: a new tool for accelerator based neutrino experiments **Eur. Phys. J. C, 2022, 82, 465**, arXiv:2112.12848

# $\delta_{CP}$ measurements with a tag-Long Basline Exp.

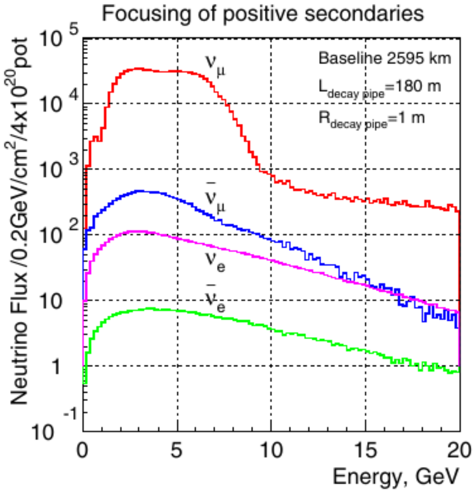
- **TagP2O** used as case study
- **Multiple ellipses** can be accessed:
  - some are more **circular**
  - **apsides** not always reached at 90 or 270°



# δCP measurements with a tag-LBL

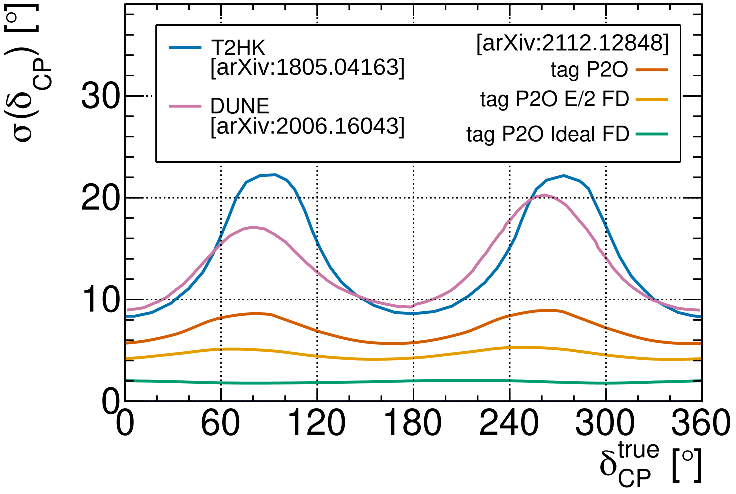
- **TagP2O** used as case study
- **Multiple ellipses** can be accessed:
  - some are more **circular**
  - **apsides** not always reached at 90 or 270°
- **Better** and **more stable** resolution
  - With ORCA:
    **6-8° precision in 10 years**
  - With a detector twice as dense
    **4-5° in 10 years**
  - **2°** if e/μ identification is perfect (10 years)

A possible path to continue studying ν oscillation
**after** DUNE/HK (**w/o multi MW beam, w/o excavation**)

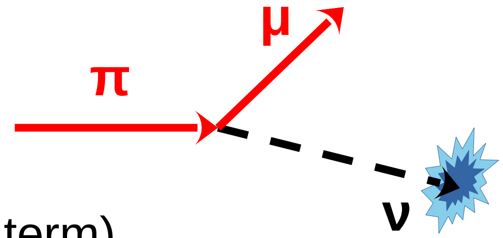


**Beam**
← spectrum
450 kW power

**Data taking**
10 years

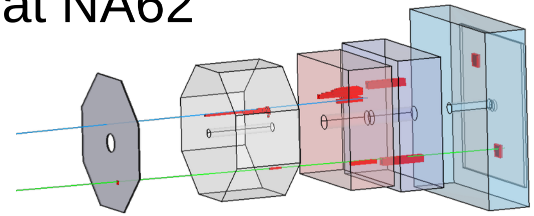


# Summary and Conclusions



- **Neutrino tagging (NuTag) 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)



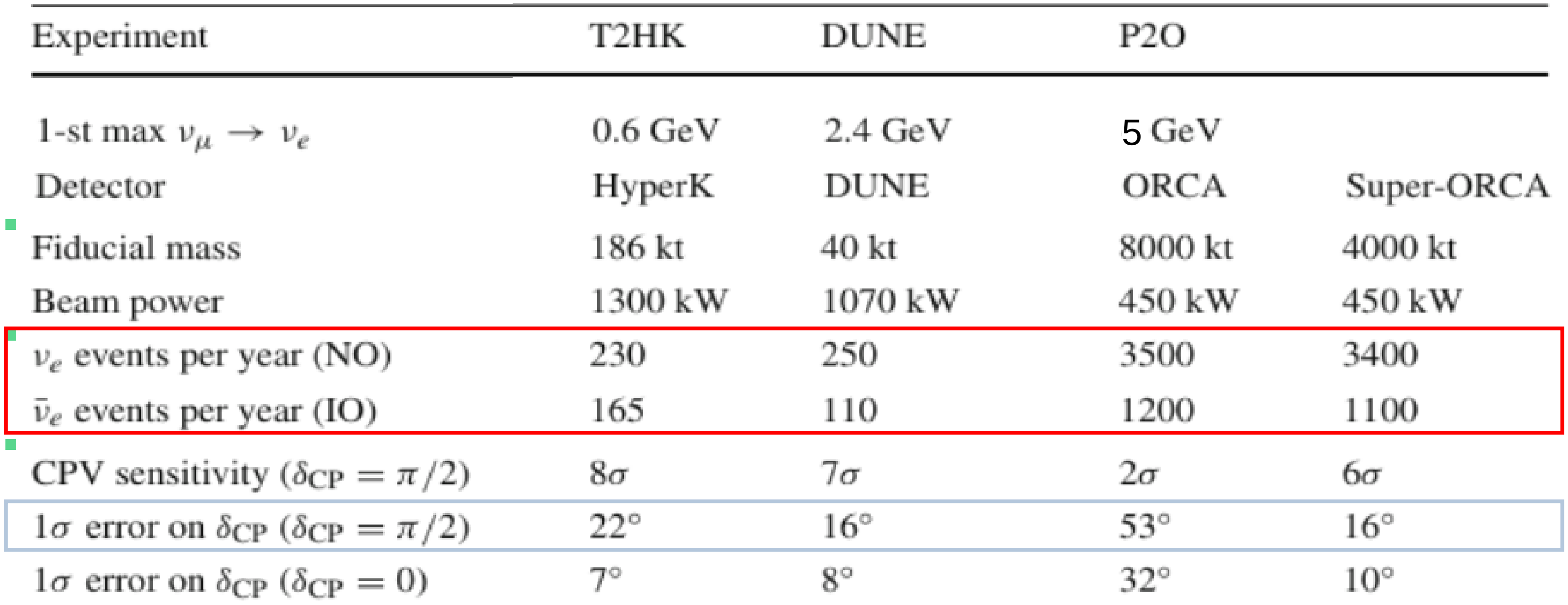
- **The first two fully tagged neutrino candidates** detected at NA62
  - A crucial step to demonstrate that neutrino tagging is feasible
  - Results to be confirmed with more data

- **A short baseline option is developing at CERN**
  - should run in the coming decade
  - strong synergy ENUBET/NuTag
  - new collaborators are welcomed

- **A possible path to continue exploring neutrino physics after DUNE/HK**

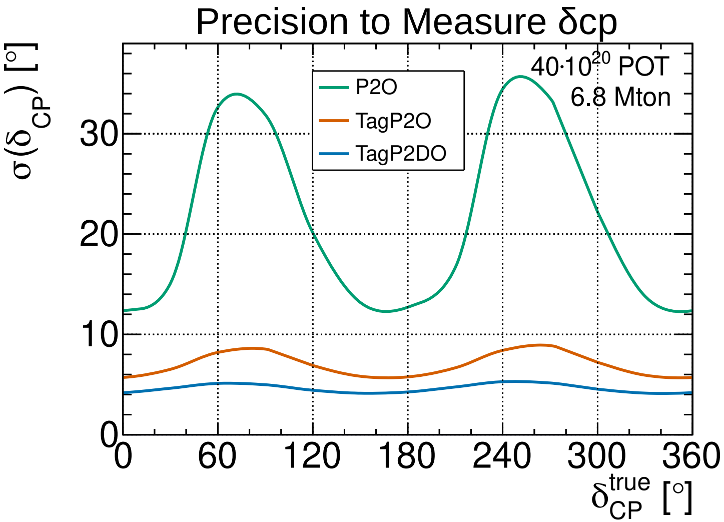
# Case Study TagP2O

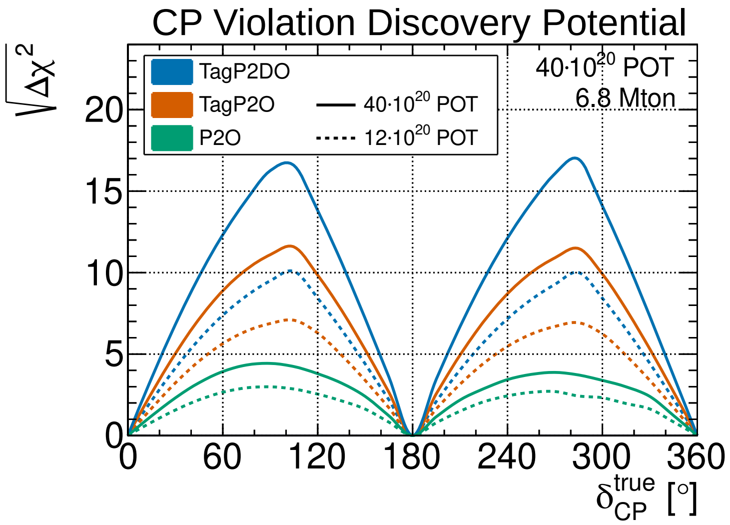
- Letter of interest Eur. Phys. J. C (2019) 79:758
- U70 beam power assumed to be upgraded from ~90kW to 450 kW, in the context of the OMEGA projet
- Event rates and $\delta_{CP}$ sensitivity **without tagging**



| Experiment | T2HK | DUNE | P2O | |
|---|---|---|---|---|
| 1-st max $\nu_\mu \to \nu_e$ | 0.6 GeV | 2.4 GeV | 5 GeV | |
| Detector | HyperK | DUNE | ORCA | Super-ORCA |
| Fiducial mass | 186 kt | 40 kt | 8000 kt | 4000 kt |
| Beam power | 1300 kW | 1070 kW | 450 kW | 450 kW |
| $\nu_e$ events per year (NO) | 230 | 250 | 3500 | 3400 |
| $\bar{\nu}_e$ events per year (IO) | 165 | 110 | 1200 | 1100 |
| CPV sensitivity ($\delta_{CP} = \pi/2$) | $8\sigma$ | $7\sigma$ | $2\sigma$ | $6\sigma$ |
| $1\sigma$ error on $\delta_{CP}$ ($\delta_{CP} = \pi/2$) | 22° | 16° | 53° | 16° |
| $1\sigma$ error on $\delta_{CP}$ ($\delta_{CP} = 0$) | 7° | 8° | 32° | 10° |

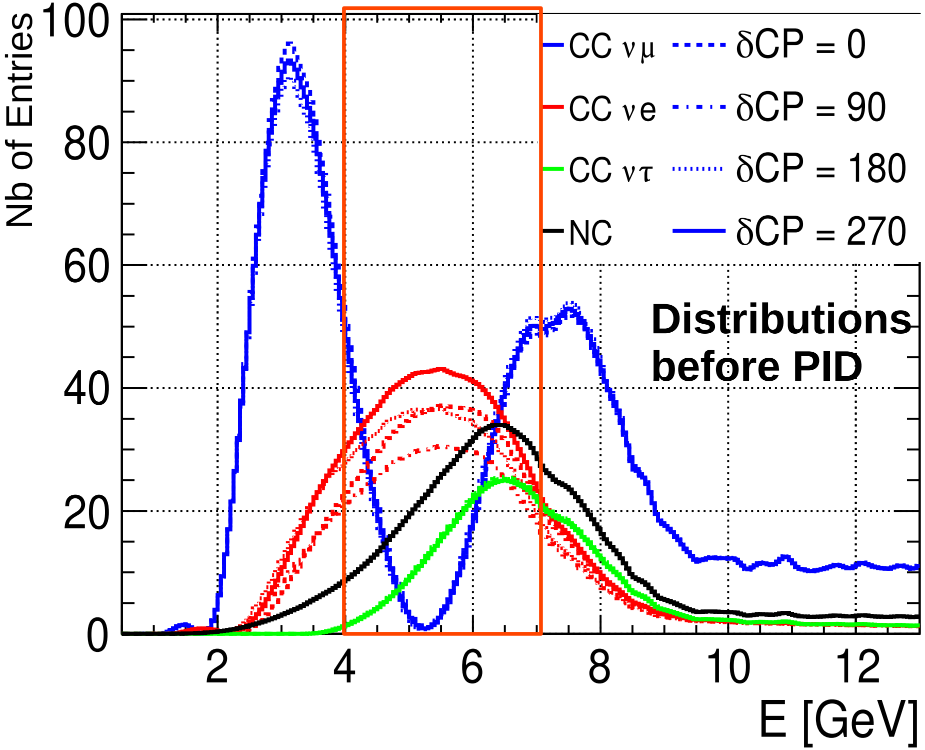
# δCP measurements with a tag-LBL

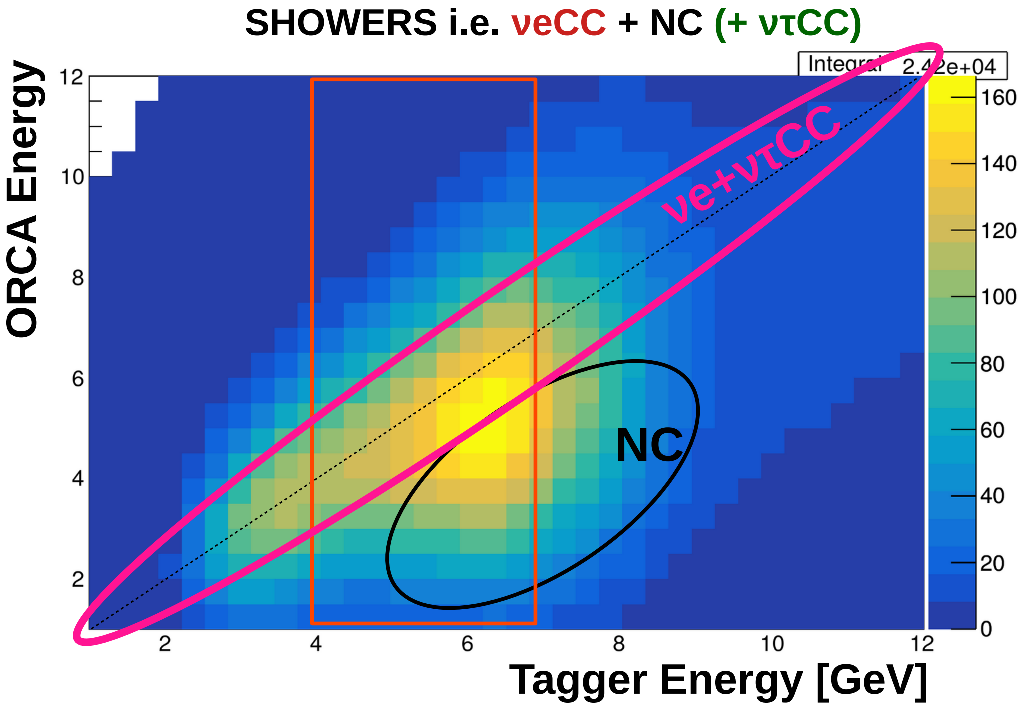




# How to measure $\delta_{CP}$ with P2O

- $\delta_{CP}$ measured using νe-CC energy distribution around 5GeV (1rst osc max)
  - **ORCA threshold ~3.5GeV**
  - **NC pollution** in νe-CC reduced comparing **visible energy vs tag-energy**



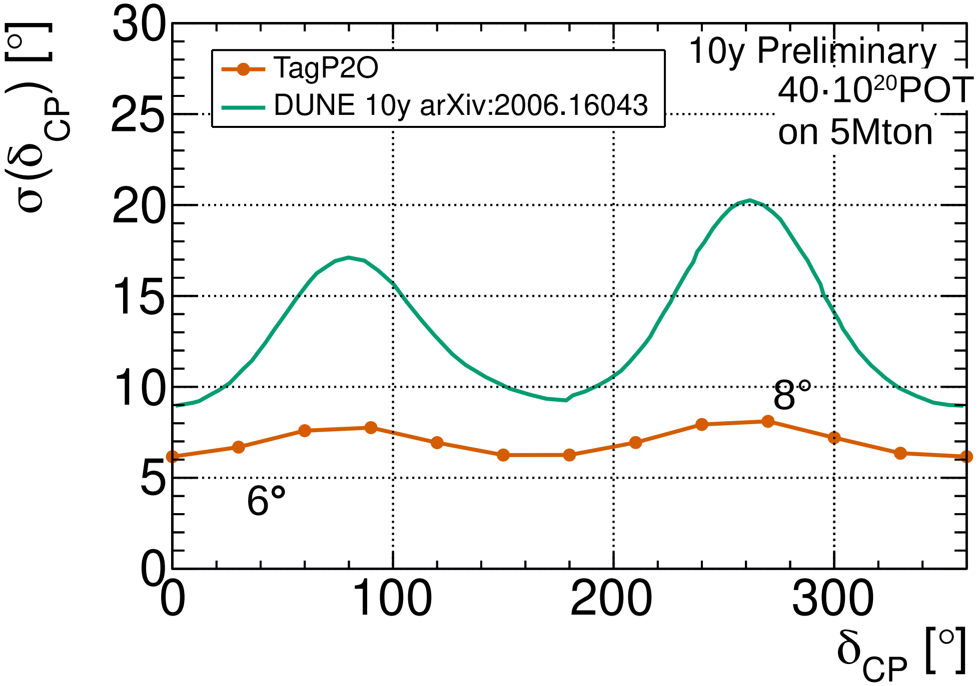


# Precision to $\delta_{CP}$ at P2O

- **Systematics** on oscillation parameters, cross section & normalisation (free)

| | |
|---|---|
| θ13 ± 0.15° | ντ ± 10% |
| θ23 ± 2° | NC ± 5% |
| Δm²31 ± 5e-3eV² | νe=νμ ± 5% |

- **Conservative** estimates:
  no PID improvement with respect to atmospheric ν was considered
- $\delta_{CP}$ precision **stable** over all values
- **<8° precision** can be achieved!

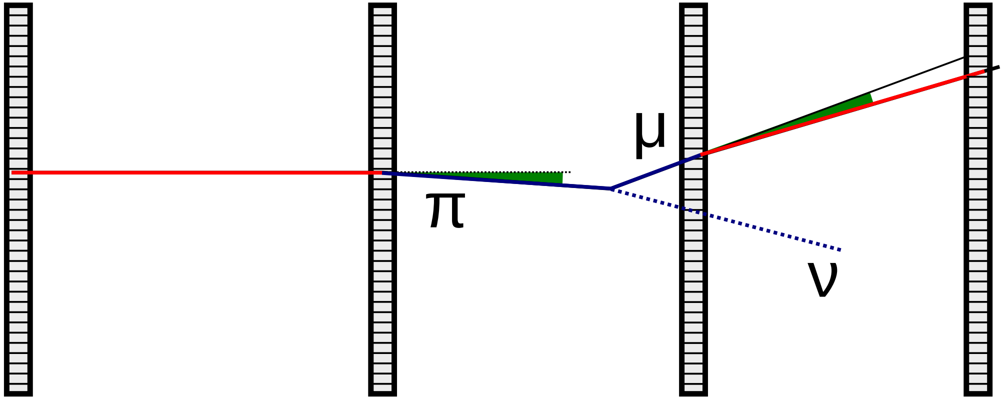


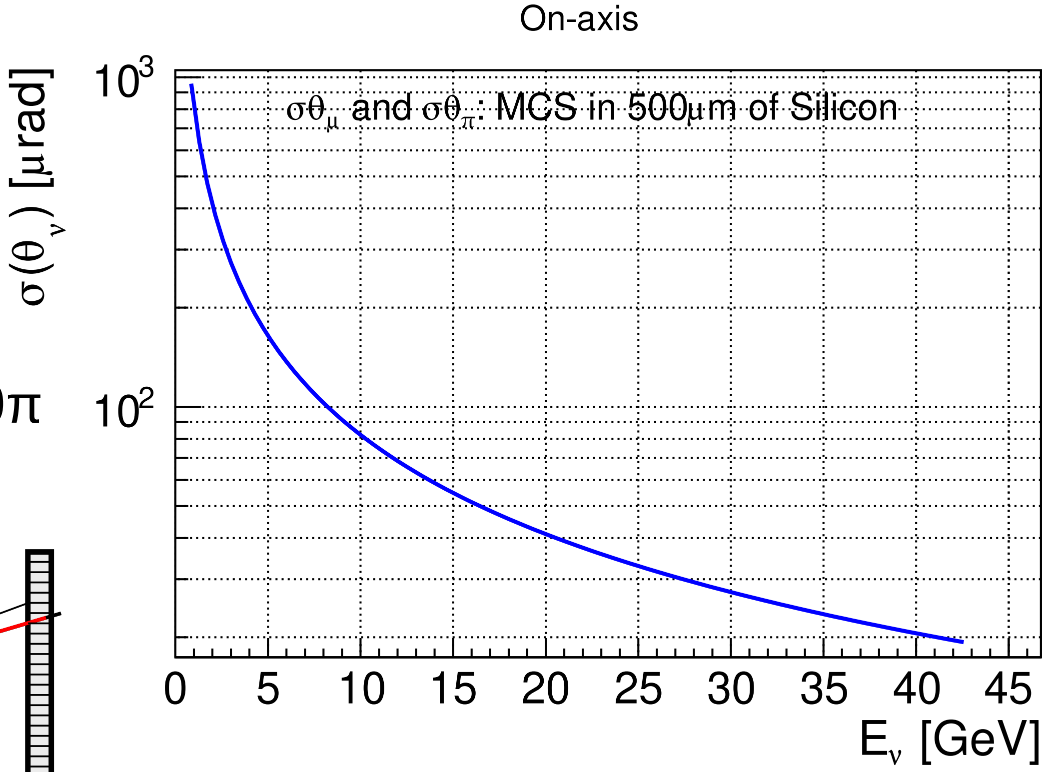
# Is 1mard ν ang. resolution achievable? YES

- When θνπ➔0 (i.e **on axis**):

  θνπ ➔ 1.3·θμπ

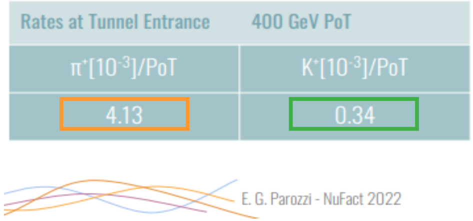
- Assume that **multiple coulomb scattering** (in 0.5% $X_0$ like at NA62) dominates the resolutions on θμπ & θπ





- **Sub-mrad prec. on $\theta_\nu$ can be achieved**

# $\nu_e$ energy control: Kaon to νe association



| Rates at Tunnel Entrance | 400 GeV PoT |
|---|---|
| $\pi^+[10^{-3}]$/PoT | $K^+[10^{-3}]$/PoT |
| 4.13 | 0.34 |

E. G. Parozzi - NuFact 2022

- **Assumptions on the beam content, based on ENUBET**
  - **Getting $9\times10^{19}$ POT in 2.5 years needs $5\times10^{13}$ protons per pulse**[a]
  - **The neutrino detector** (protoDUNE e.g.) has **time resolution** 1ns
- For any interaction in protoDUNE the nb of in time π's and K's in the beam are
  - **200 π's:** 5e13 × 4.13e-3 × 1e-9
    - π's can be identified & vetoed based on TOF+kinematics
  - **17 K's :** 5e13 × 0.34e-3 × 1e-9
    - Undecayed K (~50%) can be vetoed
    - Kμ2 and K2π can be reconstructed and vetoed
  - **The association is possible for 90% of the cases**

~~200 π's~~

17 K's

8 decayed ~~9 un-decayed~~

1 Ke3 ~~5 Kμ2~~ ~~1-2 K2π~~ 0-1 other

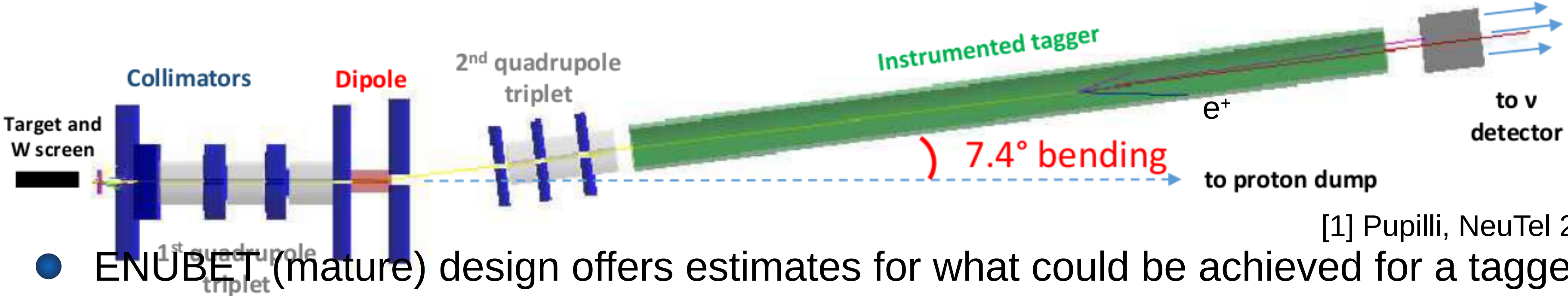
---

[a] 5e13 ppp and 3000 p per day 30 days a month 8 months per year over 2.5 year gives $9\times10^{19}$ POT

# ENUBET

- **ENUBET:** ***monitored*** beam to measure ν x-section at energies of few GeV
  - **$N(e^+) = N(K^+ \rightarrow \pi^0 e^+ \nu_e) = N(\nu_e)$**, so by **counting the $e^+$'s, one counts the $\nu_e$'s**
  - **Narrow band beam (NBB)** (10% at 8.5GeV) allows to limit the Eν spread to 20%
- NuTAG & ENUBET beam lines designed with the **same technology** (quadrupoles)

protoDUNE
500 tonne
@ 50m



[1] Pupilli, NeuTel 2019

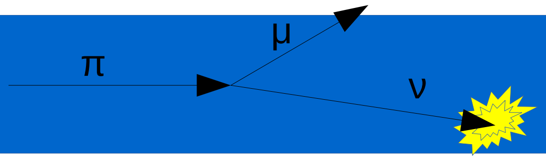
- ENUBET (mature) design offers estimates for what could be achieved for a tagged SBL
  - Nb assumes: $5\times10^{13}$ ppp, $10^{20}$ POT*, with protoDUNE as detector
  - Beam particle rate is **~MHz/mm²** at pipe end (<<10-100MHz/mm²)

| | |
|---|---|
| $N(\nu_e)$ | $10^4$ / $10^{20}$ POT |
| $N(\nu_\mu)$ | $10^6$ / $10^{20}$ POT |

* this is similar to CNGS intensity

Neutrino tagging: a new tool for accelerator based neutrino experiments **Eur. Phys. J. C, 2022, 82, 465**, arXiv:2112.12848

# Matching with tag-ν



**At $10^{11}$ ν/s, is the association tag-ν/interacting-ν working?**

Association based on **time** and **angular** coincidence:

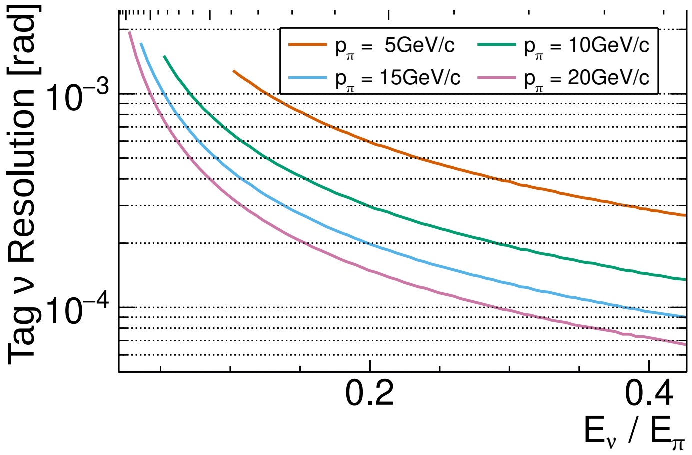
- **Time** coincidence: $t_{\nu\text{-tag}} - t_{\nu\text{-int}}$
  - Silicon Trackers will enable <10ps reso on tag-ν
  - Typical ν detector resolution is 10ns

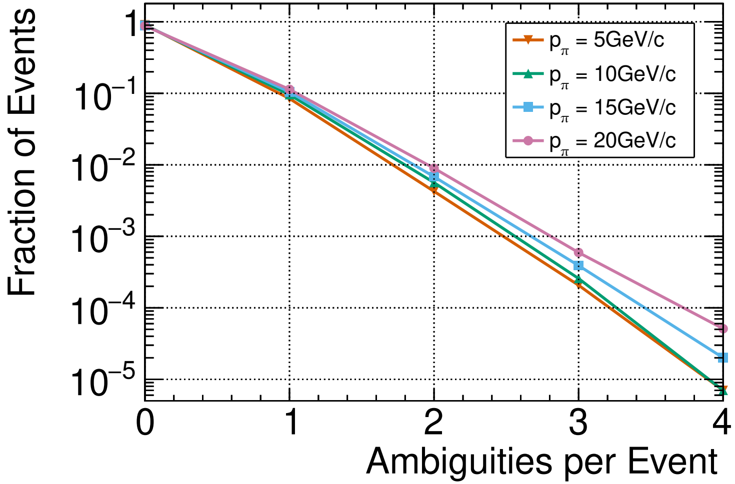
➔ About **1'000 tag-ν** are **in-time with any interacting-ν**

- **Angular** Coincidence: $\theta_{\nu\text{-tag}} - \theta_{\nu\text{-int}}$
  - **Dominant** contribution is **tag-ν resolution**
  - **Resolution is <1 mrad** (assuming a tracking plane thickness of 0.5% $X_0$)

➔ **90% of the evt can be tagged w/o ambiguity**

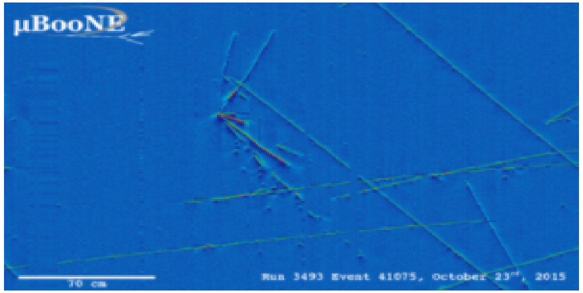
Remaining **10%** have **> 1 tag-ν matched**

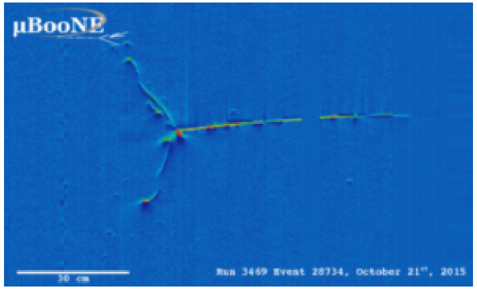


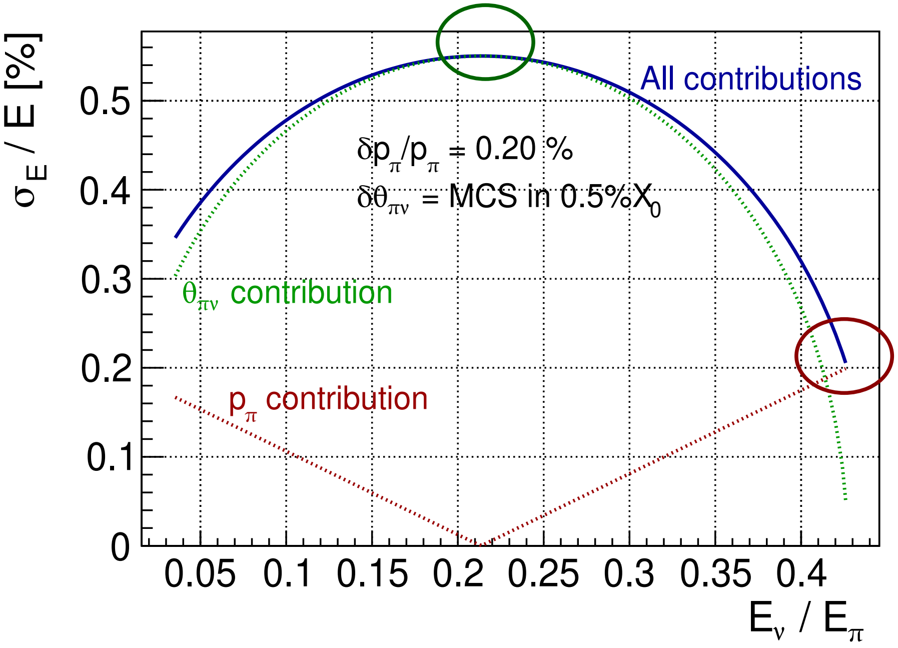


# What about Energy Resolution?

- Reconstructing a π➔μν decay is much simpler and cleaner than a ν interaction
- ν energy obtained from $p_\pi$ and $\theta_\nu$ as $E_\nu = \frac{\left(1 - m_\mu^2/m_\pi^2\right) p_\pi}{1+\gamma^2\theta_\nu^2}$
- Energy reso ranges **between** **0.2% (on axis)** **and** **0.6 %** (independent of $p_\pi$)!
- To be compared with 10-20% for the methods based on the neutrino interactions







# Tracker: Pixel Technology

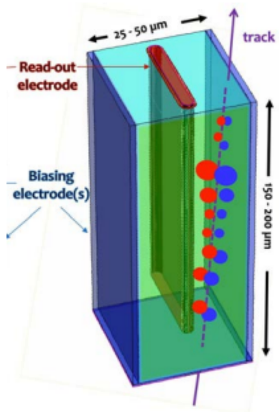
https://doi.org/10.1088/1748-0221/16/09/p09028
https://indi.to/KPGtS

- Very **ambitious specs**, similar to the ones for **HL-LHC** experiments & **HIKE**
- TimeSpot (A. Lai, INFN Cagliari)
  - Trench 3D sensors
  - Excellent **time** and **radiation resistance** (being test at $10^{17}$ $n_{eq}/cm^2$ !)
  - ASIC development started (28ns)

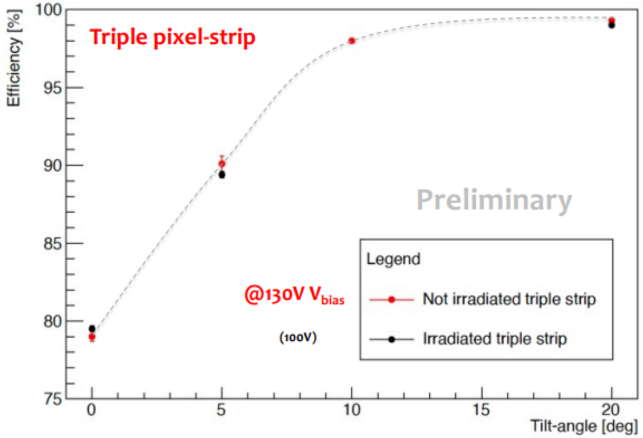
| Specification | Neutrino Tagging | NA62 ( in operation) | HIKE | HL-LHC (R&D) |
|---|---|---|---|---|
| Flux (MHz/mm$^2$) | $\mathcal{O}(10-100)$ | 2 | 8 | $\mathcal{O}(10-100)$ |
| Fluence ($n_{eq}$/cm$^2$) | $10^{16-17}$ | $2 \cdot 10^{14}/y$ | $8 \cdot 10^{14}/y$ | $10^{16-17}$ |
| Hit Time Reso. (ps) | $< 20$ | 200 | $< 50$ | $< 50$ |
| Det. Efficiency (%) | $> 99$ | $> 99$ | $> 99$ | $> 99$ |
| Thickness (% of $X_0$) | $< 0.5$ | $< 0.5$ | $< 0.5$ | $< 0.9$ |
|  | arXiv: 2112.12848 | arXiv: 1904.12837 | arXiv: 2211.16586 | CERN-LHCC-2021-012 |

https://indico.cern.ch/event/1127562/contributions/4904519/

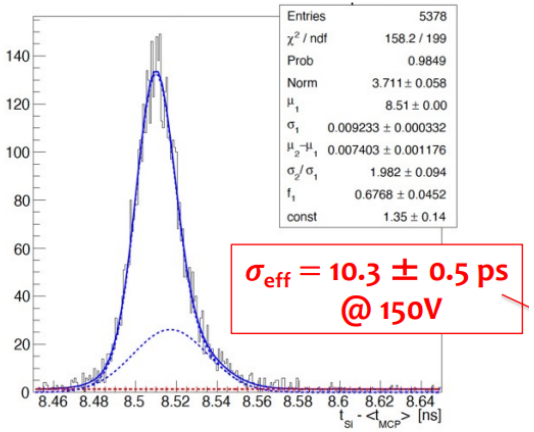
https://arxiv.org/abs/1703.08501



trenches



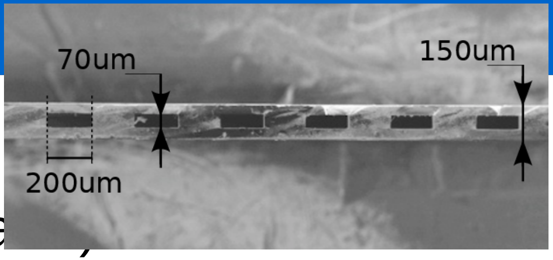
Irradiated @ 2.5 $10^{16}$ $n_{eq}/cm^2$ , $\alpha_{tilt} = 0°$



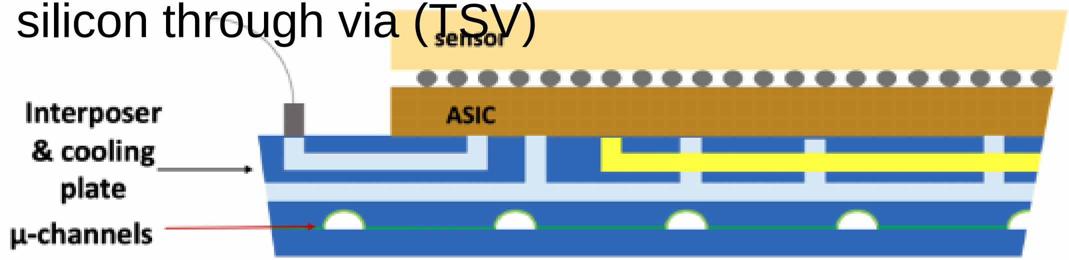
$\sigma_{eff} = 10.3 \pm 0.5$ ps @ 150V

To be compared with 11 ps @ 100 V of the not-irradiated case

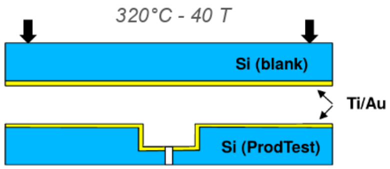
# Tracker: Cooling Plates

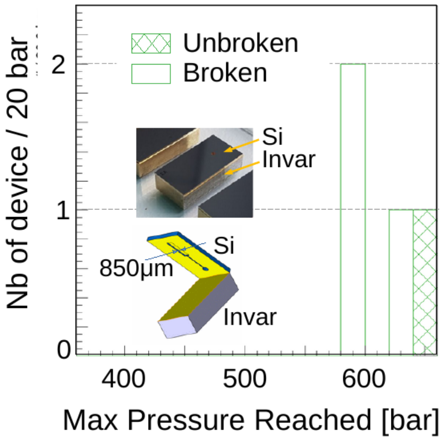


- **Micro-channel cooling** (thin + high cooling power)
- Technology pioneered by NA62 (liquid) and LHCb (bi-pha )
- For NuTAG, **a step further** in integration is needed to cover large (0.1m²) areas
  - **cooling plate serves as electronic interface** connected to ASIC with silicon through via (TSV)



- R&D on-going in Marseille using **Au thermo-compression**
  - Gold layer can be patterned to serve electrical function
  - Process compatible with Si/Si, Si/Metal (connectors) and with el
- **Timescale**
  - Prototype made of 3 planes of about 10x10cm² by 2028
  - Could be re-used at NA62

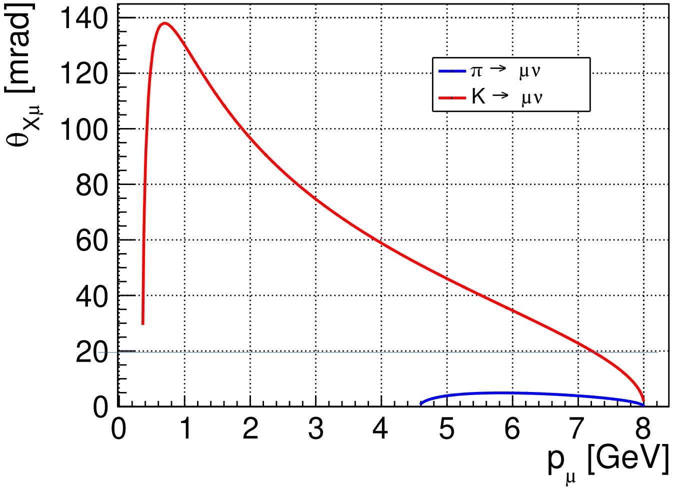


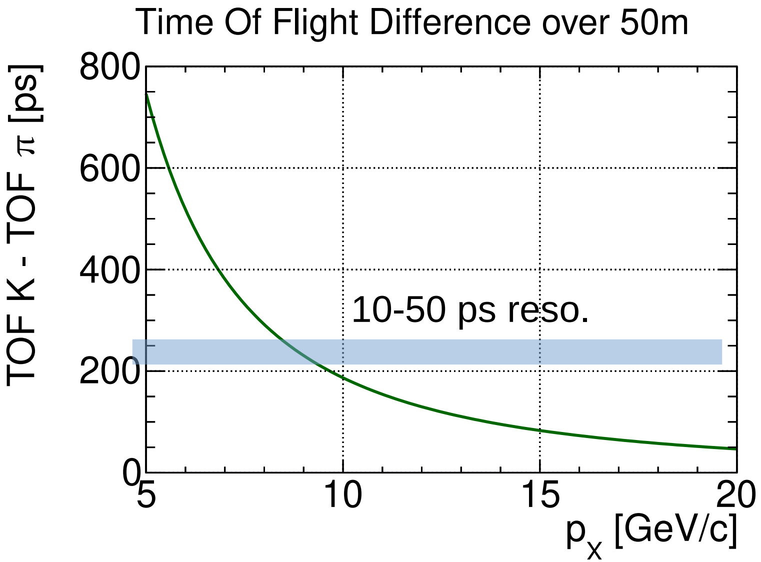


# $\nu_\mu$ cross section and interaction models

- NuTAG will reconstruct **all $\pi^+ \rightarrow \mu^+ \nu_\mu$ and $K^+ \rightarrow \mu^+ \nu_\mu$** with a <0.6% reso. on the $\nu_\mu$ energy
- Decay kinematics offers a very **good control of the background**
- **$K^+$'s and $\pi^+$'s can clearly be separated** using
  - Time-of-Flight (pixels have 10-50ps reso.)
  - Kinematics ($\theta_{X\mu}$ vs $p_\mu$ where X is π or K)

- Excellent sample (>$10^6$ νμ) to
  - **measure cross section** and **differential cross section** (wrt energy)
  - improve **interaction model**, as ν energy is **known independently of the interaction**




Time Of Flight Difference over 50m

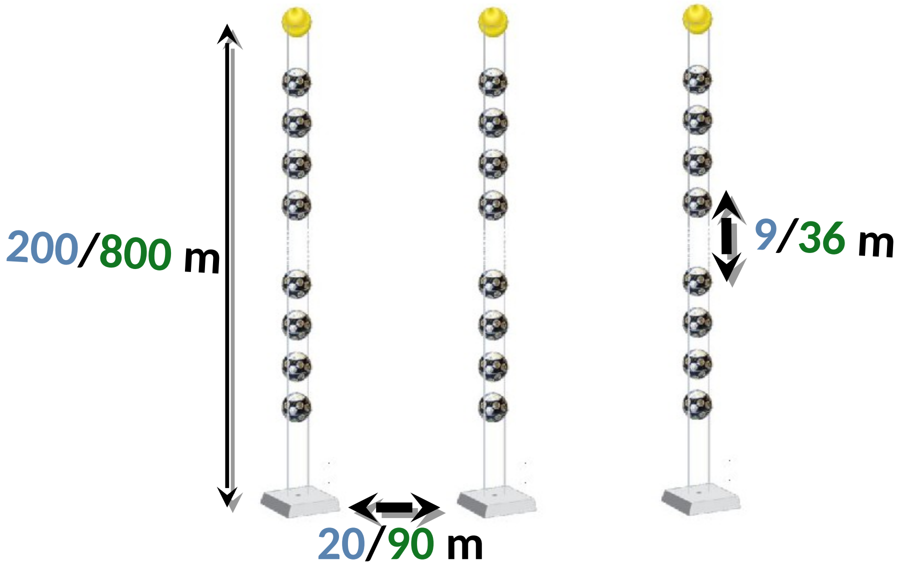
Letter of intent for KM3NeT, J. Phys., 2016, G43, 084001, arXiv:1601.07459

# KM3NeT/ORCA

- Three sites explored in **France**, **Italy** and **Greece**
- **Two detectors under construction** until ~2026:

**ORCA**:
Depth: -2500m (**France**),
Energy **thres. 3 GeV**
**Eff. Mass: 7 Mton**
**Neutrino oscillation**

**ARCA**:
Depth: -3500m (**Sicily)**
Energy **thres.: 100 GeV**
**Eff. Mass: Gton**
**Neutrino astronomy**



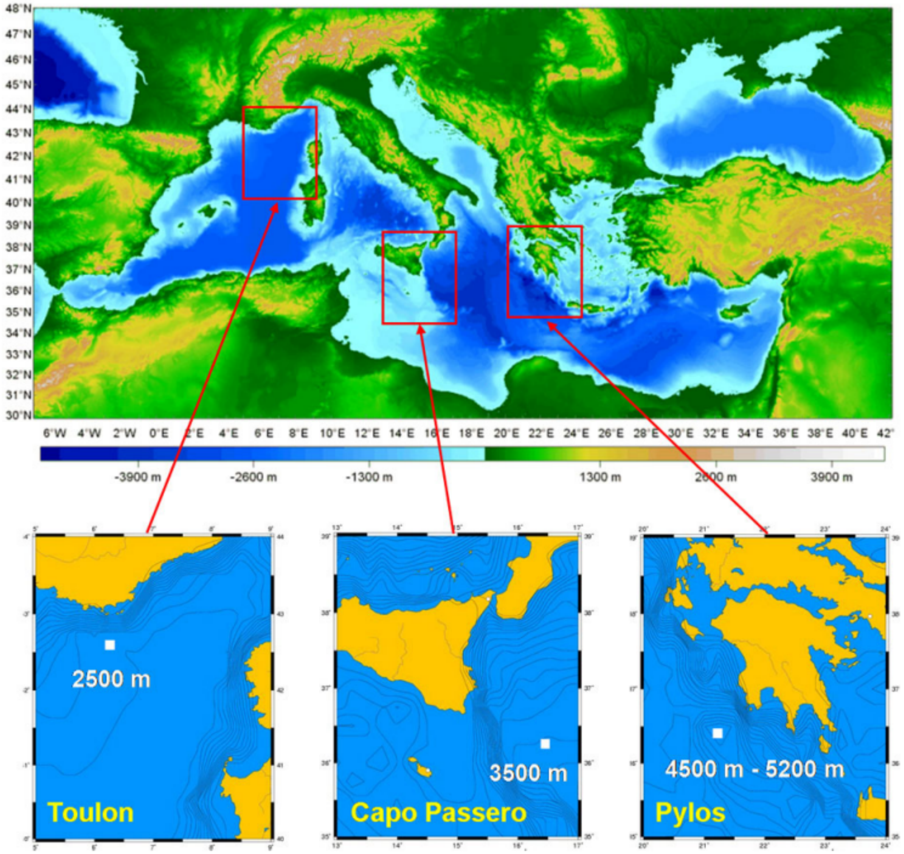
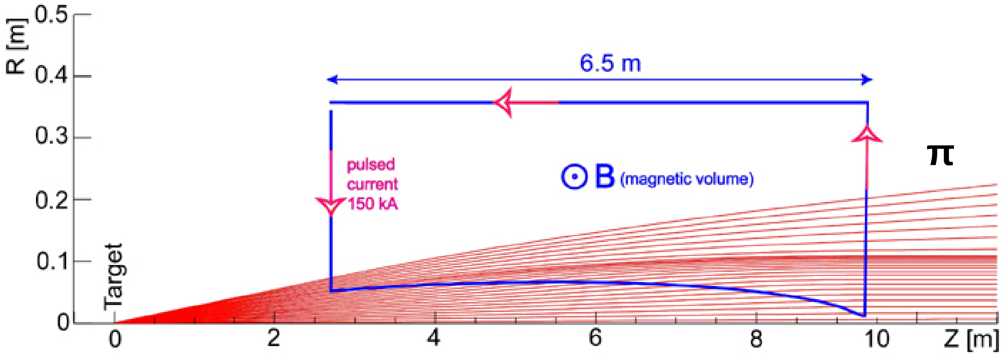


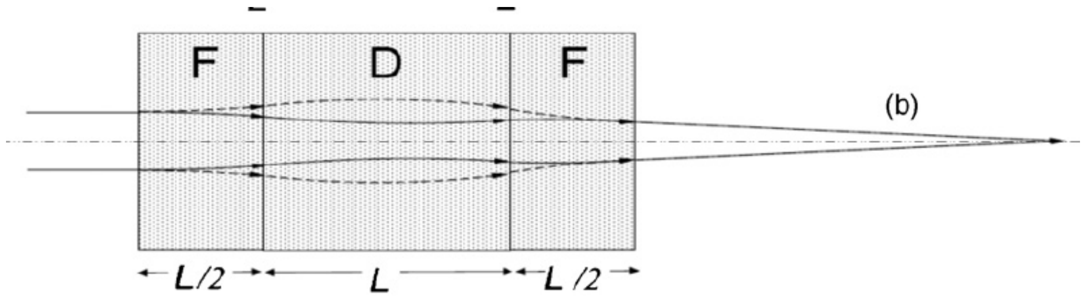
Figure 1-6: Locations of the sites of the three Mediterranean neutrino telescope projects.

# Beam line: π collimation in slow extraction

- **π collimation** is mandatory to achieve high neutrino yields
- Beam lines normally use **magnetic horns**
    - horns operate in **pulsed (μs) mode**
    - **heating** induced by the large current prevents the use in continuous **mode**



- CERN-PBC started to develop, for ENUBET & NUTAG, a static π collimation system using only **quadrupoles**



- **Advanced static solutions** (magnetic spokes, solenoid lens, cryogenic horns) were designed but never implemented