Neutrino Tagging (NuTAG)

— A new tool for accelerator based neutrino experiments —

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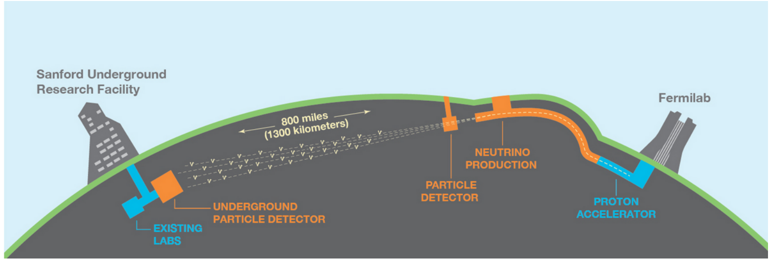
Seminar at Birmingham

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**:
  - on of the **least explored** field 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**)

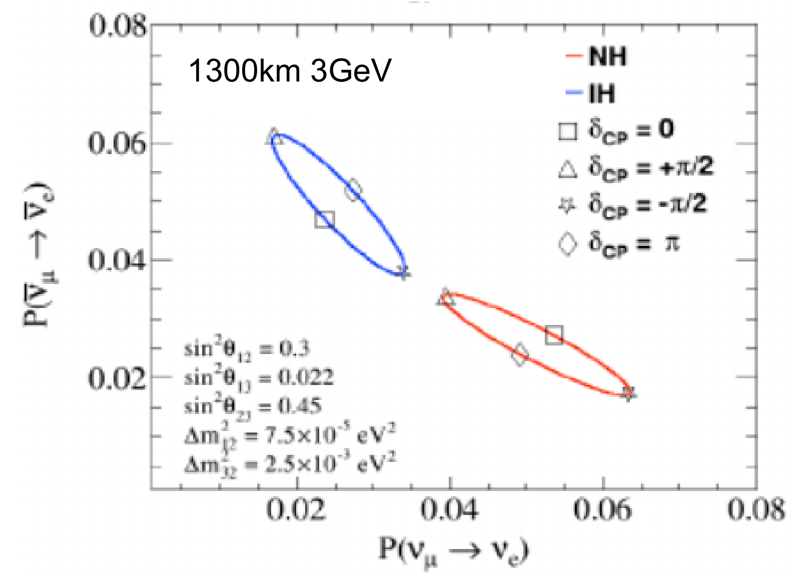


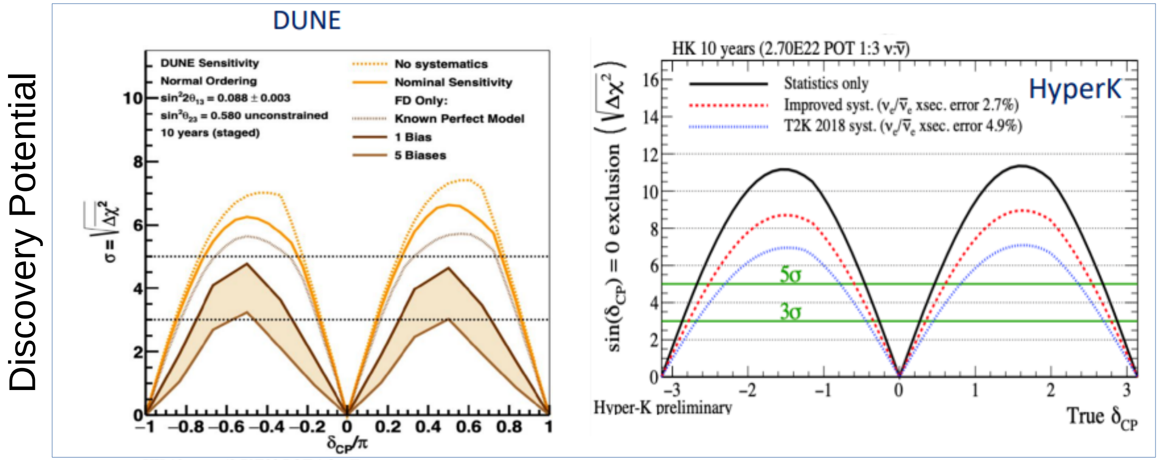
DUNE

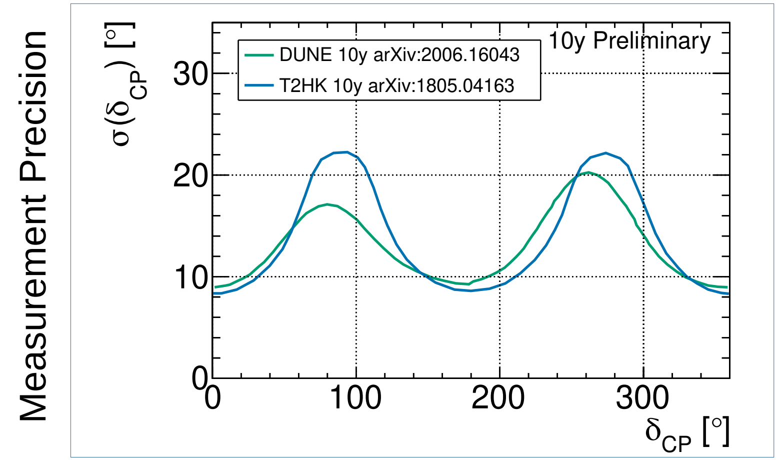
K2K → T2K → T2HK

CP violation experimental studies

- Leptonic CP violating phase $\boldsymbol{\delta_{CP}}$
  - Ranges for 0 to 360°
  - CP conserved if δCP = 0° or 180°
  - CP maximally violated at 90° and 270°
- Measurement principle:
  compare $P(\nu_\mu \rightarrow \nu_e)$ and P(**anti**-ν_μ**➔anti**-ν_e)
- Expected status **at the end of DUNE & T2HK**







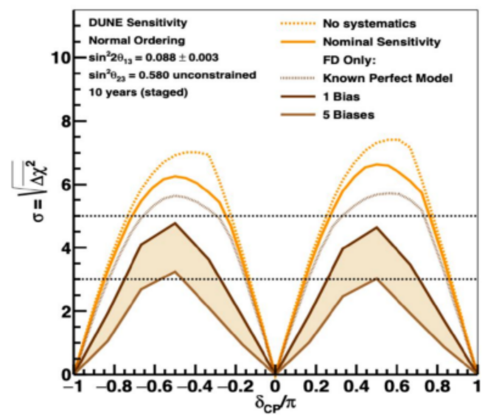
DUNE and T2HK limitations

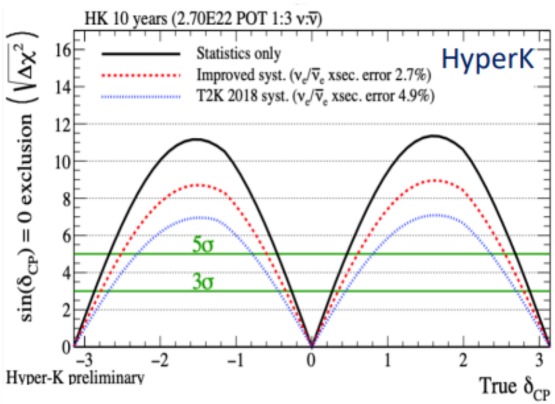
- Strong impact of the **systematic uncertainties** on
  - neutrino **cross section**
  - neutrino **flux**
  - **detector response** (e.g. energy scale)
- **Statistics** is also limited:
  ~250 ν_e/year and 150 anti-ν_e/year
- Two recommendations from **European Strategy for Particle Physics**:

> 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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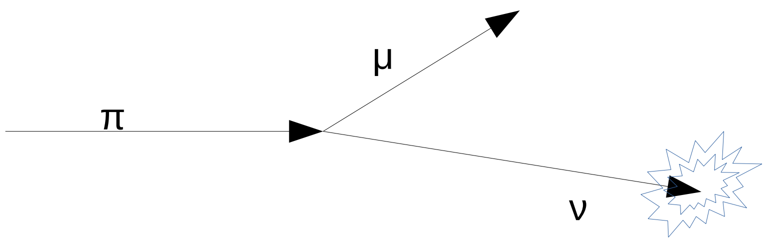
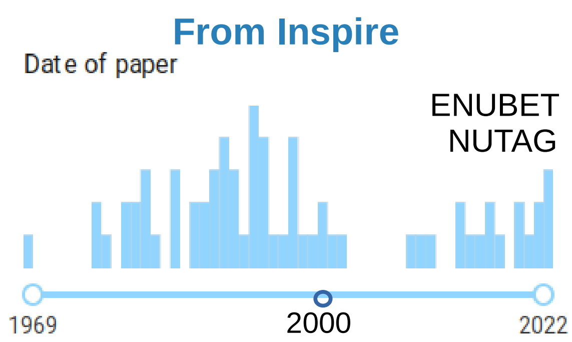
Neutrino Tagging

- 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



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

Tagging Direct Neutrinos. A First Step to Neutrino Tagging.

B. Pontecorvo

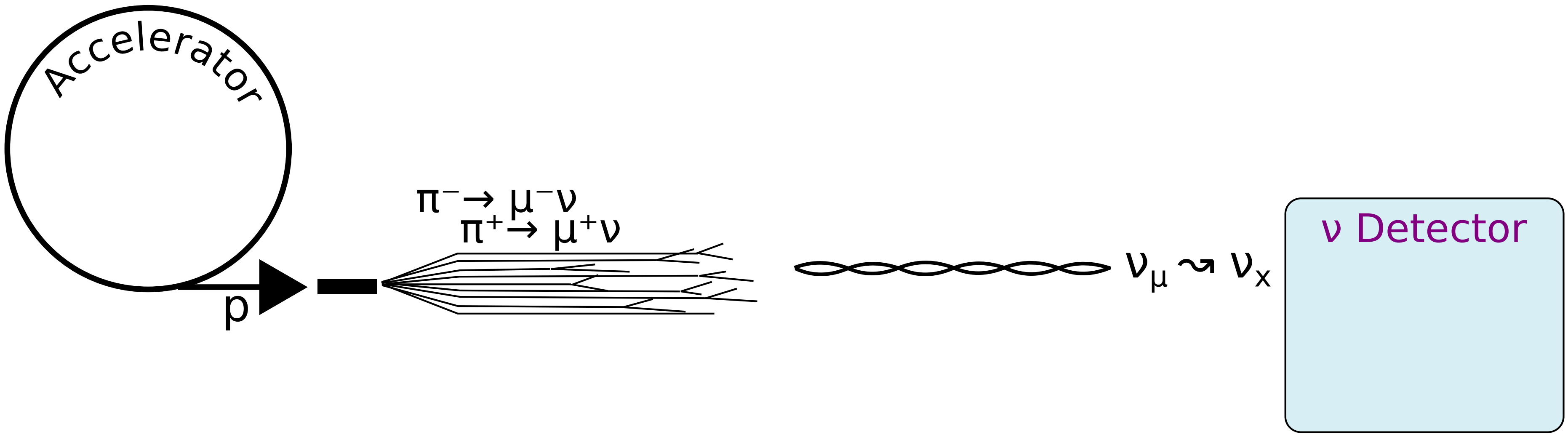
Laboratory of Nuclear Problems, Joint Institute for Nuclear Research - Dubna, USSR

(ricevuto l'1 Giugno 1979)

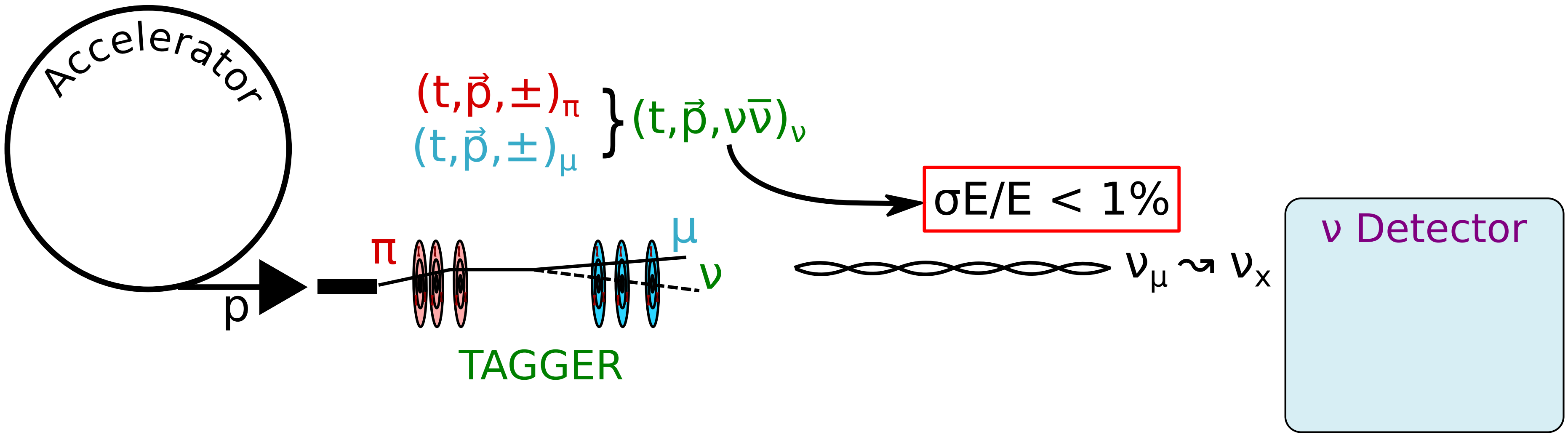
As it is well known, high-energy neutrino investigations are performed by using neutrino beams from π and K decays ($\pi \to \mu\nu$, $K \to \mu\nu$), that is by letting the pions and the kaons decay over a large distance (the so-called decay length).

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

Neutrino Tagging

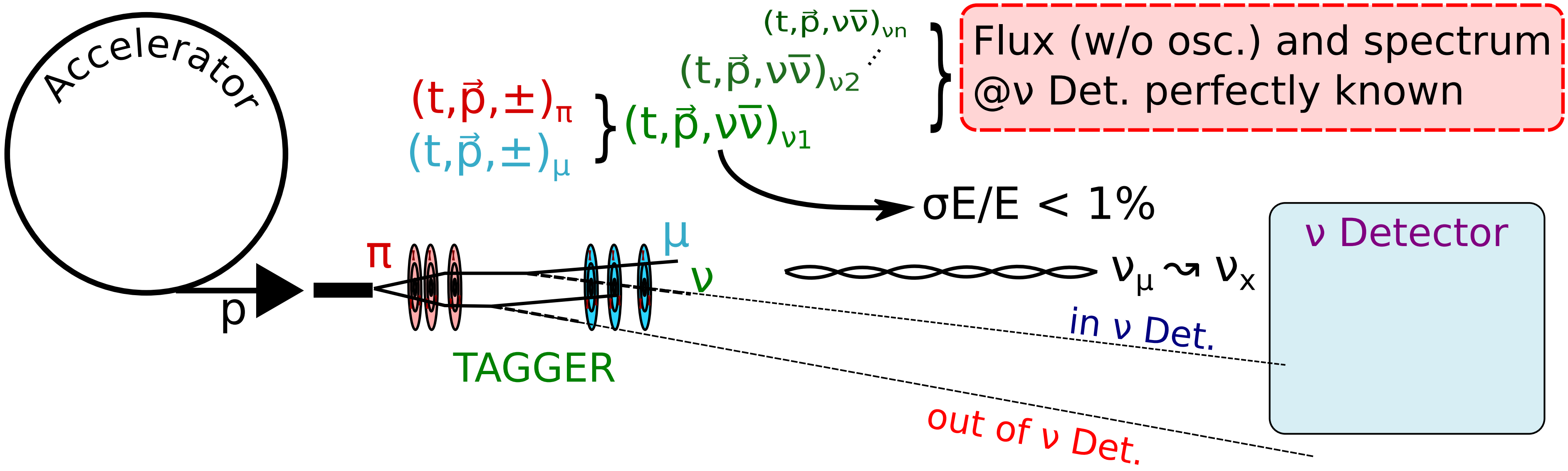


ν tagging – Beam Instrumentation

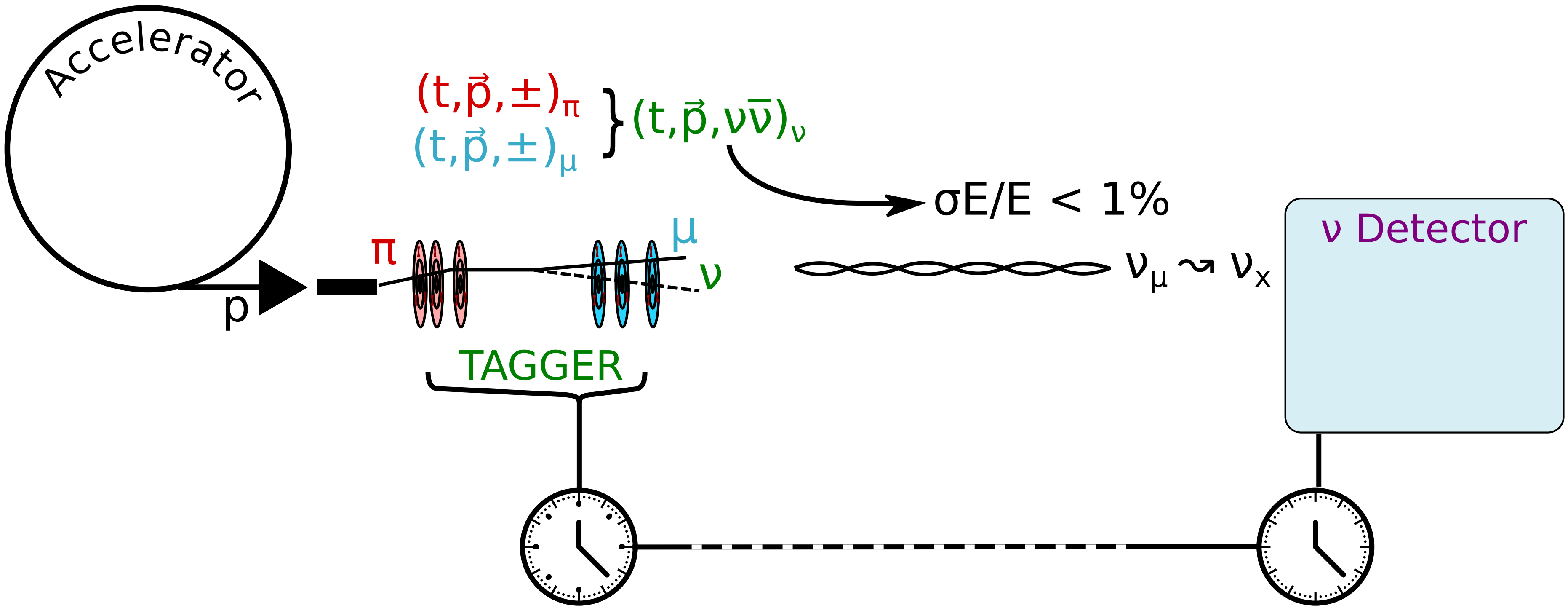


- Each neutrino is fully & precisely **characterised from its decay partners**

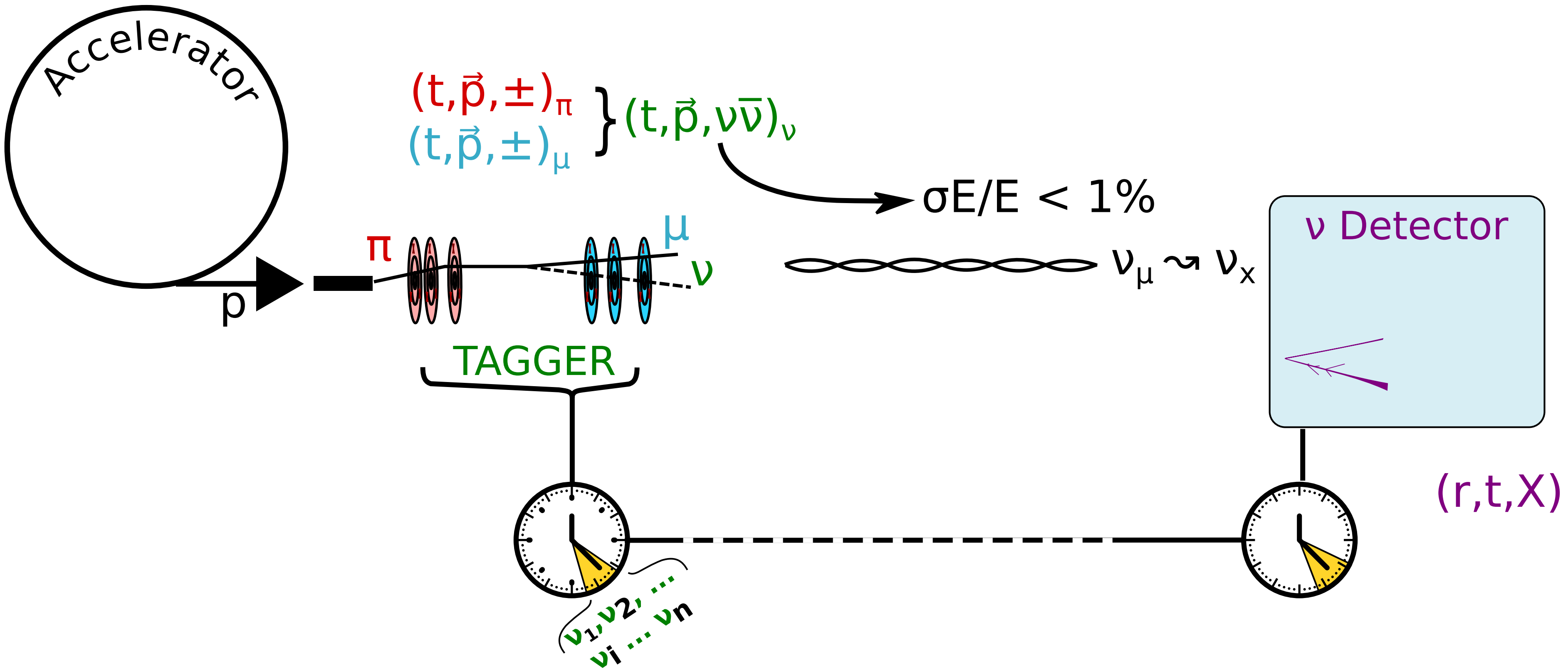
ν tagging – 1. Flux Determination



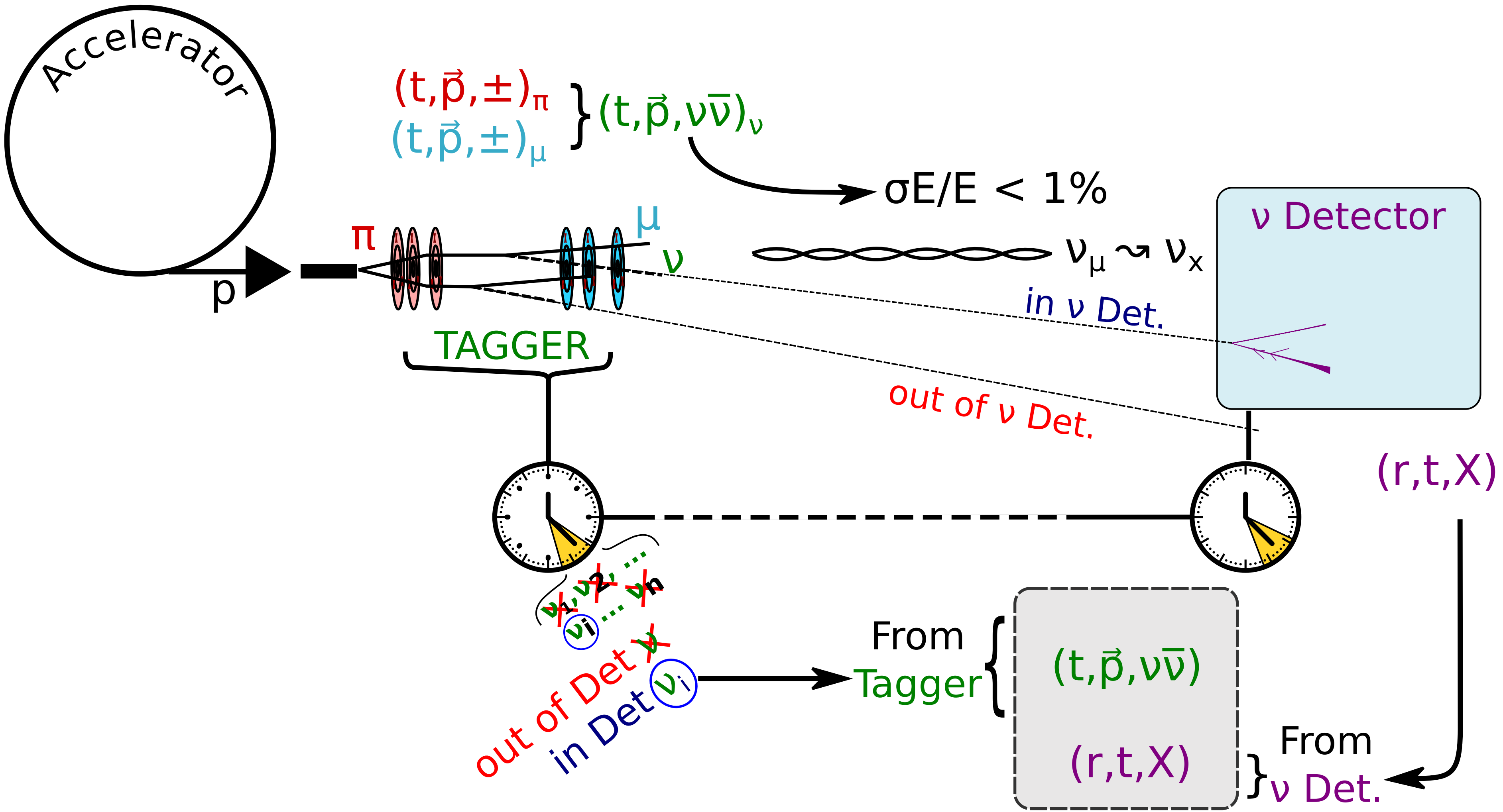
ν tagging – 2. Reco. Improvement

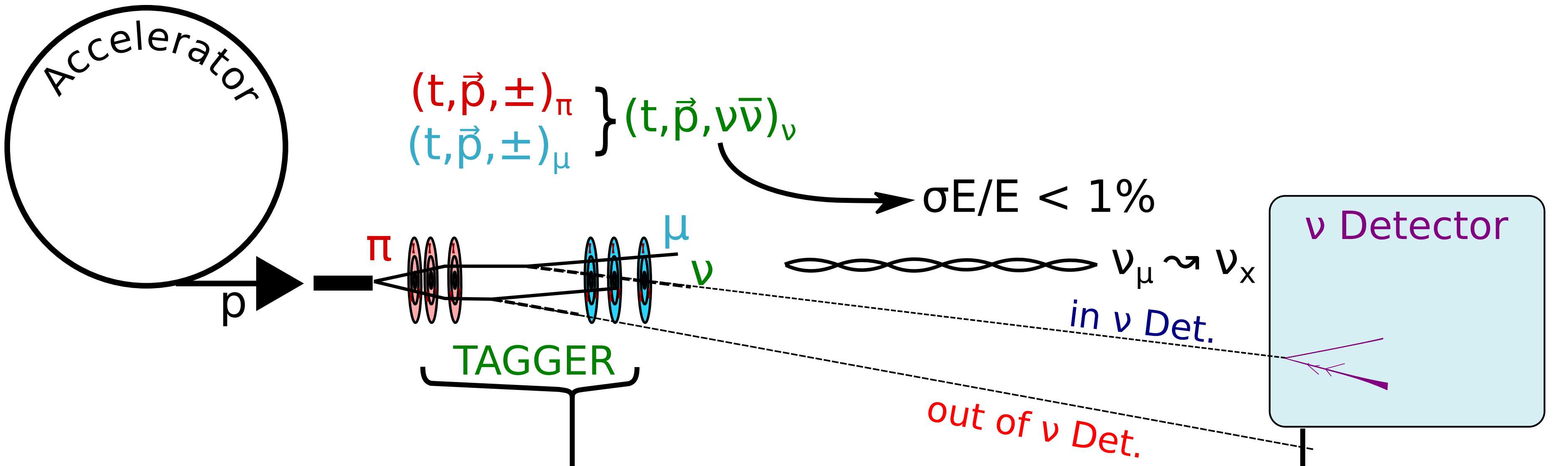


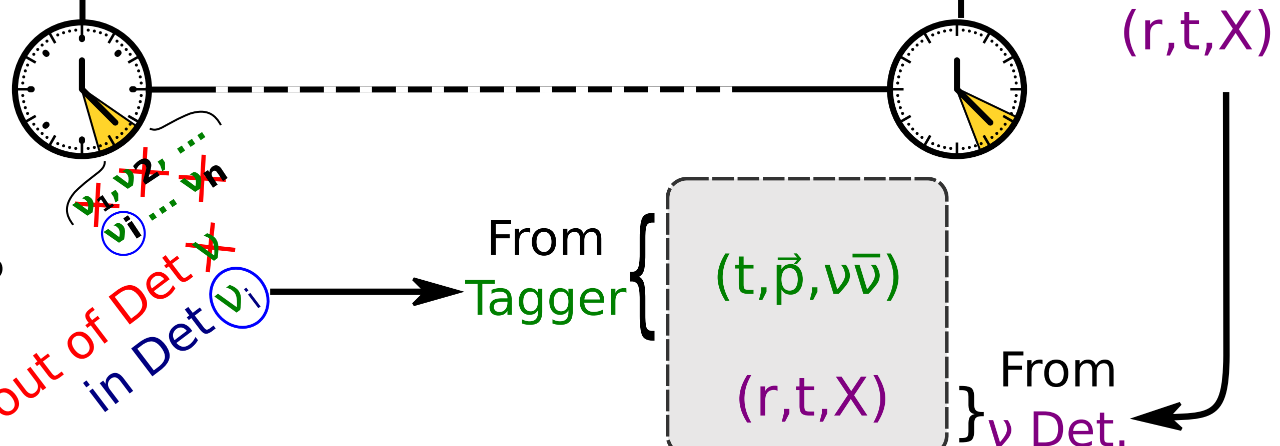
ν tagging – 2. Reco. Improvement



ν tagging – 2. Reco. Improvement







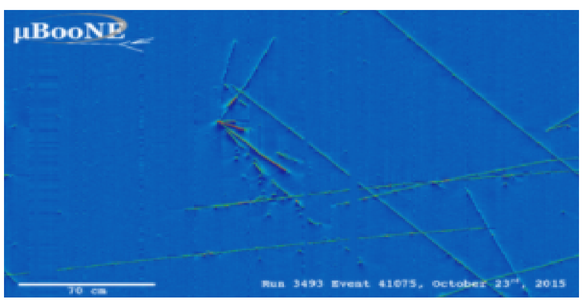
Idea Situation to study:

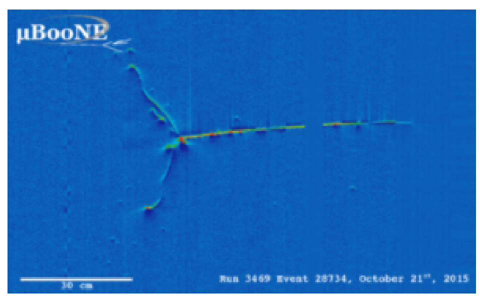
- cross-section (SBL)
- neutrino oscillation (LBL)

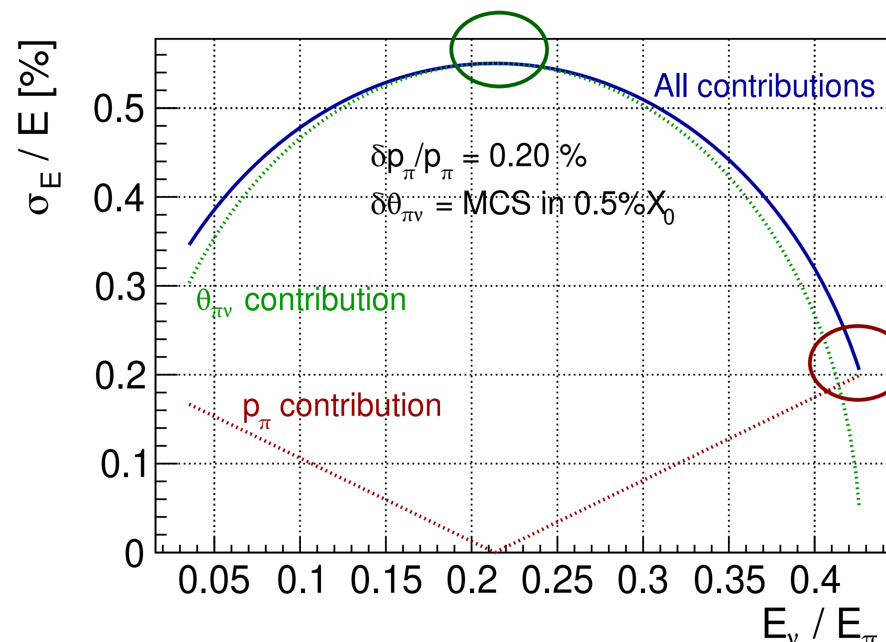
NuTAG addresses the **ESPP recommandations**

What about Energy Resolution?

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







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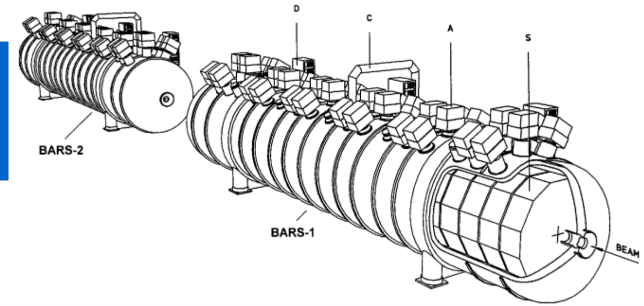
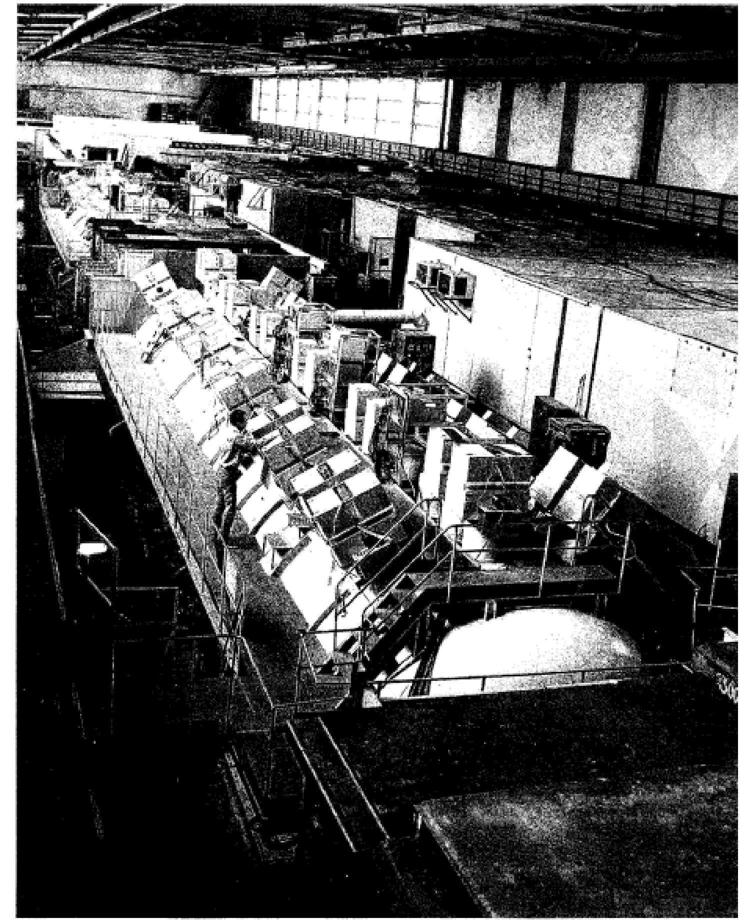
Experimental Demonstration

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





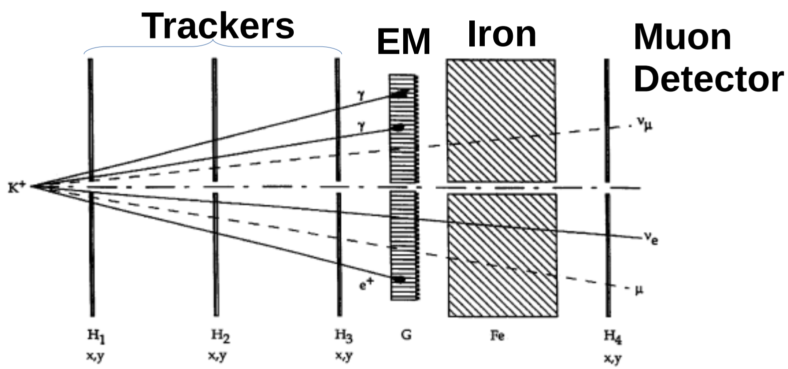
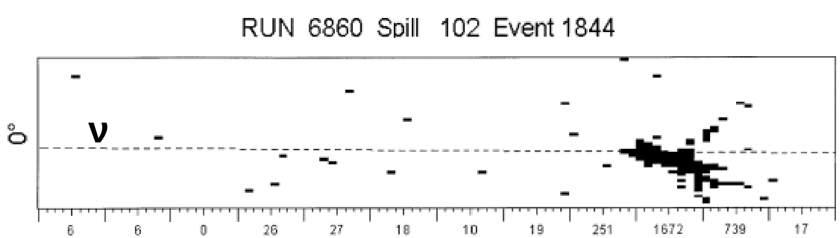


Рис. 2. Станция мечения. H1, H2, H3, H4 — двухкоординатные сцинтилляционные годоскопы (x, y); G — электромагнитный калориметр ГЕПАРД; Fe — 3-метровый железный поглотитель адронов.

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



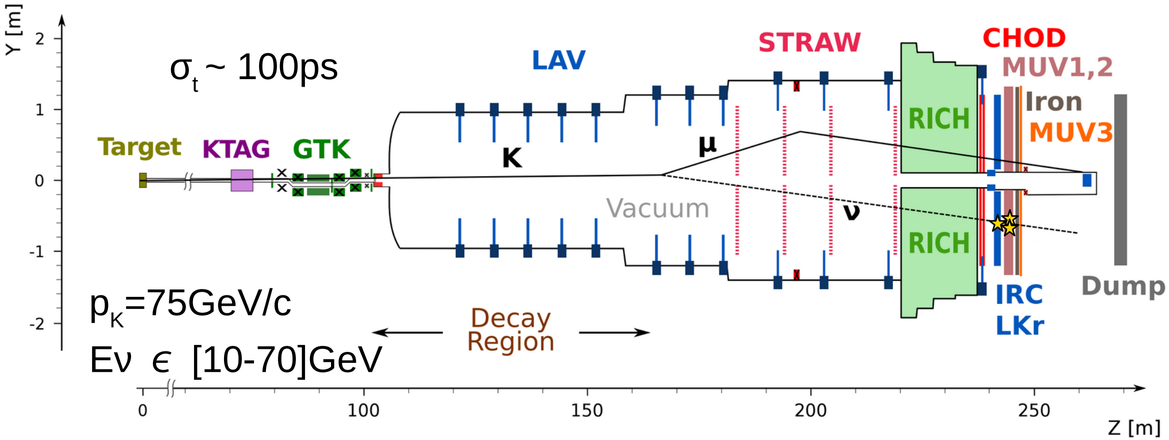
"The dotted line shows the ν_e trajectory calculated for a Kμν decay detected in the tagging station."

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

NA62

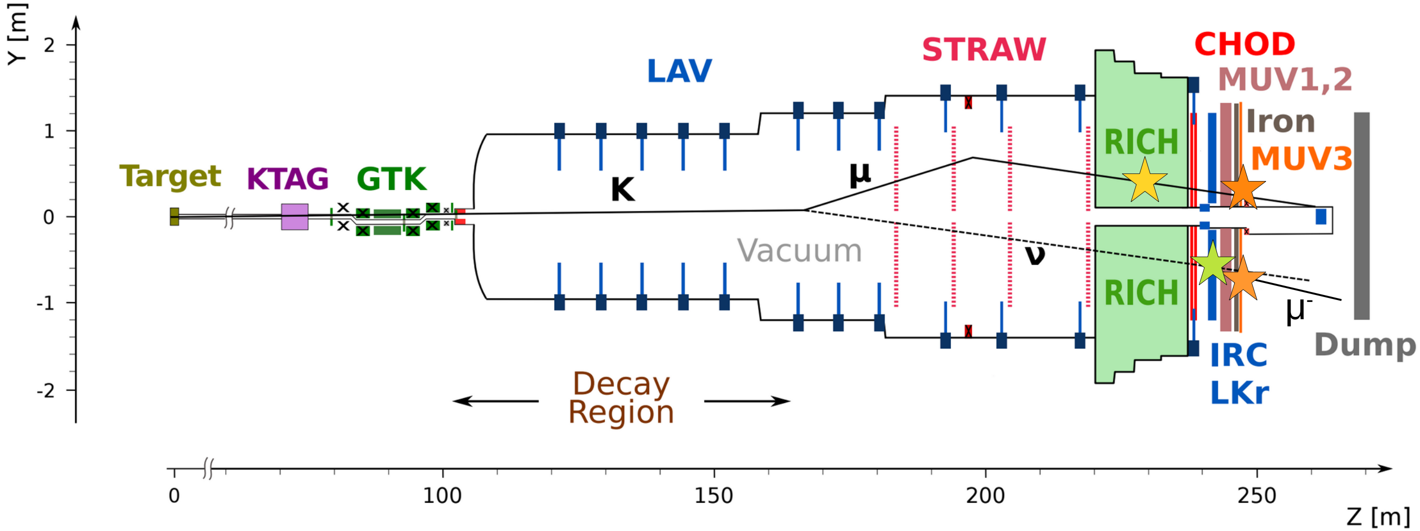
- **Neutrino tagging implemented at NA62** as a by-product
- **Calorimeters** (Lkr 20 ton and MUV1,2 66 ton) acts also **as ν detectors**
- With the O(10^{13}) K decays needed for the main analysis ($K^+ \rightarrow \pi^+ \nu\nu$) we expect:
  - **~300 ν's from $K^+ \rightarrow \mu^+ \nu_\mu$ interact in Lkr**
  - **~60 ν's from $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$ interact in LKr+MUVs**
- K^+, μ^+ and π^0 properties (t,$\vec{p}$,±) precisely measured thanks to GTK (Si-Pixel), STRAW and LKr



NA62

For more info check, the poster by Bianca De Martino at Neutrino22 https://doi.org/10.5281/zenodo.6785370

- Dedicated **trigger line** collect these events since 2022
  - muon in RICH ☆
  - energy deposit in Lkr (>5GeV) ☆
  - two muons in opposite quadrant at MUV3 ☆
- Both Kμ2 and Kμ3 **analyses are on going**
- Hopefully, some Kμ2 and Kμ3 events **will all particles (ν included) detected** will be available soon (world first!)



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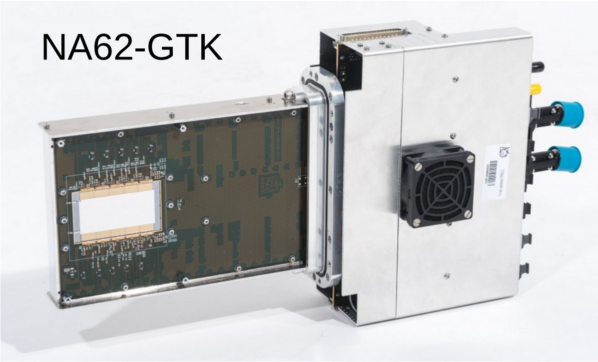
  - Beam particle rate
  - Beam line
  - Tracking technology
- Physics Case of Short and Long Base Line Tagged Neutrino Experiments

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	$10^{16\text{-}17}$ n_{eq}/cm^2	10-100 MHz/mm²

Sets the specifications for the beam line

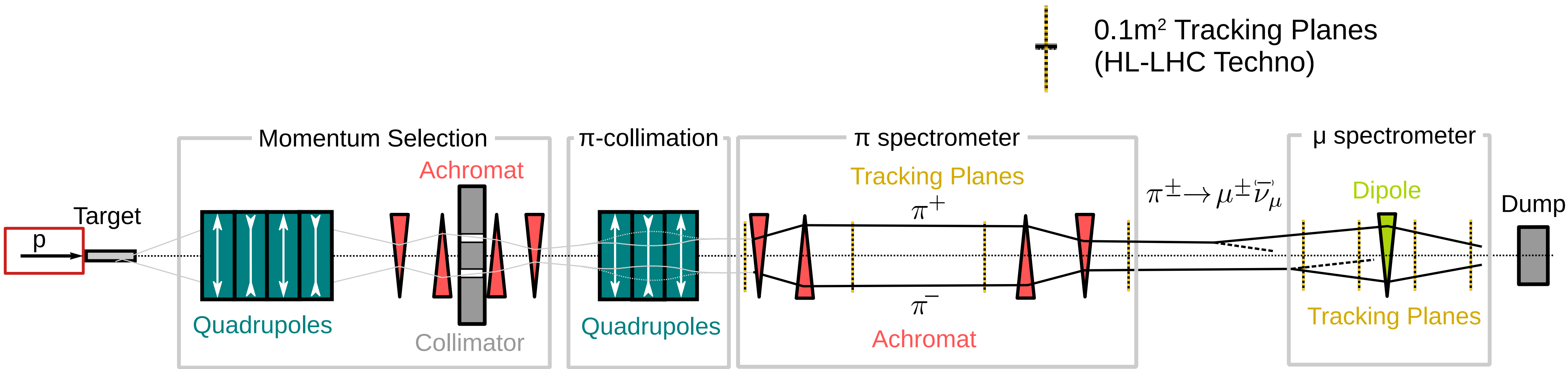


arXiv:1904.12837

- 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**

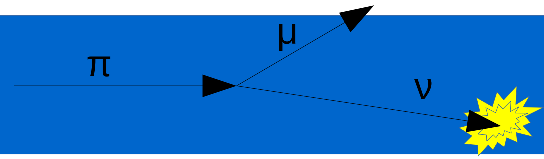
Tagged beam line conceptual design

- **Slow extraction (few sec.)** & **beam cleaning** to reduce π rate
- **Static π+ and π- Focussing Devices** replace conventional horns (see next)
- **Beam size** around **0.1 m²**
- Neutrino chirality determined evt by evt: **transport both π+ and π-**



Maximum rate for 10y operation ➔ $10^{12}\pi$/s
with 0.1m² of HL-LHC trackers

Matching with tag-ν



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

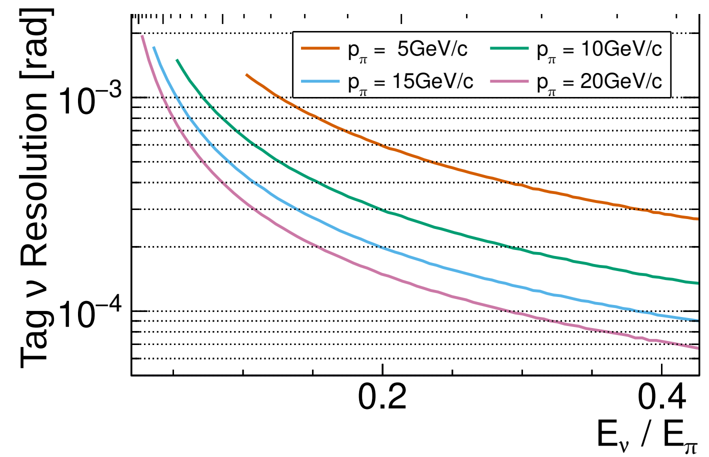
Association based on time and angular coincidence:

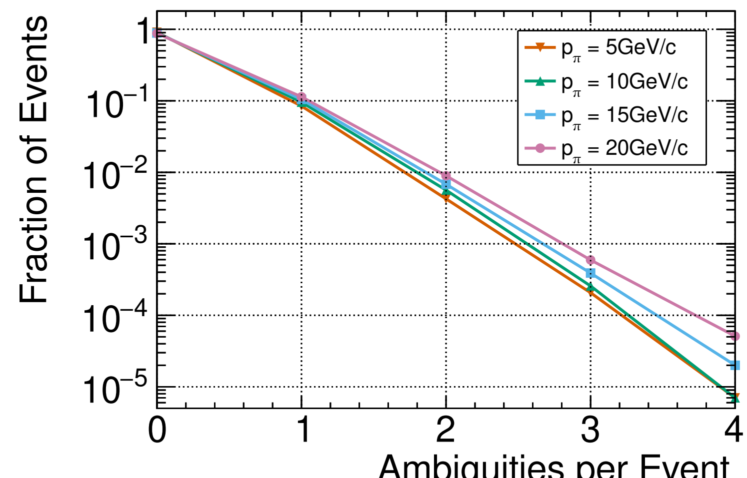
- **Time** coincidence: $t_{\nu\text{-tag}} - t_{\nu\text{-int}}$
  - Silicon Trackers will enable <10ps reso on tag-ν
  - Typical ν detector resolution is 10ns

➔ 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)

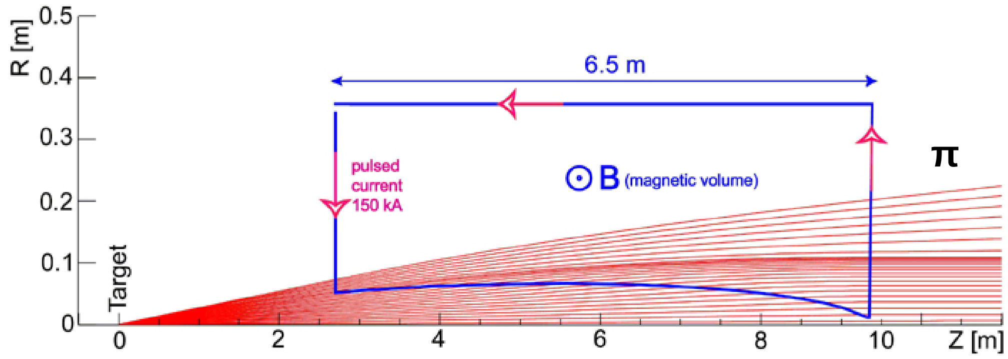
➔ **90% of the evt can be tagged w/o ambiguity**
Remaining **10%** have **> 1 tag-ν matched**

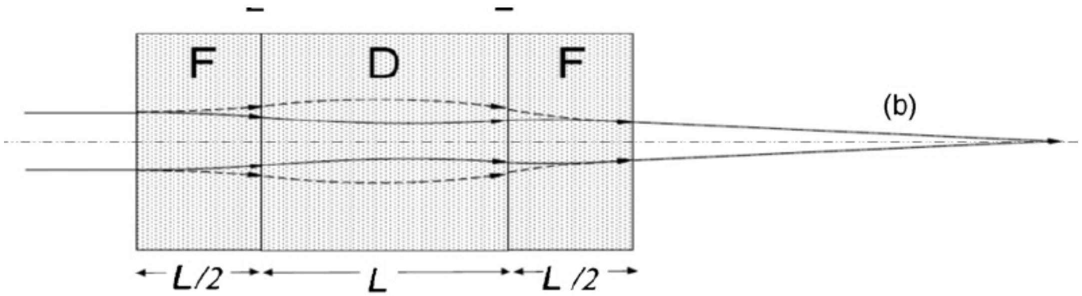




Beam line: π collimation in slow extraction

- **π collimation** is mandatory to achieve decent 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**



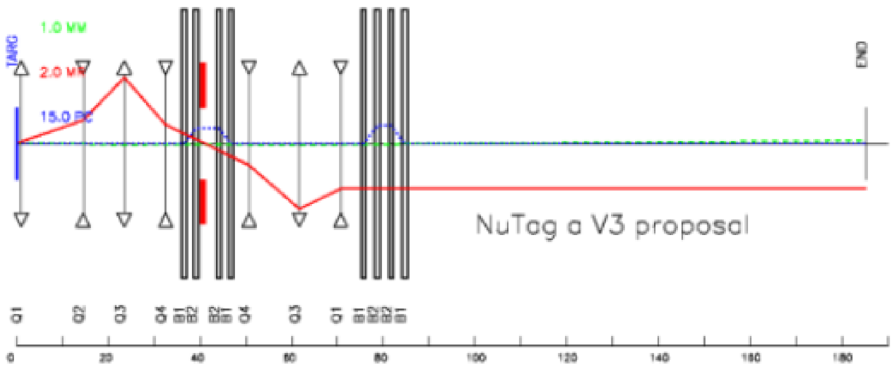


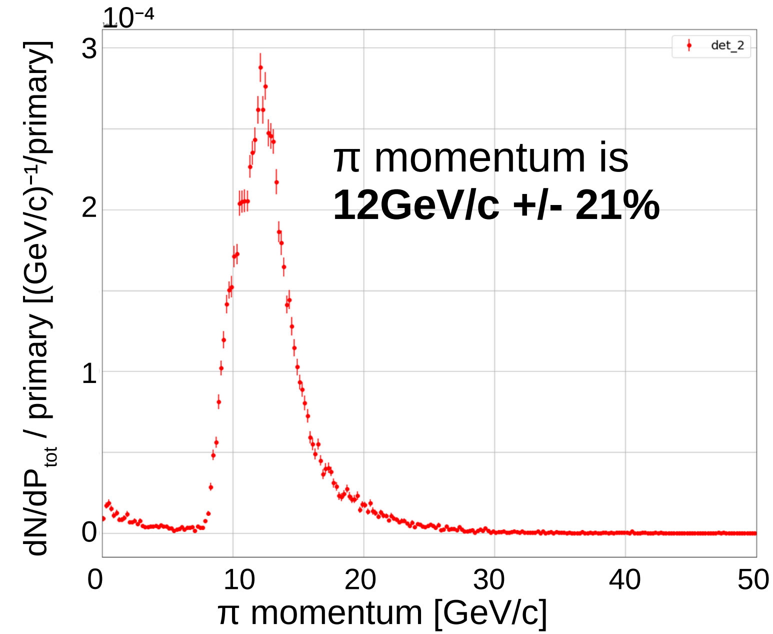
- **Advanced static solutions** (magnetic spokes, solenoid lens, cryogenic horns) were designed but never implemented

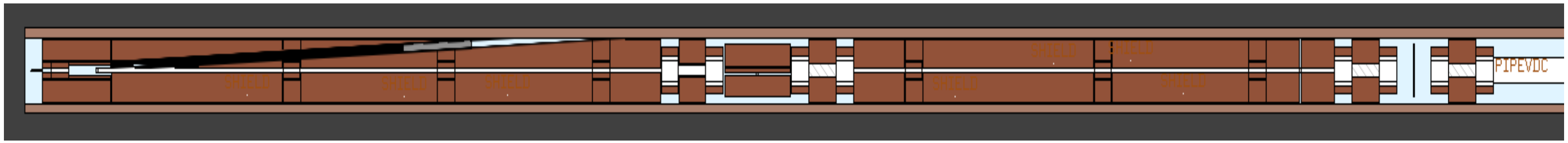
Static focusing studies (CERN)

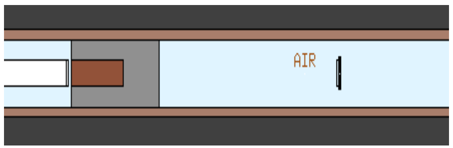
Nikolaos Charitonidis
Anna Baratto Roldan
Elisabetta Parozzi

- The double polarity line optics:
  - Production angle to evacuate primaries
  - 4 Quad. + double-achromat to select π momentum
  - 3 Quad. to collimate the beam
  - double achromat to measure π momentum





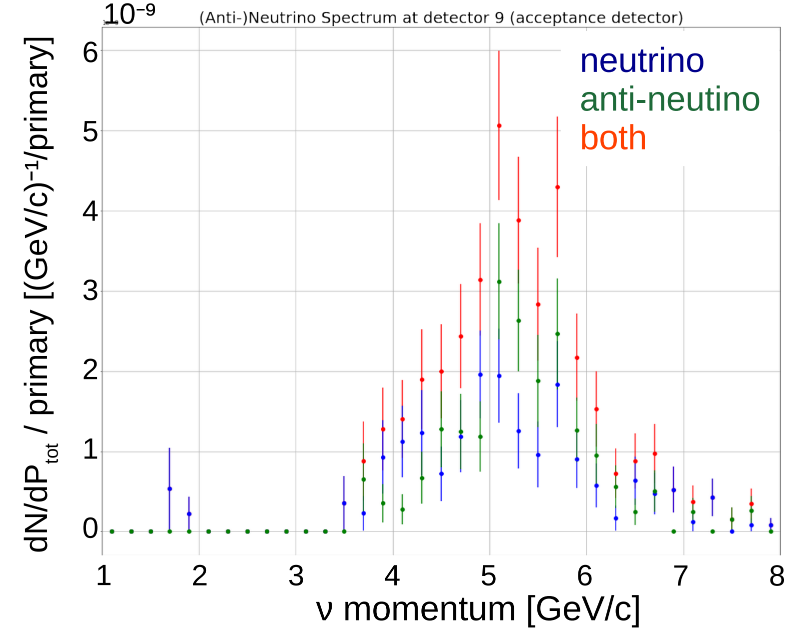


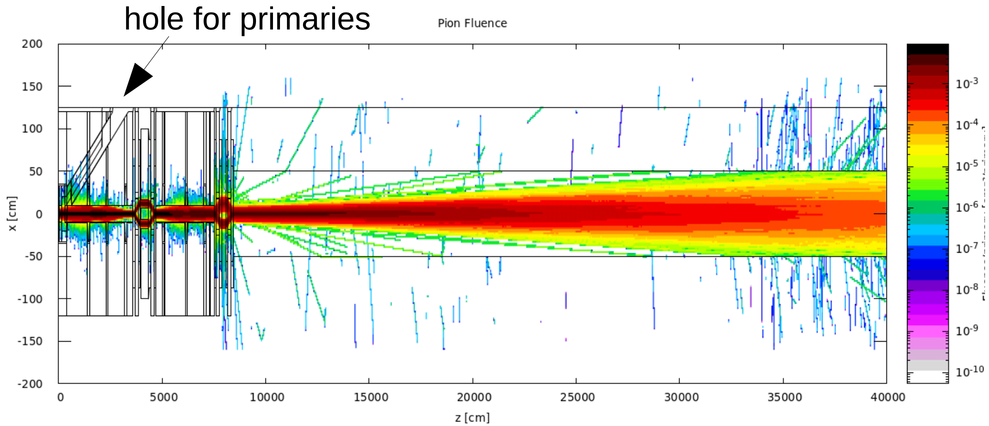


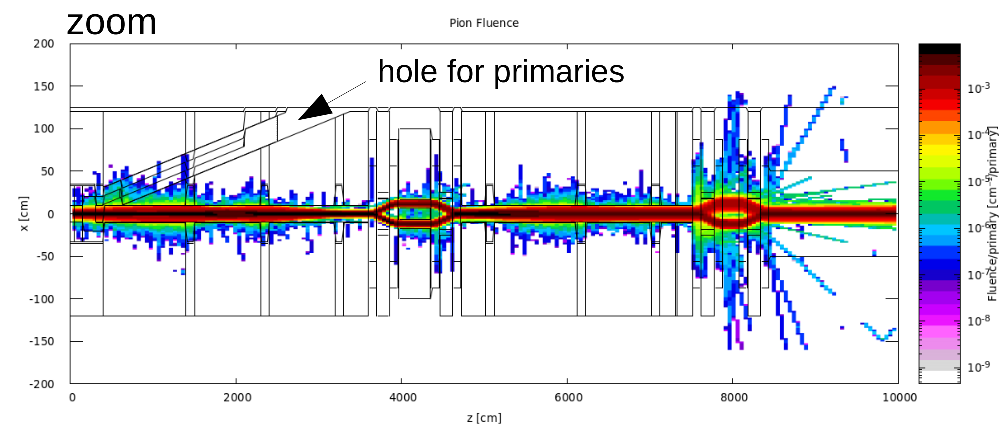
Static focusing studies (CERN)

Nikolaos Charitonidis
Anna Baratto Roldan
Elisabetta Parozzi

- Fluka **simulation**:
  - Beam **size is 40 x 12 cm**,
  - With 10^{13} protons-per-cycle (5s) the beam **particle rate at the tagger is 0.070 MHz/mm² (<<10MHz/mm2)**
- Margin to **increase the neutrino yield** (rate on axis is 1200 ν/cm² for 10^{19} POT and 400m long decay tube)
  - improve π transmission (no production angle)
  - enlarge momentum bite





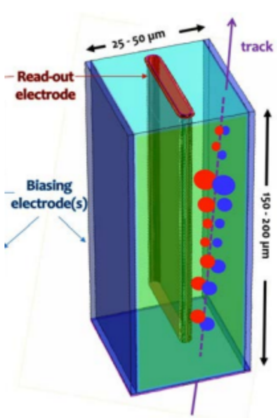


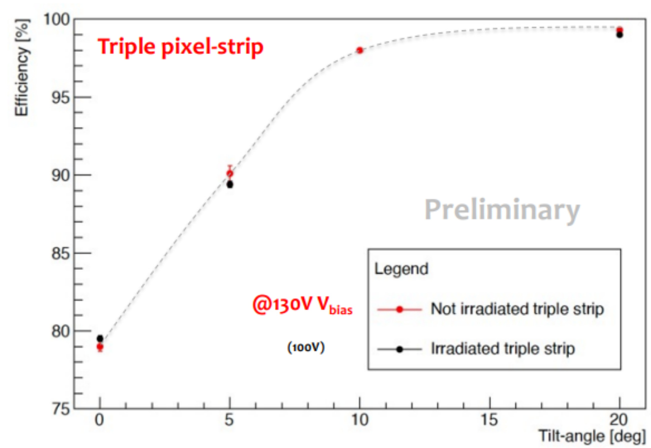
Tracker: Pixel Technology

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

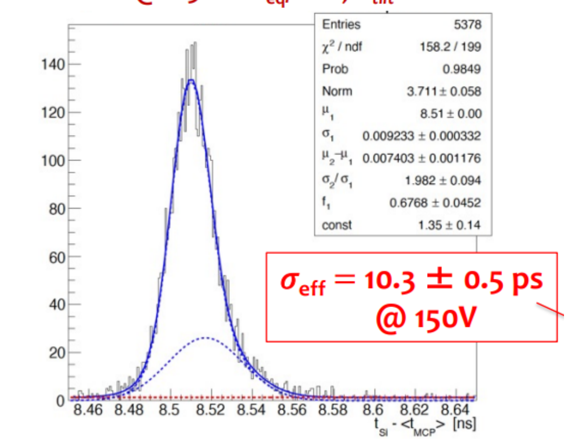
- Very **ambitious specs**, similar to the ones for **HL-LHC** experiments & **HIKE**
- TimeSpot (A. Lai, INFN Cagliari)
  - Trench 3D sensors
  - Excellent **time** and **radiation resistance** (being test at 10^{17} neq/cm^2 !)
  - ASIC development started (28ns) https://indico.cern.ch/event/1127562/contributions/4904519/ https://arxiv.org/abs/1703.08501

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





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



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

Tracker: Integration

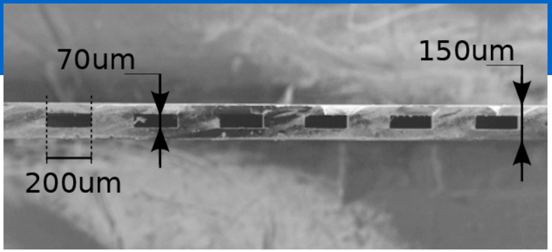
- The **mechanical+thermal+electrical integration** is very challenging
  - **large area** (100-1000cm²)
  - low **material budget** (<0.5% X0)
  - high **power consumption** (>1.5W/cm2)
  - high **efficiency** (sensor tilt, no hole)

- **Cooling performance** will ultimately determine the available ASIC power and so the **time resolution**

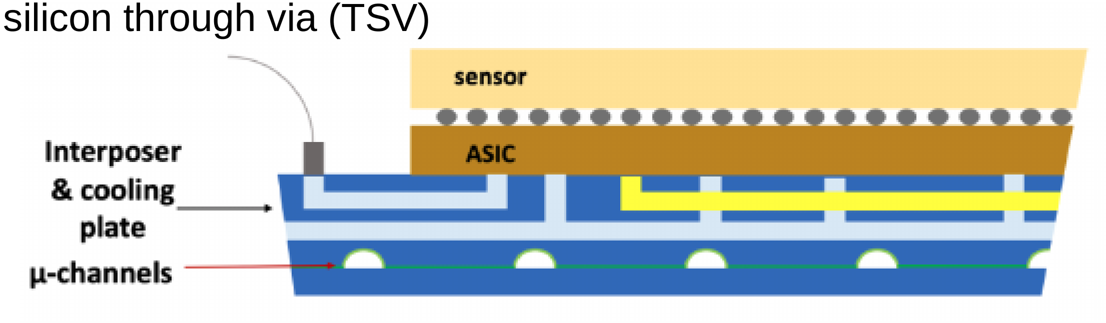
Extract from Monolith Workshop in Geneva (09.22) A. Lai

4. 4D timing is mainly not a matter of sensors or single devices, it is a matter of system constraints (power in primis, cooling, stable clock distribution, interconnectivity, data BW, material budget)

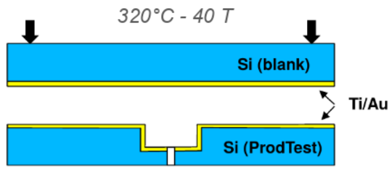
Tracker: Cooling Plates

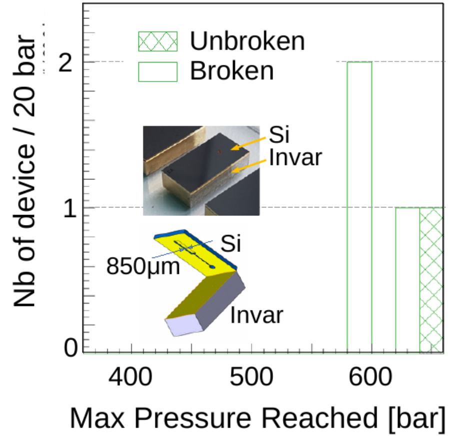


- **Micro-channel cooling** (thin + high cooling power)
- Technology pioneered by NA62 (liquid) and LHCb (bi-phasic)
- For NuTAG, **a step further** in integration is needed to cover large (0.1m²) areas
  - **cooling plate serves as electronic interface** connected to ASIC with silicon through via (TSV)



- 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 electronics
- **Timescale**
  - Prototype made of 3 planes of about 10x10cm² by 2028
  - Could be re-used at NA62



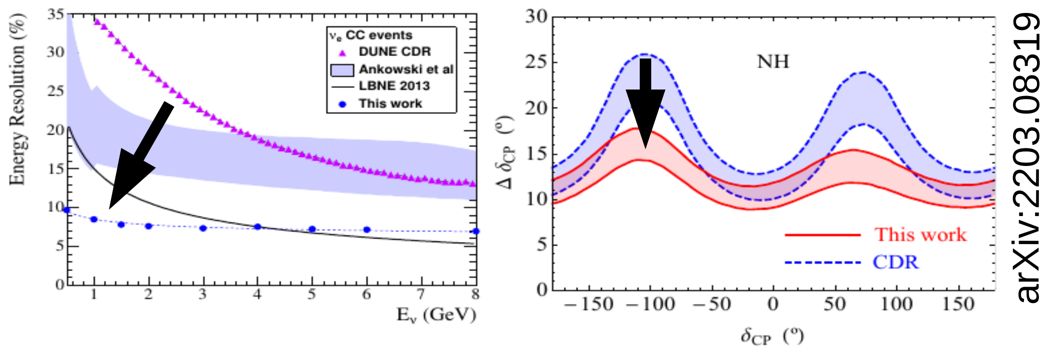


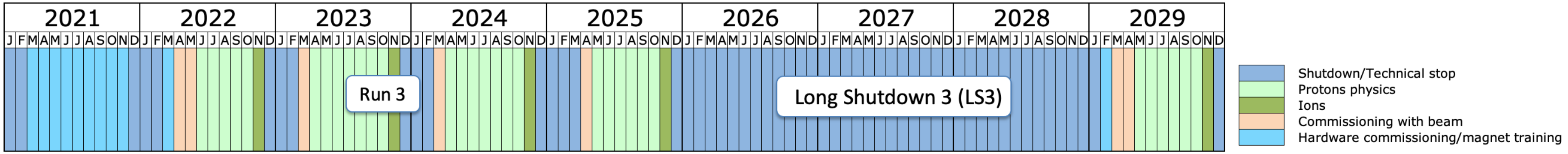
Outline

- 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
  - Short Base Line

Scientific program offer by NuTAG

- In the **short term,** a **short base line** experiment with detectors technology similar to DUNE and HK would greatly enhance their physics potential
  - measure the **absolute & differential cross section** at the 1% level for νe and νμ
  - improve the **interaction models** used to estimate the ν energy
  - strong synergy with **ENUBET** (see next)
  - Possible Time scale, implementation at CERN **after LS3**



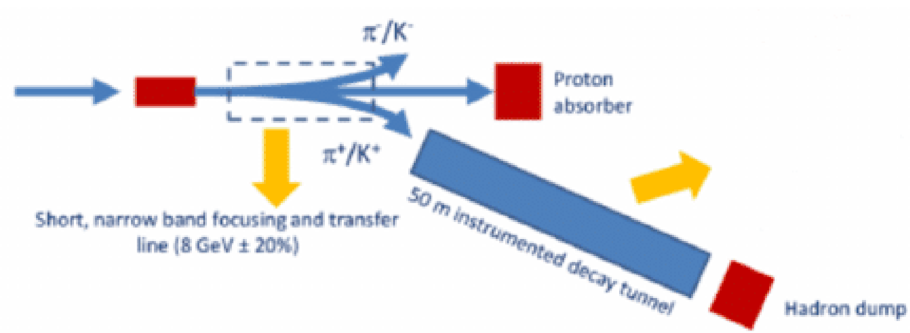


- In the **long term**, a **new kind of long baseline experiment** would allow to study neutrino oscillations with unprecedented precision (see next)

νe cross-section at SBL

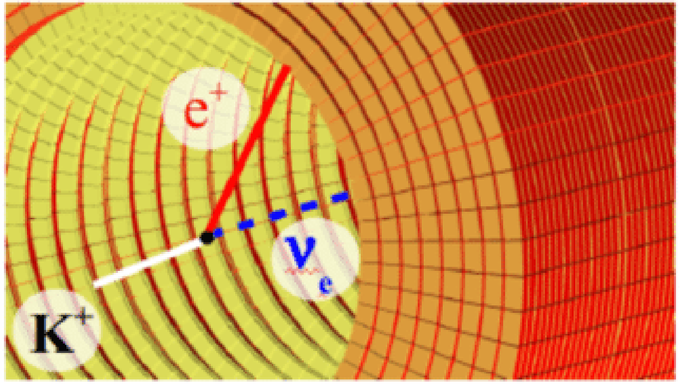
Mode	BR
$K^+ \to \mu^+ \nu_\mu$	63.56± 0.11
$K^+ \to \pi^0 e^+ \nu_e$	5.07 ± 0.04
$K^+ \to \pi^0 \mu^+ \nu_\mu$	3.352 ± 0.033
$K^+ \to \pi^+ \pi^0$	20.67 ± 0.08
$K^+ \to \pi^+ \pi^+ \pi^-$	5.583 ± 0.024
$K^+ \to \pi^+ \pi^0 \pi^0$	1.760 ± 0.023

- 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



ν_e cross-section at SBL

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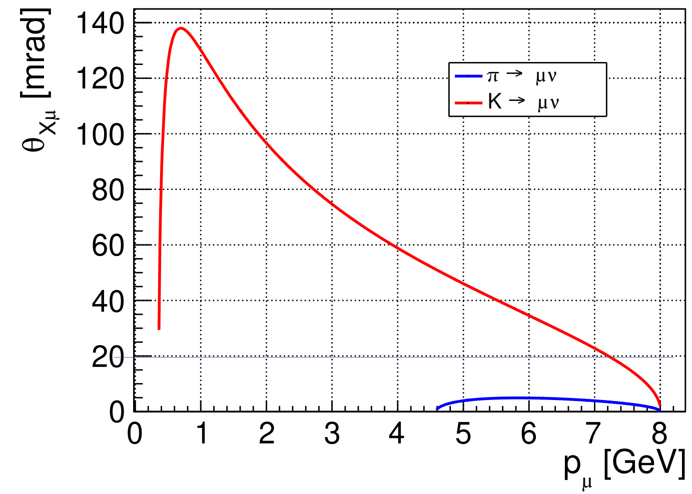
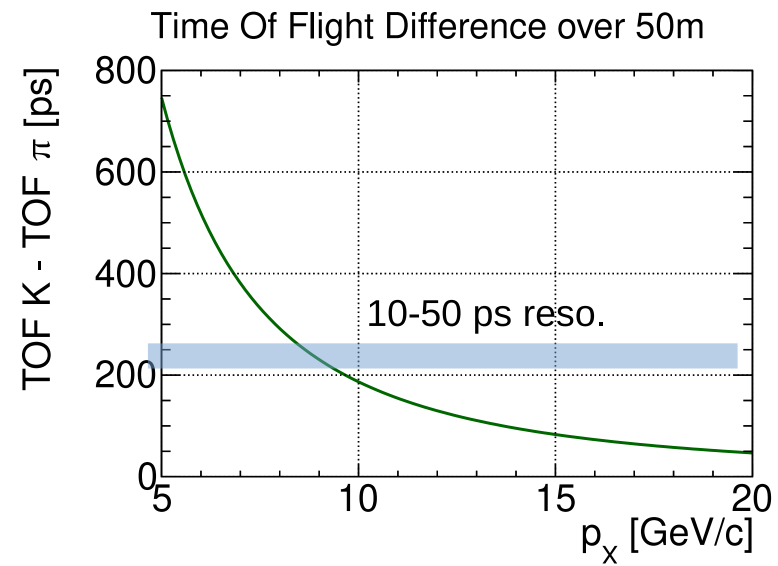
- Synergistic developments with NuTAG
  - Derive $N(K^+ \rightarrow \pi^0 e^+ \nu_e)$ from **$N(K \rightarrow \mu\nu)$** [more robust]
  - Use less POT with a wide band beam
    - K^+ and ν_e interaction can be associated (tbc)
    - K^+ momentum is know event by event
    - K^+ and K^- can be collected together

$K^+ \rightarrow \pi^0 e^+ \nu_e$

ν_μ 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 ν_μ energy
- Decay kinematics offers a very **good control of the background**
- **K^+'s and π^+'s can clearly be separated** using
  - Time-of-Flight (pixels have 10-50ps reso.)
  - Kinematics ($\theta_{X\mu}$ vs p_μ where X is π or K)





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

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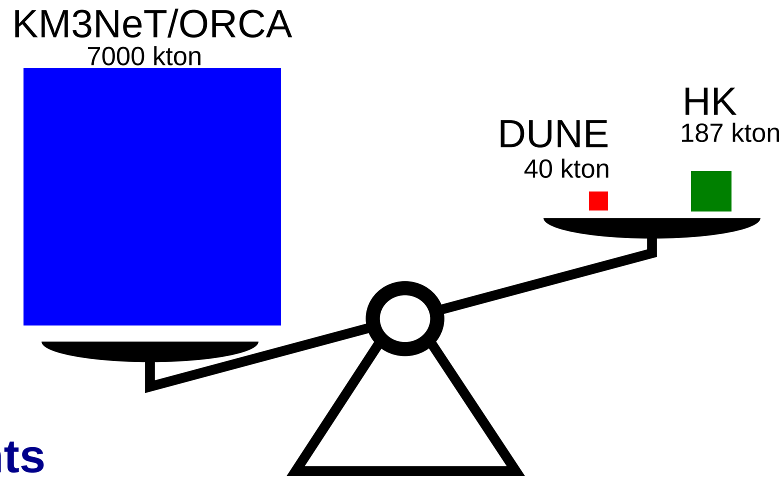
  - Long Base Line

NuTag for δ_{CP} Precison Measurement

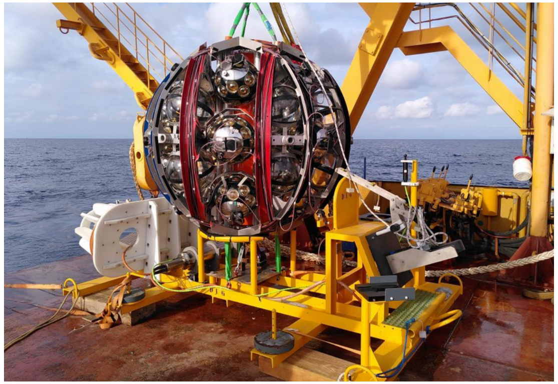
- **Future** measurements require **high statistics** and **low systematics**
- Very challenging for **conventional LBLNE**:
  - higher **power** beams
  - **larger** underground high granularity **far detectors**
  - more **precise near detector + dedicated experiments**

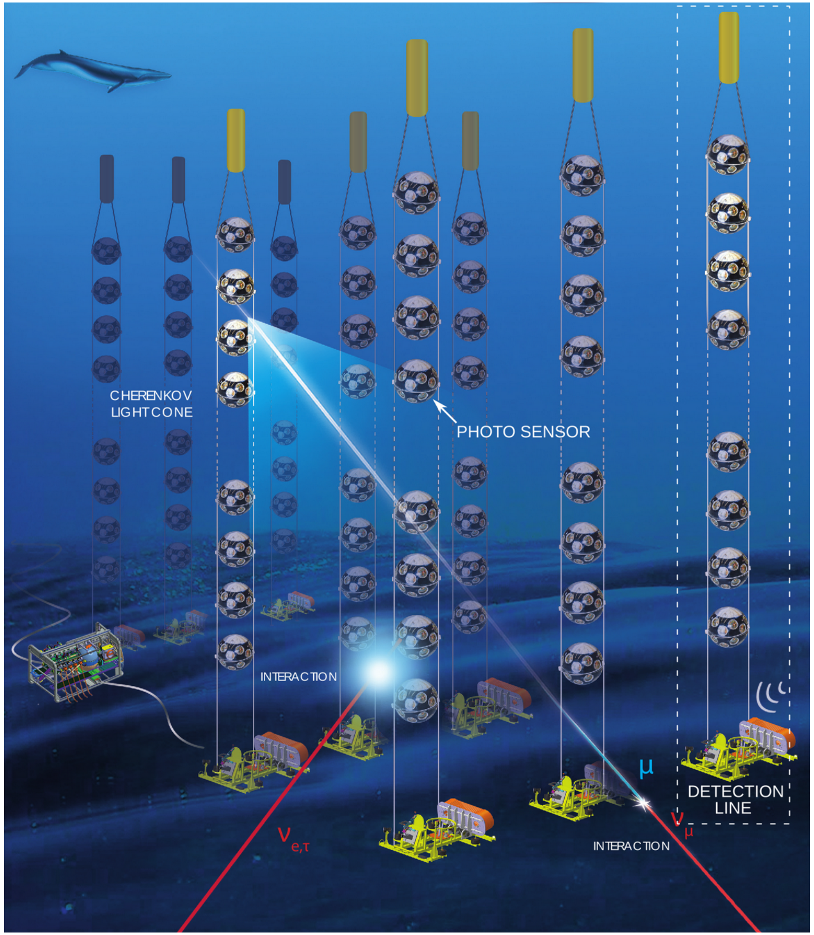


- **Alternative**:
  « ***low*** » **power tagged-beams + huge (>Mton) natural water Cerenkov detectors**
  - natural water detectors **size has virtually no limits**
  - detectors **poor granularity** (more than) **compensated by tagging**, ($\delta E/E<1\%$)
  - **reduced systematical uncertainties**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

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



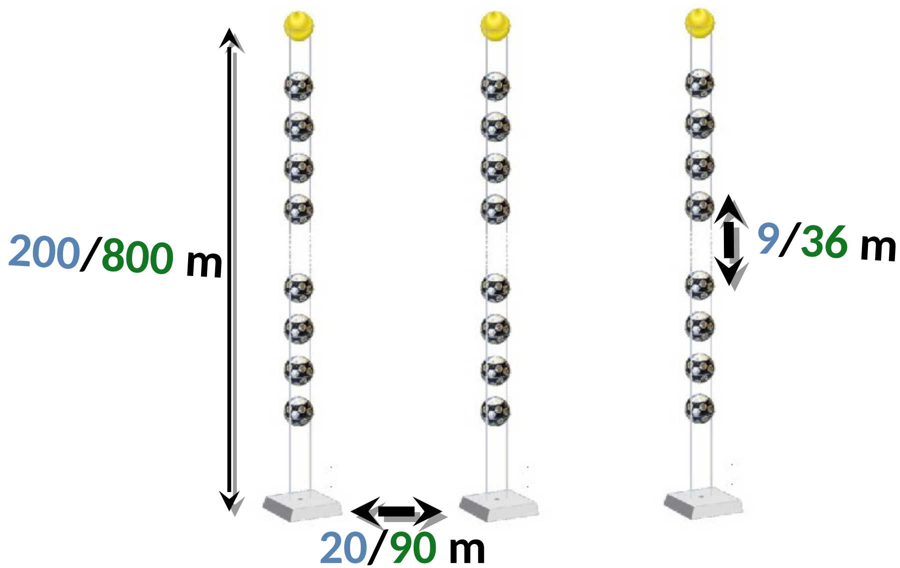


KM3NeT/ORCA

- 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



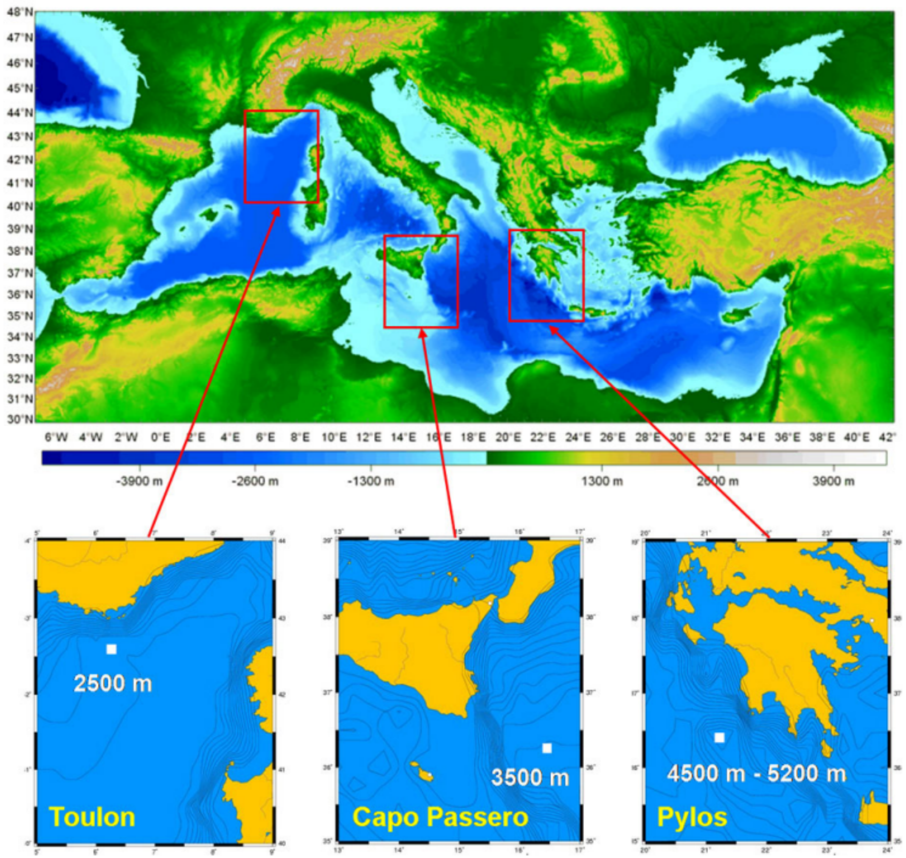
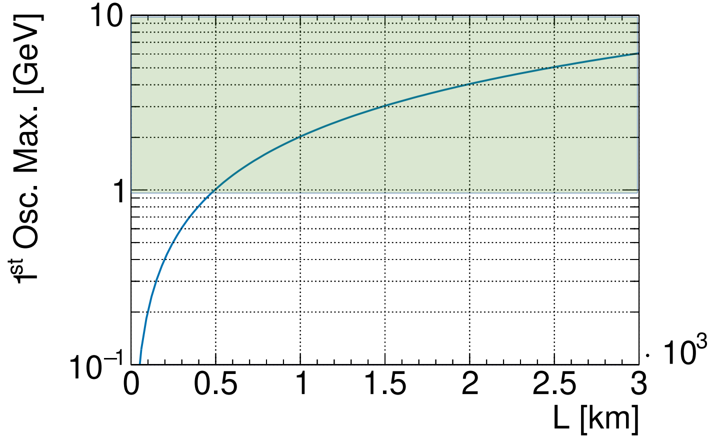
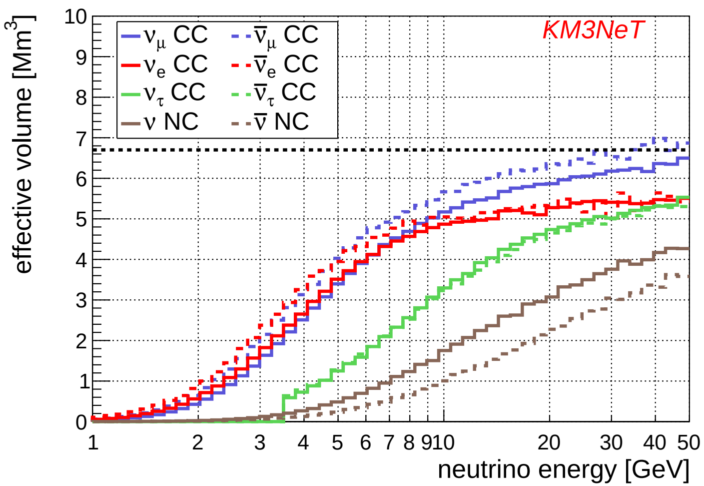


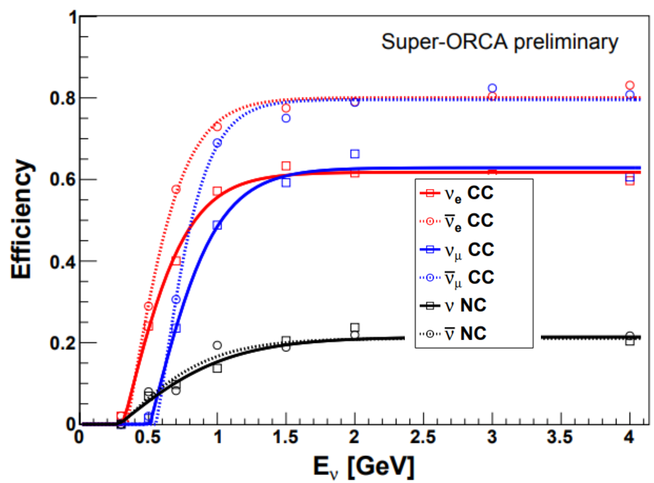
Figure 1-6: Locations of the sites of the three Mediterranean neutrino telescope projects.

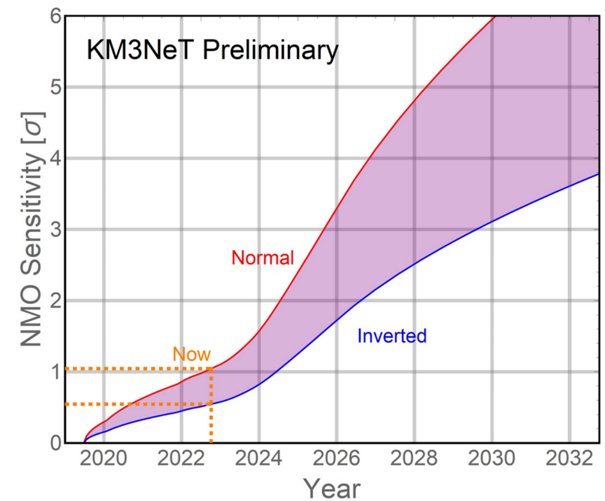
KM3NeT/ORCA for a LBL

- 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**



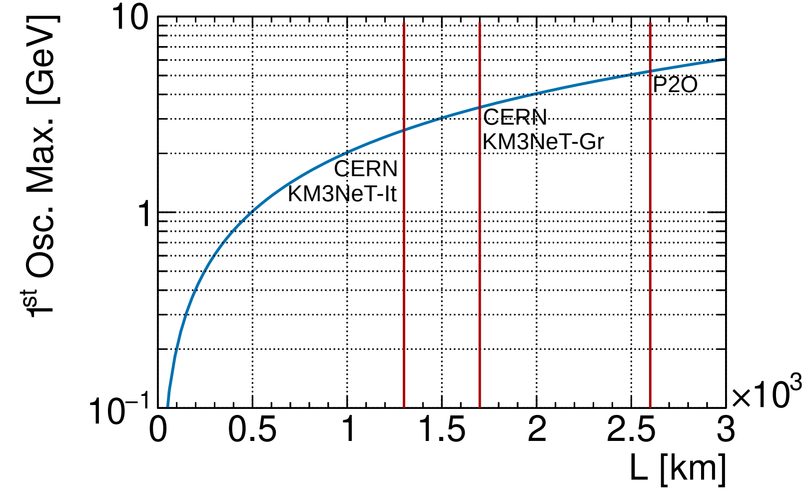






Possible Long Baseline in Europe

- 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



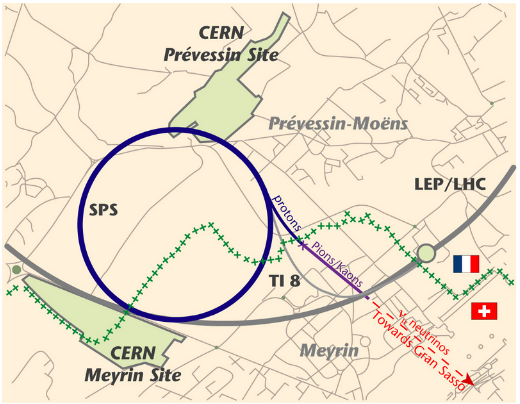
Nuclear Instruments and Methods in Physics Research A 383 (1996) 277–290

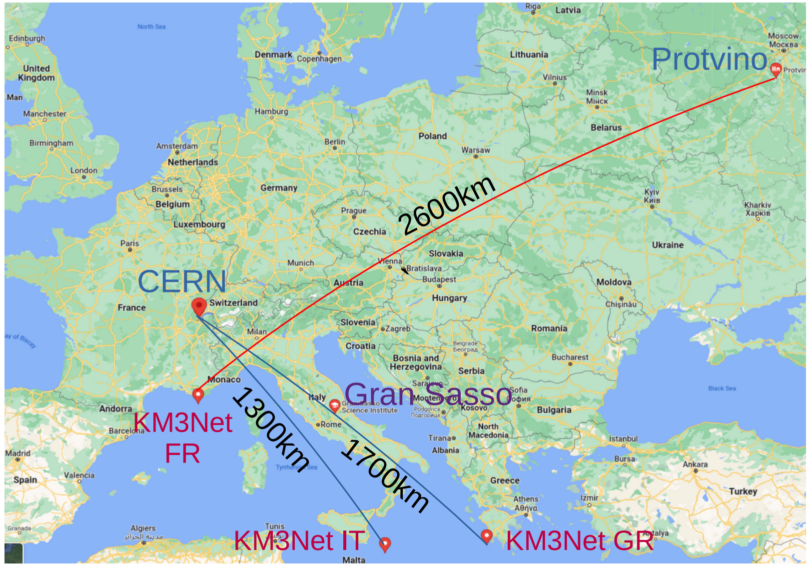
Design studies for a long base-line neutrino beam

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





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 δCP sensitivity **without tagging**

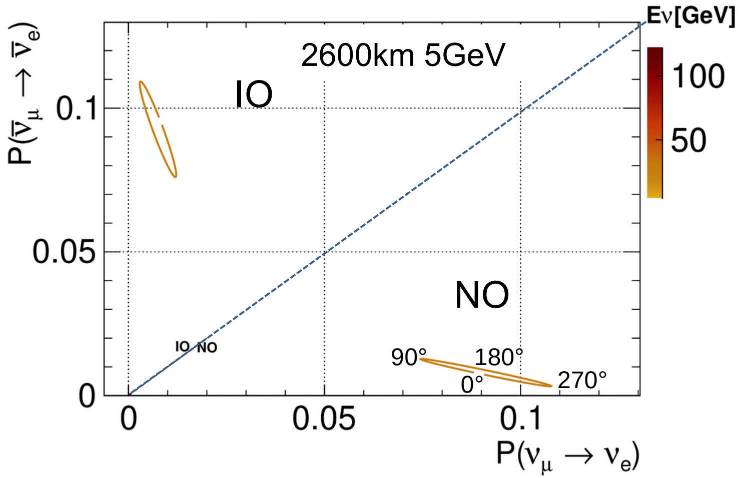
Experiment	T2HK	DUNE	P2O	
1-st max $\nu_\mu \to \nu_e$	0.6 GeV	2.4 GeV	5 GeV	
Detector	HyperK	DUNE	ORCA	Super-ORCA
Fiducial mass	186 kt	40 kt	8000 kt	4000 kt
Beam power	1300 kW	1070 kW	450 kW	450 kW
ν_e events per year (NO)	230	250	3500	3400
$\bar{\nu}_e$ events per year (IO)	165	110	1200	1100
CPV sensitivity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

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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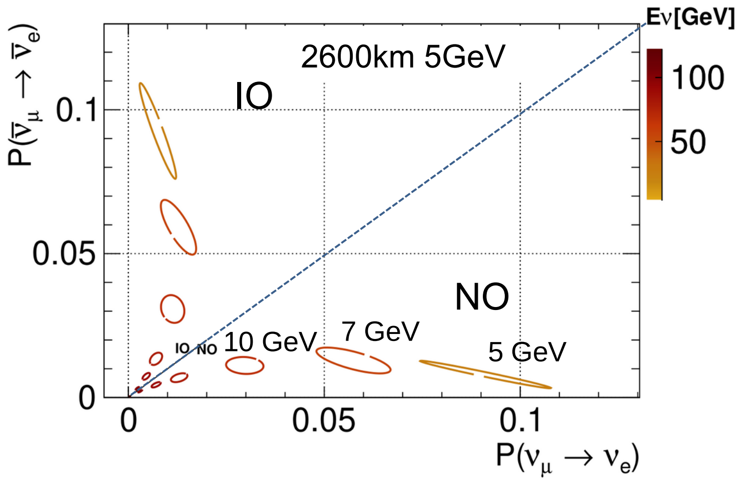

Neutrino tagging: a new tool for accelerator based neutrino experiments **Eur. Phys. J. C, 2022, 82, 465**, arXiv:2112.12848

δCP measurements with a tag-LBL

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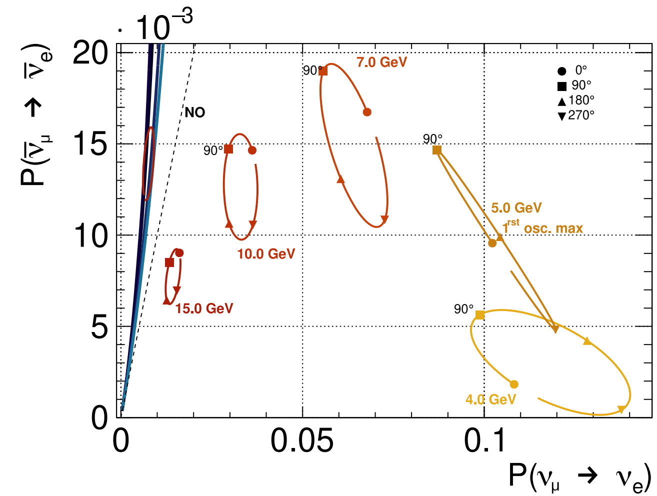
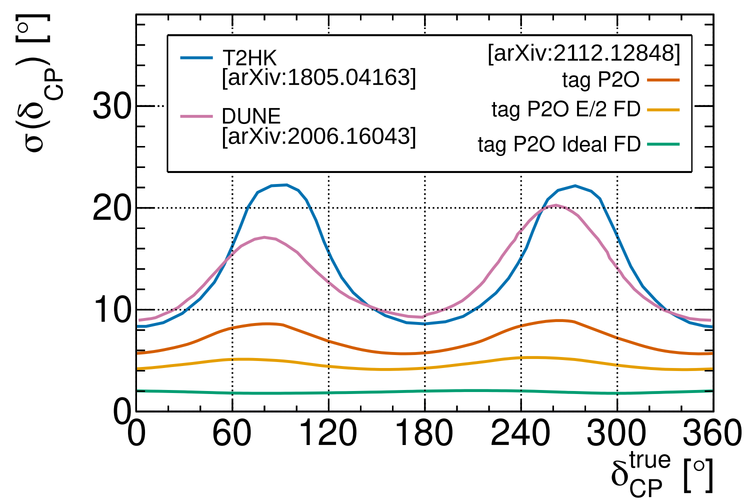




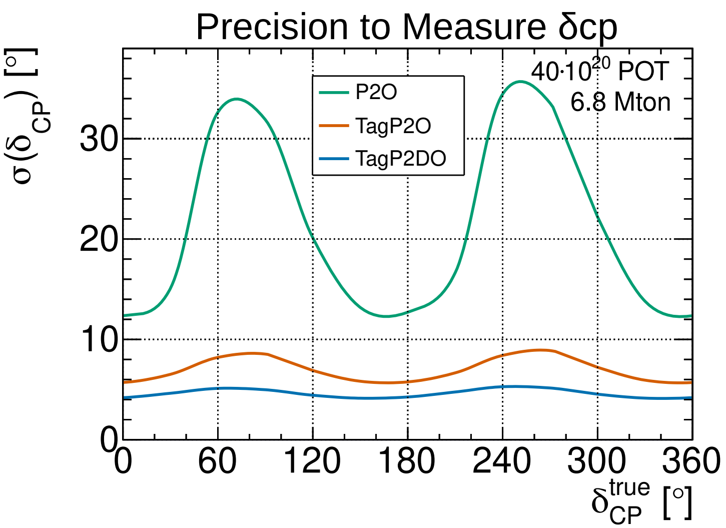
Summary and Conclusions

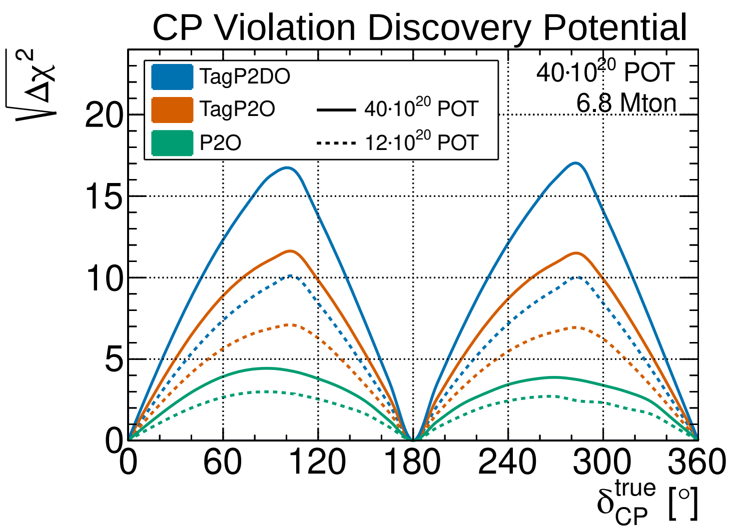
- **CP violation**: the next major discovery in neutrino physics?
  - Knowledge on **cross-section and flux** must be improved for DUNE and T2HK
  - **New methods** needed to fully address the CPV question beyond DUNE and TH2K
- **Neutrino Tagging**

  use **ν production mechanism** (in complement to ν interaction)
- Experimental **Proof of Concept** on going at NA62
- Tagging @ **SBL**:

  unique facility to refine **cross-section (νe, νμ) and interaction model**
- Tagging @ **LBL** using MegaTon scale **Natural Water Cerenkov Detector**
  - **Large neutrino sample** of the best quality (**E reso**<1%) **reduced systematics**
  - $\boldsymbol{\delta_{CP}}$ precision of **few degrees** are accessible

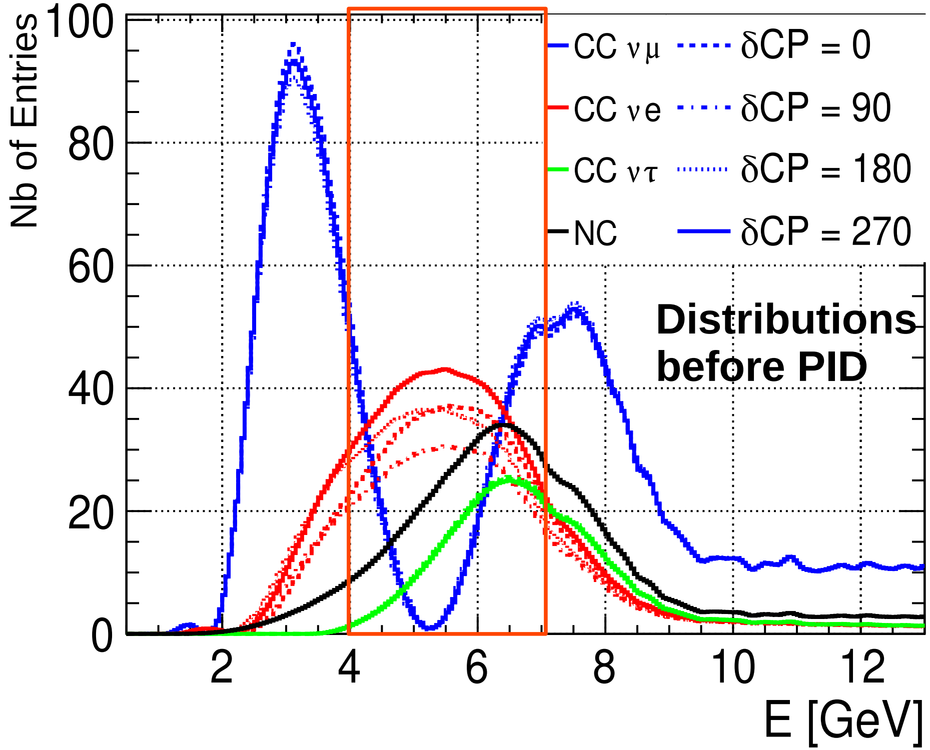
δCP measurements with a tag-LBL

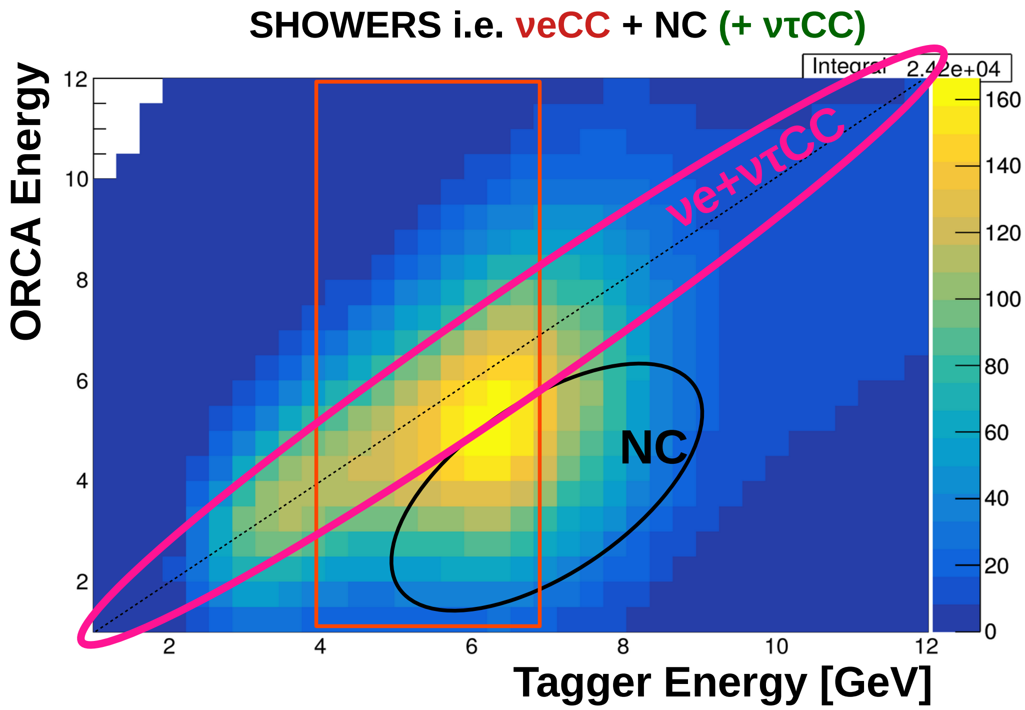




How to measure δ_{CP} with P2O

- δ_{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**



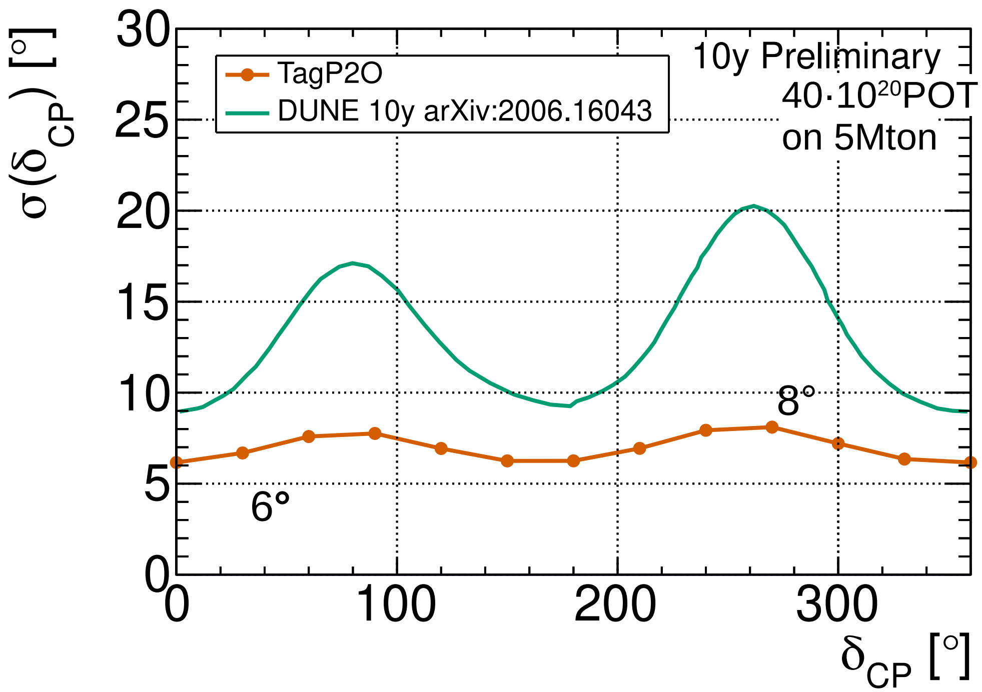


Precision to δ_{CP} at P2O

- **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
- δ_{CP} precision **stable** over all values
- **<8° precision** can be achieved!

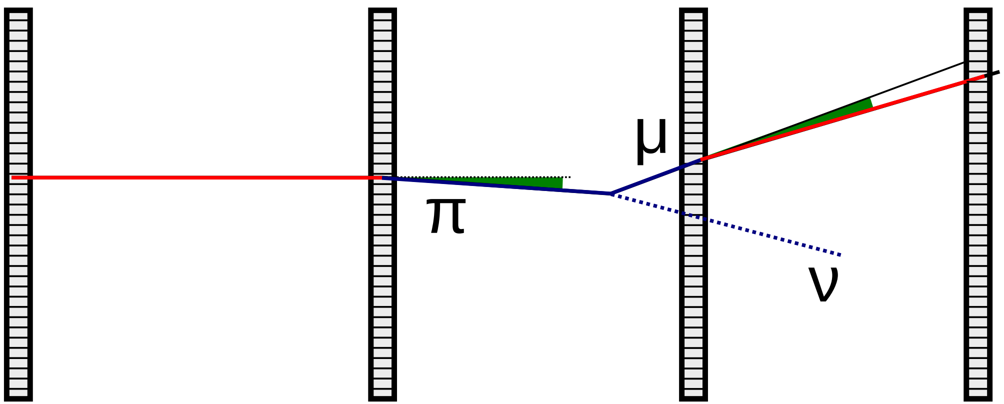


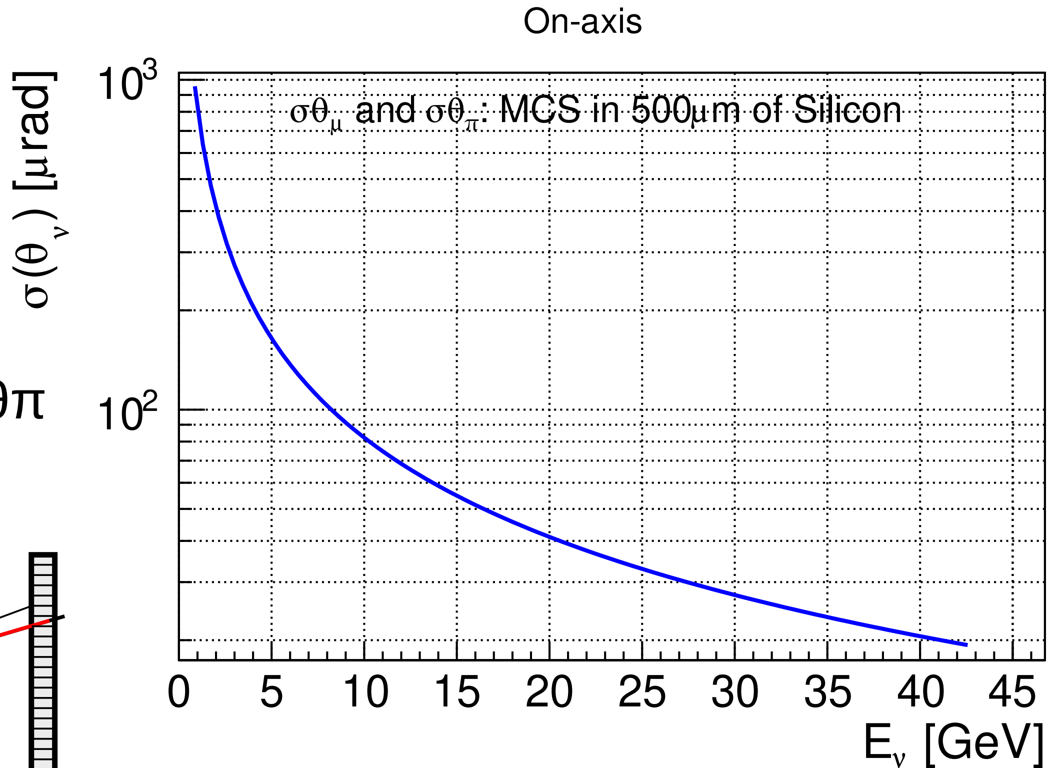
Is 1mard ν ang. resolution achievable? YES

- 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 θ_ν can be achieved**

ν_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 9×10^{19} POT in 2.5 years needs 5×10^{13} protons per pulse**
  - **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

~~200 π's~~

17 K's

8 decayed | ~~9 un-decayed~~

1 Ke3 | ~~5 Kμ2~~ | ~~1-2 K2π~~ | 0-1 other

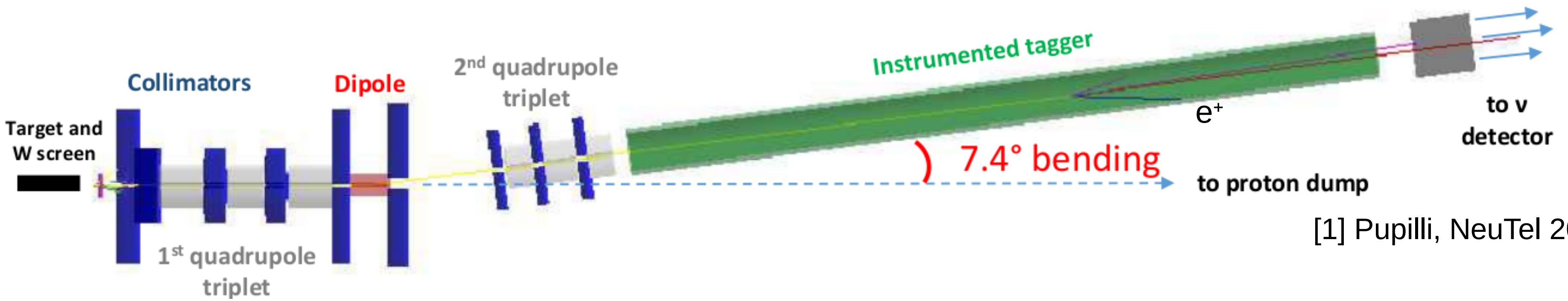
- **The association is possible for 90% of the cases**

[a] 5e13 ppp and 3000 p per day 30 days a month 8 months per year over 2.5 year gives 9×10^{19} POT

ENUBET

- **ENUBET:** ***monitored*** beam to measure ν x-section at energies of few GeV
  - **$N(e^+) = N(K^+ \to \pi^0 e^+ \nu_e) = N(\nu_e)$**, so by **counting the e^+'s, one counts the ν_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: 5×10^{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