Novel neutrino beams

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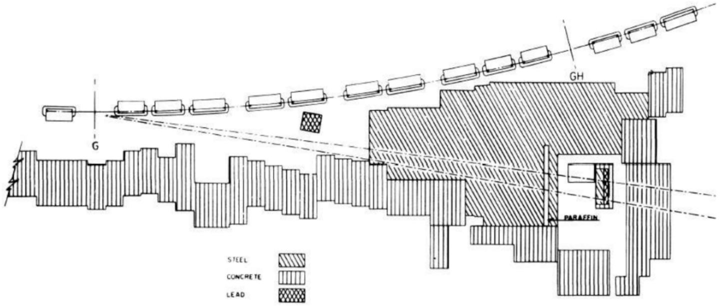
NEUTRINO
2020

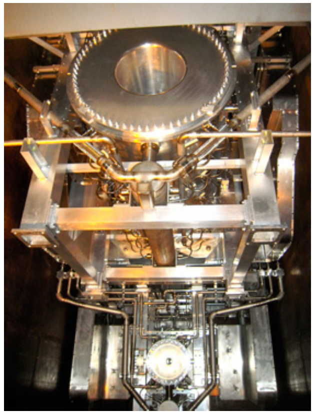
Outline

- “Monitored” beams
- Muon-based beams
- New ideas (timing)

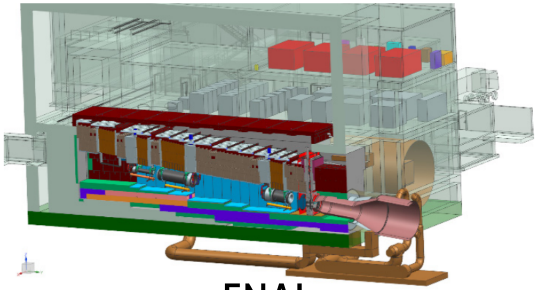

You're in the lobby. Others cannot see or hear you.

Accelerator based neutrino beams





J-PARC



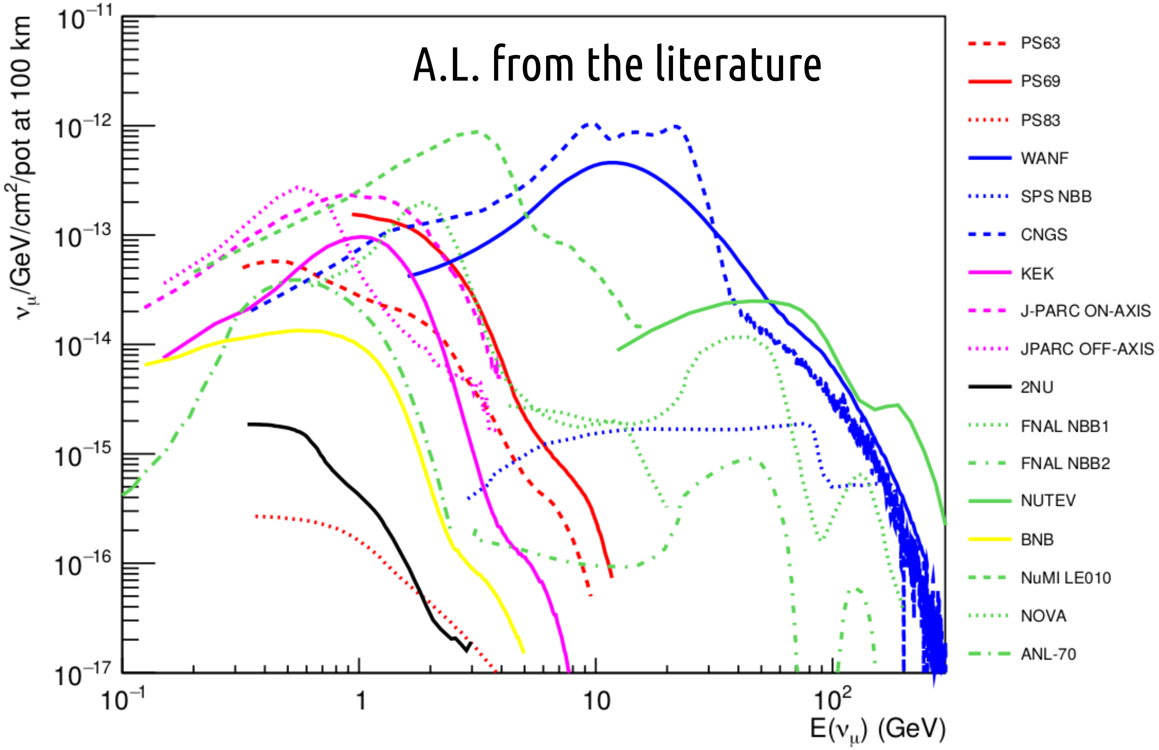
FNAL

Pion based neutrino beams have a **~60 y long history.** Lots of physics done at different energies.

Enormous **increase in intensity** → a leap in technology and complexity

More "**brute force**" than conceptual innovations. Still OK in the era of "statistical errors-dominance" and "large θ_{13}" but …

New future challenges (δ_{CP}, searches) require timely **changes** or at least **"adjustments"** in this strategy.

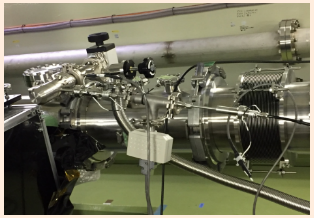


A.L. from the literature

Improvements in standard beams (*)

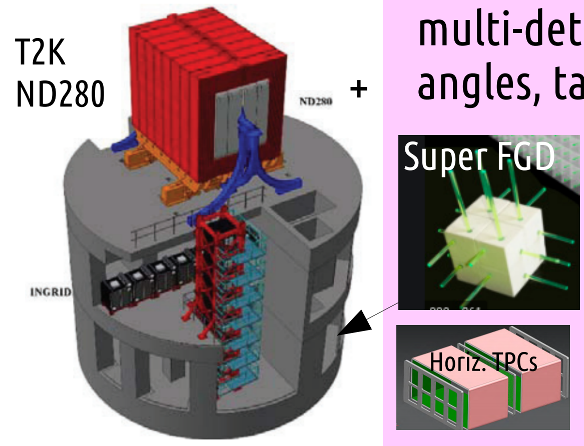
(*) examples

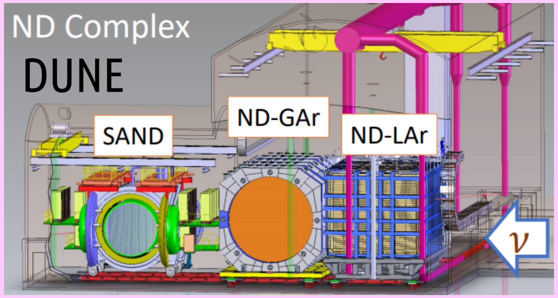
Beam monitoring systems are being enriched



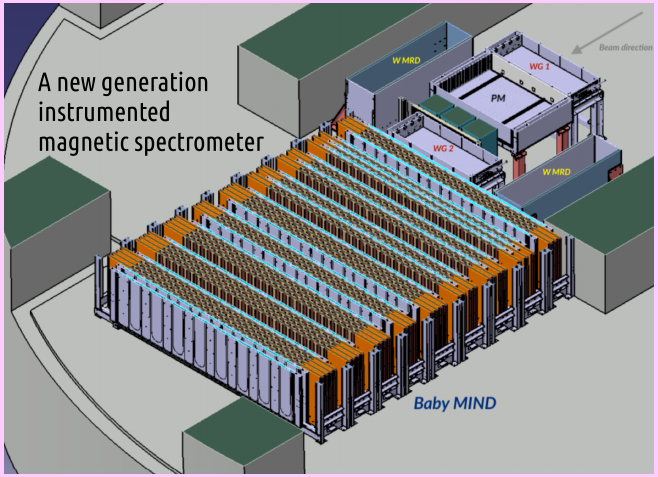
J-PARC Beam Induced Fluorescence monitor

Near detectors are(have) evolving(ed) towards multi-detector systems with variable off-axis angles, target redundancy, high-granularity.





BabyMIND+WAGASCI running @ ND280



Poster 629 M.Tenti

Poster 256 A. Sitraka

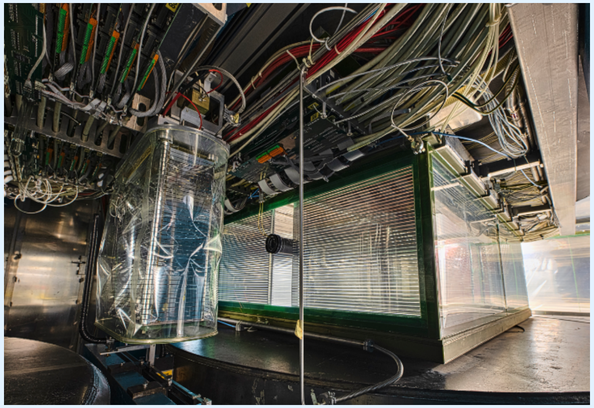
Poster 79 P. Weatherly

Pavin Matej's talk

Hadro-production data covering larger phase space with replica targets

NA61-SHINE

Poster 148 Y.Nagai



T2K target

Directions for novel neutrino beams

Still, due to reinteractions, alignment, degradation of targets etc… **flux errors > 5 %**

We should aim at doing **significantly better!**

EU strategy document (19 June 2020):

> “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**”.

How ? →

Directions for novel neutrino beams

How ? →

1) The “brave” way: use **“clean” sources** (~ easy, “textbook” flux prediction)

- unstable nuclei → β-beams
- stored muons → ν factories
- decays at rest

JSNS^2 talk Maruyama,
Takasumi’s talk

(“LHC neutrinos” are also a very interesting “perturbative QCD-based” novel beam at very high energy → see

Poster 118, M.H. Reno
Poster 249, A. Ariga (FASER))

Directions for novel neutrino beams

How ? →

1) The "brave" way: use **"clean" sources** (~ easy, "textbook" flux prediction)

- unstable nuclei → β-beams
- stored muons → ν factories →
- decays at rest

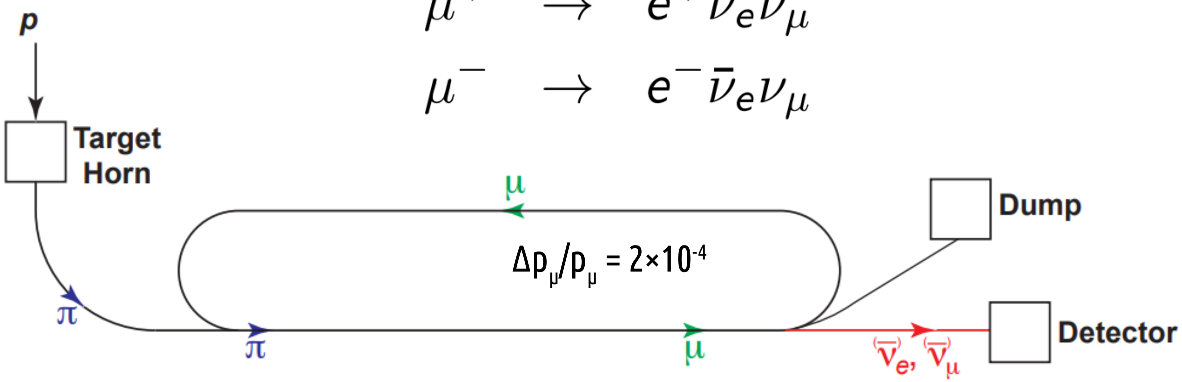
Pre-2012: use for long baseline experiments
Evolution: a short baseline setup for cross section measurements with high precision **supporting the long baseline program** which will be carried on with high intensity "meson based" HK & DUNE SuperBeams
→ **nuSTORM, MICE**

protons → (K^+, π^+) → μ decays → ν_e/ν_μ → neutrino detector

nuSTORM

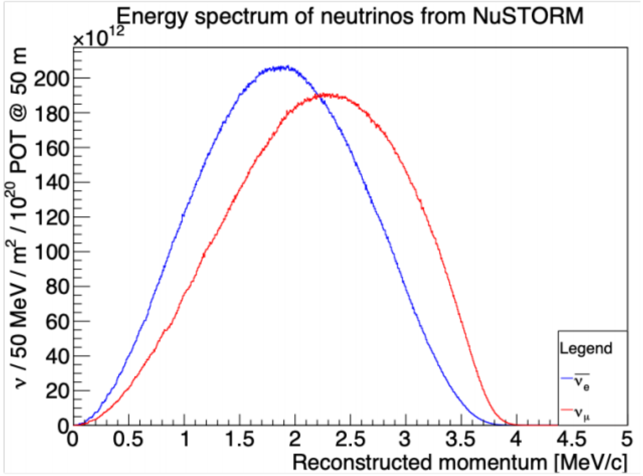
ν_e and ν_μ beams **from decay of circulating low-E muons**

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



$\Delta p_\mu / p_\mu = 2 \times 10^{-4}$

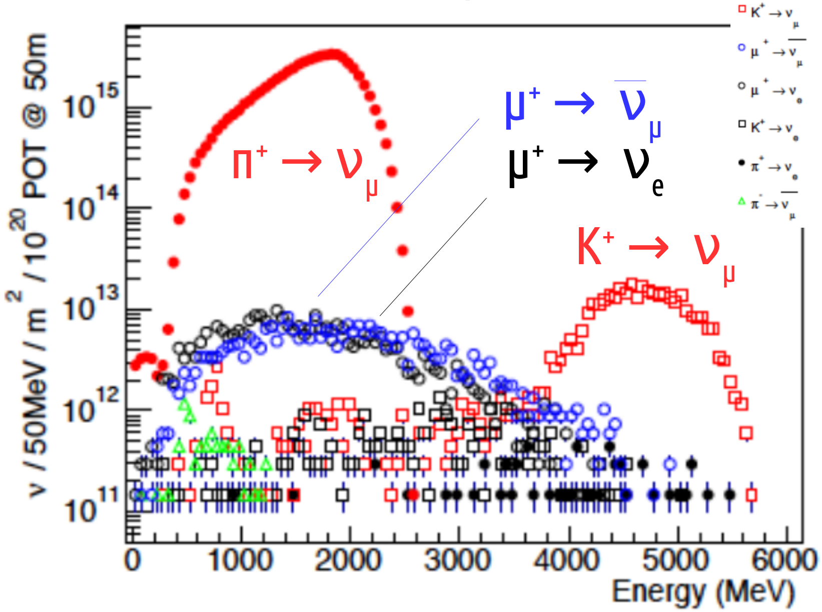
Muon parents fluxes



- 100 GeV/c p from SPS (156 kW). Fast extr. (10.5 us).
- Storage ring (1-6 GeV/c with a 16% acceptance)
- 52% of π → μ before 1st turn

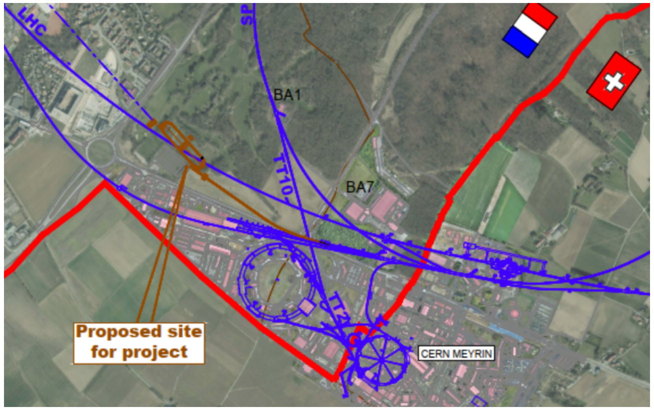
  → ν_μ flash @ "injection pass"
- 1 τ_μ ~ 27 orbits:
- For 10^{20} POT (2×10^{20} expected in 5 y) @ 50 m
  - 6.3×10^{16} ν_μ / m^2
  - 3.0×10^{14} ν_e / m^2

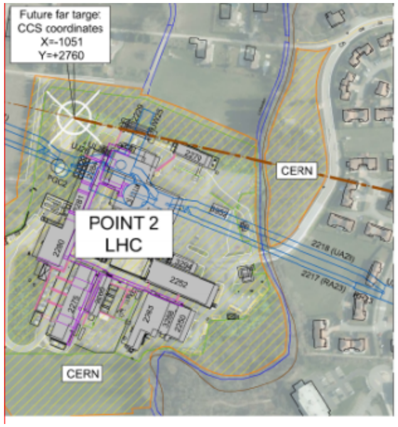
Hadronic + leptonic

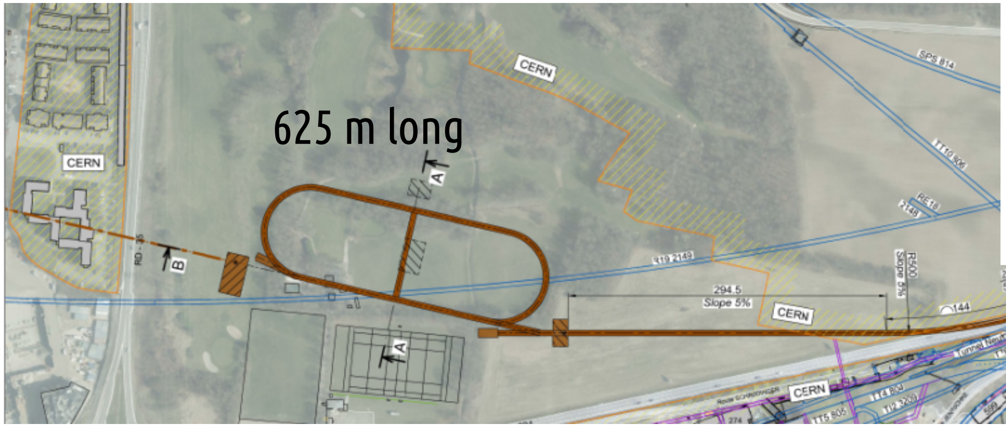


nuSTORM

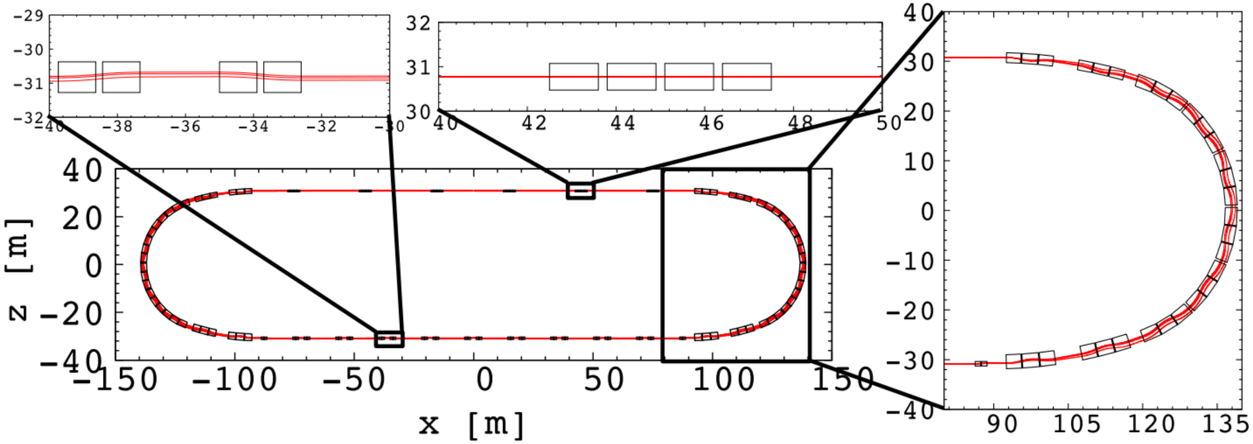
Physics Beyond Colliders study
Costing performed at CERN(*) and FNAL (PDR)
Beside cross section and sterile neutrino program
Test-bed for 6D cooling, muon collider

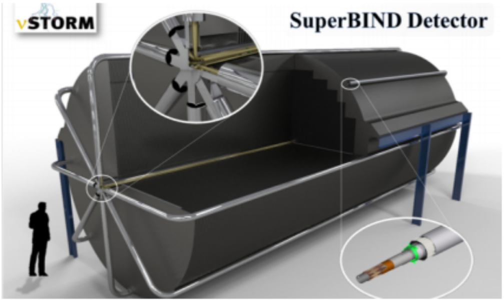





625 m long

Work package	Base cost [M$]
Primary beam line	21.1
Target station	26.7
Capture & transport	10.8
Decay ring	89.3
Near detector hall	16.8
Site work	17.4
CF other	1.8
Total	183.9

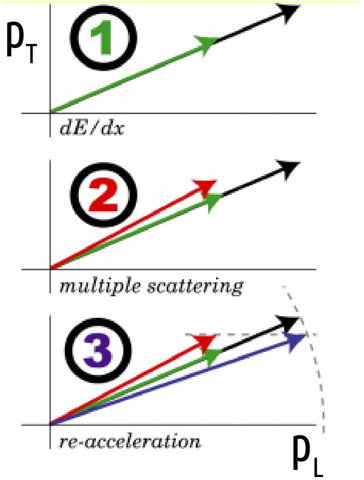




For sterile searches. For cross sections other detector schemes could be more appropriate, with similar small sizes.

(*) https://indico.cern.ch/event/837890/attachments/1921676/3196005/2019-10-21-nuSTORM-at-CERN_Feasibility-study-d1.pdf

MICE ionization cooling results



$$\frac{d\varepsilon_T}{dz} \approx -\frac{\varepsilon_T}{E_\mu \beta^2}\frac{dE_\mu}{dz} + \frac{\beta_\perp}{2mc^2\beta^3}\frac{(13.6\,MeV)^2}{E_\mu X_0}$$

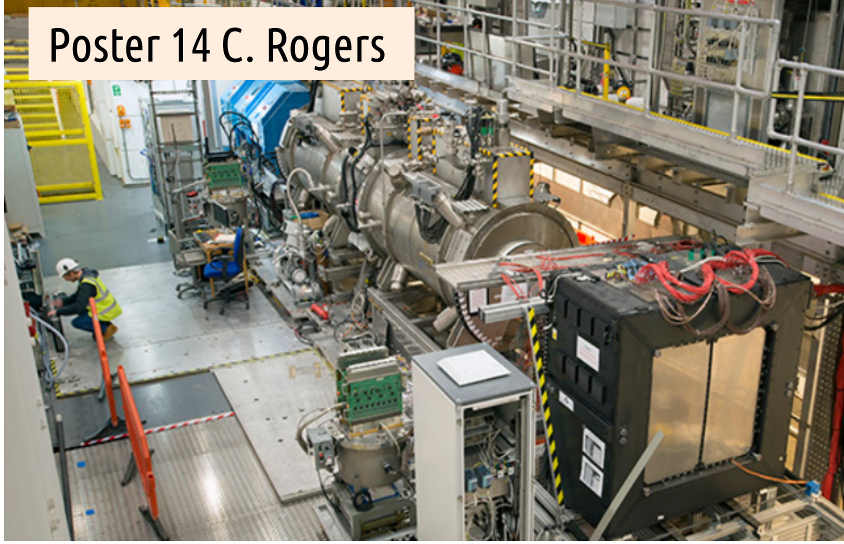
RAL ISIS synchrotron

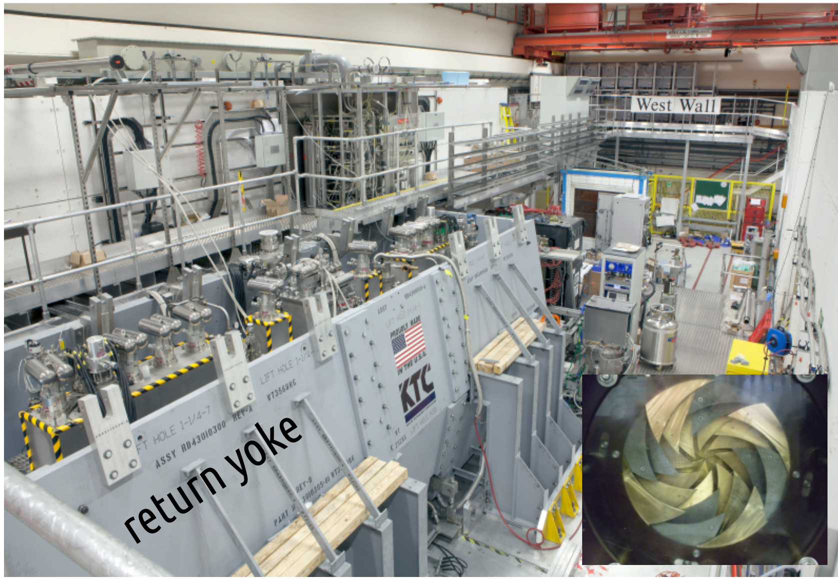
p_μ = 140-240 MeV/c.

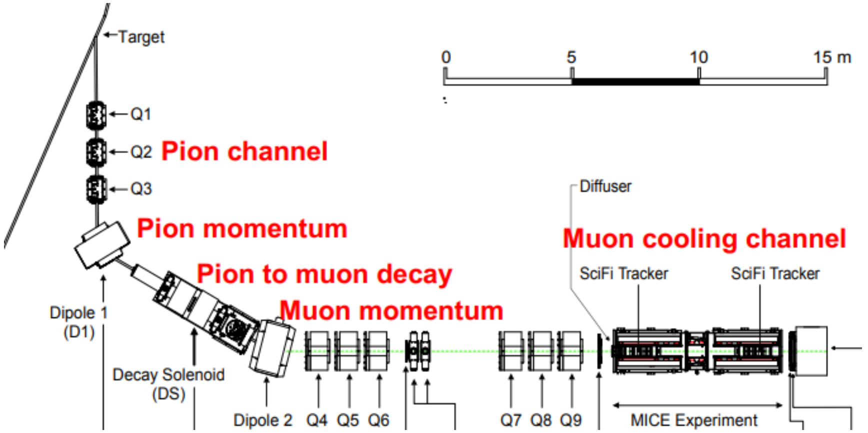
Input emittance: 4-6-10 mm

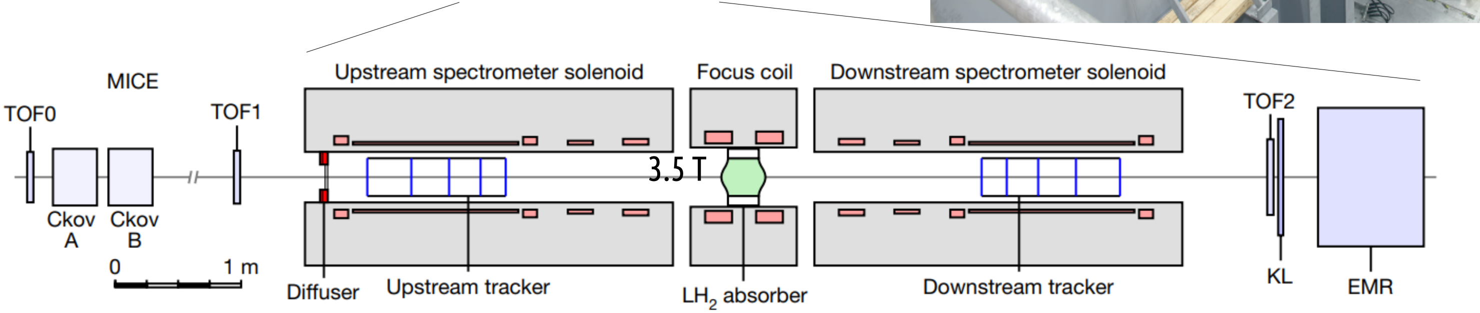
Absorbers: Lithium hydride (6.5 cm)

Liquid H (35 cm)


Poster 14 C. Rogers







MICE ionization cooling results

Nature, 5 Feb 2020 https://doi.org/10.1038/s41586-020-1958-9

Amplitude: distance of the particle from beam centroid in normalized phase space. Conserved quantity without cooling.

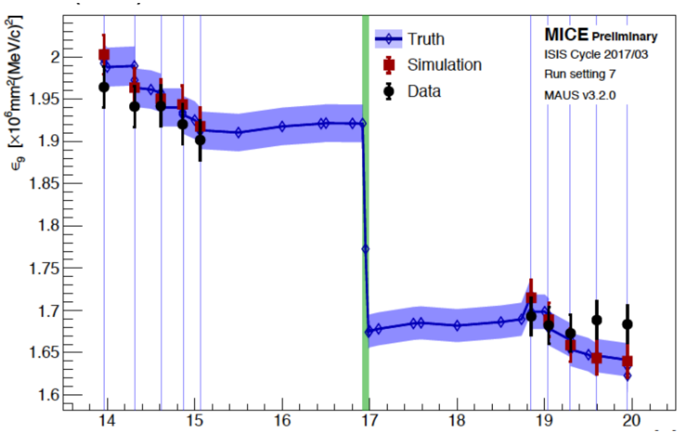
Results for a 140 MeV/c muons with normalized r.m.s. initial emittance of 10 mm. Significant (but smaller) effect also at lower input emittances (4-6 mm).

With absorbers, # of low amplitude events considerably larger in the downstream sample than in the upstream sample → increase in the number of particles in the beam core → ionization cooling effect

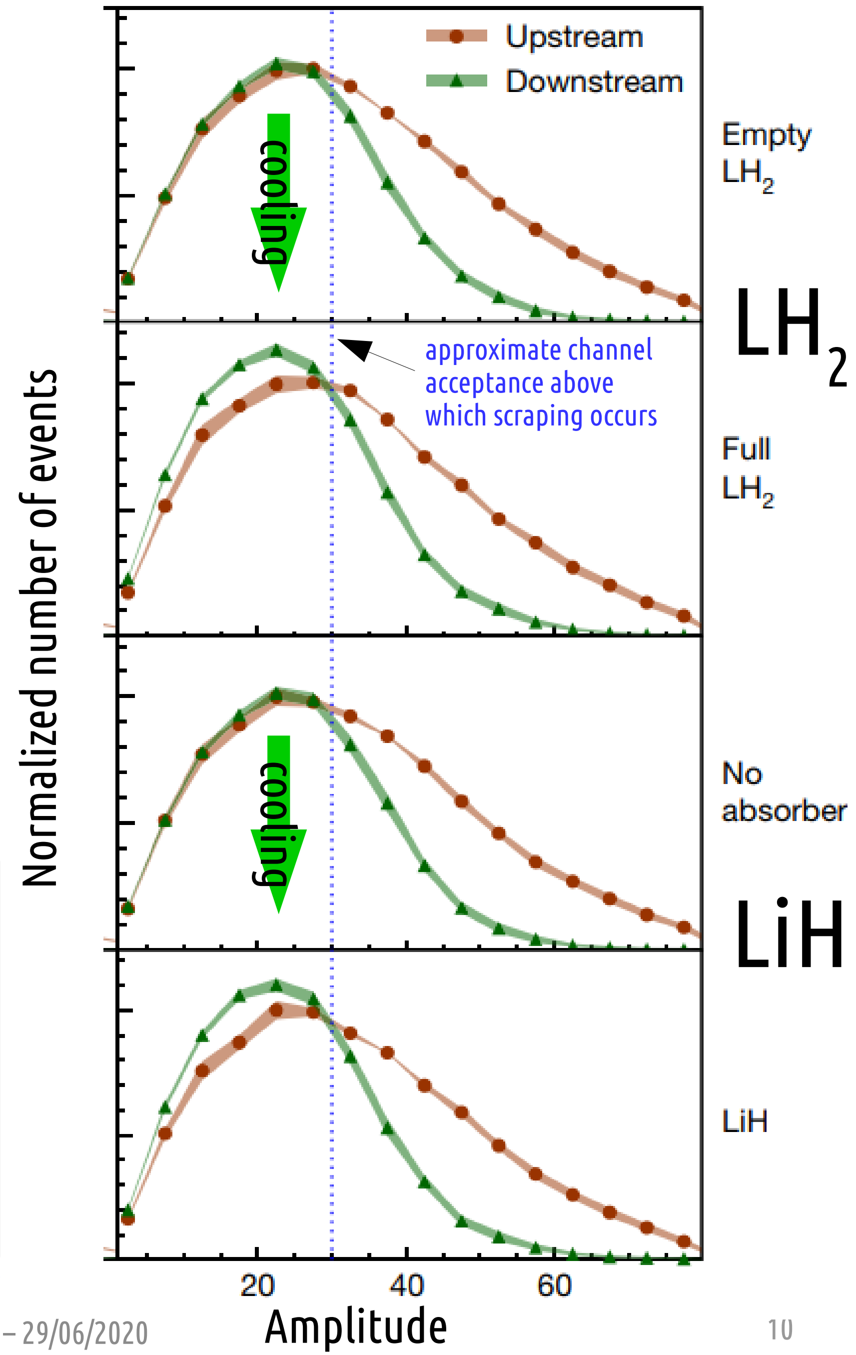
Fractional (9%) emittance z-evolution.

6 mm/140 MeV/LiH

P. Soler
CERN, 11 April 2019



upstream (u) and downstream (d) distributions scaled by 1/N^u_{max} (N^u_{max} = most populated bin in u sample).



approximate channel acceptance above which scraping occurs

Directions for novel neutrino beams

How ? →

2) “lateral thinking”: bring the usual “meson-based” beam to a new standard → use a **narrow band beam** and shift the **monitoring at the level of decays** by instrumenting the decay tunnel

Again an **ancillary facility** providing **physics input** to the long-baseline program

protons → (K^+, π^+) → K decays | dump → ν_e / ν_μ → neutrino detector

K decays → e^+/μ^+

“By-pass” **hadro-production**, **protons on target**, **beam-line efficiency** uncertainties

→ **ENUBET / NP06**

Enhanced **Ne**U**trino **BE**ams from kaon **T**agging ERC-CoG-2015, G.A. 681647, PI A. Longhin, **Padova University, INFN**

CERN Neutrino Platform: NP06

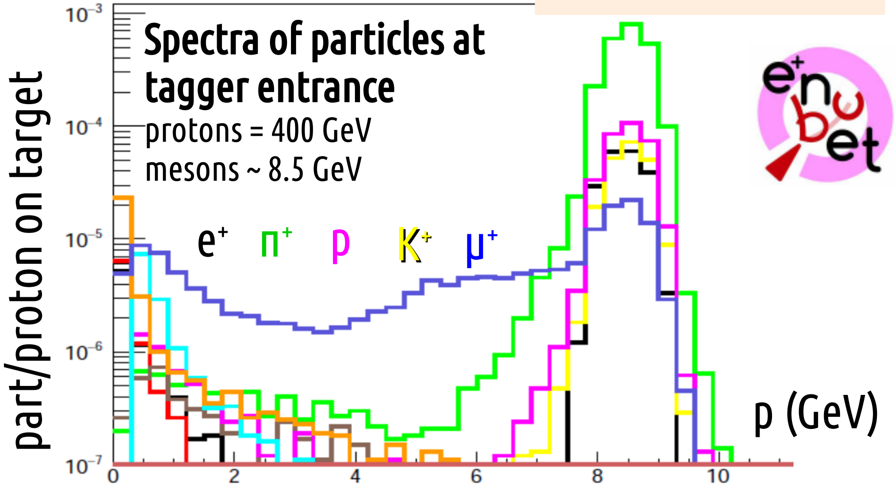
ENUBET: 60 physicists, 12 institutions

ENUBET / NP06

Poster 269 A. Branca

Aims at demonstrating the **feasibility** and **physics performance** of a neutrino beam where **lepton production is monitored at single particle level**

- **Instrumented decay region**
  $K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow$ (large angle) e^+
  $K^+ \rightarrow \mu^+ \nu_\mu \pi^0$ or $\rightarrow \mu^+ \nu_\mu \rightarrow$ (large angle) μ^+
- **ν_e and ν_μ flux prediction from e^+/μ^+ rates**

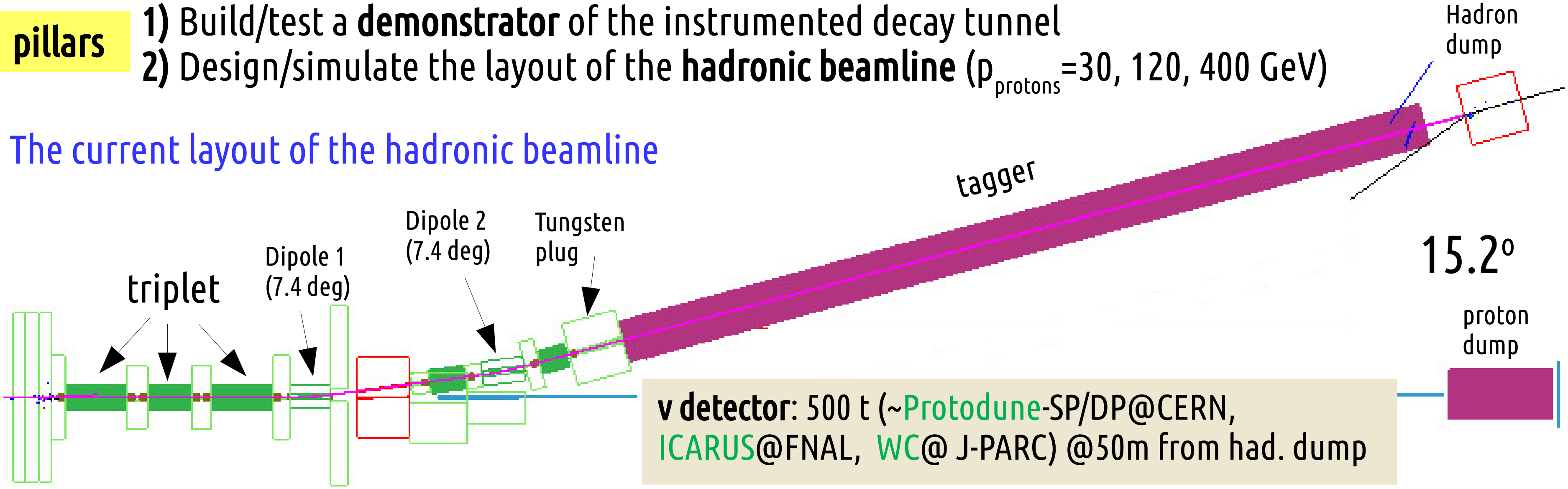


→ **collimated p-selected hadron beam** → **only decay products in the tagger** ➞ **manageable rates**
→ **narrow band beam:** E_ν-interaction radius correlations → an **a priori knowledge of the ν_μ spectra**

pillars

1) Build/test a **demonstrator** of the instrumented decay tunnel
2) Design/simulate the layout of the **hadronic beamline** ($p_{protons}$=30, 120, 400 GeV)

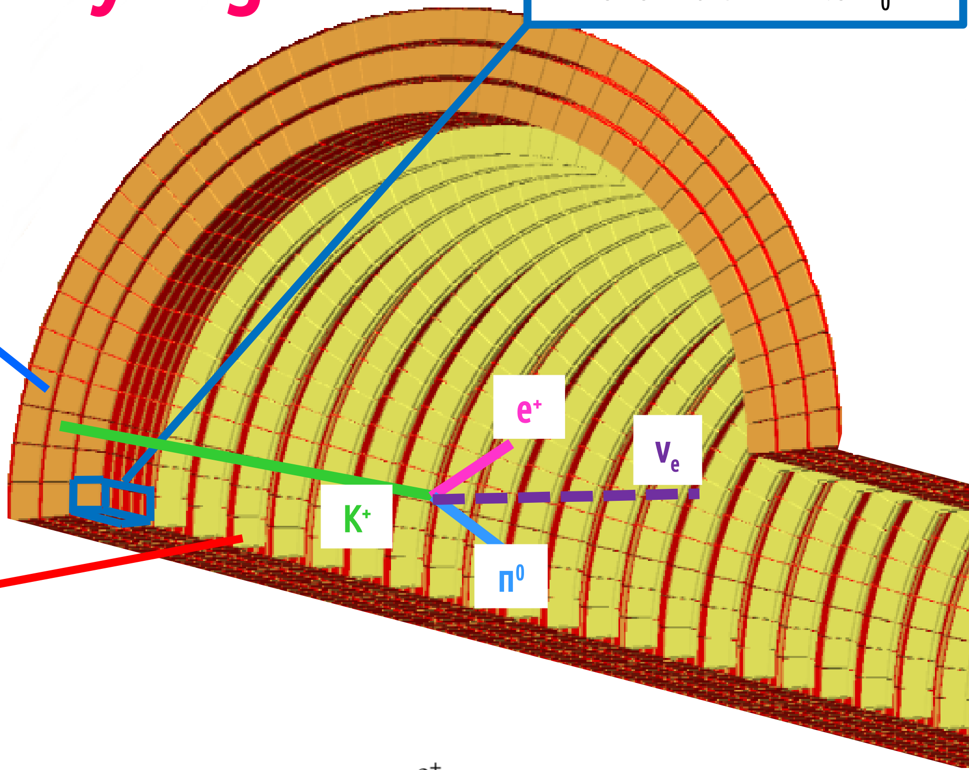
The current layout of the hadronic beamline



ν detector: 500 t (~Protodune-SP/DP@CERN, ICARUS@FNAL, WC@ J-PARC) @50m from had. dump

ENUBET: instrumented decay region

Ultra Compact Module
3×3×10 cm³ – 4.3 X_0



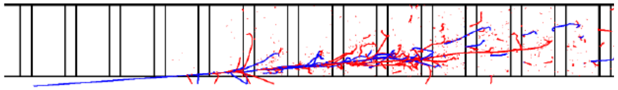
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

→ e⁺/π±/μ separation

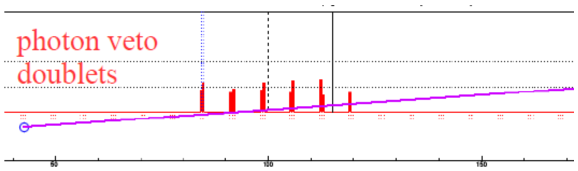


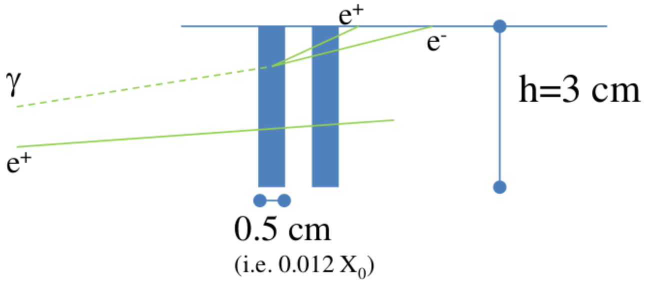
Integrated photon veto

Plastic scintillators

Rings of 3×3 cm² pads

→ π⁰ rejection





e^+ (signal) topology

π^0 (background) topology

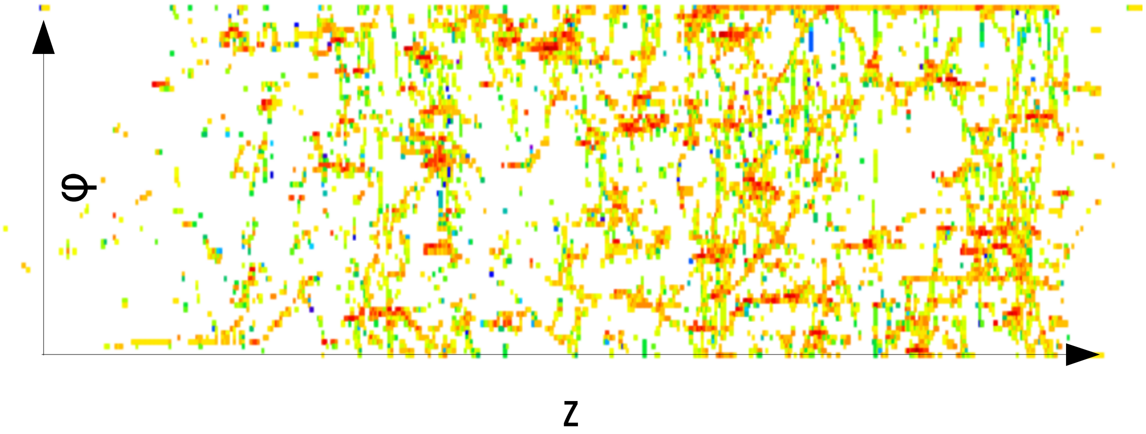
π^+ (background) topology

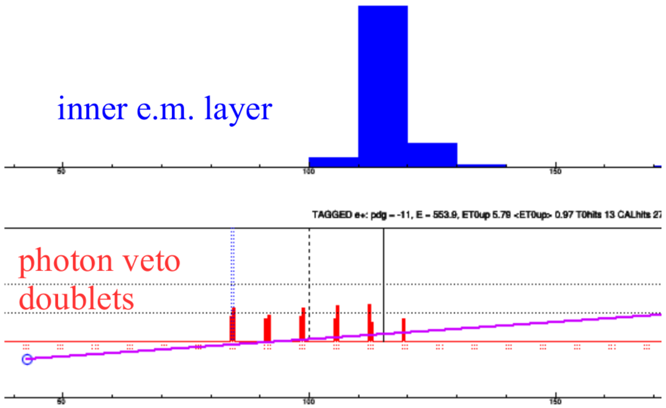
ENUBET: ν_e constraint with K_{e3} positrons reconstruction

The K_{e3} branching ratio is ~5 % and kaons are about 5-10% of the incoming hadron beam.

Full GEANT4 simulation of the detector, validated by prototype tests at CERN in 2016-2018.
Clustering of cells in space and time. Treat **pile-up** with waveform analysis. Multivariate analysis.

Hit map for e^+

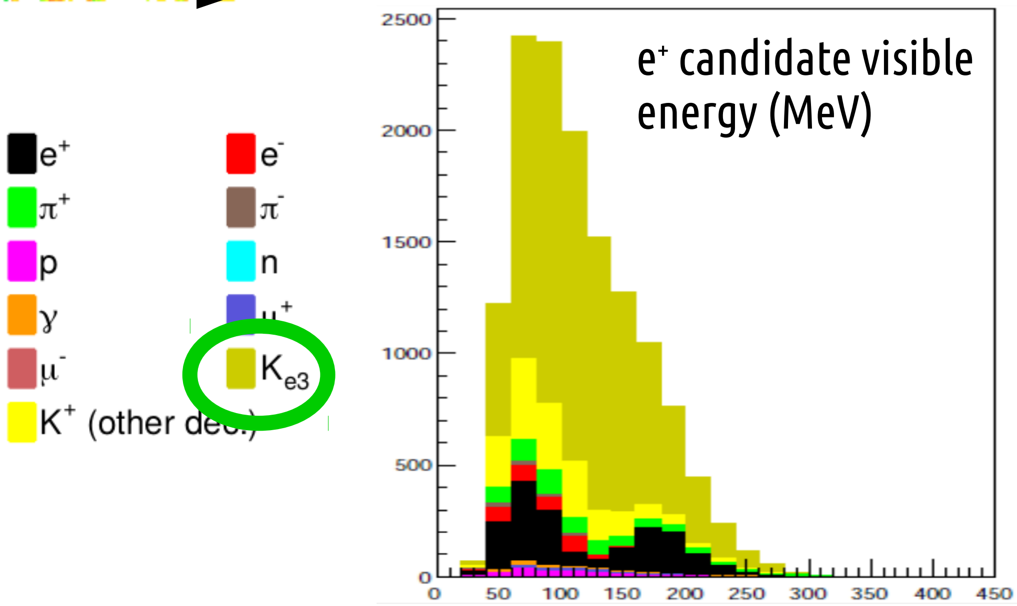




Selection quality

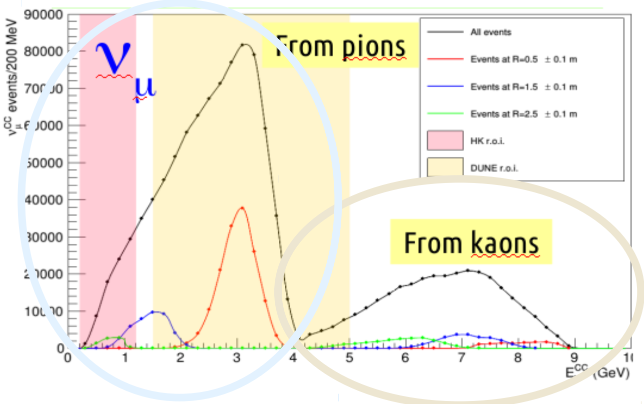
With a cut on the discriminating variable > 0.93:

S/N = 2.1 with and efficiency (*) of 24 %
(*) about half geometrical



F. Pupilli et al., PoS NEUTEL2017 (2018) 078

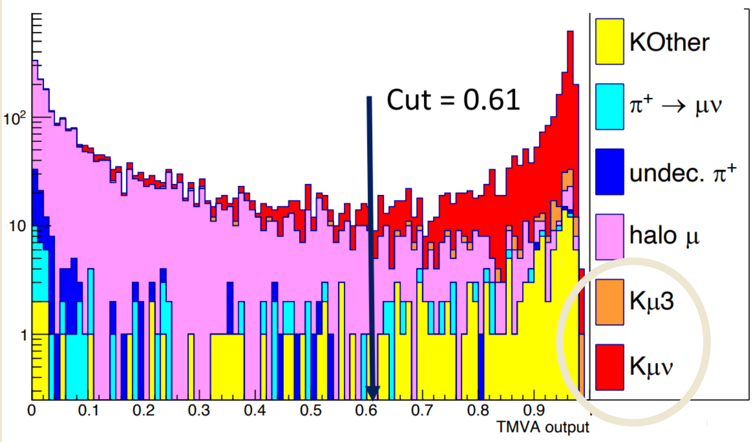
ENUBET: ν_μ constraints



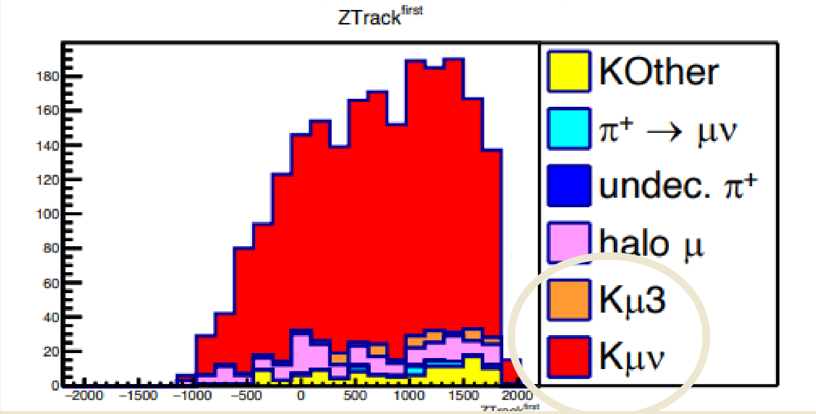
Constrain high-E ν_μ from ($K^+ \rightarrow \mu^+ \nu_\mu$ and $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$)

The main background from beam halo muons can be effectively selected out and/or used as a control sample.

efficiency 34% ($K_{\mu2}$) and 21% ($K_{\mu3}$) S/B ~ 6.1



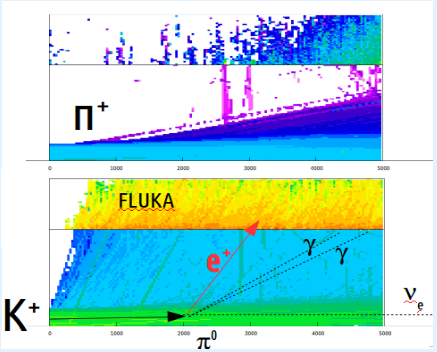
Muon reconstructed candidates →

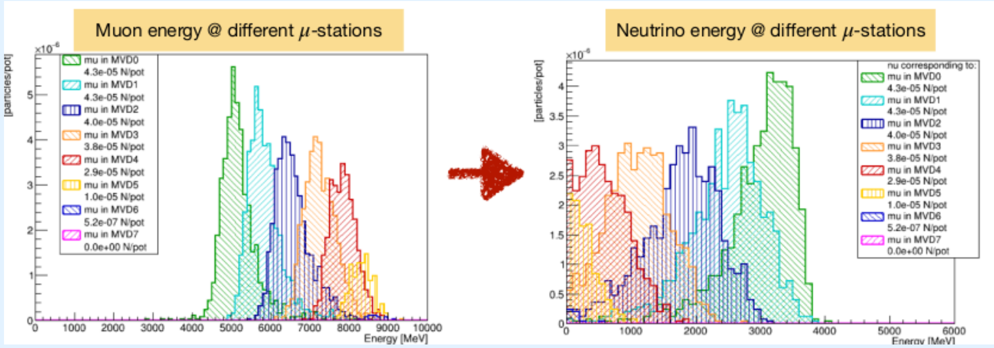


Position along the tunnel

Constrain low-E ν_μ from $\pi^+ \rightarrow \mu^+ \nu_\mu$?

In progress. Measure momentum by range with muon stations → disentangle ($\pi^+ \rightarrow \mu^+ \nu_\mu$) from halo μ.





ENUBET: flux components

98.4% from kaons
μ contribution small
(tunnel is "short")

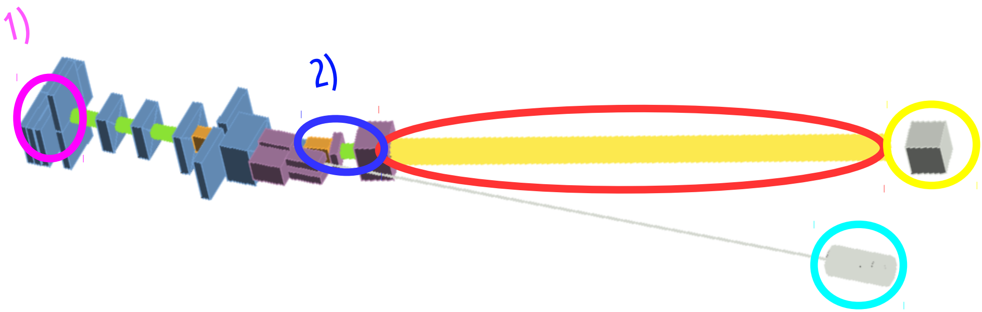
Not directly taggable components:

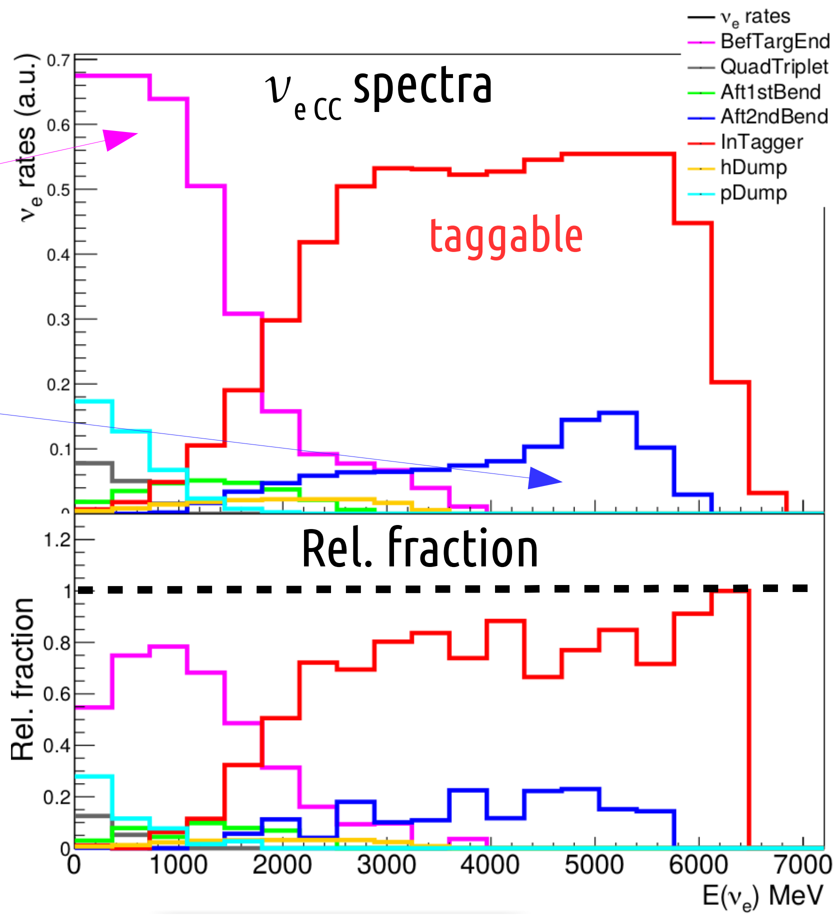
1) ν_e from $K^{0+/-}$ in the target region

→ Removable with E cut + larger bending angles

2) ν_e from K^+ in front of the tagger (pointing to the detector) 10-15% contamination

→ accounted for with simulation (geometry).



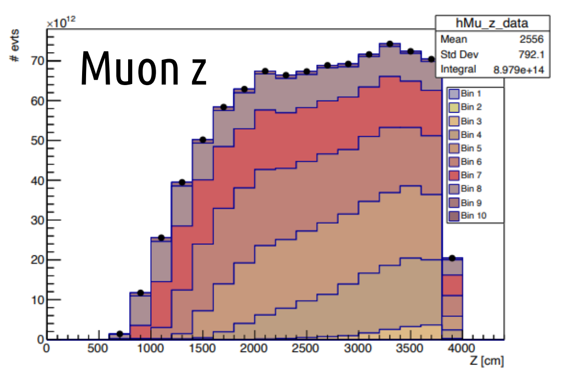


Uncertainty reduction for the tagged flux component

Constrain the flux model by exploiting correlations between the measured lepton distributions and the flux → Fit the model with data and get energy dependent corrections.

An example:

Each histogram component corresponds to a bin in neutrino energy

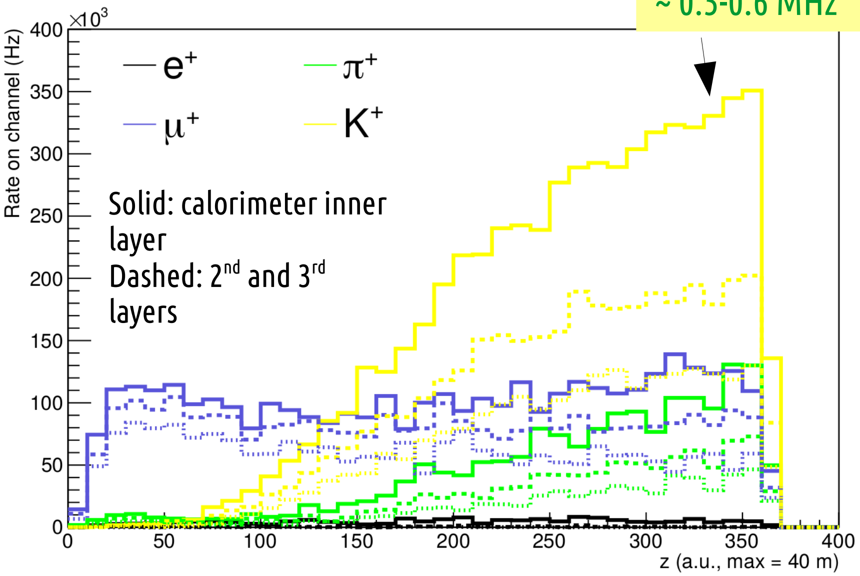


ENUBET: proton extraction, rates, pile-up

quad focusing: 2s slow extraction

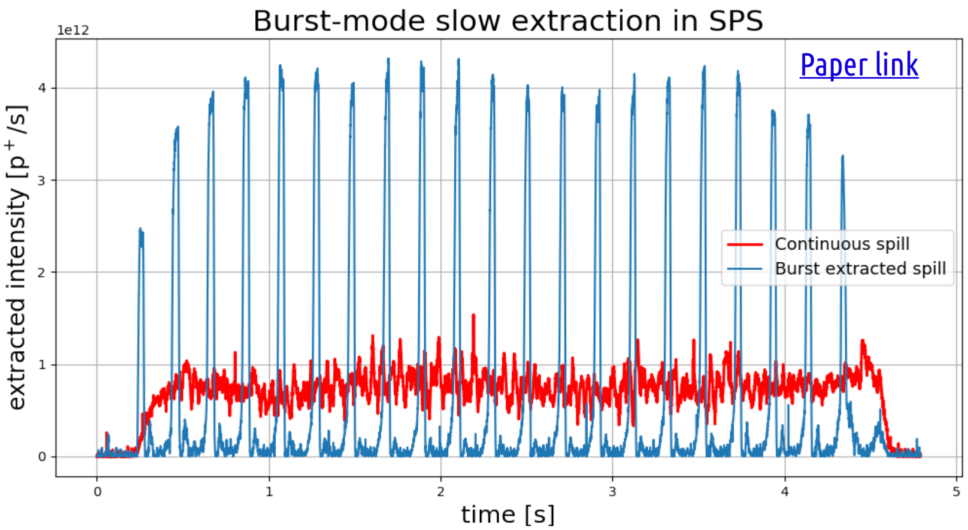
Rates in the tagger vs z

Hottest channels ~ 0.5-0.6 MHz



horn focusing: "burst mode" slow extraction
tested during machine studies at the CERN-SPS
~x10 rates increase

CERN-BE-OP-SPS



Waveform analysis algorithms developed.
With **250 MS/s** sampling:
pile-up efficiency loss stays
sub-% up to ~ 1 MHz/ch

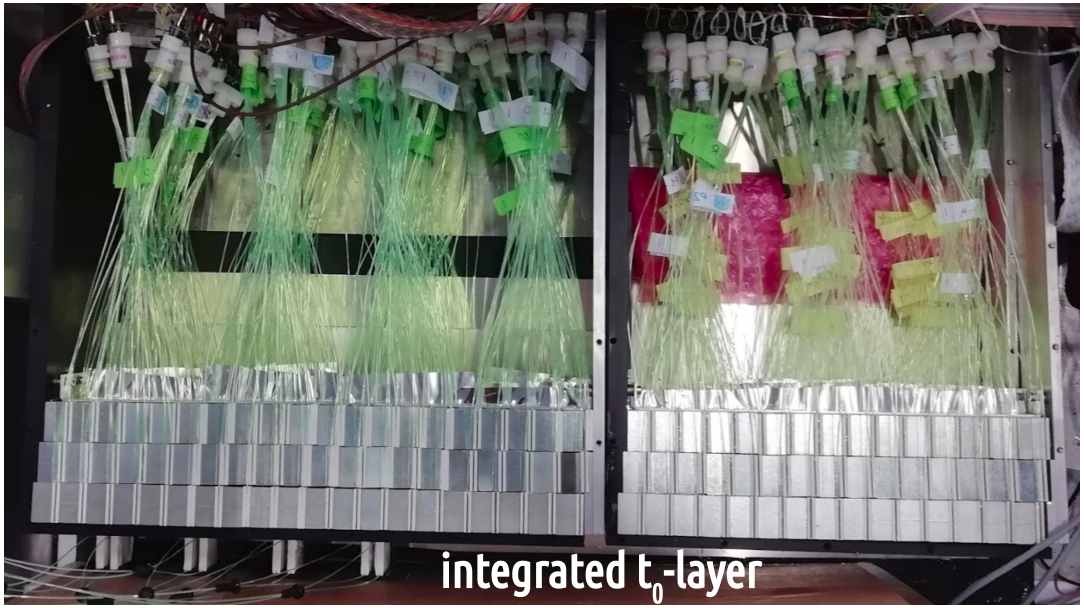
With the increased rates implied in the horn focusing scheme → **~ few % loss**

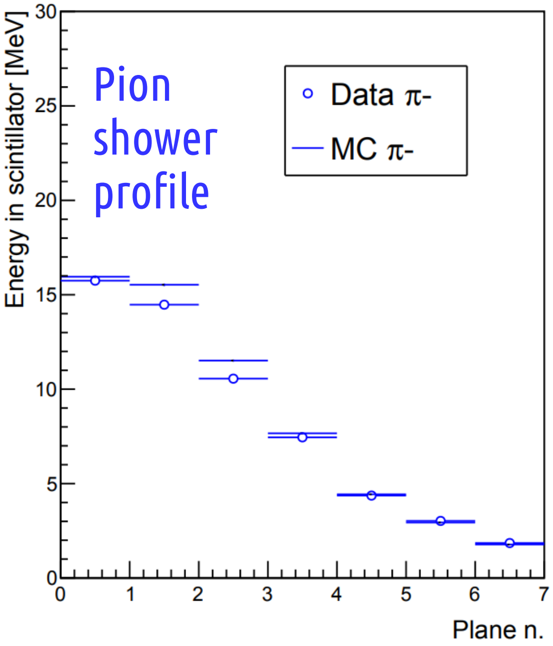
ENUBET: prototypes at the CERN-PS

ENUBET CERN-SPSC 2020 annual report link

JINST in press

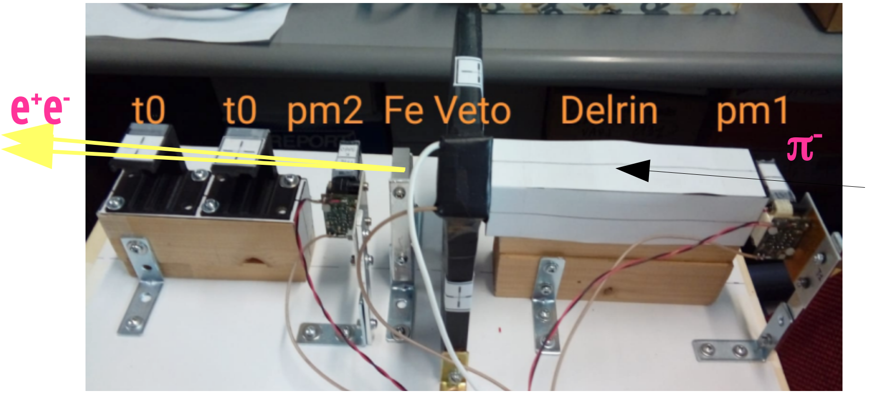
arXiv:2006.07269



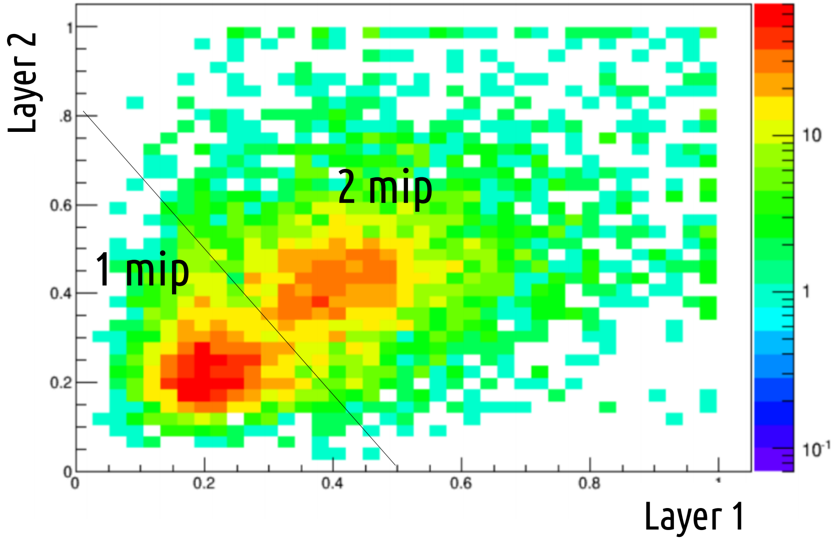


charge exchange: $\pi^- p \rightarrow n\,\pi^0\,(\rightarrow \gamma\gamma)$

Trigger: PM1 and VETO and PM2

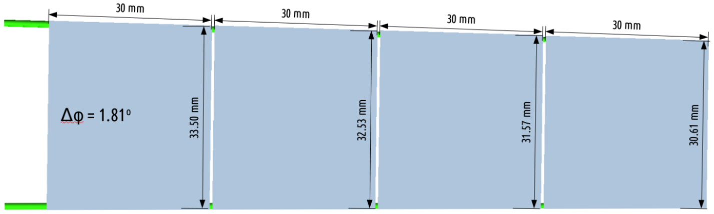


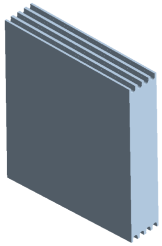
$\sigma_t \sim 400$ ps

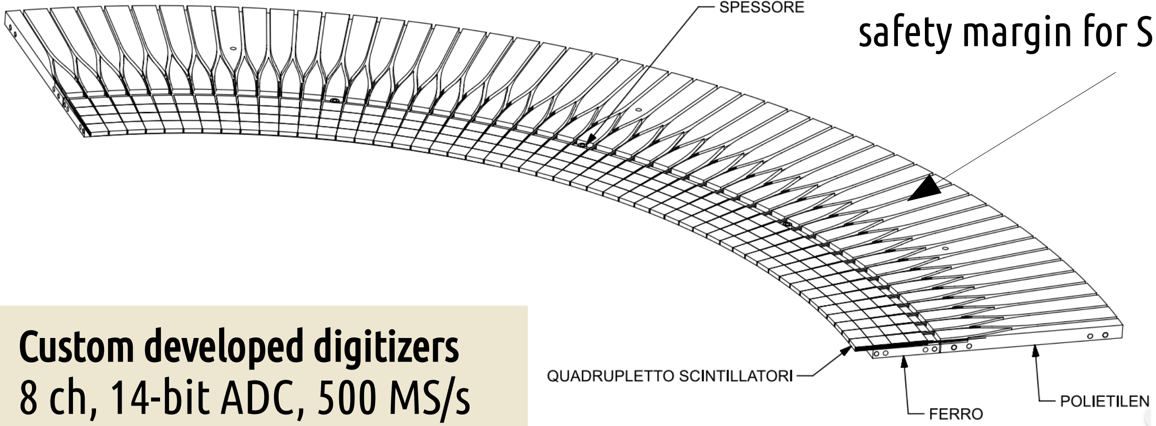


ENUBET: demonstrator

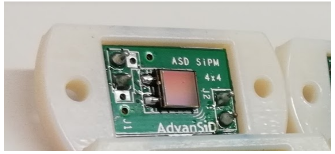
- Large prototype to demonstrate **performance**, **scalability** and **cost-effectiveness**
- Will be tested after the **LS2** at the renovated East-Area at the **CERN-PS** (2021-2022)

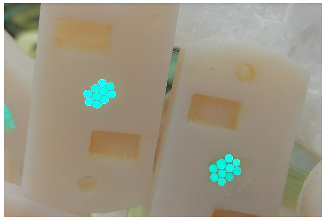


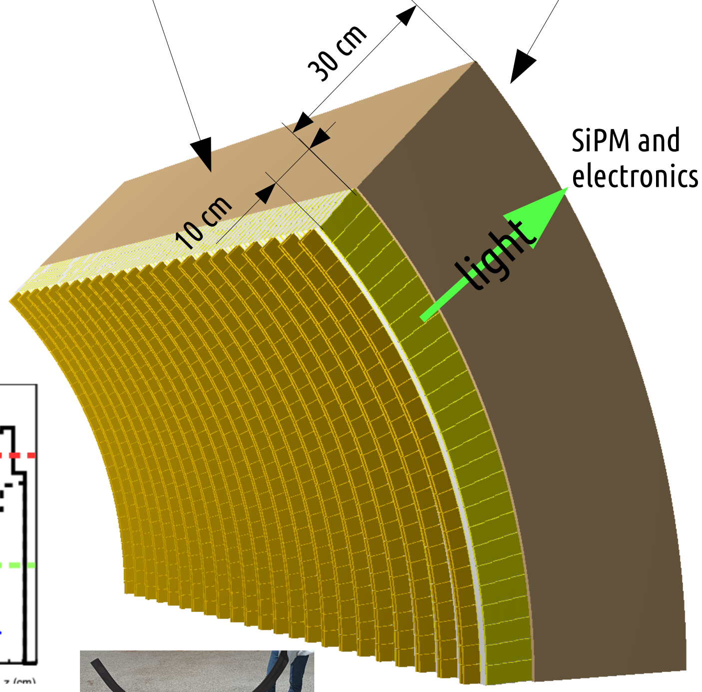




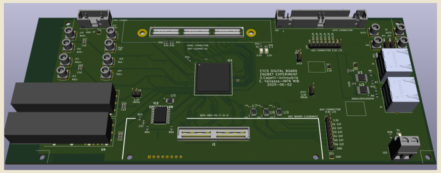
~ 30 cm of borated polyethylene → **factor ~ x 18** neutron reduction. Add safety margin for SiPM. JINST 14 (2019) P02029

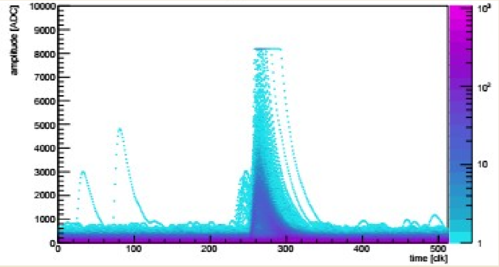




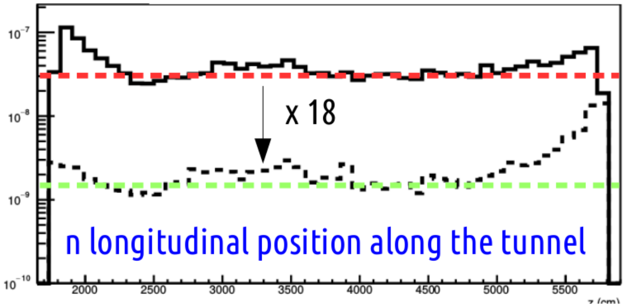


Custom developed digitizers
8 ch, 14-bit ADC, 500 MS/s
Triggerless over ~10 ms.
~40 MB/spill/ch

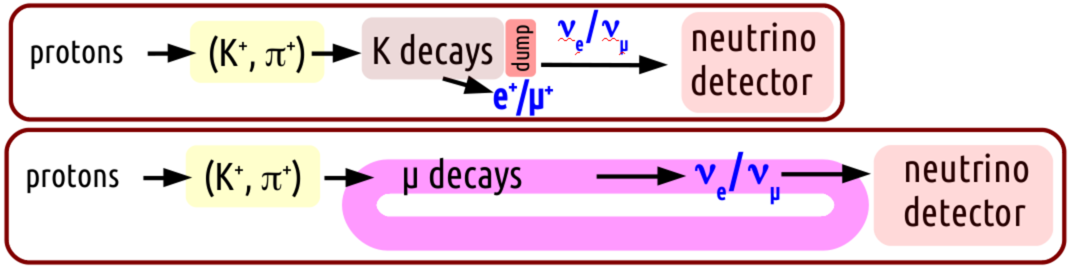




Full beamline FLUKA sim



nuSTORM & ENUBET



protons → (K^+, π^+) → K decays → ν_e/ν_μ → neutrino detector

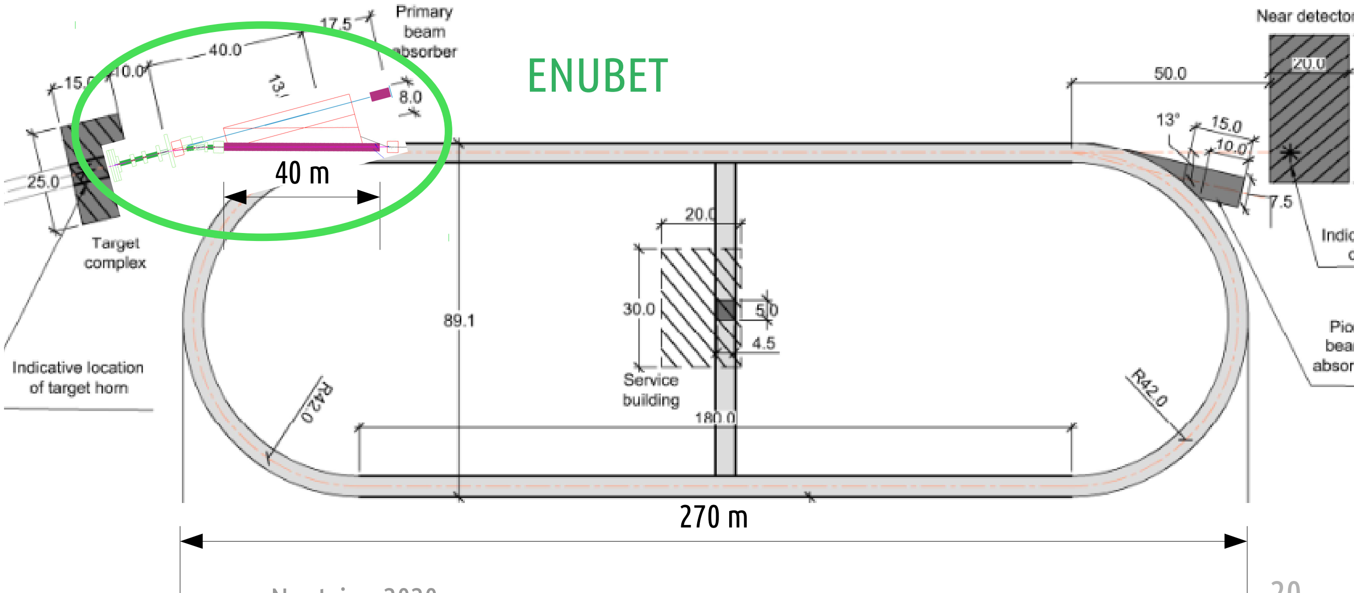
dump

e^+/μ^+

protons → (K^+, π^+) → μ decays → ν_e/ν_μ → neutrino detector

	Decay region	Hadron dump	Proton extraction	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps muons in addition → preventing a (small) ν_e pollution to K_{e3} - ν_e	Slow, 400 GeV (flexible)	Yes, similar	~100 m (some flexibility)
nuSTORM	Replaced by straight section of the ring (180 m).	No. Muons are kept: the most interesting flux parents.	Fast, 100 GeV	Yes, similar	> 300 m from target (ring straight section)

- Different concepts, budget, geometry.
- Main synergy: **target facility, 1st stage of meson focusing, proton dump**.



Directions for novel neutrino beams

How ? →

3) “technology driven”

Profit of advances/affordability of excellent **timing capabilities over large areas** →

- neutrino “time tagging” (**ENUBET**)

Directions for novel neutrino beams

How ? →

3) “technology driven”

Profit of advances/affordability of excellent **timing capabilities over large areas** →

- neutrino “time tagging” (**ENUBET**). R&D on detector technologies other than scintillators in progress.

→ time coincidences of ν_e and e^+

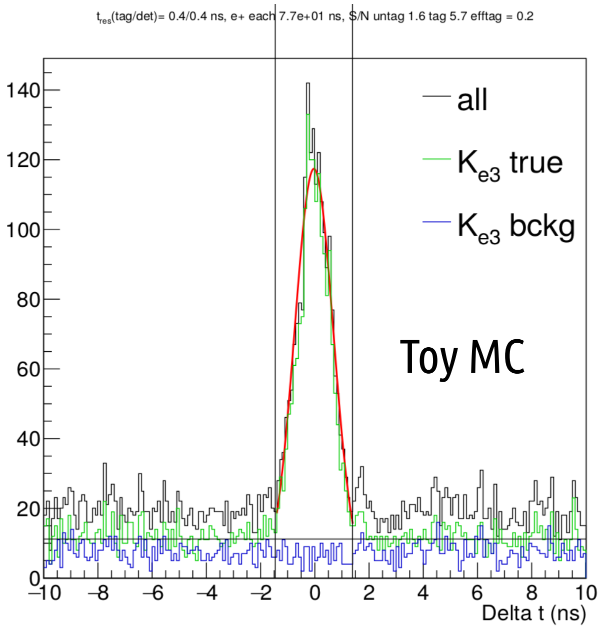
Flavour and energy determination at **interaction level** are enriched by information at the **decay level**.

2.5×10^{13} pot / 2s with 20% eff. S/N 1.6

genuine K_{e3} cand. : → **1 every ~ 77 ns**

background K_{e3} cand. ~ 0.6 x → 1 cand / ~ 130 ns

$\delta=0.4\oplus0.4$ ns resolutions →



Directions for novel neutrino beams

How ? →

3) "technology driven"

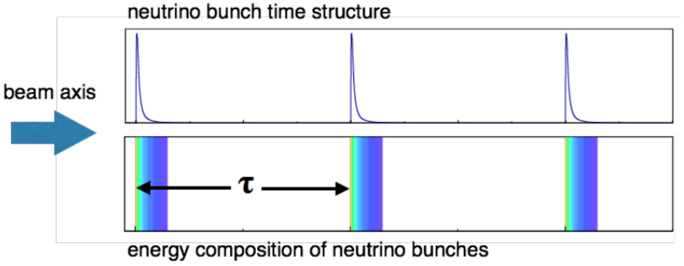
Profit of advances/affordability of excellent **timing capabilities over large areas** →

- neutrino "time tagging" (ENUBET)
- Correlations btw proton RF fine time structure ↔ neutrino E-flavour (**FNAL study 1904.01611**)

Proton RF bunching for energy-flavour discrimination

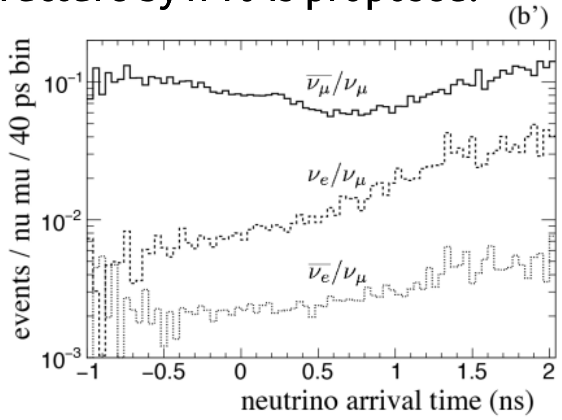
FNAL study 1904.01611

- Use relative arrival times of the ν with respect to the RF bunch structure in a WBB.
  - ν from lower-E hadron parents tend to arrive later
- **Need p-bunch O(100 ps) + commensurate σ_t in the detector**.
- Works at near and far site.
- Past attempts in MiniBooNE. A SC RF cavity to rebunch the present FNAL MI 53.1 MHz RF bunch structure by x 10 is proposed.

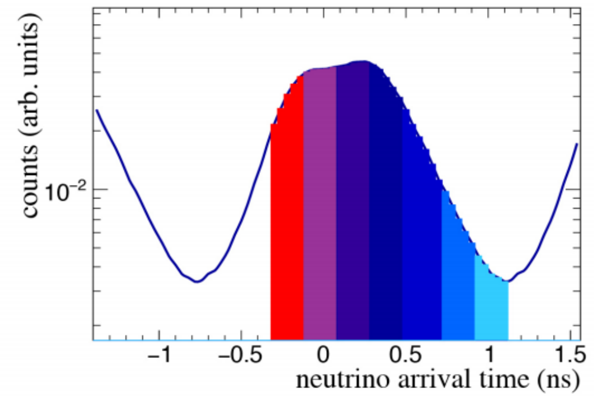


bunch width=250 ps + σ_t = 100 ps

flavour

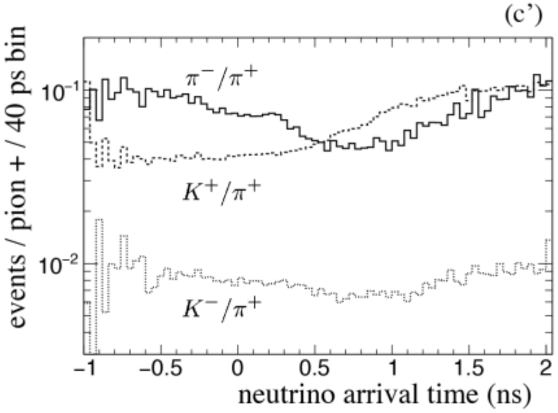


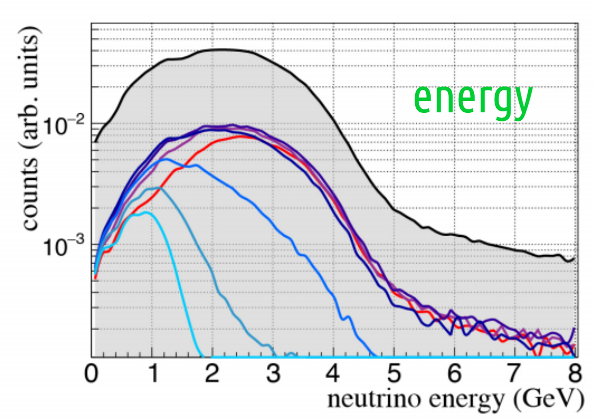
bunch width=250 ps + σ_t = 100 ps



Late neutrinos enriched in ν_e

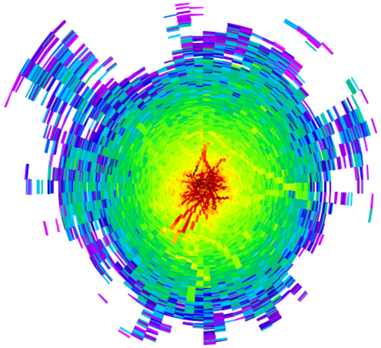
parent





energy

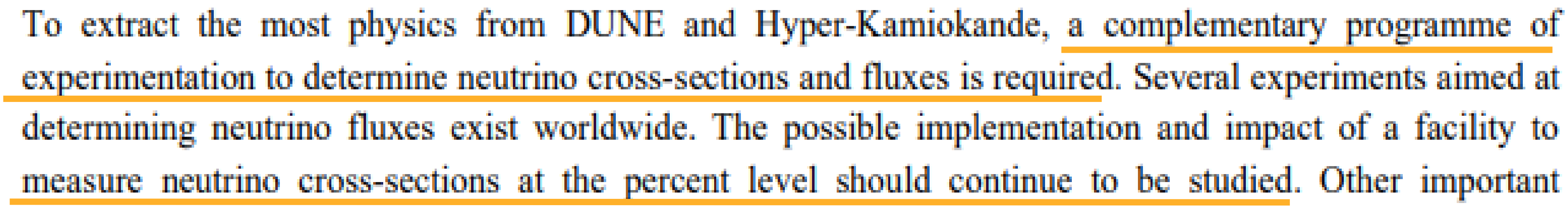
Looking ahead



In the next year **ENUBET** will release a full assessment of **systematics** on the neutrino fluxes, build a **demonstrator prototype** of the tagger and provide a **Conceptual Design Report** with **physics** and **costing.**

nuSTORM has provided last year feasibility studies at FNAL, CERN.

Getting better tools to study cross sections and second order effects seems a **worthy investment** for our community to be **capitalized by the long-baseline** projects.



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

European Strategy for Particle Physics Deliberation document (pag. 5)