Summary of the nuSTORM/ENUBET workshop

A. Longhin

Padova Univ. and INFN

NuFact. Cagliari. 11/09/2021

Outline

- nuSTORM: neutrinos from stored muons
- ENUBET: monitored meson-based beams
- common aims, problems, opportunities!

from Stefano Garau-SardegnaTurismo

Novel beams (muon based)

1) **"clean" source** (~ easy, "textbook" flux prediction)

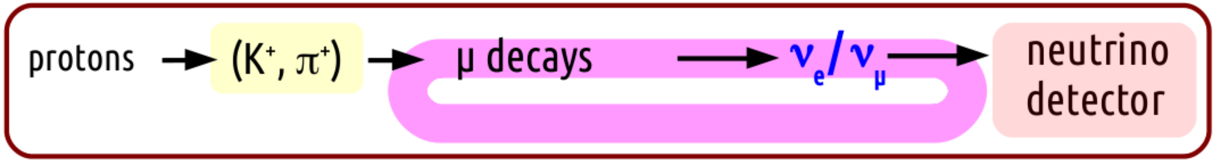
- stored muons → ν factories

Pre-2012 the prevailing idea was that these superbe sources might be **needed** to probe θ_{13} down to 10^{-5} in long baseline experiments.

Novel beams (muon based)

1) **"clean" sources** (~ easy, "textbook" flux prediction)

- stored muons → ~~ν factories~~



After-2012: large θ_{13} allows to "attack" δ_{CP} with the "old dirty" high intensity meson based beams. Still ... a muon based beam (at lower E than the standard ν-factory) could be what we need to make **superior cross section measurements at short baseline** to support the long baseline program → **nuSTORM**

Bonuses:

1) a relevant intermediate step in the path for a **muon collider (6D cooling)**

2) a test-bench to deepen the insight on possible exotic physics

Novel beams (meson based)

ENUBET

Talk by G. Brunetti

2) Conventional "meson based" beams brought to a new standard → use a **narrow band beam** and shift the **monitoring at the level of decays** by instrumenting the decay tunnel (tag high-angle leptons) → remove the main limit to cross section measurements by reducing the flux normalization uncertainty from O(5-10%) to ~O(1%).

Hadro-production (p-target) uncertainties → by-passed by lepton "counting"

An **ancillary facility** providing **physics input** to the long-baseline program: reduction of systematics thanks to unprecedented measurements of the ν_e (and ν_μ) cross sections

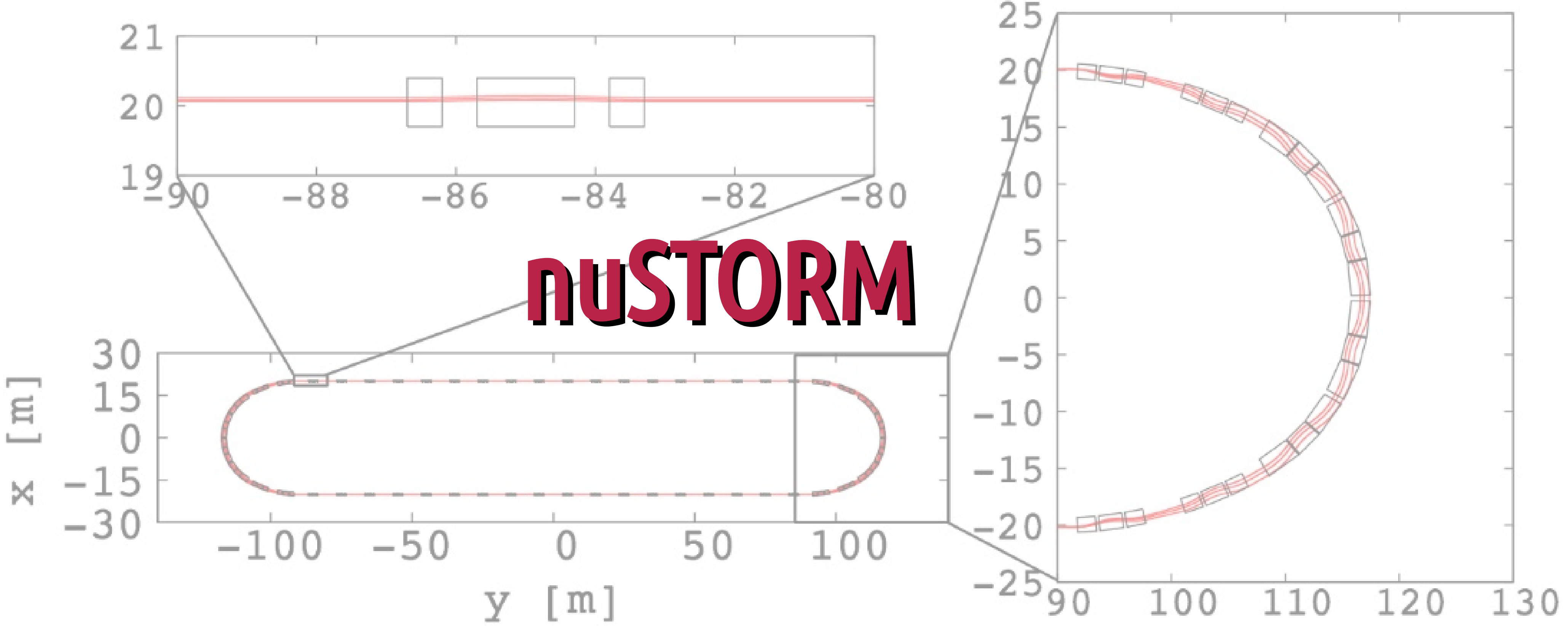
Summary of the ENUBET/nuSTORM workshop

09:00	**Lepton reconstruction in the ENUBET tagger and detectors for the high precision cross section program** *THotel*	*Fabio Pupilli* 09:00 - 09:25
	nuSTORM physics reach: cross sections and exotics *THotel*	*Luis Alvarez-Ruso* 09:25 - 09:50
	Detector R&D for the ENUBET instrumented decay region *THotel*	*Fabio Iacob* 09:50 - 10:15
10:00	**Development and optimization of the ENUBET beamline** *THotel*	*Michelangelo Pari* 10:15 - 10:40
	Design of a common beam line for ENUBET/nuSTORM *THotel*	*Jaroslaw Pasternak* 10:40 - 11:05
11:00	**Fluxes and systematics reduction with decay monitoring** *THotel*	*Antonio Branca et al.* 11:05 - 11:30
	Neutrino fluxes from nuSTORM *THotel*	*Paul Kyberd* 11:30 - 11:55
12:00	**Possible layouts at CERN** *THotel*	*Rui Franqueira Ximenes* 11:55 - 12:10

Clickable links

- Talk by F. Pupilli
- Talk by L. A. Ruso
- Talk by F. Iacob
- Talk by M. Pari
- Talk by J. Pasternak
- Talk by A. Branca
- Talk by P. Kyberd
- Talk by R. F. Ximenez

nuSTORM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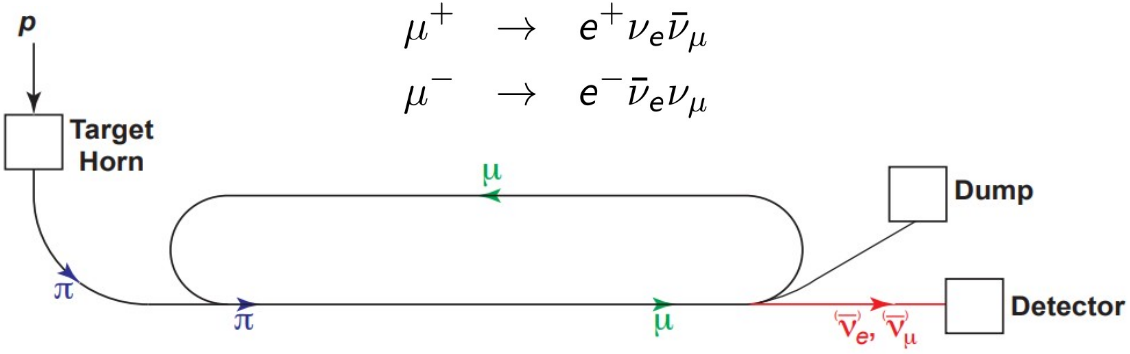
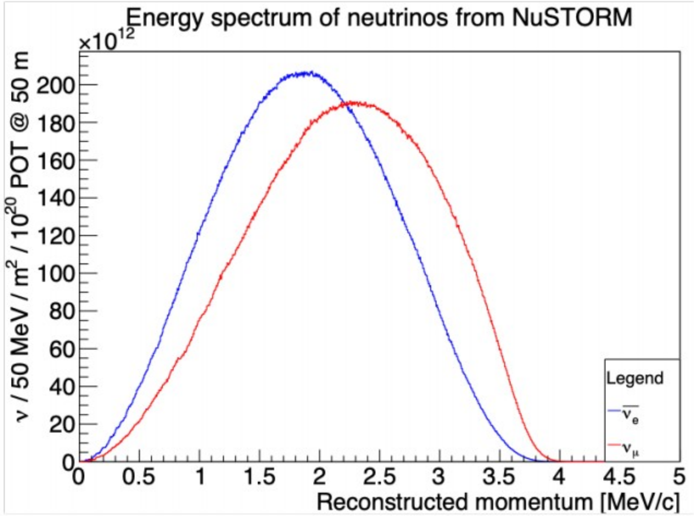
130

nuSTORM implementation at the SPS

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

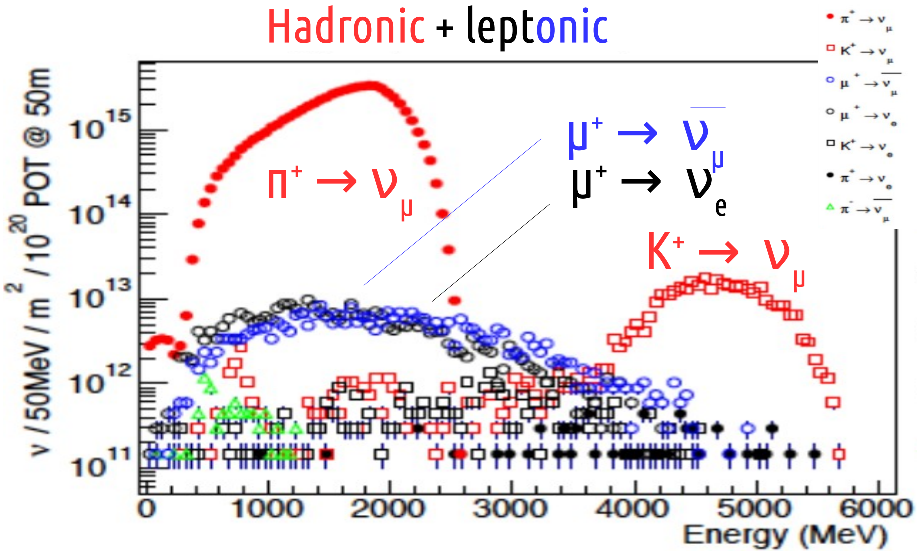
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$





- 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

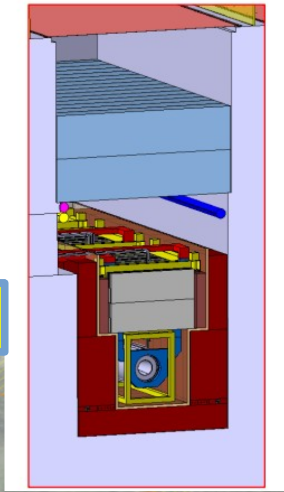
  → ν_μ flash @ “injection pass”
- 1 τ_μ ~ 27 orbits:
- For 10^{20} POT (2×10^{20} expected in 5 y) @ 50 m
  - 6.3×10^{16} ν_μ / m^2
  - 3.0×10^{14} ν_e / m^2

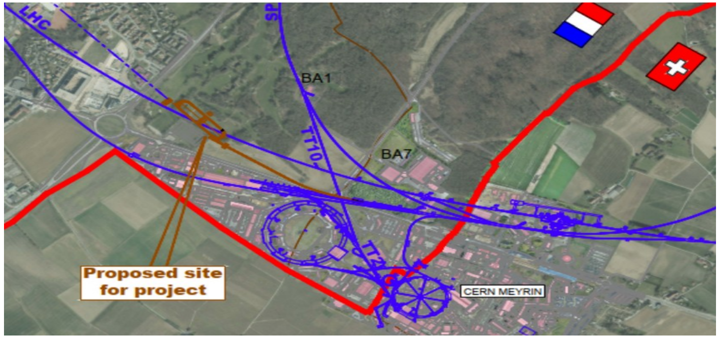


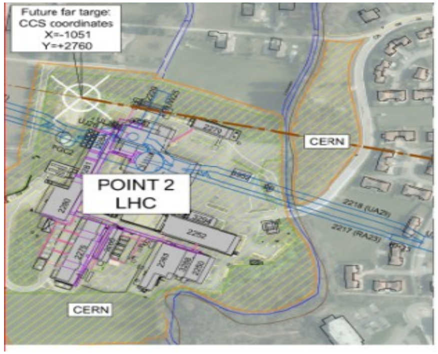
nuSTORM at the SPS

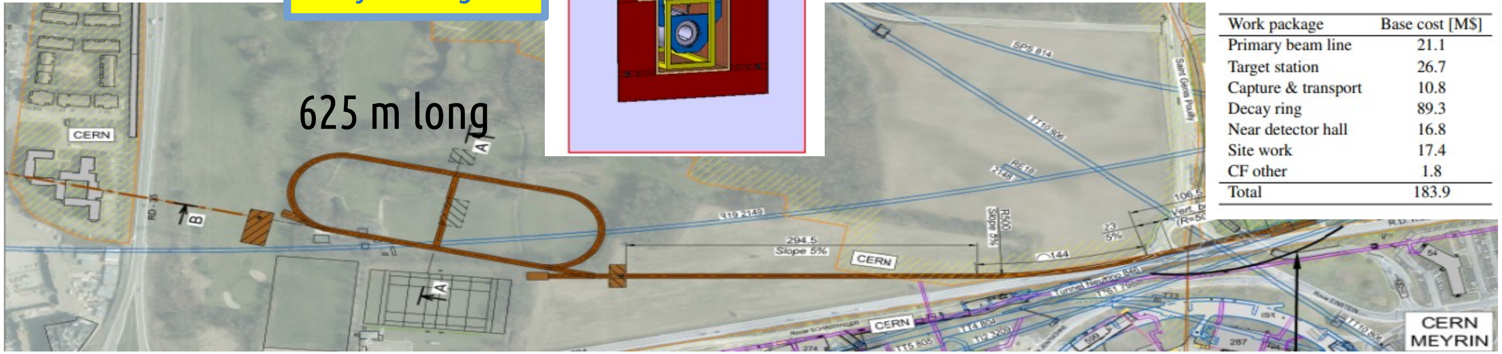
Physics Beyond Colliders study
Costing performed at CERN(*) and FNAL (PDR)
Layouts at ESS also looked into (see ESS workshop)

Maya Olvegård

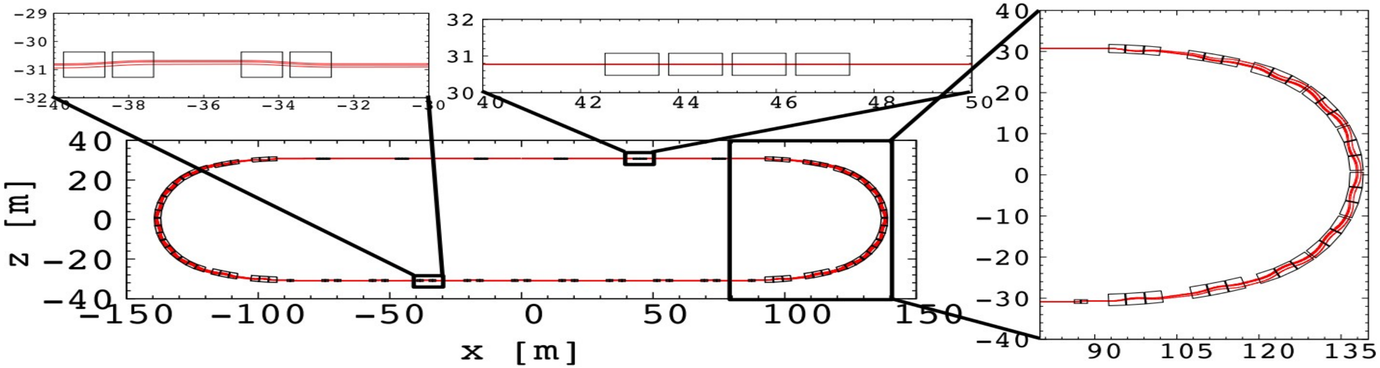


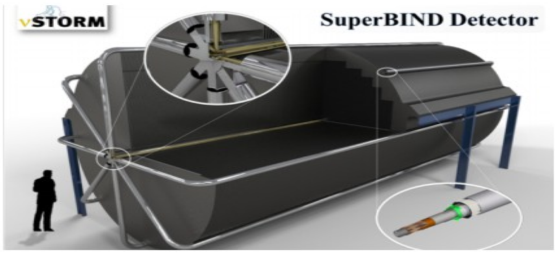






Work package	Base cost [M$]
Primary beam line	21.1
Target station	26.7
Capture & transport	10.8
Decay ring	89.3
Near detector hall	16.8
Site work	17.4
CF other	1.8
Total	183.9

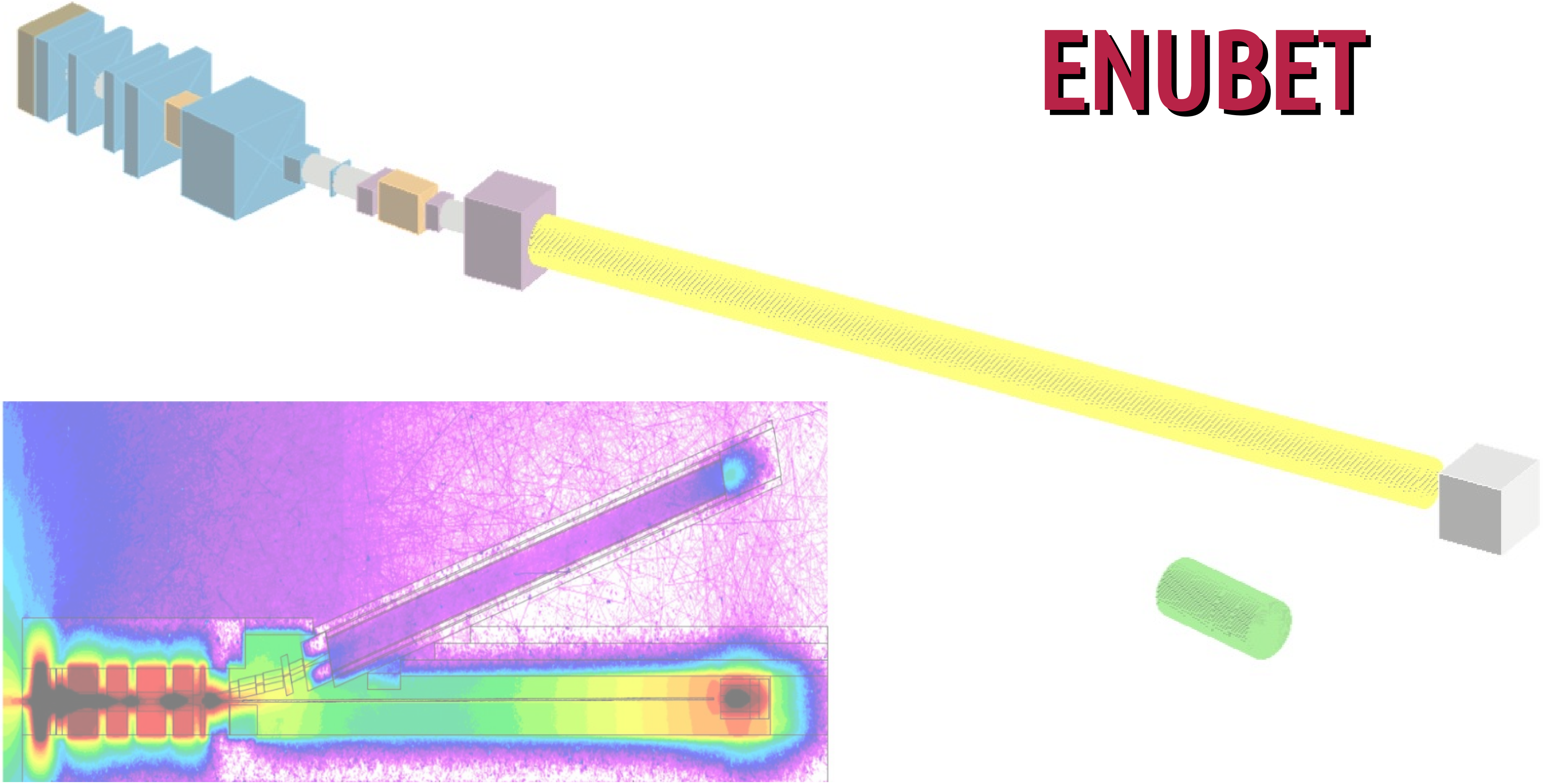




For sterile searches. For cross sections other detector schemes could be more appropriate → see later

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

ENUBET



ENUBET / NP06

Talk by G. Brunetti

A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

Enhanced NeUtrino BEams from kaon Tagging ERC-CoG-2015, G.A. 681647, PI A. Longhin, **Padova University, INFN**

- **CERN Neutrino Platform: NP06**
- **Physics Beyond Colliders CERN study**

ENUBET: 60 physicists, 12 institutions

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

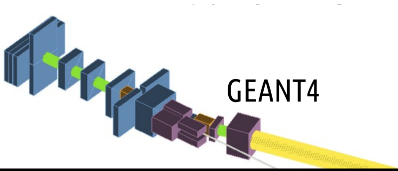
- **Instrumented decay region**
  $K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow$ (large angle) e^+
  $K^+ \rightarrow \mu^+ \nu_\mu \pi^0$ or $\rightarrow \mu^+ \nu_\mu \rightarrow$ (large angle) μ^+
- **ν_e and ν_μ flux prediction from e^+/μ^+ rates**

Requires a **collimated p-selected hadron beam**
→ only decay products hit the tagger → **manageable rates**
Requires a **"short", 40 m, tunnel** (~all ν_e from K, ~1% ν_e from μ)
→ **Bonus:** an **"a priori" constraint on the ν energy** by exploiting correlations between E_ν and the position of interactions in the detector (narrow band beams)

pillars

1) Design/simulate the layout of the **hadronic beamline**
2) Build/test a **demonstrator** of the instrumented decay tunnel

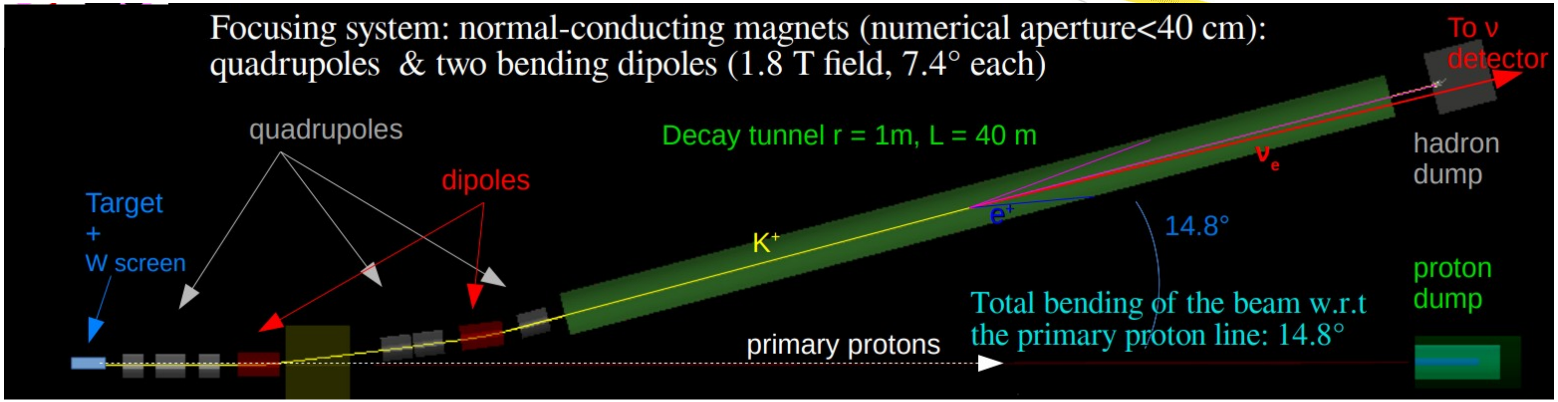
The ENUBET hadron beamline

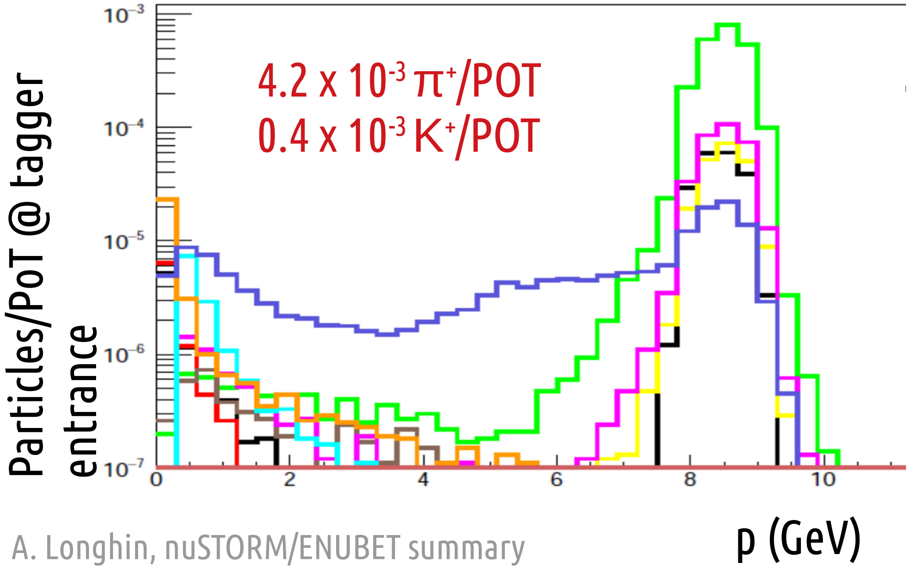


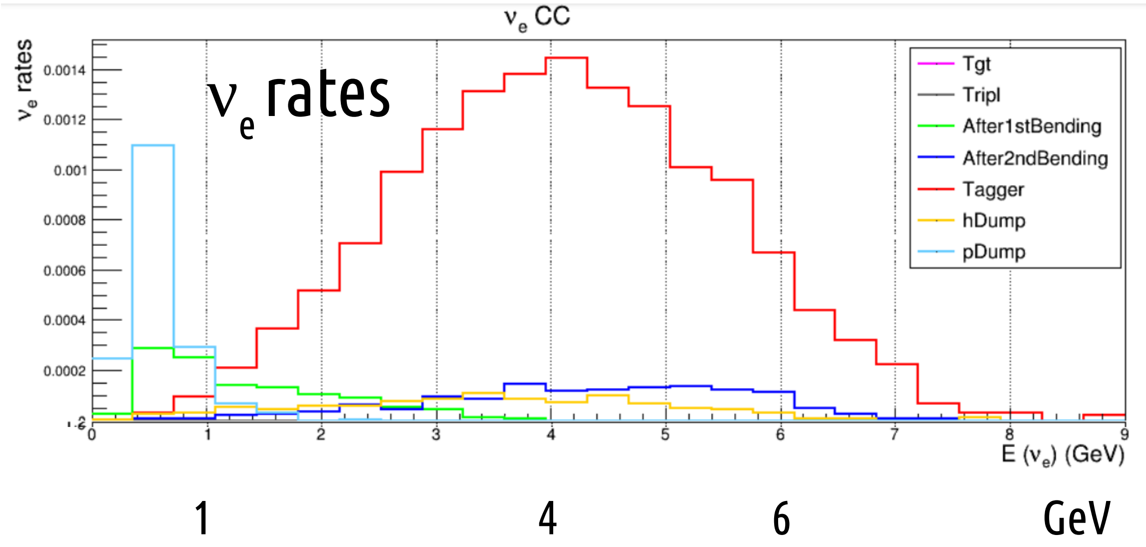
Talk by M. Pari

- Focuses 8.5 ± 5% GeV/c

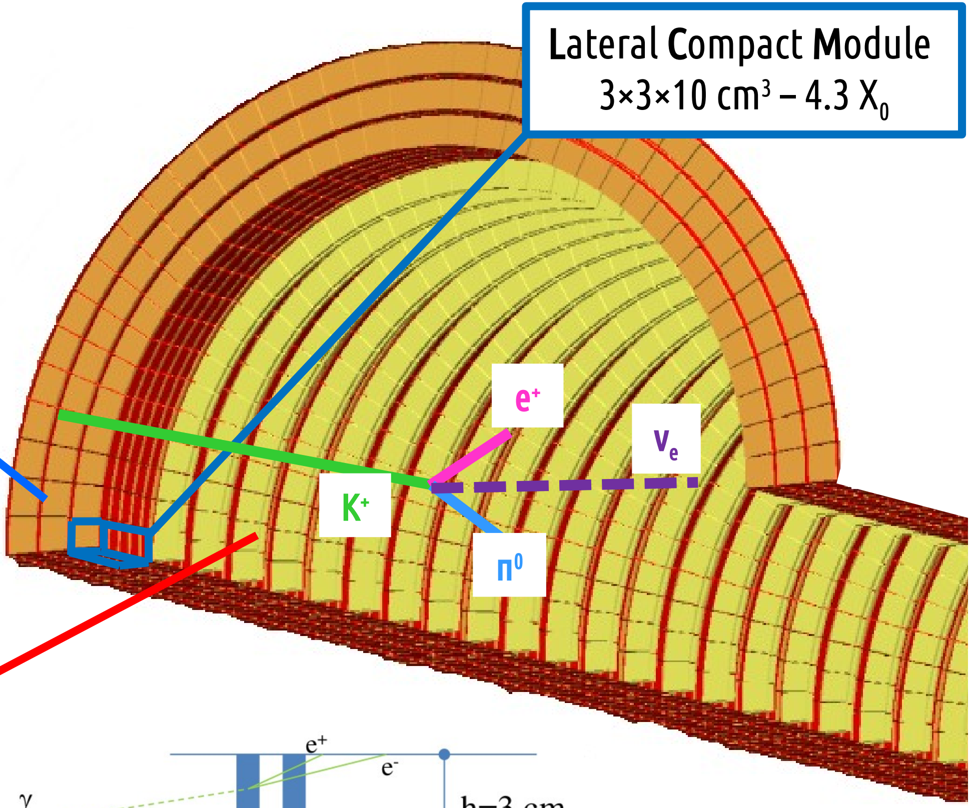
4.5×10^{19} POT/y →
10^4 ν_e^{CC} on 500 t @ 100m
from target in ~ 2 years







The lepton tagger



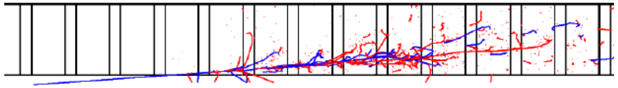
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

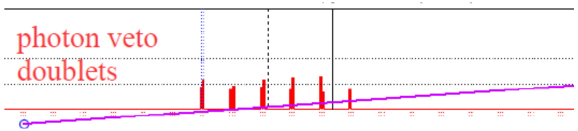
→ $e^+/\pi^\pm/\mu$ separation

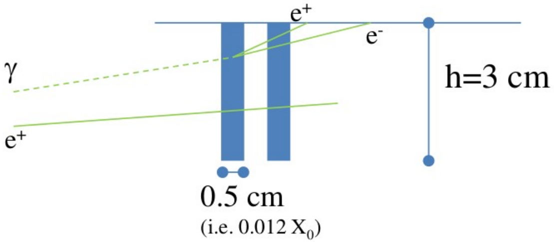


Integrated photon veto

- Plastic scintillators rings of 3×3 cm^2 pads

→ π^0 rejection





e^+ (signal) topology

π^0 (background) topology

π^+ (background) topology

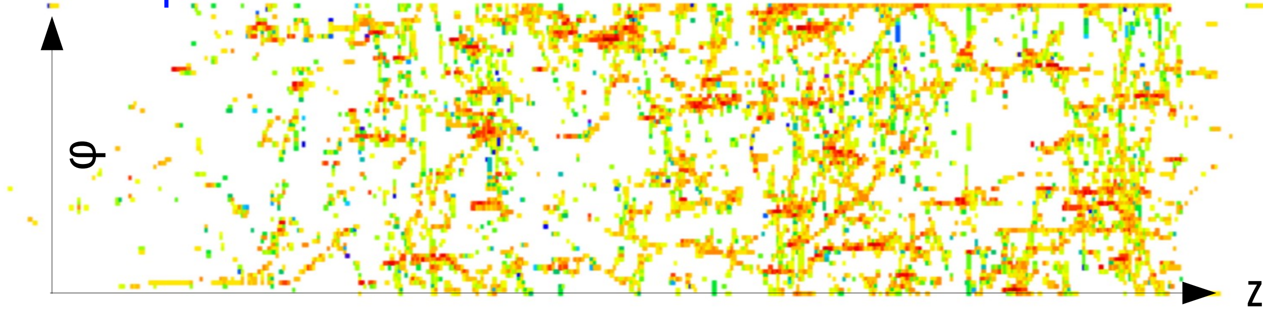
ENUBET: lepton reconstruction

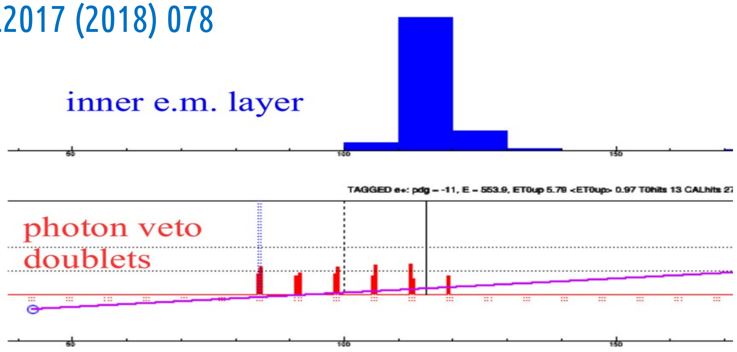
Talk by F. Pupilli

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.

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

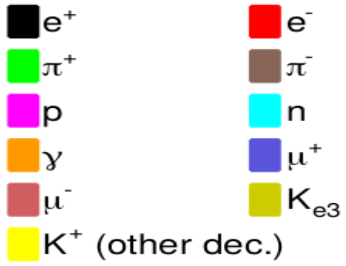
Hit map for e^+

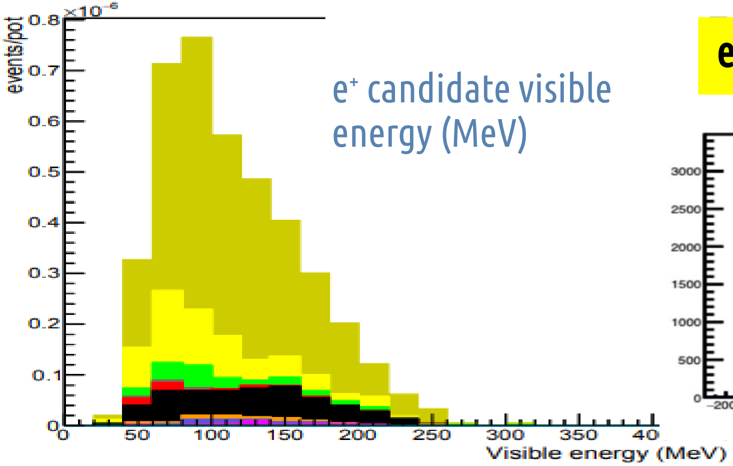




K_{e3} e+: Efficiency ~22%, S/N of ~2

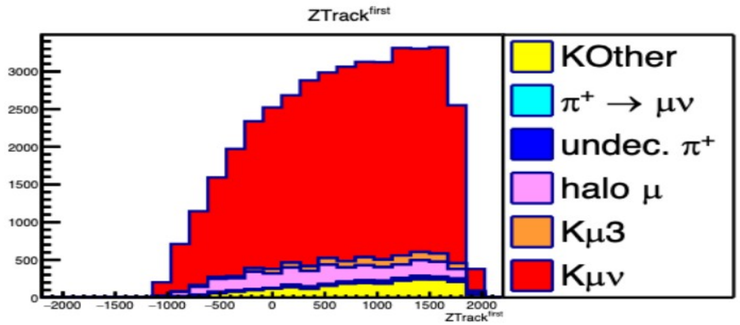
Half of efficiency loss is geometrical





e^+ candidate visible energy (MeV)

efficiency 34% ($K_{\mu 2}$) and 21% ($K_{\mu 3}$) S/B ~ 6.1



μ^+ candidate z coord (cm)

Talk by A. Branca

ENUBET: flux constraint

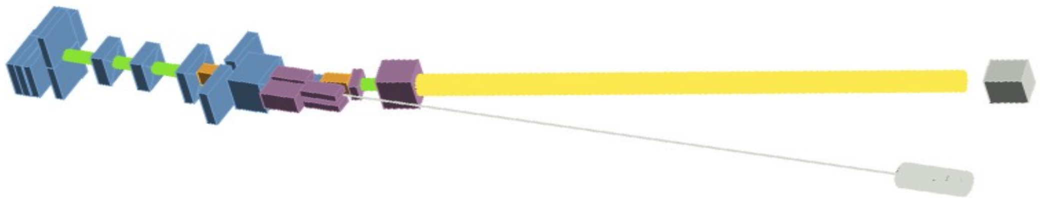
Not directly taggable components:

1) ν_e from $K^{0+/-}$ in the proton/hadron dump

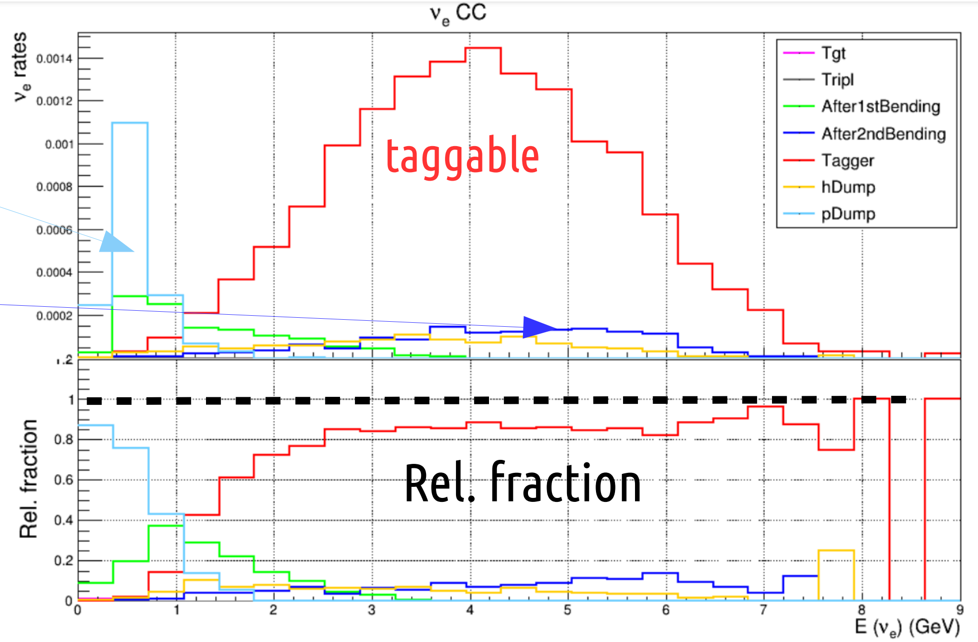
→ reduce by tuning the dump geometry/location

2) ν_e from K^+ in front of the tagger

(after 1st bend/2nd bend) ~10% contamination → accounted for with simulation (~geometrical).



$\nu_{e\,CC}$ spectra

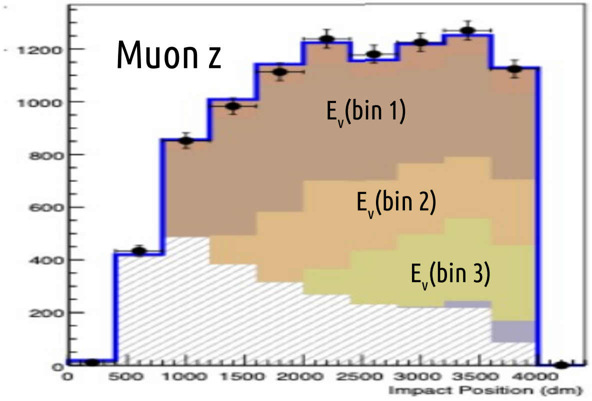


Uncertainty reduction for the tagged flux component

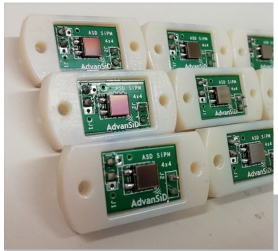
Constrain the flux model by exploiting correlations between the measured lepton distributions and the flux → Fit the model with data and get energy dependent corrections.

An example:

Each histogram component corresponds to a bin in neutrino energy



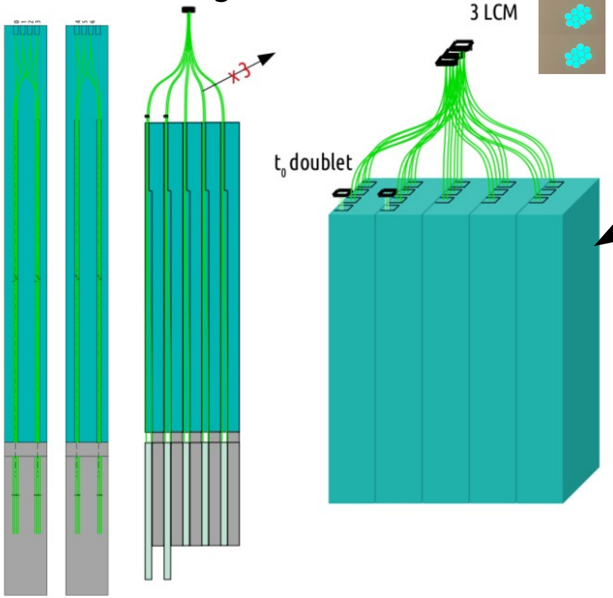
The demonstrator



Custom digitizers @ 500 MS/s

Talk by F. Iacob

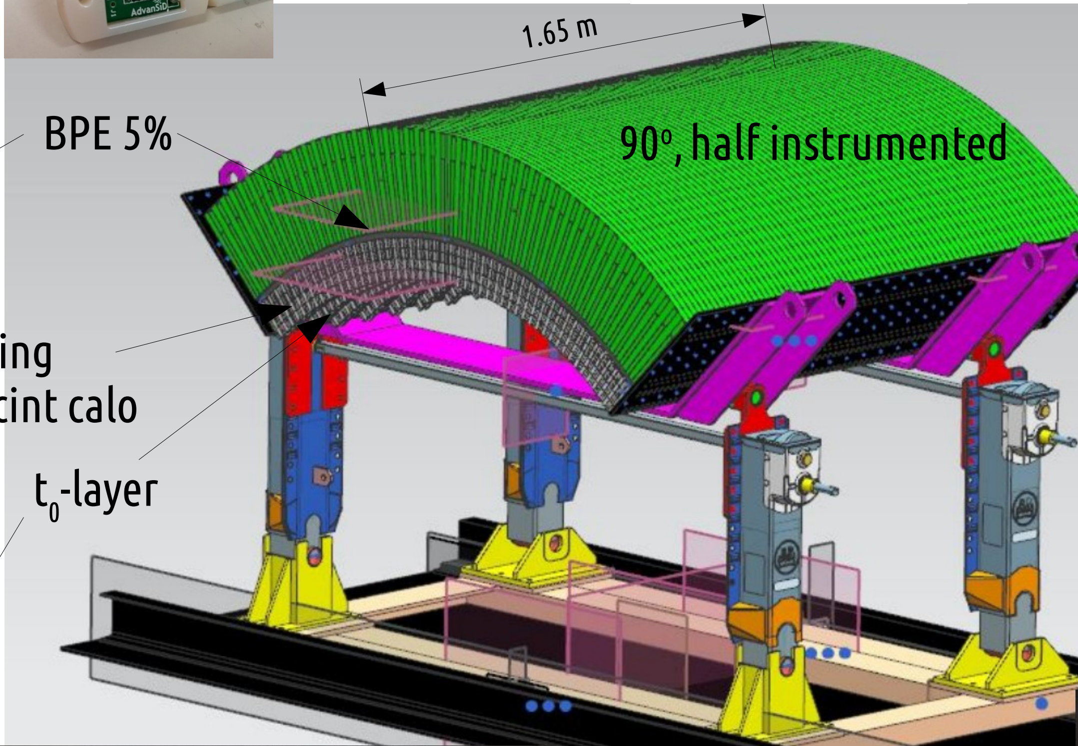
WLS routing

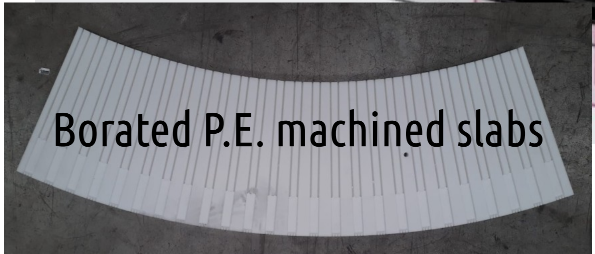


BPE 5%

Sampling iron/scint calo

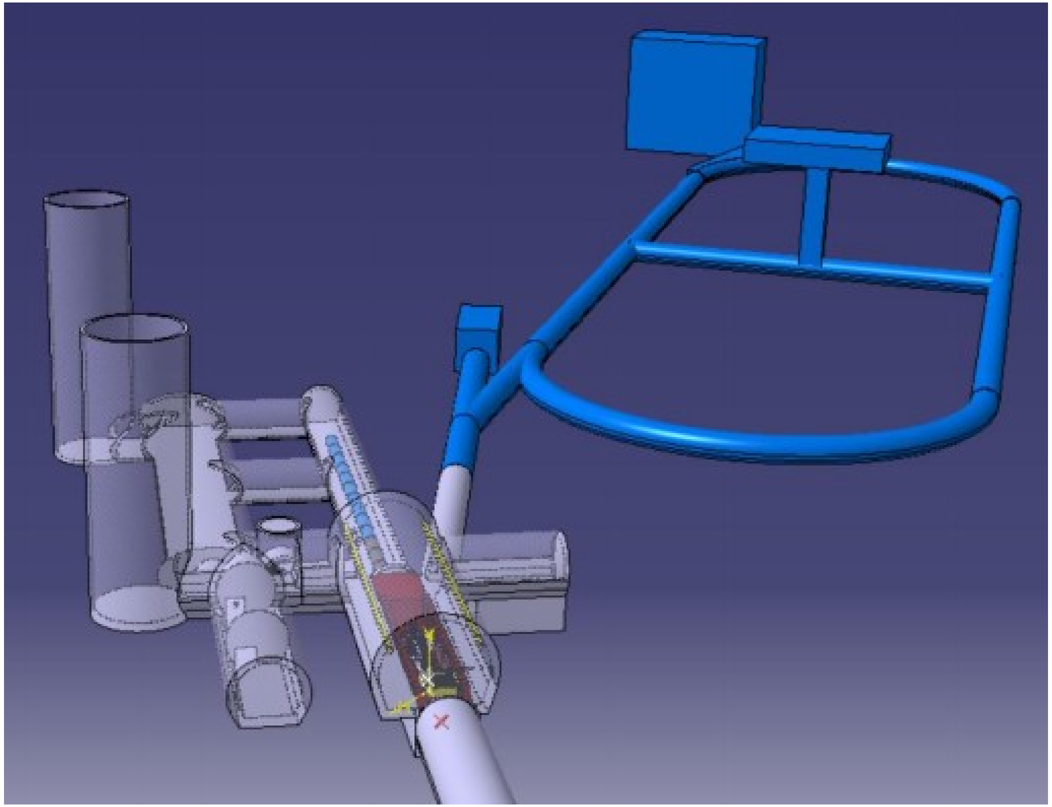
t_0-layer





3D-printed fiber concentrator

Joint opportunities



Fluxes "tunability"

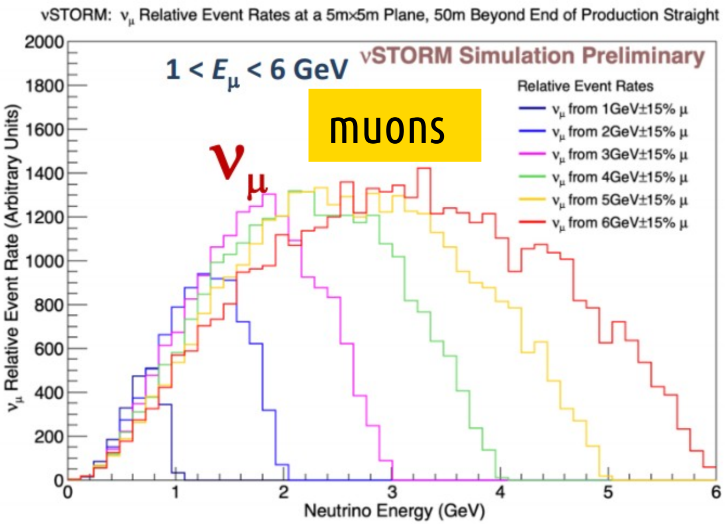
Talk by P. Kyberd

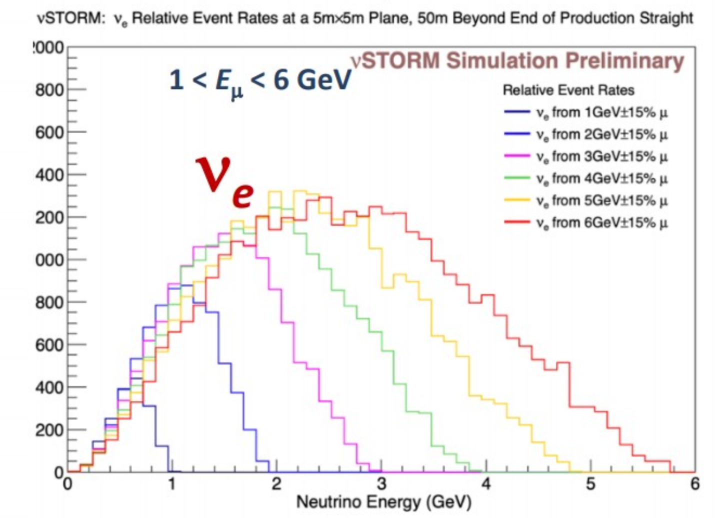
nuSTORM: vary the channeled muon energy from 1 to 6 GeV/c

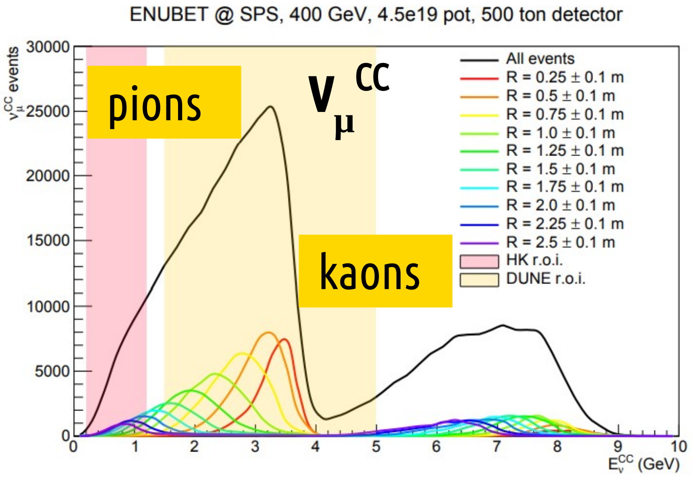
ENUBET narrow-band off-axis technique:

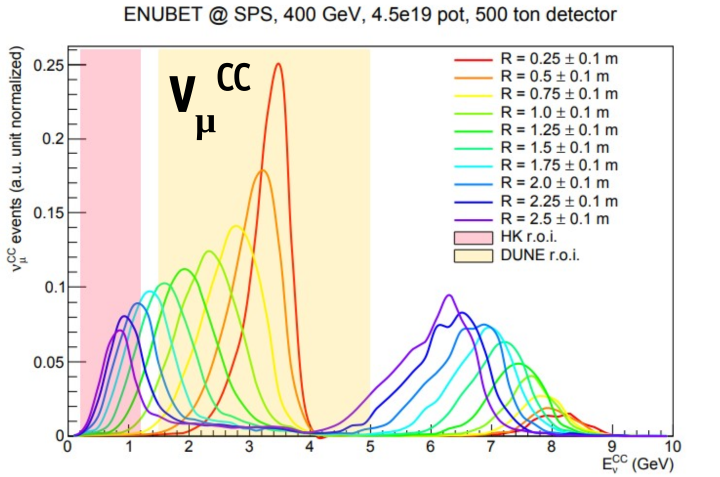
Bins in the **radial distance from the center of the beam → single-out well separated neutrino energy spectra** → strong prior for **energy unfolding**, independent from the reconstruction of interaction products in the neutrino detector. Position is an easy variable to reconstruct.

A kind of "off-axis" but without having to move the detector (thanks to the low distance of the detector) !





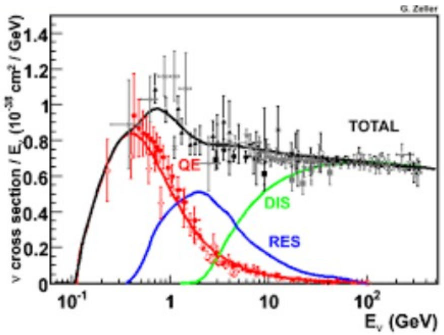




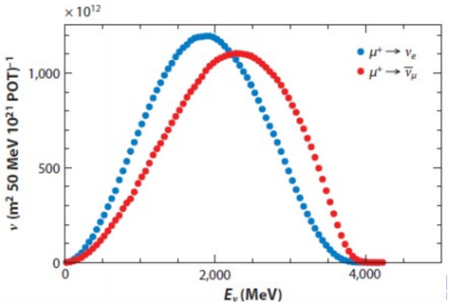
Physics reach for cross sections

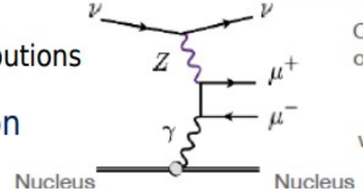
Talk by L. A. Ruso

- Quasielastic scattering
- Inelastic scattering
- Shallow inelastic scattering
- Deep inelastic scattering



- characterization of ν_e **vs** ν_μ **differences**
- better understanding of the initial state
- study of meson-exchange currents (or 2p2h)
- nuclear effects on PDF
- study of exclusive final states
  - one- and two-nucleon knockout
  - single and multiple pion production
  - **"Rare" processes**
  - strangeness production
  - coherent meson production
  - trident scattering
    - Possible BSM contributions
  - single photon emission



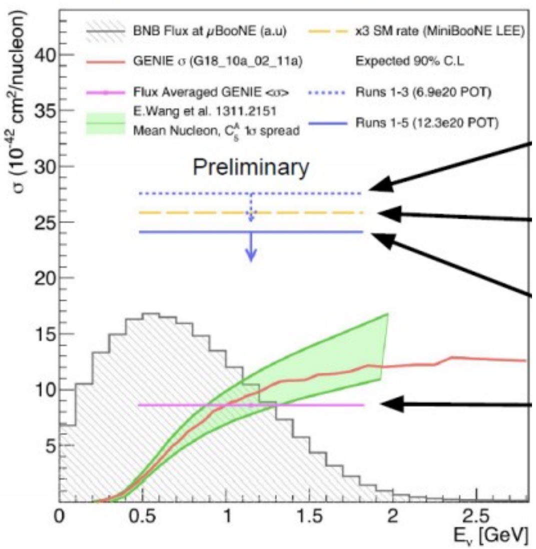


from M. Hostert

Cross section at the level of 10^{-6} of CCQE at 2 GeV

Magnetized detector with large Z nuclei is ideal.

- single photon emission



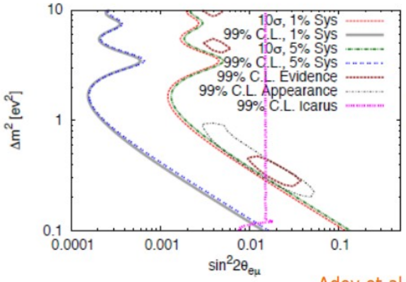
"Complement superior flux control with excellent detectors!" (disentangle processes with the hadronic final states)

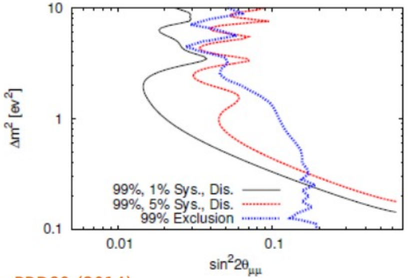
Physics reach for exotic phenomena

Talk by L. A. Ruso

Sterile ν search

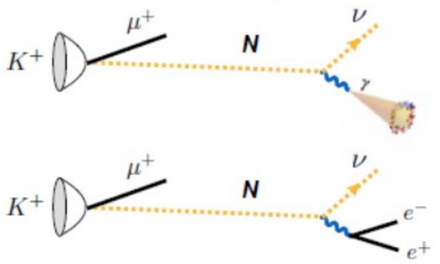
- ν**STORM** has a **unique sensitivity** to **light sterile** neutrinos.
- ν_μ **appearance** from $\nu_e \to \nu_\mu$
- $\bar{\nu}_\mu$ **disappearance** from $\bar{\nu}_\mu \to \bar{\nu}_e$
- 10^{21} POT $\approx 2 \times 10^{18}$ μ^+ decays
- 1.3 kt FD located $\sim$ 2 km away from the ND
- In a **3+1** sterile model:





Adey et al., PRD89 (2014)

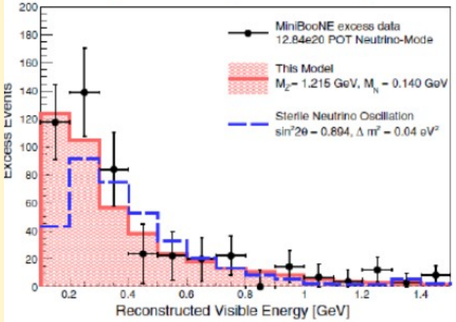
- Heavy (keV-MeV) neutrino production in decays

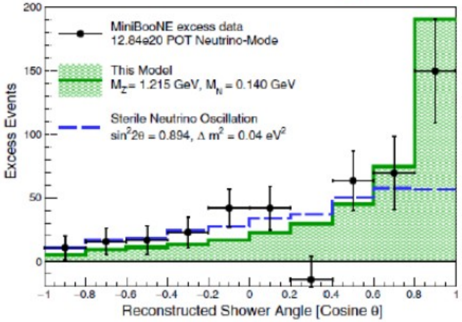


from M. Hostert

- Heavy (1-100 MeV) neutrino production in scattering
  - Proposed as possible explanations of the MiniBooNE anomaly
  - $\nu_h \to \gamma$, e$^+$e$^-$
  - experimental γ, e$^\pm$, e$^+$e$^-$ distinction required
  - ν_h can be produced:
    - EM (γ mediator), transit. mag. moment Masip et al, JHEP 1301 (2013)
    - NC (Z mediator), mixing Gninenko, PRL 103 (2009)
    - BSM (Z′ mediator) Ballet et al., PRD 99 (2019)
      Bertuzzo et al., PRL 121 (2018)
      Arguelles et al., PRL 123 (2019)
      ...

- Proposed as possible explanations of the MiniBooNE anomaly





Z′ mediator Ballet et al., PRD 99 (2019)

- On nuclear targets:

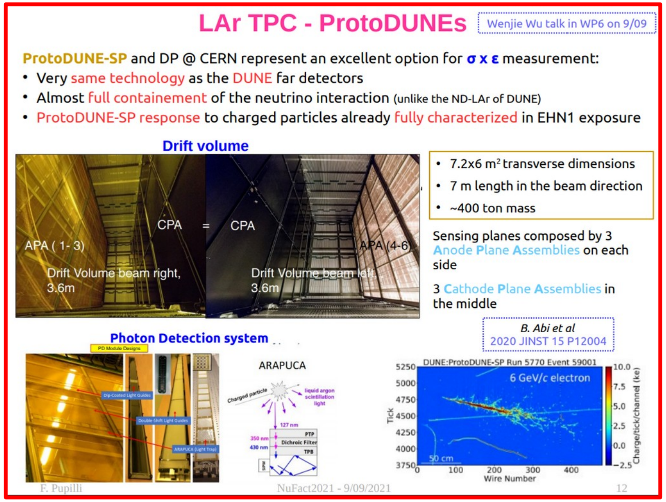
$\nu_\mu(\bar{\nu}_\mu)\, A \to \nu_h(\bar{\nu}_h)\, A$ $\leftarrow$ coherent: light mediators

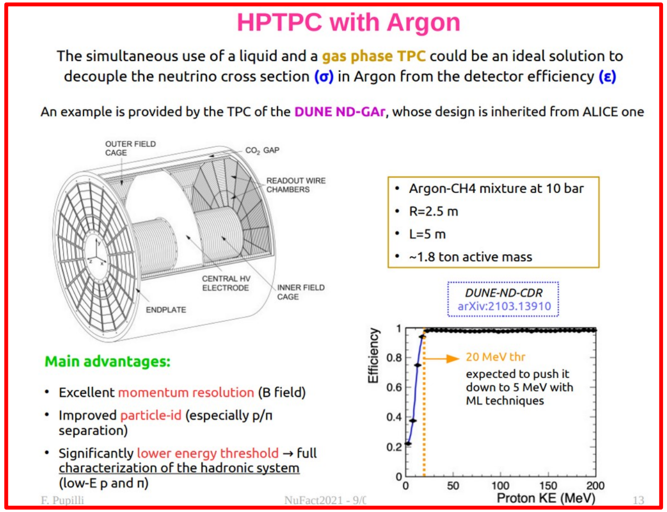
$\nu_\mu(\bar{\nu}_\mu)\, A \to \nu_h(\bar{\nu}_h)\, X$ $\leftarrow$ incoherent: heavy mediators

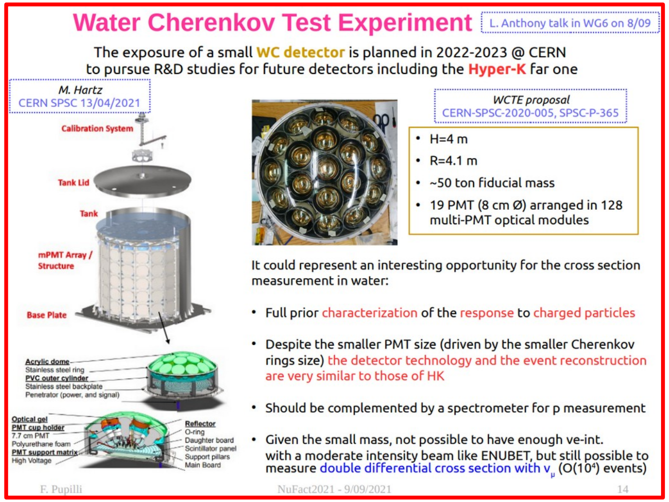
Detectors to “live up” with excellent fluxes

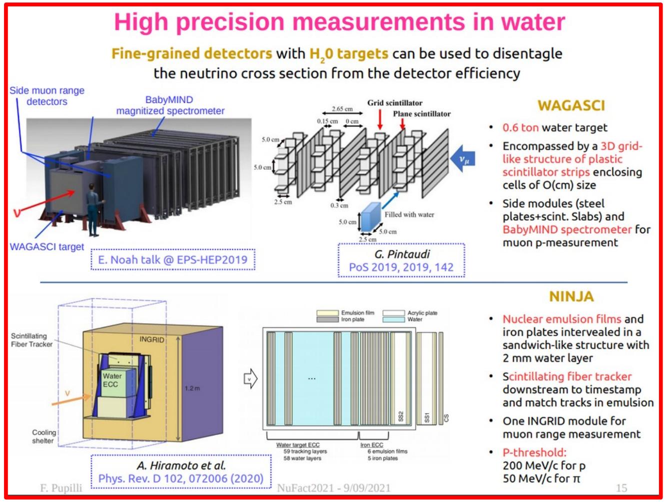
Talk by F. Pupilli

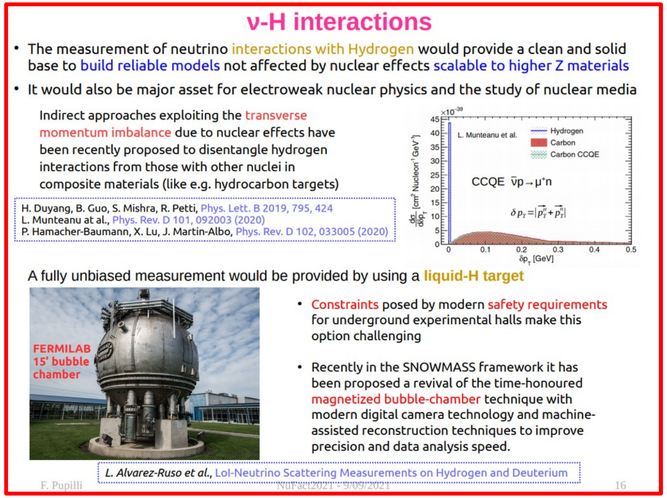
Material	“Same as far”	+ > granularity
Ar	pDUNES	GAr TPC
H_2O	WCTE	WAGASCI/ NINJA
H/D		H bubble chamber







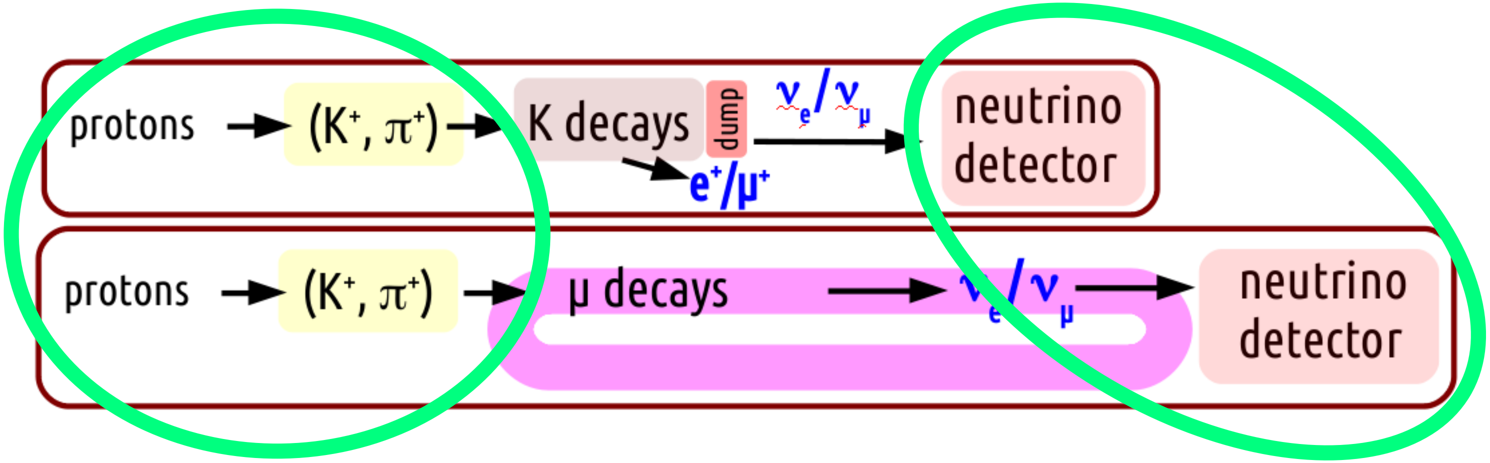




Opportunities

The first stage of nuSTORM can be seen (simplistically) as an "ENUBET without a hadron dump" where pions and muons are channeled into a ring. The "pion burst" neutrino component of nuSTORM is what ENUBET constrain thanks to the instrumented tagger → room for smart ideas to match the requirements of the two experiments.

- common points: **proton extraction line, target station, 1st stage of meson focusing, proton dump, ν-detector**



- **Similar goals** (high precision ν-fluxes) → strengthen the physics case, involve the larger community.
- Natural/mandatory to look into **possible common infrastructures** to reduce the costs.
- Not straightforward though (devil in the details) → **joint work, sharing of results, experience, tools: STARTED!**

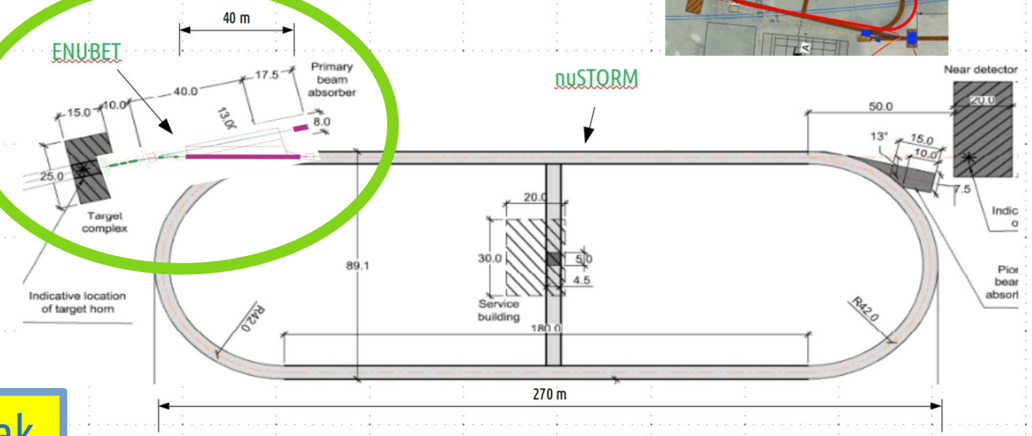
Options

Option1 ("serial"): ENUBET is much smaller, less challenging from the point of view of accelerator physics (key is really background reduction keeping a large statistical sample) → Same target+meson transfer line feeding ENUBET and, in a 2nd phase, the nuSTORM storage ring. **How similar is the desired phase space of mesons at the level of the tagger entrance / storage ring ? Is it possible to design a transfer line being flexible enough to feed a very well collimated 8.5 GeV meson beam to an instrumented decay tunnel or a wider beam to match the storage ring acceptance ?**

Talk by J. Pasternak

See also Efthymiopoulos
IPPP topical meeting on Physics with high-brightness stored muon beams
https://conference.ippp.dur.ac.uk/event/967/contributions/5072/attachments/4130/4853/ie-IPPWorkshop_11.02.2021_final.pdf

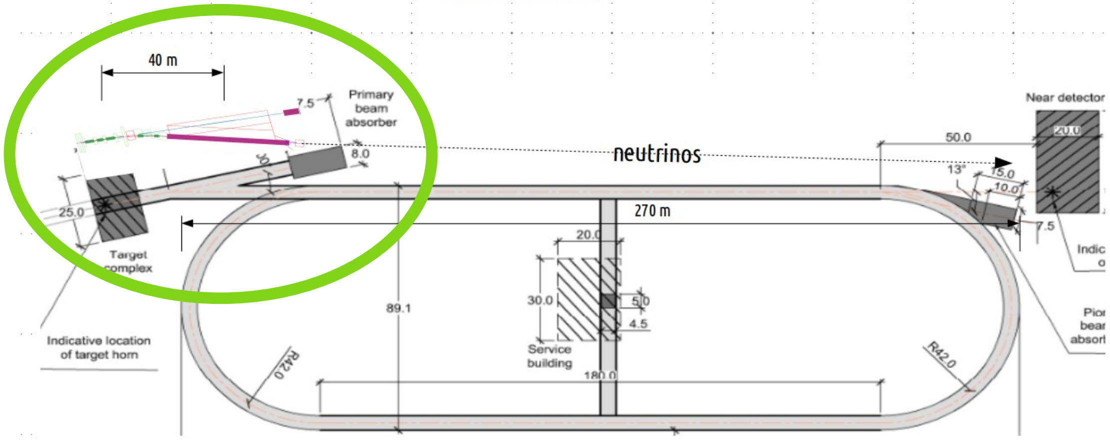
Same layout, staged/mixed operation?
Very cost effective. Stronger interdependence.



Option 2 ("parallel"): independent secondary beamlines fed by a proton beam splitter. Parallel operation, more independence. Still would allow to optimize the target station costs. **How compatible are our proton extraction schemes? (F.E. vs S.E/burst S.E.) How flexible are we in respect to using the same proton energy? Which one should it be ?**

Talk by F. Pupilli

Splitting of proton beamlines + two targets, same detector ?
Less cost effective, more degrees of freedom/parallelization

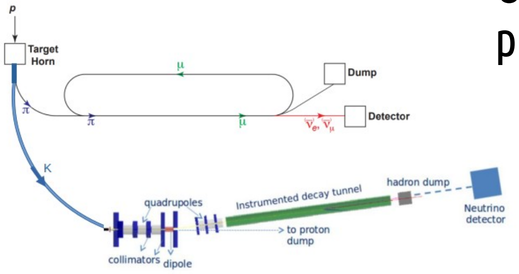


Neutrino detector → an optimal design could be perfectly good for both projects. The most significant difference is in the position (close for ENUBET, after the straight section for nuSTORM). **movable detector ? double detector ? Use other straight section of the racetrack for nuSTORM ?**

Studies for a common hadron beamline

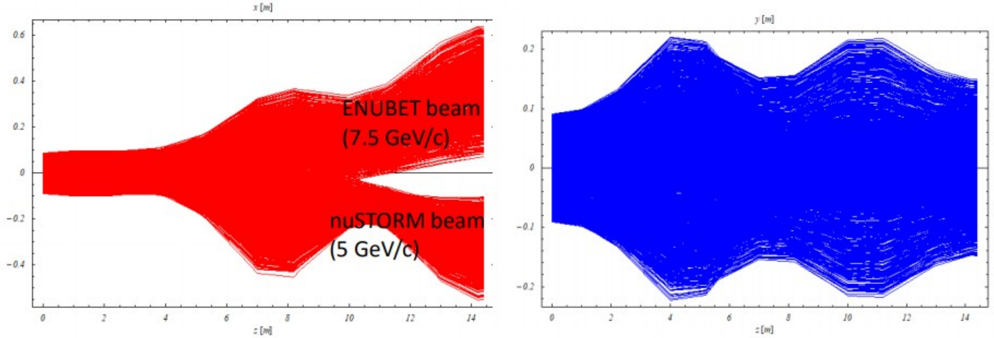
Talk by J. Pasternak

Parallel operation

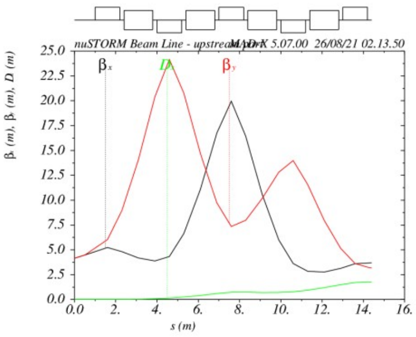


Optimal use of protons on target

Splitting

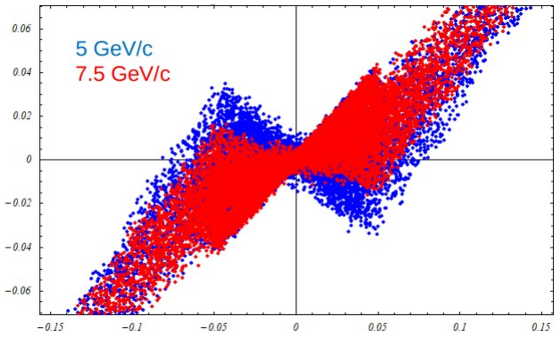


Tracking ~1000 particles along the common transport line with large momentum spread (10%). The initial alpha and beta are assumed to be the same. Good beam separation was achieved.



Common part

horn



- Horn can simultaneously provide the beams for momenta of 5GeV/c and 7.5GeV/c
  - The same current is assumed
  - The optical conditions are not identical

Conclusions

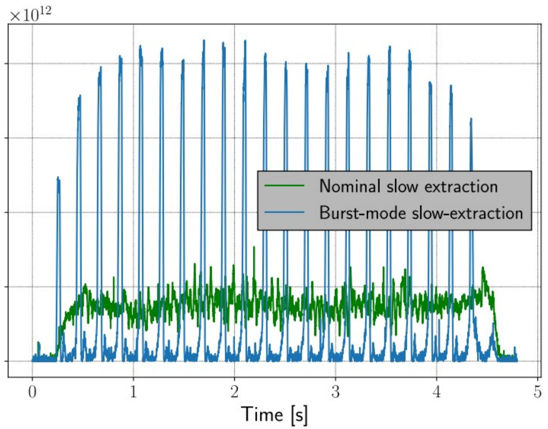
- The preliminary design of the first part of the common transport line for parallel running of ENUBET and nuSTORM was implement using a system with 5 quadrupoles and 4 bending dipoles that are placed alternatively to allow an effective generation of x-axis dispersion for separating the beams for two facilities
  - The current design requires quadrupole coefficients to be relatively large, and possibly requires to be operated with superconducting quadrupoles with the field at the poles as large as 3.5 T, subject of further optimization
  - We also started working on FFA-type lattice
  - No short stopper was found
- Further work will include the design and performance studies of downstream parts of the transport lines matched to ENUBET and nuSTORM experiments
  - Optimization of lengths and beam parameters
  - Investigation of flexibility for different operating modes

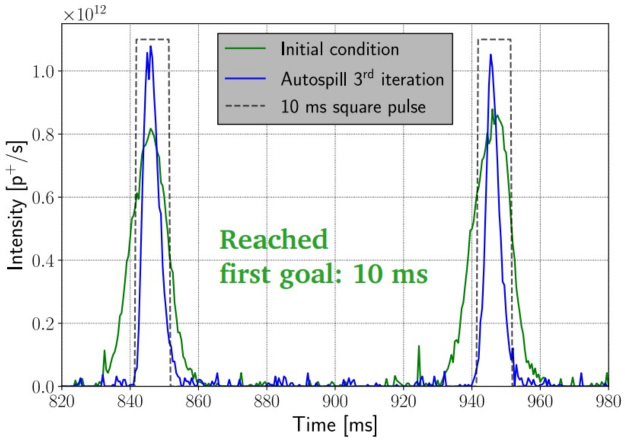
Compatibility of proton extraction schemes ?

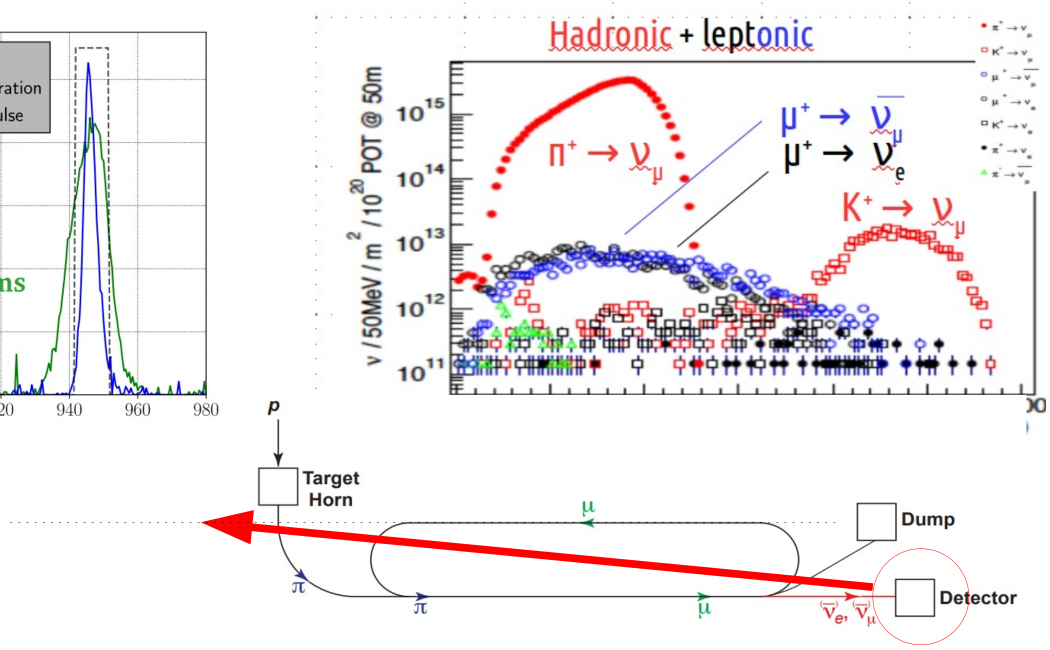
Talk by J. Pasternak

Talk by M. Pari

Is the slow-extraction or burst-mode slow extraction needed by the ENUBET tagger compatible with nuSTORM?
In principle it could be, it would become more difficult to separate neutrino from muons from the initial burst of neutrinos from meson decays. Could be solved by aligning the detector to the straight section of the racetrack opposite to the injection one. This might also help having a shorter baseline for ENUBET and a longer one for nuSTORM with the same detector. Some reduction in statistics for the baseline nuSTORM setup (with horn).





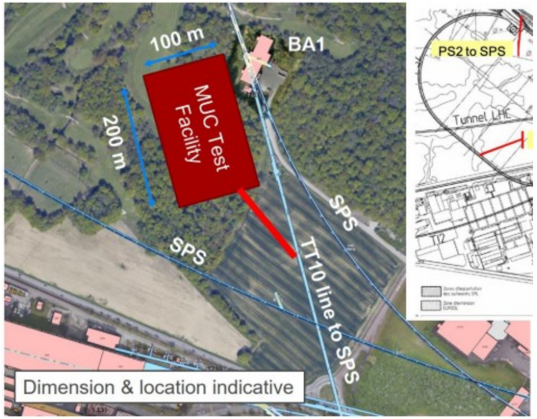


ENUBET/nuSTORM at CERN-PS μ-collider facility ?

Talk by R. F. Ximenez

Talk by D. Schulte

TT10



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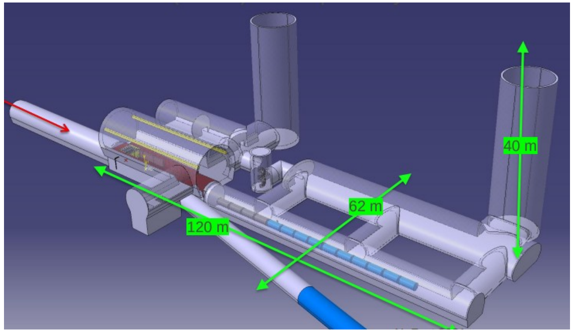
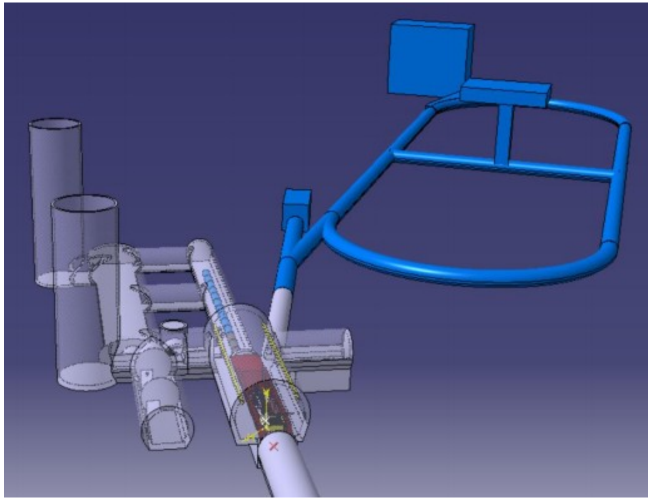


- Possible synergies with nuSTORM/ENUBET if Target complex is shared such as reduced costs, Radiation Protection, equipment, etc.
- Muon Collider facility and its integration/compatibility with nuSTORM/ENUBET should be explored
- Other alternatives focused on muon collider demonstrator objectives could be investigated



We are studying how working at 26 GeV would impact the current baselines (SPS, 100 and 400 GeV). Do we need a new PS to do the physics in reasonable amount of time ? (POT increase to cope with the reduction of primary yields). Work in progress.

Conclusions

nuSTORM: offers an **unprecedented statistics of well controlled ν_e** and a major leap toward **Neutrino Factories** and the **muon collider**.

ENUBET: a **narrow band neutrino beam at the GeV** scale to measure at O(1%) the flux, flavor and (at 10%) the energy using **lepton-neutrino correlations**. CDR and preliminary costing in ~1y timescale.

A very stimulating brainstorming process is ramping up (also thanks to this workshop!) to get the most out of these ideas. Aim is to provide an optimized and convincing proposal that could serve the needs of the neutrino community. Let's talk about this in the Round Table!

Bonus slides

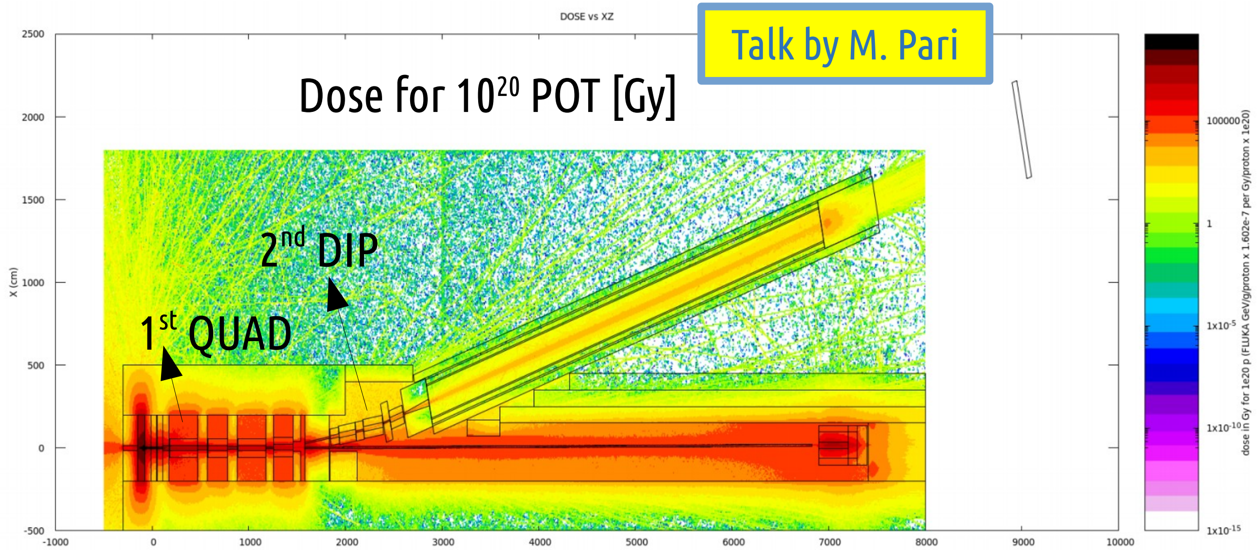
FLUKA irradiation studies

Talk by M. Pari

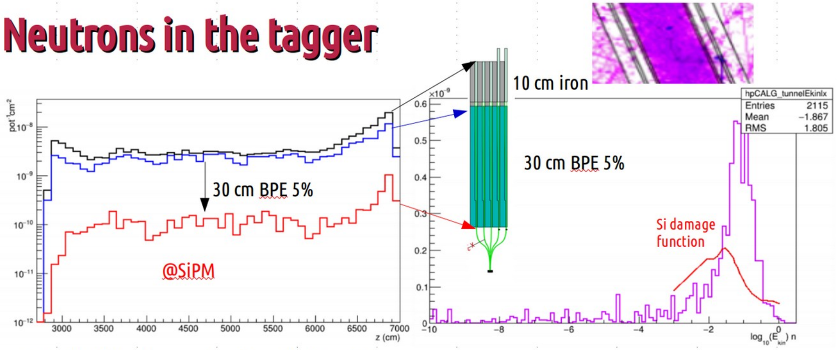
Detailed FLUKA simulation of the setup

Guided the design of the detector technology for the demonstrator

Good lifetime of instrumentation and focusing elements achieved.

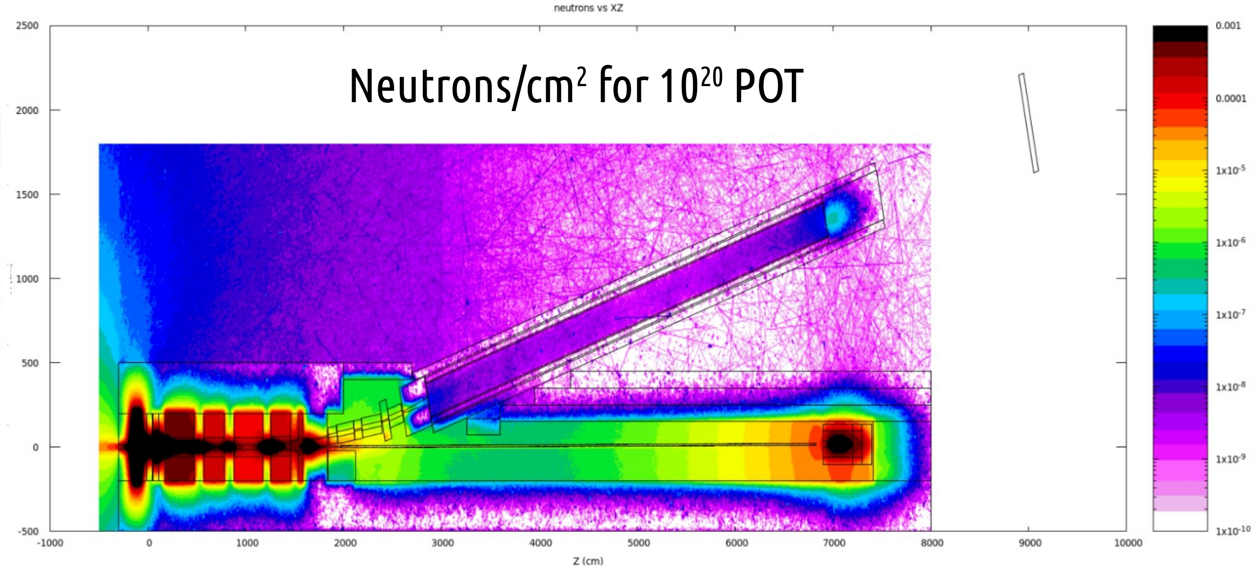


Neutrons in the tagger



BPE shielding has a **reduction effect ~ x 20**
W.r.t. to the single dipole beamline
7×10^{-11} n/POT/cm^2 ~ **10 x reduction**
(7×10^9 n/cm^2 for 10^{20} POT)

E_{kin} of surviving neutrons is O(10-100) MeV

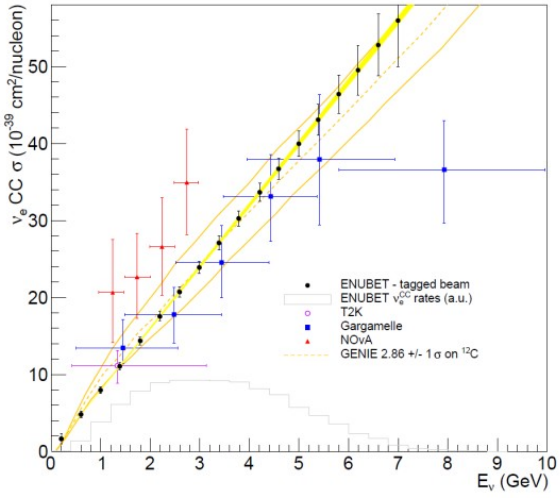


nuSTORM & ENUBET

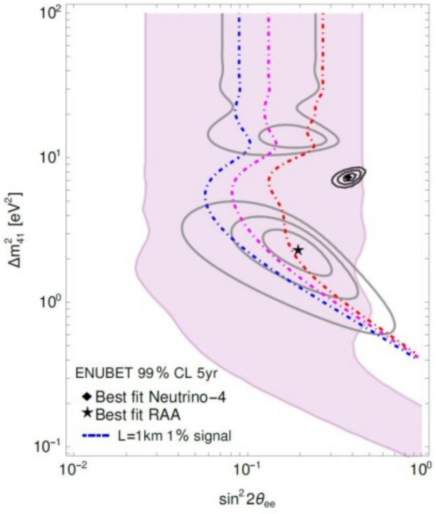
	Proton extraction/focusing (nominal energy)	Target, sec. transfer line, p-dump	Neutrino detector	Decay region	Hadron dump
ENUBET	Slow extraction (+ quad tripl) "slow" in bursts (+horn) 400 GeV	similar	Similar but at ~100 m (some flexibility)	~40 m. Instrumented.	Yes. Dumps μ in addition → preventing a (small) ν_e pollution to K_{e3} - ν_e
nuSTORM	Fast extraction (+horn) 100 GeV	similar	Similar but at > 300 m from target (ring straight section)	Replaced by straight section of the ring (180 m).	No. μ kept: the most interesting flux parents.

BSM and more opportunities

Low normalization errors is a must to further constrain sterile neutrinos or STUDY them in the - exceptionally exciting - scenario of having them discovered at FNAL !

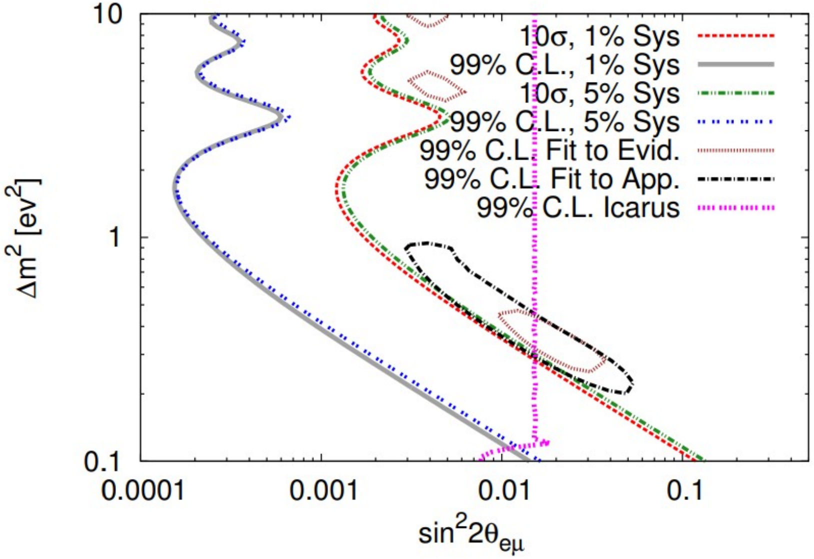


Electron neutrino cross section



Sterile neutrinos

L. Delgadillo, P. Huber, arXiv:2010.10268



Tagged neutrino beams

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

→ time coincidences of ν_e and e^+

Example with reconstructed e^+
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

Assumed time resolution: $0.4 \oplus 0.4$ ns

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

Distance corrected Δt between tagged leptons and neutrino interactions