ENUBET and the CERN neutrino programme

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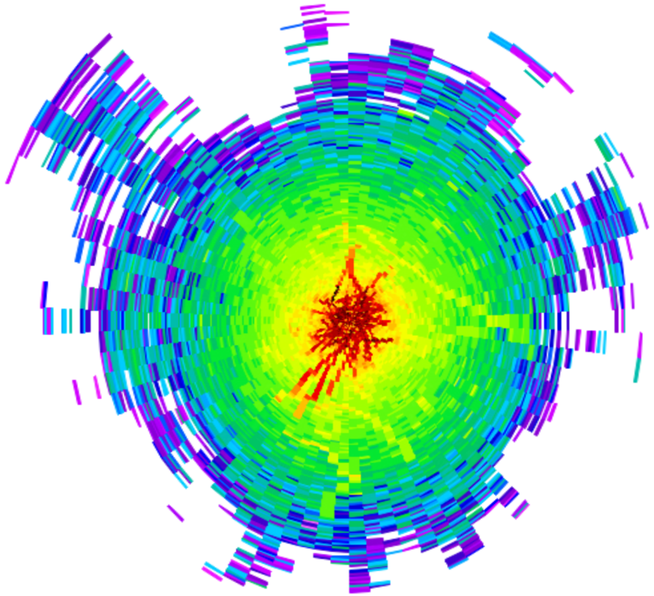
Thessaloniki, 16 June 2021

Outline

- The CERN neutrino platform
  - Next generation near detectors
  - ENUBET: physics opportunities with monitored beams
- Towards a high precision cross section facility



Neutrino related initiatives at CERN: overview

The CERN Neutrino Platform

- We are following the mandate give by the EU strategy in 2013: “pave the way ….”
- Main goal : compact the European groups around the projects of the future short and long Neutrino baselines
- CERN as a facility for R&D on future technologies (HW and SW) and partner in several neutrino research programs

Physics Beyond Colliders for neutrinos:

Phase 1) nuSTORM
Phase2) ENUBET/nuSTORM

Prototypes for current and next generation near and far detectors:

NP07 → T2K near detector upgrade

NP04 → ProtoDUNE - Dual Phase
NP02 → ProtoDUNE - Single Phase

SPSC: **WCTE** (Water Cherenkov Test Experiment)

New ideas for improved future beams:

NP06 → ENUBET

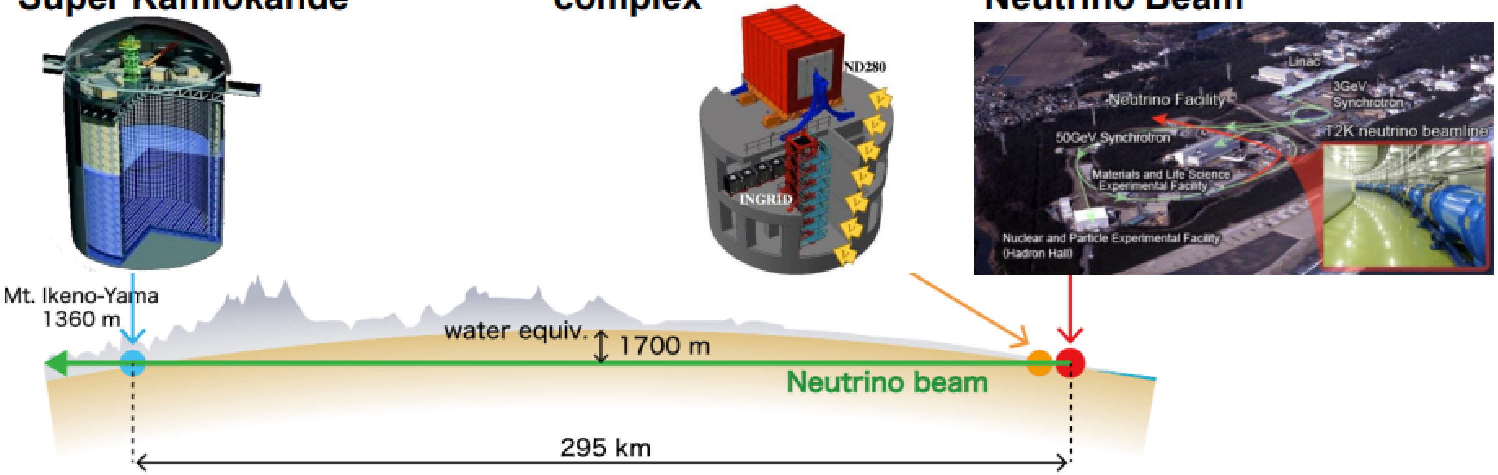
Overall this approach is proving very effective with several successful and interesting activities !

https://indico.cern.ch/event/1024587/contributions/4301474/attachments/2223838/3766194/SPSC_NP07_tlux_fv.pdf

NP07: upgrade of the T2K near detector (ND280)

T. Lux

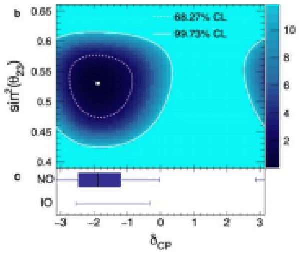
Far detector Super Kamiokande | Near detector complex | J-Parc Neutrino Beam

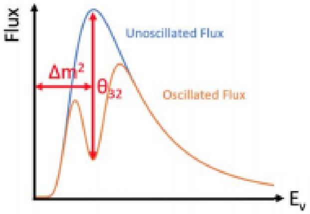


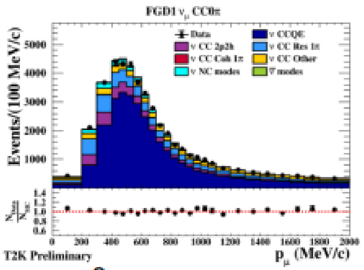
@SK
Measure oscillated beam ←

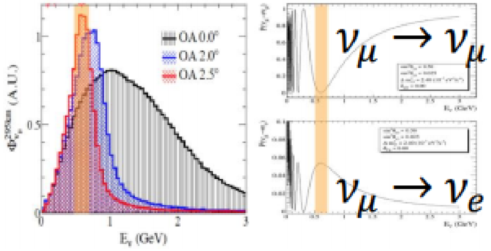
@ND280
Characterize beam and ν interactions ←

@J-PARC
Create Neutrino's off-axis beam ν_μ or $\overline{\nu}_\mu$









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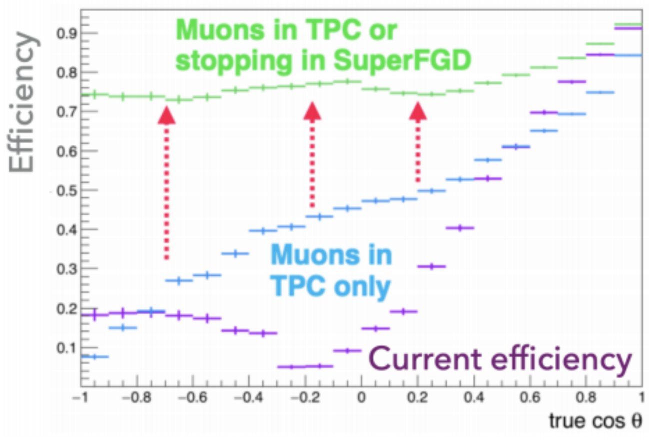
T. Lux

NP07: physics rationale

4 π detector

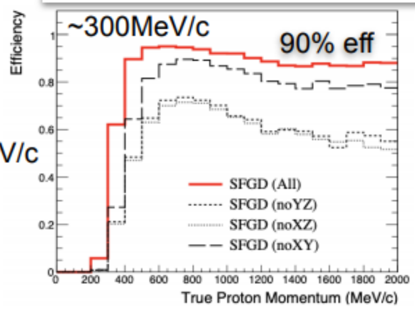


Threshold

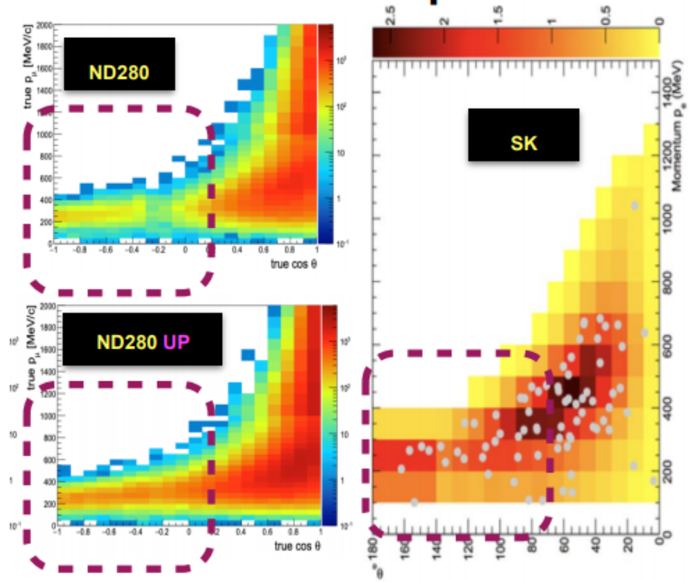
Upgraded ND280 (SuperFGD)

Current ND280

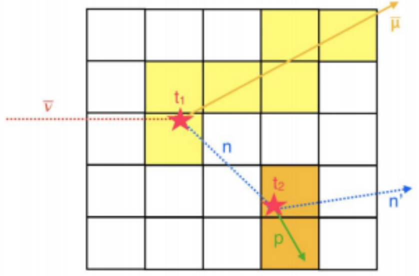
threshold: ~500MeV/c



SK Phase Space

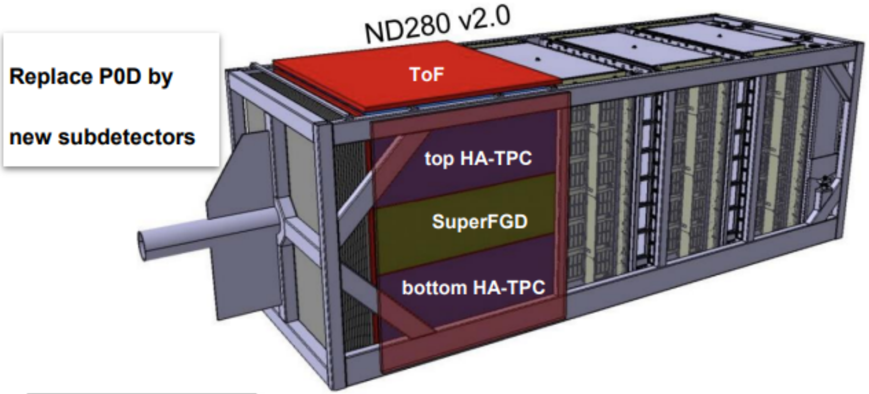


Neutron Detection



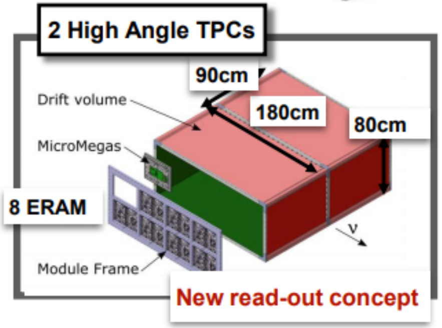
NP07: upgrade of the T2K near detector (ND280)

T. Lux

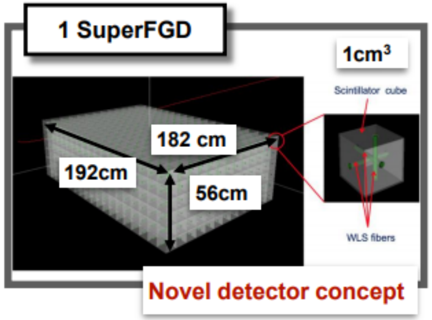


Milestones

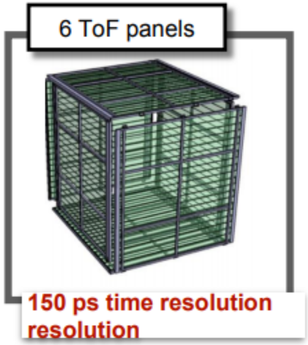
- 2018 → TDR arXiv:1901.03750
- 2021/22 final modules
- 2022 installation



NIM A 957 163286 (2020)



JINST 13, P02006 (2018)
JINST 15 P12003 (2020)



JPS Conf. Proc. 27, 011005 (2019)

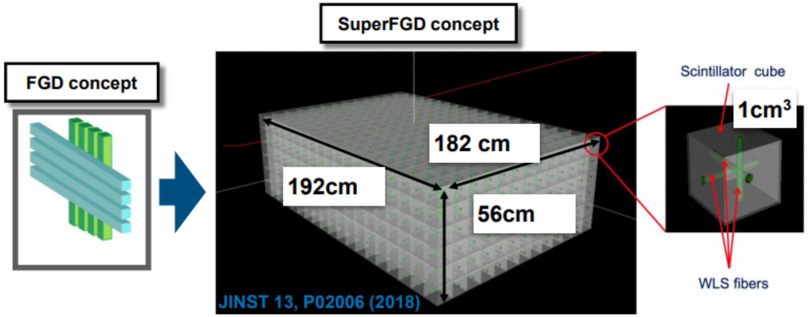
https://indico.cern.ch/event/1024587/contributions/4301474/attachments/2223838/3766194/SPSC_NP07_tlux_fv.pdf

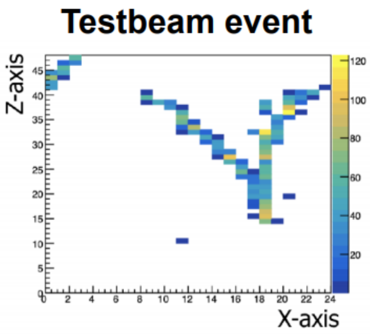
T. Lux

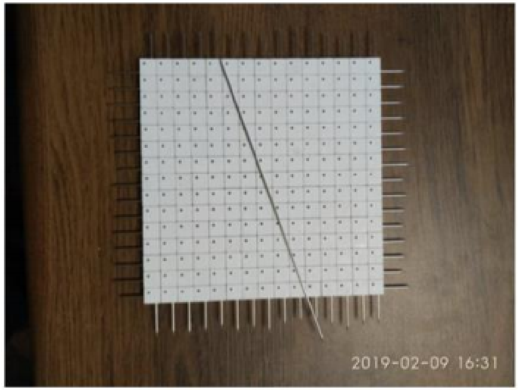
NP07: the SuperFGD detector

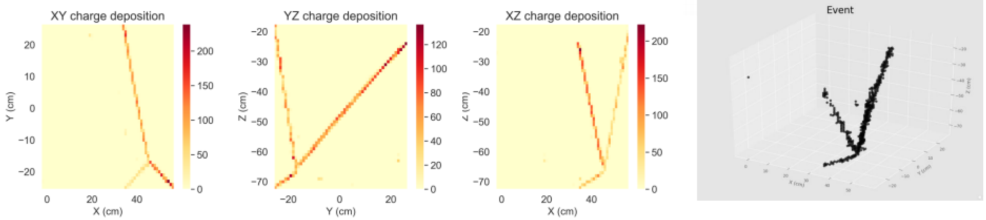
A new scintillator tracker concept (SuperFGD)

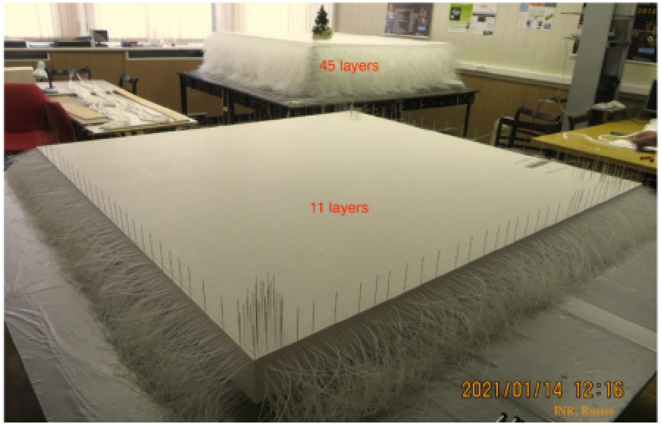
To improve the granularity the new active target will be a novel 3D tracking technology







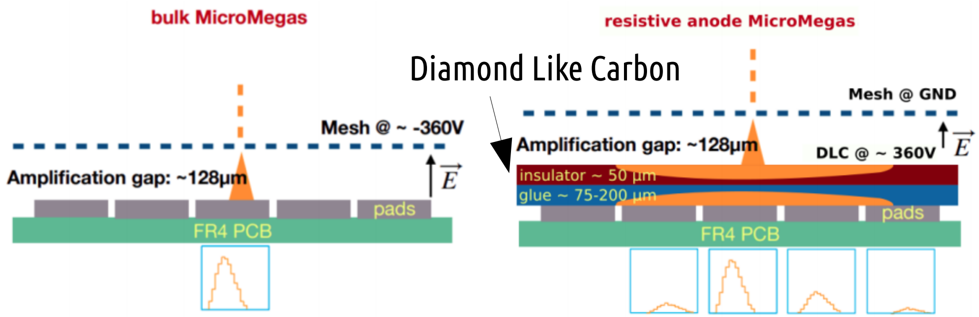


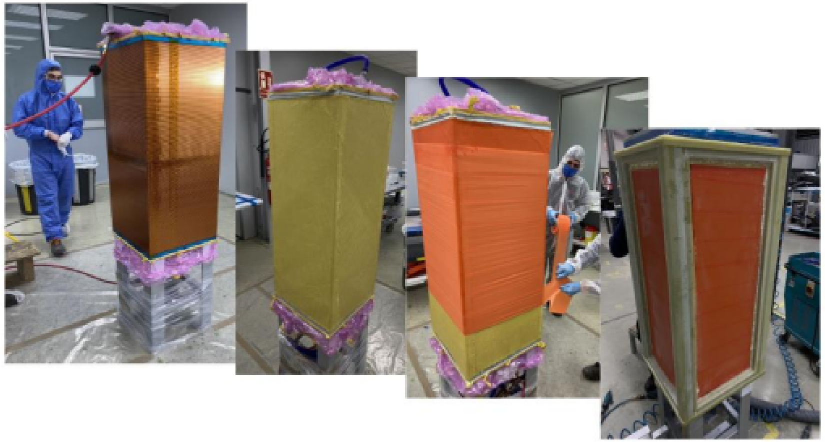


- Production of all cubes (~2.1 millions) finished.
- All cubes and holes underwent quality control
- 56 layers + 1 spare (182x192 cubes) assembled
- Transport boxes designed to ship to assembly site

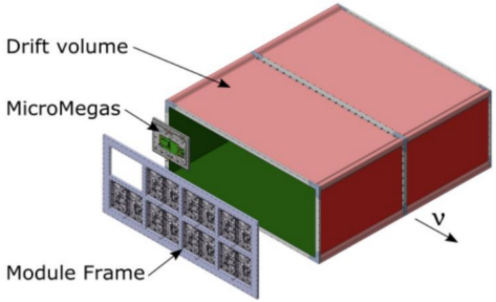
NP07: High angle - TPC

https://indico.cern.ch/event/1024587/contributions/4301474/attachments/2223838/3766194/SPSC_NP07_tlux_fv.pdf
T. Lux

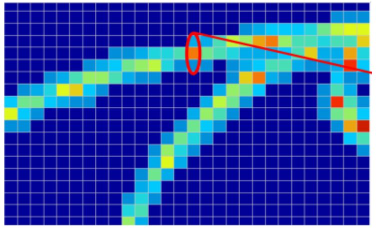


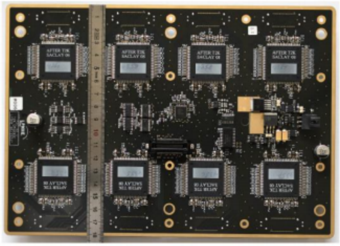


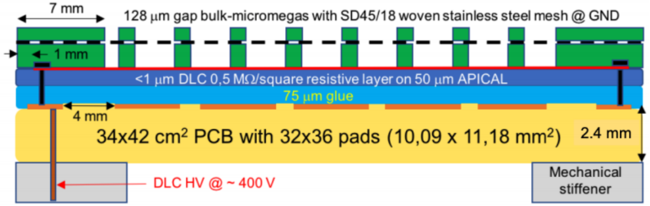
- 2 new TPCs being produced
- Dimensions: 1865x2000x820 mm3
- Composite materials for field cage
- Readout by 8 resistive Micromegas (ERAM) per side (novel technology)
- New gas system will also be installed
- Using T2K gas (95 Ar, 3 CF4, 2 iC4H10)
- Intensive test programme with cosmics and testbeam

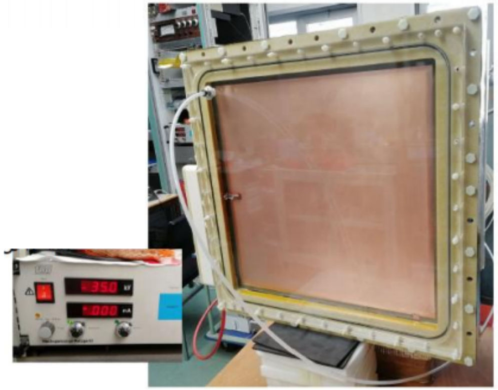


- Successfully tested:
  - Metrology
  - HV stability in air and argon up to 35 kV
  - Gas tightness



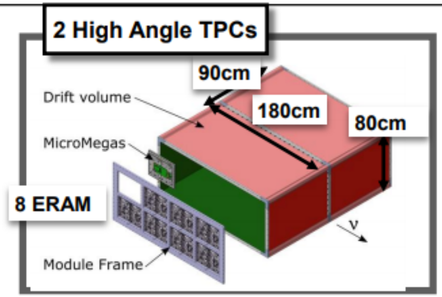




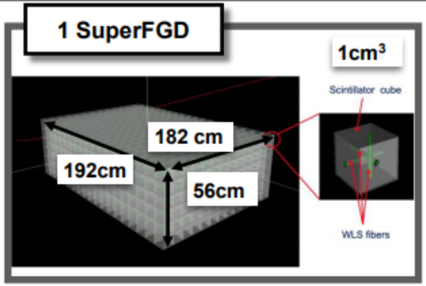


T. Lux https://indico.cern.ch/event/1024587/contributions/4301474/attachments/2223838/3766194/SPSC_NP07_tlux_fv.pdf

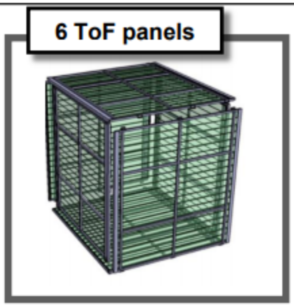
NP07: overall progress



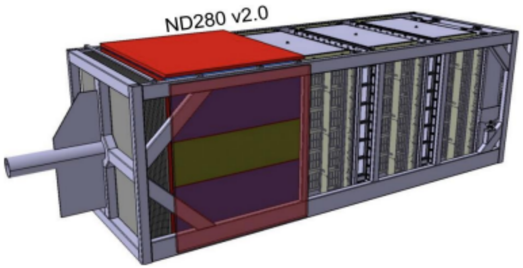
- 1^{st} half at CERN in June
- Pre-production of ERAM has started
- Gas system commissioning at CERN in summer 2021
- SPS testbeam with first half TPC in 10/2021 (if granted)
- Shipment of 2^{nd} TPC to J-PARC: spring 2022



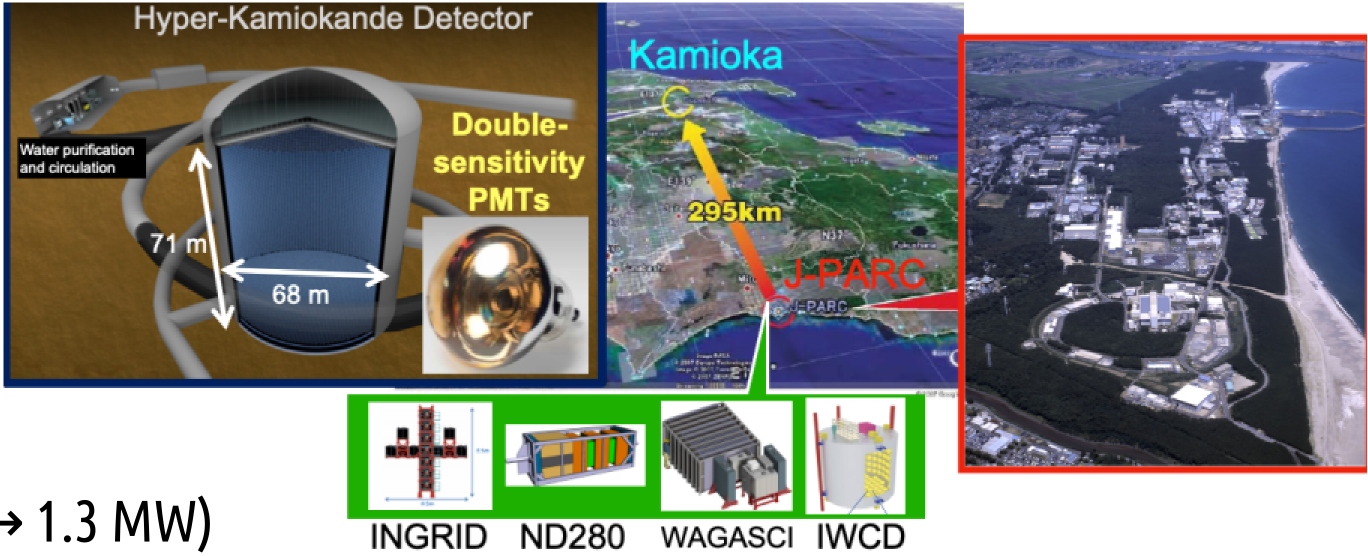
- Cube and layer production finished
- Box design finished and production to be started as soon as possible
- Assembly expected to start autumn 2021
- Electronics prototype ready in May
- Commissioning expected to start 09/2022



- All 6 modules ready at CERN
- Testing ongoing
- Integration test in summer 2021

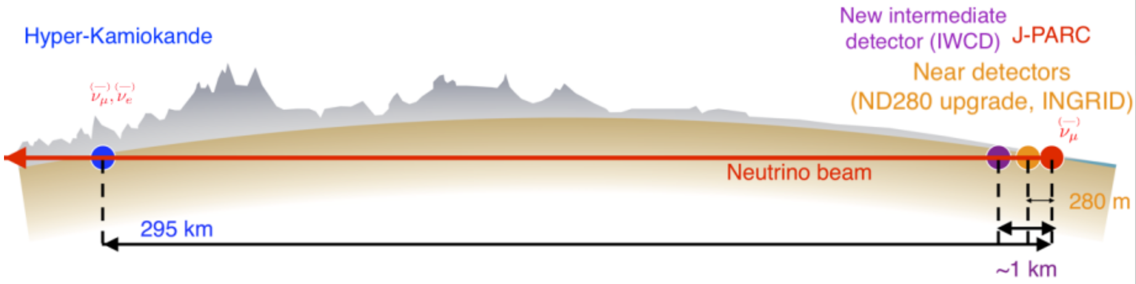


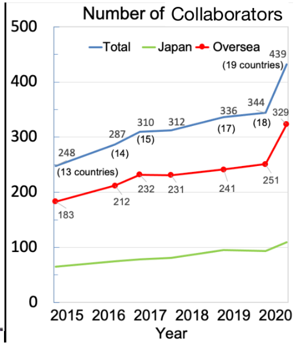
Hyper-Kamiokande



190 kton fiducial mass (8.4 x SK)
Sensitivity PMT (2x)
J-PARC beam upgrade (x2.5, 0.5 → 1.3 MW)
New Intermediate Water Cherenkov +
upgraded T2K near detector @ 280 m

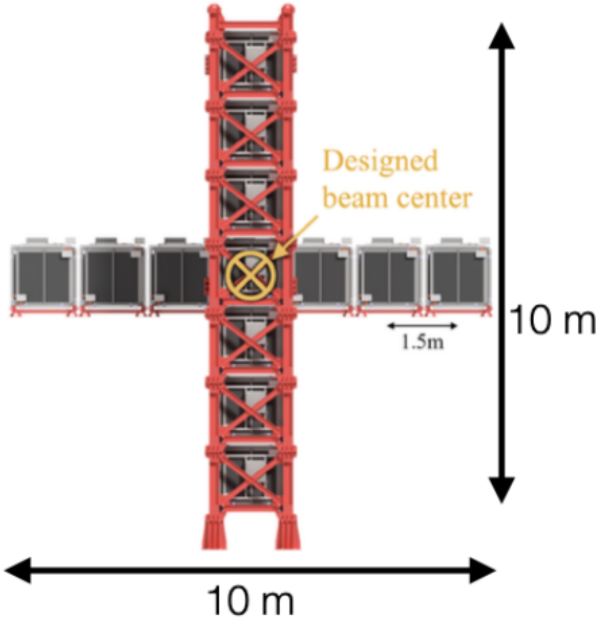
~440 collaborators, 93 inst. 19 countries





Hyper-Kamiokande near detectors

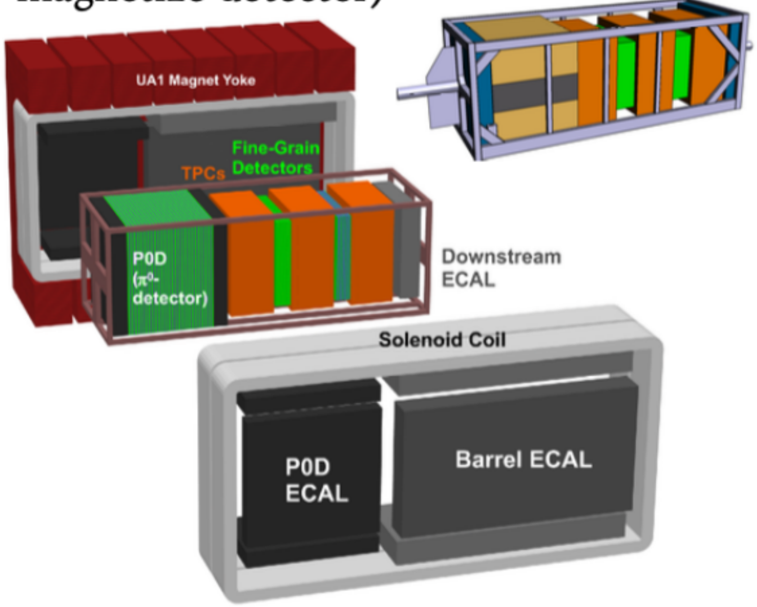
On-axis Detector (INGRID)



measure beam direction, monitor event rate.

Existing

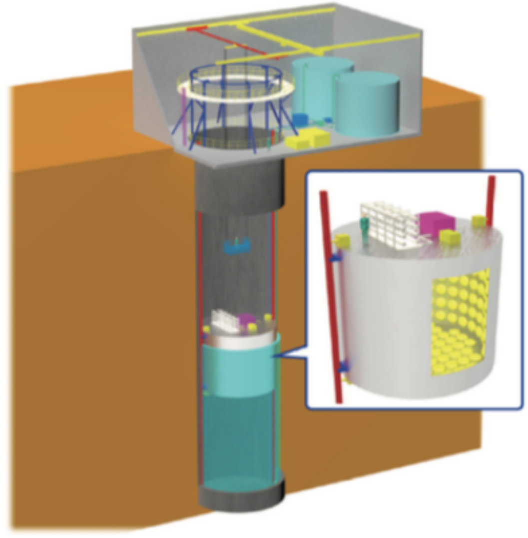
Off-axis Magnetized Tracker (ND280→ND280 Upgrade→HK magnetize detector)



charge separation (wrong-sign background), recoil system.

being upgraded.

Off-axis spanning intermediate water Cherenkov detector (IWCD)



intrinsic backgrounds, electron. (anti)neutrino cross-sections, neutrino energy vs. observables, H_2O target.

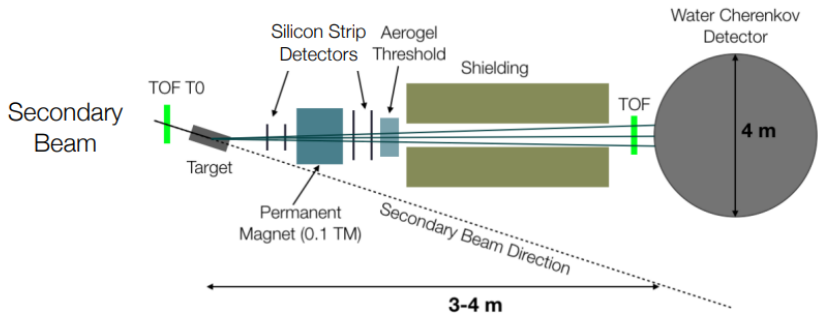
To be built

https://indico.cern.ch/event/1024587/contributions/4301475/attachments/2224851/3768654/wcte_spsc_20210413.pdf

M. Hartz

Water Cherenkov Test Experiment

- Propose a prototype water Cherenkov detector to operate in the T9 beam line in the East Area
- Study particles directly from secondary beam and with tertiary production configuration
- We propose a test experiment that is ~4 m diameter x 4 m tall
- **Particle fluxes of $\pi^{\pm}$, p, μ, e in the 300 MeV/c-1200 MeV/c range**



CERN-SPSC-2020-005; SPSC-P-365: http://cds.cern.ch/record/2712416?ln=en

- **Measurement of Cherenkov light production**
  - Currently used simulations are not consistent
  - Introduces systematic errors in event reconstruction
  - Can be measured with well characterized beam in WCTE

- **Study of energy scale calibration**
  - Muons crossing detectors used in Super-K to set energy scale
  - Systematic uncertainty of 2% needs to be reduced to 0.5% for Hyper-K
  - Can be studied with crossing muons of known energy in WCTE

- **Measurement of secondary neutron production**
  - In SK-Gd and Hyper-K, neutrons used for neutrino/antineutrino tagging, proton decay background tagging
  - Predicted rates sensitive to secondary production by pions/protons
  - Can measure secondary production in WCTE

- **Study of pion scattering**
  - T2K, Super-K and Hyper-K are using samples with pions in the final state
  - Reconstruction is challenging due to modeling of hadronic scattering with limited data on oxygen
  - Can directly measure water Cherenkov detector response to pions in WCTE

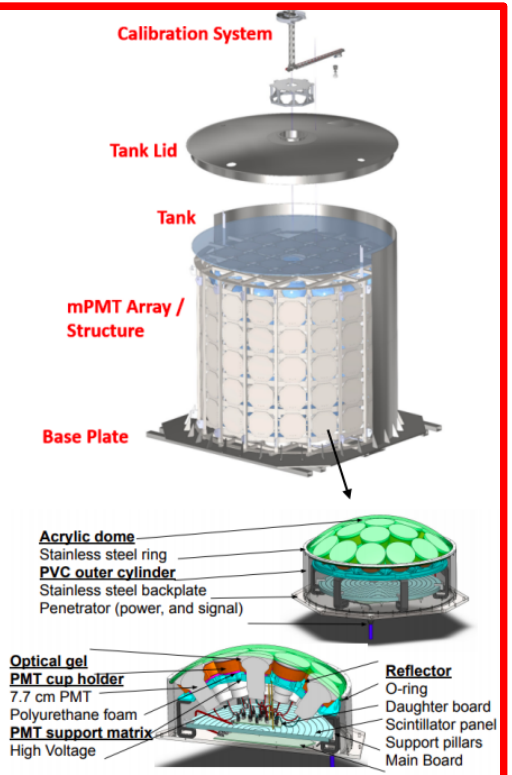
https://indico.cern.ch/event/1024587/contributions/4301475/attachments/2224851/3768654/wcte_spsc_20210413.pdf

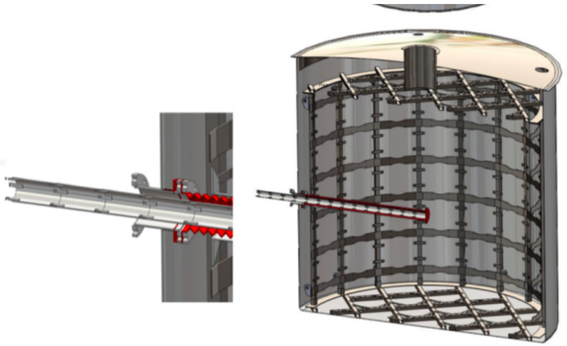
M. Hartz

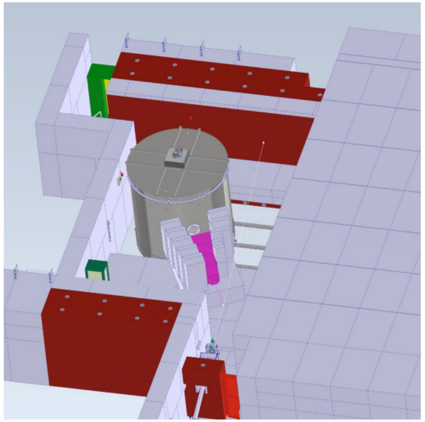
Water Cherenkov Test Experiment

The WCTE Detector

- Detector is instrumented with 130 multi-PMT modules mounted on support structure
- Multi-PMT modules each contain 19 fast 8-cm diameter PMTs, their high voltage and readout circuits
- Installed inside stainless steel 304 tank
- Calibration deployment system to deploy sources throughout detector volume
- Filled with 50 ton deionized water

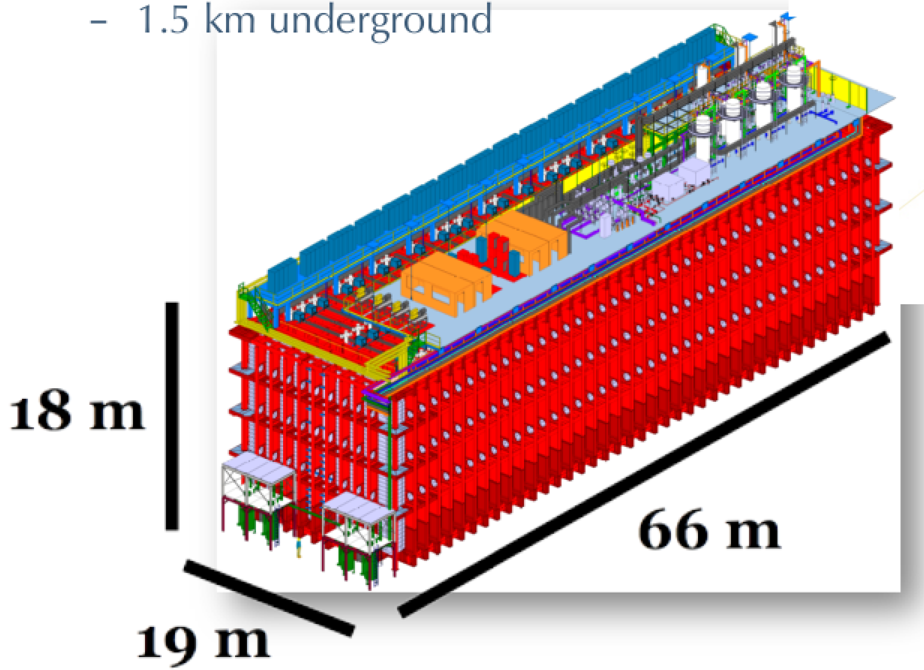


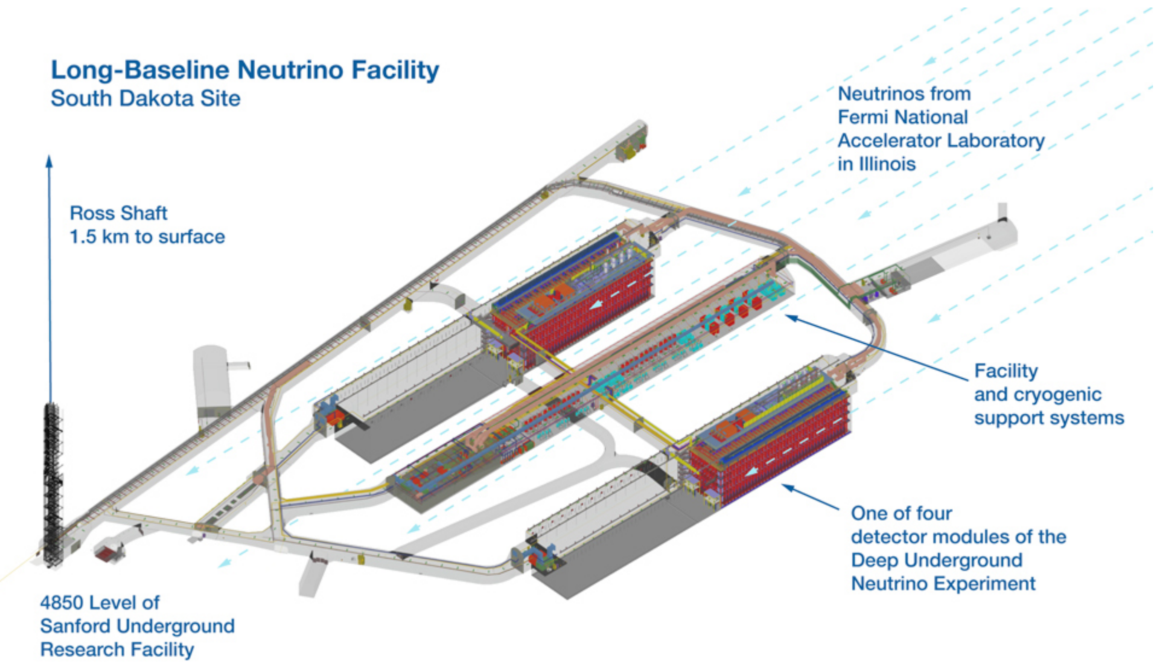




DUNE far detector

- Four (4) LArTPC FD Modules, deployed in stages
  - 17 kton each
  - 1.5 km underground

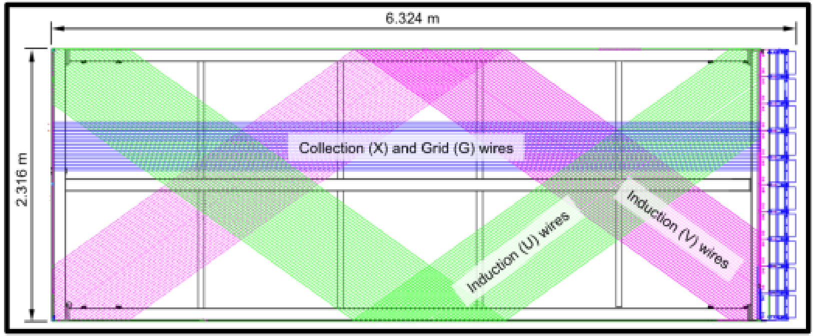




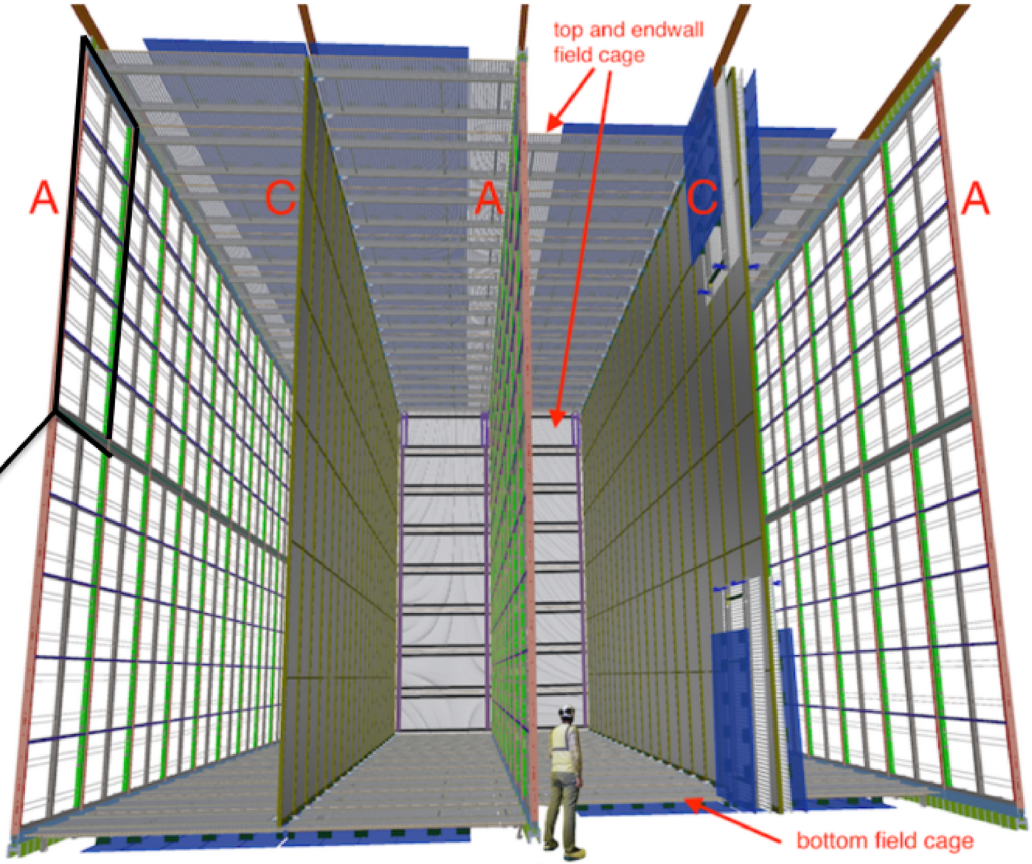
- Two far detector designs: **Horizontal Drift** and **Vertical Drift** (both employ liquid argon phase only)
- First detector module will be Horizontal Drift (HD)

DUNE far detector hor.-drift LArTPC module

- HD FD uses **modular drift cells** (scalability)
- Electric field: 500 V/cm, 3.6 m drift
- Suspended **Anode** and **Cathode Plane Assemblies** (APAs and CPAs)
- APA:
  - Wrapped induction wires, reducing number of readout channels, cabling complexity
  - Single plane of collection wires

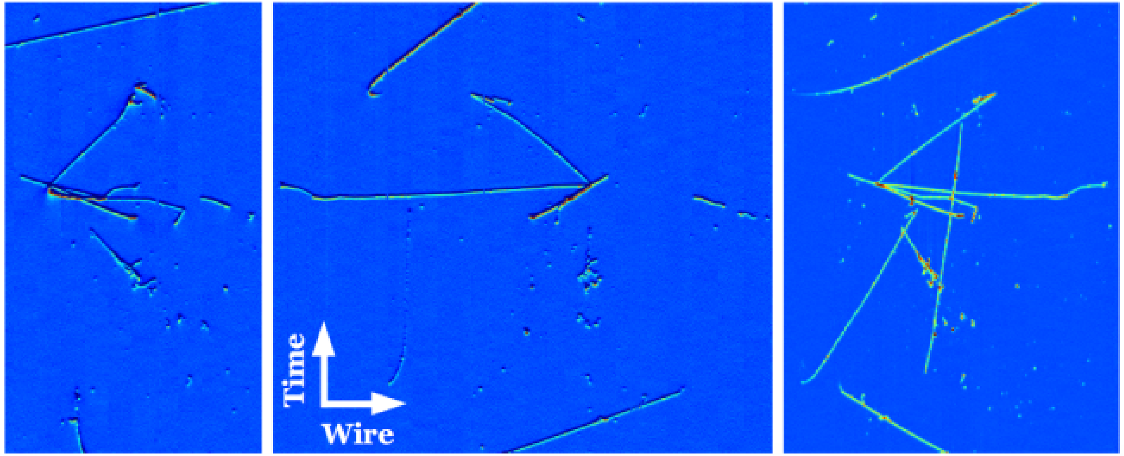


- **Photodetectors** also employed, providing timing and possibility of off-beam triggering



ProtoDUNEs @ CERN

Low-noise on all readout planes
S/N > 10 in all cases (>40 for collection plane)
Stable running (first operations in 2018)



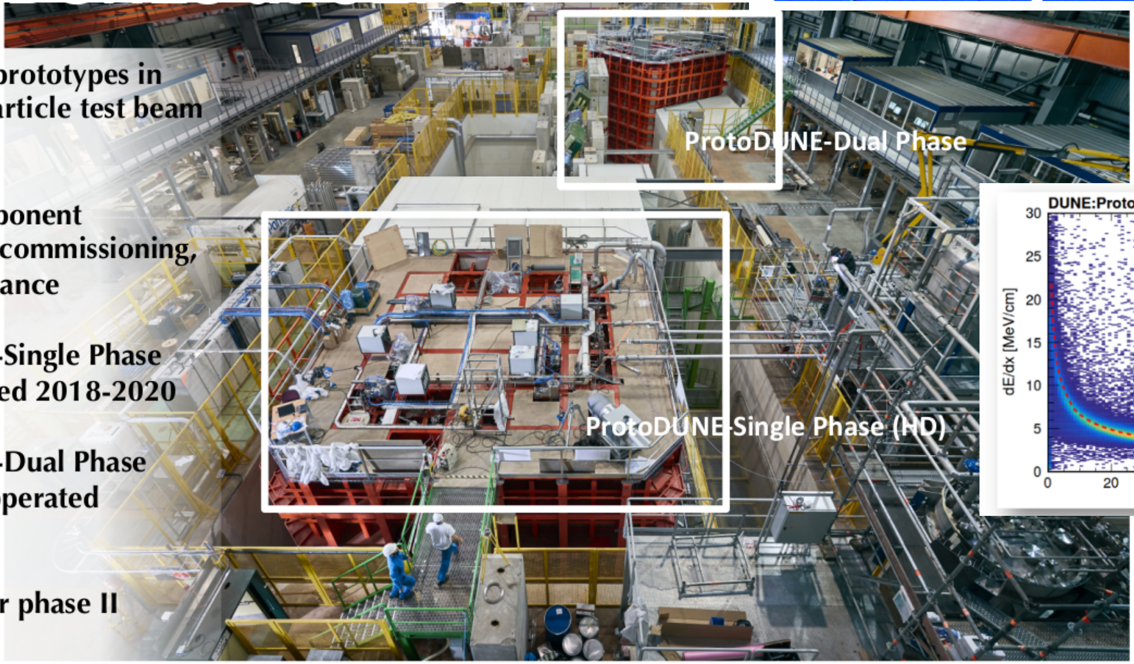
Two 1-kton prototypes in a charged particle test beam at CERN

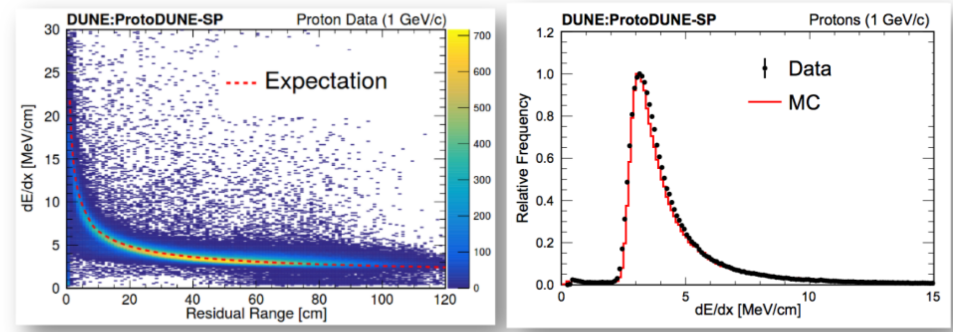
Testing component installation, commissioning, and performance

ProtoDUNE-Single Phase (HD) operated 2018-2020

ProtoDUNE-Dual Phase (LAr+GAr) operated 2019-2020

Preparing for phase II operations





JINST 15 (2020) 12, P12004

NP04: ProtoDUNE single-phase

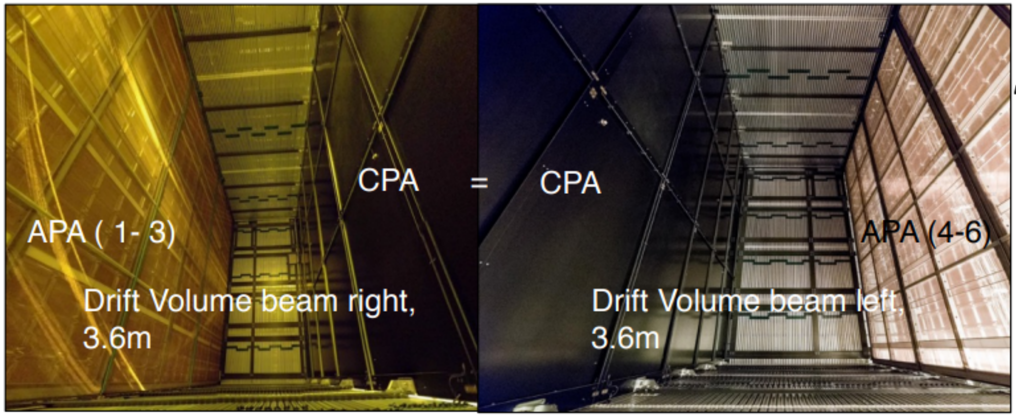
T. Yang

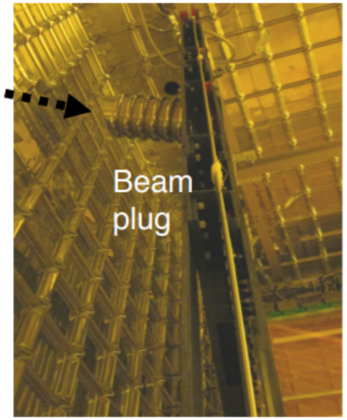
ProtoDUNE SP LAr-TPC in EHN1

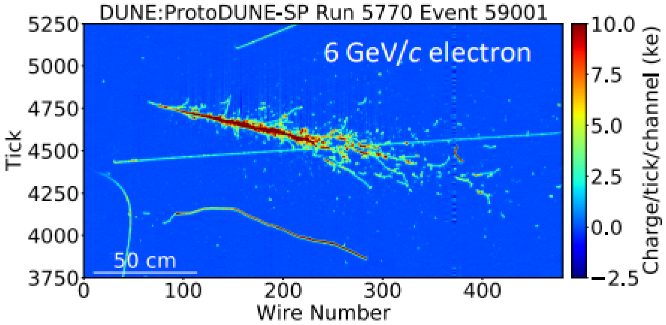
6 x Anode **P**lane **A**ssembly (APA): 3 sensing planes, 4.7mm pitch, 15 360 total ch.

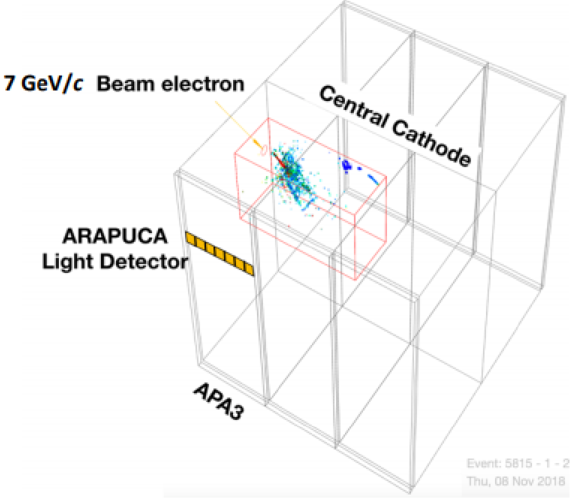
3 x Cathode **P**lane **A**ssembly (CPA)

Detector Activation - start: Sept. 21, 2018

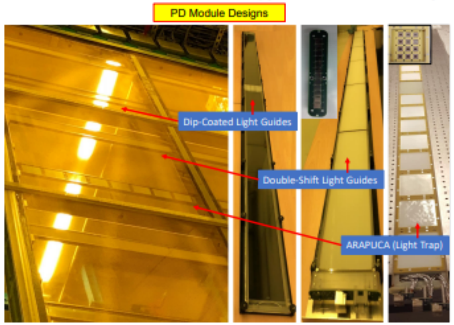


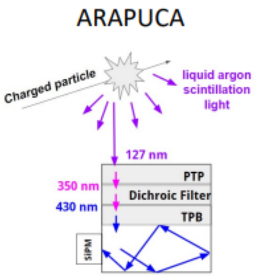






Photon **D**etectors Integrated in APA (3 different types)





Cosmic **R**ay **T**agger, 6.8 m x 6.8 m scintillator panels upstream and downstream

NP02: ProtoDUNE dual-phase

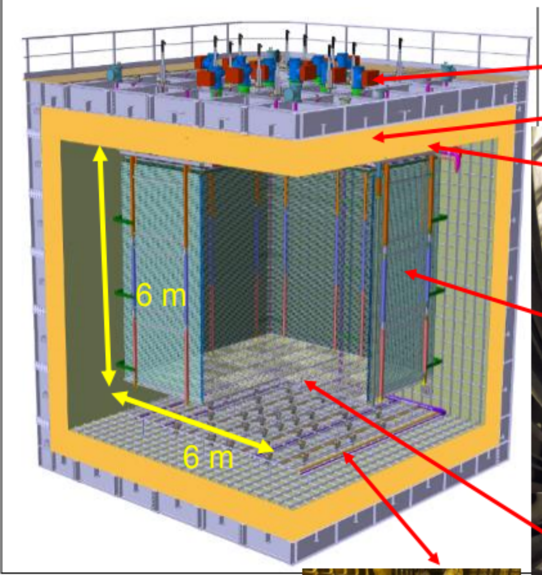
https://indico.cern.ch/event/1024587/contributions/4301476/attachments/2224856/3768154/spsc_april21.pdf

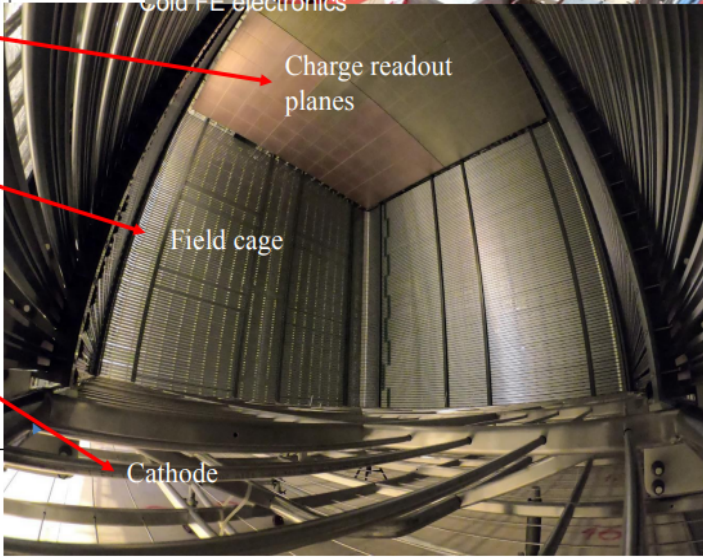
D. Autiero

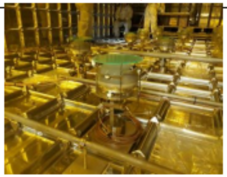
NP02/protoDUNE dual-phase

dual-phase 10 kton design based on NP02:

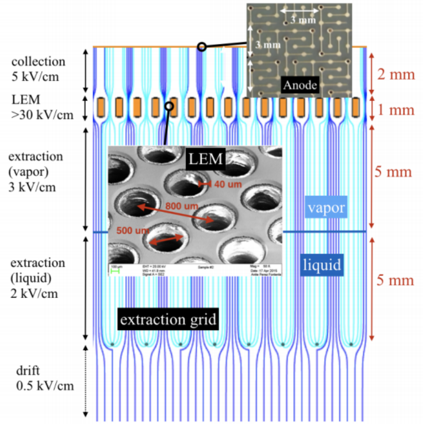
- 1/20 of active area of DP 10 kton
- NP02/protoDUNE DP 4 CRPs → DUNE 80 CRPs





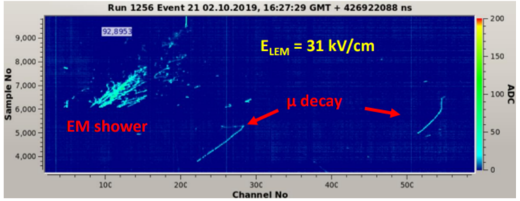


36 cryogenic photomultipliers Hamamatsu R5912-02mod with TPB coating

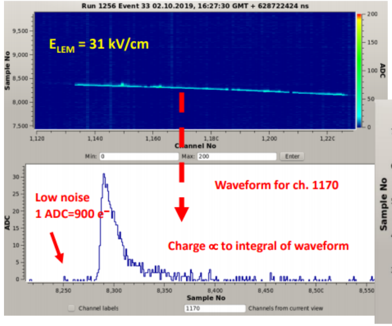


Cosmic ray events in protoDUNE dual-phase

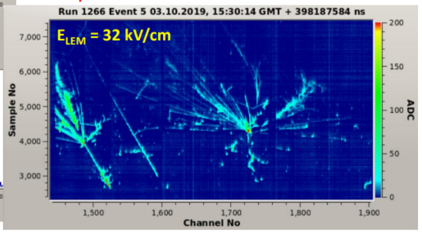
Electromagnetic shower + two muon decays



Horizontal muon track



*Multiple **hadronic interactions in a shower***



NP06: ENUBET

ENUBET: 62 physicists, 13 institutions

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

CERN Neutrino Platform: NP06

[x]Aristotle University of Thessaloniki. Thessaloniki 541 24, Greece.

Annual report

https://cds.cern.ch/record/2759849/files/SPSC-SR-290.pdf

NP06/ENUBET Annual Report for the SPSC

The ENUBET Collaboration

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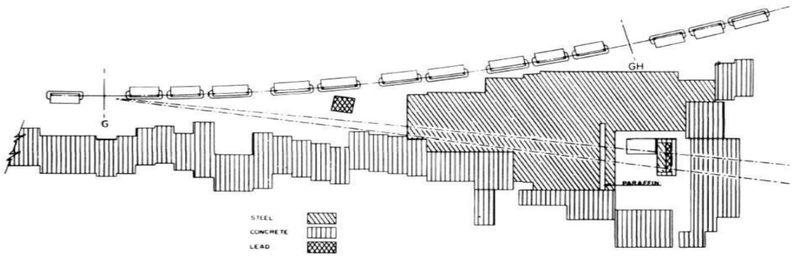
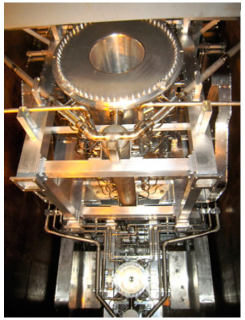
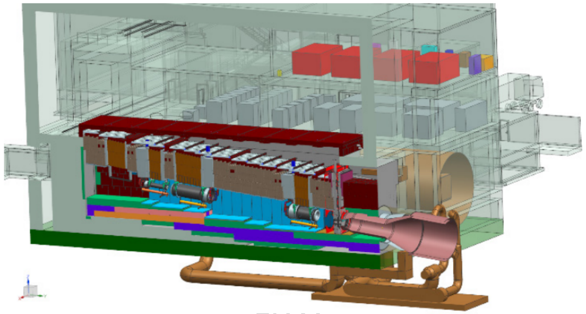
Accelerator based neutrino beams





J-PARC



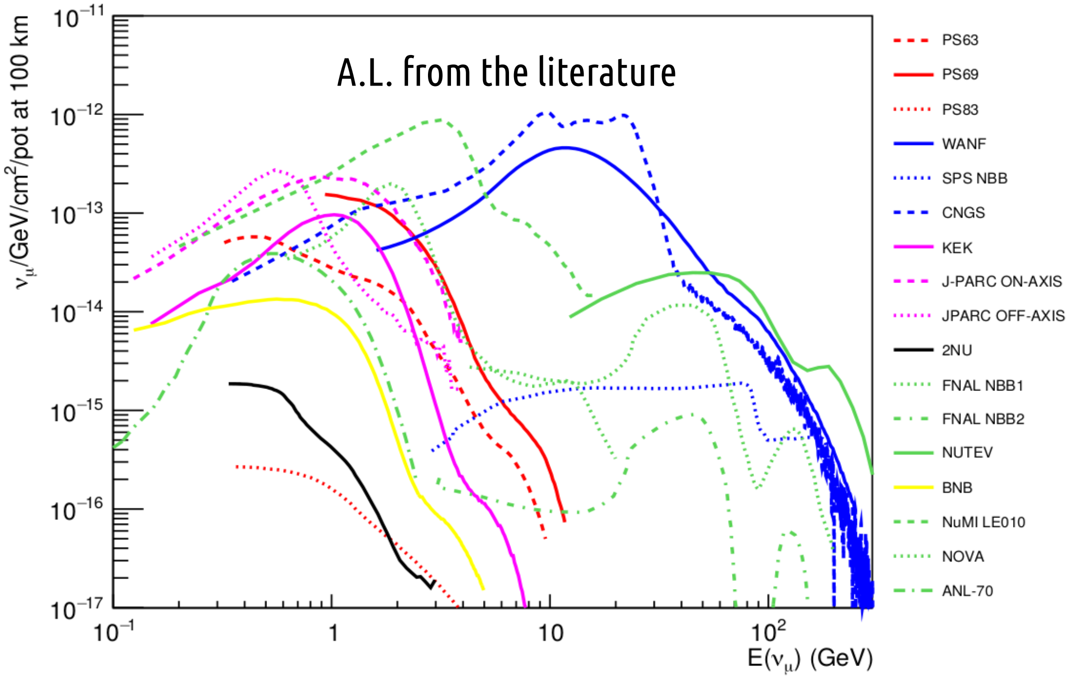
FNAL

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 ...

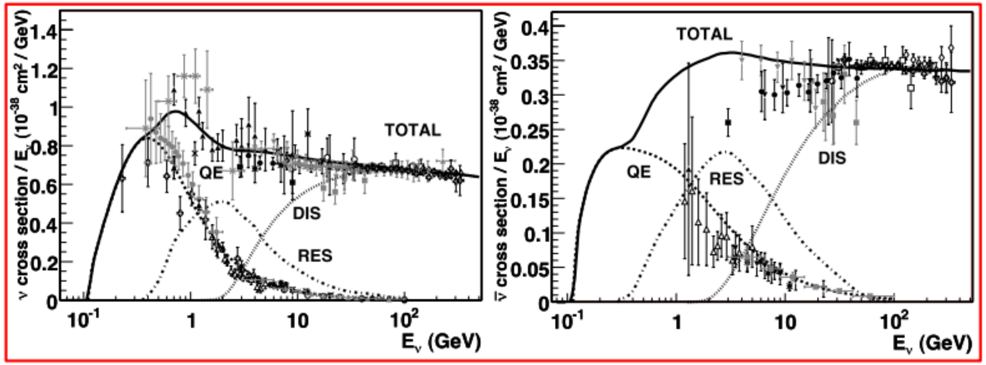
New future challenges (δ_{CP}, searches) require timely **changes** or at least **"adjustments"** in this strategy.

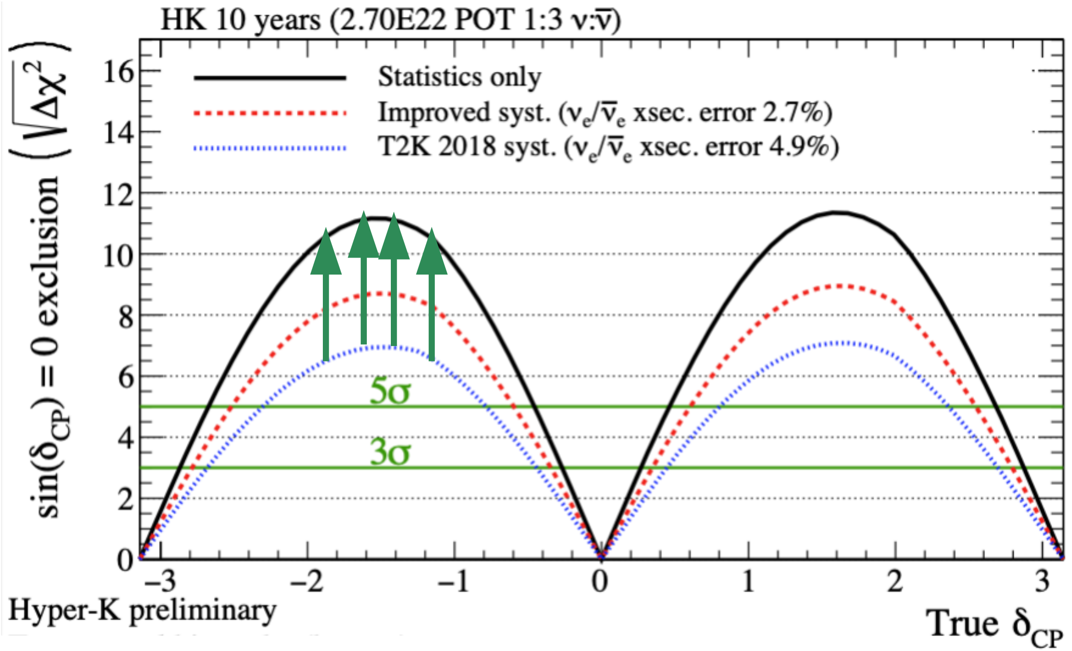


Precision for the Hyper-K/DUNE era

F. Di Lodovico, Neutrino Telescopes 2021

Improving the knowledge of (electron) neutrino and anti-neutrino cross sections in the GeV region strengthens significantly the physics reach of next generation Super-beams in construction





ENUBET and nuSTORM

(see also the **European Strategy** Physics Briefbook, arXiv:1910.11775)

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.

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

The concept of monitored neutrino beams

Conventional “meson-based” beam 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)

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

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

ENUBET / NP06

Aim: demonstrate 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**

➞ **"short", 40 m, tunnel** (~all ν_e from K, ~1% ν_e from muons)

→ **collimated p-selected hadron beam**

→ only decay products in the tagger ➞ **manageable rates**

→ **narrow band beam:**

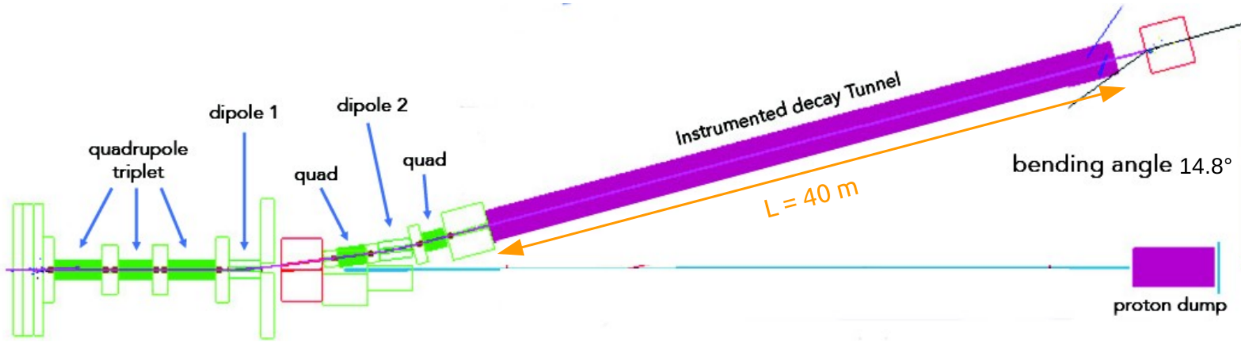
E_ν-interaction radius correlations →

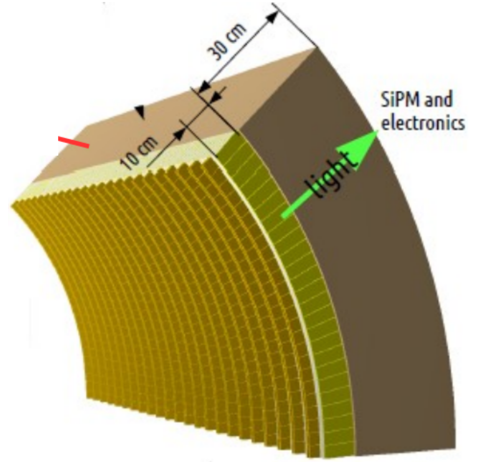
"a priori" knowledge of the ν_μ spectra

pillars

1) Build/test a **demonstrator** of the instrumented decay tunnel

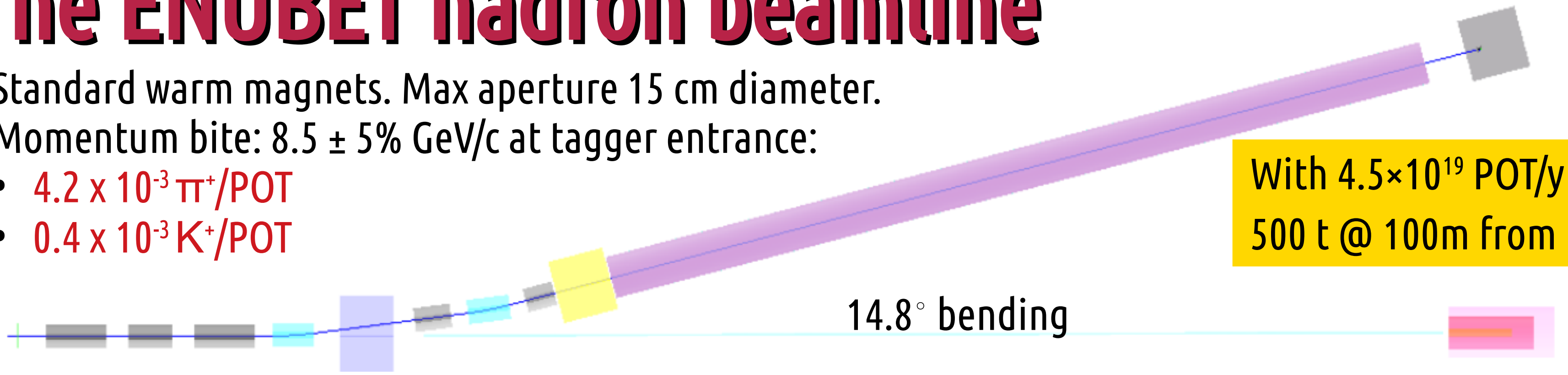
2) Design/simulate the layout of the **hadronic beamline**





The ENUBET hadron beamline

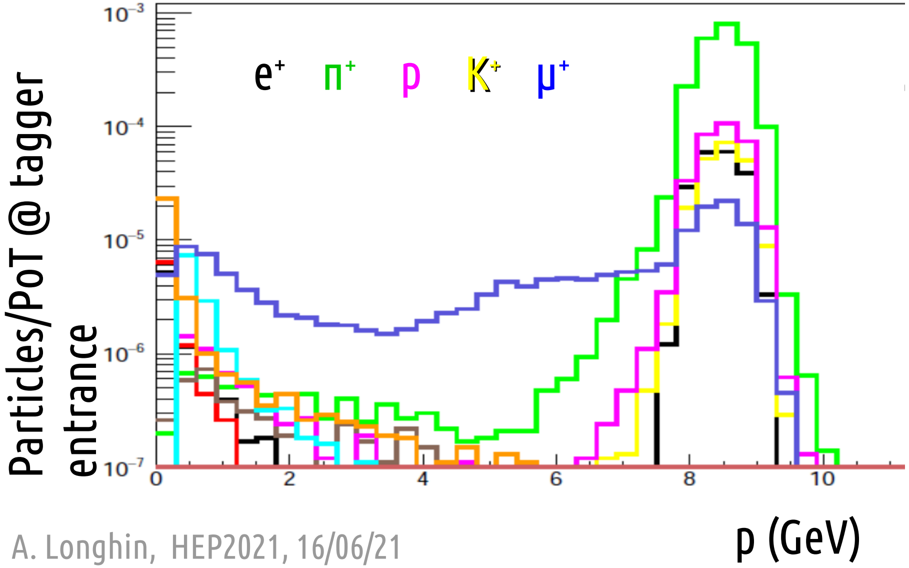
- Standard warm magnets. Max aperture 15 cm diameter.
- Momentum bite: 8.5 ± 5% GeV/c at tagger entrance:
  - 4.2×10^{-3} π^+/POT
  - 0.4×10^{-3} K^+/POT



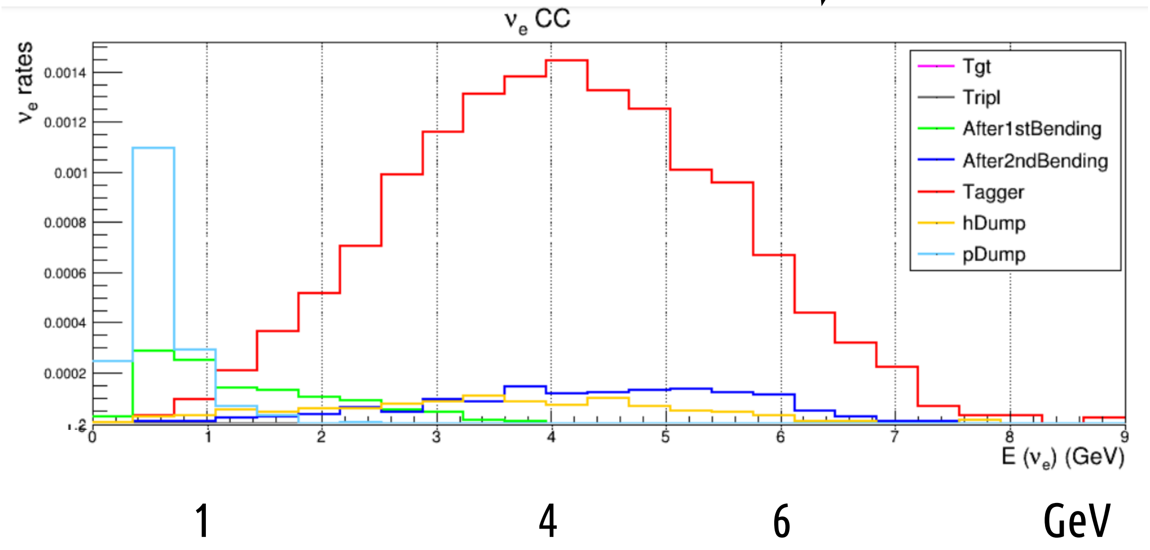
14.8° bending

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

Keeping beam backgrounds small and under control is the name of the game



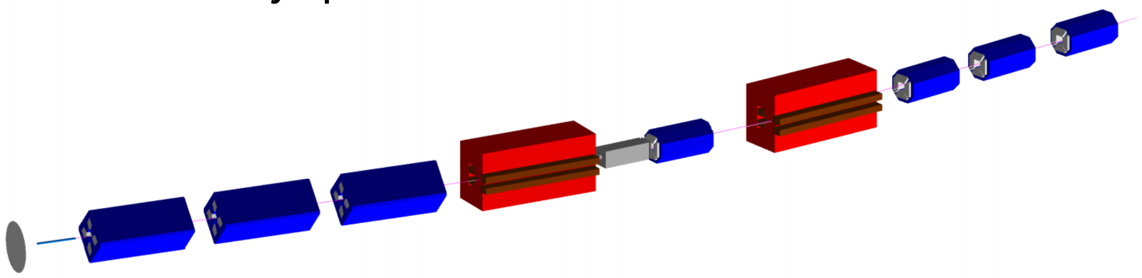
ν_e^{CC}



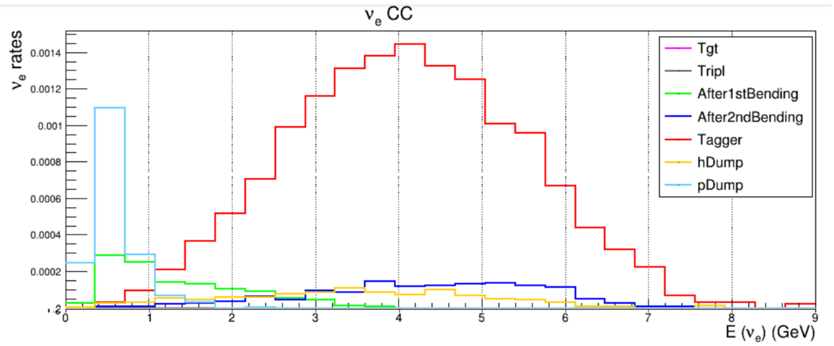
ENUBET multi-momentum transferline

- A parallel study ongoing for the hadron beamline to **add flexibility** and allow a set of **different neutrino spectra** spanning from the **“Hyper-K” to DUNE** regions of interest. Focus **8.5**, **6** or **4** GeV/c secondaries by changing the magnetic fields only.

Preliminary optics



ν_e from **8.5** GeV/c secondaries (current baseline)

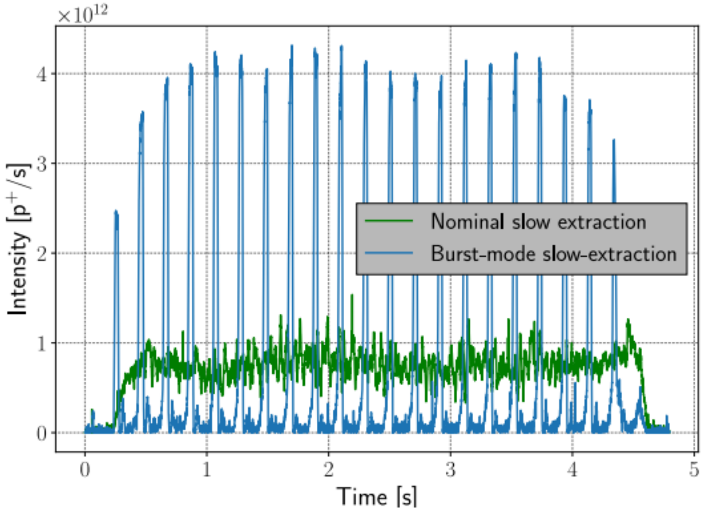


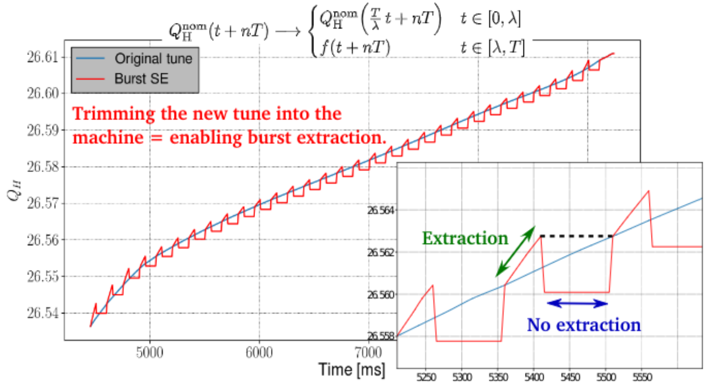
1 4 6 GeV

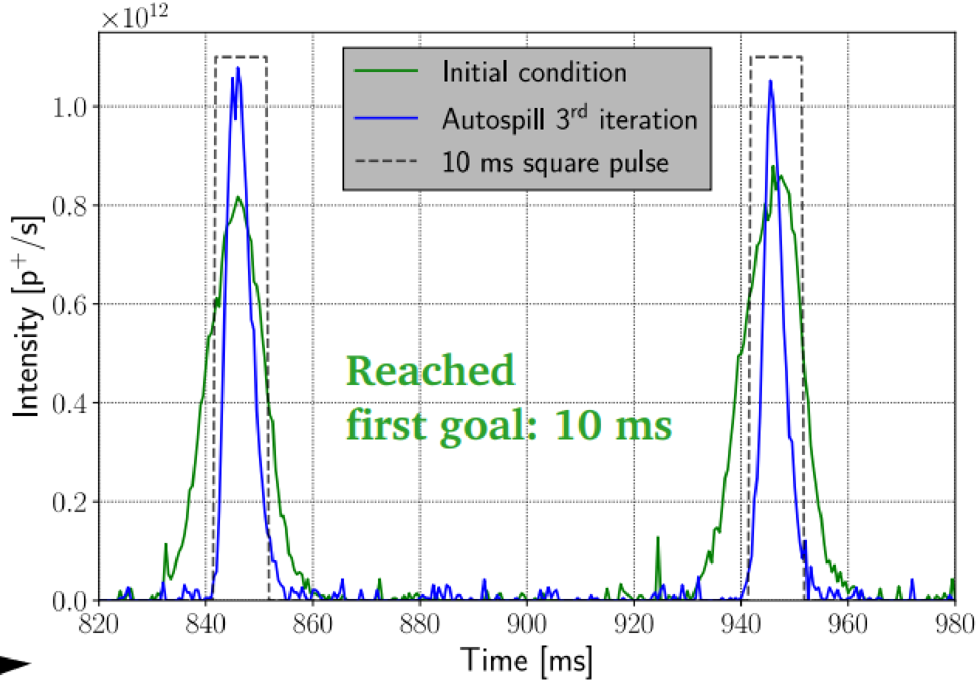
CERN-TE-ABT-BTP, BE-OP-SPS
Velotti, Pari, Kain, Goddard

Proton extraction R&D for horn focusing

before LS2: burst mode slow extraction achieved at the SPS. Iterative feedback tuning allowed to reach ~10 ms pulses without introducing losses at septa

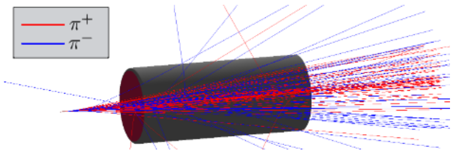




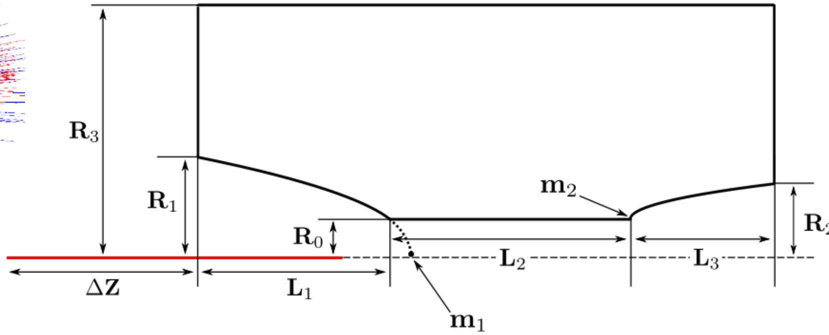


PhD thesis of M. Pari (UniPD + CERN doctoral).
Defended 23/2/21.

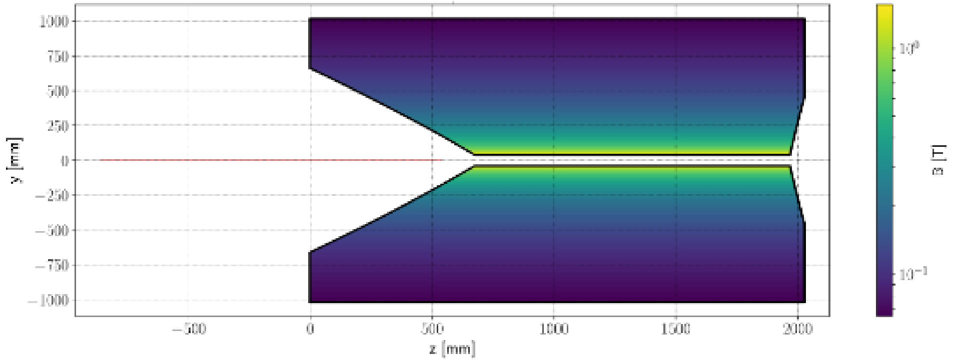
Horn optimization



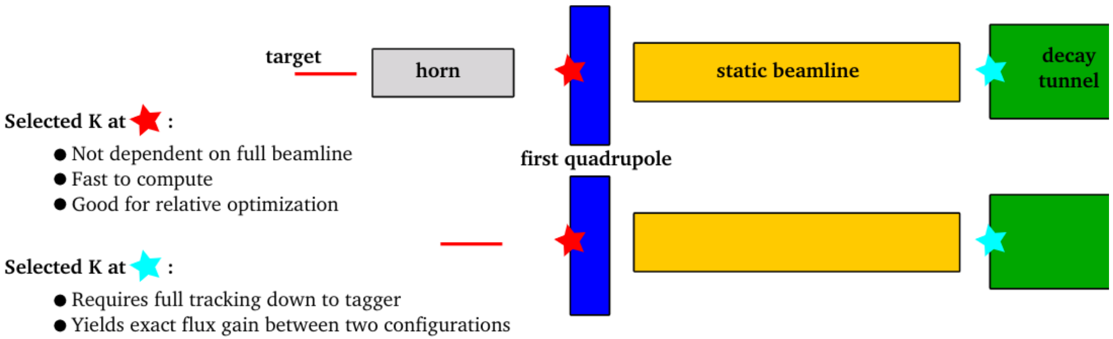
- New **double-parabolic** geometry (formerly MiniBooNE-like)
- New **genetic algorithm** implemented successfully to sample the large space of parameters.
- FoM is ~ number of collimated K^+ with p ~8.5 GeV/c
- Convergence in O(100) iterations
- First candidate designs worked out



We were able to reach values of the **standalone FoM (★) of x 3 higher than the static case**. These results confirm an improvement w.r.t. early studies.



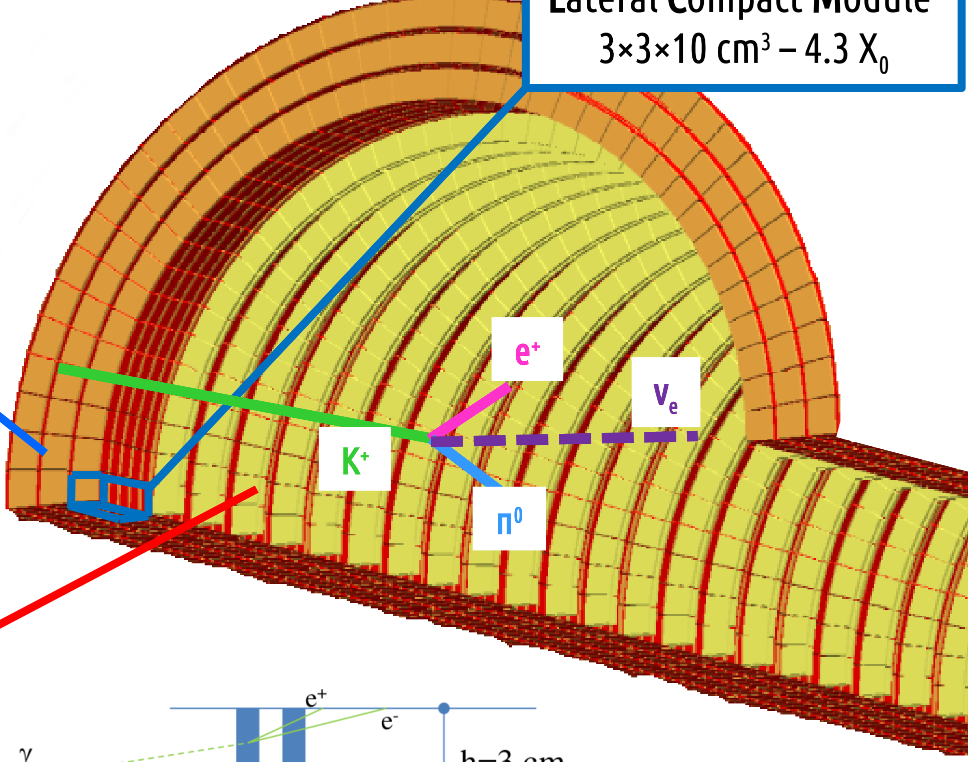
When plugged to the existing beamlines the gain factor reduces to only **x 1.5 → next step:** dedicated beamline optimization (★) to profit of the horn-option initial gain → larger apertures for initial quads.



Can extend the same systematic optimization tool.

The lepton tagger

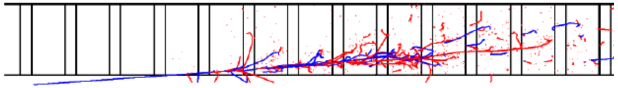
Lateral Compact Module
$3\times3\times10$ cm^3 – 4.3 X_0



Calorimeter

Longitudinal segmentation
Plastic scintillator + Iron absorbers
Integrated light readout with SiPM

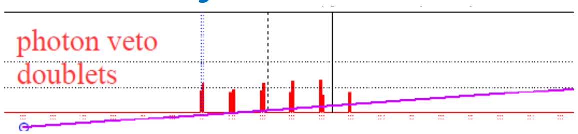
→ $e^+/\pi^\pm/\mu$ separation

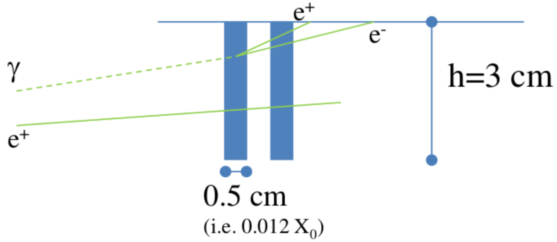


Integrated photon veto

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

→ π^0 rejection





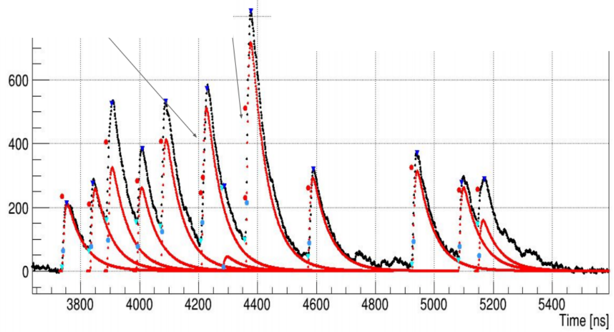
e^+ (signal) topology

π^0 (background) topology

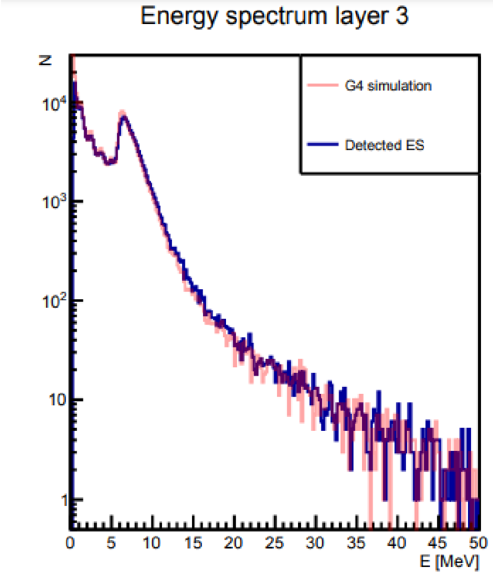
π^+ (background) topology

Waveform analysis

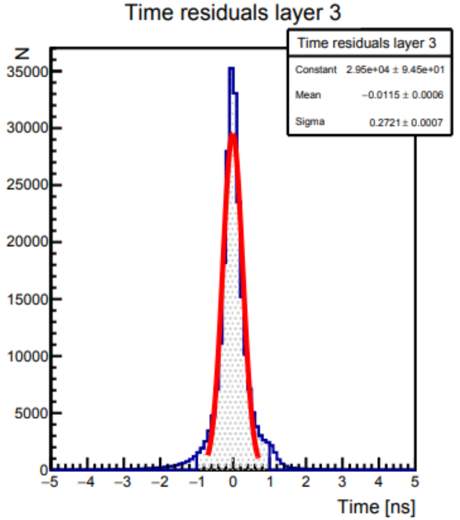
The energy is now reconstructed as it will happen for real data
i.e. considering the **amplitudes digitally-sampled signals at 500 MS/s**.
Pile-up effects treated realistically.



Matching between true level energy deposits from GEANT4 and fully reconstrucred waveforms



Matching between true and reconstructed time (1 GS/s → 270 ps)



Peak finding efficiencies:
Slow ~ 4.5 x 10^{13} POT in 2s
Fast ~ horn ~ 10 x slow

Transfer line and extraction scheme	Hit rate per LCM	detection efficiency
TLR5 slow	1.1 MHz	97.4%
TLR5 fast	10.4 MHz	89.7%
TLR6 slow	2.2 MHz	95.3%

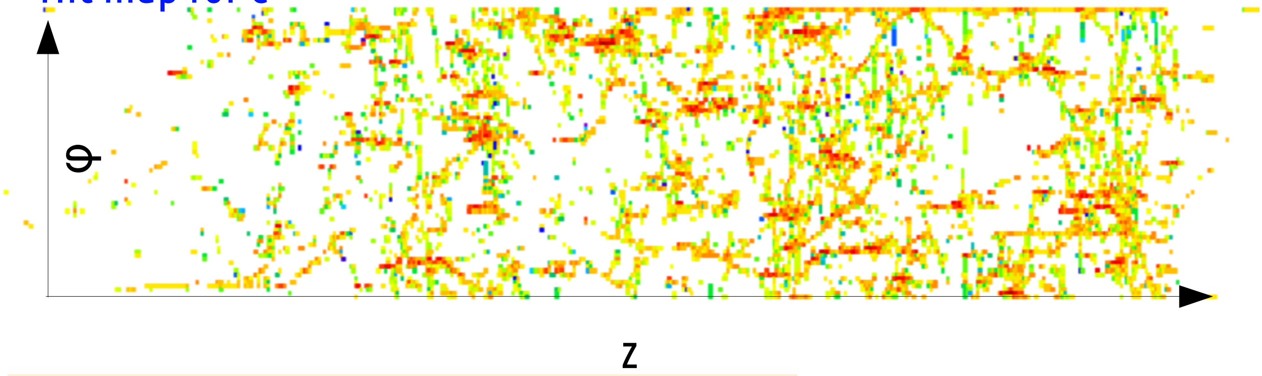
ENUBET: ν_e constraint from K_{e3} e^+ reconstruction

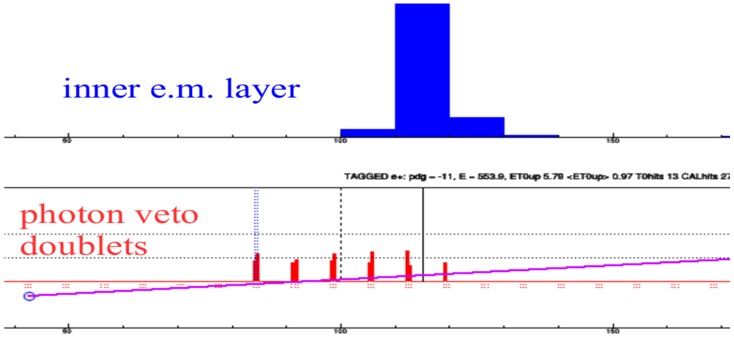
The K_{e3} branching ratio is ~5 % and kaons are about 5-10% of the incoming hadron beam.

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^+



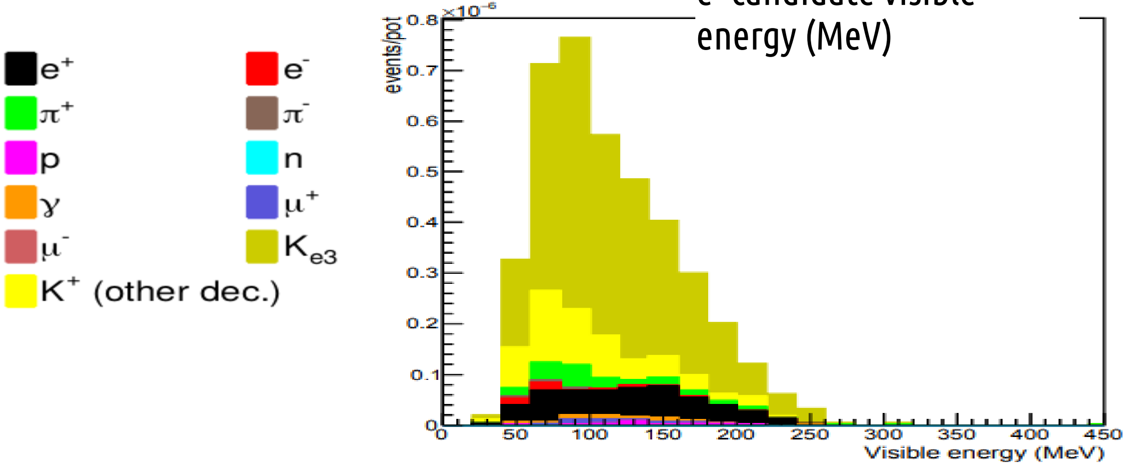


K_{e3} positron selection:

Efficiency ~22% **S/N of ~2**

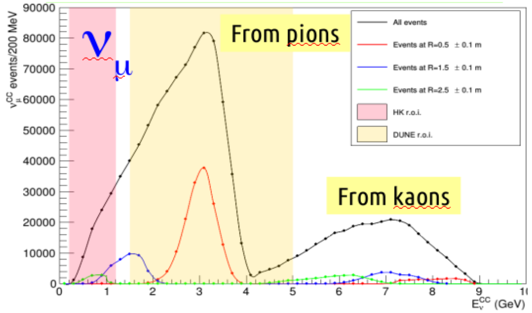
Half of efficiency loss is geometrical

e^+ candidate visible energy (MeV)



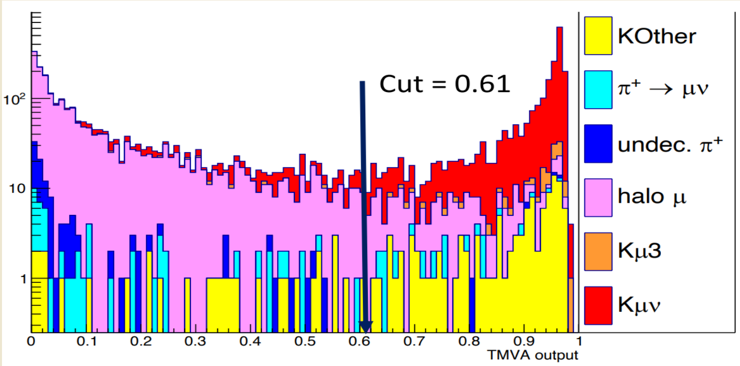
F. Pupilli et al., PoS NEUTEL2017 (2018) 078

ENUBET: ν_μ constraints from muons



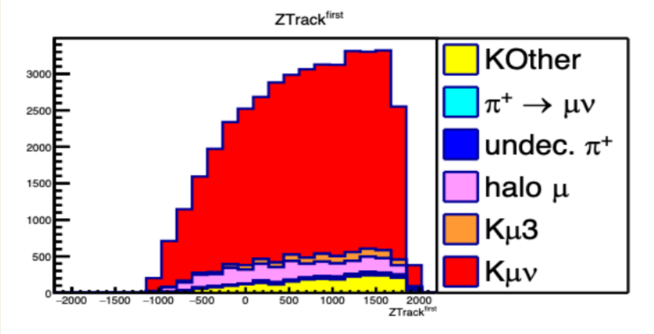
Constrain high-E ν_μ from ($K^+ \to \mu^+ \nu_\mu$ and $K^+ \to \pi^0 \mu^+ \nu_\mu$)

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



Muon reconstructed candidates

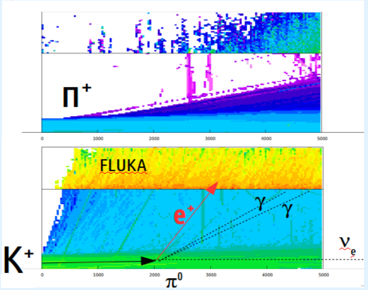
efficiency 34% ($K_{\mu2}$) and 21% ($K_{\mu3}$) S/B ~ 6.1

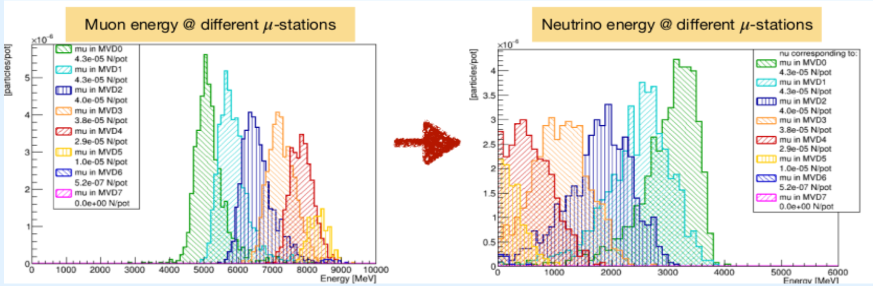


Position along the tunnel

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

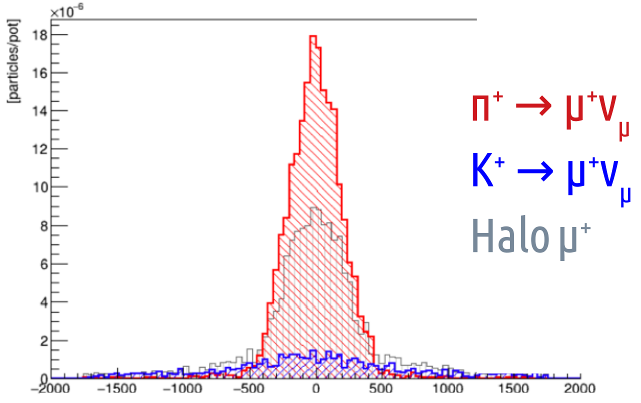
In progress. Measure momentum by range with muon stations → disentangle ($\pi^+ \to \mu^+ \nu_\mu$) from halo μ.

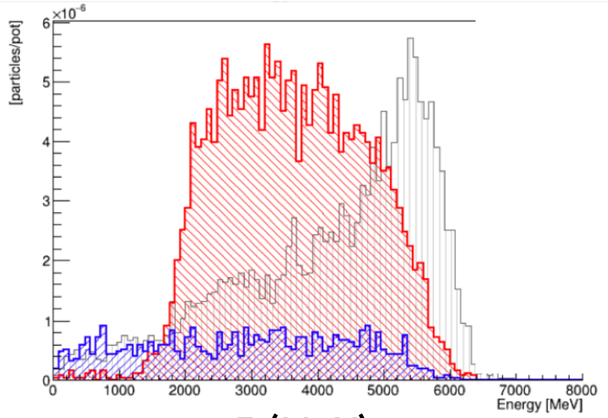


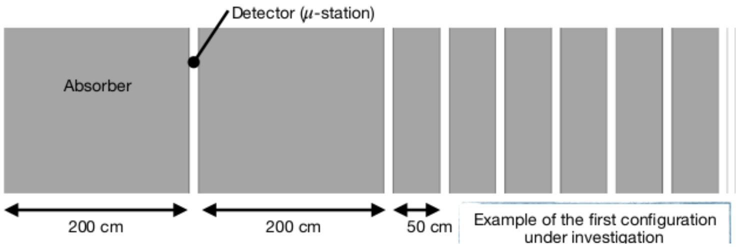


Forward region muons reconstruction

Range-meter after the hadron dump. Extends the tagger acceptance in the forward region to constrain $\pi_{\mu 2}$ decays contributing to the low-E ν_μ.

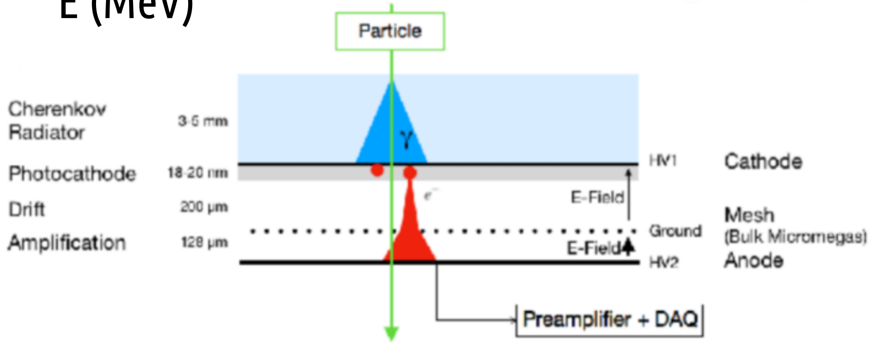


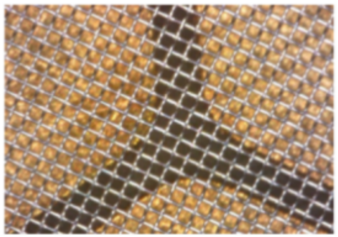




The most upstream (hottest) detector needs to cope with a muon rate of ~ 2 MHz/cm^2 and about 10^{12} 1 MeV-n$_{eq}$/cm^2.

Design being defined. Possible candidate: fast Micromegas detectors employing Cherenkov radiators + thin drift gap (PICOSEC coll.). Bonus: excellent timing.

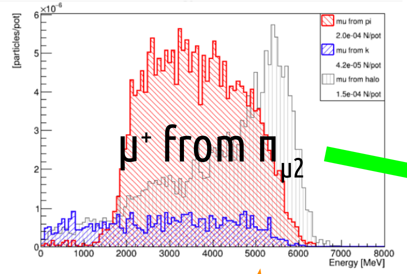


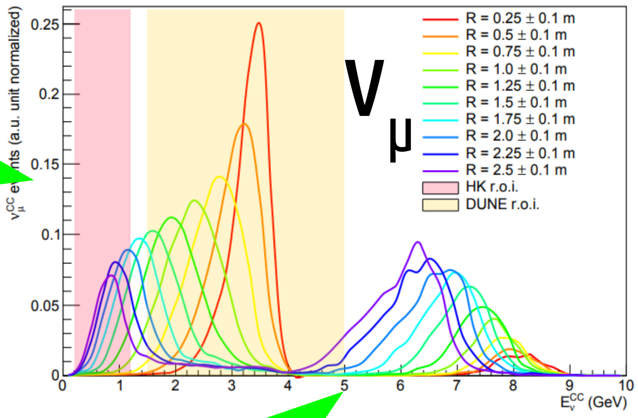


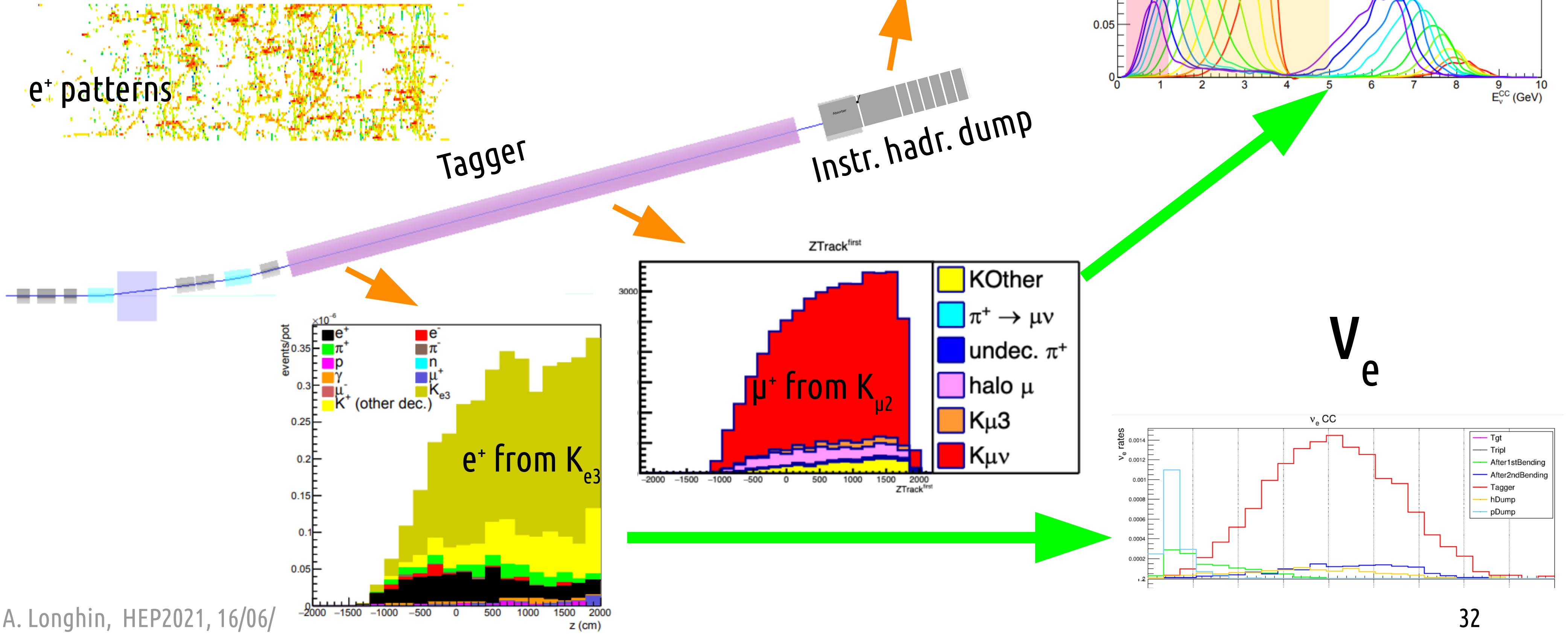
Lepton monitoring

Tagger: leptons from K (ν_e and high-E ν_μ)

Hadron dump instr: μ from π (low-E ν_μ)







ENUBET: flux constraint

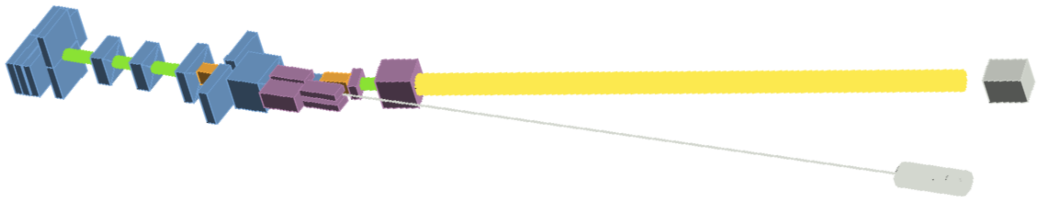
Not directly taggable components:

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

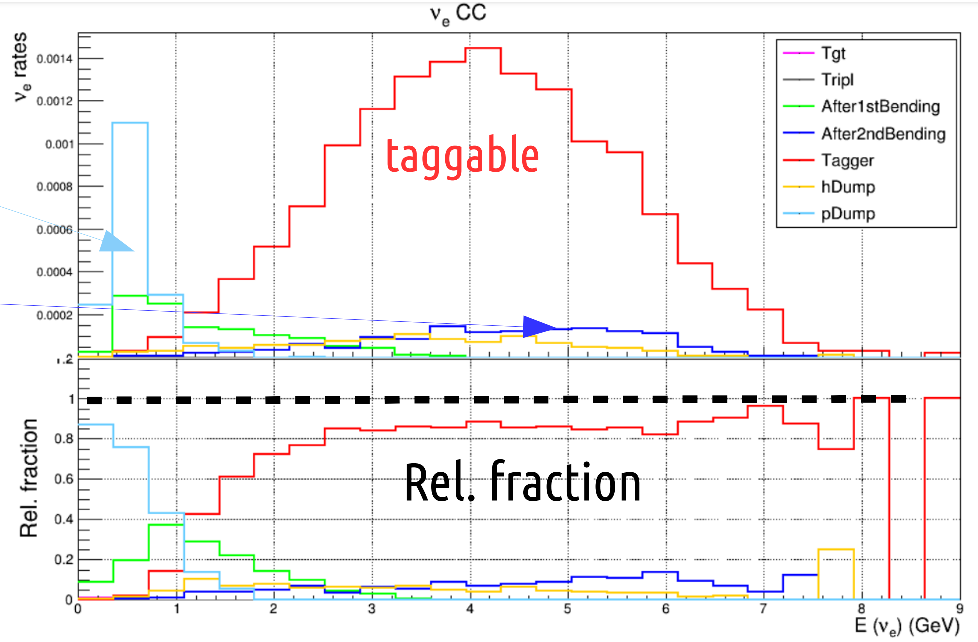
→ reduce by tuning the dump geometry/location

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

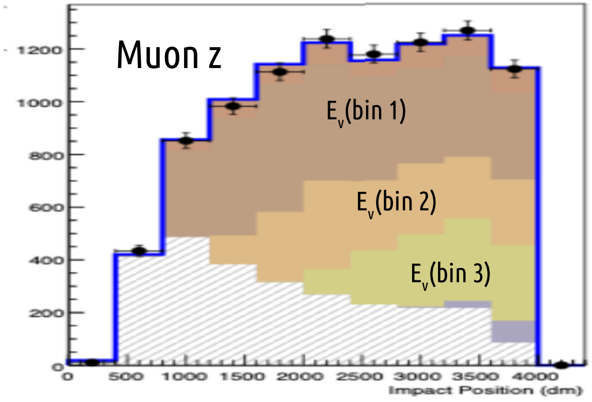


Uncertainty reduction for the tagged flux component

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



Time tagging

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

→ time coincidences of ν_e and e^+

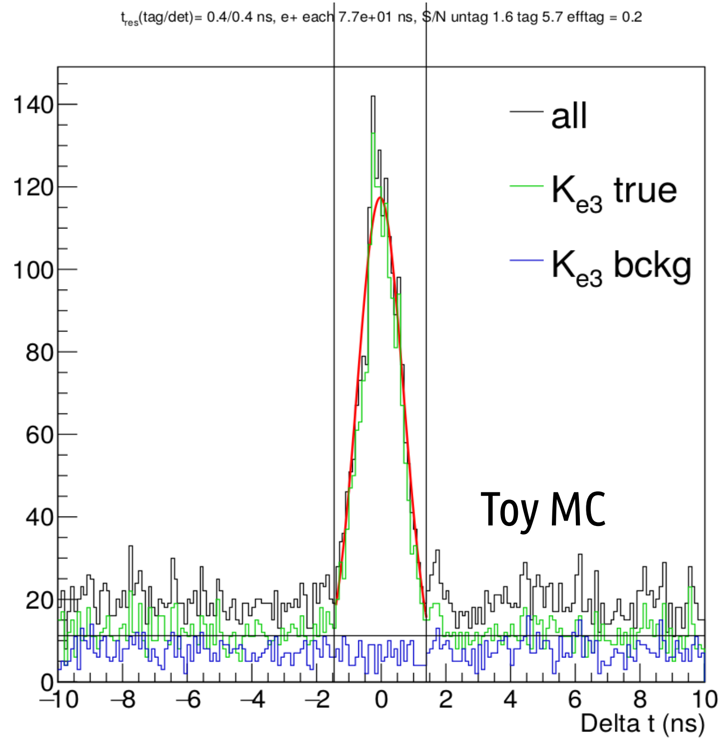
Example with reconstructed e^+
2.5×10^{13} pot / 2s with 20% eff. S/N 1.6

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

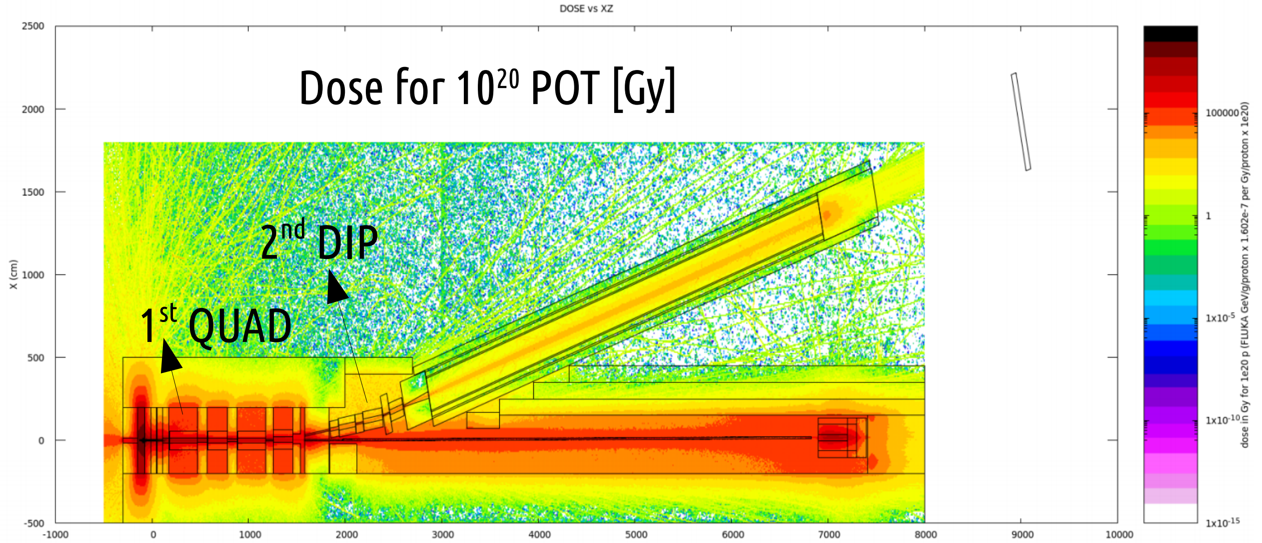


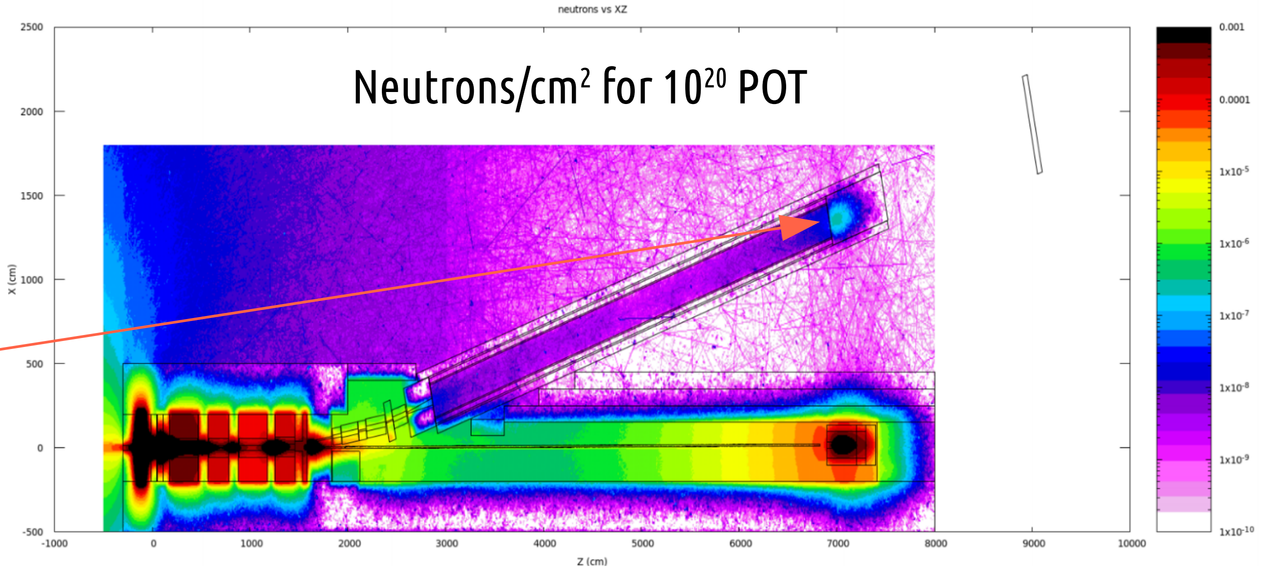
ENUBET: irradiation studies

Ensure lifetime of instrumentation and focusing elements.

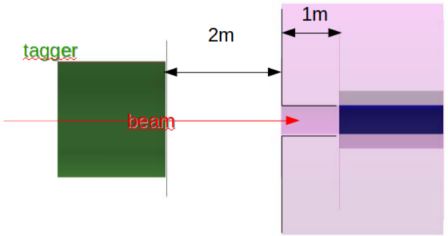
The dose at the hottest point of the quadrupole closest to the target is of about 100-300 kGy.

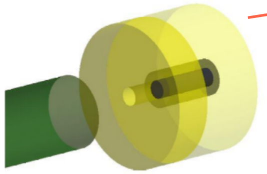
The dose at the second dipole leaves room for thinking about a SC option (could easily double/triple the bending angle)



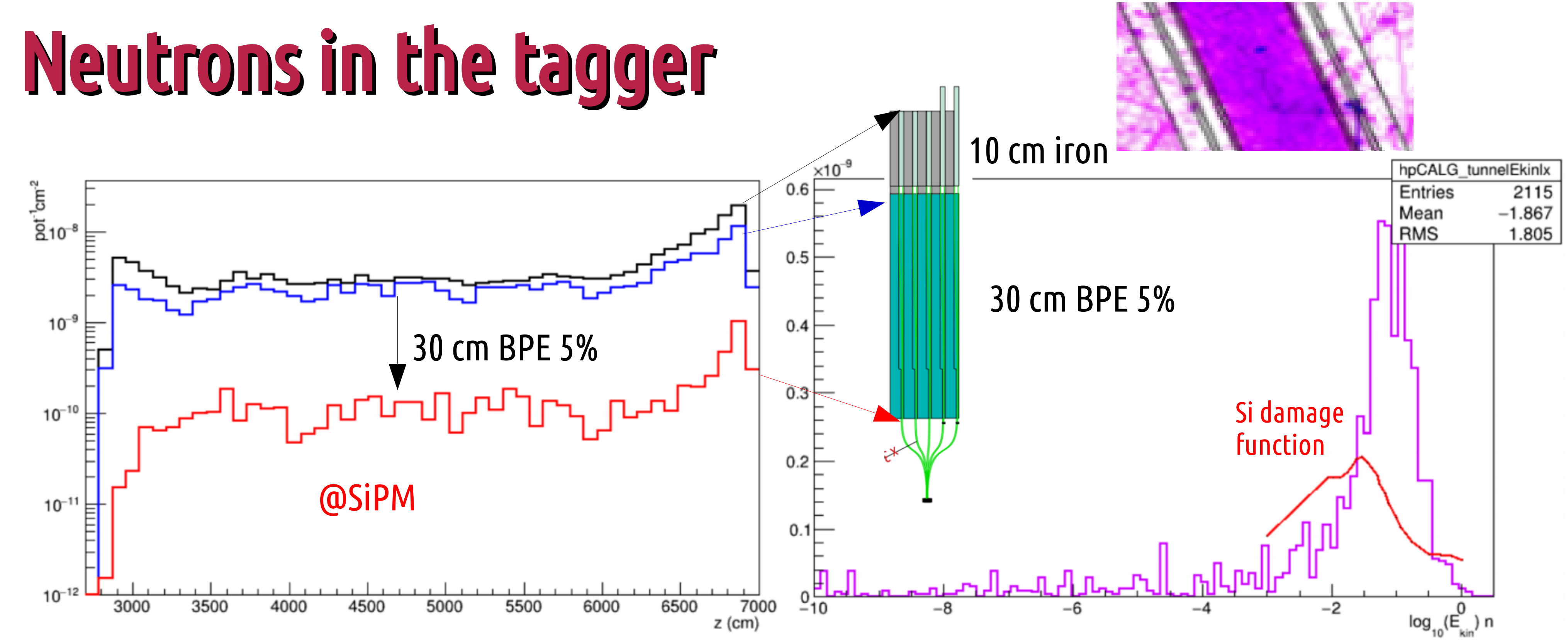


Borated concrete
Iron
Graphite





Neutrons in the tagger

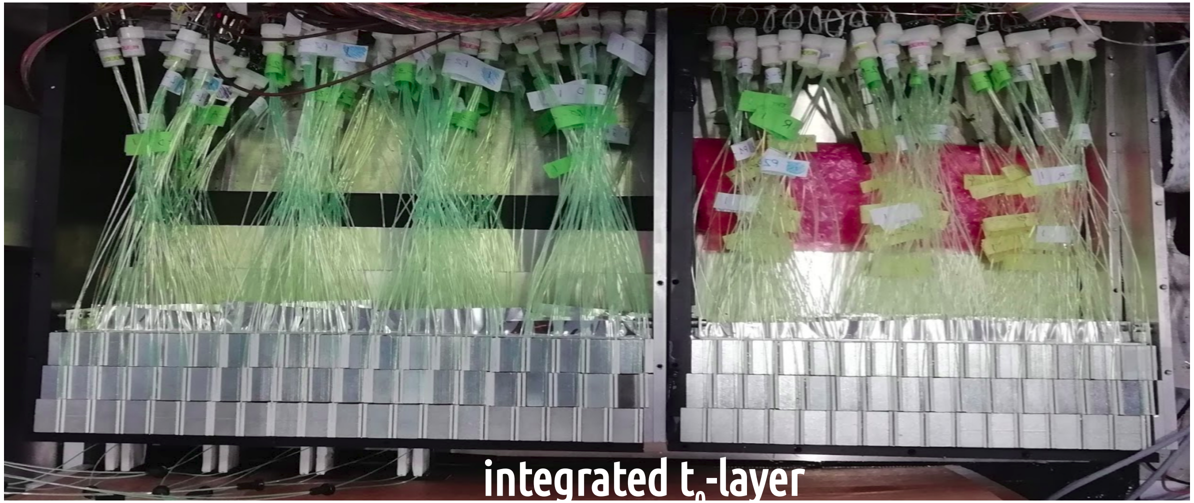


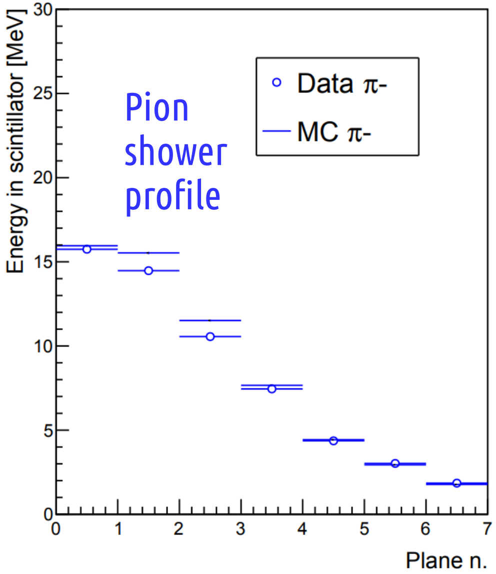
BPE shielding has a **reduction effect ~ x 20**
W.r.t. to the single dipole beamline
7 x 10^{-11} n/POT/cm^2 **~ 10 x reduction**
(7 x 10^9 n/cm^2 for 10^{20} POT)

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

JINST 15 (2020) 08, P08001

ENUBET: prototypes at the CERN-PS

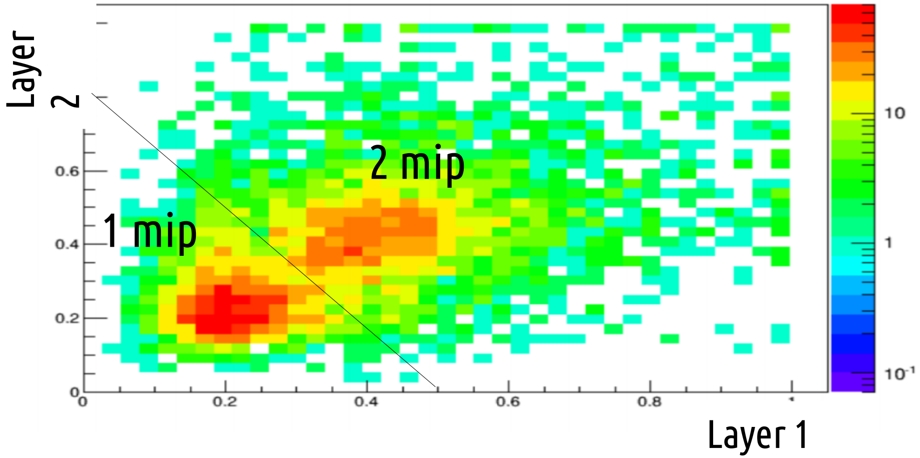




charge exchange: $\pi^- p \rightarrow n \pi^0 (\rightarrow \gamma\gamma)$

Trigger: PM1 and VETO and PM2

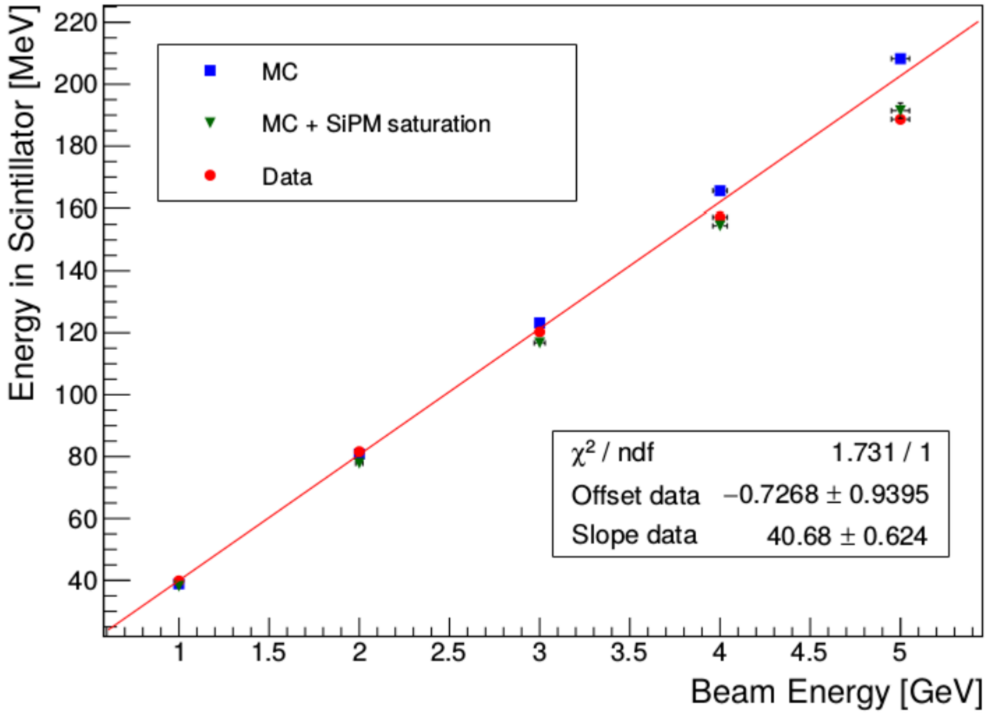
$\sigma_t \sim 400$ ps



JINST 15 (2020) 08, P08001

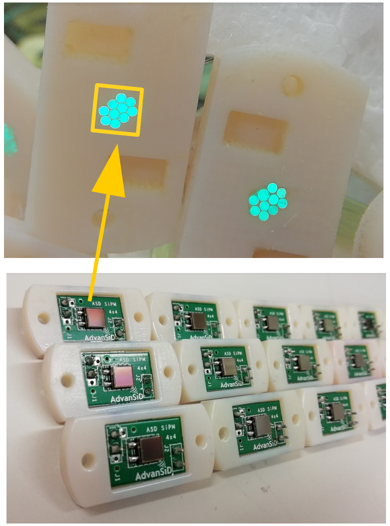
ENUBET: prototypes at the CERN-PS

$$N_{\rm fired} \simeq N_{\rm max}\left(1 - e^{-N_{\rm seed}/N_{\rm max}}\right)$$



$$N_{\rm seed} \equiv (1 + P_{x-talk}) \cdot N_{pe}$$

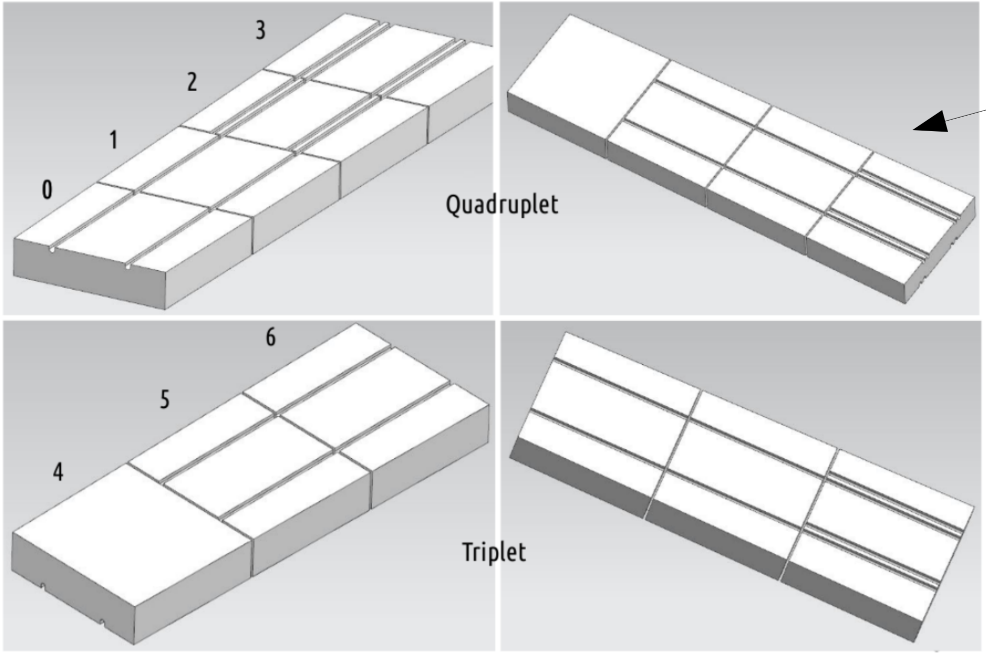
$$N_{\rm max} \simeq 5000 < 9340$$



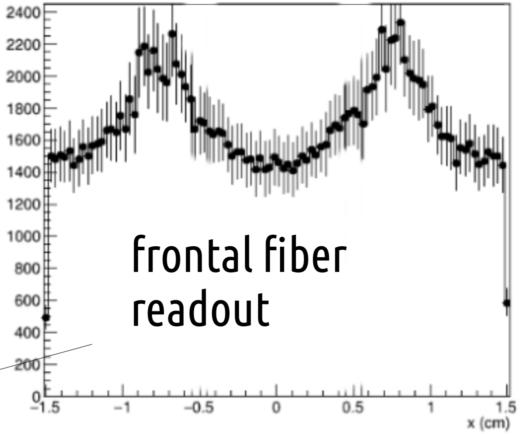
New SiPMs under test (NUV, RGB high density and low cross talk from FBK)

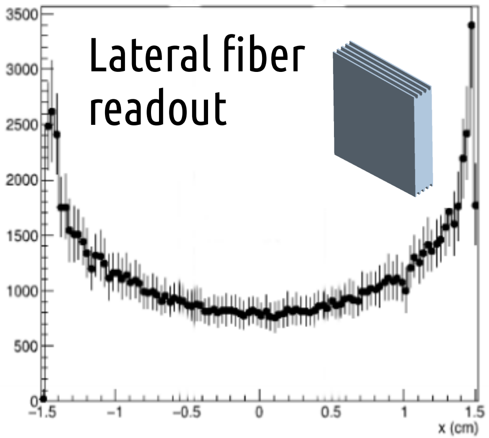
Updated light readout scheme

- From lateral to frontal light collection
- Safer for injection molding. More uniform, efficient.
- Each tile has readout grooves and “transit” grooves.
- Readout grooves on alternate sides.
- Staggering for the two tiles at larger r.

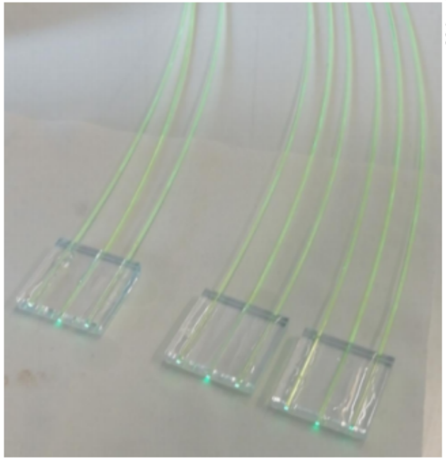


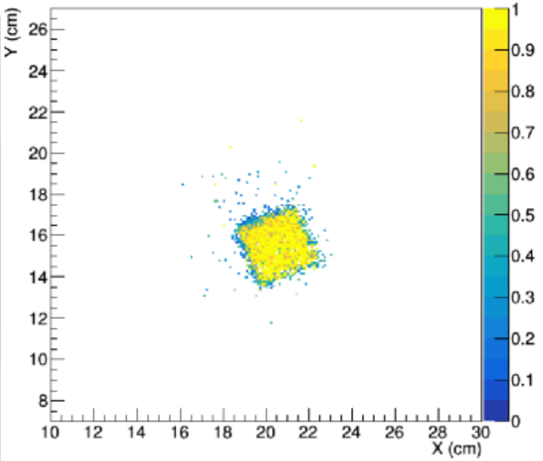
GEANT4 optical simulation





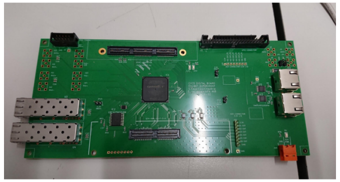
Uniformity tests with cosmic rays



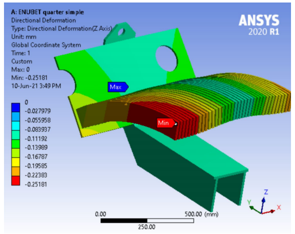


The demonstrator

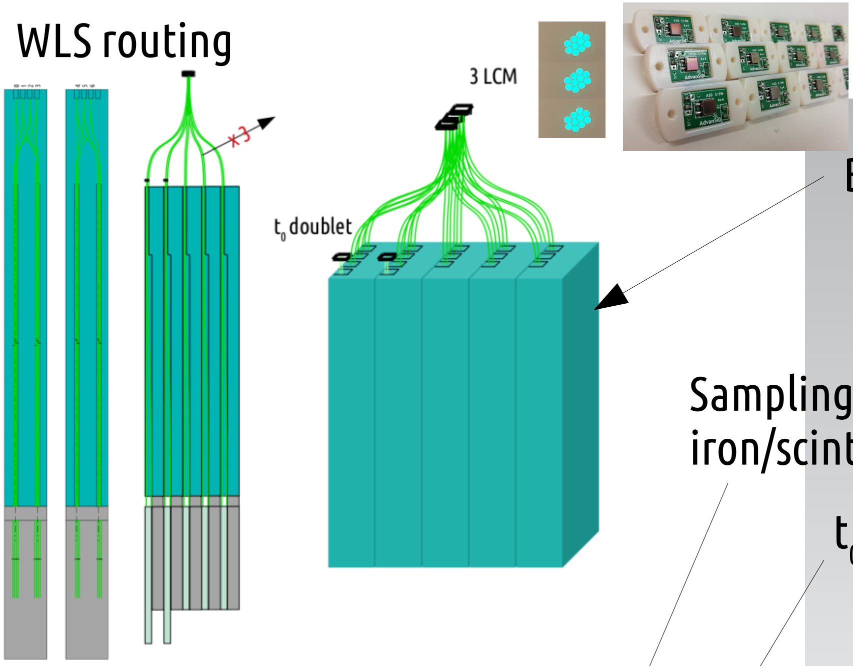
Custom digitizers @ 500 MS/s

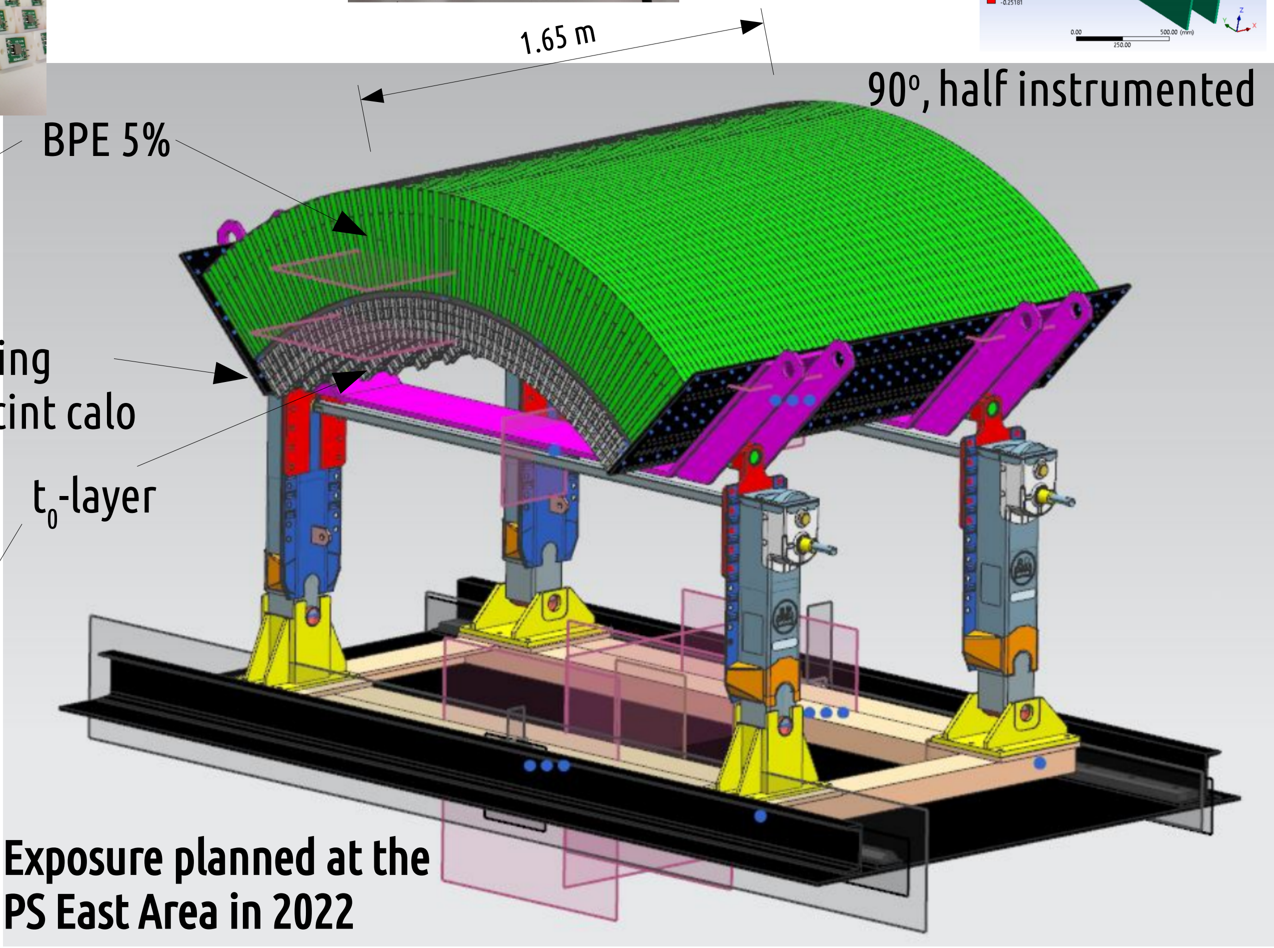


FE mech. studies



WLS routing





Exposure planned at the PS East Area in 2022

Neutrino beams from stored muons

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

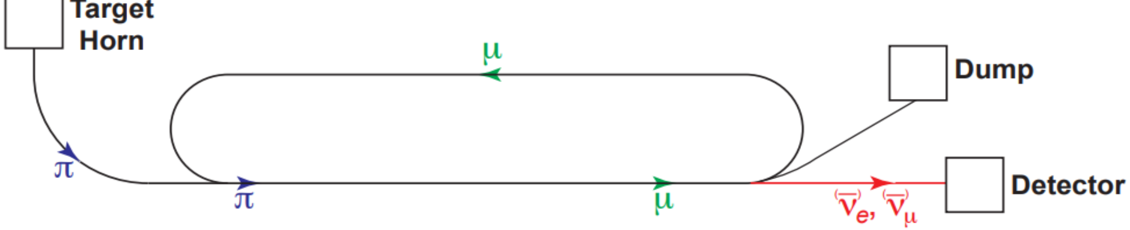
- stored muons → ν factories

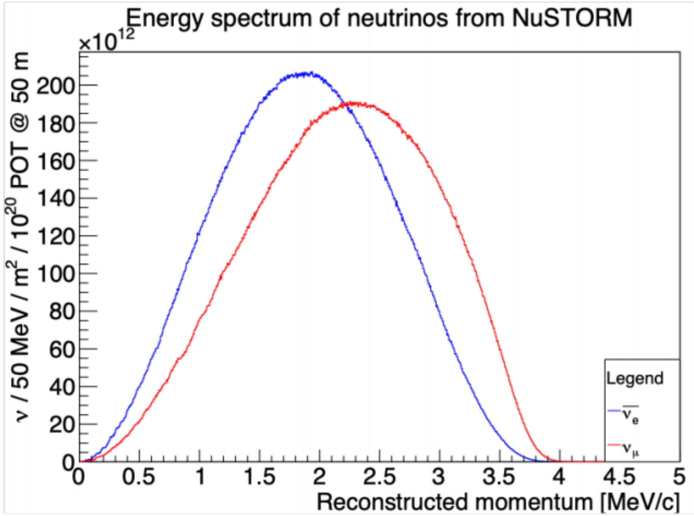
Pre-2012: use for long baseline experiments
Evolution: a short baseline setup for cross section measurements with high precision **supporting the long baseline program** which will be carried on with high intensity "meson based" HK & DUNE SuperBeams
→ **nuSTORM**

nuSTORM

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

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



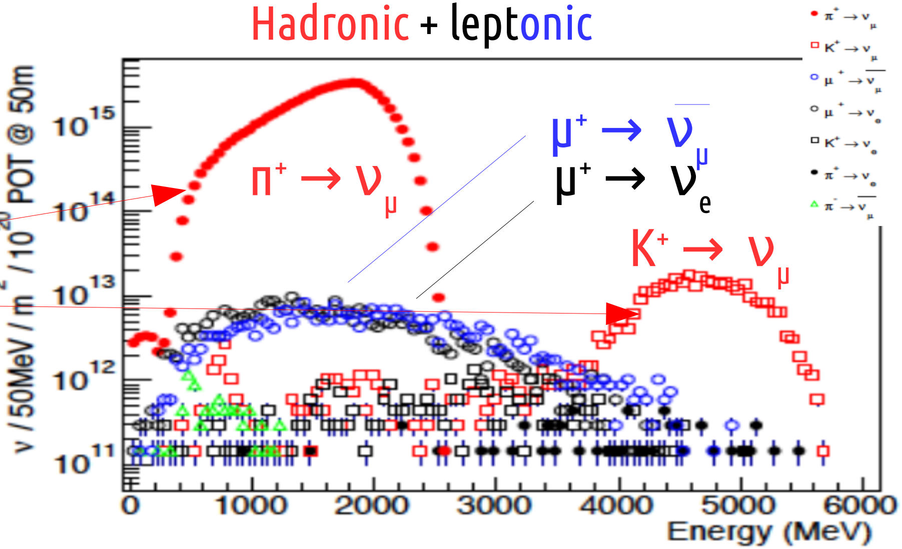


- 100 GeV/c p from SPS (156 kW). Fast extr. (10.5 us).
- Storage ring (1-6 GeV/c with a 16% acceptance)
- 52% of π → μ before 1st turn

  → ν_μ flash @ "injection pass"

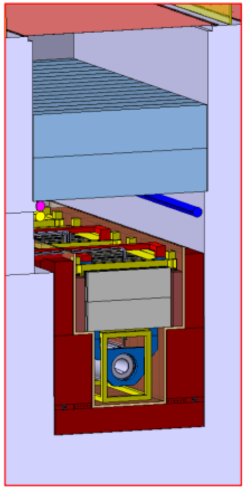
These are the components of neutrinos that ENUBET exploits and controls with the tagger

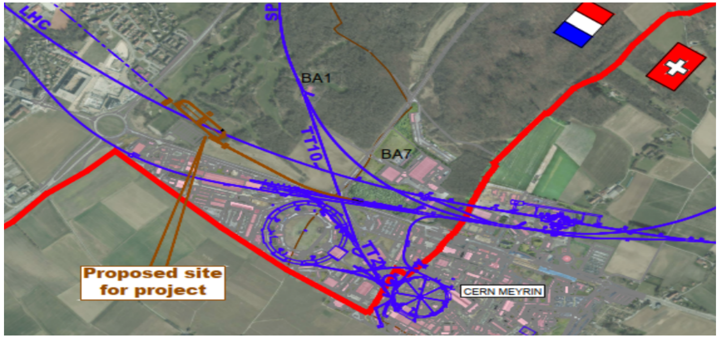
- 1 τ_μ ~ 27 orbits:
- For 10^{20} POT (2×10^{20} expected in 5 y) @ 50 m
  - 6.3×10^{16} ν_μ / m^2
  - 3.0×10^{14} ν_e / m^2

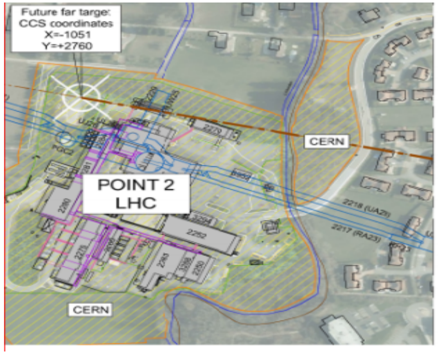


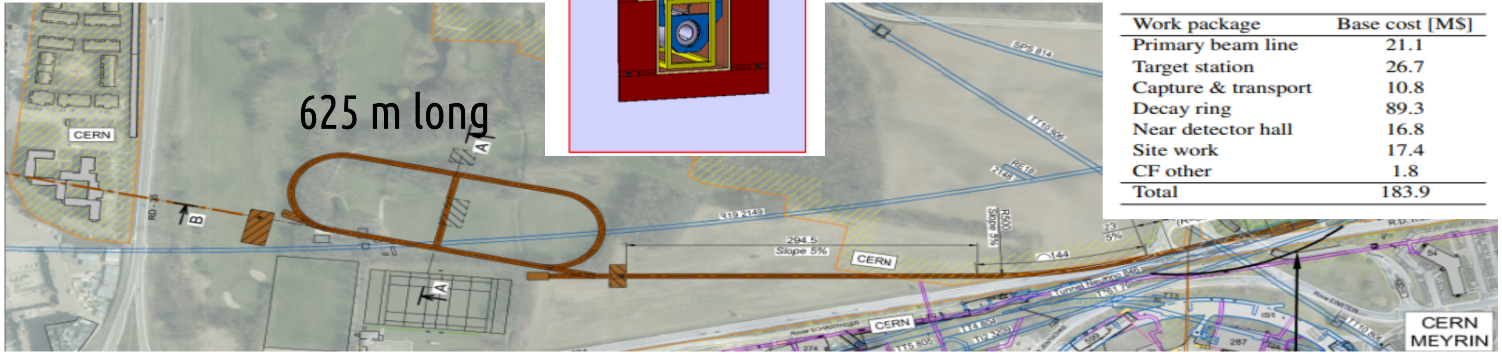
nuSTORM

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

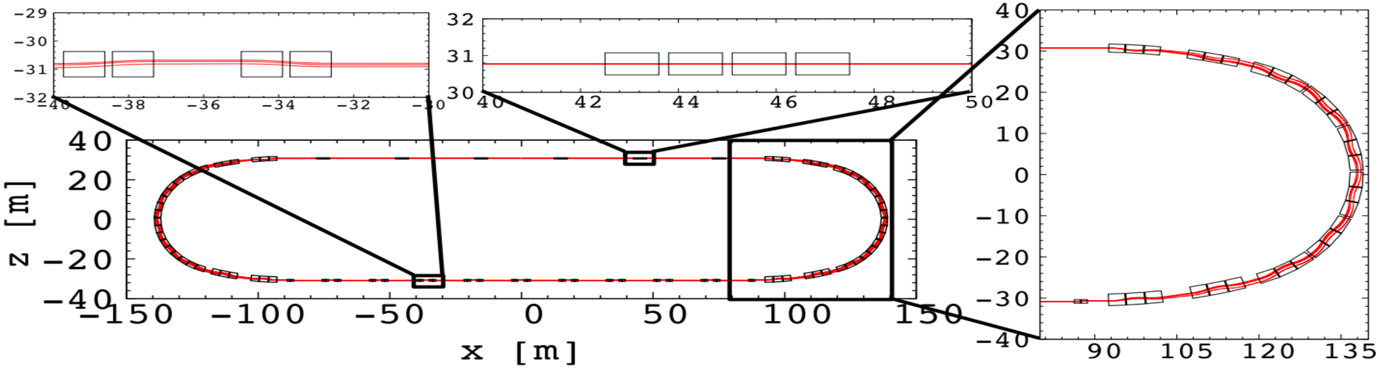


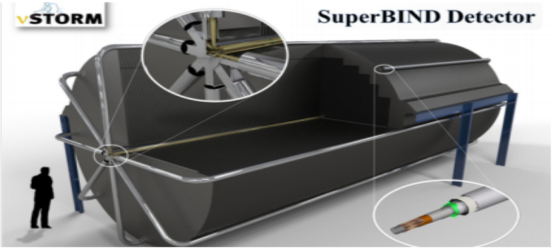






Work package	Base cost [M$]
Primary beam line	21.1
Target station	26.7
Capture & transport	10.8
Decay ring	89.3
Near detector hall	16.8
Site work	17.4
CF other	1.8
Total	183.9





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

(*) CERN-PBC-REPORT-2019-003 https://cds.cern.ch/record/2654649?ln=en

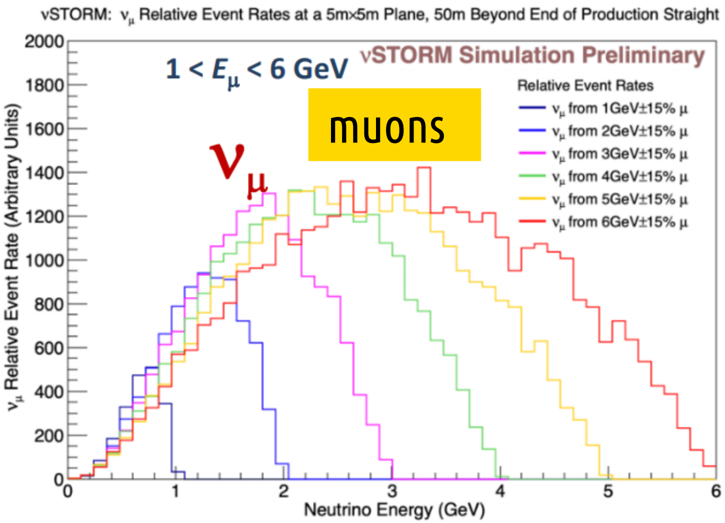
Fluxes decomposition

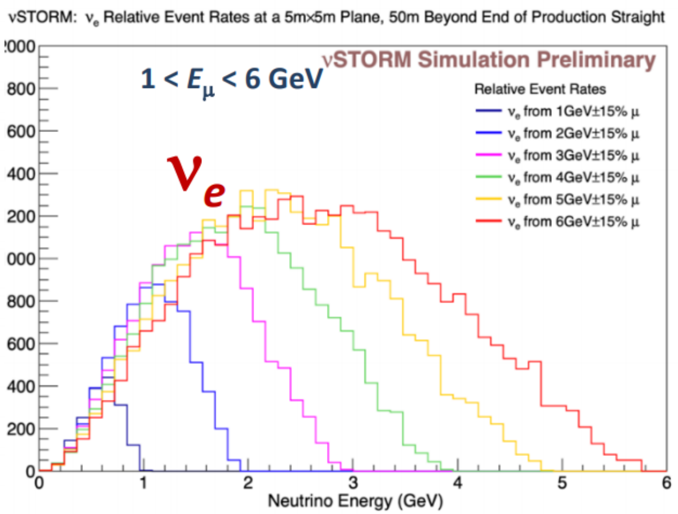
nuSTORM: vary the channeled muon energy from 1 to 6 GeV/c

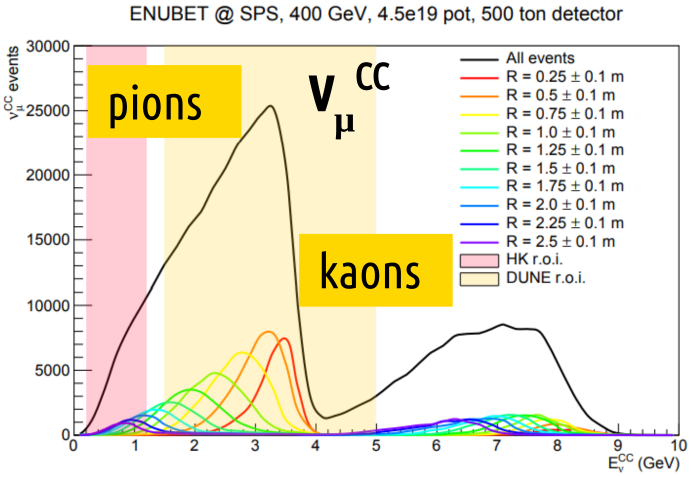
ENUBET narrow-band off-axis technique:

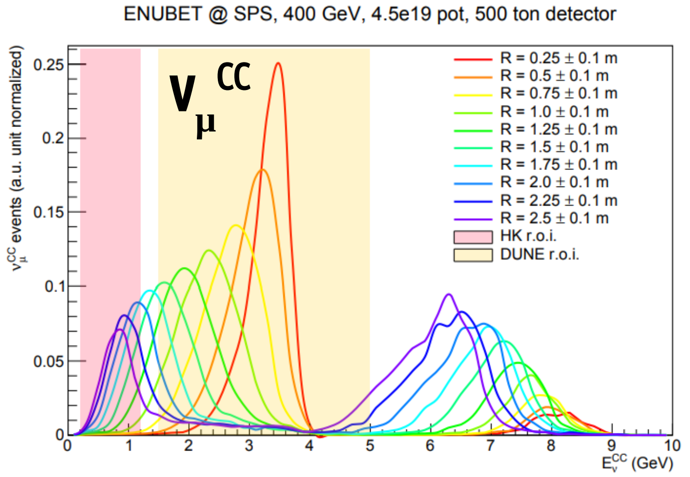
Bins in the **radial distance from the center of the beam → single-out well separated neutrino energy spectra** → strong prior for **energy unfolding**, independent from the reconstruction of interaction products in the neutrino detector. "Easy" rec. variable.

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



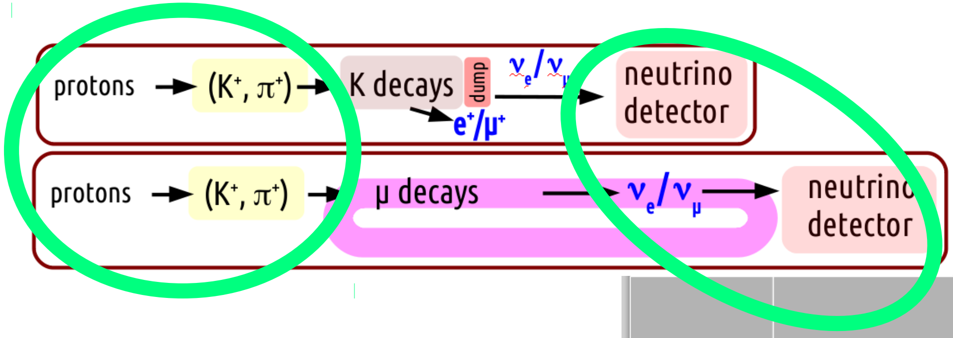






ENUBET-nuSTORM synergies

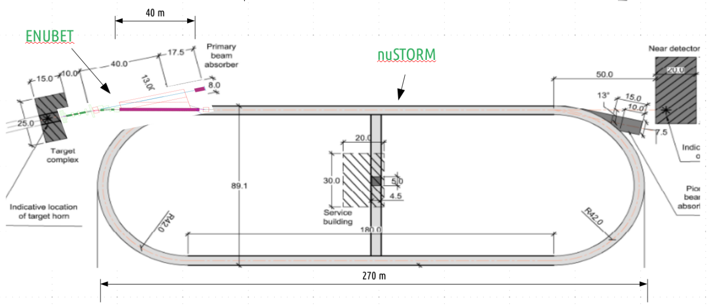
nuSTORM can be seen (simplistically) as an "ENUBET without a hadron dump" where pions and muons are channeled into a ring. Large room for smart ideas to match the requirements of the two experiments



- common points: **proton extraction line, target station, 1st stage of meson focusing, proton dump, neutrino detector (possibly)**

- But also significant differences (and scale)

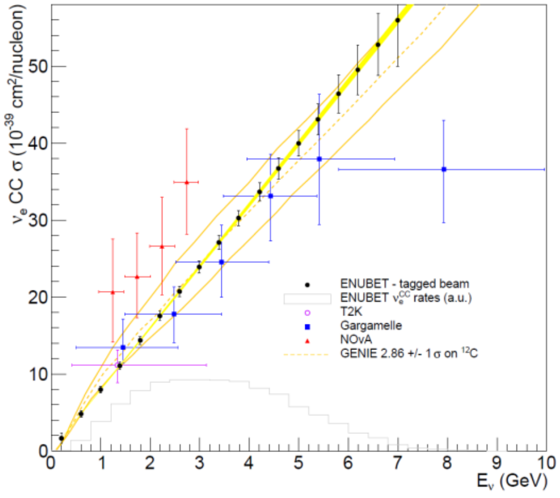
	Decay region	Hadron dump	Proton extraction, energy, focusing	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps μ in addition → preventing a (small) ν_e pollution to K_{e3} - ν_e	Slow extraction (+ quad triplets) "slow" in bursts (+horn) 400 GeV	similar	Similar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



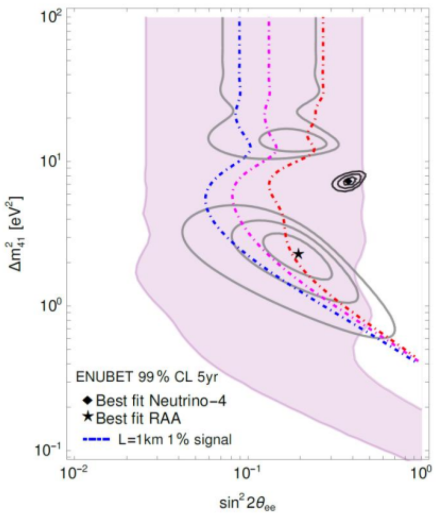
Engineering studies starting within Physics Beyond Colliders

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 !

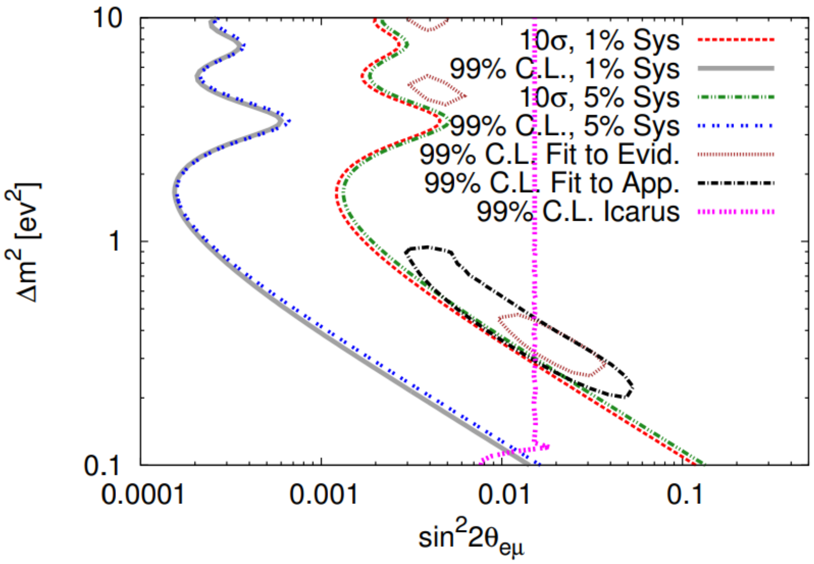


Electron neutrino cross section



Sterile neutrinos

L. Delgadillo, P. Huber, arXiv:2010.10268



Conclusions

CERN NP, SPSC: activities to support present and future neutrino physics in JP and US are in full swing (protoDUNEs, T2K near detector upgrade, WC test experiment)

+ Support to new concept beams through ENUBET/NP06: 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**.

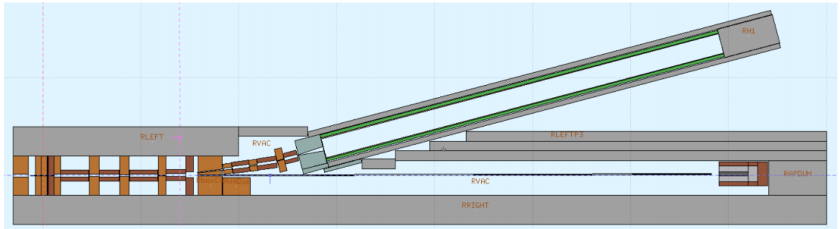
Could **fill the gap** between our knowledge of standard neutrino properties (firstly cross sections) and the **needs of the next generation experiments**. Possibly the pivotal idea to create a hub for high precision neutrino physics in EU.

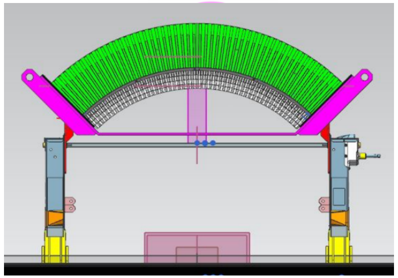
Large space for contribution on broad range of subjects from **detectors**/analysis/simulations.

ENUBET **CDR** expected in ~ 1 year. Contribution from CERN (**PBC, μ-Collider studies)** can help to make a step forward with sound studies on **implementation** and **costing**.

Bonus slides

Conclusions





- **ENUBET is on schedule** and we are entering the last phase of the project
- **The new beamline: single particle e^+/μ^+ monitoring** with good **S/B, efficiency and neutrino yields with a** much reduced **untagged-ν_e component**
  - **Multi-momentum** option on its way
- Experimental test of **"burst" slow extraction** @ SPS → could go down to 3 ms
  - **horn option** remains very appealing: further optimization ongoing
- **Frontal readout** option → **long lifetime/accessibility of SiPM**
- Completed the **test beams** campaign before CERN LS2
- **Redundant end-to-end simulation** as a framework for the treatment of **systematics**
- **Construction of the demonstrator and electronics in progress → test at PS East Hall summer 2022**

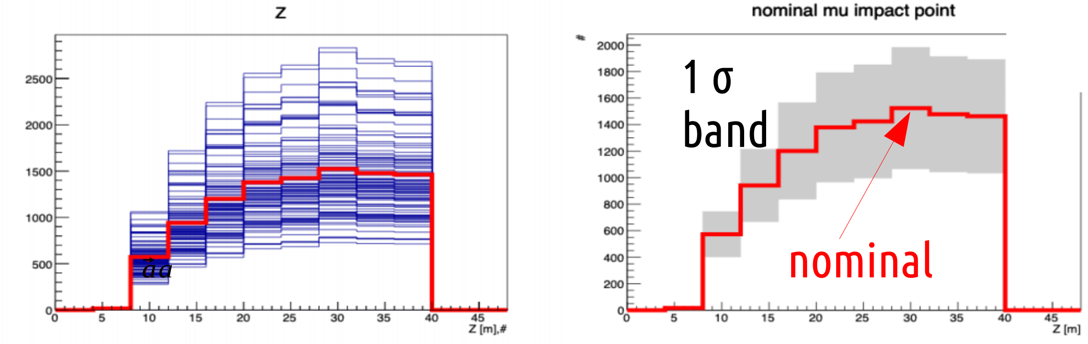
  - **PBC:** Engineering studies, explore synergies with nuSTORM
  - **Conceptual Design Report** at the end of the project (2022): **physics** and **costing**

Framework for systematics

A software framework written within **ROOFIT** to **constrain the neutrino flux from the reconstructed leptons.**

To validate the machinery the impact point along the tagger of muons from kaon decays is considered.

Uncertainty envelope created by sampling hadro-production parameters of **a toy model** (multiverse method).



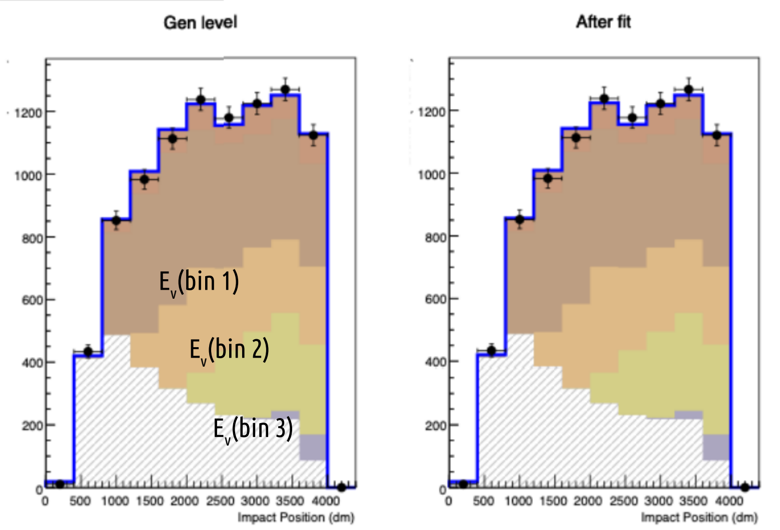
Extended likelihood fit of lepton variables with **templates in bins of the associated neutrino energy**:

$$PDF = N_S(\vec{\alpha},\vec{\beta}) \cdot S(\vec{\alpha},\vec{\beta}) + N_B(\vec{\alpha},\vec{\beta}) \cdot B(\vec{\alpha},\vec{\beta})$$

Nuisance parameters from uncertainties related to **hadroproduction** (α) and **beam parameters** (β).

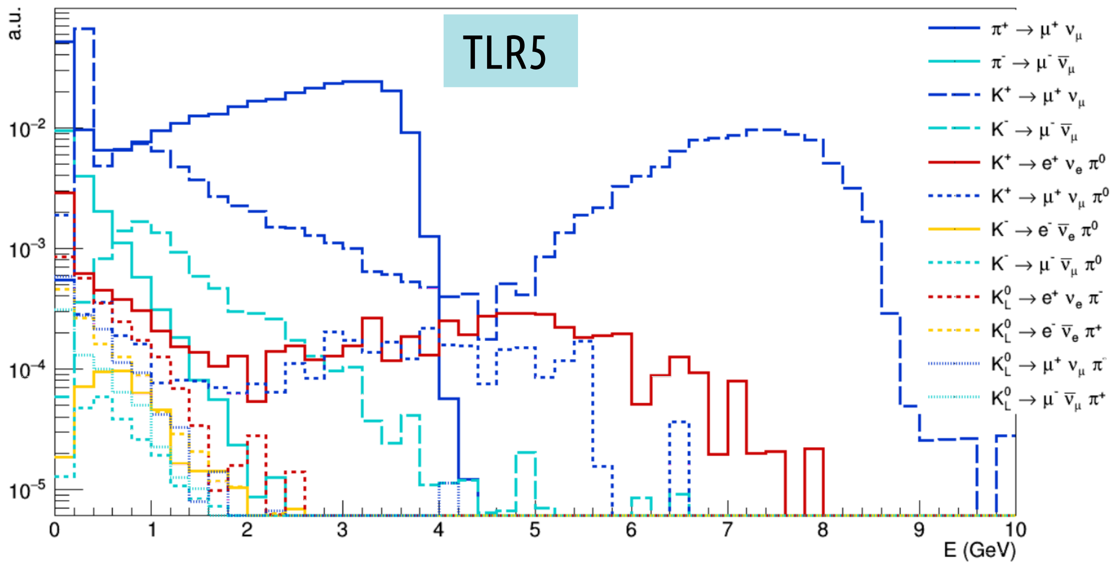
Fit the relative normalizations of the templates in E_ν → flux constraint.

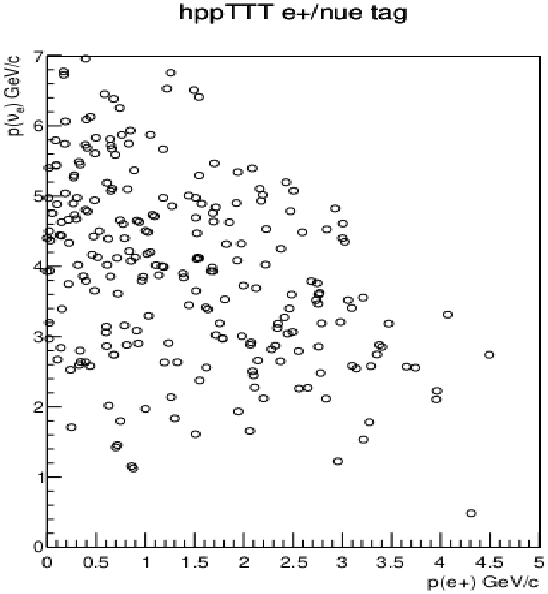
In progress: from a toy to the **real ENUBET case using full simulation.**

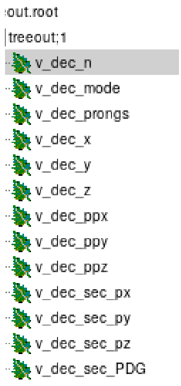


Framework for systematics

- → created a **common data model** to be used for systematic studies (G4TL+G4TAG).
- Unify p-target (FLUKA). Full simulation including the beamline G4 (G4TL). Tagger simulation and lepton reconstruction G4 (G4TAG).
- Information of **all decays producing neutrinos** is stored and linked to the parent particle at the level of target and at the tunnel entrance.
- Allows a full description of **ν-flux components** and **linking neutrinos to the relative reconstructed leptons**.







Proton extraction R&D

during LS2: burst mode slow extraction

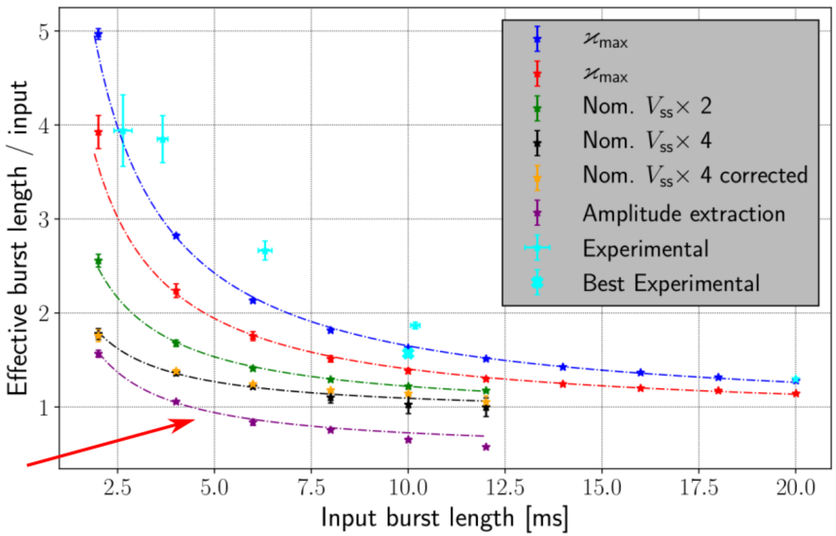
a **full simulation** to validate the experimental results and **explore possible improvements**, which could not be tested in the machine before the shutdown.

Two different methods (increase of extraction **sextupole strength** and **amplitude extraction**)

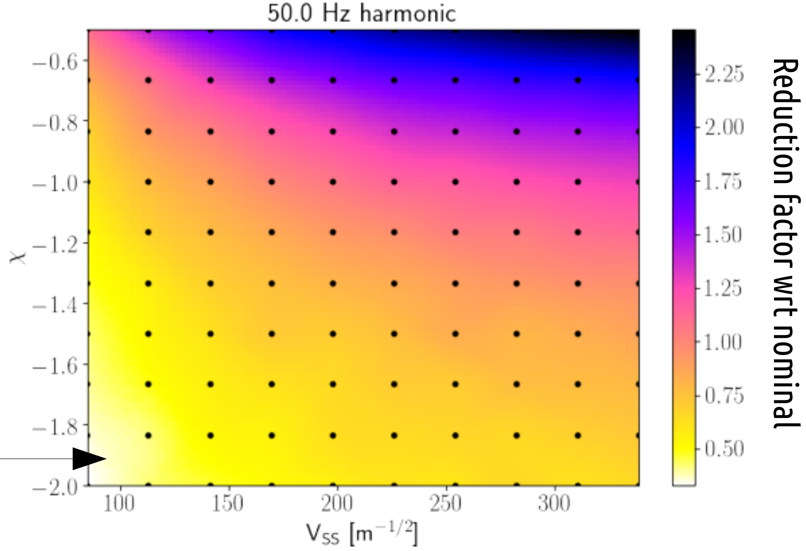
pulses between **3 and 10 ms** seems at reach without hardware interventions → tests after LS2

Reduction of ripples in the usual slow extraction

Tuning different set of sextupoles: the quad-correcting ones used to act on the chromaticity (X) and the ones used for the extraction (V_{ss})



PhD thesis of M. Pari



CERN-TE-ABT-BTP, BE-OP-SPS
Velotti, Pari, Kain, Goddard

x 2 reduction of the 50 Hz ripples amplitude expected here wrt to nominal

Target optimization

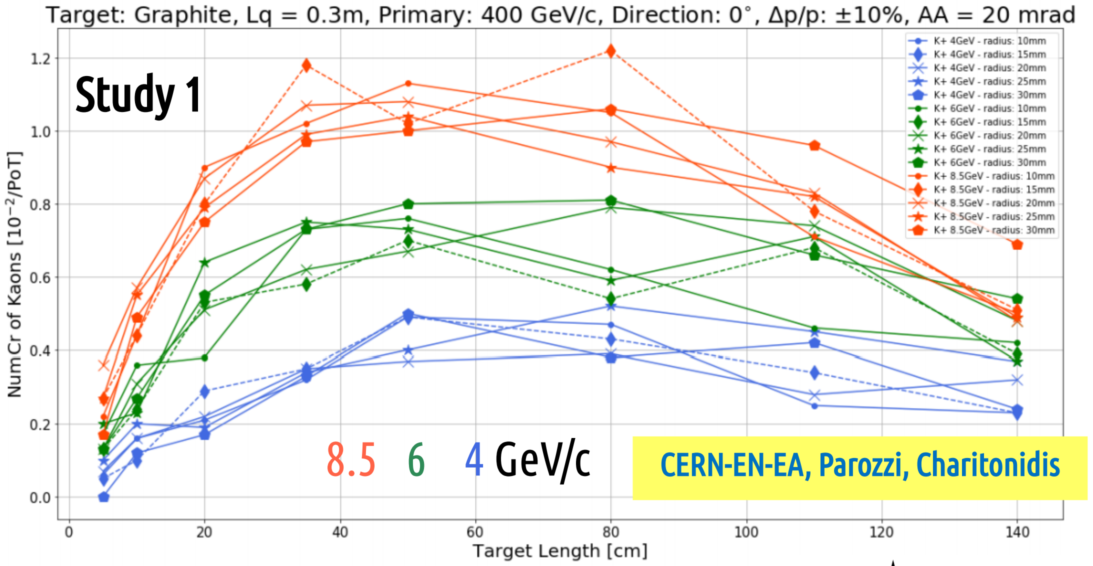
Explored the parameter space of the geometry (also tronco-conical) and some materials (graphite, Inconel) to maximise the yields of mesons in our region of interest with FLUKA.

The current targets are both more efficient and robust under the point of view of implementation and lifetime.

New baseline targets:

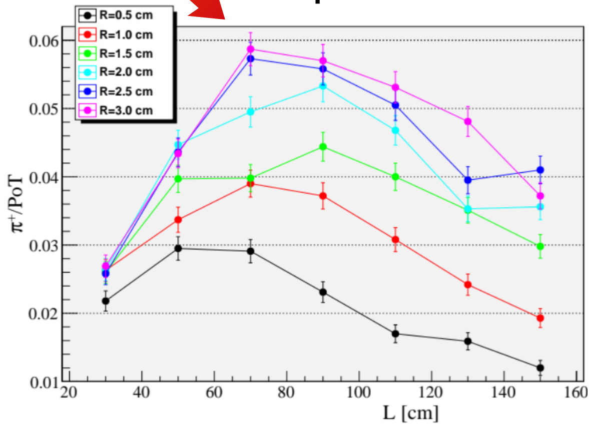
- **Graphite: L/ø = 700/60 mm**
- **Inconel: L/ø = 500/60 mm**

(*) The two studies used different choices for the FOMs

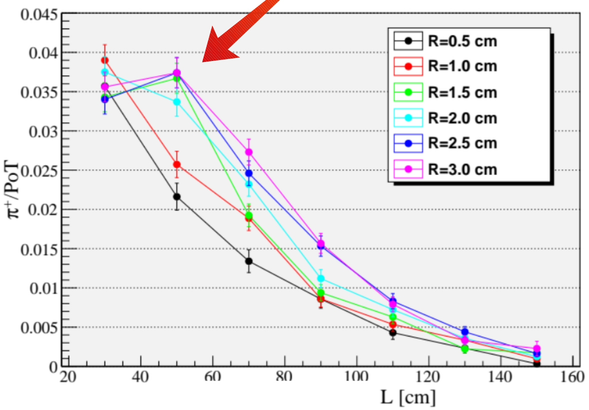


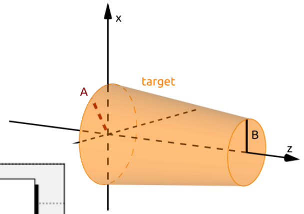
Study 2

Graphite



Inconel



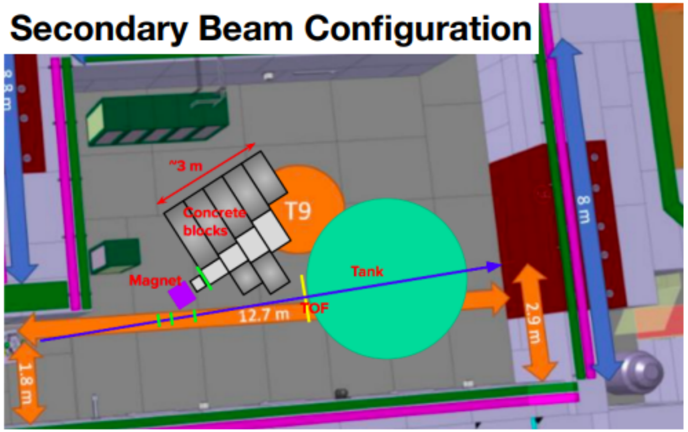


https://indico.cern.ch/event/1024587/contributions/4301475/attachments/2224851/3768654/wcte_spsc_20210413.pdf

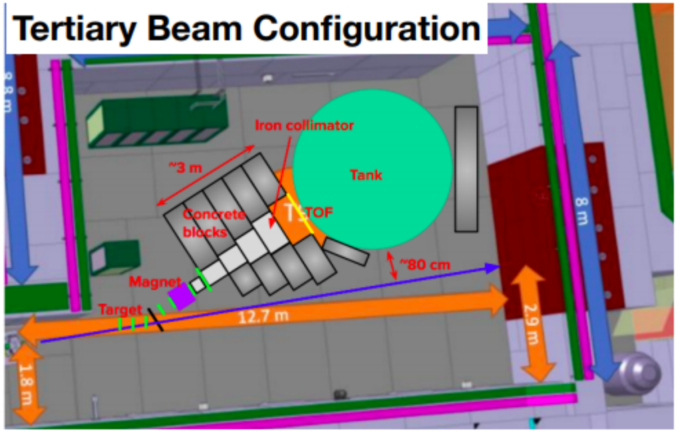
Water Cherenkov Test Experiment

Experimental Configurations

- We plan to operate in secondary and tertiary beam configurations:



Electron, muon and proton fluxes



Low momentum pion and proton fluxes

- Configurations with pure water and **$Gd_2(SO_4)_3$** loaded water (0.2% by mass) to allow for neutron detection

Target optimization

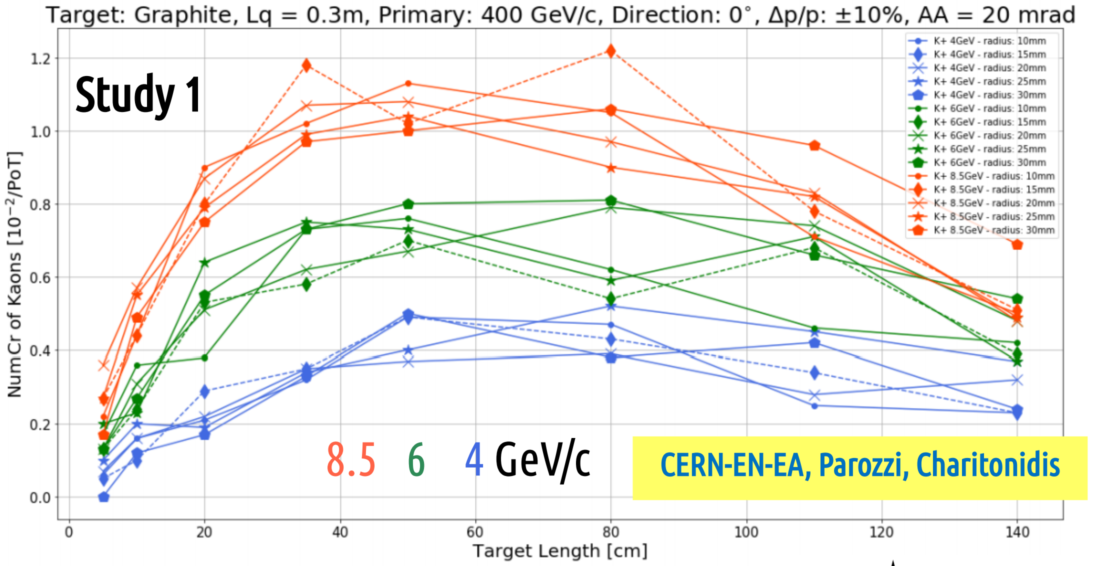
Explored the parameter space of the geometry (also tronco-conical) and some materials (graphite, Inconel) to maximise the yields of mesons in our region of interest with FLUKA.

The current targets are both more efficient and robust under the point of view of implementation and lifetime.

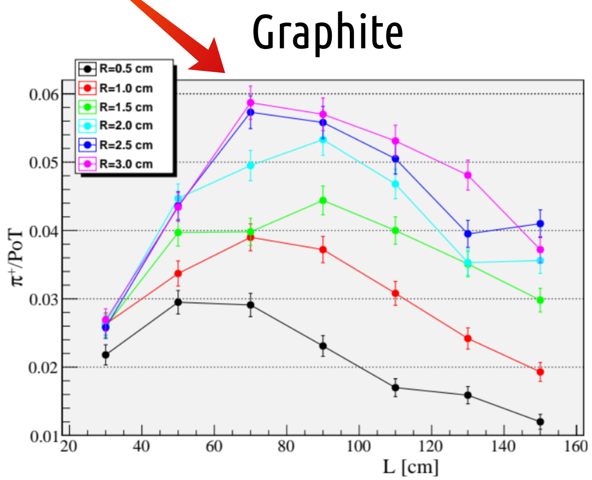
New baseline targets:

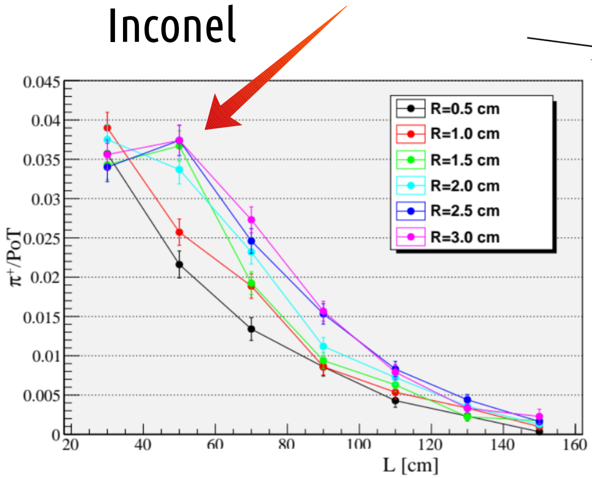
- **Graphite: L/ø = 700/60 mm**
- **Inconel: L/ø = 500/60 mm**

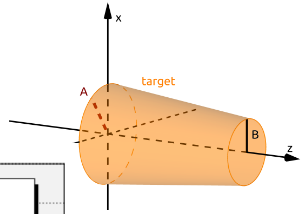
(*) The two studies used different choices for the FOMs



Study 2

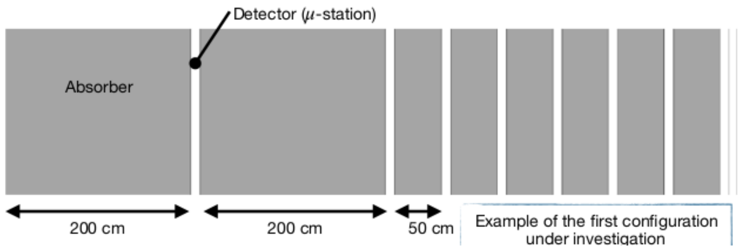




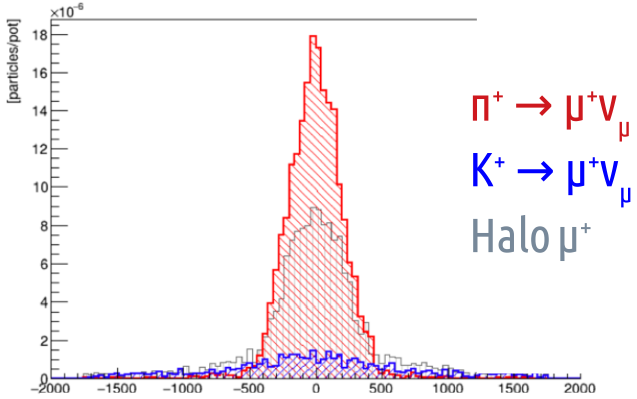


Forward region muons reconstruction

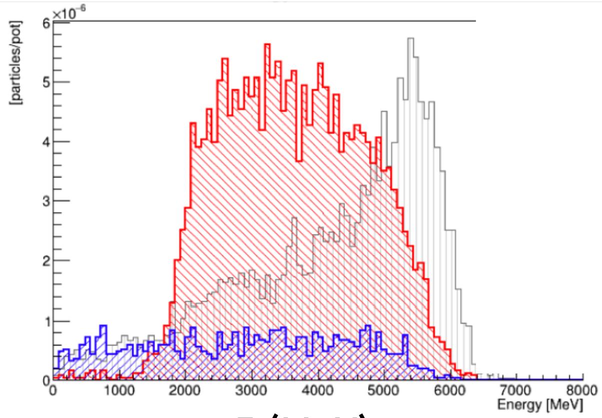
Range-meter after the hadron dump. Extends the tagger acceptance in the forward region to constrain $\pi_{\mu 2}$ decays contributing to the low-E ν_μ.



The most upstream (hottest) detector needs to cope with a muon rate of ~ 2 MHz/cm^2 and about 10^{12} 1 MeV-n_{eq}/cm^2.

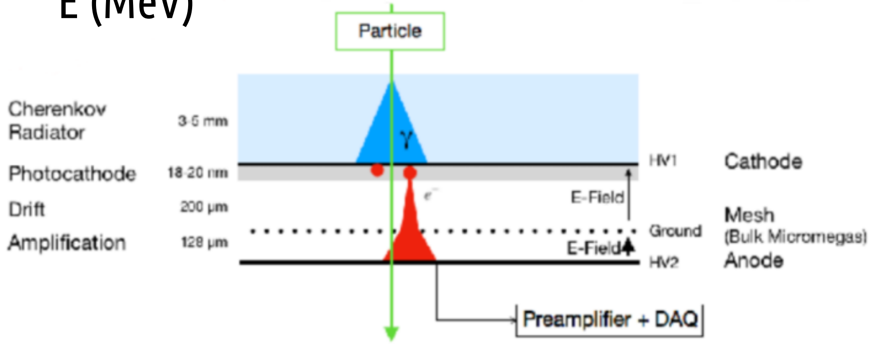


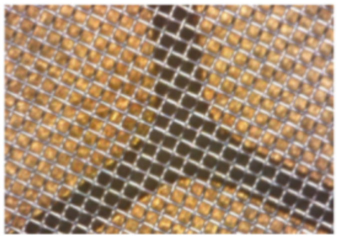
Y (mm)



E (MeV)

Design being defined. Possible candidate: fast Micromegas detectors employing Cherenkov radiators + thin drift gap (PICOSEC coll.). Bonus: excellent timing.



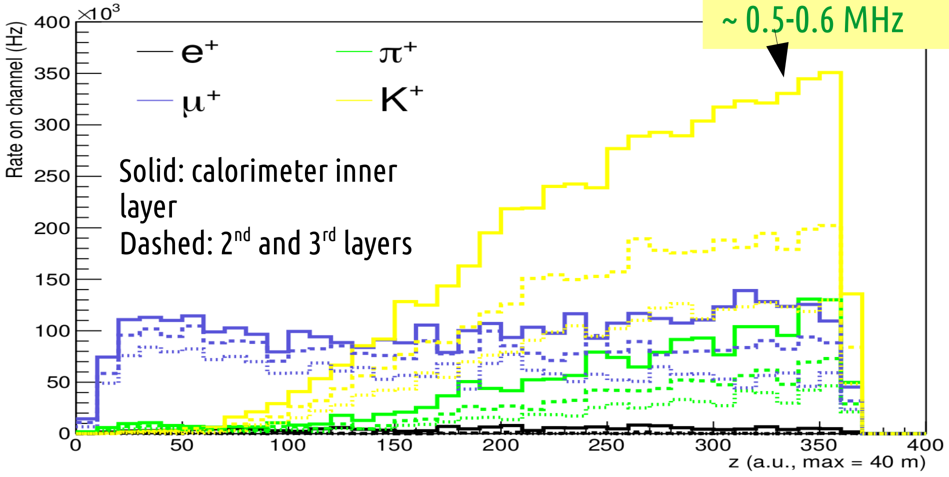


ENUBET: proton extraction, rates, pile-up

quad focusing: 2s slow extraction

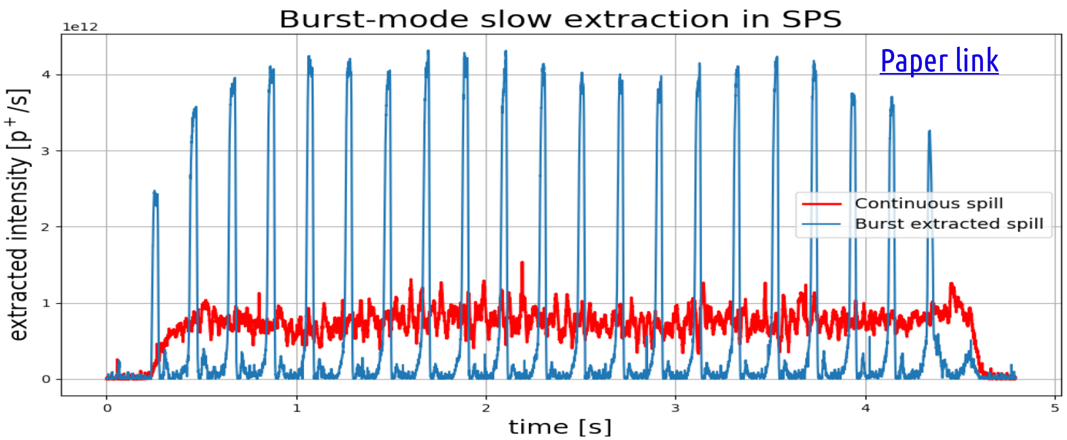
Rates in the tagger vs z

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



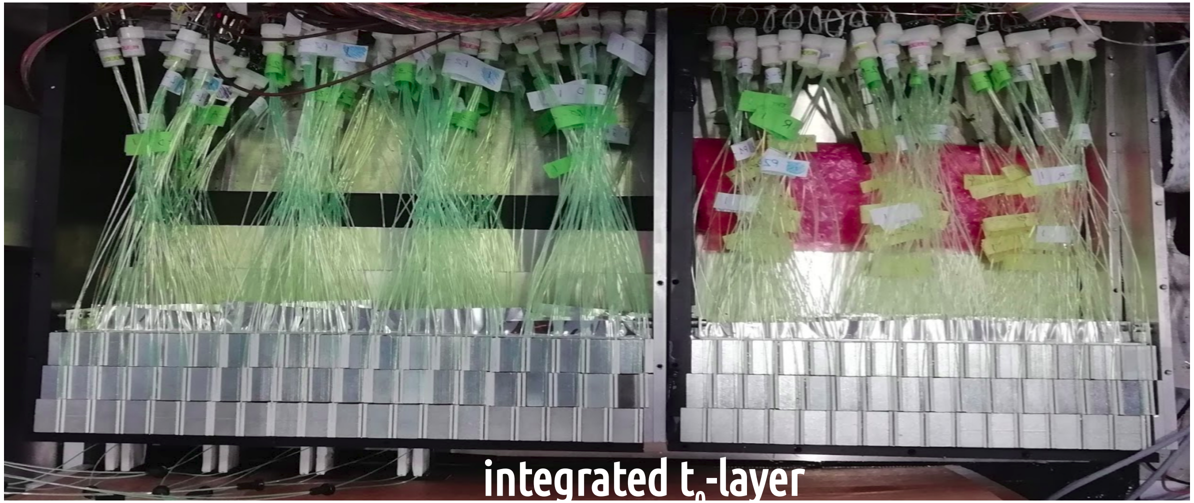
Waveform analysis algorithms developed.
With **250 MS/s** sampling:
pile-up efficiency loss stays
sub-% up to ~ 1 MHz/ch

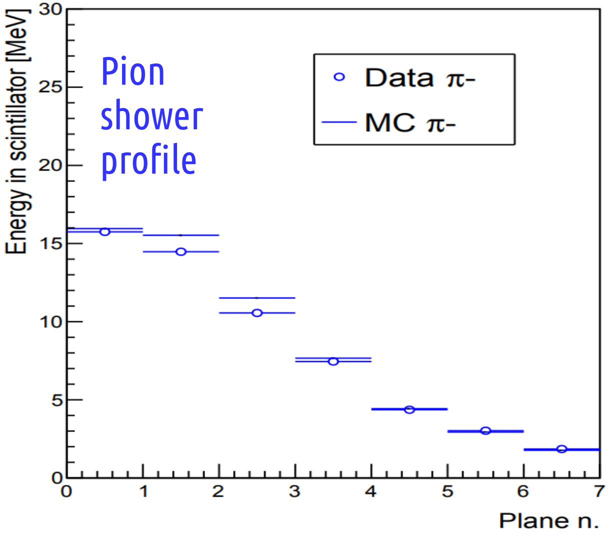
With the increased rates implied in the horn focusing scheme → **~ few % loss**

ENUBET: prototypes at the CERN-PS

ENUBET CERN-SPSC 2020 annual report link

JINST arXiv:2006.07269

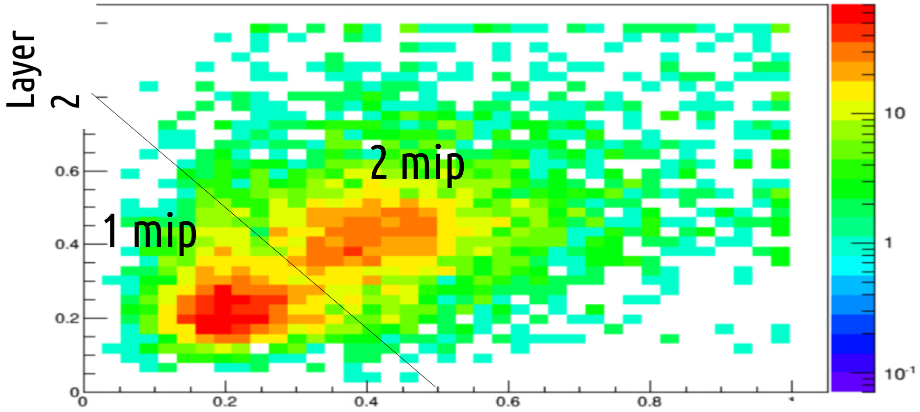




charge exchange: $\pi^- p \rightarrow n \pi^0 (\rightarrow \gamma\gamma)$

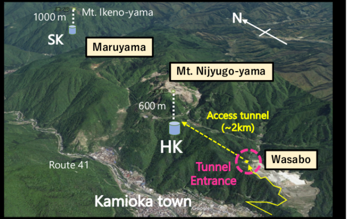
Trigger: PM1 and VETO and PM2

$\sigma_t \sim 400$ ps

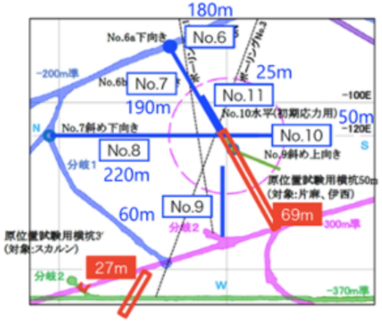


HK: construction/procurement

Entrance Yard Construction

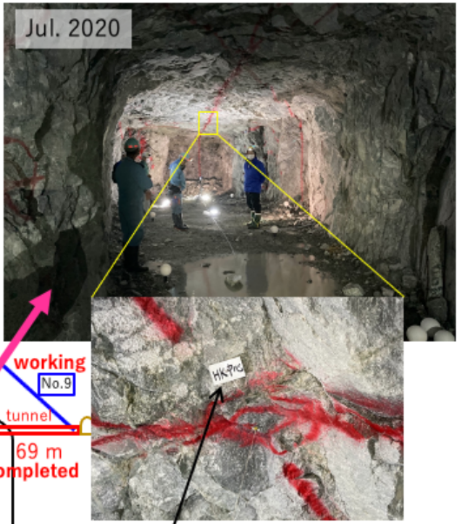


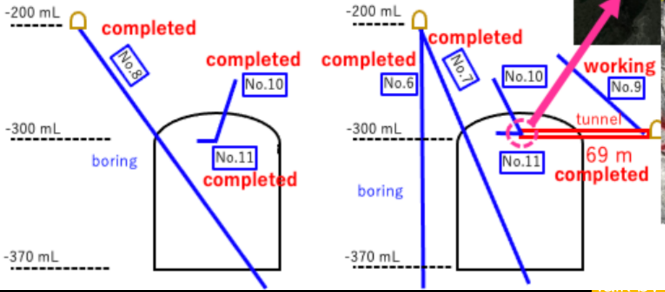
- Construction of entrance yard in Wasabo is completed.
- Construction of the waste water treatment facility at the entrance yard.



Survey tunnel

Near the center of the (future) HK dome





"HK center"

Hyper-K Detector Construction has Started

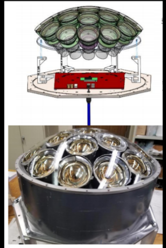
PMTs for the Inner Detector

	Super-K	Hyper-K
Number of PMTs	11,129 50cm PMTs	20,000 50cm PMTs (JPN) (+ additional PDs (Oversea))
Photo-sensitive Coverage	40 %	20 %
Single photon efficiency /PMT	~12%	~24%
Dark Rate /PMT	~4 kHz (Typical)	4 kHz (Average)
Timing resolution of 1 photon	~3 nsec	~1.5 nsec

2020/12 First six PMTs delivered to Kamioka

- Production has started on time for the 50cm PMTs with Box&Line dynode.
- 300 PMTs by March, 20,000 PMTs in total by 2026 according to the Japanese budget profile.

mPMTs


Prototype at TRIUMF


HK FD mPMT Electronics at INFN

mPMT is a vessel which houses and protects an array of 19 3" PMTs:

- improves the granularity and timing;
- additional intrinsic directional information.
- Far detector "hybrid" photocoverage: 20" PMTs and mPMTs.
- IWCD will be instrumented only with mPMTs.
- Different constraints on far detector and IWCD mPMTs.