ENUBET updates

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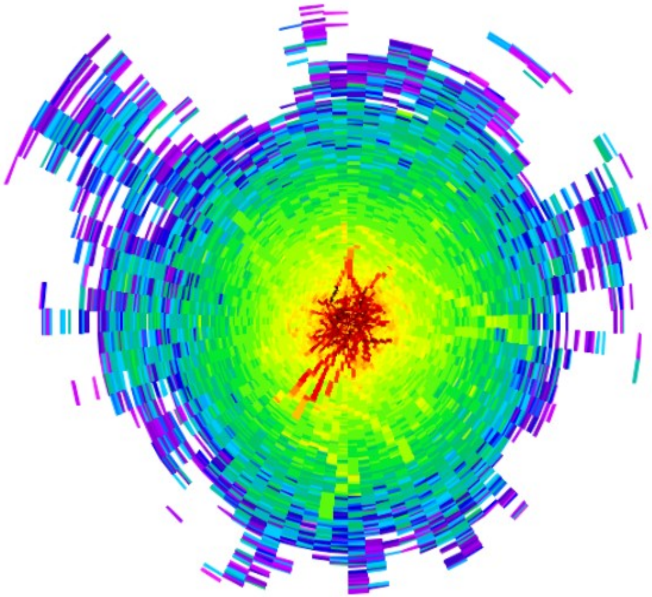
nuSTORM Collaboration Meeting
8 August 2021

Outline

- ENUBET and monitored meson-based beams (a recap)
- With nuSTORM: common goals, problems, opportunities



Directions for novel neutrino beams

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

- unstable nuclei → β-beams
- 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 + exotics
→ **nuSTORM**

Directions for novel neutrino beams

2) 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)

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

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

ENUBET / NP06

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

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**

→ **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

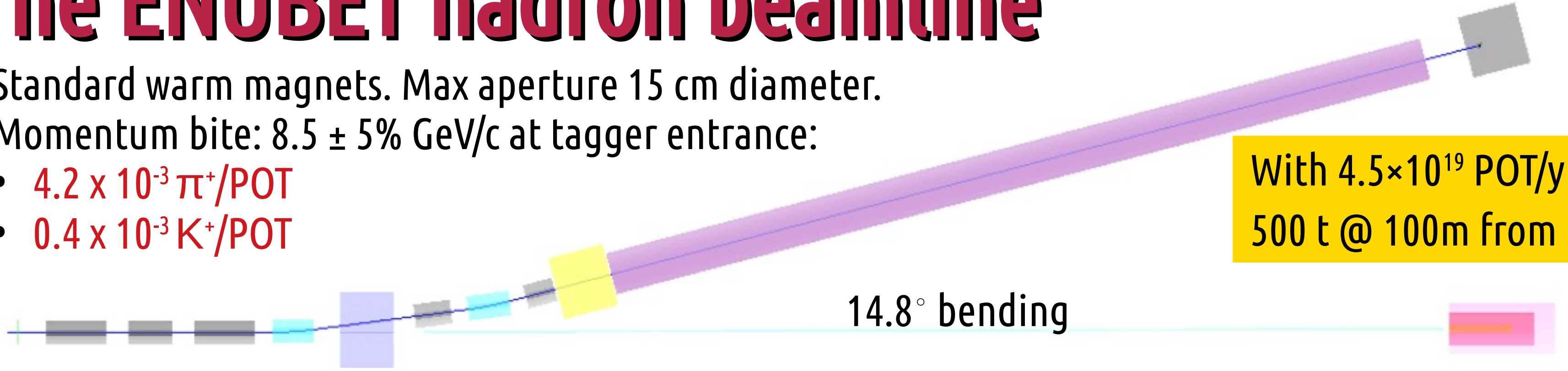
→ **"short", 40 m, tunnel** (~all ν_e from K, ~1% ν_e from muons)

pillars

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

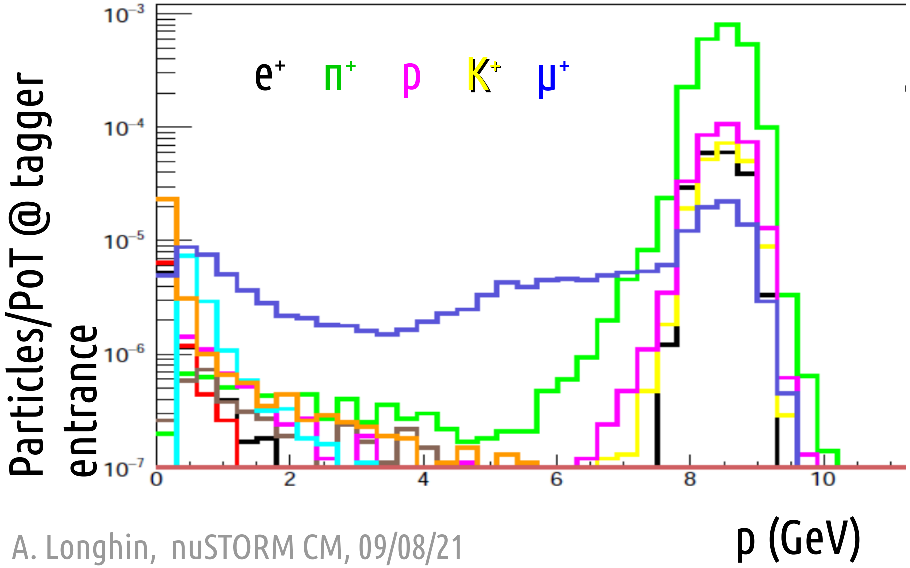
The ENUBET hadron beamline

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

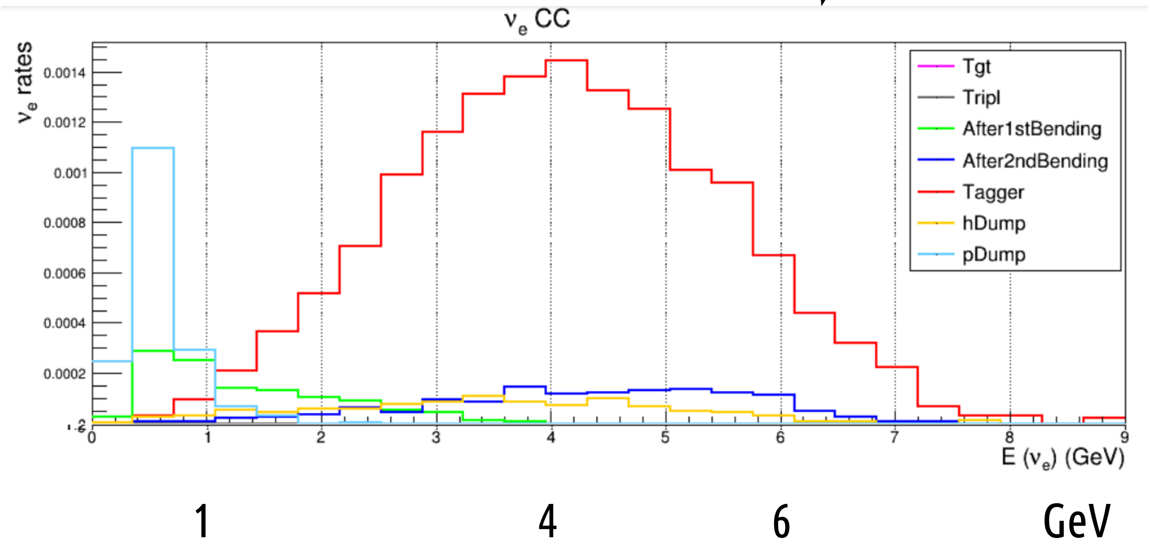


With 4.5×10^{19} POT/y → $10^4\ \nu_e^{CC}$ on 500 t @ 100m from target in ~ 2 y

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



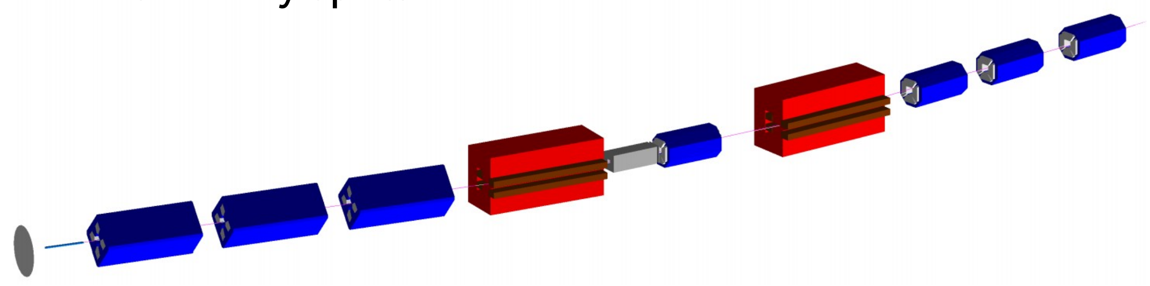
ν_e^{CC}



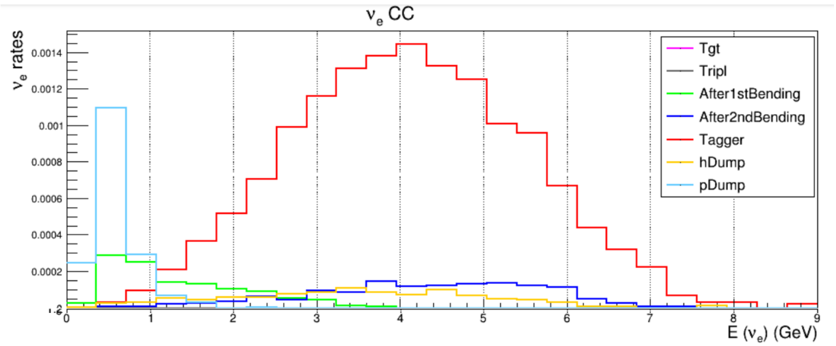
ENUBET multi-momentum transferline

- 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

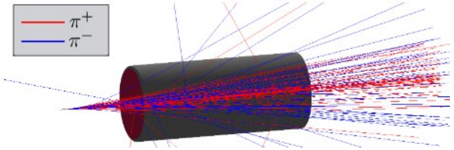


ν_e from **8.5** GeV/c secondaries (current baseline)

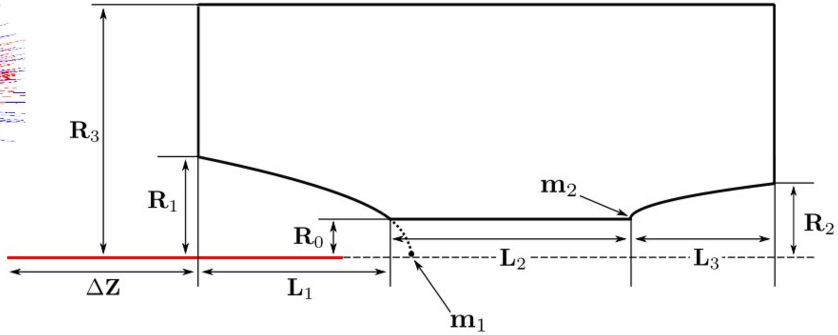


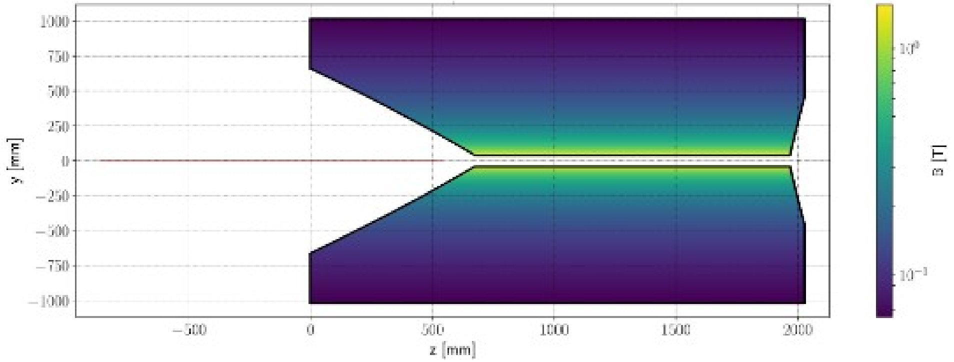
1 4 6 GeV

Horn optimization



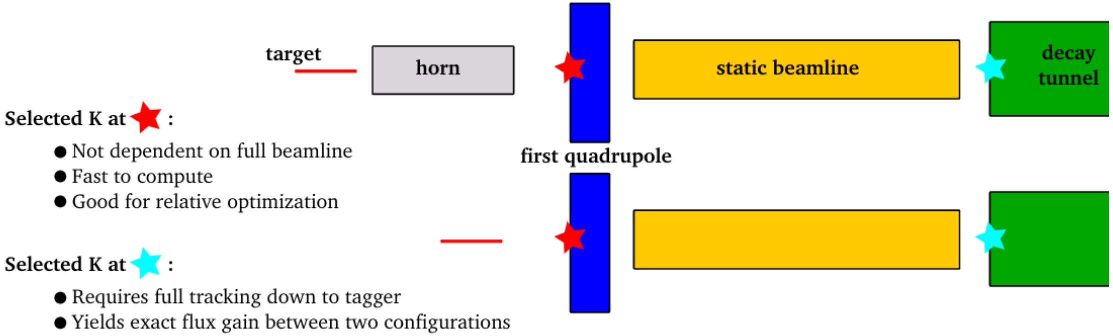
- New **double-parabolic** geometry (formerly MiniBooNE-like)
- New **genetic algorithm** implemented successfully to sample the large space of parameters.
- FoM is ~ number of collimated K^+ with p ~8.5 GeV/c
- Convergence in O(100) iterations
- First candidate designs worked out





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.

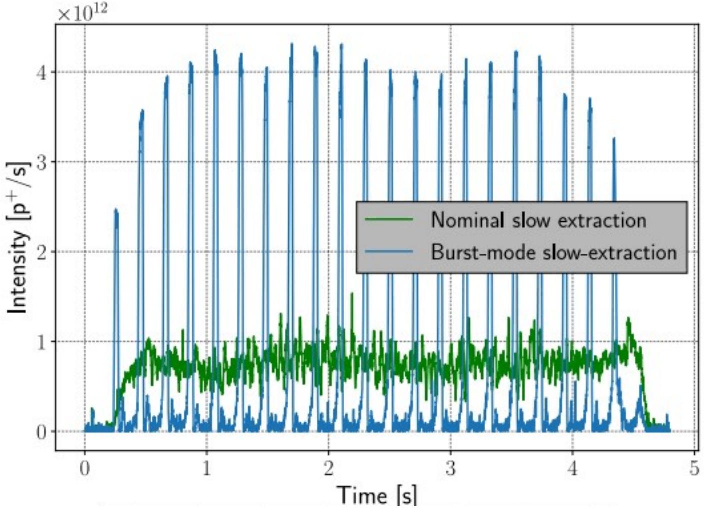


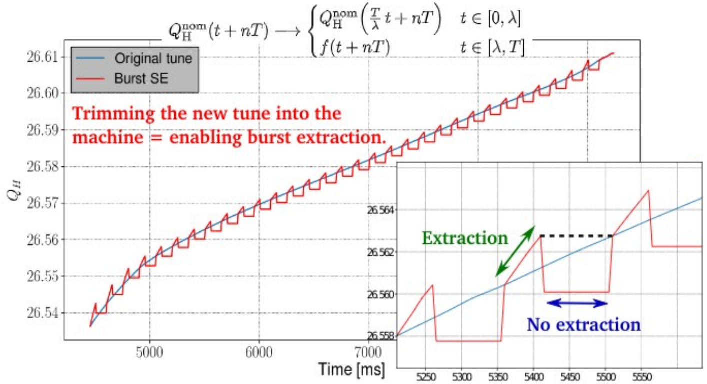
Can extend the same systematic optimization tool.

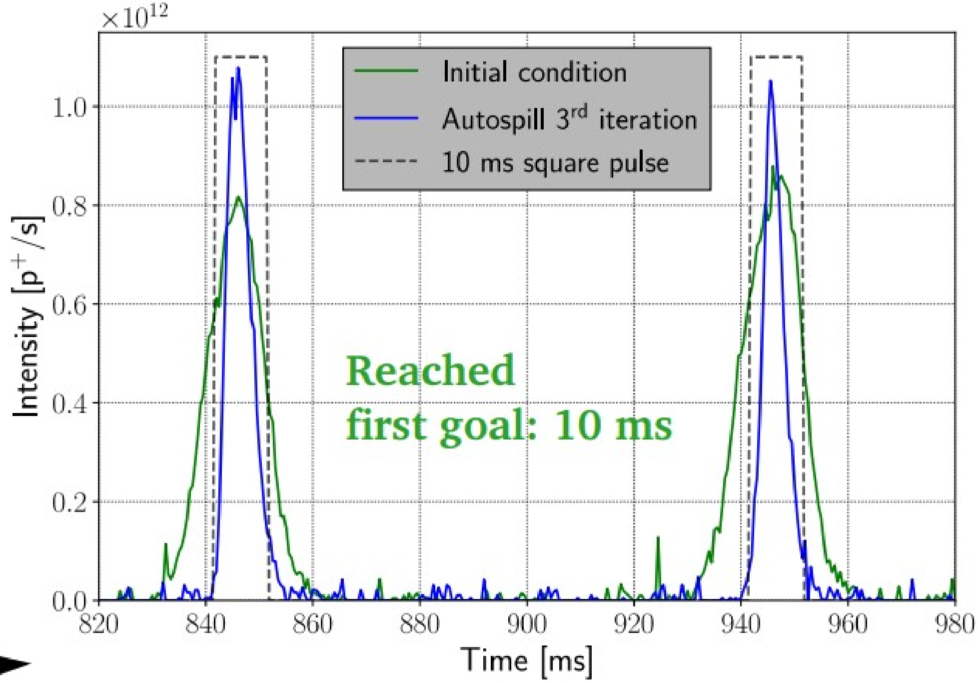
Proton extraction R&D for horn focusing

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

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







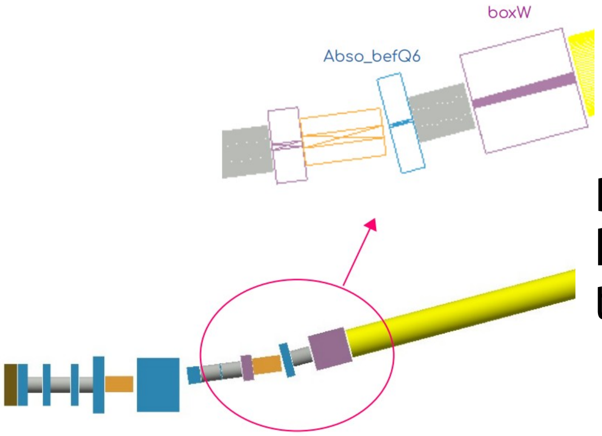
PhD thesis of M. Pari (UniPD + CERN doctoral). Defended 23/2/21.

Beamline optimization with genetic algorithm

Recent!

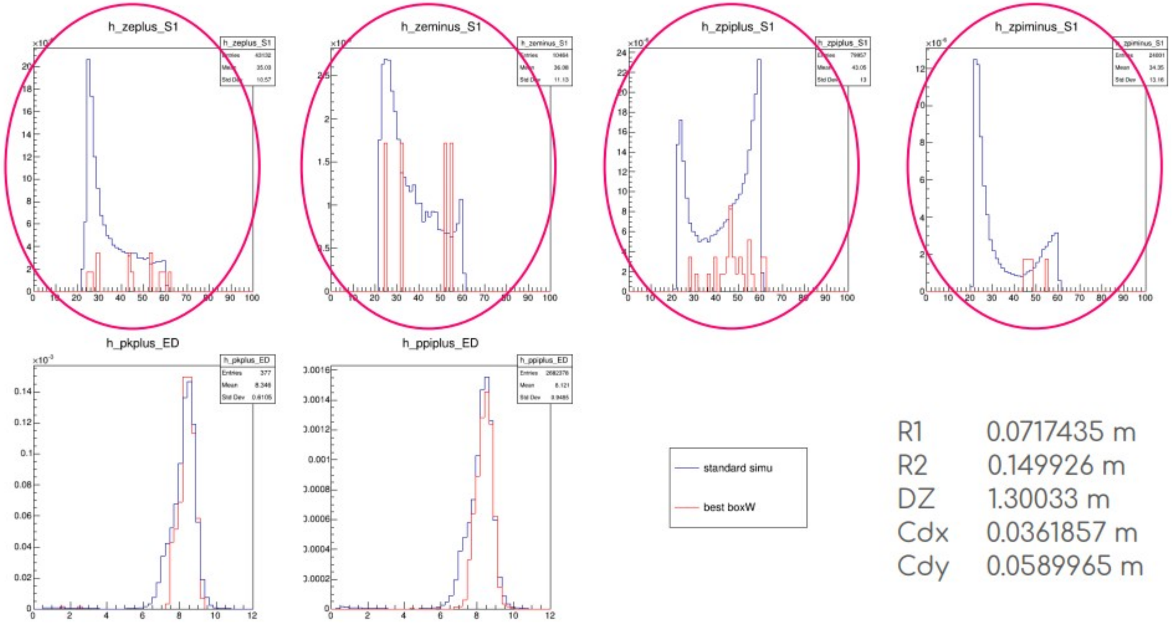
Figure Of Merit $= -\left(\pi^{+}_{TAG} + \pi^{-}_{TAG} + e^{+}_{TAG} + e^{-}_{TAG} \right) / K^{+}_{tag\ entrance}$

80 iterations: best FOM = -0.129973



Background hitting the target →

Entering π^+/K^+ →

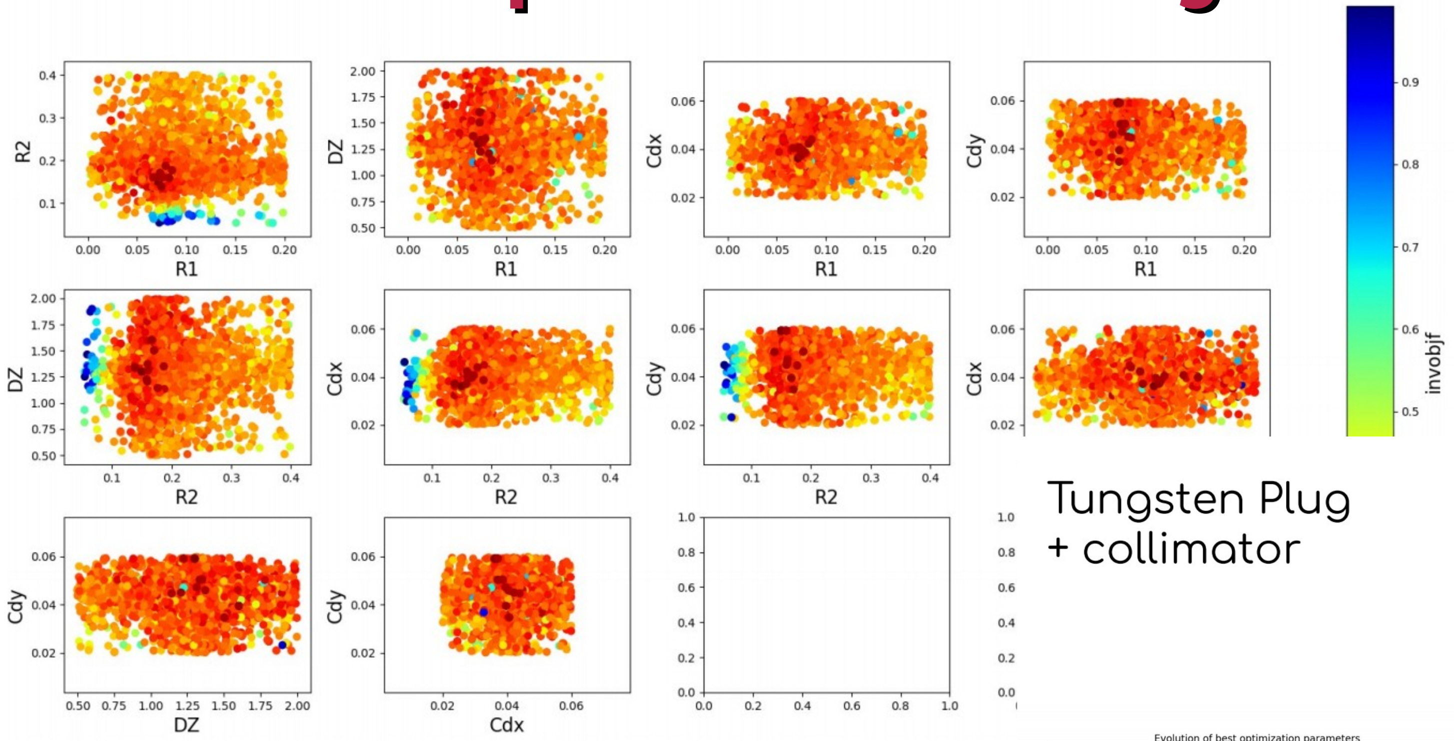


R1	0.0717435 m
R2	0.149926 m
DZ	1.30033 m
Cdx	0.0361857 m
Cdy	0.0589965 m

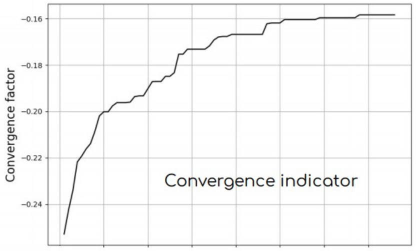
Blue = no W plug/collimator
Red = optimal configuration after 80 iterations

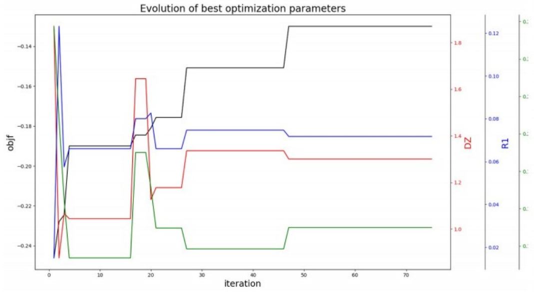
A high statistics run with this configuration is ongoing

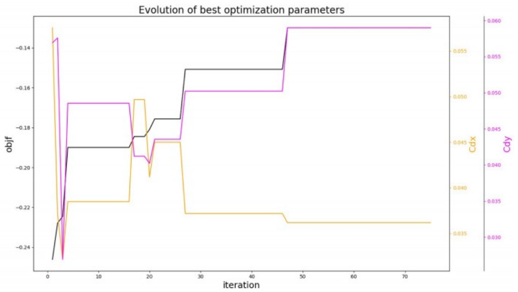
Beamline optimization with genetic algorithm



Tungsten Plug
+ collimator







The lepton tagger

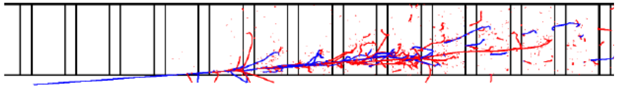
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

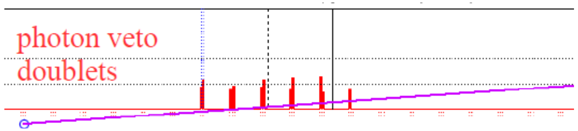
→ $e^+/\pi^\pm/\mu$ separation

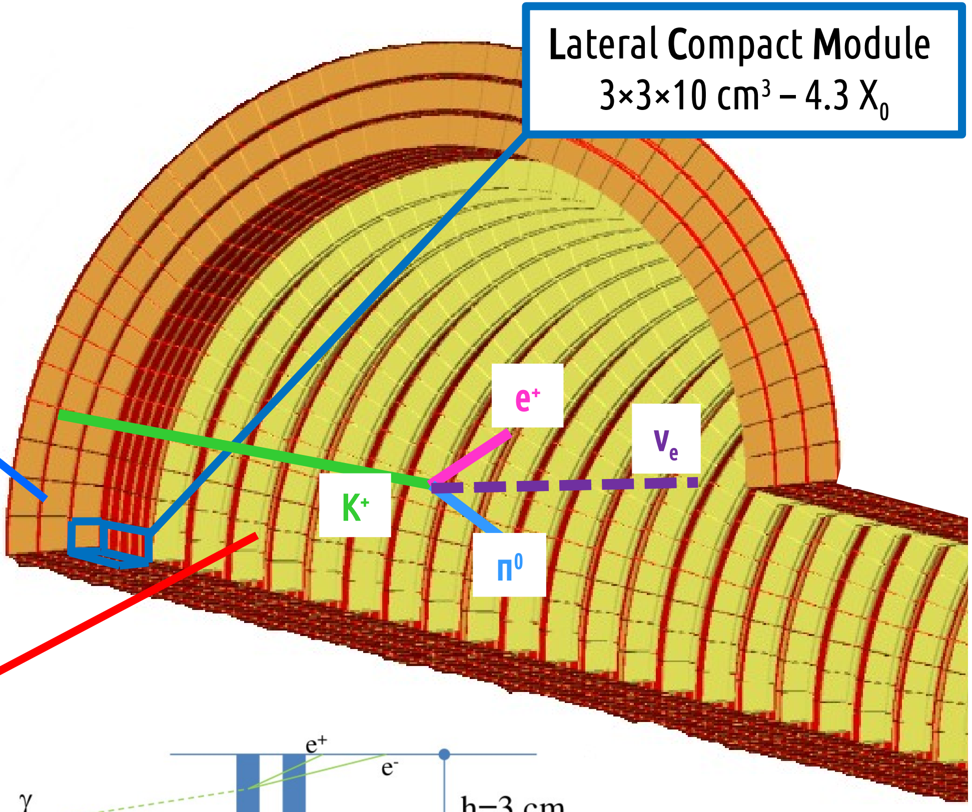


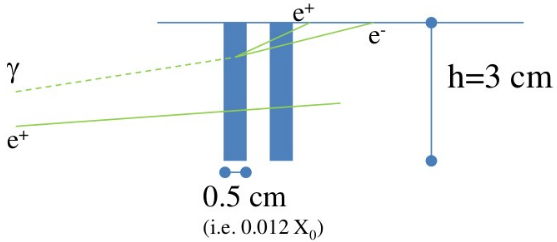
Integrated photon veto

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

→ π^0 rejection







e^+ (signal) topology

π^0 (background) topology

π^+ (background) topology

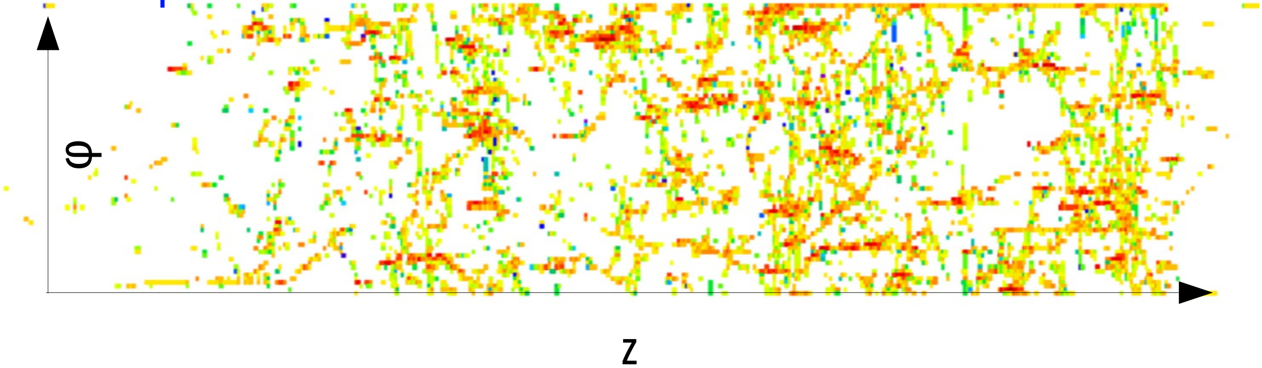
ENUBET: ν_e constraint from K_{e3} e^+ reconstruction

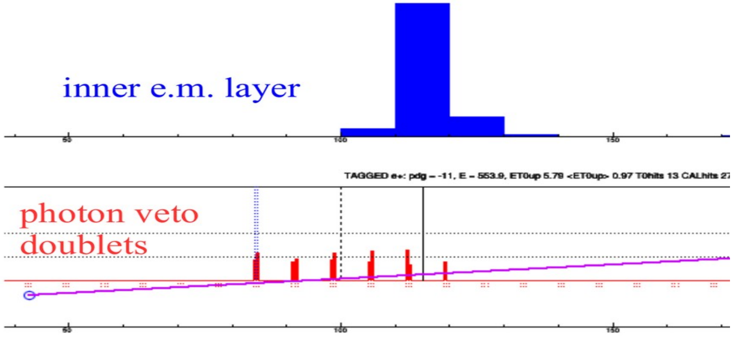
The K_{e3} branching ratio is ~5 % and kaons are about 5-10% of the incoming hadron beam.

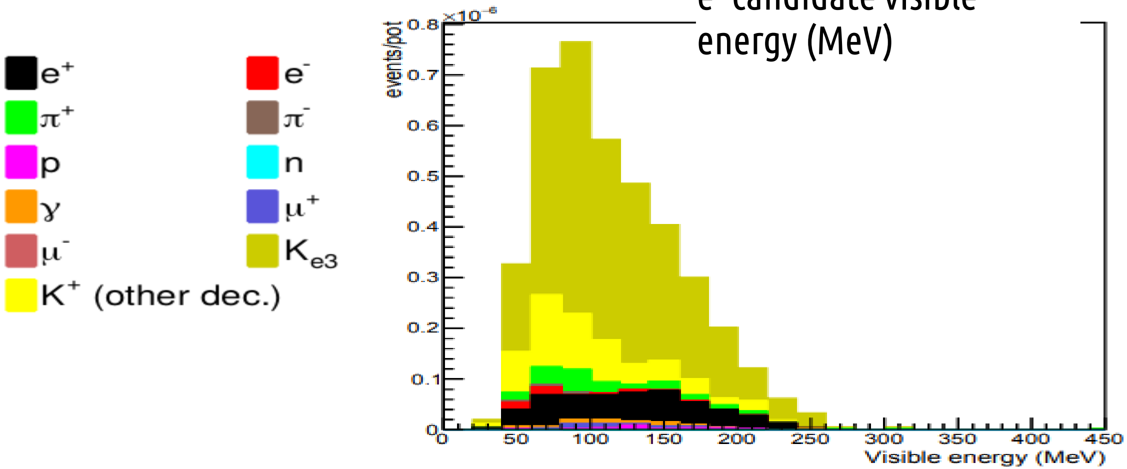
GEANT4 simulation of the detector, validated by prototype tests at CERN in 2016-2018.

Clustering of cells in space and time. Treat **pile-up** with waveform analysis. Multivariate analysis.

Hit map for e^+







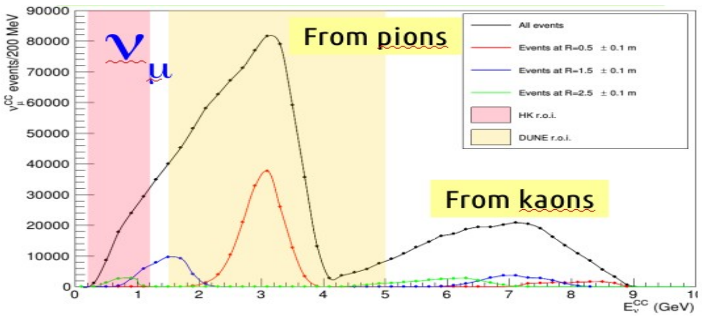
K_{e3} positron selection:

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

Half of efficiency loss is geometrical

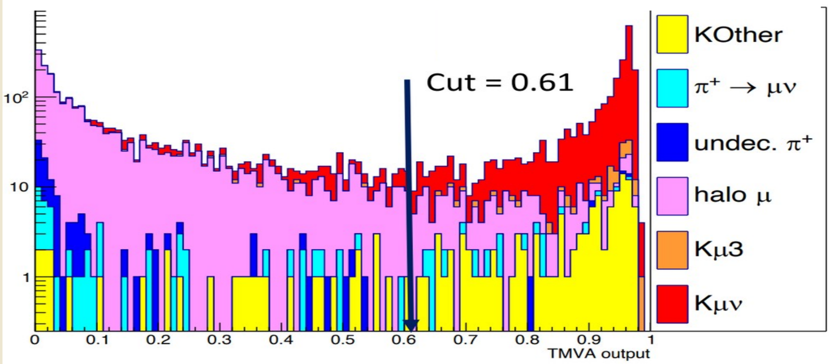
F. Pupilli et al., PoS NEUTEL2017 (2018) 078

ENUBET: ν_μ constraints



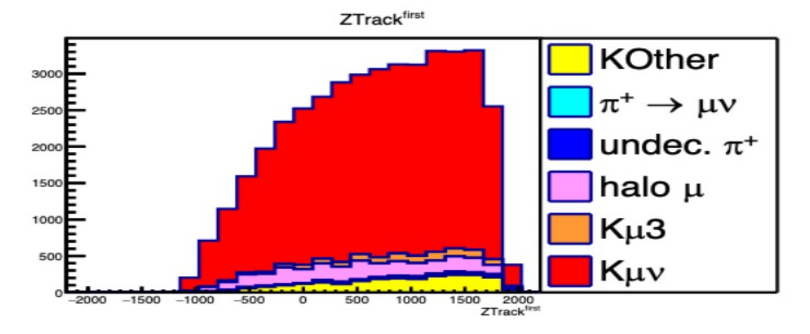
Constrain high-E ν_μ from ($K^+ \rightarrow \mu^+ \nu_\mu$ and $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$)

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



Muon reconstructed candidates

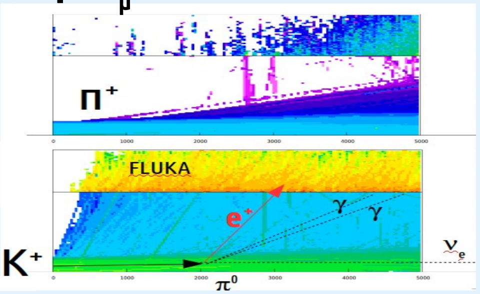
efficiency 34% ($K_{\mu2}$) and 21% ($K_{\mu3}$) S/B ~ 6.1

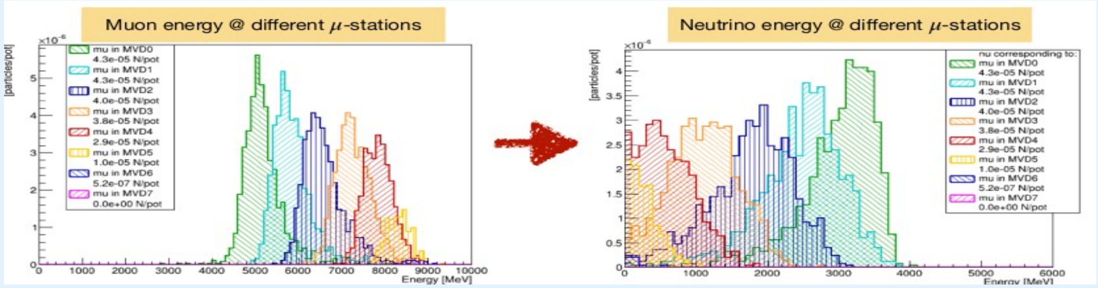


Position along the tunnel

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

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





ENUBET: flux constraint

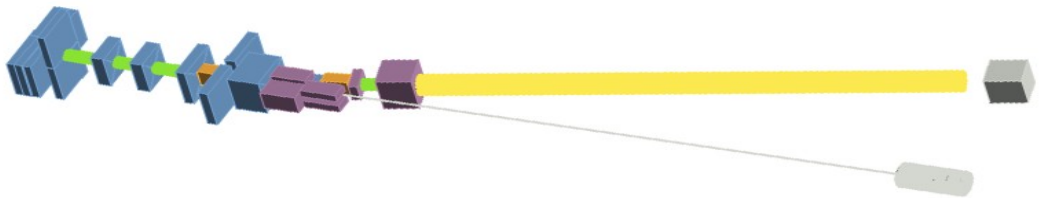
Not directly taggable components:

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

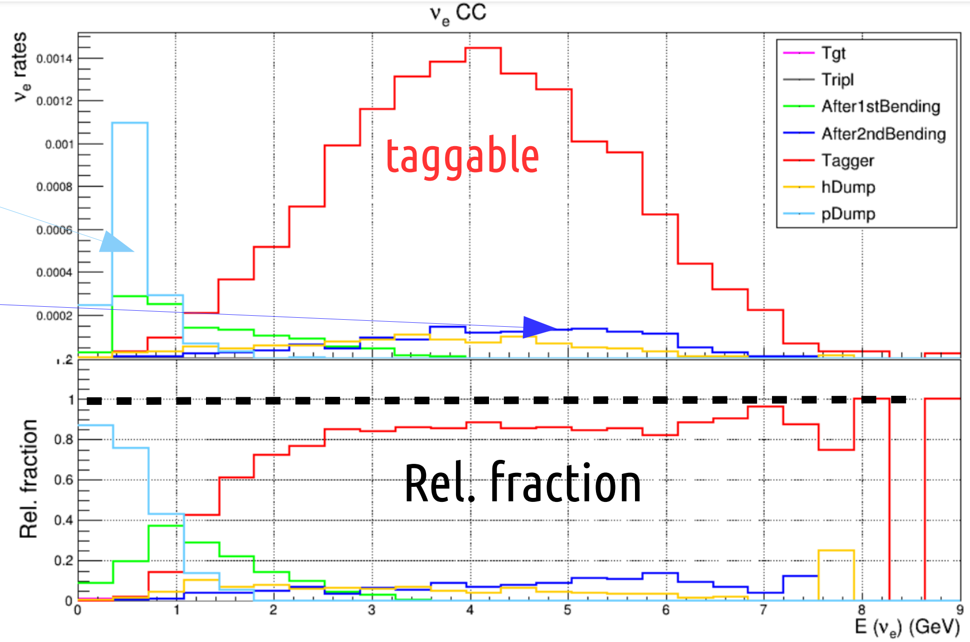
→ reduce by tuning the dump geometry/location

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

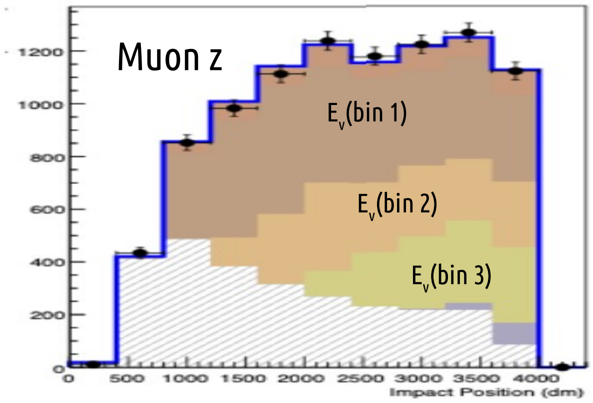


Uncertainty reduction for the tagged flux component

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



Tagged neutrino beams

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

→ time coincidences of ν_e and e^+

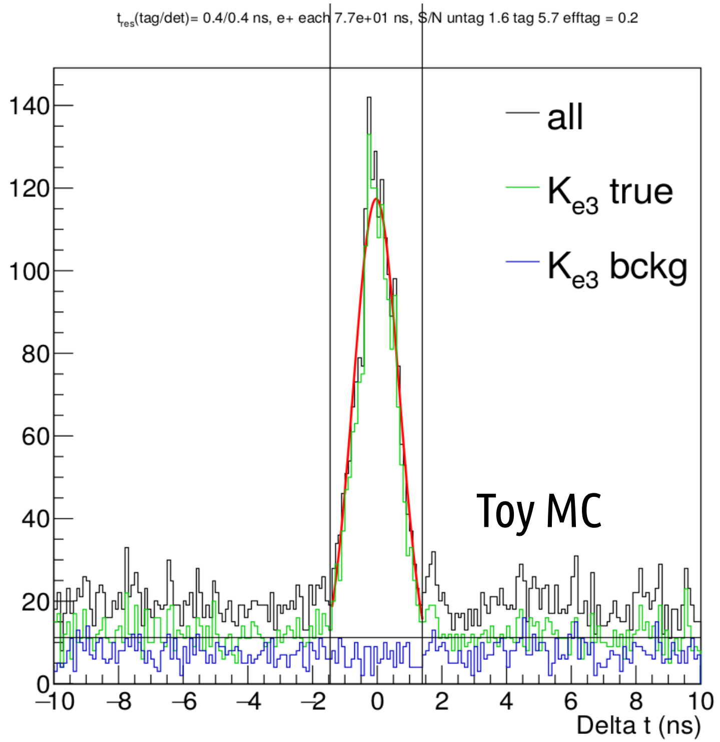
Example with reconstructed e^+
2.5×10^{13} pot / 2s with 20% eff. S/N 1.6

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

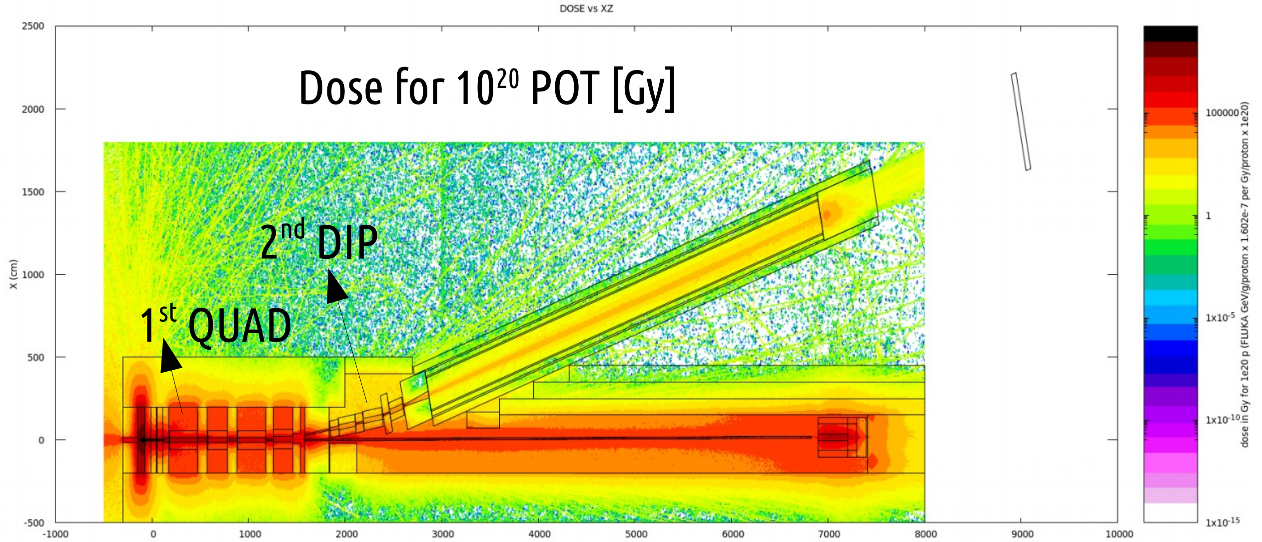


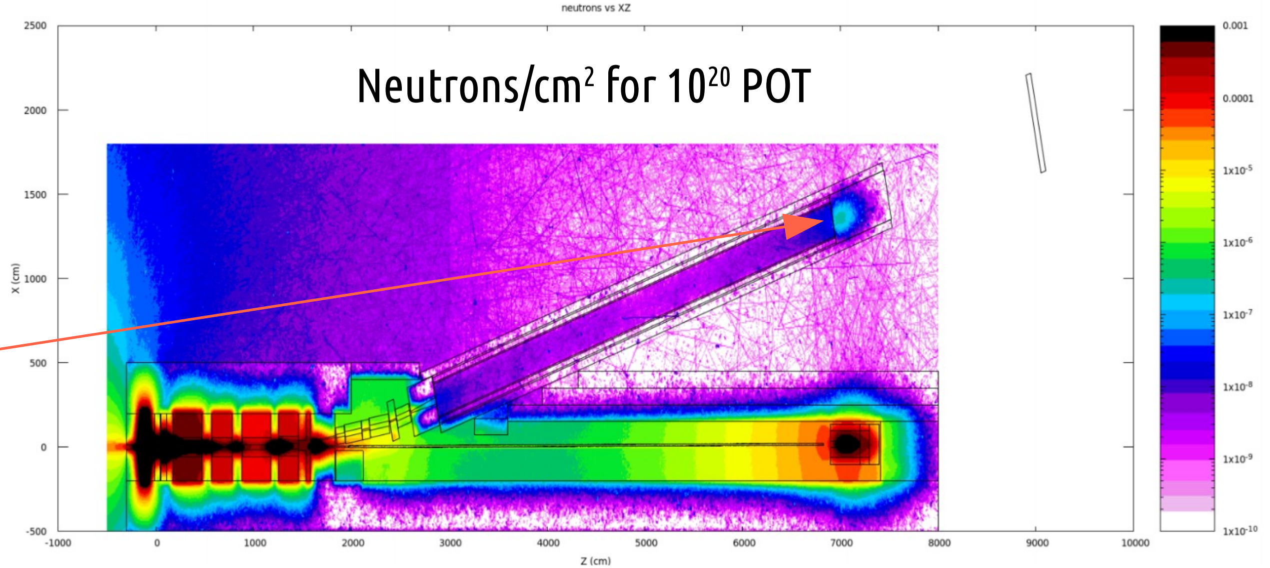
ENUBET: irradiation studies

Ensure lifetime of instrumentation and focusing elements.

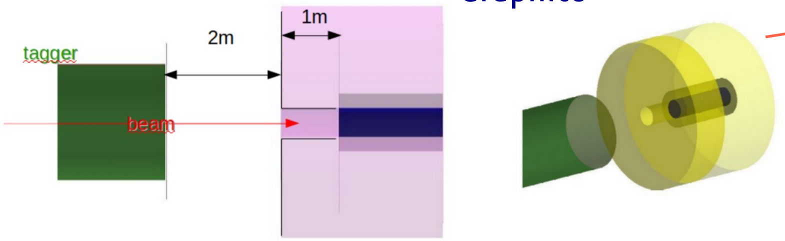
The dose at the hottest point of the quadrupole closest to the target is of about 100-300 kGy.

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

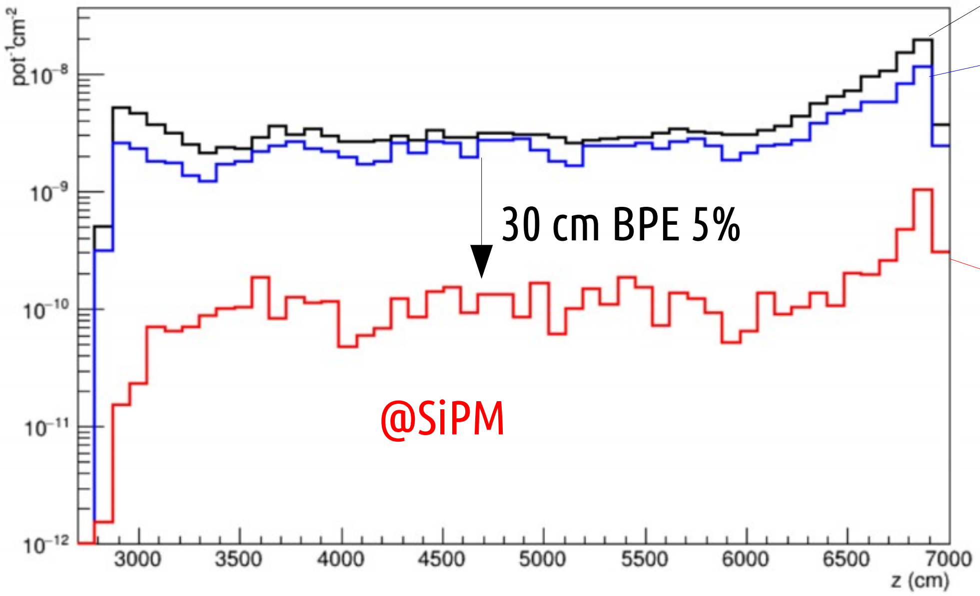


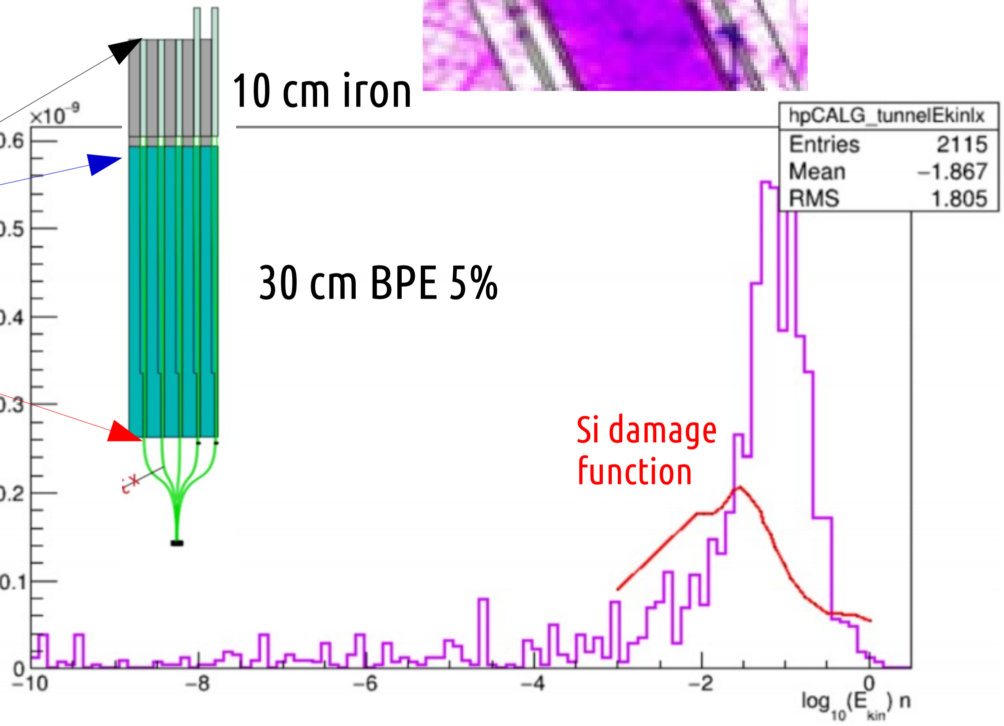


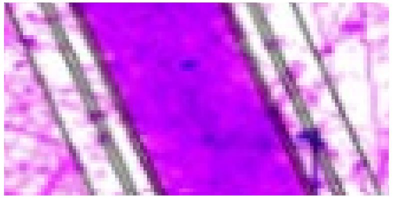
Borated concrete
Iron
Graphite



Neutrons in the tagger







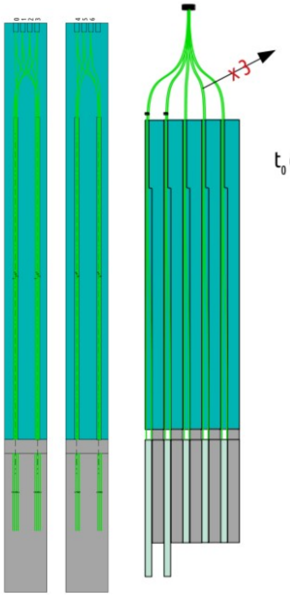
BPE shielding has a **reduction effect ~ x 20**
W.r.t. to the single dipole beamline
7×10^{-11} n/POT/cm^2 **~ 10 x reduction**
(7×10^{9} n/cm^2 for 10^{20} POT)

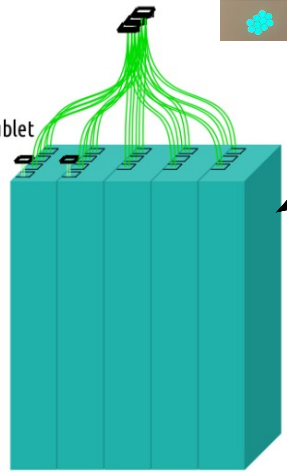
E_{kin} of surviving neutrons is O(10-100) MeV

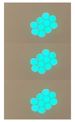
Towards the demonstrator

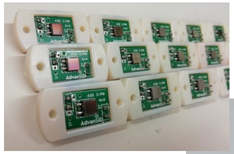
Custom digitizers
@ 500 MS/s

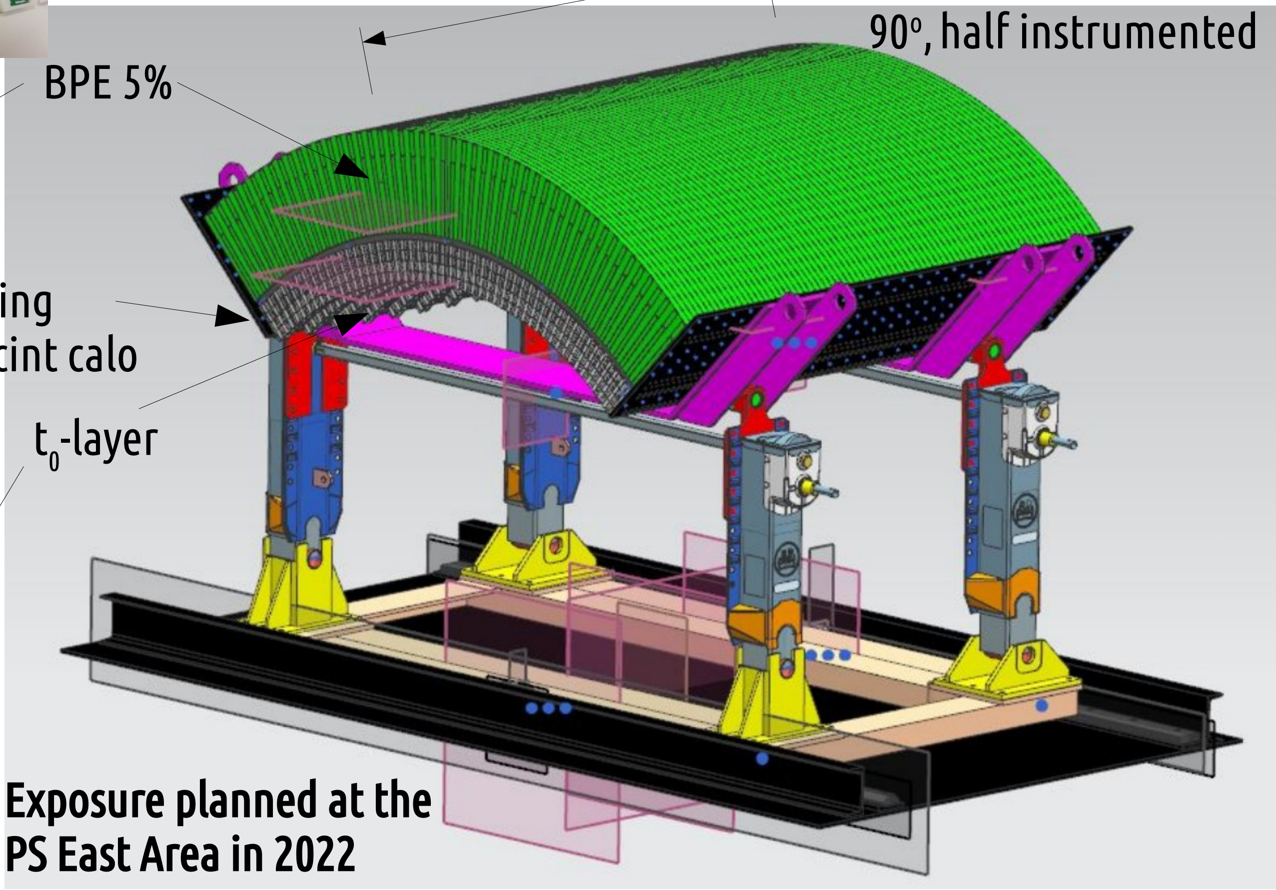
WLS routing











Sampling
iron/scint calo

t_0-layer

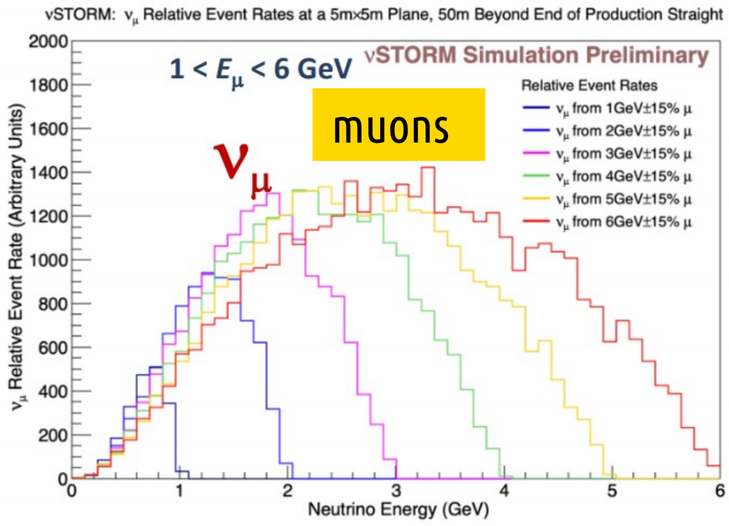
Fluxes decomposition

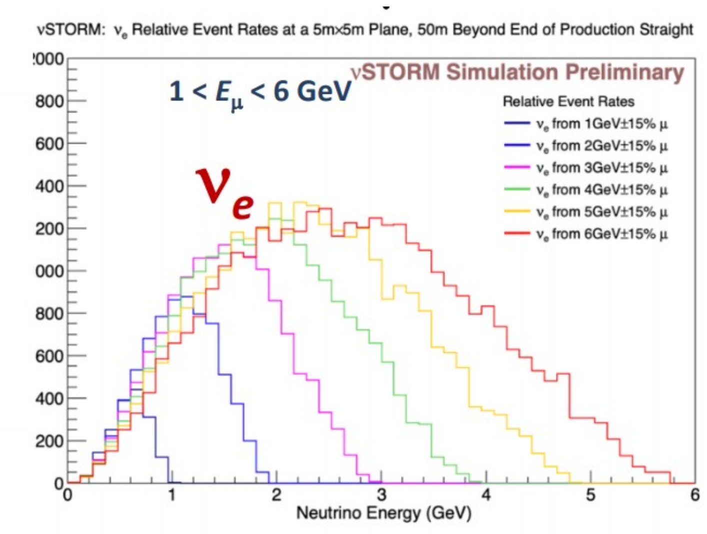
nuSTORM: vary the channeled muon energy from 1 to 6 GeV/c

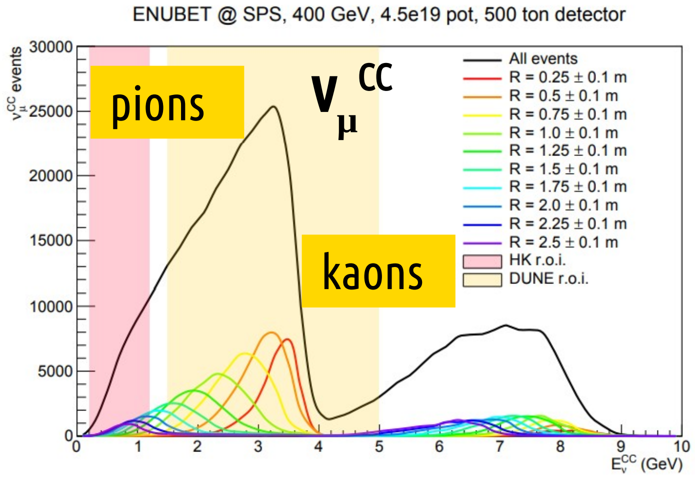
ENUBET narrow-band off-axis technique:

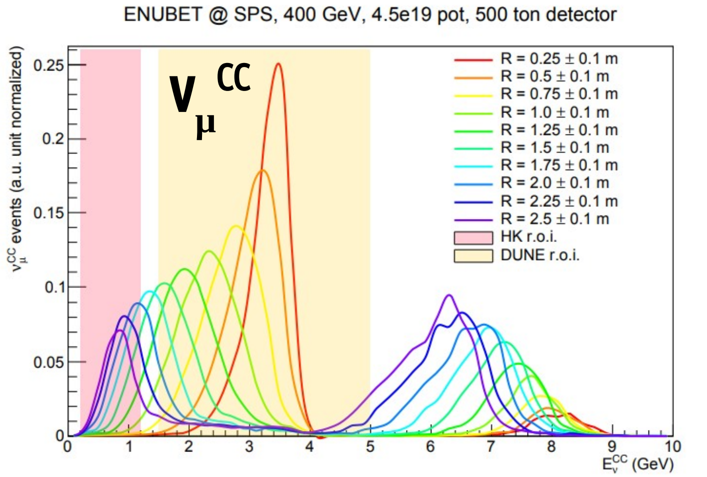
Bins in the **radial distance from the center of the beam → single-out well separated neutrino energy spectra** → strong prior for **energy unfolding**, independent from the reconstruction of interaction products in the neutrino detector. “Easy” rec. variable.

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







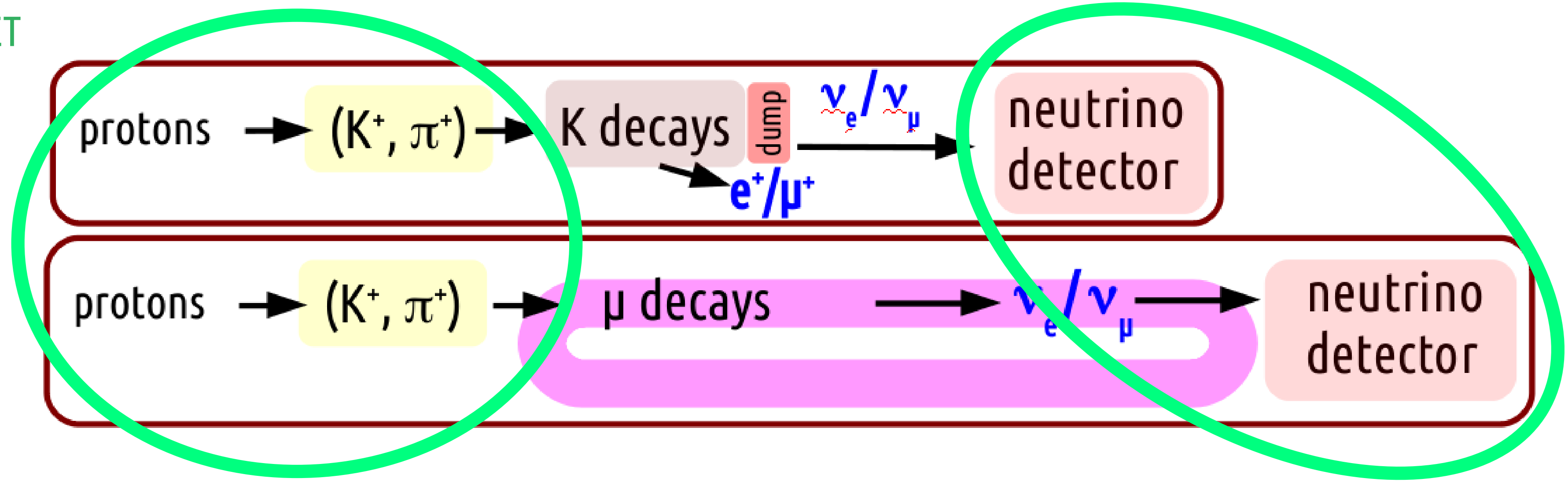


Opportunities

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. 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)**

ENUBET



Similar goals (high precision neutrino fluxes) → strengthen the physics case, involve the larger community.
Common points in the technique → natural/mandatory to look into possible common infrastructures to reduce the costs.
Sharing even only civil engineering would hugely benefit both projects.
Not straightforward though (devil in the details) → joint work, sharing of results, experience, tools.

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.

Brainstorming inputs

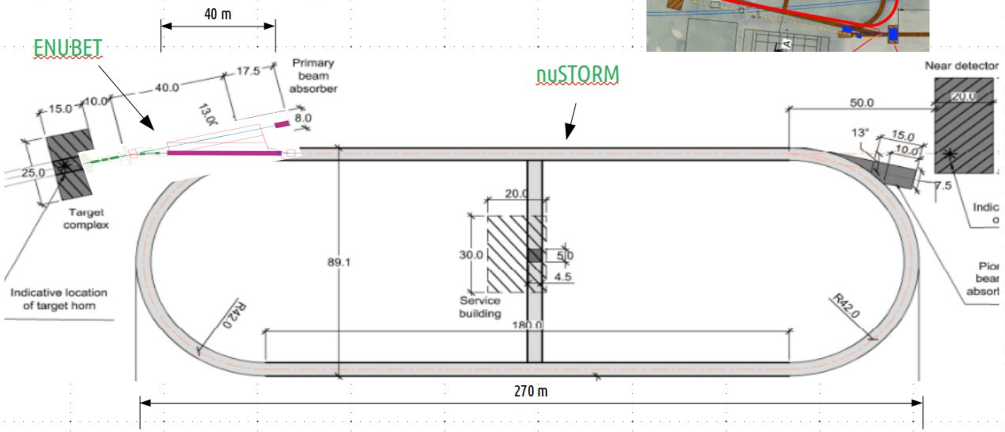
Option1 ("serial"): ENUBET is smaller, less challenging from the point of view of accelerator physics (key is really background reduction keeping a large statistical sample) → it could be sensible to think about using the same target+meson transfer line, feed the beam into an instrumented decay tunnel and in a second phase into the straight line of the muon storage ring. Key study: 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 ? (ENUBET beam is about 5 cm in diameter and has a maximal divergence of ~ 1/40).

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? How flexible are we in respect to using the same proton energy? Which one should it be ? With ENUBET we have shown that at the 400 GeV SPS we could get 10000 neCC in ~2 years with a 500 t detector at 100 m from the target. Large reduction in yields at the PS should be compensated by a lot more protons (→)

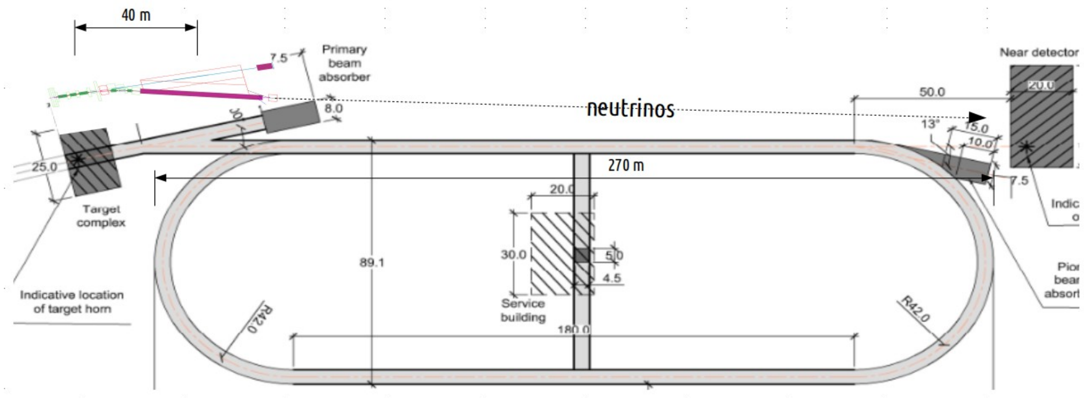
Neutrino detector → an optimal design could be perfectly good for both projects. The most significant difference is in the position (close for ENUBET, after the straight section for nuSTORM). Conceive a detector that could be "easily" replaced? Double detector ?

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.



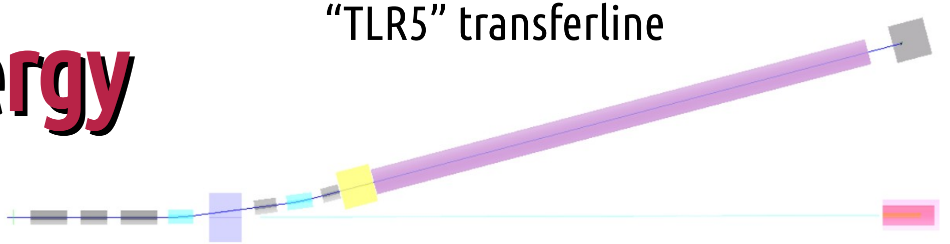
Splitting of proton beamlines + two targets, same detector ?
Less cost effective, more degrees of freedom/parallelization



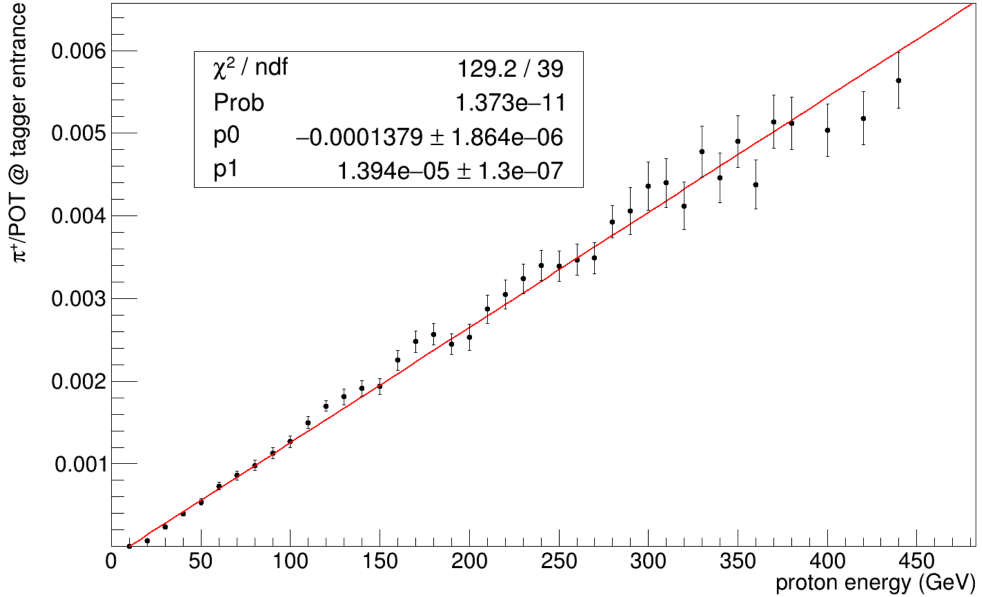
"Flexibility" with proton energy

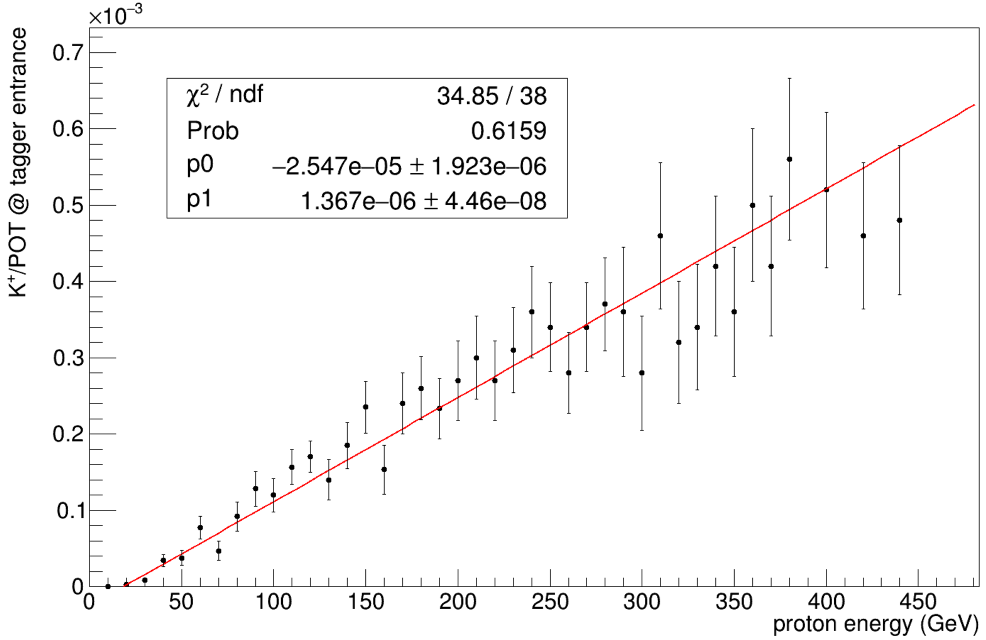
Brutal exercise: how many π^+/K^+ do reach the entrance of the lepton tagger varying the proton energy from 0 to 400 GeV/c keeping the same optics and target? Estimated with FLUKA target simulation (fixed geometry, 70 cm rod of graphite, 6 cm diameter) + full geant4 simulation of the beamline. 8.5 GeV/c mesons rates → directly reflects into ν fluxes. →

"TLR5" transferline



Factor ~ 25 less pions/proton (50 for kaons) passing from 400 to 28 GeV/c (400/28 = 14). How much can we gain with more protons and a dedicated design of a low-energy beamline ?





Conclusions

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

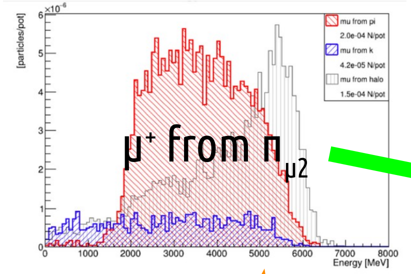
ENUBET: a **narrow band neutrino beam at the GeV** scale to measure at O(1%) the flux, flavor and (at 10%) the energy using **lepton-neutrino correlations**.

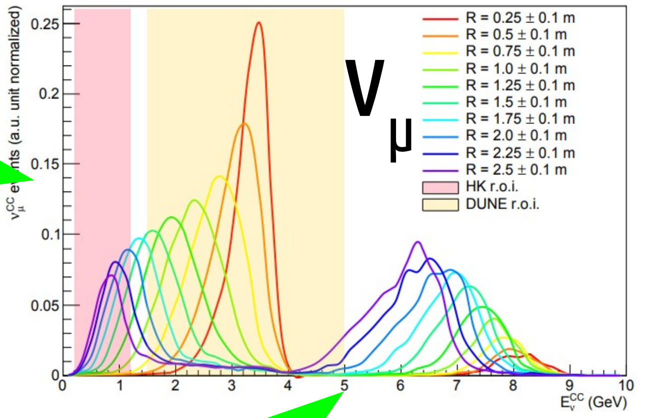
Let's try to work together to confirm/disprove(?) possible common opportunities in a quantitative and convincing way! → joint session at nuFact perfect occasion for visibility and to trigger the process.

Lepton monitoring

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

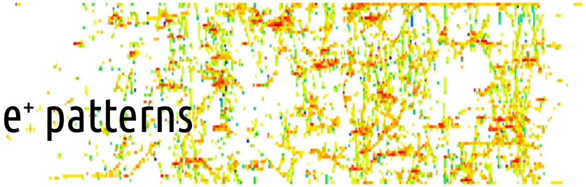
Hadron dump instr: μ from π (low-E ν_μ)

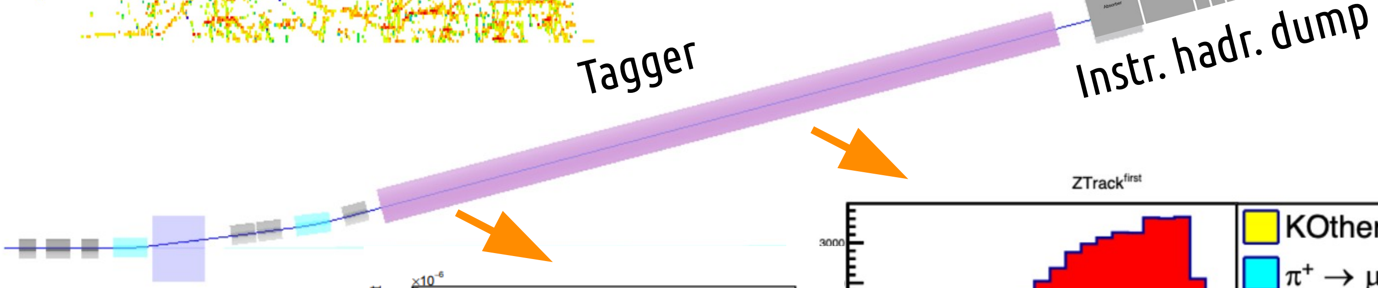


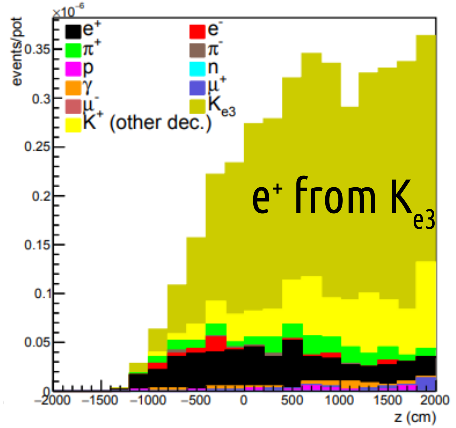


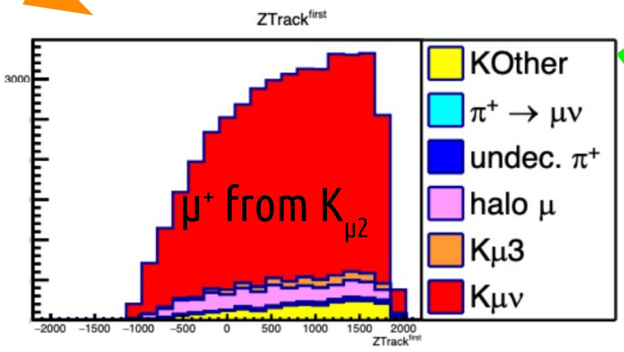
ν_μ

e+ patterns

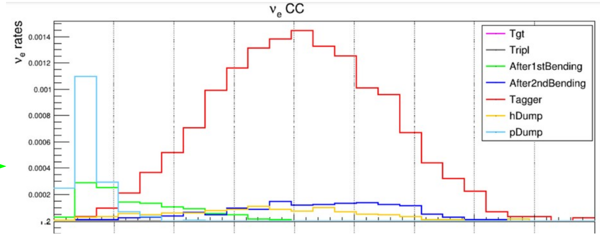




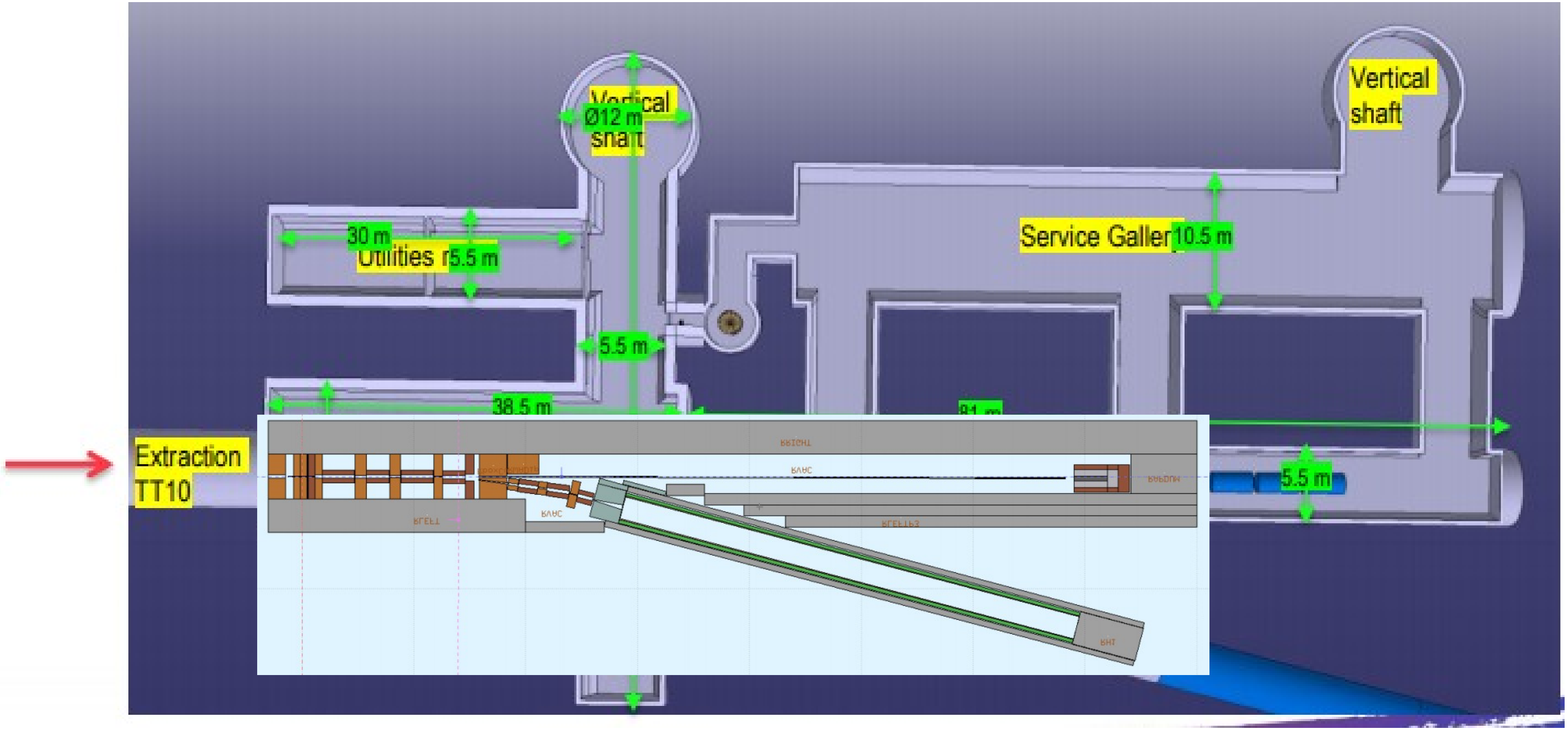




ν_e



ENUBET at CERN-PS ?



Power needed to compensate

Instantaneous power:

power[MW] = 1.6e-16 [pot/s] x E[GeV]

Assuming 2.25e13 pot/s

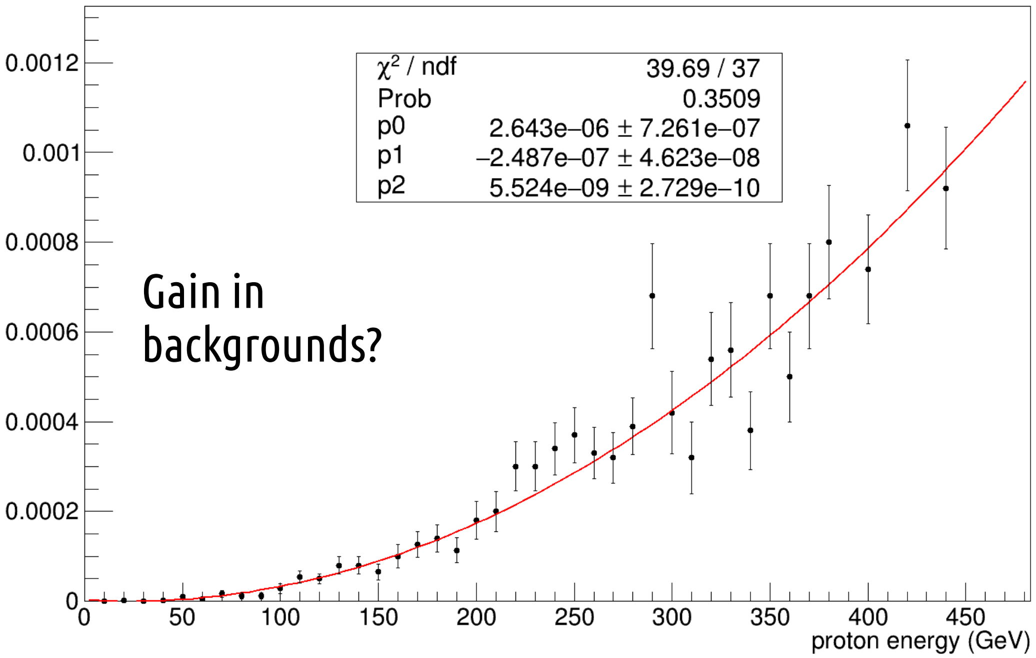
@400 GeV → 1.44 MW
@28 GeV → 100 kW

80 kW @ 28 GeV = **1.8e13 pot/ s**
80 kW = 8e4 J/s
28 GeV = 2.8e10 eV = 2.8e10 x 1.6e-19 J = 4.48e-9 J
Power = 4.48e-9 J x pot/s
pot/s = (8e4 J/s) /(4.48e-9 J) = **1.8e13 pot/s**

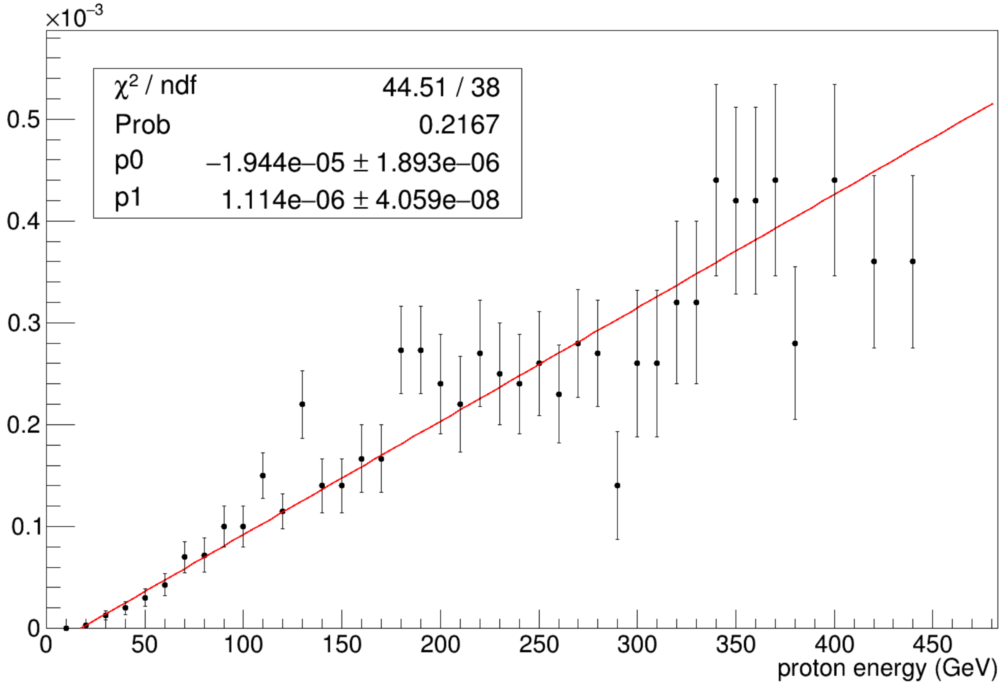
To compensate a factor 50 → 5 MW beam at 28 GeV

e^+, mu^+ yields per proton

e^+ at tagger entrance / pot



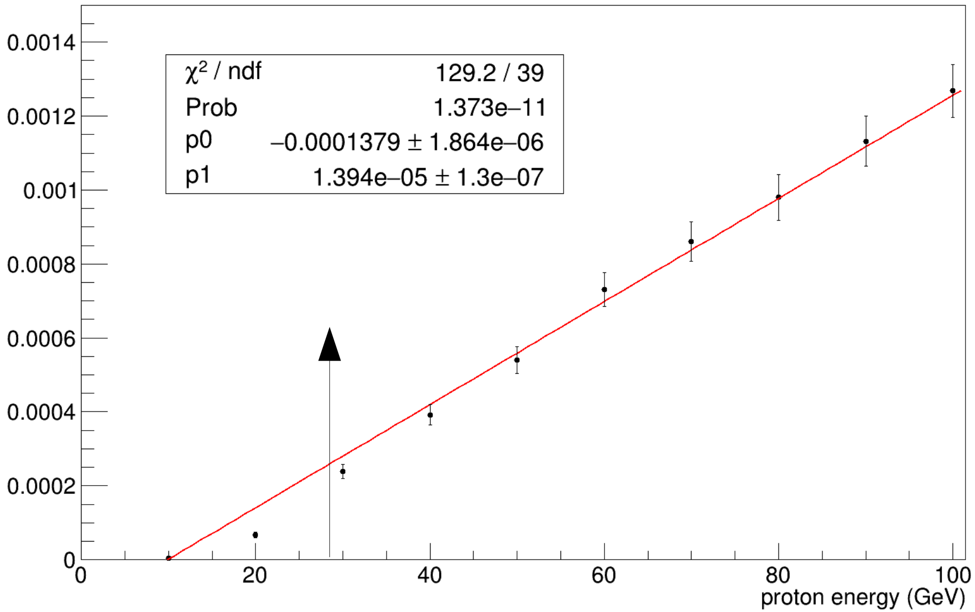
mu^+ at tagger entrance / pot

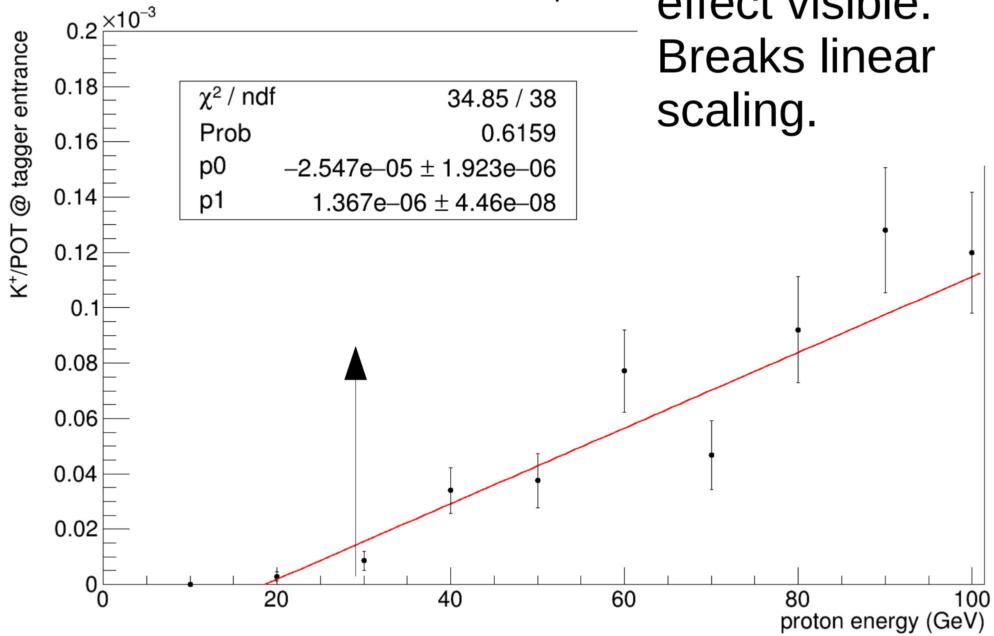


K+, pi+ yields per proton (0-100 GeV/c)

Red line is a global linear fit

Some threshold effect visible. Breaks linear scaling.





@28 GeV → ~ 2e-4 pi+/pot ~ 1e-5

@400 GeV → ~ 50e-4 pi+/pot ~ 50e-5 K+/pot

Per proton we have a factor ~ 25 less pions and 50 less kaons passing from 400 to 28 GeV/c (400/28 = 14)

Older results

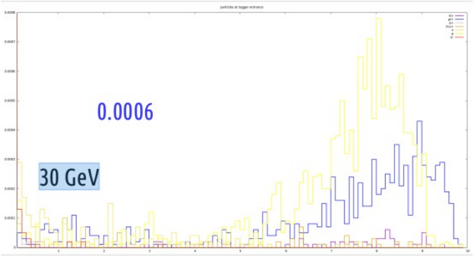
particles at tagger entrance

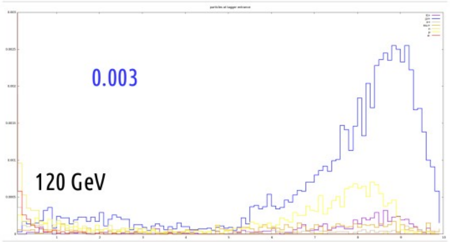
5 cm W electron filter

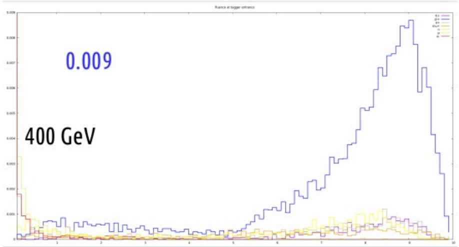
(10^5 pot, half for 400 GeV)

Old beamline 1 dipole (x14 less pions)

e^+
π^+
p







Static TL with 2 Dipoles - Numbers

- **Protons on Target: 450, 400, 120, 30 GeV, G4beamline** run with Fluka Target File with **ONLY π/K, Configuration**: Triplet + Bending + Quad → Tunnel

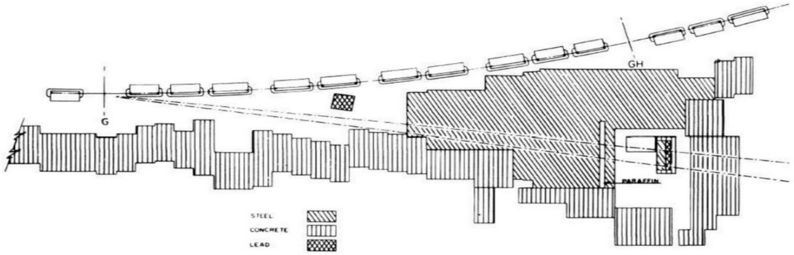
	π+				K+			
Configuration Reference Design [EPJ C75 (2015) 155]	**@ Tunnel Entrance (6.5 – 10.5 GeV) [10-3] /POT**		**Factor w.r.t. ENUBET Reference Design [EPJ C75 (2015) 155]** HORN	STATIC	**@ Tunnel Entrance (6.5 – 10.5 GeV) [10-3] /POT**		**Factor w.r.t. ENUBET Reference Design [EPJ C75 (2015) 155]** HORN	STATIC
HORN εxx' & εyy' = 0.15, 85% eff, 20% mom bite	450	**33.5**			450	**3.73**		
	120	**16.6**			120	**1.69**		
	30	**4.0**			30	**0.39**		
STATIC 80μSr, 20% mom bite	450	**3.65**			450	**0.43**		
	120	**1.25**			120	**0.16**		
	30	**0.24**			30	**0.027**		
POT En (GeV)		**in/out Tunnel**				**in/out Tunnel**		
450	**29.9**	90.5%	1.1 (-)	8.2 (+)	**2.3**	52.1%	1.6 (-)	5.3 (+)
400	**28.6**	90.2%	1.2 (-)	7.8 (+)	**1.9**	51.1%	2.0 (-)	4.4 (+)
120	**10.8**	90.5%	1.5 (-)	8.6 (+)	**0.8**	48.7%	2.1 (-)	5.0 (+)
30	**1.9**	89.1%	2.1 (-)	7.9 (+)	**0.13**	43.6%	3.0 (-)	4.8 (-)

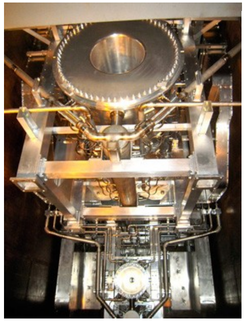
- **Protons on Target: 450 GeV, G4beamline** run with Fluka Target File with **ONLY π/K, Configuration**: Triplet + Bending1 + Bending2 → Tunnel

POT En (GeV)		**in/out Tunnel**				**in/out Tunnel**		
450	**34.1**	**98.3%**	**1.02 (+)**	**9.3 (+)**	**3.9**	**64.9%**	**1.05 (+)**	**9.1 (+)**

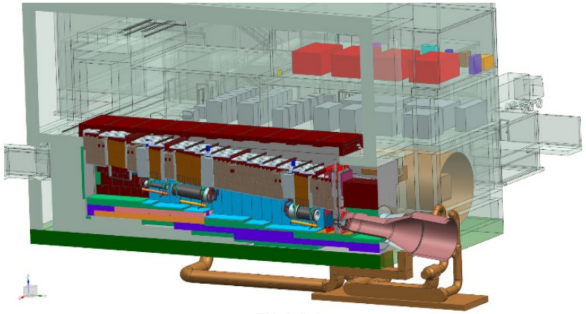
18/01/2018 G. Brunetti 22

Accelerator based neutrino beams





J-PARC



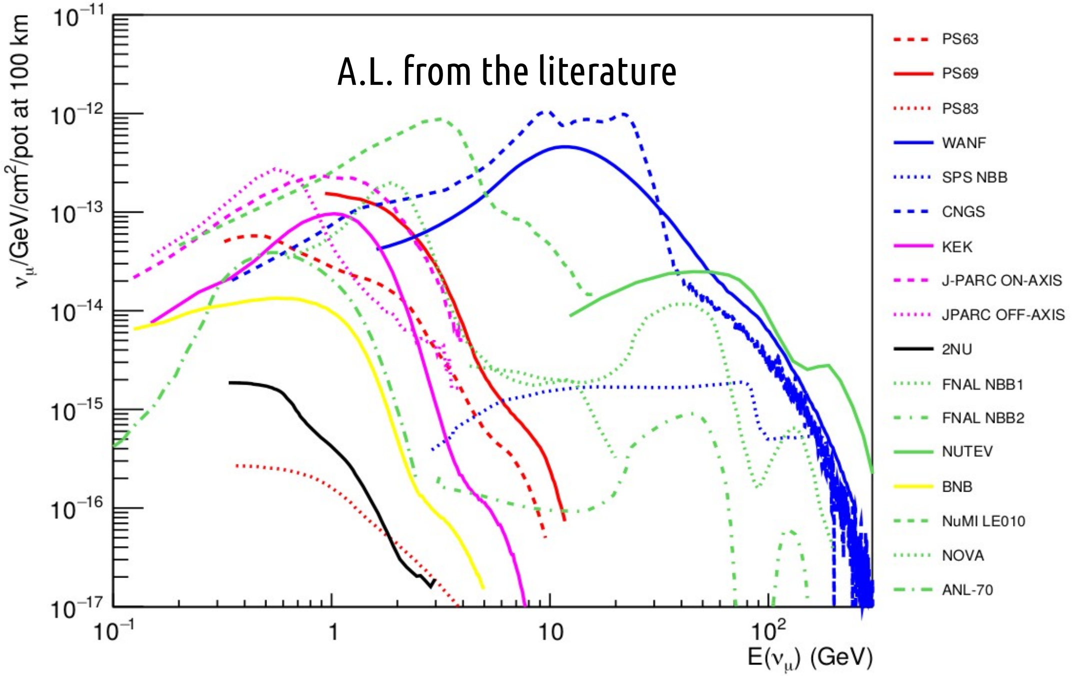
FNAL

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 ...

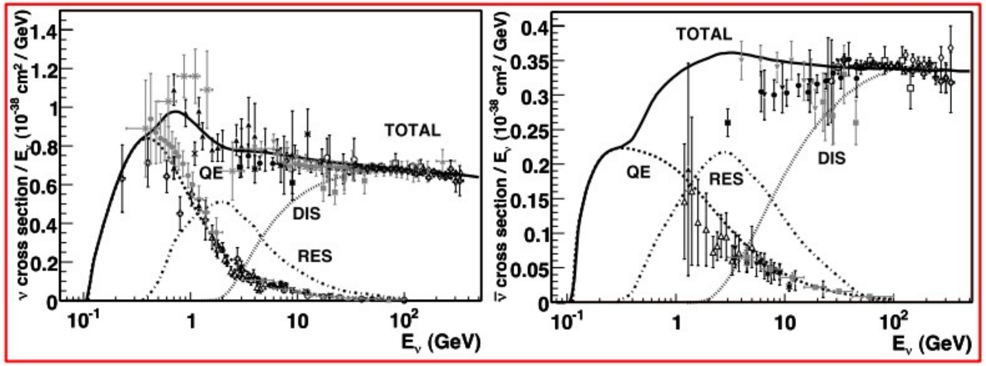
New future challenges (δ_{CP}, searches) require timely **changes** or at least **"adjustments"** in this strategy.

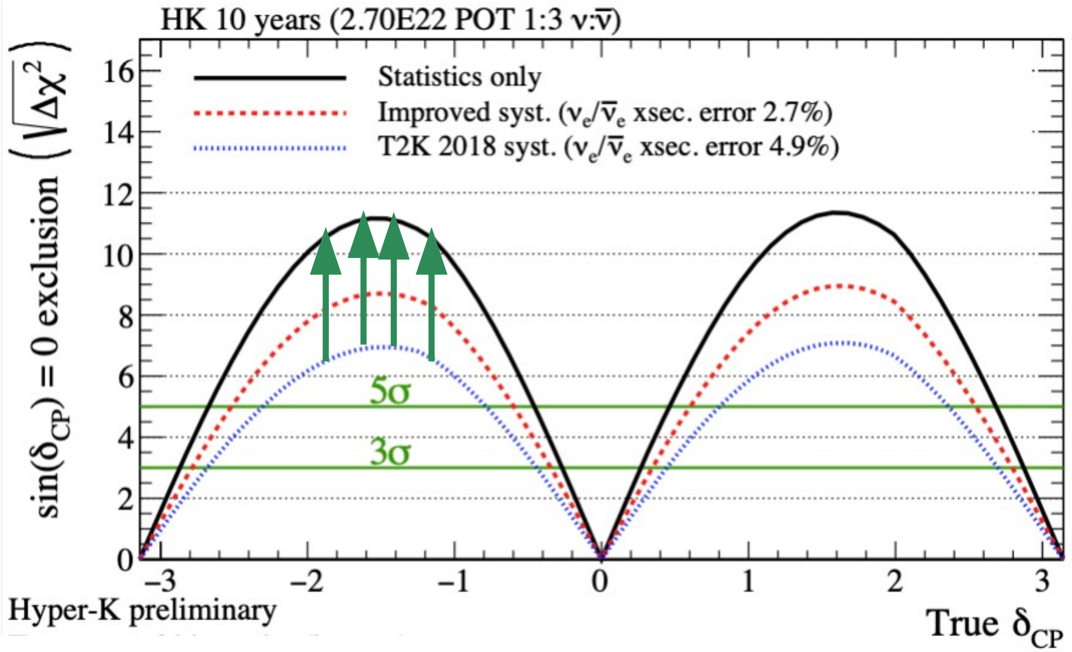


Precision for the Hyper-K/DUNE era

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





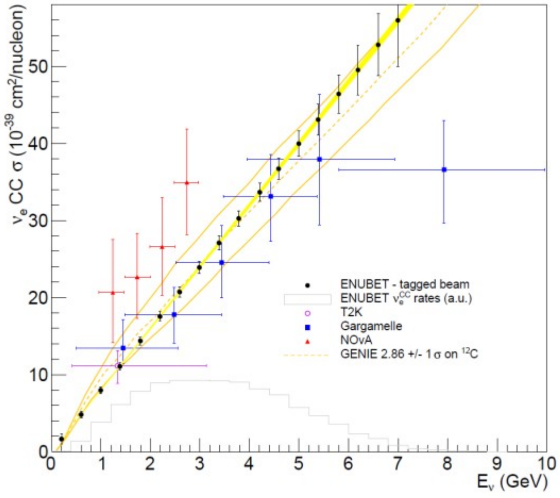
ENUBET and nuSTORM

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

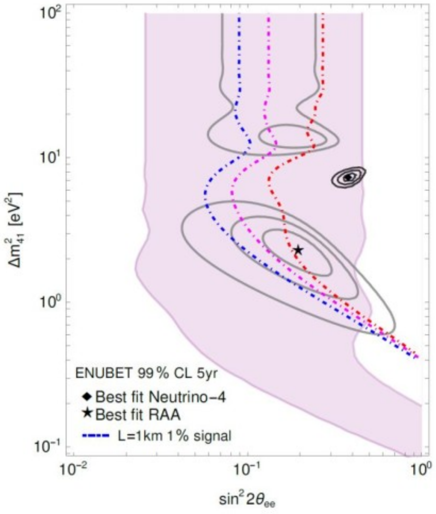
To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.

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 !

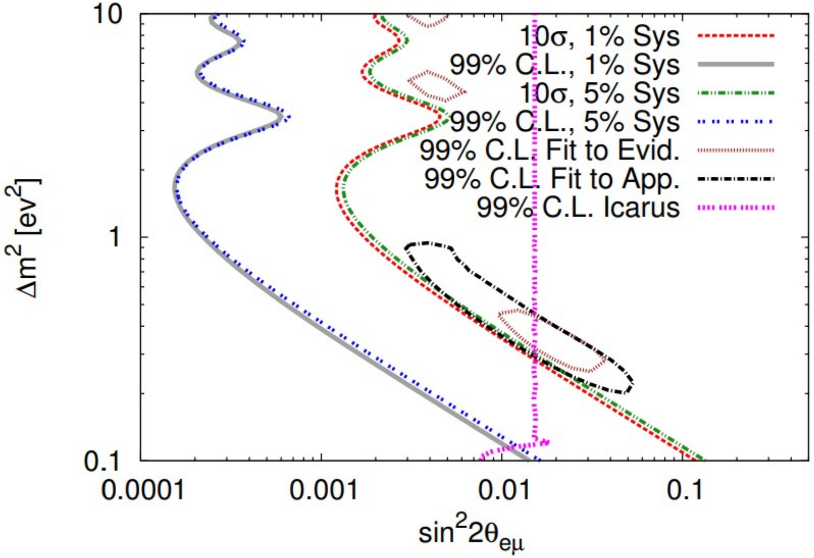


Electron neutrino cross section



Sterile neutrinos

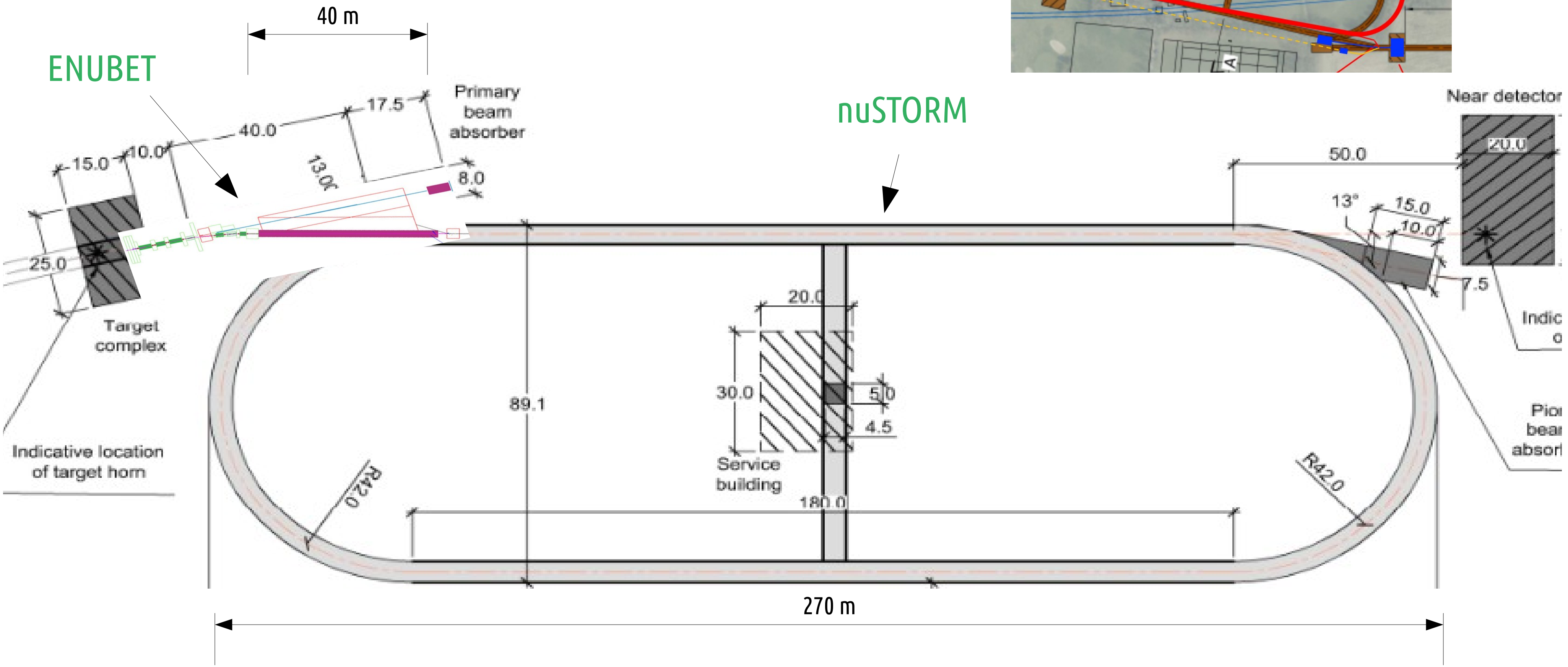
L. Delgadillo, P. Huber, arXiv:2010.10268



Bonus slides

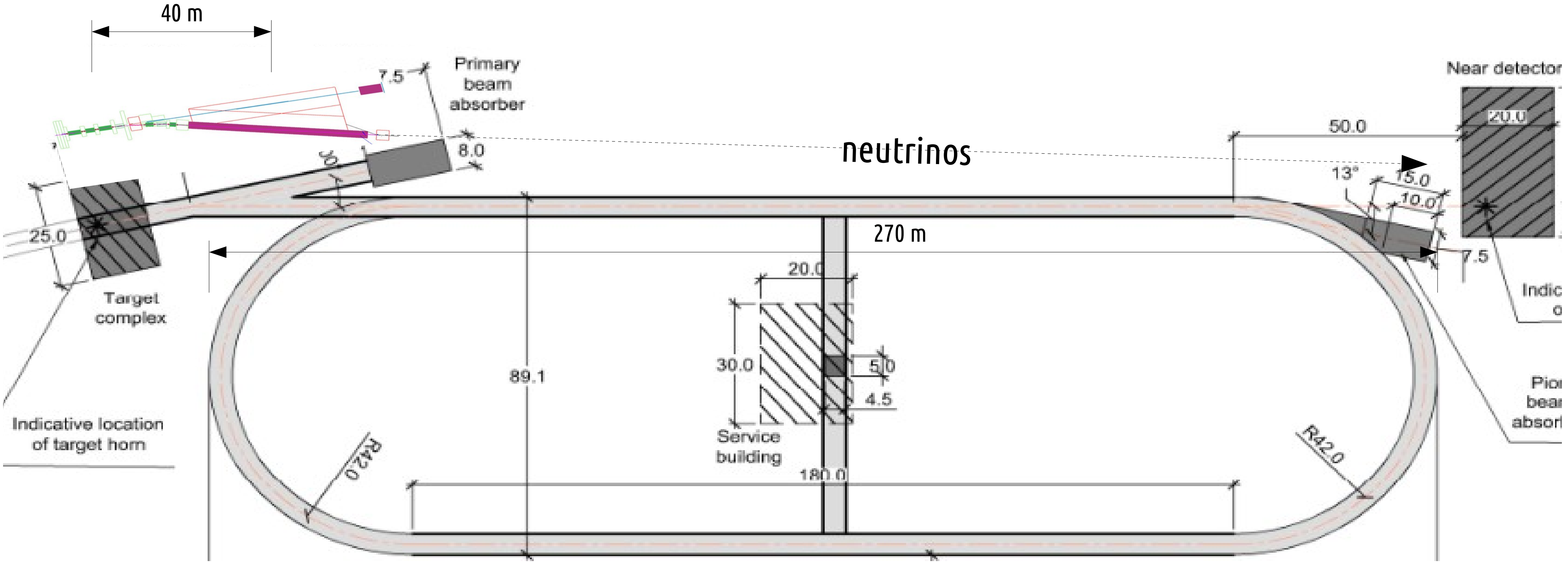
See also Efthymiopoulos
IPPP topical meeting pn Physics with high-brightness stored muon beams
https://conference.ippp.dur.ac.uk/event/967/contributions/5072/attachments/4130/4853/ie-IPPWorkshop_11.02.2021_final.pdf

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



Initial thoughts

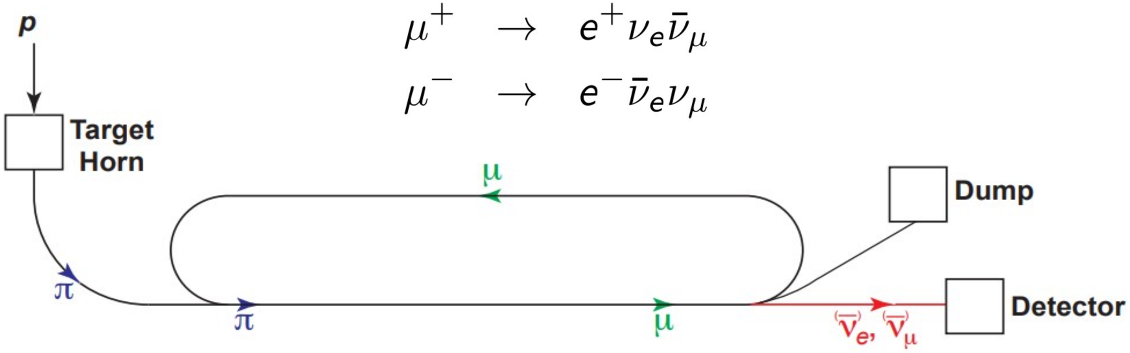
Splitting of proton beamlines + two targets, same detector ?
Less cost effective, more degrees of freedom/parallelization

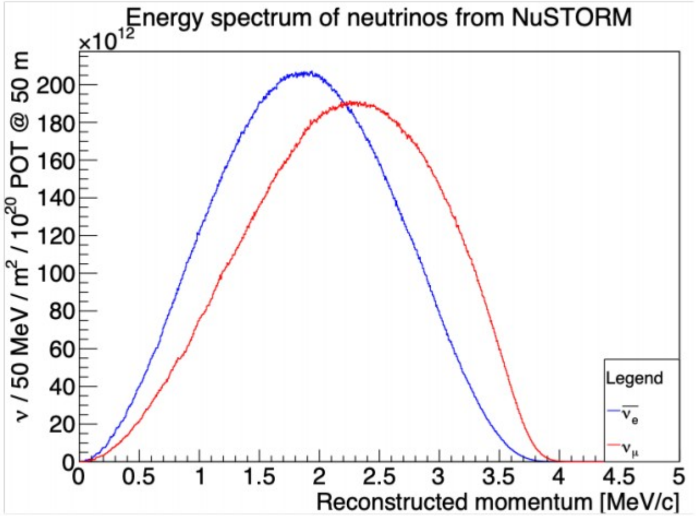


nuSTORM

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

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

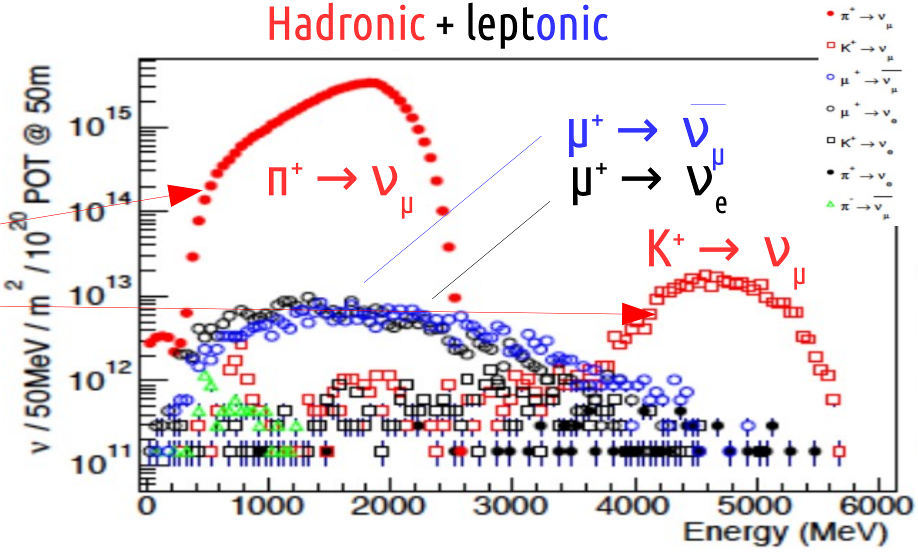




- 100 GeV/c p from SPS (156 kW). Fast extr. (10.5 us).
- Storage ring (1-6 GeV/c with a 16% acceptance)
- 52% of $\pi \rightarrow \mu$ before 1st turn

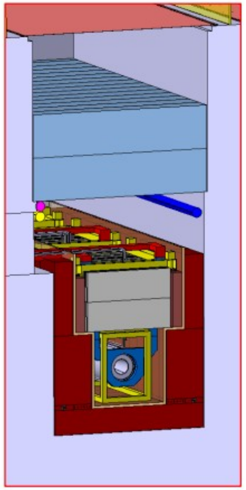
  $\rightarrow \nu_\mu$ flash @ "injection pass"

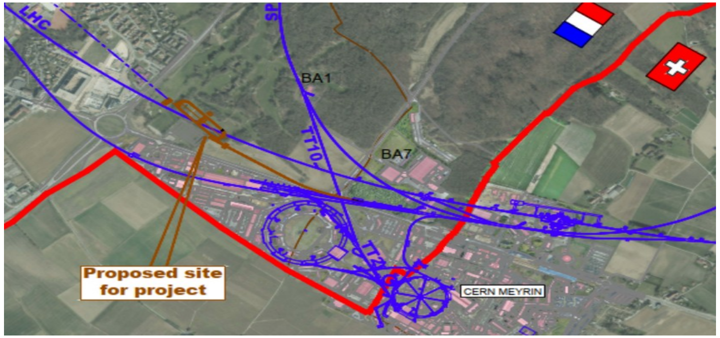
  These are the components of neutrinos that ENUBET exploits and controls with the tagger
- 1 τ_μ ~ 27 orbits:
- For 10^{20} POT (2×10^{20} expected in 5 y) @ 50 m
  - 6.3×10^{16} ν_μ / m^2
  - 3.0×10^{14} ν_e / m^2

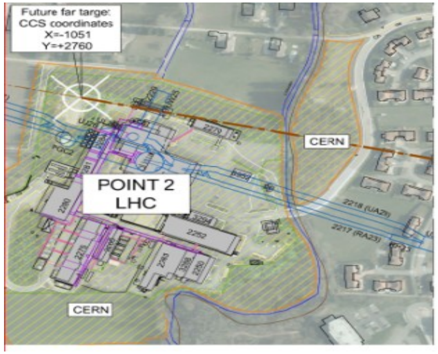


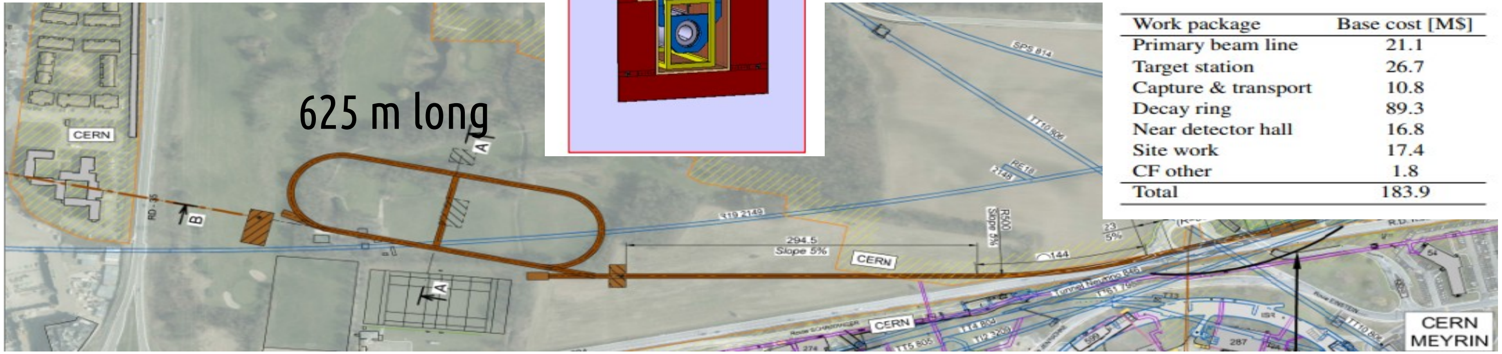
nuSTORM

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

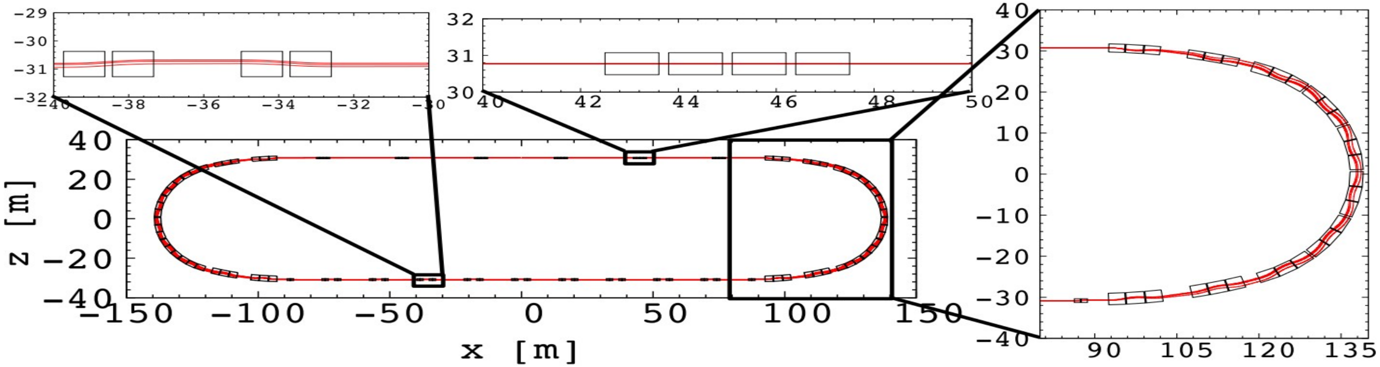


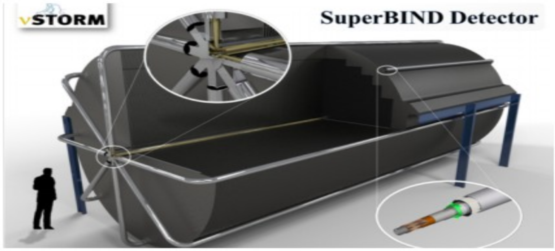






Work package	Base cost [M$]
Primary beam line	21.1
Target station	26.7
Capture & transport	10.8
Decay ring	89.3
Near detector hall	16.8
Site work	17.4
CF other	1.8
Total	183.9



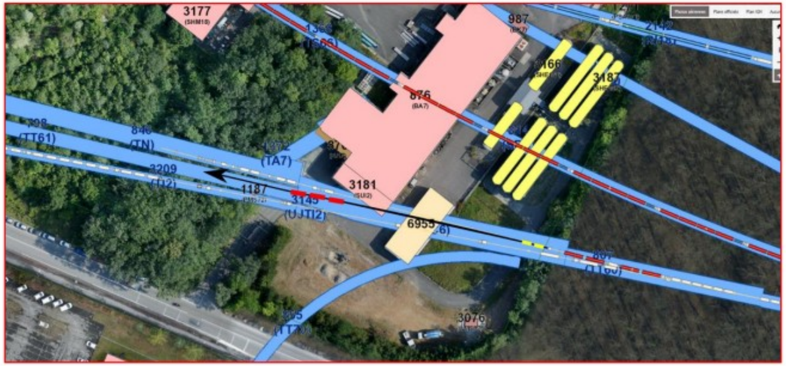


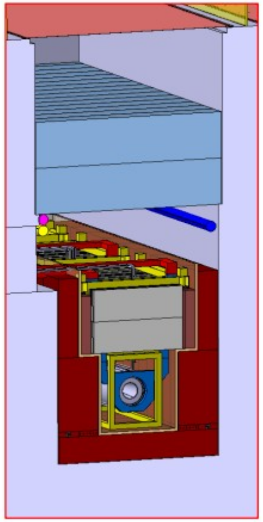
For sterile searches. For cross sections other detector schemes could be more appropriate, with similar small sizes.

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

nuSTORM in PBC: conclusion of 1 phase

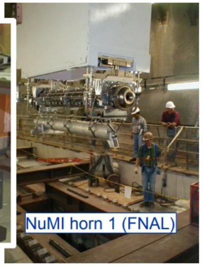
CERN-PBC-2019-003





Targetry – applicable examples

- **Target and horn development could profit from existing experience and design existing worldwide, from NuMI, CNGS to T2K beamlines**
- **All applicable for nuSTORM / ENUBET**



ENUBET & nuSTORM - implementation

Option B: split the incoming beam to two targets and two horn systems like ESSnuSB

pros:

- separated target/capture system for each project, possibly tuned to its needs

cons:

- beam sharing, reduced flux to each project
- requires development of fast cycling magnets, 0.25Hz

Option A: Use a solenoid to capture both signs of secondaries, followed by focusing elements and dipole to distribute the charged beam to nuSTORM & ENUBET

pros:

- Easy solution can allow // operation of the two projects
- The layout can be adjusted to allow pointing the neutrinos to the same detector
- The solenoid option can work at any pulse duration

cons:

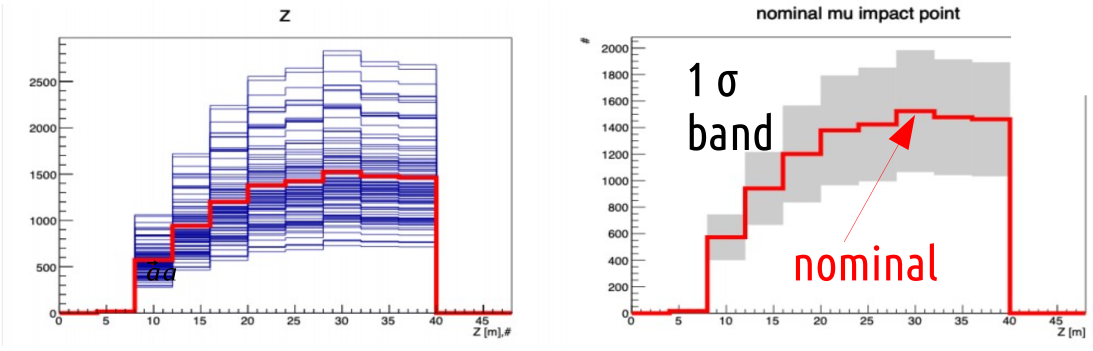
- requires development of a solenoid solution!

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).



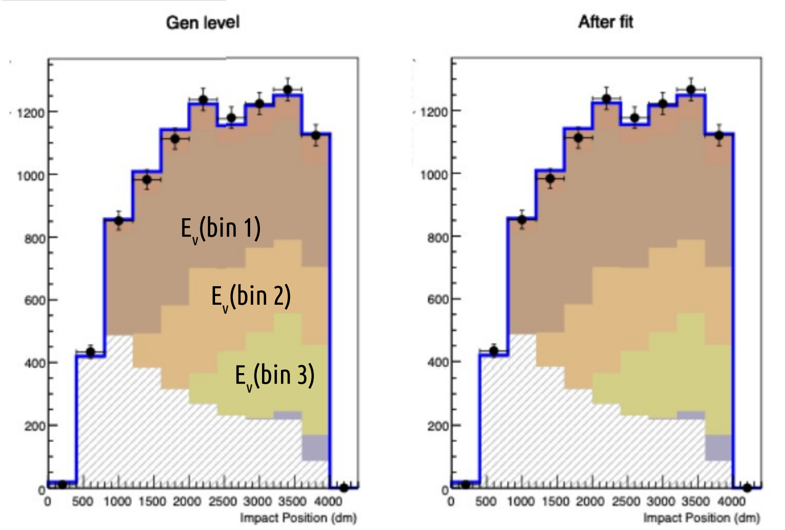
Extended likelihood fit of lepton variables with **templates in bins of the associated neutrino energy**:

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

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

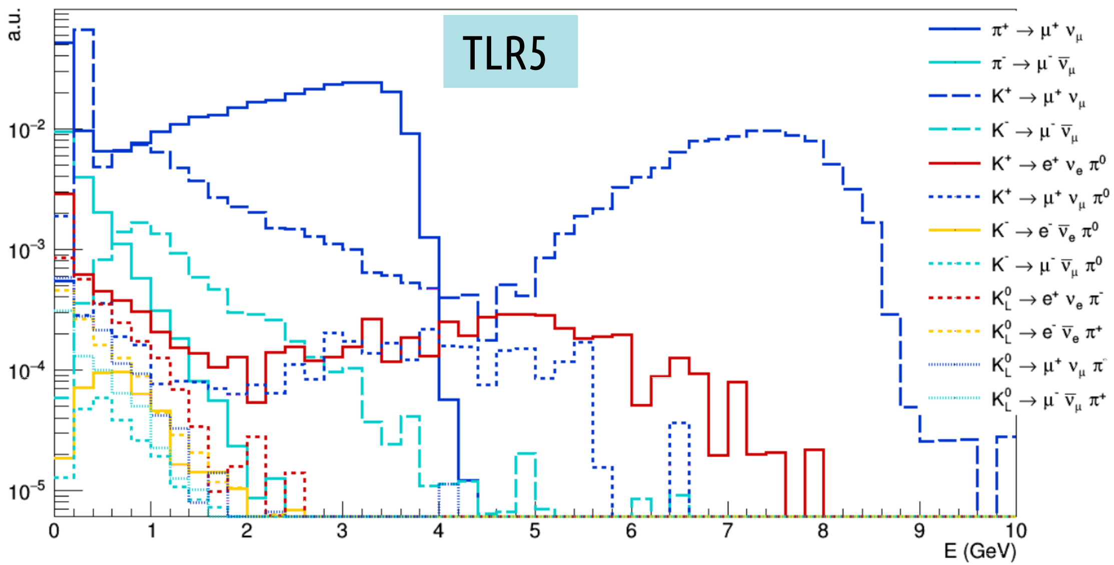
Fit the relative normalizations of the templates in E_ν → flux constraint.

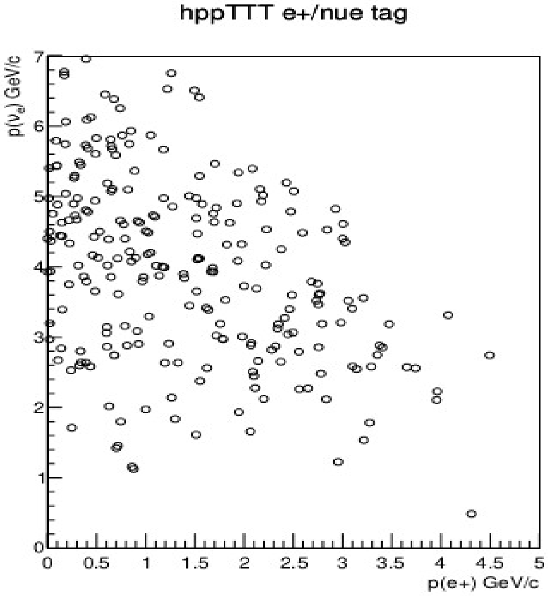
In progress: from a toy to the **real ENUBET case using full simulation.**



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**.

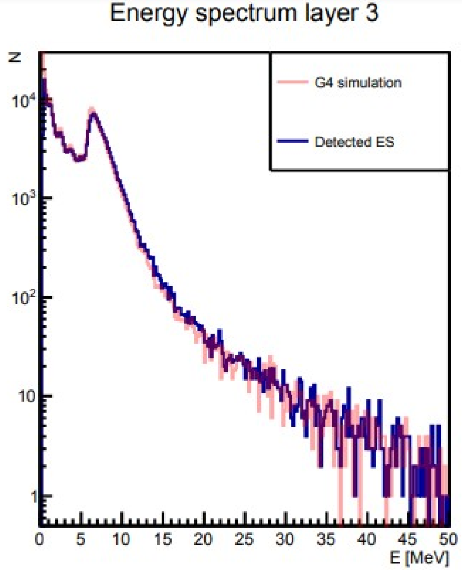




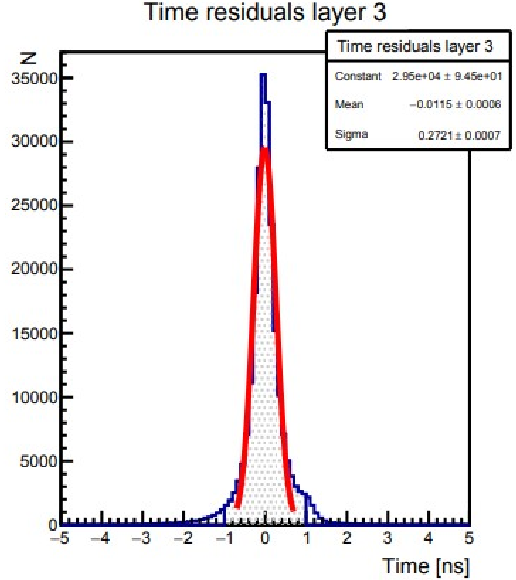
Waveform analysis

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 rigorously.

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



Matching between true and reconstructed time (500 MS/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%

Proton extraction R&D

during LS2: burst mode slow extraction

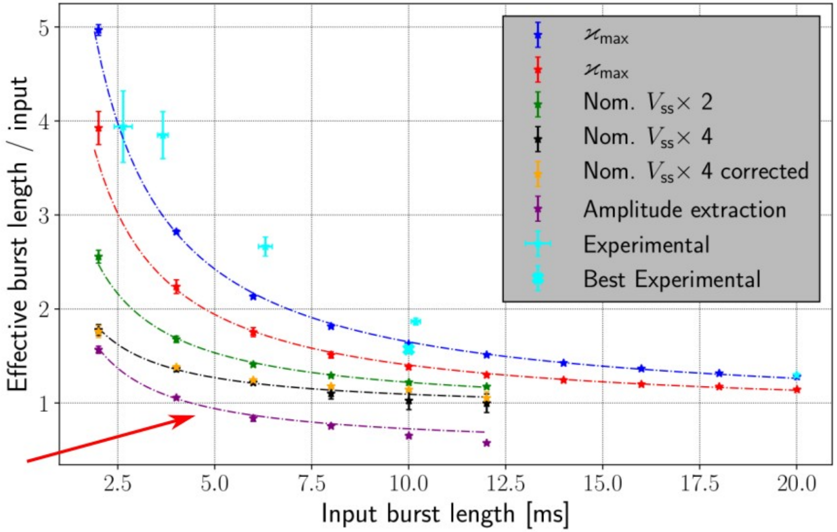
a **full simulation** to validate the experimental results and **explore possible improvements**, which could not be tested in the machine before the shutdown.

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

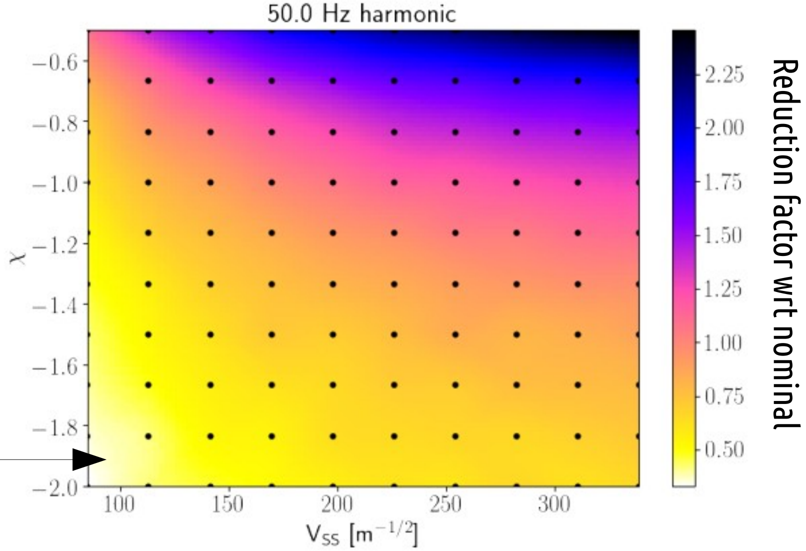
pulses between **3 and 10 ms** seems at reach without hardware interventions → tests after LS2

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



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

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

Target optimization

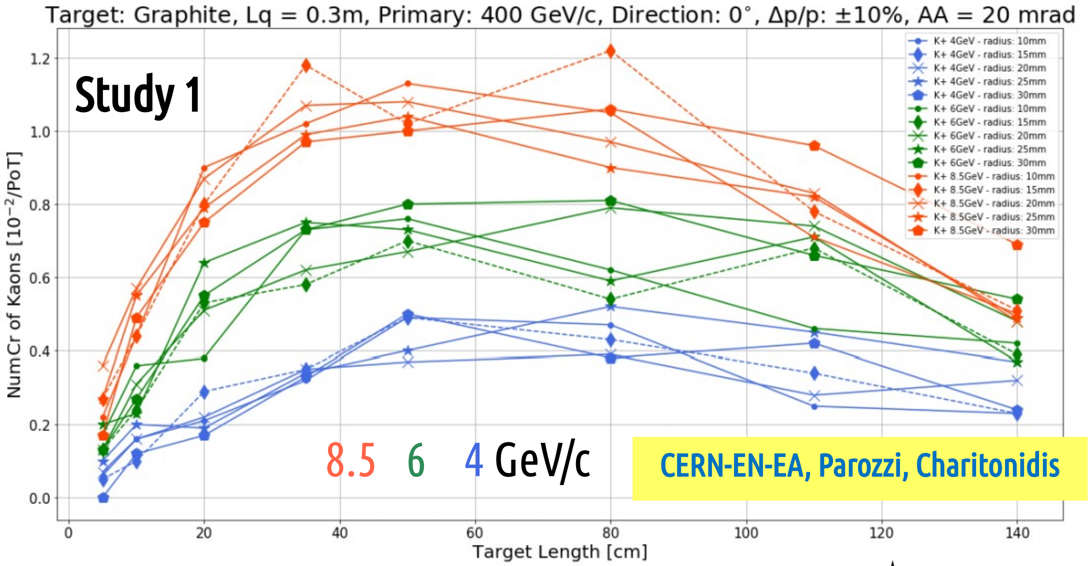
Explored the parameter space of the geometry (also tronco-conical) and some materials (graphite, Inconel) to maximise the yields of mesons in our region of interest with FLUKA.

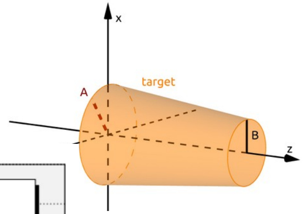
The current targets are both more efficient and robust under the point of view of implementation and lifetime.

New baseline targets:

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

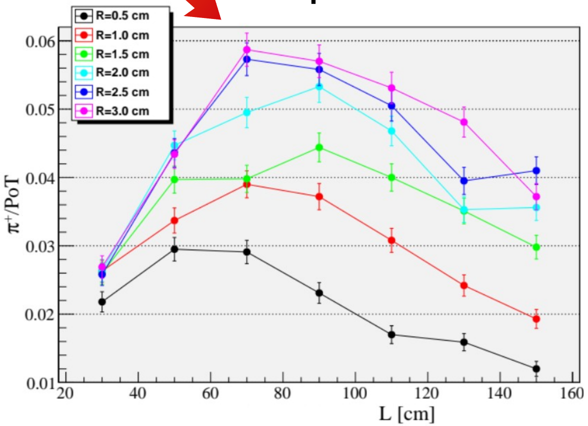
(*) The two studies used different choices for the FOMs



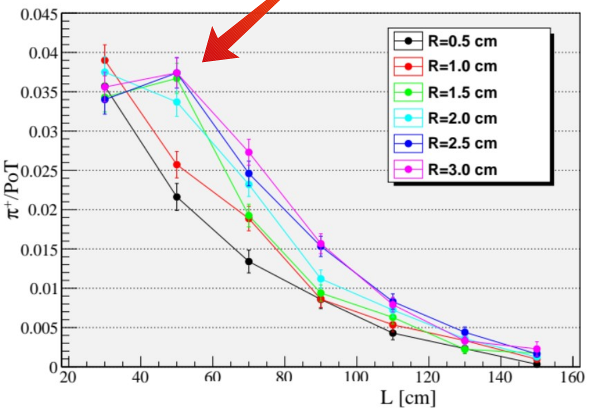


Study 2

Graphite

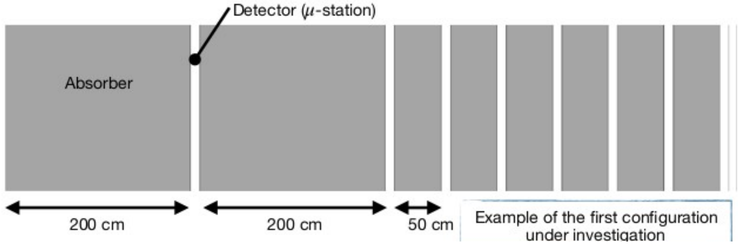


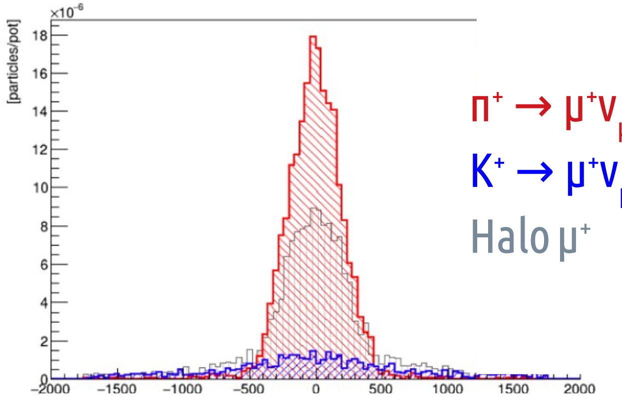
Inconel



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.



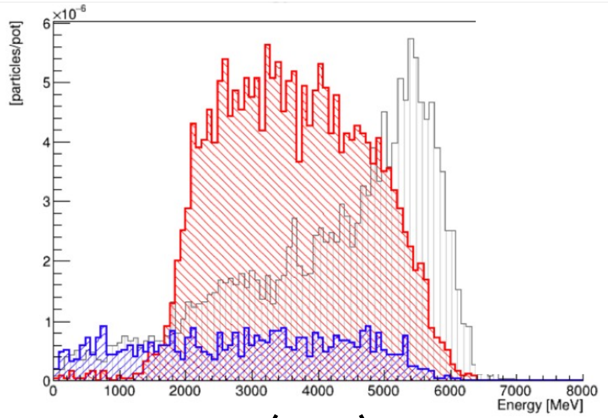


Y (mm)

$\pi^+ \rightarrow \mu^+\nu_\mu$

$K^+ \rightarrow \mu^+\nu_\mu$

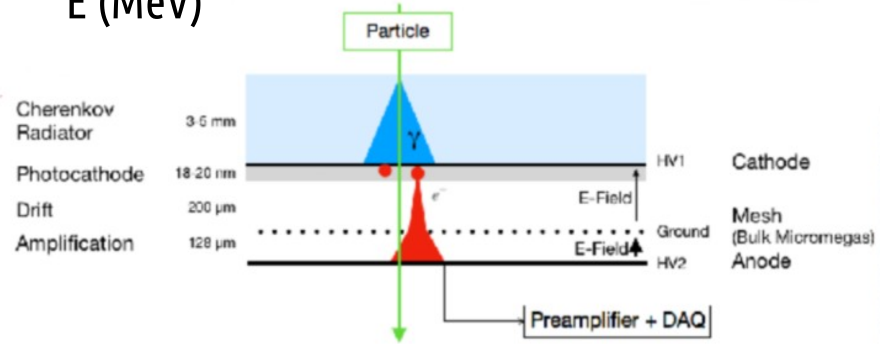
Halo μ^+

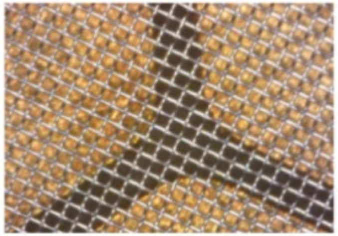


E (MeV)

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

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





Annual report, coll. growth, extension

[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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New forces from **Thessaloniki Univ**.

Already active on:
- waveform processing algorithms

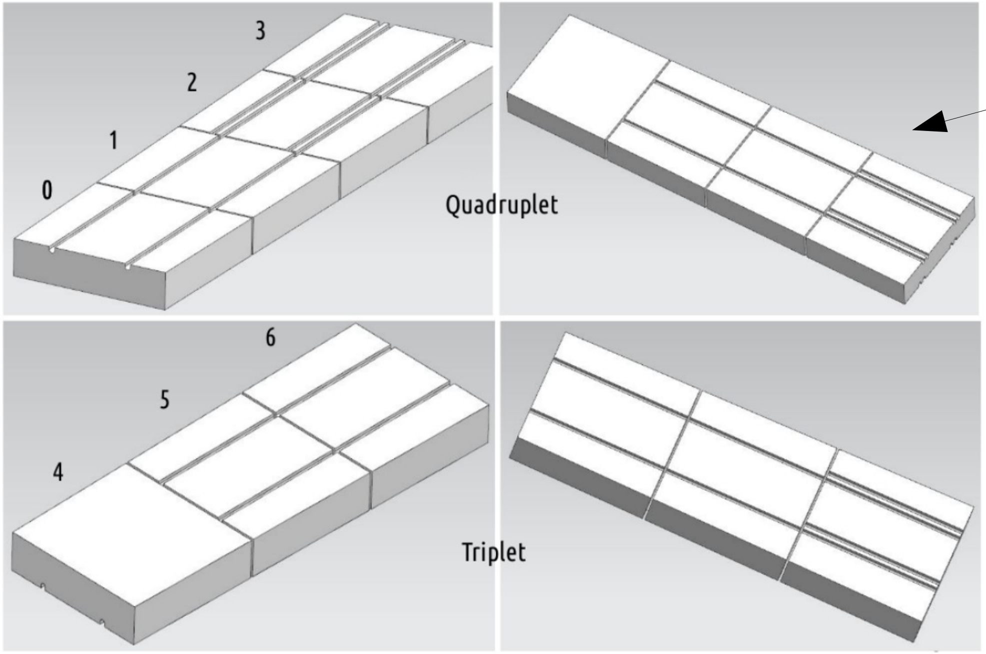
Next:
- members of the PICOSEC collaboration (fast MicroMegas with reduced gap)

- instrumentation of the forward region: physics and detector studies (also at next test beams)

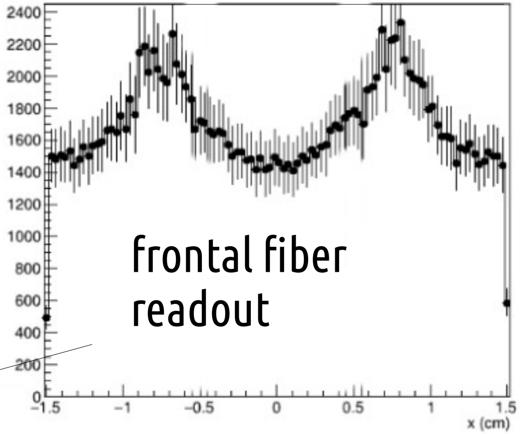
The ERC project has been extended by 12 months up to June 2022.

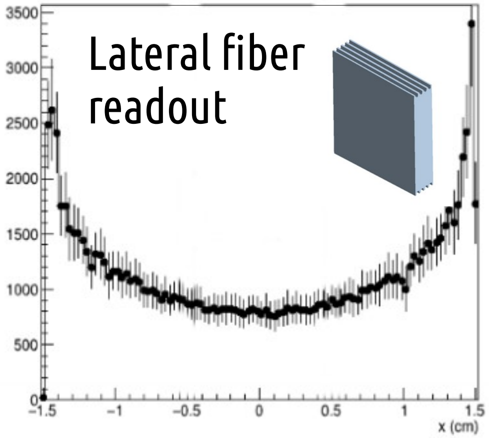
Updated light readout scheme

- 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.

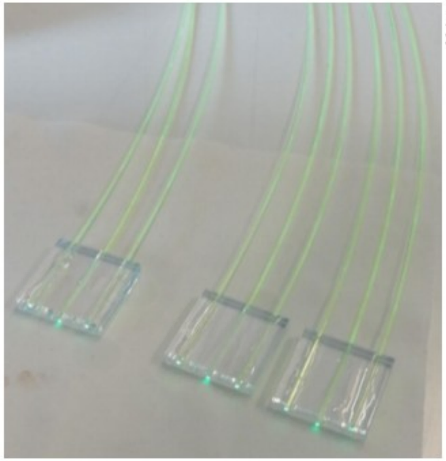


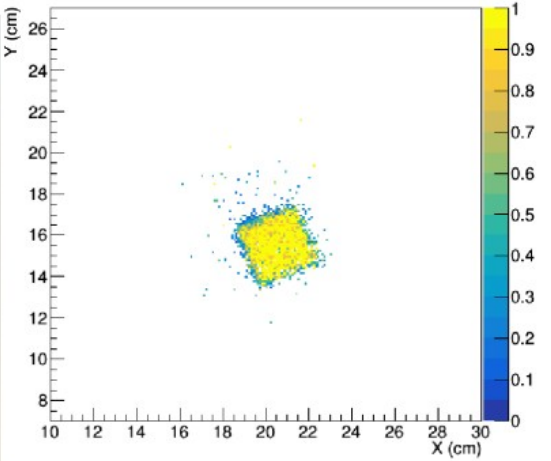
GEANT4 optical simulation





Uniformity tests with cosmic rays

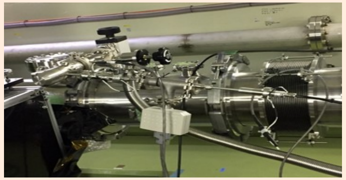




Improvements in standard beams (*)

(*) examples

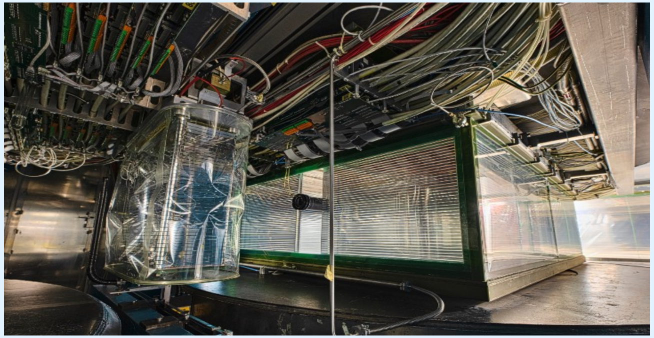
Beam monitoring systems are being enriched

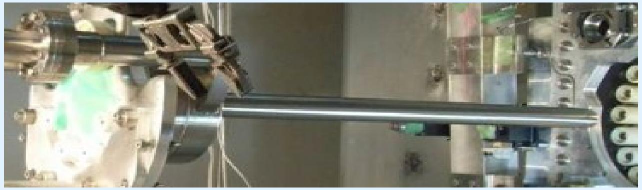


[J-PARC Beam Induced Fluorescence monitor]

Hadro-production data covering larger phase space with replica targets

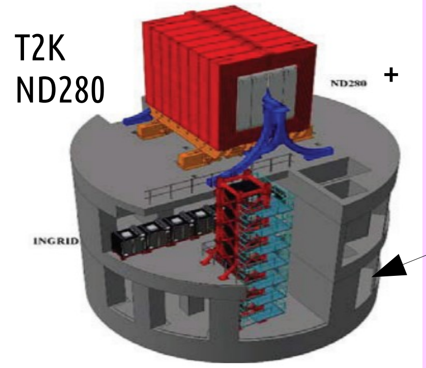
NA61-SHINE

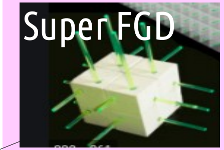


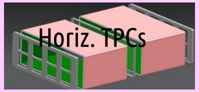


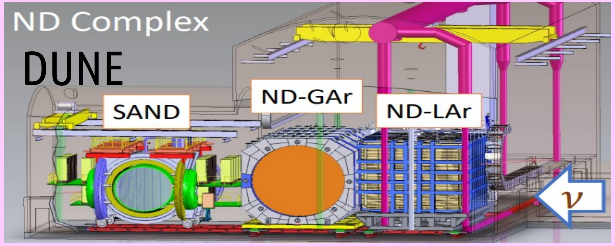
T2K target

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

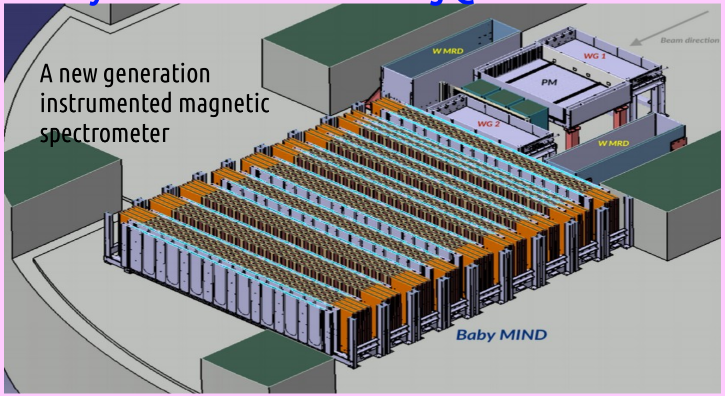








BabyMIND+WAGASCI running @ ND280

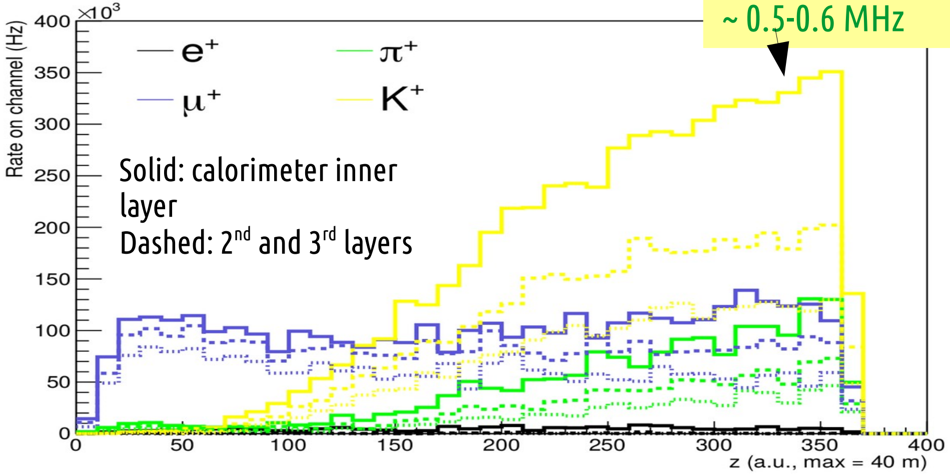


ENUBET: proton extraction, rates, pile-up

quad focusing: 2s slow extraction

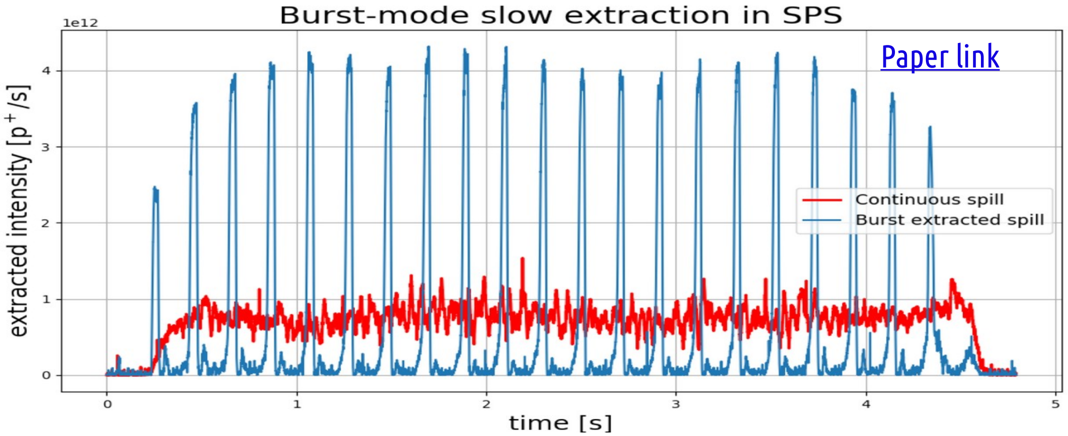
Rates in the tagger vs z

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



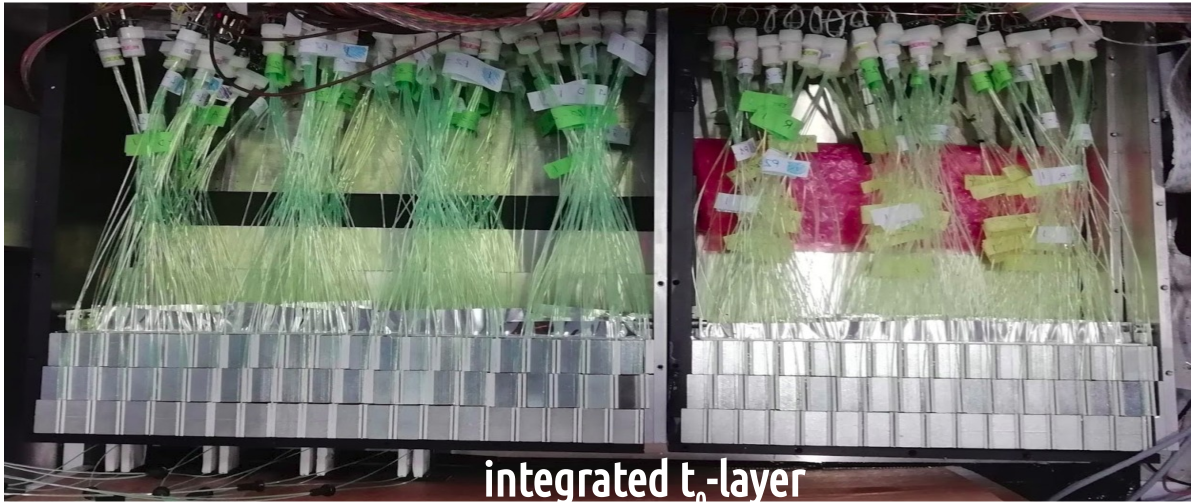
Waveform analysis algorithms developed.
With **250 MS/s** sampling:
pile-up efficiency loss stays
sub-% up to ~ 1 MHz/ch

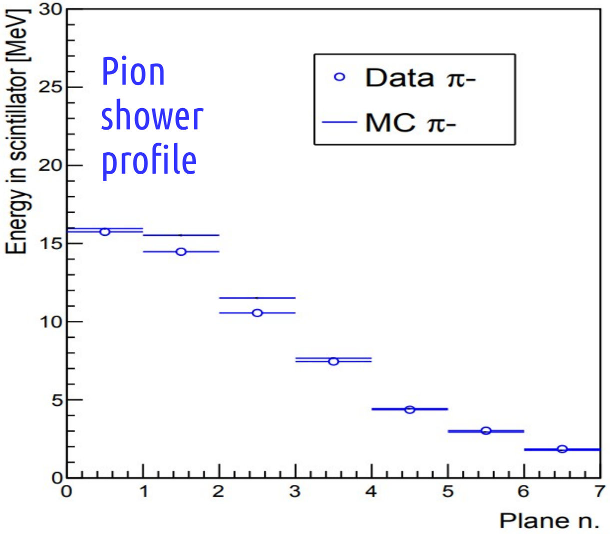
With the increased rates implied in the horn focusing scheme → **~ few % loss**

ENUBET: prototypes at the CERN-PS

[ENUBET CERN-SPSC 2020 annual report link]

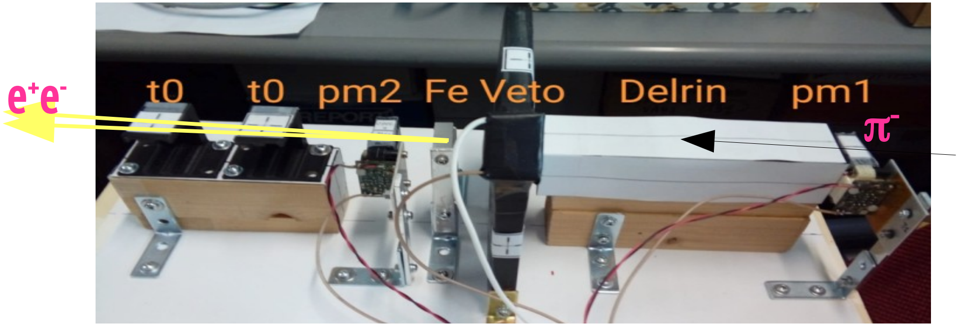
JINST arXiv:2006.07269





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

Trigger: PM1 and VETO and PM2



$\sigma_t \sim 400$ ps