This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 681647).

The NP06/ENUBET Project

A. Branca* - University of Milano-Bicocca & INFN Sezione di Milano-Bicocca

*on behalf of the ENUBET Collaboration

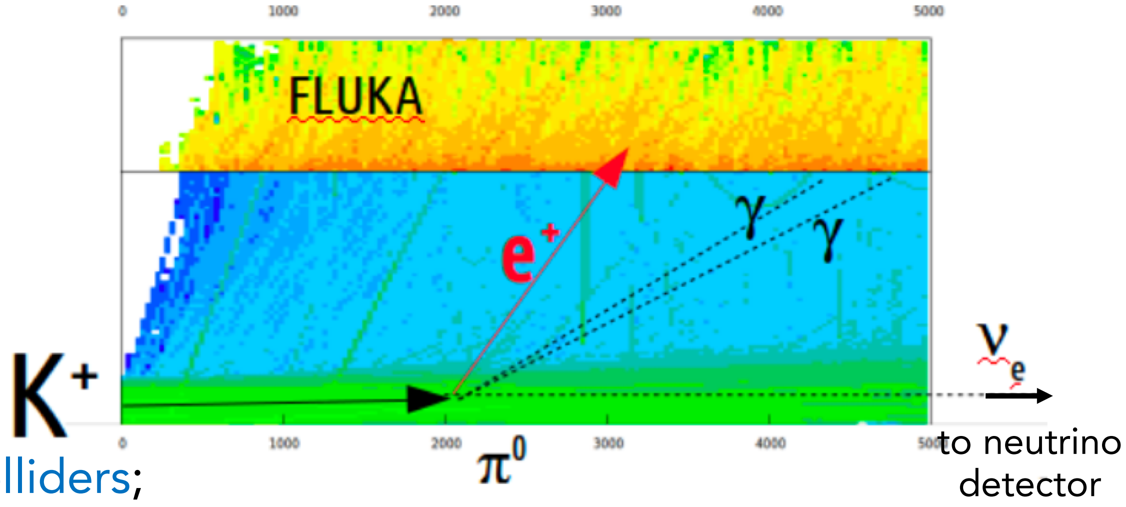
32nd Rencontres de Blois, October 17-22, 2021 – Blois, Loire Valley, France

Outline

- ENUBET is the project for the realization of the first monitored neutrino beam. In the next slides:
  - how to reach the purpose of the project;
  - physics performance, status and next steps;

- ENUBET: ERC Consolidator Grant, June 2016 – May 2021 (now extended to 2022 to overcome COVID difficulties). PI: A. Longhin;

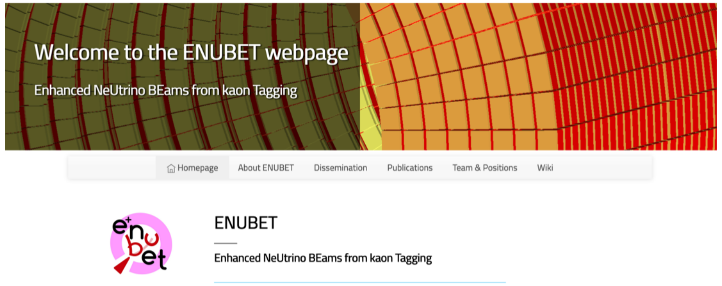
- Since April 2019: ENUBET also a CERN Neutrino Platform Experiment – NP06/ENUBET – and part of Physics Beyond Colliders;



to neutrino detector

- ENUBET Collaboration: 60 physicists & 13 institutions; Spokespersons: A. Longhin, F. Terranova; Technical Coordinator: V. Mascagna;

Visit our webpage for further info and material!
https://www.pd.infn.it/eng/enubet/



Welcome to the ENUBET webpage

Enhanced NeUtrino BEams from kaon Tagging

ENUBET

Enhanced NeUtrino BEams from kaon Tagging

Systematics matter!

Next generation long-baseline experiments (DUNE & HyperK) conceived for precision ν-oscillation measurements:

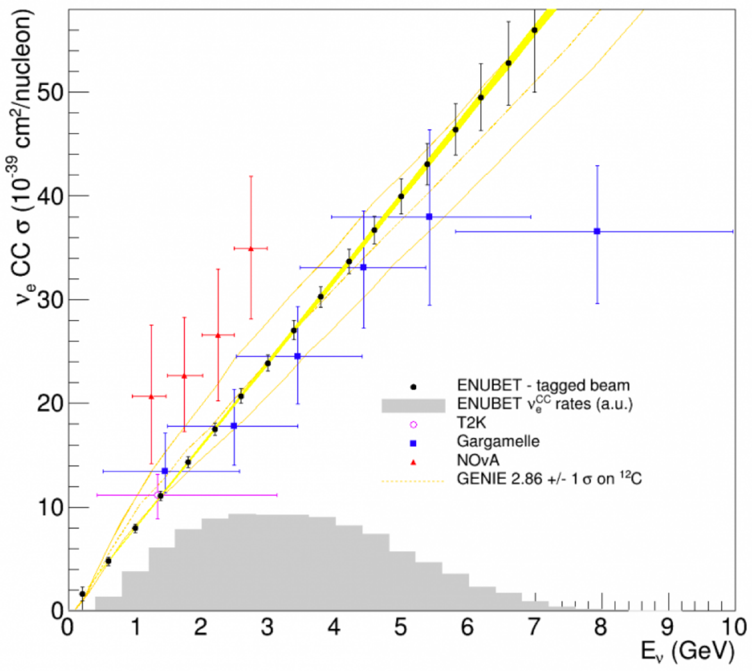
- test the 3-neutrino paradigm;
- determine the mass hierarchy;
- test CP asymmetry in the lepton sector;

$$N_{\nu_e}^{FAR} = P_{\nu_\mu \to \nu_e} \cdot \underset{\uparrow}{\sigma_{\nu_e}} \cdot \underset{\uparrow}{\Phi_{\nu_\mu}^{FAR}}$$

Very good knowledge needed!

Moreover ν-interaction models would benefit from improved precision on cross-sections measurements

ENUBET impact on σ_{ν_e}



The purpose of ENUBET: design a narrow-band neutrino beam to measure

- neutrino cross-section and flavor composition at 1% precision level;
- neutrino energy at 10% precision level;

From the **European Strategy for Particle Physics Deliberation document**:

To extract the most physics fromDUNE 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.

ENUBET: the first monitored neutrino beams

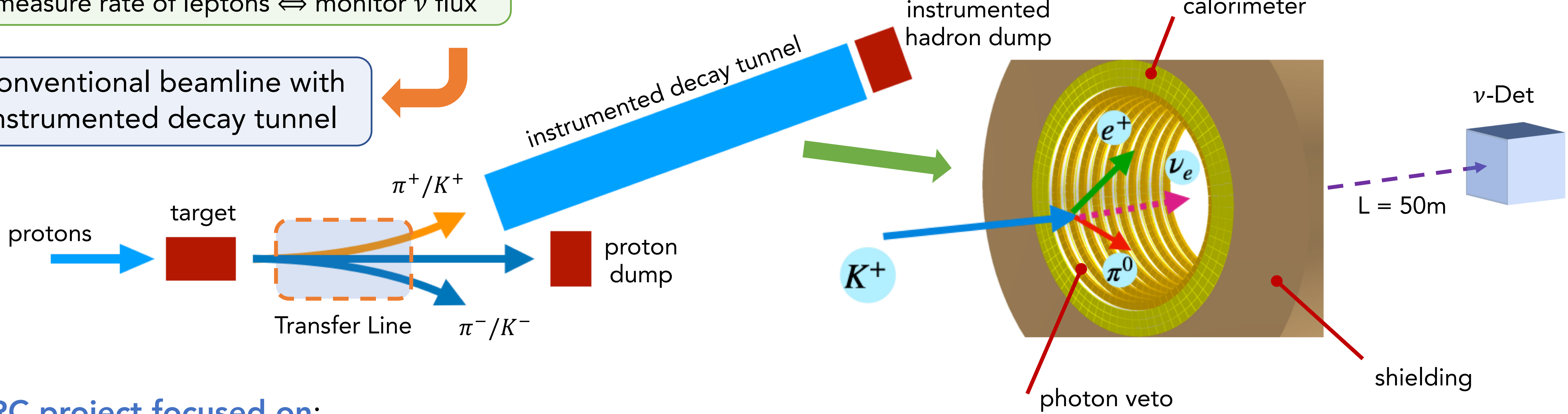
How do we achieve such a precision on the neutrino cross-section, flavor composition and energy?

Monitored ν flux from narrow-band beam

measure rate of leptons ⇔ monitor ν flux

Conventional beamline with instrumented decay tunnel

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



- **ERC project focused on**:
  measure positrons (instrumented decay tunnel) from K_{e3} $\Longrightarrow$ determination of ν_e flux;
- **As CERN NP06 project**:
  extend measure to muons (instrumented decay tunnel) from $K_{\mu\nu}$ and (replacing hadron dump with range meter) $\pi_{\mu\nu}$ $\Longrightarrow$ determination of ν_μ flux;

Main systematics contributions are bypassed: hadron production, beamline geometry & focusing, POT;

Proton extraction schemes

Two possible options

Static "Slow extraction" scheme

continuous extraction of the full intensity in few seconds

PRO:

- ✓ Negligible pile-up effects: reduced rates at the instrumented decay tunnel;
- ✓ Monitoring of ν_μ from pion decays after the hadron dump;
- ✓ Possibility to develop time-tagged neutrino beams;

Developed Static Transfer Line (see next slides)

CONS:

- larger running time (more POT) to reach the wanted ν_e interaction statistics;

Horn-pulsed "Fast Extraction" scheme

all protons extracted in O(1-10 μs) by kicker magnets

PRO:

- ✓ Larger ν_e interaction statistics in a shorter time (i.e. higher ν_e/POT):
  - horn helps to focus more kaons & pions;
  - larger yields achieved @ decay tunnel;

CONS:

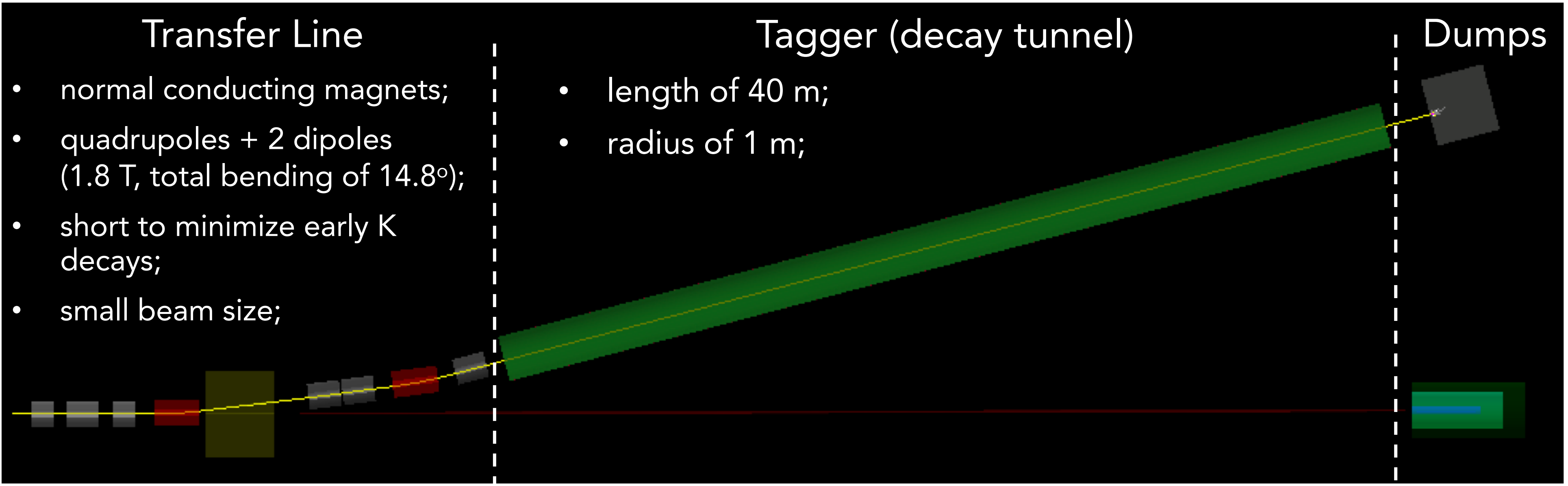
- Pile-up effects are not negligible in this case!

SOLUTION:

- ➢ Burst-Mode Slow Extraction scheme (see next slides);

The Static Transfer Line

Transfer Line + **Tagger** + **Dumps** layout (**G4Beamline**) : optimized for 8.5 GeV beam



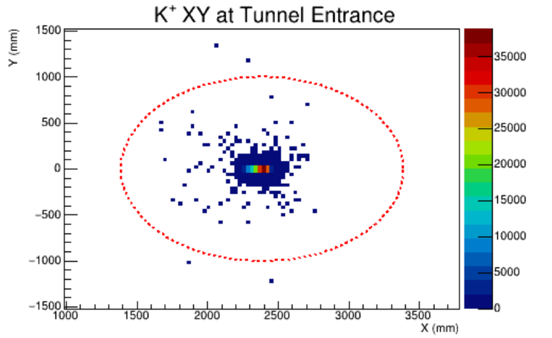
Transfer Line

- normal conducting magnets;
- quadrupoles + 2 dipoles (1.8 T, total bending of 14.8°);
- short to minimize early K decays;
- small beam size;

Tagger (decay tunnel)

- length of 40 m;
- radius of 1 m;

Dumps



Rates @ Tunnel entrance for 400 GeV POT (values @ 8.5 GeV ± 5%)

π^+ $[10^{-3}]$/POT	K^+ $[10^{-3}]$/POT
4.2	0.4

~2X w.r.t. previous results

Large bending angle of 14.8°:

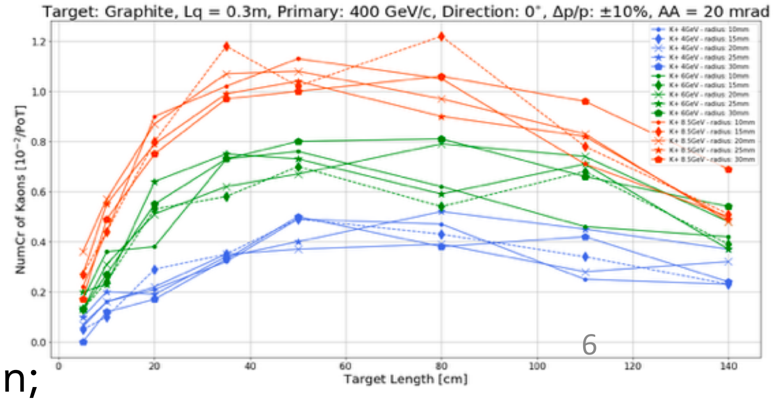
- better collimated beam + reduced muons background + reduced ν_e from early decays;

Shielding:

- absorbers and rock volumes: included in complete simulation;
- in progress: optimization/design of absorbers + collimators of last section;
- tungsten foil downstream target: suppress positron background;

Target optimization (FLUKA & G4Beamline):

- maximize K & π production: scan geometry and test different materials;
- employing optimized graphite target (L=70cm/R=3cm). Inconel under consideration;



Static TL: ν_e^{CC} energy distribution

A total ν_e^{CC} statistics of 10^4 events in ~2 years

- @ SPS with $4.5 \cdot 10^{19}$ POT/year;
- 500 ton detector @ 50 m from tunnel end;

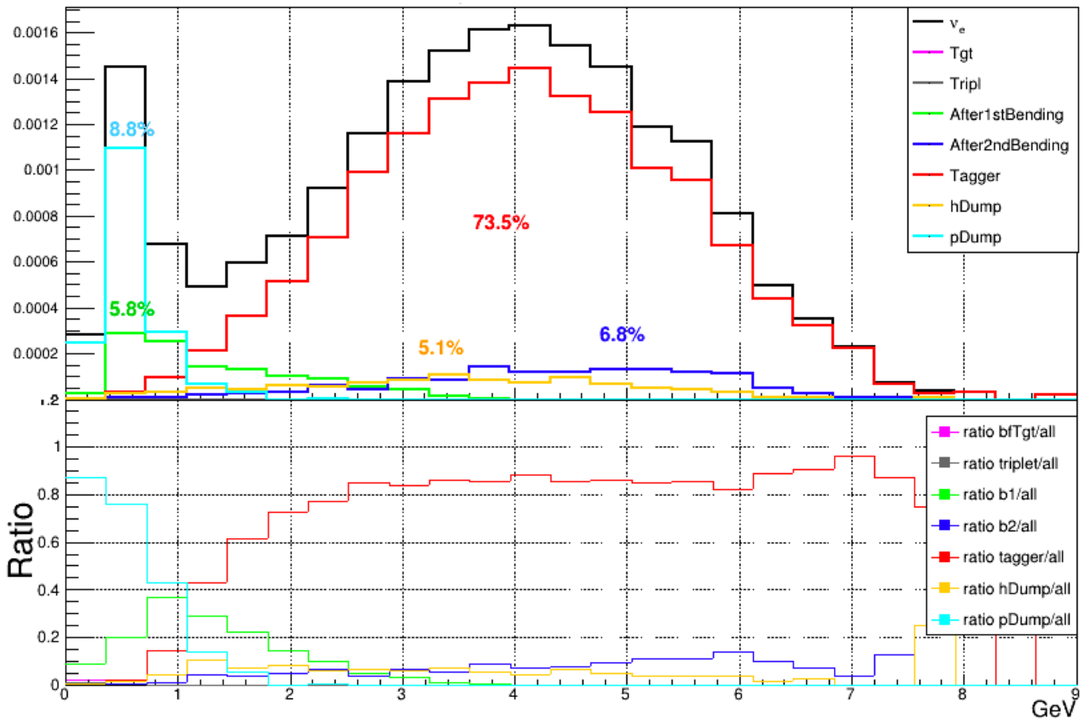
Taggable component

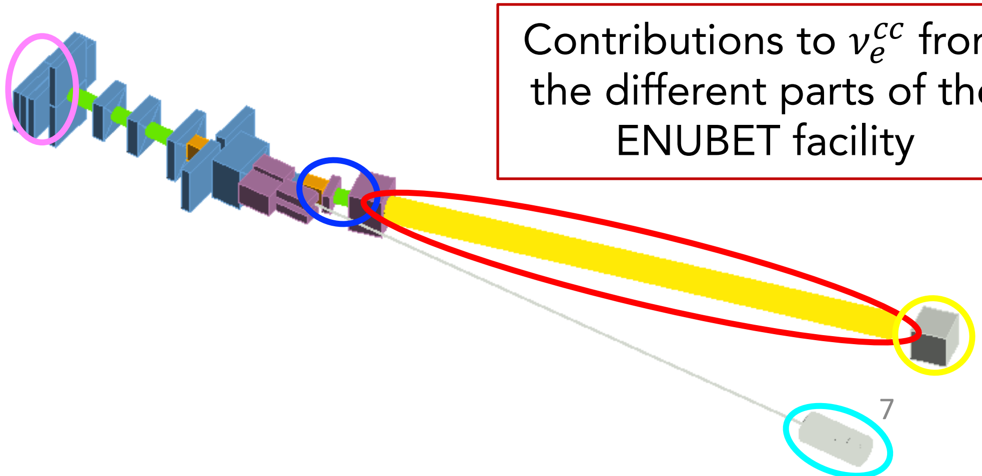
73.5% of total ν_e flux is produced by decays in the tunnel (more than 80% above 1 GeV)

Non taggable components:

- **Below 1 GeV**: main component produced in p-dump
  - clear separation from taggable ones (energy cut);
  - further improvements in separation optimizing p-dump position;
- **Above 1 GeV**: contributions from straight section before tagger and hadron-dump;
  - rely on simulation for this component;

ν_e CC spectra





Contributions to ν_e^{cc} from the different parts of the ENUBET facility

Static TL: ν_μ^{CC} energy distribution

Narrow-band off-axis Technique

Narrow momentum beam O(5-10%)

(E_ν,R) are strongly correlated

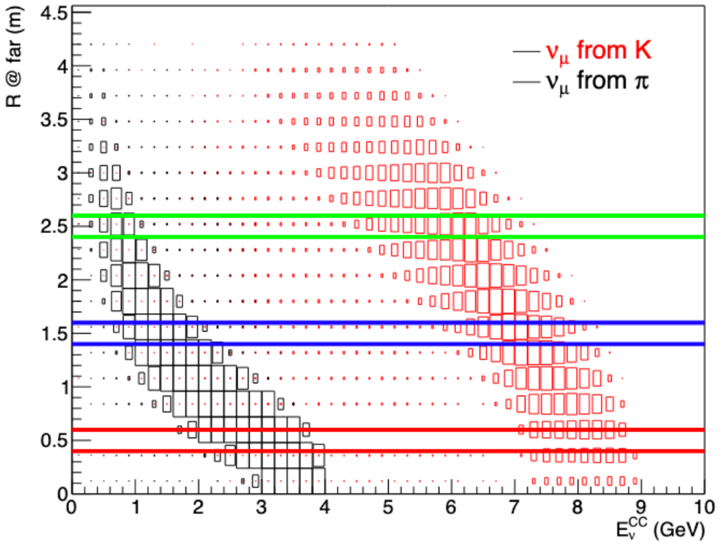
E_ν = neutrino energy;

R = radial distance of interaction vertex from beam axis;

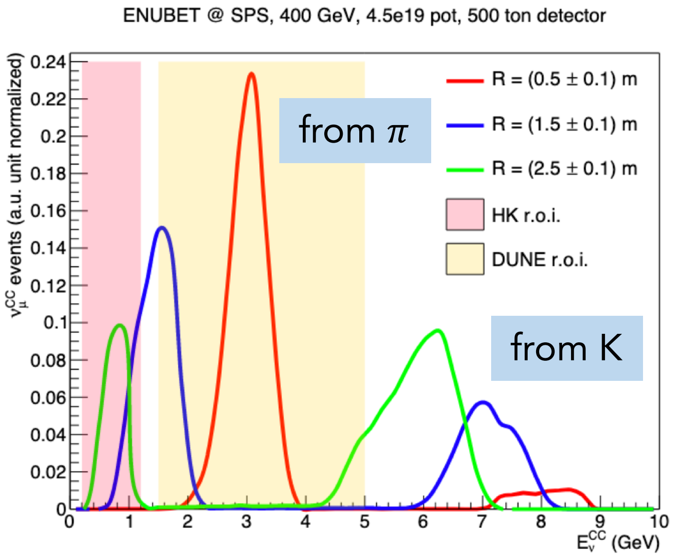
F. Acerbi et al., CERN-SPSC-2018-034

Precise determination of E_ν:
no need to rely on final state particles from ν_μ^{CC} interaction

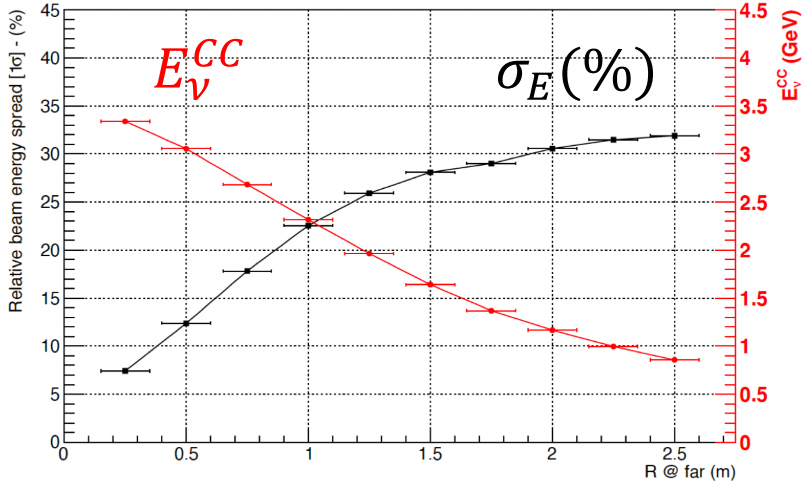
- 8-25% E_ν resolution from π in DUNE energy range;
- 30% E_ν resolution from π in HyperK energy range (DUNE optimized TL w/ 8.5 GeV beam):
  - ongoing R&D: Multi-Momentum Beamline (4.5, 6 and 8.5 GeV) => HyperK & DUNE optimized;



select slices in R windows



π/K populations well separated



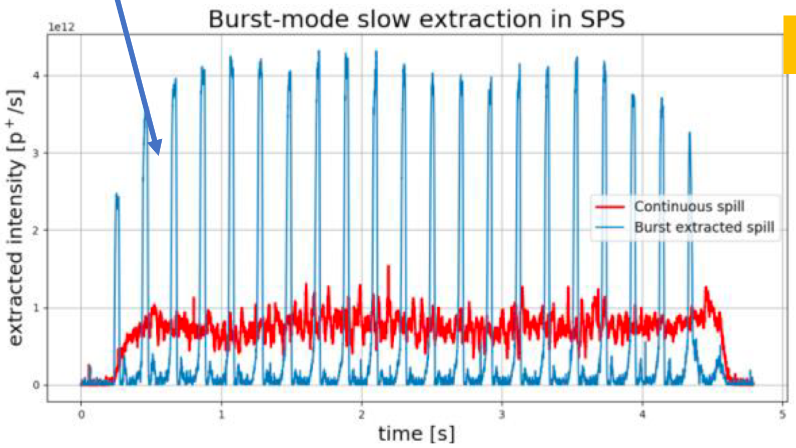
from pion peaks at different R

Horn based focusing

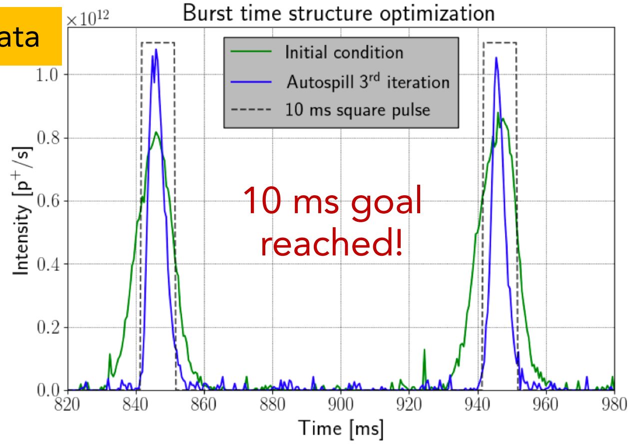
M.Pari et al., Phys. Rev. Accel. Beams 24, 083501 (2021)

Boosting the neutrino flux → Employ magnetic Horn → Overkilling pile-up @ tunnel

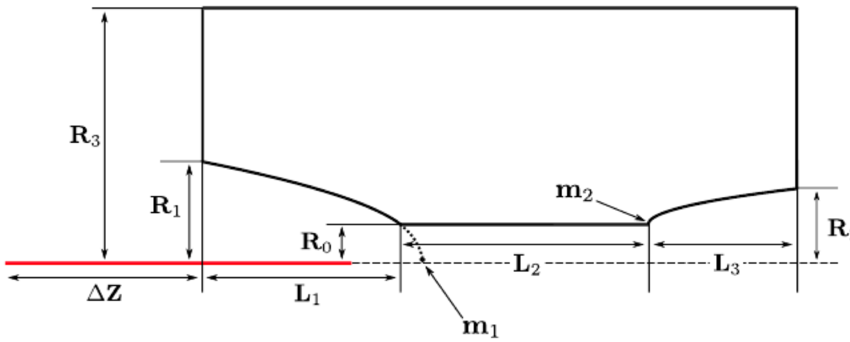
Burst mode slow extraction: multiple ms-long pulses slow-extracted during flat-top → compatible with Horn and pile-up @ tunnel



from real data



New double parabolic geometry implemented



Dedicated tests at CERN-SPS:

- successfully implemented;
- optimized down to 10 ms length @ 10 Hz;

From simulation studies:

- 3 to 10 ms pulse length can be reached;

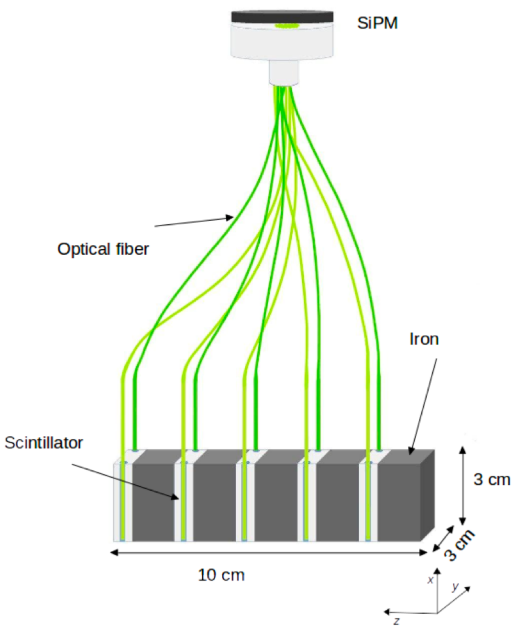
Horn optimization: search for best shape & current values to maximize flux

- developed a dedicated optimization algorithm based on Genetic Algorithm;
- reached FOM* 3x static beamline;
- NEXT: further studies on dedicated beamline fine-tuned for horn;

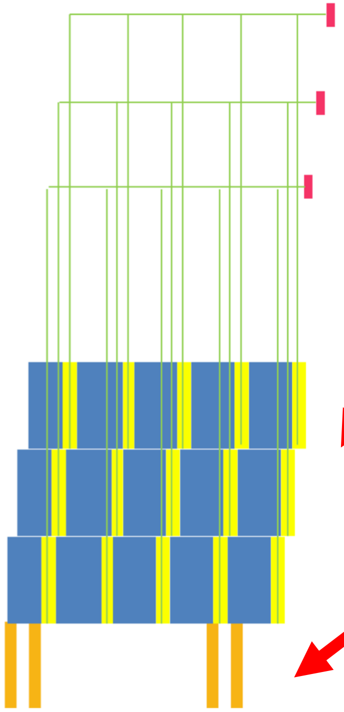
*FOM = # of K^+ within momentum bite focused at first quadrupole after the horn => beamline independent

Decay tunnel instrumentation schematics

A Lateral readout Compact Module LCM



Calorimeter layout



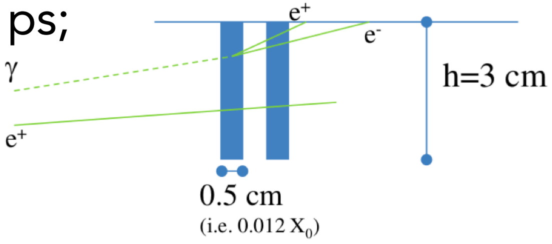
beam

Calorimeter with $e/\pi/\mu$ separation capabilities:

- sampling calorimeter: sandwich of plastic scintillators and iron absorbers;
- three radial layers of LCM;
- longitudinal segmentation;
- WLS-fibers/SiPMs for light collection/readout;

Photon-Veto allows π^0 rejection and timing:

- plastic scintillator tiles arranged in doublets forming inner rings;
- time resolution of ~400 ps;



Exploit event topology for PID

e^+ (signal) topology

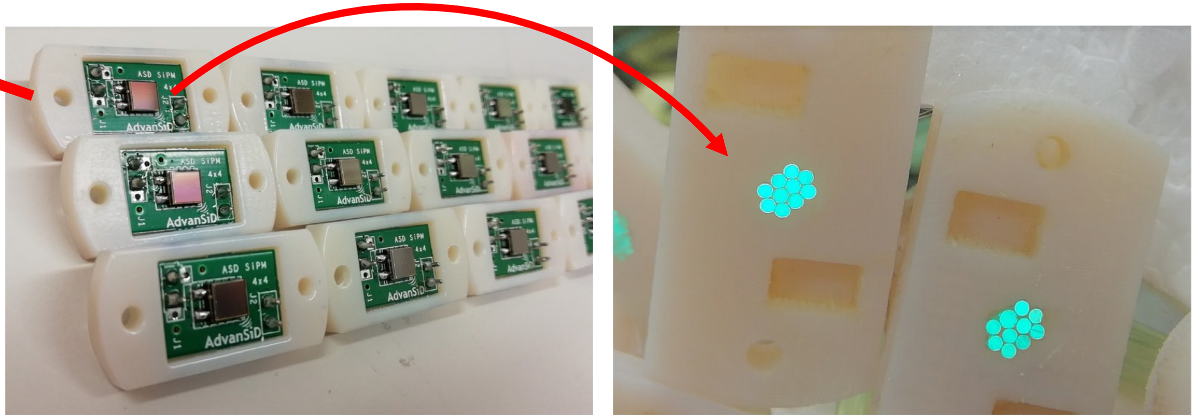
π^0 (background) topology

π^+ (background) topology

Decay tunnel instrumentation prototype & tests

Prototype of sampling calorimeter built out of LCM with lateral WLS-fibers for light collection

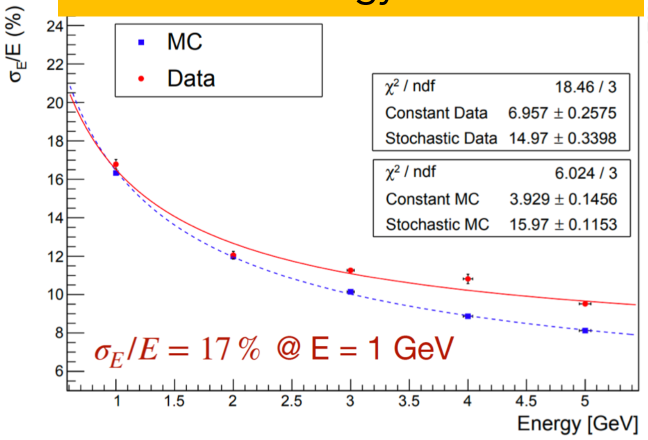
Large SiPM area (4x4 mm^2) for 10 WLS readout (1 LCM)



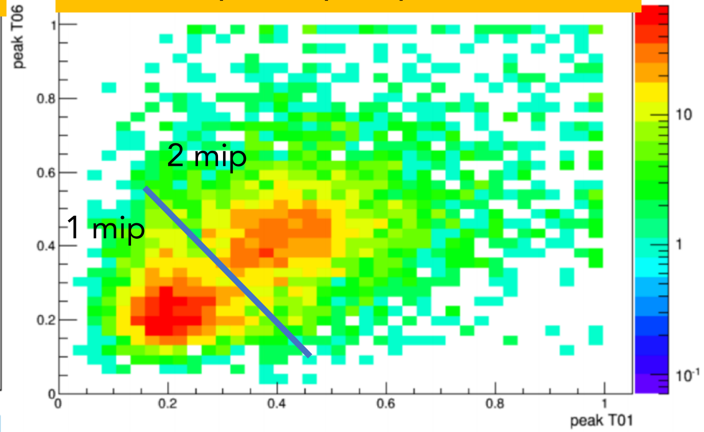
SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging

Tested during 2018 test-beams runs @ CERN TS-P9

Electron energy resolution



1mip/2mip separation



Status of calorimeter:

- ✓ longitudinally segmented calorimeter prototype successfully tested;
- ✓ photon veto successfully tested;
- ➢ custom digitizers: in progress;

Choise of technology: finalized and cost-effective!

F. Acerbi et al, JINST (2020), 15(8), P08001

Lepton reconstruction and identification

K_{e3} positron reconstruction to constrain ν_e

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

✓ **Full GEANT4 simulation of the detector**: validated by prototype tests at CERN in 2016-2018; hit-level detector response; pile-up effects included (waveform treatment in progress); event building and PID algorithms (2016-2020);

Analysis chain:

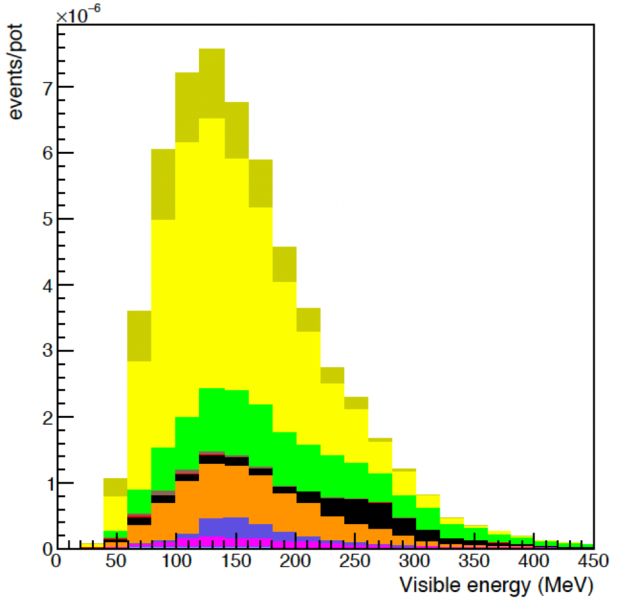
1. Event builder: start from event seed and cluster energy deposits compatible in space and time;
2. $e\ /\ \pi\ /\ \mu\ /\ \gamma$ separation: multivariate analysis (MLP-NN from TMVA) exploiting 19 variables (energy pattern in calorimeter, event topology, photon-veto);

Analysis performance

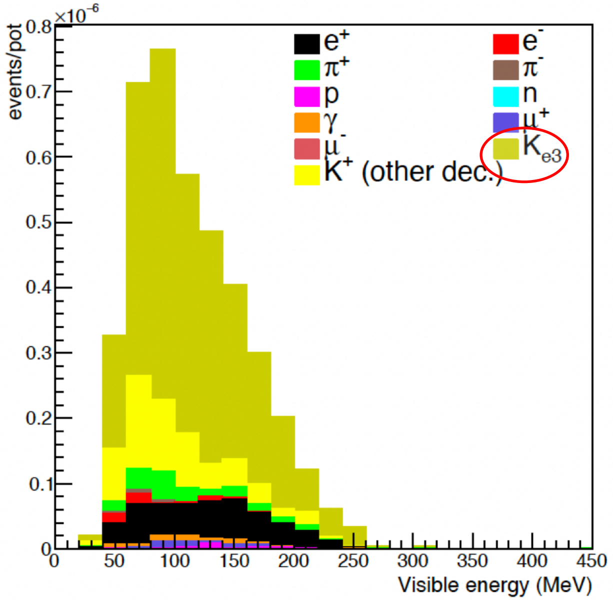
S/N = 2.1

Efficiency = 22% (~half geometrical)

Visible energy - Builder



Visible energy - NN



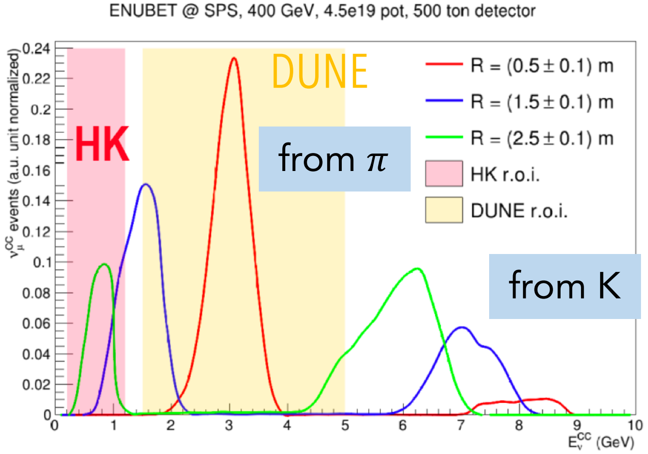
K_{e3} BR ~5% and K make $\sim 5 - 10\%$ of beam composition

New TL has larger meson yield but also increased hit-rate (~2.7×): PID performance still good!

Lepton reconstruction and identification

$K_{\mu 2,3}$ muon reconstruction to constrain high-energy ν_μ

✓ **High angle muons**: reconstruction of track in tagger with dedicated event builder and multi variate analysis. Main background from halo muons is identified and can be used as control sample



Analysis chain:

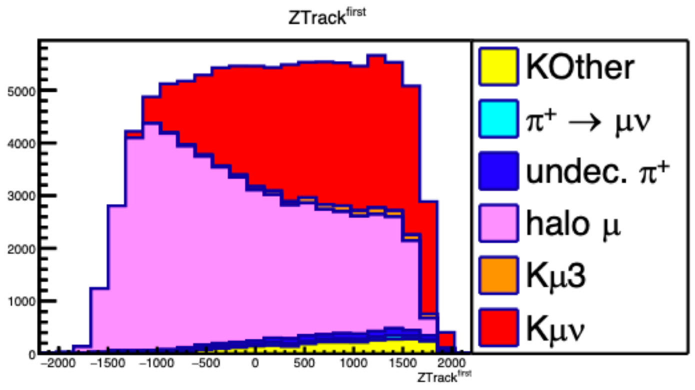
1. Event builder: start from event seed and cluster energy deposits compatible in space and time;
2. μ-like background separation: multivariate analysis (MLP-NN from TMVA) exploiting 13 variables (energy pattern, track isolation and topology);

Analysis performance

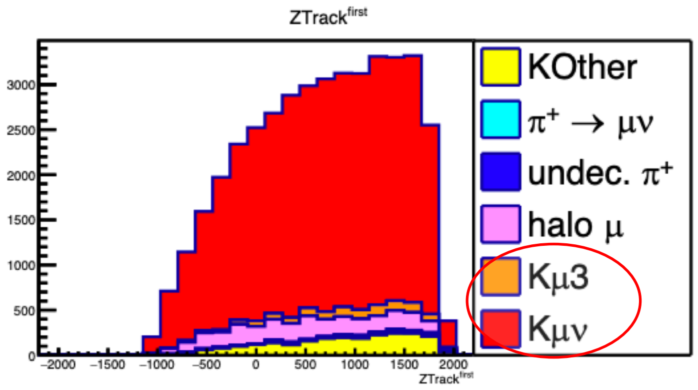
S/N = 6

Efficiency = 34% (~half geometrical)

Tagger impact point - Builder



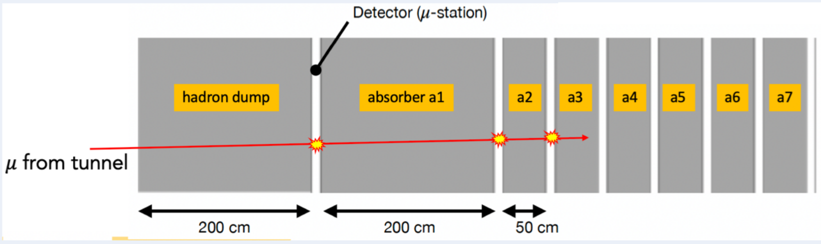
Tagger impact point - NN



$\pi_{\mu\nu}$ low angle muons: out of tagger acceptance

hadron dump instrumentation

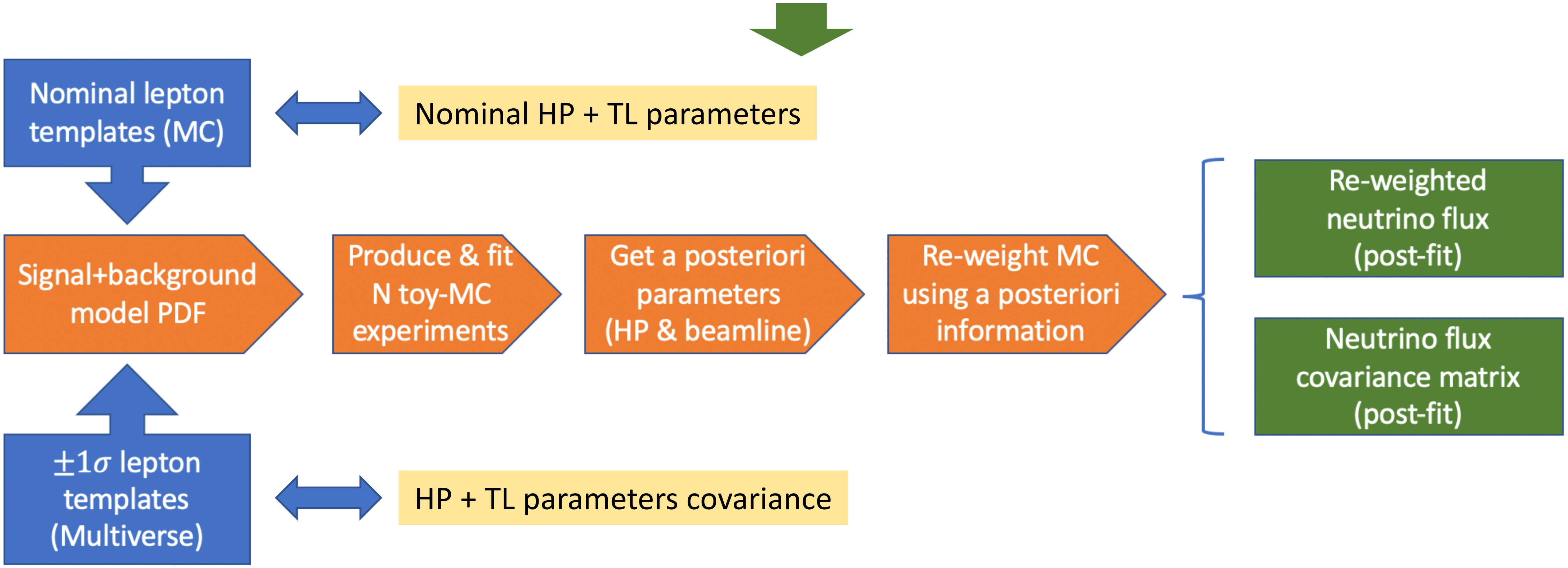
Work in progress!



ν-Flux: assessment of systematics

Monitored ν flux from narrow-band beam: measure rate of leptons ⟺ monitor ν flux

- build a Signal + Background model to fit lepton observables;
- include hadro-production (HP) & transfer line (TL) systematics as nuisances;



Nominal lepton templates (MC)

Nominal HP + TL parameters

Signal+background model PDF

Produce & fit N toy-MC experiments

Get a posteriori parameters (HP & beamline)

Re-weight MC using a posteriori information

Re-weighted neutrino flux (post-fit)

Neutrino flux covariance matrix (post-fit)

$\pm 1\sigma$ lepton templates (Multiverse)

HP + TL parameters covariance

Used toy hadro-production model and mock kinematic variables as test-bench to develop tools and procedure

ν-Flux: assessment of systematics

Model PDF:

$$\mathrm{PDF}_{\mathrm{Ext.}}(\mathrm{N}_{\mathrm{exp}}, \vec{\alpha}, \vec{\beta}) = \mathrm{N}_{\mathrm{S}}(\vec{\alpha}, \vec{\beta}) \cdot \mathrm{S}(\vec{\alpha}, \vec{\beta}) + \mathrm{N}_{\mathrm{B}}(\vec{\alpha}, \vec{\beta}) \cdot \mathrm{B}(\vec{\alpha}, \vec{\beta})$$

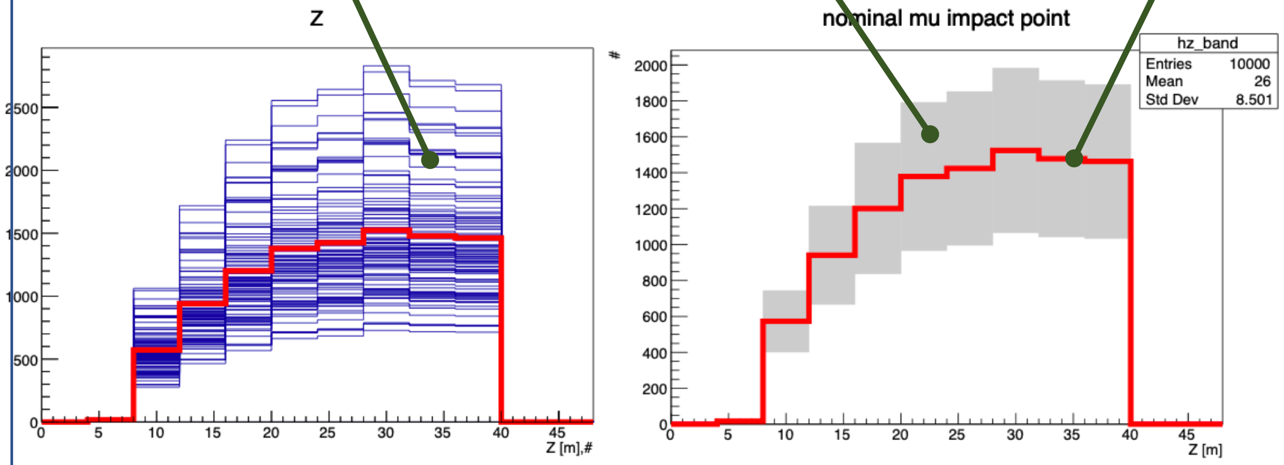
α =hadro-production nuisances / β= transfer line nuisances

Templates: impact point of μ from $K_{\mu\nu}$

Re-weighted distribution from possible nuisance values

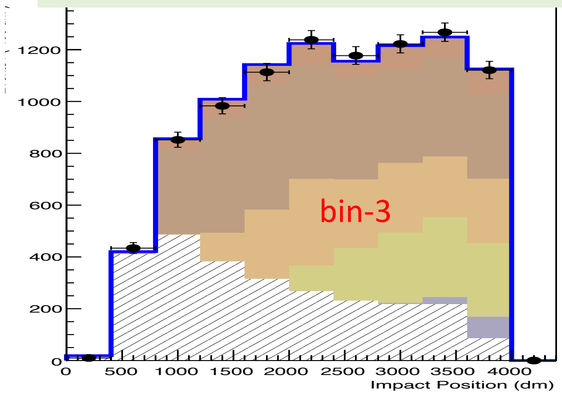
$\pm 1\sigma$ error band

Nominal



Exploit multiverse method to propagate uncertainty on hadroproduction to observables

Example: one toy-MC experiment

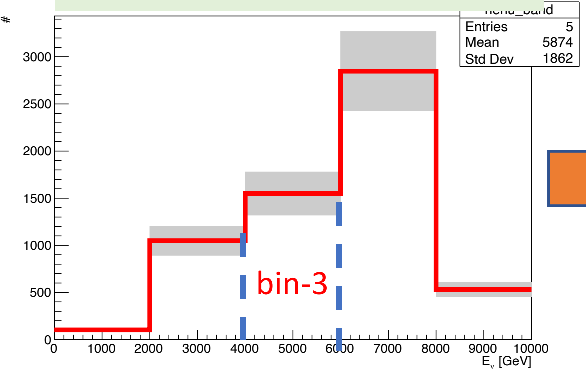


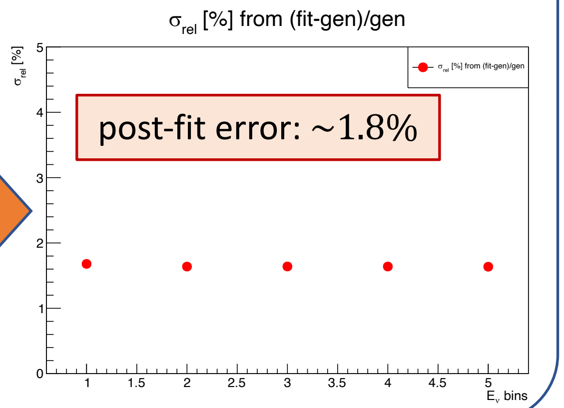
Preliminary result on toy-model

✓ test performed on 500 toy-MC experiments;

✓ constrain on ν-flux @ 1.8% starting from initial systematics of 15%;

E_ν spectrum: 15% error (pre-fit)





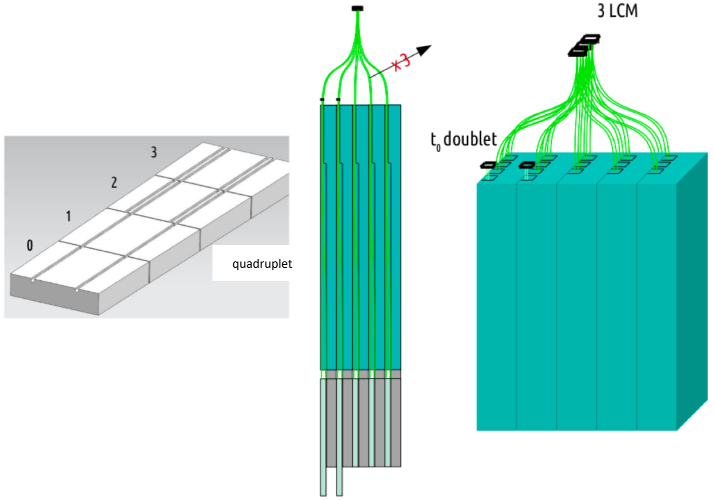
post-fit error: ~1.8%

Next steps:

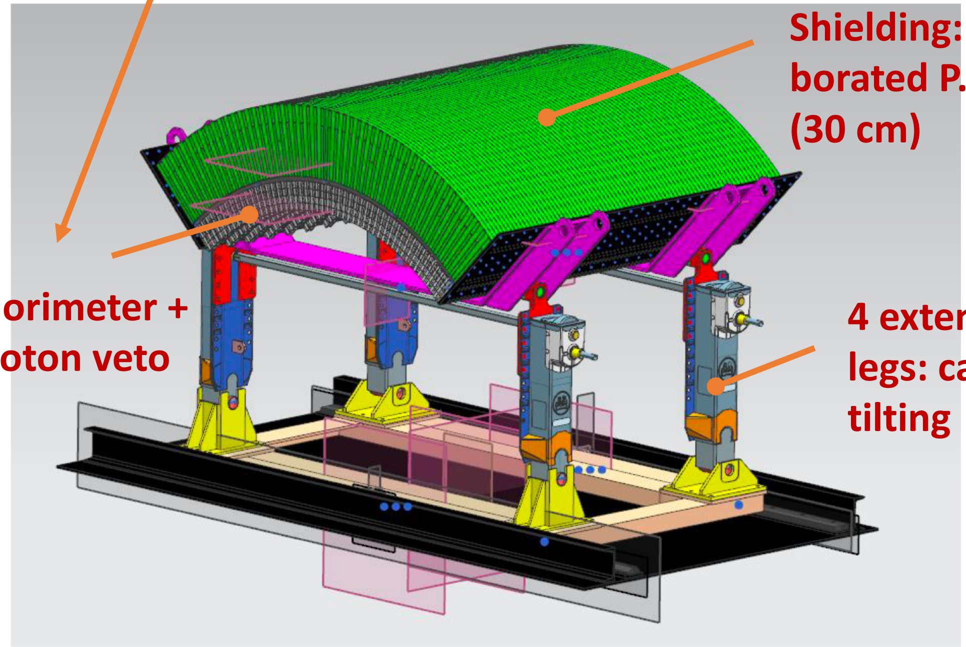
- use real hadro-production data (NA56/SPY @ 400 GeV POT) and related systematics for MC correction;
- exploit ENUBET full simulation to construct templates and their variations;

The demonstrator

New frontal readout scheme & fibers bundling



10 WLS fibers (1 LCM) bundled to a 4 ×4 mm^2 SiPM



Shielding: borated P.E. (30 cm)

calorimeter + photon veto

4 extendible legs: calorimeter tilting

- ❖ building a detector prototype to demonstrate:
  - performance;
  - scalability;
  - cost-effectiveness;

Under test-beam @ CERN in 2022

- ❖ 1.65 m longitudinal & 90° in azimuth;
- ❖ 75 layers of: iron (1.5 mm thick) + shintillator (7 mm thick):
  - => 12X3 LCMs;
- ❖ instrument the central 45° part: rest is kept for mechanical considerations;
- ❖ modular design: can be extended to a full 2π object by joining 4 similar detectors (minimal dead regions);
- ❖ new light readout scheme with frontal grooves instead of lateral grooves:
  - driven by large scale scintillator manufacturing: safer production and more uniform light collection;
  - performed GEANT4 optical simulation validation;
  - ongoing measurements of efficiency maps;
- ❖ scintillators in production phase: UNIPLAST in collab. w/ INR;
- ❖ ENUBINO: pre-demonstrator w/ 3 LCM @ test-beam soon;

Conclusions

- **ENUBET: the goal is to realize the first monitored neutrino beam for high-precision (O(1%)) neutrino cross-section measurements:**
  - ERC project started in 2016;
  - CERN experiment (NP06) within Neutrino-Platform in 2019;
  - part of Physics Beyond Collider framework;
- **Two options for the beam transfer line:**
  - static transfer line: 10^4 ν_e^{CC} events in 2 years (@ SPS) w/ last version;
  - horn based: developed burst-mode slow-extraction scheme & fine-tuned horn;
  - multi-momentum beamline ongoing R&D: DUNE & HyperK optimized;
- **decay tunnel instrumentation design is finalized:**
  - prototypes test-beams @ CERN: technology validation;
  - building final demonstrator to be tested @ PS East Hall in 2022;
- **Detector simulation and PID studies done:**
  - developed full GEANT4 simulation of calorimeter;
  - finalizing waveform to fully asses the pile-up effects;
  - very good PID performance achieved on both positron and muon reconstruction;
- **Full simulation and assessment of systematics in progress:**
  - procedure developed and tested on toy hadro production model: ready to implement for real ENUBET;

ENUBET project is on schedule and in the last stage

Conceptual Design Report @ project end in 2022: physics and costs definition

Thank you for your attention!

Additional Material

Signal reconstruction performance

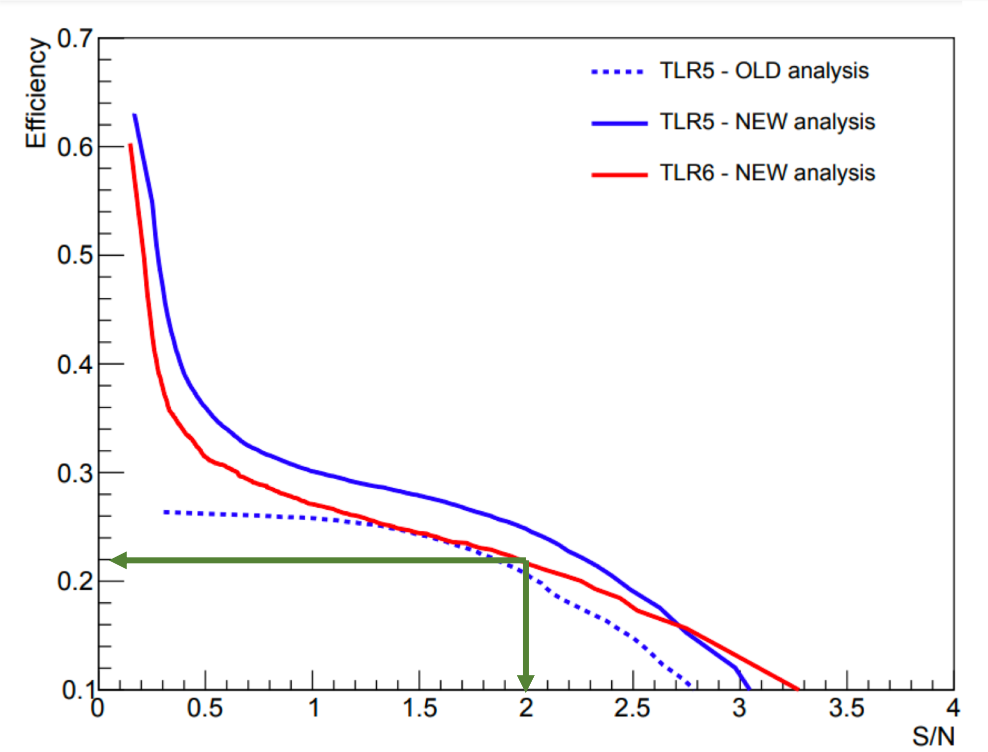
New TLR6 has higher meson yields w.r.t. previous TLR5, but also higher hit rate in the calorimeter: PID performance are preserved

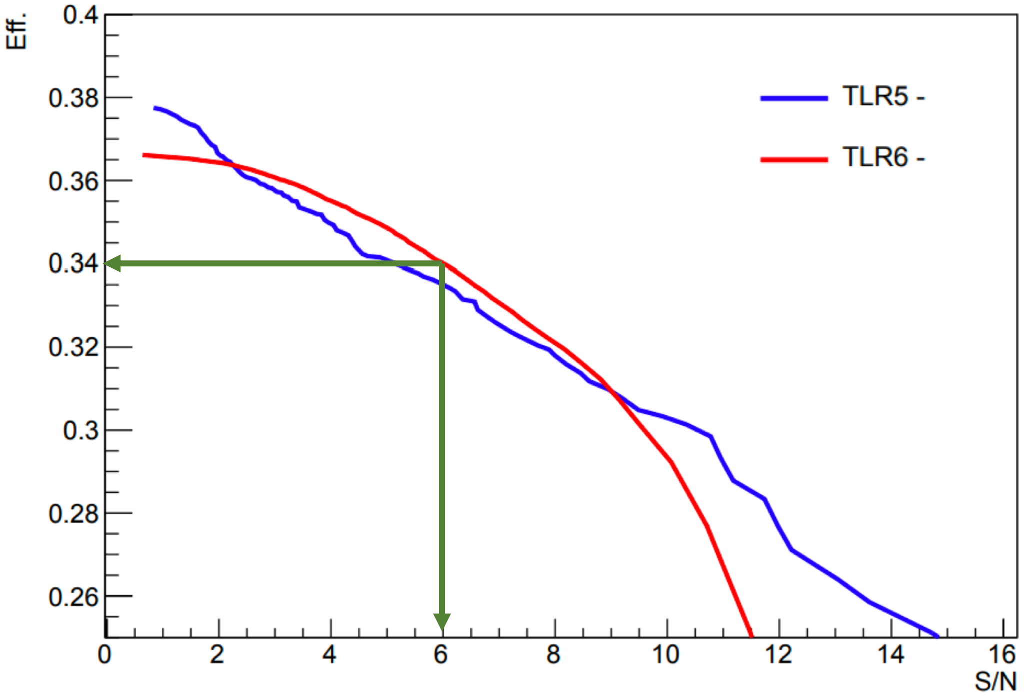
K_{e3} PID performance:

ε = 22%   &   S/N = 2

$K_{\mu\nu}$ PID performance:

ε = 34%   &   S/N = 6





Chosen working points correspond to maximum of $\varepsilon_S \times p$

ε_S= signal efficiency
p = purity

OLD -> NEW analysis: t0-layer information embedded in multivariate analysis

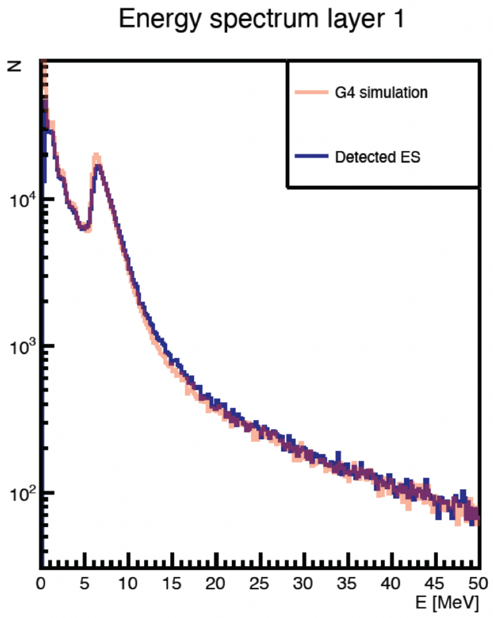
Waveform simulation & pile-up

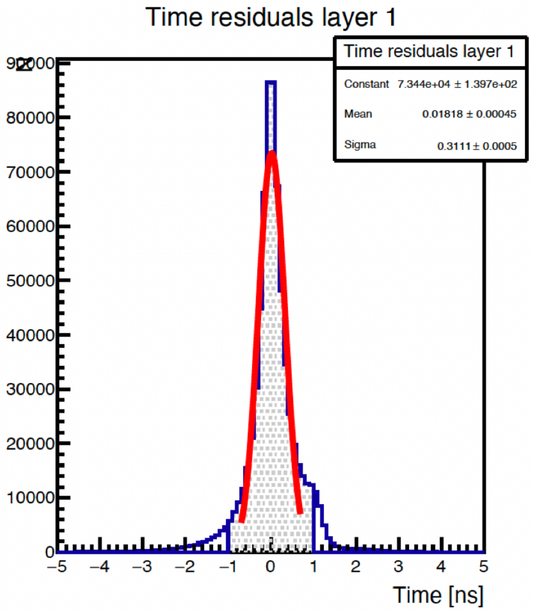
The implementation of waveform generation in the full simulation is being finalized:

- GEANT4 hit-level energy deposits are converted into photons hitting SiPMs (~15 phe/MeV, from test-beams & cosmic rays measurements);
- SiPM response simulated using GoSiP software: fine control on all sensor parameters;
- waveforms are processed with a pulse-detection algorithm: time and energy information are evaluated;
- results is used as input for event building;

Complete assessment of pile-up effects on detector performance

pulse-detection algorithm optimized for faithful energy evaluation, high efficiency, and accurate time resolution


Energy spectrum layer 1


Time residuals layer 1

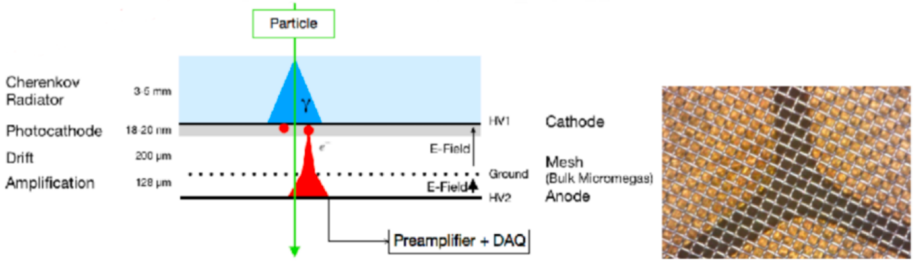
Transfer line and extraction scheme	Hit rate per LCM	detection efficiency
TLR5 slow	1.1 MHz	97.4%
TLR5 fast	10.4 MHz	89.7%
TLR6 slow	2.2 MHz	95.3%

Slow extraction = 4.5×10^{13} POT in 2 s;
Fast extraction (horn) = 10× slow extraction;

Lepton reconstruction and identification:

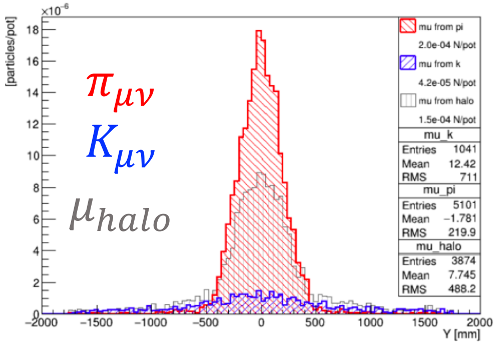
$\pi_{\mu 2}$ muon reconstruction to constrain low-energy ν_μ

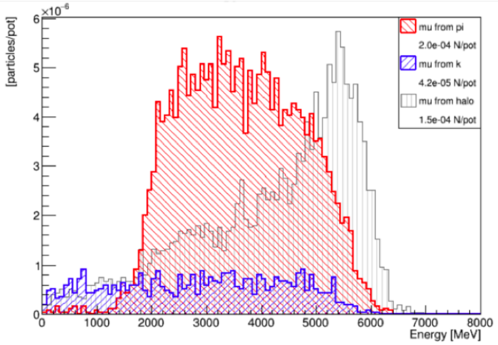
✓ **Low angle muons**: out of tagger acceptance, need muon stations after hadron dump

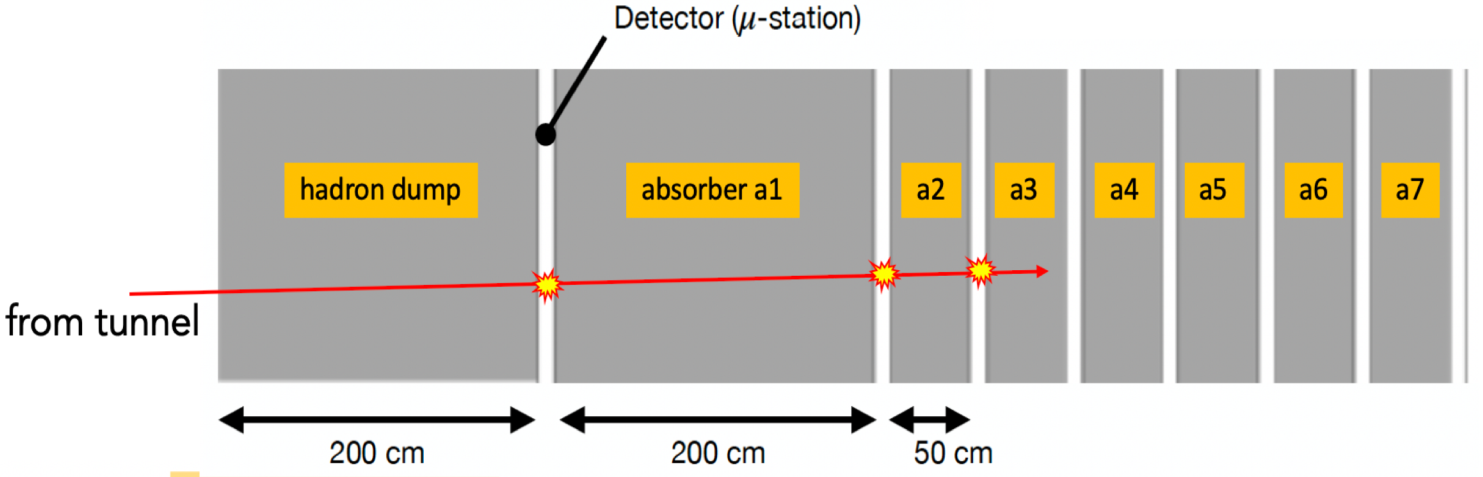


Possible candidates: micromega detectors with Cherenkov radiators (PICOSEC Collaboration)

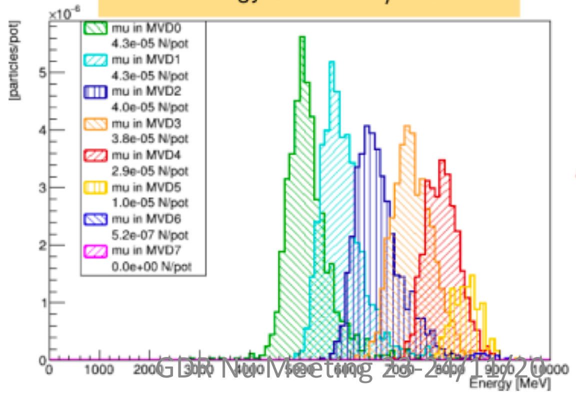
Exploit differences in distributions to disentangle components



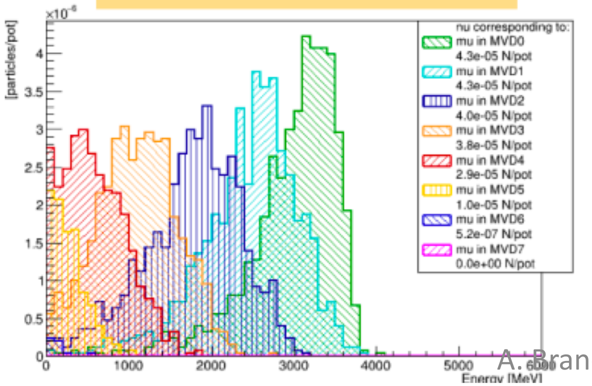




Muon energy @ different μ-stations



Neutrino energy @ different μ-stations



Exploit:

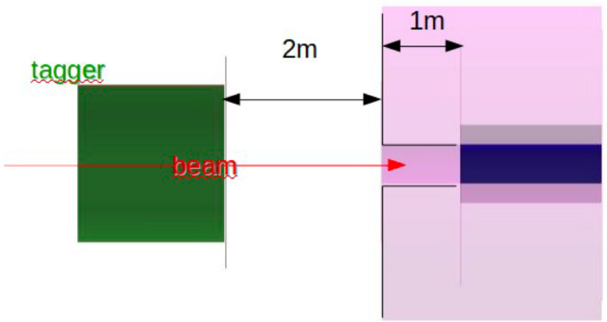
- correlation between number of traversed stations (muon energy from range-out) and neutrino energy;
- difference in distribution to disentangle signal from halo-muons;

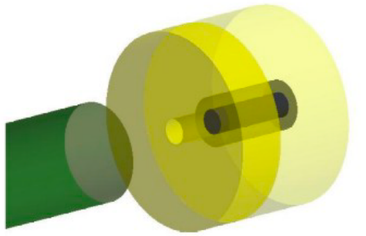
Detector technology: constrained by muon and neutron rates;

Systematics: punch through, non uniformity, efficiency, halo-μ;

Dumps

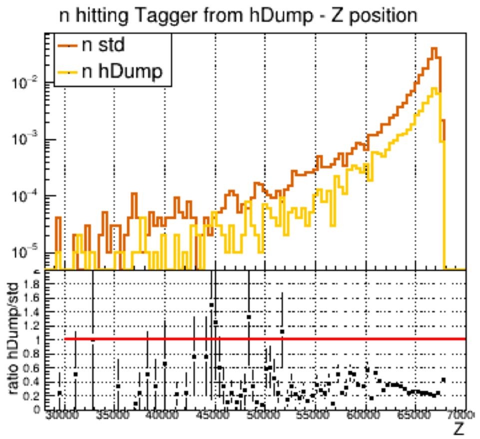
Hadron dump:





graphite core (50 cm diameter), inside layer of iron (1 m diameter), covered by borated concrete (4 m diameter) + 1 m of borated concrete placed in front of hadron-dump with opening for beam;

- ➢ design optimized to reduce the backscattering;
- reduction of the flux all along the tagger;
- in the last part of the tunnel, where neutron fluence is higher, ratio w.r.t. standard dump is ~0.2;



Proton dump:

similar structure, 3 cylindrical layers: 3 m long graphite core, surrounded by aluminum, covered by iron;

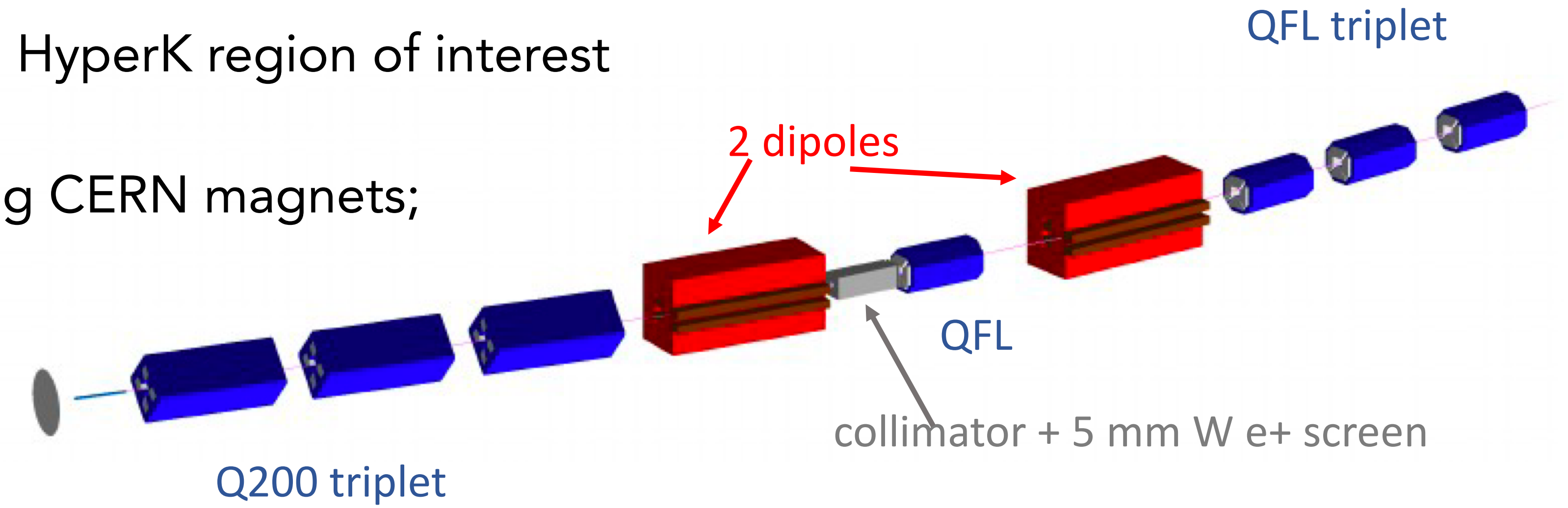
- ➢ final position will be optimized to reduce neutrinos produced here and crossing detector;

Transfer line R&D

Multi-momentum transfer line: 4, 6 & 8.5 GeV

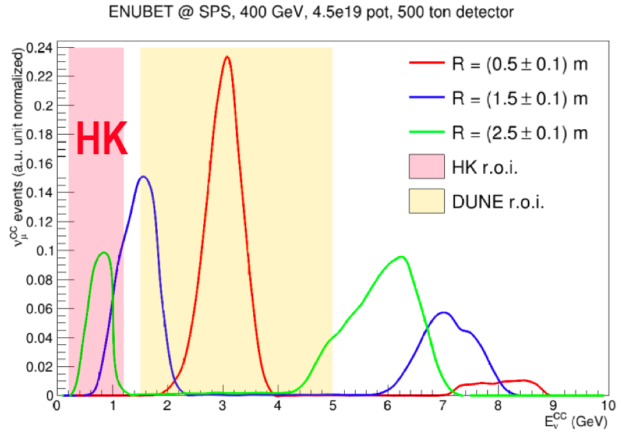
- ➢ would allow to explore also the HyperK region of interest at lower energy;
- current design based on existing CERN magnets;

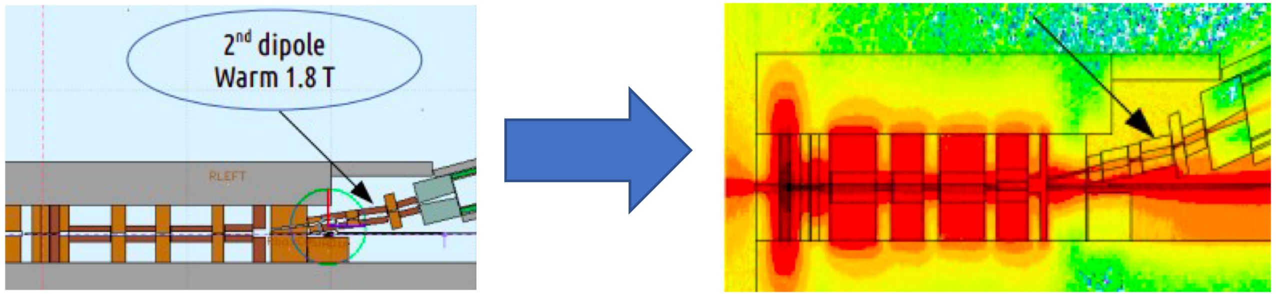
optics optimization: TRANSPORT & G4beamline. Results will be validated with MADX/PTC-TRACK: estimate high-order effects. Background reduction studies: with FLUKA.



Super conducting dipole:

- ➢ could achieve a better separation of the taggable ν_e component from the non taggable one;
- investigating possibility for 2nd dipole: static transfer line fully implemented in FLUKA to estimate ionizing doses and neutron fluence;



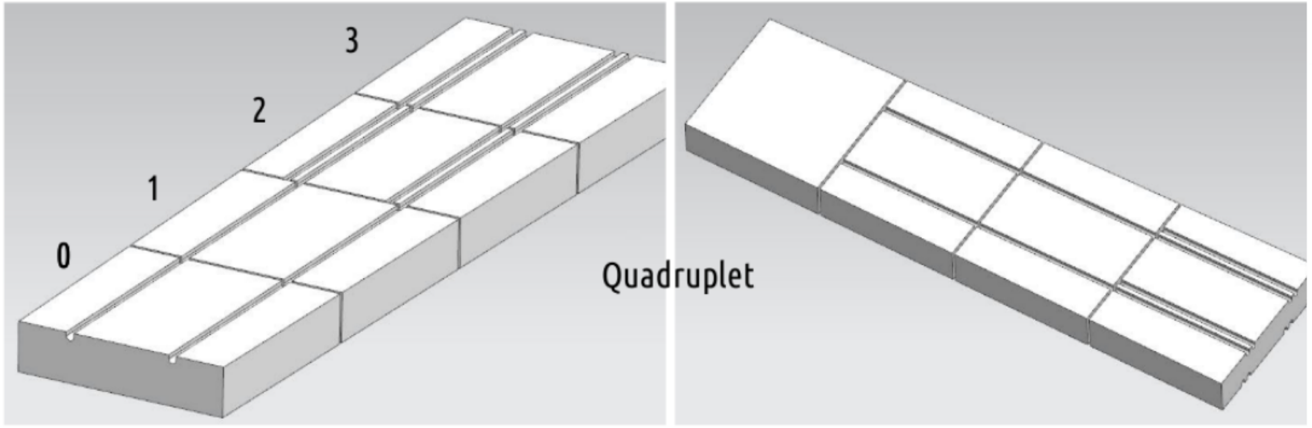


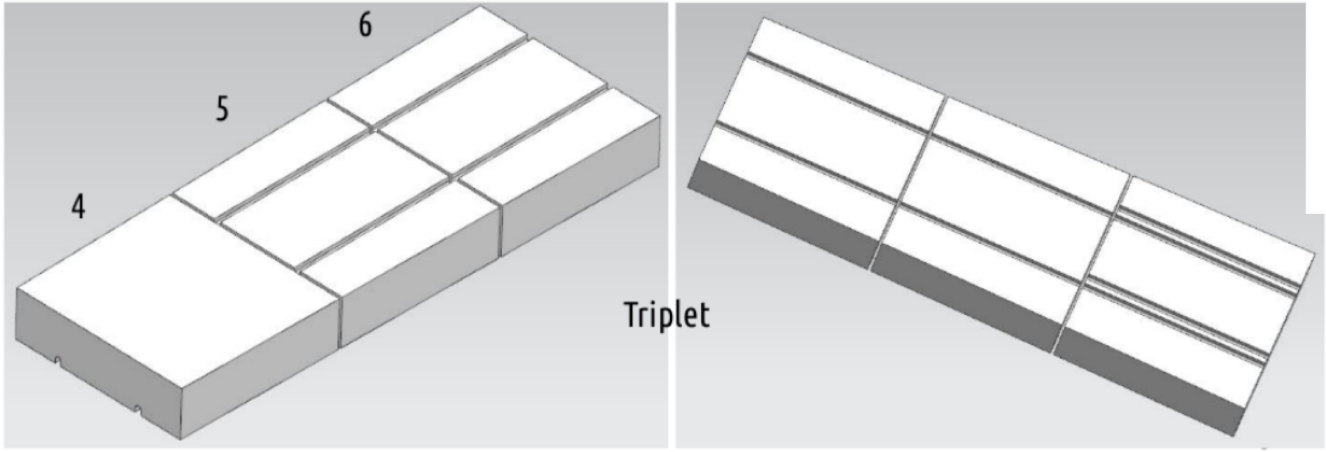
For a 2s spill 0.055 mJ/cm³ => 0.027 mW/cm³ during the 2s slow extraction: looks safe, from LHC studies critical power much higher

https://journals.aps.org/prab/pdf/10.1103)/PhysRevSTAB.18.061002)

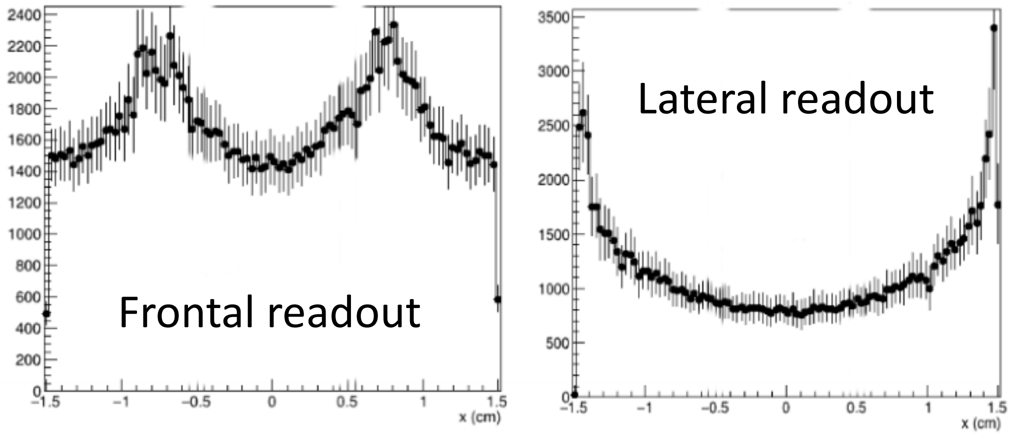
New light readout scheme

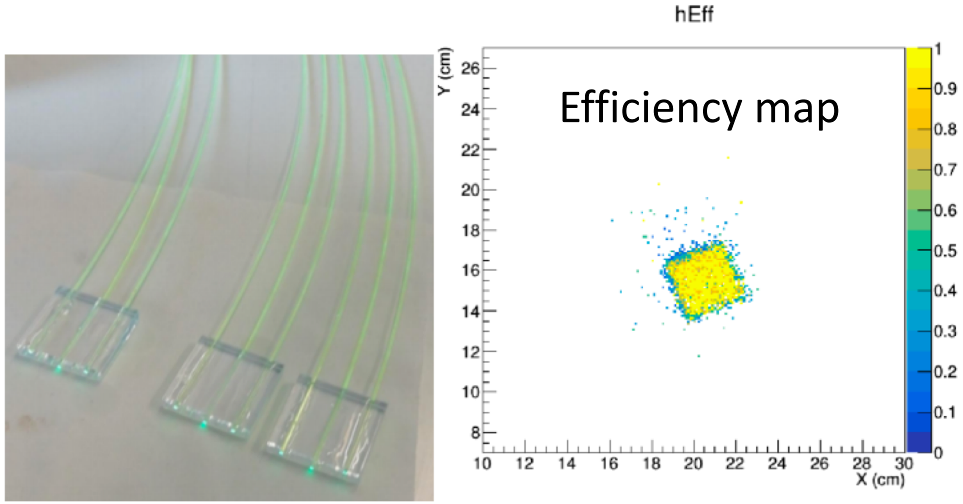
- moved from lateral to frontal light readout;
- safer production: injection molding => transit grooves milled => surface treatment (chemical etching) => readout grooves milled;
- better uniformity and higher efficiency;





GEANT4 optical simulation

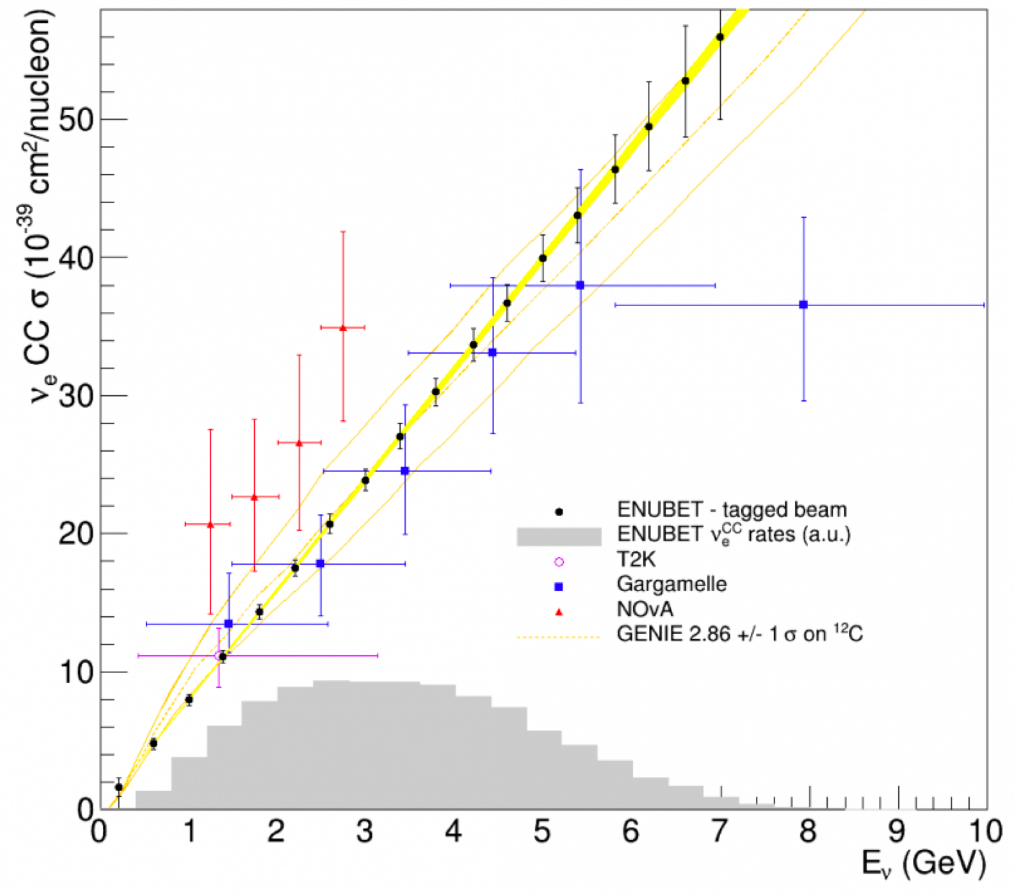




Tests with cosmic rays

Physics opportunities

Electron neutrino cross section



Sterile neutrino

[L. Delgadillo, P. Huber, Phys. Rev. D 103, 035018 (2021)]