The ENUBET monitored neutrino beam and its implementation at CERN

Leon Halić*
on behalf of the NP06/ENUBET Collaboration

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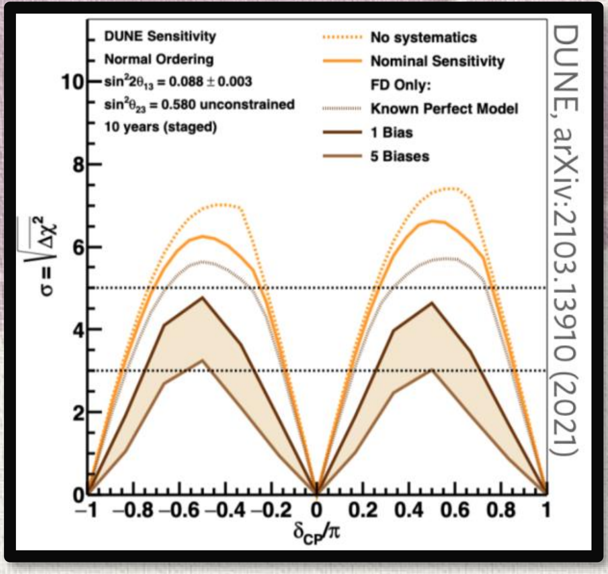
*Ruđer Bošković Institute, Zagreb, Croatia

Accelerator based neutrino experiments have moved from statistics- to the systematics-dominated era

$$\frac{d^2N}{dEdt}(E_\nu) = P(\nu_\mu \rightarrow \nu_e)\Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)$$

Knowledge of neutrino interaction cross section and neutrino flux dominate the final systematic uncertainty of the experiment

Neutrino cross section uncertainty is stuck at 10-30% level, while the community needs are closer to 1% cross section uncertainty



ENUBET – What is needed?

Measure neutrino flux of neutrino cross section experiments to a precision of <1% for both ν_e and ν_μ – generally known at 10%

Measure neutrino energy without relying on the final state – no biases coming from nuclear reinteractions

Use the most common target material used in long baseline neutrino experiments – water and liquid argon

Monitored beams are beams with unprecedented control over neutrino flux and offer precision on the flux of <1%

Monitored narrow-band neutrino beams can measure neutrino energy a-priori by using the narrow-band off-axis technique – O(10%) precision

ProtoDUNE (LAr) and WCTE (H_2O) at CERN provide a perfect opportunity to act as neutrino detectors for a monitored neutrino beam

Enhanced Neutrino Beams from kaon Tagging

F. Acerbi[1], I. Angelis[21], L. Bomben[2,3], M. Bonesini[3], F. Bramati[3,4], A. Branca[3,4], C. Brizzolari[3,4], G. Brunetti[3,4], M. Calviani[6], S. Capelli[2,3], S. Carturan[7], M.G. Catanesi[8], S. Cecchini[9], N. Charitonidis[6], F. Cindolo[9], G. Cogo[10], G. Collazuol[5,10], F. Dal Corso[5], C. Delogu[5,10], G. De Rosa[11], A. Falcone[3,4], B. Goddard[6], A. Gola[1], D. Guffanti[3,4], L. Halić[20], F. Iacob[5,10], C. Jollet[16], V. Kain[6], A. Kallitsopoulou[24], B. Kliček[20], Y. Kudenko[13], Ch. Lampoudis[21], M. Laveder[5,10], P. Legou[24], A. Longhin[a,5,10], L. Ludovici[15], E. Lutsenko[2,3], L. Magaletti[8,14], G. Mandrioli[9], S. Marangoni[3,4], A. Margotti[9], V. Mascagna[22,23], N. Mauri[9], J. McElwee[16], L. Meazza[3,4], A. Meregaglia[16], M. Mezzetto[5], M. Nessi[6], A. Paoloni[17], M. Pari[5,10], T. Papaevangelou[24], E.G. Parozzi[4], L. Pasqualini[9,18], G. Paternoster[1], L. Patrizii[9], M. Pozzato[9], M. Prest[2,3], F. Pupilli[5], E. Radicioni[8], A.C. Ruggeri[11], G. Saibene[2,3], D. Sampsonidis[21], C. Scian[10], G. Sirri[9], M. Stipčević[20], M. Tenti[9], F. Terranova[3,4], M. Torti[3,4], S.E. Tzamarias[21], E. Vallazza[3], F. Velotti[6], L. Votano[17]

72 Physicists

ENUBET

17 Institutions

ENUBET – A monitored neutrino beam

ERC Project
(2016-2022)

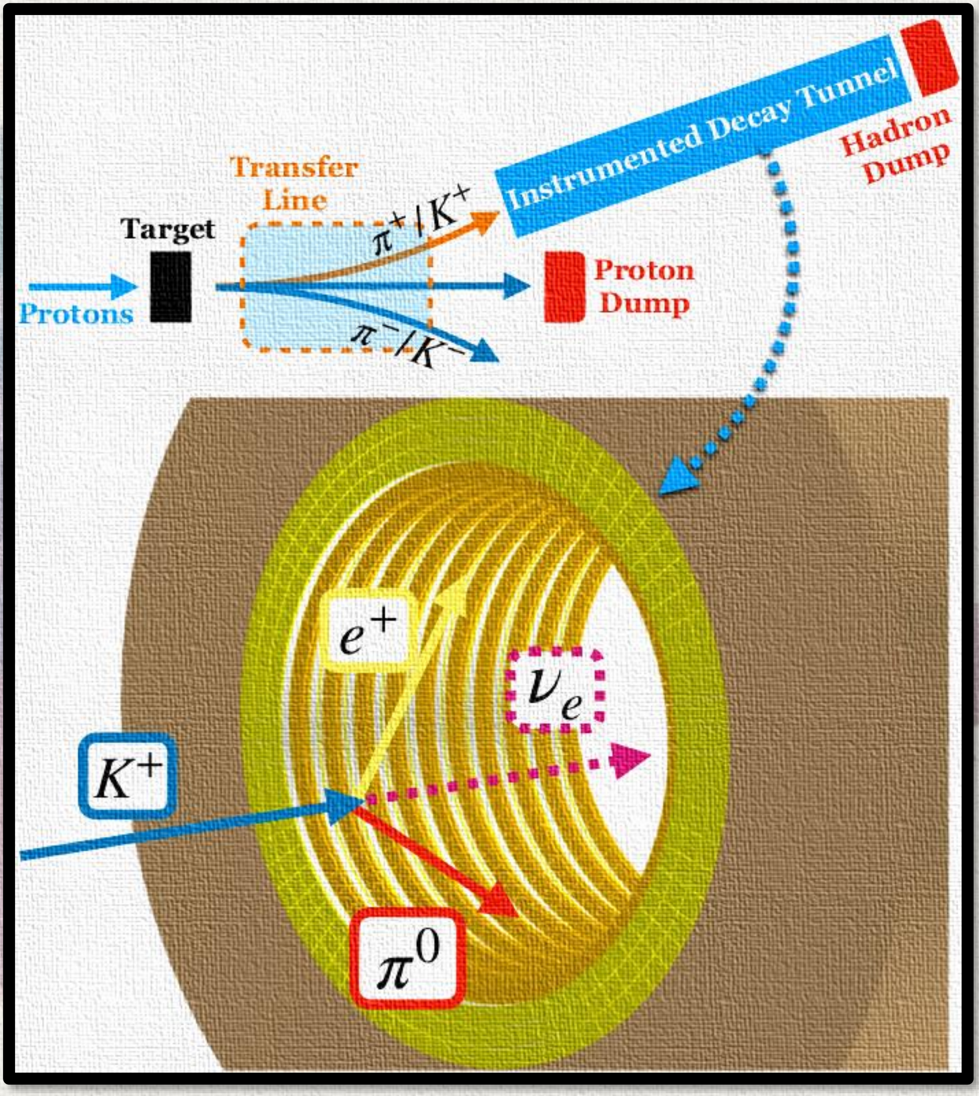
Aim: Measure positrons from K_{e3} decay (in tunnel) to determine the ν_e flux

$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$

CERN Neutrino Platform
(2019-present)

Aim: Extend measurement to antimuons from $K_{\mu 2}$ (in tunnel) and $\pi_{\mu\nu}$ (in dump) decays to determine ν_μ flux

$$\pi^\pm \rightarrow \mu^\pm + \bar{\nu}_\mu \quad K^\pm \rightarrow \mu^\pm + \bar{\nu}_\mu$$

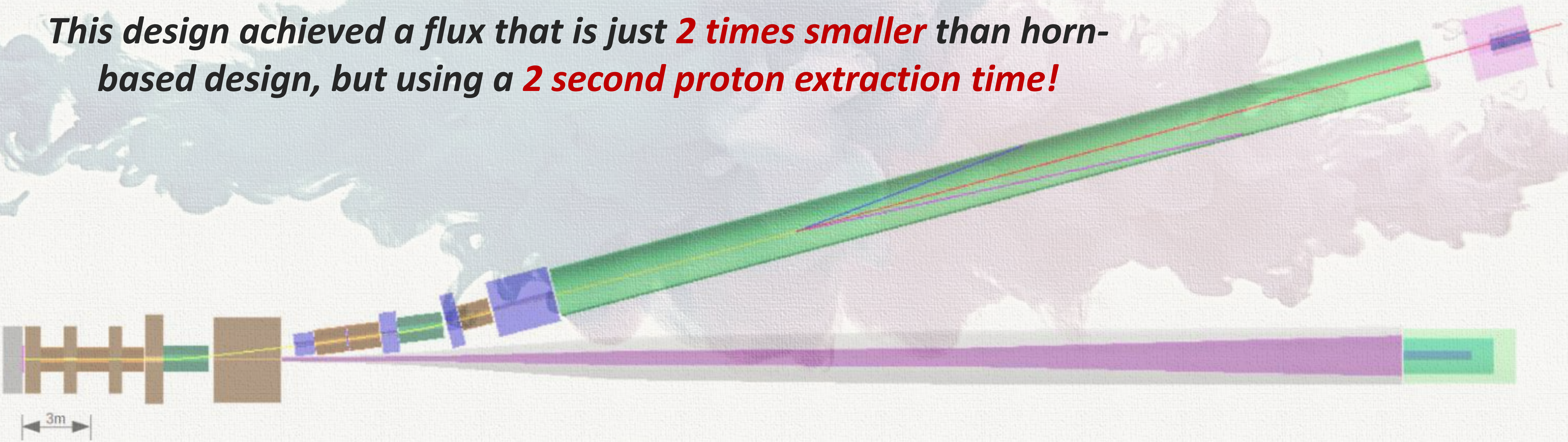


ENUBET – Challenges & Solutions

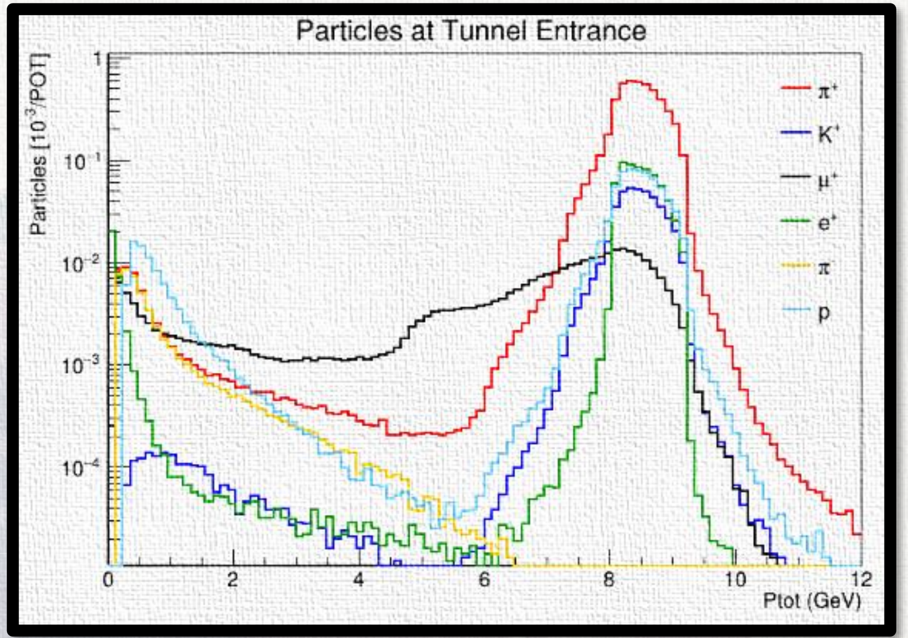
*Conventional neutrino beams with fast extractions and a horn system lead to a **large pile-up** and **saturation** of the instrumentaion in the decay tunnel – we need a **slow extraction system***

ENUBET** uses a completely **static focusing system** where focusing at 8.5 GeV/c is acommplished by **quadrupoles

*This design achieved a flux that is just **2 times smaller** than horn-based design, but using a **2 second proton extraction time!***



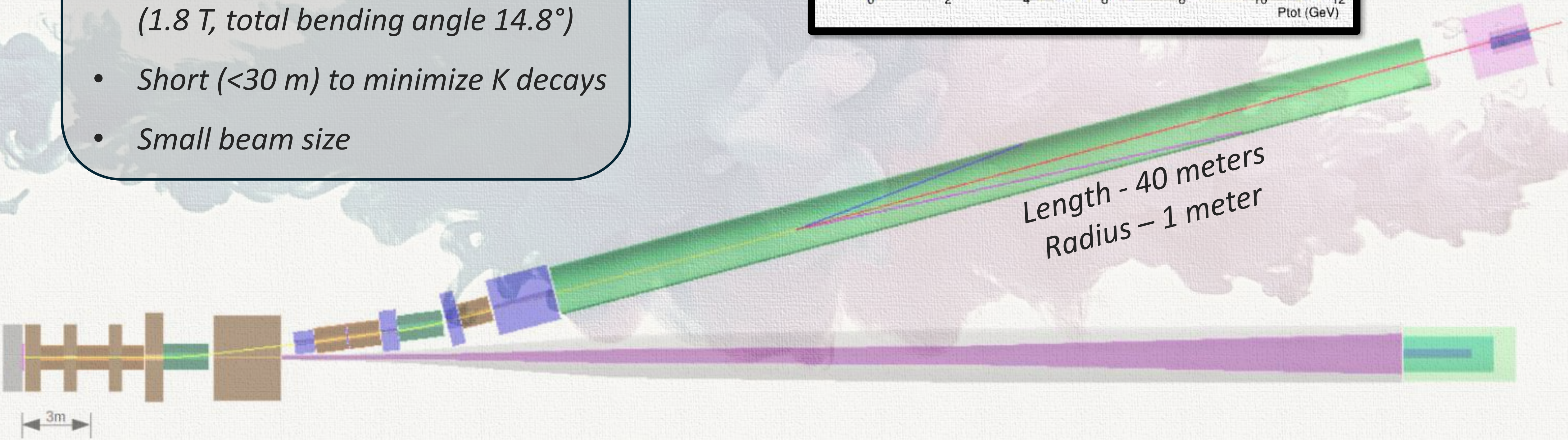
ENUBET – Challenges & Solutions



Transfer Line

- *Normal conducting magnets*
- *Quadrupoles + 2 dipoles*

  (1.8 T, total bending angle 14.8°)
- *Short (<30 m) to minimize K decays*
- *Small beam size*



ENUBET – Decay tunnel instrumentation

Photon & π^0 Veto

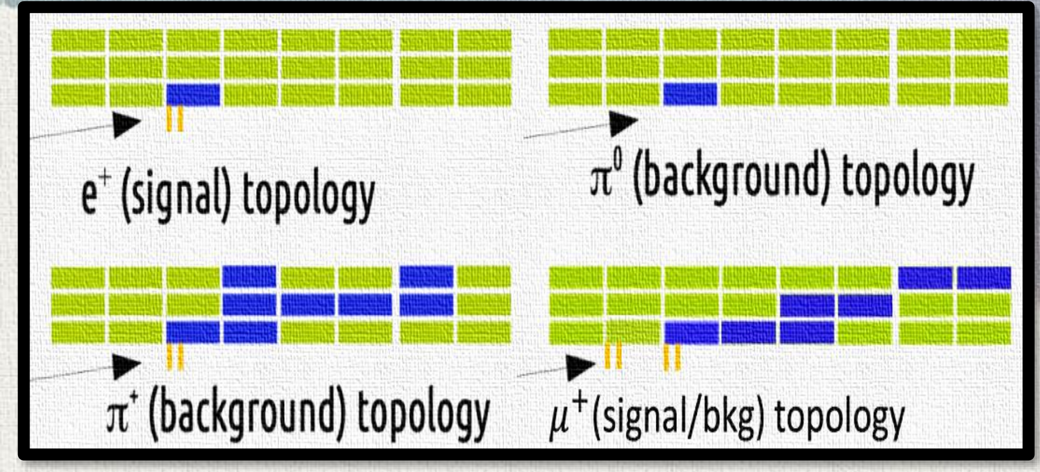
Plastic scintillator tiles forming the inside ring

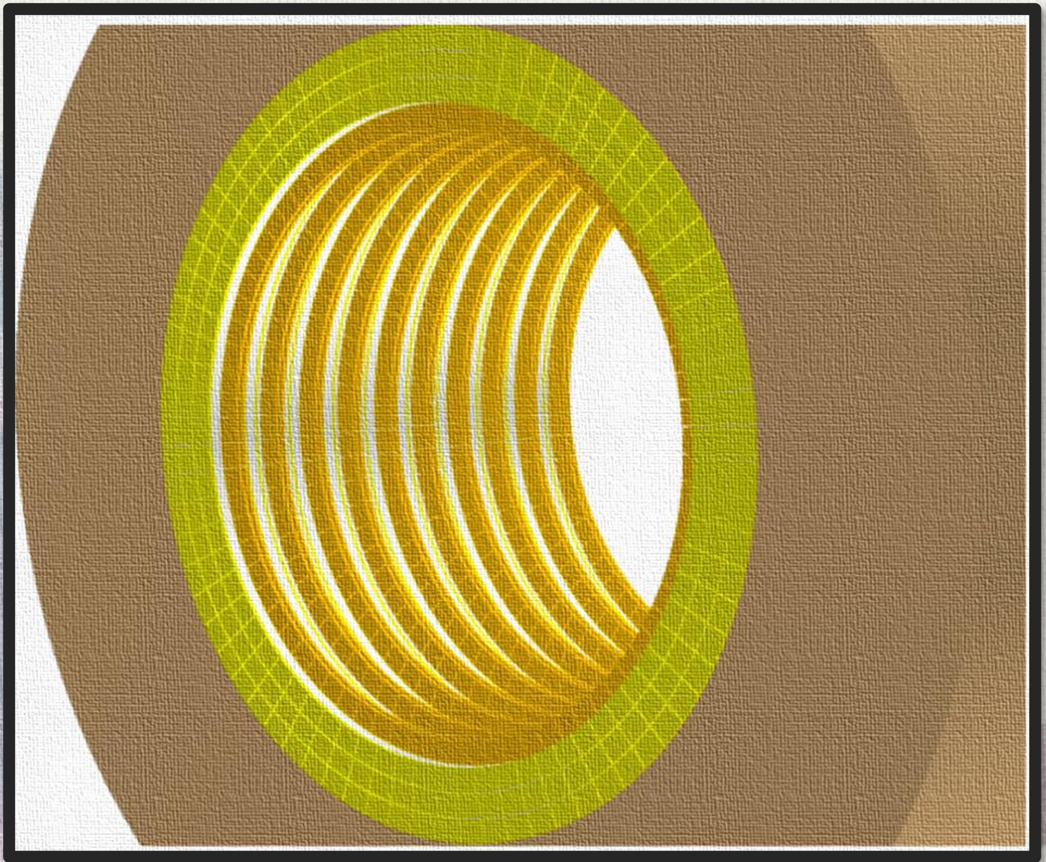
Calorimeter

Plastic scintillator and iron interlayered

3 radial layers

WLS fibers to SiPM for light collection

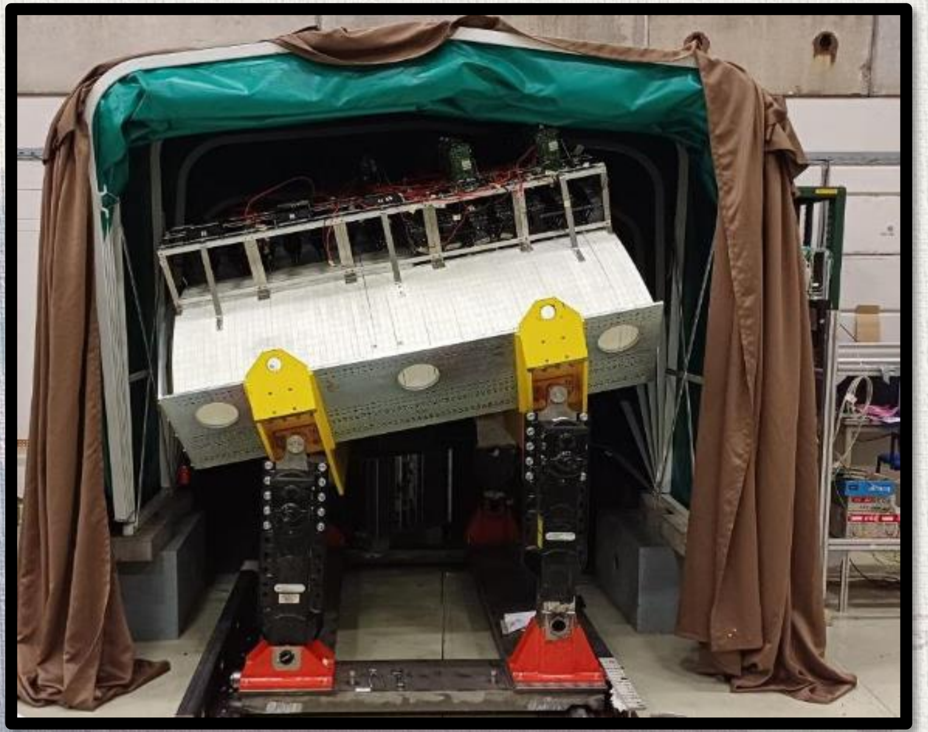




Hadron dump instrumentation

Muon stations to monitor muons from pion decays which have low scattering angle (misses decay tunnel walls)

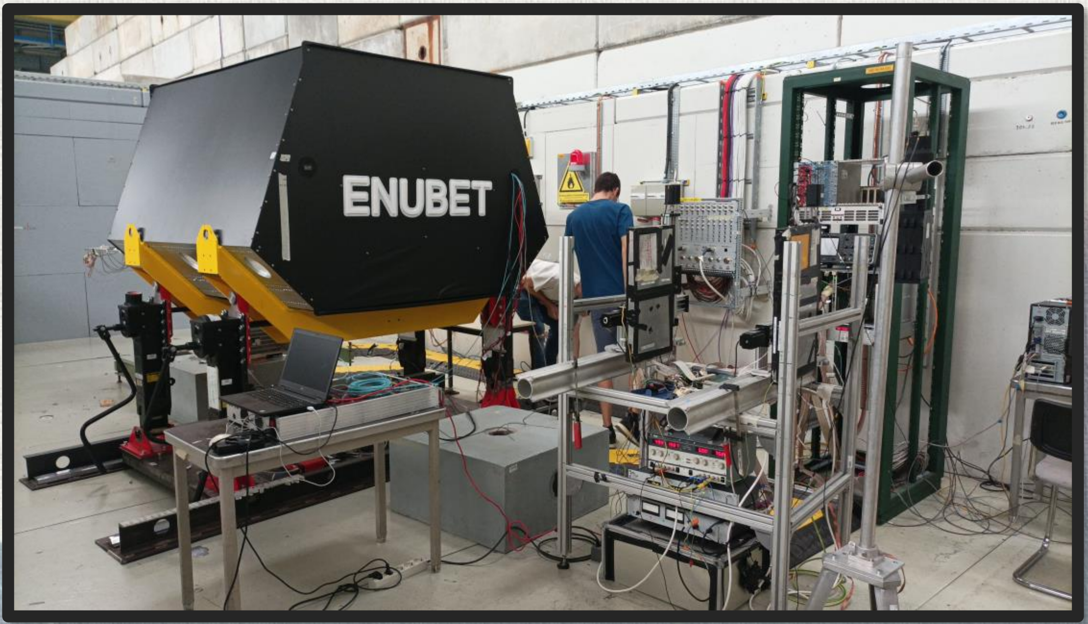
ENUBET – The Demonstrator



Specifications

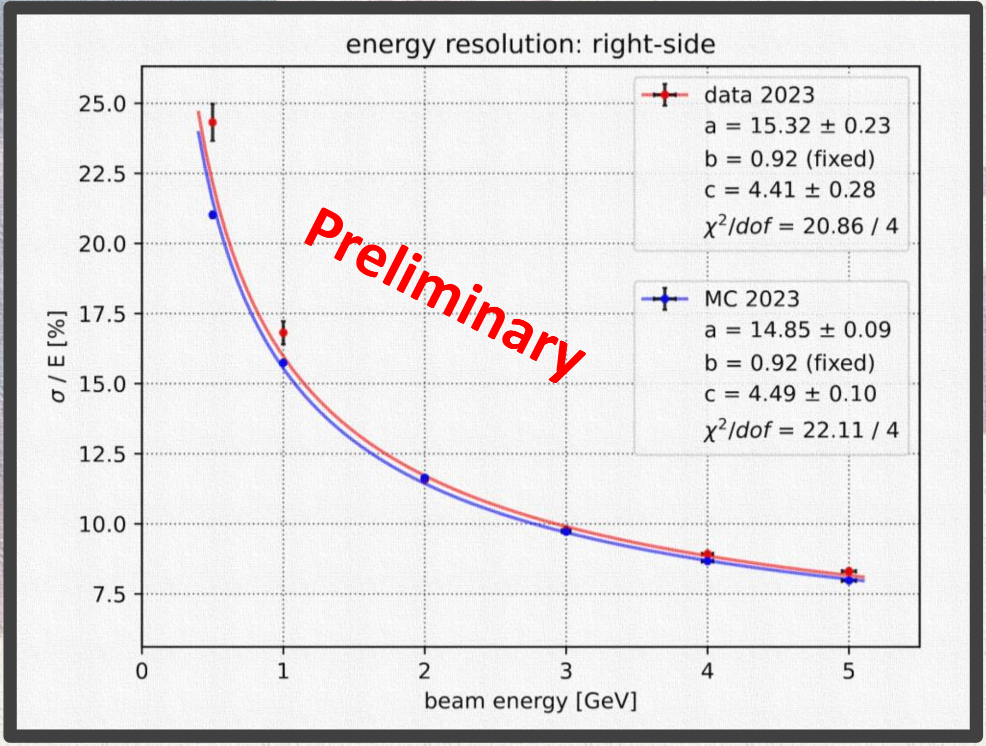
- *1.65 m long, π/4 coverage*
- *Scintillator tiles: 4335*
- *WLS fiber: 4.5 km*
- *SiPM channels: 1275*
- *64ch boards (CAEN A5202): 22*

ENUBET – Beamtests



Beamtests were performed in 2022, 2023 and 2024

Data from all these are in analysis – publication in coming months

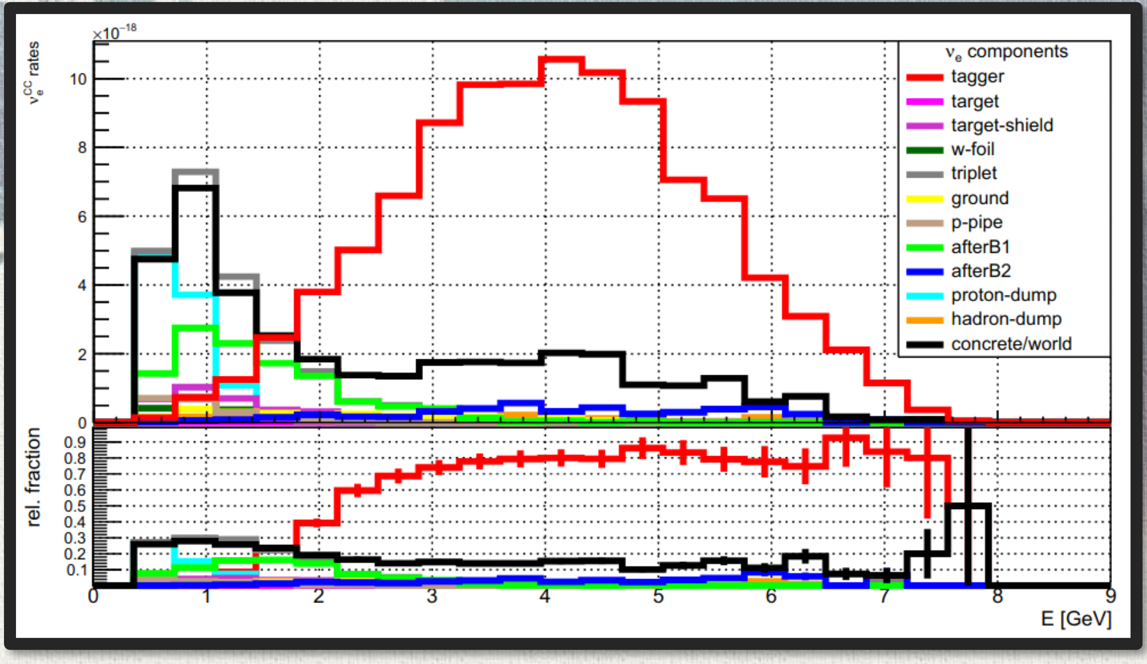


ENUBET – Beam design and performance

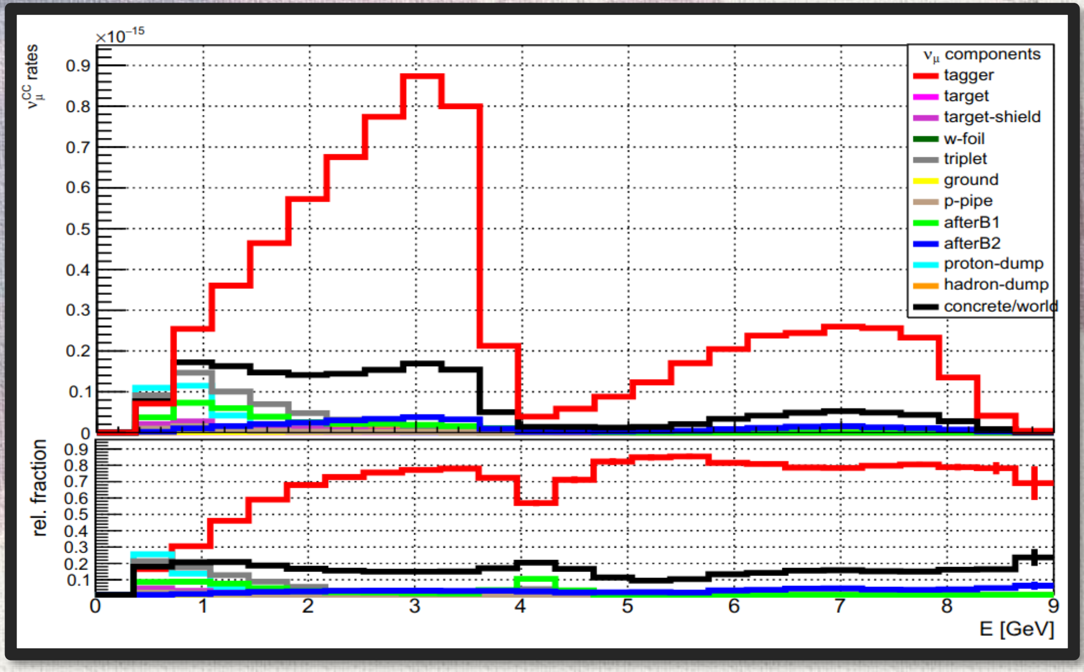
CERN SPS** proton driver with 400 GeV protons and **2 s spill

Detector baseline is 50 m with 500 t target mass

~4000 ν_e CC/year
@ 4.5 x 10^{19} POT



9 x 10^4 ν_μ CC/year ($K_{\mu 2}$) and 22.5 x 10^4 ν_μ CC/year ($\pi_{\mu\nu}$)
@ 4.5 x 10^{19} POT

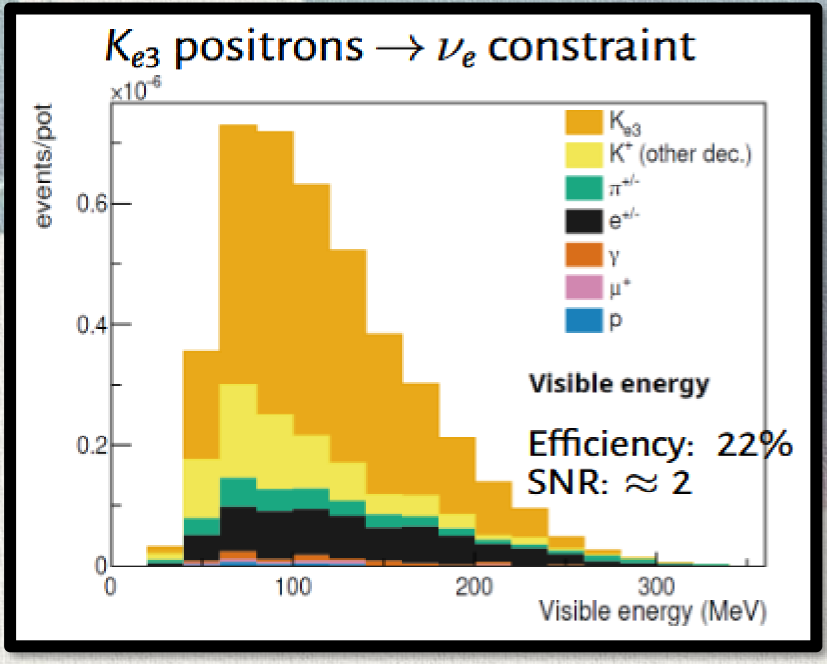


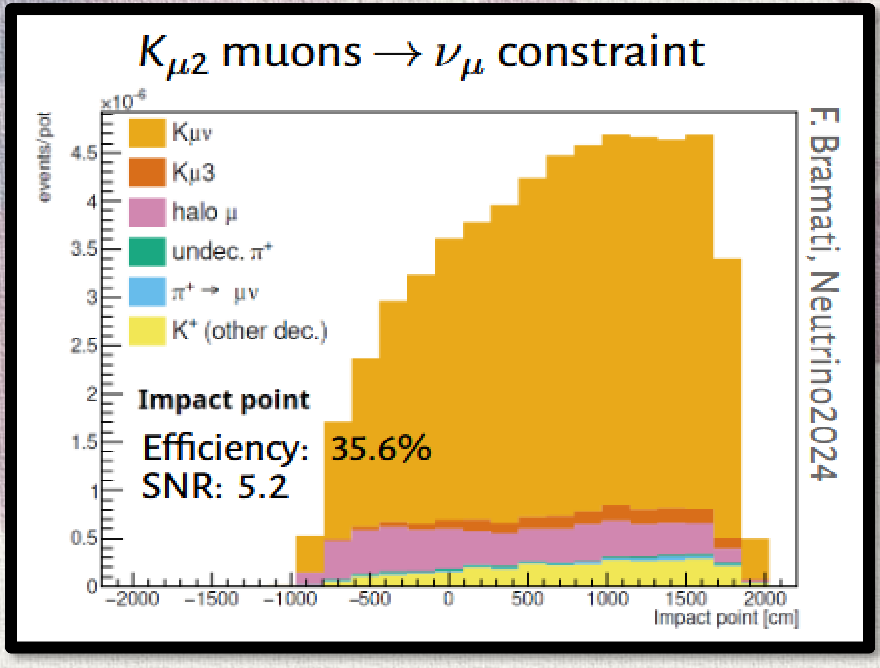
ENUBET – Beam design and performance

*Full **GEANT4 simulation** of the instrumented decay tunnel – validated by prototype tests at CERN*

***Large angle positrons** and **muons** from K decays reconstructed by searching for patterns in E_{dep} in tagger*

Signal identification done using a Neural Network trained on a set of discriminating variables



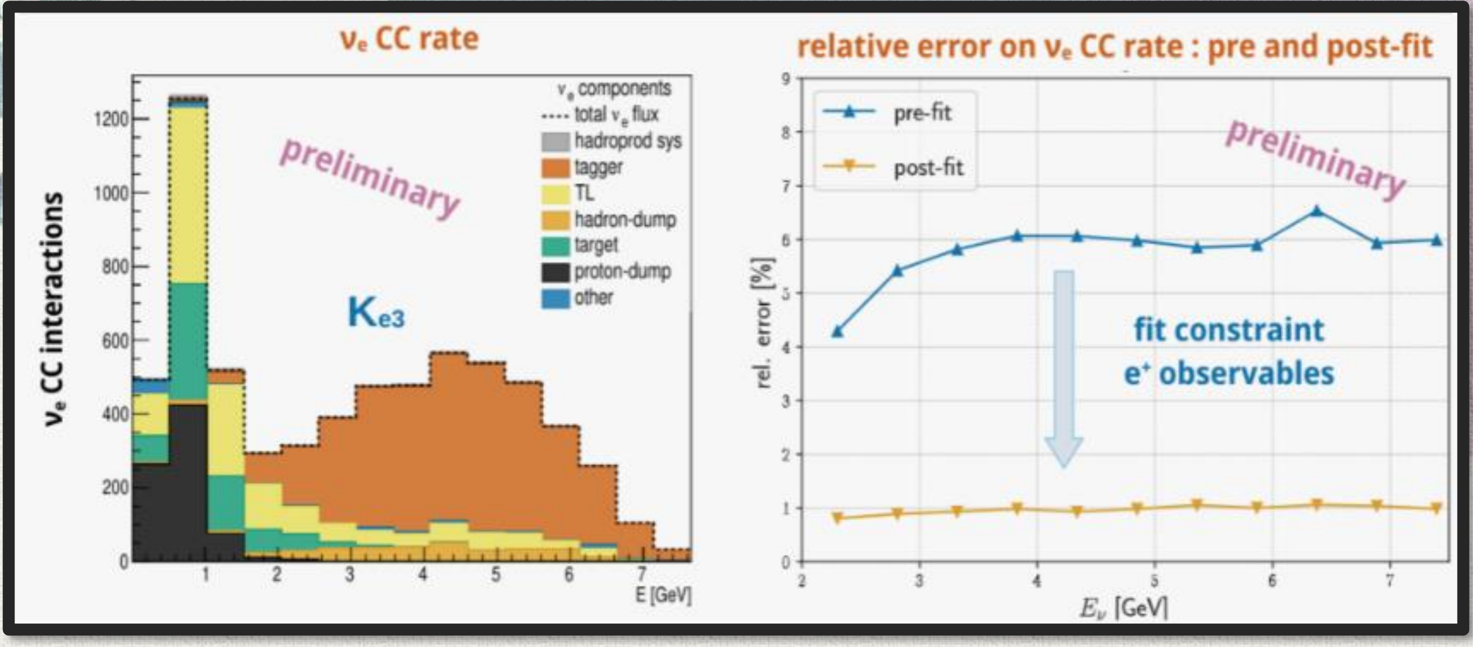


ENUBET – Determination of neutrino flux

*To establish the **flux precision**, we performed the same systematic assessment analysis performed by experiments like Minerva or T2K*

*Dominant systematic extracted from experimental data (NA56/SPY) – **6% uncertainty** on flux*

Rate, position and energy distribution** of positrons from K decays measured in the tunnel used as a **prior



Flux uncertainty drop

6%

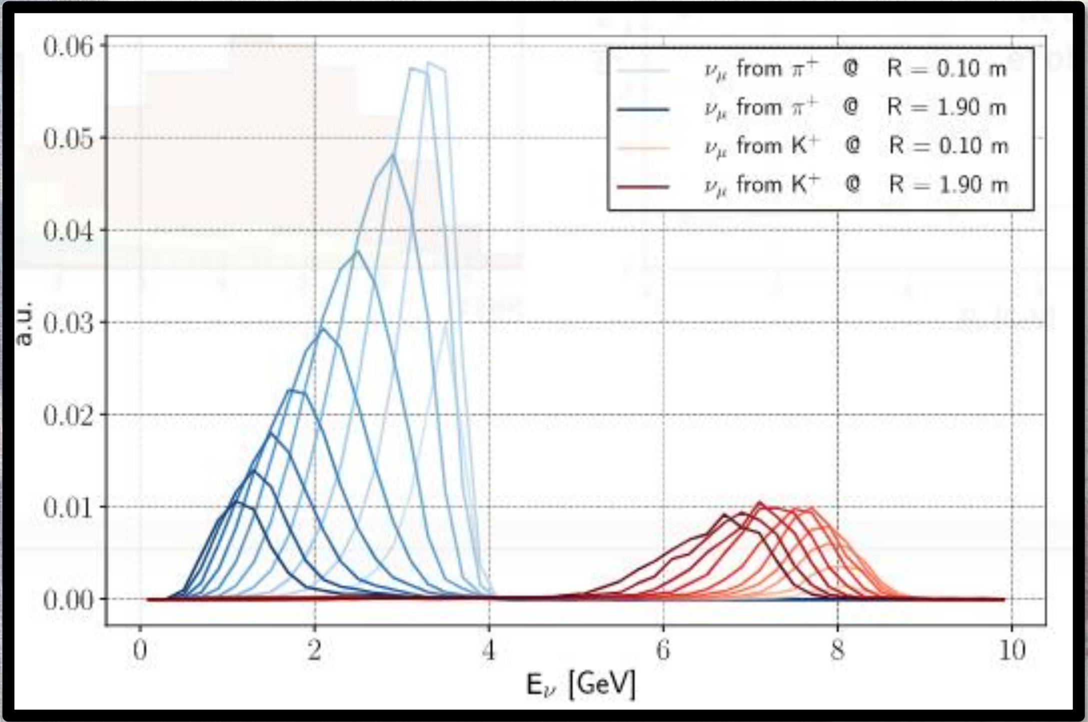
1%

ENUBET – A priori measurement of neutrino energy

Possible only for ν_μ coming from $K_{\mu 2}$ decays

Narrow-band off-axis technique

When the beam has narrow momentum, O(5-10%), neutrino energy and radial distance of interaction vertex are strongly correlated



No need to rely on final state particles from ν_μ CC interactions

10-25% E_ν resolution from π decays in the DUNE energy range

ENUBET – the way beyond ENUBET

Limitations of the current ENUBET design

- *Facility optimized for DUNE, but we want to cover also lower energies*
- *Number of POT is too high to run ENUBET @ CERN in parallel with SHiP*
- *Inadequate statistics at low energy, especially below 2 GeV*

Short-Baseline Neutrinos @ Physics Beyond Colliders – SBN@PBC

Proposal under study by CERN, ENUBET, NuTAG and the CERN Neutrino Platform to address such limitations and set the ground for the next generation of cross section experiment

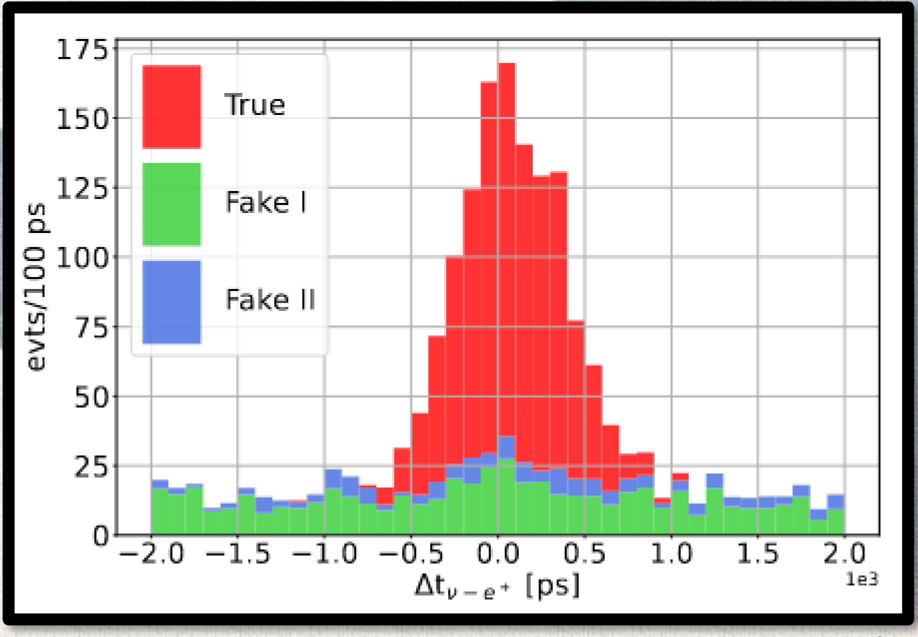
Preliminary results of beamline from SBN@PBC

- *Can run at lower secondary momenta (4-8.5 GeV/c)*
- *Achieves ENUBET performance with 33% of the POT needed in the original design*
- *Collects large ν_μ statistics in the 1-2 GeV range*
- *Improved E_ν resolution by measuring parent momentum and exploiting time tagging*

ENUBET – Time Tagged Neutrino Beam

Time Tagged Neutrino Beam

***Matching** detected **neutrinos** with corresponding detected **charged leptons** in the instrumented decay tunnel*



$\sigma_t = 200 \oplus 200\, ps$ $\quad E_\nu > 1.5$ *GeV* $\quad$ *SNR ≈ 3/4*

***Time coincedence** between **neutrino** event in the detector and **lepton** event in the tagger*

*Even better tagging by introducing the **NuTAG concept** – silicon trackers in the beamline to monitor the neutrino parent*

Expected E_ν resolution: 1%

ENUBET – Summary

Monitored neutrino beam is not longer an interesting idea, it is now a matured technology

We can measure the charged leptons in a decay tunnel using a horn-less beam

- *DUNE energy range (ENUBET)*
- *DUNE + Hyper-Kamiokande energy range (SBN@PBC)*
- *ESSnuSB energy range (ESSnuSB+)*

ENUBET design fulfills all requirements for a new generation of cross section experiments

- *Statistical error <1% with a 500 ton detector*
- *Flux systematic uncertainties <1%*
- *Estimate of the neutrino energy with 10-25% precision*

Moving towards an experimental proposal for implementation at CERN using ProtoDUNE and/or WCTE

Common effort of ENUBET, NuTAG, and CERN to overcome current limitations and exploit time tagging

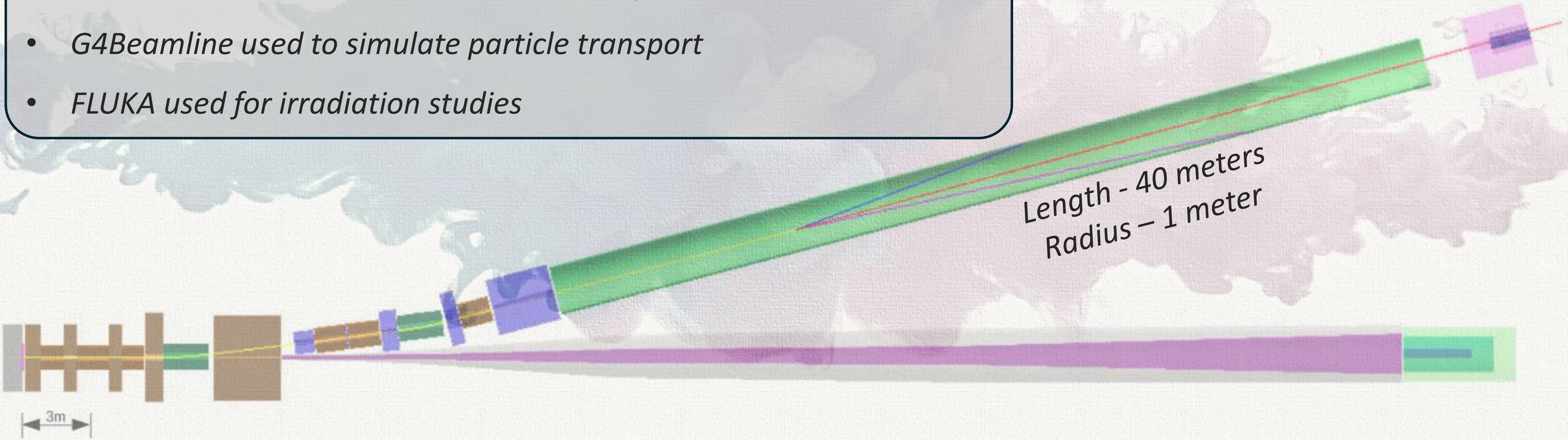
Backup Slides

ENUBET – Challenges & Solutions

- *Particle rate at the tunnel: below 100 kHz/cm² using a hornless beam*
- *Radiation dose at the tunnel detector well below 10 Gy and 10^{11} n/cm²*

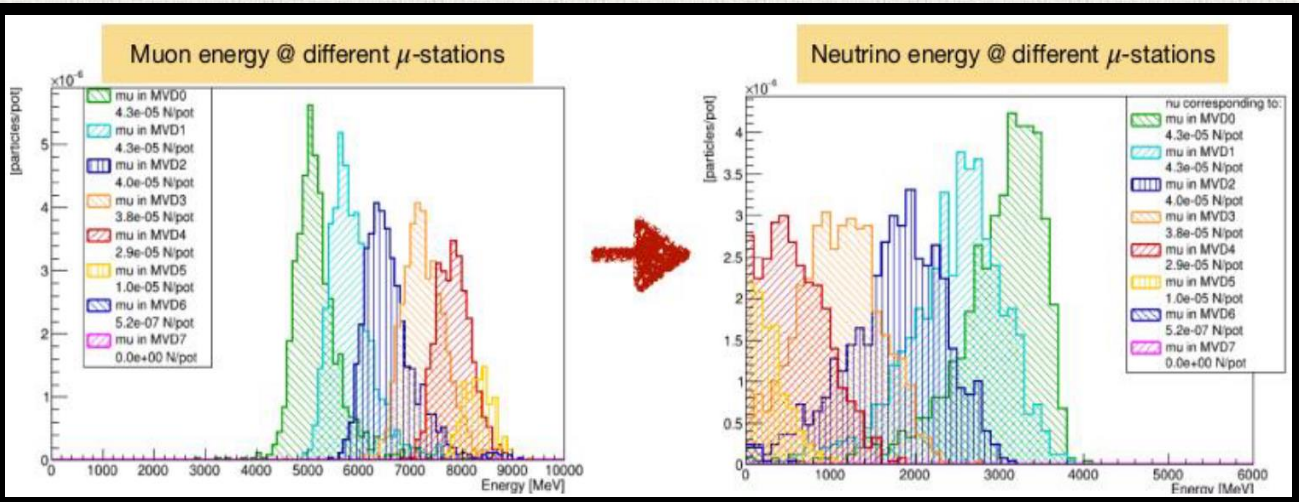
Simulation

- *5% momentum bite centered at 8.5 GeV, optimized with TRANSPORT*
- *G4Beamline used to simulate particle transport*
- *FLUKA used for irradiation studies*



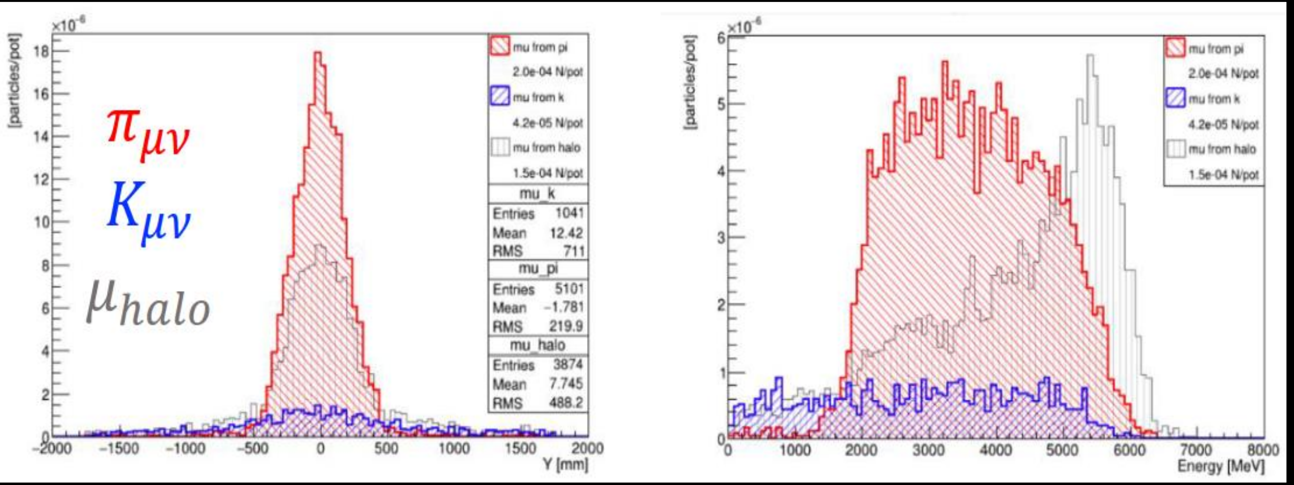
ENUBET – Hadron dump instrumentations

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

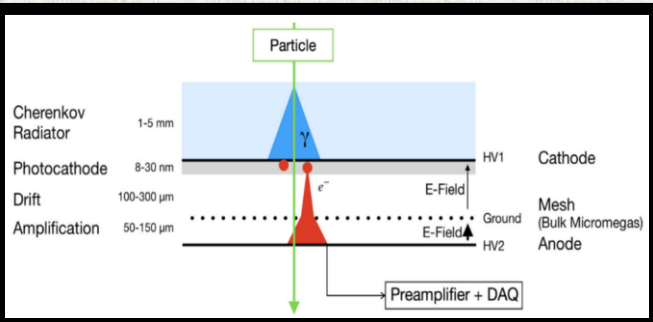


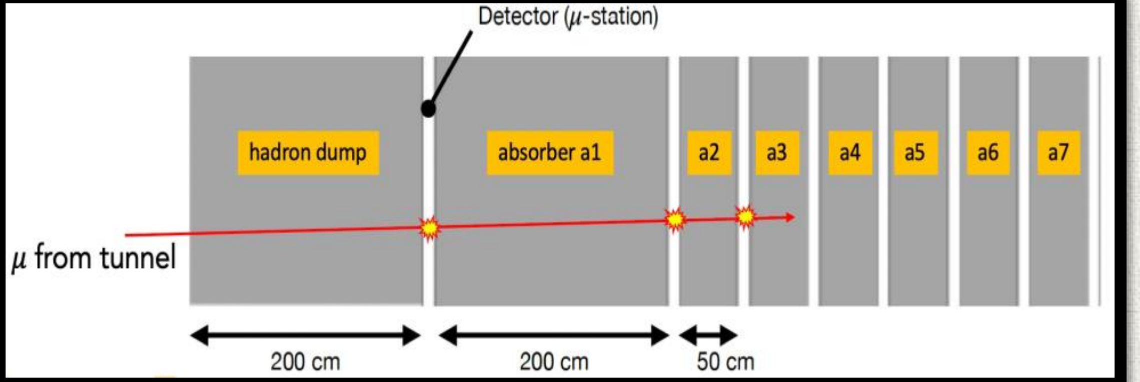
Exploiting correlation between number of traversed stations and neutrino energy

Exploit differences in distributions to disentangle signal from halo-muons

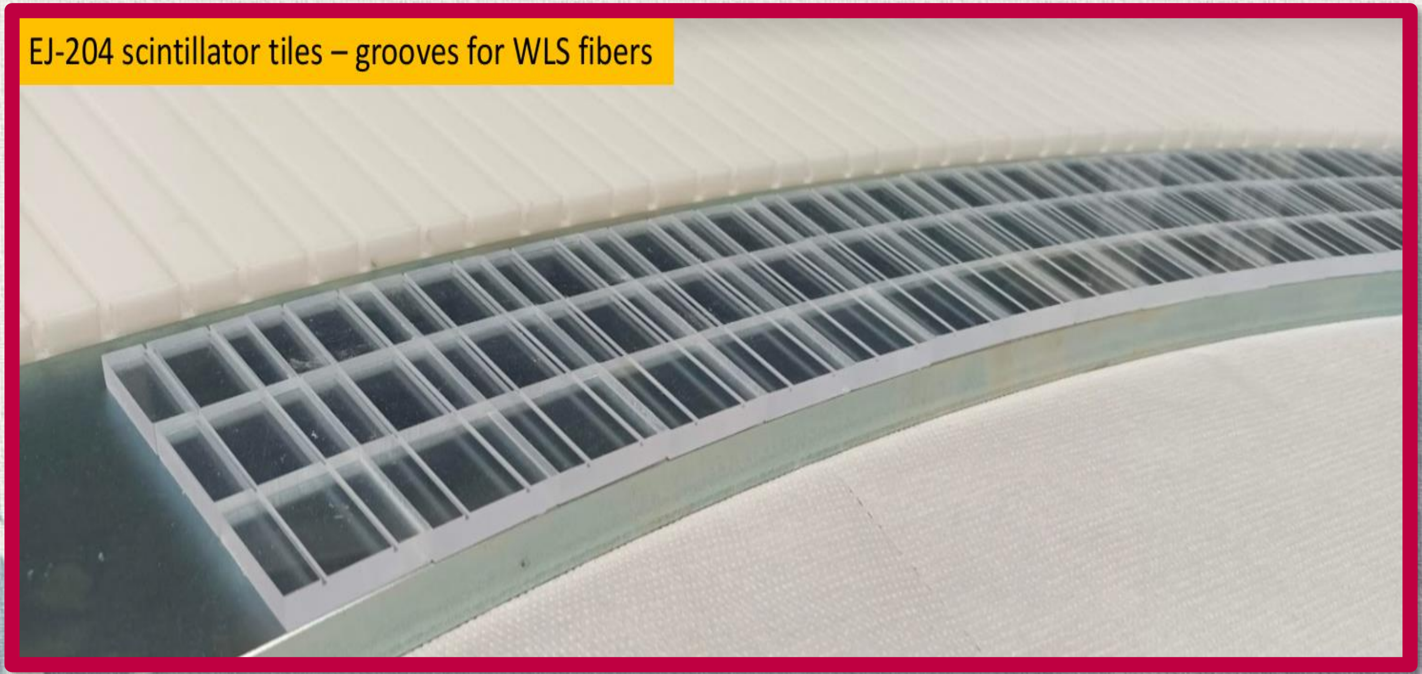


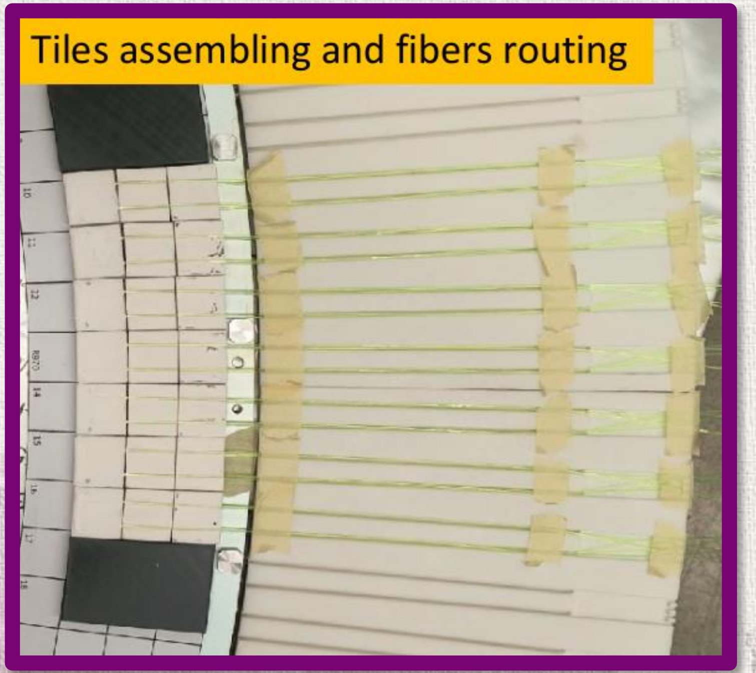
PICOSEC Micromegas Detector for ENUBET

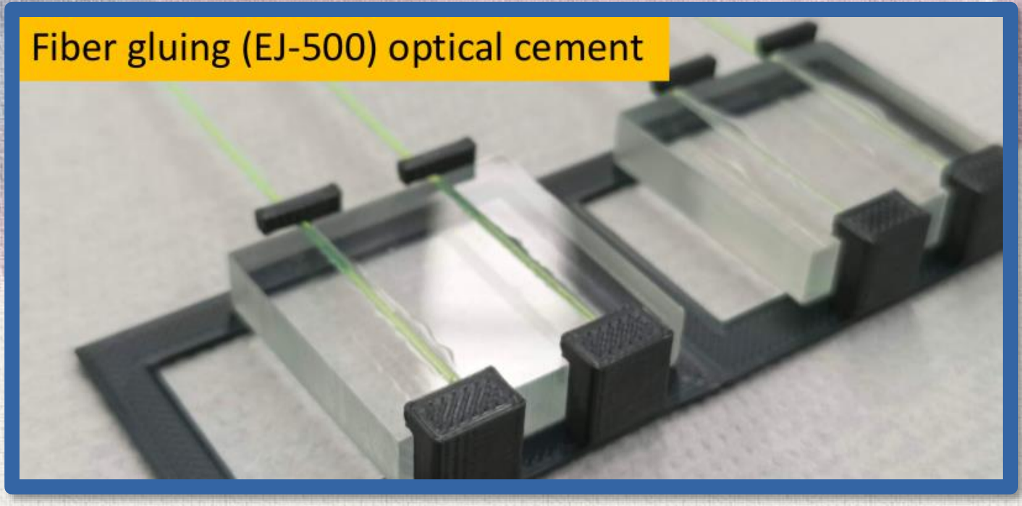




ENUBET – Demonstrator construction







ENUBET – Narrow-band off-axis technique