Towards a high precision neutrino cross section measurement: the ENUBET monitored neutrino beam

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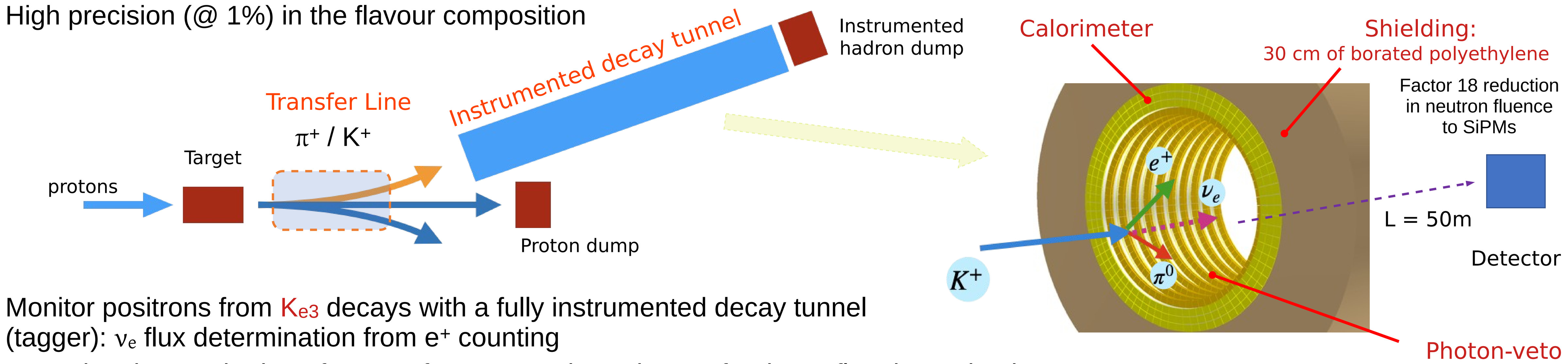
The idea of monitored neutrino beams

ENUBET (**E**nhanced **N**e**U**trino **BE**ams from kaon **T**agging): a narrow-band beam for the precision era of ν physics:

- Knowledge of absolute ν_e / ν_μ flux at 1% level
- Energy of the neutrino determined at 10% level
- High precision (@ 1%) in the flavour composition

ν-beam based experiments would benefit from better cross-section knowledge: sensitivity enhancement equivalent to build larger mass ν -detectors !

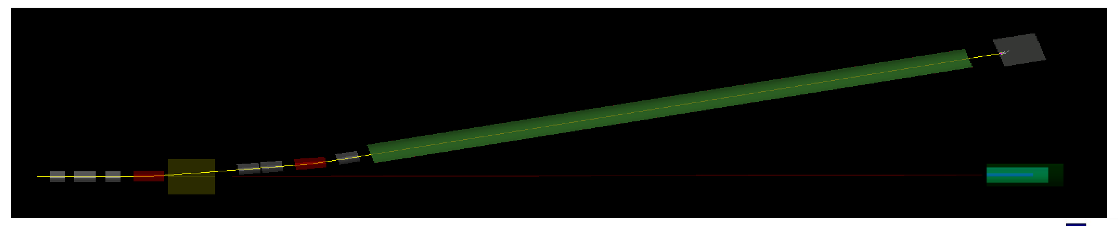


- Monitor positrons from K_{e3} decays with a fully instrumented decay tunnel (tagger): ν_e flux determination from e^+ counting
- Extend to the monitoring of muons from $K_{\mu\nu}$ and $\pi_{\mu\nu}$ decays for the ν_μ flux determination
- Lepton counting allows a direct flux prediction that bypasses the uncertainties coming from hadron production yields at target, beamline simulation and proton-on-target (POT) counting

Design and optimization of the hadronic beamline

Layout of the Static Transfer Line:

- Selection of secondary K^+ / π^+ with momentum p = 8.5 GeV/c ± 10%
- Large bending angle of 14.8° (2 dipoles)
- Optimised graphite target (L = 70 cm, R = 3 cm)
- Tungsten foil downstream target to suppress e^+ background

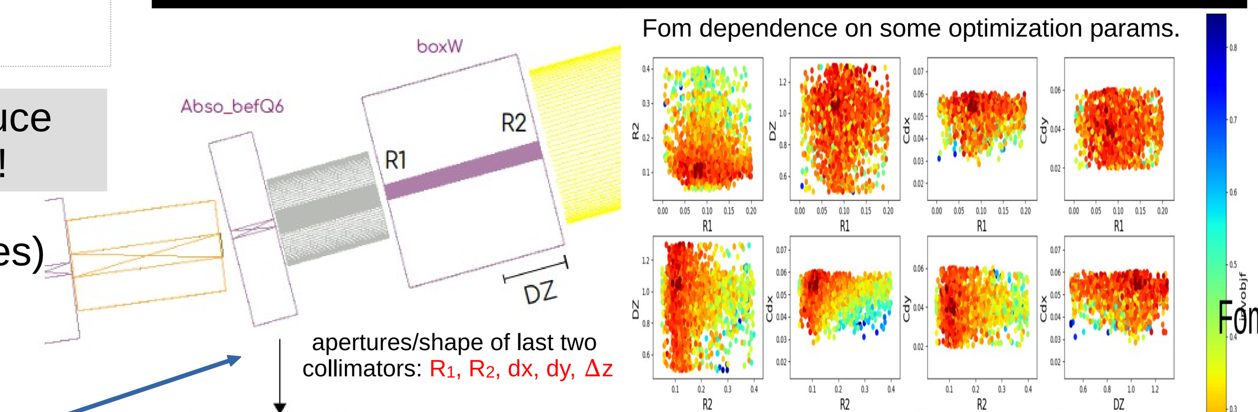


The optimization of the beamline is a crucial task in order to produce an intense & well collimated beam of K / π @ tagger entrance !

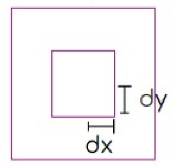
Multi-parametric problem (choice of fields, collimators, apertures)

GEANT4 beamline simulation + external control cards for all system parameters

- Optimization of a figure of merit (fom) w/ a genetic algorithm :
  - scan the parameter space of the beamline in order to find a configuration minimizing halo particles in the tagger while preserving a large meson yield

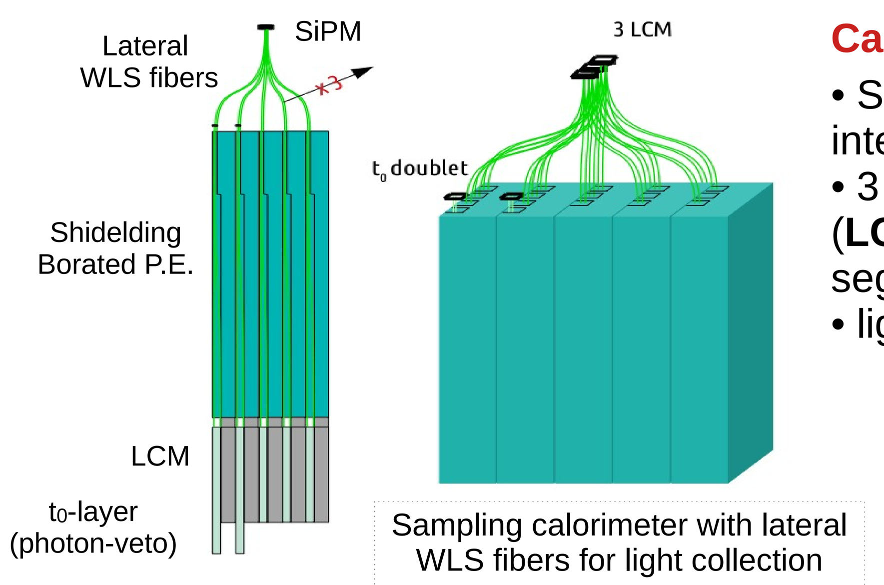


apertures/shape of last two collimators: R_1, R_2, dx, dy, Δz



Transfer line	π^+ $[10^{-3}/POT]$ $[8.5 \pm 5\%]$ GeV/c	K^+ $[10^{-3}/POT]$ $[8.5 \pm 5\%]$ GeV/c	Ratio w.r.t previous results
previous TL	2.05	0.185	
TLR5	3.4	0.28	1.5
TLR6	4.2	0.4	2

The instrumented decay tunnel: the final demonstrator



Sampling calorimeter with lateral WLS fibers for light collection

Calorimeter with $e^+/\pi^+/\mu^+$ separation capabilities

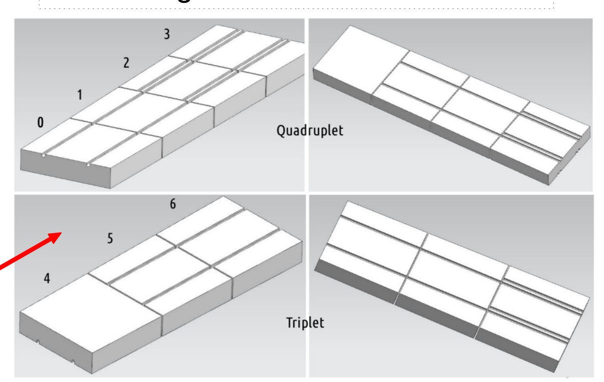
- Sampling calorimeter: 1.5 cm iron slabs interleaved by 0.5 cm plastic scintillator tiles
- 3 radial layers of **L**ateral **C**ompact **M**odules (**LCM**: 3 × 3 × 10 cm³ – 4.3X₀) w/ longitudinal segmentation
- light collection/readout: WLS fibers & SiPMs

Photon-veto allows π^0 rejection

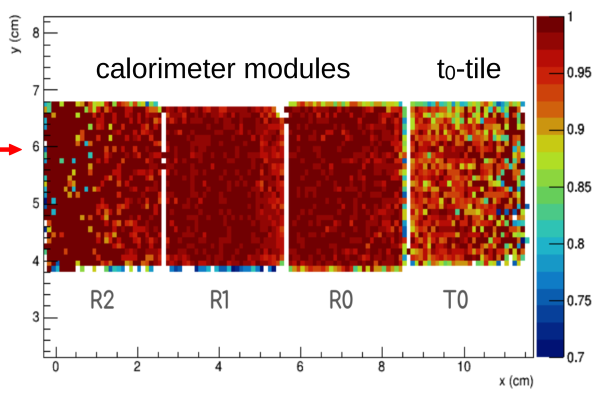
- 3 × 3 cm² plastic scintillator tiles
- time resolution of ~ 400 ps

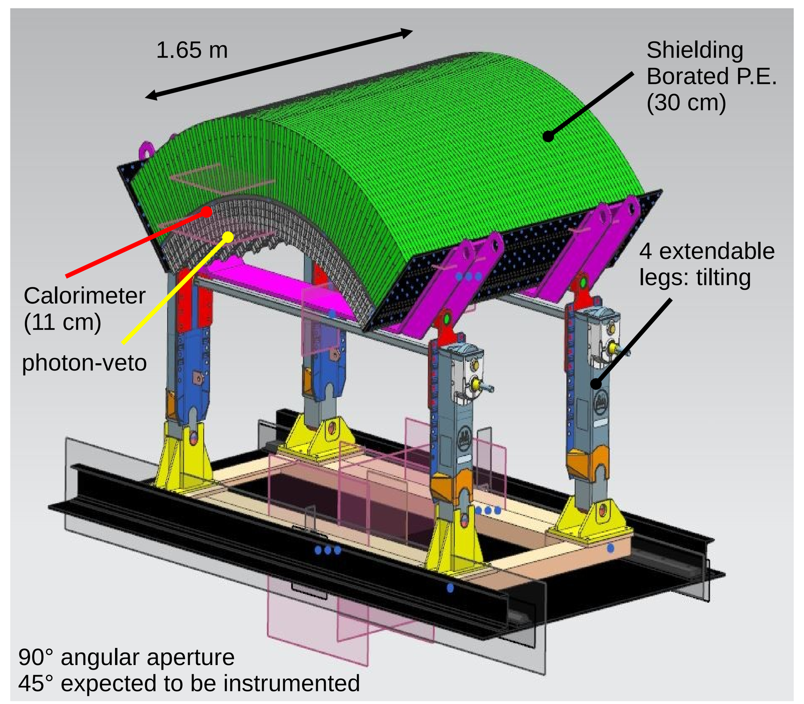
Final demonstrator by October 2022 @ CERN: ENUBET part of the **Neutrino Platform** as **NP06/ENUBET**

Frontal grooves readout scheme



Efficiency maps of the prototype





- New light readout scheme w/ **frontal grooves** instead of lateral grooves driven by large scale scintillator production
  - ⇒ safer production and more uniform light collection
- pre-demonstrator prototype w/ 3 LCMs (ENUBINO)
  - ✔tested @ CERN PS-T9 in November 2021 to study the uniformity of response and efficiency maps

The demonstrator instrumentation corresponds to 15(z) × 3(r) × 25(ϕ) (=1125) calorimeter channels
15(z) × 2(layers) × 25(ϕ) (=750) t_0-layer channels

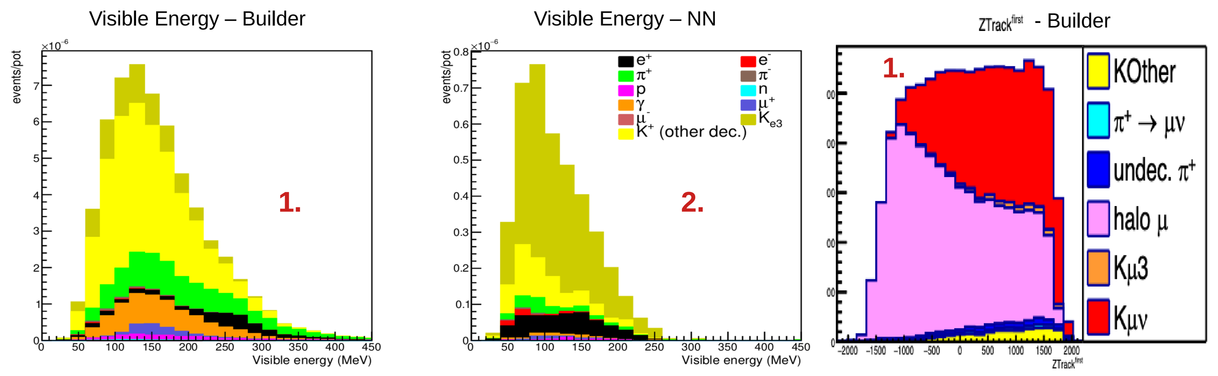
Lepton Reconstruction and PID

Full GEANT4 simulation of the detector (validated for e^+ reconstruction by prototype tests at CERN during 2016-2018):

- particle propagation and decay from transfer line to detector
- hit level detector response
- pile-up effects included

K_{e3} reconstruction: ϵ ~ 22 % & S/N ~ 2

$K_{\mu\nu}$ reconstruction: ϵ ~ 34 % & S/N ~ 6



Instrumenting the hadron-dump will allow to monitor also muons from pion decays: evaluating detector technology in collaboration with Thessaloniki University

Analysis chain:

1. Event builder: identify LCM with energy deposit as seed of the event. Cluster neighbour LCM deposits compatible with particle
2. signal/background separation: multivariate analysis (MLP-NN from TMVA) exploiting energy pattern deposition in calorimeter, event topology and photon-veto energy deposition variables

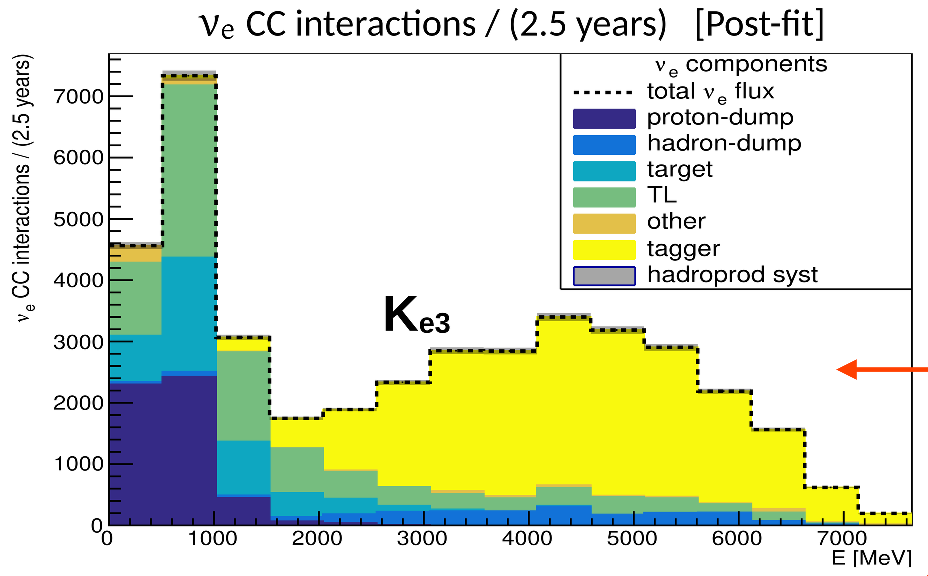
The assessment of flux systematic uncertainties

1.
- Sources of systematic uncertainties w/ major impact on ν flux: **hadron production yields** & **beamline geometry / focusing**
- Geant4 provides info on particle decays and histories ⇒ propagation of systematics from their sources up to ν flux
- **Lepton monitoring** ⇒ charged leptons measured @ calorimeter are related to ν flux @ detector

2.
- **Hadroproduction** (HP) data collected by NA20 and NA56/SPY are used as input to reweight MC events giving origin to ν
- **Multi-universes method** : propagation of syst. uncertainties on HP model parameters both to lepton observables and ν flux
- Distributions of the **lepton observables** measured by calorimeter: visible energy vs z impact point along the tagger
- Build a signal + background model PDF from nominal and ±1σ lepton observables. The variations in the normalization and shape of lepton observable templates - due to HP uncertainties - are modeled by means of nuisance parameters (RooFit).

3.
- By means of the correlation existing between the number of events and HP weights, the fit to lepton observables can be exploited to set constraints on the HP weight maps ⇒ reweight ν flux post-fit
- Results obtained for a finite statistics (600 MPOT) and extrapolated to the statistics that will be collected (~ 4.5 · 10¹⁹ POT)
- **Exploit lepton monitoring to set a constraint on ν flux ⇒ ν flux precision enhancement at 1% level**

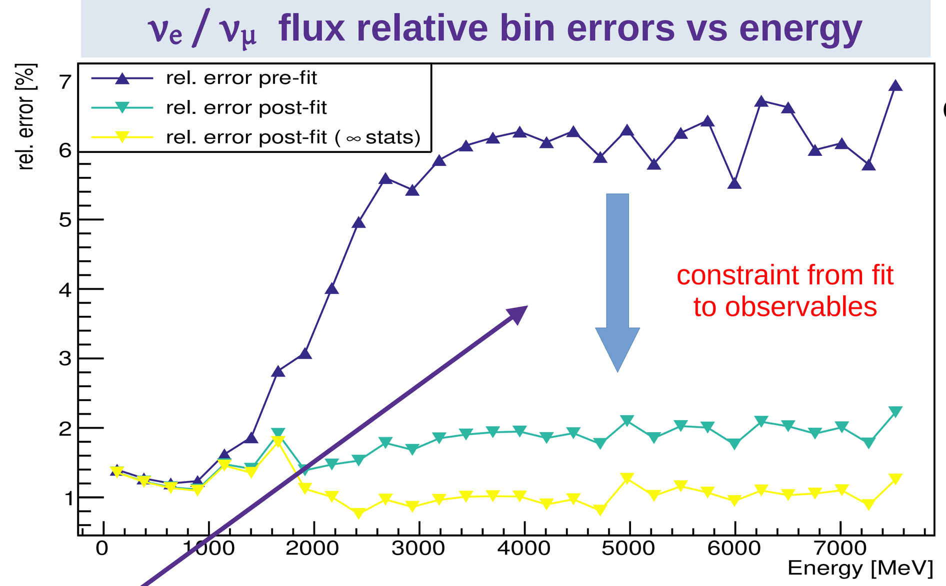
ν_e CC interactions / (2.5 years) [Post-fit]



Total number of ν_e / ν_μ CC interactions w/ detector in 2.5 yrs of data-taking (4.5 · 10¹⁹ POT)

Detector made w/ 500 Ton of LAr, located at 50 m from the end of tunnel, area 6 x 6 m².

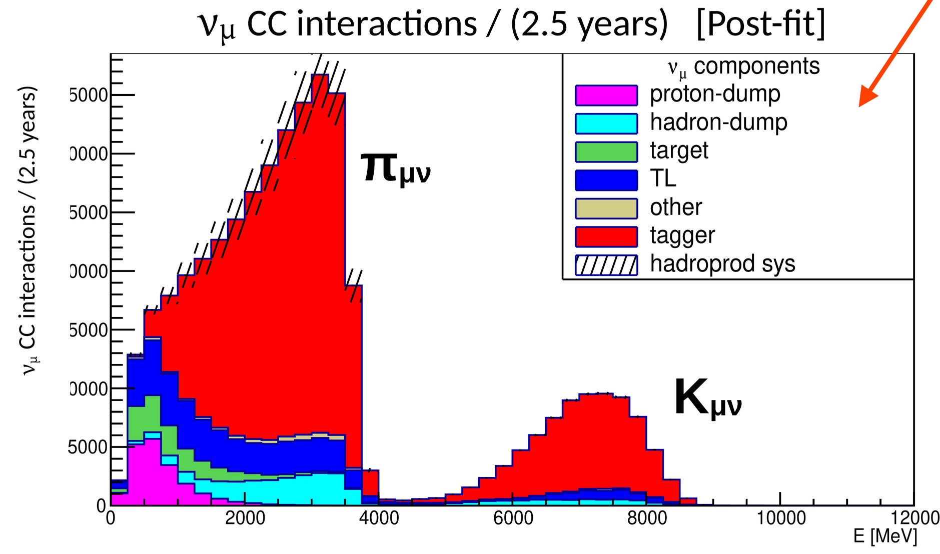
ν_e / ν_μ flux relative bin errors vs energy



error ~ 6 - 7 % [pre-fit]

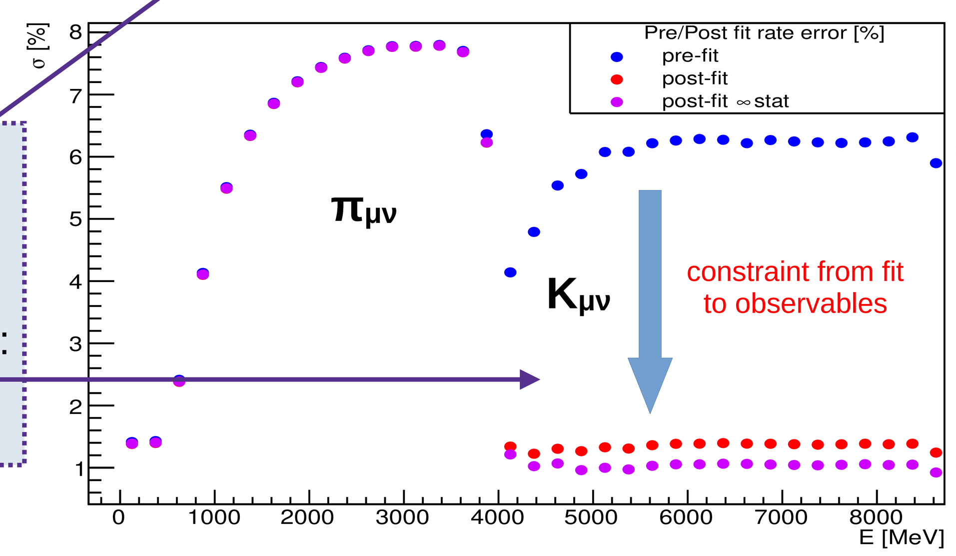
error ~ 1 % [∞ stats]

ν_μ CC interactions / (2.5 years) [Post-fit]



Error on flux for ν_e : from ~ 6 - 7% to ~ 2% (~1% @ infinite statistics)

Error on flux for ν_μ from K : from ~ 6% to ~ 1.4% (~1% @ infinite statistics)



error ~ 6 % [pre-fit]

error ~ 1 % [∞ stats]

✔ First end-to-end assessment of systematics due to HP in a monitored ν beam, proving to reach the sought-after precision

➢ Next: assessment of ν flux systematic uncertainties related to beamline parameters (magnetic fields, alignments) and detector effects

References:

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checkout more @ http://enubet.pd.infn.it