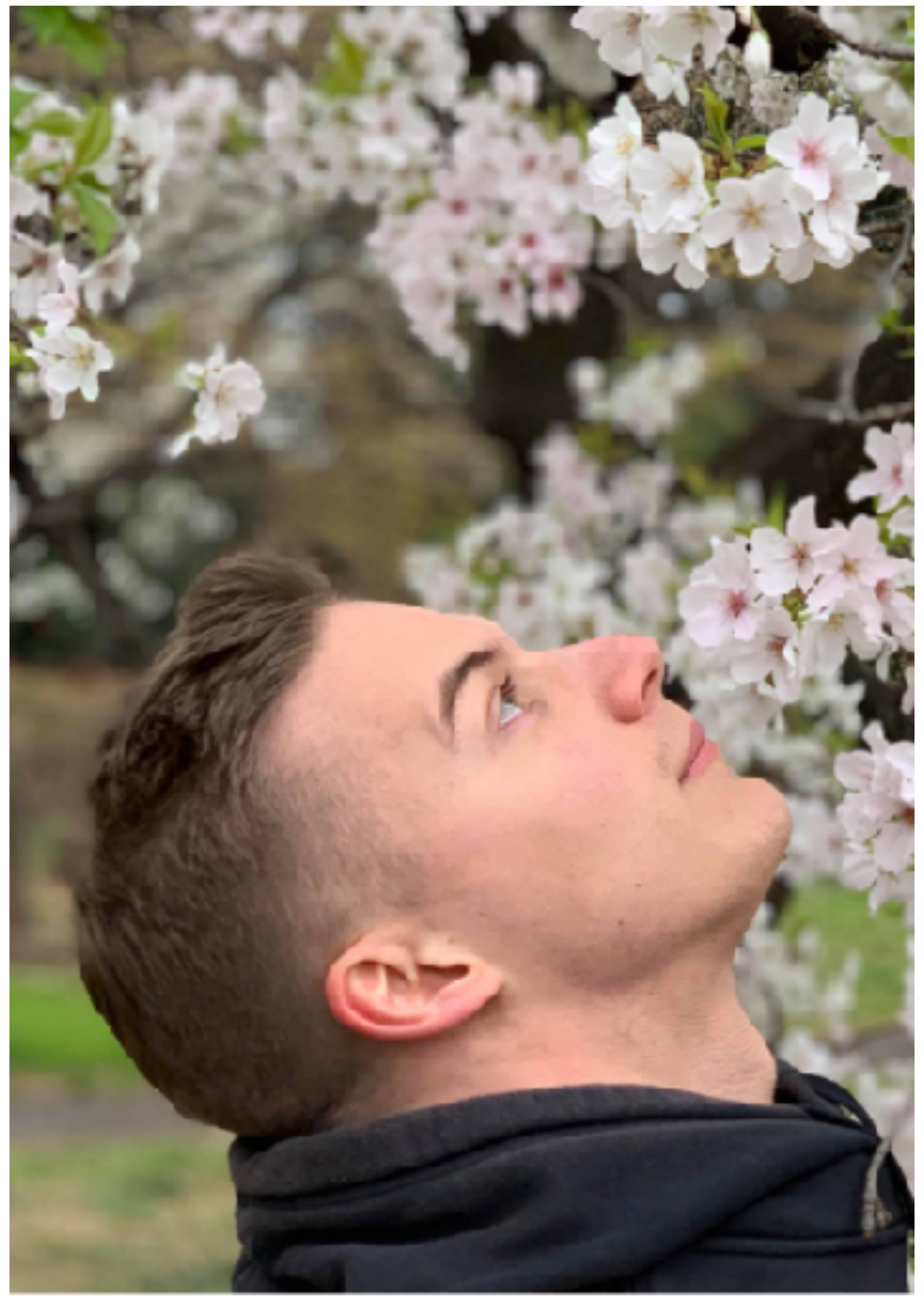
Monitoring neutrino beams with ENUBET

A precision cross-section story



Jordan McElwee*

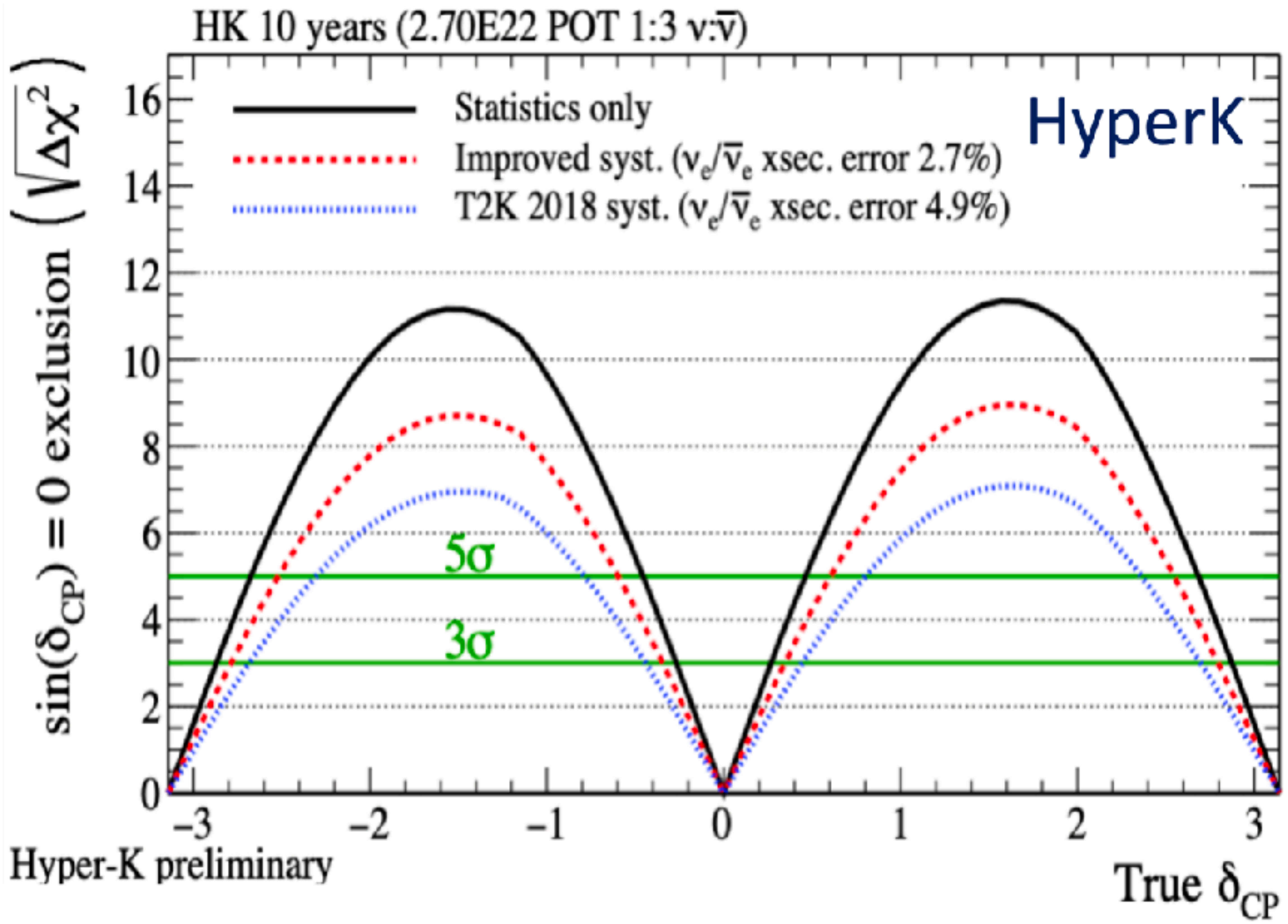
10th October 2024

IRN @ Amphi Vulpian

*on behalf of the ENUBET collaboration

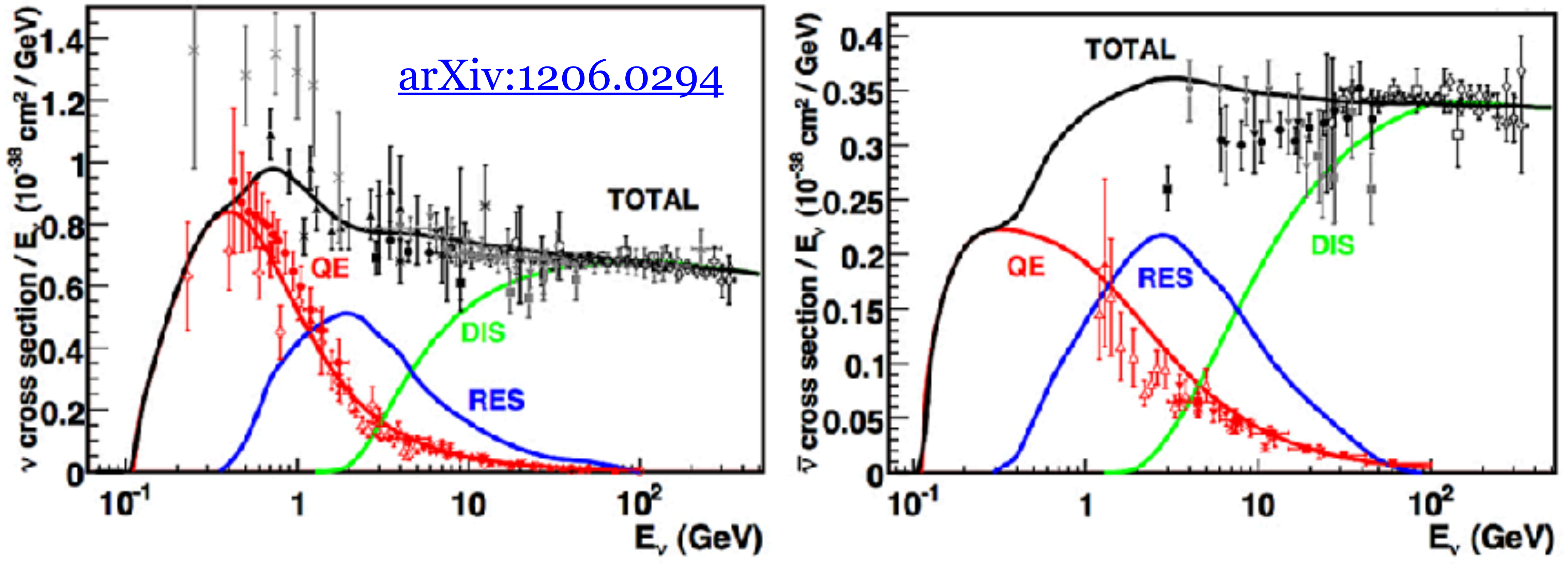
Introduction

- Neutrino experiments have moved from the **statistics-** to the **systematics-dominated** era
- Next generation experiments (DUNE, HyperK, *etc.*) aim to measure δ_{CP}



$$N_e(E_\nu) = P(\nu_\mu \to \nu_e)\Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)$$

- Cross-section measurements convoluted with the neutrino flux
- Neutrino flux modelling limits this measurement with an uncertainty ~5-10%*
- Compounded neutrino-interaction uncertainties and detector effects



arXiv:1206.0294

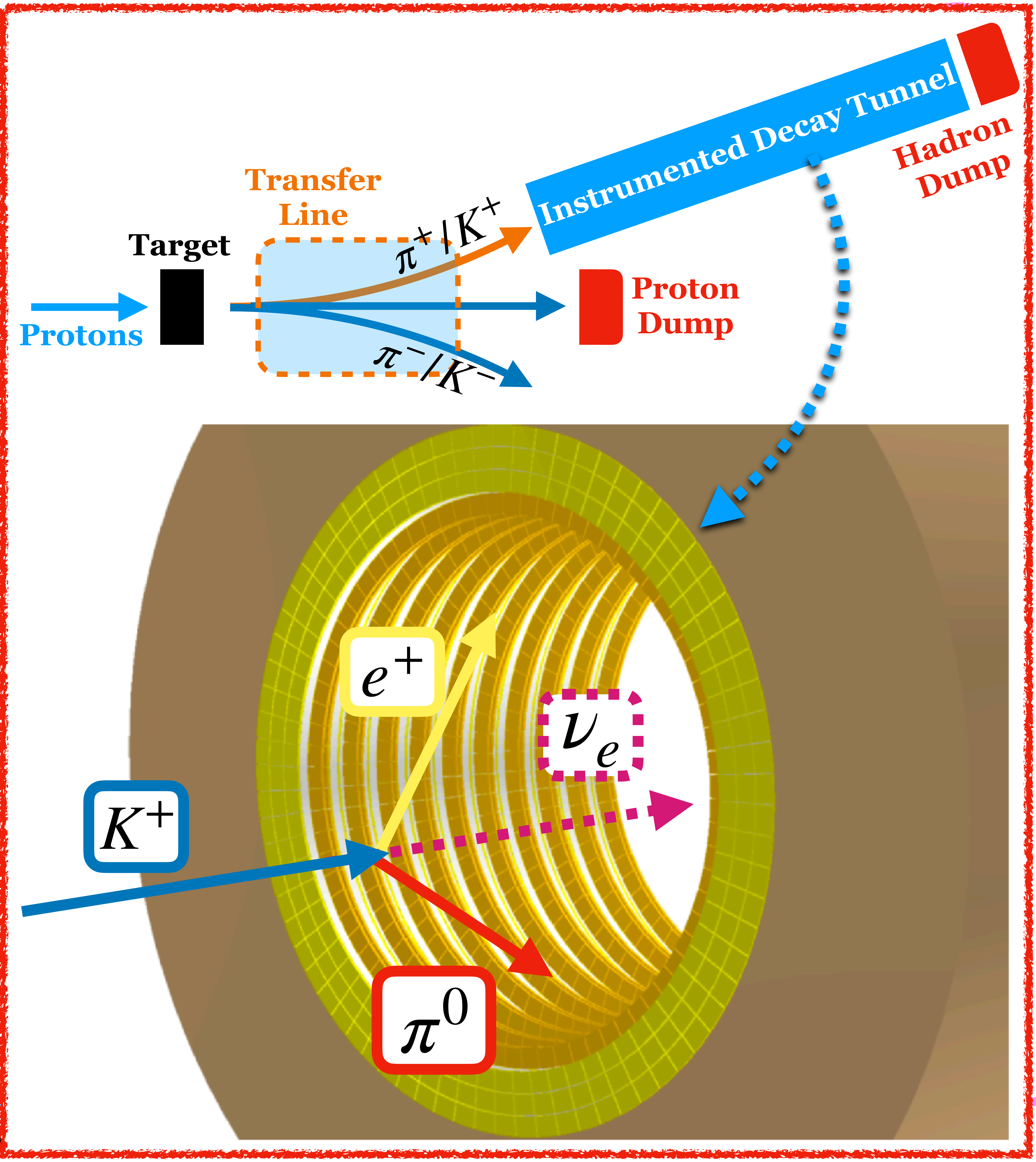
*Current best limit is 3.22% from MINERvA, arXiv:2209.05540.

ENUBET

- **ENUBET** (Enhanced NeUtrino BEams from Kaon tagging) aims to be the first **monitored** neutrino beam
  - Providing high precision cross-section measurements
- Conventional, narrow-band beam with an **instrumented** decay tunnel
- 'Intelligent' tunnel monitors leptons associated with neutrinos at the **single-particle** level
- Measures neutrino flux directly, bypassing other flux related systematics
  - Hadron production
  - Beamline geometry and focussing
  - Protons on target (PoT)

Initial proposal:

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



ENUBET

ERC Project

(2016-2022)

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

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

PI: A. Longhin

CERN Neutrino Platform

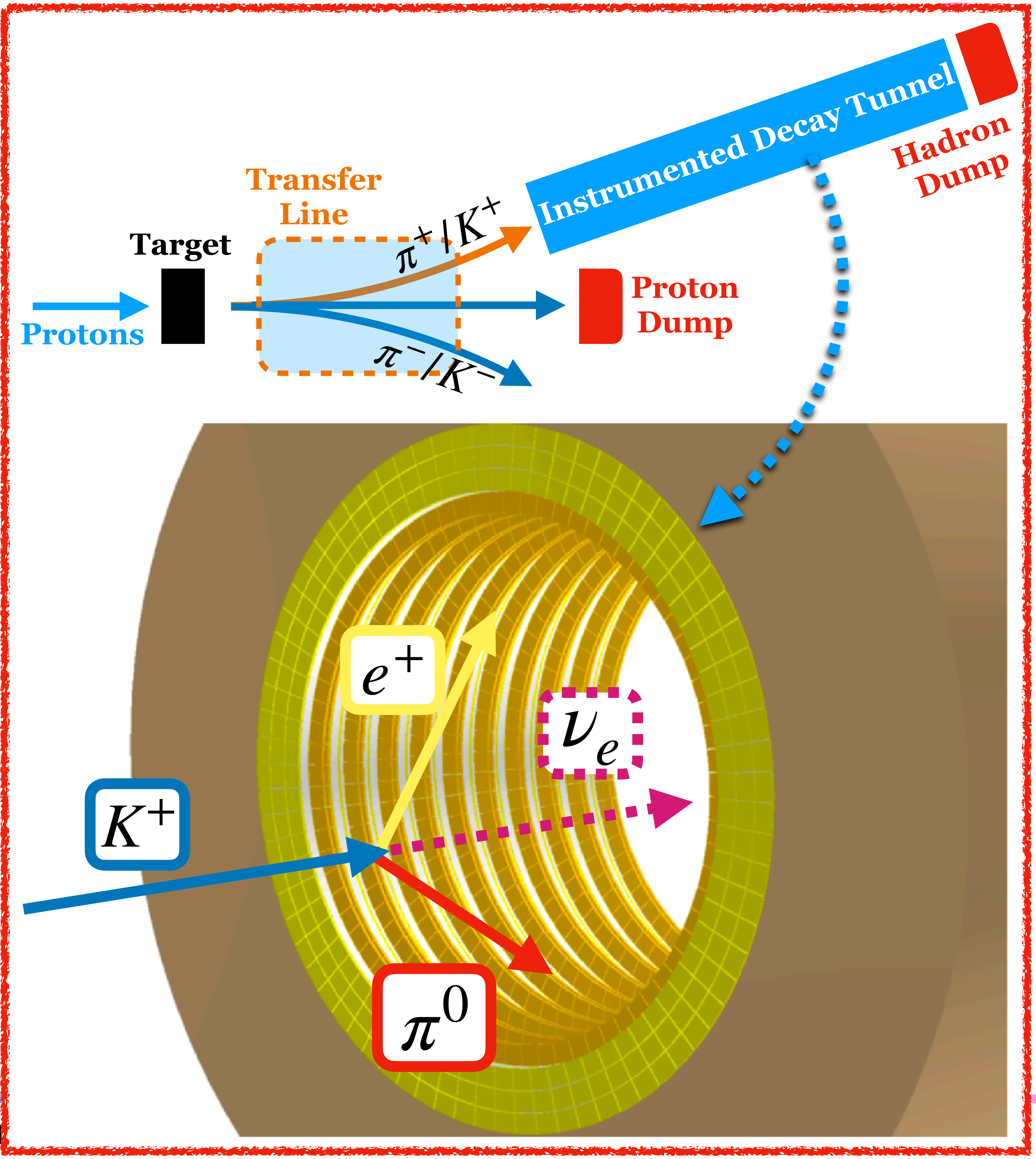
(2019-Present)

Designated: NP06/ENUBET

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

Part of the Physics Beyond Colliders initiative.

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



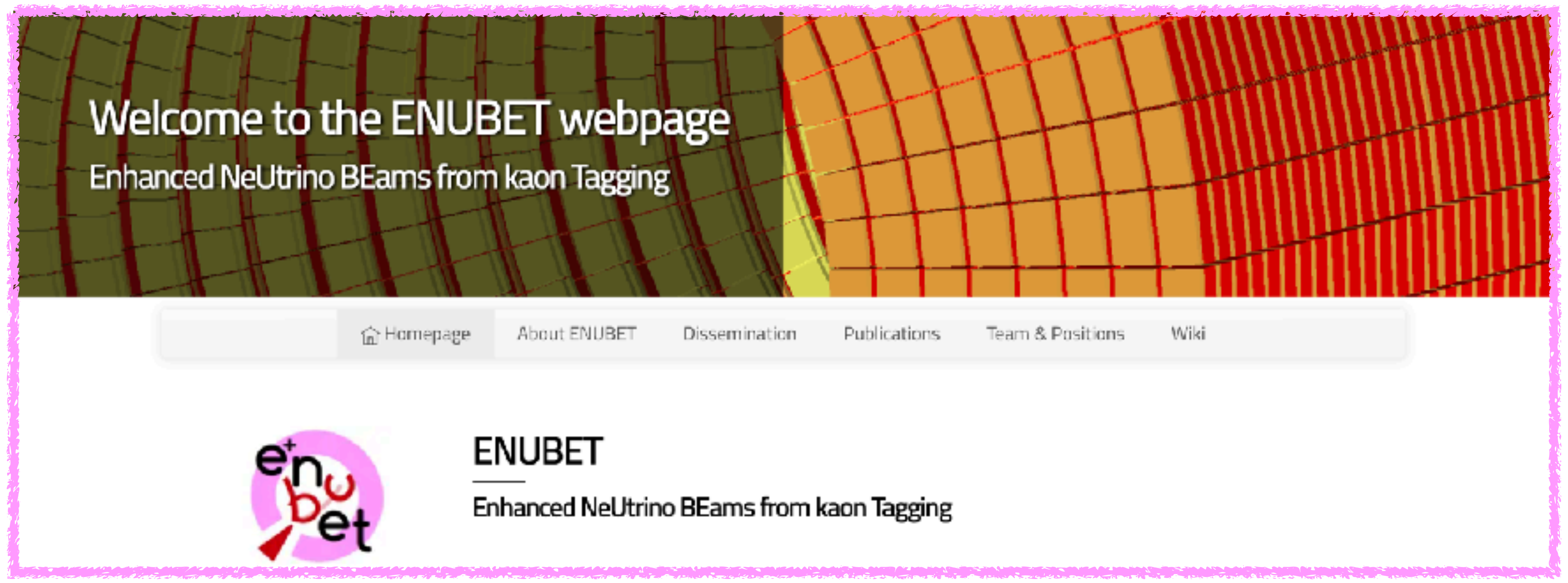
The ENUBET Collaboration

6 Countries

17 Institutions

72 Physicists

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]



Welcome to the ENUBET webpage

Enhanced NeUtrino BEams from kaon Tagging

ENUBET

Enhanced NeUtrino BEams from kaon Tagging

Beamline

Full G4 Simulation available: arXiv:2308.09402

Target

- 70 cm long, 3 cm radius graphite
- Tungsten foil downstream to suppress positrons

Dumps

- 2 dumps: proton and hadron
- Optimised to avoid backscattering flux in tunnel

Transfer Line

- **5% momentum bite** centered at **8.5 GeV/c**, optimised with TRANSPORT
- G4Beamline used for particle transport and interactions
- FLUKA used for irradiation studies
- Length optimised to reduce early hadron decays

Decay tunnel / Tagger

- Large bending angle reduces μ and ν_e background from early decays
- Length tuned to maximise K_{e3} decays

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- Focussing quadrupoles (orange)
- Bending dipoles (dark green)
- 26.7 m in length

Beamline

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Decay tunnel / Tagger

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- 40 m long
- 1 m wide
- At an angle of 14.8° to proton beam

Beamline

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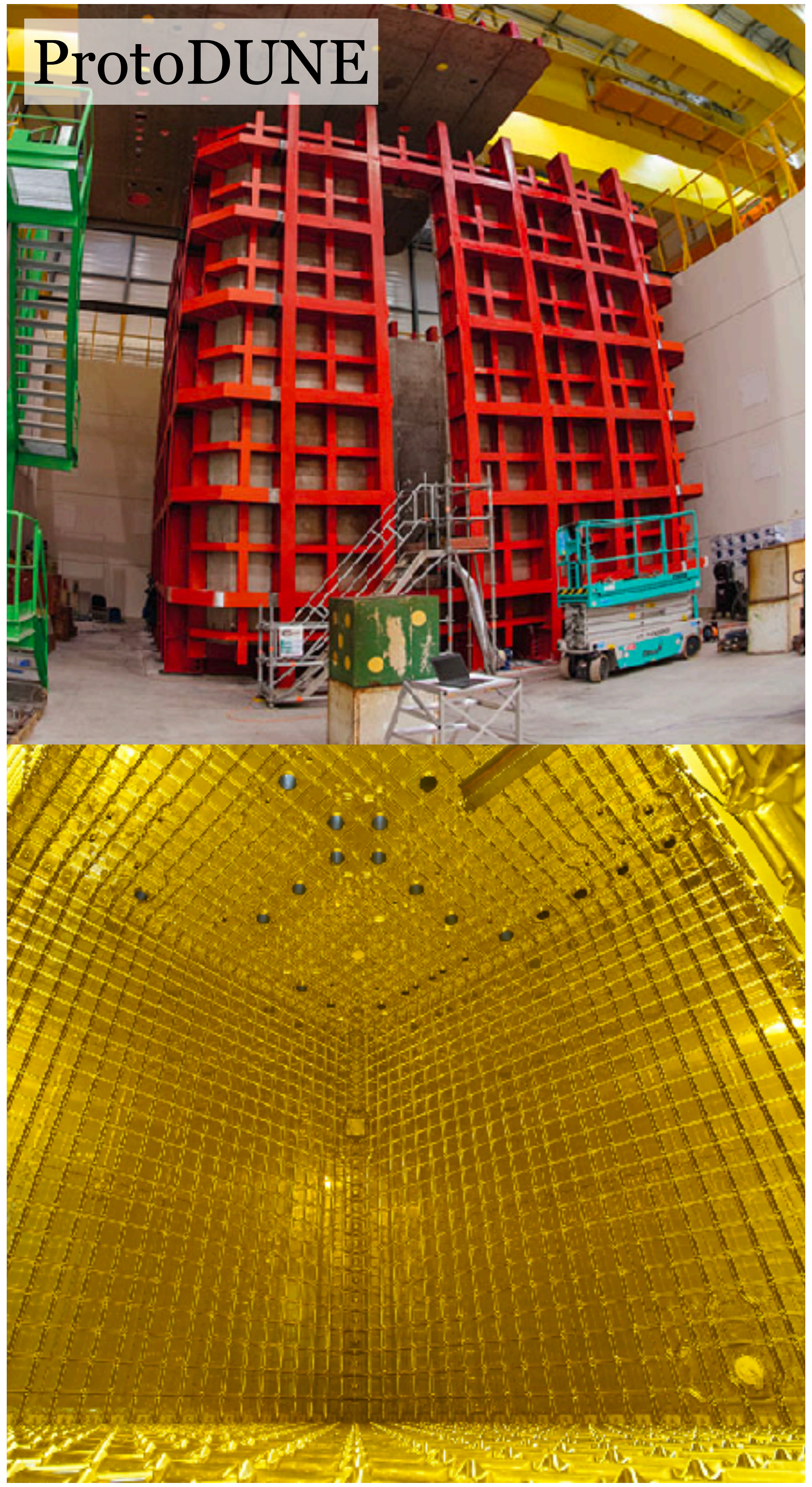
Decay tunnel / Tagger

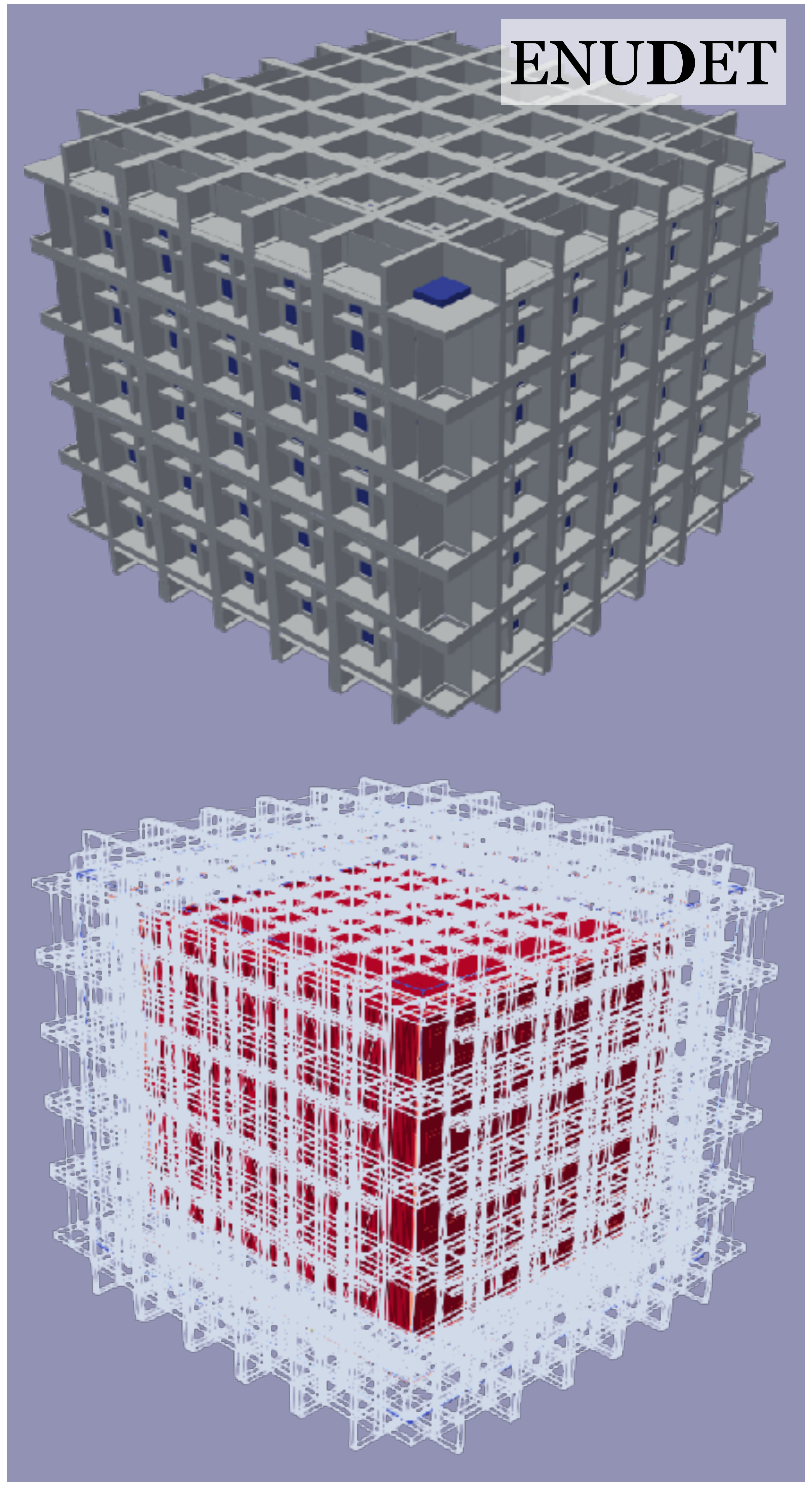
- Large bending angle reduces μ and ν_e background from early decays
- Length tuned to maximise K_{e3} decays

- Graphite core
- Iron middle layer
- Surrounded by borated concrete

The ν_e Beam

- 4.5×10^{19} PoT/year at CERN SPS
- 500 t detector, 50 m from the tunnel
- ~10^4 ν_e CC events in 2 years
- ~80% of the ν_e component above 2 GeV is monitored





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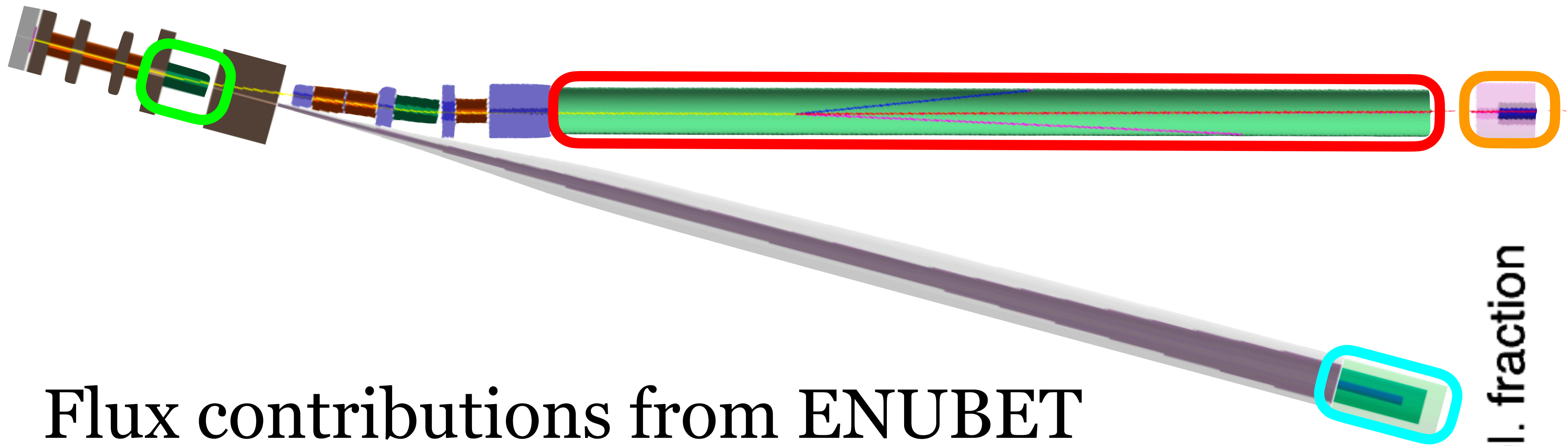
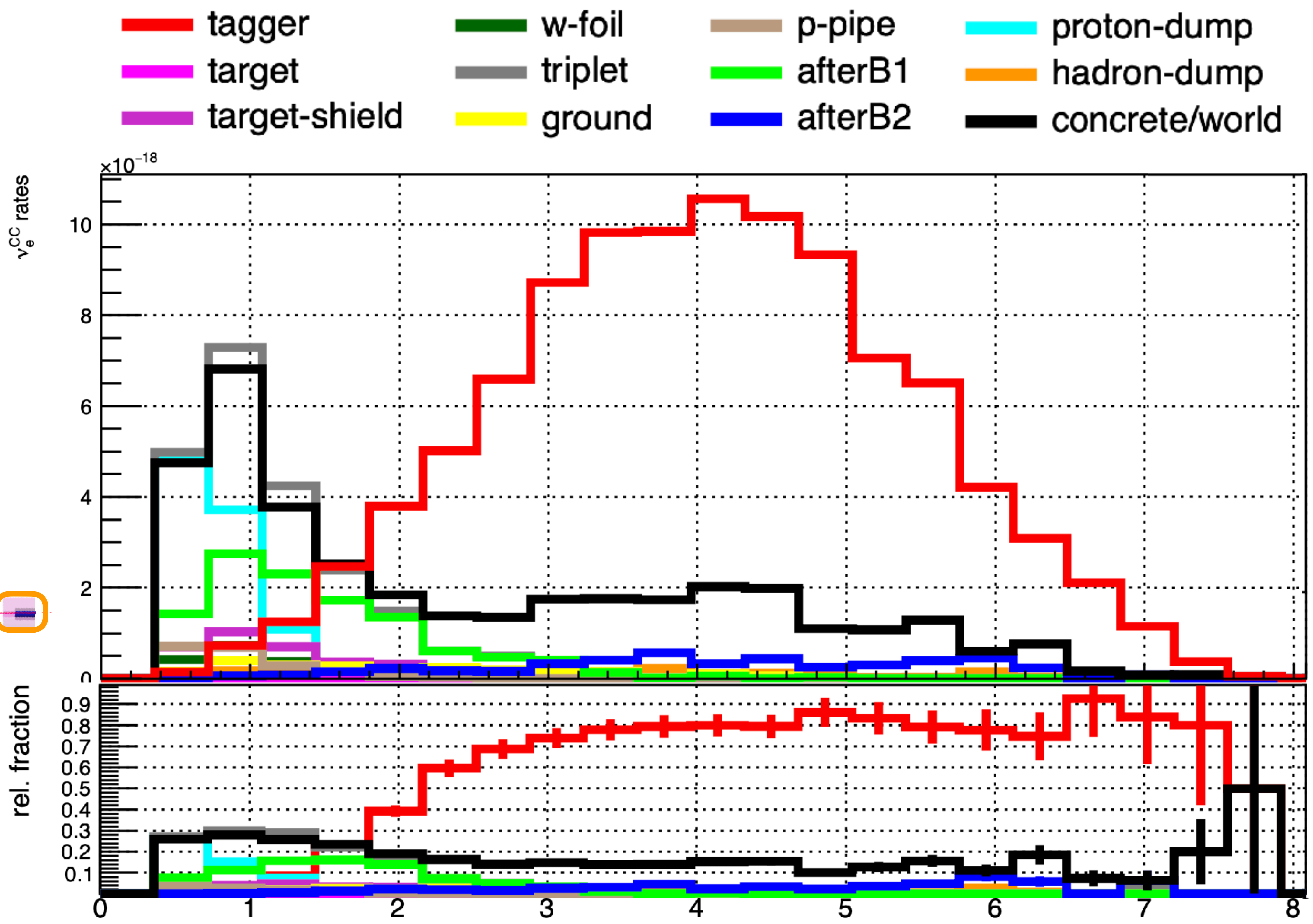


Flux contributions from ENUBET facility

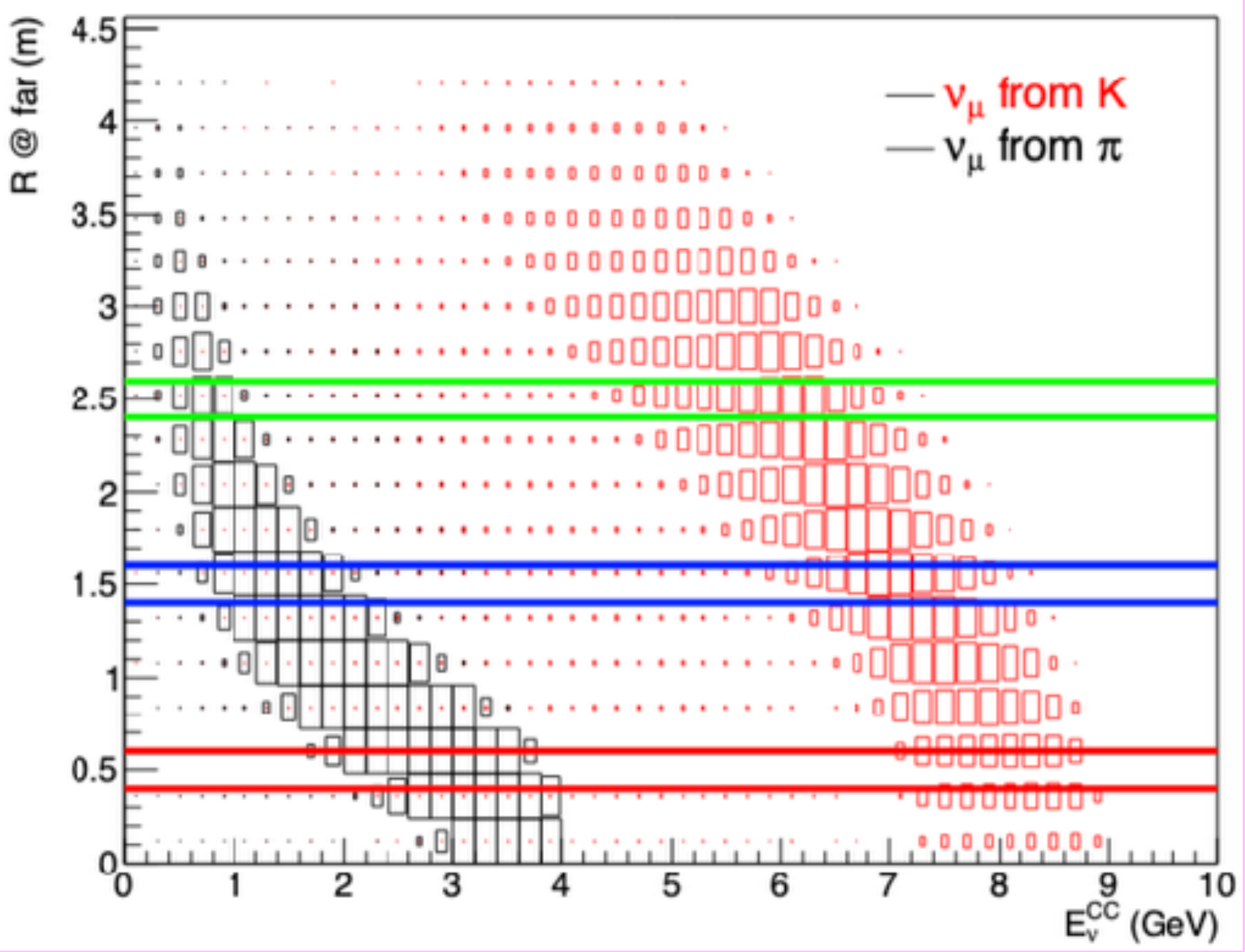


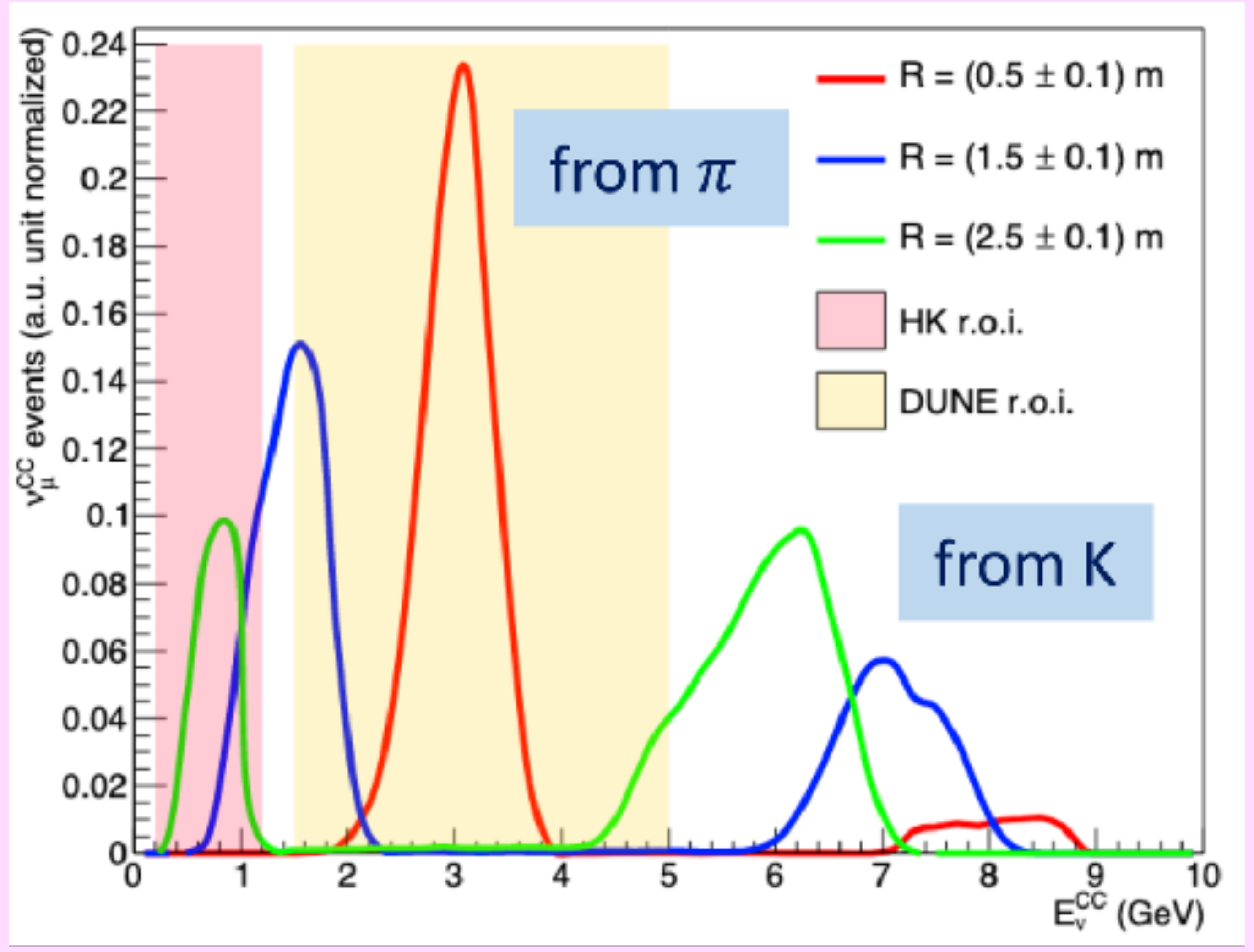
The ν_μ Beam

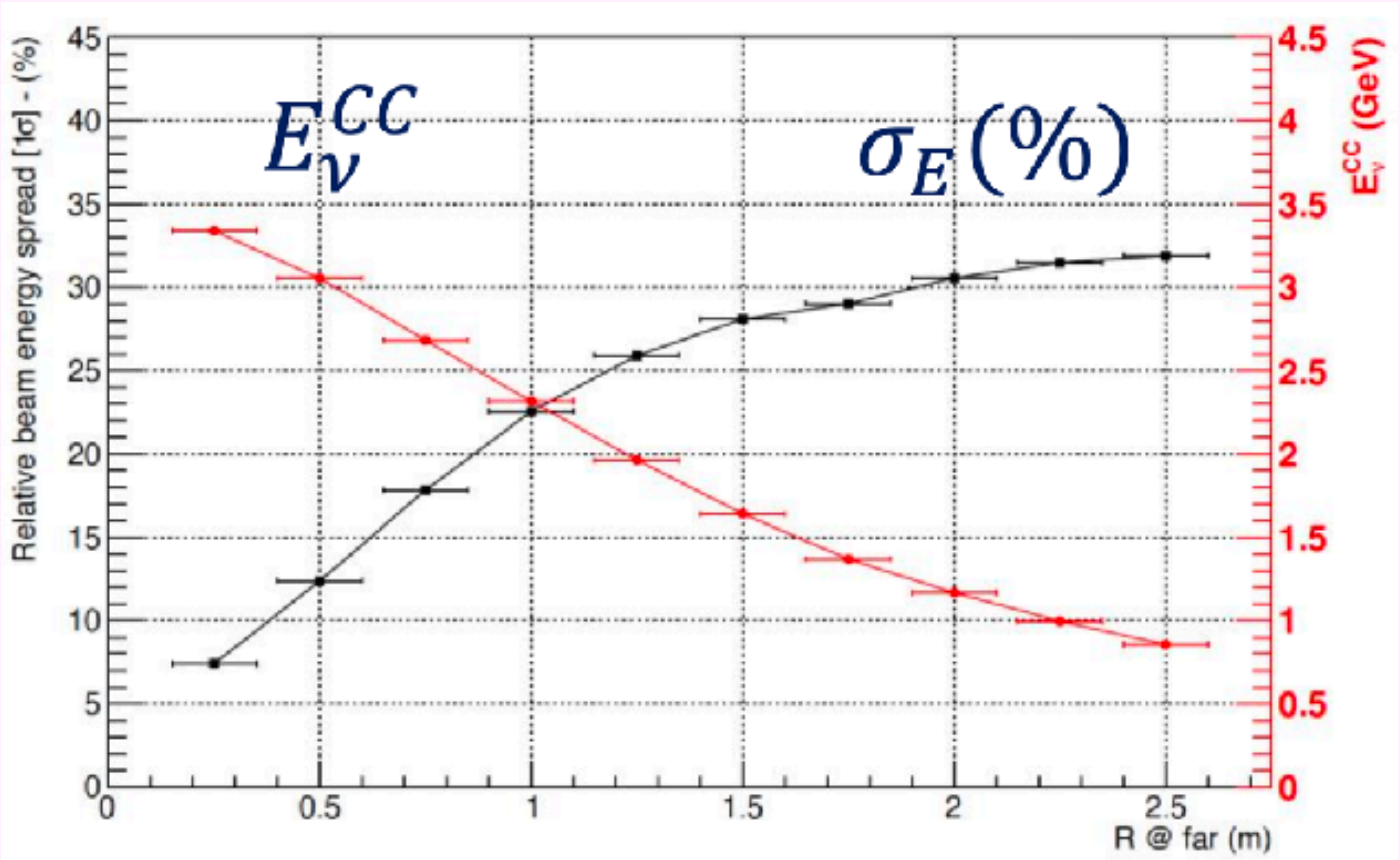
- Similar to T2K, we can use the narrow-band off-axis technique
- A strong correlation between neutrino energy, E_ν, and radial distance of vertex from beam axis, R

Precise determination of E_ν:

1. Constrained by interaction vertex
2. No reliance on final state reconstruction (no pesky neutrino-nucleus interactions)







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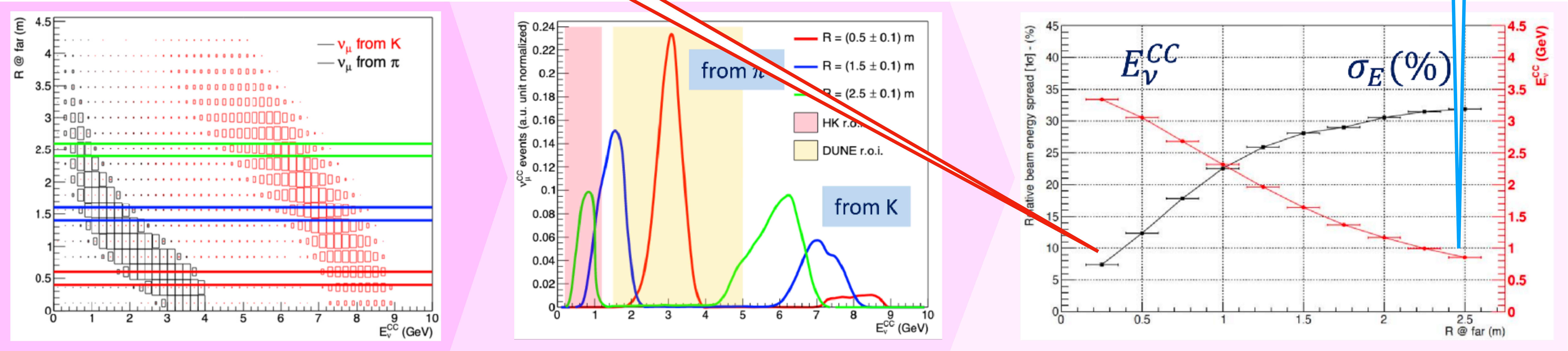
8-25% resolution in DUNE ROI

R&D efforts for DUNE and HK optimisation with a multi-momentum beamline

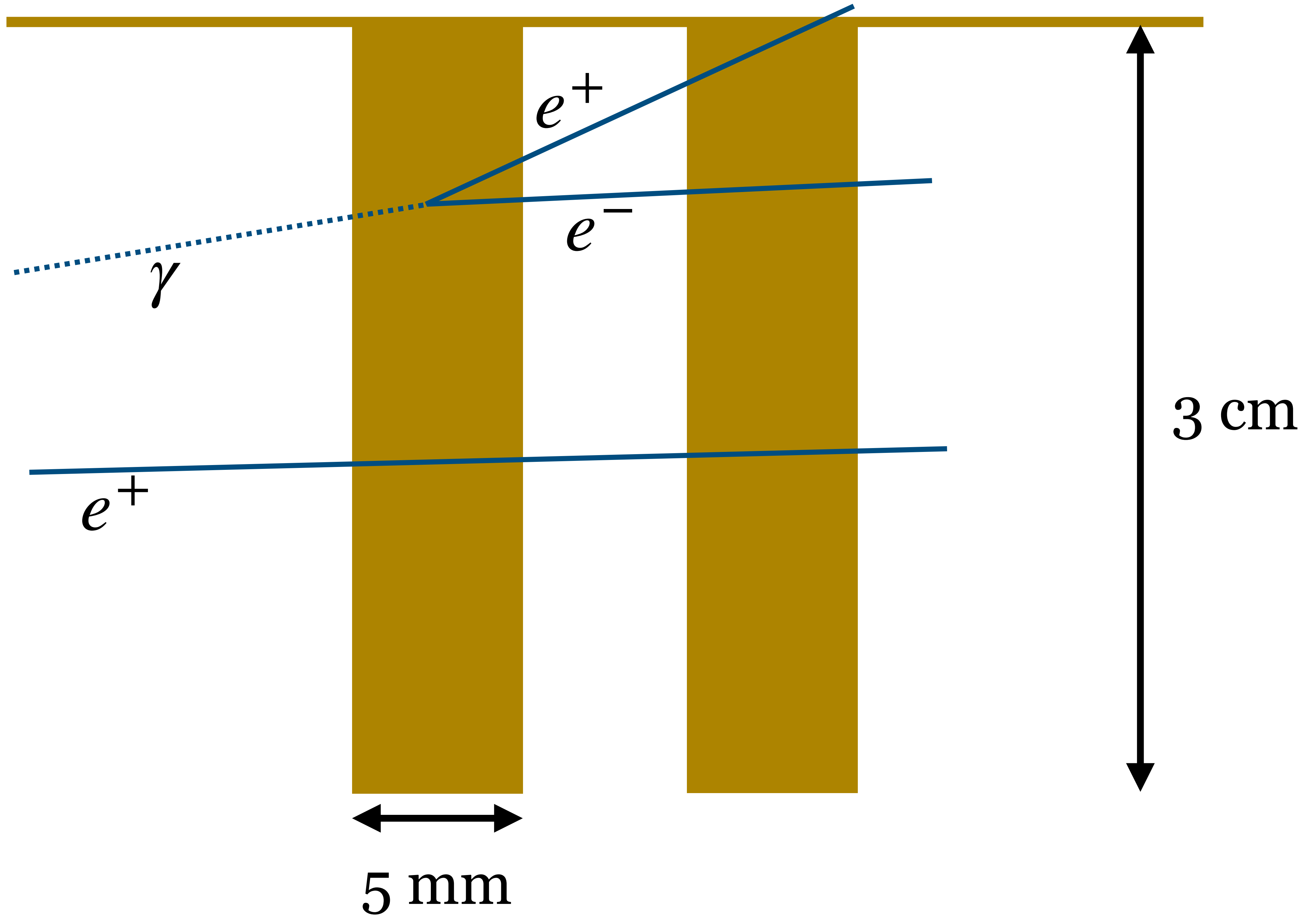
30% resolution in HK ROI

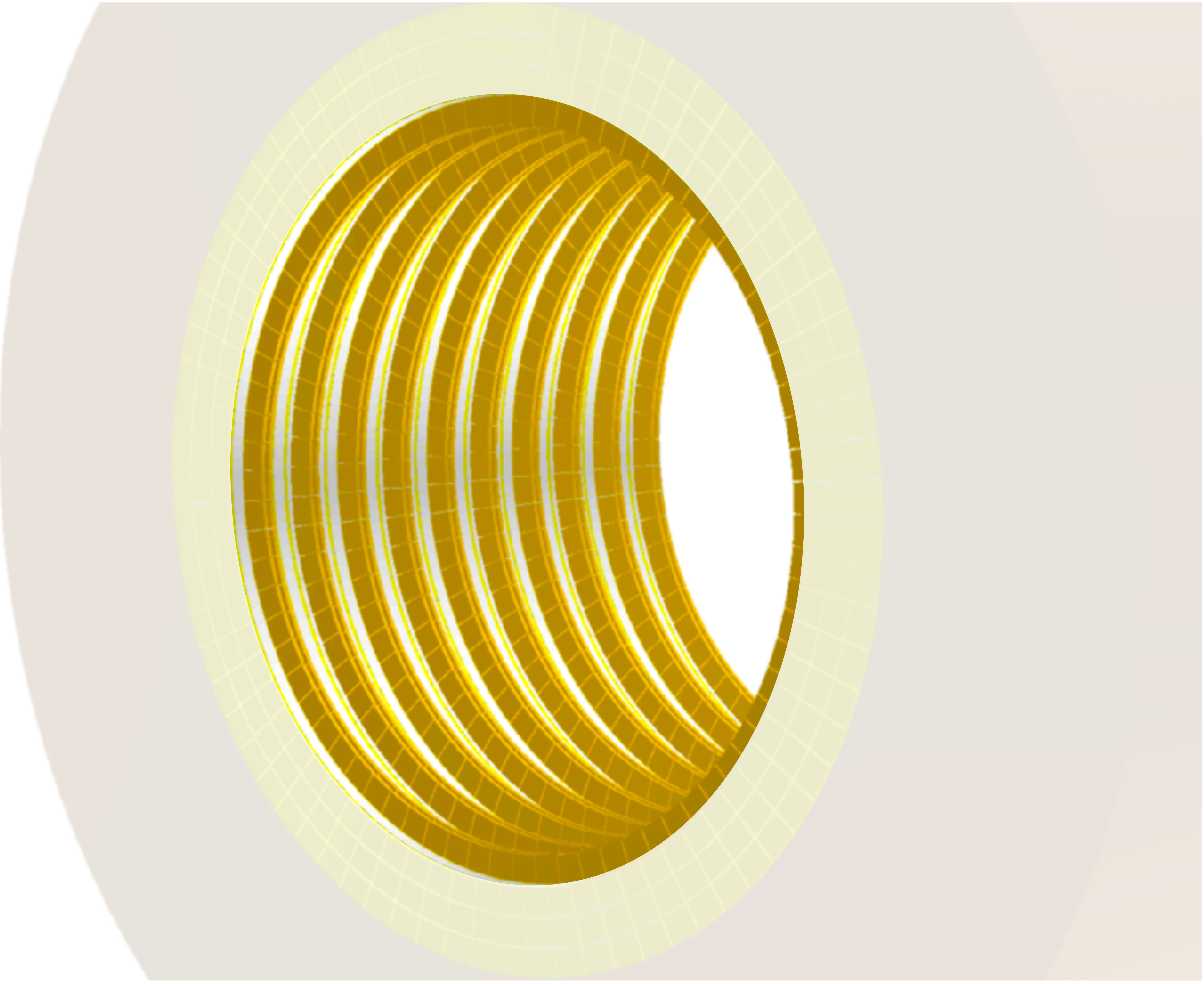


The Tagger

Photon Veto

- Plastic scintillator tiles in doublets forming inner rings
- Time resolution of ~400 ps





The Tagger

Photon Veto

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Calorimeter

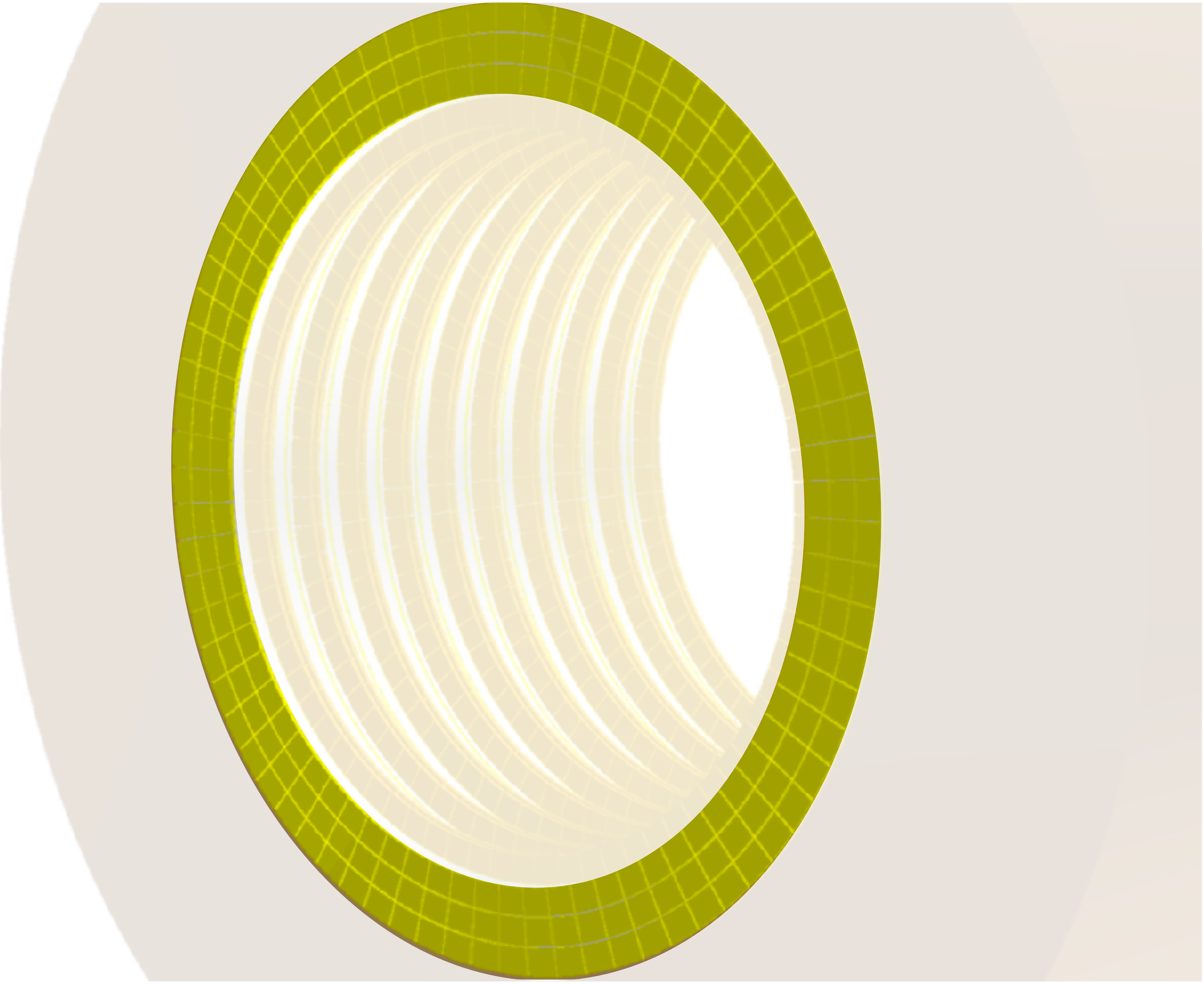
- Sampling calorimeter: sandwich plastic scintillator and iron target
- 3 radial layers of lateral readout calorimetric modules (LCMs)
- WLS fibres to SiPMs for light collection

e^+ (signal) topology

π^0 (background) topology

π^+ (background) topology

μ^+(signal/bkg) topology



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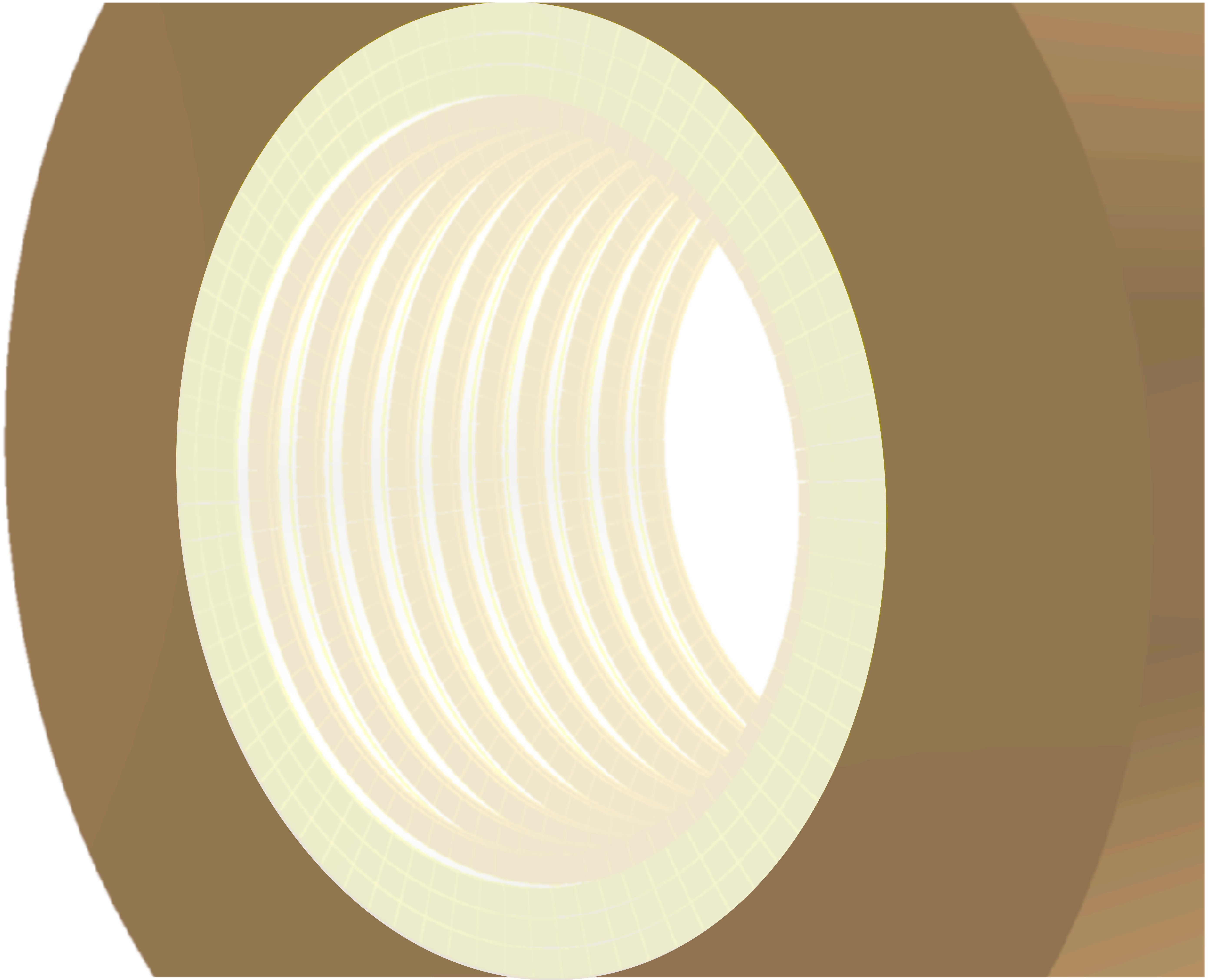
Shielding

- 30 cm borated polyethylene
- SiPMs placed outside to reduce neutron flux (factor of 18)



Lepton Reconstruction

Sec. 8: arXiv:2308.09402

- GEANT4 detector simulation was validated with prototype tests @ CERN, 2016-2018
  - Pile-up effects are included (waveform treatment in progress)
- Event building and PID algorithms available
  - Developed between 2016 and 2020
  - e^+ and μ from K^+ selected by searching for energy clusters
  - PID completed with a MLP trained on discriminating variables: *E* deposition, topology, photon veto *etc.*

K_{e3} positrons: ν_e

S/N = 2

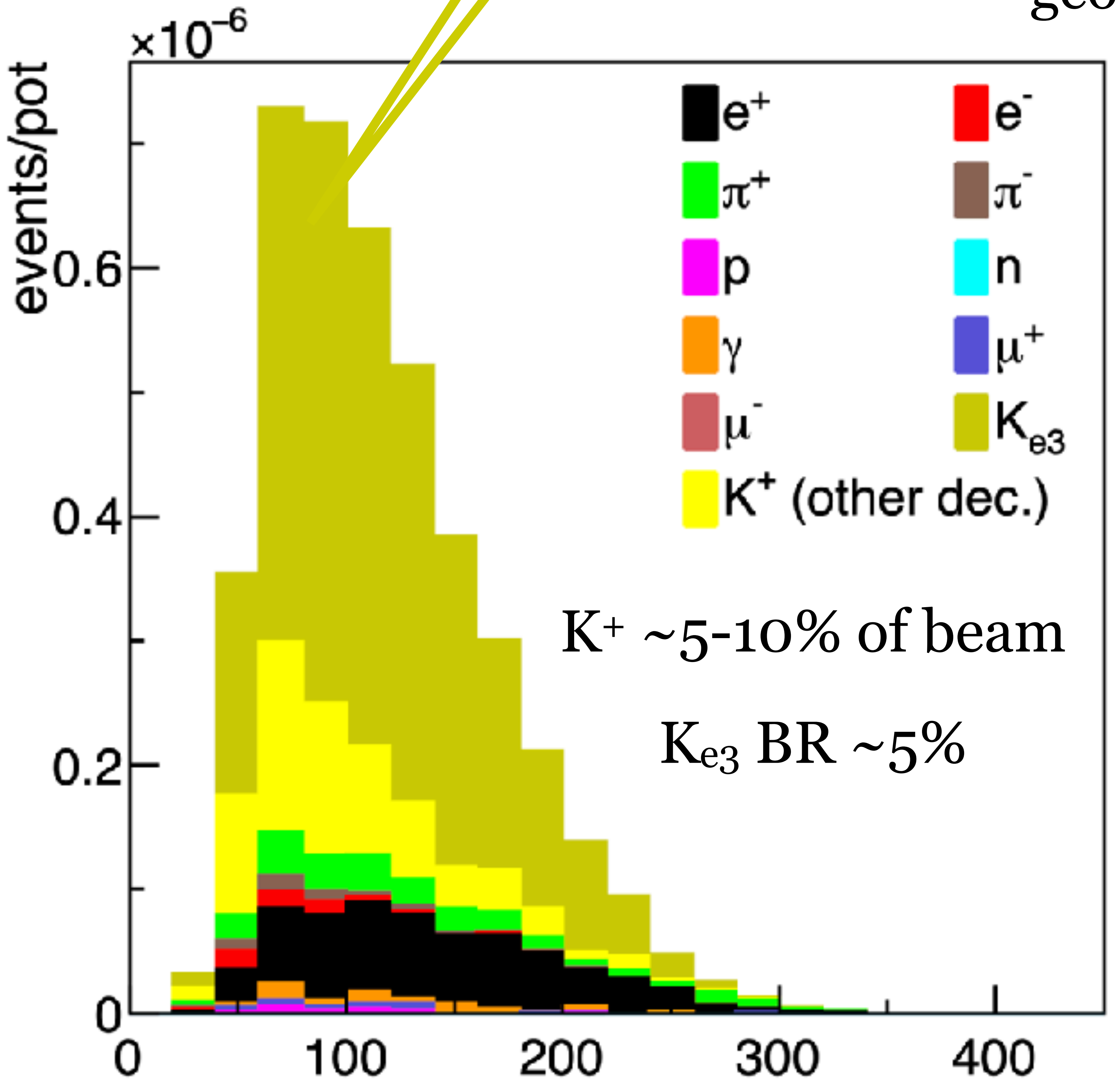
Eff = 22%

$K_{\mu2}$ muons: ν_μ

S/N = 6

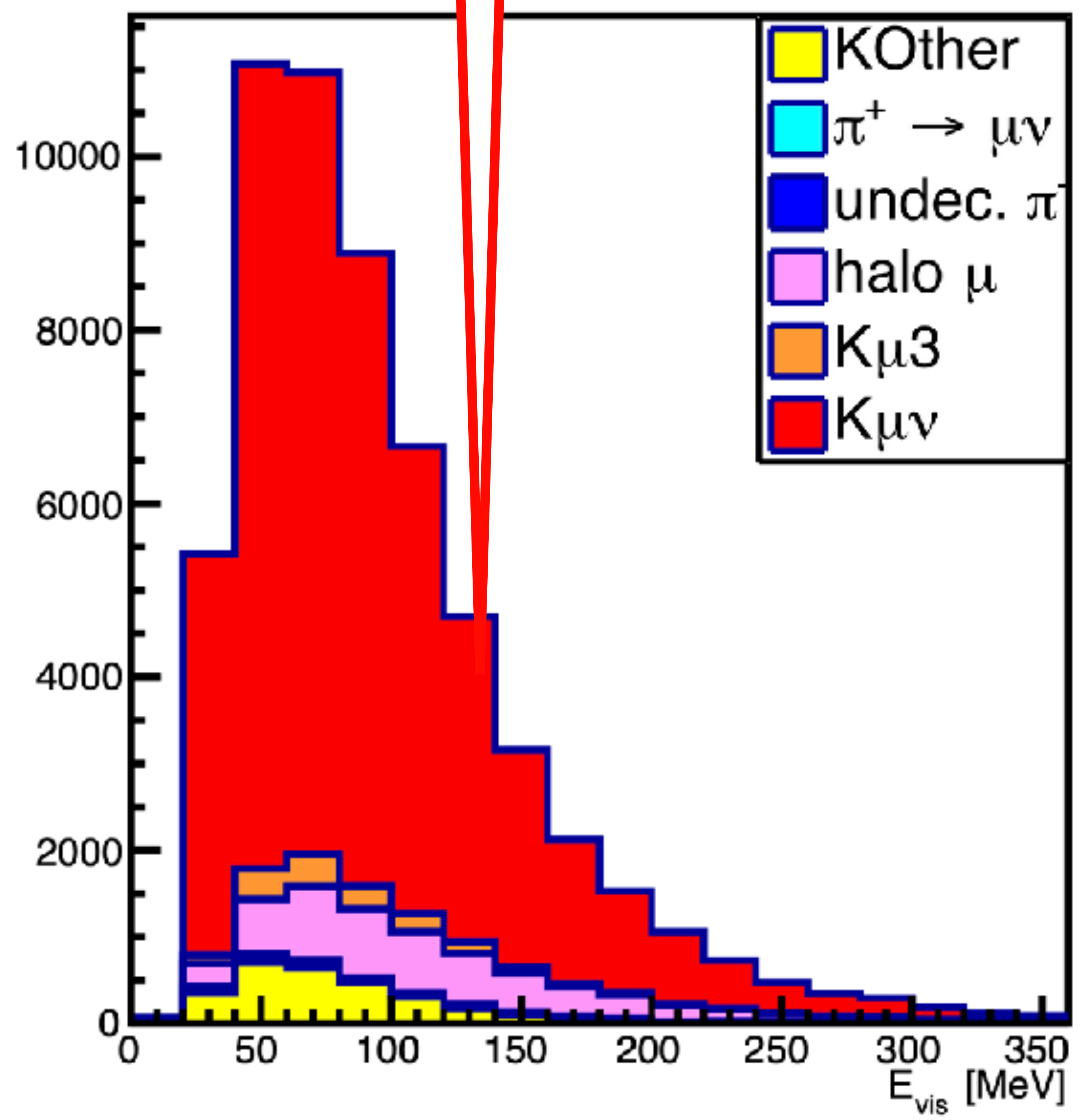
Eff = 34%

Efficiency is half geometrical



K^+ ~5-10% of beam

K_{e3} BR ~5%



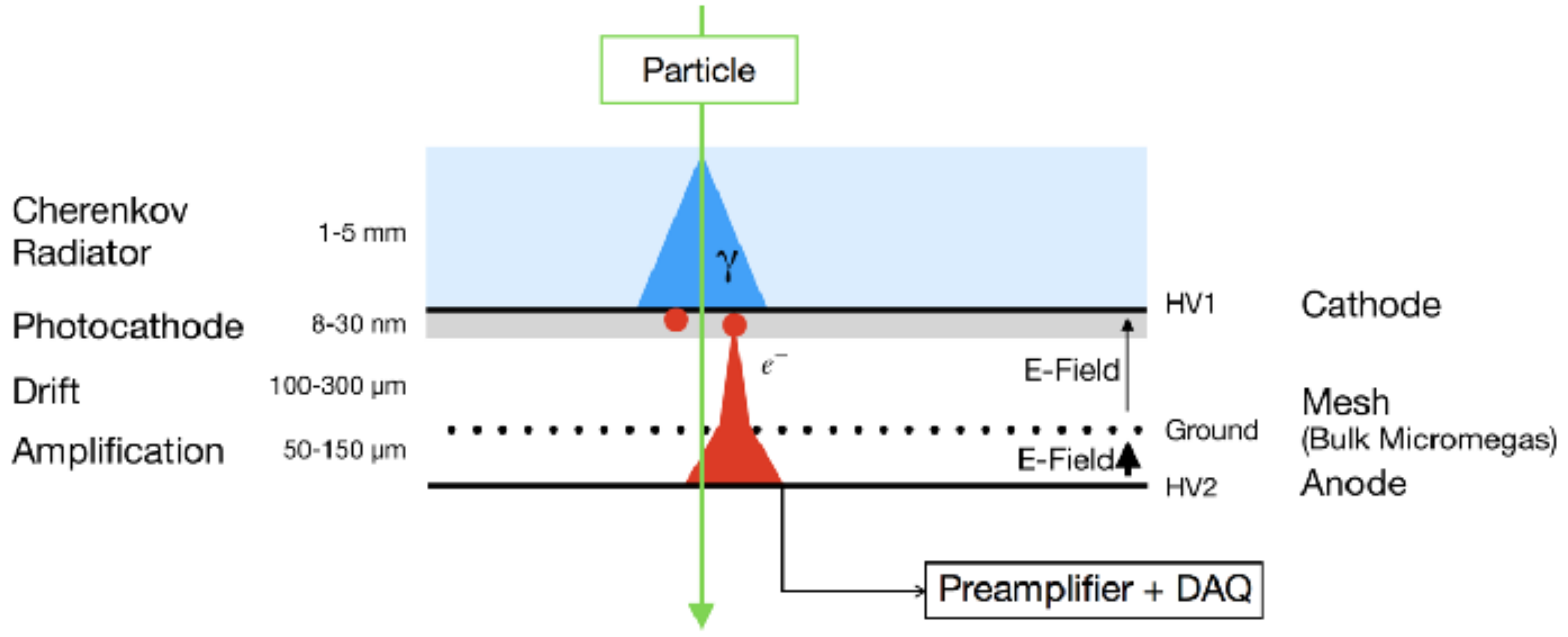
Forward Lepton Reconstruction

- Measuring $\pi_{\mu 2}$ muons constrains low-energy ν_μ
- Low angle muons at out of tagger acceptance
  - Need muon stations post-hadron dump
- Detector constraints: muons rate (~2 MHz/cm²), radiation hardness (~10¹² MeV-n$_{eq}$/cm²)

PIMENT

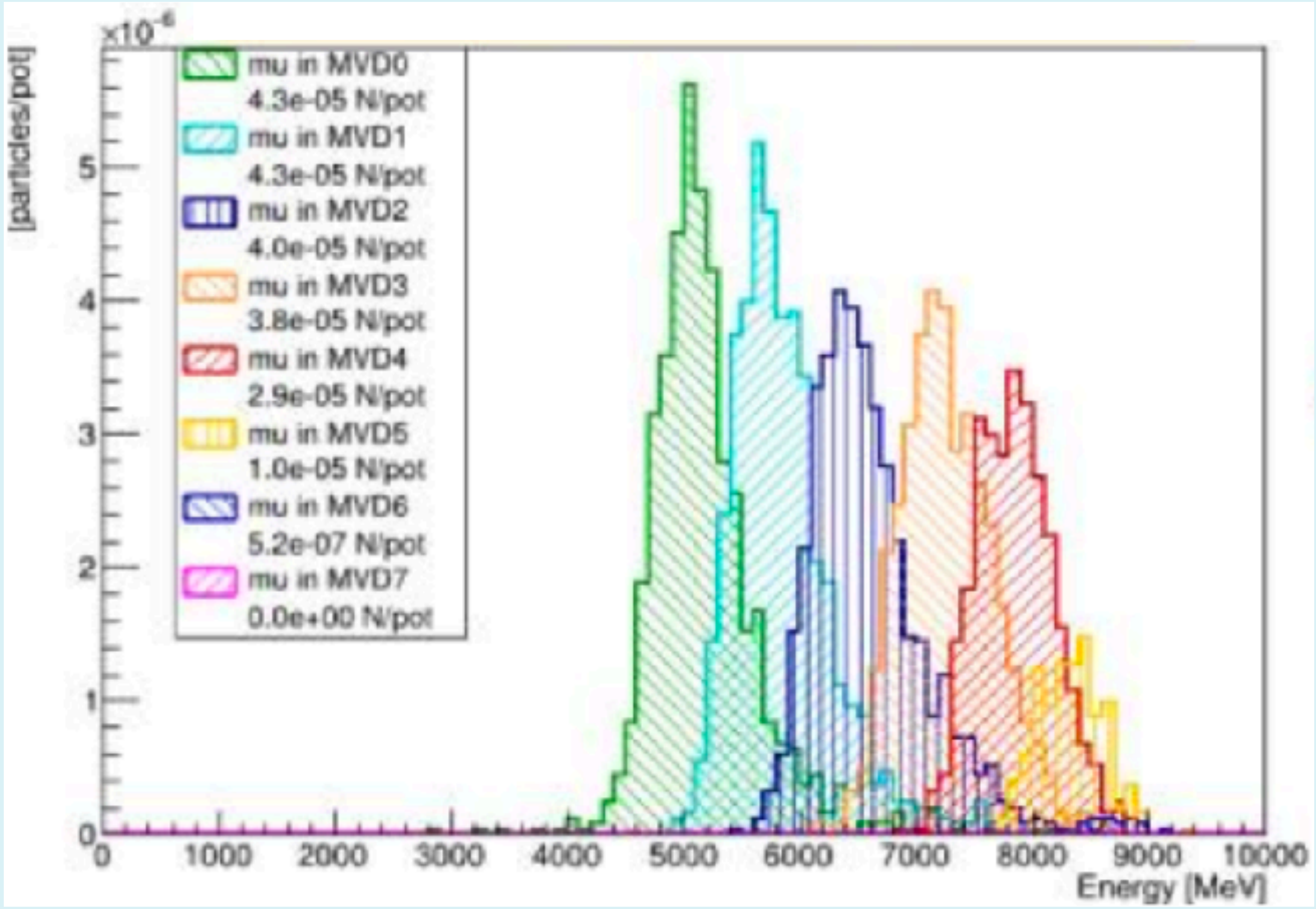
PICOSEC Micromegas Detector for ENUBET

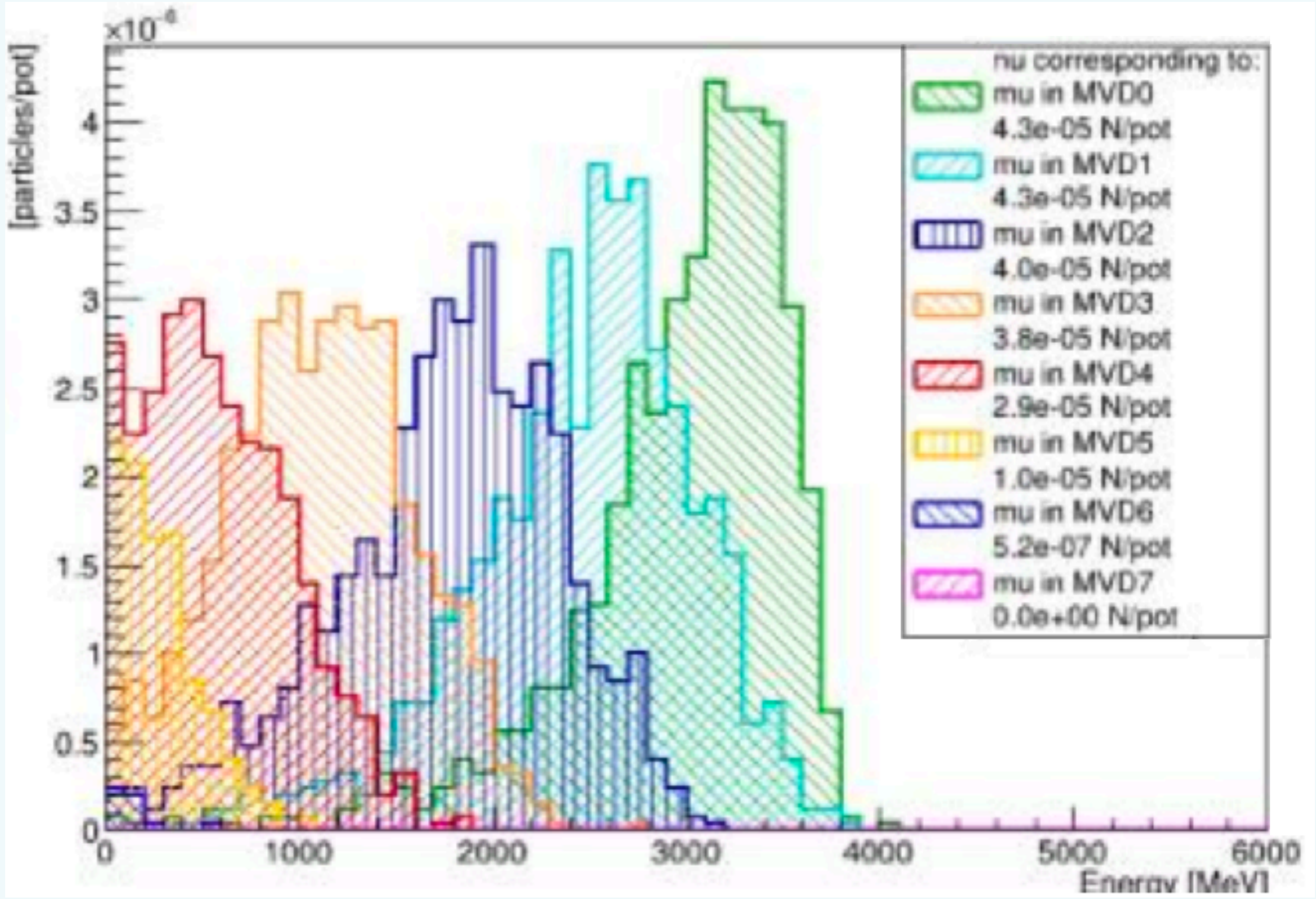
Fast micromega detector with sub-25 ps precision.



Correlation between traversed stations and neutrino energy can be exploited.

Upstream station is the ‘hottest’ and constrains detector technology.





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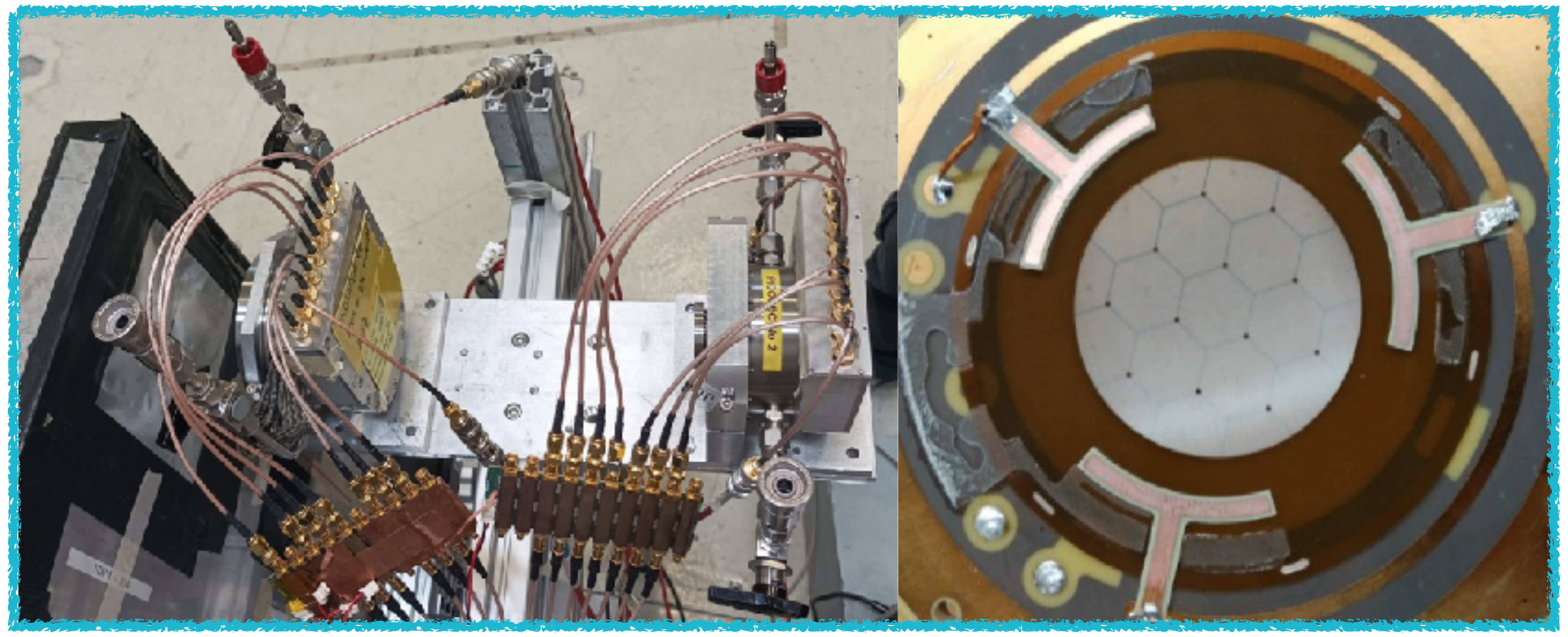

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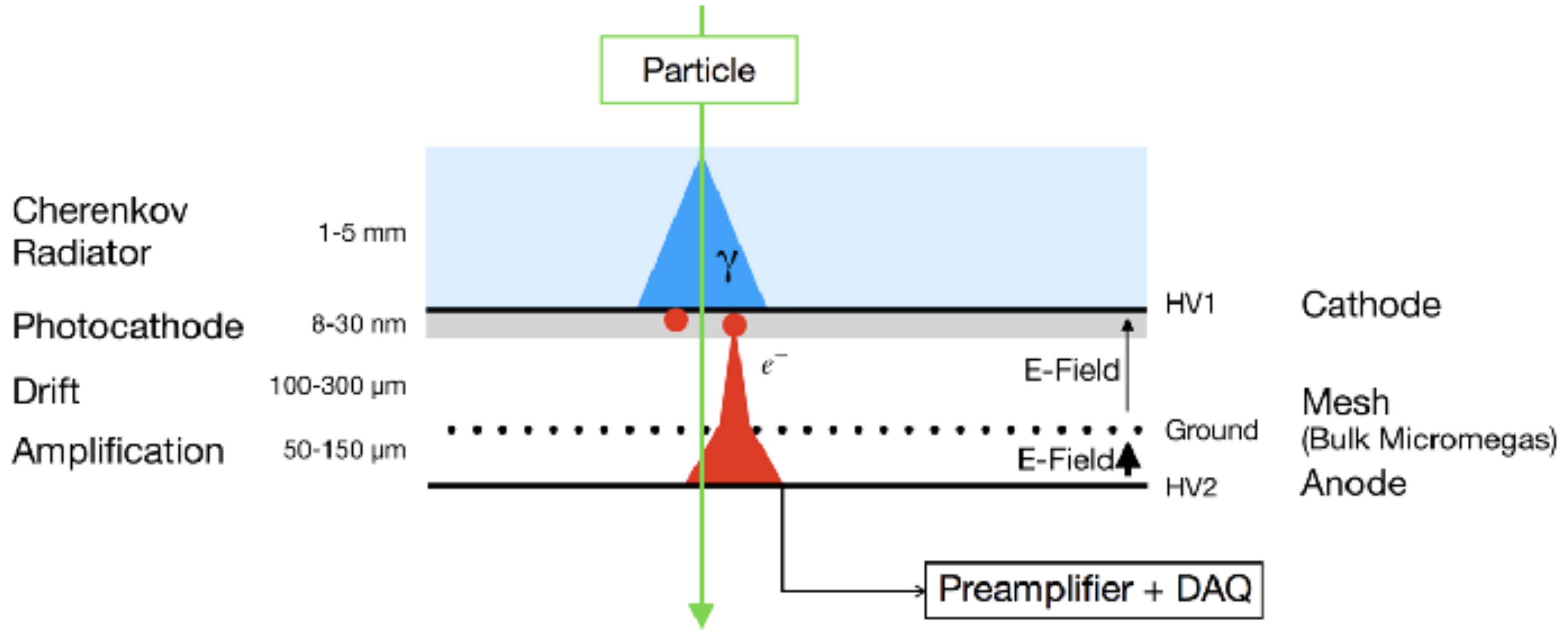
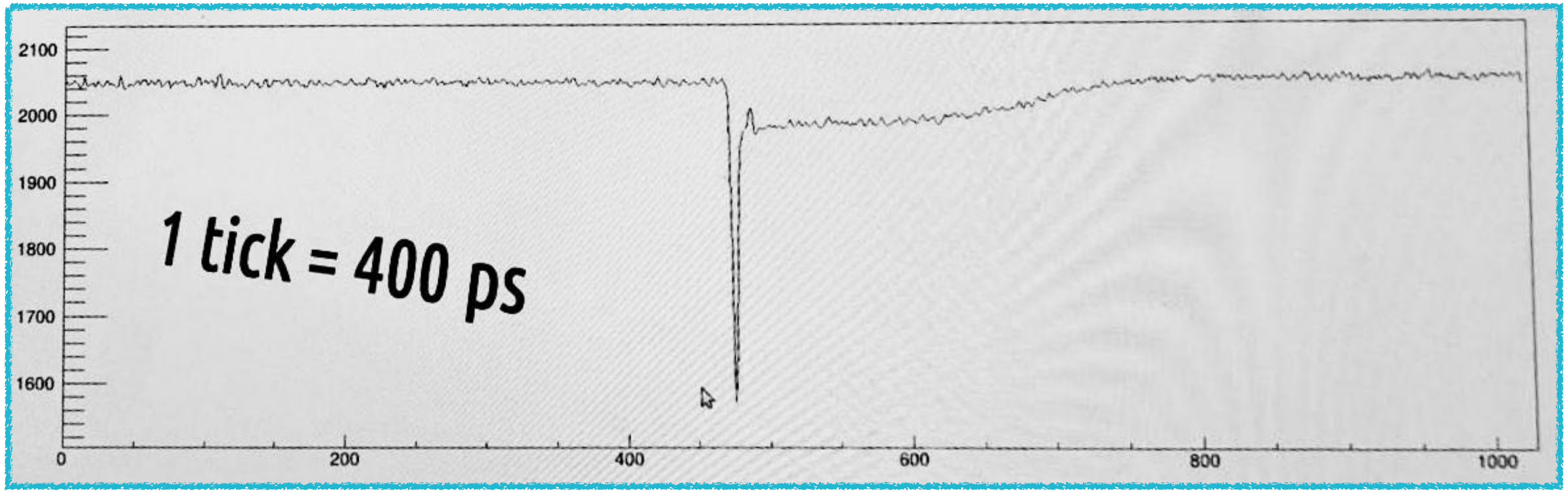


- Tested in T9 with the demonstrator (later!) in Aug. 2024
- Achieving a few 10s of ps resolution



1 tick = 400 ps

Flux Systematics

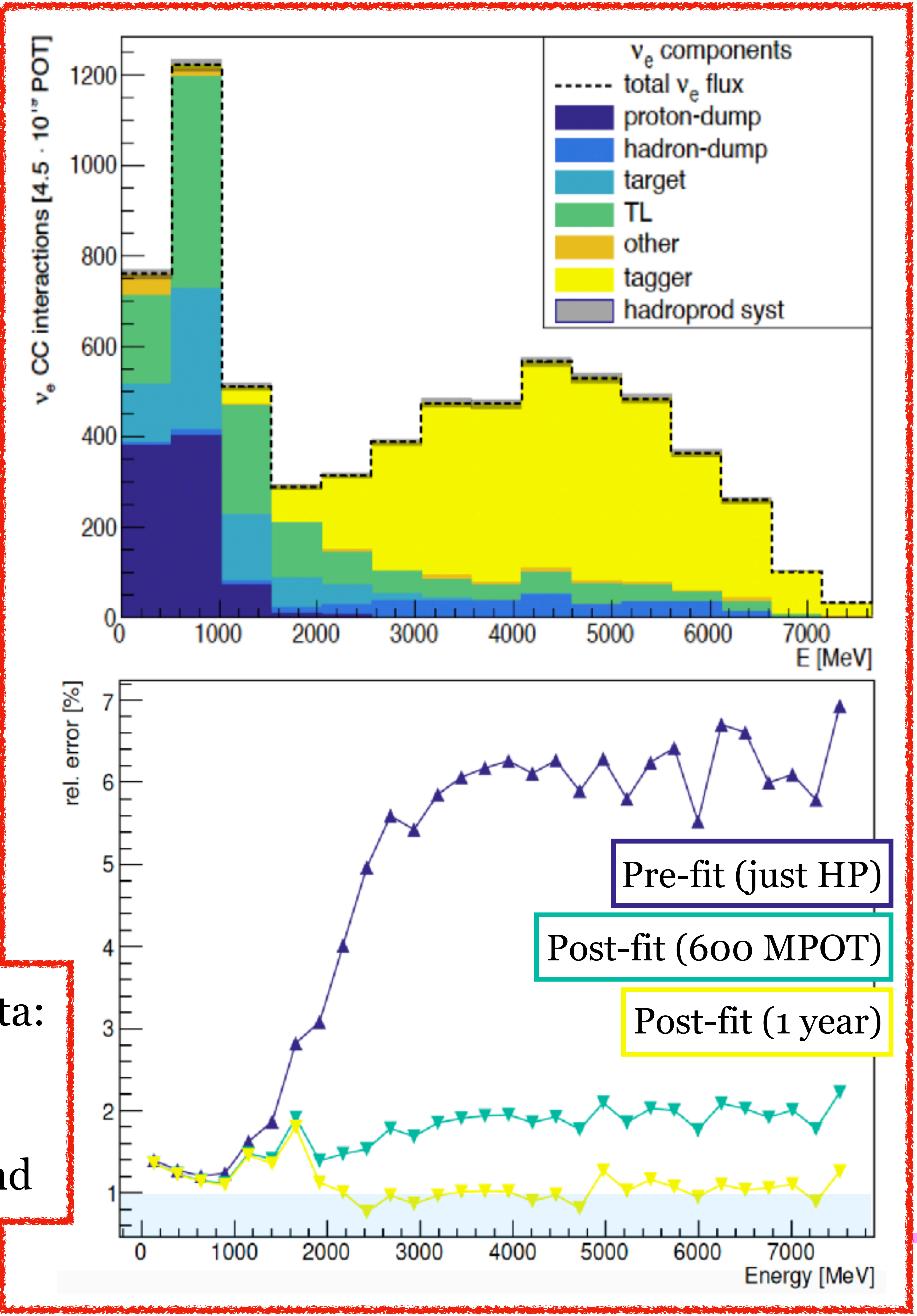
- Use a signal + background model to fit lepton observables and calculate the total uncertainty
- Without lepton monitoring constraints:
  - Flux uncertainty dominated by hadro-production* systematics (~6%)
- Including lepton tagging information:
  - Flux uncertainty reduced to ~1%

ENUBET GOAL REACHED

Total rates calculated for 1 year of data:

- SPS @ CERN, 4.5×10^{19} POT

- 500 t detector, 50 m from tunnel end



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*Hadro-production [illegible] from NA56/SPY experiment

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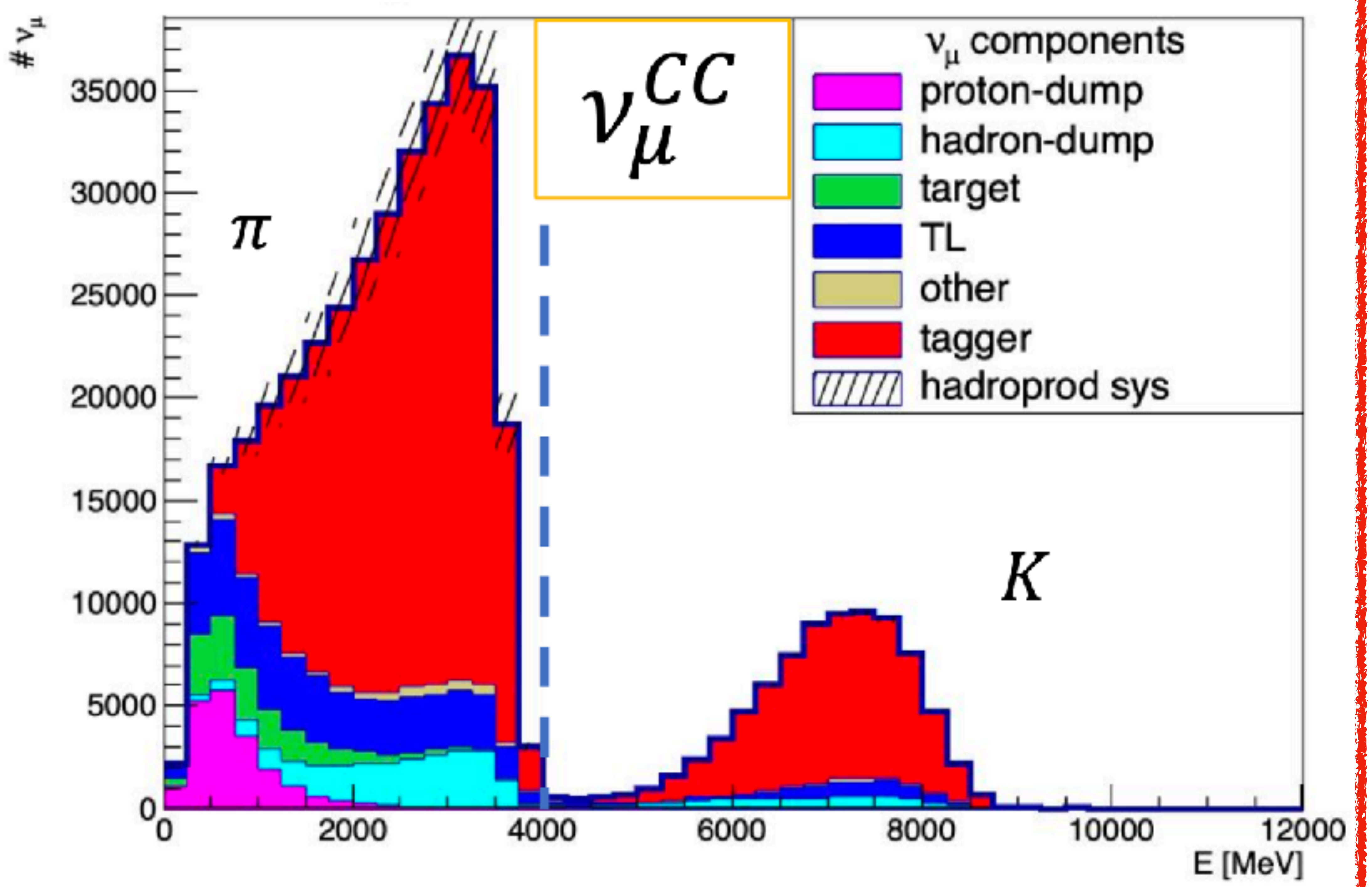

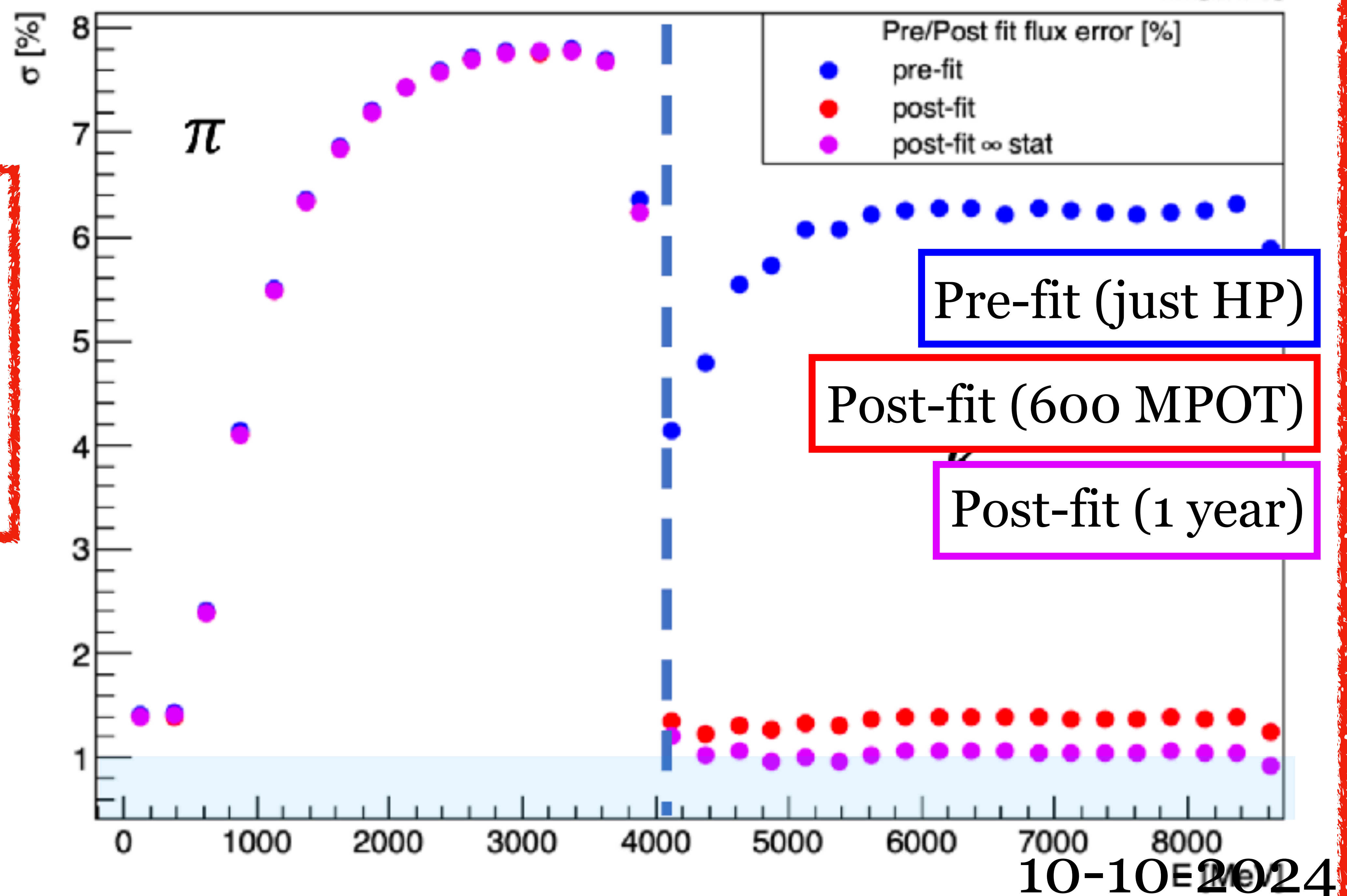

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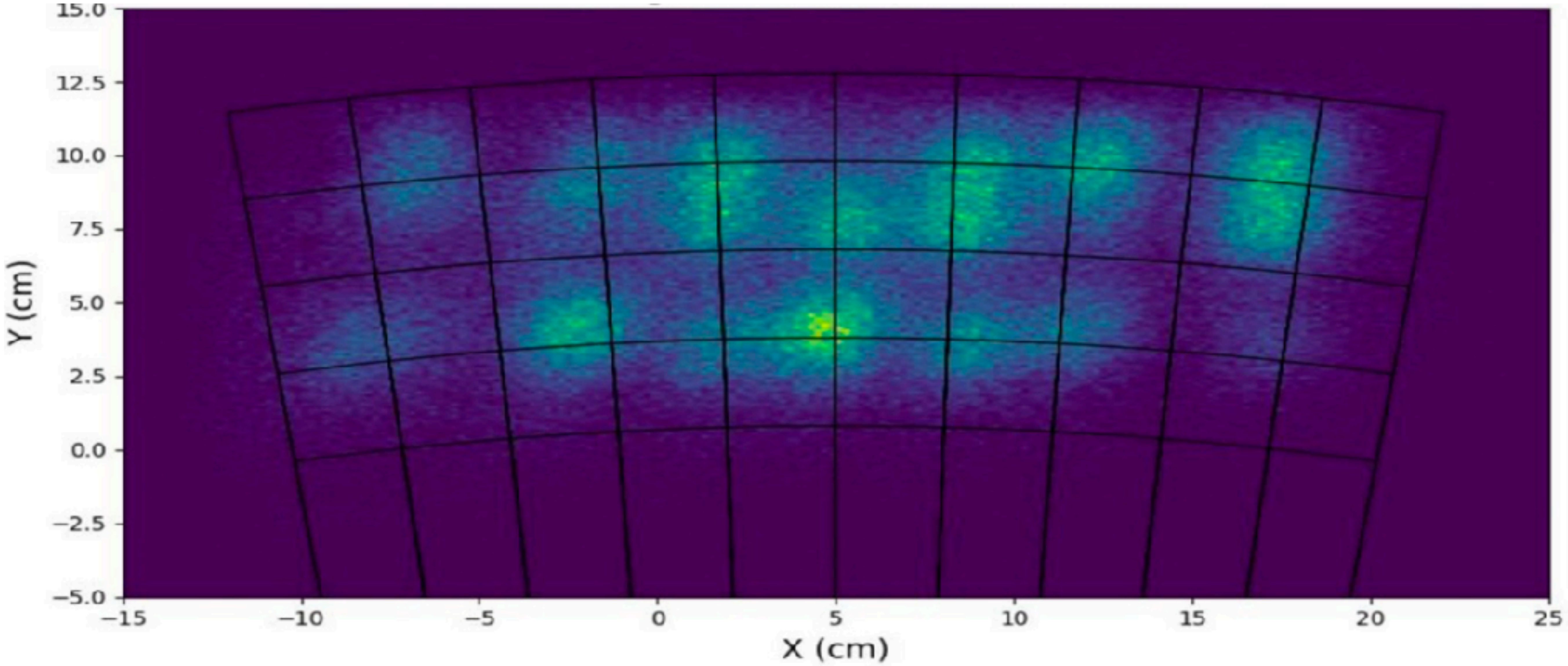
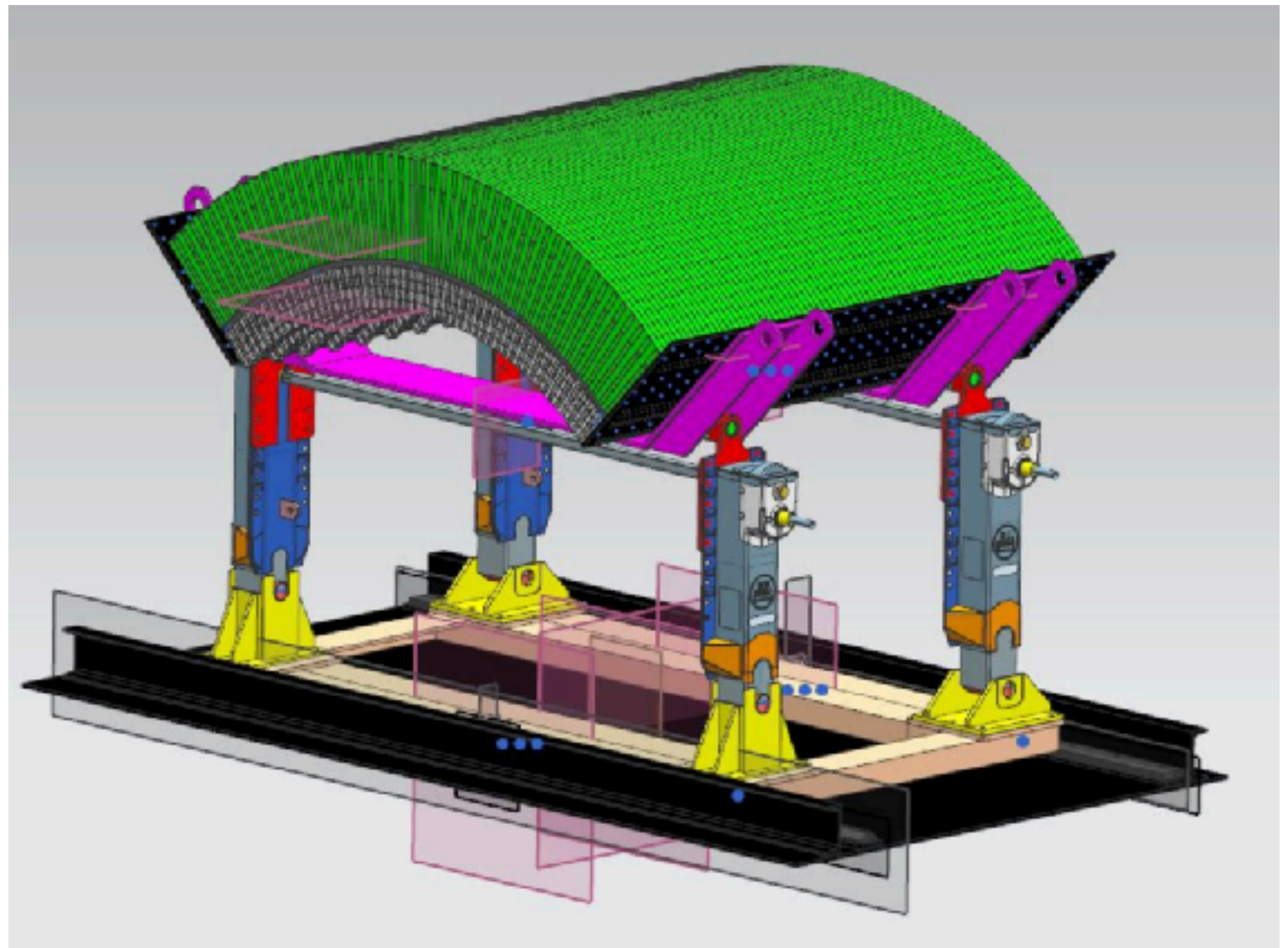
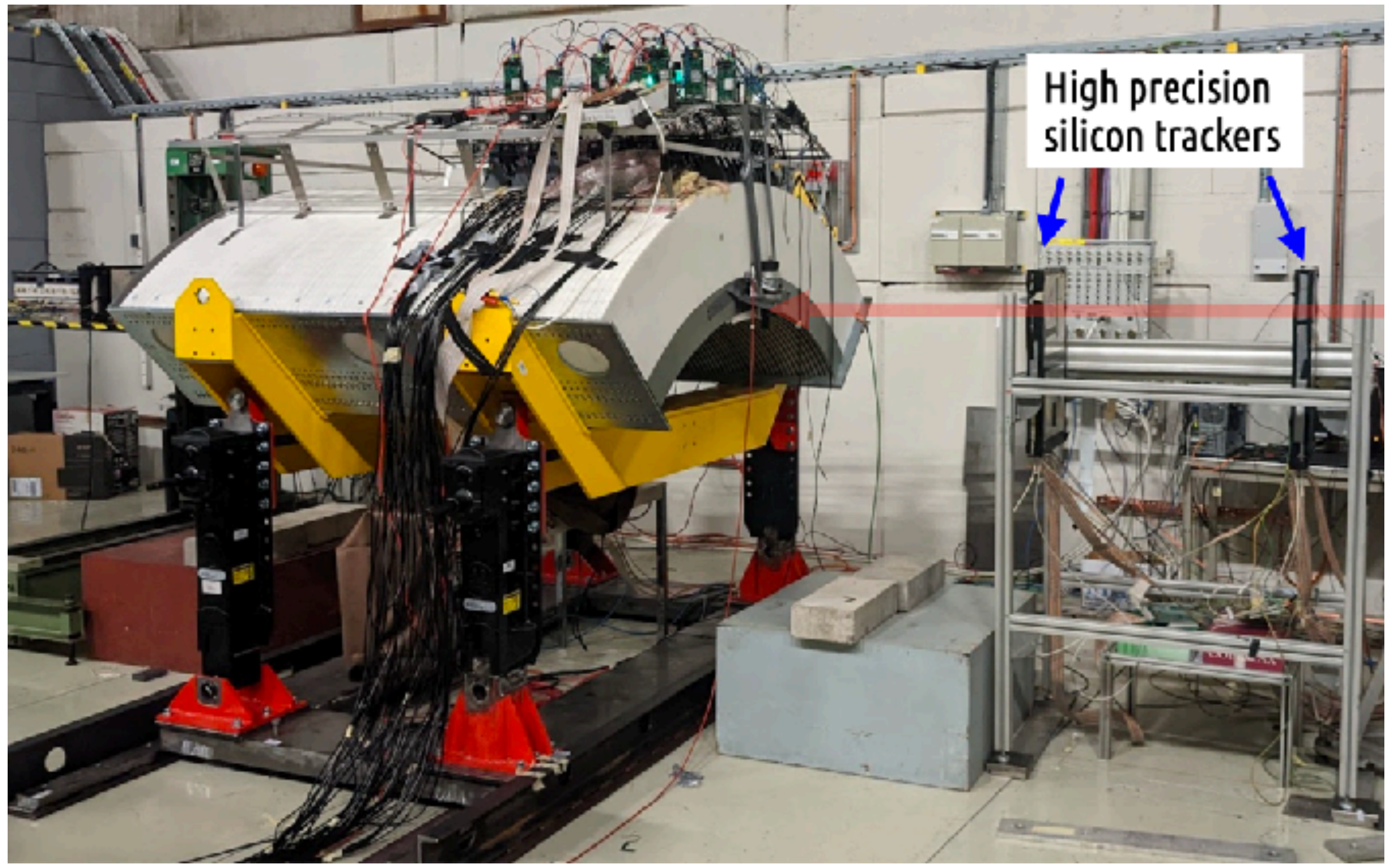
*Hadro-pro[illegible] from NA56/SPY experiment

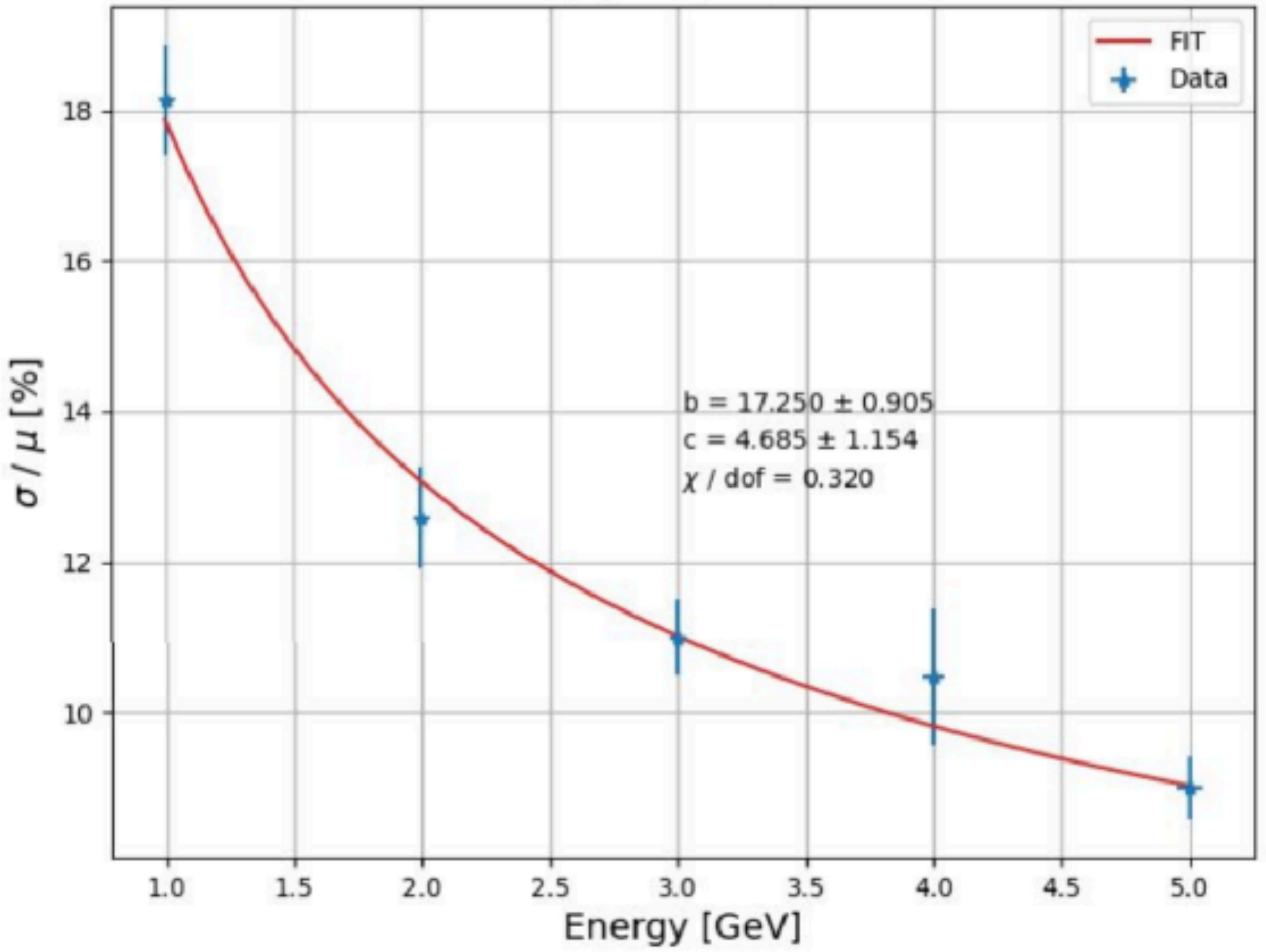
The Demonstrator

- Part of the decay tunnel was built and tested @ CERN in October 2022
  - The culmination of the ERC grant!
  - 1.65 m long, 3.5 ton, 90° coverage
  - 75 layers of: 1.5 cm iron, 7 mm scintillator
- Modular design to increase coverage easily

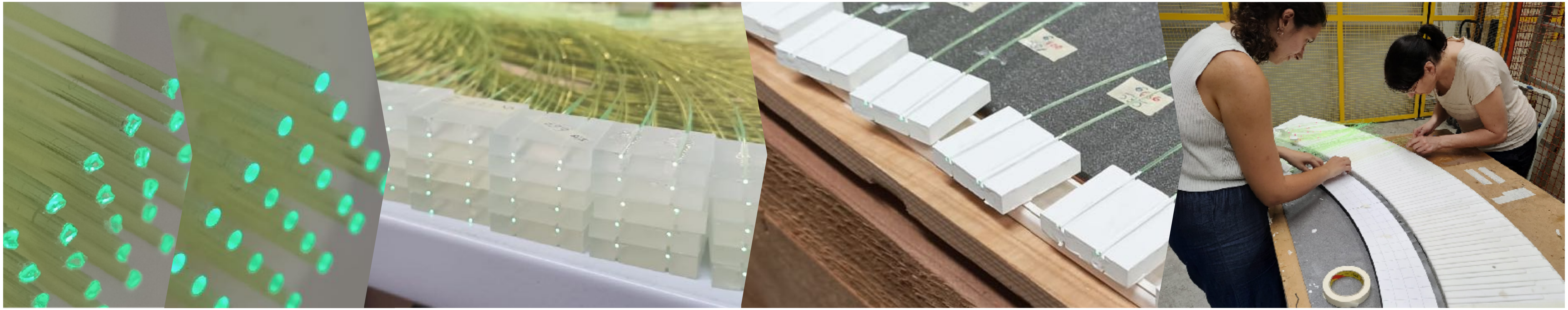


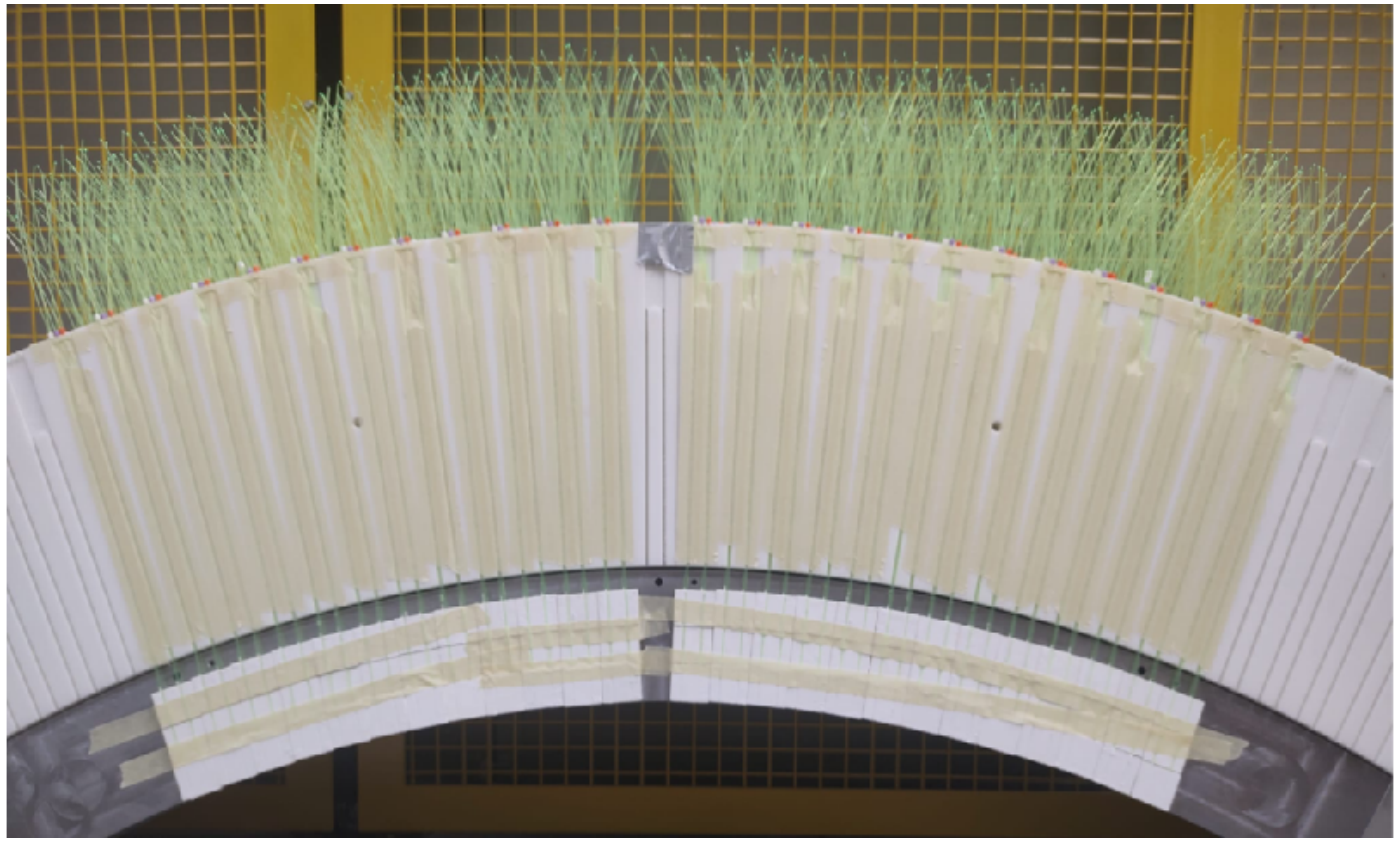






Demonstrator 2.0





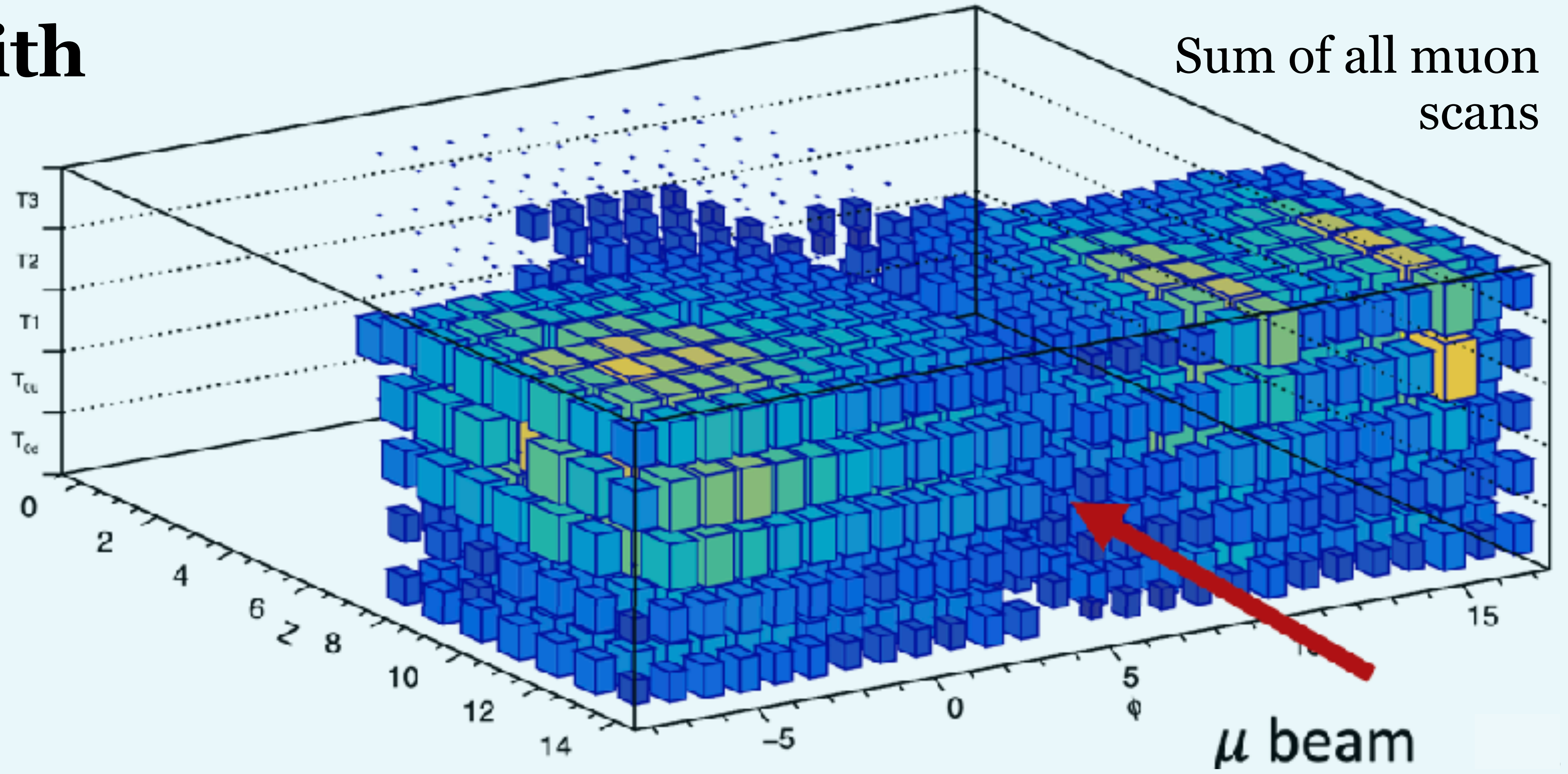
Demonstrator 2.0

*Terms and conditions apply.

Demonstrator 2.0 @ CERN

Calibration runs with 10 GeV muons

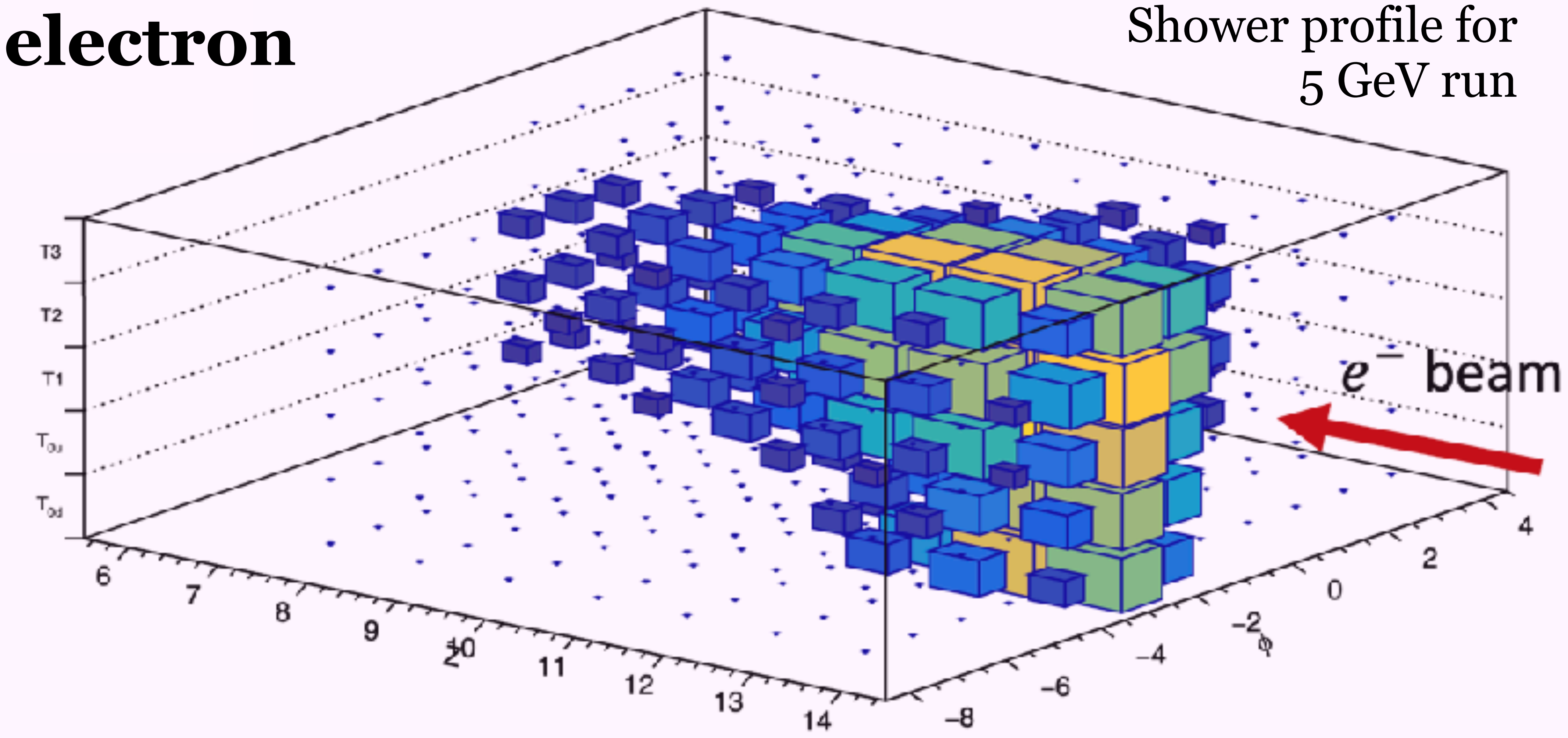
- All channels covered with lots of statistics
- Allow good equalisation of channels



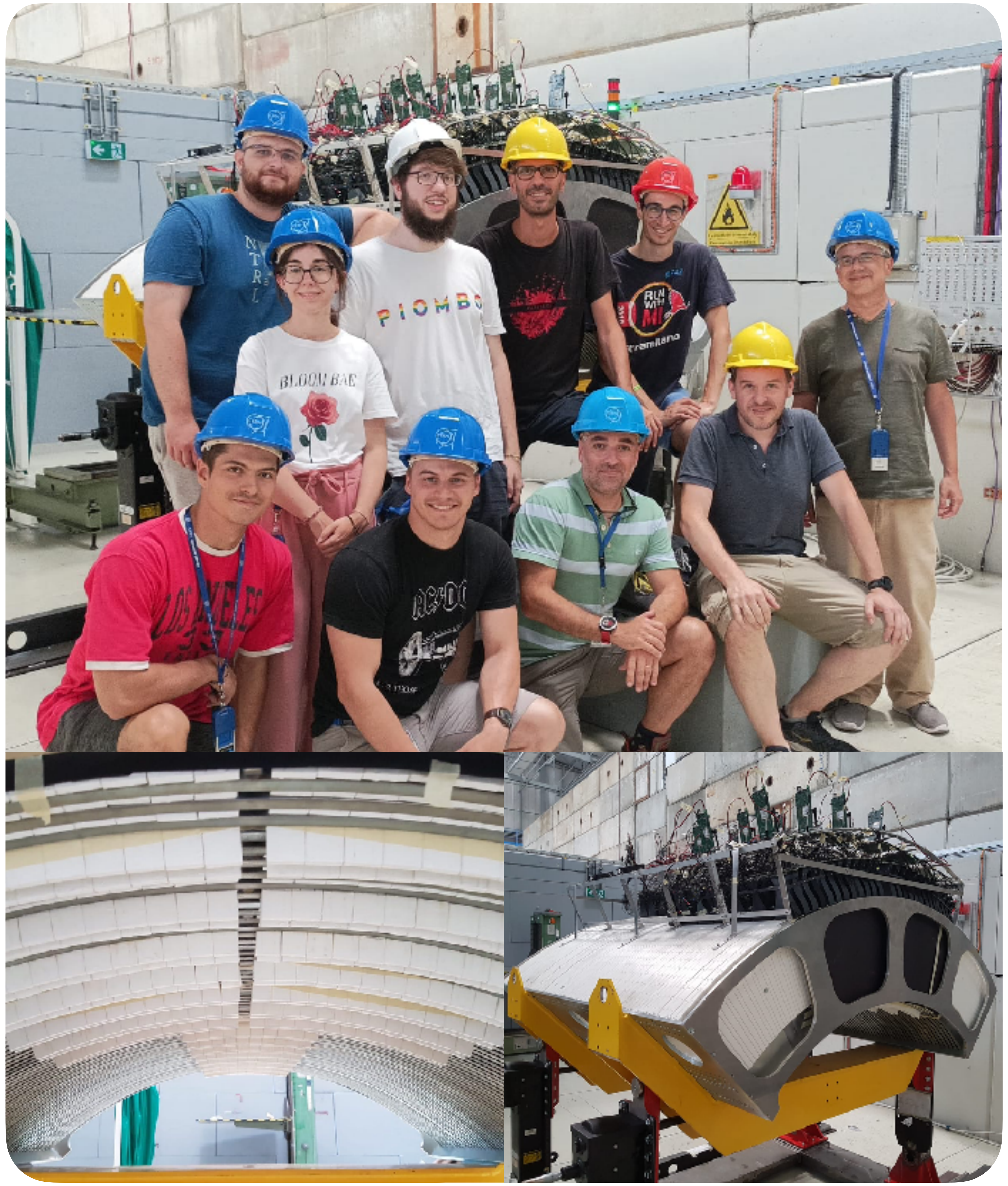
Sum of all muon scans

Energy scans with electron beams

- Scans with different energies
- Performed for linearity and resolution studies

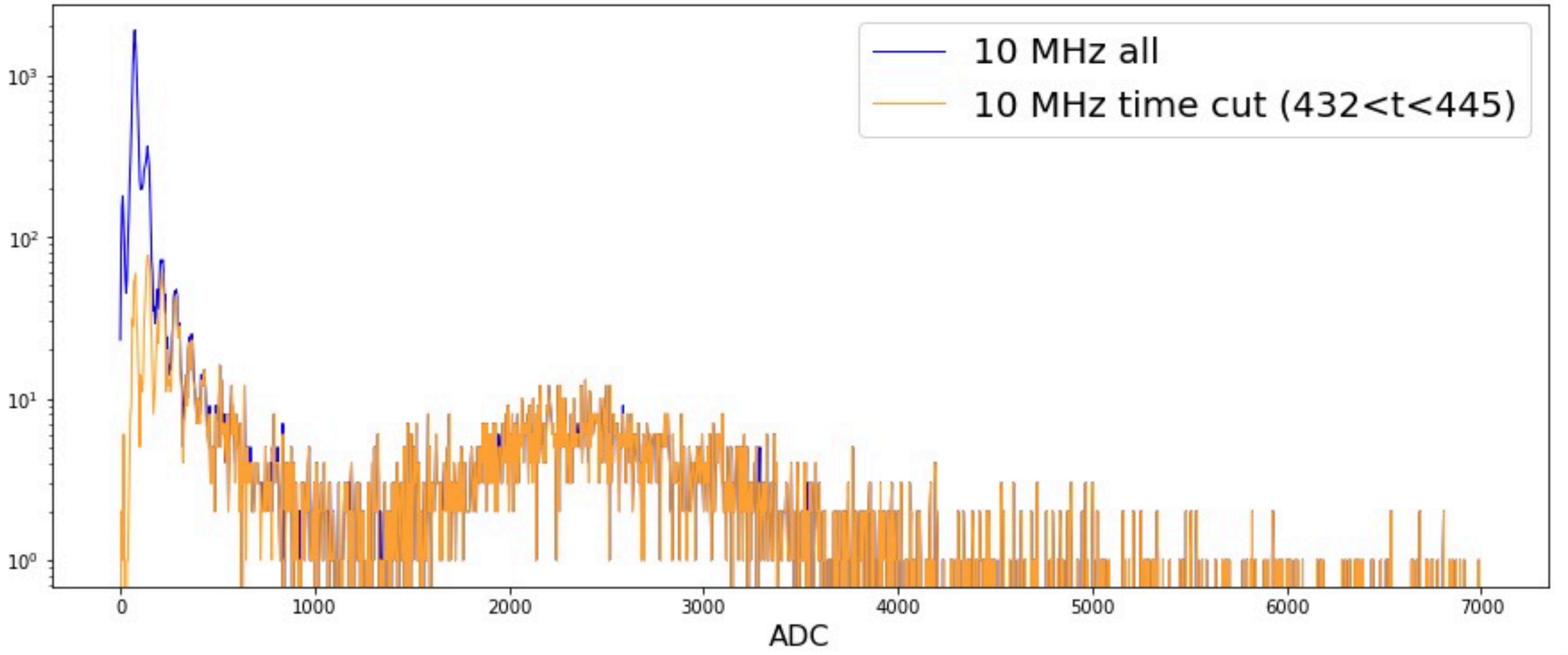


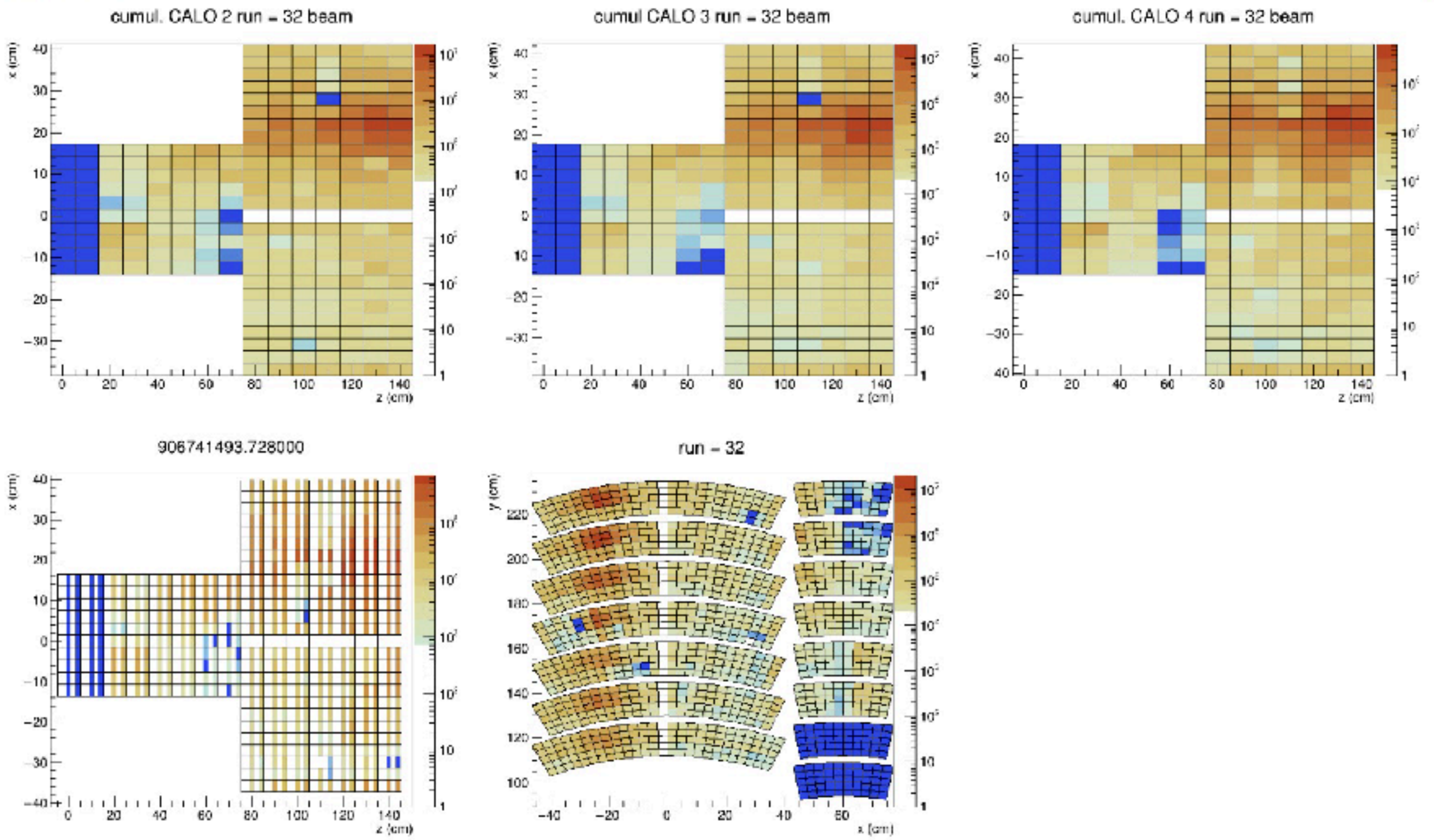
Shower profile for 5 GeV run

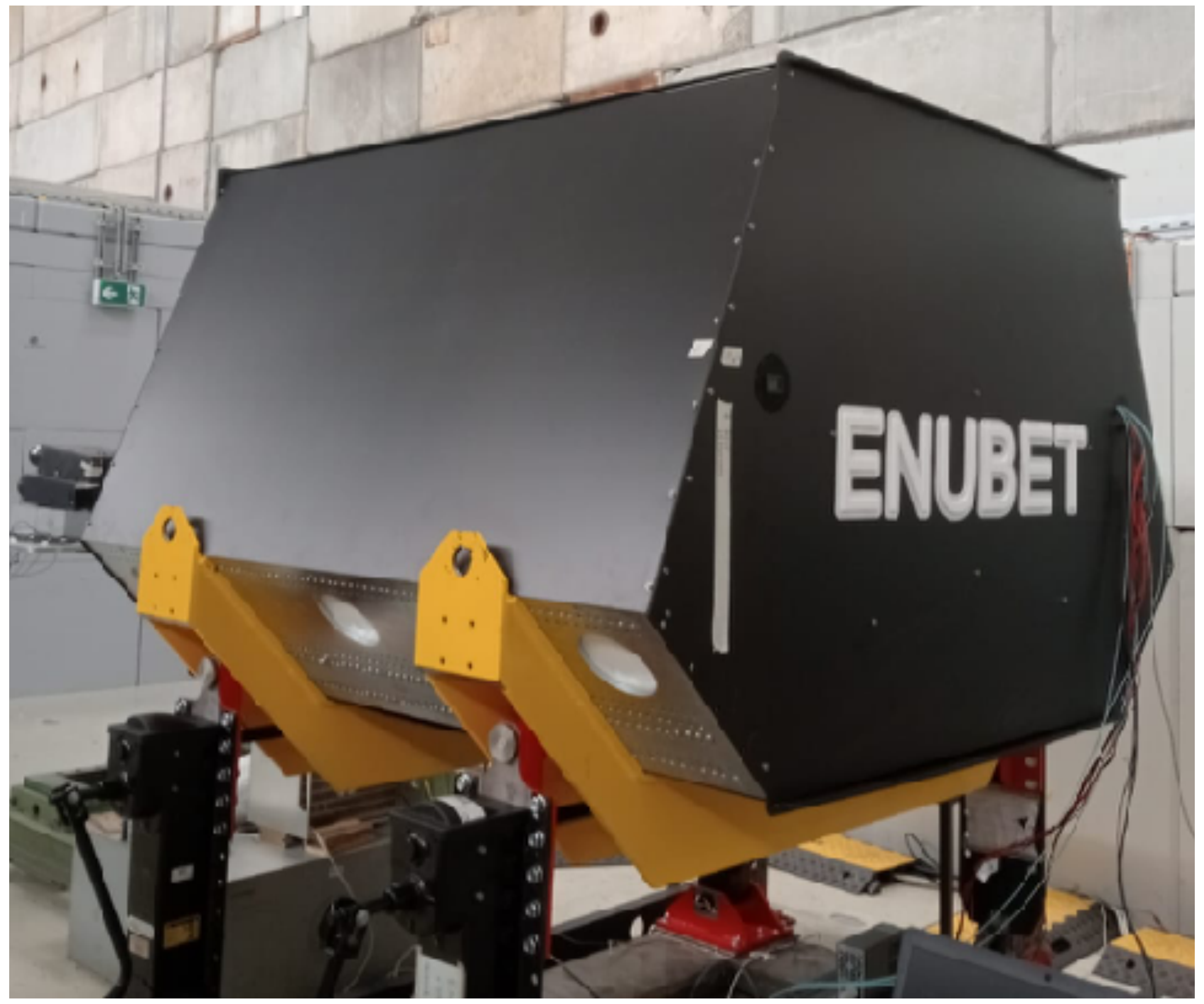


Demonstrator 2.5

- Another testbeam at T9 in Aug. 2024
- All channels were connected together for the first time!
- A new dark box for shielding also tested
  - ‘The Coffin’

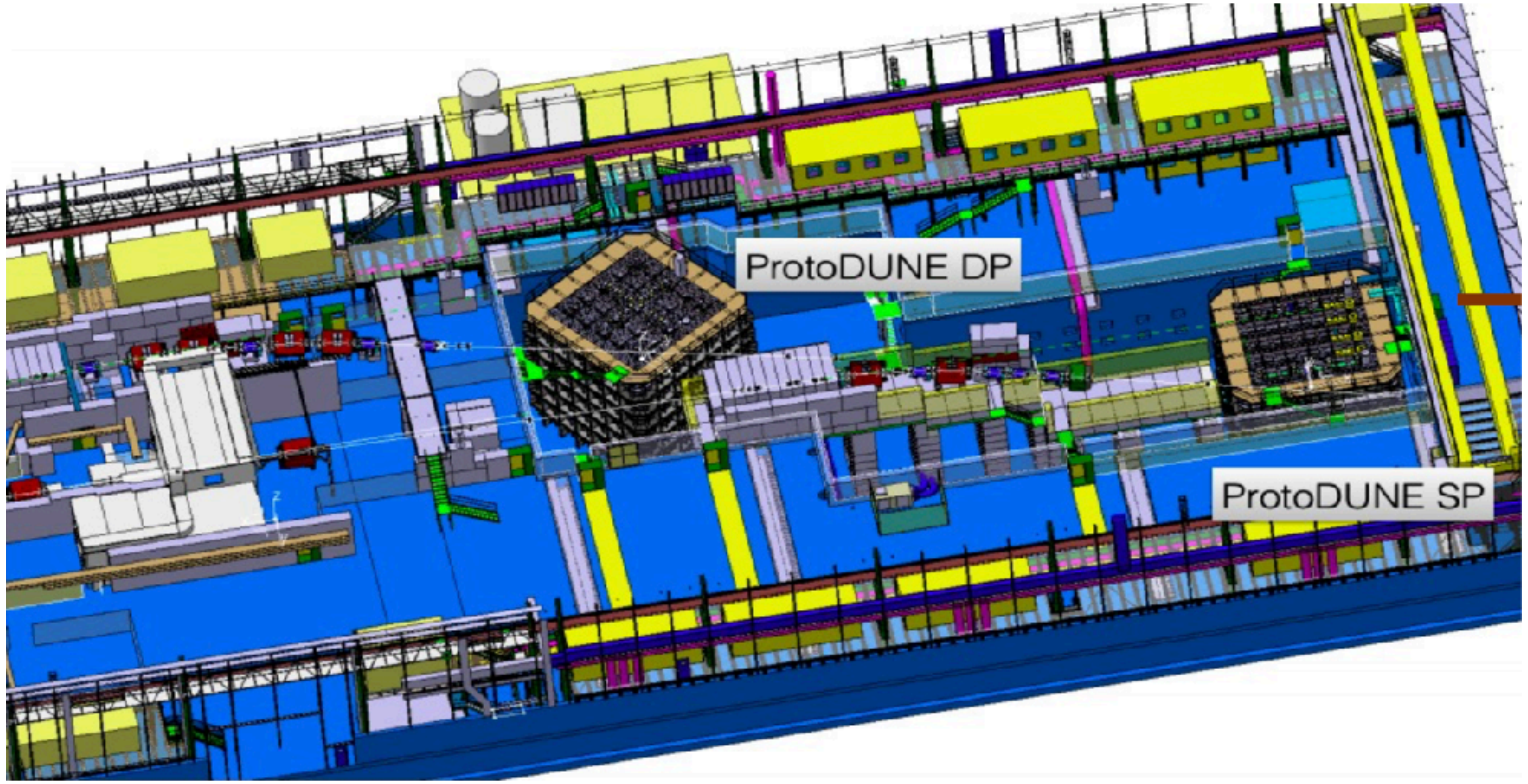


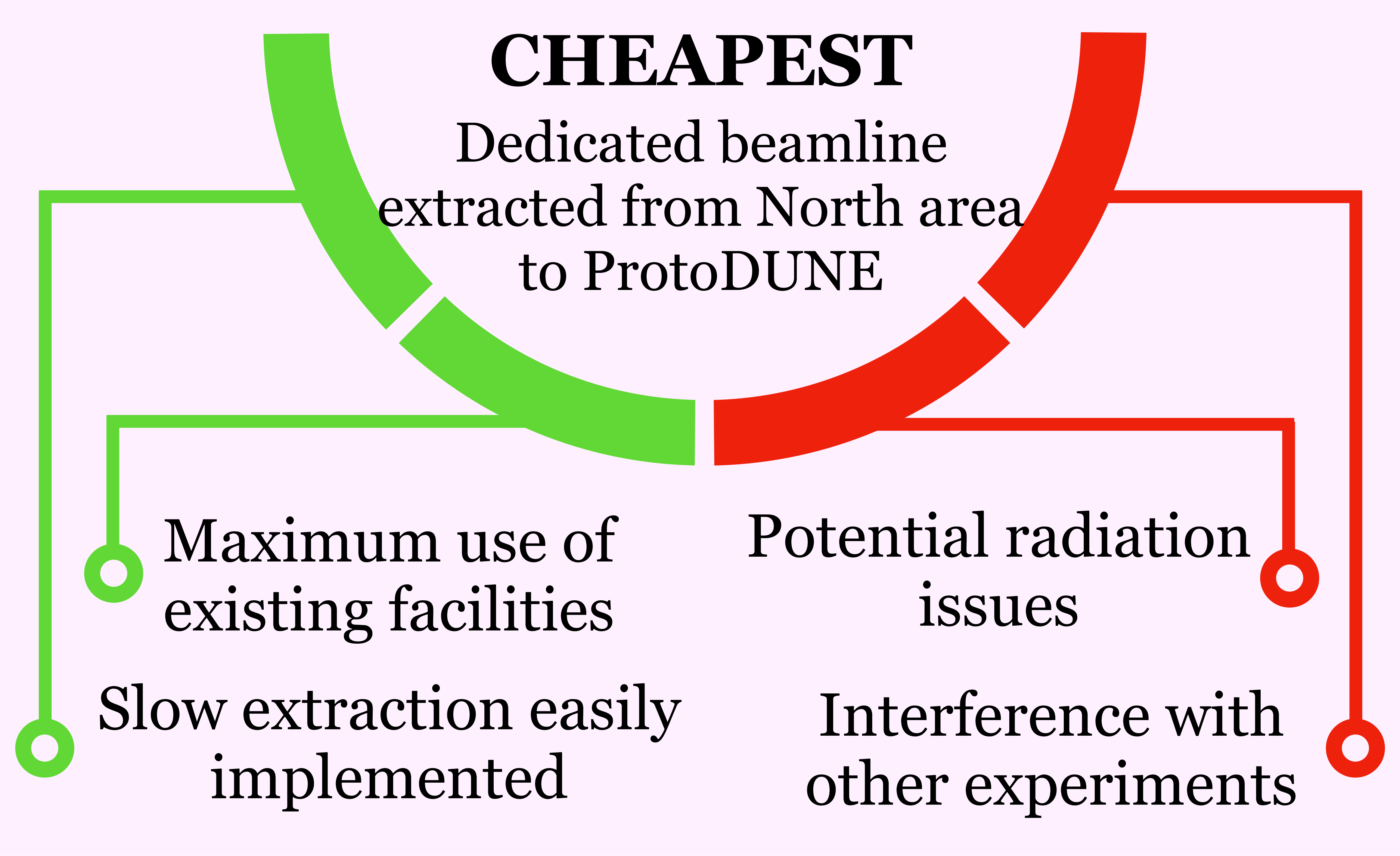




Implementation

- Propose a short baseline neutrino beam experiment @ CERN after 2030 (parallel with HK and DUNE)
- Studies and discussions ongoing under Physics Beyond Colliders framework
- This could be done in the North Area exploiting existing detectors (ProtoDUNE)





CHEAPEST

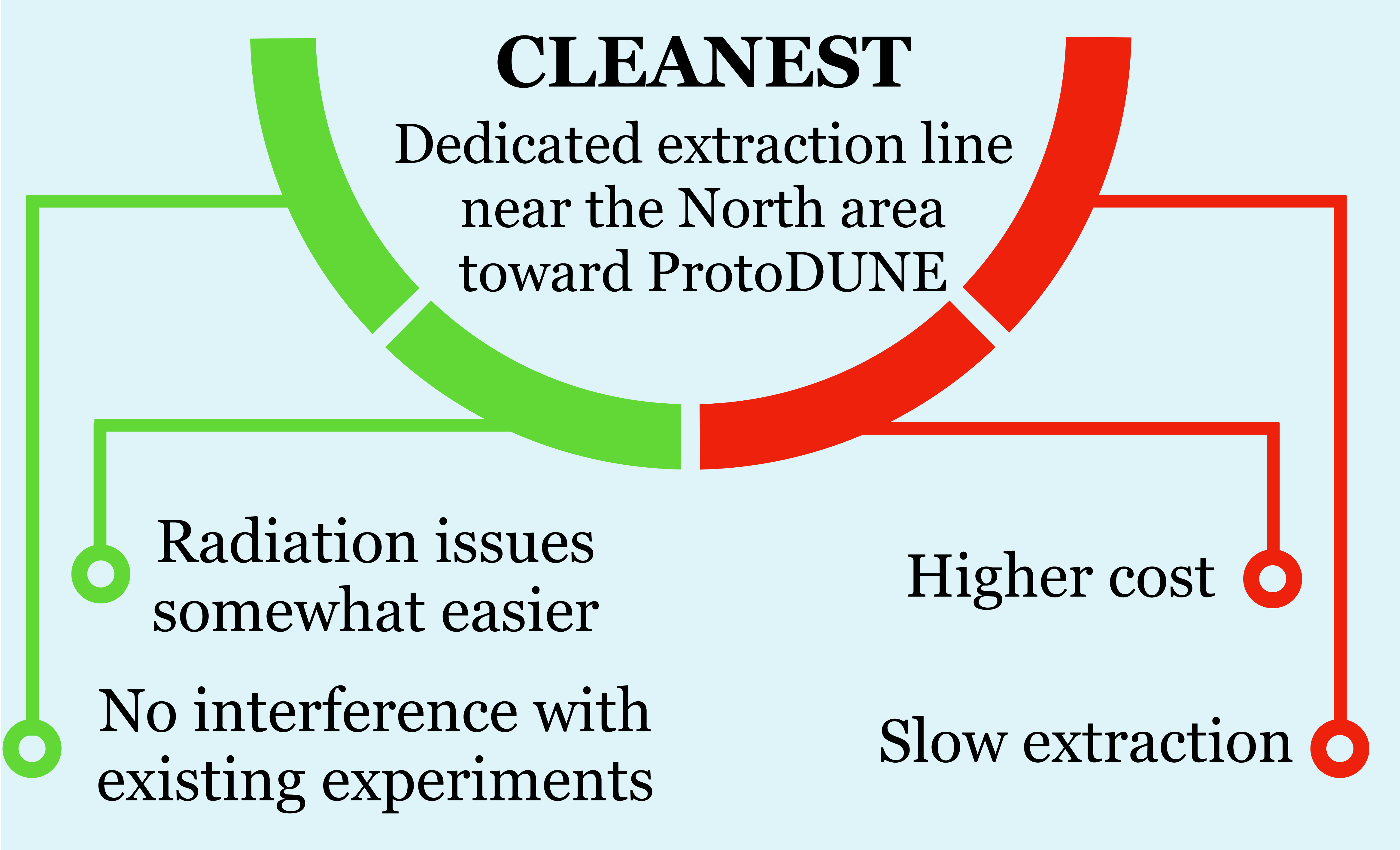
Dedicated beamline extracted from North area to ProtoDUNE

Maximum use of existing facilities

Slow extraction easily implemented

Potential radiation issues

Interference with other experiments



CLEANEST

Dedicated extraction line near the North area toward ProtoDUNE

Radiation issues somewhat easier

No interference with existing experiments

Higher cost

Slow extraction

Conclusions

- **Monitored neutrino beams are a reality!** Proof of concept is almost complete - demonstrated in both simulation and experimentally
  - Critical for next generation neutrino experiments

ERC project completed - demonstrated the technique.

Another beam test in 2023 and another request likely in 2024.

PIMENT (ANR 2022-2024)

- Constrain the 2-body ν_μ flux
- Assessing PICOSEC performance in the dump

Physics Beyond Colliders (NP06)

- Starting to address the issue of implementation at CERN
- During LHC Run IV, in parallel with DUNE and Hyper-Kamiokande
- Assess the possibility of using ProtoDUNE as the neutrino detector
- Optimal location would exploit the SPS slow extraction

Thank you

Supplementary

What is required?

Branca, A. et al., Symmetry 2021, 13, 1625

A cross-section facility to achieving a precision of <1% in ν_e and ν_μ fluxes

Reduce neutrino flux systematics

- Combine hadro-production and ν-e scattering data (**5-10%**)
- Monitored neutrino beams (**0.5-1%**)
- Muon storage ring, *e.g.* nuSTORM (**<1%**)

Constrain E_ν w/o energy reconstruction

- Narrow band beams with movable detectors (a 'monochromatic' beam)
- Monitored neutrino beam with a 'narrow band off-axis' technique

Low Z targets w/ same near and far detector

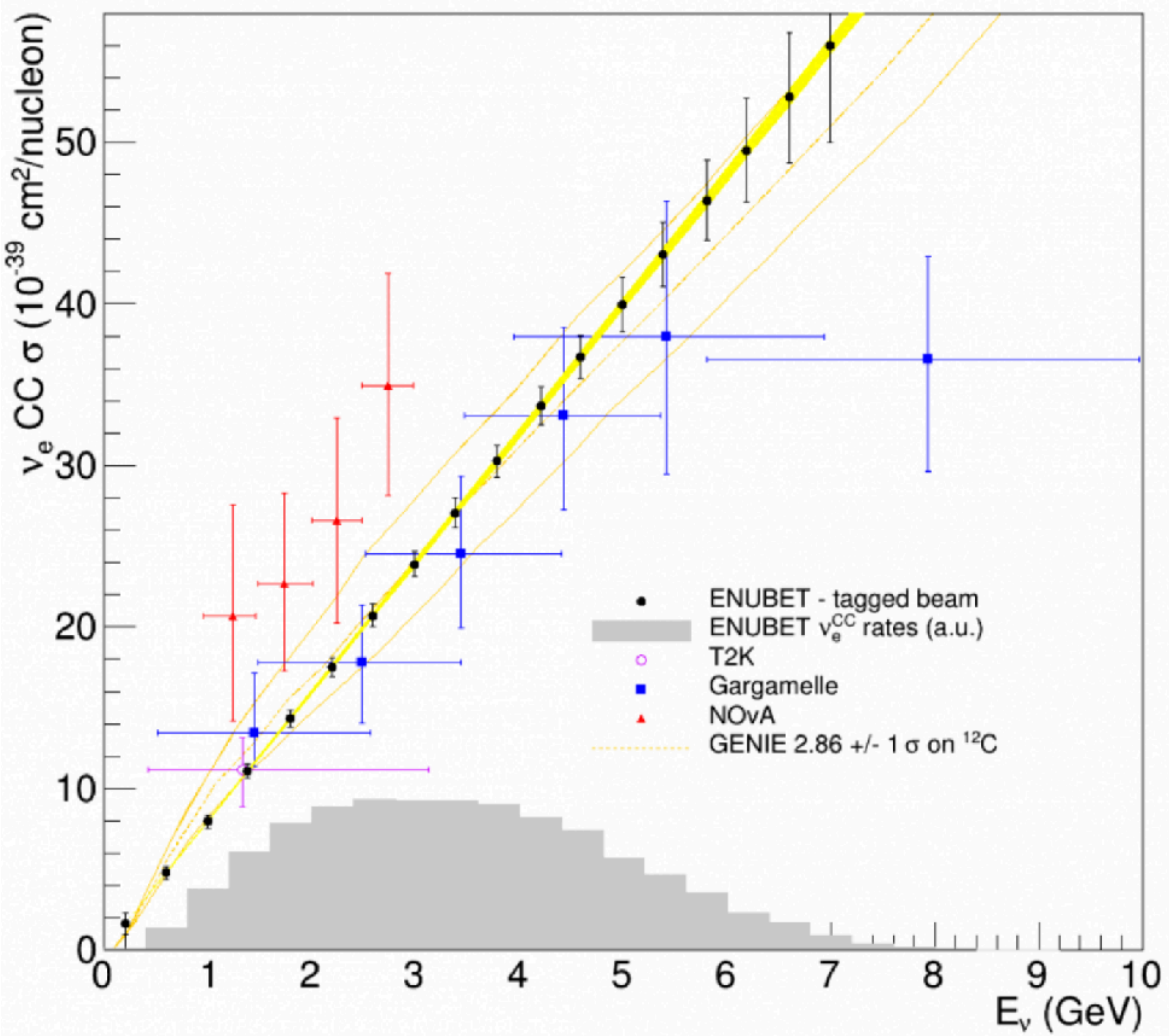
- Near detectors are good, but problems with deconvoluting flux and cross-section (and different phase space)
- New experiments with novel detectors and beam

Large statistics (double-differential x-secs)

- Not an issue for ν_μ
- $\mathcal{O}(10^4)$ ν_e in conventional and monitored beams
- $\mathcal{O}(10^6)$ in all flavours in muon storage rings

J. McElwee

The aim of ENUBET



Purpose of ENUBET - A narrow-band neutrino beam to measure:

- Neutrino cross-section and flavour composition at a 1% precision level
- Neutrino energy at 10% precision

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

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.

Demonstrator Wars: 1.0 vs 2.0

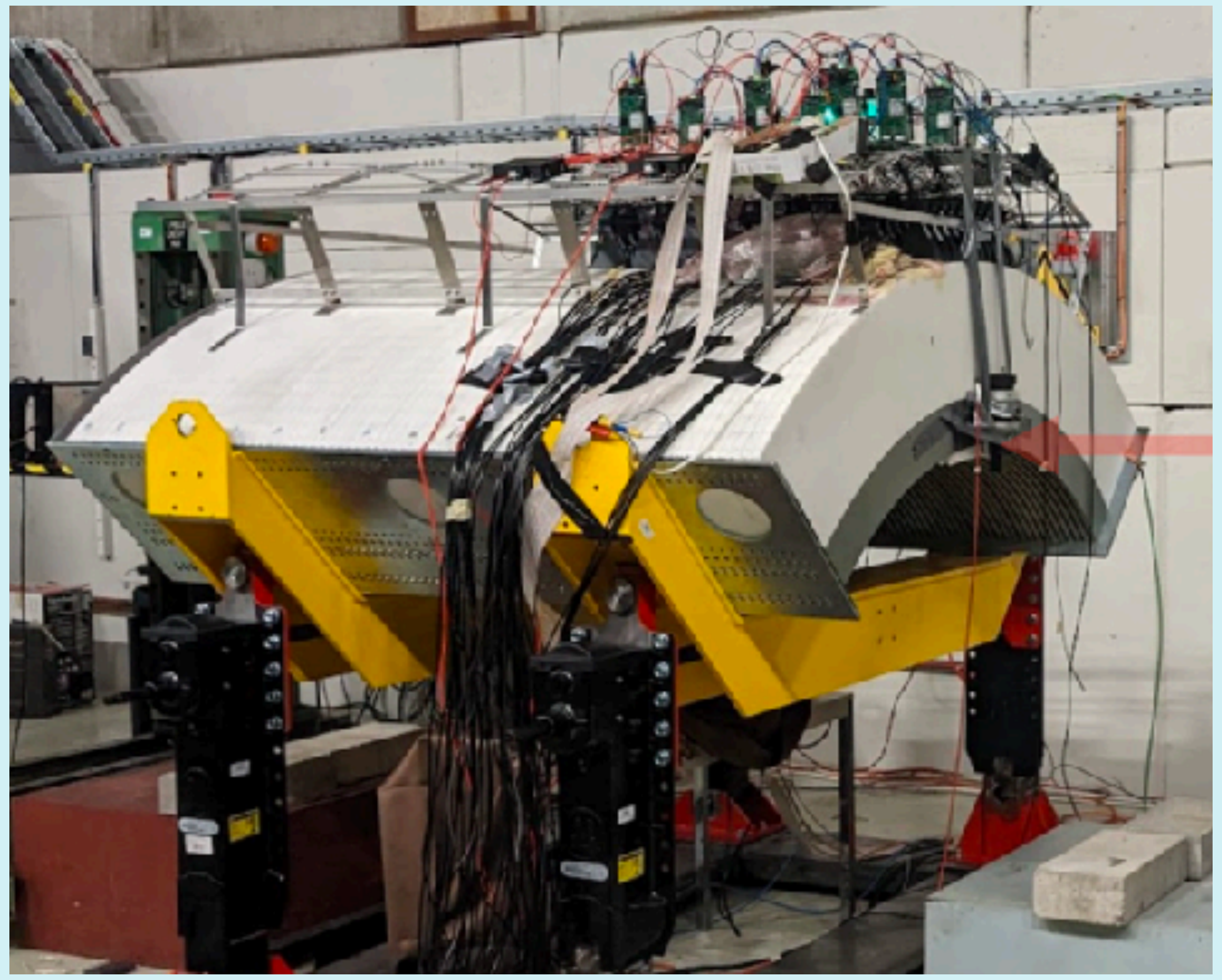
1.0

8 z-layers

10 ϕ-sectors

400 channels

2022



2023

+7 z-layers

25 ϕ-sectors each

+875 channels

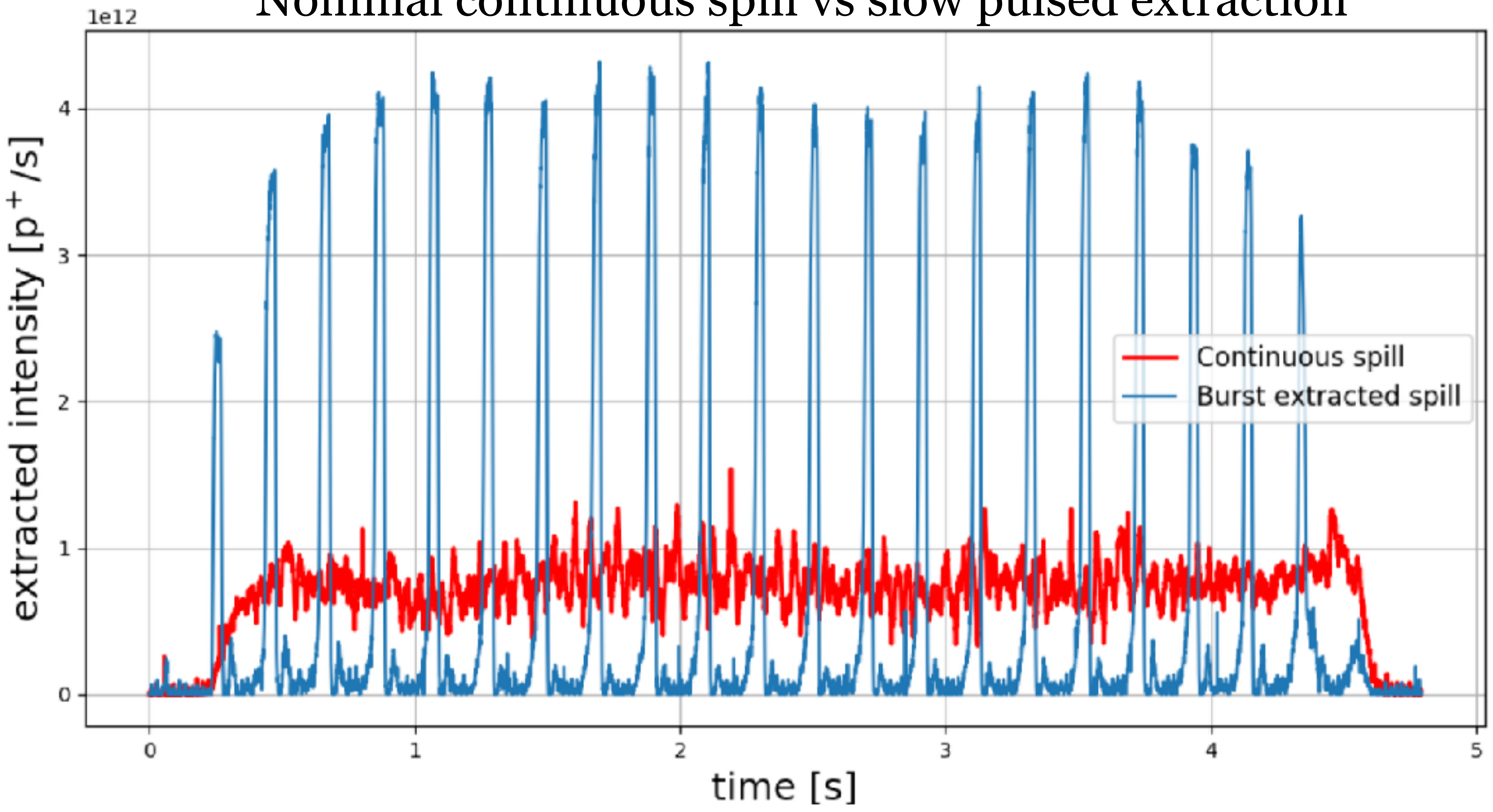
2.0

Parameter	Quantity	
	1.0	2.0
Scintillator tiles	1,360	4,335
WLS	1.5 km	4.8 km
Channels (SiPM)	400	1,275
Front-end boards	80	255
Interface boards	8	22
Read-out boards	8	22
CAEN Digitisers	45 ch	—

Proton Extraction

- ENUBET cannot use the fast-extraction scheme used by most experiments
  - Pile-up and instrumentation saturation problems

Nominal continuous spill vs slow pulsed extraction



Original design: Pulsed horn in “burst proton extraction” mode

- Pulse every 100 ms
- 10 ms pulse width

2020 design: A collection of dipoles and quadrupoles in a “static focusing system”

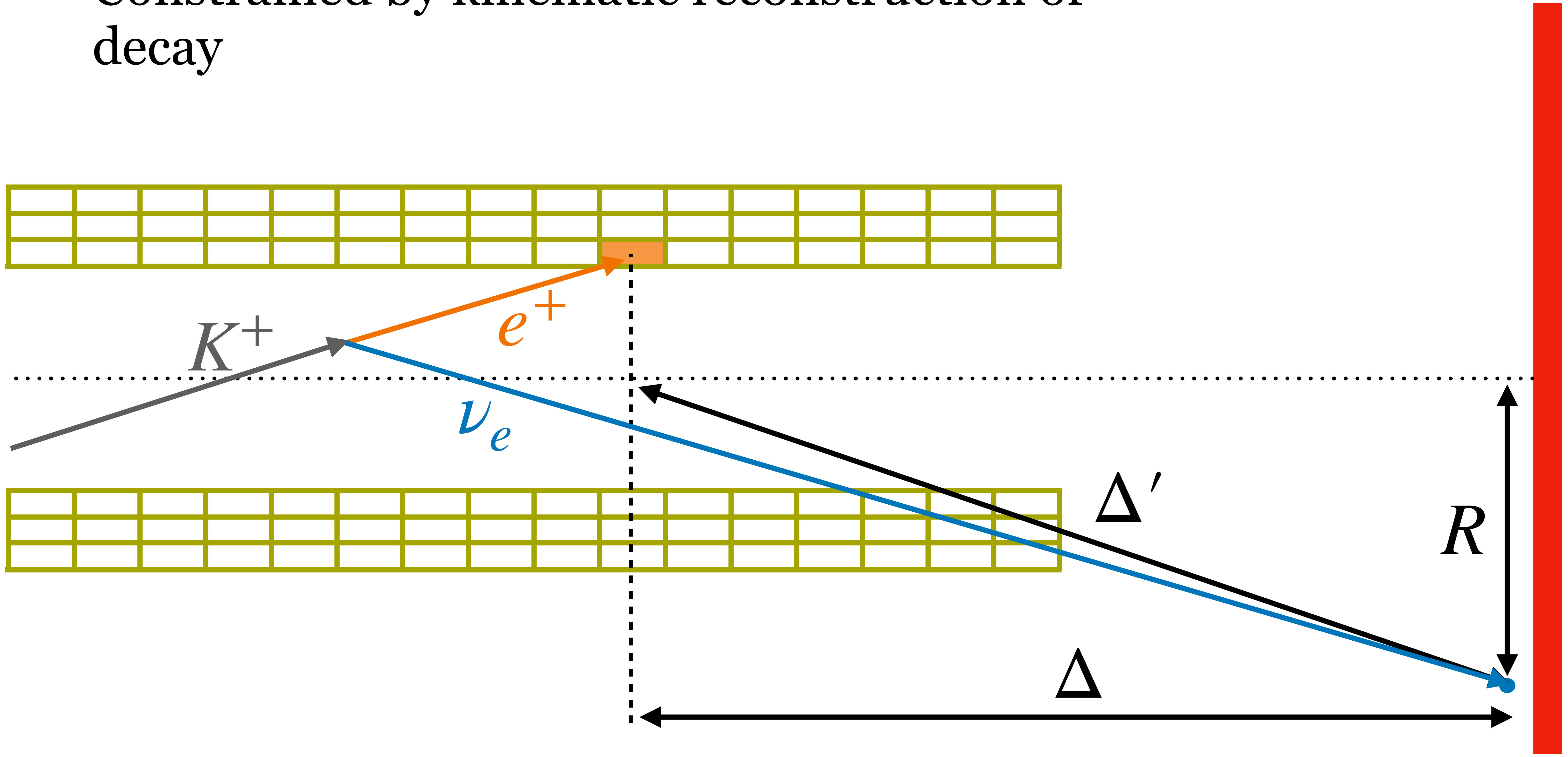
- Continuous extraction over 2 secs
- Flux only 2 times smaller than with a horn
- Rate at tagger reduced by an order of magnitude

Time Tagging #1

Sec. 11: arXiv:2308.09402

- Neutrino **flavour** easily identified
  - From corresponding charged lepton
- Neutrino **energy** determined more precisely
  - Constrained by kinematic reconstruction of decay

ENUBET could be a **time-tagged** neutrino beam by exploiting **time coincidences** of ν_e and e^+.



$t_\nu \rightarrow$ Neutrino detection time

$t_e \rightarrow$ Positron detection time

$$\Delta' = \sqrt{\Delta^2 + R^2}$$

$$\delta t = t_\nu - \frac{\Delta'}{c} - t_e$$

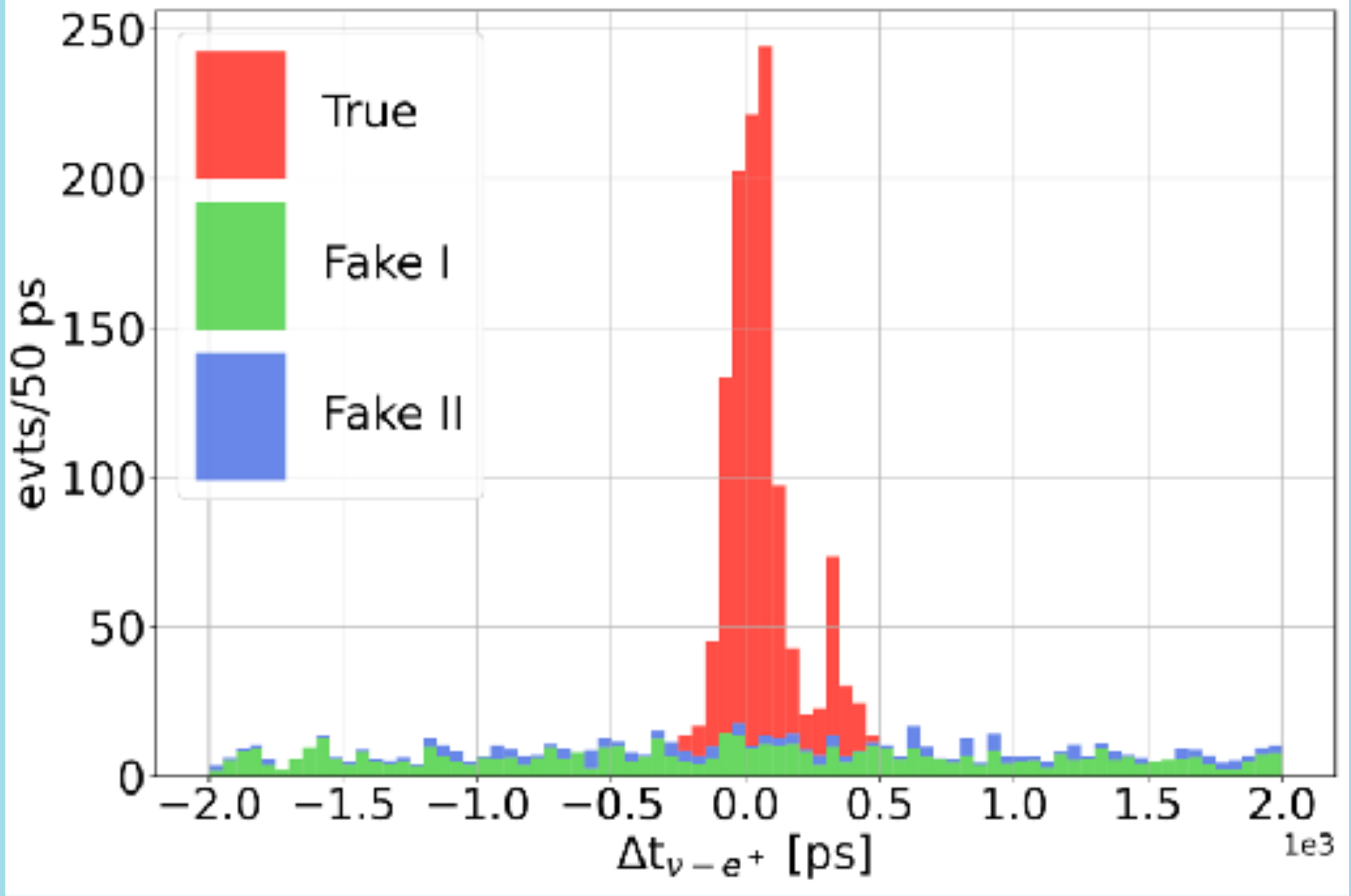
Time Tagging #2

Sec. 11: arXiv:2308.09402

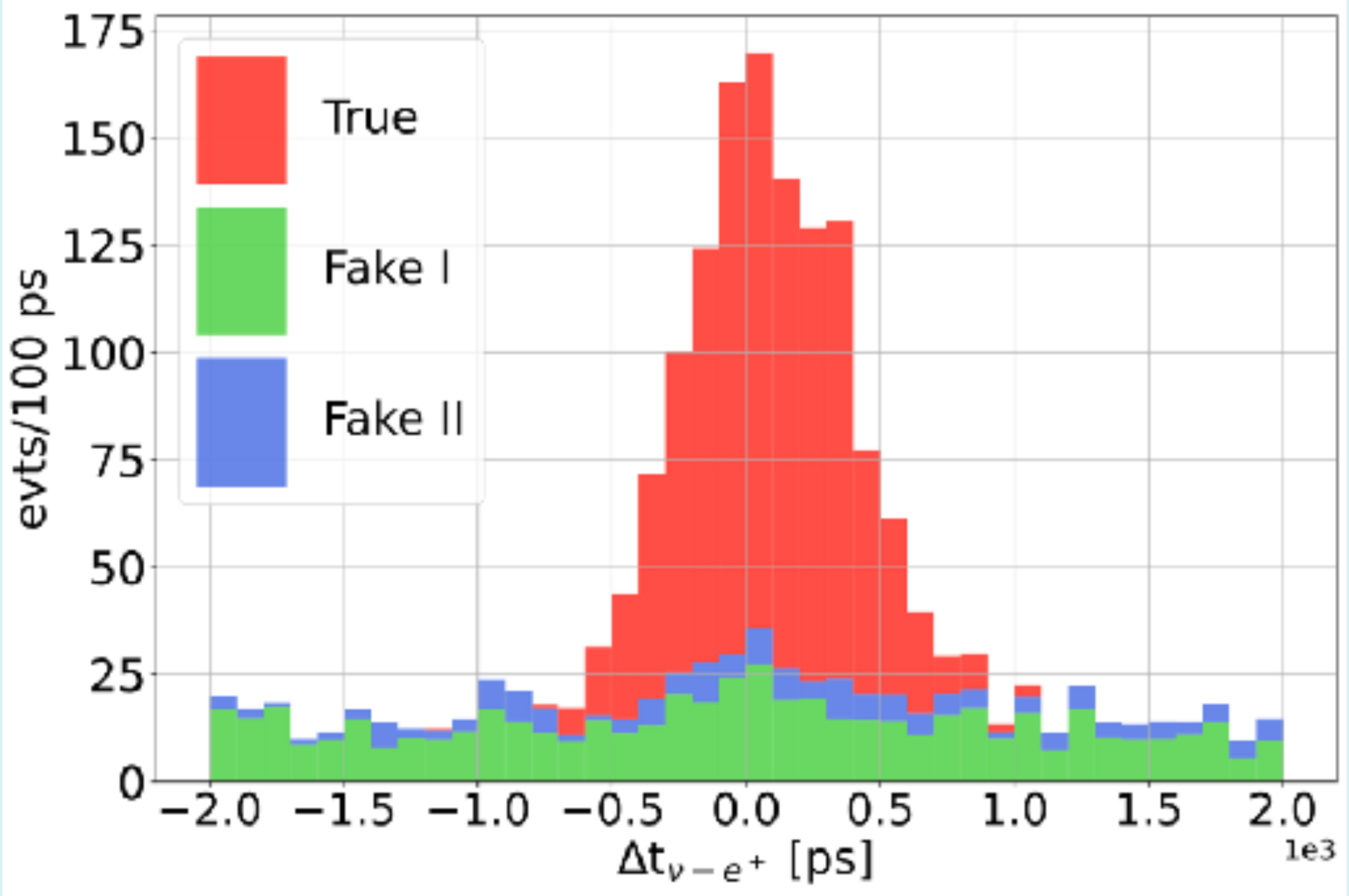
- Used a full beamline simulation with PID algorithms
- Results support ENUBET becoming a tagged beam
  - If time resolution improved to 200 ps
  - ~2 smaller than current resolution

ENUBET could be a **time-tagged** neutrino beam by exploiting **time coincidences** of ν_e and e^+.

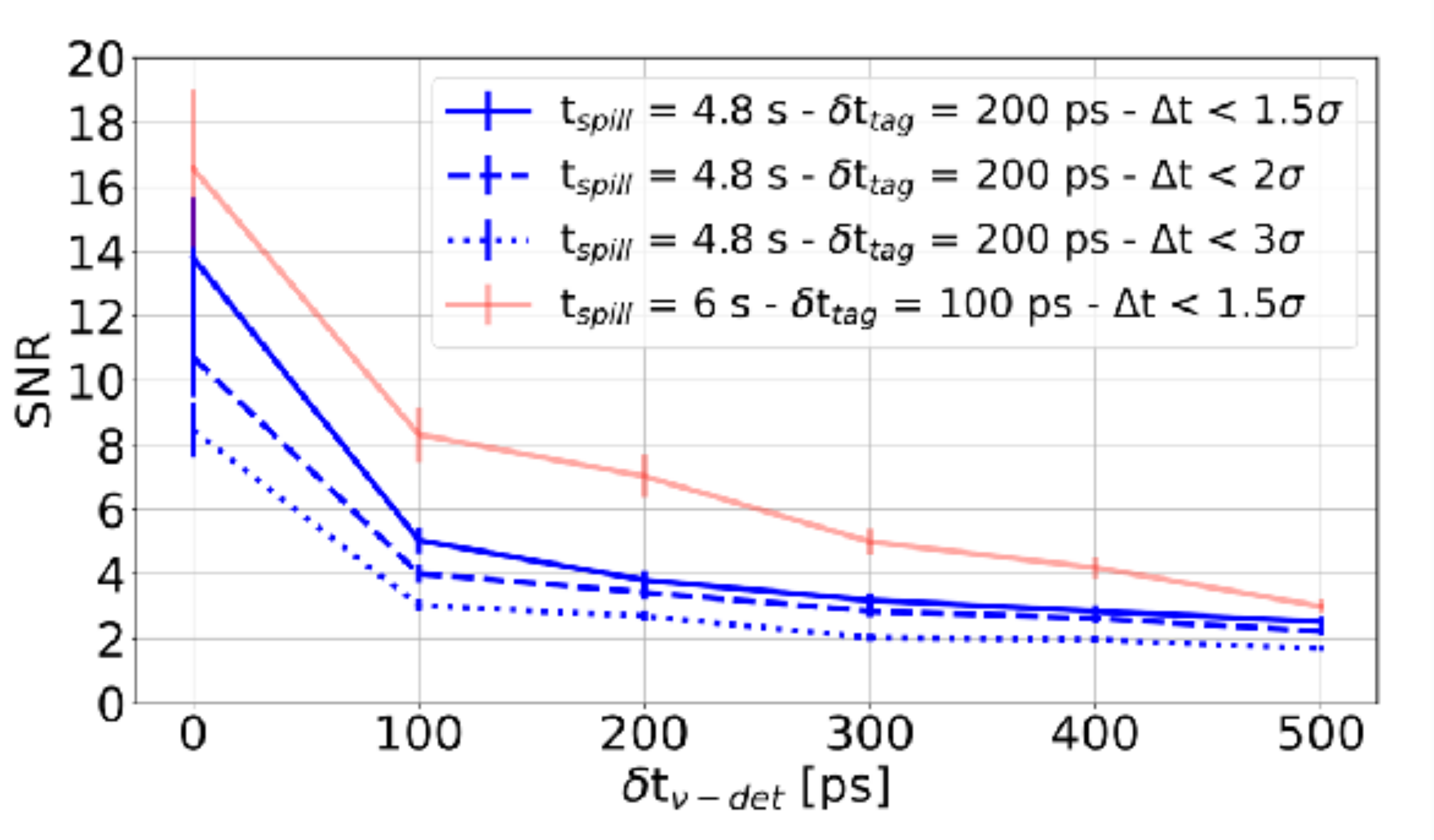
🟩 False positives from ν inside tagger 🟦 False positives from ν outside tagger



Perfect time resolution has an intrinsic 74 ps spread.

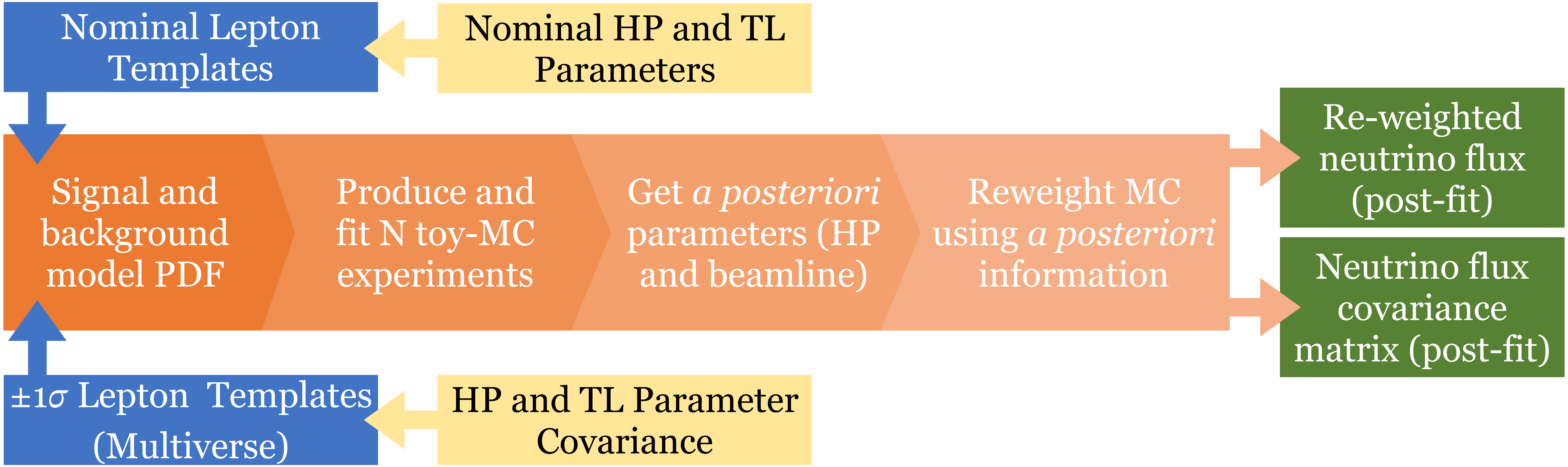


Efficiency smearing assuming resolution of ~200 ps.



Efficiency: 75.6%, S/N: 3.8, with previous resolution.

Flux Constraint Algorithm



Nominal Lepton Templates

Nominal HP and TL Parameters

Signal and background model PDF

Produce and fit N toy-MC experiments

Get *a posteriori* parameters (HP and beamline)

Reweight MC using *a posteriori* information

Re-weighted neutrino flux (post-fit)

Neutrino flux covariance matrix (post-fit)

$\pm 1\sigma$ Lepton Templates (Multiverse)

HP and TL Parameter Covariance

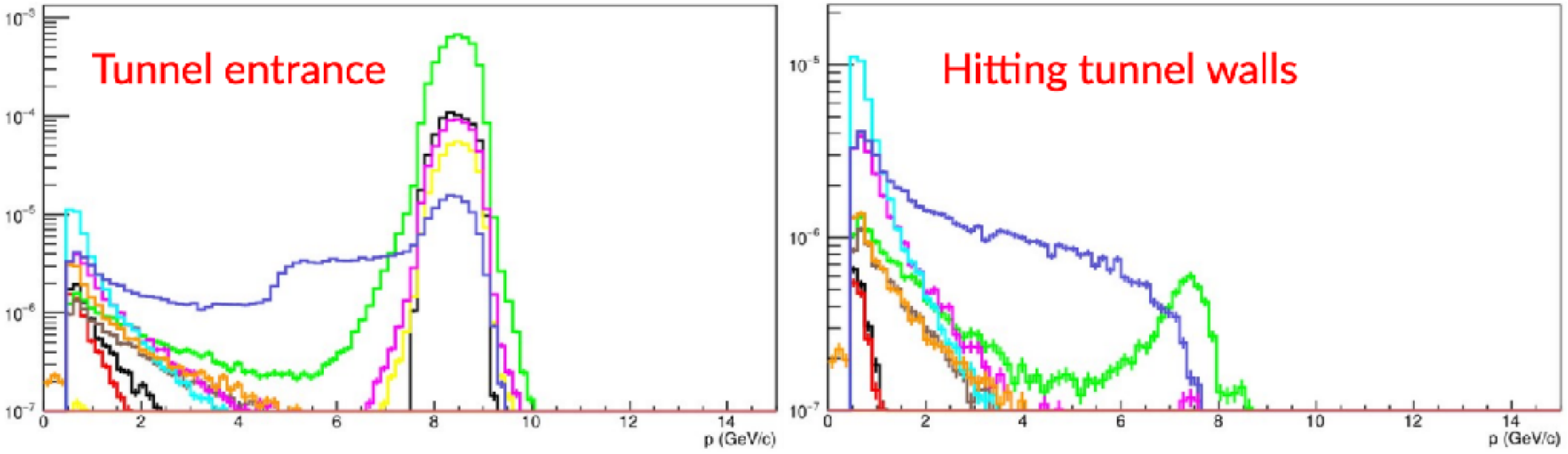
- Extended maximum likelihood fit
- Build a signal+background model to fit lepton observables

- Hadro-production data from NA56/SPY experiment (reweight MC lepton templates)
- Hadro-production included as nuisance parameters

Beamline #2

Transfer line design a trade-off between:

1. Larger meson yield (larger ν flux) 2. Low background on tunnel walls



Full facility implemented in GEANT4:

- Control over all parameters
- Access to full particle histories

Thus a complete assessment of ν flux systematics

π^+	K^+
4.6	0.4

Rates @ tunnel entrance $[10^{-3}/\text{PoT}]$

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We now have a twitter!

@enubet

ENUBET

@enubet

Official page for the ENUBET/NP06 experiment a monitored neutrino beam project for high precision neutrino measurements. Funded by @ERC_Research from 2016-2022.

Science & Technology pd.infn.it/eng/enubet/abo...

Joined June 2023

ENUBET

Enhanced NeUtrino BEams from kaon Tagging