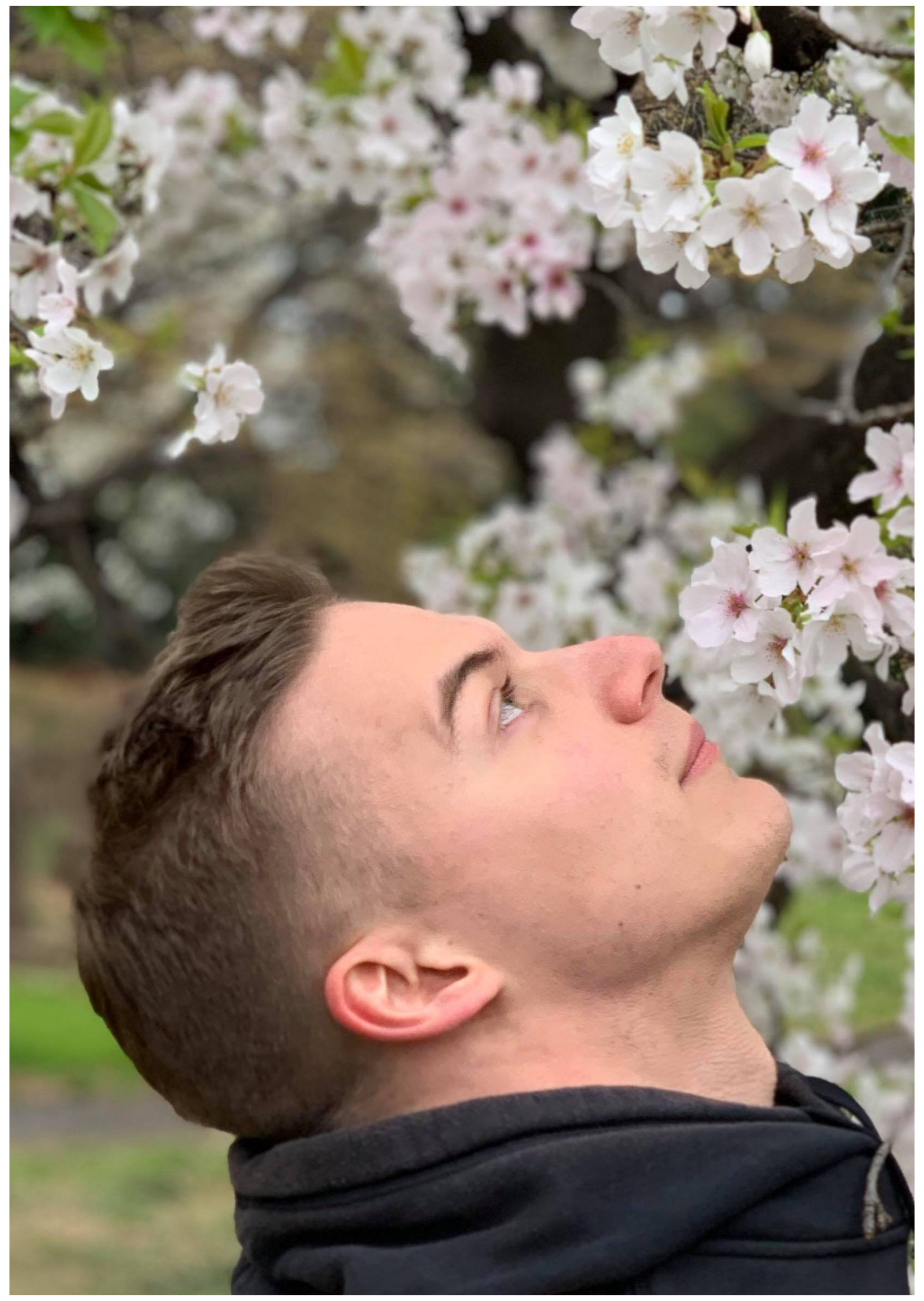
ENUBET @ CERN

Towards the implementation of a neutrino cross section experiment with a monitored neutrino beam



Jordan McElwee*

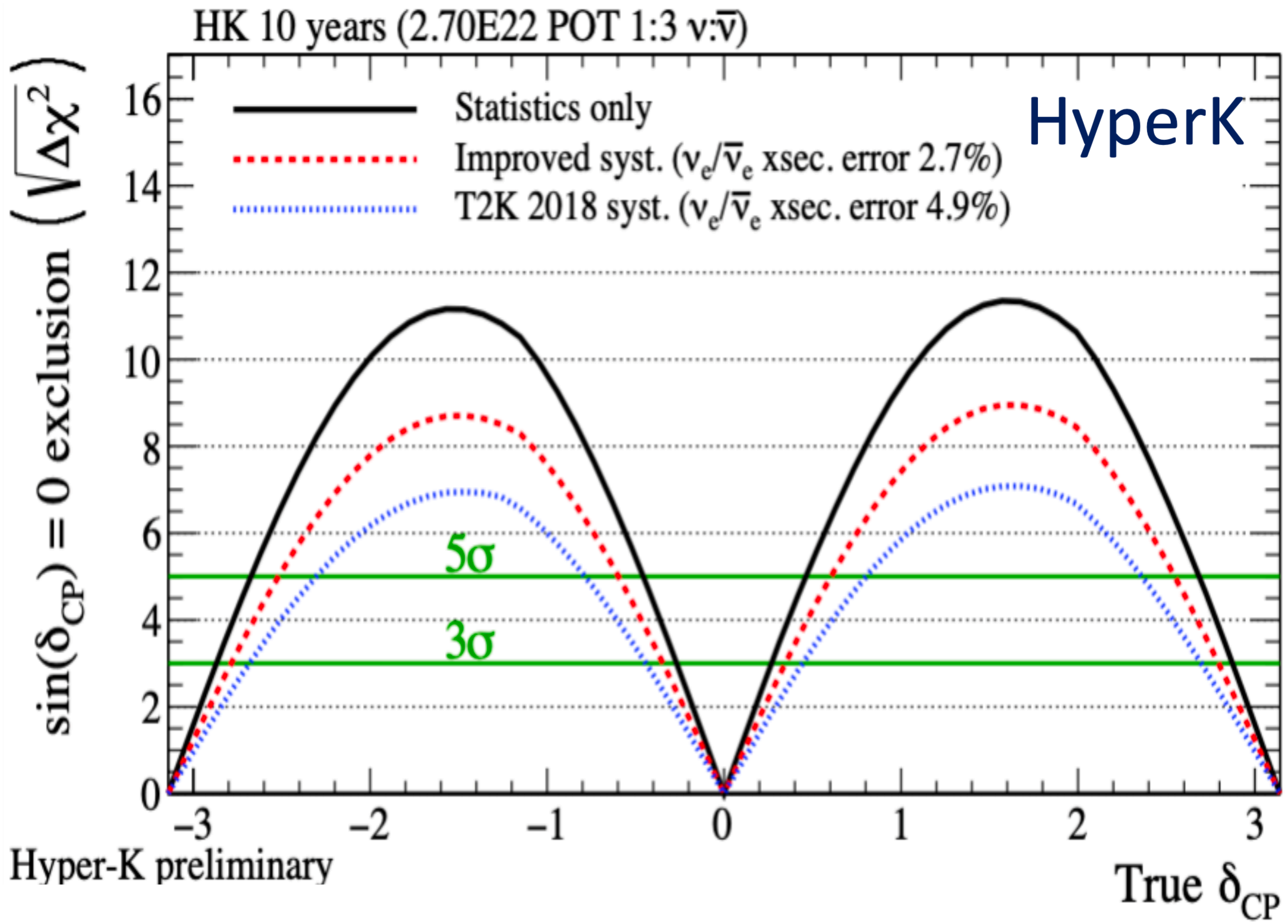
17th July 2023

ICNFP @ OAC, Crete

*on behalf of the ENUBET collaboration

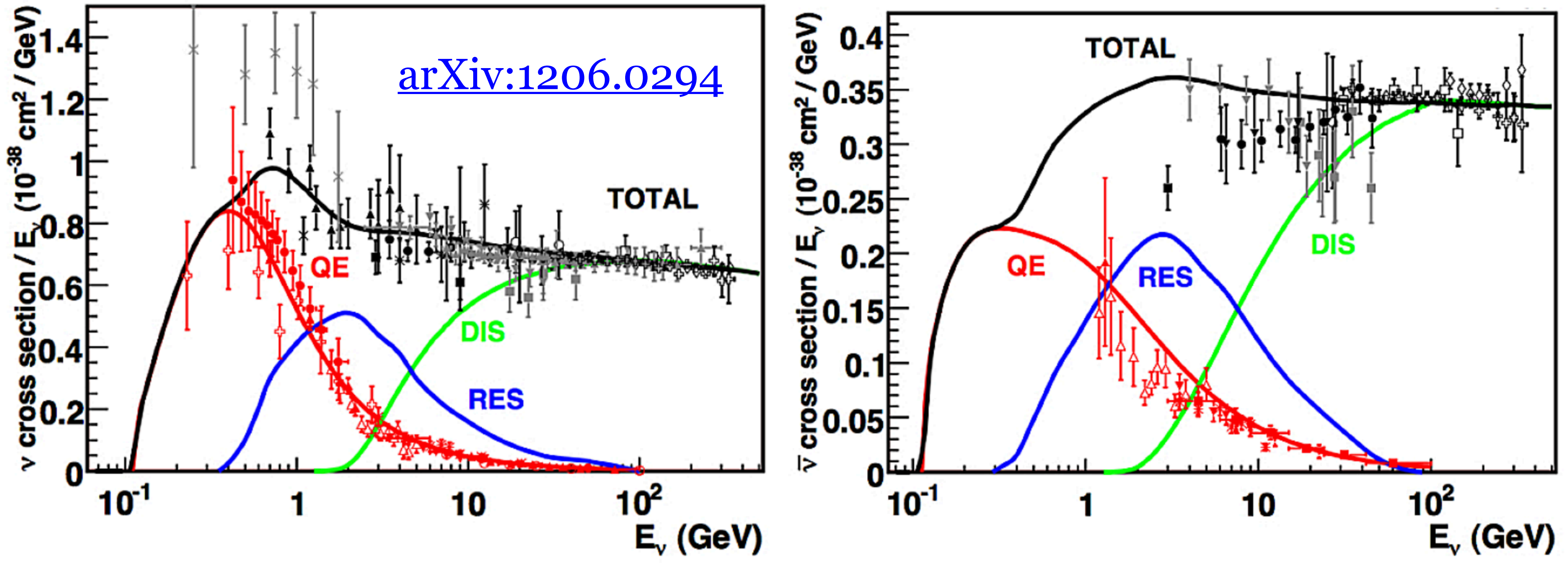
Introduction

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



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

- 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



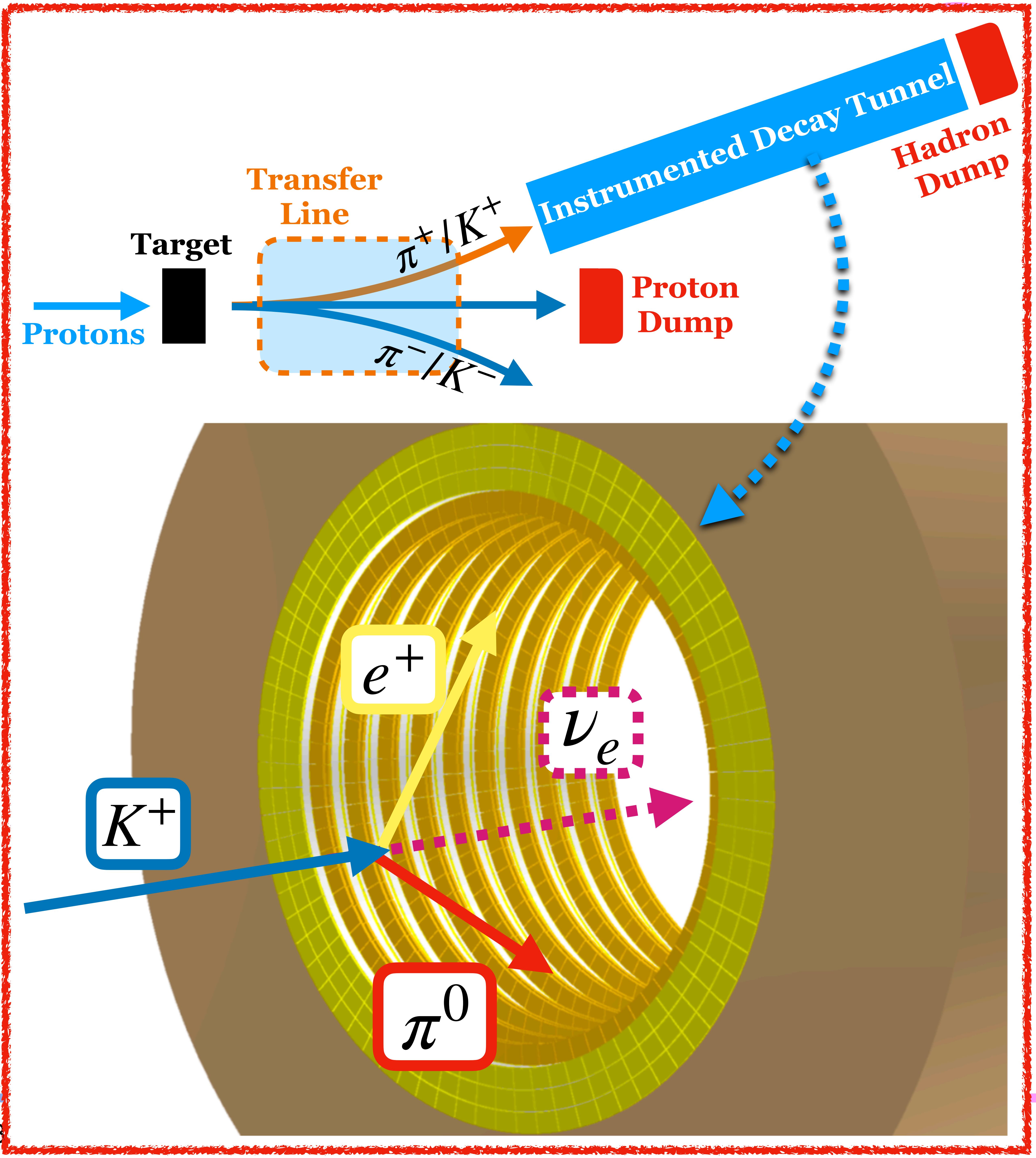
*Current best limit is 3.22% from MINERvA, arXiv:2209.05540.

ENUBET

- **ENUBET** (Enhanced NeUtrino BEams from Kaon tagging) aims to be the first **monitored** neutrino beam
- 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

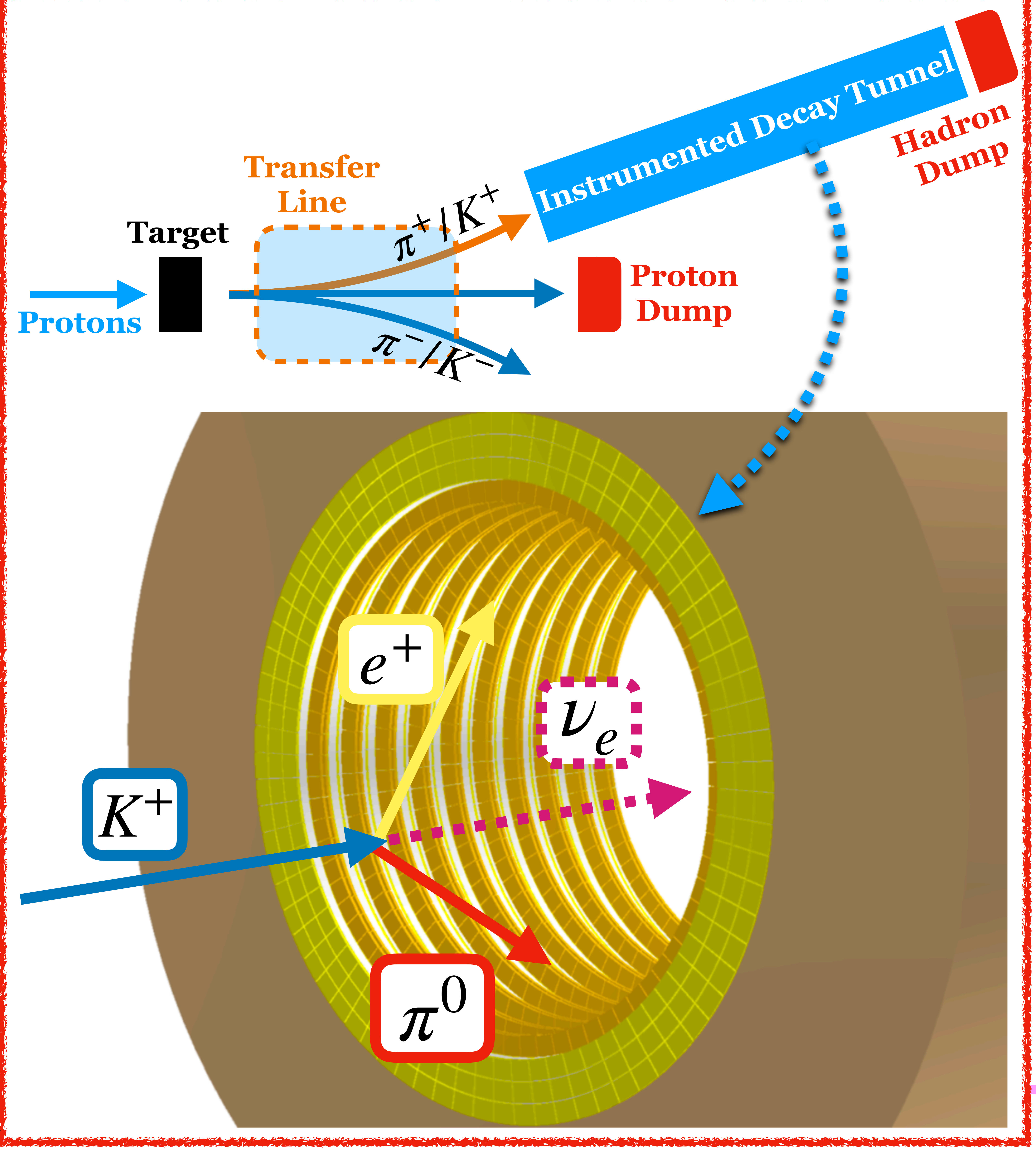
(2019-Present)

Designated: NP06/ENUBET

Aim: Extend measurement to anti-muons from $K_{\mu2}$ (in tunnel) and $\pi_{\mu\nu}$ (in dump) decays to determine ν_μ flux.

Part of the Physics Beyond Colliders initiative.

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



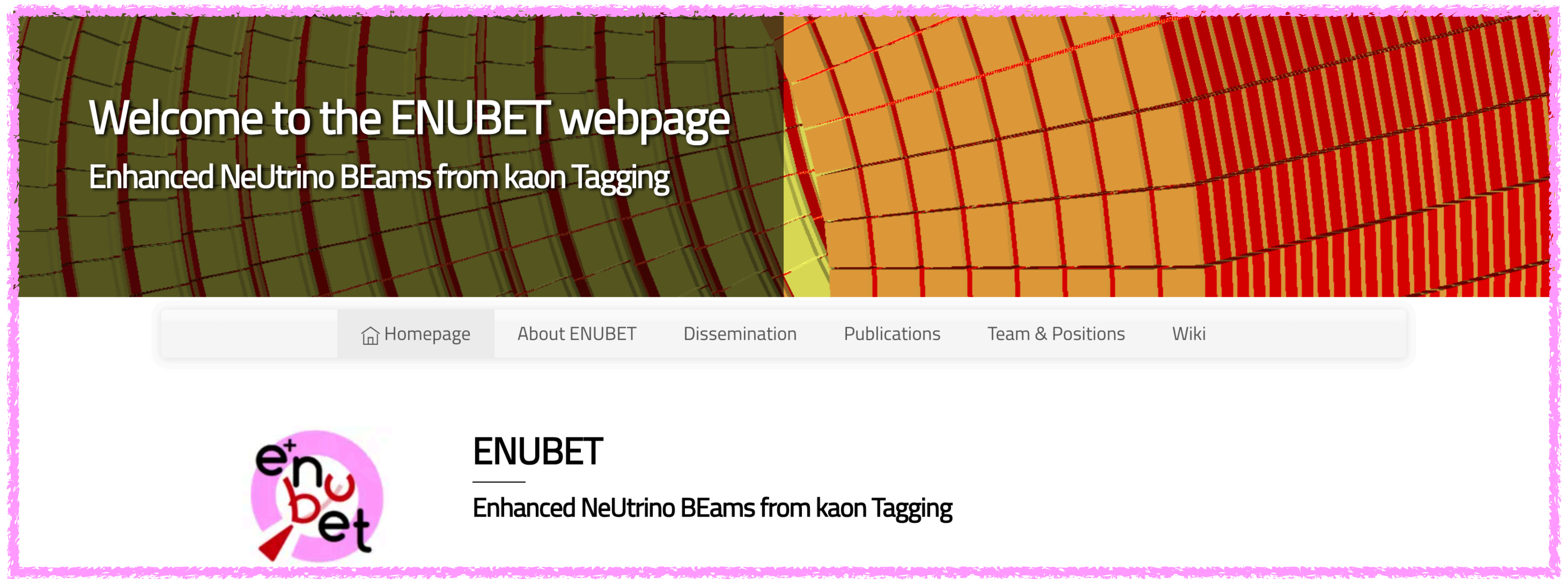
The ENUBET Collaboration

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]



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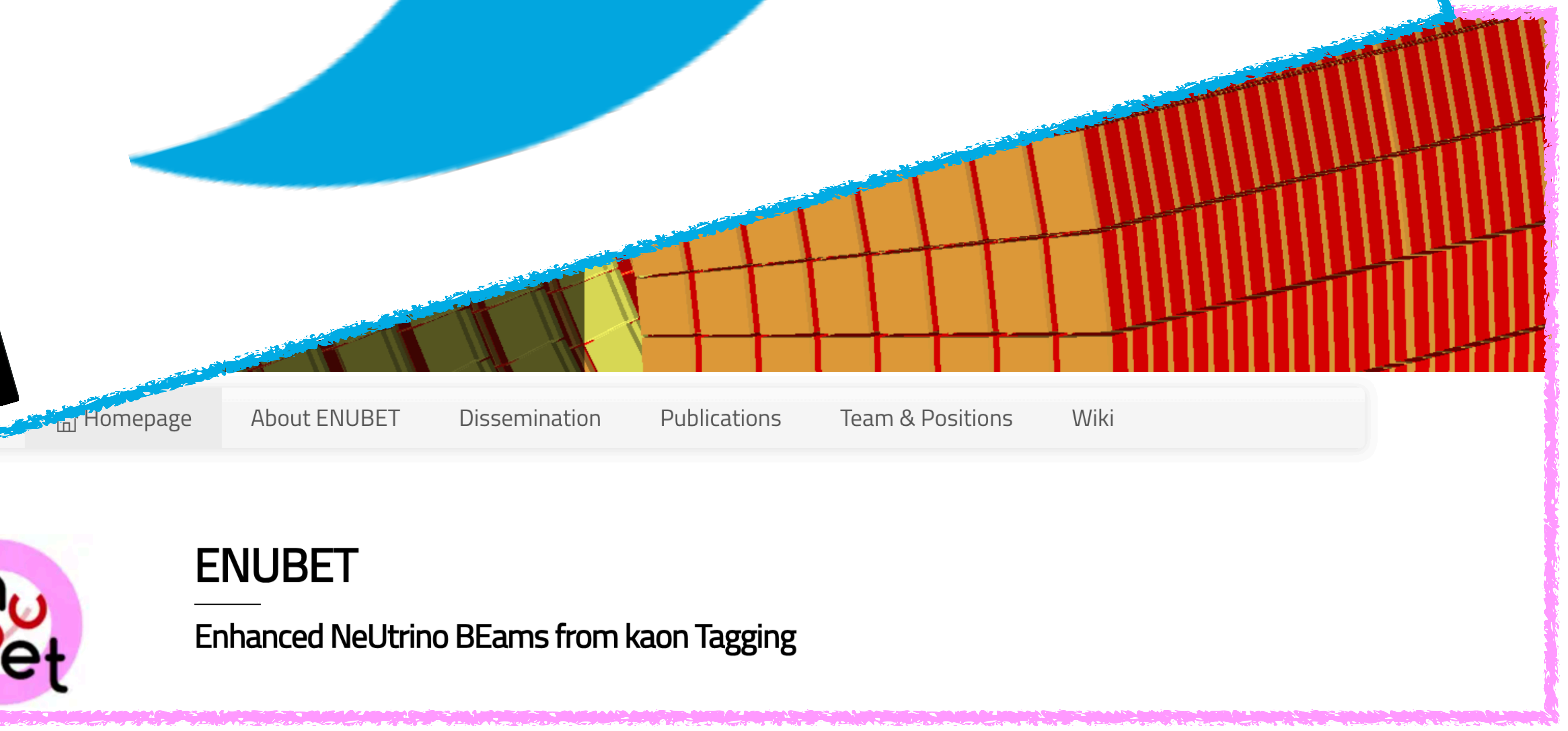
ffanti[3,4],
k[20],
[10], L.
, A.
gaglia[16],
arozzi[4],
illi[5], E.
i[9], M.
[3], F.

We now have a twitter!

@enubet



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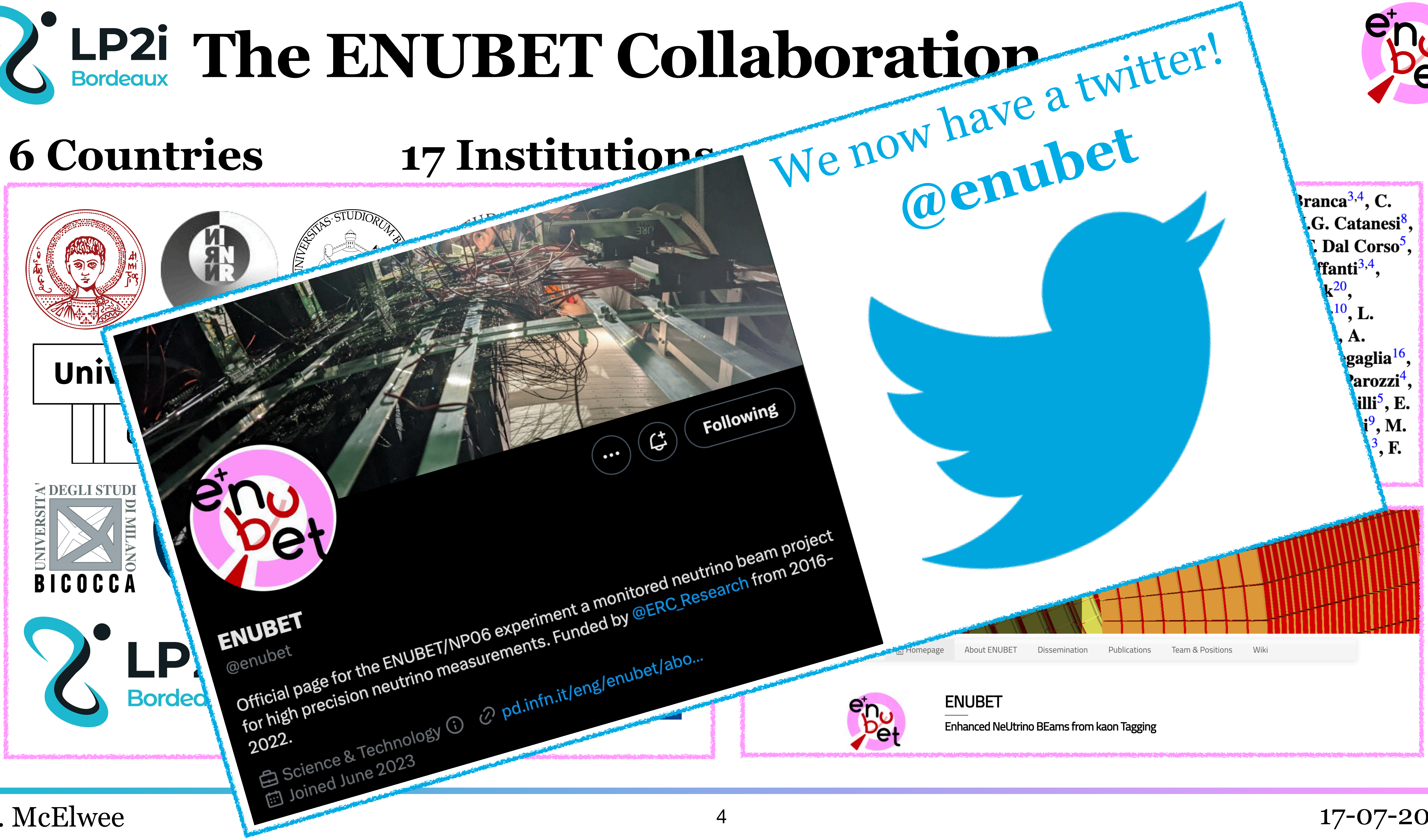

Beamline

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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- 70 cm long, 3 cm radius graphite
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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

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

Beamline

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
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- 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

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

Beamline

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

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

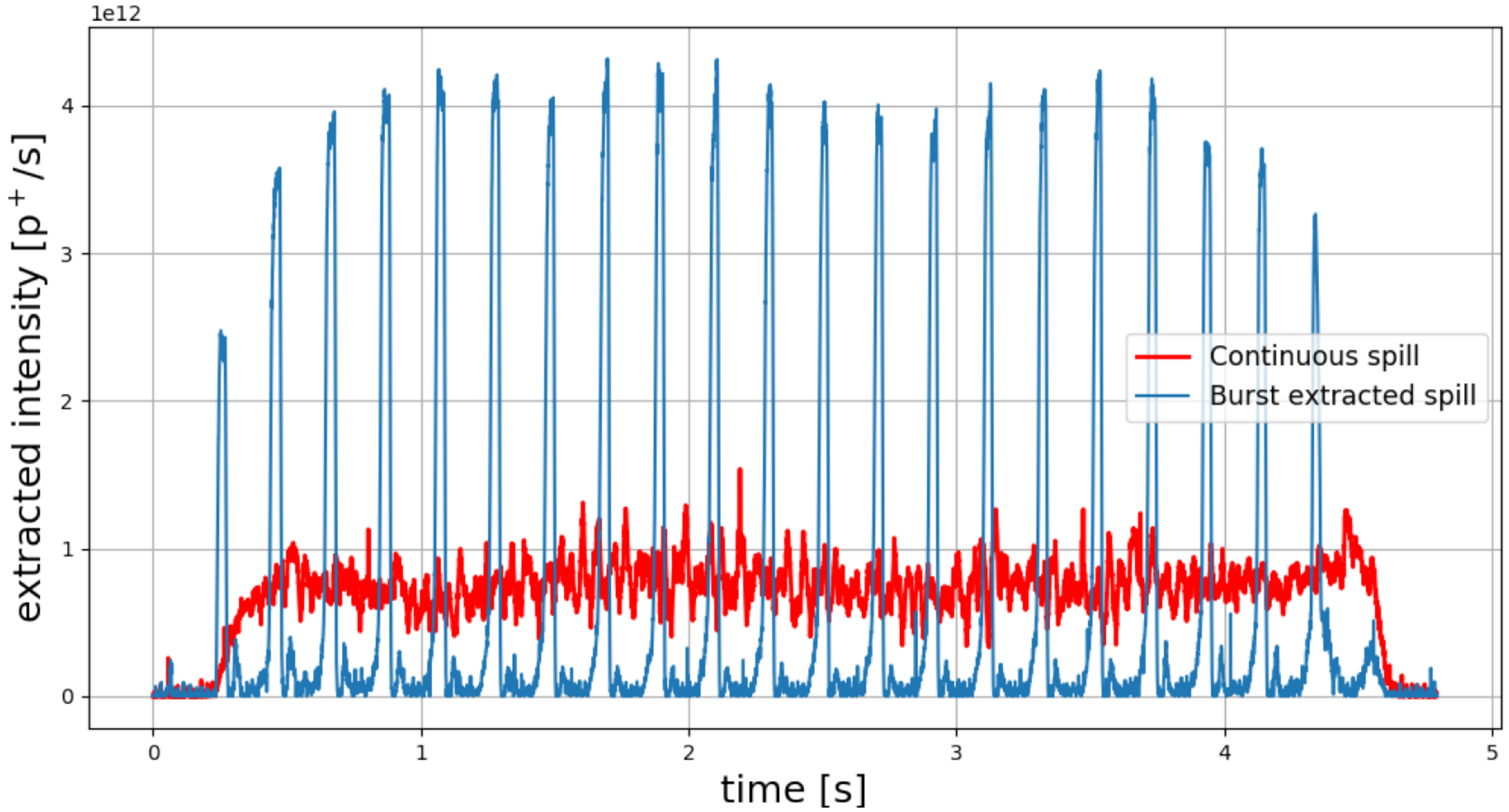
Dumps
- 2 dumps: proton and hadron
- Optimised to avoid backscattering flux in tunnel

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

Proton Extraction

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

Original design: Horn pulsed every 100 ms for 10 ms pulse (“burst proton extraction”)



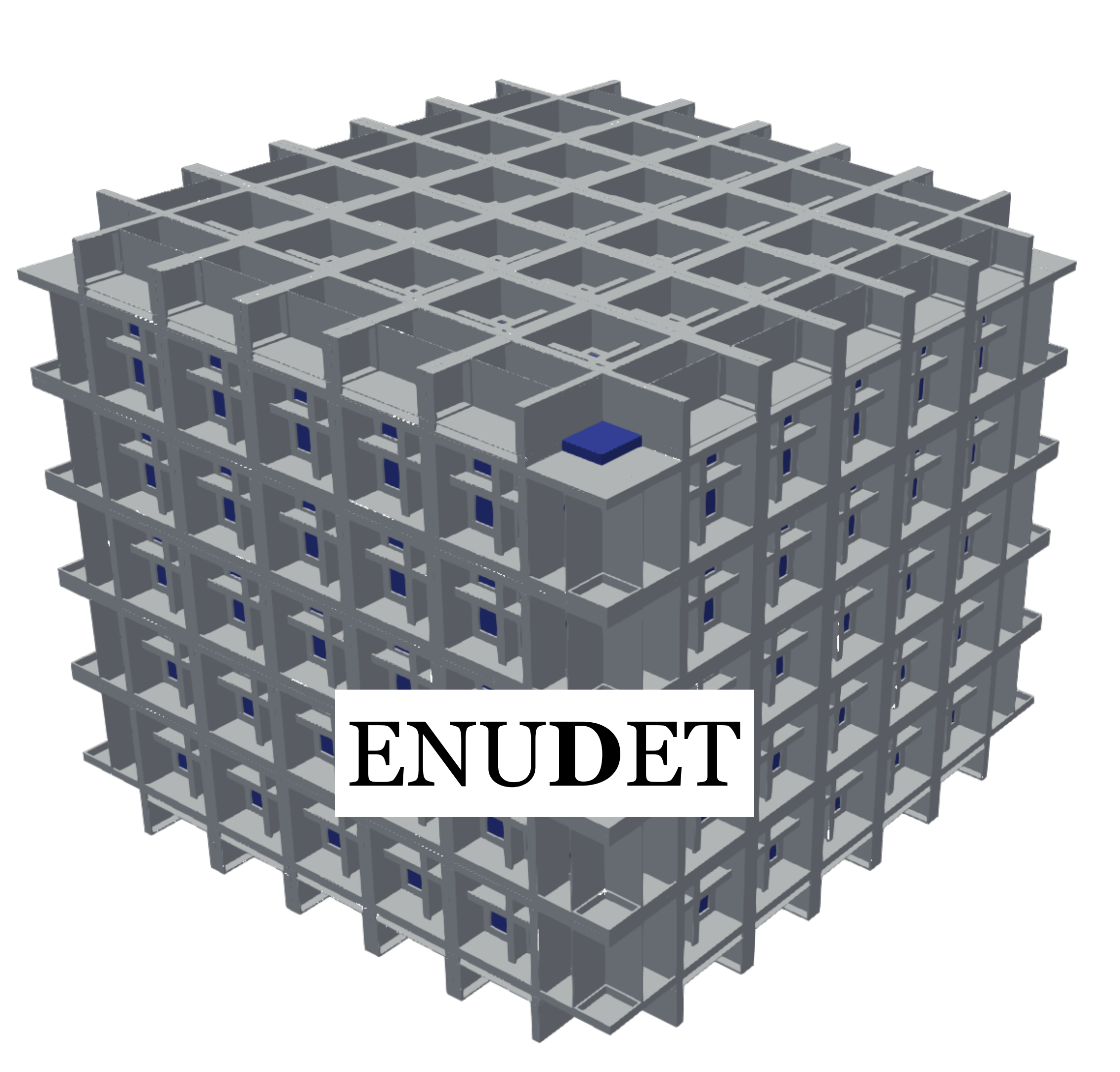
2020 design: “Static focusing system” using dipoles and quadrupoles for a continuous extraction over 2 secs.

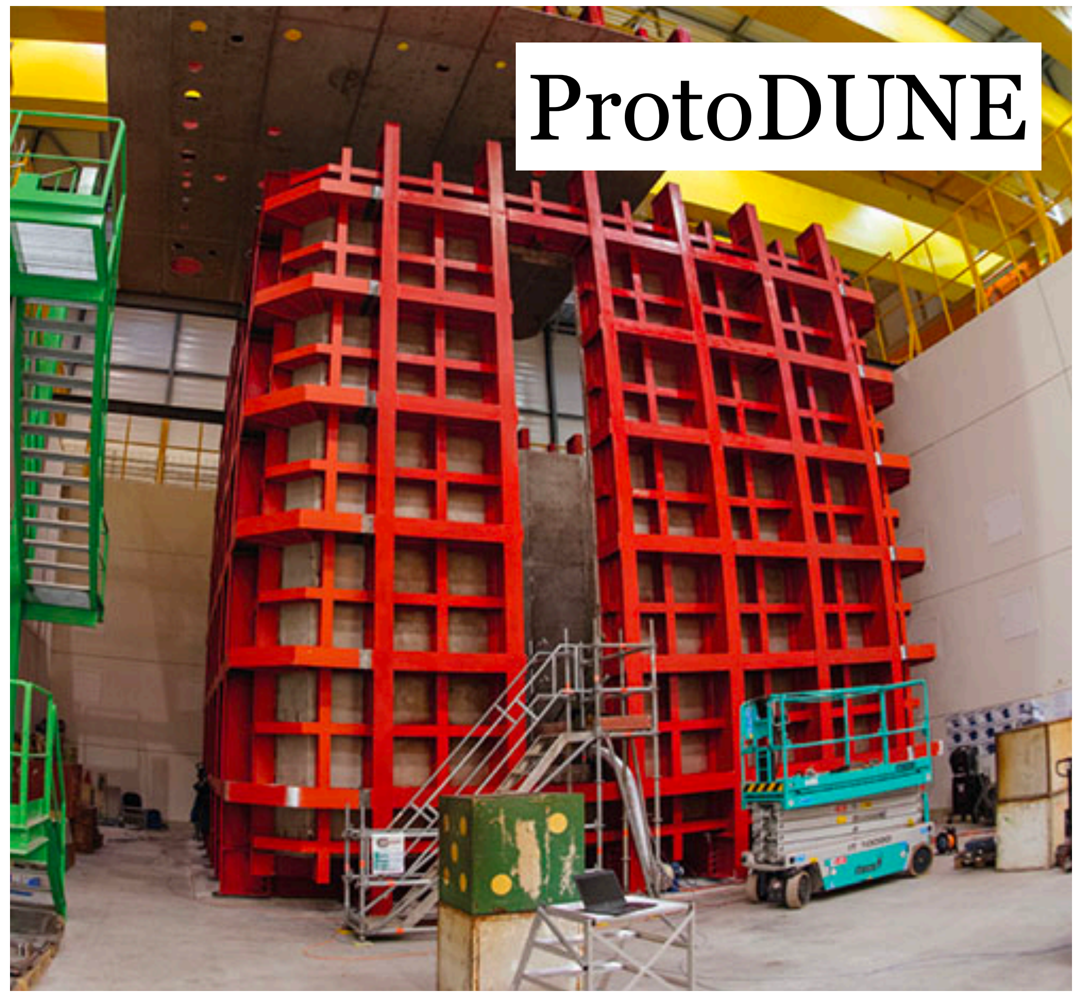
- Slow extracted flux only 2 times smaller than horn method
- Rate at the tagger reduced by an order of magnitude

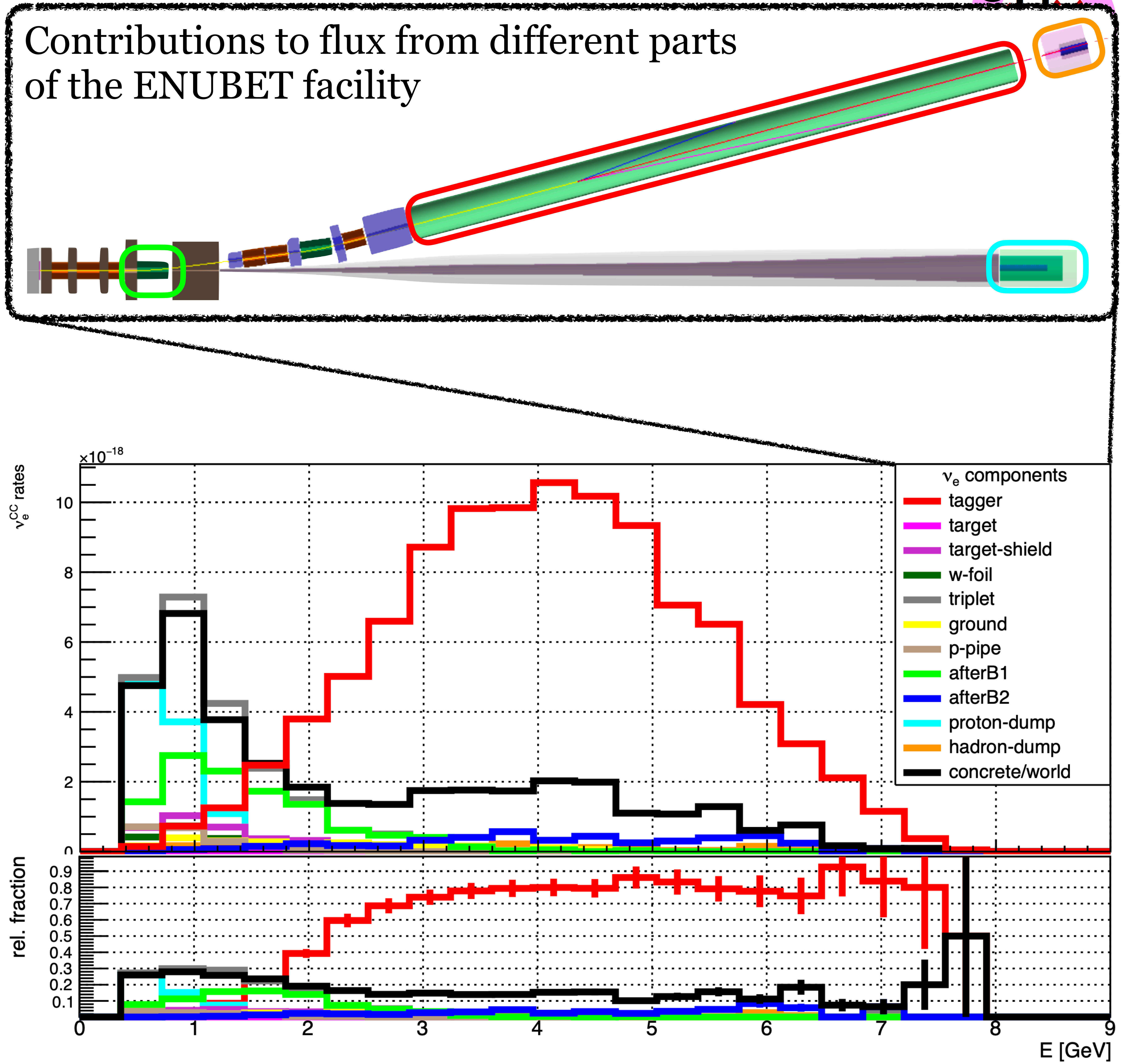
Demonstration of the slow pulsed extraction with the nominal continuous spill.

The ν_e Beam

- 4.5×10^{19} PoT/year at the CERN SPS
- Assume a 500 t detector, 50 m from the decay tunnel (such as ProtoDUNE)
- We expect 10^4 ν_e CC events each year
- ~80% of the ν_e component above 2 GeV is monitored







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

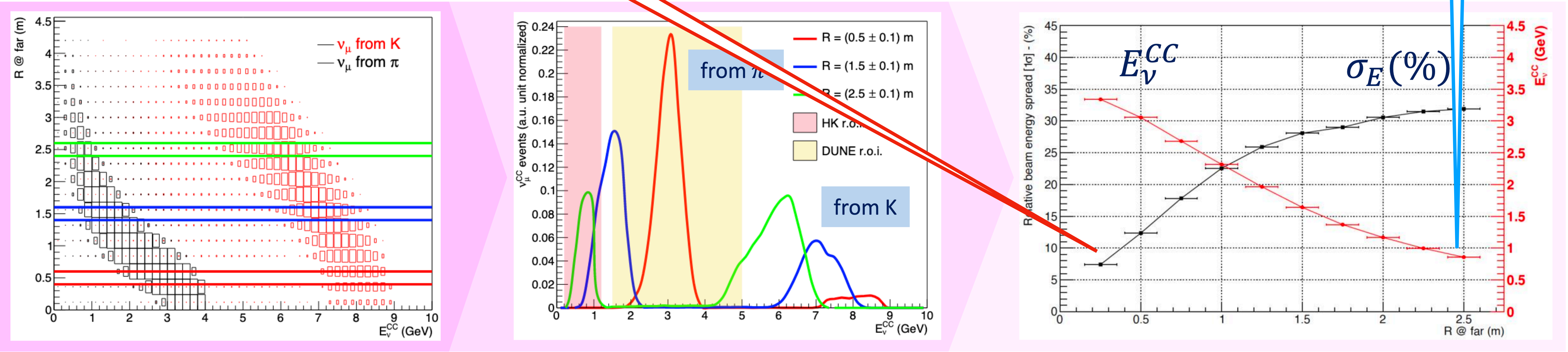
Precise determination of E_ν:

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

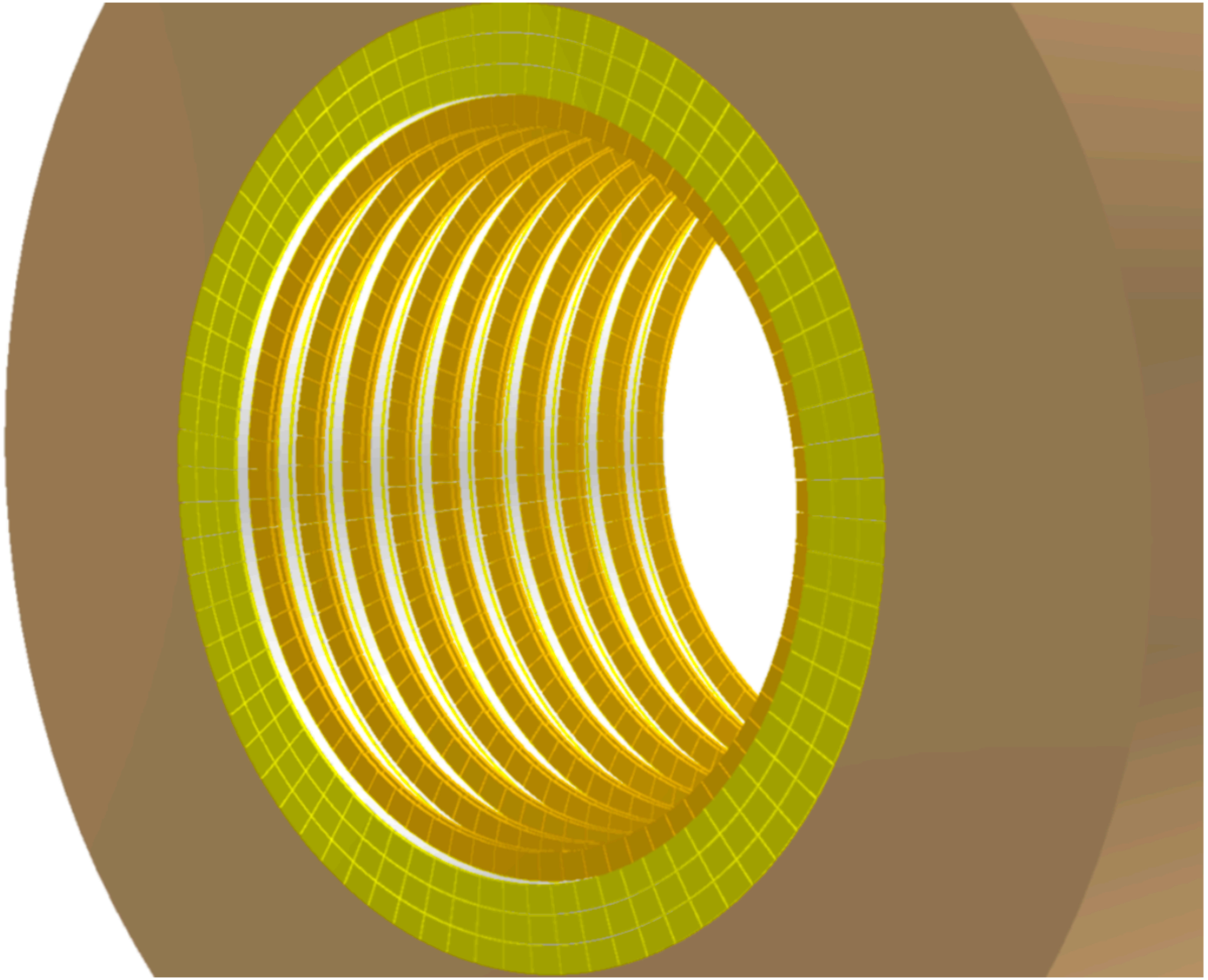
8-25% resolution in DUNE ROI

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

30% resolution in HK ROI



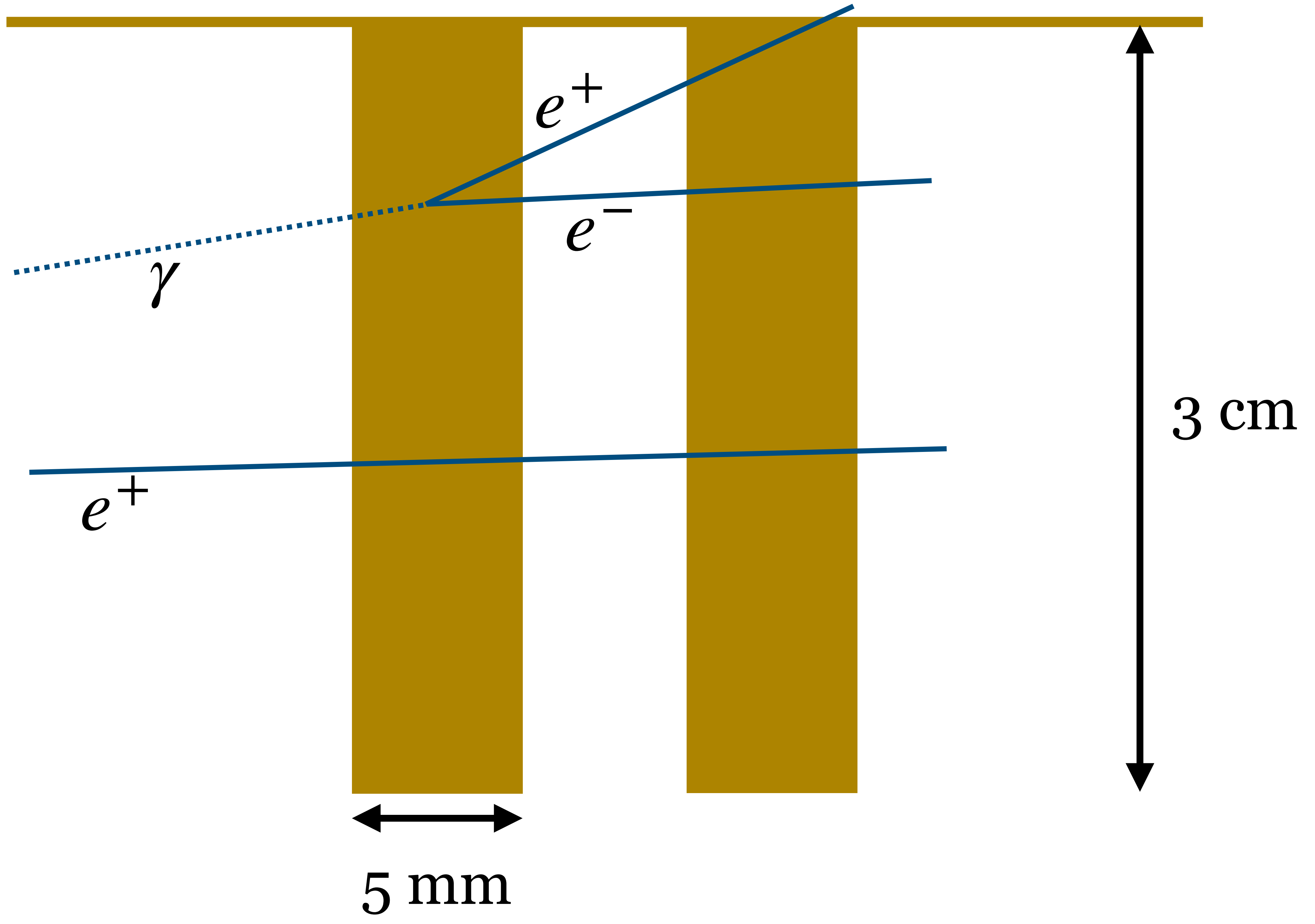
The Tagger

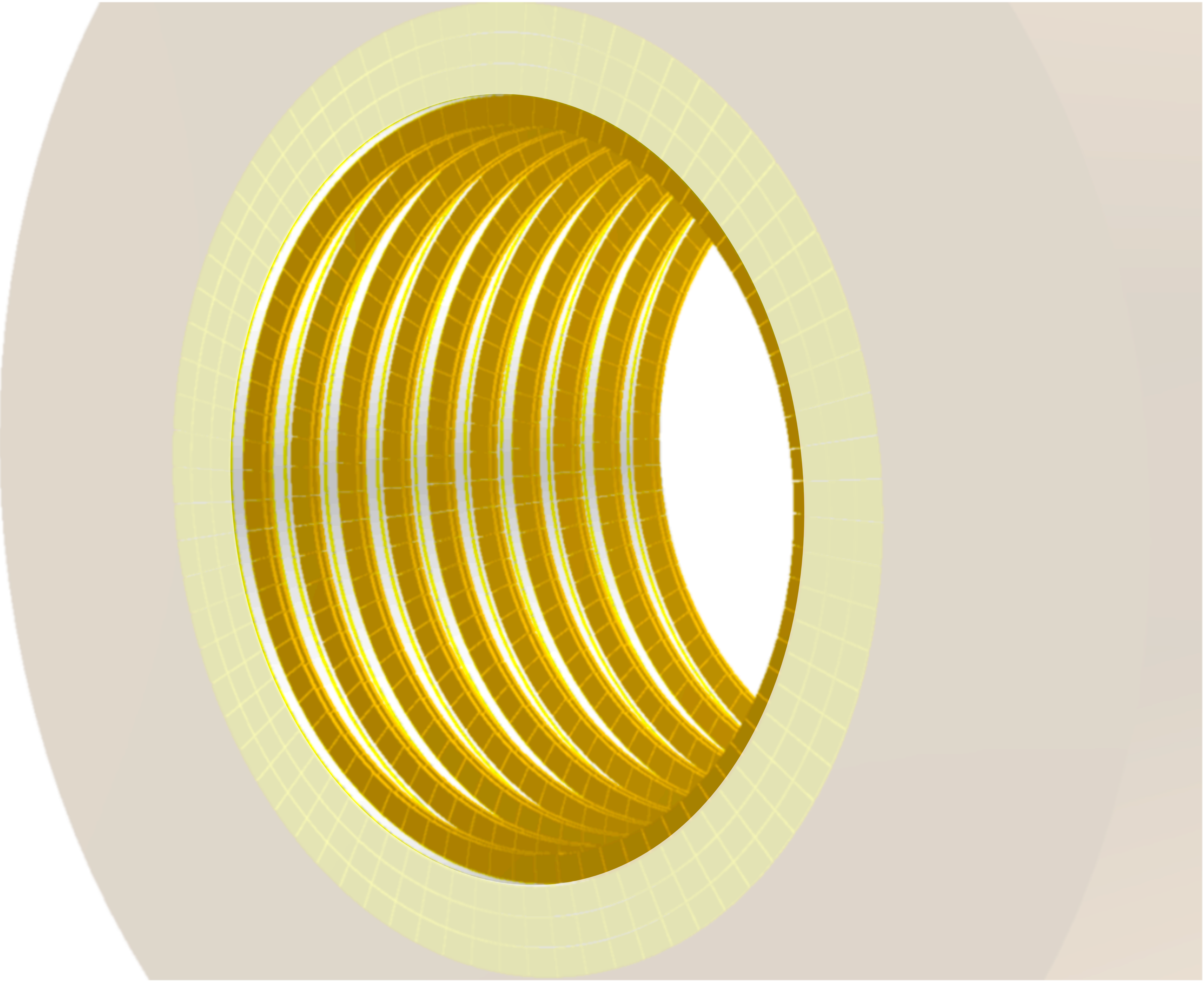


The Tagger

Photon Veto

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





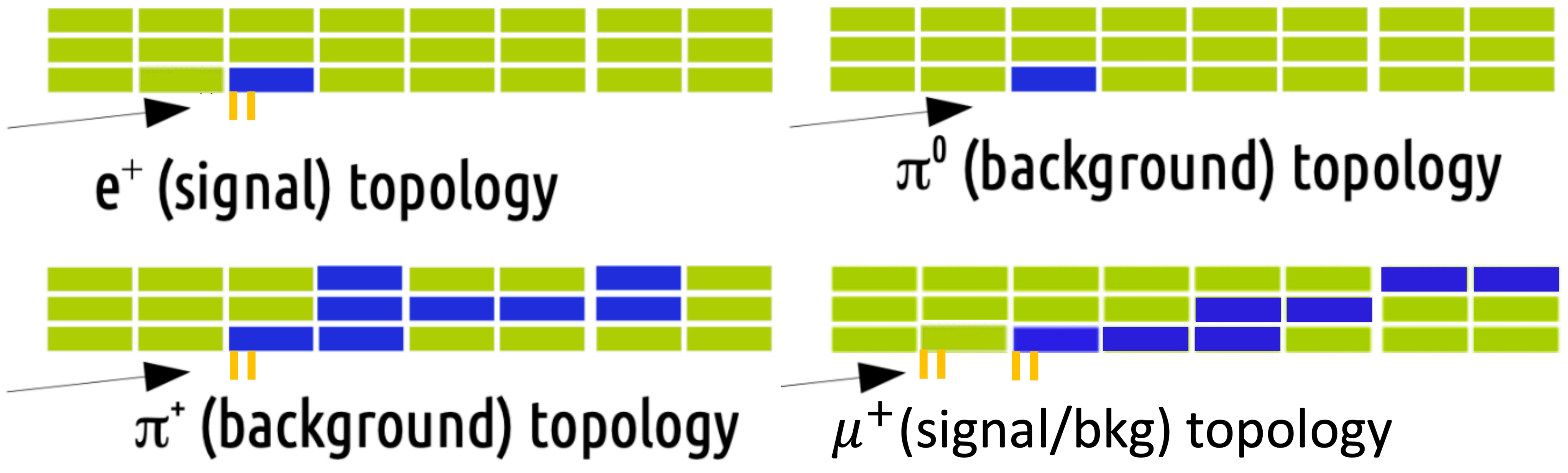
The Tagger

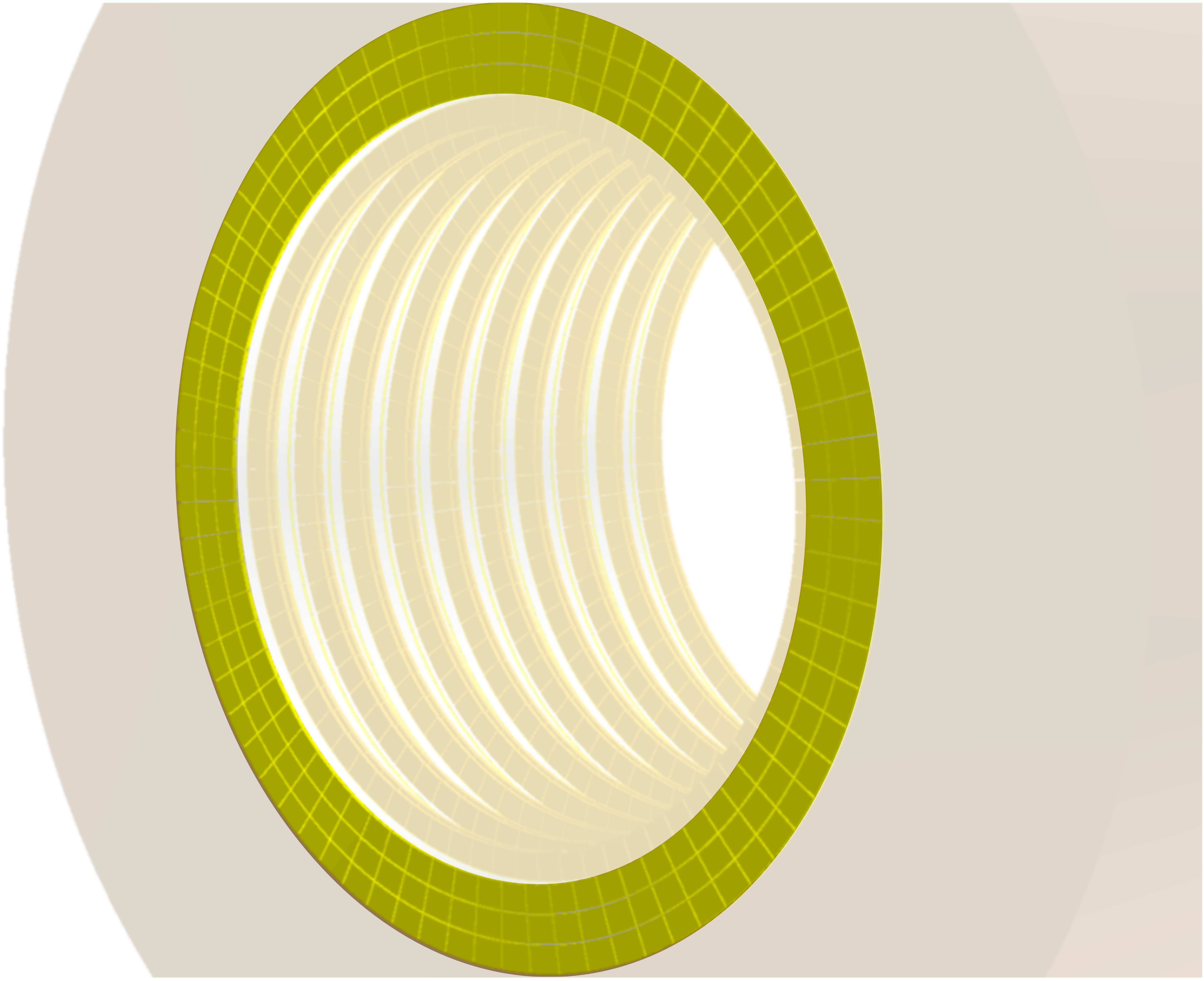
Photon Veto

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

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





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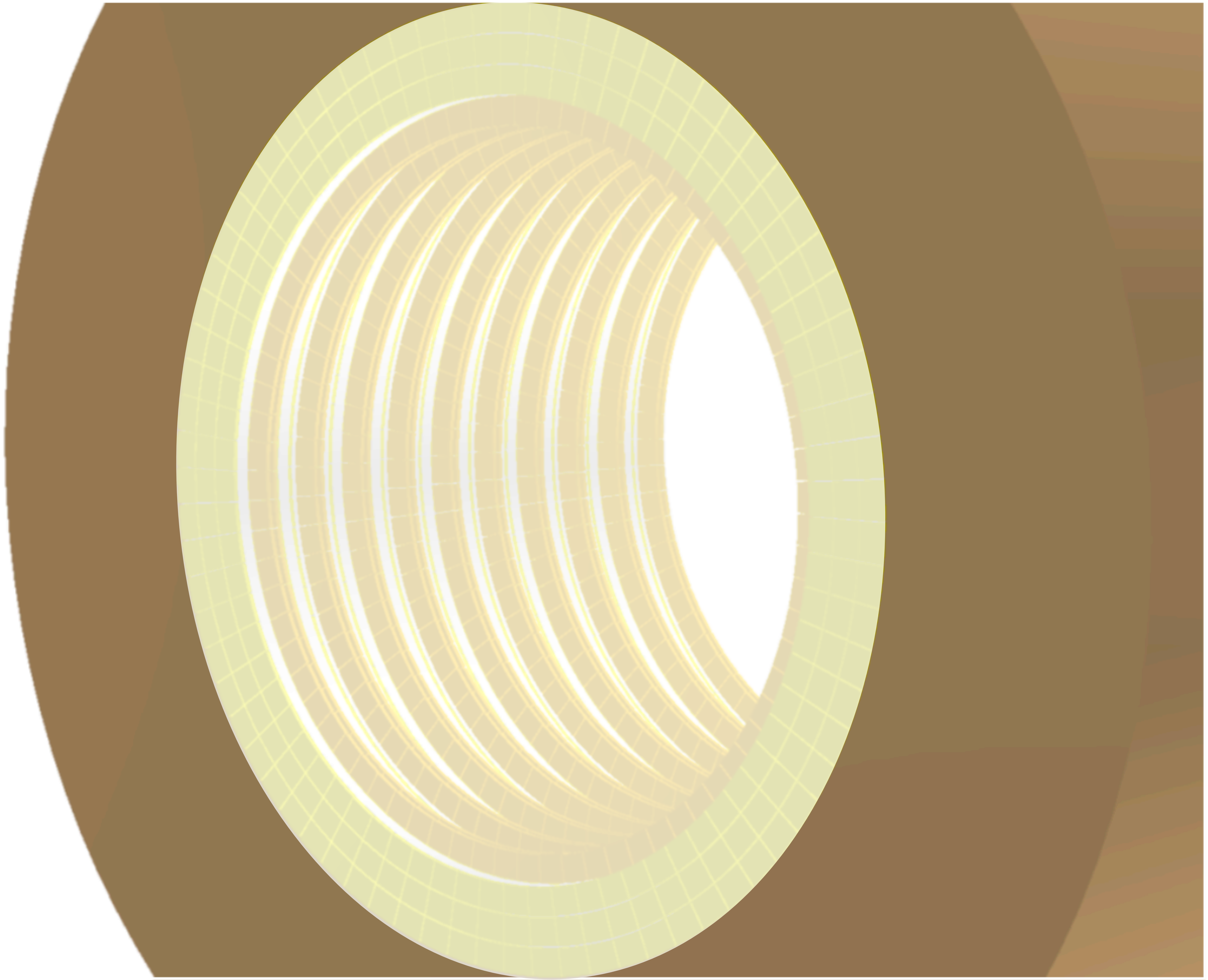
Shielding

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



Lepton Reconstruction

- 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

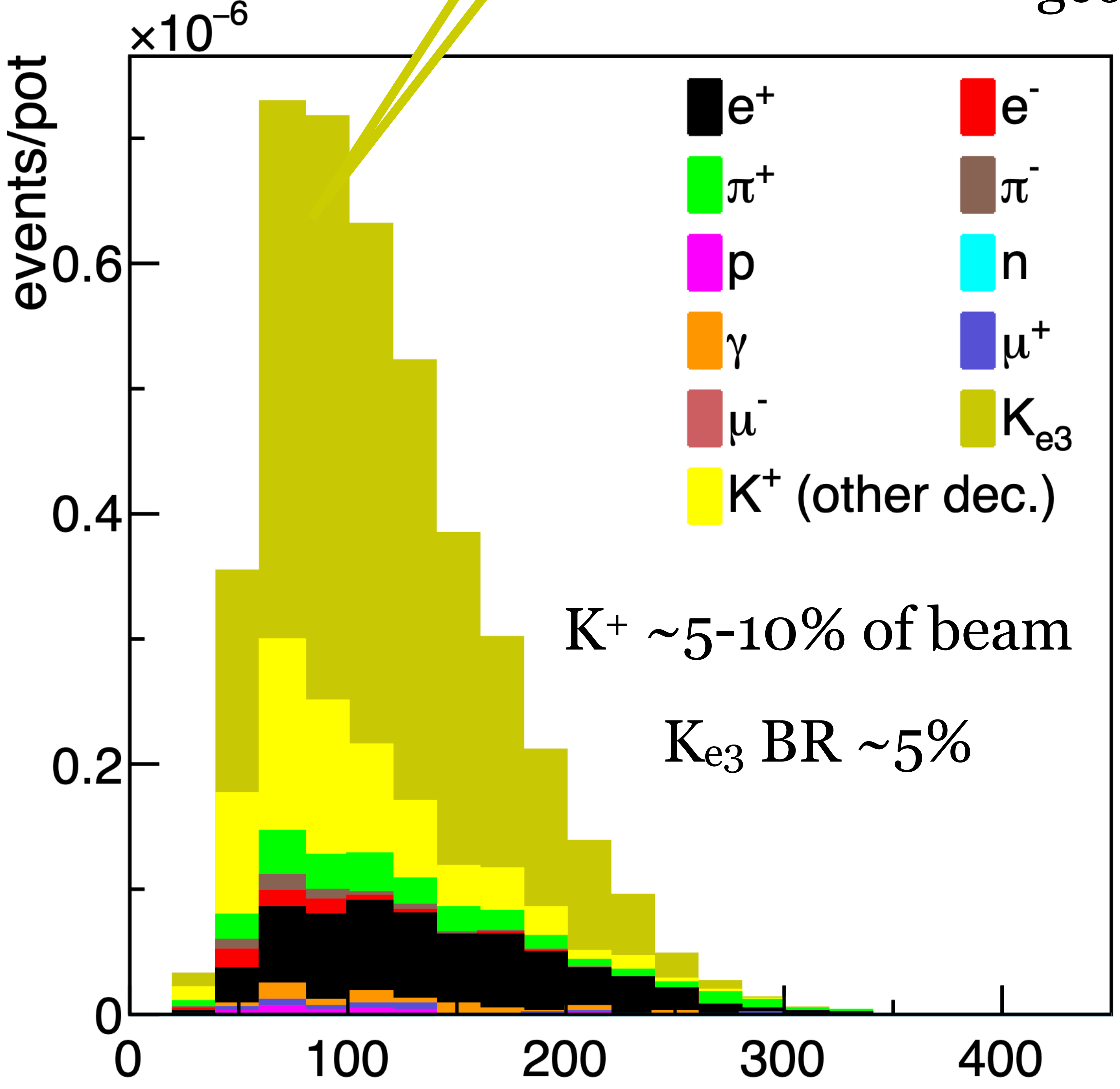
Eff = 22%

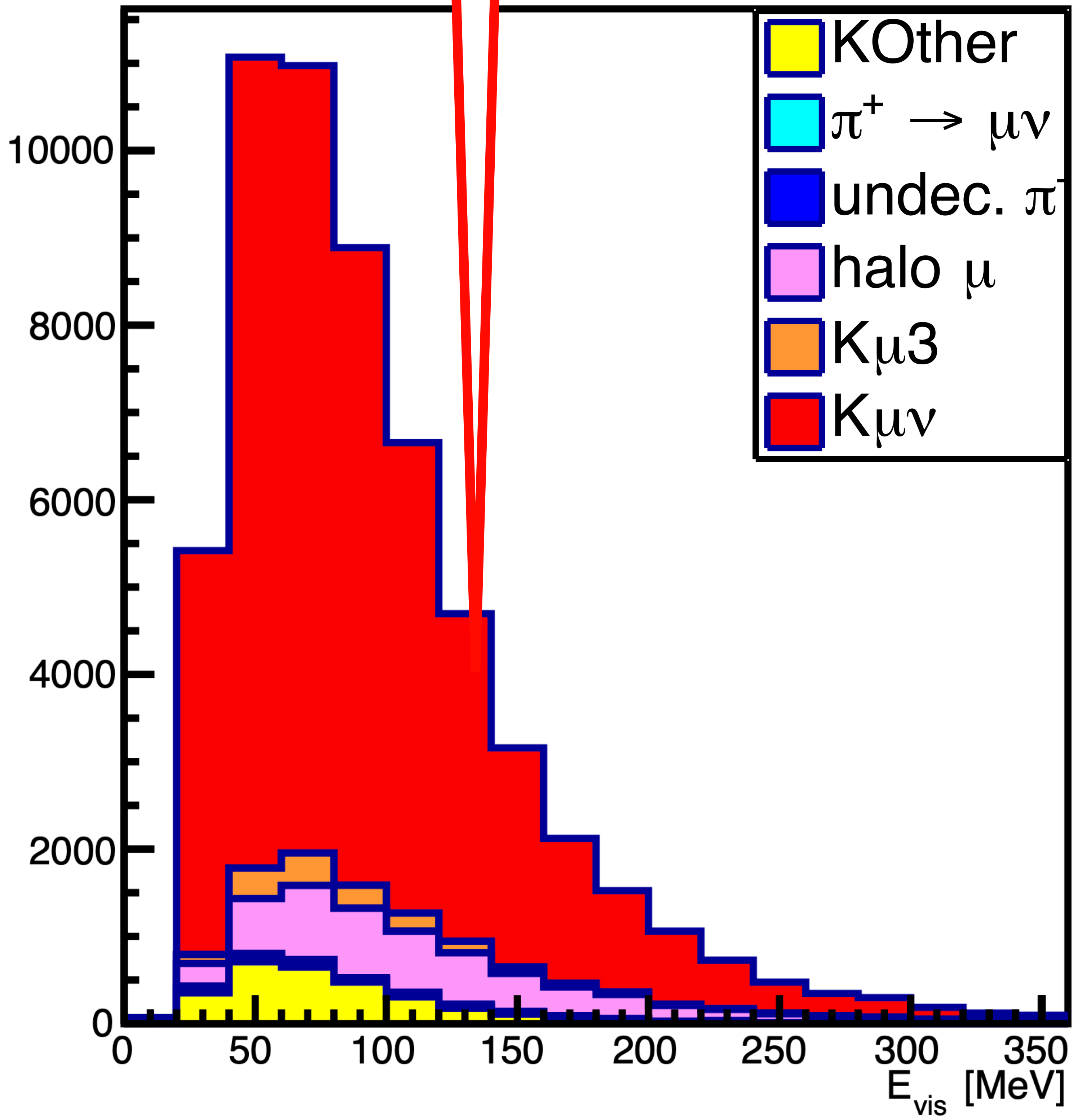
$K_{\mu 2}$ muons: ν_μ

S/N = 6

Eff = 34%

Efficiency is half geometrical





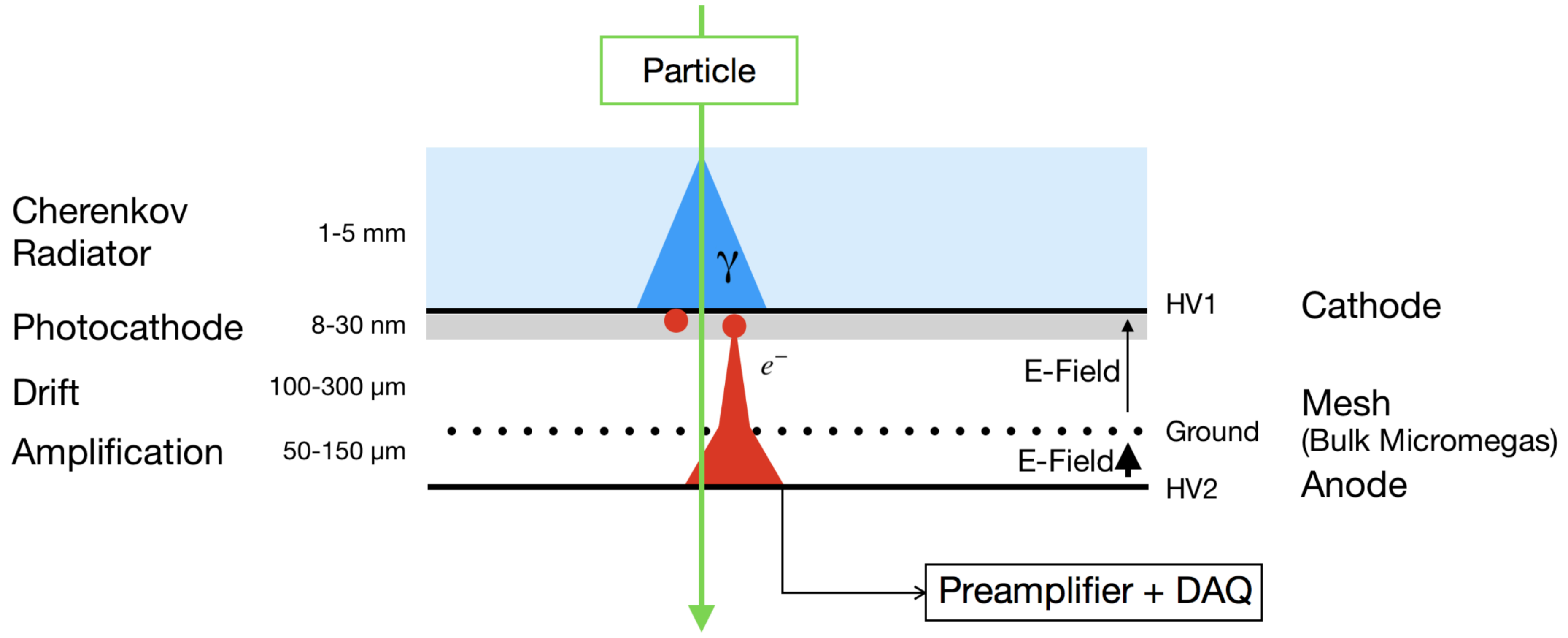
Forward Lepton Reconstruction

- 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

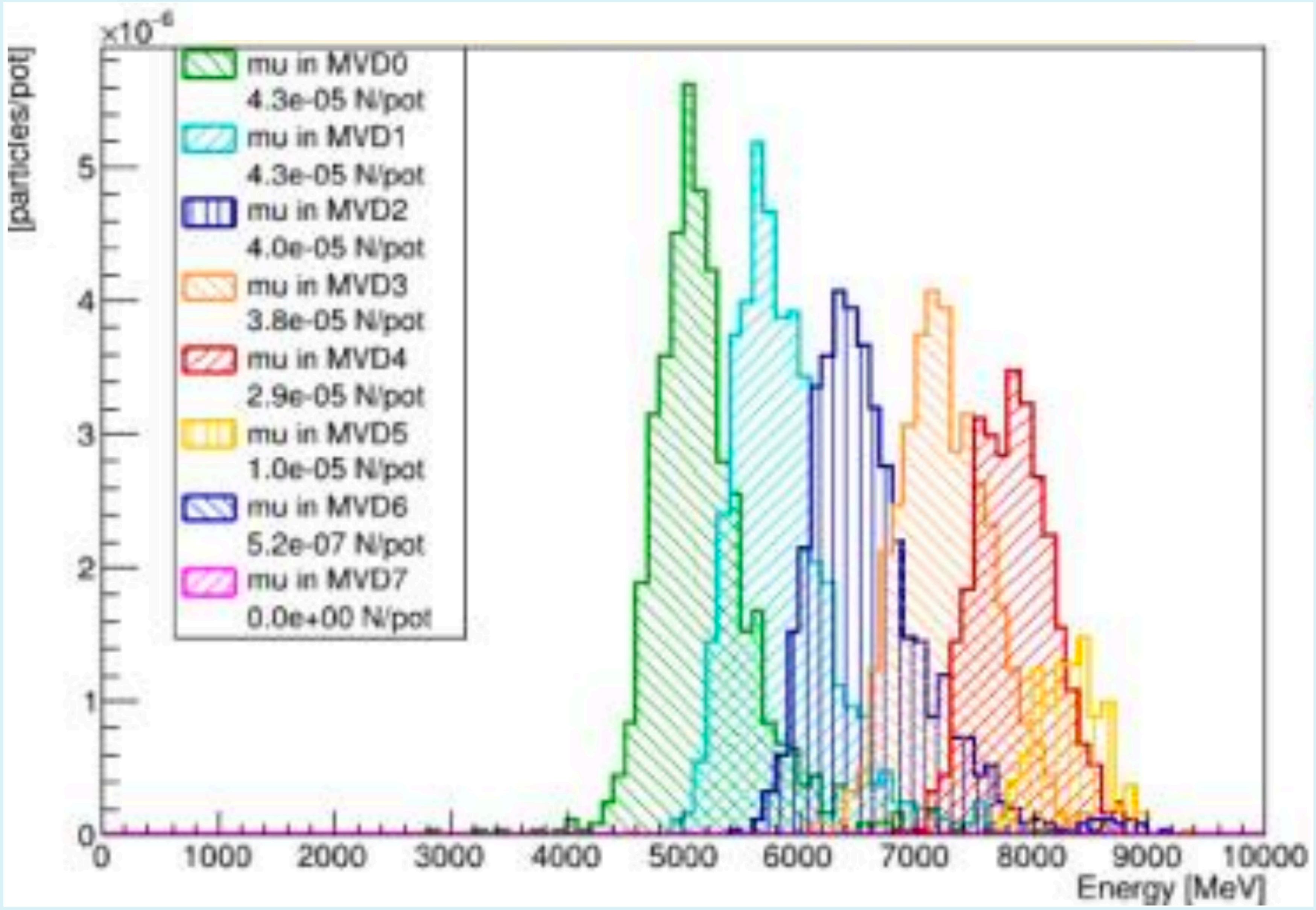
PICOSEC Micromegas Detector for ENUBET

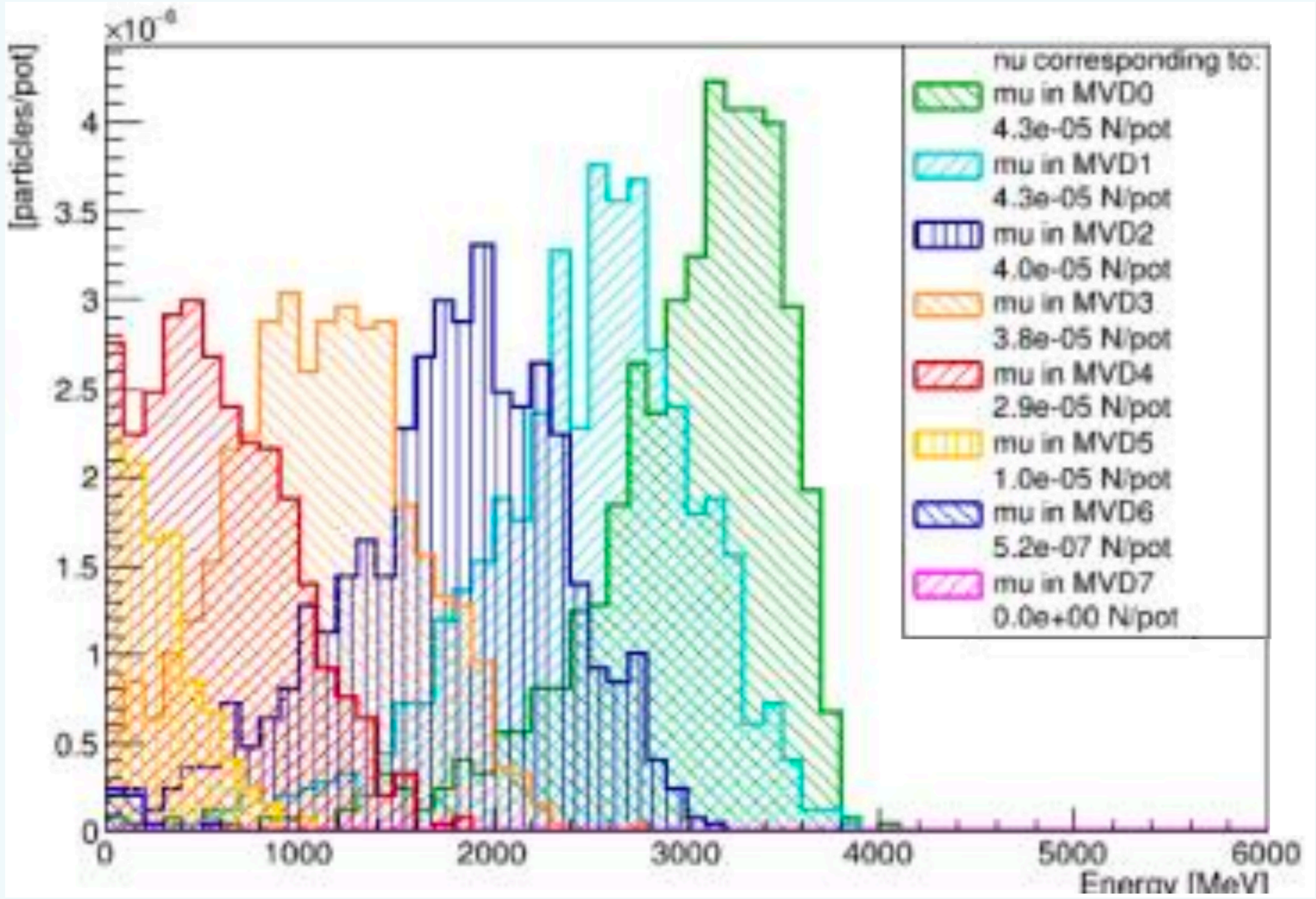
Fast micromega detector with sub-25 ps precision.



Correlation between traversed stations and neutrino energy can be exploited.

Upstream station is the 'hottest' and constrains detector technology.





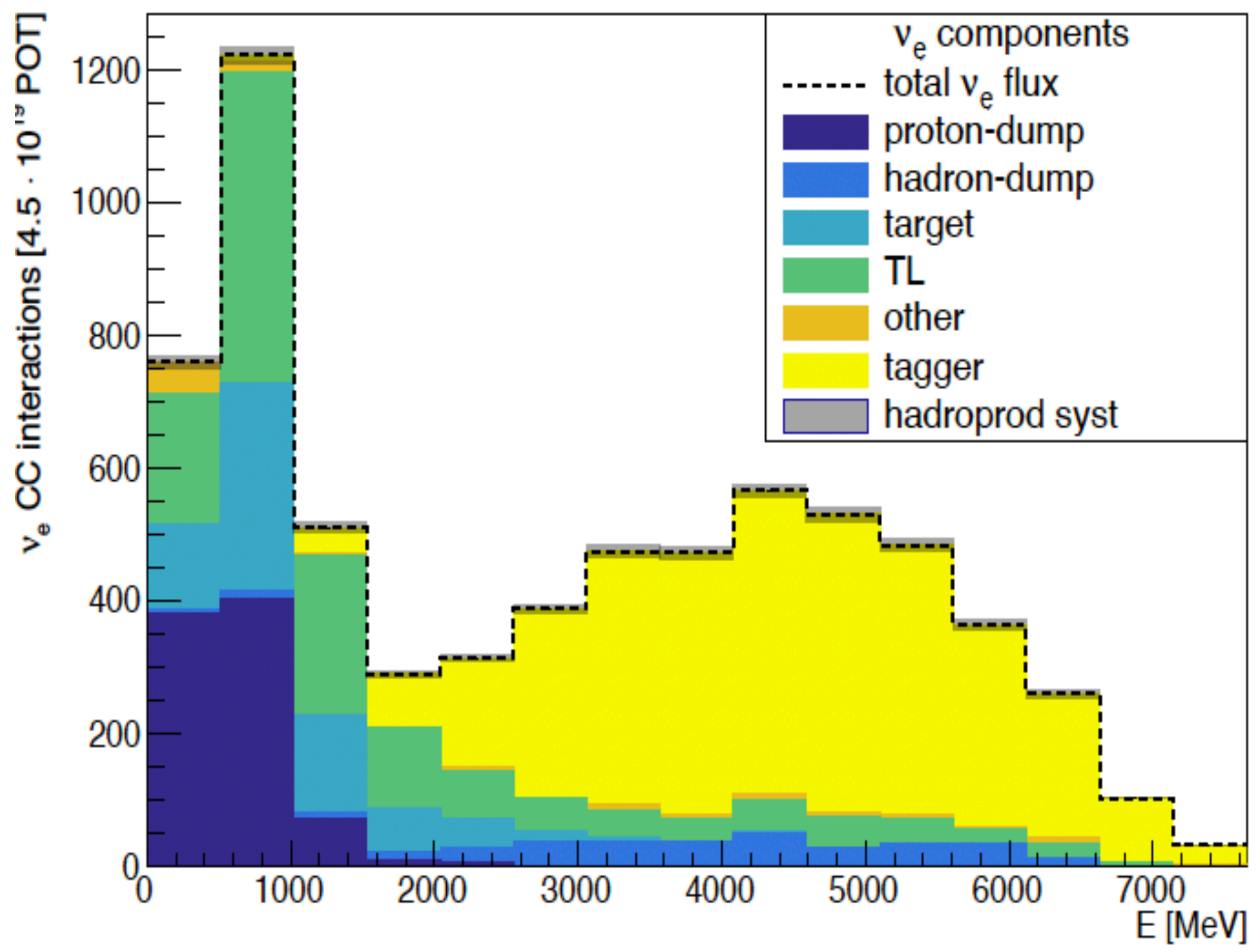
Flux Systematics

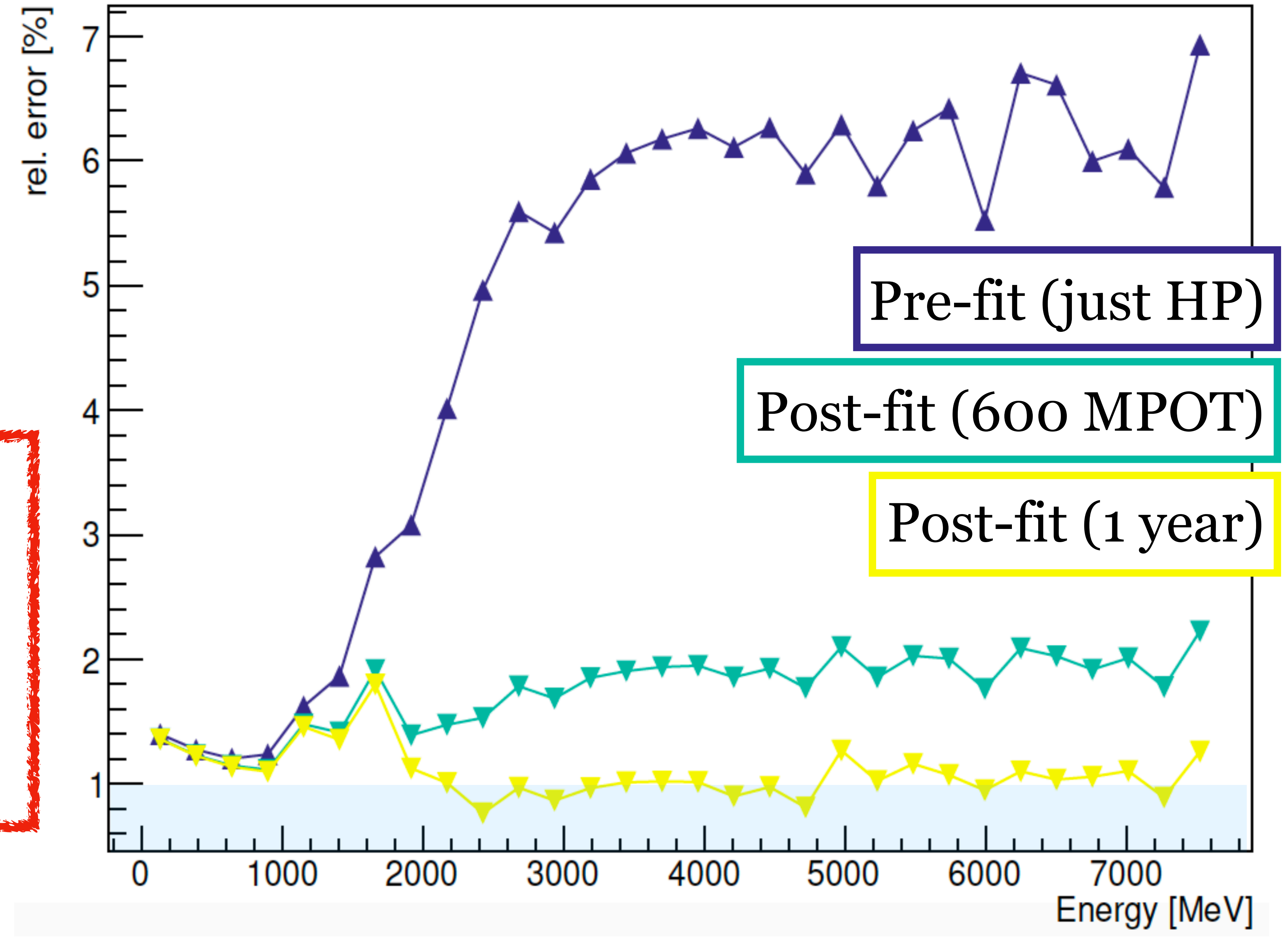
- Use a signal + background model to fit lepton observables and calculate the total uncertainty
- Without lepton monitoring constraints:
  - Flux uncertainty dominated by hadro-production* systematics (~6%)
- Including lepton tagging information:
  - Flux uncertainty reduced to ~1%

*Ha[illegible]o-pro[illegible] from NA56/SPY experiment

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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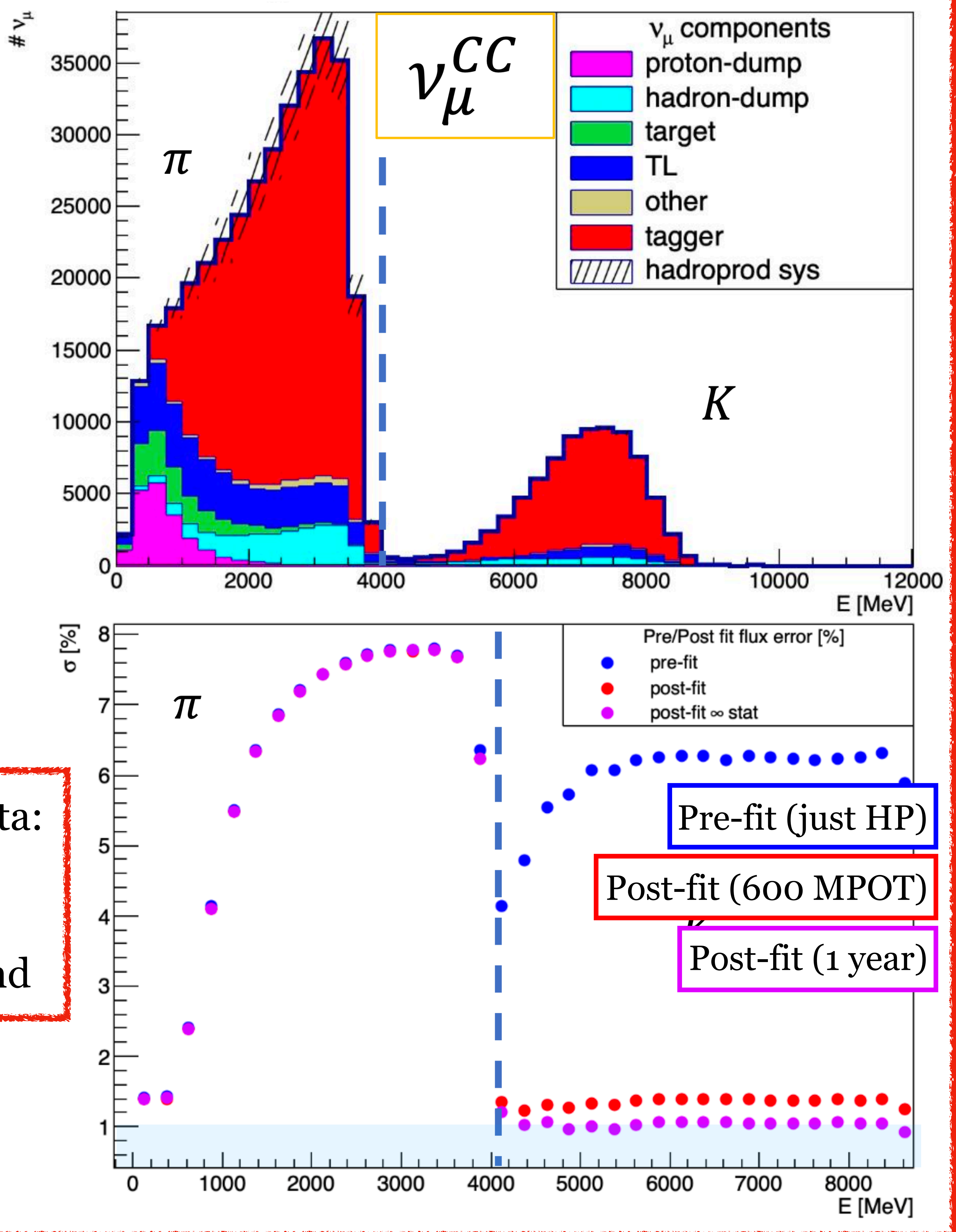
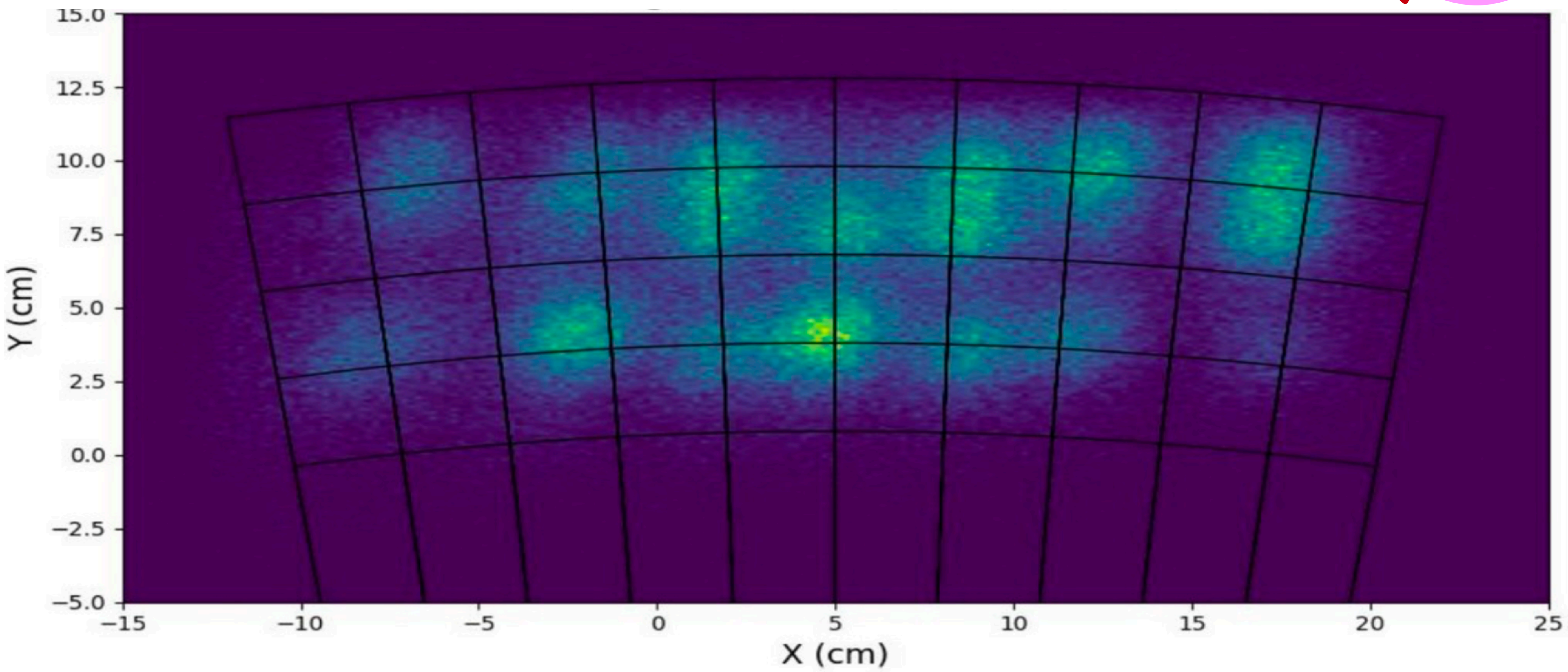
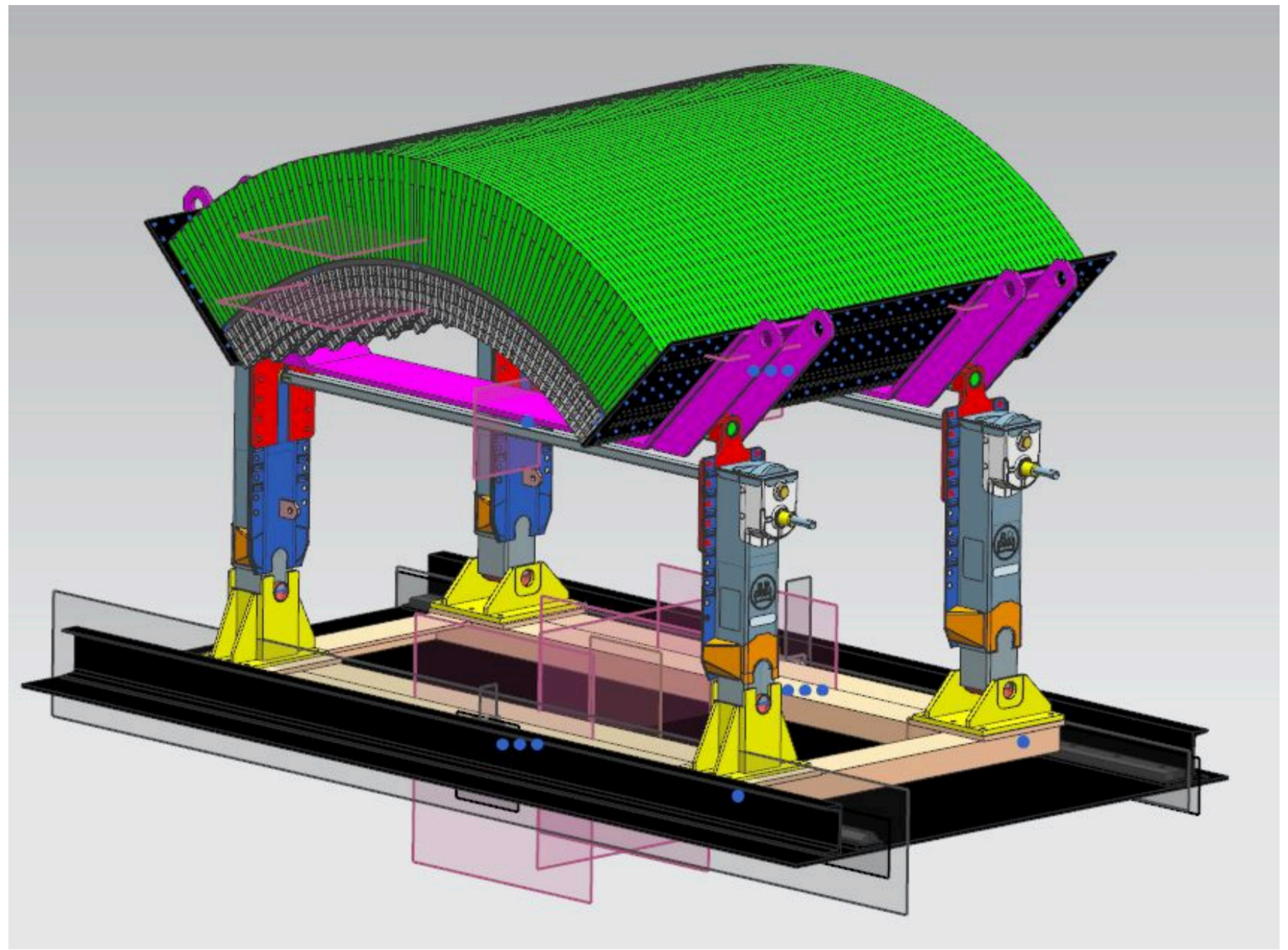


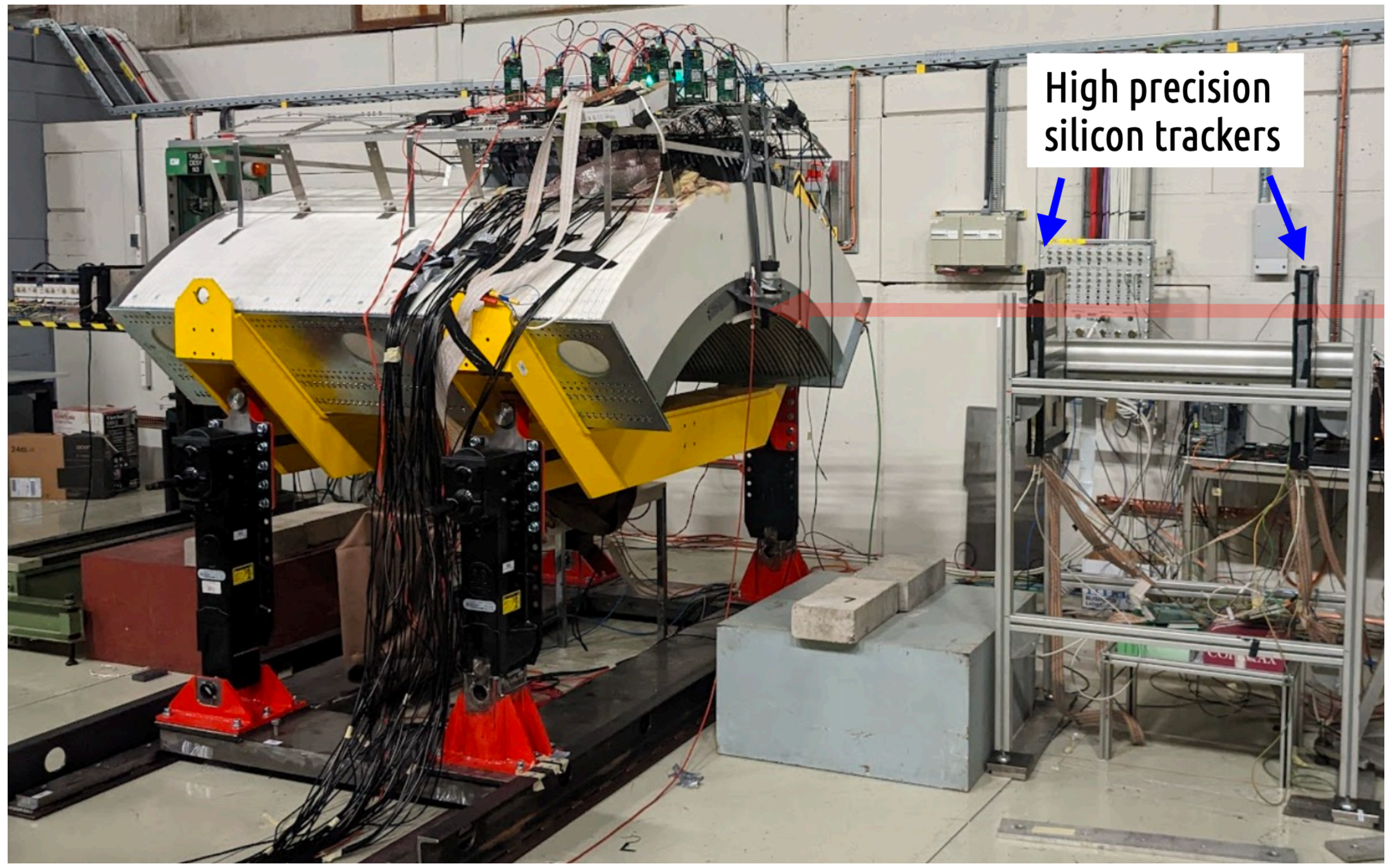
*Hadro-pro... from NA56/SPY experiment

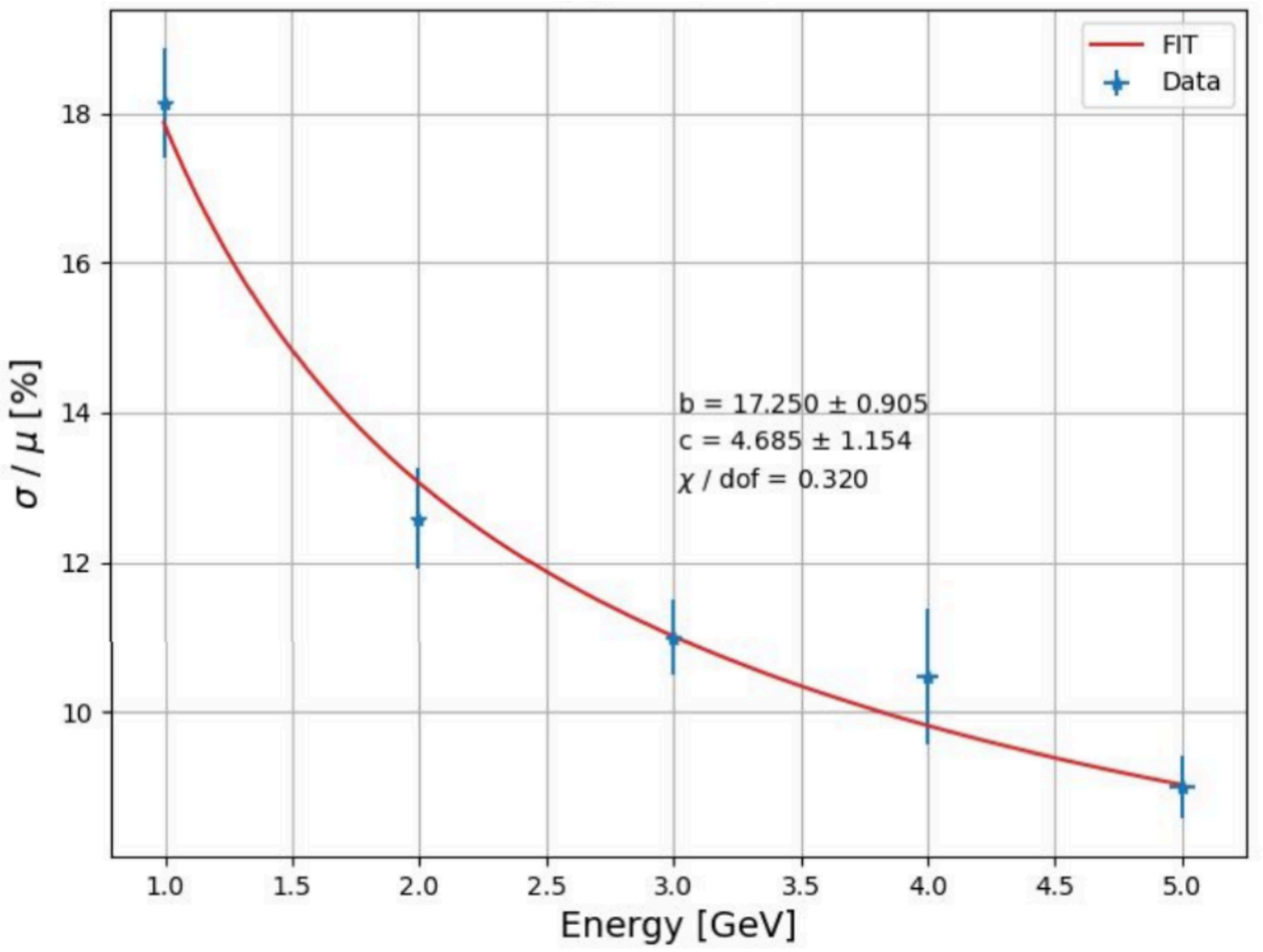
The Demonstrator

- 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

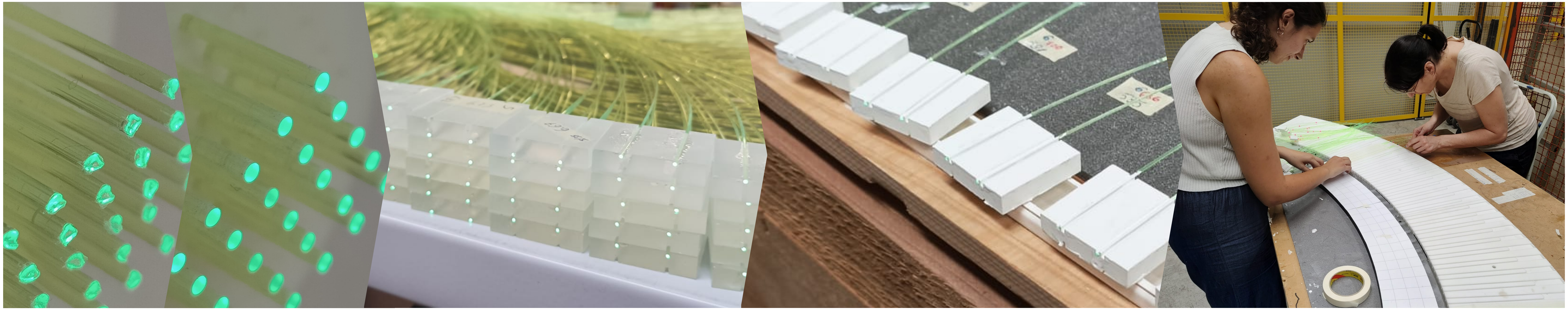


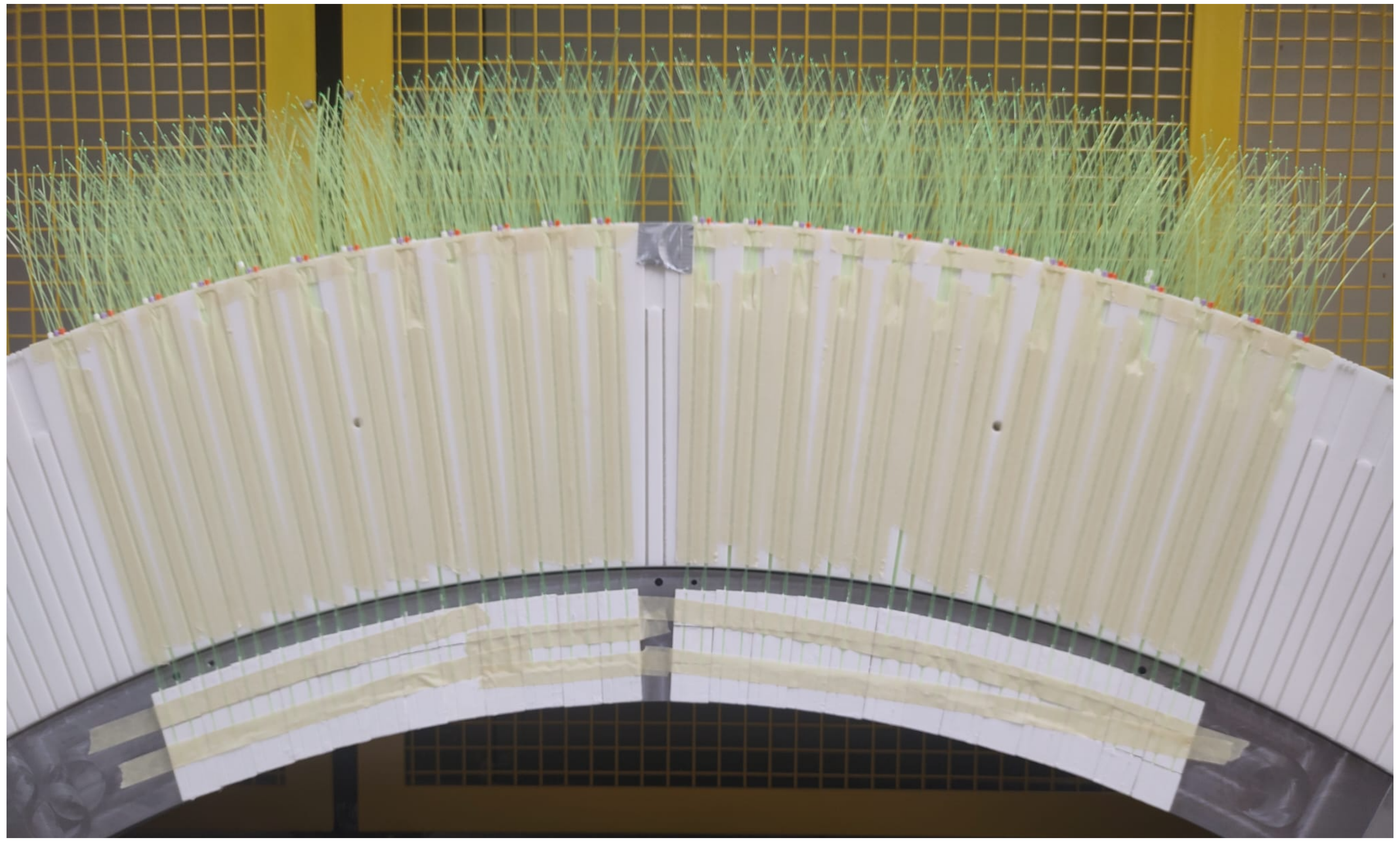






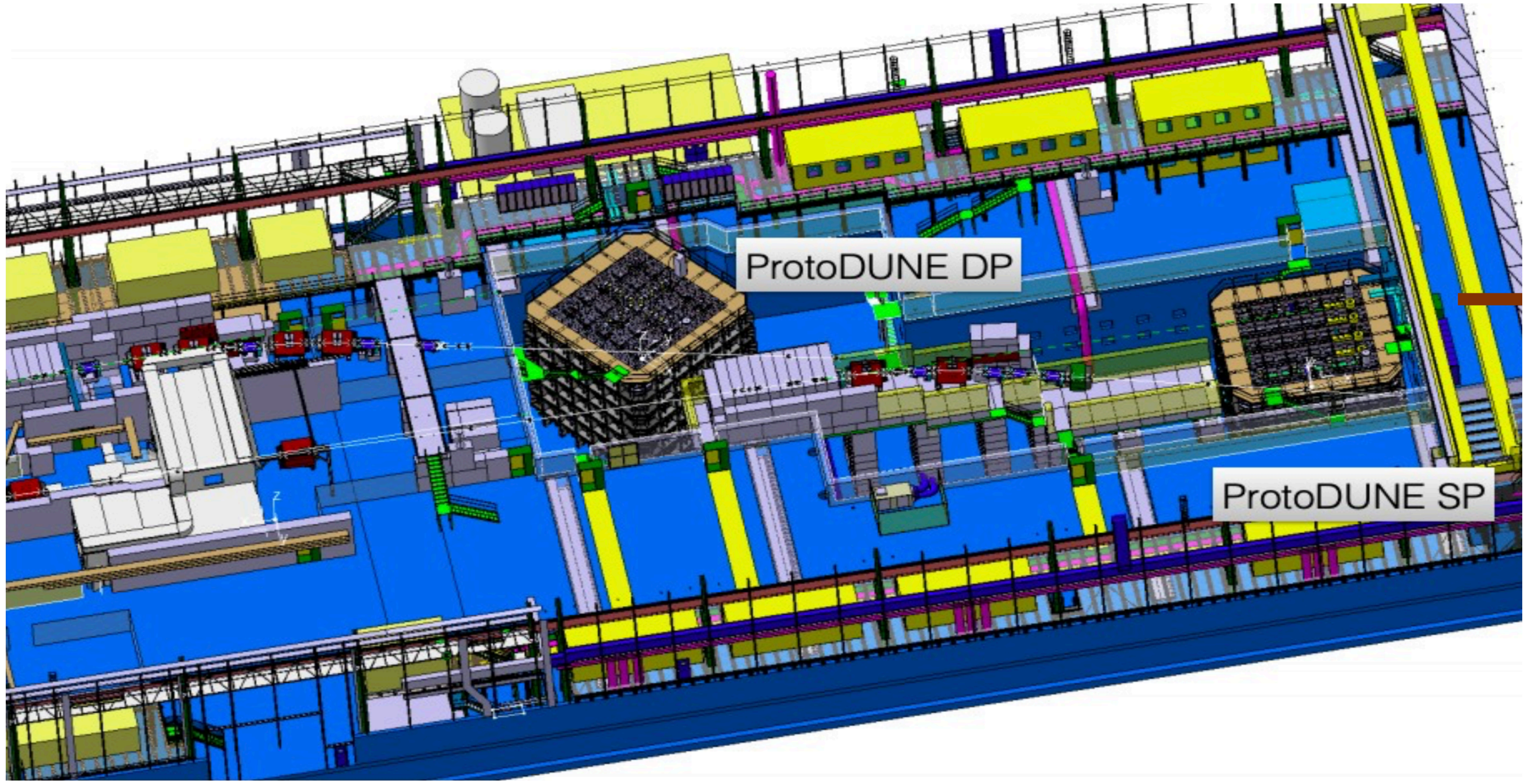
Demonstrator 2.0





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

We need a cross-section facility to achieve a precision of <1% in ν_e and ν_μ fluxes.

Reduce dominant systematics on neutrino flux:

- 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 without energy reconstruction:

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

Use same target as far detectors and low Z targets

- 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 cross-sections)

- 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

Demonstrator-22 → Demonstrator-23

2022: 8 upstream z layers with 10 ϕ sectors (400 ch)

2023:

- add 7 downstream z layers with 25 ϕ sectors
  - passing from 400 to 400+875 = **1275 channels**
- Possibly instrument a few channels with **custom digitizers**
- Larger acceptance:
  - we will take a run in “decay region” mode i.e. with the detector off-beam to try and detect K decay products

2022

Parameter	Quantity or range
Scintillator tiles (7 shapes)	1360
WLS	1.5 km
Channels (SiPM) Hamamatsu (50 μm cell)	400 240, 4×4 mm^2 - calo, 160 3×3 mm^2, t_0
Fiber concentrators (FE boards)	80
Interface boards	8
read-out boards (A5202)	8
CAEN digitizers	45 ch
horizonthal movement	$\sim$ 1 m
vertical tilt	up to $\sim$ 200 mrad

2023