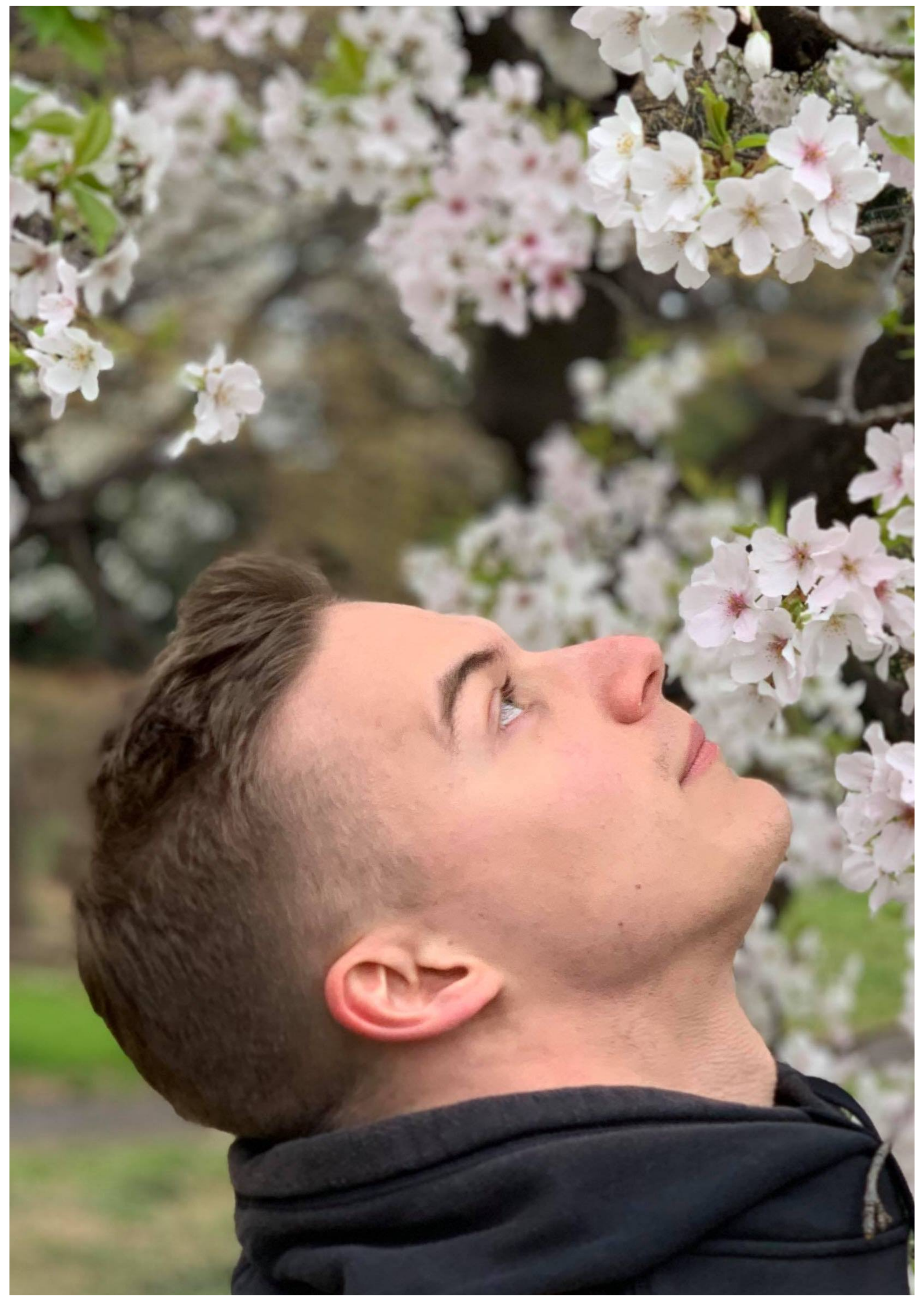
Monitoring neutrino beams with ENUBET

A precision cross-section story



Jordan McElwee*

28th November 2023

IRN @ KIT

*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}

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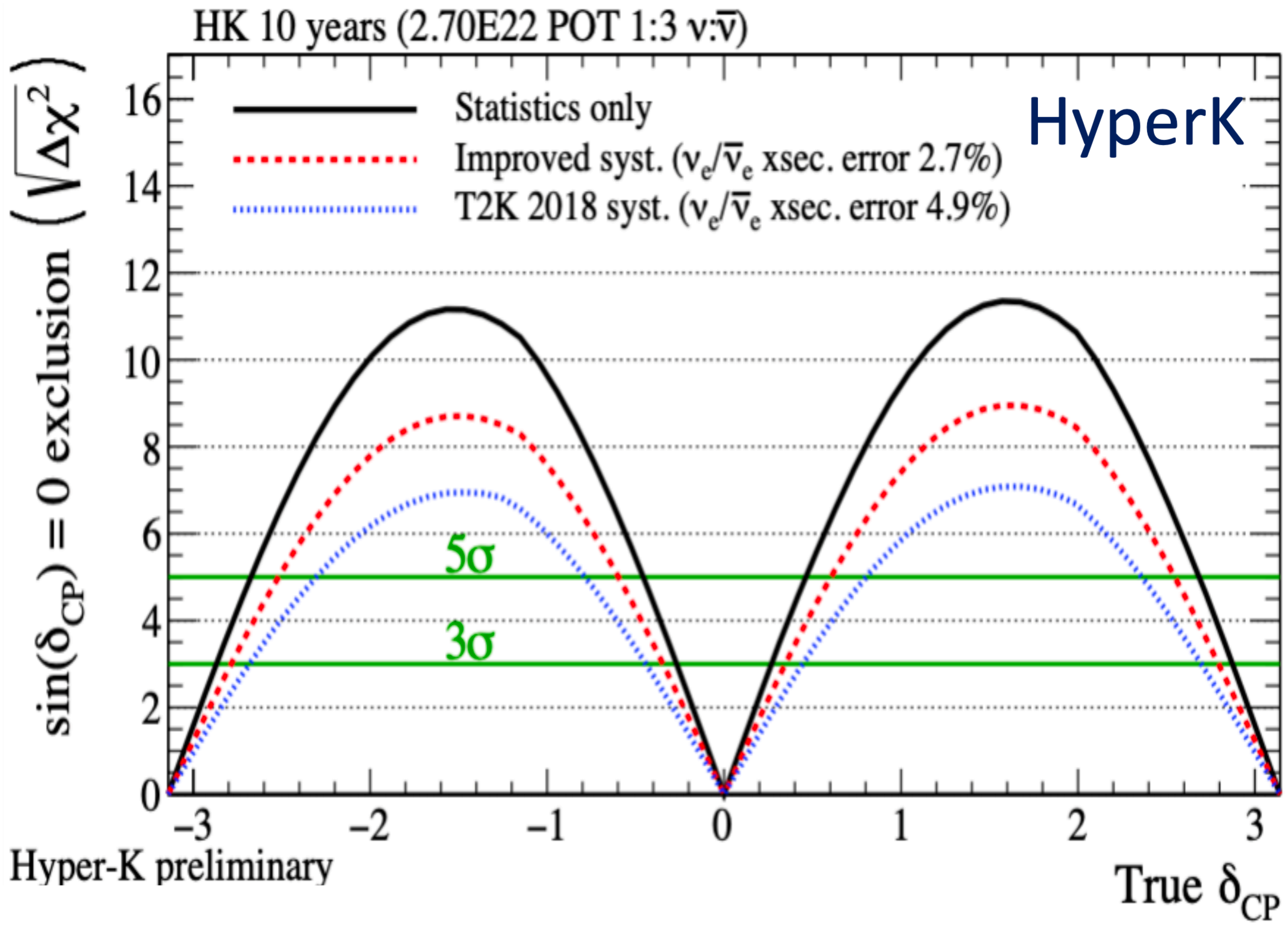

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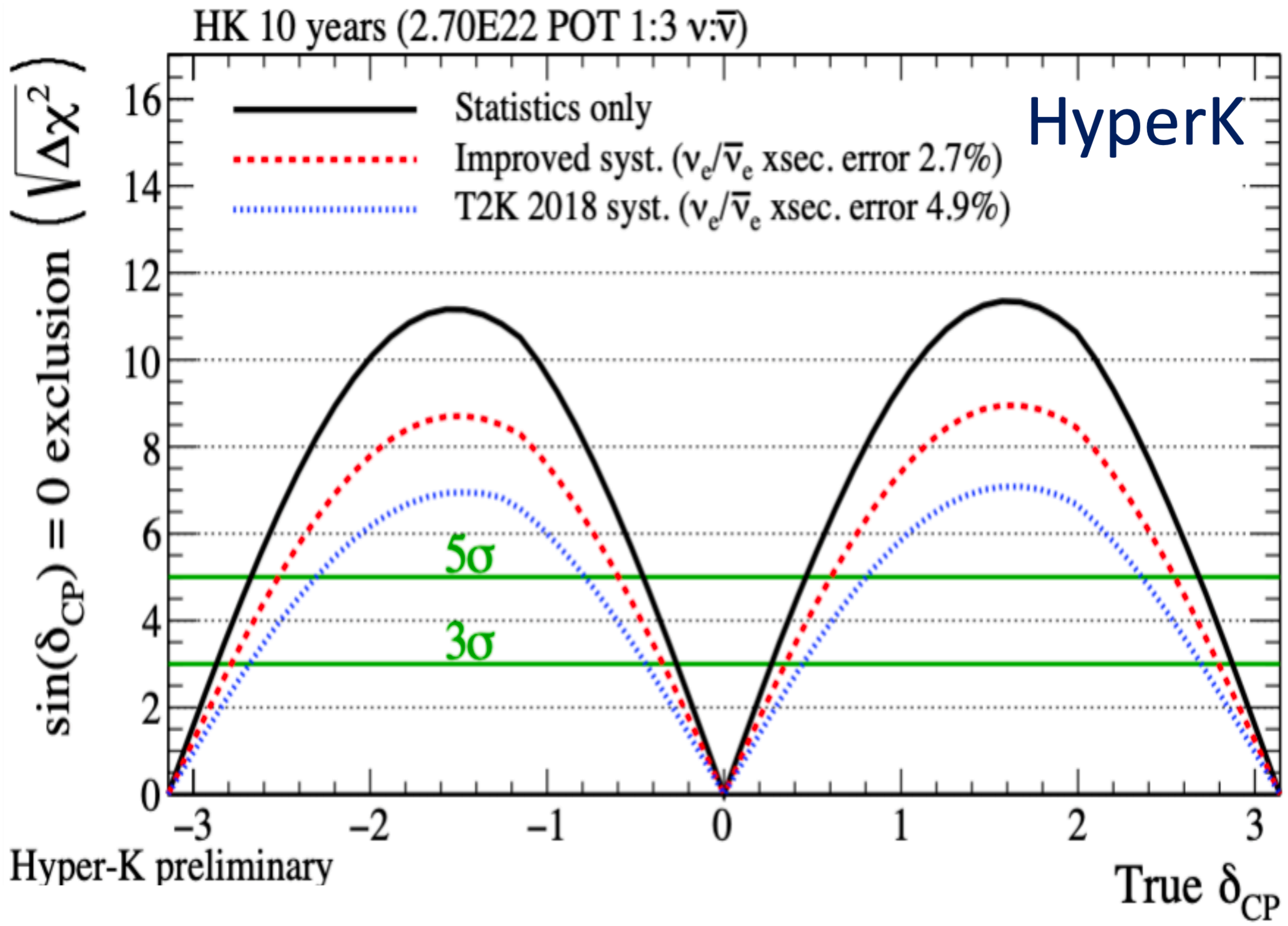

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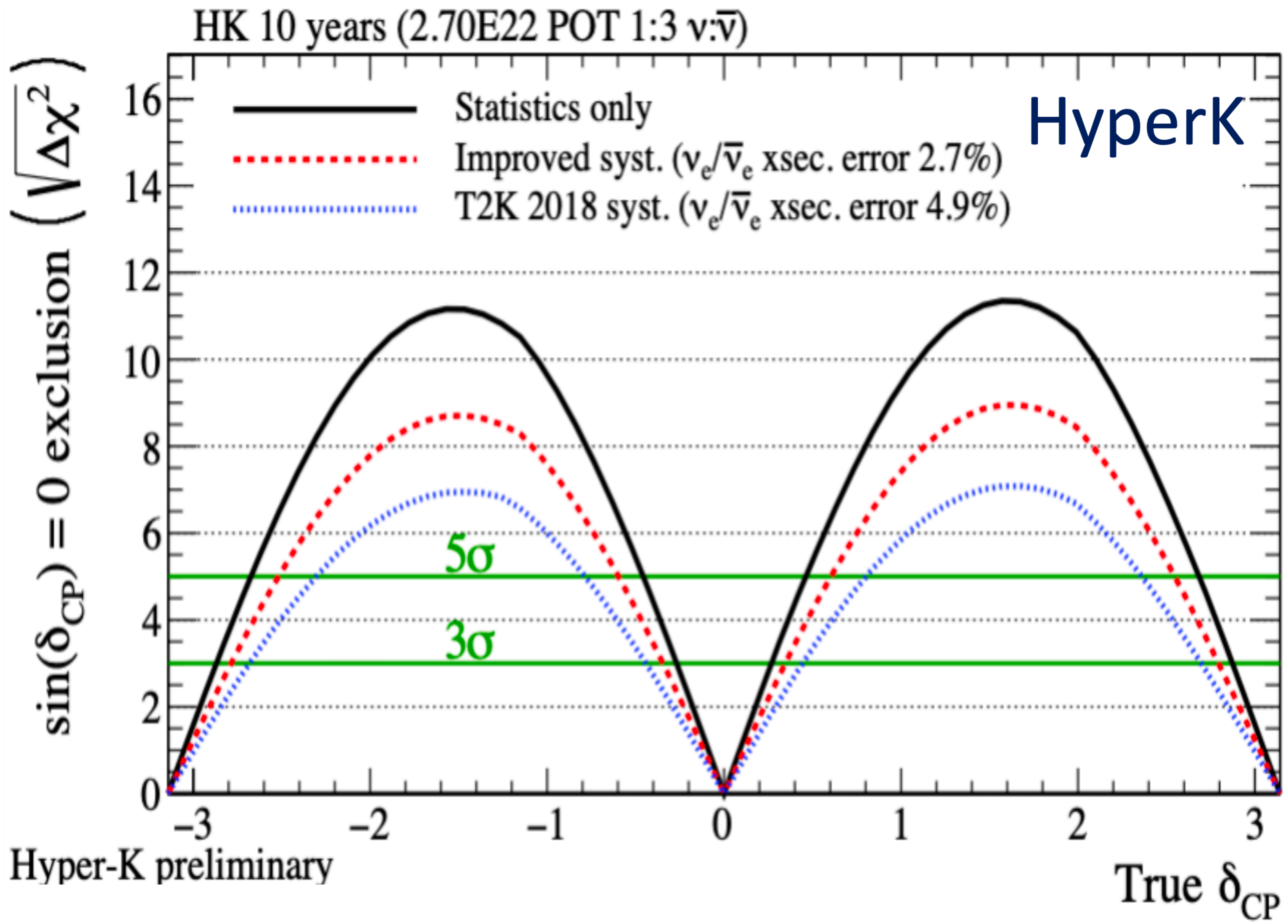

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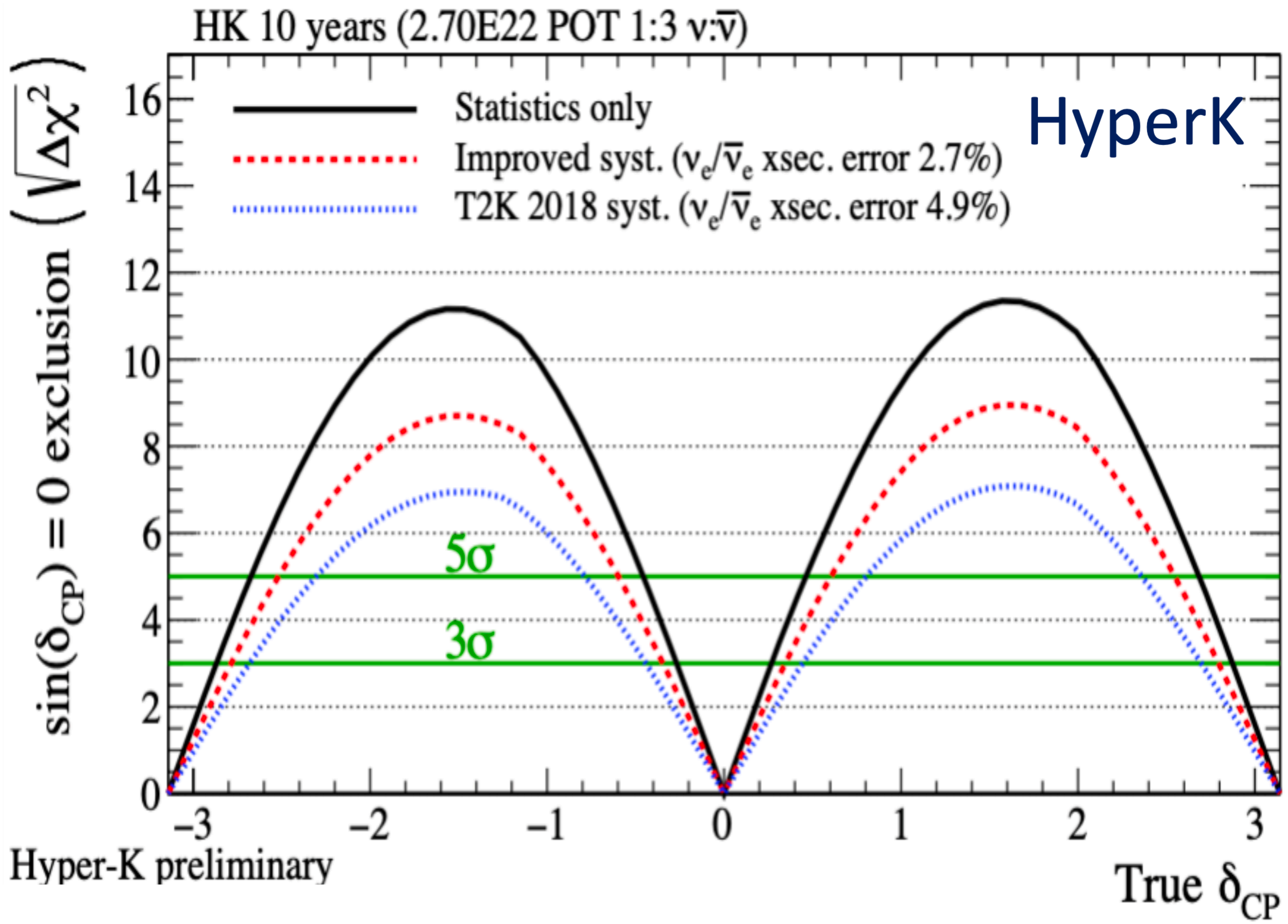

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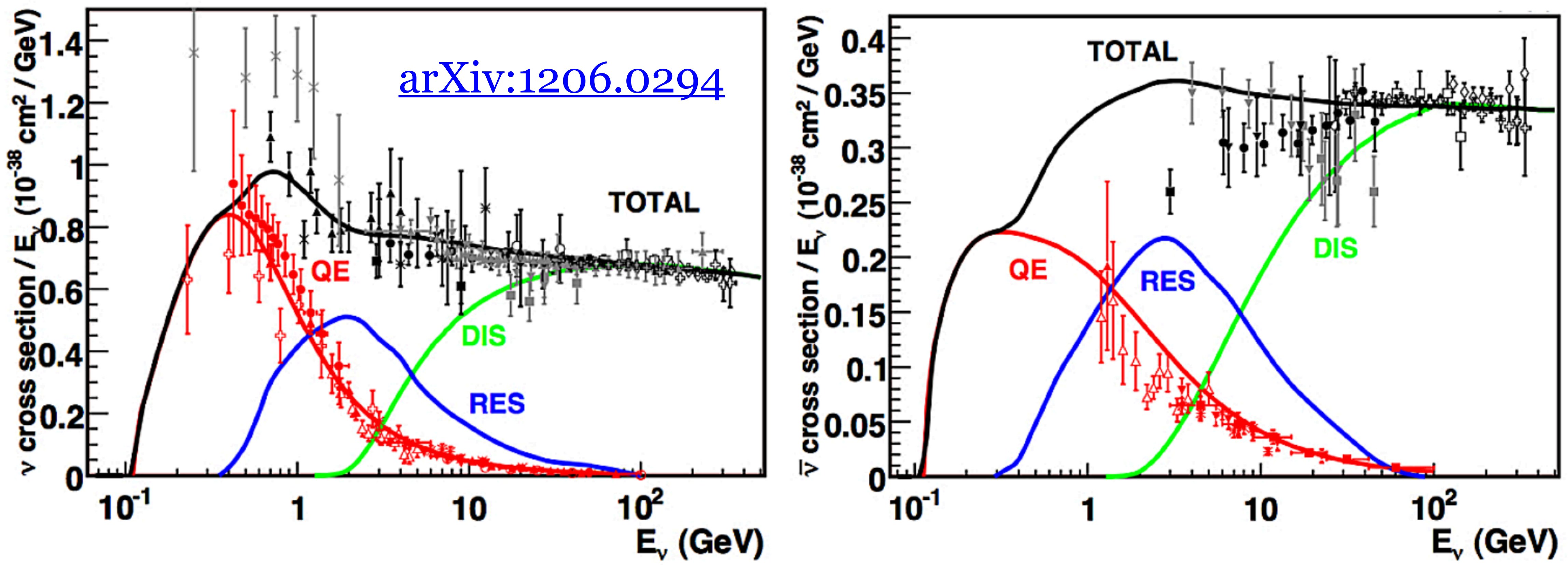
- Compounded neutrino-interaction uncertainties and detector effects



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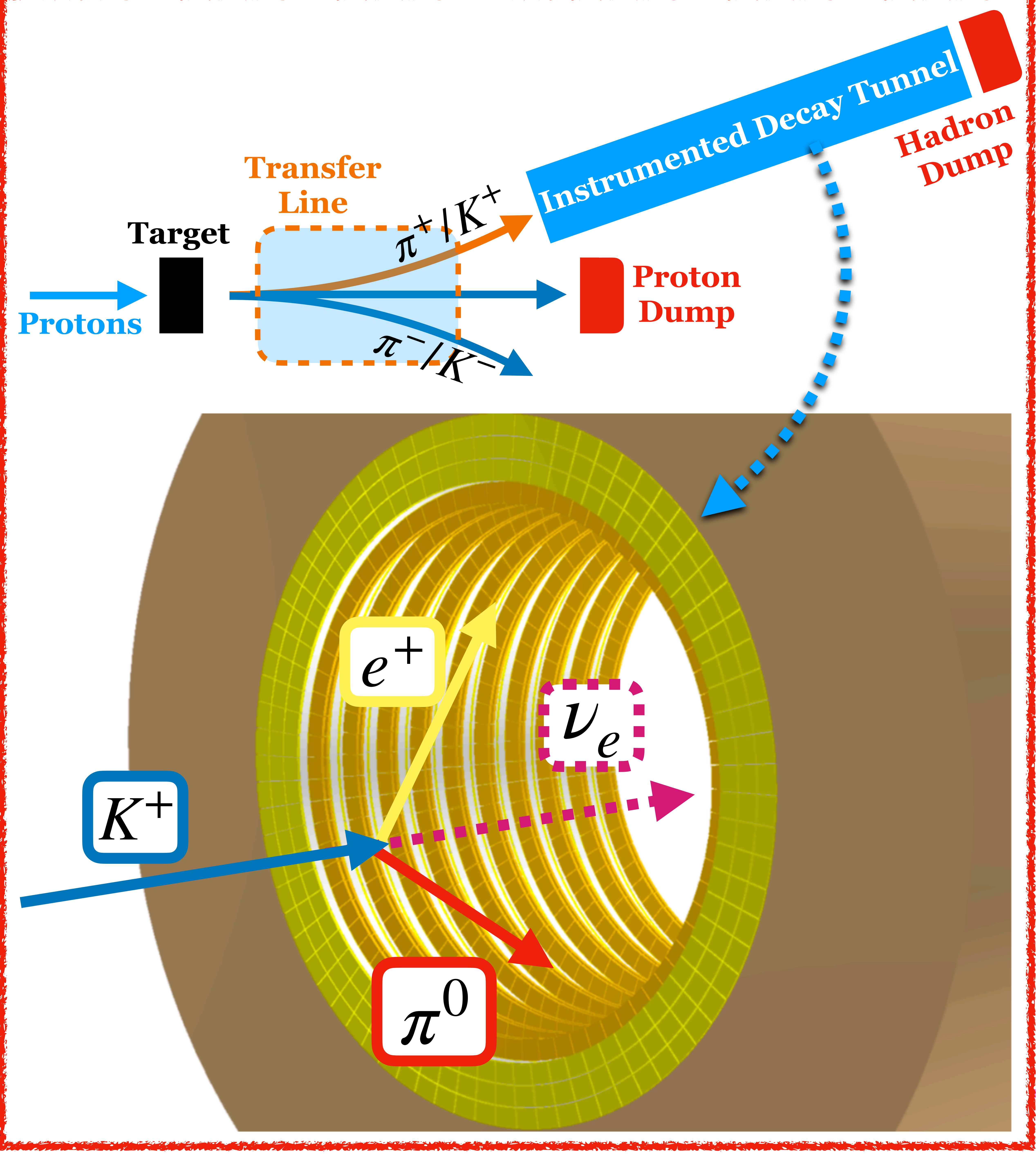
ENUBET

- **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.

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

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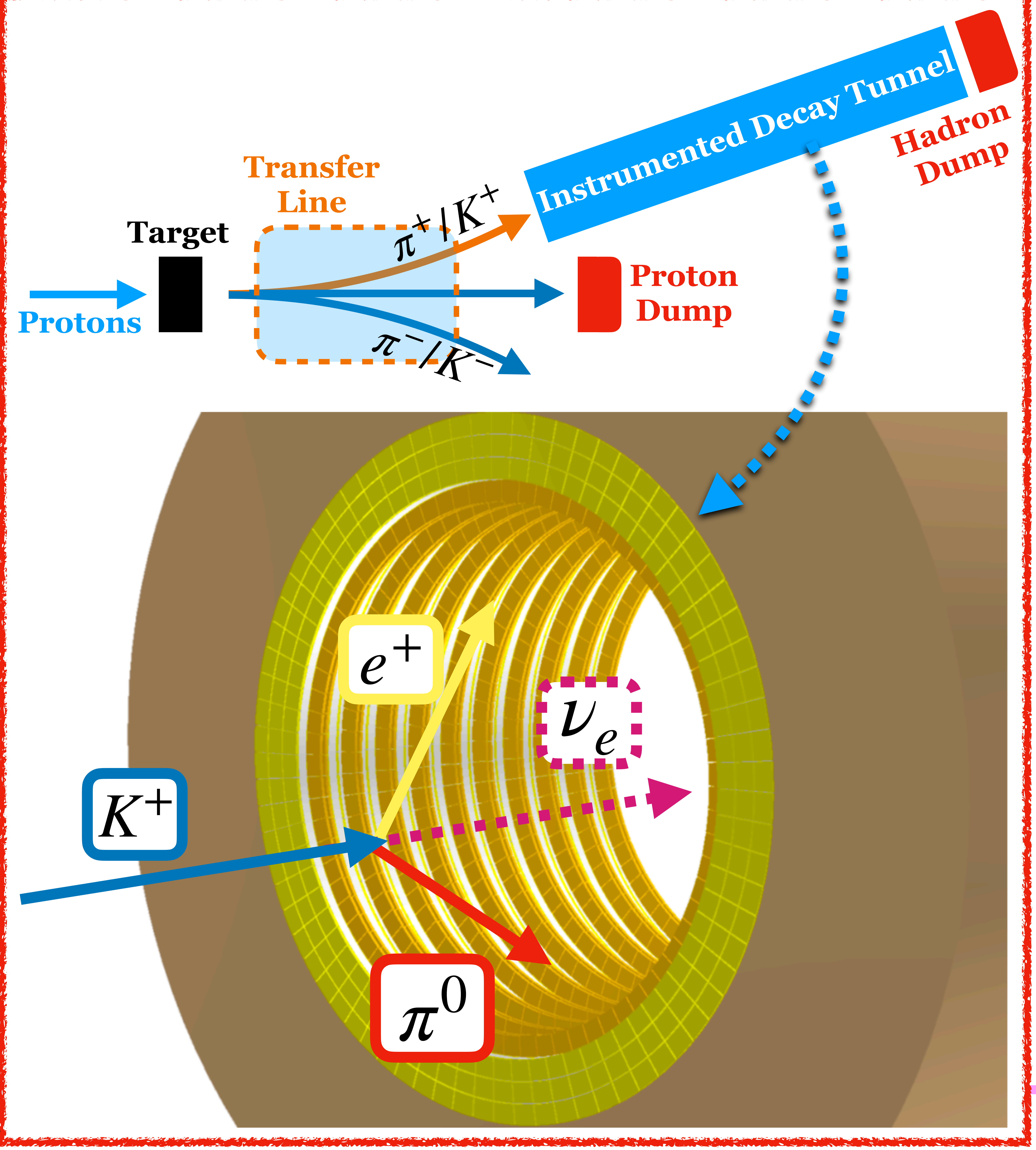

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CERN Neutrino Platform

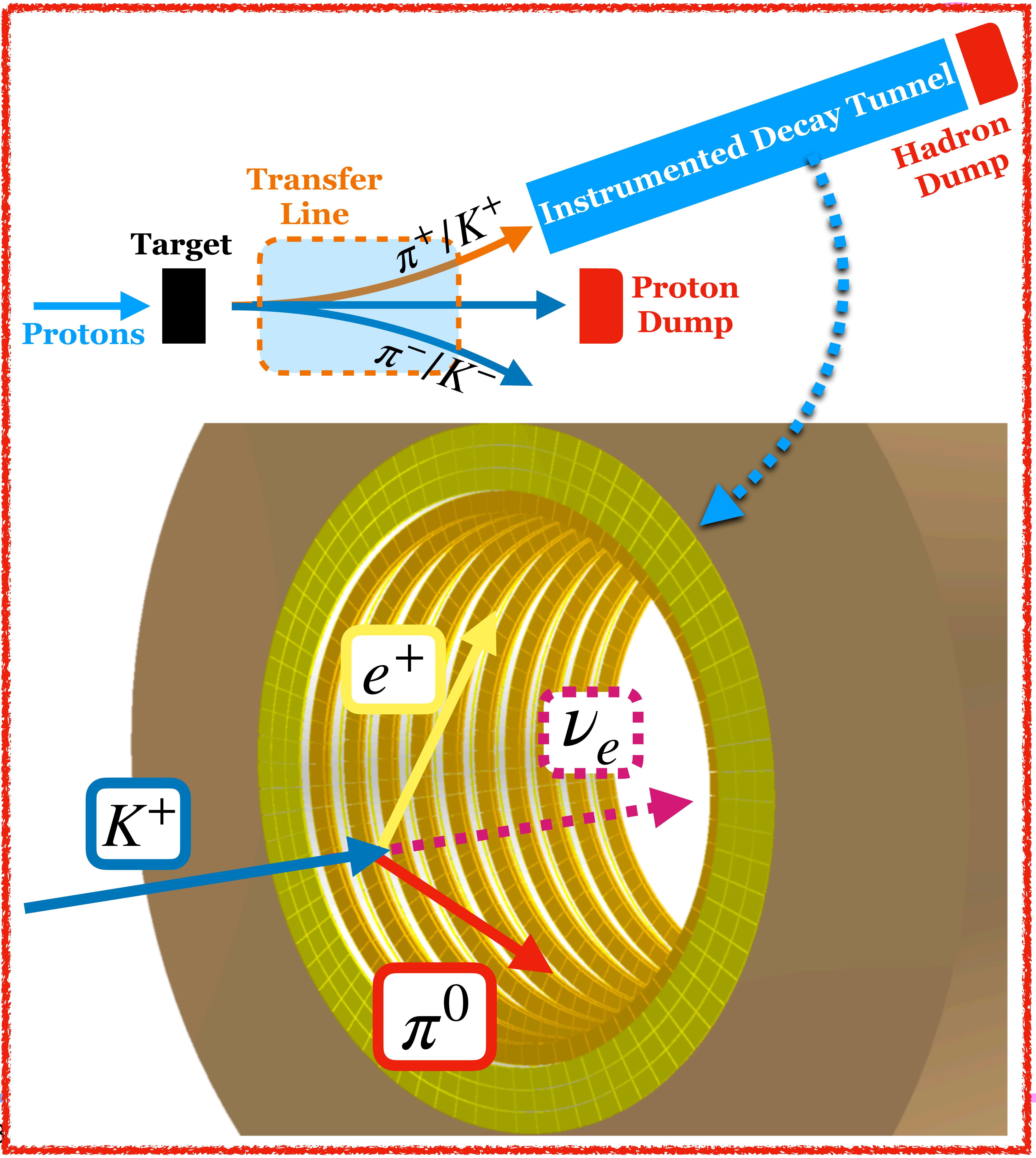
(2019-Present)

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.

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



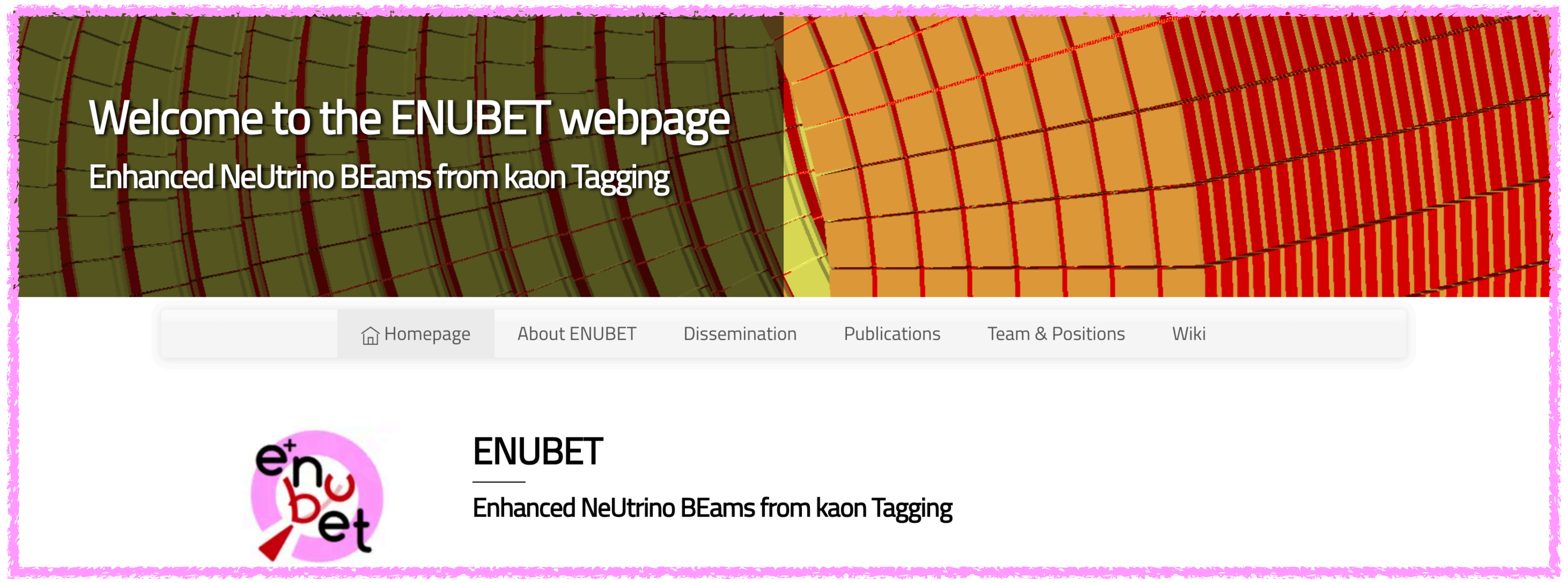
The ENUBET Collaboration

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]



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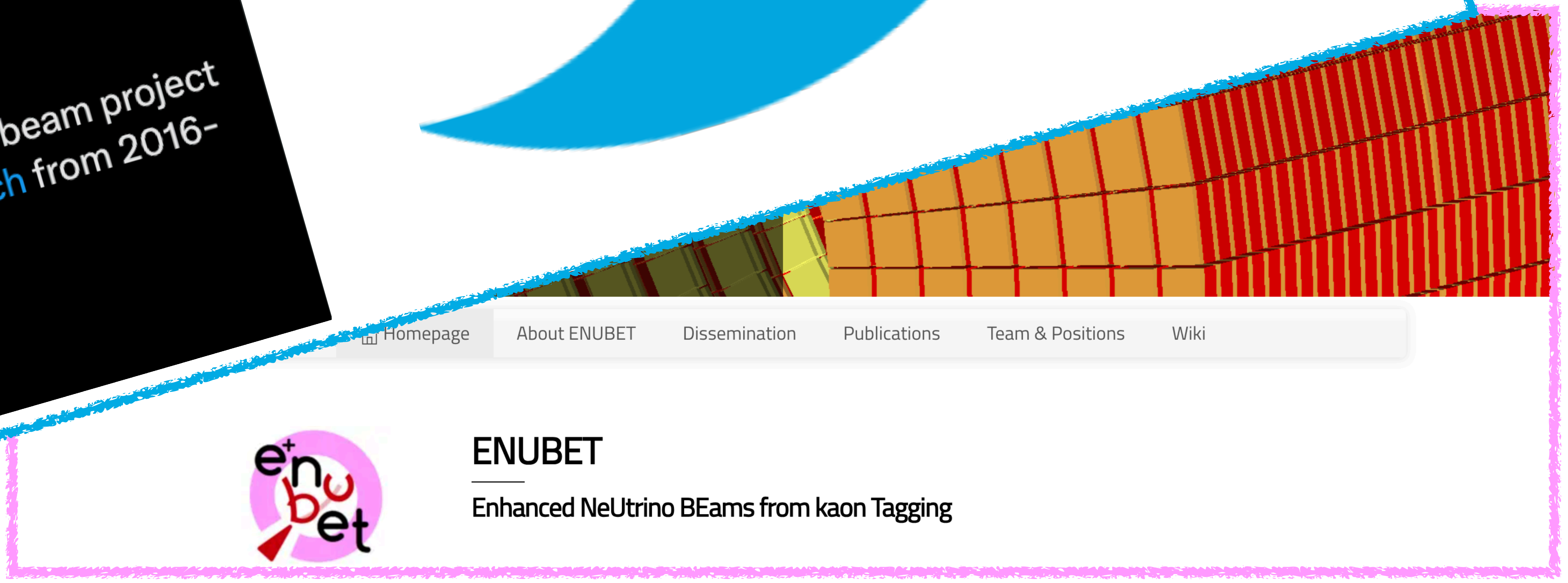
We now have a twitter!

@enubet



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Univ

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

LP2i Bordeaux

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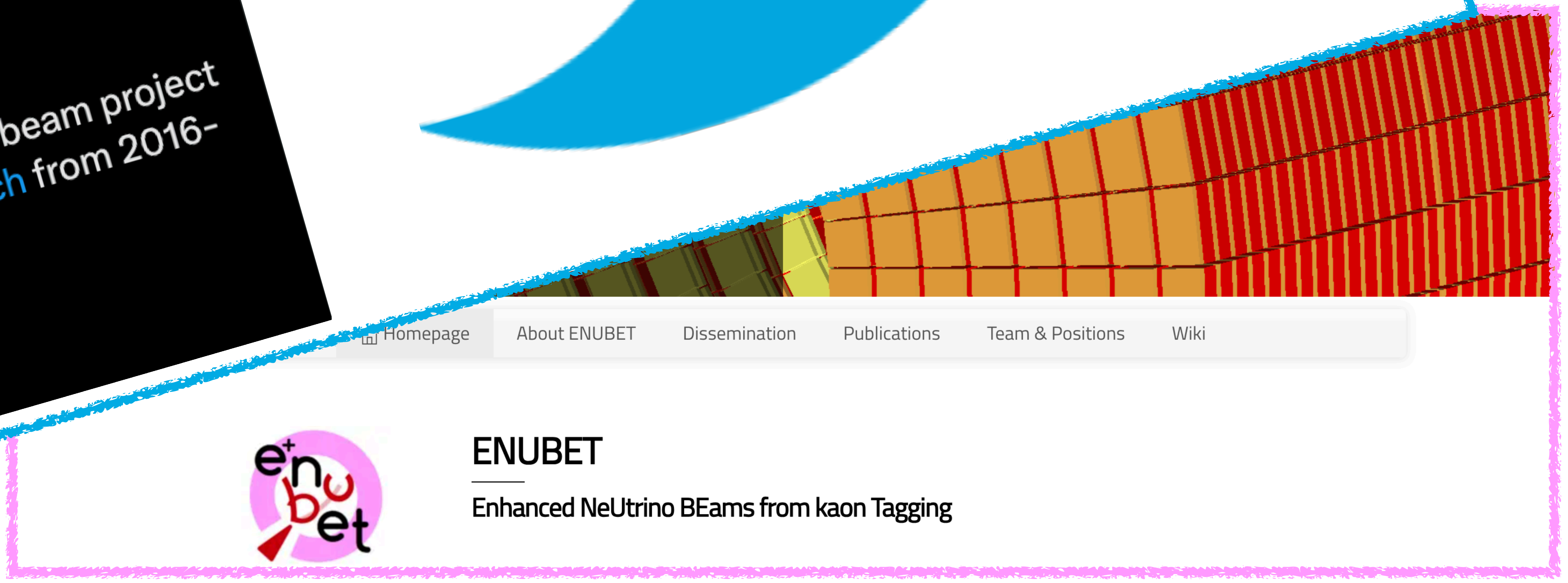

Beamline

Full G4 Simulation available: [arXiv:2308.09402](https://arxiv.org/abs/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

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Dumps

- 2 dumps: proton and hadron
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- 40 m long
- 1 m wide
- At an angle of 14.8° to proton beam

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Dumps

- 2 dumps: proton and hadron
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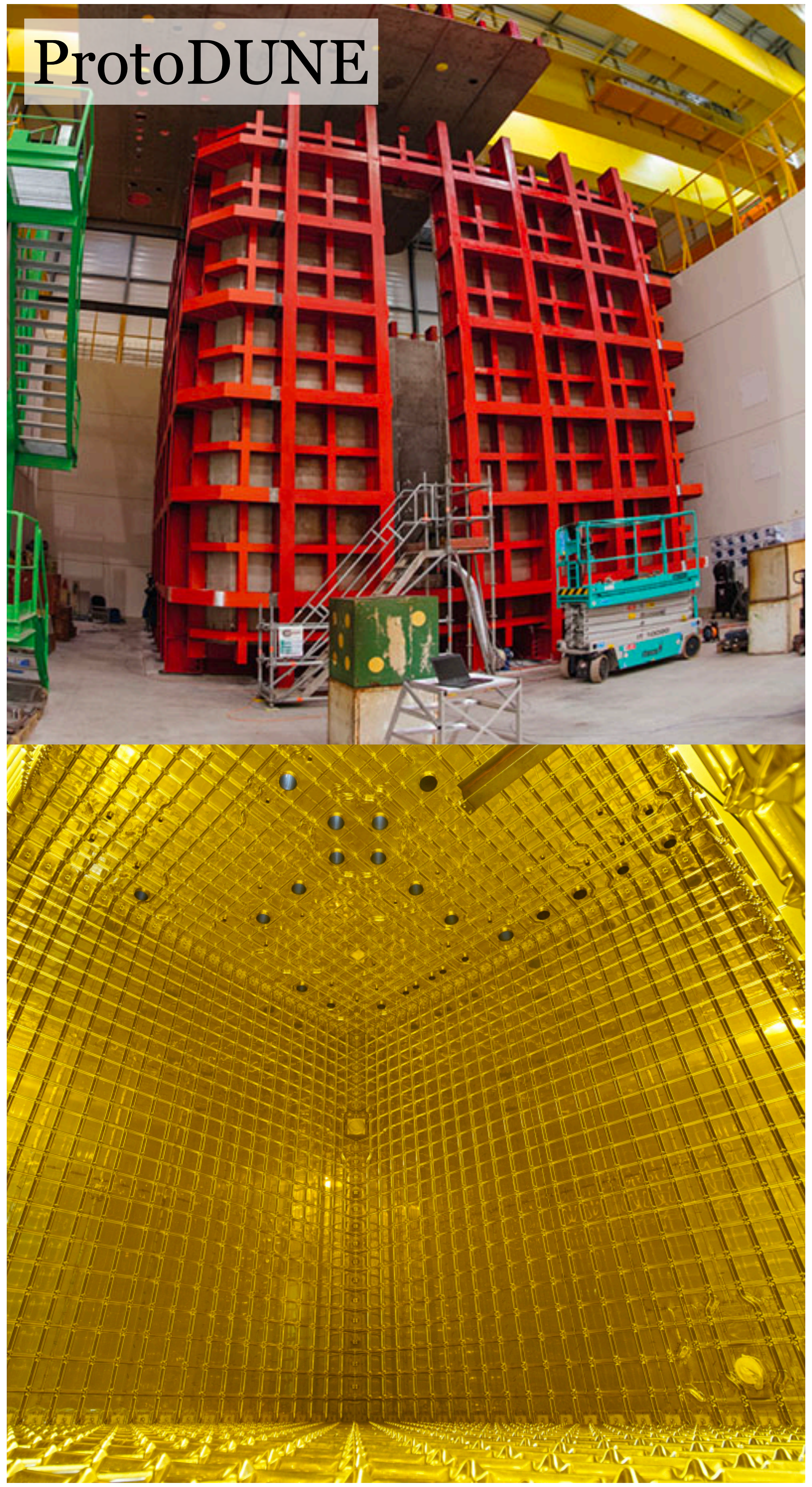
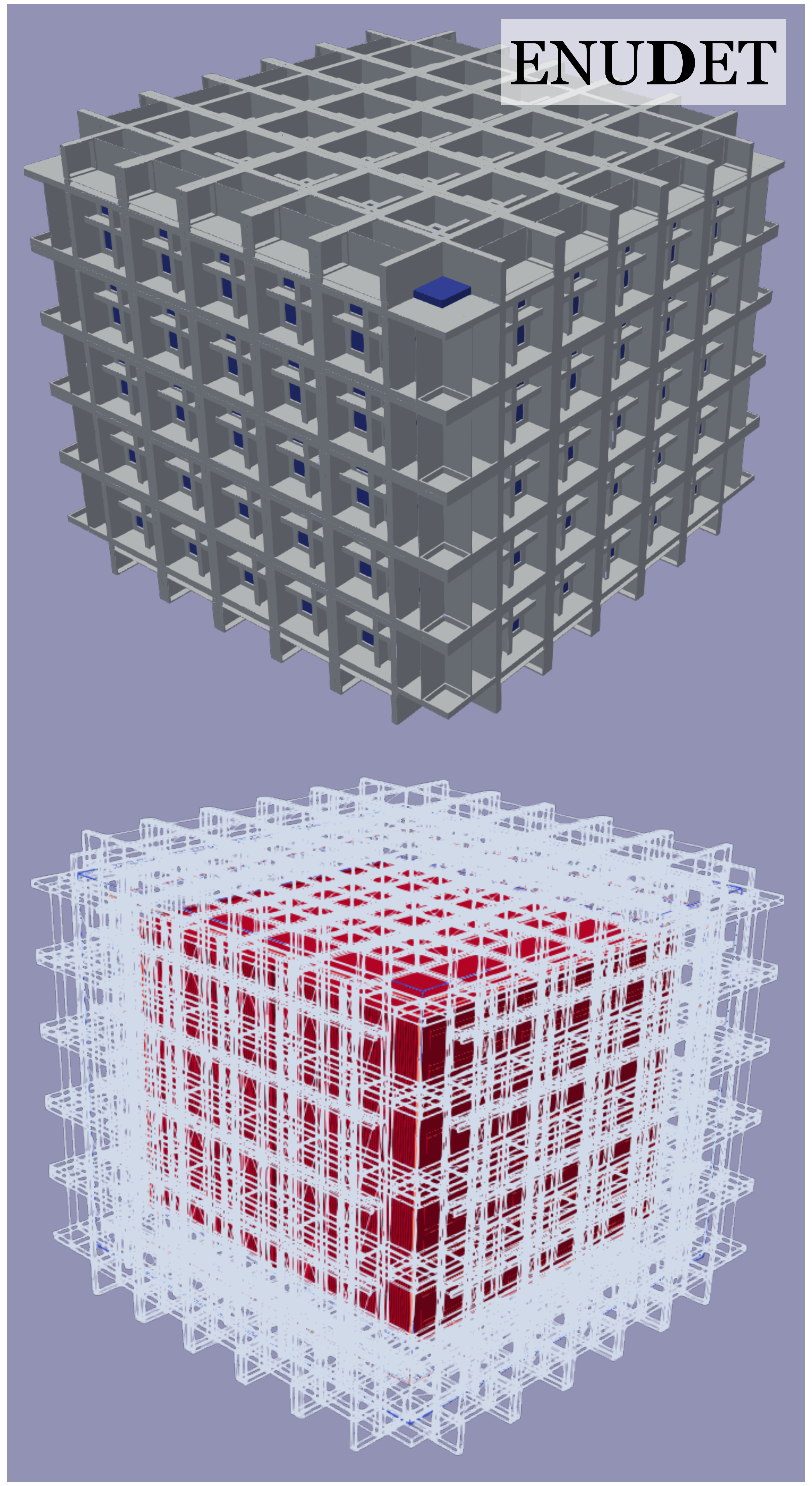
- Graphite core
- Iron middle layer
- Surrounded by borated concrete

The ν_e Beam

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





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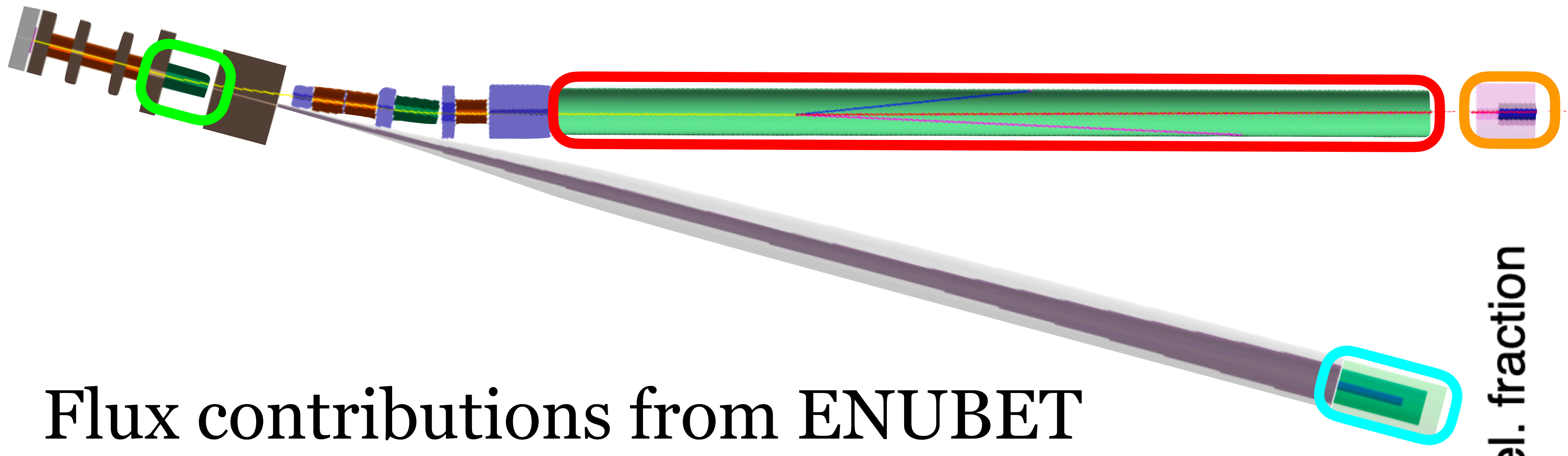
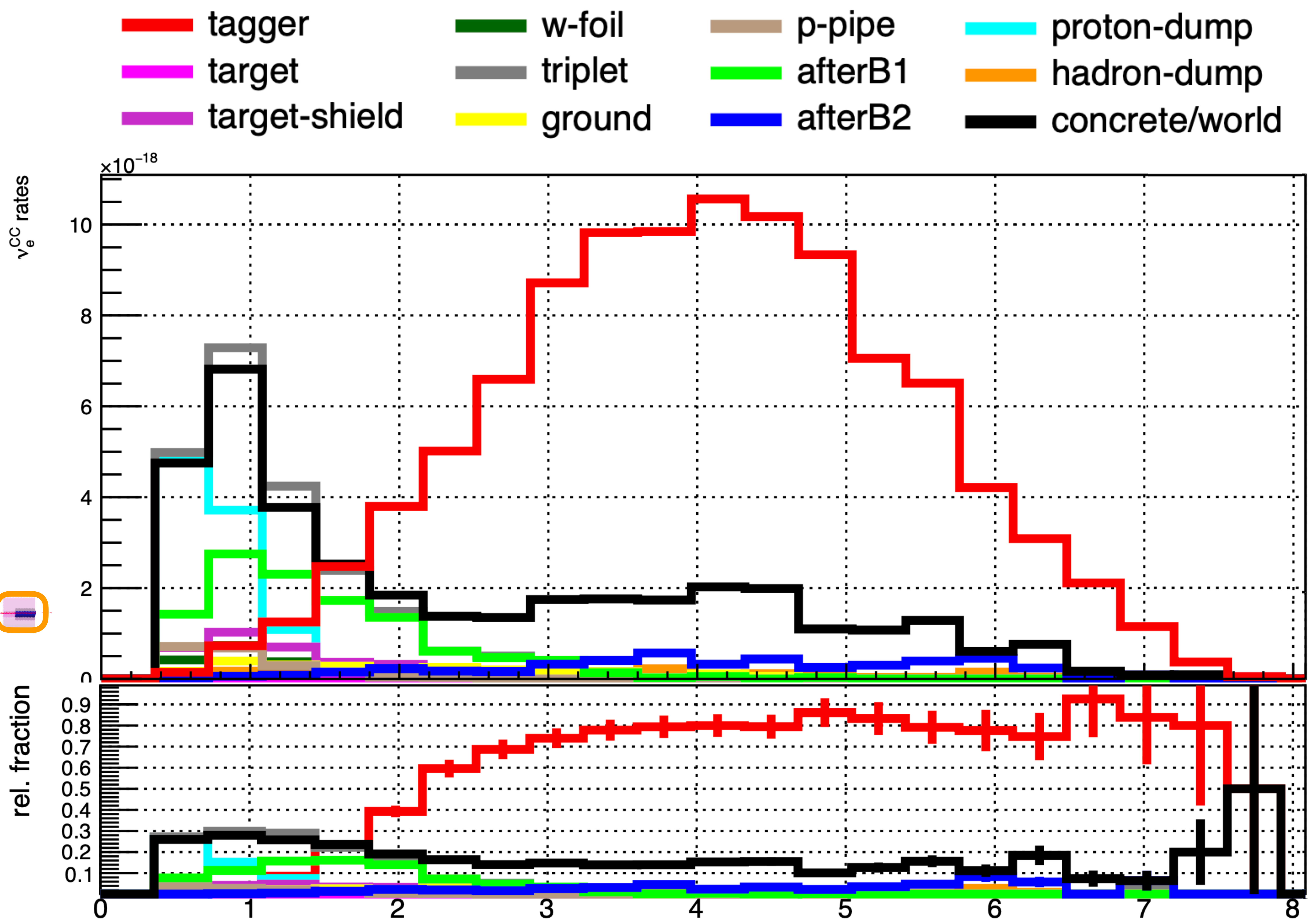


Flux contributions from ENUBET facility



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- 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

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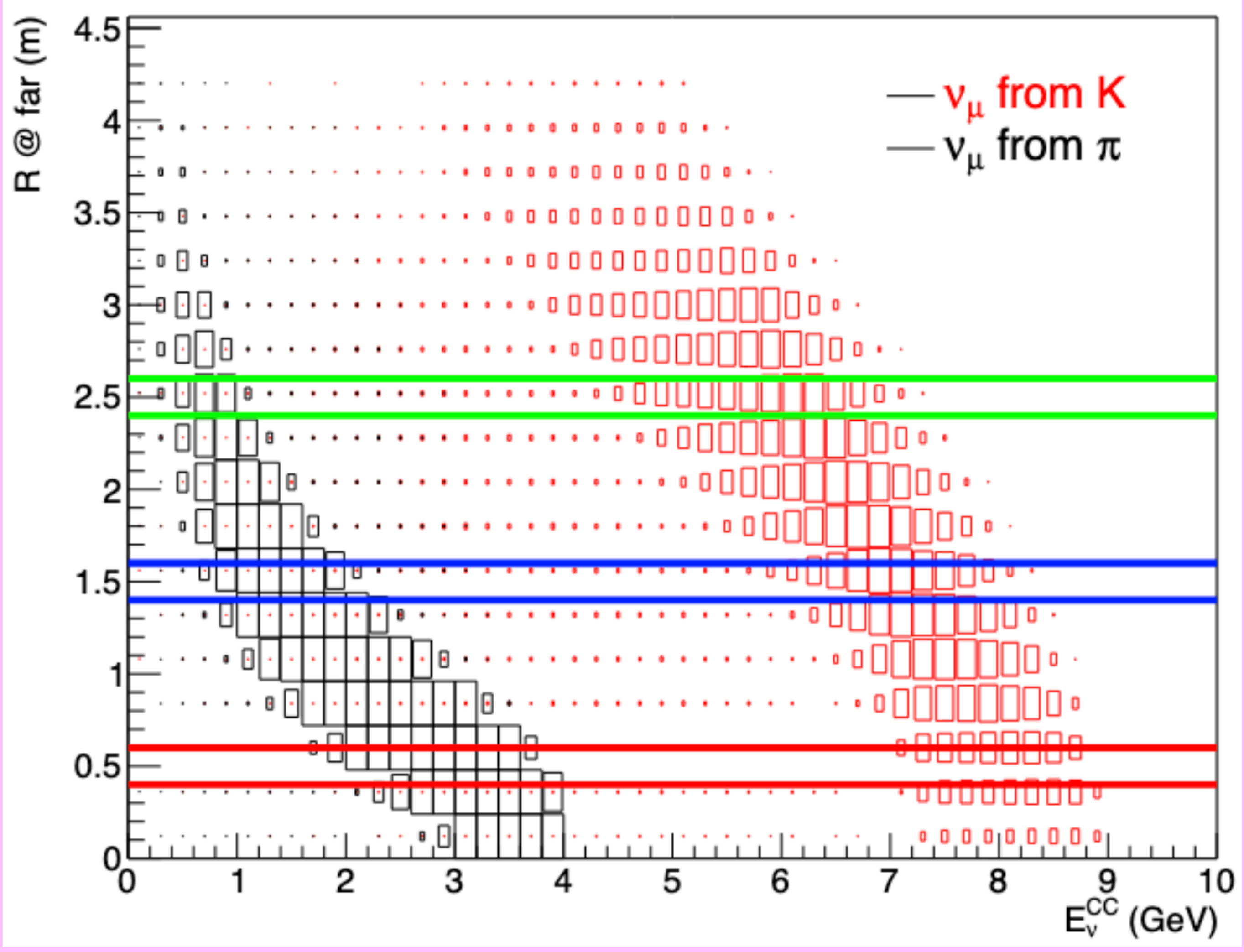
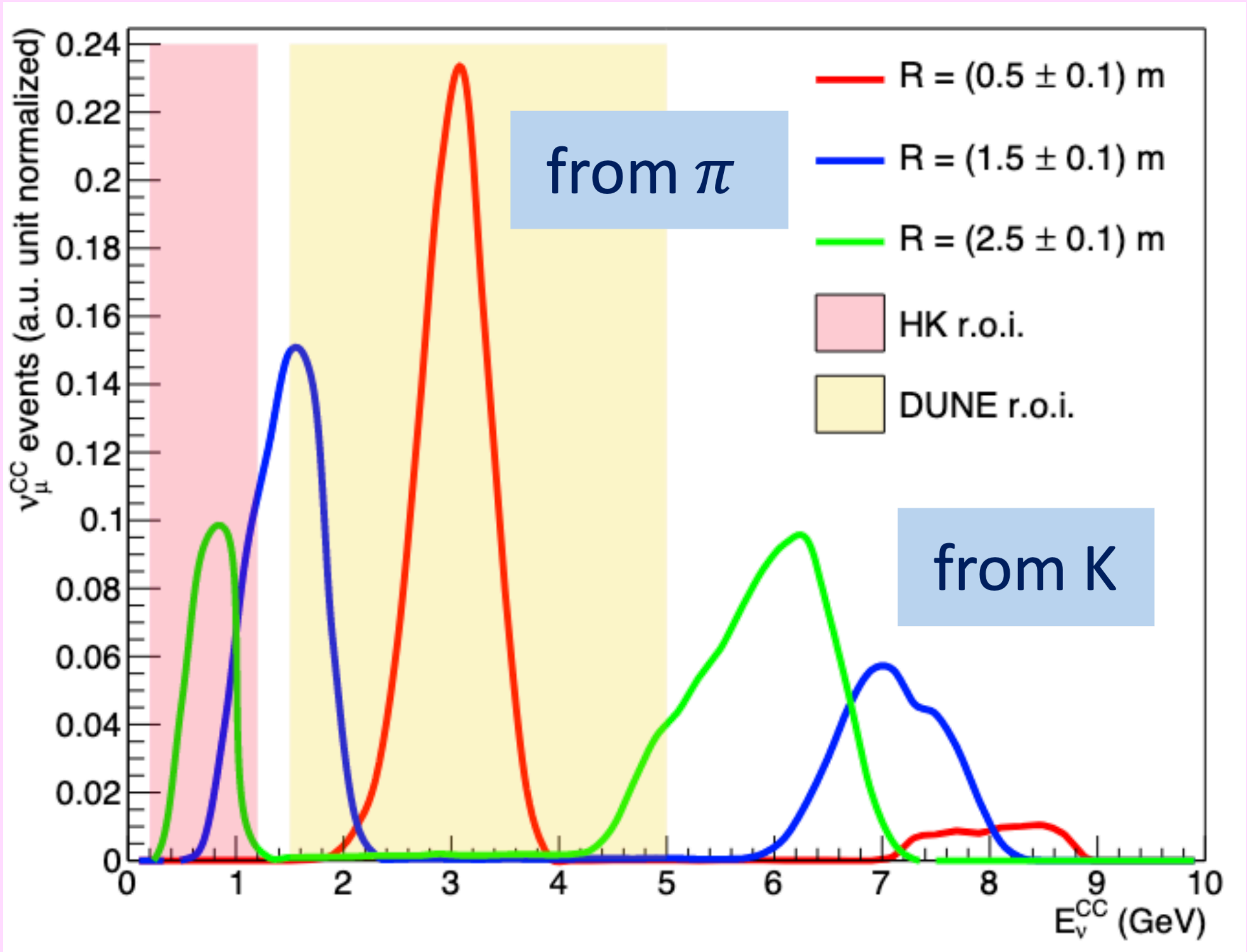
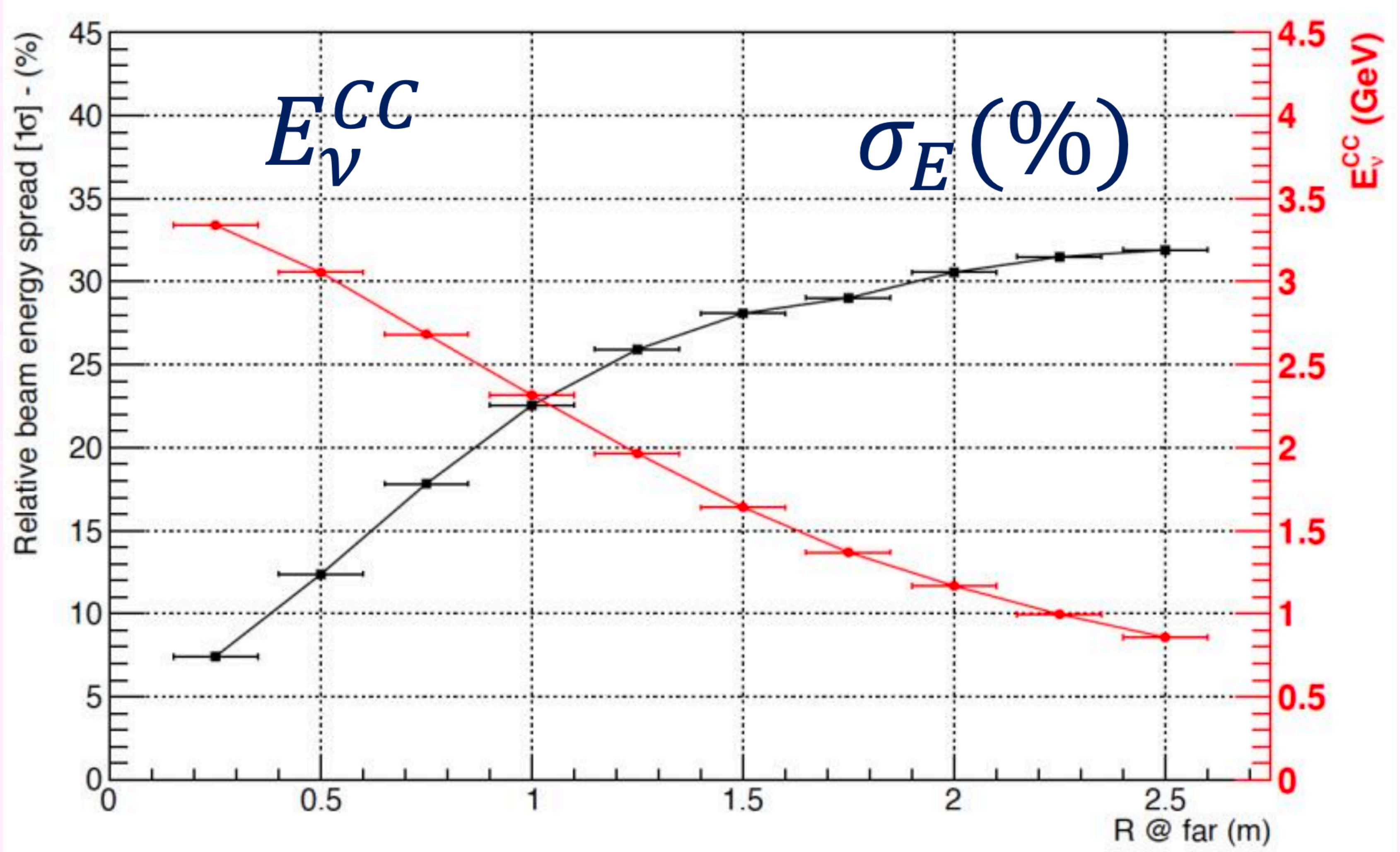
Precise determination of E_ν:

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







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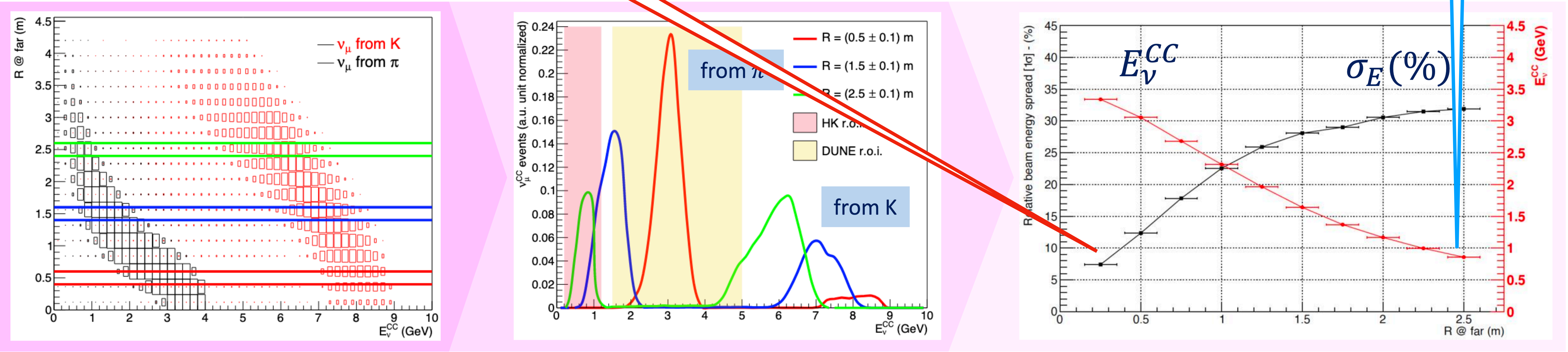
8-25% resolution in DUNE ROI

30% resolution in HK ROI



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

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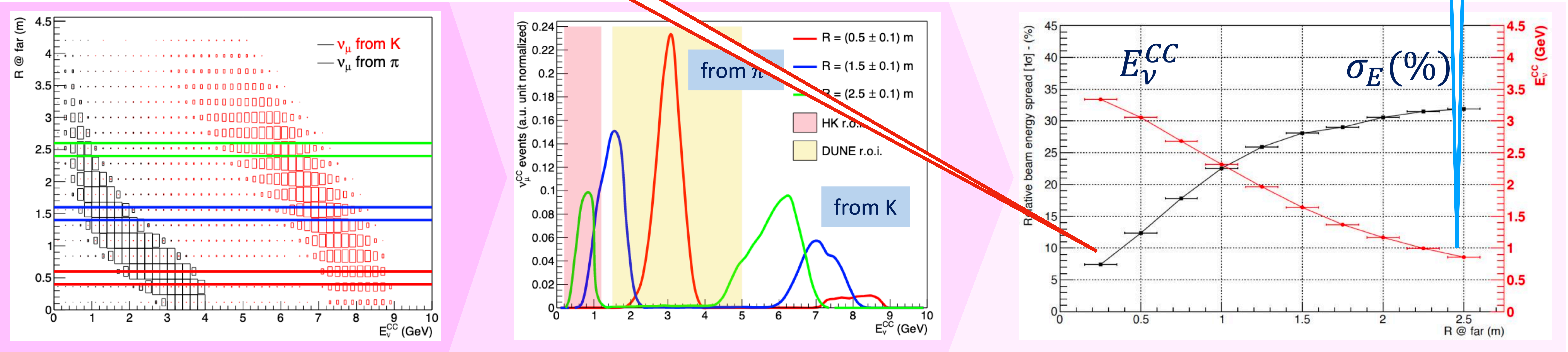
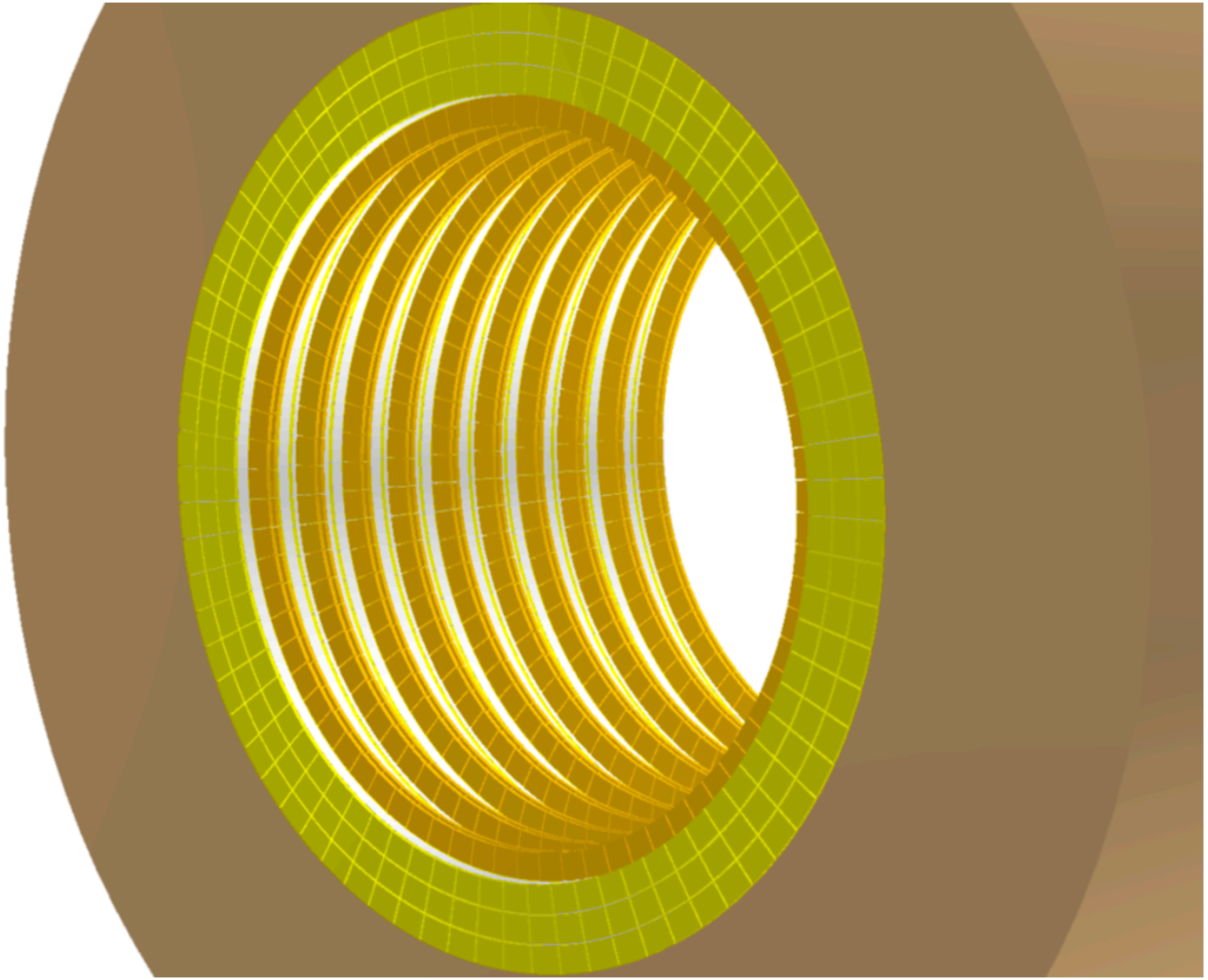


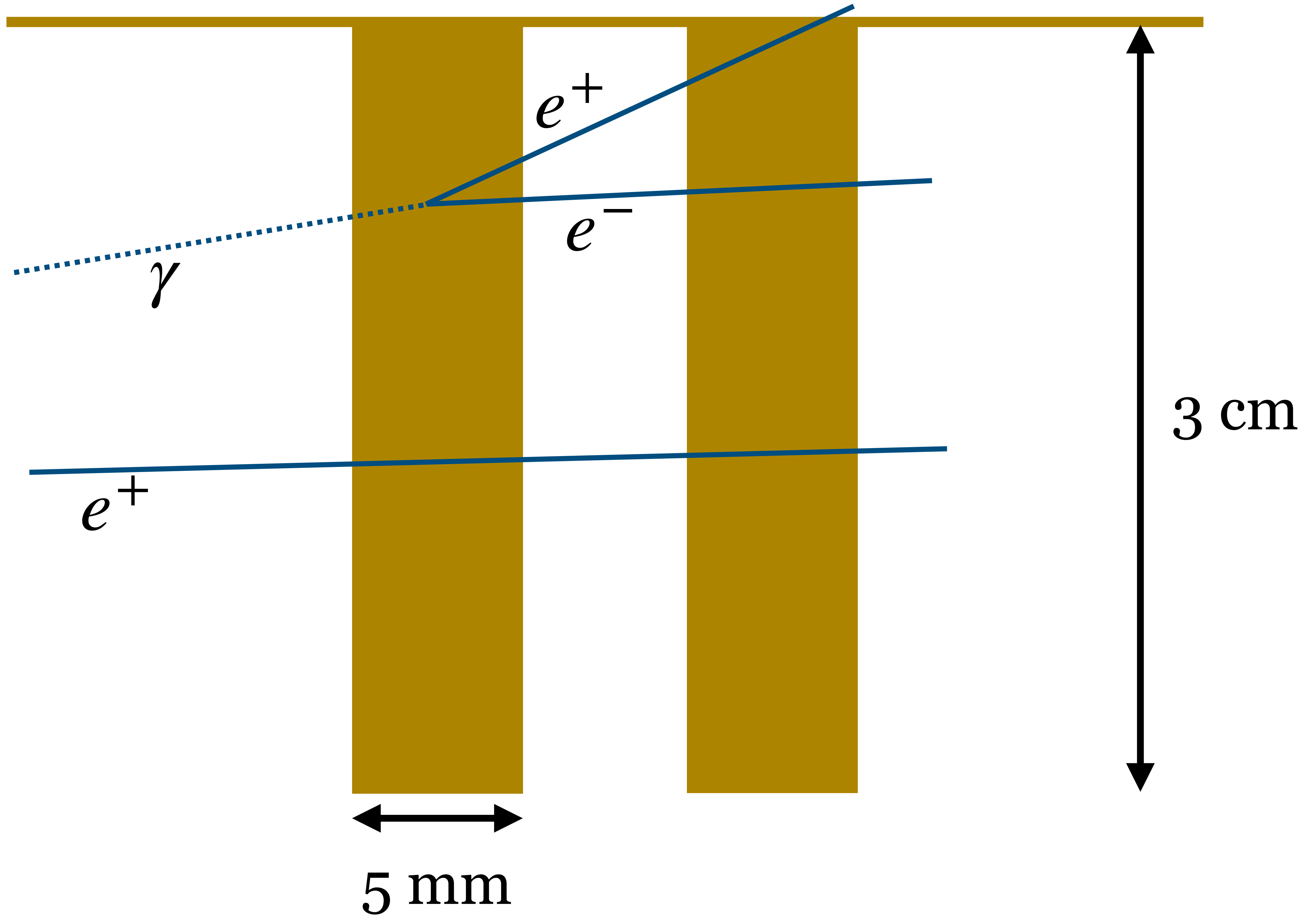
The Tagger

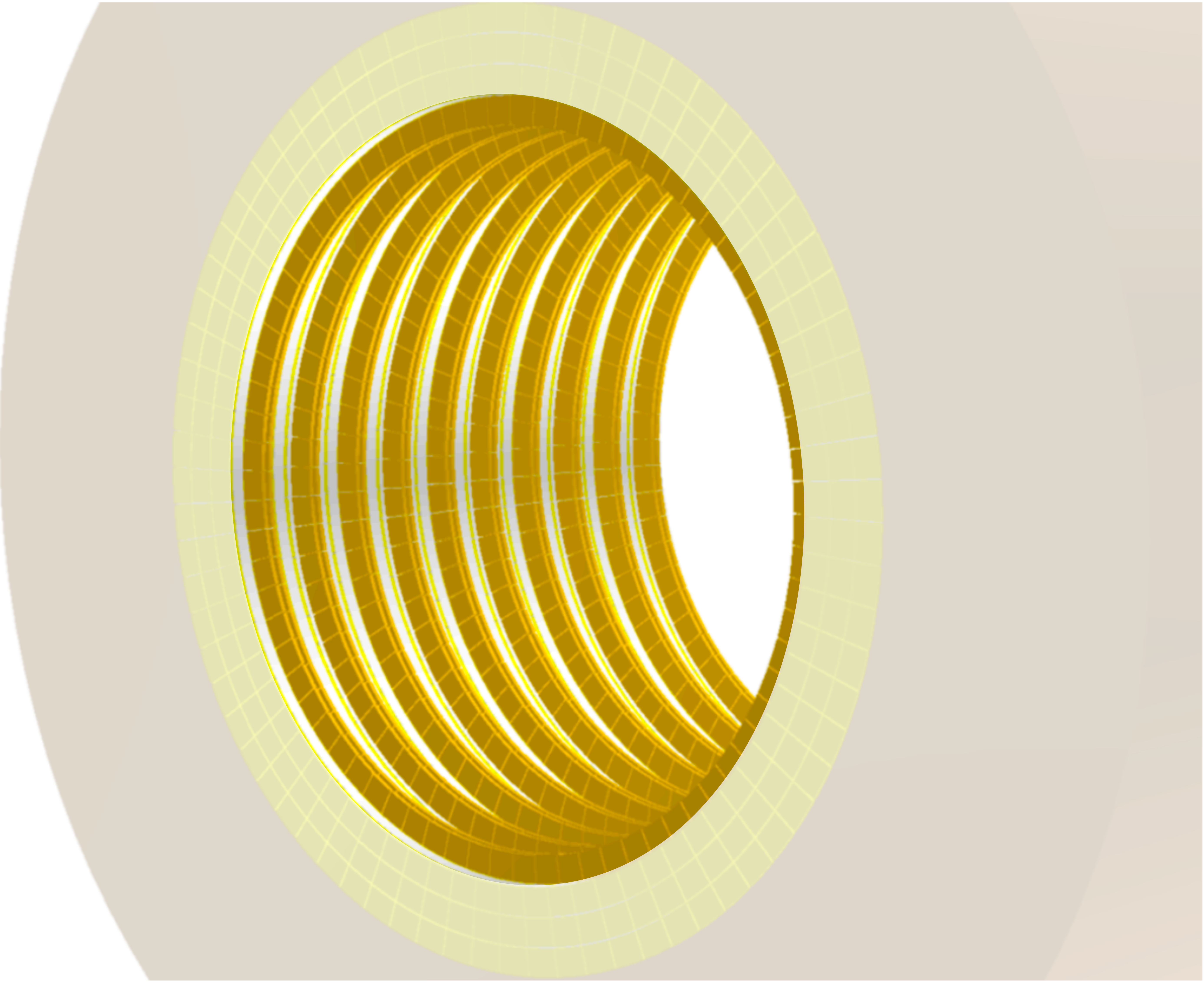


The Tagger

Photon Veto

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





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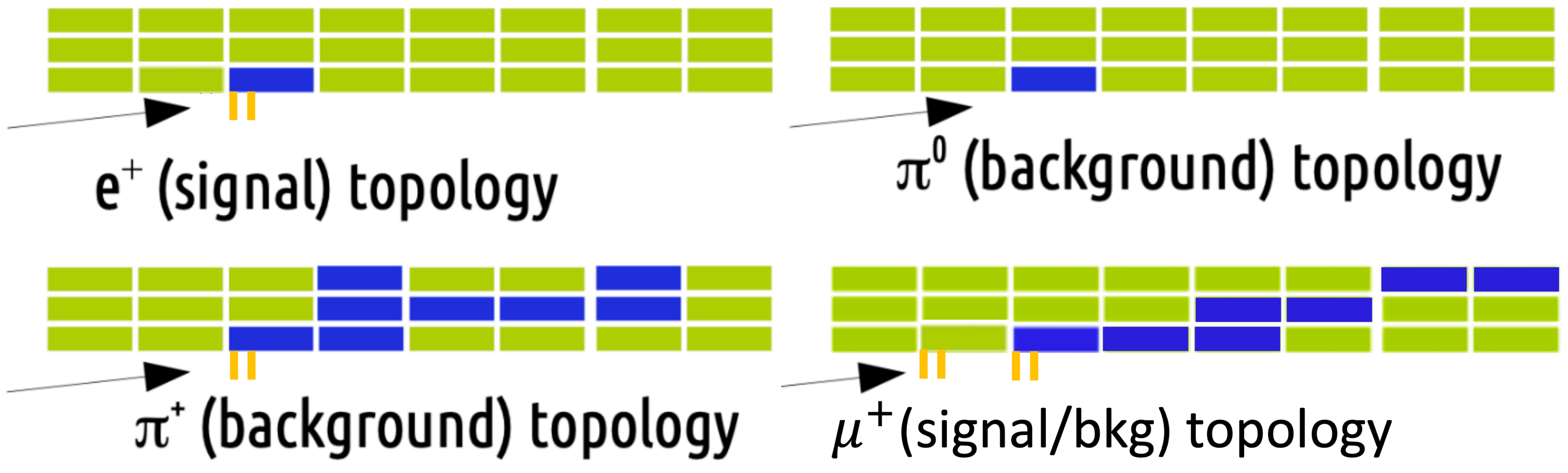
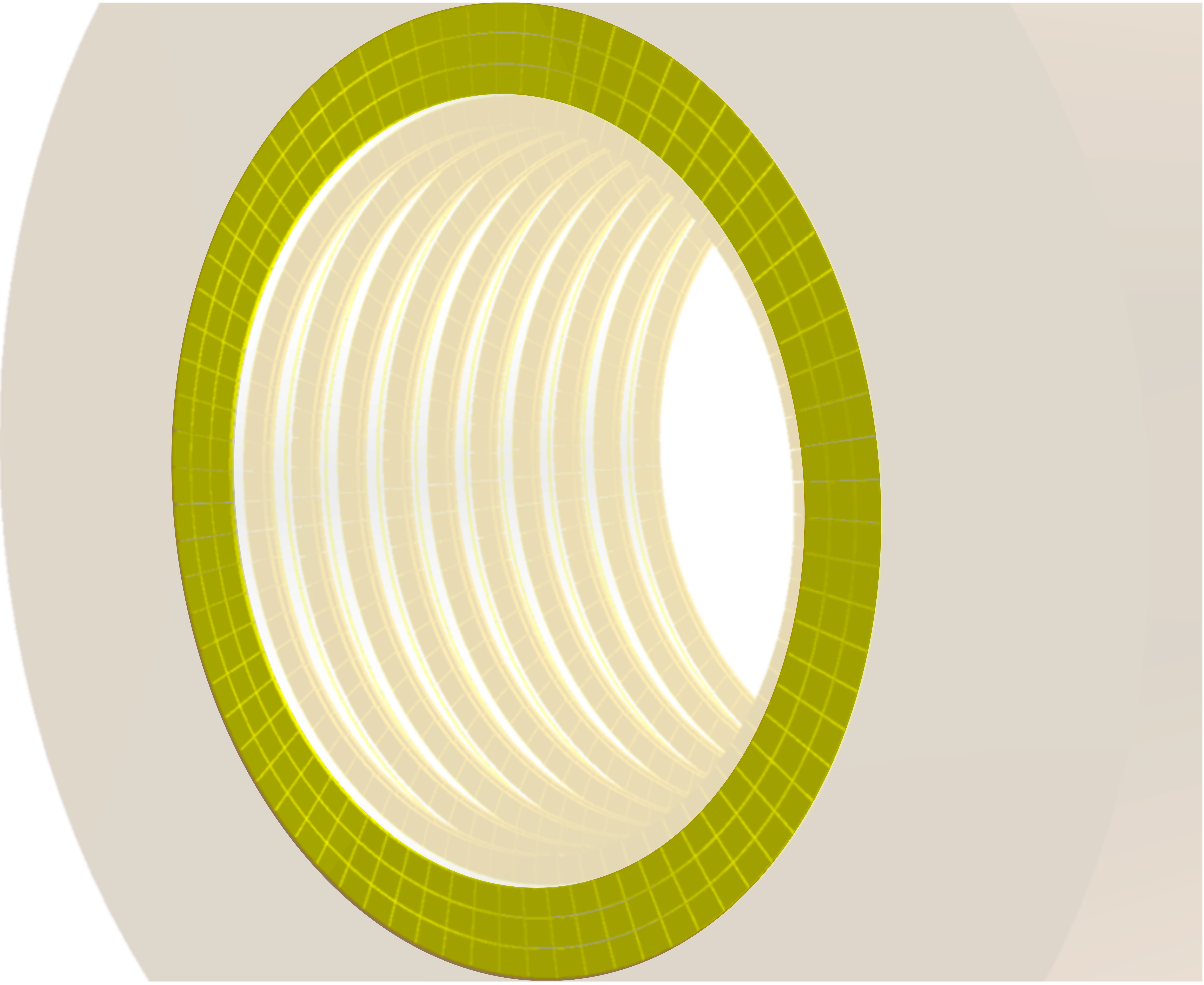
Calorimeter

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





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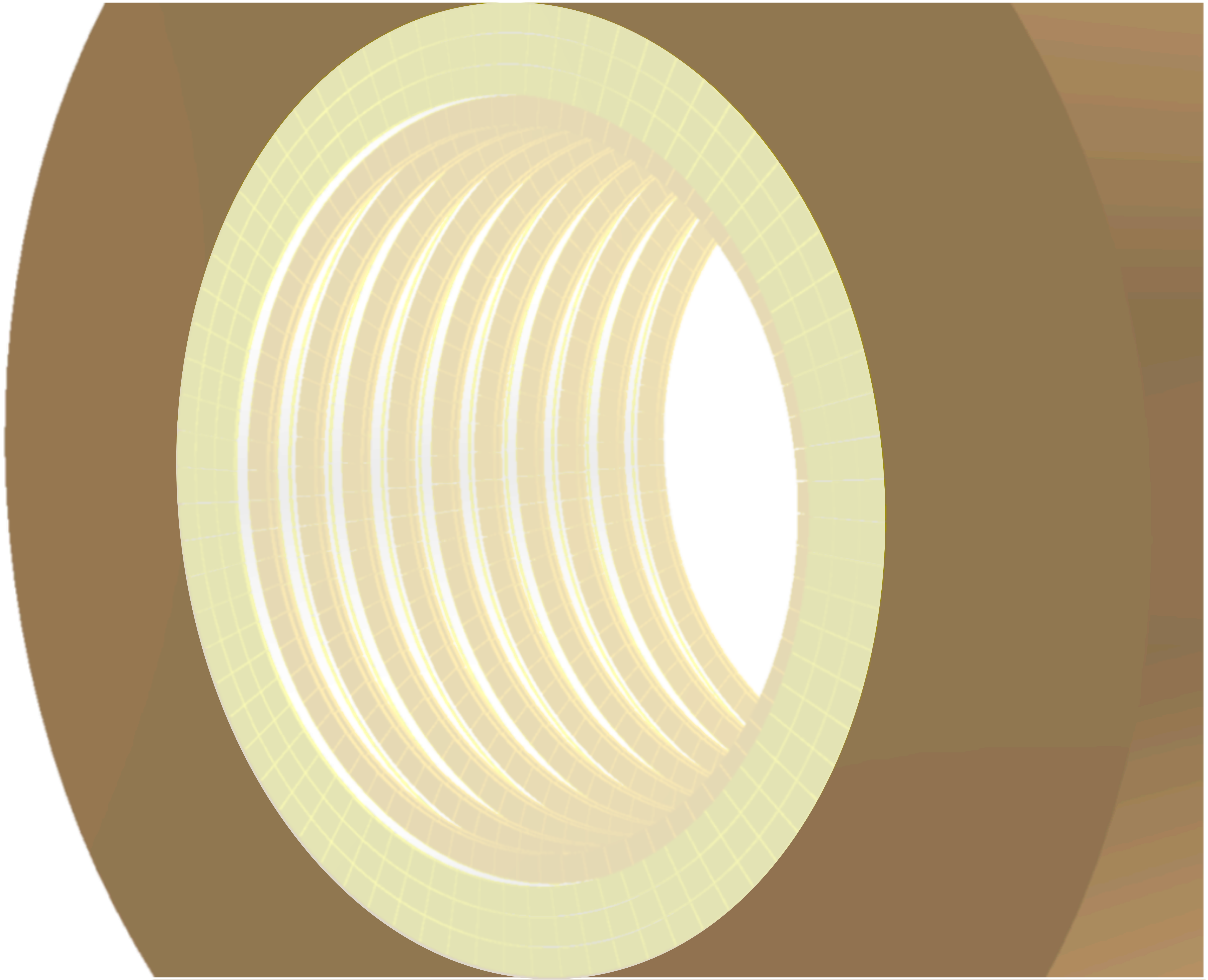
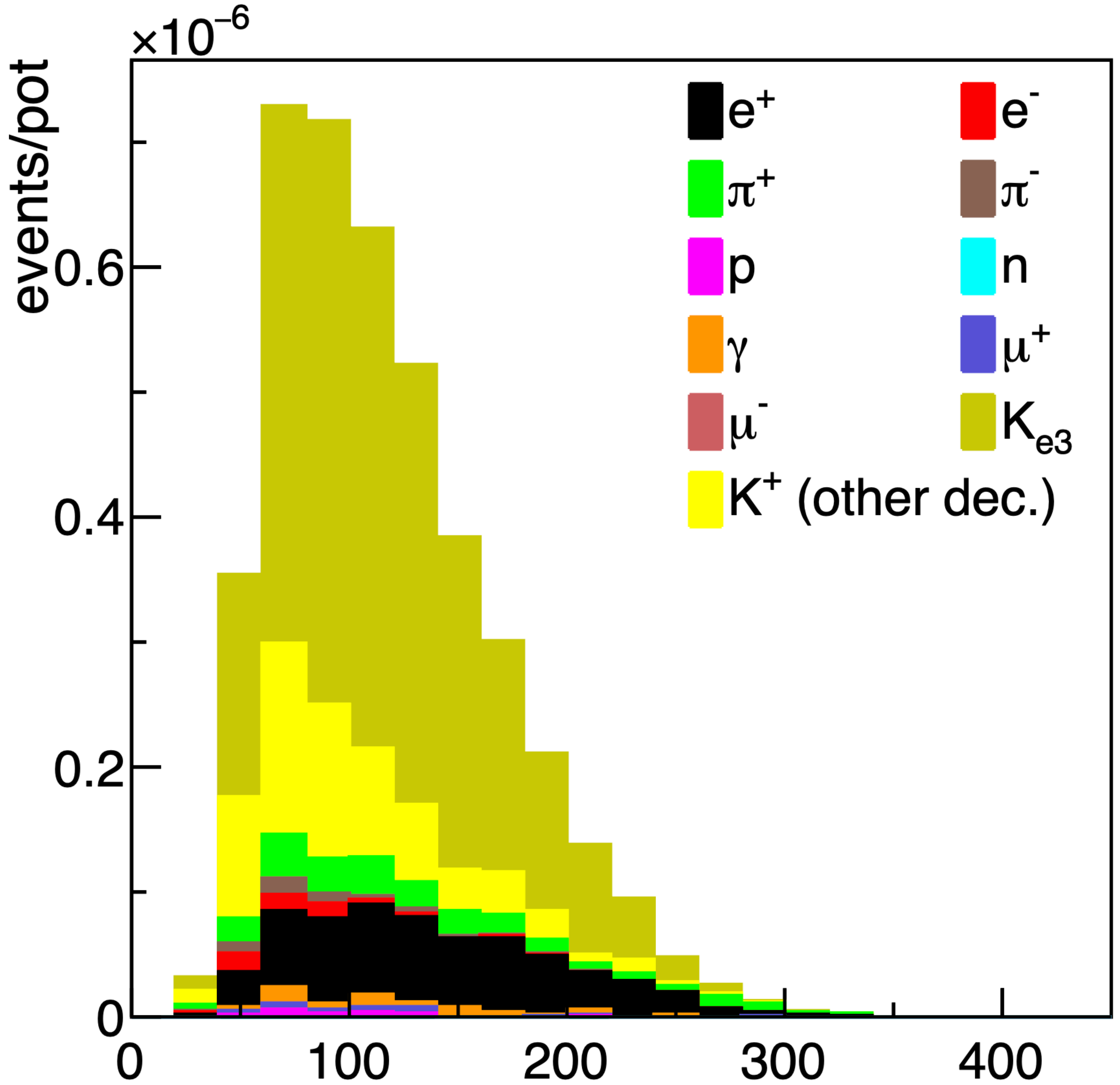
Shielding

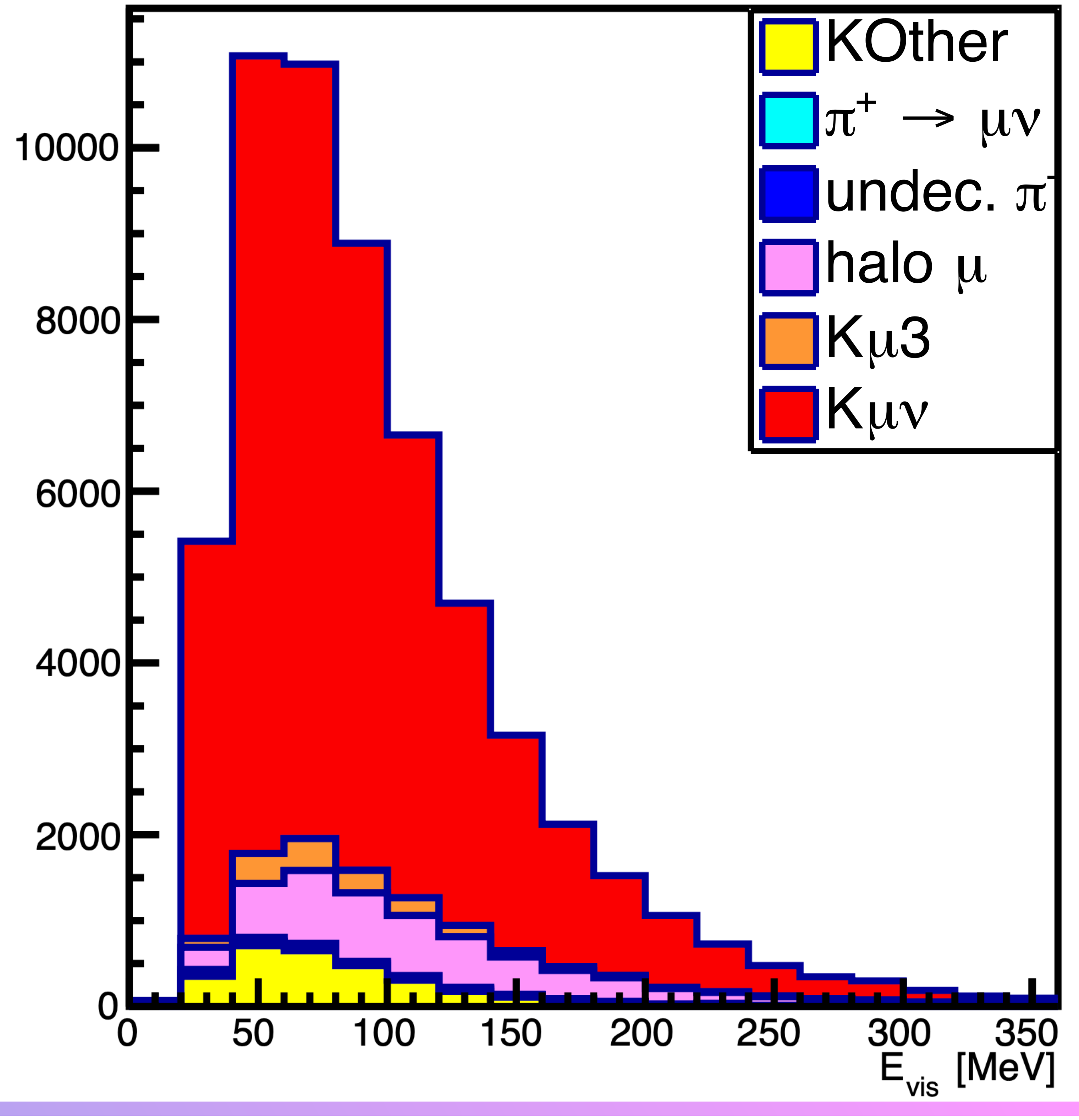
- 30 cm borated polyethylene
- SiPMs placed outside to reduce neutron flux (factor of 18)



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.*





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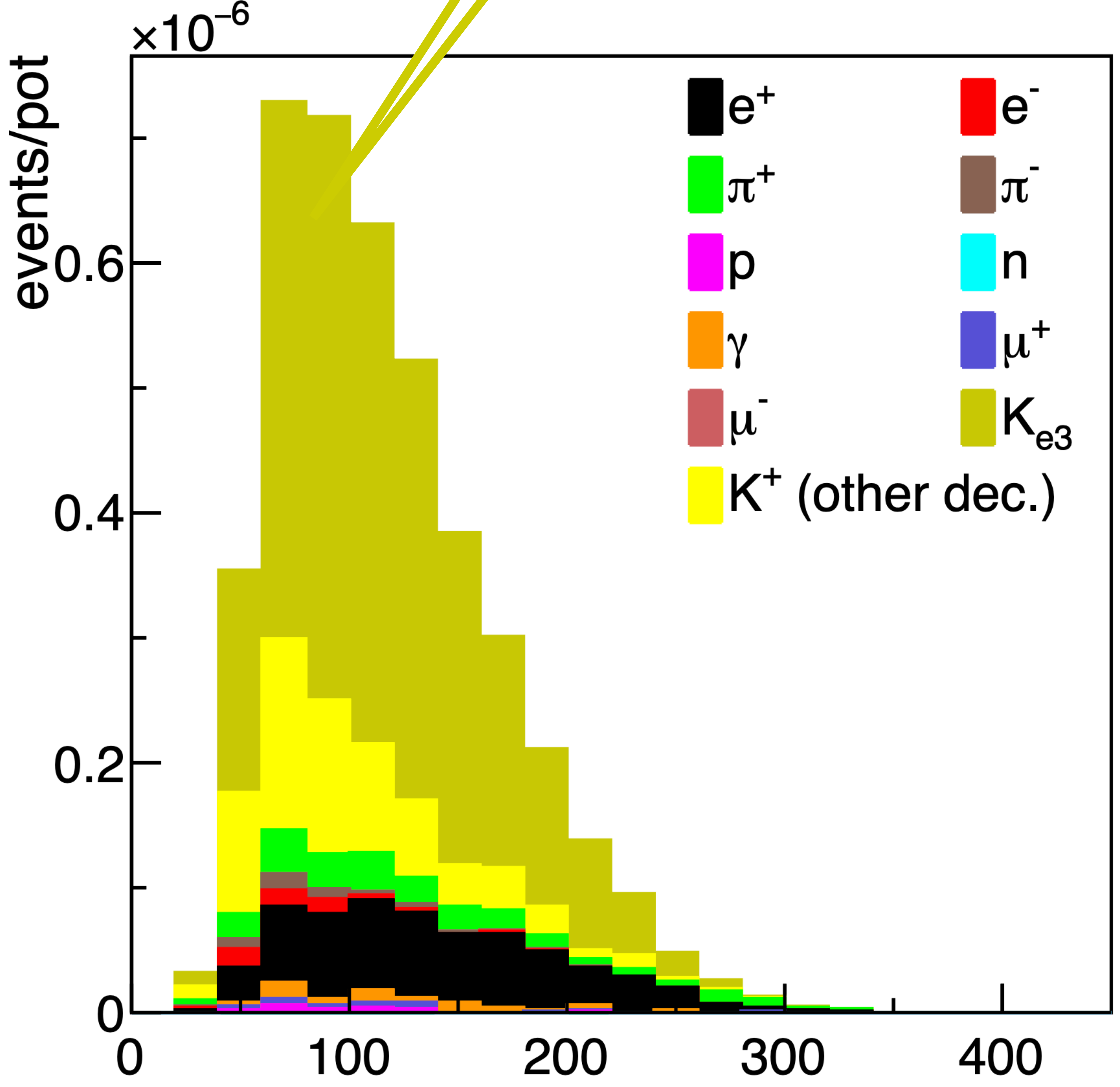
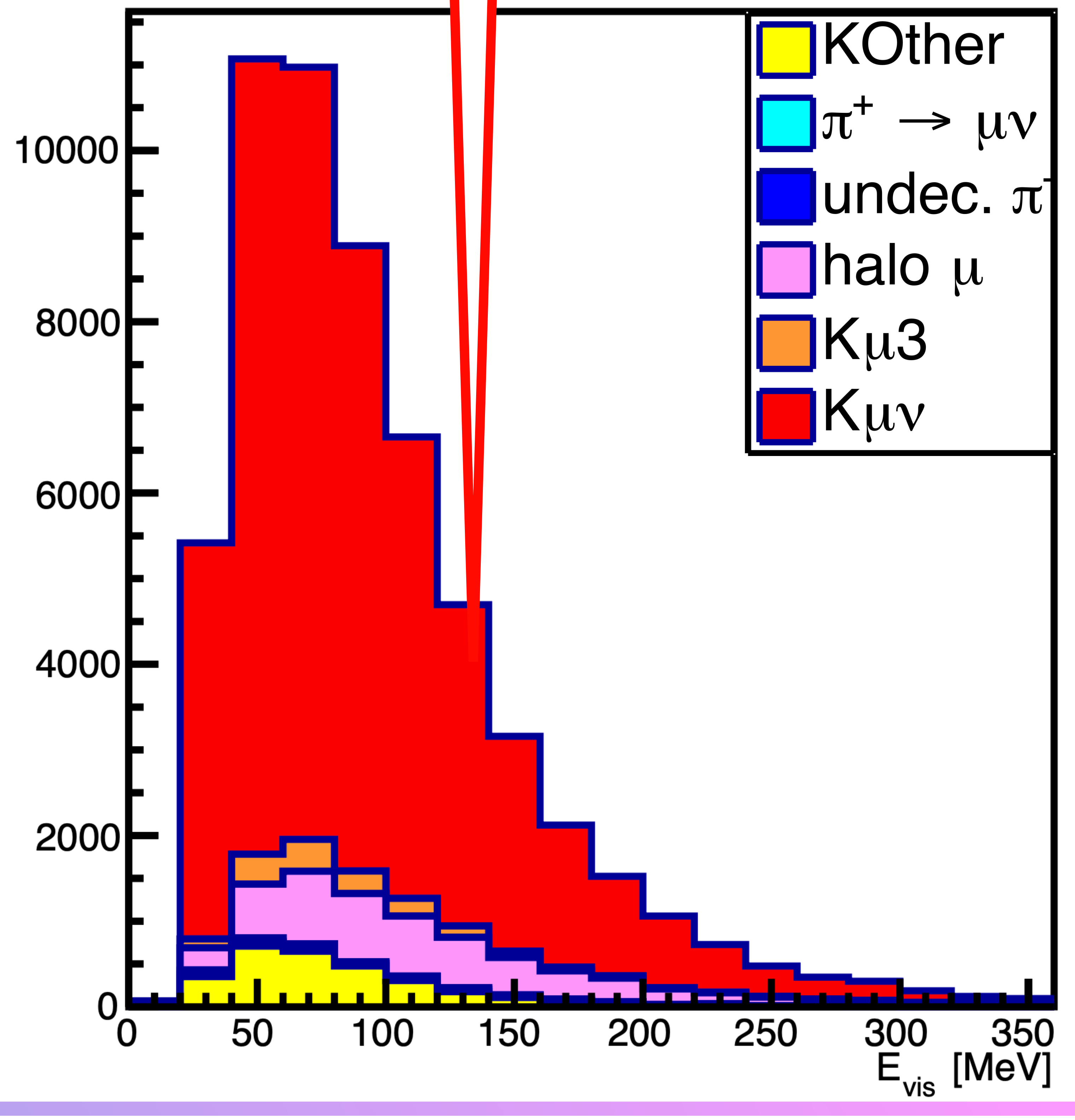
K_{e3} positrons: ν_e
S/N = 2
Eff = 22%



$K_{\mu 2}$ muons: ν_μ
S/N = 6
Eff = 34%



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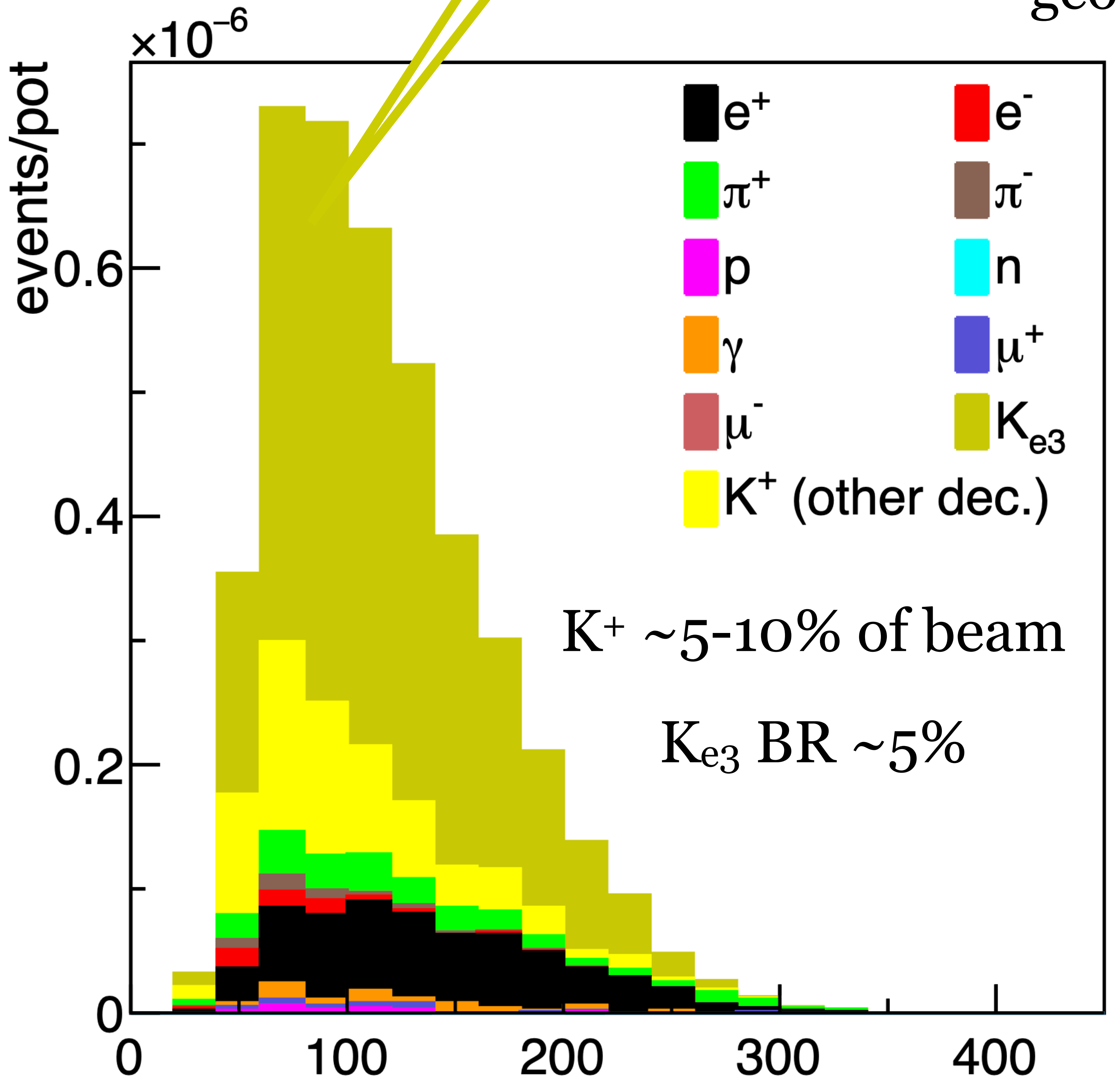
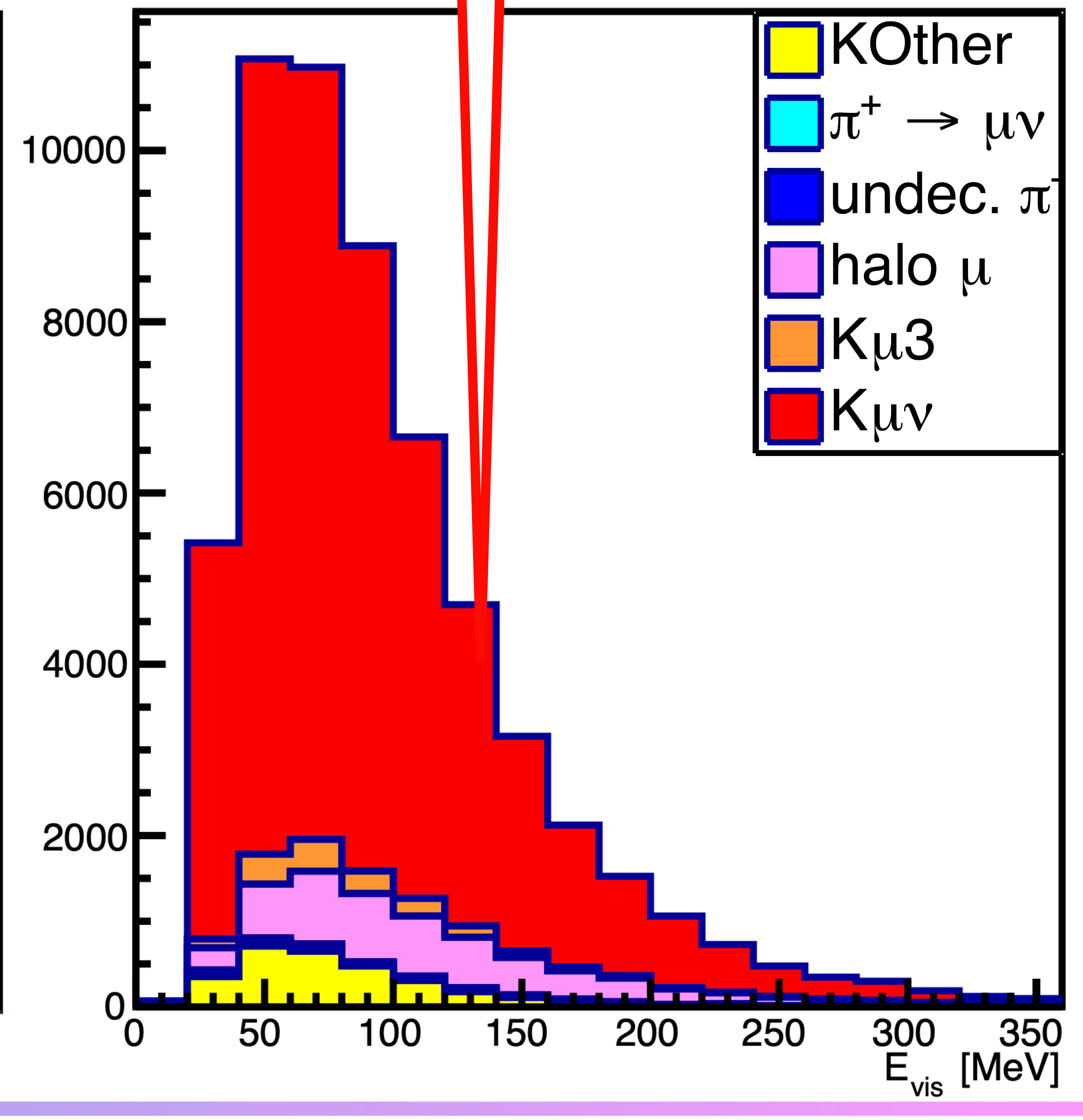
Efficiency is half geometrical



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/cm^2), radiation hardness (~10^{12} $MeV\text{-}n_{eq}/cm^2$)

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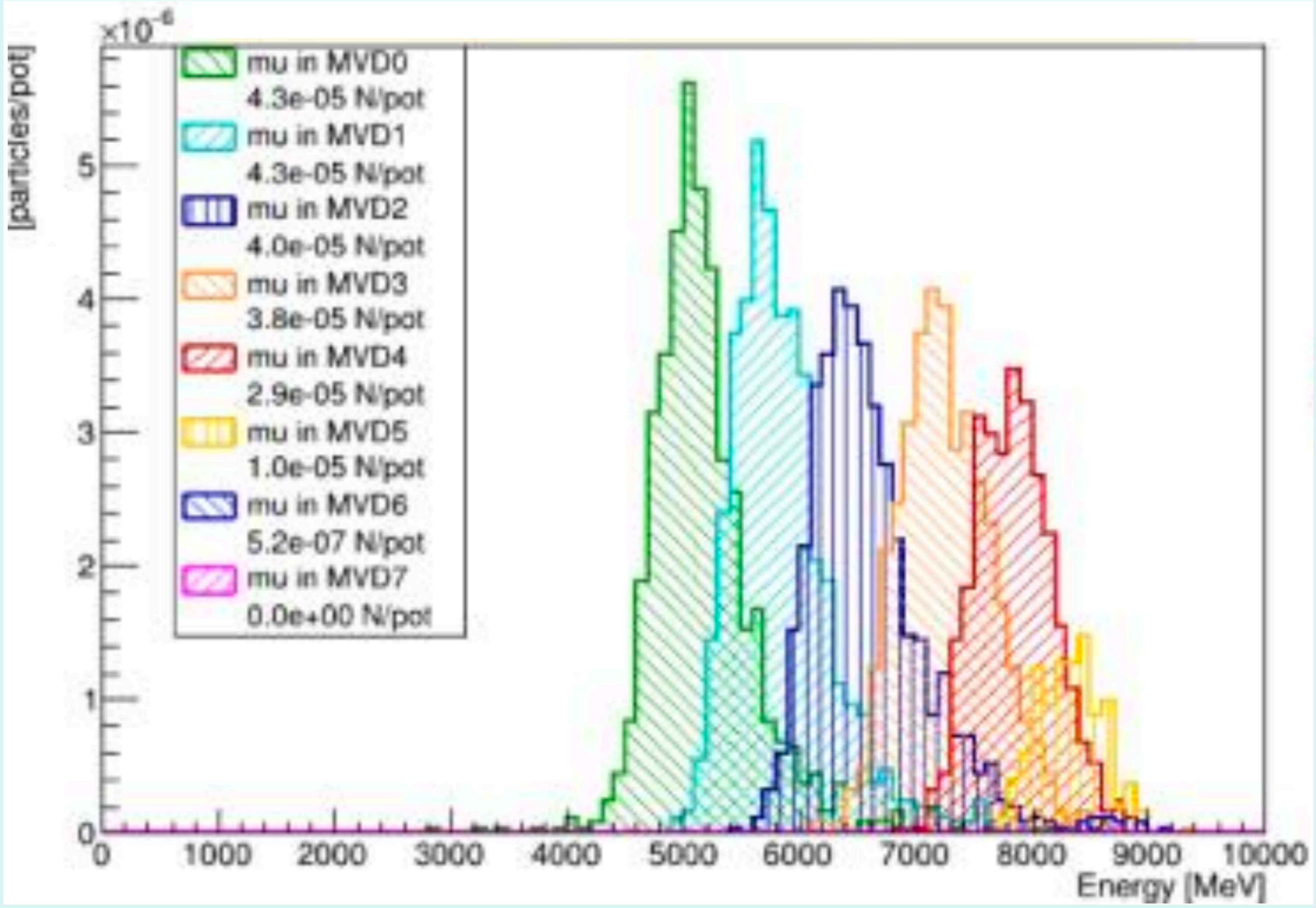
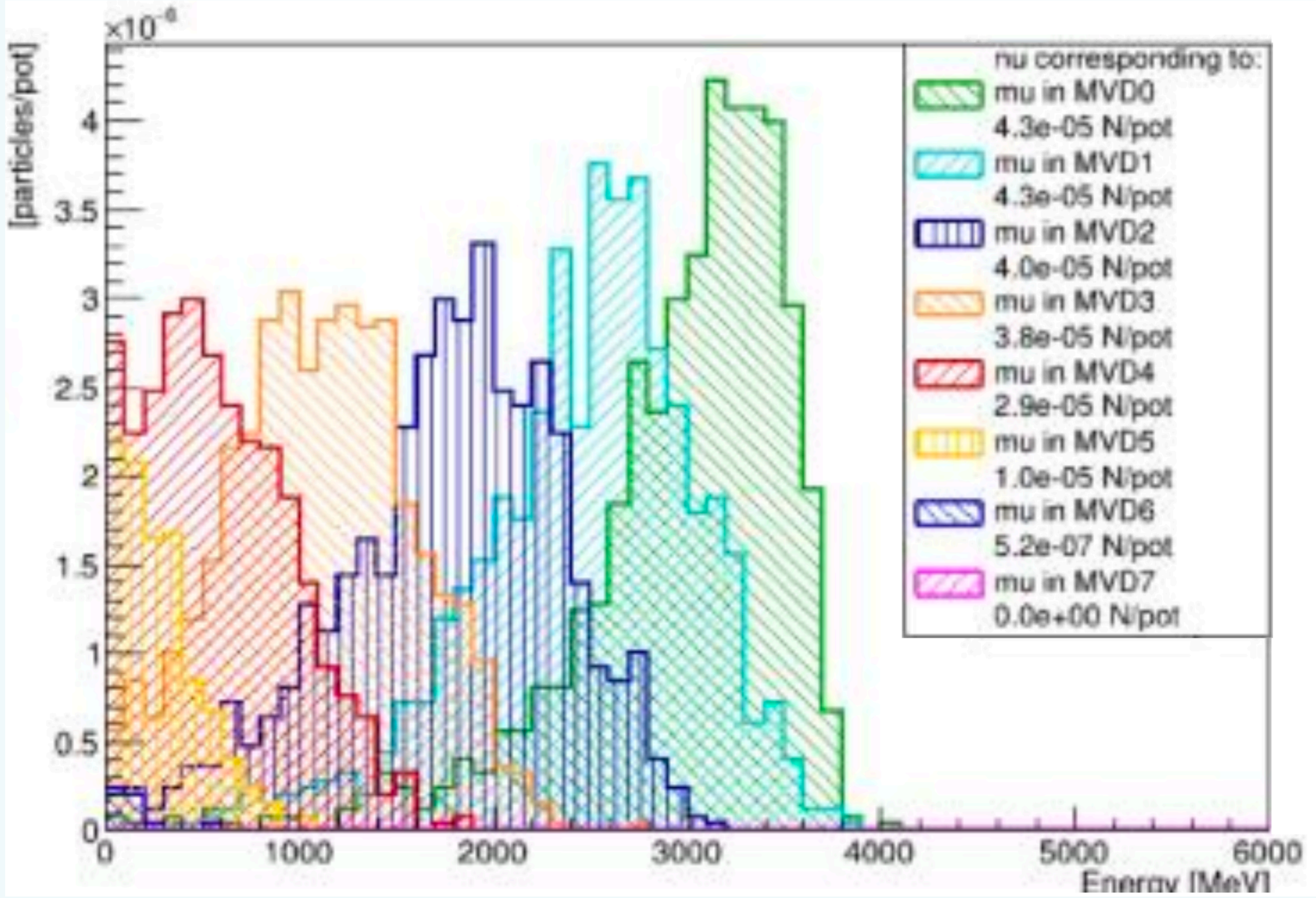
Correlation between traversed stations and neutrino energy can be exploited.

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





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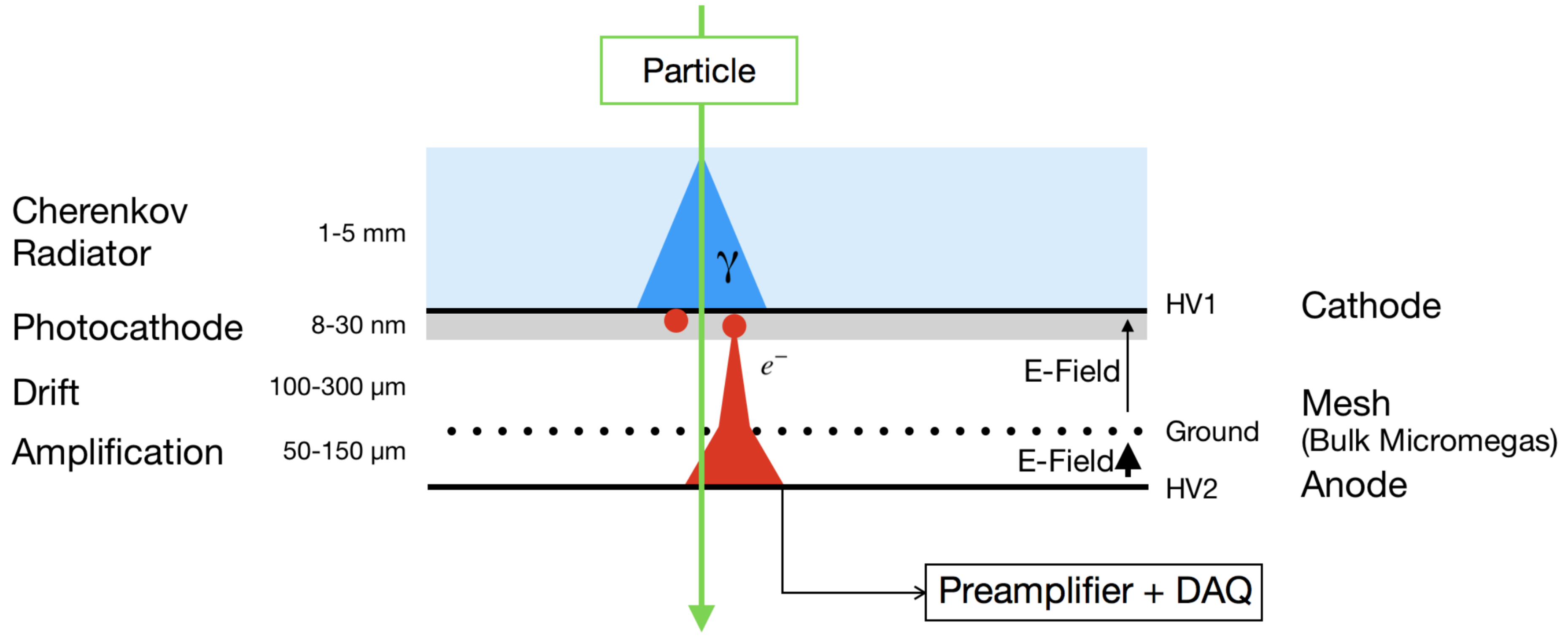
PIMENT

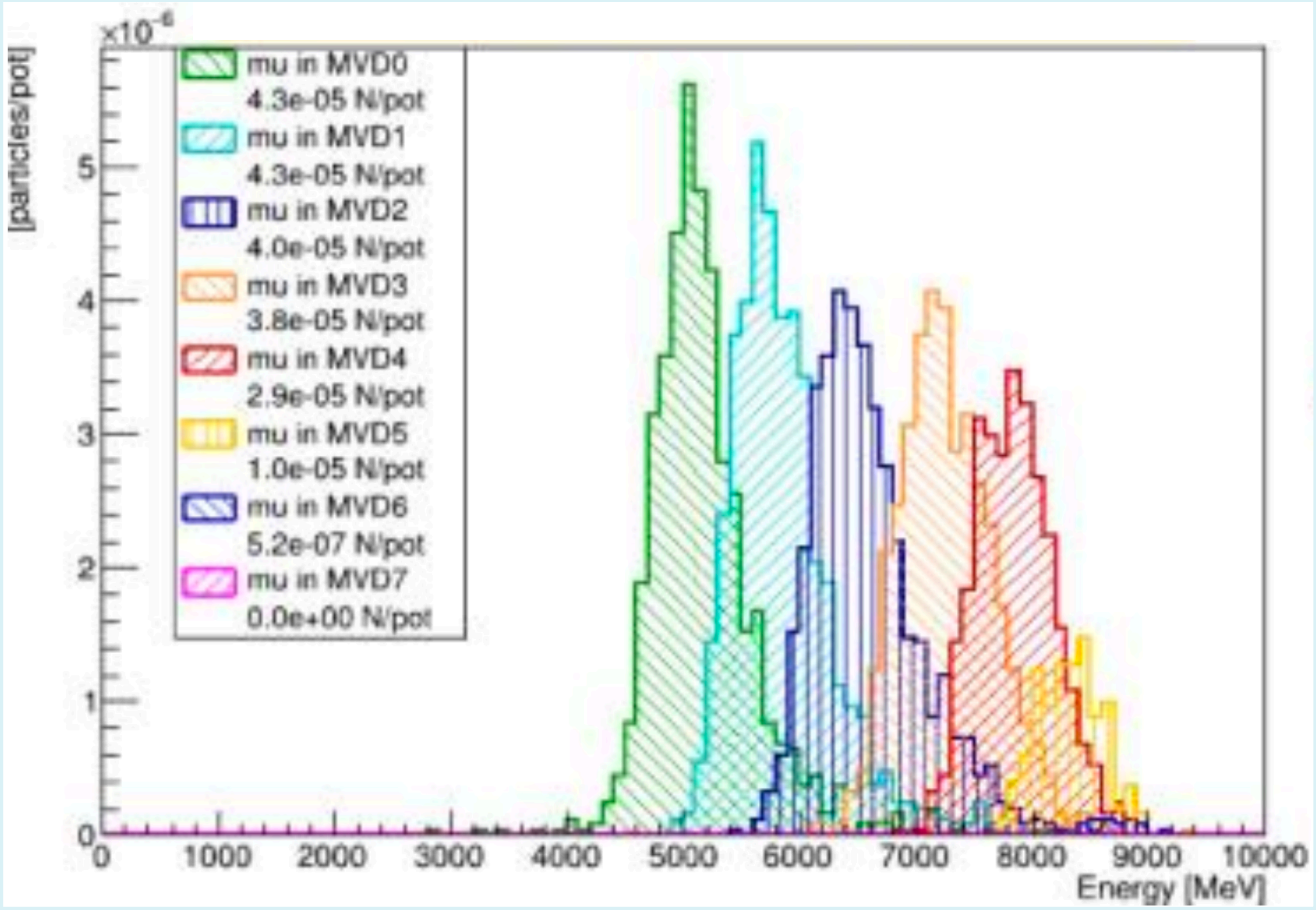
PICOSEC Micromegas Detector for ENUBET

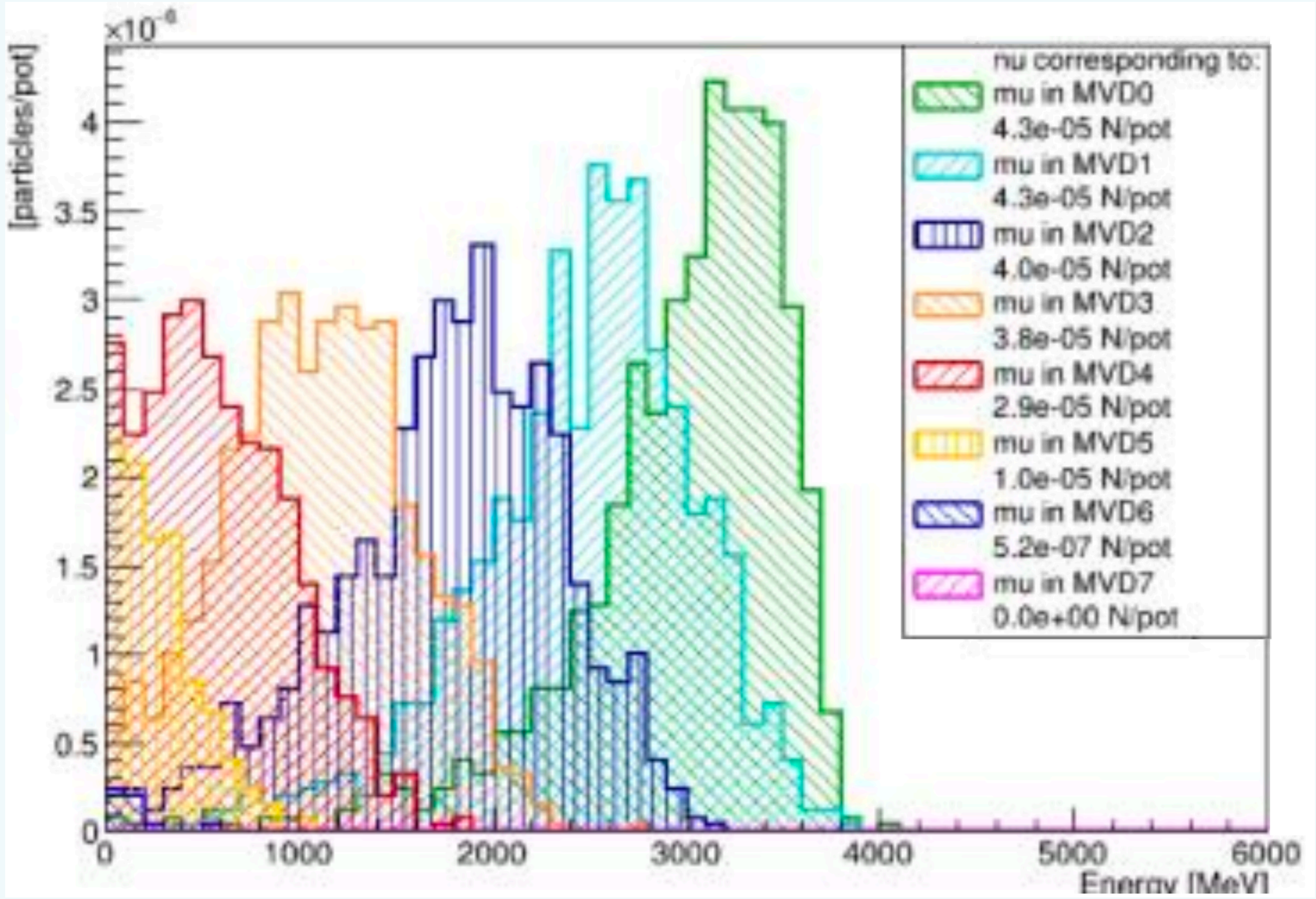
Fast micromega detector with sub-25 ps precision.



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%

*Hadro-production data from NA56/SPY experiment

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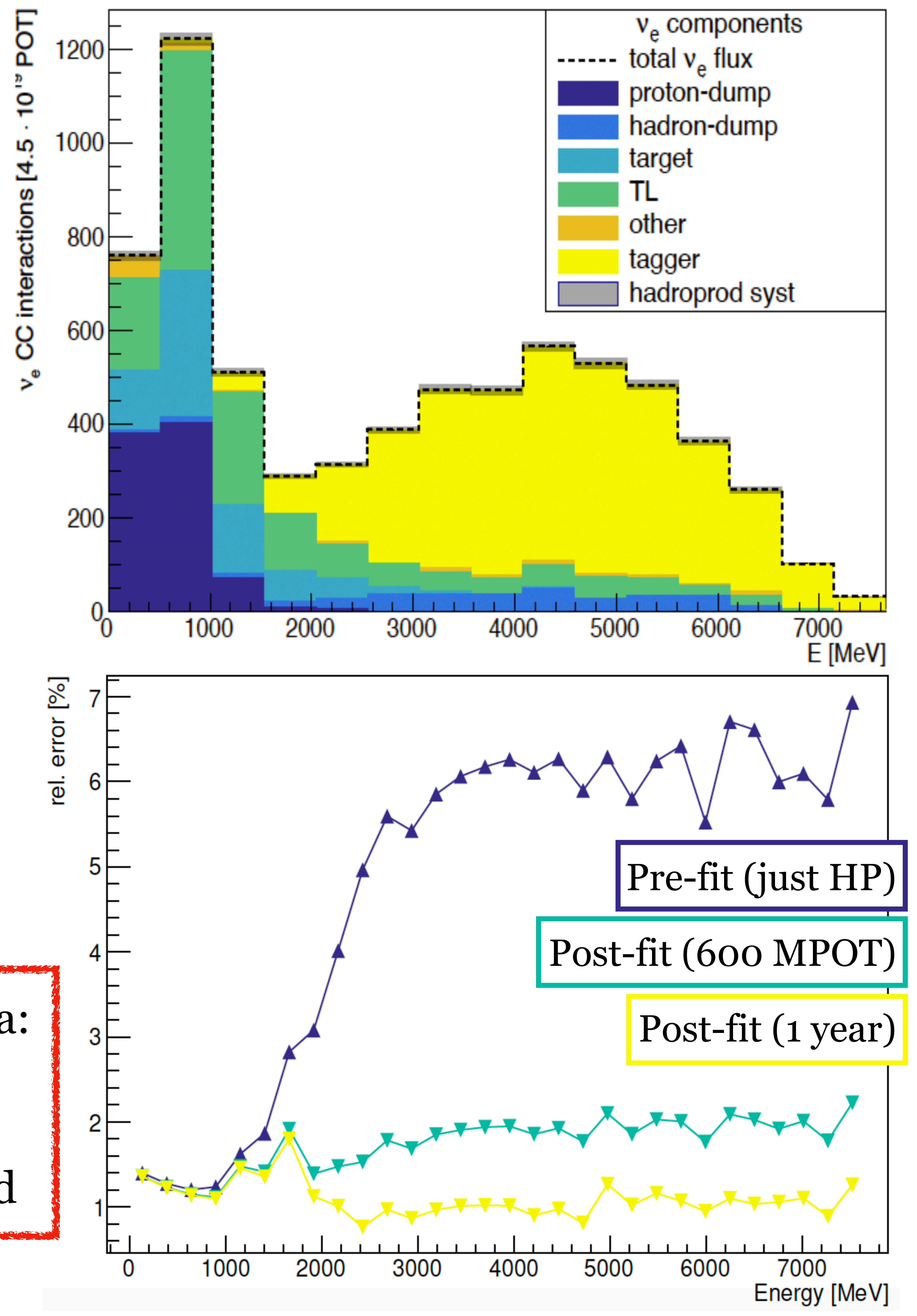

Total rates calculated for 1 year of data:

- SPS @ CERN, 4.5×10^{19} POT

- 500 t detector, 50 m from tunnel end

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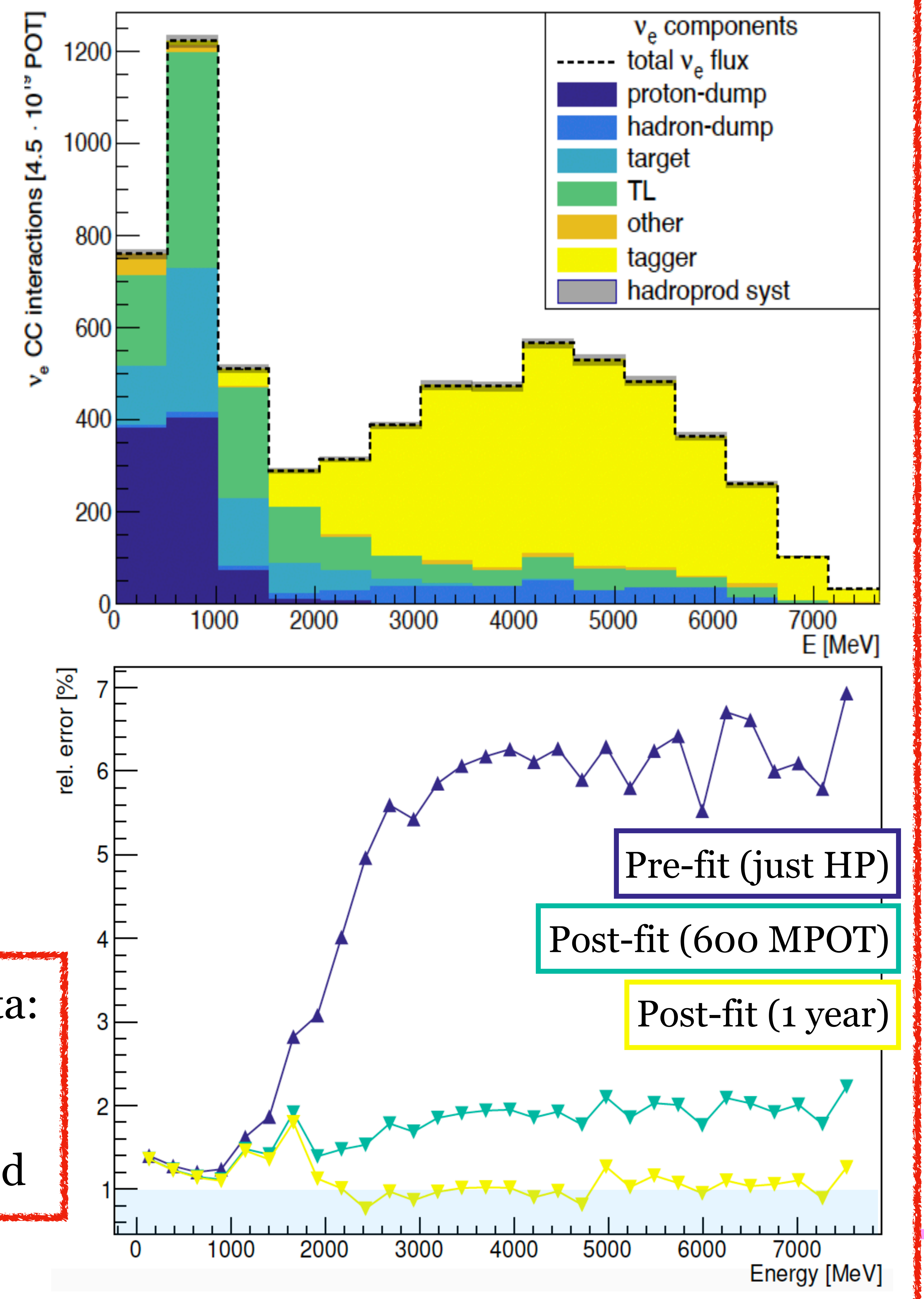

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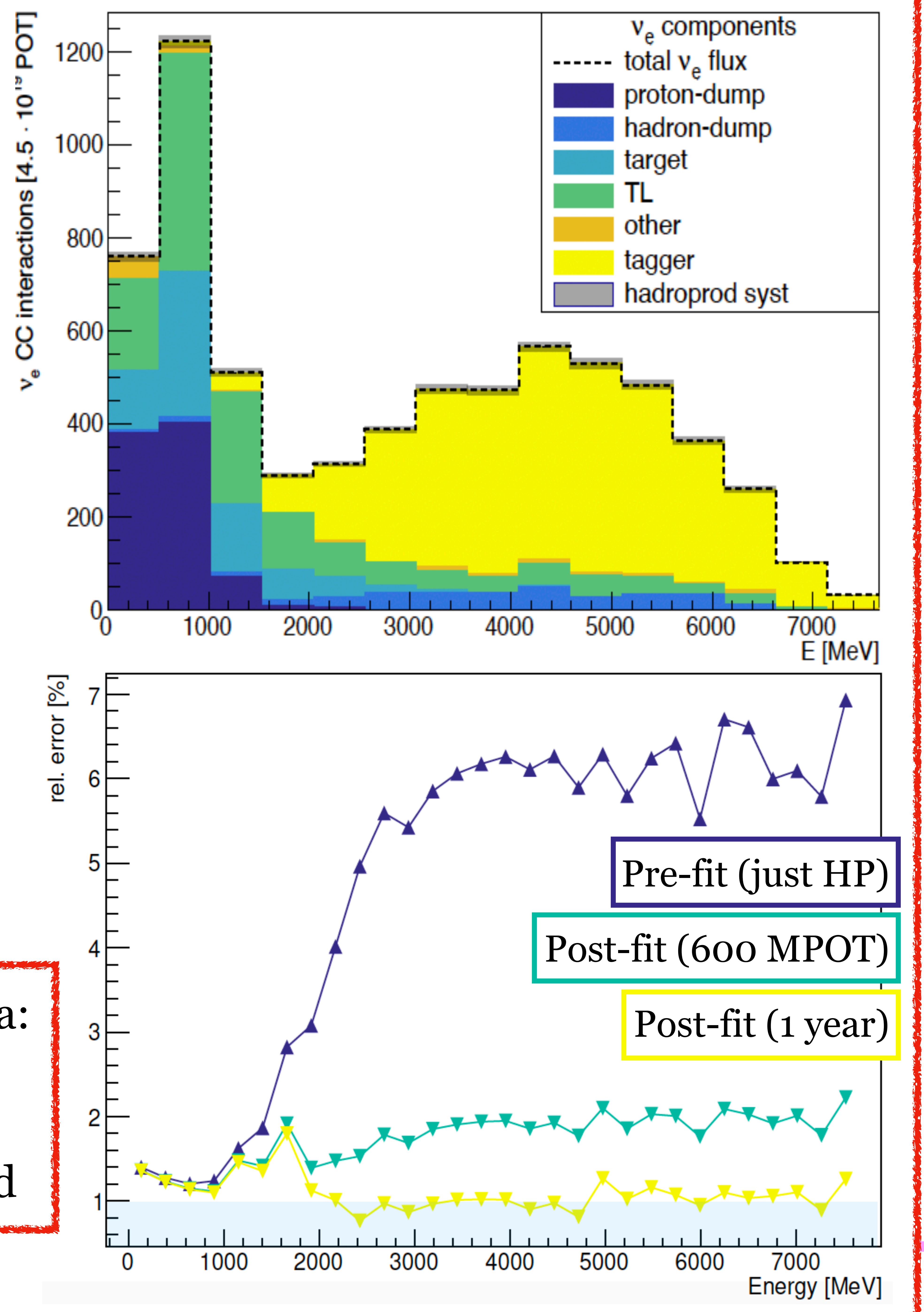

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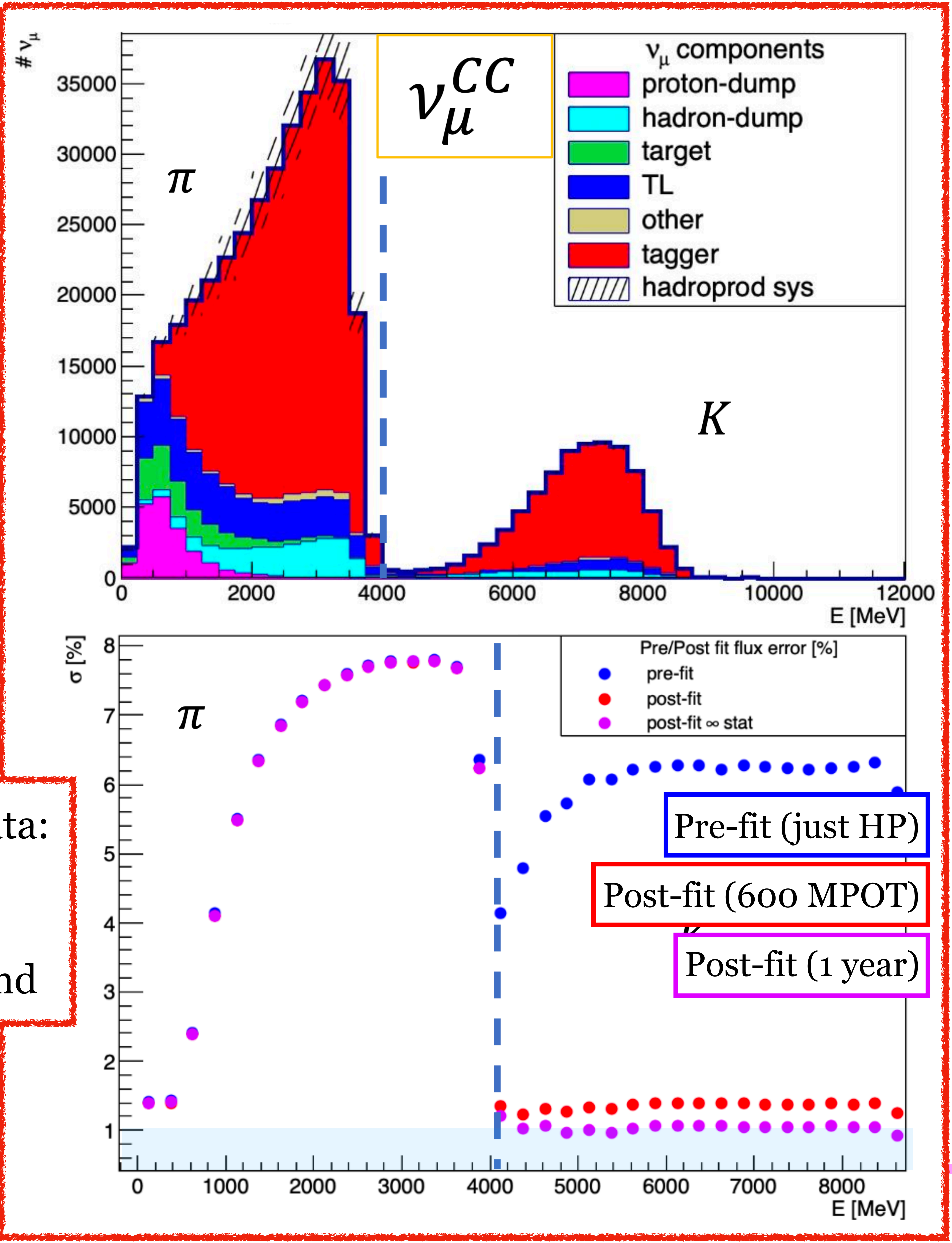
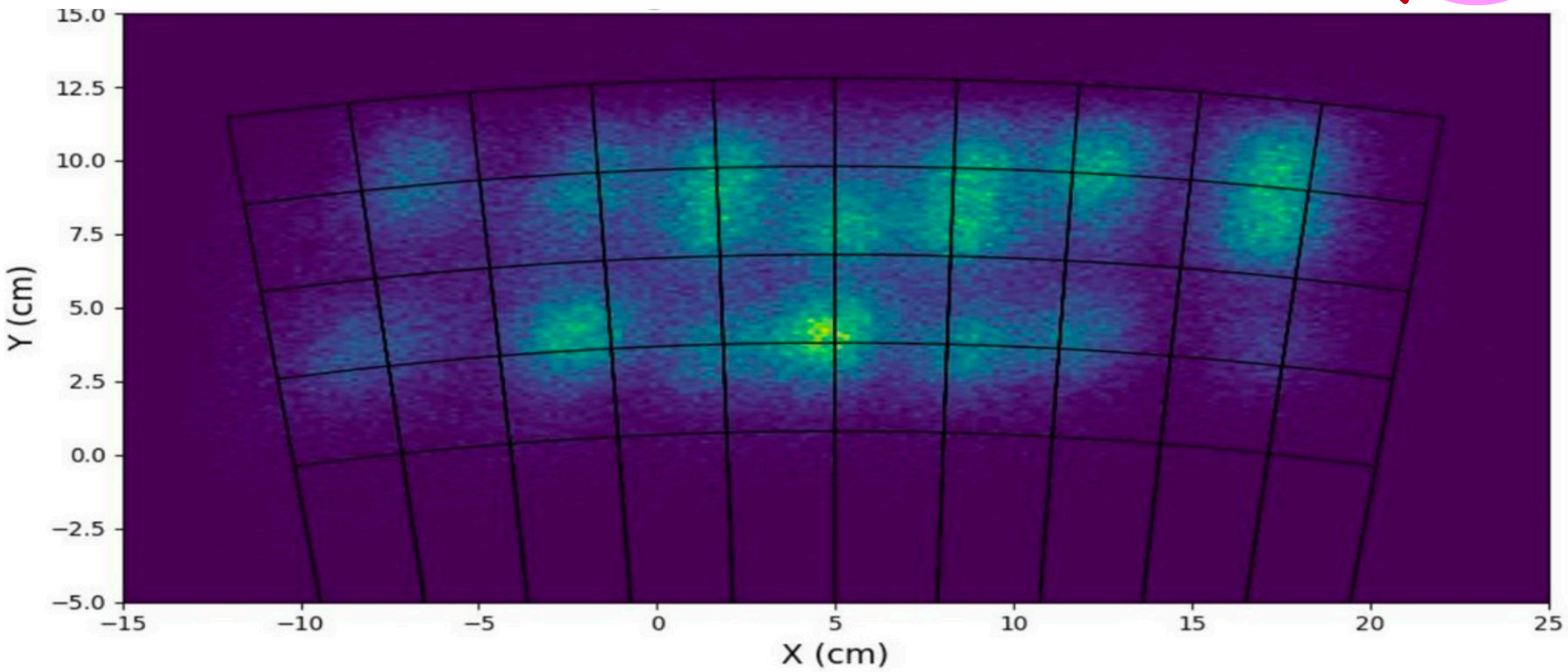
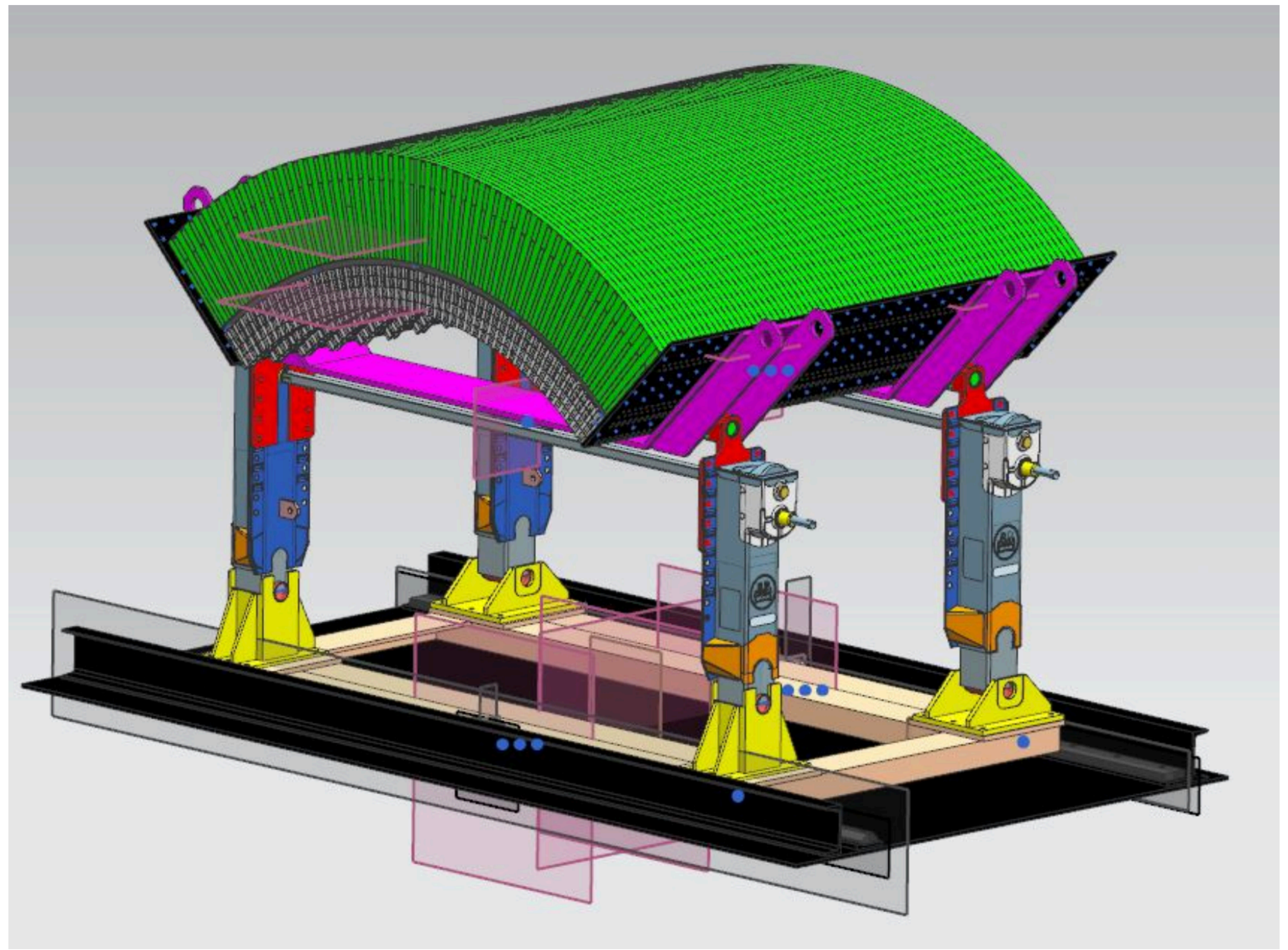


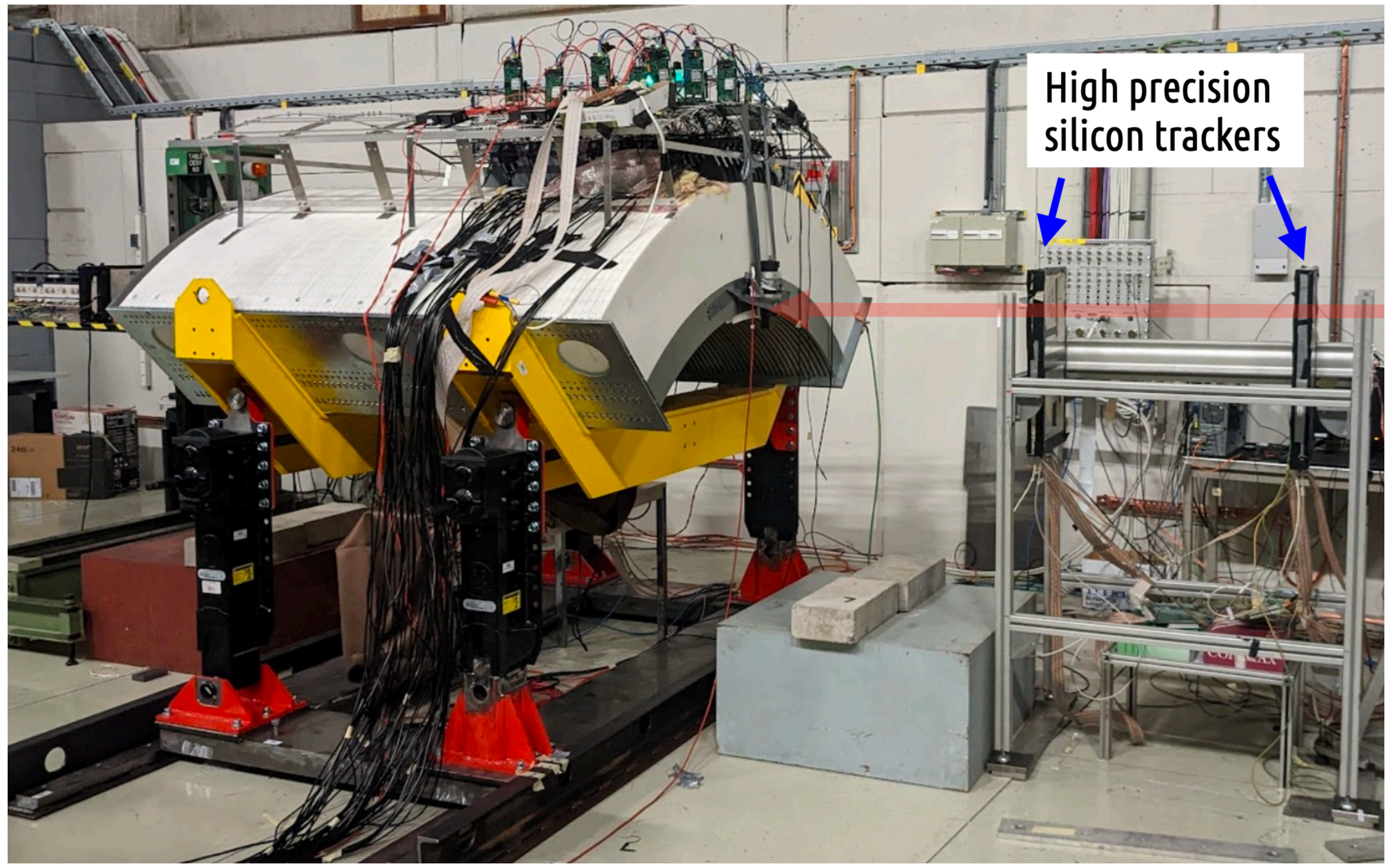
*Ha[illegible]o-pro[illegible] from NA56/SPY experiment

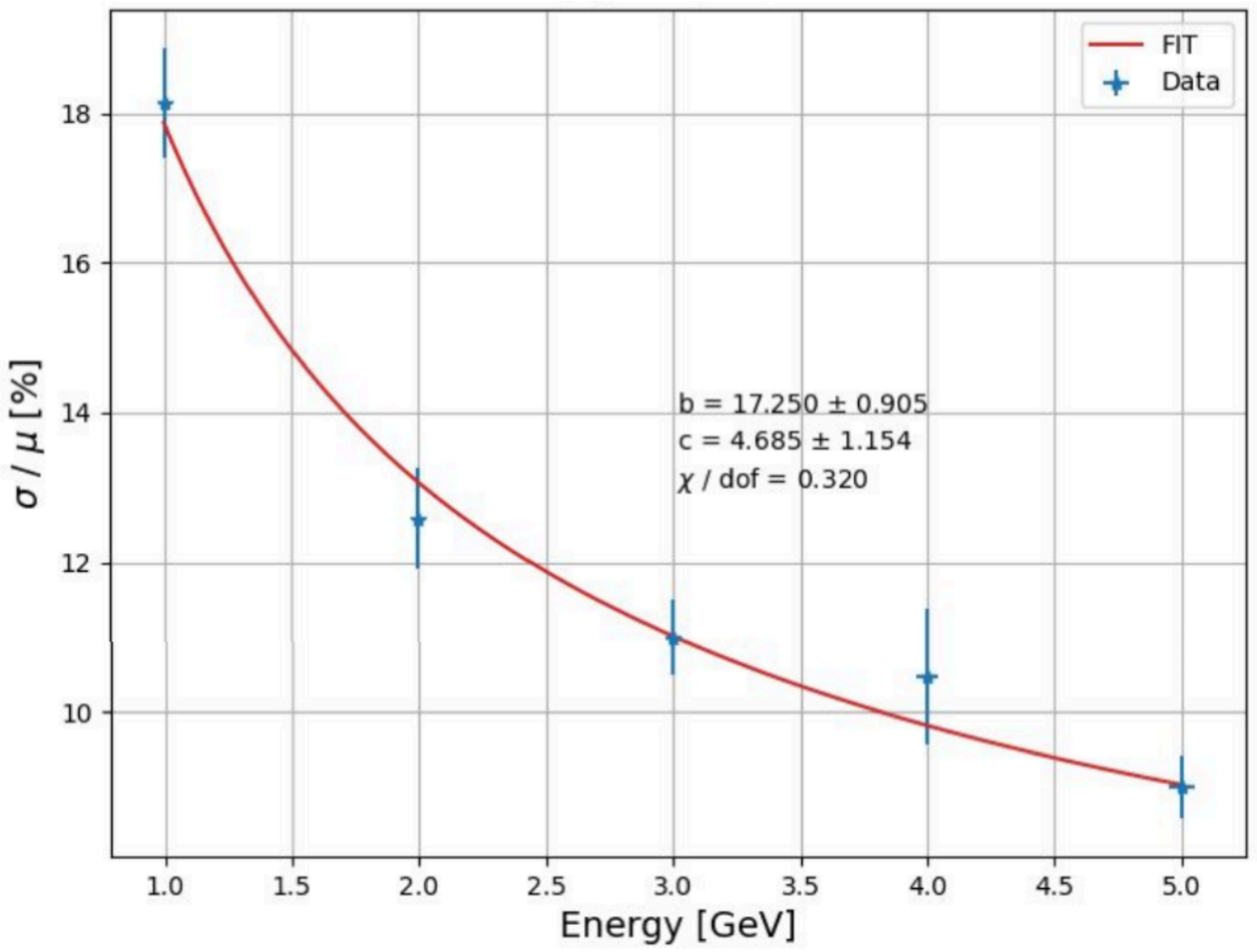
The Demonstrator

- 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

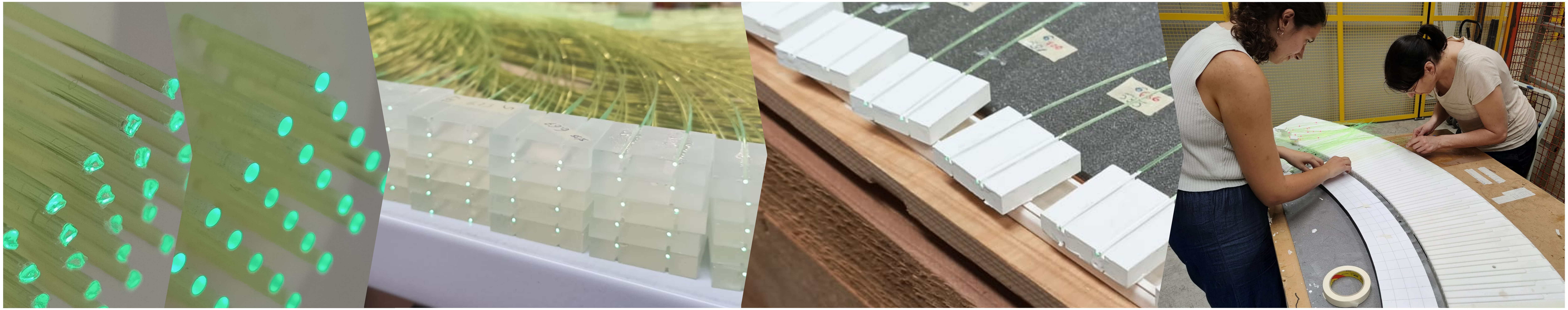


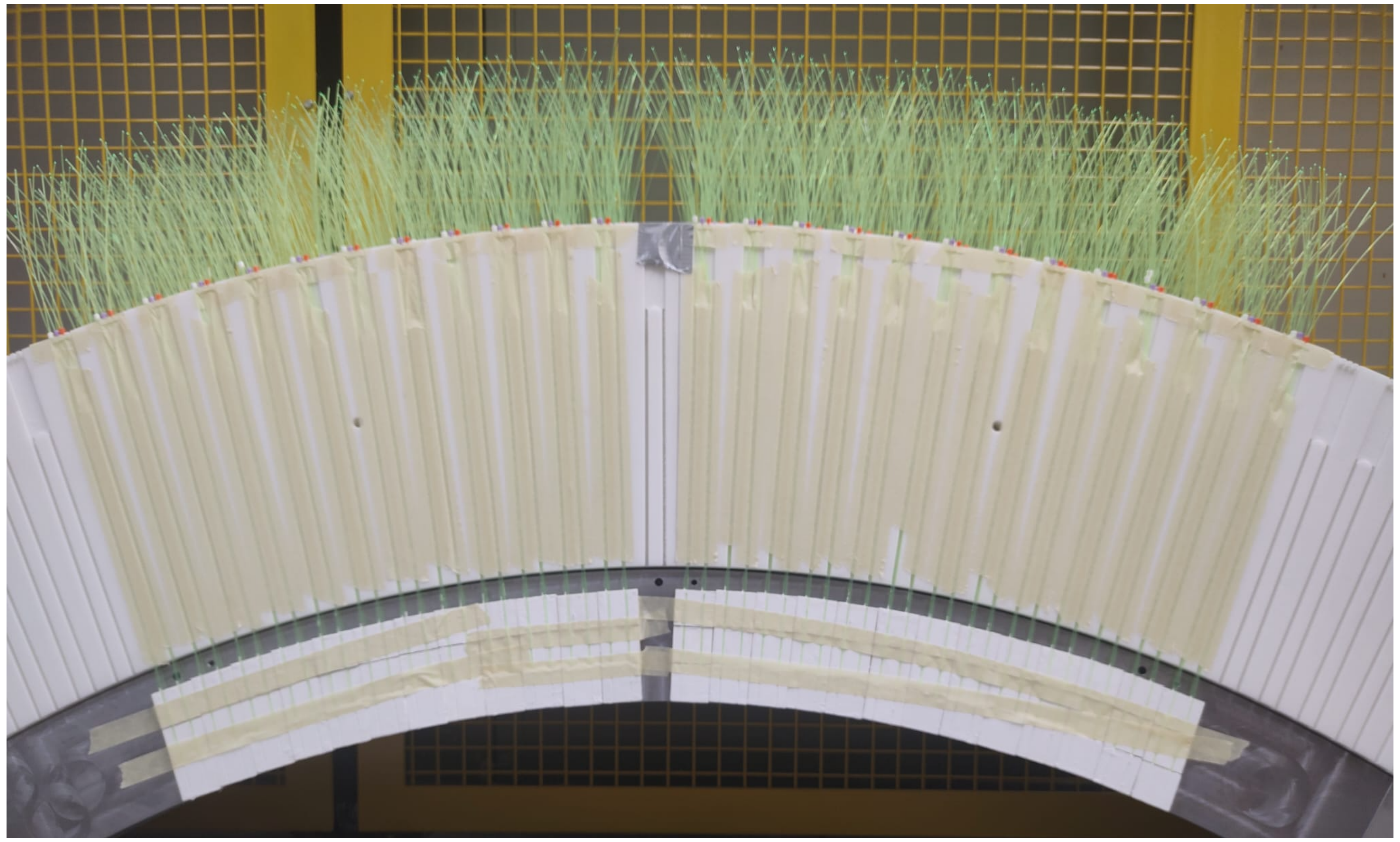






Demonstrator 2.0





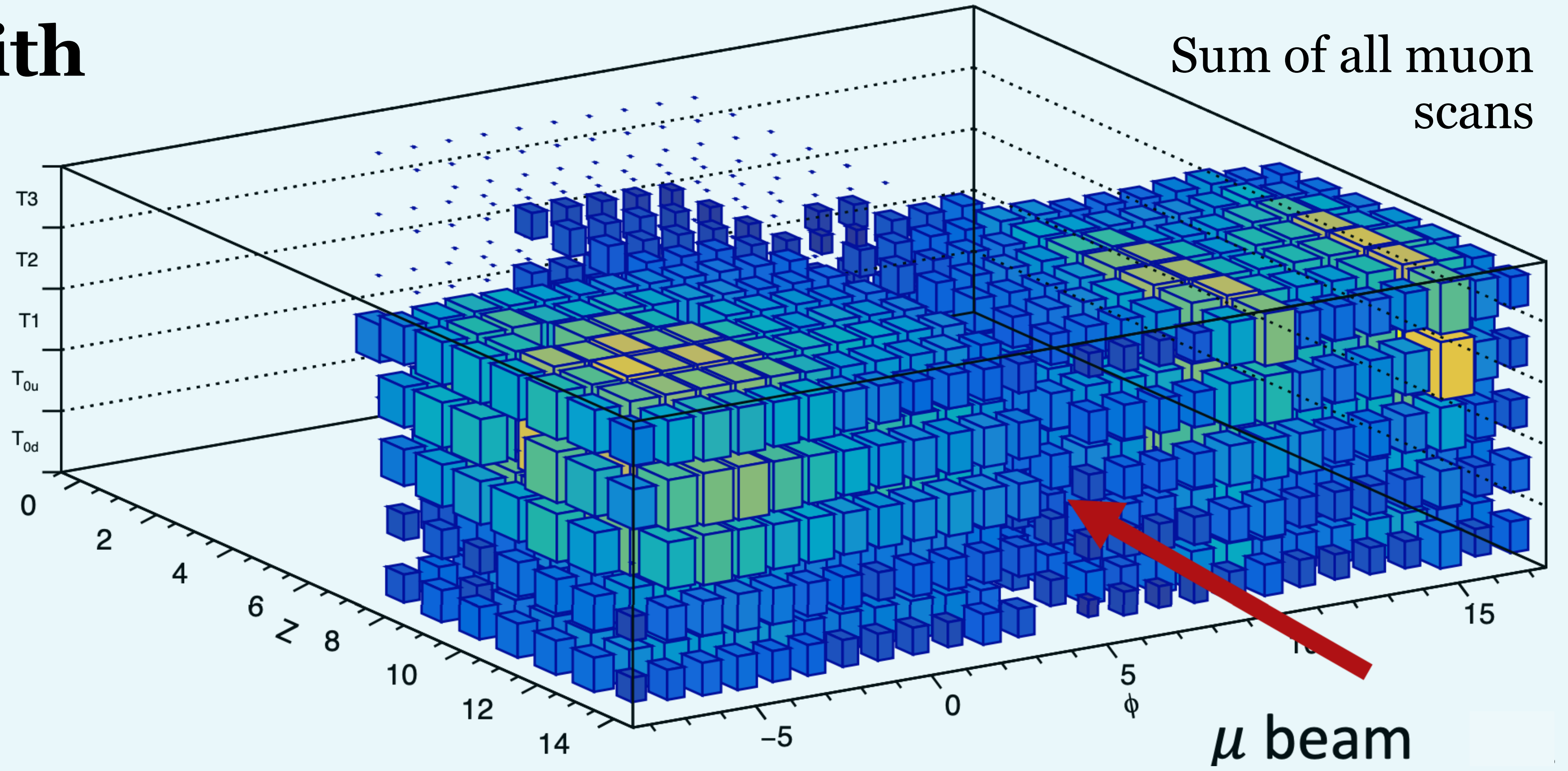
LP2i Bordeaux

Demonstrator 2.0

Demonstrator 2.0 @ CERN

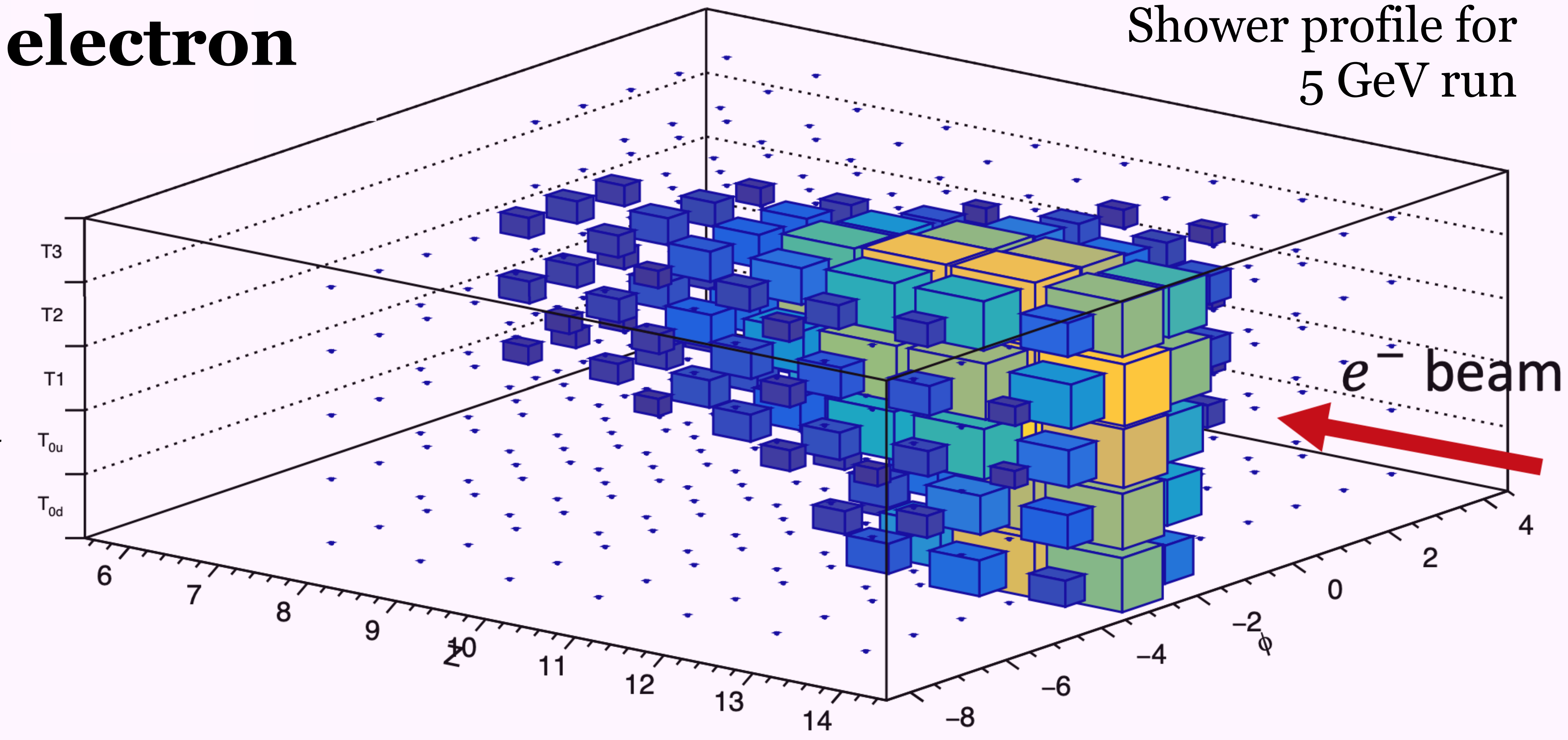
Calibration runs with 10 GeV muons

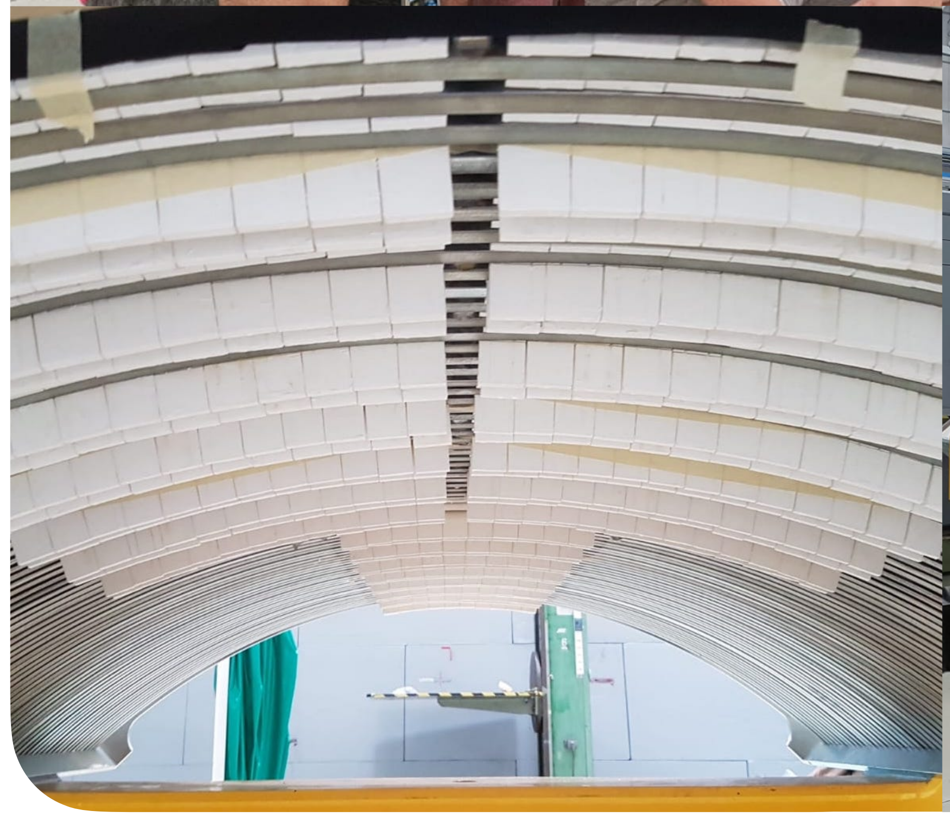
- All channels covered with lots of statistics
- Allow good equalisation of channels



Energy scans with electron beams

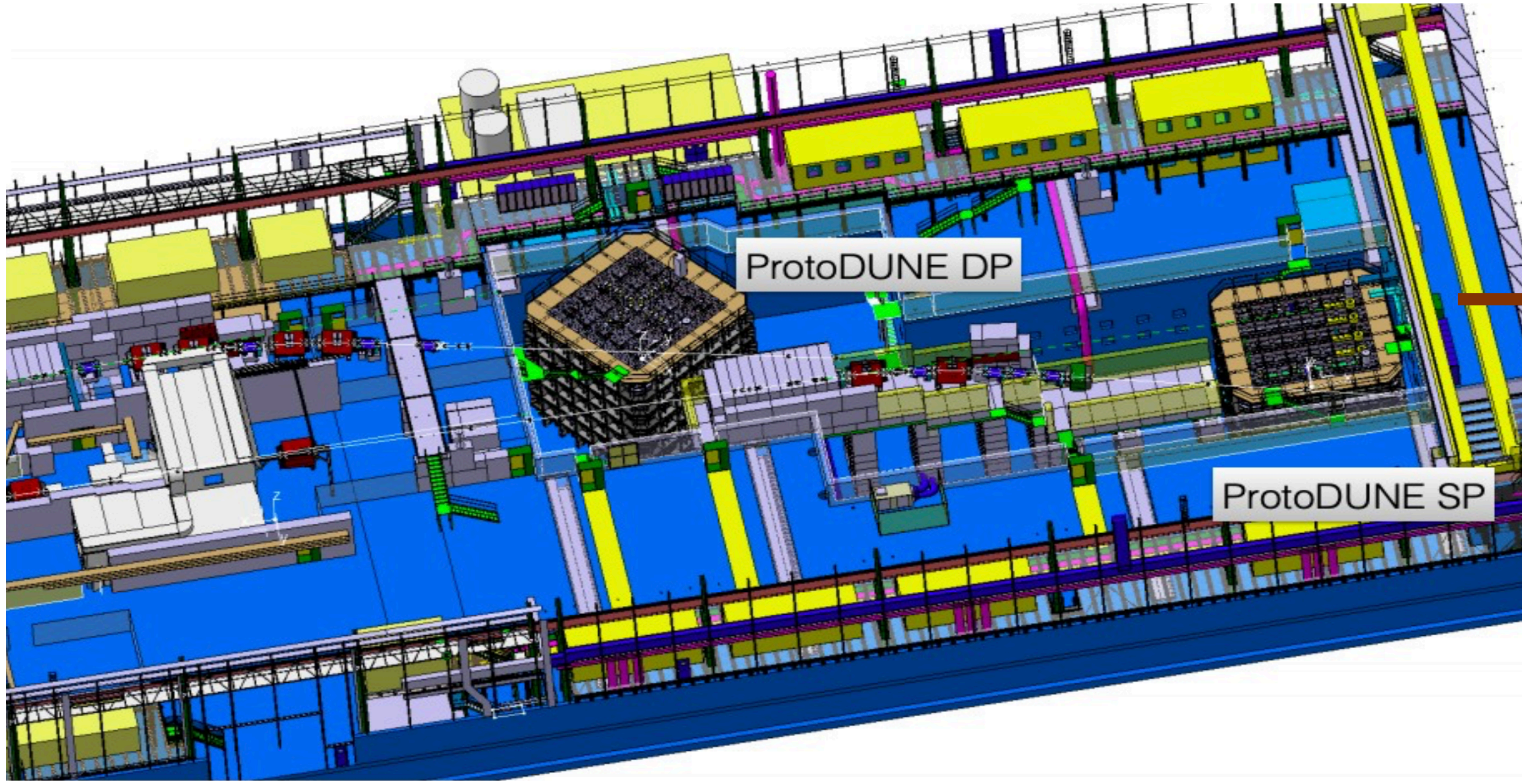
- Scans with different energies
- Performed for linearity and resolution studies





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)



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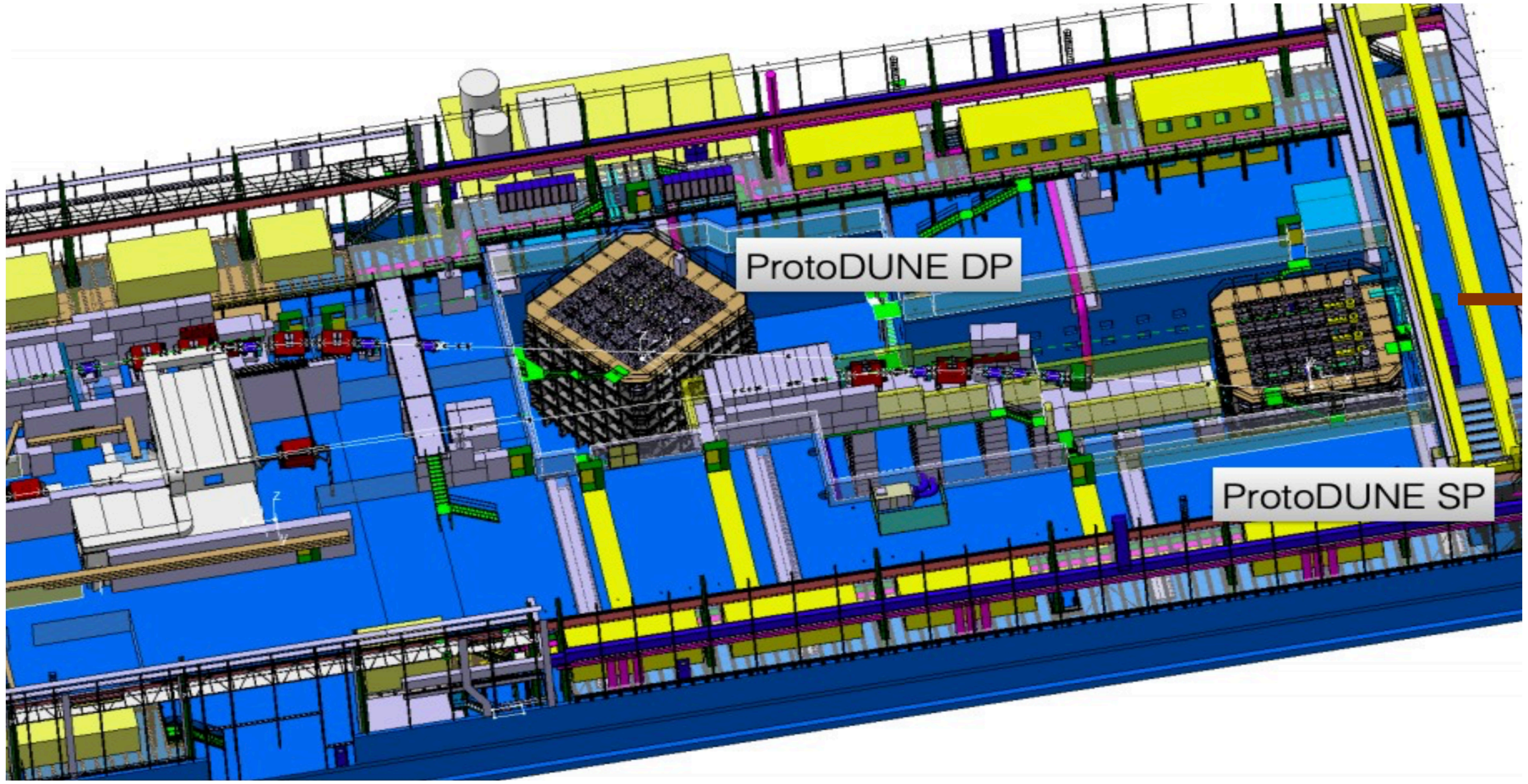

CHEAPEST

Dedicated beamline extracted from North area to ProtoDUNE

Maximum use of existing facilities

Slow extraction easily implemented

Potential radiation issues

Interference with other experiments

Implementation

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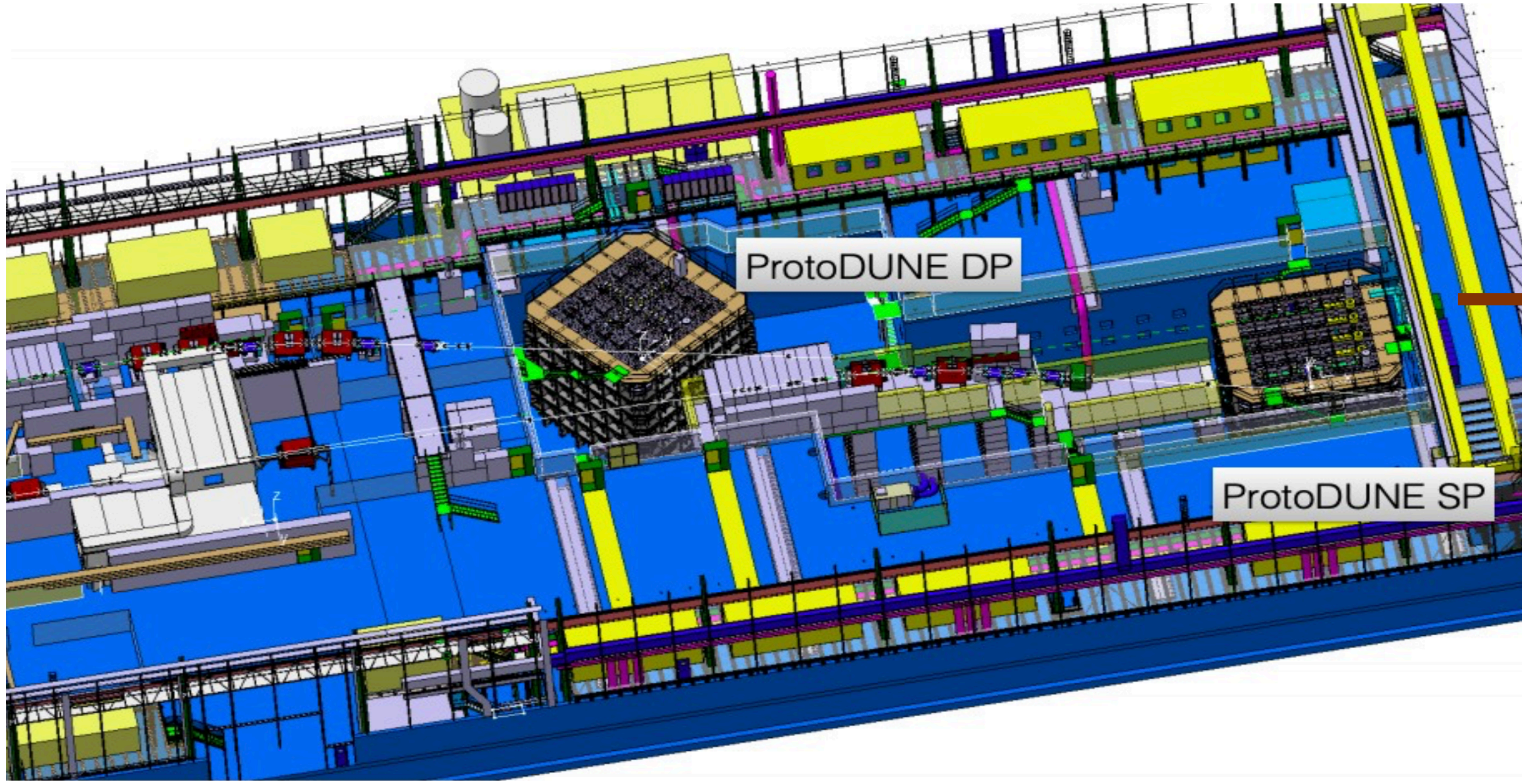


CHEAPEST

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

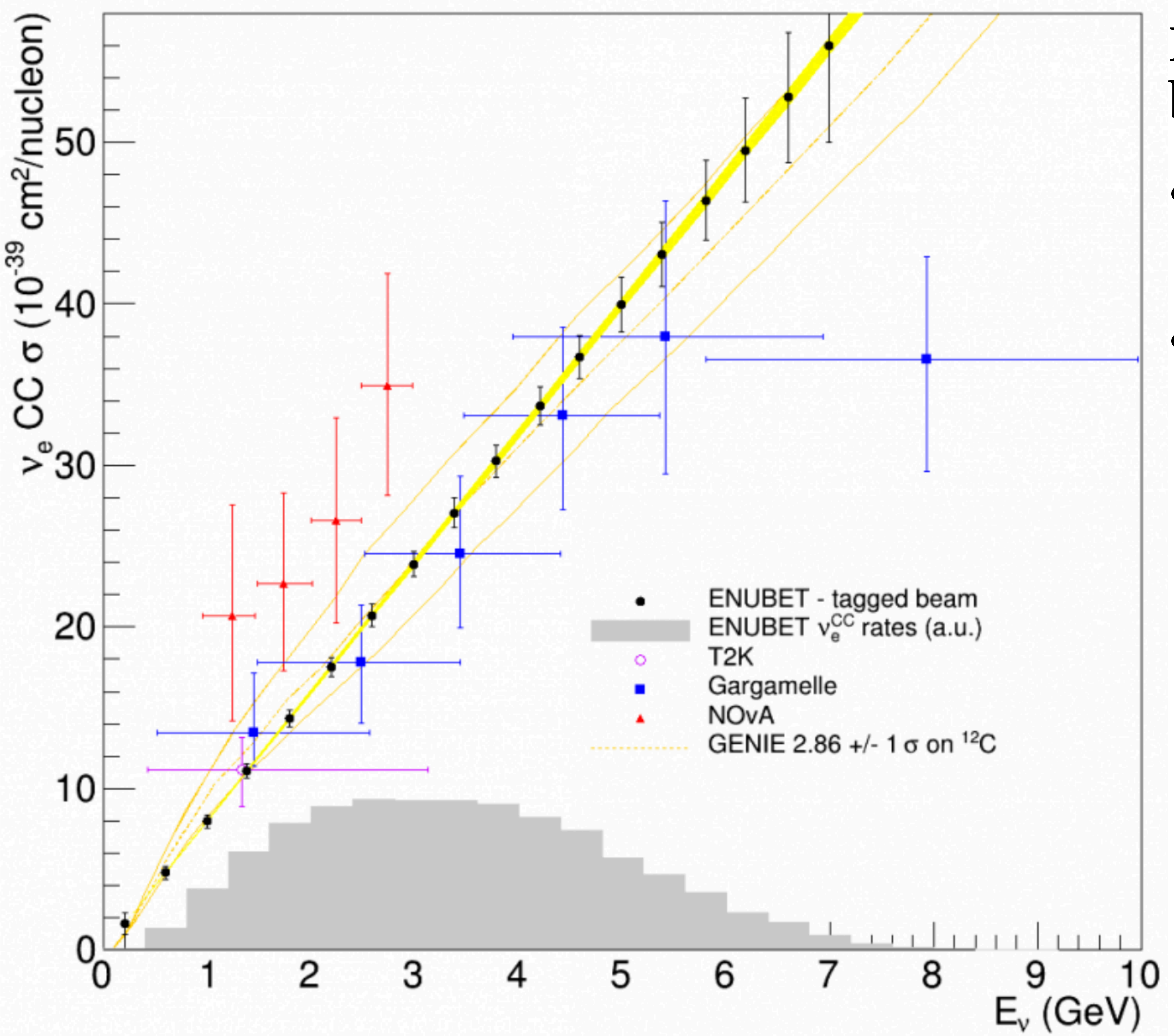
Low Z targets w/ same near and far detector

- 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

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

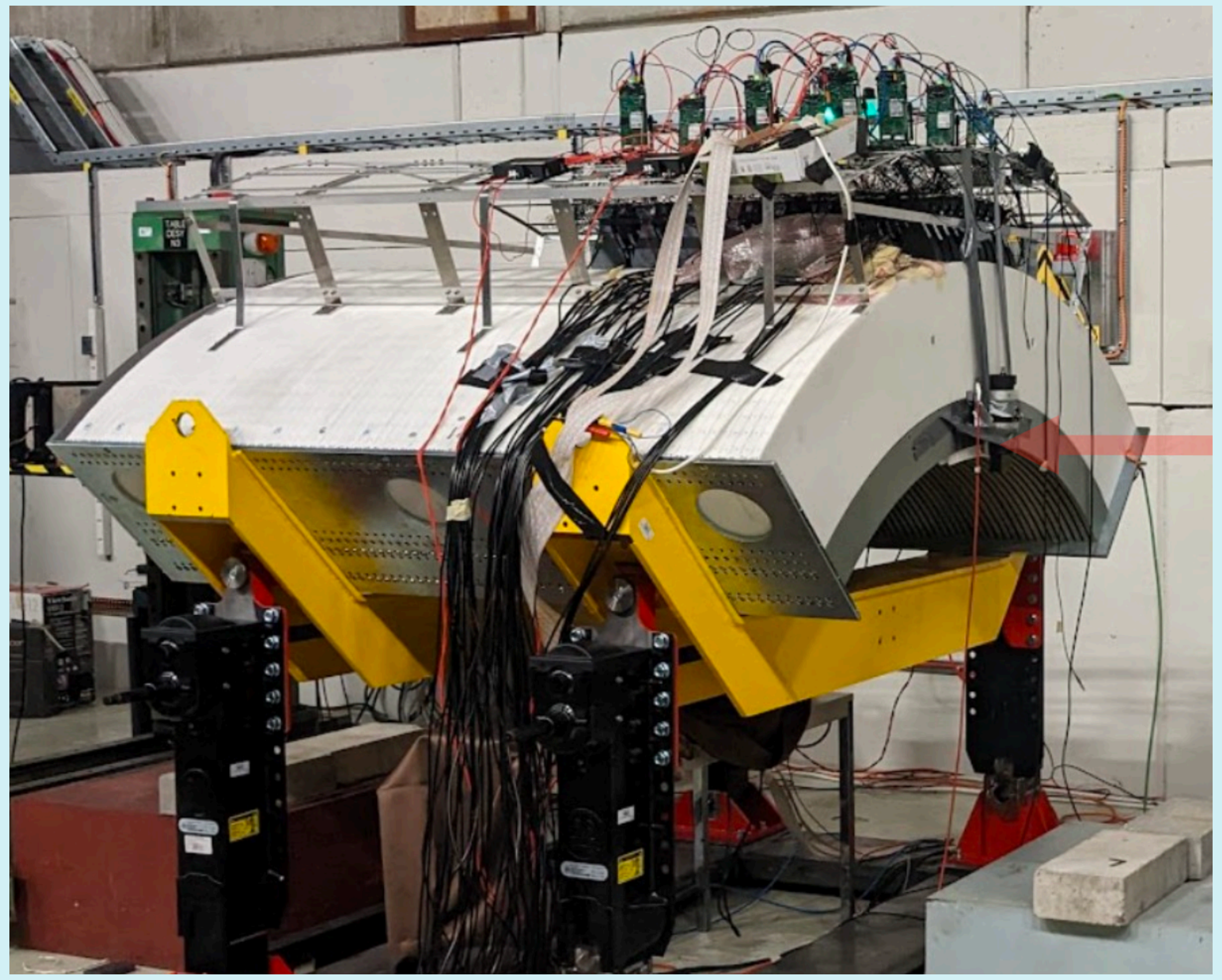
1.0

8 z-layers

10 ϕ-sectors

400 channels

2022



2023

+7 z-layers

25 ϕ-sectors each

+875 channels

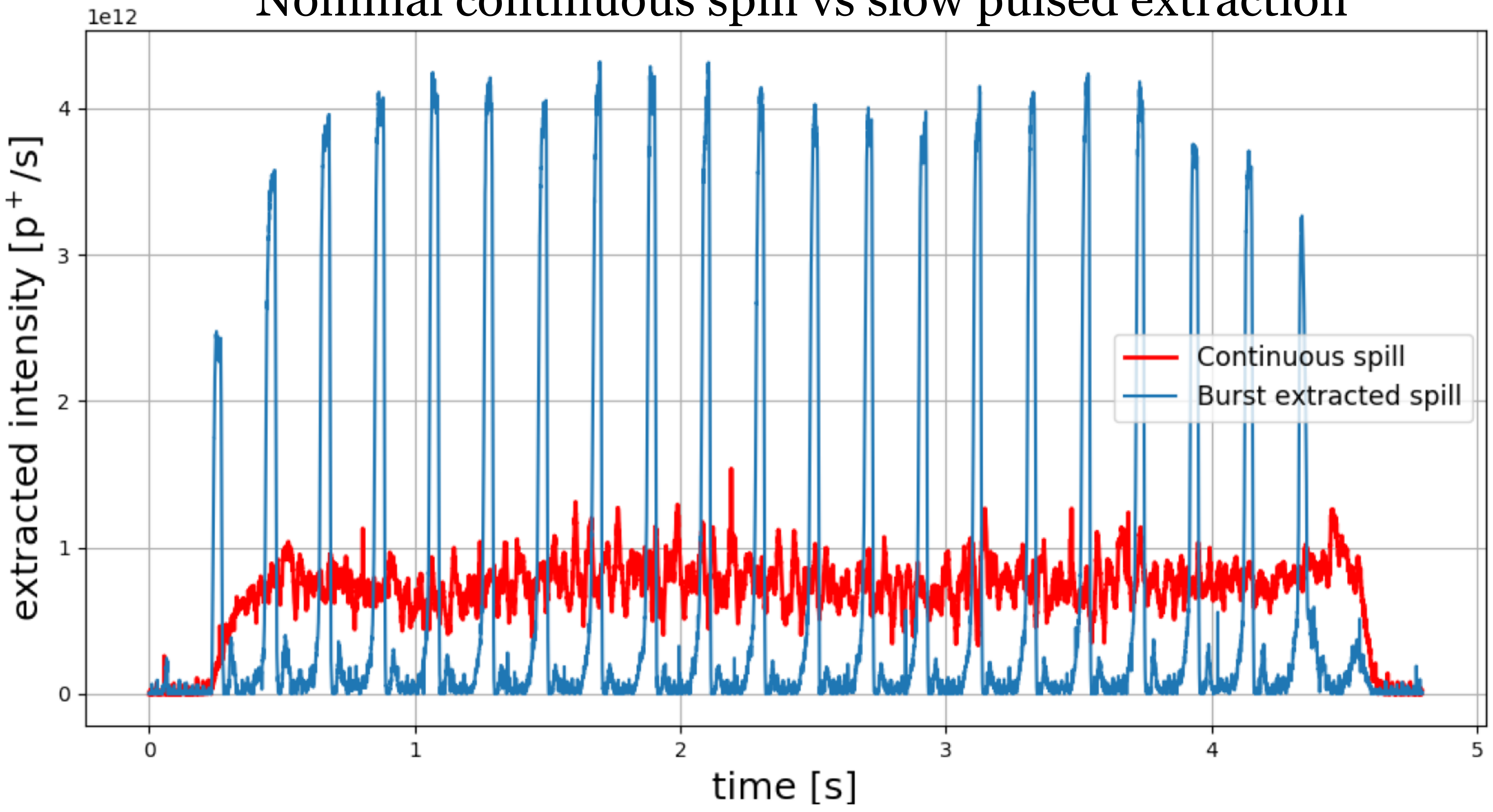
2.0

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

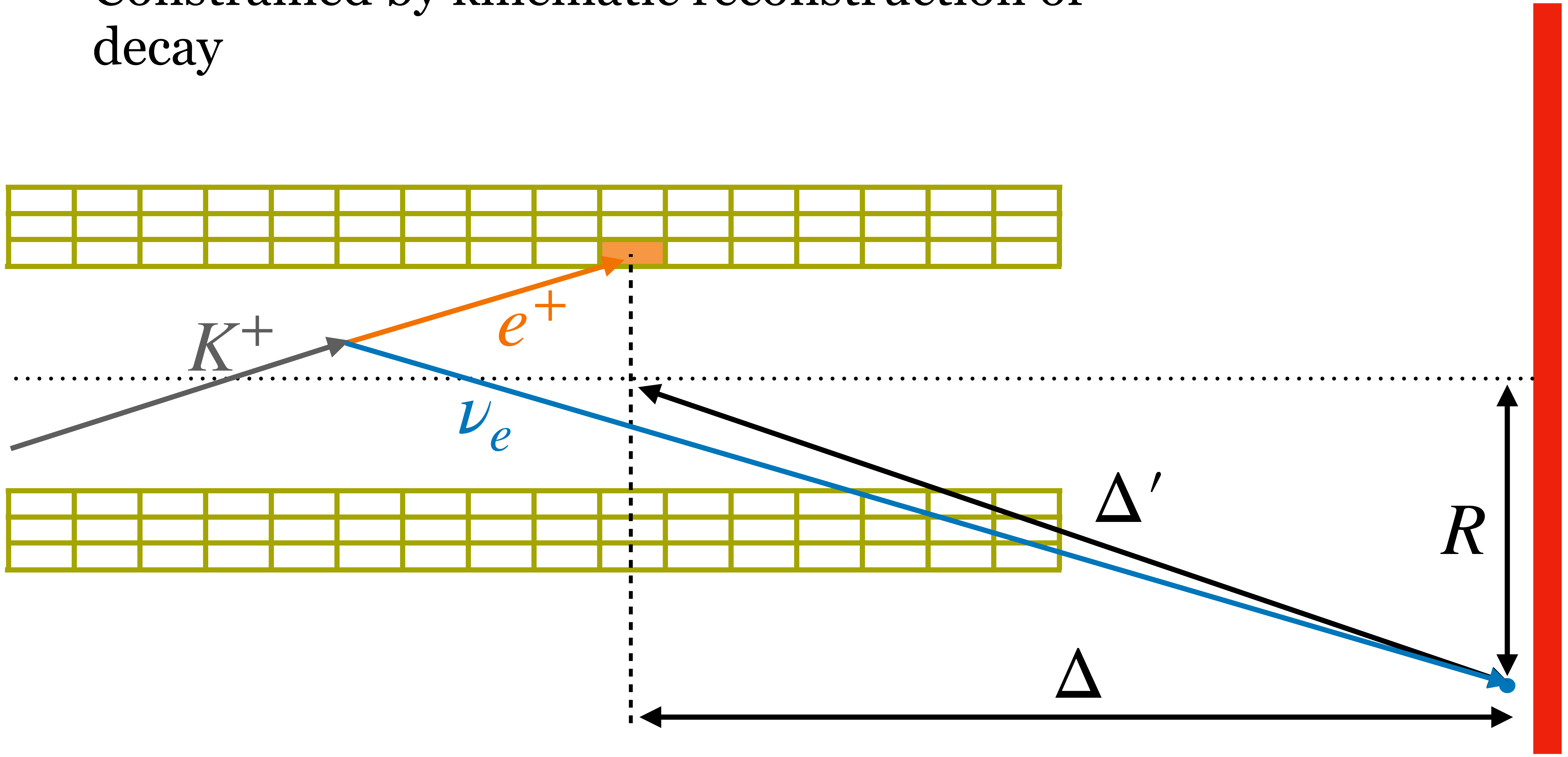
2020 design: A collection of dipoles and quadrupoles in a "static focusing system"

- 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

- 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

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

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

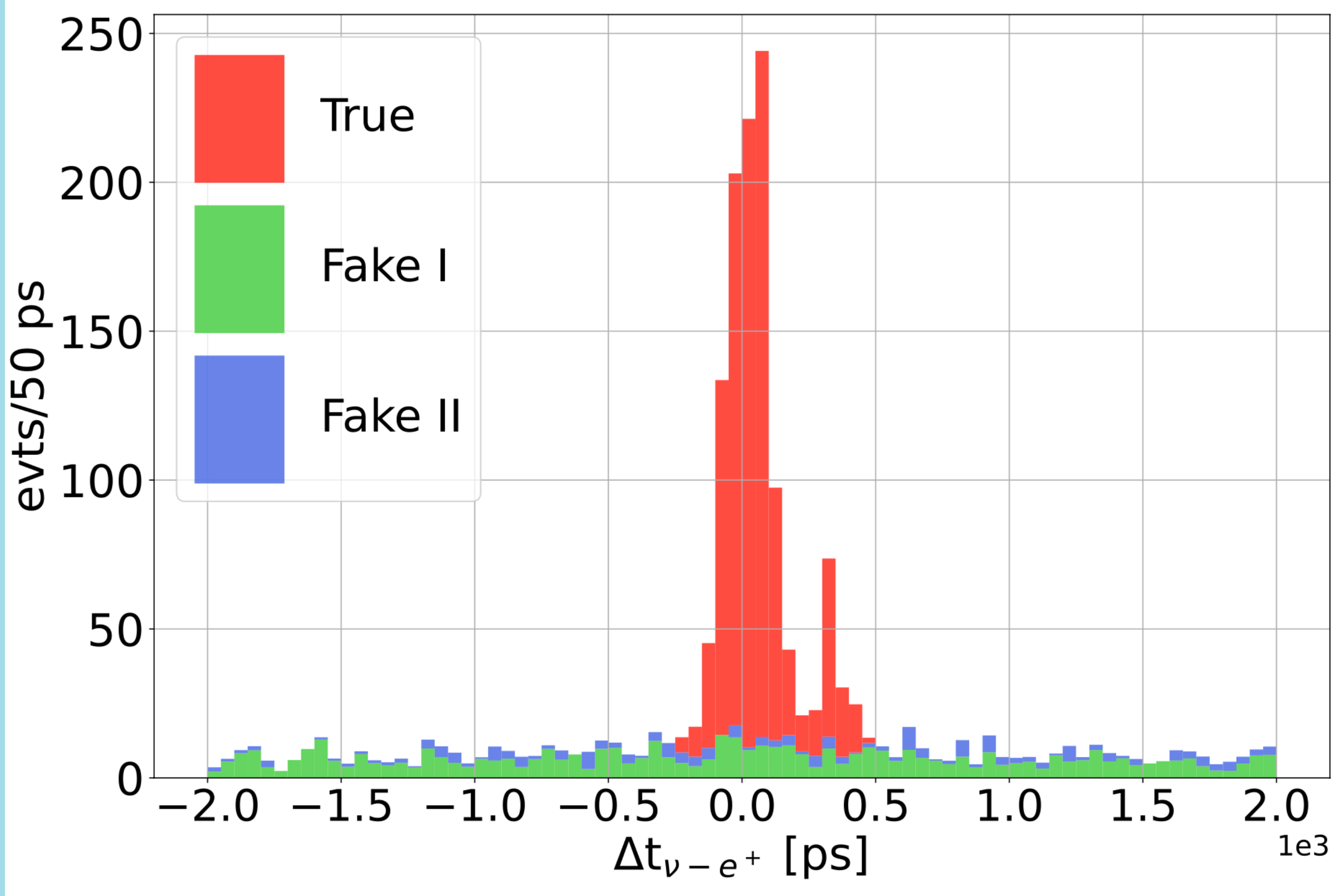
Time Tagging #2

- 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

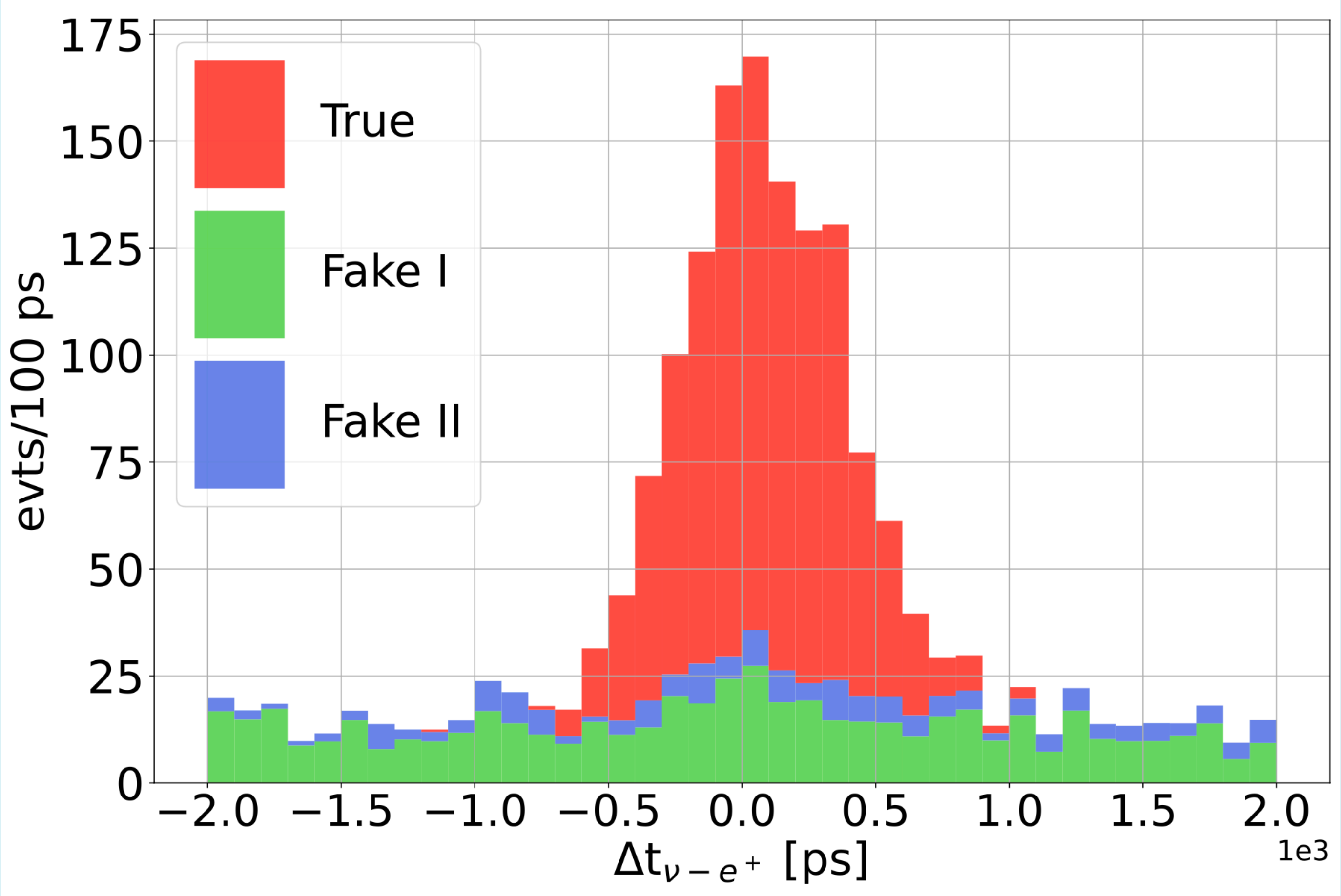
ENUBET could be a **time-tagged** neutrino beam by exploiting **time coincidences** of ν_e and e^+.

False positives from ν inside tagger

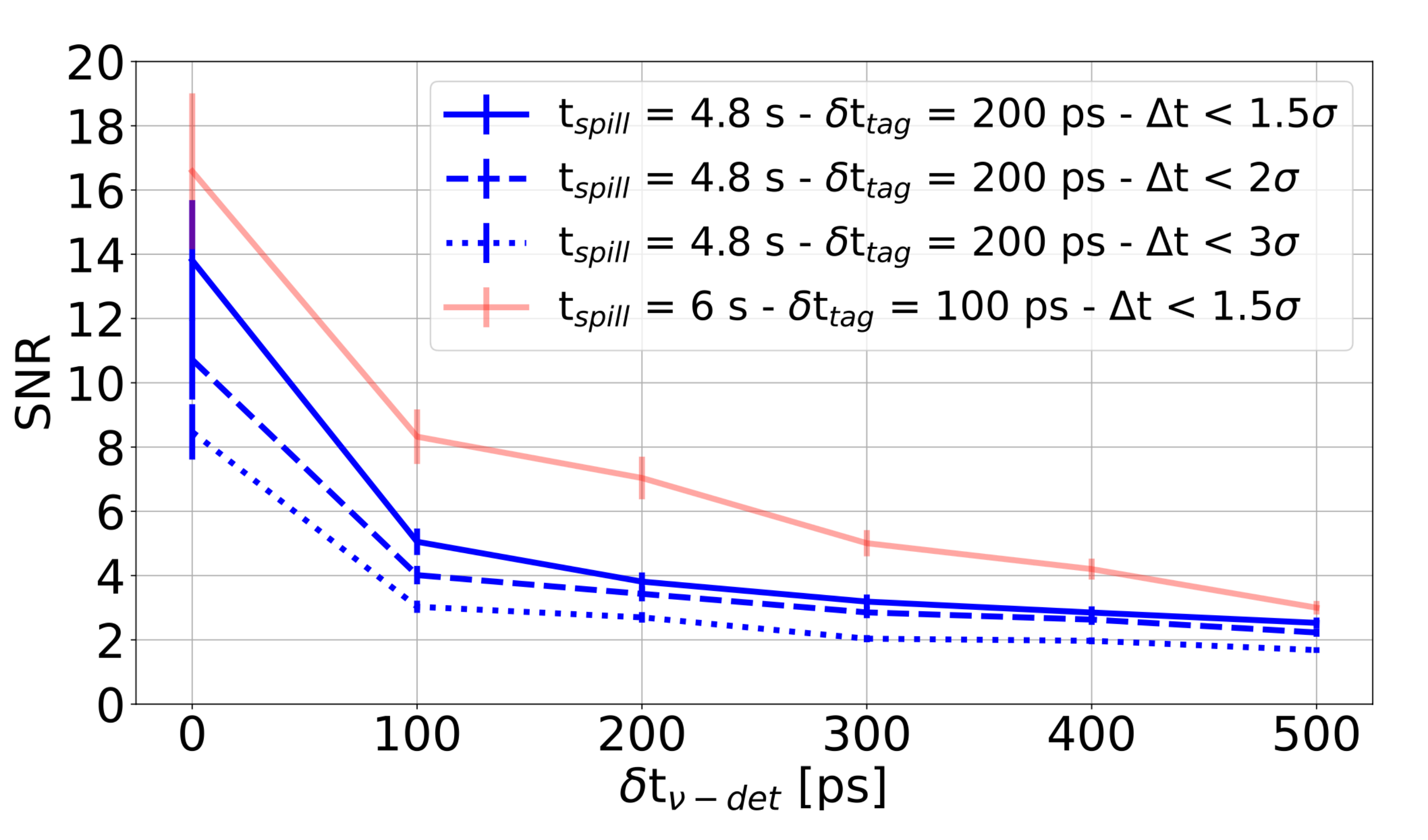
False positives from ν outside tagger



Perfect time resolution has an intrinsic 74 ps spread.

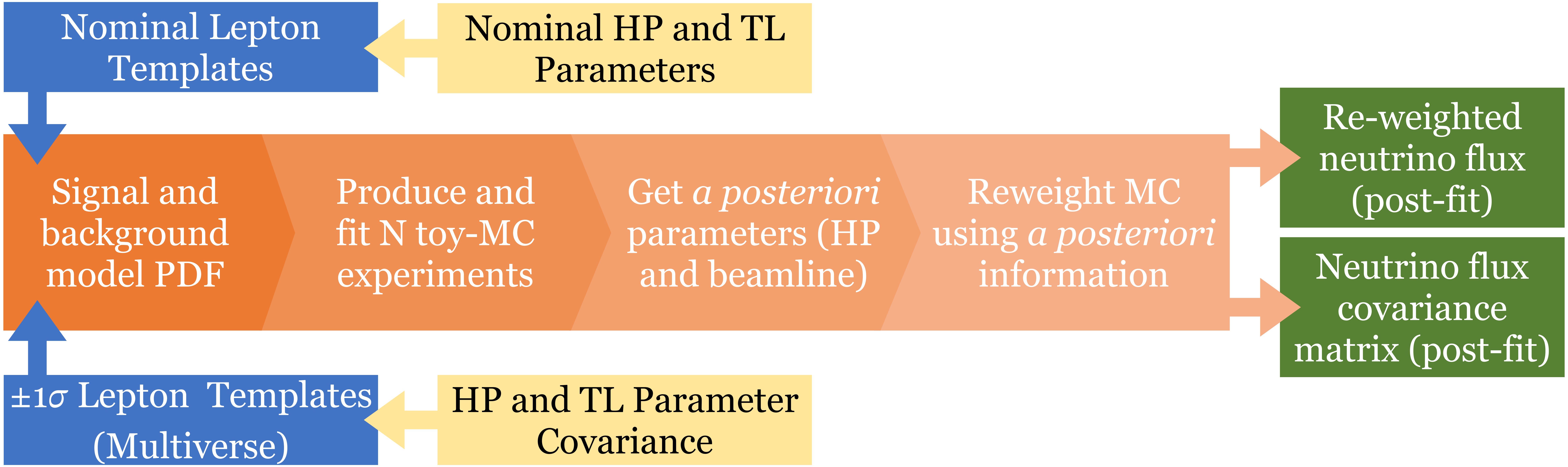


Efficiency smearing assuming resolution of ~200 ps.



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

Flux Constraint Algorithm



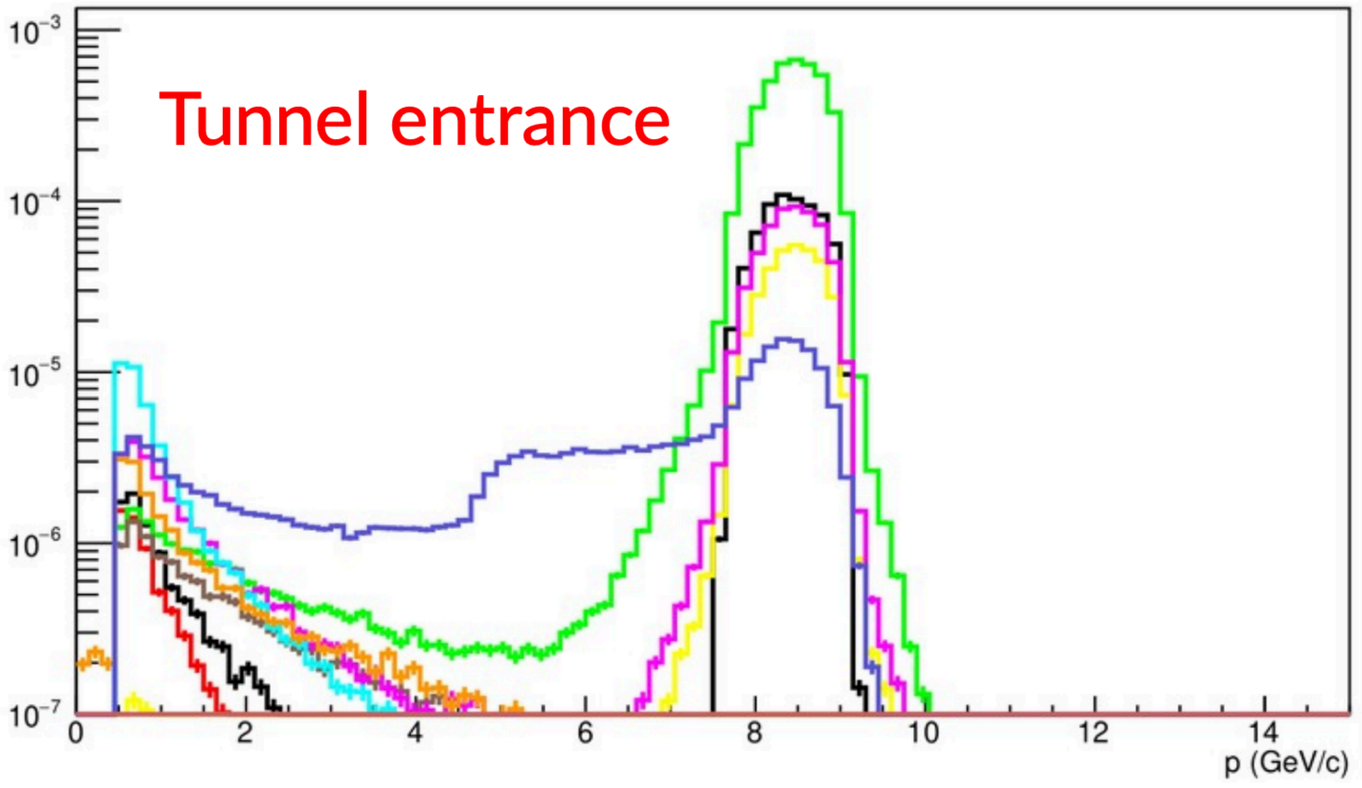
- Extended maximum likelihood fit
- Build a signal+background model to fit lepton observables

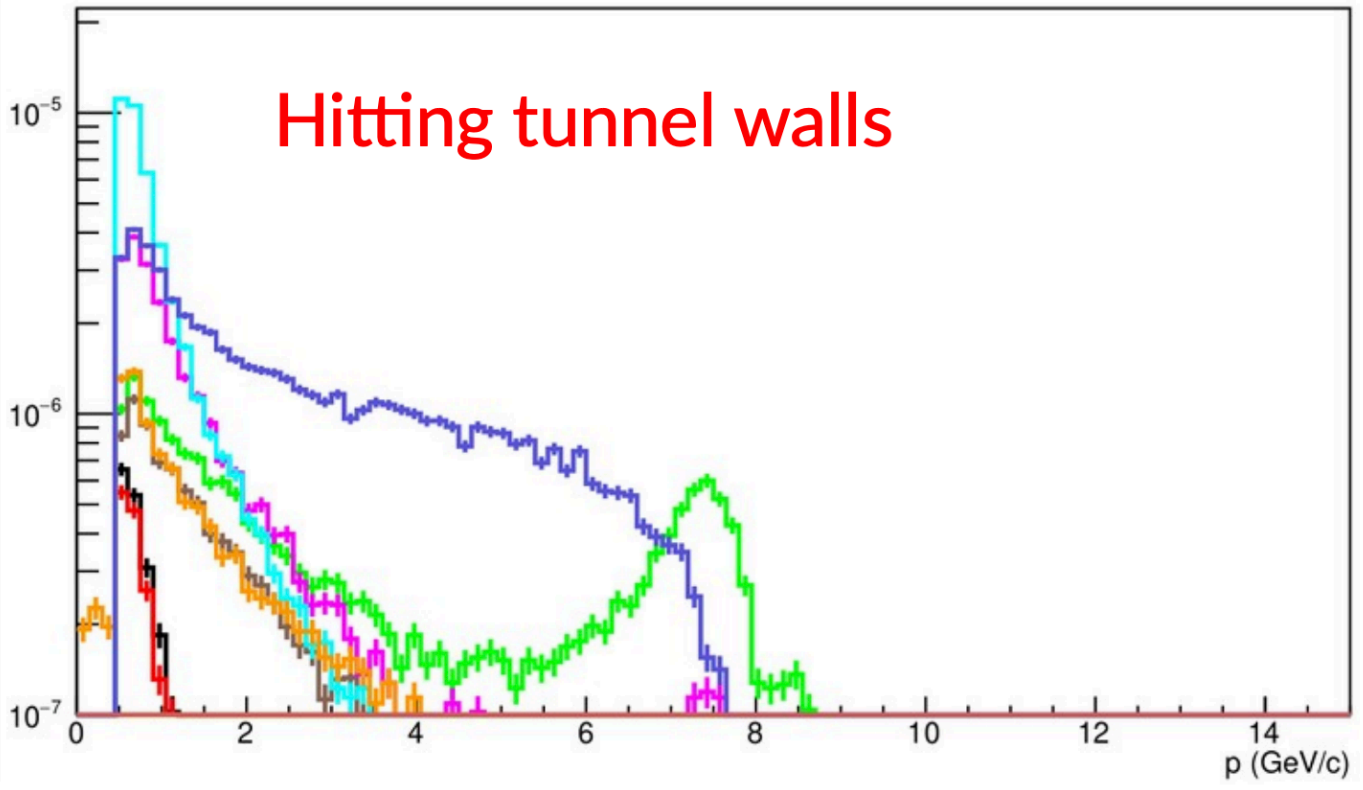
- Hadro-production data from NA56/SPY experiment (reweight MC lepton templates)
- Hadro-production included as nuisance parameters

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 $[10^{-3}/\text{PoT}]$

Publications #1

Tagged Neutrino Beams

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J. Bortfeldt et al., “PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector”, NIM A 903, 317-325 (2018), arXiv:1712.05256 [physics.ins-det].

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M. Pari et al., “Characterization of the slow extraction frequency response”, Phys. Rev. Accel. Beams 24(8), 083501 (2021).

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F. Acerbi et al., “A high precision neutrino beam for a new generation of short baseline experiments”, EPPS (2018), arXiv:1901.04768 [physics.ins-det].

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A. Longhin, F. Terranova, “The NP06/ENUBET SPSC annual report”, CERN Status Report, CERN-SPSC-2023-014 ; SPSC-SR-327 (2023).

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M. Torti, “The NP06/ENUBET Project: Towards a Monitored Neutrino Beam”, MUPB 77, 415-417 (2022).

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