



Monitoring neutrino beams with ENUBET

A precision cross section story



Jordan McElwee*

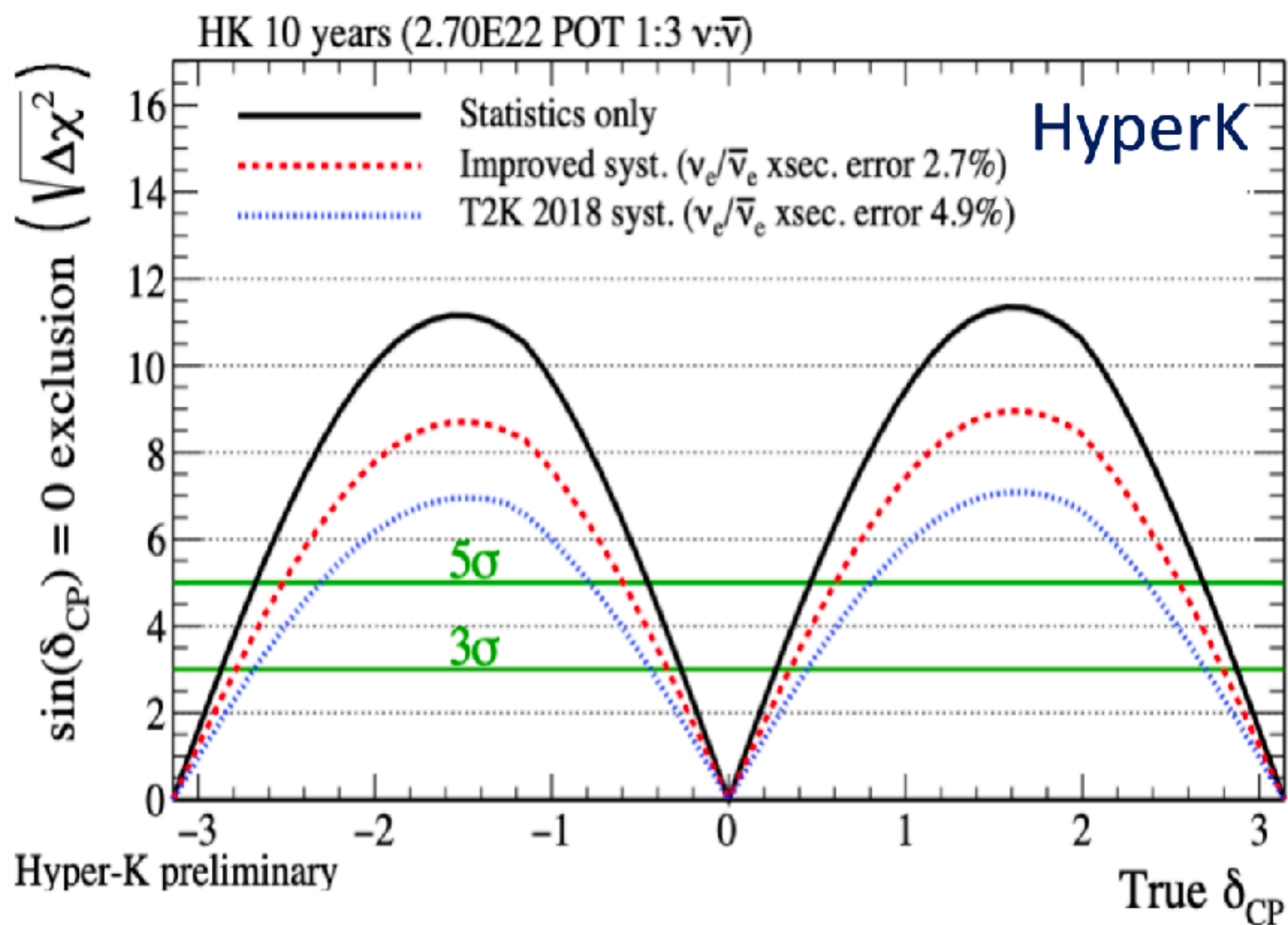
22nd October 2024

Rencontres de Blois

*on behalf of the ENUBET collaboration

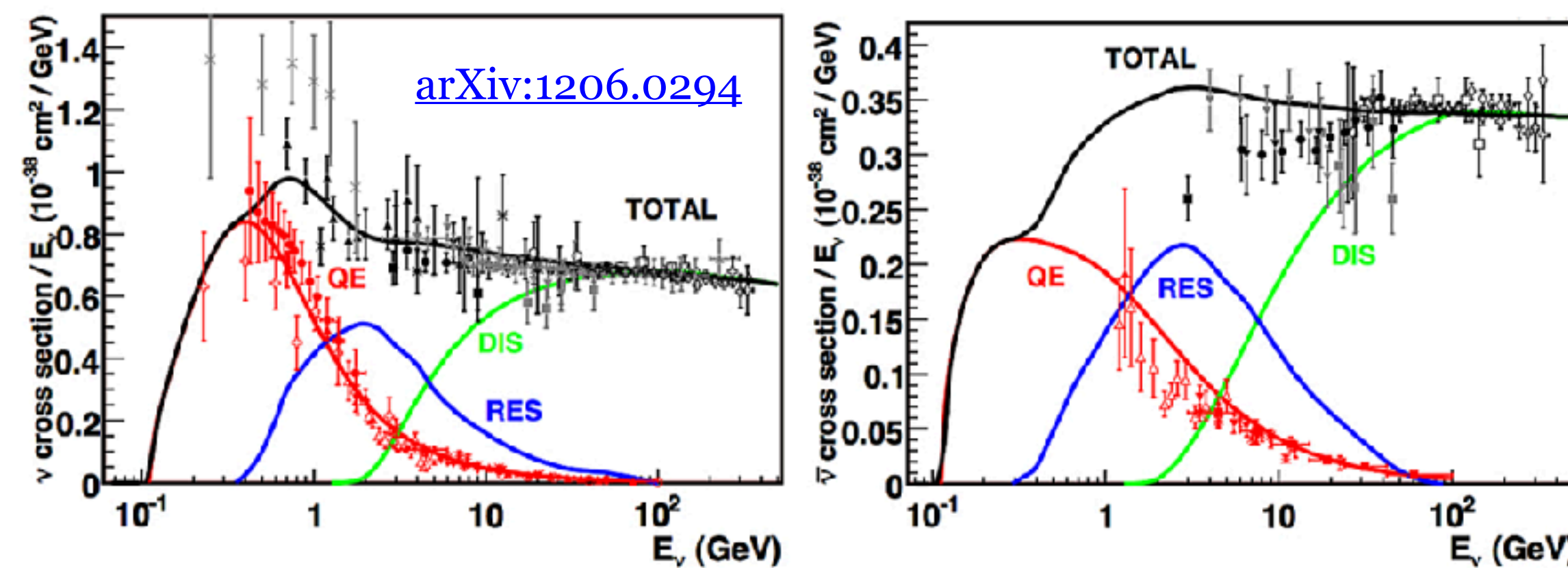


- Neutrino experiments have moved from the **statistics-** to the **systematics-dominated** era
- Next generation experiments (DUNE, HyperK, *etc.*) aim to measure δ_{CP}



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

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

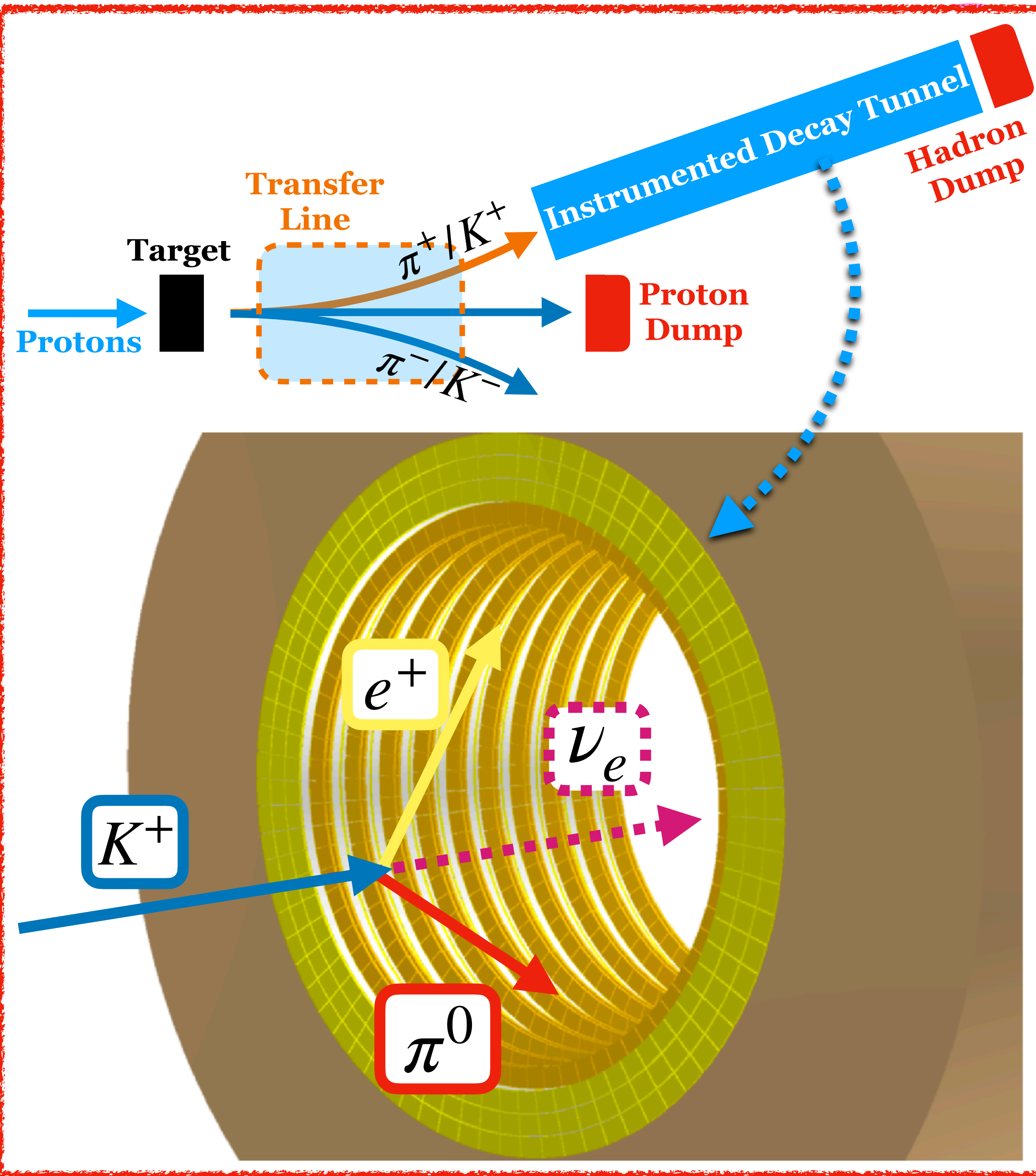


*Current best limit is 3.22% from MINERvA, [arXiv:2209.05540](https://arxiv.org/abs/2209.05540).

- **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:

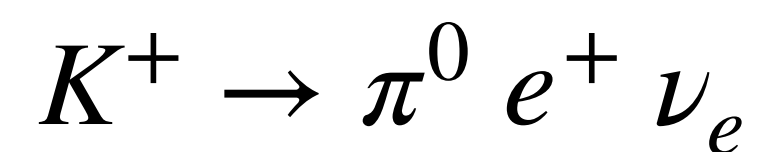
[A. Longhin, L. Ludovici, F. Terranova, EPJ C75 \(2015\) 155.](#)



ERC Project

(2016-2022)

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



PI: A. Longhin

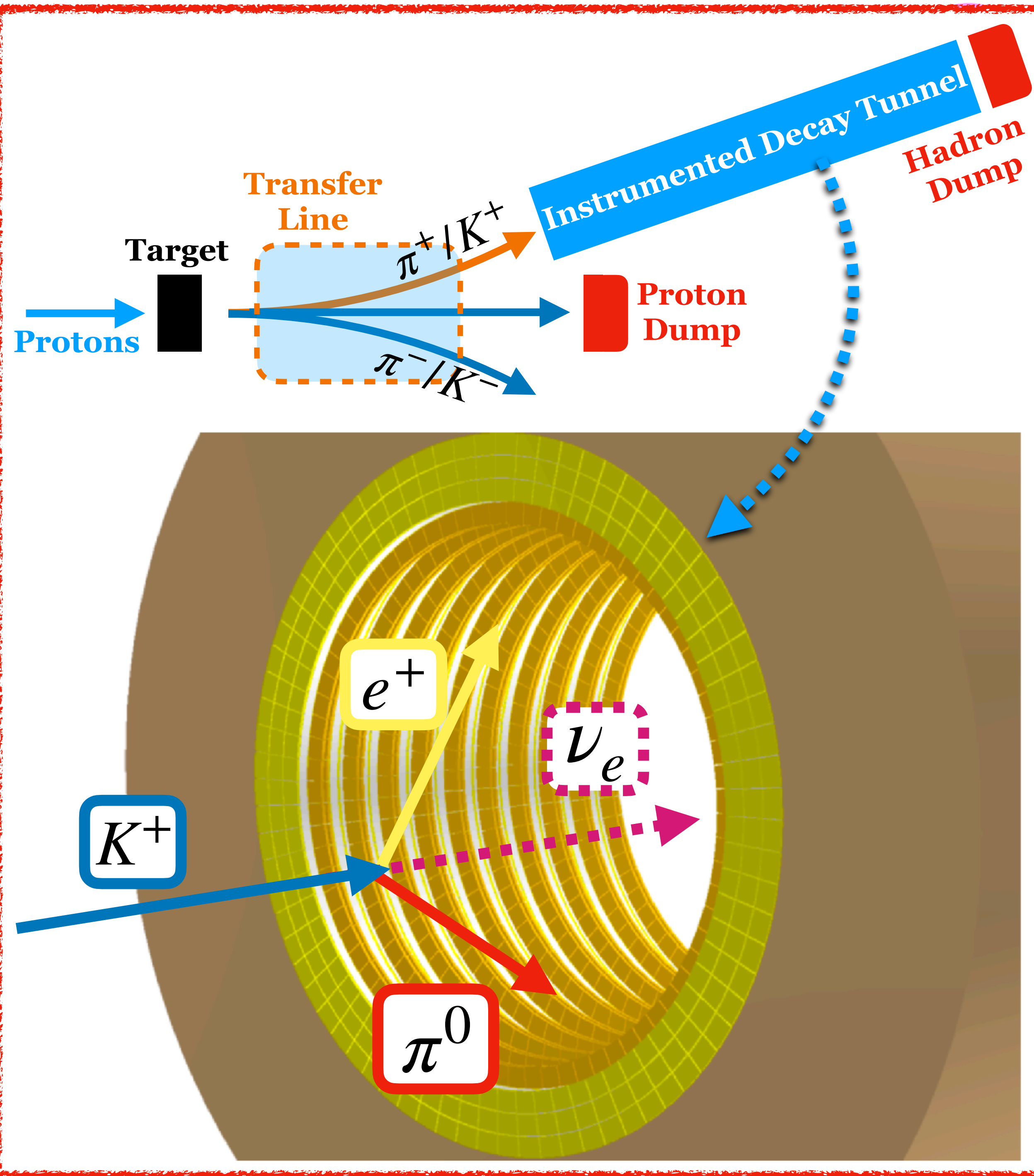
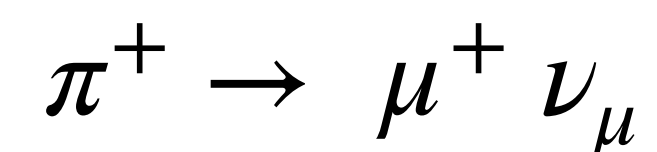
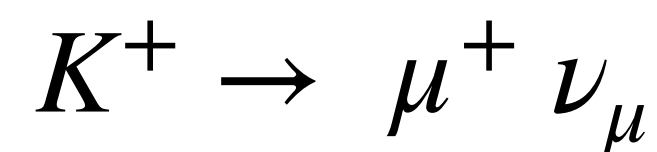
CERN Neutrino Platform

(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.

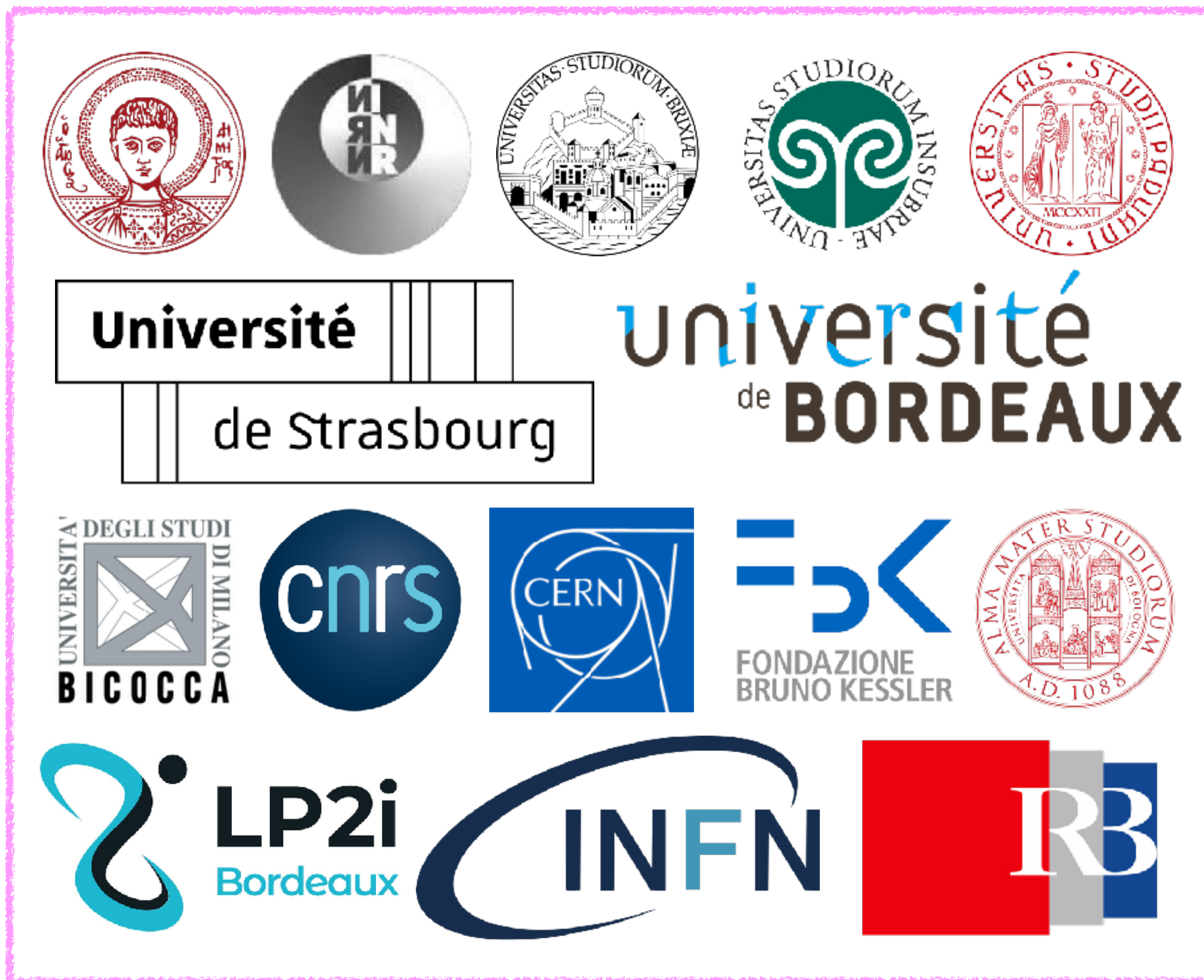
Part of the Physics Beyond Colliders initiative.



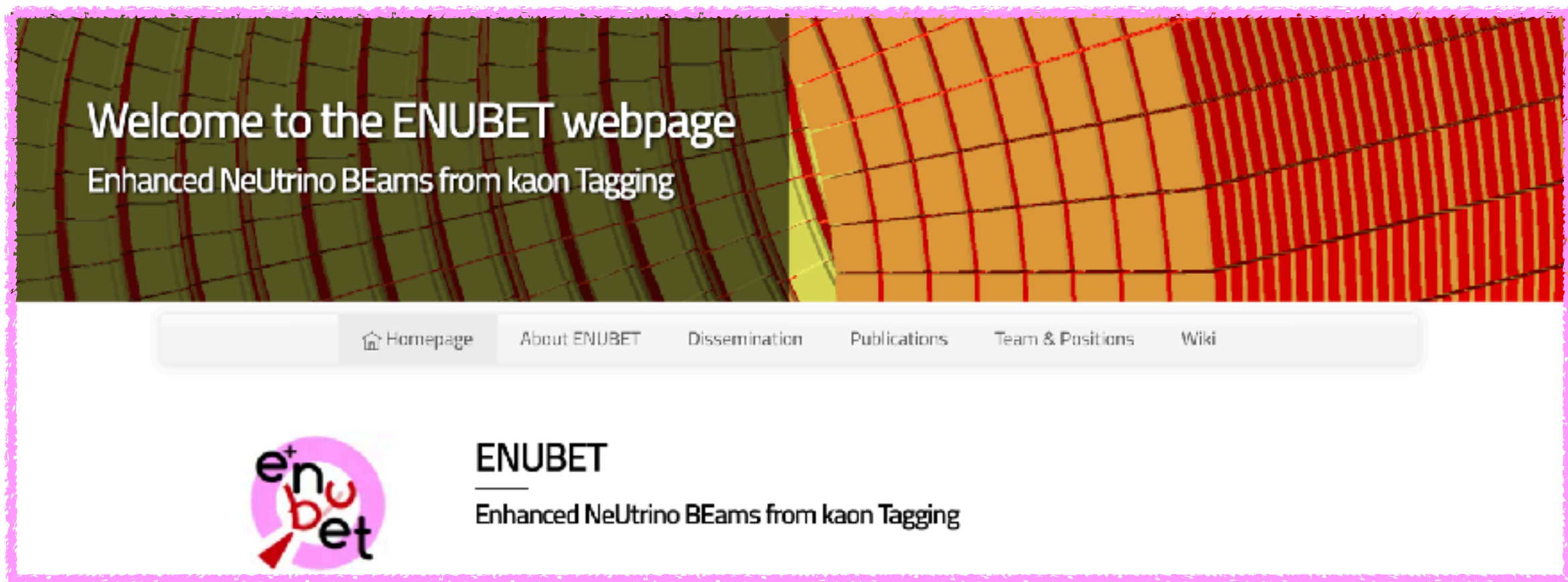
6 Countries

17 Institutions

72 Physicists



F. Acerbi¹, I. Angelis²¹, L. Bomben^{2,3}, M. Bonesini³, F. Bramati^{3,4}, A. Branca^{3,4}, C. Brizzolari^{3,4}, G. Brunetti^{3,4}, M. Calviani⁶, S. Capelli^{2,3}, S. Carturan⁷, M.G. Catanesi⁸, S. Cecchini⁹, N. Charitonidis⁶, F. Cindolo⁹, G. Cogo¹⁰, G. Collazuol^{5,10}, F. Dal Corso⁵, C. Delogu^{5,10}, G. De Rosa¹¹, A. Falcone^{3,4}, B. Goddard⁶, A. Gola¹, D. Guffanti^{3,4}, L. Halić²⁰, F. Iacob^{5,10}, C. Jollet¹⁶, V. Kain⁶, A. Kallitsopoulou²⁴, B. Kliček²⁰, Y. Kudenko¹³, Ch. Lampoudis²¹, M. Laveder^{5,10}, P. Legou²⁴, A. Longhin^{5,10}, L. Ludovici¹⁵, E. Lutsenko^{2,3}, L. Magaletti^{8,14}, G. Mandrioli⁹, S. Marangoni^{3,4}, A. Margotti⁹, V. Mascagna^{22,23}, N. Mauri⁹, J. McElwee¹⁶, L. Meazza^{3,4}, A. Mereaglia¹⁶, M. Mezzetto⁵, M. Nessi⁶, A. Paoloni¹⁷, M. Pari^{5,10}, T. Papaevangelou²⁴, E.G. Parozzi⁴, L. Pasqualini^{9,18}, G. Paternoster¹, L. Patrizzii⁹, M. Pozzato⁹, M. Prest^{2,3}, F. Pupilli⁵, E. Radicioni⁸, A.C. Ruggeri¹¹, G. Saibene^{2,3}, D. Sampsonidis²¹, C. Scian¹⁰, G. Sirri⁹, M. Stipčević²⁰, M. Tenti⁹, F. Terranova^{3,4}, M. Torti^{3,4}, S.E. Tzamarias²¹, E. Vallazza³, F. Velotti⁶, L. Votano¹⁷



Target

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

Dumps

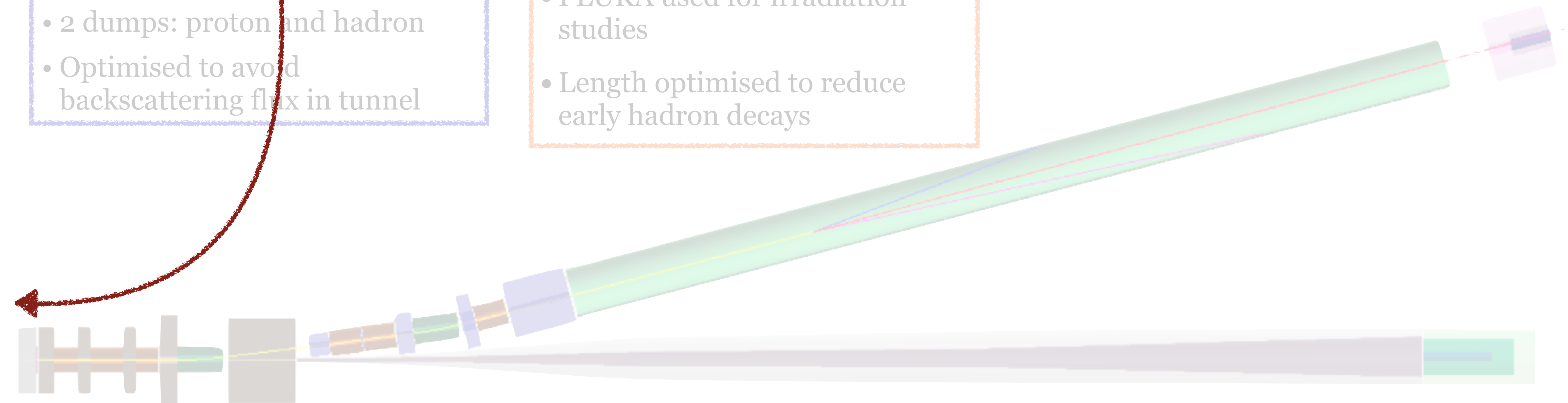
- 2 dumps: proton and hadron
- Optimised to avoid backscattering flux in tunnel

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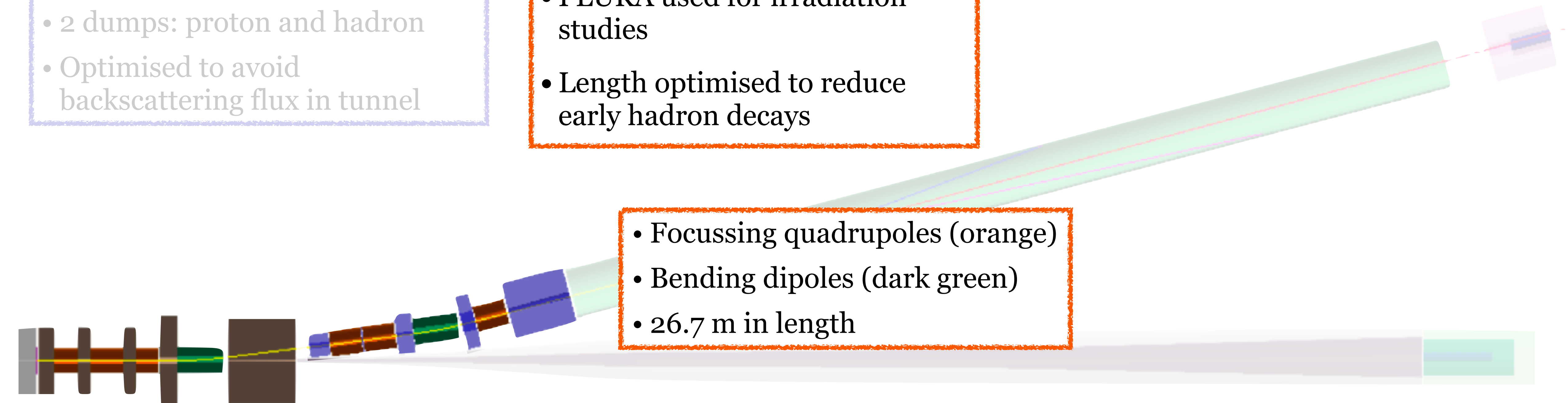
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- Focussing quadrupoles (orange)
- Bending dipoles (dark green)
- 26.7 m in length



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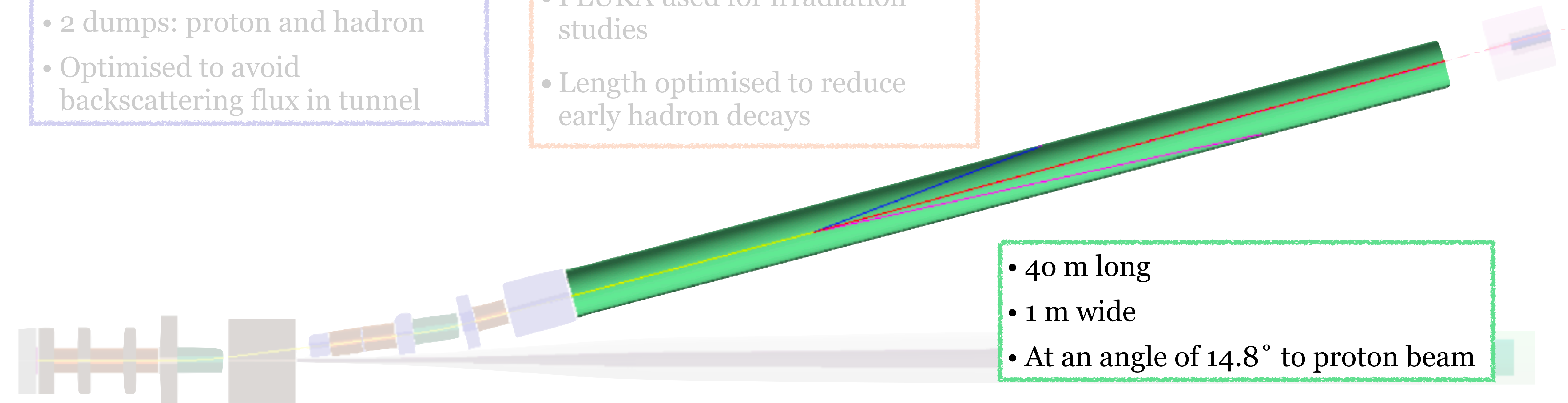
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- 40 m long
- 1 m wide
- At an angle of 14.8° to proton beam



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Dumps

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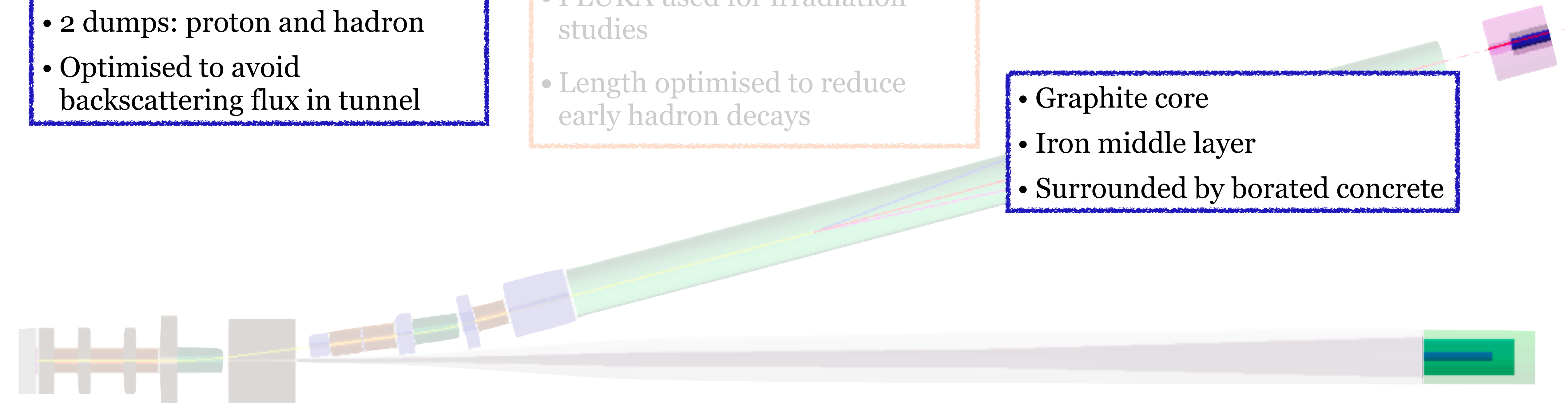
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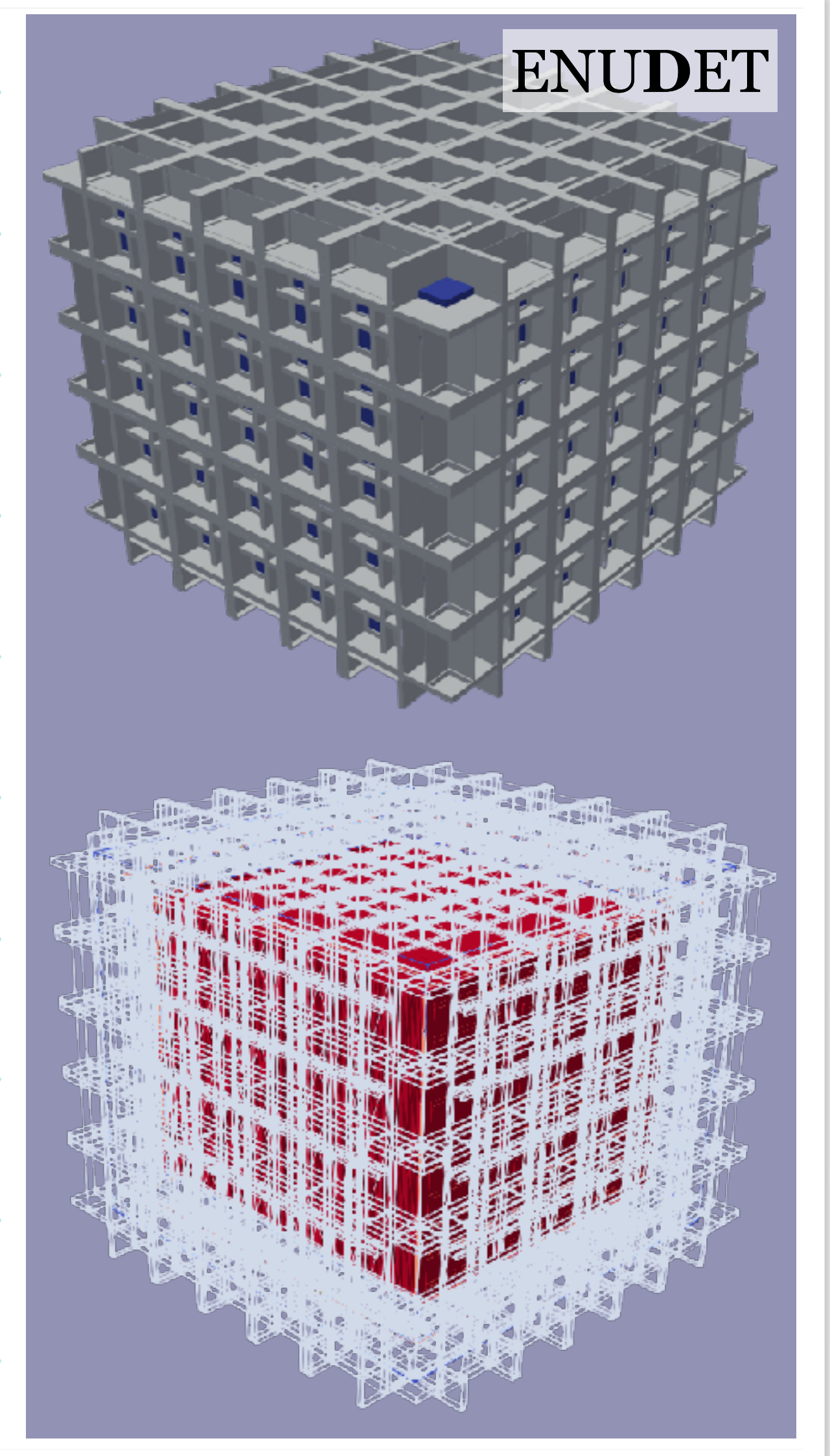
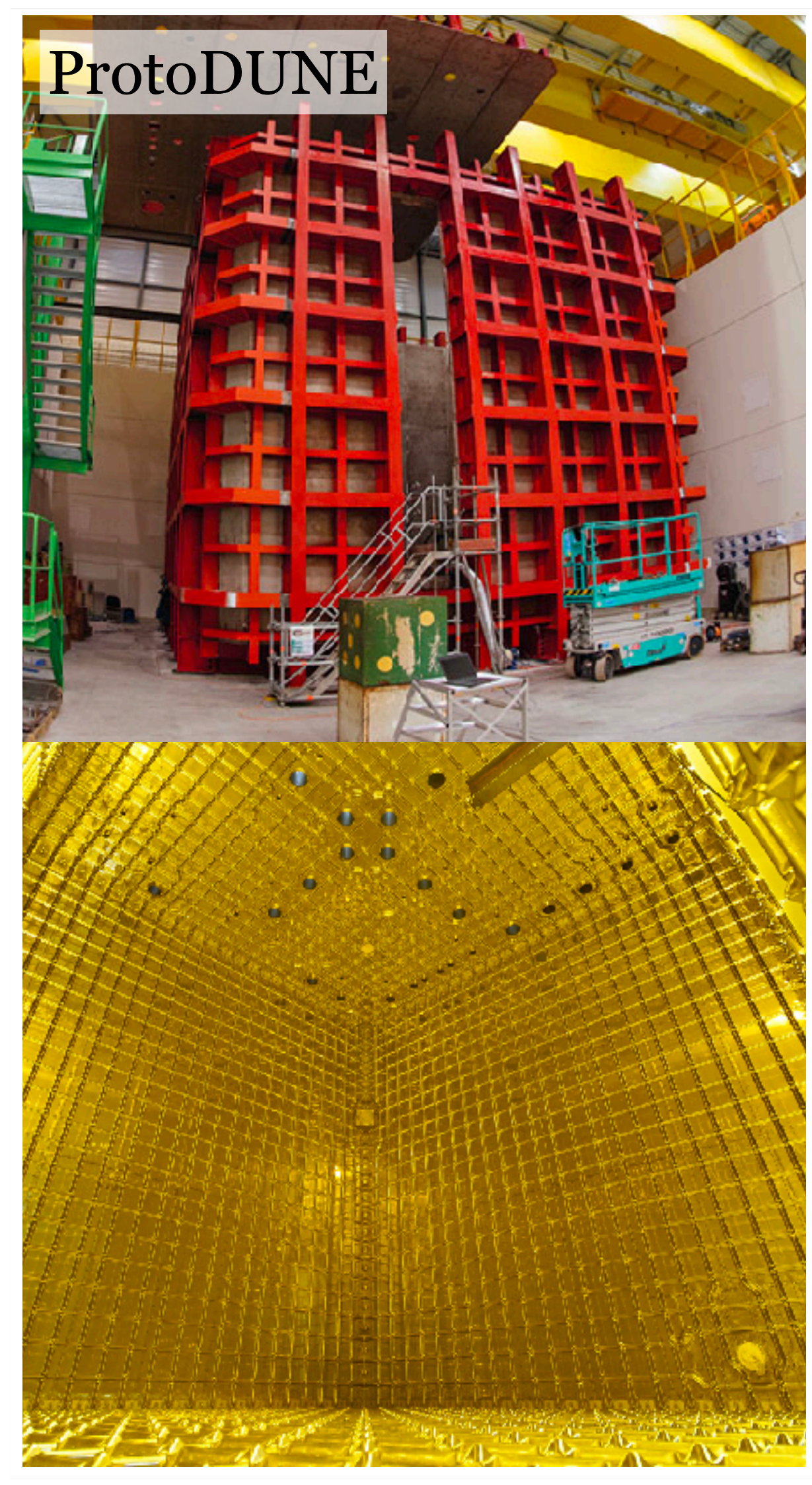
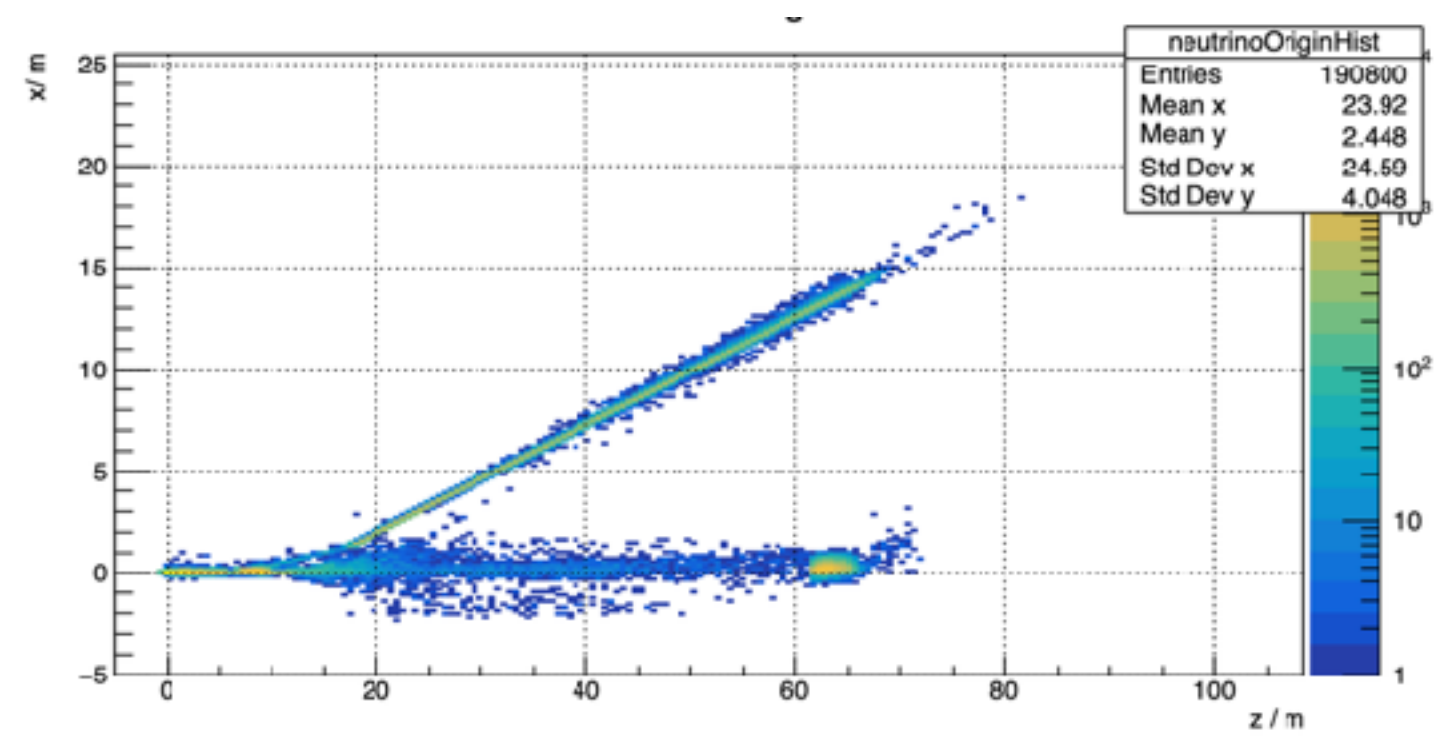
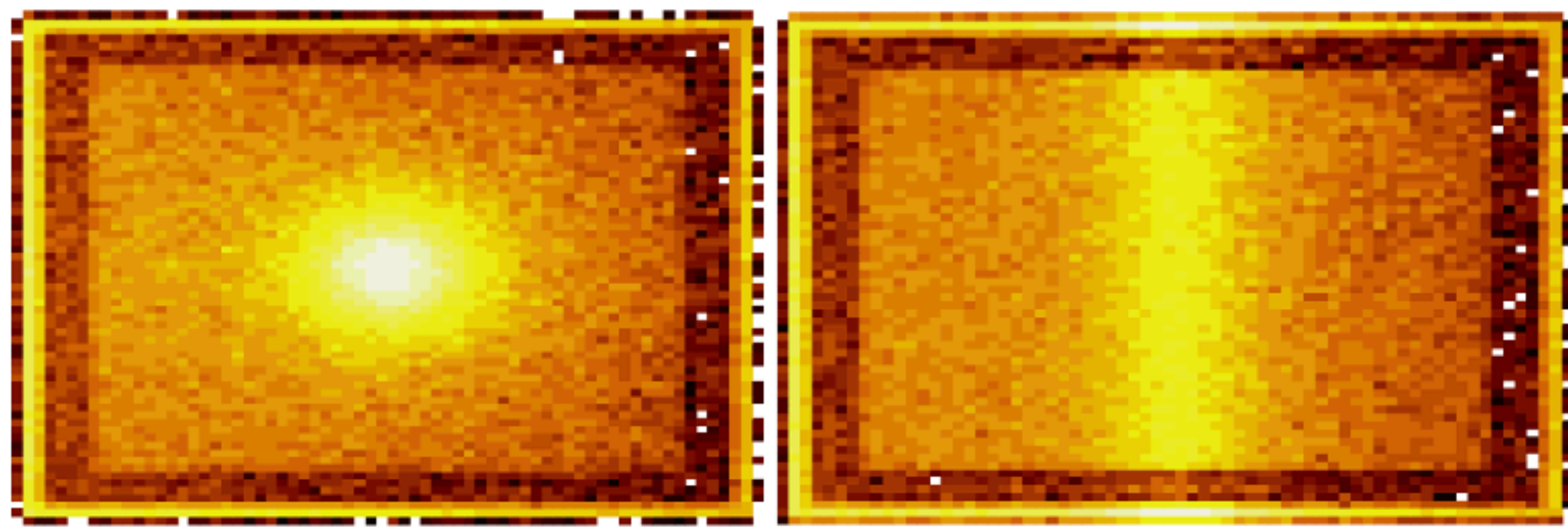
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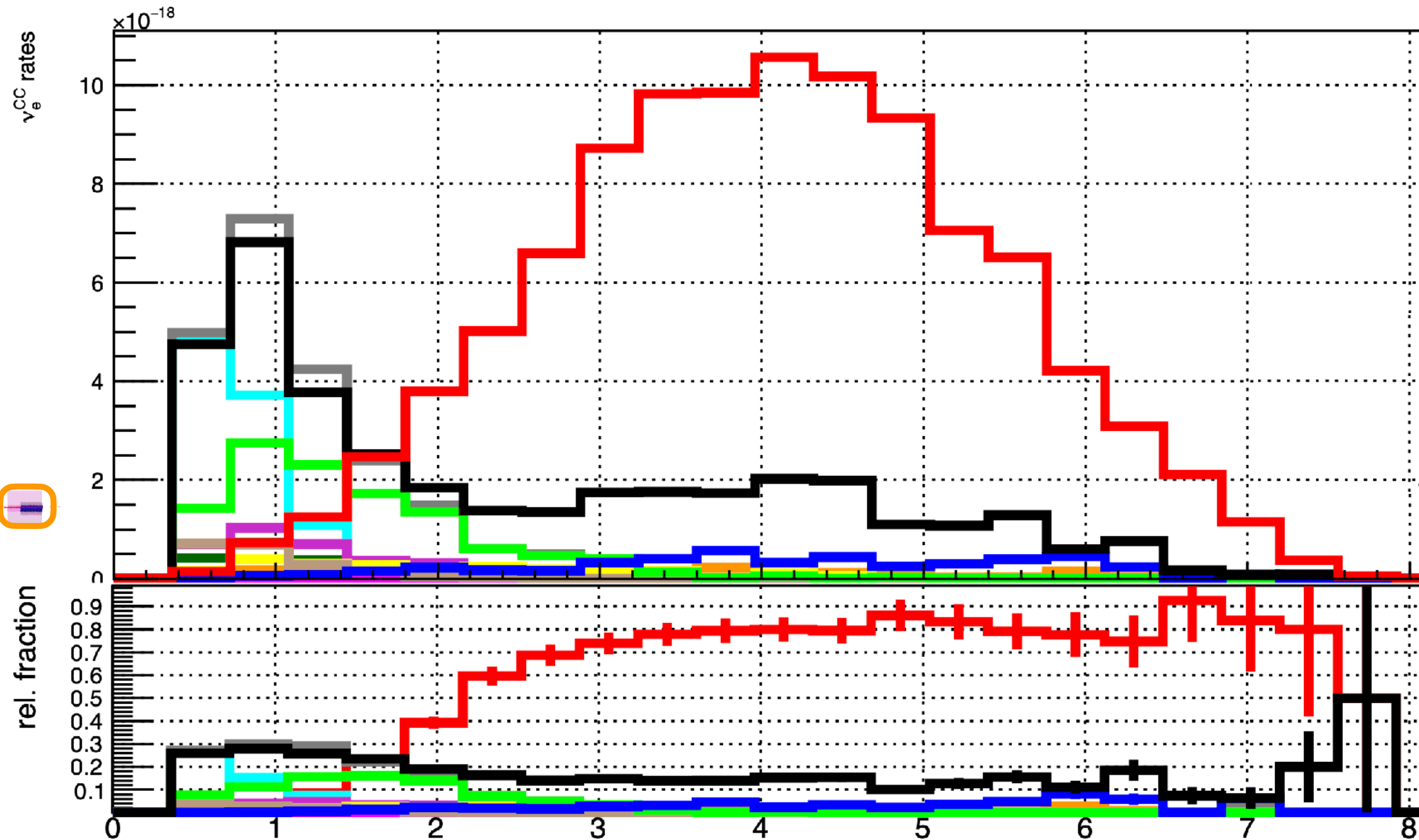
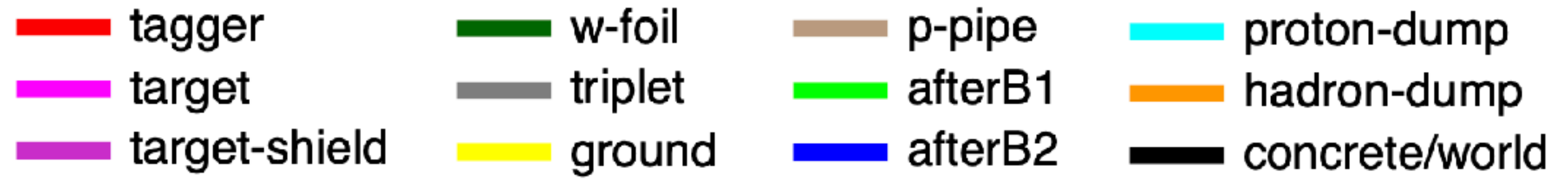
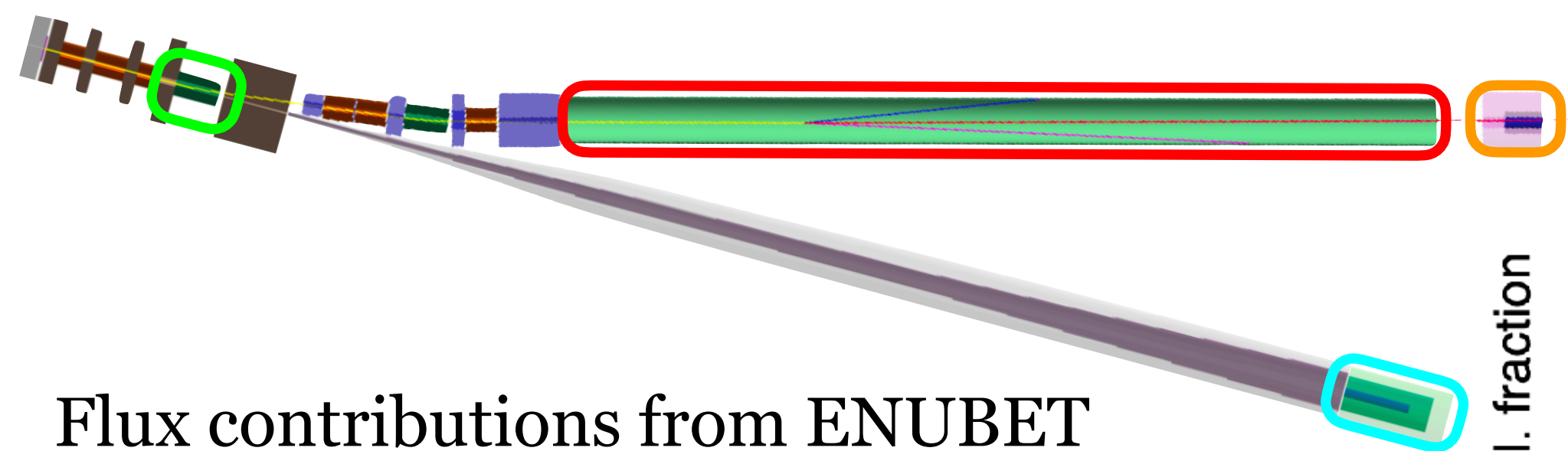
- Graphite core
- Iron middle layer
- Surrounded by borated concrete



- 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
- $\sim 80\%$ of the ν_e component above 2 GeV is monitored



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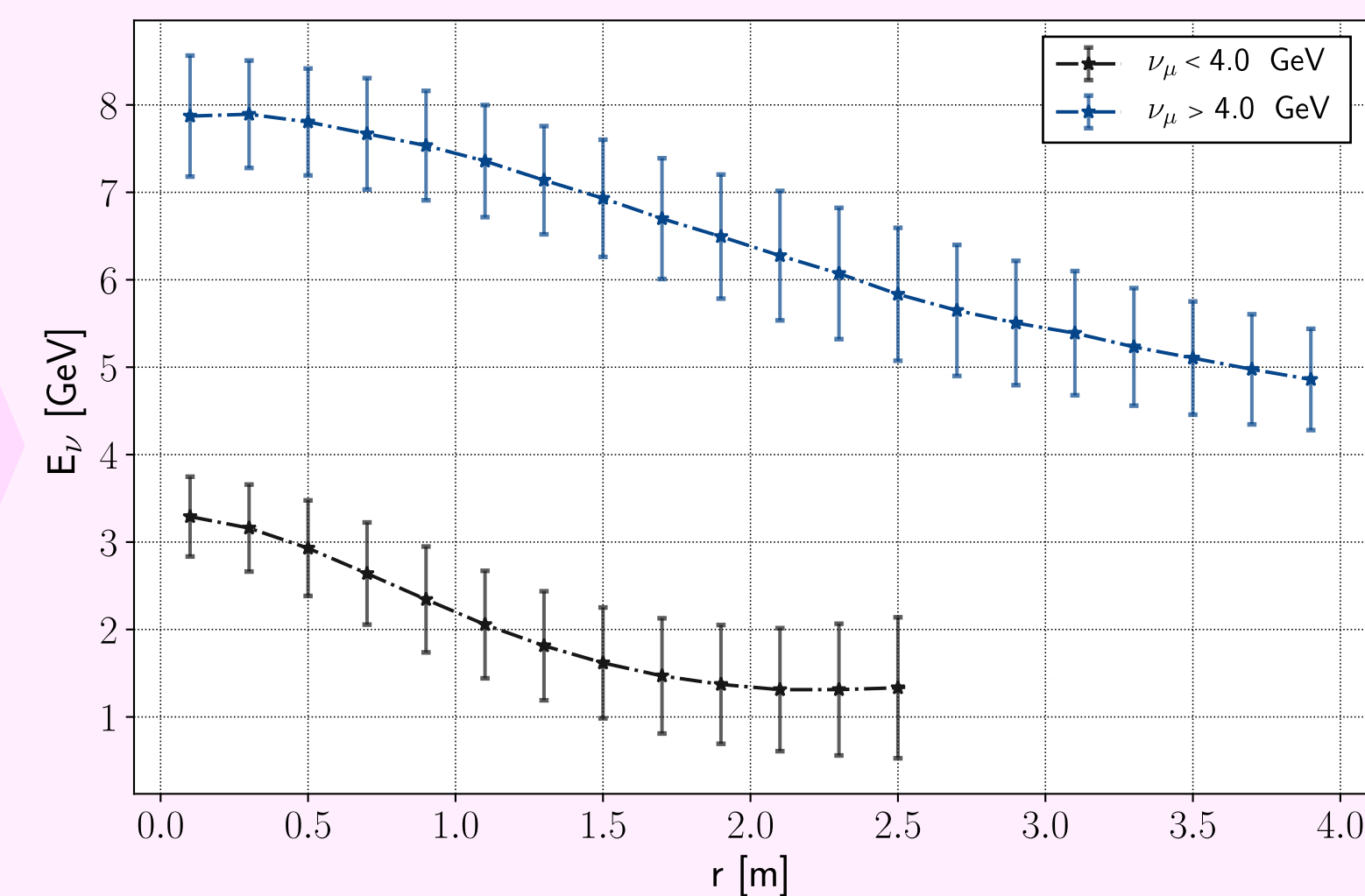
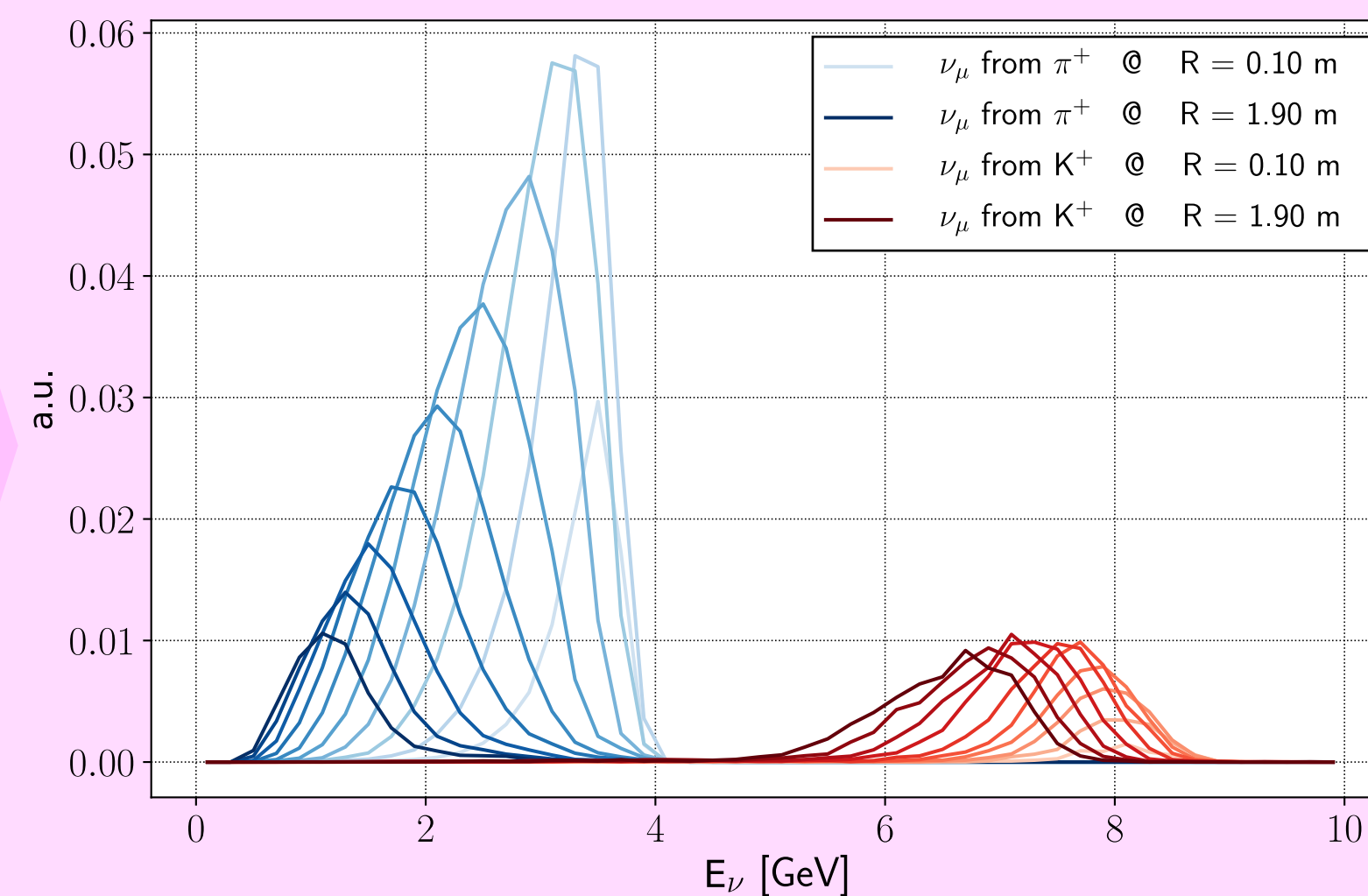
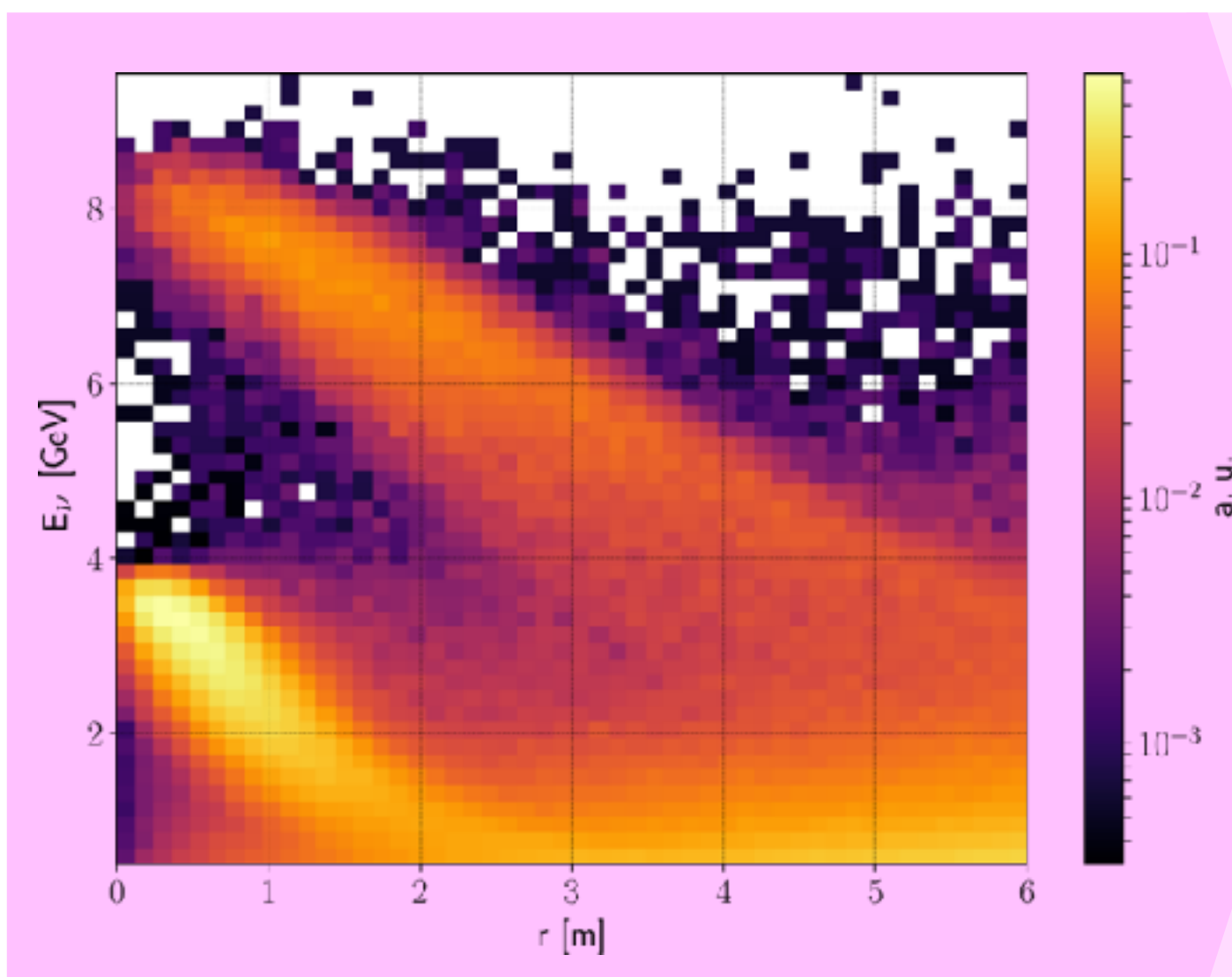




- Similar to T2K, we can use the narrow-band off-axis technique
- A strong correlation between neutrino energy, E_ν , and radial distance of vertex from beam axis, R

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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- A strong correlation between neutrino energy, E_ν , and radial distance of vertex from beam axis, R

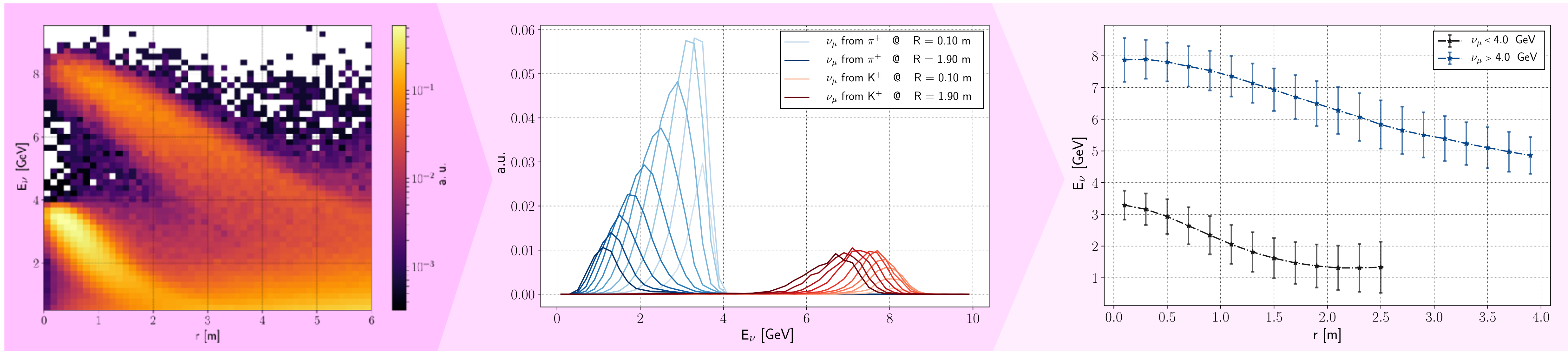
Precise determination of E_ν :

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8-25% resolution in DUNE ROI

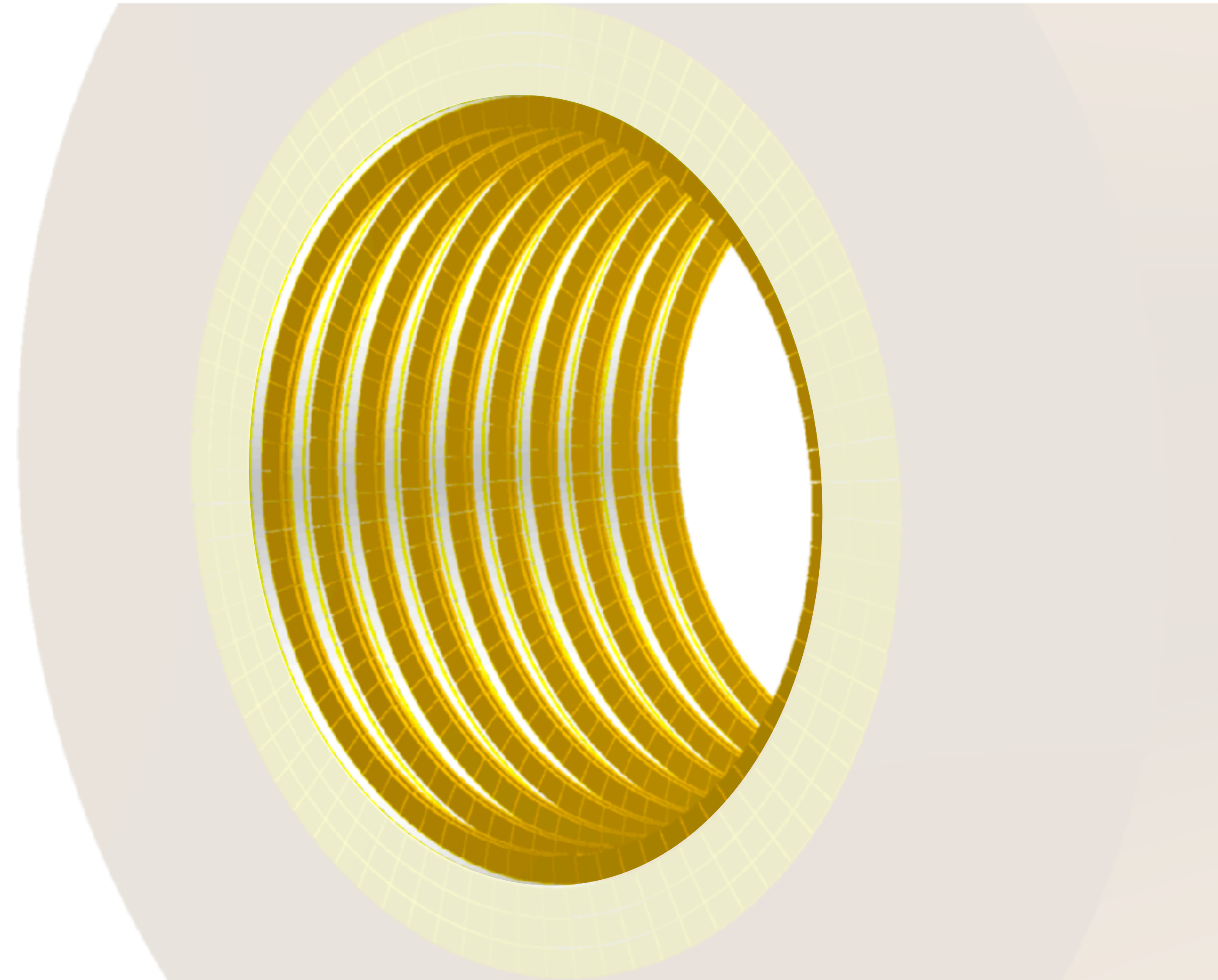
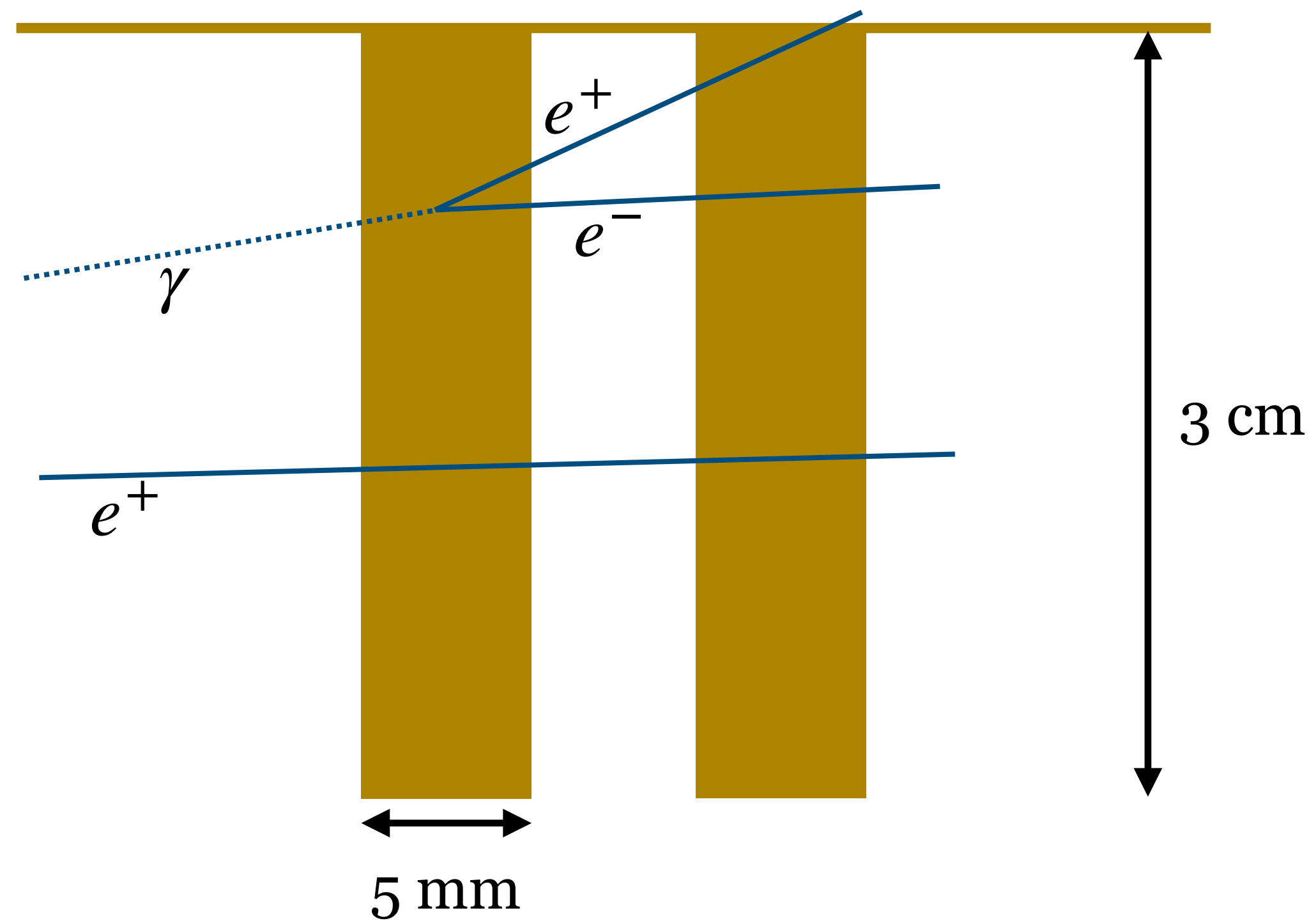
R&D efforts for **DUNE** and **HK** optimisation with a multi-momentum beamline

30% resolution in HK ROI



Photon Veto

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

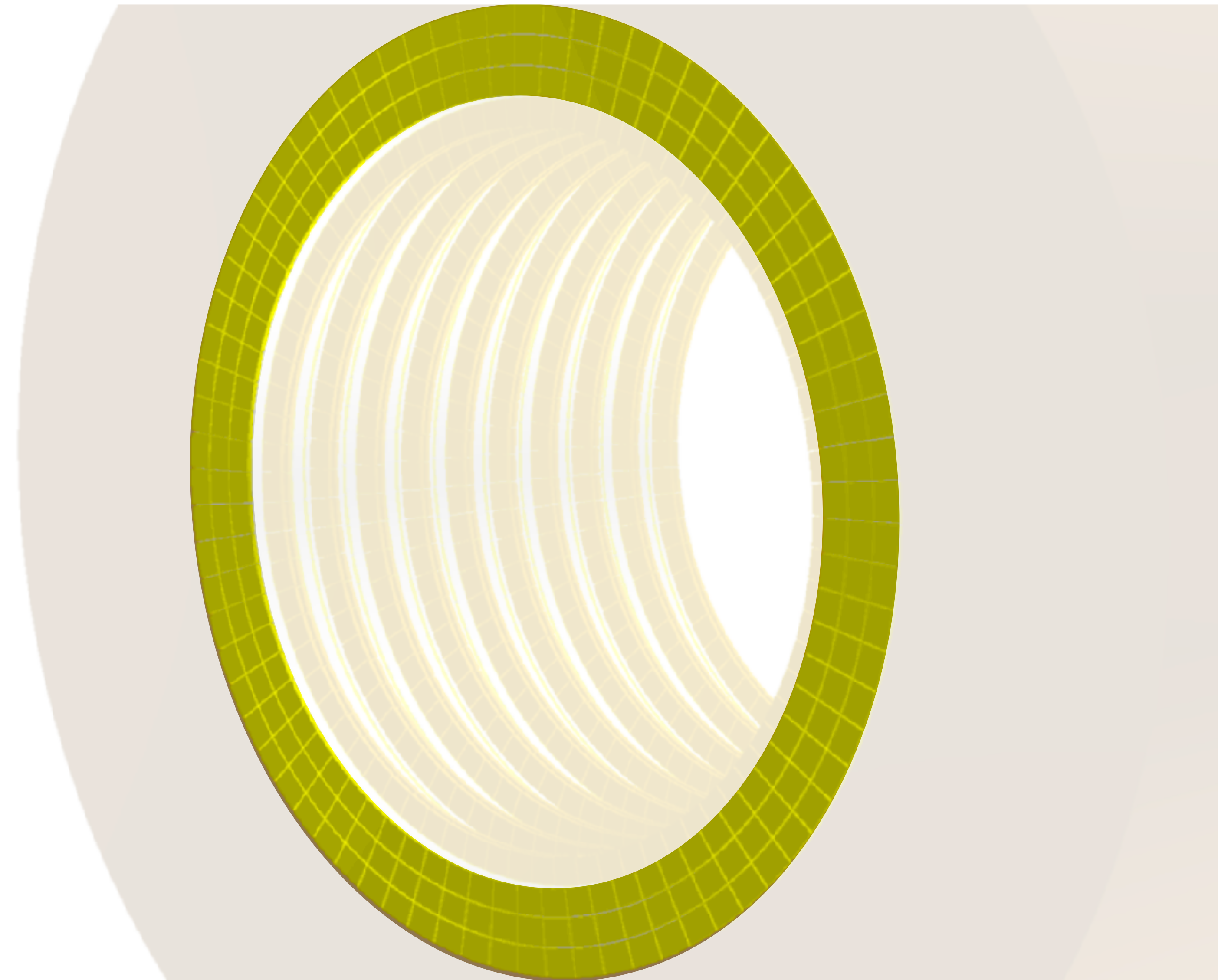
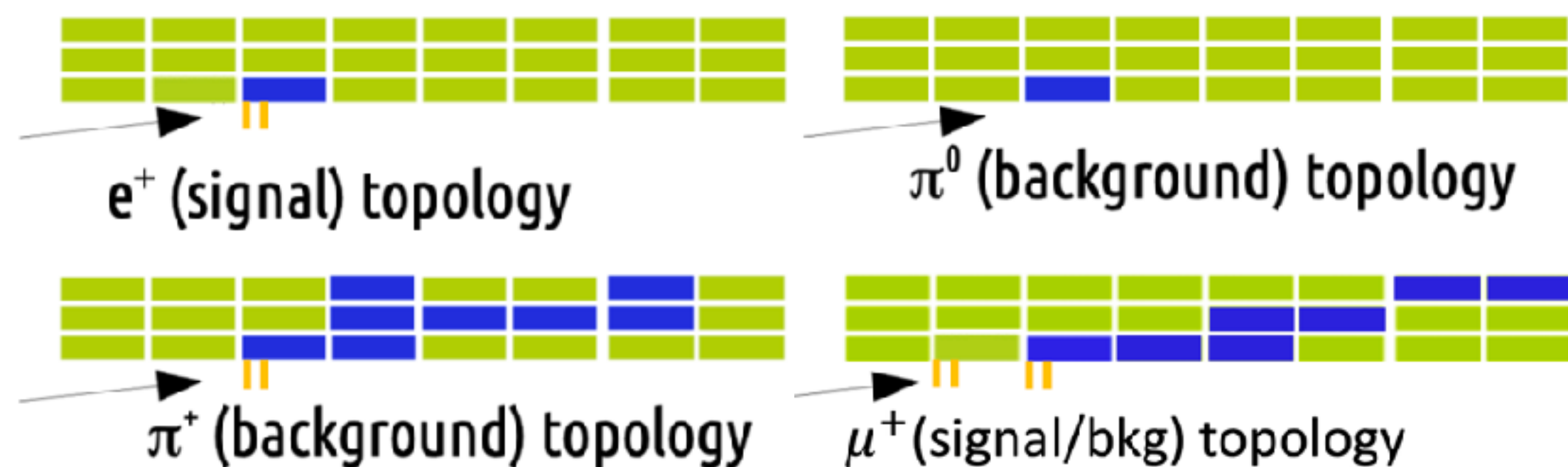


Photon Veto

- 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



Photon Veto

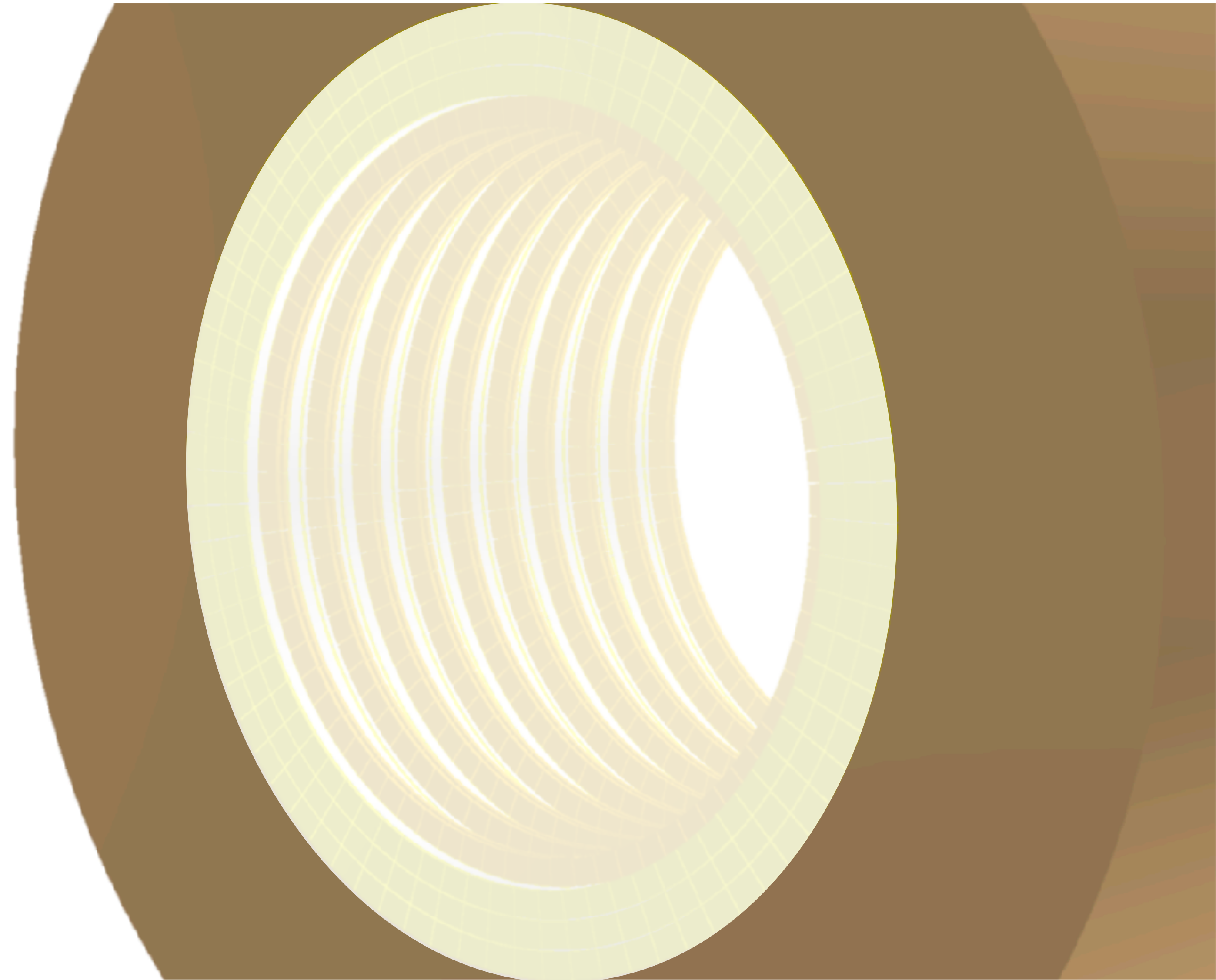
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- 3 radial layers of lateral readout calorimetric modules (LCMs)
- WLS fibres to SiPMs for light collection

Shielding

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



- 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

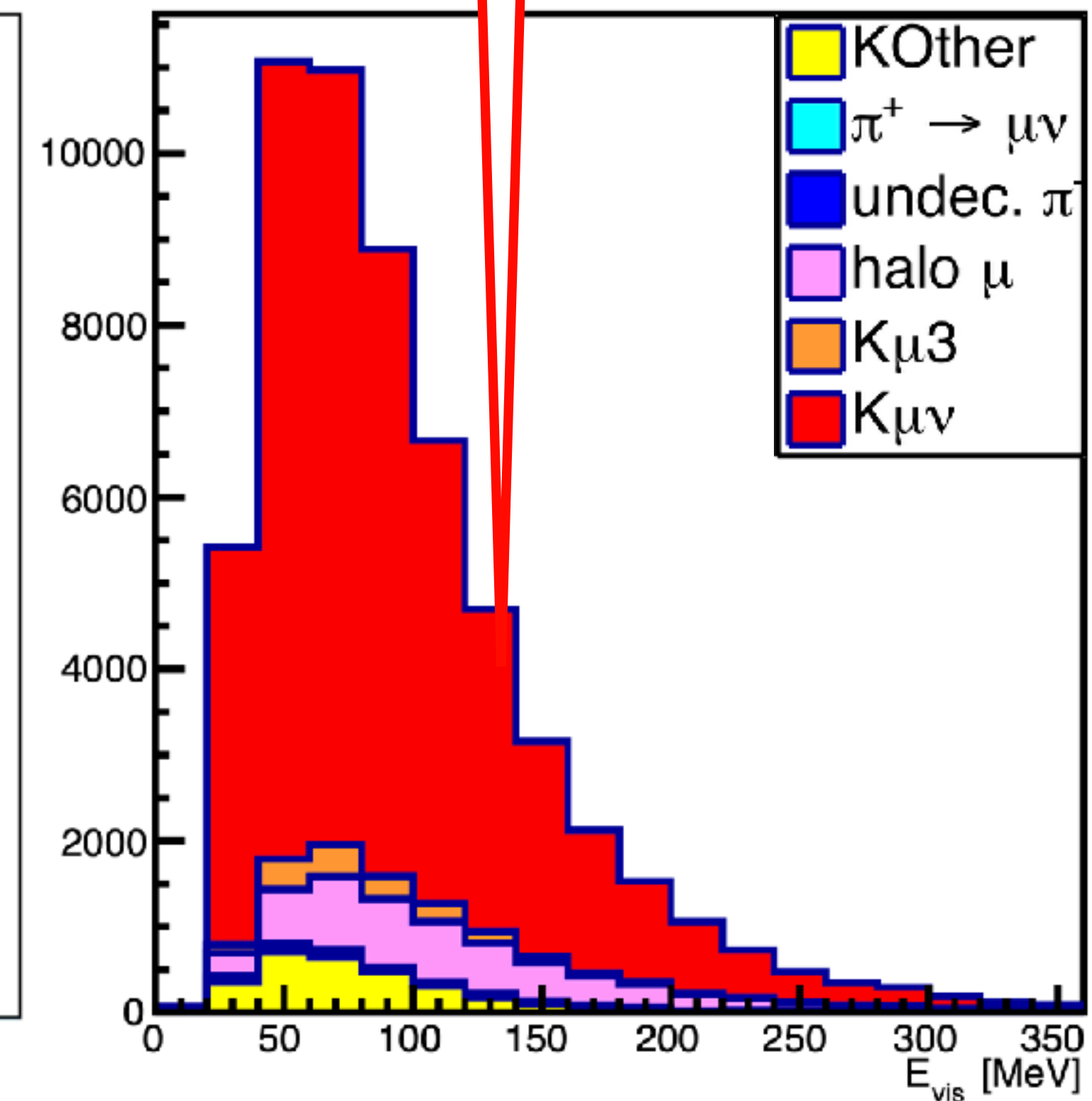
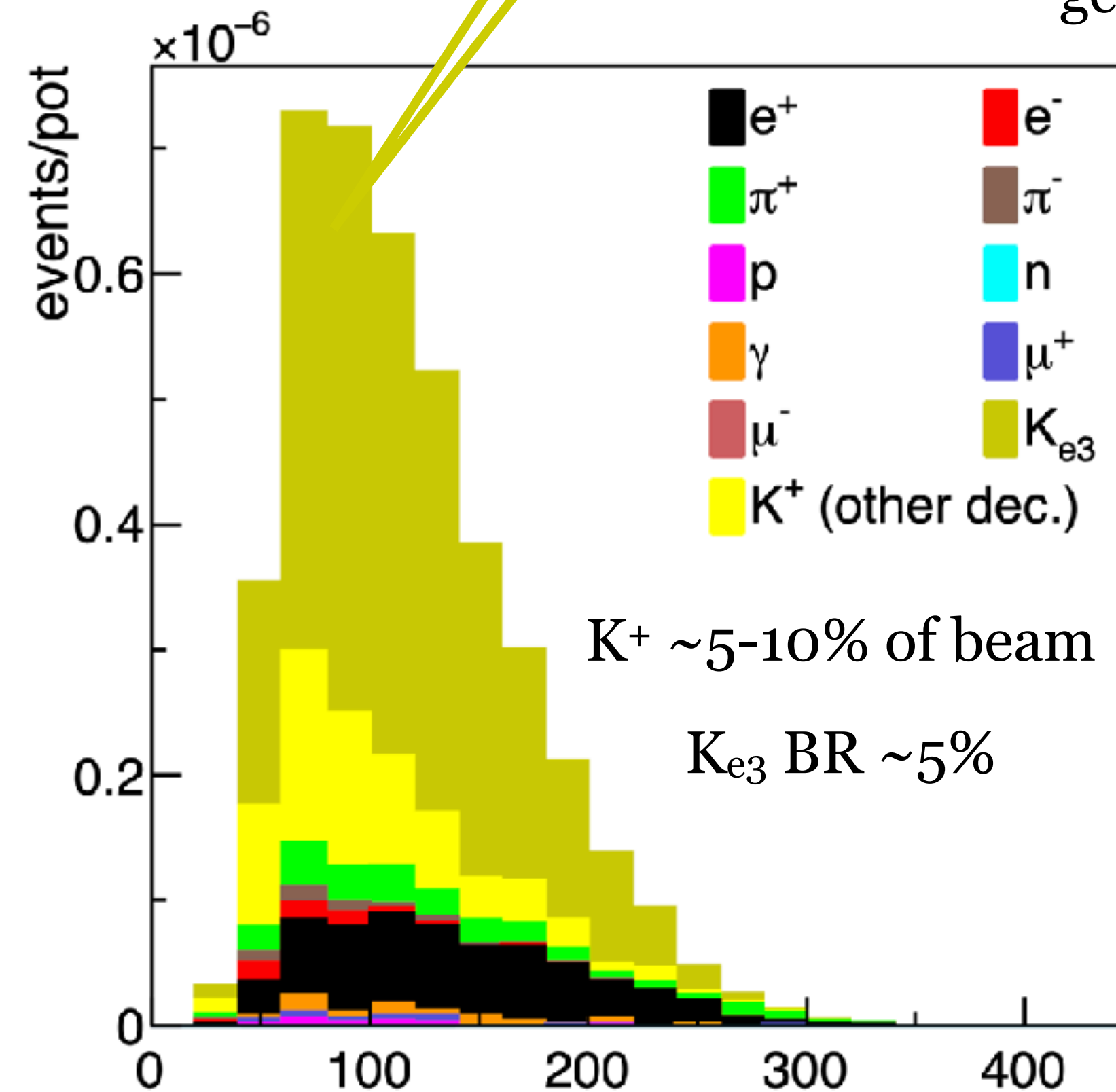
Eff = 22%

$K_{\mu 2}$ muons: ν_μ

S/N = 6

Eff = 34%

Efficiency is half geometrical

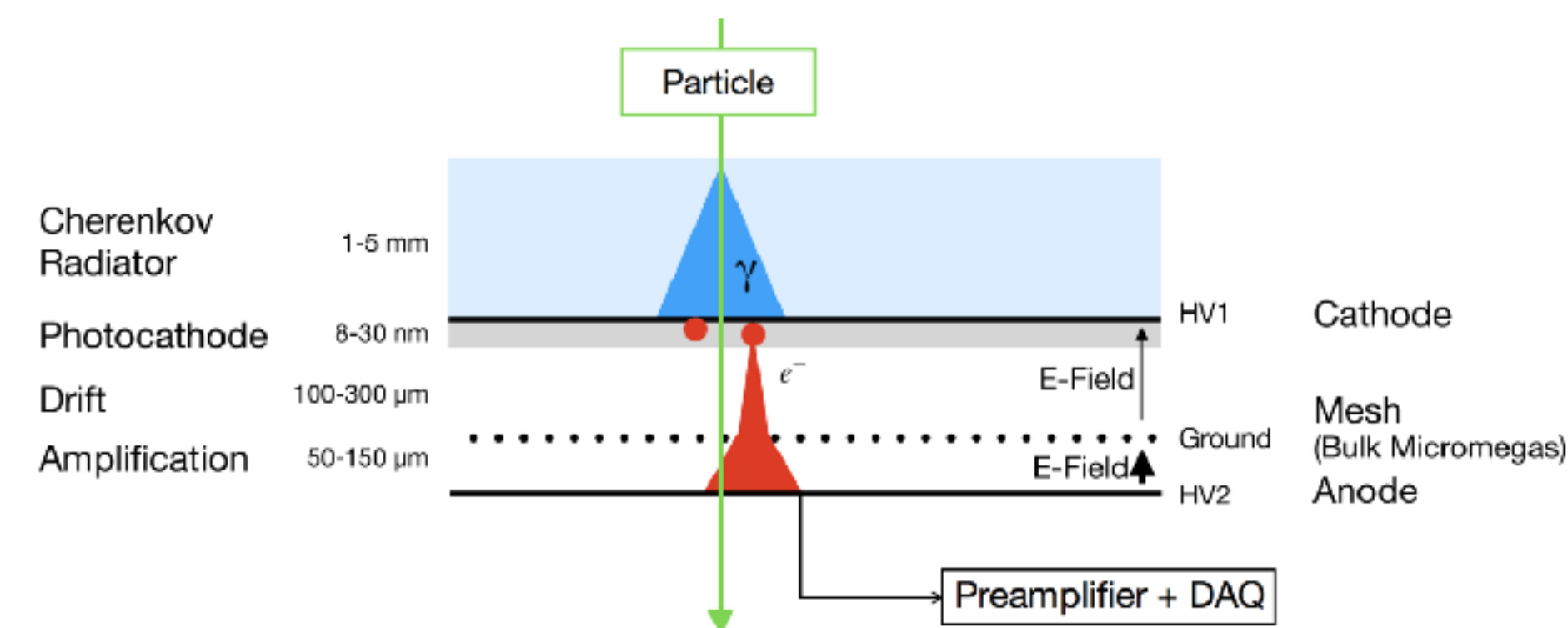


- Measuring $\pi_{\mu 2}$ muons constrains low-energy ν_{μ}
- Low angle muons at out of tagger acceptance
 - Need muon stations post-hadron dump
- Detector constraints: muons rate ($\sim 2 \text{ MHz/cm}^2$), radiation hardness ($\sim 10^{12} \text{ MeV-n}_{\text{eq}}/\text{cm}^2$)

PIMENT

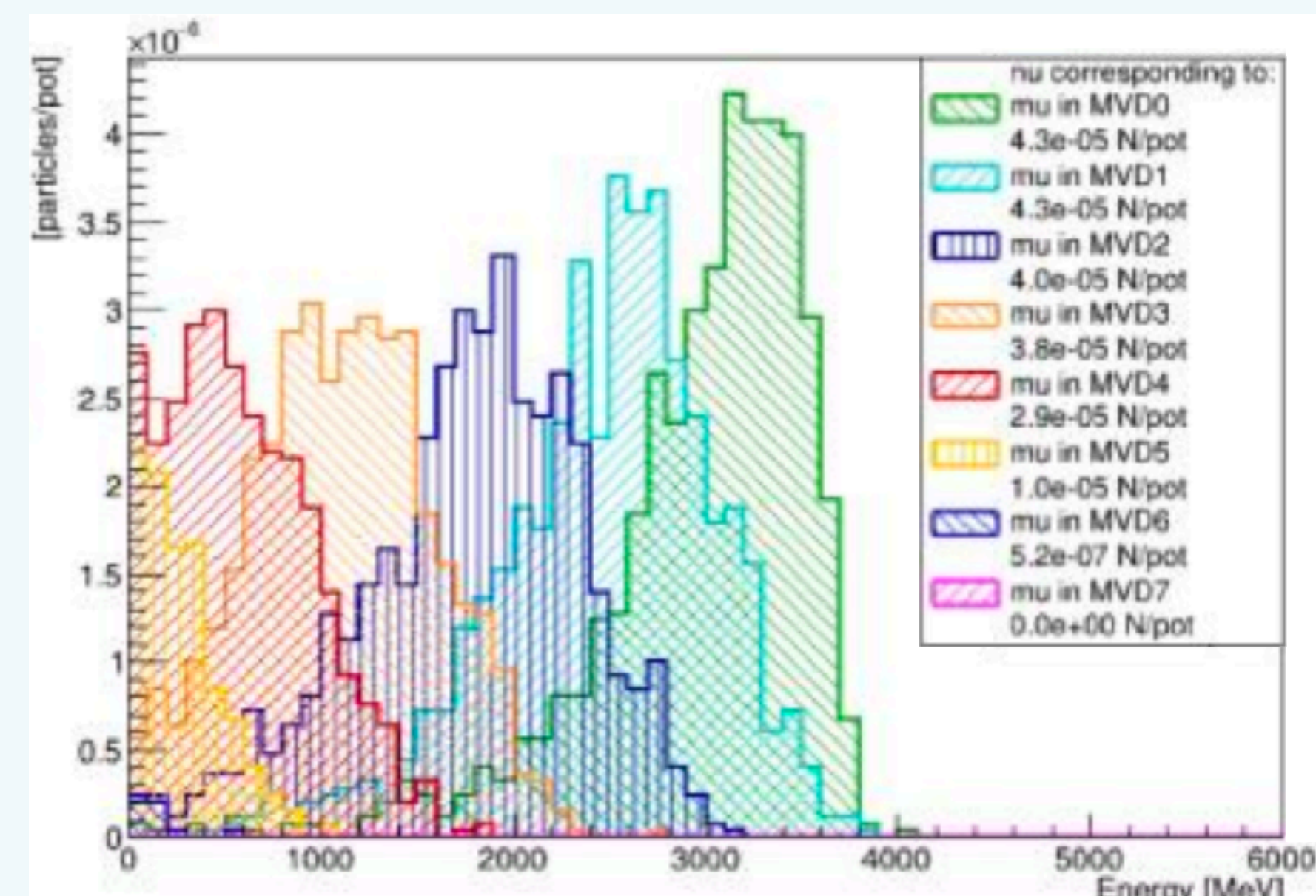
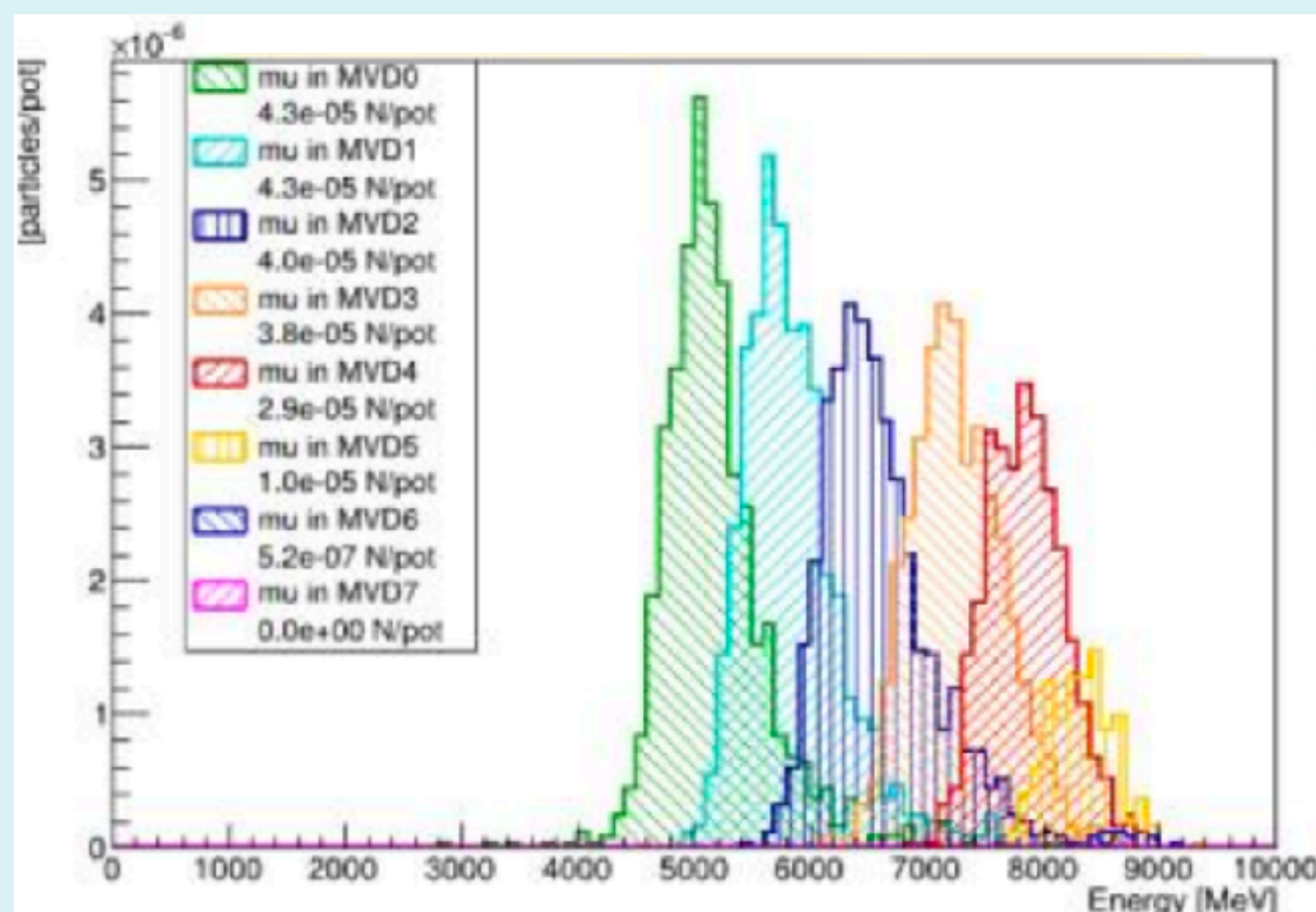
PICOSEC Micromegas
Detector for ENUBET

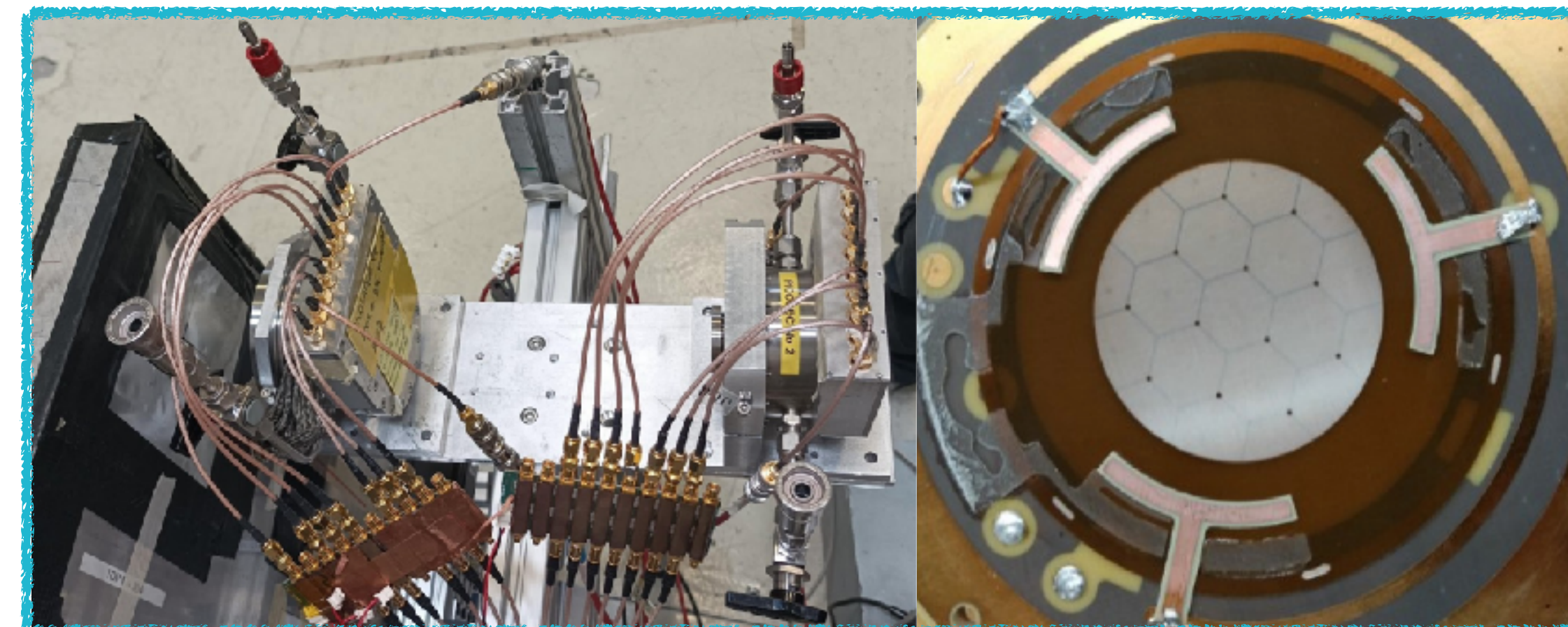
Fast micromega
detector with sub-25
ps precision.



Correlation between traversed stations and neutrino energy can be exploited.

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

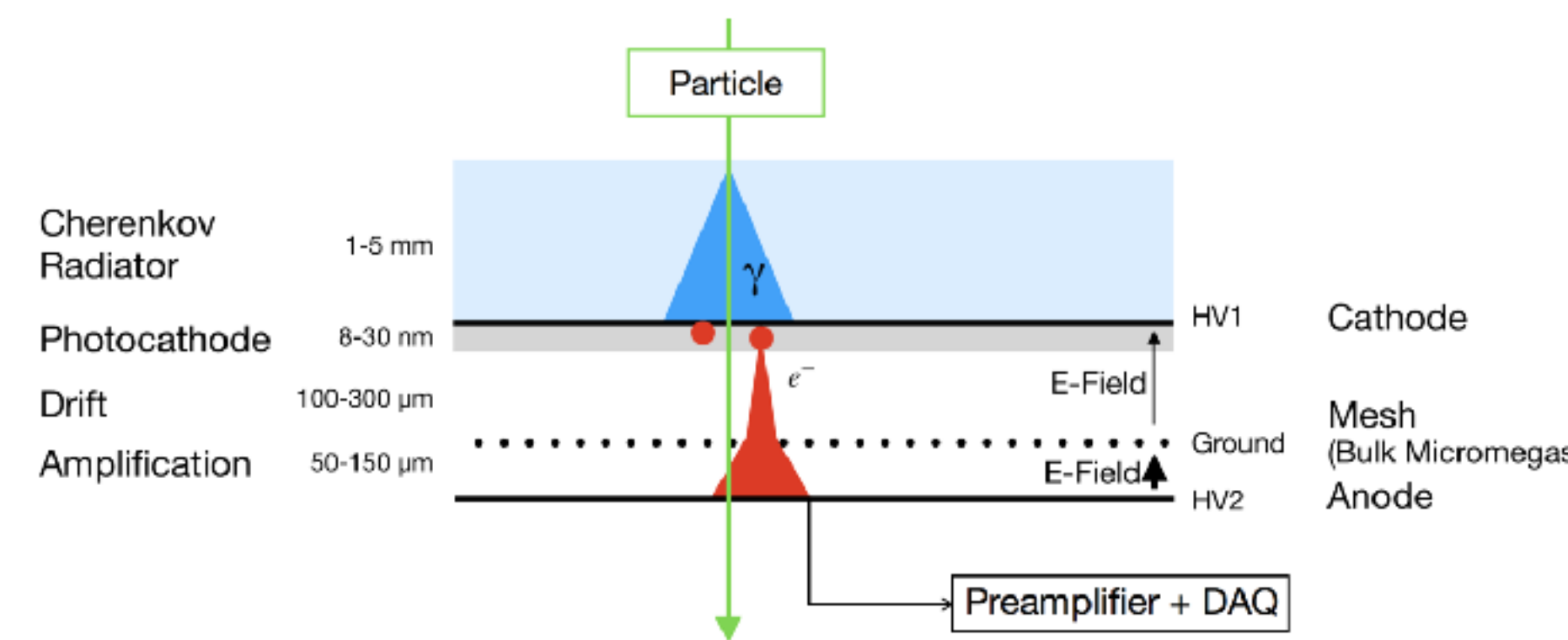




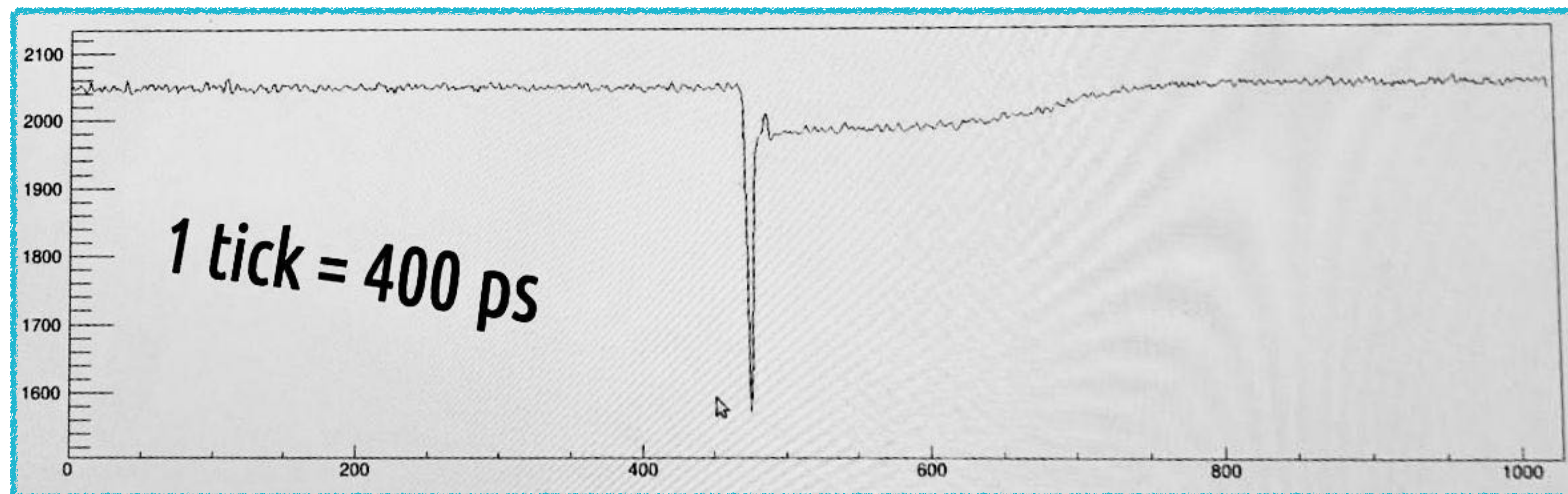
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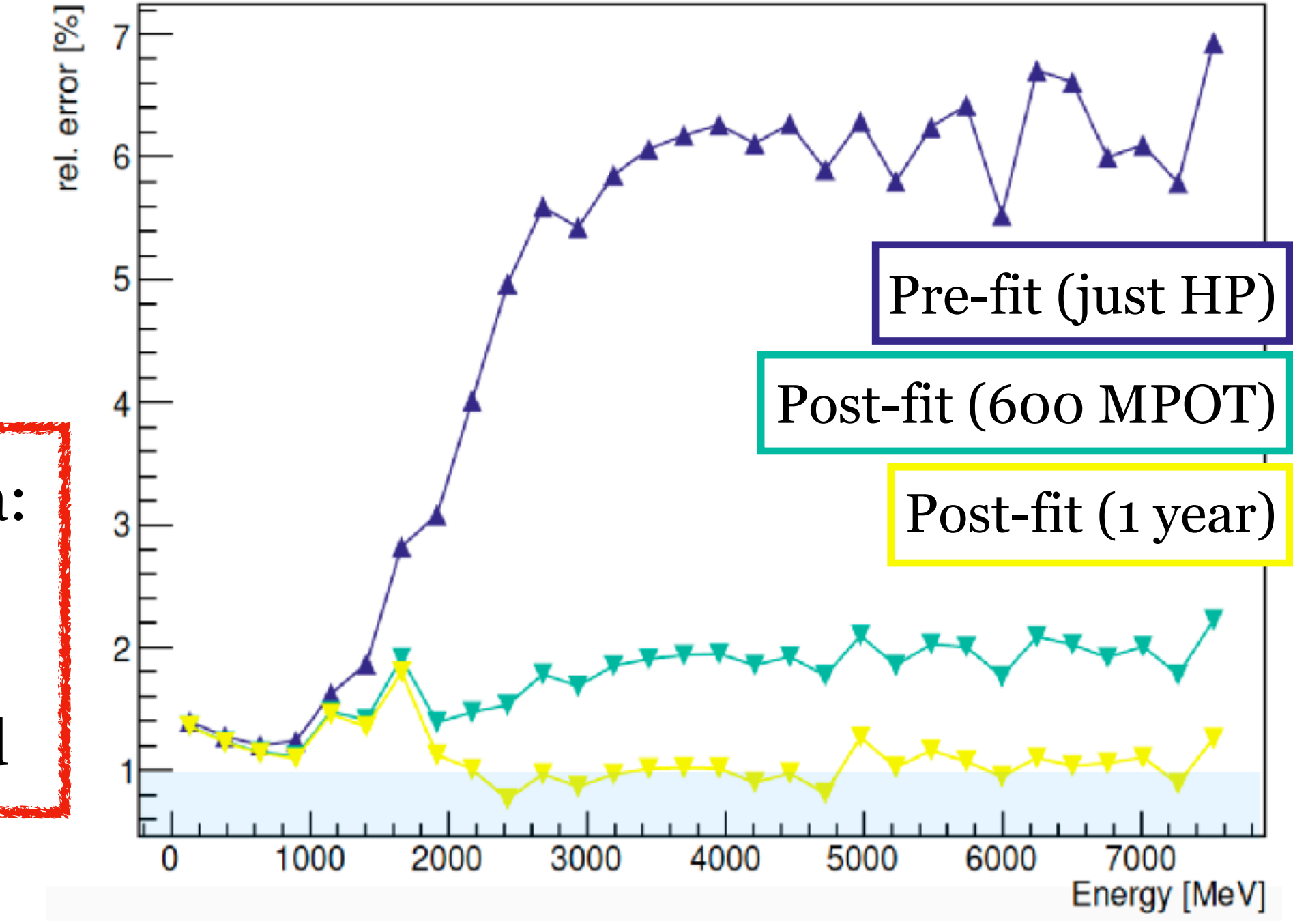
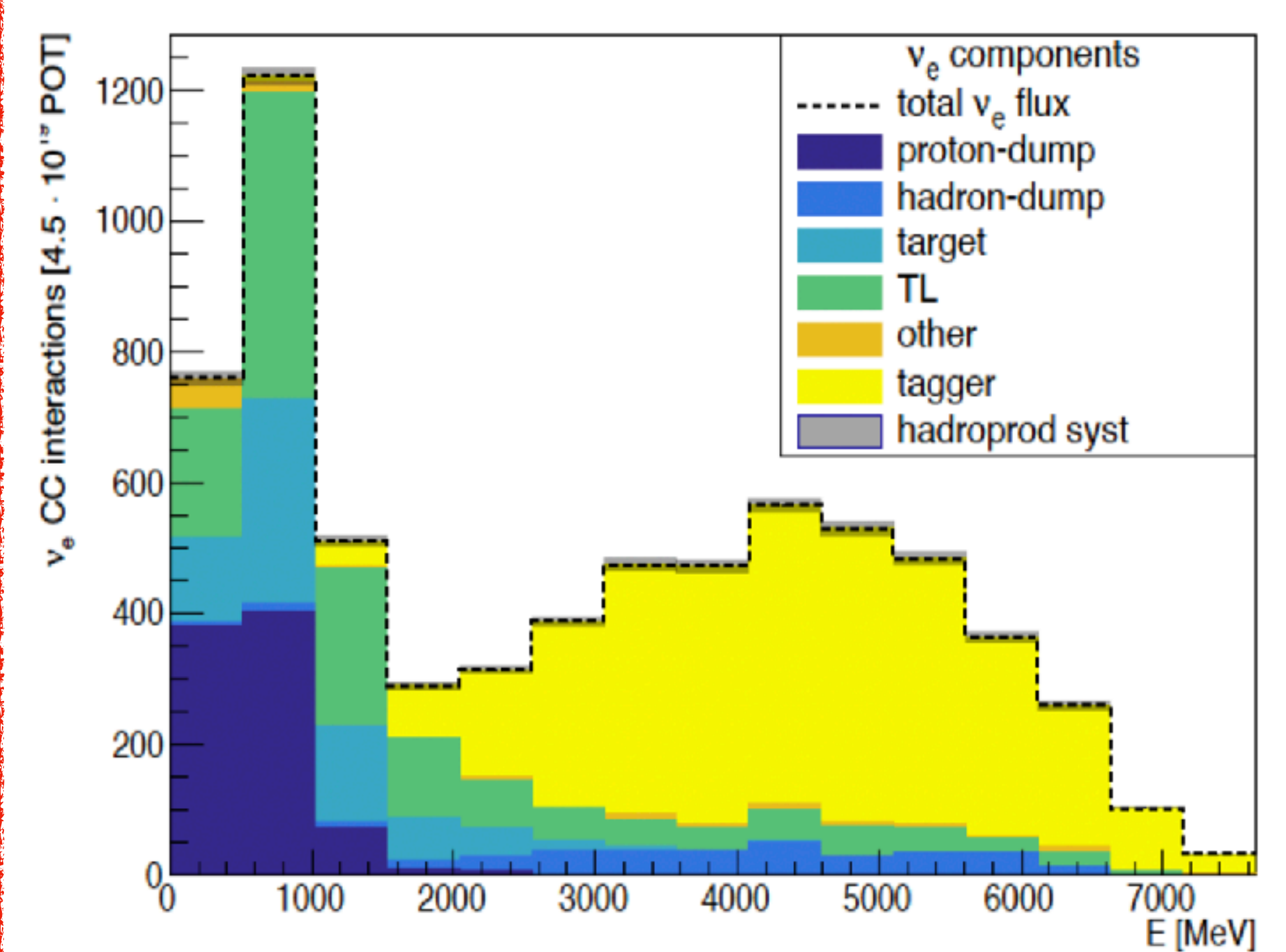
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- Tested in T9 with the demonstrator (later!) in Aug. 2024
- Achieving a few 10s of ps resolution



- 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%

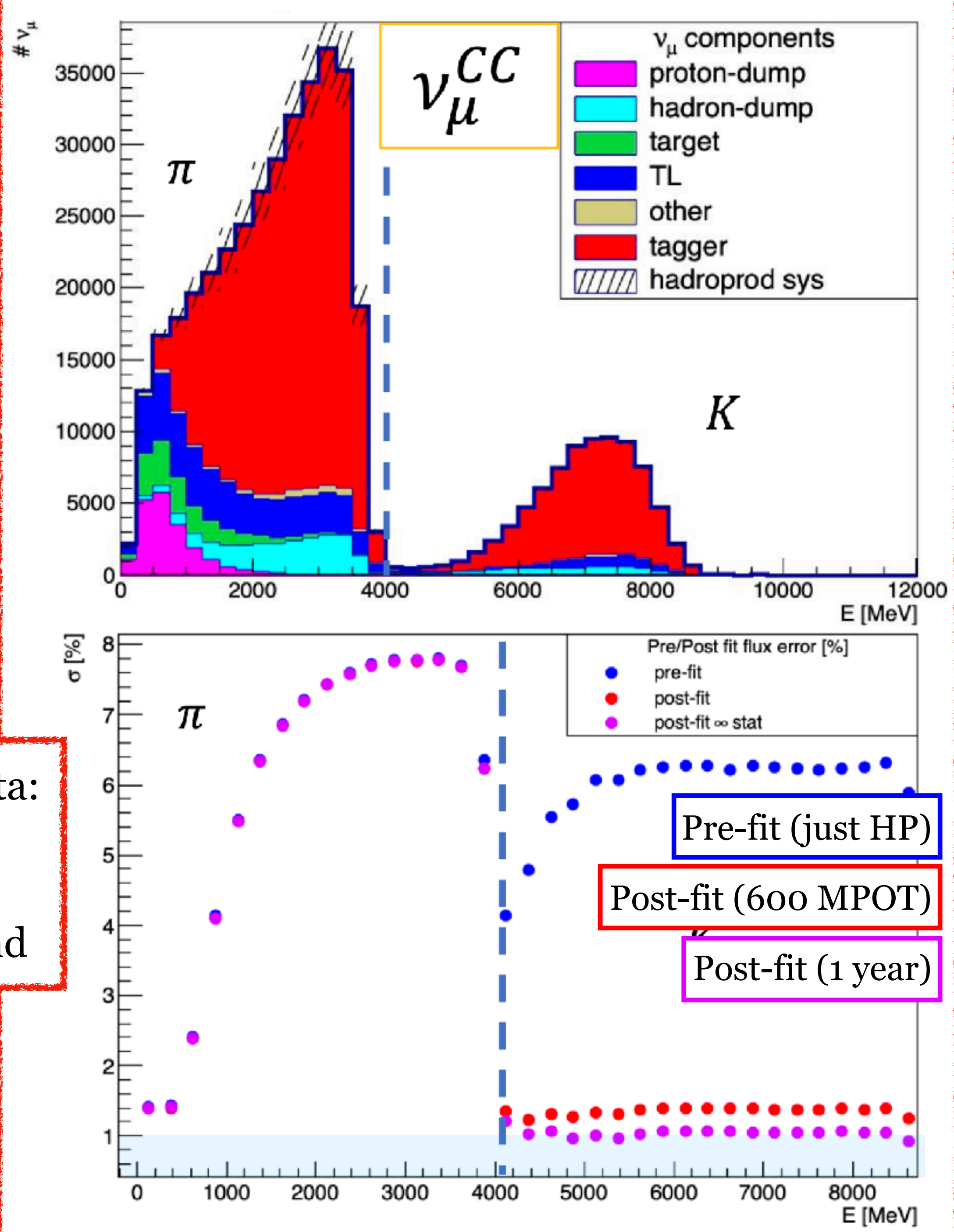


Total rates calculated for 1 year of data:

- SPS @ CERN, 4.5×10^{19} POT
- 500 t detector, 50 m from tunnel end

*Hadro-prod from NA56/SPY experiment

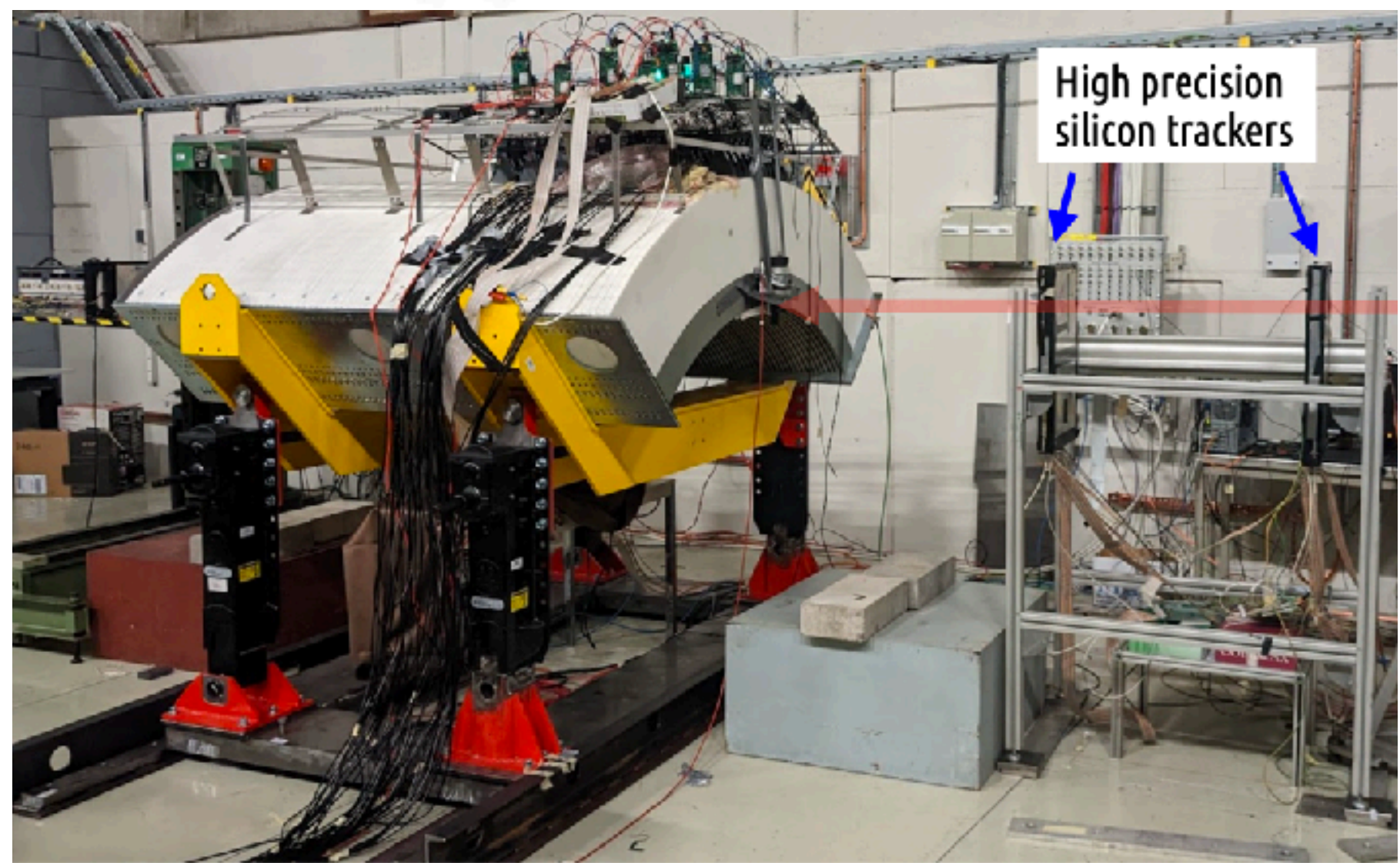
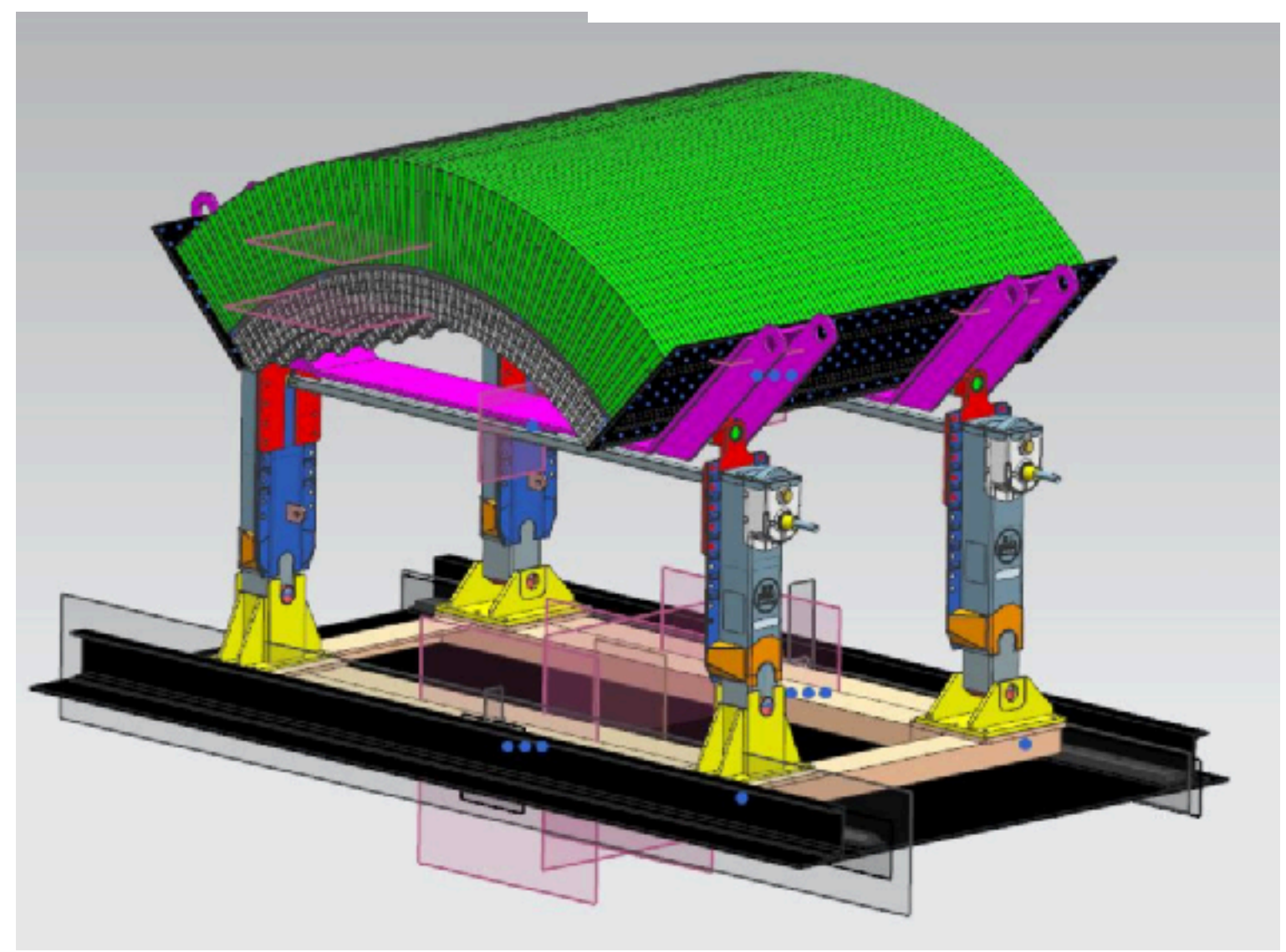
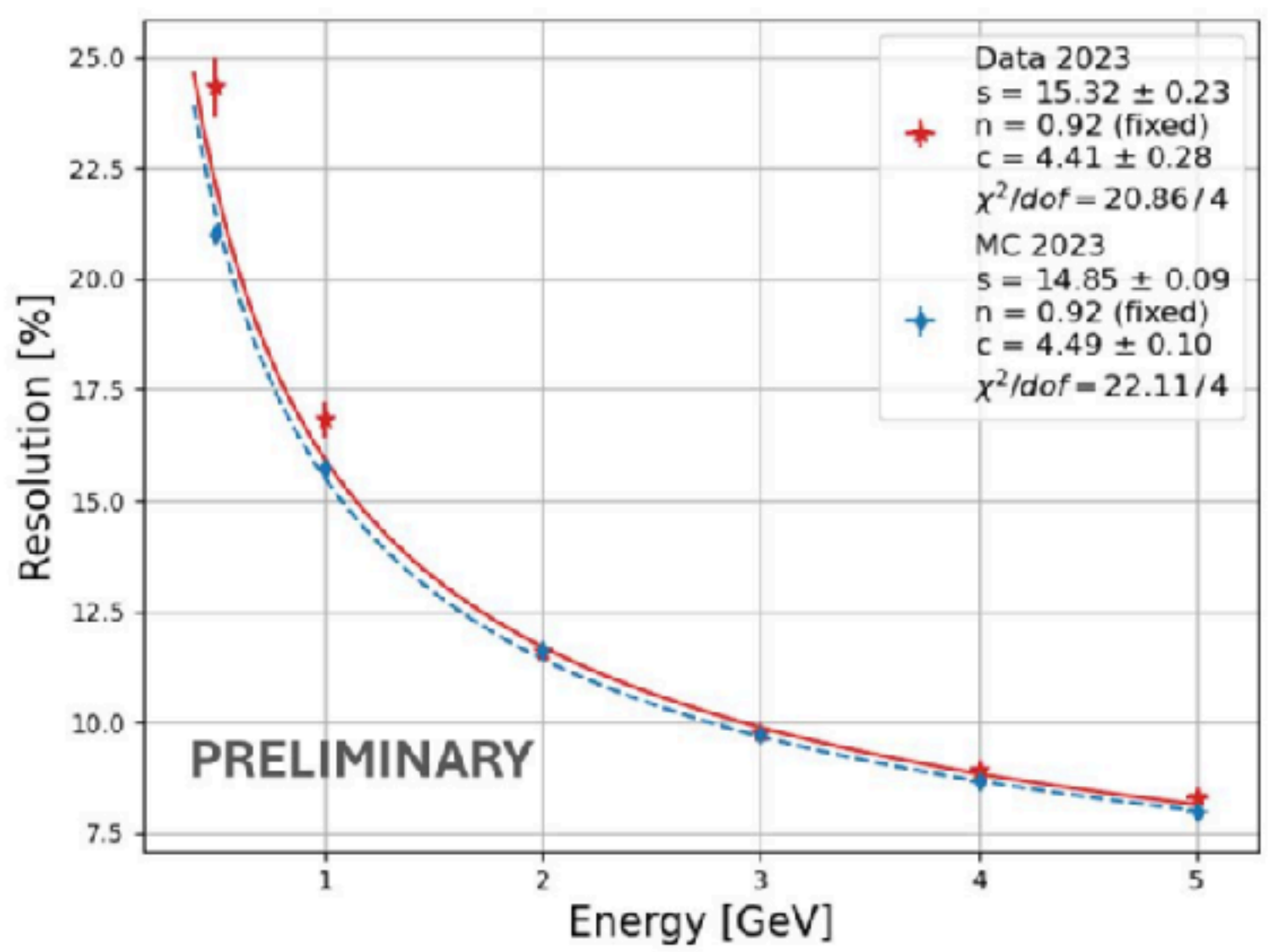
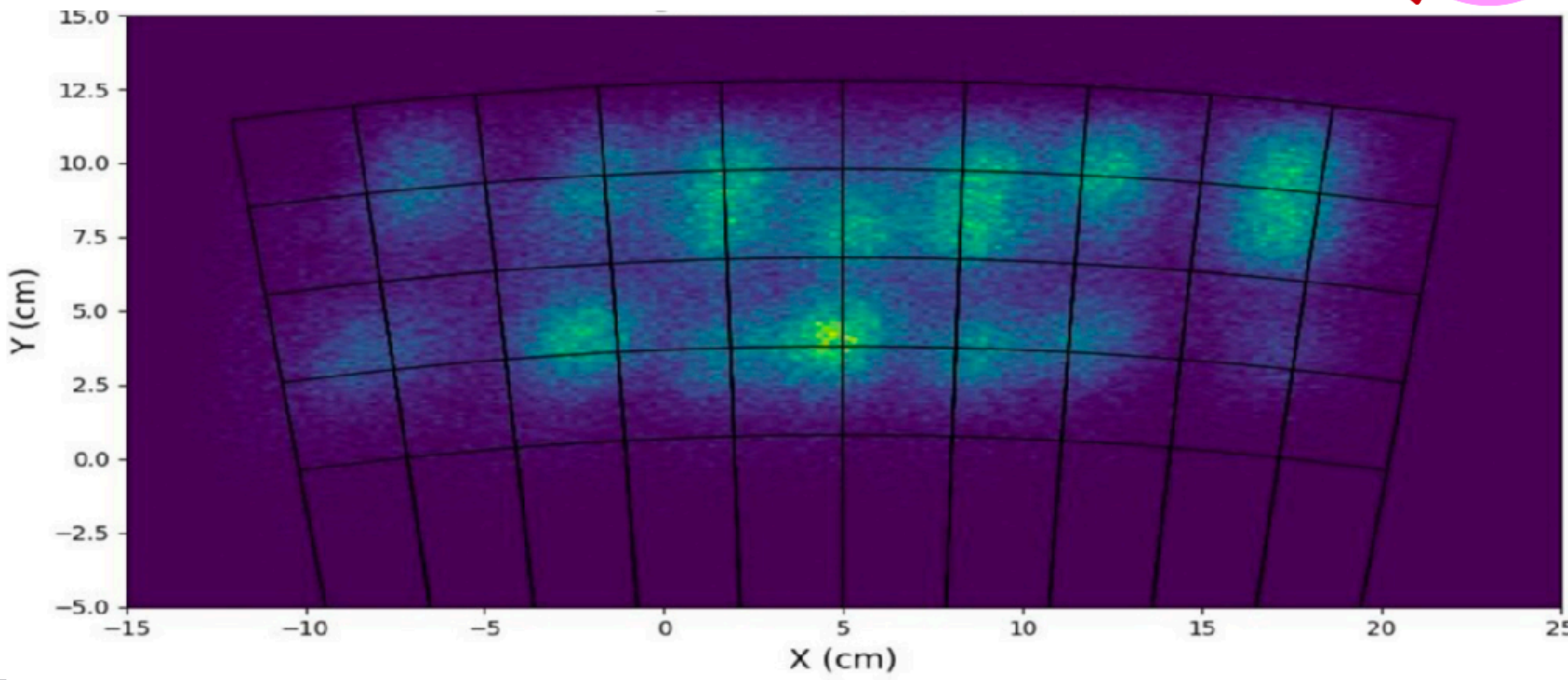
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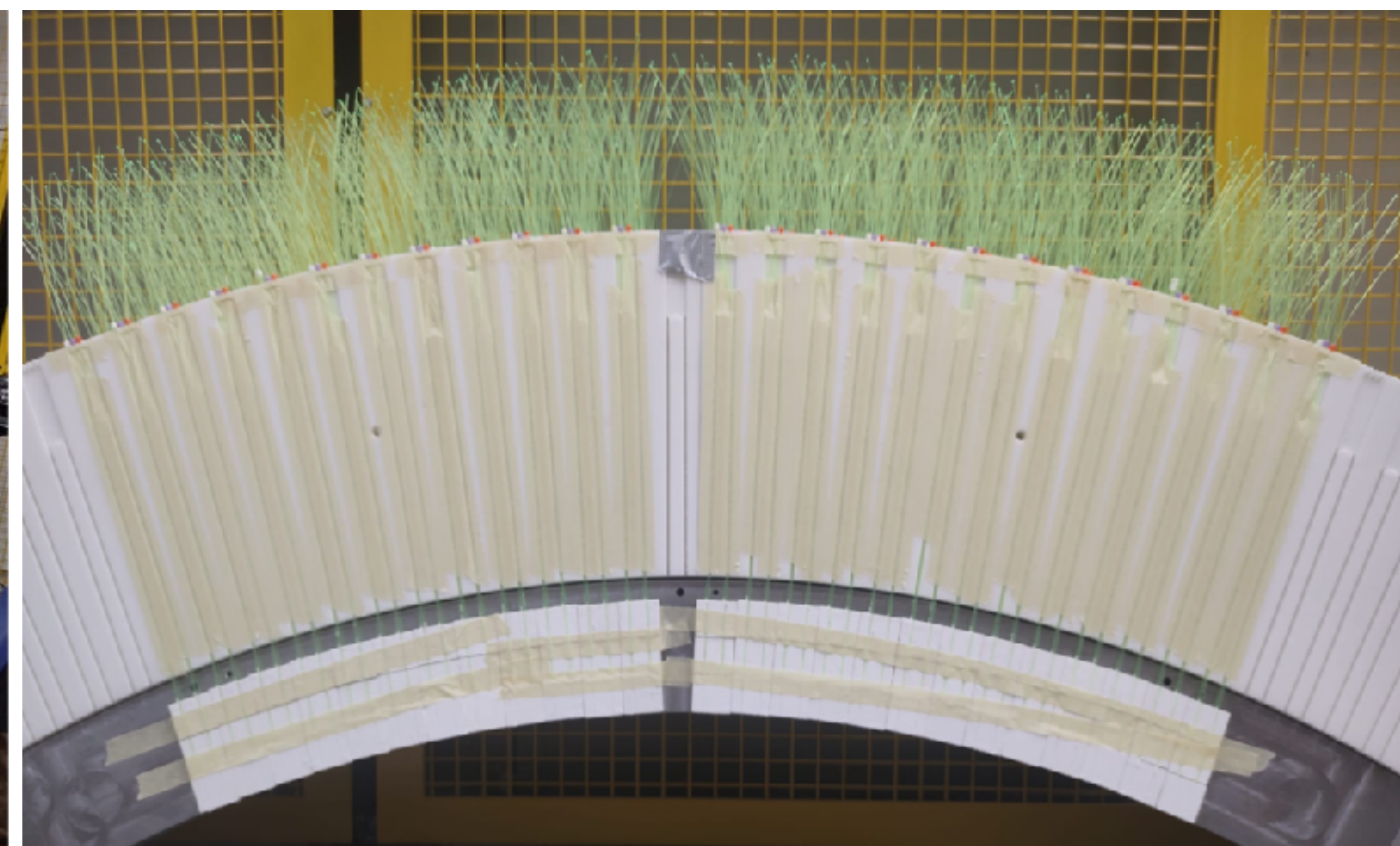
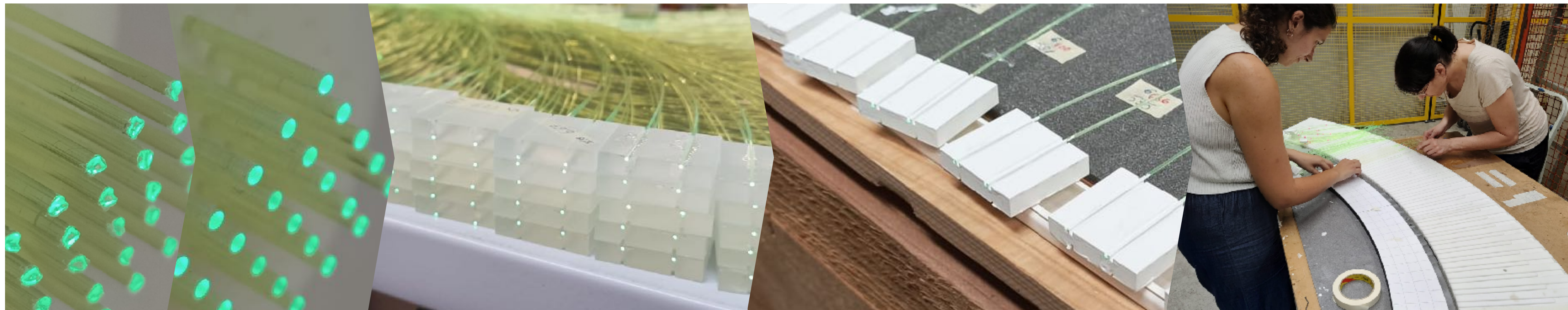


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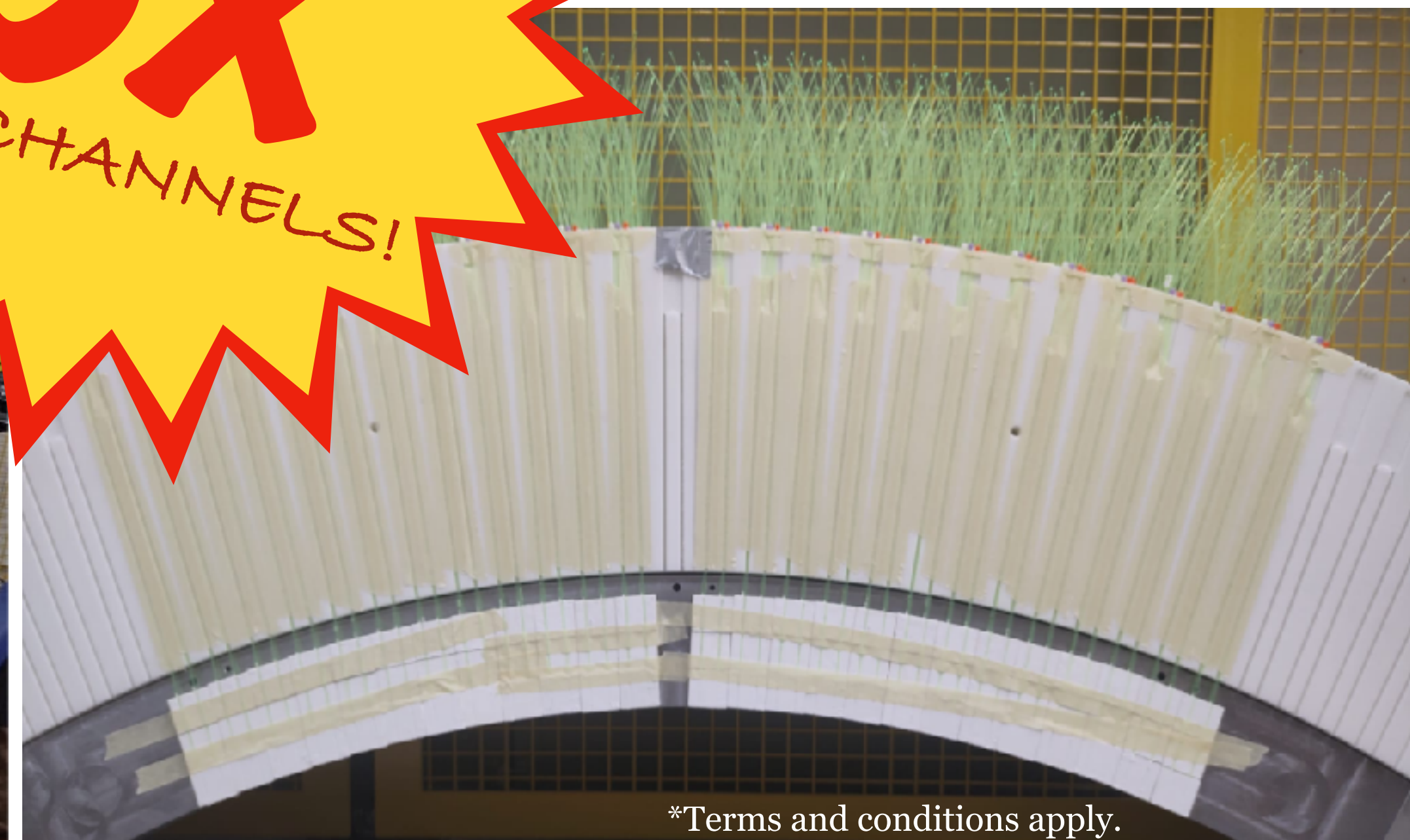
- Part of the decay tunnel was built and tested @ CERN in October 2022
 - The culmination of the ERC grant!
 - 1.65 m long, 3.5 ton, 90° coverage
 - 75 layers of: 1.5 cm iron, 7 mm scintillator
- Modular design to increase coverage easily







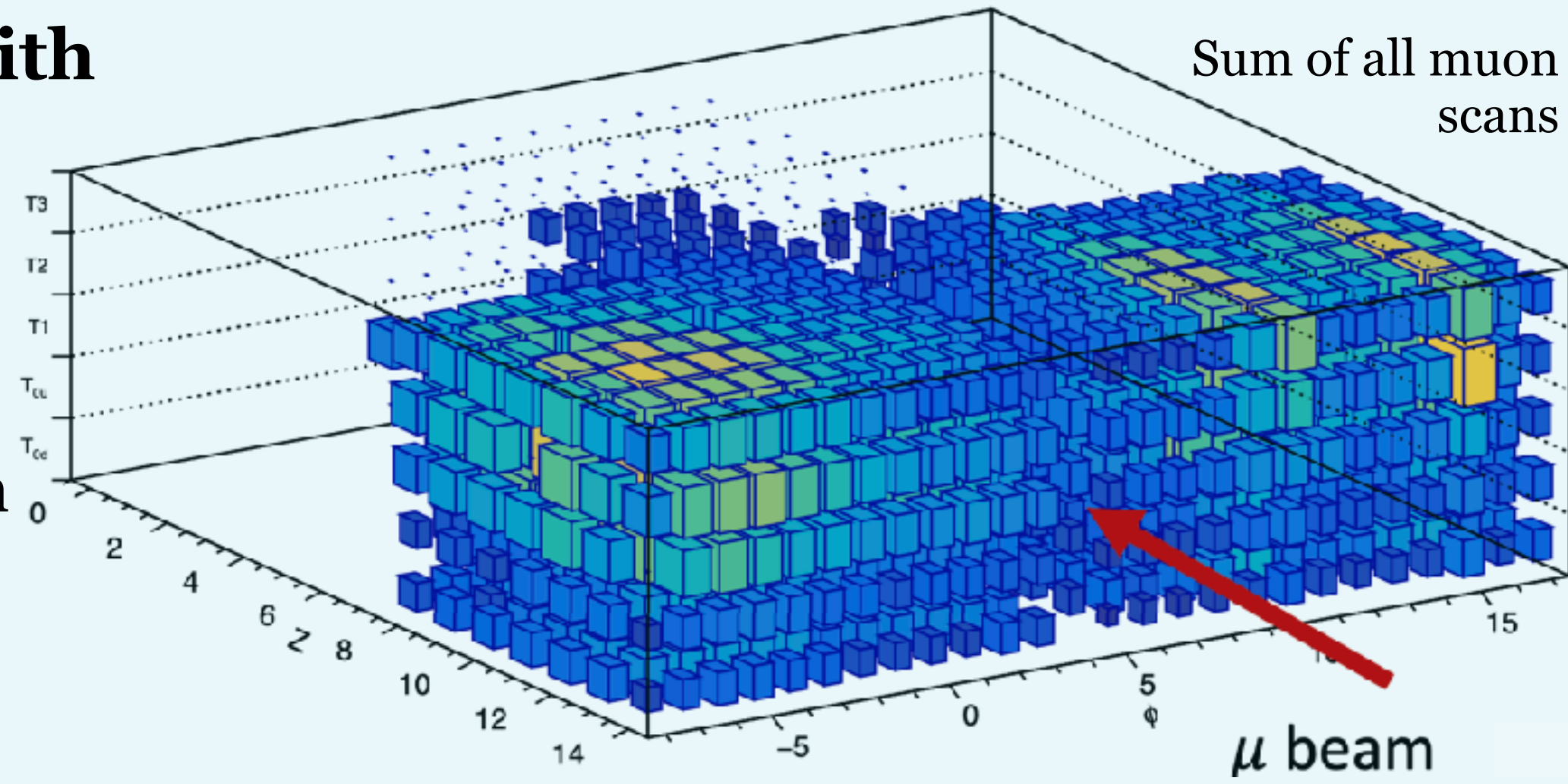
**NOW WITH*
3x
THE CHANNELS!



**Terms and conditions apply.*

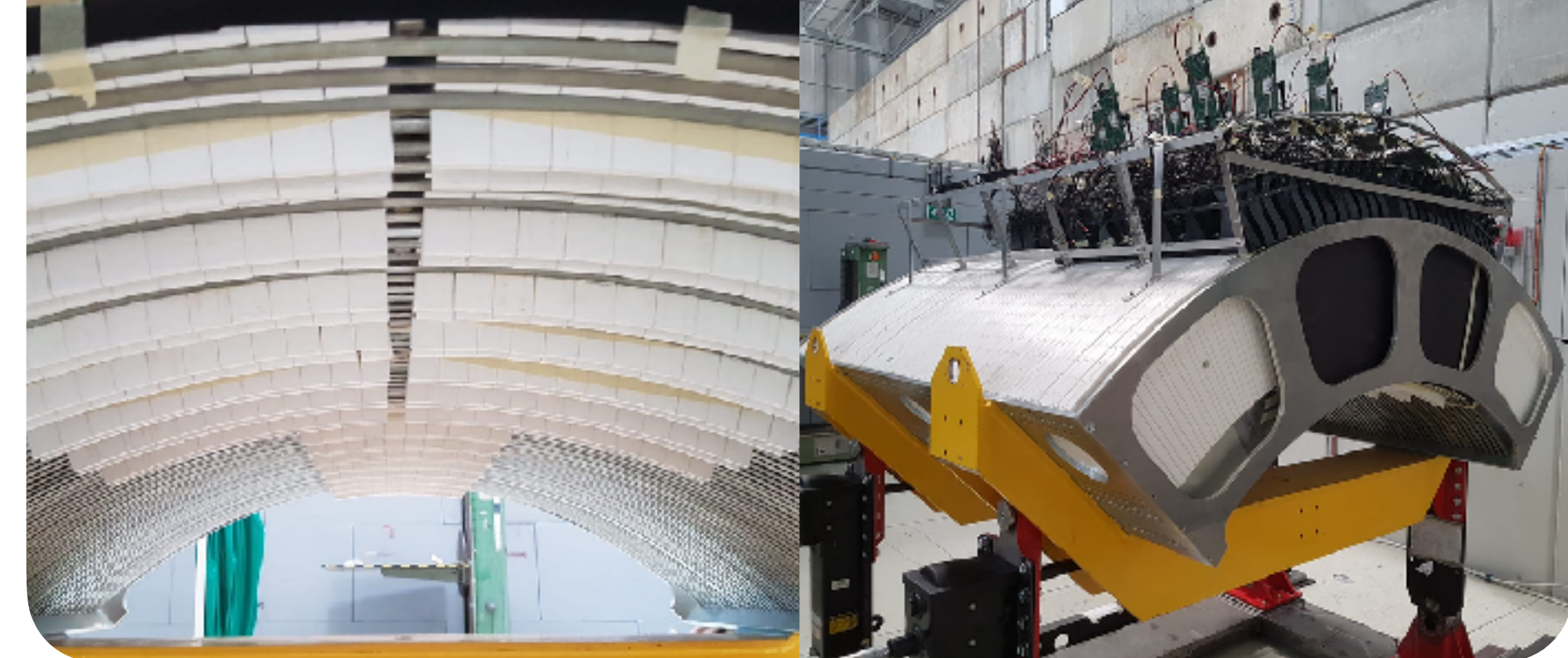
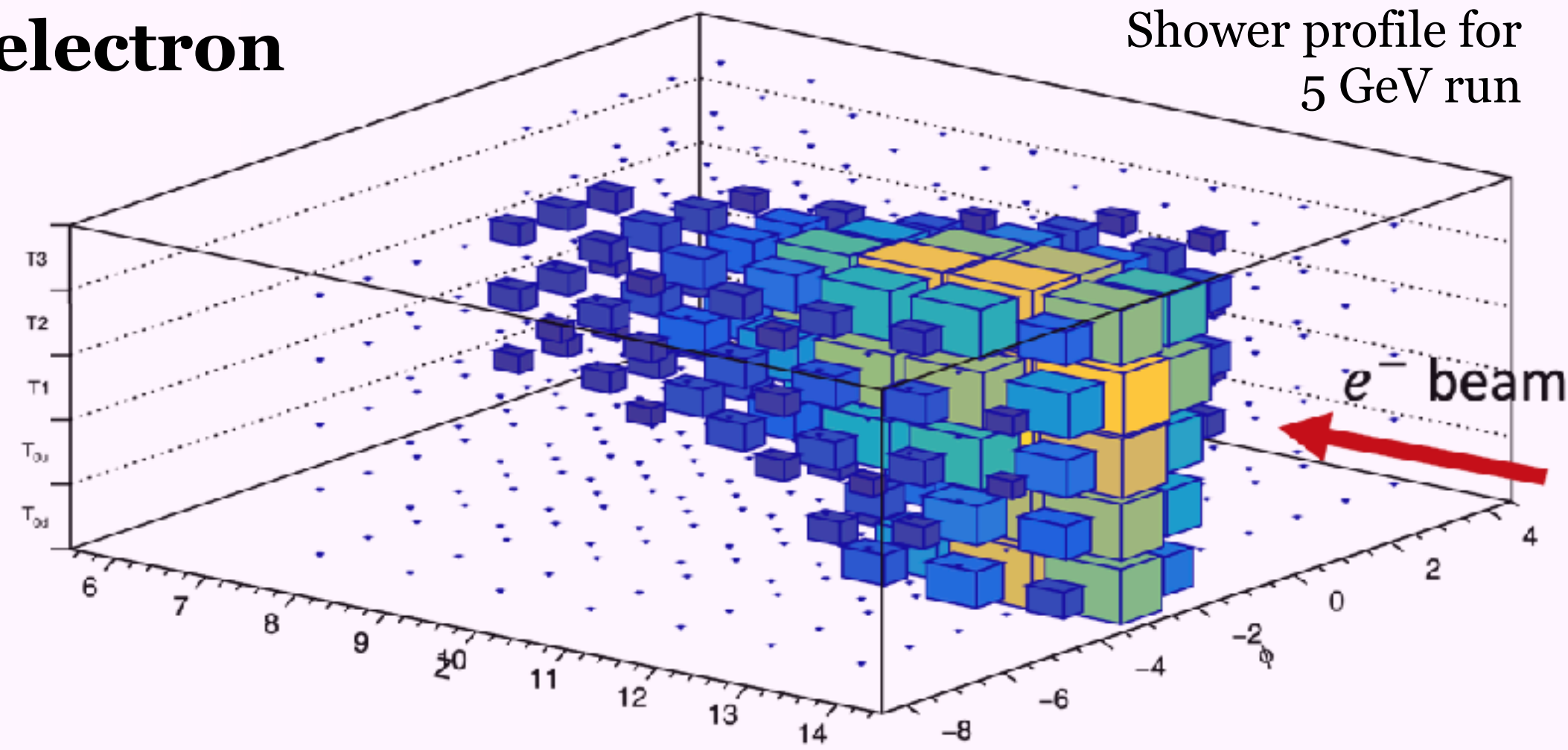
Calibration runs with 10 GeV muons

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



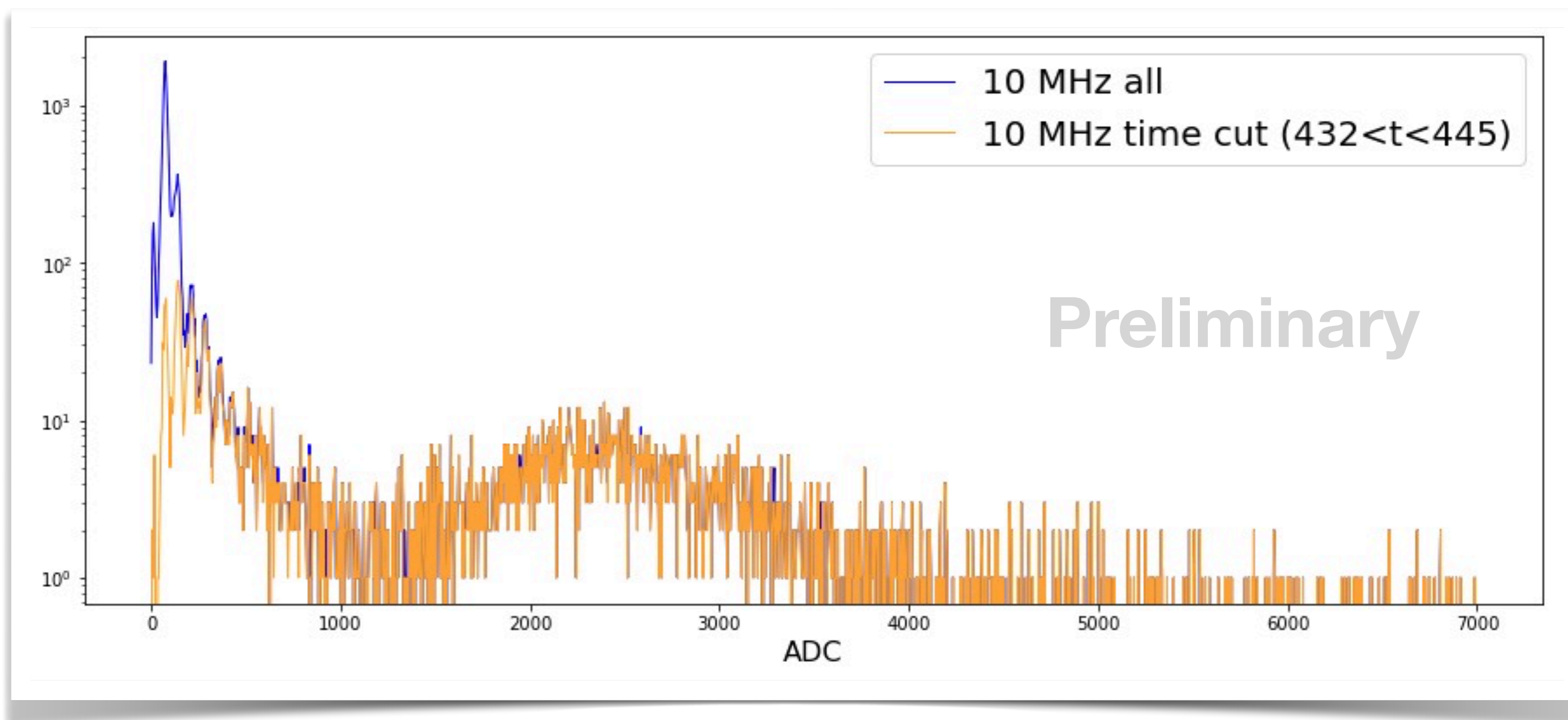
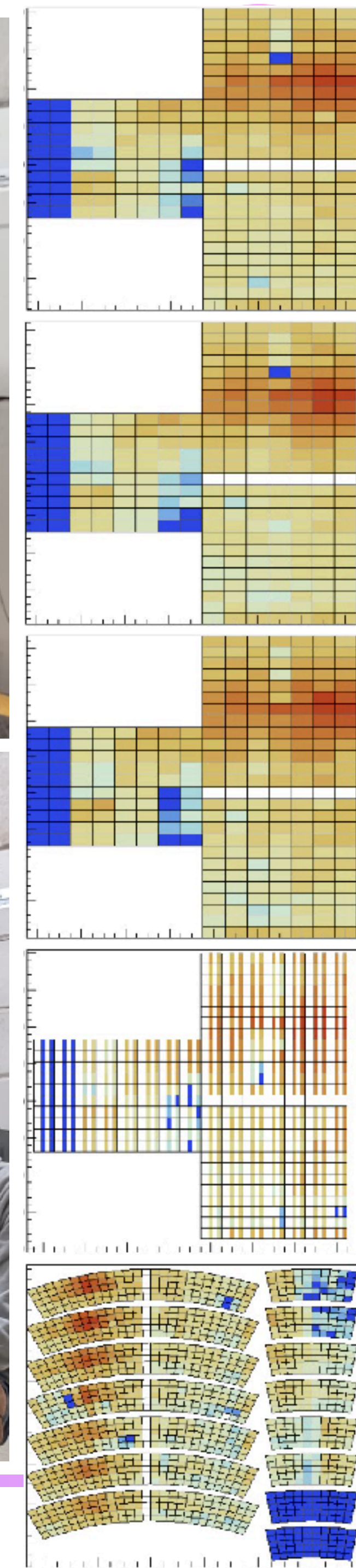
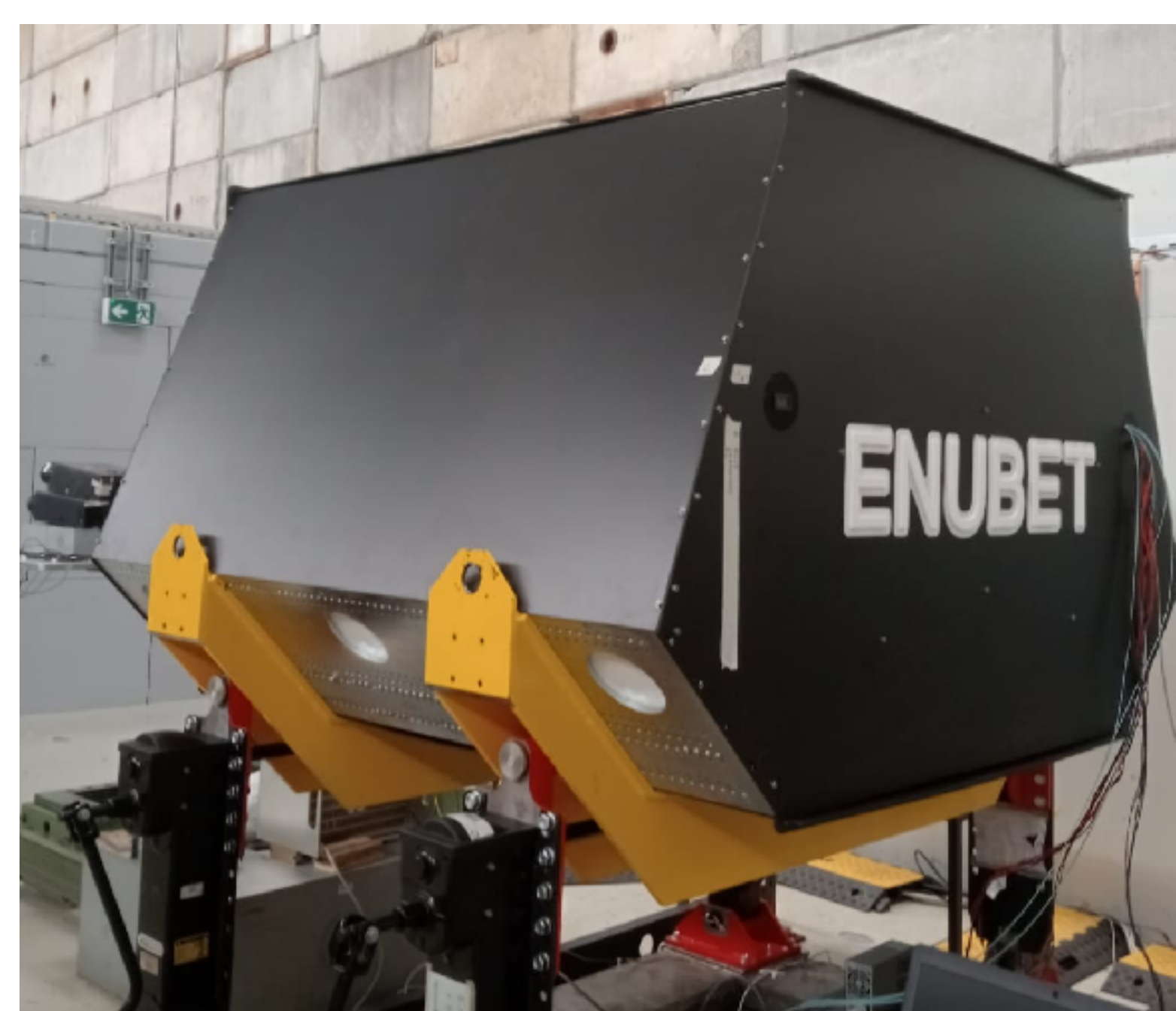
Energy scans with electron beams

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



LP2i Bordeaux 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’

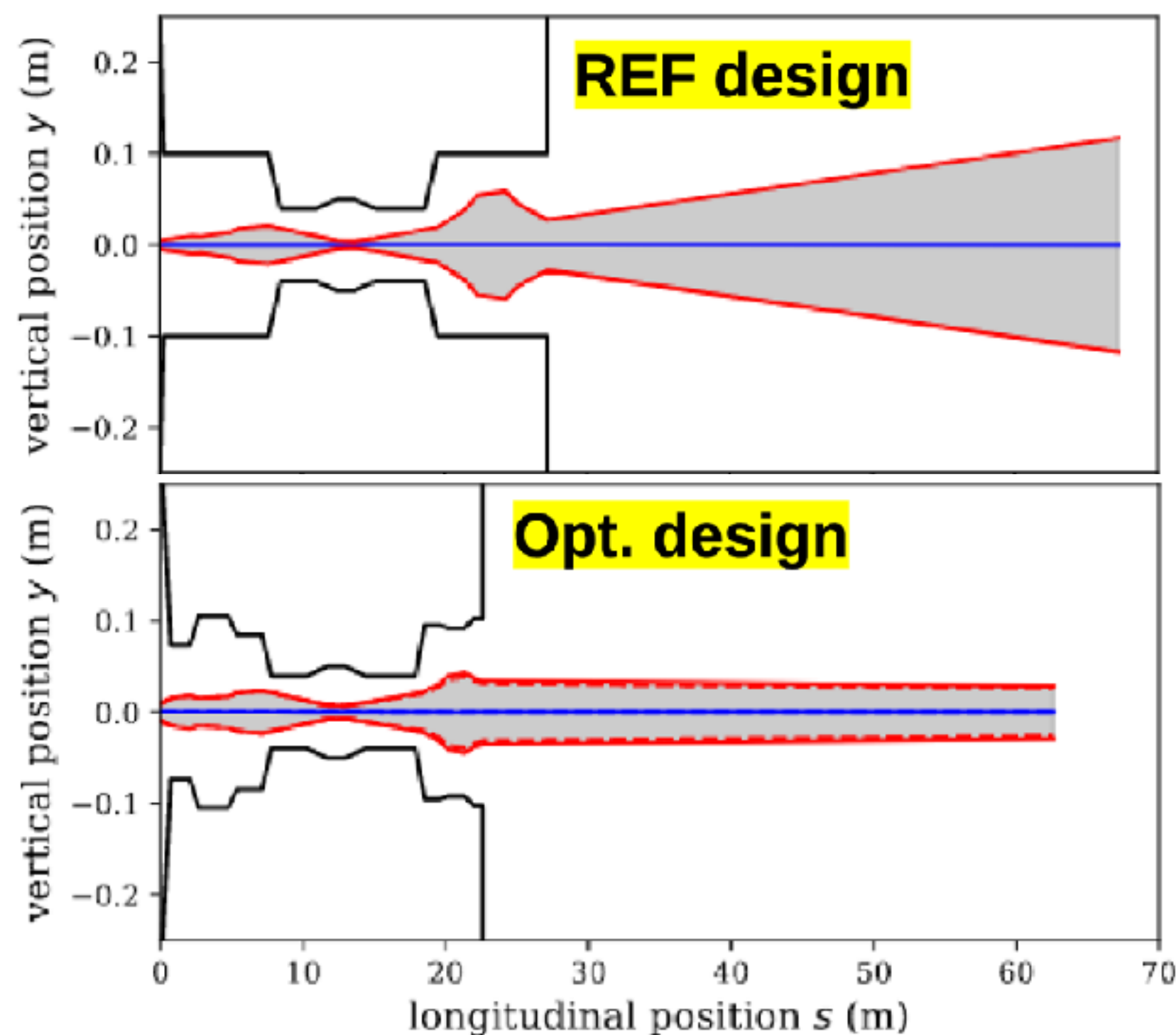


- Current design plans interfere with SHiP
 - Both need a large number of PoT
- Optimised for DUNE
 - Would like to include the HK region

New Proposal!

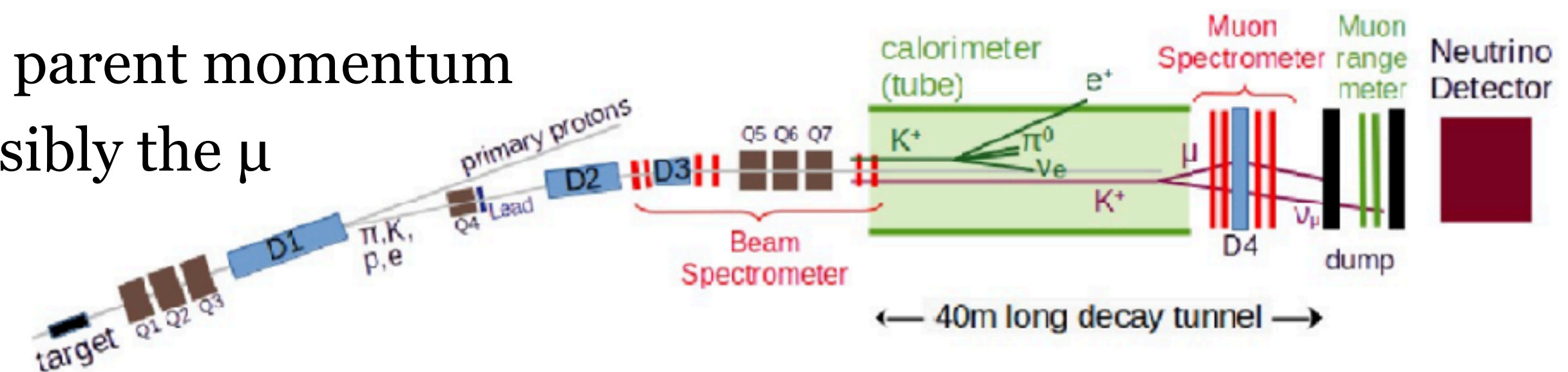
The proposal (Physics Beyond Colliders Short Baseline Neutrinos) is being studied by CERN, ENUBET and NuTAG. A new optimised beamline that can also run at lower secondary momenta (8.5 - 4 GeV).

- Achieves ENUBET results at 1/3 PoT originally required
- Also large statistics in the 1-2 GeV region for ν_μ CC
- Can exploit time-tagging to enhance energy resolution



NuTAG adds silicon trackers

- Tags the parent momentum
- Also possibly the μ



Courtesy M. Perrin-Terrin



- **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.

More test beams in 2023 and 2024, with work ongoing for full calibration.

PIMENT (ANR 2022-2024)

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

Physics Beyond Colliders (NP06)

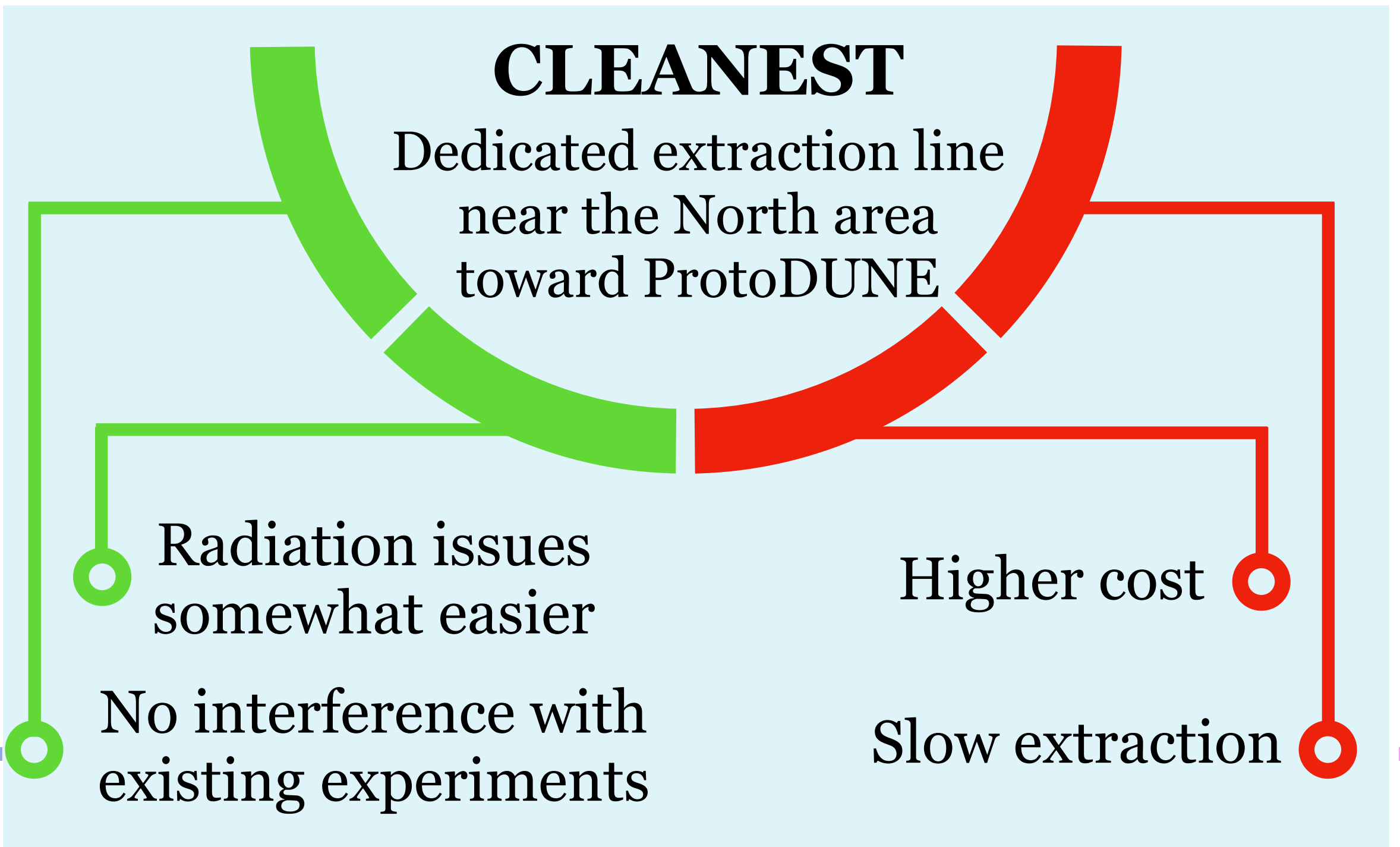
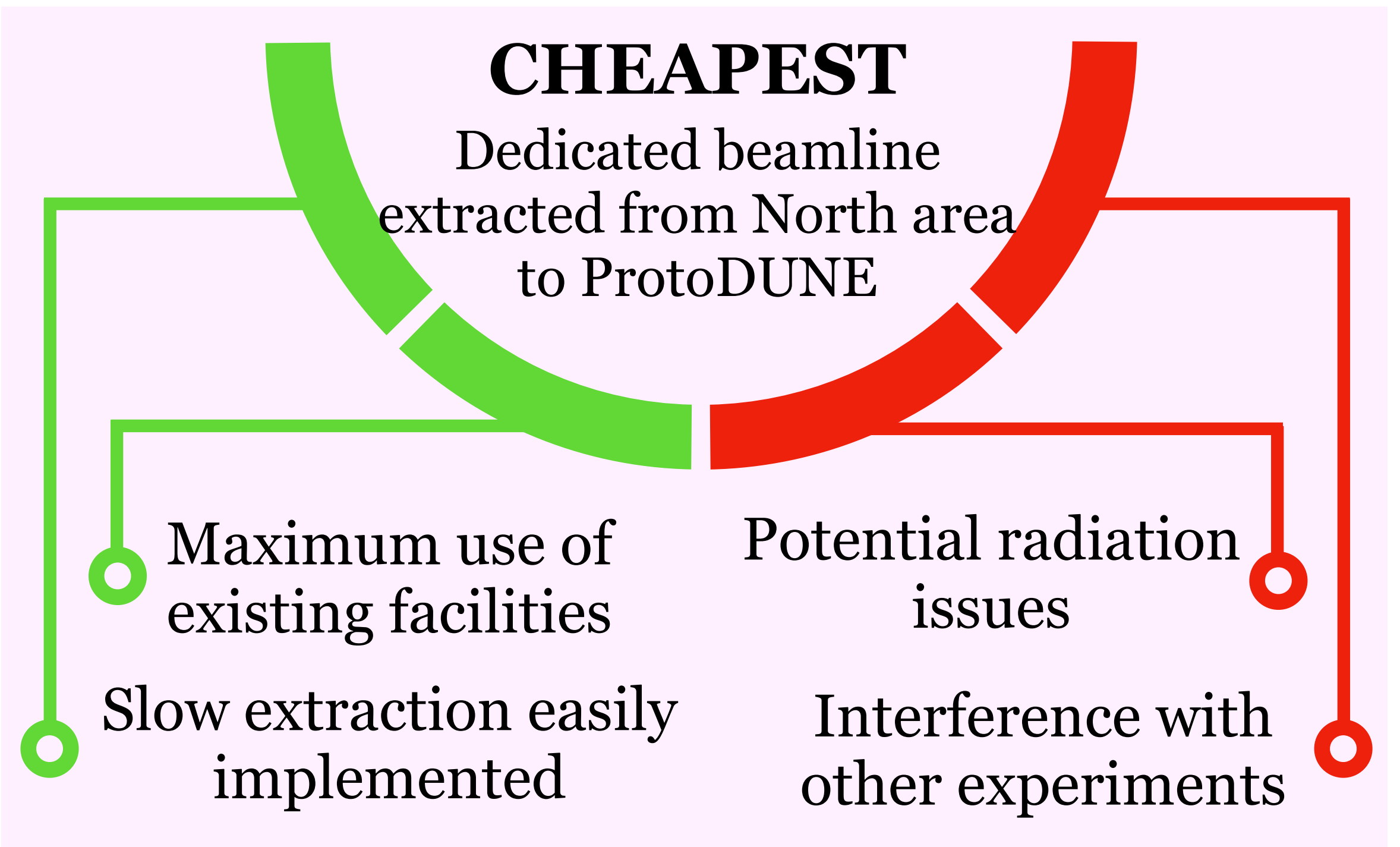
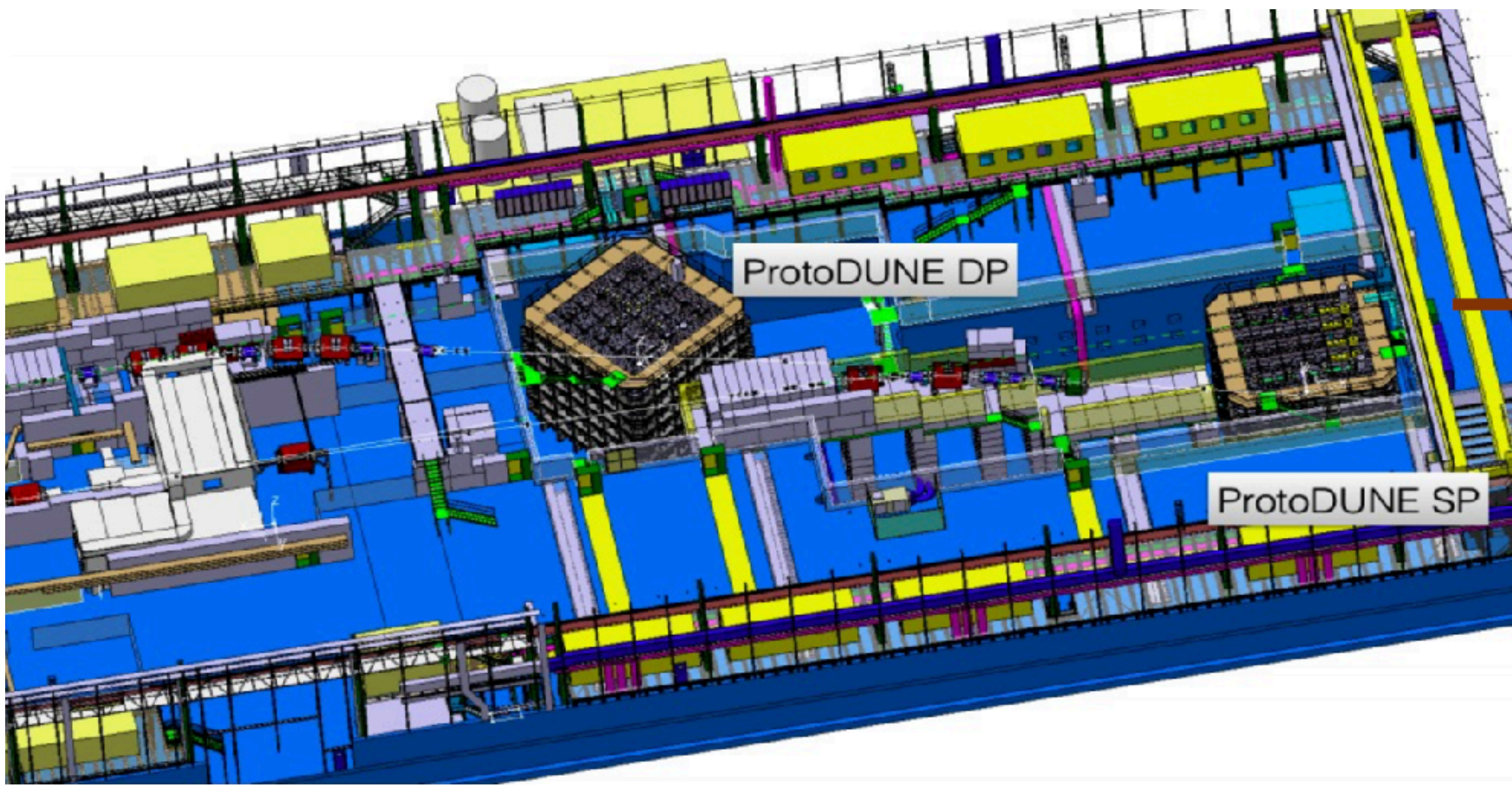
- Starting to address the issue of implementation at CERN
- During LHC Run IV, in parallel with DUNE and Hyper-Kamiokande
- Assess the possibility of using ProtoDUNE as the neutrino detector
- Optimal location would exploit the SPS slow extraction

Thank you



Supplementary

- 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)



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

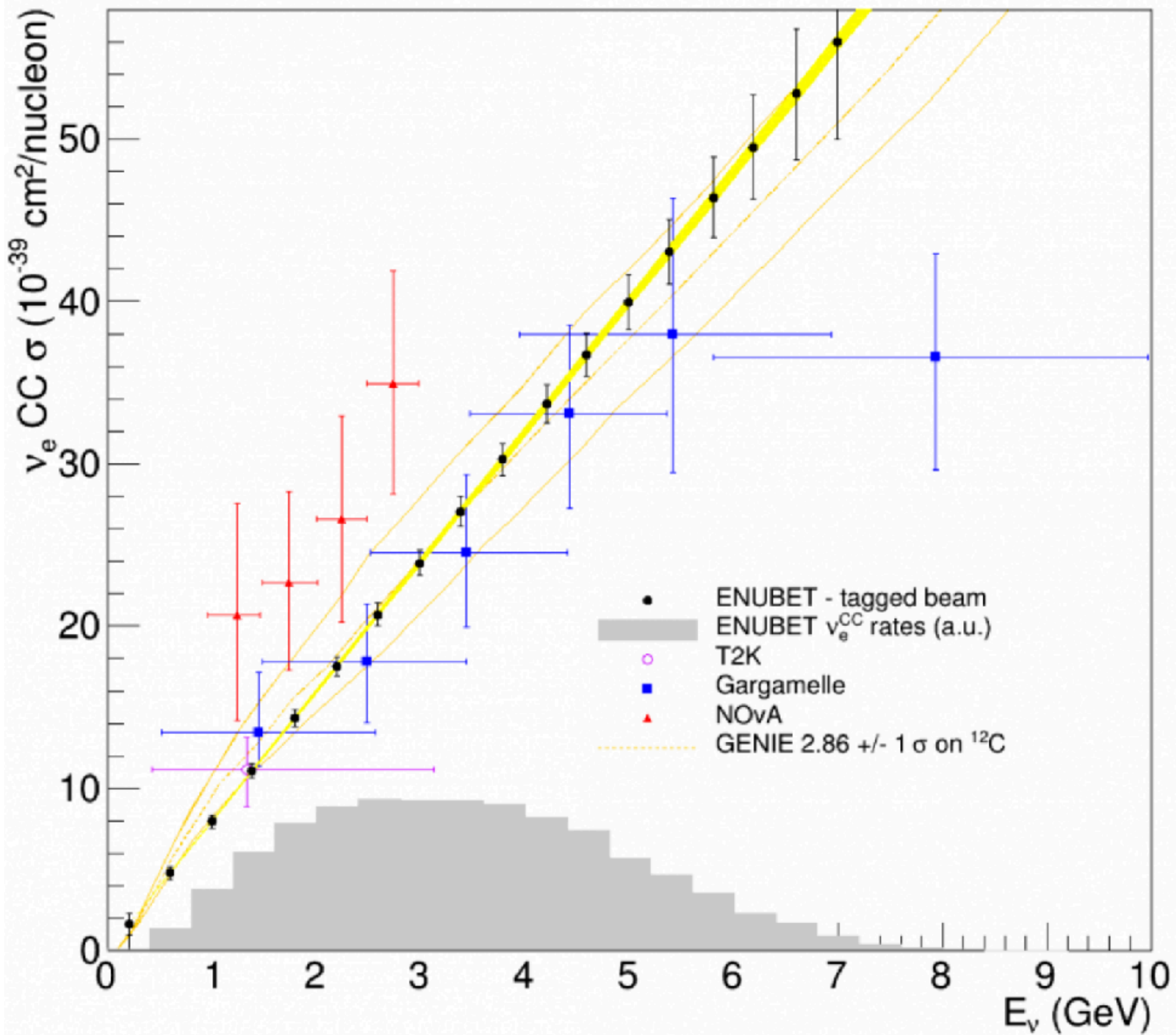
- Narrow band beams with movable detectors (a ‘monochromatic’ beam)
- Monitored neutrino beam with a ‘narrow band off-axis’ technique

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



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.**

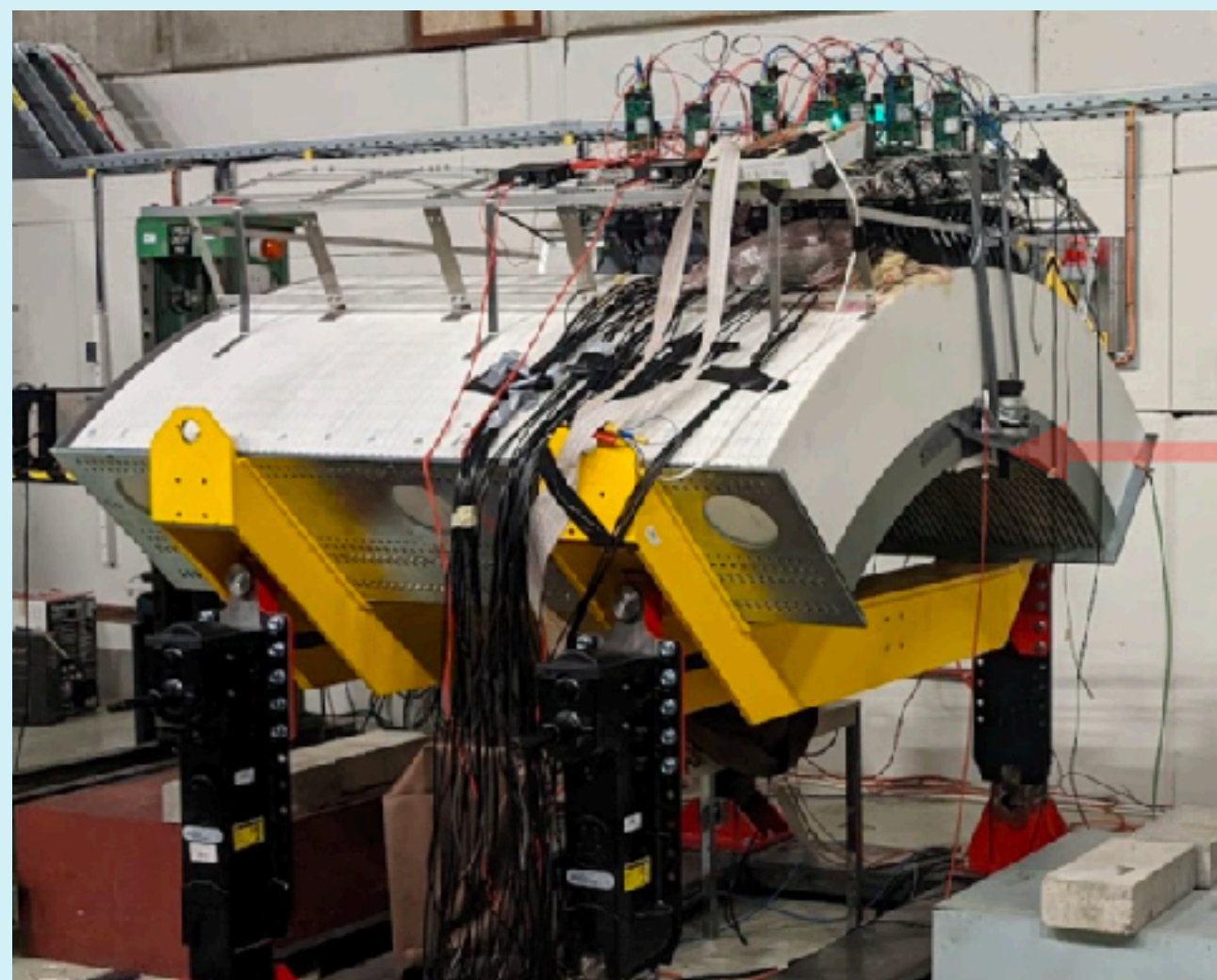
1.0

8 z-layers

10 ϕ -sectors

400 channels

2022



2023

+7 z-layers

25 ϕ -sectors each

+875 channels

2.0

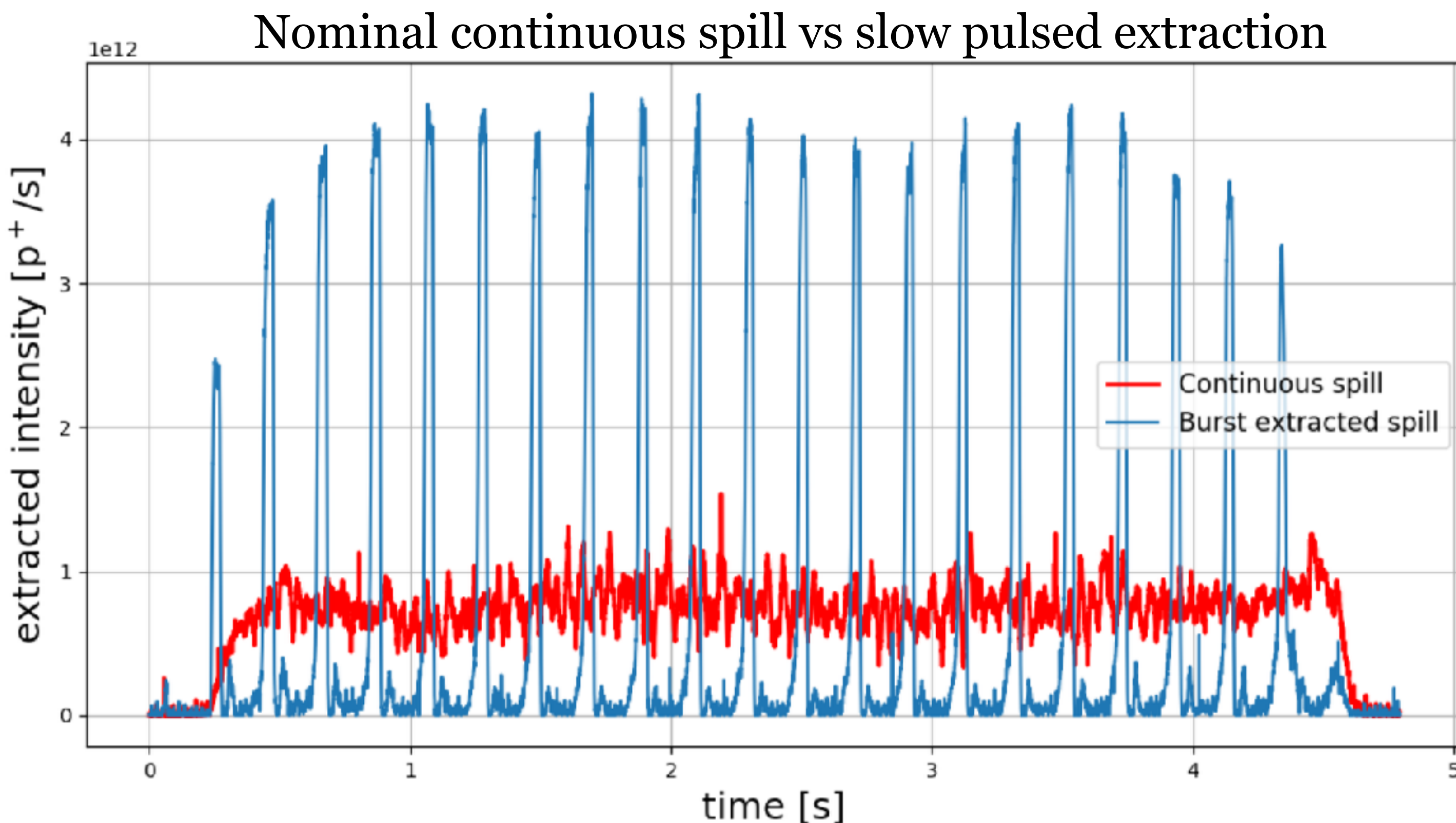


Parameter	Quantity	
	1.0	2.0
Scintillator tiles	1,360	4,335
WLS	1.5 km	4.8 km
Channels (SiPM)	400	1,275
Front-end boards	80	255
Interface boards	8	22
Read-out boards	8	22
CAEN Digitisers	45 ch	—

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

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

- Pulse every 100 ms
- 10 ms pulse width



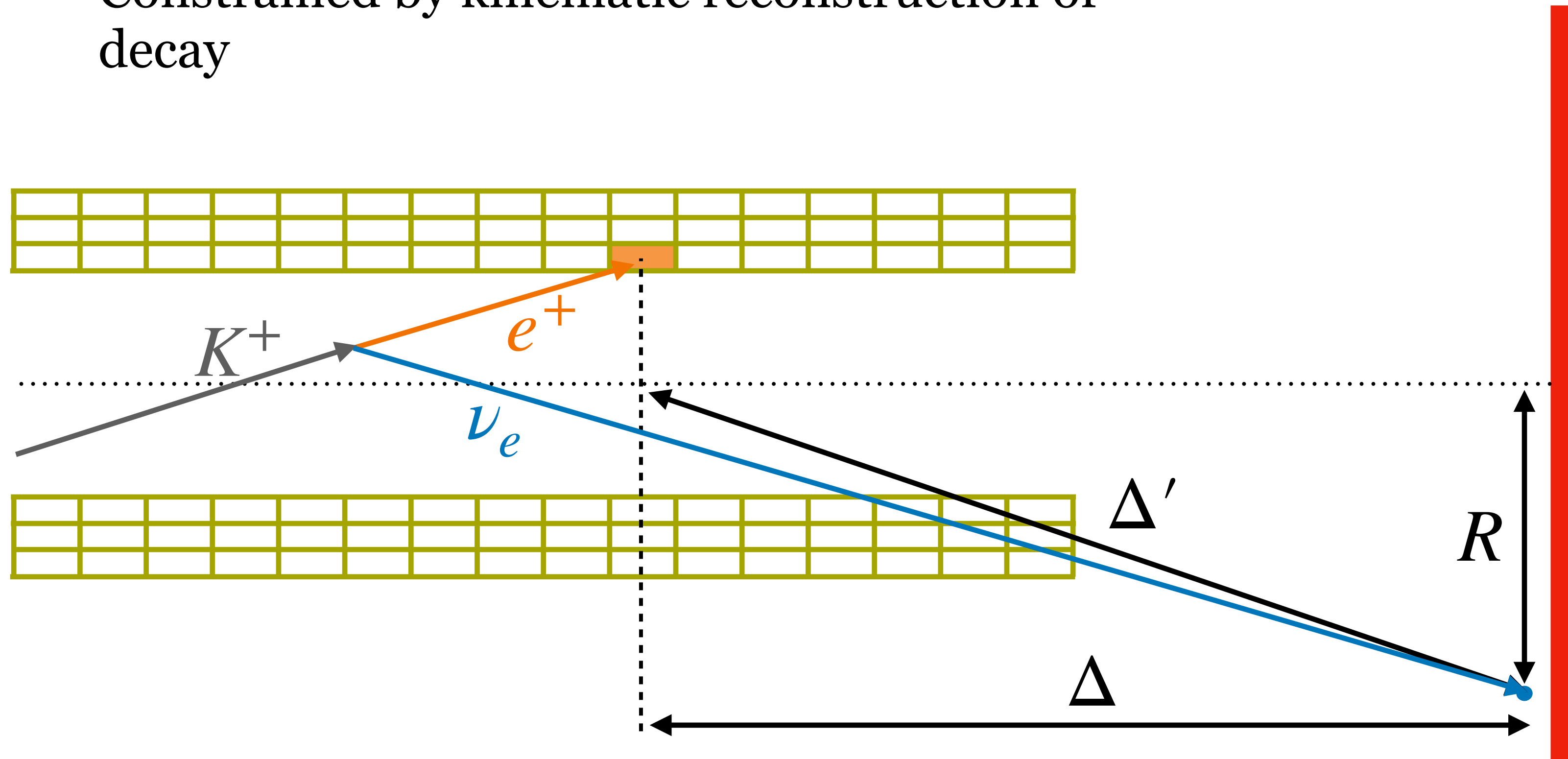
2020 design: A collection of dipoles and quadrupoles in a “static focusing system”

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



- 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

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

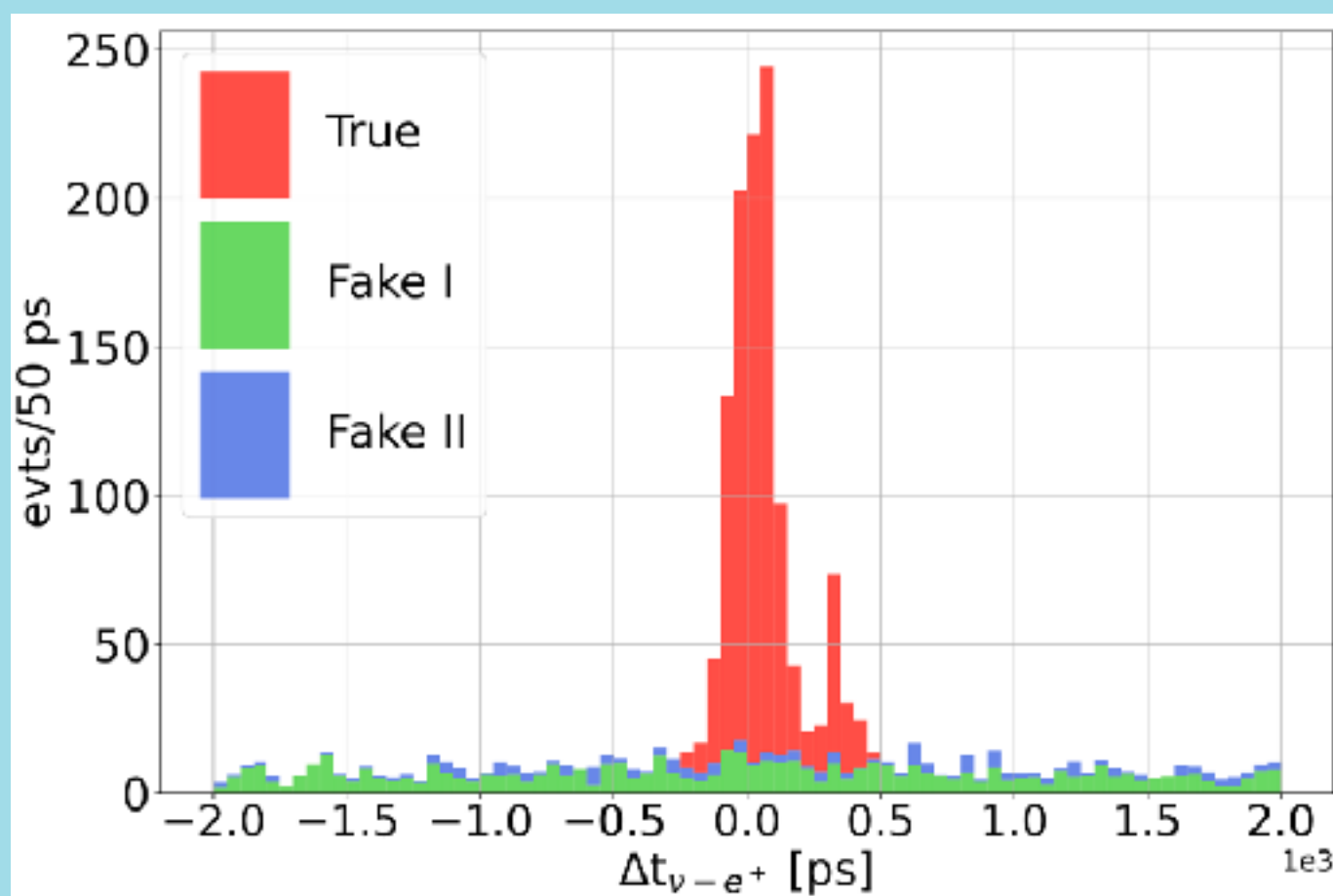
$$\delta t = t_\nu - \frac{\Delta'}{c} - t_e$$



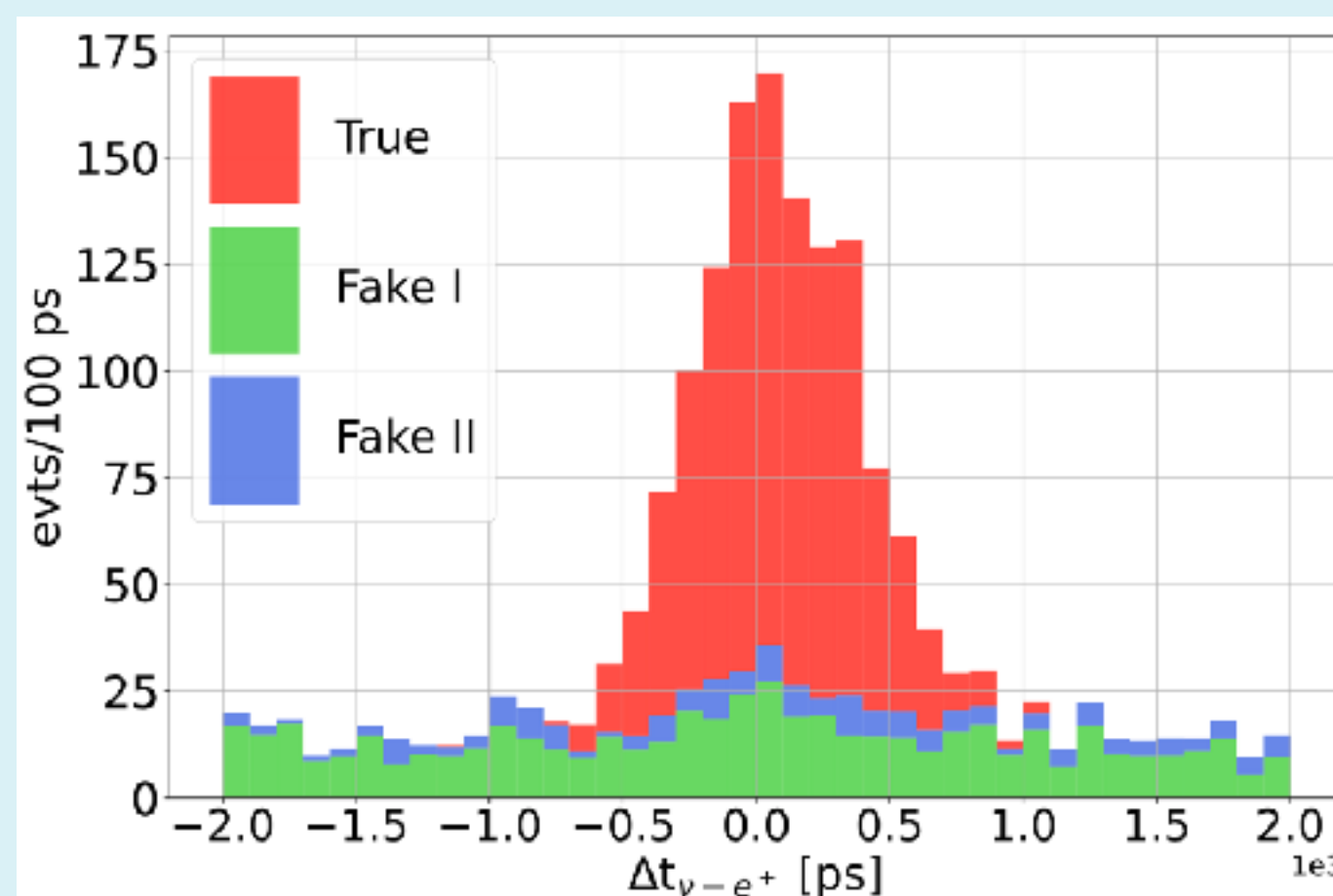
- Used a full beamline simulation with PID algorithms
- Results support ENUBET becoming a tagged beam
 - If time resolution improved to 200 ps
 - ~2 smaller than current resolution

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

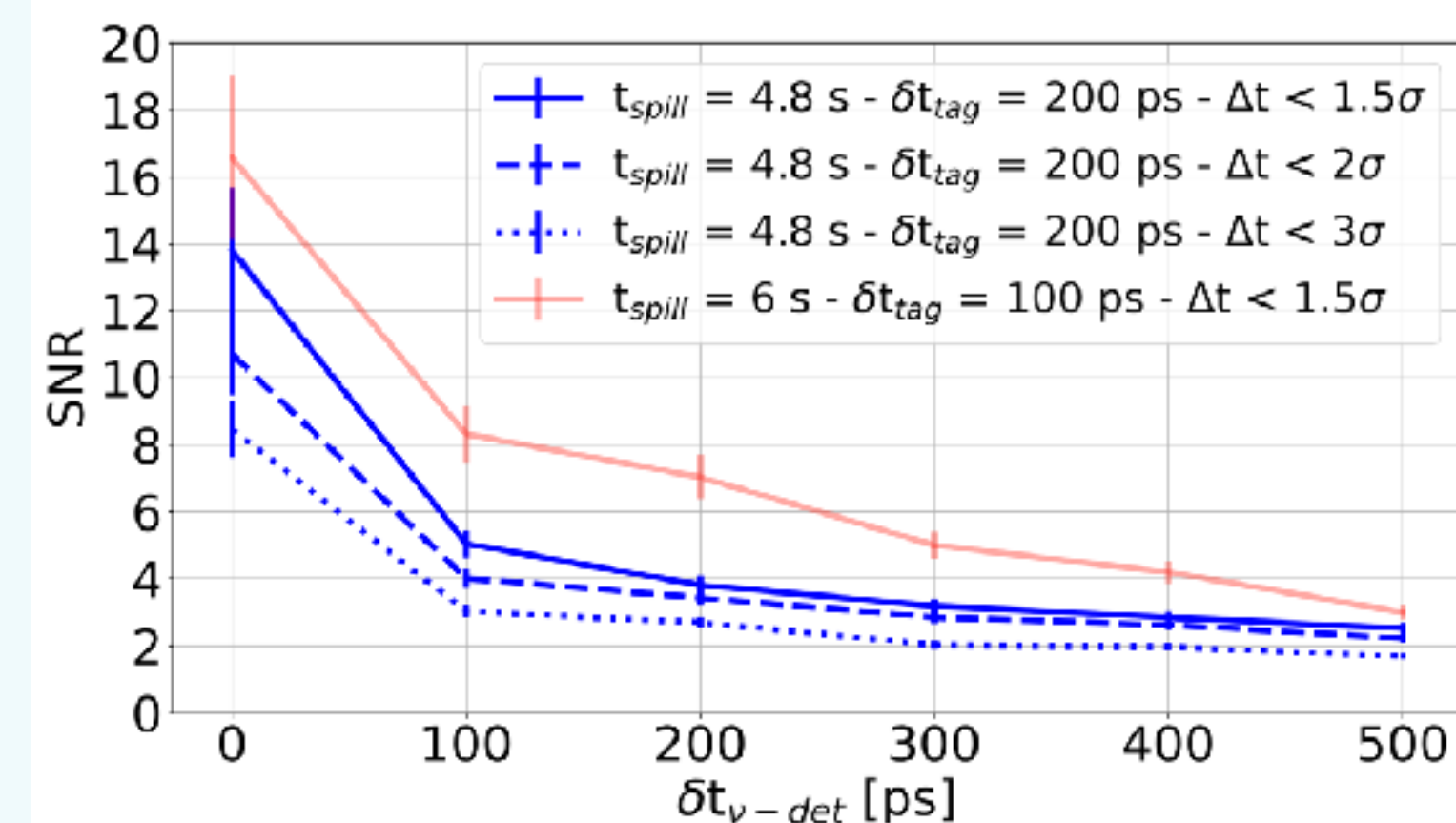
■ False positives from ν inside tagger ■ False positives from ν outside tagger



Perfect time resolution has an intrinsic 74 ps spread.



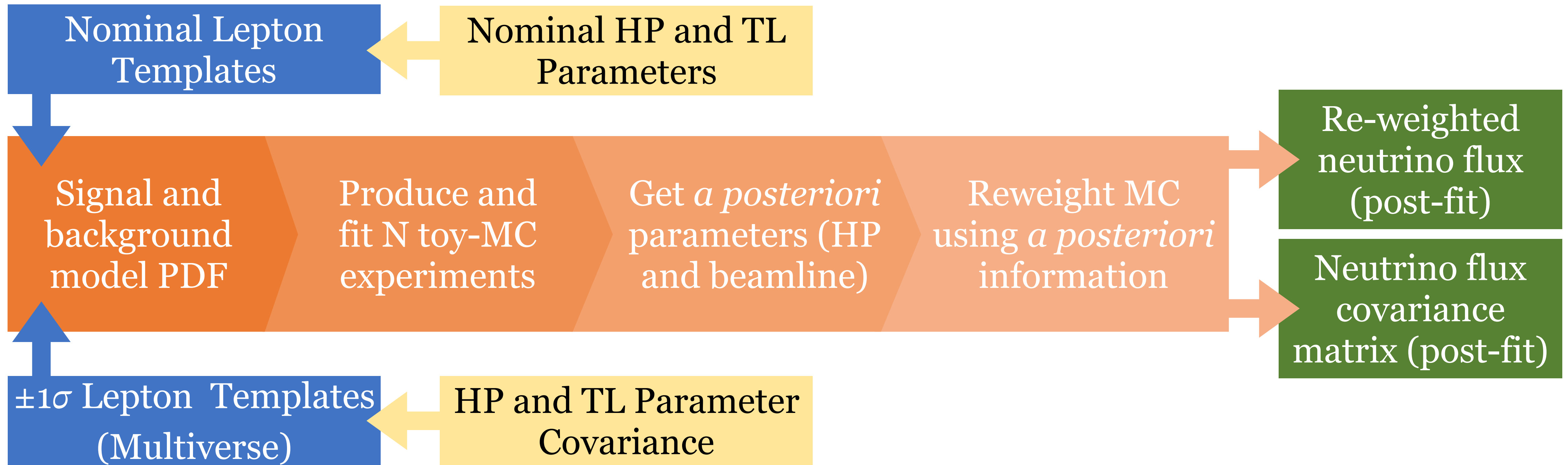
Efficiency smearing assuming resolution of ~200 ps.



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



Flux Constraint Algorithm

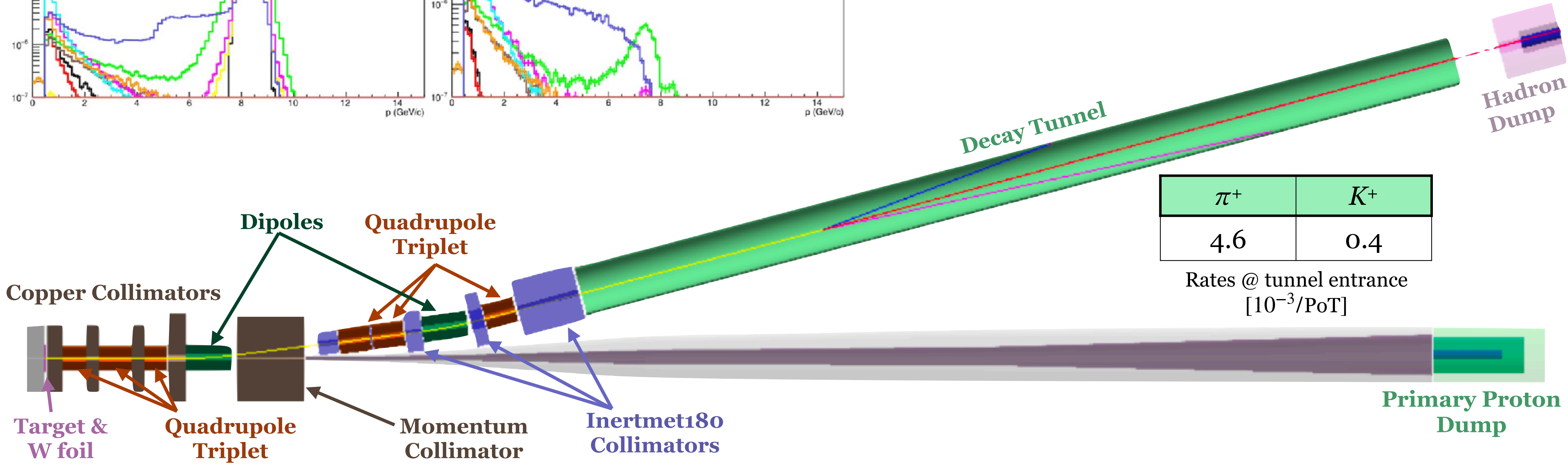
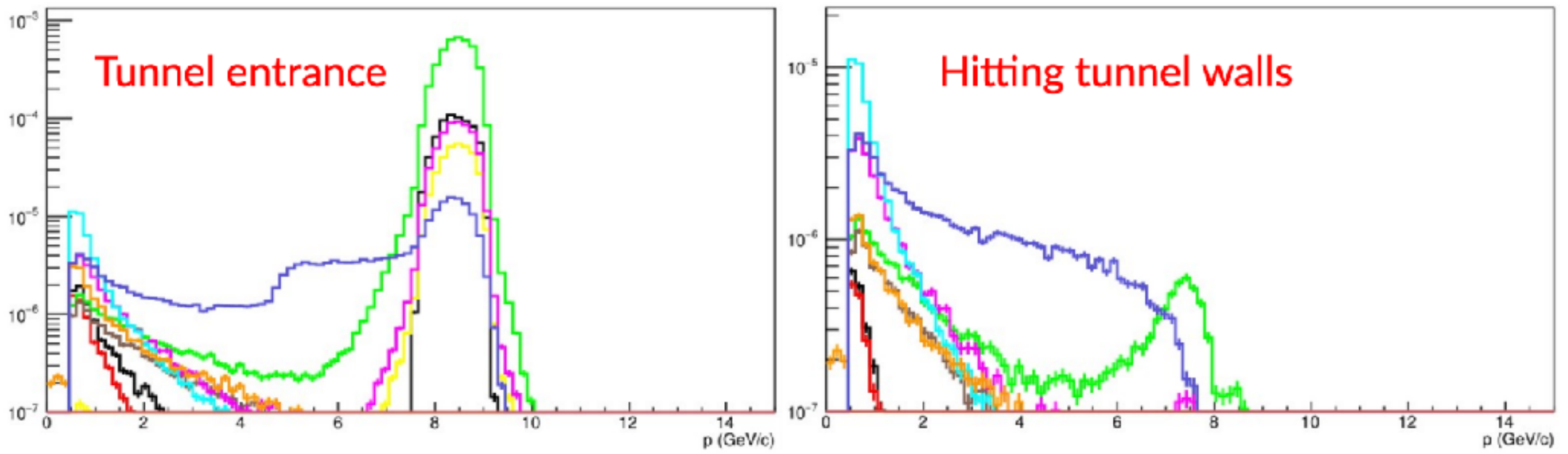


- Extended maximum likelihood fit
- Build a signal+background model to fit lepton observables

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

Full facility implemented in GEANT4:
 - Control over all parameters
 - Access to full particle histories
Thus a complete assessment of ν flux systematics

Transfer line design a trade-off between:
 1. Larger meson yield (larger ν flux) 2. Low background on tunnel walls



π^+	K^+
4.6	0.4

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



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The ENUBET Collaboration



6 Countries

17 Institutions

We now have a twitter!
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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
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ENUBET
Enhanced NeUtrino BEams from kaon Tagging

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