nuSCOPE
a short-baseline neutrino experiment at CERN for high-precision cross-section measurements

Laura Munteanu (CERN)

on behalf of the nuSCOPE Collaboration

EPS-HEP, Marseille

11 July 2025

Neutrino experiments in the precision era

Accelerator-based long baseline (LBL) neutrino experiments aim to **precisely measure** neutrino oscillations and **probe CP violation** in the lepton sector

Experiment	ν_μ events	ν_e events	Systematic error
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NOvA Neutrino 2024 talk	384	181	~5%

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DUNE Phys. Rev. D **105**, 072006	**~15000***	**~3500***	**Need ~1-3%**

**Scaled to 10 years*

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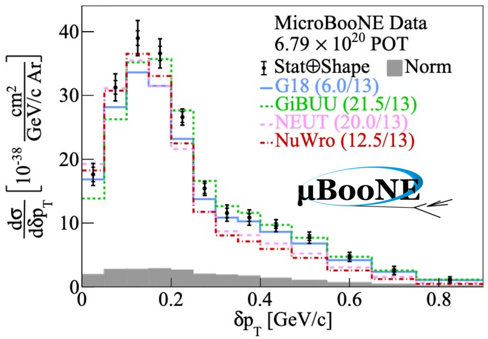
Sample		Flux⊗Interaction (%)	Total (%)
1Rμ	ν	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	3.4 (11.8)	4.0 (12.0)
1Re	ν	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	5.0 (13.1)	14.3 (18.7)

Bottlenecks:
- Systematic errors due to cross-sections and flux
- Neutrino energy reconstruction

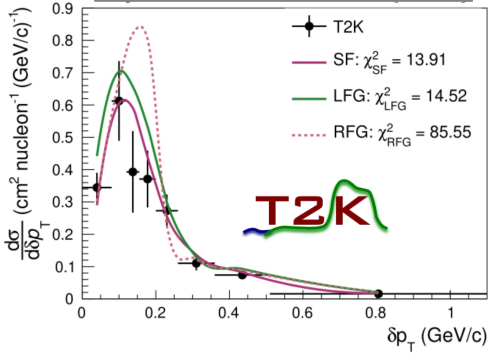
Can't we just measure neutrino cross sections?

We do, but…

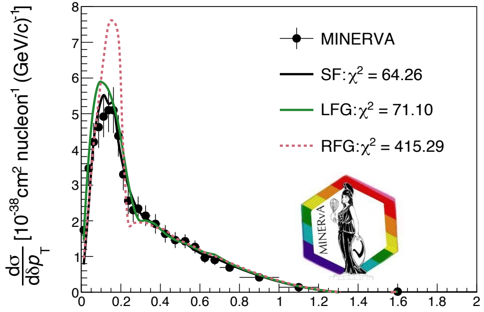
arXiv:2301.03700



Phys. Rev. D 98, 032003 (2018)

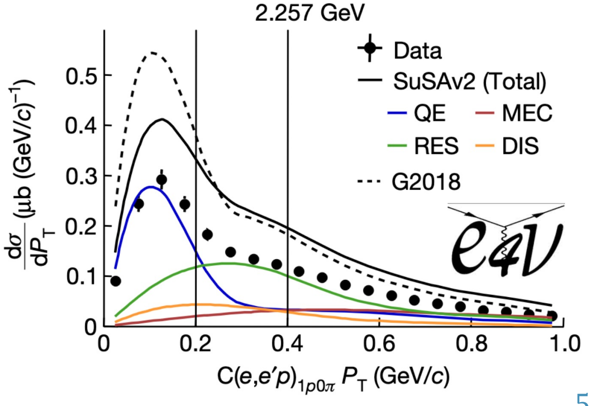


Phys. Rev. Lett. 121, 022504 (2018)



arXiv:2407.10962

Nature 599, p. 565–570 (2021)



Can't we just measure neutrino cross sections?

We do, but…

No model is able to describe global neutrino scattering measurements

Our measurements tell us that all the models are wrong ***but not why***

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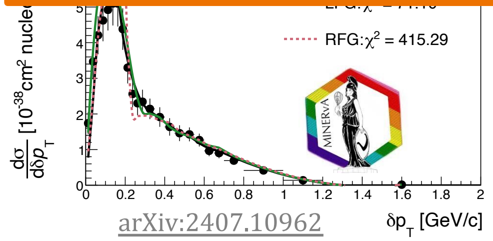
p-values of model comparisons to measurements

(red if excluded at <0.05)

Measurement	N_{bins}	SF/SF*	LFG	RFG	More 2p2h	More FSI	Less FSI	More π abs.	Less π abs.
T2K $\delta\alpha_T$	8	0.01	0.00	0.00	0.00	0.00	0.02	0.06	0.02
T2K δp_T	8	0.08	0.69	0.00	0.00	0.02	0.07	0.00	0.18
MINERvA $\delta\alpha_T$	12	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00
MINERvA δp_T	24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MINERvA p_N	24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MicroBooNE $\delta\alpha_T$	7	0.02	0.45	0.62	0.07	0.18	0.00	0.02	0.01
MicroBooNE δp_T	13	0.12	0.42	0.00	0.33	0.23	0.02	0.13	0.10
MicroBooNE δp_T low $\delta\alpha_T$	11	0.26	0.23	0.14	0.37	0.44	0.10	0.28	0.24
MicroBooNE δp_T mid-low $\delta\alpha_T$	12	0.07	0.40	0.19	0.23	0.38	0.00	0.08	0.06
MicroBooNE δp_T mid-high $\delta\alpha_T$	13	0.04	0.23	0.02	0.16	0.22	0.01	0.05	0.04
MicroBooNE δp_T high $\delta\alpha_T$	13	0.03	0.13	0.08	0.12	0.09	0.01	0.04	0.03

arXiv:2407.10962



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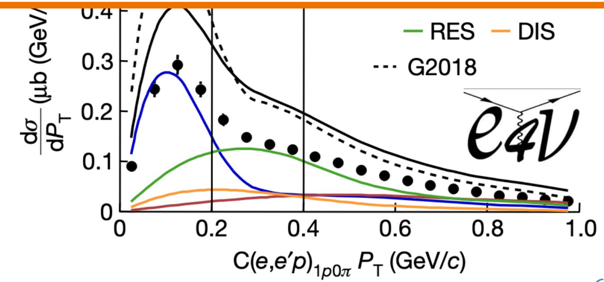
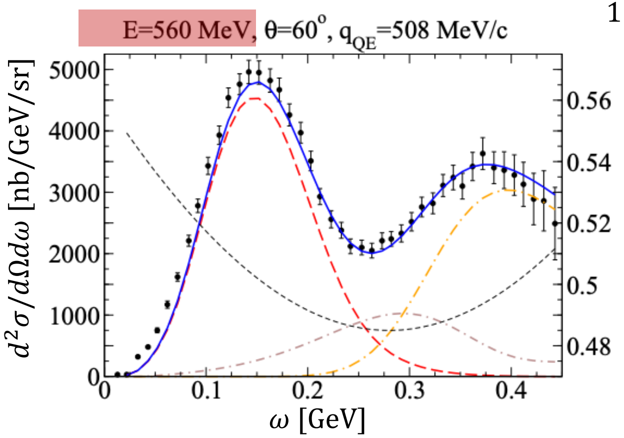


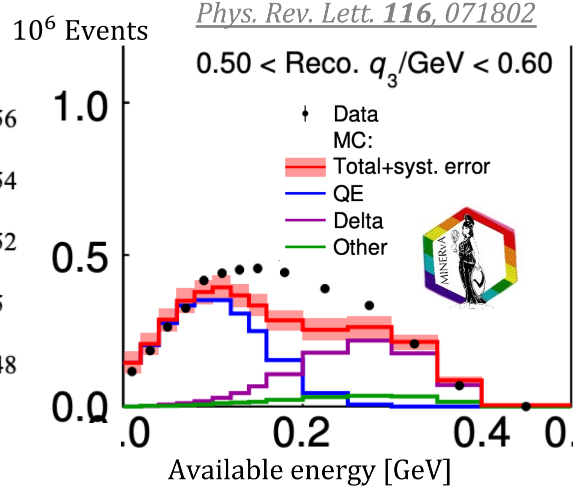
Why is it so difficult?

Electron scattering vs **neutrino** scattering



Phys. Rev. D 94, 013012 (2016)

*Phys. Rev. Lett. **116**, 071802*



Monochromatic, well-known flux

Broad-band, poorly known flux

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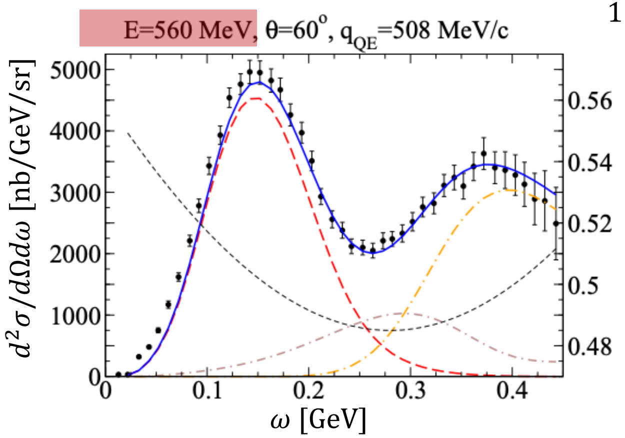
Electron scattering vs **neutrino** scattering



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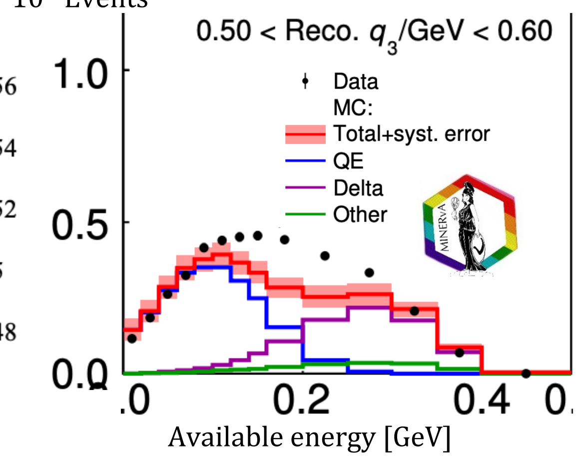

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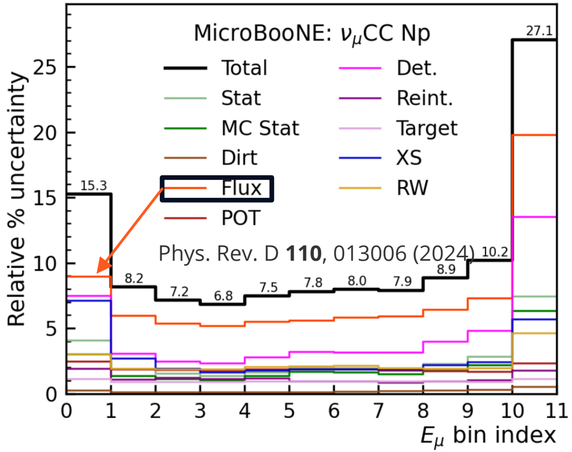
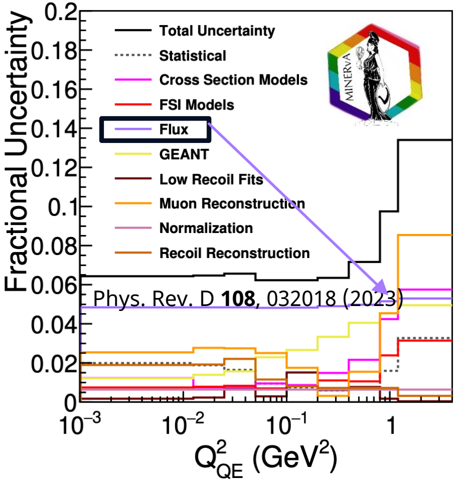
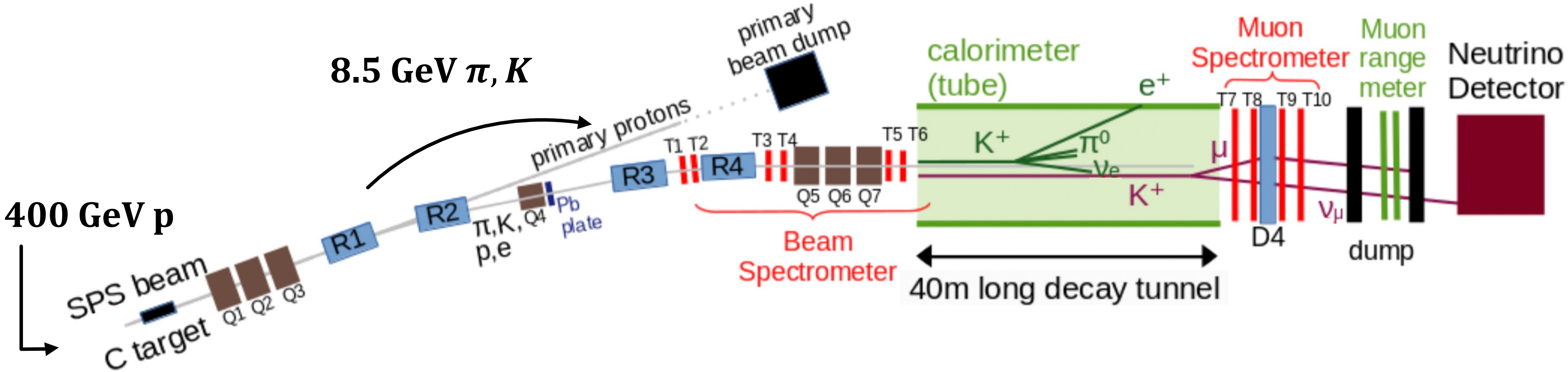


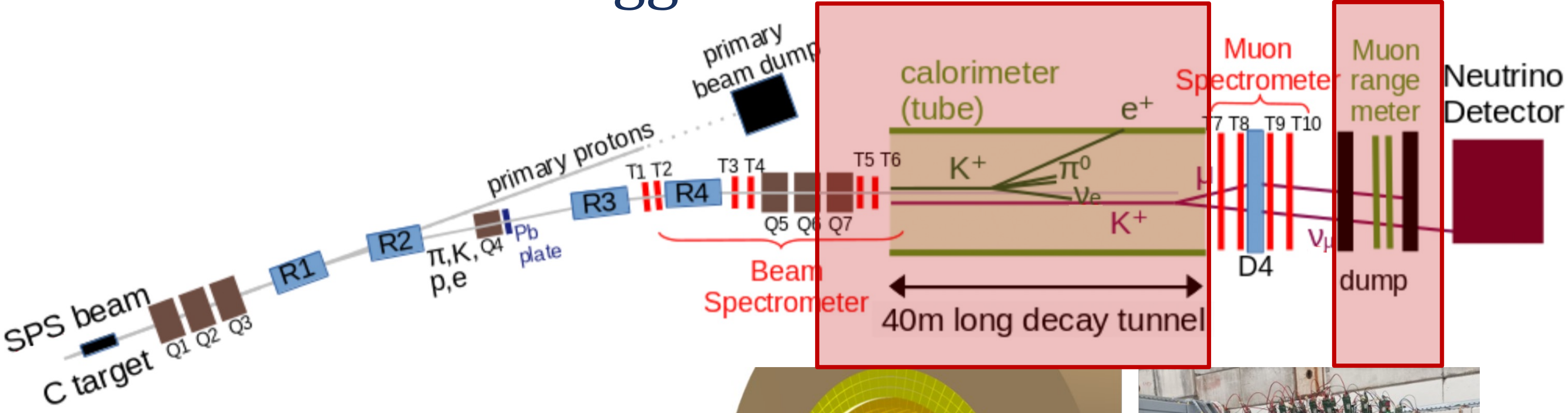


nuSCOPE (Neutrino SPS Complex for Precision Experiments)

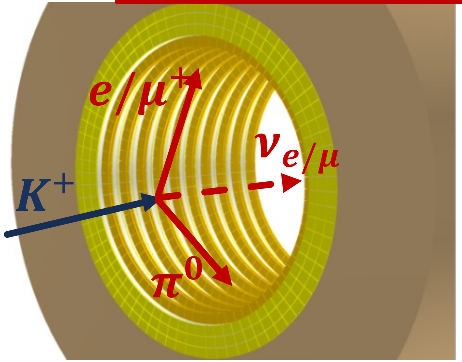
- Previous working name: SBN@CERN
- nuSCOPE is a result of the merge of the **ENUBET** and **NuTAG** collaborations
- Aim: investigate the physics we can probe with monitored and tagged neutrino beams at the SPS
- Input submitted to the ESPPU: https://arxiv.org/abs/2503.21589

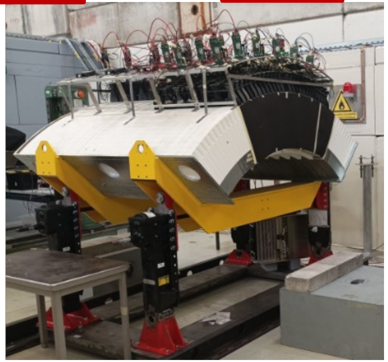


A **monitored** and tagged neutrino beam



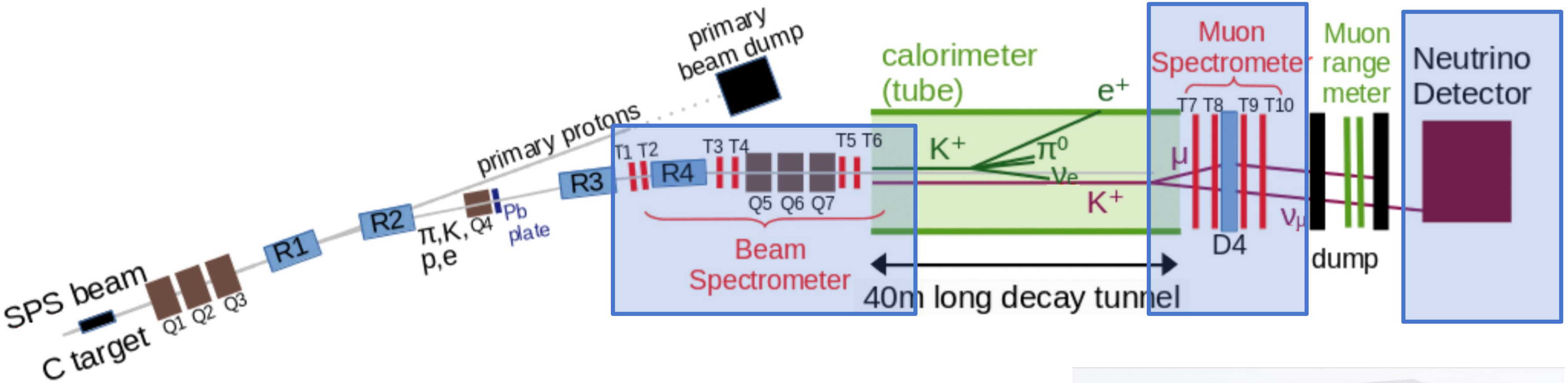
- Instrumented calorimeter decay tunnel & hadron dump
- Identifies the decay products of mesons producing neutrinos



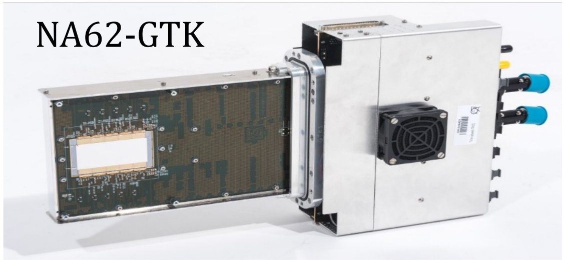


Performance of a section of the decay tunnel tested at CERN T9 Test Beam facility under NP06/ENUBET
Eur. Phys. J. C **83**, 964 (2023)

A monitored and **tagged** neutrino beam



- State-of-the-art **silicone detectors** to track incoming mesons and outgoing muons
- **Unique association** between each neutrino interacting in the detector with its parents

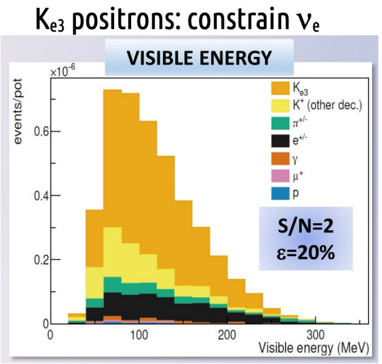


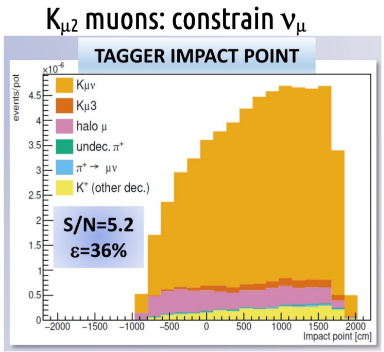
Phys.Lett.B 863 (2025) 139345

A first tagged neutrino candidate observed by NA62

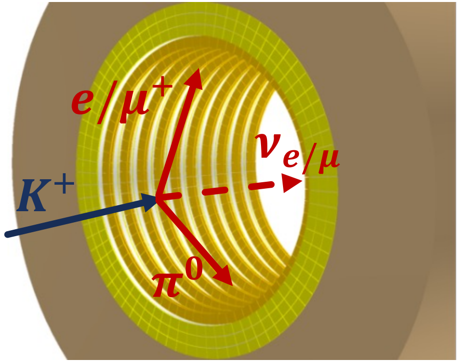
What does nuSCOPE bring to the table?

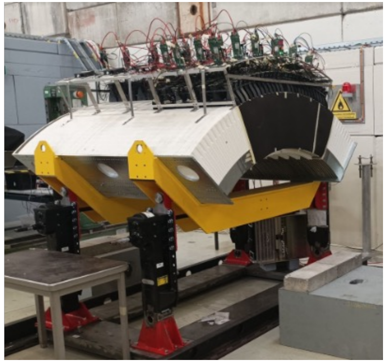
Monitored beam: ~1% flux uncertainties





Lepton distributions from calorimeter and tagger (see slides from A. Longhin)





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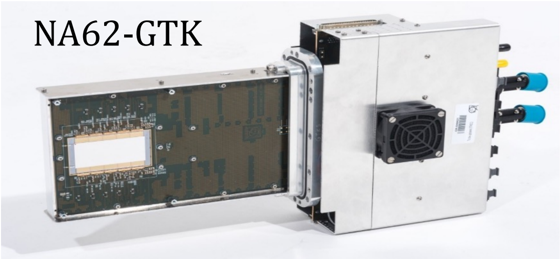
Neutrino tagging: measure neutrino energy event-by-event



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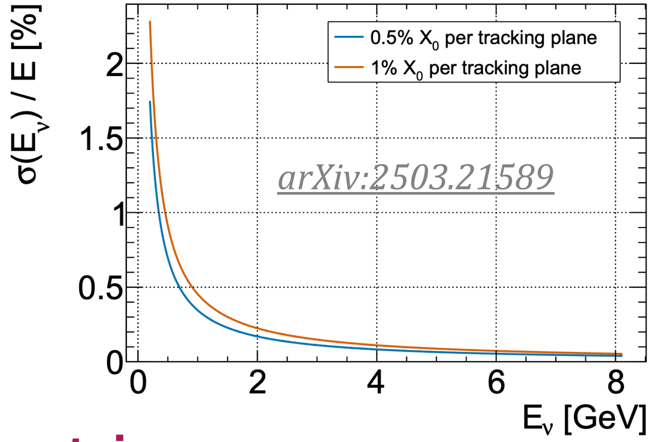

It is possible to measure neutrino energy event-by-event with <1% resolution

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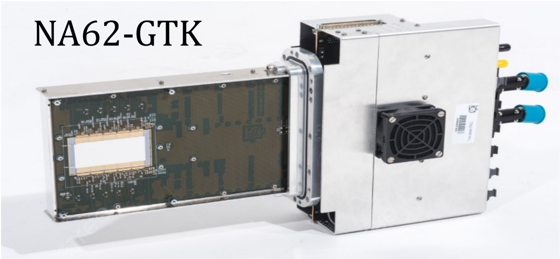
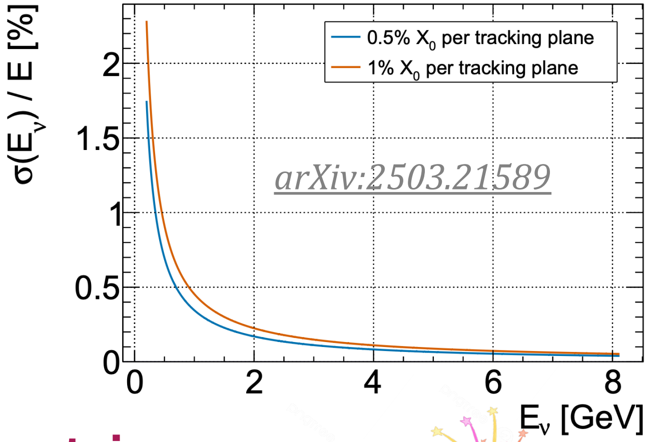


[Phys.Lett.B 863 (2025) 139345]



[arXiv:2503.21589]

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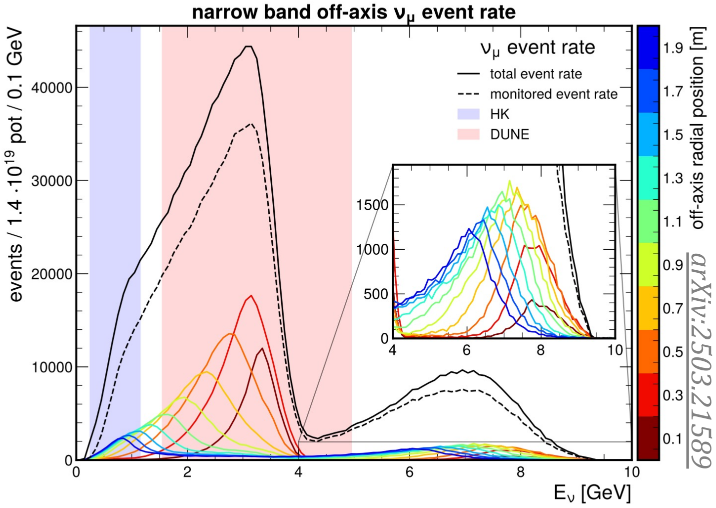
- Monitored beam: ~1% flux uncertainties
- Neutrino tagging: measure neutrino energy event-by-event
- Wide range of energies: covers both DUNE and HK regions of interest



arXiv:2503.21589

What does nuSCOPE bring to the table?

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Neutrino tagging: measure neutrino energy event-by-event

Wide range of energies: covers both DUNE and HK regions of interest

This relies on:

- Slow extraction beam, low intensity (10^{13}protons/9.6s spill)
- Large detectors – $\mathcal{O}(1kt)$ – close to decay tunnel
- Excellent beamline ($\mathcal{O}(10-100)$ps) and detector ($\mathcal{O}(1)$ns) timing resolution

Examples of measurements nuSCOPE can make

See arXiv:2503.21589 for full list

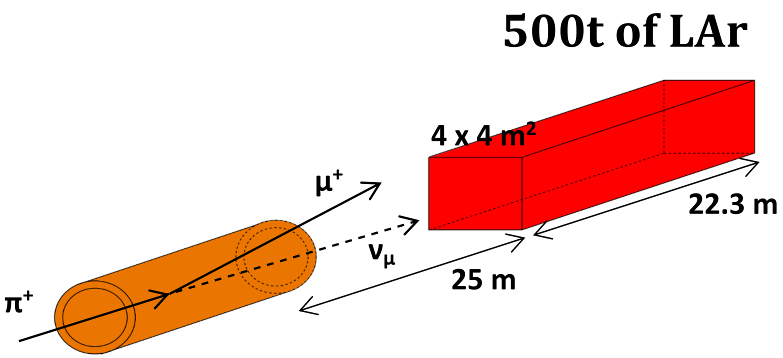
Studies done assuming $1.4{\times}10^{19}$ *POT*

(5 years of running, POT to ensure compatibility with fixed target experiments e.g. SHiP)

Reference setup

Current preliminary studies performed assuming a simplistic detector design

- Began with LAr detector, but plan to expand to water target
- Reference model is GENIE `AR23_20i_00_000`



Low beam intensity compensated by **large detector size** and **proximity to beam**

- $\mathbf{1.0{\times}10^6}$ monitored $\boldsymbol{\nu_\mu}$ events
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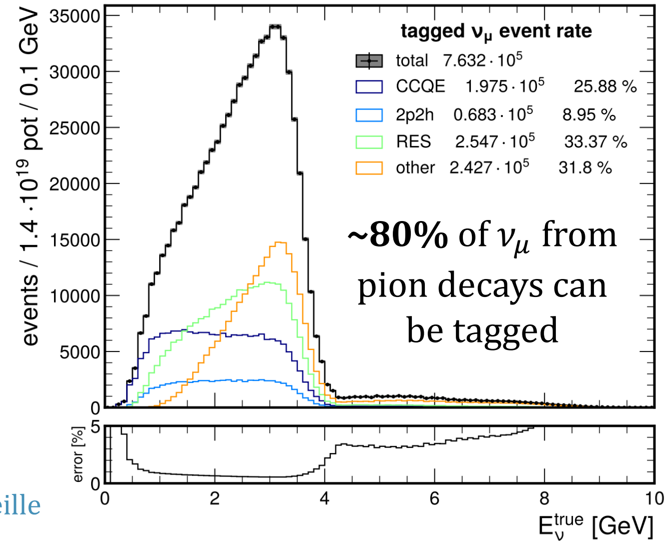
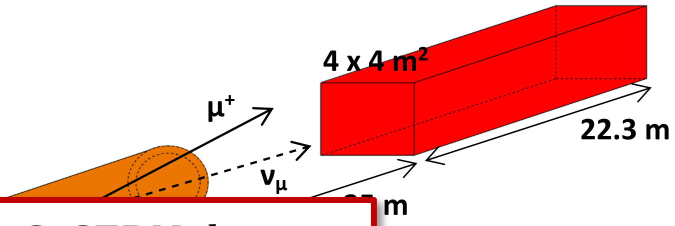


Reference setup

500t of LAr



Current preliminary studies performed assuming a simplistic detector design

- Began with LAr detector, but plan to expand to water target
- Reference model i

We will host an **open workshop** @ CERN during 13-15 October to discuss the detector design
https://indico.cern.ch/event/1548855/

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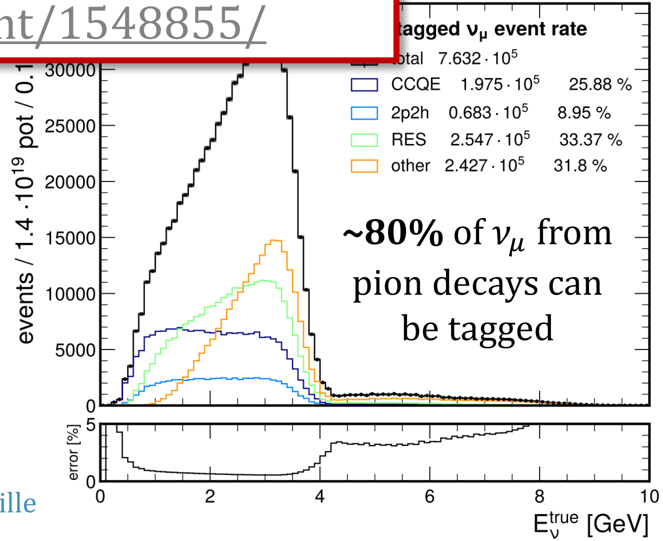
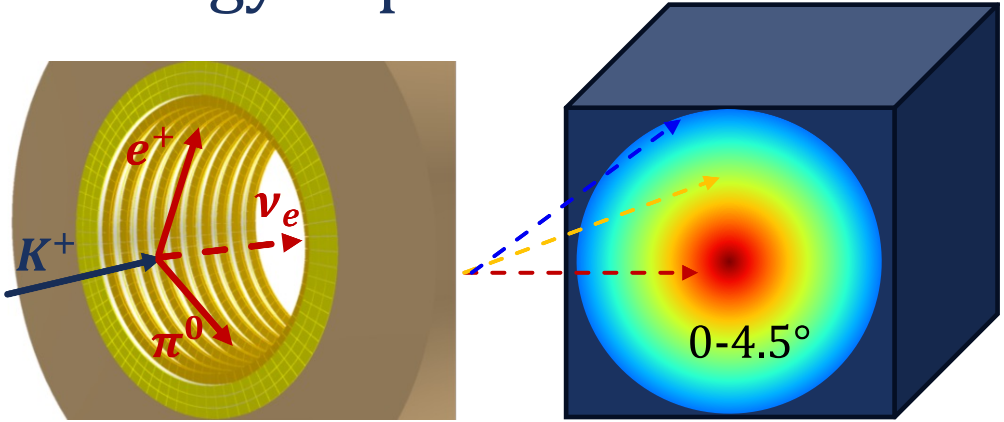
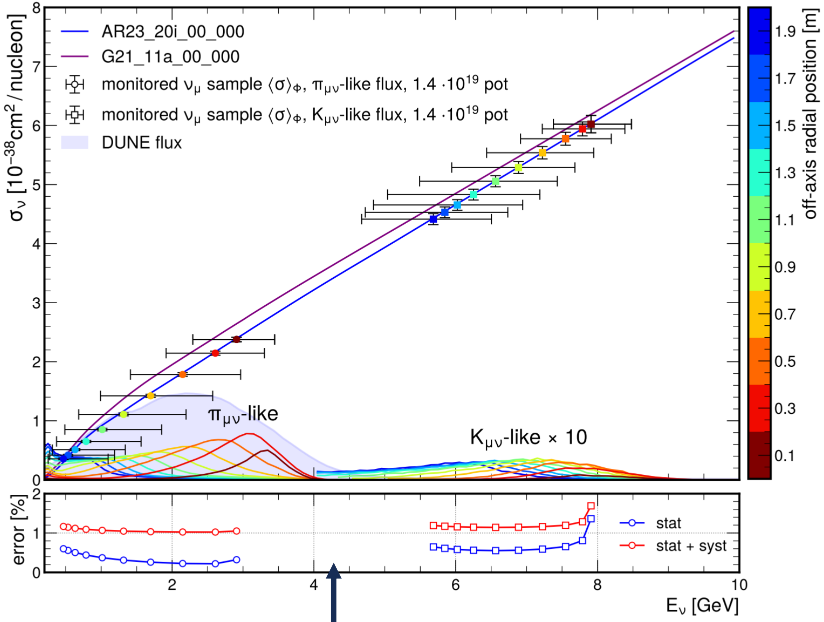


~80% of ν_μ from pion decays can be tagged

Energy dependence of the neutrino cross section



By monitoring

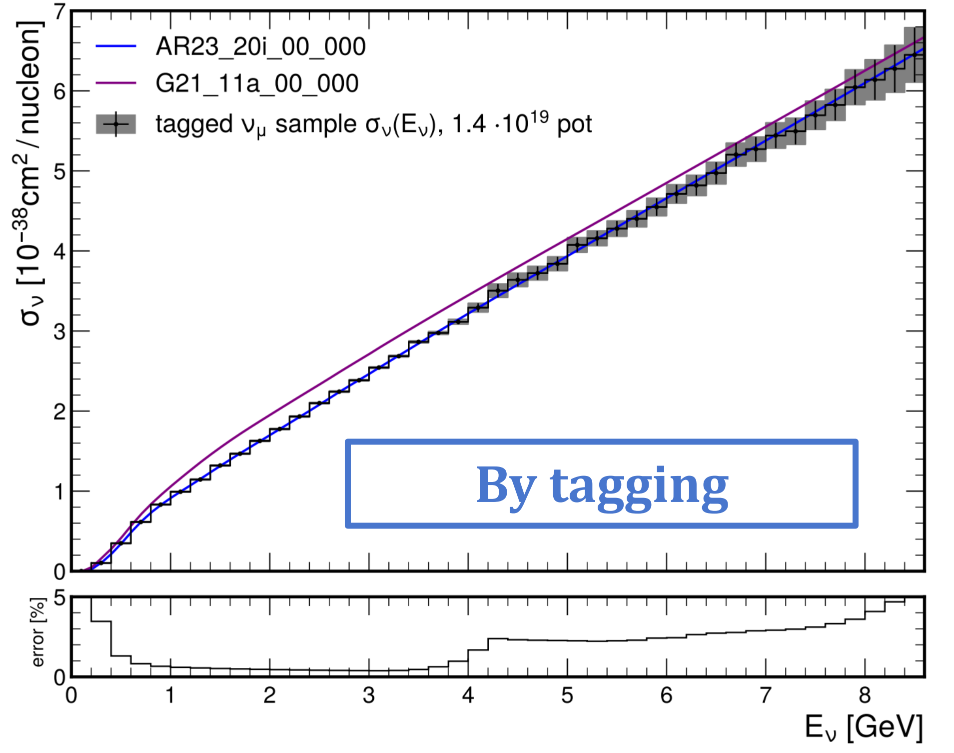


Exploit angular dependence of neutrino energy to obtain **narrow off-axis fluxes**

Multiple **flux-averaged measurements of total cross-section**

<1% systematic error on flux

Energy dependence of the neutrino cross section



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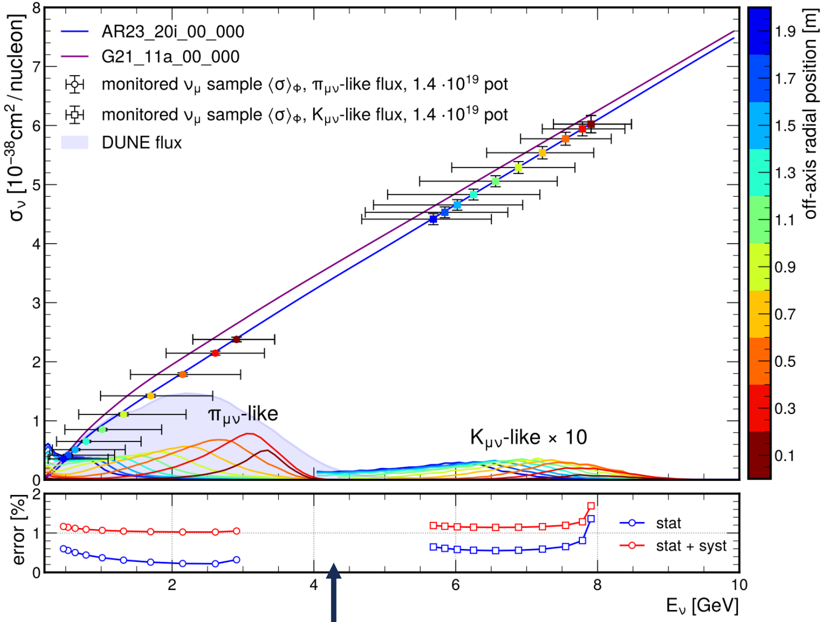
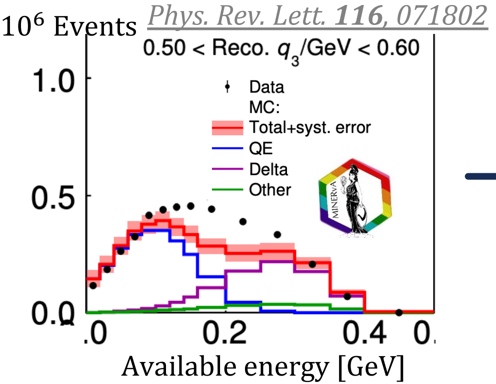
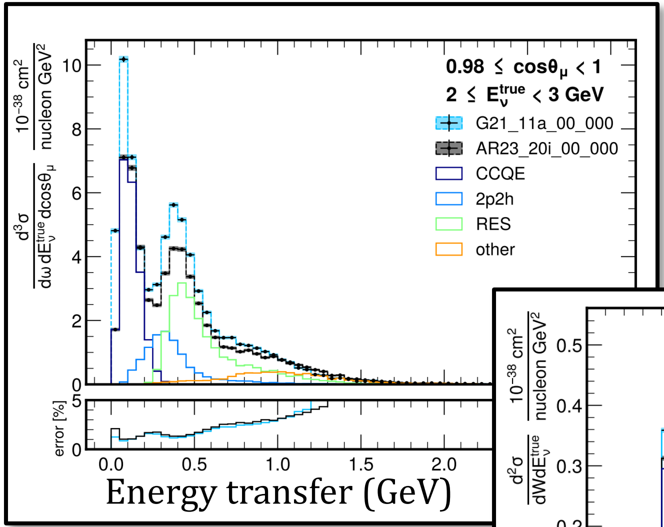
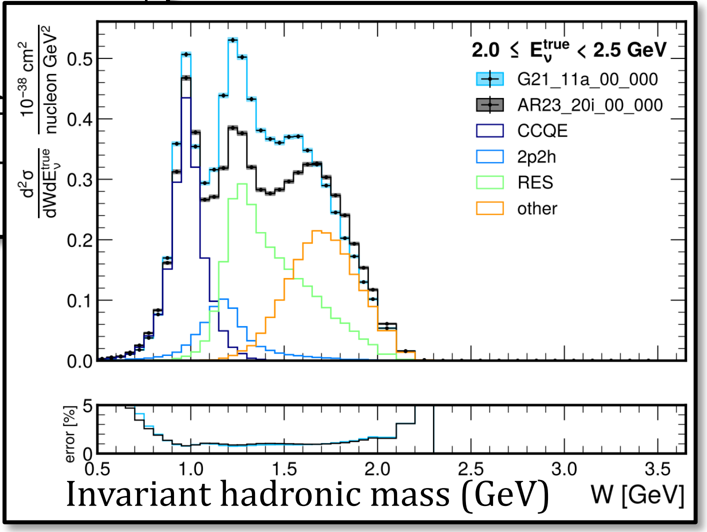


<1% systematic error on flux

Electron scattering-like measurements with neutrinos



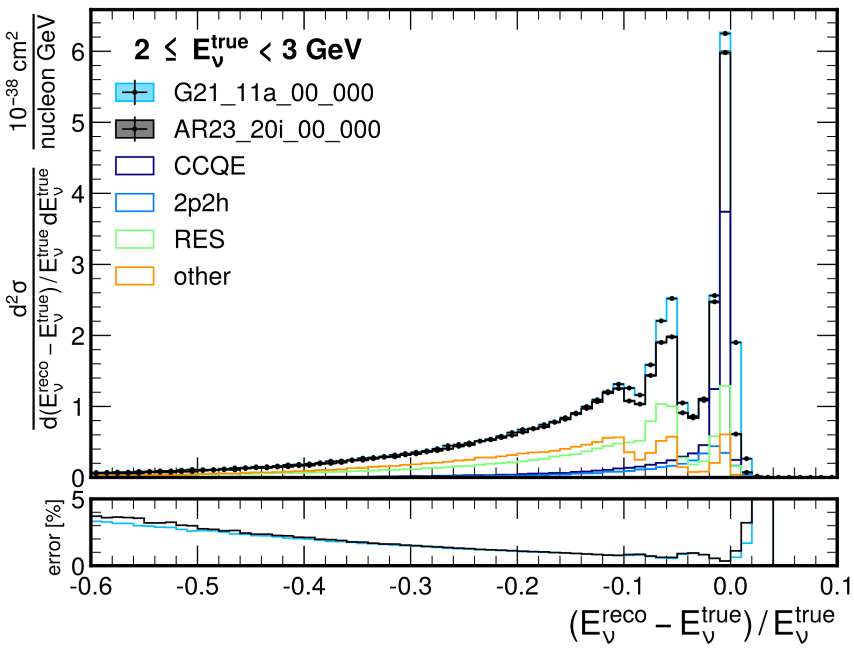




Large model disagreement

Gives access to fundamental nuclear physics processes

Calibration of detector energy response



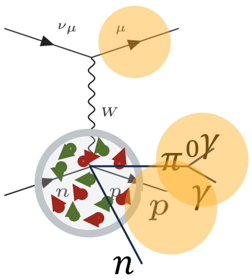
Can measure the **difference between true and reconstructed neutrino energy**

$$E_\nu^{reco} = E_\mu + \sum_{i=\pi^\pm,p} T_i + \sum_{i=\pi^0,\gamma} E_i$$

"visible" energy using calorimetric method (like DUNE, NOvA, MINERvA)

Measures the amount of invisble energy carried away by neutrons and neutrinos

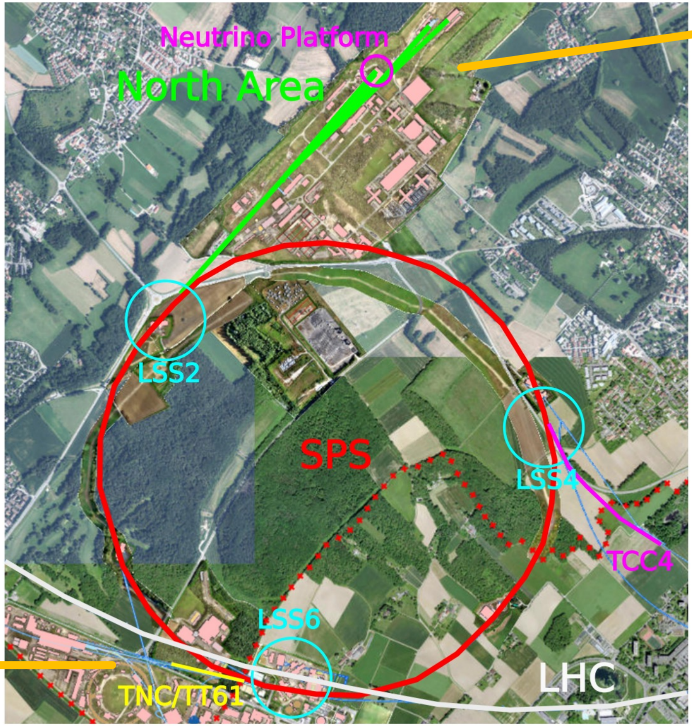
Calibrate out nuclear effects

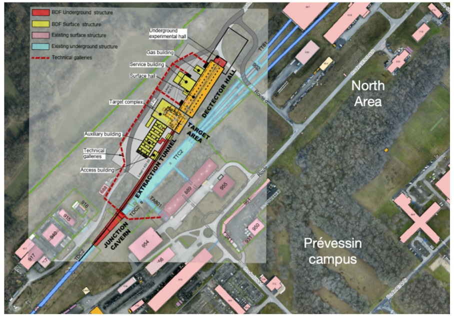


Possible implementation at CERN

Feasibility studies conducted by CERN Accelerator & Technology Sector – **2 sites identified**

Proton sharing is compatible with other fixed target experiments (e.g. SHiP)

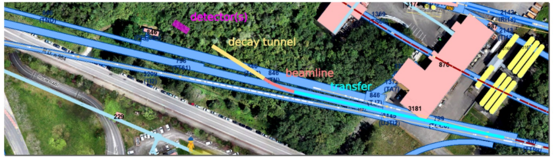




North Area (ECN4)

Feasibility studies ongoing under the umbrella of **Physics Beyond Colliders**

Meyrin (LSS6)



Synergies: why should you care?

Comprehensive effort with **lots of opportunities**

- Accelerator studies
- Beamline detectors/instrumentation
  - E.g. **Silicon trackers** taking inspiration from LHCb-VELO & new R&D for HiLumi LHC
  - Need to cope with event rates of 20 GHz!
- Neutrino detector
  - We need a fast LAr detector !
  - High coverage **photo-detection system**
  - **Containment** and design optimization
- Collaboration with **nuclear theory** community

Summary

- Neutrino oscillations entering the **precision** measurement era
  - Will be hindered by systematic uncertainties due to **neutrino cross sections**
- nuSCOPE uses a monitored and tagged neutrino beam
  - Reduces flux uncertainties <1%
  - **Neutrino energy event-by-event measurement**
- Extensive measurement program
- Opportunities for **incisive R&D activities**

If you are interested, join us for a workshop @ CERN (13-15 October)
https://indico.cern.ch/event/1548855/