nuSCOPE

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

Laura Munteanu (CERN)

on behalf of the nuSCOPE Collaboration

NuFACT 2025, Liverpool

4 September 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
T2K arXiv:2303.03222	318	94	~5%
NOvA Neutrino 2024 talk	384	181	~5%

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Hyper-K arXiv:2505.15019	**~9000**	**~2500**	**Need ~1-3%**
DUNE Phys. Rev. D **105**, 072006	**~15000***	**~3500***	**Need ~1-3%**

**Scaled to 10 years*

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T2K arXiv:2303.03222

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

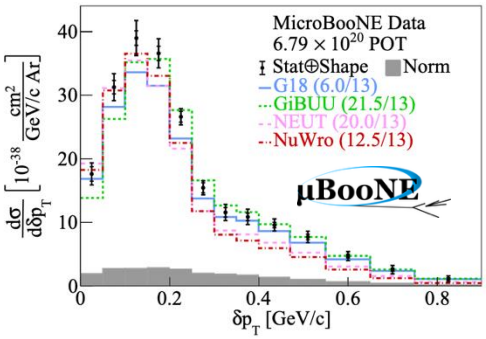
Bottlenecks:

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

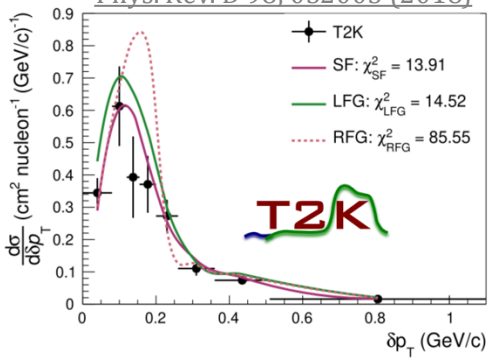
Can’t we just measure neutrino cross sections?

We do, but…

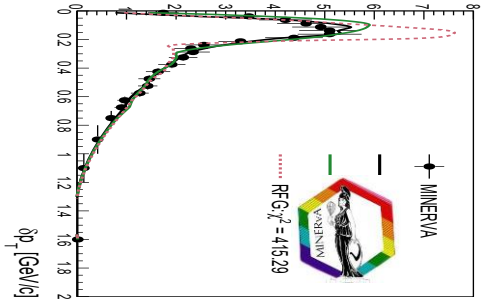
arXiv:2301.03700



Phys. Rev. D 98, 032003 (2018)

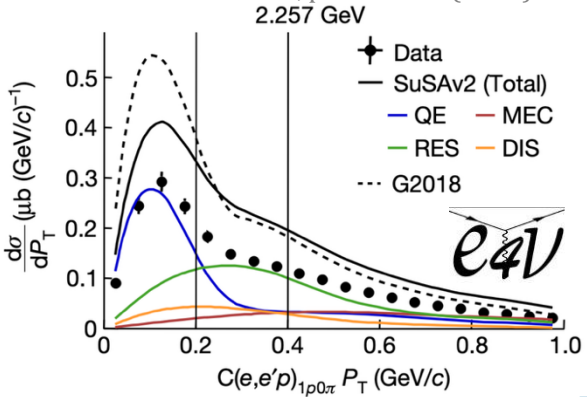


Phys. Rev. Lett. 121, 022504 (2018)



arXiv:2407.10962

Nature 599, p. 565–570 (2021)



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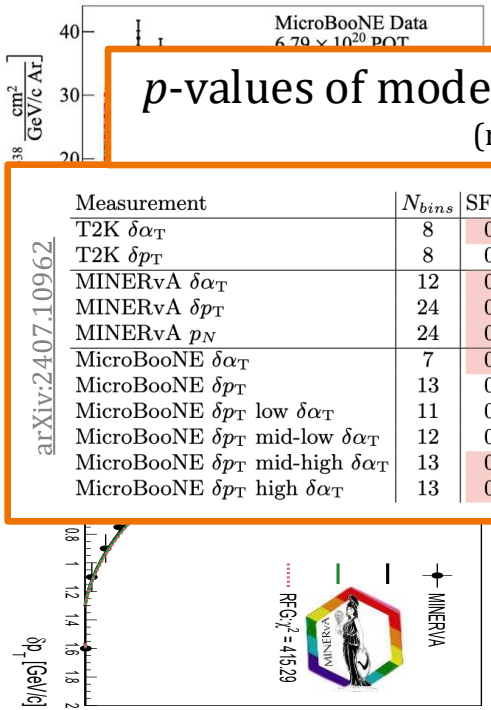

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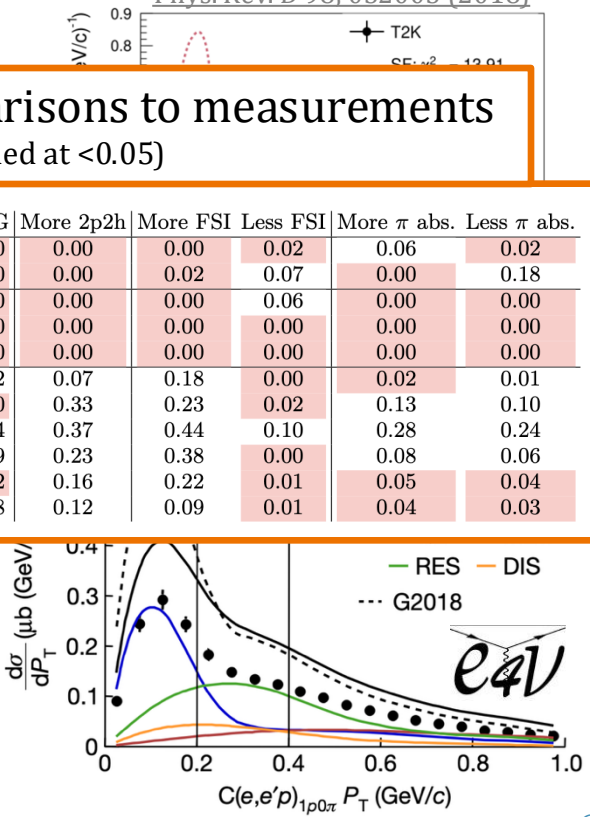

p-values of model comparisons to measurements

(red if excluded at <0.05)

arXiv:2407.10962

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
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No model is able to describe global neutrino scattering measurements

*Our ν measurements tell us that all the models are wrong **but not why/where or how to fix them***

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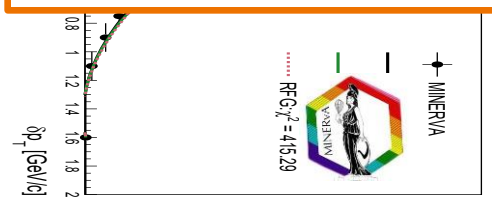

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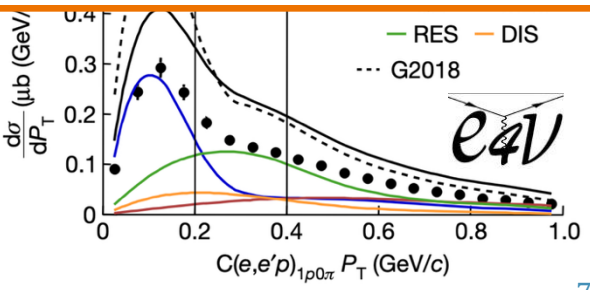
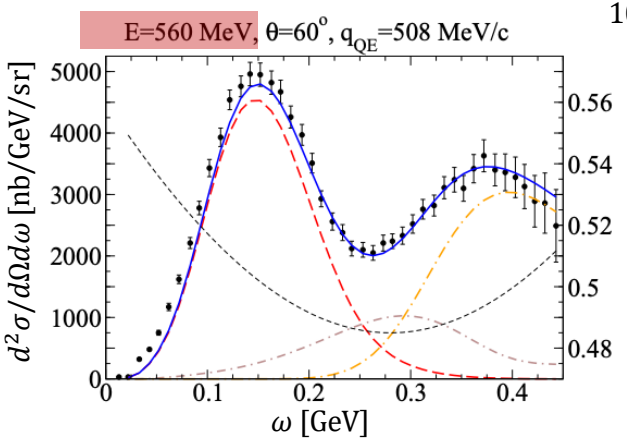
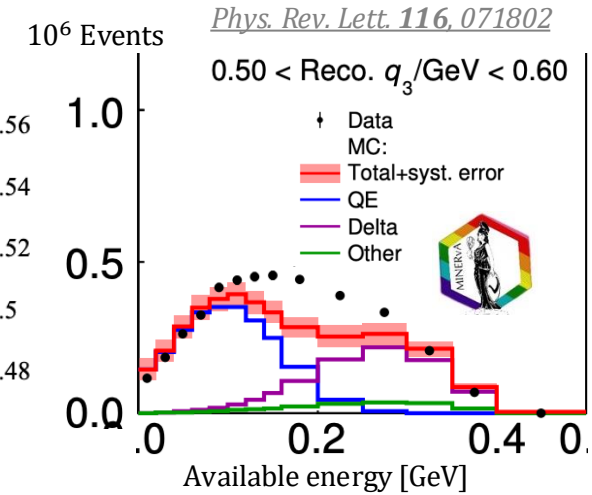


Why is it so difficult?

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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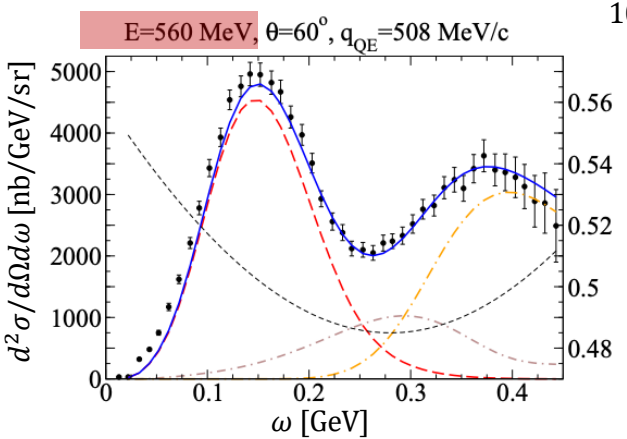

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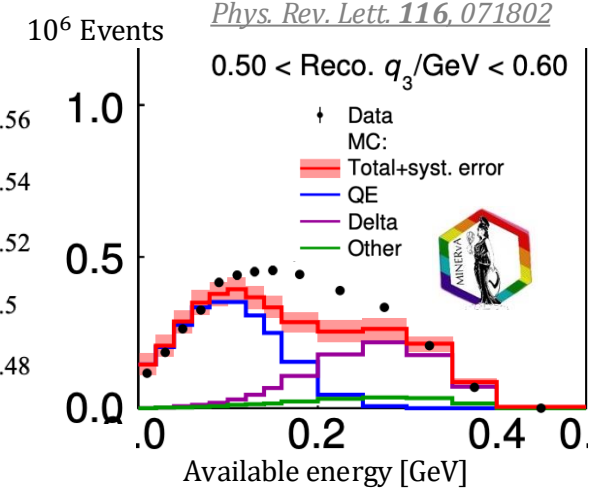

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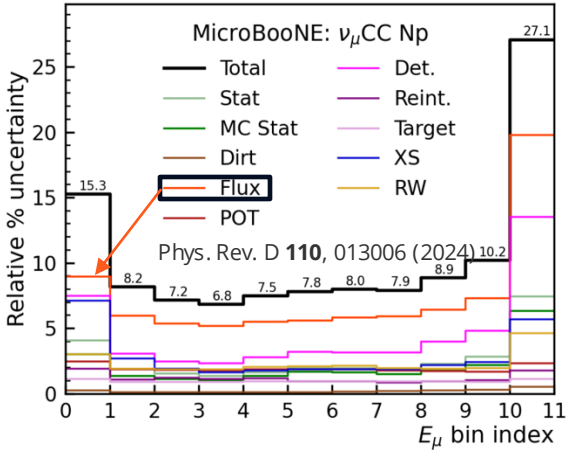
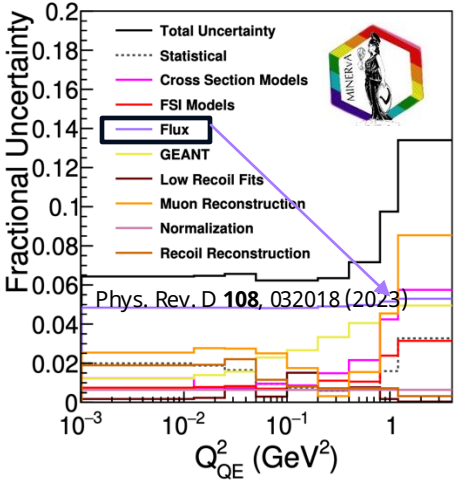
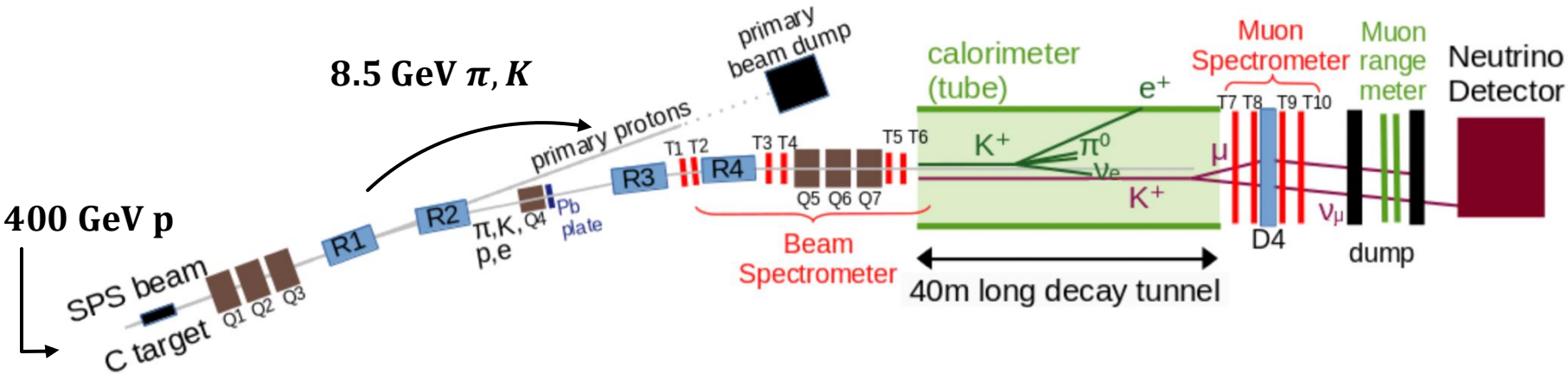




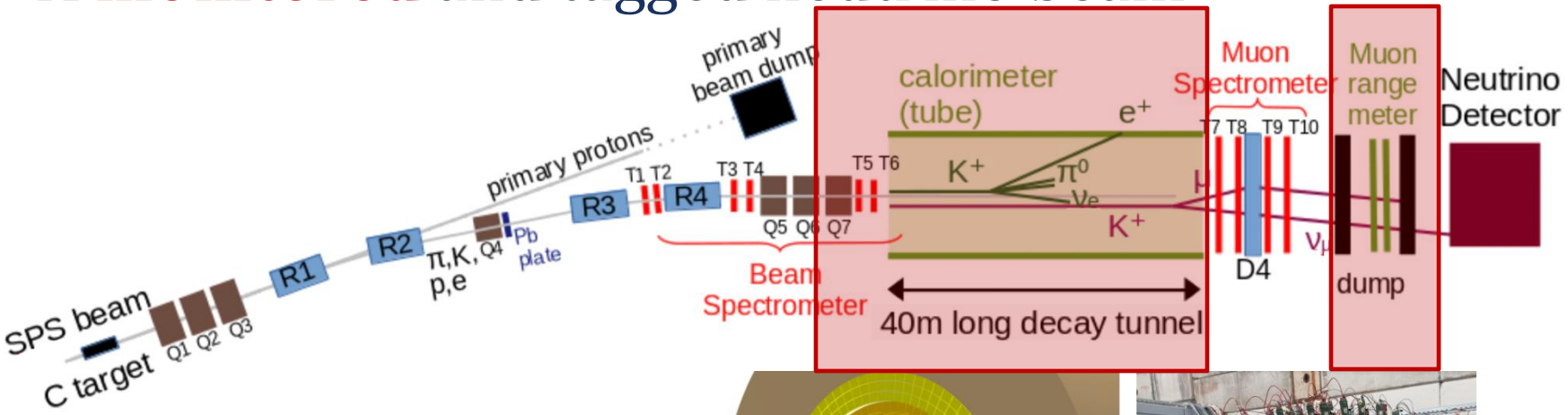
Enter

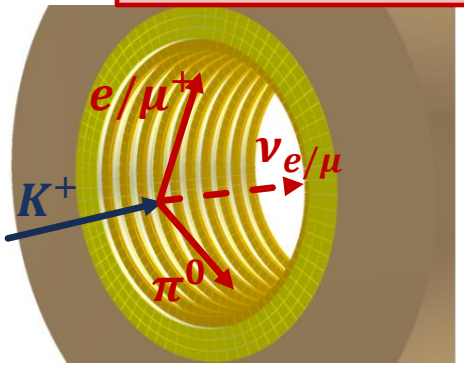
nuSCOPE (Neutrino SPS Complex for Precision Experiments)

- 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

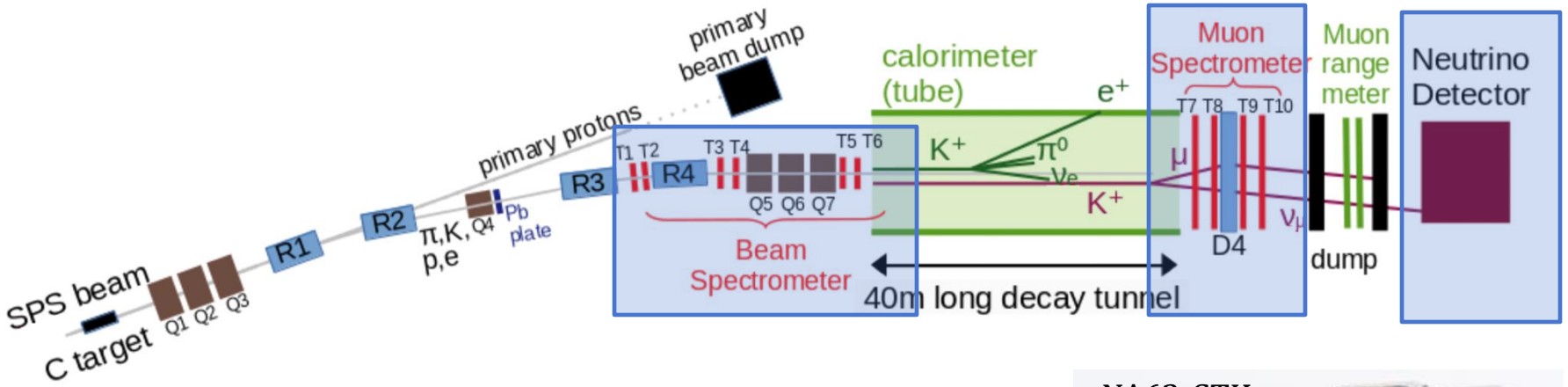




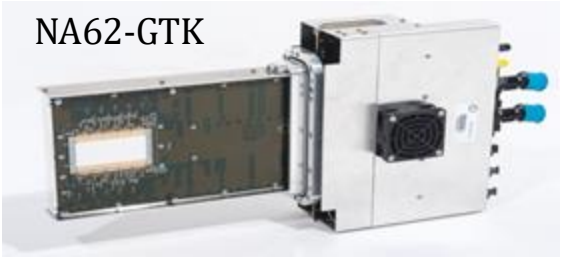
- Instrumented calorimeter decay tunnel & hadron dump
- Identifies the decay products of mesons producing neutrinos

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

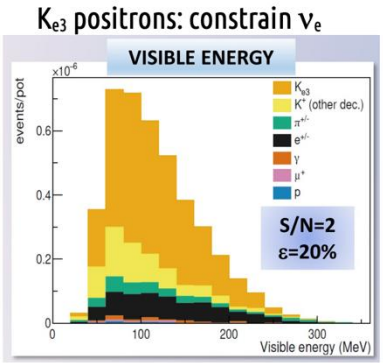


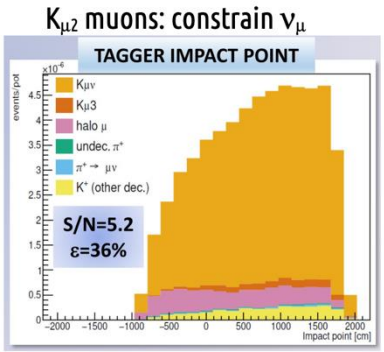
Phys.Lett.B 863 (2025) 139345

A first tagged neutrino candidate observed by NA62

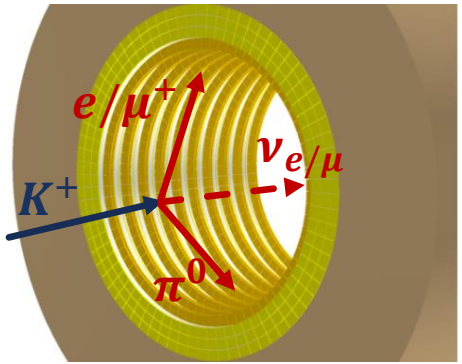
What does nuSCOPE bring to the table?

- ☑ Monitored beam: ~1% flux uncertainties





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



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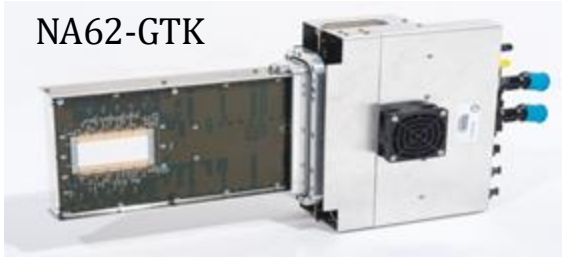

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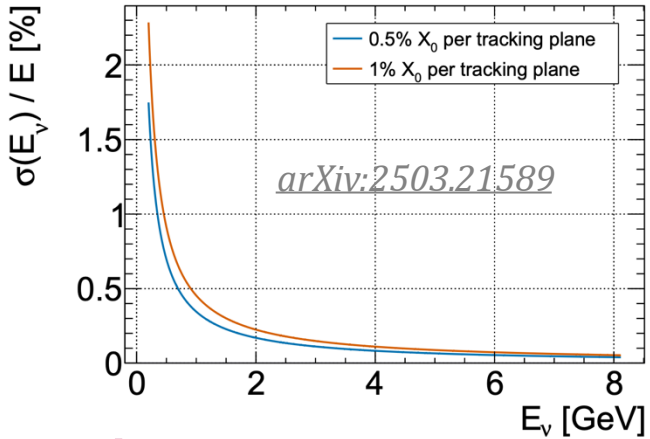

It is possible to measure neutrino energy event-by-event with <1% resolution

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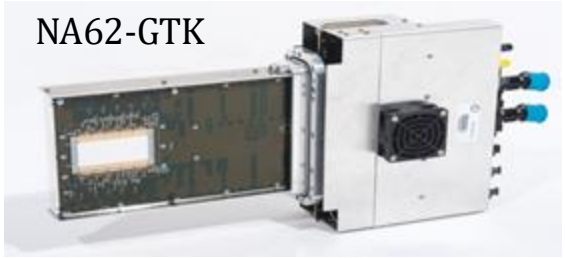

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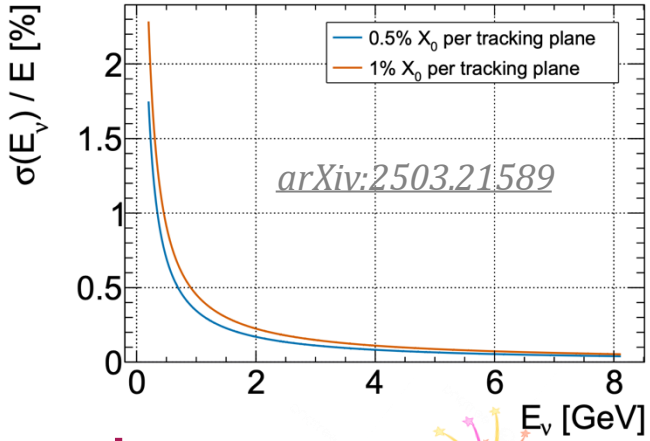

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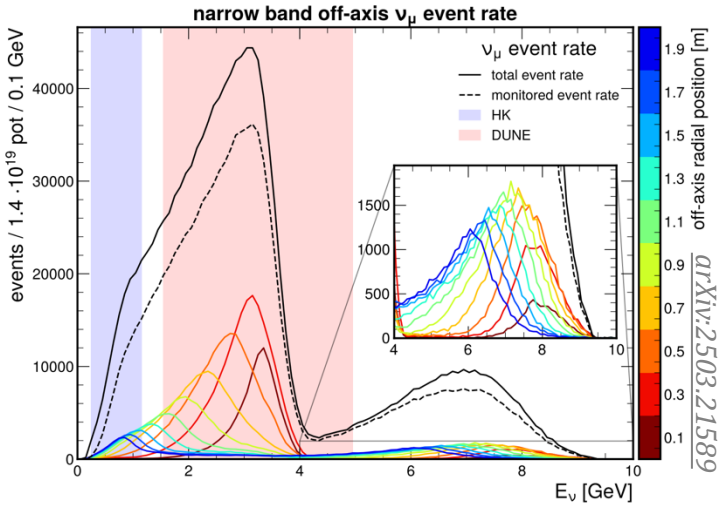
- ✓ Wide range of energies: covers both DUNE and HK regions of interest



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This relies on:

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

Examples of measurements nuSCOPE can make

See arXiv:2503.21589 for full list

Studies done assuming 1.4×10^{19} *POT*

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

Sensitivity studies led by **Filippo Bramati** (LAr), **Mara Pripon** (water)

Reference setup

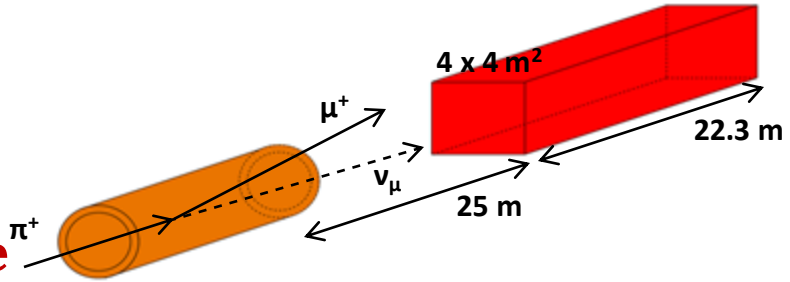
500t of LAr/100t of water

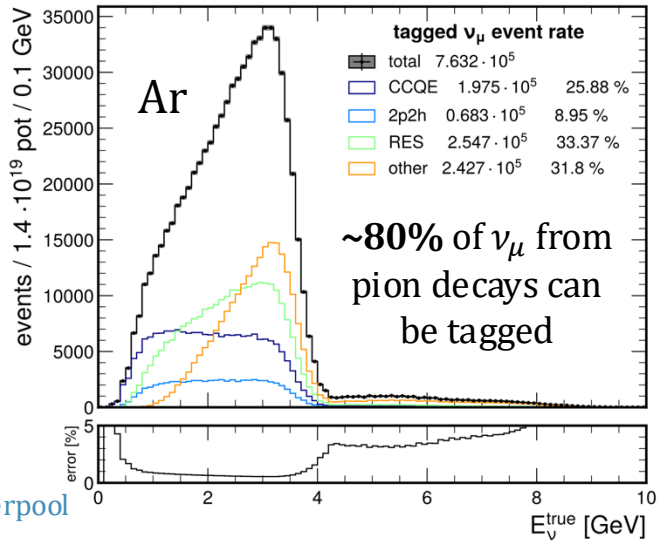
Current preliminary studies performed assuming a simplistic detector design

- Reference model is GENIE `AR23_20i_00_000`

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

- $O(1.0 \times 10^6)/O(1.2 \times 10^4)$ monitored ν_μ/ν_e CC events in both LAr and water
- **Tagging performance:**
  - 7.6×10^5 tagged ν_μ **CC** events in LAr (500t)
  - 1.4×10^5 tagged ν_μ **CC** events in water (100t)
    - Of which **52k** tagged ν_μ **CC0π** events





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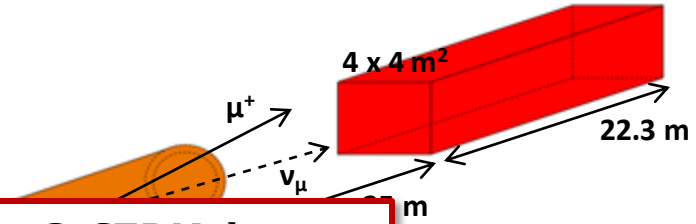
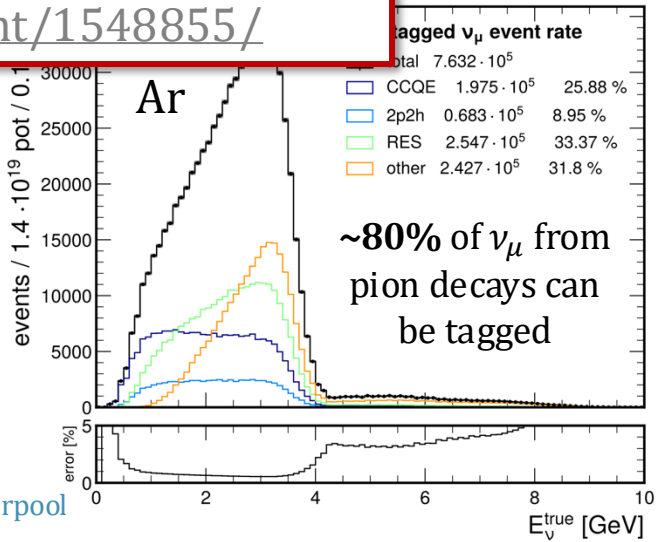
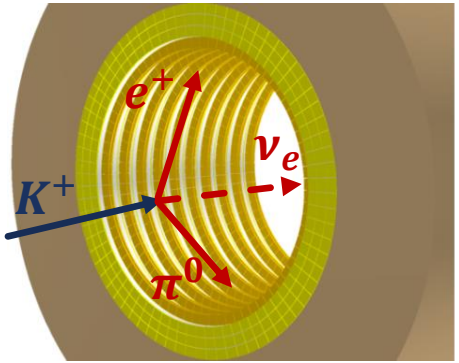
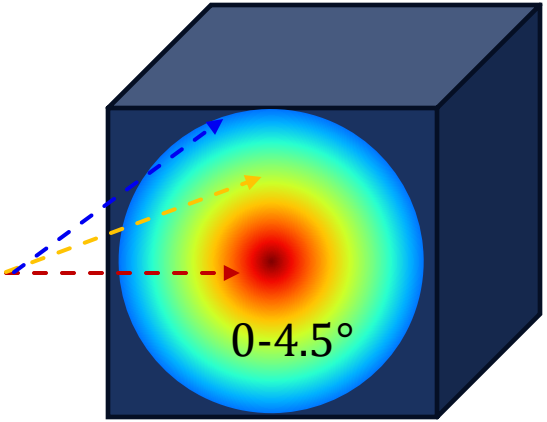


We will host an **open workshop** @ CERN during 13-15 October to discuss the detector design
https://indico.cern.ch/event/1548855/

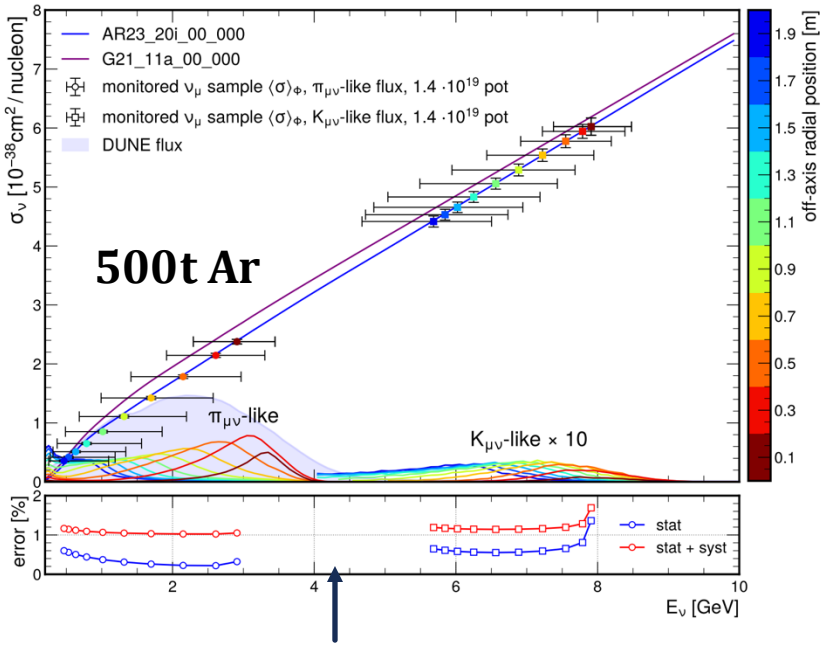


Energy dependence of the neutrino cross section





By monitoring



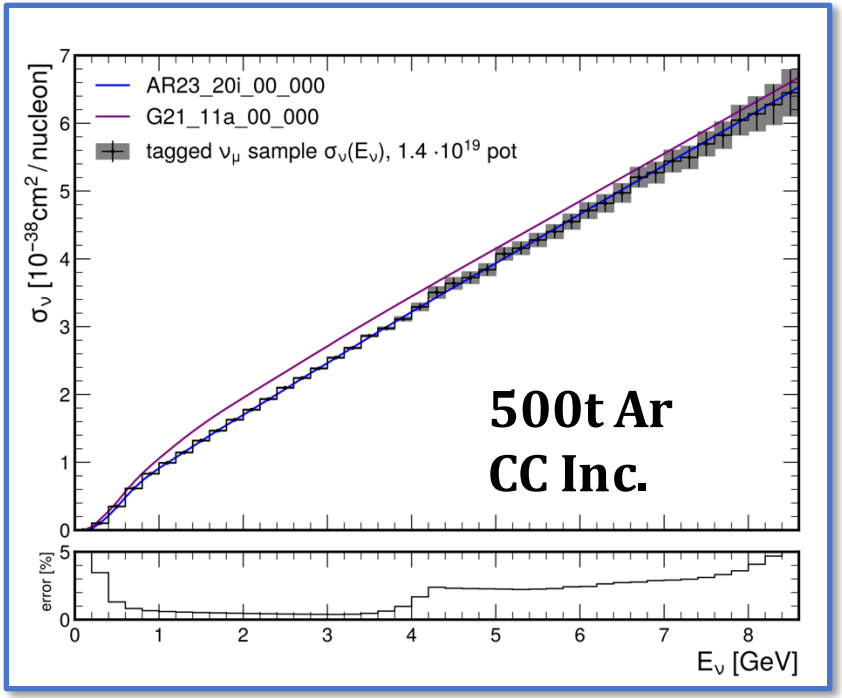
Exploit angular dependence of neutrino energy to obtain **narrow off-axis fluxes**

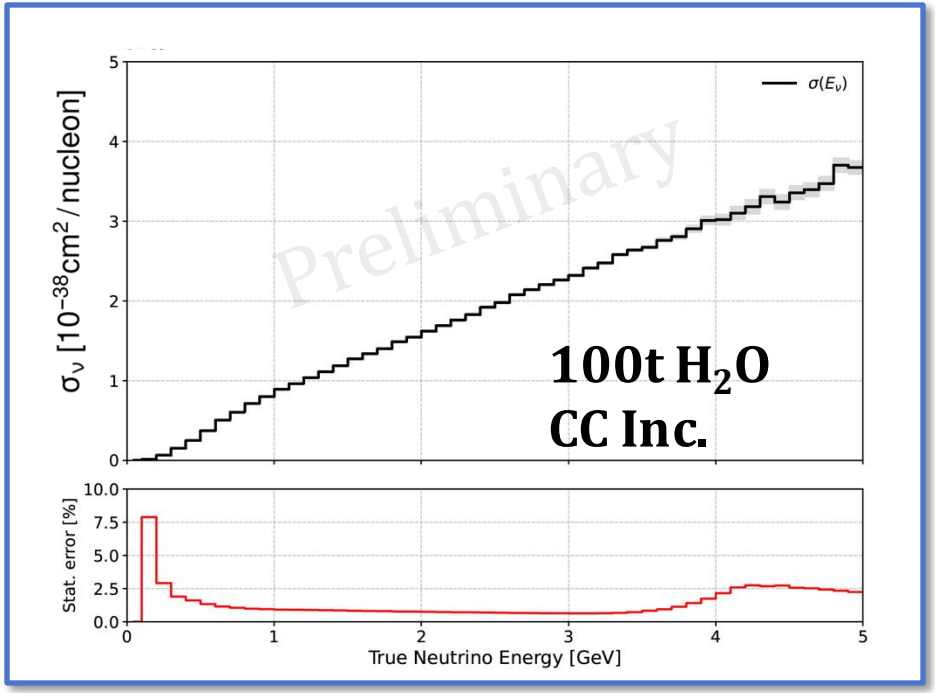
Multiple **flux-averaged measurements of total cross-section**

<1% systematic error on flux

Energy dependence of the neutrino cross section

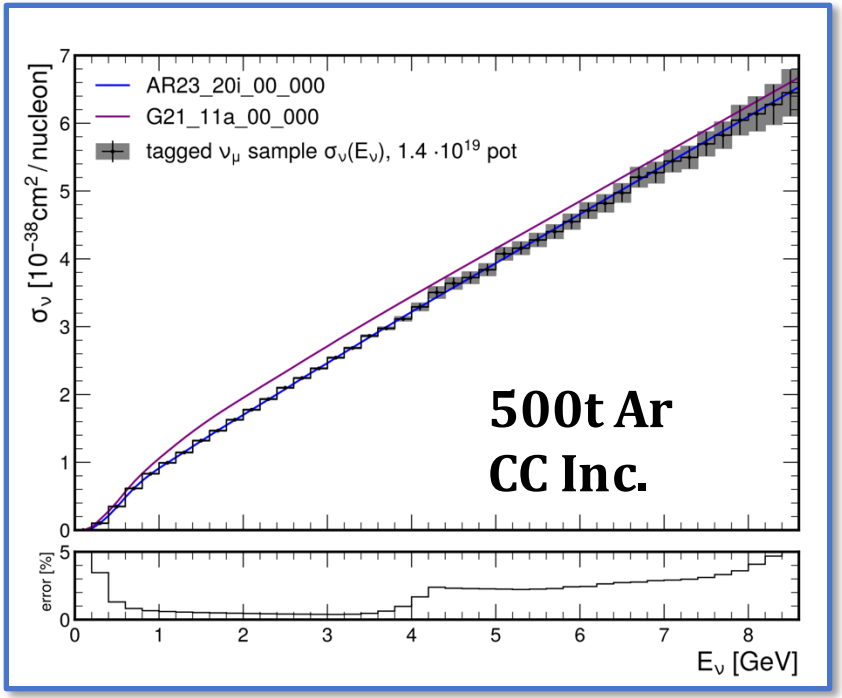
By tagging

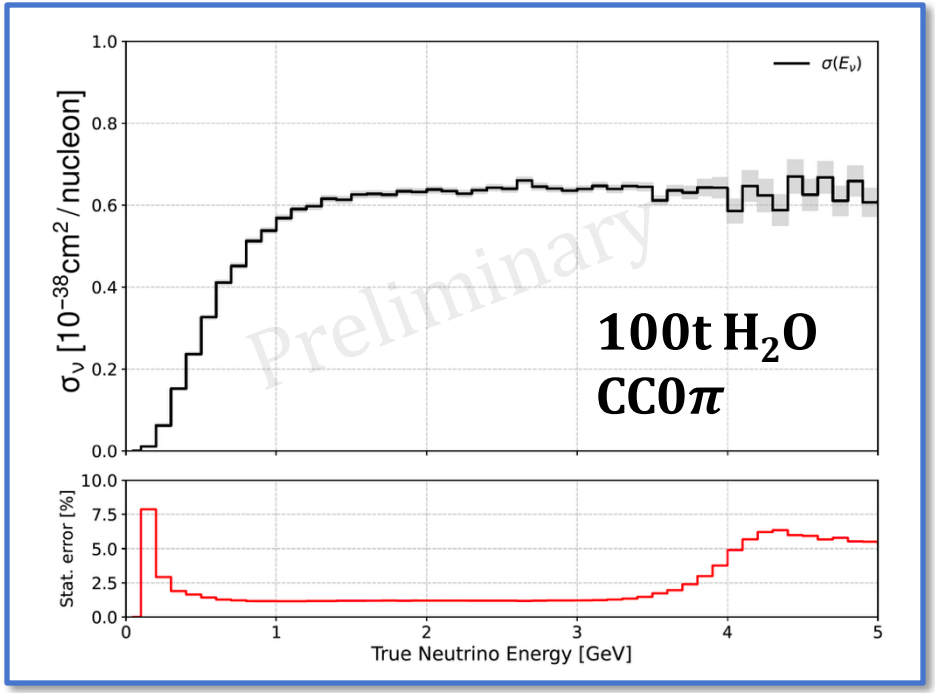




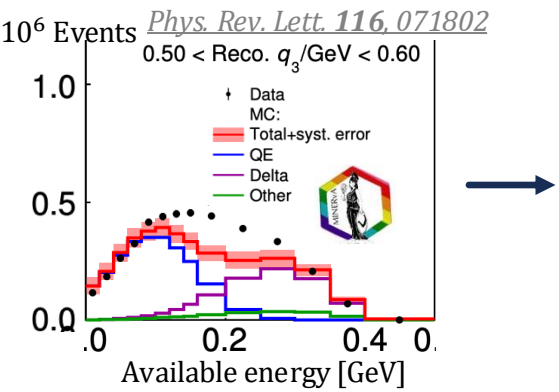
Energy dependence of the neutrino cross section

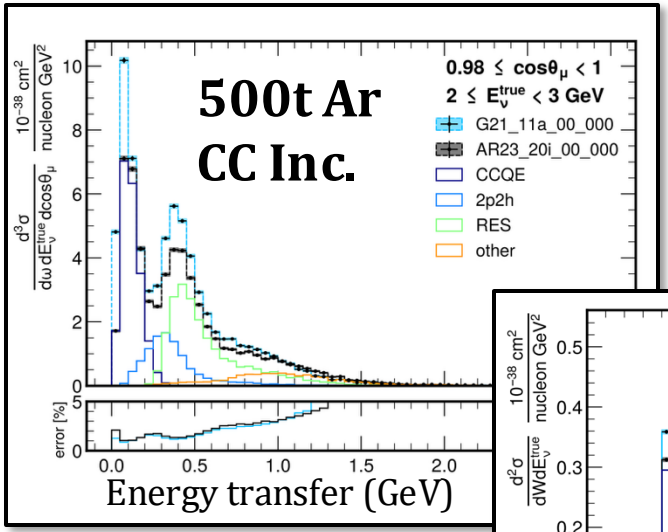
By tagging



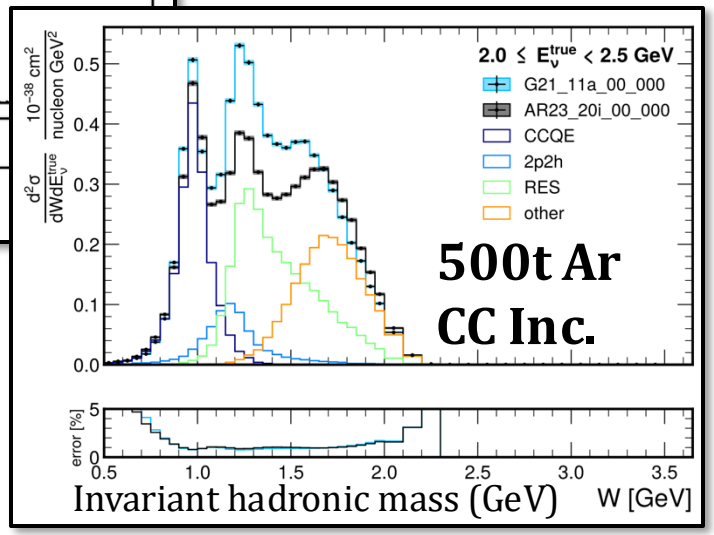


Electron scattering-like measurements with neutrinos



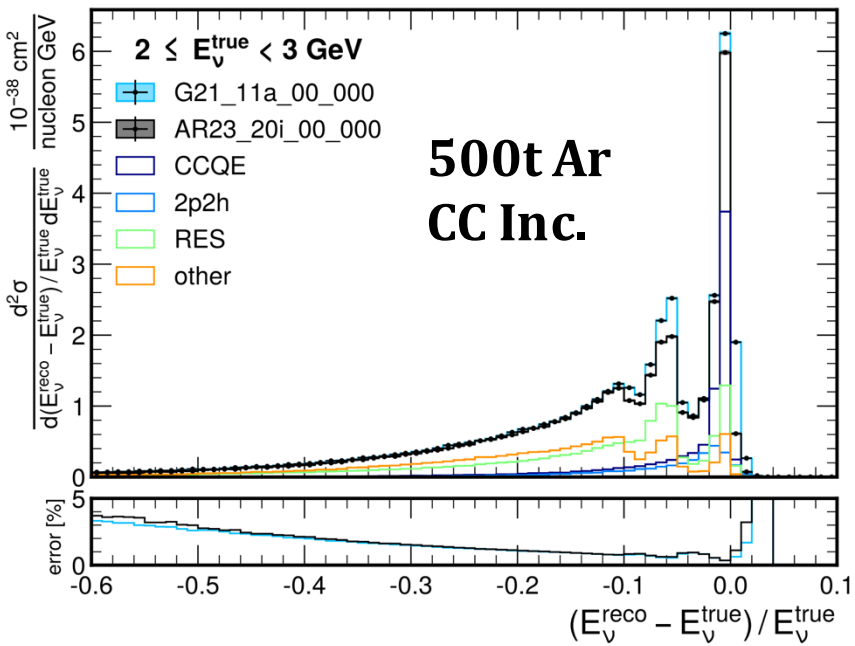


Large model disagreement



Gives access to fundamental nuclear physics processes

Calibration of detector energy response



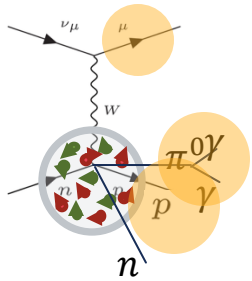
Can measure the **difference between true and reconstructed neutrino energy**

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

"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



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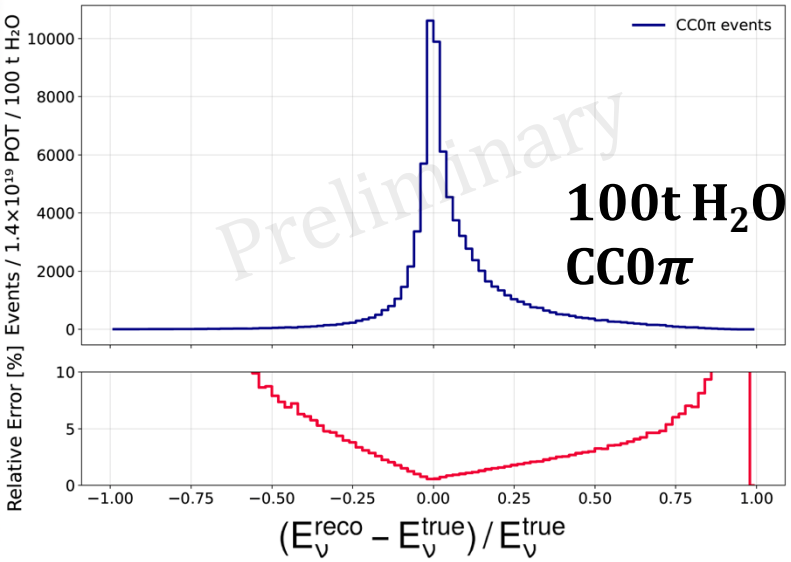


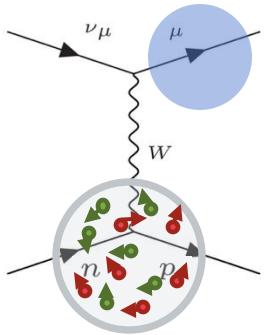
Can measure the **difference between true and reconstructed neutrino energy**

$$E_\nu^{QE} = \frac{1}{2}\frac{m_\ell^2 + (m_N^{eff})^2 - m_{N'}^2 - 2E_\mu m_N^{eff}}{E_\ell - |\vec{p_\ell}|\cos\theta_\ell - m_N^{eff}},$$

$$m_N^{eff} = m_N - E_b,$$

"QE" energy using kinematic reconstruction (T2K/SK/HK)

Measures the neutrino energy bias due to Fermi motion, npnh, FSI…



Calibrate out nuclear effects

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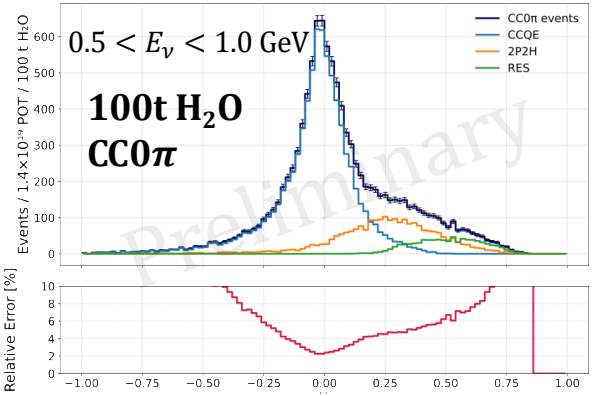

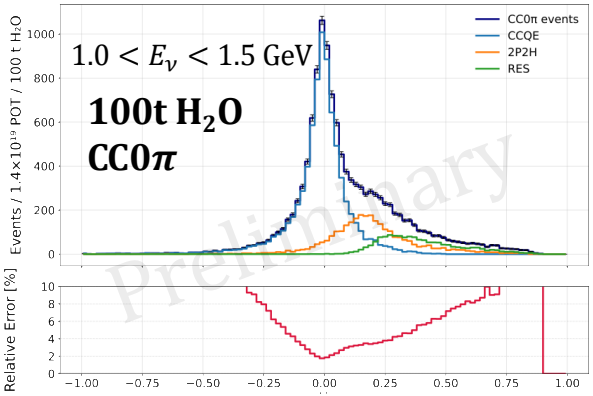

$(E_\nu^{reco} - E_\nu^{true}) / E_\nu^{true}$

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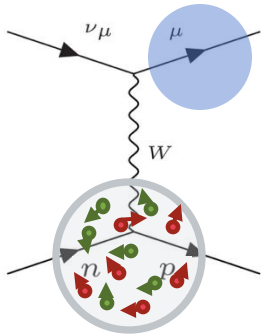
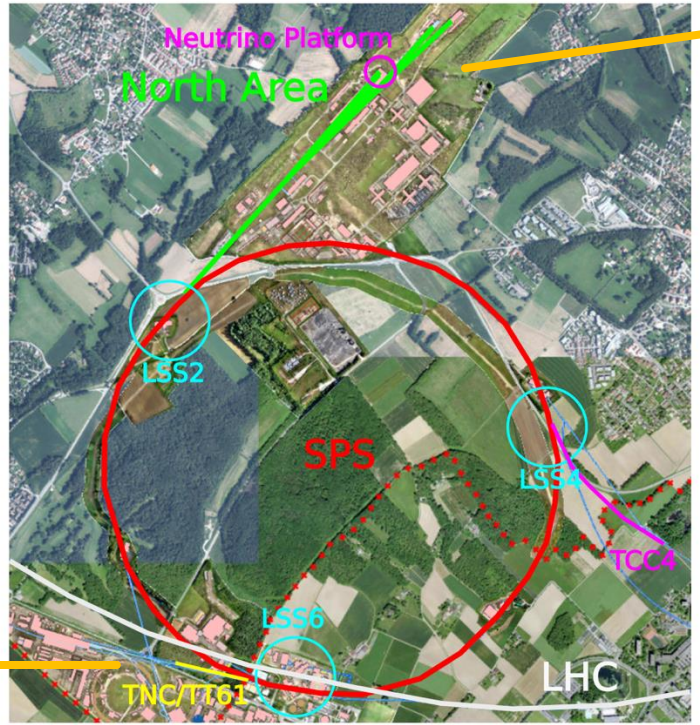
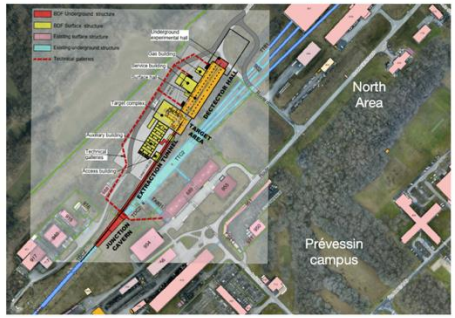


Calibrate out nuclear effects

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** neutrino 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/

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