IRN Neutrino meeting Paris, 3-4 November 2025

Claude Vallée, CPPM Marseille

SUMMARY of the nuSCOPE WORKSHOP
held at CERN on 13-15 October 2025

for details on nuSCOPE see A. Longhin's talk at past IRN

https://indico.cern.ch/event/1548855/

Goals of the workshop: *inform the community about nuSCOPE and get feedback on beam instrumentation challenges, neutrino detectors design and physics motivations*

This summary:

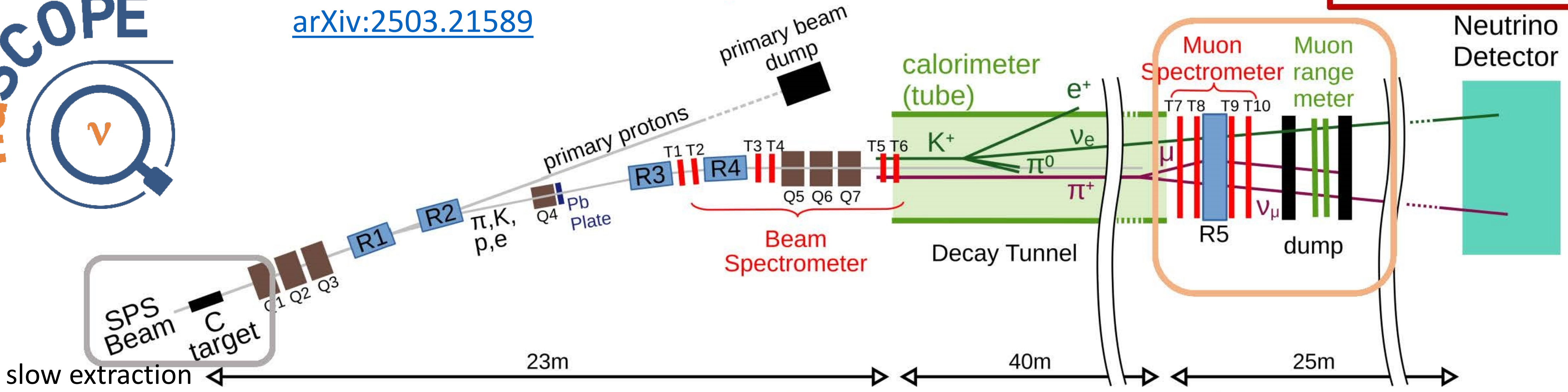
1. Short reminder of nuSCOPE features
2. Beam instrumentation challenges
3. Neutrino detectors design
4. Physics motivations
5. nuSCOPE project next steps

nuSCOPE FEATURES

BEAM LAYOUT

arXiv:2503.21589

Liquid argon and water Cherenkov/ WBLS



Proton accelerator:
CERN SPS (400 GeV/c)
Carbon target

Instrumented static focusing system
Two quadrupole triplet, four dipoles, six silicon trackers for momentum measurement and tagging

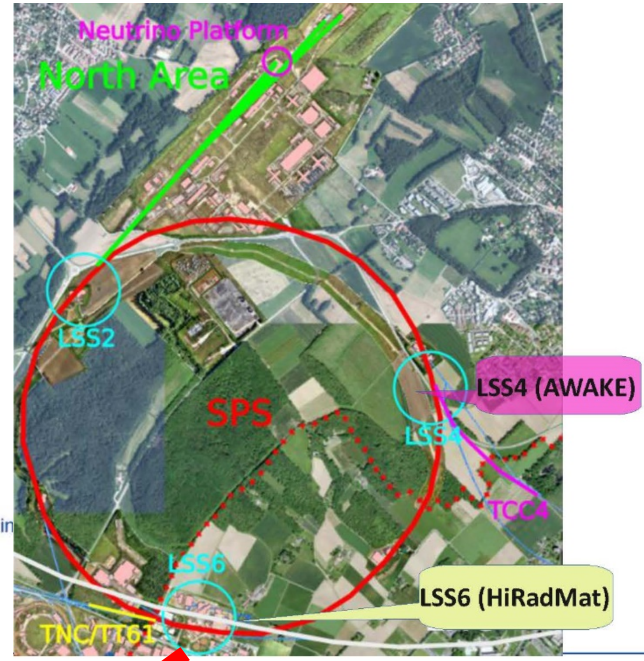
Instrumented decay tunnel
Segmented Fe-scint calorimeter for lepton monitoring in the tunnel wall

Instrumented dump
Muon spectrometer and muon range-meter

nuSCOPE FEATURES cont'd

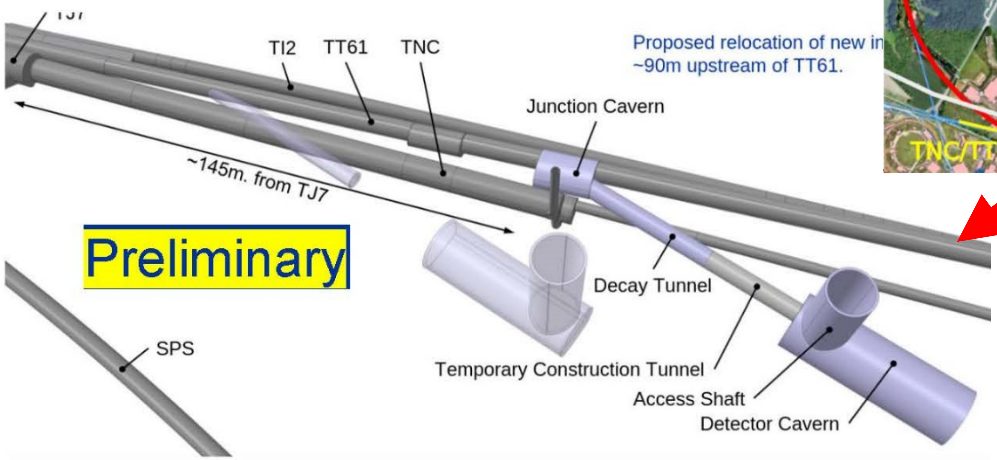
Charitonidis

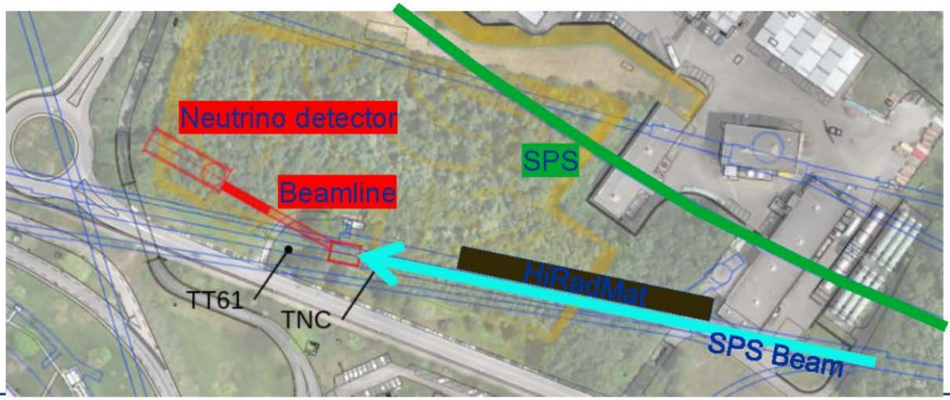
IMPLEMENTATION AT CERN



Possible implementation in LSS6 /TNC/TCC6

- HiRadMat facility located today on the first third of the TNC tunnel
- TT61 tunnel 'mostly' vacant, with some old magnetic elements & beam instrumentation & a shielded part used for the HiRadMat experiments
- Already shielded underground area
- HiRadMat operation remains in parallel





Terranova

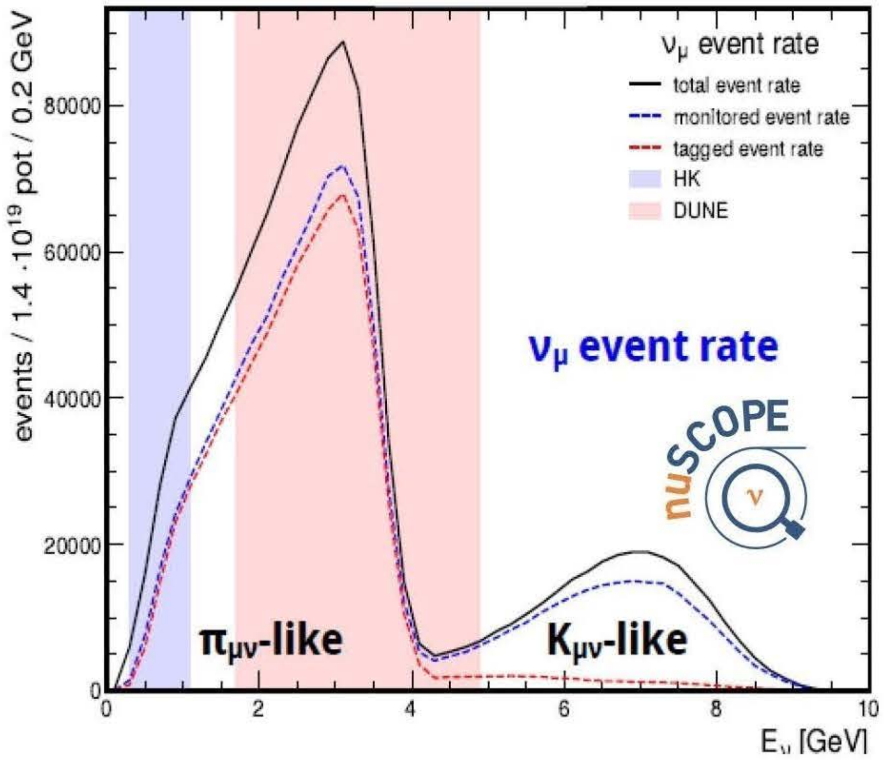
nuSCOPE FEATURES cont’d

EVENT RATES

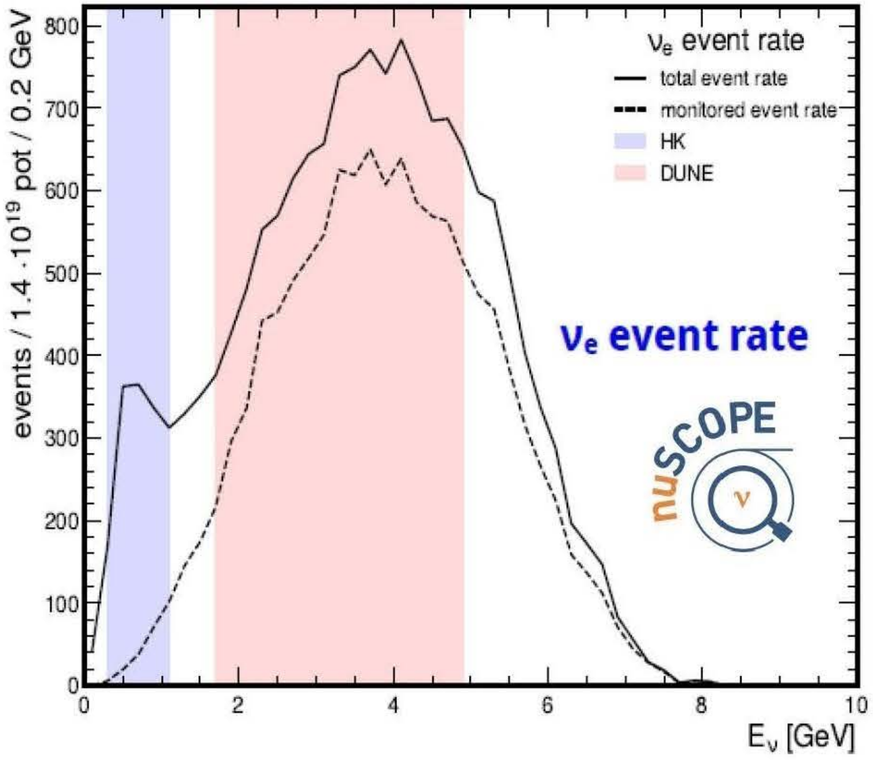
500t LAr detector, ~5 years, 1.4 10^{19} PoTs

Operation compatible with other SPS Fixed Target programs incl. SHiP

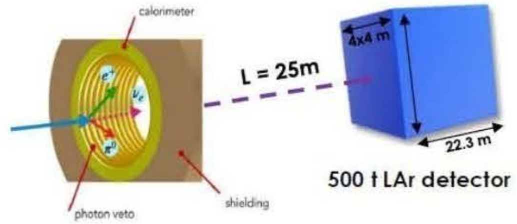
~10^6 ν_μ



~10^4 ν_e



	events / $1.4 \cdot 10^{19}$ PoT
total ν_μ	1.3×10^6
total ν_e	1.7×10^4
total monitored ν_μ	1.0×10^6
total monitored ν_e	1.2×10^4
total tagged ν_μ	7.6×10^5



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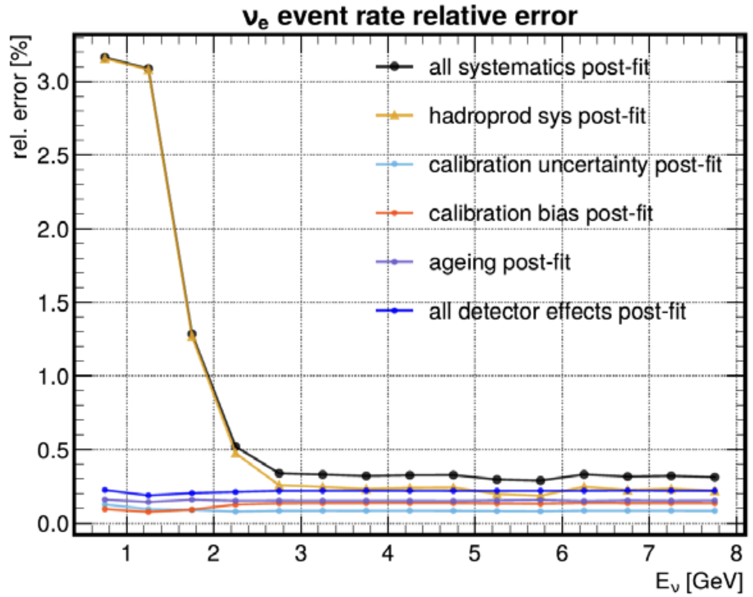
Branca

nuSCOPE FEATURES cont’d

ν_e MONITORING

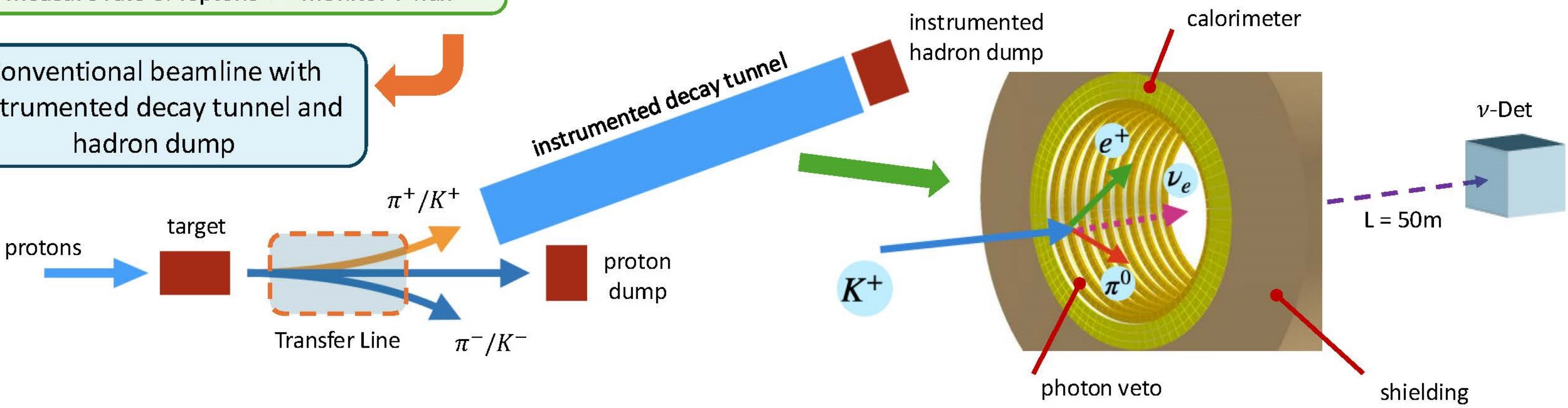


A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

Monitored ν flux from narrow-band beam

measure rate of leptons $\Leftrightarrow$ monitor ν flux

Conventional beamline with instrumented decay tunnel and hadron dump



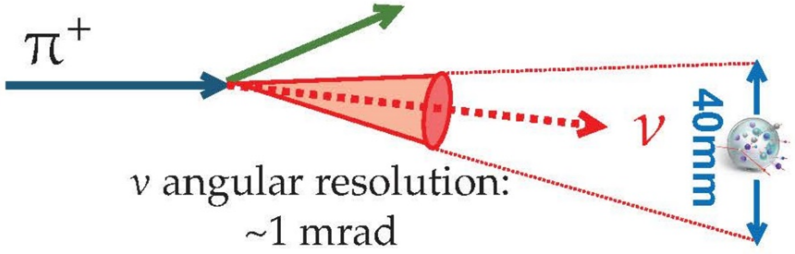
Perrin-Terrin

nuSCOPE FEATURES cont'd

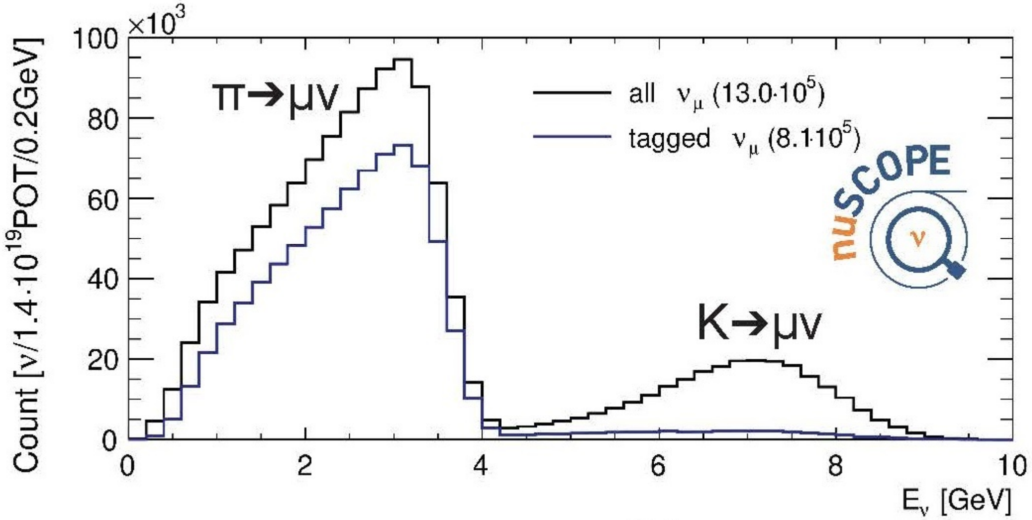
ν_μ TAGGING

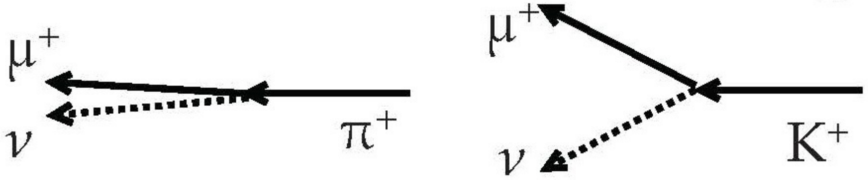
Association is performed using **time and space coincidences**

	Neutrino Dectector	Tagger
Time Resolution	**300 ps**	<10ps
Space Resolution	1mm	**40mm**

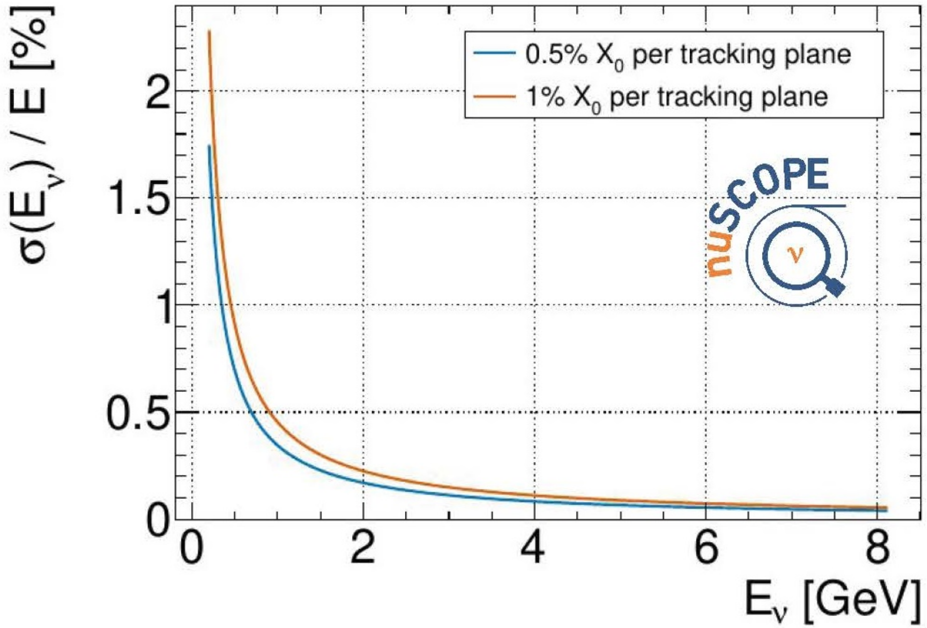


ν_μ tagging efficiency





ν_μ energy resolution



Terranova

nuSCOPE FEATURES cont'd

Technical readiness of nuSCOPE

Is nuSCOPE "ready for construction"? While most of the facility relies on validated technologies, there are still areas that require full confirmation. In particular,

Beamline		
Design	OK	Still room for improvement in reduction of non-monitored ν
Components	OK	Standard and existing (at CERN) components
Slow extraction	in progress	Depends on final implementation
Infrastructure	in progress	Depends on final implementation

Diagnostics for lepton monitoring/tagging		
Decay tunnel instrumentation	OK	ENUBET R&D (2016-2022)
Hadron dump	in progress	ENUBET+PIMENT R&D (2021-ongoing)
Silicon tracking planes	R&D	The technologies are identified within HL-LHC R&D but not yet fully validated
Outer tracking planes and muon spectrometer	in progress	Technologies are identified but design and validation in progress

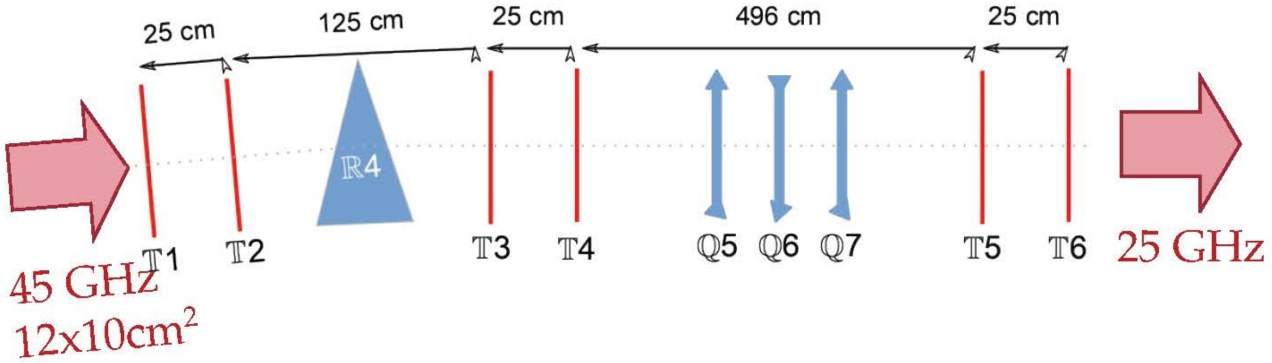
Neutrino detectors		
Liquid argon	in progress	Based on ProtoDUNE's technologies with enhanced light detection (ProtoDUNE Run III)
Water Cherenkov - WBLS	OK	Based on WCTE's technology or Water Based Liquid Scintillators (WBLS)
Muon catcher and cosmic ray veto	in progress	Depends on final implementation

Perrin-Terrin

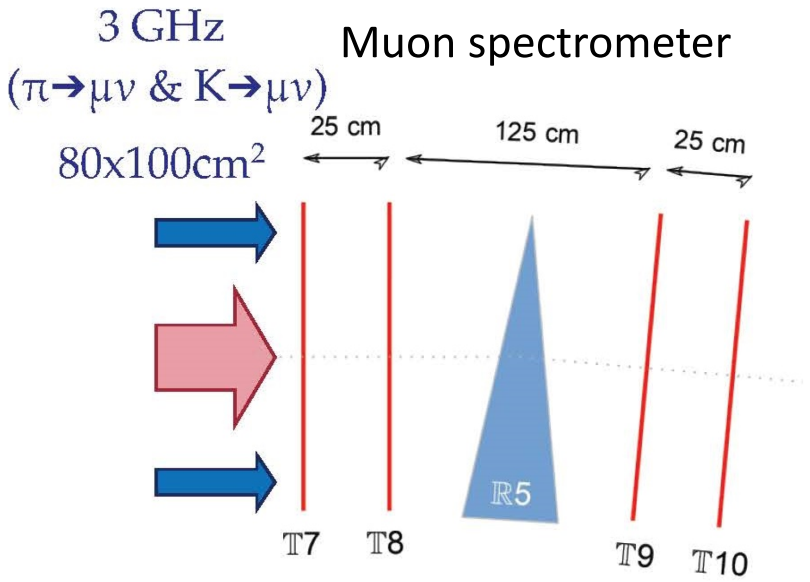
BEAM INSTRUMENTATION CHALLENGES

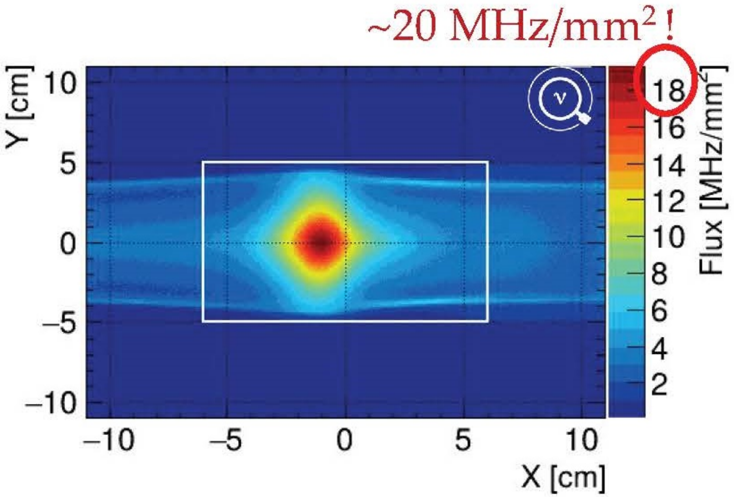
BEAM RATES AND COMPOSITION

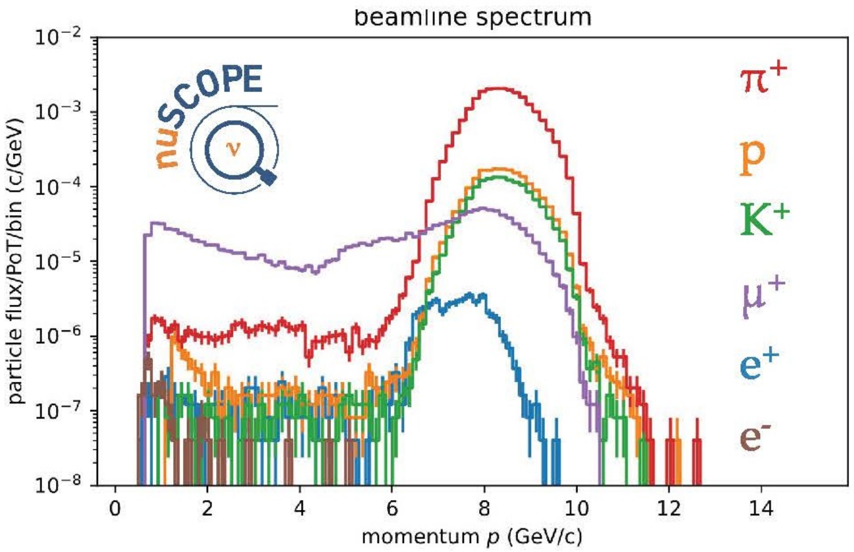
Beam spectrometer

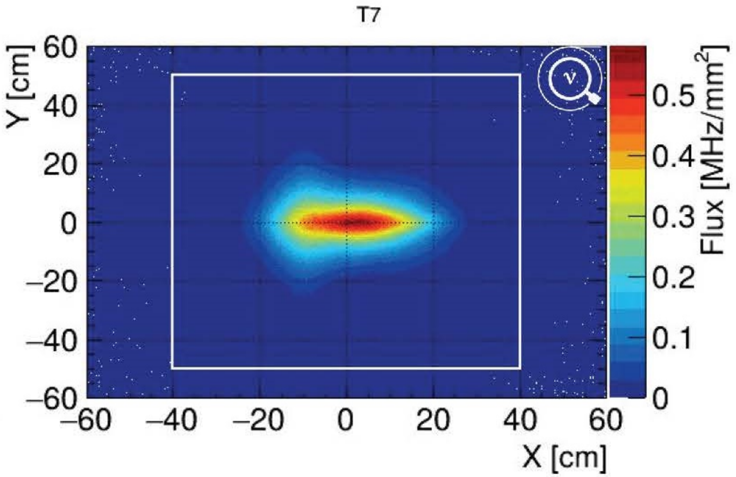


Muon spectrometer









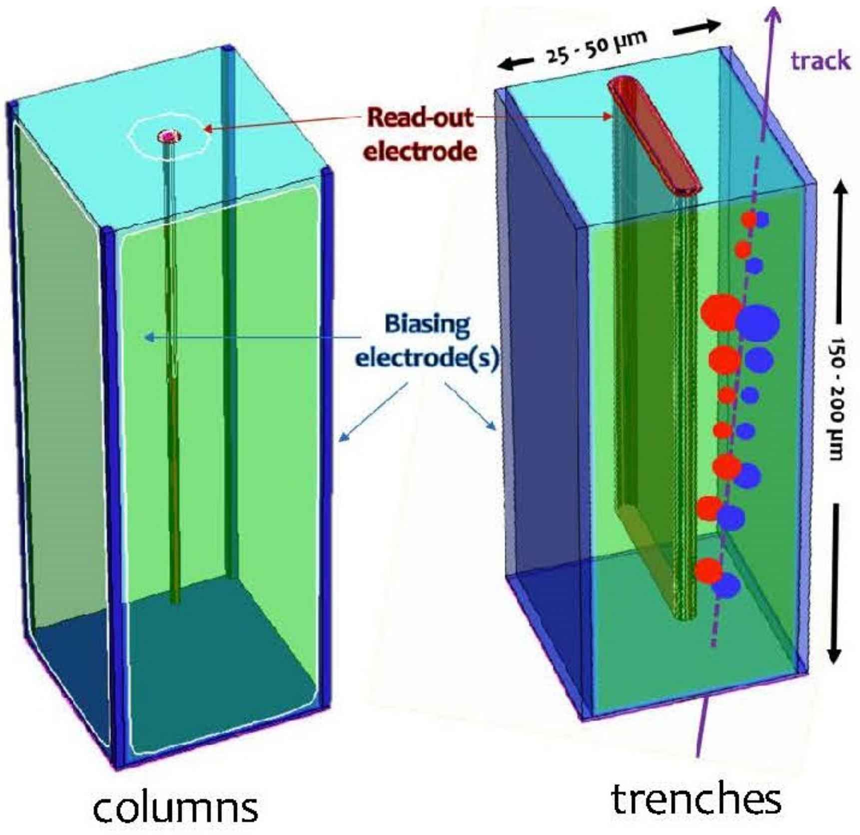
BEAM INSTRUMENTATION CHALLENGES cont'd

Lai

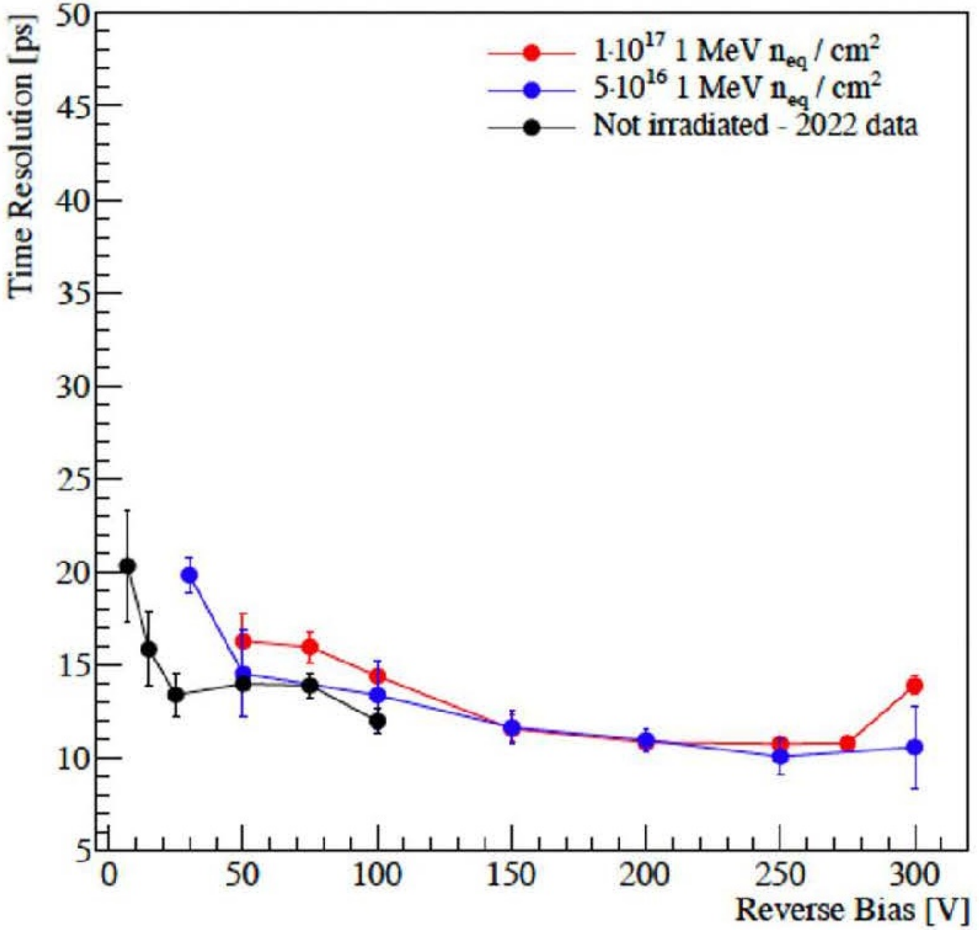
BEAM SPECTROMETER SENSOR

TimeSPOT
TIME and SPace real-time Operating Tracker

3D sensor developed for HL-LHC (LHCb VELO upgrade)
already meets nuSCOPE timing and radiation hardness specifications



Column or trench aspect ratio ≈ 30:1



Lai

BEAM INSTRUMENTATION CHALLENGES cont'd

BEAM SPECTROMETER SENSOR

Final design may move to "columns" option instead of "trench" for easier industrial production and stitching suitability

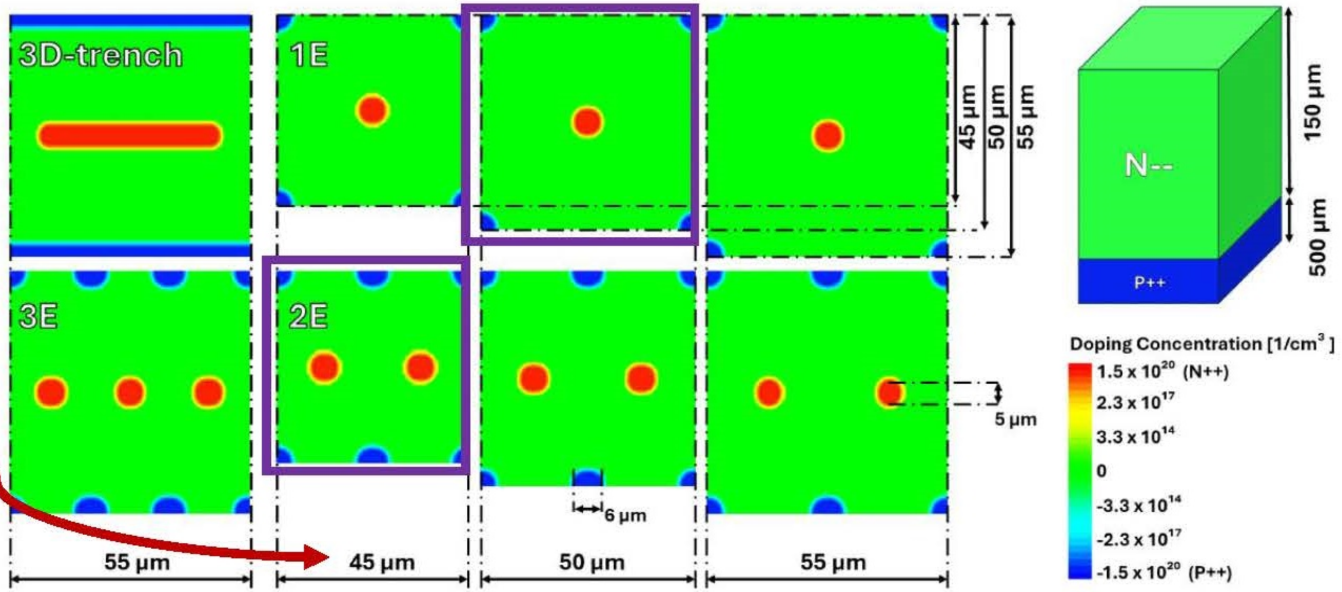
3D flavours

3D-trench (TimeSPOT, 55µm) best for timing
Techically difficult to be made of smaller pitch

Columns simpler to produce (ATLAS-CMS, yield > 50%)
45-2E comparable to 3D-trench up to 80% CCT, with less Capacitance

Idea to test also larger thickness (50µm, 200 µm depth)

A. Loi et al, doi.org/10.3390/s25030926



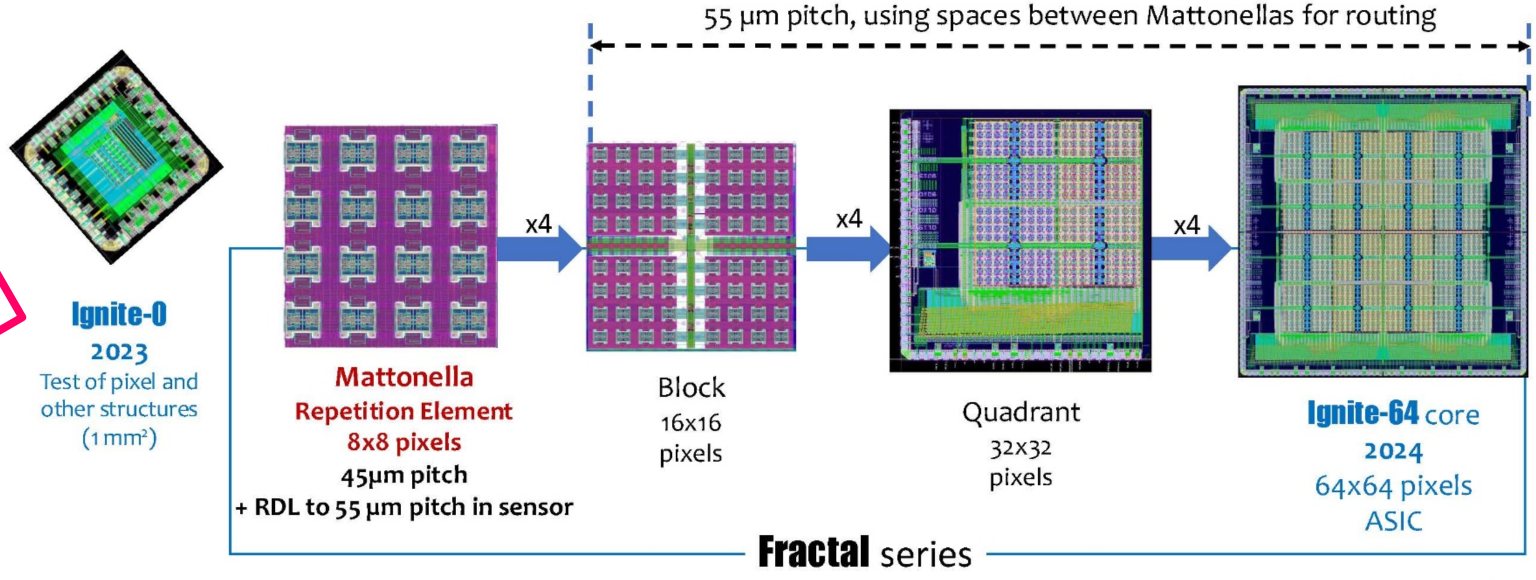
BEAM INSTRUMENTATION CHALLENGES cont'd

BEAM SPECTROMETER ASIC

2 parallel development lines

IGNITE
(INFN)

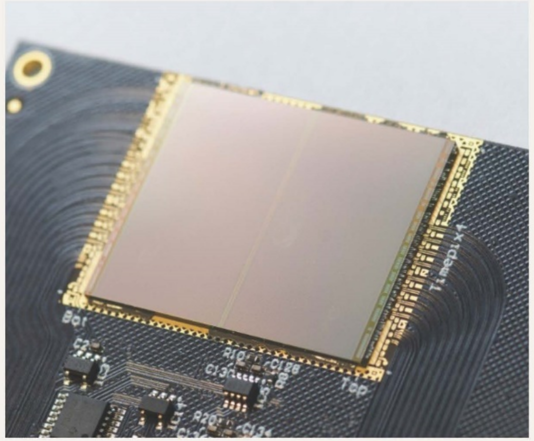
Lai



Caratelli

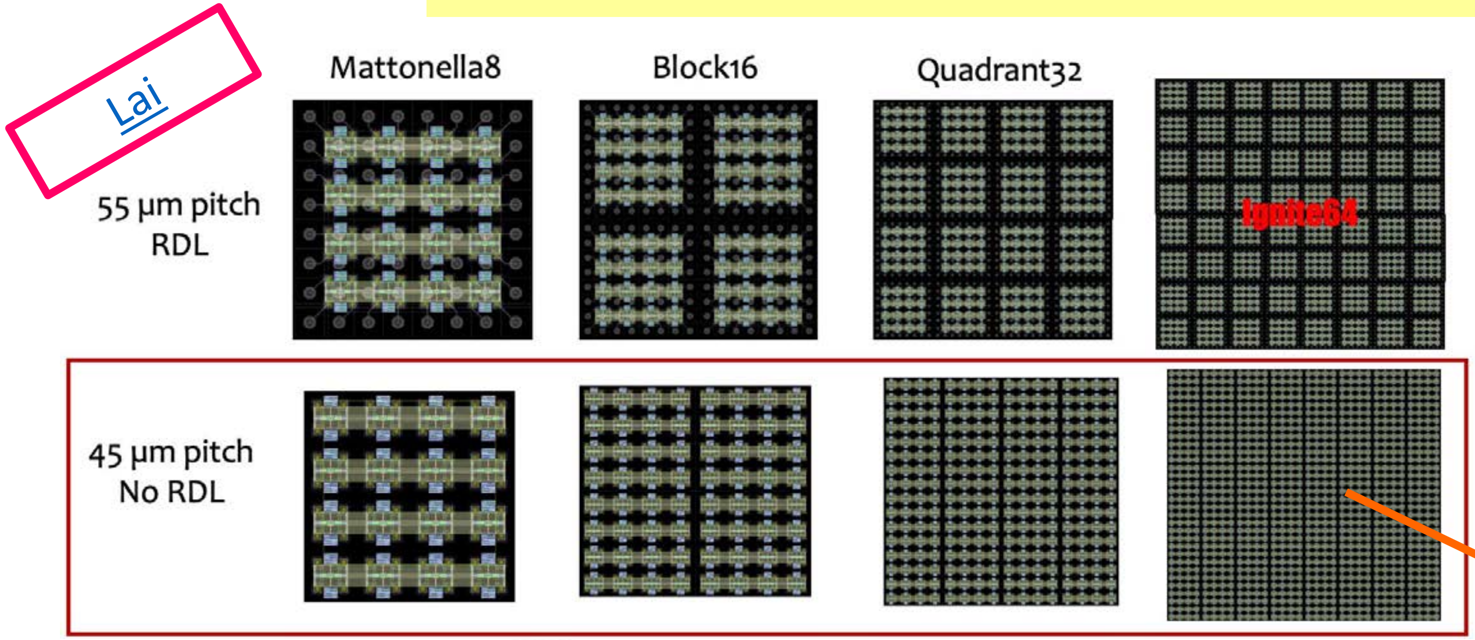
TIMEPIX/PICOPIX
(CERN)

Technology		65nm
Pixel Size		55µm x 55µm
Pixel arrangement		4-side abatable
Sensitive area		6.94 cm²
Tracking	Mode	TOT and TOA
	Max rate	$3.58 \cdot 10^{6}$ hits·s⁻¹ mm⁻¹
	Max Pixel rate	10.8 KHz/pixel
Imaging	Mode	CRW: PC (8 or 16 bit)
	Max count rate	5×10^{9} hits·s⁻¹ mm⁻¹
TOT energy resolution		< 1Kev
Time resolution		195ps bin → ~60ps$_{RMS}$
Readout bandwidth		16 x 10.24 Gb/s
Minimum threshold		500e⁻
Radiation tolerance		No

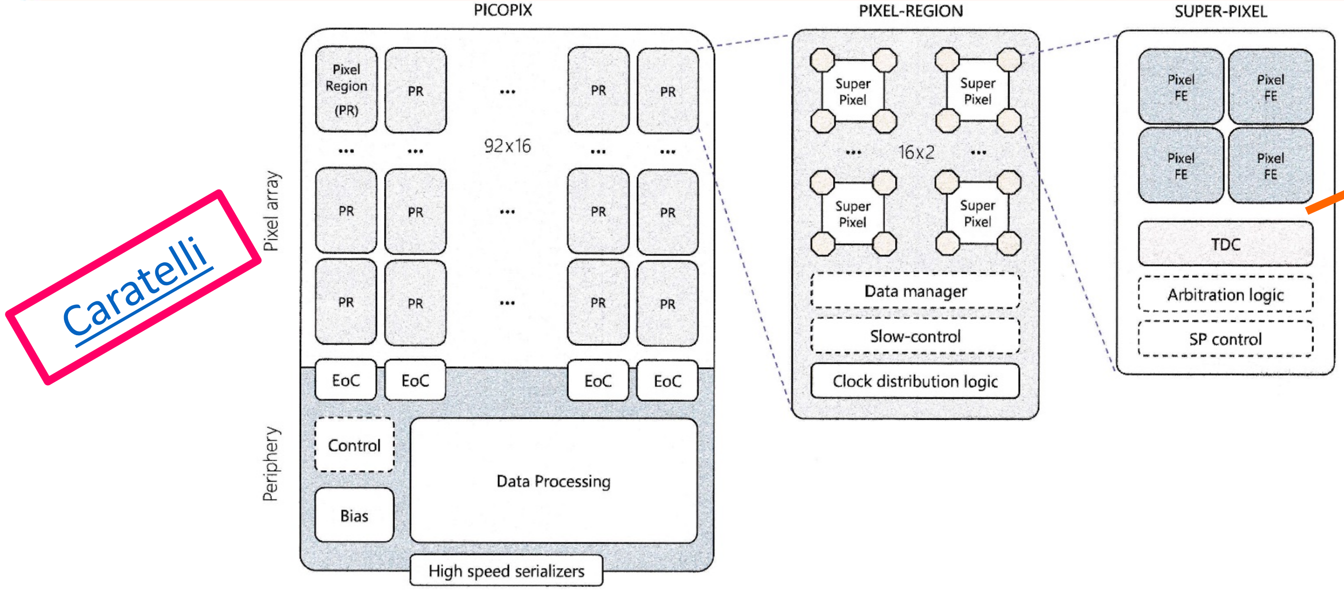


BEAM INSTRUMENTATION CHALLENGES cont'd

BEAM SPECTROMETER ASIC



IGNITE-ER



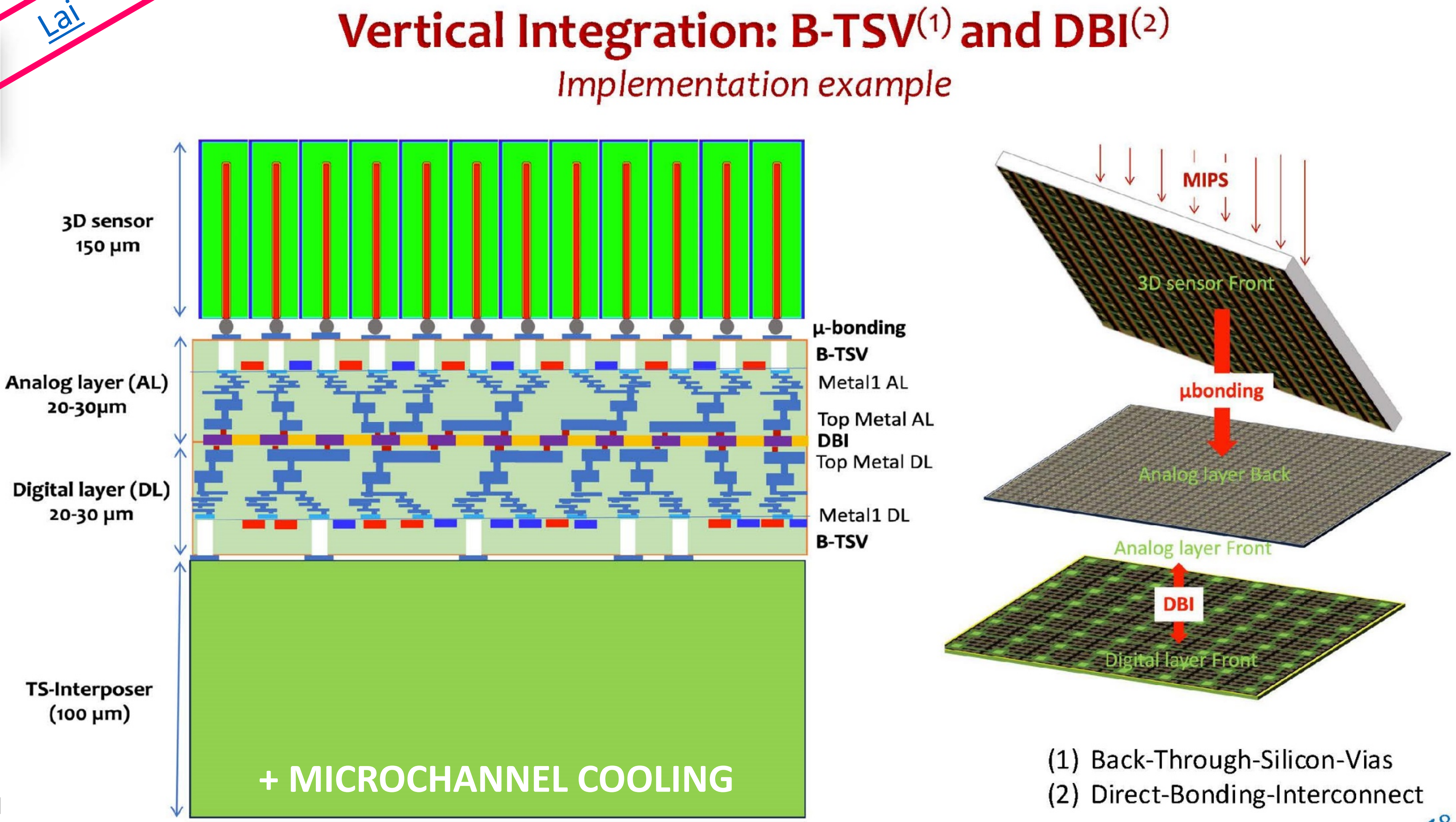
PICOPIX

submission to common multi-project in Q2/2026

BEAM INSTRUMENTATION CHALLENGES cont'd

SENSOR/ASIC INTEGRATION

Lai



(1) Back-Through-Silicon-Vias
(2) Direct-Bonding-Interconnect

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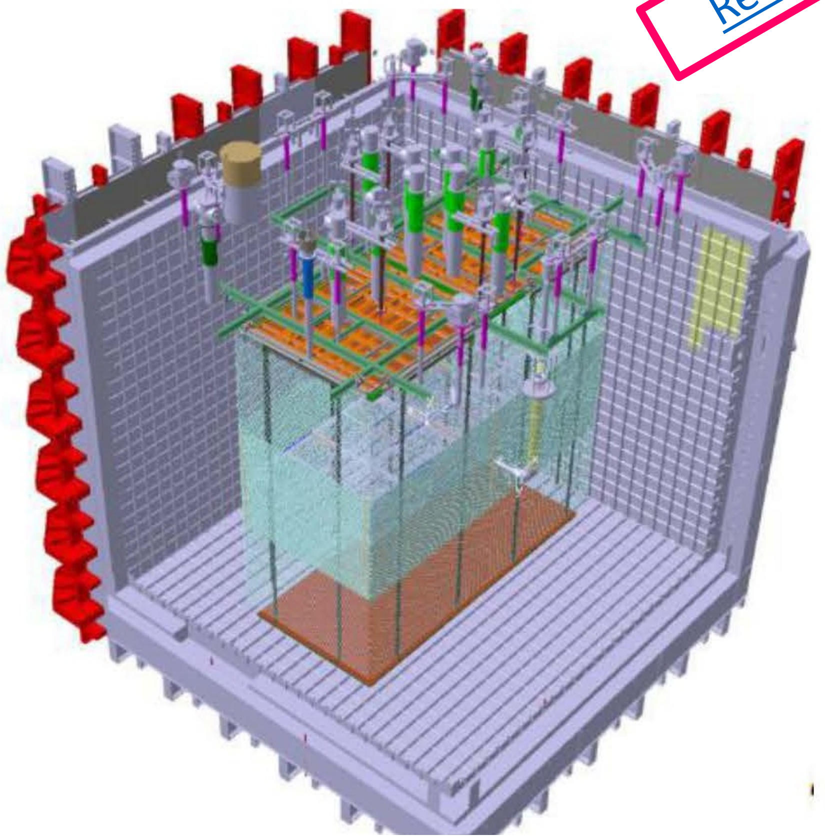
NEUTRINO DETECTORS DESIGN

Terranova

ProtoDUNE-VD Run III (2027-28)

Resnati



WCTE

Karlen

LAr main challenge: event timing <~ 300ps

WC main challenge: PID

Botella

Cavanna

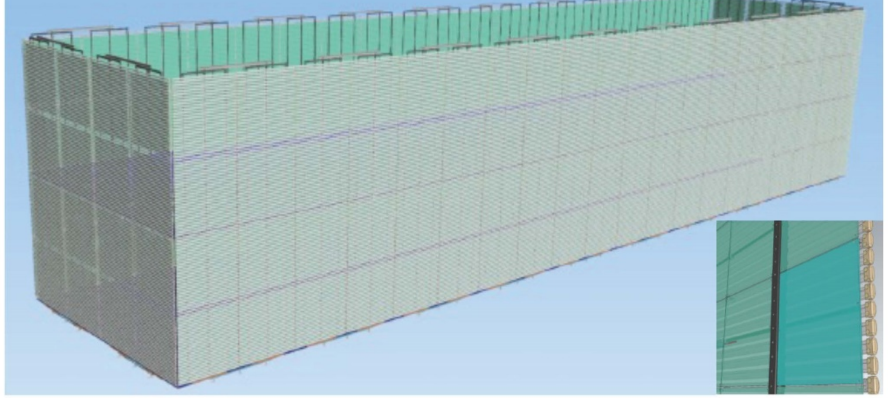
NEUTRINO DETECTORS DESIGN cont’d: LAr timing

New LAr technologies under development for DUNE Phase II

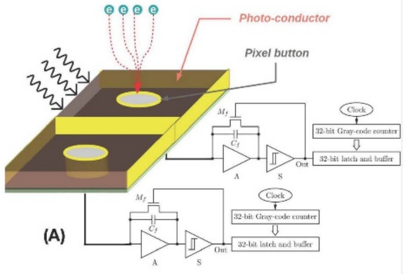
but with focus on photon detection coverage&efficiency, NOT sub-ns Δt

- “DUNE Phase II: scientific opportunities, detector concepts, technological solutions”, JINST 19 (2024) 12, P12005
- Several alternatives related to photodetection are being explored for next FD modules:
  - APEX (*Flavio’s talk*), PoWER, SoLAr, ARIADNE, Q-Pix-LILAr

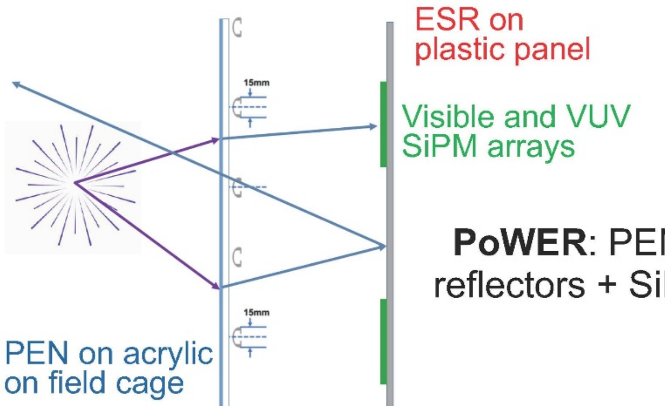
APEX: X-ARAPUCAs placed at field cage



ARIADNE: Dual-phase optical charge (S2 produced in THGEMs) readout with fast cameras (TimePix3)



Q-Pix-LILAr: coating a charge readout pixel with a type of photo-conductive material



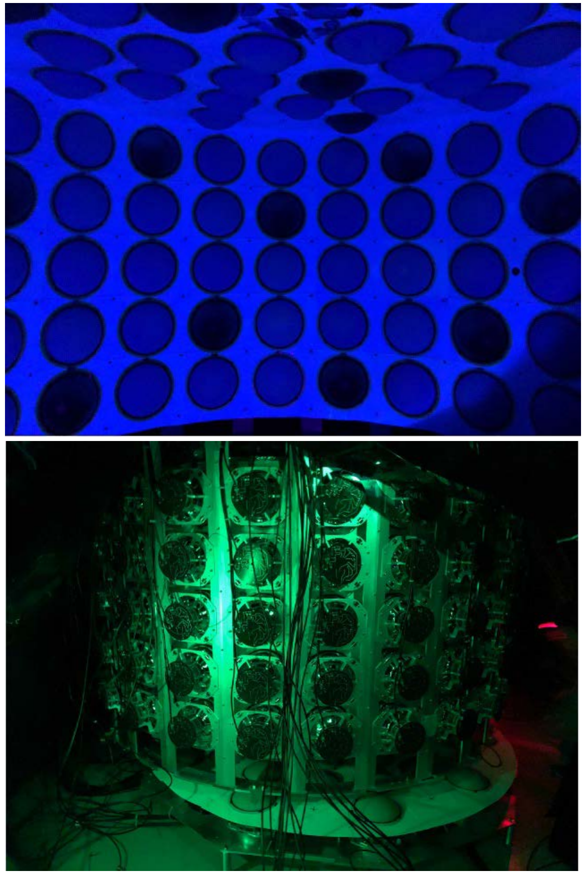
PoWER: PEN + reflectors + SiPMs

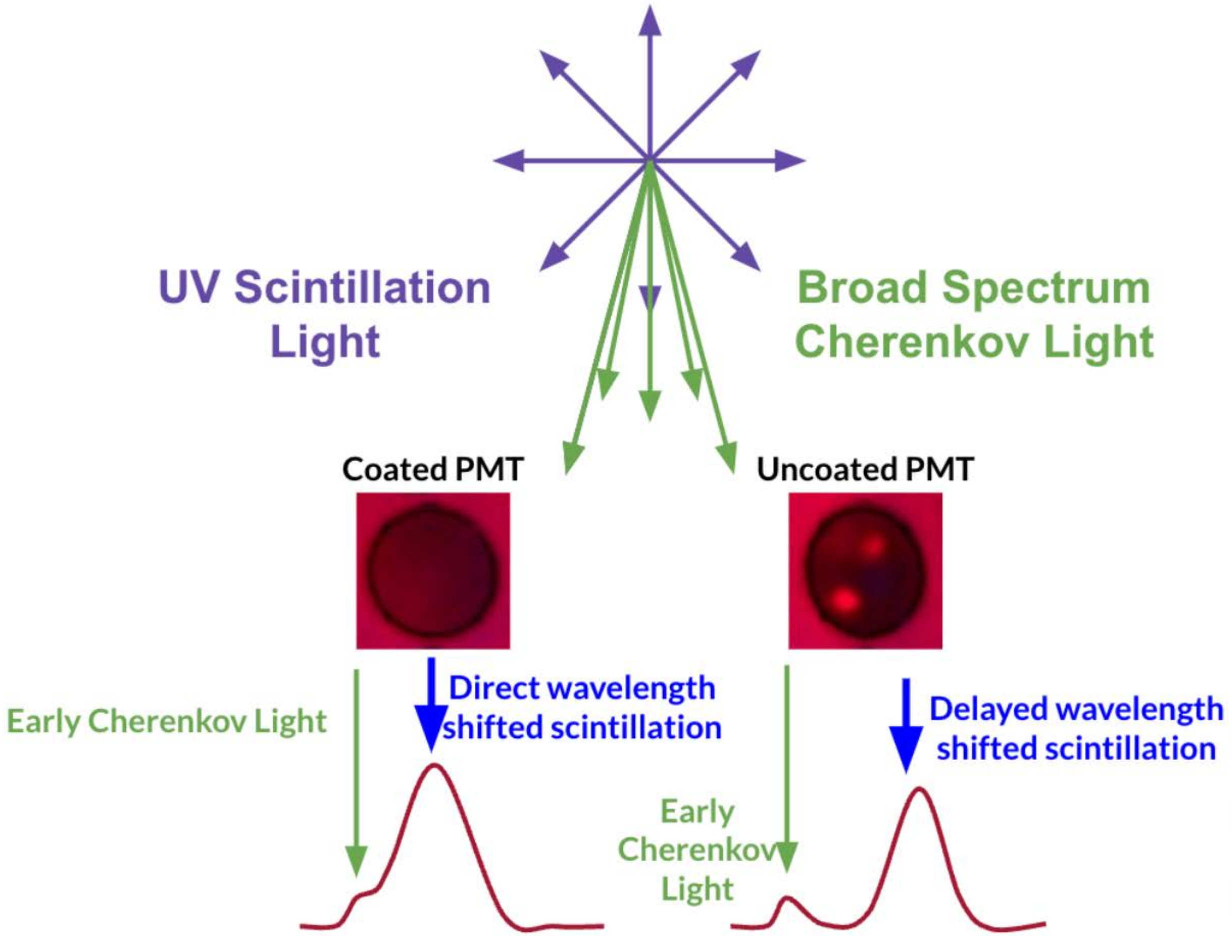
NEUTRINO DETECTORS DESIGN cont'd: LAr timing

Newmark

CERENKOV light in addition to SCINTILLATION
may be a way to sub-ns timing

Coherent CAPTAIN-Mills (CCM) 10t-detector





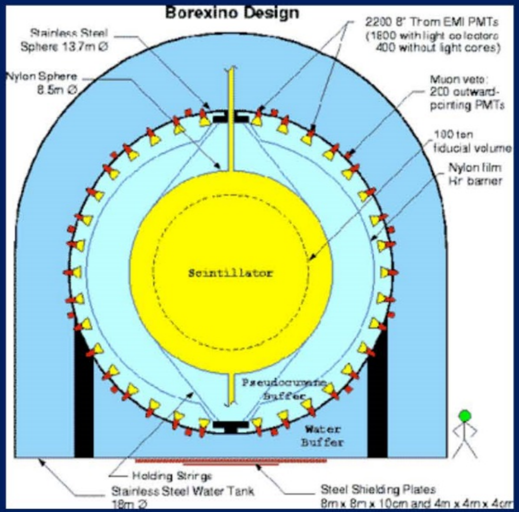
NEUTRINO DETECTORS DESIGN cont’d: Water hybrid detectors

SCINTILLATION+CERENKOV hybrid detection also developed in Water Based Scintillator Detectors → **THEIA**

Candidate for DUNE FD4

Klein

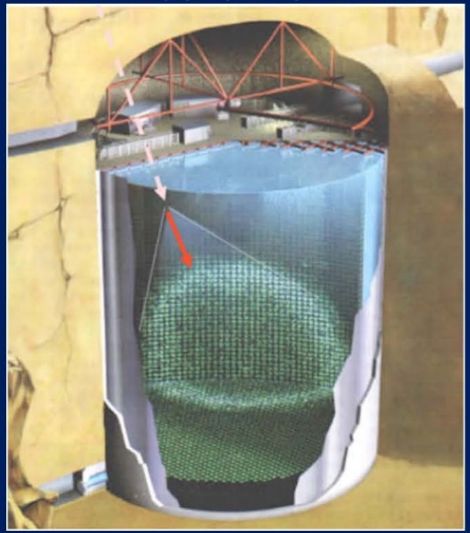
scintillation



- Low threshold
- Excellent calorimetry
- Low-energy PID (α vs β)
- Neutron ID

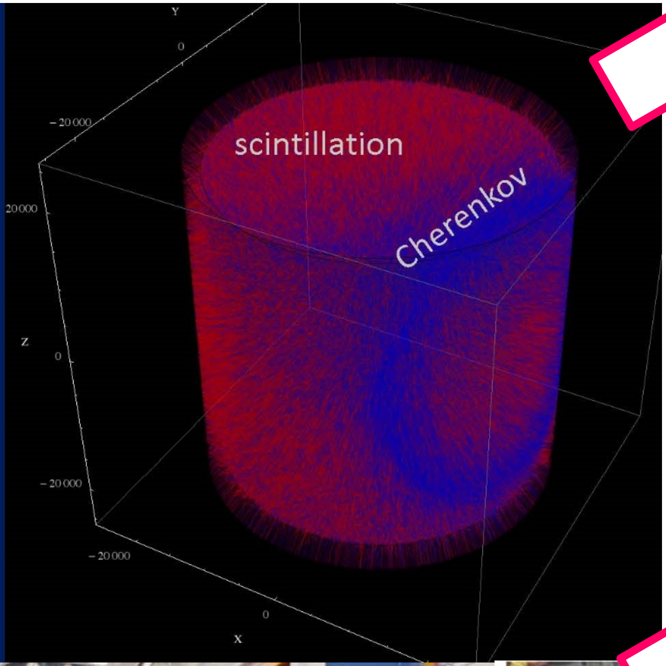
+

cerenkov

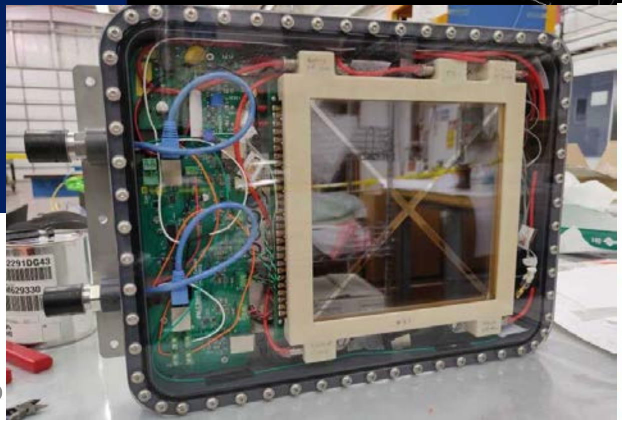


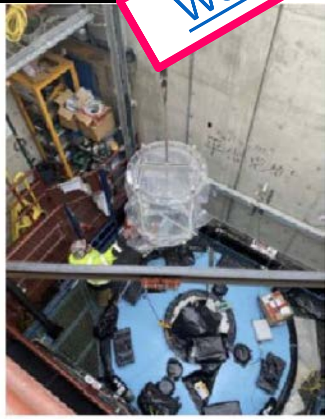
- High-energy PID
- Directionality
- Multi-particle tracking
- Excellent timing

=



Wetstein





Sub-ns readout of Cerenkov light developed by the ANNIE experiment with LAPPDs →

worksho

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PHYSICS MOTIVATIONS

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%
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

T2K arXiv:2303.03222

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

PHYSICS MOTIVATIONS cont'd:
REFERENCE SETUP FOR SIMULATIONS

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Reference setup

500t of LAr/100t of water

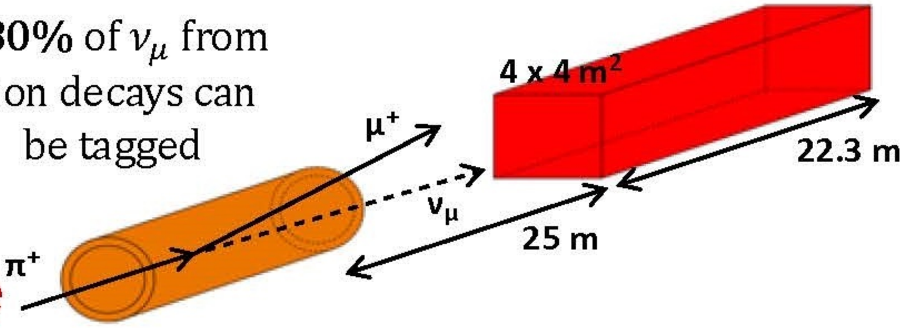
Current preliminary studies performed assuming a simplistic detector design

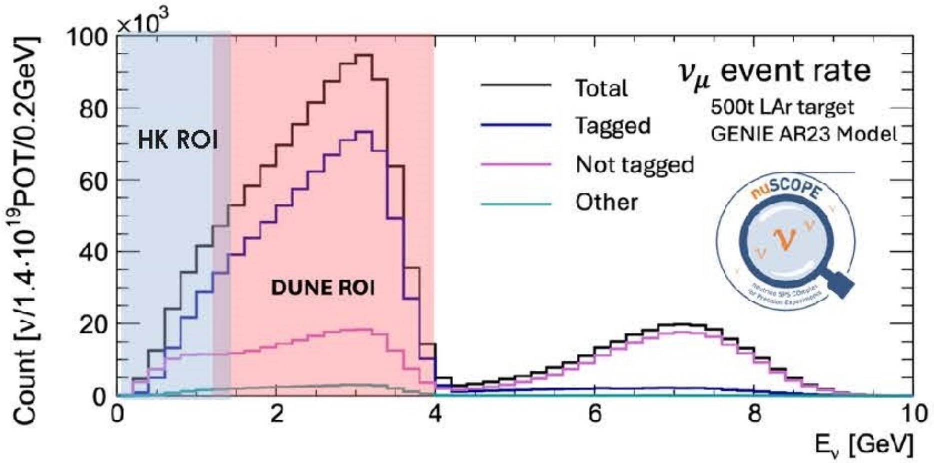
- Reference model is GENIE `AR23_20i_00_000`

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

- $O(1.0\times10^6)/O(1.2\times10^4)$ 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 **CC0**π events

~80% of ν_μ from pion decays can be tagged





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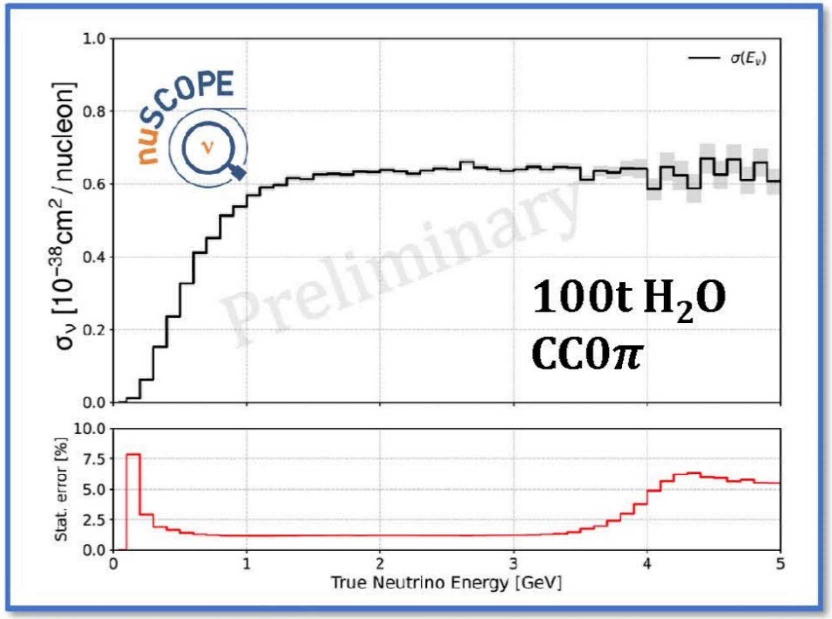
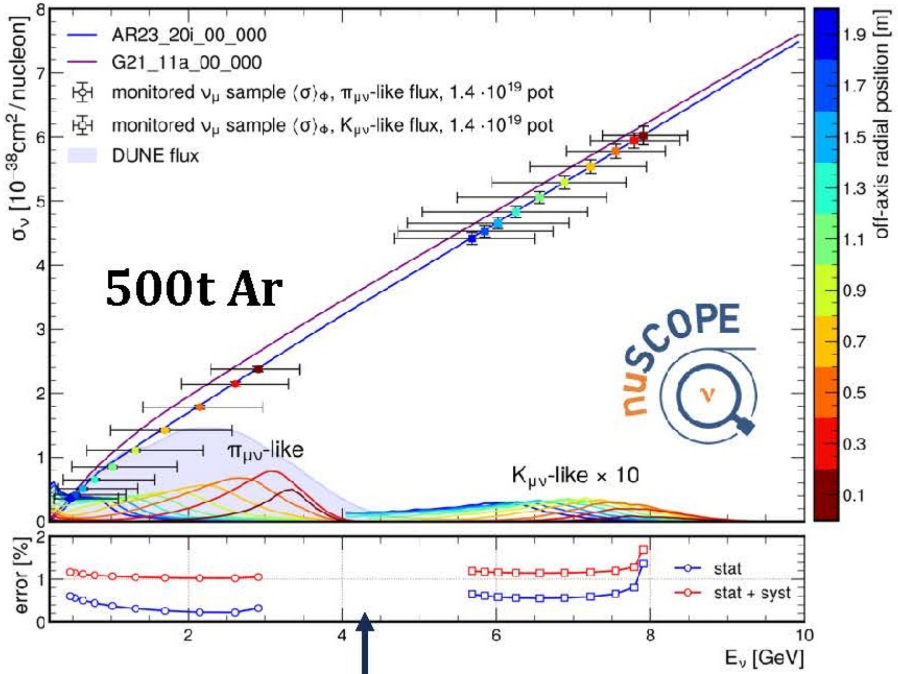
PHYSICS MOTIVATIONS cont'd : ν_μ CROSS-SECTIONS

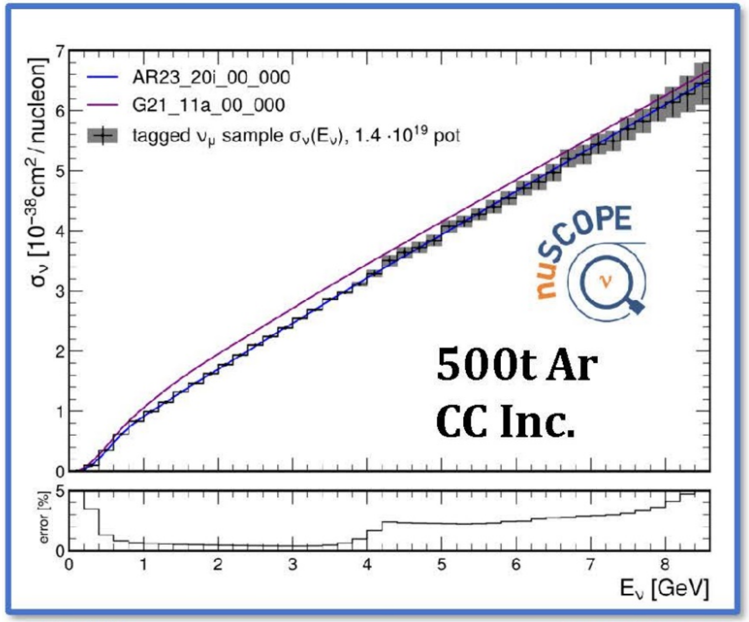


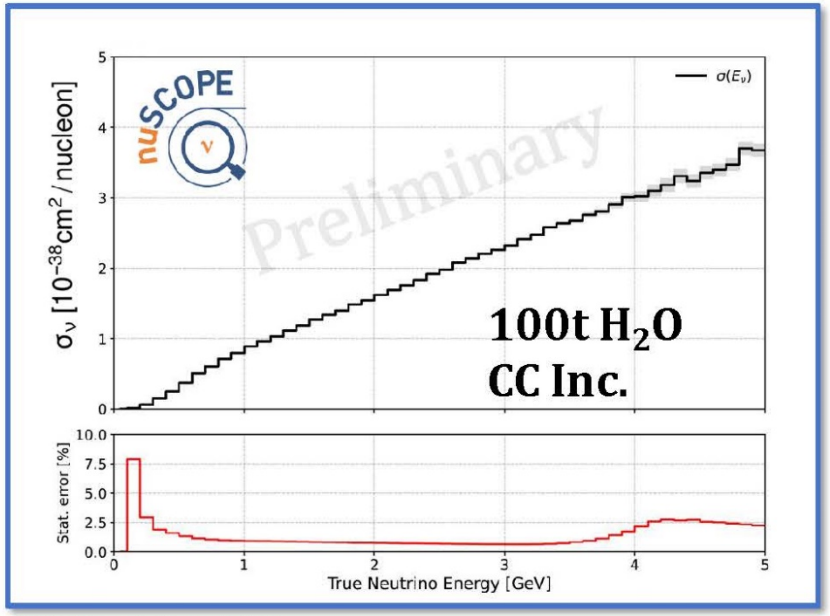
%-level precision expected as function of energy

By monitoring

By tagging







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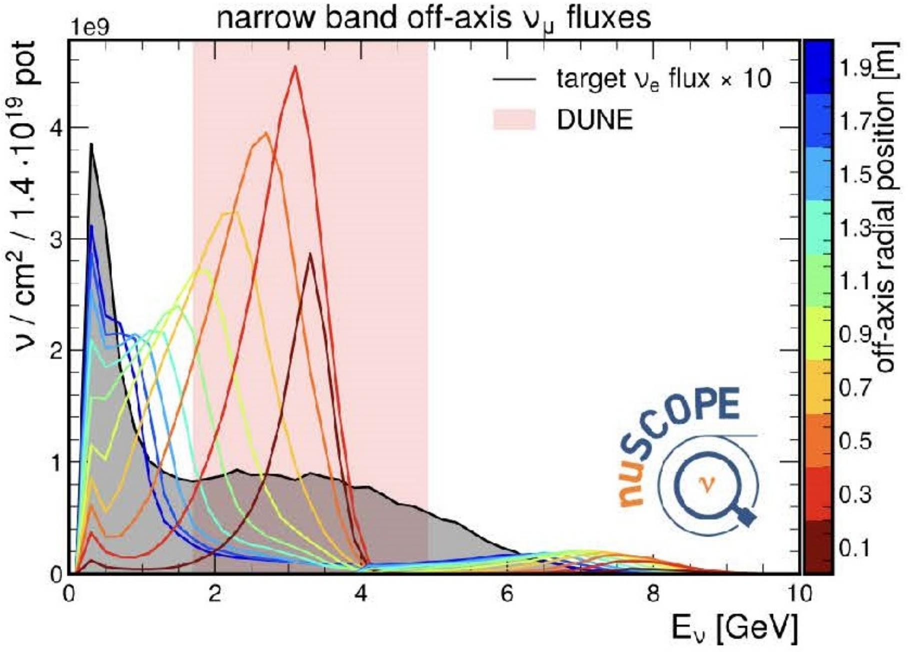
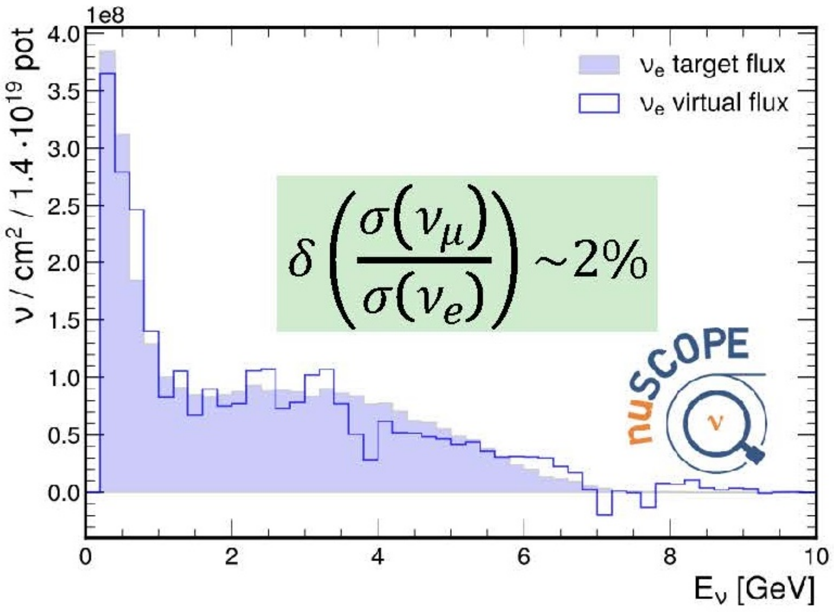
PHYSICS MOTIVATIONS cont'd : ν_e CROSS-SECTION

Constraining the ν_μ/ν_e cross section ratio





NBOA technique can be used with PRISM to obtain a virtual ν_μ flux with the same shape as the ν_e flux

This measurement can be improved by using the tagged flux (studies ongoing)

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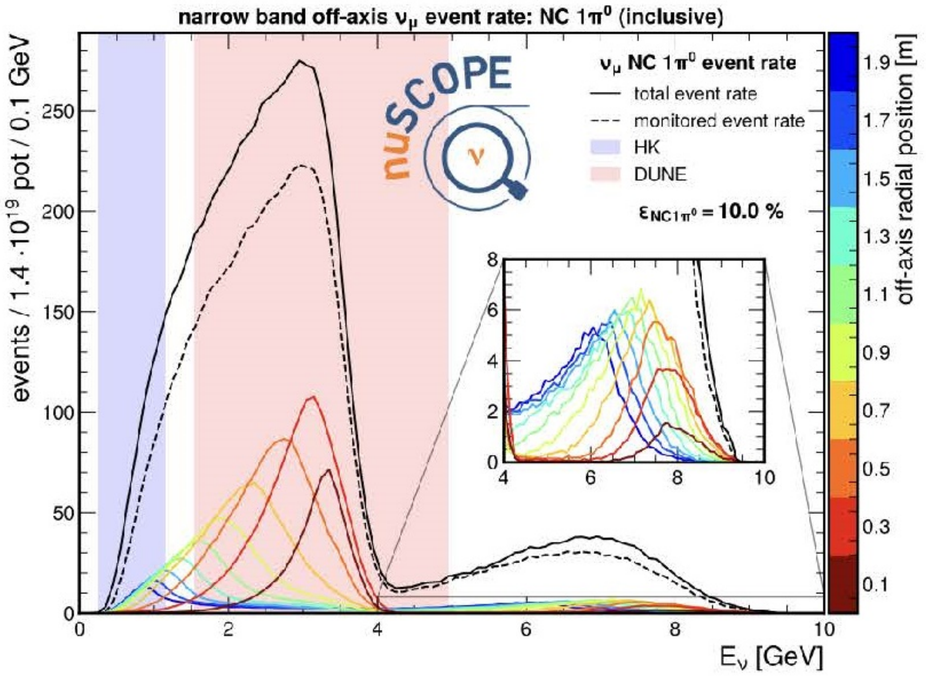
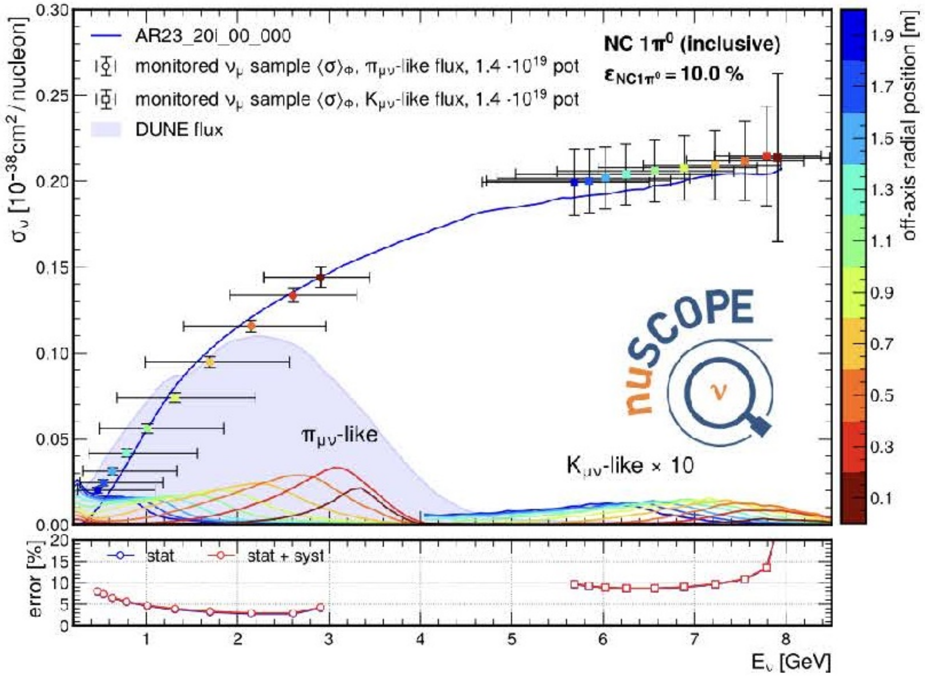
PHYSICS MOTIVATIONS cont'd : BACKGROUNDS

Constraining the NCπ^0 cross section





NBOA technique can be applied to measure the NCπ^0 cross section

(background for oscillation searches)

This measurement can be improved by using the tagged flux (studies ongoing)

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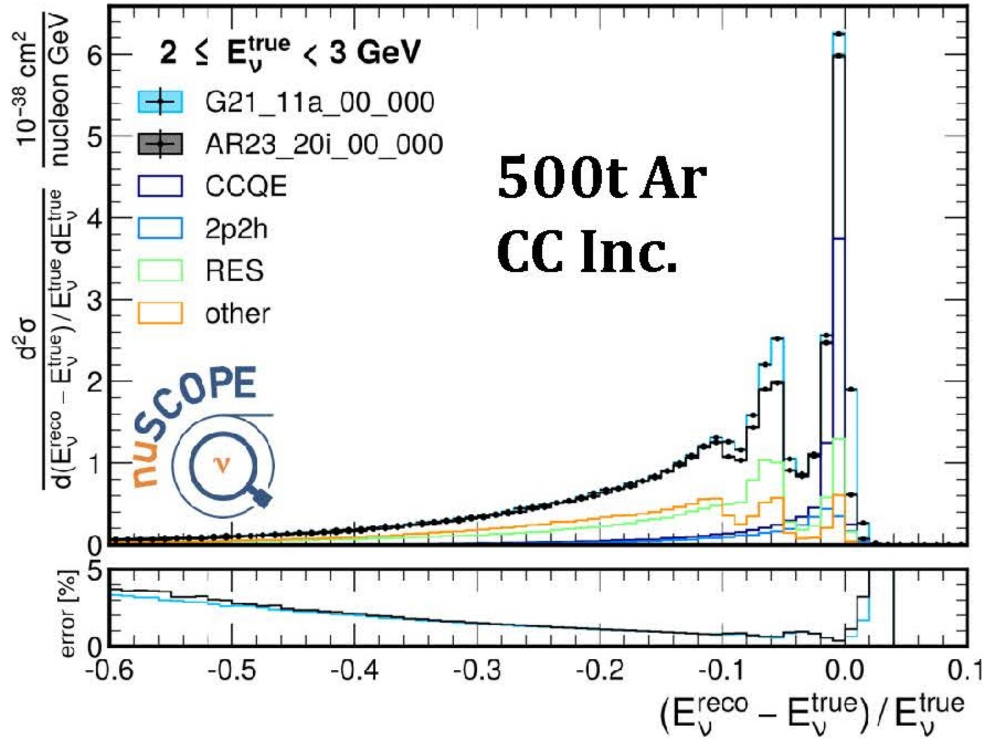
PHYSICS MOTIVATIONS cont'd : ENERGY SMEARING in LAr

Calibration of detector energy response



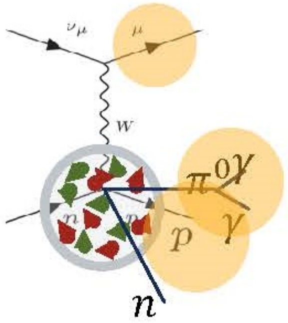
Can measure the **difference between true and reconstructed neutrino energy**

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

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

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

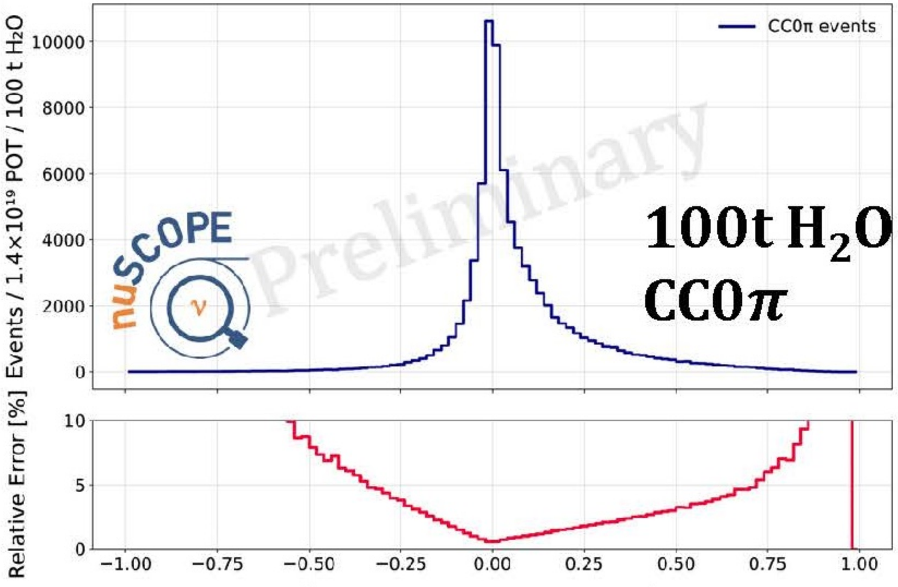
Calibrate out nuclear effects



PHYSICS MOTIVATIONS cont'd : ENERGY SMEARING in WATER

Munteanu

Calibration of detector energy response



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

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

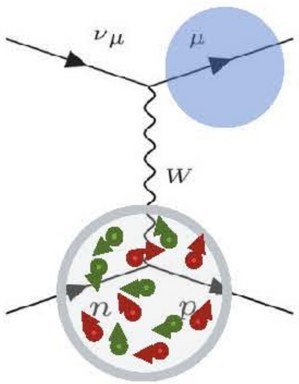
$$E_\nu^{QE} = \frac{1}{2}\frac{m_\ell^2 + (m_N^{eff})^2 - m_{N'}^2 - 2E_\mu m_N^{eff}}{E_\ell - |\vec{p_\ell}|\cos\theta_\ell - m_N^{eff}},$$

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

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

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

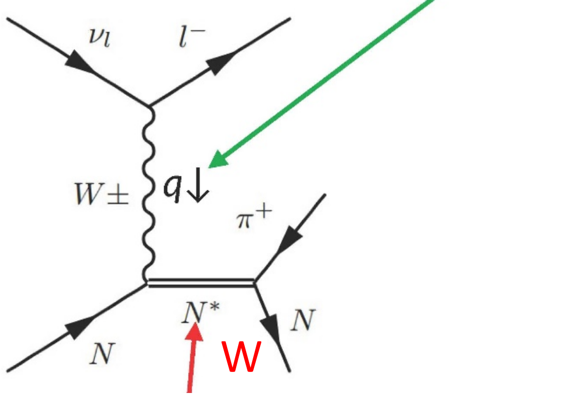
Calibrate out nuclear effects



PHYSICS MOTIVATIONS cont'd: NUCLEAR PROCESSES

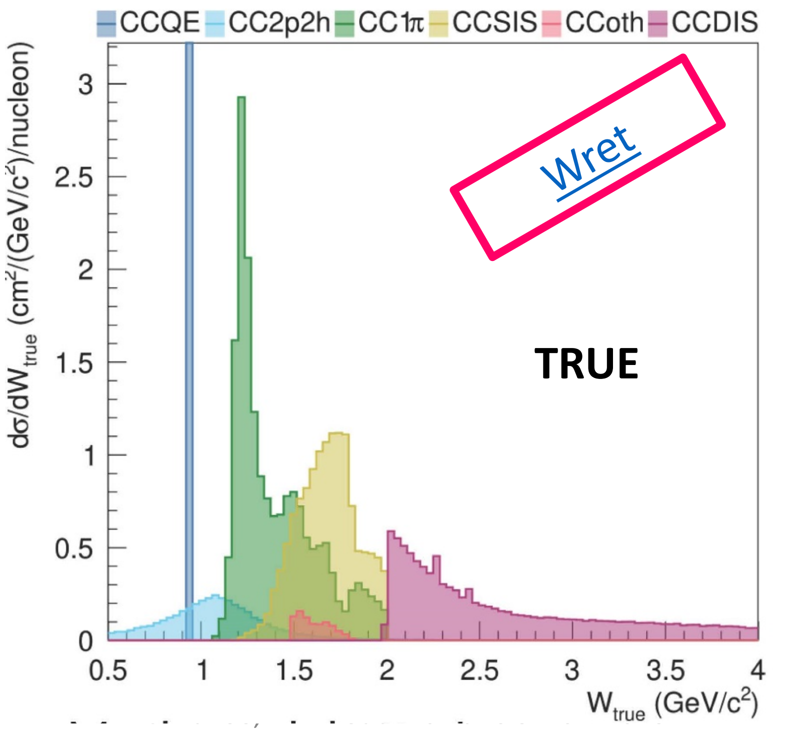
Knowing individual neutrino true energy
allows separation of various nuclear processes
from pure lepton kinematics as in e-scattering experiments

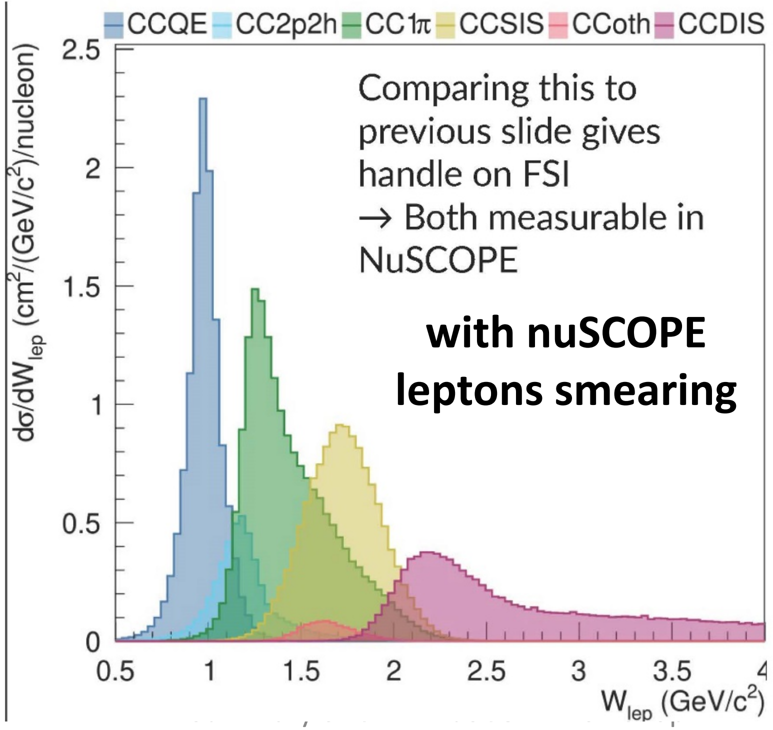
Q^2 is invariant four-momentum squared, $Q^2 = -q^2$

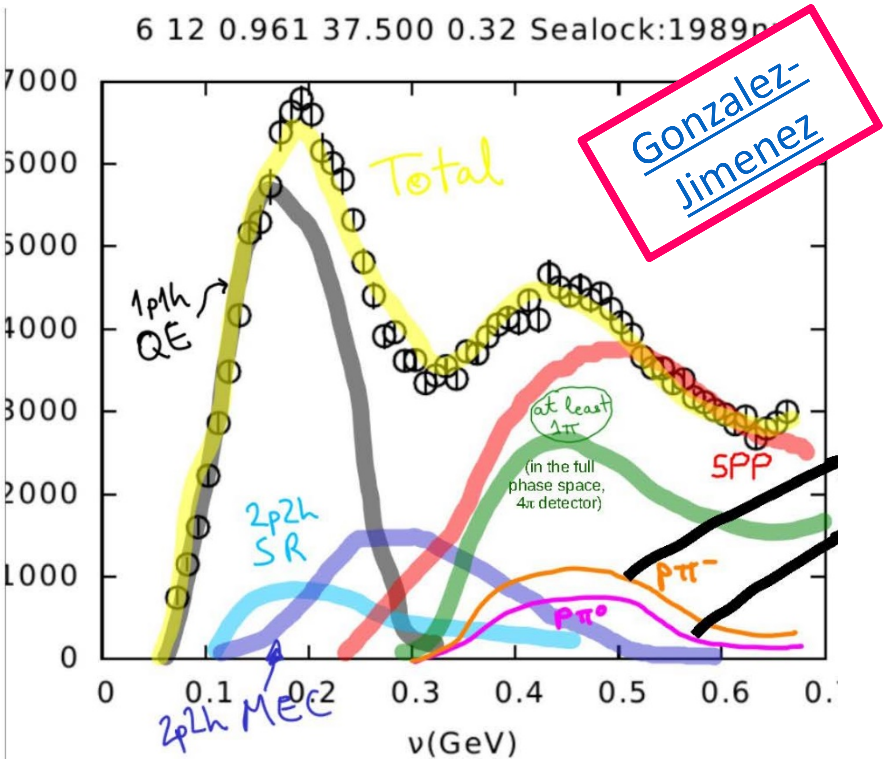


If we keep dreaming...

- What about the lepton-based W reconstruction?



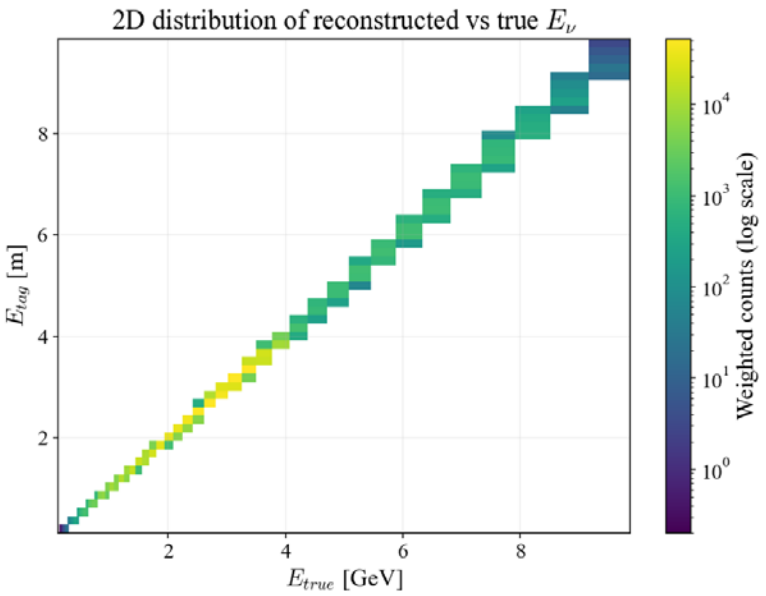


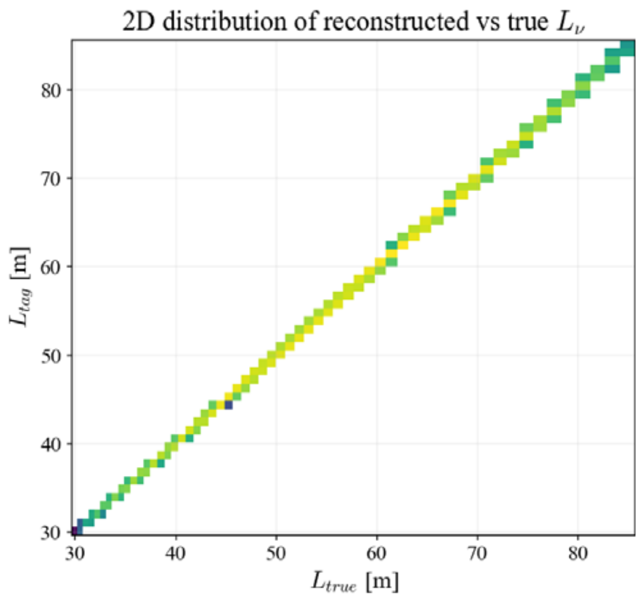


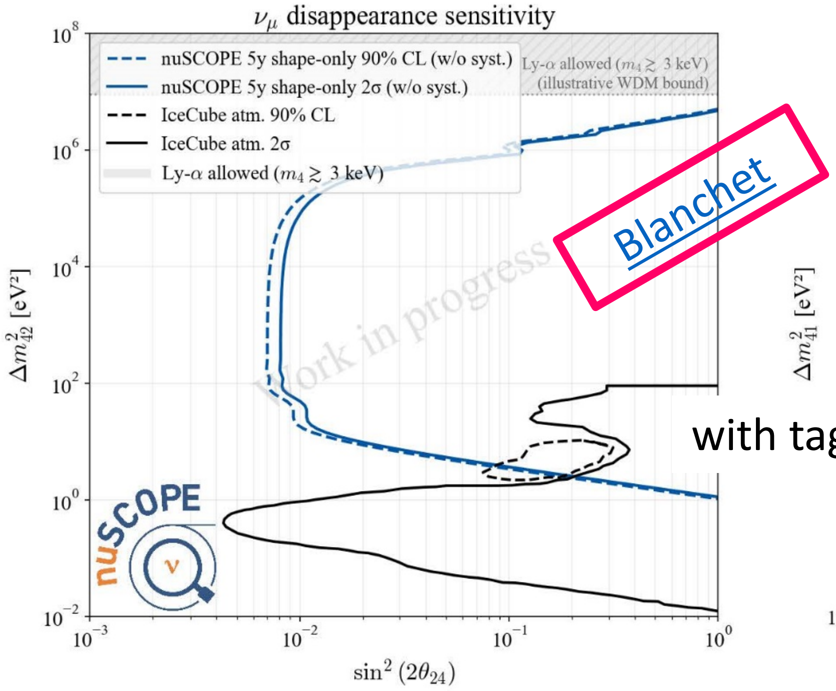
PHYSICS MOTIVATIONS cont'd: STERILE NEUTRINOS

Tagging provides event by event high-precision estimation of $E_{true} - L_{true}$ and efficient background rejection for:

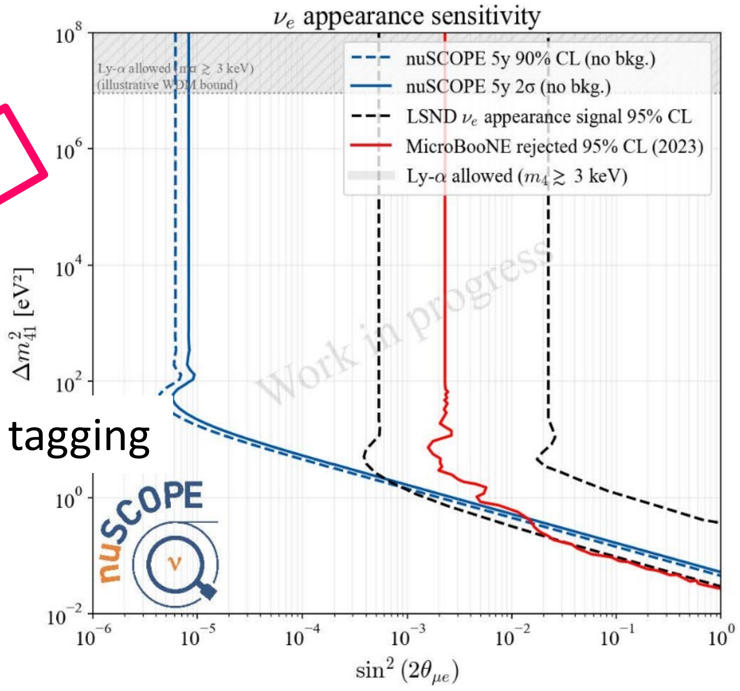
- **ν_μ disappearance (statistical)**
- **ν_e appearance (single event)**

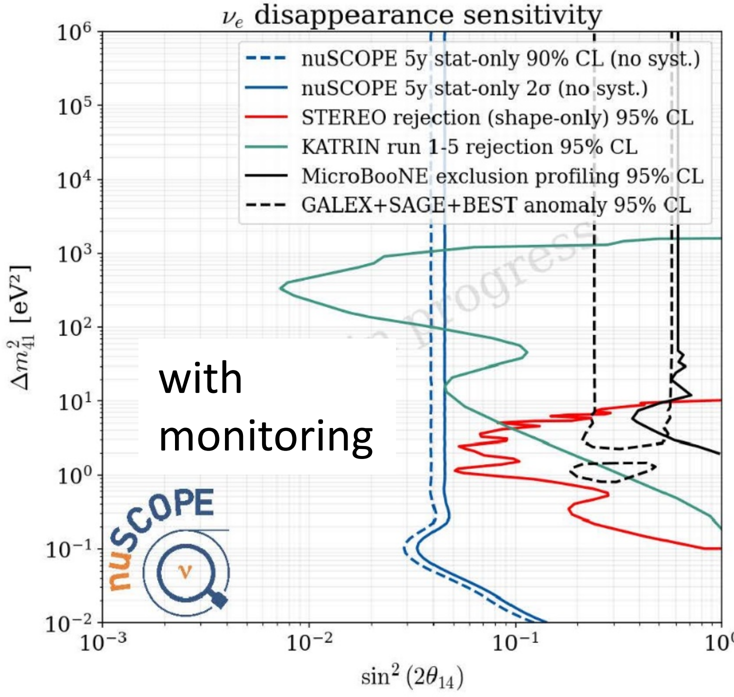






with tagging

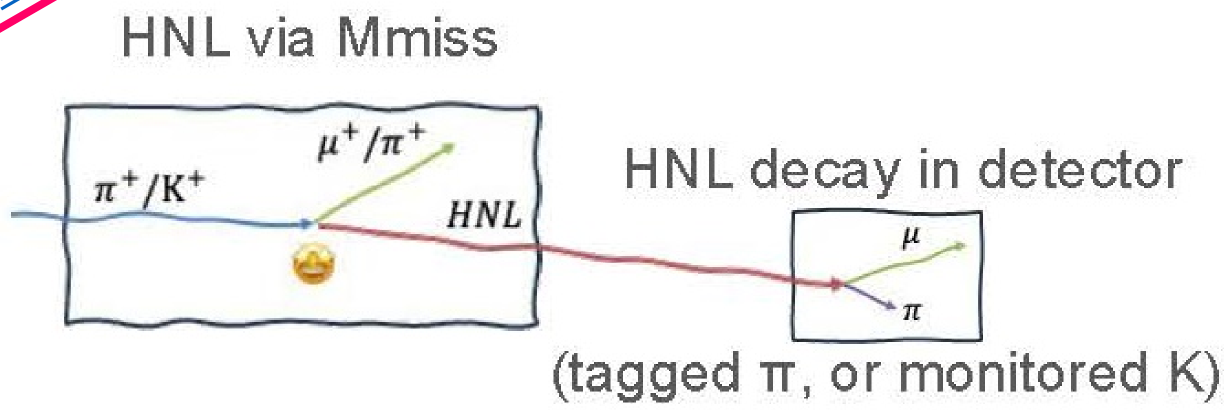




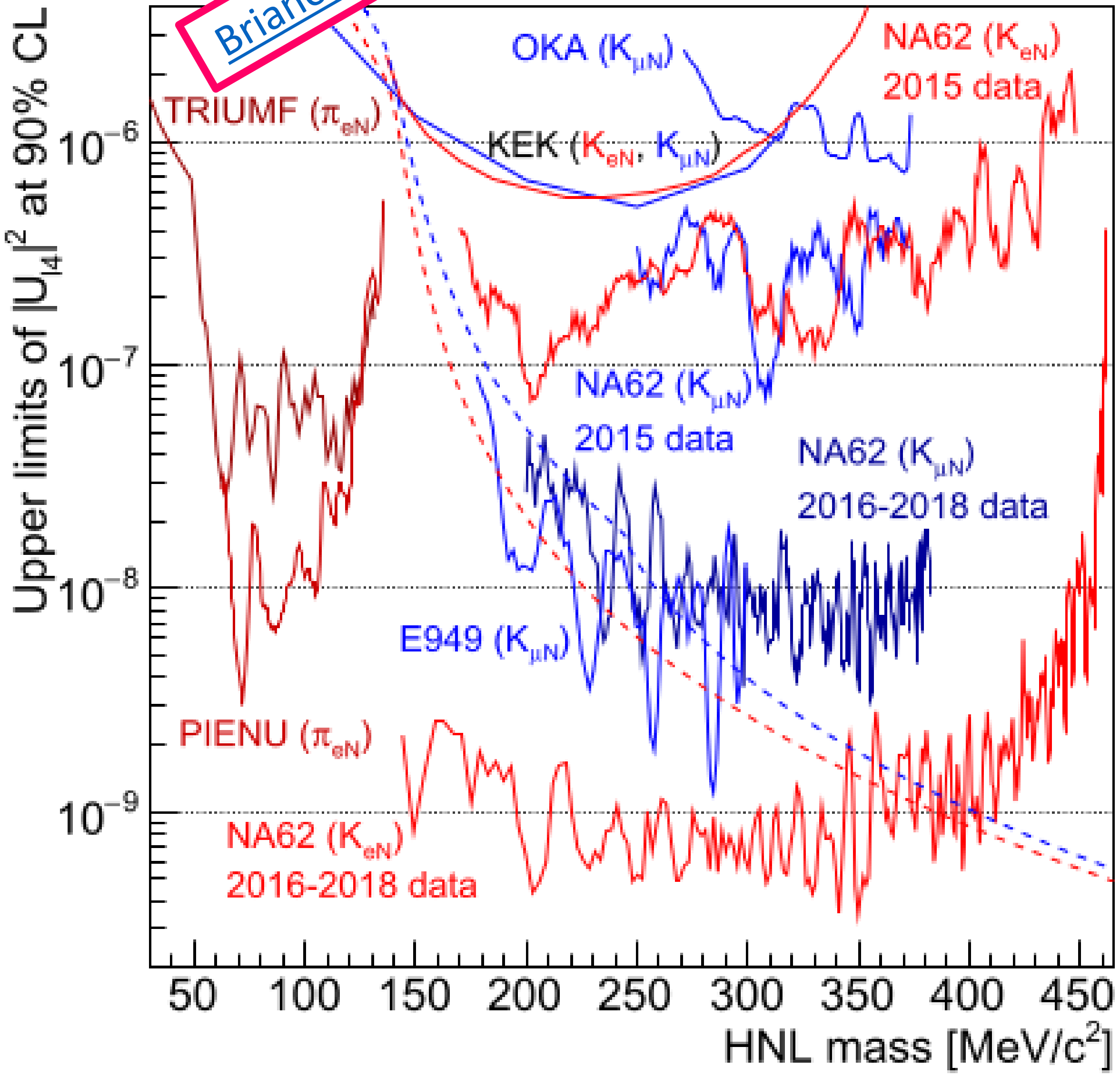
PHYSICS MOTIVATIONS cont'd:
HNLs from K decays

#K (nuSCOPE) >> #K (NA62)

Dolan



Briano Olvera



Potential future improvement on NA62 limits → depending on background control

nuSCOPE PROJECT NEXT STEPS

nuSCOPE potential well accounted for in the EPPSU Physics Briefing Book

PBB Excerpts

Dolan

6.2.3 Improving systematic uncertainties

Standard beams may not be enough

The main limitations of the neutrino-nucleus cross-section measurements using near detectors and other dedicated experiments in standard neutrino beams are the low number of events available of ν_e and $\bar{\nu}_e$, the impact of the flux uncertainty, and the limited neutrino energy resolution, which does not allow for the separate measurement of the different nuclear effects that contribute to the cross-section at different energies (see Sect. 6.3). Various projects have been

...

nuSCOPE is a potential solution!

width) could be scanned by tuning the muon beam energy. Finally, the nuSCOPE proposal [ID101] has been put forward at the Neutrino Platform to construct an instrumented proton beam line based on slow extraction to enable a monitored neutrino beam, where the lower instantaneous intensity allows to directly measure the parent K, π decays to precisely determine the ν_μ, and ν_e neutrino fluxes. Furthermore, in the case of two-body decays (ν_μ), the detected neutrinos can be *tagged*, i.e., associated with the parent meson decay, and their energy reconstructed on an event-by-event basis. nuSCOPE is proposed to operate at the CERN SPS beam, collecting about 10^6 tagged (10^4 monitored) charged-current $\nu_\mu(\nu_e)$ interactions, using about 2.5×10^{18} protons on target per year. The necessary detector technology for beam instrumentation has either been demonstrated with prototypes or is being developed. Both the overall flux rate and the energy of muon neutrinos event-by-event can be known with $< 1\%$ precision. Knowing the neutrino energy with such precision, independently on any cross-section and flux model, allows a direct constraints on the map between energy seen in a detector and the true neutrino energy, resolving a pivotal source of uncertainty for neutrino oscillation measurements at accelerators.

nuSCOPE PROJECT NEXT STEPS cont'd

Terranova

ACTION PLAN FOR COMING YEAR :

- ***Completion of NP06/ENUBET demonstrators beam tests***
- ***nuSCOPE design consolidation with CERN and external institutes support*** *(beam extraction, optics and instrumentation)*
- ***Physics case and ν detectors design consolidation with full community***

GOAL is to ESTABLISH the nuSCOPE COLLABORATION towards an EoI to SPSC by FALL 2026

nuSCOPE PROJECT NEXT STEPS cont'd

HOW TO FOLLOW/SUPPORT/CONTRIBUTE/JOIN ?

- **nuSCOPE mailing lists:** https://e-groups.cern.ch/e-groups/EgroupsSearchForm.do
  (search for "nuSCOPE" and subscribe to the general and/or working group mailing lists)
- **nuSCOPE public web site:** https://nuscope.web.cern.ch/

Current nuSCOPE Institutes: