Neutrino Tagging

Mathieu PERRIN-TERRIN

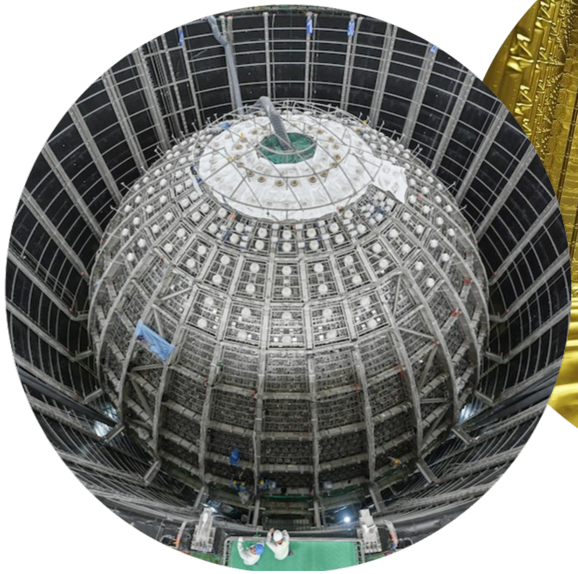
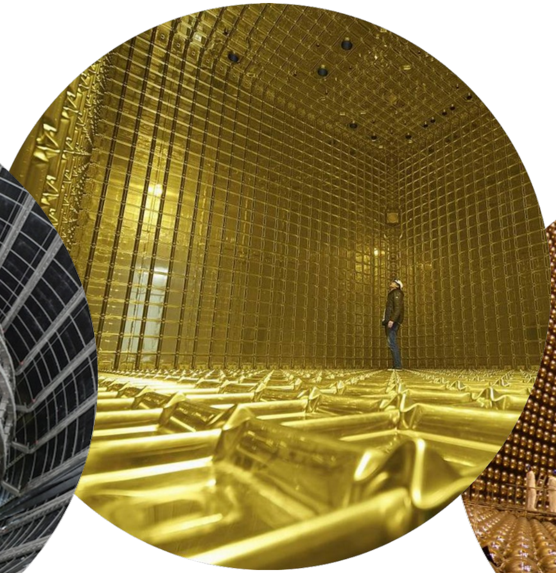
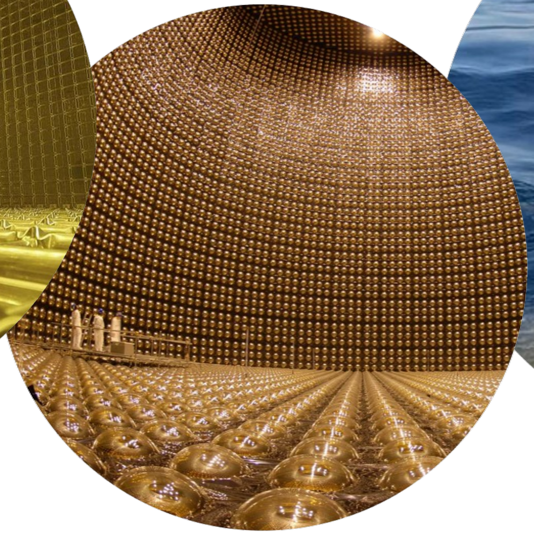
Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France.

Outline

- Introduction
  - scientific context
  - neutrino tagging concept
- Proof-of-principle with existing data (NA62)
- The nuSCOPE project
  - motivations
  - design
  - physics case
  - technology
- Longer terms perspectives
- Conclusions

To start… A Note of Optimistism

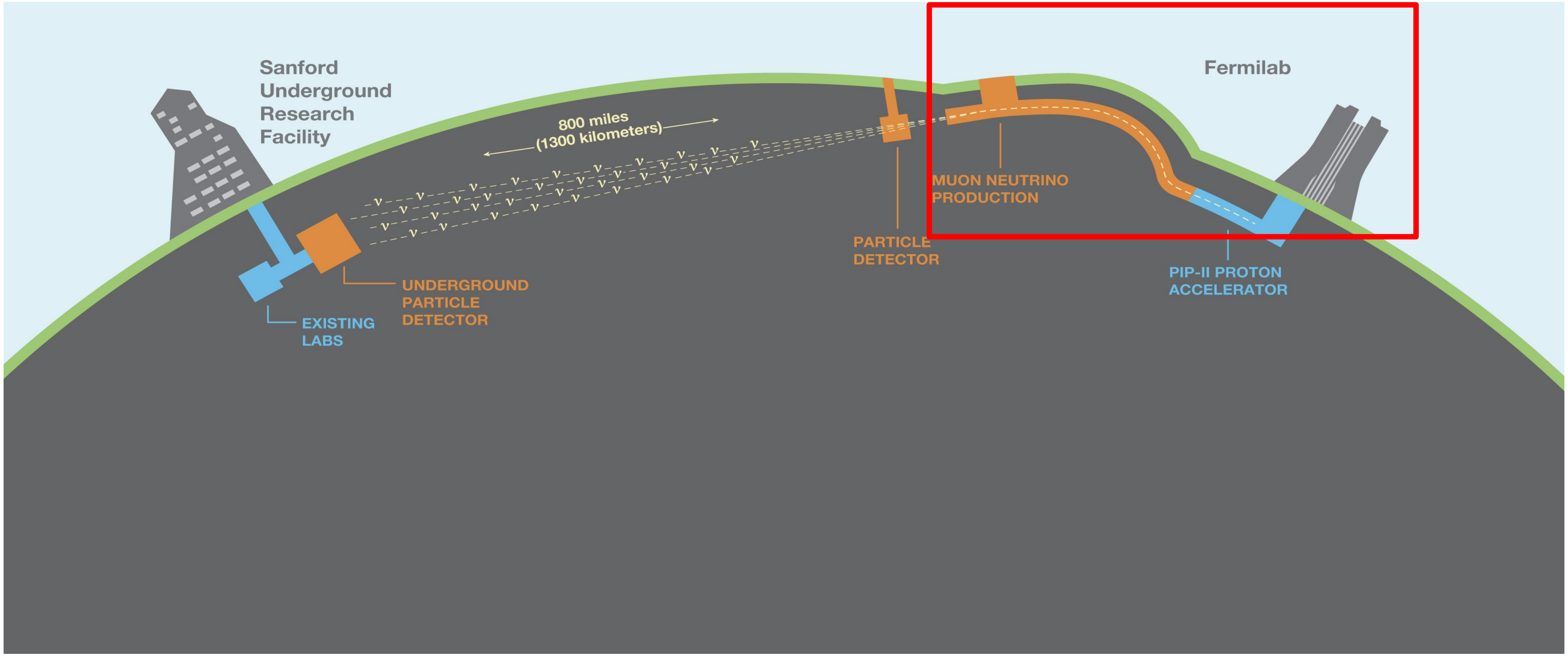
- We are living privileged **times for experimental neutrino physics**
- Major experiments (KM3NeT, IC-Upgrade, JUNO, DUNE, HyperK) started (or are about) ➔ plenty of data to chew on!

- New experiments will allow to explore uncharted territory: NMO, leptonic CP violation etc...

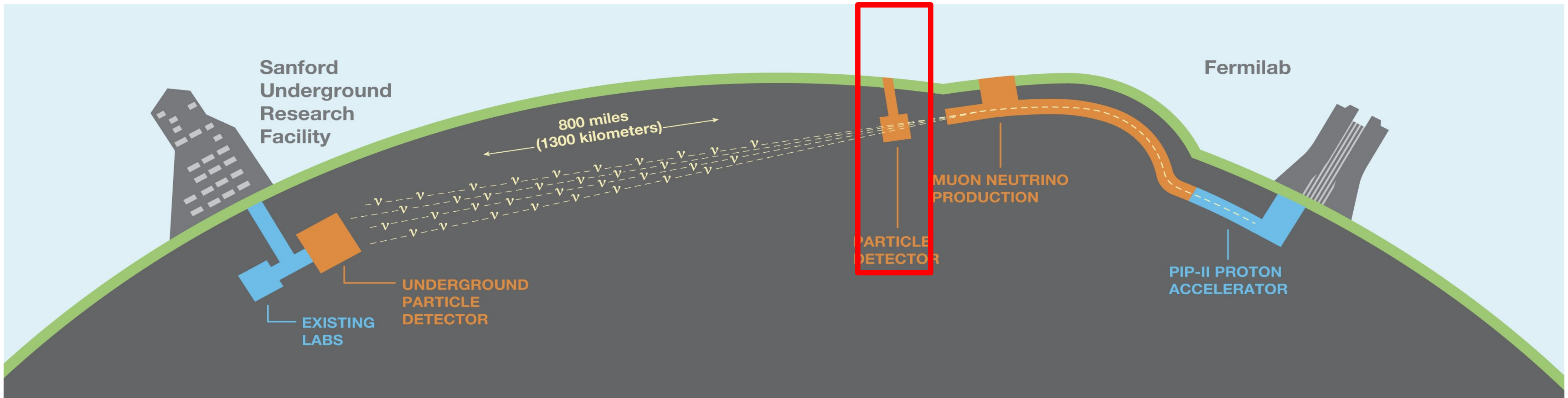
Recall on Long baseline neutrino experiments

Protons collided on target produce mesons that decay to neutrinos (**π➔μν**)



Recall on Long baseline neutrino experiments

ν beam characterised
(rate, energy, flavour)
with a **near detector**

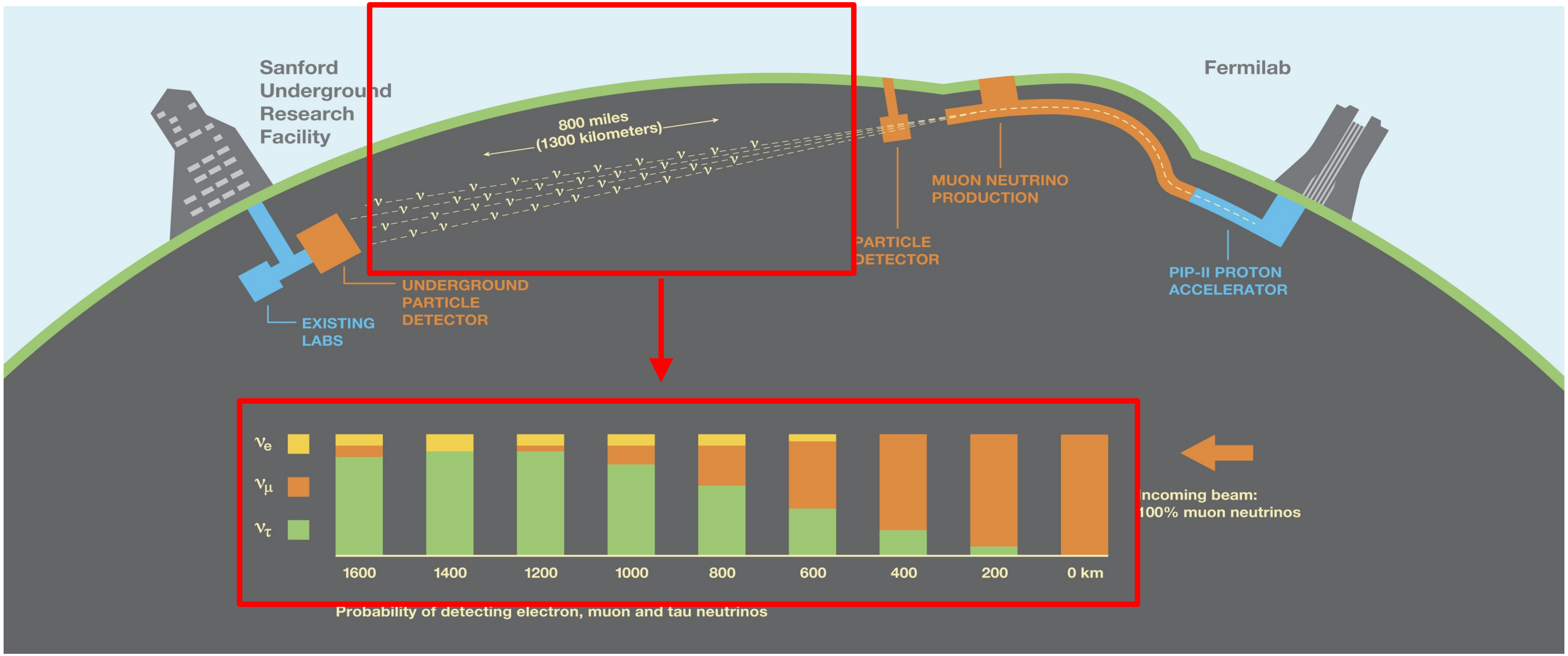


$$\mathrm{N}_{\nu_\mu}^{\mathrm{ND}}(E_{\mathrm{reco}}) = \Phi(E_{\mathrm{true}})\sigma(E_{\mathrm{true}})\epsilon(E_{\mathrm{true}})S(E_{\mathrm{true}}, E_{\mathrm{reco}})$$

Flux | **Intraction cross-section** | **Efficiency** | **Energy Response**

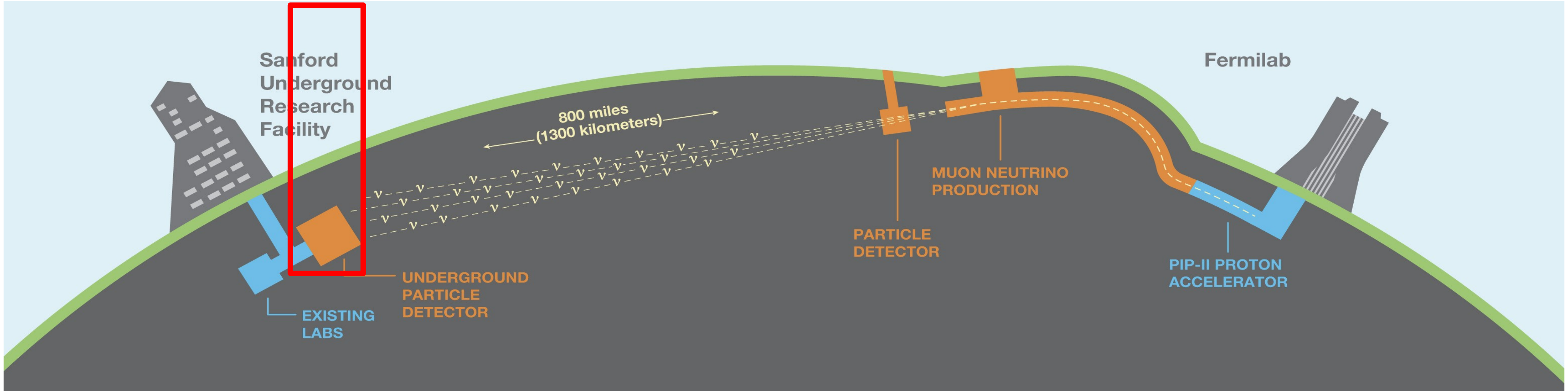
Recall on Long baseline neutrino experiments

Neutrinos propagate through Earth crust and "**oscillate**"



Recall on Long baseline neutrino experiments

ν beam characterised
(rate, energy, flavour)
with a **far detector**



$$\mathrm{N}^{\mathrm{ND}}_{\nu_\mu}(E_{\mathrm{reco}}) = \Phi(E_{\mathrm{true}})\sigma(E_{\mathrm{true}})\epsilon(E_{\mathrm{true}})S(E_{\mathrm{true}}, E_{\mathrm{reco}})$$

$$\mathrm{N}_{\nu_e}(E_{\mathrm{reco}}) = P_{\nu_\mu \to \nu_e}(E_{\mathrm{true}})\Phi(E_{\mathrm{true}})\sigma(E_{\mathrm{true}})\epsilon(E_{\mathrm{true}})S(E_{\mathrm{true}}, E_{\mathrm{reco}})$$

Recall on Long baseline neutrino experiments

- **Cancellation Far to Near detector** is only approximate
  - energy spectrum at ND and FD are substantially different due to detector acceptances

$$N^{ND}_{\nu_\mu}(E_{reco}) = \Phi^{ND}(E_{true})\sigma(E_{true})\epsilon(E_{true})S(E_{true}, E_{reco})$$

$$N^{FD}_{\nu_e}(E_{reco}) = P_{\nu_\mu \to \nu_e}(E_{true})\Phi^{FD}(E_{true})\sigma(E_{true})\epsilon(E_{true})S(E_{true}, E_{reco})$$

- Next experiments (DUNE HyperK) will collect 10-100 times larger than their predecessors
- To exploit this statistical precision, **systematic uncertainties must be reduced**

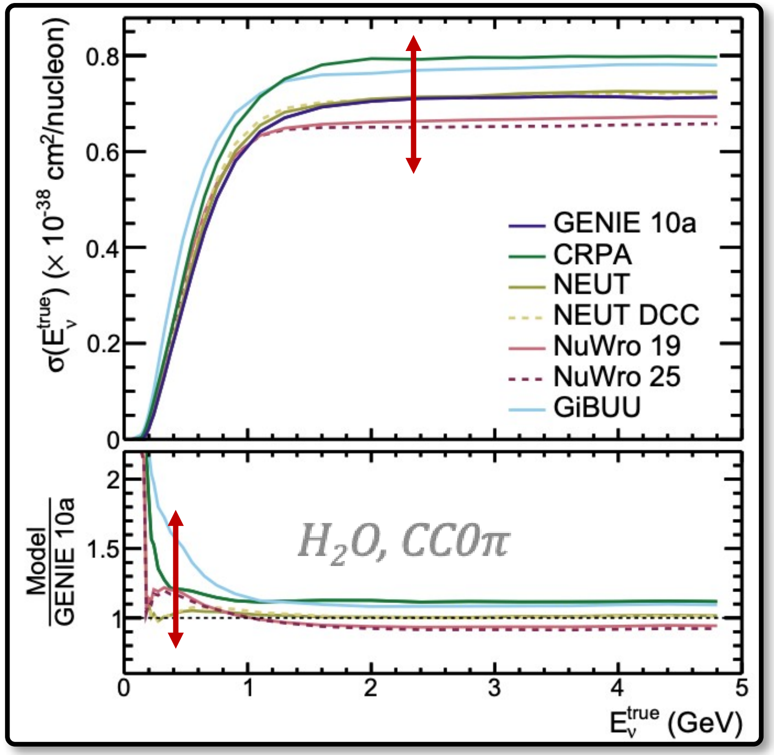
Exp.	**ν_μ**	**anti-ν_μ**	**ν_e**	**anti-νe**	**Syst. Errors**
T2K	318	137	94	16	**5%**
NoVa	211	105	82	33	
HyperK	~10k	~14k	~2k	~2k	**needs 1-3%**
DUNE	~7k	~3.5k	~1.5k	~0.5k	

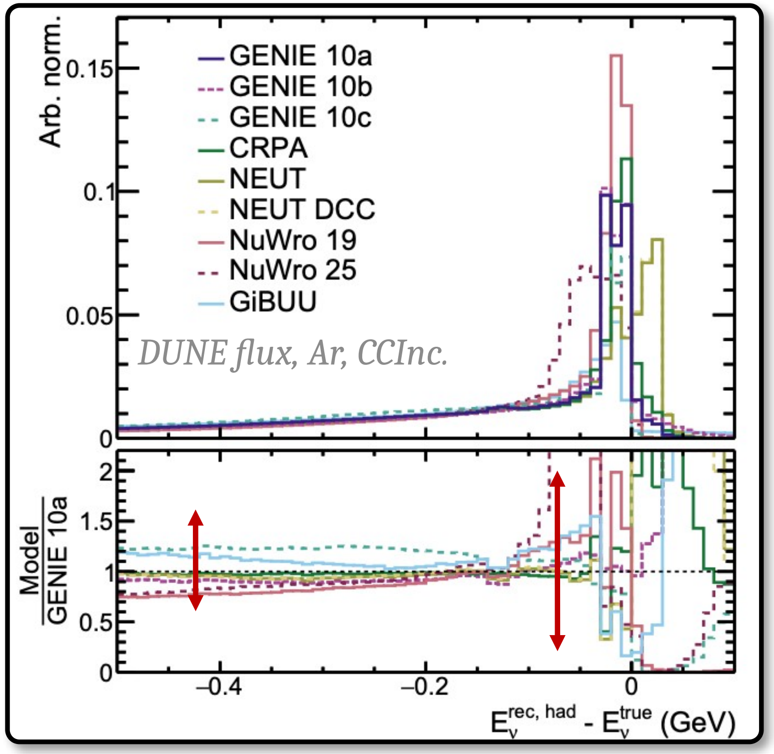
Courtesy L. Munteanu

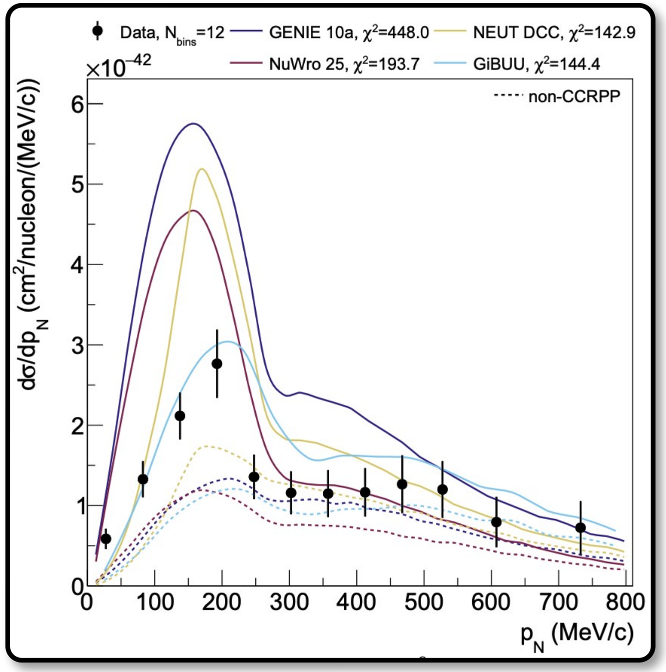
Systematic Uncertainties

[arXiv:2605.28671]

- Dominant systematic errors arise from **neutrino interactions**
  - better control of the neutrino flux (differential) is needed



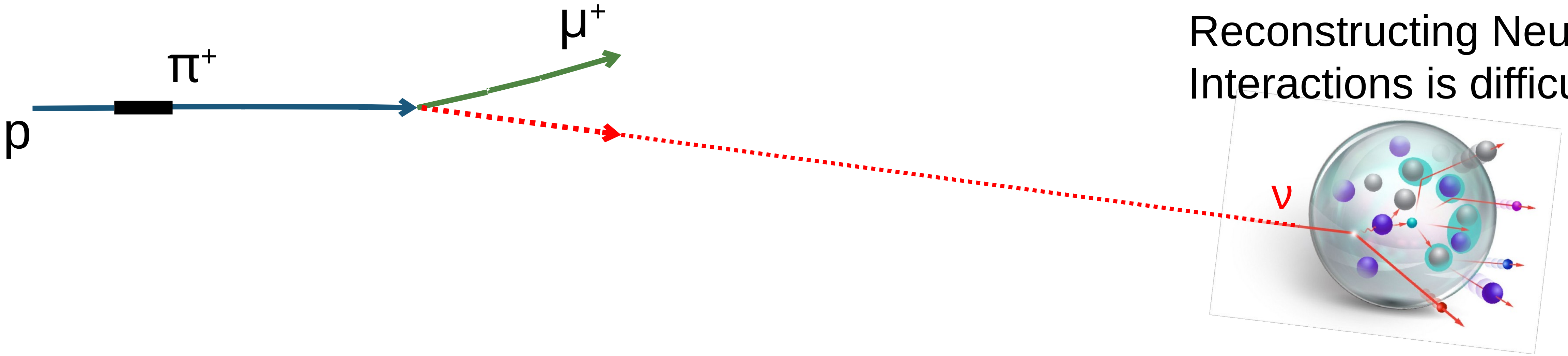




Comparisons with experimental measurements are inconclusive

Model differences between 20-50%

Neutrino Tagging: an novel approach



Reconstructing Neutrino Interactions is difficult !

Energy Resolution 20%

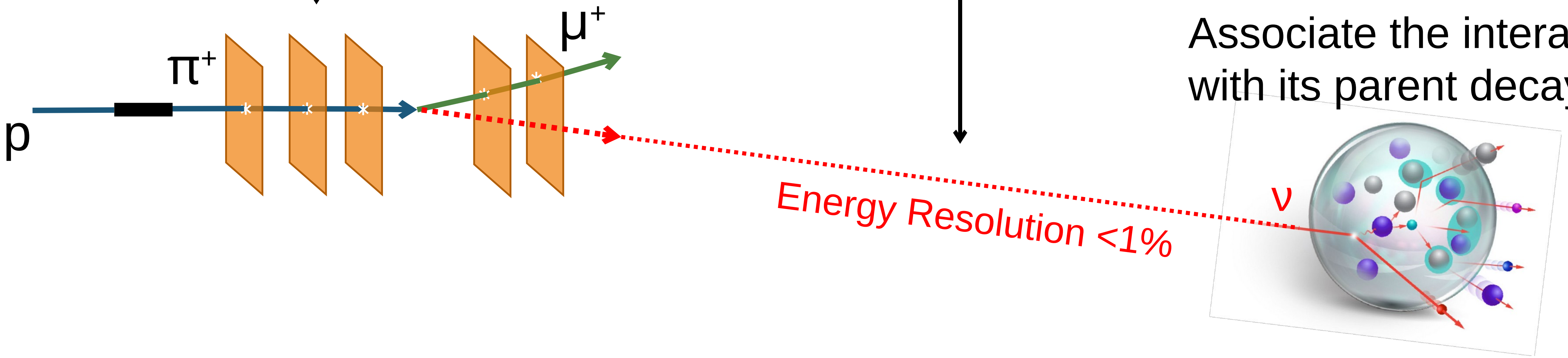
⚠️ Key Slide

Neutrino Tagging: an novel approach

Instrument beamline to track π^+ and μ^+

Reconstruct **precisely** ν_μ properties from π^+ and μ^+

Associate the interaction with its parent decay



[Eur. Phys. J. C , 82 , 465 (2022)]

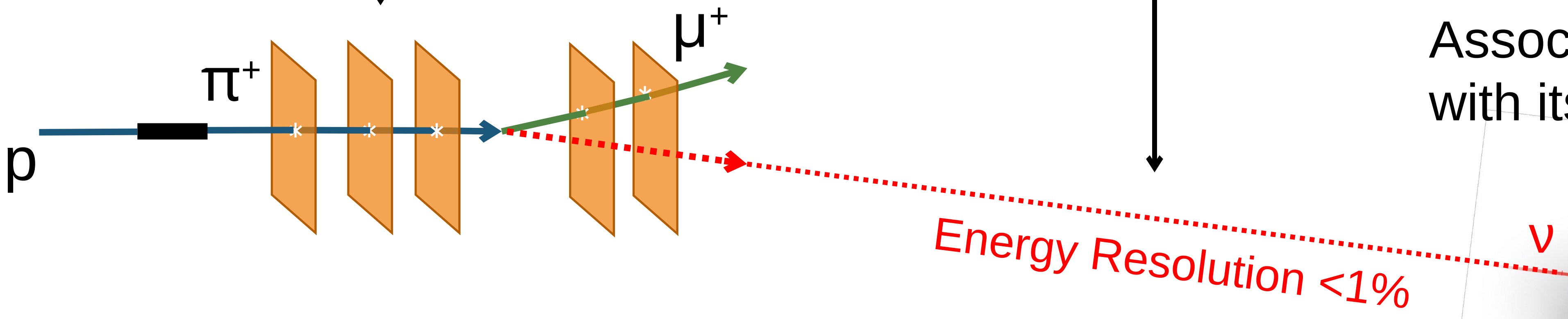
⚠️ Key Slide

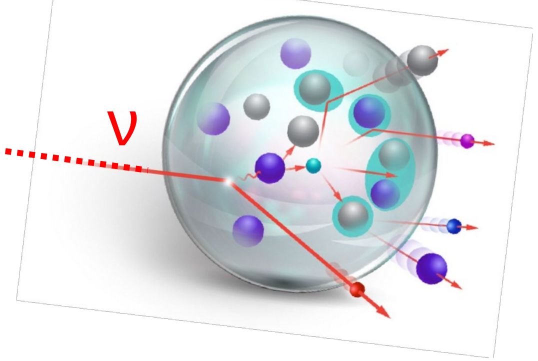
Neutrino Tagging: an novel approach

Instrument beamline to track π^+ and μ^+

Reconstruct **precisely** ν_μ properties from π^+ and μ^+

Associate the interaction with its parent decay





Ideal setup to study:
- ν interactions
- ν oscillations

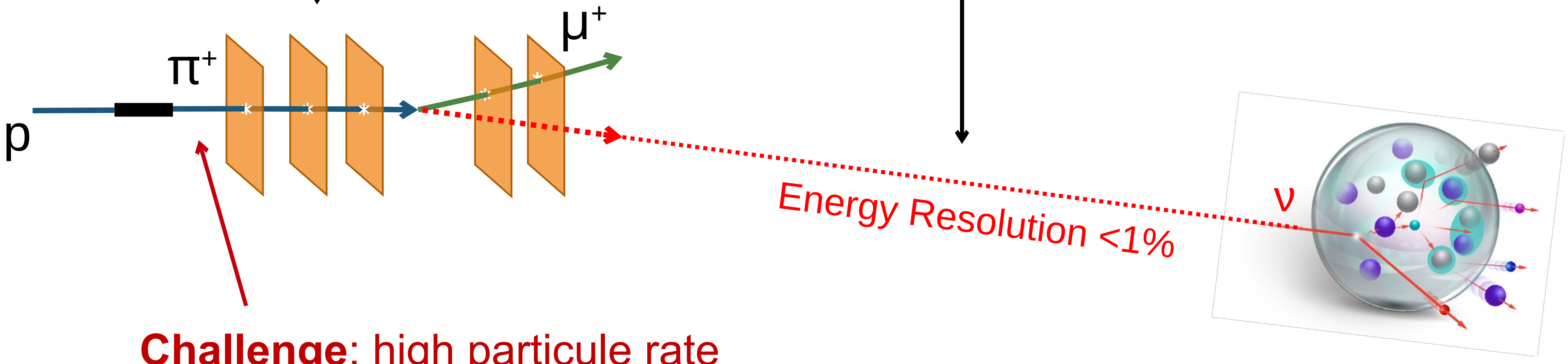
[Eur. Phys. J. C , 82 , 465 (2022)]

⚠️ Key Slide

Neutrino Tagging: an novel approach

Instrument beamline to track π^+ and μ^+

Reconstruct **precisely** ν_μ properties from π^+ and μ^+



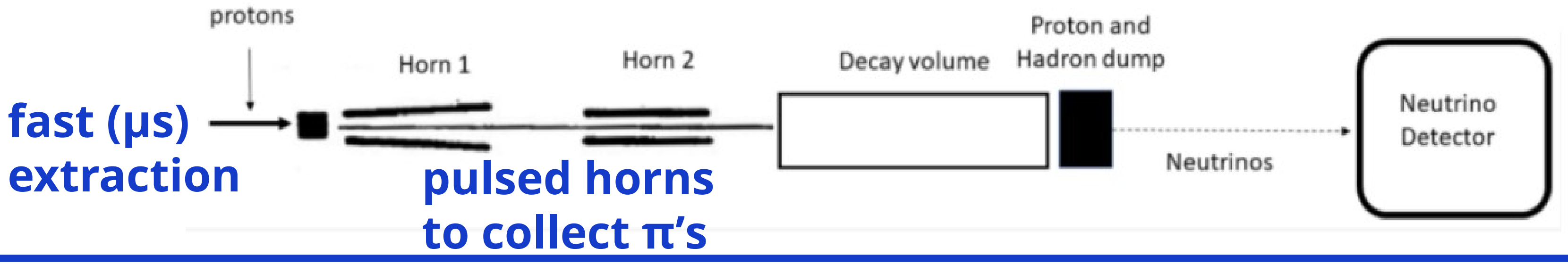
Challenge: high particle rate
(at nuSCOPE: $10^{10\text{-}11}$ π^+/s)

[Eur. Phys. J. C , 82 , 465 (2022)]

⚠️ Key Slide

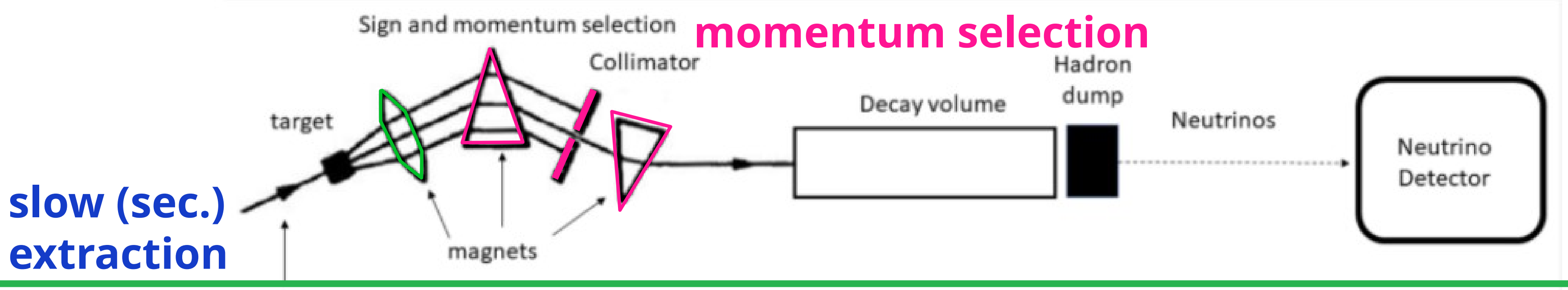
The Challenge – Beam Particle Rate

At **conventional beamlines** (e.g. DUNE), **particle rate is “huge”** (~10^{18} part/s)



A tagged beam requires an **alternative beamline design**, using:

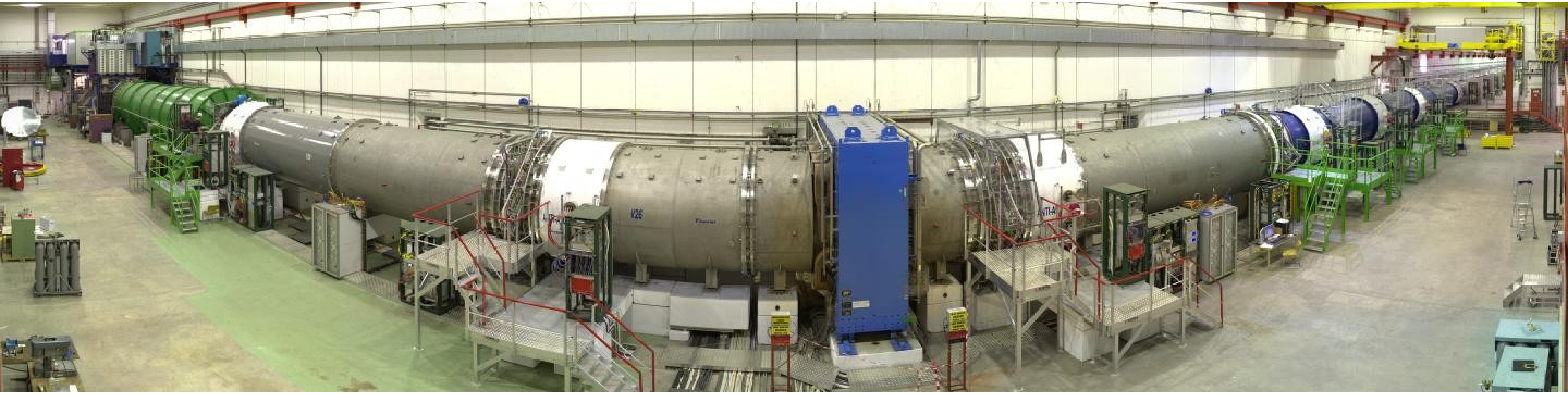
- **Slow extraction** (few sec. long pulse instead of μs) with **static focusing**
- **Momentum selection** (remove soft π’s)
- Large (10x10cm²) **beam transverse size** (what really matters is part/s/cm²)



Outline

- Introduction
  - scientific context
  - neutrino tagging concept
- **Proof-of-principle with existing data (NA62)**
- The nuSCOPE project
  - motivations
  - design
  - physics case
  - technology
- Longer terms perspectives
- Conclusions

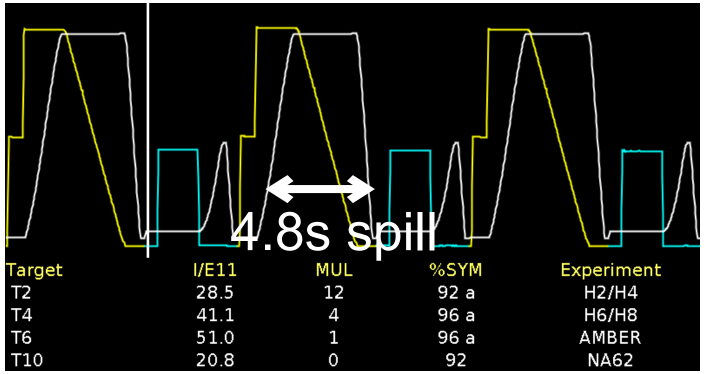
A running demonstrator — NA62



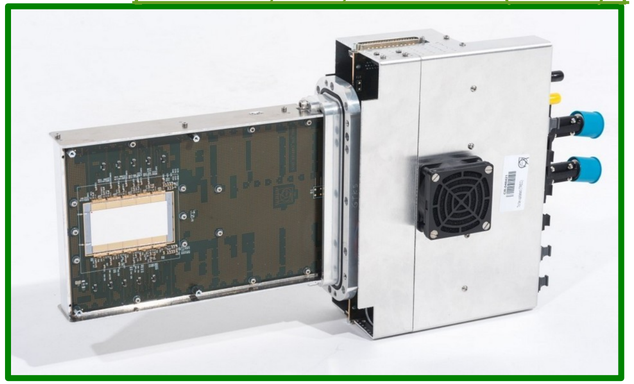
- Fixed target **kaon experiment** at CERN SPS (2015-present)
- **Goal**: measure $B(K^+ \to \pi^+ \nu\nu) =_{\mathrm{SM}} (7.86 \pm 0.061) \times 10^{-11}$
- ~10^{12} kaon decays per year, mostly $K^+ \to \mu^+ \mu_\mu$
- **Instrumentation** available to detect the $\boldsymbol{K^+}$, $\boldsymbol{\mu^+}$ and $\boldsymbol{\nu_\mu}$ CC interaction

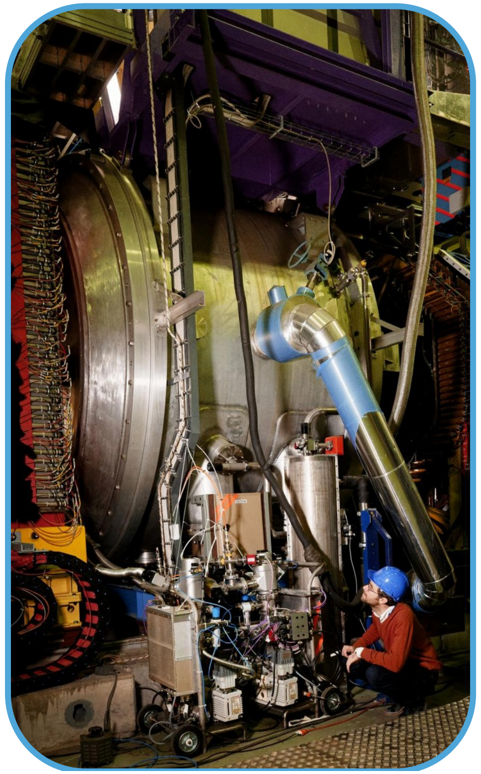
JINST, 12(05):P05025, 2017.

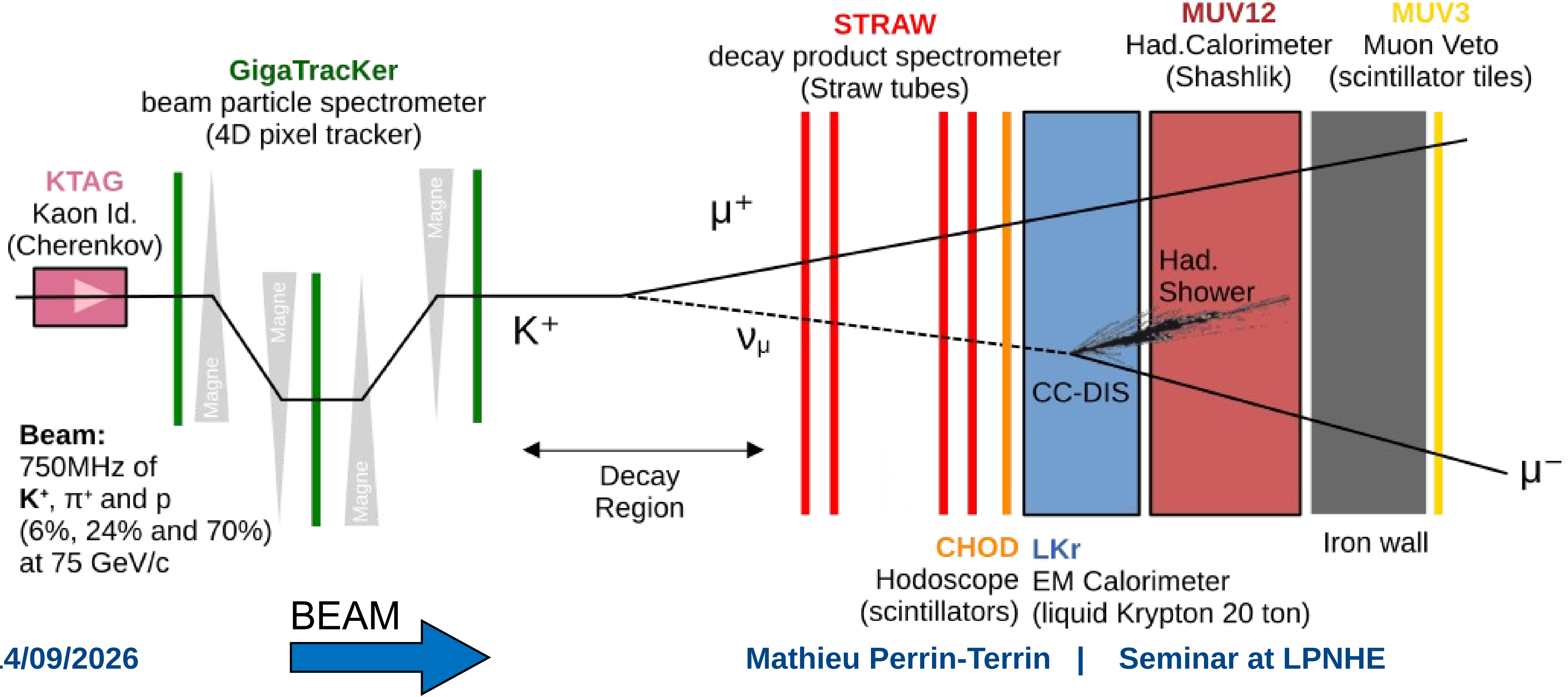
NA62 Simplified Layout

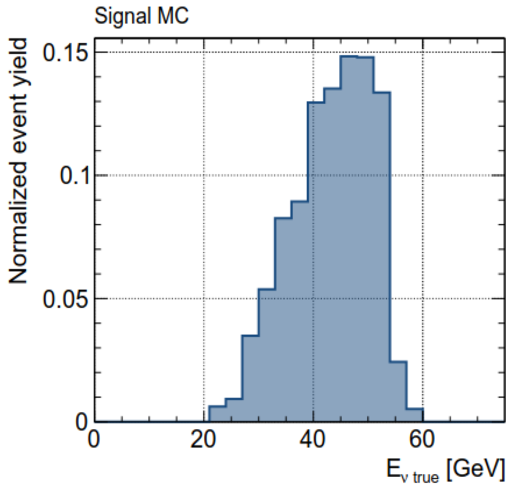


[JINST , 14 , P07010 (2019)]









The first tagged neutrino candidate of NA62

- **Data collected in 2022** with a dedicated ν trigger line
- About **~5×10^{12} K^+ decays** were collected
- Expected **signal** events:

$$0.208 \pm 0.013_{\mathrm{stat}} \pm 0.009_{\mathrm{syst}}$$

- Expected **background** events:

$$0.034^{+0.041}_{-0.023}\Big|_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}}$$

The first tagged neutrino candidate of NA62

- **Data collected in 2022** with a dedicated ν trigger line
- About **~5×10¹² *K*⁺ decays** were collected
- Expected **signal** events:

$$0.208 \pm 0.013_{\rm stat} \pm 0.009_{\rm syst}$$

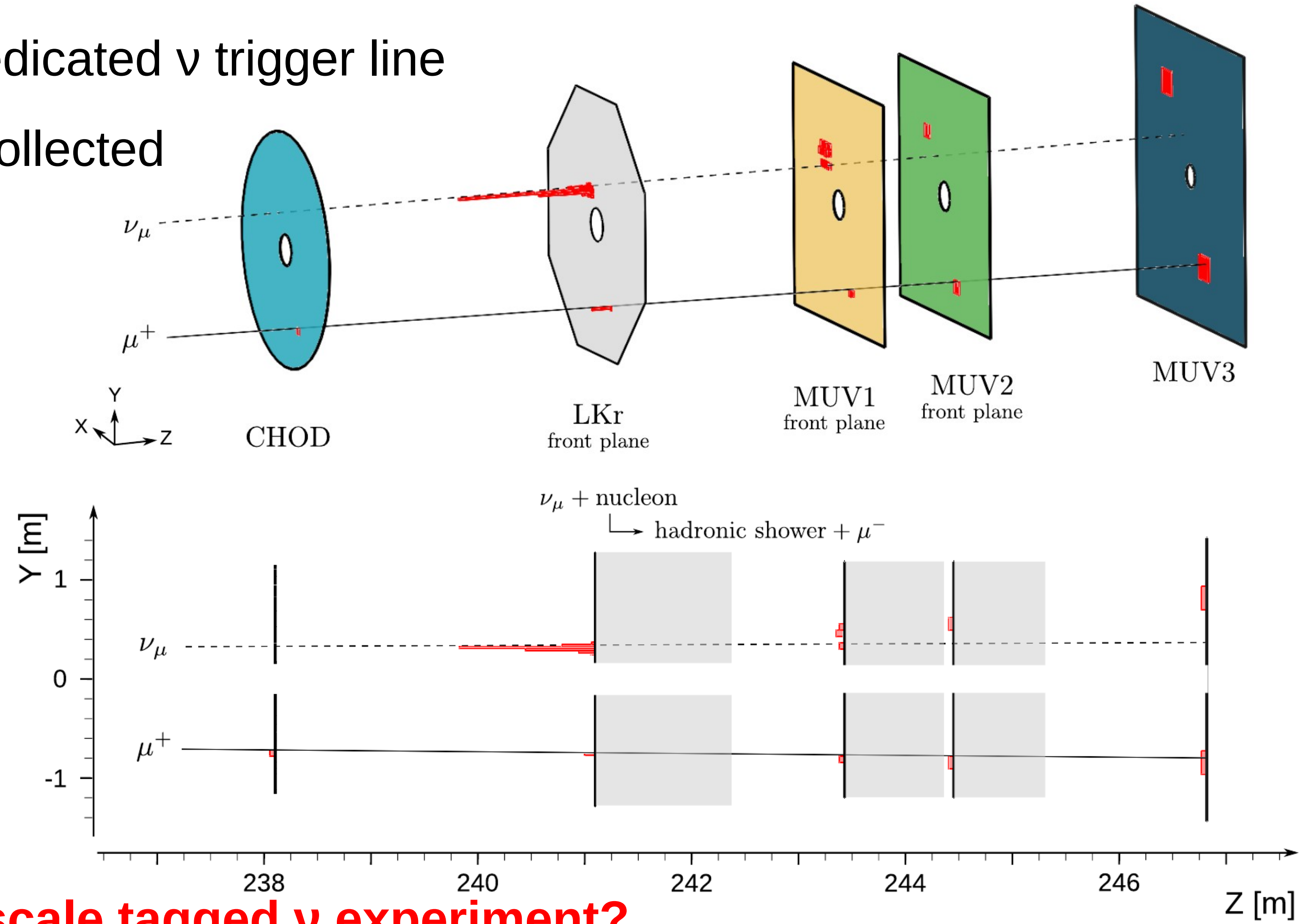
- Expected **background** events:

$$0.034^{+0.041}_{-0.023}\Big|_{\rm stat} \pm 0.004_{\rm syst}$$

- **One signal event observed**

$$\mathrm{E}_\nu = \mathrm{E}_{\mathrm{K}+} - \mathrm{E}_{\mu+} = 52.09\mathrm{GeV}$$
$$\sigma_{\mathrm{E}_\nu}/\mathrm{E}_\nu = 0.34\%$$

[PLB 863 (2025) 139345]



- **How to go from NA62 to a full scale tagged ν experiment?**

Outline

- Introduction
  - scientific context
  - neutrino tagging concept
- Proof-of-principle with existing data (NA62)
- **The nuSCOPE project**
  - motivations
  - design
  - physics case
  - technology
- Longer terms perspectives
- Conclusions

The nuSCOPE project

- A **short baseline ν experiment** with a **tagged and monitored beam**
- Born in 2025 as the merger of the nuTAG and ENBUET concepts
- **Goal:** open the path to precision physics in neutrino oscillations by measuring with high precision the **neutrino interaction cross-sections** on various targets
- **Ressources:**
  - ESPPU Contribution arxiv.2503.21589
  - Kick-off workshop organised at CERN INDICO
  - Article on CERN Couier May/June 2026
    Neutrinos on the clock

CERNCOURIER

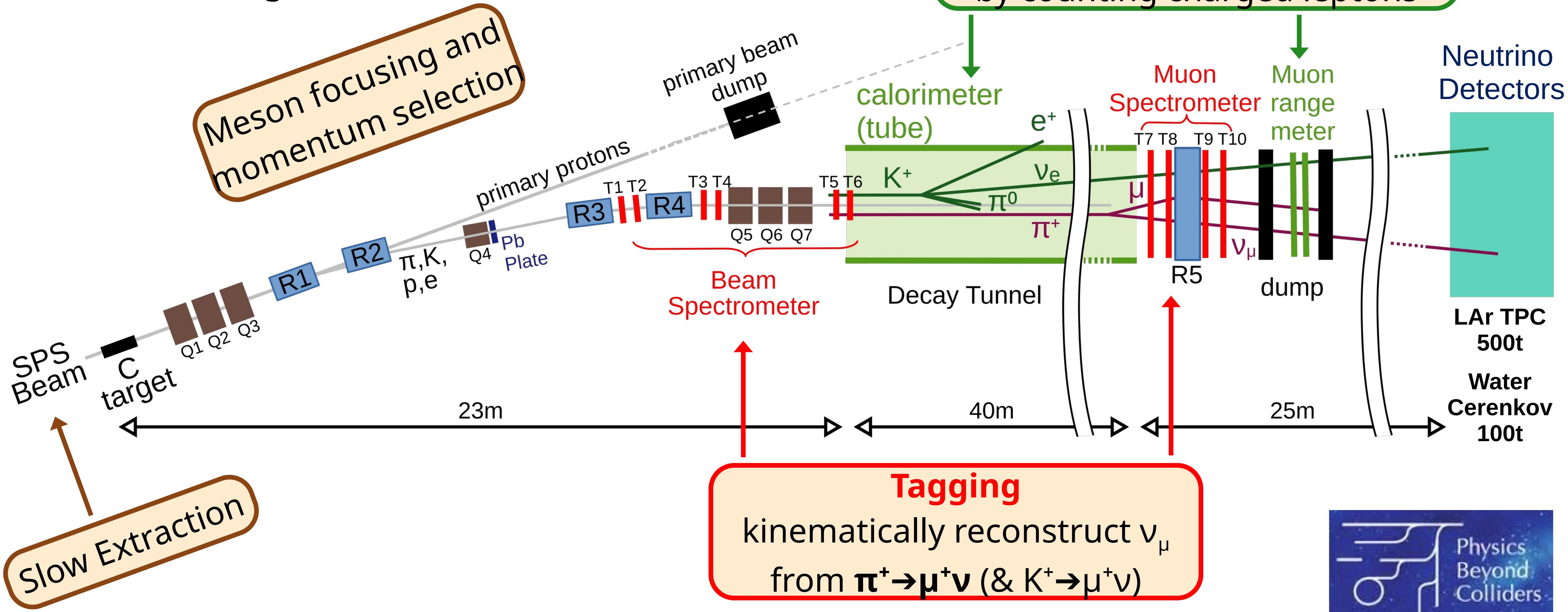
https://nuscope.web.cern.ch/

Beam line Design

Optimised in collaboration with CERN and based on ENUBET design

Monitoring estimate

- ν_e flux from $K^+ \rightarrow \pi^0 e^+ \nu_e$
- ν_μ flux from $K^+ \rightarrow \mu^+ \nu$ and $\pi^+ \rightarrow \mu^+ \nu$ by counting charged leptons



Tagging

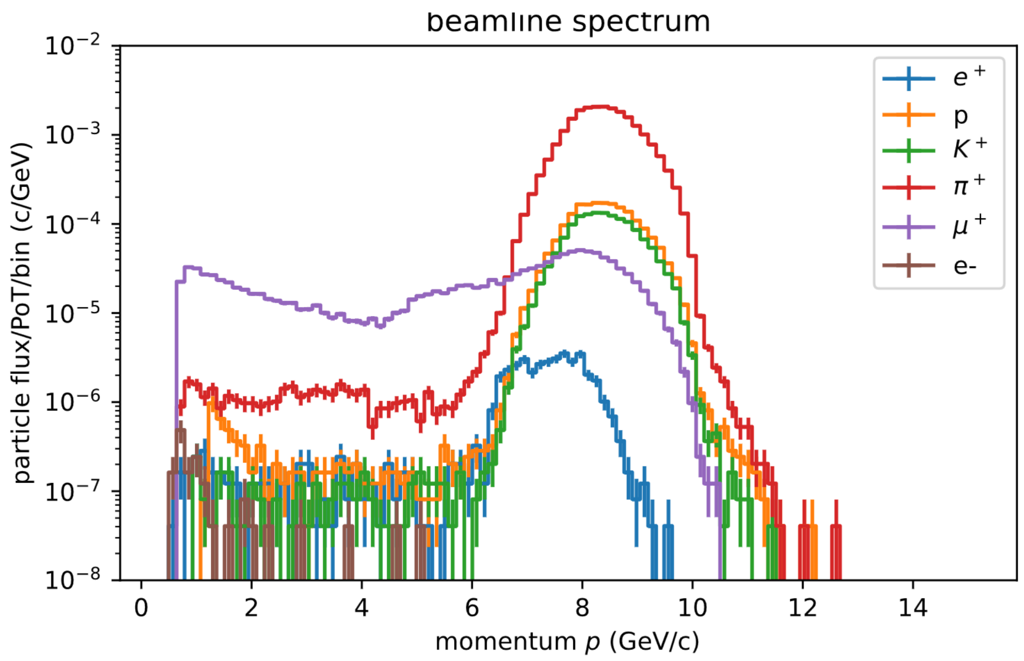
kinematically reconstruct ν_μ from $\pi^+ \rightarrow \mu^+ \nu$ (& $K^+ \rightarrow \mu^+ \nu$)

Physics Beyond Colliders

Beam Parameters

- **Proton consumption**
  - allow to collect in <5years **10^4 ν_e-CC** (~**10^6 $\nu\mu$-CC**) with a protoDUNE like detector (**500t LAr**)
  - fully compatible (<**25% of TCC2**) with approved CERN experiments (including ShiP)
- **Central meson momentum** of 8.5 GeV/c) to matched DUNE and HyperK spectra

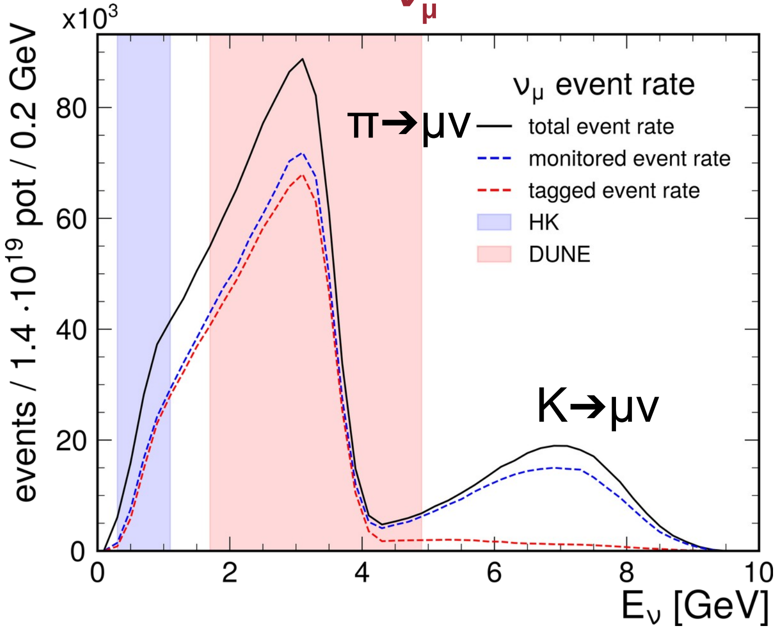
Parameter	Value
Primary proton momentum (GeV/c)	400
Beamline meson momentum (GeV/c)	max. 8.5
Proton-beam spill duration	slow (4.8 s to 9.6 s)
Spill intensity (protons/spill)	1×10^{13}
Event rate (THz)	1 – 2
Instantaneous power on target (W)	170 – 340
(K^+, π^+) yield per proton	$(1.3 \times 10^{-3}, 1.9 \times 10^{-2})$
(K^+, π^+) rate (GHz)	max. (2.7, 40)
Annual proton intensity (protons/year)	$2.1–3.2 \times 10^{18}$
Total proton requirement (protons)	1.4×10^{19}



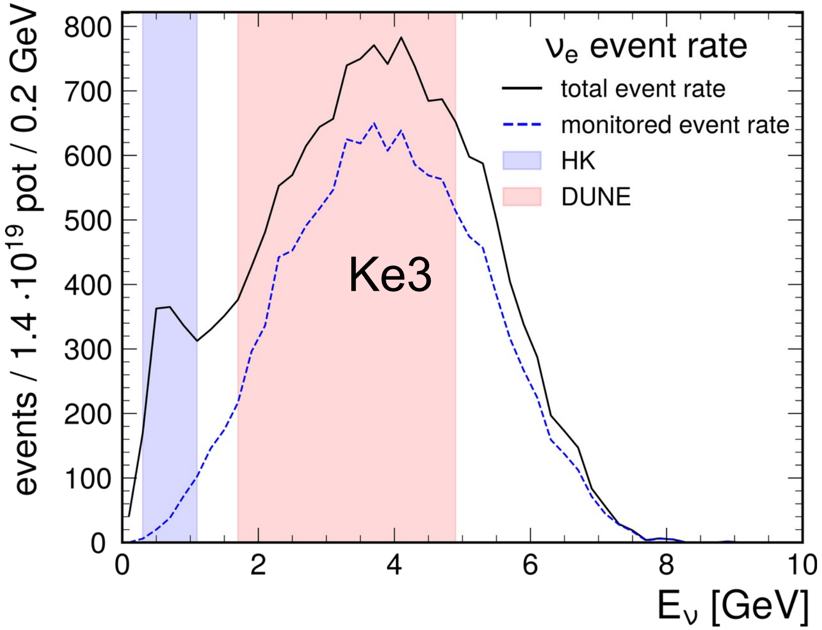
Neutrino detector and interaction rates

- **Reference detectors:**
  - **500t of liquid argon** ($4x4x22.3m^3$) similar to protoDUNEs at 25m from decay tunnel end
    Improved time reso. (0.3 - 1ns) assuming more photon coverage (R&D for 3rd/4th module)
  - **100t water Cerenkov or WBLS detector**:
    studies ongoing to optimise the size and placement
- **Large fraction of neutrino are monitored and tagged**

ν_μ



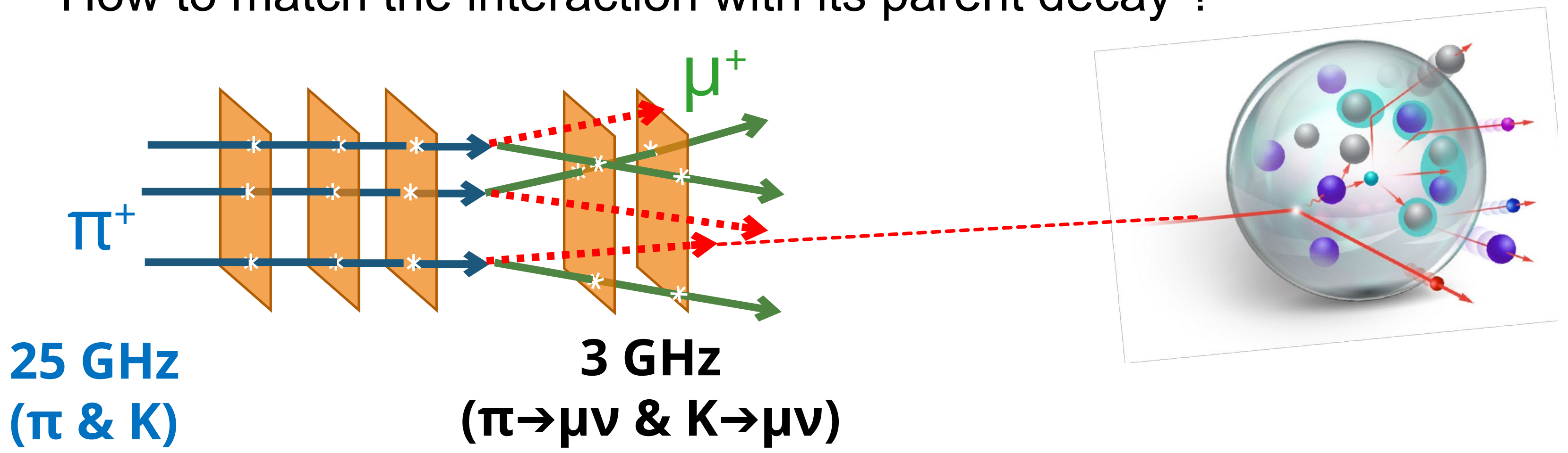
ν_e

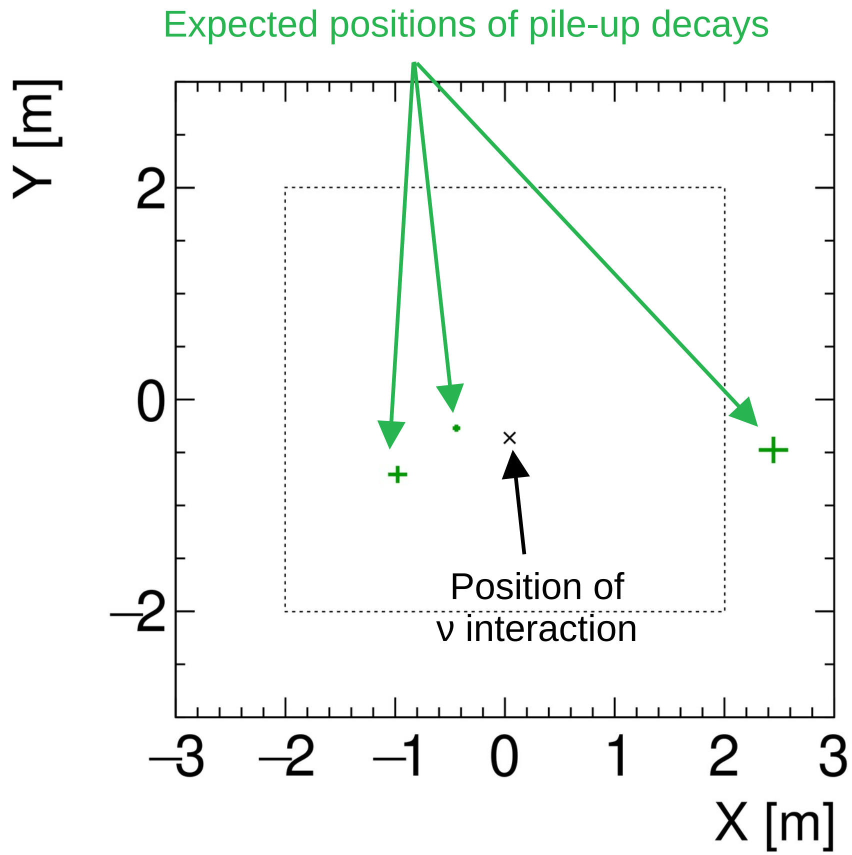


	Event per 1.4×10^{19} POT	
	500t LAr	**100t Water**
ν_μ	1.3×10^6	
Monitored ν_μ	1.0×10^6	
Tagged ν_μ	**7.6×10^5**	**1.4×10^5**
ν_e	1.7×10^4	
Monitored ν_e	1.2×10^4	

Tagging Performance

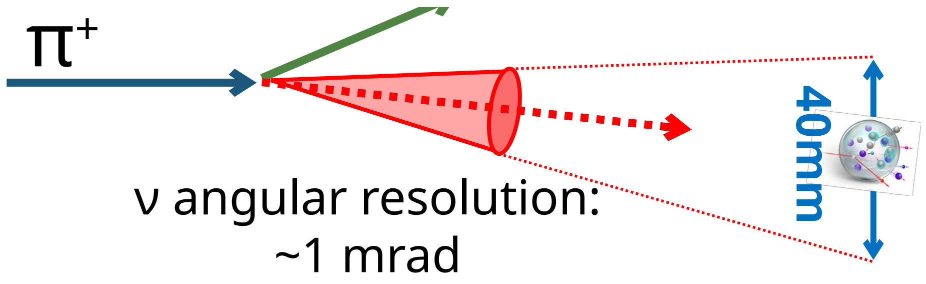
How to match the interaction with its parent decay ?





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

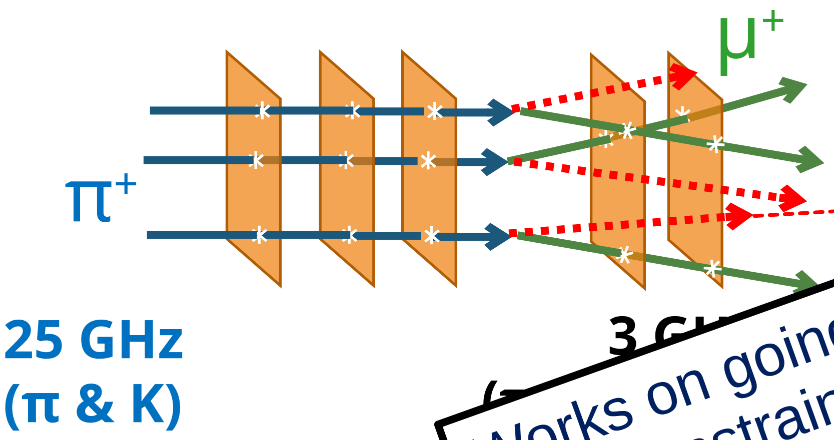
	Neutrino Dectector	Tagger
Time Resolution	**300 ps**	<10ps
Space Resolution	1mm	**40mm**

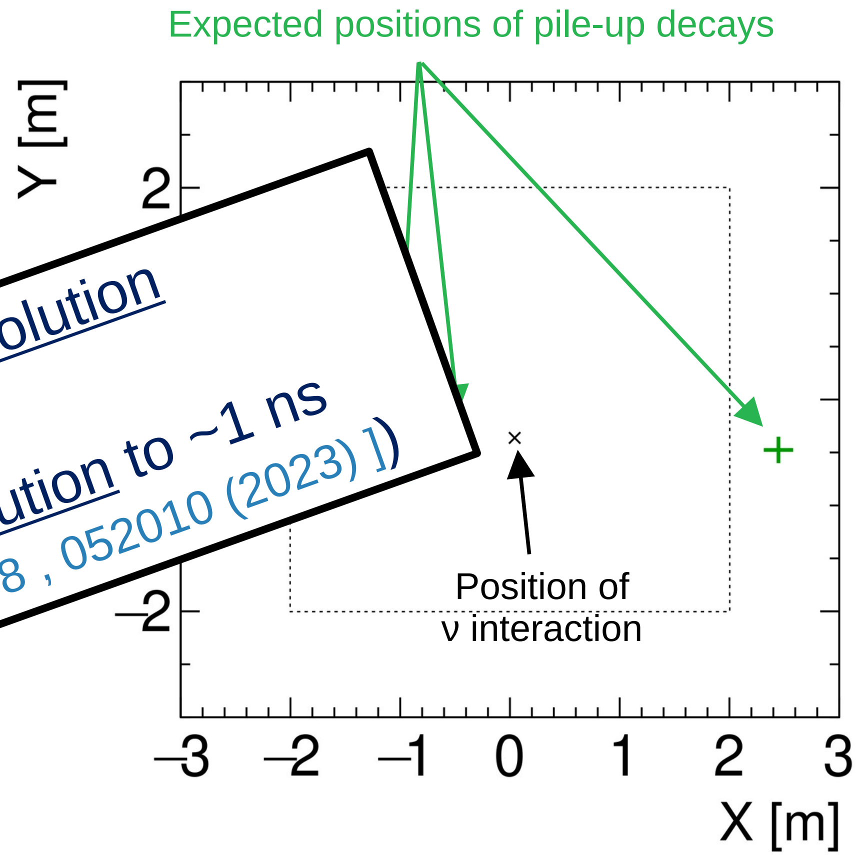


On average: 2 **in-time pile-up decays.**
Ambiguity resolved using spacial coincidence

Tagging Performance

How to match the interaction with its parent decay ?



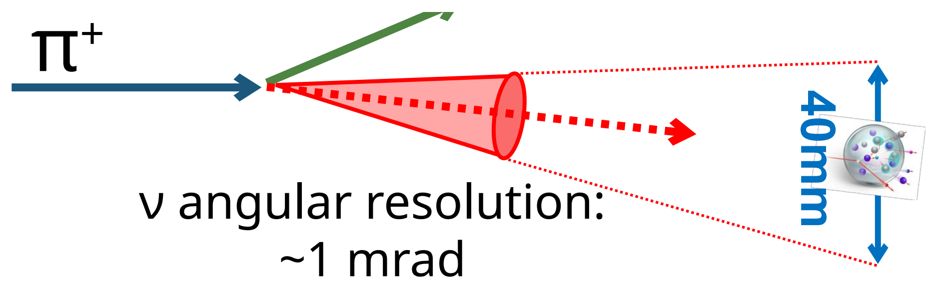


Works on going to improve Tagger's spacial resolution
(overconstrained decay fit)

→ relax specs on neutrino detector time resolution to ~1 ns
(state of the art MicroBooNE [Phys. Rev. D , 108 , 052010 (2023)])

Association is per… d **space coincidences**

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



On average: 2 **in-time pile-up decays.**
Ambiguity resolved using spacial coincidence

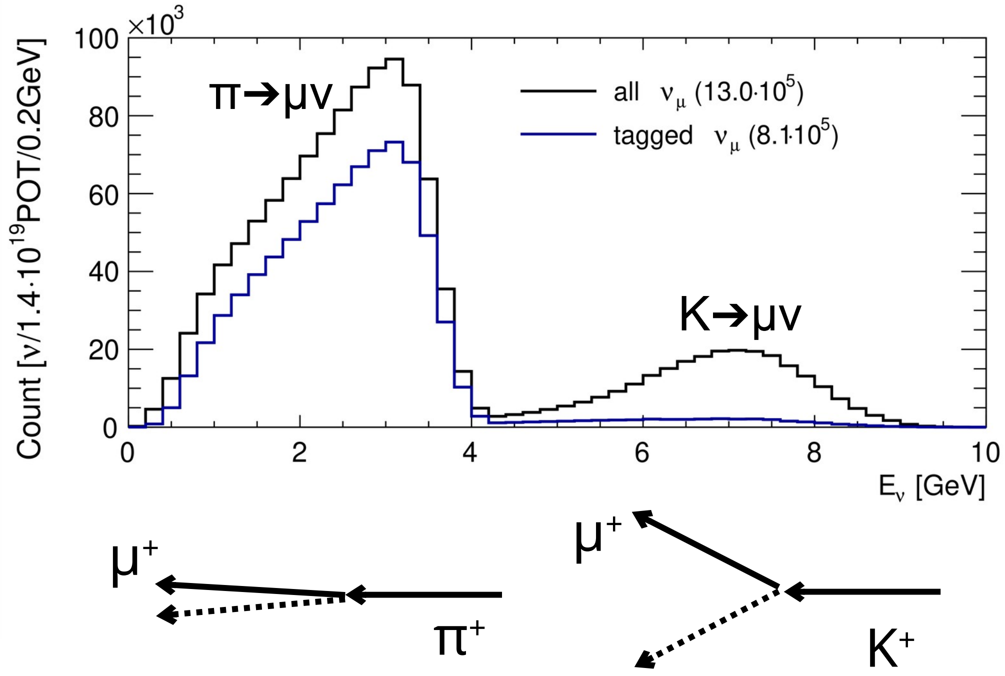
Tagging Efficiency

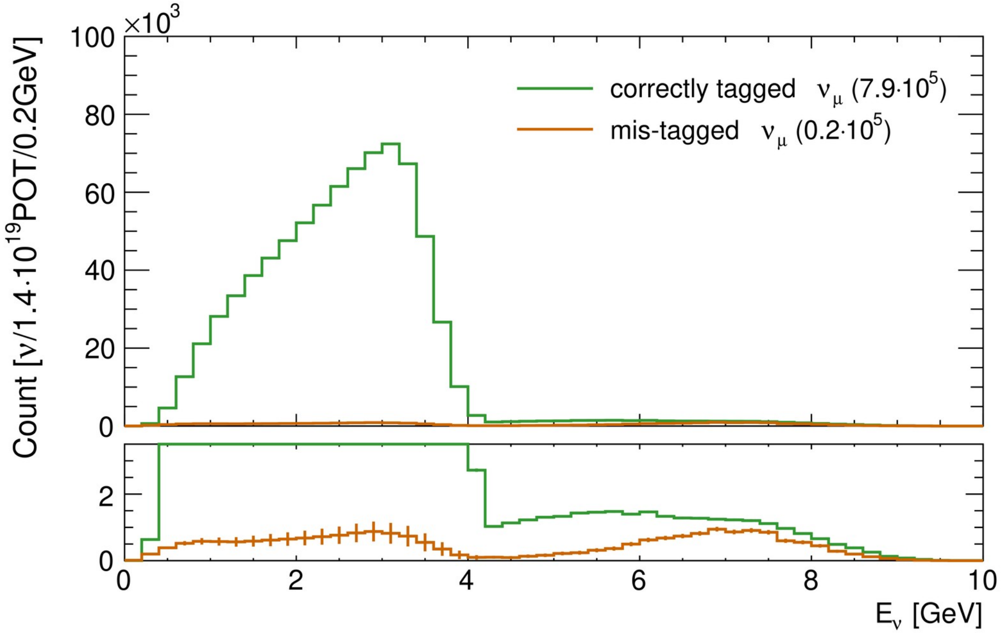
Tagging efficiency

- about **80% for π➔μν**
- lower for K➔μν: μ is emitted at larger angle outside spectrometer acceptance

Mis-tagging

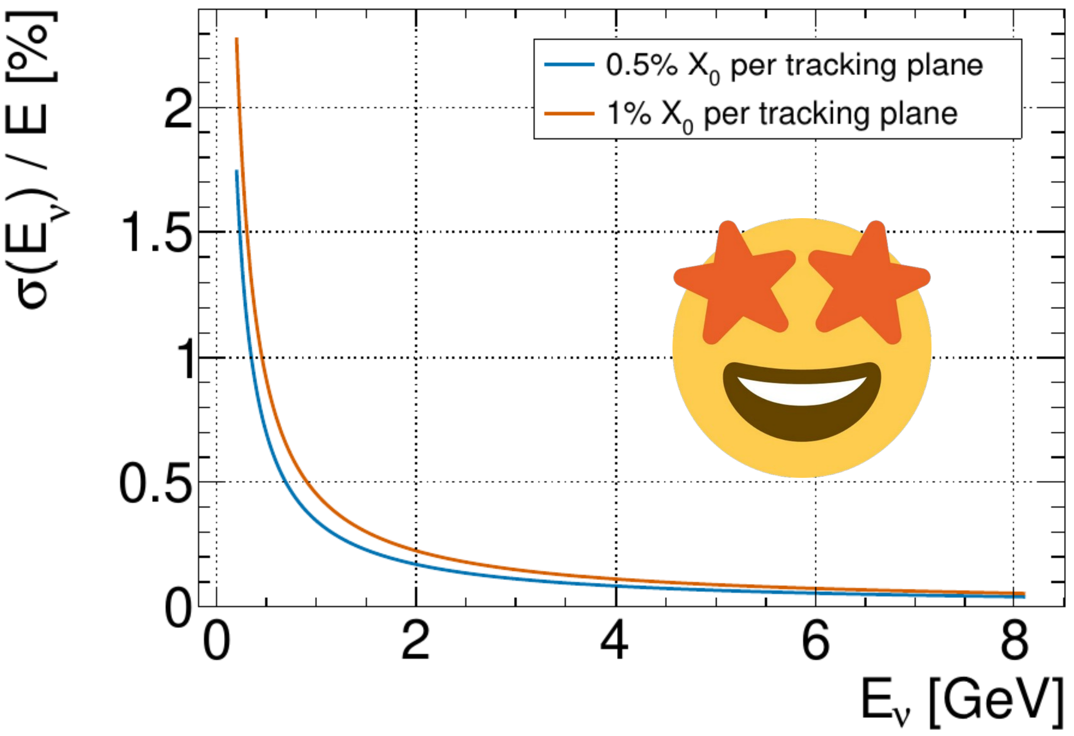
- low (<1%) between 1-4 GeV/c
- higher for K➔μν and at low energy (worse angular resolution)
- measurable on data



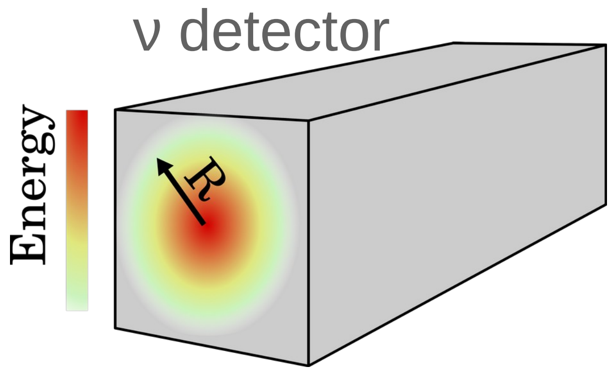


Energy Resolution

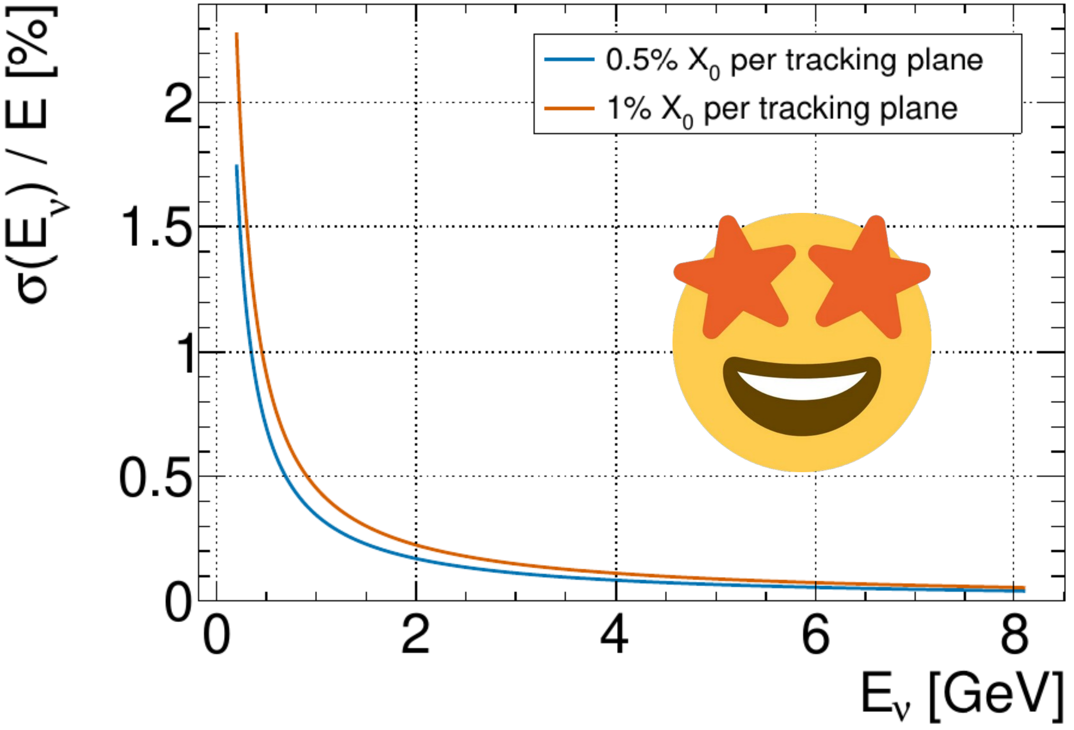
- Muon neutrino **energy estimated independently of interaction**
- **Tagging** gives **individual ν_μ energy with subpercent precision**

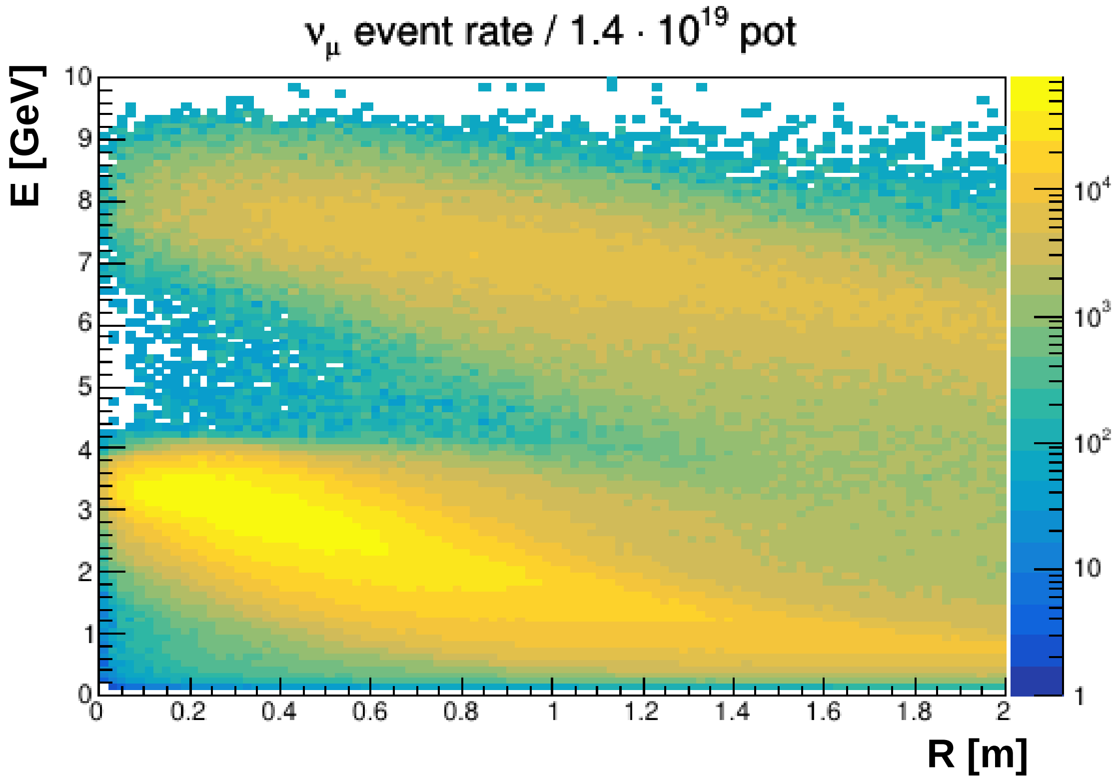


Energy Resolution

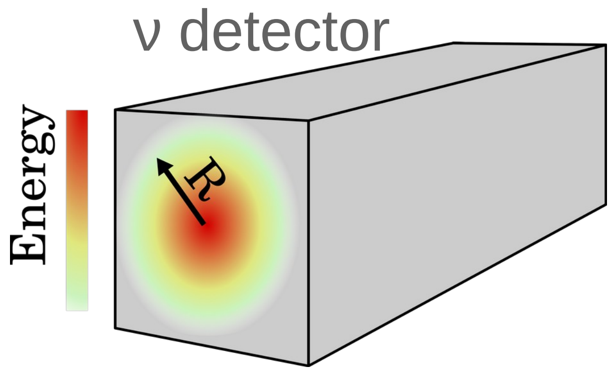


- Muon neutrino **energy estimated independently of interaction**
- **Tagging** gives **individual ν_μ energy with subpercent precision**
- **Monitoring** enables to select neutrinos **samples where energy is kown at 10-20%**

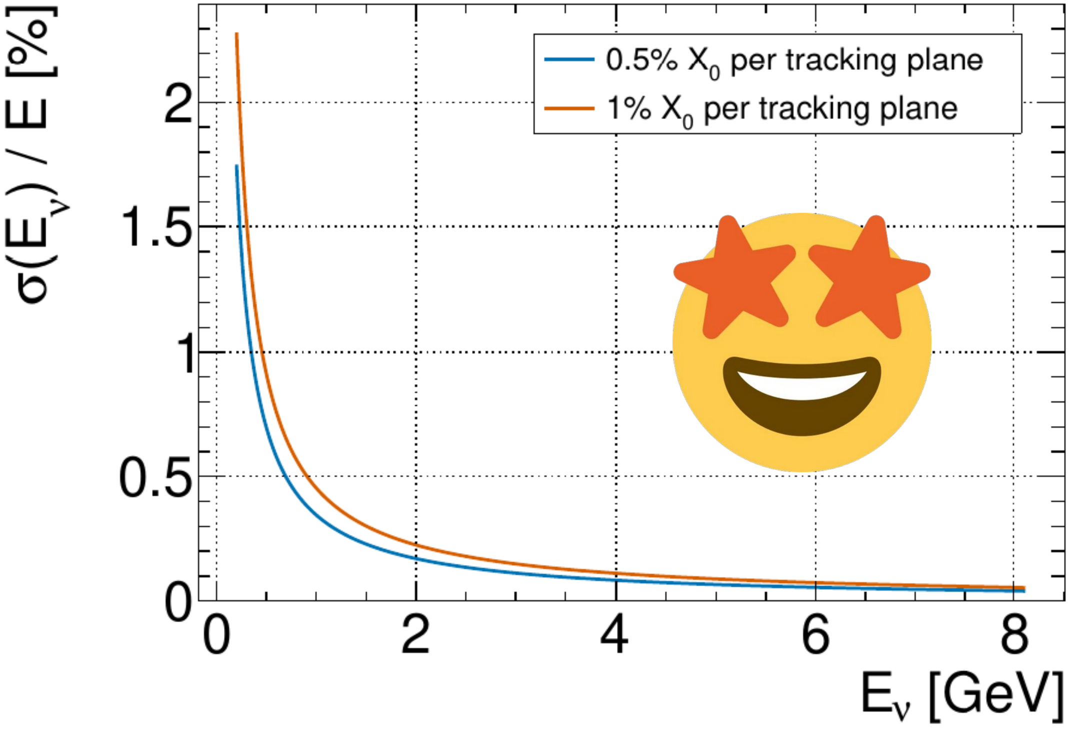


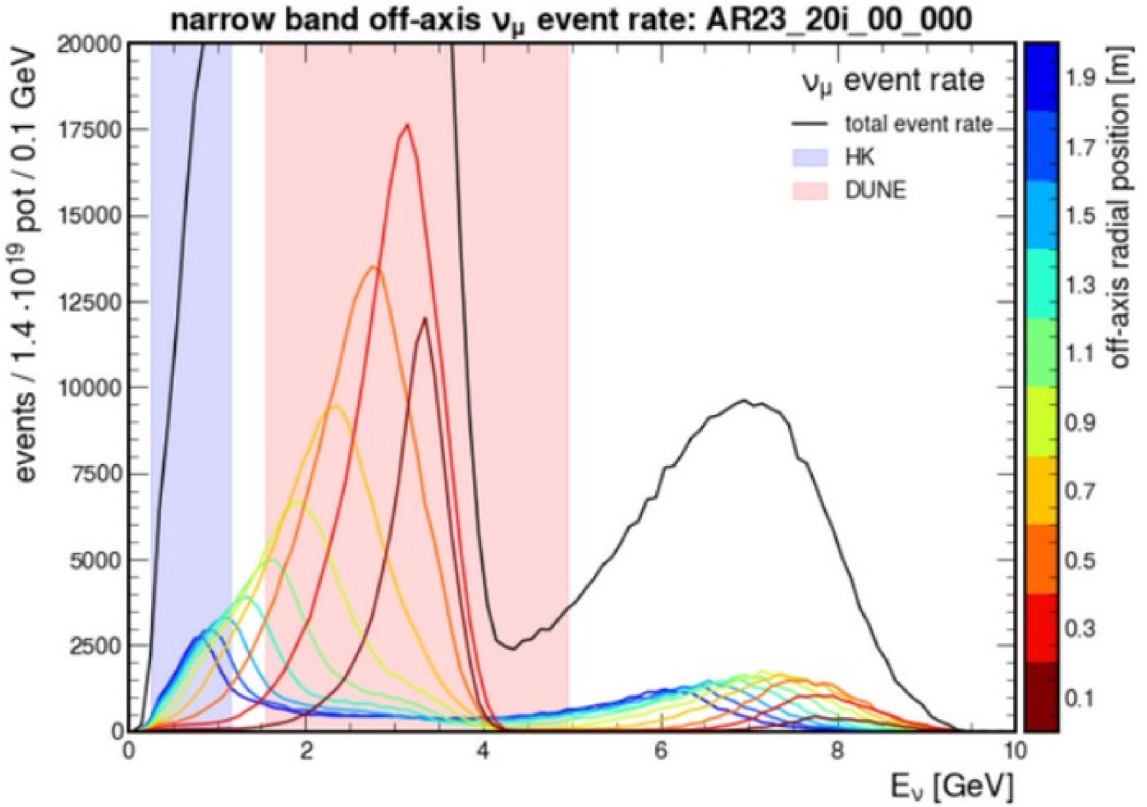


Energy Resolution



- Muon neutrino **energy estimated independently of interaction**
- **Tagging** gives **individual ν_μ energy with subpercent precision**
- **Monitoring** enables to select neutrinos **samples where energy is kown at ~10%** (NBOA)



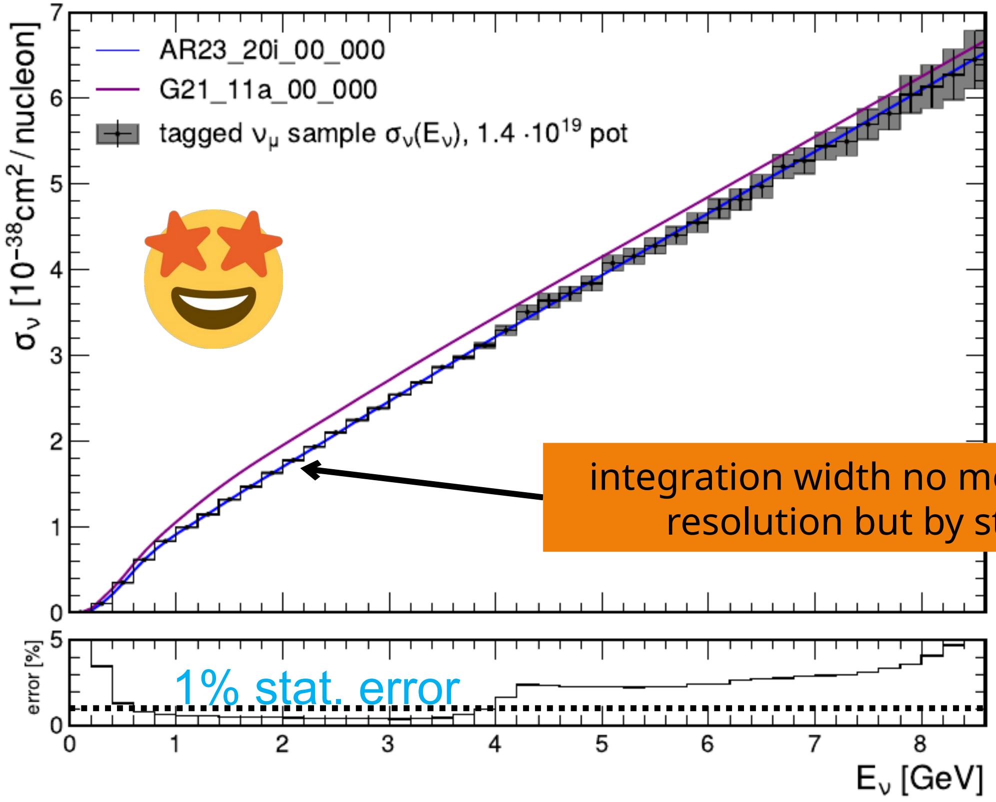


Cross section as function of energy

ν_μ cross section energy dependence:

crucial to extrapolate flux between near and far detectors

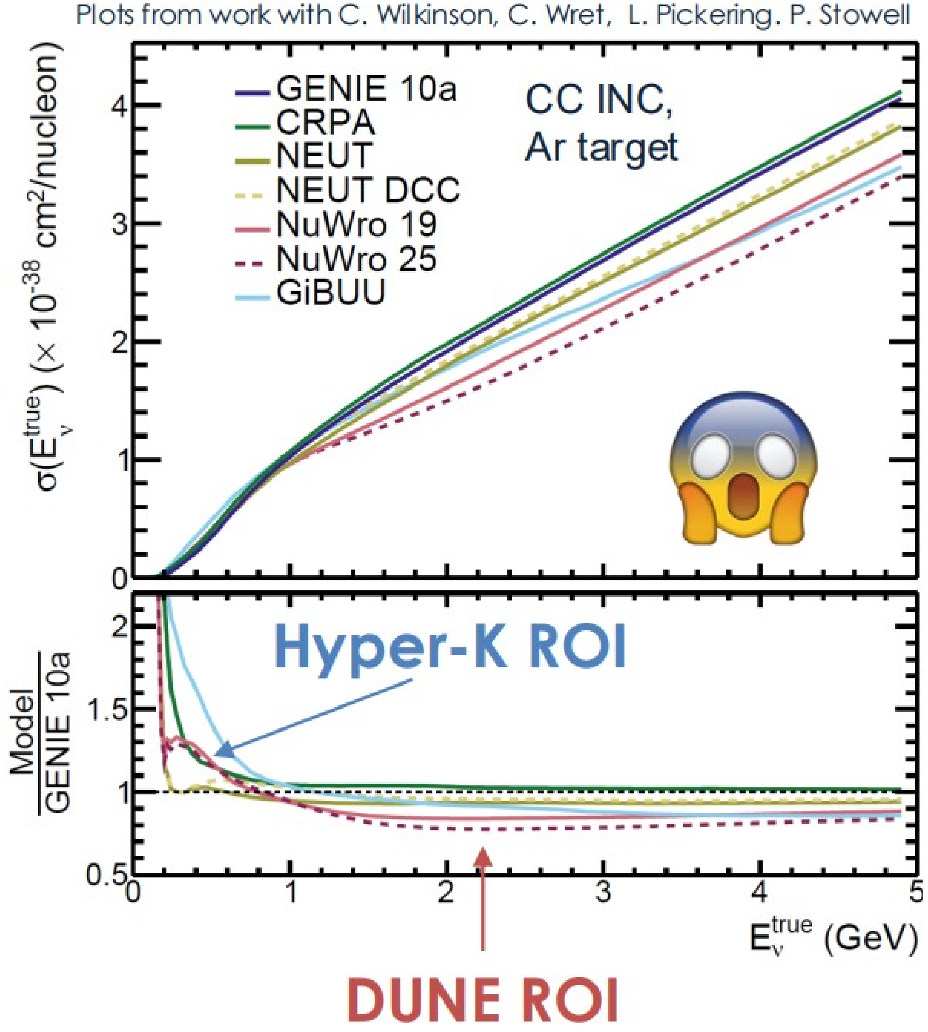
Study by F. Bramati



integration width no more driven by resolution but by statistics !

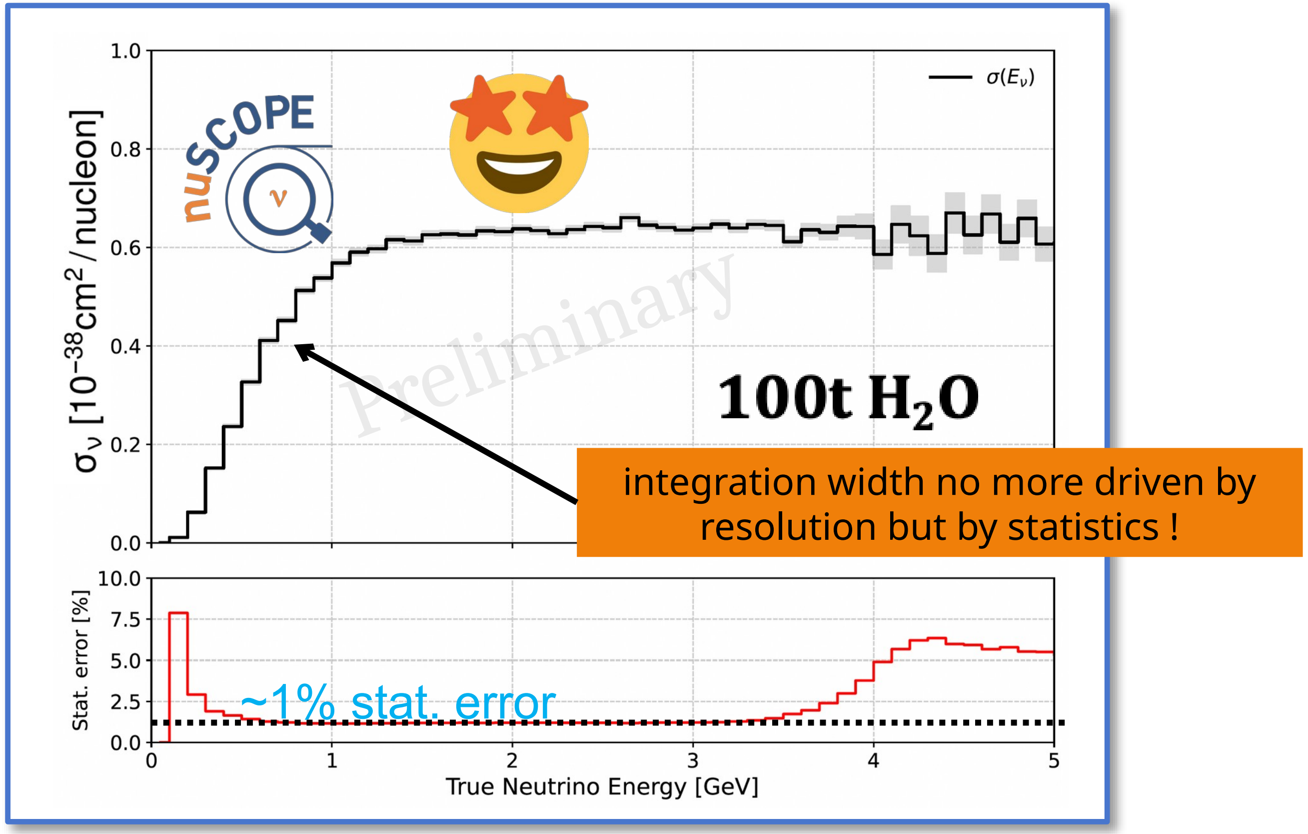
500t of Argon
CC inclusive

Credit S. Dolan

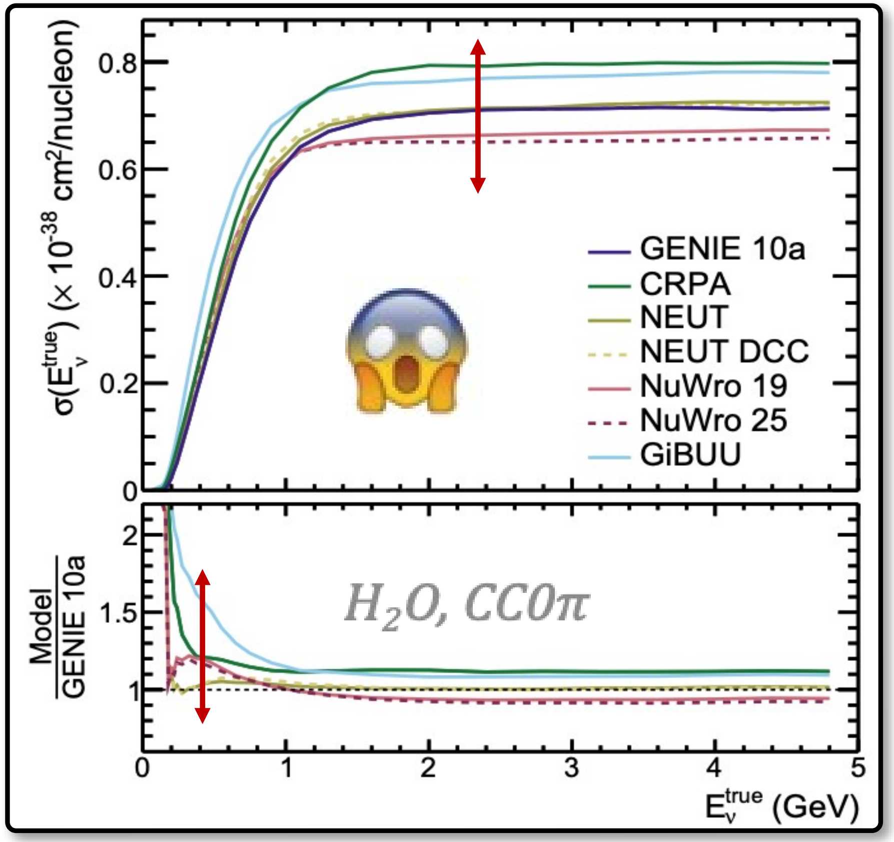


Cross section as function of energy

ν_μ cross section energy dependence:
crucial to extrapolate flux between near and far detectors

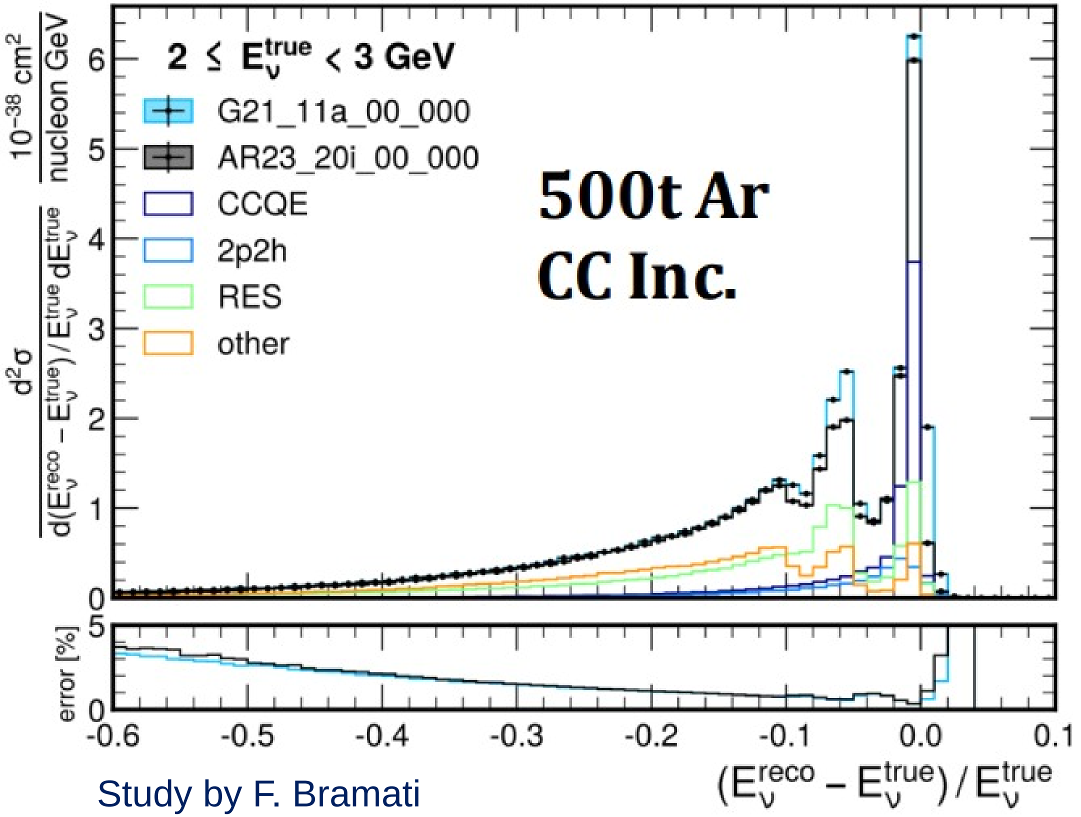


CC0π inclusive



Energy Smearing

Slide from L. Munteanu



Study by F. Bramati

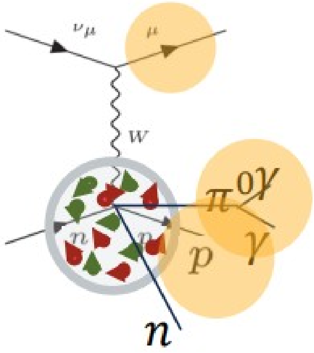
Can measure the **difference between true and reconstructed neutrino energy**

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

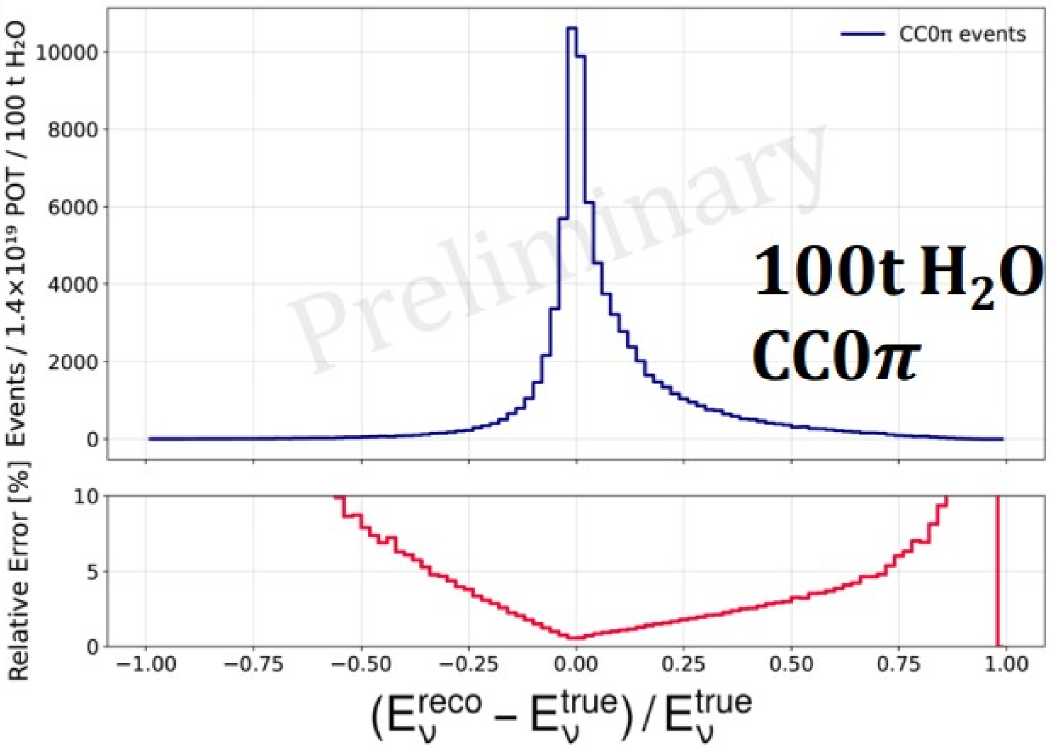
"visible" energy using calorimetric method (like DUNE, NOvA, MINERvA)

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

Calibrate out nuclear effects



Energy Smearing



Study by M. Pripon

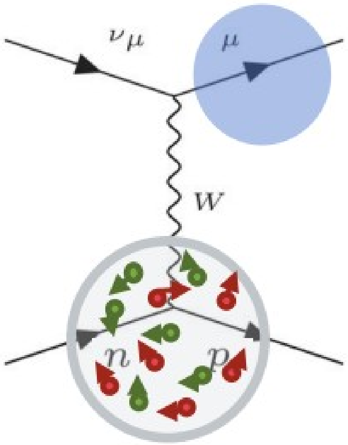
Can measure the **difference between true and reconstructed neutrino energy**

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

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

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

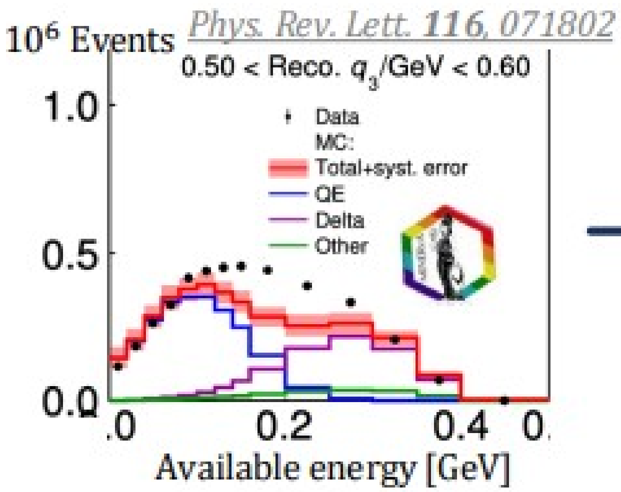
Measures the neutrino energy bias due to Fermi motion, npnh, FSI…

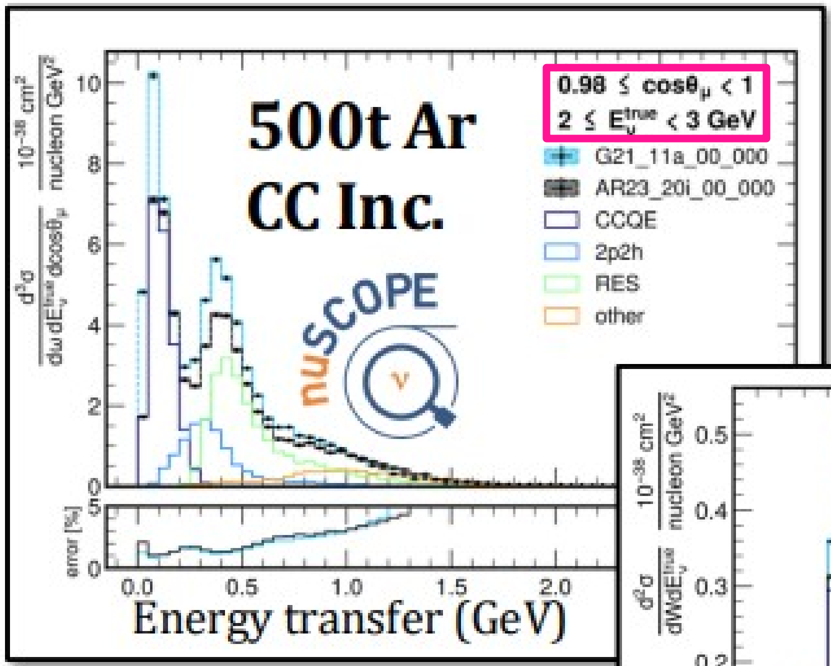


Calibrate out nuclear effects

Electron like scattering experiments with ν

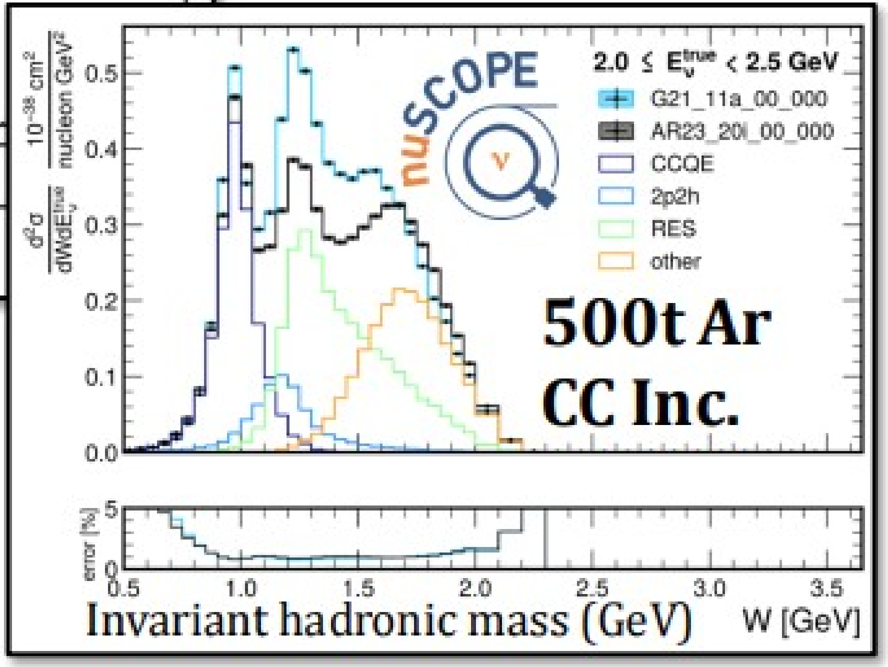
- Large statistics allows for multi-differential measurements
- Tagging allows to measure Q^2 and W from the leptons only





Large model disagreement

Study by F. Bramati



Gives access to fundamental nuclear physics processes

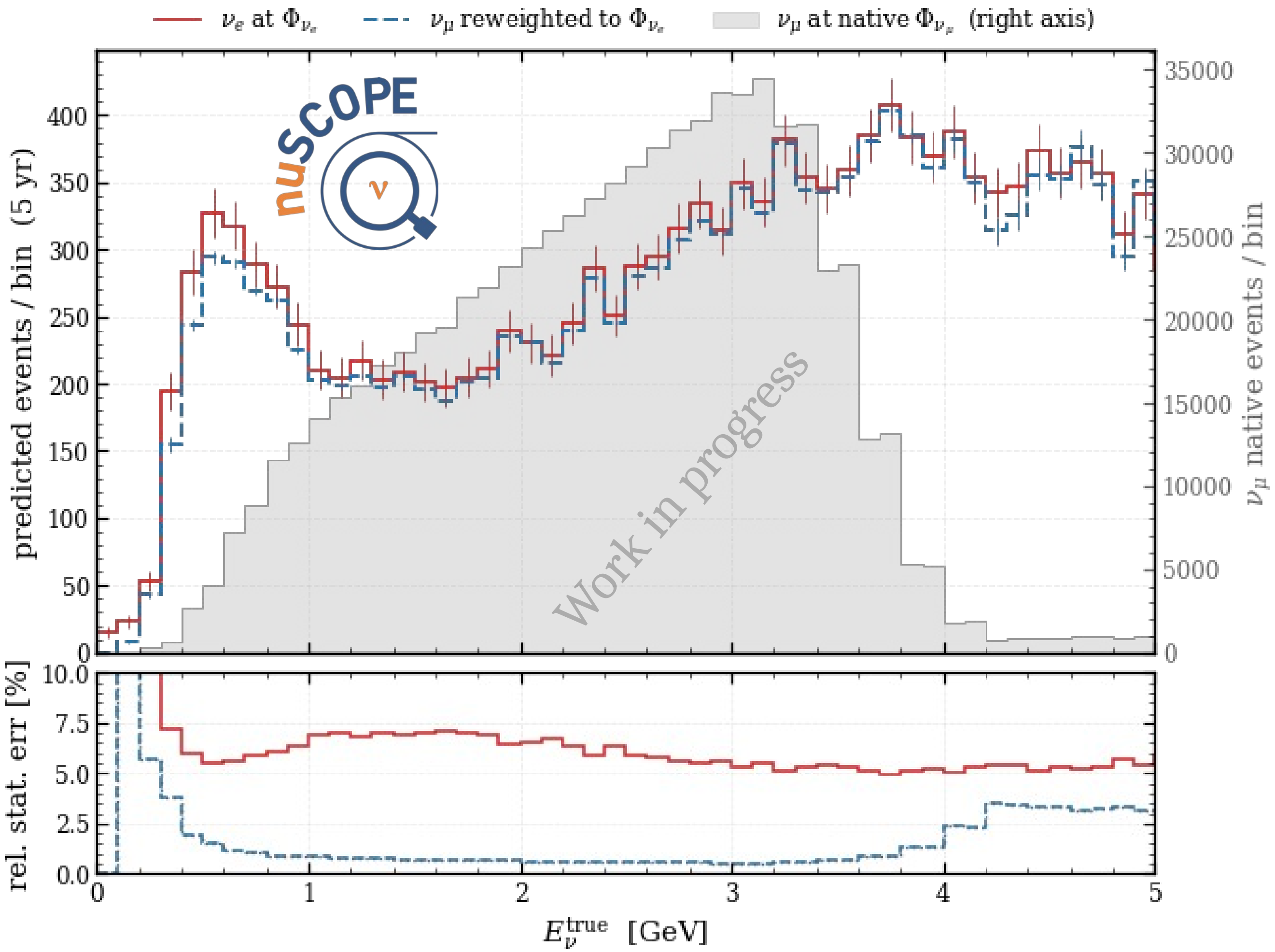
Constraining the ν_μ/ν_e cross section ratio

Measuring the ν_e/ν_μ cross section ratio in a traditional neutrino beam is challenging: ν_μ and ν_e fluxes are different and measurements are flux averaged

With nuSCOP, the **tagged ν_μ flux** can be reweighted to match exactly the **monitored ν_e flux (1% flux uncertainty)** to take a consistent flux-averaged cross-sction ratio

Theory uncertainty: 3%

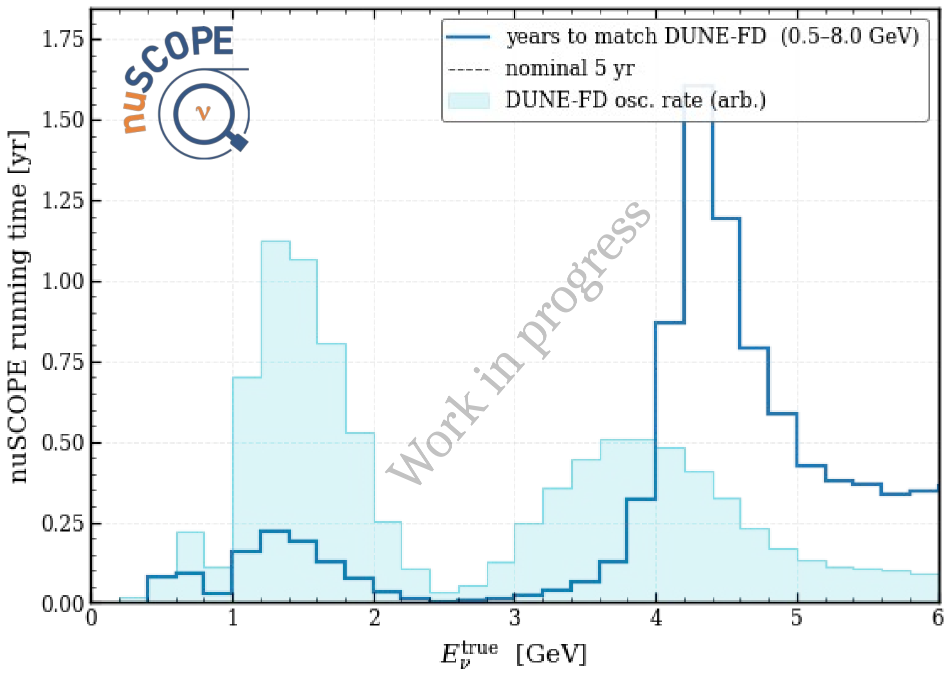
Phys.Rev.D 108 (2023) L031301



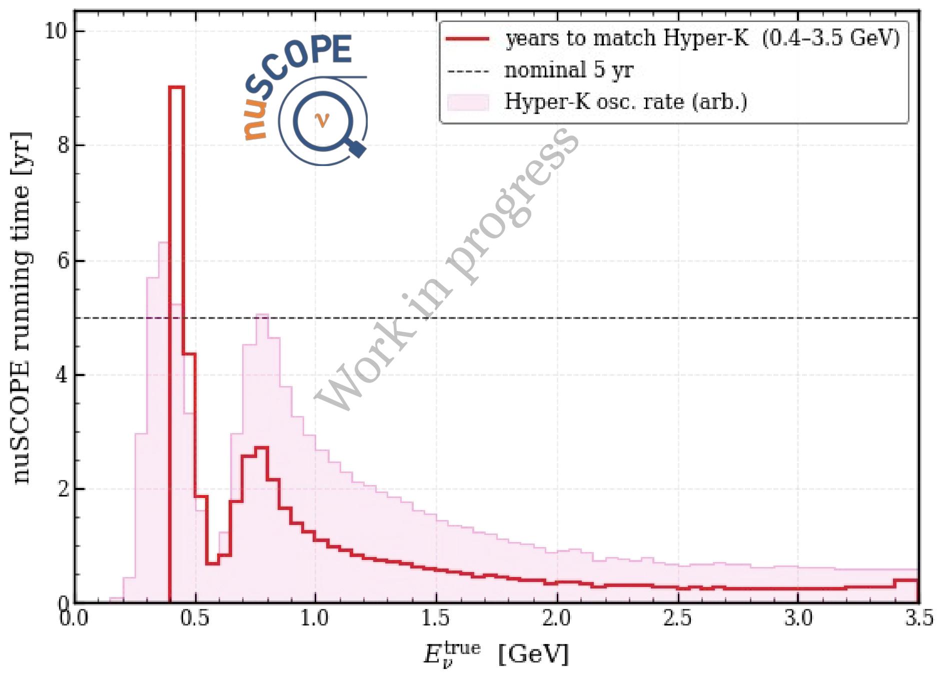
$$\frac{\sigma_{\nu_\mu}}{\sigma_{\nu_e}} = 0.971 \pm 0.0078 \quad (\mathbf{0.801}\ \%)$$

How long would it take

- Number of years for nuSCOPE to reach the statistical uncertainty level expected at DUNE and HyperK after ~10 years of operation*



Can provide informative constraints in the region of the oscillation maxima of DUNE **almost immediately** once operation starts



Can provide informative constraints in the region of the oscillation maximum of Hyper-K **within ~1 year** once operation starts

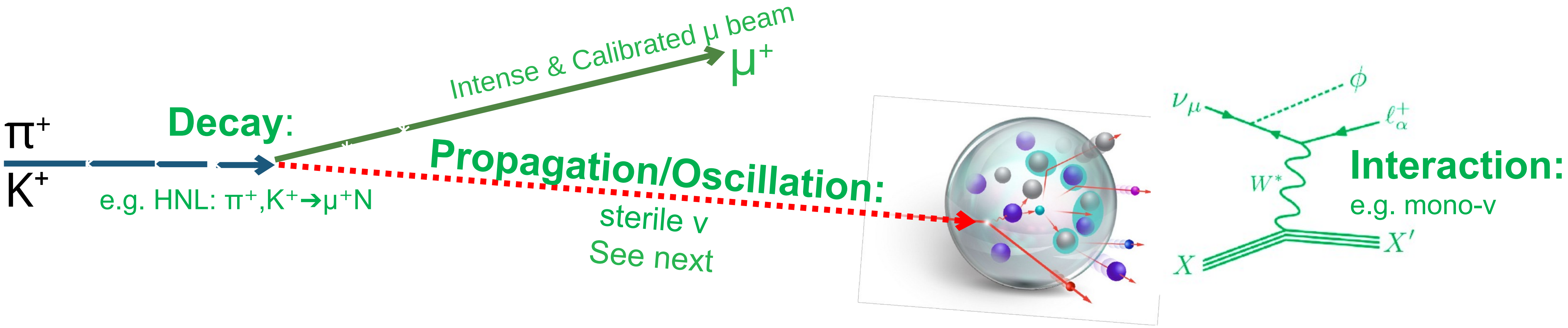
* time at which the statistical uncertainty should be comparable to the systematic one

Even richer physics program

Neutrino Interactions

large ν interaction samples.
flux knowledge, energy resolution

Beyond Standard Model



Kaon Physics

ultra rare decay exploiting large stats

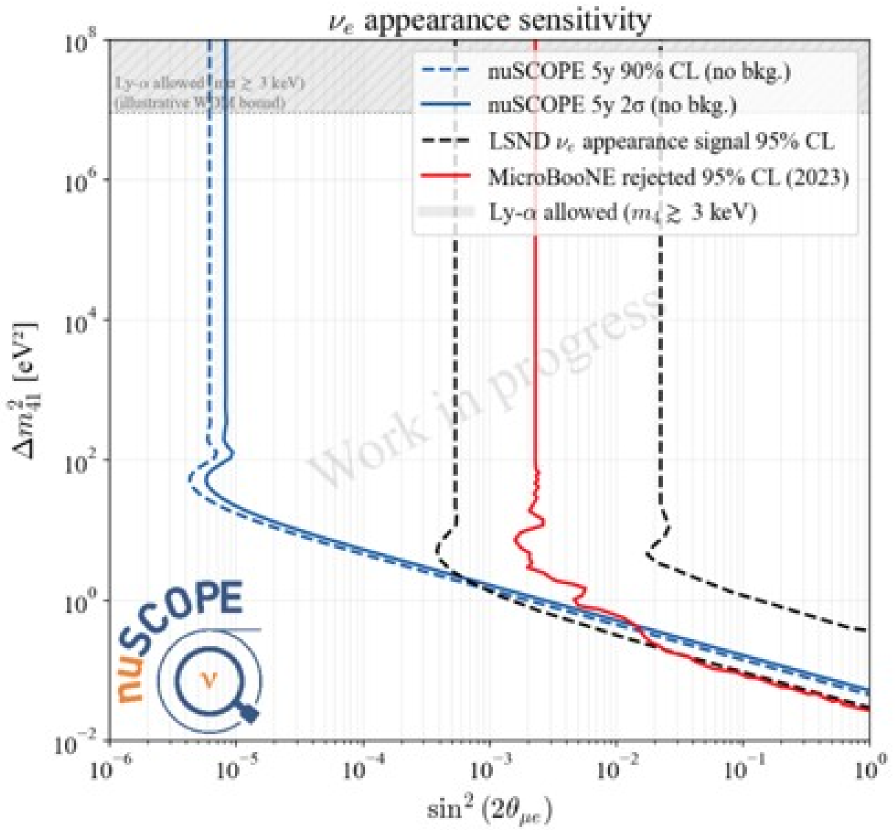
Nuclear Physics/QCD

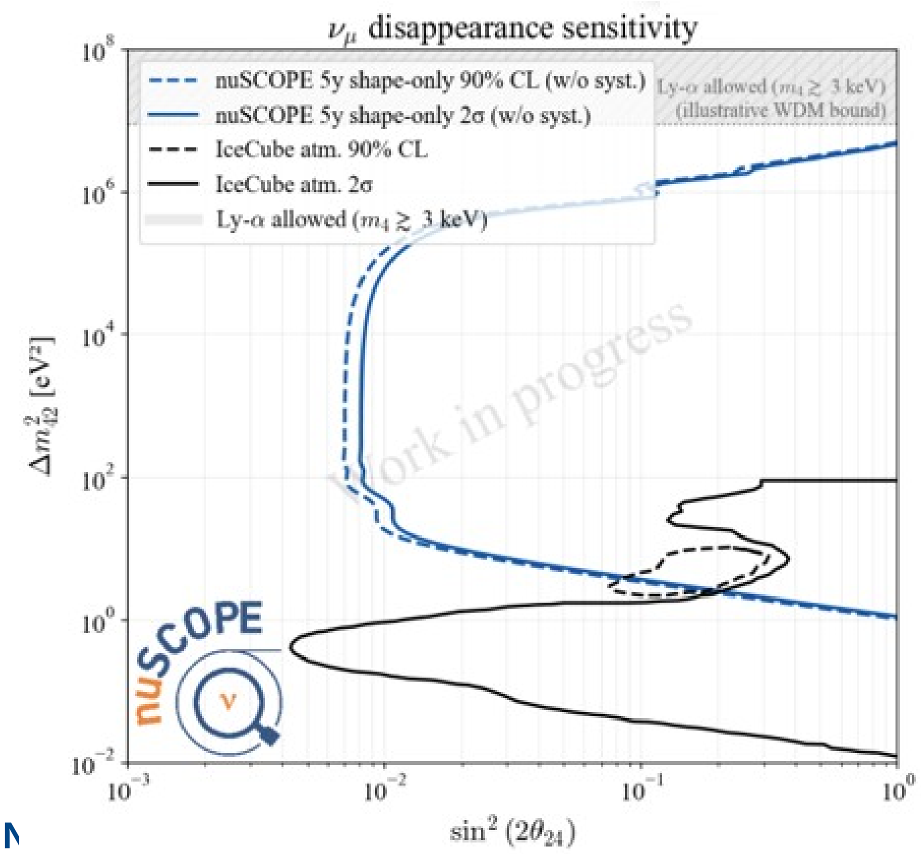
repeat electron scattering exp. but with ν as probe
access axial structure…

Short baseline oscillations

- nuSCOPE opens new possibilities as:
  - **neutrino energy** is precisely known (1<%)
  - **baseline** is precisely known (mm)
  - **initial flavour** of ν_μ is known (apperance)

A Novel Approach to Short Baseline Oscillation Searches Using Neutrino Tagging with nuSCOPE
https://arxiv.org/pdf/2606.14263





Pausing a minute

This is very nice, but can we do it?

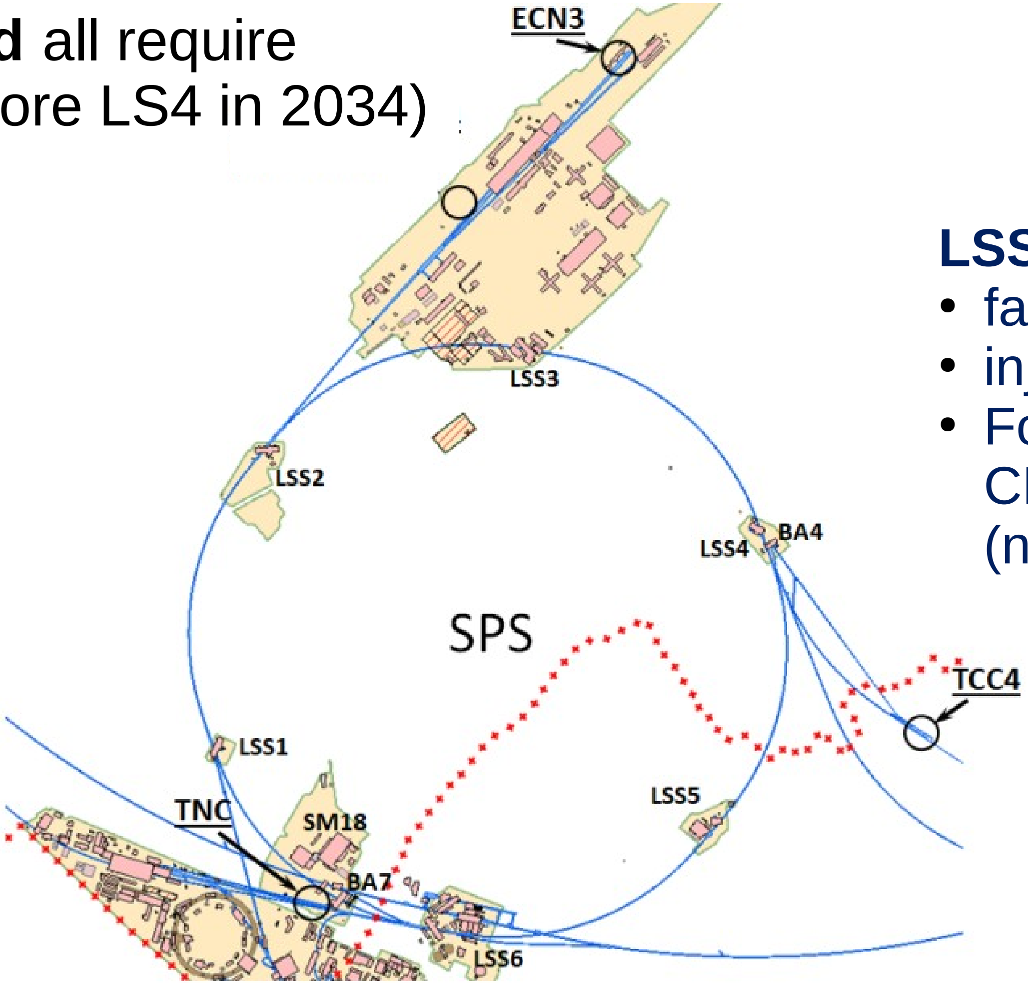
- Where?
- How?
  (i.e. technology)

Possible Implementations

- Studies performed under the umbrella of CERN Physics Beyond Colliders
- **Three options are considered** all require works on SPS (not do-able before LS4 in 2034)

LSS2 North Area
- reference facility for fixed target exp.
- slow extraction
- numerous experiments (inc. neutrino platform)

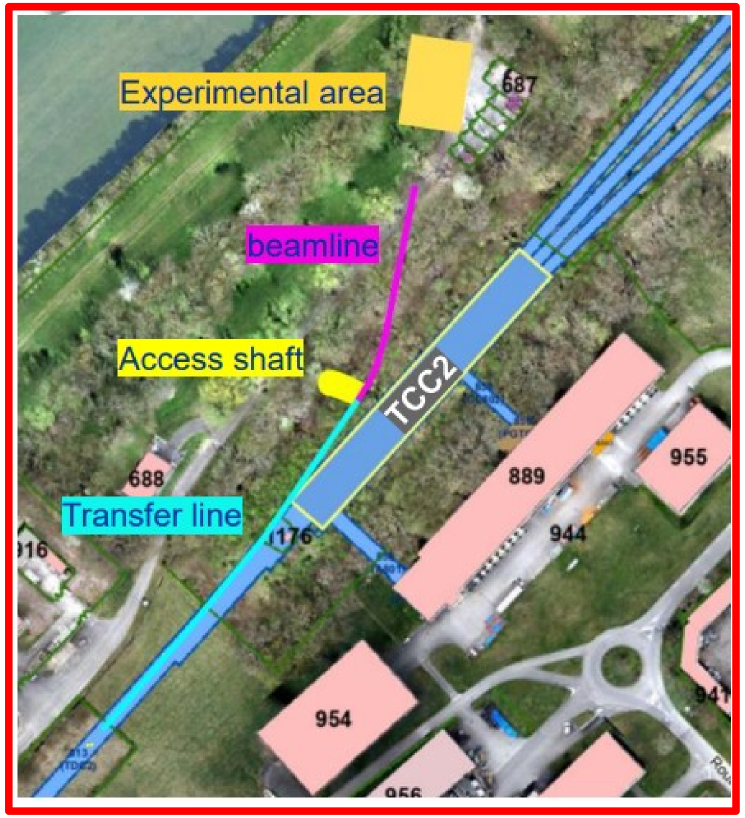
LSS6 (TNC)
- fast extraction (µs)
- injection to LHC Beam1
- Formerly housing ν exp. now only HiRadMat



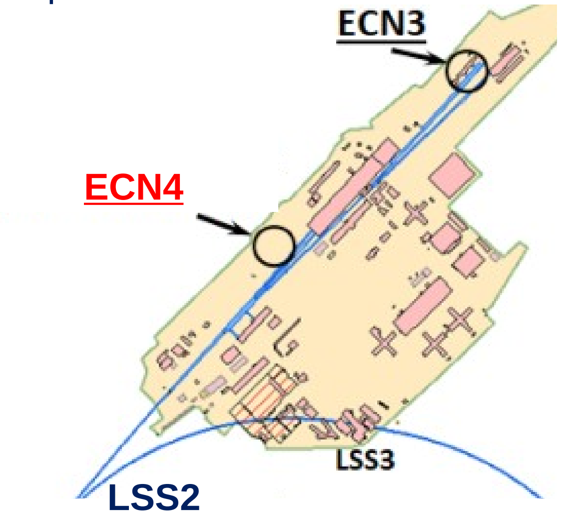
LSS4
- fast extraction (µs)
- injection to LHC Beam2
- Formerly housing CNGS now AWAKE (no space available)

LSS2 – The obvious choice?

- **New underground cavern** needed as
  - radioprotection prevents using surface building (including EHN1 housing the protoDUNEs)
  - existing underground (ECN3) cavern already used (ShiP)
- Similar option **already studied for SHiP** (ECN4*) but nuSCOPE requirements are significantly lower
- **Pros/Cons**
  - 👍 new facility with full flexibility
  - 👍 slow extraction avaiable
  - 👎 technical challenge (beam splitter)
  - 👎 minimal shielding from cosmics
  - 👎 proton sharing (shared SPS cycle)



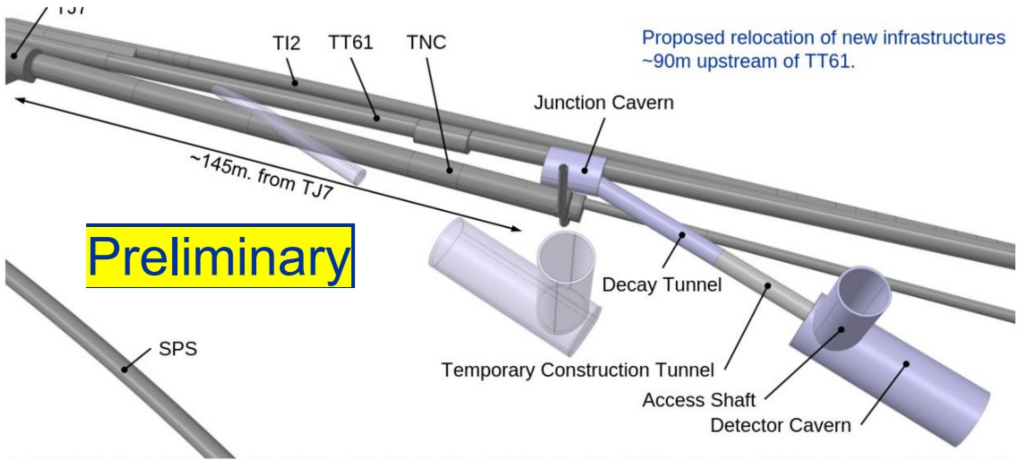
* https://cds.cern.ch/record/2802785

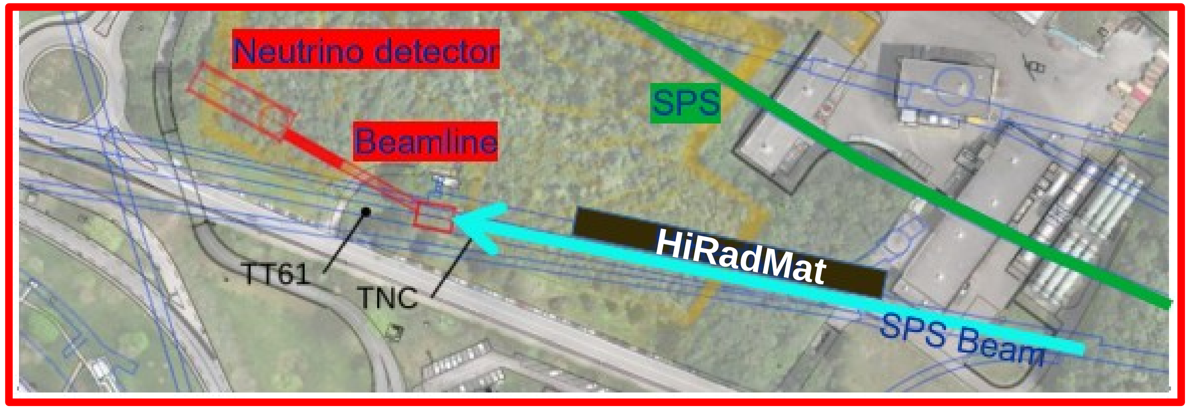


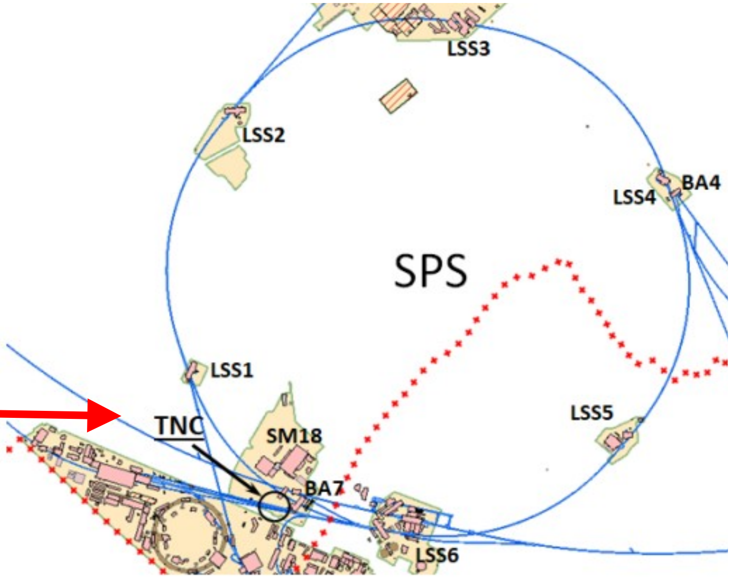
LSS6 – The most promising option!

*https://cds.cern.ch/record/2918573

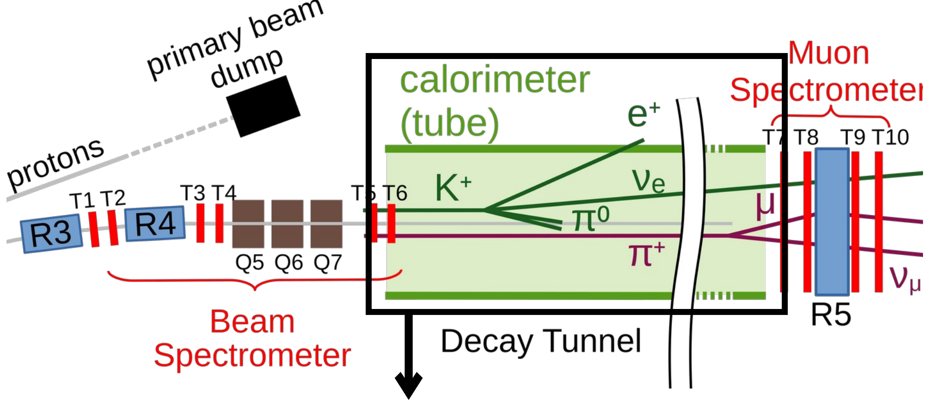
- **No slow extraction** in LSS6 (electrostatic septa are missing)
- Could be restored with a **non-local extraction*** without modifing the LHC extractions
- nuSCOPE could be **implemented in TNC**
  - 👍 shielding from cosmics (underground location)
  - 👍 advantageous for proton sharing (SPS cycles)
  - 👎 need excavation
  - 👎 need to restore slow extraction



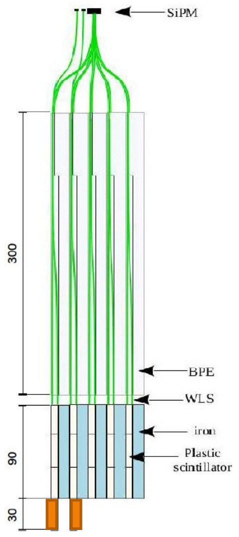




Monitoring Instrumentation



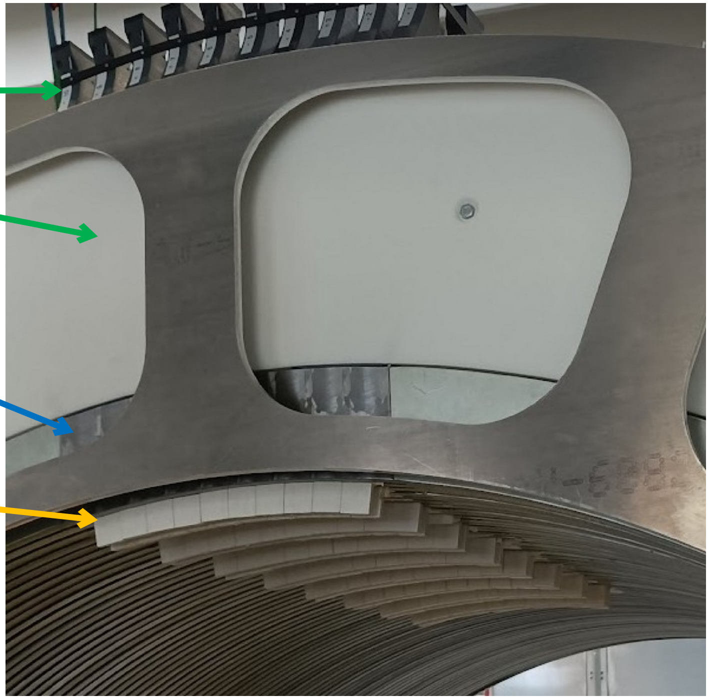
Segmented calorimeter build from **elementary cells**



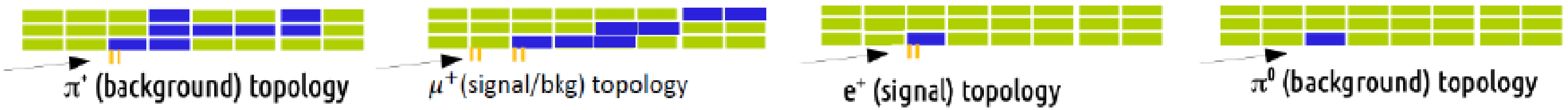
SiPM readout
behind 30cm of boroted polyethylene

Three radial layers of sampling calorimeter
(iron/scintillator/Wave length shiting fibers) x 5

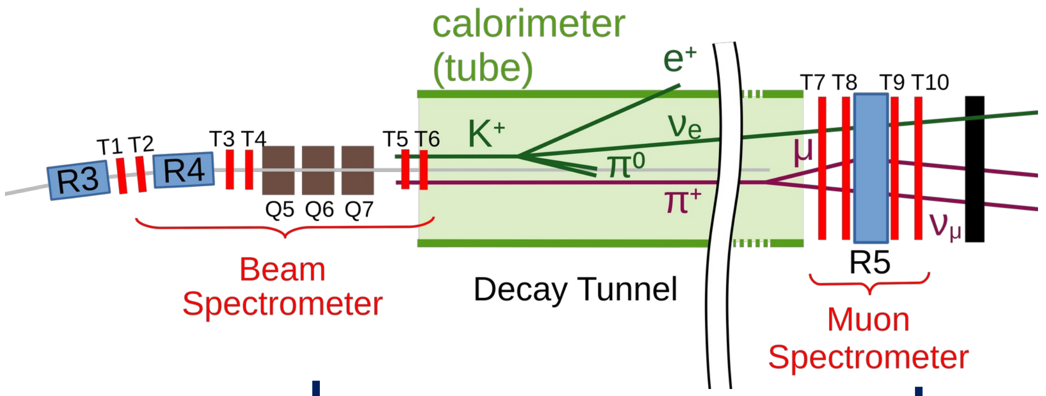
Two layers of scintillator to reject π^0
(plastics scintillator, 400ps time reso)



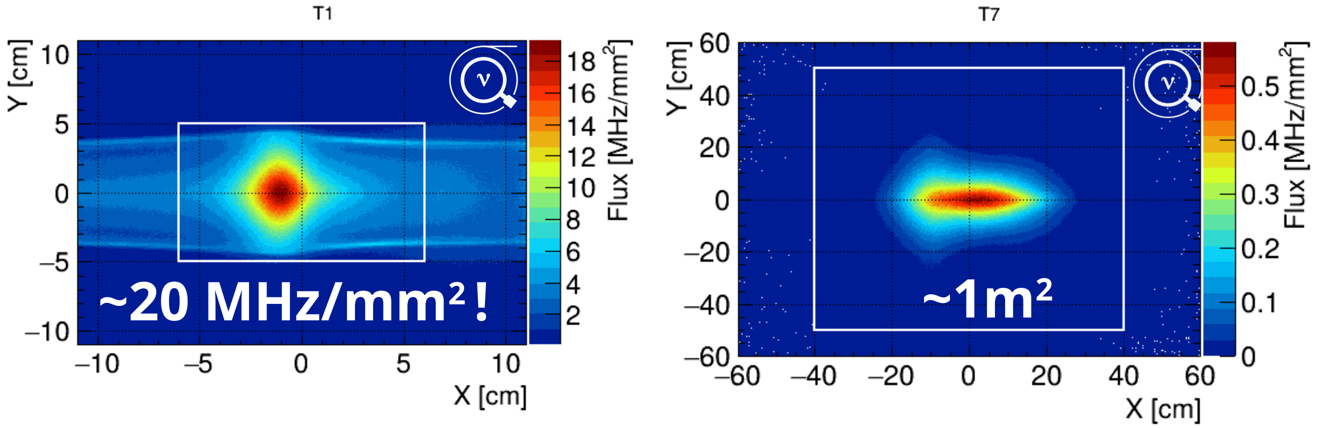
Particle identification based on the energy deposit pattern



Tagging Instrumentation



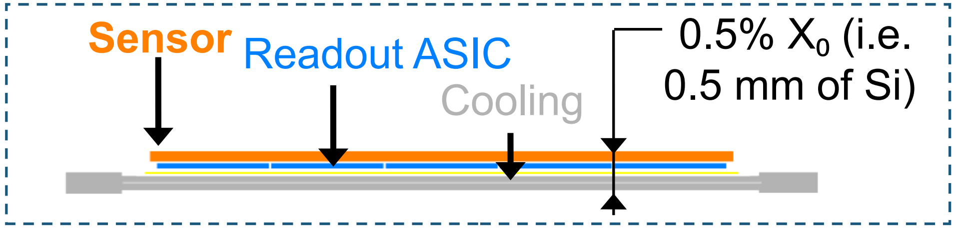
Specifications [units]	Beam Spectro.	Muon Spectro.	LHCb-VELO (2028)	NA62-GTK (since 2014)
Peak Dose [Mrad]	700	60	$> 10^3$	16
Peak Fluence [$1\text{MeV}n_{eq}/\text{cm}^2$]	1×10^{16}	6×10^{14}	5×10^{16}	4.5×10^{14}
Peak Rate [MHz/mm^2]	20	0.6	$10 - 100$	2
Time Resolution [ps]	< 40	< 100	< 50	< 130
Pixel Pitch [μm]	300		45	300
Material Budget [X_0]	$< 1\%$		0.8%	0.5%



- **Beam Spectrometer**
  - **Time reso & rate beyond state of the art by factor 10**
  - **Aligned with LHCb** upgrade and other R&D projects (see next)
- **Muon Spectrometer**
  - Time reso and material budget challenging on such **large scale**

LHCb U2 Upgrade: Technology

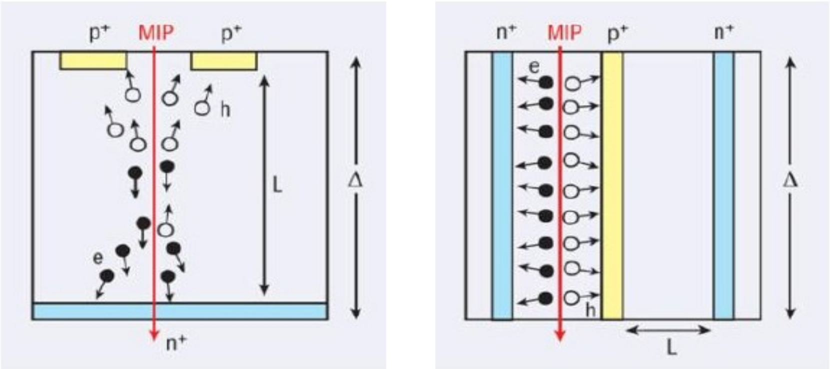
Hybrid pixel technology



New sensor technology based on two innovations

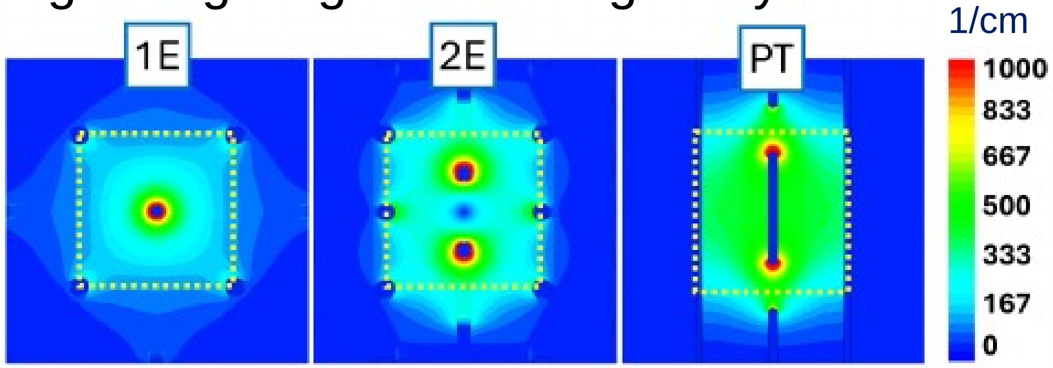
1/ Planar → 3D: drift distance (L) decoupled from sensor thickness (Δ)

Planar

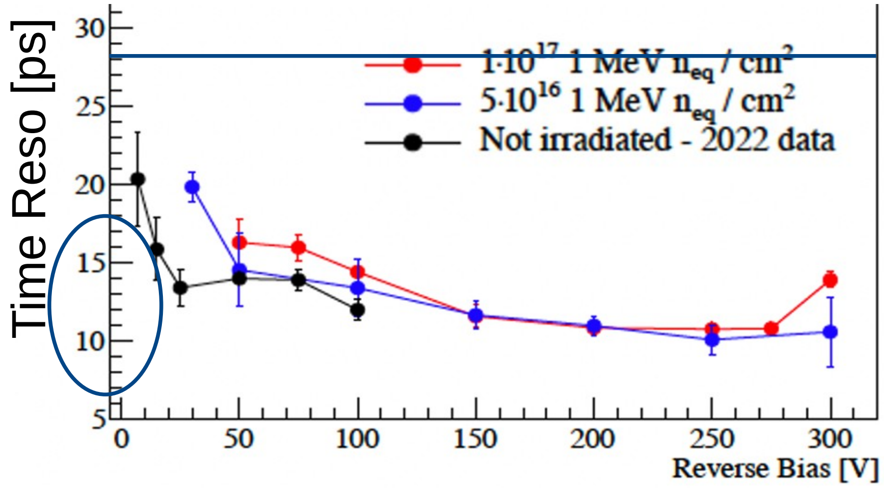


3D

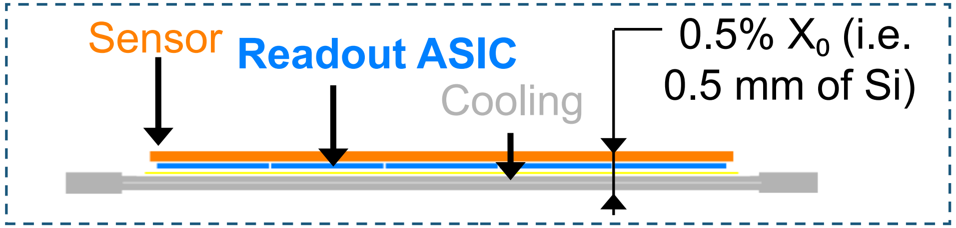
2/ Electrode geometry optimised for high weighting field homogeneity



Time Resolution < 20 ps after massive irradiation $10^{17} n_{eq}/cm^2$!



LHCb U2 Upgrade: Technology

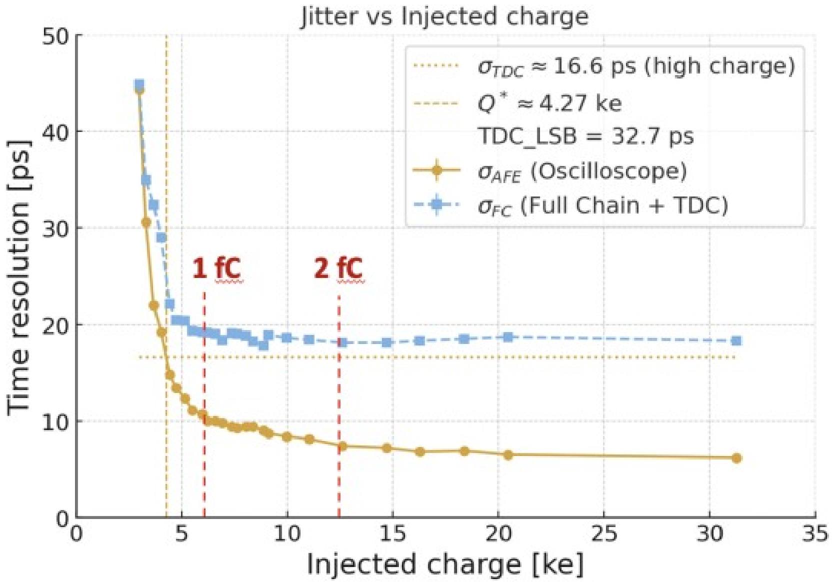


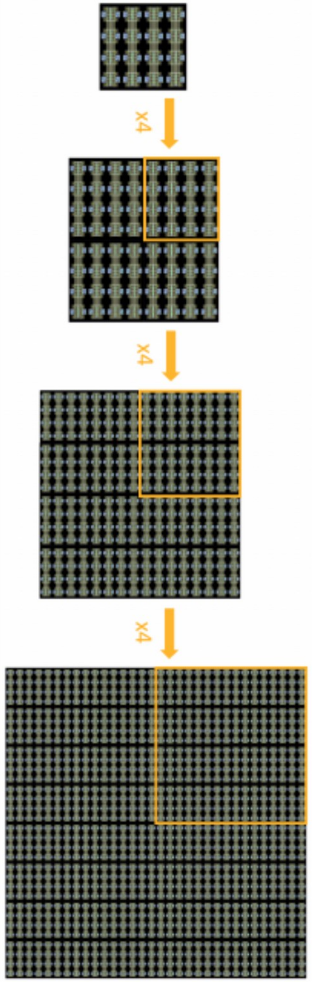
New ASIC: Two R&Ds based on CMOS 28nm

IGNITE/TIMESPOT (INFN)

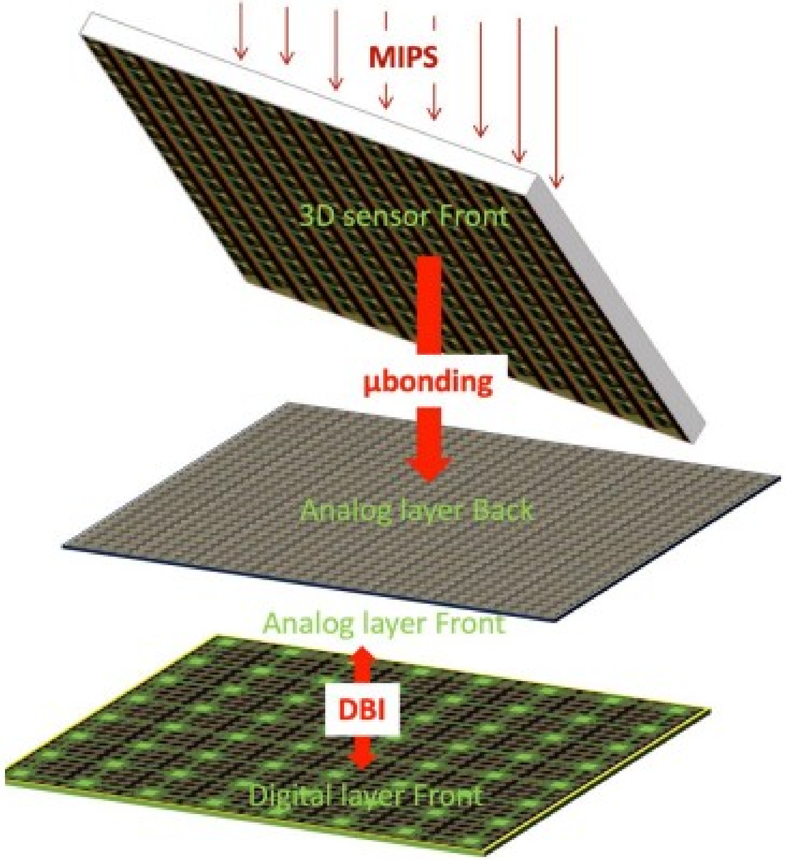
- **Fractal Design:** repeat structures small enough to be fully simulated, produced, and tested
- Scale to large size using **vertical integration**
- **First tests of Ignite32/64** very promising: <20 ps before hybridisation

.



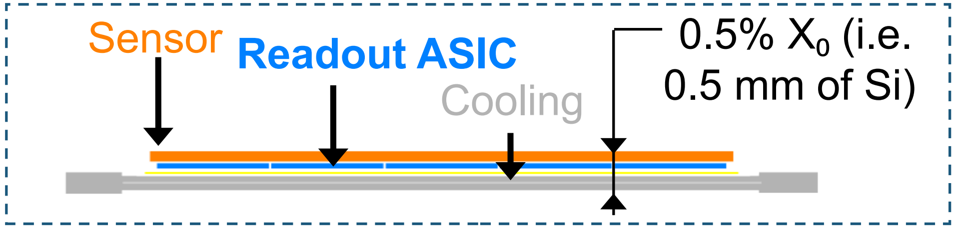


Fractal Design



Vertical integration

LHCb U2 Upgrade: Technology

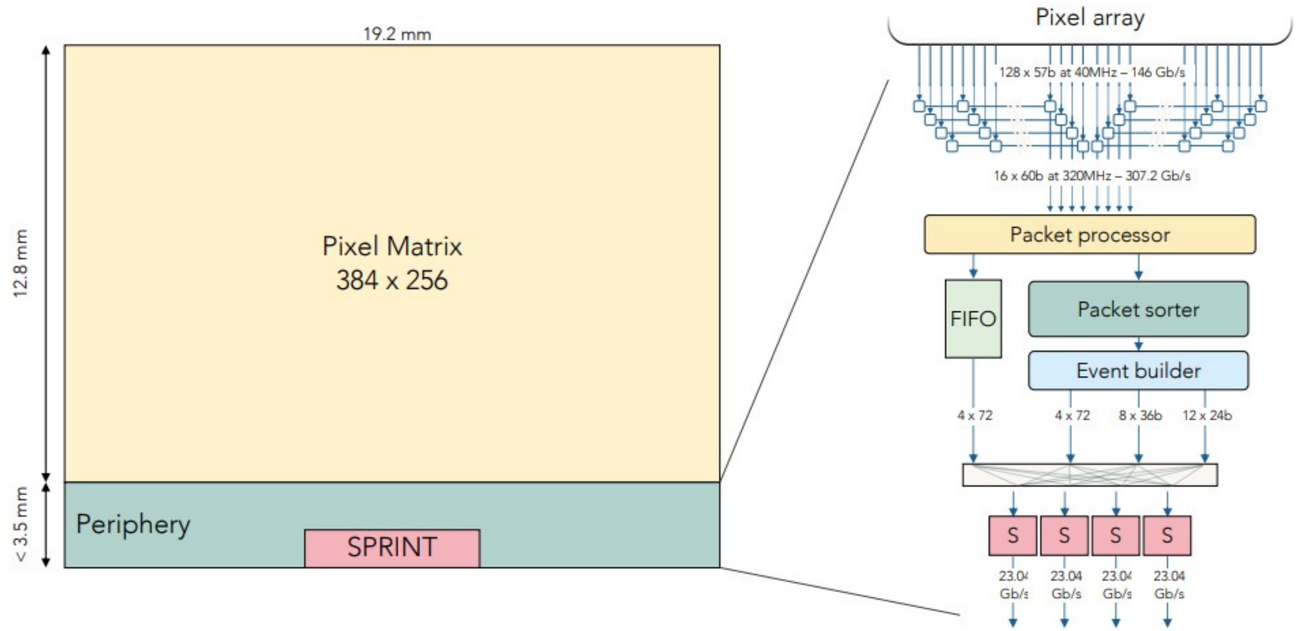


New ASIC: Two R&Ds based on CMOS 28nm

PICOPIX (CERN/NIKHEF)

- Continuation of the **TimePix series**

- More **“classical” design** (end of column, no vertical integration)
- Integration of numerous **data processing functionalities** (calibration, clustering…)
- **R&D Strategy**: **full scale ASIC** submission (no demonstrator)

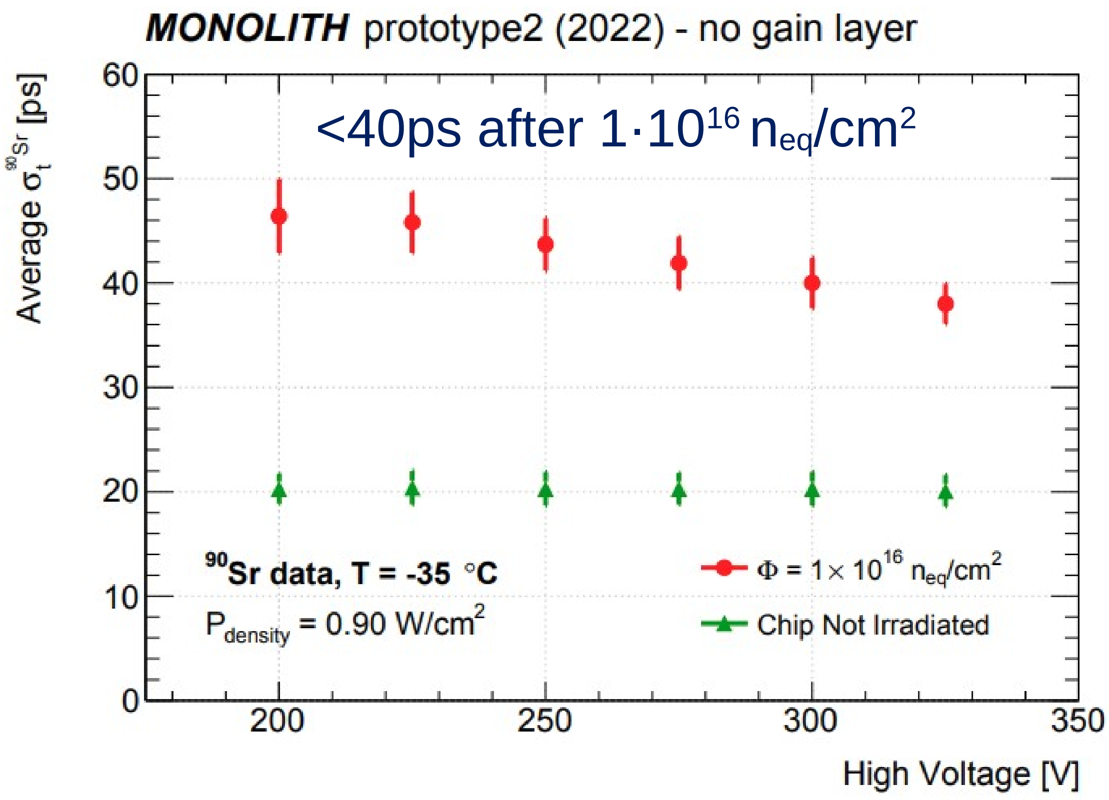


Common submission IGNITE/PICOPIX in 2026

Alternative technology BiCMOS Monolithic pixels

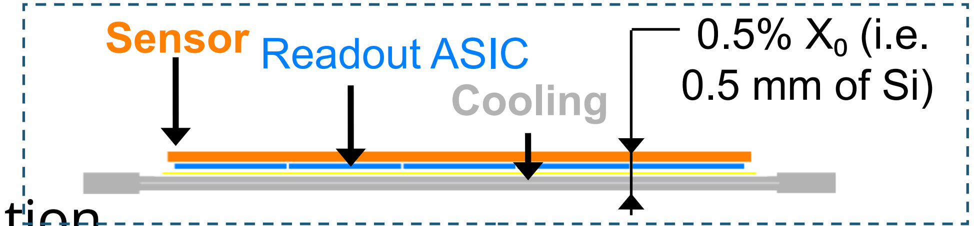
Technology developped at University of Geneva

- **BiCMOS** process: Si/Ge (SG13G2 IHP 130 nm)
- **Monolithic** technolgy
  (cheaper and thinner than hybrid)
- **Front end exploiting HBT***
  - Low noise
  - Large bandwidth
  - Low power
- **Excellent time resolution 20 ps**
- Promising results concering **radiation hardness**
  40 ps after 1×10^{16} n_{eq}/cm^2
- Already used in FASER (pre-shower application)

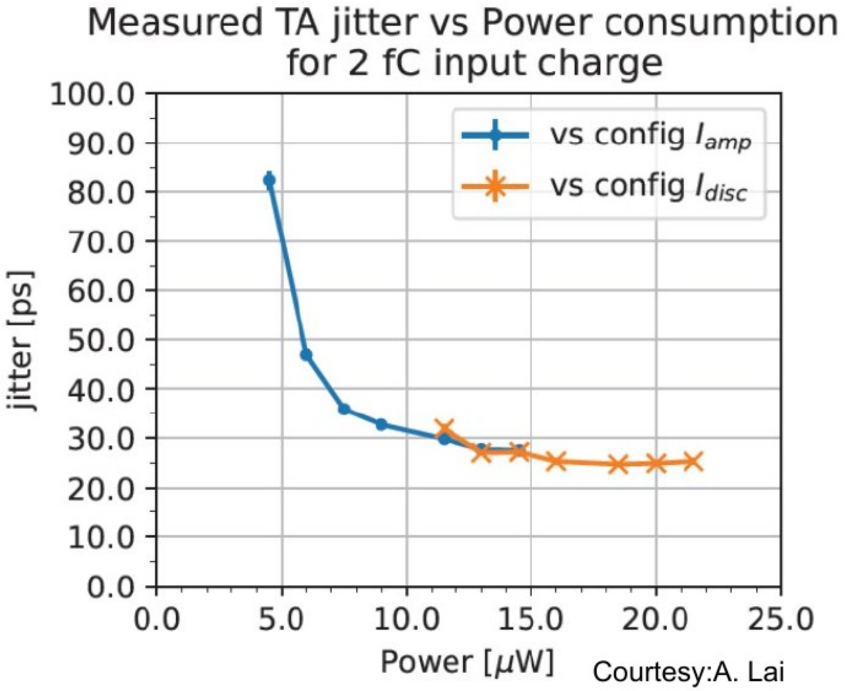


* Heterojunction Bipolar Transistor

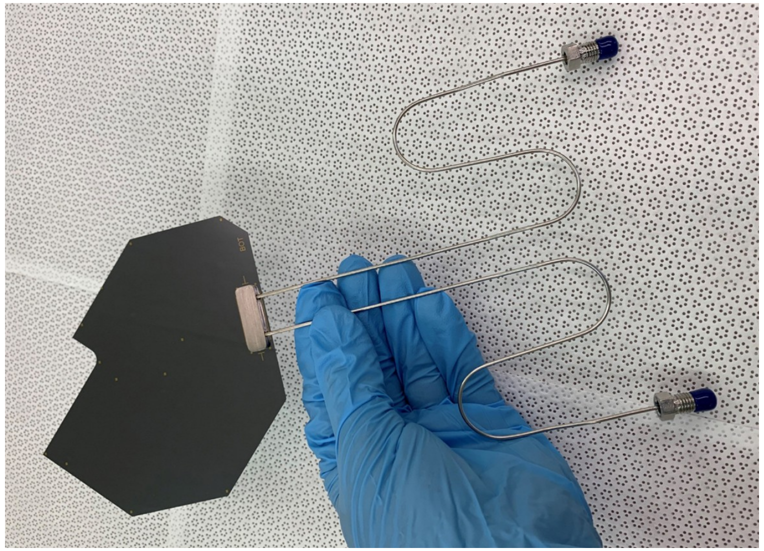
Cooling

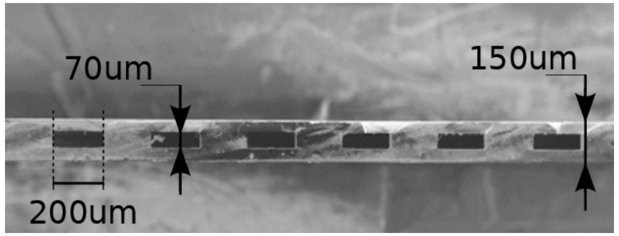


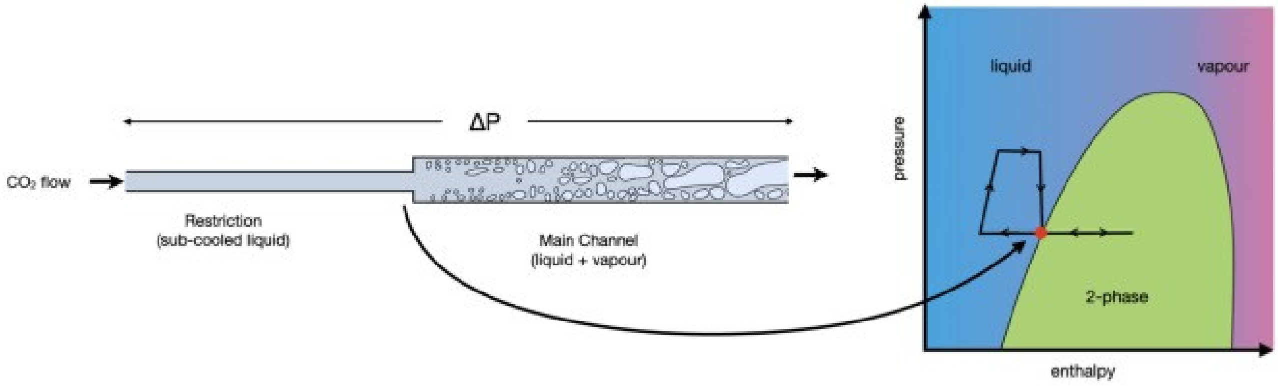
- **Cooling:** essential for radiation hardness and time resolution
- **Power density** (1-2W/cm^2) and **material budget** (<0.5%X_0) only achievable with **micro-channel cooling**
- Technology pioneered by LHCb and NA62
- On going R&T at IN2P3 (CPPM, LPNHE, LPC, LEGI)



Courtesy:A. Lai



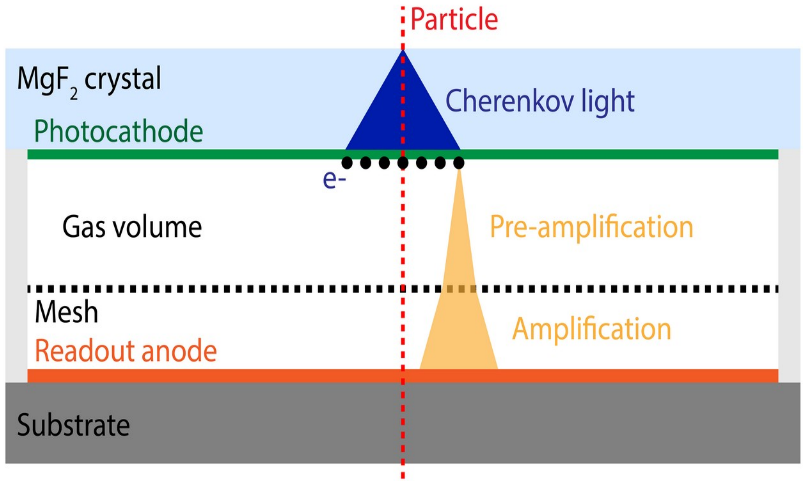


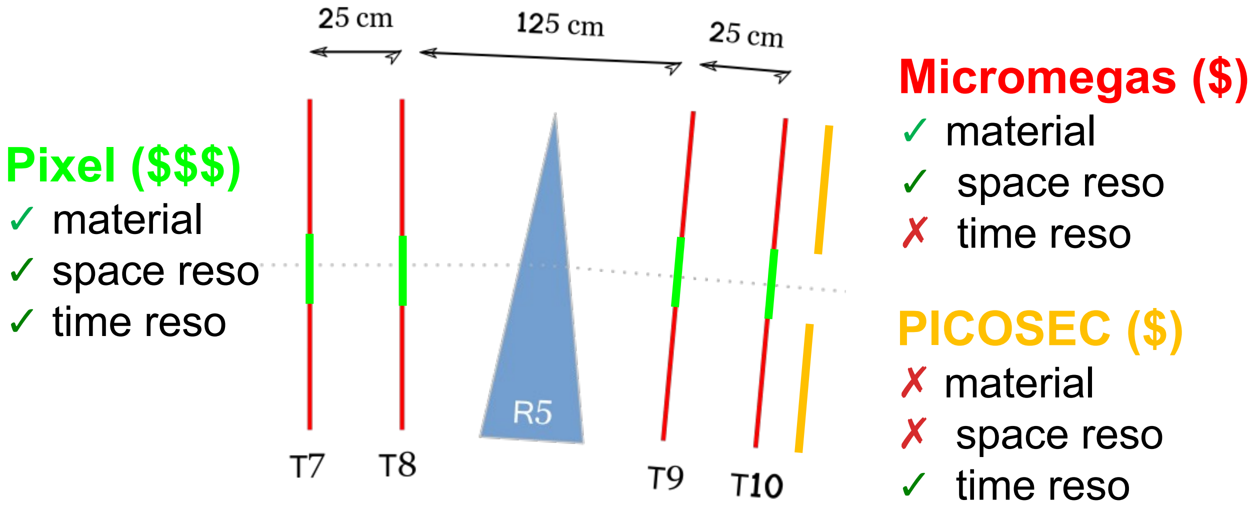


Tracking Technology – Muon Spectrometer

- **Specifications:**
  - **rate** and **time resolutions** are **accessible**
  - **size** (1m2) is challenging**Hybrid solution using**
- **Inner region: Pixels**
  Candidate Technology: HV-CMOS Cactus
- **Outer region**: **micromegas** + **timing layer**
  Candidate Technology:
  Micromegas and Picosec Micromega

Specifications [units]	Beam Spectro.	Muon Spectro.
Peak Dose [Mrad]	700	60
Peak Fluence [$1\text{MeV}n_{eq}/\text{cm}^2$]	1×10^{16}	6×10^{14}
Peak Rate [MHz/mm^2]	20	0.6
Time Resolution [ps]	< 40	< 100
Pixel Pitch [μm]	300	
Material Budget [X_0]	$< 1\%$	





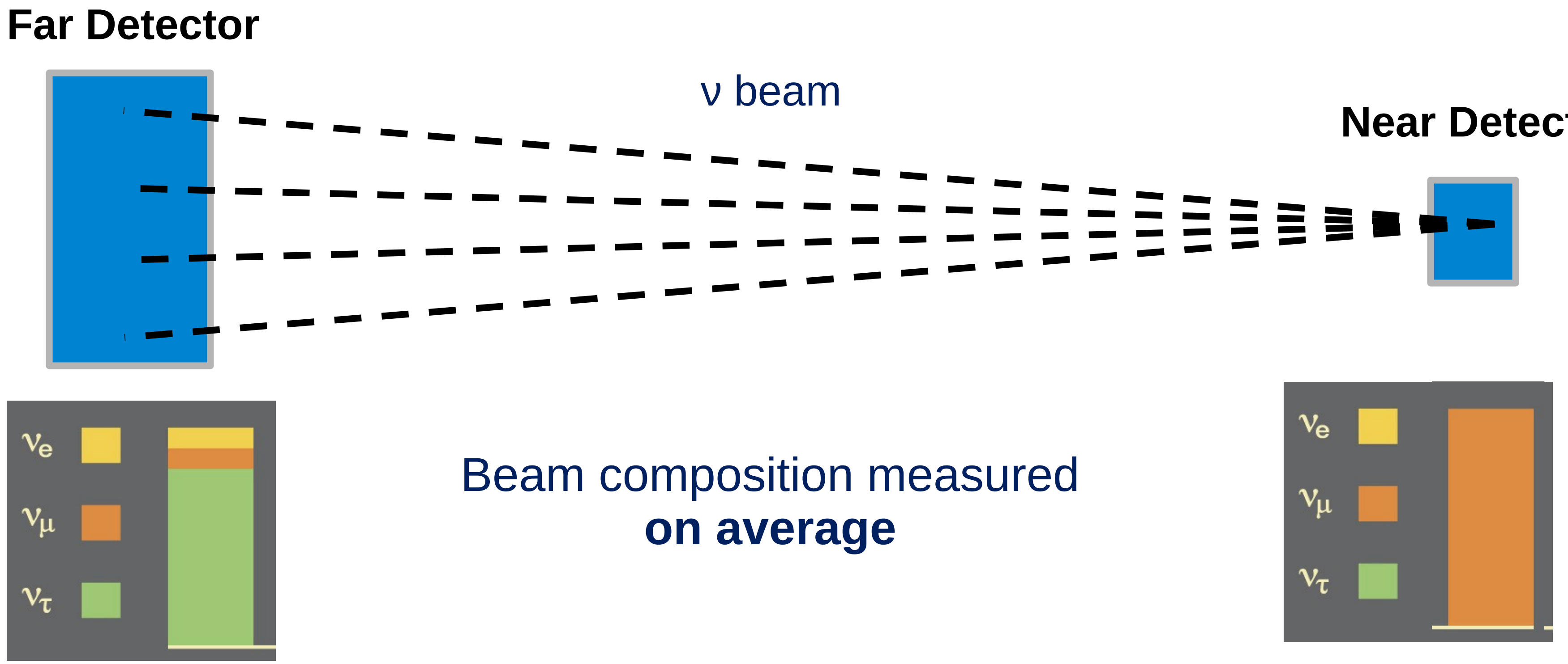
hybrid solution

Outline

- Introduction
  - scientific context
  - neutrino tagging concept
- Proof-of-principle with existing data (NA62)
- The nuSCOPE project
  - motivations
  - design
  - physics case
  - technology
- **Longer terms perspectives**
- Conclusions

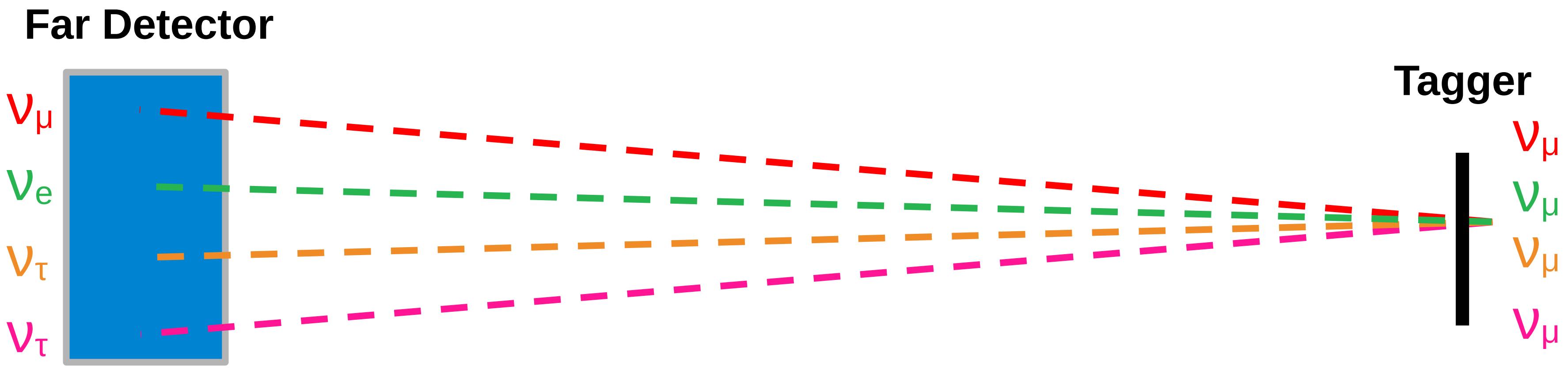
What about tagged LBL

- **Ideal setup to study oscillations**
  - know **individually neutrino energy** with sub-percent precision
  - know **individually which neutrinos changed (or not) flavour**
- **But require very large detectors to compensate for beam intensity limitation (tagger)**



What about tagged LBL

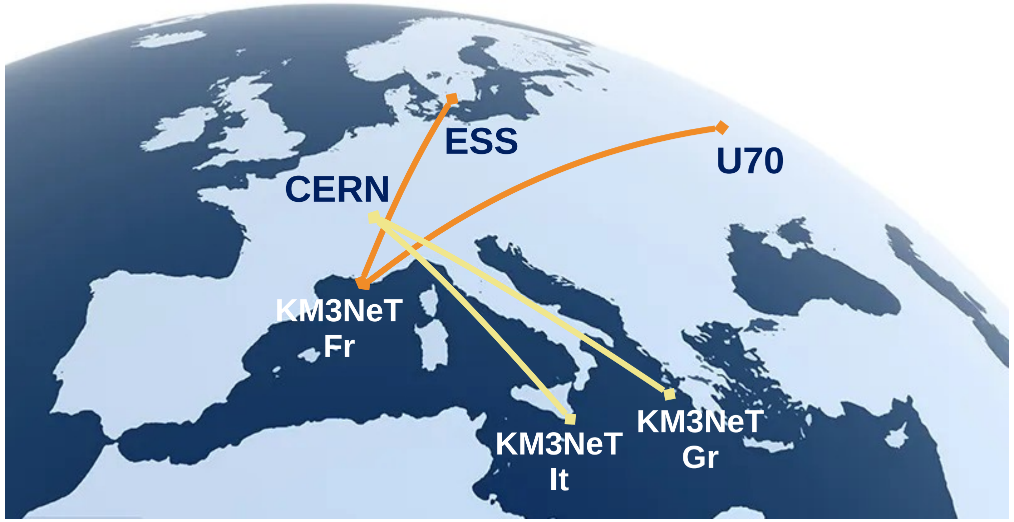
- **Ideal setup to study oscillations**
  - know **individually neutrino energy** with sub-percent precision
  - know **individually which neutrinos changed (or not) flavour**
- **But require very large detectors to compensate for beam intensity limitation (tagger)**



Muon neutrinos individually tracked
from creation to interaction
(after propagation and oscillation)

What about tagged LBL

- **Ideal setup to study oscillations**
  - know **individually neutrino energy** with sub percent precision
  - know **individually which neutrinos changed (or not) flavour**
- Require very **large detectors** to compensate for **beam intensity limitation** (tagger)
- Tagged LBL with **neutrino telescope** (ORCA-like)
  - very lair volume e.g. ORCA: 7Mton (vs DUNE 40kton)
  - energy threshold >1GeV
  - tagging precision compensating for detector coarseness (expect for PID)

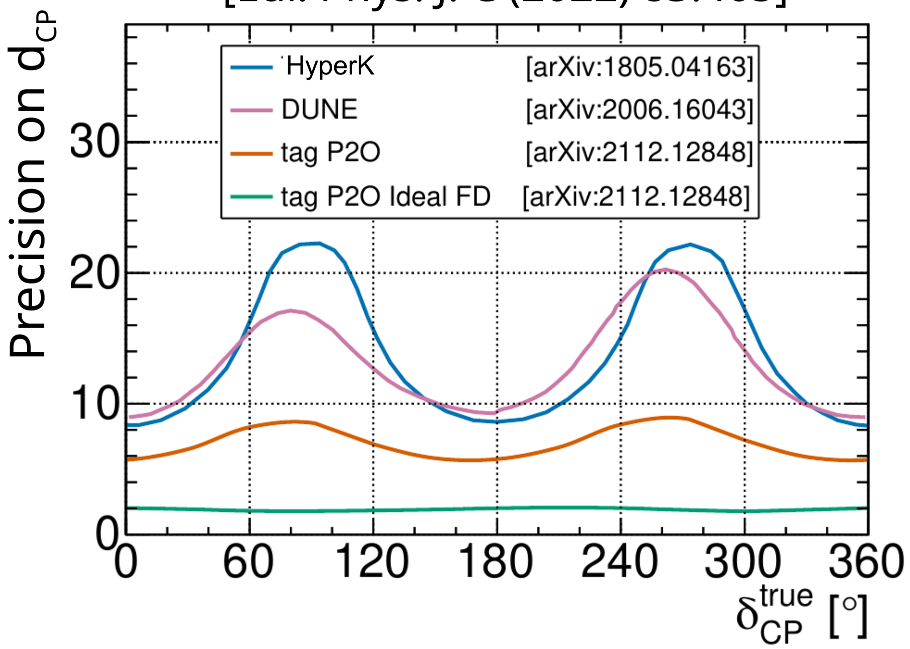


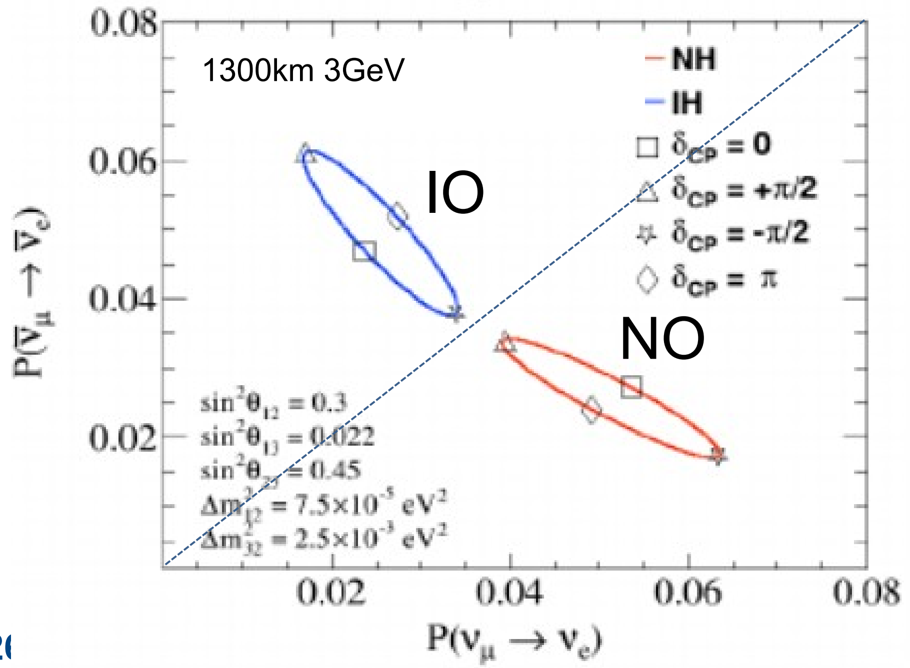
		Baseline km	Energy GeV	
U70	KM3NeT-Fr	2600	5.0	See P2O
ESS	KM3NeT-Fr	1500	2.9	
CERN	KM3NeT-It	1300	2.5	
CERN	KM3NeT-Gr	1700	3.3	See NESTOR, C2GT

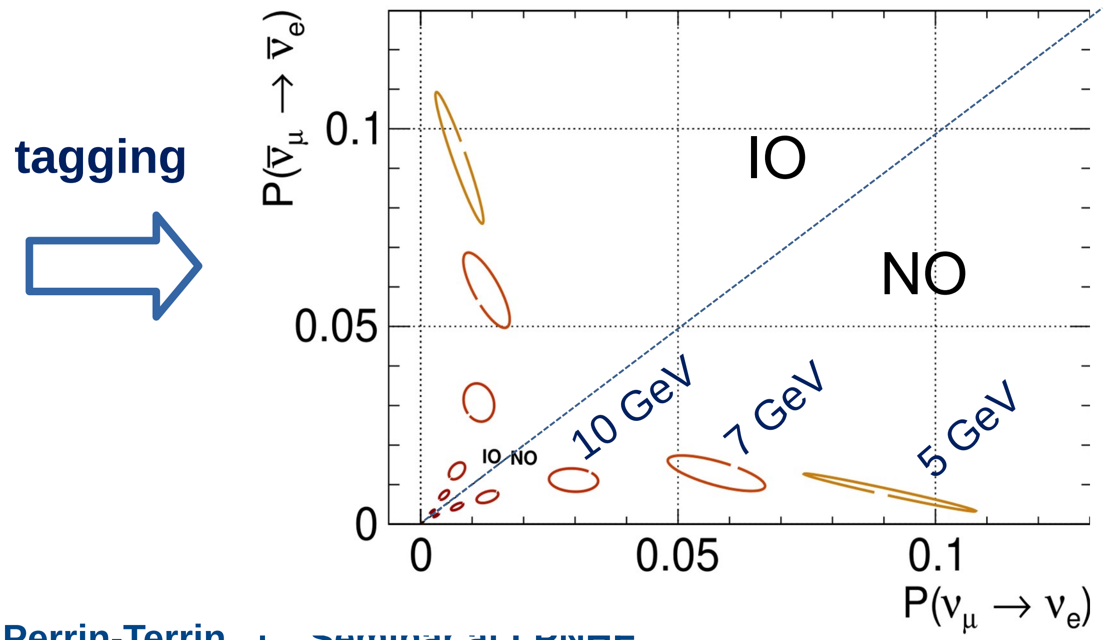
What about tagged LBL

- **Preliminary studies** are encouraging
  - beamline design [within PBC] (EPJC 2024 84:1024)
  - sensitivity studies (EPJC 2022 83:465)
- Tagging give access to **multiple ellipses** on bi-probability plot
  - some are more circular
  - apsides not always reached at 90 or 270°
  - only with a wide band beam (challenging without horn)

[Eur. Phys. J. C (2022) 83:465]



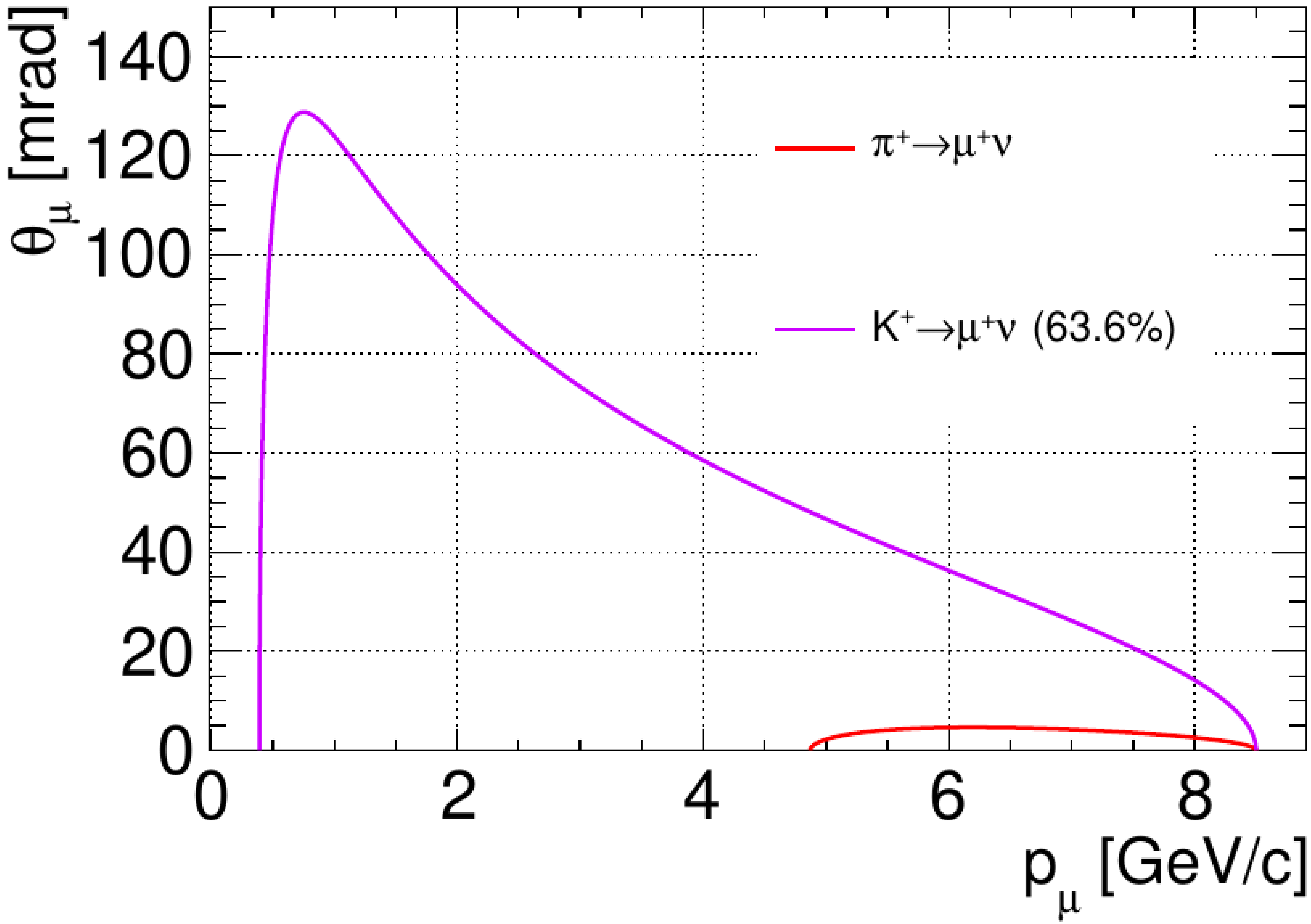




Conclusions

- **Remember**: we are living privileged times for experimental ν physics
- **Neutrino tagging** is finally **becoming possible** thanks to technological progress
  - a first tagged neutrino candidate was observed at NA62
- A new international collaboration – **nuSCOPE** – is forming
  - aim at delivering **landmark measurements on ν interactions** using tagging and monitoring
  - **physics case** is already **compelling** and **keeps growing**
  - experiment **technological readiness is high** and offer **unique R&D opportunities**
  - **Current proto-Collaboration comprises 25 institutions, 14 new ones expressed interest**
- Publication of an **Expression of Interest** for nuSCOPE foreseen by the **end of 2026**

Kinematics

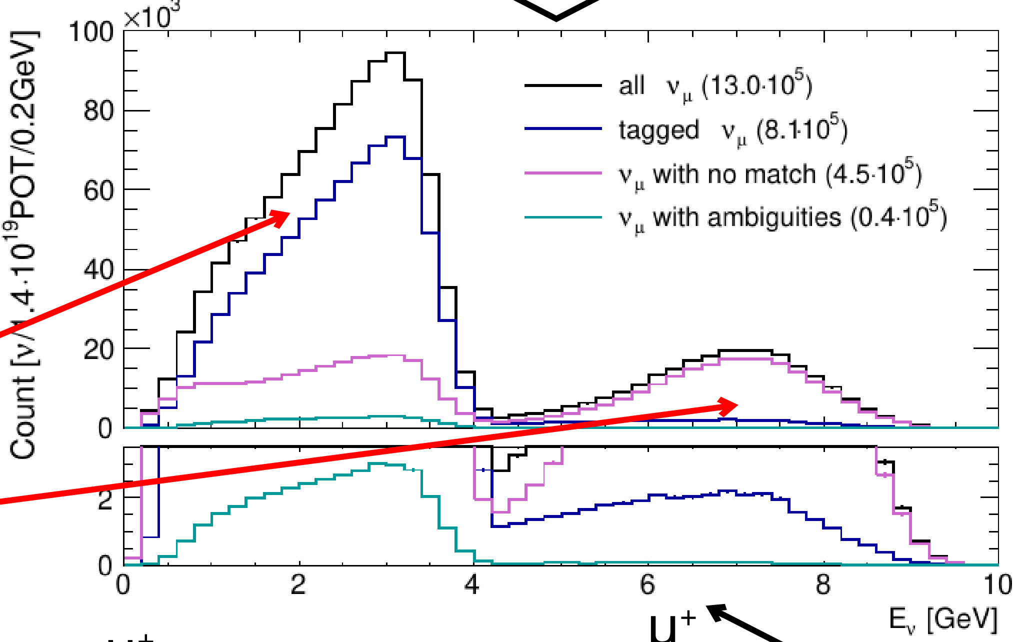


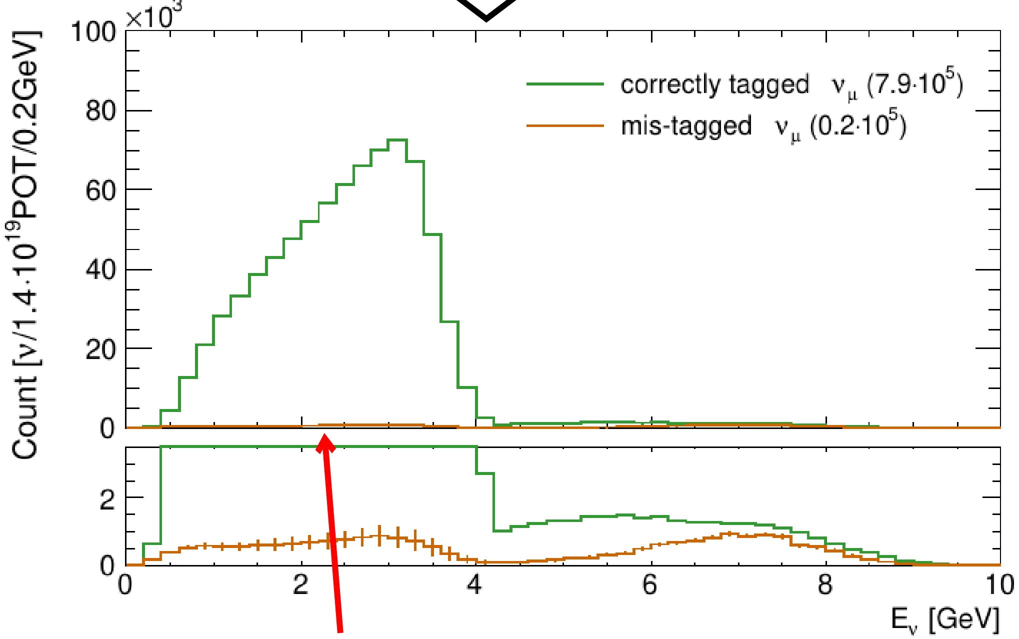
θ_μ [mrad]
140
120
100
80
60
40
20
0
0
2
4
6
8
p_μ [GeV/c]
$\pi^+ \to \mu^+ \nu$
$K^+ \to \mu^+ \nu$ (63.6%)

Tagging Efficiency

Three outcomes for matching algorithm

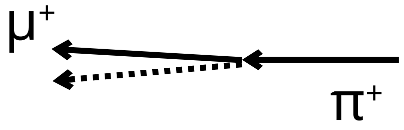
- no matching decay is found (no match)
- exactly one matching decay is found (tagged)
  - and it is the correct one
  - but it is NOT the correct one (mistag)
- >1 matching decays is found (ambiguities) ➔ these can be discarded

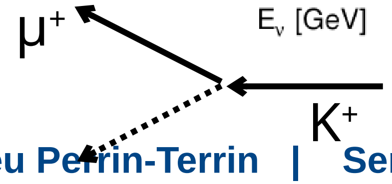




Tagging efficiency
- high for $\pi \rightarrow \mu\nu$
- (~80%)
- lower for $K \rightarrow \mu\nu$ (larger μ angle)

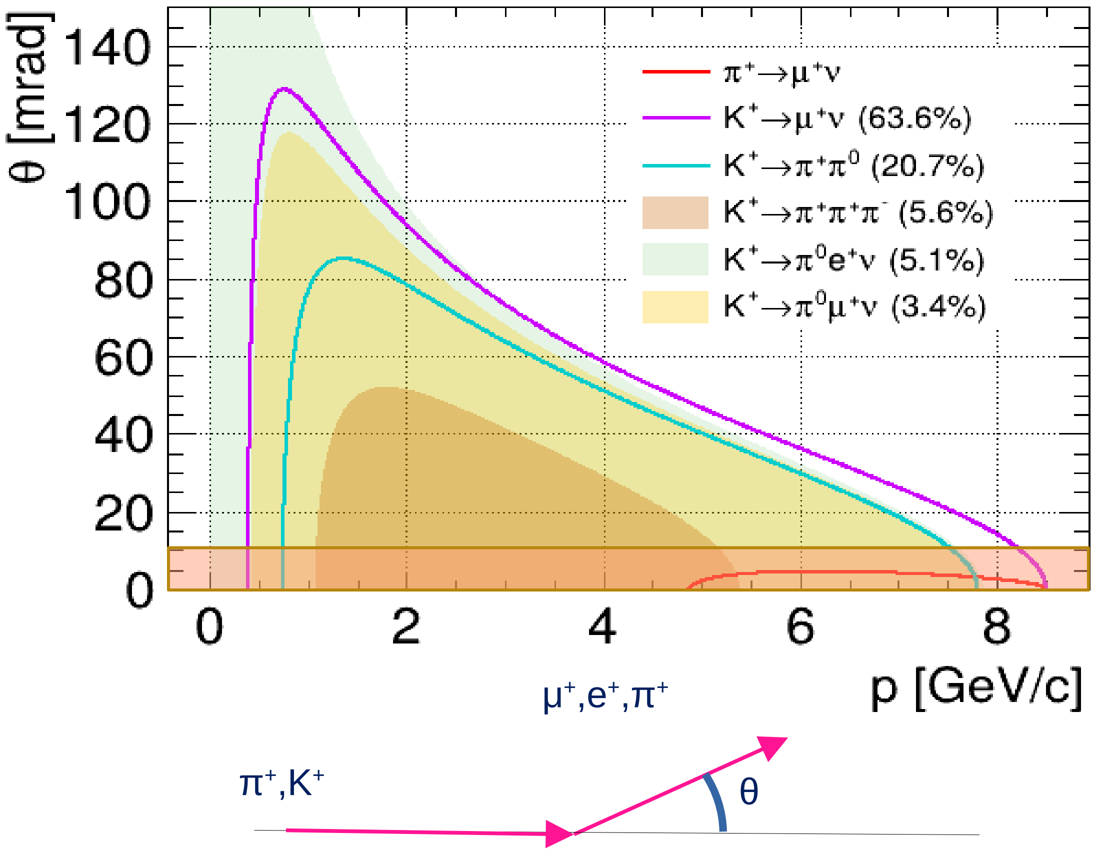
mis-tag is low (<1%)



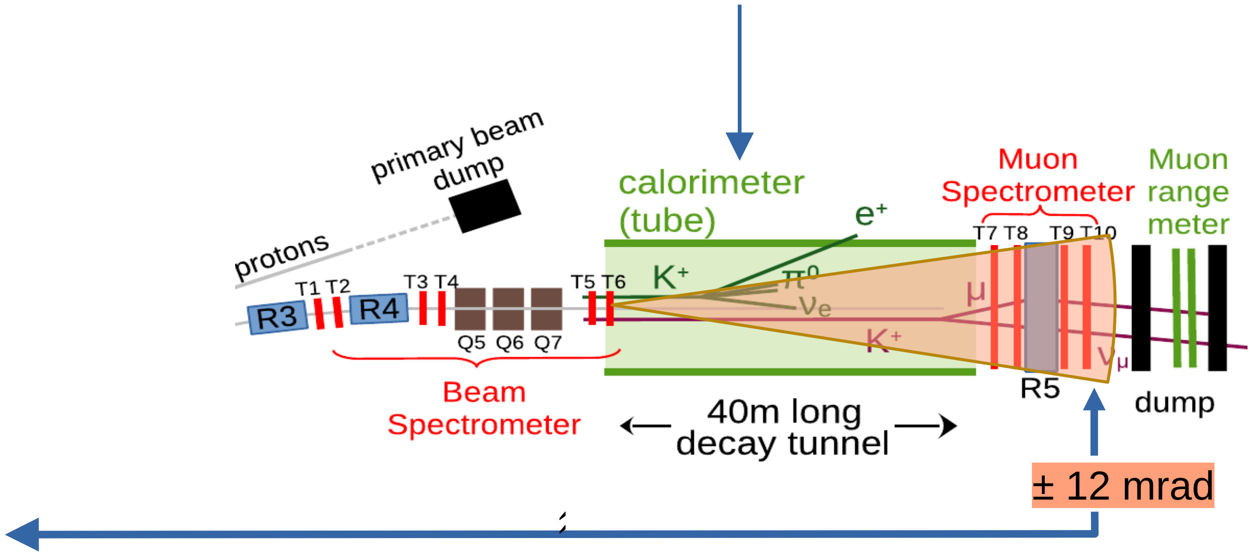


Complementarity Tagging/Monitoring

Space angle between mother (K^+,π^+)
and charged daughter (μ^+,π^+,e^+)

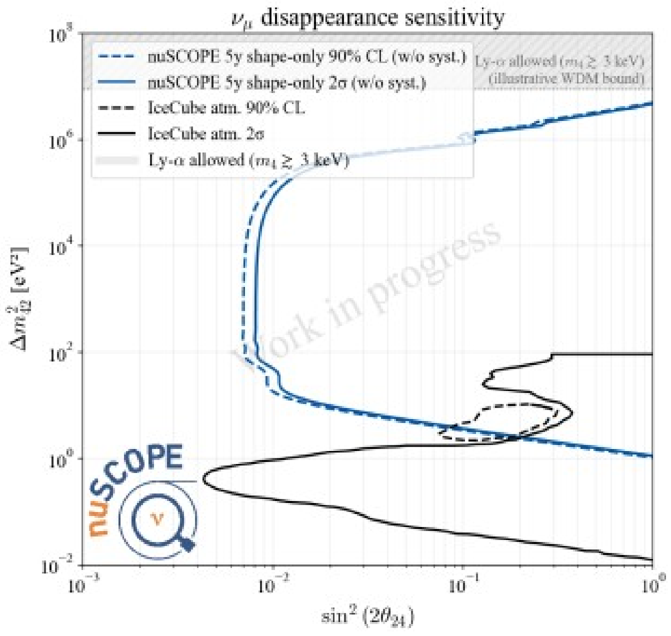


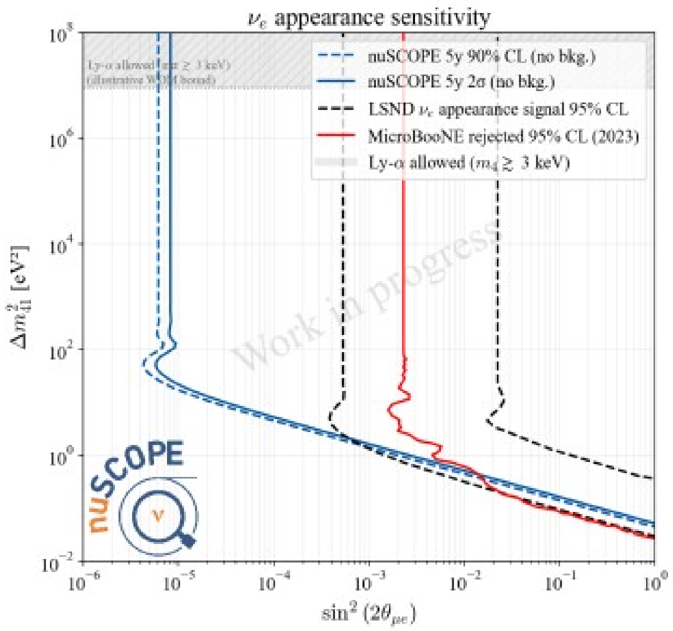
Tunnel Wall Instrumentation

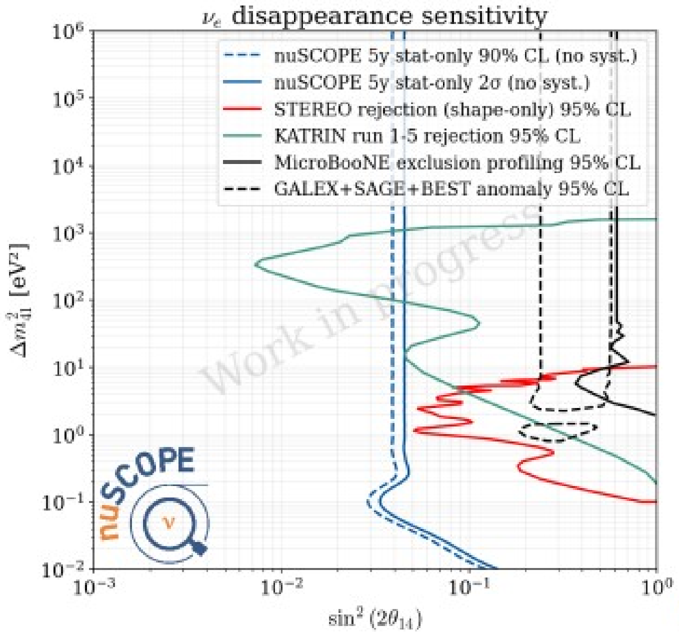


Sterile Neutrino at nuSCOPE

- nuSCOPE is an opportunity to test **long standing anomalies in neutrino exp. field**
- **Pioneering true L/E probe** thanks to neutrino tagging
- Very precise energy and position resolution → **almost no smearing on oscillations patterns**
- 3 simultaneous oscillation channels
  - $\nu_\mu \rightarrow \nu_\mu$: very precise spectrum shape analysis
  - $\nu_\mu \rightarrow \nu_e$: tagging cancels flux and x-section uncertainty limitations
  - $\nu_e \rightarrow \nu_e$: flux and x-sec constrains from ν_μ allows to test the disappearance



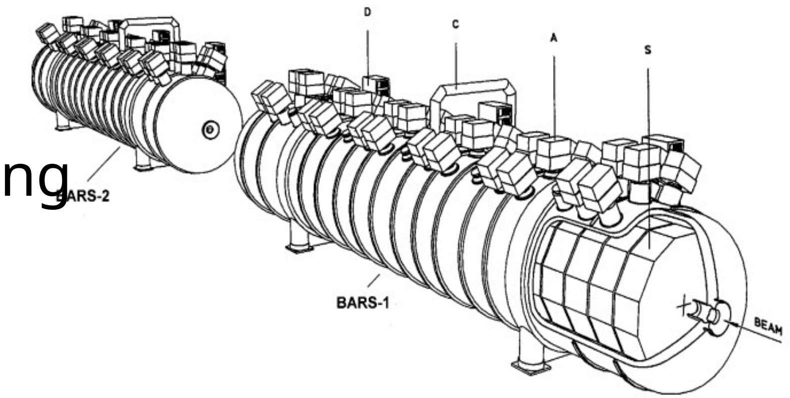




6

Study by A. Blanchet

A first attempt…



Serphukov, 1980’s : the Tagged Neutrino Facility (TNF) using the Big ARgon Spectrometer (BARS): 2 x 216t of LAr

Stopped in the 1990’s, limited legacy

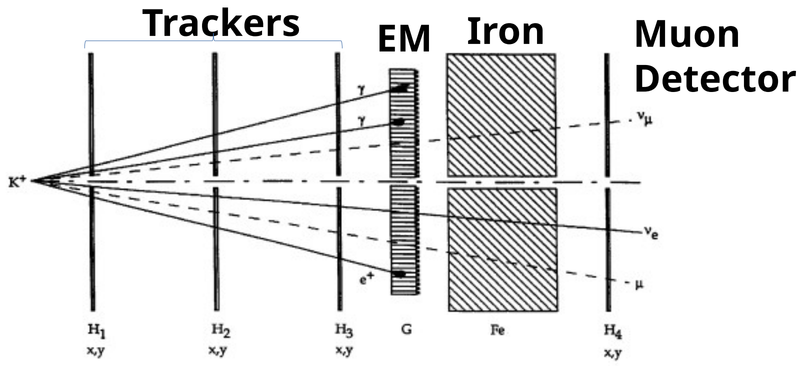
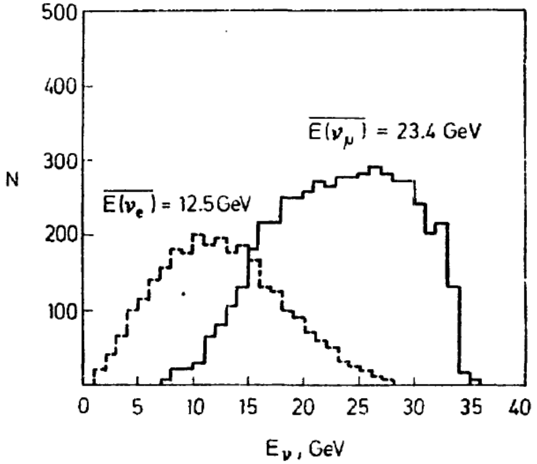


Рис. 2. Станция мечения. H1, H2, H3, H4 — двухкоординатные сцинтилляционные годоскопы (x, y); G — электромагнитный калориметр ГЕПАРД; Fe — 3-метровый железный поглотитель адронов.

http://web.ihep.su/library/pubs/prep1997/ps/97-32.pdf



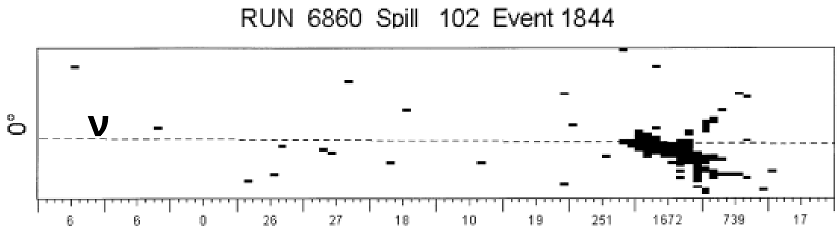
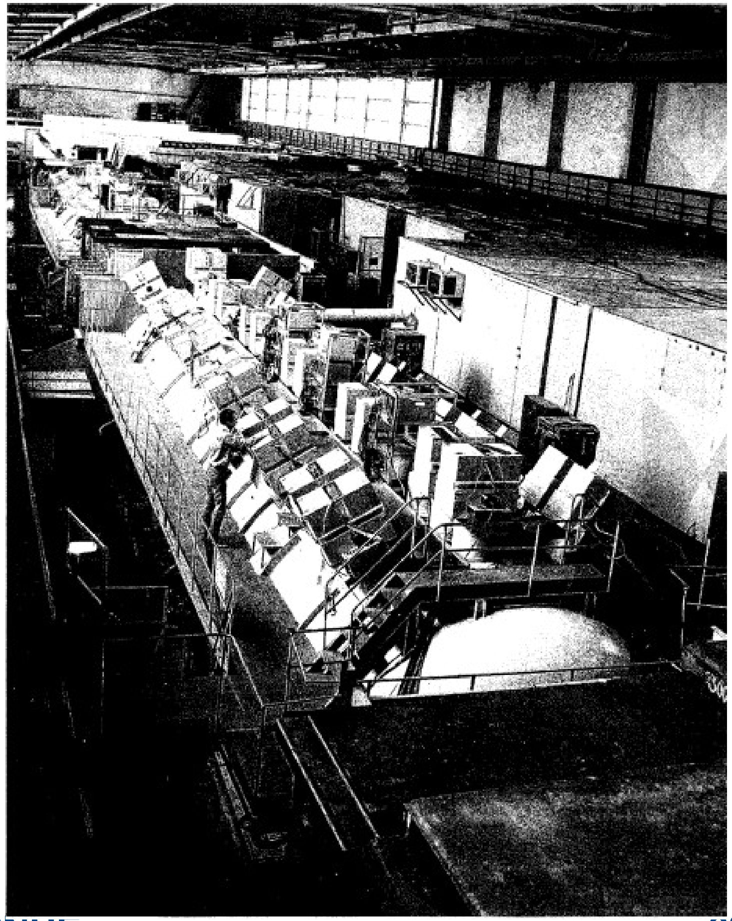


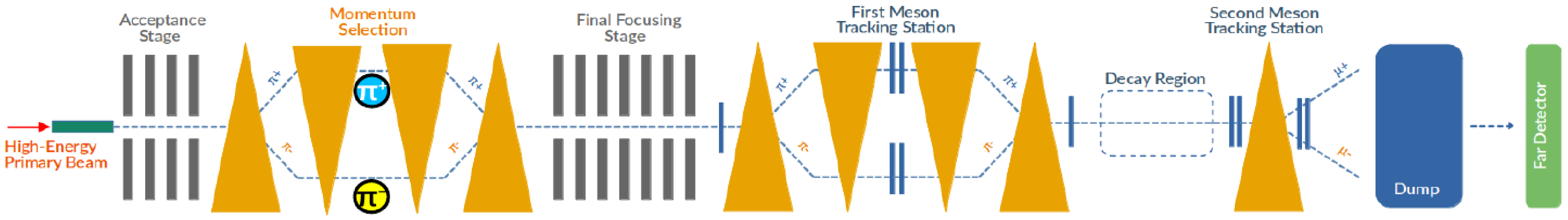
Fig. 4. 0°-projection of the neutral current tagged ν_μ interaction in the BARS. The dotted line shows the ν_μ trajectory calculated for a $K_{\mu 2}$-decay detected in the tagging station.

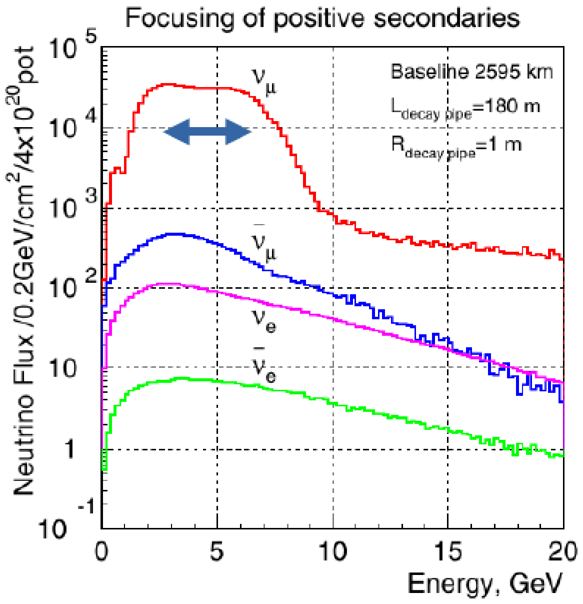
“The dotted line shows the ν_e trajectory calculated for a Kμν decay detected in the tagging station.”

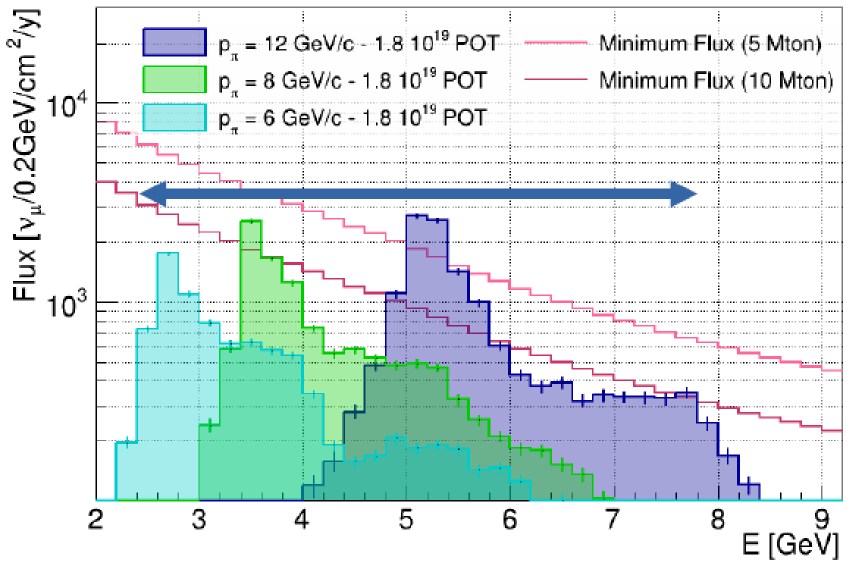


Tagged LBL Beamline

- Beam line designed to exploit the fact that the tagger determines the neutrino chirality (ν / $\bar{\nu}$): both π^+ and π^- are transported







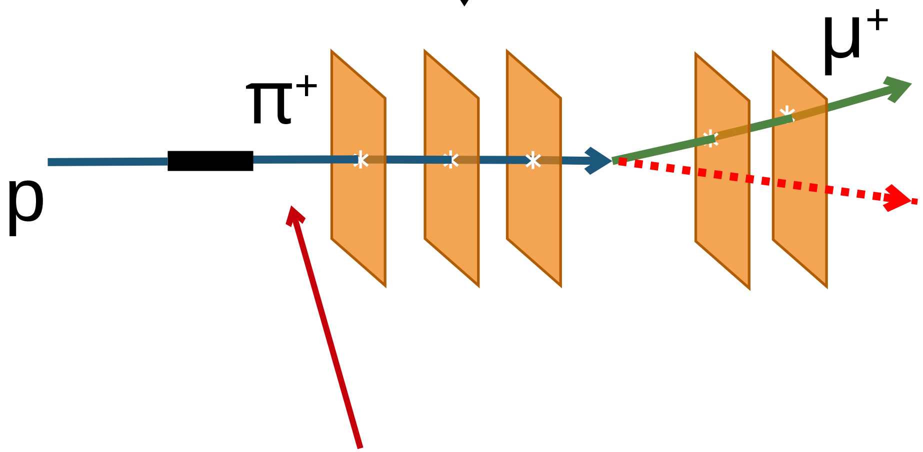
- Flux is sufficently intense but too narrow to fully take advantge of the tagging energy resolution

  => more studies are needed

Neutrino Tagging: an novel approach

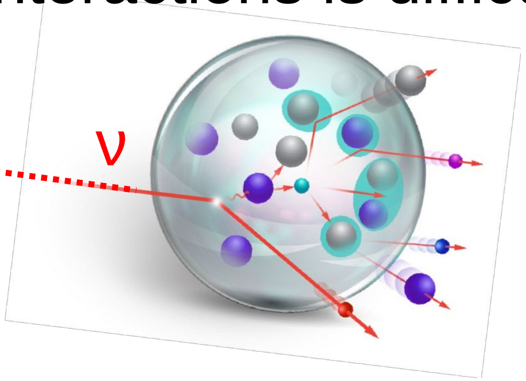
Instrument beamline to track π^+ and μ^+

Reconstruct **precisely** ν_μ properties from π^+ and μ^+



Reconstructing Neutrino Interactions is difficult !

Energy Resolution <1%



Challenge: high particule rate
At nuSCOPE: $10^{10\text{-}11}$ π^+/s

Energy Resolution 20%

[Eur. Phys. J. C , 82 , 465 (2022)]

CERN to Pylos

[E. Ball, S. Katsanevas, N. Vassilopoulos NIMA , 383 , 277--290 (1996)]

http://km3net.phys.uoa.gr/nestor/hena/location/cern_nestor.htm

----------	λ / in deg	φ / in deg
CERN	6.0732	46.2442
GRAN-SASSO	13.5744	42.4525
NESTOR	21.3500	36.3500
Coordinates of CERN, GRAN-SASS0, NESTOR		

	Az / in deg	α / in deg	Distance
GRAN-SASSO	122.502	3.283 (5.73%)	731Km
NESTOR	124.1775	8.526 (13.5%)	1676Km
Angular pointing and distance from CERN			

SPS/LSS4 to LHC/P8. On a two dimensional projection CERN, Gran Sasso and NESTOR are lined up. Calculations by Mayoud (CERN) show that a ν beam pointing to NESTOR would have to be diverted by only 1° to the west in azimuth and 5° or 7.5% downwards in declination, with respect to the one pointing to Gran Sasso.

https://cds.cern.ch/record/338290/files/p192.pdf

C2GT: intercepting CERN neutrinos to Gran Sasso in the Gulf of Taranto to measure θ_{13}

[Eur. Phys. J. C , 49 , 1117--1142 (2007)]

A.E. Ball[1], A. Braem[1], L. Camilleri[1], A. Catinaccio[1], G. Chelkov[2], F. Dydak[1], A. Elagin[2], P.K. Frandsen[1], M. Gostkin[2], A. Grant[1], A. Guskov[2], C. Joram[1], Z. Krumshteyn[2], H. Müller[1], H. Postema[1], M. Price[1], T. Rovelli[3], D. Schinzel[1], J. Séguinot[4], G. Valenti[3], R. Voss[1,a], J. Wotschack[1], A. Zhemchugov[2]

[1] CERN, Geneva, Switzerland
[2] Joint Institute for Nuclear Research, Dubna, Russia
[3] Dipartimento di Fisica, Università degli Studi di Bologna and INFN, Bologna, Italy
[4] Institut de Physique Corpusculaire, Collége de France, Paris, France

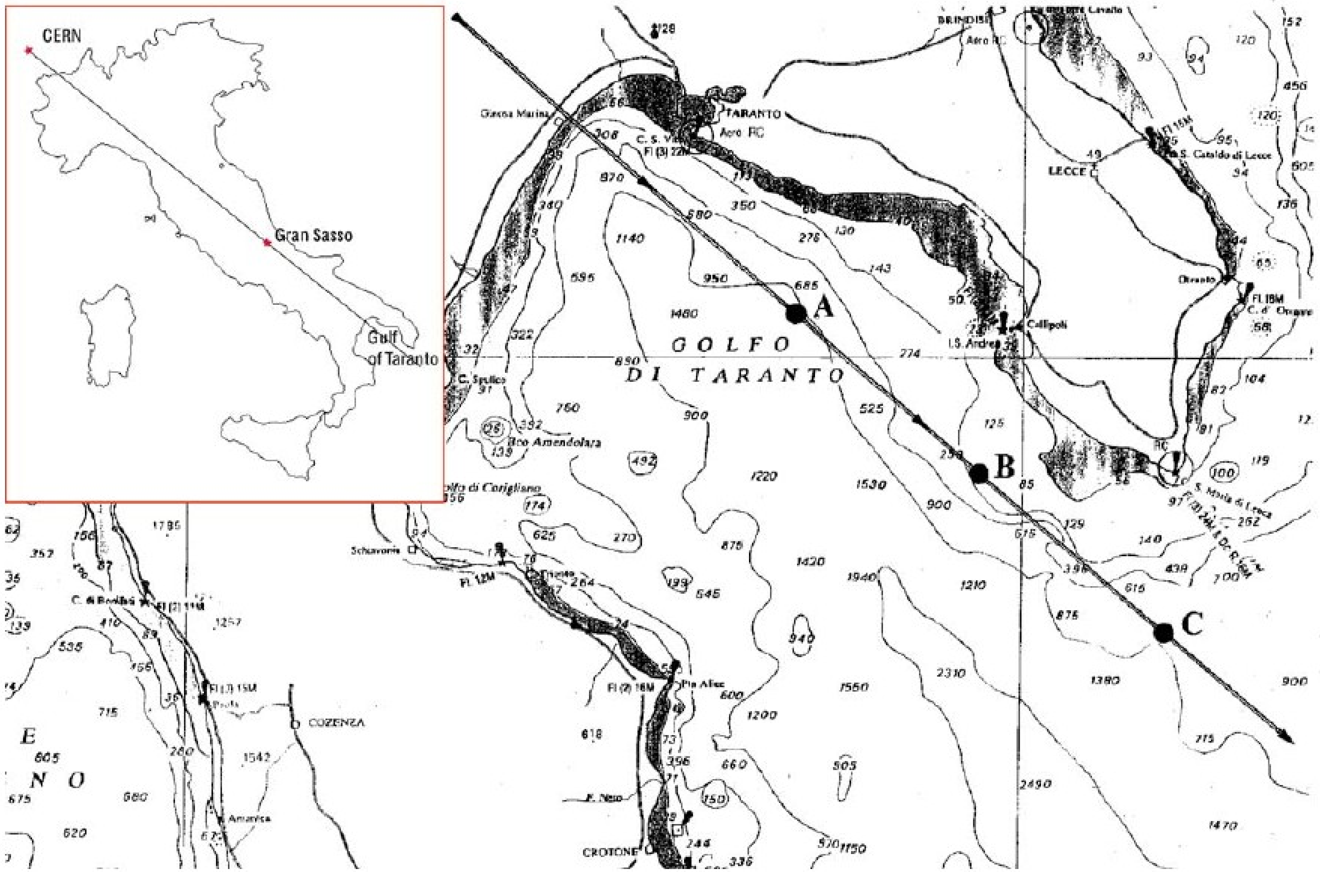


Fig. 1. Chart of the Gulf of Taranto. The axis of the CNGS is shown as a *solid line*. For orientation, the points A, B, and C show locations separated by 50 km, with B at a distance of 1200 km from CERN. In practice, the C2GT detector would be located slightly south-west of the line, i.e., at positions that are not exactly vertical below the beam axis

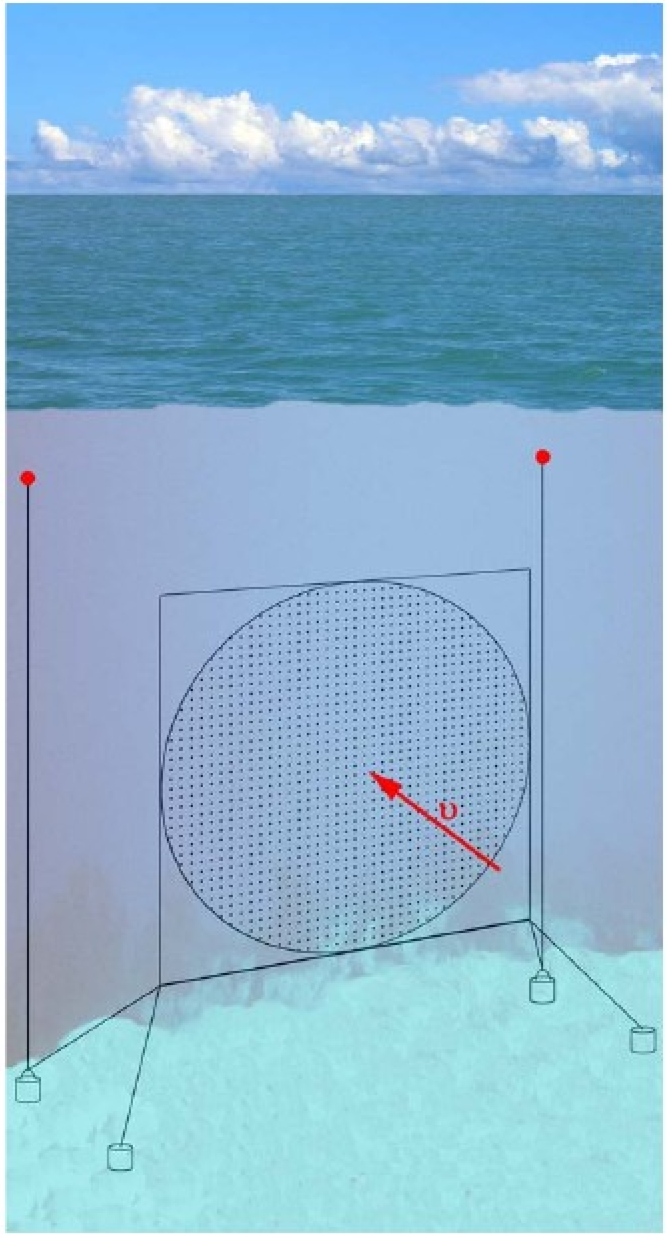
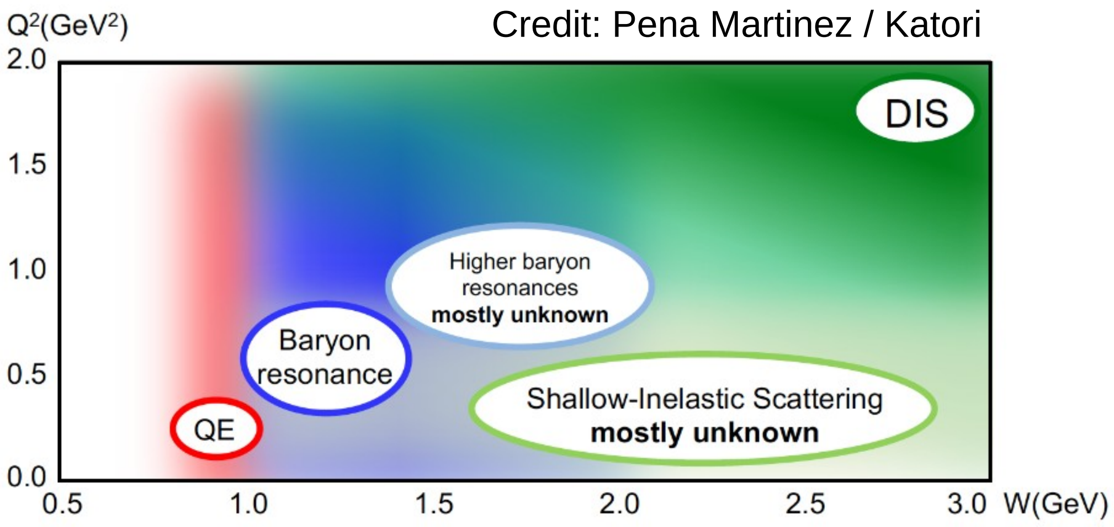
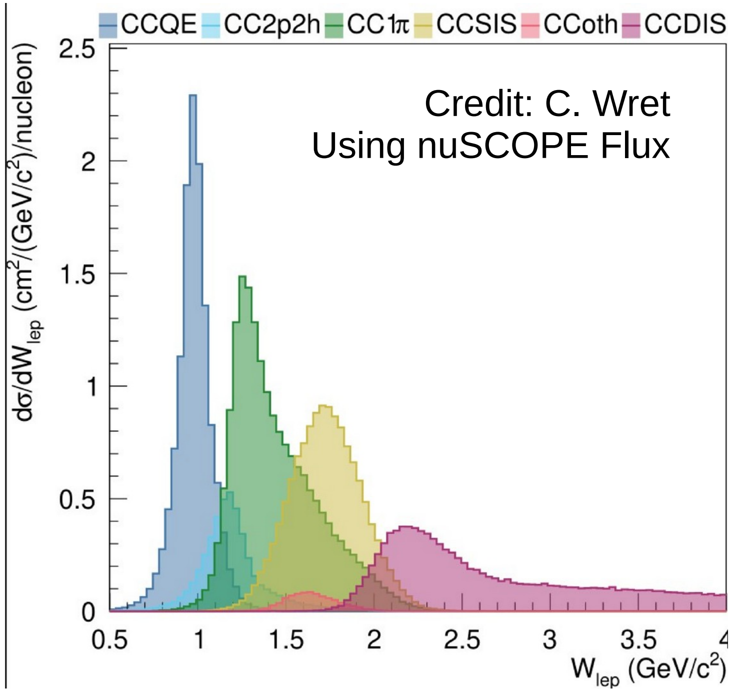


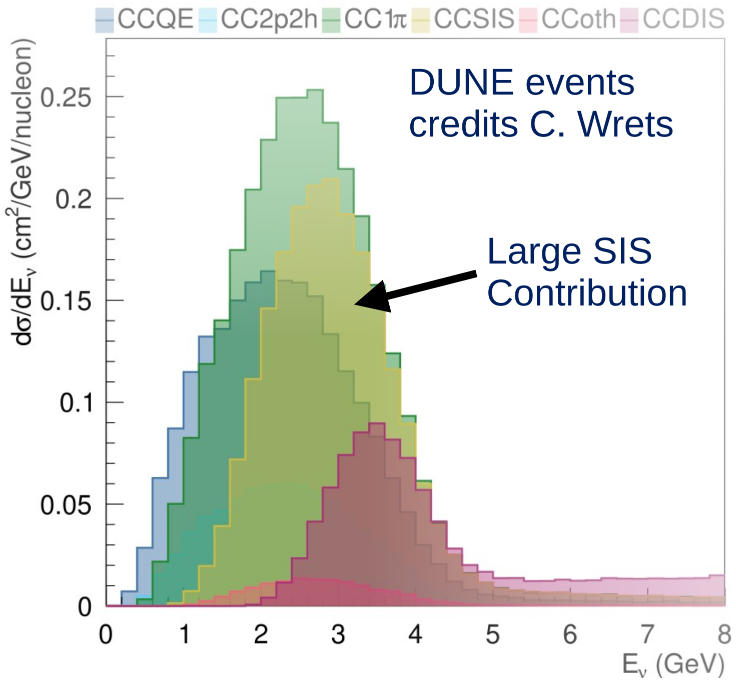
Fig. 2. Schematic view of the underwater detector (not to scale), including the lower mooring system. The upper mooring system, which completes the stabilization of the structure, is not shown

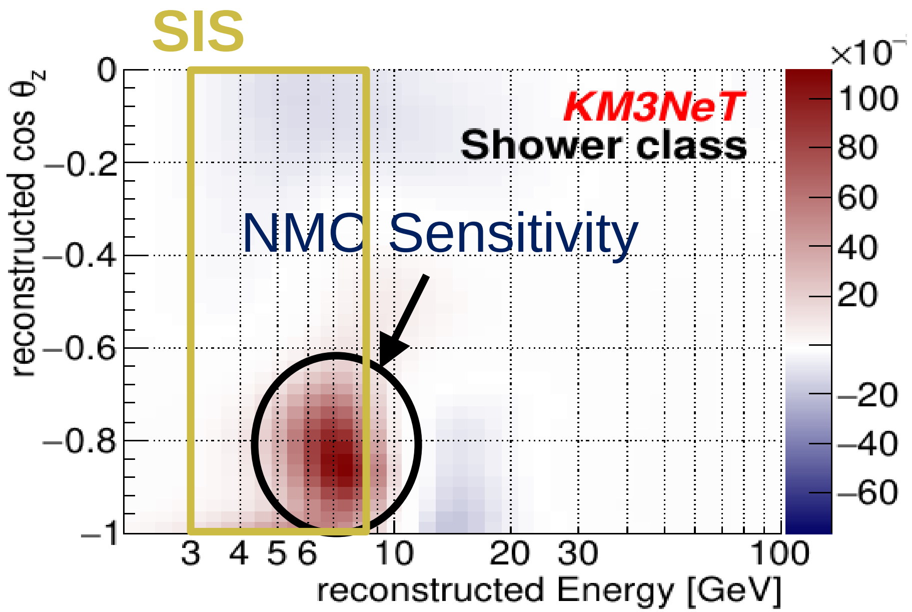
SIS Transition

- **Transition** from Resonant to DIS is poorly known and may **ORCA/IC and DUNE**
- SIS can be uniquely studied at nuSCOPE using ν energy resolution (Q^2 and **W** measurable from leptons only)



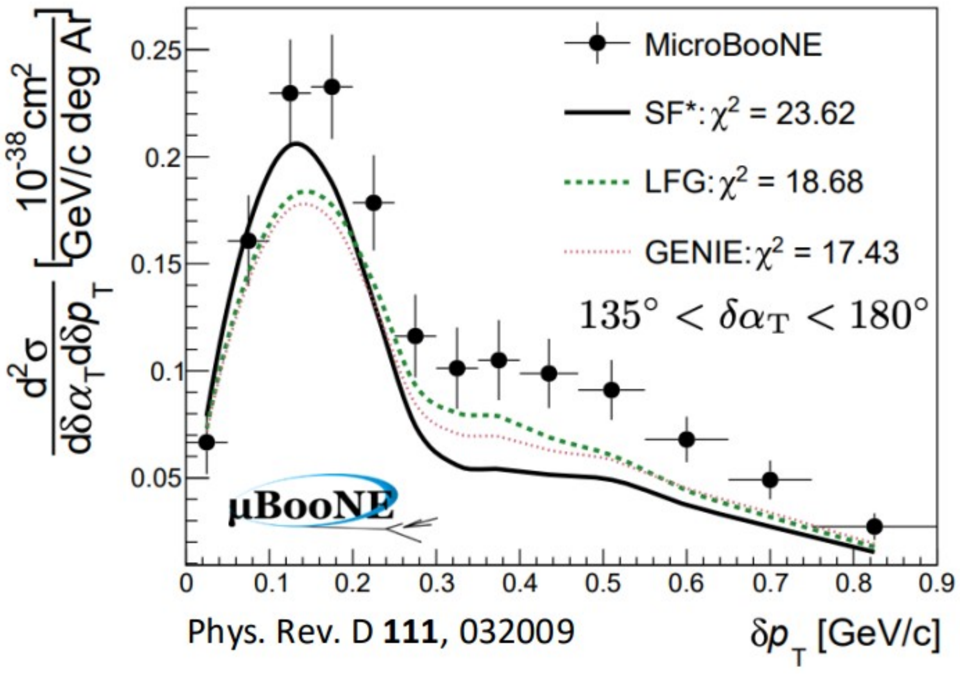


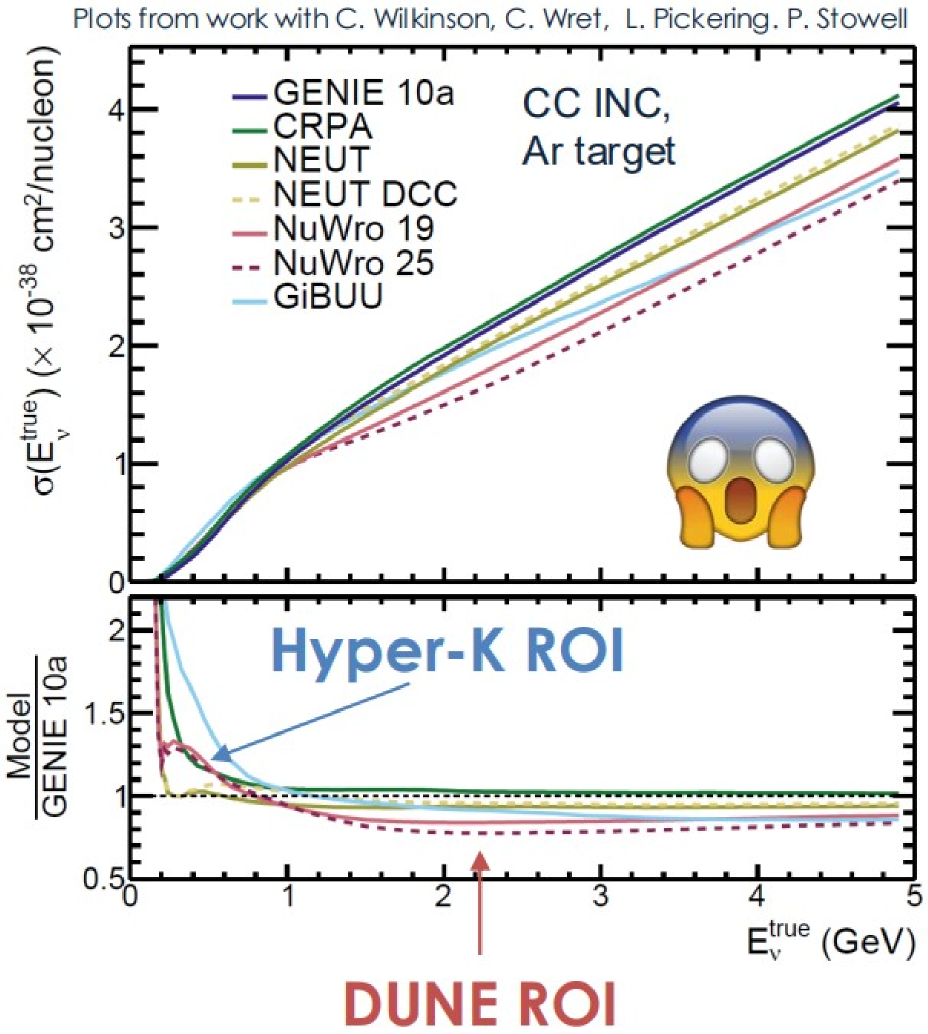




Systematic Uncertainties

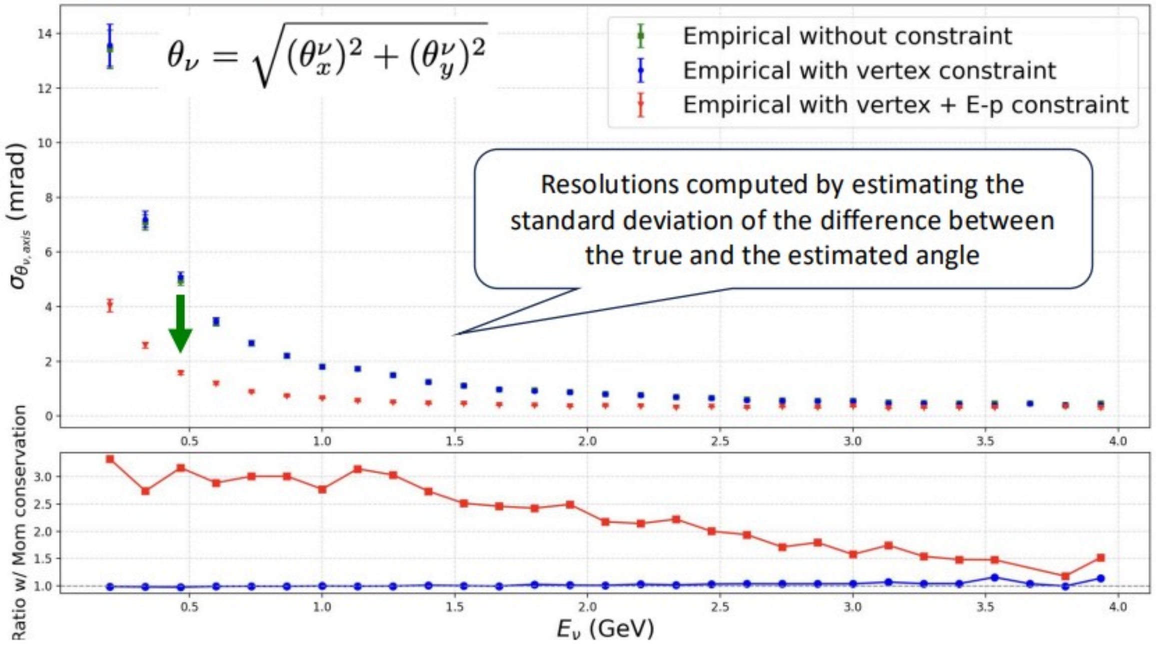
- Dominant systematic errors arise from **neutrino interactions**
- Large discrepancies between **theoretical models**
- **Experimental data** (high stat.) indicate that no model is correct but don't tell us why (limited by syst. errors)

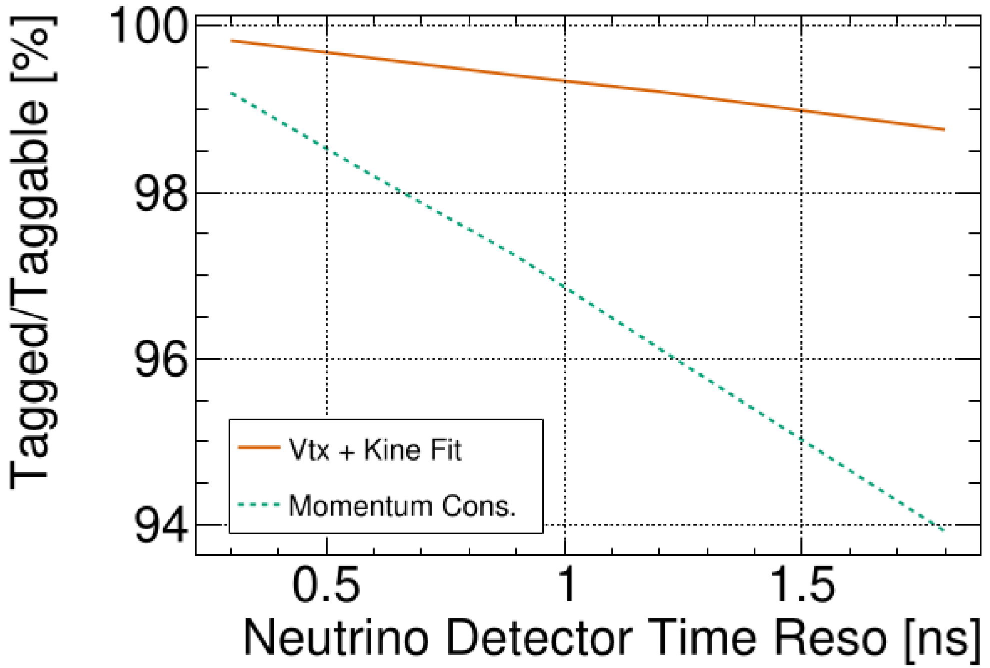




Neutrino Detector Time Resolution

- **New decay reconstruction** (kinematic fit) significantly improves (x2) the resolution on neutrino direction
- With improved reco, a **~1ns time resolution is sufficient** to recover ESPPU tagging efficiency

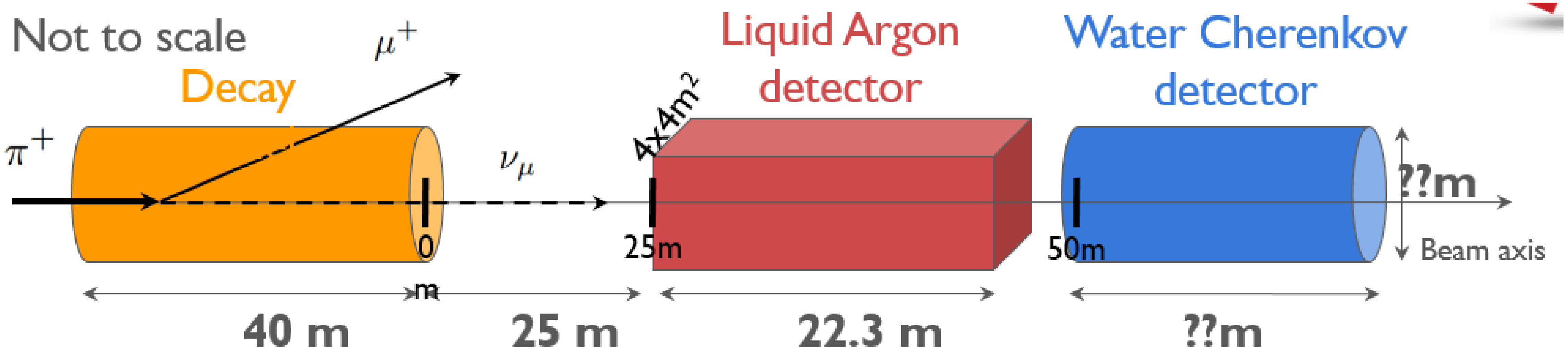




- **More refined preformance** accounting for more realistic tracking effects (ghost and fake tracks) and realistic beam composition (full BDSim simulation) expected for **EoI**

Water Cerenkov Detector Design

- **Water Cerenkov detector design** (size and position) is progressing



Water Cerenkov Detector Design

- **Water Cerenkov detector design** (size and position) is progressing

Fiducial volume dimension	100t D4	100t D3	100t D5	315t D4	333t D5	339t D6
Diameter [m]	4	3	6	4	5	6
Length [m]	8	14	6	25	17	12

@25 m

Interaction	100t D4	100t D3	100t D5	315t D4	333t D5	339t D6
Total sub 1.5 GeV	2.7807×10^4	3.1062×10^4	2.2779×10^4	7.6046×10^4	6.9133×10^4	5.8841×10^4
(% of total)	*(29.5%)*	*(21.3%)*	*(33.0%)*	*(27.0%)*	*(31.2%)*	*(34.5%)*
Contained	1.7011×10^4	1.6856×10^4	1.4511×10^4	5.2189×10^4	5.3803×10^4	4.8271×10^4
(% of total cont.)	*(74.9%)*	*(51.5%)*	*(83.8%)*	*(44.4%)*	*(54.3%)*	*(64.1%)*
(% of sub-GeV)	*(61.2%)*	*(54.3%)*	*(63.7%)*	*(68.6%)*	*(77.8%)*	*(82.0%)*
Uncontained	1.0795×10^4	1.4206×10^4	8.2678×10^3	2.3856×10^4	1.5330×10^4	1.0570×10^4
(% of total uncont.)	*(15.1%)*	*(12.6%)*	*(16.0%)*	*(14.5%)*	*(12.5%)*	*(11.1%)*
(% of sub-GeV)	*(38.8%)*	*(45.7%)*	*(36.3%)*	*(31.4%)*	*(22.2%)*	*(18.0%)*

@50 m

Interaction	100t D4	100t D3	100t D5	315t D4	333t D5	339t D6
Total sub 1.5 GeV	1.7869×10^4	1.3131×10^4	1.6411×10^4	4.5233×10^4	4.9737×10^4	4.3260×10^4
(% of total)	*(22.1%)*	*(12.3%)*	*(27.9%)*	*(19.4%)*	*(25.9%)*	*(29.2%)*
Contained	9.6915×10^3	6.5256×10^3	9.0337×10^3	2.7956×10^4	3.4448×10^4	3.2934×10^4
(% of total cont.)	*(63.1%)*	*(33.5%)*	*(79.4%)*	*(32.3%)*	*(45.0%)*	*(56.7%)*
(% of sub-GeV)	*(54.2%)*	*(49.7%)*	*(55.0%)*	*(61.8%)*	*(69.3%)*	*(76.1%)*
Uncontained	8.1776×10^3	6.6058×10^3	7.3768×10^3	1.7277×10^4	1.5289×10^4	1.0325×10^4
(% of total uncont.)	*(12.5%)*	*(7.6%)*	*(15.6%)*	*(11.8%)*	*(13.3%)*	*(11.5%)*
(% of sub-GeV)	*(45.8%)*	*(50.3%)*	*(45.0%)*	*(38.2%)*	*(30.7%)*	*(23.9%)*