



Reconstruction algorithm for neutrino tagging at nuSCOPE

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On behalf of the nuSCOPE collaboration

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Outline

I. Neutrino Tagging for nuSCOPE: Physical context and objective

II. Decay reconstruction method

- Toy Monte-Carlo assumptions
- Track reconstruction
- Decay reconstruction and estimation of neutrino parameters

II. First results

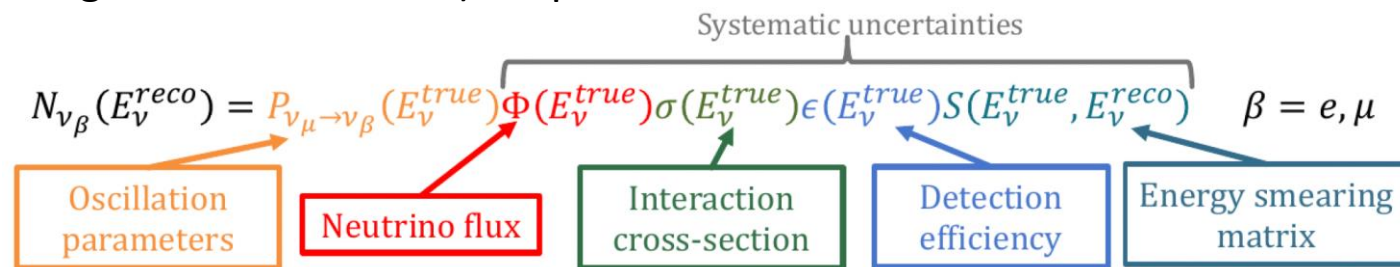
- Track fitting
- Track finding

III. Conclusions and perspectives

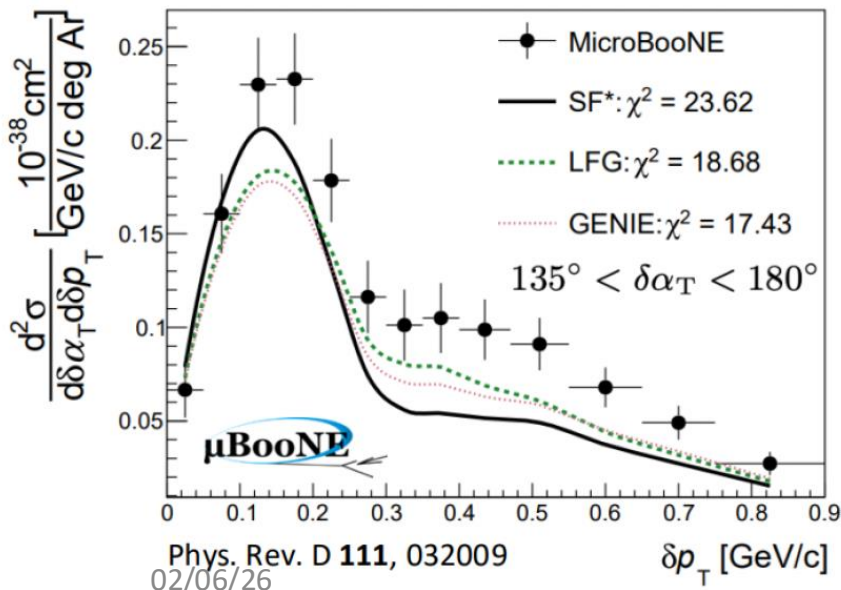
I. nuSCOPE: physics motivation

Context:

- **DUNE, HK** will collect large ν samples (10-100 times larger than **T2K, NoVa**) for precision neutrino oscillation measurements
- Oscillation parameter measurements accuracy will be limited by systematic uncertainties
- Systematics must be reduced from $\sim 5\%$ to **1-3%**



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



Dominant systematic uncertainty: **interaction cross-section** due to large discrepancies between theoretical models

I. nuSCOPE: a monitored and tagged beam

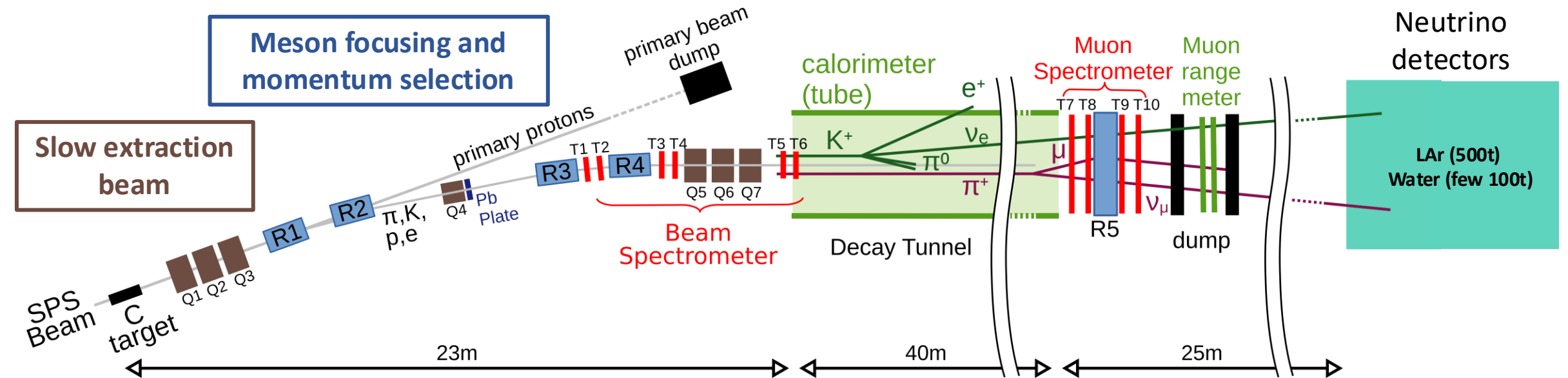
Main goals: high-precision GeV-scale neutrino cross-section measurements on different nuclear targets (argon and water)

Two complementary strategies (merging of ENUBET and nuTAG):

- **monitoring:** constrain the neutrino flux by counting charged leptons of :

- ν_e flux from $K^+ \rightarrow \pi^0 e^+ \nu_e$
- ν_μ flux from $K^+ \rightarrow \mu^+ \nu_\mu$ and $\pi^+ \rightarrow \mu^+ \nu_\mu$

- **tagging:** reconstruct individual ν_μ from parent decay kinematics



Target precision of 1% for ν_μ cross-section: flux normalization $\sim 5-10\% \rightarrow 1\%$ and energy reconstruction $10\% \rightarrow 1\%$

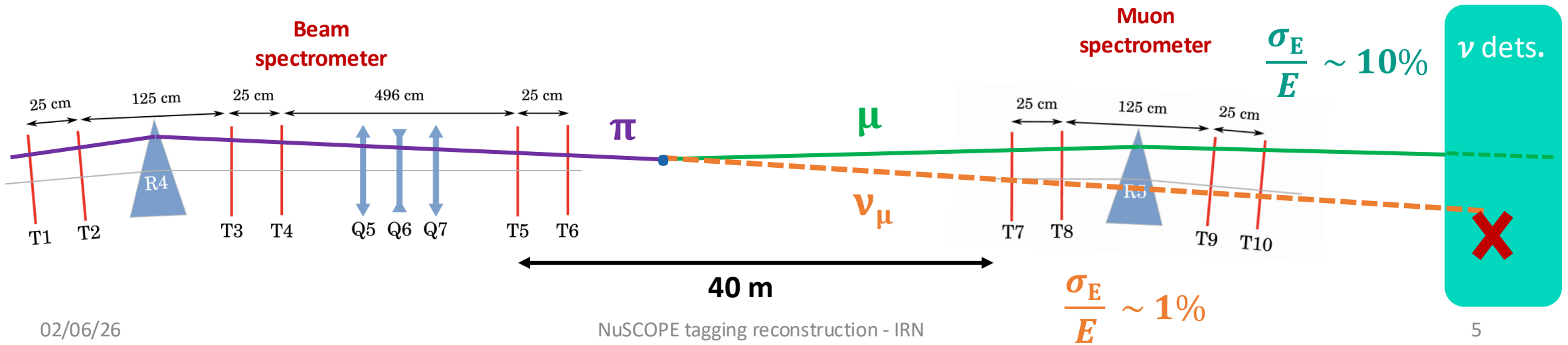
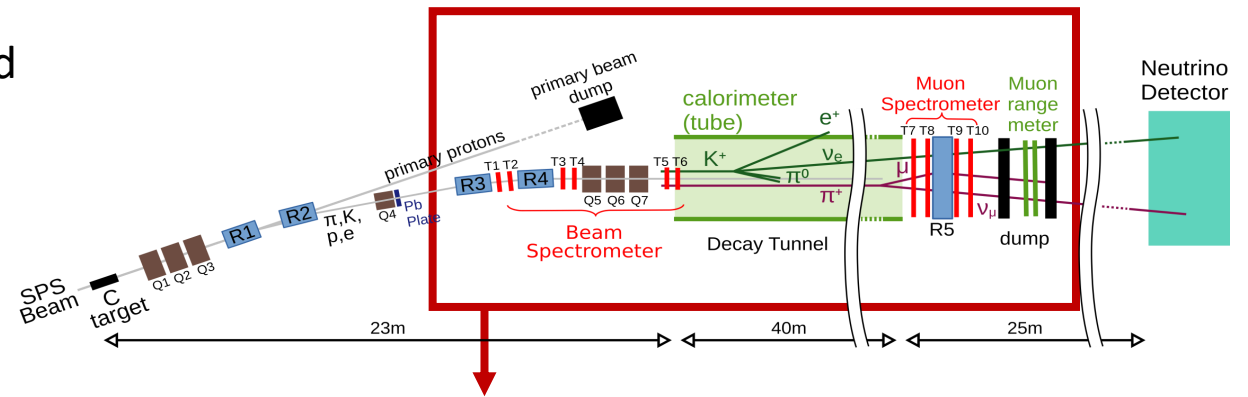
I. Neutrino Tagging for nuSCOPE

Neutrino tagging principle:

1. Detection of a ν_μ in the neutrino detector
2. Reconstruction of π and μ
3. π / μ association
4. Estimation of the reconstructed ν_μ from $\pi \rightarrow \mu + \nu_\mu$
5. Time-space association between the **detected** ν_μ and the **reconstructed** ν_μ

Perrin-Terrin Mathieu
Neutrino Tagging: a new tool for accelerator based neutrino experiments
(2022)
[arXiv:2112.12848](https://arxiv.org/abs/2112.12848)

nuSCOPE
A short-baseline neutrino beam at CERN
 for high-precision cross-section measurements **(2025)**
[arXiv:2503.21589](https://arxiv.org/abs/2503.21589)

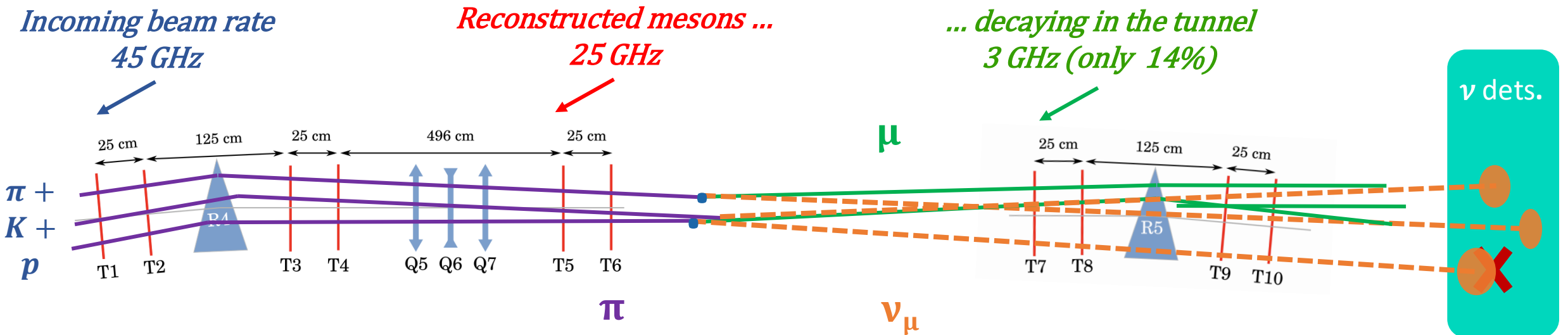


I. Neutrino Tagging for nuSCOPE: time-space association

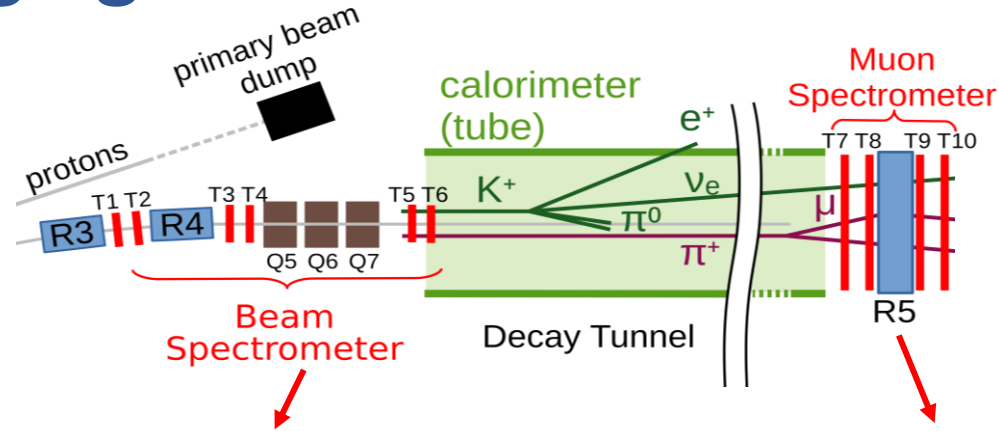
For a detected neutrino: ~ 2 pile-up decays **in time** ($3\sigma_t$)

Ambiguities resolved using spatial coincidence

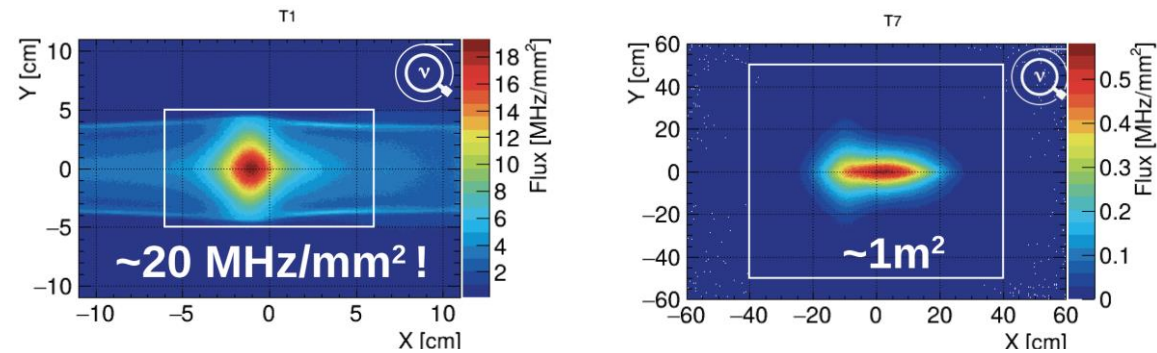
	Tracking planes	Neutrino det.
Time reso.	<10ps	$\sigma_t = 300$ ps
Space reso.	40um	1mm



I. Neutrino Tagging for nuSCOPE: instrumentation specification



Trackers



Specifications [units]	Beam Spectro.	Muon Spectro.	LHCb-VELO (2028)	NA62-GTK (since 2014)
Peak Rate [MHz/mm ²]	20	0.6	10 – 100	2
Time Resolution [ps]	< 40	< 100	< 50	< 130
Pixel Pitch [μm]	300	300	45	300

Time resolution & rate **beyond state of the art** by a factor 10
 But **aligned with LHCb upgrade**

I. Neutrino Tagging for nuSCOPE: tagging efficiency

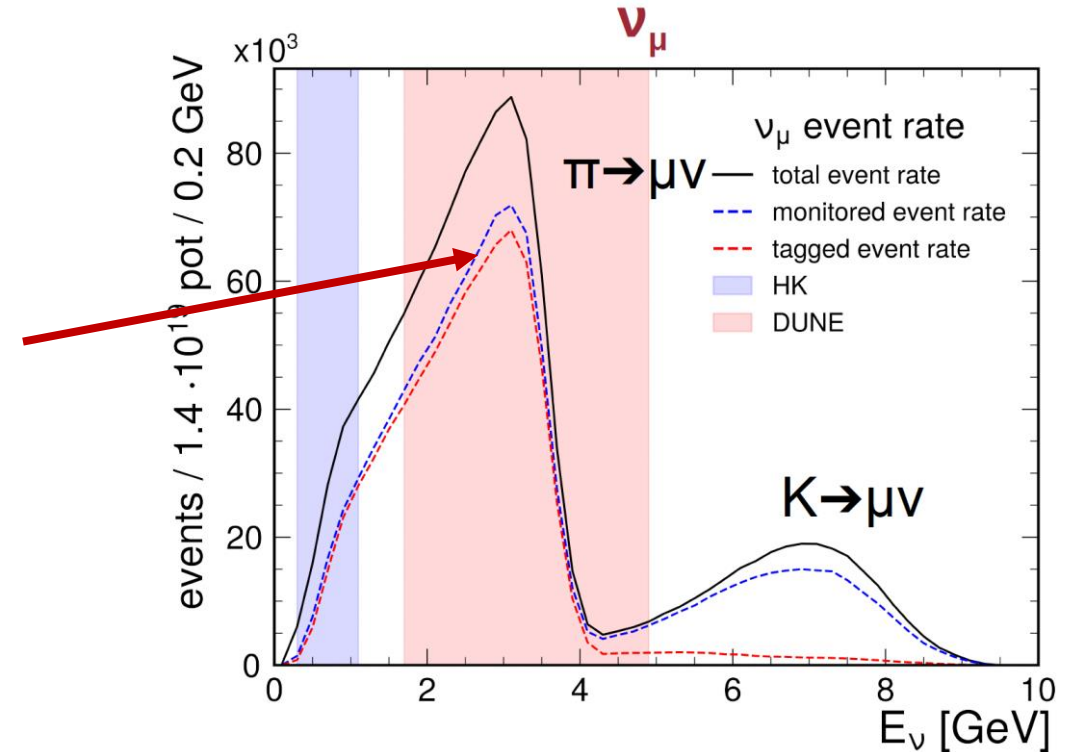
Result from EPPSU paper

Good fraction of tagged events assuming:

- Perfect tracking
- Neutrino det time reso: 300 ps (optimistic)
- Simple decay reconstruction

The goal of this work is to take into account:

- Track reconstruction errors
- Realistic neutrino det time reso (~ 1 ns)
- Improved decay reconstruction



	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	0.76×10^6	0.14×10^6
ν_e	1.7×10^4	
Monitored ν_e	1.2×10^4	

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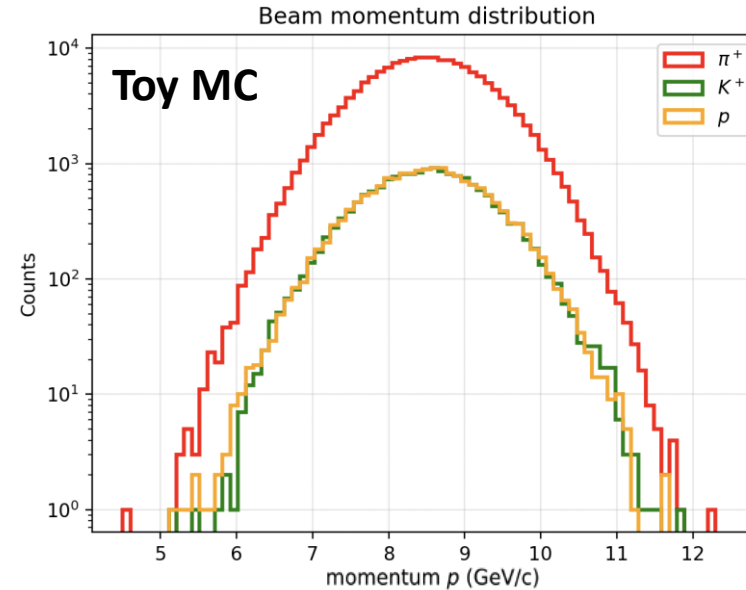
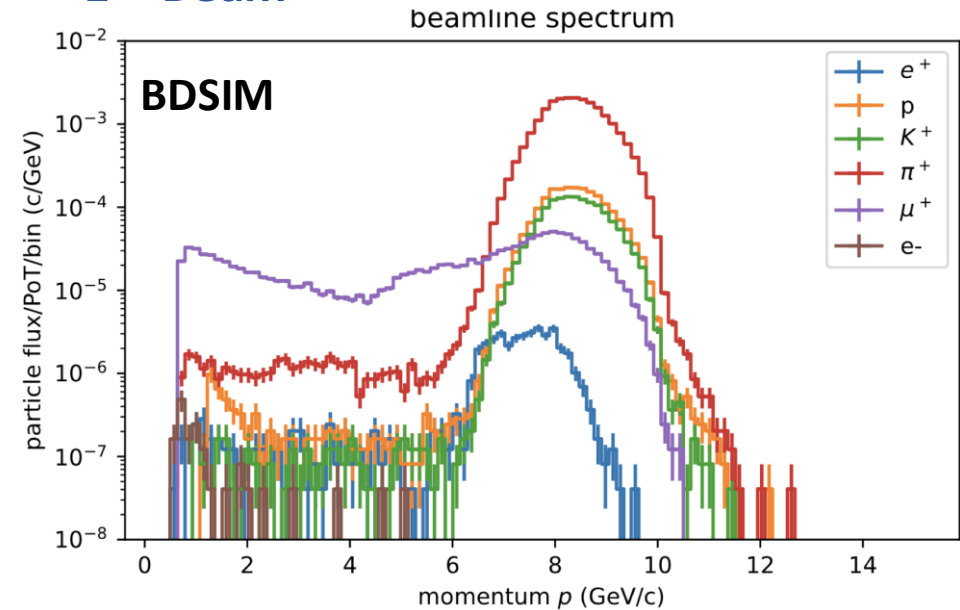
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I. Toy Monte-Carlo assumptions

1 – Beam

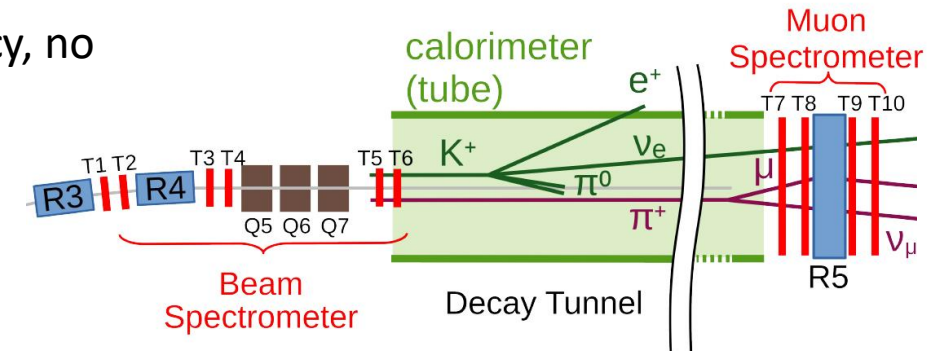


Rate	27 GHz
Composition	82.6 % π^+ 8.7 % K^+ 8.7 % p
Momentum	8.5 ± 0.8 GeV
Divergence	0.01 rad
Transverse size	30 cm

2 – Simplified nuSCOPE setup

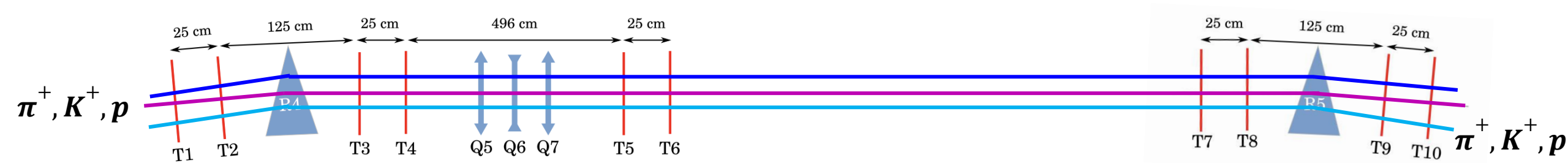
- Trackers:** Multiple Coulomb Scattering but detector with 100% efficiency, no charge sharing, no noisy hit

	Beam spect.	Muon spect.
Time reso	40 ps	
Pixel pitch	55 μ m	



II. Reconstruction method: overview

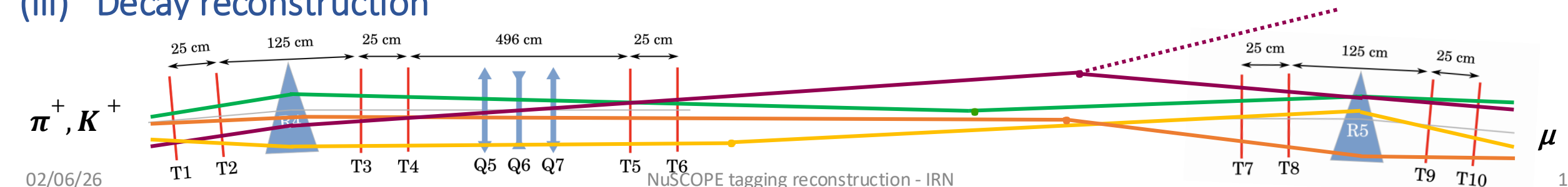
(i) **Reduce combinatorics:** Filtering out undecayed particles ($\sim 160/180$ particles for time window 6.3 ns)



(ii) Independent track reconstructions of parent meson and daughter muon (~ 20 particles after (i))



(iii) Decay reconstruction

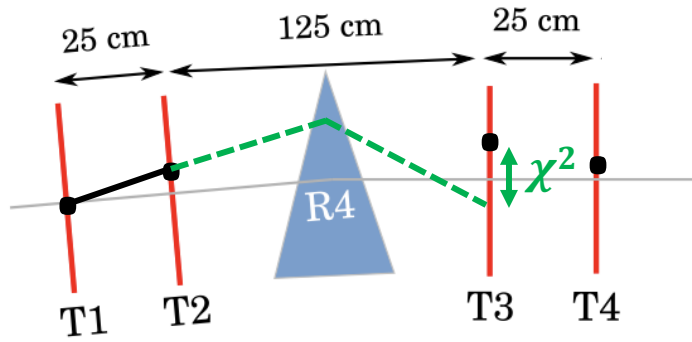


(i) Filtering out undecayed particles

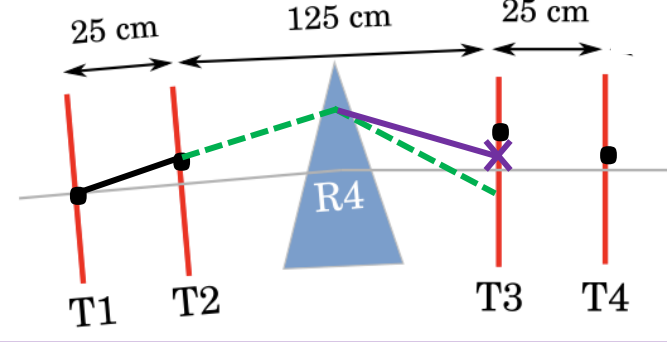
- **Challenge:** 180 hits per planes give $180^{10} \sim 10^{22}$ possible tracks. **Exhaustive search is computationally impossible.**
- **Method:** **AlfaBT Global reconstruction** (Always First Assign Best Track) through all trackers

Method developed and validated at NA62

Step 1 Build candidate tracks by propagating a Kalman filter while removing bad tracks (χ^2 threshold)



1- Prediction of state vector
 $(x, y, t, \theta_x, \theta_y, \propto 1/p)$



2- Estimation of state vector:
Update with the measurement (x, y, t)
+ Quantification of **associated uncertainties**

Step 2 Hits/track association:

- select the **best candidate track (smallest χ^2)**
- remove all candidate tracks with hit(s) in common with the **best track**
- go back to 2.i.

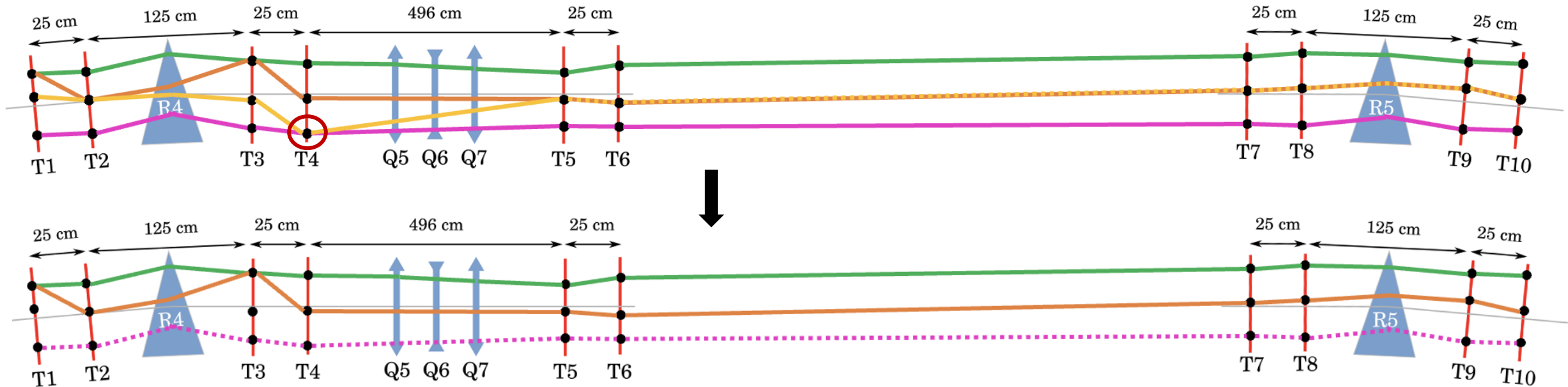
(i) Filtering out undecayed particles

- **Method: AlfaBT reconstruction** (Always First Assign Best Track)

Step 1 Build candidate tracks by propagating a Kalman filter while removing bad tracks (high- χ^2)

Step 2 Hits/track association :

- select the **best candidate track (smallest χ^2)**
- remove all candidate tracks with hit(s) in common with the **best track**
- go back to 2.i.



II. Reconstruction method: overview

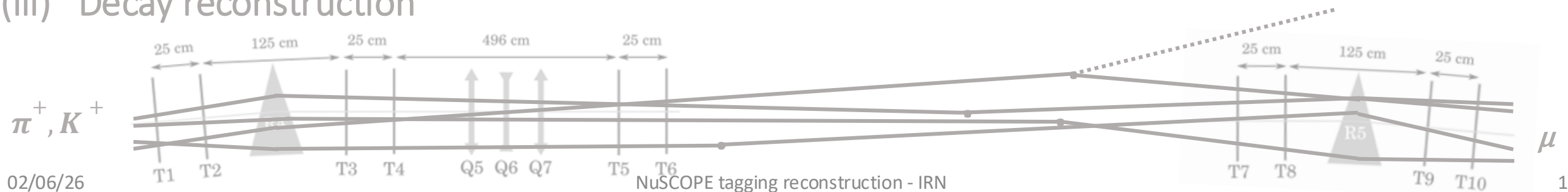
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(ii) Independent track reconstructions of parent meson and daughter muon (~ 20 particles after (i))

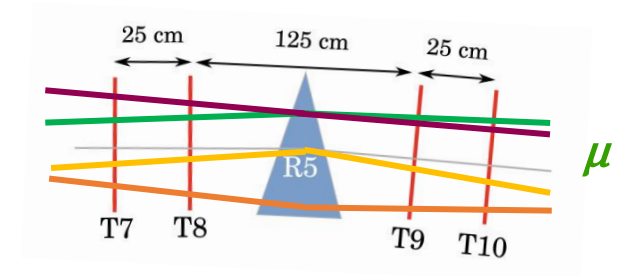
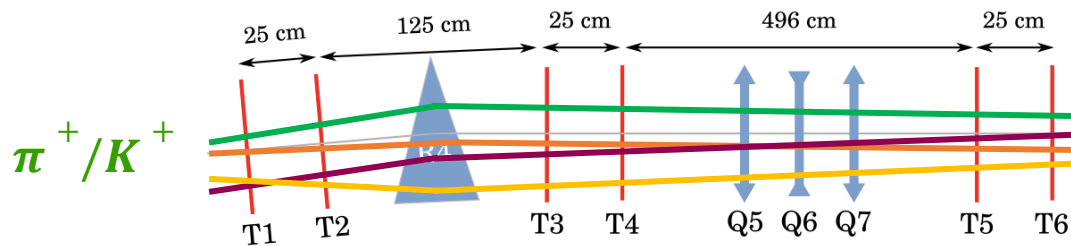


(iii) Decay reconstruction



(ii) Track reconstruction in both spectrometers

- Method: **AlfaBT Global reconstruction** in each spectrometer (T1-T6 & T7-T10) on remaining hits



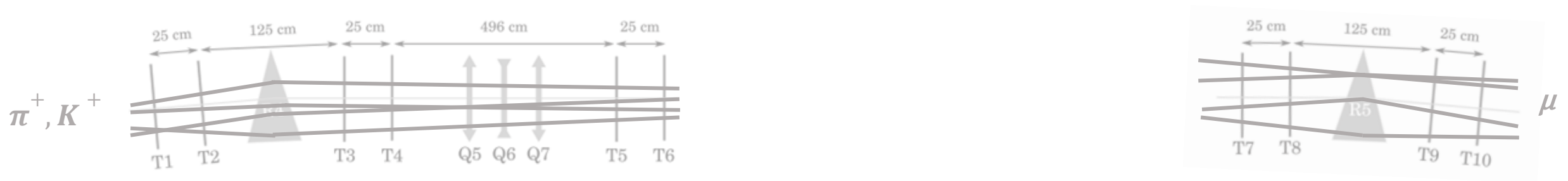
Output: candidate tracks with good χ^2 are retained as potential mother meson or daughter muon candidates for the reconstruction of decays

II. Reconstruction method: overview

(i) Reduce combinatorics: Filtering out undecayed particles ($\sim 160/180$ particles for time window 6.3 ns)



(ii) Independent track reconstructions of parent meson and daughter muon (~ 20 particles after (i))



(iii) Decay reconstruction



II. Decay reconstruction method

- **For all possible meson / μ pairs:** estimate the four-momentum of the ν based on the reconstructed trajectories of the meson and μ + uncertainties (given by Kalman based algorithm)
- **Estimation method:** Lagrangian minimization through **iterative constrained least-squares**

Initialization

Meson/ μ angles and momenta: provided by the Kalman filter of beam and muon spectrometers

Vertex: point of closest approach between the meson and μ trajectories

Constrained least-squares

- **12 measurements** and **16 unknown parameters**

$$(x_\nu, y_\nu, z_\nu, t_\nu, x_\pi, y_\pi, \theta_{x,\pi}, \theta_{y,\pi}, \frac{1}{p_\pi}, t_\pi, x_\mu, y_\mu, \theta_{x,\mu}, \theta_{y,\mu}, \frac{1}{p_\mu}, t_\mu)$$

- Vertex: 6 geometrical constraints (**10 parameters**)

- E-p conservation: estimations projected on the hypersurface where the missing mass of the meson / μ system is null (**9 parameters**)

→ The 7 ν_μ parameters $(x_\nu, y_\nu, z_\nu, t_\nu, \vec{p}_\nu)$ are then derived

- **Association:** based on reconstructed decay χ^2

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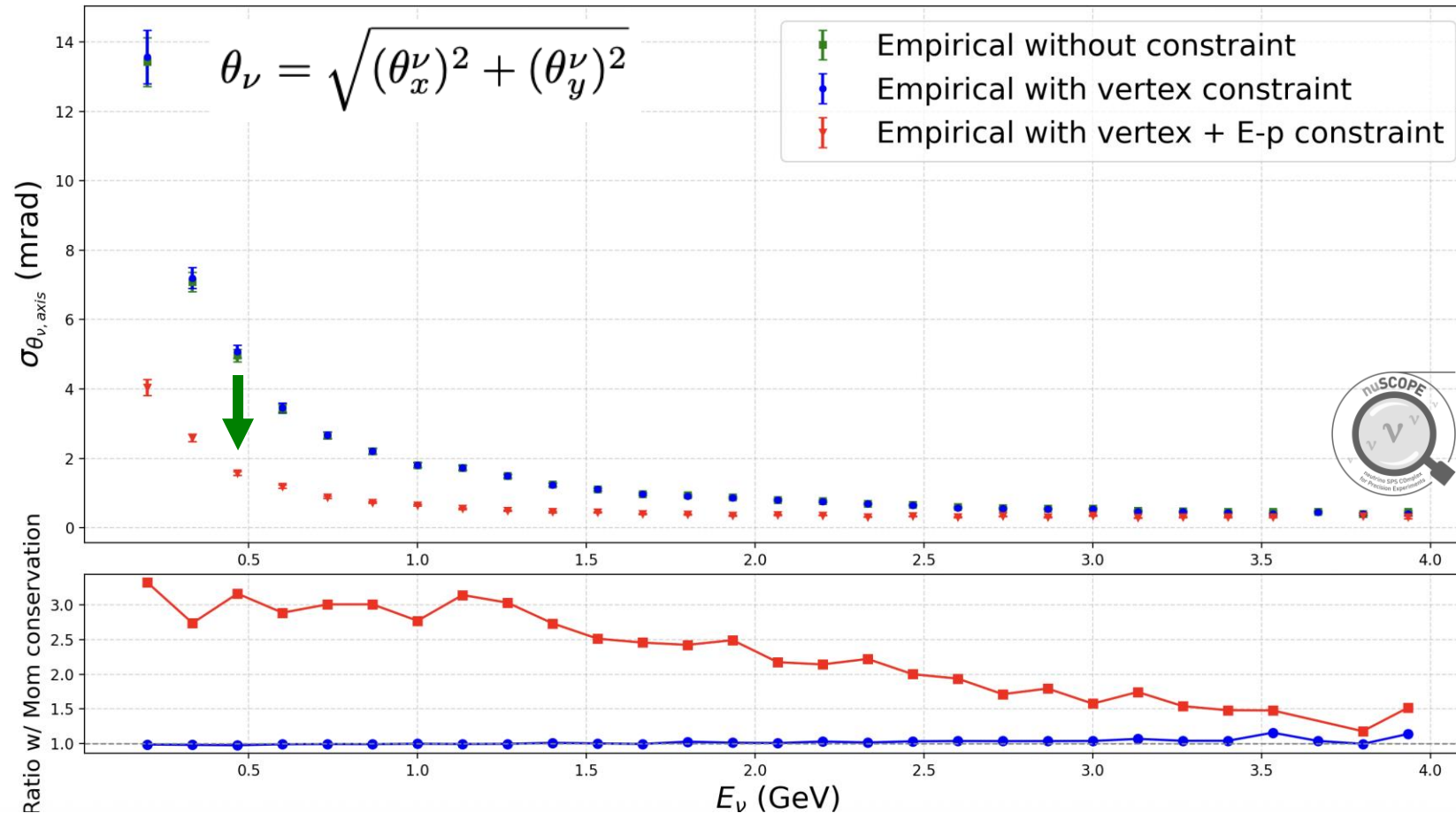
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III. Results on track fitting: neutrino angular resolution improvement with constrained fit

Monte-Carlo simulation on 10.000 events **assuming perfect meson/ μ association:**



By including E-p constraint, angular resolution is:

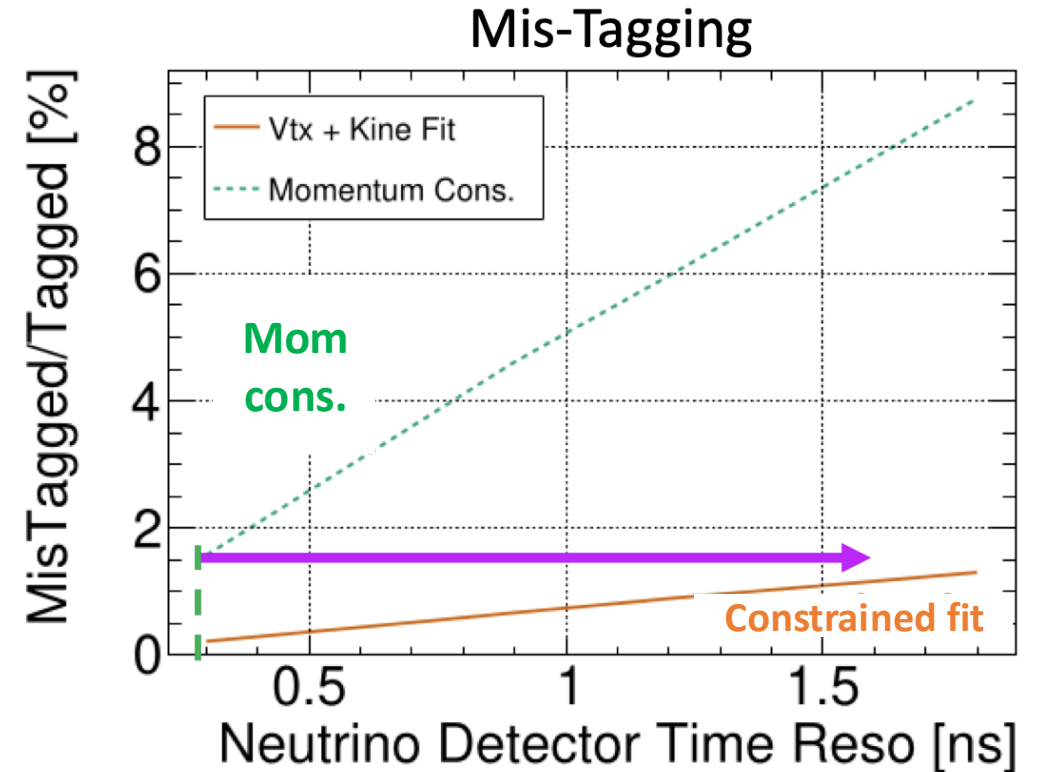
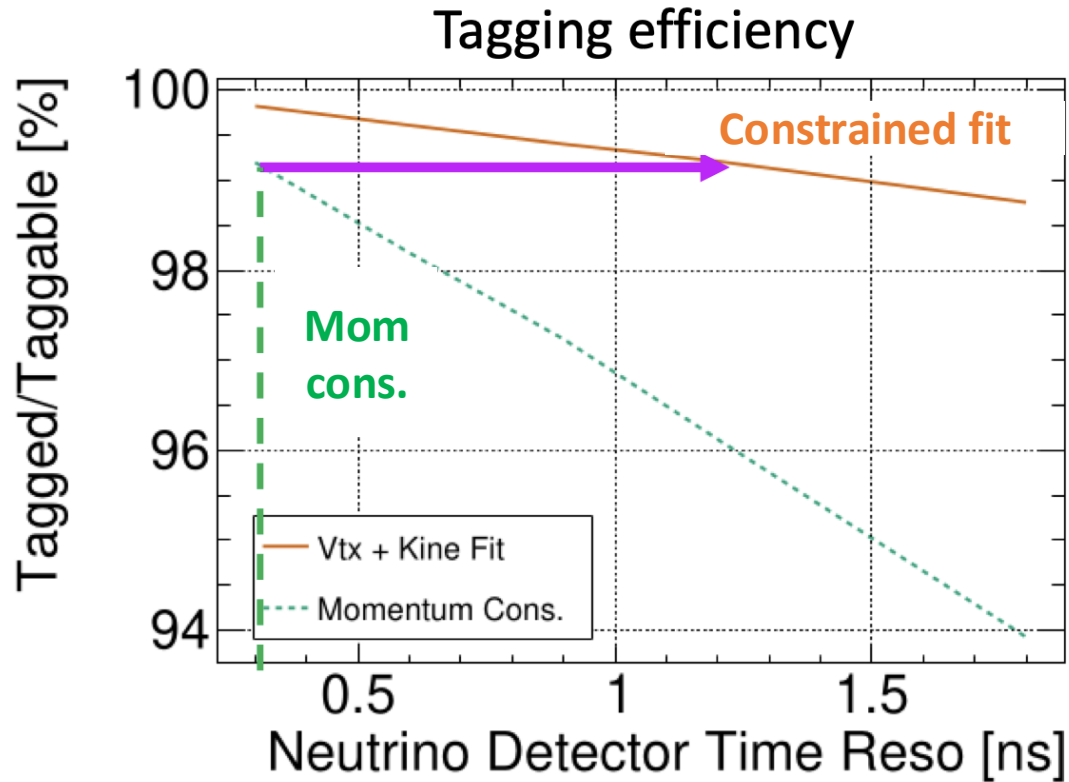
- improved by up to a factor of 3
- < 1 mrad for neutrinos above 1 GeV

What do we gain ?



III. Results on track fitting: relaxing neutrino detector time resolution

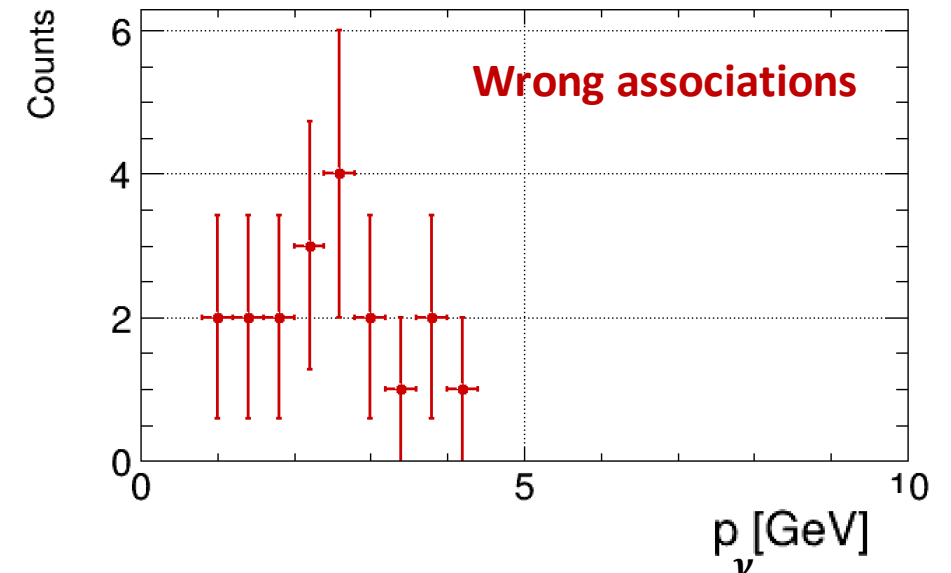
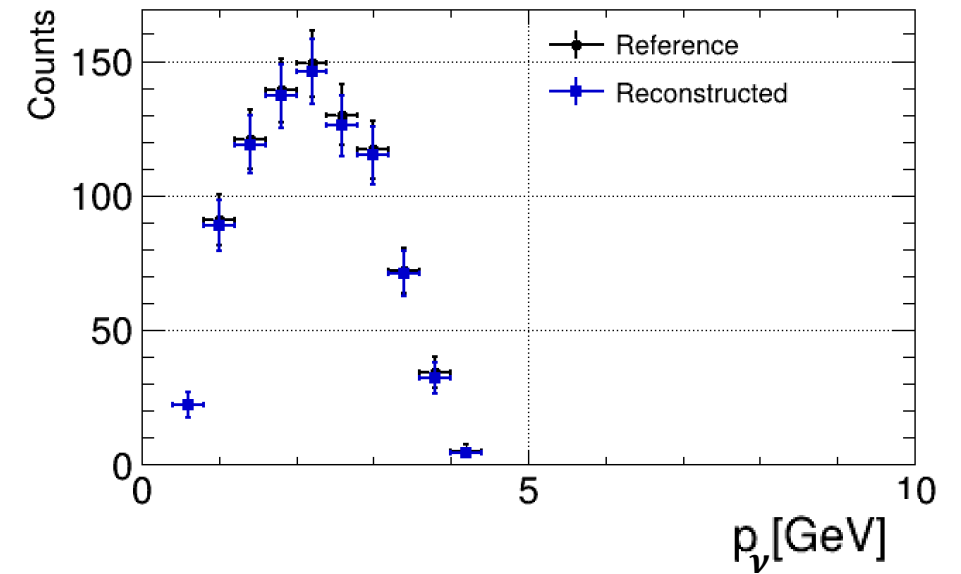
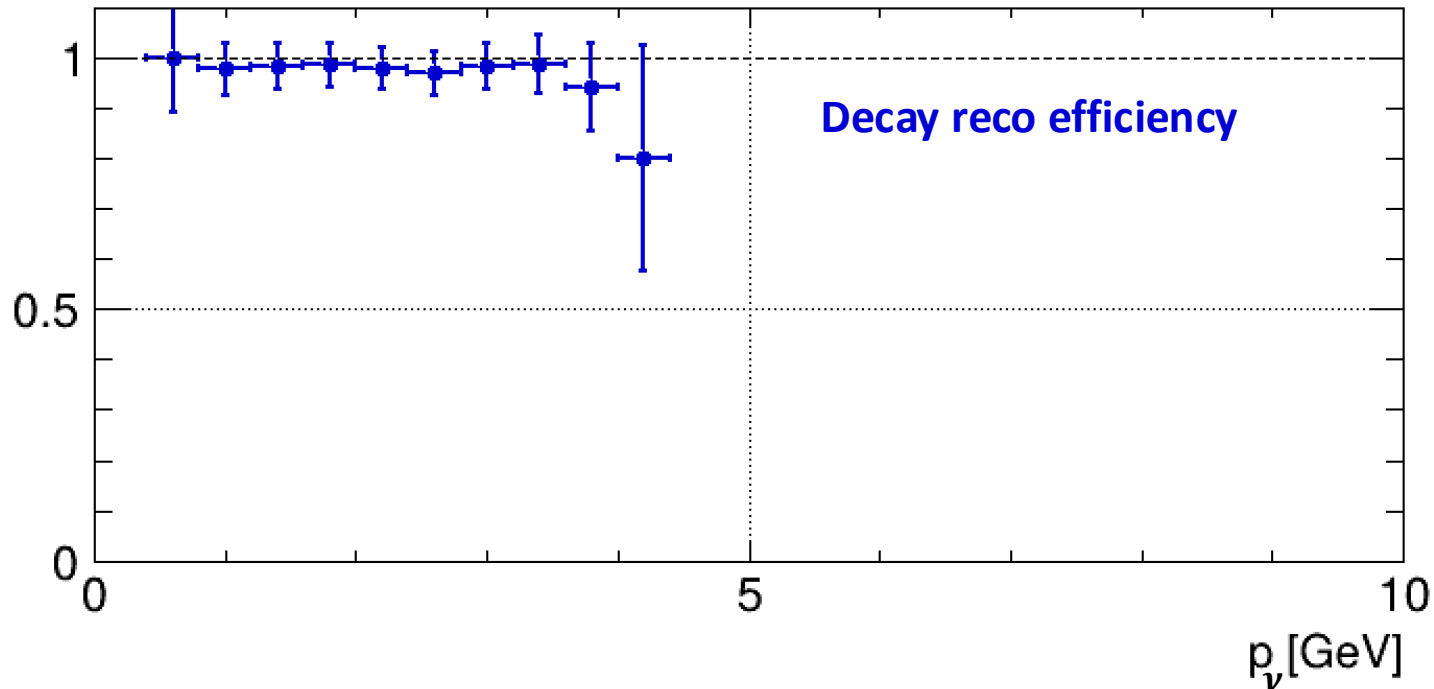
Assuming perfect meson/ μ association:



Constrained fit: improves ν_μ angular resolution \rightarrow relaxes the time resolution requirement

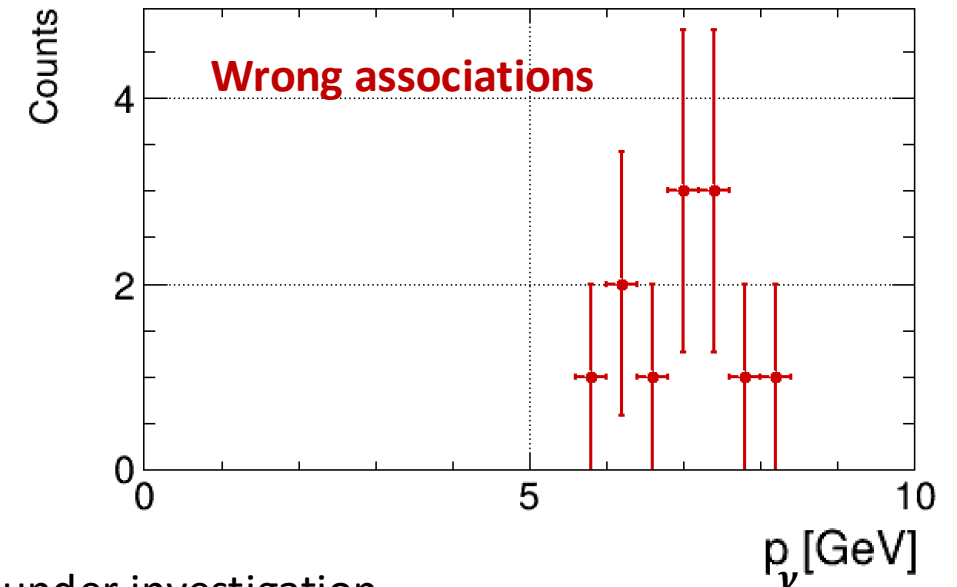
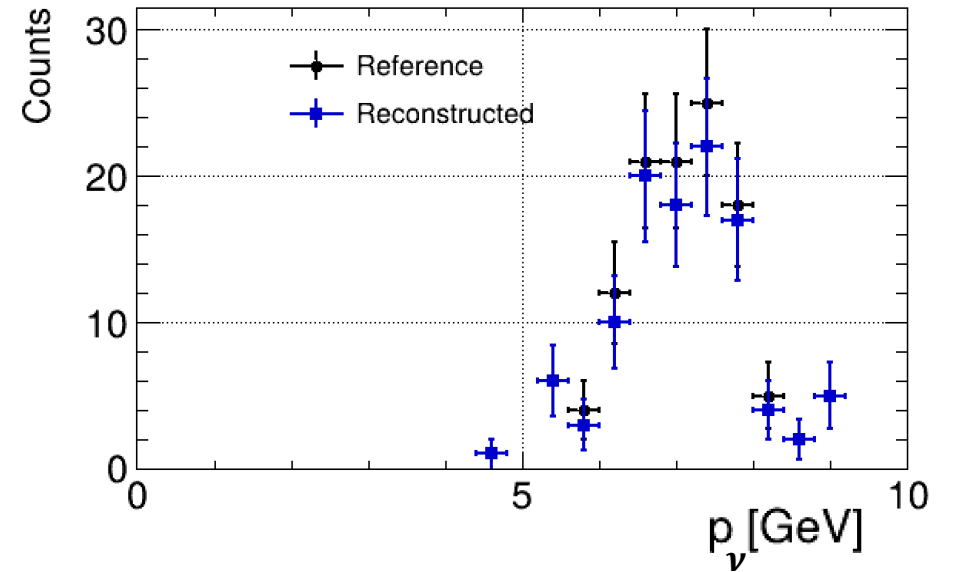
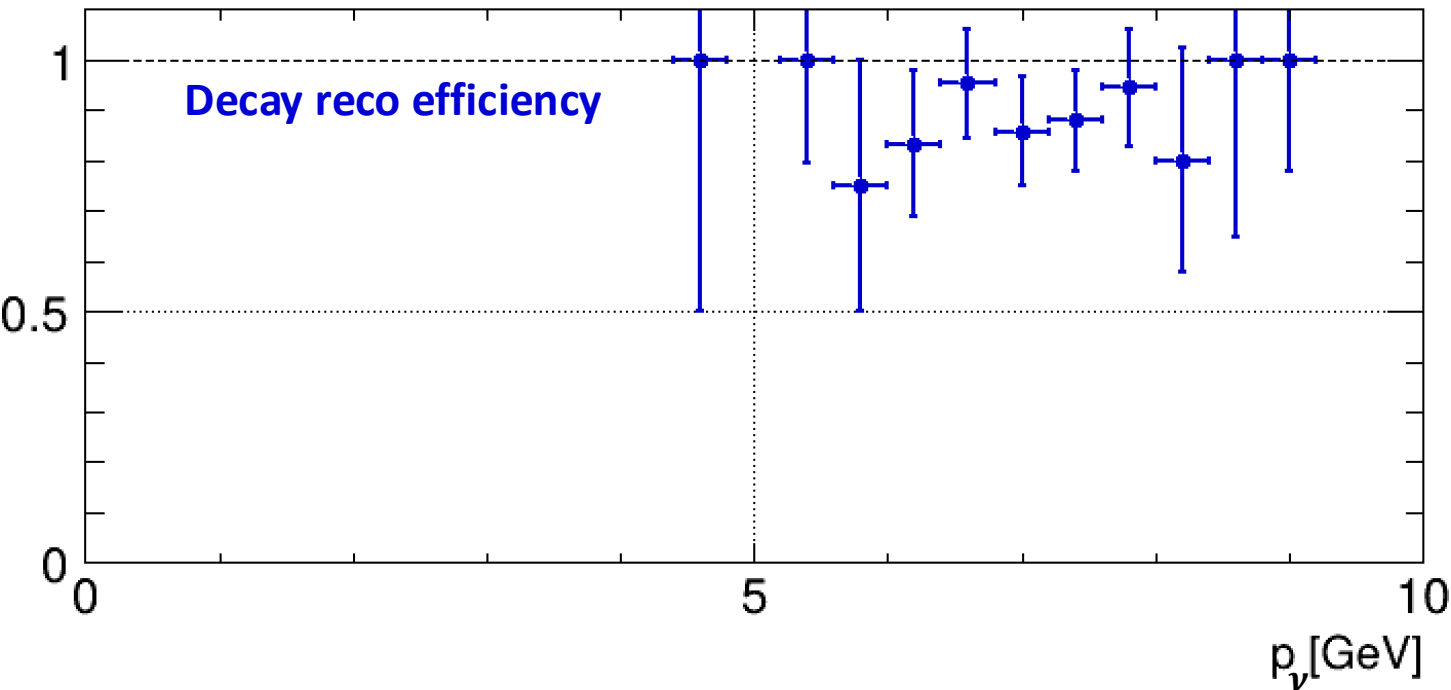
III. Results on track finding: decay reconstruction of pions

- For 1000 reference neutrino detections:
 - π/K and μ of reference in acceptance
 - ν_μ of reference in acceptance
 - 25 GHz pile-up rate
- Decay reco efficiency vs. ν_μ momentum for $\pi = 97\%$



III. Results on track finding: decay reconstruction of kaons

- For 1000 reference neutrino detections:
 - π/K and μ of reference in acceptance
 - ν_μ of reference in acceptance
 - 25 GHz pile-up rate
- Decay reco efficiency vs. ν_μ momentum $K = 90\%$

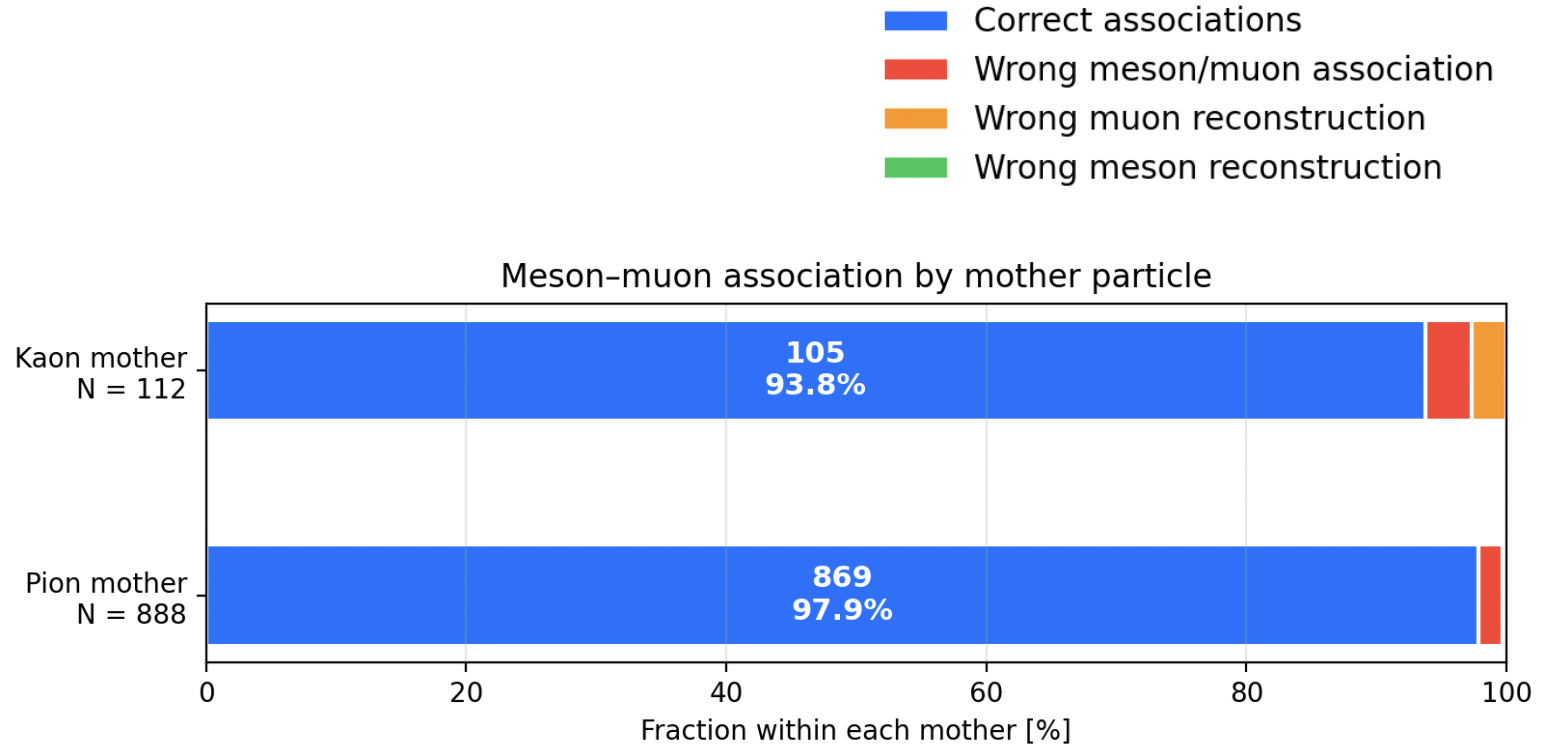


III. Results on track finding: origins of wrong decay reconstructions

- For 1000 reference neutrino detections:
 - π/K and μ of reference in acceptance
 - ν_μ of reference in acceptance
 - 25 GHz pile-up rate
 - Time window: 6.3ns

- 80% of wrong reconstructions due to wrong *meson*/ μ associations
- The rest is wrong μ reconstruction

Improvement strategy: test pair swaps of *meson*/ μ candidate pairs to recover some incorrect associations



Conclusion and perspectives

Implementation of a constrained kinematic fit

- Improve angular resolution by a factor > 2
- Required neutrino detector time resolution is relaxed by factor 4 while preserving tagging efficiency

Development of algorithms for the particle tracking and a decay reconstruction

- High decay reconstruction efficiencies (97% for pion decays and 90% for K decays)
- Promising preliminary results for tagging efficiency including reconstruction errors

Next steps

- Write the thesis 😊
- nuSCOPE Expression of Interest by end of 2026 including tagging efficiency study with all reconstruction errors