NEW PHYSICS SEARCHES IN BEAM DUMP AT NA62

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ON BEHALF OF THE NA62 COLLABORATION

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DIS2026

The NA62 Experiment

- NA62 is located in ECN3 hall at the CERN North Area
- SPS provides a 400 GeV Proton Beam
- Fixed target experiment
- Secondary beam of 6% K^+ with 75 GeV (Kaon factory)

The NA62 Physics Programme

Flavour Physics

Main goal: $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ measurement

[PoS(EPS-HEP2025)299]

Precision measurements of K^+ decays

$K^+ \to \pi^0 e^+ \nu \gamma$
$K^+ \to \pi^+ \gamma \gamma$
$K^+ \to \pi^+ \mu^+ \mu^-, \ldots$

Forbidden K^+ decays (LFV, LNV)

$K^+ \to \pi^+ e^+ \mu^-$
$K^+ \to \pi^- e^+ e^+$
$K^+ \to \pi^- \mu^+ e^+, \ldots$

Exotic searches

Normal data taking mode

- Search for **HNLs** in π^+ decay [j.physletb.2025.140119]

Beam dump mode

- Search for leptonic final states for **dark photon** [PhysRevLett.133.111802]
- Search for **ALPs** with $\gamma\gamma$ final states
- Search for semi leptonic final states for **HNLs**

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Flavour Physics

Main goal: $BR(K^+ \to \pi^+ \nu\bar{\nu})$ measurement

NEXT TALK

[PoS(EPS-HEP2025)299]

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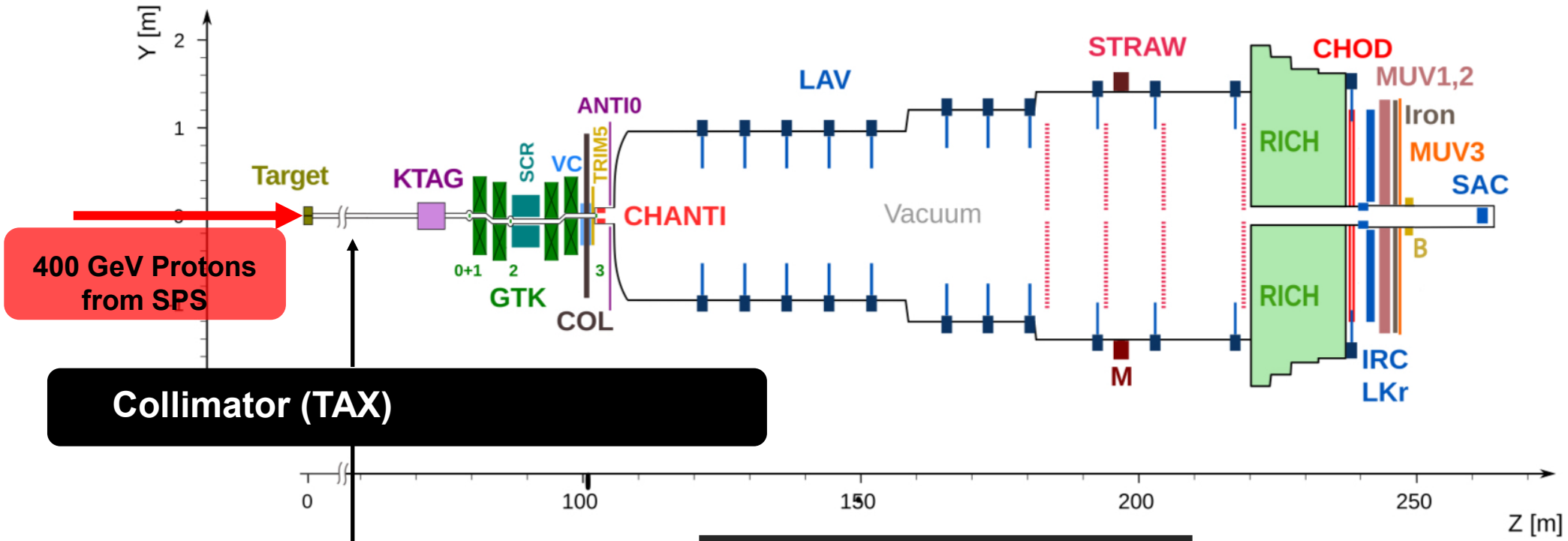
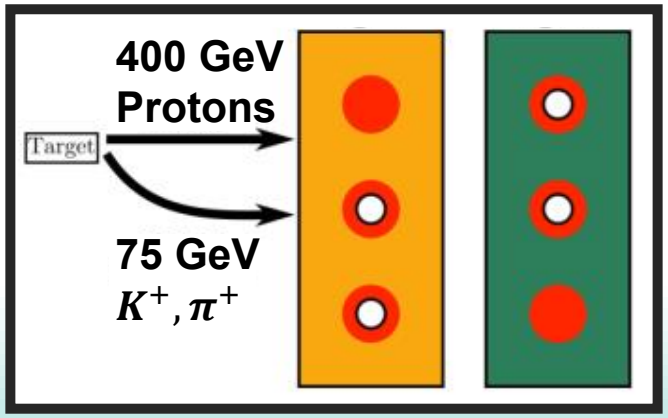
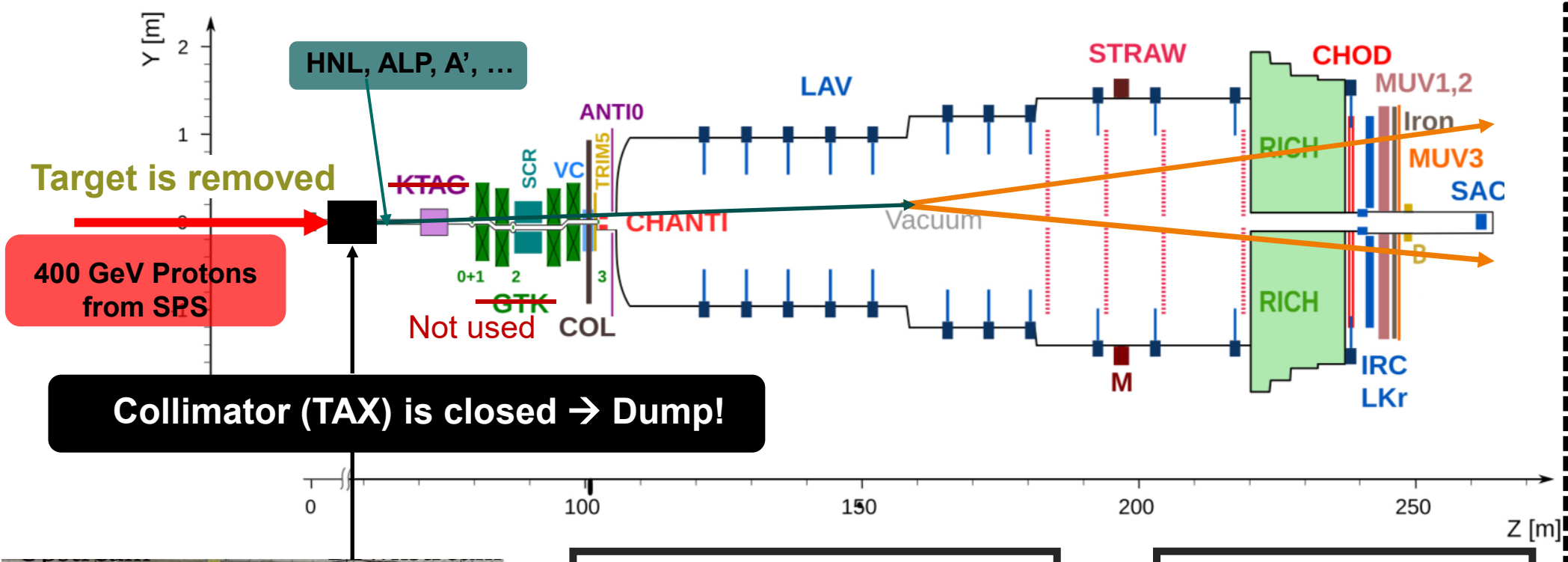
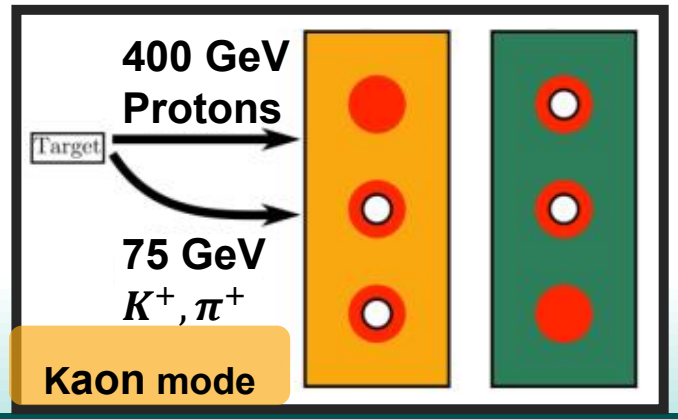
The NA62 Detector

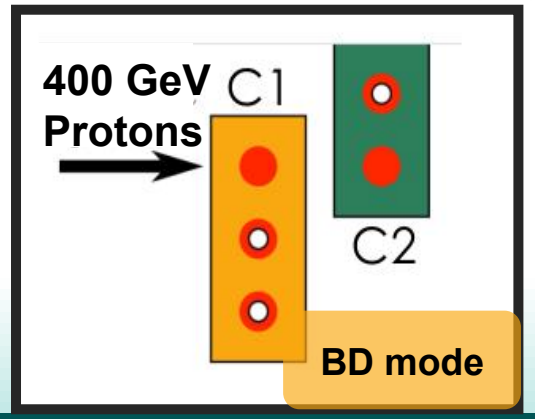




NA62 Detector in Beam Dump Mode







Veto Detectors

ANTI0, LAV, CHANTI

Downstream Tracker

STRAW

Em. Calorimeter

LKR

Hadronic Calorimeter

MUV1,2

Particle Identification

RICH, MUV3

Trigger

CHOD

Search Motivation for **H**eavy **N**eutral **L**eptons

- Coupling of HNLs N_I to Higgs doublet H and SM lepton doublet L_α:

$$\mathcal{L} \subset \sum_I F^*_{\alpha I}\, \bar{L}_\alpha\, \sigma_2 H^* N_I \longrightarrow U_{\alpha I} \approx \frac{|F_{\alpha I}| v}{\sqrt{2}\, m_{N_I}}$$

Yukawa coupling

mixing with SM neutrinos

- HNLs are a well-motivated extension to SM:
  - **Neutrino Masses**
  - **Baryon Asymmetry**
- **Production** in dump **via D mesons**
- Various HNL coupling scenarios tested simultaneously (different $U_e : U_\mu : U_\tau$)
- Targeted parameter space in **mass range** $\sim$ **400 *MeV* to 2 *GeV***
- From 2021, 2023, 2024 beam dump data: $(6.3 \pm 1.3) \times 10^{17}$ PoT

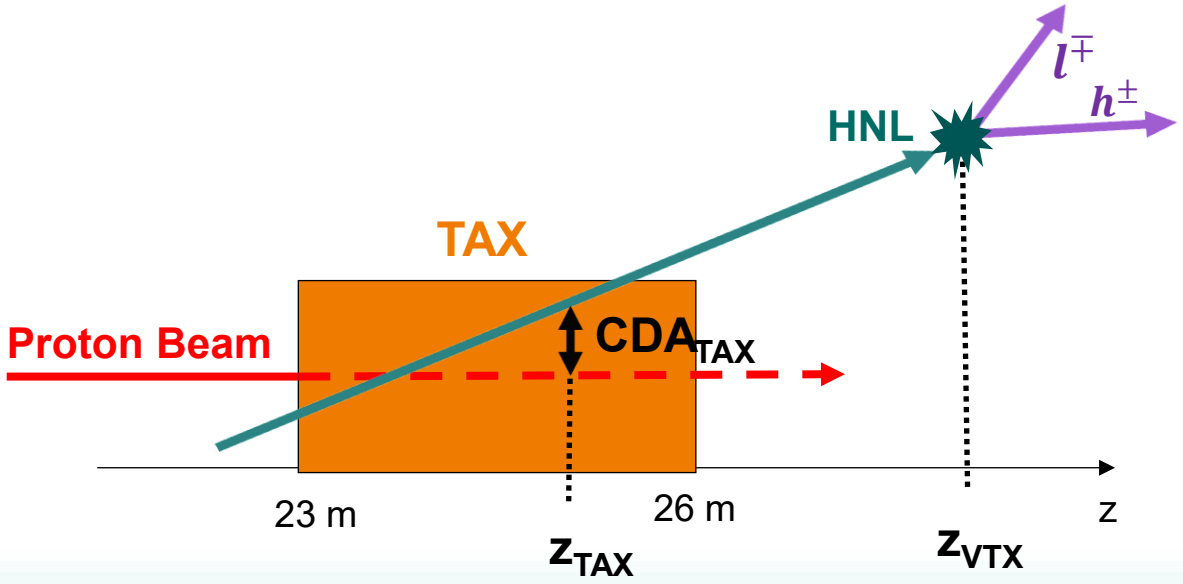
Analysis Strategy

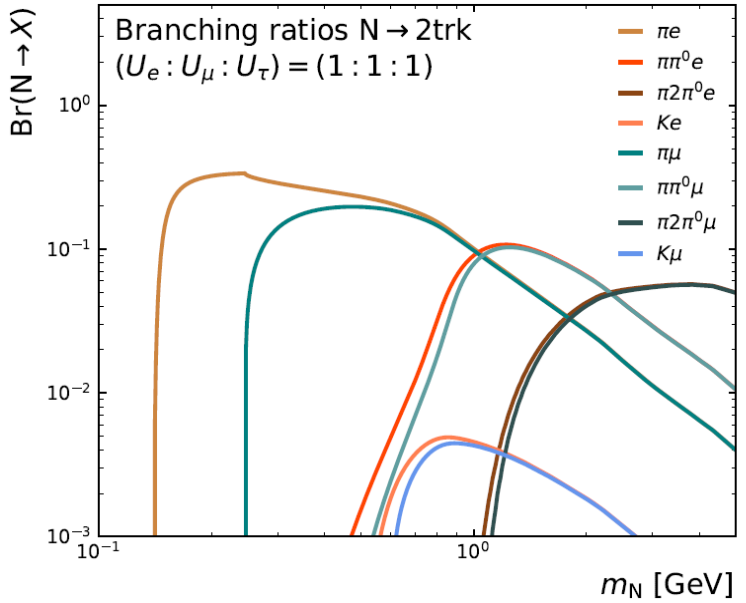
- Analysis focuses **on closed final states:**

$$h^{\pm}\, l^{\mp} \text{ with } h^{\pm} \in \left(\pi^{\pm}, \pi^{\pm}\pi^{0}, \pi^{\pm}2\pi^{0}, K^{\pm}\right),\ l^{\mp} \in \left(e^{\mp}, \mu^{\mp}\right)$$

→ **Vertex reconstruction** in **F**iducial **V**olume (FV)

→ Backtracking of HNL to production **point at TAX**





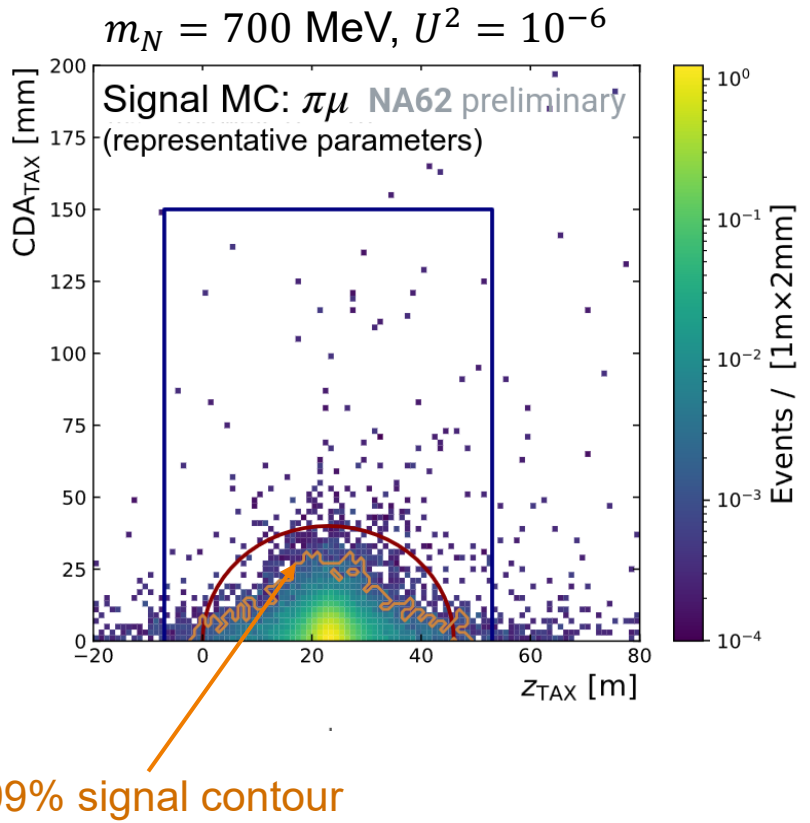
Channels are excellent for probing the targeted HNL parameter space

Event Selection

- **S**ignal **R**egion selection
- **Two tracks** with **opposite charge** (+ 1,2 or 4 neutral clusters in the electromagnetic calorimeter (LKr))
- **Good quality** of the reconstructed **vertex in FV**
- **Time coincidence** of tracks, trigger, and neutral cluster
- **No in-time veto** from LAV or geometrically associated in-time veto from Chanti of ANTI0
- Two neutral cluster with invariant mass $m = m_{\pi^0} \pm 15\ MeV$:

  → π^0 association

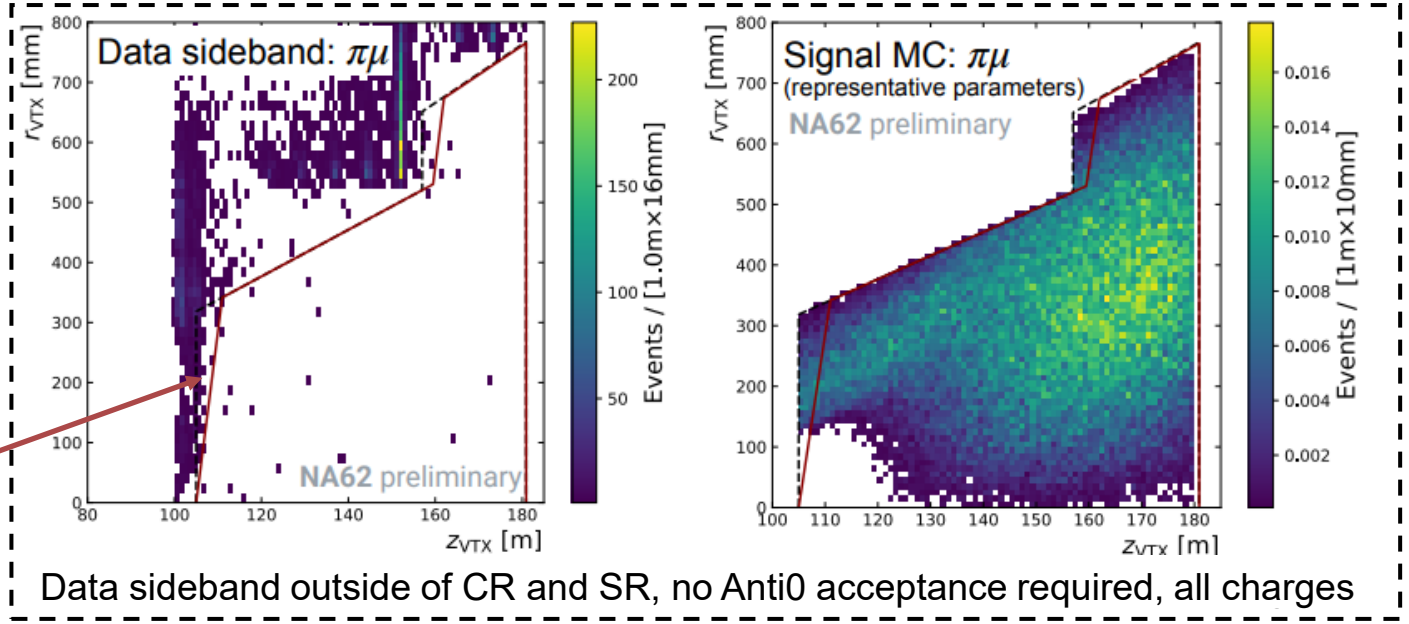
SR and CR kept blind until final box opening!



→ Almost all of the Signal is in the SR

Optimizing the Fiducial Volume

1. **Minimizing leakage of fake vertices** from interactions in upstream material
2. **Maximizing acceptance to HNLs** originating from charmed meson production
3. **Simplicity of resulting geometry**

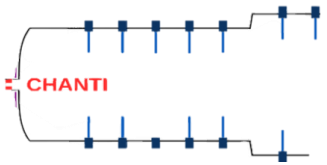


Data sideband outside of CR and SR, no Anti0 acceptance required, all charges

Shape of FV defined by 4 cones

(red line)

- Detector geometry



- Leakages of fake events grow with the radius r_{VTX}

Backgrounds

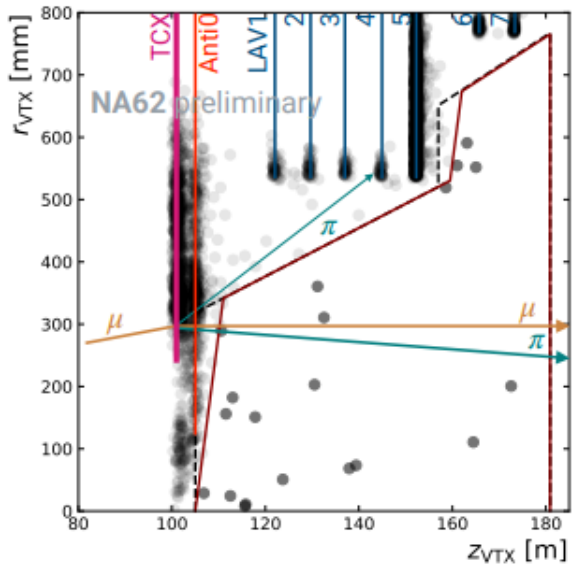
Three main background categories identified

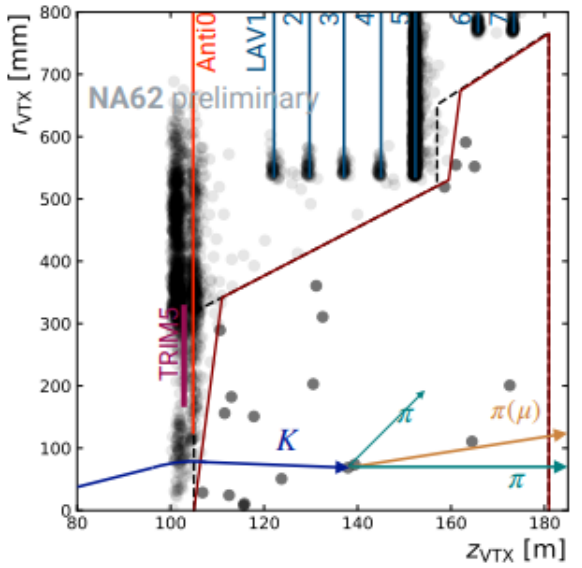
1. Prompt **muon interactions**
   - Photo-nuclear interactions of muons with material surrounding FV (e.g. $\mu \to \mu + \pi^+ + \pi^-$ and one π is lost)
   - events in acceptance, virtually fully vetoed by FV request and active veto systems $\mathcal{O}(1000)$

2. Decays of **upstream hadrons**
   - charged hadrons recaptured by (TRIM5) magnet, enter FV through uninstrumented center of ANTI0
   - partially reconstructed decay mimics signal (e.g. $\mathrm{K}^+ \to \pi^+ + \pi^+ + \pi^-$)
   - $\mathcal{O}$(few events) in acceptance, inherently hard to veto

3. Random **coincidence of unrelated tracks**
   - negligible for considered final states

[1]





[1] Data sideband outside of CR and SR, no Anti0 acceptance required

Prompt Muon Interactions

Large statistics of muon interactions are **needed** in MC

First try: First principle MC→ Big oversampling → non-physical assumptions → Data discrepancy

Prompt Muon Interactions

Large statistics of muon interactions are **needed** in MC

~~First principle MC → Big oversampling → non physical assumptions → Data discrepancy~~

Data driven backward MC (PUMAS):

1. From single μ track **data** the ***μ*-spectrum downstream** is known
   → PUMAS **backwards propagates** the ***μ*-spectrum upstream** (where no measurement is possible)
2. Particle gun in **forward MC** samples from upstream μ-spectrum.
   → Comparison between data and MC
3. Discrepancies can be resolved by unfolding in kinematic variables and **reweighting** the upstream μ-spectrum.

Prompt Muon Background Validation

Challenge: Statistics of the MC sample is too low to evaluate the expectations for the veto systems (and CR/SR) for the $\pi\mu X, \pi e X$ channels

Solution: $e\mu$ events used as a proxy to calculate rejection factors

- They share the same production mechanism
- Similar behavior of CDA_{TAX} Vs z_{TAX}

Validation with **sideband outside CR** and **SR:**

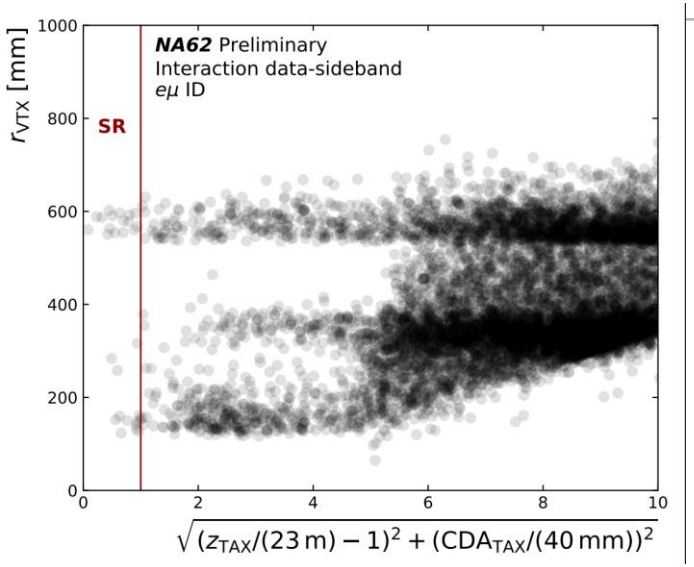
PID	$e\mu$			$\pi\mu$		
condition	N_{exp}	N_{obs}	$p(L < L_{obs})$	N_{exp}	N_{obs}	$p(L < L_{obs})$
no veto	$251 \pm 41\|_{stat} \pm 125\|_{syst}$	214	0.78	$13 \pm 7\|_{stat} \pm 5\|_{syst}$	11	0.91
CHA	$229 \pm 40\|_{stat} \pm 114\|_{syst}$	174	0.65	$13 \pm 7\|_{stat} \pm 5\|_{syst}$	7	0.56
CHA-LAV	$18 \pm 8\|_{stat} \pm 9\|_{syst}$	28	0.43	$6.5 \pm 2.8\|_{stat} \pm 2.8\|_{syst}$	0	0.22
CHA-A0	$25 \pm 20\|_{stat} \pm 13\|_{syst}$	1	0.14	$3.0 \pm 0.6\|_{stat}{}^{+1.6}_{-1.2}\|^{*}_{syst}$	1	0.51
CHA-LAV-A0	$\mathbf{1.5 \pm 0.3\|_{stat}{}^{+2.4}_{-1.1}\|^{*}_{syst}}$	**0**	**0.62**	$\mathbf{1.0 \pm 0.1\|_{stat} \pm 0.5\|^{*}_{syst}}$	**0**	**0.67**

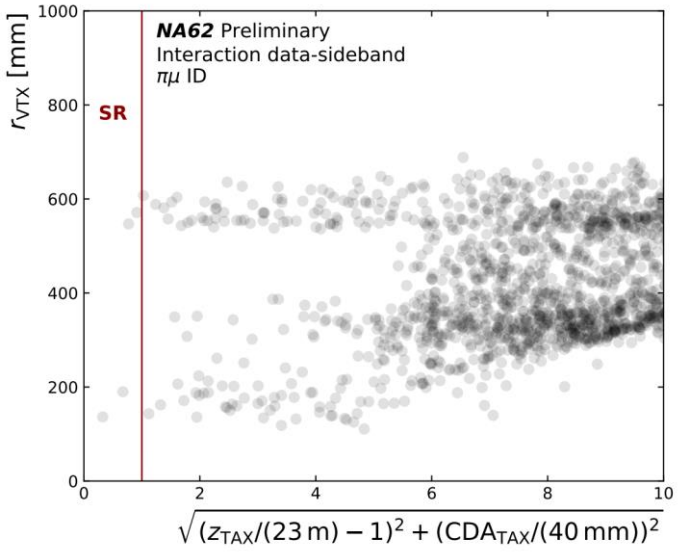
All charge events in FV. Entries marked with * derived from rejection factors and contain both stat. and syst. uncertainty

Good agreement of expectations with data

N_{exp} from prompt μ interactions after **full selection**:

below $\mathbf{1.3 \times 10^{-4}}$ **in CR**, below $\mathbf{3 \times 10^{-5}}$ **in SR**

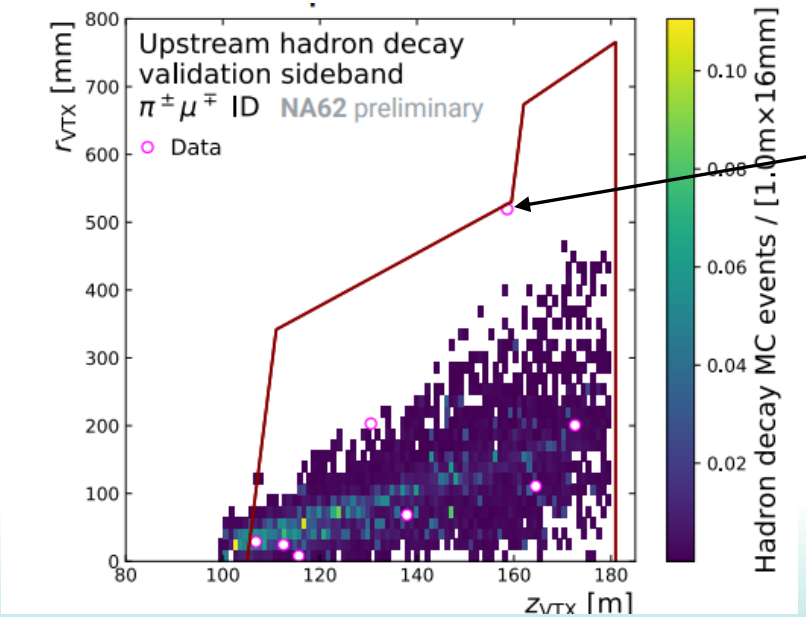




Upstream Hadron Decays

Estimation of upstream background with **MC** using a **data-based hadron gun**:

- Single K^+ tracks (identified by RICH are back extrapolated upstream)
- Back extrapolated K^+ as a gun for NA62MC
- Upscaling until observed $K^+_{3\pi}$



Validation on sideband outside CR and SR

- No CHANTI and ANTI0 veto and association requirements
  → increase of statistics for comparison

Hadron events and prompt events:

channel	$N_{exp} \pm \delta N_{exp}$	N_{obs}	$p(L < L_{obs})$
$\pi^\pm\mu^\mp$	$9.4 \pm 2.0\|^{+4.4}_{-3.5}\|_{syst}$	8	0.93
$\pi^\pm\mu^\mp\pi^0$	$(3.4 \pm 0.5\|^{+2.2}_{-1.5}\|_{syst}) \times 10^{-2}$	0	> 0.99
$\pi^\pm\mu^\mp 2\pi^0$	$(2.9 \pm 0.3\|^{+3.6}_{-1.9}\|_{syst}) \times 10^{-3}$	0	> 0.99
$K^\pm\mu^\mp$	$0.14 \pm 0.01\|^{+0.08}_{-0.05}\|_{syst}$	0	> 0.99
$\pi^\pm e^\mp$	$2.0 \pm 0.1\|^{+1.0}_{-0.9}\|_{syst}$	2	> 0.99
$\pi^\pm e^\mp\pi^0$	$(2.9 \pm 0.3\|^{+1.4}_{-1.3}\|_{syst}) \times 10^{-2}$	0	> 0.99
$\pi^\pm e^\mp 2\pi^0$	$(2.8 \pm 0.9\|^{+1.3}_{-1.1}\|_{syst}) \times 10^{-4}$	0	> 0.99
$K^\pm e^\mp$	$(8.5 \pm 2.0\|^{+3.8}_{-3.5}\|_{syst}) \times 10^{-3}$	0	> 0.99

Good agreement of expectations with data

Total Expected Background Overview

N_{exp} after full selection in CR and SR fully **dominated by hadron decays** events

channel	$N_{\text{exp}}^{\text{CR}} \pm \delta N_{\text{exp}}^{\text{CR}}$	$N_{\text{exp}}^{\text{SR}} \pm \delta N_{\text{exp}}^{\text{SR}}$
$\pi^{\pm}\mu^{\mp}$	$(1.1^{+0.8}_{-0.6}) \times 10^{-2}$	$(9.3^{+7.4}_{-5.3}) \times 10^{-3}$
$\pi^{\pm}\mu^{\mp}\pi^0$	$(2.0^{+1.9}_{-1.2}) \times 10^{-6}$	$(1.4^{+1.2}_{-0.8}) \times 10^{-6}$
$\pi^{\pm}\mu^{\mp}2\pi^0$	$(1.0^{+2.5}_{-0.8}) \times 10^{-7}$	$(2.0^{+6.0}_{-1.7}) \times 10^{-8}$
$K^{\pm}\mu^{\mp}$	$(5.6^{+6.5}_{-3.5}) \times 10^{-6}$	$(2.8^{+2.9}_{-1.8}) \times 10^{-6}$
$\pi^{\pm}e^{\mp}$	$(2.6^{+2.7}_{-1.7}) \times 10^{-3}$	$(2.9^{+3.4}_{-2.0}) \times 10^{-3}$
$\pi^{\pm}e^{\mp}\pi^0$	$(3.2^{+3.9}_{-2.2}) \times 10^{-5}$	$(3.5^{+4.7}_{-2.5}) \times 10^{-5}$
$\pi^{\pm}e^{\mp}2\pi^0$	$(1.5^{+4.3}_{-1.3}) \times 10^{-9}$	$(3.0^{+10.1}_{-2.6}) \times 10^{-10}$
$K^{\pm}e^{\mp}$	$(5.9^{+8.8}_{-4.3}) \times 10^{-7}$	$(6.0^{+10.5}_{-4.7}) \times 10^{-7}$

Search is essentially background-free

Probability of non-zero observation from background only hypothesis: 1.6% in CR and 1.5% in SR

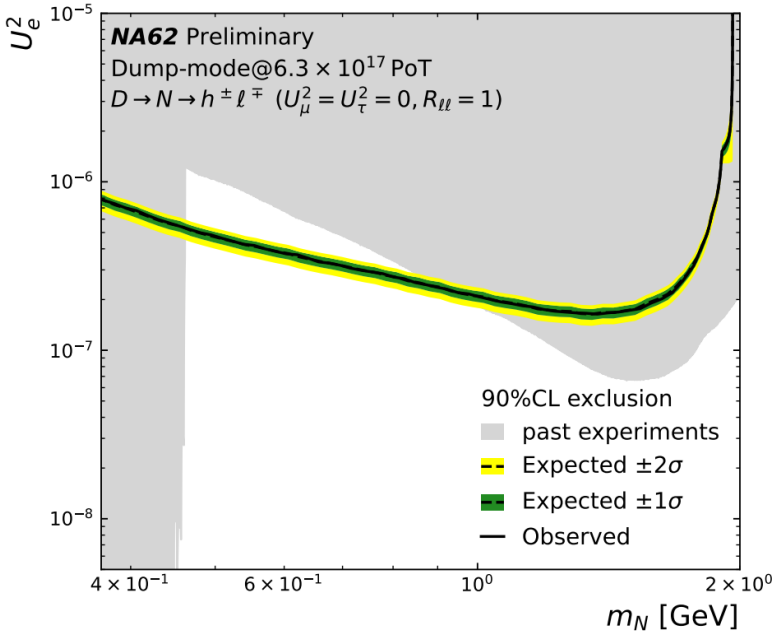
Final Result and Interpretation

No event observed across all signal categories

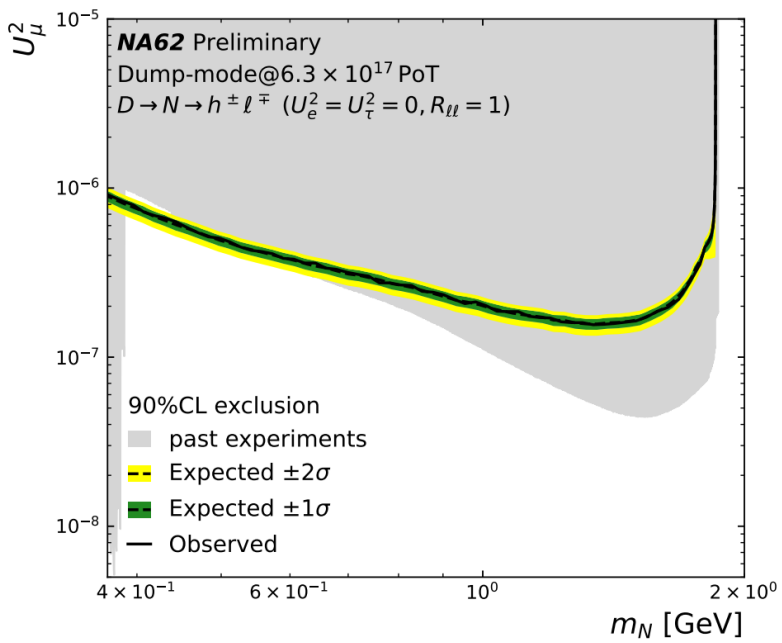
Final Result and Interpretation

90 % CL exclusion for various HNL coupling scenarios $U_{\alpha I} \approx \frac{|F_{\alpha I}|v}{\sqrt{2}\, m_{N_I}}$

BC6



BC7

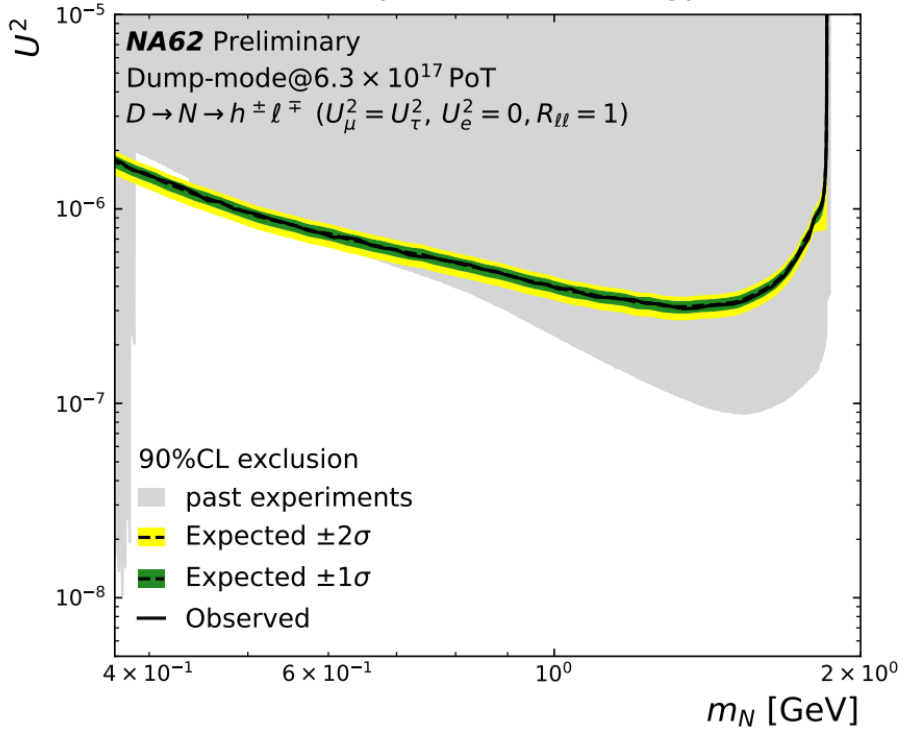


Model interpretation using ALPINIST software framework [JHEP 02(2025)140]

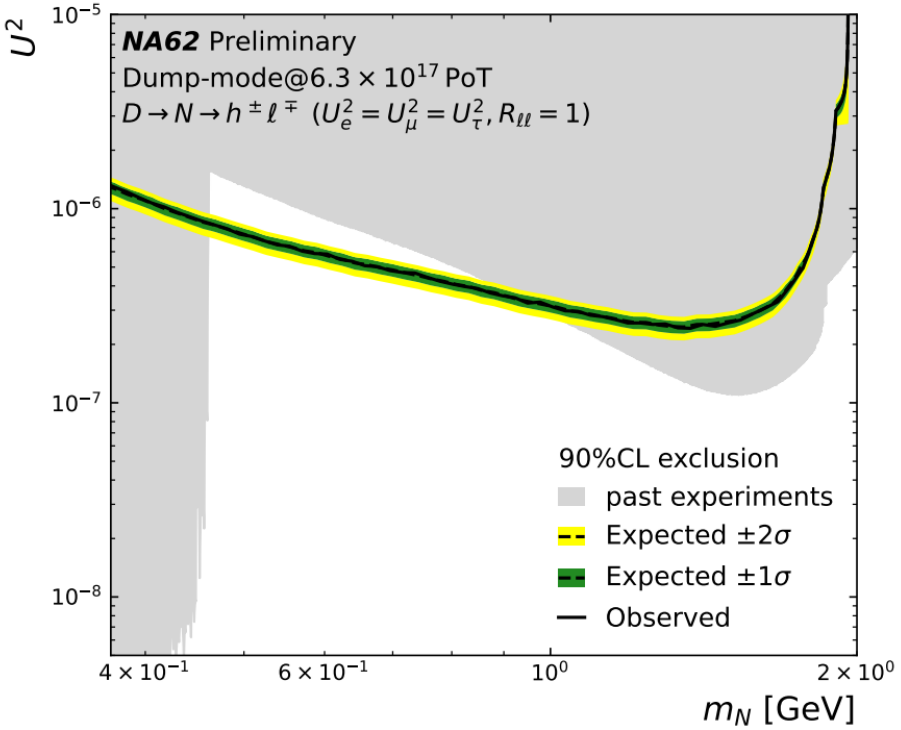
Final Result and Interpretation

Interpretation of results with **phenomenologically relevant coupling structures** [EPJC 82(2022)12,1176]

DKL3a (normal ordering)



DKL3b (inverse ordering)



Model interpretation using ALPINIST software framework [JHEP 02(2025)140]

Summary

- Preliminary results on the **beam dump search for Heavy Neutral Leptons** with data collected by the NA62 experiment in beam-dump mode have been presented:
  - Analysis essentially **background-free**
  - **Blind analysis technique** – **No signal candidate observed**
  - **Excluded parameter space** at level of $U^2 < 10^{-6}$ for HNL masses in 500-1000 MeV range
- Incorporation of 2025 and 2026 data will increase the statistical power by ≈ 2
- Searches for dark-sector particles e.g. with di-gamma final states or di-leptonic final states with the combined data set are ongoing

Backup

Data Driven Backward MC

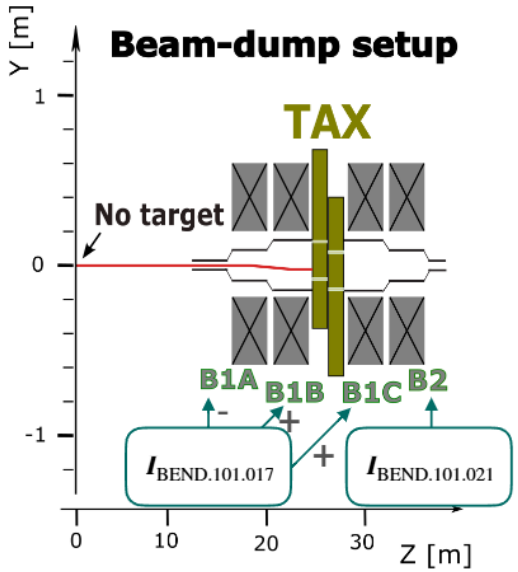
1. From single μ track **data** the **μ-spectrum downstream** is known
   → PUMAS **backwards propagates** the **μ-spectrum upstream** (where no measurement is possible)
2. Particle gun in **forward MC** samples from upstream μ-spectrum.
   → Comparison between data and MC
3. Discrepancies can be resolved by unfolding in kinematic variables and **reweighting** the upstream μ-spectrum.

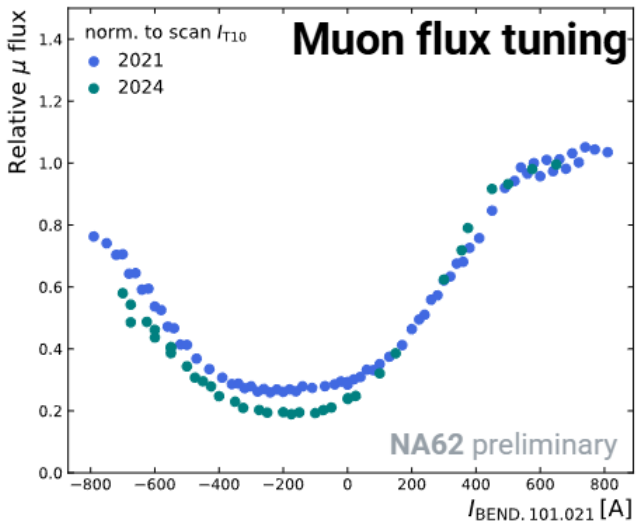
Discrepancies originate from:

1. Systematic error in MC (treatment of multiple scattering in GEANT4, PUMAS)
2. Sweeping of muons

→ Backward MC only done for 2021 data taking conditions

→ Unfolding and reweighting can adjust for difference in data taking conditions





Particle Identification:

CloPID: Classifier based on a Convolutional neural network (CNN)

identification probability
p_{ID} is too low

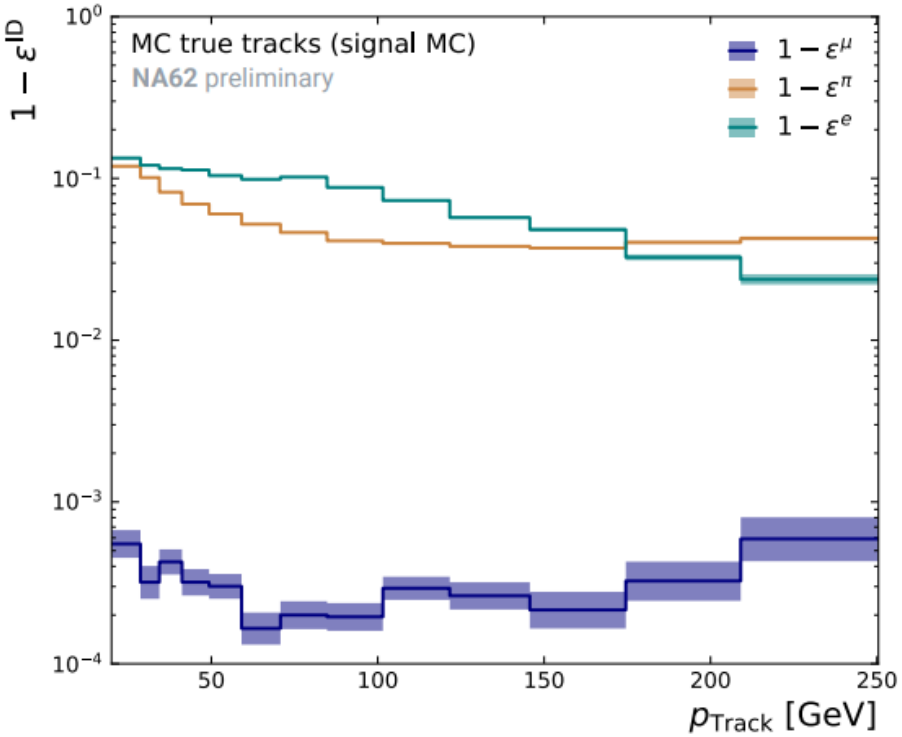
Spectrometer-Calorimeter Association-tool: based on boosted decision trees (BDTs)

identification probability
p_{ID} is too low

PID Algorithm from di-lepton Analysis: based on E/p ratio with E from LKr Cluster and p from STRAW track

identification as hadron

RICH used to separate Kaons and Pions



Systematic Uncertainties

Main source of **uncertainty**:
Integrated PoT ($\approx 20\,\%$) due to T10 intensity uncertainty
→ Paper by CERN-BE (study in an advanced stage) is planning to reduce this

Source	Uncertainty	Relative correction
Statistics	0.4 %	–
PID $h\mu/he$	1.5 %/2.3 %	– / −1.2 %
NewCHOD association	0.6 %	−1.2 %
Trigger	0.2 %	−1.0 %
Straw quality and resolution	1.5 %	–
LAV random veto	–	−0.7 %
A0 random veto	–	−0.4 %
CHA random veto	0.1 %	−0.2 %
Total $h\mu/he$	2.3 %/2.9 %	−3.5 %/−4.7 %

Summary of uncertainties and corrections to the signal selection efficiency.
Difference between final states featuring μs and es is due to PID validation.

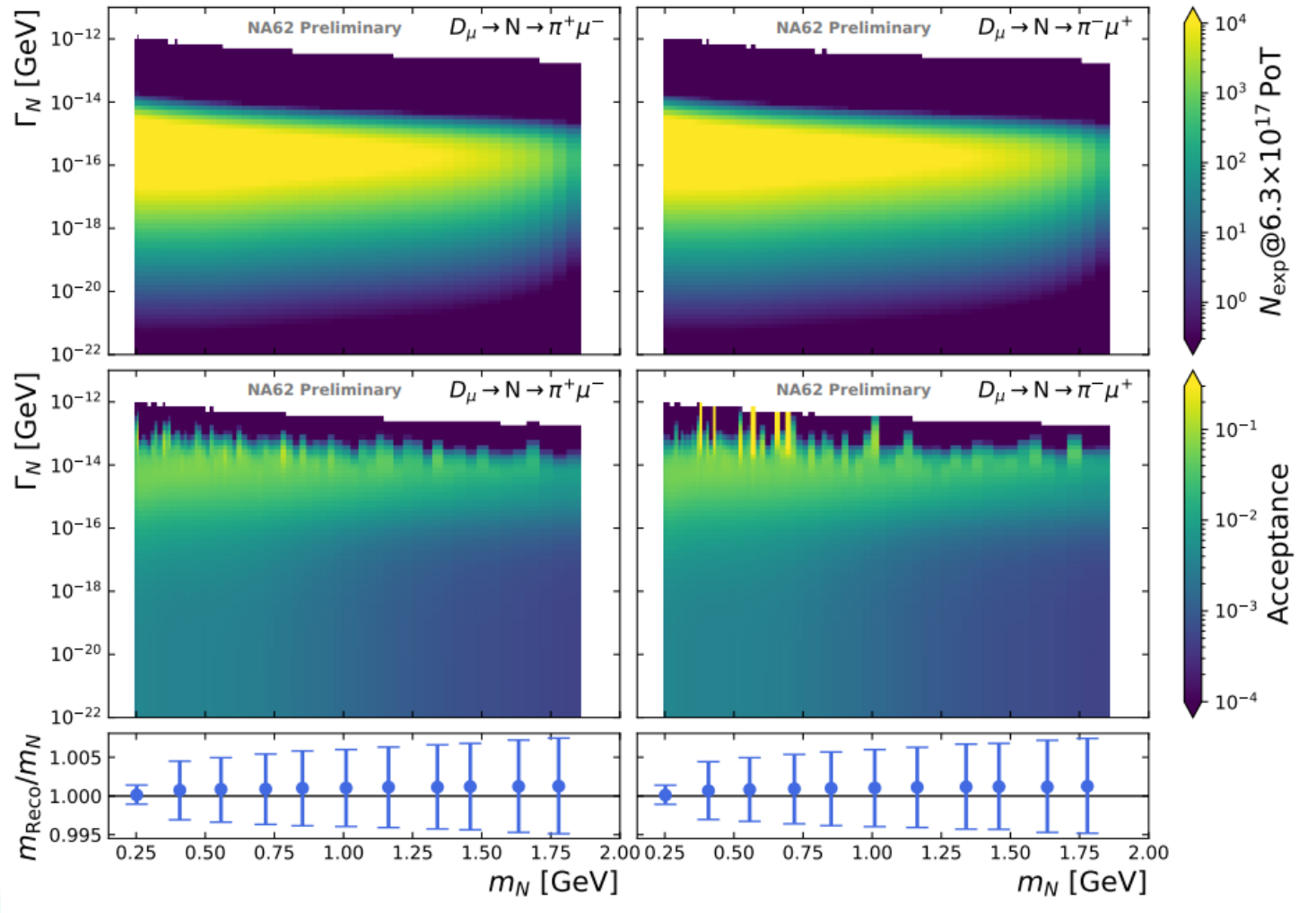
Main source of **theory uncertainty**:
description of D meson production ($\approx 30\,\%$)

Further information on theory related uncertainty can be found in [JHEP 02 (2025) 140]

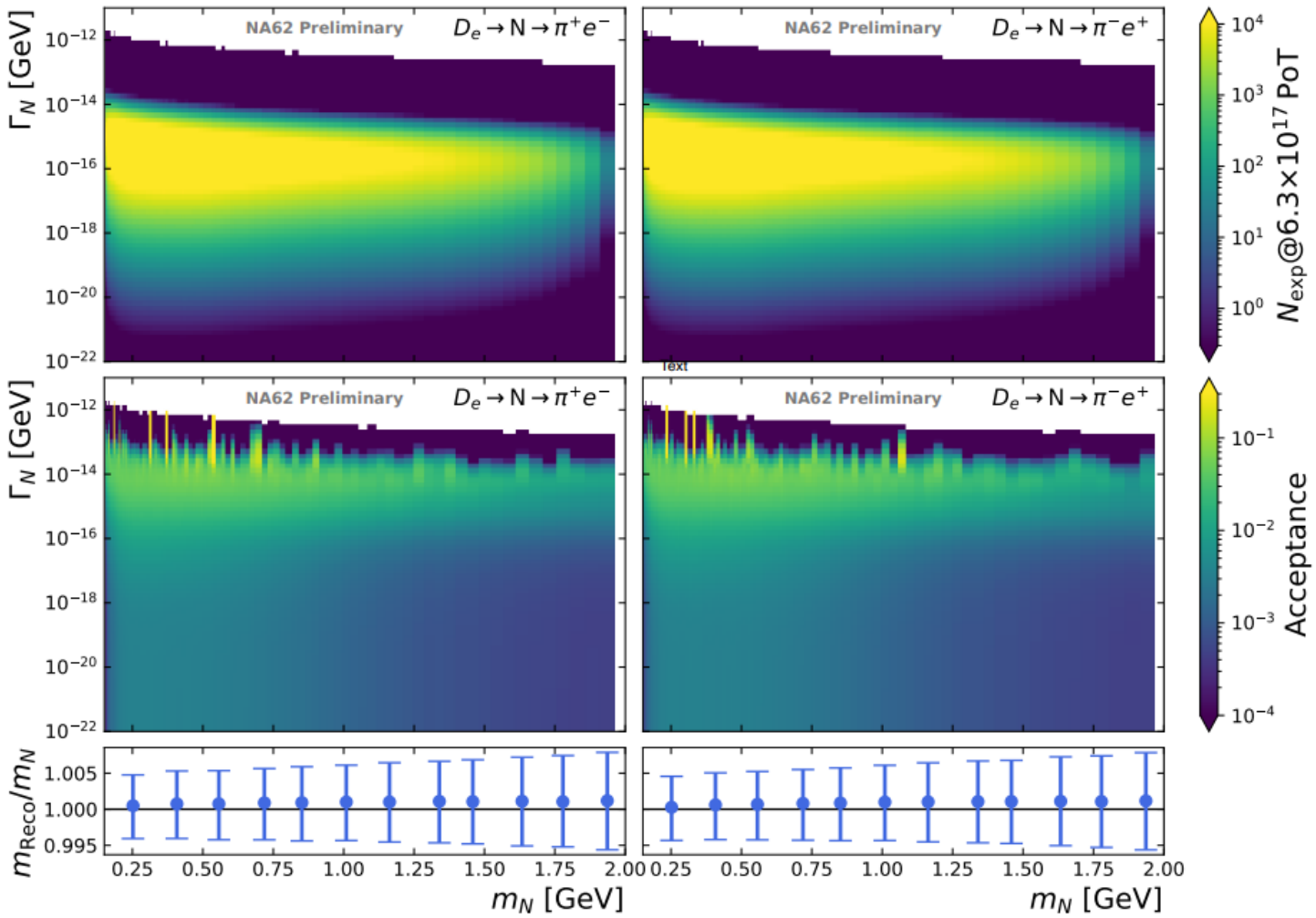
Analysis Sensitivity

$$N_{exp} = POT \times \chi_{pp\to N} \times \mathcal{B}(N \to \pi\mu) \times P_{rd} \times A_{acc} \times A_{trig}$$

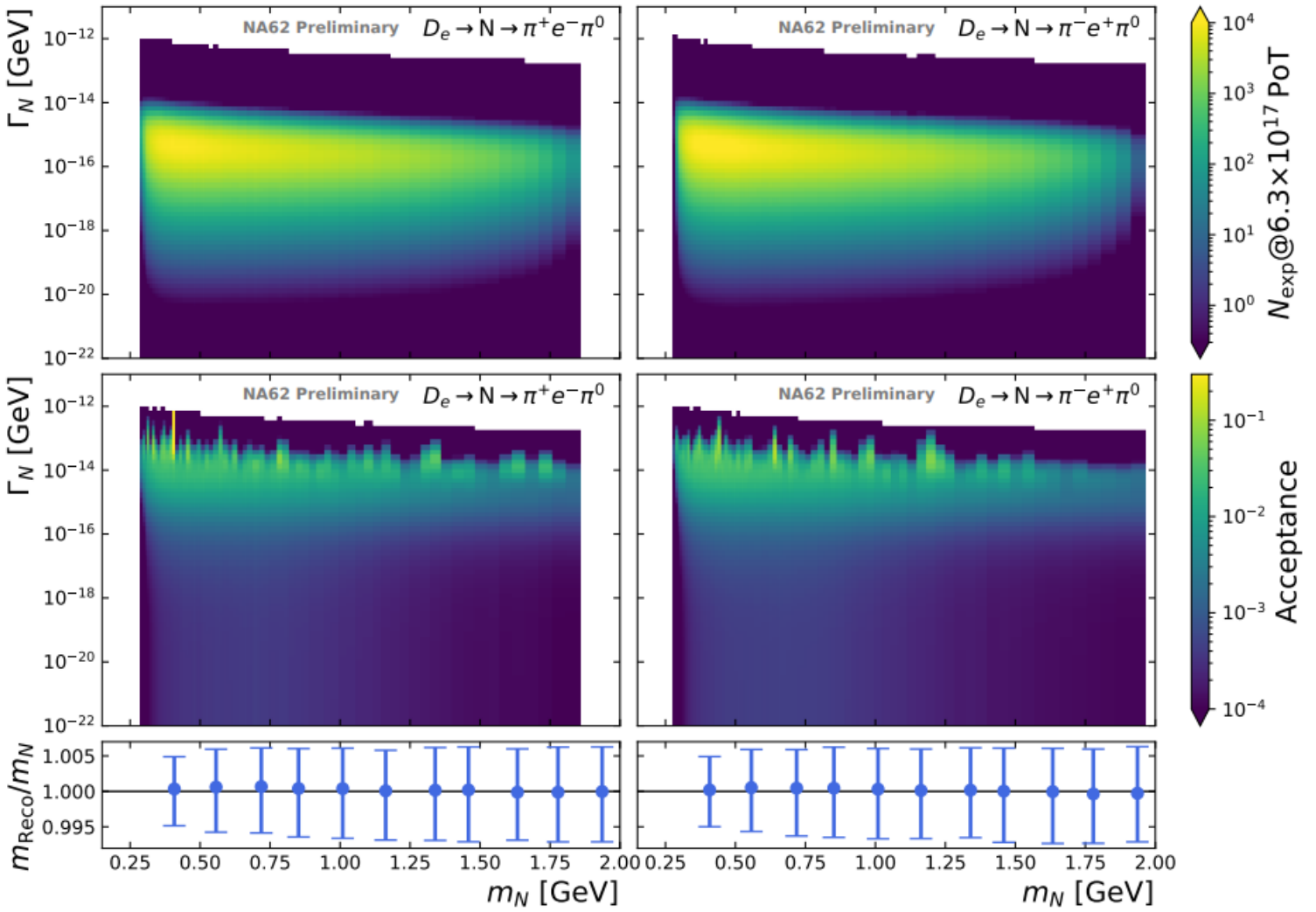
$POT =$	$(6.3 \pm 1.3) \times 10^{17}$
$\chi_{pp\to N}$	HNL production probability
$\mathcal{B}(N \to \pi\mu)$	branching fraction
P_{rd}	probability to reach NA62 decay volume and decay therein
$A_{acc} \times A_{trig}$	signal selection and trigger efficiencies



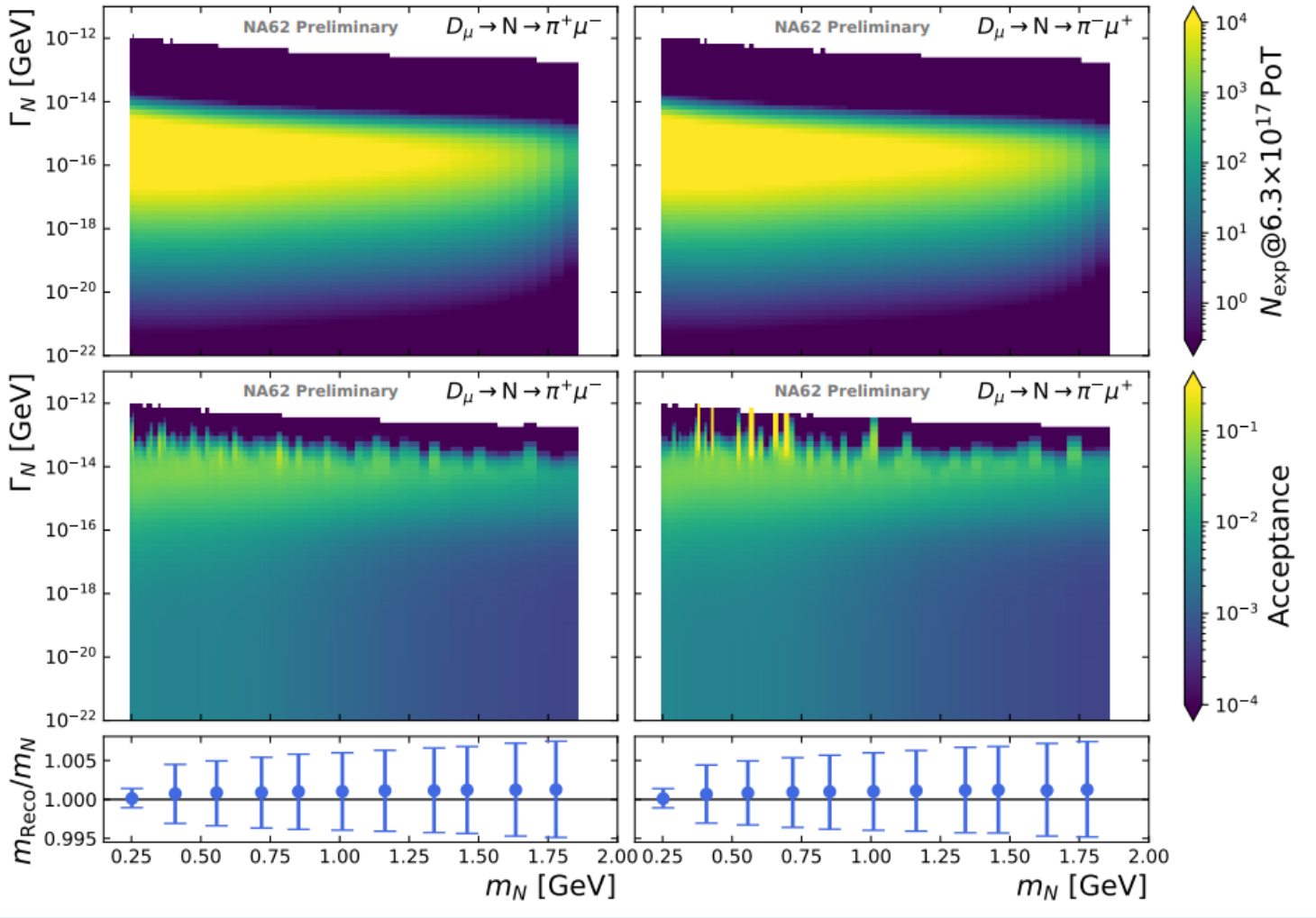
Analysis Sensitivity



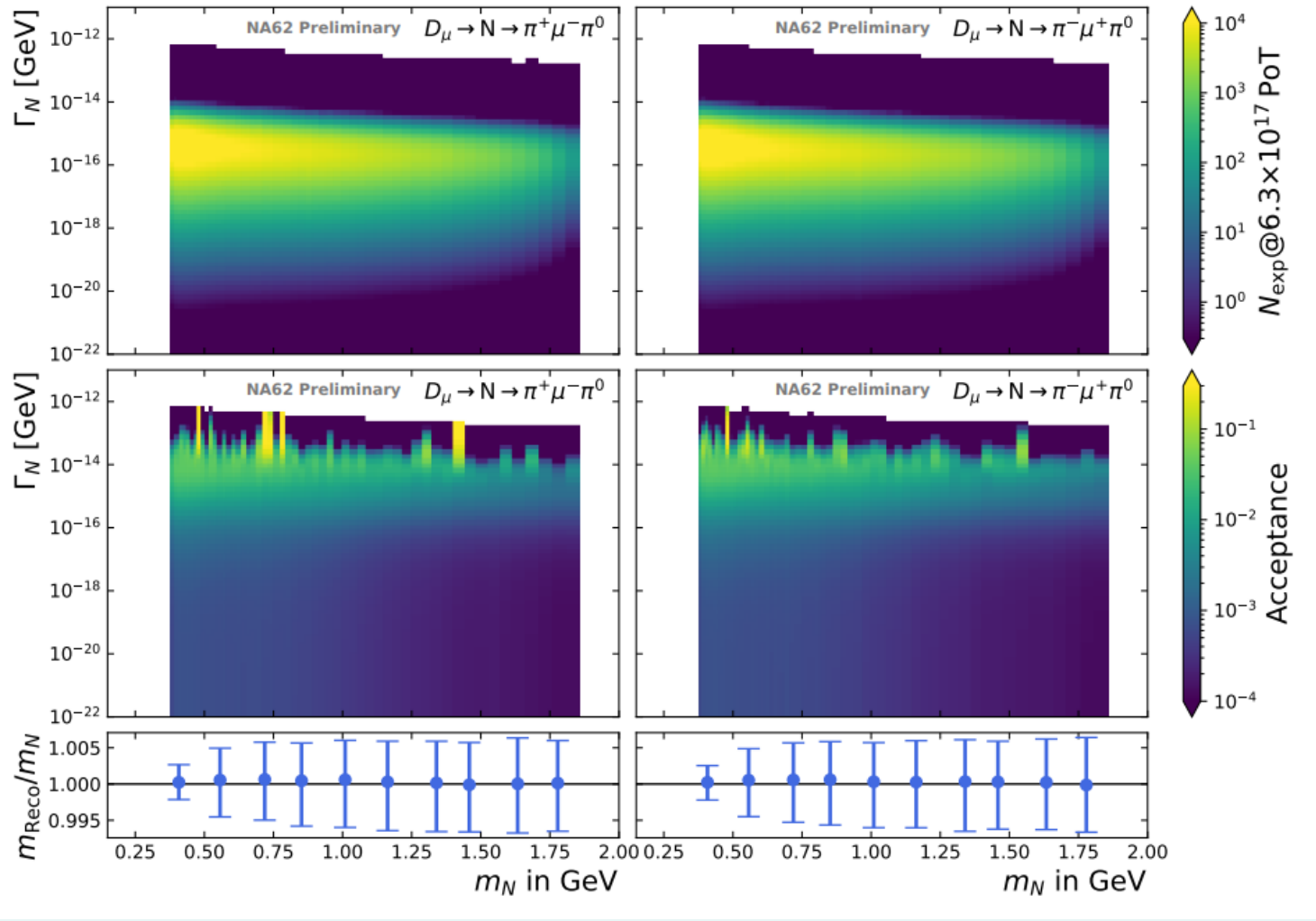
Analysis Sensitivity



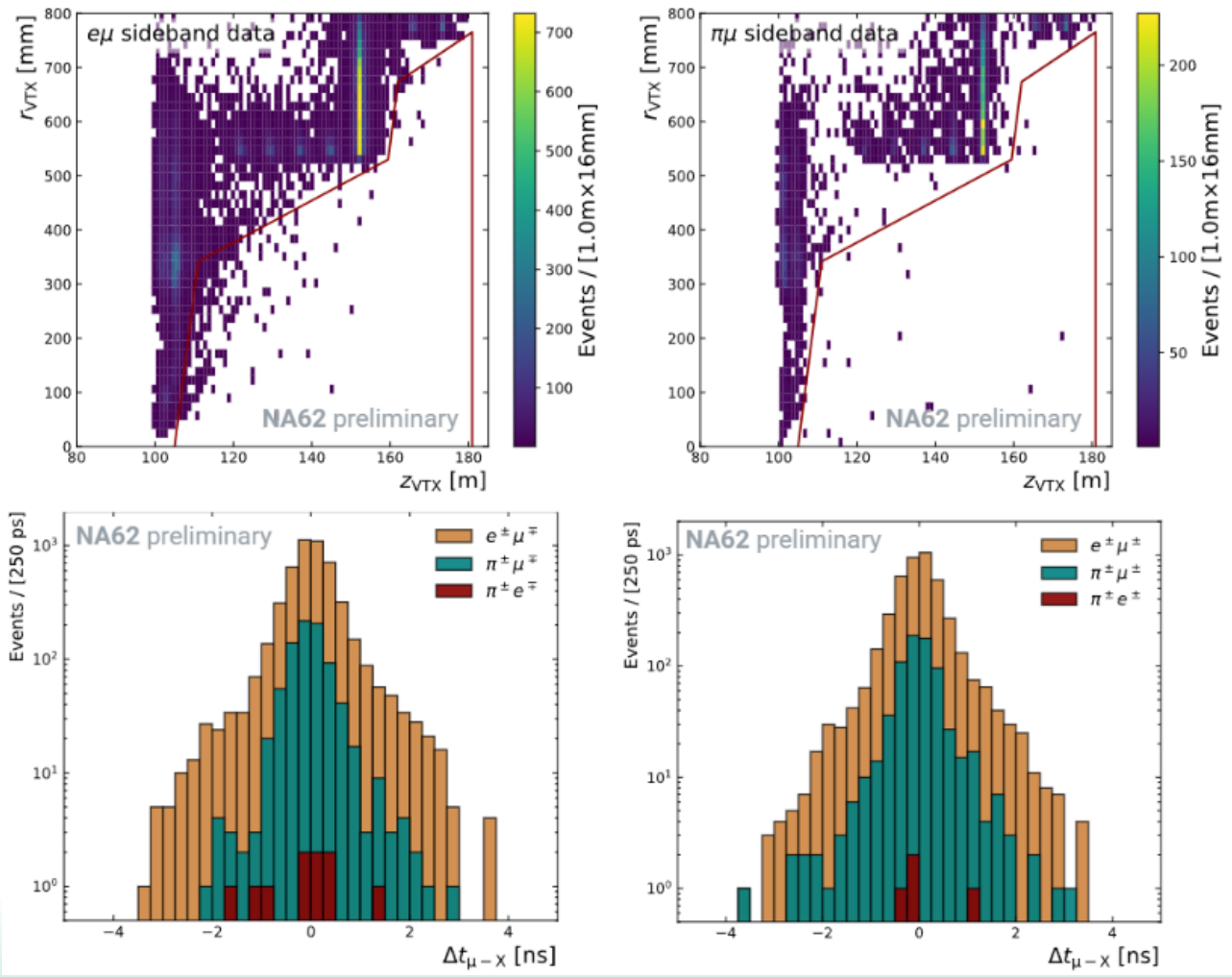
Analysis Sensitivity



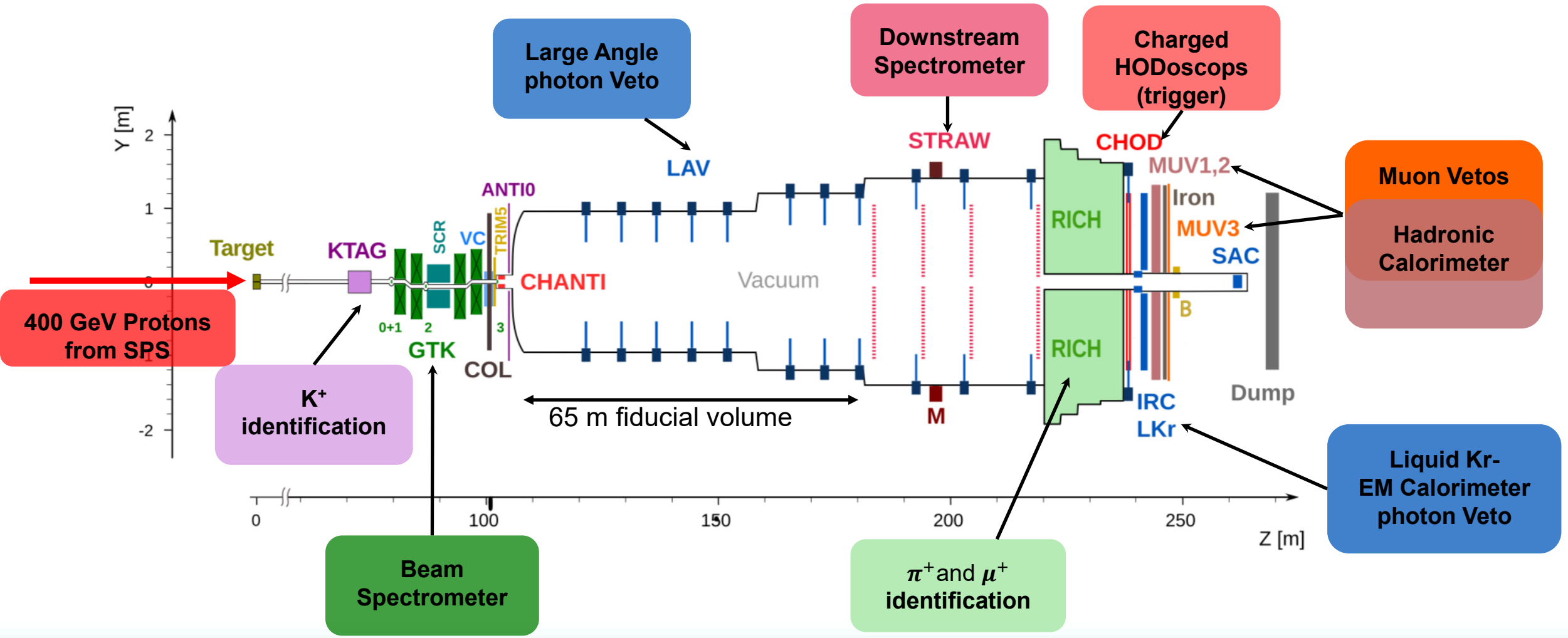
Analysis Sensitivity



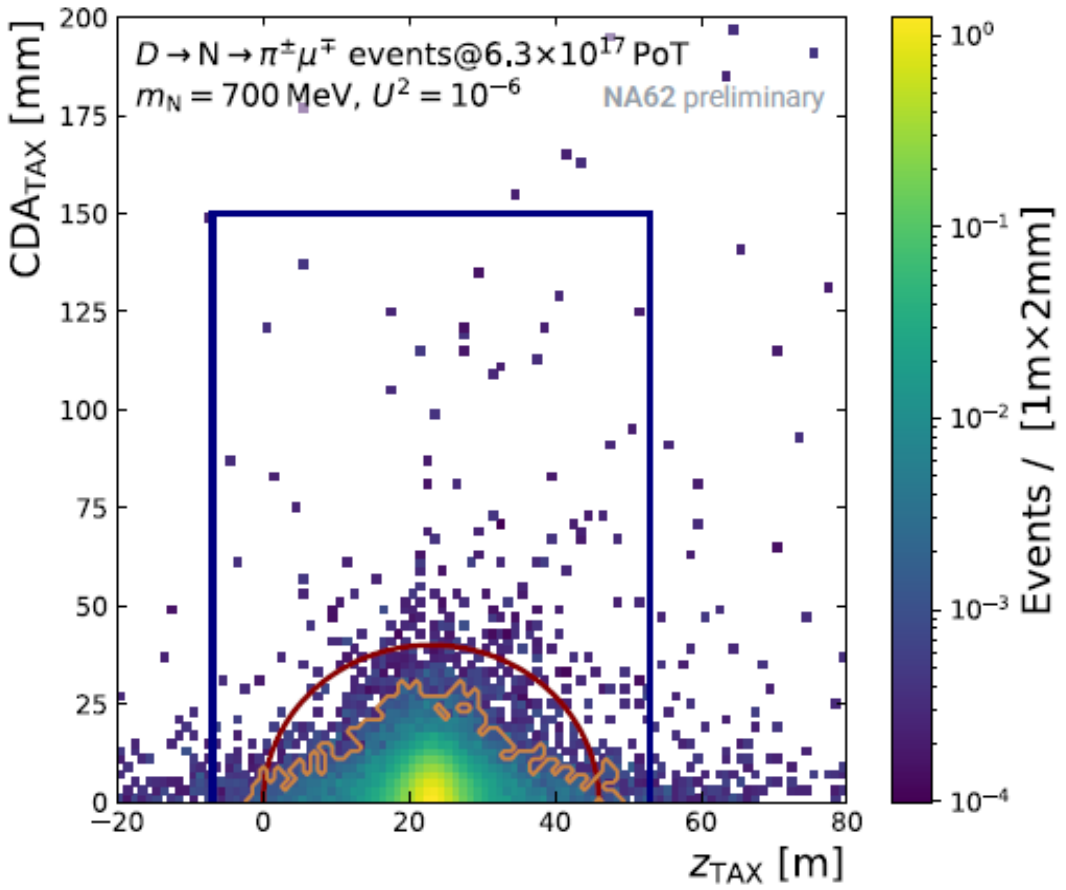
$e\mu$ Vs $\pi\mu$ Data Sideband Timing and Vtx Position

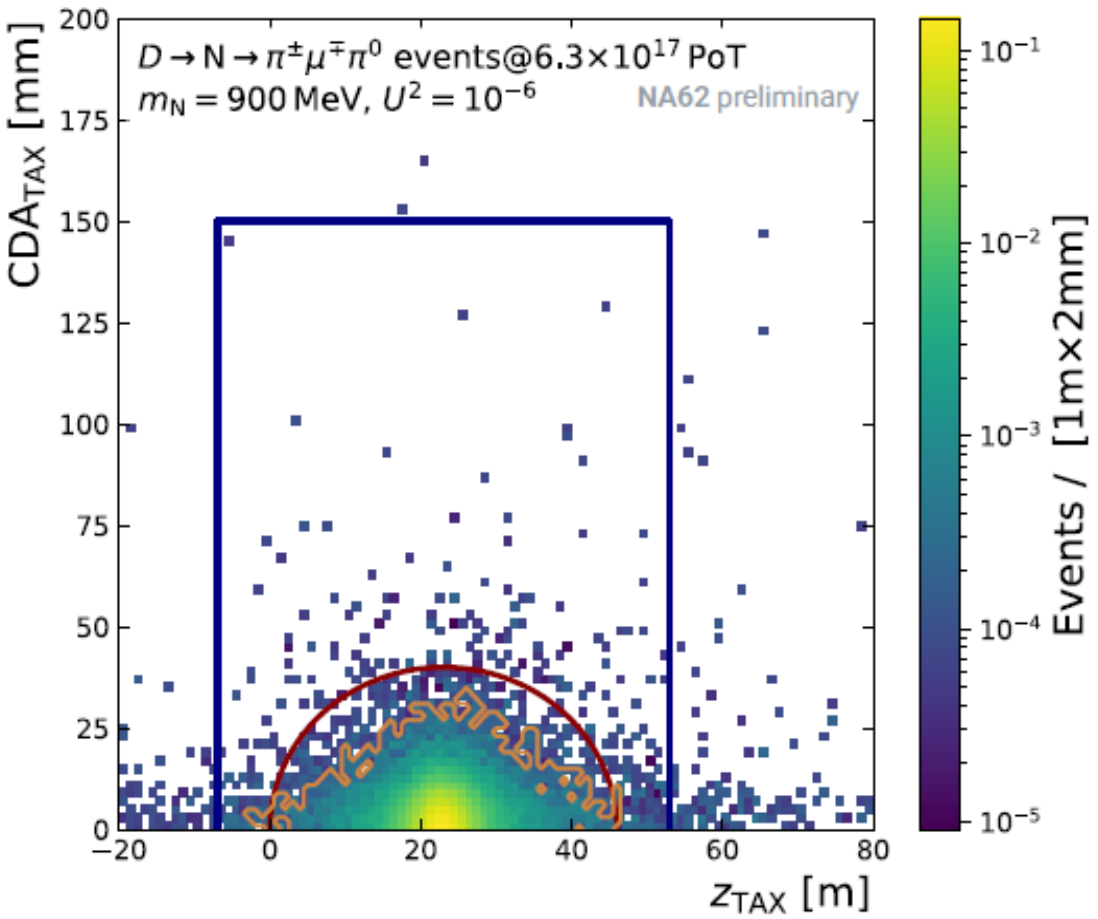
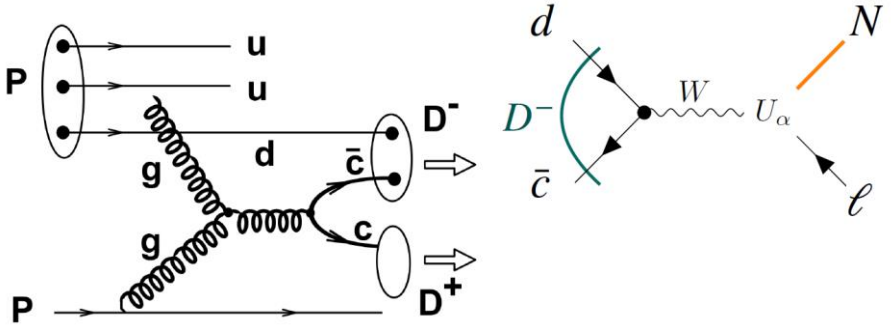


The NA62 Detector



$\pi\mu$ Vs $\pi\mu\pi^0$ Reconstructed Origin Distribution





Example for HNL Production in Beam Dump