High level performance of the NA62 RICH detector

RICH2025 workshop

Mainz, September 11-15

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INFN Perugia

Outline

- NA62 experiment
- NA62 RICH detector
- RICH PID in a single-track final state
- RICH PID in a multi-track final state
- Conclusions

NA62 experiment

NA62: fixed target experiment at CERN SPS

ECN3 hall at CERN

Technique:
Kaon decays in flight

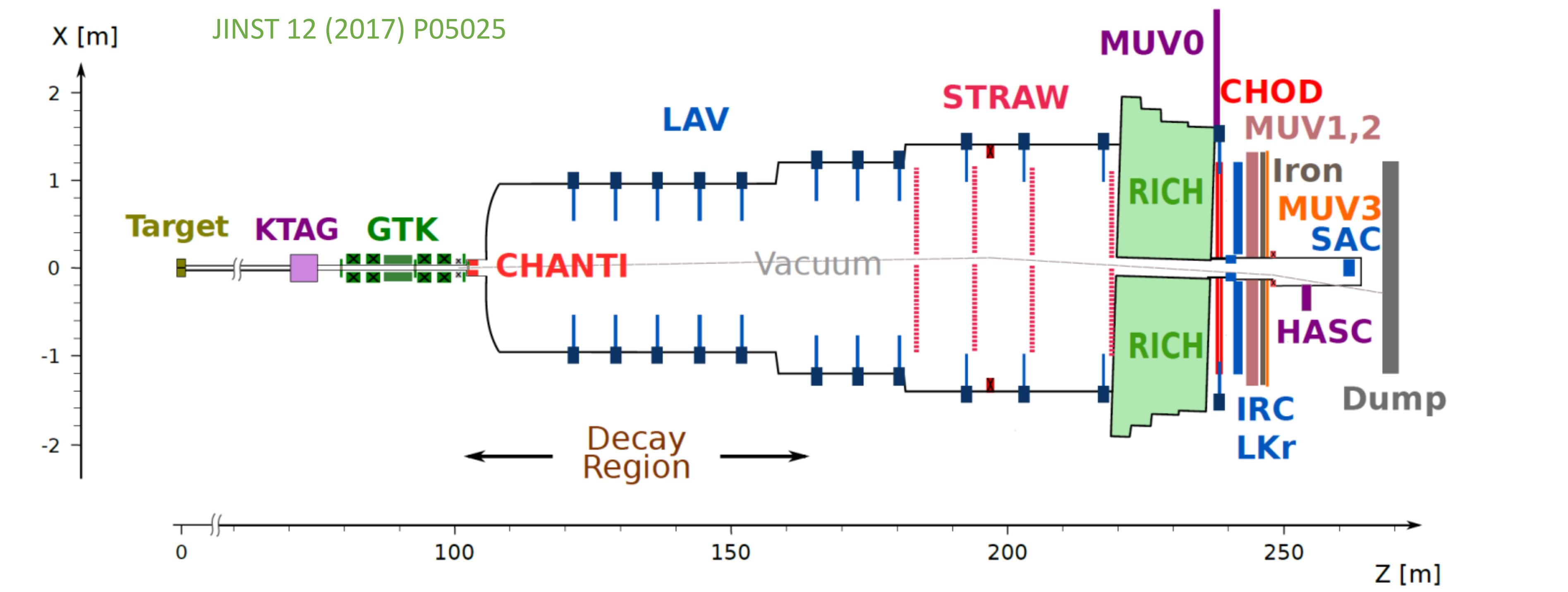
Timeline:
- 2015: commissioning
- 2016-2018: Run 1
- **2021-2024: Run 2**

- 2025-2026: Run 2

Primary goal:
Measure BR($K^+ \rightarrow \pi^+ \nu\nu$)

NA62 collaboration: ~300 participants, ~30 institutions

NA62 setup



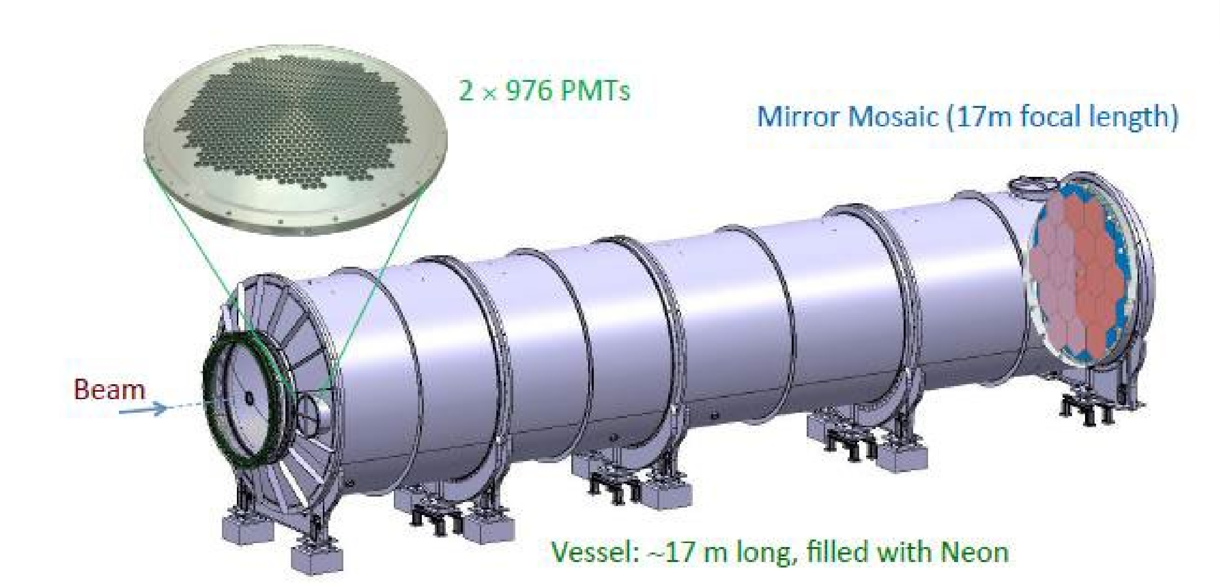
Primary beam:
- 400 GeV/c protons
- 3×10^{12} protons per spill

Secondary beam:
- 75 GeV/c (±1%)
- Beam angular spread < 100 μrad
- 70% pions, 6% K^+, 24% protons

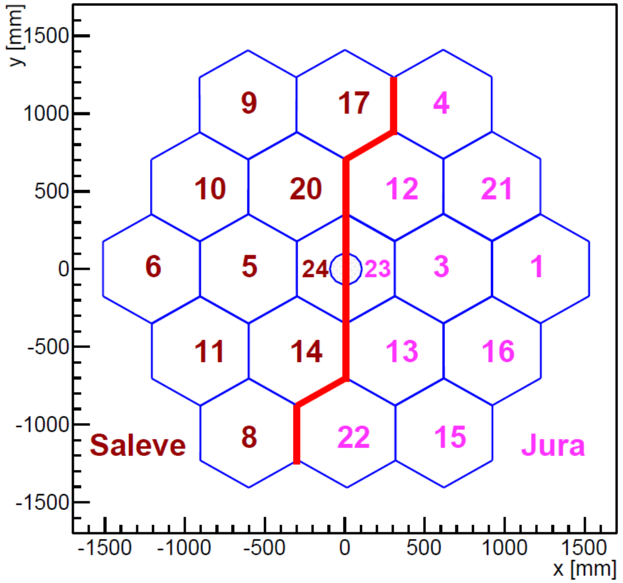
Key detectors:
- PID: KTAG, RICH, LKr, MUV1-2, MUV3
- Momentum: GTK, STRAW
- Time: GTK, KTAG, RICH, CHOD
- Photon veto: LAV, LKr, IRC, SAC

NA62 RICH

Gas vessel
- 17 m long, 200 m^3
- Neon @ atmospheric pressure



Mirrors
- Mosaic of 20 mirrors
- 18 hexagonal, 2 semihexagonal
- 2 groups (Jura and Saleve)



Light sensors
- 1952 Hamamatsu R7400-U03 PMTs
- Arranged in two disks
- Sensor position optimized for positively charged tracks
- Not optimal for negatively charged tracks due to the acceptance

RICH performance

Low level performance

- Mirror alignment
- Spatial resolution (single hit and ring with β=1)
- Time resolution (single hit and ring with β=1)
- Trends of basic RICH quantities in time

See the talk by F. Bucci (11.09.2025)

High level performance

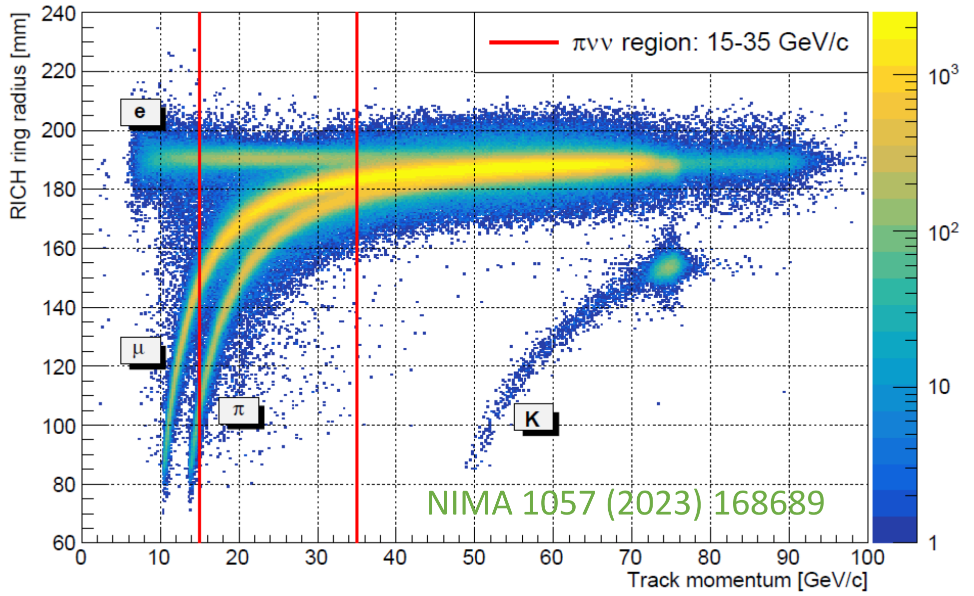
- PID for 1-track final states
- PID for 3-track final states

This talk

PID with RICH

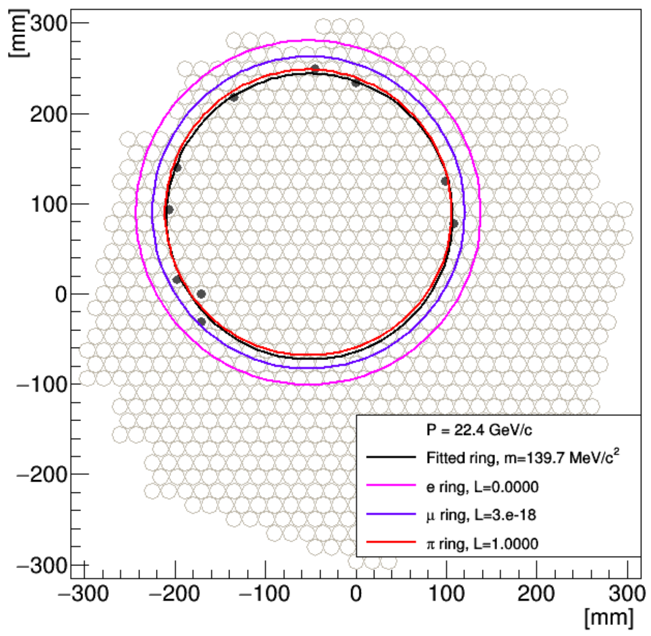
General approach to PID:
- Measure PID with the data as a function of momentum

R-based PID
- Only single-track final states
- Momentum P from spectrometer
- Ring radius R from the single ring (or track-seeded) fit
- Calculate m(RICH) $m^2(RICH) = p^2 \cdot \left(\frac{F^2 \cdot n^2}{F^2+R^2} - 1\right)$
- PID = cut on m(RICH)



Likelihood-based PID
- Any final states
- P for each track from spectrometer
- Expected R calculated for each mass hypothesis
- Calculate likelihoods for mass hypotheses (e, μ, π, K, noise)
- PID = select the largest likelihood and/or cut on likelihood ratio

Example of a single ring fit and expected rings



NA62 recent results

- $K^+ \to \pi^+ \nu \nu$ — Single-track final state
  - $BR(K^+ \to \pi^+ \nu \nu)$ JHEP 02 (2025) 191
  - spin-off: $K^+ \to \pi^+ X$ JHEP 03 (2021) 58 — paper on Run1+2 analysis in preparation
- Precision measurements
  - $K^+ \to \pi^+ \gamma \gamma$ PLB 850 (2024) 138513
  - spin-off: $K^+ \to \pi^+ X$, $X \to \gamma \gamma$
- LFV/LNV decays — Multi-track final state
  - $K^+ \to \pi \mu e$ PRL 127 (2021) 131802
  - $K^+ \to \pi^- l^+ l^+$ PLB 797 (2019) 134794; PLB830 (2022) 137172
  - $K^+ \to \pi^- \pi^0 e^+ e^+$ PLB 830 (2022) 137172
  - $K^+ \to \mu^- \nu e^+ e^+$ PLB 838 (2023) 137679
  - $K^+ \to \pi^0 \pi \mu e$ PLB 859 (2024) 139122
- HNL production in kaon decays
  - $K^+ \to l^+ N$ PLB807 (2020) 135599, PLB816 (2021) 136259
- HNL production in pion decays
  - $\pi^+ \to e N$ Paper in preparation
- Beam dump searches for Hidden Sectors
  - $A' \to l^+ l^-$ PRL 133 (2024) 111802
  - $X \to$ hadronic states Eur. Phys. J. C85 (2025) 571
- Neutrino tagging PLB 863 (2025) 139345

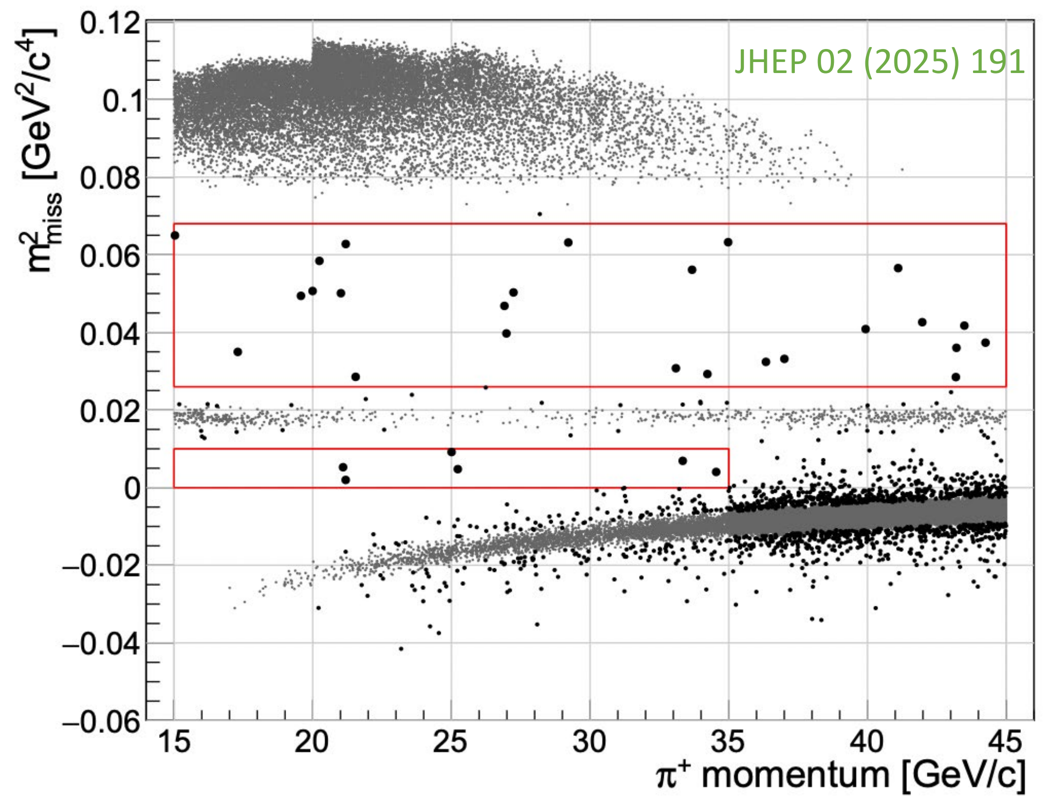
RICH PID essential

RICH PID in a single-track final state

NA62 main goal: BR($K^+ \to \pi^+ \nu\nu$)

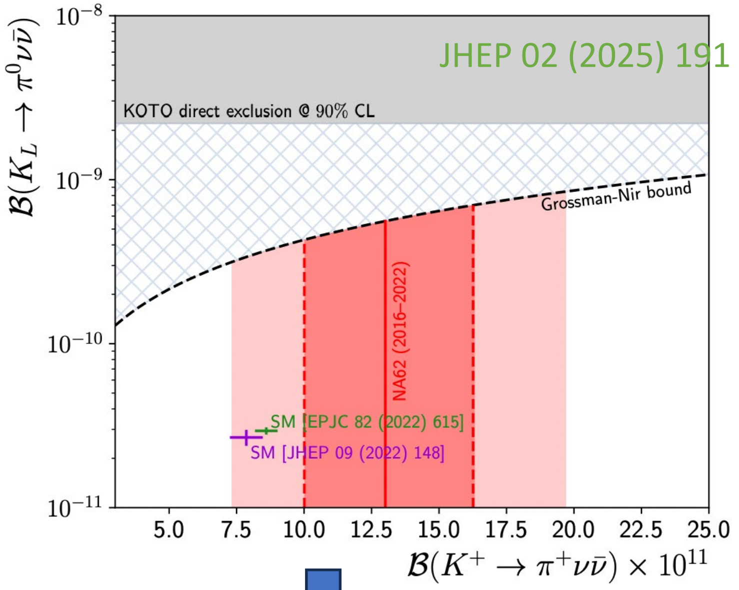
Integrated 2016-2022 data: $N_{bg} = 18^{+3}_{-2}$, $N_{obs} = 51$

2021-2022 data



- Background only hypothesis rejected with significance > 5σ

$$\mathscr{B}_{16-22}(K^+ \to \pi^+ \nu \bar{\nu}) = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$$



- BR central value in agreement with SM within 2σ

RICH PID in the $K^+ \to \pi^+ \nu\nu$ analysis

One of main backgrounds: $K^+ \to \mu^+ \nu$ (Kμ2)

- BR(Kμ2) = 0.63
- $O(10^{12})$ suppression needed

- Kinematics: $O(10^4)$
- PID with hadron calorimeters: $O(10^5)$
- PID with RICH: $O(10^3)$

RICH PID studies

NIMA 1057 (2023) 168689

NIMA 1057 (2023) 168689

Data samples

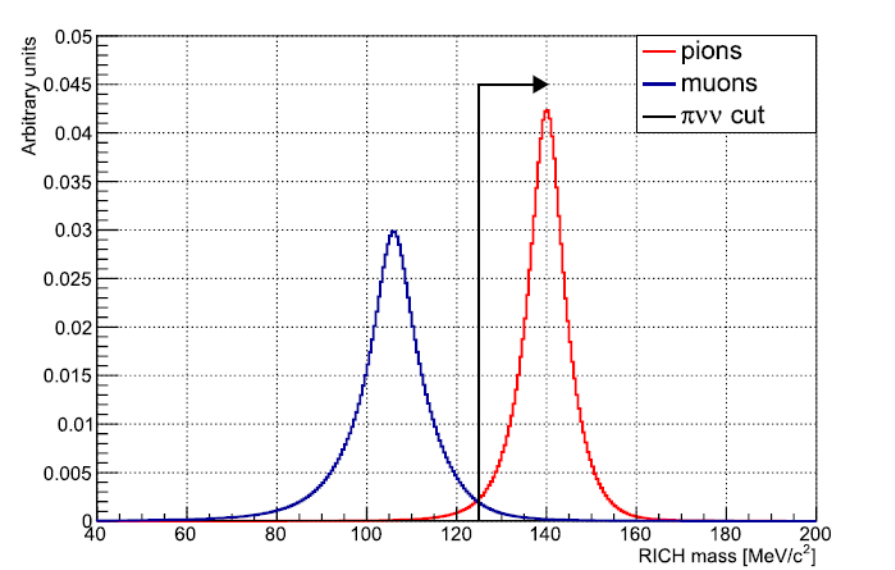
- Run2, partial (2021-2024)

Samples for PID studies

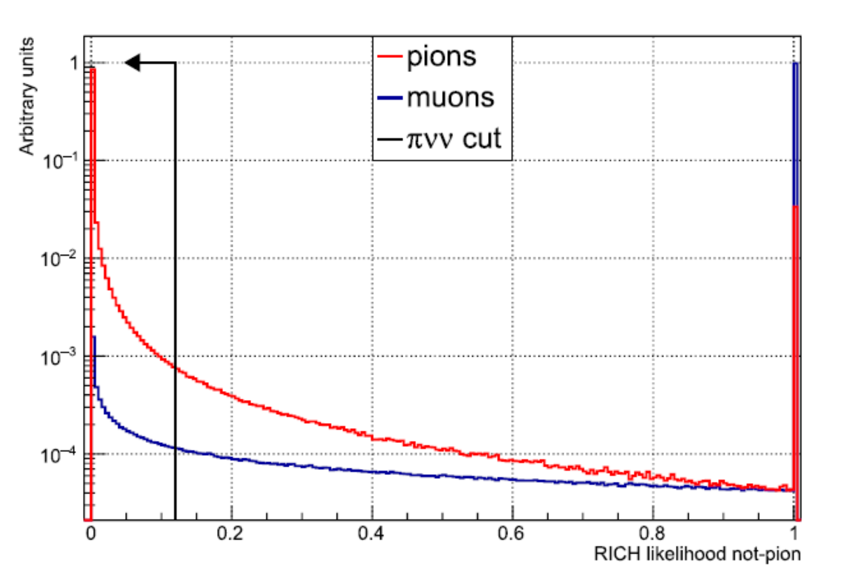
- Kμ2 for muons
- $K^+ \to \pi^+ \pi^0$ for pions

Event selection

- Kinematic selection
- PID without RICH
- 1 candidate in RICH



$$m^2(RICH) = p^2 \cdot \left(\frac{F^2 \cdot n^2}{F^2 + R^2} - 1\right)$$



$$L(!\,\pi) = \frac{\max\{L(e), L(\mu), L(K), L(noise)\}}{L(\pi)}$$

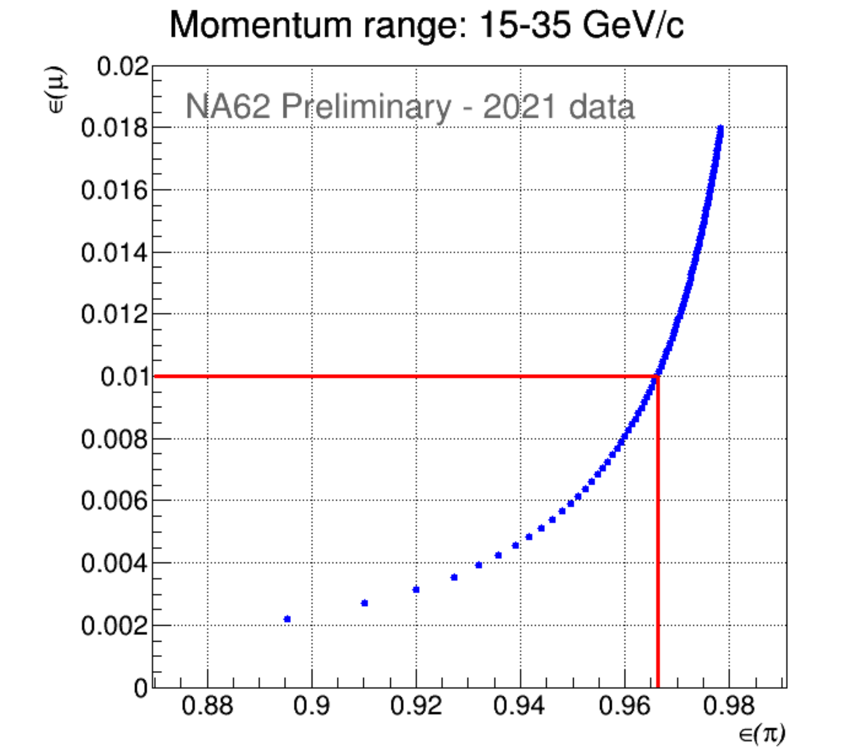
2 PID studies

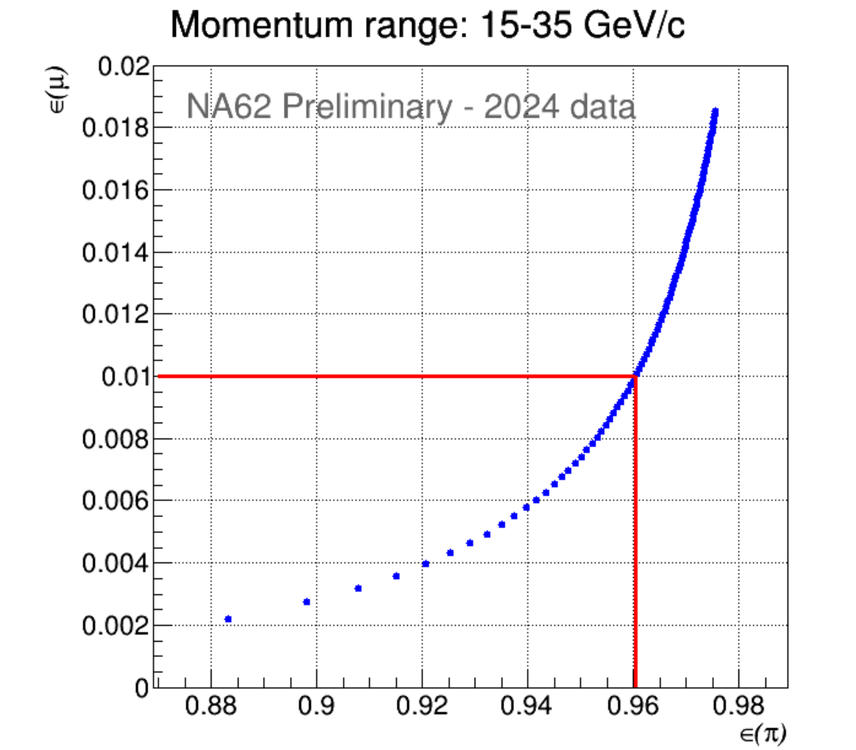
- **ROC curve**: scan over L(!π) in 15-35 GeV/c momentum range
- **πνν selection**: cut on RICH mass and L(!π) applied, scan over momentum

RICH PID studies: ROC curve

Reference point: ε(μ) = 1%

Year	ε(π)
2021	96.63(2)%
2022	96.47(2)%
2023	96.06(3)%
2024	96.04(3)%



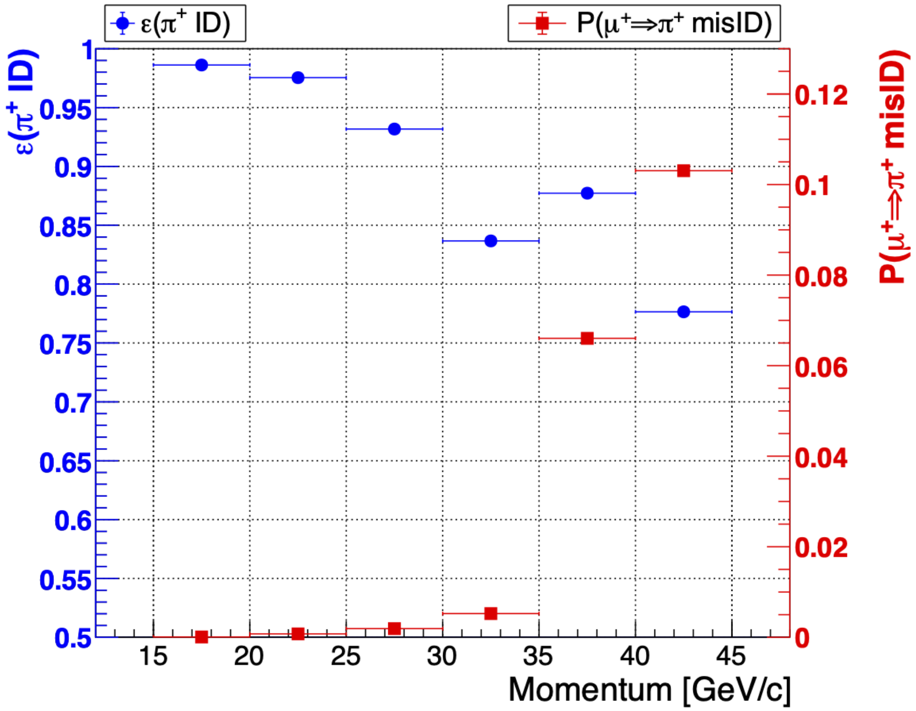


Stable performance during Run2 data taking

RICH PID studies: $K^+ \to \pi^+ \nu\nu$ selection

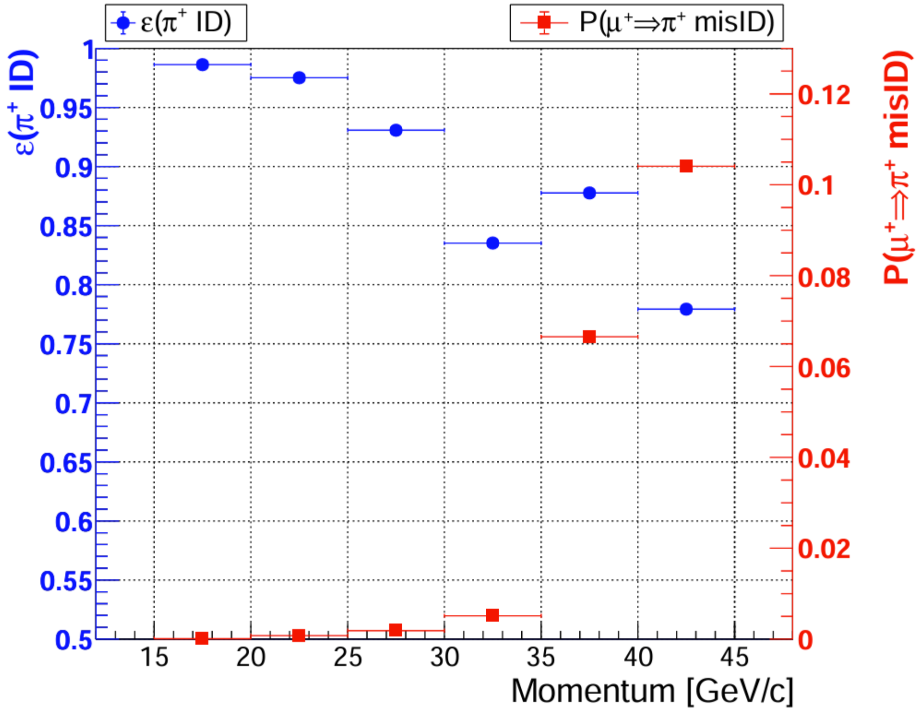
- RICH PID is optimised in 5 GeV momentum bins

2022 data



JHEP 02 (2025) 191

2024 data



2025 NA62 Status Report to the CERN SPSC - CERN Document Server

RICH PID studies: $K^+ \rightarrow \pi^+ \nu\nu$ selection

p=15-20 GeV
$L(!\pi) < 0.16$, $m_{RICH} \in (121, 200\ \text{MeV})$

	2021	2022	2023	2024
ε(π)	0.997	0.997	0.997	0.997
ε(μ)	$4.9(5)*10^{-5}$	$5.0(2)*10^{-5}$	$5.9(2)*10^{-5}$	$4.9(1)*10^{-5}$

p=25-30 GeV
$L(!\pi) < 0.09$, $m_{RICH} \in (125, 200\ \text{MeV})$

	2021	2022	2023	2024
ε(π)	0.945	0.945	0.939	0.940
ε(μ)	$1.8*10^{-3}$	$1.8*10^{-3}$	$1.8*10^{-3}$	$1.8*10^{-3}$

p=40-45 GeV
$L(!\pi) < 0.82$, $m_{RICH} \in (112, 200\ \text{MeV})$

	2021	2022	2023	2024
ε(π)	0.805	0.800	0.784	0.785
ε(μ)	0.103	0.103	0.103	0.104

Stable performance during Run2 data taking

RICH PID in a multi-track final state

Search for $K^+ \to \pi^- e^+ e^+$

Data:
- Run 1 (2016-2018)

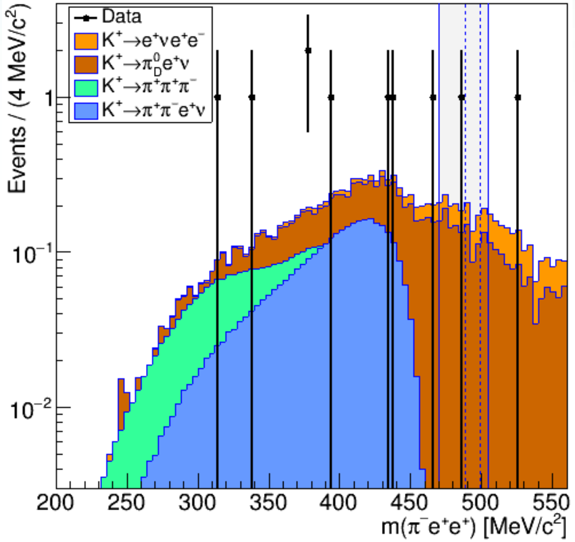
Main features
- blind analysis
- A(sig) = 4.23%
- $N_K = 9.79(31) \times 10^{11}$
- SES = 2.4×10^{-11}

Normalisation: $K^+ \to \pi^+ e^+ e^-$
- $N(K^+ \to \pi^+ e^+ e^-) = 9483$

Expected bkg
- N = 0.43(9)

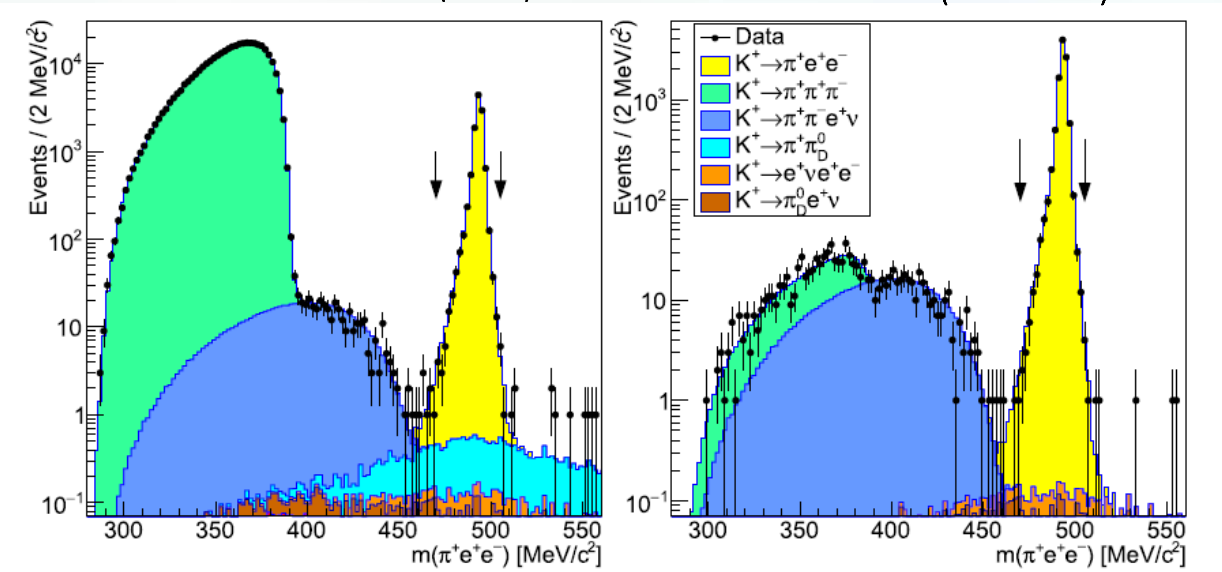
signal: $M(\pi^- e^+ e^+)$

with RICH PID



normalisation: $M(\pi^+ e^+ e^-)$

without RICH PID (main) | with RICH PID (validation)



PLB830 (2022) 137172

After unblinding: $N_{observed} = 0$ → **$BR(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11}$ (90% CL)**

Factor of 12 improvement wrt previous limit: $BR < 6.4 \times 10^{-10}$ (90% CL)

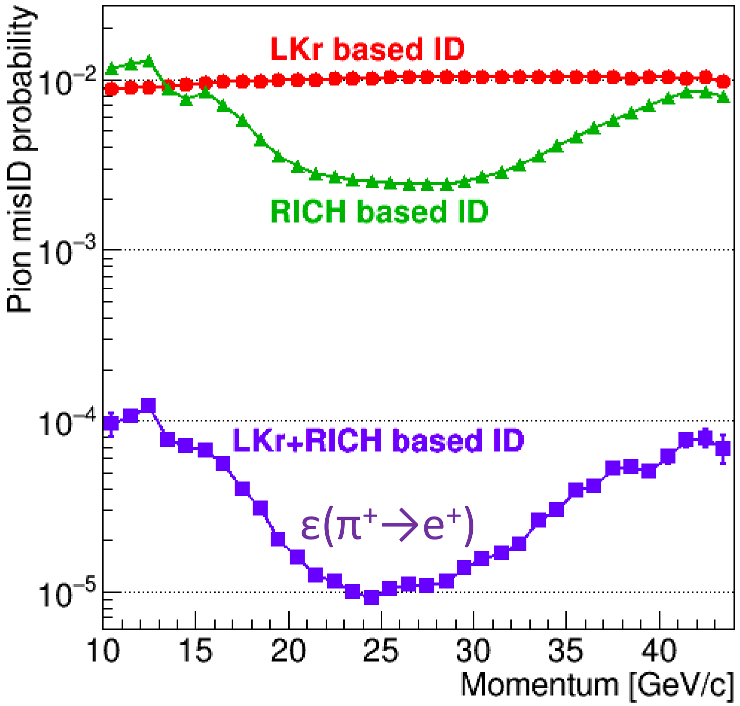
PID in the $K^+ \to \pi^- e^+ e^+$ selection

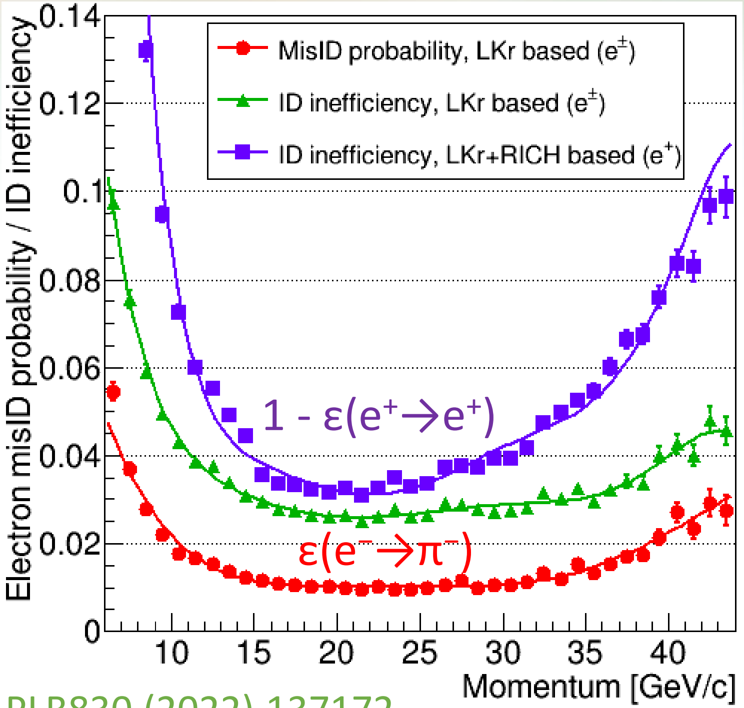
Bkg from $K^+ \to \pi^+ e^+ e^-$

Bkg from $K^+ \to \pi^+ \pi^0$, $\pi^0 \to e^+ e^- \gamma$

Identified as e^+ e^+ π^-

RICH PID is crucial to suppress these bkgs





PLB830 (2022) 137172

LKr+RICH PID for e^+ PID

- LKr PID: $0.9 < E/p < 1.1$
- RICH PID: cut on likelihood ratio
- **Data-driven approach**: cuts for data, weights for MC
- $\varepsilon(\pi \to e)$ measured on $K^+ \to \pi^+ \pi^+ \pi^-$ sample
- $\varepsilon(e \to \pi)$, $\varepsilon(e \to \pi)$ measured on $K^+ \to e^+ \nu \pi^0$ sample

RICH provides additional rejection factor up to 10^3

Conclusions

NA62 RICH is fundamental for PID

- ❑ RICH PID works well only for positively charged tracks (due to the acceptance)
- ❑ $K^+ \to \pi^+ \nu \nu$ analysis: $O(10^3)$ suppression of $K^+ \to \mu^+ \nu$ bkg with ($\mu^+ \to \pi^+$) misID
- ❑ LNV search in $K^+ \to \pi^- e^+ e^+$: $O(10^3)$ suppression of bkg with ($\pi^+ \to e^+$) misID
- ❑ PID performance stable in time

Future plans

- Collect data in 2025-2026

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- RICH PID works well only for positively charged tracks (due to the acceptance)
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THANK YOU!

Spare