

A new measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio at the NA62 experiment

Radoslav Marchevski

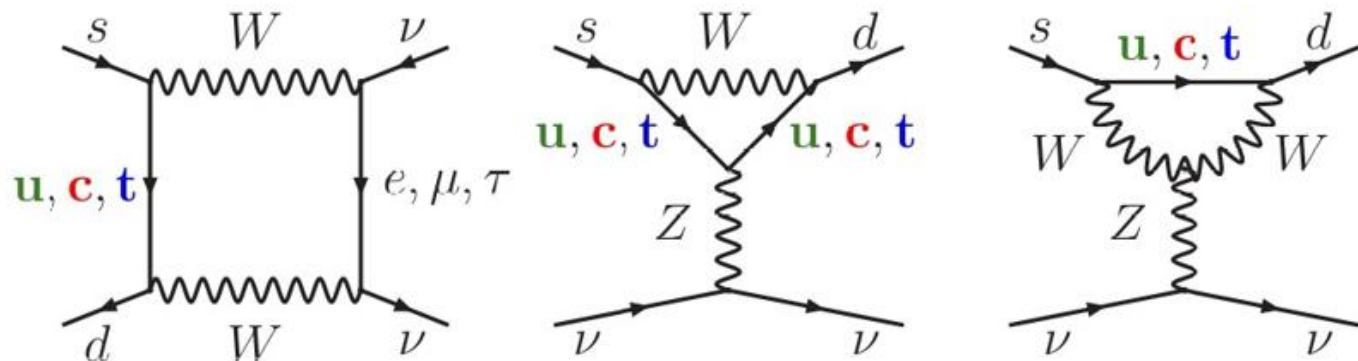
on behalf of the NA62 coillaboration

EPFL



XIX International Conference on Interconnections between Particle Physics and Cosmology, PPC 2026
Sydney, Australia, August 31st – September 4th, 2026

Golden modes $K \rightarrow \pi \nu \bar{\nu}$: SM and beyond

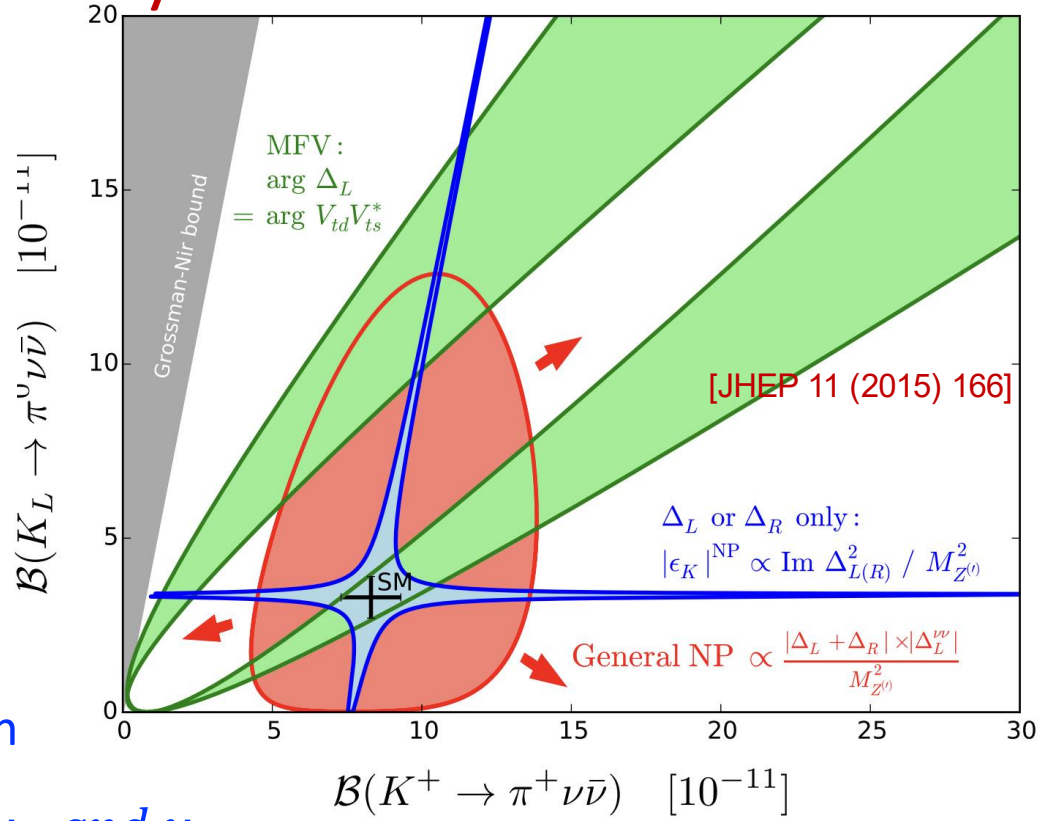


- $s \rightarrow d$ transition sensitive to the CKM structure of the SM:
 - **tree-level FCNCs forbidden $\rightarrow$ loop + CKM suppression**
- Theoretically clean process: **dominated by short-distance physics**
- $K - \pi$ Form Factor (FF) extracted from $K \rightarrow \pi l \nu_l$: **sub-% precision**
- Sensitive to new physics in the lepton sector as well: **involves ν_e, ν_μ , and ν_τ**

Theory Status

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}} \approx 8.5 \times 10^{-11} (\pm 5\%)$$
$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{SM}} \approx 3 \times 10^{-11} (\pm 6\%)$$

Recent SM calculations: [Buras et al. EPJC 82 (2022) 7, 615][Allwicher et al., PLB 861 (2025) 139295]
(differences in SM calculations from the choice of CKM parameters: see [Eur.Phys.J.C 84 (2024) 4, 377][arXiv:2607.19055])



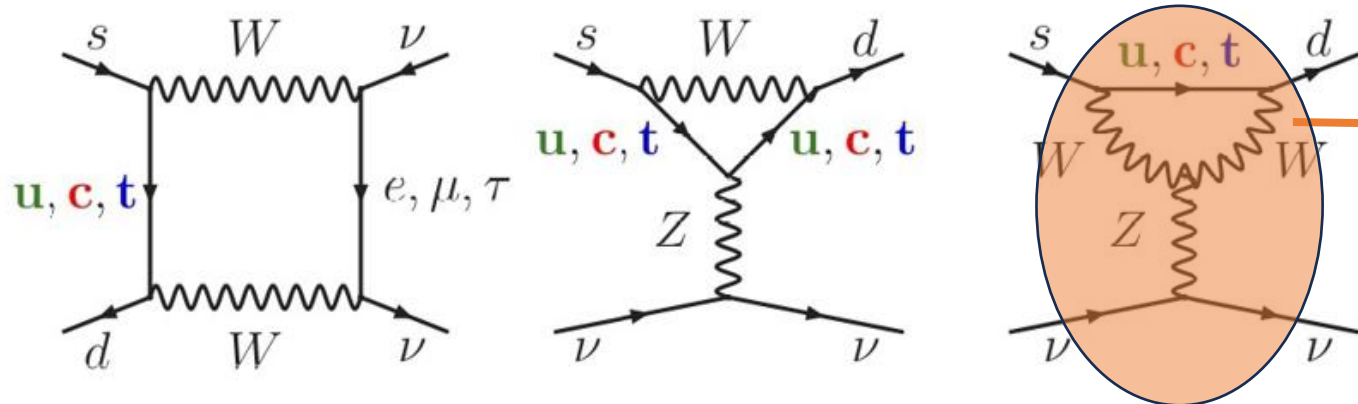
Experimental Status

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{2016-22}^{\text{NA62}} = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$$

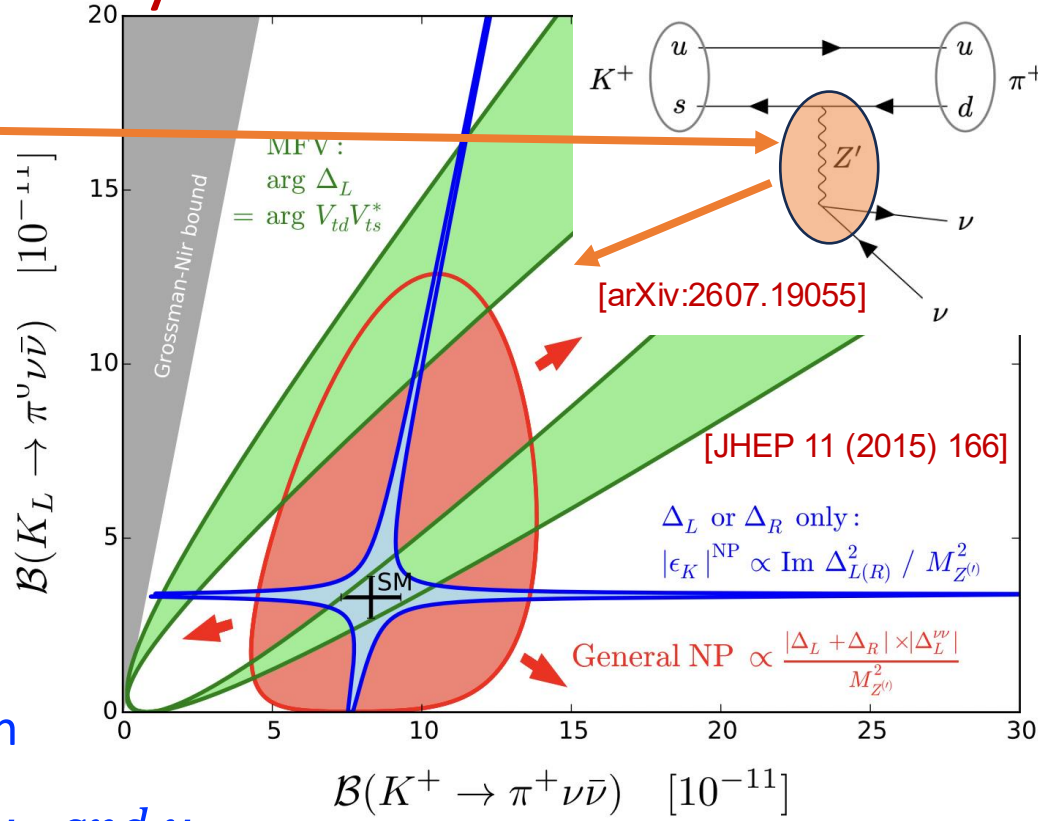
$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{2021}^{\text{KOTO}} < 2 \times 10^{-9}$$

NA62: [JHEP 02 (2025) 191]
KOTO: [PRL 134 (2025) 081802]

Golden modes $K \rightarrow \pi \nu \bar{\nu}$: SM and beyond



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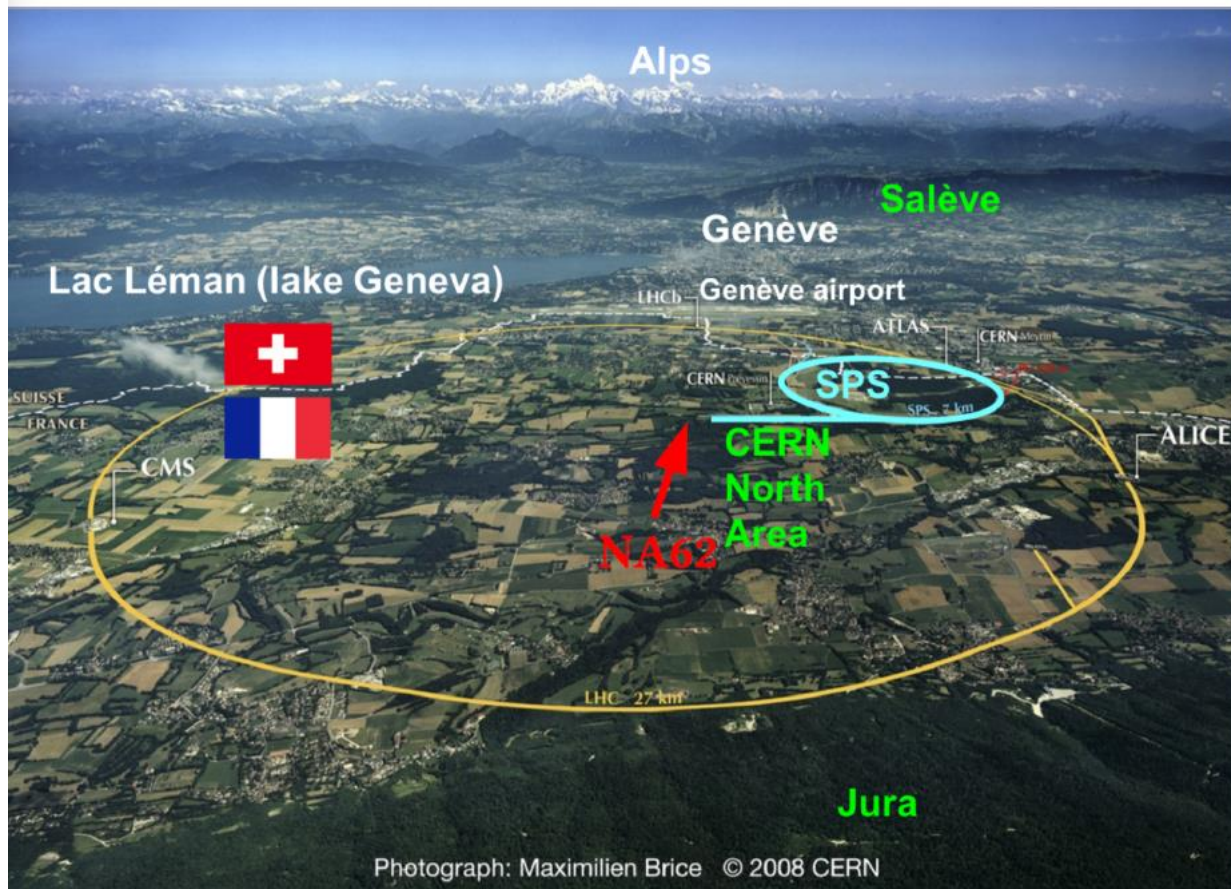
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NA62 experiment at CERN

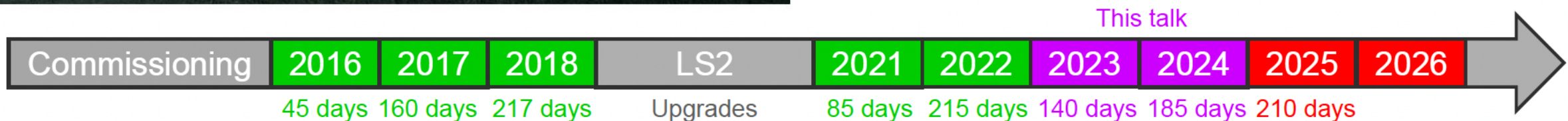


~ 200 collaborators from 35 institutions



High precision kaon experiment:

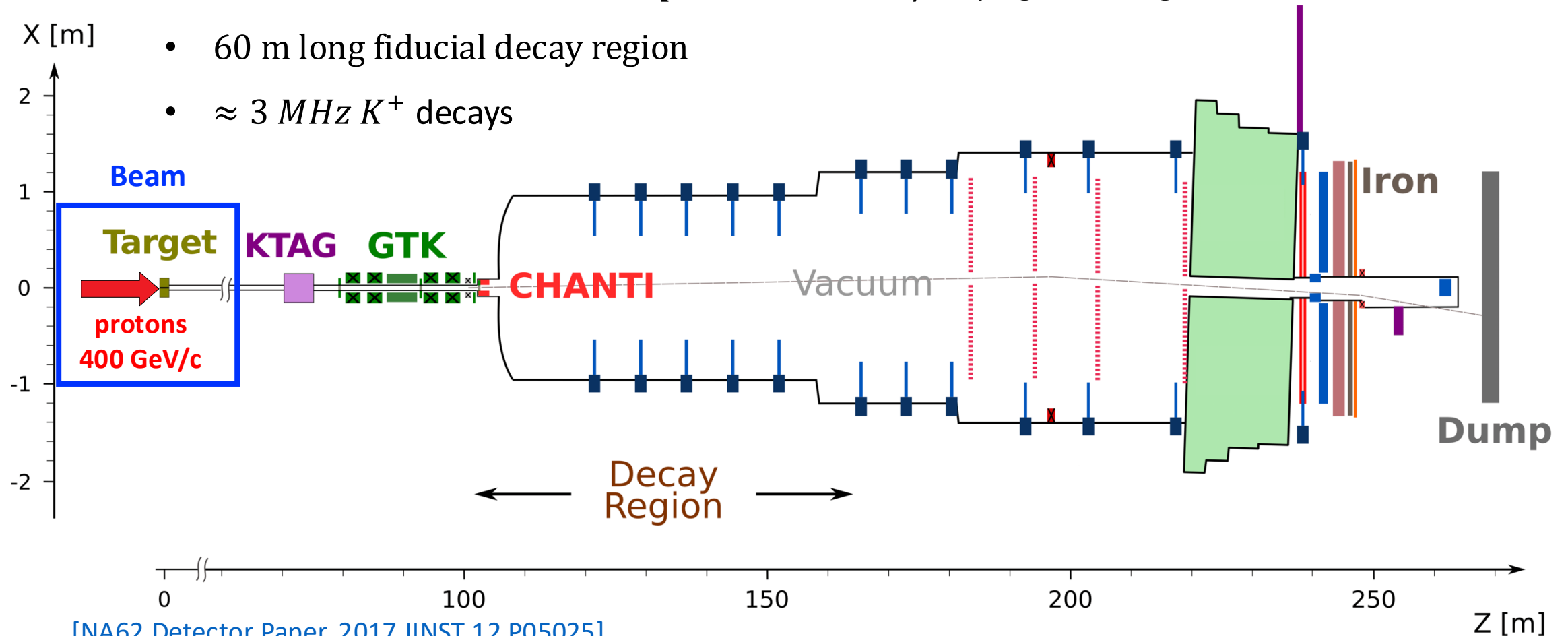
- *Primary goal:* $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ measurement
- *Technique:* fixed-target and decay in flight
- Previous results: [PLB 791 (2019) 156] [JHEP 11 (2020) 042][JHEP 06 (2021) 093] [JHEP 02 (2025) 191]
- *Broad physics program:*
 - precision measurements of kaon and pion decays
 - HNL and LFV/LNV searches in kaon and pion decays
 - Hidden Sector searches with kaons + dump mode
 - neutrino tagging



NA62 experiment

Secondary beam:

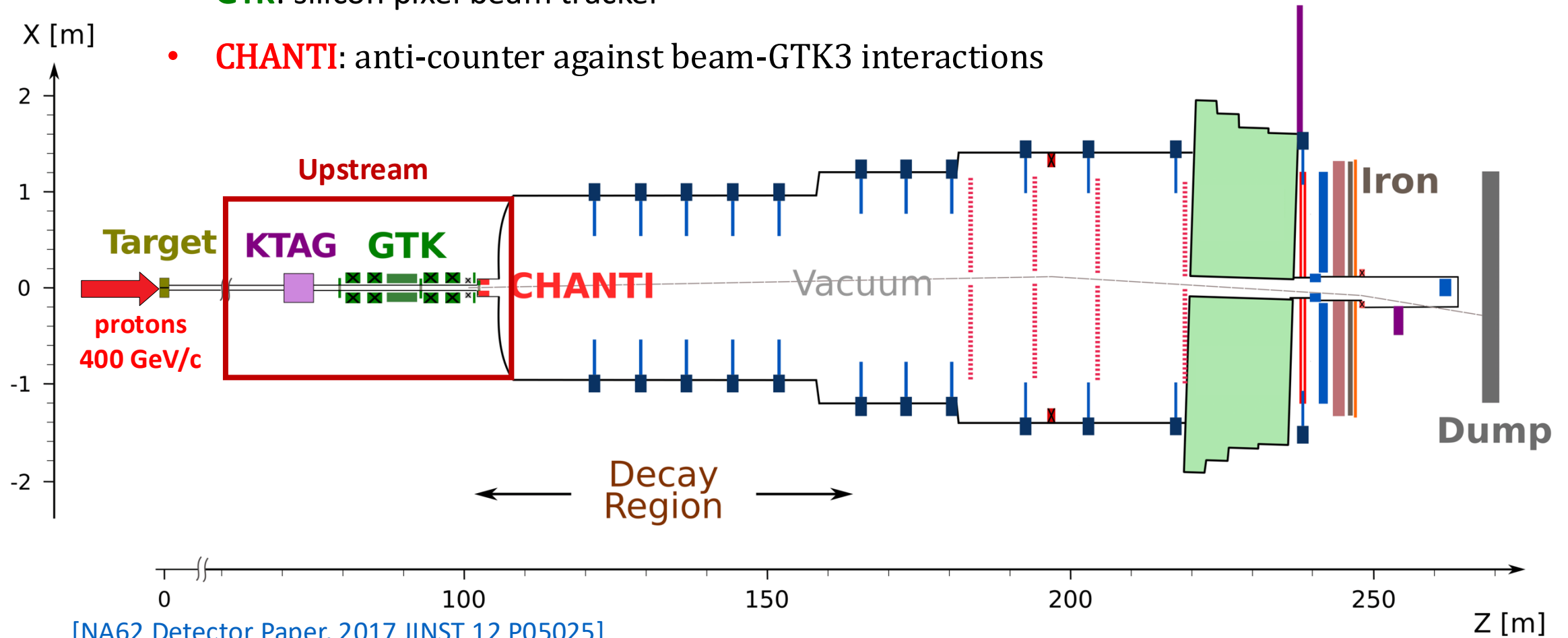
- unseparated positively-charged beam: π^+ (70%), p (23%), K^+ (6%)
- almost monochromatic beam: $p = 75 \pm 1 \text{ GeV}/c$ flying at 0° angle
- 60 m long fiducial decay region
- $\approx 3 \text{ MHz } K^+$ decays



NA62 experiment

Upstream region (K^+):

- **KTAG**: differential Cherenkov counter for K^+ ID
- **GTK**: silicon pixel beam tracker
- **CHANTI**: anti-counter against beam-GTK3 interactions

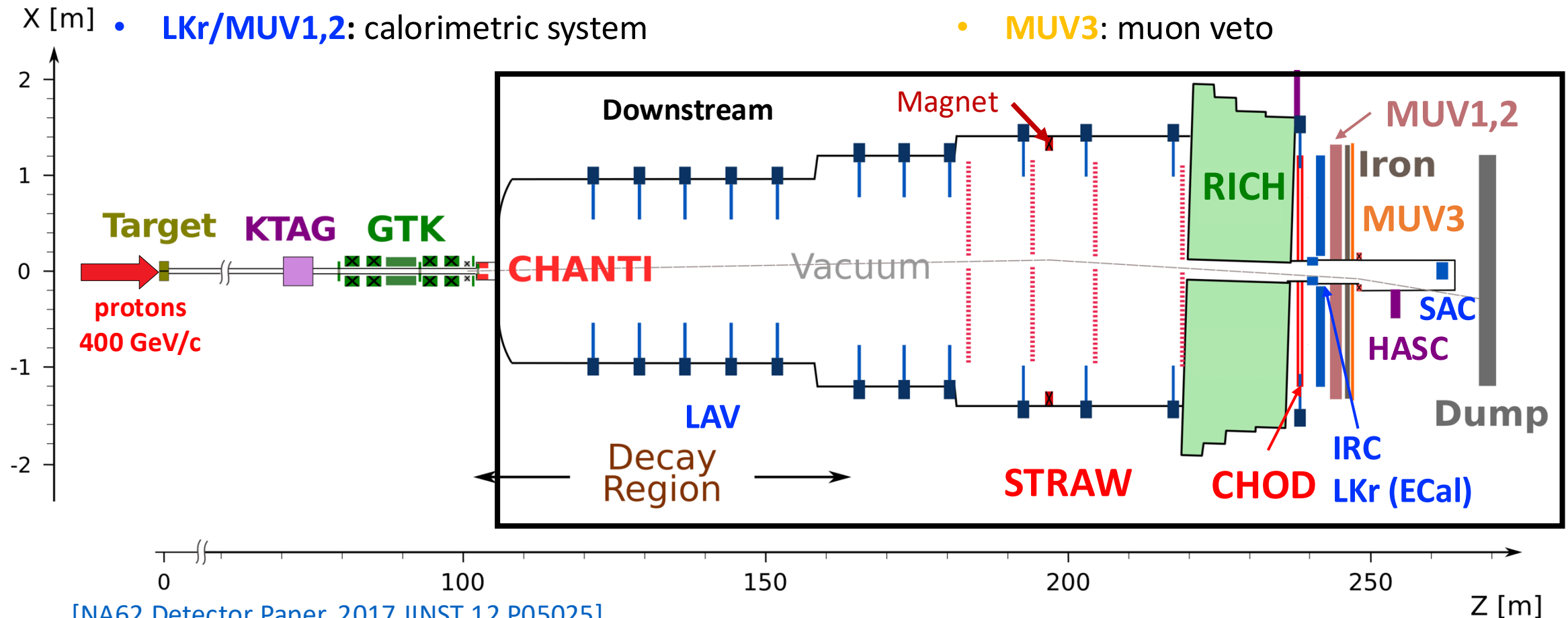


[NA62 Detector Paper, 2017 JINST 12 P05025]

NA62 experiment

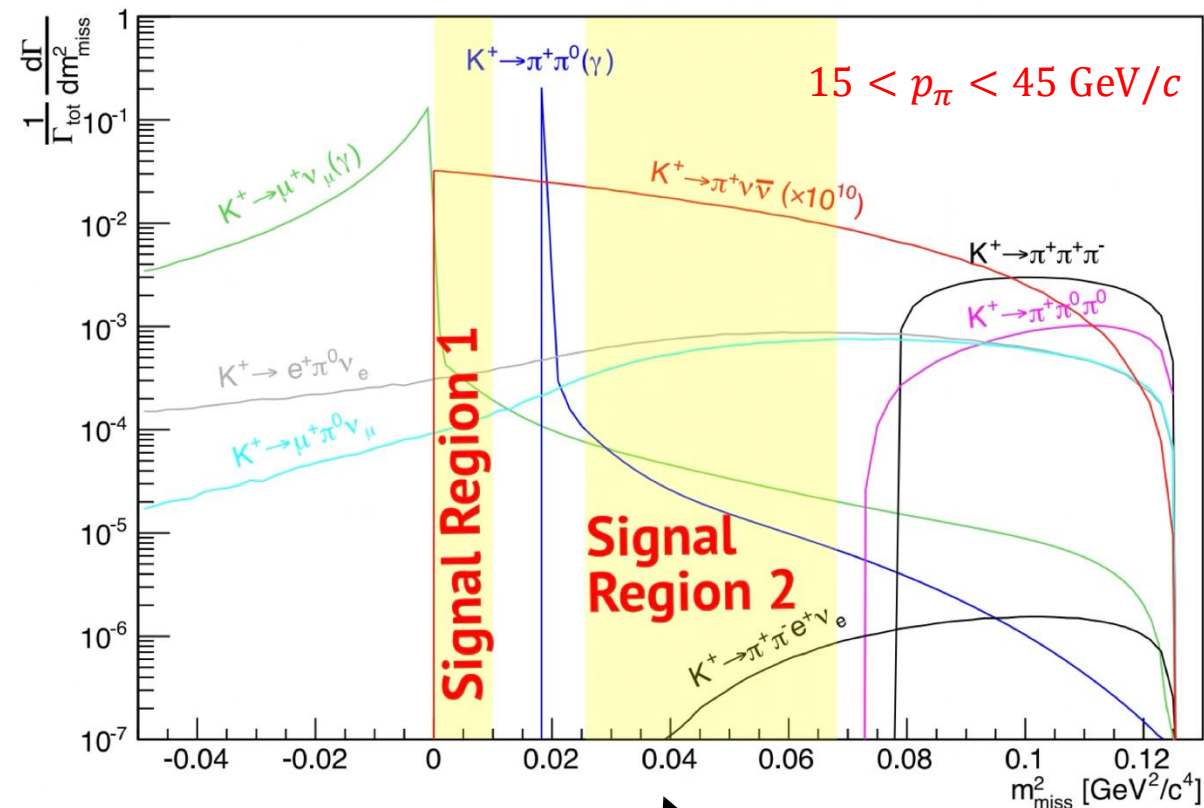
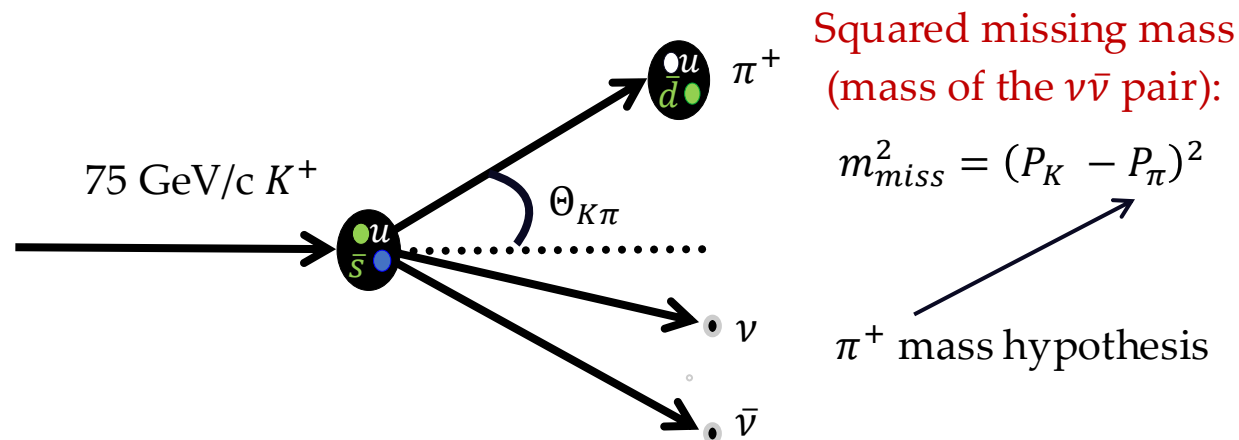
Downstream region (π^+):

- **STRAW**: straw spectrometer in vacuum ($1.6\% X_0$)
- **CHOD**: scintillator hodoscopes
- **LKr/MUV1,2**: calorimetric system
- **RICH**: Cherenkov detector for $\pi/\mu/e$ ID
- **LAV/IRC/SAC**: photon veto detectors
- **MUV3**: muon veto



[NA62 Detector Paper, 2017 JINST 12 P05025]

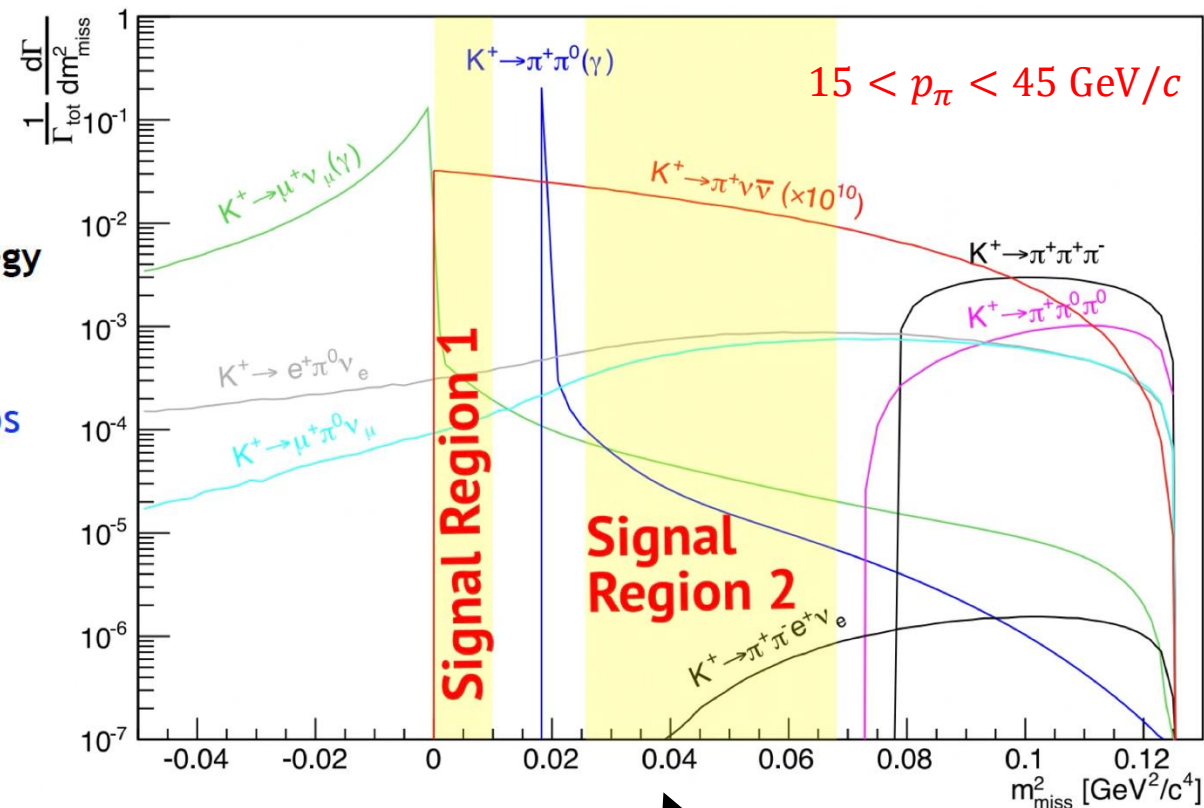
Analysis strategy



- Highly boosted decay: $(75 \pm 1) \text{ GeV}/c \ K^+$ ($\gamma \sim 150$)
- Large undetectable missing energy carried away by the neutrinos
- All energy from visible particles must be detected
- π^+ momentum range $15 - 45 \text{ GeV}/c$ ($E_{\text{miss}} > 30 \text{ GeV}$)
- Hermetic detector coverage and $O(100\%)$ detector efficiency needed

Analysis strategy

Decay mode	Branching Ratio [PDG]	Rejection strategy
$K^+ \rightarrow \mu^+ \nu_\mu$	$(63.56 \pm 0.11) \%$	PID
$K^+ \rightarrow \pi^+ \pi^0$	$(20.67 \pm 0.08) \%$	π^0/γ vetos
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	$(5.583 \pm 0.024) \%$	kinematics
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$	
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	8.4×10^{-11} [benchmark SM value]	



**“Flat signal”
peaking background**

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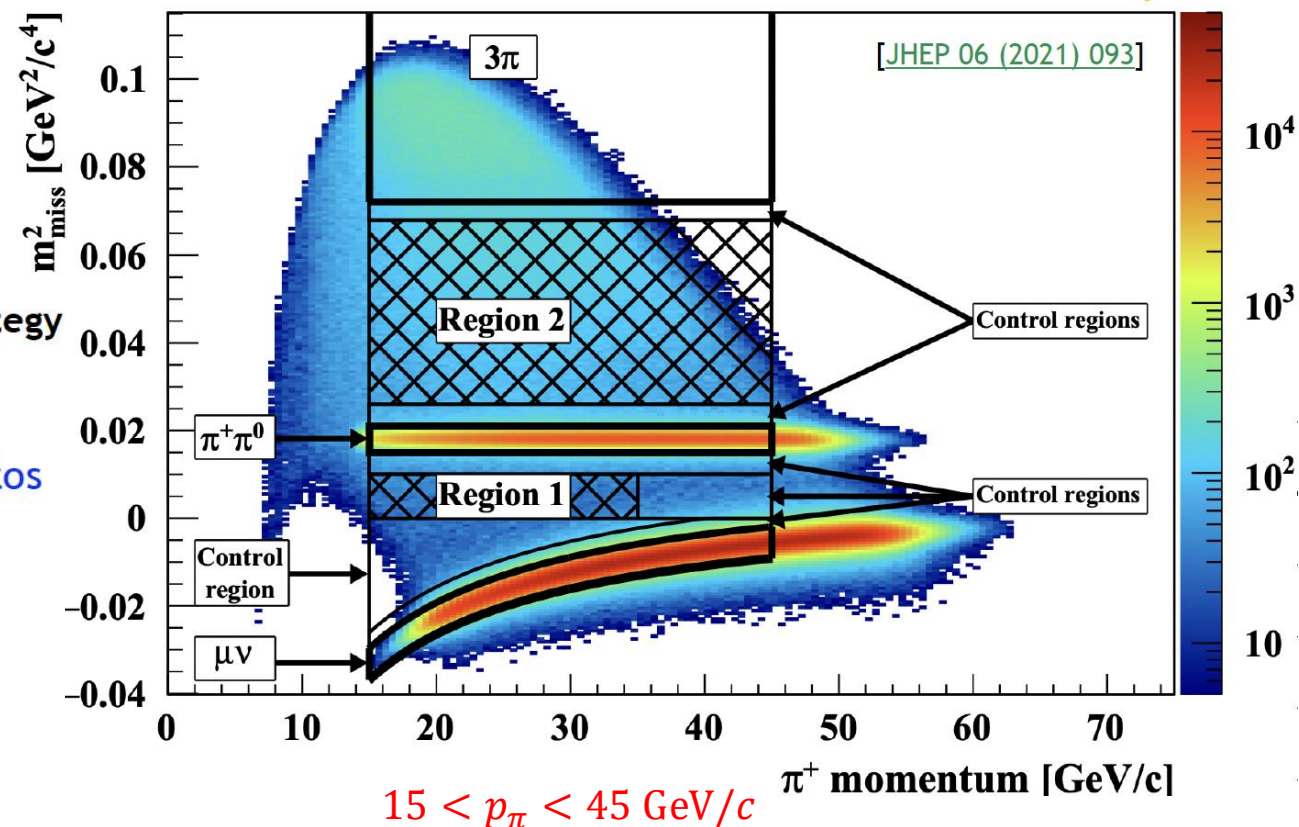
Rejection strategy

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π^0/γ vetos

kinematics

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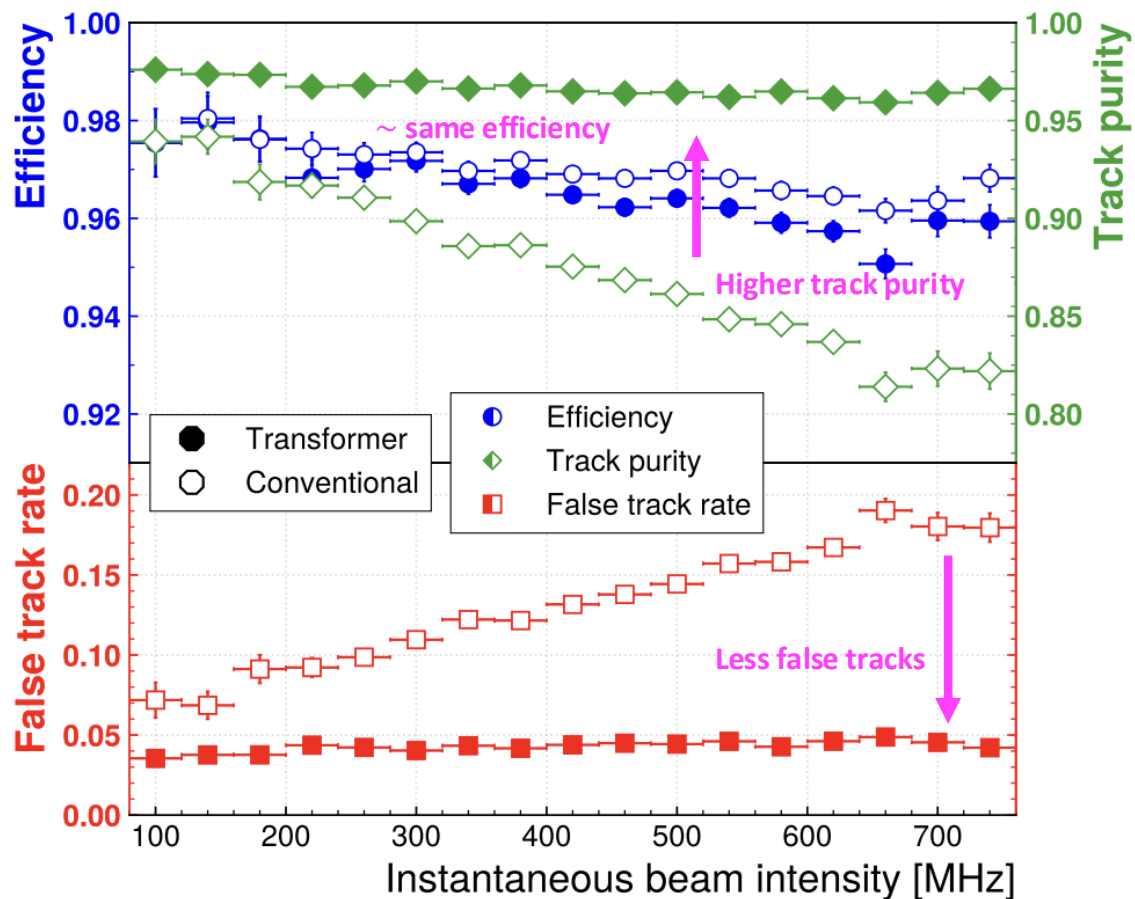
• Requirements:

- Kinematic suppression – $O(10^4)$
- μ^+ rejection – $O(10^7) \Rightarrow P(\mu^+ \rightarrow \pi^+ \text{ misID}) = (1.3 \pm 0.1) \times 10^{-7}$ with $\varepsilon(\pi \text{ ID}) = 75.3\%$
- π^0 rejection – $O(10^7) \Rightarrow \eta_{\pi^0} = (1.24 \pm 0.04) \times 10^{-8}$ with $\varepsilon_{RV} = 72.3\%$
- Time resolution – $O(100 \text{ ps})$

Improvements for the 2023 – 2024 analysis

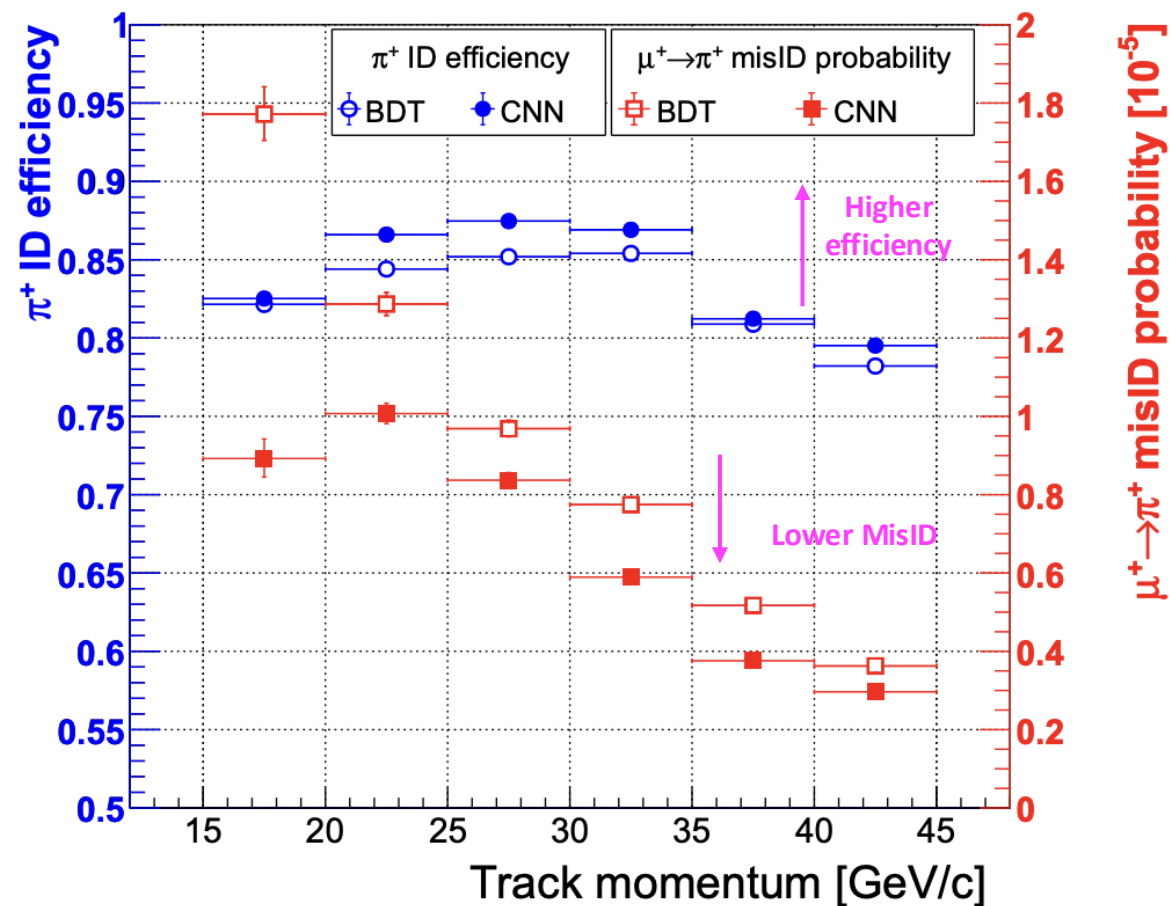
$K^+ - \pi^+$ matching

New: 4D beam tracking with ML



Calorimetric π^+/μ^+ PID

New: new CNN-based classifier

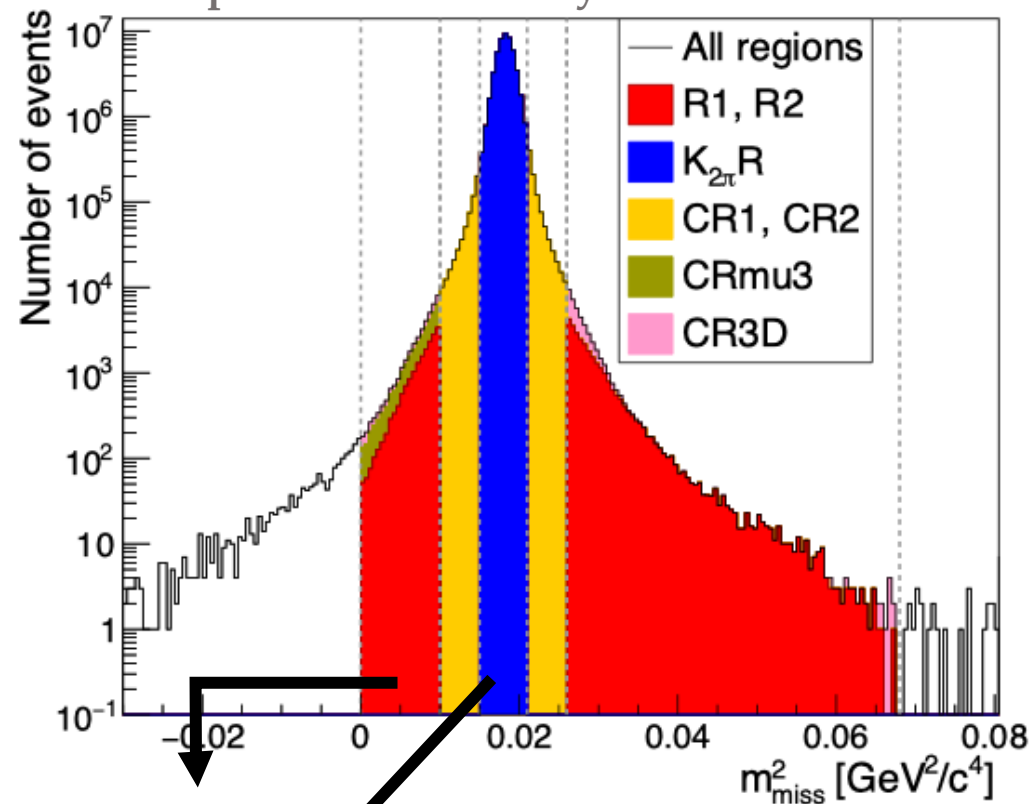
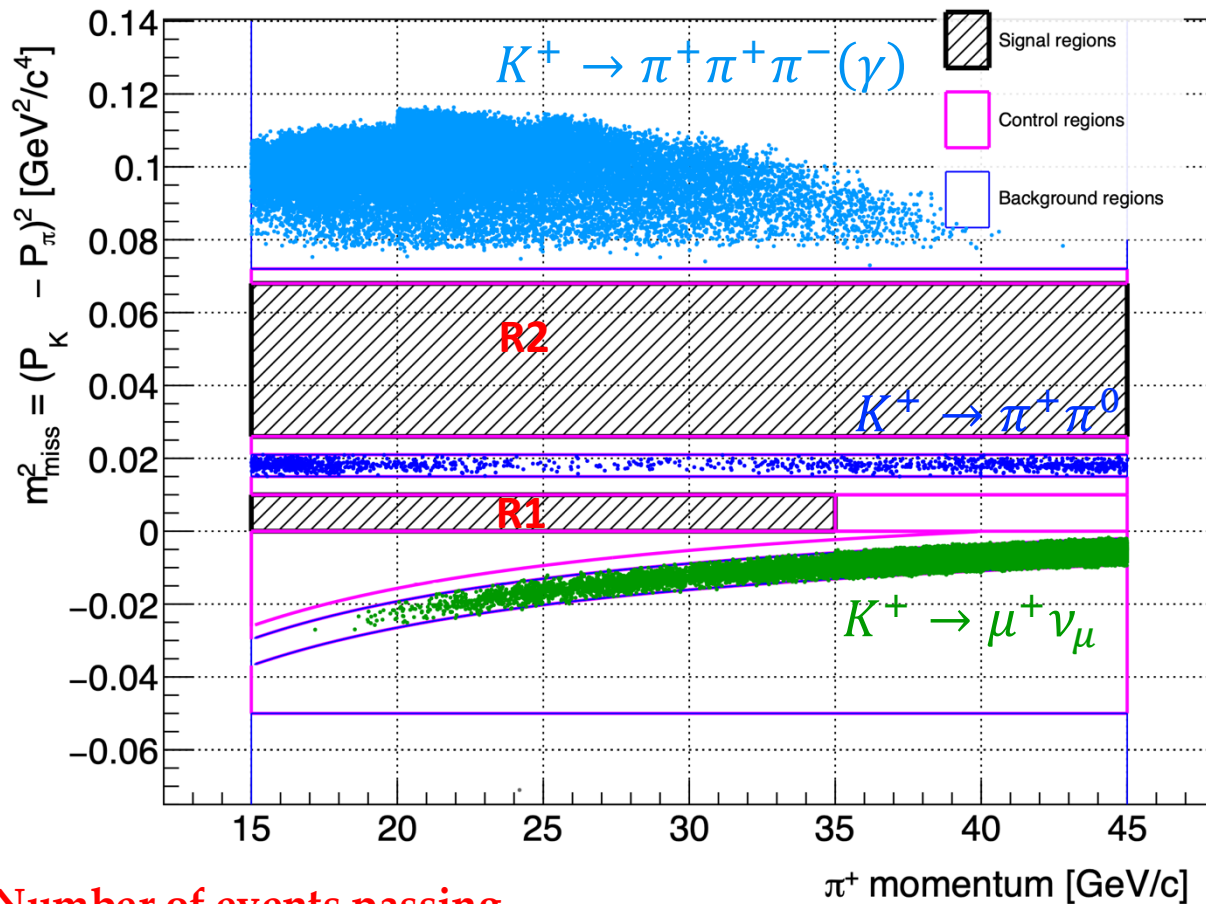


[arXiv:2607.16413]

Background from m_{miss}^2 mis-reconstruction

$$K^+ \rightarrow \pi^+ \pi^0(\gamma)$$

Control sample of $K^+ \rightarrow \pi^+ \pi^0$ events with $\pi^0 \rightarrow \gamma\gamma$, both photons detected by the LKr



$$N_{bg} = N_{bkgR} \cdot f_{tail} = N_{bkgR} \cdot \frac{N_{SR}^{CS}}{N_{bkgR}^{CS}}$$

Control Sample events in Signal Region

Control Sample events in Background Region

$$\begin{aligned} N_{bg}(K^+ \rightarrow \pi^+ \pi^0(\gamma)) &= 1.07 \pm 0.07 \\ N_{bg}(K^+ \rightarrow \mu^+ \nu_\mu) &= 1.2 \pm 0.2 \\ N_{bg}(K^+ \rightarrow \pi^+ \pi^+ \pi^-) &= 0.25 \pm 0.05 \end{aligned}$$

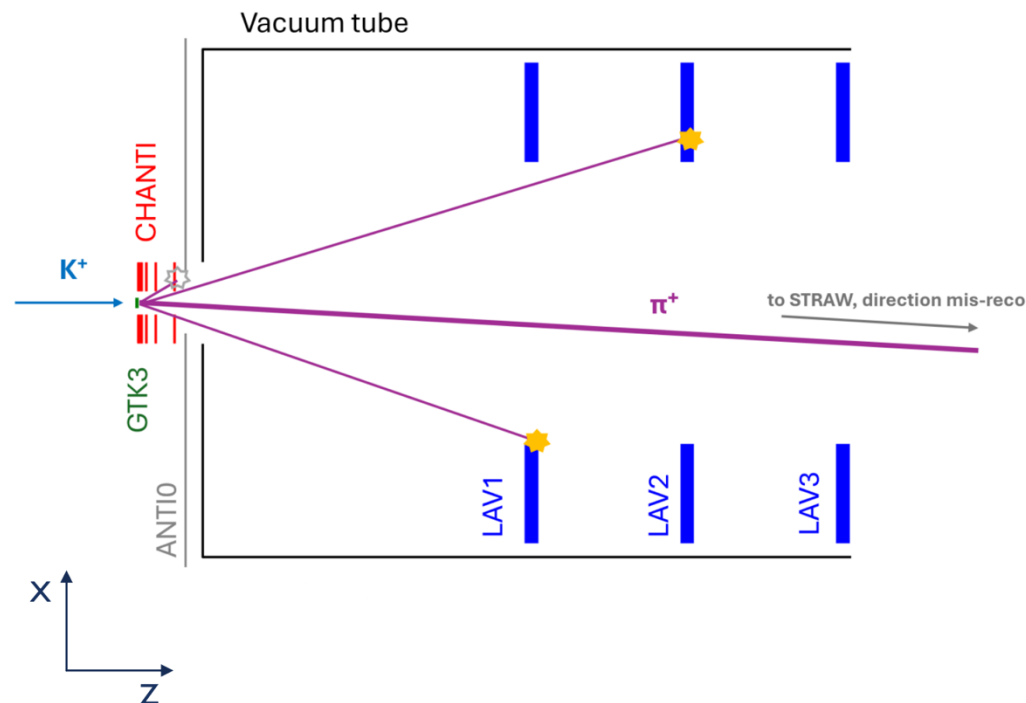
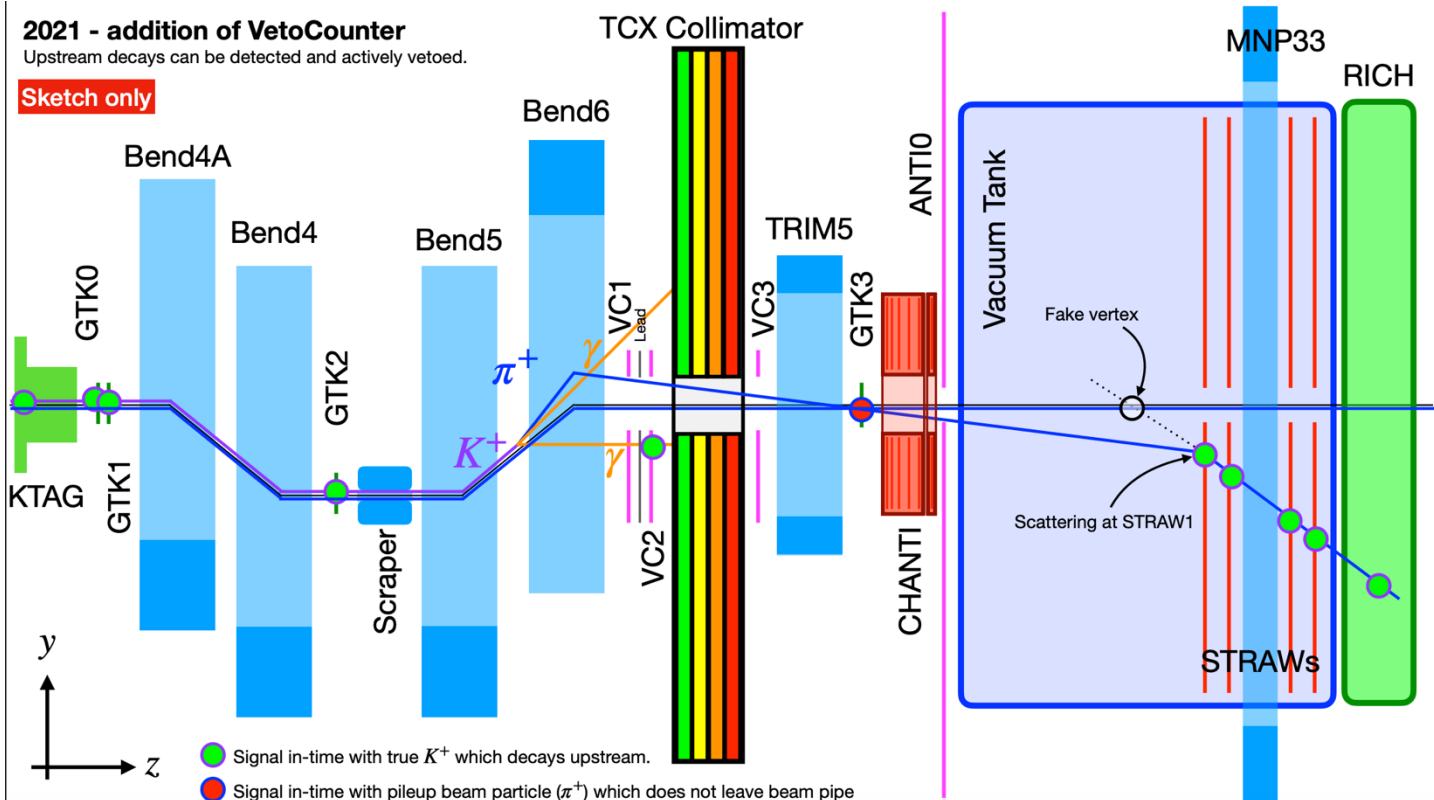
Upstream background

Decays or interactions of beam particles upstream of the fiducial volume (62% of total background)

2021 - addition of VetoCounter

Upstream decays can be detected and actively vetoed.

Sketch only



Upstream decays suppressed by factor 2 using VetoCounter (VC)

LAV1 veto reduces total background by 30% in 2023–24 dataset with $\mathcal{O}(\%)$ signal loss

Fully data-driven background evaluation:

$$N_{\text{bg}}^{\text{Ups.}} = 7.4_{-2.2}^{+2.8}$$

Signal sensitivity

$$N_{\pi\nu\bar{\nu}}^{\text{SM,exp}}(p_i) = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{\text{SM}}}{\mathcal{B}_{\text{SES}}(p_i)} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{\text{SM}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} D_0 N_{\pi\pi}(p_i) \varepsilon_{\text{trig}}(p_i) \varepsilon_{\text{RV}}$$

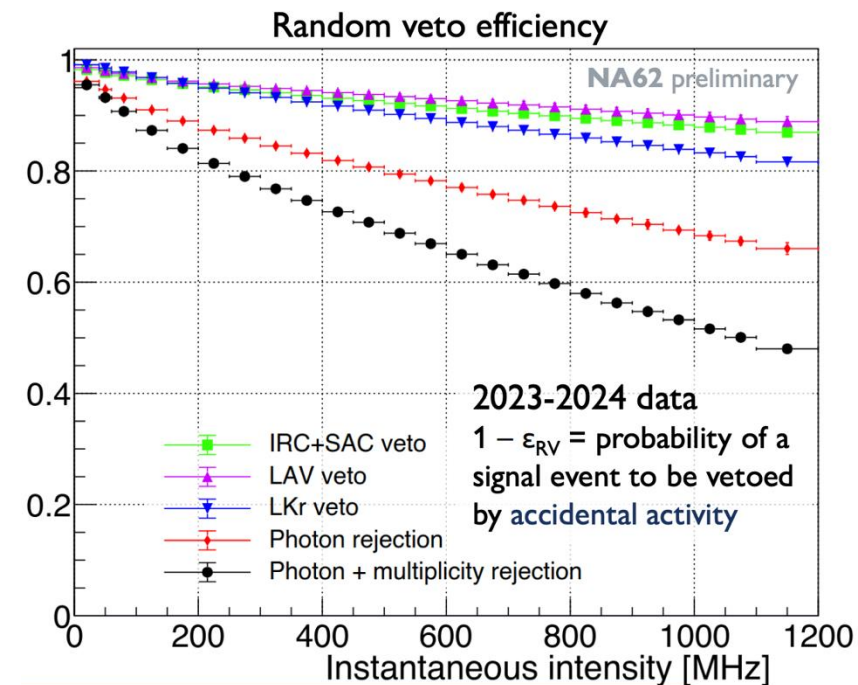
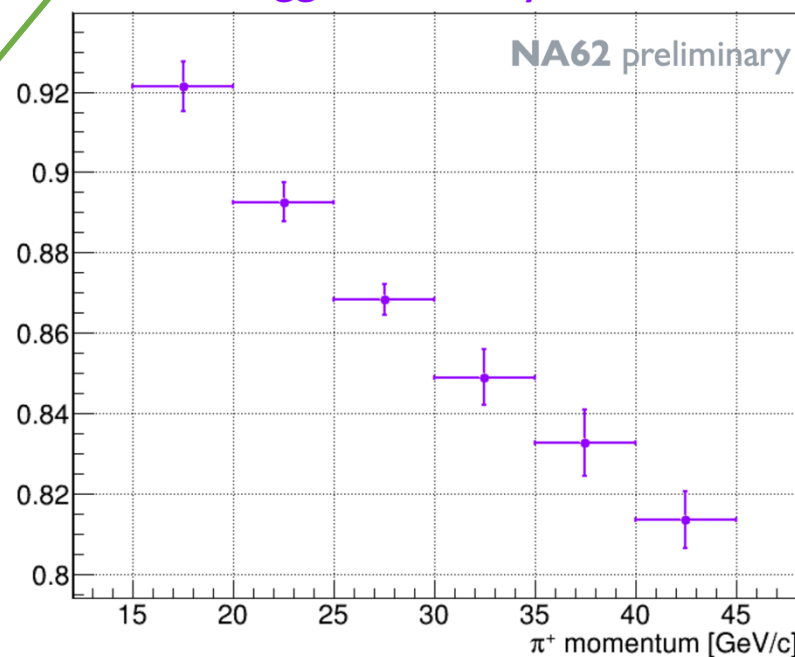
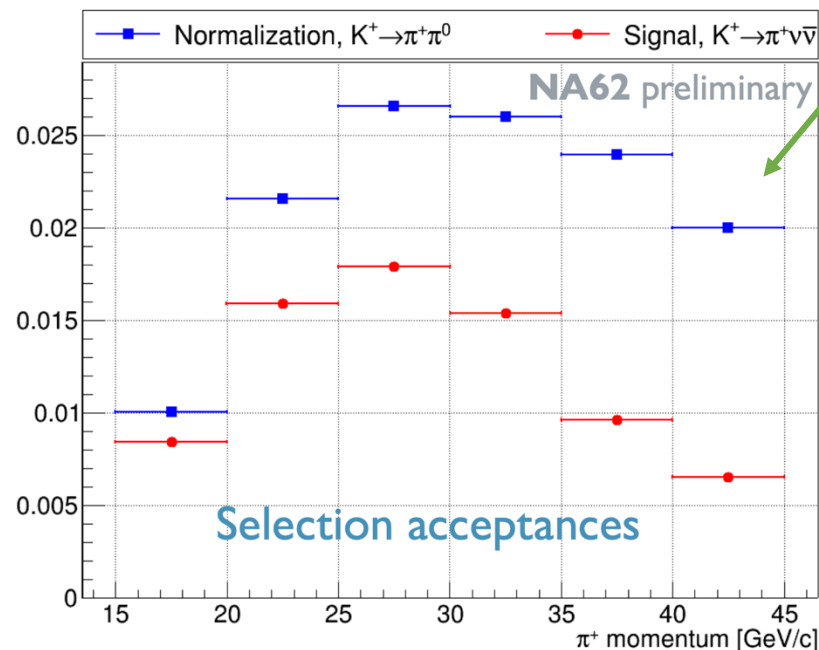
8.4×10^{-11}
(benchmark value)

Normalisation trigger
downscale = 400

of normalisation
events

20.7% [PDG]

Trigger efficiency ratio



- Acceptances evaluated at 0 intensity
- Intensity dependence captured in ε_{RV}
- $\varepsilon_{\text{trig}} = (86.4 \pm 1.2)\%$
- Improved systematics evaluation

- Improved RV efficiency: $1.14 \times \varepsilon_{\text{RV}}$
 - Mainly due to $600 \rightarrow 450$ MHz
(operational conditions optimization
from August 2023 [SPSC-SR-345])

Signal sensitivity and background expectation

[arXiv:2607.16413]

$$N_{\pi\nu\bar{\nu}}^{\text{SM,exp}}(p_i) = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{\text{SM}}}{\mathcal{B}_{\text{SES}}(p_i)} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{\text{SM}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} D_0 N_{\pi\pi}(p_i) \varepsilon_{\text{trig}}(p_i) \varepsilon_{\text{RV}}$$

Quantity	Value
$N_{\pi\pi}$	Number of normalisation events
$A_{\pi\pi}$	Normalisation acceptance
N_K	Effective number of K^+ decays
$A_{\pi\nu\bar{\nu}}$	Signal acceptance
$\varepsilon_{\text{trig}}$	Trigger efficiency ratio
ε_{RV}	Random veto efficiency
$\mathcal{B}_{\text{SES}}$	Single event sensitivity
$N_{\pi\nu\bar{\nu}}^{\text{SM}}$	Number of expected SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events

Background	Events
$K^+ \rightarrow \pi^+ \pi^0(\gamma)$	1.19 ± 0.10
$K^+ \rightarrow \mu^+ \nu(\gamma)$	1.39 ± 0.29
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	0.25 ± 0.05
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	$1.59^{+0.51}_{-0.43}$
$K^+ \rightarrow \pi^+ \gamma \gamma$	0.04 ± 0.04
$K^+ \rightarrow \pi^0 \ell^+ \nu$	< 0.001
Upstream	$7.5^{+2.9}_{-2.2}$
Total	$12.0^{+2.9}_{-2.2}$

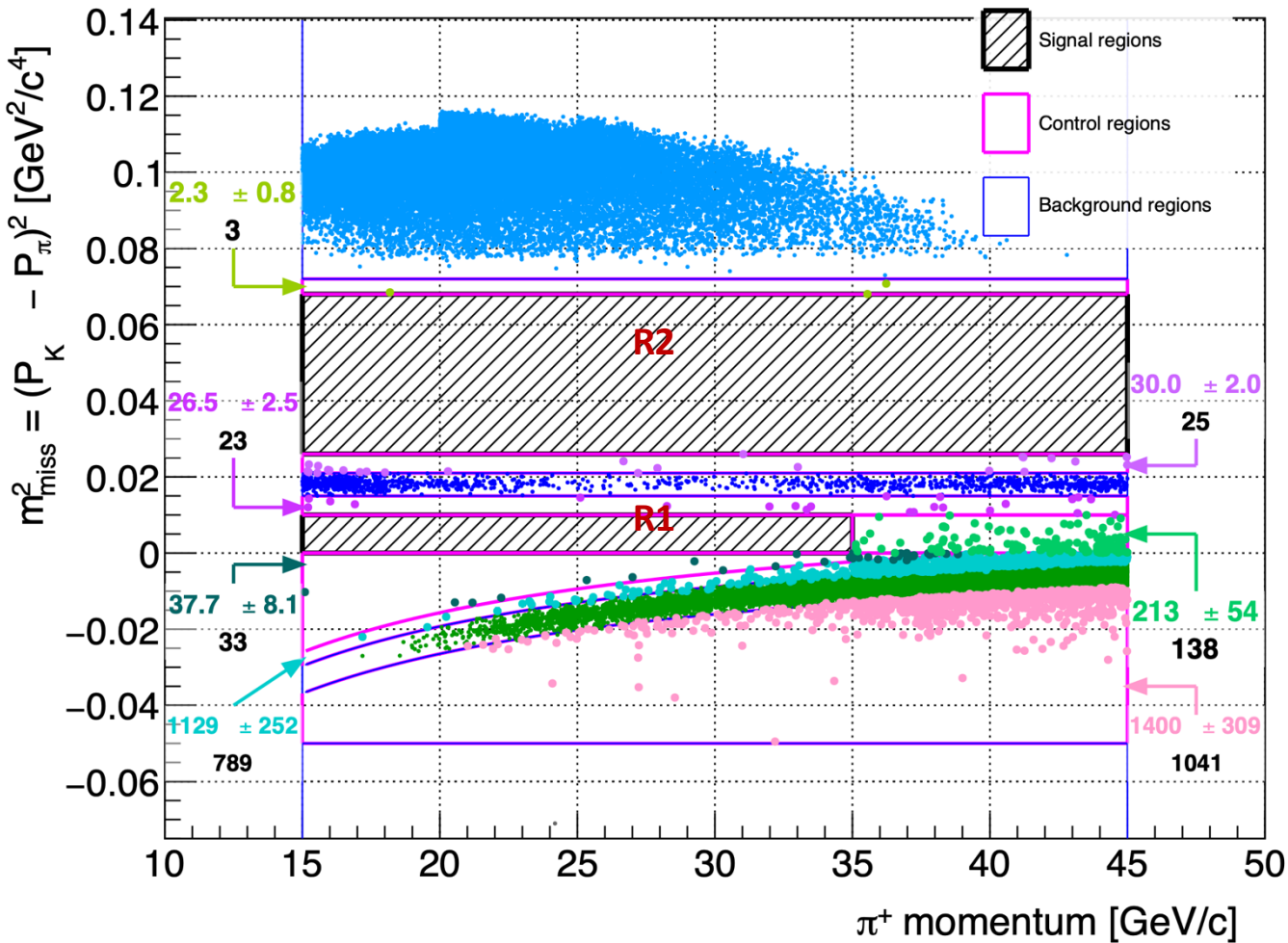
- $2.3 \times$ number of SM signal events expected than 2021-22 data analysis
- 2023+2024: $\sqrt{S+B}/S \approx 0.25$ compared to 0.5 for previous analysis
- By far the most sensitive analysis so far

Combining with previous 2016—22 dataset:

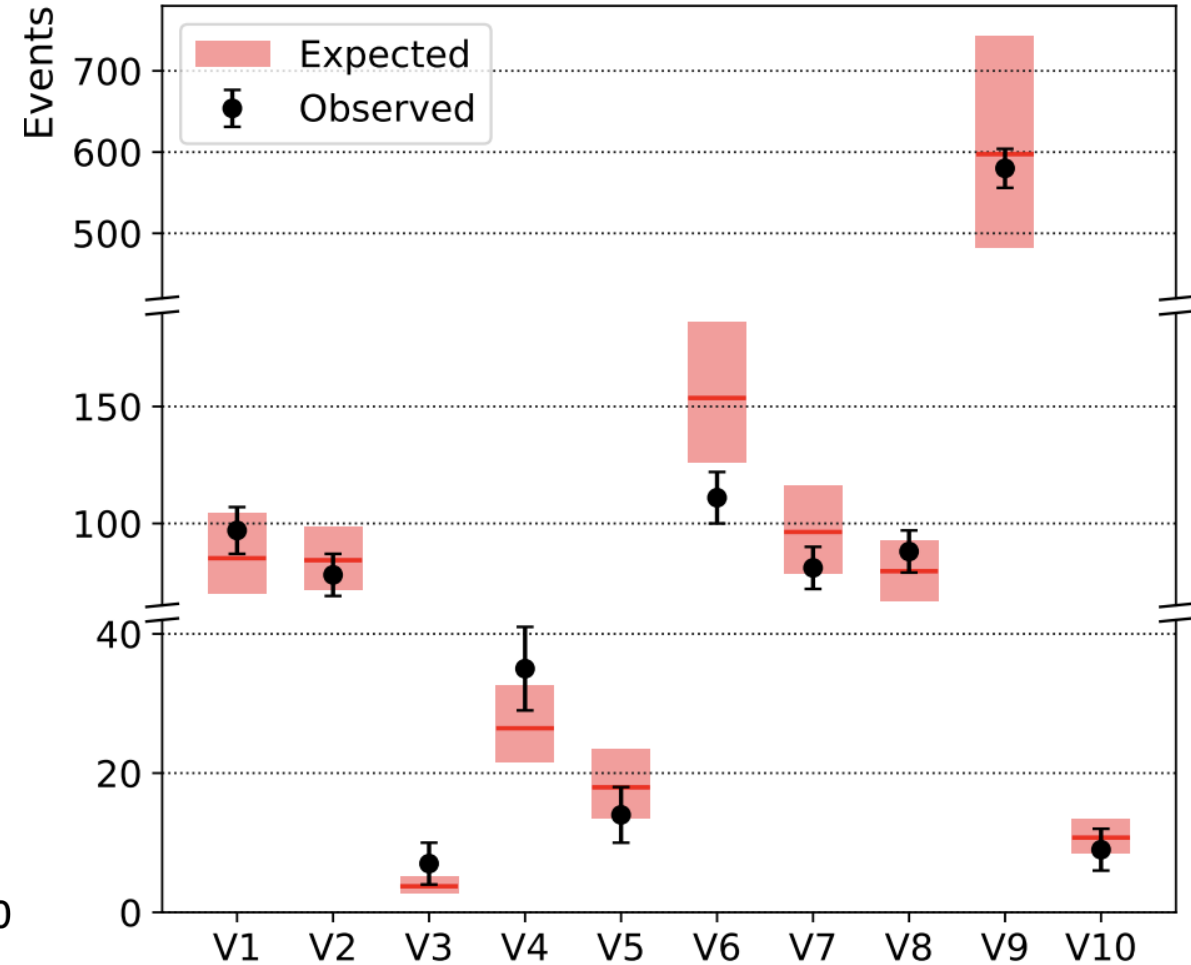
$$N_{bg} = 30^{+4}_{-3}, N_{\pi\nu\bar{\nu}}^{\text{SM,exp}} = 43 \pm 1$$

$\Rightarrow$ expected SM significance $> 5\sigma$

Background validation



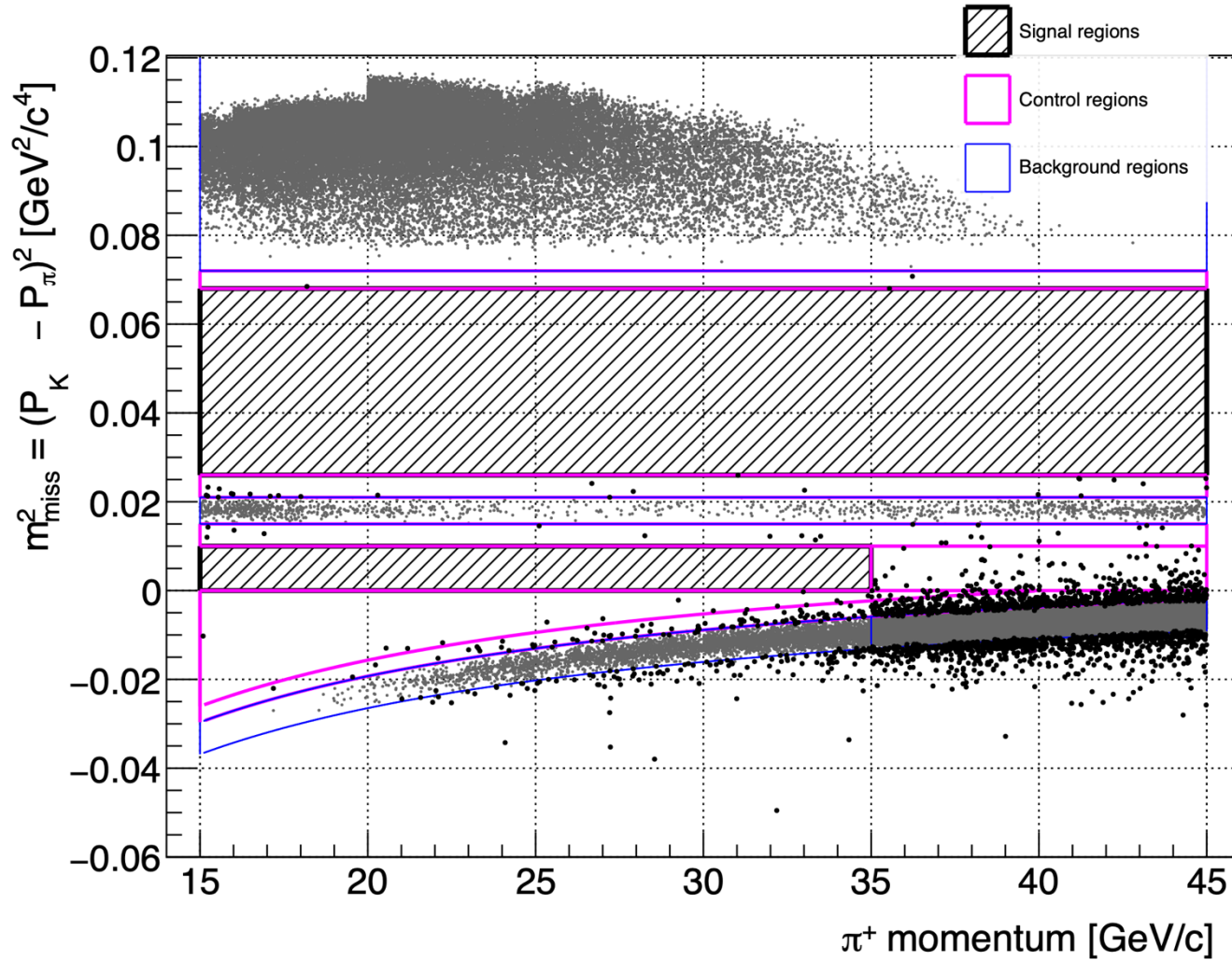
Use control regions to validate predictions for K^+ decays in FV:
 p - value = 0.65



Validate upstream background with 10 independent samples enriched with different upstream background mechanisms:
 p - value = 0.79

Background regions

2023-2024 data



Expected SM signal: $N_{\pi\nu\bar{\nu}}^{SM} \approx 23$

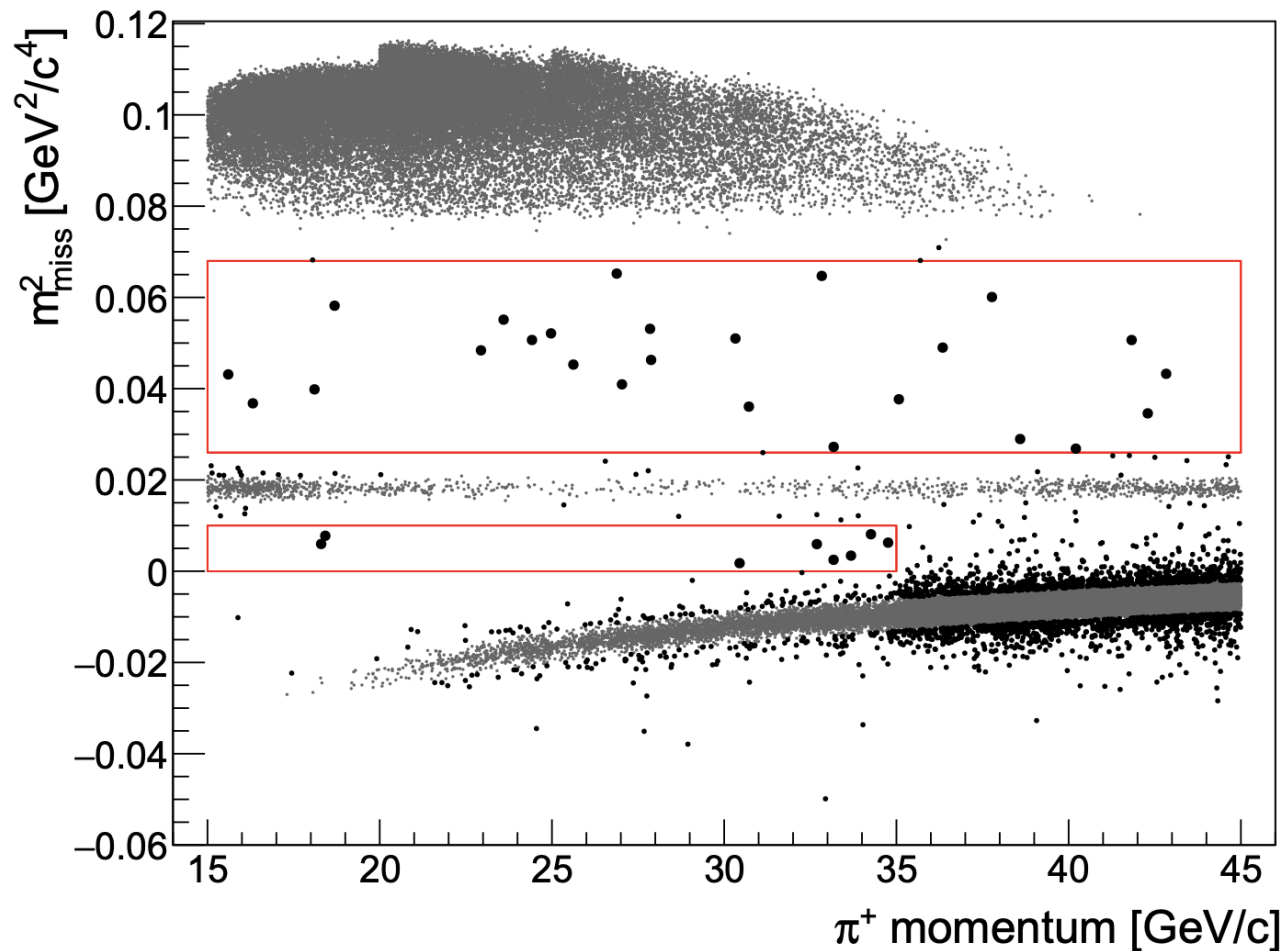
Expected background: $N_{bg} = 12.0^{+2.9}_{-2.2}$

Observed: $N_{obs} = ?$

Signal regions

2023-2024 data

[arXiv:2607.16413]

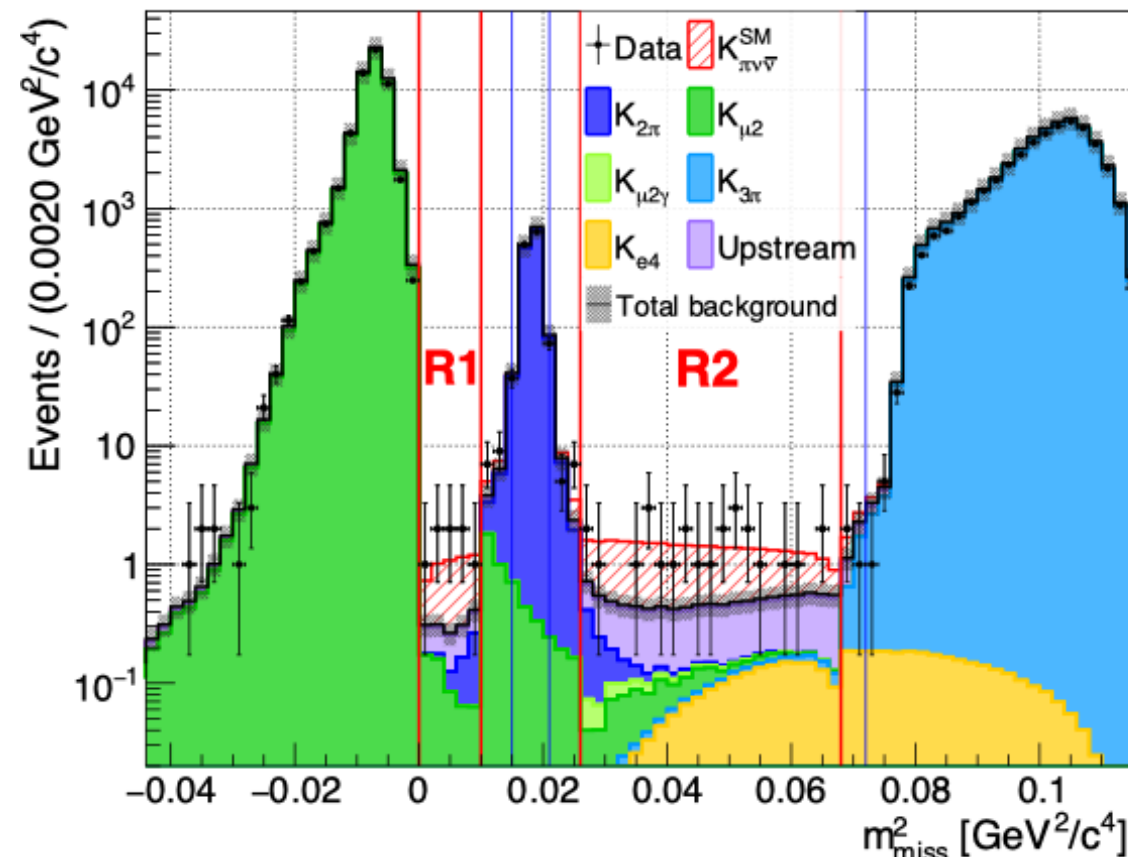


Expected SM* signal: $N_{\pi\nu\bar{\nu}}^{SM} = 22.9 \pm 1.1$

Expected background: $N_{bg} = 12.0^{+2.9}_{-2.2}$

Observed: $N_{obs} = 33$

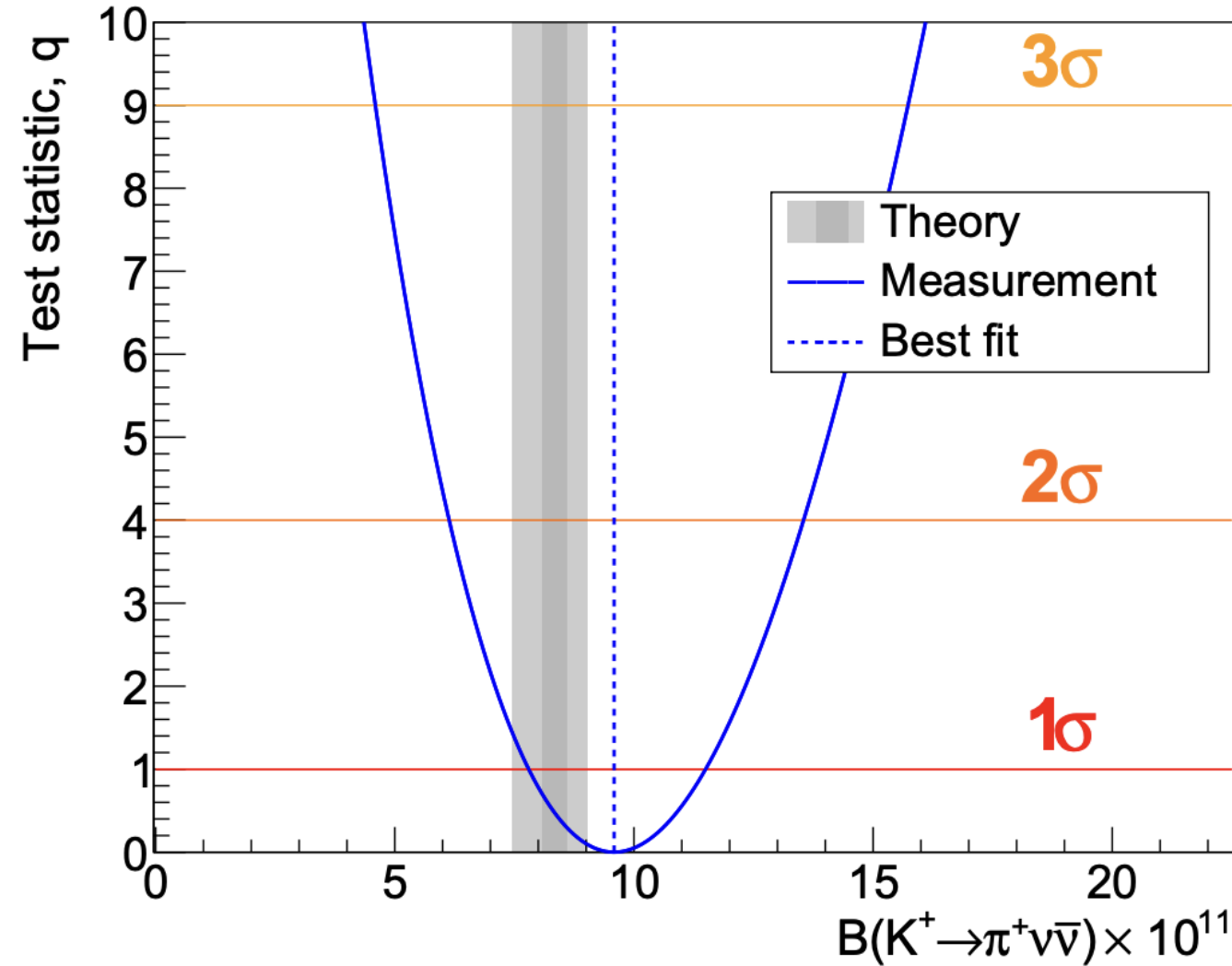
1D projection with different background predictions & SM signal expectation* with $\mathcal{B}_{SM} = 8.4 \times 10^{-11}$ [not a fit]:



$$\mathcal{B}_{\pi\nu\bar{\nu}}^{23-24} = \left(7.2^{+2.2}_{-1.9} \Big|_{stat} \quad {}^{+0.9}_{-0.9} \Big|_{syst} \right) \times 10^{-11} = \left(7.2^{+2.3}_{-2.1} \right) \times 10^{-11}$$

Combine: 2016—2024 dataset

[arXiv:2607.16413]

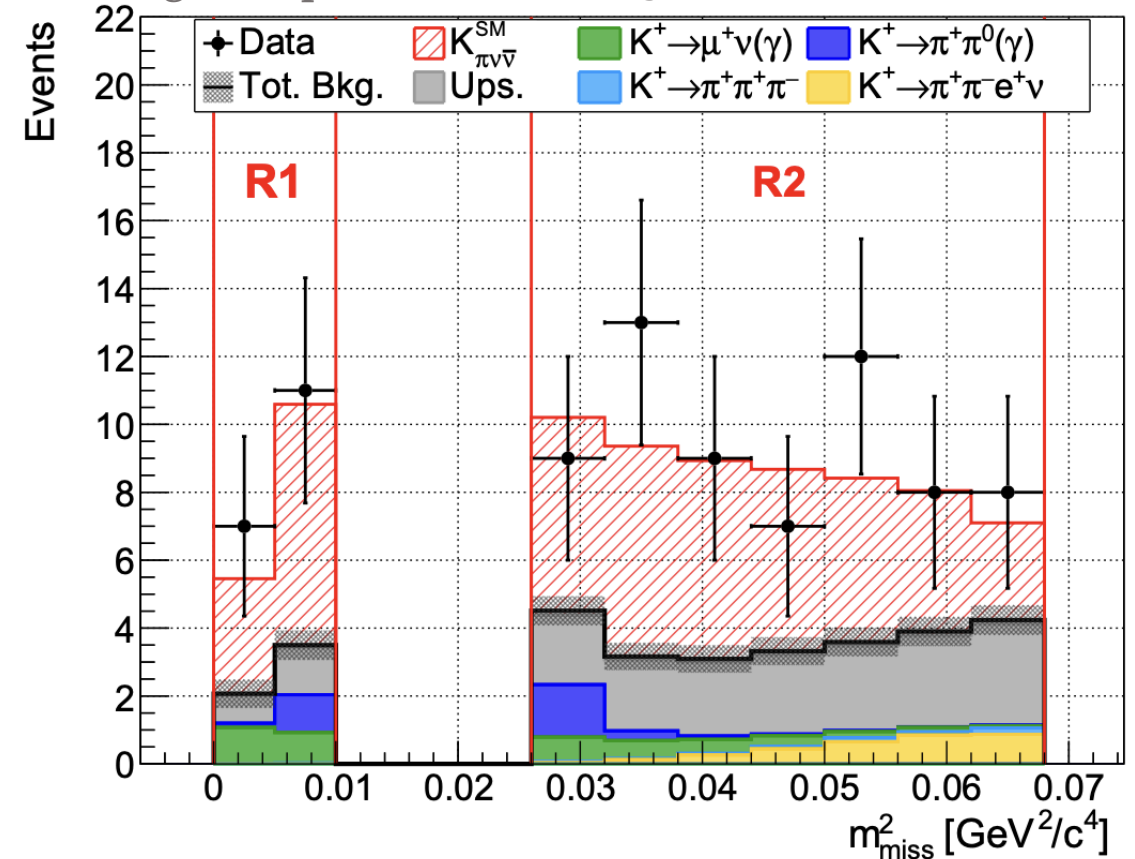


Expected SM* signal: $N_{\pi\nu\bar{\nu}}^{SM} = 43 \pm 1$

Expected background: $N_{bg} = 30^{+4}_{-3}$

Observed: $N_{obs} = 84$

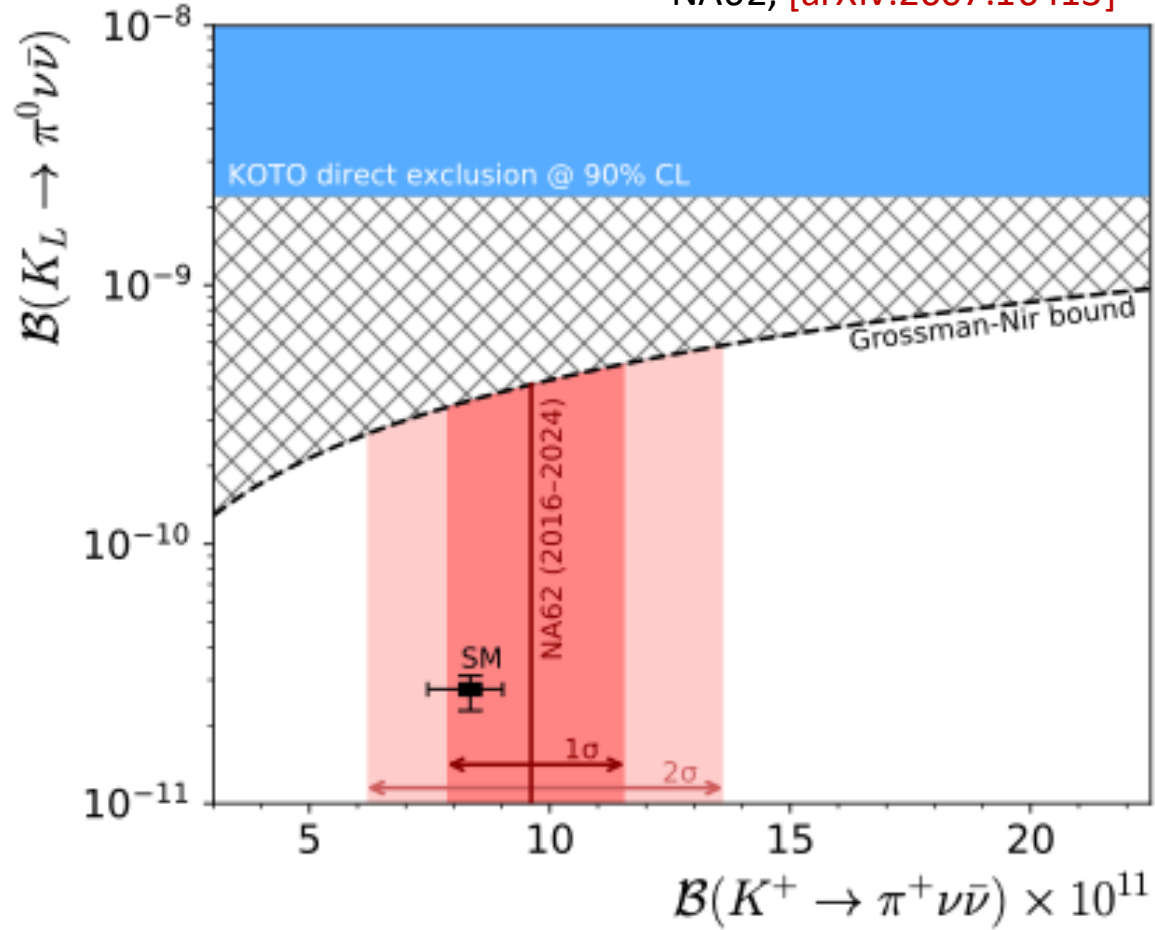
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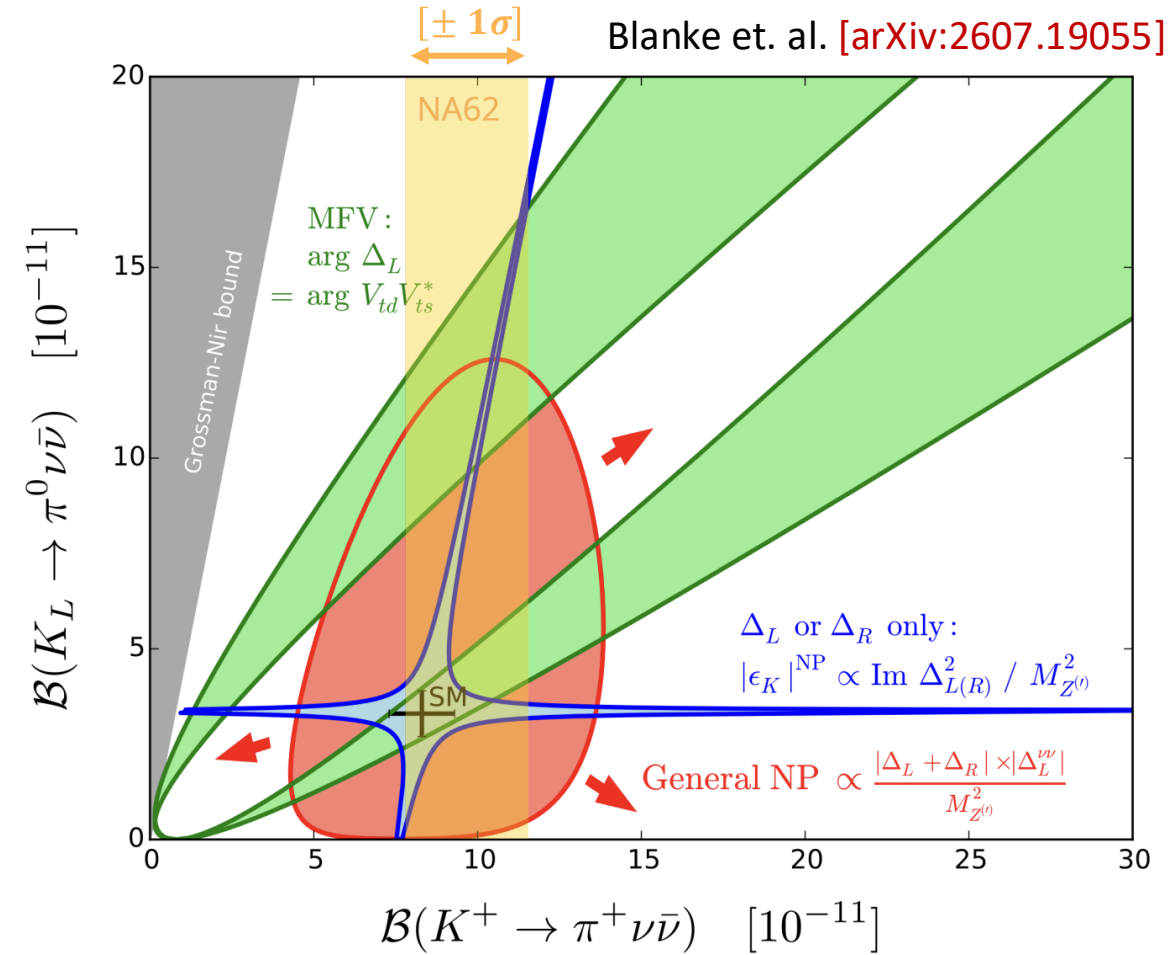
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-24} = \left(9.6^{+1.8}_{-1.6} \Big|_{stat} \quad {}^{+0.8}_{-0.6} \Big|_{syst} \right) \times 10^{-11} = \left(9.6^{+1.9}_{-1.8} \right) \times 10^{-11}$$

The global picture

NA62, [arXiv:2607.16413]

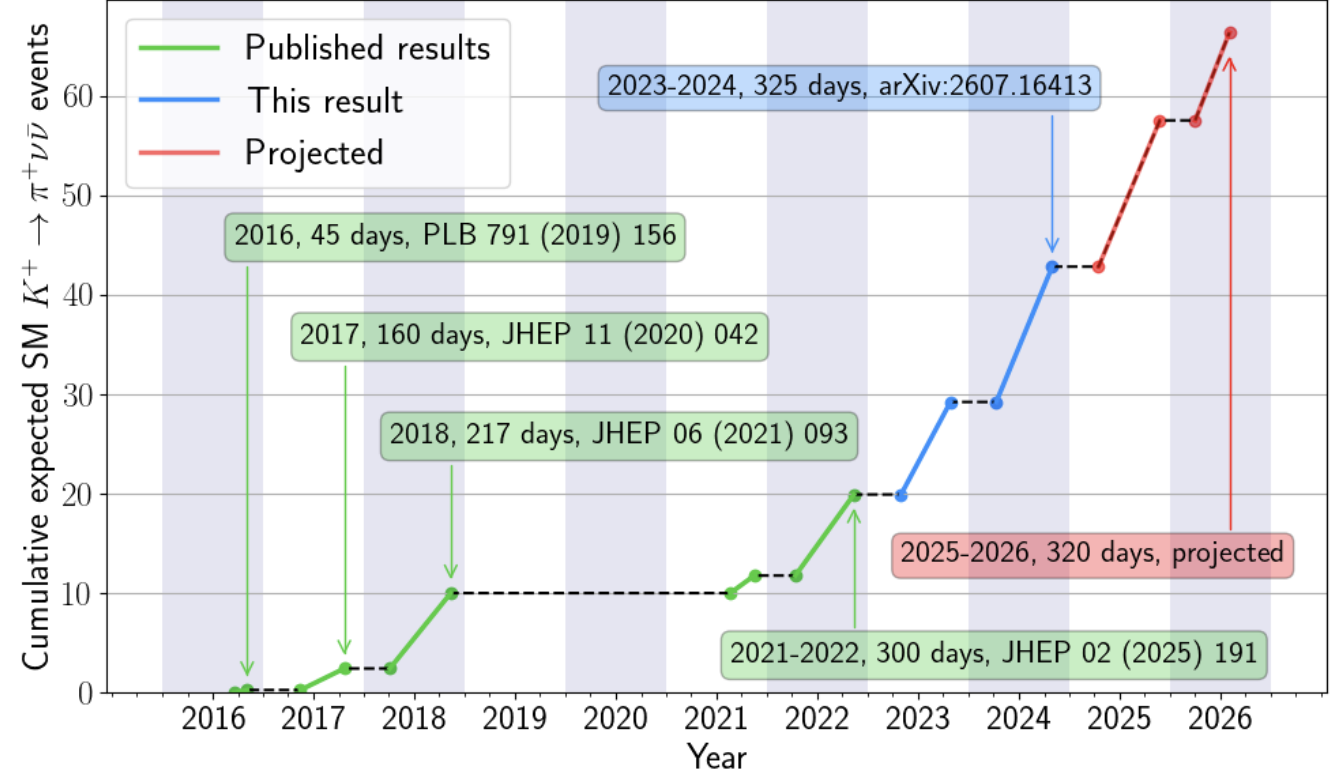
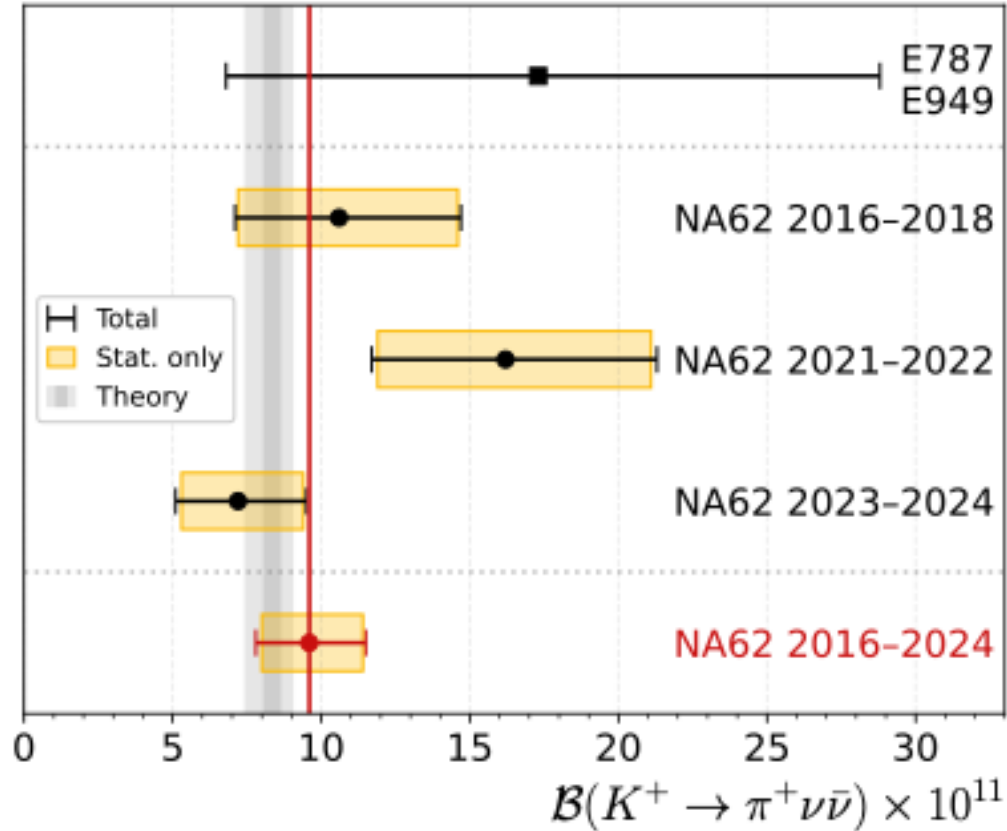


Blanke et. al. [arXiv:2607.19055]



- $\mathcal{B}_{\pi\nu\bar{\nu}}^{16-24}$ is compatible with SM – within the 20% uncertainty
- BUT: still a lot of space for New Physics in rare kaon decays [arXiv:2607.19055]
 - **NA62:** (improve) $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, **LHCb:** $K_S \rightarrow \mu^+ \mu^-$, **KOTO-II:** $K_L \rightarrow \pi^0 \nu \bar{\nu}$, $K_L \rightarrow \pi^0 \ell^+ \ell^-$, ...

Conclusion and prospects



- *2x signal acceptance * flux + Backgrounds reduced = major sensitivity boost: expected SM significance $> 5\sigma$*
- **Branching ratio measured to $< 20\%$ precision**
 - $\mathcal{B}_{\pi\nu\bar{\nu}}^{16-24} = (9.6^{+1.9}_{-1.8}) \times 10^{-11}$ (result compatible with SM)
- *2025—2026 dataset incoming (1/3 of total): target BR precision improvement 20% $\rightarrow$ 15%*