



FACULTY
OF MATHEMATICS
AND PHYSICS
Charles University



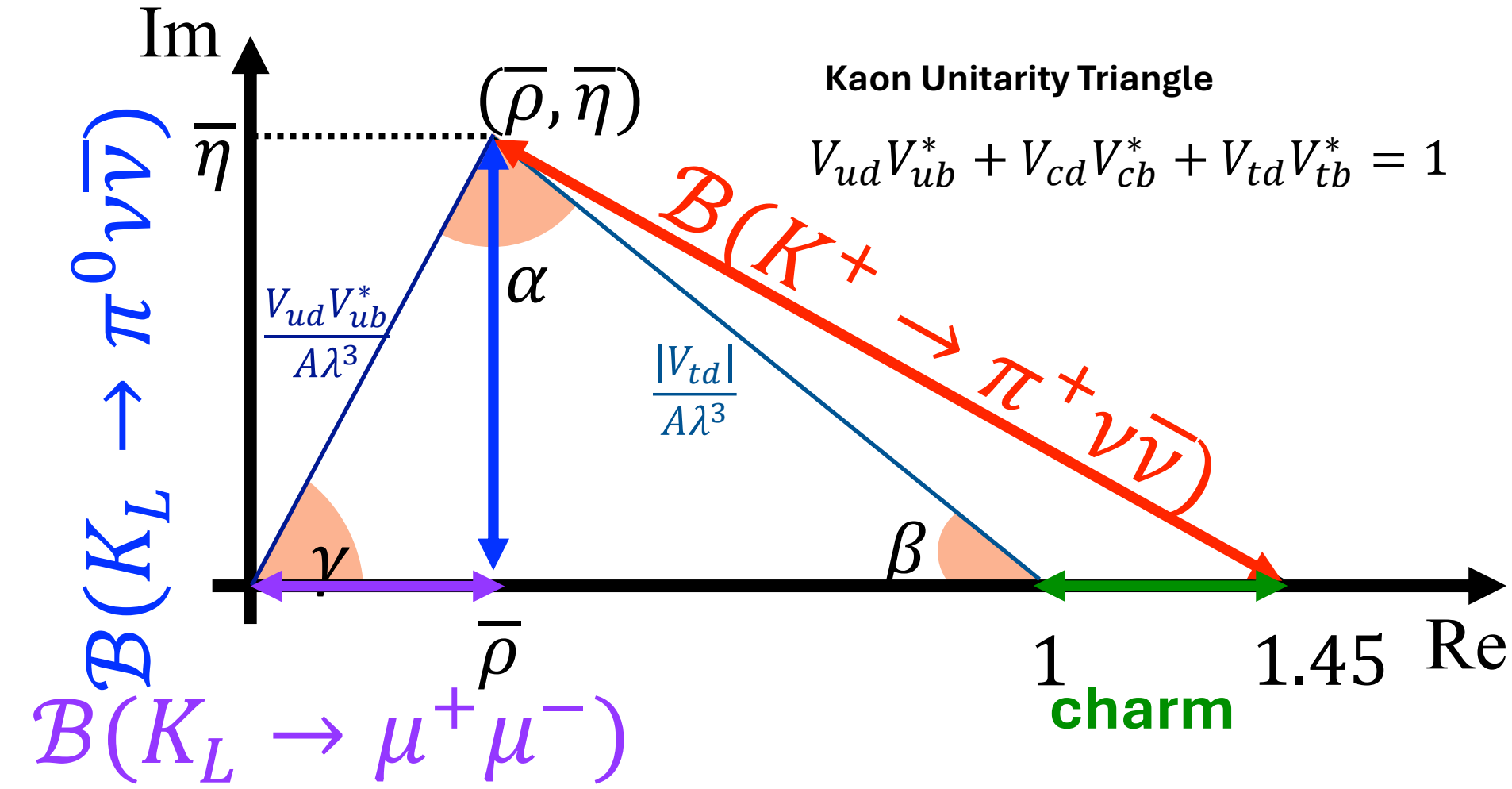
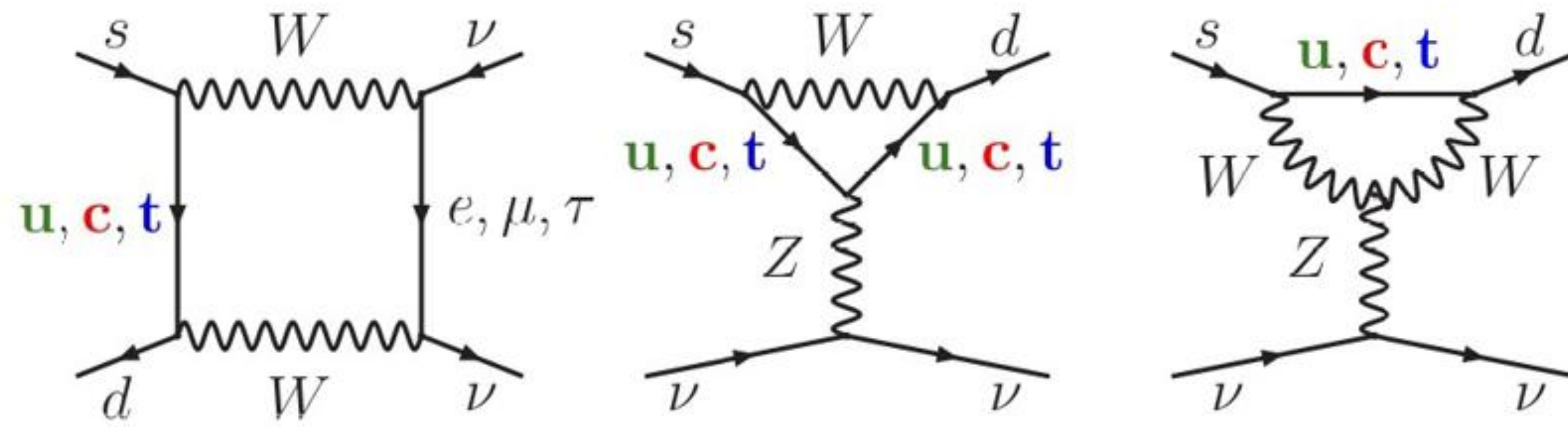
NA62 experiment:
Ultra-rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
Michal Koval
IPNP

Outline

1. New NA62 result: measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
 - Seminar-like presentation
 - Result obtained from analysis of 2023 – 2024 dataset
<https://home.cern/news/news/physics/na62-collaboration-refines-measurement-rare-particle-decay>
2. Zoom in at one aspect of the analysis: backgrounds

$K \rightarrow \pi \nu \bar{\nu}$: Precision test of the SM

SM: Z-penguin & box diagrams



- $\mathcal{B}(K \rightarrow \pi \nu \bar{\nu})$ highly suppressed in SM

- GIM mechanism & maximum CKM suppression $s \rightarrow d$ transition: $\sim \frac{m_t}{m_W} |V_{ts}^* V_{td}|$

- Theoretically clean \Rightarrow high precision SM predictions

- Dominated by short distance contributions.

- Hadronic matrix element extracted from $\mathcal{B}(K \rightarrow \pi l \nu)$ decays via isospin rotation.

Decay Mode BR	SM [Buras et al. EPJC 82 (2022) 7, 615]	SM [D'Ambrosio et al. JHEP 09 (2022) 148]	Experimental Status in 2022
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.1}_{-3.5}) \times 10^{-11}$ (NA62)
$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 2 \times 10^{-9}$ (KOTO)

Differences in SM calculations from choice of CKM parameters:
[\[Eur.Phys.J.C 84 \(2024\) 4, 377\]](#)

NA62 (2016–18 data): [\[JHEP 06 \(2021\) 093\]](#)

KOTO (2021 data): [\[Eur.Phys.J.C 84 \(2024\) 4, 377\]](#)

$K \rightarrow \pi \nu \bar{\nu}$: Beyond the SM

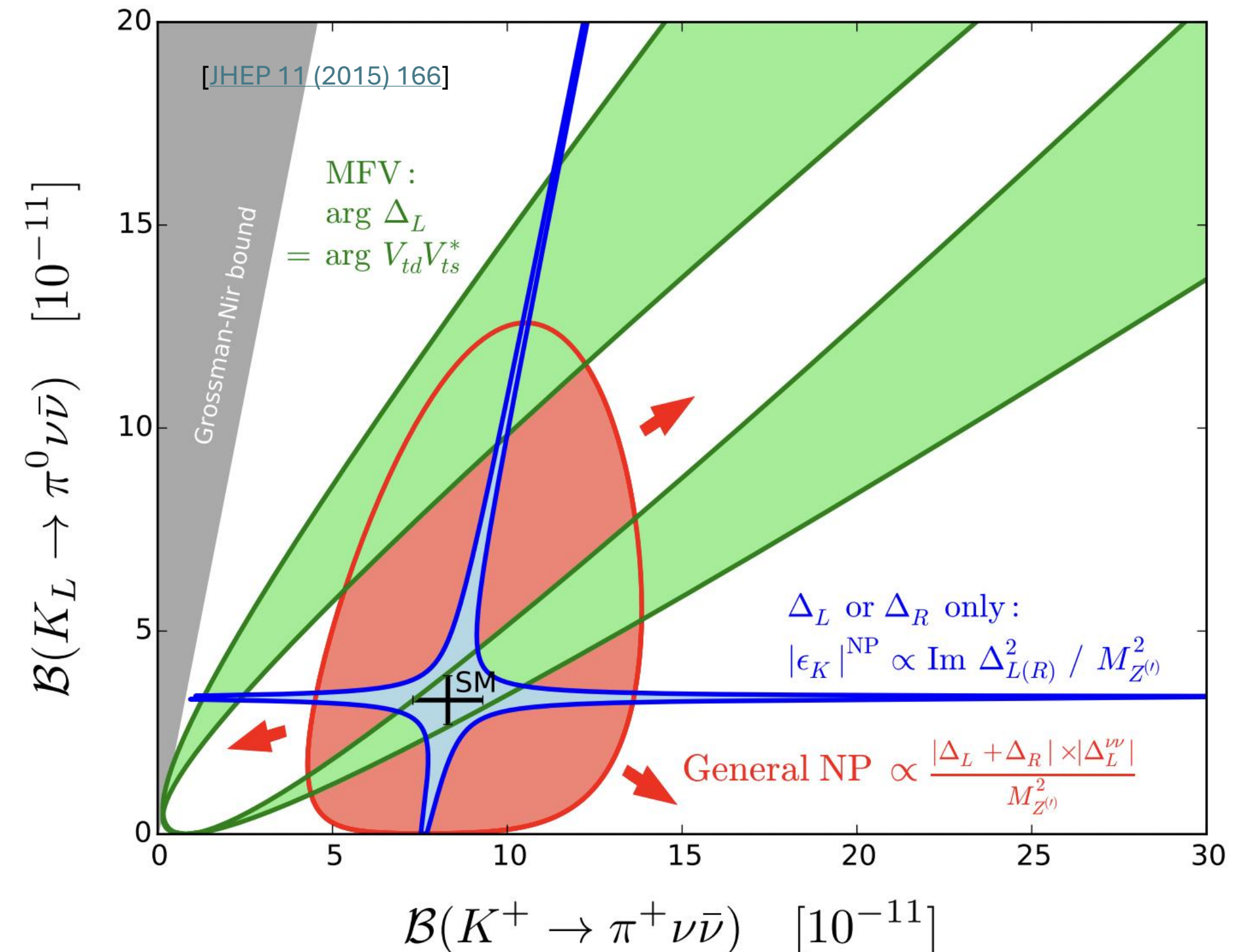
- Correlations between BSM contributions to BRs of K^+ and K_L modes [JHEP 11 (2015) 166].
 - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ϵ'/ϵ , ΔM_B , B-decays) [JHEP 12 (2020) 097][PLB 809 (2020) 135769].
- Leptoquarks [EPJ.C 82 (2022) 4, 320], Interplay between CC and FCNC [JHEP 07 (2023) 029], NP in neutrino sector [EPJ.C 84 (2024) 7, 680] and additional scalar/tensor contributions [JHEP 12 (2020) 186][arXiv:2405.06742] ...

- **Green:** CKM-like flavour structure
 - Models with Minimal Flavour Violation
- **Blue:** new flavour-violating interactions where LH or RH currents dominate
 - Z' models with pure LH/RH couplings
- **Red:** general NP models without above constraints
- **Grossman-Nir Bound:** model-independent relation

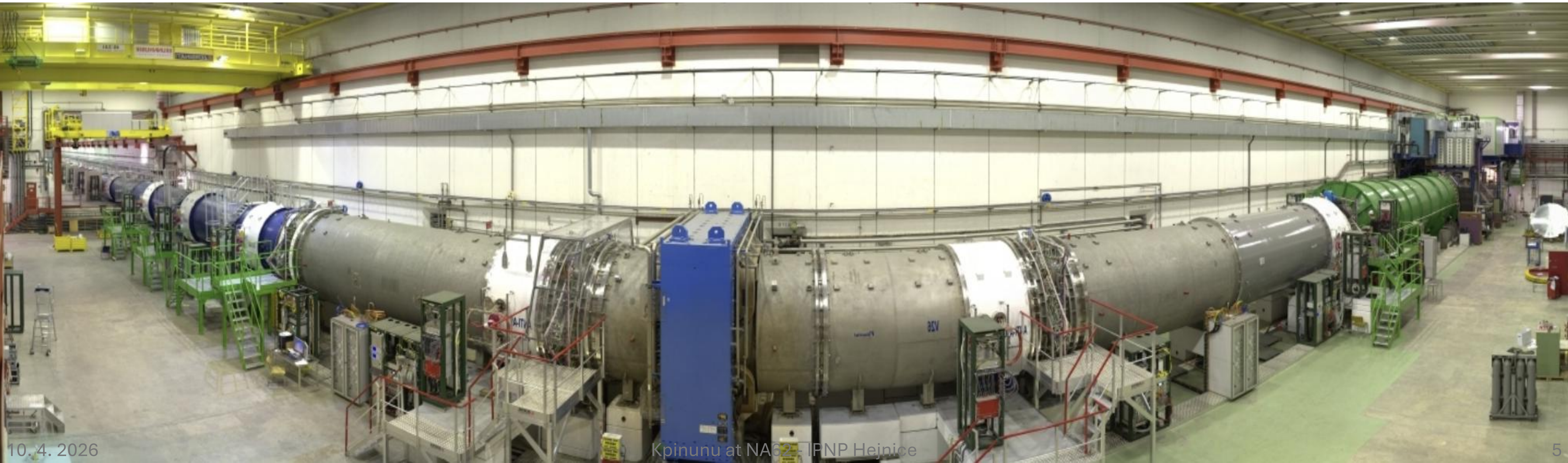
[PLB 398 (1997) 163-168]

$$\frac{\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \tau_{K^+}}{\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \tau_{K_L}} \simeq 1$$

$$\Rightarrow \mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \lesssim 4.3 \cdot \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$$

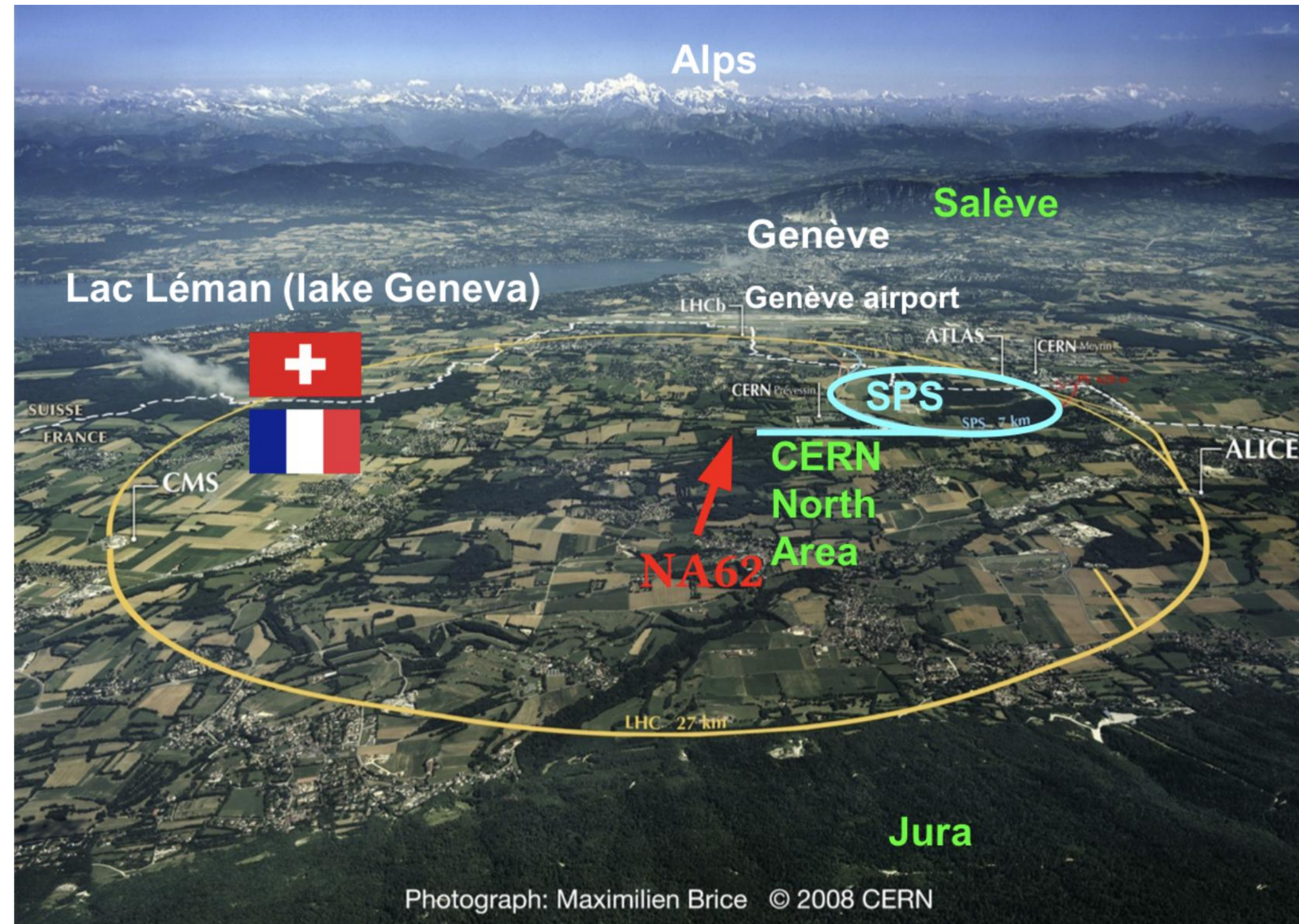


NA62: The kaon factory at the CERN North Area

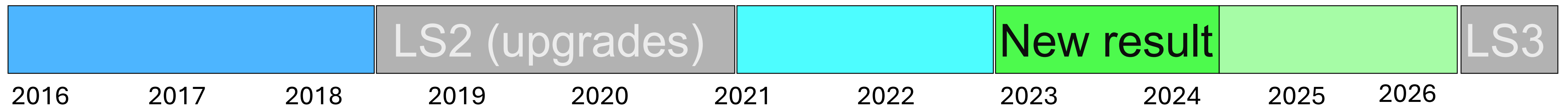


The NA62 Experiment at CERN

~200 collaborators from ~30 institutions.



- **Primary goal:** measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
- **New Technique:** K^+ decay-in-flight
- **Results:** [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
- **Broader physics program:**
 - Rare K^+ decays (e.g. $K^+ \rightarrow \pi^+ \gamma \gamma$ [PLB 850 (2024) 138513])
 - LNV/LFV decays (e.g. $K^+ \rightarrow \pi^- (\pi^0) e^+ e^+$ [PLB 830 (2022) 137172])
 - Exotics (e.g. Dark photon [PRL 133 (2024) 11, 111802])
- **Data taking**
 - 2016 Commissioning + Physics run (45 days).
 - 2017 Physics run (160 days).
 - 2018 Physics run (217 days).
 - 2021 Physics run (85 days).
 - 2022 Physics run (215 days).
 - 2023 Physics run (150 days).
 - 2024 Physics run (204 days).
 - 2025 Physics run (200 days).
 - 2026 Physics run (the last one ☹️) ongoing



The NA62 Collaboration



NA62 Collaboration meeting
Birmingham, UK, 2024

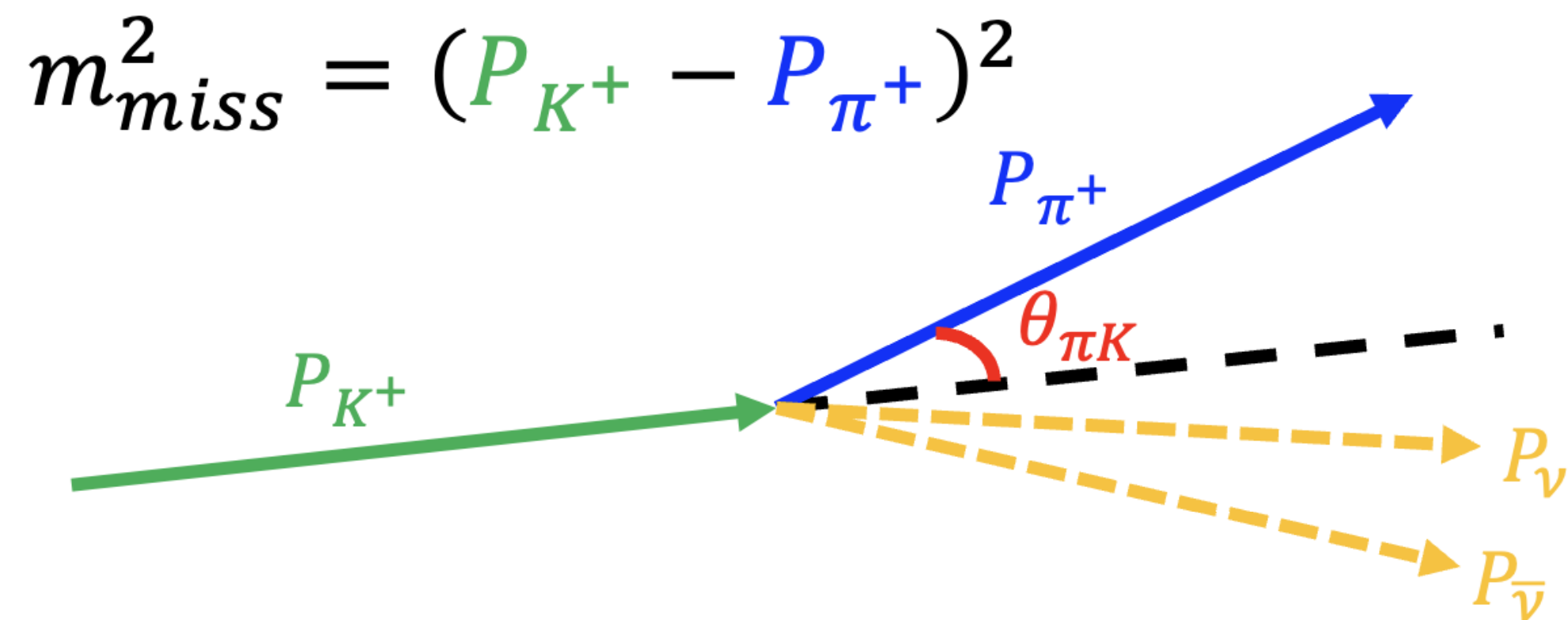


NA62 Collaboration meeting
Perugia, Italy, 2025

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at NA62

NA62 Strategy:

- Tag K^+ and measure momentum.
- Identify π^+ and measure momentum.
- Match K^+ and π^+ in time & form vertex.
- Determine $m_{miss}^2 = (P_K - P_\pi)^2$
- Reject any additional activity.



NA62 Performance Keystones:

- $\mathcal{O}(100)ps$ timing between detectors
- $\mathcal{O}(10^4)$ background suppression from kinematics
- $> 10^7$ muon rejection
- $> 10^7$ rejection of π^0 from $K^+ \rightarrow \pi^+ \pi^0$ decays

Decay mode	Branching Ratio [PDG]
$K^+ \rightarrow \mu^+ \nu_\mu$	$(63.56 \pm 0.11)\%$
$K^+ \rightarrow \pi^+ \pi^0$	$(20.67 \pm 0.08)\%$
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	$(5.583 \pm 0.024)\%$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$

$$K^+ \rightarrow \pi^+ \nu \bar{\nu} \quad \approx 10^{-10}$$

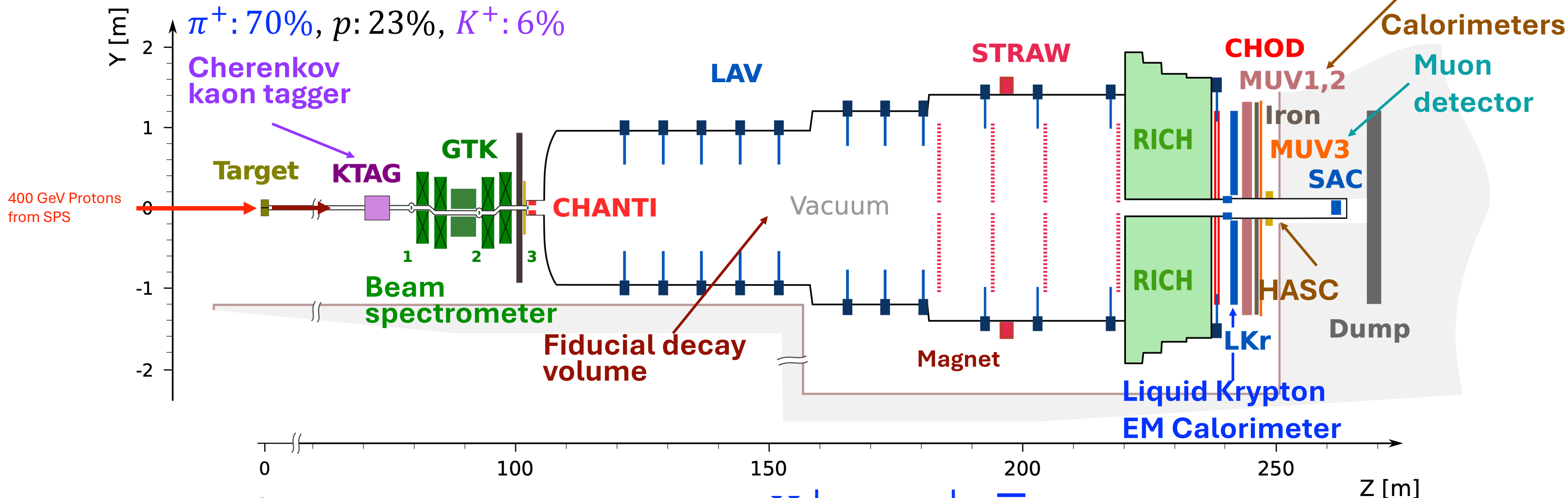
NA62 beamline & detector

[JINST 12 (2017) 05, P05025]

Secondary $75 \text{ GeV}/c$ beam:

π^+ : 70%, p : 23%, K^+ : 6%

Cherenkov
kaon tagger



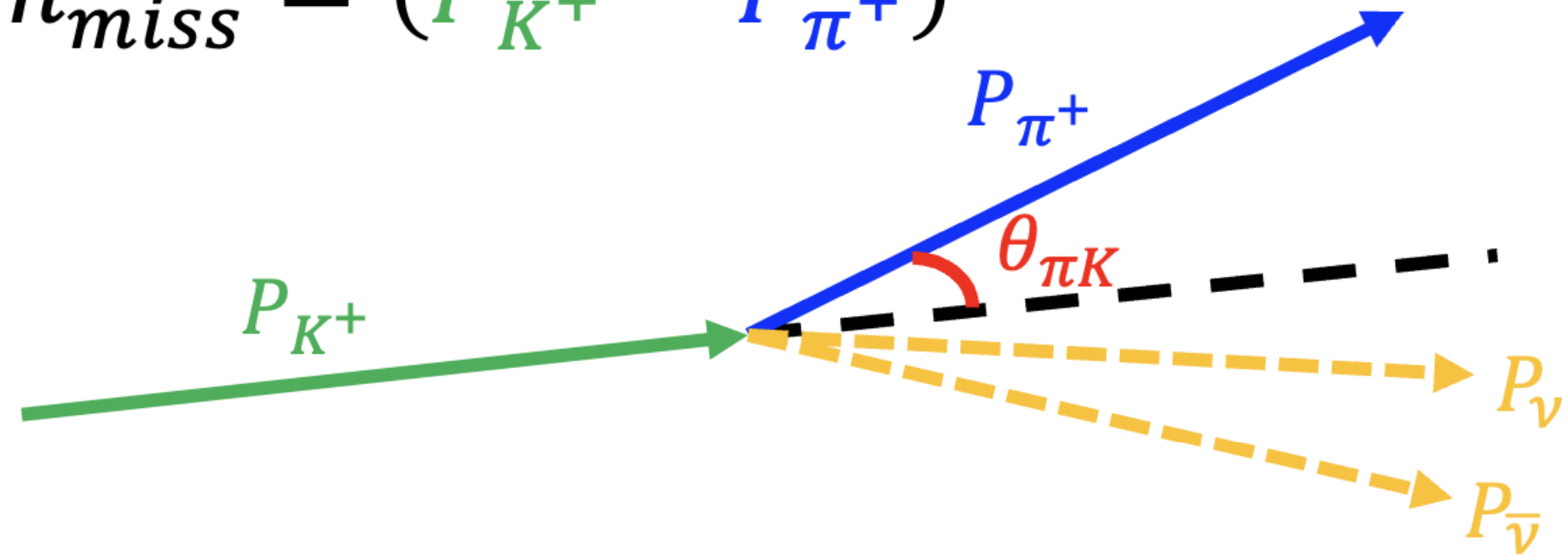
- Designed & optimised for study of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$:
 - **Particle tracking:** beam particle (GTK) & downstream tracks (STRAW)
 - **PID:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
 - **Comprehensive veto systems:** CHANTI (beam interactions), LAV, LKr, IRC, SAC (γ)

NA62 beamline & detector



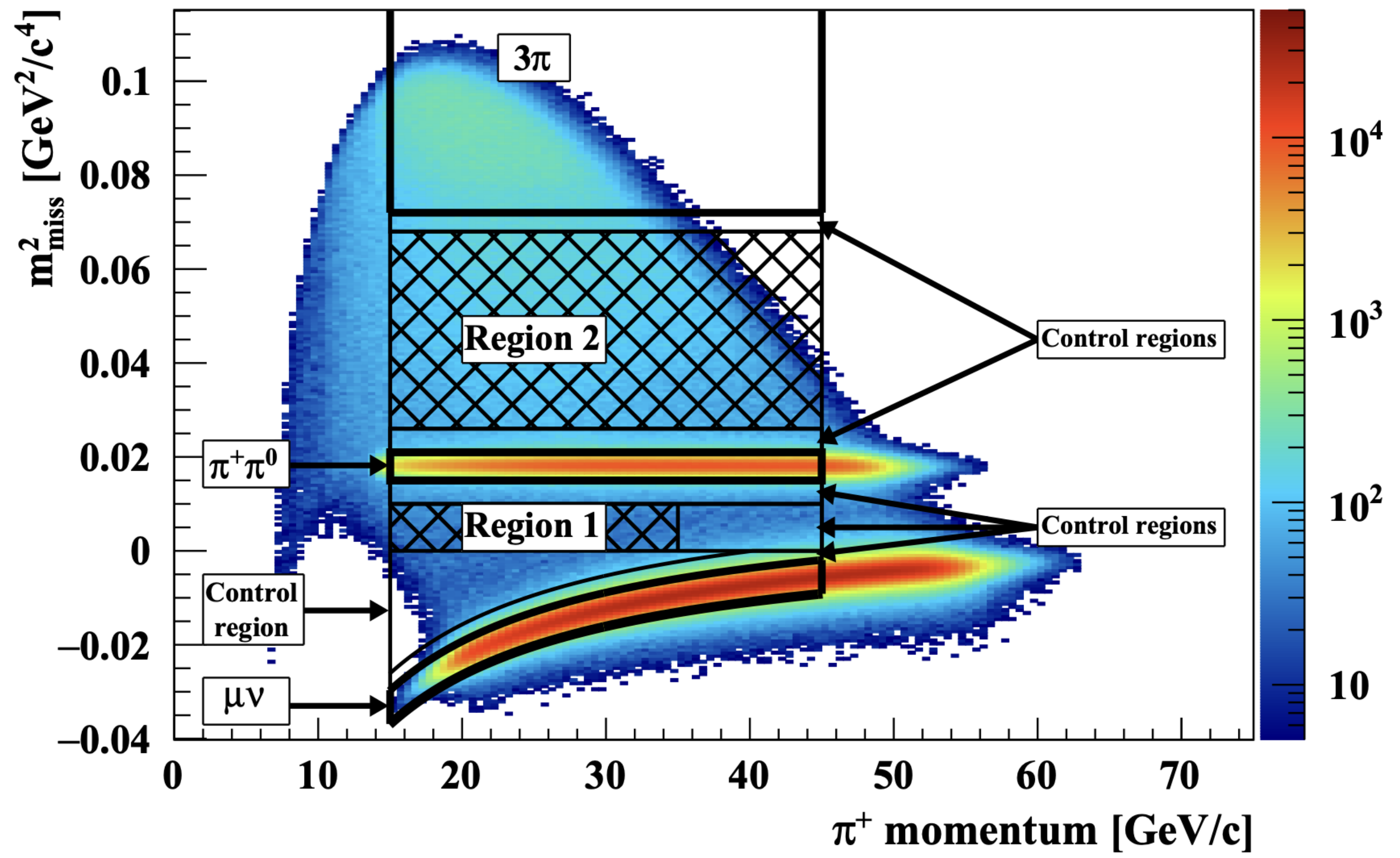
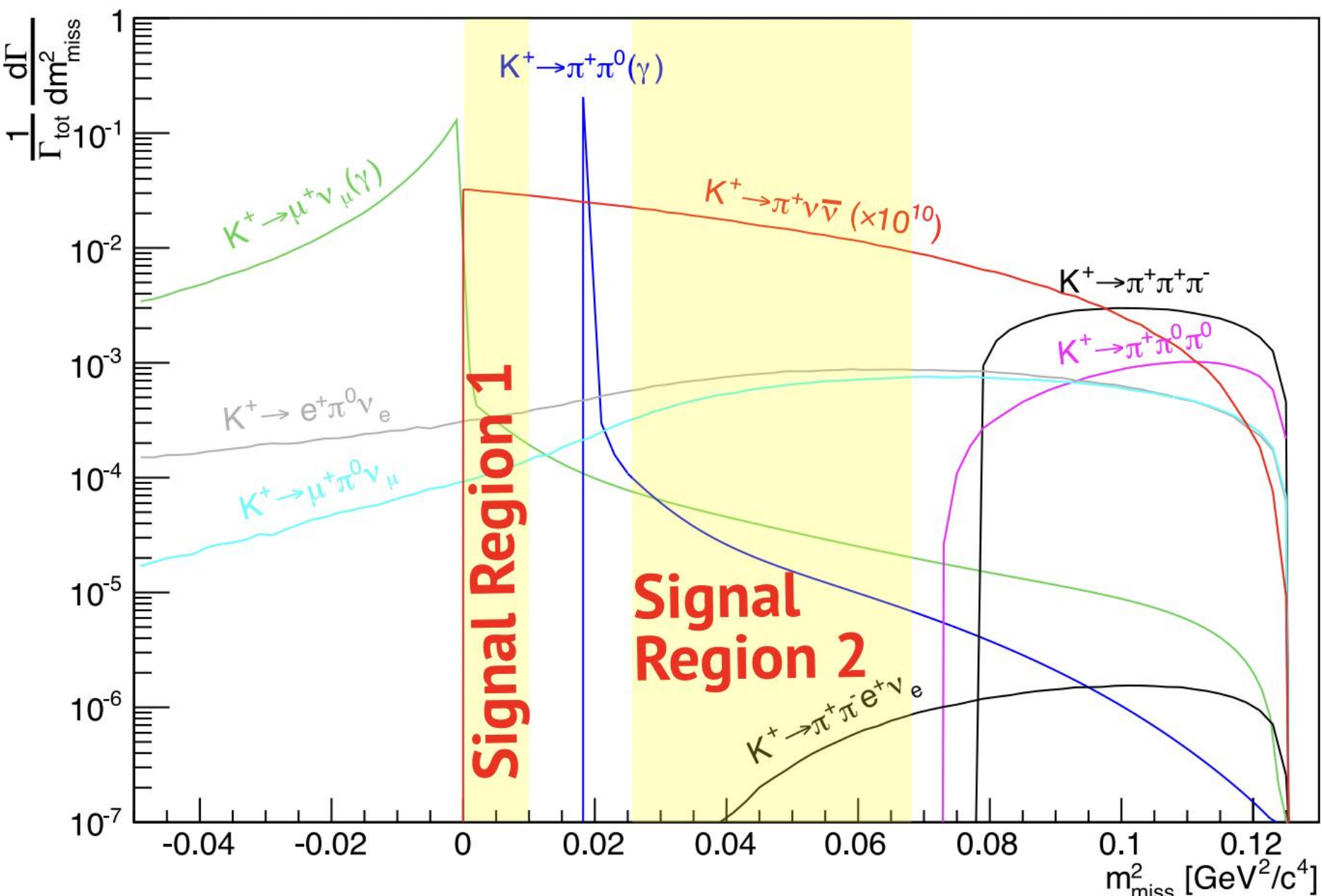
Kinematic constraints & signal regions

$$m_{miss}^2 = (P_{K^+} - P_{\pi^+})^2$$



$\mathcal{O}(10^4)$ background suppression from kinematics

[JHEP 06 (2021) 093]



π^+ momentum range: 15—45 GeV/c

Analysis overview

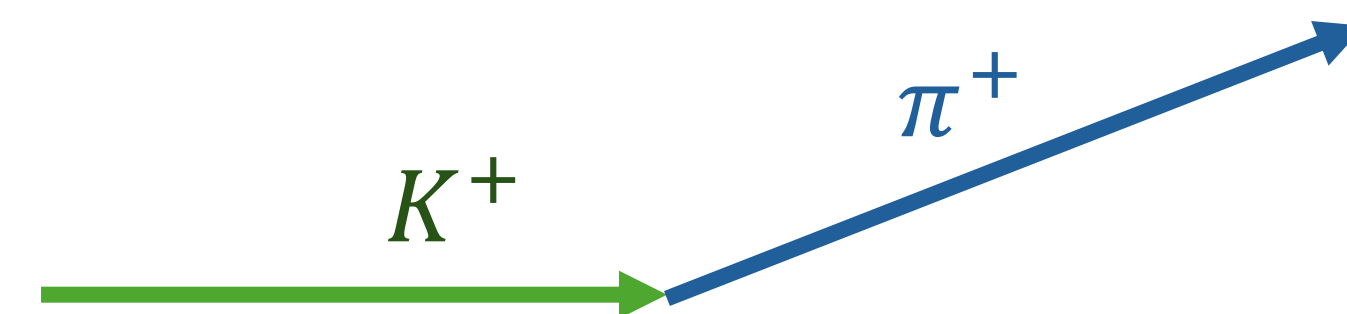
Measurement principle:

- Measure ratio of **signal** $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ to **normalisation** $K^+ \rightarrow \pi^+ \pi^0$
- Select and count events
- Subtract background
- Correct for efficiencies

$$\frac{\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})}{\mathcal{B}(K^+ \rightarrow \pi^+ \pi^0)} \approx \frac{N_{\pi\nu\nu} - N_{bckg}}{N_{\pi\pi}} \frac{\epsilon_{\pi\pi}}{\epsilon_{\pi\nu\nu}}$$

Event selection:

- **Normalisation:** 1 downstream track; identified as π^+ ; $K^+ - \pi^+$ matching (space & time); upstream vetos.
- **Signal:** same as normalisation selection + full photon and detector multiplicity cuts (reject all extra activity).



Blind analysis:

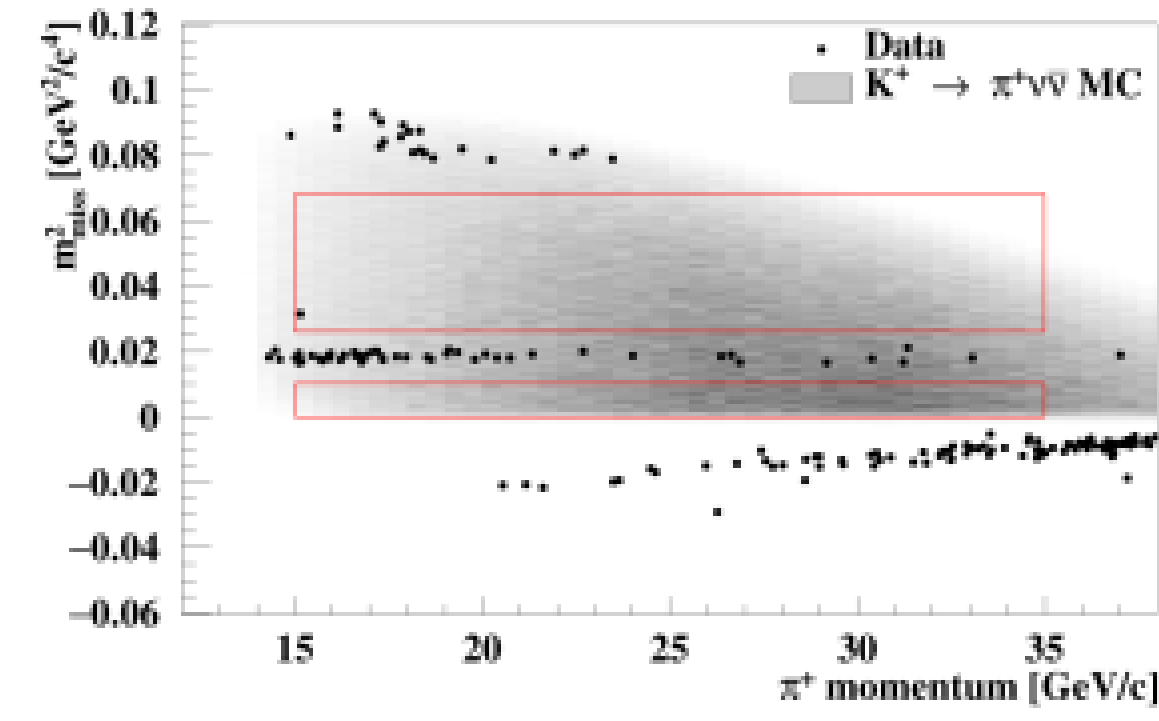
- Estimate background without looking inside the signal regions (in the data)

NA62 results with 2016 – 2022 dataset

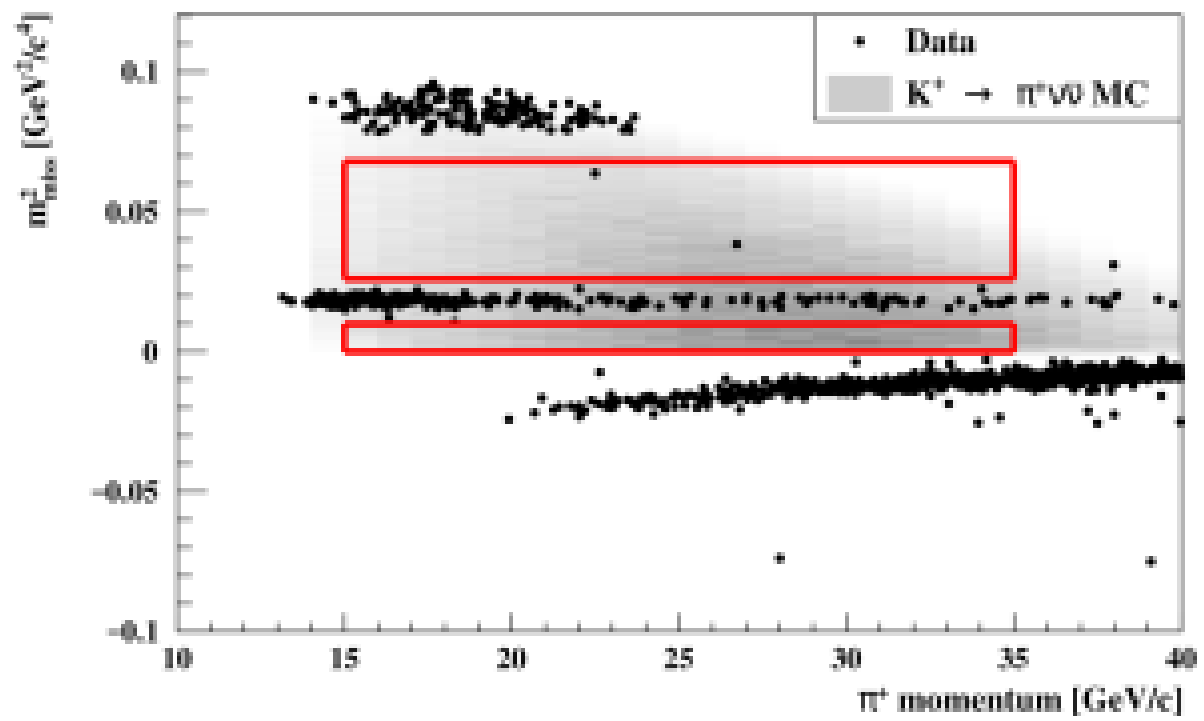
(* $N_{\pi\nu\bar{\nu}}^{\text{SM,exp}}$ assumes benchmark $\mathcal{B}_{\text{SM}} = 8.4 \times 10^{-11}$)

Data-taking year(s)	[Reference]	N_{bg}	$N_{\pi\nu\bar{\nu}}^{\text{SM,exp}}$	N_{obs}
2016	[PLB 791 (2019) 156]	$0.152^{+0.093}_{-0.035}$	0.267 ± 0.020	1
2017	[JHEP 11 (2020) 042]	1.46 ± 0.33	2.16 ± 0.13	2
2018	[JHEP 06 (2021) 093]	$5.42^{+0.99}_{-0.75}$	7.58 ± 0.40	17
2021–2022	[JHEP 02 (2025) 191]	$11.0^{+2.1}_{-1.9}$	9.91 ± 0.34	31
2016–2018	[JHEP 06 (2021) 093]	$7.03^{+1.05}_{-0.82}$	10.01 ± 0.42	20
2016–2022	[JHEP 02 (2025) 191]	18^{+3}_{-2}	19.9 ± 0.5	51

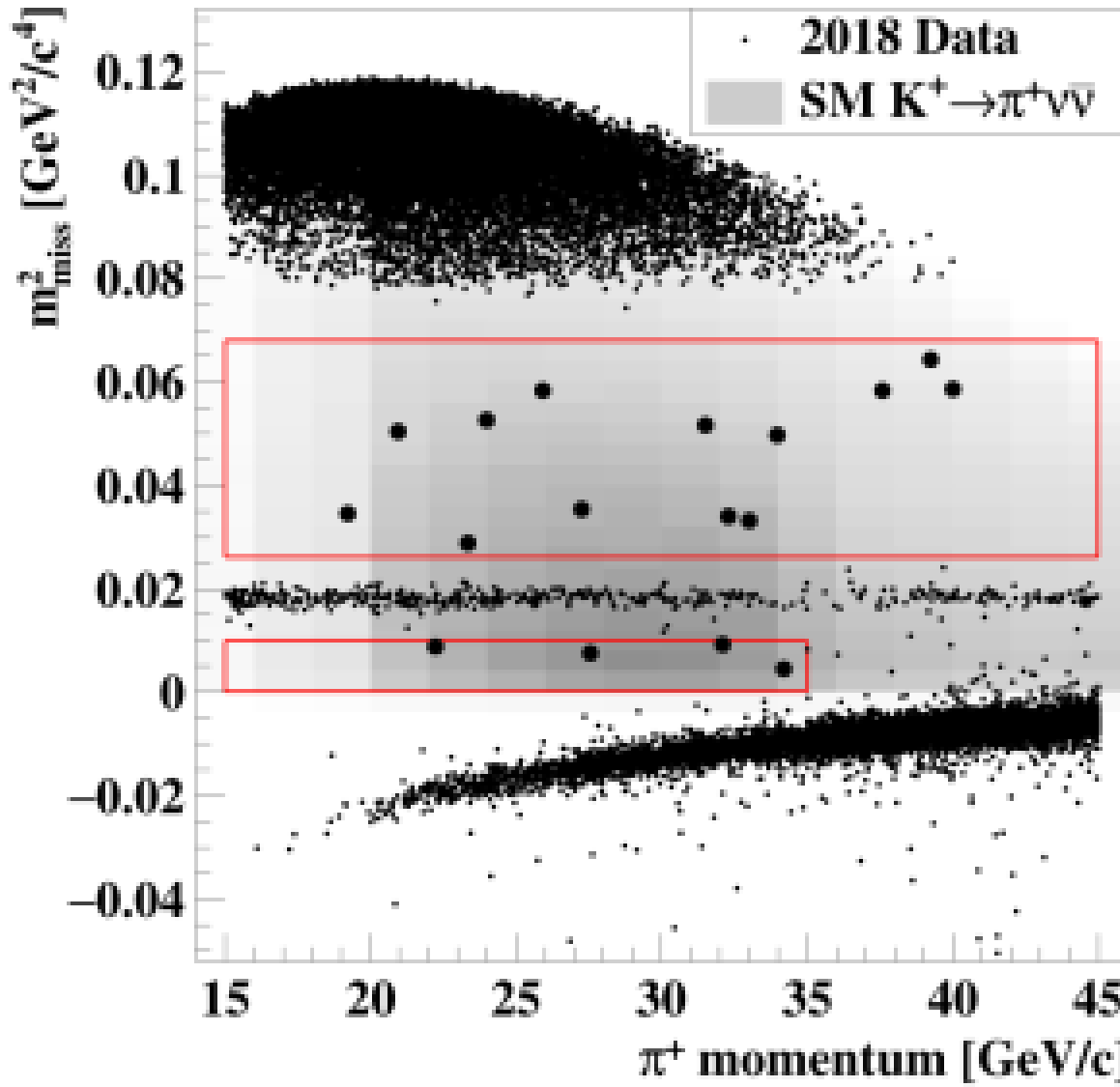
2016 data [PLB 791 (2019) 156]



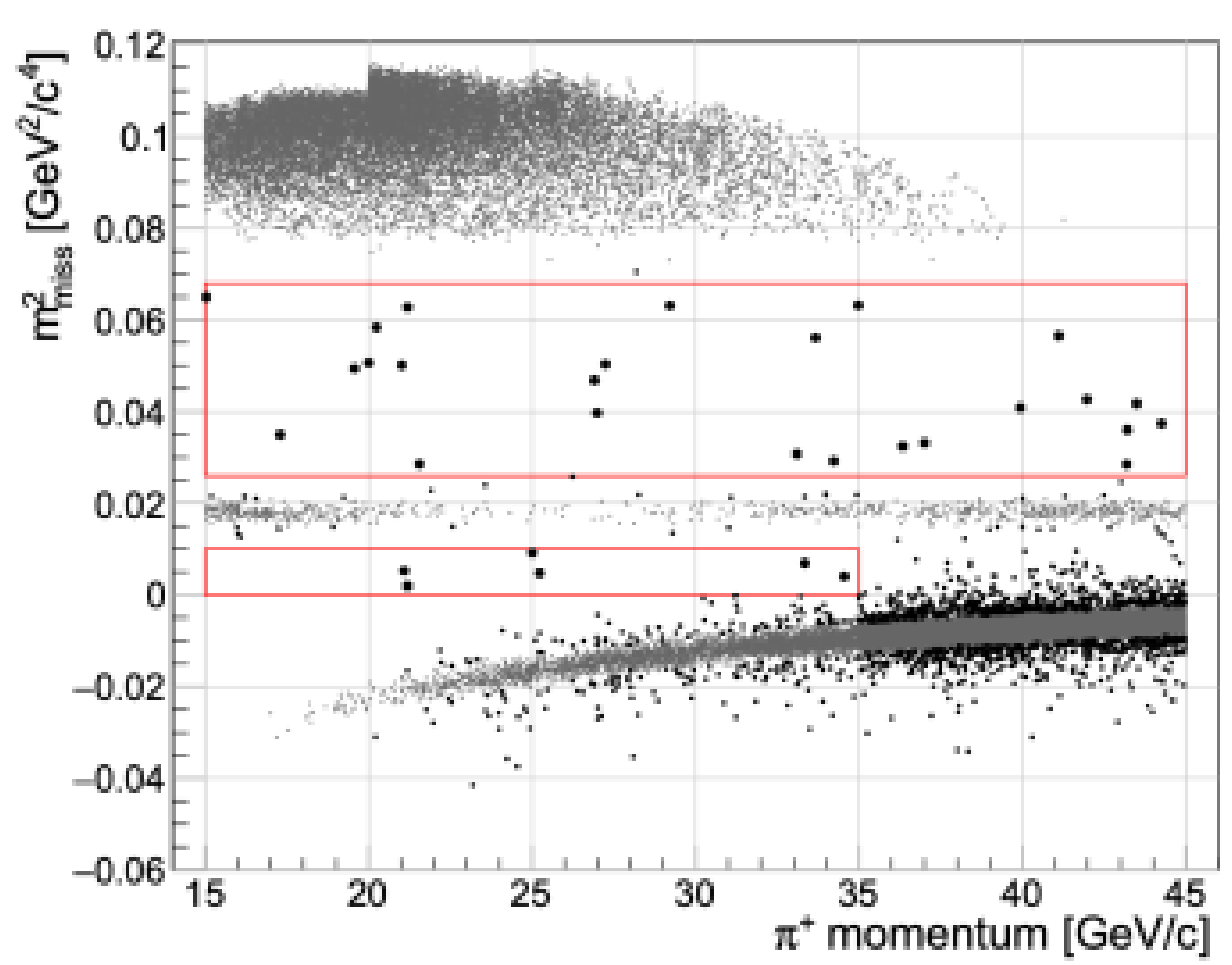
2017 data [JHEP 11 (2020) 042]



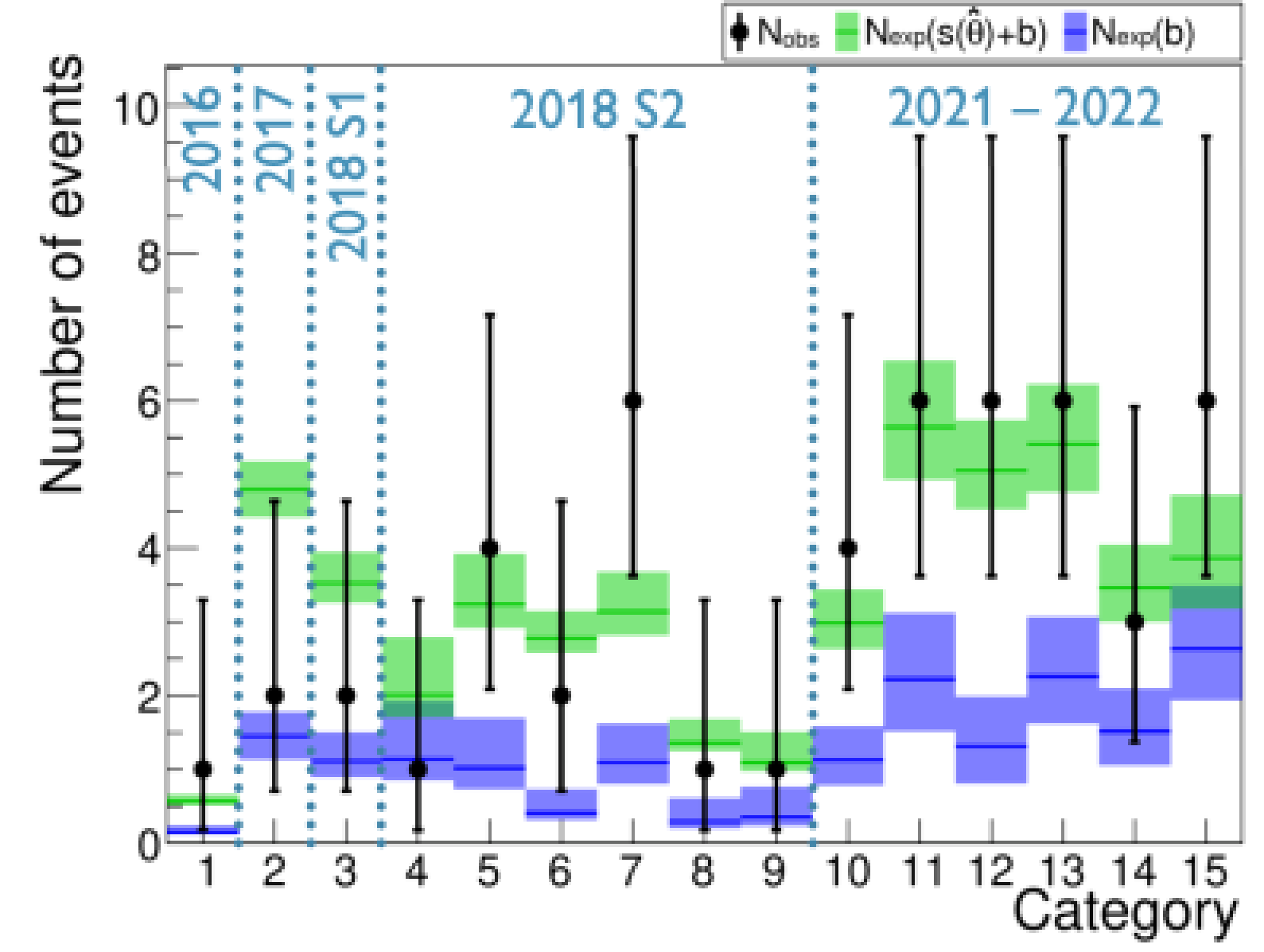
2018 data [JHEP 06 (2021) 093]



2021-22 data [JHEP 02 (2025) 191]



Statistical combination:



NA62 results with 2016 – 2022 dataset

BNL E787/E949 experiment

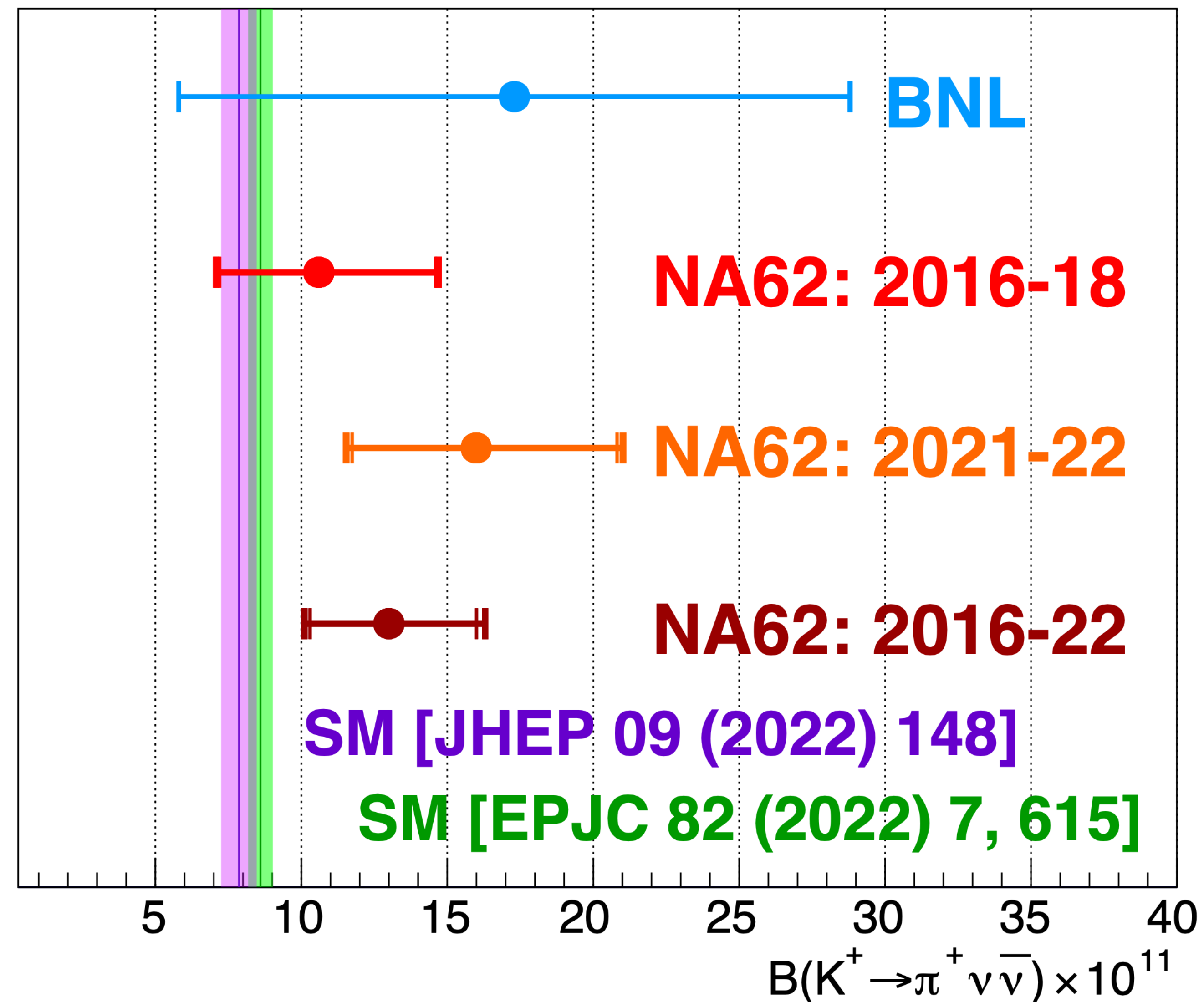
[[Phys.Rev.D 79 \(2009\) 092004](#)]

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$$

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{21-22} = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11}$$

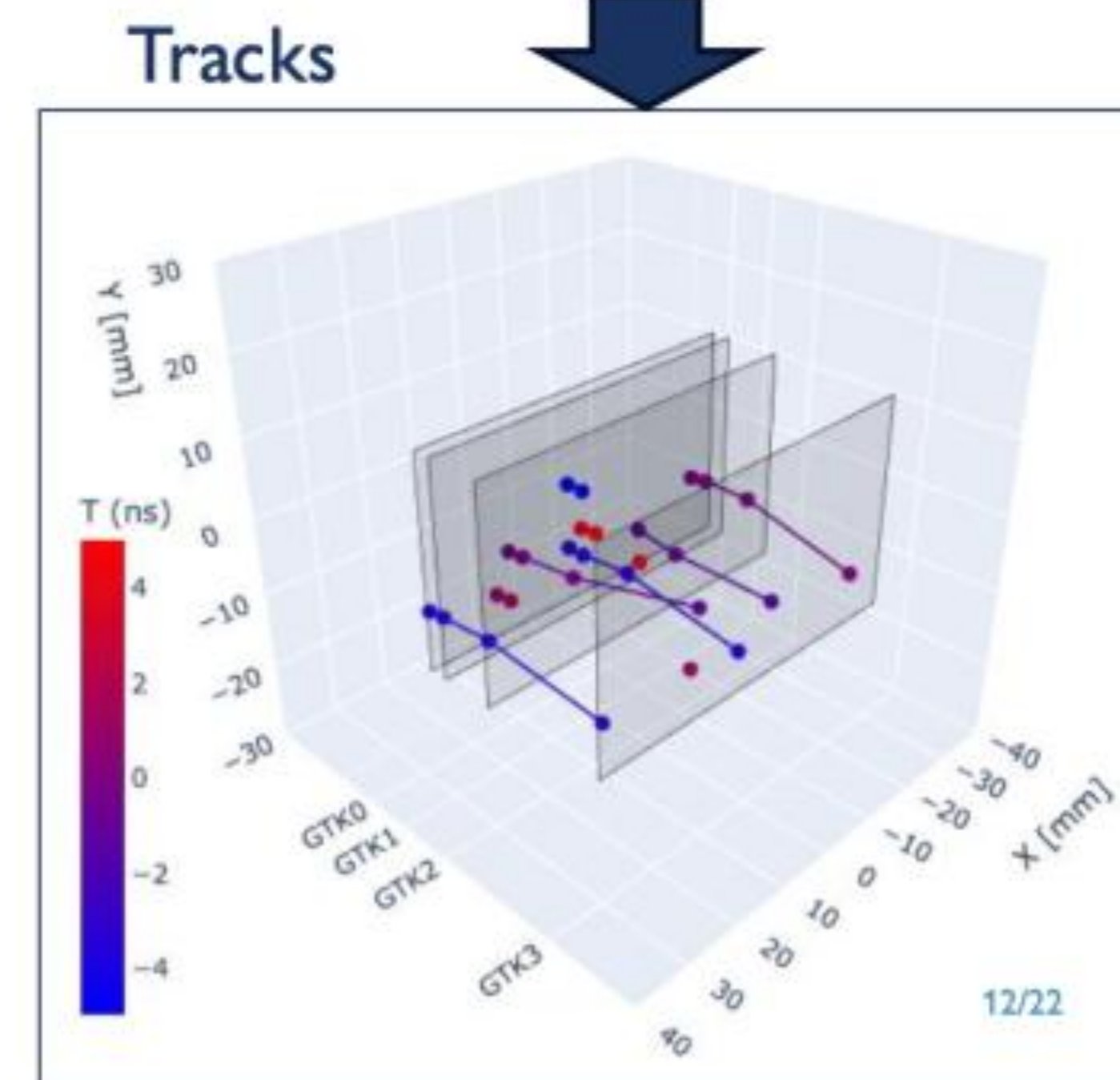
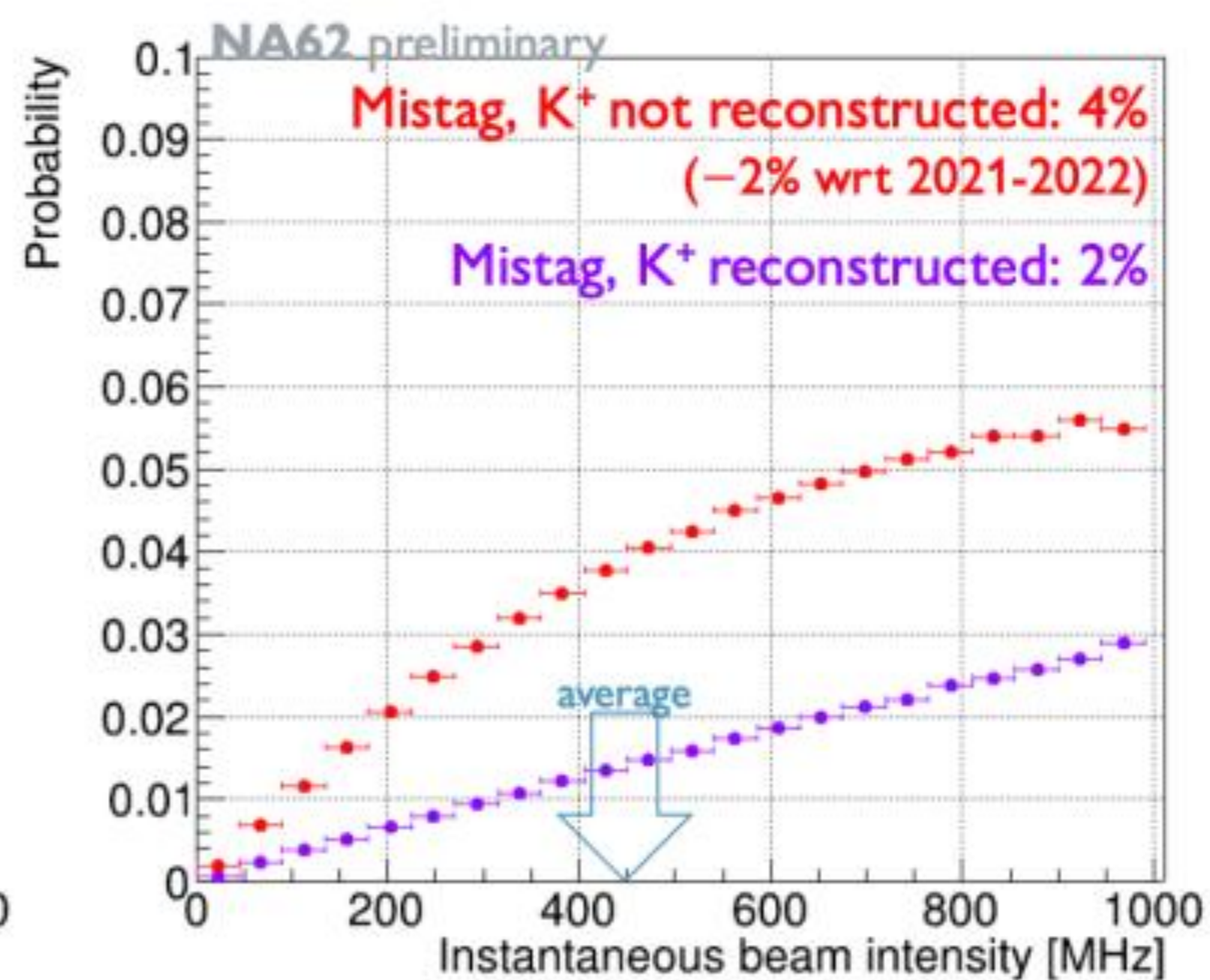
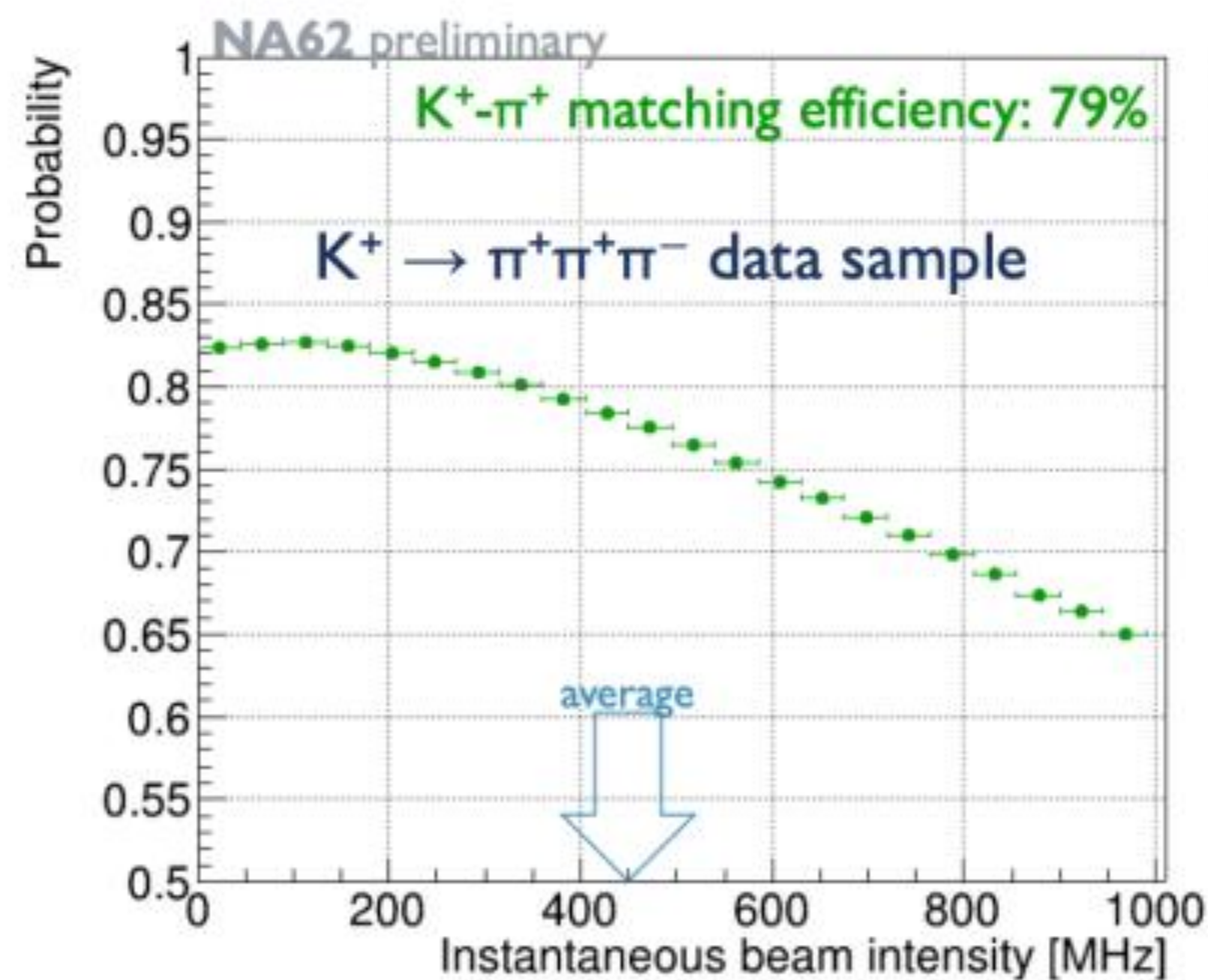
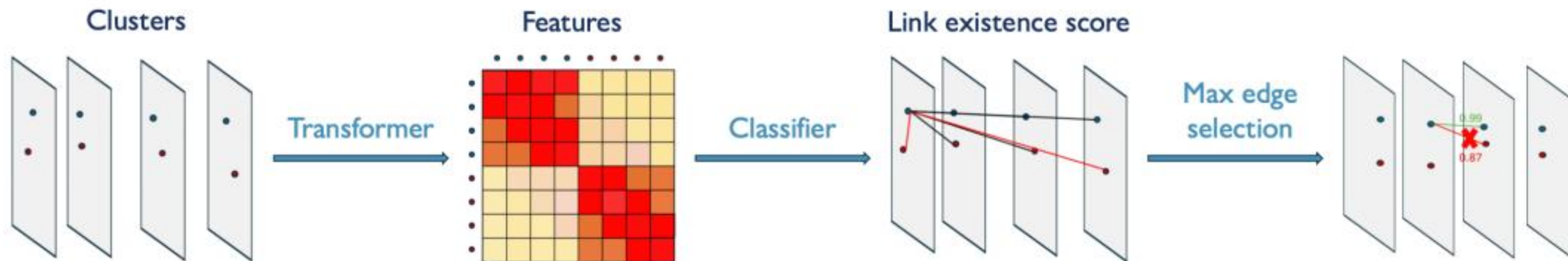
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$$

- NA62 results are consistent
- Central value 1.5—1.7 σ above SM
- Fractional uncertainty: 25%
- Bkg-only hypothesis rejected with significance $Z>5$
- First observation of the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay

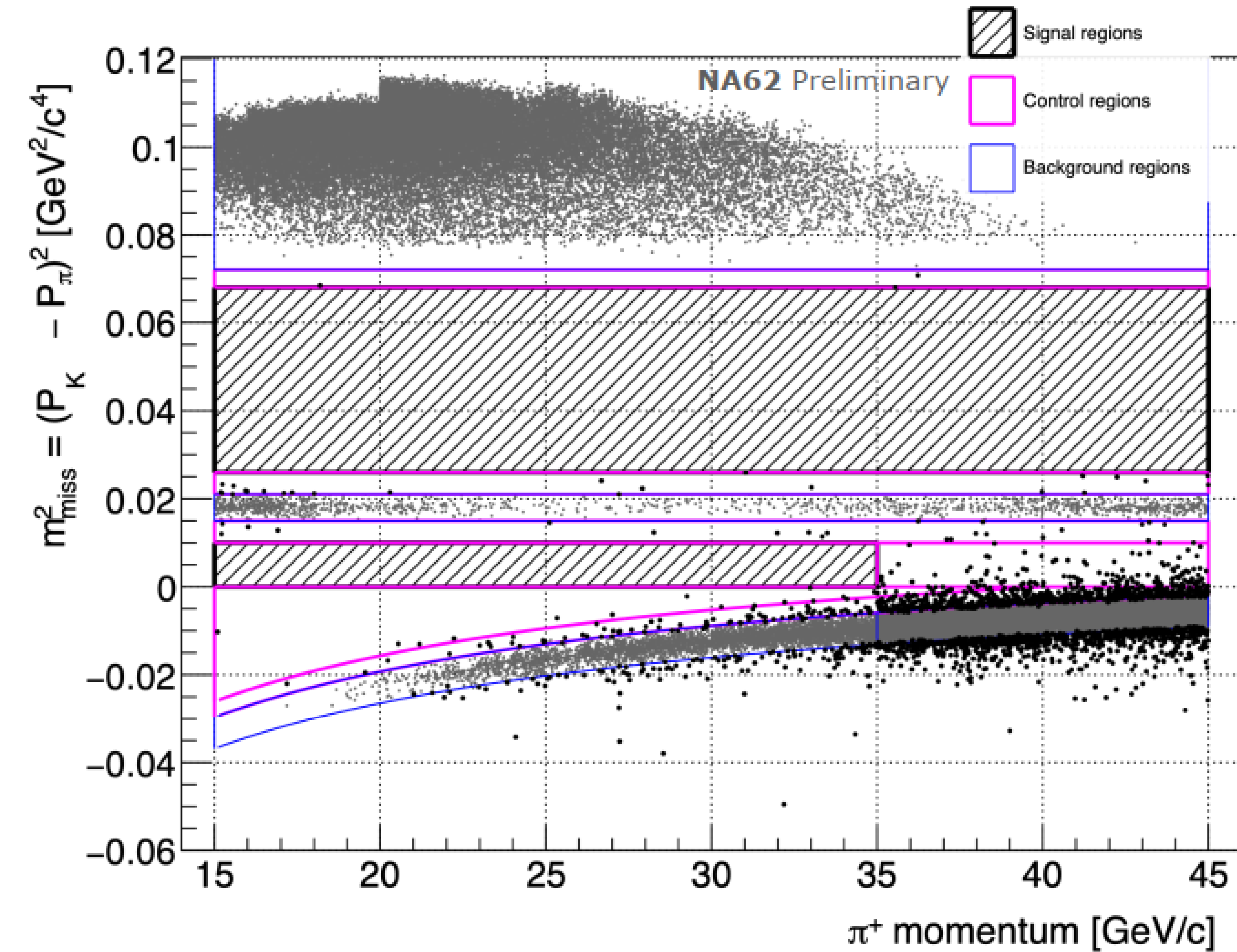


Analysis of 2023 – 2024 data

An example: improvement wrt. previous analysis: Beam track reconstruction using machine learning



NA62 results with 2023 – 2024 dataset



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

Expected background, $N_{bg} = 11.9^{+2.9}_{-2.3}$

Observed, $N_{obs} = ?$

NA62 results with 2023 – 2024 dataset

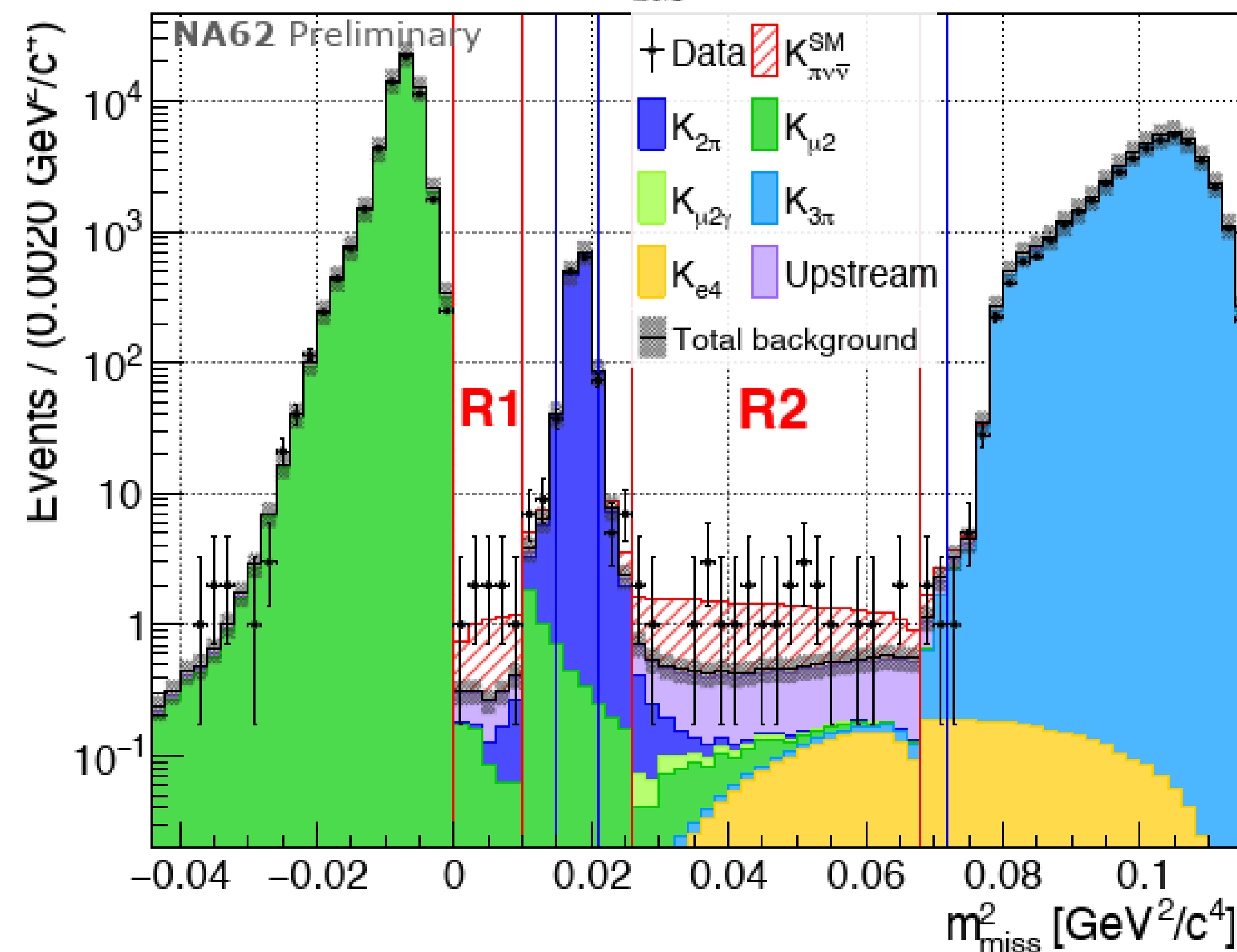
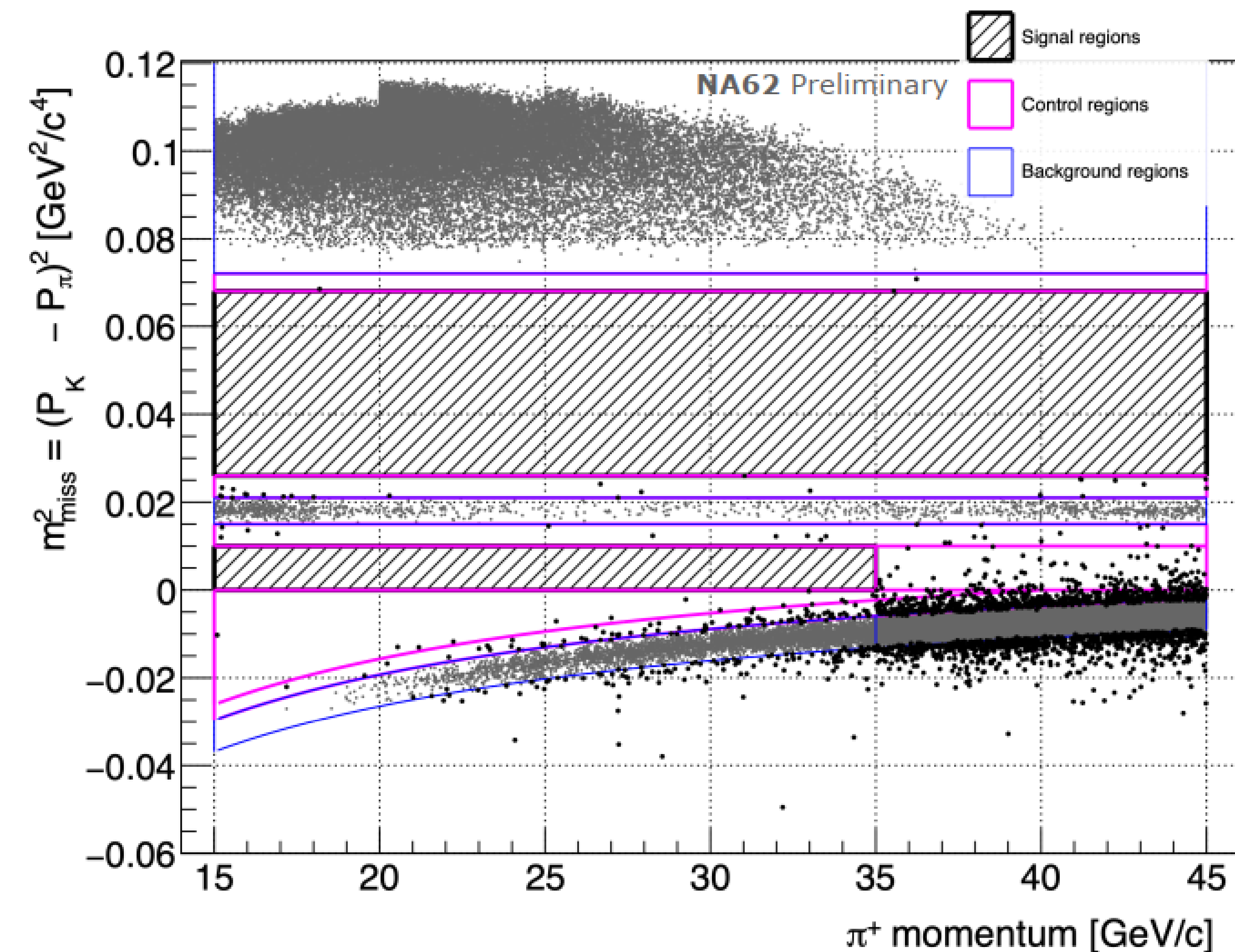


Expected SM* signal, $N_{\pi\nu\bar{\nu}}^{SM} = 22.9 \pm 1.1$

Expected background, $N_{bg} = 11.9^{+2.9}_{-2.3}$

Observed, $N_{obs} = 33$

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



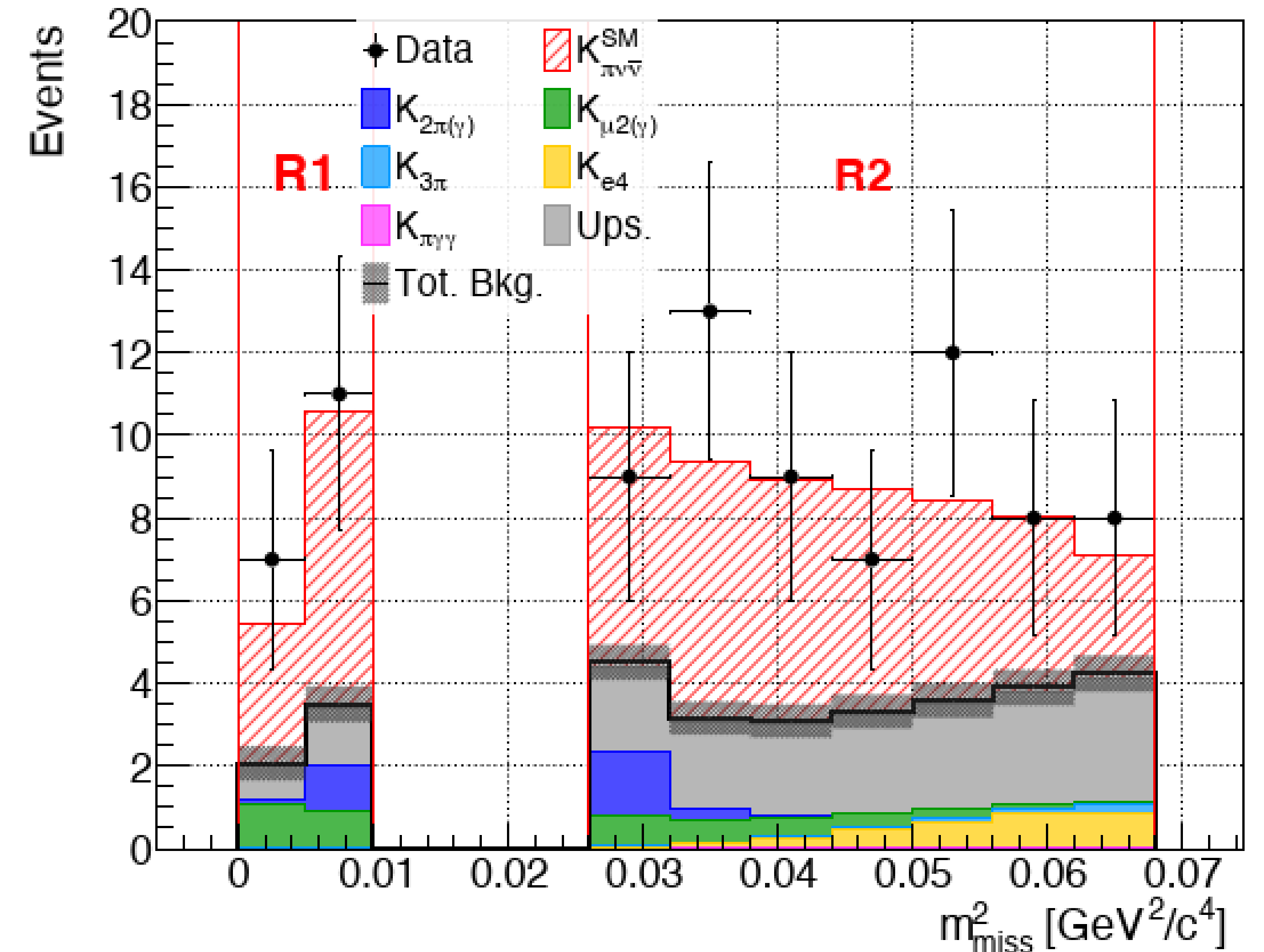
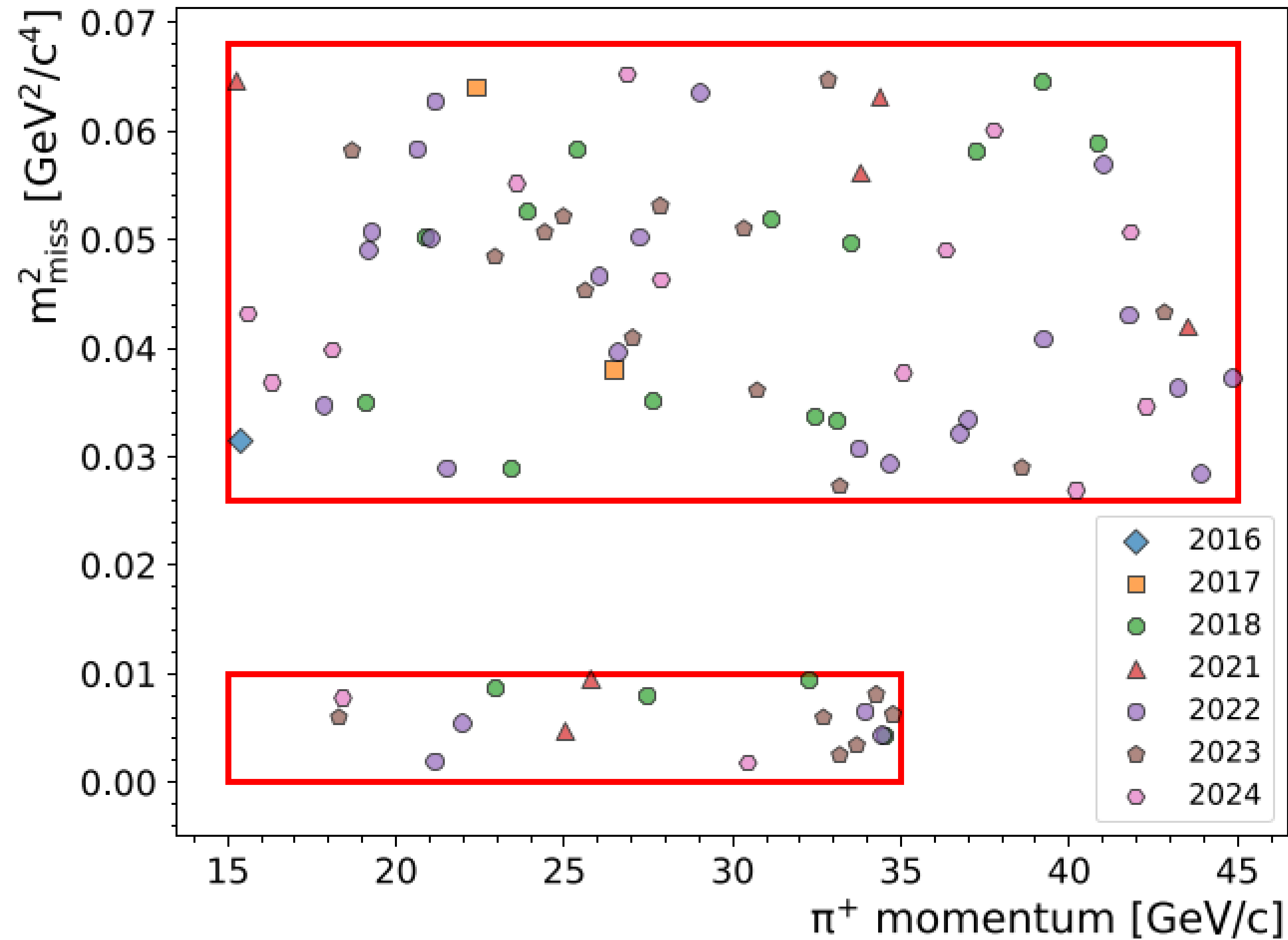
Combined 2016 – 2024 dataset

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

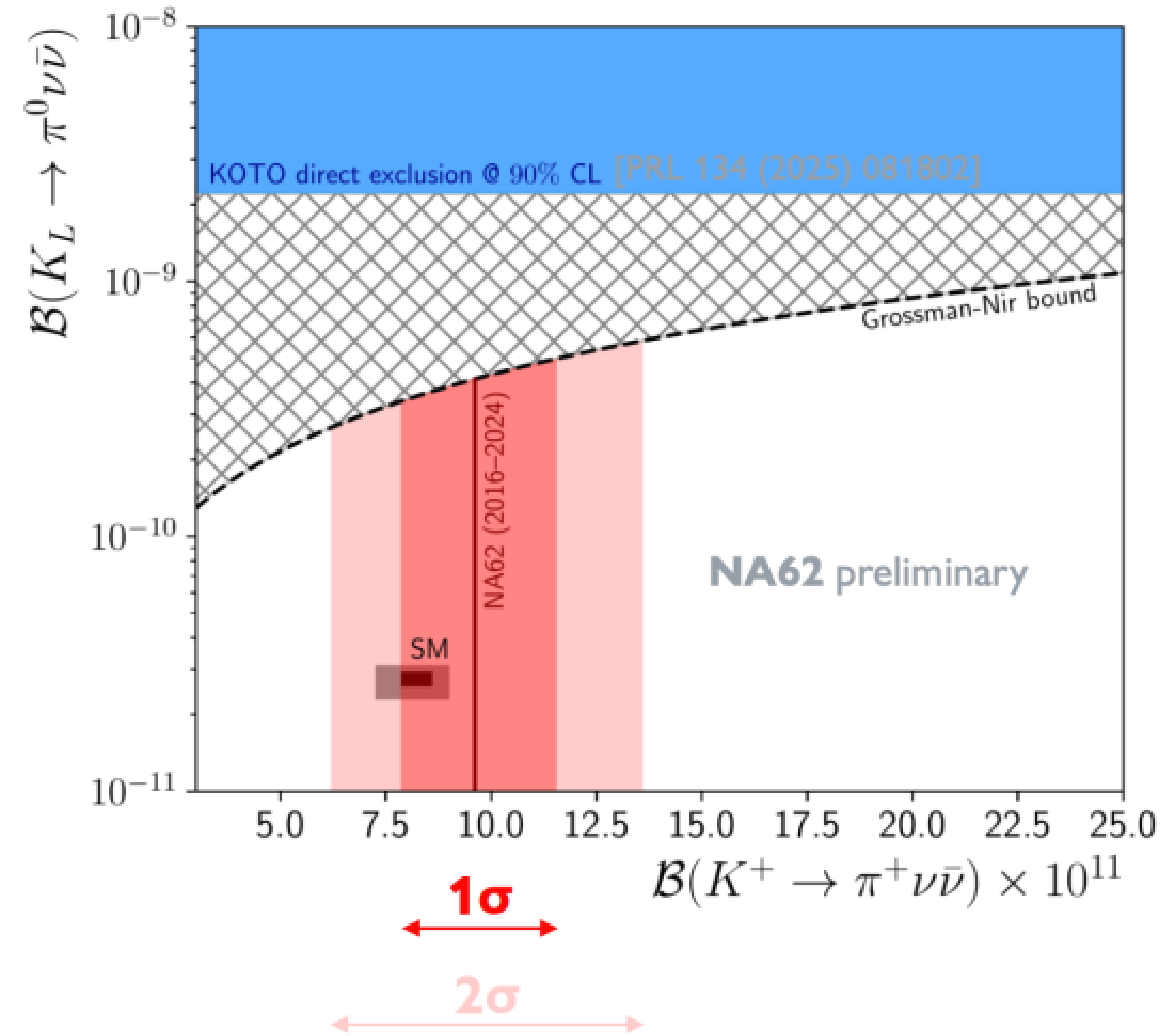
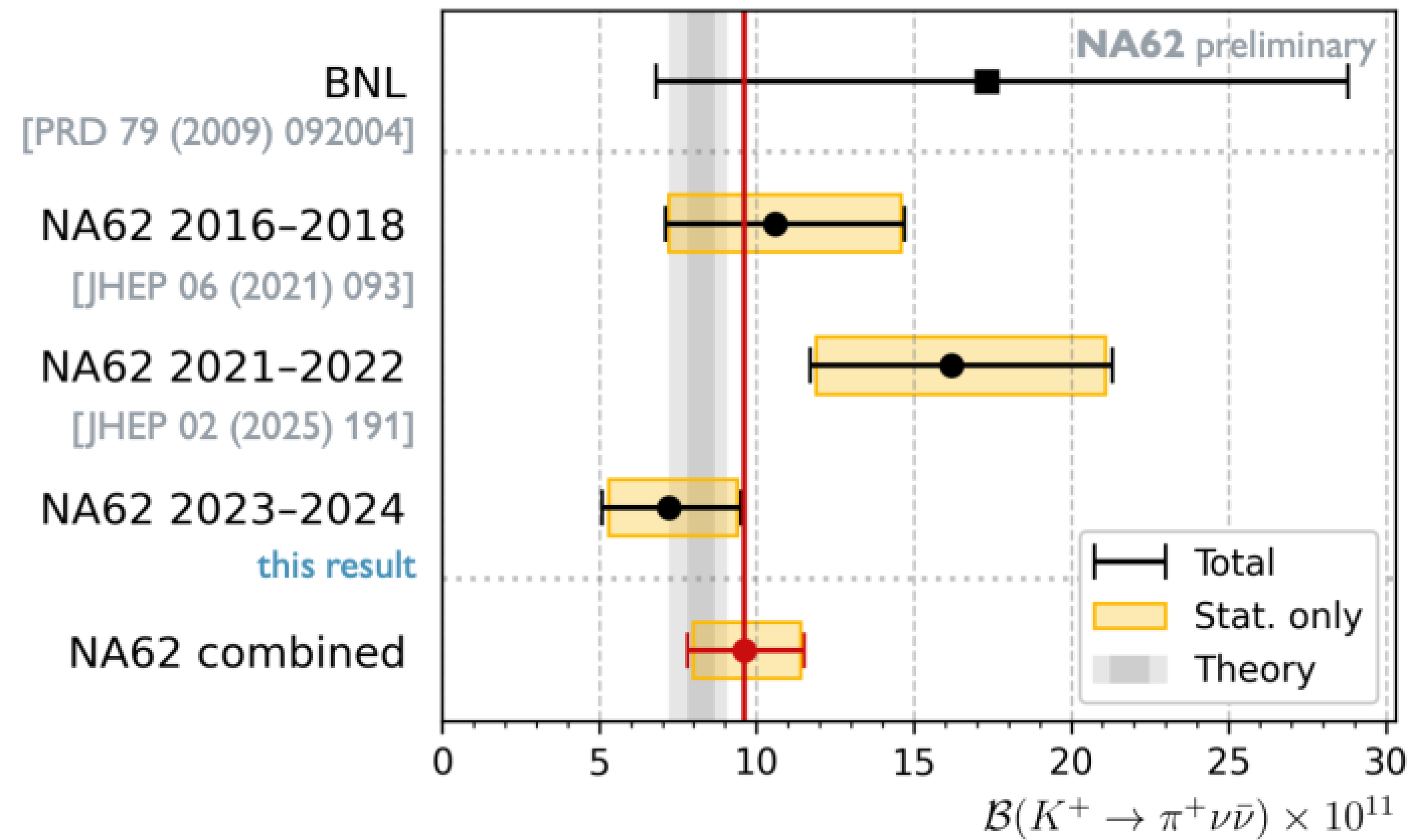
Expected background, $N_{bg} = 30_{-3}^{+4}$

Observed, $N_{obs} = 84$

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



Combined 2016 – 2024 dataset



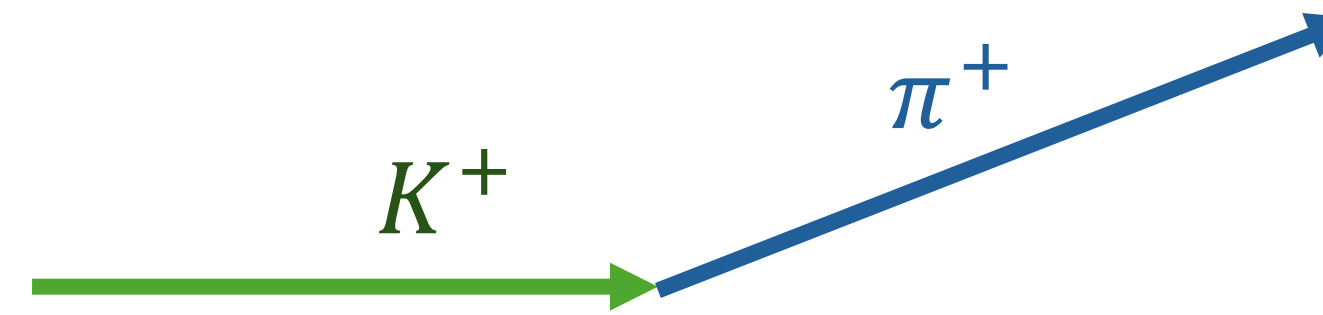
$$\mathcal{B}_{16-24}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \left(9.6 \left(\begin{matrix} +1.8 \\ -1.6 \end{matrix} \right)_{\text{stat}} \left[\begin{matrix} +0.8 \\ -0.6 \end{matrix} \right]_{\text{syst}} \right) \times 10^{-11} = \left(9.6_{-1.8}^{+1.9} \right) \times 10^{-11}$$

Part 2: talking about backgrounds



$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at NA62 is all about backgrounds

Experimental signature:

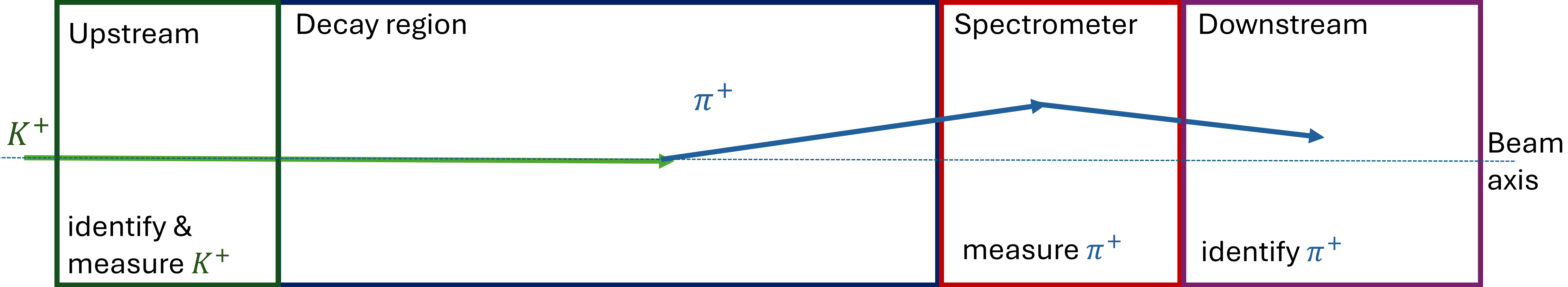


Background = wrong identification of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Can come from:

- Making a mistake in particle identification ($\mu \rightarrow \pi$)
- Missing extra particles in the final state
- Coincidental processes happening in the apparatus

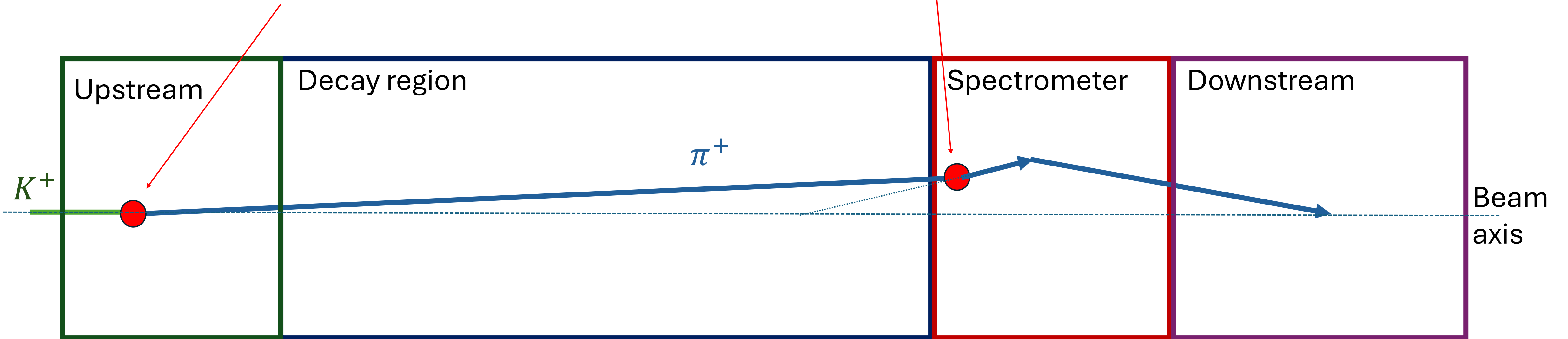
Signal event detection



The largest background: Upstream

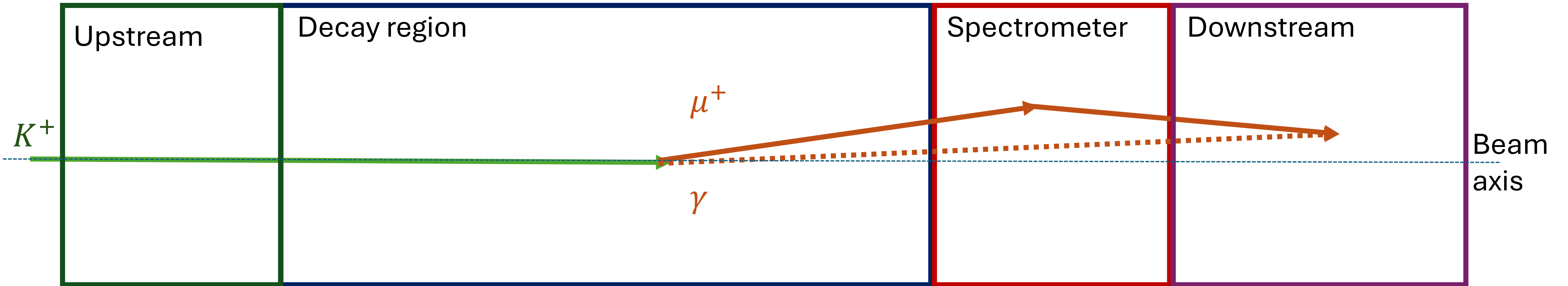
Kaon decay or
interaction upstream

Pion large-angle scattering



- Scattering in the Spectrometer make the π^+ point to the decay region
- Downstream detectors see only single π^+

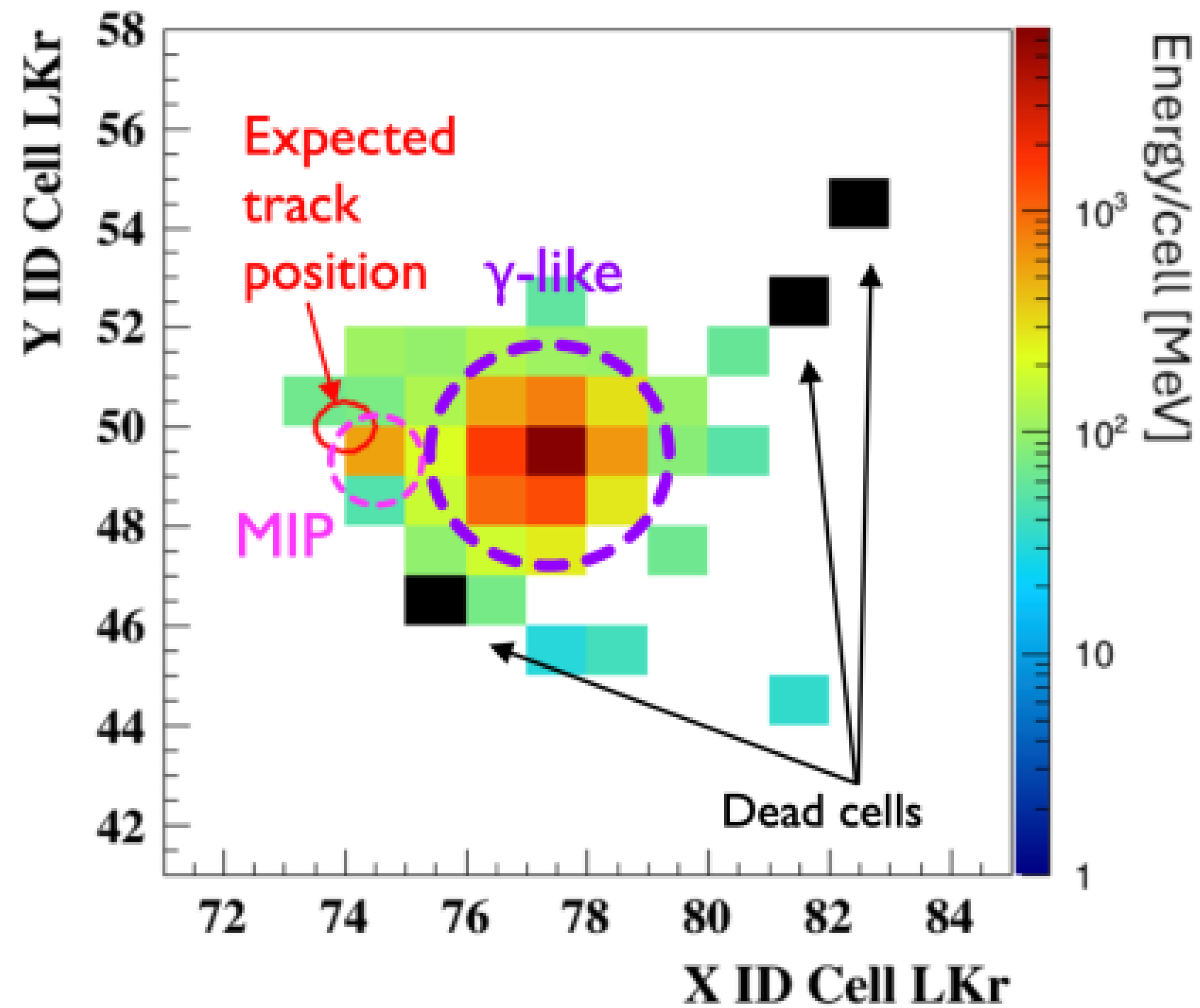
The latest discovered background: $K^+ \rightarrow \mu^+ \nu \gamma$



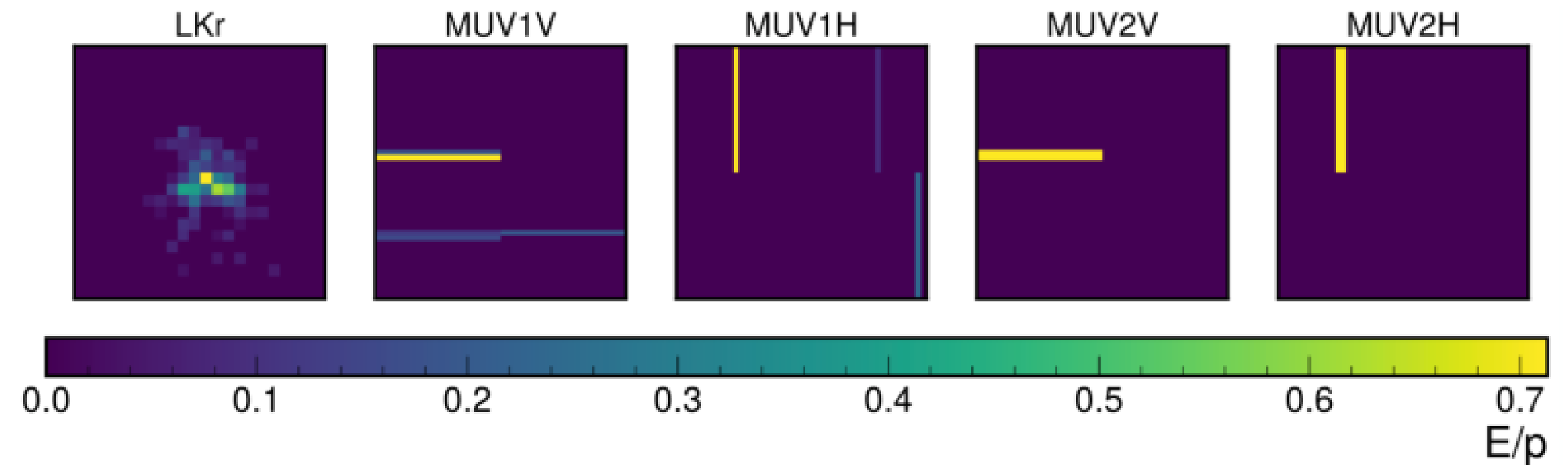
- Track reconstruction: OK
- Particle identification can fail if photon hits downstream calorimeters close to the impact point of the muon track ($\mu \rightarrow \pi$)

$K^+ \rightarrow \mu^+ \nu \gamma$ background suppression

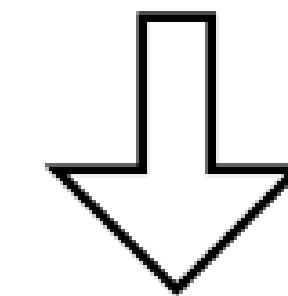
$K^+ \rightarrow \mu^+ \nu \gamma$ Background



Convolutional Neural Network (CNN)



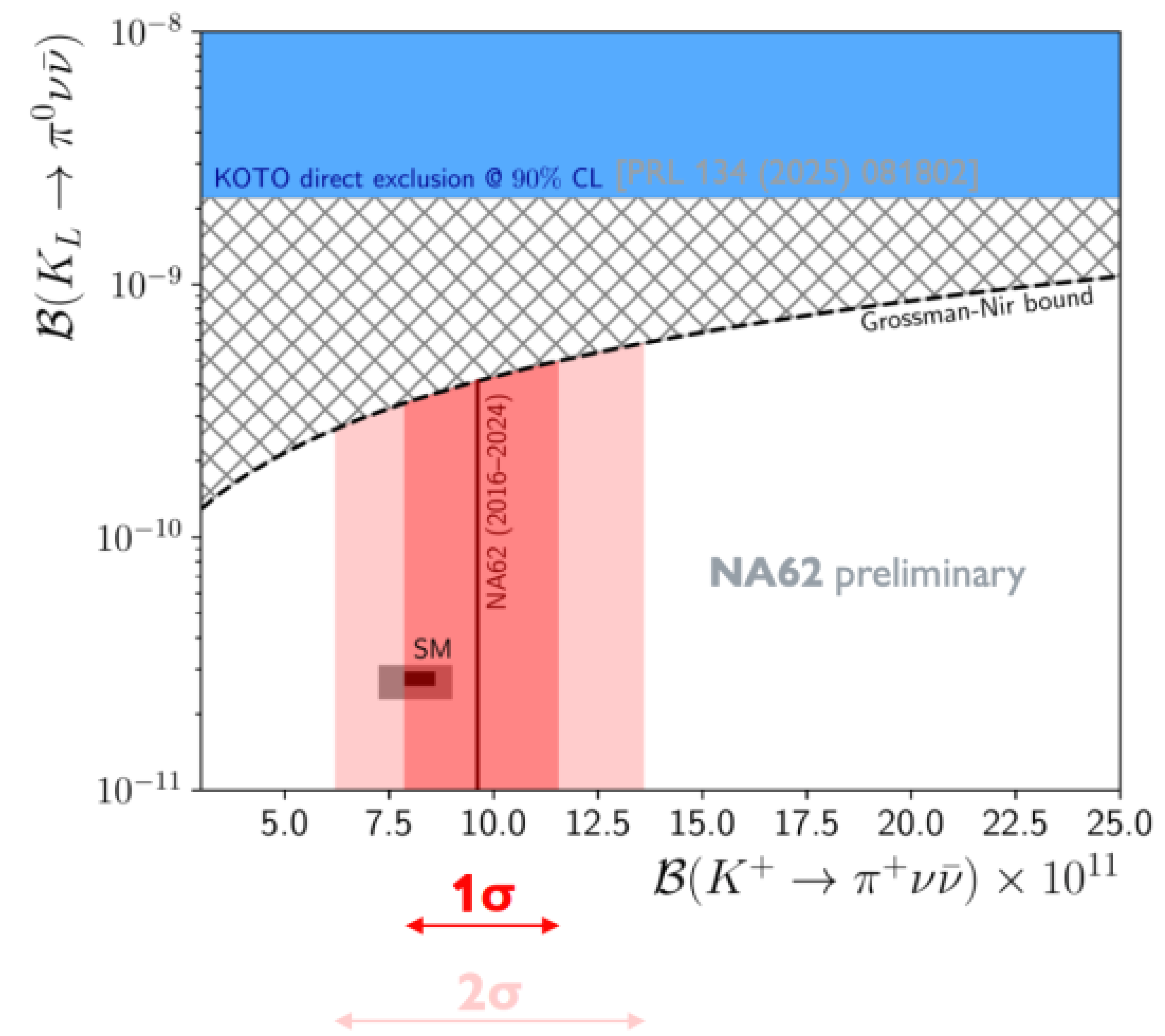
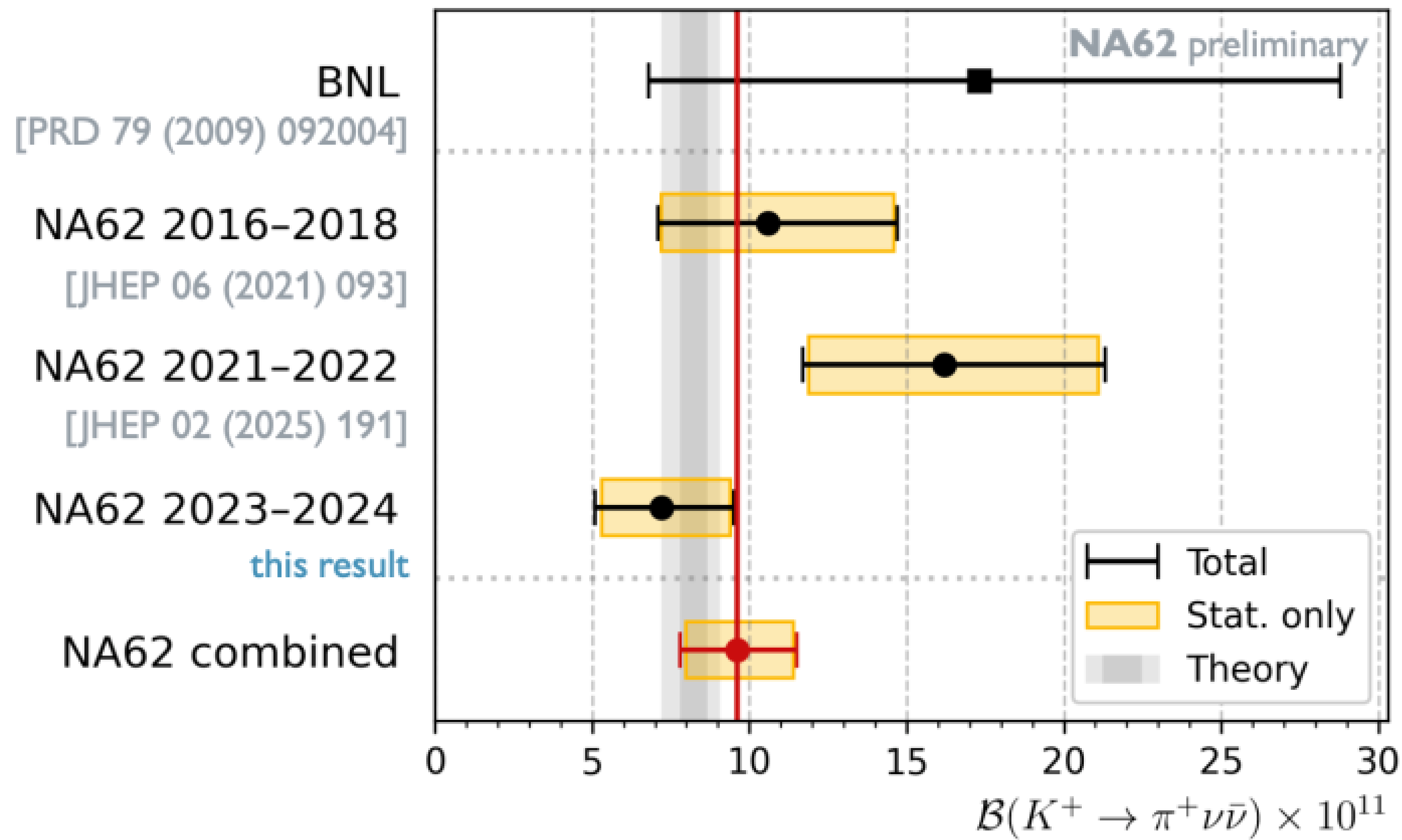
- **Inputs:** Data E/p images in time slides (19k numbers)
- **Model:** ResNet architecture (2.8M parameters)



- Single merged $\mu^+ \gamma$ cluster mis-ID as π^+
- Veto using $m_{miss, \mu \nu \gamma}^2 = (P_K - p_\mu - p_\gamma)^2 \approx 0$

$N_{bg}(K^+ \rightarrow \mu^+ \nu)$ reduced by 16%

$N_{bg}(K^+ \rightarrow \mu^+ \nu \gamma)$ reduced by 70%



$$\mathcal{B}_{16-24}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \left(9.6 \begin{matrix} +1.8 \\ -1.6 \end{matrix} \text{stat} \begin{matrix} +0.8 \\ -0.6 \end{matrix} \text{syst} \right) \times 10^{-11} = \left(9.6_{-1.8}^{+1.9} \right) \times 10^{-11}$$

It's just one number, but the way to it has been long.

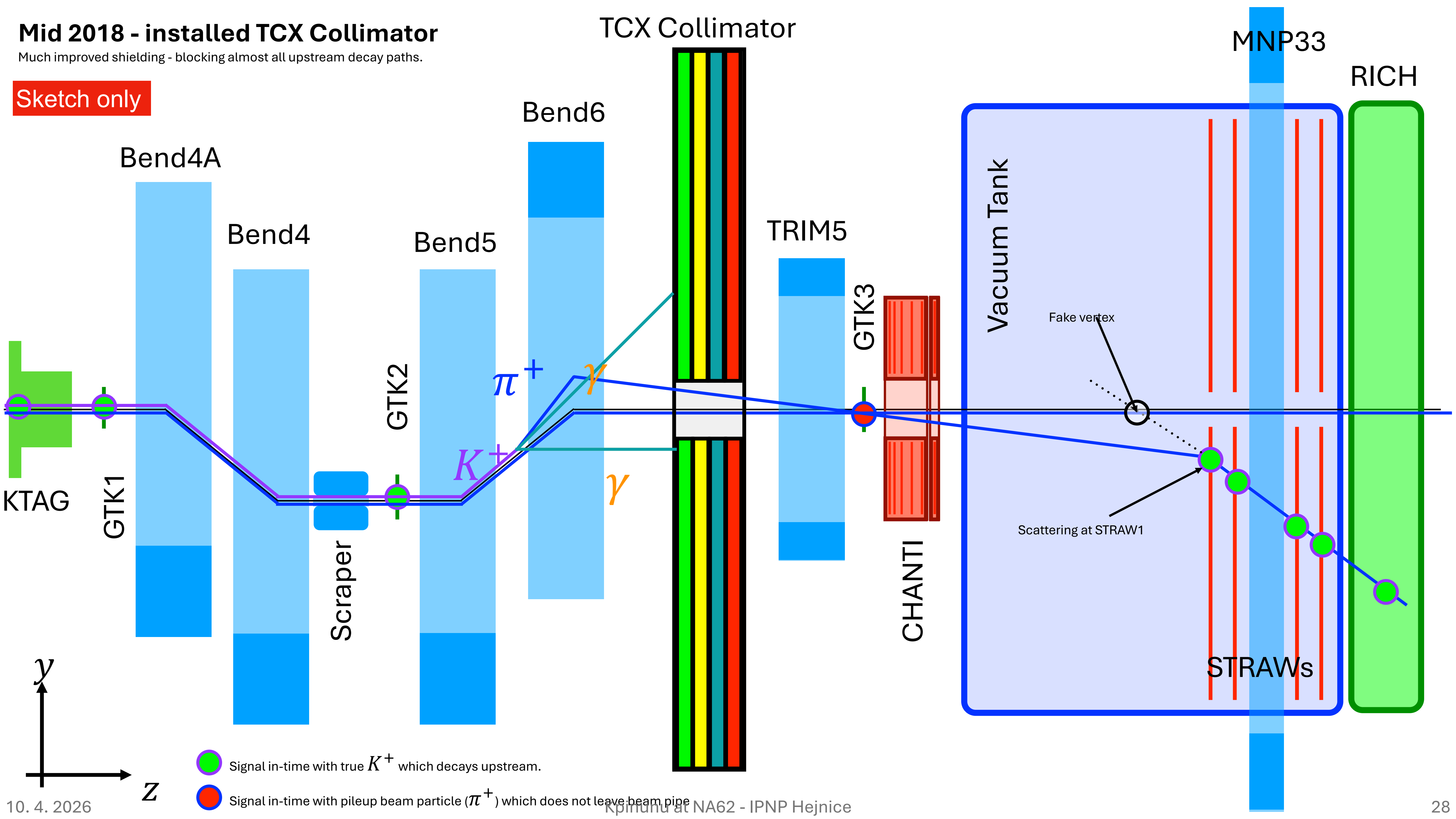
Backup

Mid 2018 - installed TCX Collimator

Much improved shielding - blocking almost all upstream decay paths.

Sketch only

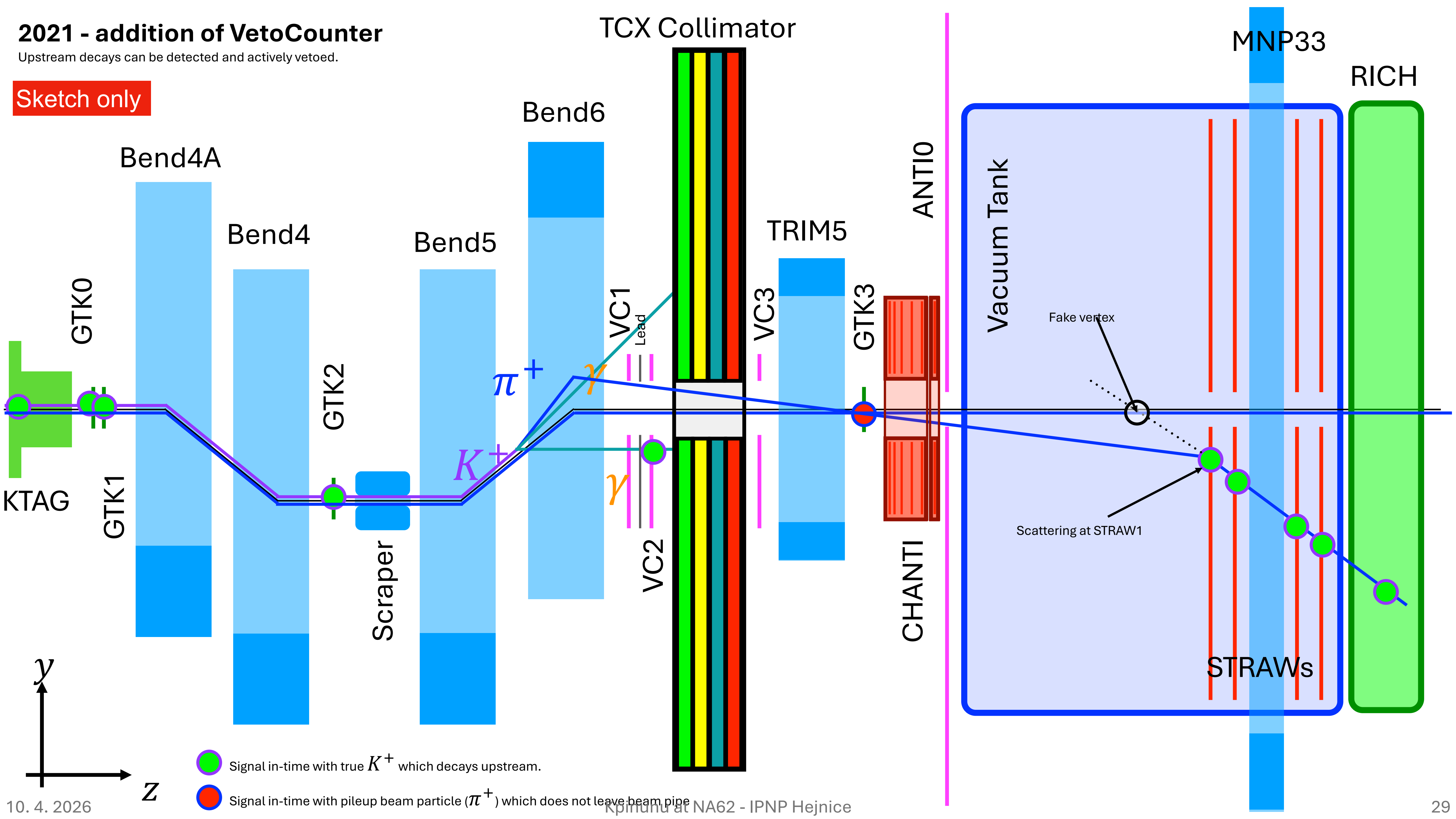
TCX Collimator



2021 - addition of VetoCounter

Upstream decays can be detected and actively vetoed.

Sketch only



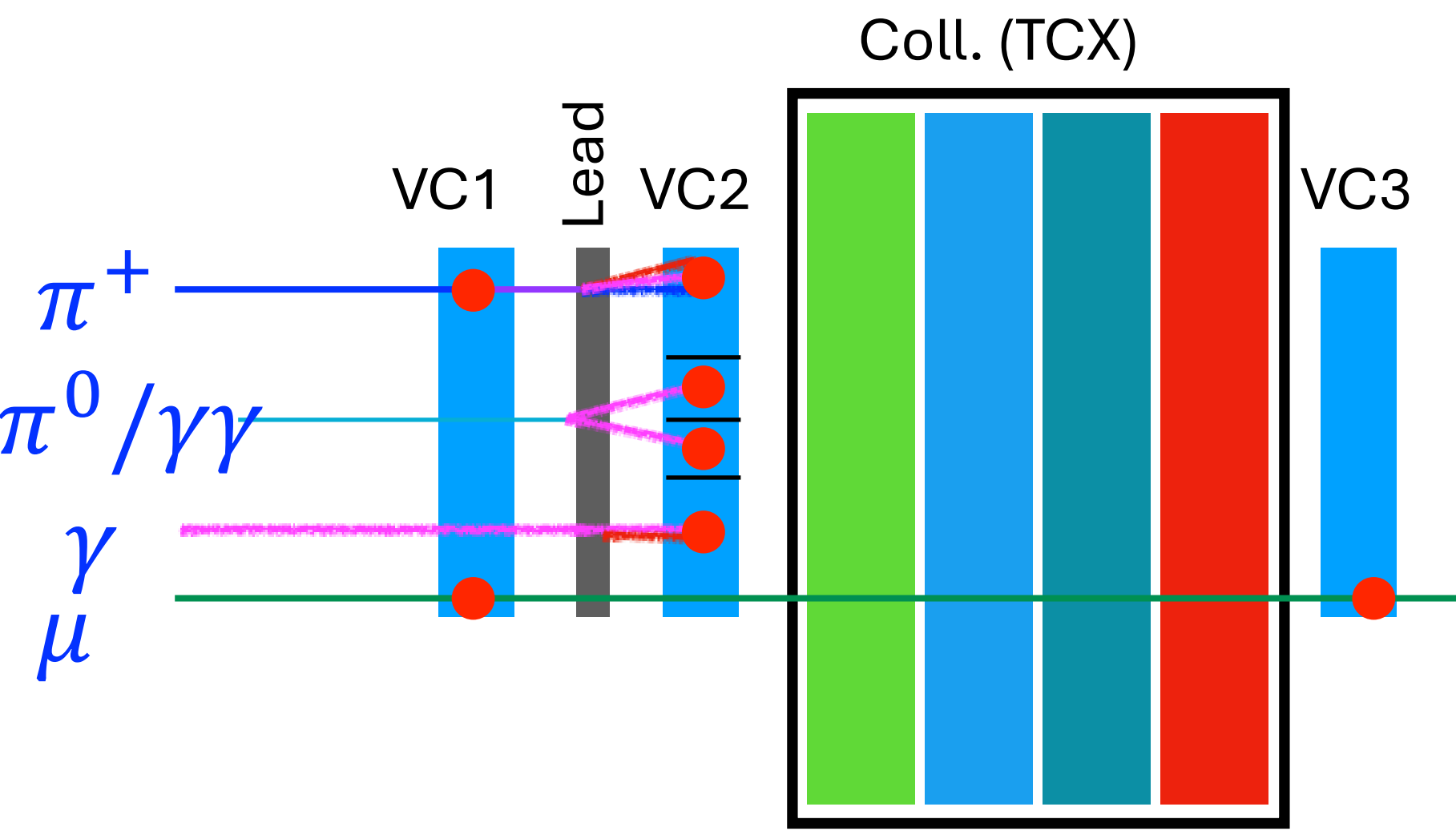
New upstream vetos: VetoCounter & ANTI0



Scintillator tiles

MTs

[FELIX readout: [Streaming Readout Workshop talk 2021](#)]



VetoCounter

- Detect particles from decays upstream of final collimator.
- **Factor ~3 rejection** with ~2% accidental veto.



Scintillator tiles & SiPMs



ANTI0

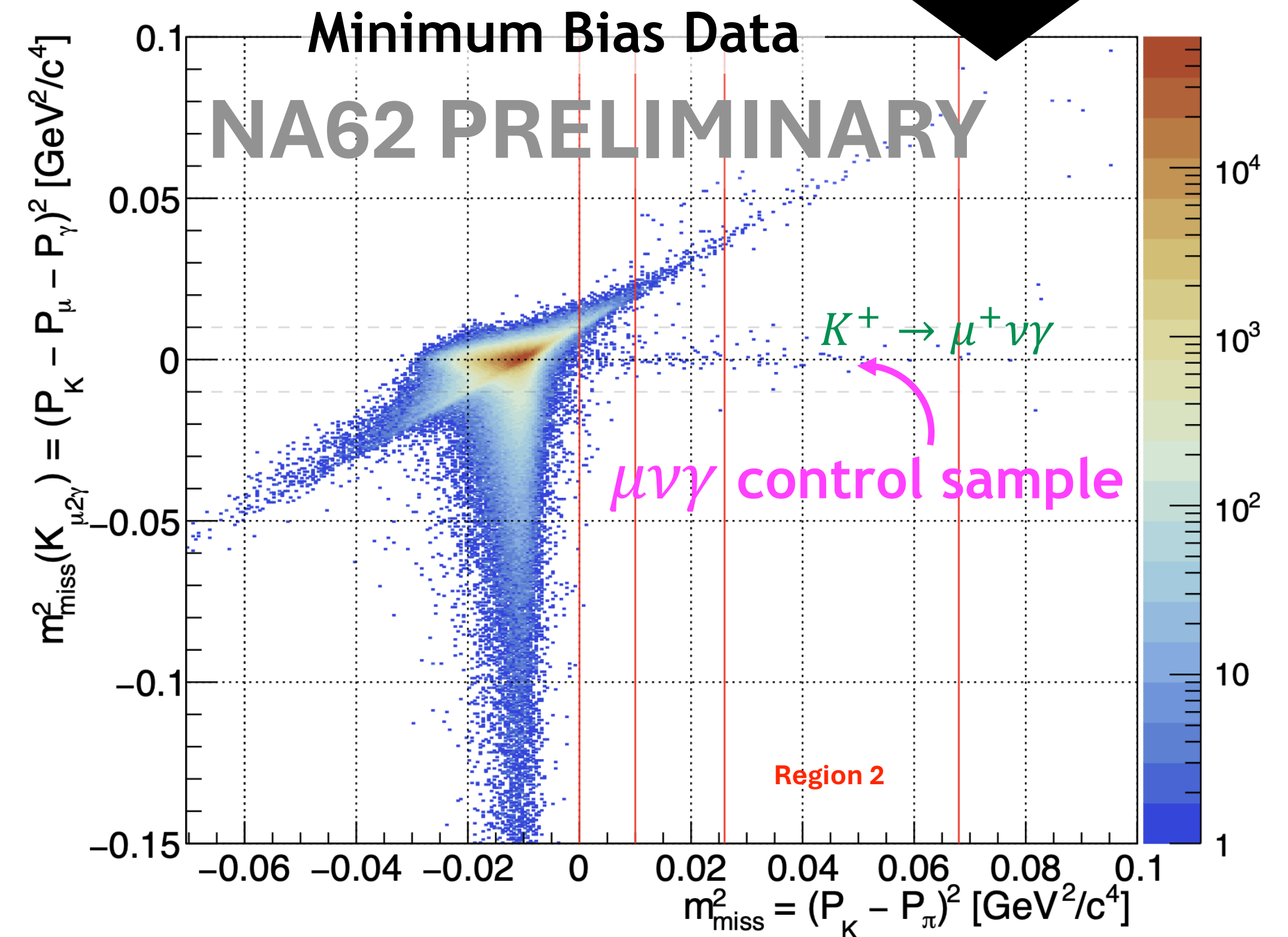
- Detect particles up to ~1 m from beam line.
- **Reject ~20% of upstream background** with <1% signal loss.

[SRSG report 2023] [EP Newsletter, Dec21]

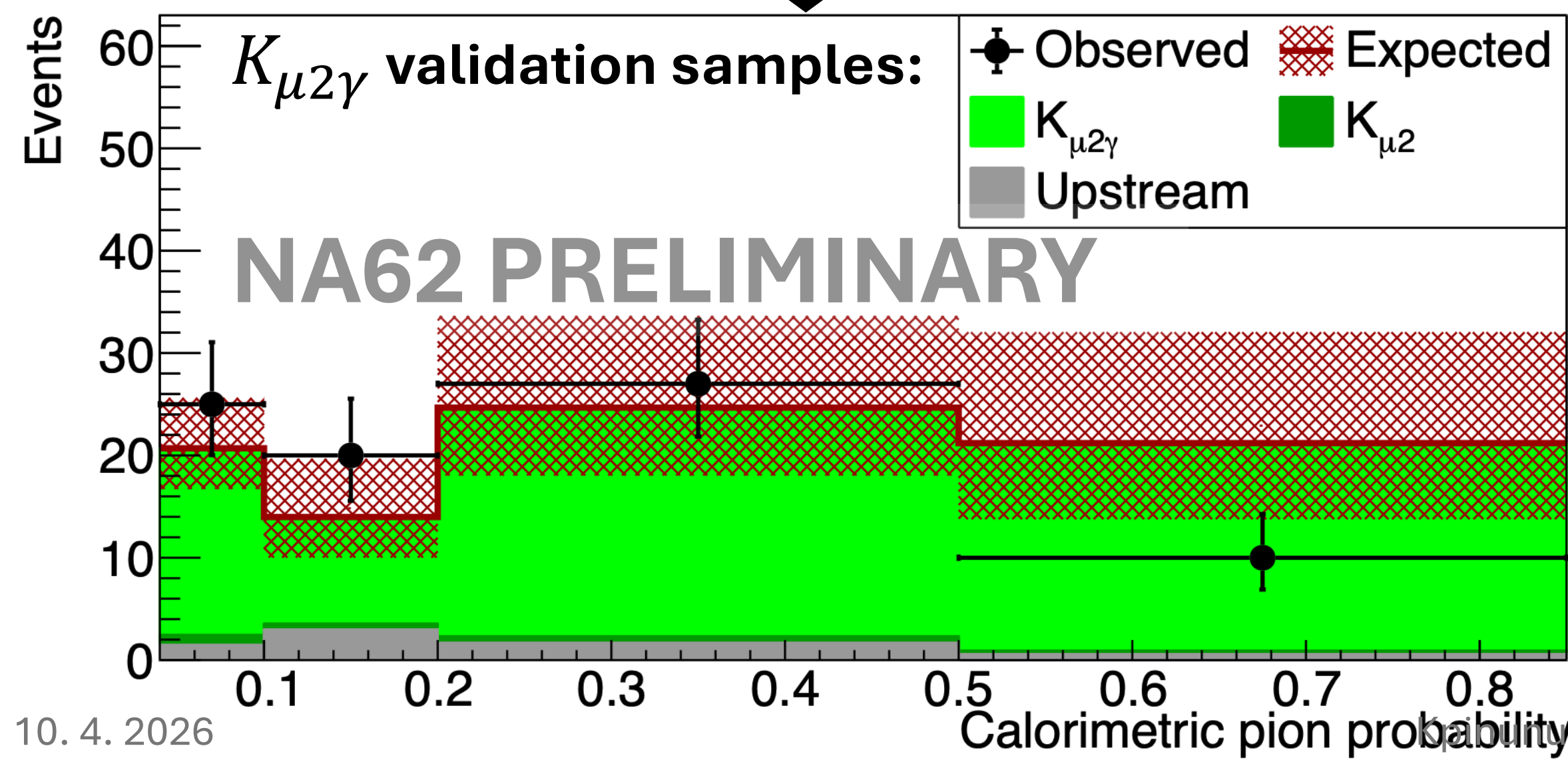
$K^+ \rightarrow \mu^+ \nu \gamma$ Background

- Kinematically select $K^+ \rightarrow \mu^+ \nu \gamma$ events: $m_{miss}^2(K_{\mu 2 \gamma}) = (P_K - P_\mu - P_\gamma)^2$
 - P_K : 4-momentum of K^+ from GTK (as normal)
 - P_μ : 4-momentum of track with μ^+ mass hypothesis.
 - P_γ : reconstructed from energy and position of LKr cluster (and position of $K^+ - \mu^+$ vertex).

Evaluate background expectation using $\mu \nu \gamma$ control sample from MinimumBias trigger, not applying Calorimetric BDT classifier and MUV3 signal:



Validation: data sample with PID = “less pion-like” (Calo BDT bins below π^+ bin).



- Before $K^+ \rightarrow \mu^+ \nu \gamma$ veto: found excess of events at $p > 35 \text{ GeV}/c$ in Region 2 relative to 2016–18 data.
- Additional background identified and studied in data control samples & MC.
- $K^+ \rightarrow \mu^+ \nu \gamma$ veto added to selection criteria for final analysis.