Observation of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay and measurement of its branching ratio at NA62

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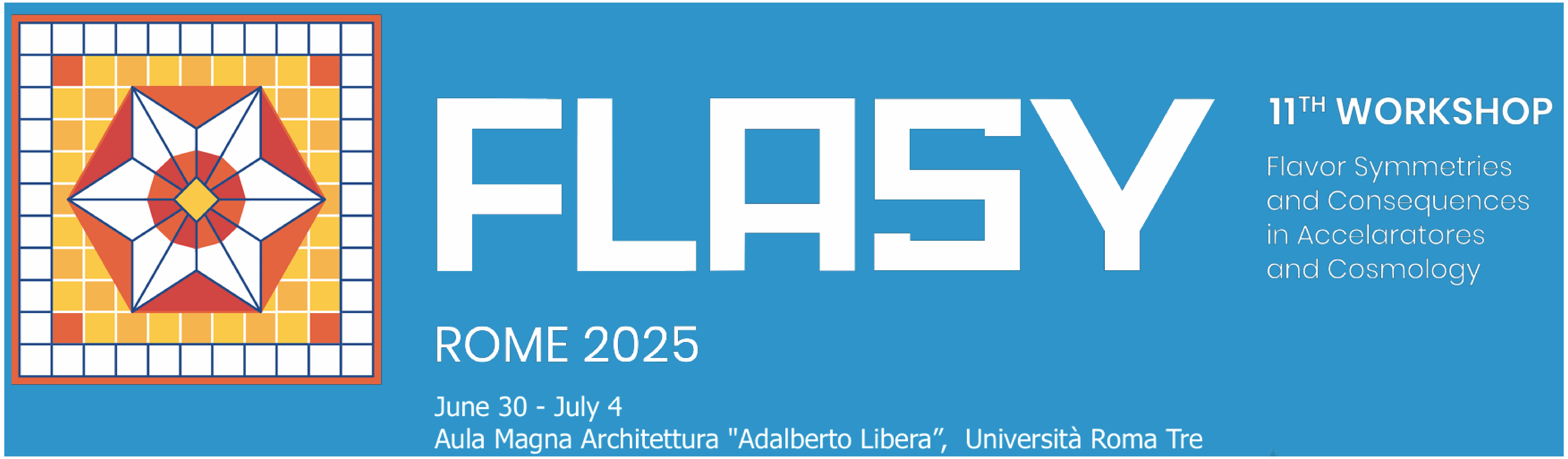
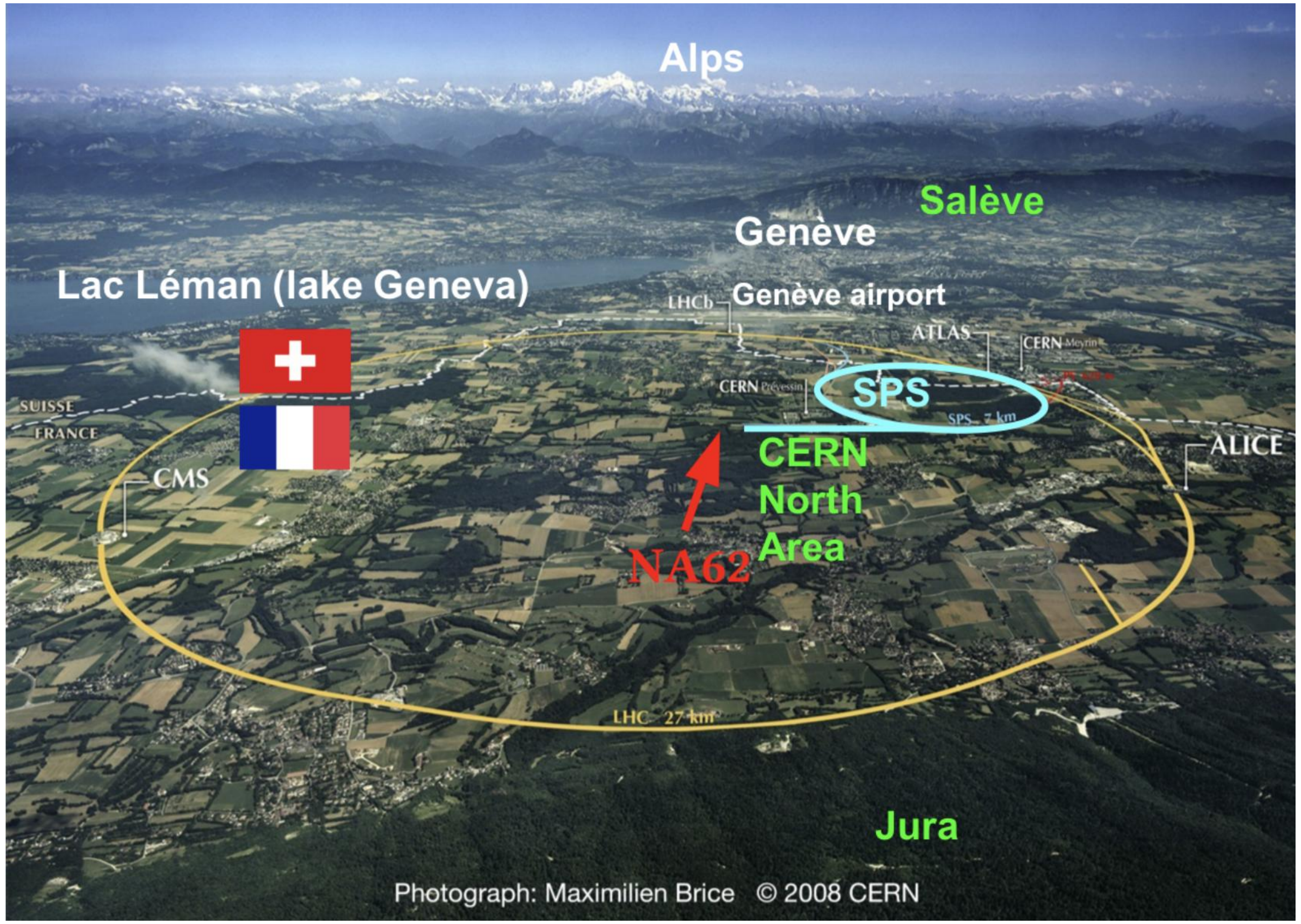


The NA62 experiment at CERN

~200 collaborators from ~30 institutions.

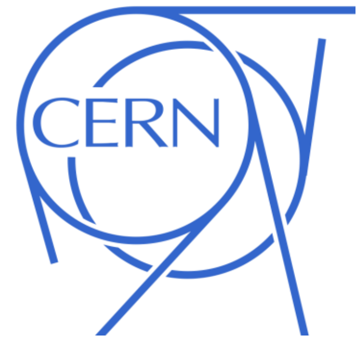


- **Primary goal: measurement of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$**
- **New Technique: K^+ decay-in-flight**
- **Run1 results:** [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
- **Broader physics programme:**
  - **Precision measurements of kaon and pion decays**
  - **HNL and LNV/LFV searches in kaon decays**
  - **Hidden Sector searches with kaons and in dump mode**
- **Data taking**
  - 2016 Commissioning + Physics run (45 days).
  - 2017 Physics run (160 days).
  - 2018 Physics run (217 days).
  - 2021 Physics run (85 days [10 beam dump]). } New result!
  - 2022 Physics run (215 days). }
  - 2023 Physics run (150 days [10 beam dump]).
  - 2024 Physics run (204 days [12 beam dump, 7 low int.]).
  - 2025 Physics run (~210 days foreseen, started in April)

LS2 (upgrades) | **New result!** | LS3

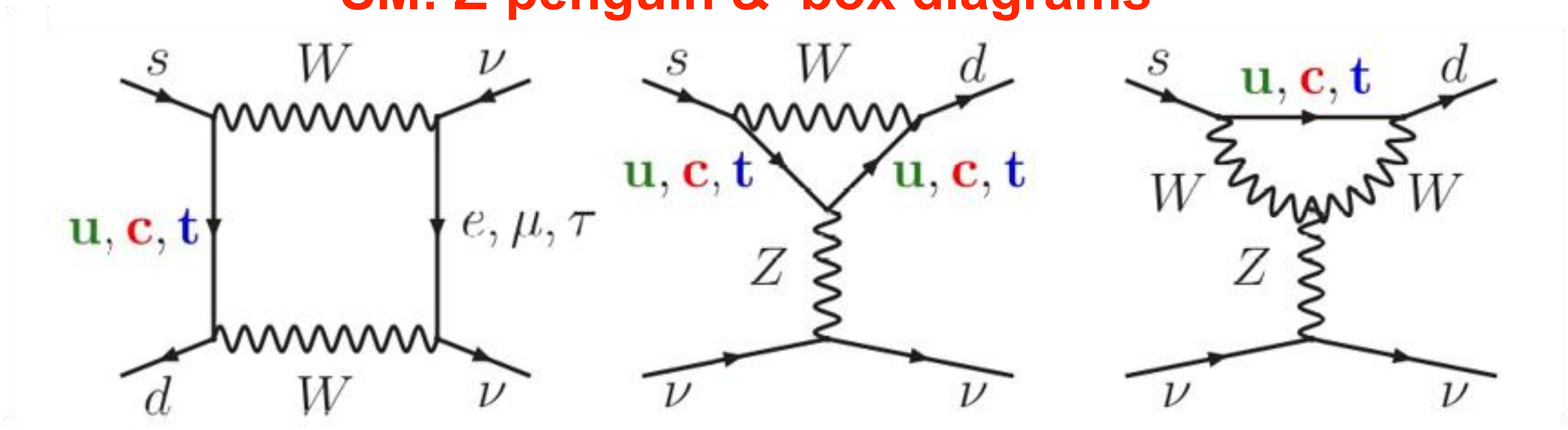
2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026

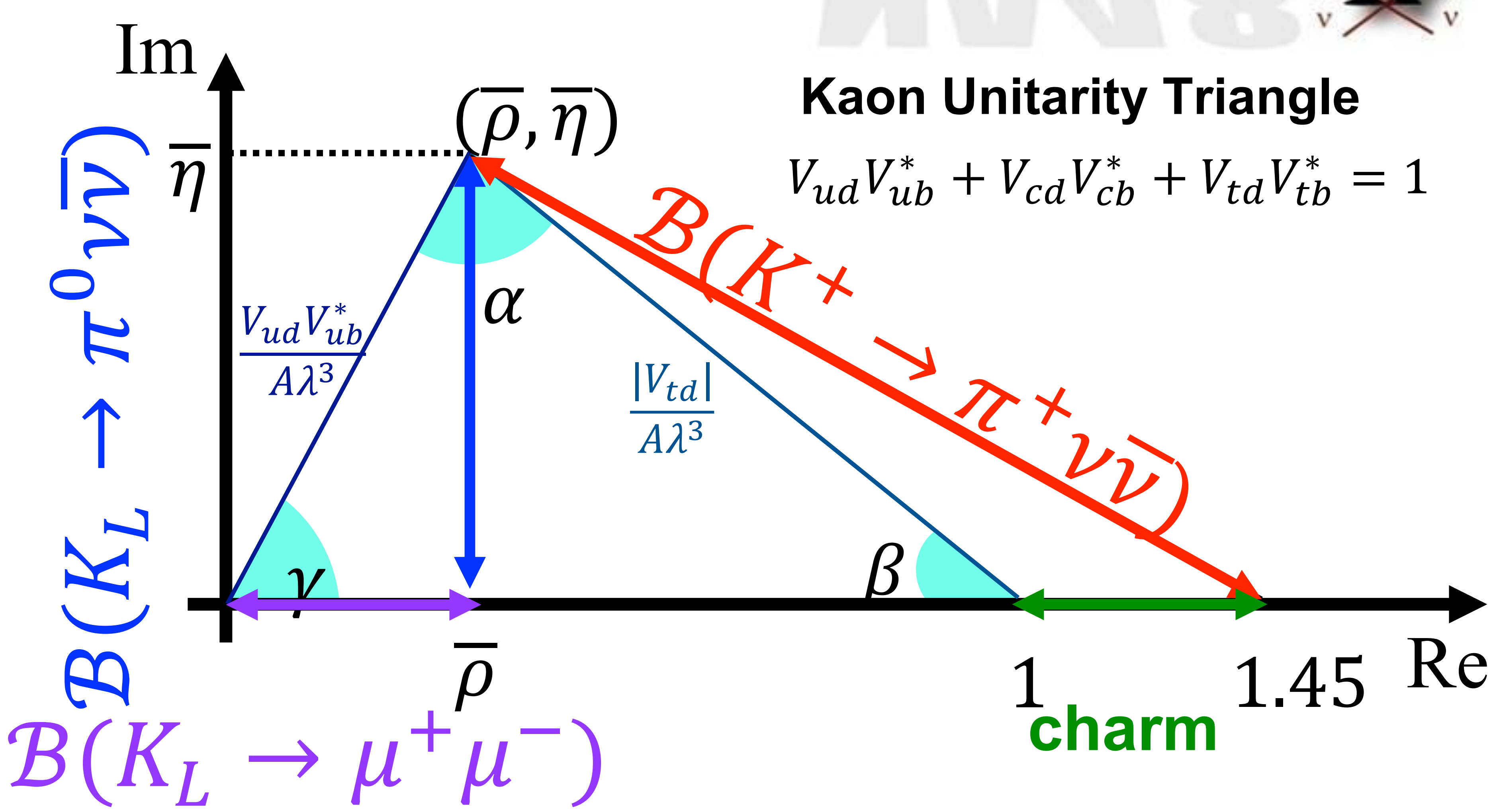
New result: JHEP 02 (2025) 191



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

SM: Z-penguin & box diagrams





- $\mathcal{B}(K \to \pi\nu\bar{\nu})$ **highly suppressed** in SM
  - GIM mechanism & maximum CKM suppression $s \to d$ transition: $\sim \frac{m_t^2}{m_W^2}|V_{ts}^* V_{td}|$
- Theoretically clean ⇒ high precision SM predictions
  - Dominated by short distance contributions.
  - Hadronic matrix element extracted from $\mathcal{B}(K \to \pi l\nu)$ 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
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.1}_{-3.5}) \times 10^{-11}$ (NA62)
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 2.2 \times 10^{-9}$ (KOTO)

Differences in SM calculations from choice of CKM parameters: [EPJC 84 (2024) 4, 377]

NA62 (2016–18 data): [JHEP 06 (2021) 093]
KOTO (2021 data): [PRL 134 (2025) 081802]

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

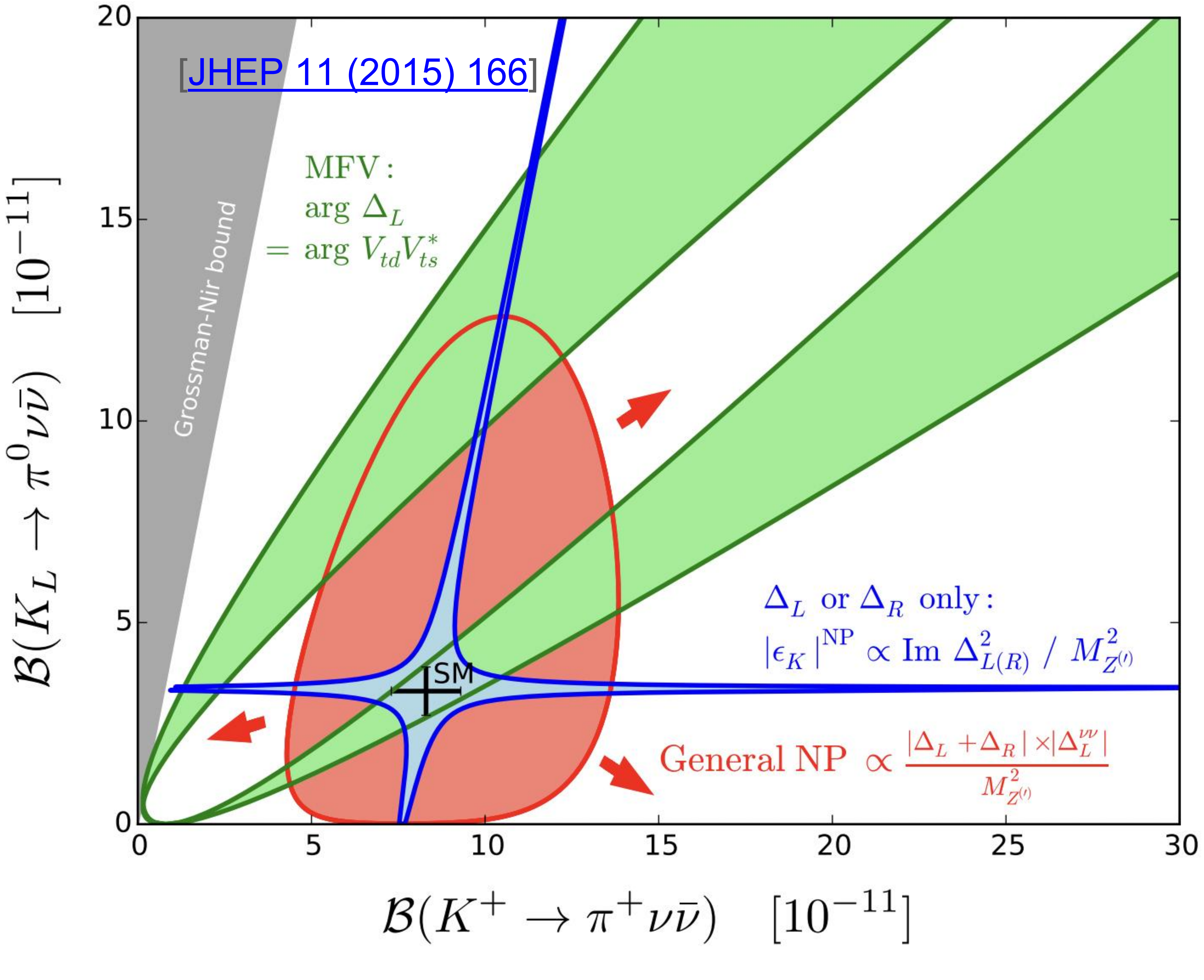
- Correlations between BSM contributions to BRs of K^+ and K_L modes [JHEP 11 (2015) 166].
  - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ε'/ε, ΔM_B, B-decays) [JHEP 12 (2020) 097][PLB 809 (2020) 135769].
- Leptoquarks [EPJ.C 82 (2022) 4, 320], Interplay 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]

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

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



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

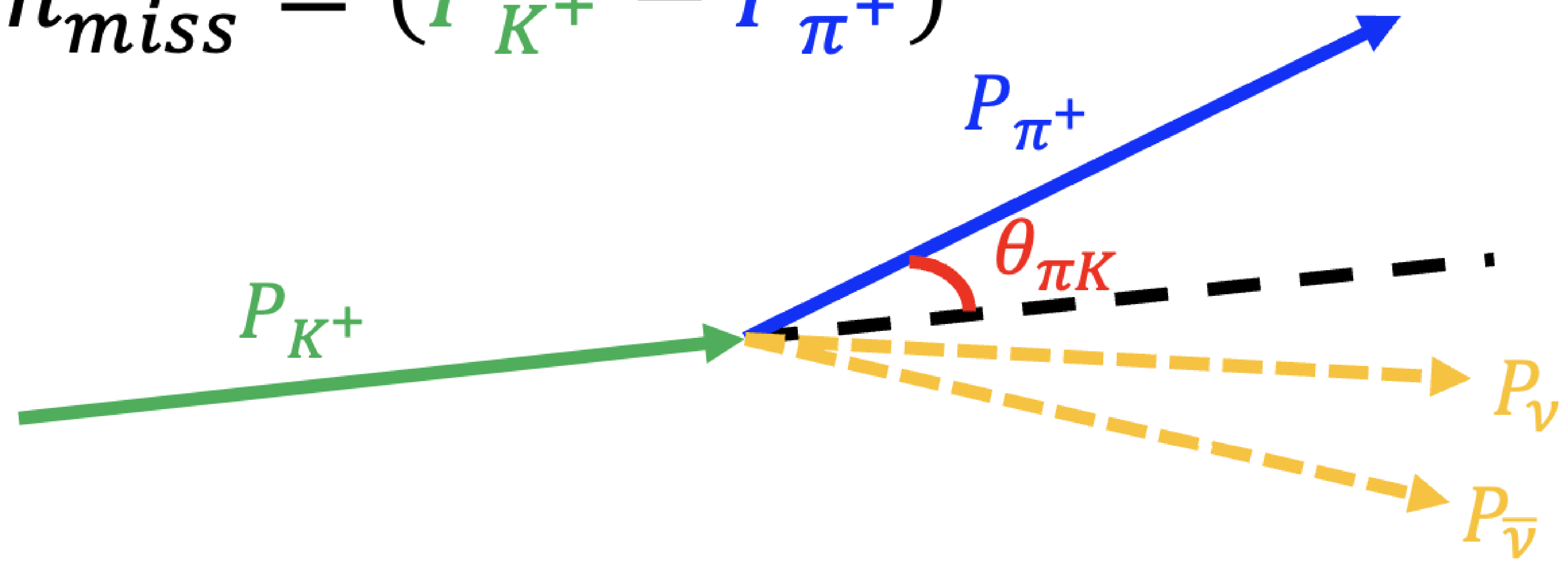
NA62 Strategy:

- Tag K^+ and measure momentum.
- Identify π^+ and measure momentum.
- Match K^+ and π^+ in time & form vertex.
  - Determine $m^2_{miss} = (P_K - P_\pi)^2$
- 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 $K^+ \to \pi^+\pi^0$ decays

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

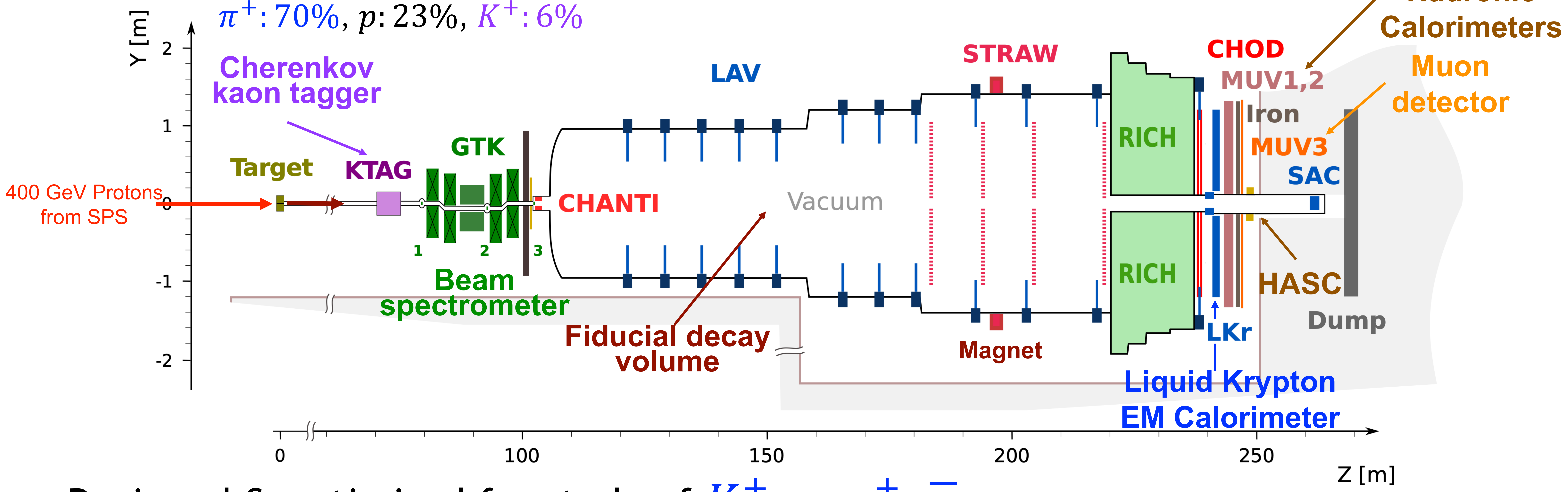


Decay mode	Branching Ratio [PDG]
$K^+ \to \mu^+\nu_\mu$	$(63.56 \pm 0.11)\%$
$K^+ \to \pi^+\pi^0$	$(20.67 \pm 0.08)\%$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024)\%$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$
$K^+ \to \pi^+\nu\bar{\nu}$	$\approx 10^{-10}$

NA62 beamline & detector

[JINST 12 (2017) 05, P05025]

Secondary $75\,GeV/c$ beam:
$\pi^+: 70\%,\ p: 23\%,\ K^+: 6\%$

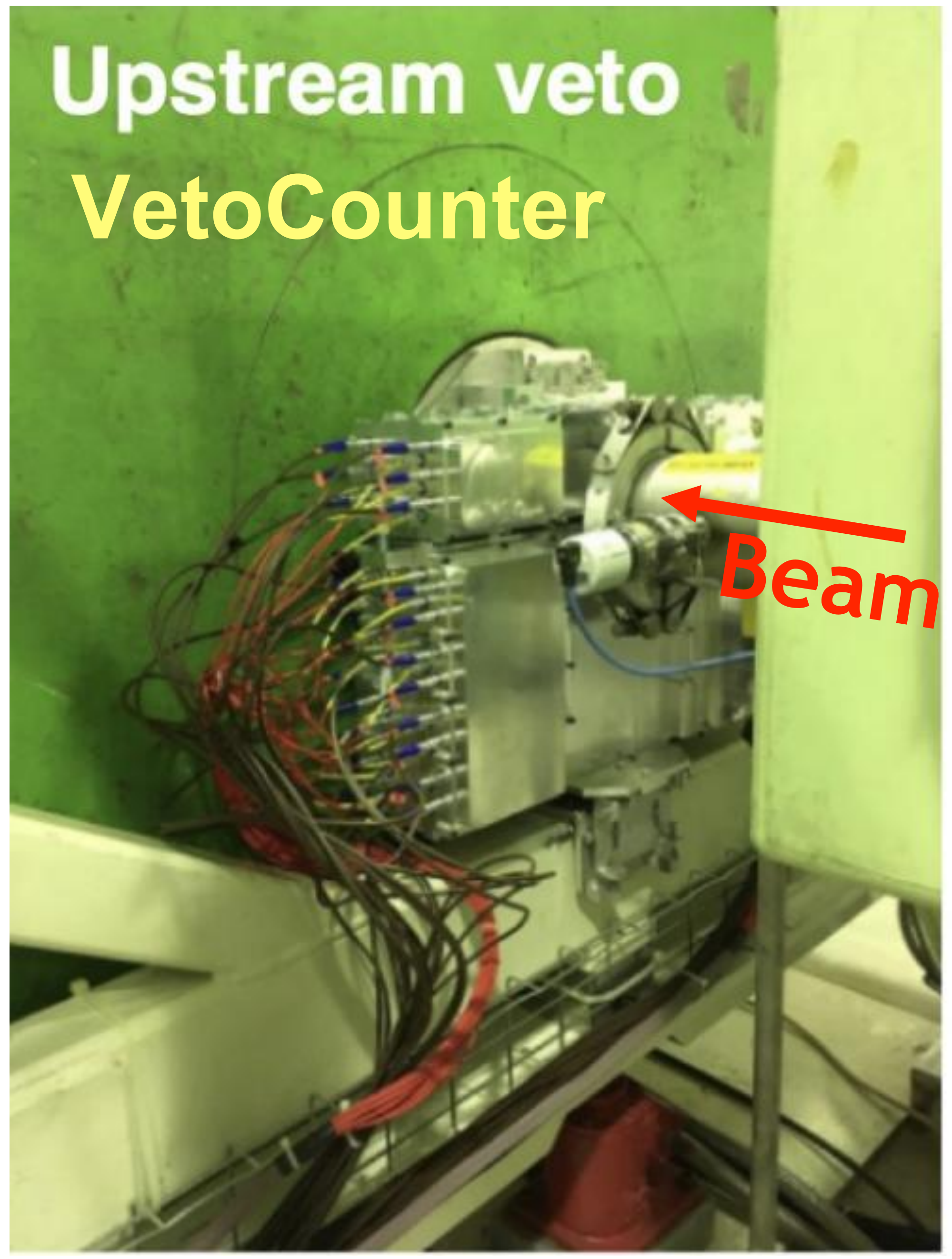


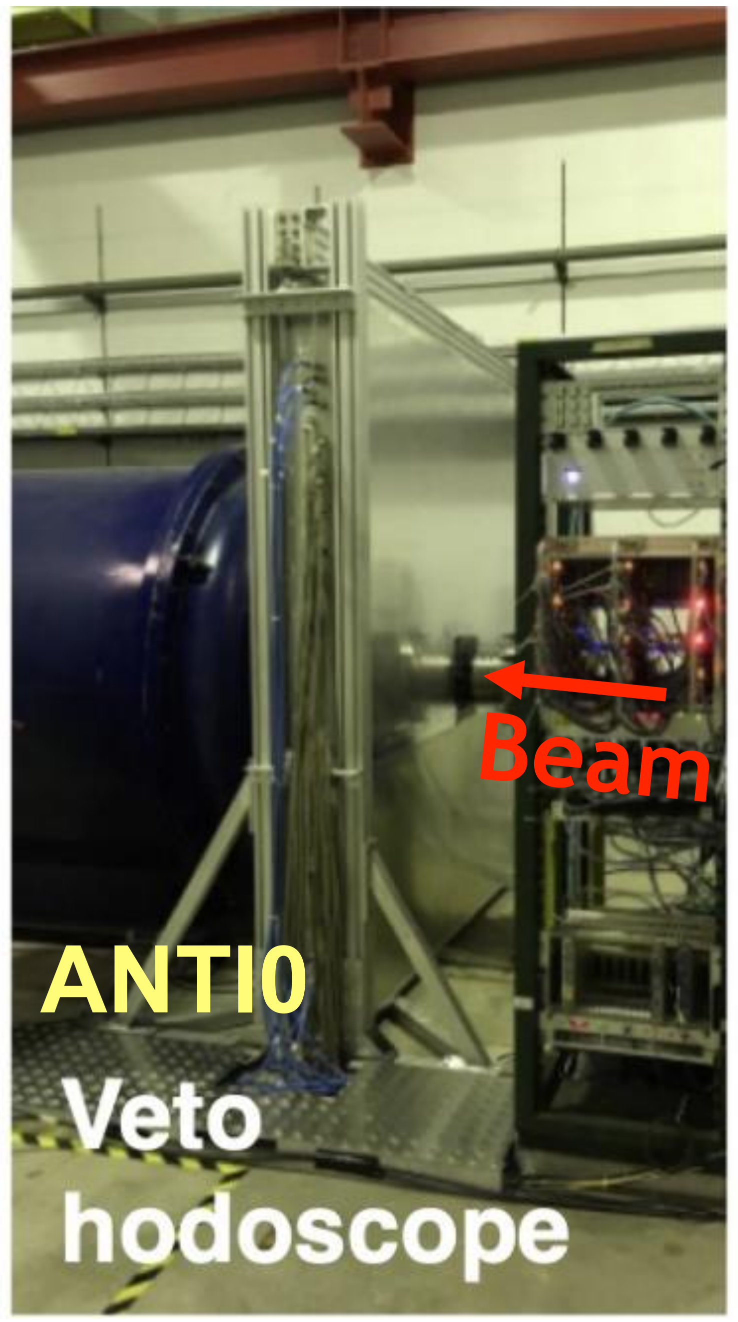
- Designed & optimised for study of $K^+ \to \pi^+ \nu \bar{\nu}$:
  - **Particle tracking:** beam particle (GTK) & downstream tracks (STRAW)
  - **PID:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
  - **Comprehensive veto systems:** CHANTI (beam interactions), LAV,LKr,IRC,SAC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

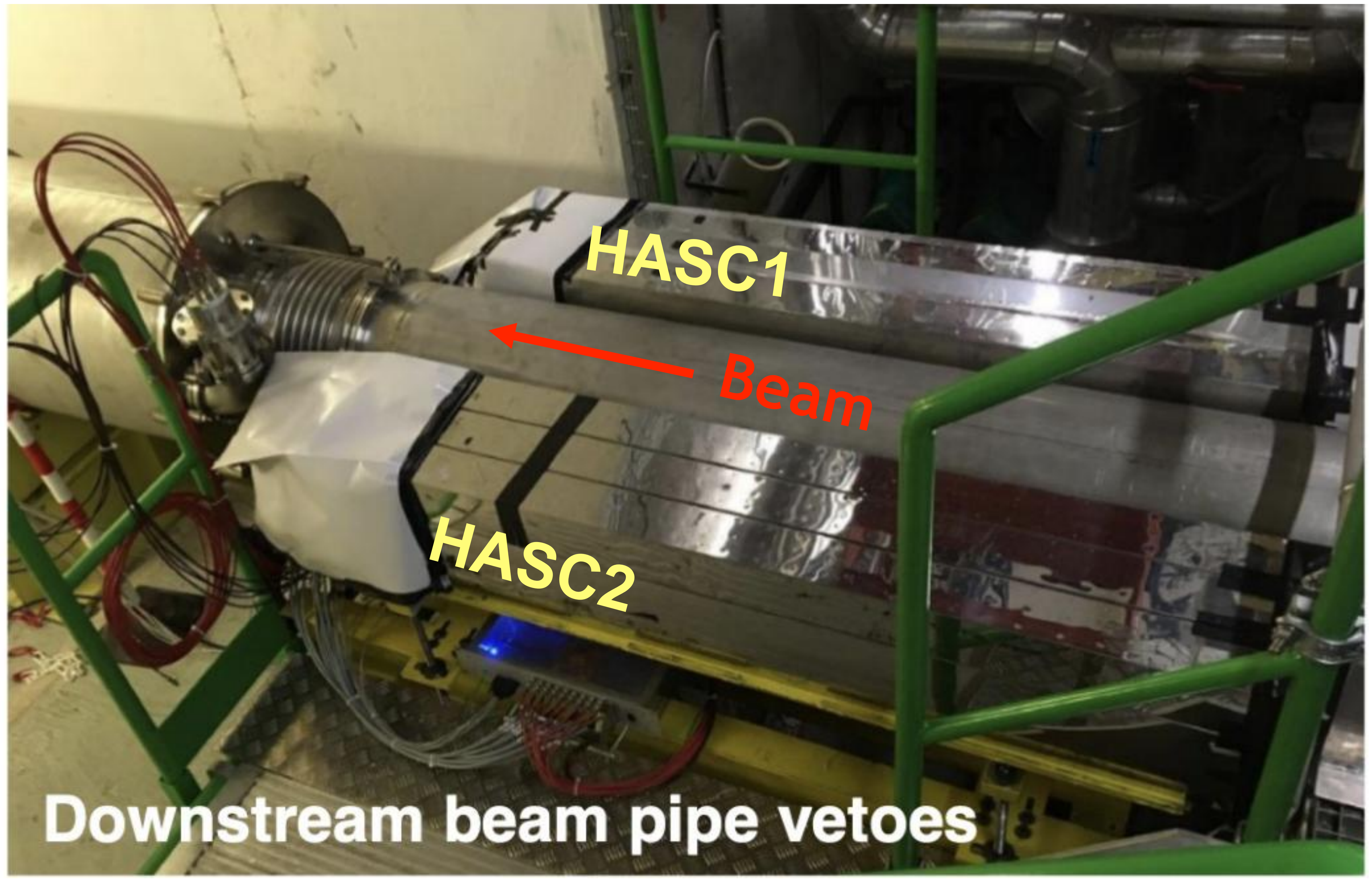
NA62 upgrades for 2021-22 data taking

- New detectors, installed during LS2:
  - 4th GTK (Kaon beam tracker) & rearrange GTK achromat (GTK2 upstream of scraper).
  - New upstream veto (VetoCounter) & veto hodoscope (ANTI0) upstream of decay volume.
  - Additional veto detector (HASC2) at end of beam-line.
- **Intensity increased by** $\sim 35\%$ with respect to 2018 [450 → 600 MHz].
- **Improvements to the trigger configuration.**

New detectors installed in 2021:



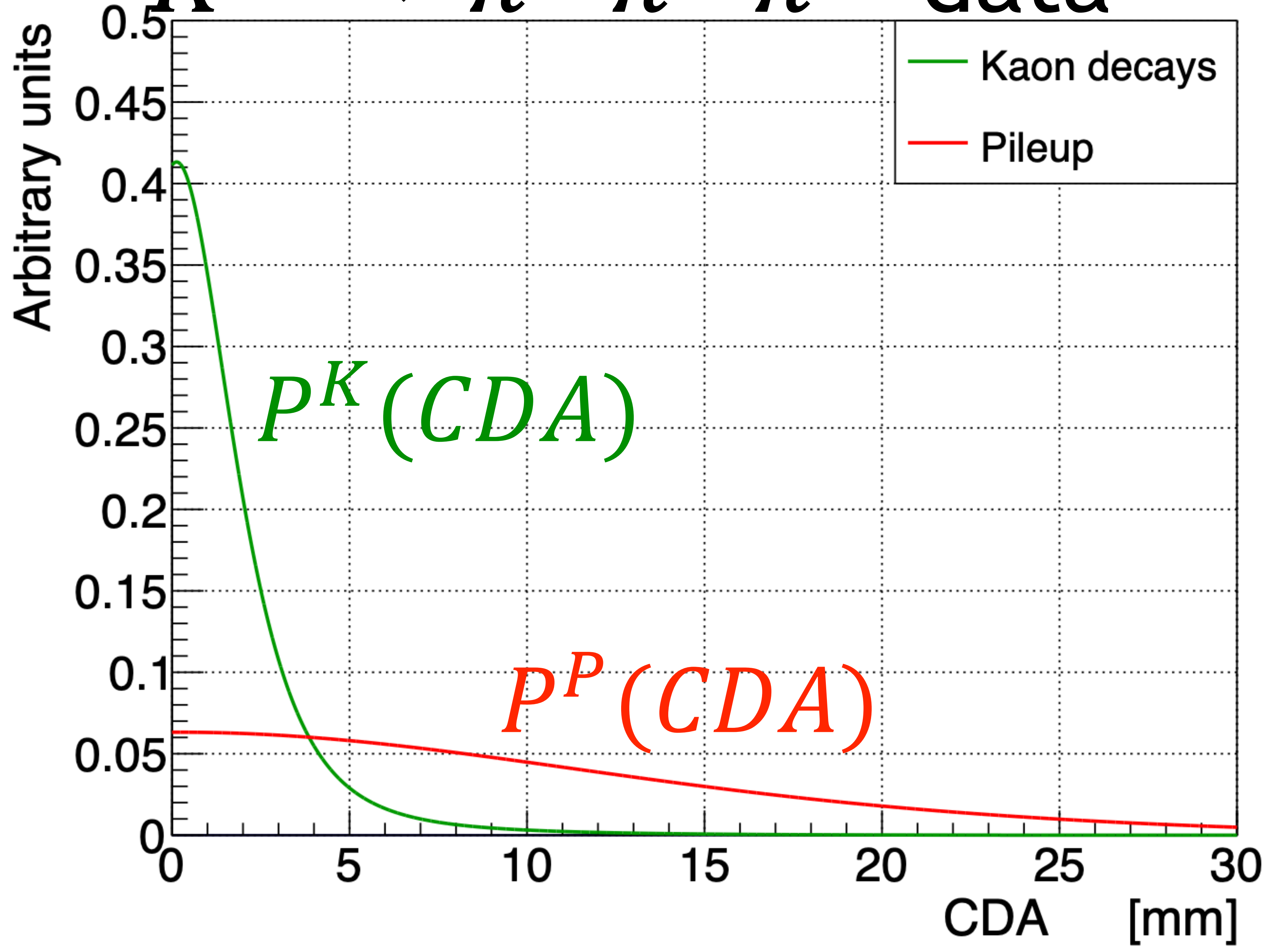




Bayesian classifier for $K^+ - \pi^+$ matching

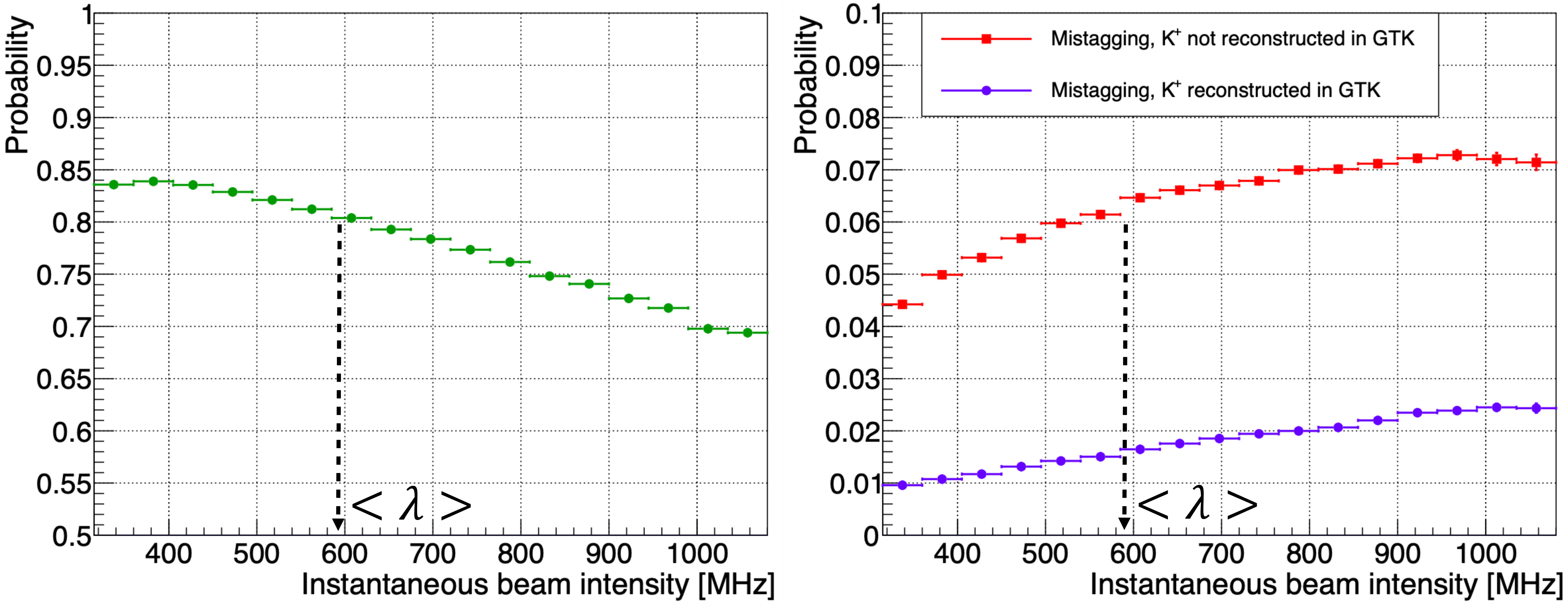
Example of selection update

- **Inputs:** spatial (CDA) & time (ΔT_+) matching, intensity/pileup (N_{GTK}) [prior]
  - Models for PDFs/Prior from $K^+ \to \pi^+\pi^+\pi^-$ data



- **Output:** posterior probability of GTK track = true K^+
  - Use likelihoods of kaons (K) and pileup (P)
  - Likelihood ratio used to select true match when $N_{GTK} > 1$

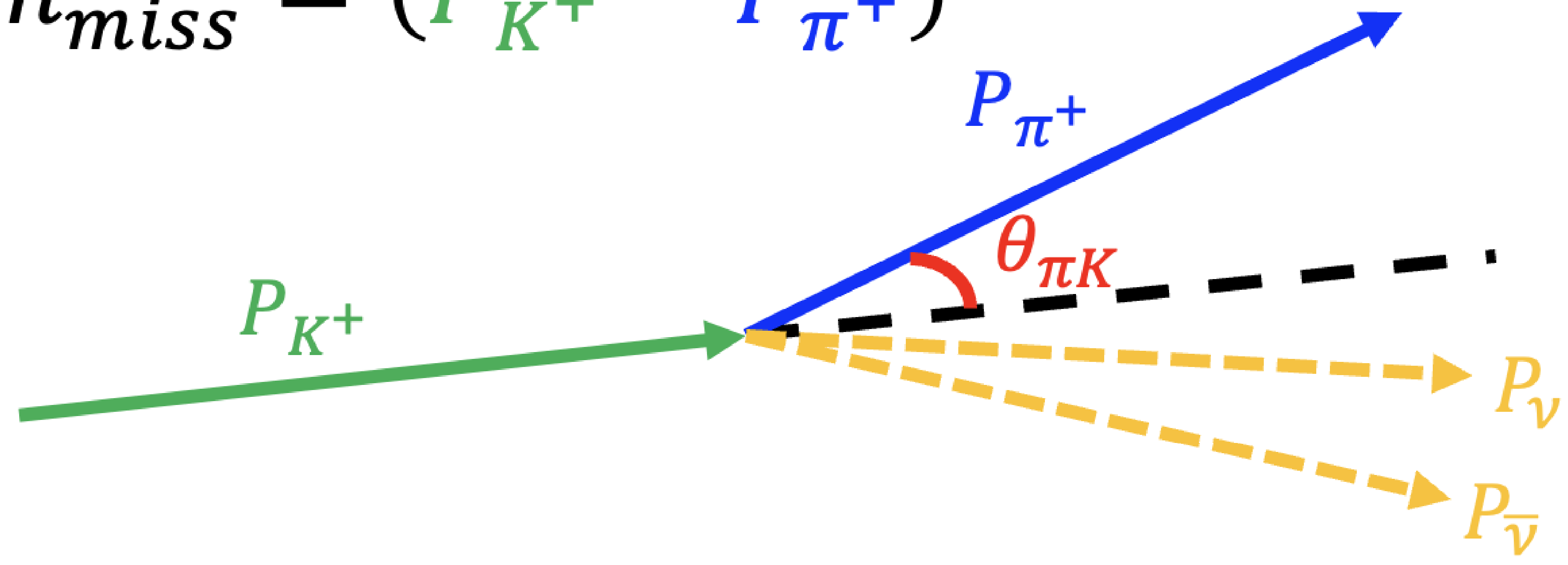
$\varepsilon = 80\%$ $\quad P^P_{mistag} = 6\%$ $\quad P^K_{mistag} = 2\%$

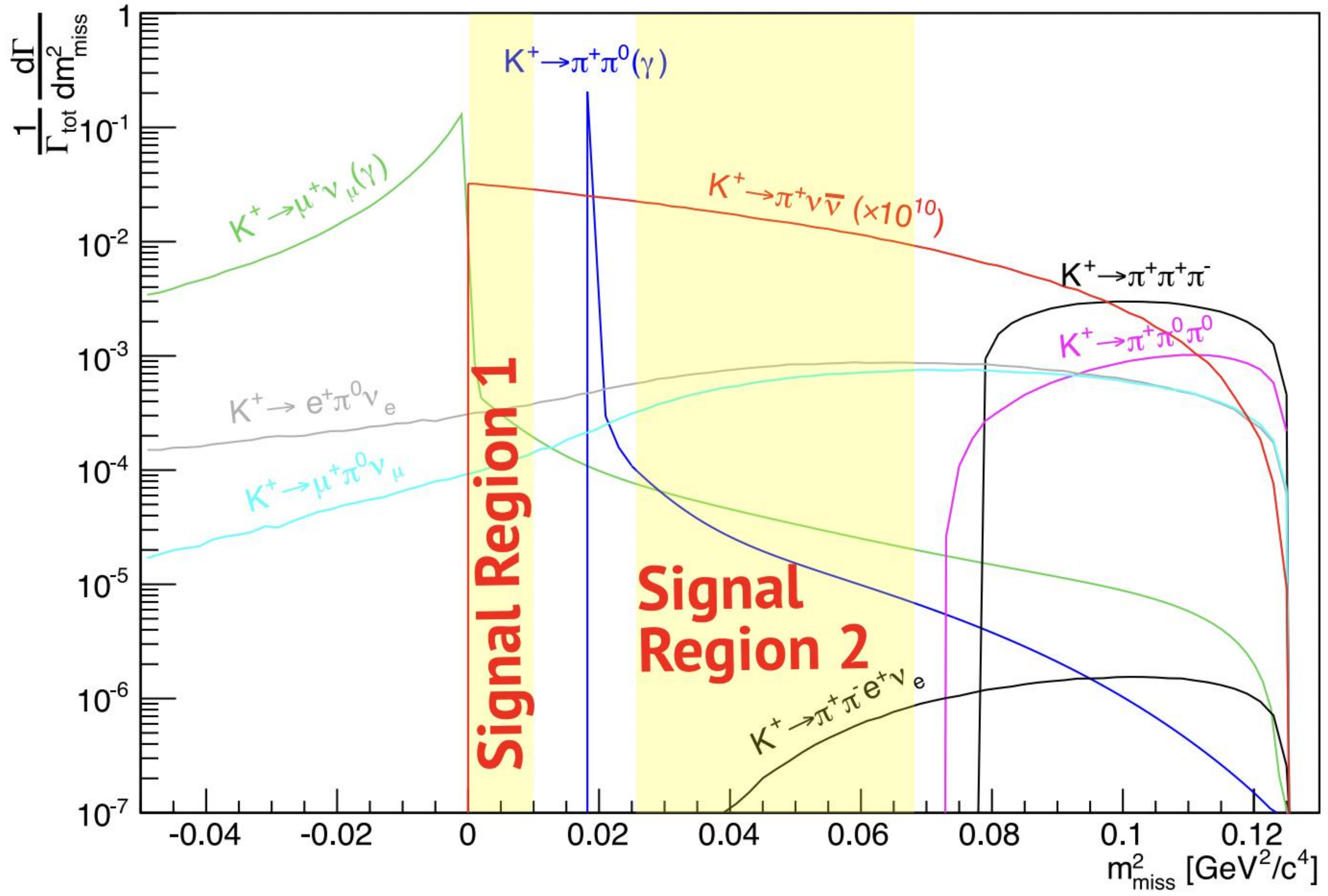


- Efficiency improved (+10%) and mistagging probability maintained.

Kinematic constraints & signal regions

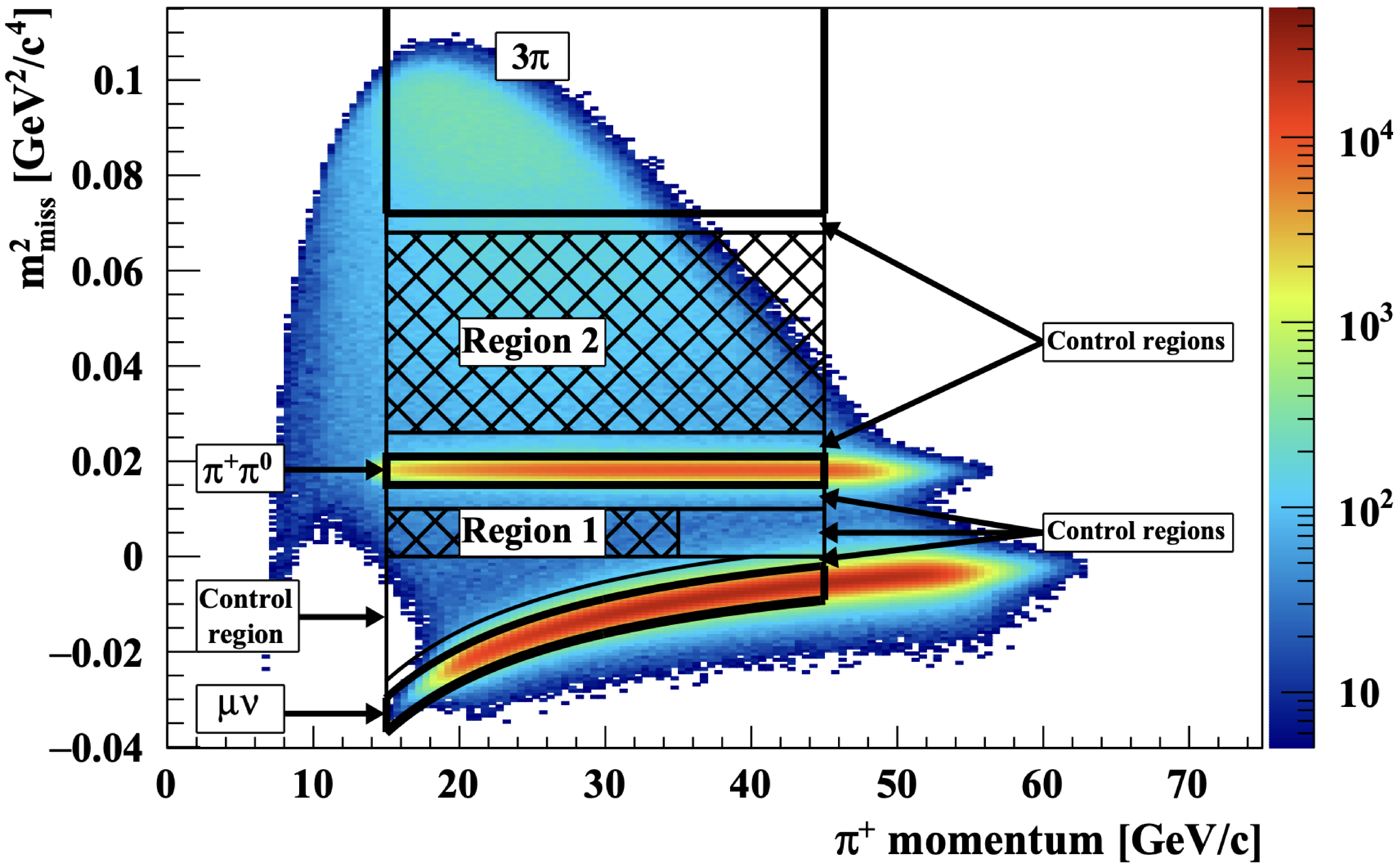
$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$





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

[JHEP 06 (2021) 093]



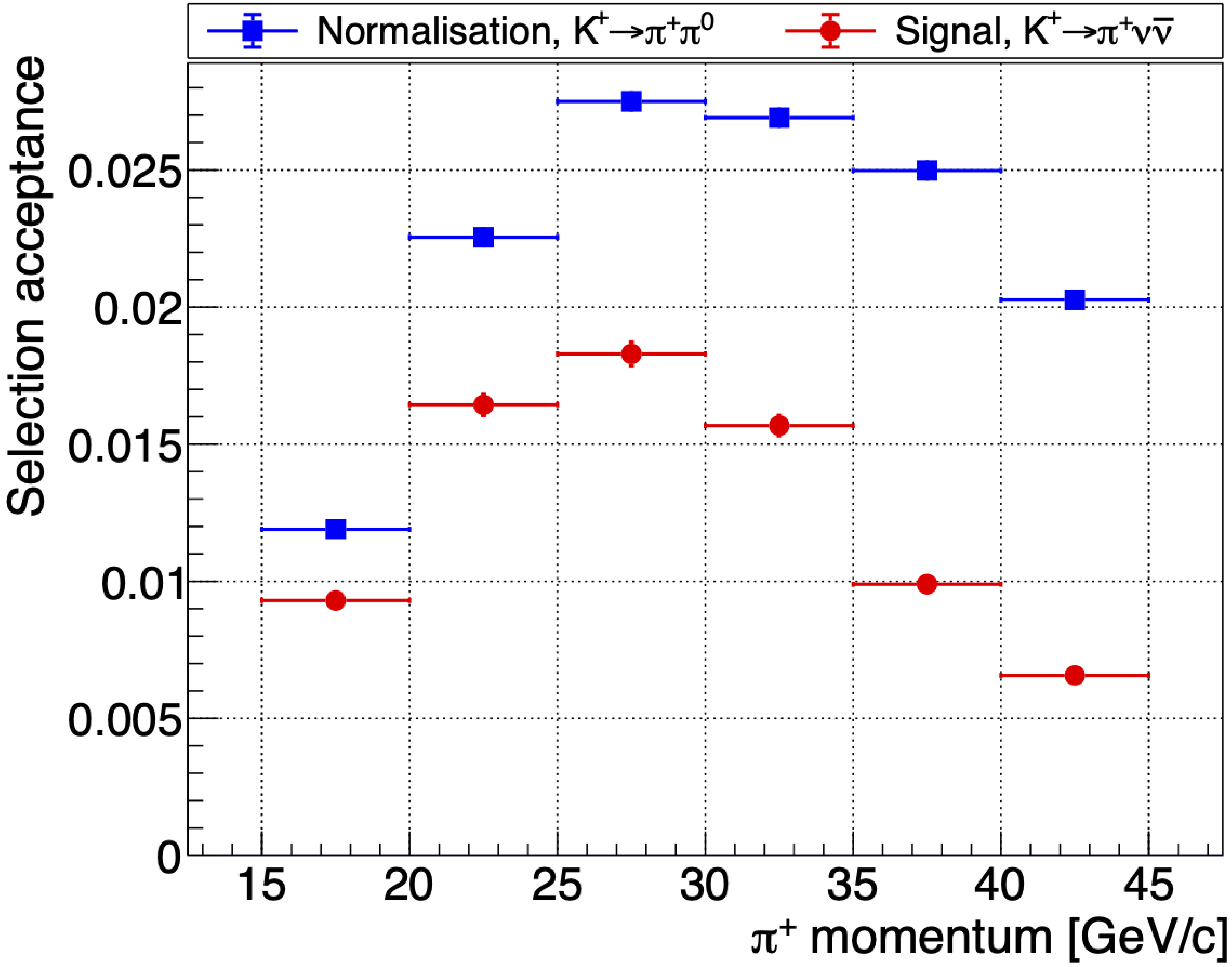
π^+ momentum range: 15—45 GeV/c

Signal sensitivity: acceptances

Acceptances

Analysis is performed in (5 GeV/c) bins of momentum:

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



Case	OLD 2018 (S2)	NEW 2021-22	
Norm.	11.8%	13.4%	**+15%**
Signal	(6.37±0.64)%	(7.62±0.22)%	**+20%**

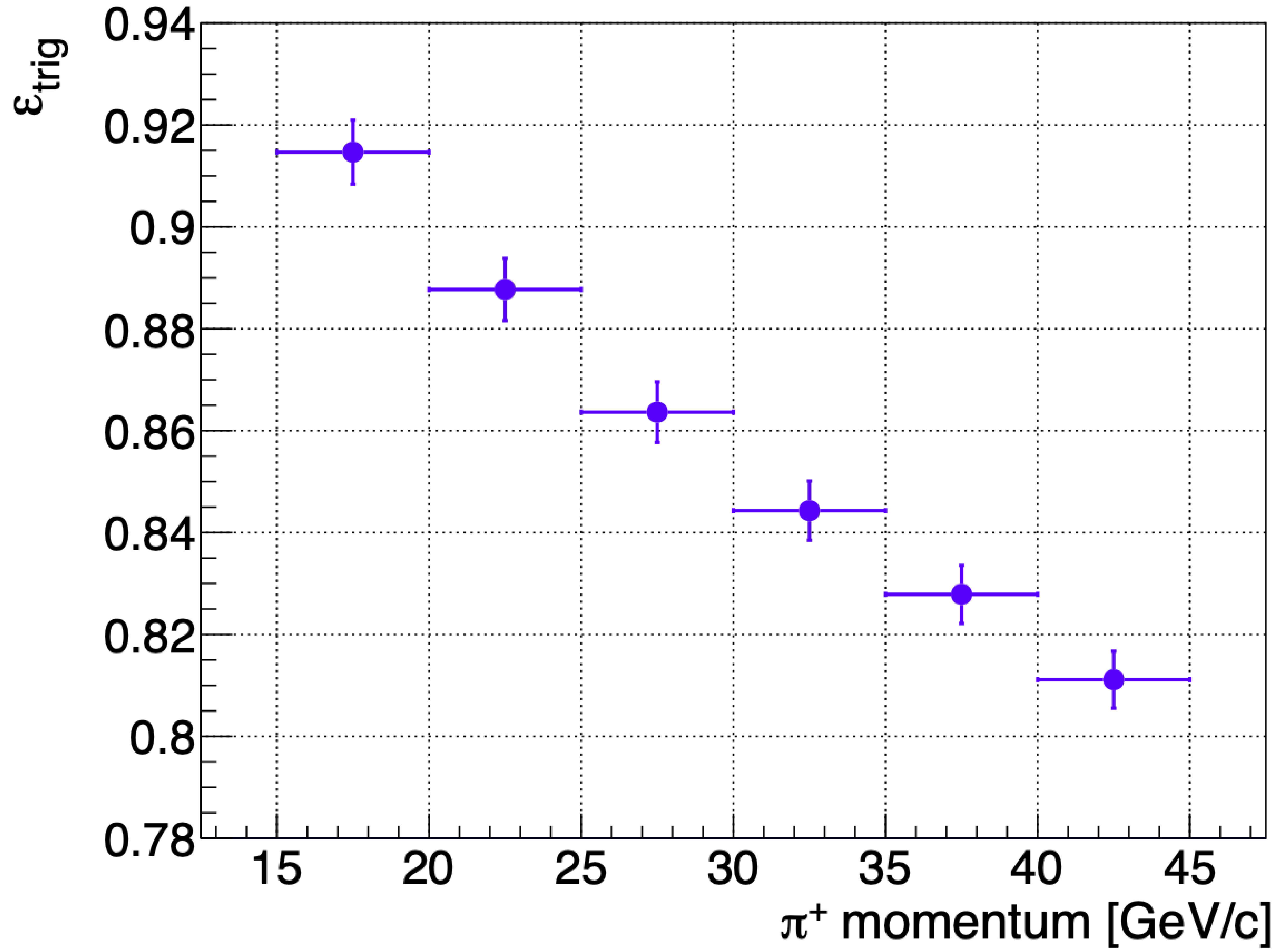
- Increased selection efficiencies.
  - New K-pi matching technique.
  - Re-tuned vertex conditions.
  - Relaxation of some vetos.
- Improved precision (plus improved systematic uncertainty evaluation).

Acceptances evaluated at 0 intensity.
Intensity dependence captured in ε_{RV}

Signal sensitivity: trigger efficiencies

Analysis is performed in (5 GeV/c) bins of momentum:

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



$$\varepsilon_{trig} = \frac{\varepsilon_{sig}}{\varepsilon_{norm}}$$

$$\varepsilon_{trig}(new) = (85.9 \pm 1.4)\%$$

$$\varepsilon_{trig}(2018) = (89 \pm 5)\%$$

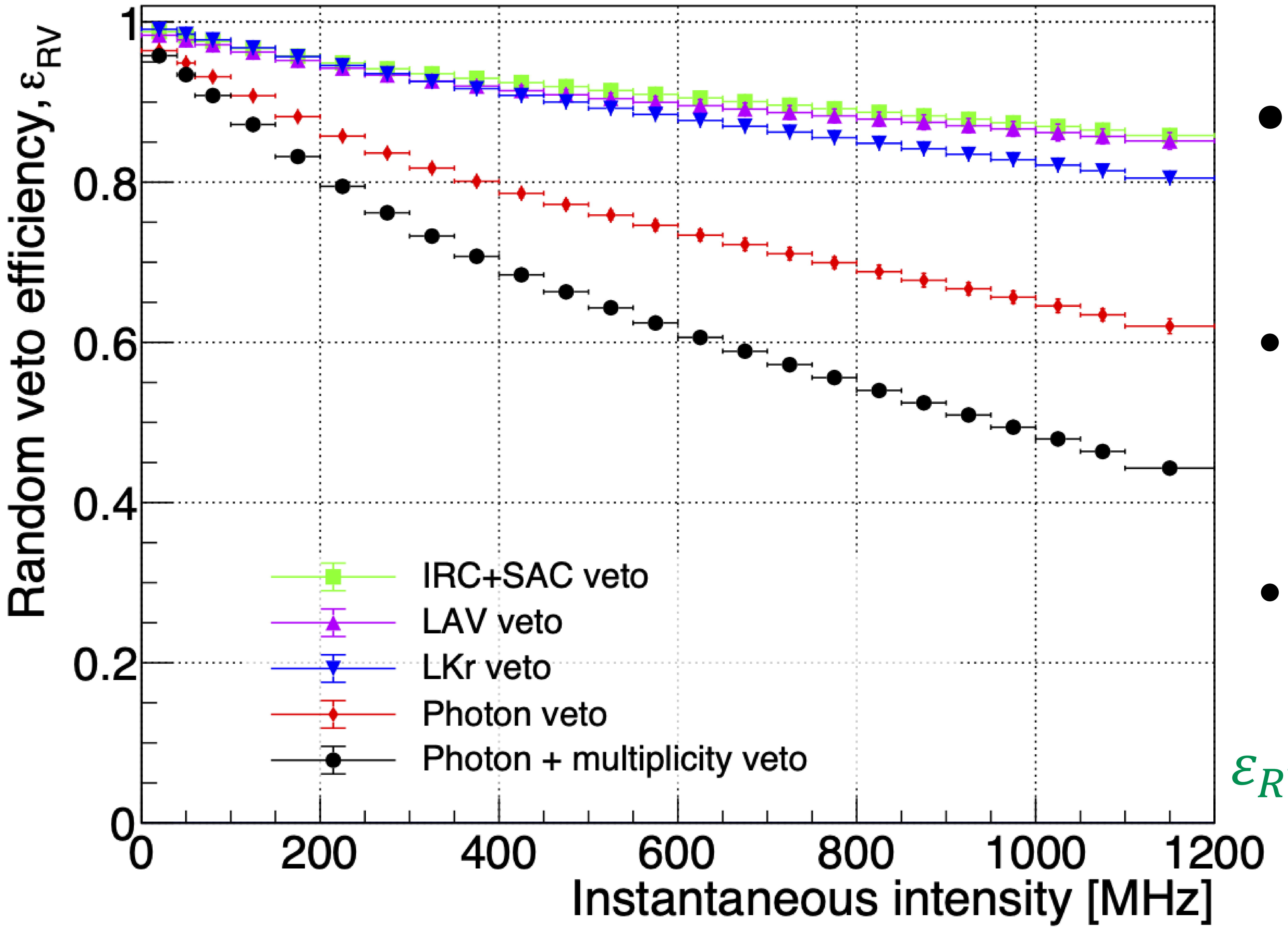
- Trigger efficiency ratio:
  - **New:** several components in both normalisation & signal triggers: **partial cancellation**.
  - **Old:** in 2016—18 data normalised with fully independent min bias trigger (**no cancellation**).

- Improved precision by factor 3 with reduced systematic uncertainty.

Signal sensitivity: random veto

ε_{RV} is independent of track momentum (related to additional activity only)

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



- ε_{RV} **= Random Veto Efficiency:**
  - $1 - \varepsilon_{RV}$ **= Probability of rejecting a signal event due to additional activity.**
- Balance:
  - Strict vetos ⇒ lower efficiency
  - Loose vetos ⇒ higher background
- **Operational intensity higher** but re-tuning vetos means ε_{RV} **is comparable:**

$$\varepsilon_{RV}(new, \overline{\lambda_{21-22}} \approx 600\,MHz) = (63.2 \pm 0.6)\%$$

$$\varepsilon_{RV}(old, \overline{\lambda_{2018}} \approx 400\,MHz) = (66 \pm 1)\%$$

Signal sensitivity: results

$$N_K = \frac{N_{\pi\pi} D_0}{\mathcal{B}_{\pi\pi} A_{\pi\pi}} \qquad \mathcal{B}_{SES} = \frac{1}{N_K \varepsilon_{RV} \varepsilon_{trig} A_{\pi\nu\bar{\nu}}}$$

- Display integrals (15—45 GeV/c, 2021+22) for summary tables.

* Acceptances evaluated at 0 intensity.

$N_{\pi\pi}^{\text{eff}}$	Effective number of normalisation events	$(1.953 \pm 0.005) \times 10^8$
$A_{\pi\pi}$	Normalisation acceptance	$(13.410 \pm 0.005)\%$
N_K	Effective number of K^+ decays	$(2.85 \pm 0.01) \times 10^{12}$
$A_{\pi\nu\bar{\nu}}$	Signal acceptance	$(7.62 \pm 0.22)\%$
$\varepsilon_{\text{trig}}$	Trigger efficiency ratio	$(85.9 \pm 1.4)\%$
ε_{RV}	Random veto efficiency	$(63.2 \pm 0.6)\%$
$\mathcal{B}_{\text{SES}}$	Single event sensitivity	$(8.48 \pm 0.29) \times 10^{-12}$
$N_{\pi\nu\bar{\nu}}^{\text{SM}}$	Number of expected SM $K^+ \to \pi^+\nu\bar{\nu}$ events	9.91 ± 0.34

$$N_{\pi\nu\bar{\nu}}^{exp} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{SES}}$$

Assuming $\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$:

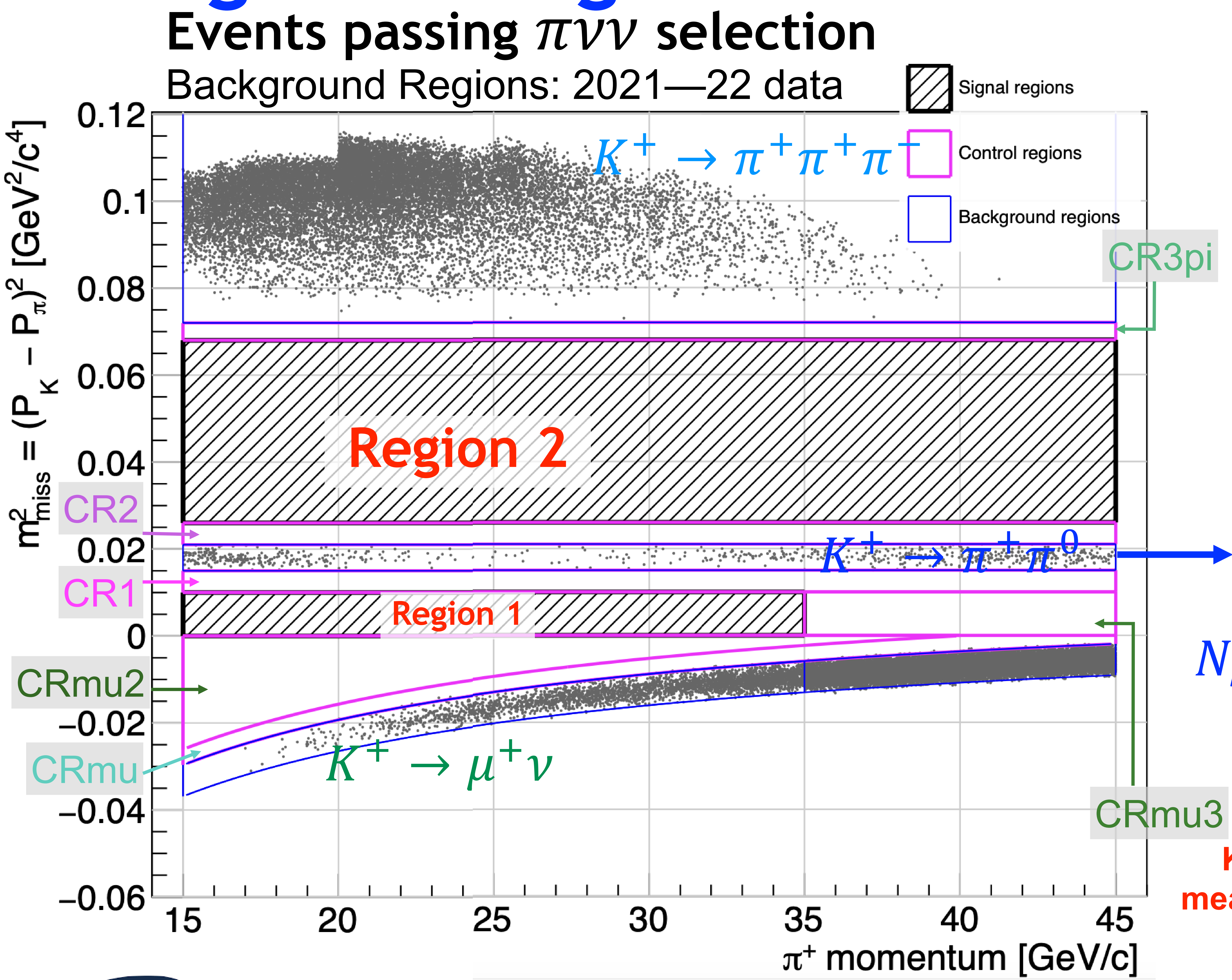
2021-22: $N_{\pi\nu\bar{\nu}} = \mathbf{9.91} \pm 0.34$

c.f. 2016—18 : $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

Double expected signal by including 2021—22 data.

- **Significant improvement in SES uncertainty:**
  - old: 6.3% —> new: 3.5%. Due to:
    - trigger efficiency cancellations
    - improved procedures for evaluation of acceptances and ε_{RV}

Background regions & estimations



Backgrounds from kinematic misreconstruction tails in m^2_{miss}

Number of events passing signal selection in background region

Control sample events in Signal Regions

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

Kinematic tail fraction: measured in control sample

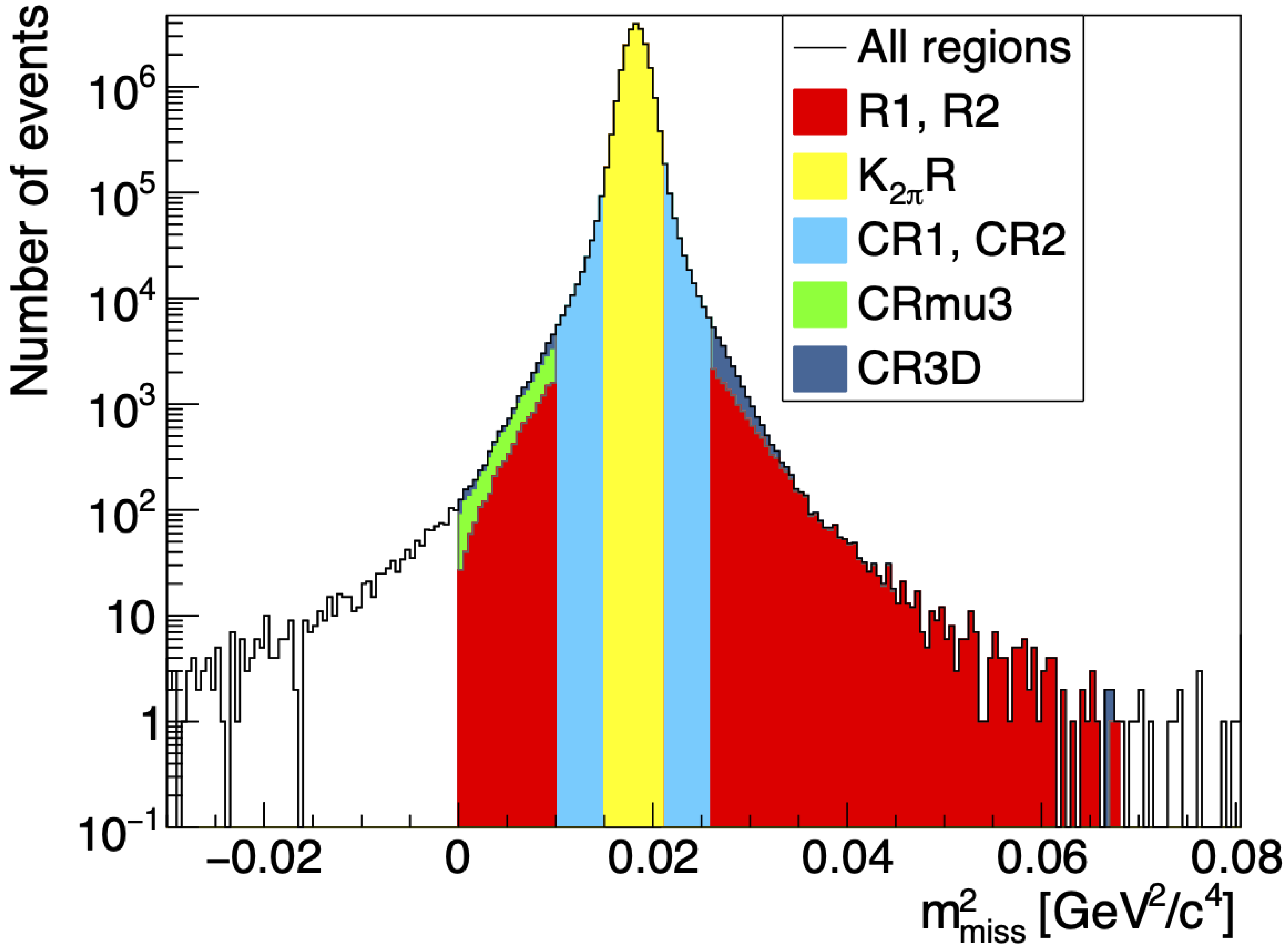
Control sample events in Background Region

Background estimations in signal regions validated with control regions

Backgrounds from kinematic tails

$K^+ \to \pi^+\pi^0$

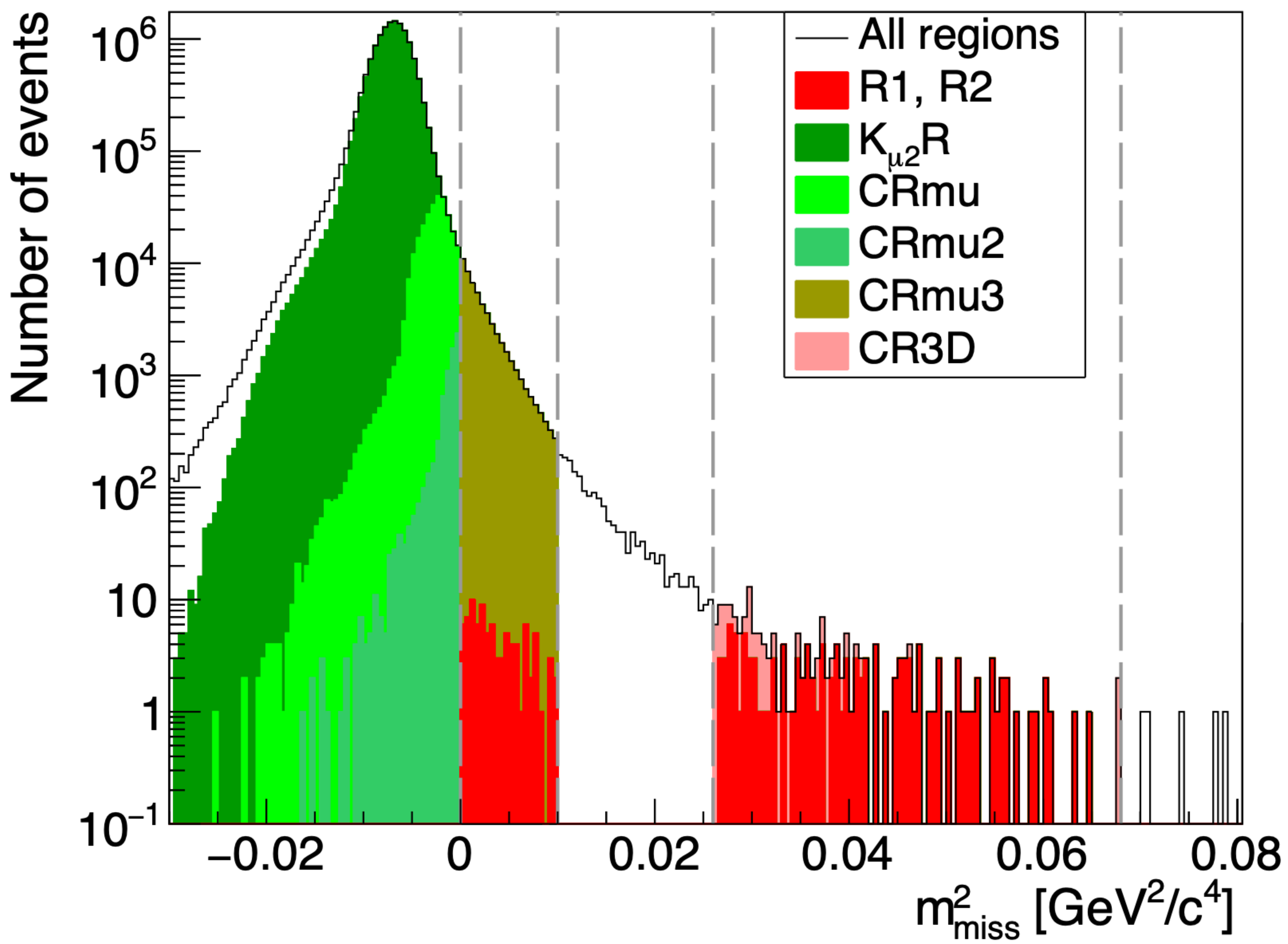
control sample of $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ and 2 photons detected in LKr:



$$N_{bg}(K^+ \to \pi^+\pi^0) = 0.76 \pm 0.04$$

$K^+ \to \mu^+\nu$

control sample of $K^+ \to \mu^+\nu$ events with RICH PID=π^+ and Calo PID=μ^+:



- <1% contribution from $K^+ \to \mu^+\nu$ followed by $\mu^+ \to e^+\nu\nu$

$$N_{bg}(K^+ \to \mu^+\nu) = 0.87 \pm 0.19$$

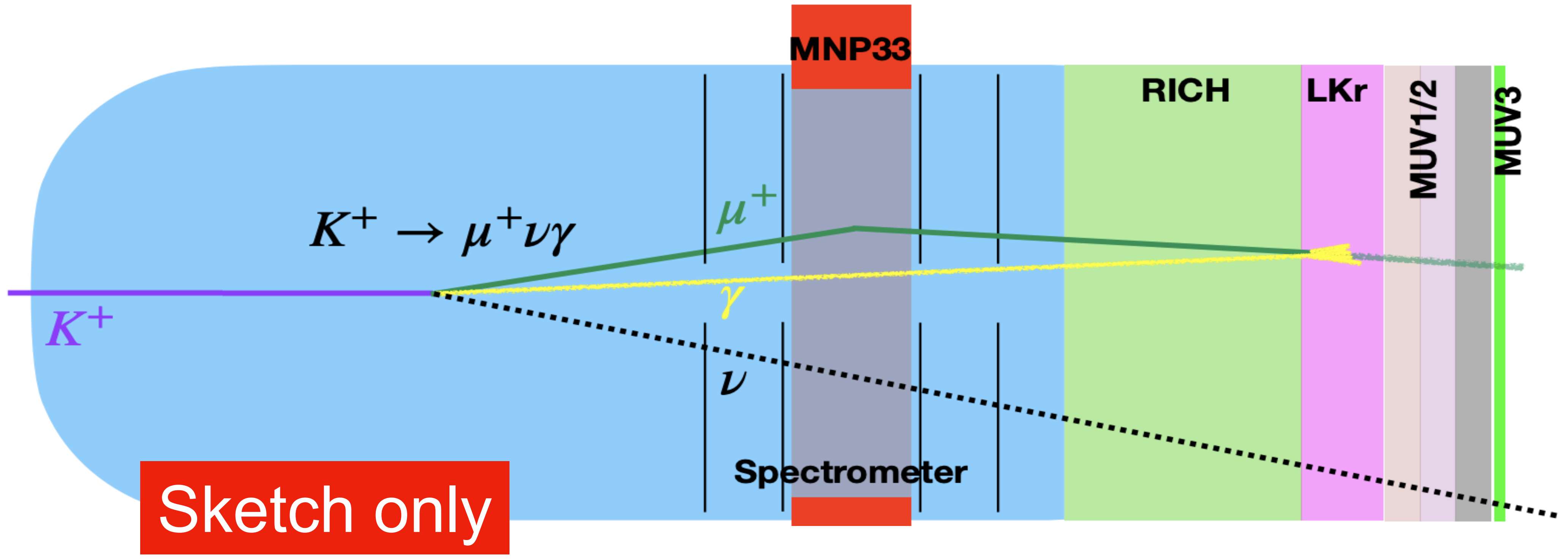
$K^+ \to \pi^+\pi^+\pi^-$

- Use MC to measure f_{tail}:

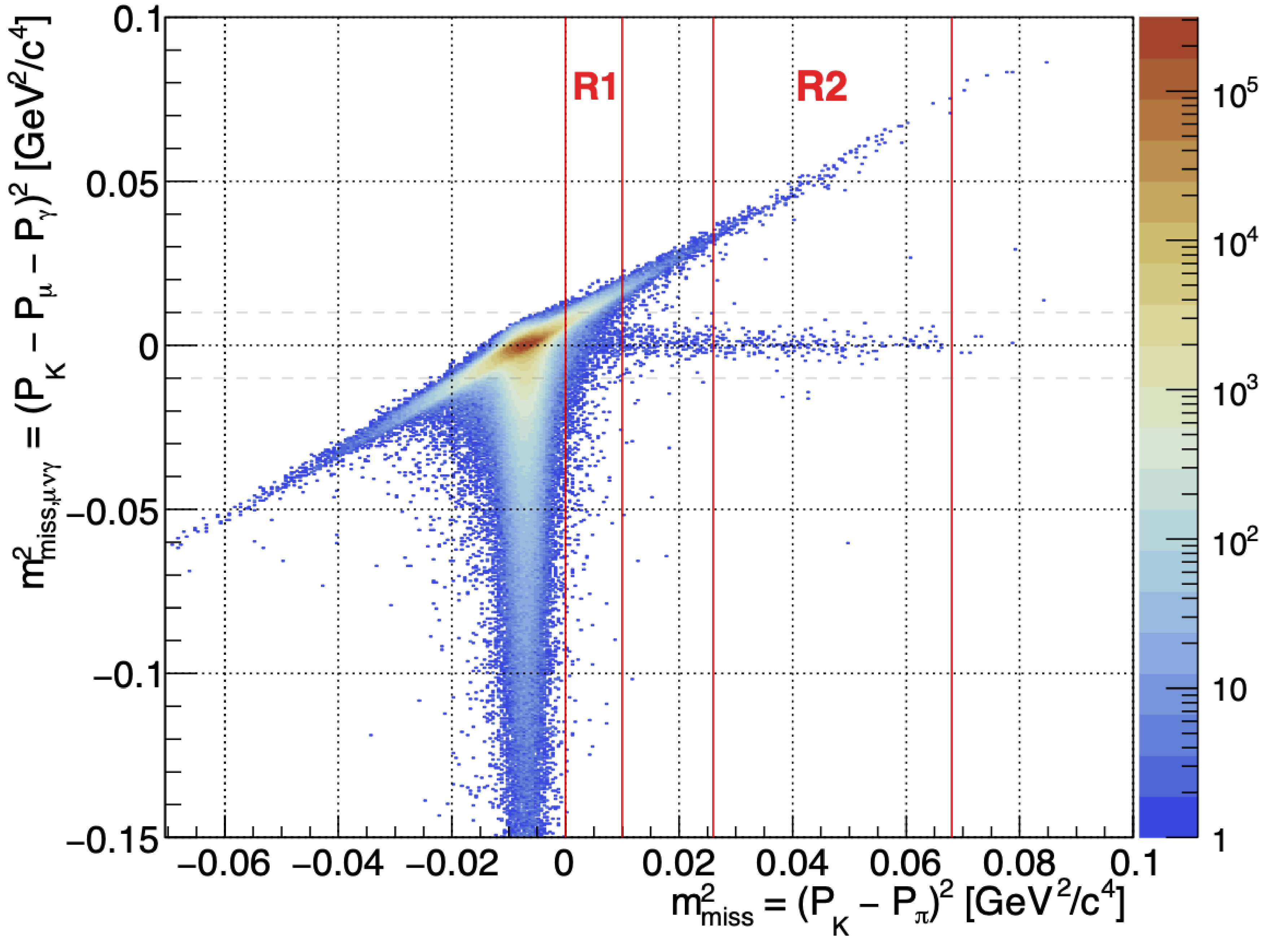
$$N_{bg}(K^+ \to \pi^+\pi^+\pi^-) = 0.11 \pm 0.03$$

Radiative decays: $K^+ \to \pi^+\pi^0\gamma$ & $K^+ \to \mu^+\nu\gamma$

- $K^+ \to \pi^+\pi^0\gamma$ **: not included in "kinematic tails" estimation if the radiative photon is detected in LAV, LKr, IRC or SAC.**
  - Suppression: photon vetos, rejection with additional γ is 30x stronger.
  - Estimation: tails from MC + measured single photon rejection efficiency : $N_{bg}(K^+ \to \pi^+\pi^0\gamma) = 0.07 \pm 0.01$
  - Validation: m^2_{miss} control regions (CR1,2)
- $K^+ \to \mu^+\nu\gamma$ **: not included in "kinematic tails" estimation if γ overlaps μ^+ at LKr, leading to misID as π^+**
  - Suppression: based on $(P_K - P_\mu - P_\gamma)^2$ and E_γ with γ = LKr cluster (mis)associated to muon.
    - Necessary for 2021—22 data, since Calorimetric PID degraded at higher intensities.
  - Estimation: min. Bias data control sample with signal in MUV3 : $N_{bg}(K^+ \to \mu^+\nu\gamma) = 0.82 \pm 0.43$
  - Validation: data sample without $K^+ \to \mu^+\nu\gamma$ veto and PID = "less pion-like" (Calo BDT bins below π^+ bin).

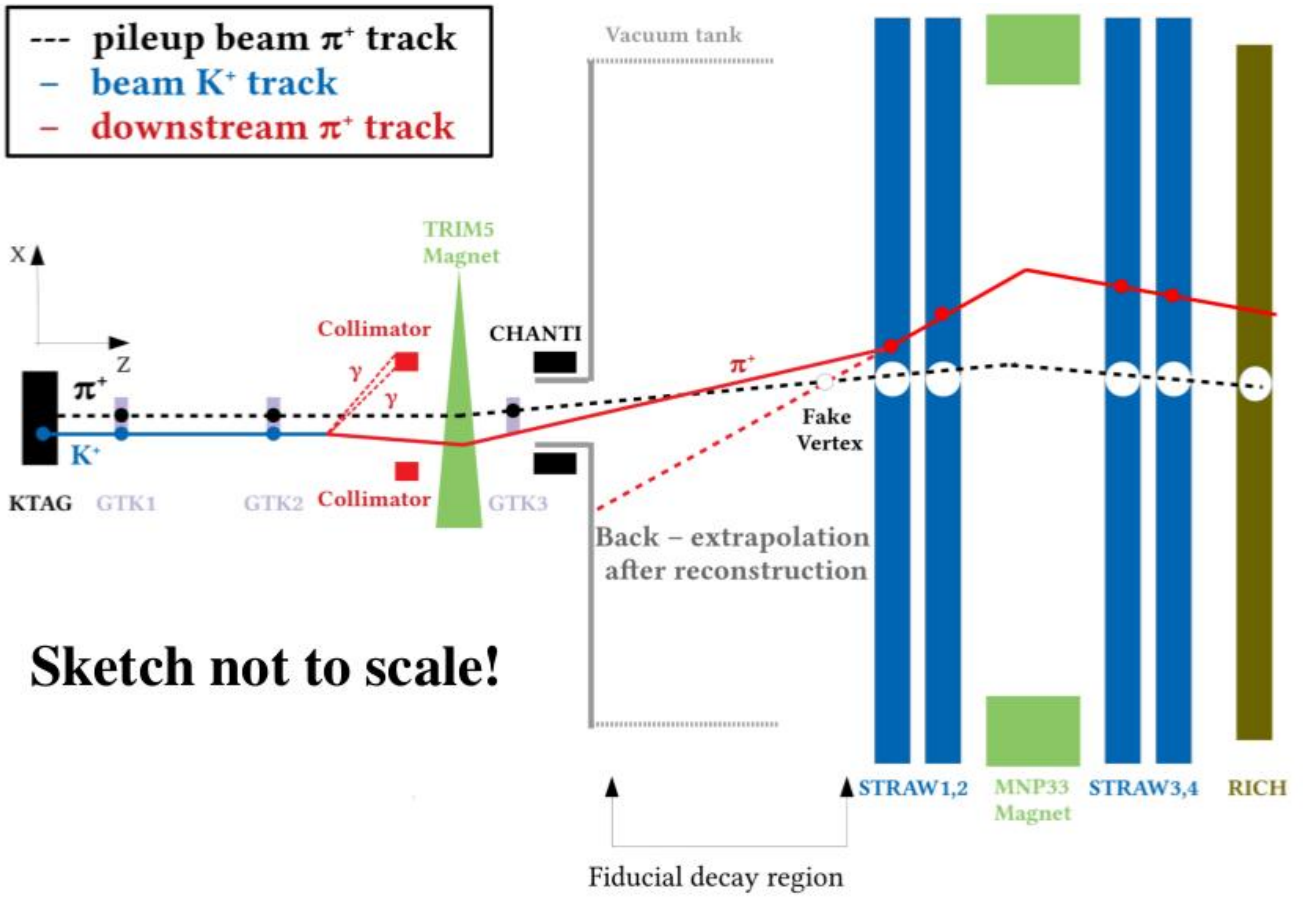


- Before $K^+ \to \mu^+\nu\gamma$ veto: found excess of events at $p > 35\,GeV/c$ in Region 2 relative to 2016—18 data.
- Additional background identified and studied in data control samples & MC.
- $K^+ \to \mu^+\nu\gamma$ veto added to selection criteria for final analysis.



Upstream background mechanism

- A kaon decays upstream the fiducial decay region
- Only a π+ enters the fiducial decay region
- There is an in-time pileup beam particle (in GTK)
- The upstream π+ is scattered in the first STRAW chamber, and a fake vertex in the fiducial decay region is reconstructed



Upstream background evaluation

$$N_{bg} = \sum_i N_i f_{cda} P_i^{match}$$

N Upstream Reference Sample: signal selection but invert CDA cut (CDA>4mm)

f_{cda} Scaling factor : bad cda —> good cda

P_{match} Probability to pass $K^+ - \pi^+$ matching

Calculate using bins (i) of $(\Delta T_+, N_{GTK})$

[Updated to fully data-driven procedure]

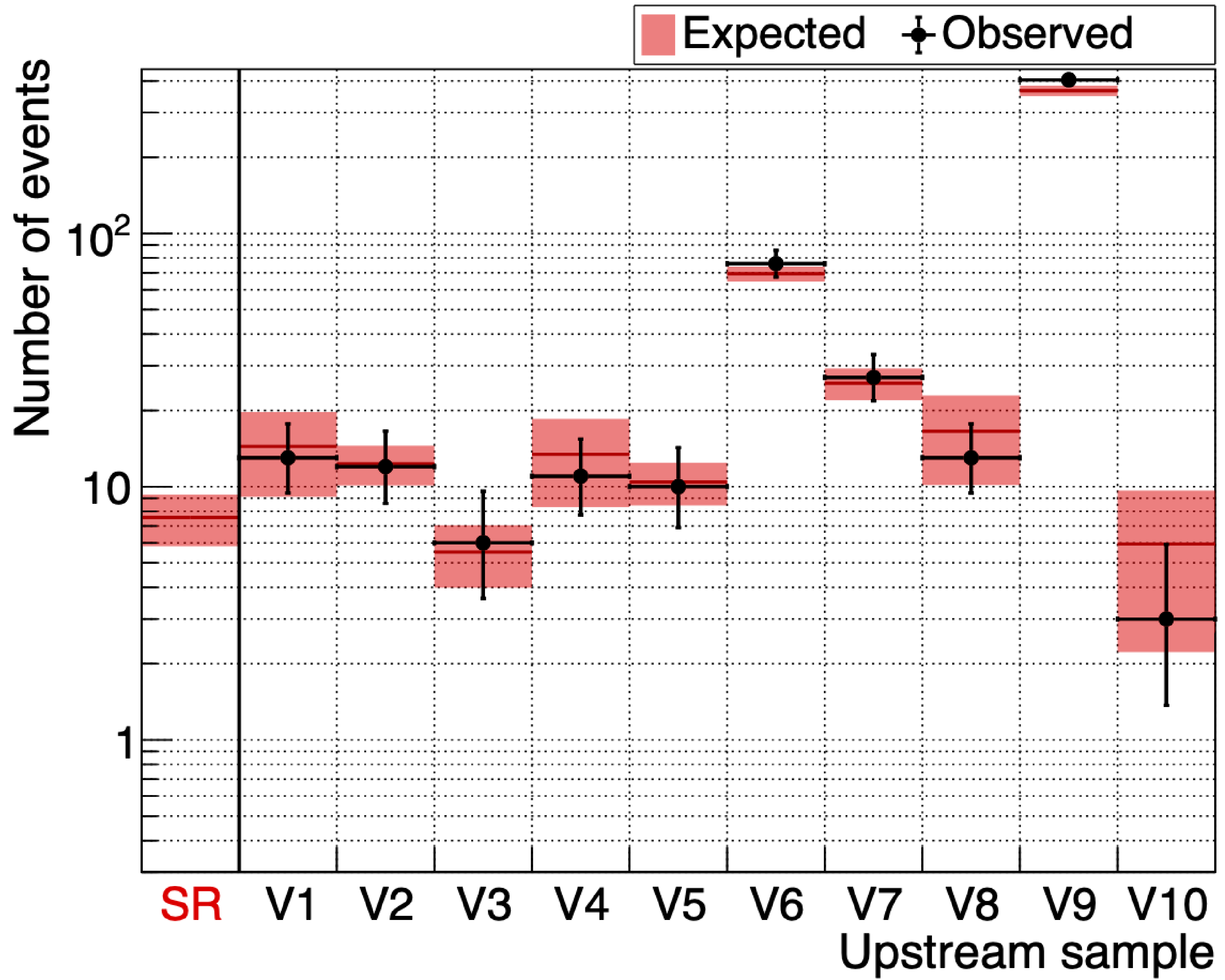
$N = 51 \quad f_{CDA} = 0.20 \pm 0.03 \quad < P_{match} > = 73\%$

$$N_{bg}(Upstream) = 7.4^{+2.1}_{-1.8}$$

- **Upstream reference sample contains all known upstream mechanisms**
  - N provides normalisation
  - f_{CDA} **depends only on geometry**
  - P_{match} **depends on** $(\Delta T_+, N_{GTK})$

VALIDATION SAMPLES:

invert & loosen upstream vetos to enrich with different mechanisms



Summary of expectations

Backgrounds

Background	Events
$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89^{+0.33}_{-0.27}$
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
$K^+ \to \pi^0\ell^+\nu$	< 0.001
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.0^{+2.1}_{-1.9}$

Signal Sensitivity

$$\mathcal{B}_{SES} = (0.848 \pm 0.029) \times 10^{-11}$$

$$N^{SM,exp}_{\pi\nu\bar{\nu}} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}}$$

Assuming $\mathcal{B}^{SM}_{\pi\nu\bar{\nu}} = 8.4 \times 10^{-11}$:

2021-22: $N_{\pi\nu\bar{\nu}} = \mathbf{9.91} \pm 0.34$

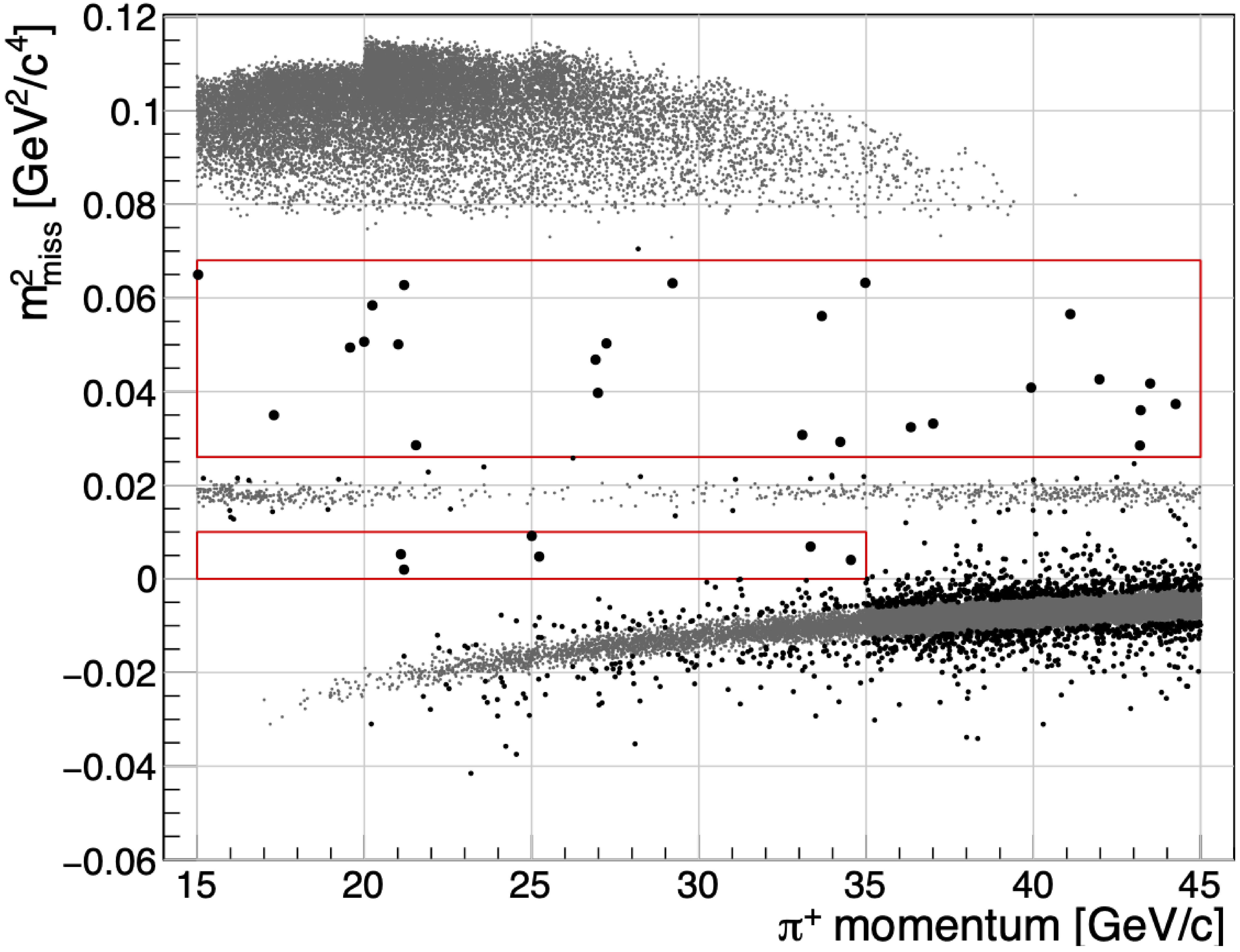
c.f. 2016–18 : $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

→ Expected signal doubled by including 2021–22 data

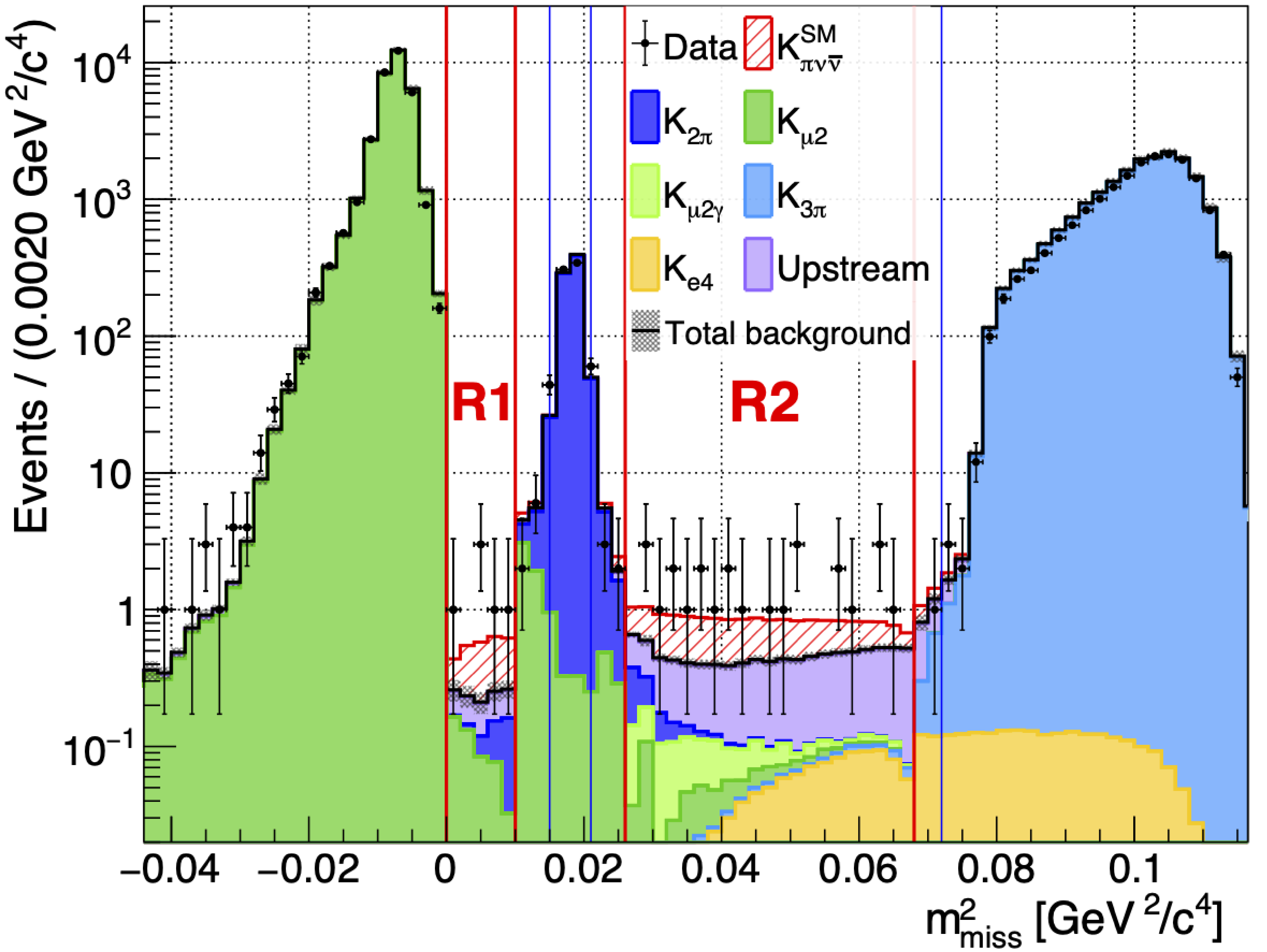
- $N^{SM}_{\pi\nu\bar{\nu}}$ per SPS burst: 2.5×10^{-5} in 2022
  - c.f. 1.7×10^{-5} in 2018. ⇒ **signal yield increased by 50%**
- Sensitivity for BR $\sim \sqrt{S+B}/S$ similar but improved with respect to 2018 analysis, for same amount of data

Signal regions: 2021—22 Data

2021—22 data



1D projection with differential background predictions & SM signal expectation [not a fit]:



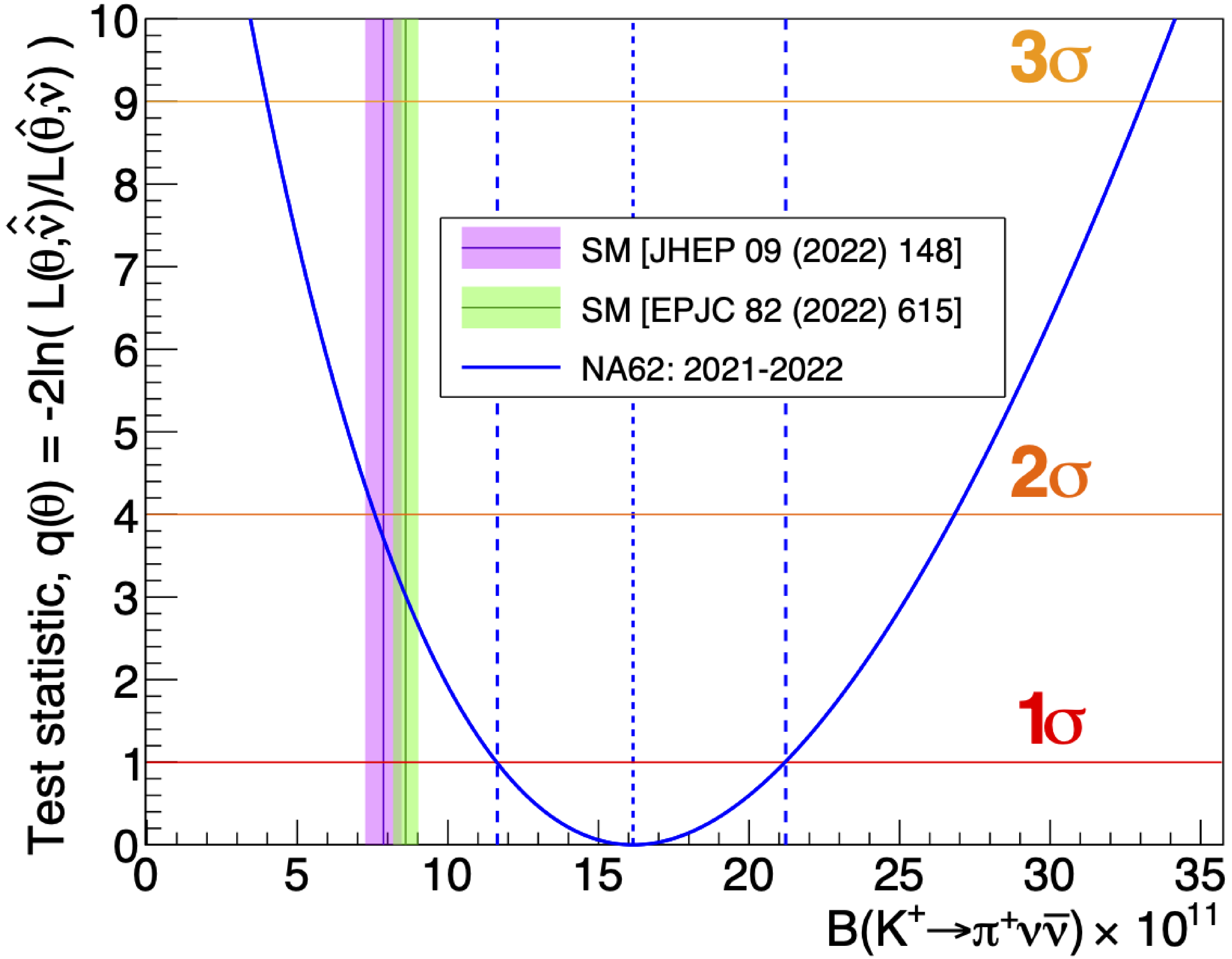
Expected SM signal: $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

Expected background: $N_{bg} = 11.0^{+2.1}_{-1.9}$

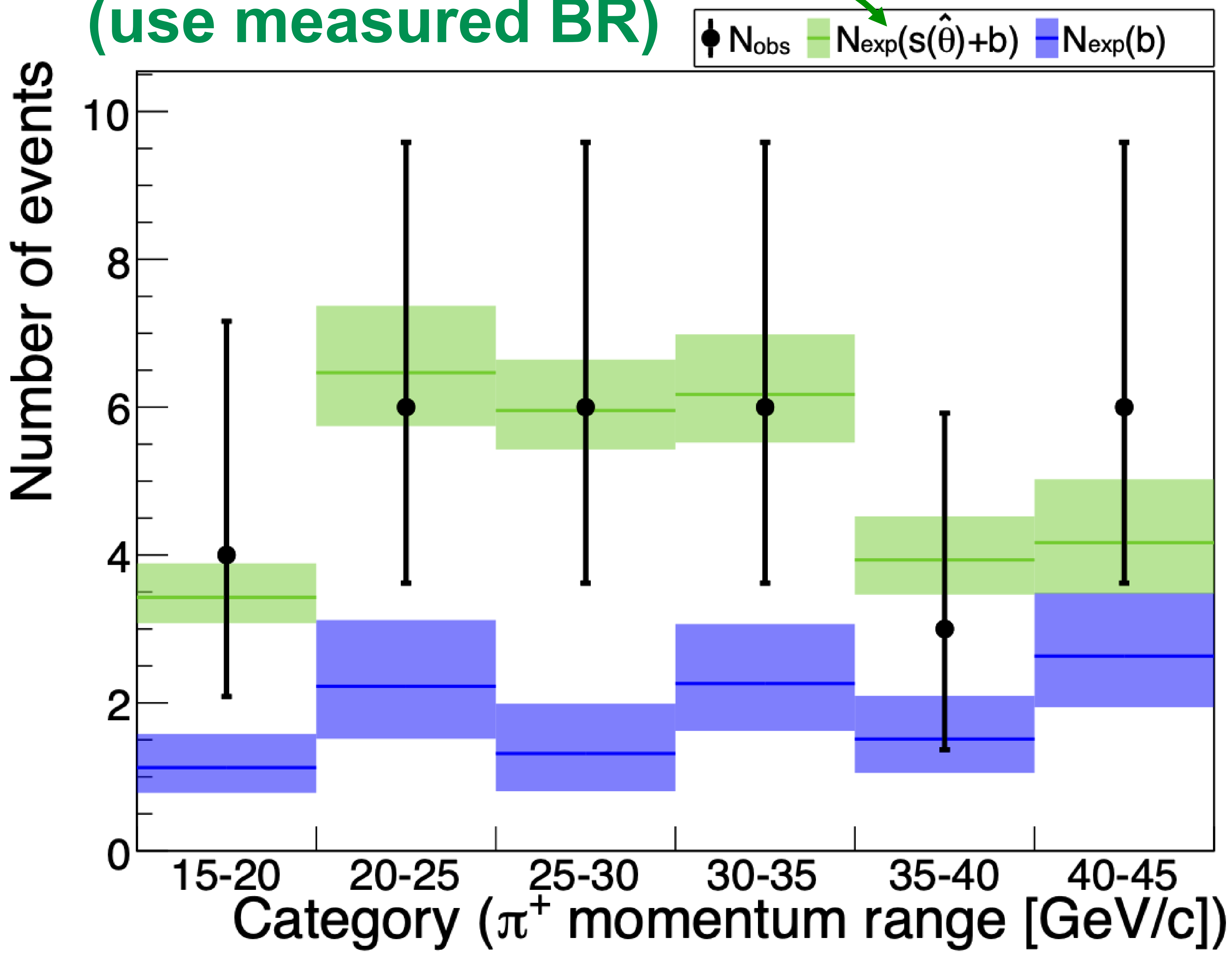
Observed: $N_{obs} = 31$

Results: 2021—22 Data

- Measure $\mathcal{B}_{\pi\nu\bar{\nu}}$ and 68% (1σ) confidence interval using a profile likelihood ratio test statistic $q(\theta)$



- Use 6 (momentum bin) categories

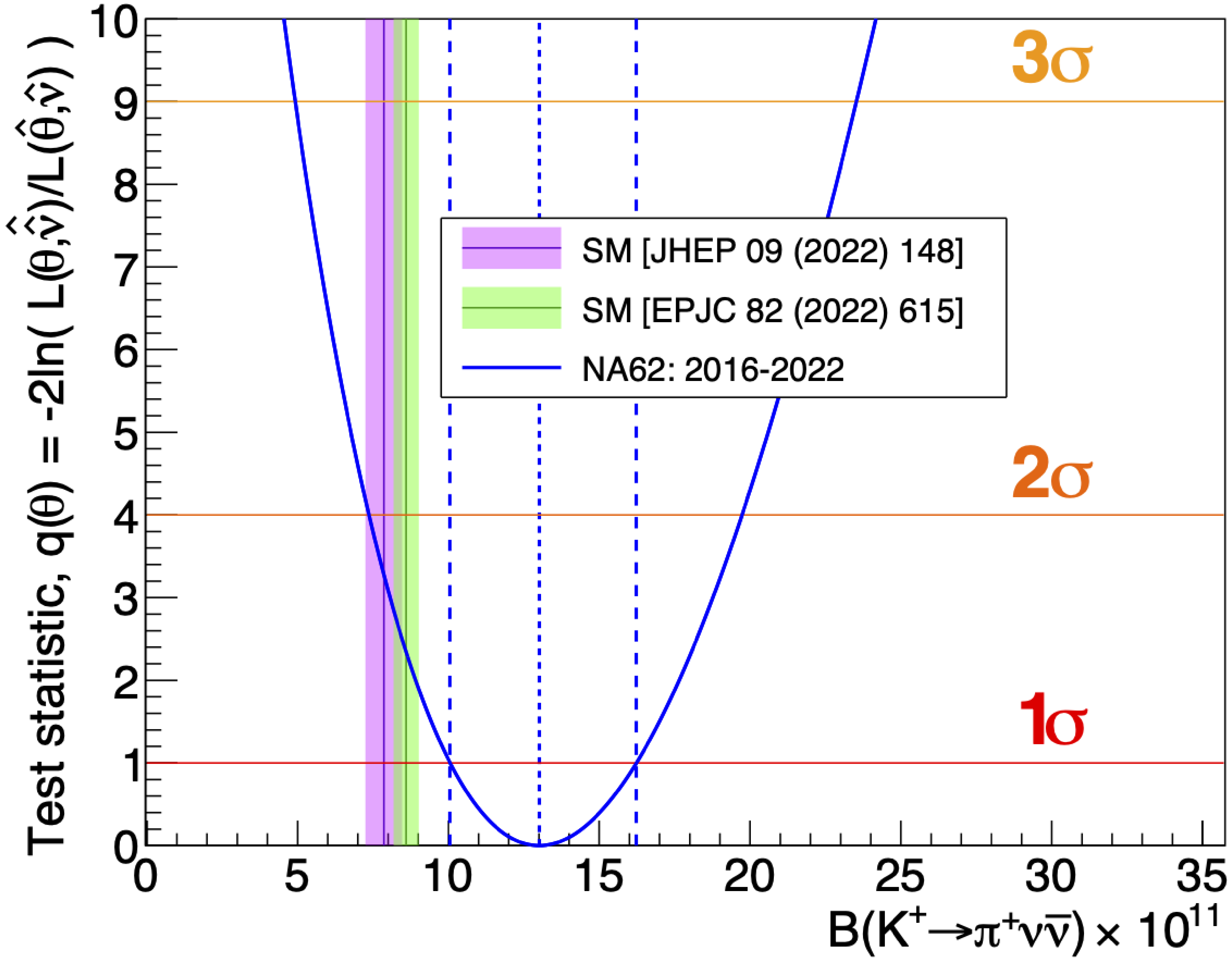


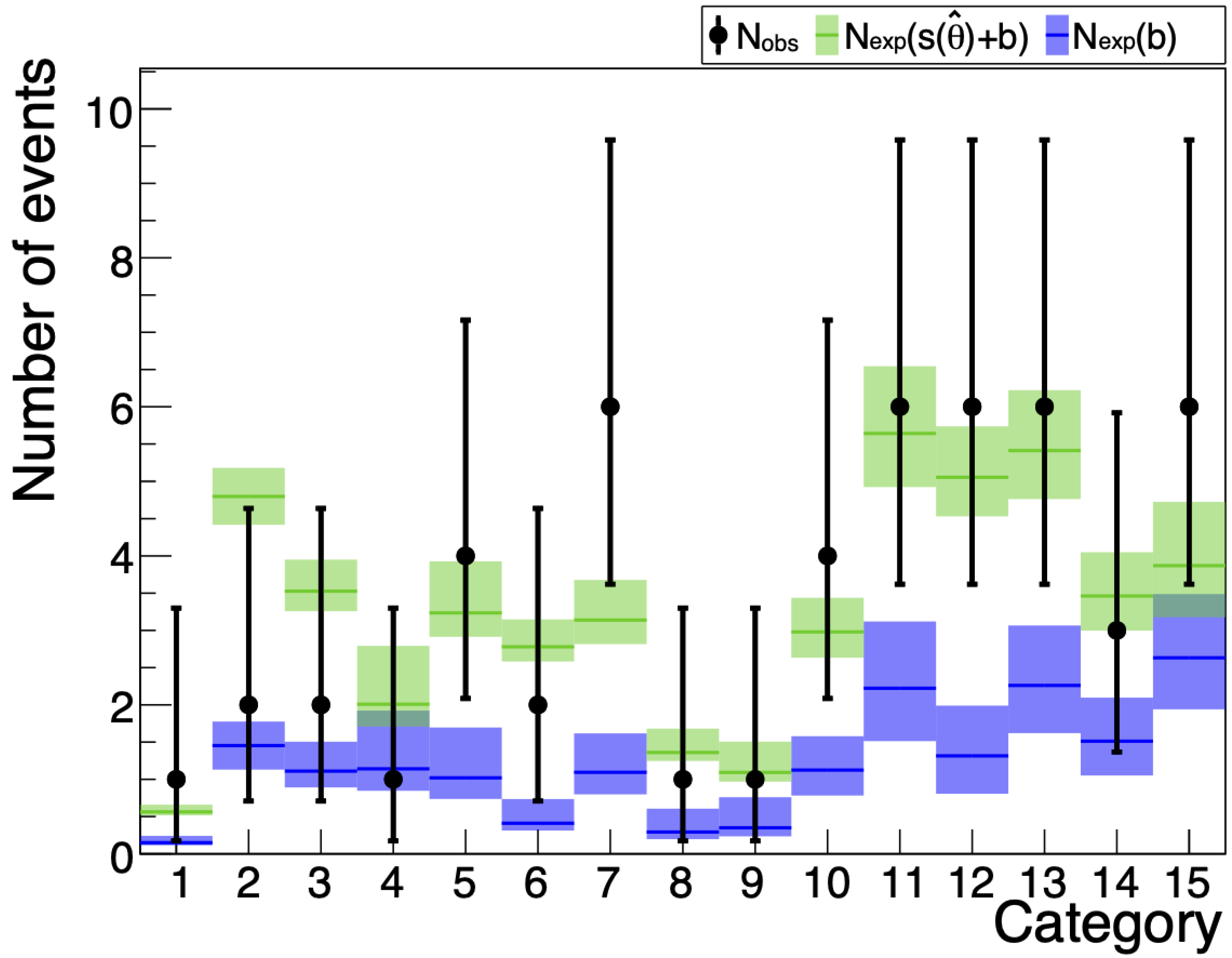
$$\mathcal{B}_{21-22}(K^+ \to \pi^+\nu\bar{\nu}) = \left(16.2^{+5.1}_{-4.5}\right) \times 10^{-11} = \left(16.2\ \left(^{+4.9}_{-4.3}\right)_{stat}\ \left(^{+1.4}_{-1.4}\right)_{syst}\right) \times 10^{-11}$$

Evaluate statistical-only component by repeating procedure assuming exact knowledge of signal and background expectations

Combining NA62 results: 2016—22

- Integrating 2016—22 data: $N_{bg} = 18^{+3}_{-2}$, $N_{obs} = 51$.
  - **Background-only hypothesis** p-value = 2×10^{-7} ⇒ **significance $Z > 5$**





$$\mathcal{B}_{16-22}(K^+ \to \pi^+\nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11} = (13.0\ (^{+3.0}_{-2.7})_{stat}\ (^{+1.3}_{-1.3})_{syst}) \times 10^{-11}$$

Results in context

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{BNL} = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$$

[PRD 79 (2009) 092004]

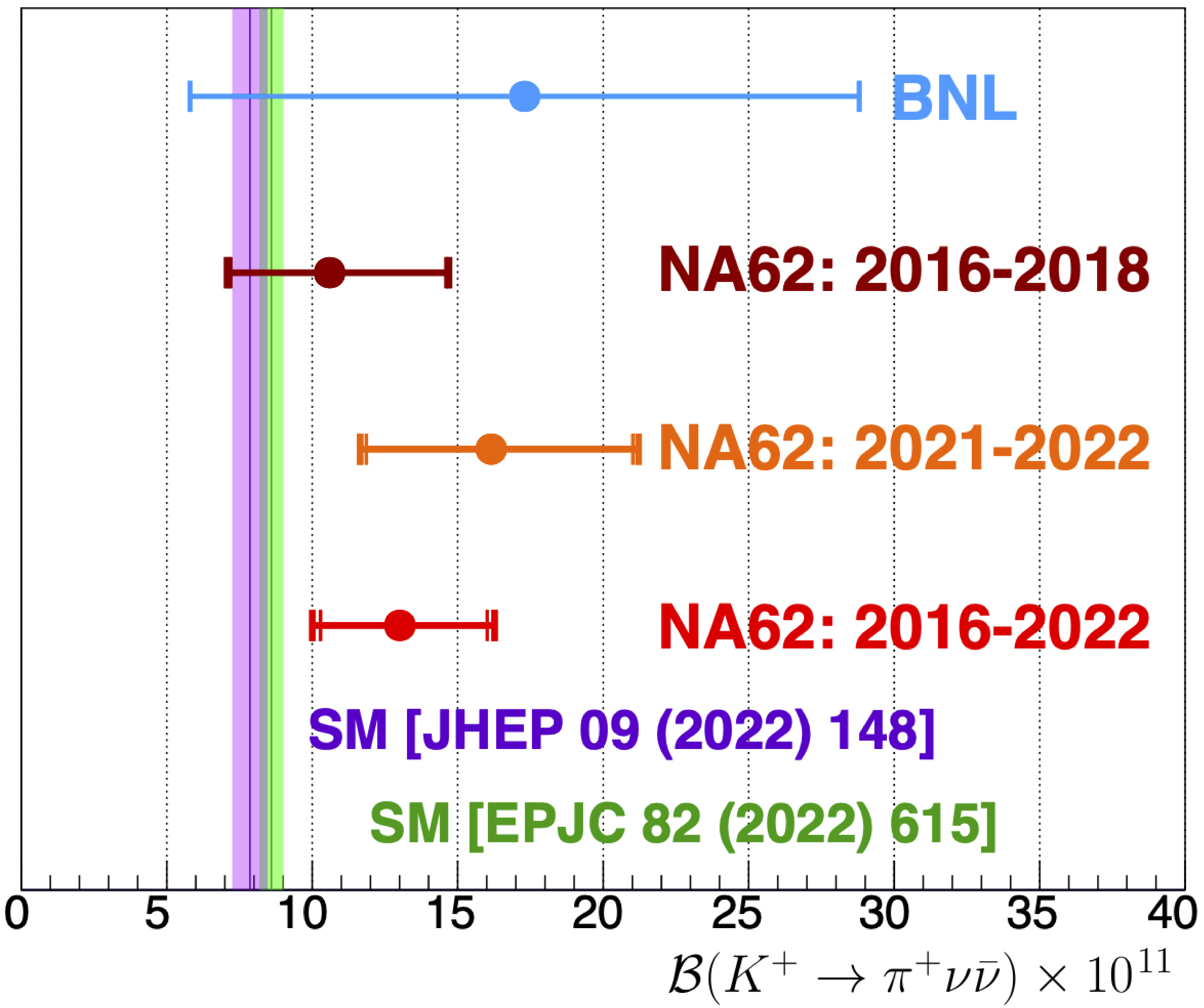
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$$

[JHEP 06 (2021) 093]

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{21-22} = \left(16.2^{+5.1}_{-4.5}\right) \times 10^{-11}$$

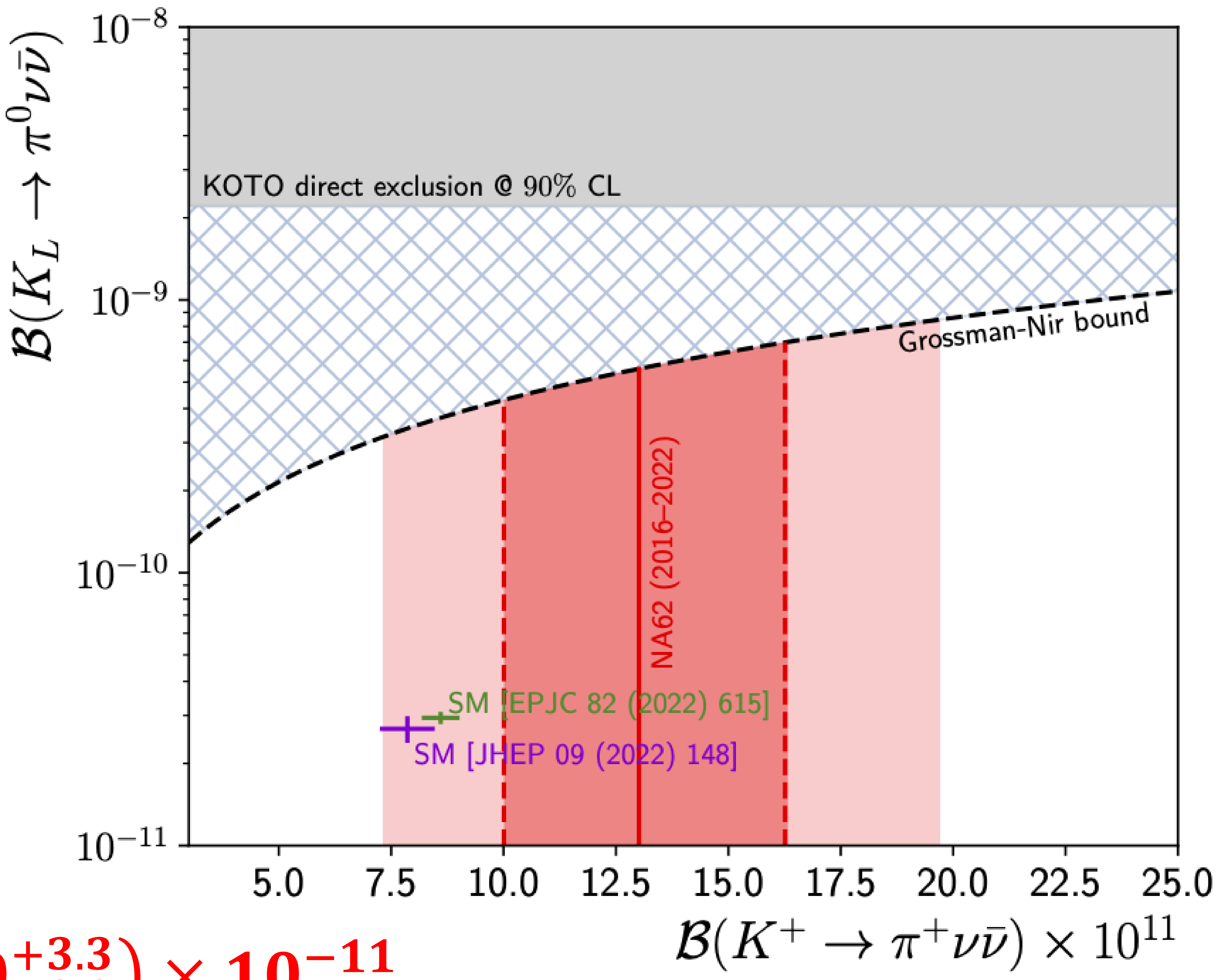
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$$

- NA62 results are consistent
- Central value moved up (now 1.5—1.7σ above SM)
- Fractional uncertainty decreased: 40% to 25%
- Bkg-only hypothesis rejected with significance Z>5



Results in context

- Fractional uncertainty: 25%
- Bkg-only hypothesis rejected with significance Z>5
- **Observation of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay with BR consistent with SM prediction, within 1.7σ**
  - **Need full NA62 data-set to clarify SM agreement or tension**



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

2σ range : [7.4 — 19.7] $\times 10^{-11}$

Correlations with other meson decays

- New study of $K^+ \to \pi^+ \nu\bar{\nu}$ decay using NA62 2021–22 dataset, combined with 2016–18:

  [JHEP 02 (2025) 191]

- $\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$
- BR consistent with SM prediction within 1.7σ
- **Need full NA62 data-set to clarify SM agreement or tension, considering also correlations with other meson decay channels**

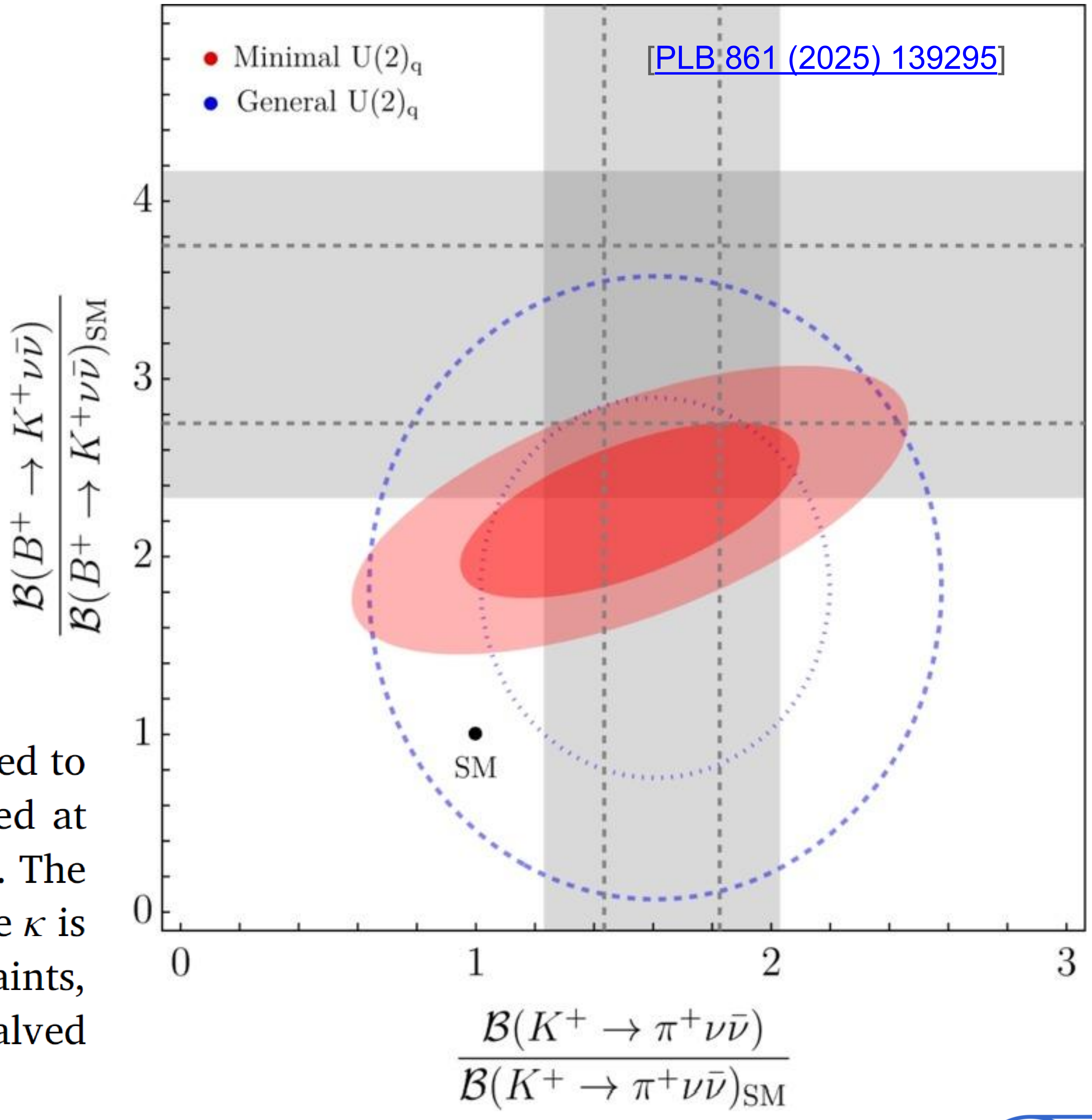


Fig. 6. Correlation between $\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$ and $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$, normalized to their SM predictions. The red areas denote the parameter regions favored at 1σ and 2σ from a global fit in the limit of minimal $U(2)_q$ breaking ($\kappa = 1$). The dashed and dotted blue curves are 1σ and 2σ regions from a global fit where κ is a free parameter. The gray bands indicate the current experimental constraints, while the dashed gray lines highlight near-future projections assuming halved experimental uncertainties.

23-24 working-in-progress data analysis

- 2024 data-taking conditions lead to a slightly higher signal yield per spill:
  - lower signal loss due to random activity in veto detectors that compensates the lower number of normalization events
- increase of the overall expected signal yield, given the smoother and therefore more efficient collection of SPS spills

[2025 NA62 SPSC Report]

Dataset	2022	2023	2024
Number of spills $[10^3]$	326	363	519
$<$ Beam intensity $>$ [GHz]	0.57	0.48	0.41
$< N_{\pi\pi}/\text{spill} > \ [10^2]$	4.9	4.7	4.4
$N_K \ [10^{12}]$	2.3	2.5	3.3
ε_{RV}	0.63	0.68	0.73
$N_{\pi\nu\nu}$	8	9	13
$N_{\pi\nu\nu}/\text{spill} \ [10^{-5}]$	2.5	2.5	2.6
$B_{\text{total}}/N_{\pi\nu\nu}$	1.1	1.1	1.0

The addition of the 2023-2024 dataset is expected at least to double the signal yield of the already published 2016-2022 dataset, with the same level of relative background

Conclusions

- New study of $K^+ \to \pi^+ \nu\bar{\nu}$ decay using NA62 2021—22 dataset, combined with 2016—18: [JHEP 02 (2025) 191]

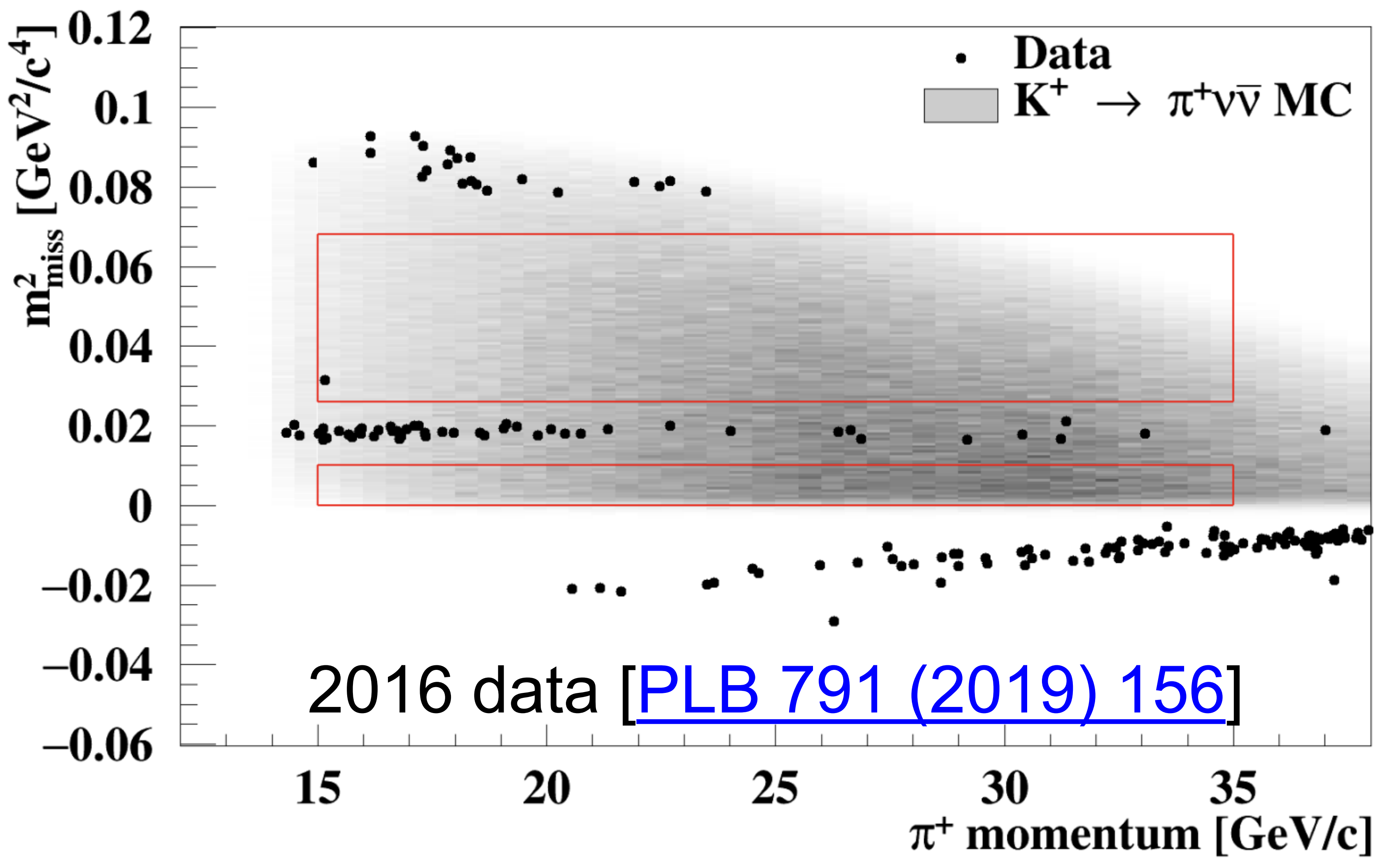
- $\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$
- 25% relative precision achieved
- BR consistent with SM prediction within 1.7σ

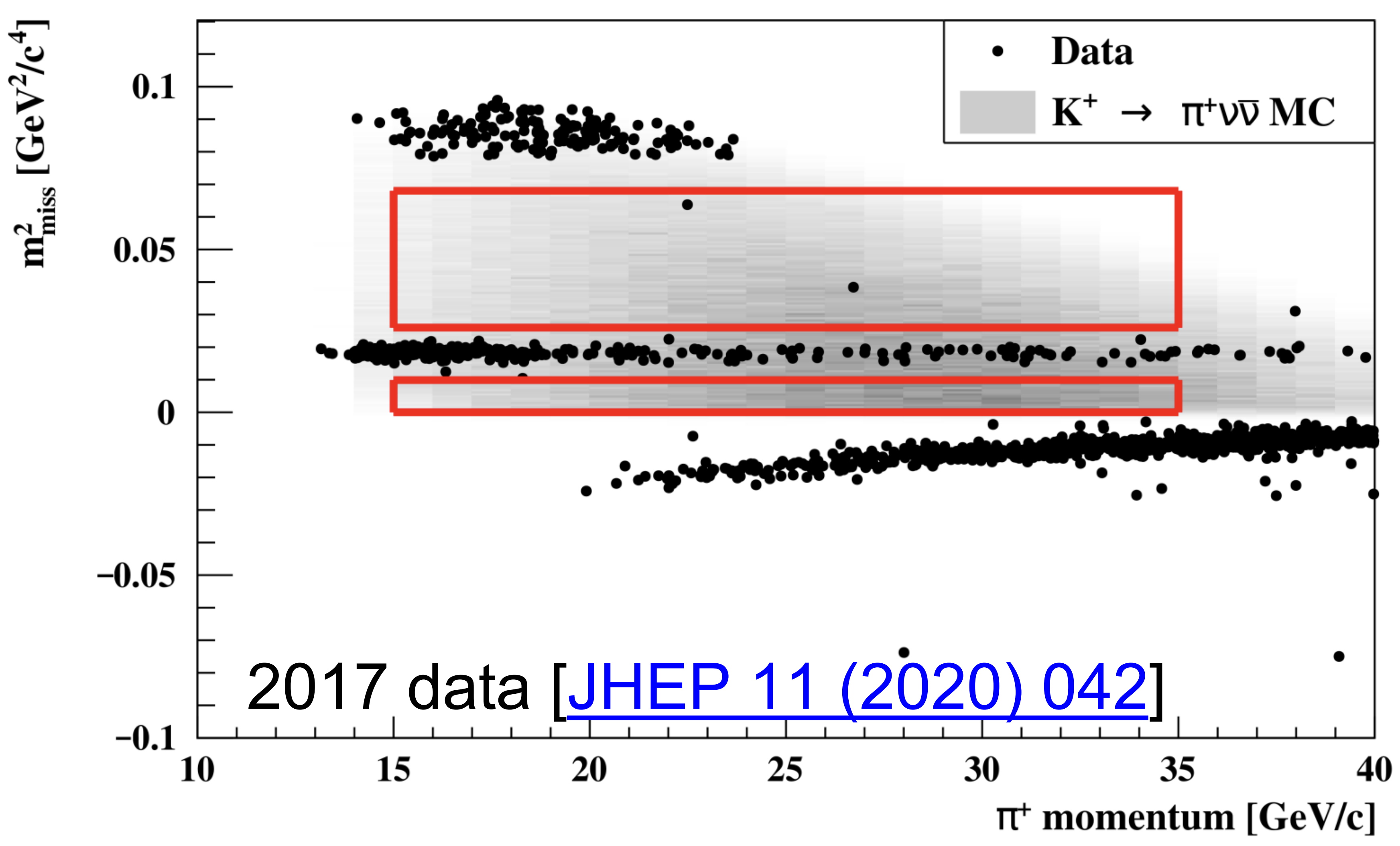
- Background-only hypothesis rejected with significance Z>5
- First observation of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay

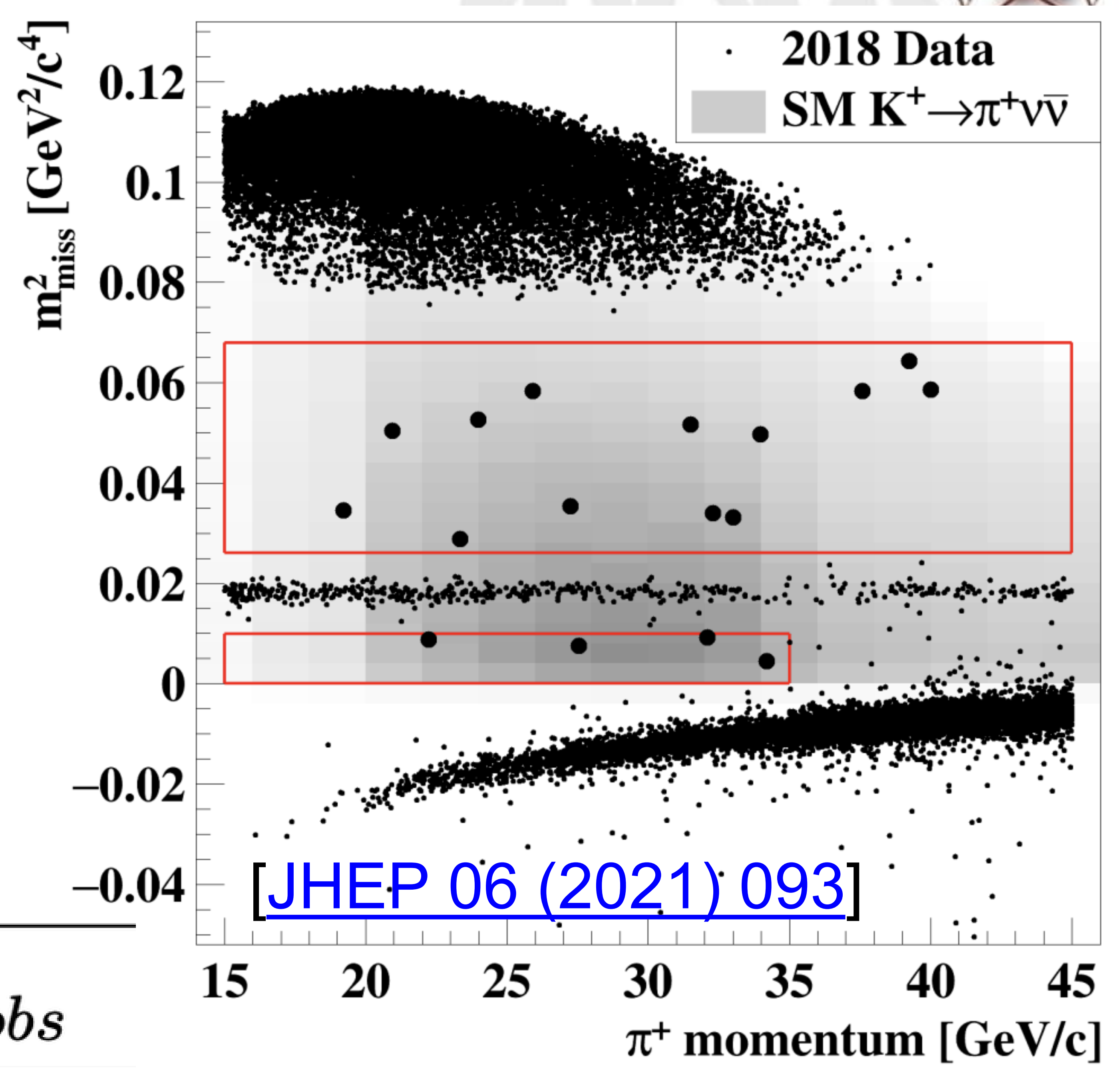
- **Need full NA62 data-set to clarify SM agreement or tension**
- **2023—LS3 data-set collection & analysis in progress, to achieve precision better than 20%**

Supplemental

The story so far: $K^+ \to \pi^+ \nu\bar{\nu}$ with 2016—18 data







Data-taking year	[Reference]	N_{bg}	$N_{\pi\nu\bar{\nu}}^{SM,exp}$	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
2016–18	[JHEP 06 (2021) 093]	$7.03^{+1.05}_{-0.82}$	10.01 ± 0.42	20

$N_{\pi\nu\bar{\nu}}^{SM,exp}$ assumes: $\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$

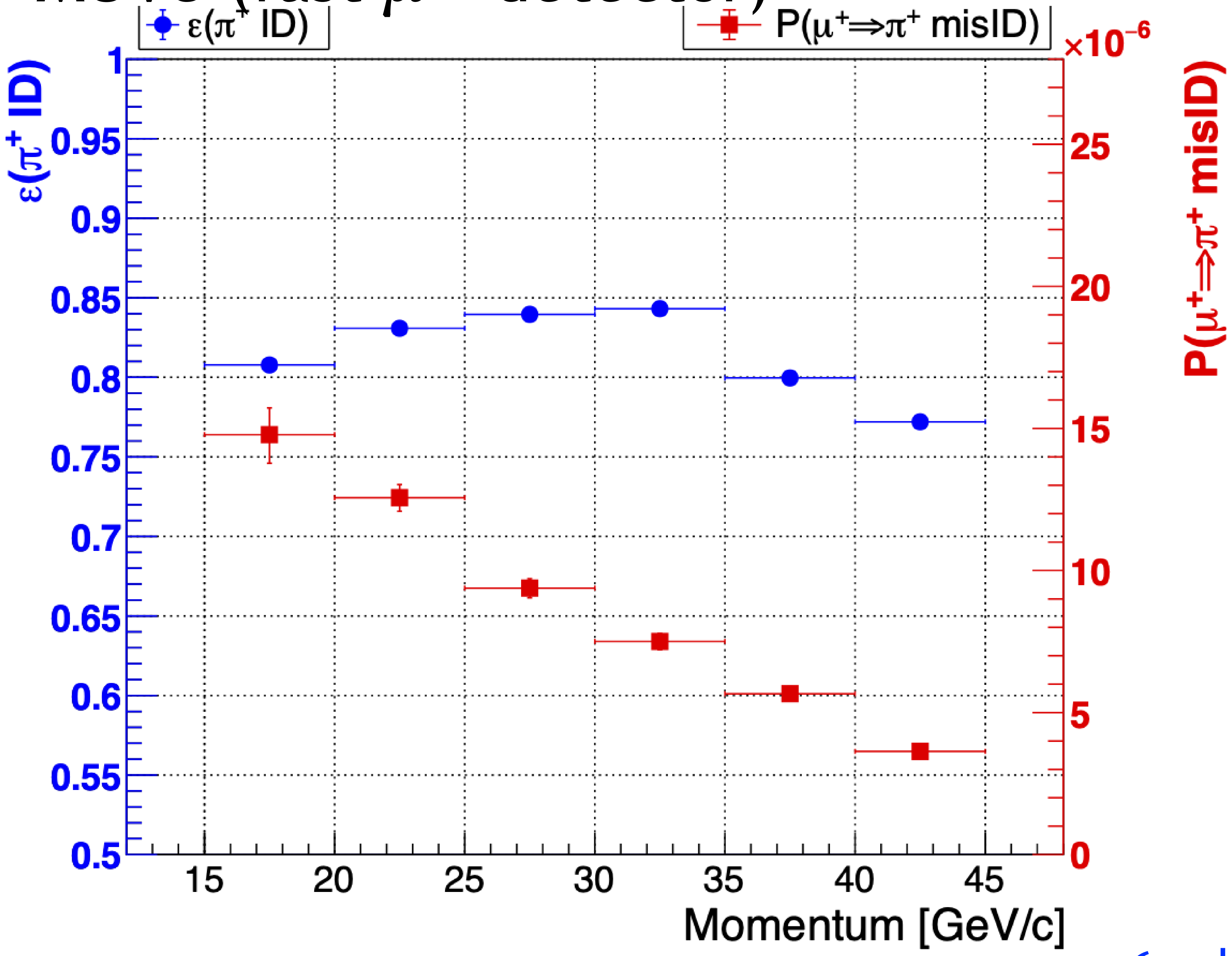
Statistical combination: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}\big|_{stat} \pm 0.9_{syst}) \times 10^{-11} @ 68\%\ CL$

Background-only hypothesis: $p = 3.4 \times 10^{-4} \Rightarrow$ significance = 3.4σ

Particle ID performance : 2021—22 data

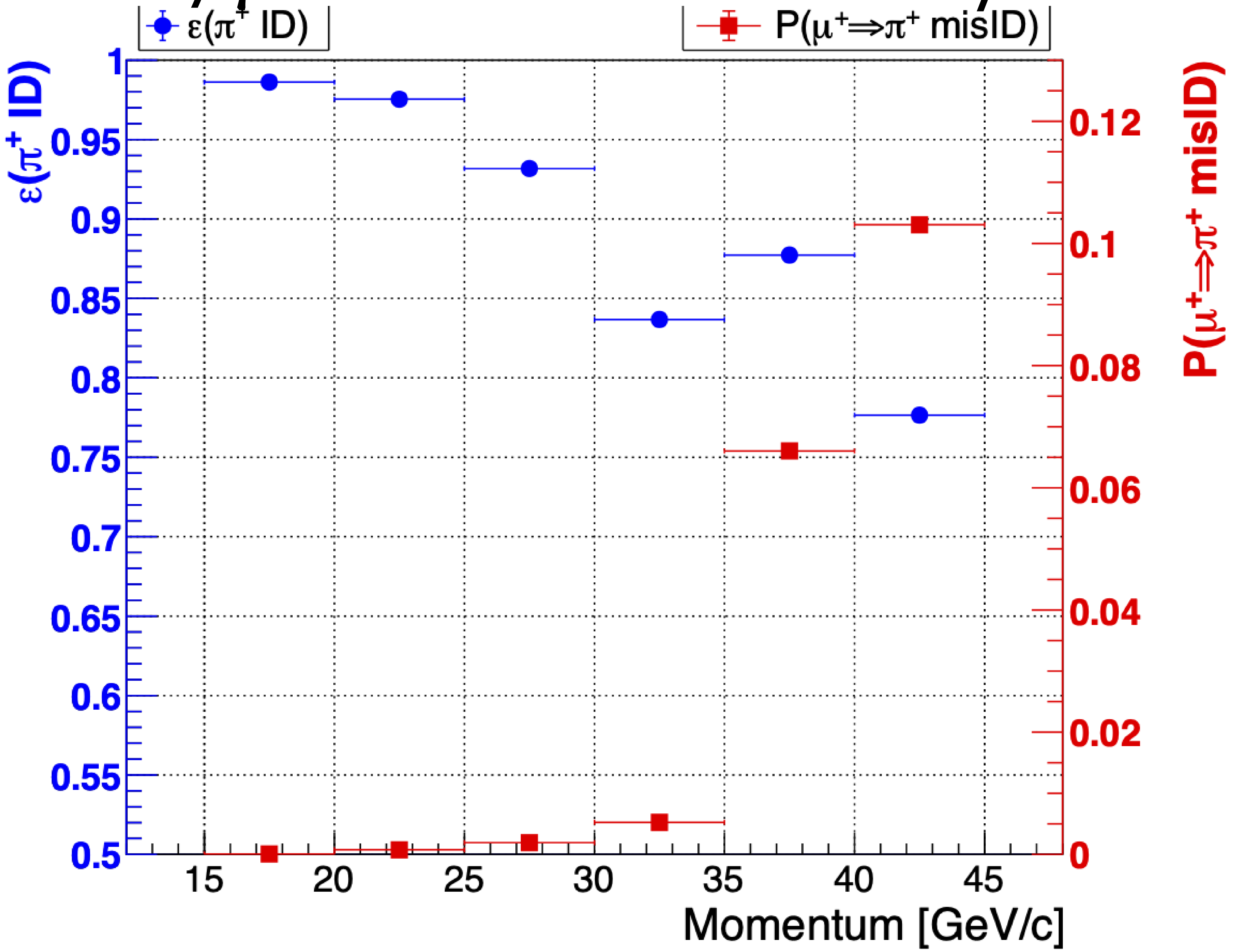
Calorimeters

- Use BDT classifier for LKr & MUV1,2
- + **MUV3** (fast μ^+ detector)



RICH

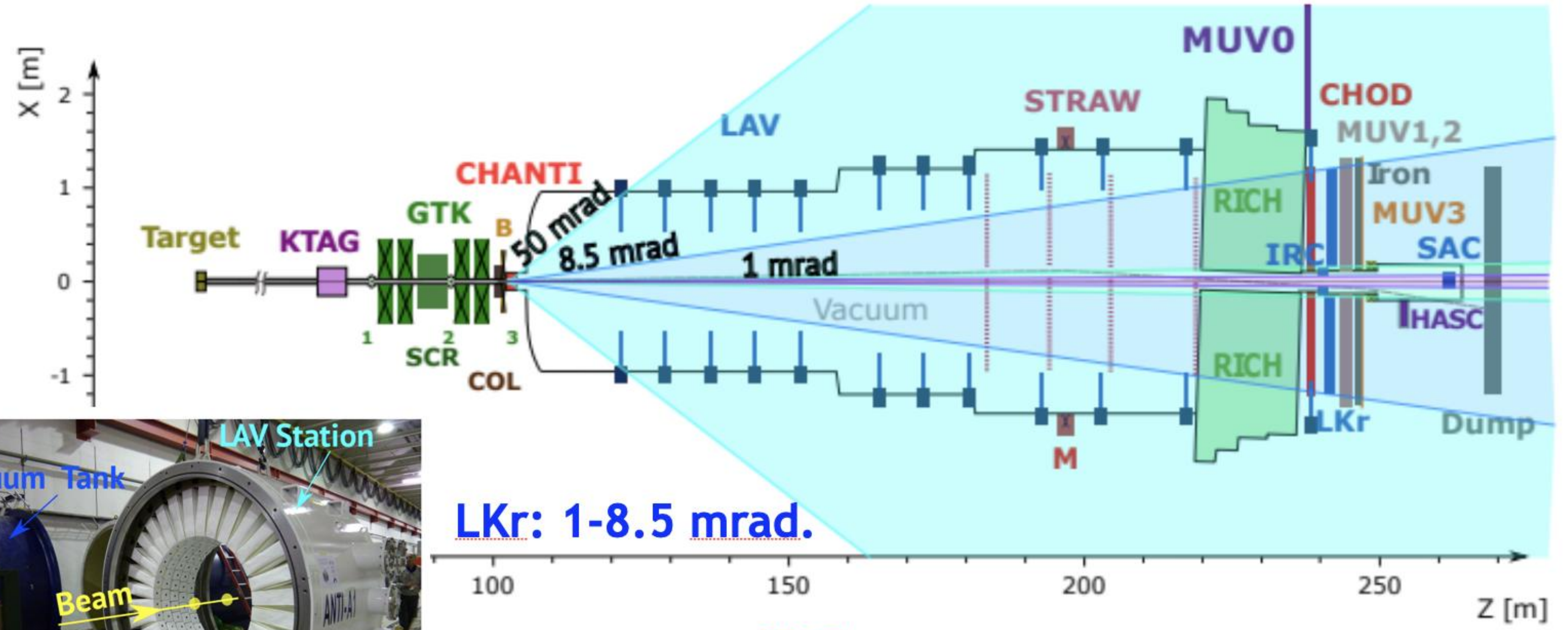
Designed to distinguish between π^+/μ^+ with $15-35\,GeV/c$

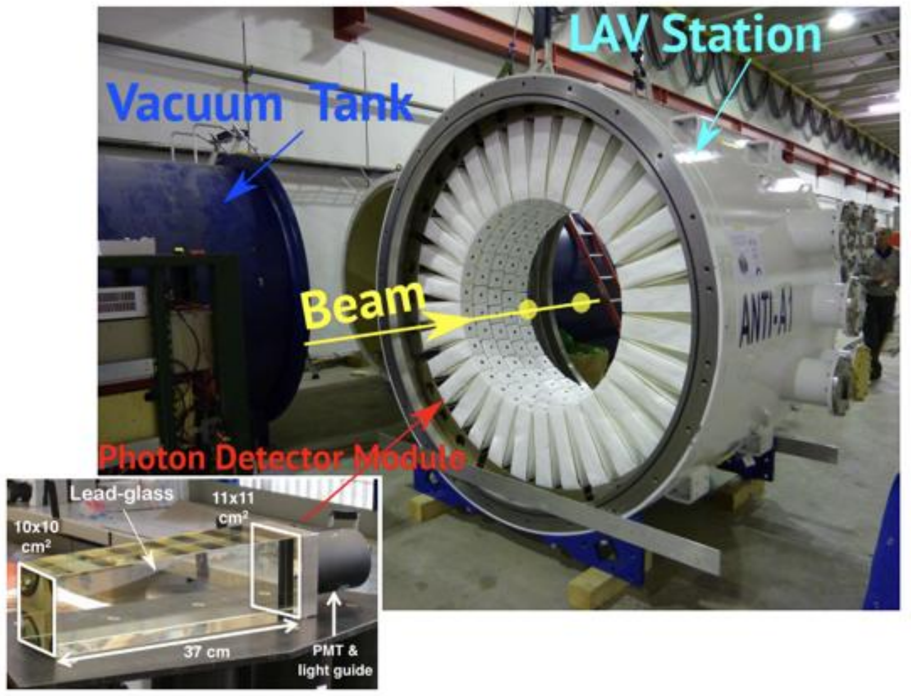


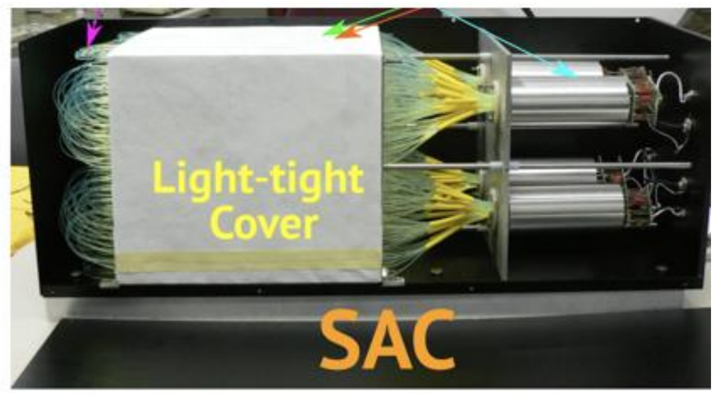
$\mathrm{P}(\pi^+) = 73\ \%$

$\mathrm{P}(\mu^+ \Rightarrow \pi^+) = (1.3 \pm 0.2) \times 10^{-8}$

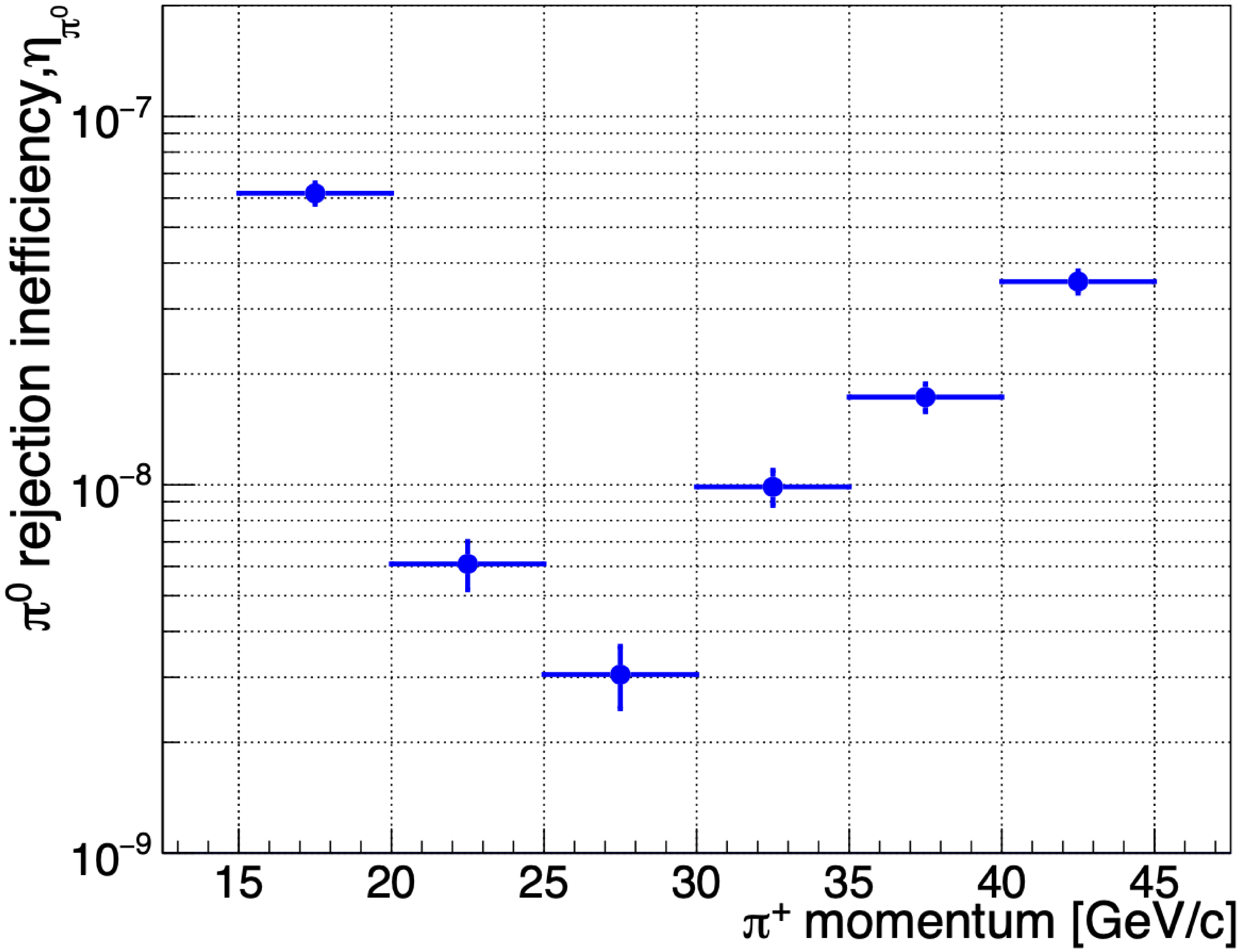
Comprehensive photon veto system: 21—22







Control sample of $K^+ \to \pi^+\pi^0$



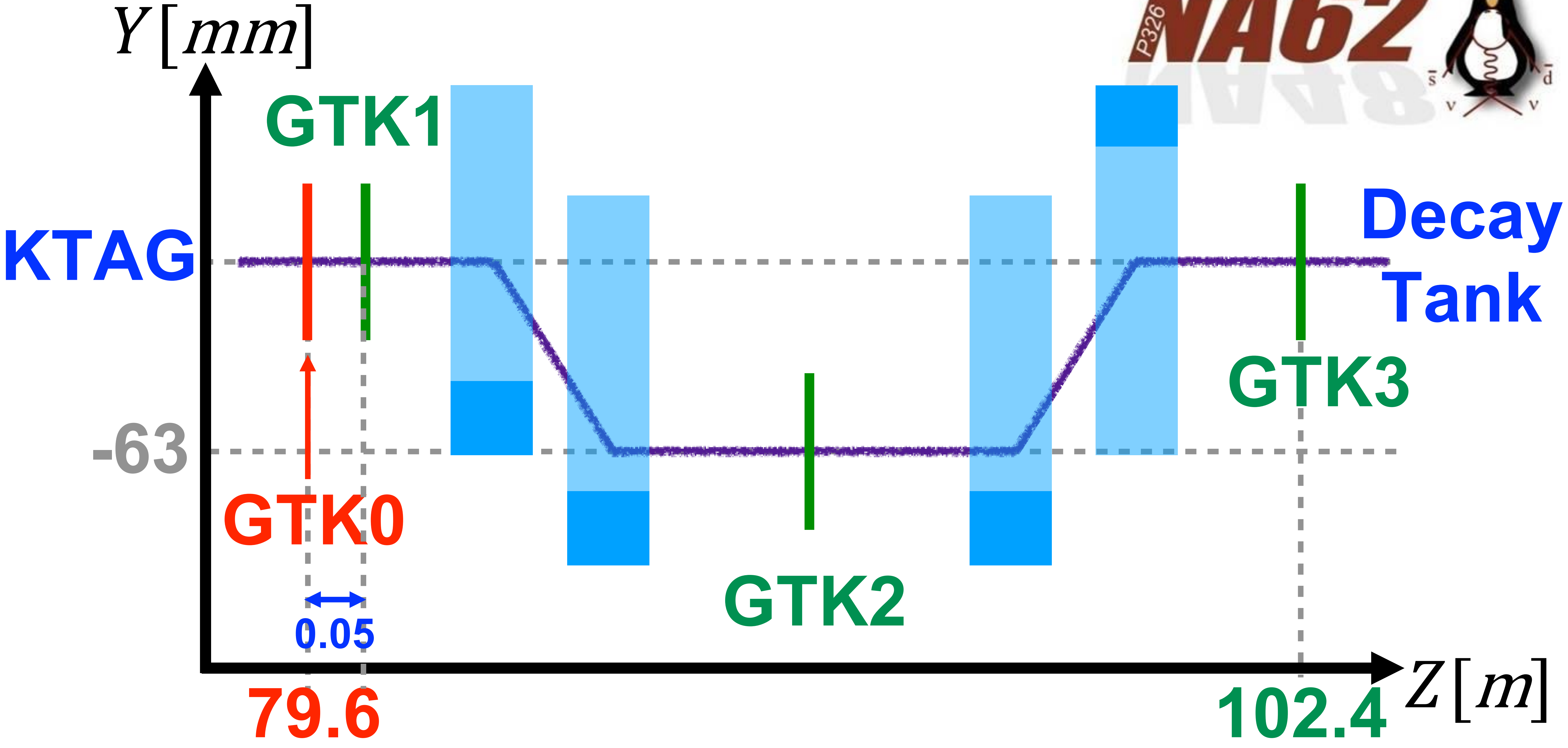
- Probability of $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$ events passing all photon veto conditions:

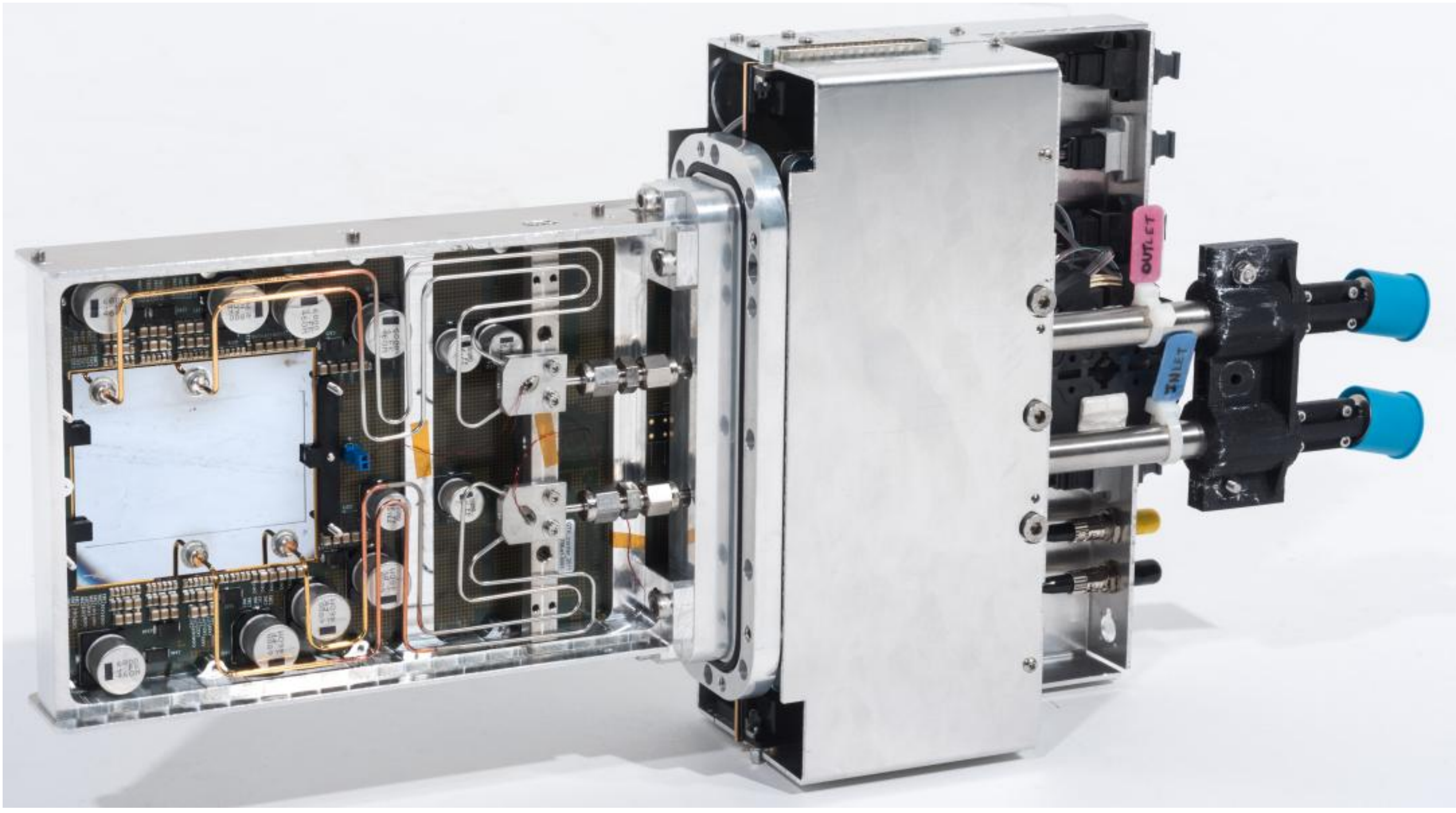
$$\eta_{\pi^0} = (1.72 \pm 0.07) \times 10^{-8}$$

- **Meets target: combined γ/π^0 rejection of $\mathcal{O}(10^8)$**

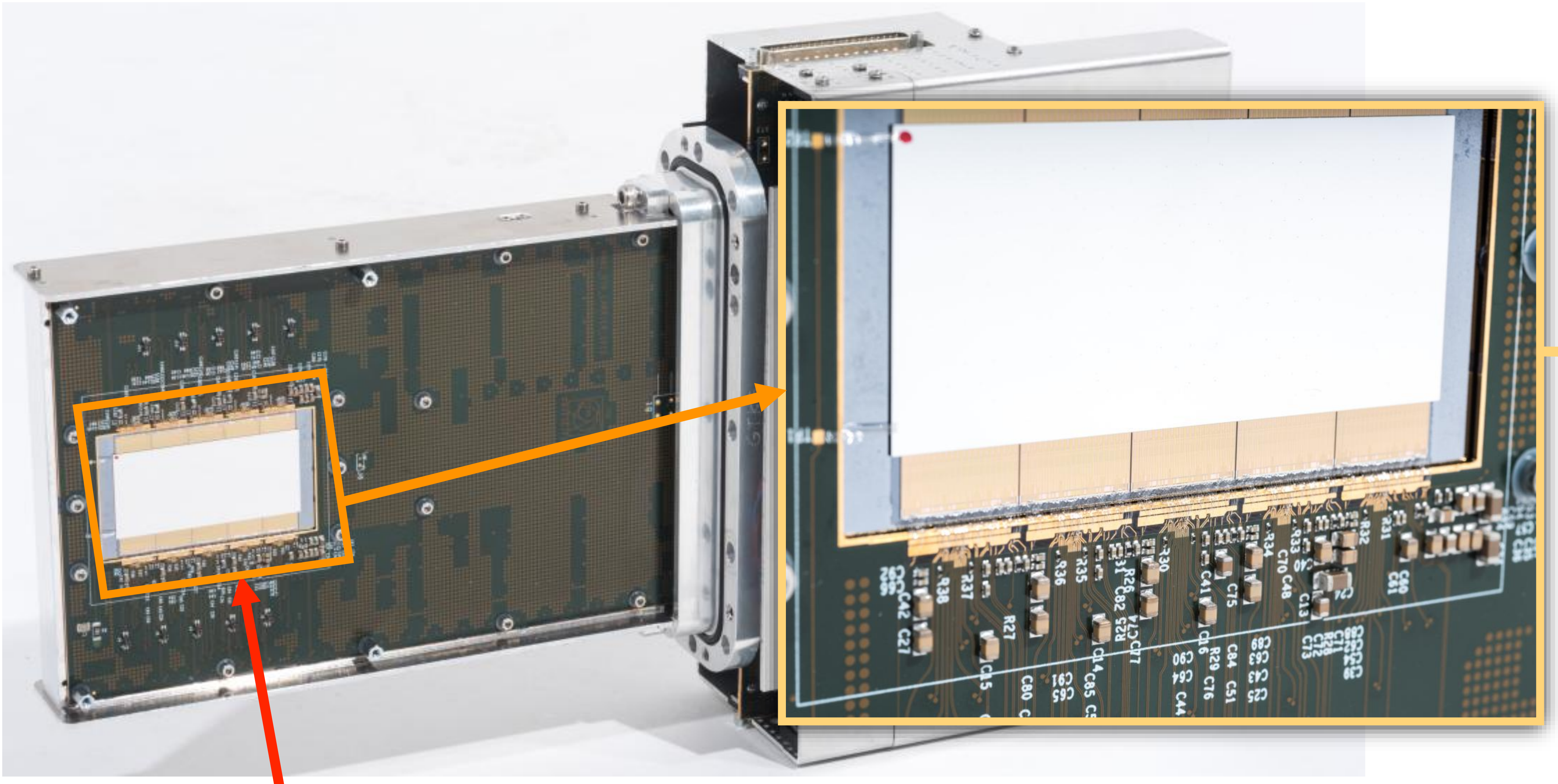
4th GTK station

- Si Pixel detector exposed to ~1GHz beam.
- Essential for $K^+ - \pi^+$ matching.
  - Measures K^+ 3-mom. & time
- 4th GTK station improves efficiency & pileup resilience.

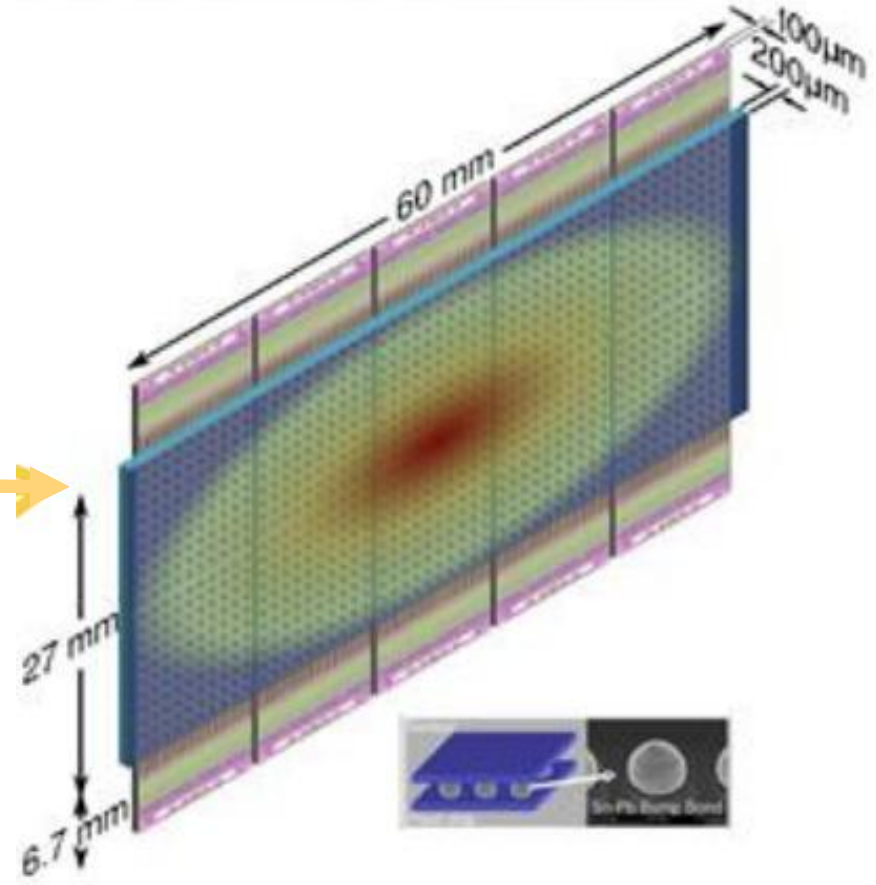




Cooling plate

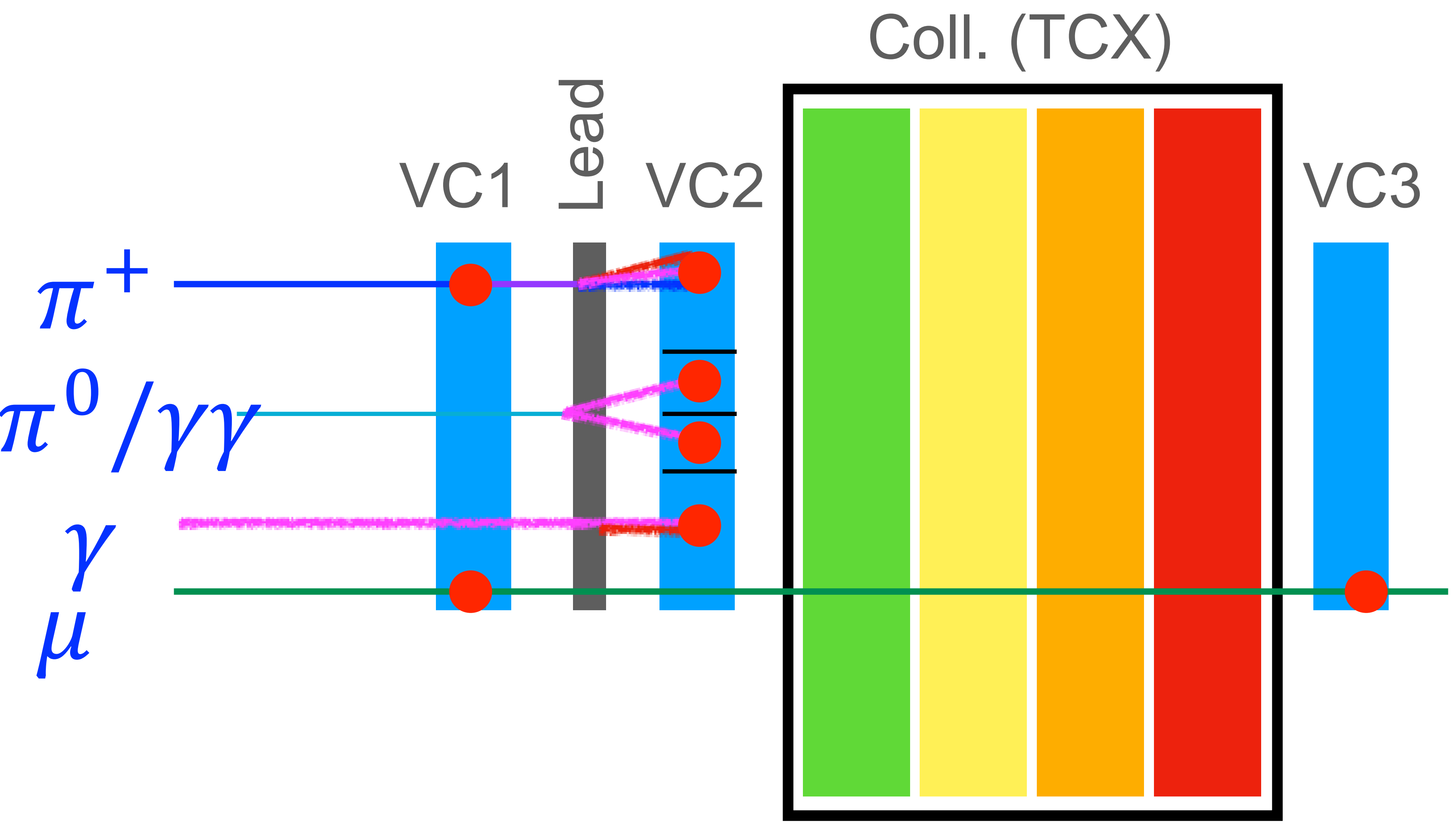


Si Pixels ~(30x60 mm active area)



New upstream vetos: VetoCounter & ANTI0

[FELIX readout: Streaming Readout Workshop talk 2021]



VetoCounter

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

ANTI0

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

[SPSC report 2023][EP Newsletter, Dec21]

Mid 2018 - installed TCX Collimator
Much improved shielding - blocking almost all upstream decay paths.
Sketch only
TCX Collimator
MNP33
RICH
Bend6
Bend4A
Bend4
Bend5
TRIM5
GTK3
Vacuum Tank
Fake vertex
GTK2
π^+
γ
K^+
γ
KTAG
GTK1
Scraper
CHANTI
Scattering at STRAW1
STRAWs
y
z
Signal in-time with true K^+ which decays upstream.
Signal in-time with pileup beam particle (π^+) which does not leave beam pipe

2021 - addition of VetoCounter

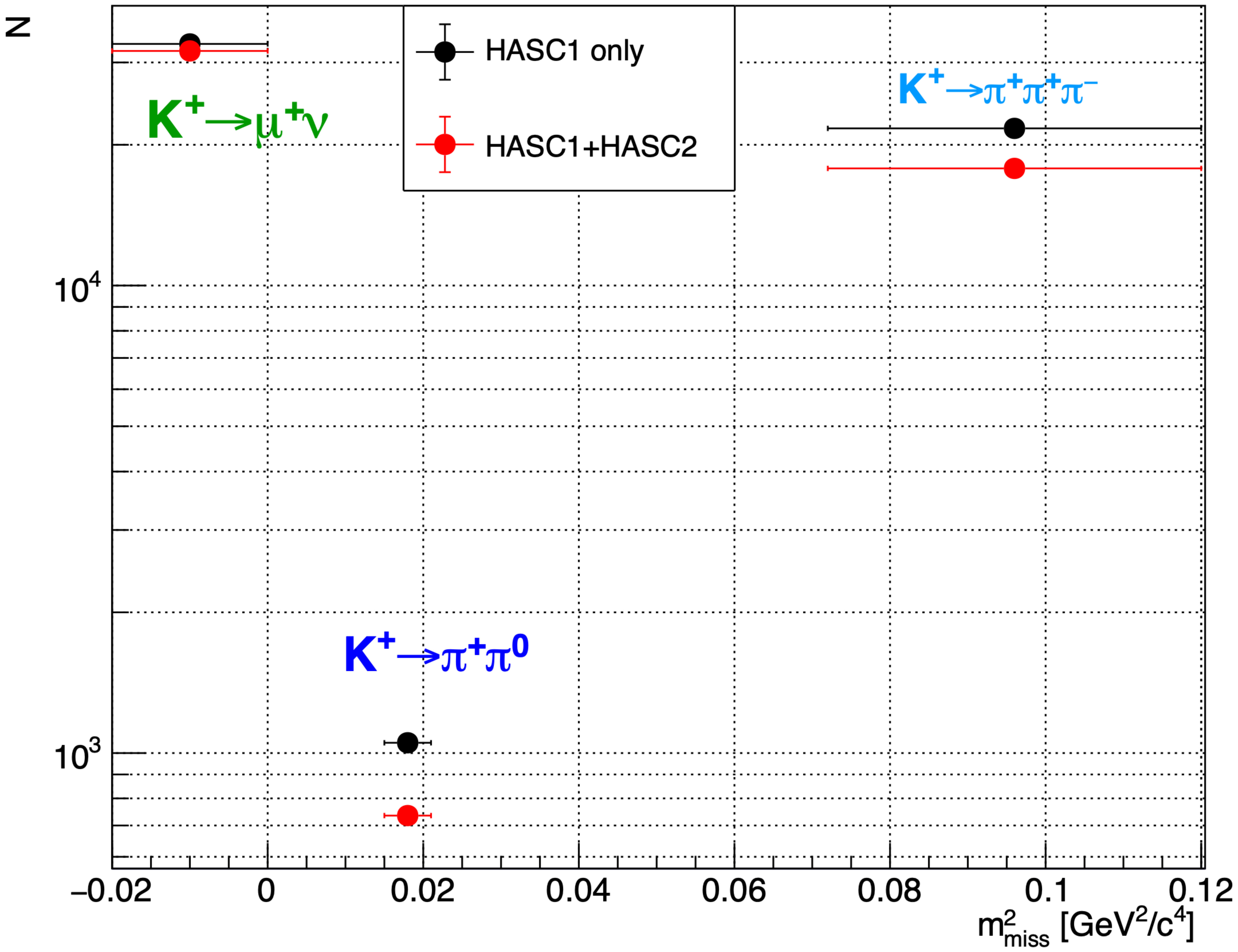
Upstream decays can be detected and actively vetoed.

HASC2 veto

- $K^+ \rightarrow \pi^+\pi^0$ **was 2nd largest background for 2018 analysis.**
- Addition of HASC2:
  - **30% less** $K^+ \rightarrow \pi^+\pi^0$
  - 18% less $K^+ \rightarrow \pi^+\pi^+\pi^-$
  - 3.5% less $K^+ \rightarrow \mu^+\nu$
  - with only 1.5% signal loss

Events passing $\pi^+\nu\bar{\nu}$ selection

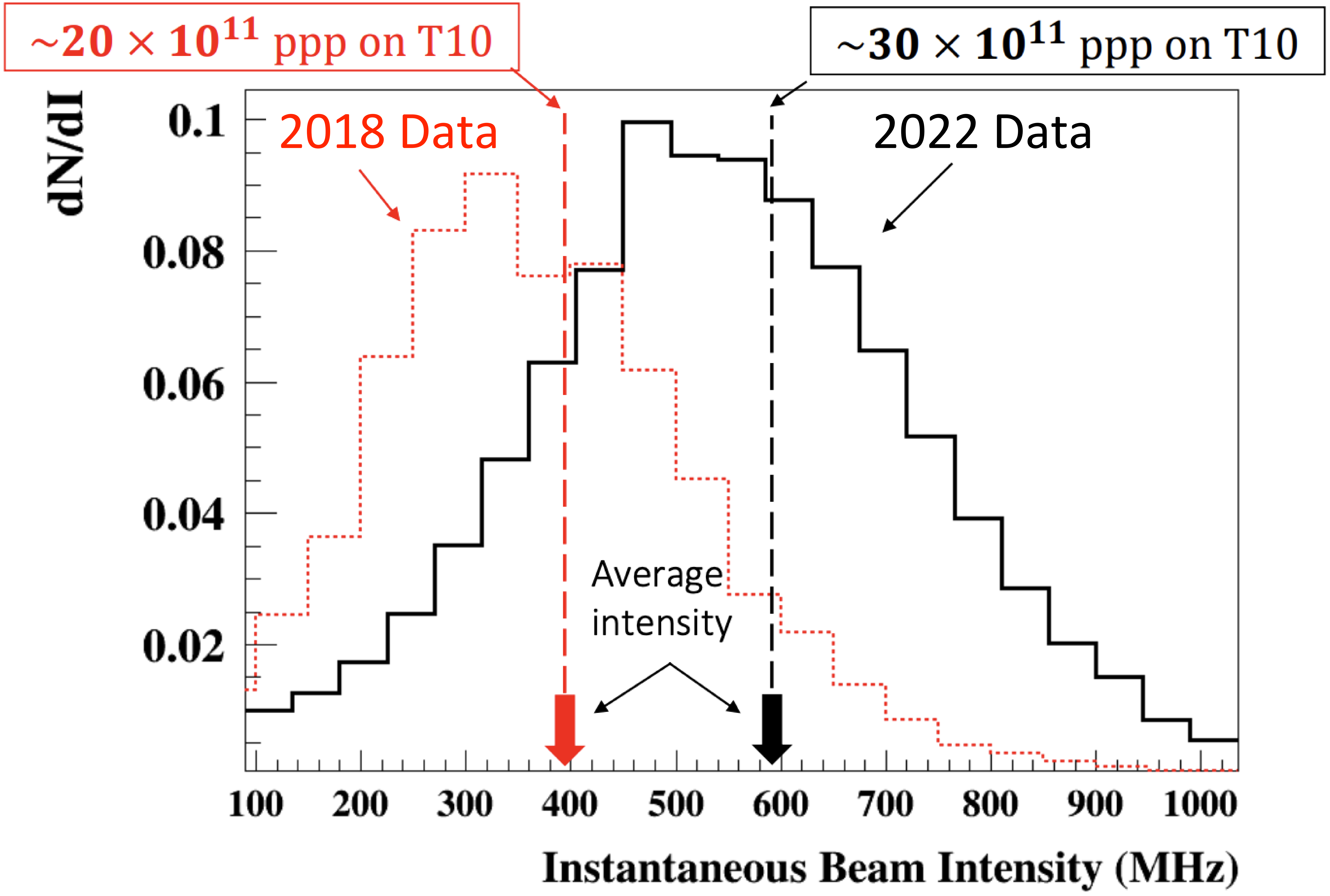
(modifying HASC veto: study integral of background regions)



Example $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma\gamma$ event
Not detected due to inefficiencies and/or missed interaction products
Sketch only
MNP33 Dipole Magnet
MUV0
LAV12
RICH
LKr
MUV1,2
MUV3
Iron wall
Dipole Magnet
Photon interaction with RICH flange
IRC
Beam pipe
SAC
Dump
CHODs
HASC1
STRAW
STRAW
γ
γ
π^+
e^-
e^+
x
z

2021 - add HASC2
Additional downstream particles can be vetoed.
Sketch only
MNP33
Dipole Magnet
MUV0
LAV12
RICH
LKr
MUV1,2
MUV3
Iron wall
Dipole
Magnet
Photon interaction
with RICH flange
IRC
HASC2
SAC
Beam pipe
Dump
γ
γ
π+
e−
e+
CHODs
HASC1
STRAW
STRAW
x
z

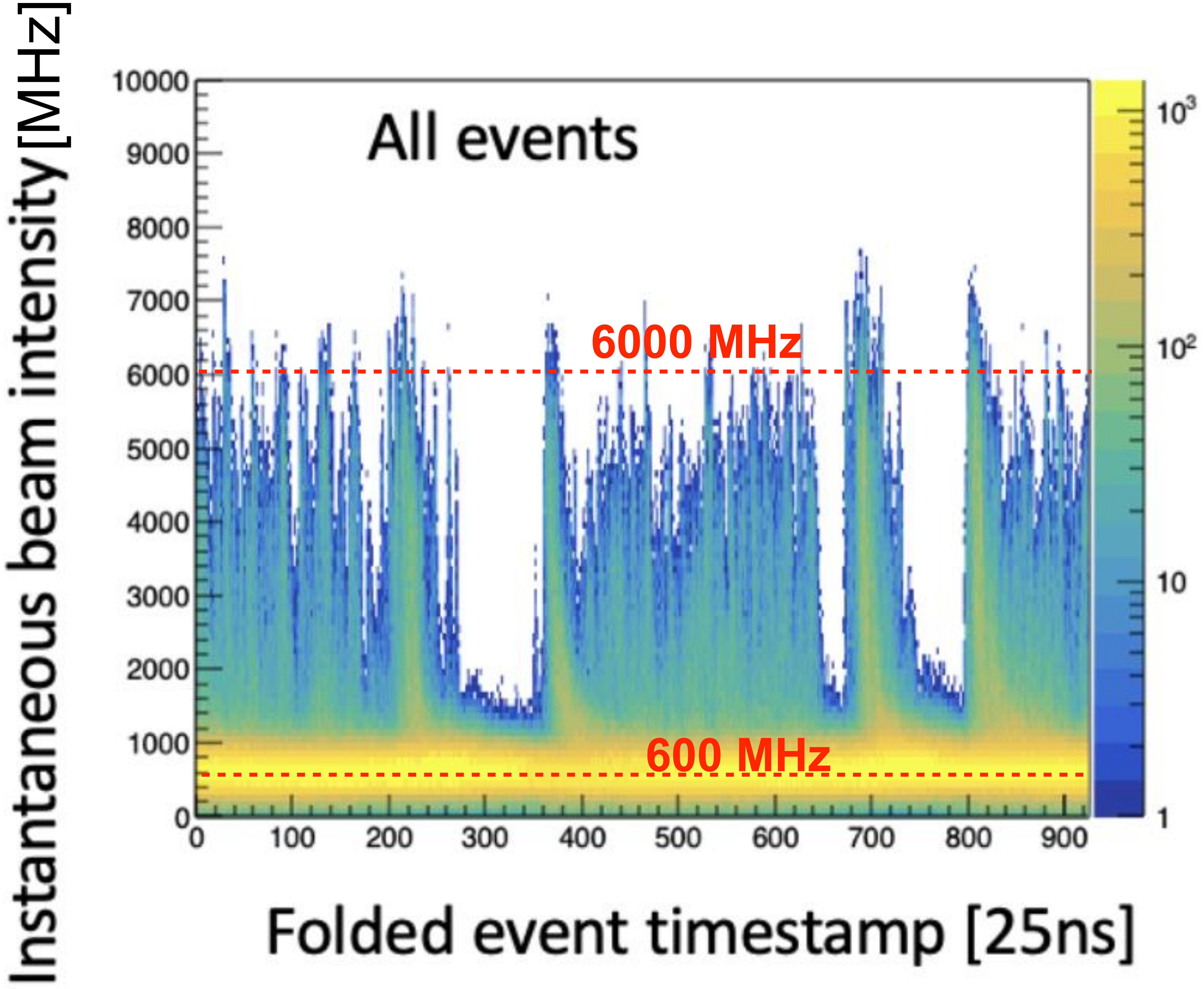
Beam intensity: 2018 vs 2022

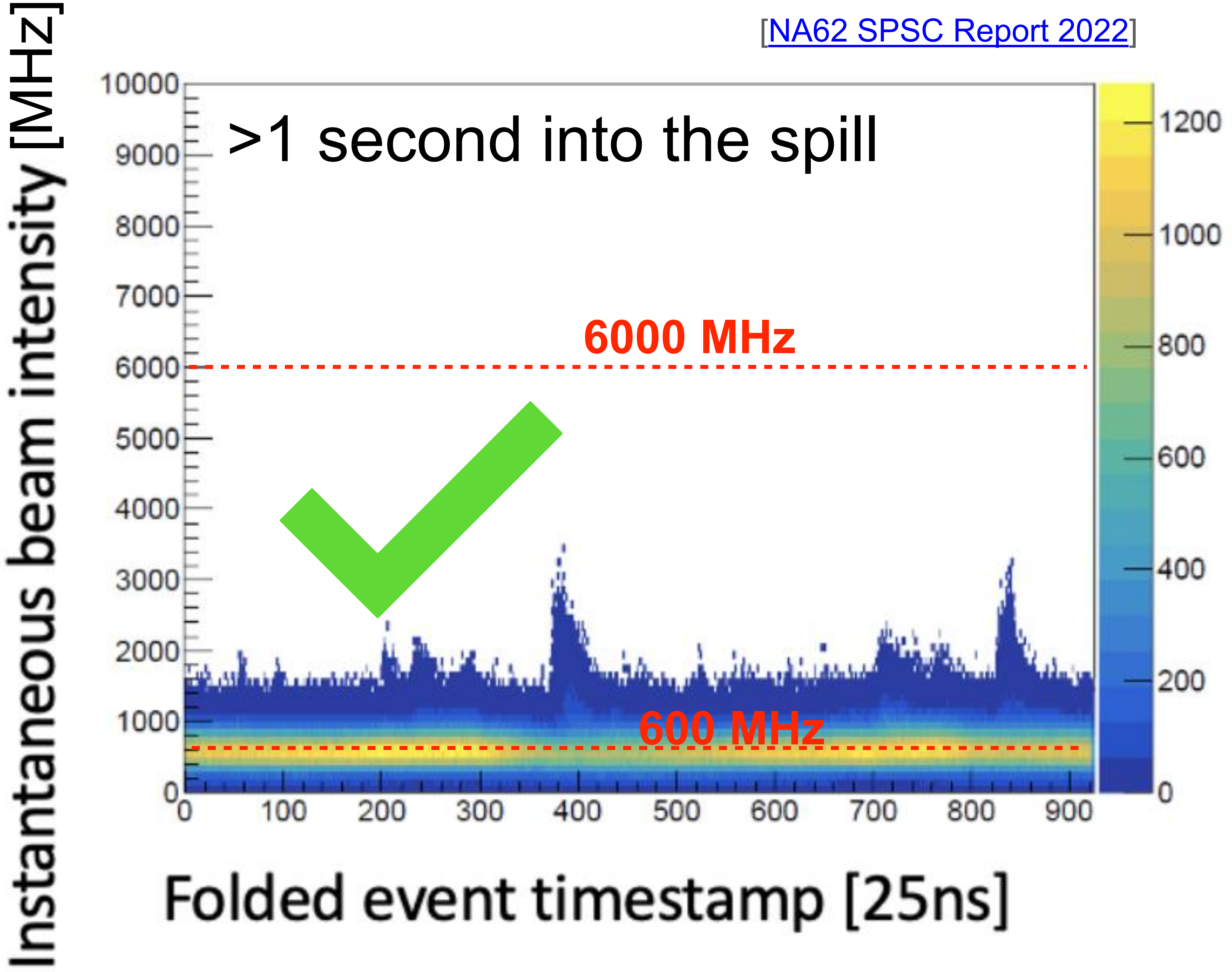


- Average beam intensity increased.
- NA62 "Full intensity" with 4.8s spill = 600 MHz

2021 instantaneous beam intensity

[NA62 SPSC Report 2022]





- Remove events in first 1s of 4.8s spill for 2021 data only.
  - DAQ overwhelmed by instantaneous rates up to 10x higher than design.

Analysis strategy

Triggers:

- **Minimum Bias:** $K^+ \to \mu^+ \nu$
- **Normalisation:** $K^+ \to \pi^+ \pi^0$
- **Signal:** $K^+ \to \pi^+ \nu \bar{\nu}$ candidates

- RICH multiplicity (reference time)
- Signal in CHODs
- No signal in MUV3(μ veto)
- Tag K^+ (≥ 5 KTAG sectors)
- <40 GeV in LKr ($\pi^0 / \gamma / e$ veto)
- LAV veto (downstream of vertex)

Common conditions

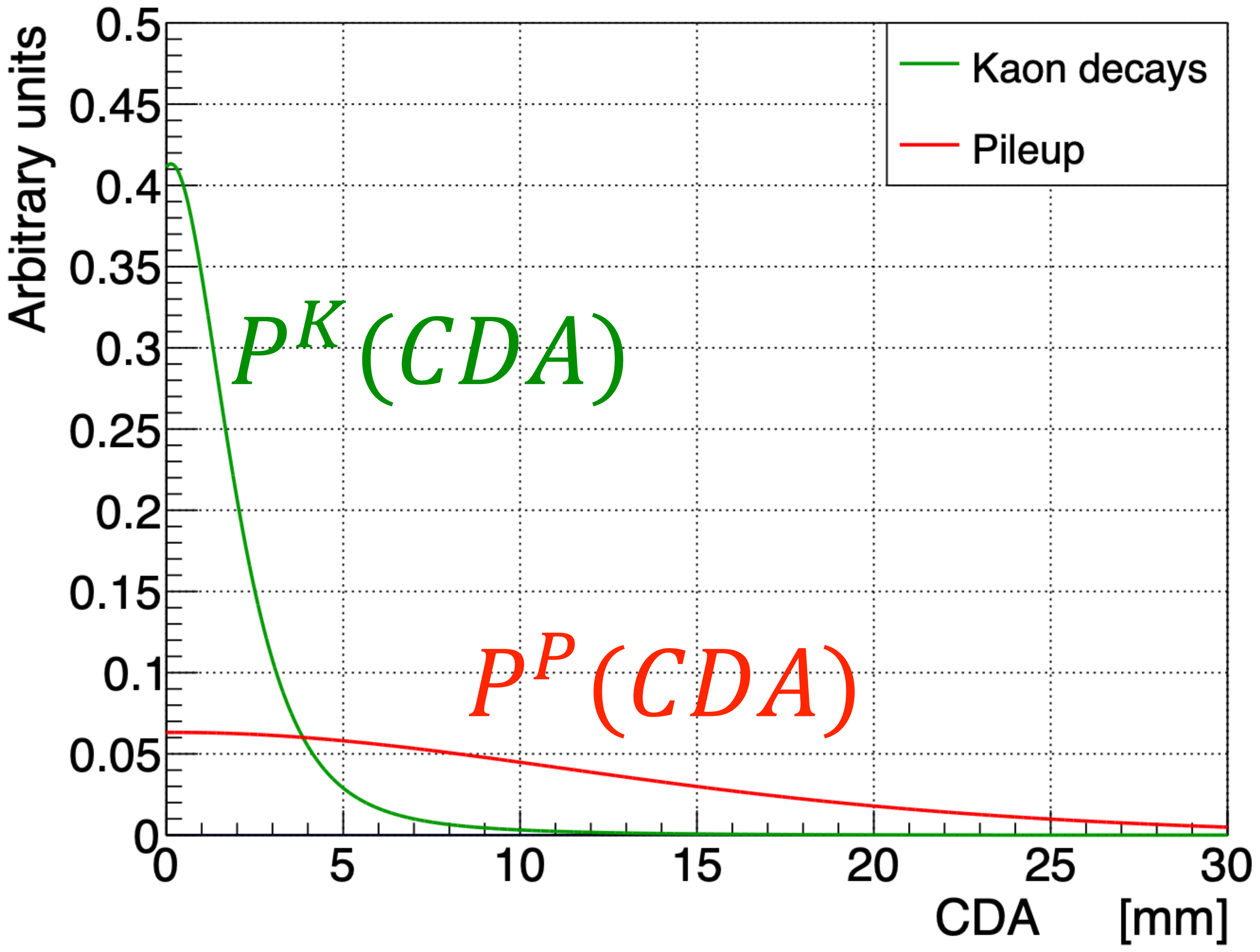
+ add more conditions

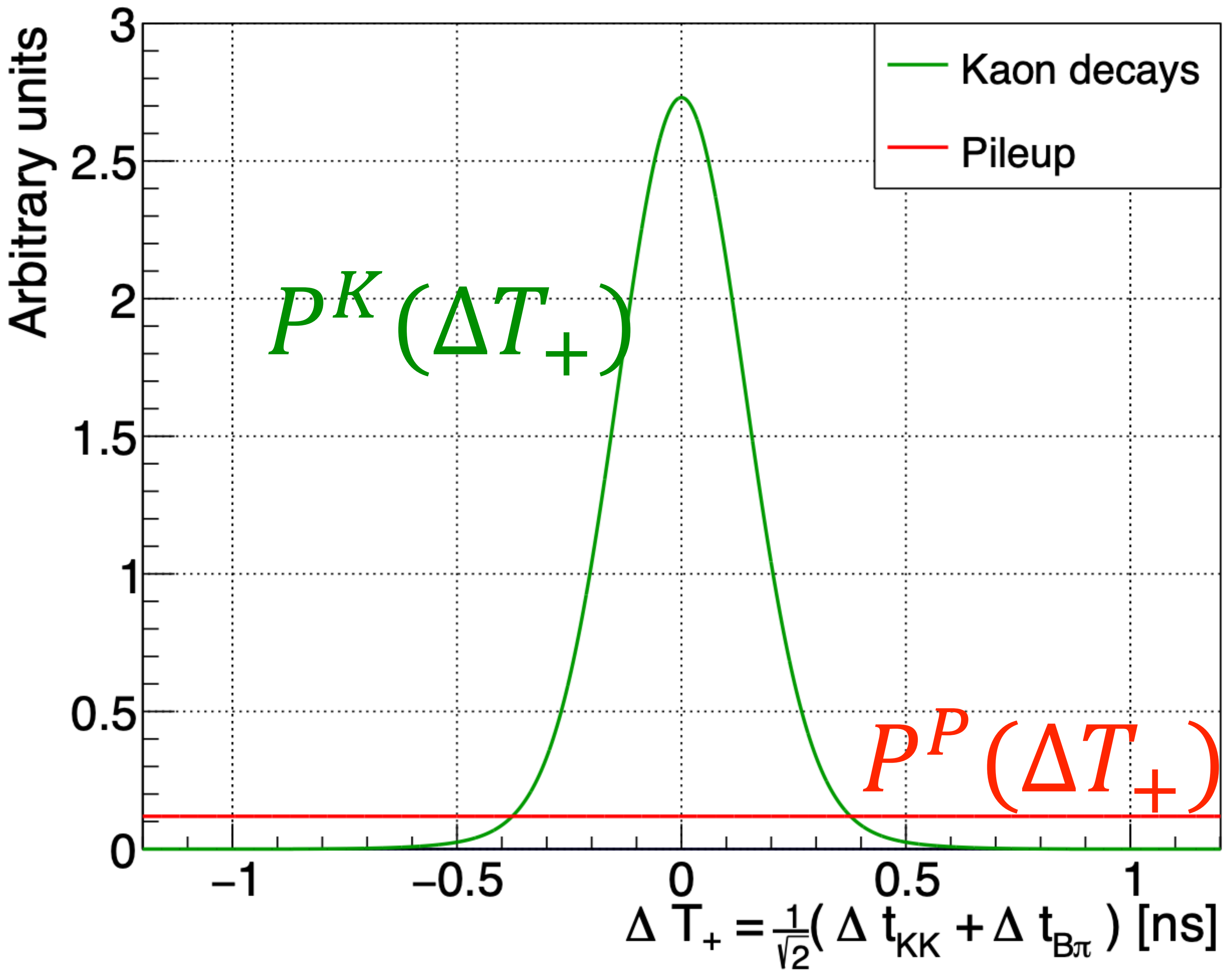
Selection:

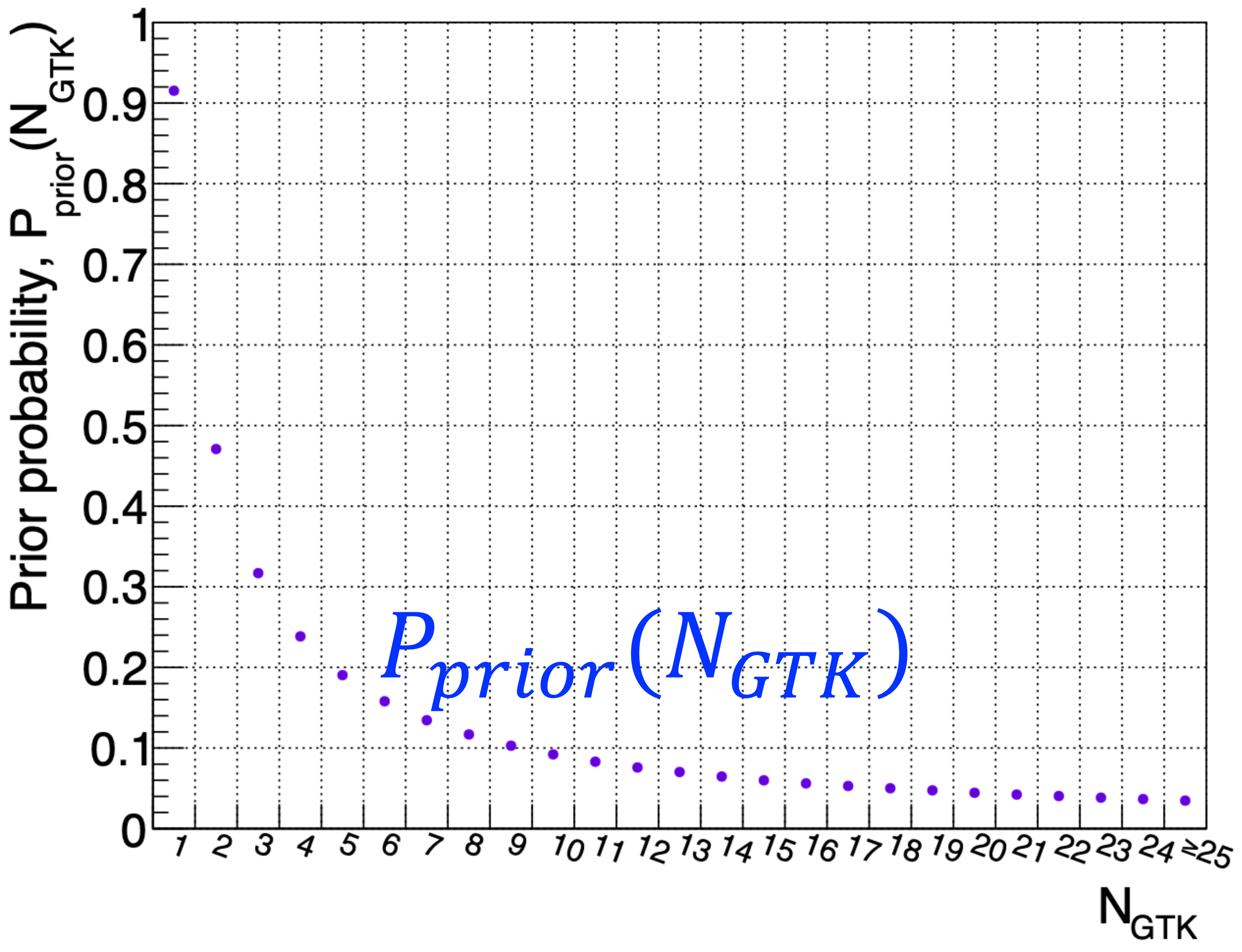
- **Normalisation** $K^+ \to \pi^+ \pi^0$: 1 downstream track (only); identified as π^+; $K^+ - \pi^+$ matching (space & time); upstream vetos.
- **Signal** $K^+ \to \pi^+ \nu \bar{\nu}$ candidates: same as normalisation selection + full photon and detector multiplicity cuts (reject all extra activity).

Bayesian classifier for $K^+ - \pi^+$ matching

- **Inputs:** spatial (CDA) & time (ΔT_+) matching, intensity/pileup (N_{GTK}) [prior]
  - Models for PDFs/Prior from $K^+ \to \pi^+\pi^+\pi^-$ data.







Example of selection update

- **Output:** posterior probability of GTK track = true K^+
  - Use likelihoods of kaons (K) and pileup (P)
  - Likelihood ratio used to select true match when $N_{GTK} > 1$
- Efficiency improved (+10%) and mistagging probability maintained.

Signal sensitivity

- Normalisation channel: $K^+ \to \pi^+\pi^0$, momentum range $p \in [15{,}45]\,GeV/c$.

Effective number of K^+ decays, N_K:

$$N_K = \frac{N_{\pi\pi} D_0}{\mathcal{B}_{\pi\pi} A_{\pi\pi}}$$

Number of normalisation events

Downscaling factor of normalisation trigger (generally 400)

Branching ratio of $K^+ \to \pi^+\pi^0$ decay

Acceptance of normalisation selection

Single event sensitivity:

(Branching ratio corresponding to expectation of 1 event)

$$\mathcal{B}_{SES} = \frac{1}{N_K \varepsilon_{RV} \varepsilon_{trig} A_{\pi\nu\bar{\nu}}}$$

Random veto efficiency

Trigger efficiency (ratio)

Signal selection acceptance

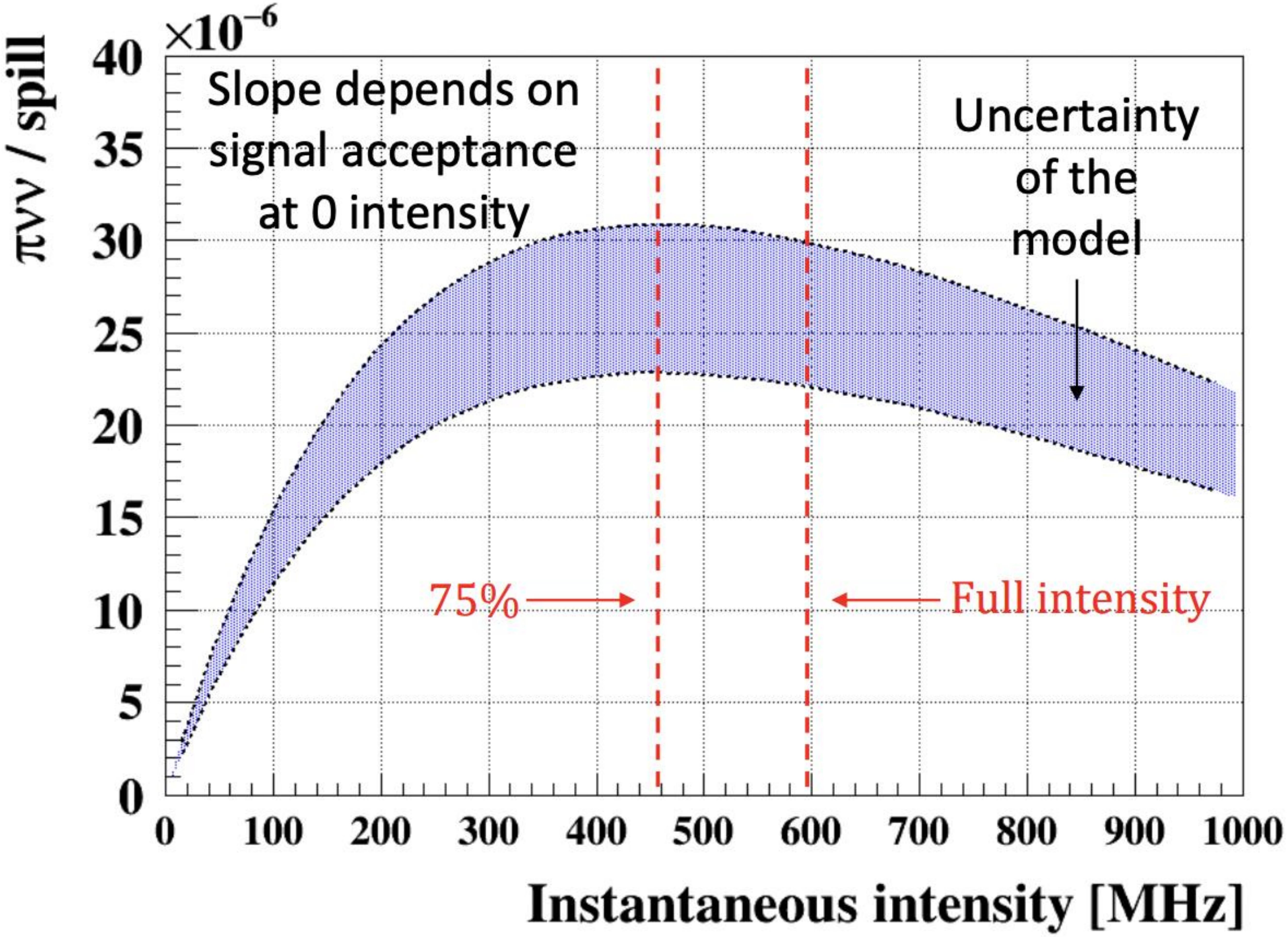
Number of expected SM events:

(For comparison to previous results use $\mathcal{B}^{SM}_{\pi\nu\bar{\nu}} = 8.4 \times 10^{-11}$ but results are independent of this choice)

$$N^{SM}_{\pi\nu\bar{\nu}} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}}$$

Optimum NA62 intensity

Selected signal yield vs intensity



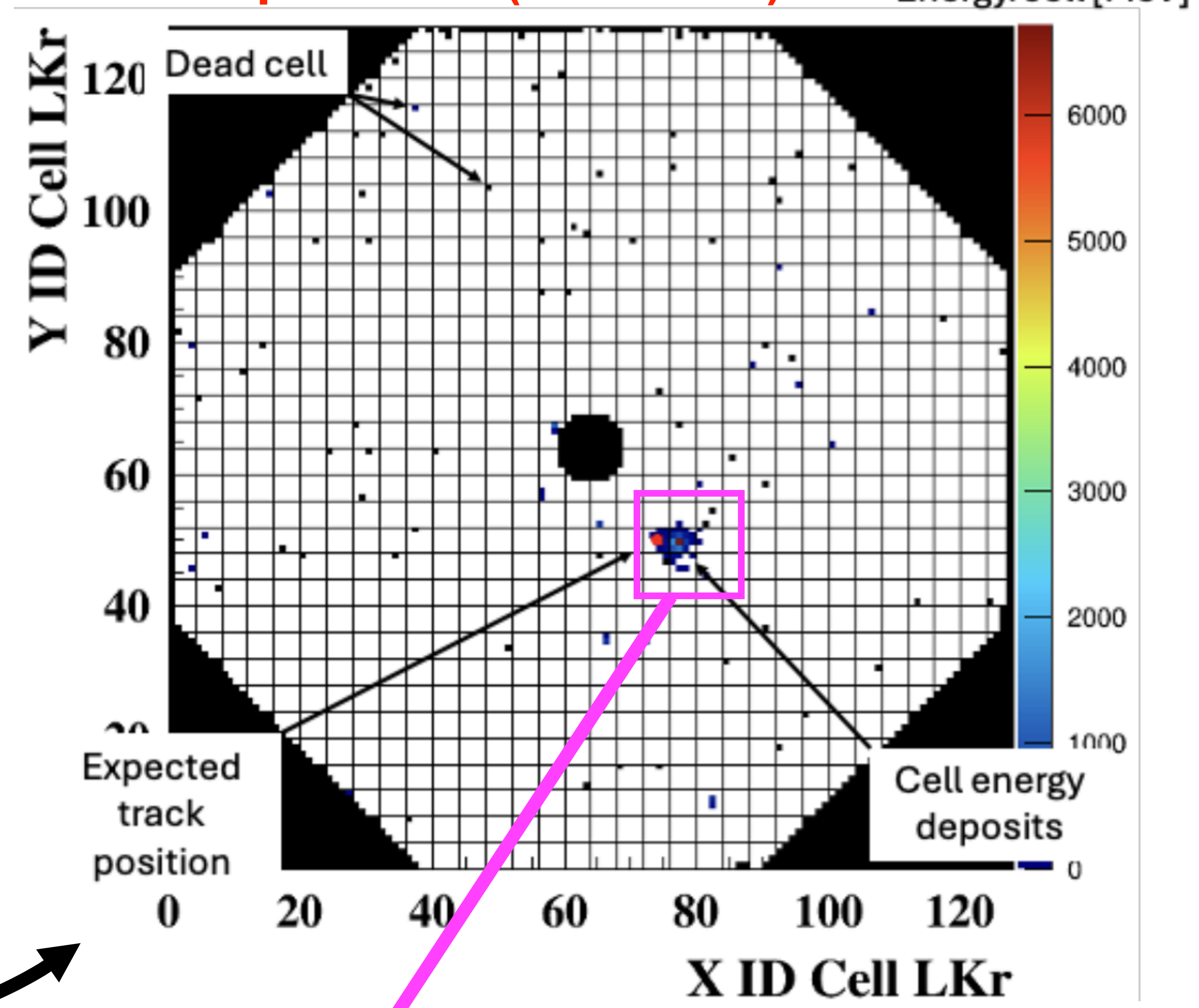
- Saturation of expected signal yield with intensity. Mainly due to:
  - Paralyzable effects from TDAQ dead time and trigger veto windows.
  - Offline selection, due to veto conditions.
- Main sources of uncertainty for model:
  - Online time-dependent mis-calibrations.
  - Fit uncertainty.
- **From August 2023 operate at optimal intensity** (~75% of full) to maximise $\pi\nu\nu$sensitivity
  - Maximise signal yield
  - lower expected background
  - Higher DAQ efficiency

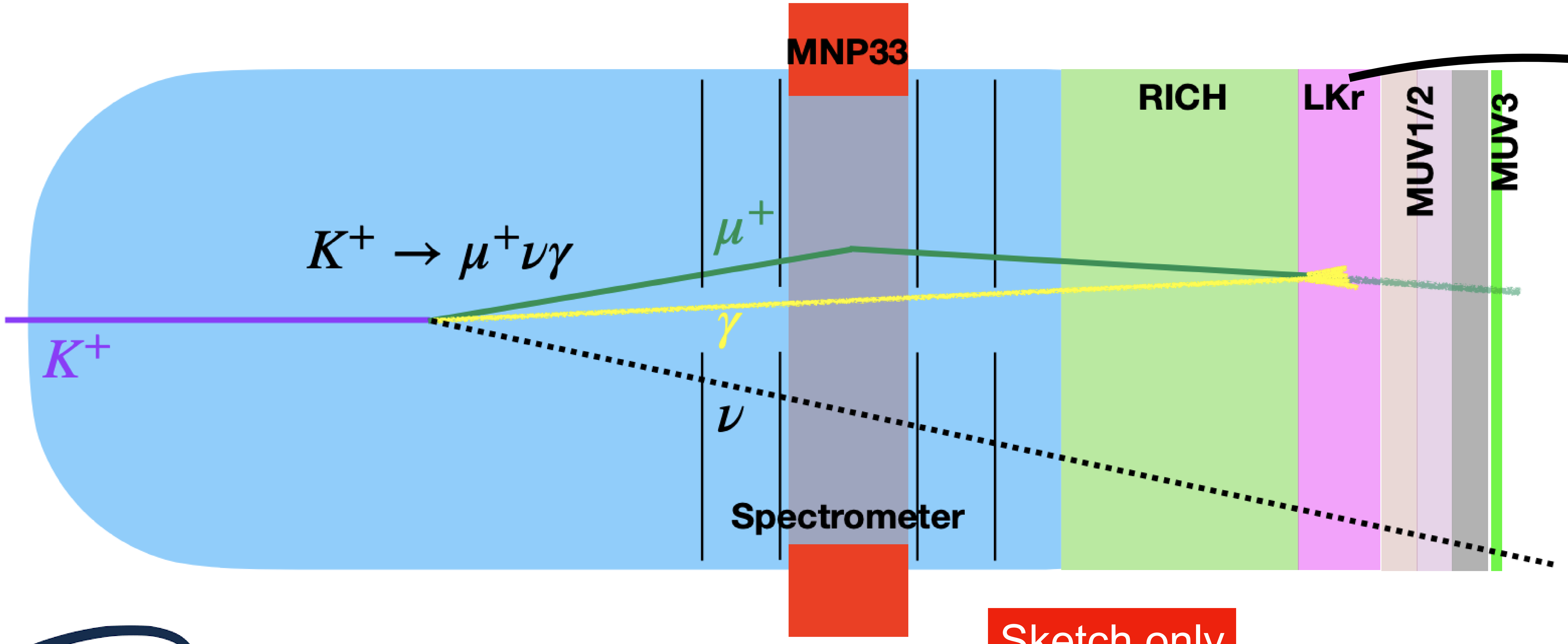
Studies of **2021—22 data** at high intensity **were crucial** to establish optimal intensity

Background mechanism: $K^+ \to \mu^+ \nu \gamma$

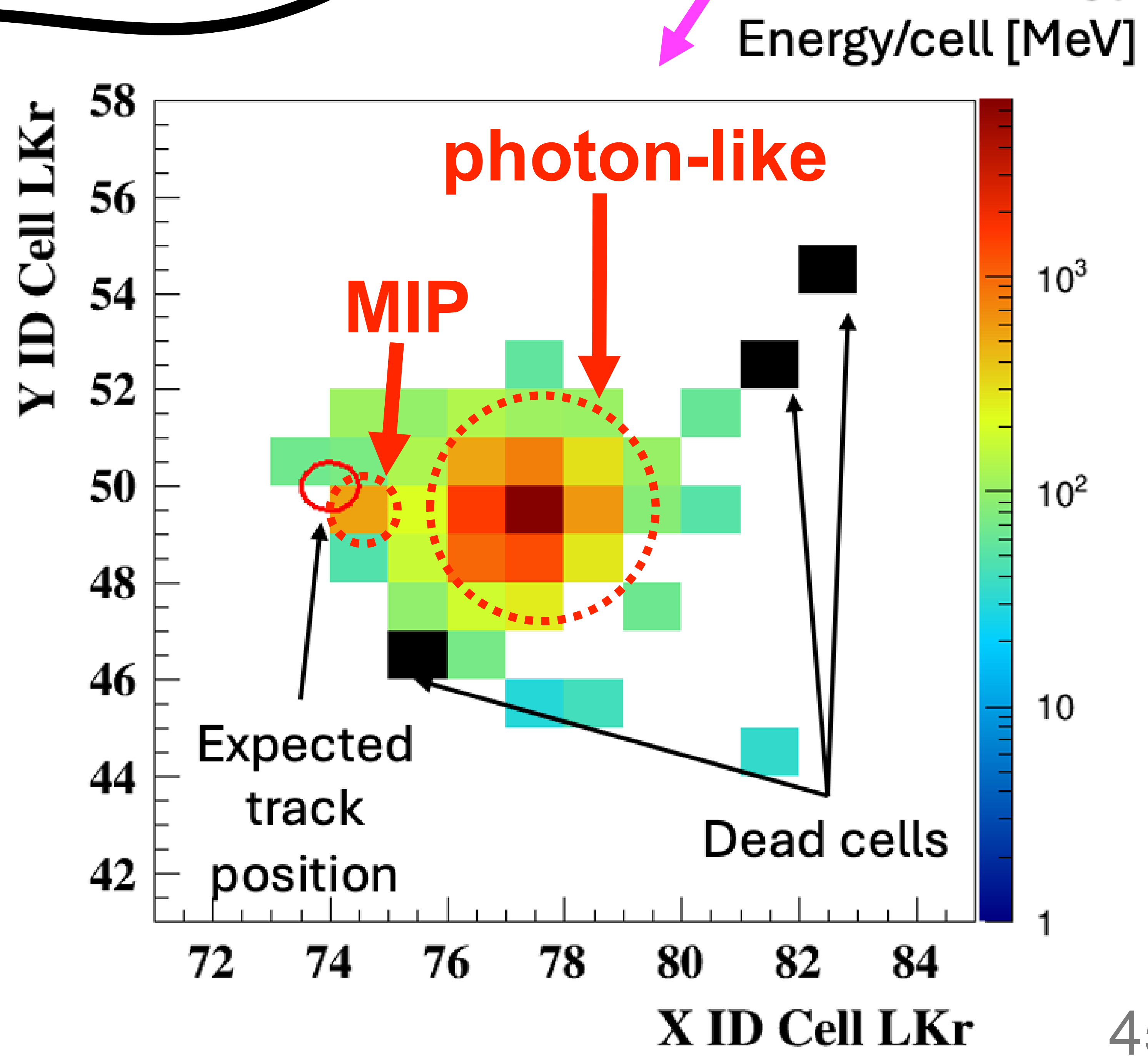
- $K^+ \to \mu^+ \nu \gamma$ decay with fairly energetic photon ($E_\gamma > 5\,GeV$) and high momentum μ^+ ($p \gtrsim 35\,GeV/c$).
- γ and μ^+ hit LKr together and are misidentified as a π^+.
- No rejection power from photon vetos (LKr γ cluster associated to track).
- Additional γ naturally shifts $m^2_{miss} = (P_K - P_\pi)^2$ towards higher values (i.e. towards signal regions).

Example event (2022 data):





Sketch only

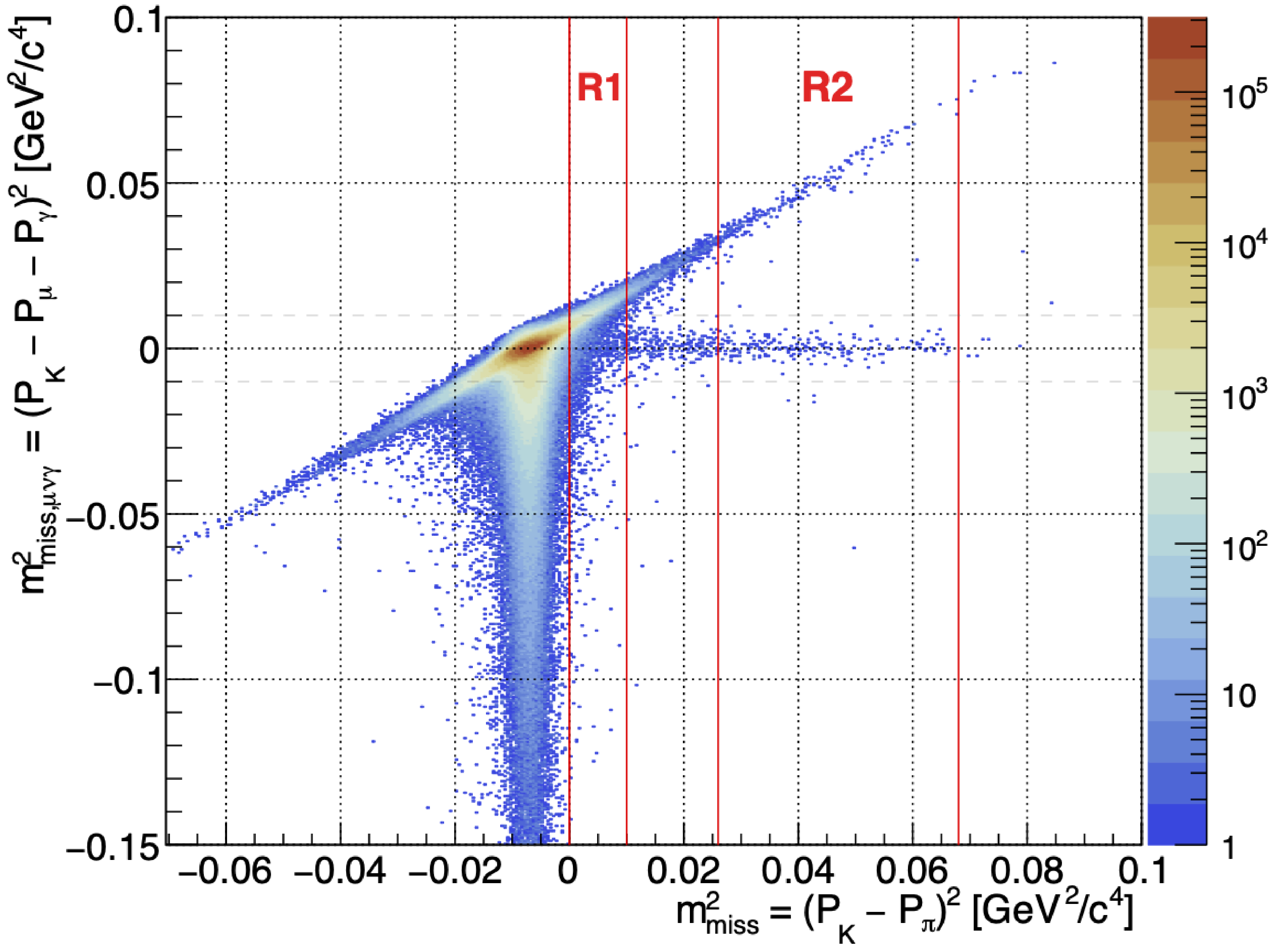


$K^+ \to \mu^+\nu\gamma$ Background

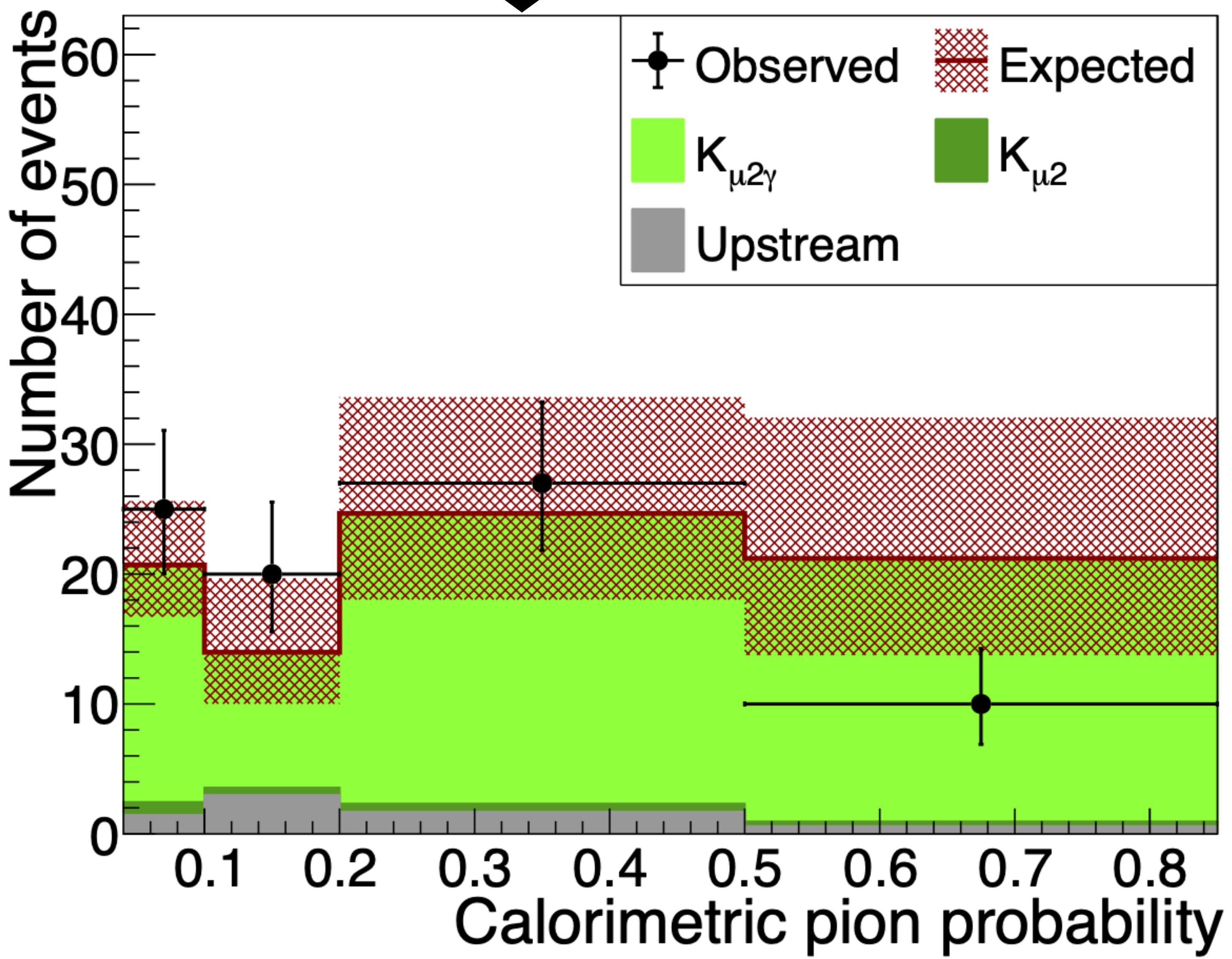
- Kinematically select $K^+ \to \mu^+\nu\gamma$ events: $m^2_{miss}(K_{\mu 2\gamma}) = (P_K - P_\mu - P_\gamma)^2$
  - P_K : 4-momentum of K^+ from GTK (as normal)
  - P_μ : 4-momentum of track with μ^+ mass hypothesis.
  - P_γ : reconstructed from energy and position of LKr cluster (and position of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

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

Minimum Bias Data



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



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

Other backgrounds

- $K^+ \rightarrow \pi^+\pi^- e^+\nu \ (K_{e4})$
  - No clean control samples for K_{e4} in data: Use 2×10^9 simulated decays.

Effective # of K+

Random veto & trigger efficiencies

Acceptance : $A_{K_{e4}} = \frac{N_{MC}^{sel}}{N_{MC}^{gen}} = (1.3 \pm 0.3) \times 10^{-8}$

$$N_{bg}(K^+ \rightarrow \pi^+\pi^- e^+\nu) = N_K \varepsilon_{RV} \varepsilon_{trig} \mathcal{B}_{K_{e4}} A_{K_{e4}}$$

Branching ratio of K_{e4} (from PDG)

$$N_{bg}(K^+ \rightarrow \pi^+\pi^- e^+\nu) = 0.89^{+0.33}_{-0.27}$$

- $K^+ \rightarrow \pi^0 \ell^+ \nu$ and $K^+ \rightarrow \pi^+ \gamma\gamma$:
  - Evaluated with simulations.
  - **Negligible contributions to total background.**

$$N_{bg}(K^+ \rightarrow \pi^0 \ell^+ \nu) < 1 \times 10^{-3}$$

$$N_{bg}(K^+ \rightarrow \pi^+ \gamma\gamma) = 0.01 \pm 0.01$$

Upstream background evaluation

$$N_{bg} = \sum_i N_i f_{cda} P_i^{match}$$

N — Upstream Reference Sample: signal selection but invert CDA cut (CDA>4mm)

f_{cda} — Scaling factor : bad cda —> good cda

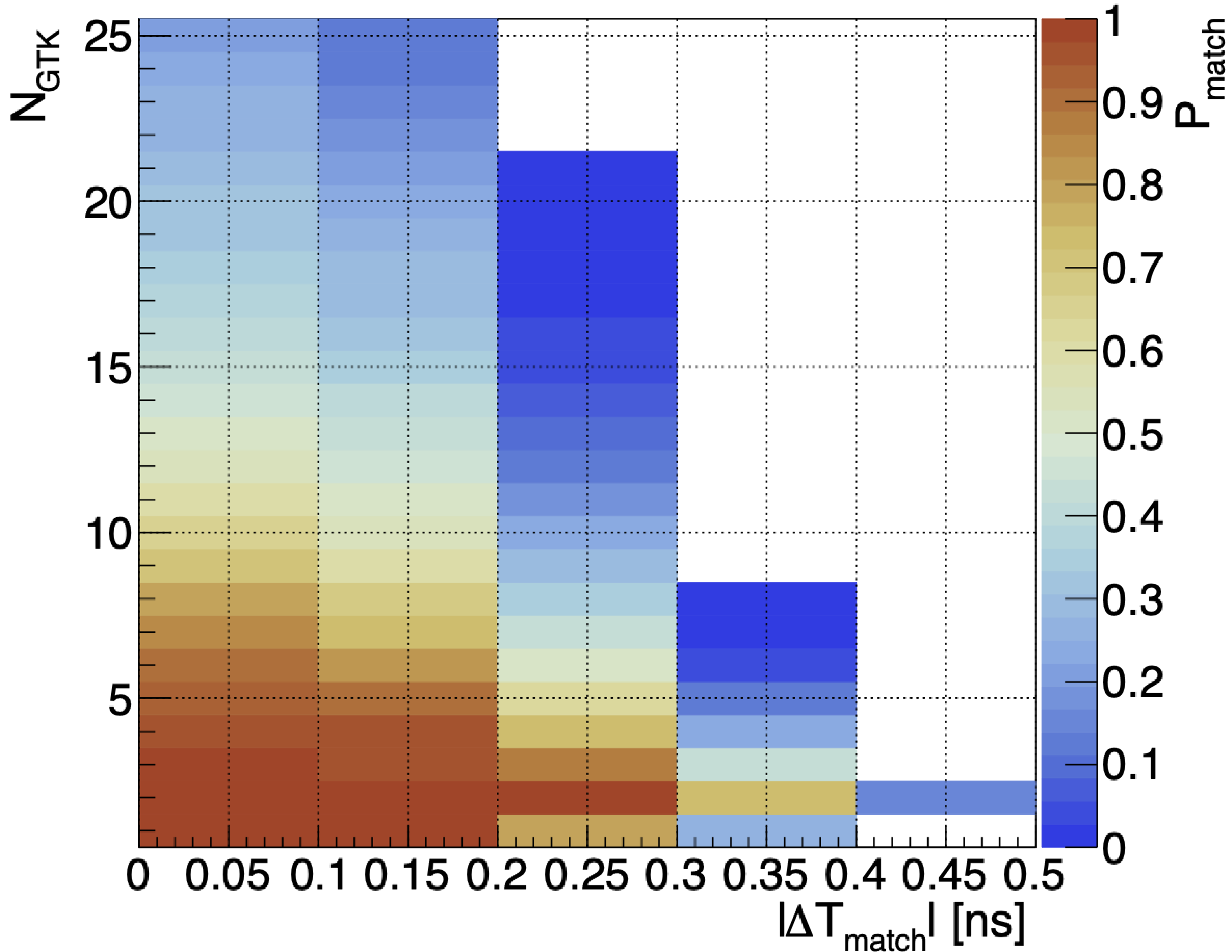
P_{match} — Probability to pass $K^+ - \pi^+$ matching

Calculate using bins (i) of $(\Delta T_+, N_{GTK})$
[Updated to fully data-driven procedure]

$N = 51 \quad f_{CDA} = 0.20 \pm 0.03 \quad < P_{match} > = 73\%$

$$N_{bg}(Upstream) = 7.4^{+2.1}_{-1.8}$$

- **Upstream reference sample contains all known upstream mechanisms.**
  - N provides normalisation.
- f_{CDA} **depends only on geometry.**
- P_{match} **depends on** $(\Delta T_+, N_{GTK})$.



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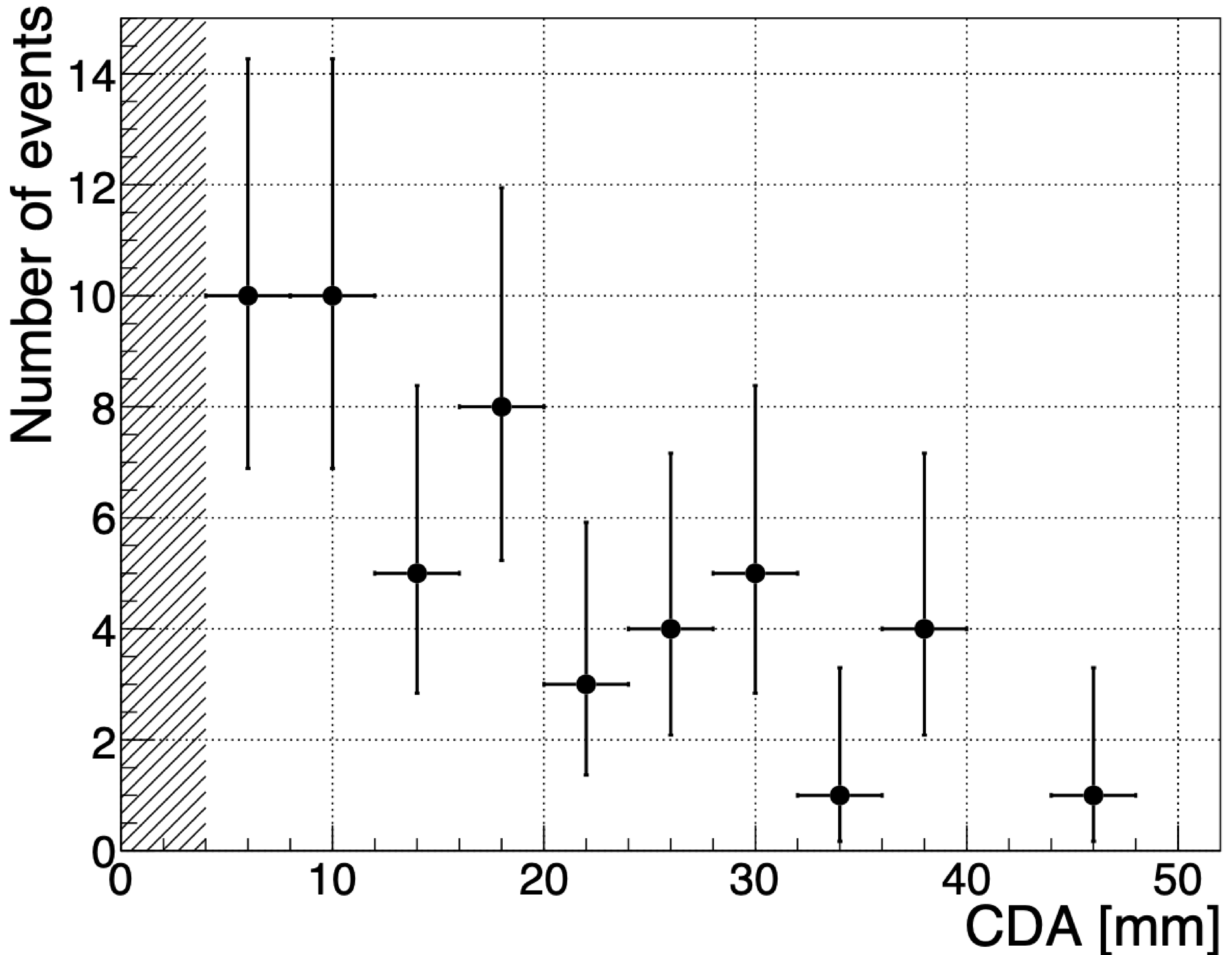
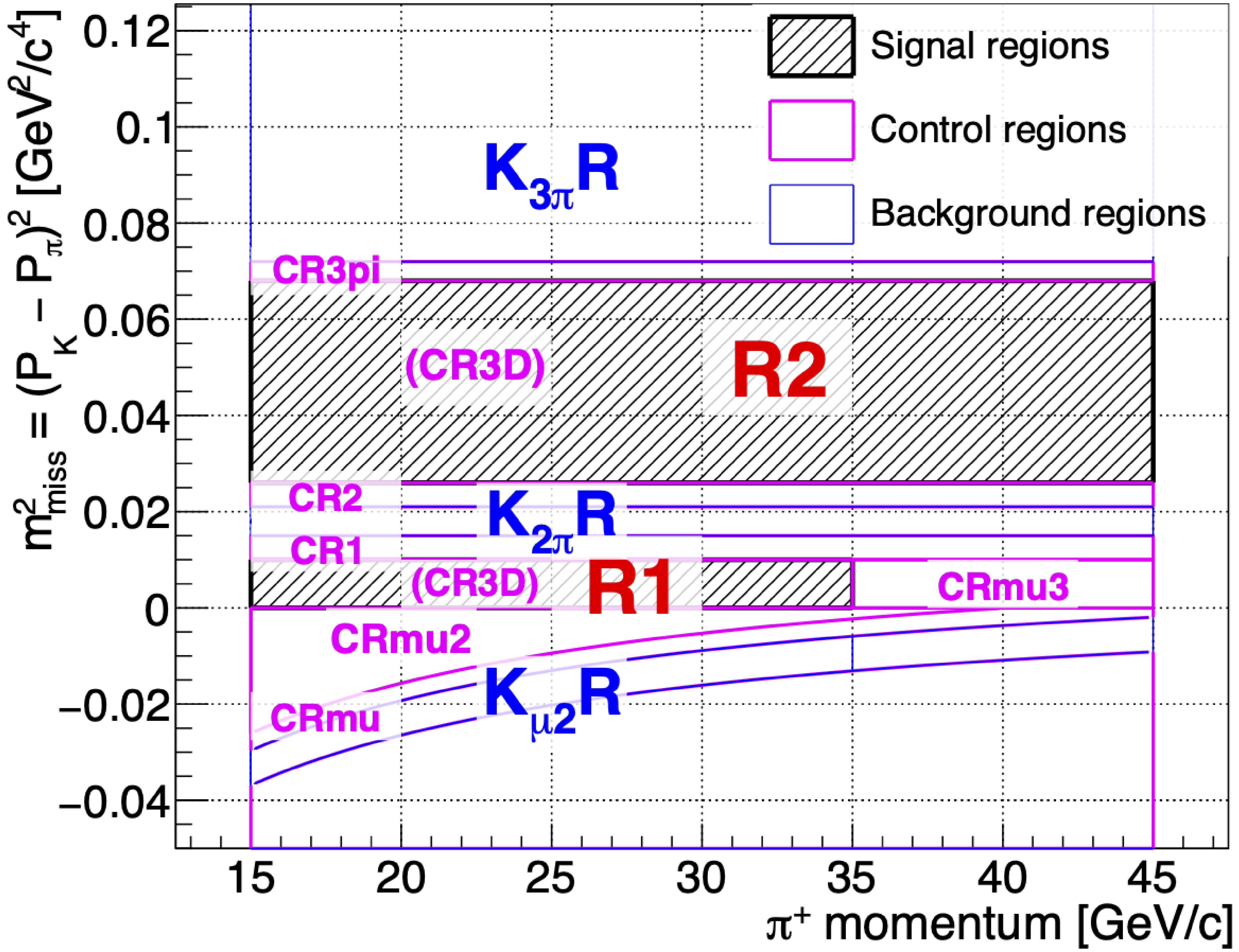
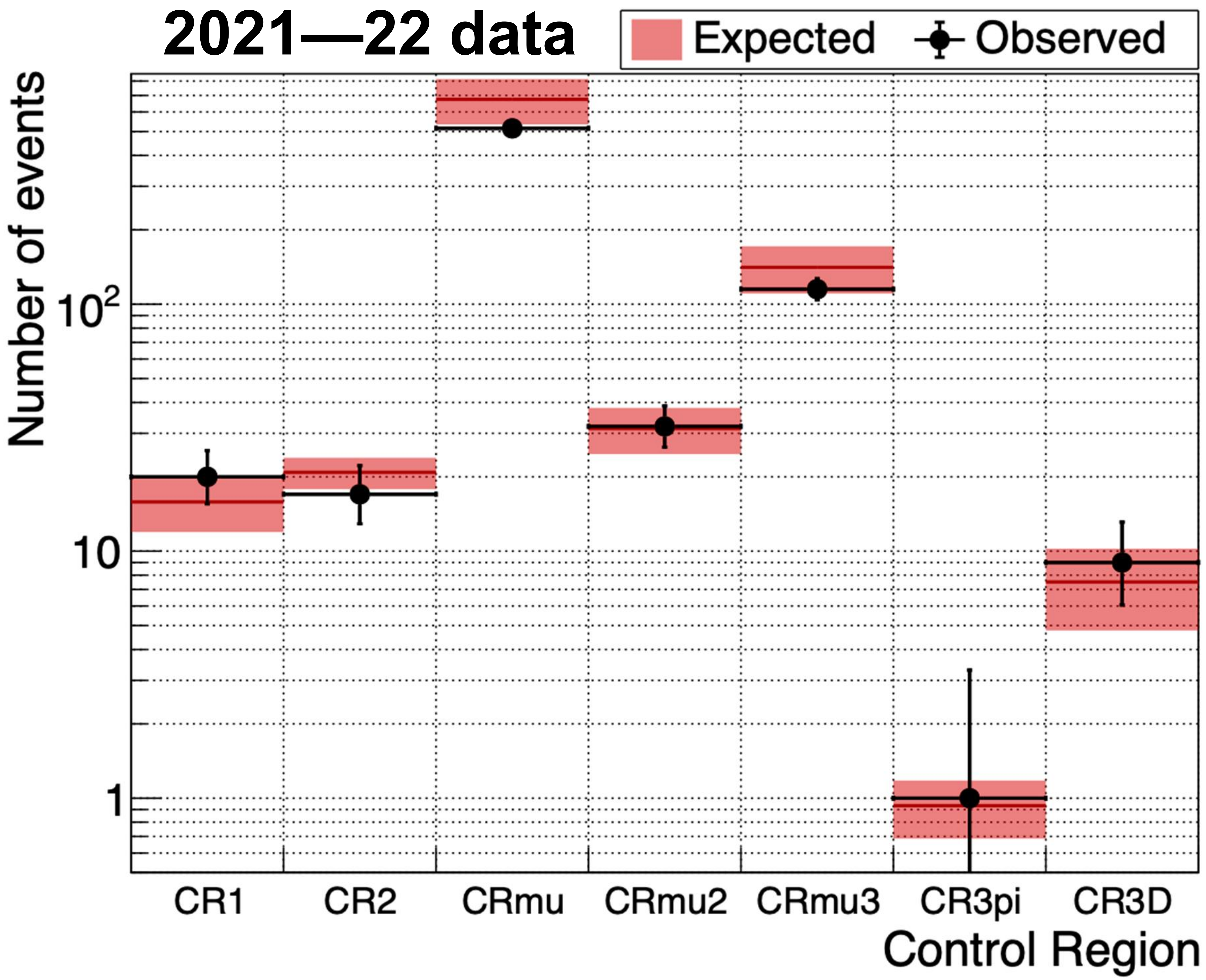


Kinematic regions and control regions

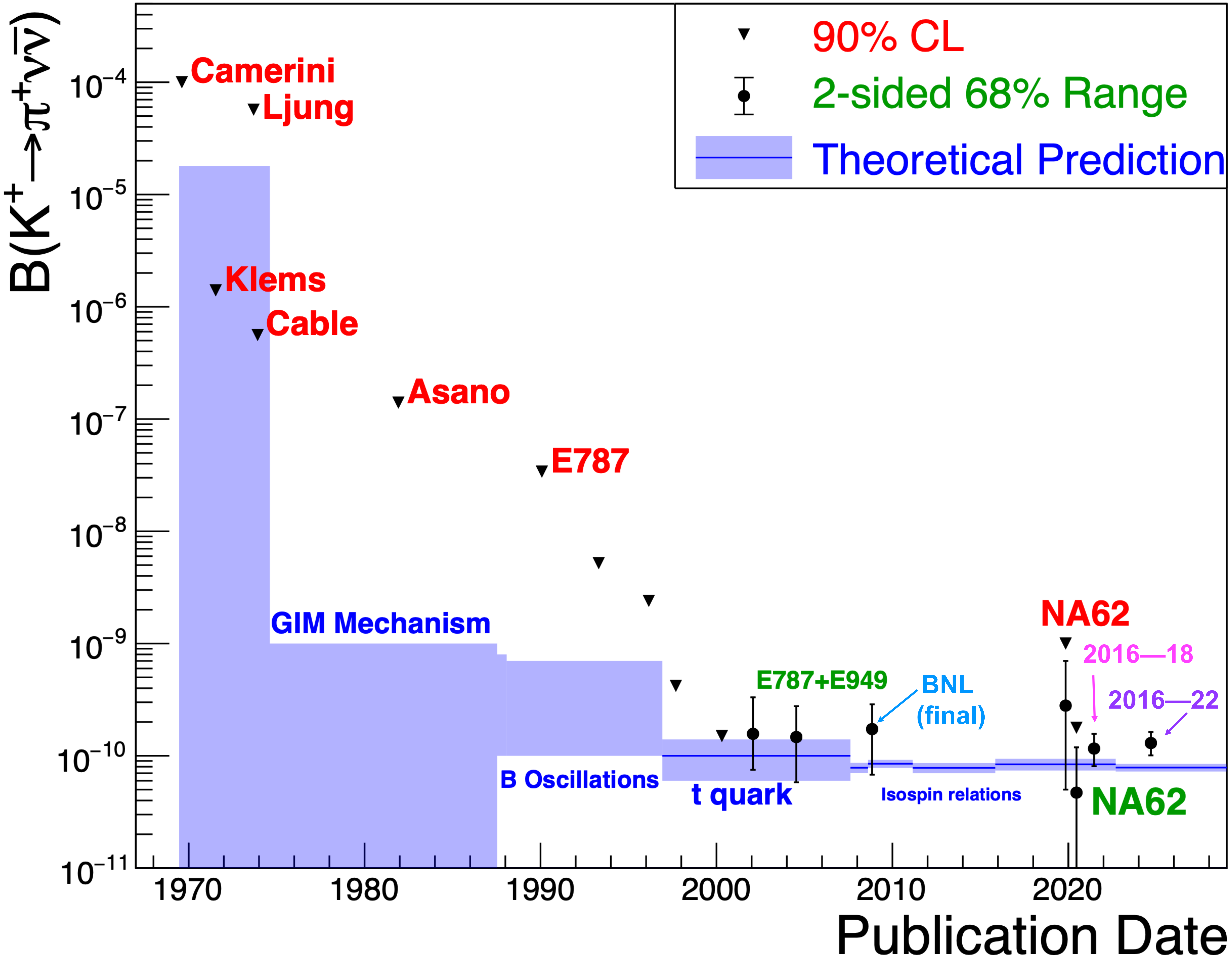




- **Signal regions**
- **Control regions:** used to validate background predictions.
- **Background regions:** used as "reference samples" for some background estimates.

Results in context: the long story of $K^+ \to \pi^+ \nu\bar{\nu}$

- Experimental measurements:
  - Camerini et al. [PRL 23 (1969) 326-329]
  - Klems et al. [PRD 4 (1971) 66-80]
  - Ljung et al. [PRD 8 (1973) 1307-1330]
  - Cable et al. [PRD 8 (1973) 3807-3812]
  - Asano et al. [PLB 107 (1981) 159]
  - E787 :
    - [PRL 64 (1990) 21-24]
    - [PRL 70 (1993) 2521-2524]
    - [PRL 76 (1996) 1421-1424]
    - [PRL 79 (1997) 2204-2207]
    - [PRL 84 (2000) 3768-3770]
    - [PRL 88 (2002) 041803]
  - E949 (+E787)
    - [PRL 93 (2004) 031801]
    - [PRL 101 (2008) 191802]
  - NA62:
    - 2016 data: [PLB 791 (2019) 156]
    - 2016+17 data: [JHEP 11 (2020) 042]
    - 2016—18 data: [JHEP 06 (2021) 093]
    - 2016—22 data: [JHEP 02 (2025) 191]
- Theory:
  - [Phys.Rev. 163 (1967) 1430-1440]
  - [PRD 10 (1974) 897]
  - [Prog.Theor.Phys. 65 (1981)]
  - [PLB 133 (1983) 443-448]
  - [PLB 192 (1987) 201-206]
  - [Nucl.Phys.B 304 (1988) 205-235]
  - [PRD 54 (1996) 6782-6789]
  - [PRD 76 (2007) 034017]
  - [PRD 78 (2008) 034006]
  - [PRD 83 (2011) 034030]
  - [JHEP 11 (2015) 033]
  - [JHEP 09 (2022) 148]



The NA62 published results (2022-25)

1. Search for hadronic decays of feebly-interacting, particles at NA62, EPJC 85 (2025) 571.
2. First detection of a tagged neutrino in the NA62 experiment, Phys. Lett. B 863 (2025) 139345.
3. Observation of the $K^+ \to \pi^+\nu\bar{\nu}$ decay and measurement of its branching ratio, JHEP 02 (2025) 191.
4. First search for $K^+ \to \pi^0\pi\mu e$ decays, Phys. Lett. B 859 (2024) 139122.
5. Search for leptonic decays of the dark photon at NA62, Phys. Rev. Lett. 133 (2024) 111802.
6. Measurement of the $K^+ \to \pi^+\gamma\gamma$ decay, Phys. Lett. B 850 (2024) 138513.
7. Search for K^+ decays into the $\pi^+e^+e^-e^+e^-$ final state, Phys. Lett. B 846 (2023) 138193.
8. A study of the $K^+ \to \pi^0e^+\nu\gamma$ decay, JHEP 09 (2023) 040.
9. Search for dark photon decays to $\mu^+\mu^-$ at NA62, JHEP 09 (2023) 035.
10. A search for the $K^+ \to \mu^-\nu e^+e^+$ decay, Phys. Lett. B 838 (2023) 137679.
11. A measurement of the $K^+ \to \pi^+\mu^+\mu^-$ decay, JHEP 11 (2022) 011.
12. Searches for lepton number violating $K^+ \to \pi^-(\pi^0)\, e^+e^+$ decays, Phys. Lett. B 830 (2022) 137172.

The NA62 published results (2018-21)

1. Search for Lepton Number and Flavor Violation in K+ and π0 Decays, Phys. Rev. Lett. 127 (2021) 131802.
2. Measurement of the very rare K+ → π+ν ¯ν decay, JHEP 06 (2021) 093.
3. Search for K+ decays to a muon and invisible particles, Phys. Lett. B 816 (2021) 136259.
4. Search for a feebly interacting particle X in the decay K+ → π+X, JHEP 03, (2021) 058.
5. Search for π0 decays to invisible particles, JHEP 02, (2021) 201.
6. An investigation of the very rare K+ → π+ν ¯ν decay, JHEP 11 (2020) 042.
7. Search for heavy neutral lepton production in K+ decays to positrons, Phys. Lett. B 807 (2020) 135599.
8. Searches for lepton number violating K+ decays, Phys. Lett. B 797 (2019) 134794.
9. Search for production of an invisible dark photon in π0 decays, JHEP 1905 (2019) 182.
10. First search of K+ → π+ν ¯ν using the decay-in-flight technique, Phys. Lett. B 791 (2019) 156.
11. Search for heavy neutral lepton production in K+ decays, Phys. Lett. B 778 (2018) 137.