New physics searches with kaon and pion decays at NA62

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(on behalf of NA62 Collaboration)

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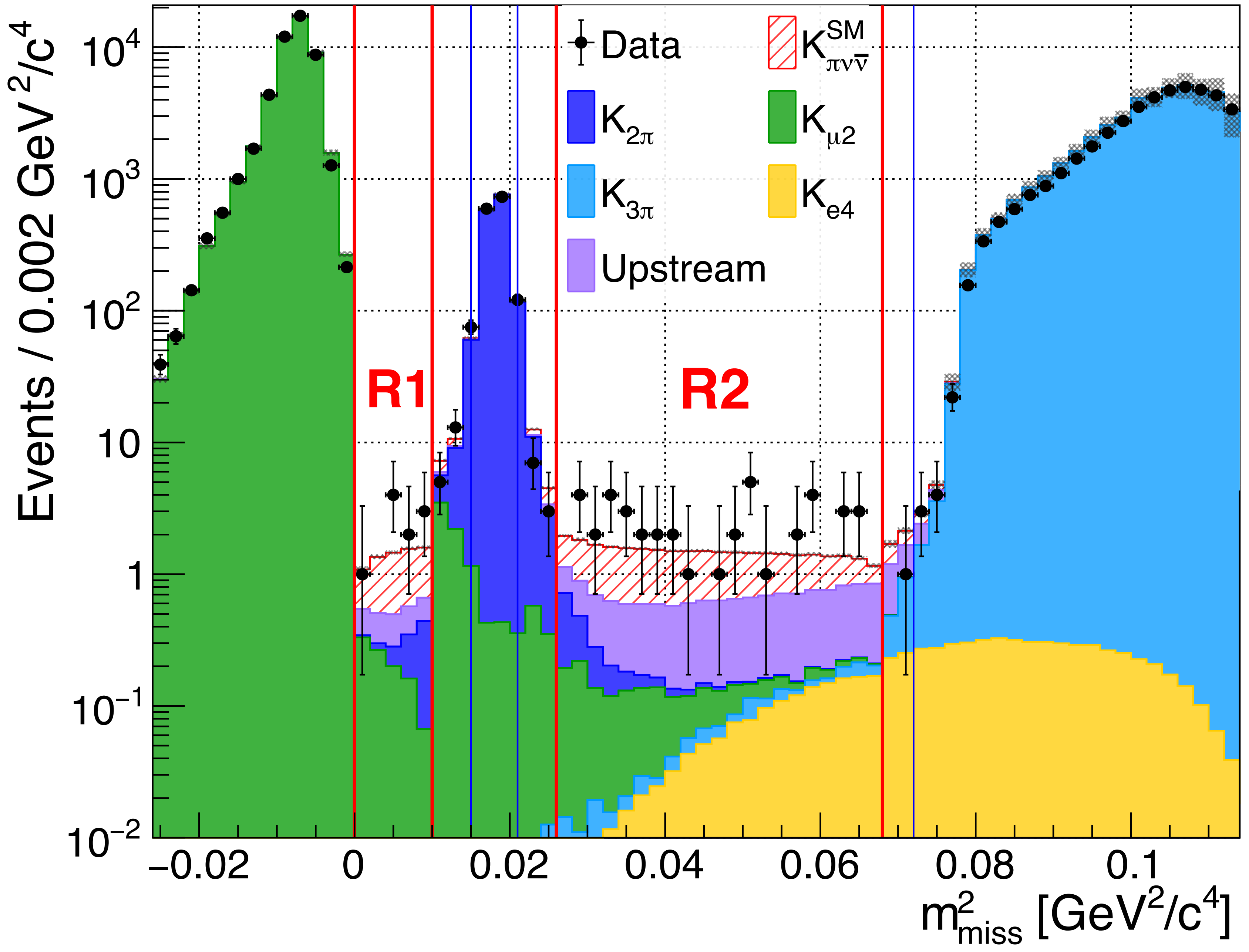
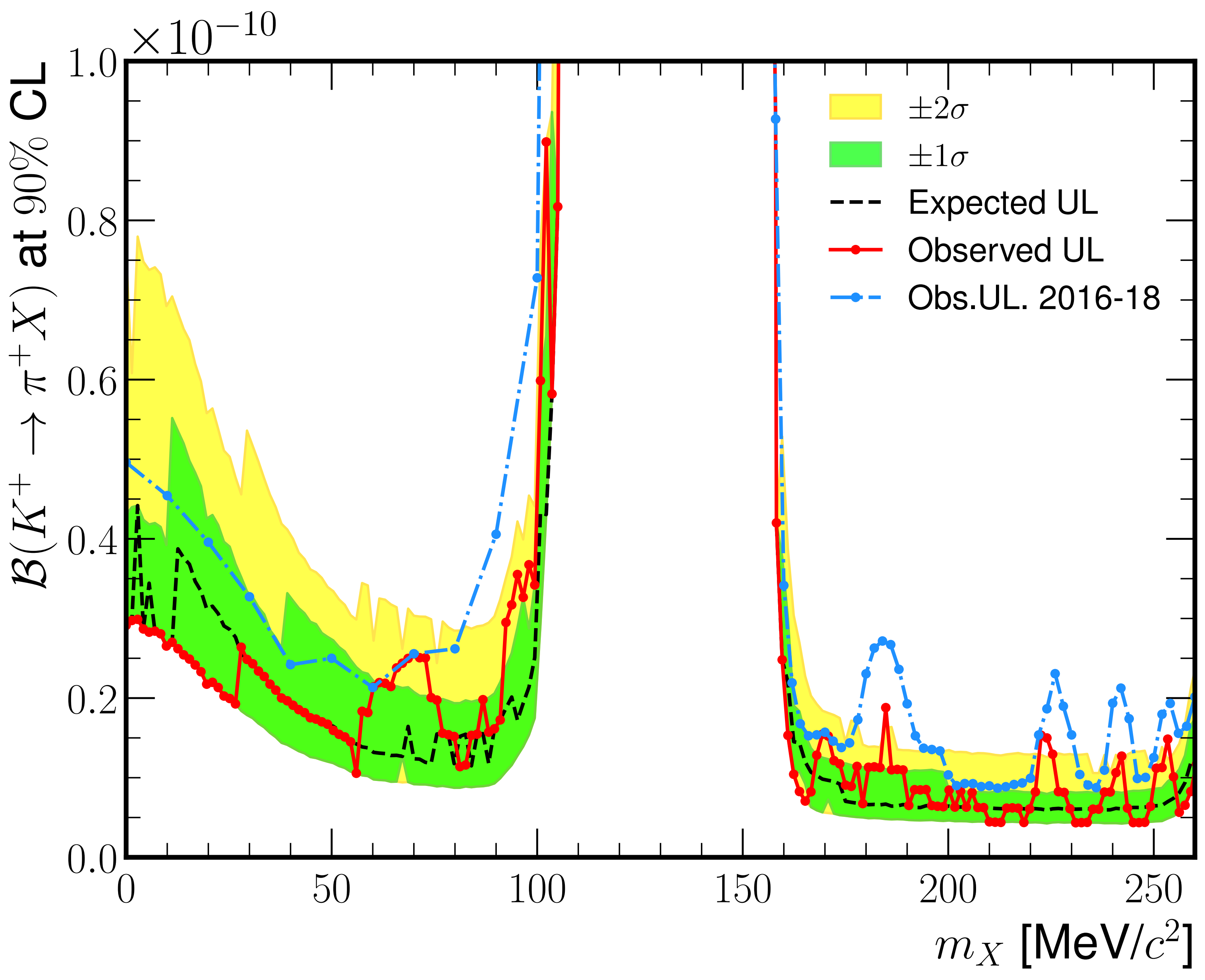
Rencontres de Moriond 2026 - EW, La Thuile

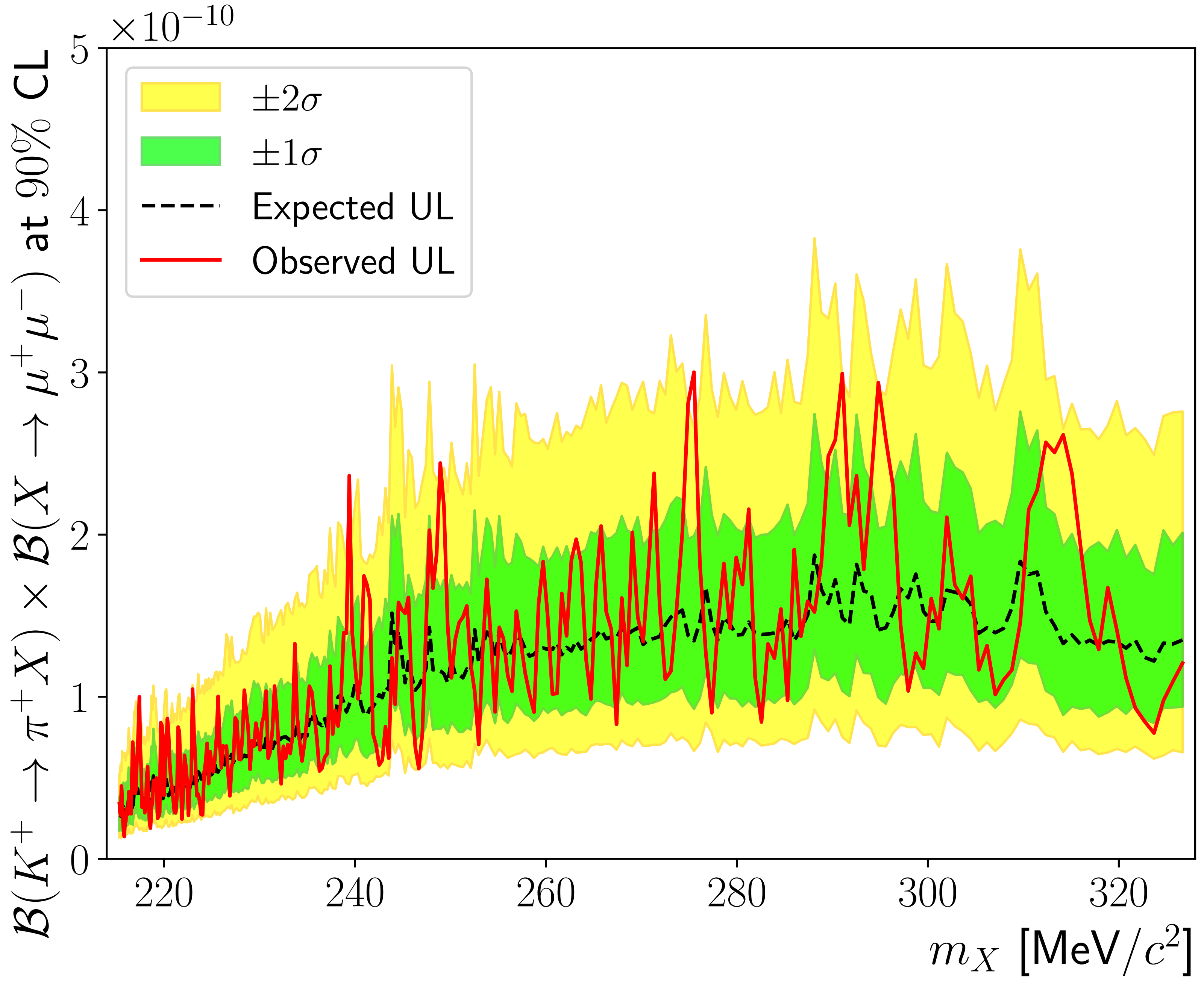
Searches for $K^+ \to \pi^+ X$ at NA62

JHEP 11 (2025) 143

- Same signature as $K^+ \to \pi^+ \nu \bar{\nu}$ except $m^2_{miss} = (P_K - P_\pi)^2 = m^2_X$
  - Peak search: (SM) $K^+ \to \pi^+ \nu \bar{\nu}$ is the dominant background!
- Set model-independent Br upper limits for $K^+ \to \pi^+ X_{inv}$
  - Evaluate the acceptance for any X lifetime $\to Br_{UL}(m_X, \tau_X)$
- Evaluate limit for $K^+ \to \pi^+ X, X \to \mu^+ \mu^-$ using NA62 $K^+ \to \pi^+ \mu^+ \mu^-$ result [JHEP 11 (2022) 011]







BSM constraints from $K^+ \to \pi^+ X$

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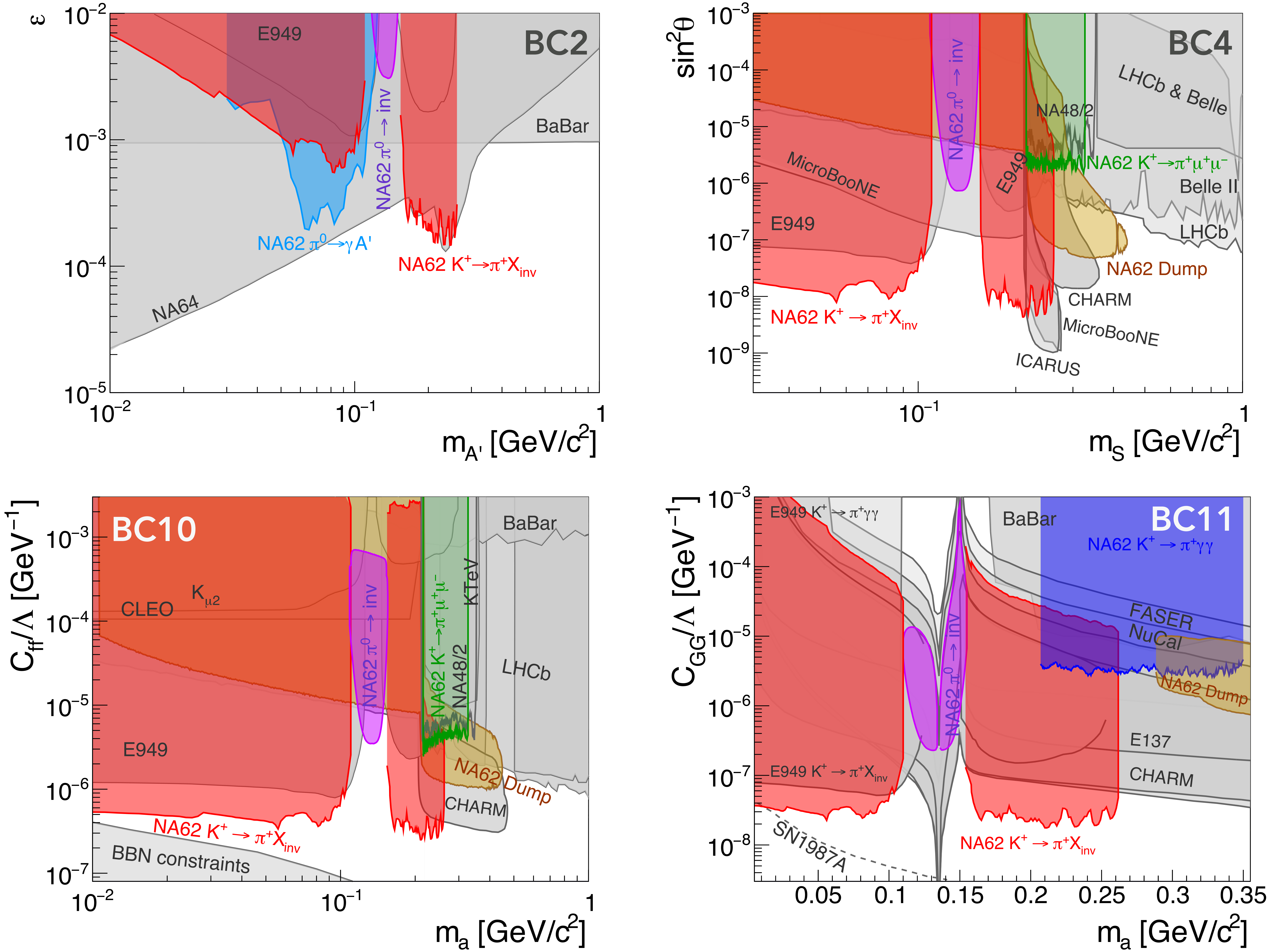
- BC2: Dark photon (invisible)
- BC4: Dark scalar
- BC10: ALP with quark coupling
- BC11: ALP with gluon coupling
- Axion: see independent analysis from public data (before NA62 paper) [arxiv:2503.05865]
  - World-leading limit on axion-down-strange coupling
    $$(F_V)_{23} > 1.1 \times 10^{12}$$

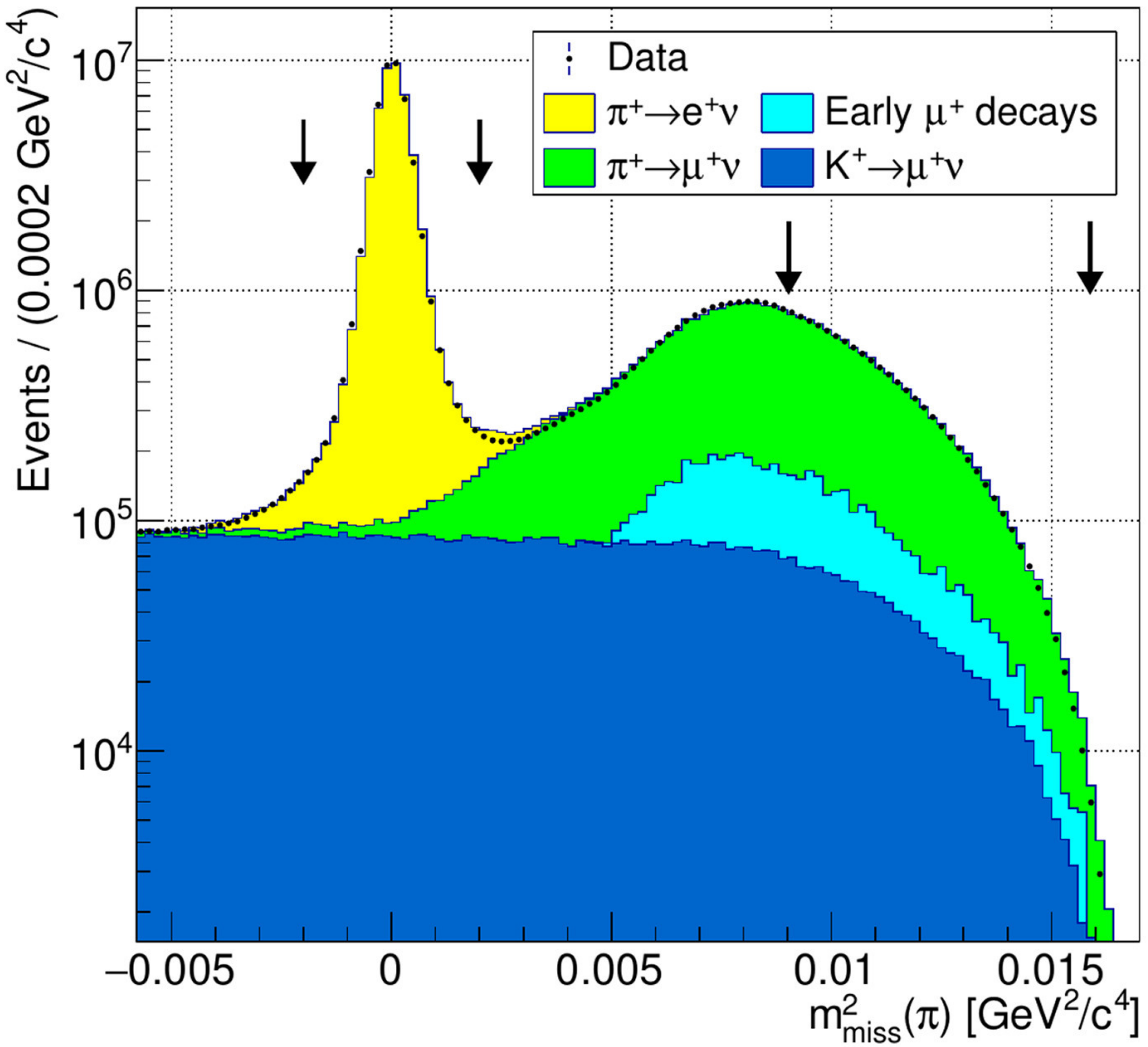


Search for $\pi^+ \to e^+ N$ with NA62

Phys. Lett. B 872 (2026) 140119

Analysis strategy

- $\pi^+ \to e^+ N$ decay is characterized by a single positron in the final state, similarly to the SM $\pi^+ \to e^+ \nu$ decay
- Experimental signature:
  - π^+ with 4-momentum P_{π^+} in the initial state
  - e^+ with 4-momentum P_{e^+} and missing energy in the final state
- m^2_{miss} is the key variable:
  - $m^2_{miss}(\pi^+) = (P_{\pi^+} - P_{e^+})^2$
- Selection for each HNL mass hypothesis (m_{HNL}) includes a "mass window" condition: $|m^2_{miss} - m^2_N| < 1.5\,\sigma_{m^2_N}$: background is proportional to mass resolution.
- Resolution is crucial to resolve possible HNL mass splitting.



$$N_\pi = \frac{N^\pi_{SM} - N^\pi_{K^+\to\mu^+\nu}}{A^\pi_e \cdot \mathcal{B}(\pi^+ \to e^+\nu_e) + A^\pi_\mu \cdot \mathcal{B}(\pi^+ \to \mu^+\nu_\mu)} = (6.54 \pm 0.03) \times 10^{12}$$

HNL results from 2017-2024 dataset

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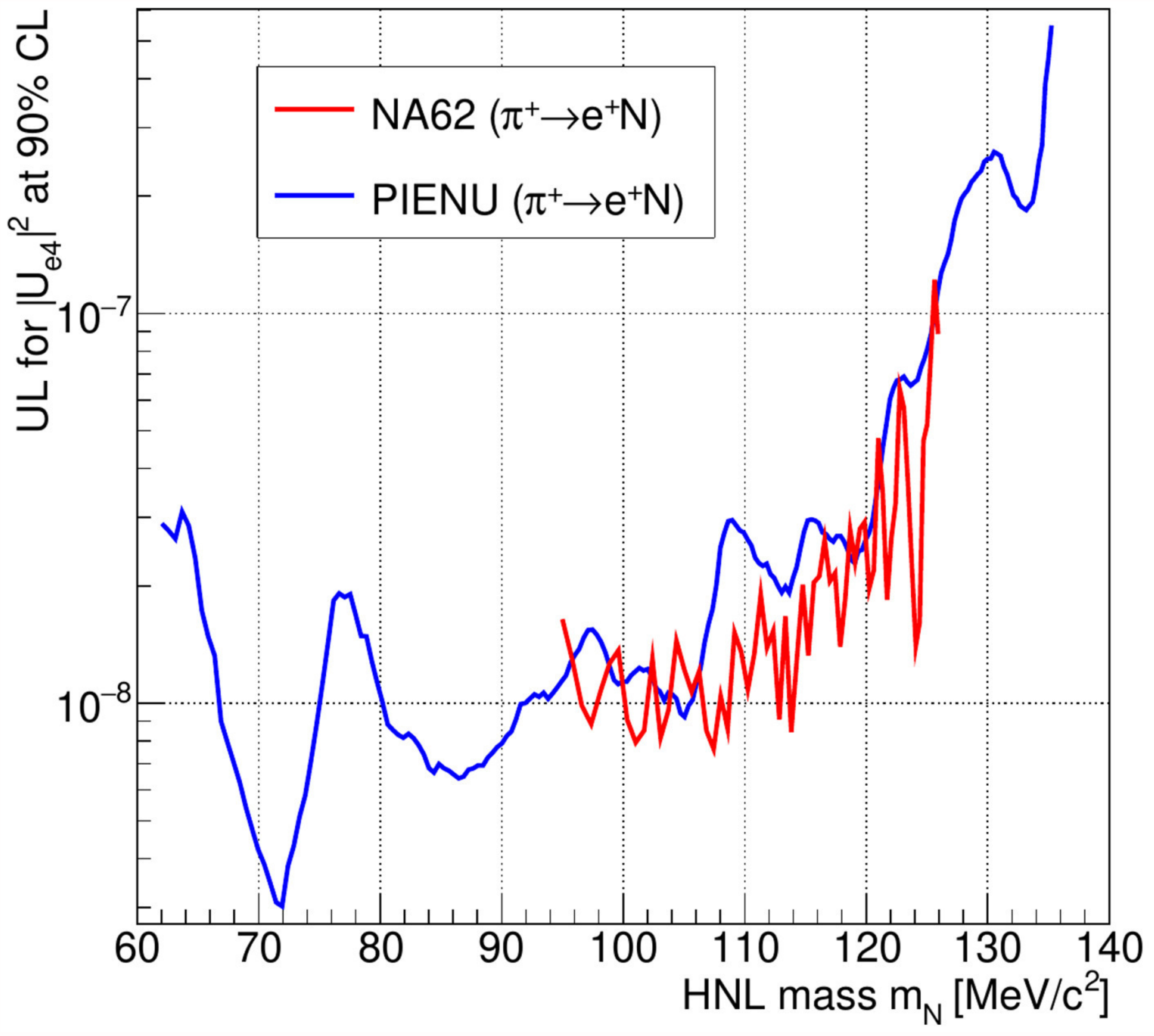
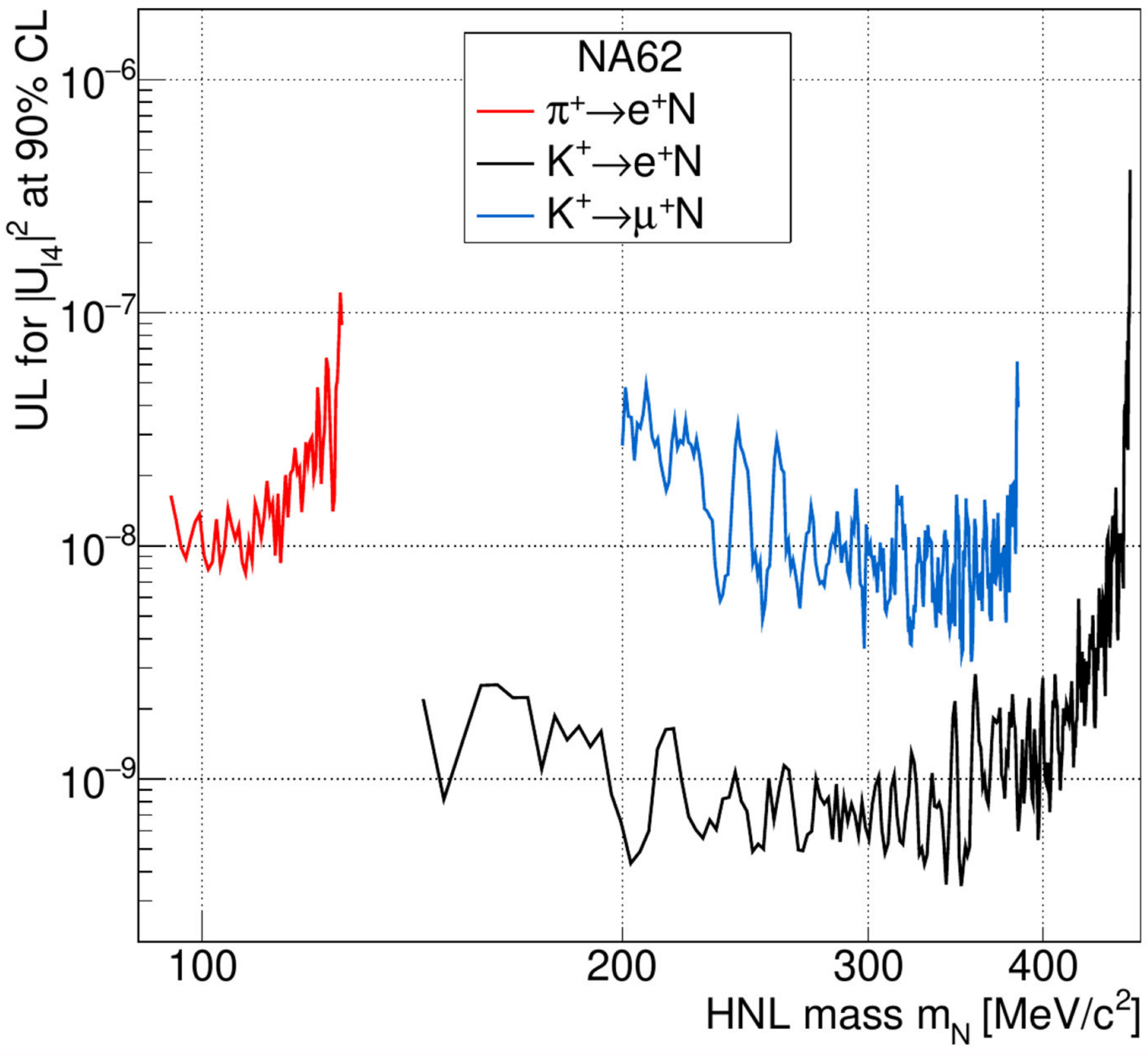


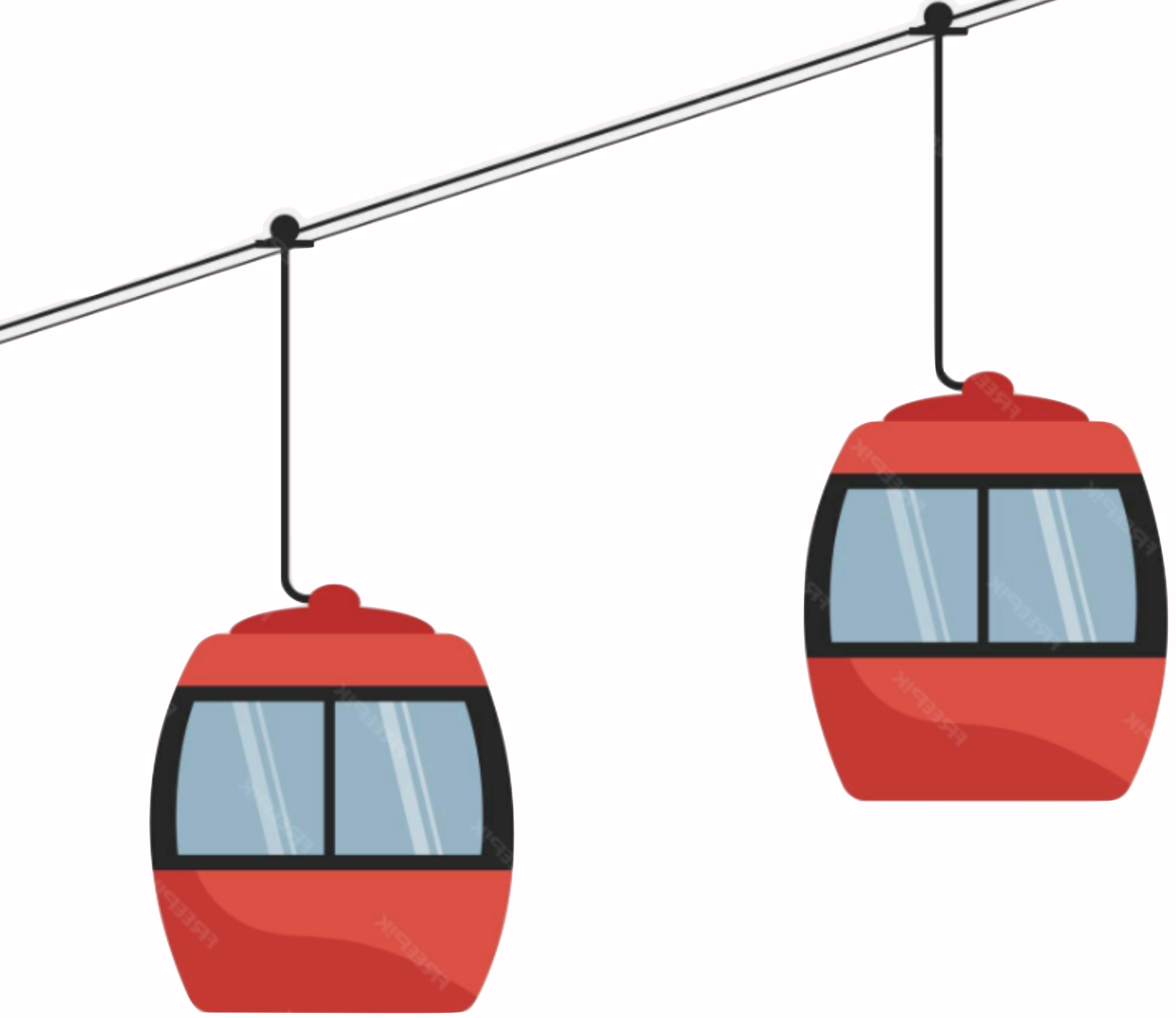
Phys. Lett. B807 (2020) 135599



Conclusions

- Constraints on the production of a hidden-sector particle X derived from studies of the rare kaon decays $K^+ \to \pi^+ \nu \bar{\nu}$, $K^+ \to \pi^+ \gamma\gamma$ and $K^+ \to \pi^+ \mu^+ \mu^-$
  - Scenarios where X is invisible or visible (decaying to a pair of SM particles) are considered
  - New limits obtained for a vector particle decaying to invisible final states, as well as for scalar and ALPs
  - Interpretation of the $K^+ \to \pi^+ \nu \bar{\nu}$ measurement to search for $K^+ \to \pi^+ X_{inv}$ extended to the 2016-2022 dataset, provides world-leading constraints in the m_X ranges $0 - 100$ MeV/c^2 and $150 - 260$ MeV/c^2

- A search for HNL production in $\pi^+ \to e^+ N$ decays performed using the data collected in 2017–2024
  - Upper limits for the mixing parameter $|U_{e4}|^2$ established at the 10^{-8} level over the HNL mass range $95 - 126\, MeV/c^2$
  - Improved sensitivity in terms of $|U_{e4}|^2$ is expected including future NA62 data



Backup

A kaon factory at CERN

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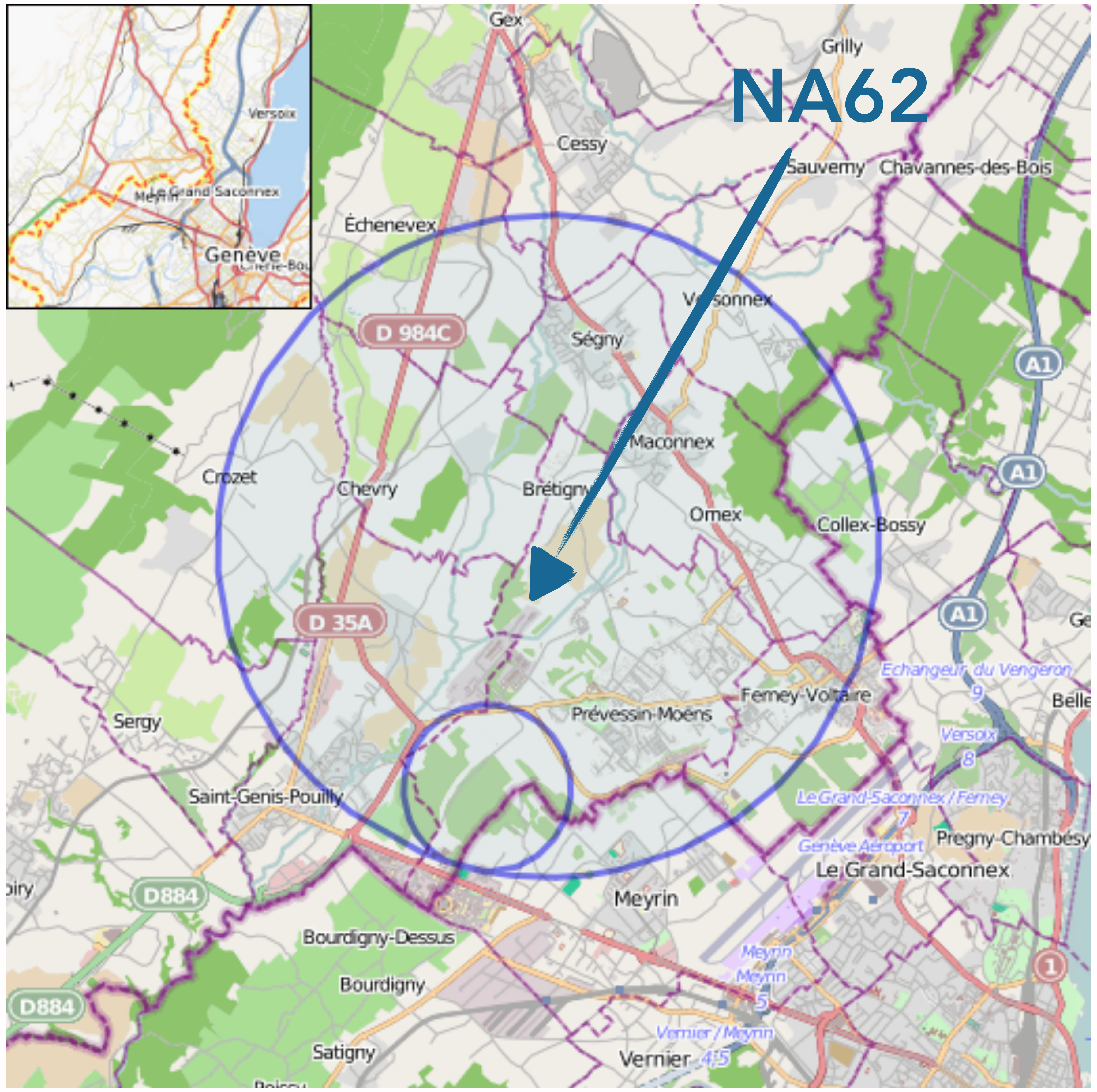

- Beam from the SPS: **400 GeV/c protons** on Be target
- Secondary 75 GeV/c beam hadrons (70% π, 24% p and **6%** K)
- **Decay in flight:** K^+ decay in a 60 meters long volume

The main aim of NA62 is to study the FCNC process $K^+ \to \pi^+ \nu \bar{\nu}$

Timeline of the NA62 Experiment:

2009-2014	2016-2018	2019-2021	2021-2026
Detector R&D Installation	Run1	LS2 upgrade	Run 2

Detector overview in kaon mode

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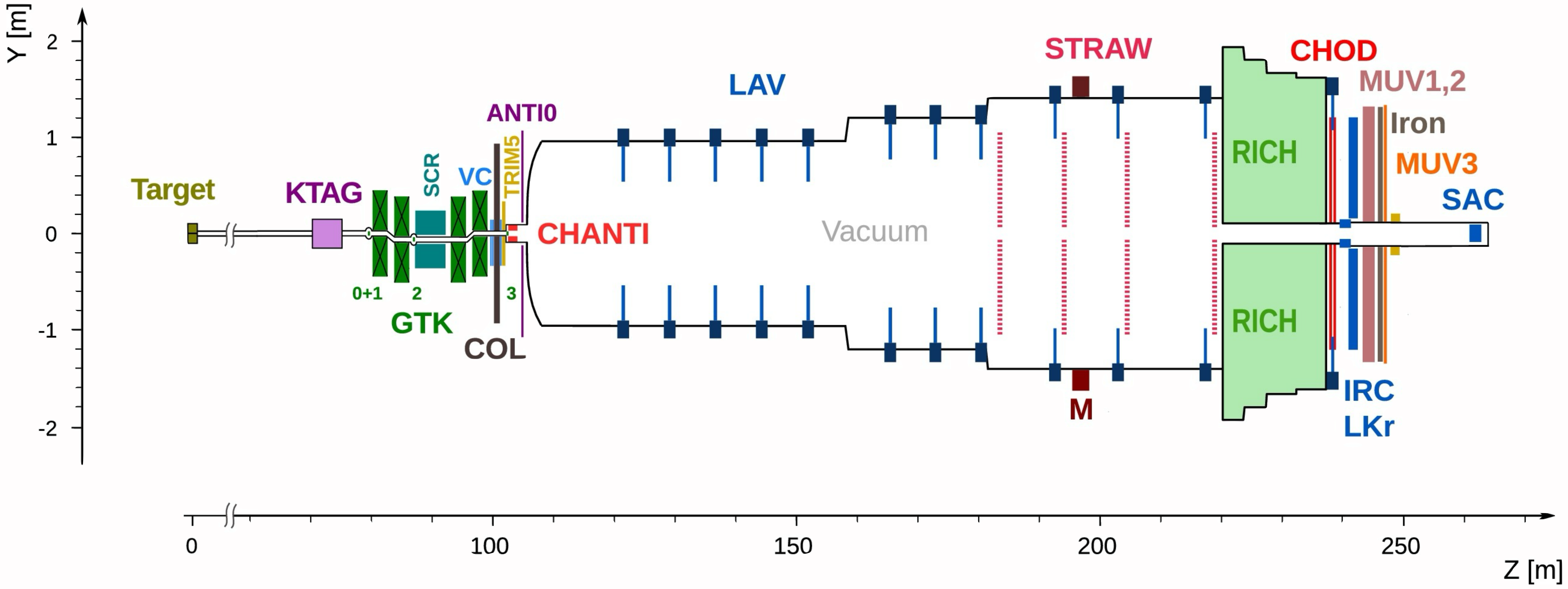
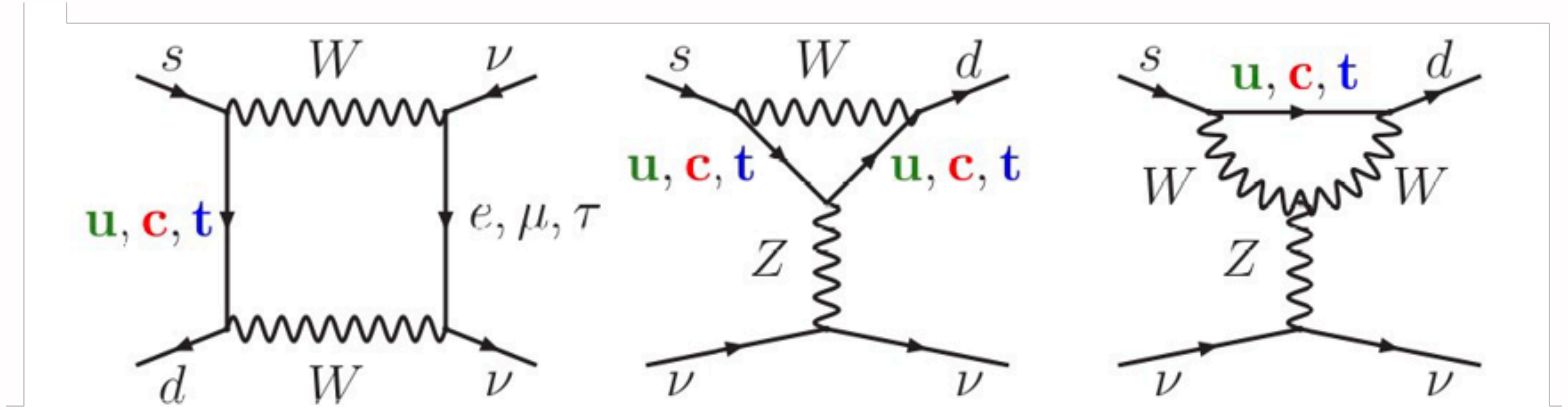


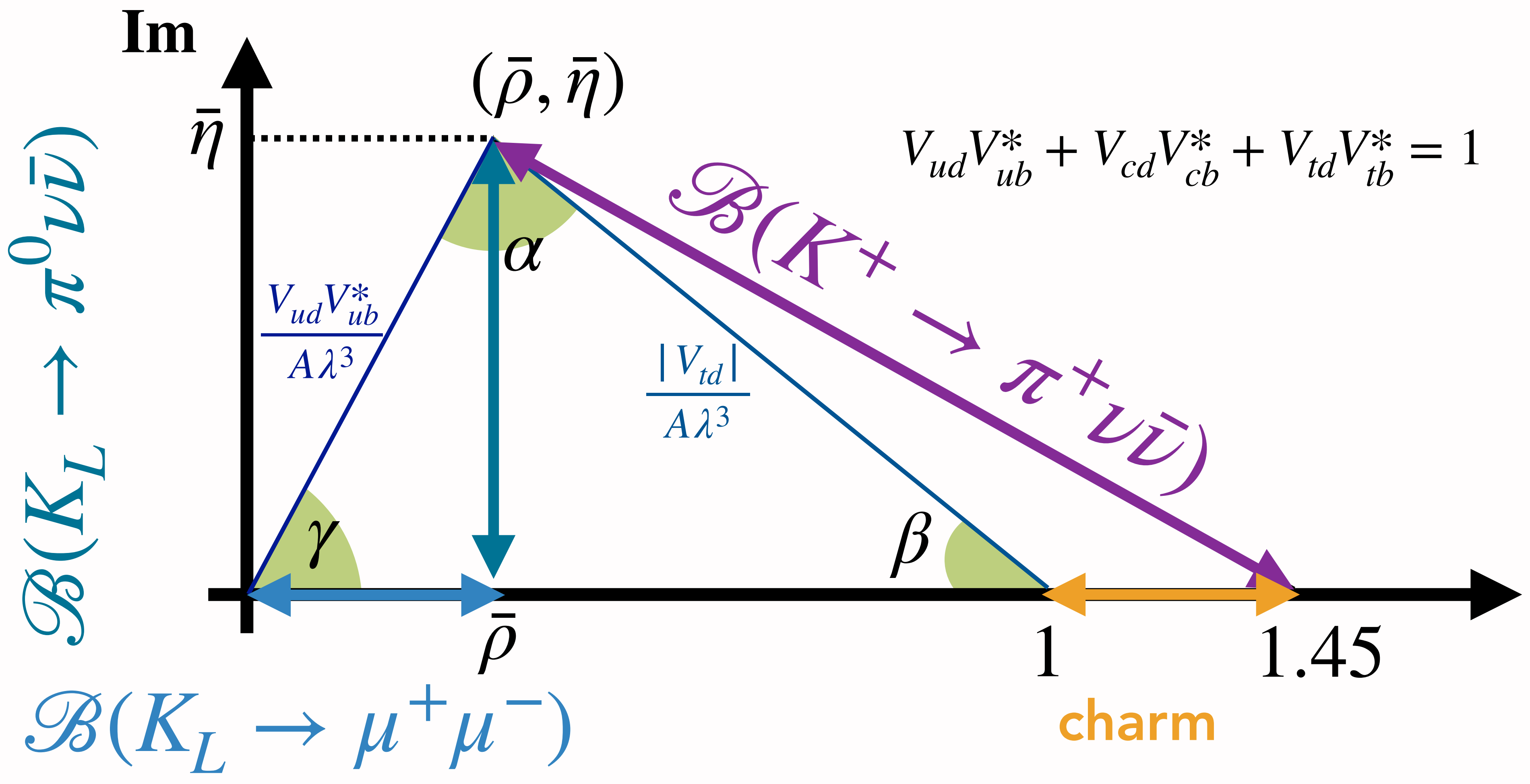
- Beam from the SPS: **400 GeV/c protons** on Be target
- Secondary 75 GeV/c beam hadrons (70% π, 24% p and **6%** K)
- **Decay in flight:** K^+ decay in a 60 meters long volume

$K \to \pi\nu\bar{\nu}$ to test Standard Model

SM: diagrams Z-penguin & box



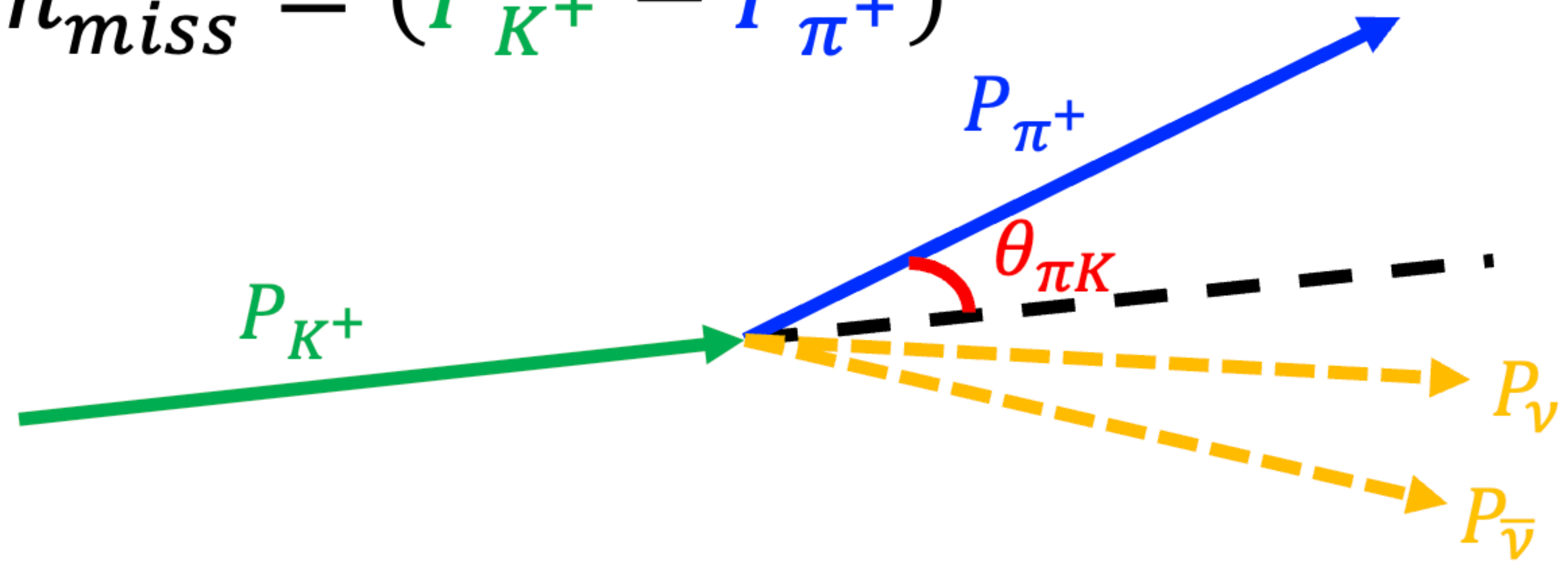
Unitarity triangle



- $\mathcal{B}(K \to \pi\nu\bar{\nu})$ **highly suppressed in SM**
  - GIM mechanism & maximum CKM suppression ($s \to d$ transition): $\sim \frac{m_t}{m_W} \left| V_{ts}^* V_{td} \right|$
- **Theoretically clean $\Rightarrow$ high precision SM predictions:**
  - Dominated by short distance contributions
  - Hadronic matrix element extracted from $\mathcal{B}(K \to \pi^0 \ell^+ \nu_\ell)$ decays via isospin rotation

$K^+ \to \pi^+ \nu \bar{\nu}$ with the NA62 experiment

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



NA62 performance keystones:

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

NA62 strategy

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

Decay mode	Branching Ratio [PDG]	
$K^+ \to \mu^+\nu_\mu$	$(63.56 \pm 0.11)\,\%$	
$K^+ \to \pi^+\pi^0$	$(20.67 \pm 0.08)\,\%$	
$K^+ \to \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024)\,\%$	
$K^+ \to \pi^+\pi^-e^+\nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$	
$K^+ \to \pi^+\nu\bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$	[SM]

Buras et al. EPJC 82 (2022) 7, 615

Signal sensitivity

Effective number of K^+ decays, N_K

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

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

- Number of normalisation events ($N_{\pi\pi}$)
- Downscaling factor of normalisation trigger (generally 400) (D_0)
- Branching ratio of the $K^+ \to \pi^+\pi^0$ ($\mathcal{B}_{\pi\pi}$)
- Acceptance of the normalisation selection ($A_{\pi\pi}$)

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 efficiency (ε_{RV})
- Trigger efficiency (ratio) (ε_{trig})
- Signal selection acceptance ($A_{\pi\nu\bar{\nu}}$)

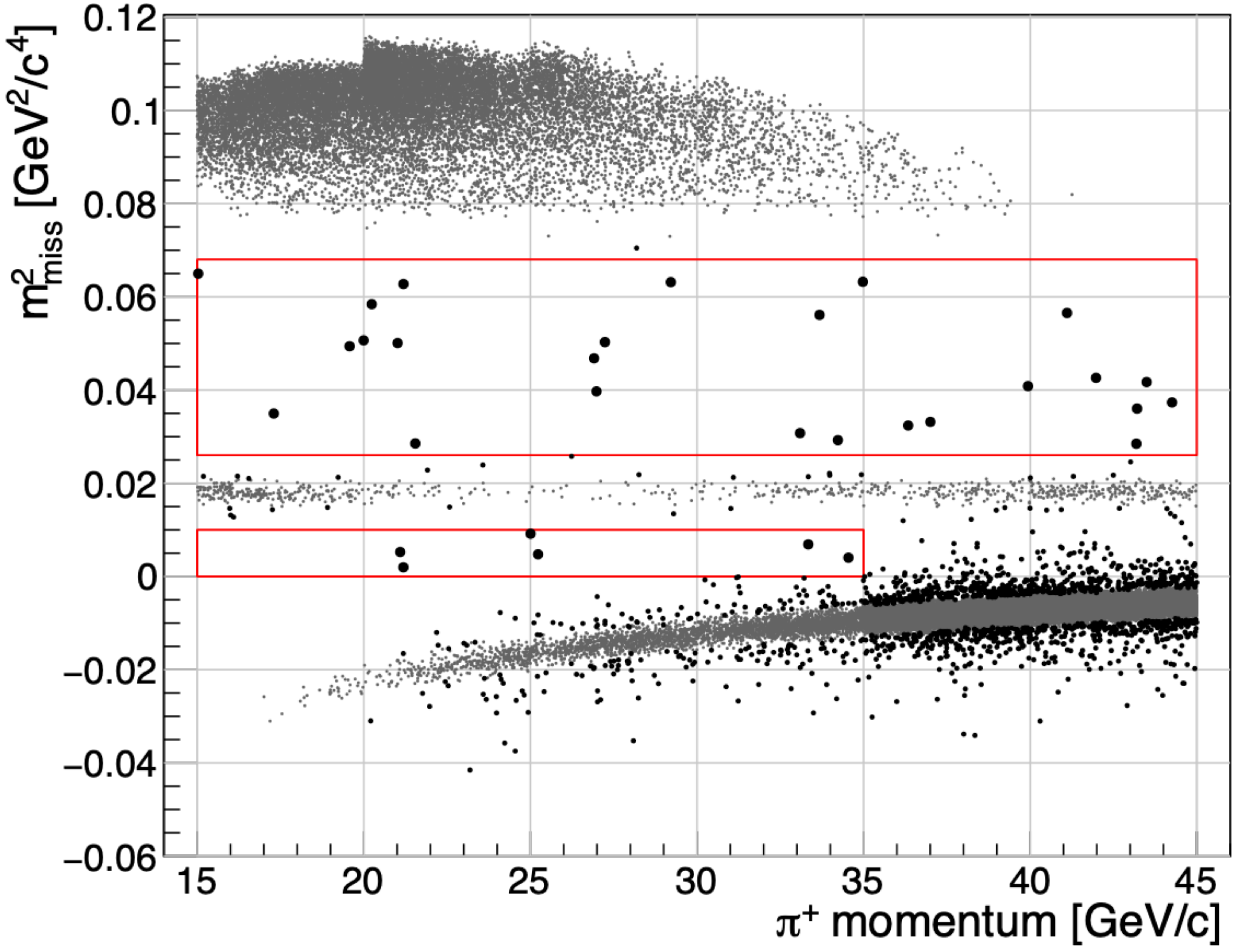
Number of expected SM events:

(For comparison to previous results use $\mathcal{B}^{SM}_{\pi\nu\bar{\nu}} = 8.4 \times 10^{-11}$ [JHEP 11 (2015) 166], but results are independent of this choice)

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

Observed events: 2021-2022 dataset

2021-22 data

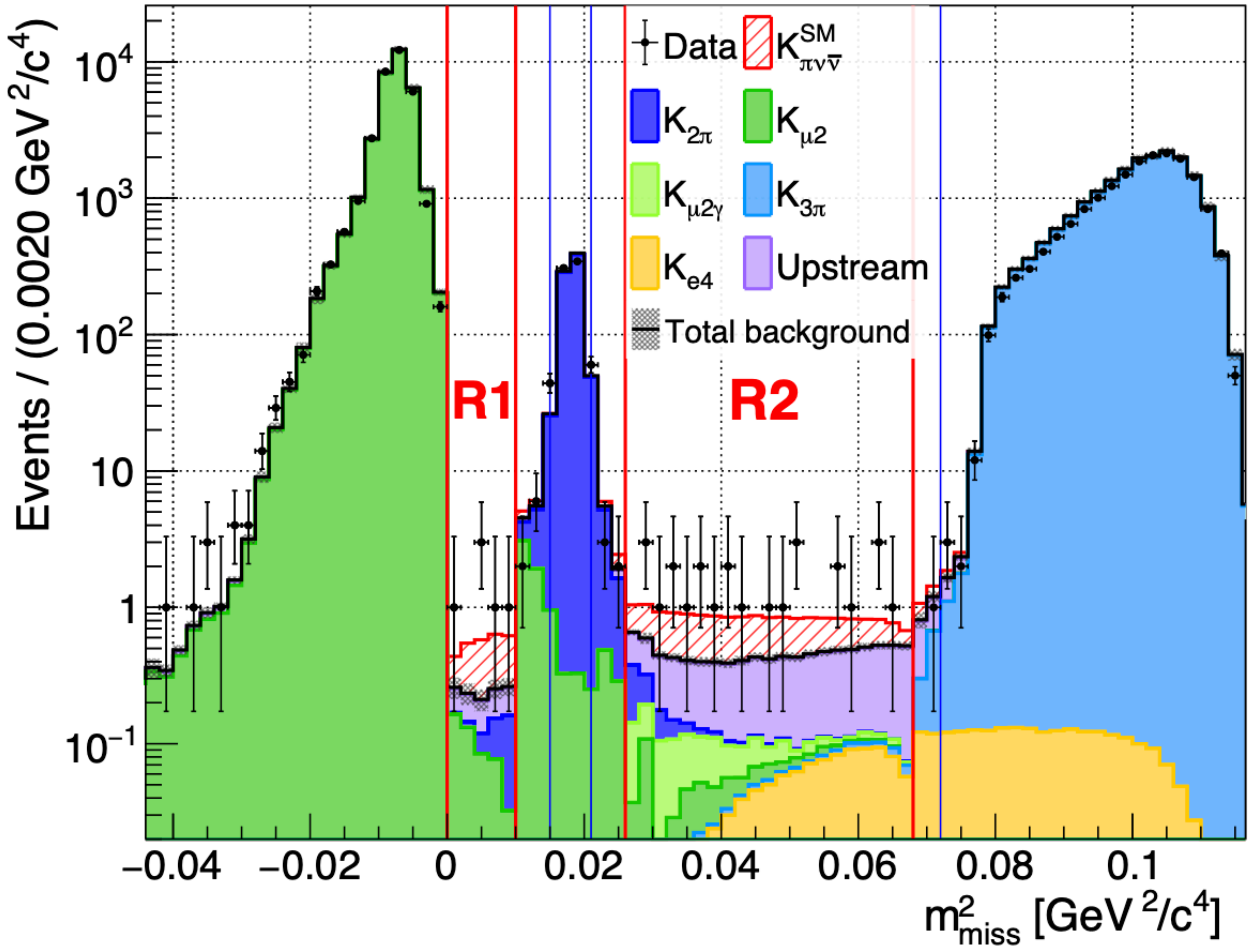


SM expected events, $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

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

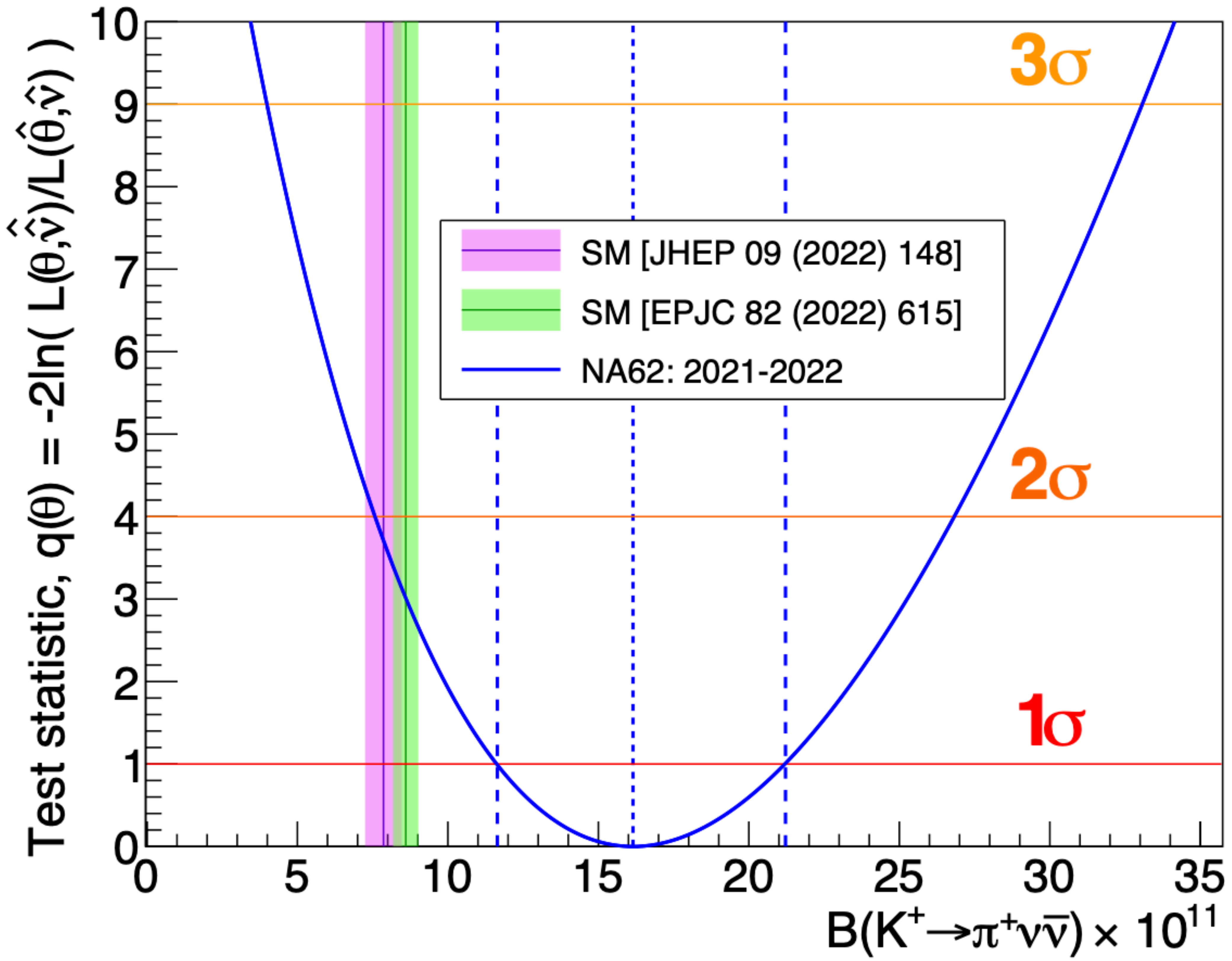
Observed, $N_{obs} = 31$

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



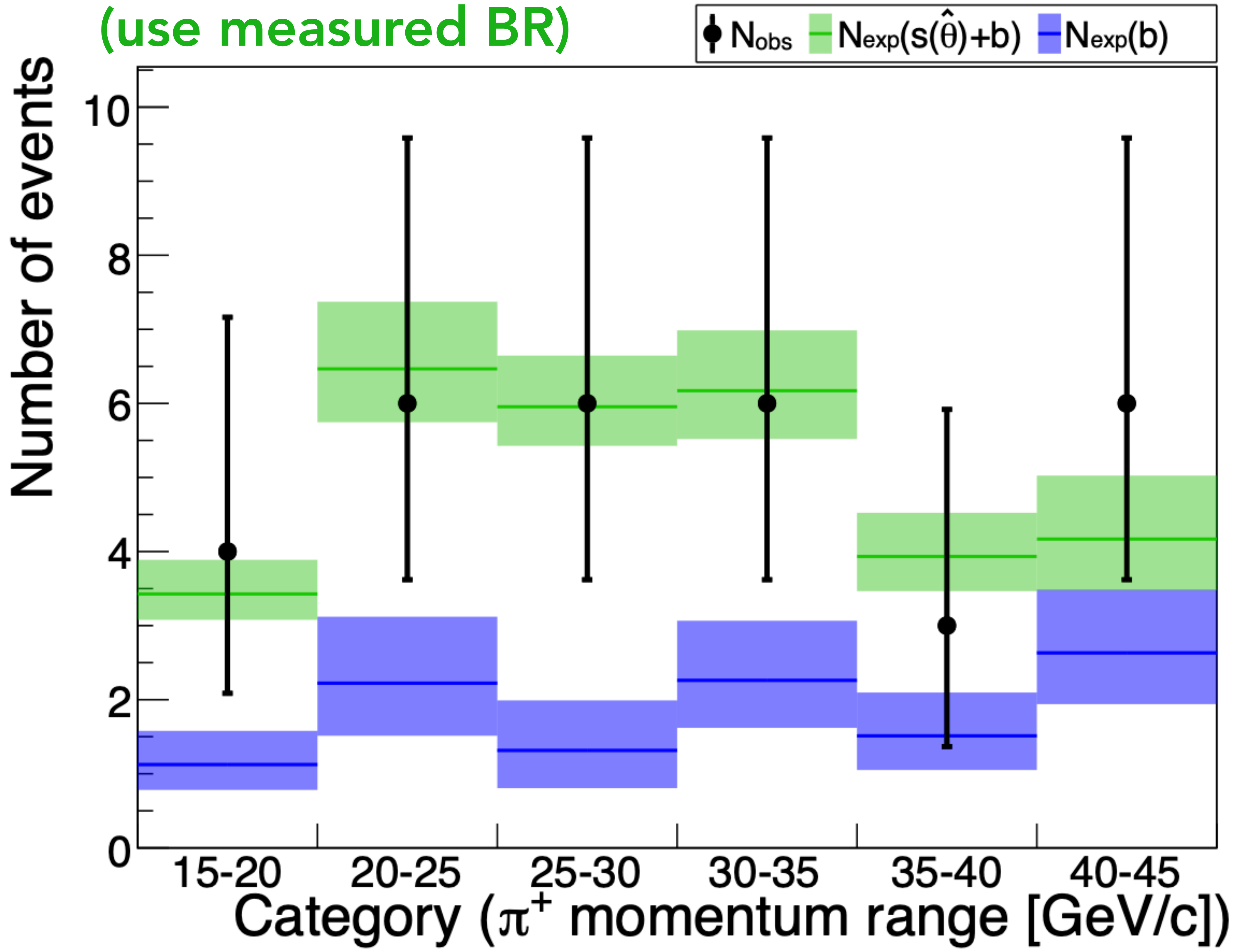
Results: 2021–2022 data

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



Use 6 (momentum bin) categories

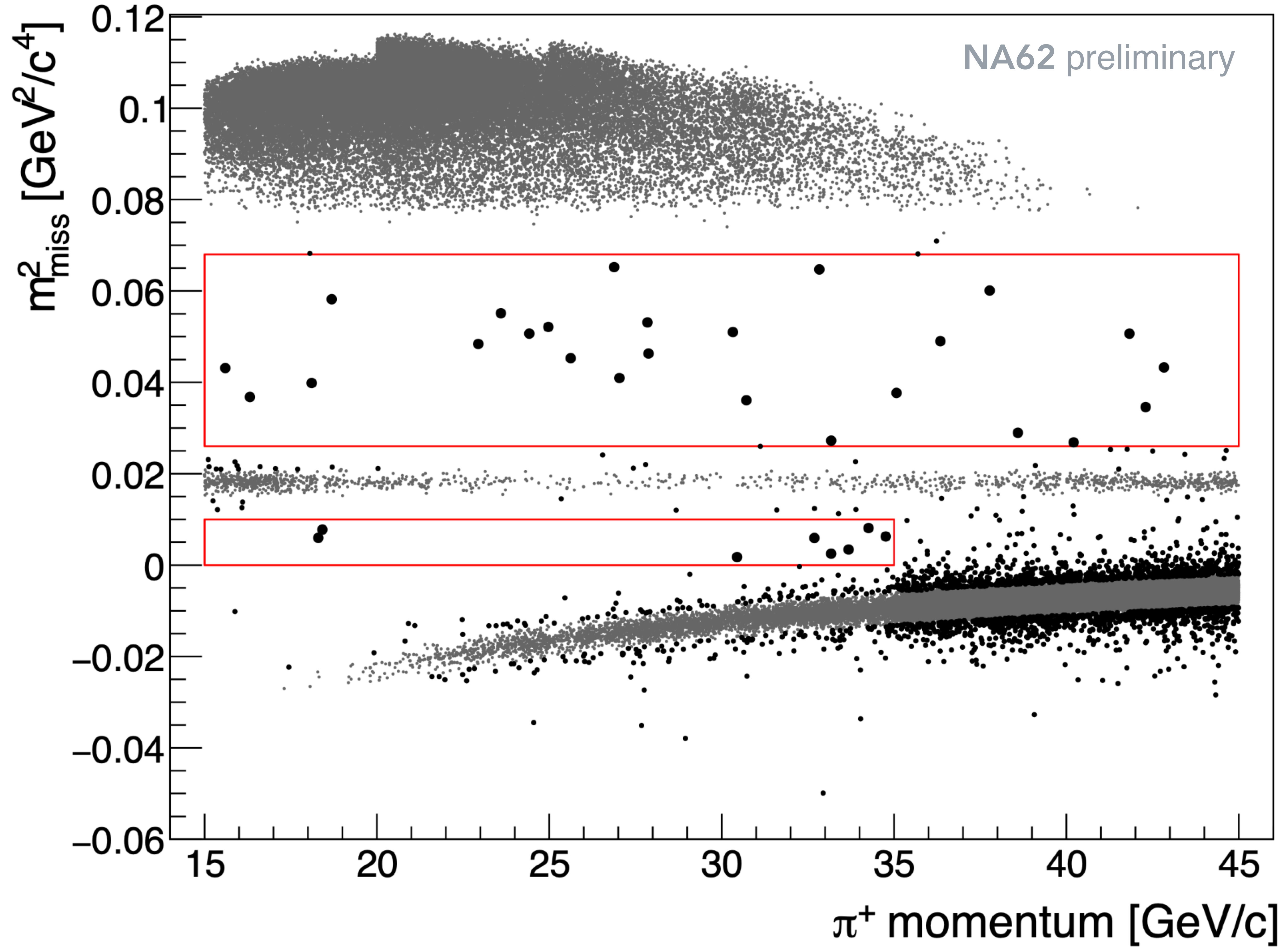
After fit (use measured BR)



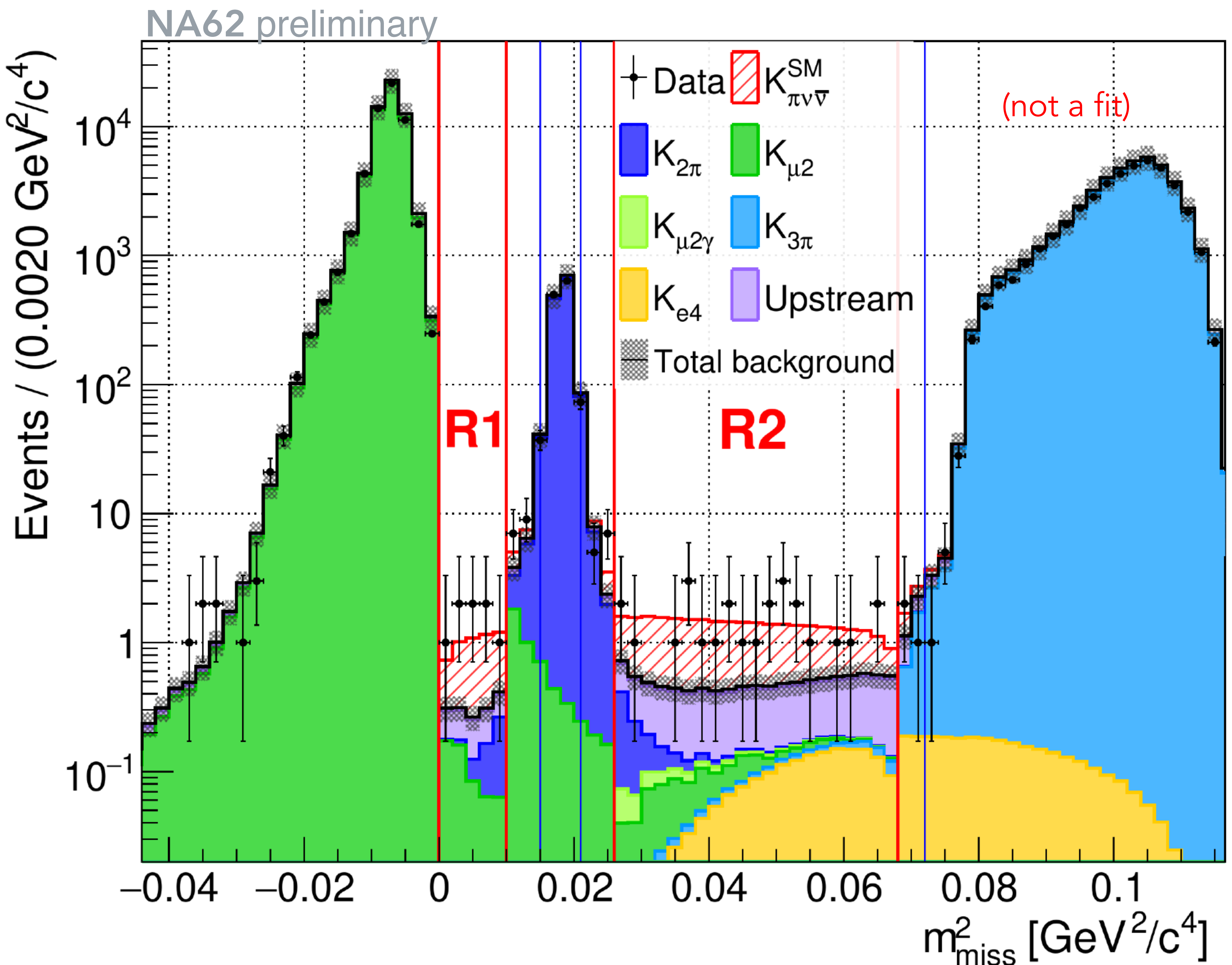
$$\mathscr{B}_{21-22}(K^+ \to \pi^+\nu\bar{\nu}) = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11} = \left(16.0 \left({}^{+4.8}_{-4.2}\right)_{stat} \left[{}^{+1.4}_{-1.3}\right]_{syst}\right) \times 10^{-11}$$

Observed events: 2023-2024 dataset

Preliminary
See X. Chang talk

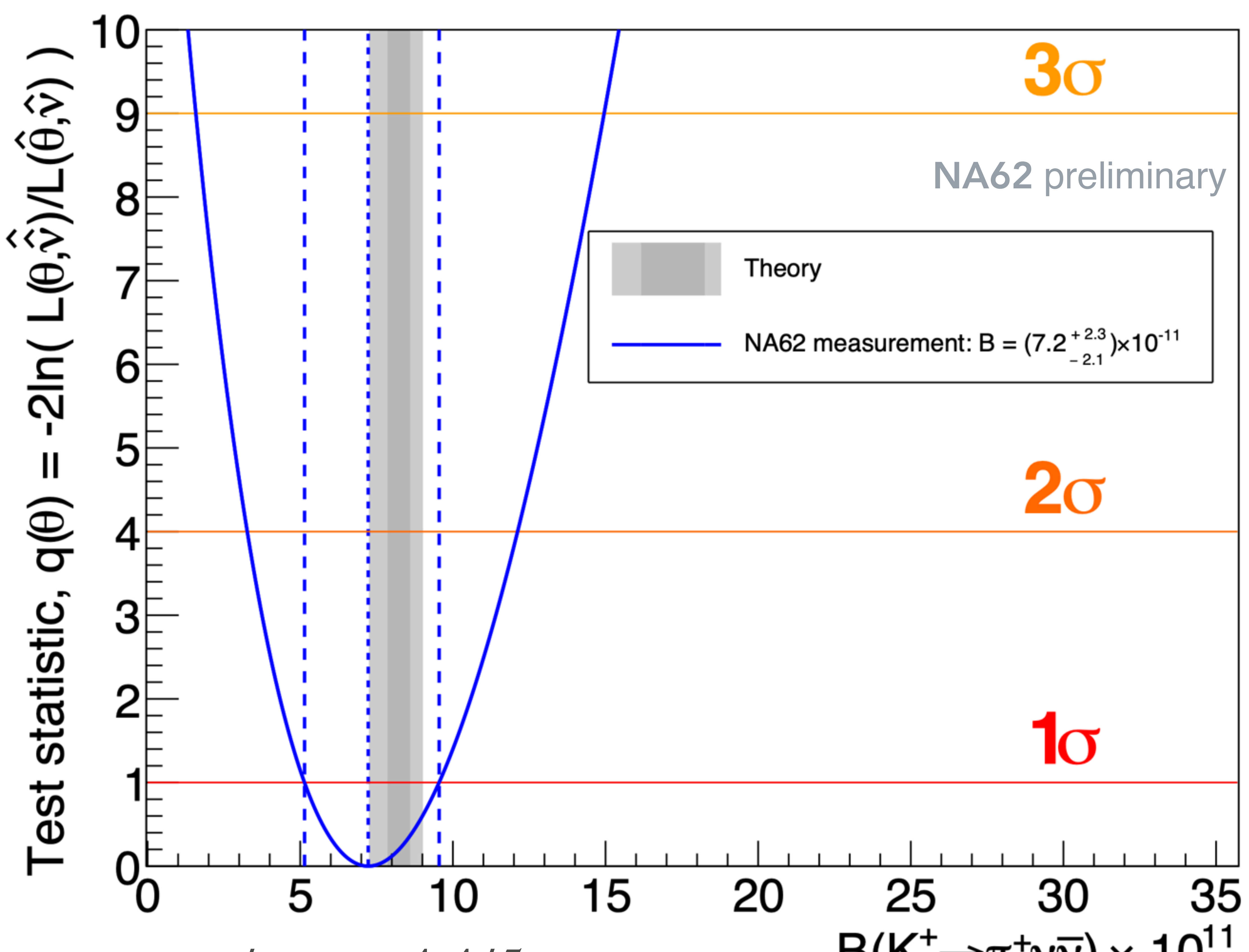


- Expected SM signal: 22.9 ± 1.1 assuming $\mathscr{B}_{SM} = 8.4 \times 10^{-11}$
- Estimated background: $11.9^{+2.9}_{-2.3}$
- Observed: **33**

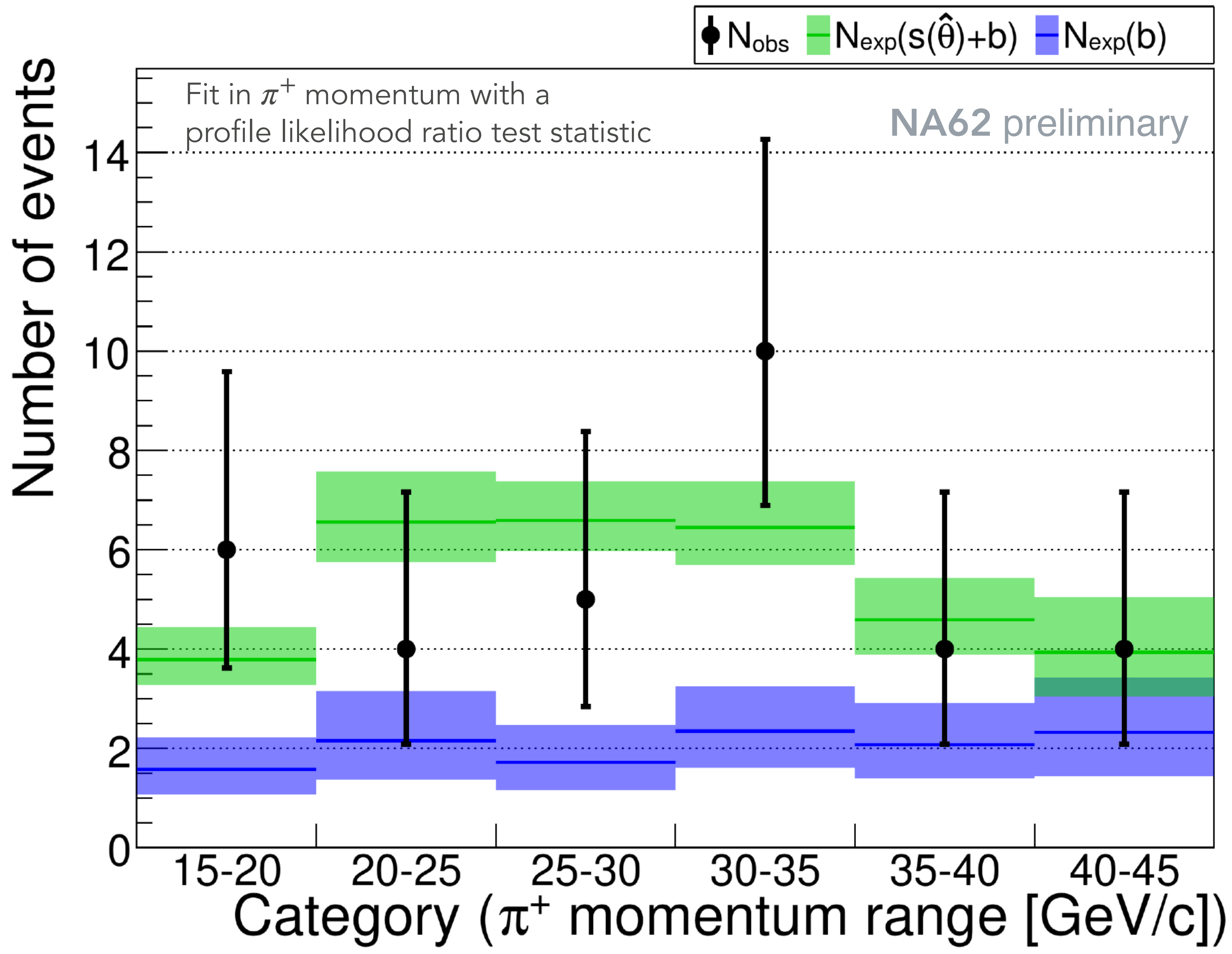


Br measurement: 2023-2024 data

Preliminary
See X. Chang talk



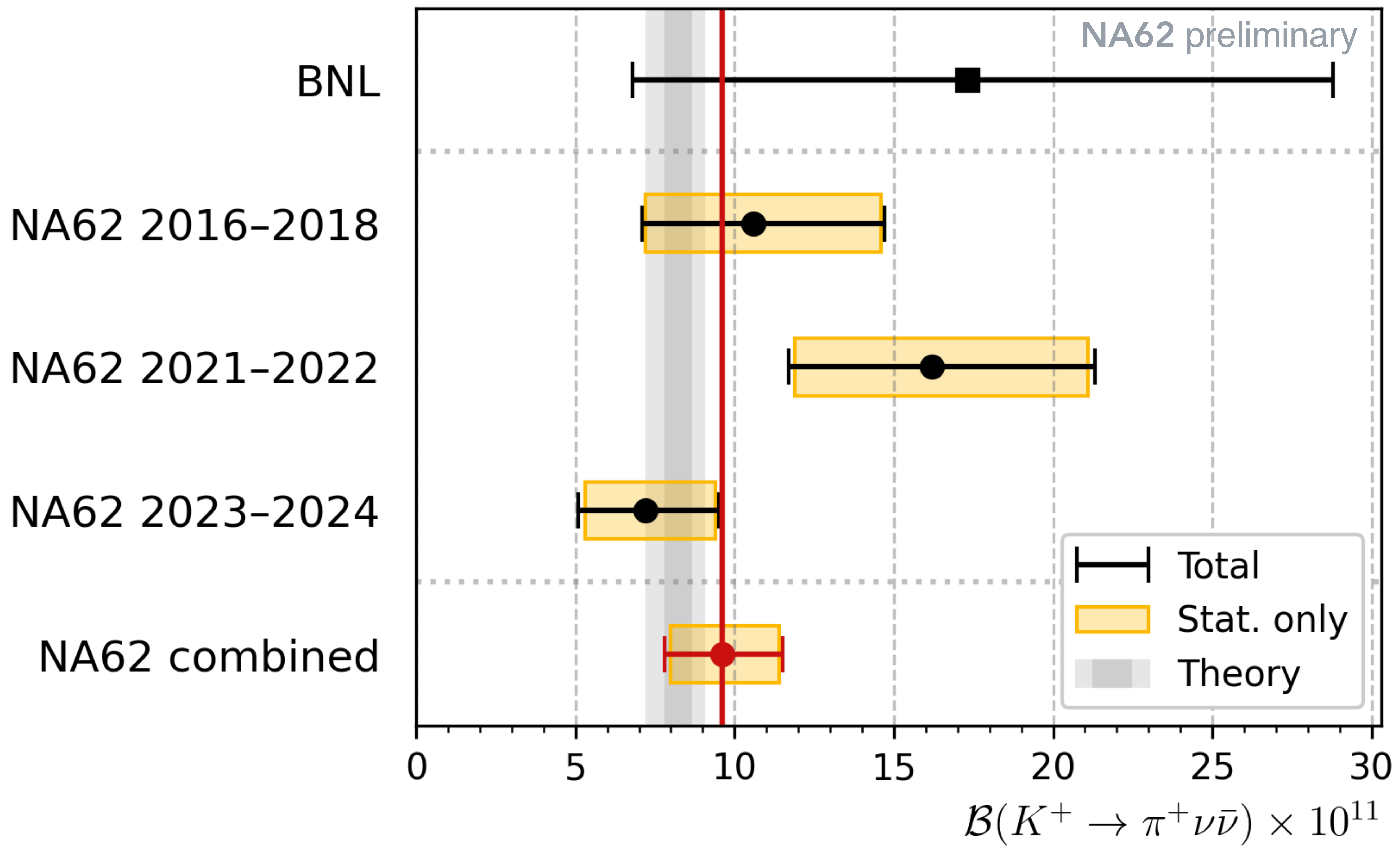
$q_{min}/n_{dof} = 4.4/5$

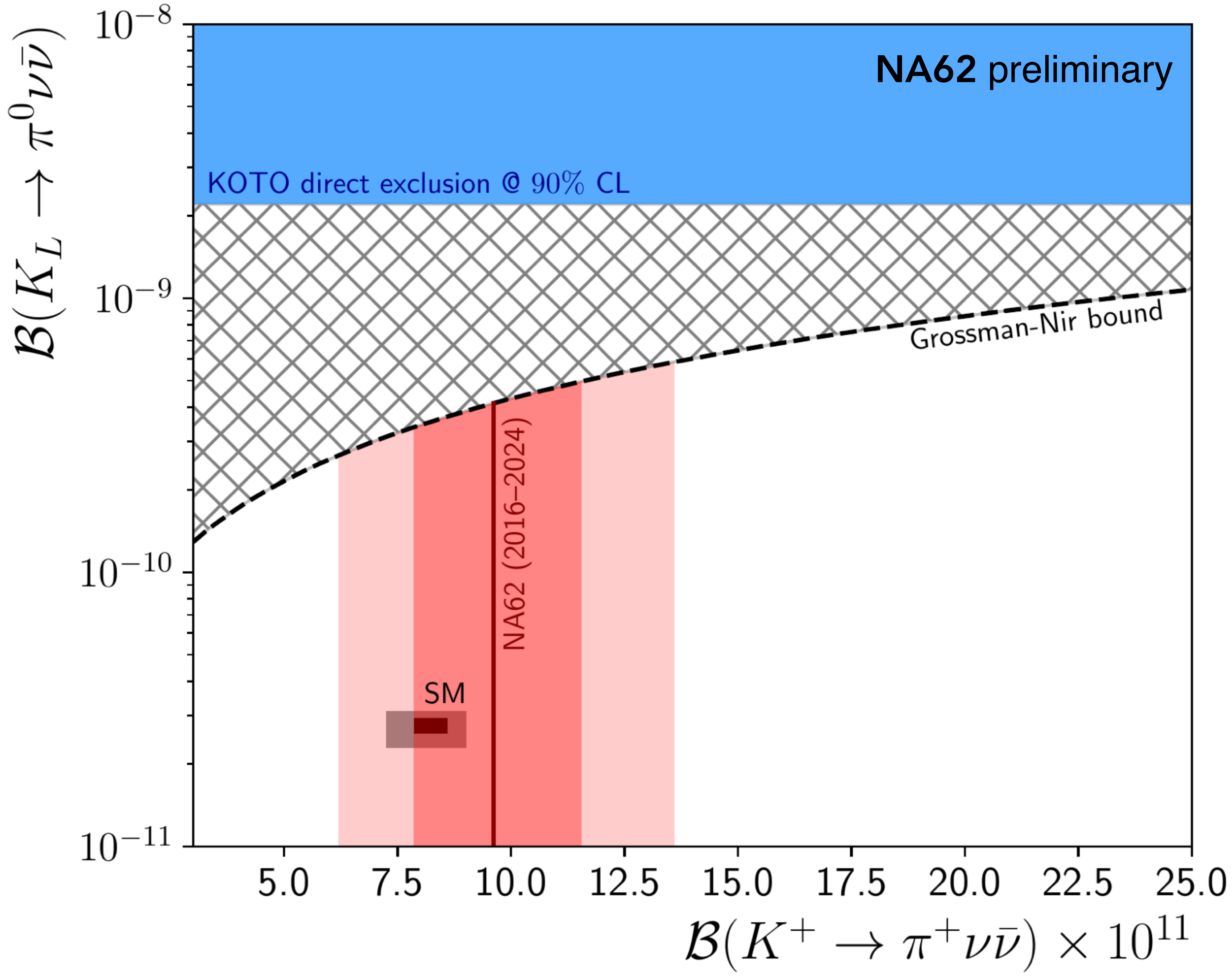


$$\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu})_{23-24} = (7.2^{+2.2}_{-1.9}|_{stat} {}^{+0.9}_{-0.9}|_{syst}) \times 10^{-11} = (7.2^{+2.3}_{-2.1}) \times 10^{-11}$$

Results in context

Preliminary
See X. Chang talk





NA62 and the dark sector searches

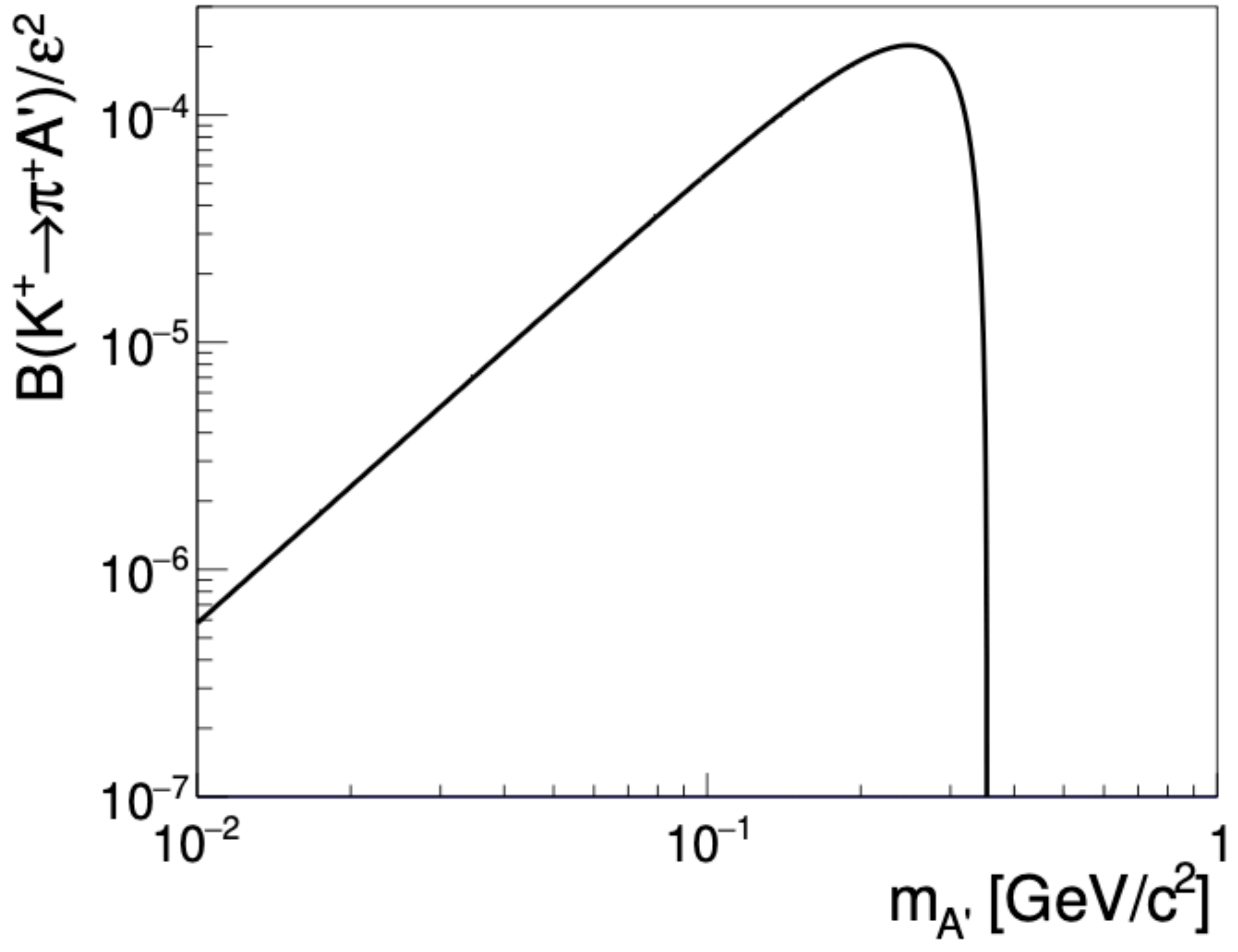
Dump mode	$e^+e^-, \mu^+\mu^-$, hadrons	A', S, ALPs	Phys.Rev.Lett. 133 (2024) 11, 111802 Eur.Phys.J.C 85 (2025) 5, 571
Kaon decays	invisible, $\mu^+\mu^-$	A', S, ALPs, HNL	Phys.Lett.B 846 (2023) 138193 JHEP 03 (2021) 058 Phys.Lett.B 816 (2021) Phys.Lett.B 807 (2020)
Pion decays	invisible	Vector portal , A'	JHEP 02 (2021) 201 JHEP 05 (2019) 182

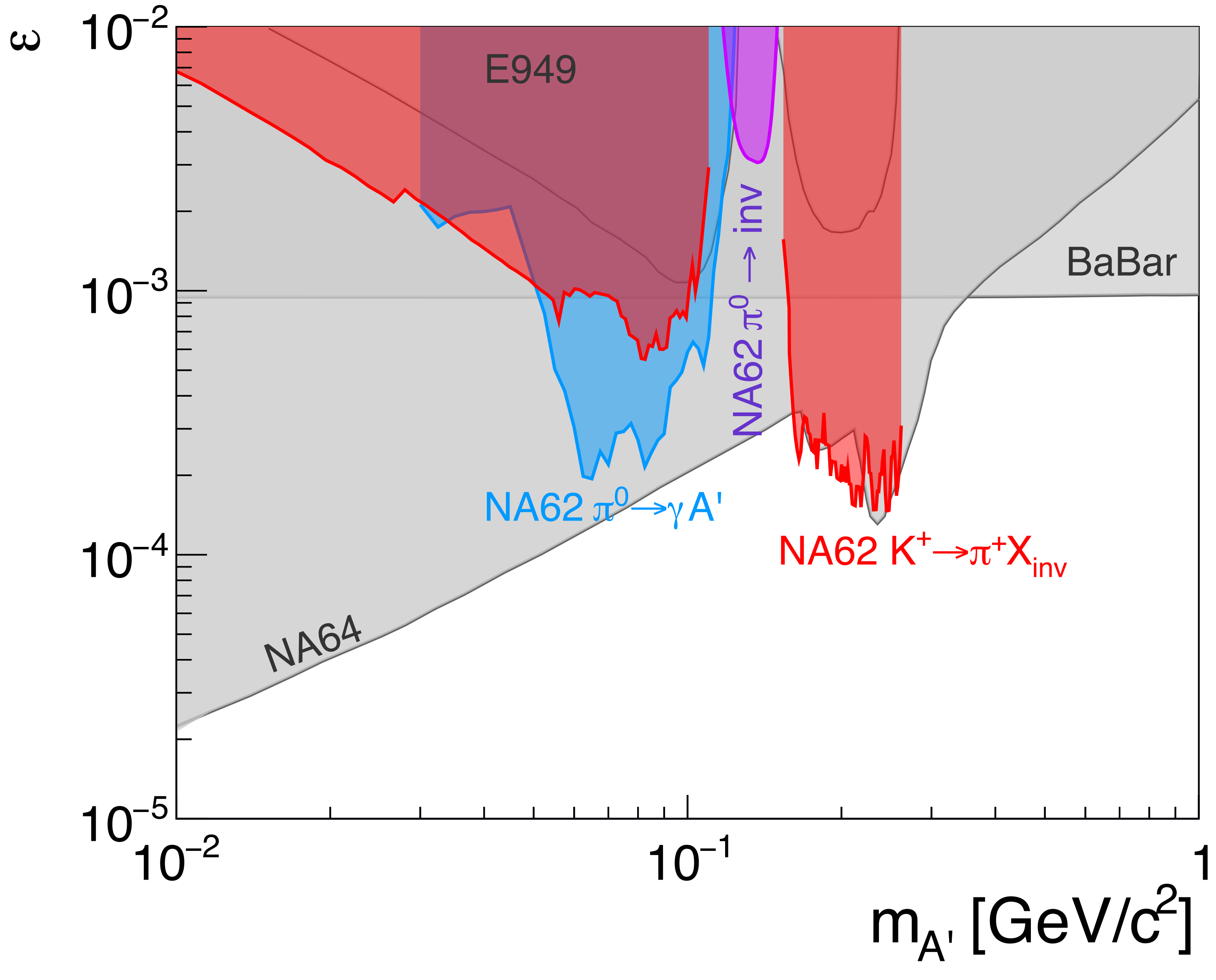
Dark sector dictionary

Benchmark	BSM particle (X)	Type	Coupling to SM	Search
BC1	dark photon (A')	vector	ε	$\mu^+\mu^-$
BC2	dark photon (A')	vector	ε	invisible
BC4	dark scalar (S)	scalar	θ	invisible, $\mu^+\mu^-$
BC4-inv	dark scalar (S)	scalar	θ	invisible
BC10	axion-like particle (a)	pseudoscalar	C_{ff} (to fermions)	invisible, $\mu^+\mu^-$
BC10-inv	axion-like particle (a)	pseudoscalar	C_{ff} (to fermions)	invisible
BC11	axion-like particle (a)	pseudoscalar	C_{GG} (to gluons)	invisible, $\gamma\gamma$

The vector portal: $K^+ \to \pi^+ A' (A' \to inv.)$ decay BC2

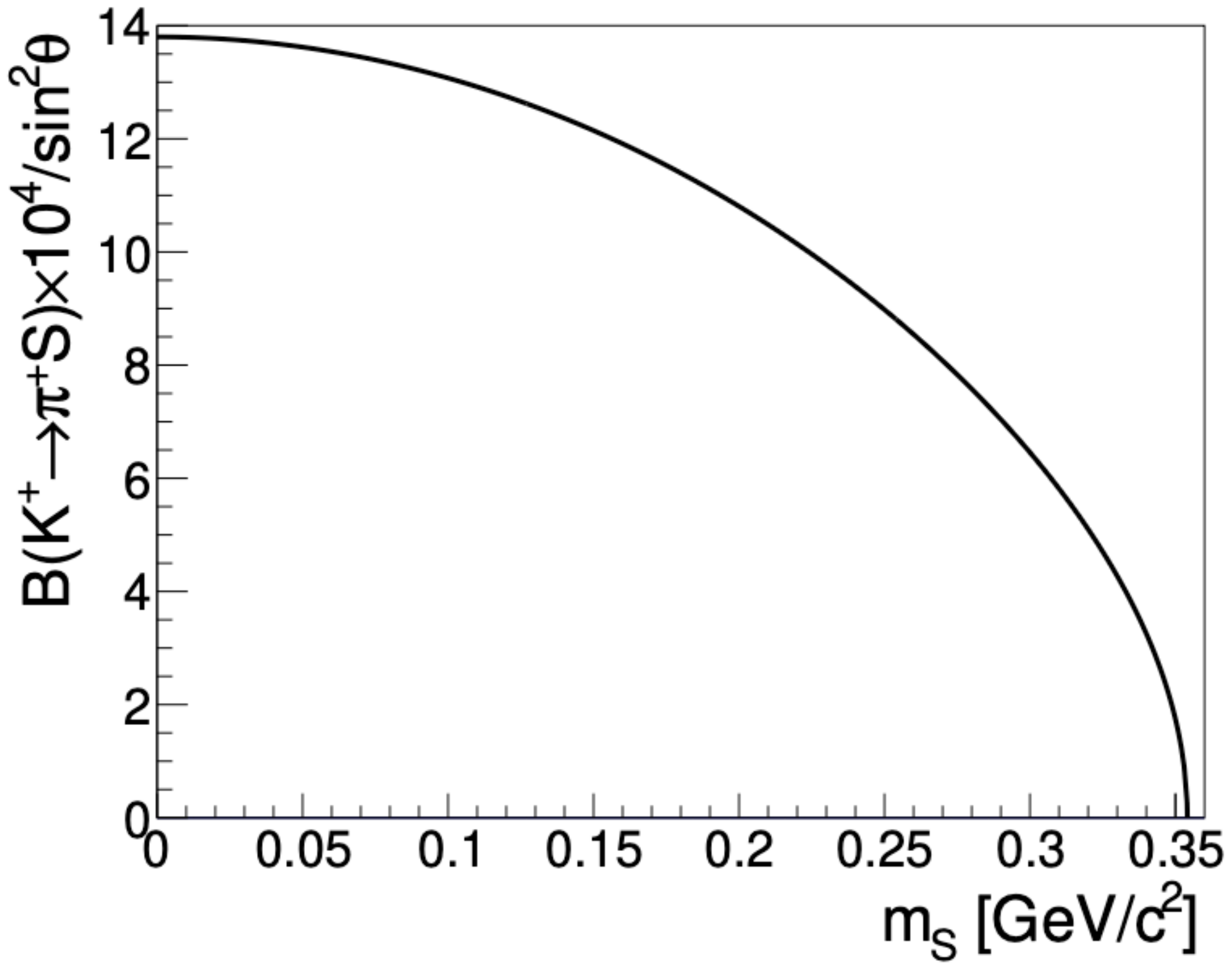
$$|\mathcal{M}| = \frac{e\varepsilon |W(z)| m_{A'}}{16\pi^2 m_K^2} \sqrt{\lambda(m_K^2, m_\pi^2, m_{A'}^2)}$$

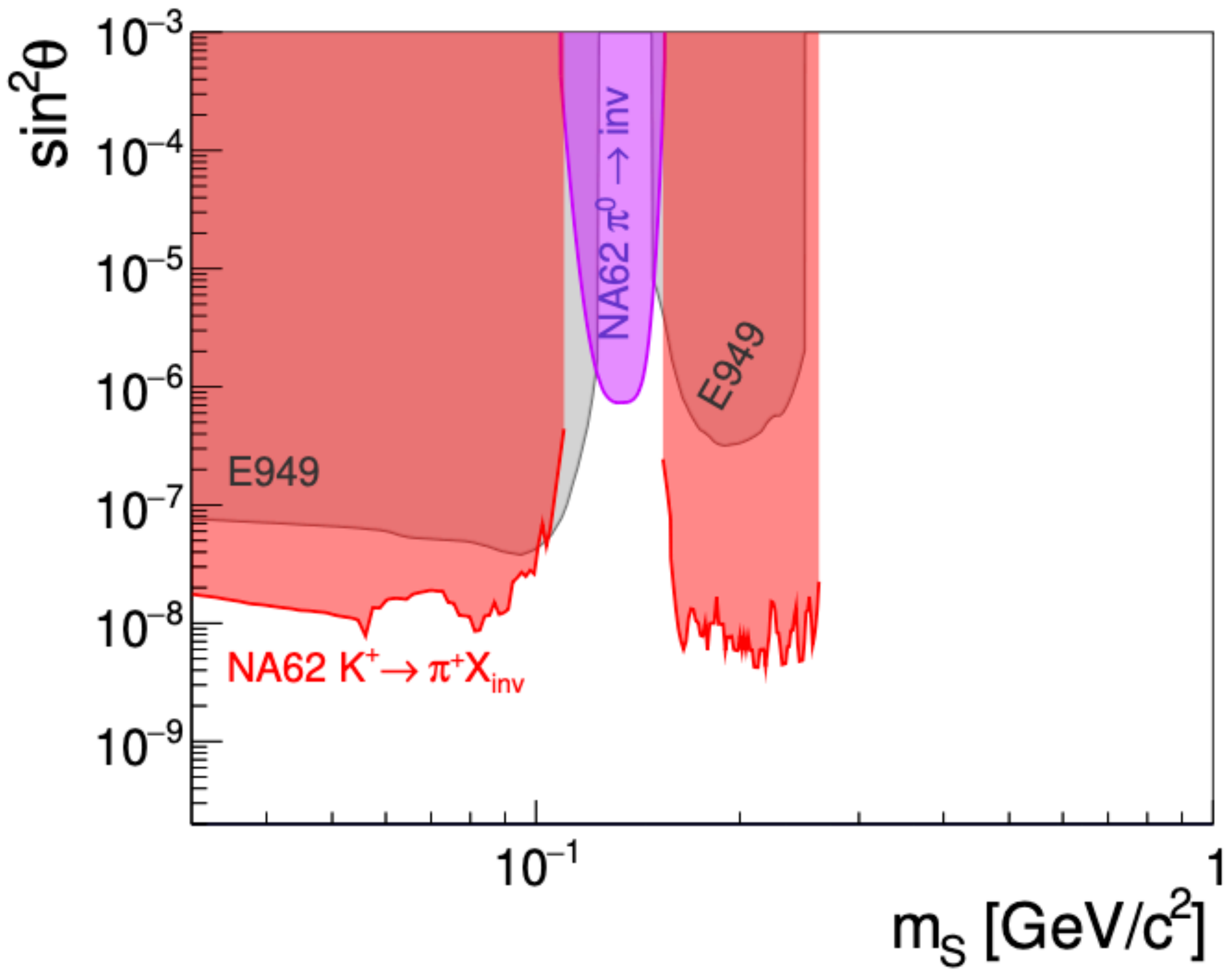




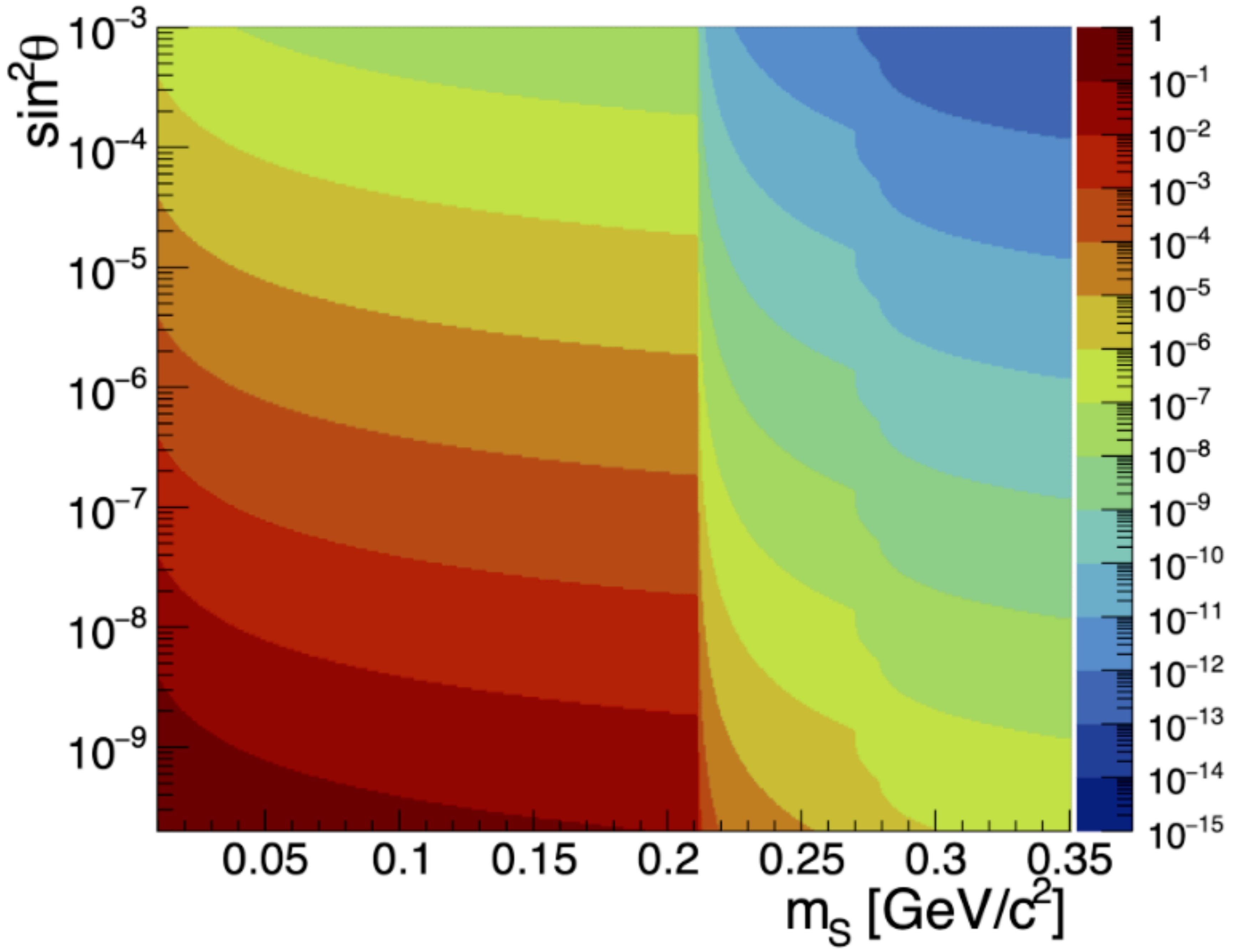
The scalar portal: $K^+ \to \pi^+ S\,(S \to inv.)$ decay BC4-inv

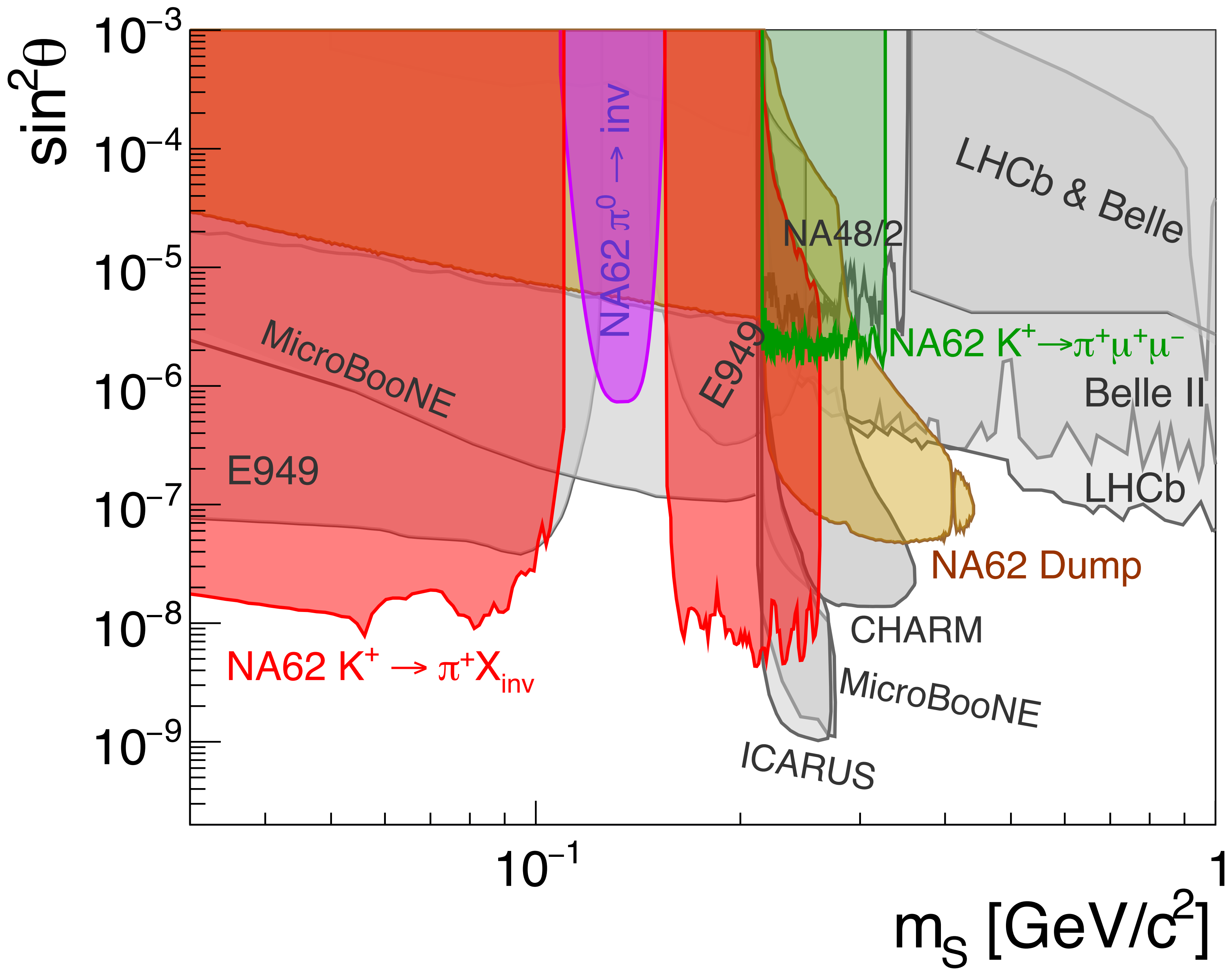
$$|\mathcal{M}| = \frac{1}{2}\left(\frac{m_K^2 - m_\pi^2}{m_s - m_d}\right)\left(\frac{m_S}{v}\frac{3\sqrt{2}G_F}{16\pi^2}m_t^2|V_{ts}^* V_{td}|\right)\sin\theta = \sqrt{(8\pi\Gamma_K m_K)\,C}\,\sin\theta$$





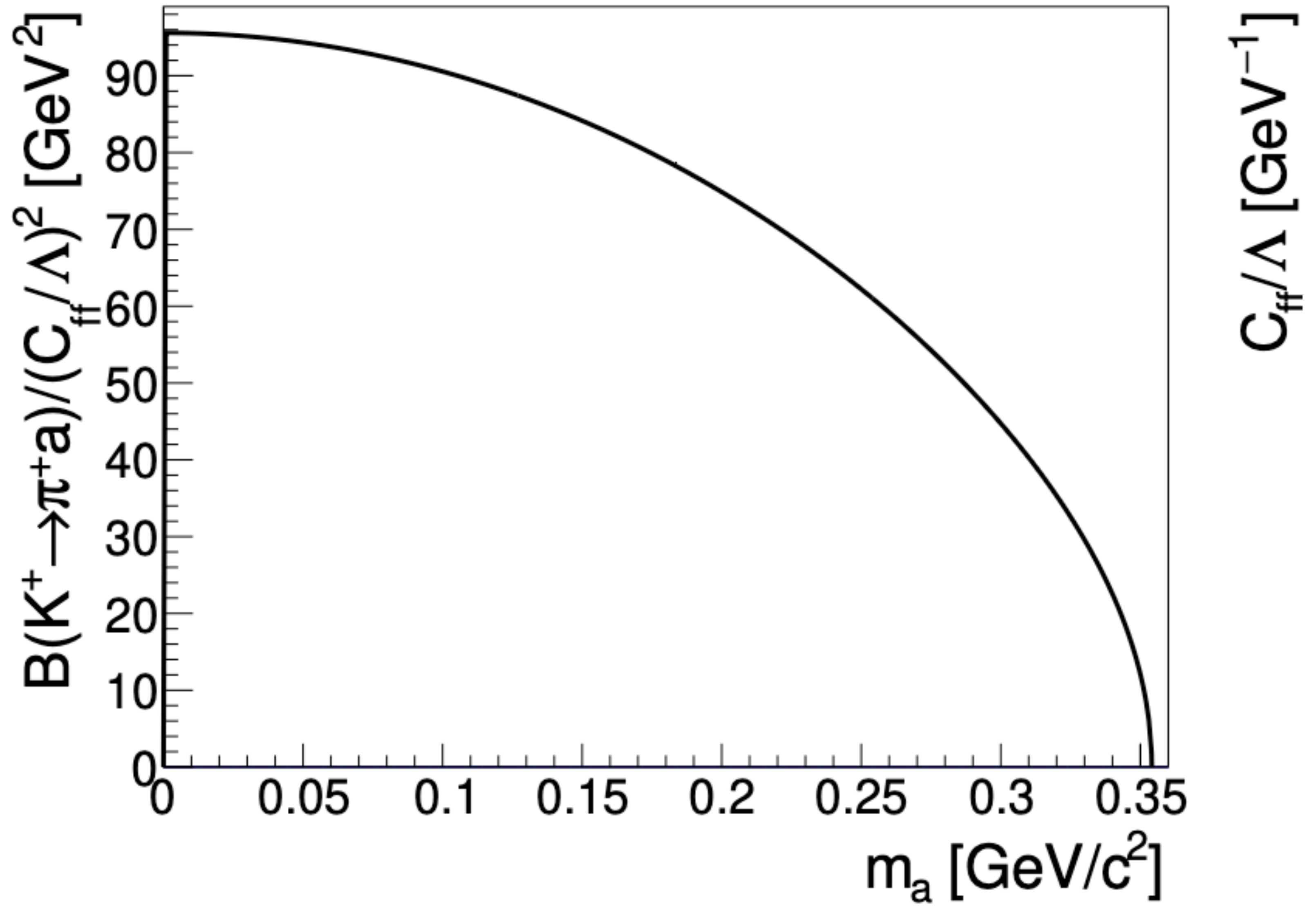
The scalar portal: $K^+ \to \pi^+ S\,(S \to \mathit{visible})$ decay BC4

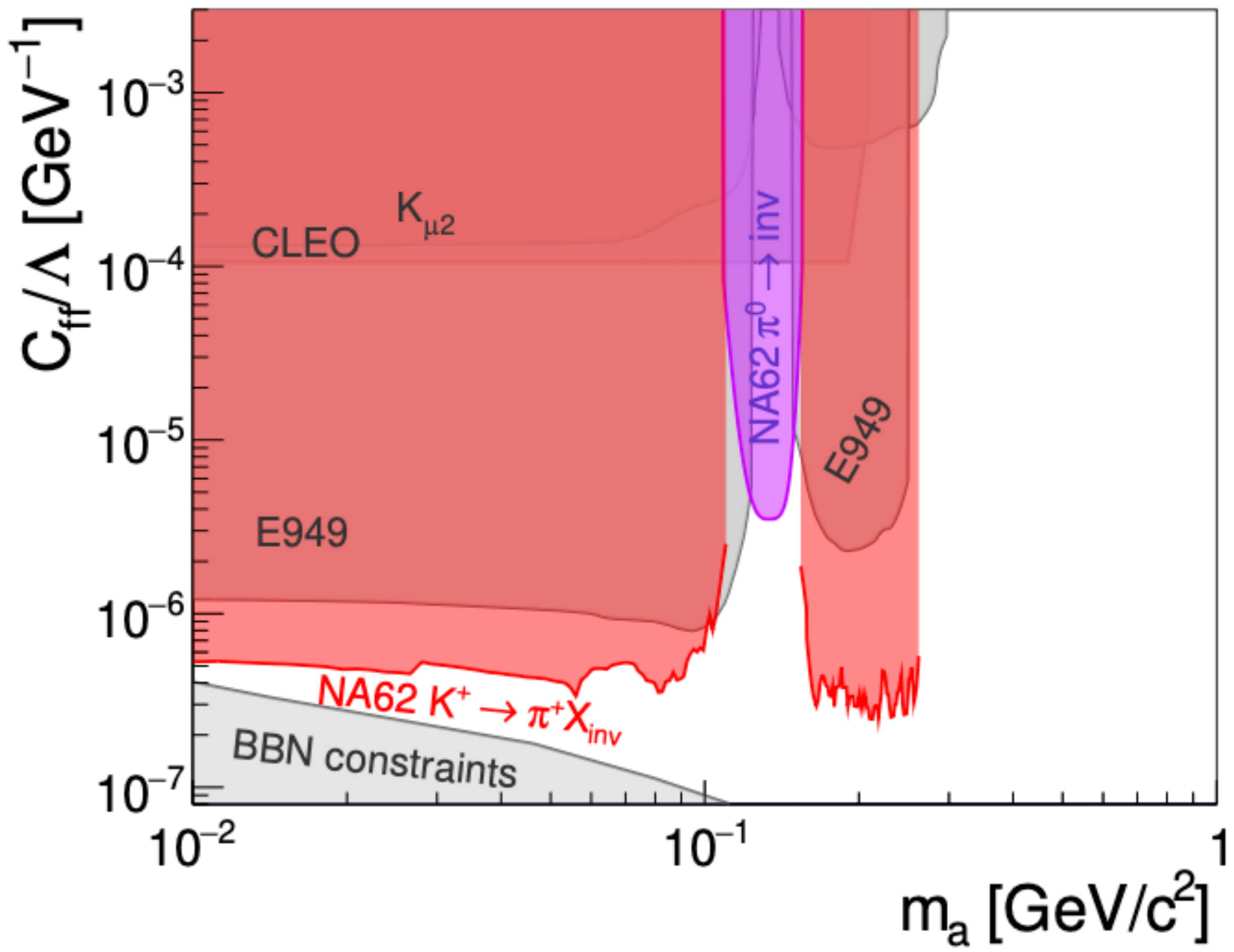




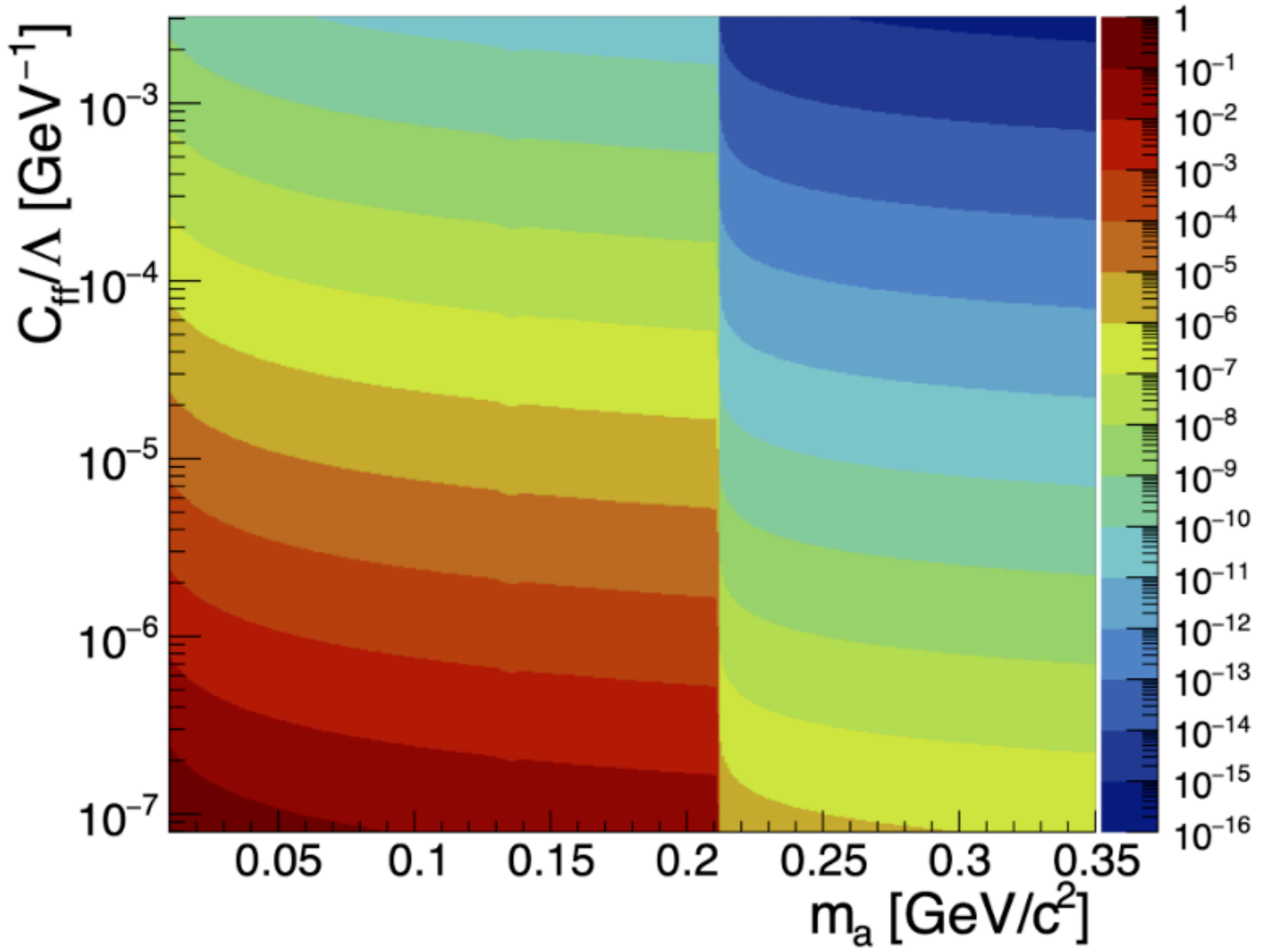
ALP coupling to SM fermions: $K^+ \to \pi^+ a\,(a \to inv)$

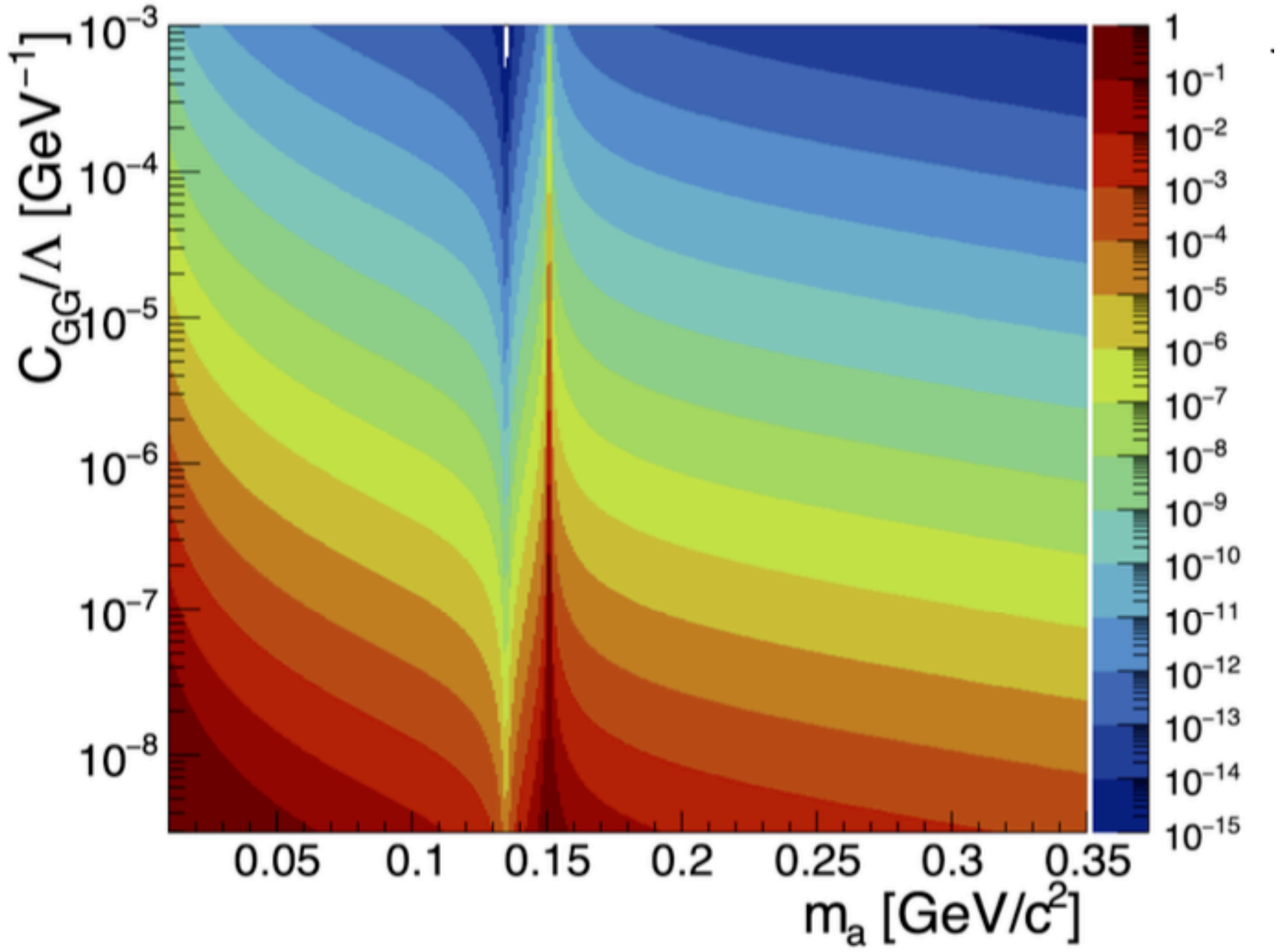
$$
\begin{aligned}
|\mathcal{M}| = \frac{N_8}{4f}\Bigg[& 16c_{GG}\frac{(m_K^2-m_\pi^2)(m_K^2-m_a^2)}{4m_K^2-m_\pi^2-3m_a^2} \\
& +6(c_{uu}+c_{dd}-2c_{ss})m_a^2\frac{m_K^2-m_a^2}{4m_K^2-m_\pi^2-3m_a^2} \\
& +(2c_{uu}+c_{dd}+c_{ss})(m_K^2-m_\pi^2-m_a^2)+4c_{ss}m_a^2 \\
& +(k_d+k_D-k_s-k_S)(m_K^2+m_\pi^2-m_a^2)\Bigg] \\
& -\frac{m_K^2-m_\pi^2}{2f}[k_q+k_Q]^{23}.
\end{aligned}
$$

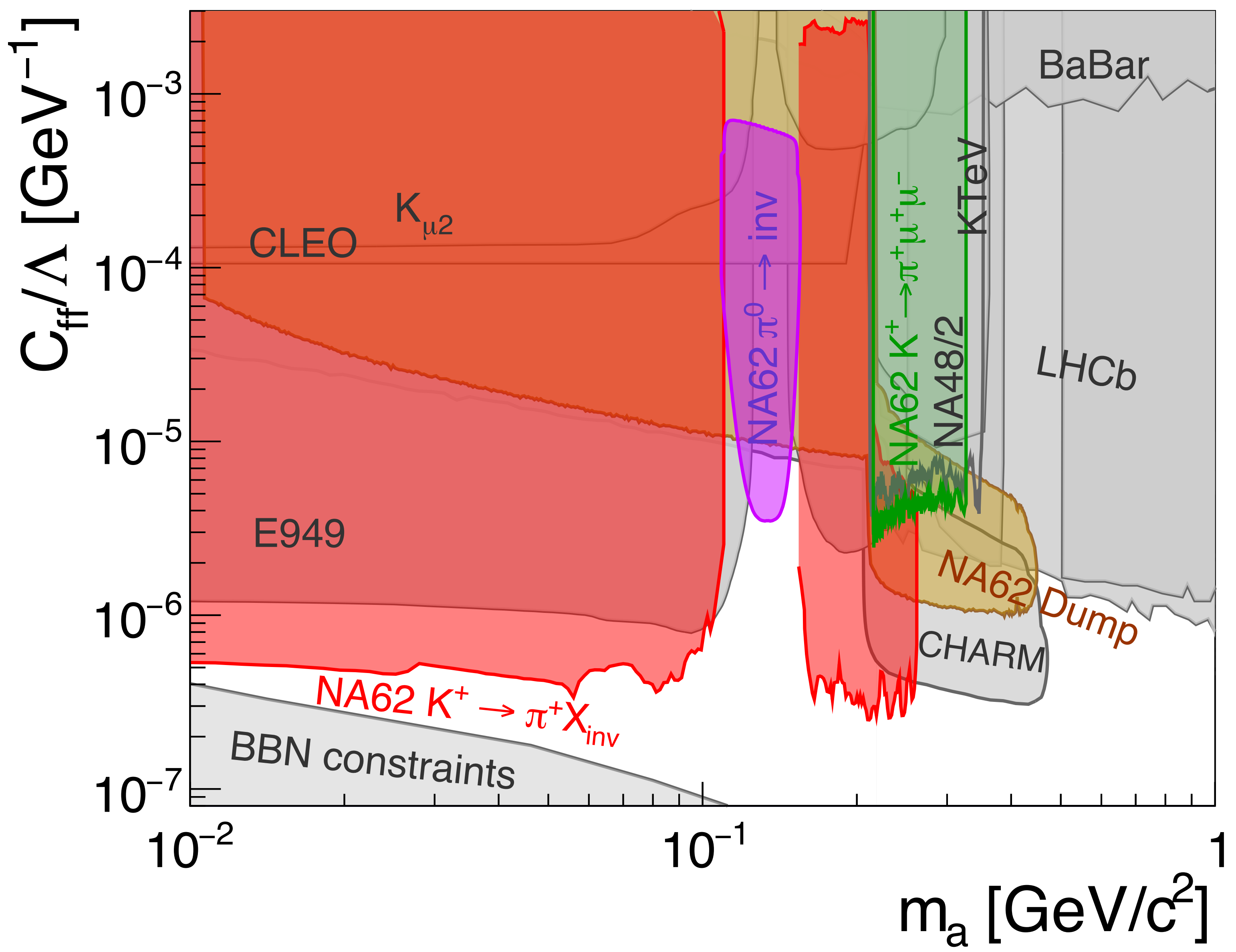


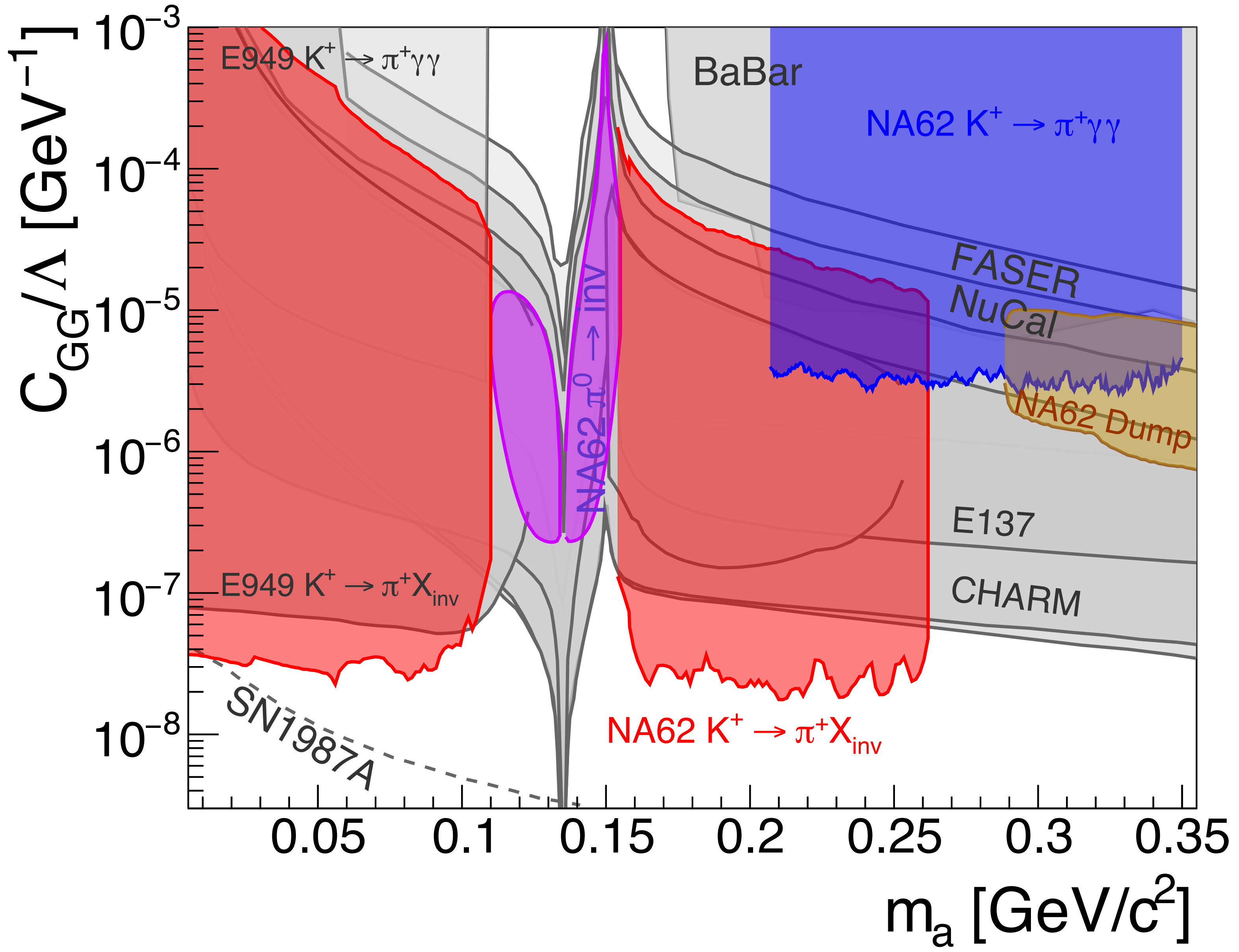


ALPs: $K^+ \to \pi^+ a\,(a \to vis)$

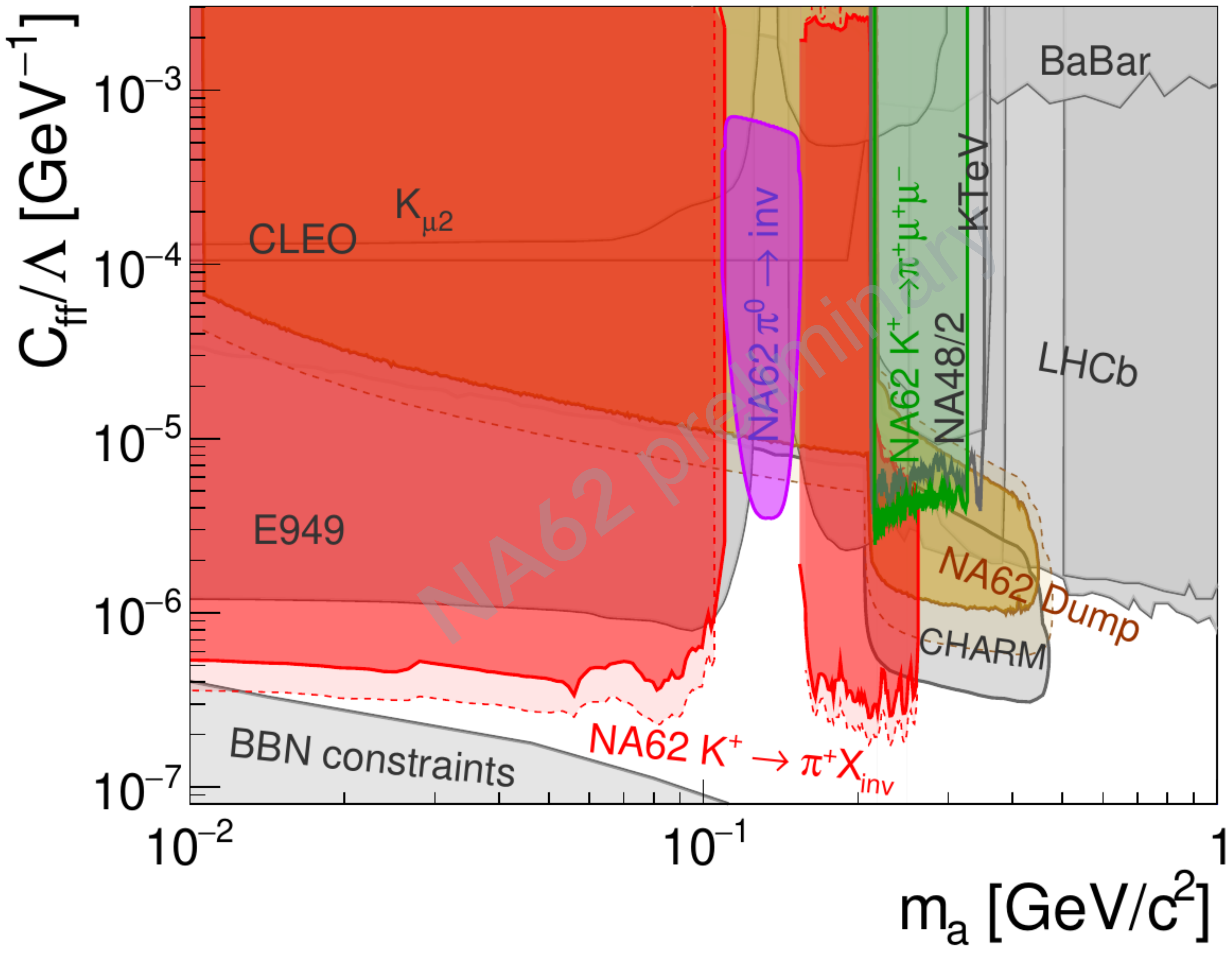








ALPs: final dataset projection

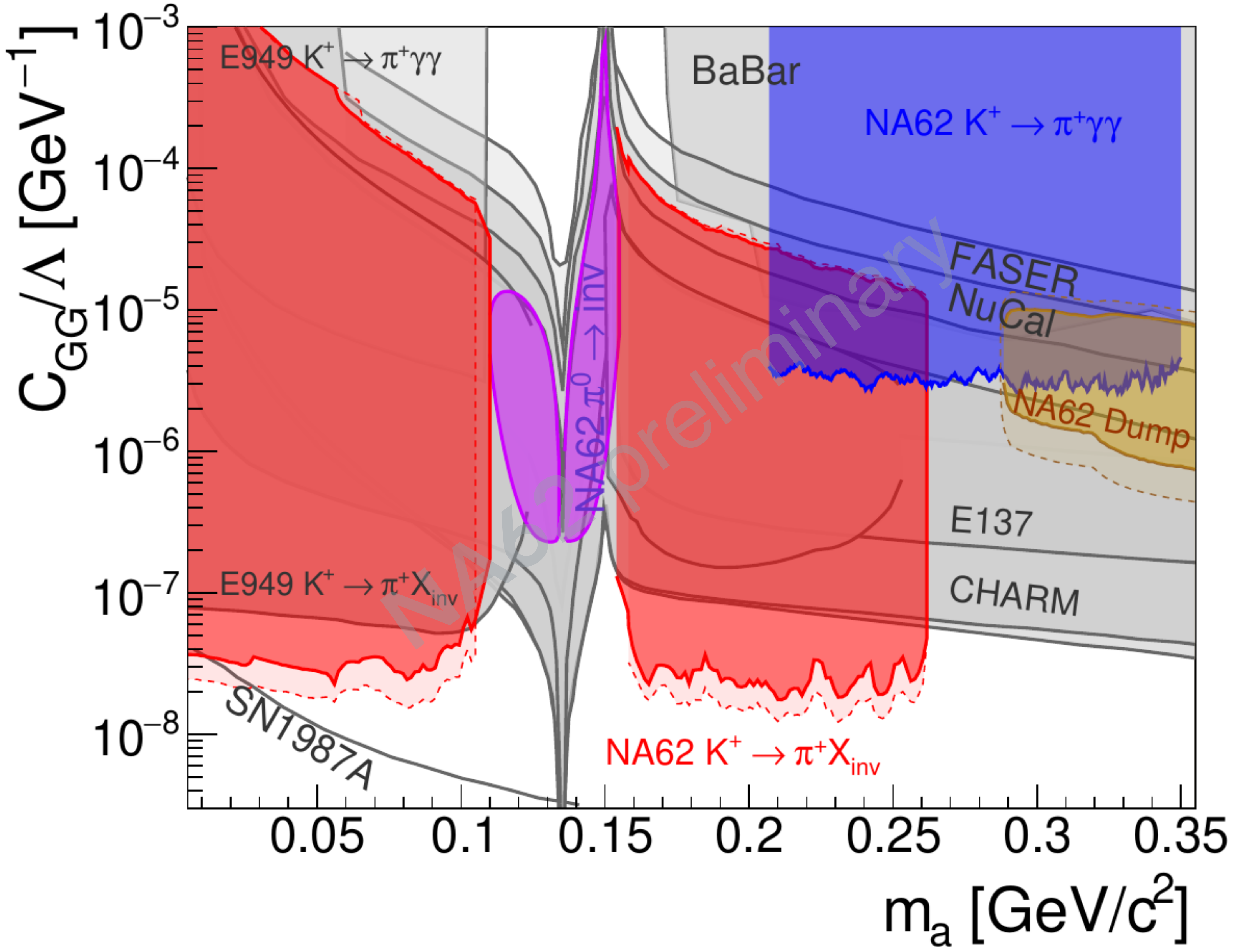


$K^+ \to \pi^+ X(X \to e^+e^-)$ @ NA62:

- Sensitivity still to be studied

$K^+ \to \pi^+ X(X \to \mu^+\mu^-)$ @ NA62:

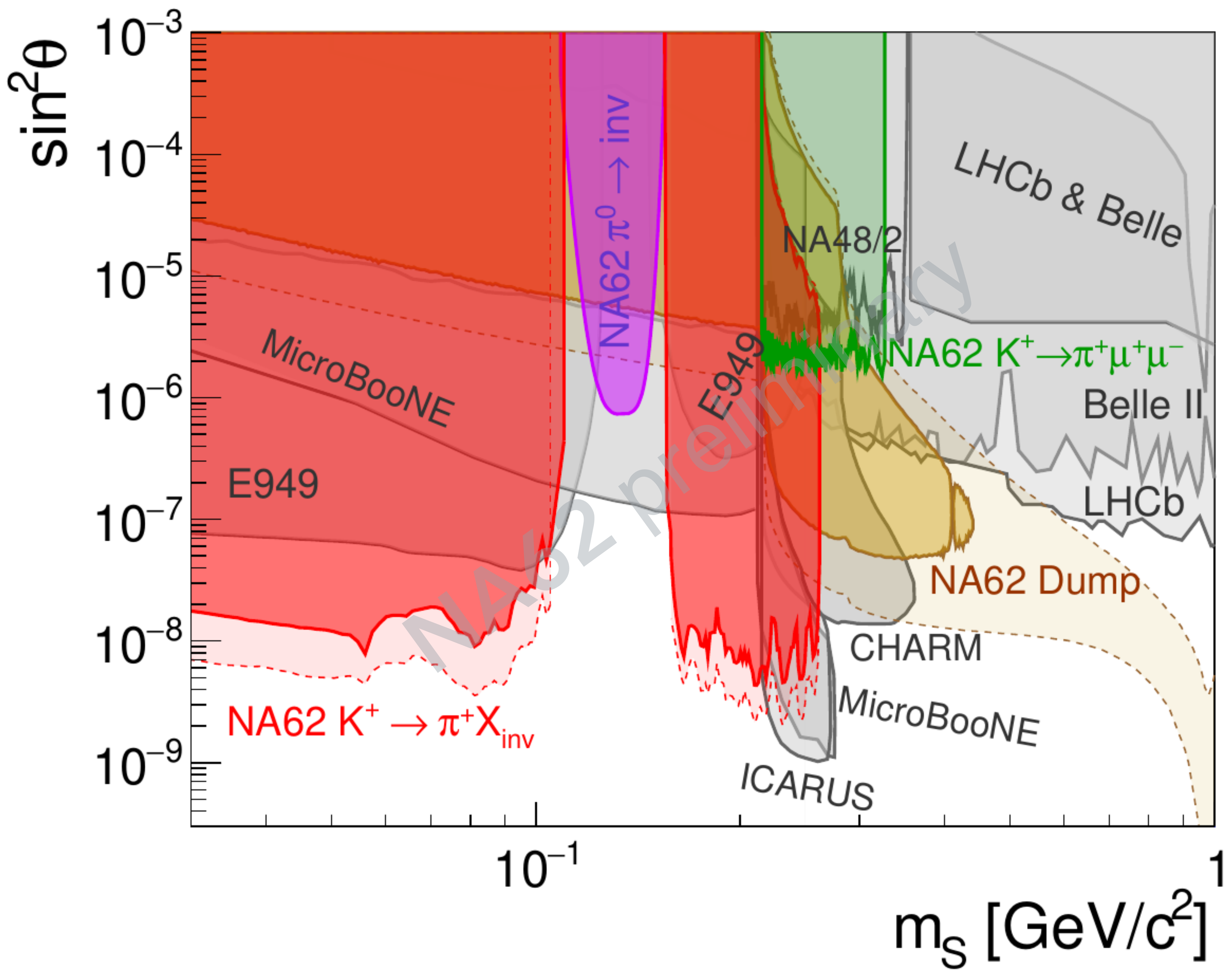
- ~ $\sqrt{2}\times$ improvement expected with final 2016-2026 dataset

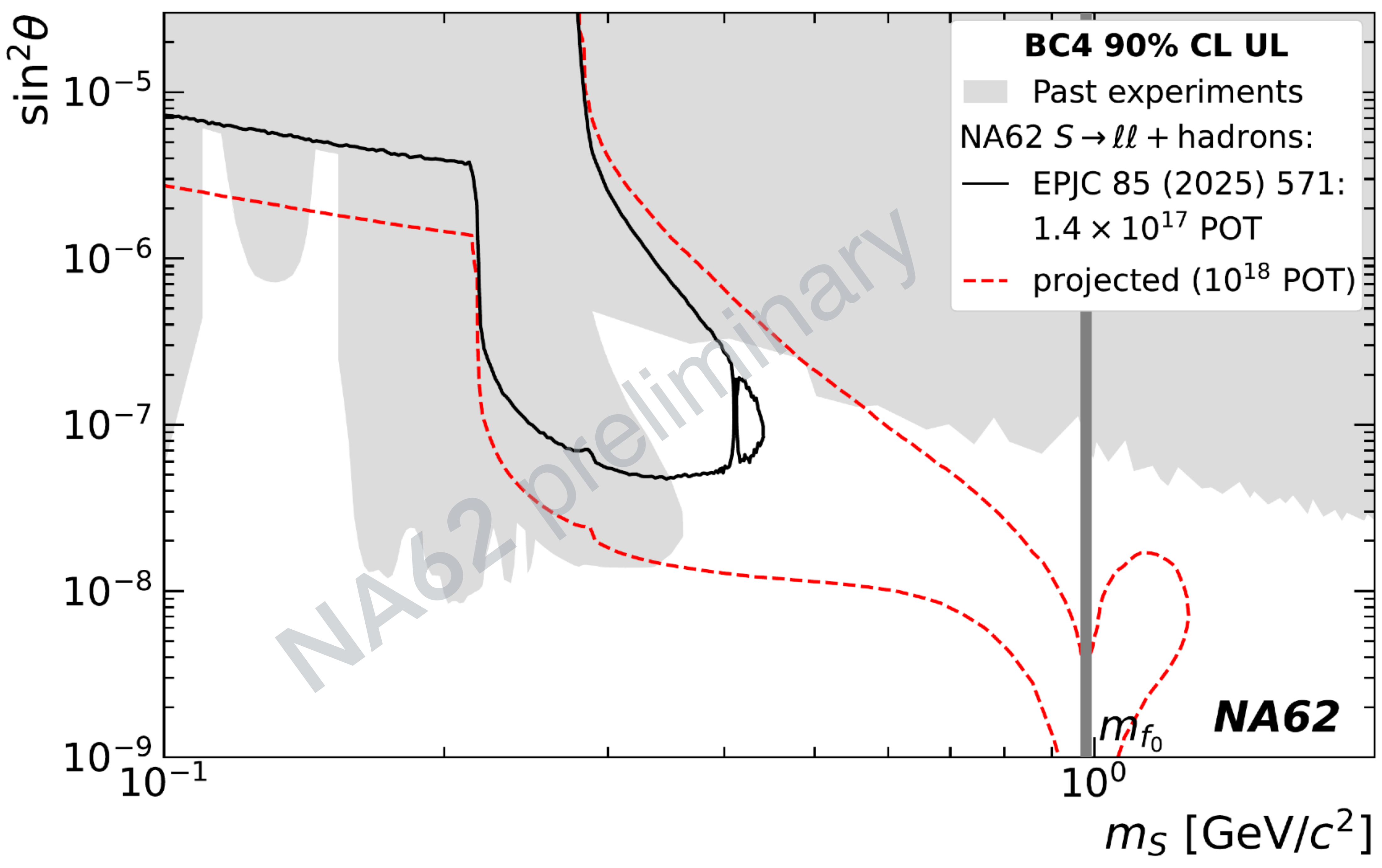


$K^+ \to \pi^+ X(X \to \gamma\gamma)$ @ NA62:

- ~ $\sqrt{2}\times$ improvement expected with final 2016-2026 dataset

Dark scalar: final dataset projection





$K^+ \to \pi^+ X(X \to e^+e^-)$ @ NA62:

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$K^+ \to \pi^+ X(X \to \mu^+\mu^-)$ @ NA62:

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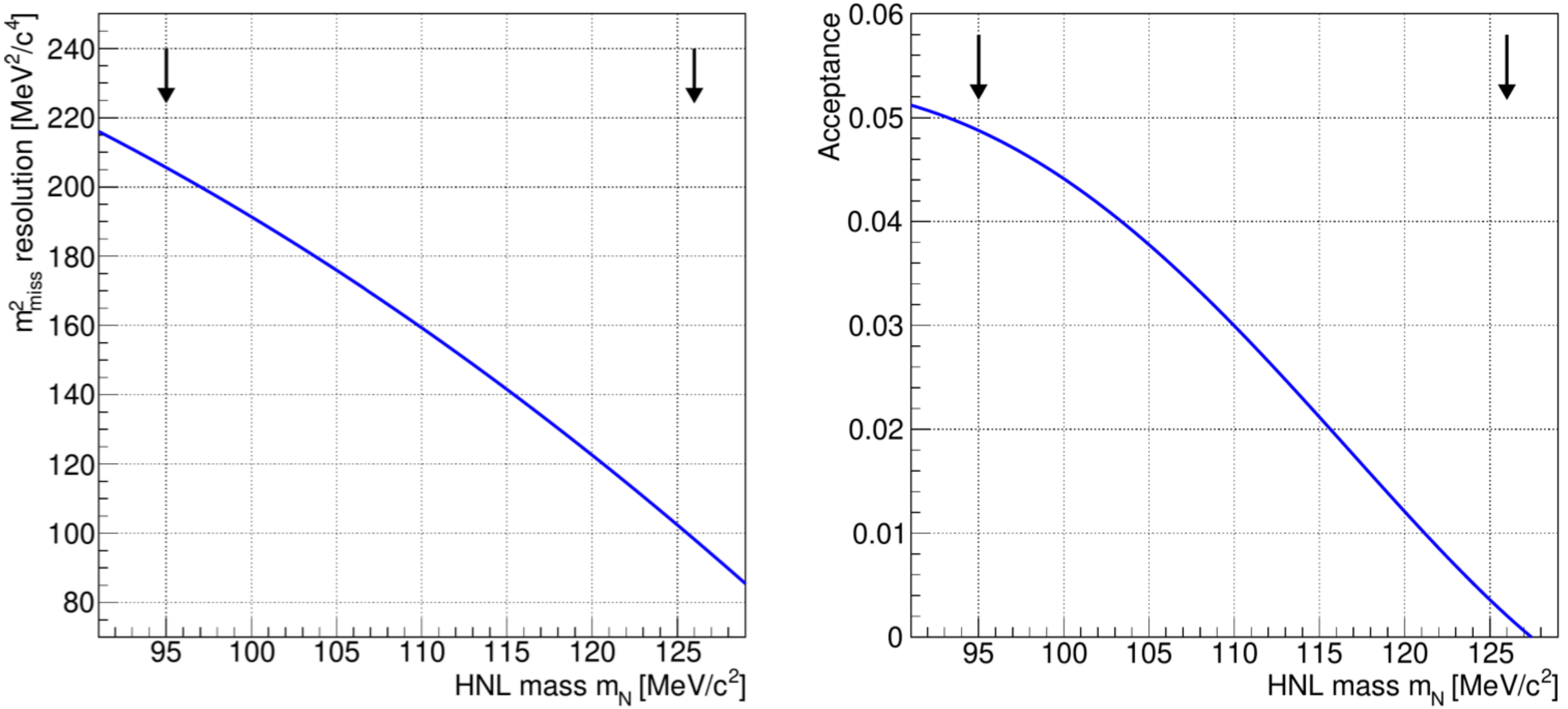
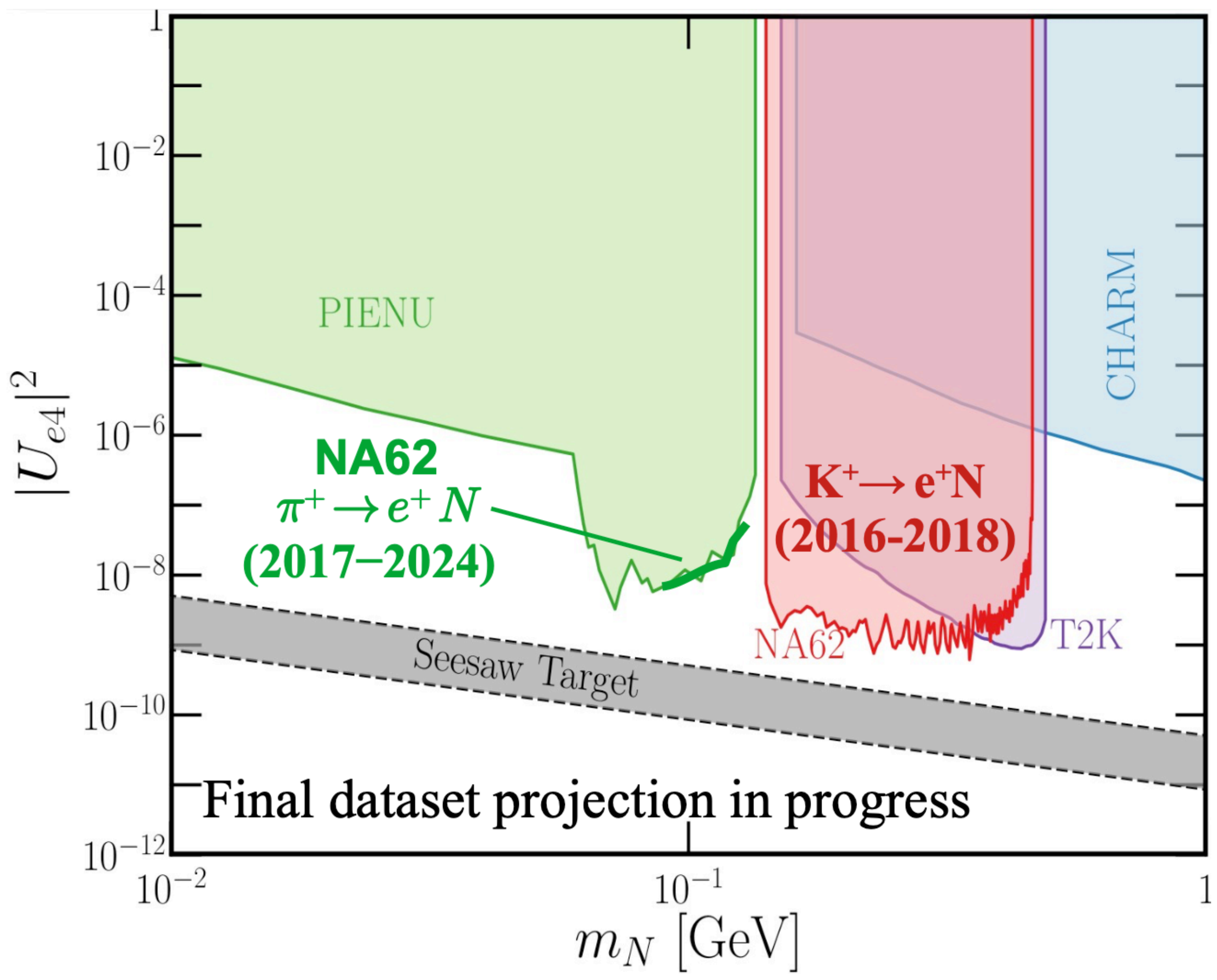
$\pi^+ \to e^+N$: mass resolution and acceptance

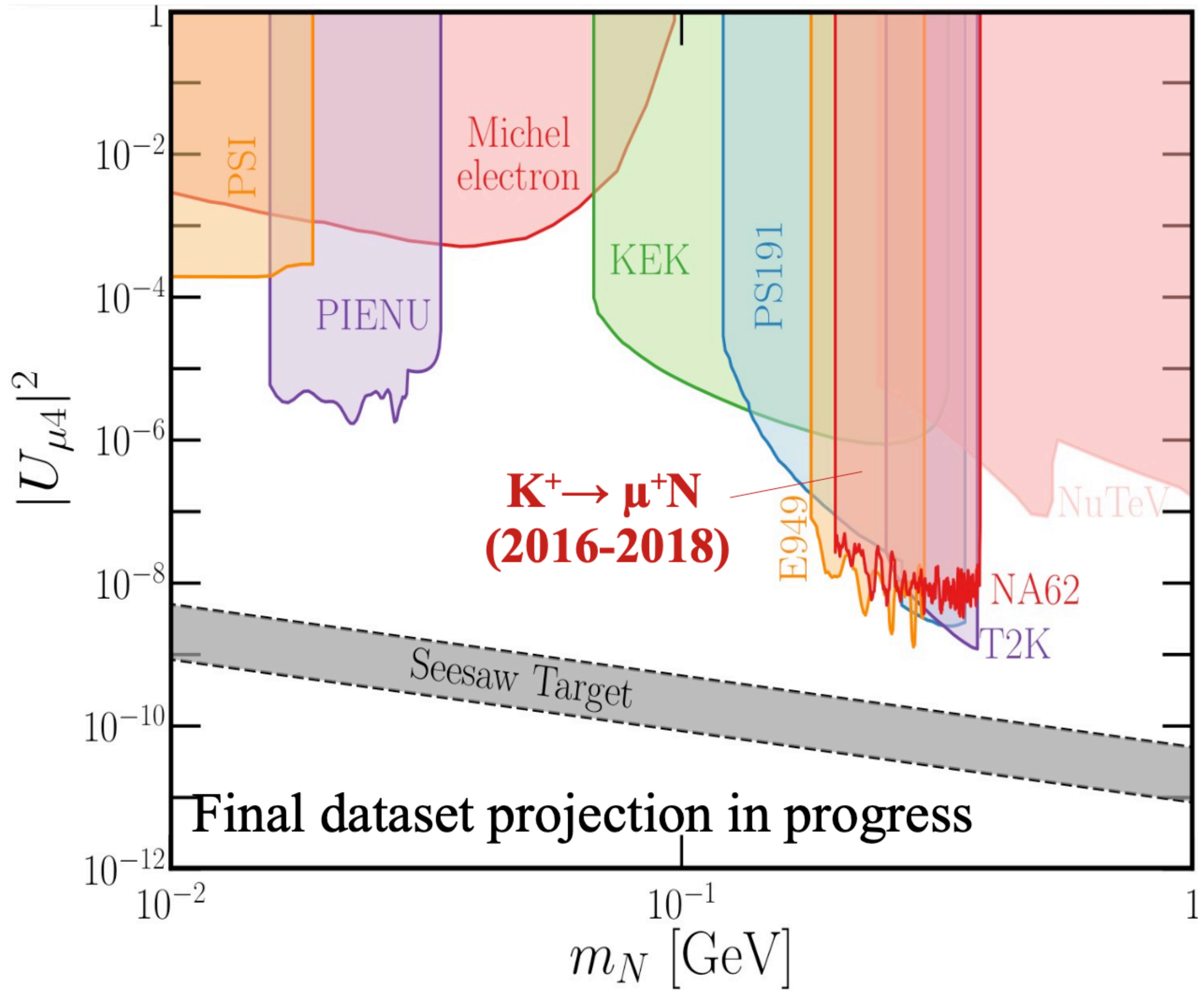
Phys. Lett. B 872 (2026) 140119



- ➡ Selection for each HNL mass hypothesis (m_{HNL}) includes a "mass window" condition: $|m^2_{miss} - m^2_N| < 1.5\,\sigma_{m^2_N}$: background is proportional to mass resolution.
- ➡ Resolution is crucial to resolve possible HNL mass splitting.

HNLs: final dataset projections





$K^+ \to \ell^+ N$ (and $\pi^+ \to e^+ N$): currently background-limited, sensitivity ~ $1/\sqrt{N_K}$

Final dataset (2016-2026) projection:

Expect > 4x the statistics of 2016-2018 → ~ 2x improvement on the $K^+ \to \ell^+ N$ ULs on $|U_{\ell 4}|^2$