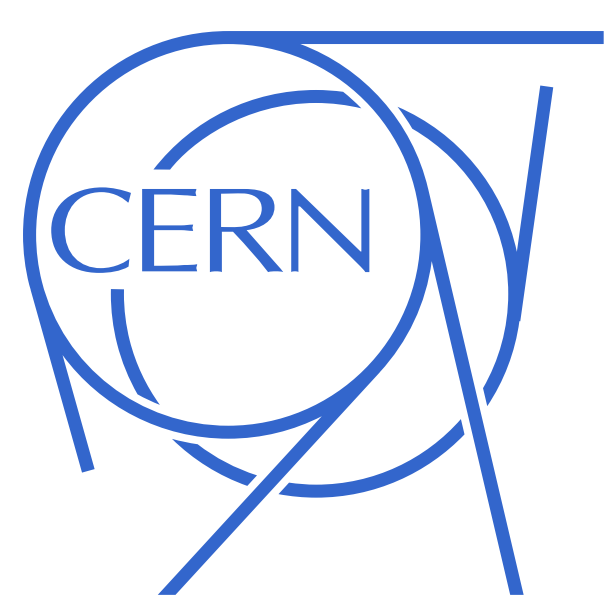




PASCOS 2026
Sheffield, 22–26 June 2025



Latest results from the NA62 experiment

Joel Swallow (CERN)



Contents:

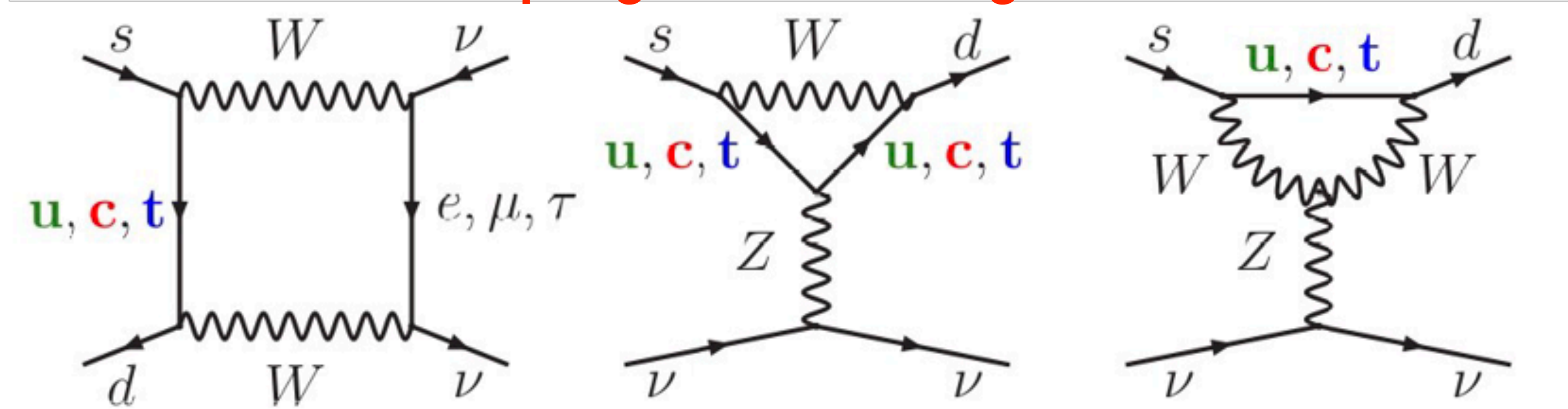
- New measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
 - Golden modes $K \rightarrow \pi \nu \bar{\nu}$ in the SM and beyond, NA62 detector upgrades & performance
- Recent highlights from broad NA62 physics program
 - Rare decays: e.g. $K^+ \rightarrow \mu^+ \nu \mu^+ \mu^-$
 - Precision measurements: e.g. $(K^+ \rightarrow e^+ \nu \gamma)_{SD}$
 - Exotics searches in kaon mode (e.g. $K^+ \rightarrow \pi^+ X$, $\pi^+ \rightarrow e^+ N$) & dump mode

New measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

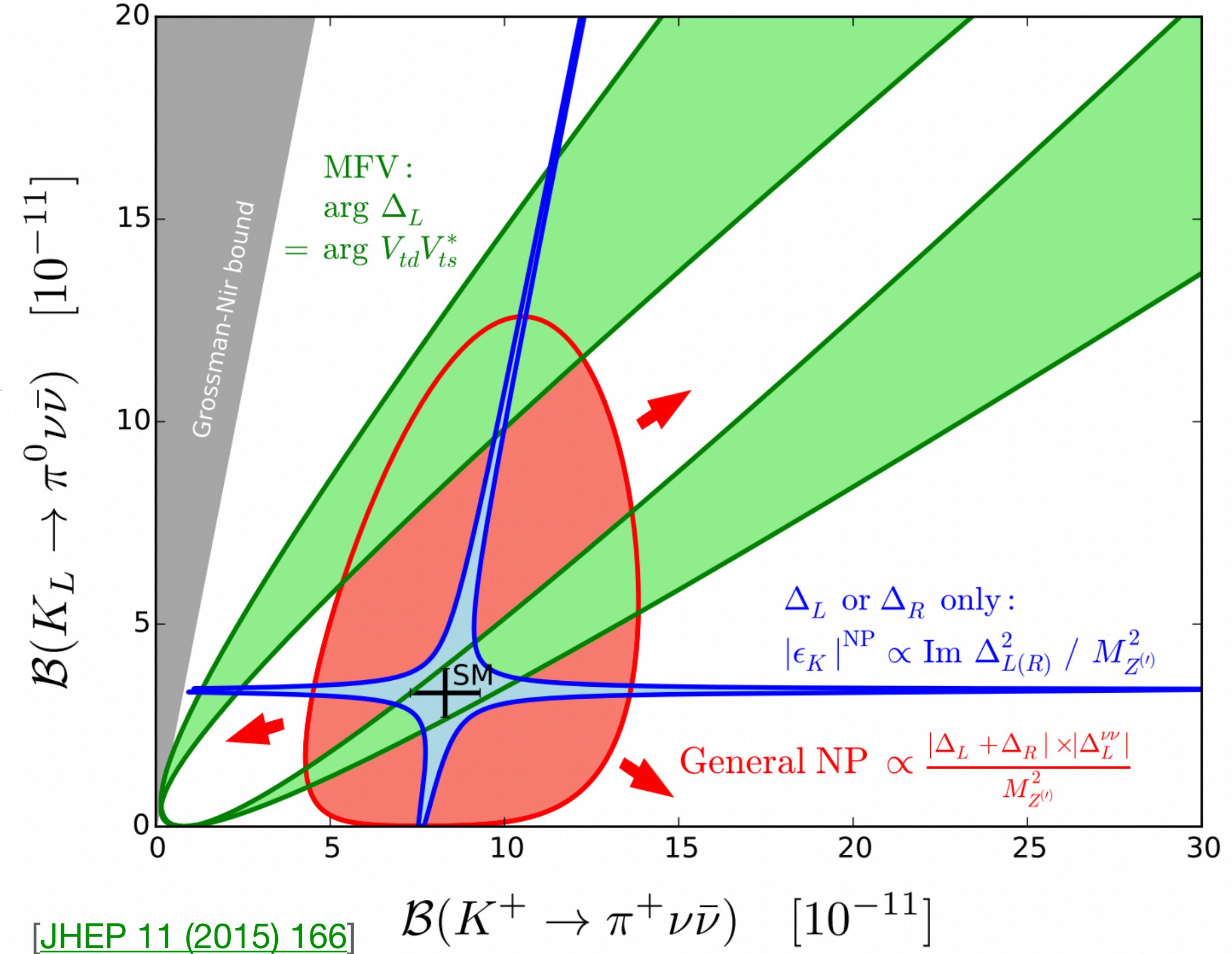
[[La Thuile 26](#), [Moriond EW 26](#)]

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

SM: Z-penguin & box diagrams



- $\mathcal{B}(K \rightarrow \pi \nu \bar{\nu})$ highly suppressed in SM
 - GIM mechanism & maximum CKM suppression.
- Theoretically clean $\Rightarrow$ high precision SM predictions
- High sensitivity to New Physics up to $\mathcal{O}(100)$ TeV

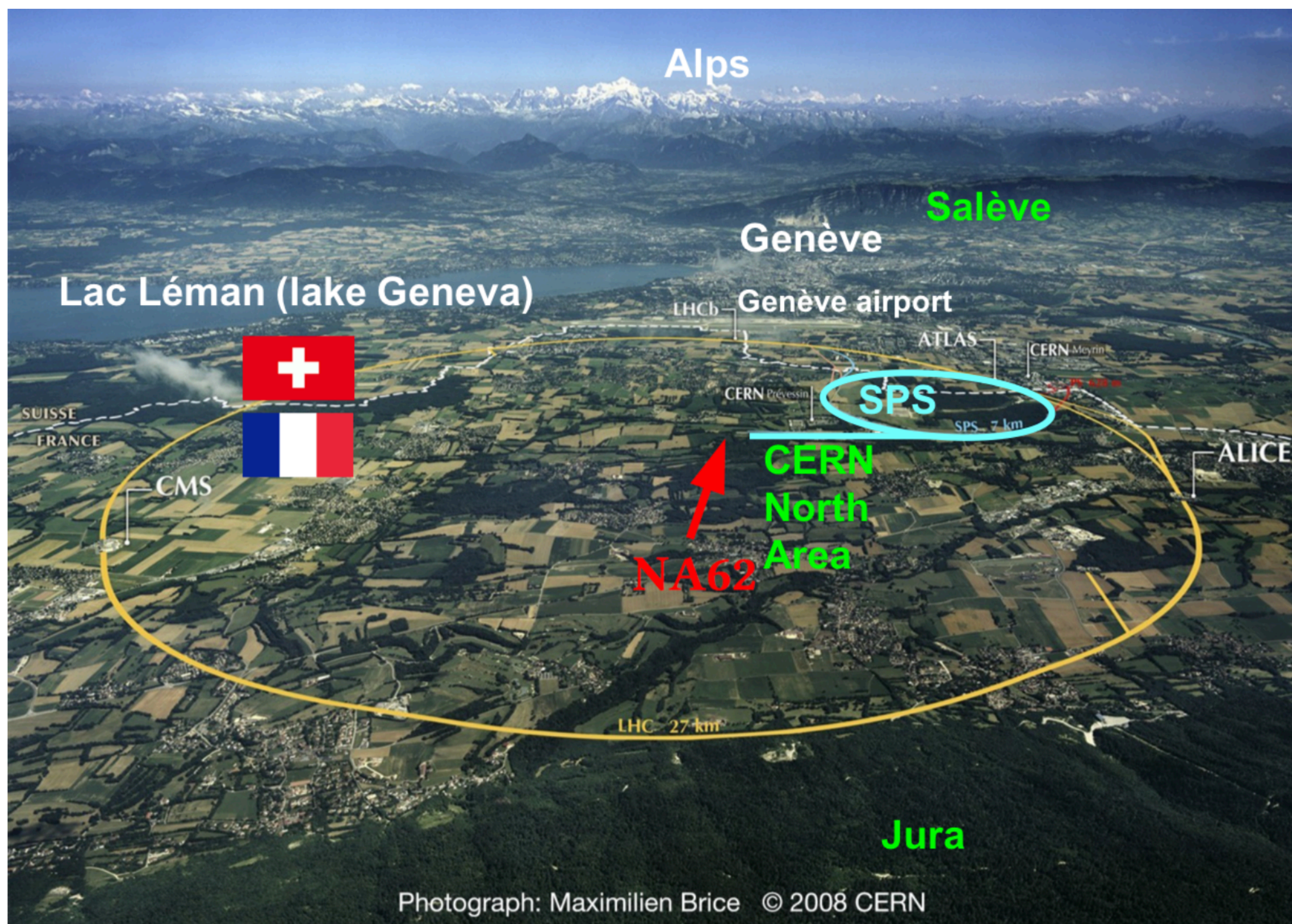


Mode	SM Branching Ratio [1]	SM Branching Ratio [2]	Experimental Status
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6 \pm 4.0) \times 10^{-11}$ NA62 16–18
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 2 \times 10^{-9}$ KOTO (2021 data)

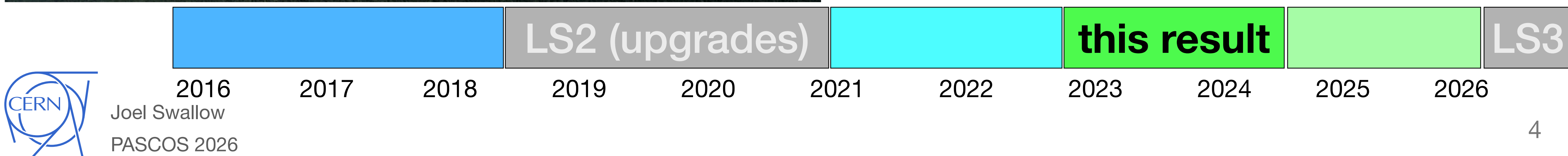
The NA62 Experiment at CERN



~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\]](#) [\[JHEP 02 \(2025\) 191\]](#)
- Broader physics programme: [see [Kaon2025](#) & [CKM25](#)]
 - 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 [10 beam dump]).
 - 2022 Physics run (215 days).
 - 2023 Physics run (150 days [10 beam dump]).
 - 2024 Physics run (204 days [12 dump] {5 low intensity}).
 - 2025 Physics run (200 days [10 dump]{7 Low Intensity}).
 - 2026 Physics run (Ongoing...)



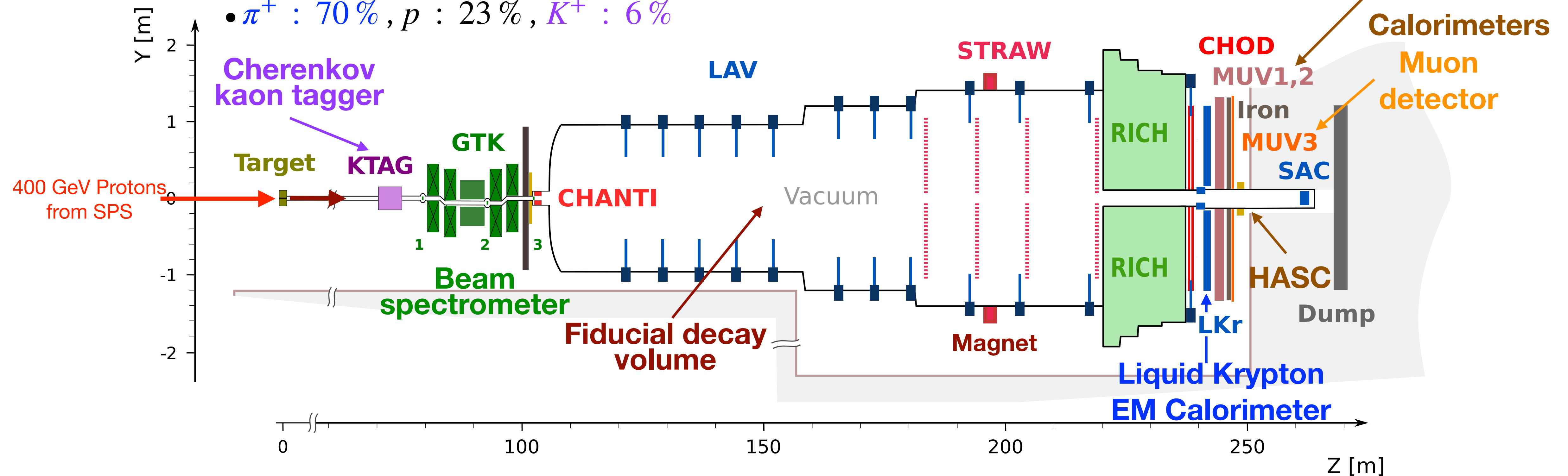
NA62 beamline & detector

[JINST 12 (2017) 05, P05025]



Secondary 75 GeV/c beam:

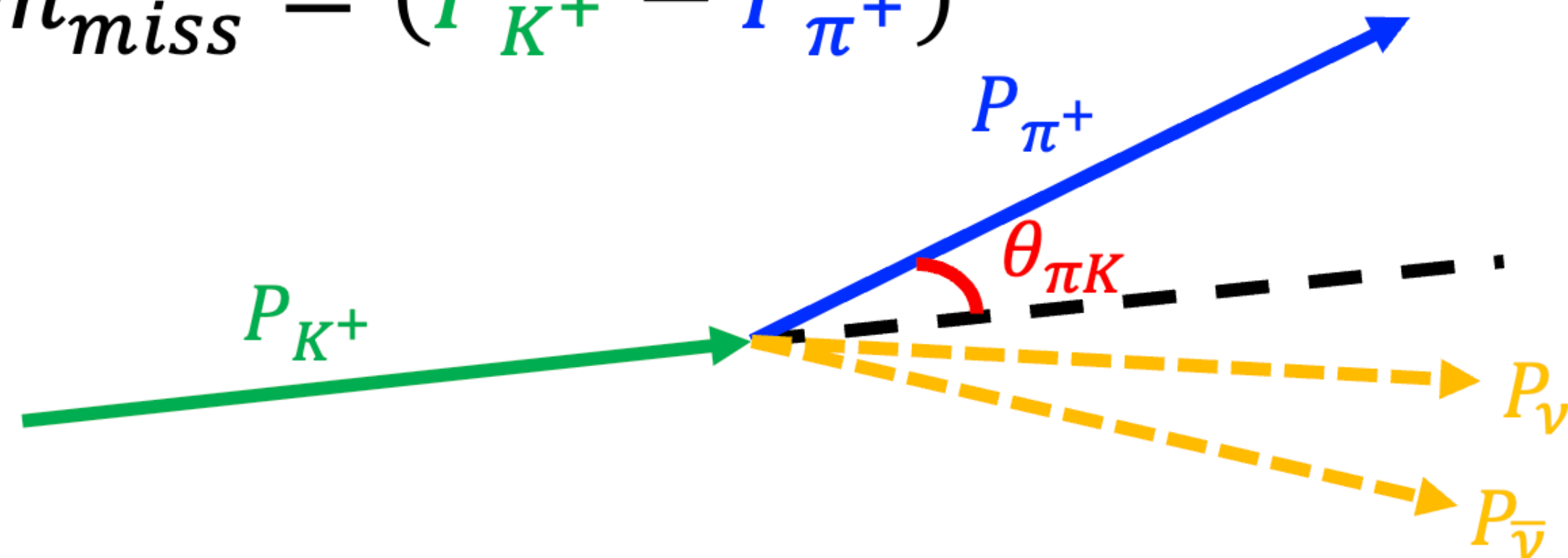
- π^+ : 70 % , p : 23 % , K^+ : 6 %



- 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)

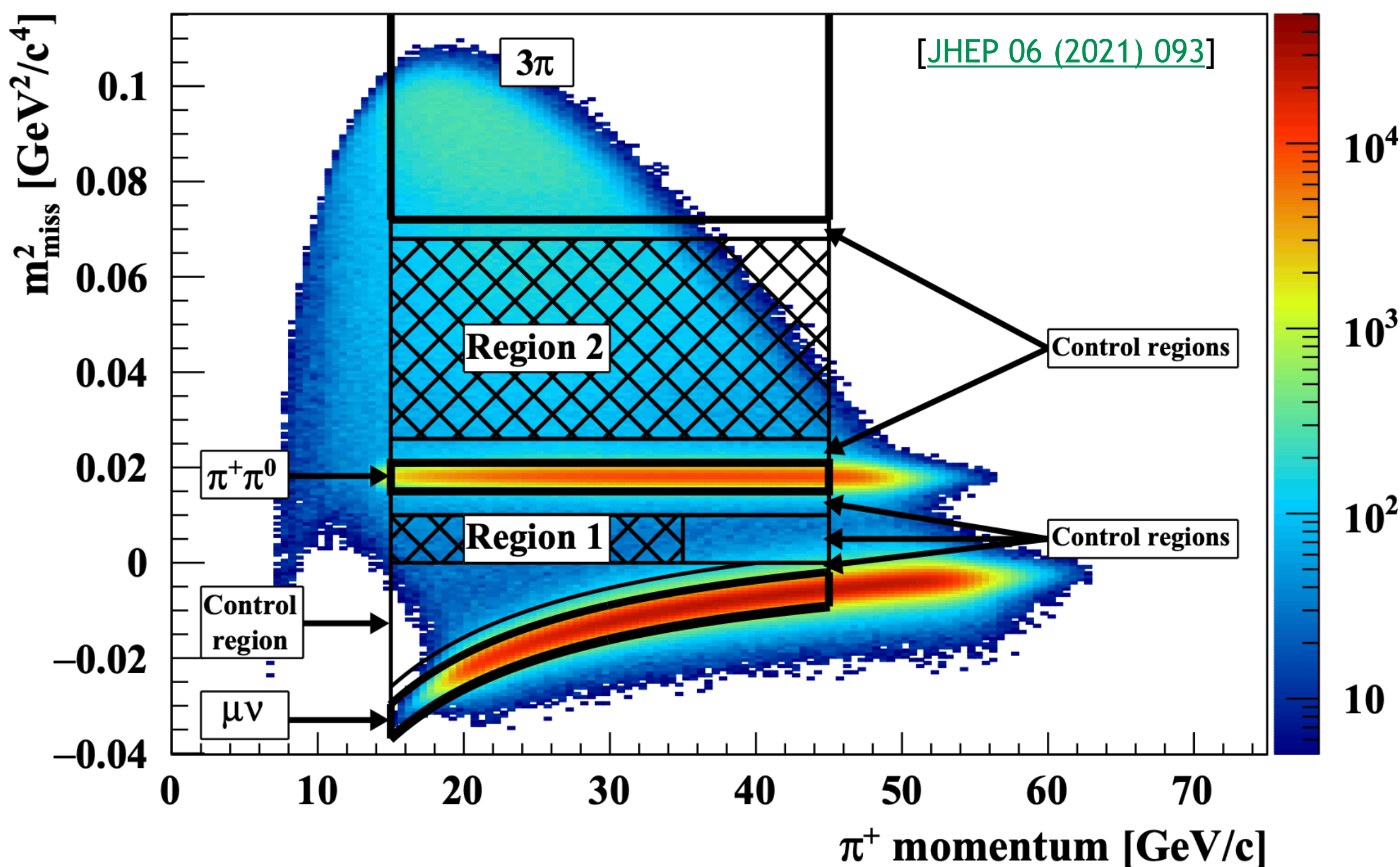
Kinematics

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



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

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

$$(8.60 \pm 0.42) \times 10^{-11} \text{ [SM]}$$

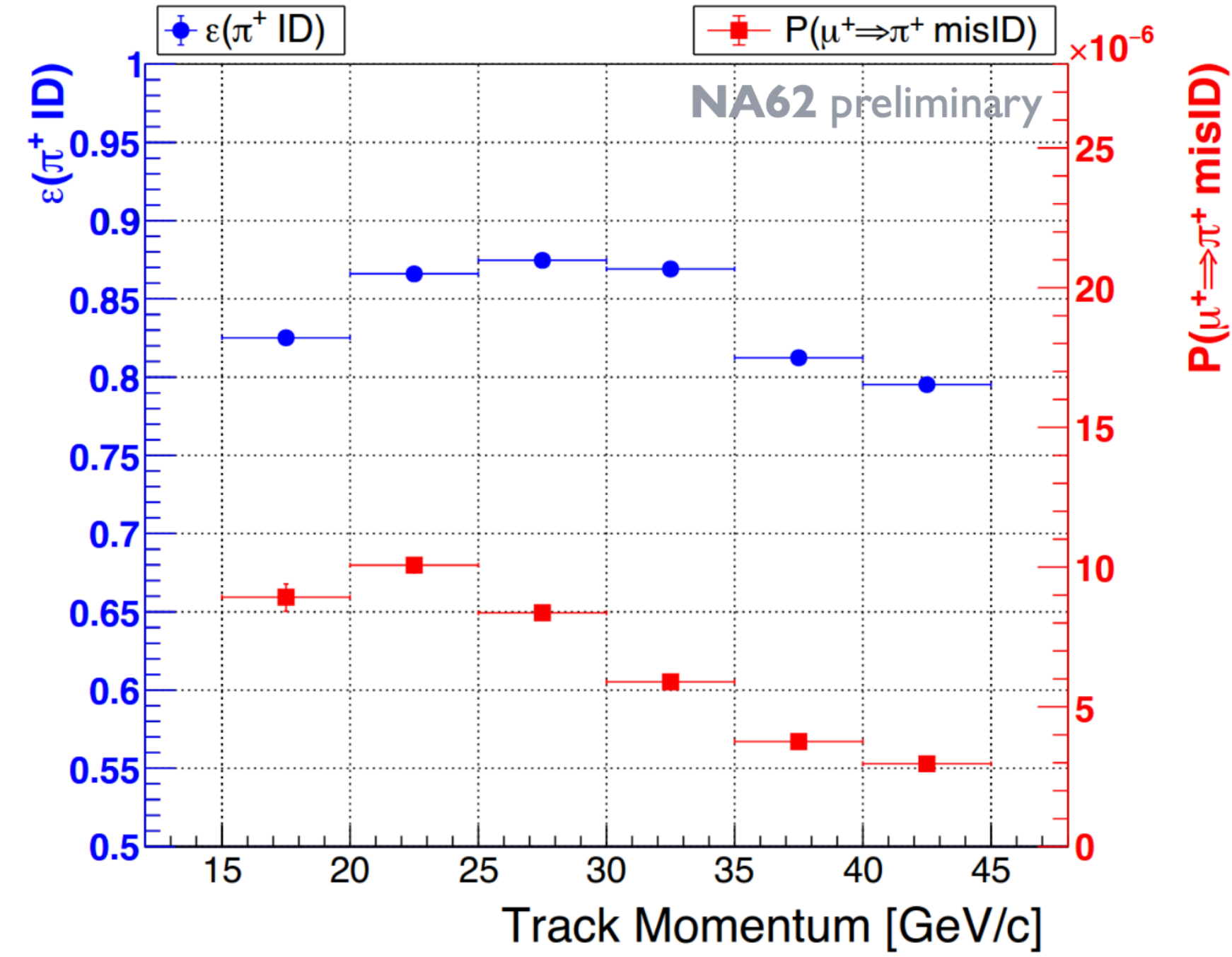
[Buras et al. EPJC 82 \(2022\) 7, 615](#)

π^+ momentum range: 15–45 GeV/c

Joel Swallow

PASCOS 2026

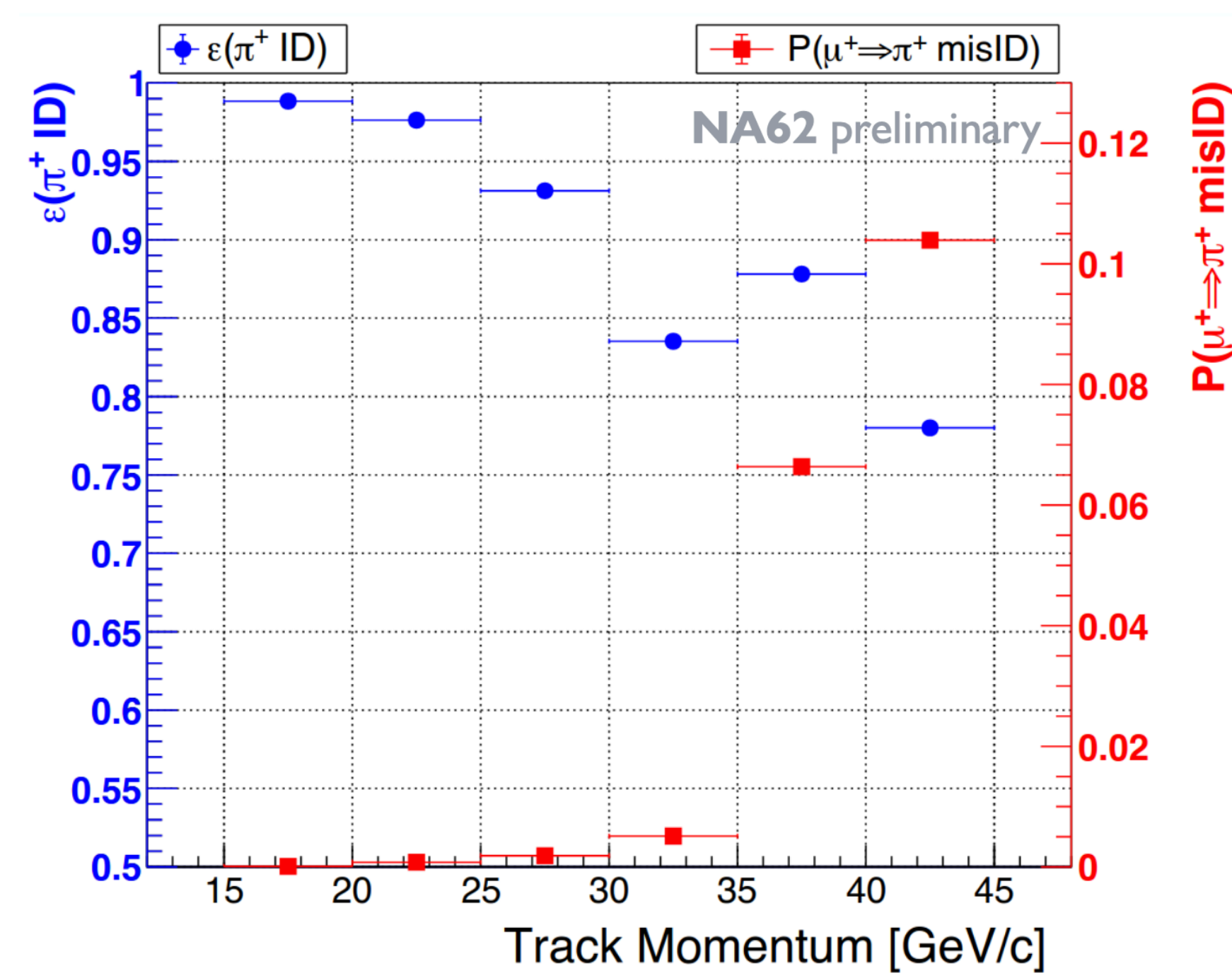
Calorimeters
(LKr + MUV12+MUV3)



Particle ID

- 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

RICH



$$\epsilon(\pi \text{ ID}) = 75.3 \%$$

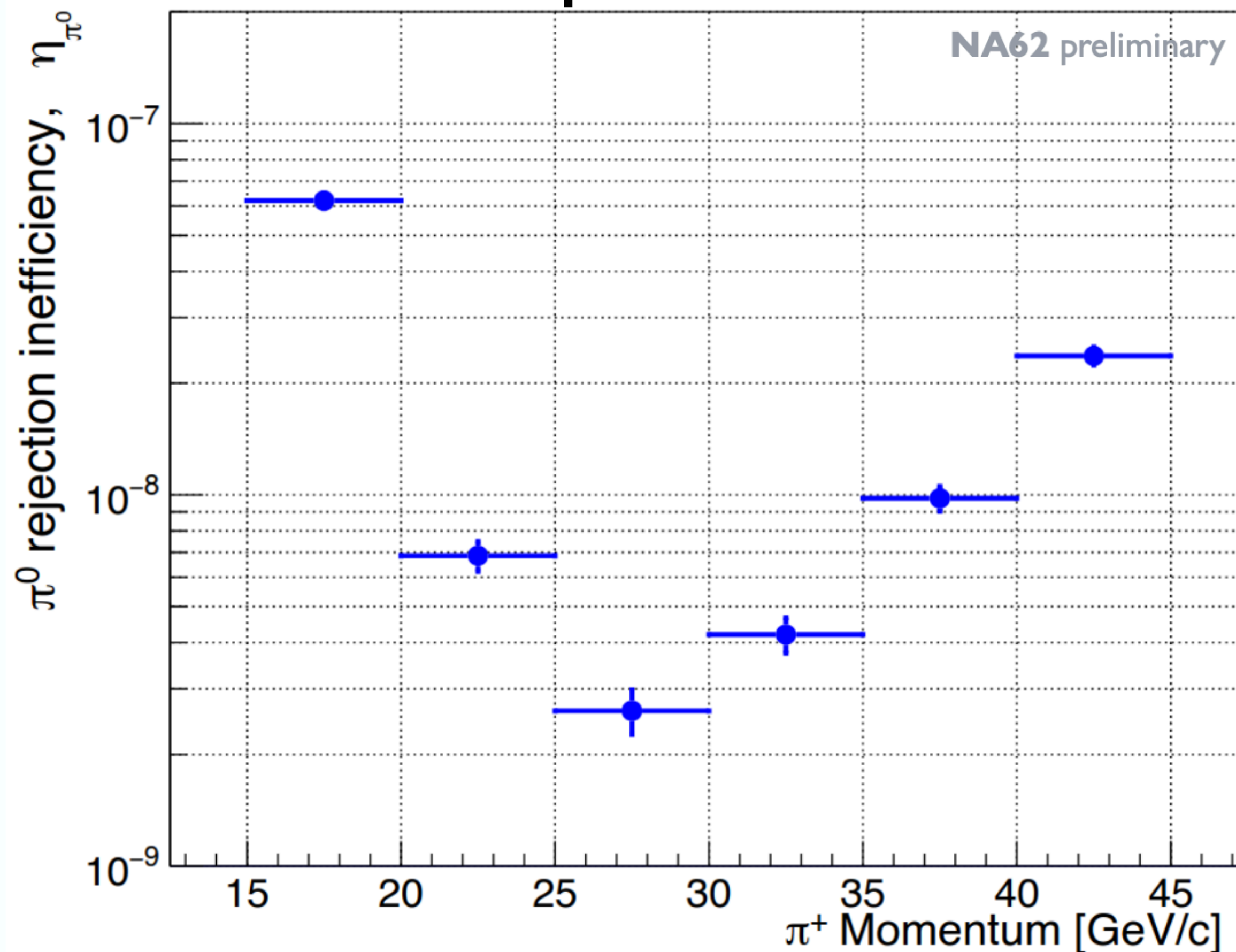
$$P(\mu^+ \text{ misID as } \pi^+) = (1.3 \pm 0.1) \times 10^{-7}$$

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

$$K^+ \rightarrow \pi^+ \nu \bar{\nu} \quad 8.4 \times 10^{-11} \quad [\text{benchmark SM value}]$$

Photon Rejection

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



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

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

$$\eta_{\pi^0} = (1.24 \pm 0.04) \times 10^{-8}$$

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

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

$$8.4 \times 10^{-11} \quad [\text{benchmark SM value}]$$

c.f. 2021–22 result: $\eta_{\pi^0} = (1.72 \pm 0.07) \times 10^{-8}$

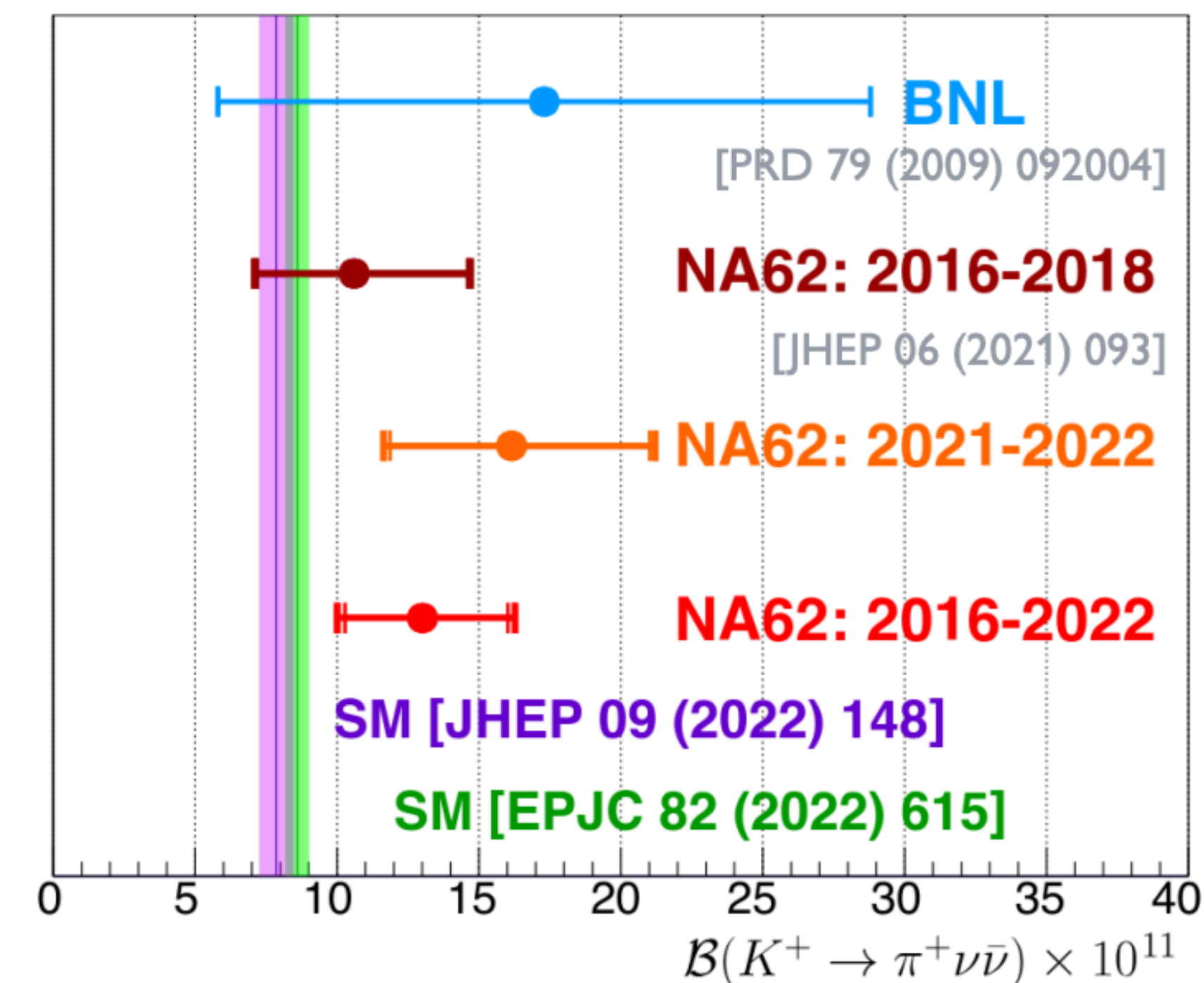
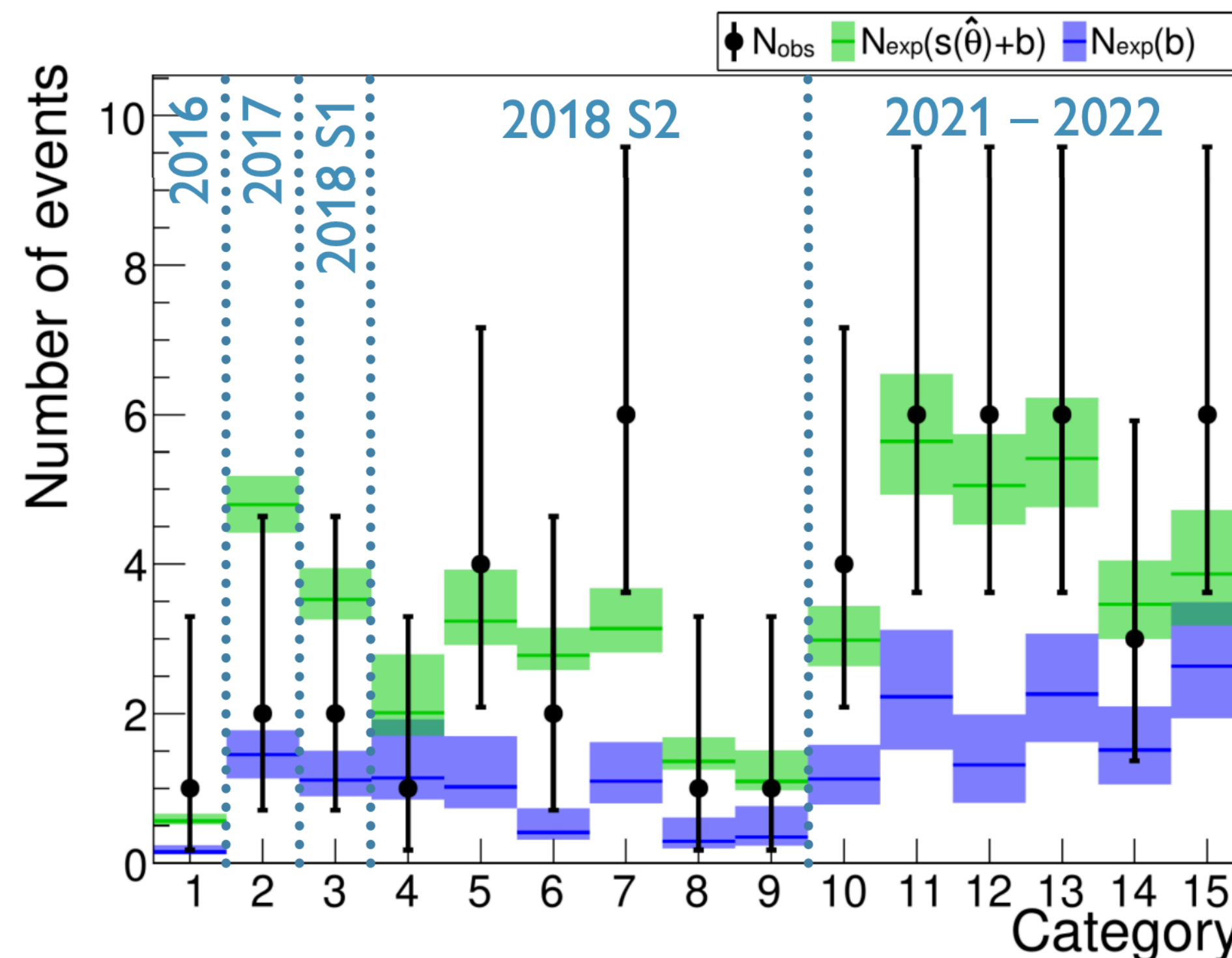
Previous NA62 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ results



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

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]

Data-taking year(s)	[Reference]	N_{bg}	$N_{\pi\nu\bar{\nu}}^{\text{SM,exp}}$	N_{obs}
2016–2018	[JHEP 06 (2021) 093]	$7.03^{+1.05}_{-0.82}$	10.01 ± 0.42	20
2021–2022	[JHEP 02 (2025) 191]	$11.0^{+2.1}_{-1.9}$	9.91 ± 0.34	31
2016–2022	[JHEP 02 (2025) 191]	18^{+3}_{-2}	19.9 ± 0.5	51



$$\mathcal{B}_{2016-22}^{\text{NA62}}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \left(13.0^{+3.0}_{-2.9} \left|_{\text{stat}} \begin{matrix} +1.3 \\ -1.3 \end{matrix} \right|_{\text{syst}} \right) \times 10^{-11} = \left(13.0^{+3.3}_{-3.0} \right) \times 10^{-11}$$

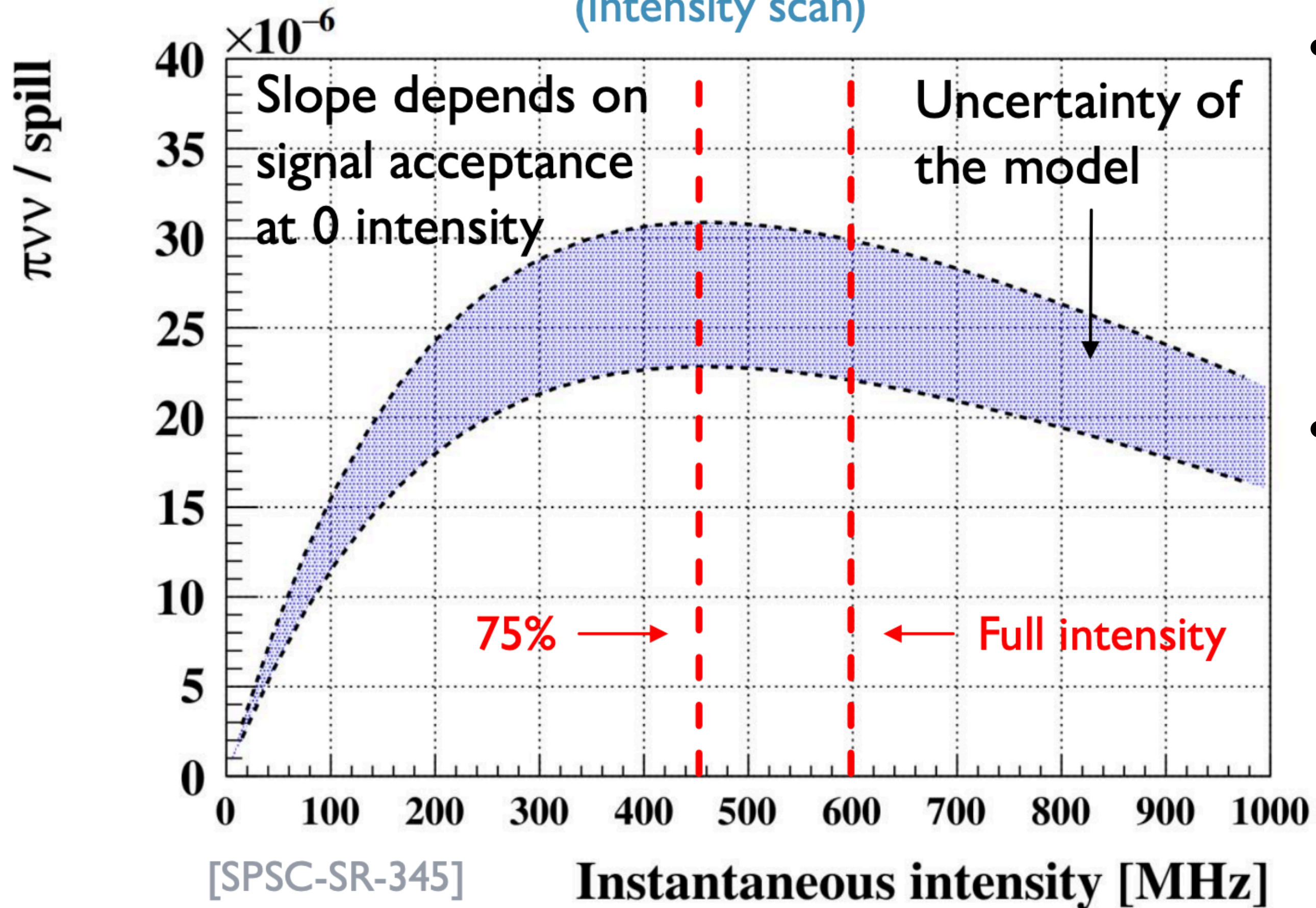
In background-only hypothesis: $p = 2 \times 10^{-7} \Rightarrow \text{significance} > 5\sigma$.

Smallest BR ever measured at $> 5\sigma$ significance !

Updates: optimal intensity

Studies on 2023 data

(intensity scan)

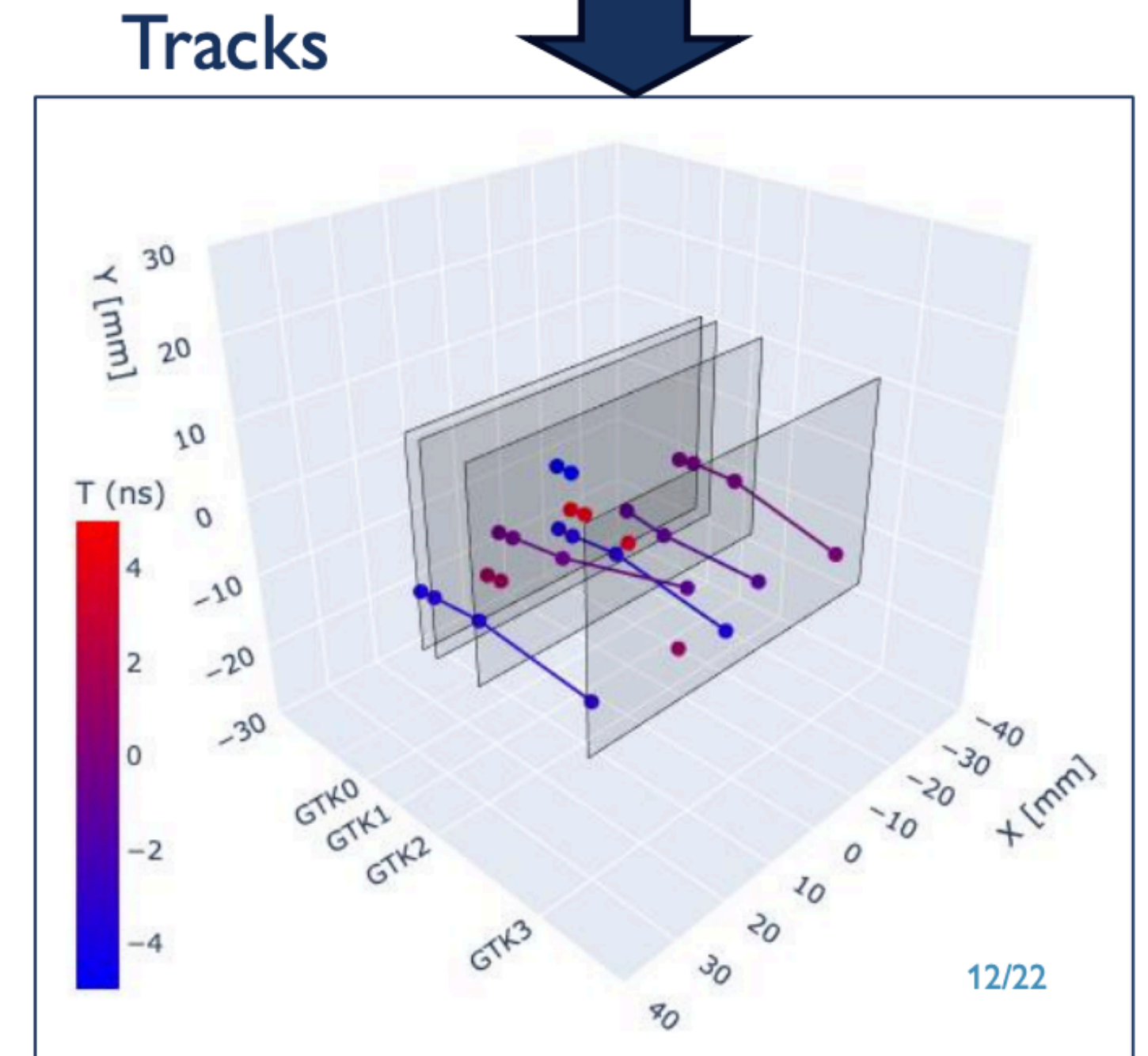
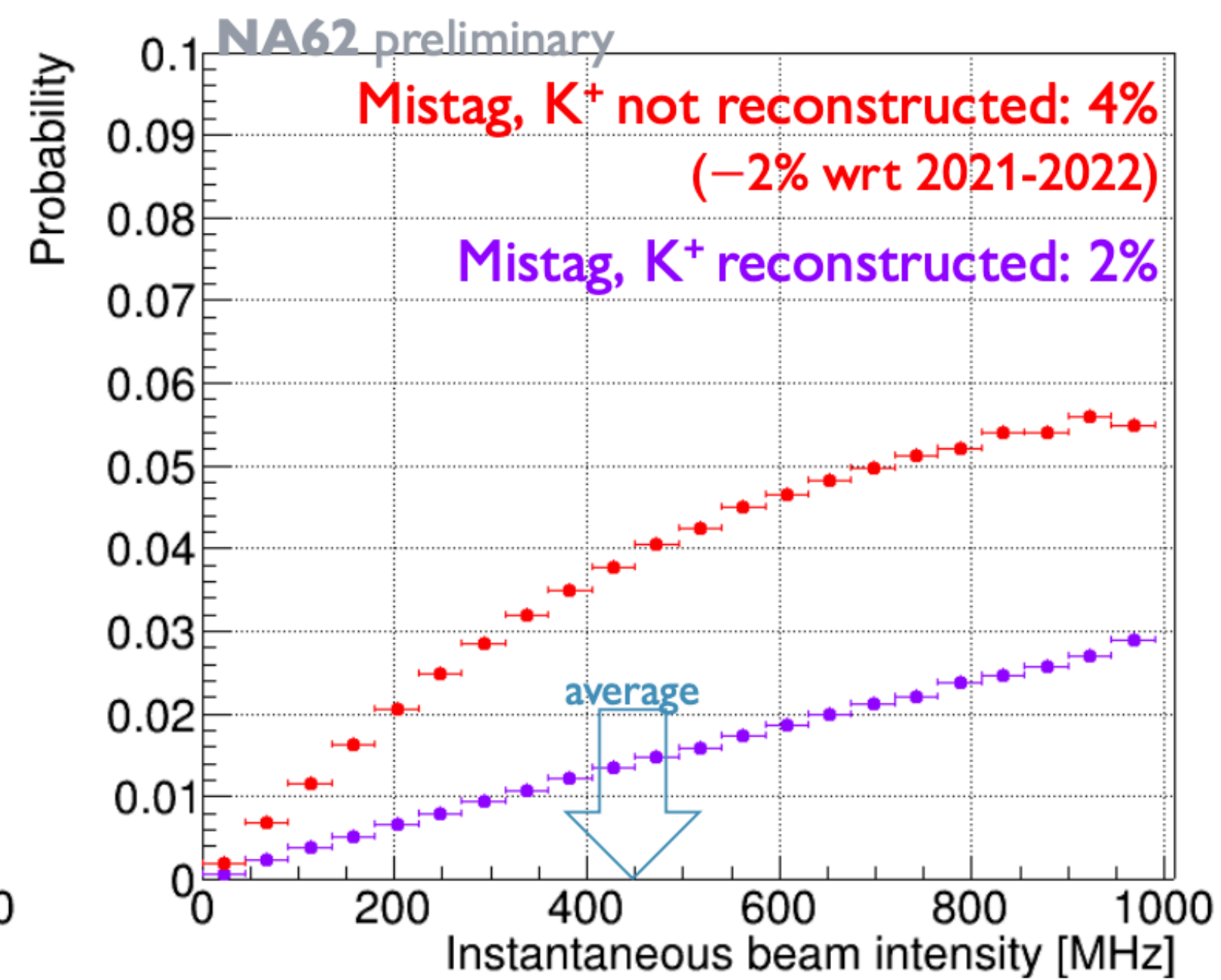
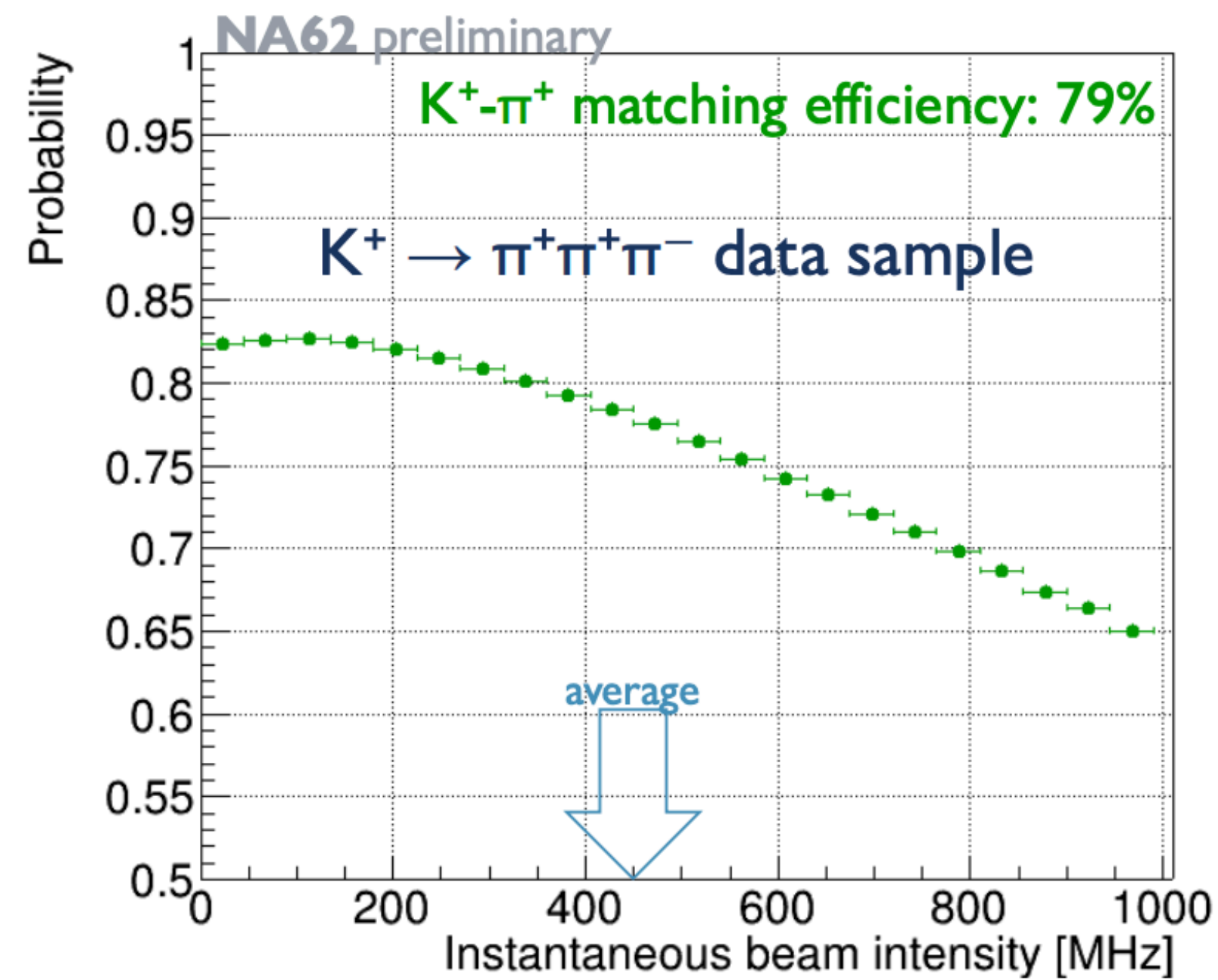
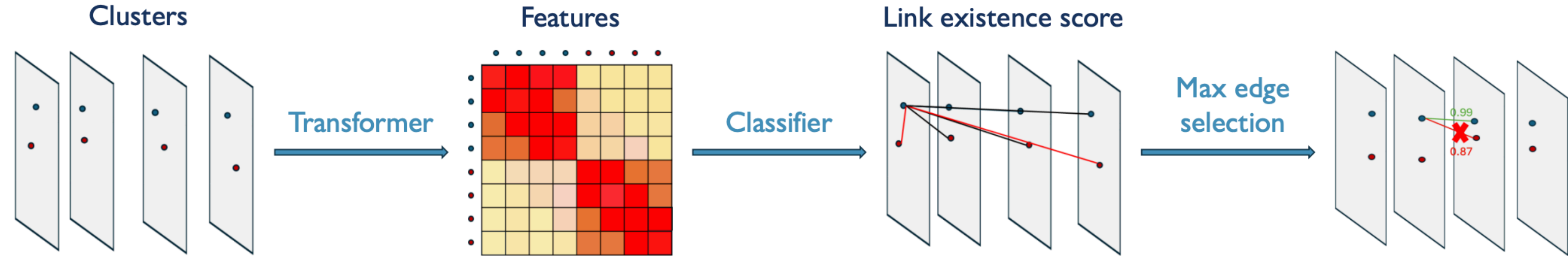


- Note: “instantaneous intensity” estimator is measured using the number of signals in time sidebands of GTK beam tracker.

- 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.
- From mid-2023 operate at optimal intensity (~75% of full) to maximise $\pi\nu\bar{\nu}$ sensitivity (2023-24 wrt 2022 data)
 - Higher DAQ efficiency
 - Average collected spills per day 2.7k (+40%)
 - Fraction of good data quality spills 0.93 (+20%)
 - Maximise signal yield:
 - average $N_{\pi\nu\bar{\nu}}^{SM}/\text{spill} = 26 \times 10^{-6}$ (+5%)

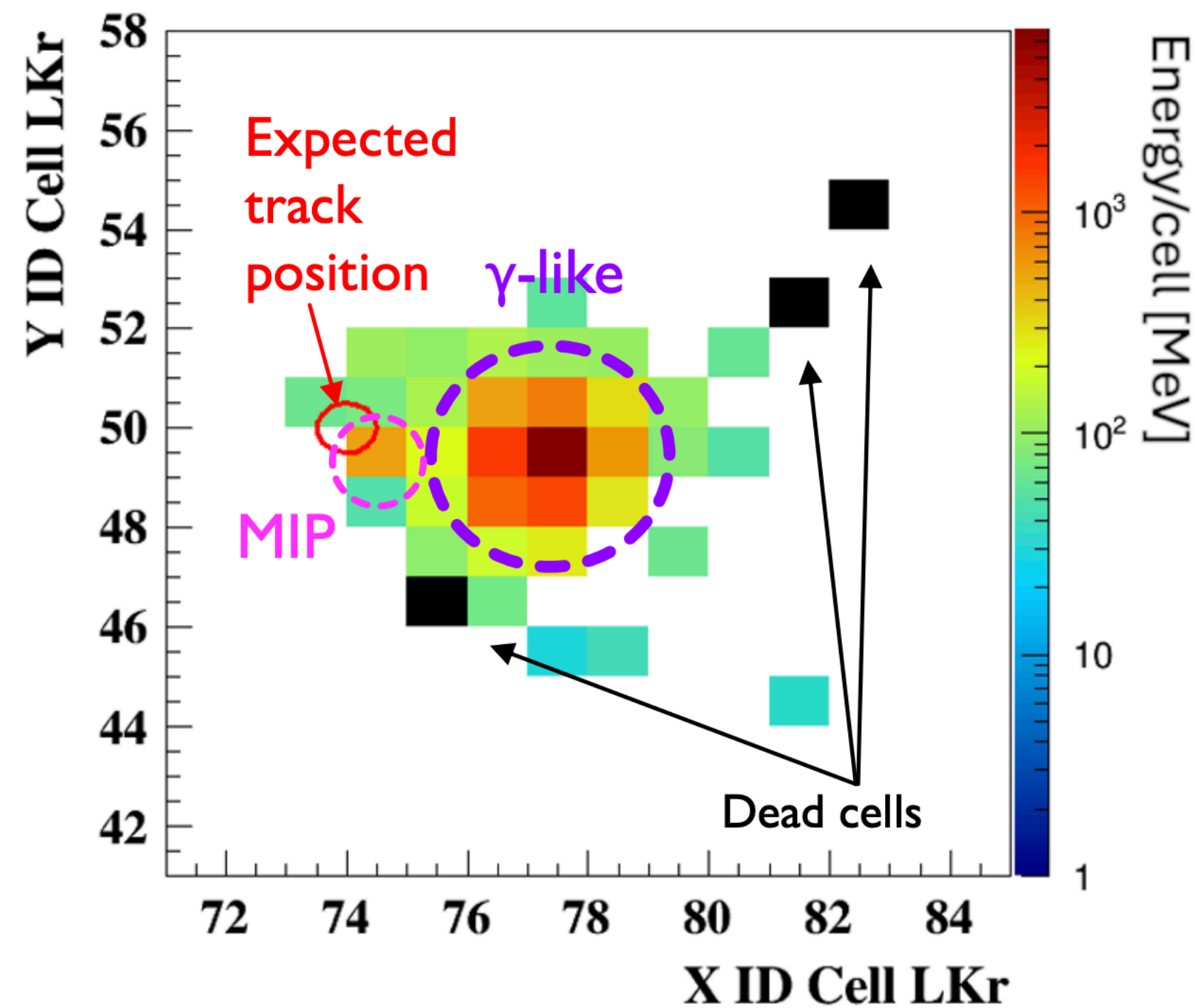
2023-2024 data-set larger and better quality

GTK 4D Beam Tracking : Machine Learning

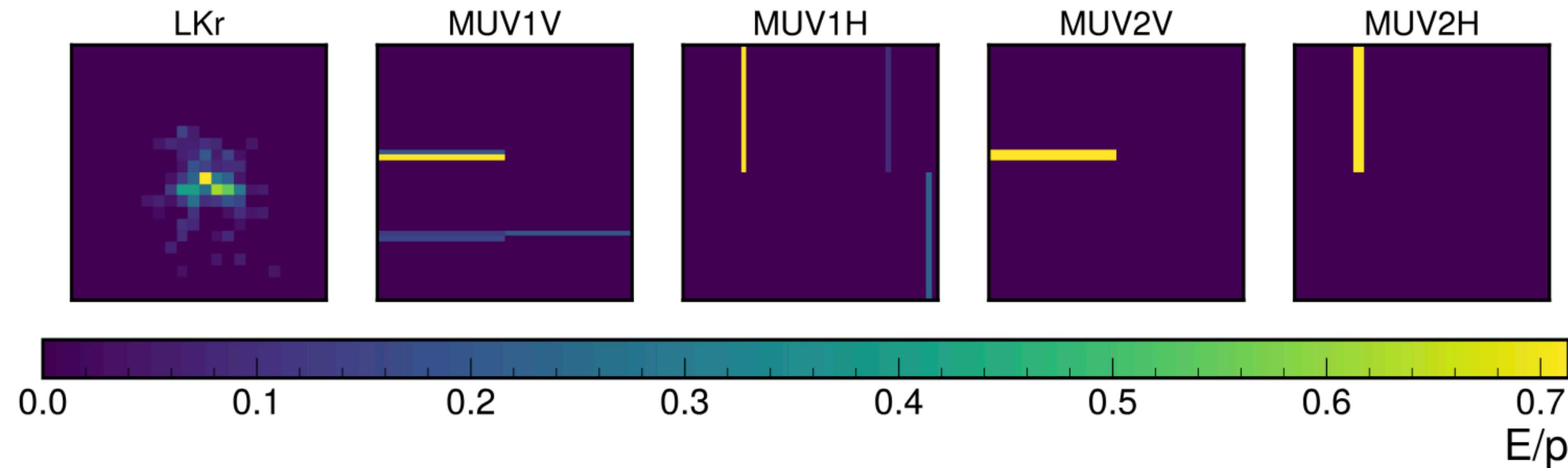


Calorimetric Particle ID : Machine Learning

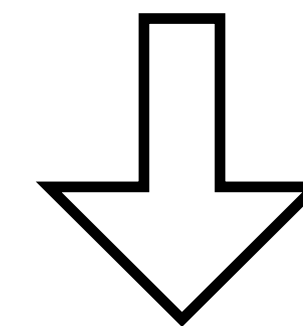
$K^+ \rightarrow \mu^+ \nu \gamma$ Background



Convolutional Neural Network (CNN)



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



$N_{bg}(K^+ \rightarrow \mu^+ \nu)$ reduced by 16%
 $N_{bg}(K^+ \rightarrow \mu^+ \nu \gamma)$ reduced by 70%

Upstream Background

Decays or interactions of beam particles upstream of fiducial volume



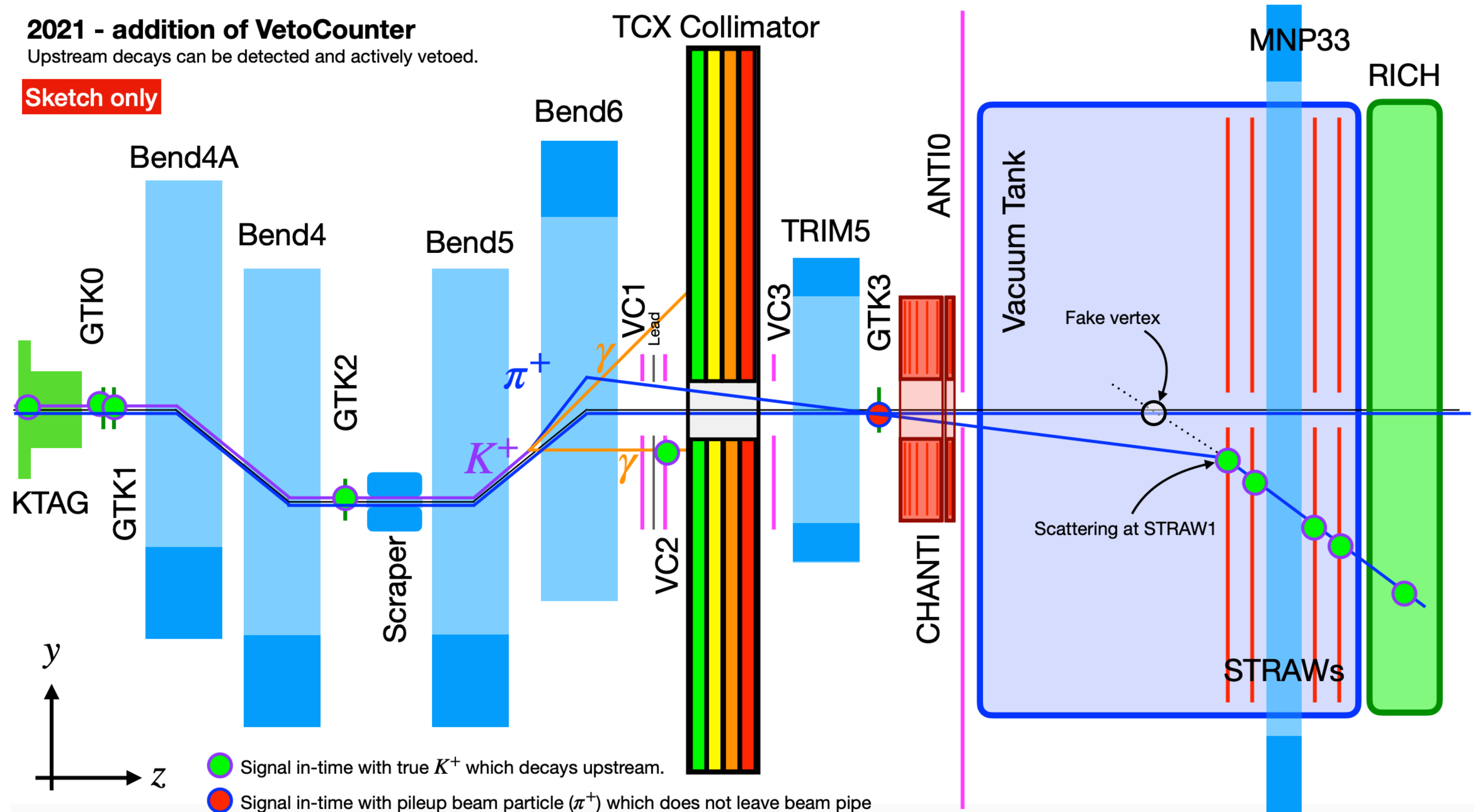
Upstream decays suppressed by factor 2 using VetoCounter

62% of total background

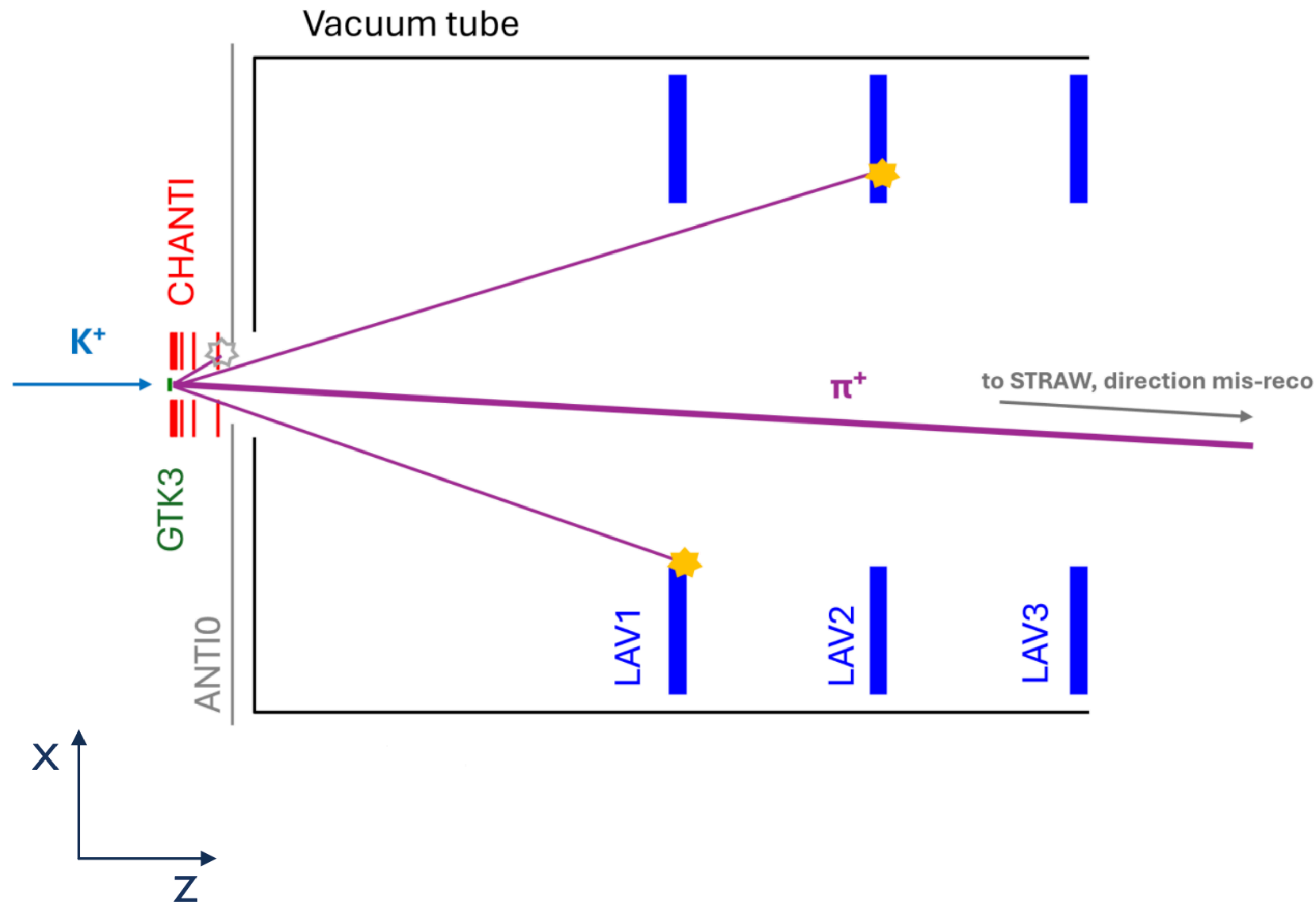
2021 - addition of VetoCounter

Upstream decays can be detected and actively vetoed.

Sketch only

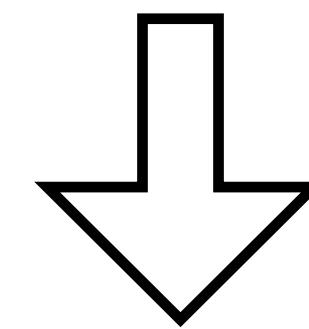


Upstream Inelastic Interactions Veto



Veto Strategy

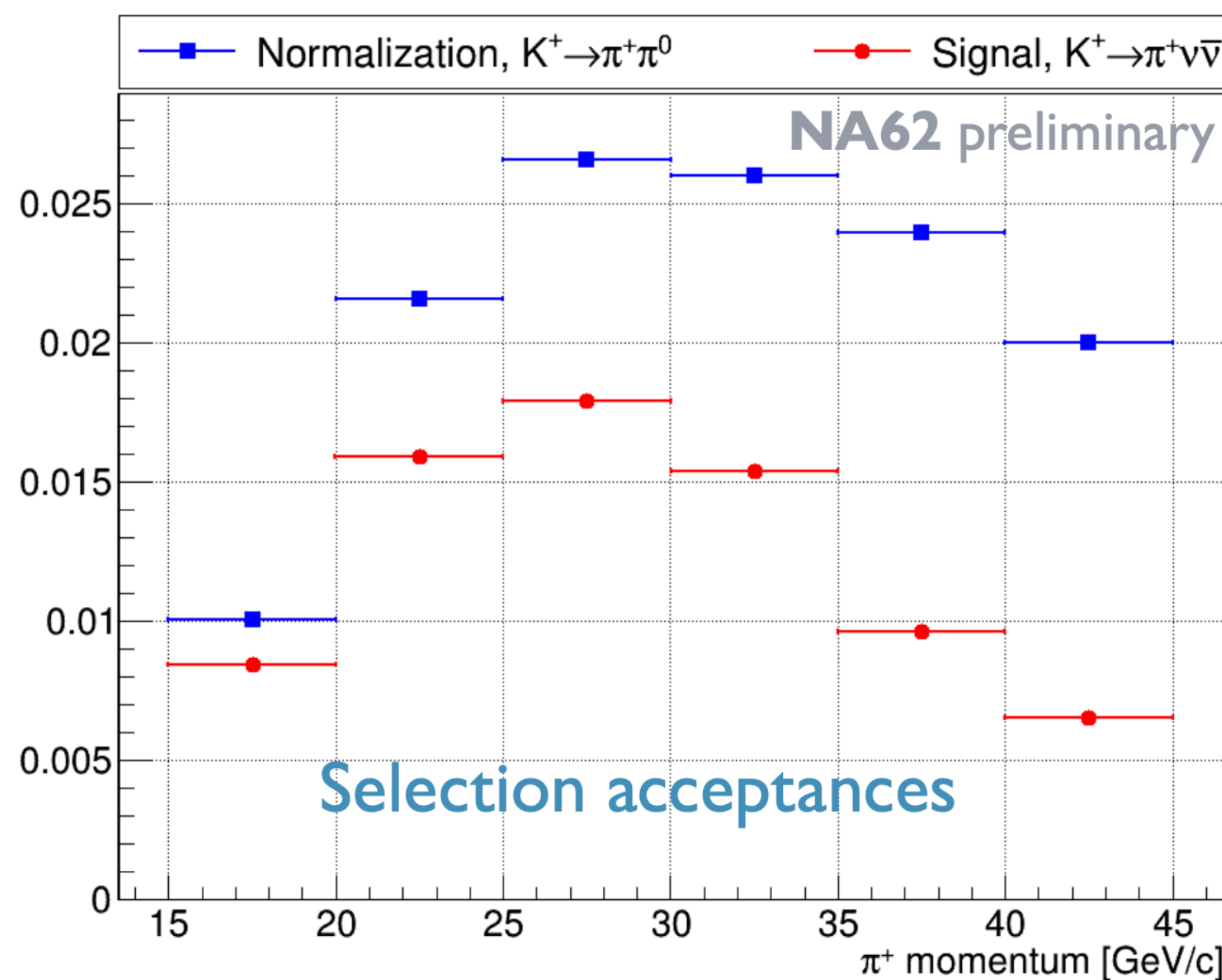
- Up to 2022:
 - LAV2+ trigger veto, 6ns window
 - Offline CHANTI Veto
- From 2023:
 - Relaxed L1 LAV trigger veto (only LAVs downstream of K-pi vertex, 4ns window)
 - Offline CHANTI & **LAV1** vetos



- Inelastic interactions control sample enlarged 10x
- **LAV1 veto reduces total background by 30%** in 2023–24 dataset with $\mathcal{O}(\%)$ signal loss

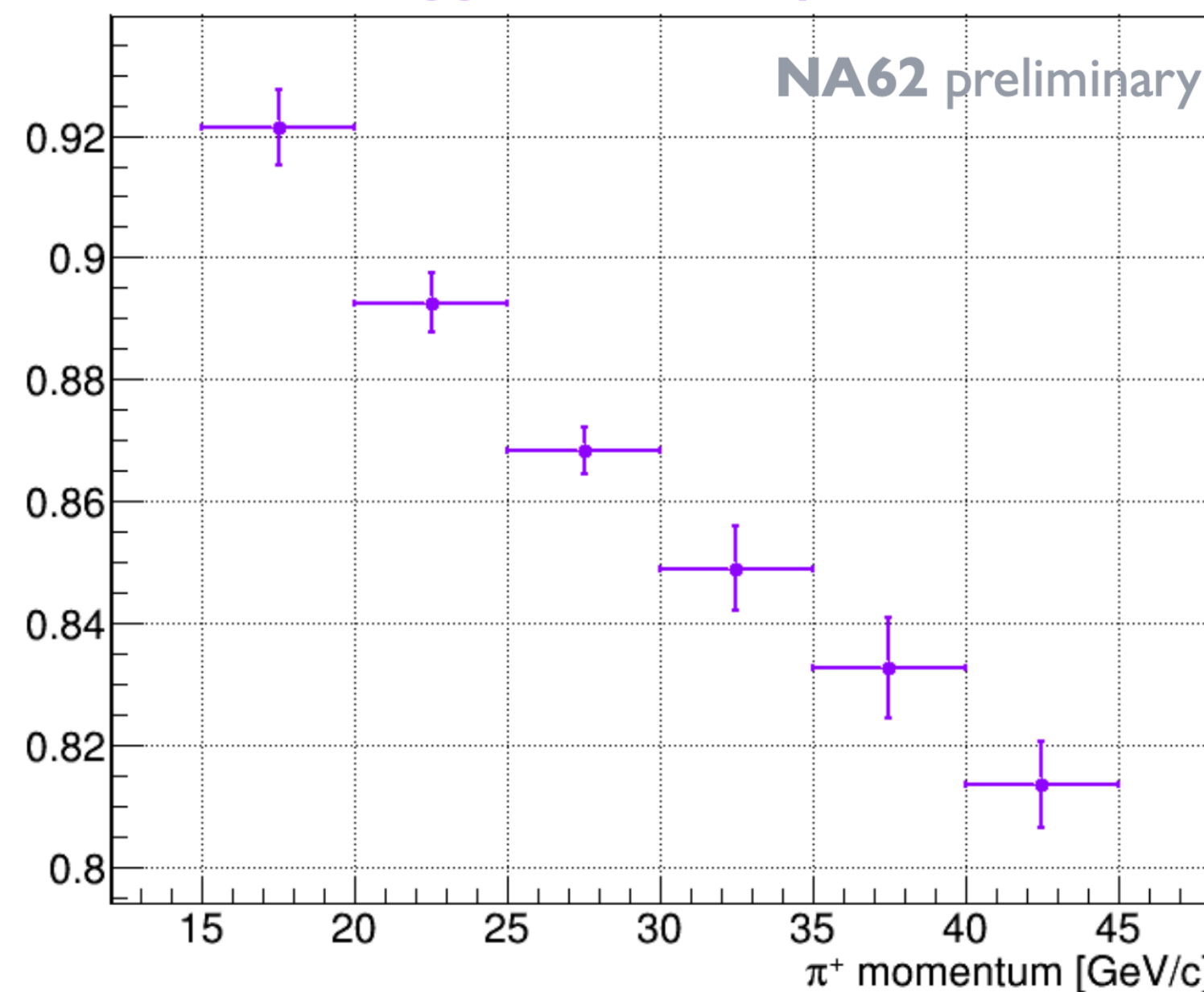
Signal Sensitivity

$$N_{\pi\nu\bar{\nu}}^{\text{SM,exp}}(p_i) = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{\text{SM}}}{\mathcal{B}_{\text{SES}}(p_i)} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{\text{SM}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} \underbrace{D_0}_{\text{Normalisation trigger downscale} = 400} \underbrace{N_{\pi\pi}(p_i)}_{\text{count normalisation events}} \underbrace{\varepsilon_{\text{trig}}(p_i)}_{\text{Trigger efficiency ratio}} \underbrace{\varepsilon_{\text{RV}}}_{\text{Random veto efficiency}}$$

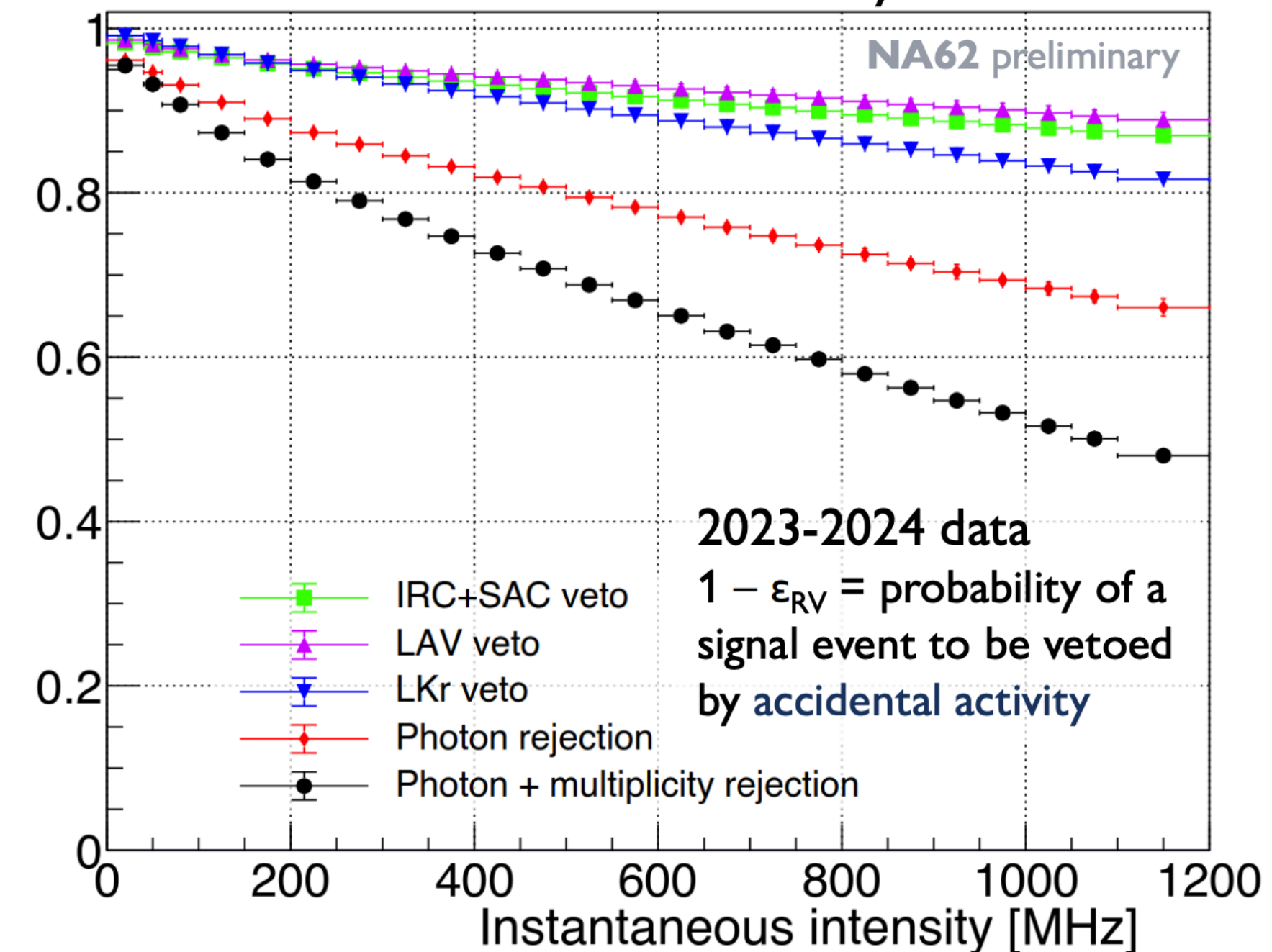


20.7 %
[PDG]

Trigger efficiency ratio



Random veto efficiency



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

$$\varepsilon_{\text{trig}} = (86.4 \pm 1.2) \%$$

Improved systematics evaluation

• $1.14 \times \varepsilon_{\text{RV}}$:

- Mainly due to 600 → 450 MHz
- + Improvement in one-track selection

Signal Sensitivity

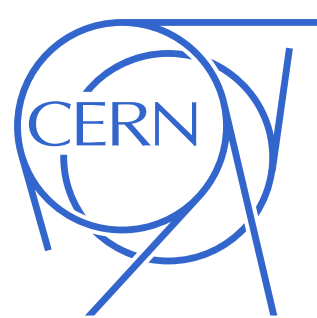


$$N_{\pi\nu\bar{\nu}}^{\text{SM,exp}}(p_i) = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{\text{SM}}}{\mathcal{B}_{SES}(p_i)} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{\text{SM}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} D_0 N_{\pi\pi}(p_i) \epsilon_{trig}(p_i) \epsilon_{RV}$$

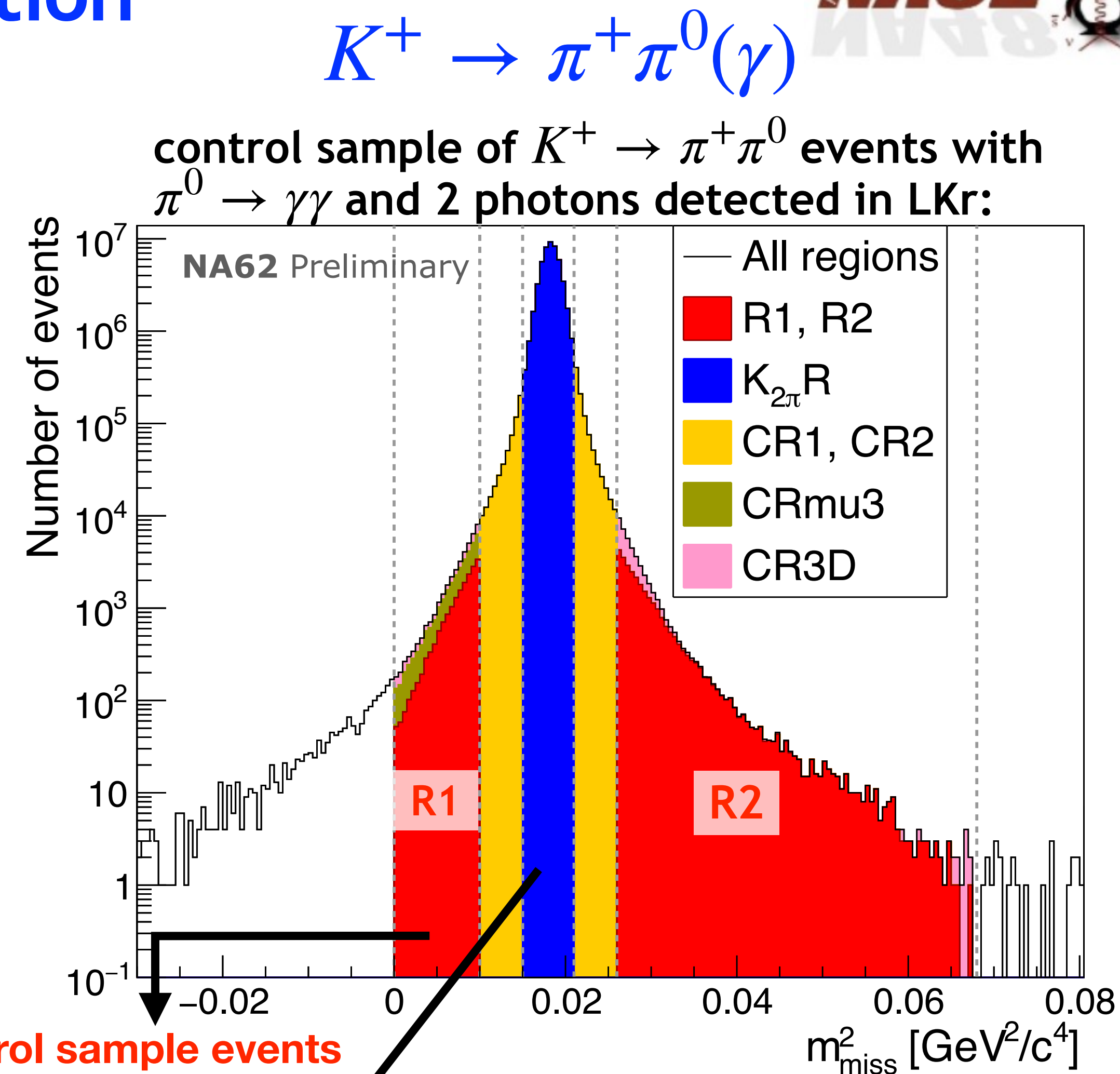
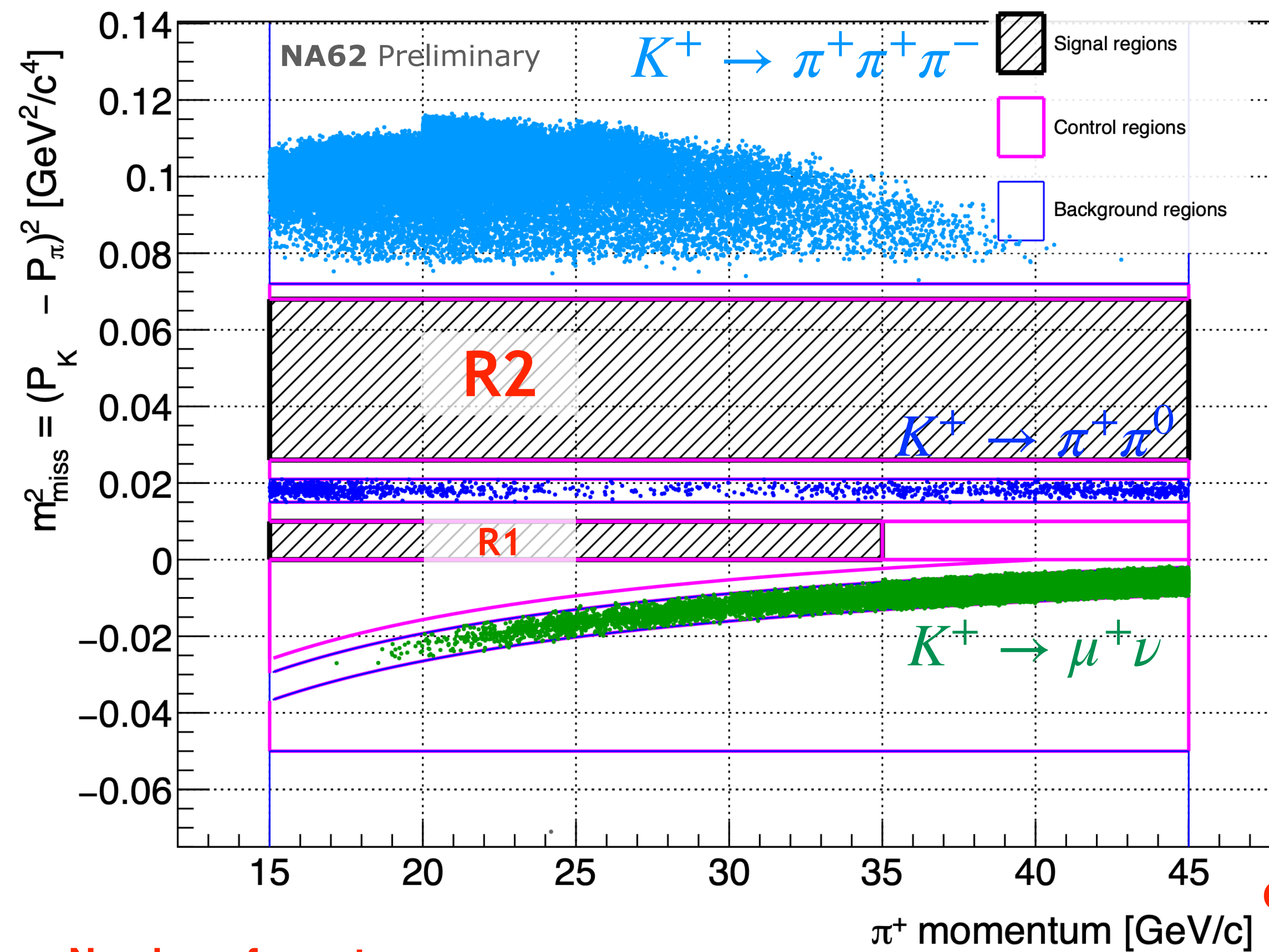
		2021–2022 [JHEP 02 (2025) 191]	2023–2024 (this analysis)
$N_{\pi\pi}$	Normalisation $K^+ \rightarrow \pi^+\pi^0$	1.95×10^8	3.93×10^8
$A_{\pi\pi}$	Normalisation acceptance	$(13.410 \pm 0.005)\%$	$(12.971 \pm 0.009)\%$
N_K	Effective K^+ decays	2.85×10^{12}	5.93×10^{12}
$A_{\pi\nu\bar{\nu}}$	Signal acceptance	$(7.62 \pm 0.22)\%$	$(7.36 \pm 0.33)\%$
ϵ_{trig}	Trigger efficiency	$(85.9 \pm 1.4)\%$	$(86.4 \pm 1.2)\%$
ϵ_{RV}	Random veto efficiency	$(63.2 \pm 0.6)\%$	$(72.3 \pm 0.7)\%$
$\mathcal{B}_{SES}$	Single event sensitivity	$(0.85 \pm 0.03) \times 10^{-11}$	$(0.37 \pm 0.02) \times 10^{-11}$
$N_{\pi\nu\bar{\nu}}^{\text{SM,exp}}$	Number of expected SM events	9.9 ± 0.3	22.9 ± 1.1

2023–2024 wrt
2021–2022:

- **2x** normalisation statistics
- **1.14x** random veto efficiency
- **2.3x** number of SM signal events expected



Backgrounds From m_{miss}^2 mis-reconstruction



Number of events
passing signal selection
in background region

Kinematic tail fraction:
measured in control sample

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

Control sample events
in Signal Regions

Control sample events
in Background Region

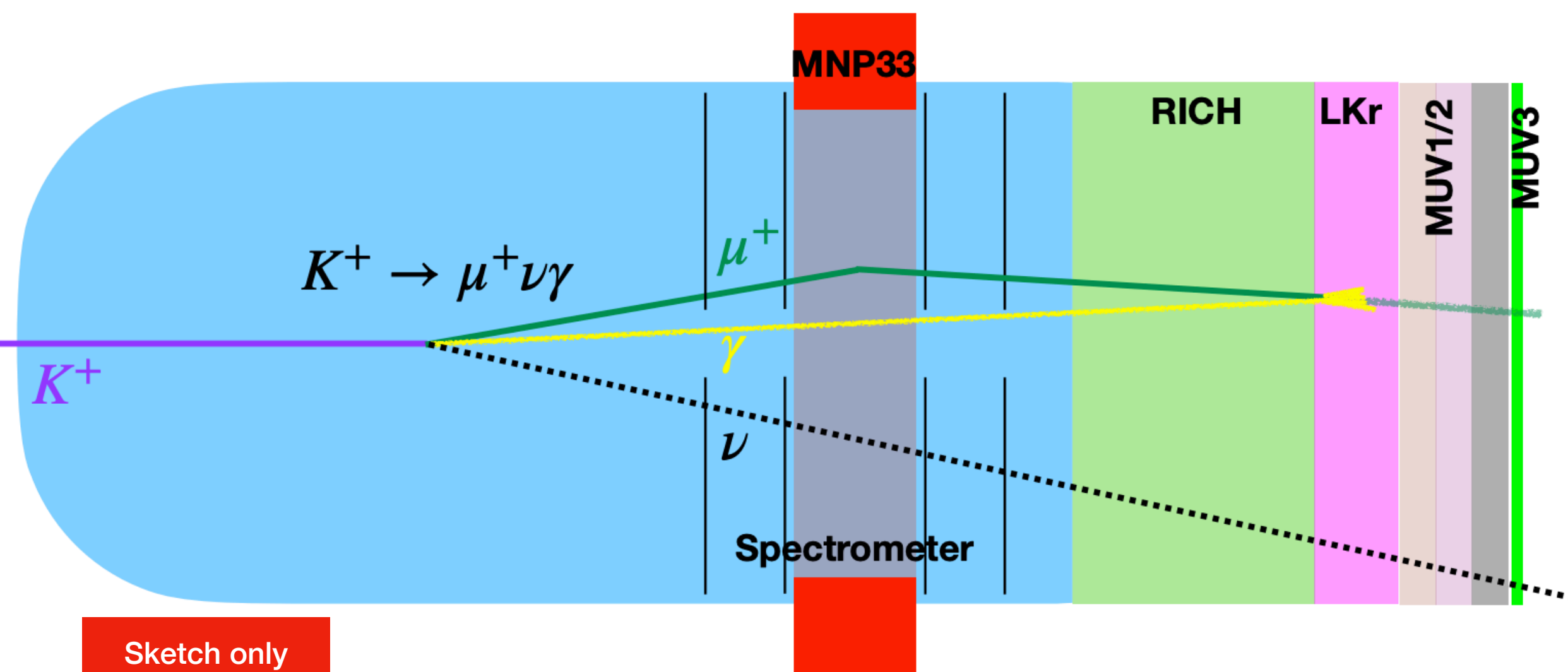
$$N_{bg}(K^+ \rightarrow \pi^+ \pi^0(\gamma)) = 1.07 \pm 0.07$$

$$N_{bg}(K^+ \rightarrow \mu^+ \nu) = 1.2 \pm 0.2$$

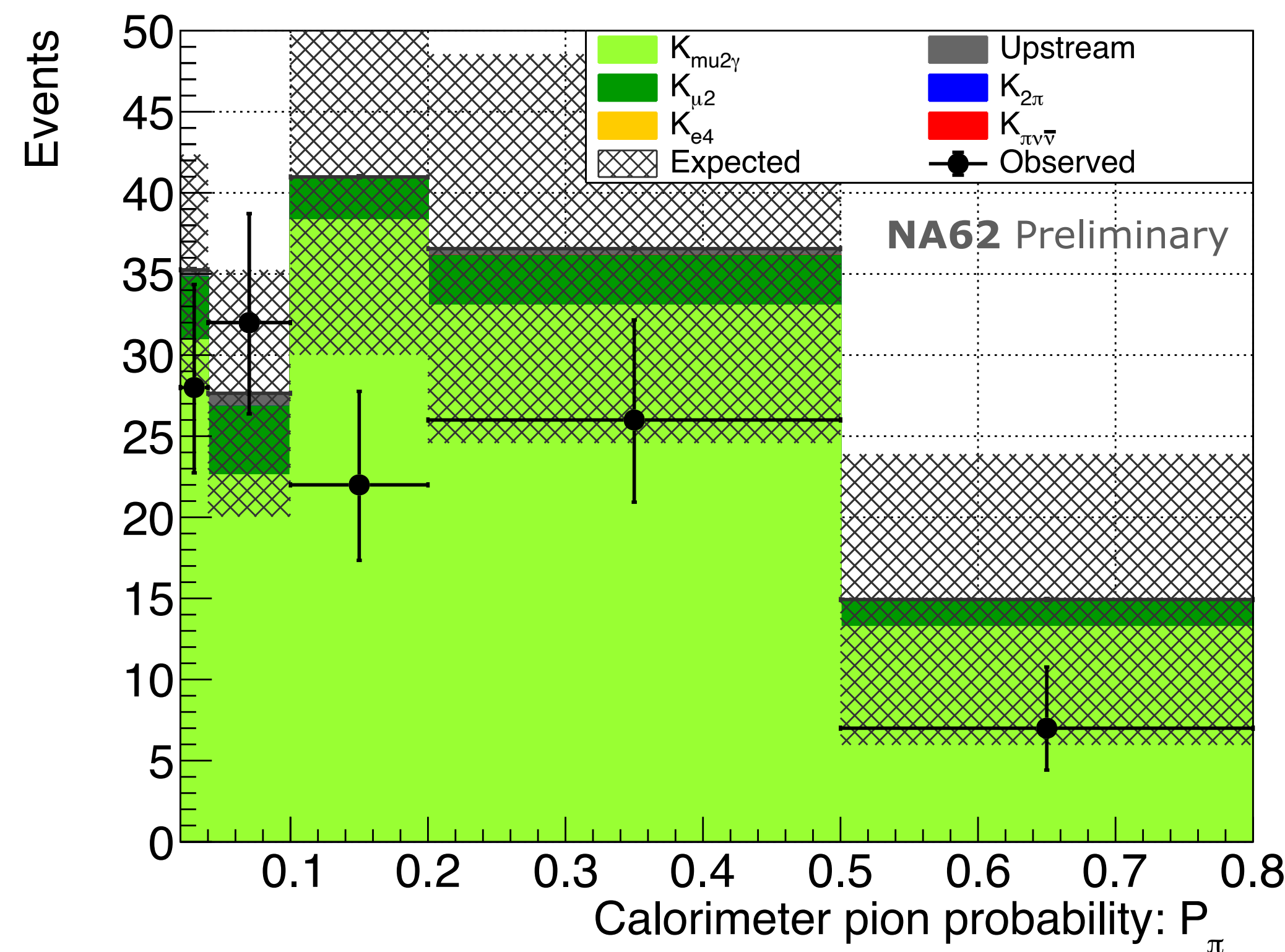
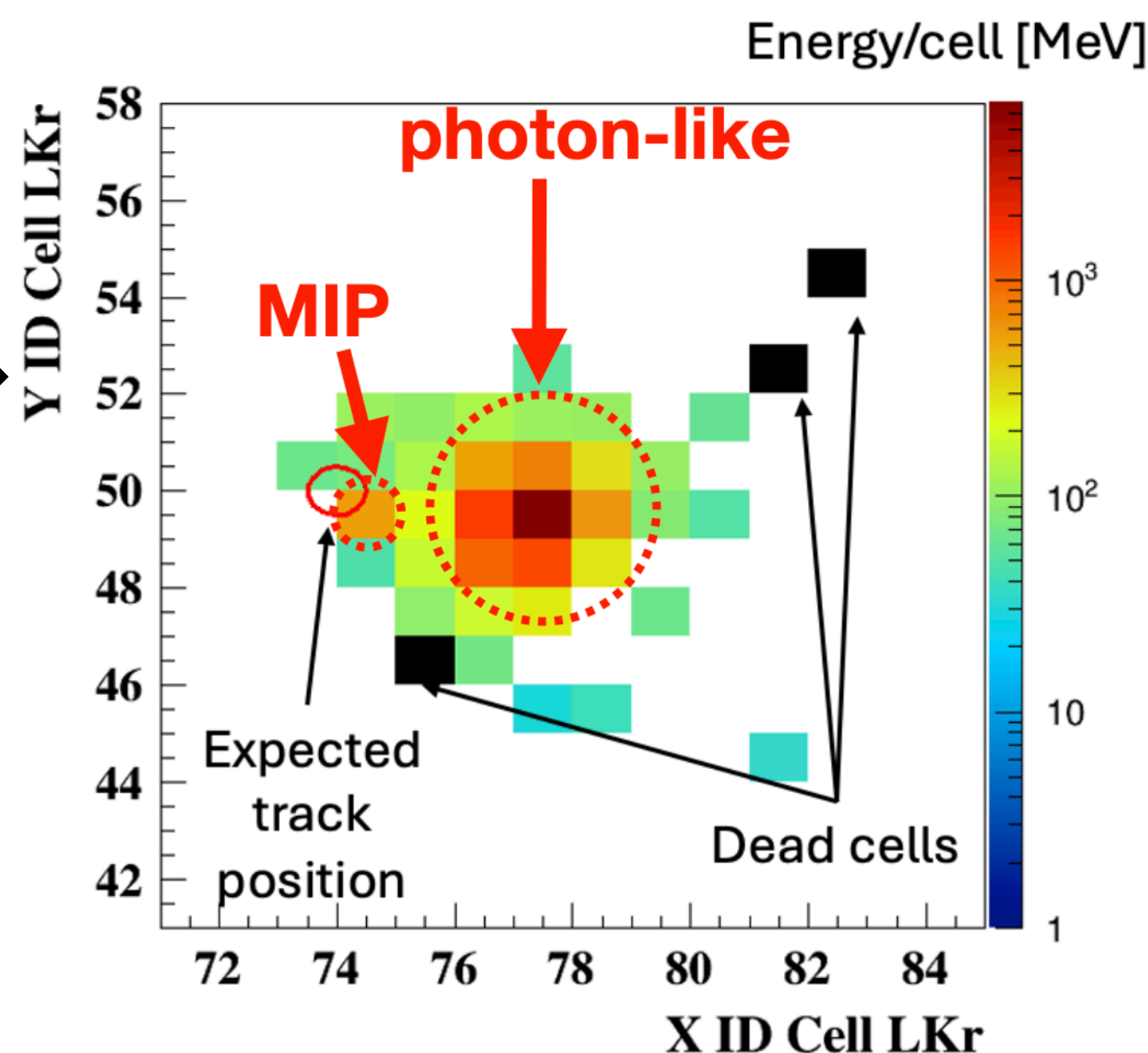
$$N_{bg}(K^+ \rightarrow \pi^+ \pi^+ \pi^-) = 0.25 \pm 0.05$$

$K^+ \rightarrow \mu^+ \nu \gamma$ Background & CNN PID

- 2021–22 data: kinematically select & veto with $m_{miss}^2(K_{\mu 2\gamma}) = (P_K - P_\mu - P_\gamma)^2$
- 2023–24: New CNN classifier for Calo. PID vetos 70% of the residual $K^+ \rightarrow \mu^+ \nu \gamma$ background.
- Validate predictions in Calo PID sidebands.



2022 data: example of $\gamma + \mu^+$ overlap in LKr.



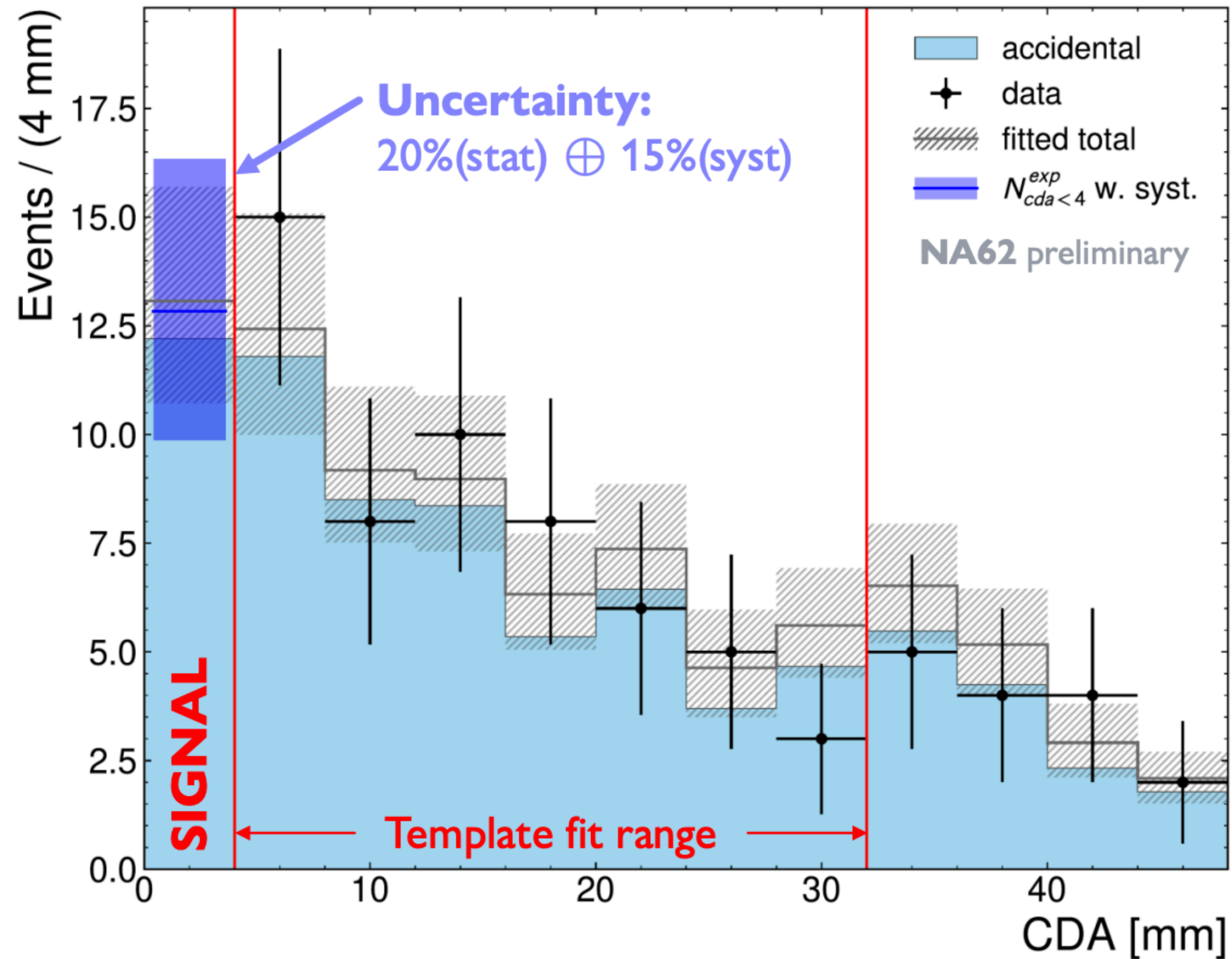
Upstream Background

Decays or interactions of beam particles upstream of fiducial volume



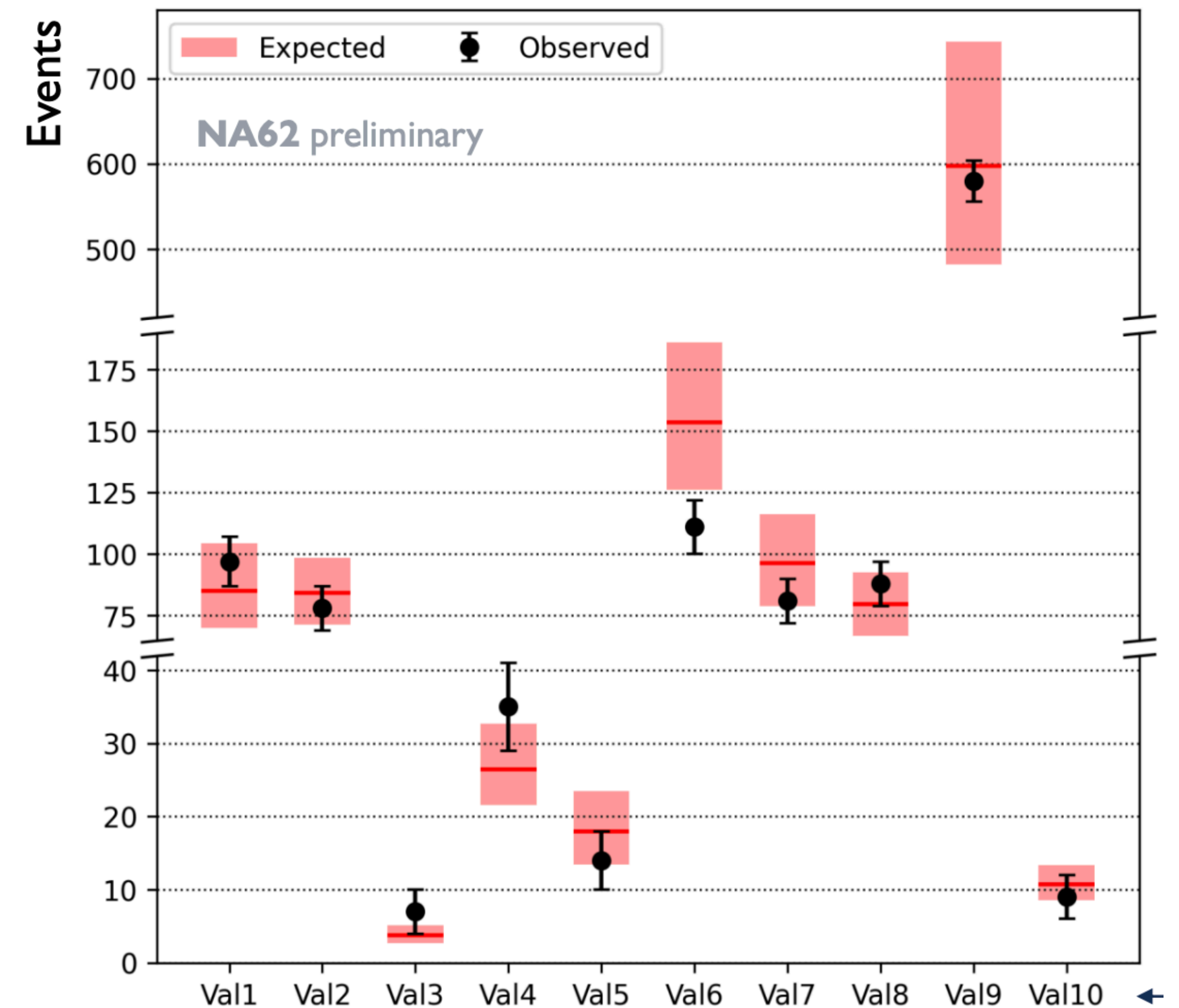
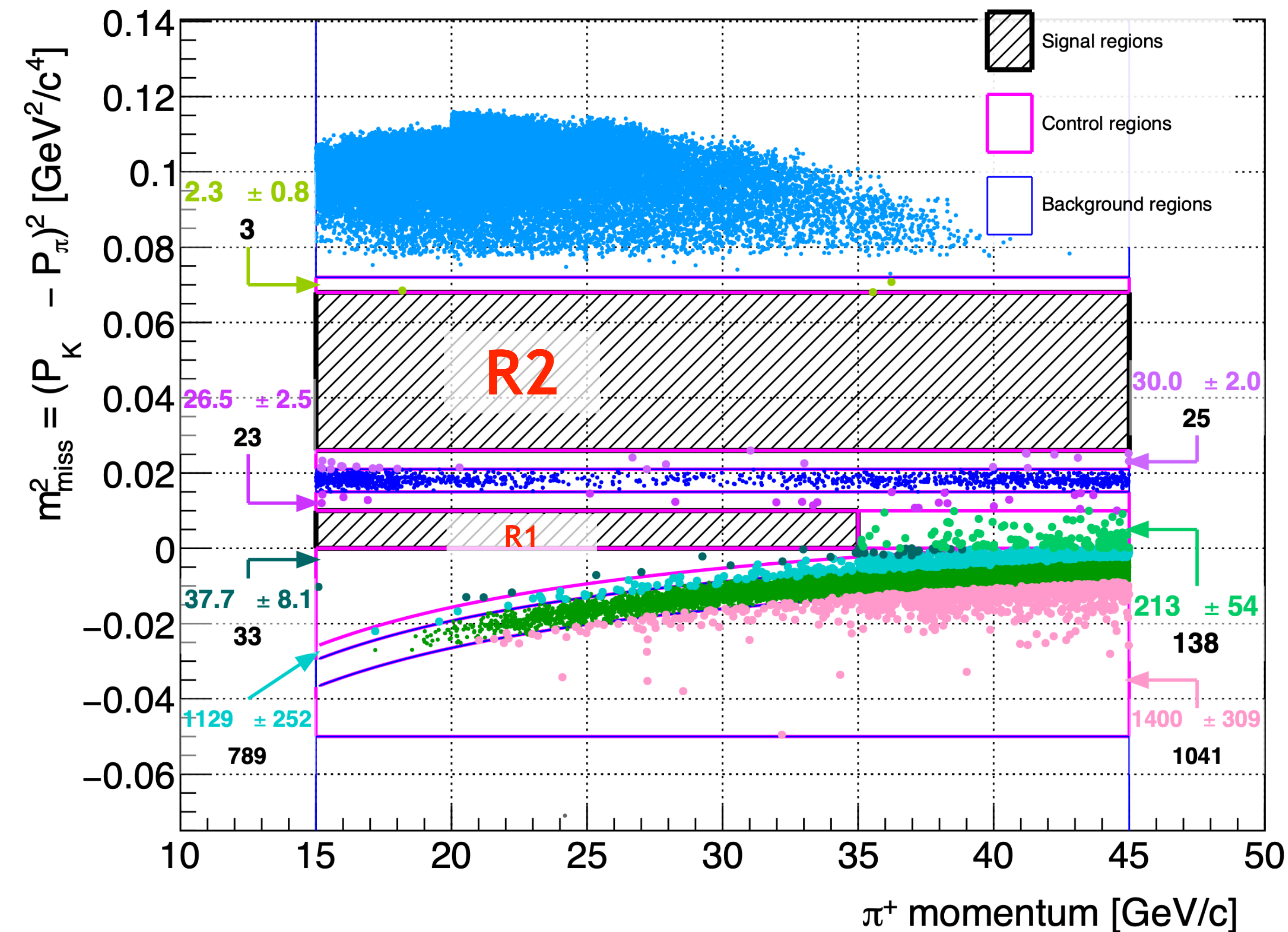
$$N_{bg}^{Ups.} = (1 - f_{match}) \sum_i N_i^{URS} f_{cda} P_i^{match}$$

- Fully data-driven estimation
- **Upstream Reference Sample:** enriched with all known upstream background mechanisms.
- **CDA:** closest distance of approach between K^+ and π^+ candidates.
- Extrapolation to signal region (f_{cda}) via **template fit** (new - previously linear approximation)
- Two templates from data: accidental-like & interaction-like.
- **New understanding:** dominated by accidental-like events.



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

Background Validation



- Use control regions to validate predictions for K^+ decays in FV: $p - \text{value} = 0.65$

- Validate upstream background with 10 independent samples enriched with different upstream background mechanisms: $p - \text{value} = 0.79$

Backgrounds

	2021–2022 [JHEP 02 (2025) 191]	2023–2024 (this analysis)
$K^+ \rightarrow \pi^+ \pi^0 (\gamma)$	0.83 ± 0.05	1.19 ± 0.10
$K^+ \rightarrow \mu^+ \nu (\gamma)$	1.70 ± 0.47	1.39 ± 0.29
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	0.11 ± 0.03	0.25 ± 0.05
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	$0.89^{+0.33}_{-0.27}$	$1.59^{+0.51}_{-0.43}$
$K^+ \rightarrow \pi^+ \gamma \gamma$	0.01 ± 0.01	0.04 ± 0.04
$K^+ \rightarrow \pi^0 \ell^+ \nu$	< 0.001	< 0.001
Upstream	$7.4^{+2.1}_{-1.8}$	$7.4^{+2.8}_{-2.2}$
Total	$11.0^{+2.1}_{-1.9}$	$11.9^{+2.9}_{-2.3}$
$N_{\pi\nu\bar{\nu}}^{\text{SM,exp}}$	9.9 ± 0.3	22.9 ± 1.1

data-driven

estimated with MC

fully data-driven

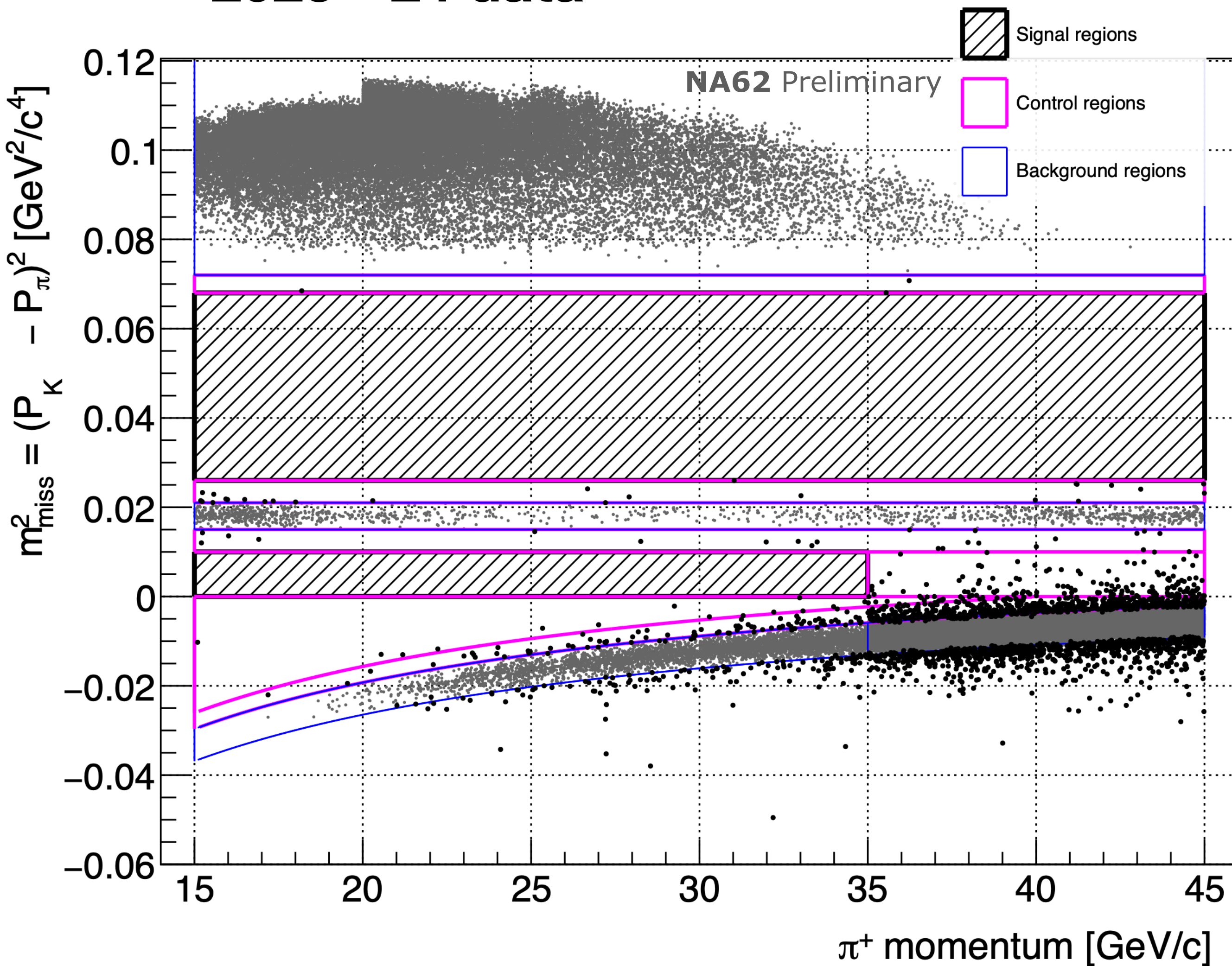
- 2023+2024: $\sqrt{S + B/S} \approx 0.25$
 - c.f. ≈ 0.5 for previous analysis)
- By far the most sensitive analysis yet!

- Better π^0 rejection
- Better μ^+ mis-ID
- Upstream background rejection improved

Combining with previous 2016–22 datasets:
 $N_{bg} = 30^{+4}_{-3}$, $N_{\pi\nu\bar{\nu}}^{\text{SM,exp}} = 43 \pm 1$
 $\Rightarrow$ **expected SM significance $> 5\sigma$**

Signal regions

2023–24 data



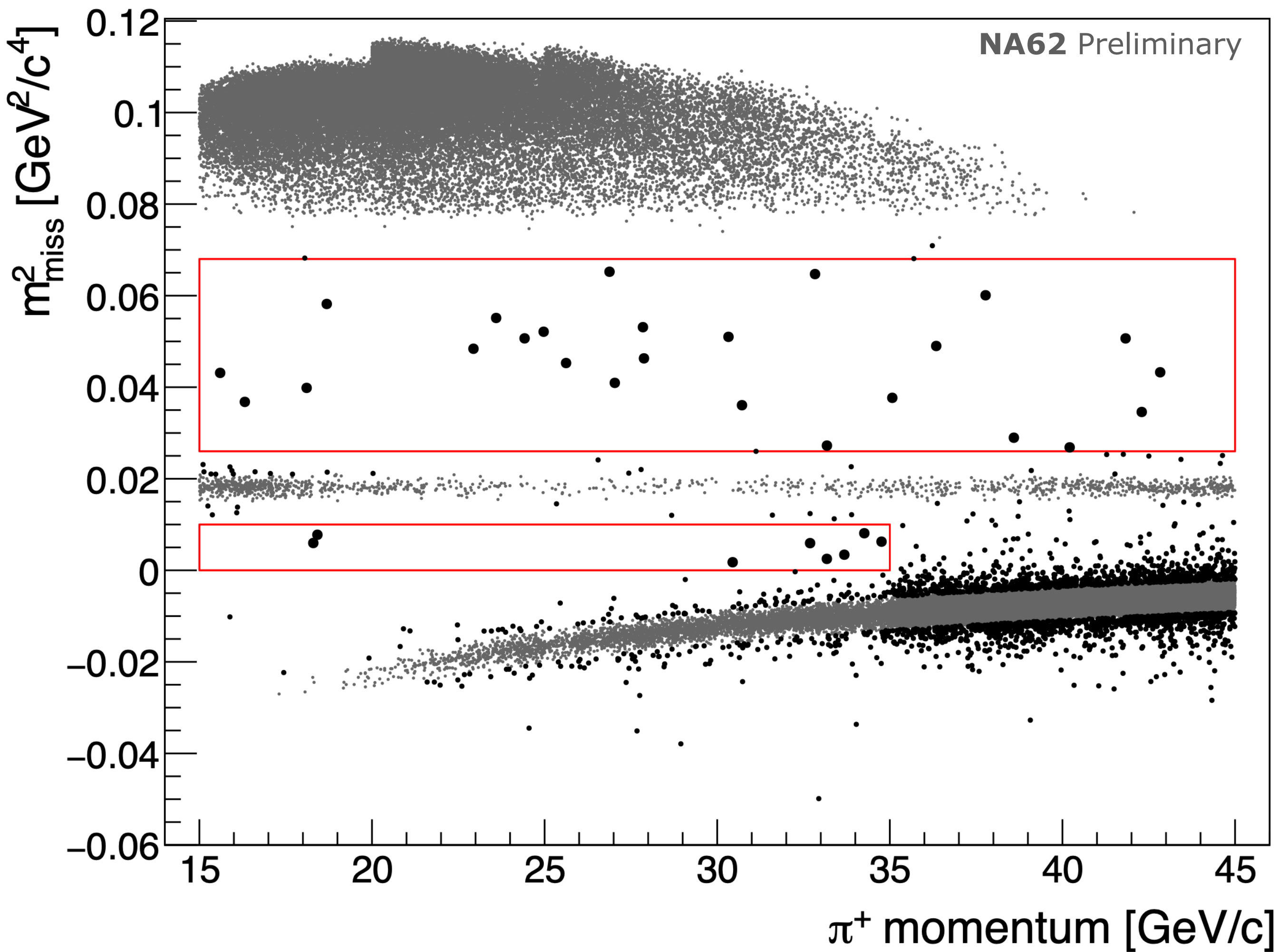
Expected SM signal, $N_{\pi\nu\bar{\nu}}^{SM} \approx 23$

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

Observed, $N_{obs} = ?$

Signal regions

2023–24 data

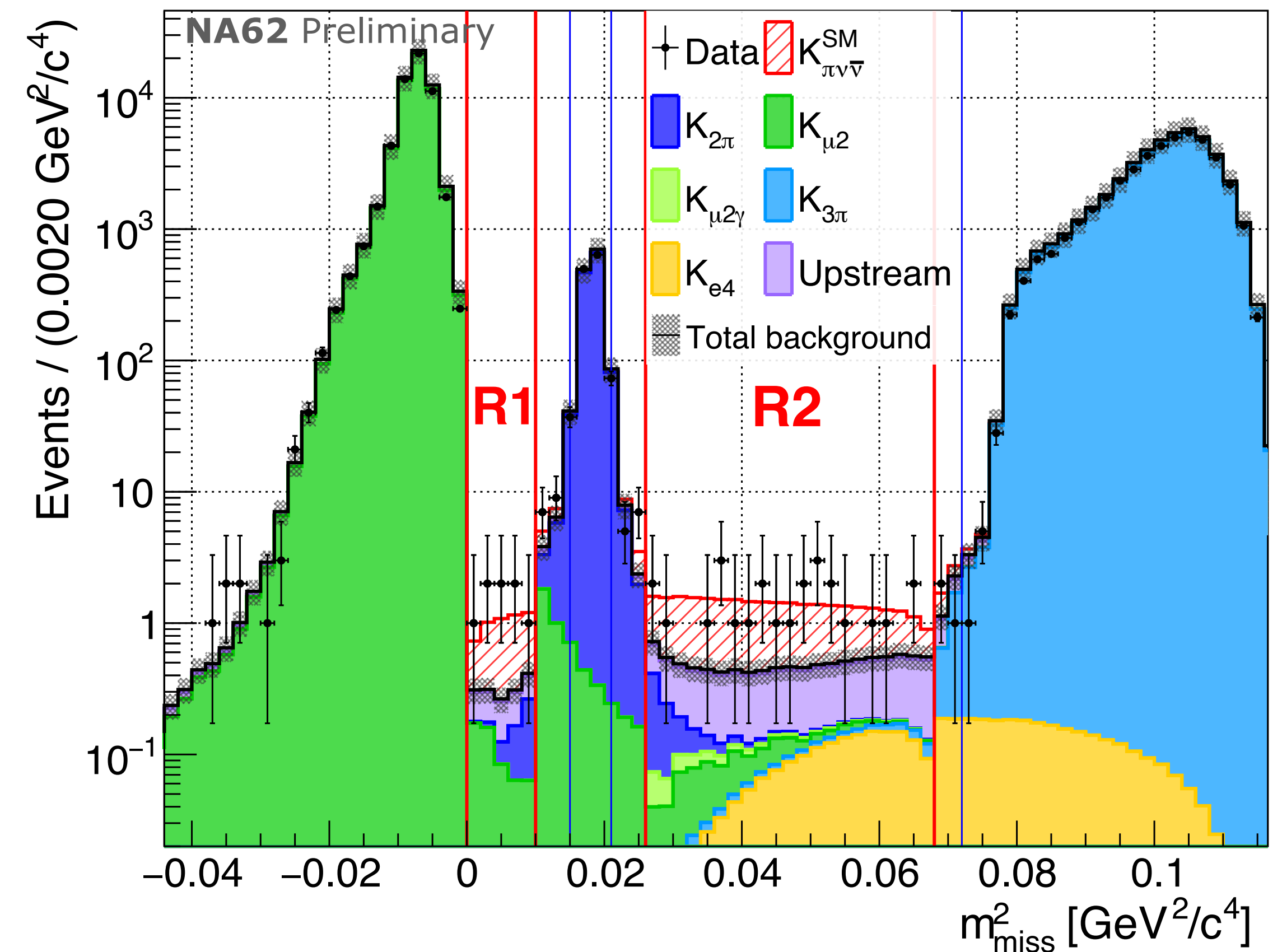


Expected SM* signal, $N_{\pi\nu\bar{\nu}}^{SM} = 22.9 \pm 1.1$

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

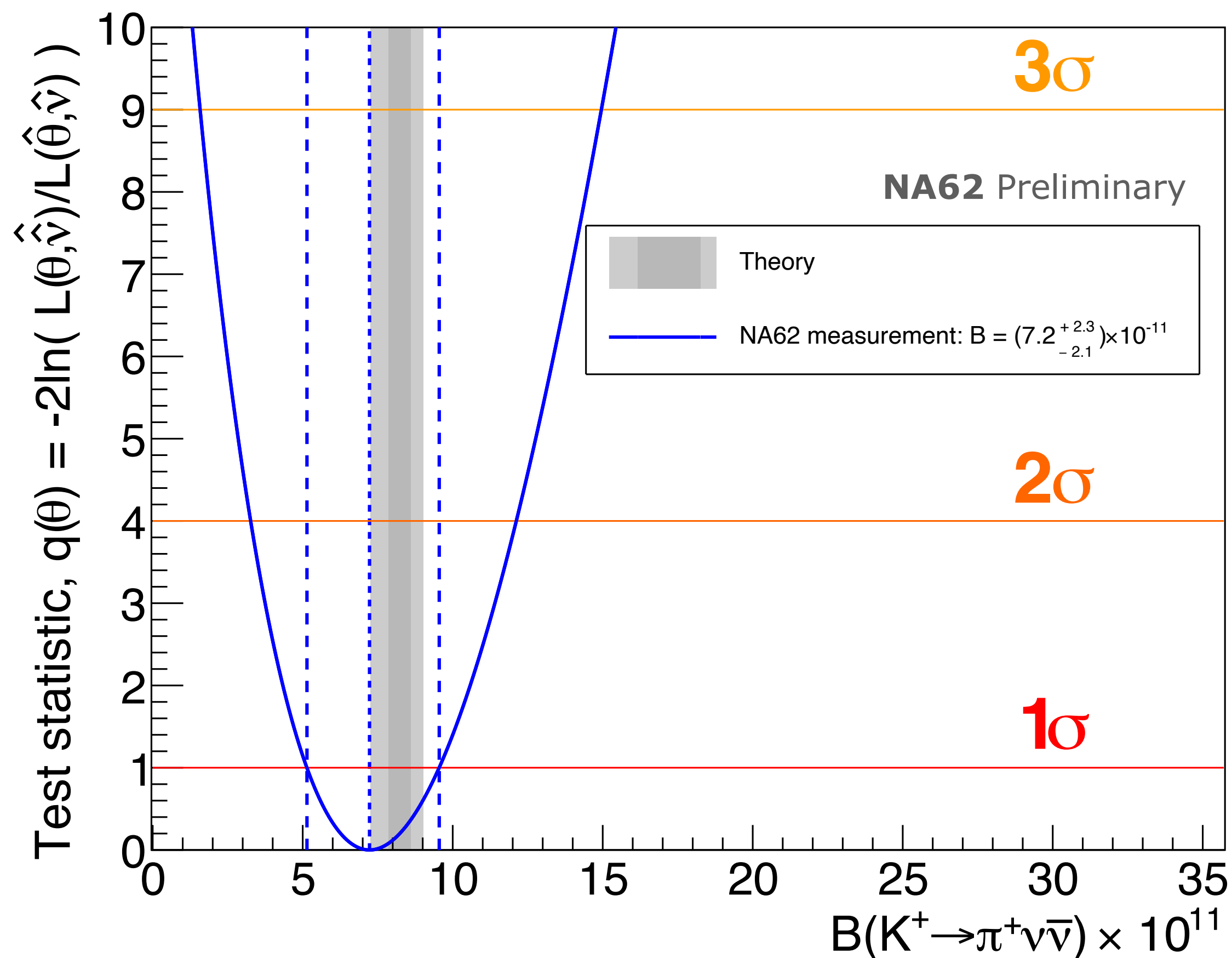
Observed, $N_{obs} = 33$

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

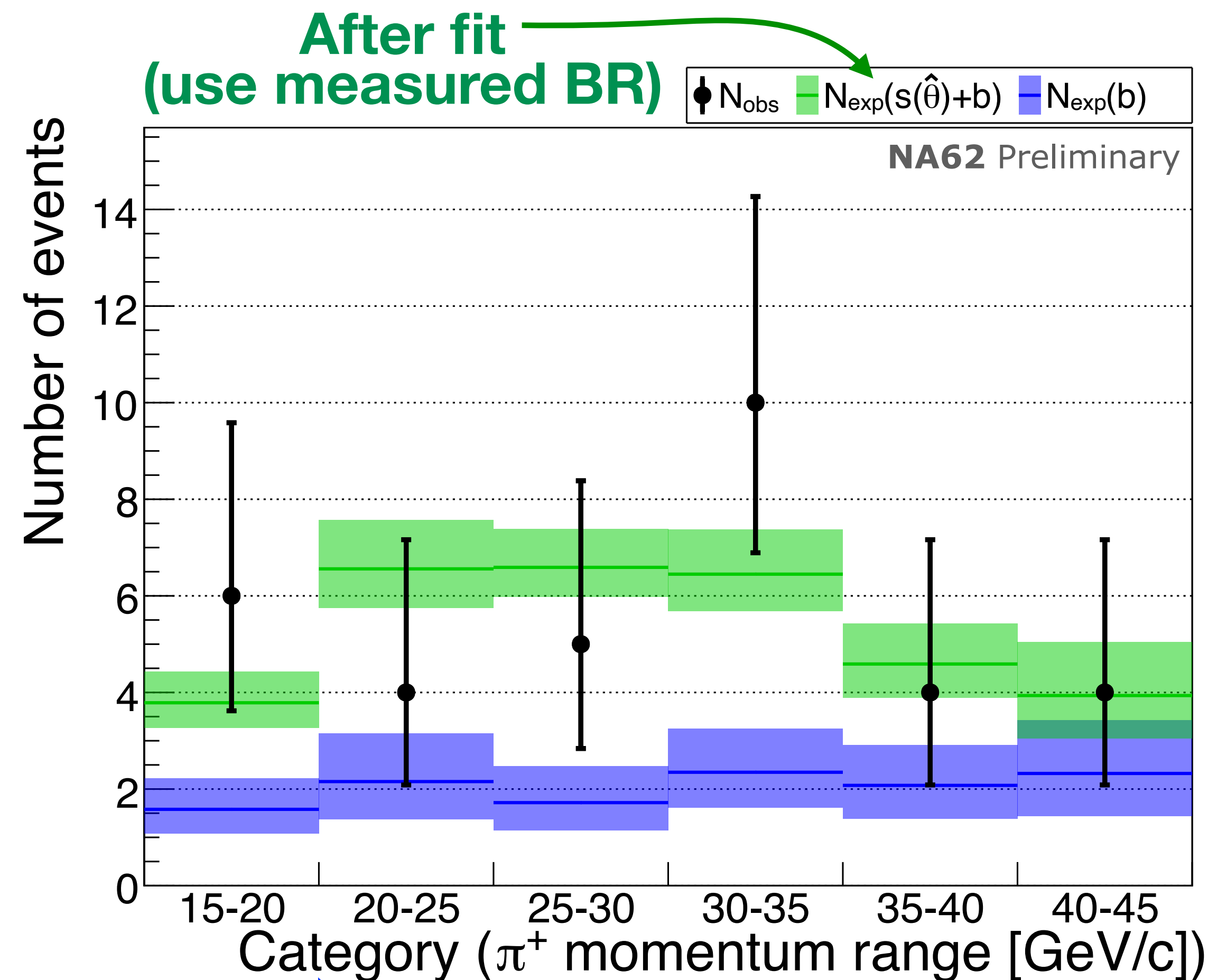


Results: 2023-24 Data

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

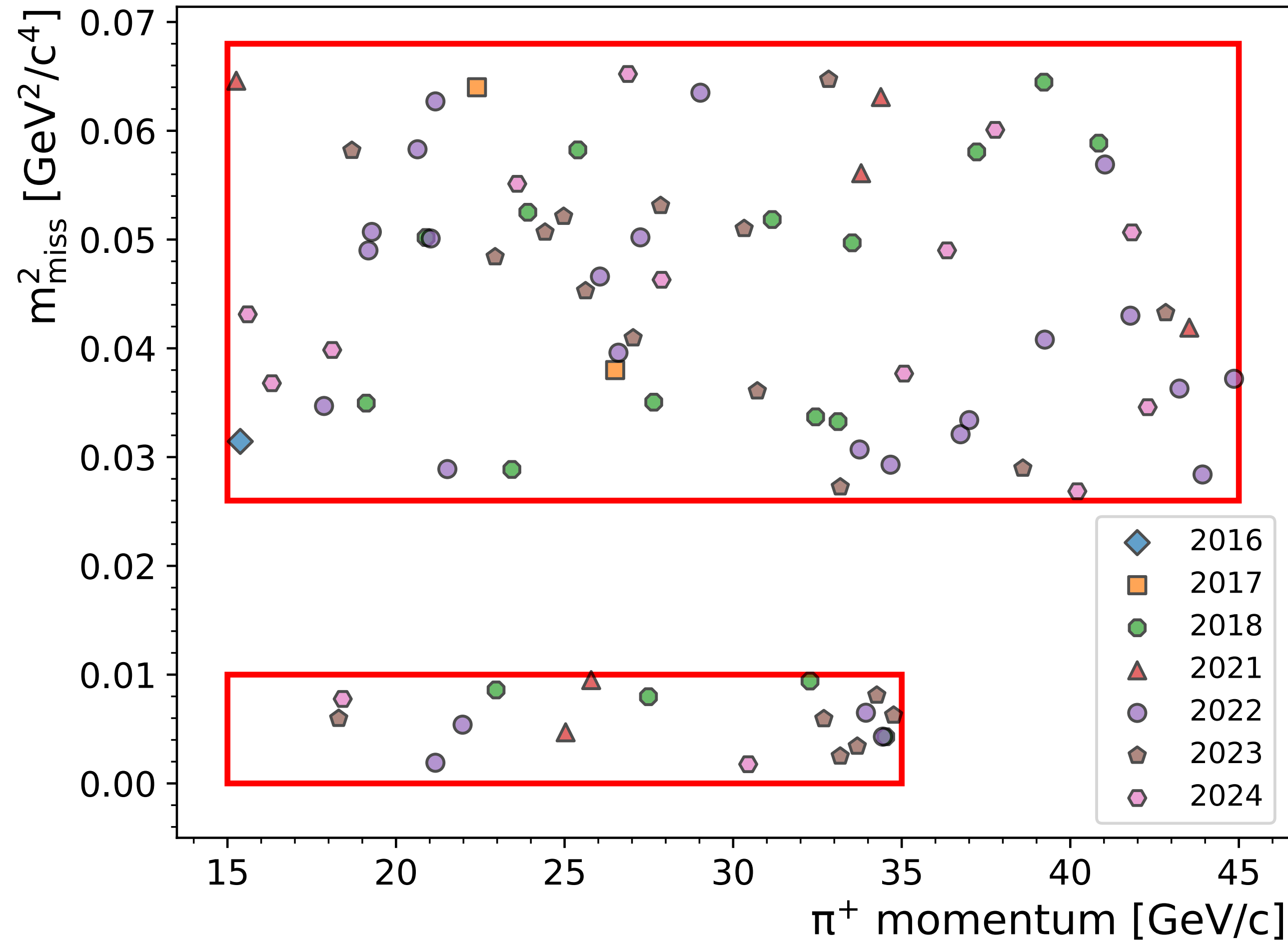


- Use 6 (momentum bin) categories



$$\mathcal{B}_{23-24}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \left(7.2 \left({}^{+2.2}_{-1.9} \right)_{\text{stat}} \left[{}^{+0.9}_{-0.9} \right]_{\text{syst}} \right) \times 10^{-11} = \left(7.2^{+2.3}_{-2.1} \right) \times 10^{-11}$$

Combine: 2016–2024 dataset

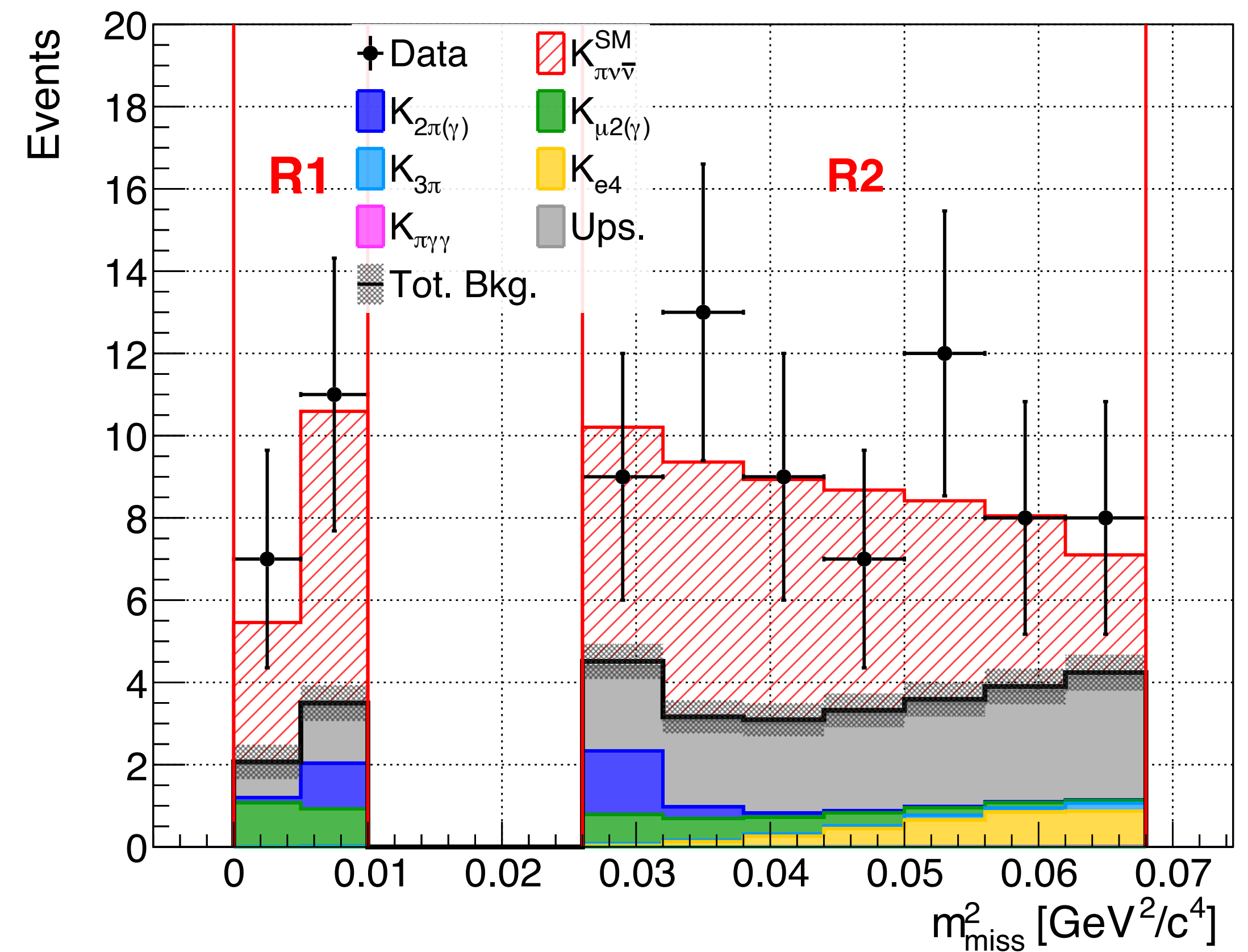


Expected SM* signal, $N_{\pi\nu\bar{\nu}}^{SM} = 43 \pm 1$

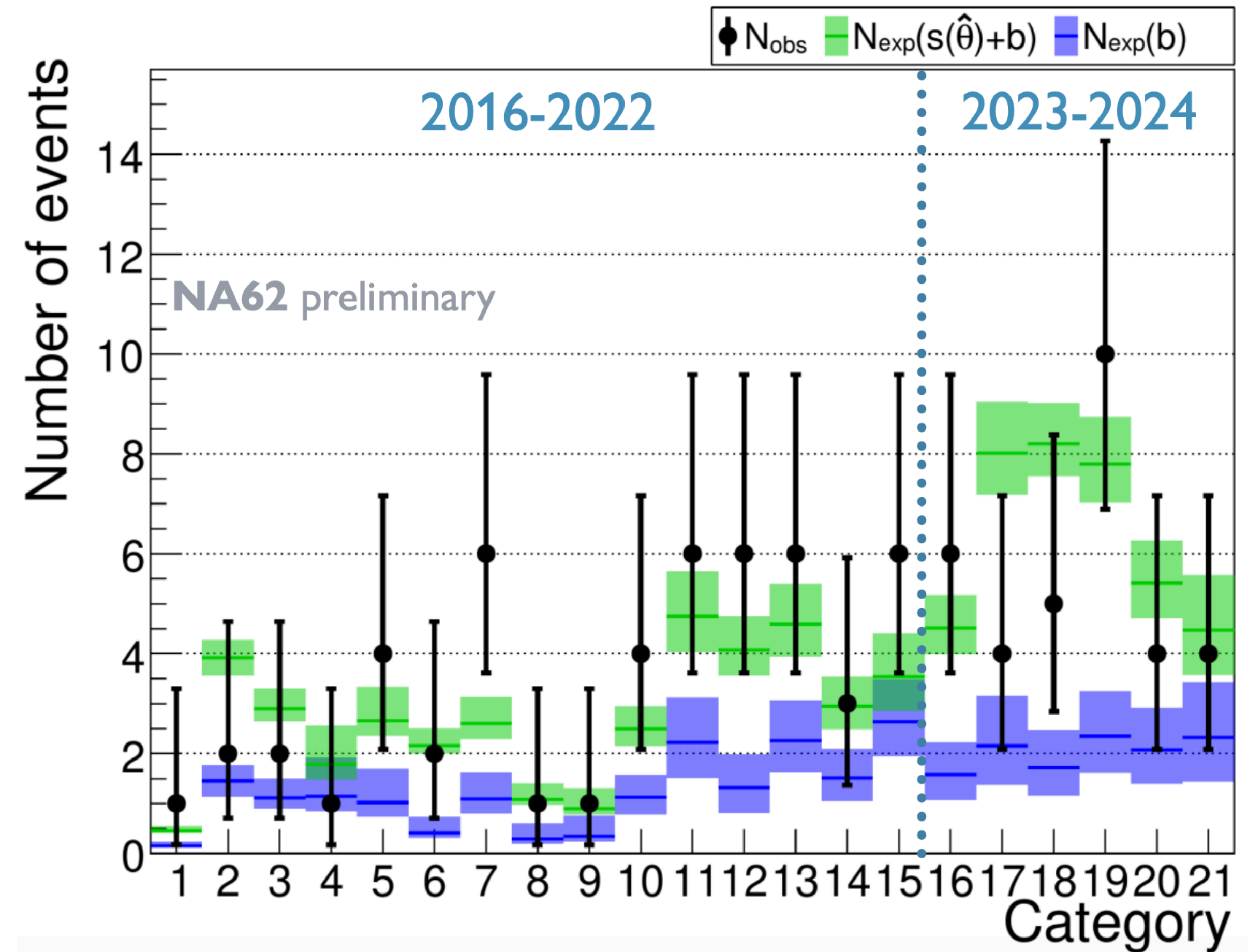
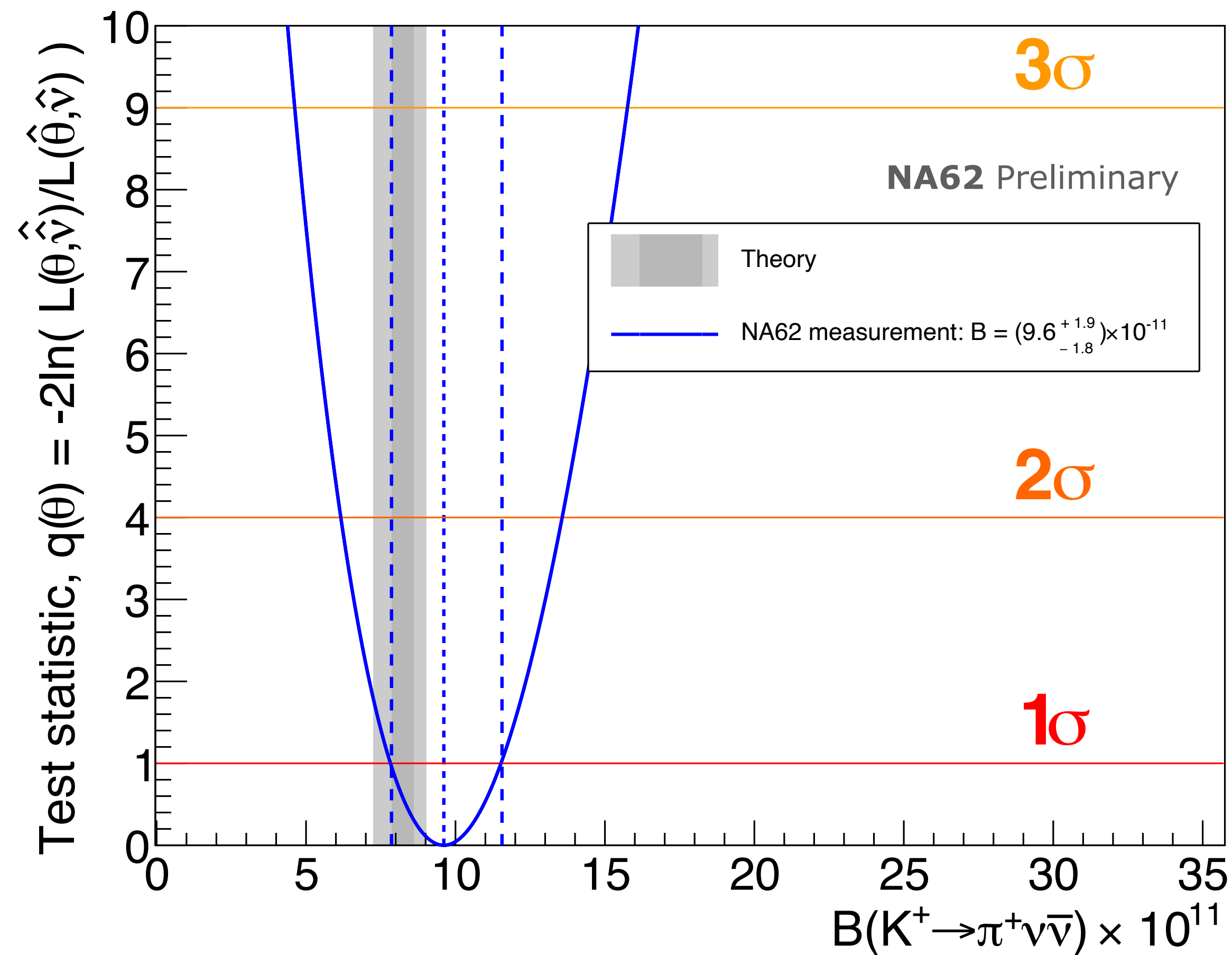
Expected background, $N_{bg} = 30^{+4}_{-3}$

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]:

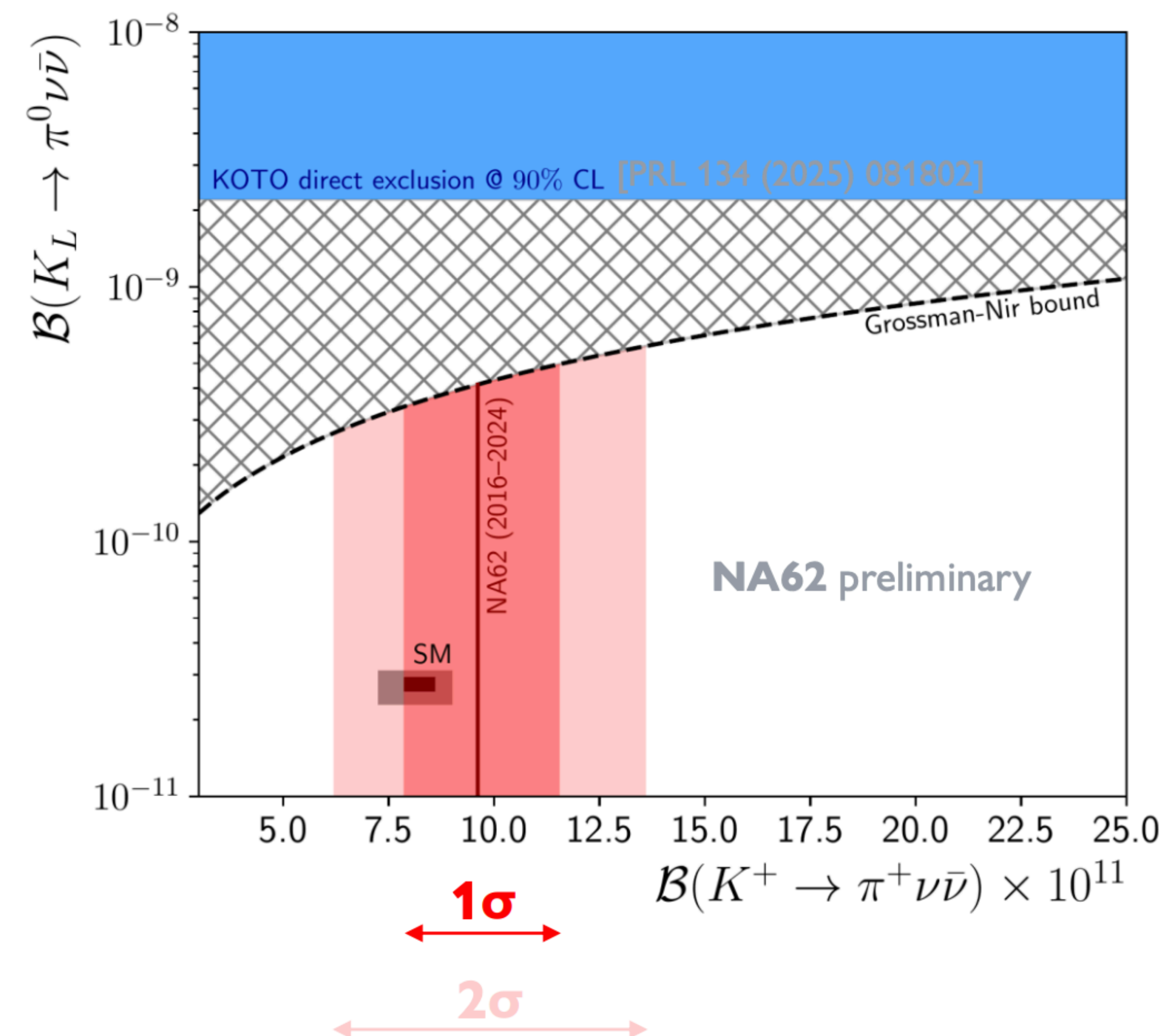
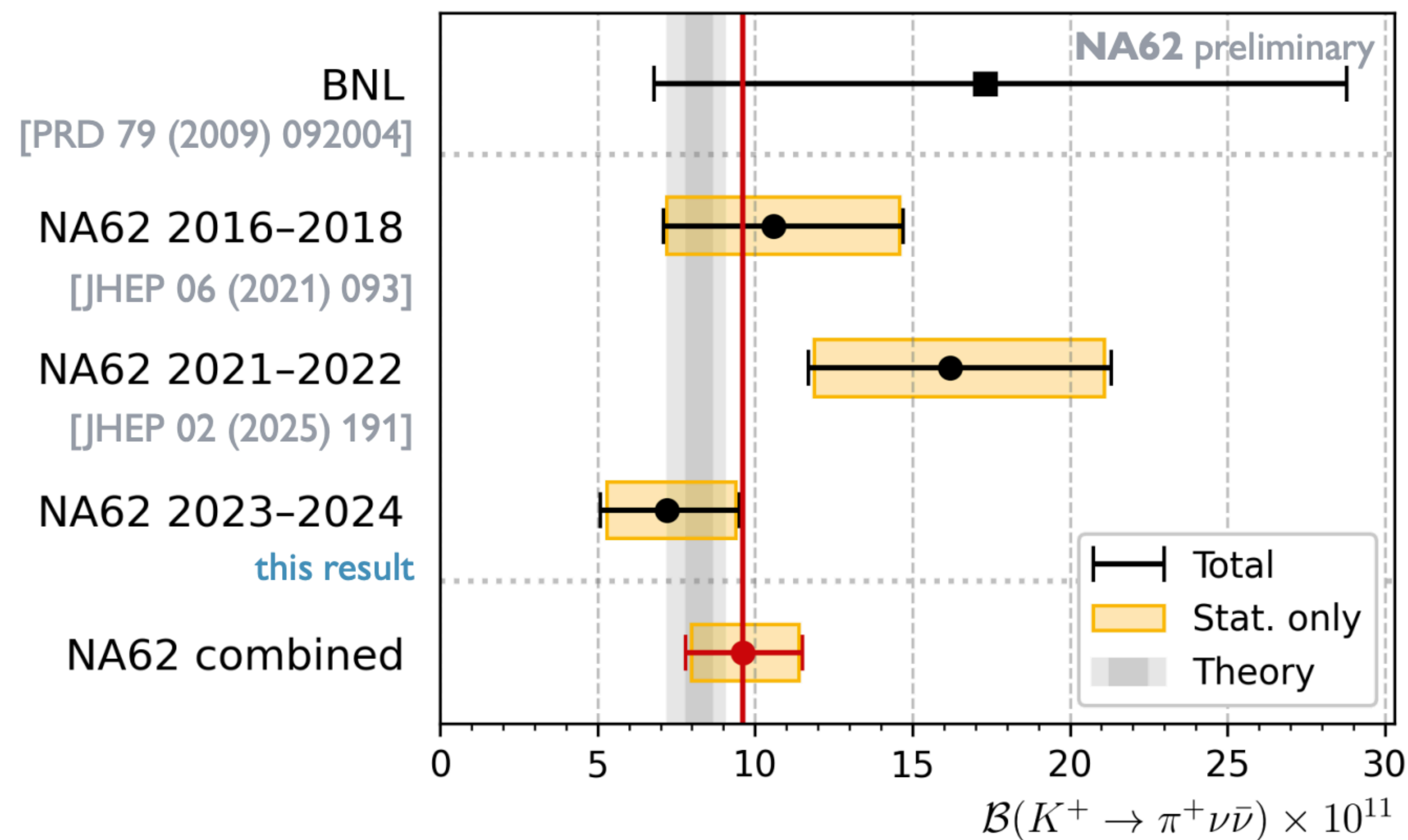


Results: 2016-24 Data



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

The Global Picture



- Expected SM signal more than doubled + Backgrounds reduced = major sensitivity boost.
 - Expected SM significance $> 5\sigma$.
- Branching ratio measured to $< 20\%$ precision. Result compatible with SM.
- 2025-2026 dataset incoming, stay tuned!

Precision measurements & rare decays

- $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ [[JHEP 11 \(2022\) 011](#)]
- $K^+ \rightarrow \pi^+ e^+ \nu \gamma$ [[JHEP 09 \(2023\) 040](#)]
- $K^+ \rightarrow \pi^+ e^+ e^+ e^-$ [[PLB 846 \(2023\) 138193](#)]
- $K^+ \rightarrow \pi^+ \gamma \gamma$ [[PLB 850 \(2024\) 138513](#)]
- $\pi^0 \rightarrow e^+ e^-$ [[Moriond2024](#)]
- $K^+ \rightarrow \mu^+ \nu \mu^+ \mu^-$ [[KAON25](#)]
- $K^+ \rightarrow e^+ \nu \gamma$ [[KAON25](#)]
- $K^+ \rightarrow \pi^+ \pi^+ \pi^- \gamma$ [[KAON2025](#)]

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

- 2016 data [[PLB 791 \(2019\) 156](#)]
- 2017 data [[JHEP 11 \(2020\) 042](#)]
- 2018 data [[JHEP 06 \(2021\) 093](#)]
- 2021-2022 data [[JHEP 02 \(2025\) 191](#)]
- 2023-2024 [this talk]

Forbidden decays

- $K^+ \rightarrow \pi^- \ell^+ \ell^+$ [[PLB 797 \(2019\) 134794](#)]
- $K^+ \rightarrow \pi \mu e$ & $\pi^0 \rightarrow \mu e$ [[PRL 127 \(2021\) 131802](#)]
- $K^+ \rightarrow \pi^- (\pi^0) e^+ e^-$ [[PLB 830 \(2022\) 137172](#)]
- $K^+ \rightarrow \mu^- \nu e^+ e^+$ [[PLB 838 \(2023\) 137679](#)]
- $K^+ \rightarrow \pi^0 \pi \mu e$ [[PLB 859 \(2024\) 139122](#)]

Invisible particles

- $\pi^0 \rightarrow \gamma A'$ [[JHEP 05 \(2019\) 182](#)]
- $K^+ \rightarrow e^+ N$ [[PLB 807 \(2020\) 135599](#)]
- $\pi^0 \rightarrow \text{inv.}$ [[JHEP 02 \(2021\) 201](#)]
- $K^+ \rightarrow \mu^+ + \text{inv.}$ [[PLB 816 \(2021\) 136259](#)]
- $K^+ \rightarrow \pi^+ + \text{inv.}$ [[JHEP 11 \(2025\) 143](#)]
- $\pi^+ \rightarrow e^+ N$ [[PLB 872 \(2026\) 140119](#)]

Dump Mode

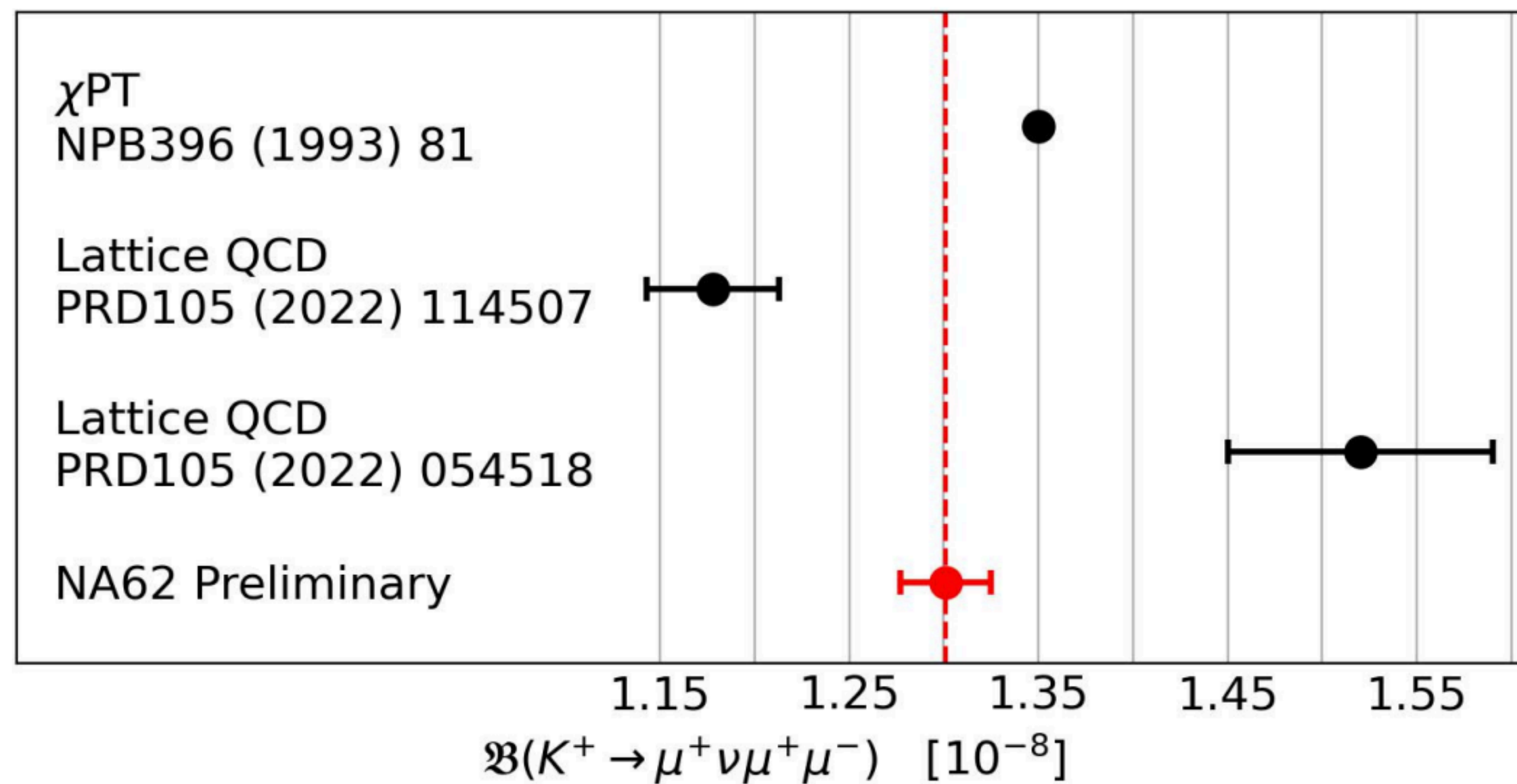
- $A' \rightarrow \mu^+ \mu^-$ [[JHEP 09 \(2023\) 035](#)]
- $A' \rightarrow e^+ e^-$ [[PRL 133 \(2024\) 111802](#)]
- $A' \rightarrow \text{hadrons}$ [[EPJC 85 \(2025\) 571](#)]
- HNL search [[Moriond QCD](#)]

Neutrino Tagging: [[PLB 863 \(2025\) 139345](#)]

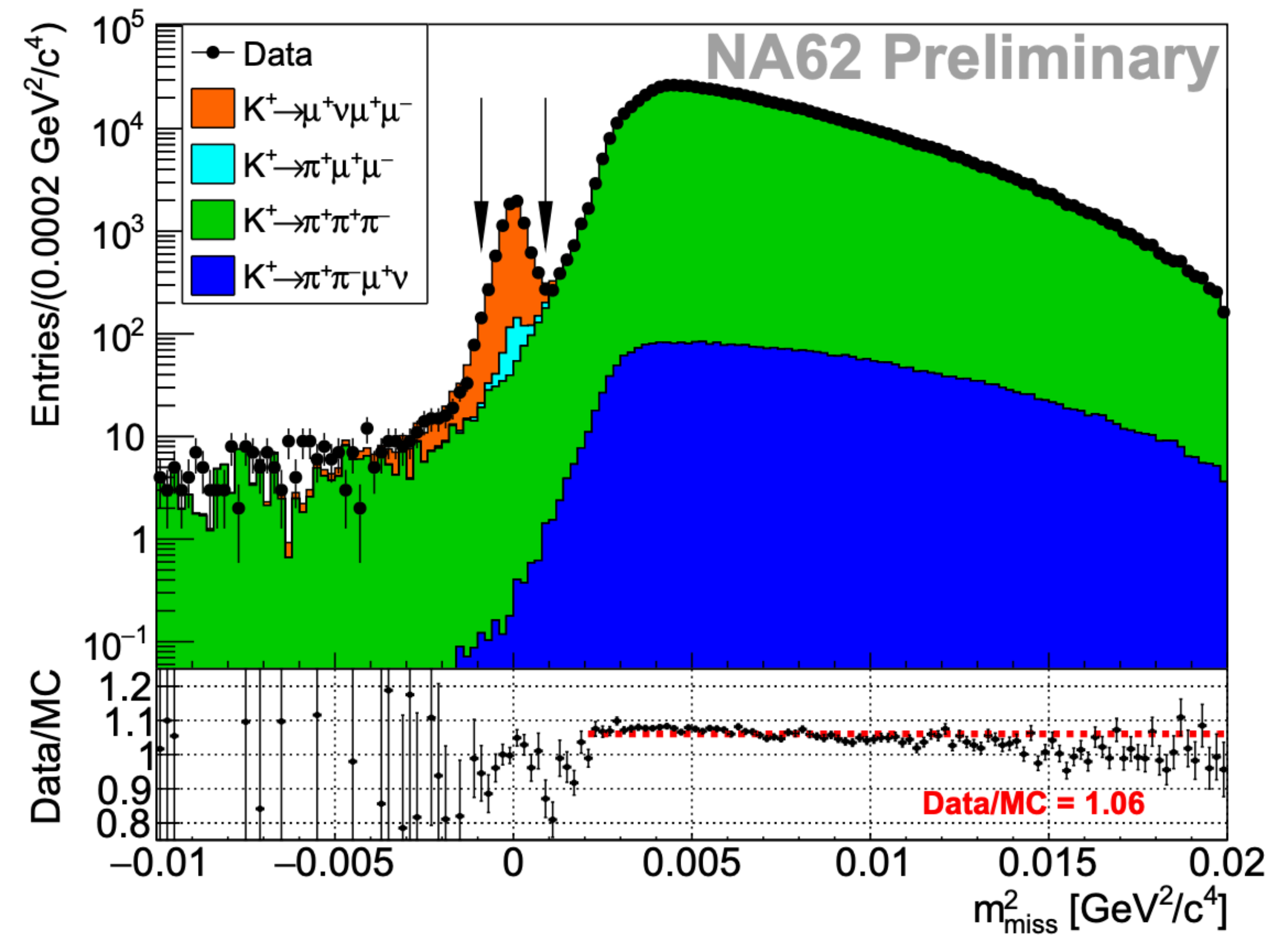
First observation of $K^+ \rightarrow \mu^+ \nu \mu^- \mu^+$

- Dominated by SD, ~30% IB, SM ChiPT calculation at $\mathcal{O}(p^4)$ [NPB 396 (1993) 81]
- Experimental challenge: background from $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ with $\pi^\pm \rightarrow \mu^\pm \nu$ decays-in-flight and/or $\pi^\pm \Rightarrow \mu^\pm$ misID.
- Normalise to $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ (BR measured by NA62 [JHEP 11 (2022) 011]) ~bkg-free.
- 2017–2024 data: 8288 signal candidates with ~10% background of $N_{bkg} = 892 \pm 11_{\text{stat}} \pm 54_{\text{syst}}$

$$\mathcal{B}(K^+ \rightarrow \mu^+ \nu \mu^+ \mu^-) = (1.301 \pm 0.017_{\text{stat}} \pm 0.012_{\text{syst}} \pm 0.012_{\text{ext}}) \times 10^{-8} = (1.301 \pm 0.024) \times 10^{-8}$$



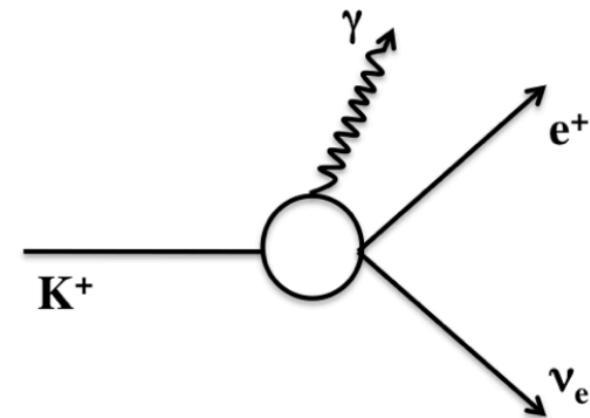
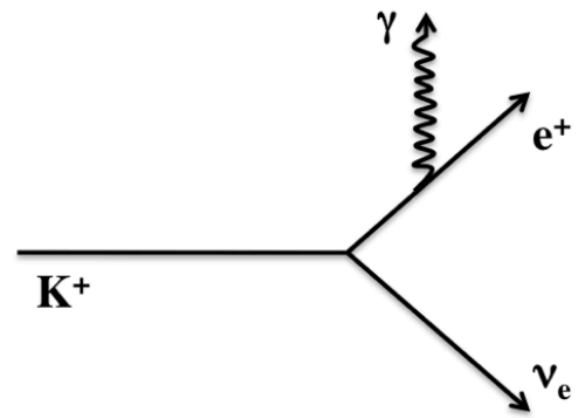
Update (since plot was made!): recent update to Lattice prediction: [arXiv:2605.22727]
New calculation of form factors



Measurement of SD $K^+ \rightarrow e^+ \nu \gamma$ BR

Inner Bremsstrahlung (IB)

Structure Dependent (SD)



+ (INT)

$$BR[K_{e2\gamma}(SD^+)] = \frac{N_{Ke2\gamma}^{obs} - N_{Ke2\gamma}^{bkg}}{N_{Ke3}^{obs}} \cdot \frac{Acc_{Ke3}}{Acc_{Ke2\gamma}} \cdot \frac{\epsilon_{Ke3}^{Trg}}{\epsilon_{Ke2\gamma}^{Trg}} \cdot BR(K_{e3}) \cdot BR(\pi^0 \rightarrow \gamma\gamma)$$

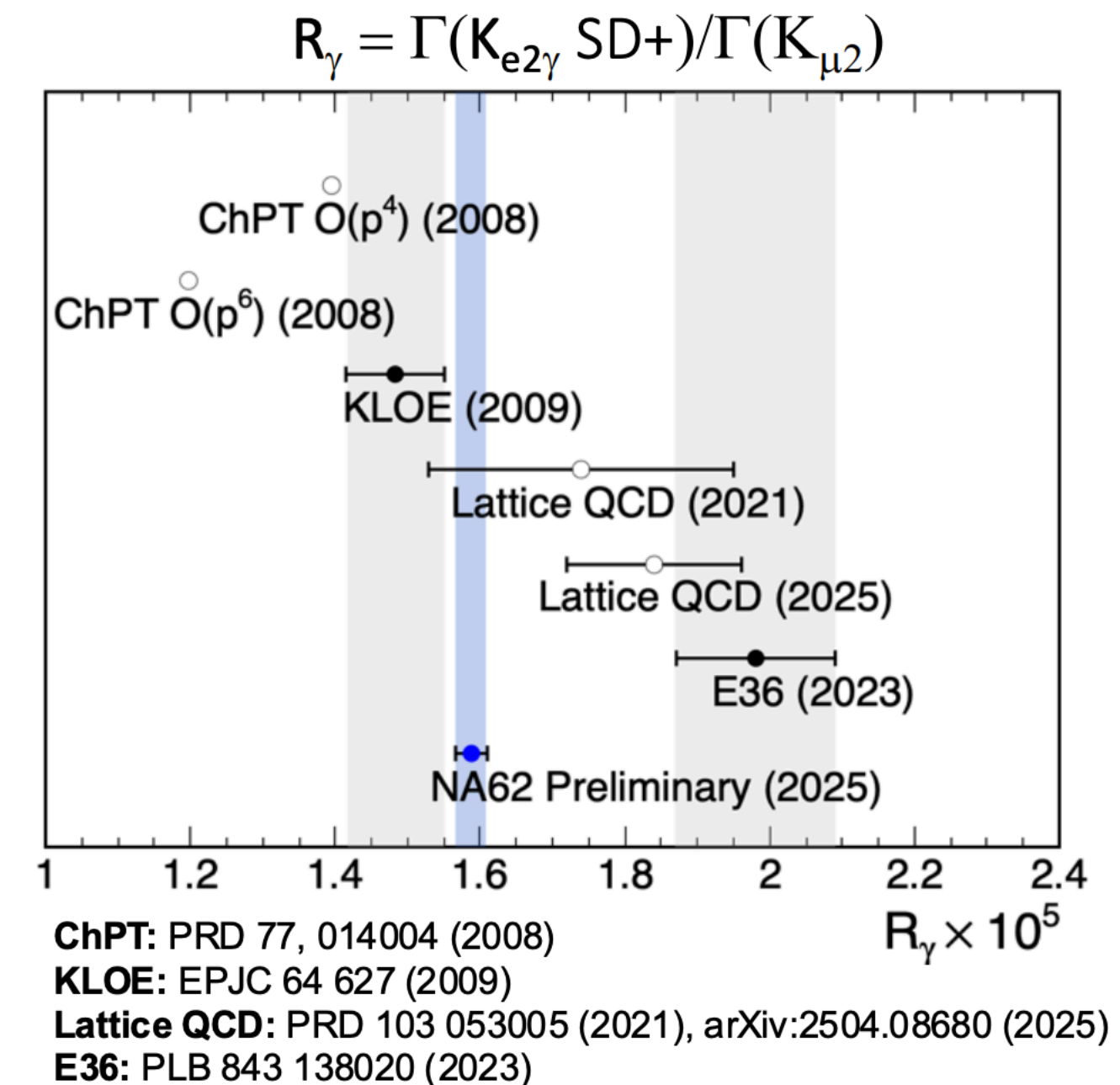
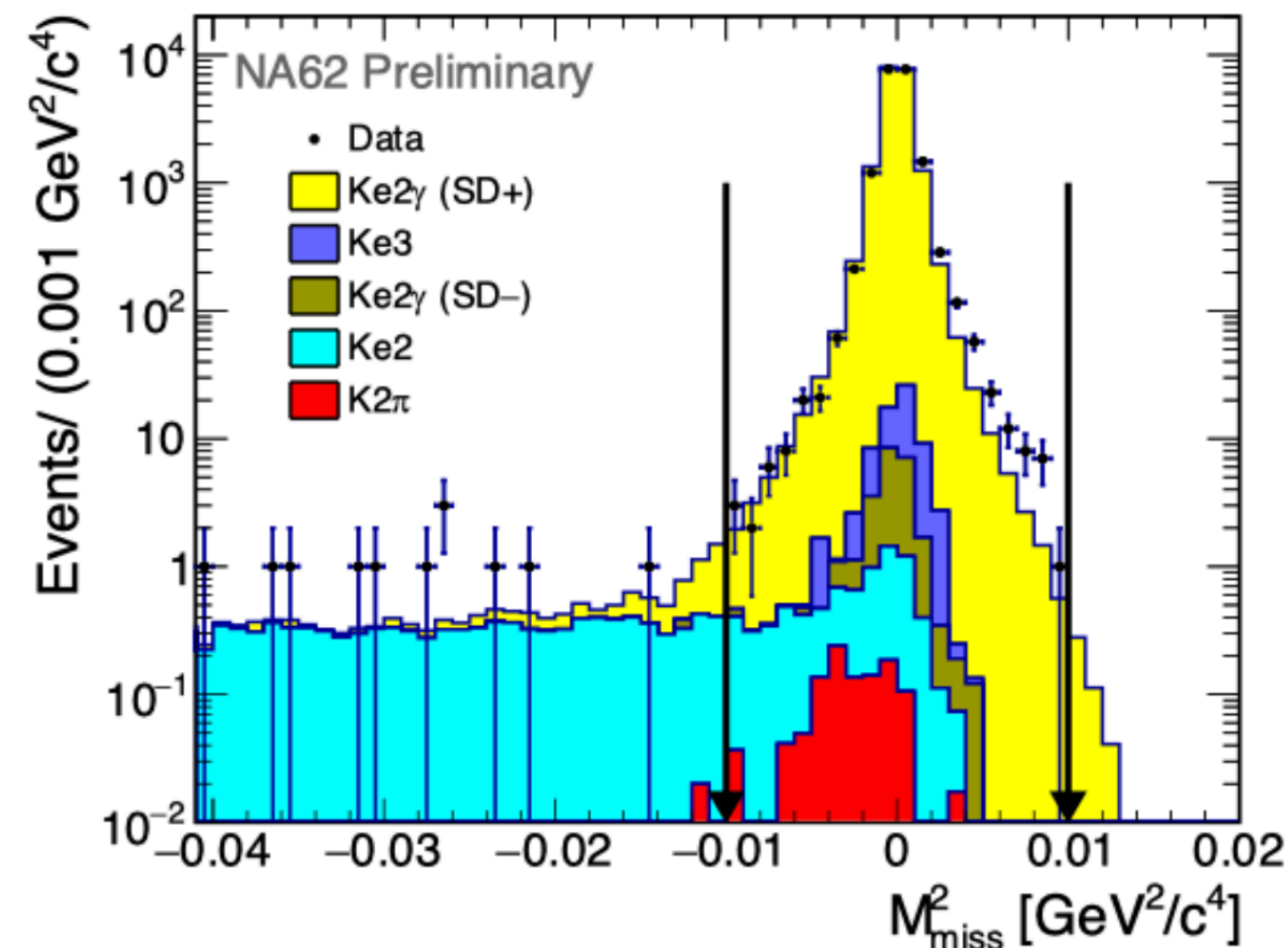
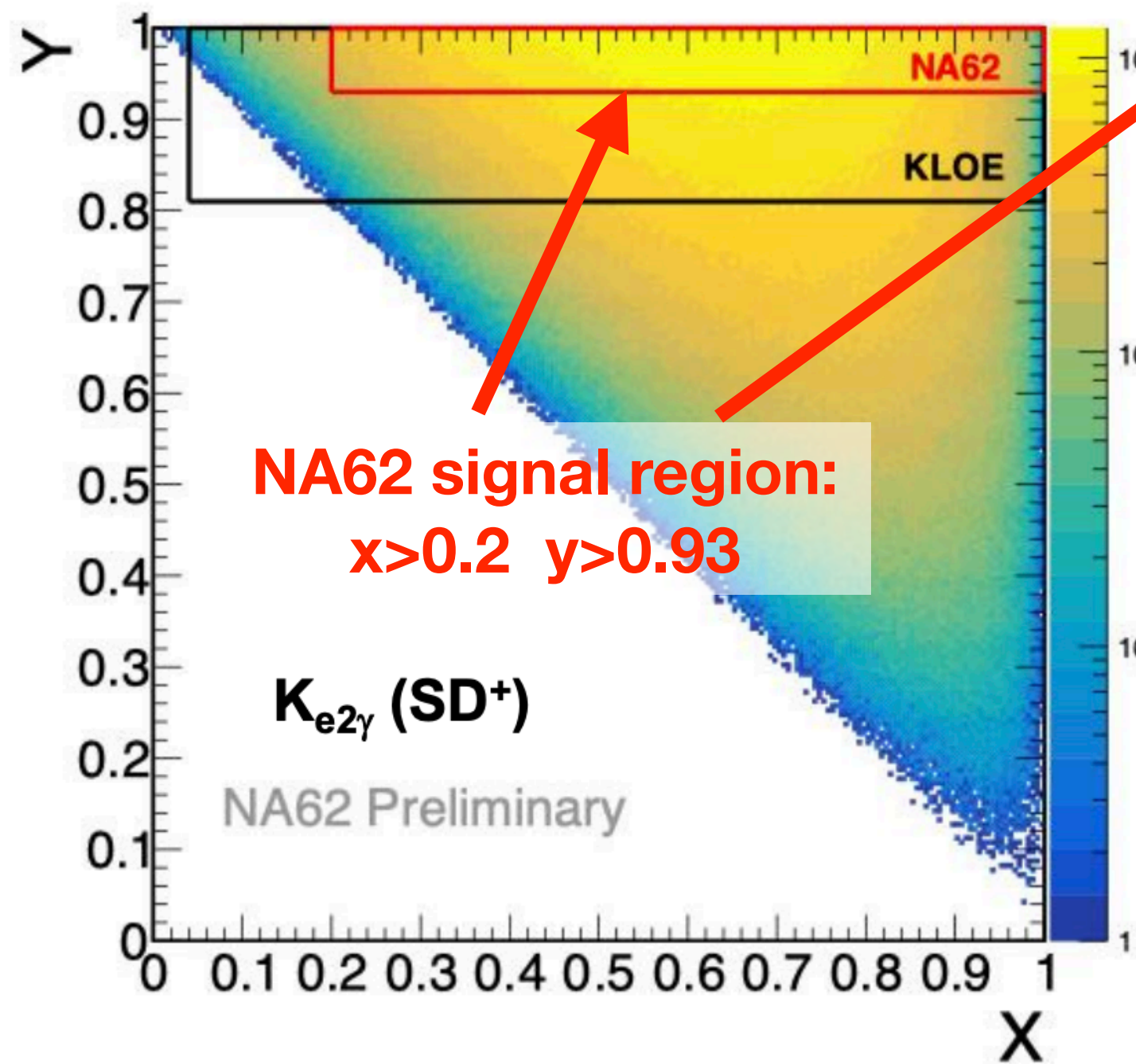
IB amplitude: divergent for $2E_\gamma/m_K = x \rightarrow 0$ • Normalise to $K^+ \rightarrow \pi^0 e^+ \nu$: 62×10^6 events $B/S \approx 10^{-5}$

$$x = \frac{2E_\gamma}{m_K}; y = \frac{2E_e}{m_K}$$

• 2017+18 data: 18929 candidates with $N_{bg} = 72 \pm 8$ ($B/S = 0.4\%$)

$$\mathcal{B}(K^+ \rightarrow e^+ \nu \gamma, SD+) = (4.66 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.04_{ext}) \times 10^{-6} = (4.66 \pm 0.06) \times 10^{-6}$$

• Extrapolating to KLOE kinematic phase-space for comparison:
 $R_\gamma = (1.59 \pm 0.02) \times 10^{-5}$ (~10x more precise than PDG average)

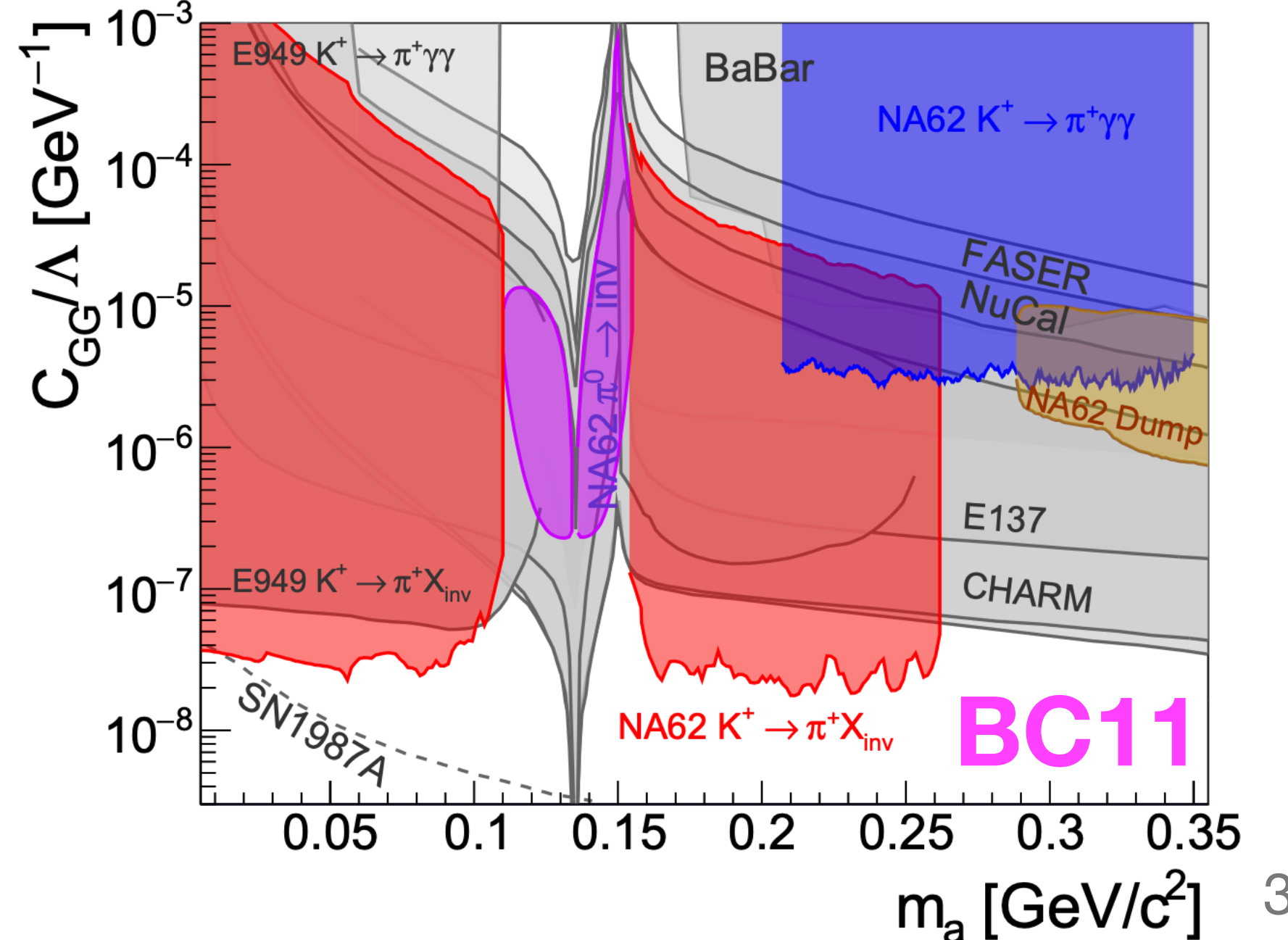
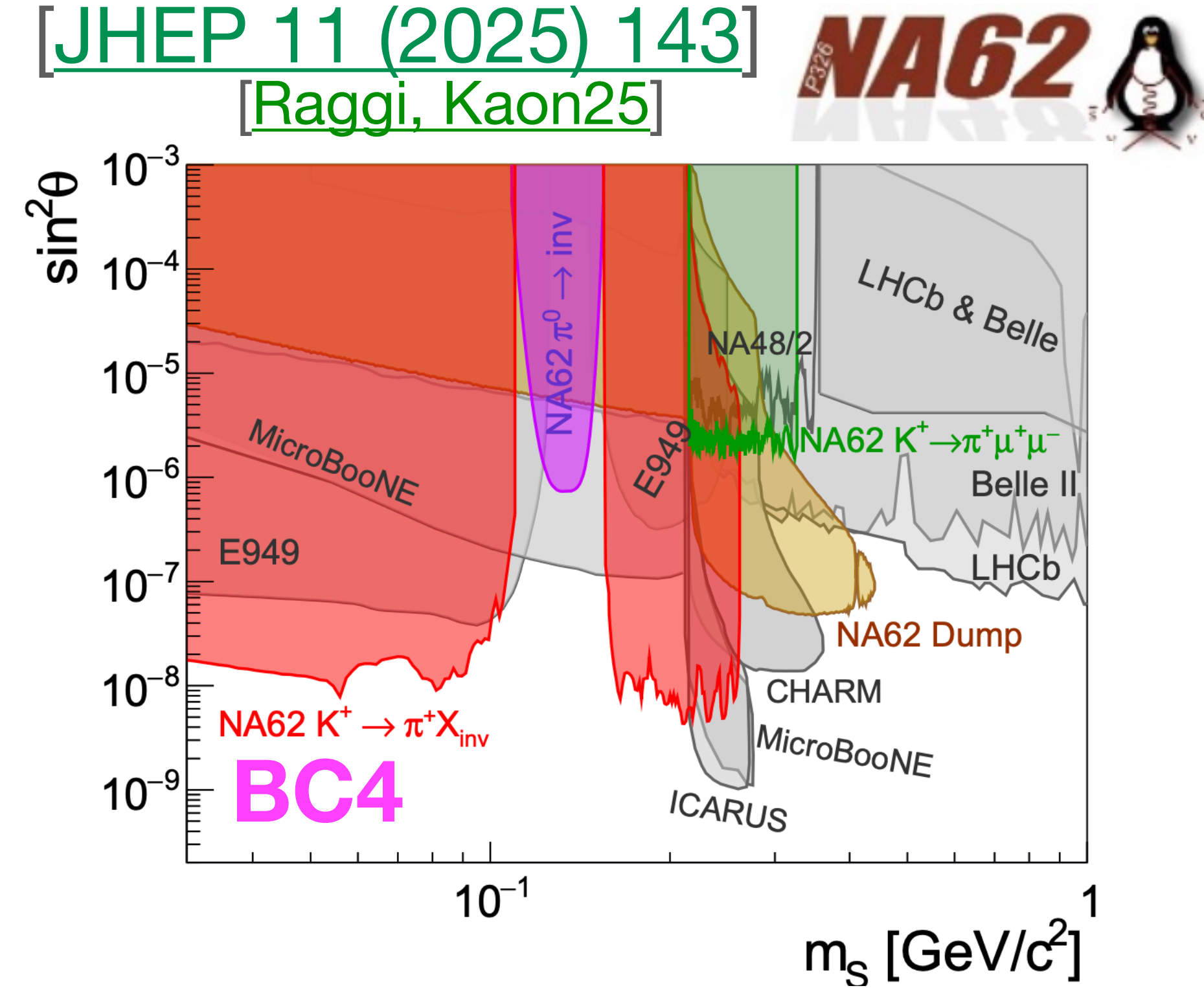
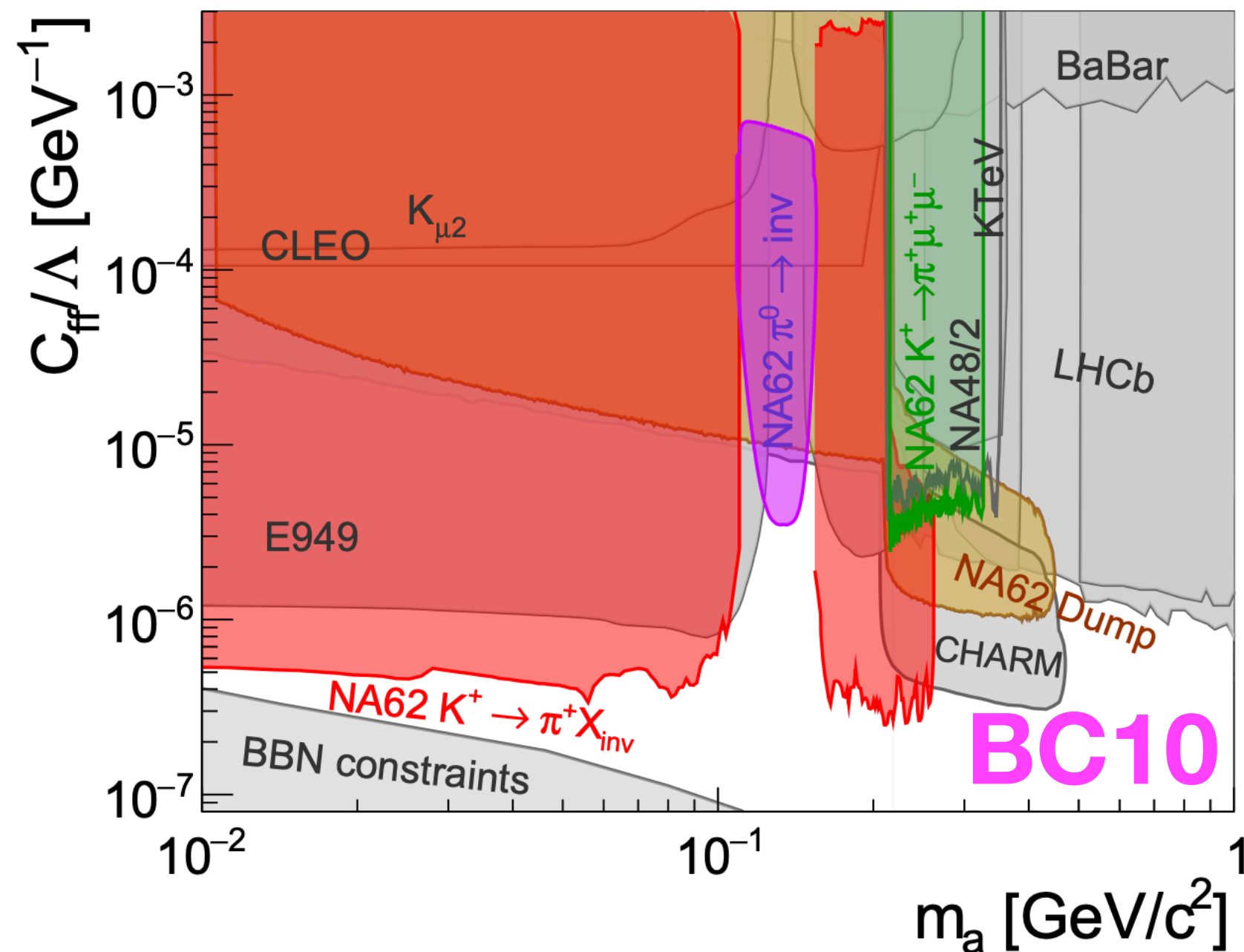
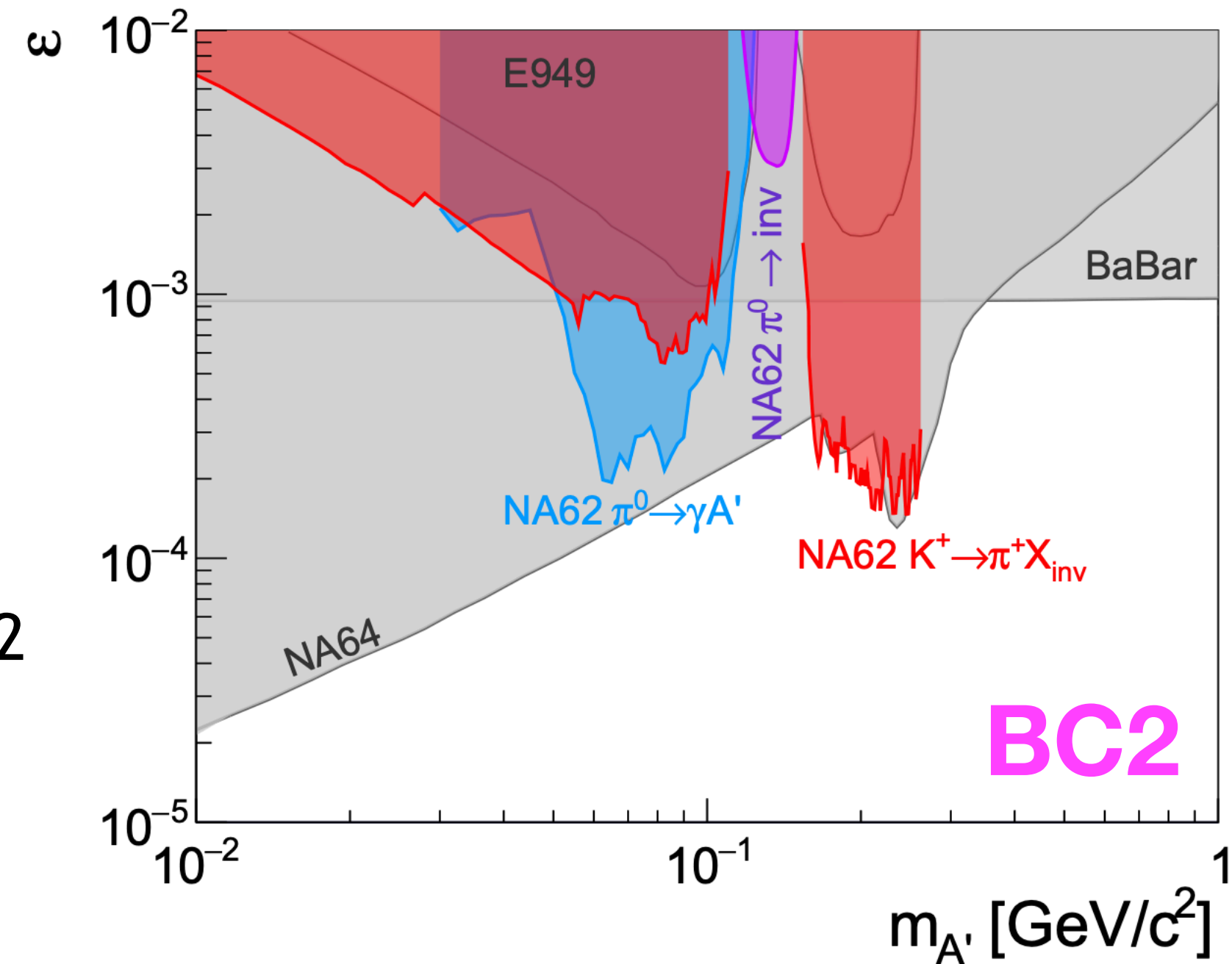


BSM constraints from $K^+ \rightarrow \pi^+ X$

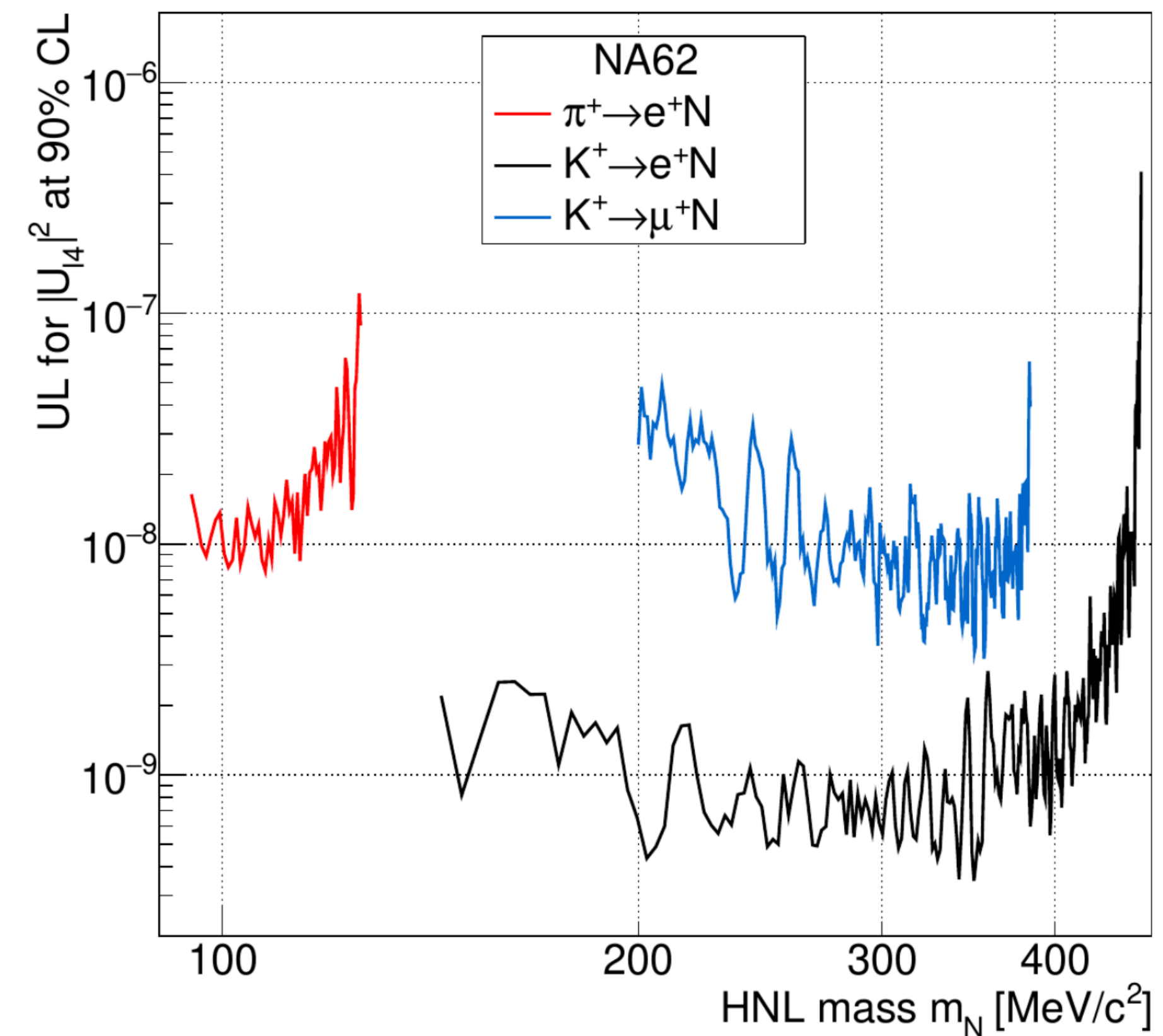
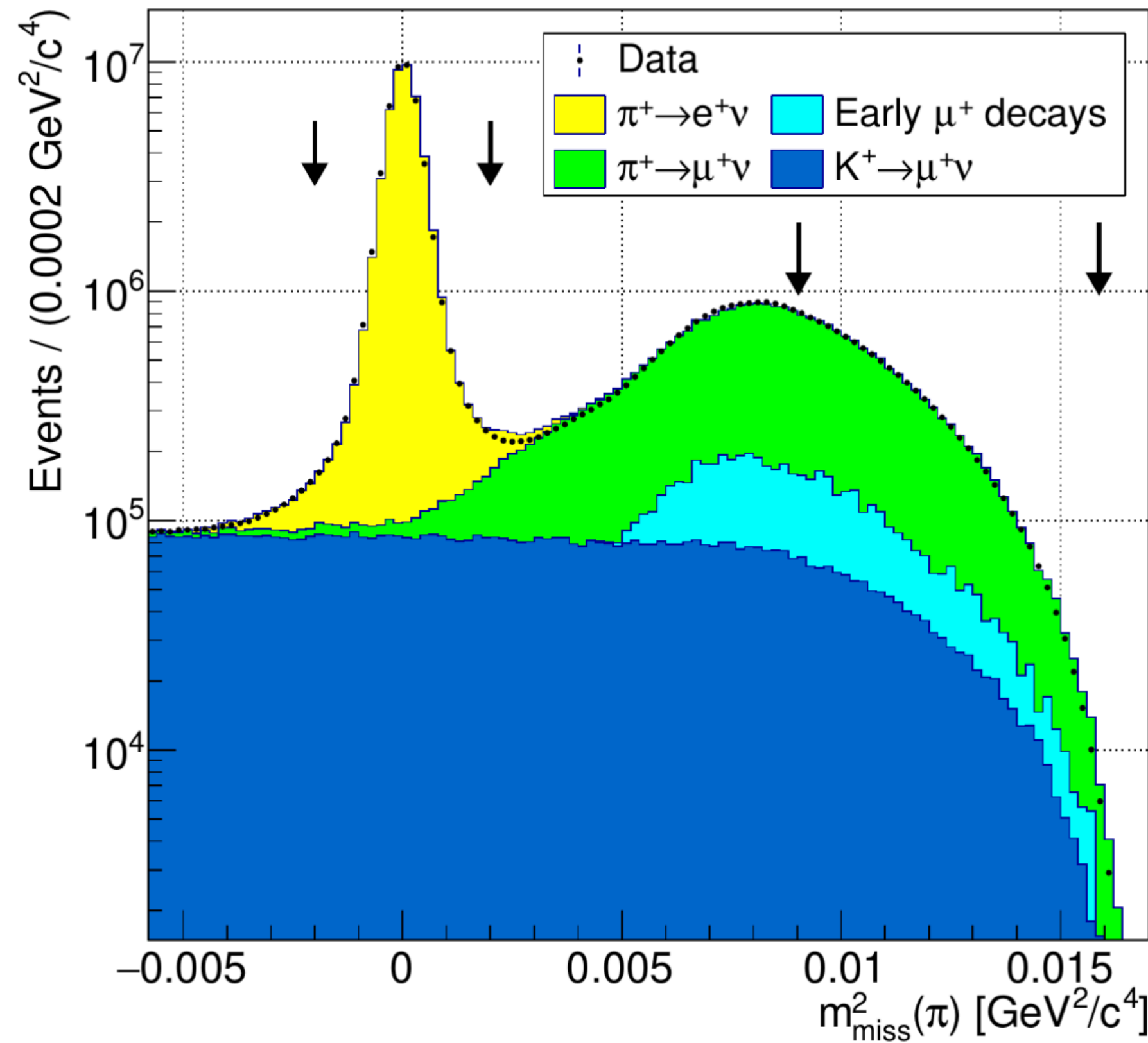
2016–22 dataset

- Same signature as $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ except $m_{miss}^2 = (P_K - P_\pi)^2 = m_X^2$
- Set model-independent BR upper limits for $K^+ \rightarrow \pi^+ X_{inv}$.
- **New:** also evaluate limits for $K^+ \rightarrow \pi^+ X, X \rightarrow \mu^+ \mu^-$ using NA62 $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ result [[JHEP 11 \(2022\) 011](#)]

- BC2: Dark Photon
- BC4: Dark Scalar
- BC10: ALP with quark coupling
- BC11: ALP with gluon coupling
- Axion: see independent analysis form public data (before NA62 paper) [[arXiv:2503.05865](#)]
 - World-leading limit on axion-down-strange coupling $|(F_V)_{sd}| > 1.6 \times 10^{12}$



Search for HNLs: $\pi^+ \rightarrow e^+ N$ [PLB 872 (2026) 140119]



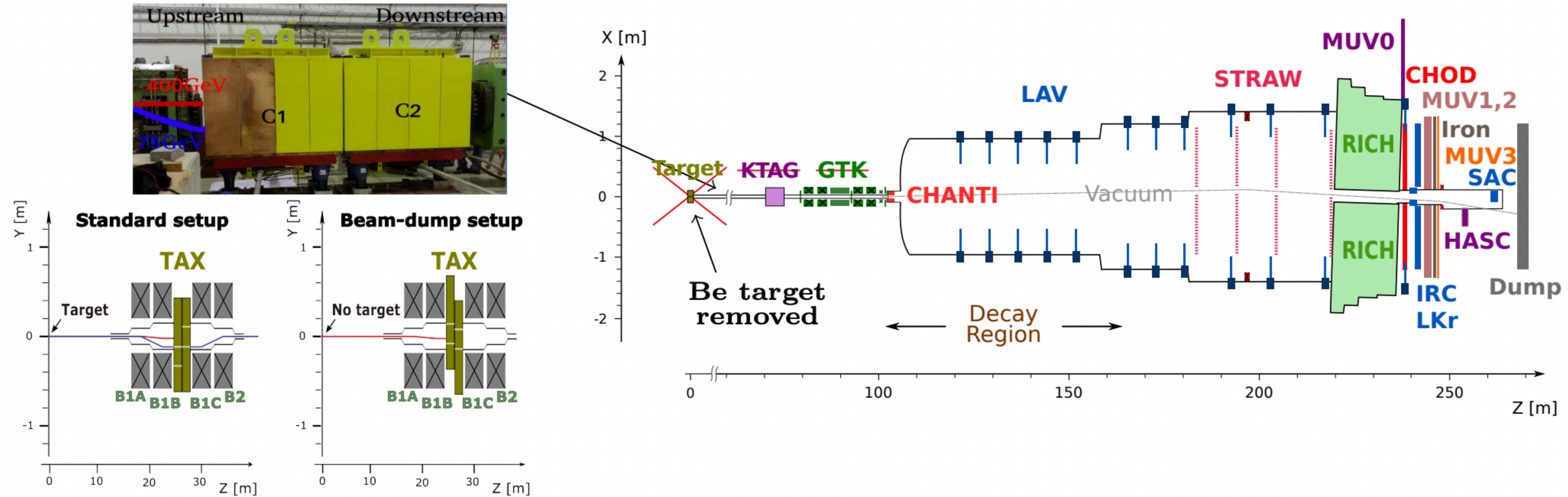
- Peak search: $m_{\text{miss}}^2 = (P_\pi - P_e)^2 = m_N^2$
- Data-driven background estimate (sideband fits)
- No significant excess — set upper limits on HNL benchmark model

$$N_\pi = 6.5 \times 10^{12}$$

$$\mathcal{B}(\pi^+ \rightarrow e^+ N) = \mathcal{B}(\pi^+ \rightarrow e^+ \nu) \rho(m_N) |U_{e4}|^4$$

Exotic Searches : NA62 beam dump mode

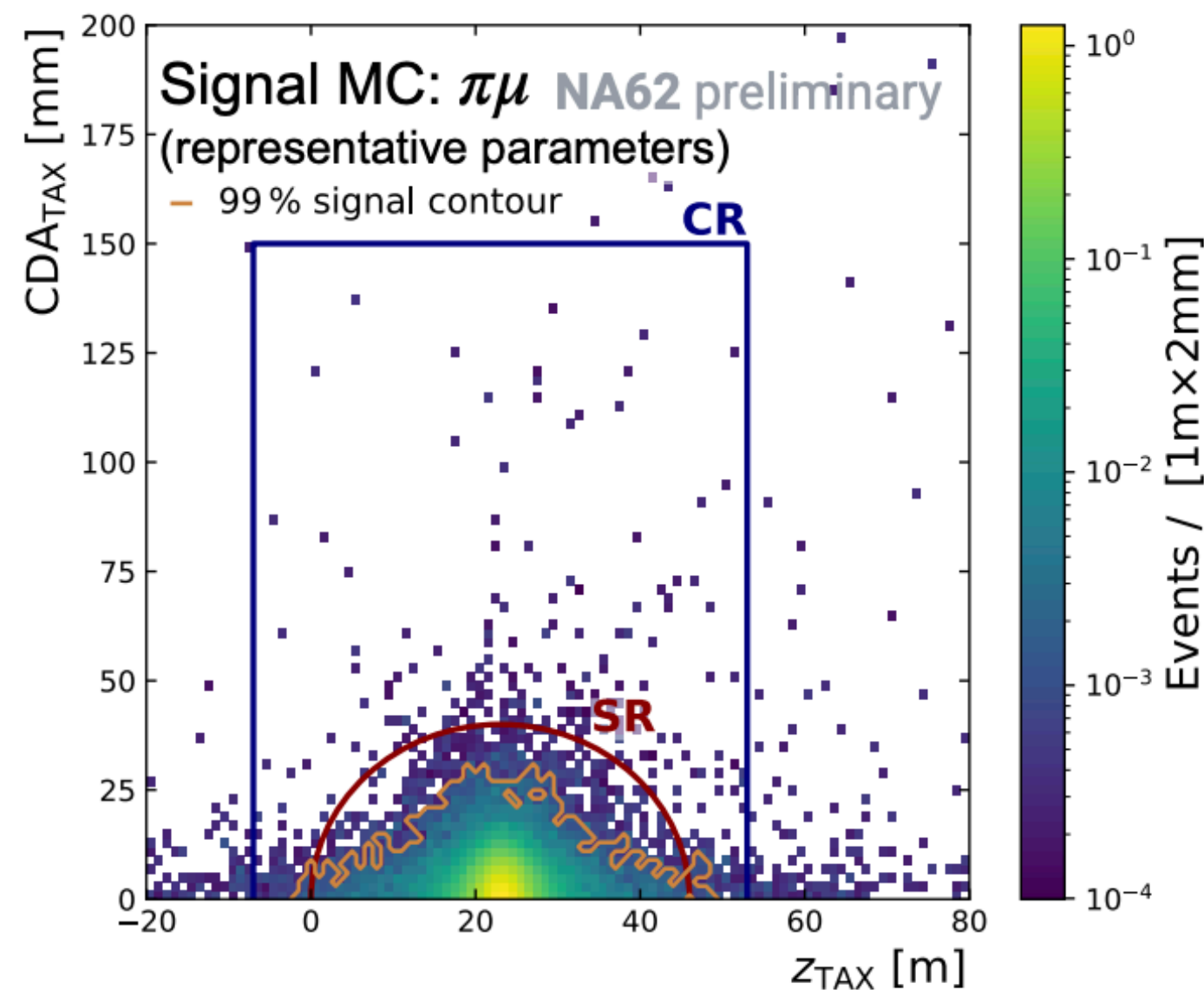
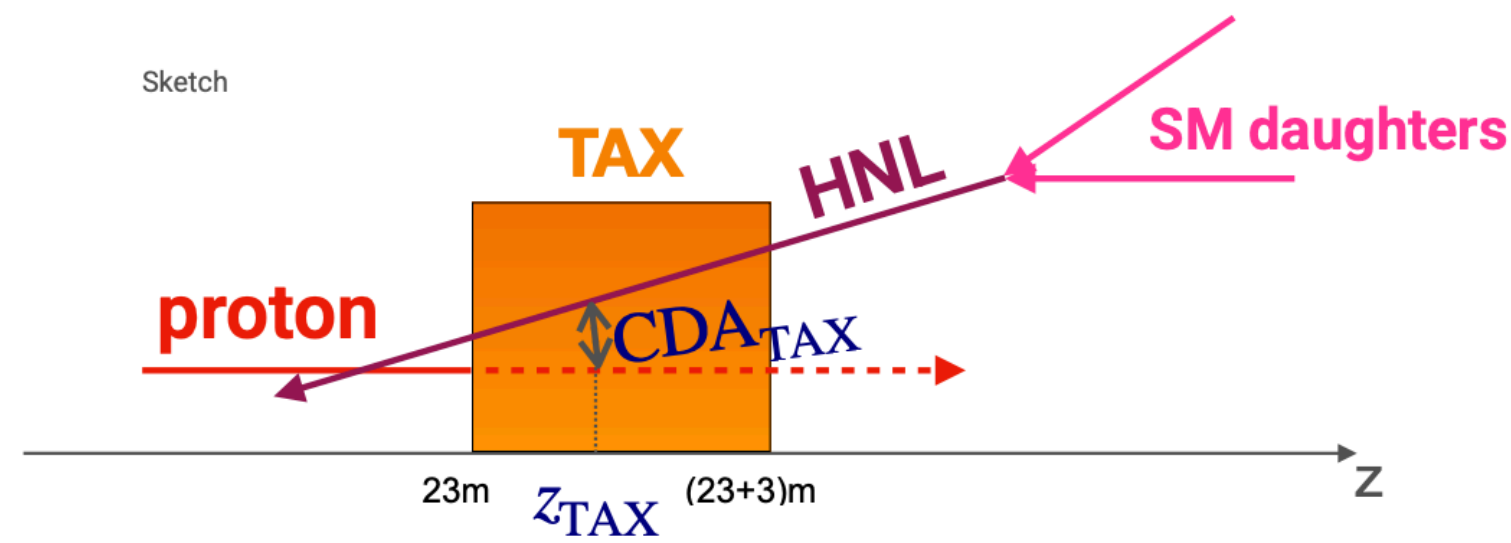
- target removed and TAX closed, KTAG and GTK not used:



Search for LLP produced in TAX (beam dump) flying into FV and decaying to visible SM particles detected downstream.

Search for HNL in Dump mode (2016–2024 data)

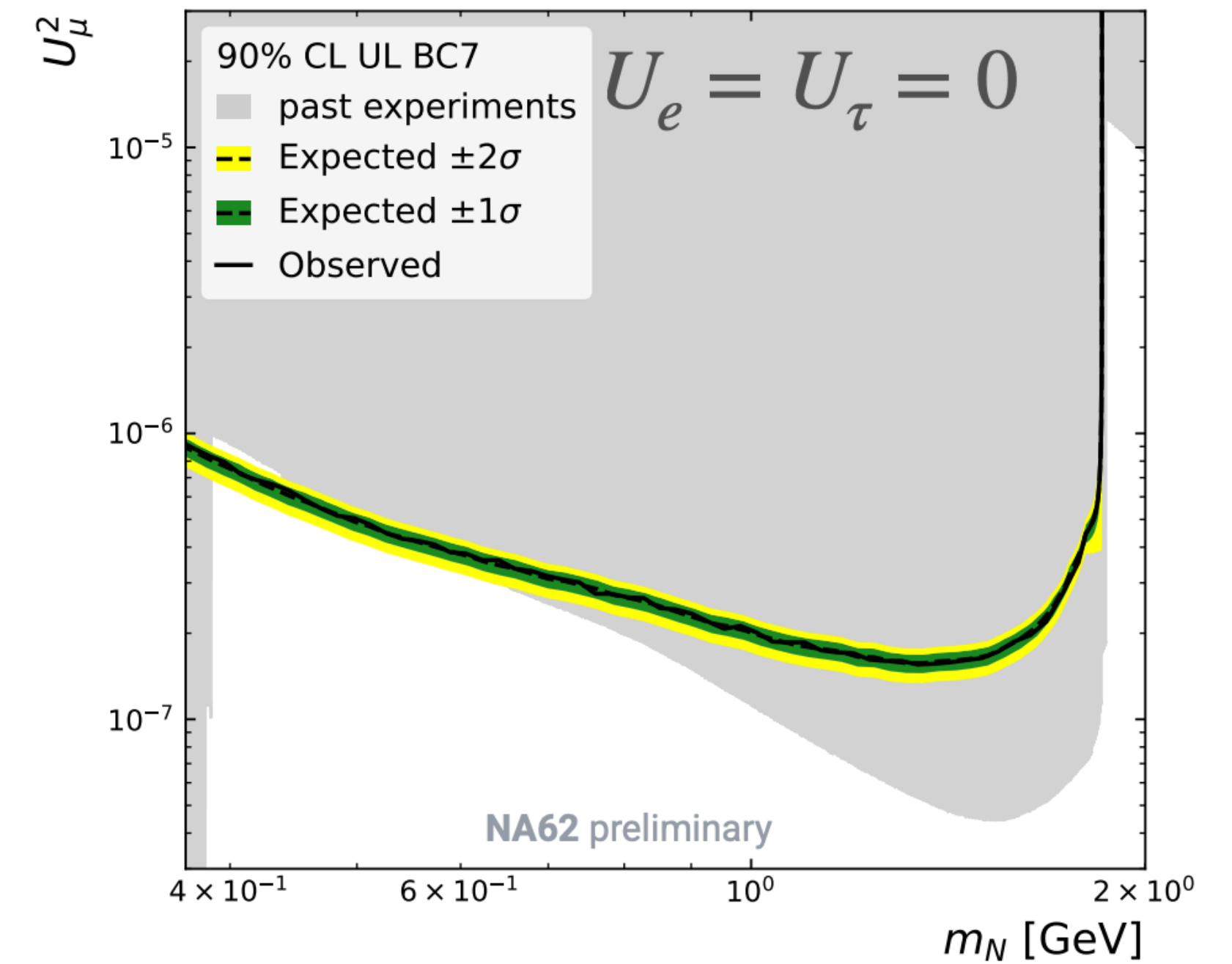
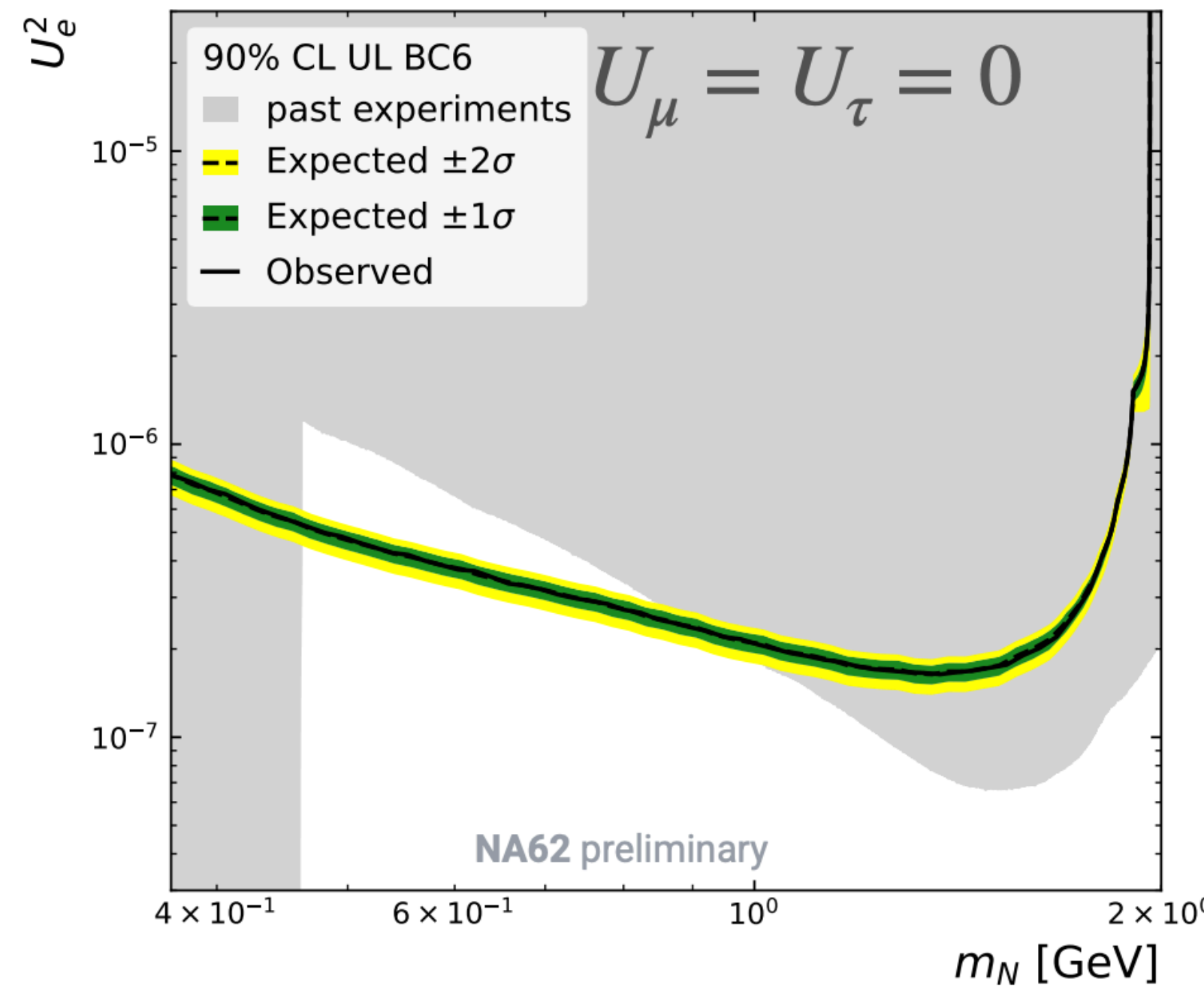
- Search for HNL decaying to a variety of final states involving hadrons+leptons



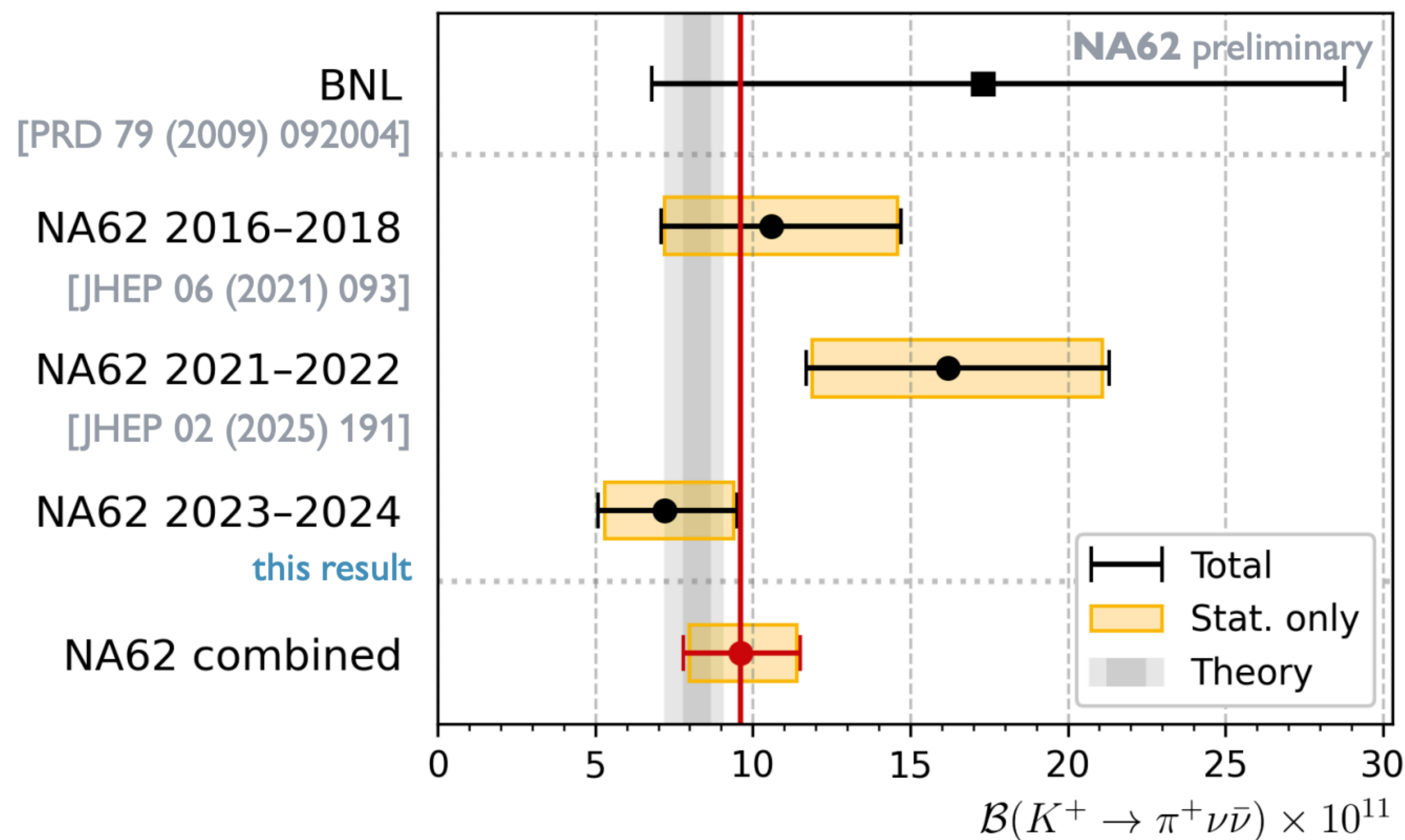
Distribution of $\pi^\pm\mu^\mp$ in origin coordinates.
Signal MC ($m_N = 700\text{ MeV}$, $U^2 = 10^{-6}$)

channel	$N_{\text{exp}}^{\text{CR}} \pm \delta N_{\text{exp}}^{\text{CR}}$	$N_{\text{exp}}^{\text{SR}} \pm \delta N_{\text{exp}}^{\text{SR}}$
$\pi^\pm\mu^\mp$	$(1.1^{+0.8}_{-0.6}) \times 10^{-2}$	$(9.3^{+7.4}_{-5.3}) \times 10^{-3}$
$\pi^\pm\mu^\mp\pi^0$	$(2.0^{+1.9}_{-1.2}) \times 10^{-6}$	$(1.4^{+1.2}_{-0.8}) \times 10^{-6}$
$\pi^\pm\mu^\mp 2\pi^0$	$(1.0^{+2.5}_{-0.8}) \times 10^{-7}$	$(2.0^{+6.0}_{-1.7}) \times 10^{-8}$
$K^\pm\mu^\mp$	$(5.6^{+6.5}_{-3.5}) \times 10^{-6}$	$(2.8^{+2.9}_{-1.8}) \times 10^{-6}$
$\pi^\pm e^\mp$	$(2.6^{+2.7}_{-1.7}) \times 10^{-3}$	$(2.9^{+3.4}_{-2.0}) \times 10^{-3}$
$\pi^\pm e^\mp\pi^0$	$(3.2^{+3.9}_{-2.2}) \times 10^{-5}$	$(3.5^{+4.7}_{-2.5}) \times 10^{-5}$
$\pi^\pm e^\mp 2\pi^0$	$(1.5^{+4.3}_{-1.3}) \times 10^{-9}$	$(3.0^{+10.1}_{-2.6}) \times 10^{-10}$
$K^\pm e^\mp$	$(5.9^{+8.8}_{-4.3}) \times 10^{-7}$	$(6.0^{+10.5}_{-4.7}) \times 10^{-7}$

- Essentially background-free
 - Largest background from decays of hadrons produced upstream of FV
- Probability of non-zero observation in SR = 1.5%
- 0 events observed
- Model interpretation using ALPINIST [JHEP 02(2025)140]



Conclusions



New measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

- Double signal + reduce background: major sensitivity boost.
- Expected SM significance $> 5\sigma$.
- Branching ratio measured with $< 20\%$ precision.
- Result compatible with SM.

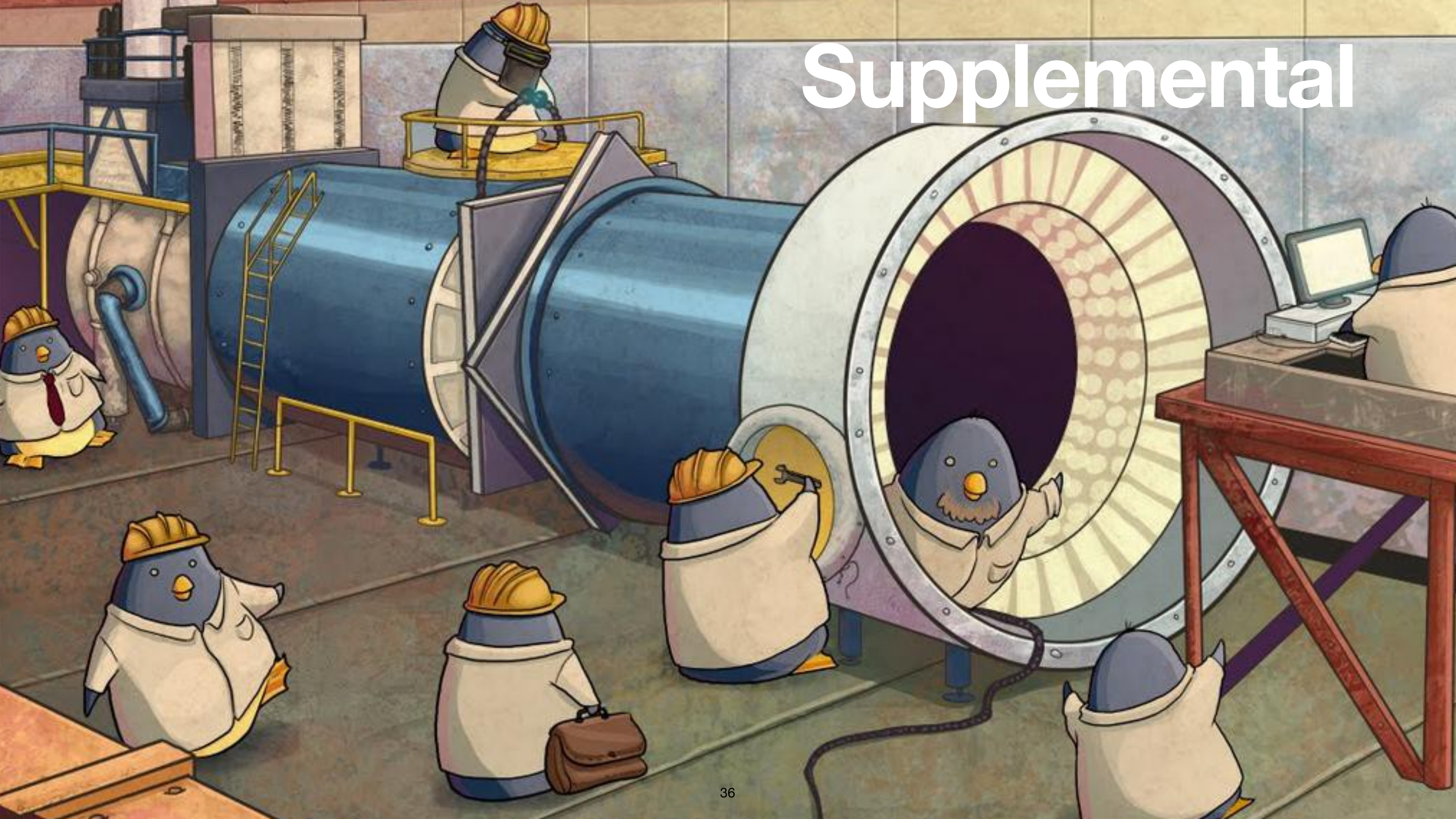
Broad NA62 program

- Dark sector searches: $K^+ \rightarrow \pi^+ + \text{inv.}$, $\pi^+ \rightarrow e^+ N$, HNLs in Dump mode
- Precision K^+ decay measurements: $K^+ \rightarrow \pi^+ \pi^+ \pi^- \gamma$, $K^+ \rightarrow e^+ \nu \gamma$
- First observation of $K^+ \rightarrow \mu^+ \nu \mu^+ \mu^-$

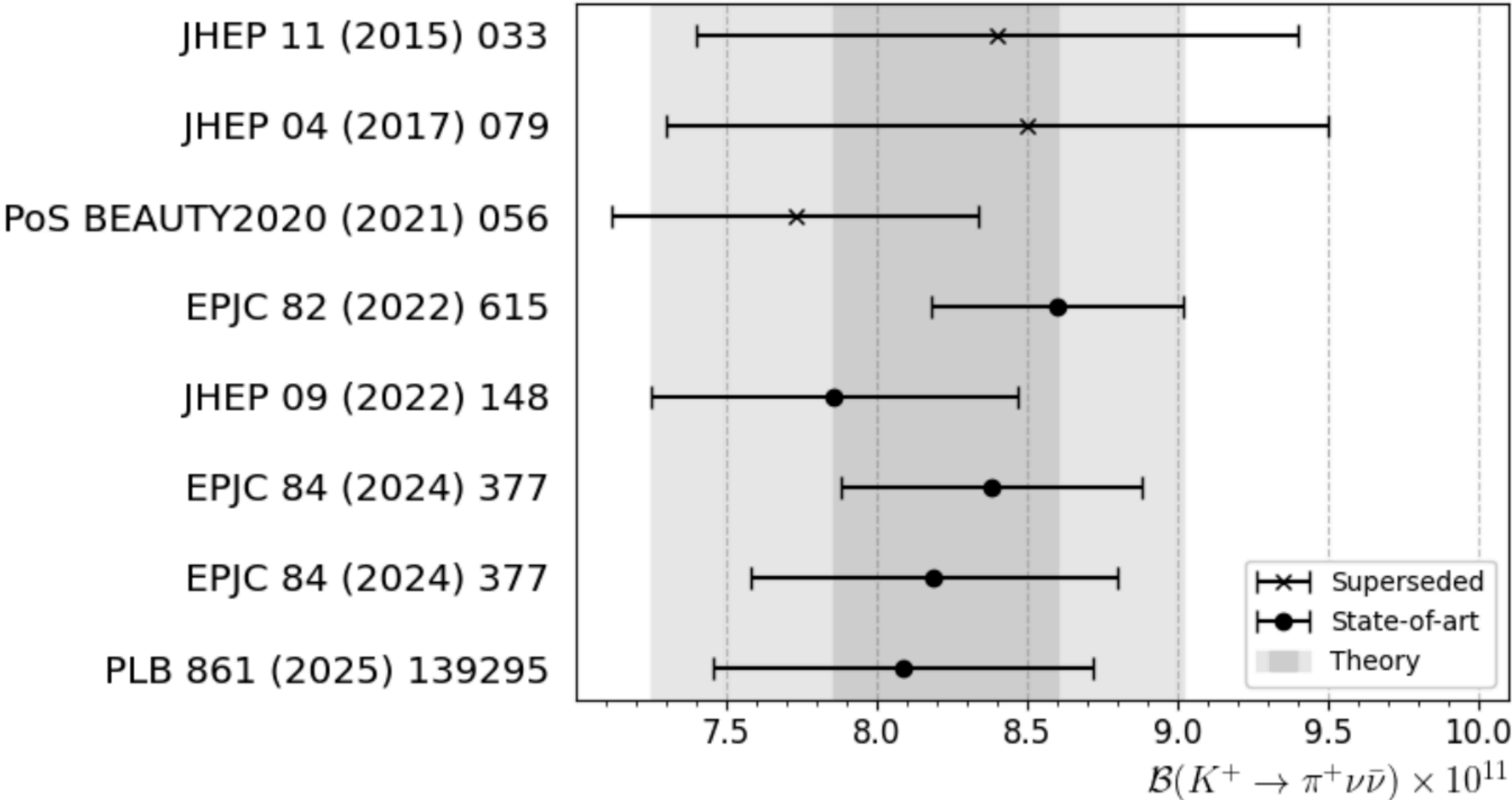
$$\mathcal{B}_{16-24}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (9.6_{-1.8}^{+1.9}) \times 10^{-11}$$

2025-2026 dataset incoming ... stay tuned!

Supplemental

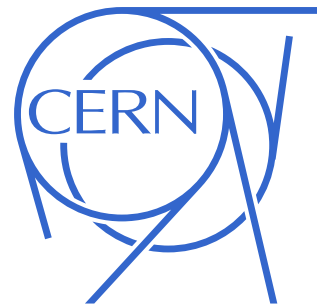


$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: Recent SM Predictions



- For this talk **benchmark value** :
 $\mathcal{B}_{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 8.4 \times 10^{-11}$
- **Strategy for [2]** : use CKM parameters from global fits
 - (e.g CKMfitter/UTfit [[EPJC 84 \(2024\) 4, 377](#)])
- **Strategy for [1]** : re-express to avoid $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \propto |V_{cb}|^4$ with inclusive/exclusive tension and associated uncertainty.

Mode	SM Branching Ratio [1]	SM Branching Ratio [2]	Experimental Status
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$	$(13.0^{+3.3}_{-3.0}) \times 10^{-11}$
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 2.2 \times 10^{-9}$



^Recent SM calculations [1:Buras et al. EPJC 82 (2022) 7, 615][2:D'Ambrosio et al. JHEP 09 (2022) 148]
(Differences in SM calculations from choice of CKM parameters: see [[Eur.Phys.J.C 84 \(2024\) 4, 377](#)])

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

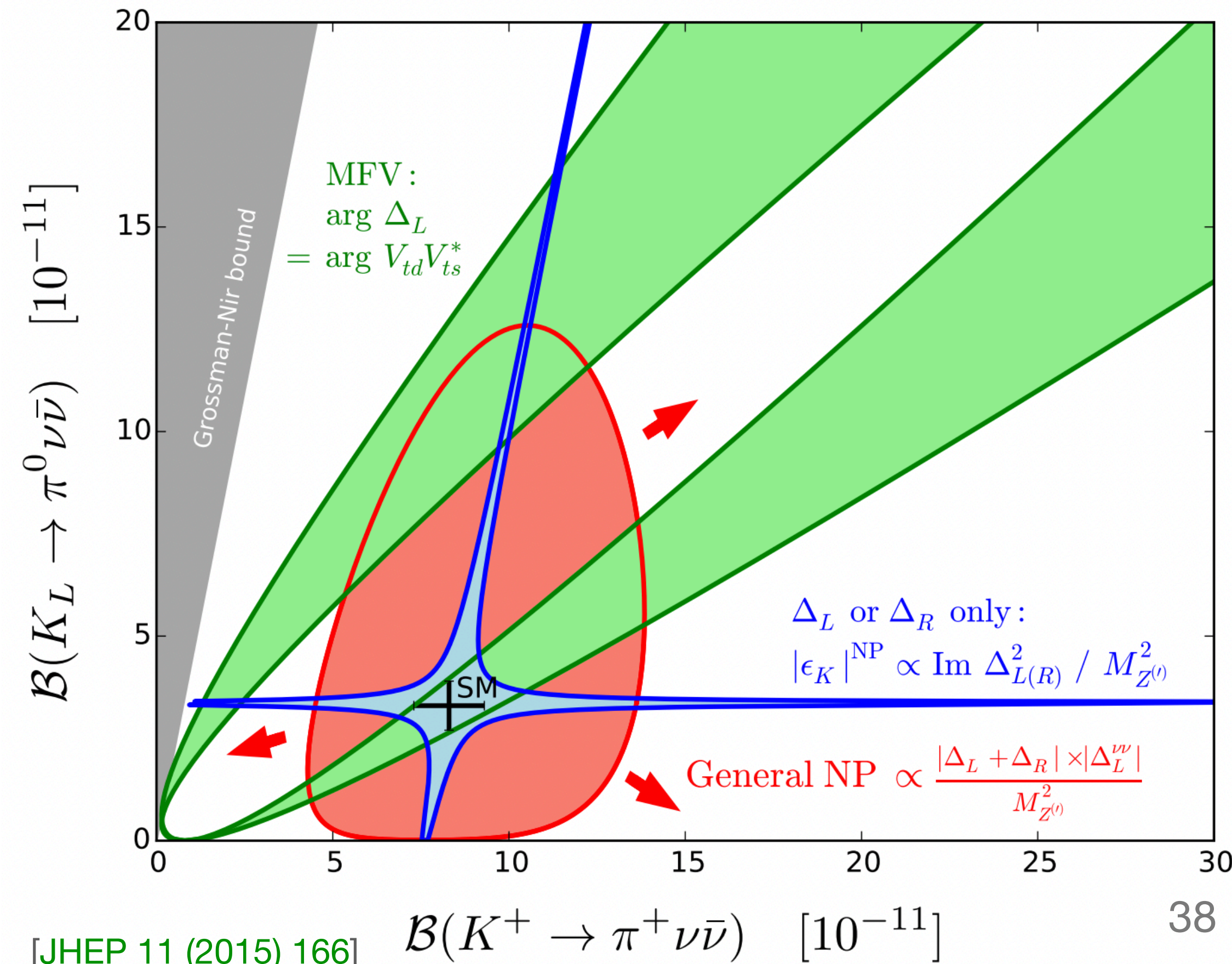
- Correlations between BSM contributions to BRs of K^+ and K_L modes [[JHEP 11 \(2015\) 166](#)].
 - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ϵ'/ϵ , ΔM_B , B-decays) [[JHEP 12 \(2020\) 097](#)][[PLB 809 \(2020\) 135769](#)].
- Leptoquarks [[EPJ.C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

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

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



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

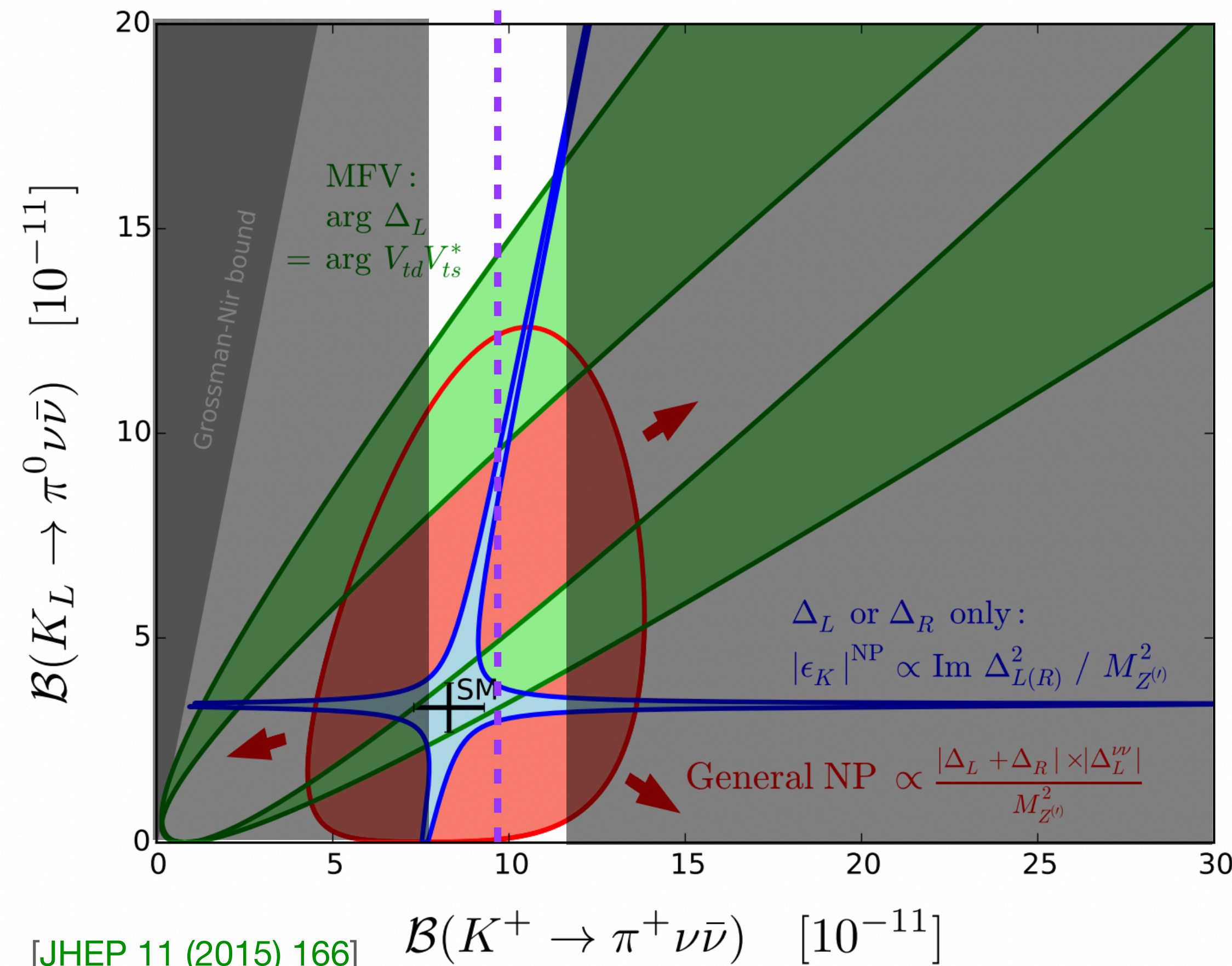
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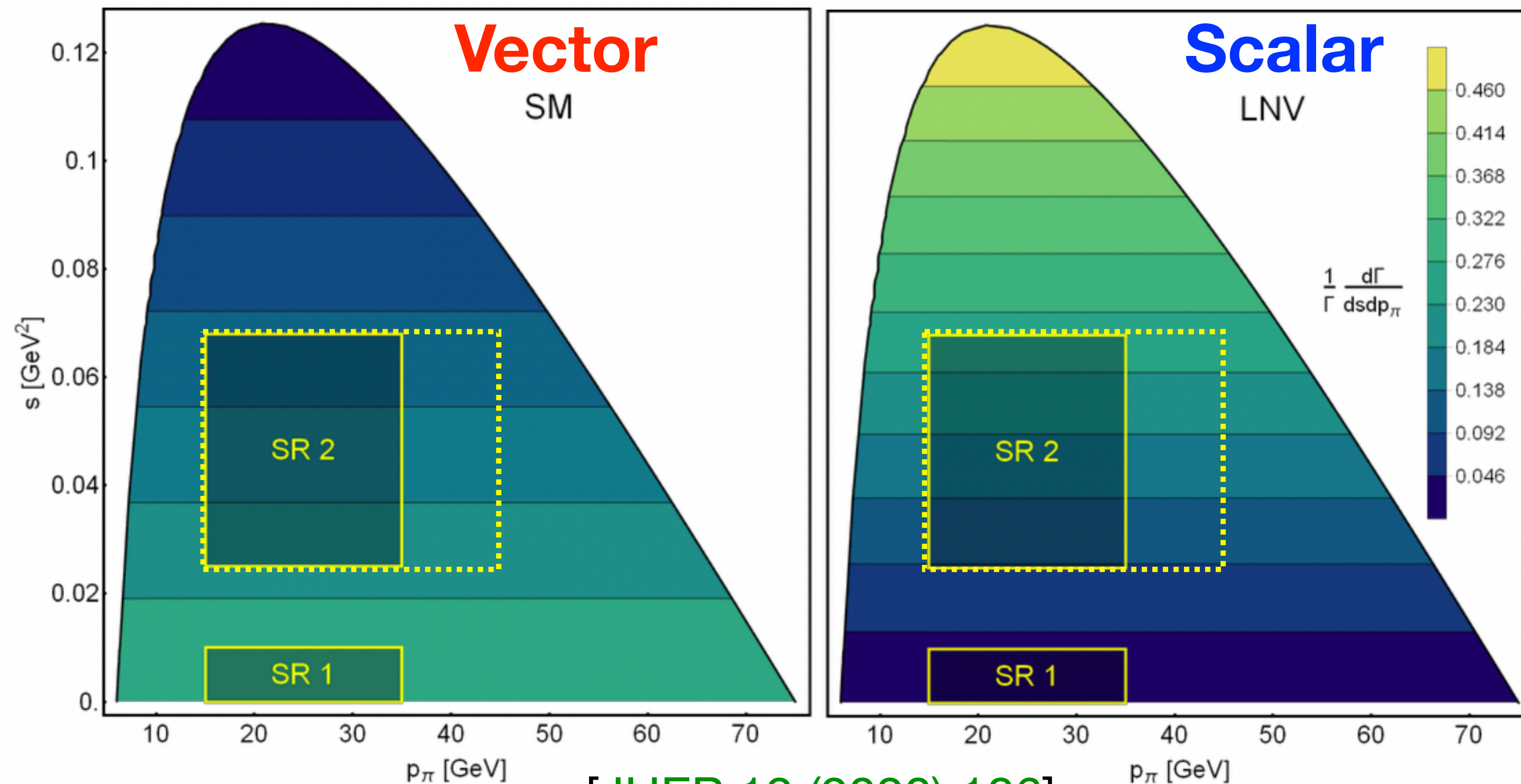
[[PLB 398 \(1997\) 163-168](#)]

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

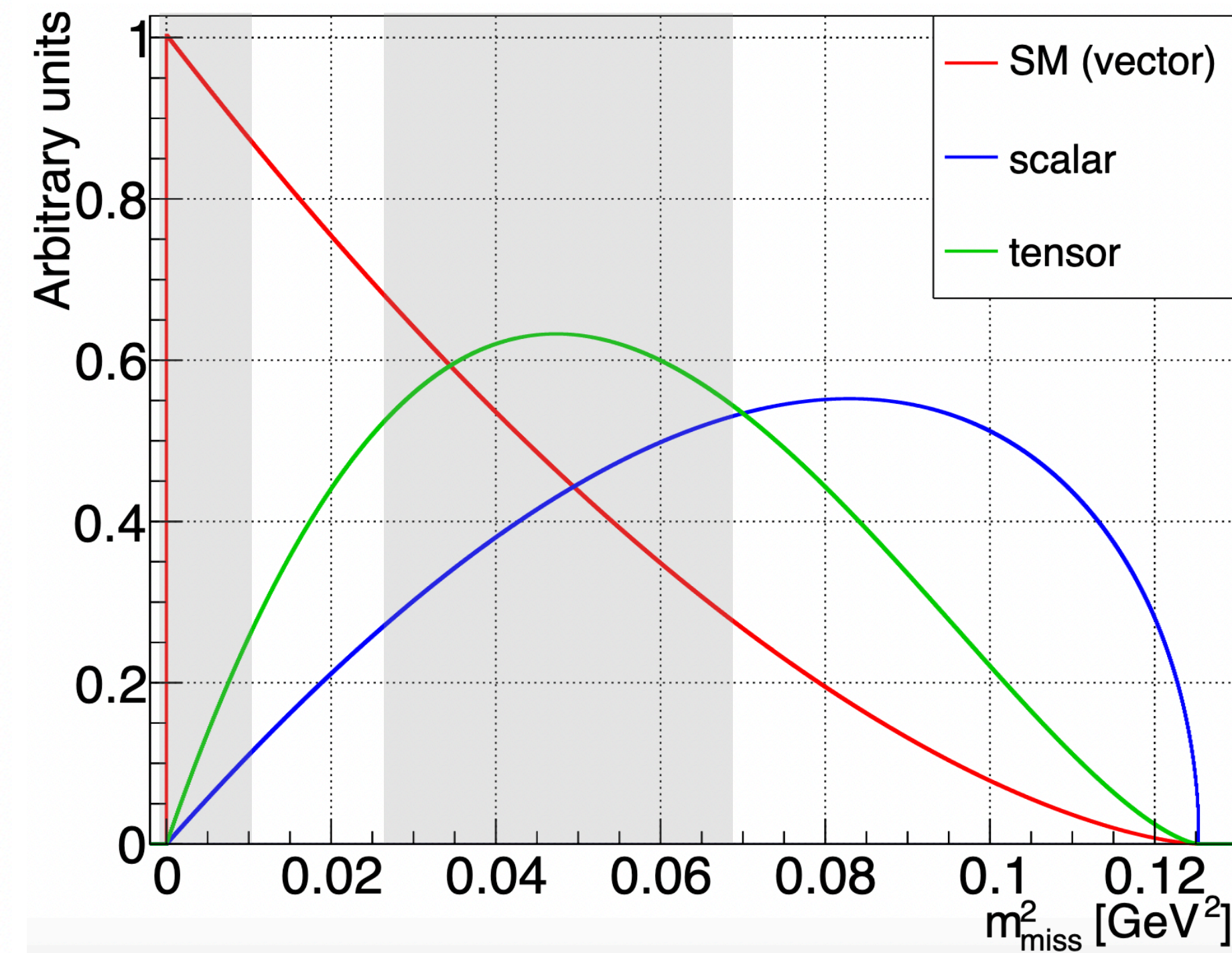
$$\Rightarrow \mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \lesssim 4.3 \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$$



What is the nature of the $K \rightarrow \pi \nu \bar{\nu}$ decay?

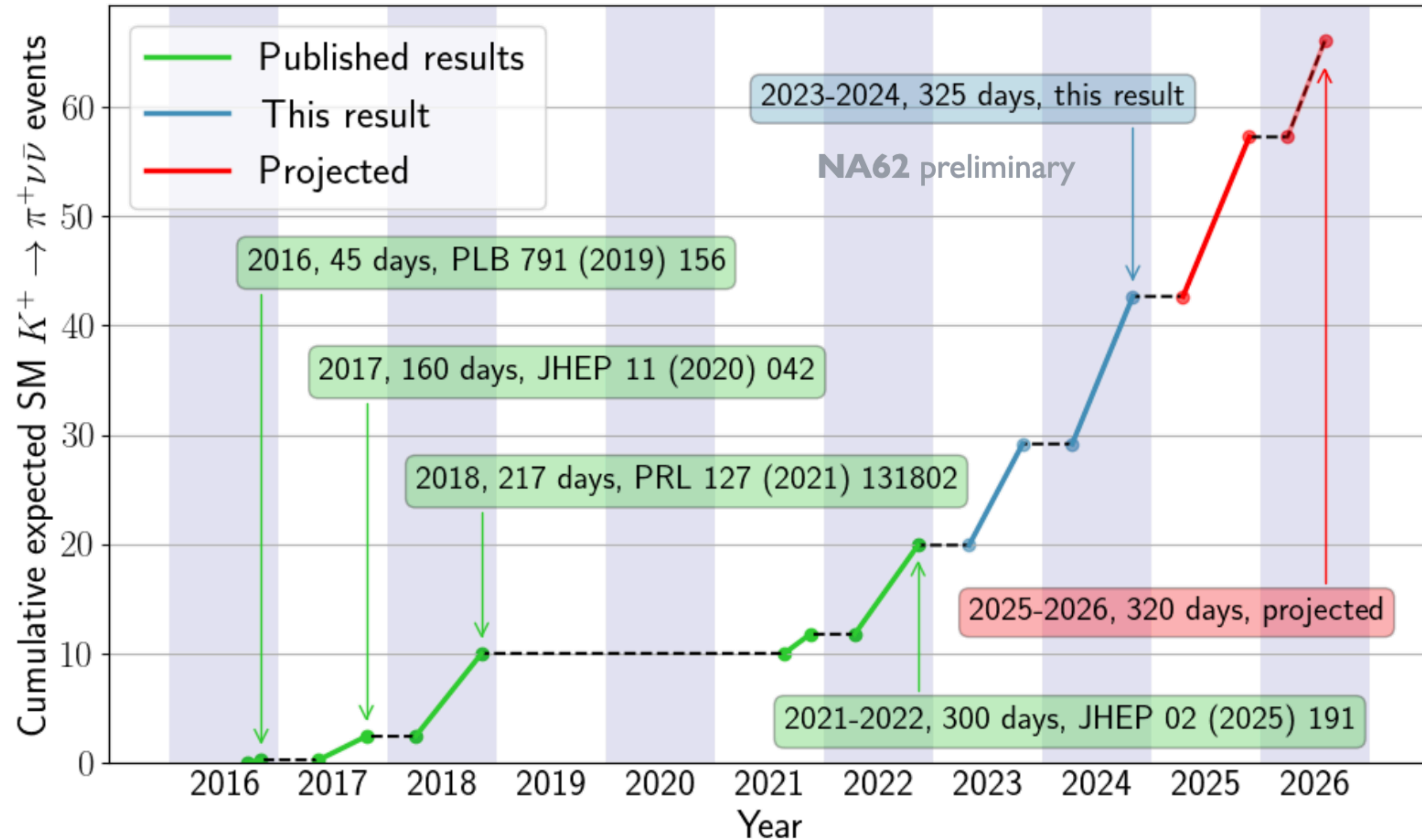


[JHEP 12 (2020) 186]



- In SM: vector form factor.
- BSM: possible vector, scalar, tensor contributions.
- Differential measurement could show presence of new physics.

Prospects



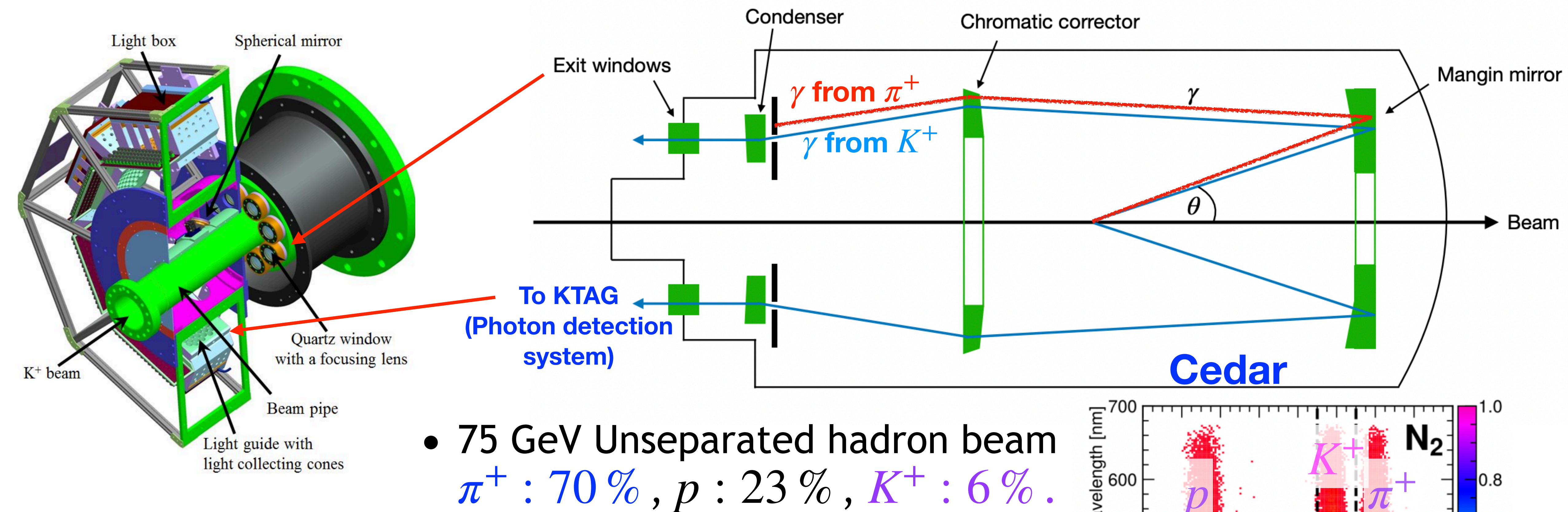
- Current: 2016–2024

- Expected SM* signal, $N_{\pi\nu\bar{\nu}}^{SM} = 43 \pm 1$
- Expected background, $N_{bg} = 30^{+4}_{-3}$
- Observed, $N_{obs} = 84$

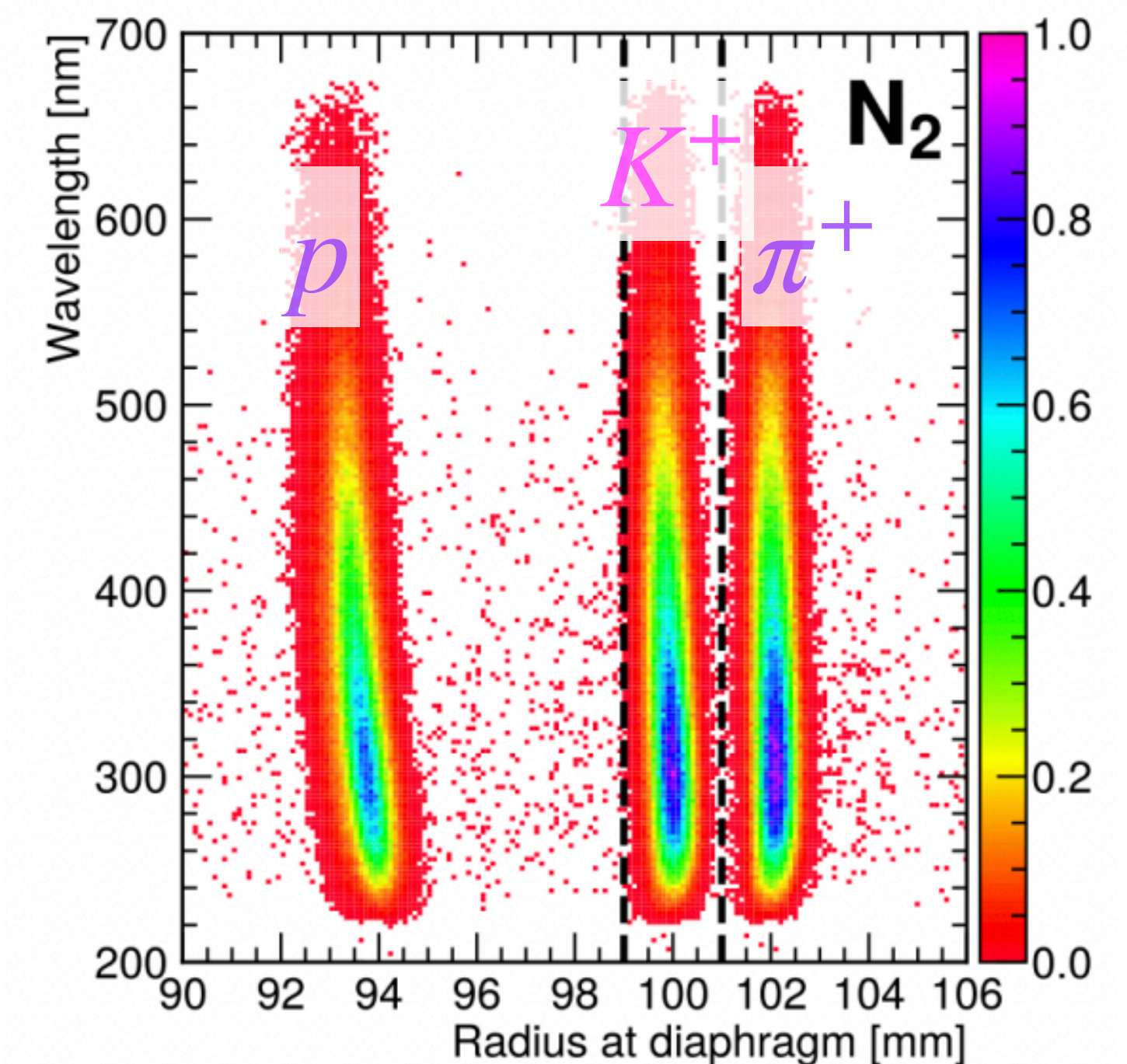
- Full: 2016–2026

- Expect ~1/3 of data still to come (2025+2026)
- Improve BR precision further: from 20% towards 15%.
- Study kinematic distributions (shapes).

Cedar & KTAG : K^+ tagging with threshold Cherenkov counter



- Use fixed diaphragm to select ONLY Cherenkov light from K^+ (adjust diaphragm width and gas pressure in CEDAR to ensure powerful K^+/π^+ discrimination).

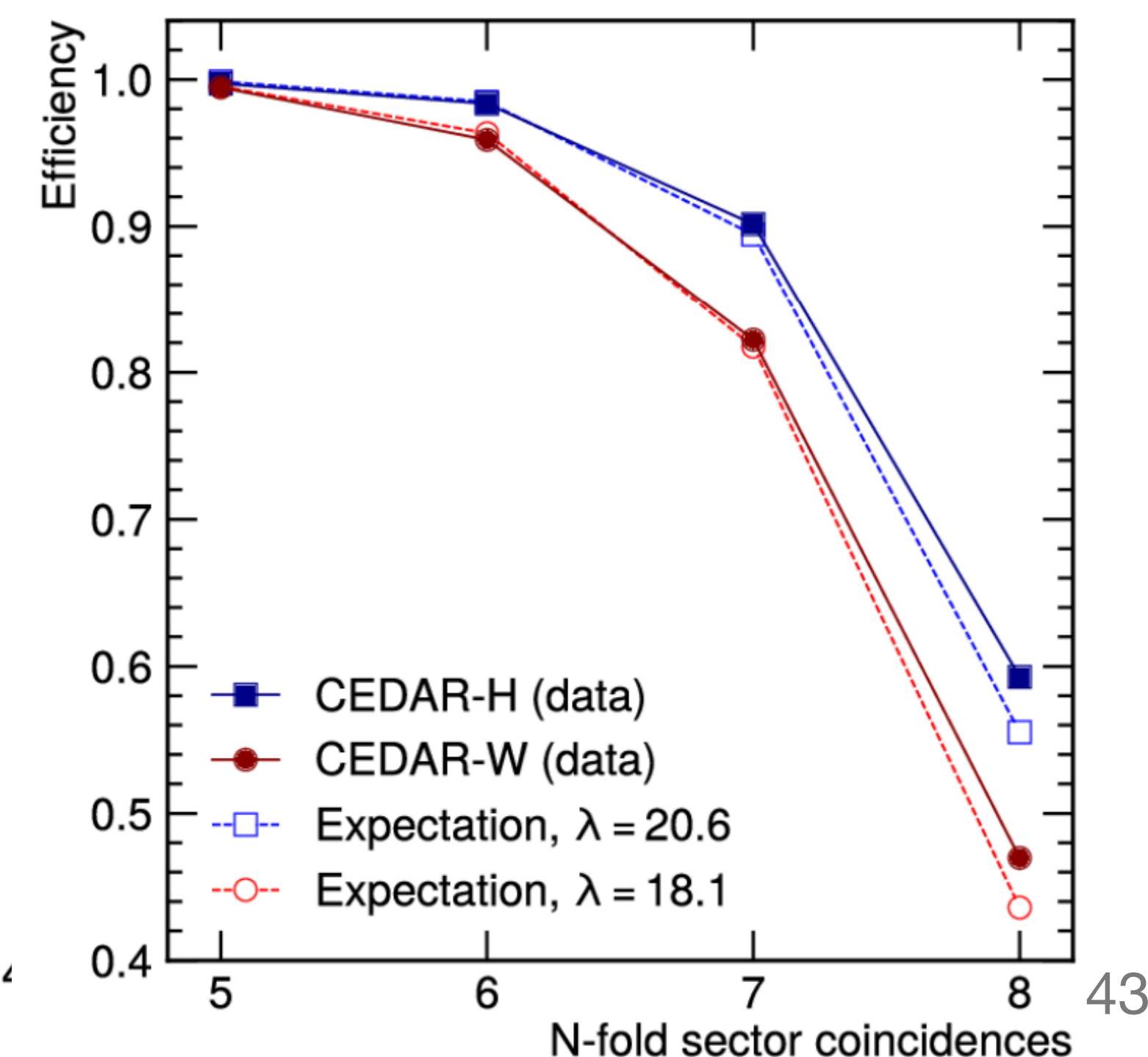
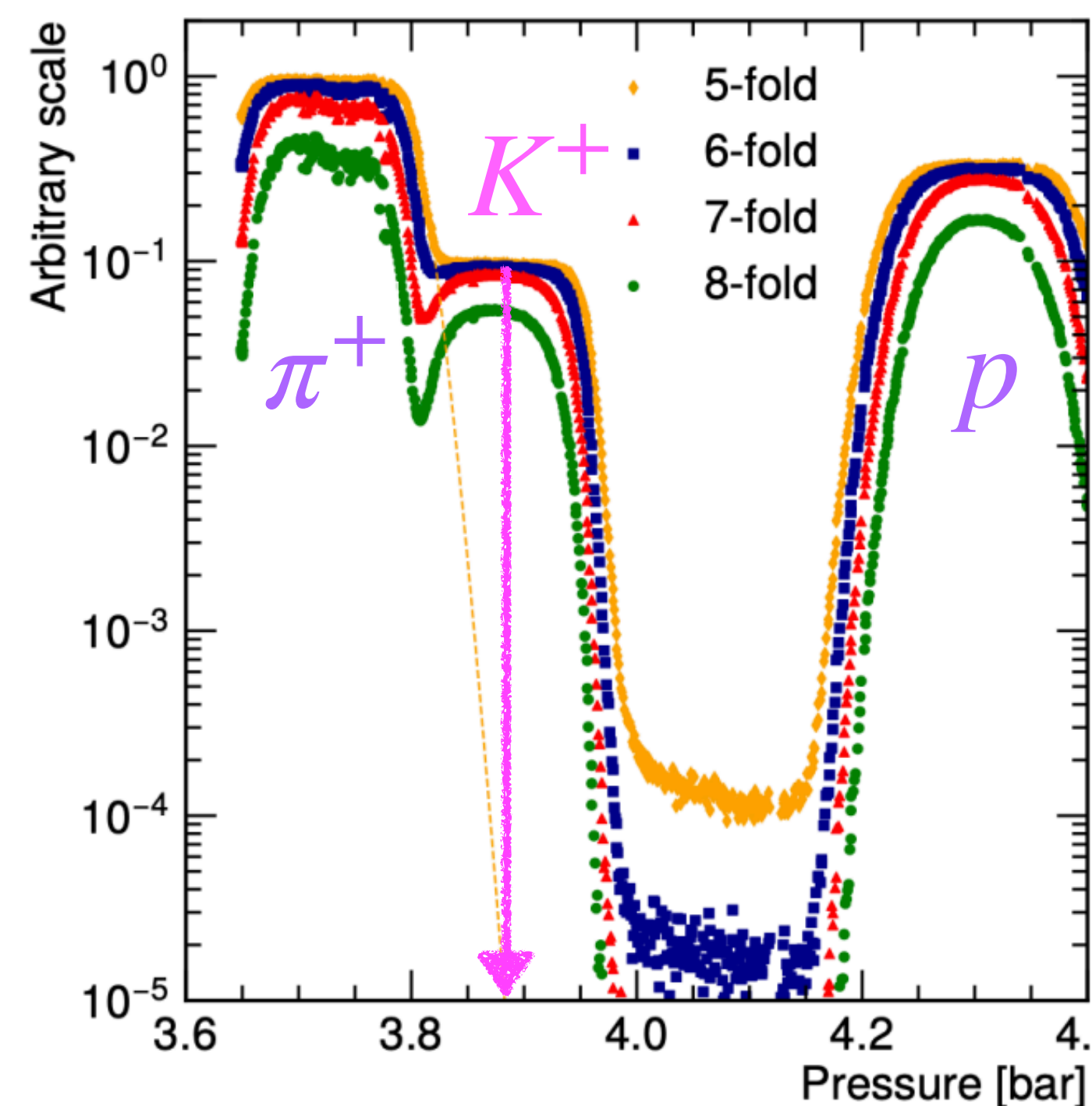


New Cedar-H : installed in 2023

- CEDAR-W filled with N_2 at 1.7 bar was biggest contributor to material in beam line ($39 \times 10^{-3} X_0$) .
- New CEDAR-H filled with H_2 at 3.8 bar:
 - Reduces material to $7.3 \times 10^{-3} X_0$: reducing multiple scattering.
 - But new optics required to account for different optical properties of H_2 .
- Successful test beam in 2022 (at CERN,H6) and installation in NA62 in **early 2023**.

- **Cedar-H Performance at NA62:**

- **>99.5% efficiency** for 5-fold coincidence.
- **π^+ mistag probability: 10^{-4}**
- **~65ps time resolution**
- **30% reduction** in elastically scattered beam particles.

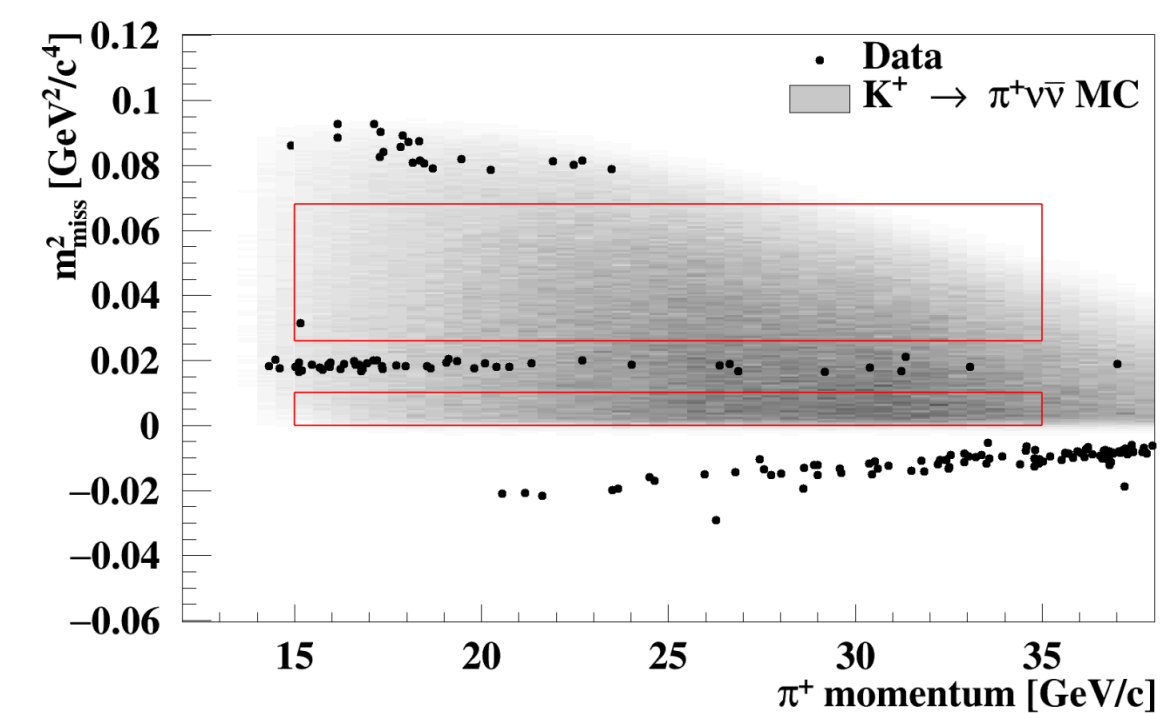


Previous NA62 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ results

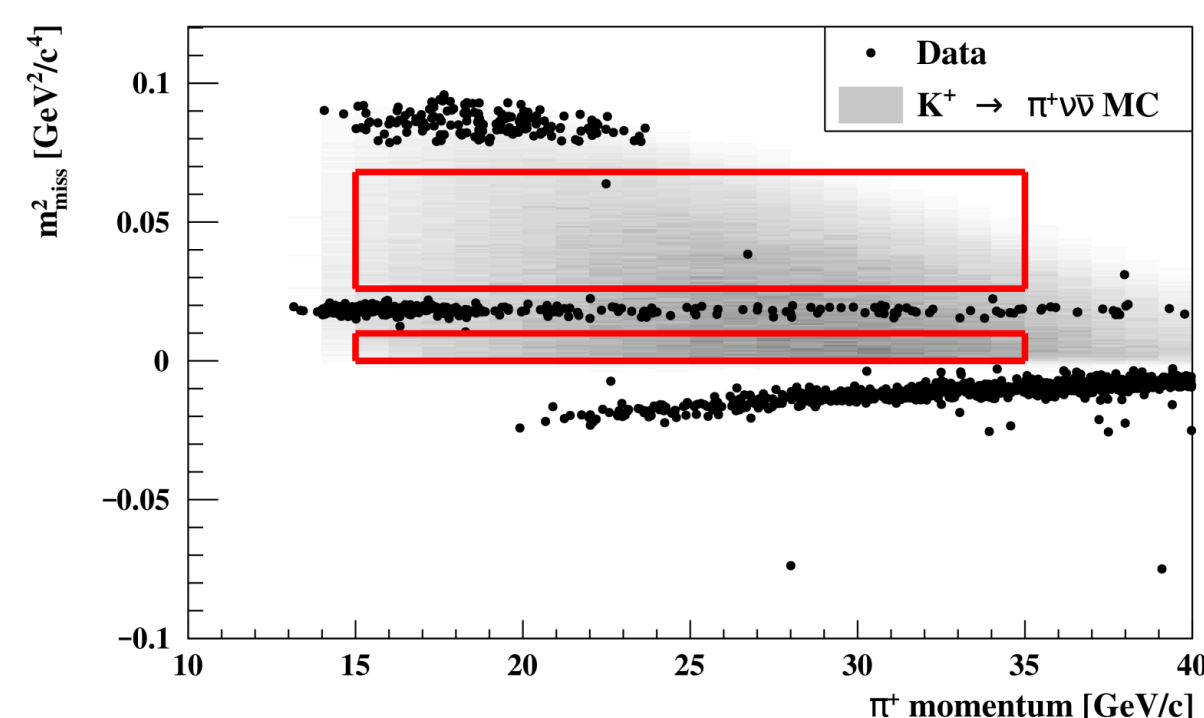


(* $N_{\pi\nu\bar{\nu}}^{\text{SM,exp}}$ assumes benchmark $\mathcal{B}_{\text{SM}} = 8.4 \times 10^{-11}$)

2016 data [PLB 791 (2019) 156]

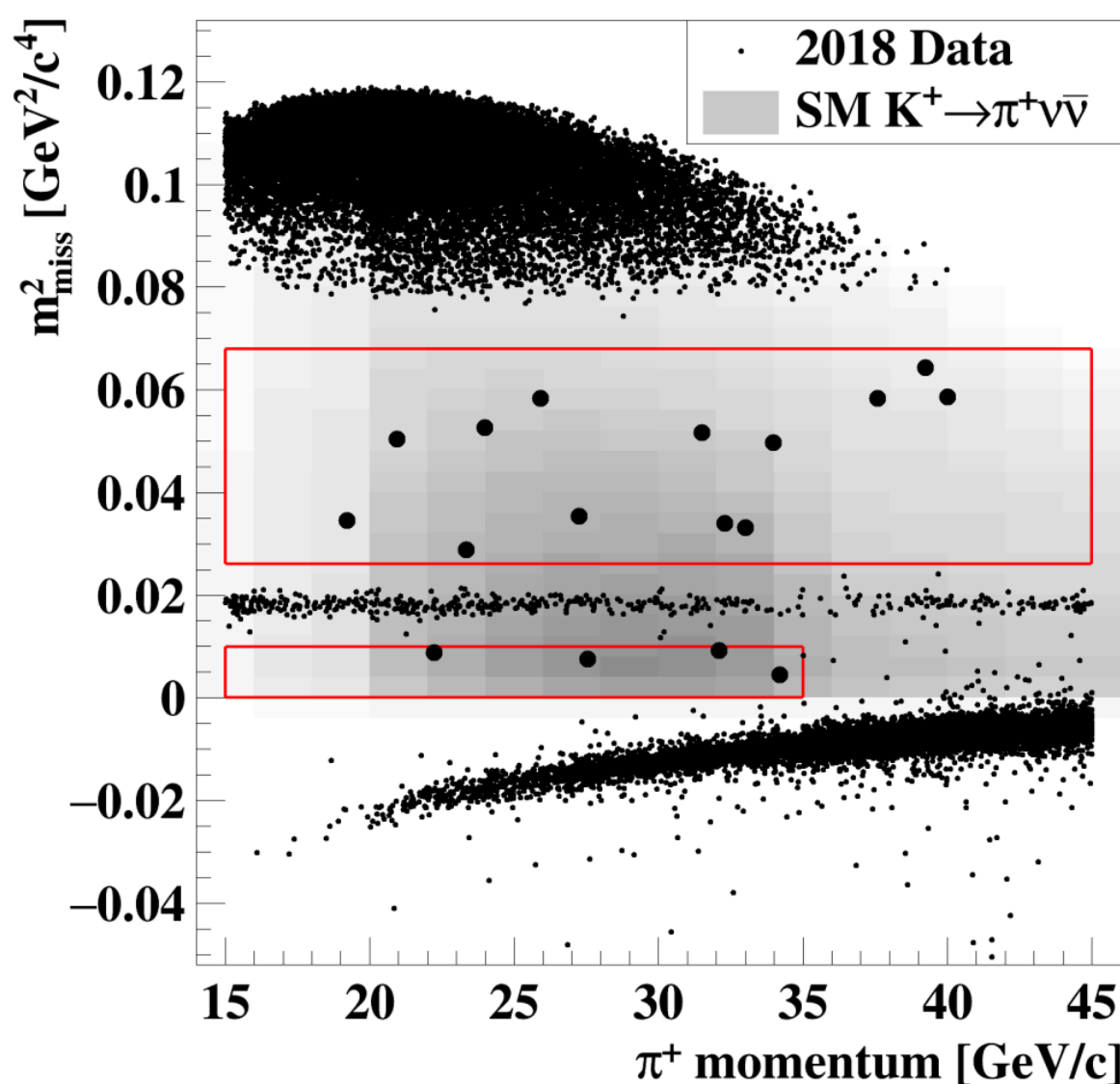


2017 data [JHEP 11 (2020) 042]

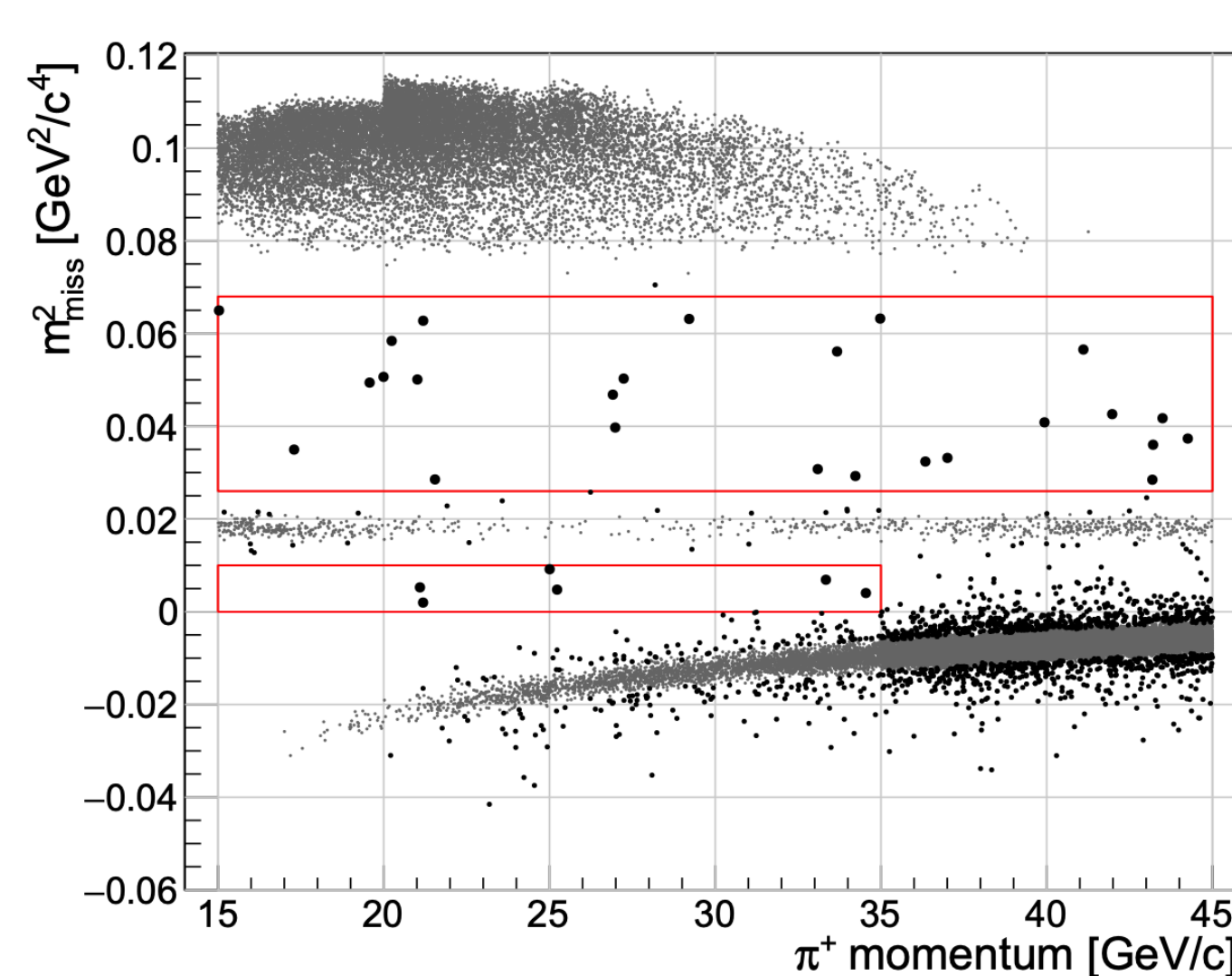


Data-taking year(s)	[Reference]	N_{bg}	$N_{\pi\nu\bar{\nu}}^{\text{SM,exp}}$	N_{obs}
2016	[PLB 791 (2019) 156]	$0.152^{+0.093}_{-0.035}$	0.267 ± 0.020	1
2017	[JHEP 11 (2020) 042]	1.46 ± 0.33	2.16 ± 0.13	2
2018	[JHEP 06 (2021) 093]	$5.42^{+0.99}_{-0.75}$	7.58 ± 0.40	17
2021–2022	[JHEP 02 (2025) 191]	$11.0^{+2.1}_{-1.9}$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

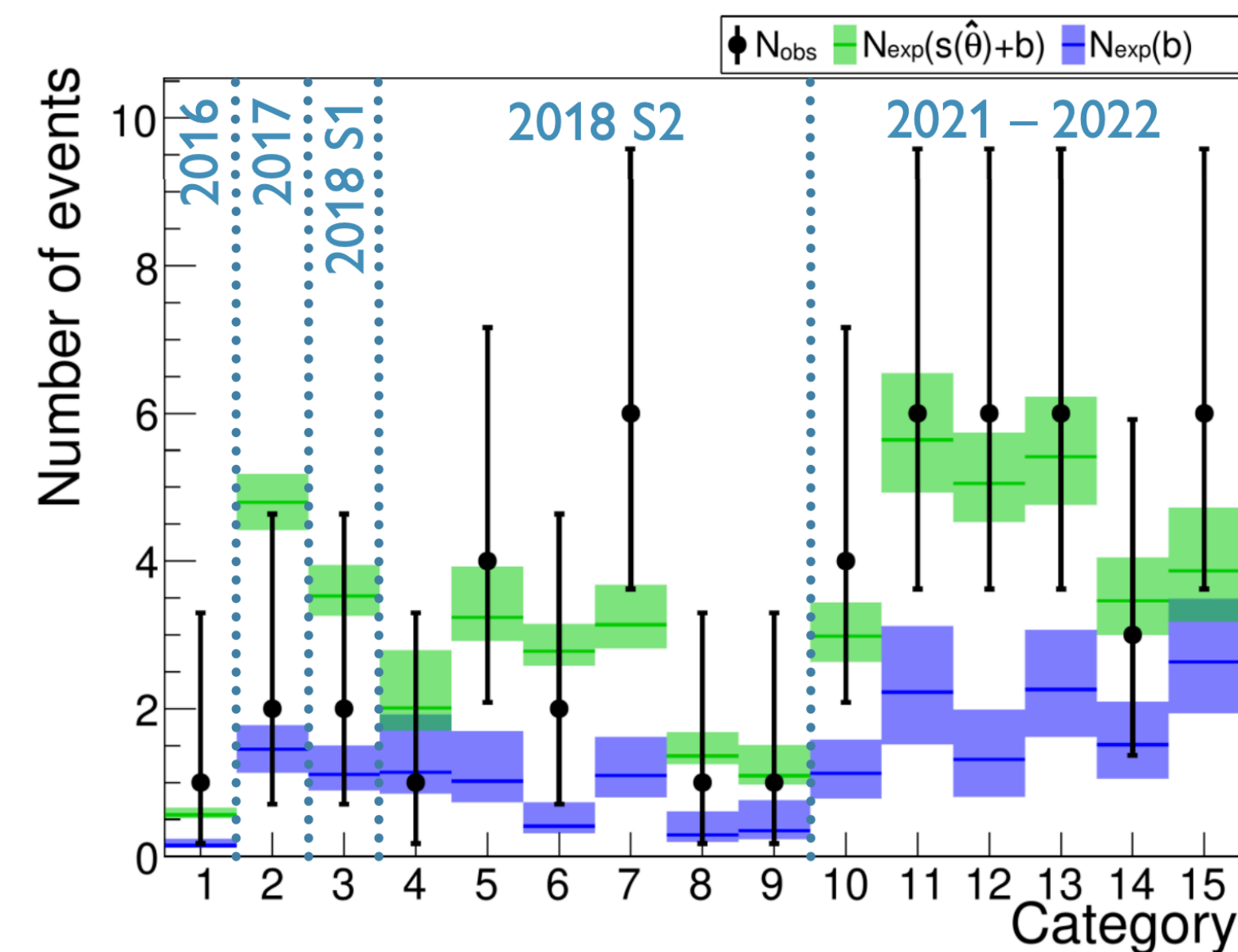
2018 data [JHEP 06 (2021) 093]



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



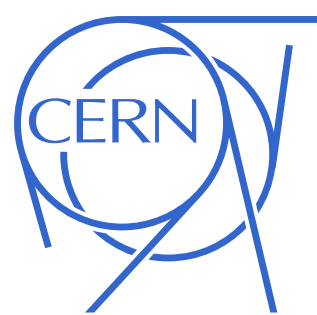
Statistical combination:



$$\mathcal{B}_{2016-22}^{\text{NA62}}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \left(13.0^{+3.0}_{-2.9} \left|_{\text{stat}} \begin{matrix} +1.3 \\ -1.3 \end{matrix} \right|_{\text{syst}} \right) \times 10^{-11} = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$$

In background-only hypothesis: $p = 2 \times 10^{-7} \Rightarrow \text{significance} > 5\sigma$.

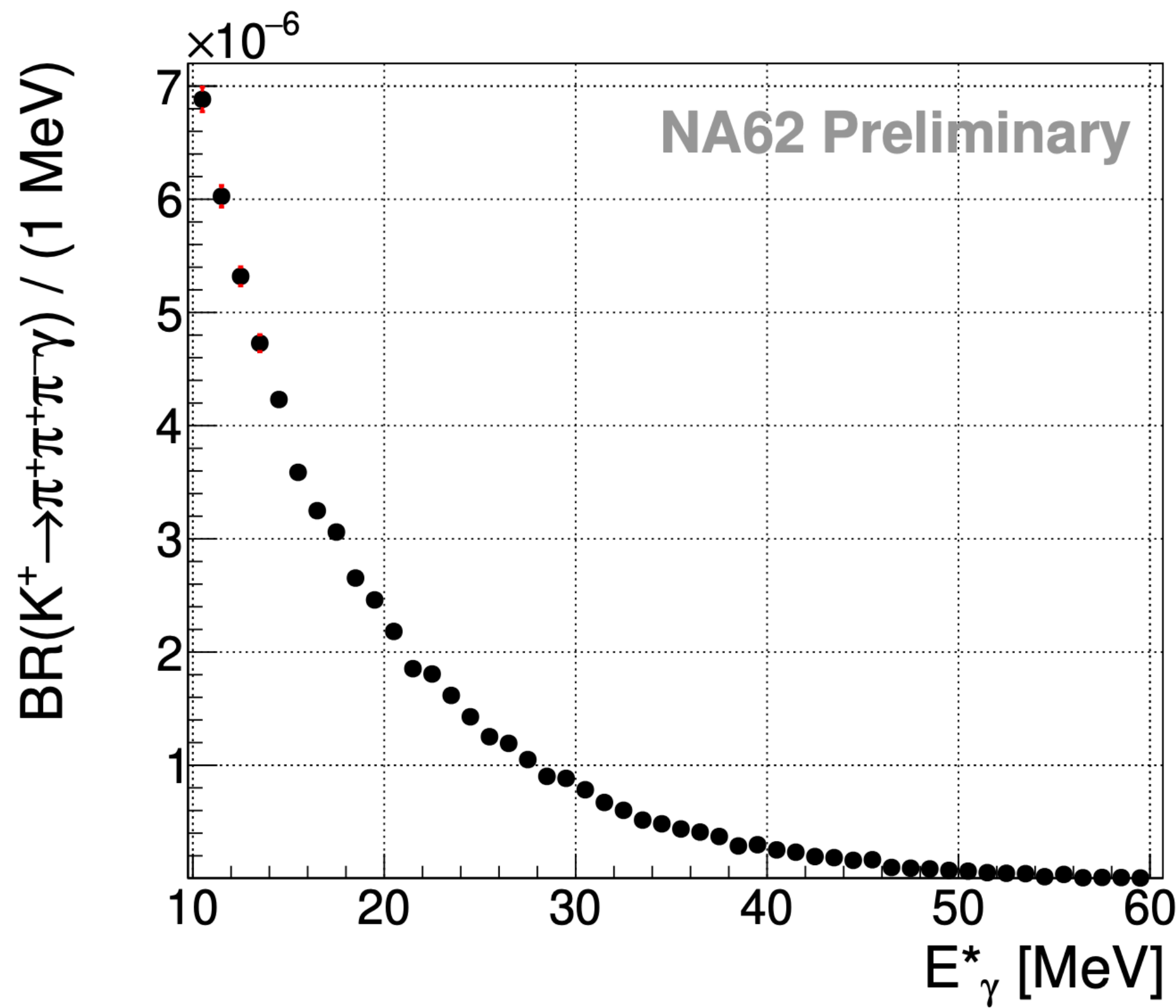
Smallest BR ever measured at $> 5\sigma$ significance !



NA62 Broad Physics Program



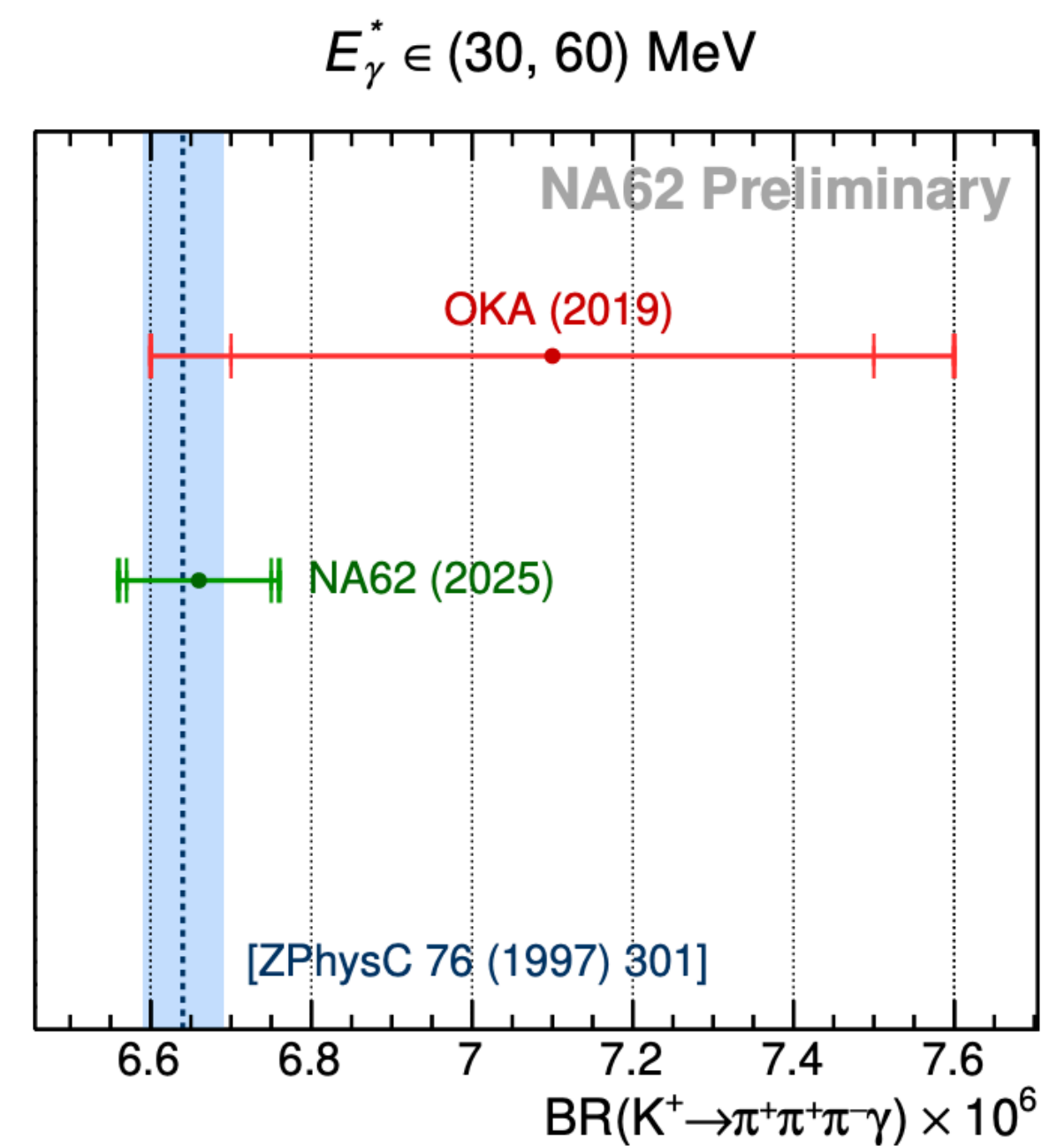
Study of $K^+ \rightarrow \pi^+ \pi^+ \pi^- \gamma$



E_γ^* [MeV]	$\mathcal{B}_{\text{NA62}}(E_\gamma^*)$ Preliminary	$\mathcal{B}_{\text{Theory}}(E_\gamma^*)$ [ZPhysC 76 (1997) 301]	$\mathcal{B}_{\text{OKA}}(E_\gamma^*)$ [EPJC 79 (2019) 1]
10–20	$(4.22 \pm 0.05) \cdot 10^{-5}$	$(4.36 \pm 0.04) \cdot 10^{-5}$	
20–30	$(1.42 \pm 0.02) \cdot 10^{-5}$	$(1.43 \pm 0.01) \cdot 10^{-5}$	
30–40	$(4.86 \pm 0.09) \cdot 10^{-6}$	$(4.93 \pm 0.05) \cdot 10^{-6}$	$(5.17 \pm 0.34) \cdot 10^{-6}$
40–50	$(1.53 \pm 0.05) \cdot 10^{-6}$	$(1.44 \pm 0.01) \cdot 10^{-6}$	$(1.55 \pm 0.12) \cdot 10^{-6}$
50–60	$(2.80 \pm 0.31) \cdot 10^{-7}$	$(2.69 \pm 0.03) \cdot 10^{-7}$	$(3.5 \pm 0.5) \cdot 10^{-7}$
60–70		$(1.36 \pm 0.02) \cdot 10^{-8}$	$(1.1 \pm 0.6) \cdot 10^{-8}$
10–60	$(6.30 \pm 0.06) \cdot 10^{-5}$	$(6.45 \pm 0.06) \cdot 10^{-5}$	
30–60	$(6.66 \pm 0.10) \cdot 10^{-6}$	$(6.64 \pm 0.05) \cdot 10^{-6}$	
30–70		$(6.65 \pm 0.05) \cdot 10^{-6}$	$(7.1 \pm 0.4_{\text{stat}} \pm 0.3_{\text{syst}}) \cdot 10^{-6}$

• Precision test of χ_{PT} at $\mathcal{O}(p^4)$.

- BR measurement at % precision for $E_\gamma^* = 10\text{--}60$ MeV.
- First measurement at 10–30 MeV
 - Good agreement with theory & OKA
 - Improving experimental precision by factor 2–4

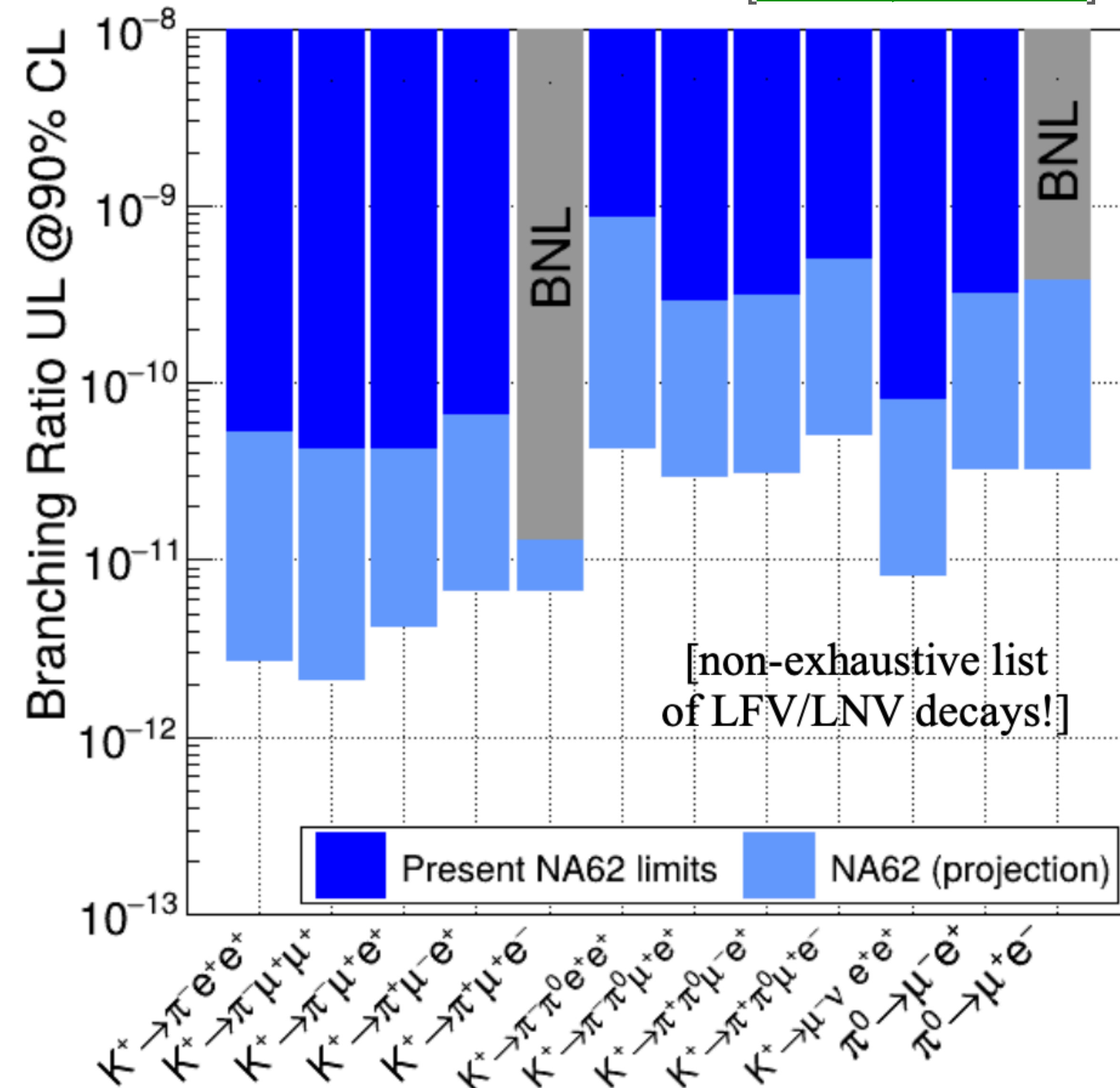


Summary of LNV/LFV Searches at NA62

[Goudzovski, KAON25]

[Massri, KAON25]

- Dedicated set of di-lepton multi-track triggers run in parallel, downscaling $D \sim 2 - 10$ in 2016–18
 - Trigger improvements: $D = 1$ ($\geq$ late 2023)
- 10 world-leading limits just using 2016–18 data
 - Sensitivity not limited by background
- 2016–26 di-lepton dataset equivalent to $\mathcal{O}(10^{13})$ K^+ decays
 - Sensitivity to K^+ and π^0 LNV/LFV decays with $\mathcal{B} \sim \mathcal{O}(10^{-11} - 10^{-12})$



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

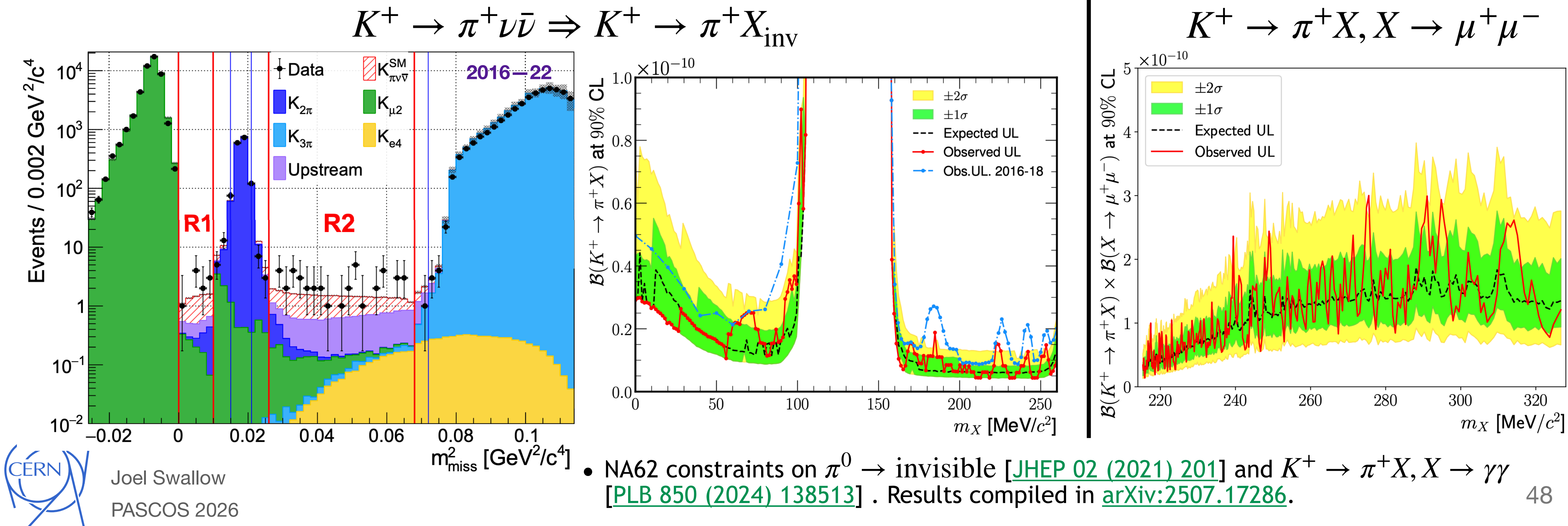
[JHEP 11 (2025) 143]

2016–22 dataset



[Raggi, Kaon25]

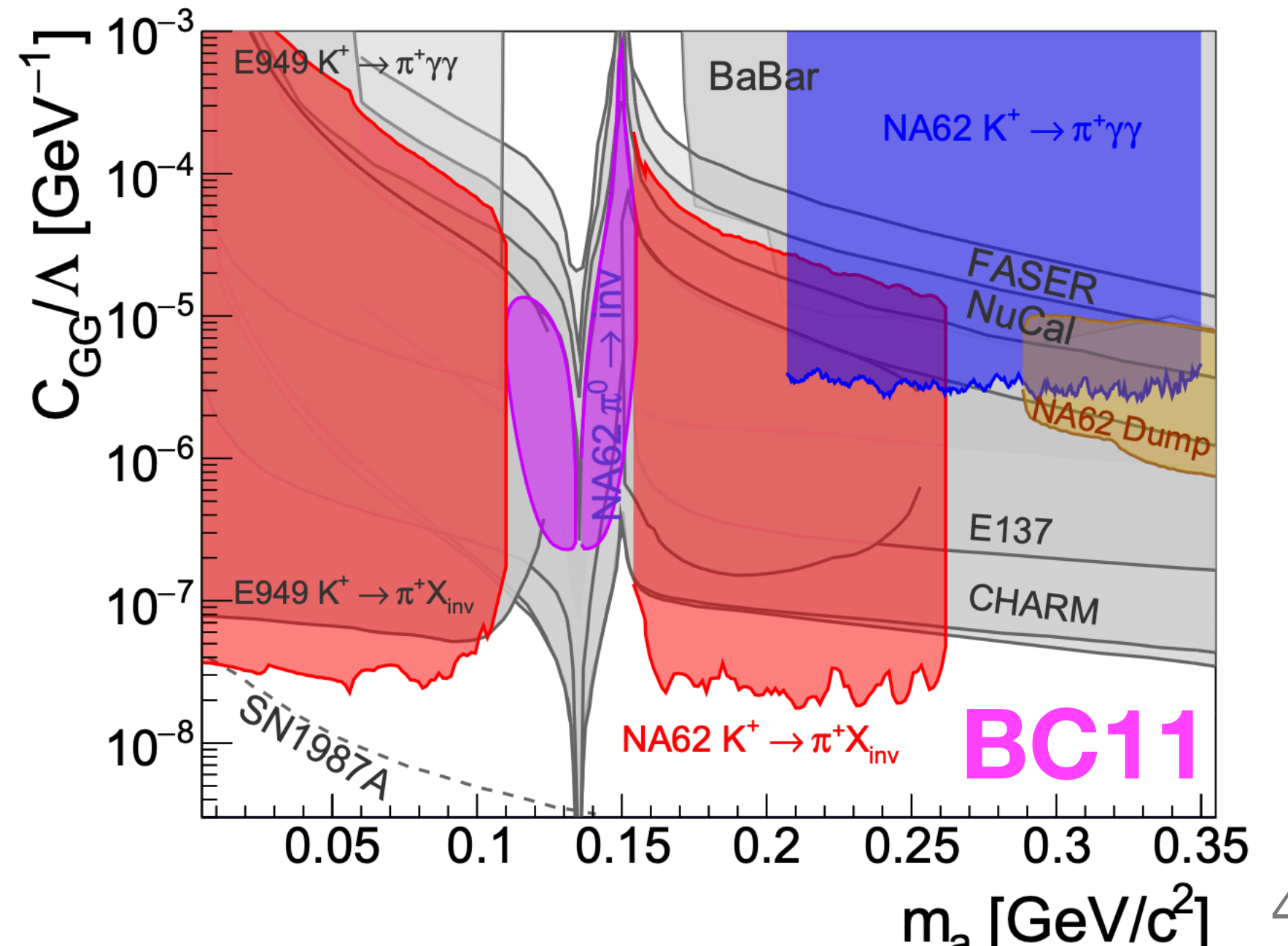
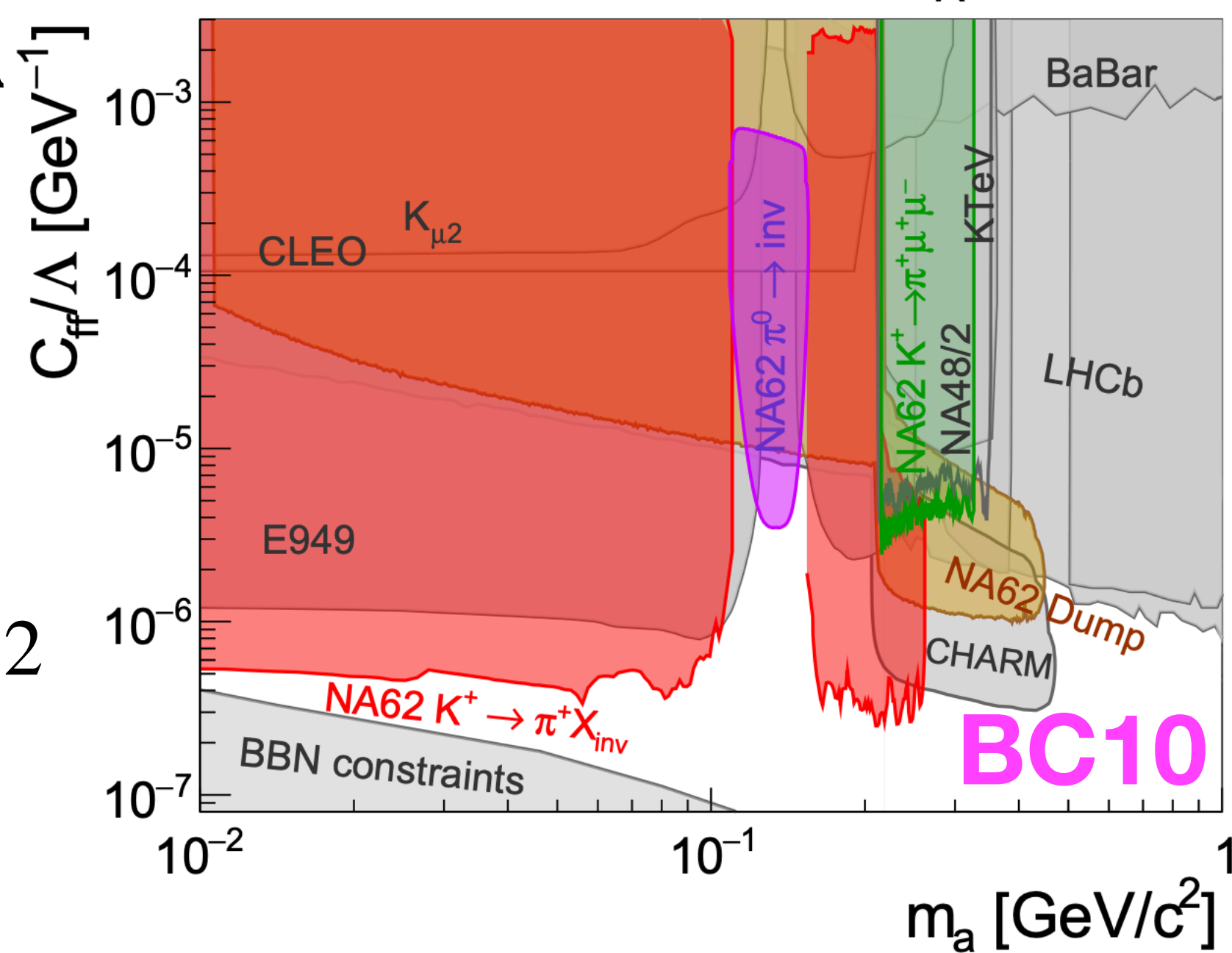
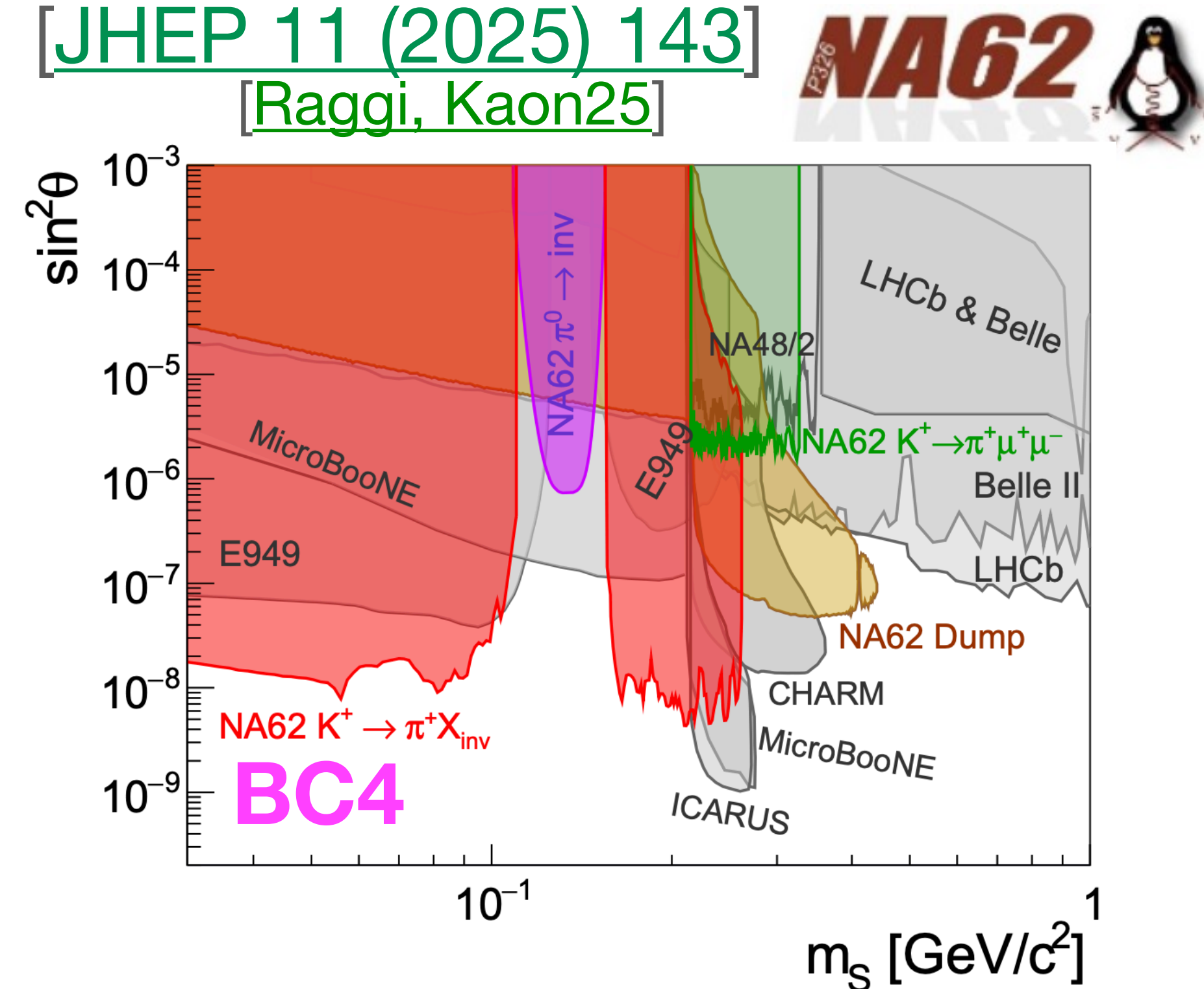
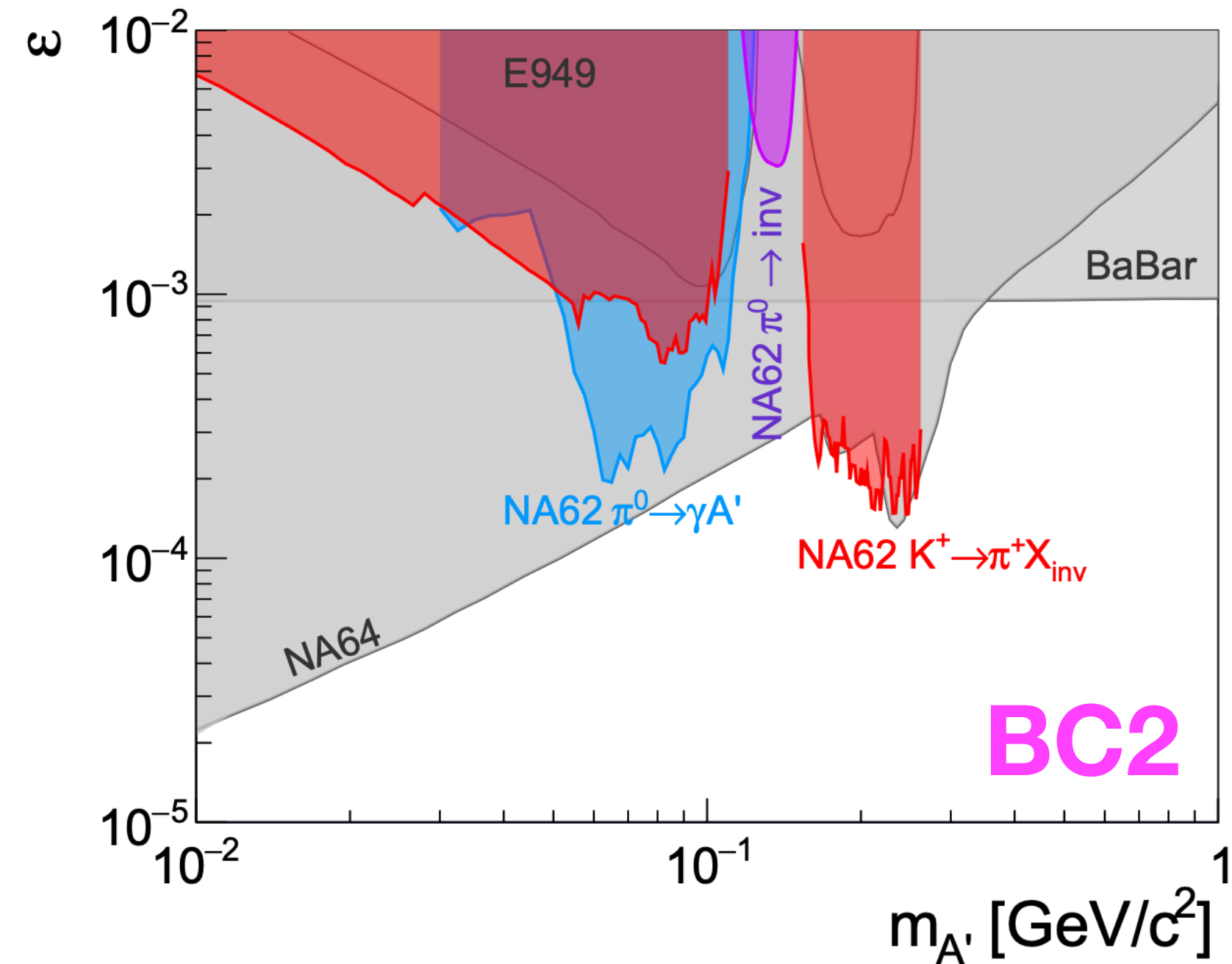
- Same signature as $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ except $m_{miss}^2 = (P_K - P_\pi)^2 = m_X^2$
 - Peak search: (SM) $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is the dominant background!
- Set model-independent BR upper limits for $K^+ \rightarrow \pi^+ X_{inv}$: new - extend to 2016–22 dataset
 - Evaluate acceptance for any X lifetime $\Rightarrow \mathcal{B}_{UL}(m_X, \tau_X)$
- **New:** also evaluate limits for $K^+ \rightarrow \pi^+ X, X \rightarrow \mu^+ \mu^-$ using NA62 $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ result [JHEP 11 (2022) 011]



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

2016–22 dataset

- BC2: Dark Photon
- 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](https://arxiv.org/abs/2503.05865)]
- World-leading limit on axion-down-strange coupling
 $|(F_V)_{sd}| > 1.6 \times 10^{12}$



Tagged neutrinos at NA62

[PLB 863 (2025) 139345]

- Using 2022 NA62 data:
- Expected signal:

$$N_{\text{signal}}^{\text{exp}} = 0.208 \pm 0.013_{\text{stat}} \pm 0.009_{\text{syst}}$$
- Background (dominated by $K^+ \rightarrow \mu^+ \nu$ + pileup):
 - $$N_{\text{bg}}^{\text{exp}} = 0.034^{+0.041}_{-0.023} |_{\text{stat}} \pm 0.004_{\text{syst}}$$

- Detect 1 candidate**
 $K^+ \rightarrow \mu^+ \nu$ tagged ν event!
- Demonstrates the feasibility of the neutrino tagging technique.

