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

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Contents:

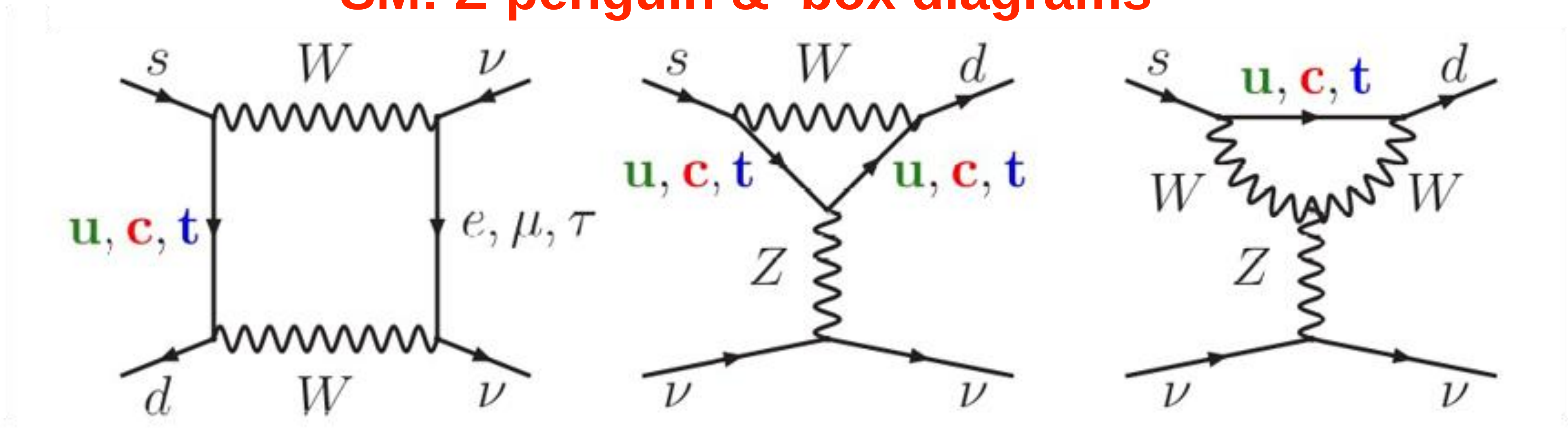
- The golden modes $K \to \pi\nu\bar{\nu}$ in the SM and beyond
- NA62 after LS2: detector upgrades & performance
- New measurement of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$

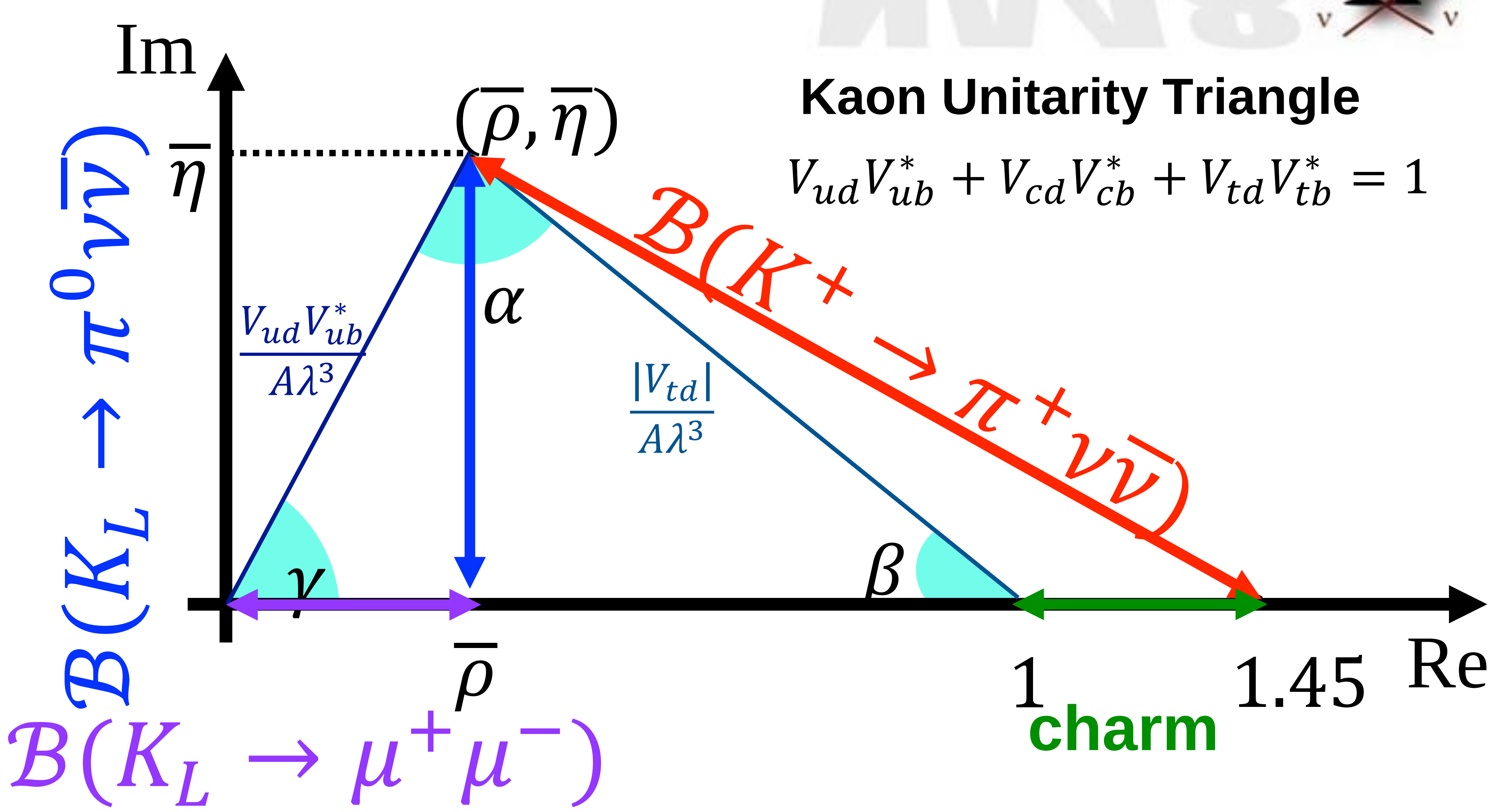
Rare Kaon Decays:
SM and Beyond

The golden modes $K \to \pi\nu\bar{\nu}$

$K \to \pi\nu\bar{\nu}$: 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: $\sim \frac{m_t}{m_W}|V_{ts}^* V_{td}|$
- 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)
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 2 \times 10^{-9}$ (KOTO)

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

NA62 (2016–18 data): [JHEP 06 (2021) 093]
KOTO (2021 data): [Eur.Phys.J.C 84 (2024) 4, 377]

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

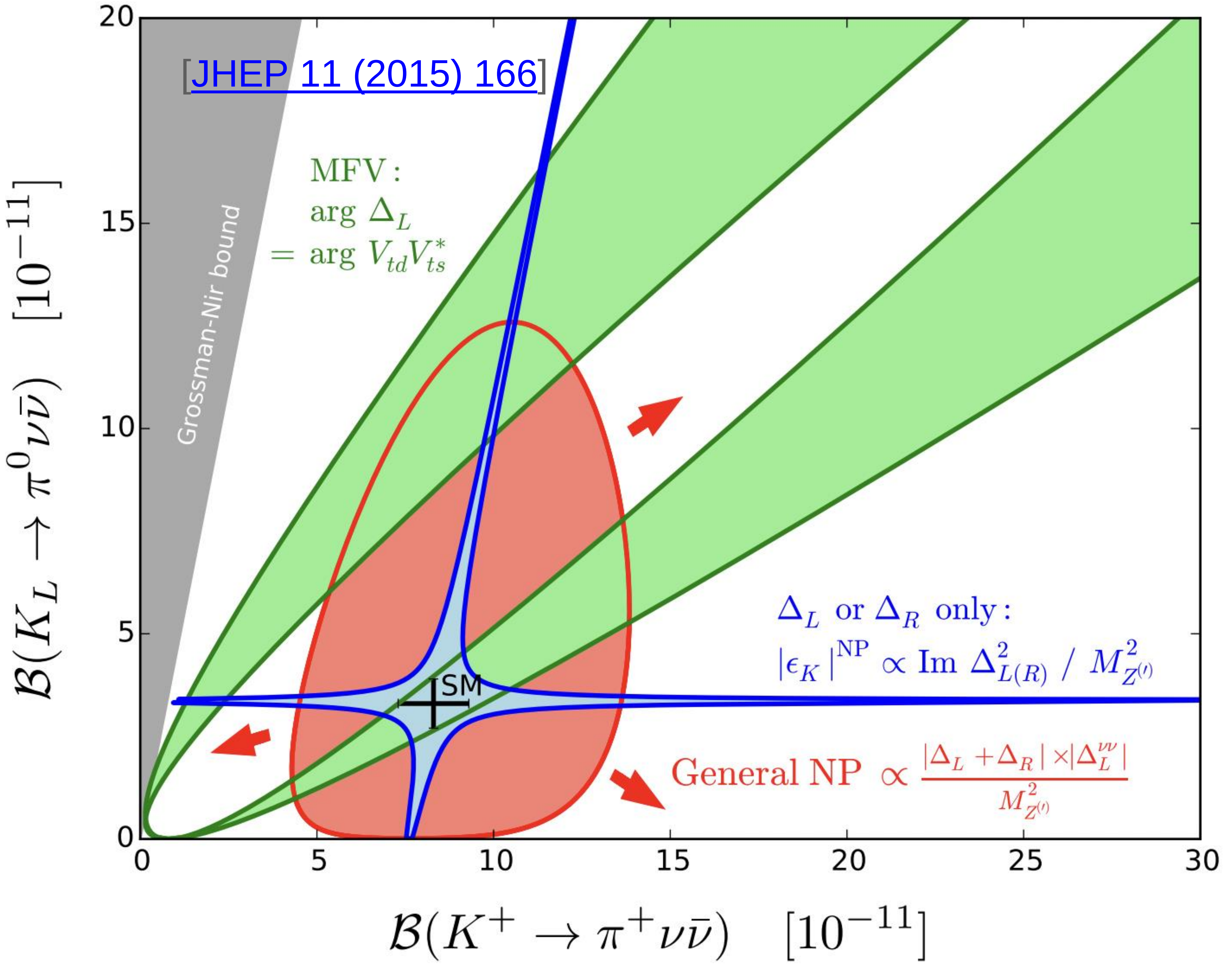
- Correlations between BSM contributions to BRs of K^+ and K_L modes [JHEP 11 (2015) 166].
  - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ε'/ε, ΔM_B, B-decays) [JHEP 12 (2020) 097][PLB 809 (2020) 135769].
- Leptoquarks [EPJ.C 82 (2022) 4, 320], Interplay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

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

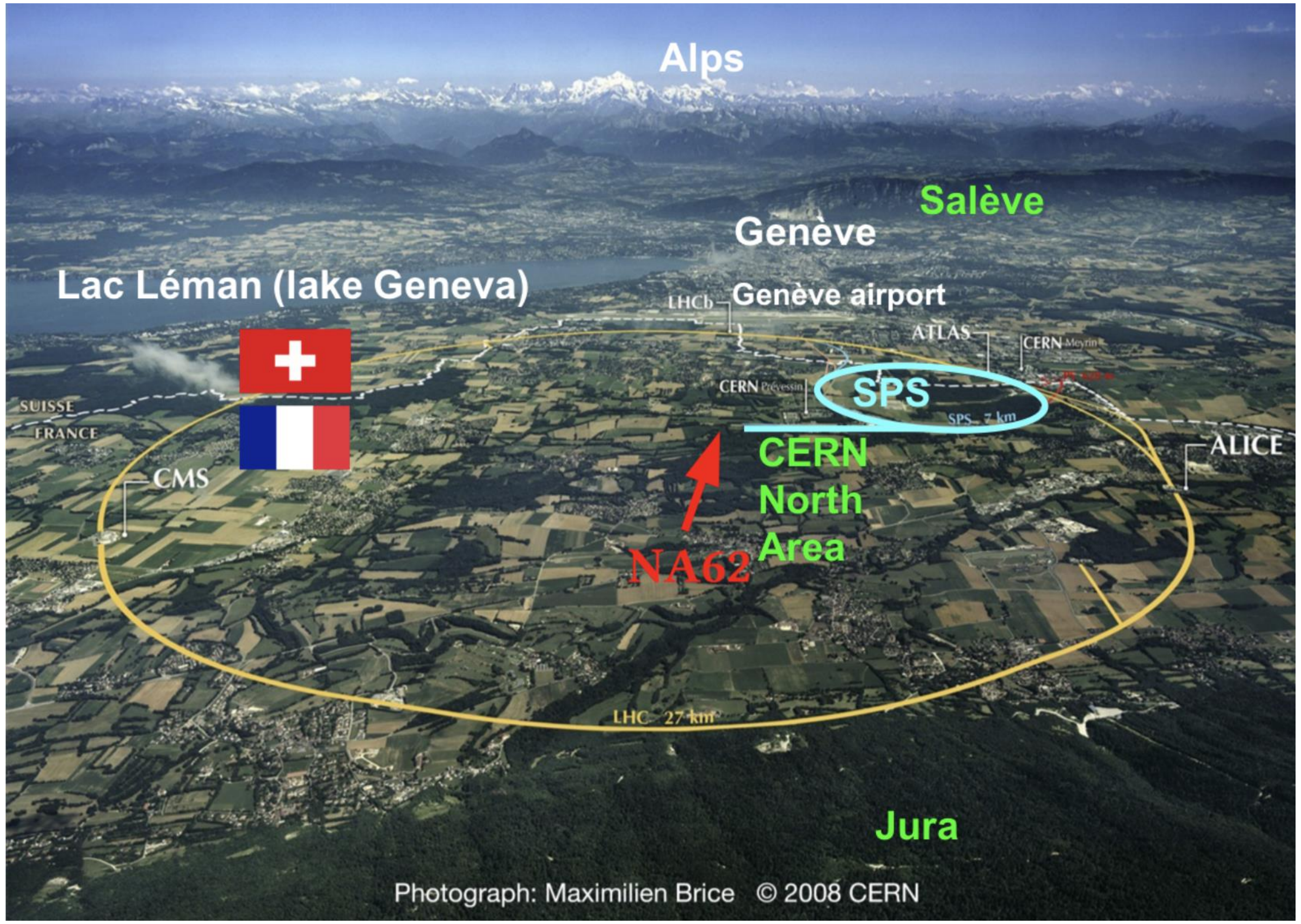
$$\Rightarrow \mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \lesssim 4.3 \cdot \mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$$



NA62:
The K^+ factory at the CERN North Area

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
- **Results:** [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
- **Broader physics programme:**
  - Rare K^+ decays (e.g. $K^+ \to \pi^+\gamma\gamma$ [PLB 850 (2024) 138513])
  - LNV/LFV decays (e.g. $K^+ \to \pi^-(\pi^0)e^+e^+$ [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 ongoing …

2016–2018	2019–2021	2021–2022	2023–2024	2024–2025	
	LS2 (upgrades)	this result			LS3

2016 2017 2018 2019 2020 2021 2022 2023 2024 2025

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

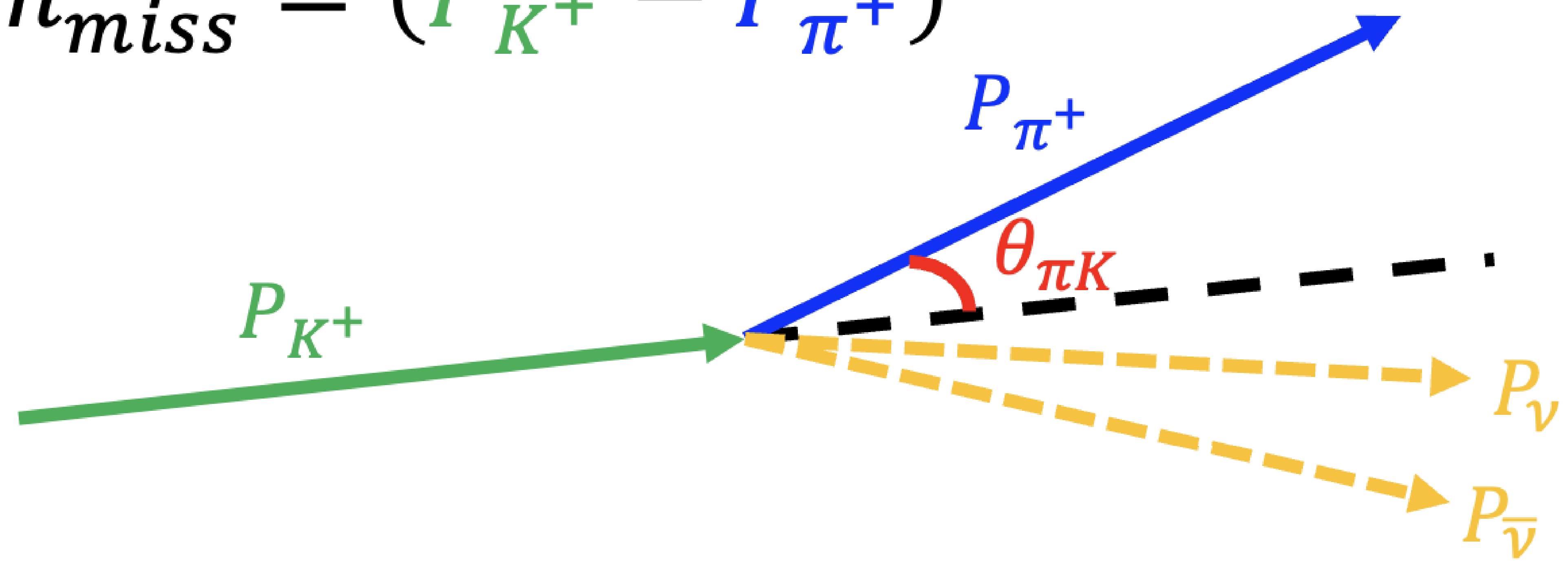
NA62 Strategy:

- 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

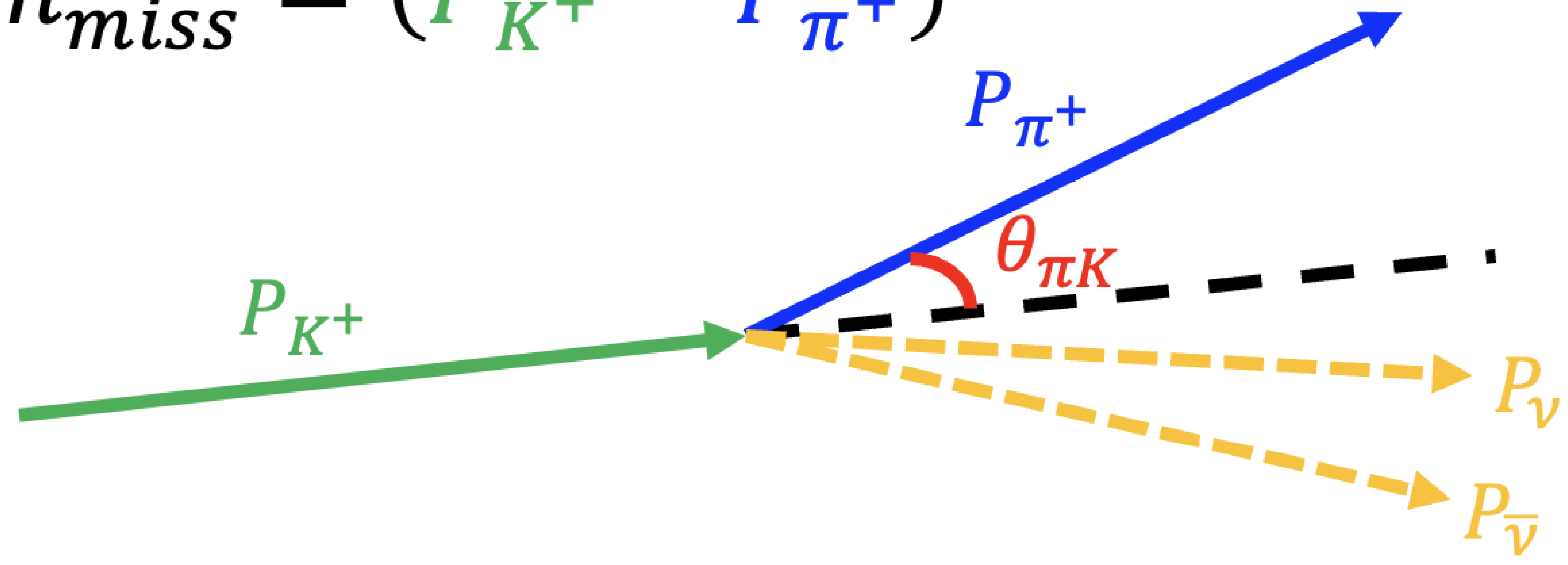
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$

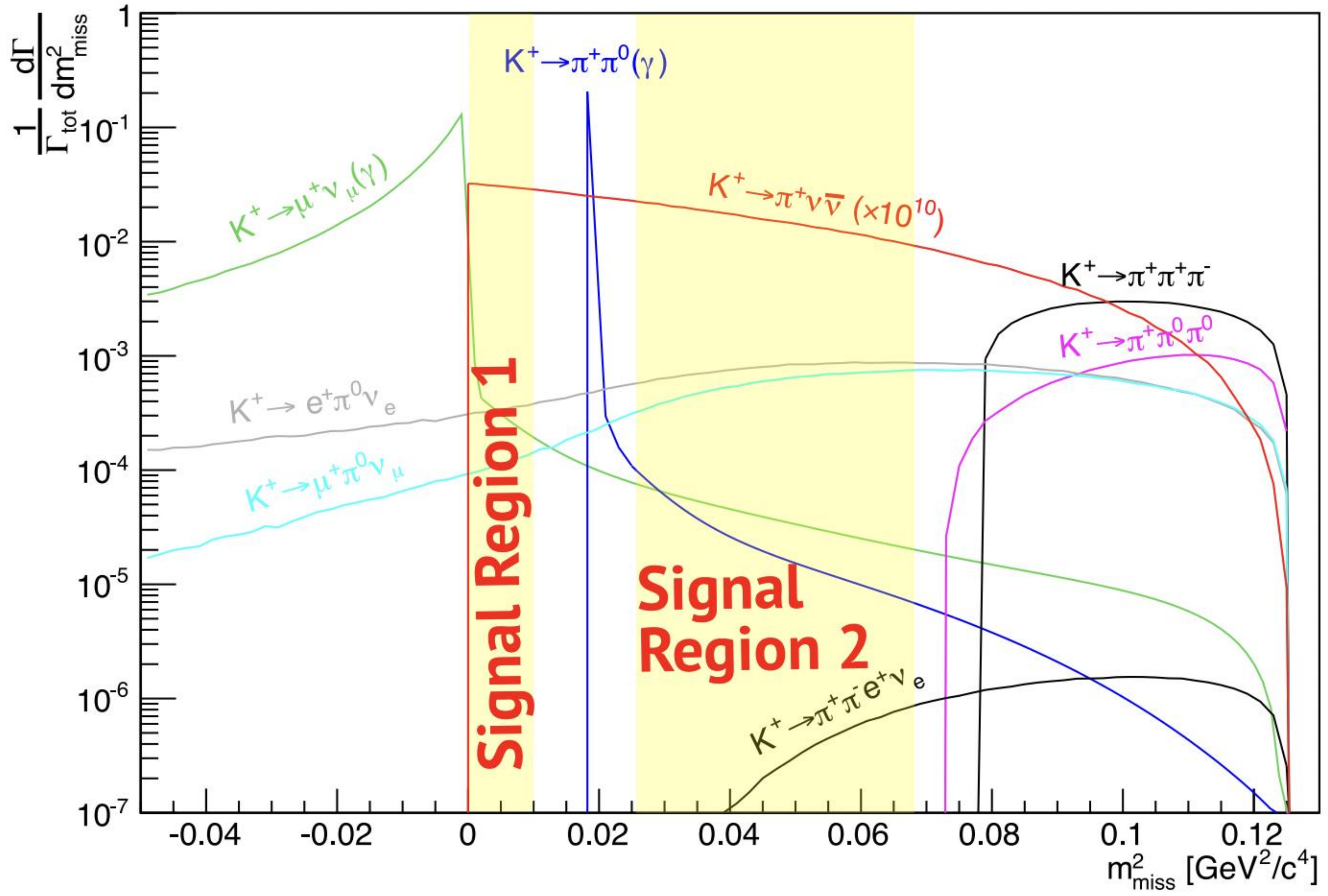


Decay mode	Branching Ratio [PDG]
$K^+ \to \mu^+\nu_\mu$	$(63.56 \pm 0.11)\%$
$K^+ \to \pi^+\pi^0$	$(20.67 \pm 0.08)\%$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024)\%$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$
$K^+ \to \pi^+\nu\bar{\nu}$	$\approx 10^{-10}$

Kinematic constraints & signal regions

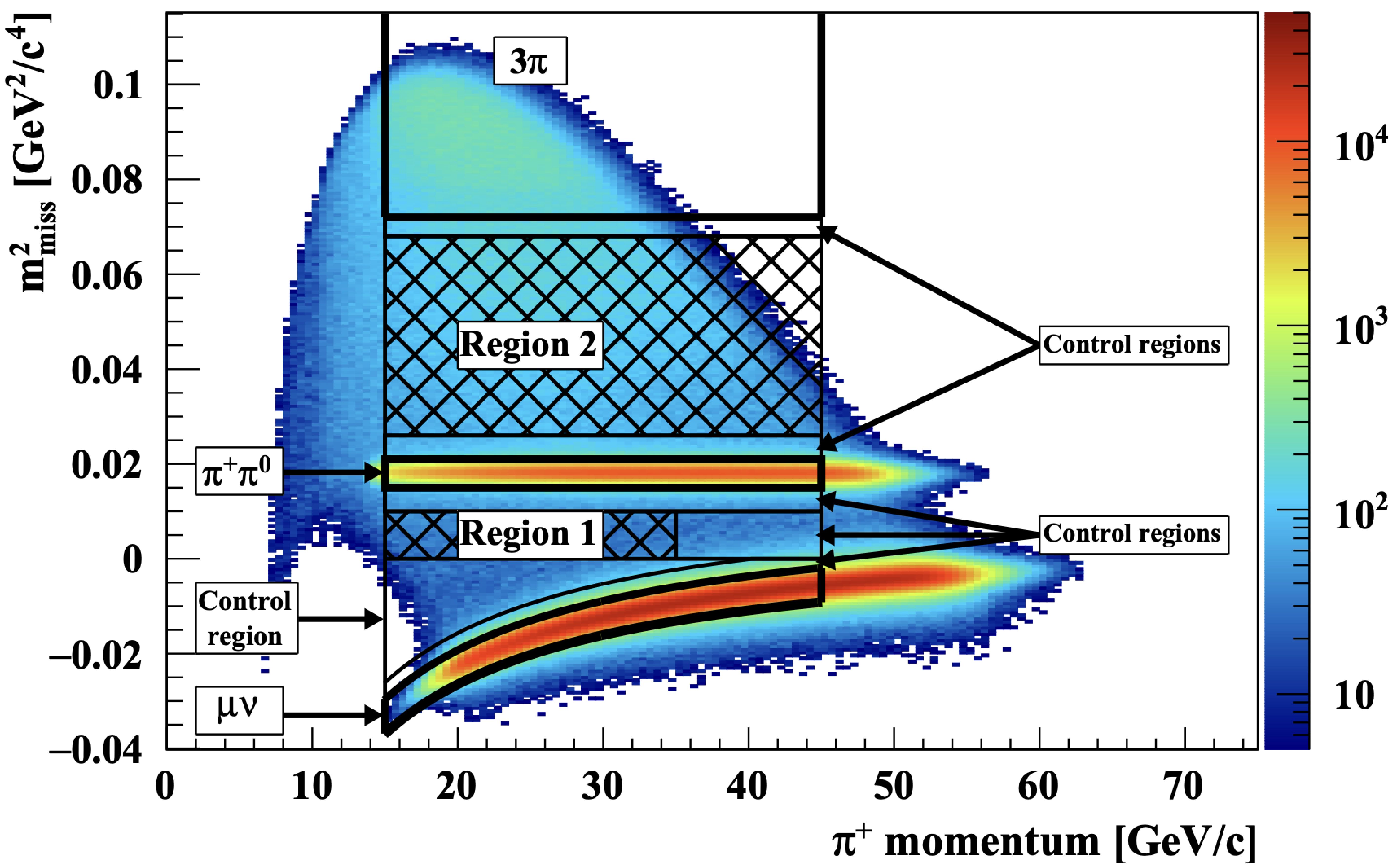
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$





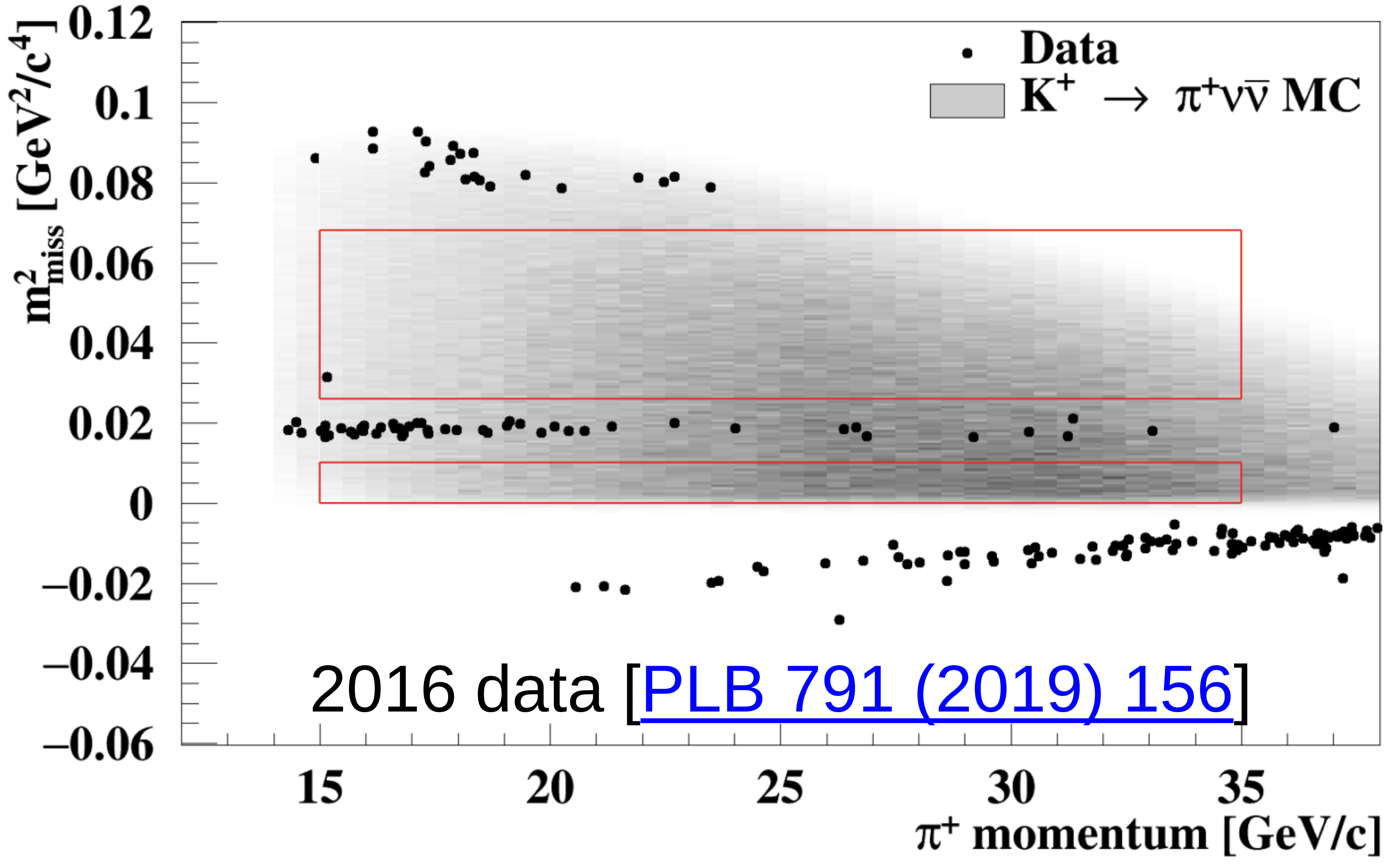
$\mathcal{O}(10^4)$ background suppression from kinematics

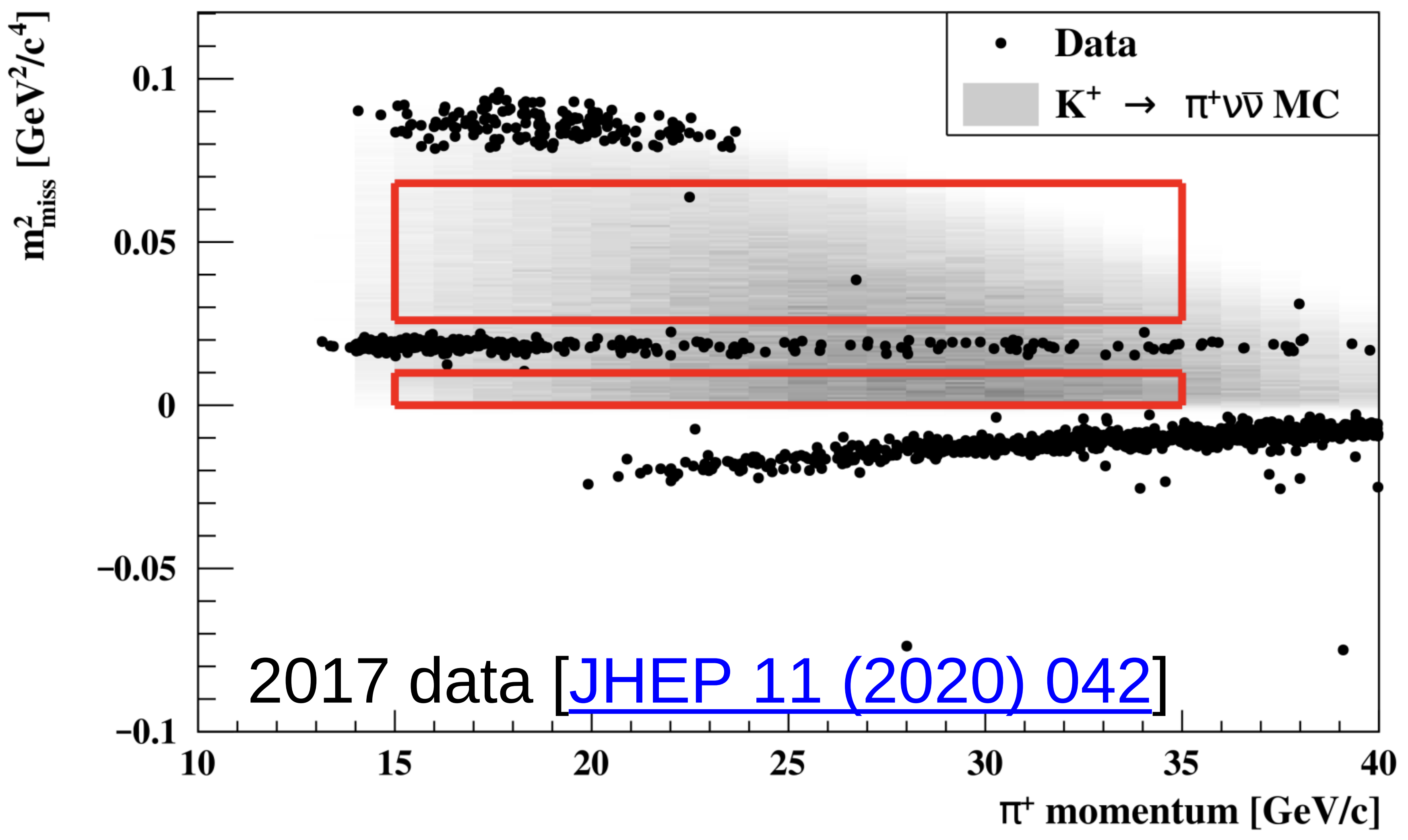
[JHEP 06 (2021) 093]

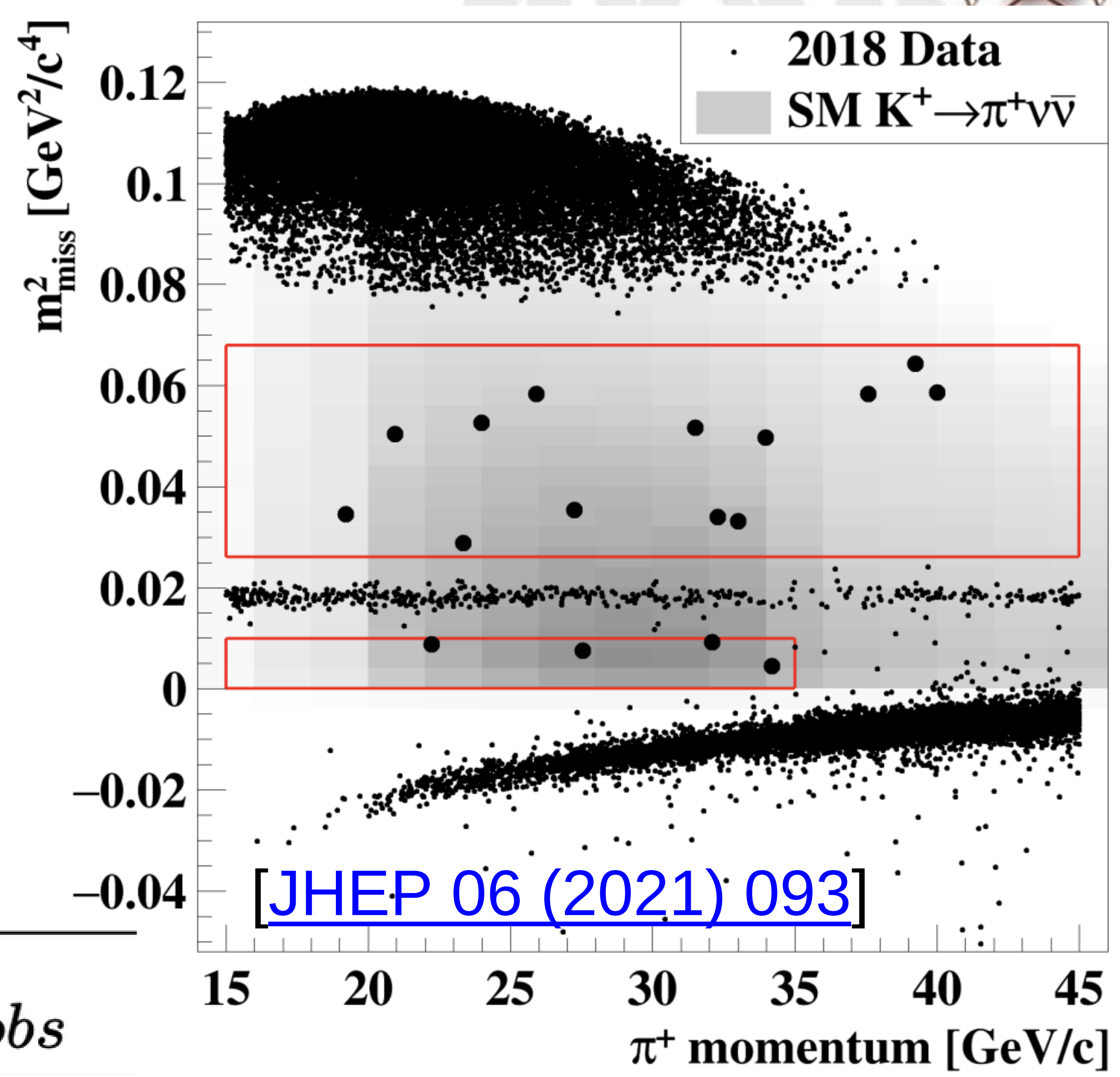


π^+ momentum range: 15—45 GeV/c

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







Data-taking year	[Reference]	N_{bg}	$N^{SM,exp}_{\pi\nu\bar{\nu}}$	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

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

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

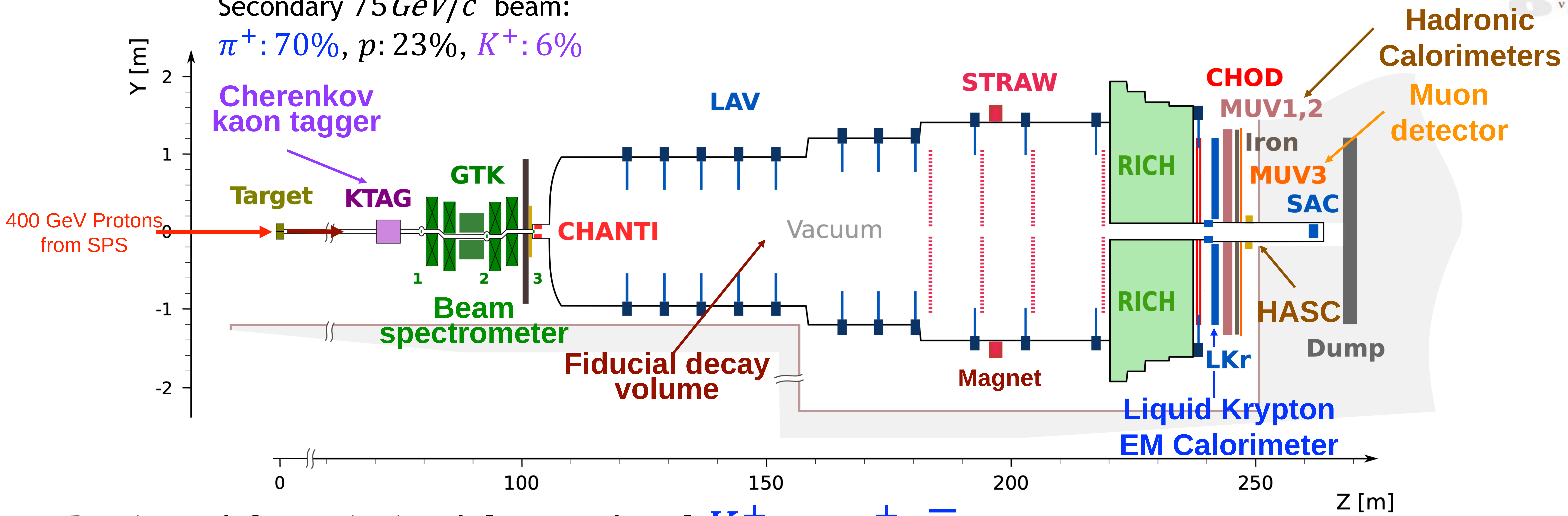
Background-only hypothesis: $p = 3.4 \times 10^{-4}$ ⇒ significance = 3.4σ

NA62 Detector, Upgrades & Performance

NA62 beamline & detector

[JINST 12 (2017) 05, P05025]

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

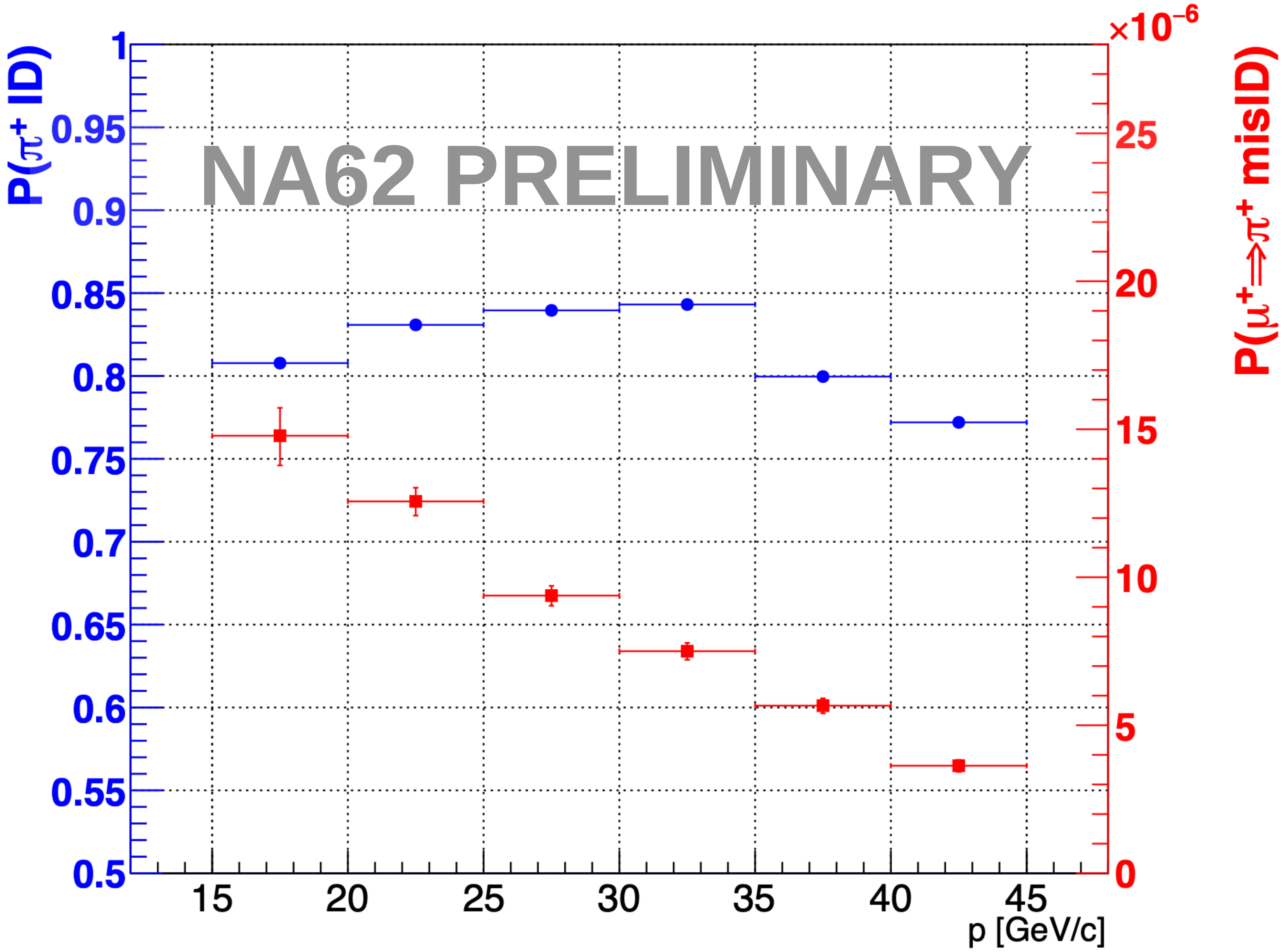


- Designed & optimised for study of $K^+ \to \pi^+ \nu \bar{\nu}$:
  - **Particle tracking:** beam particle (GTK) & downstream tracks (STRAW)
  - **PID:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
  - **Comprehensive veto systems:** CHANTI (beam interactions), LAV,LKr,IRC,SAC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

Particle ID performance : 2021—22 data

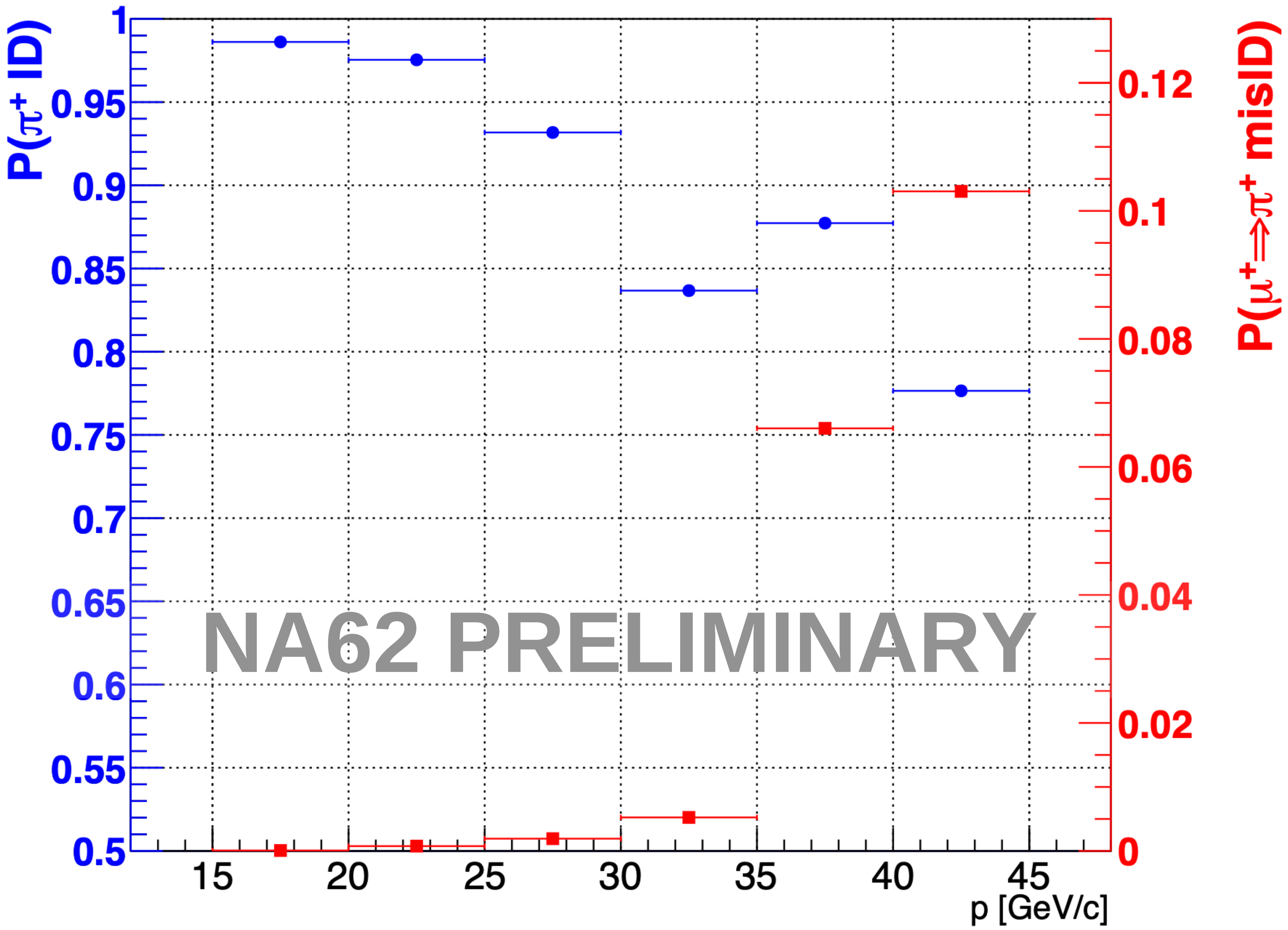
Calorimeters

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



RICH

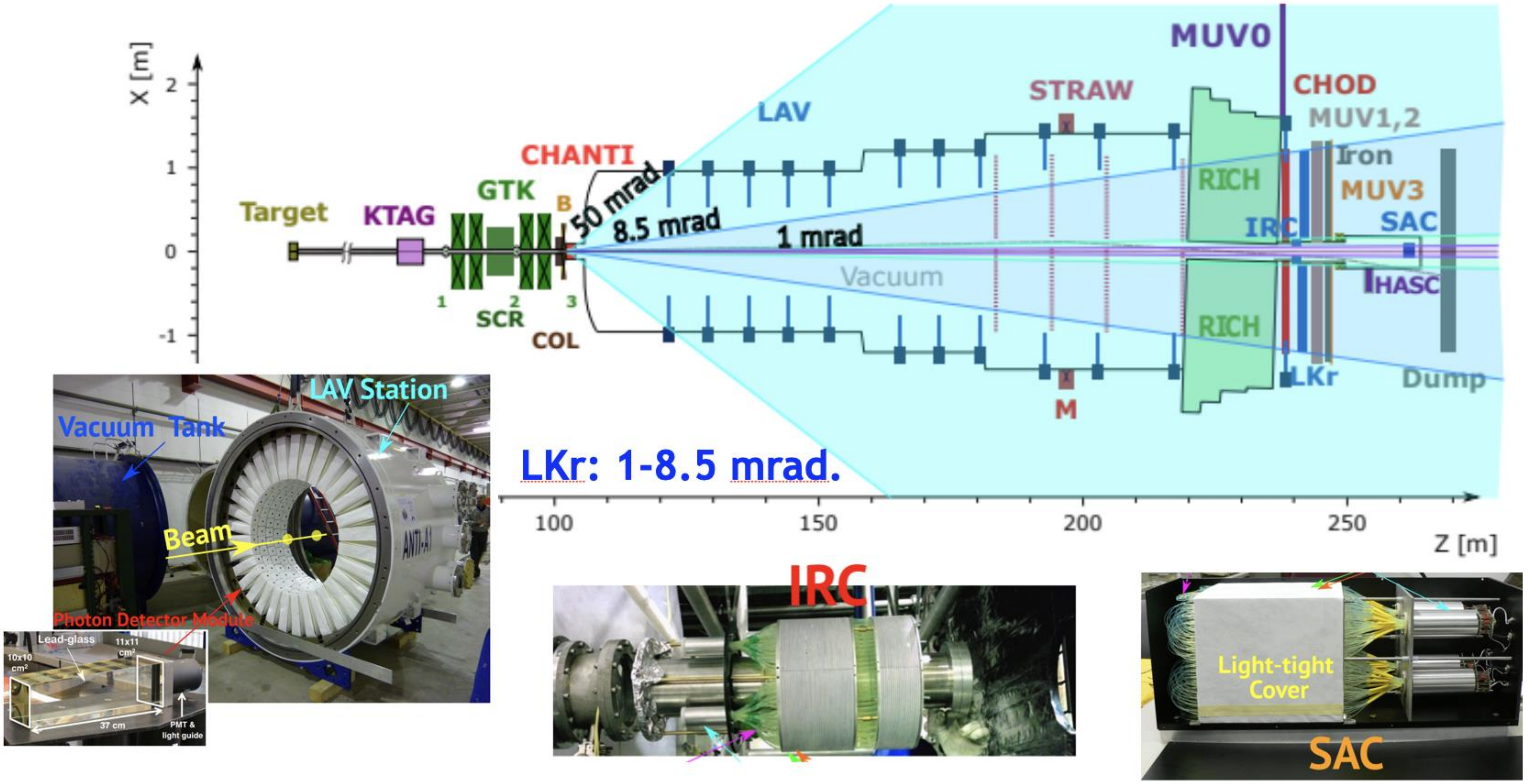
Designed to distinguish between π^+/μ^+ with $15 - 35\, GeV/c$

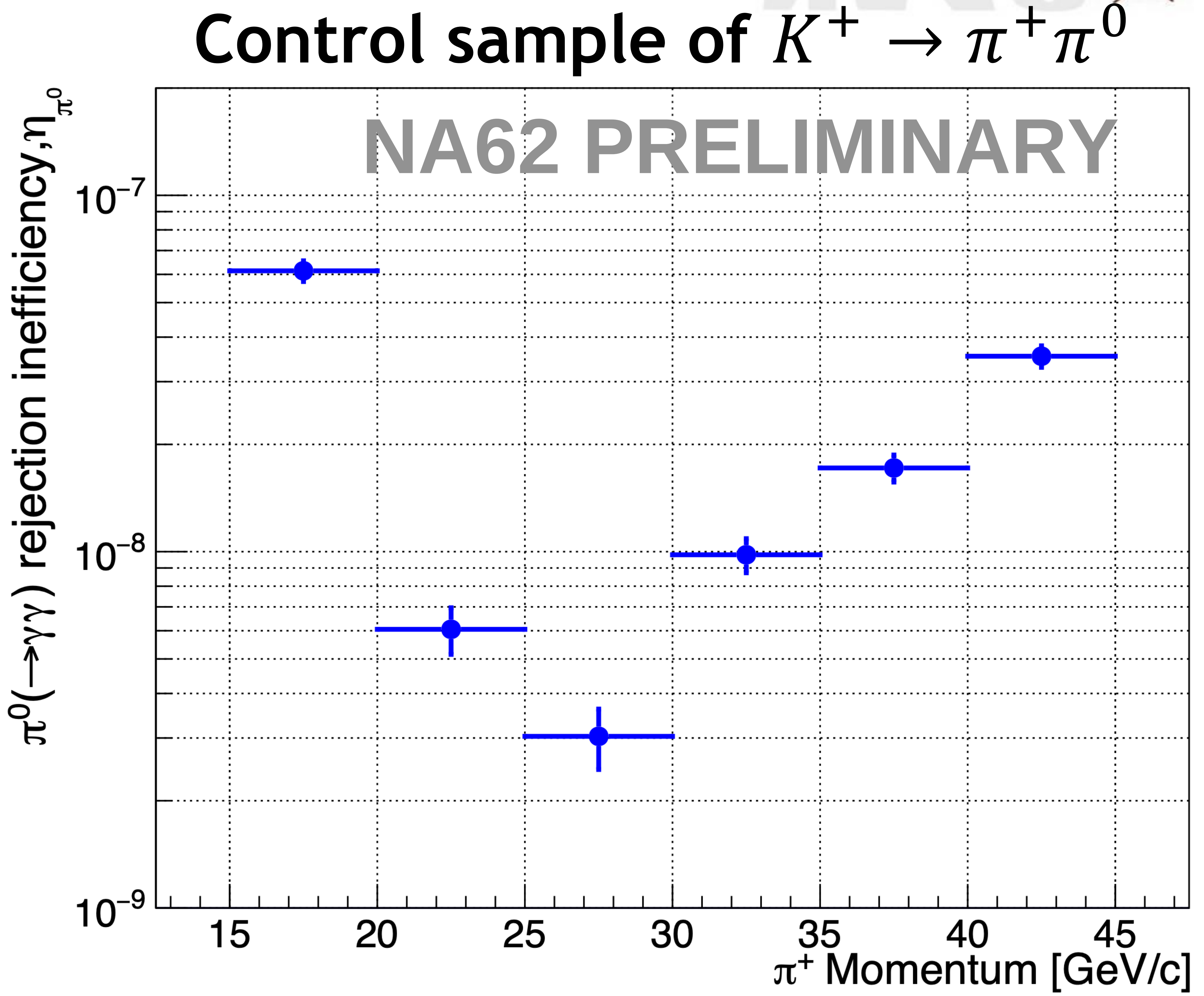


$$\mathrm{P}(\pi^+) = 73\ \%$$

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

Comprehensive photon veto system: 21—22





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

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

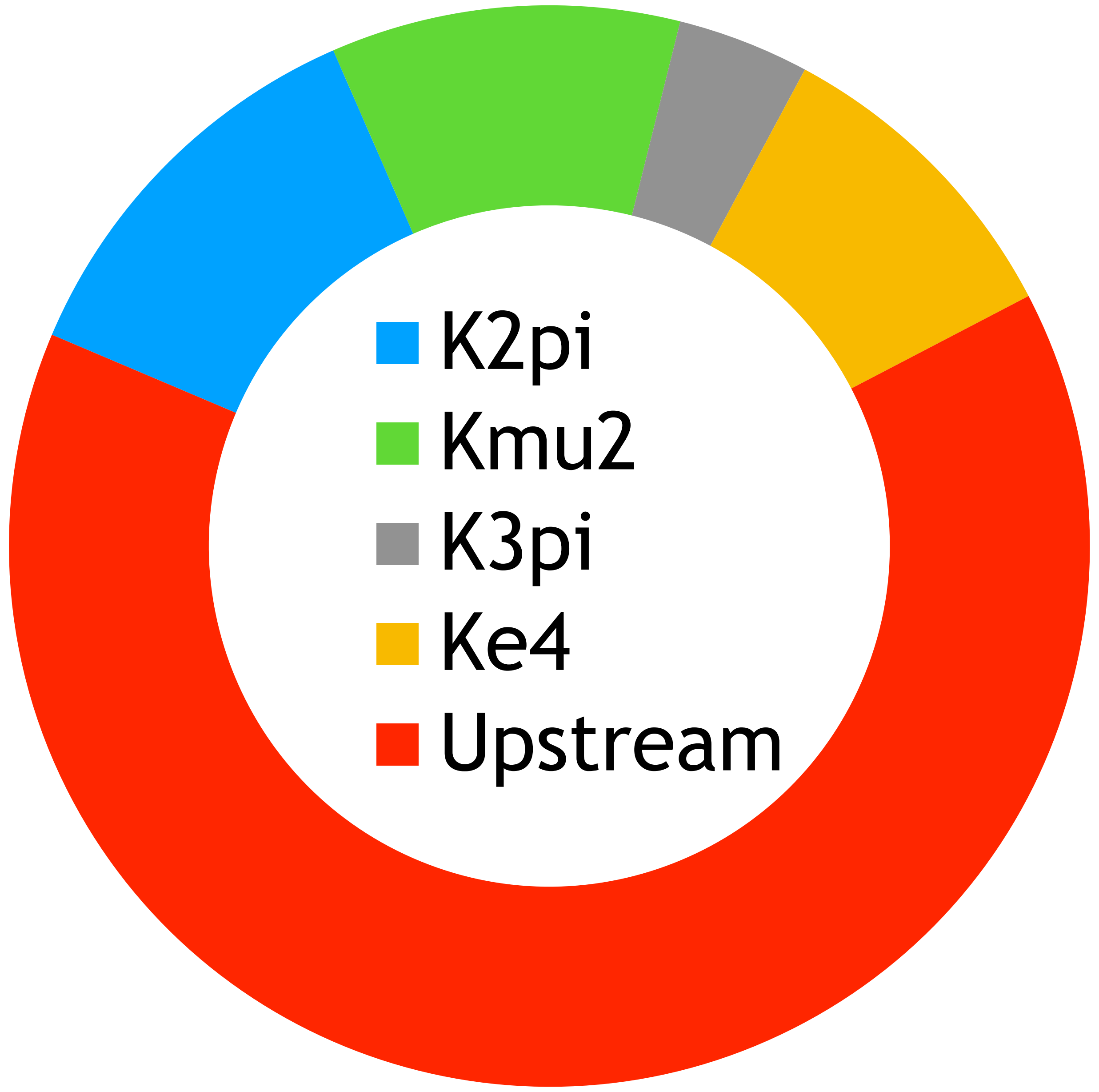
- **Meets target: combined γ/π^0 rejection of $\mathcal{O}(10^8)$**

Upgrading NA62

- 2016—18 analysis proved NA62 technique.
- Limitation: tight cuts to reject backgrounds ⇒ reduces signal efficiency.
- To improve: need new tools to control background.

Background	N(exp) 2018 (S2)
Upstream	$2.76^{+0.90}_{-0.70}$
$K^+ \to \pi^+\pi^0$	0.52 ± 0.05
$K^+ \to \mu^+\nu$	0.45 ± 0.06
$K^+ \to \pi^+\pi^-e^+\nu$	0.41 ± 0.10
$K^+ \to \pi^+\pi^+\pi^-$	0.17 ± 0.08
Total	$4.31^{+0.91}_{-0.72}$

K^+ decays in decay tank



Upstream background

Largest backgrounds:

1. Upstream
2. $K^+ \to \pi^+\pi^0$

Veto by detecting previously missed particles…

Mid 2018 - installed TCX Collimator

Much improved shielding - blocking almost all upstream decay paths.

2021 - addition of VetoCounter

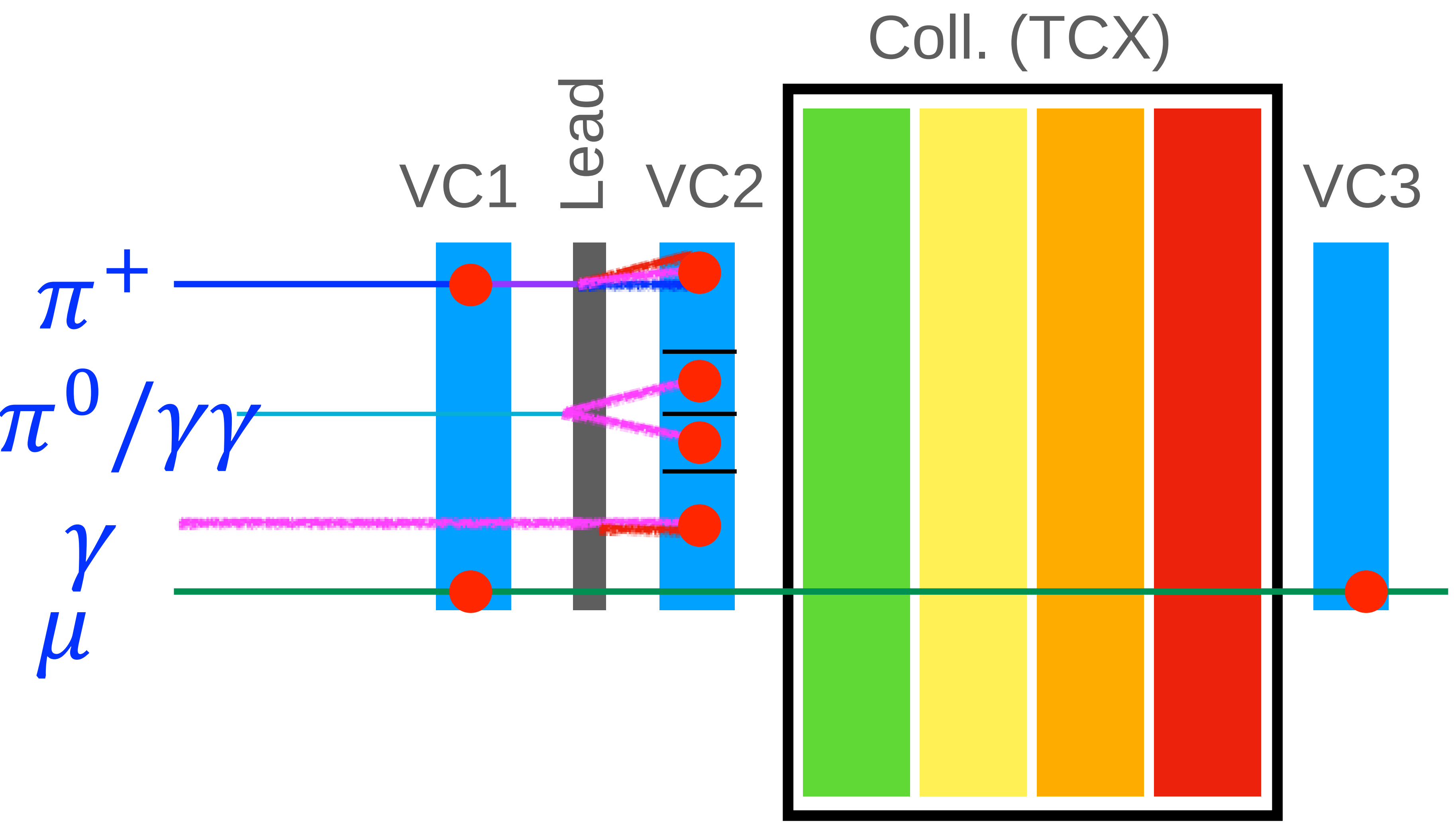
Upstream decays can be detected and actively vetoed.

Signal in-time with true K^+ which decays upstream.

Signal in-time with pileup beam particle (π^+) which does not leave beam pipe

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.

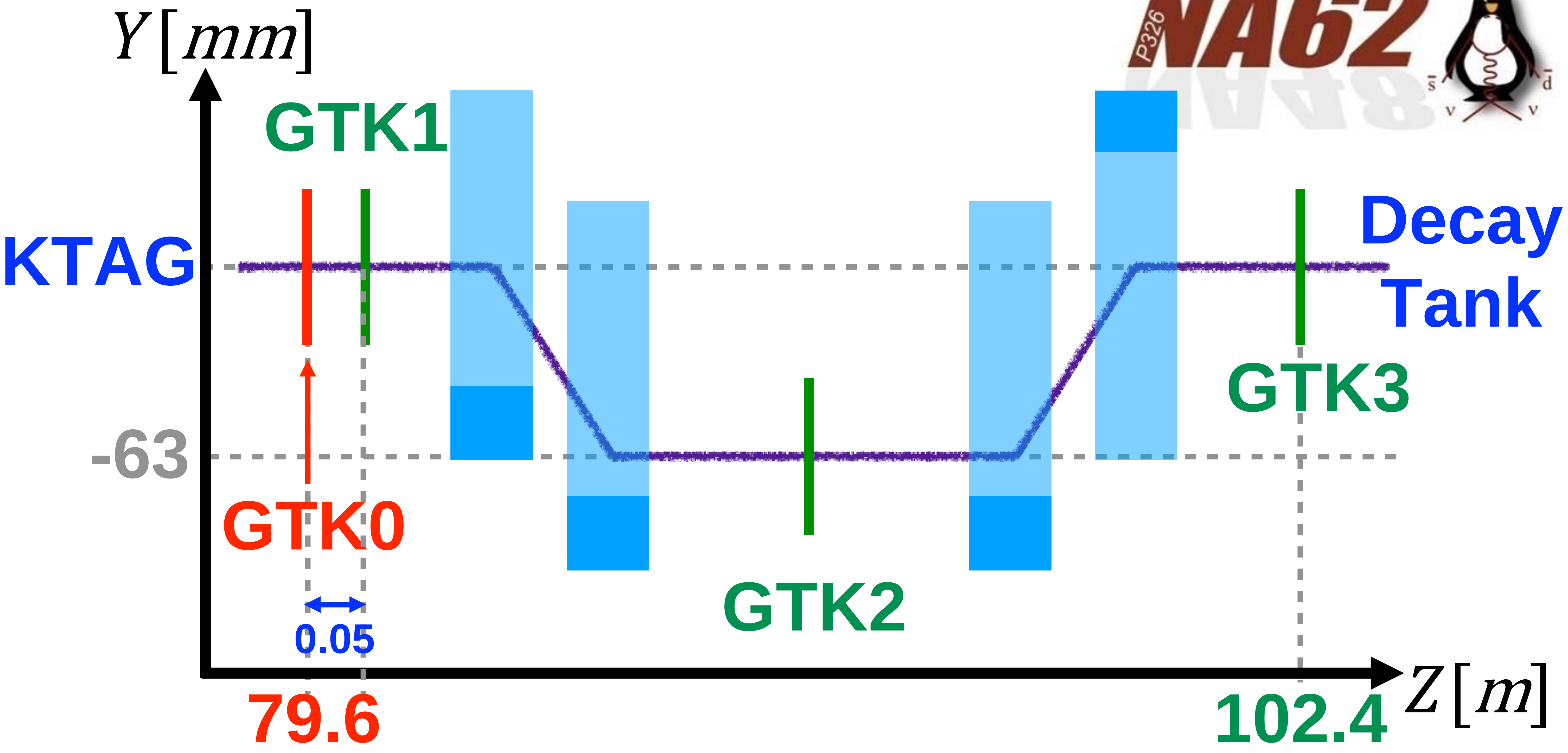
ANTI0

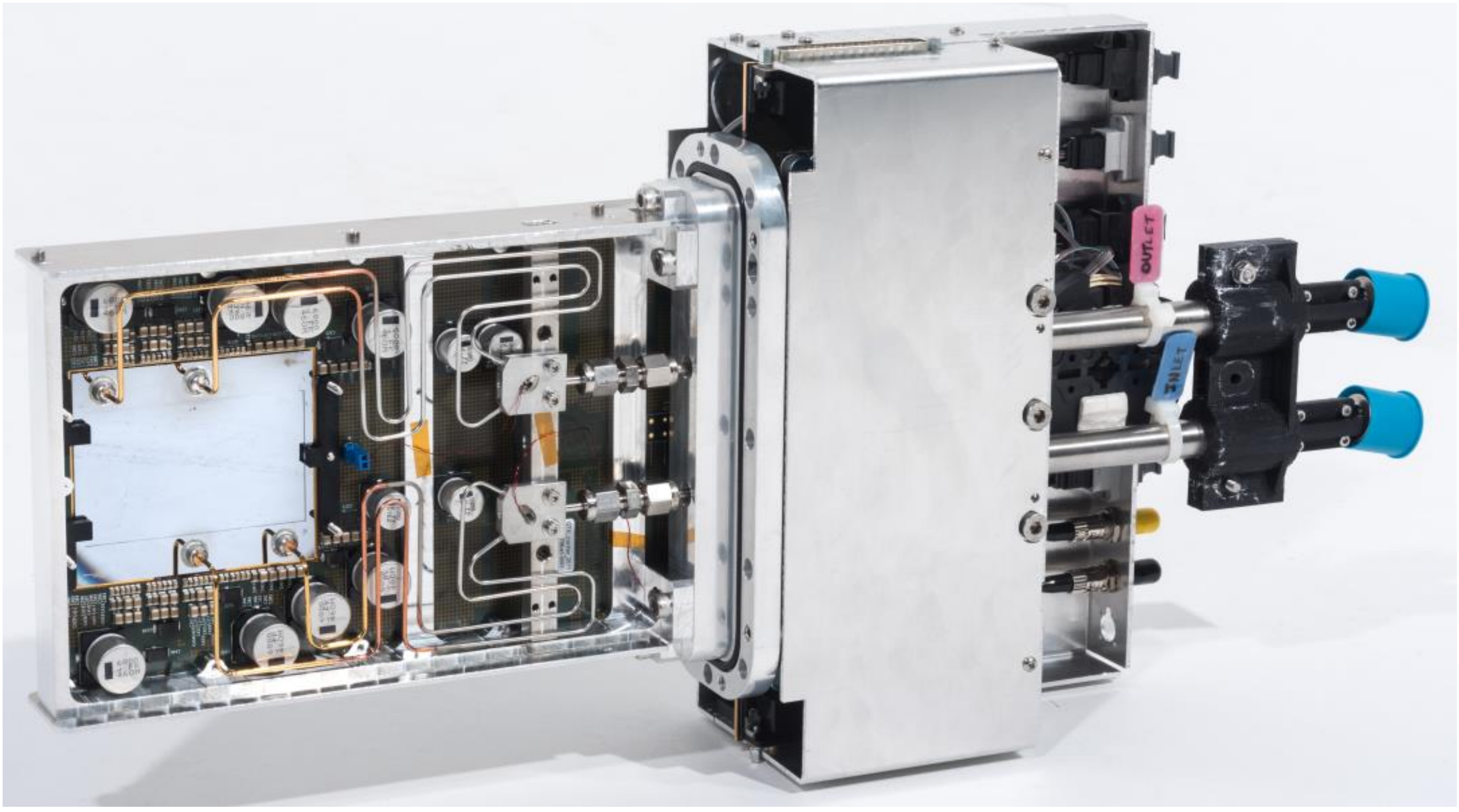
- Detect particles up to ~1 m from beam line.
- **Reject ~20% of upstream background** with <1% signal loss.

[SPSC report 2023][EP Newsletter, Dec21]

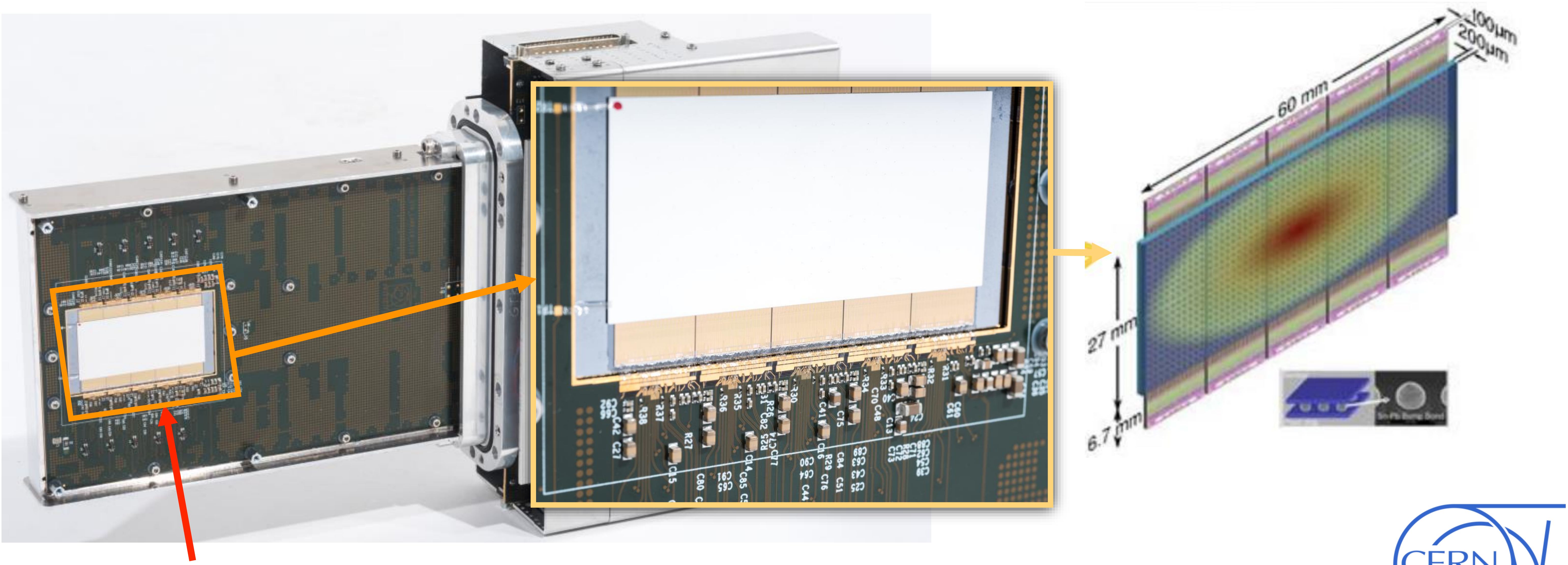
4th GTK station

- 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)


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

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

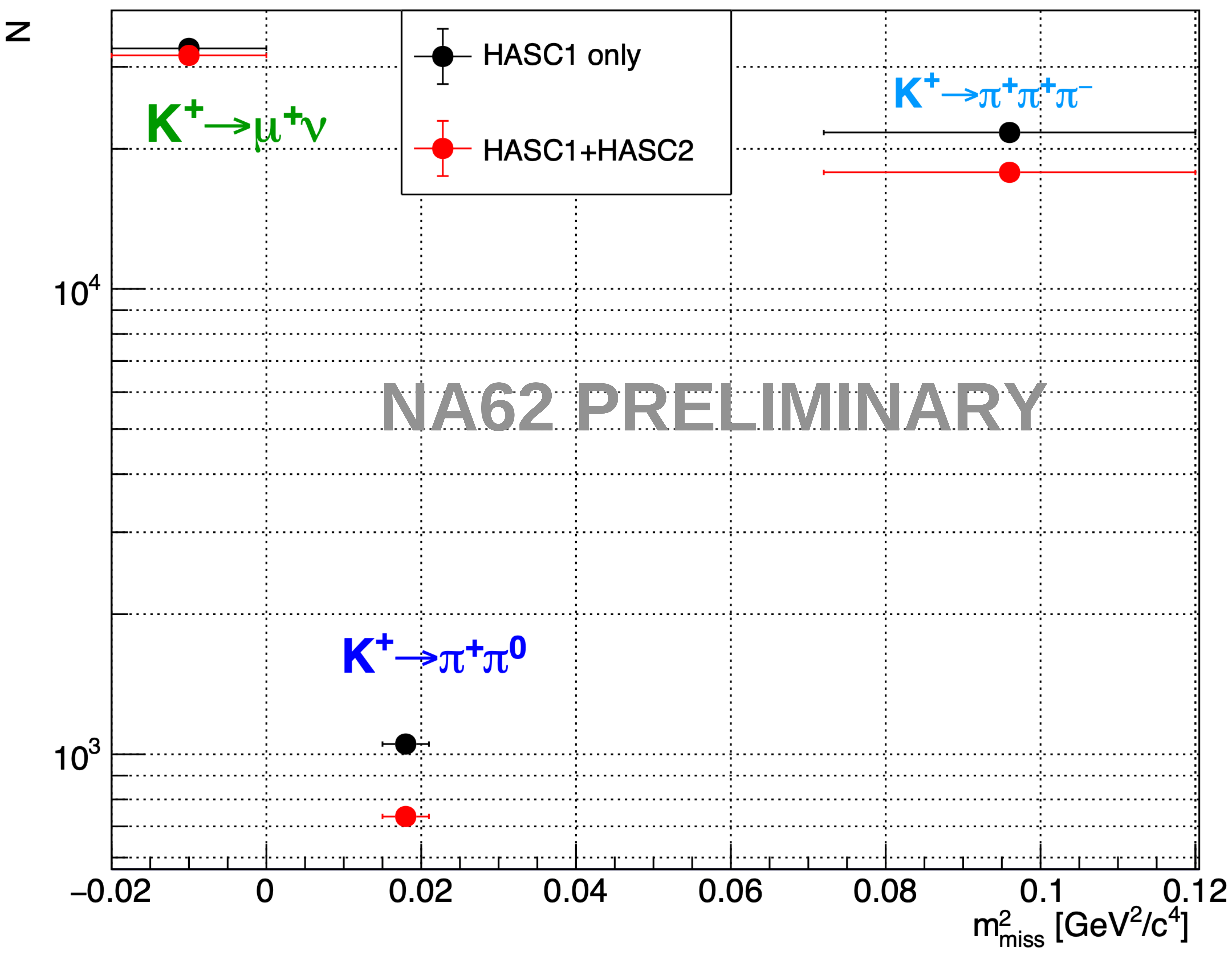
HASC2 veto

- $K^+ \rightarrow \pi^+\pi^0$ **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

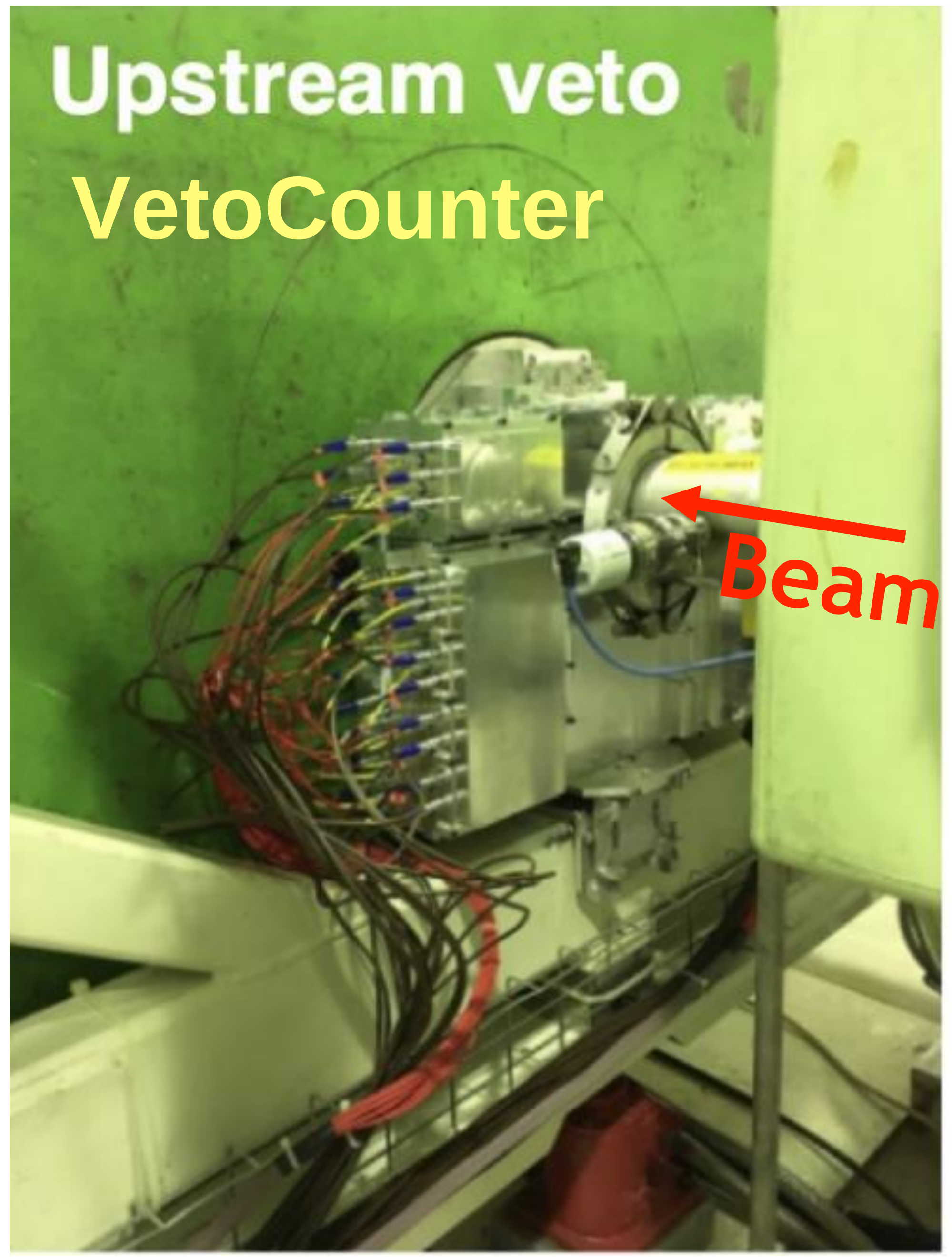
(modifying HASC veto: study integral of background regions)

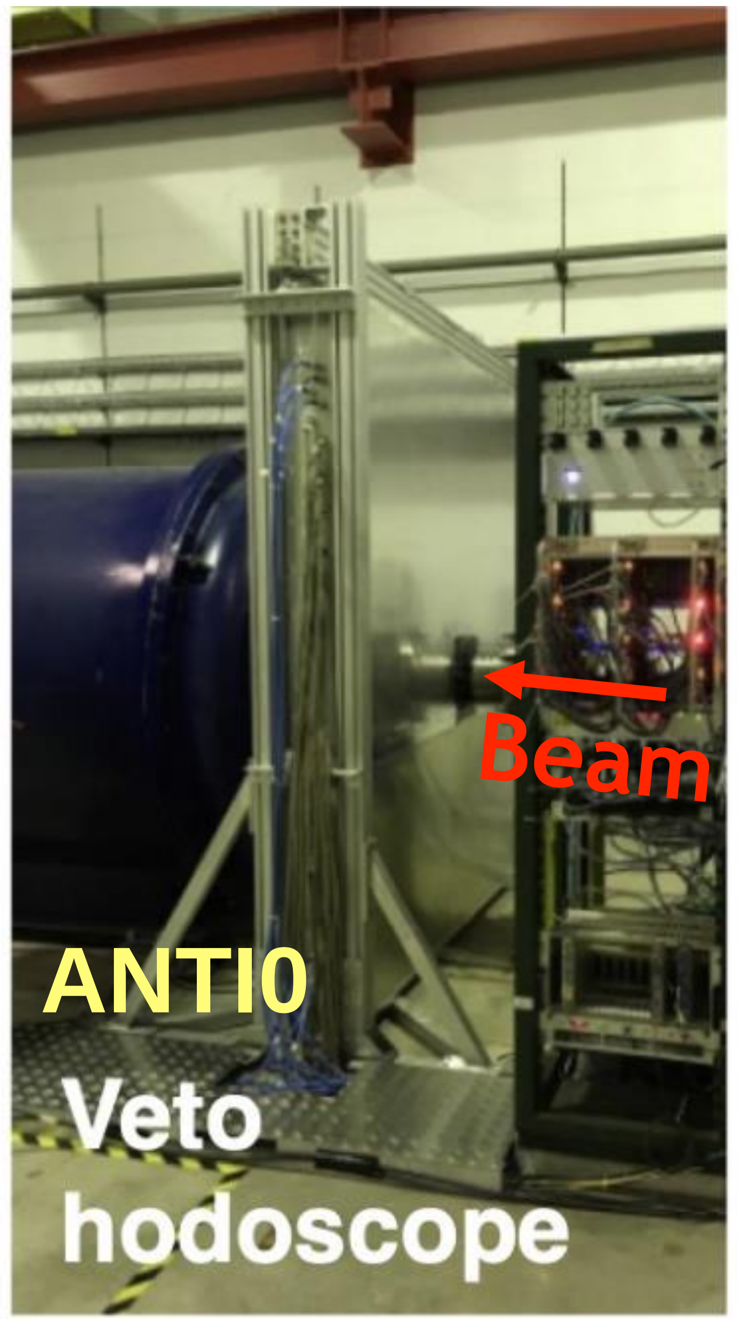


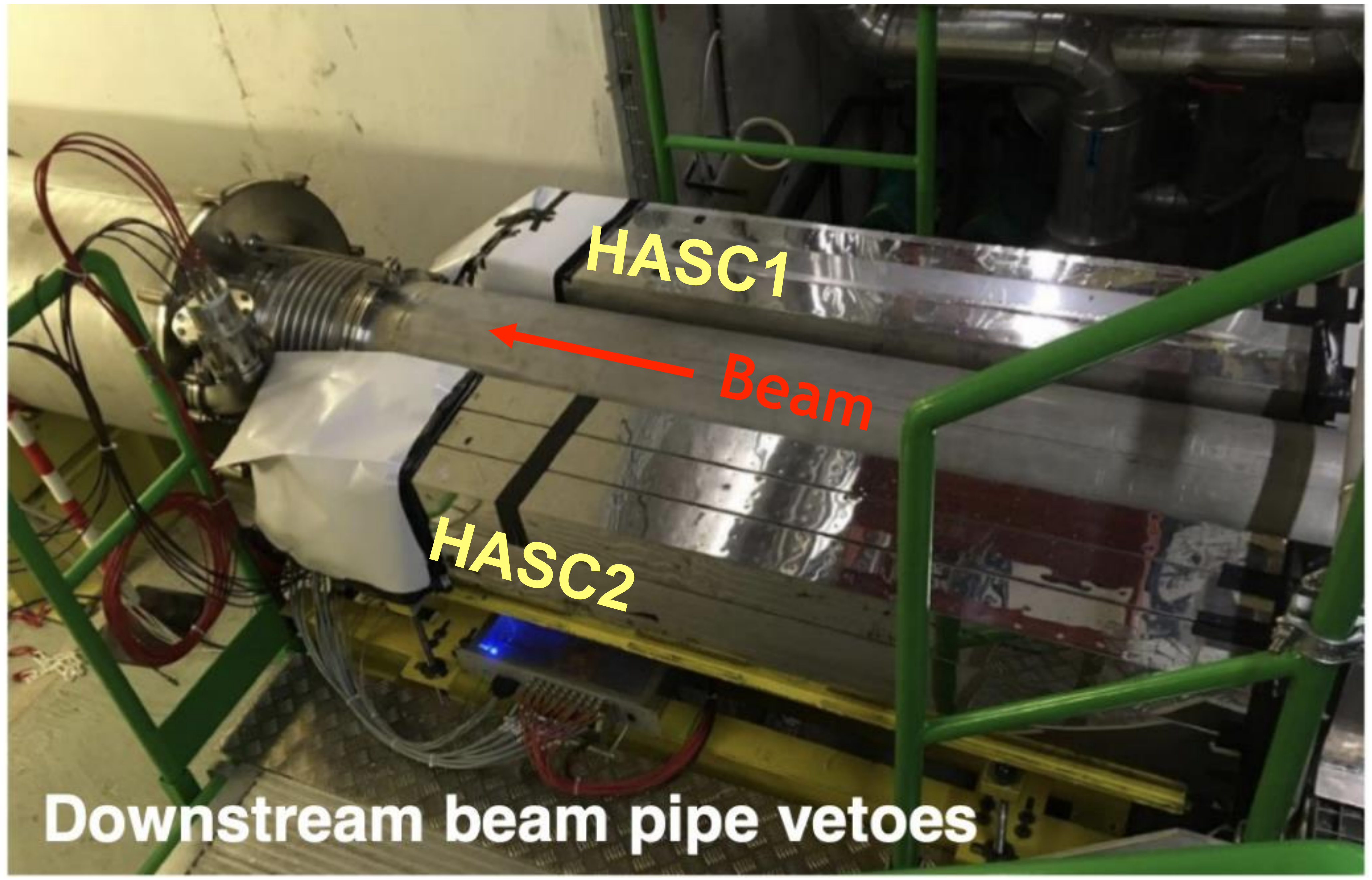
Summary of NA62 upgrades

- 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.**

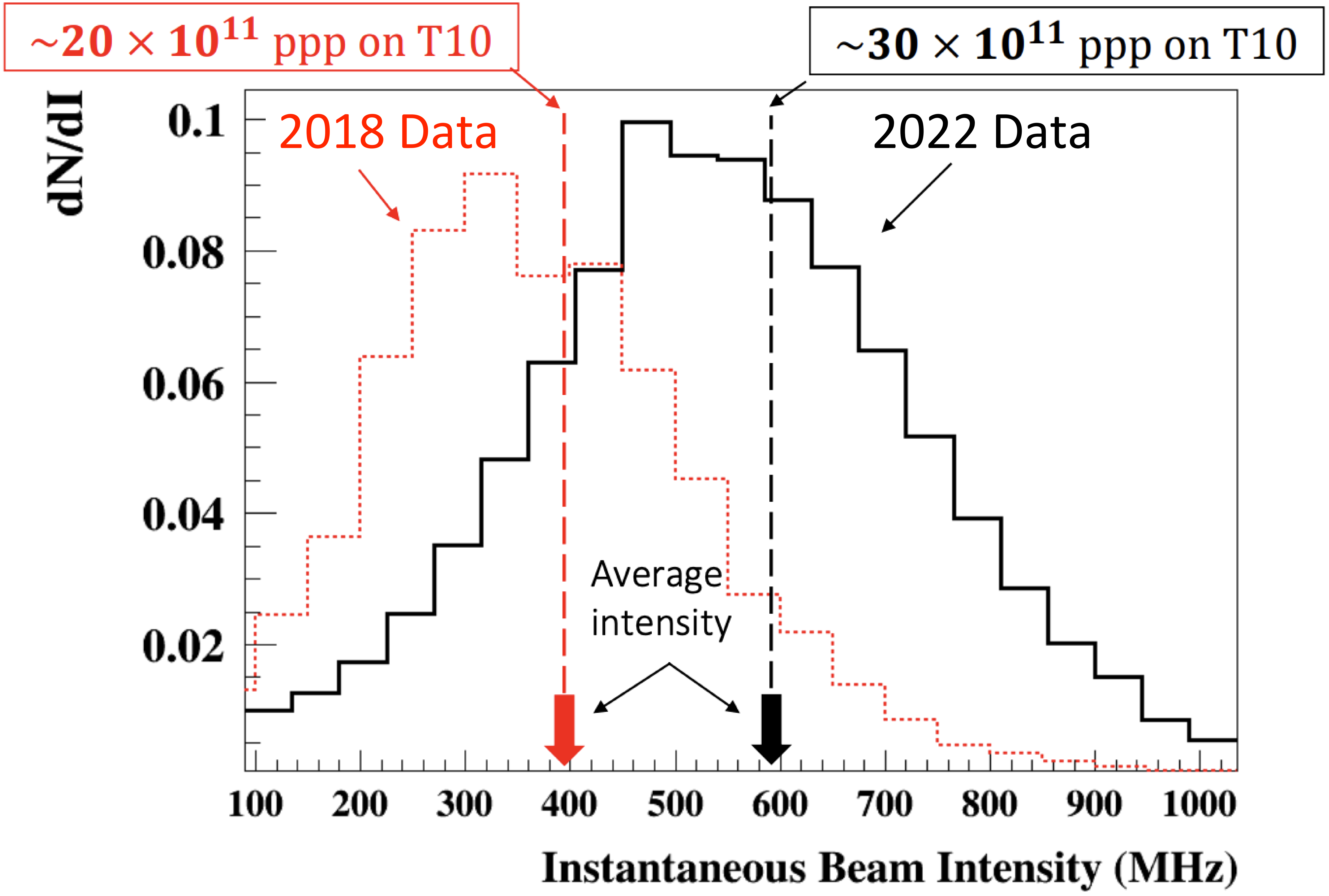
New detectors installed in 2021:







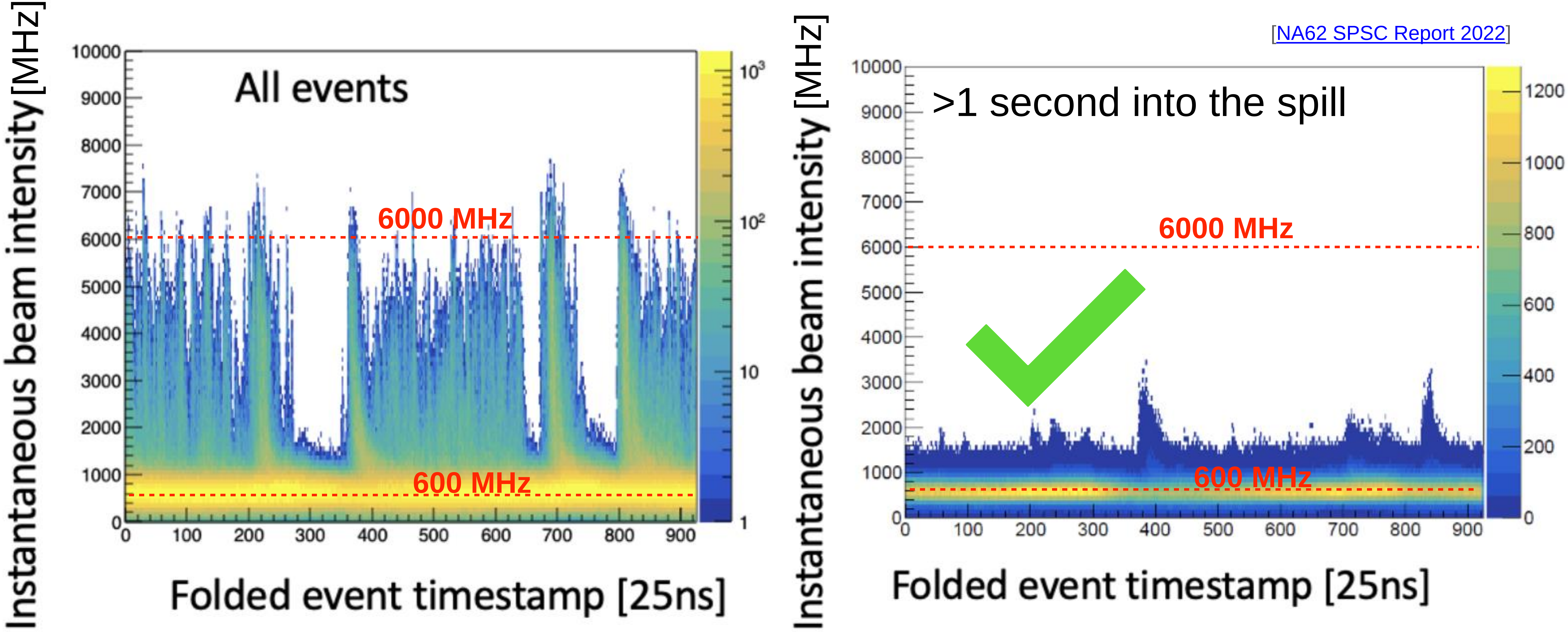
Beam intensity: 2018 vs 2022



- 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 <u>2021 data only</u>.
  - DAQ overwhelmed by instantaneous rates up to 10x higher than design.

$K^+ \to \pi^+ \nu\bar{\nu}$: Analysis of new data

2021–2022 data : Signal Sensitivity

Analysis strategy

NA62

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).

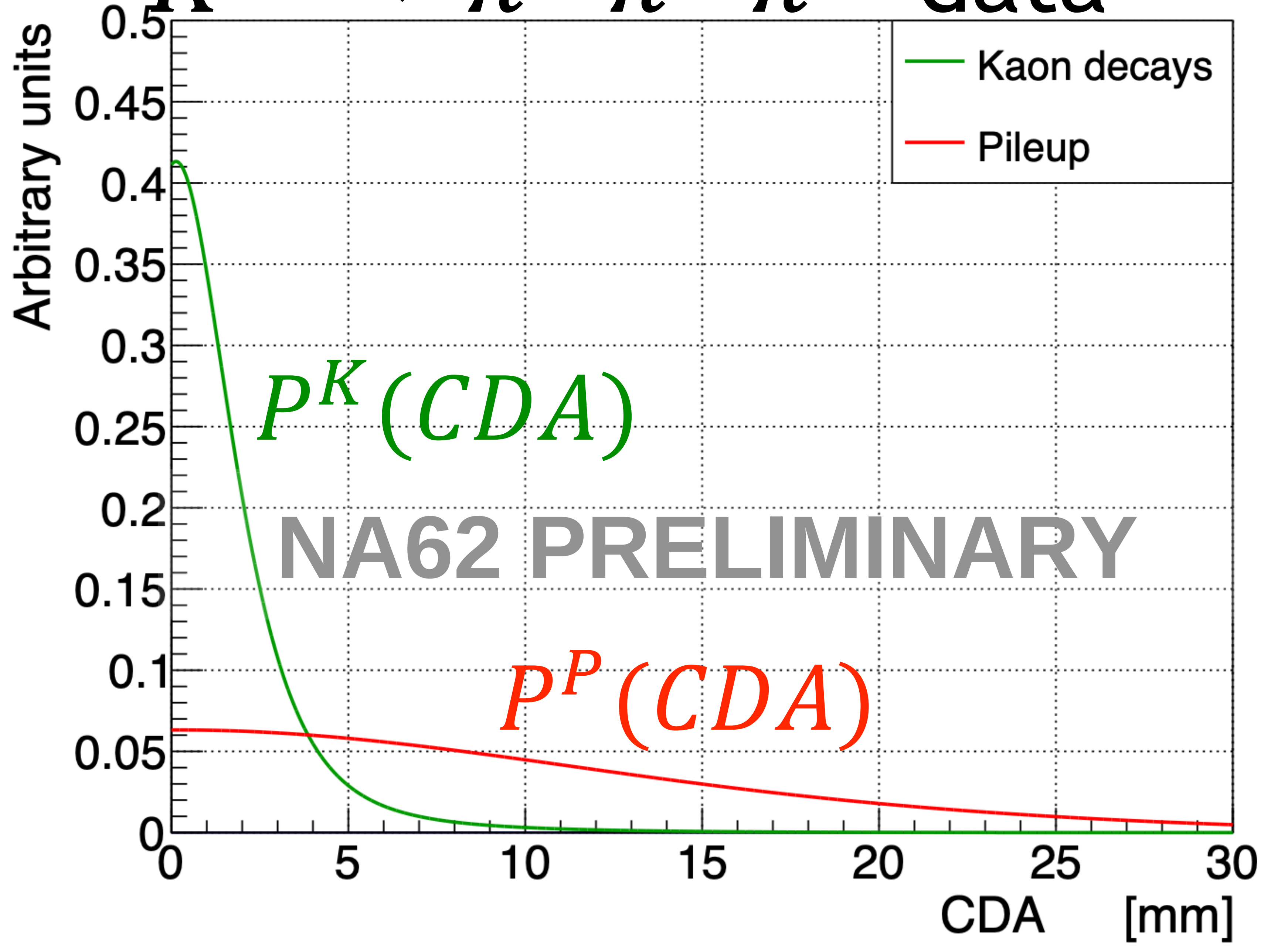
INFN

CERN

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

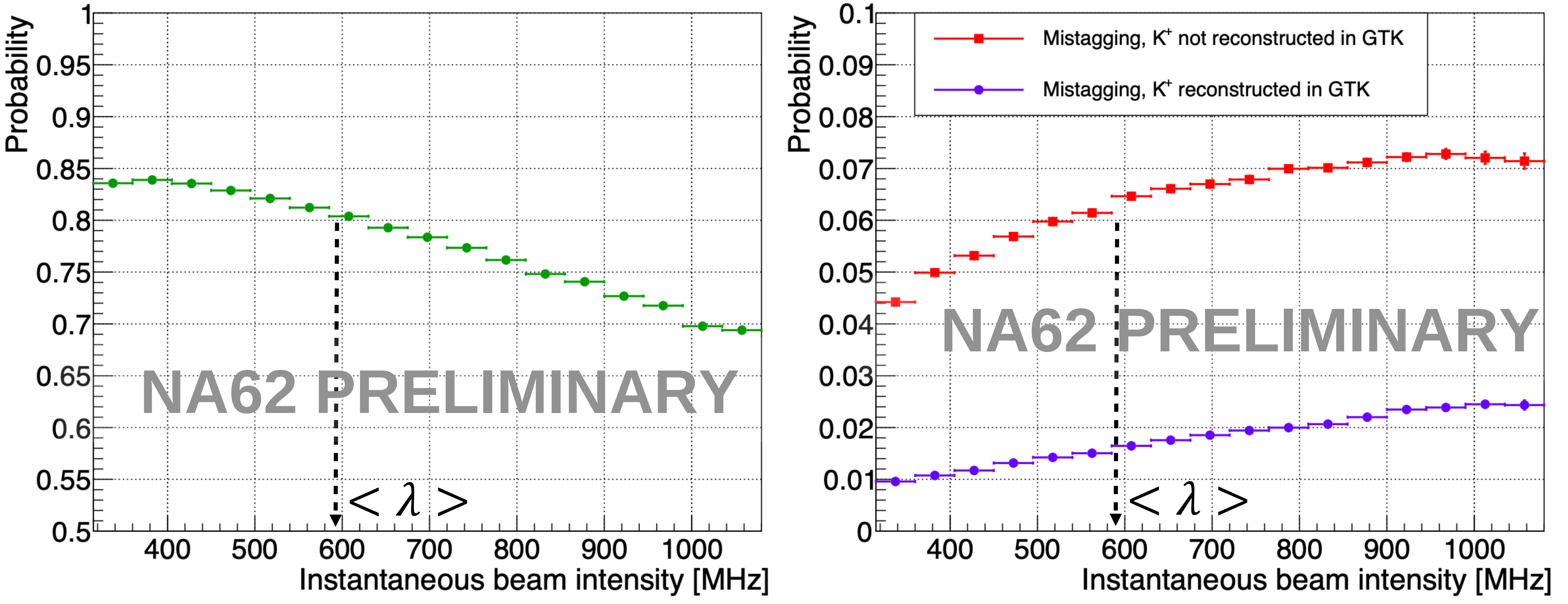
Example of selection update

- **Inputs:** spatial (CDA) & time (ΔT_+) matching, intensity/pileup (N_{GTK}) [prior]
  - Models for PDFs/Prior from $K^+ \rightarrow \pi^+\pi^+\pi^-$ 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 $N_{GTK} > 1$

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



- 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: $N_{\pi\pi}$
- Downscaling factor of normalisation trigger (generally 400): D_0
- Branching ratio of $K^+ \to \pi^+\pi^0$ decay: $\mathcal{B}_{\pi\pi}$
- Acceptance of 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 veto 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 $\mathcal{B}^{SM}_{\pi\nu\bar{\nu}} = 8.4 \times 10^{-11}$ but results are independent of this choice)

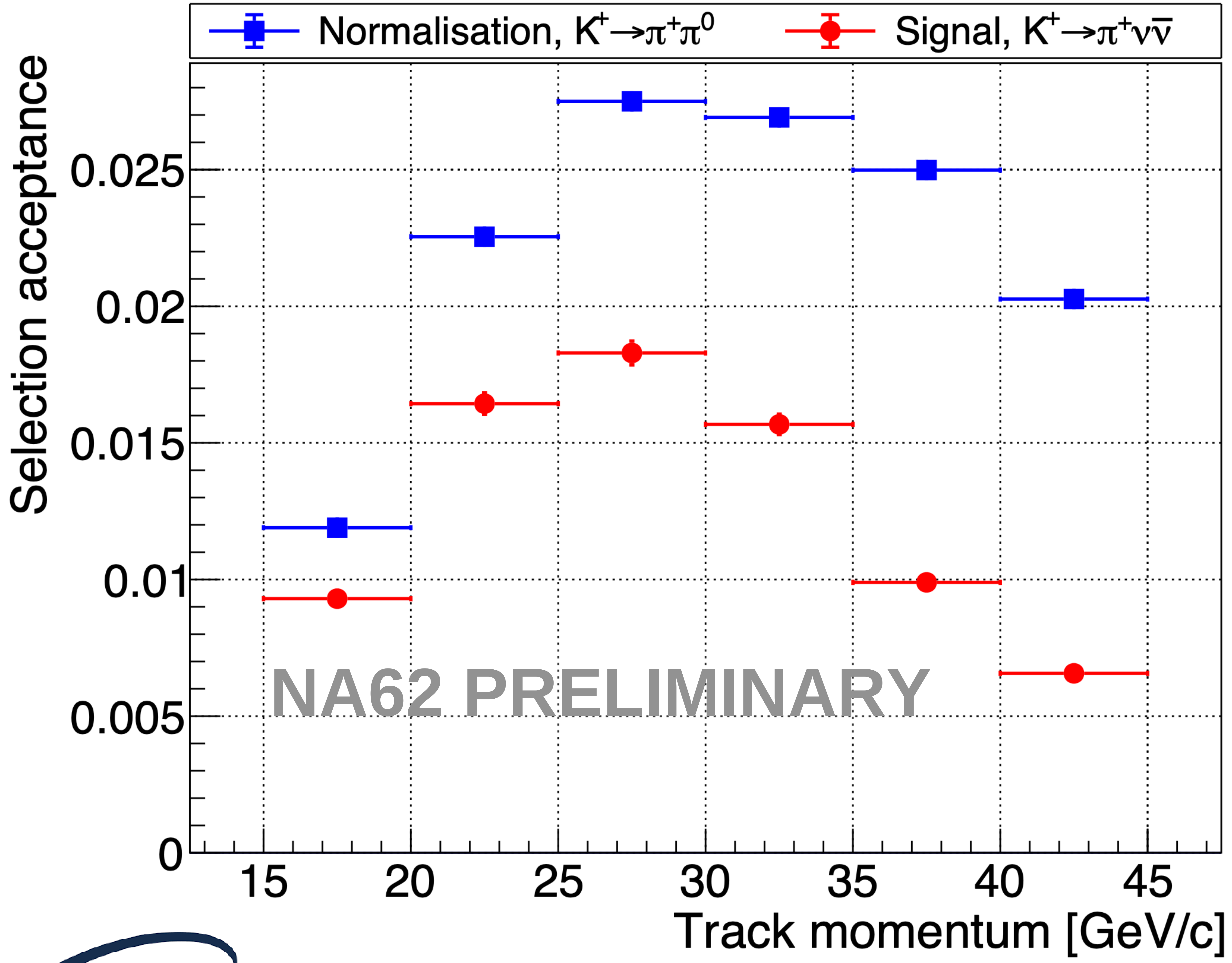
$$N^{SM}_{\pi\nu\bar{\nu}} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}}$$

Acceptances

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

Acceptances

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



Case	OLD 2018 (S2)	NEW 2021-22	
Norm.	11.8%	13.4%	**+15%**
Signal	(6.37±0.64)%	(7.61±0.18)%	**+20%**

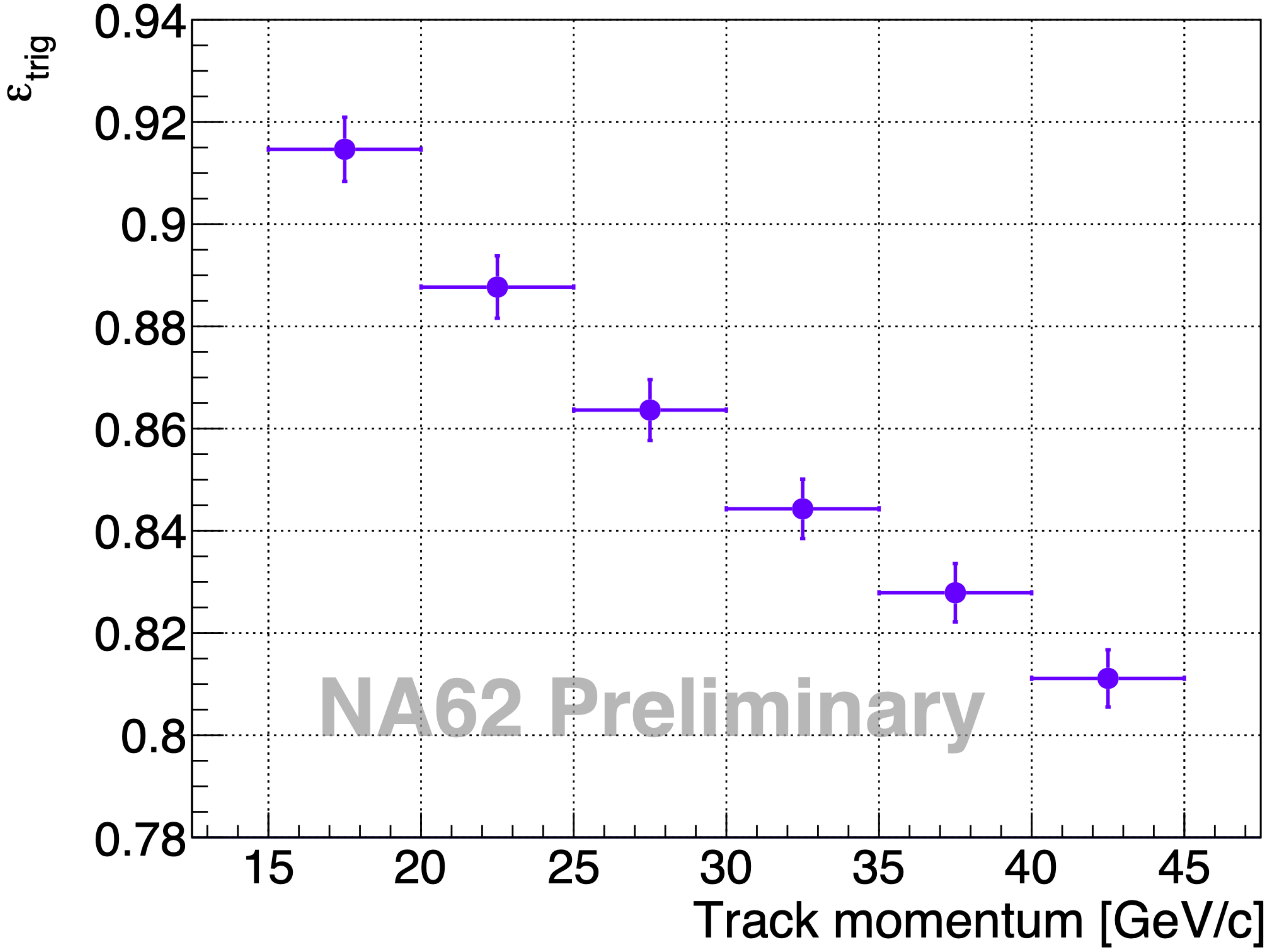
- Increased selection efficiencies.
  - New K-pi matching technique.
  - Re-tuned vertex conditions.
  - Relaxation of some vetos.
- Improved precision (plus improved systematic uncertainty evaluation).

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

Trigger efficiencies

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

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



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

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

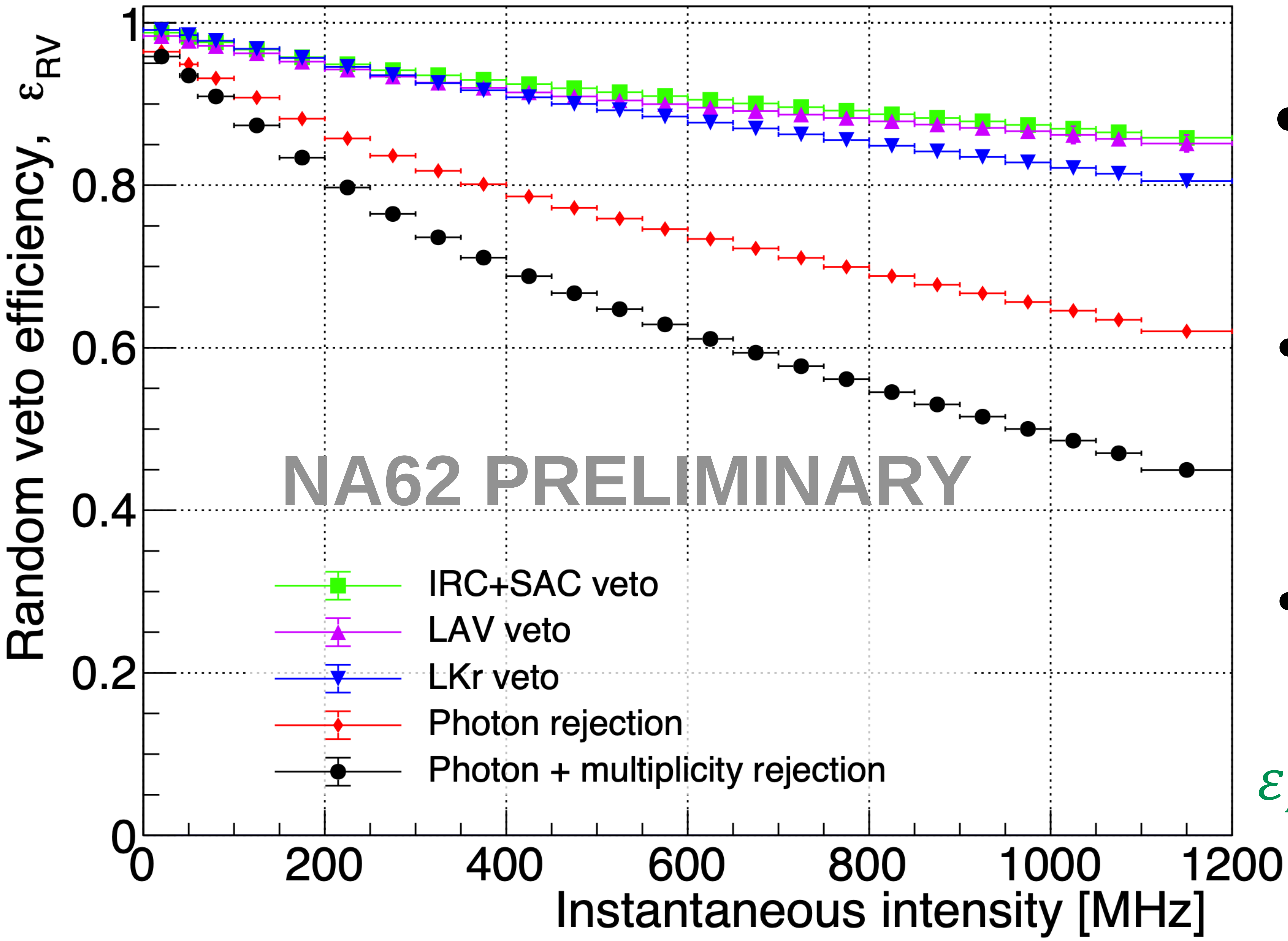
$$\varepsilon_{trig}(2018) = (89 \pm 5)\%$$

- Trigger efficiency ratio:
  - **New:** several components in both normalisation & signal triggers: **partial cancellation**.
  - **Old:** in 2016—18 data normalise with fully independent min bias trigger (**no cancellation**).
- Improved precision by factor 3 with reduced systematic uncertainty.

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:**

$$\varepsilon_{RV}(new, \overline{\lambda_{21-22}} \approx 600\,MHz) = (63.6 \pm 0.6)\%$$

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

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.

$N_{\pi\pi}$	Normalisation $K^+ \to \pi^+\pi^0$	2.0×10^8
$A_{\pi\pi}$	Normalisation acceptance	$(13.410 \pm 0.005)\%$
N_K	Effective K^+ decays	2.9×10^{12}
$A_{\pi\nu\bar{\nu}}$	Signal acceptance	$(7.6 \pm 0.2)\%$
ε_{trig}	Trigger efficiency	$(85.9 \pm 1.4)\%$
ε_{RV}	Random veto efficiency	$(63.6 \pm 0.6)\%$
$\mathcal{B}_{SES}$	Single event sensitivity	$(0.84 \pm 0.03) \times 10^{-11}$

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

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

2021—22: $N_{\pi\nu\bar{\nu}} = 10.00 \pm 0.34$

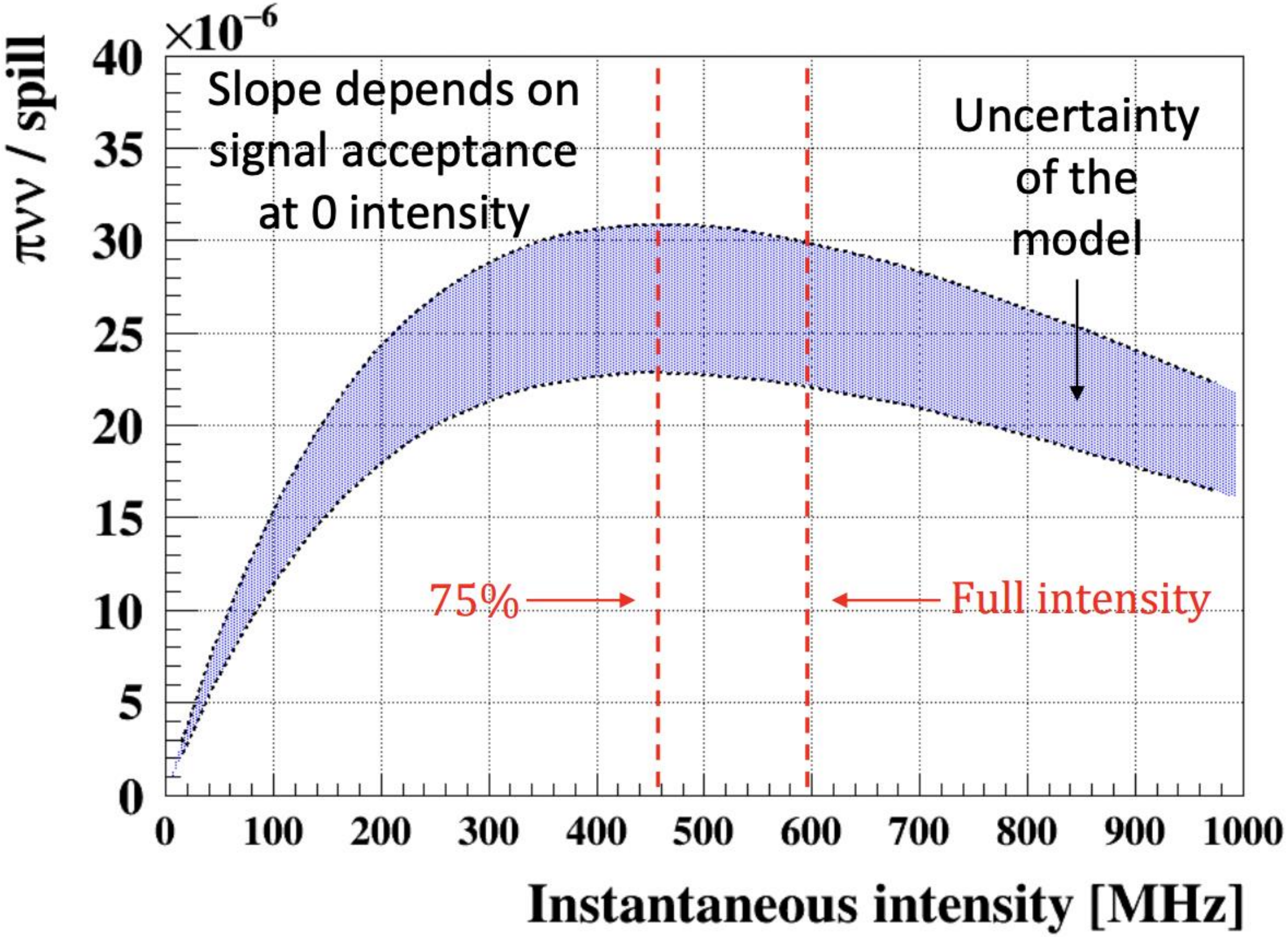
c.f. 2016—18 : $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

Double expected signal by including 21—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}

Optimum NA62 intensity

Selected signal yield vs intensity



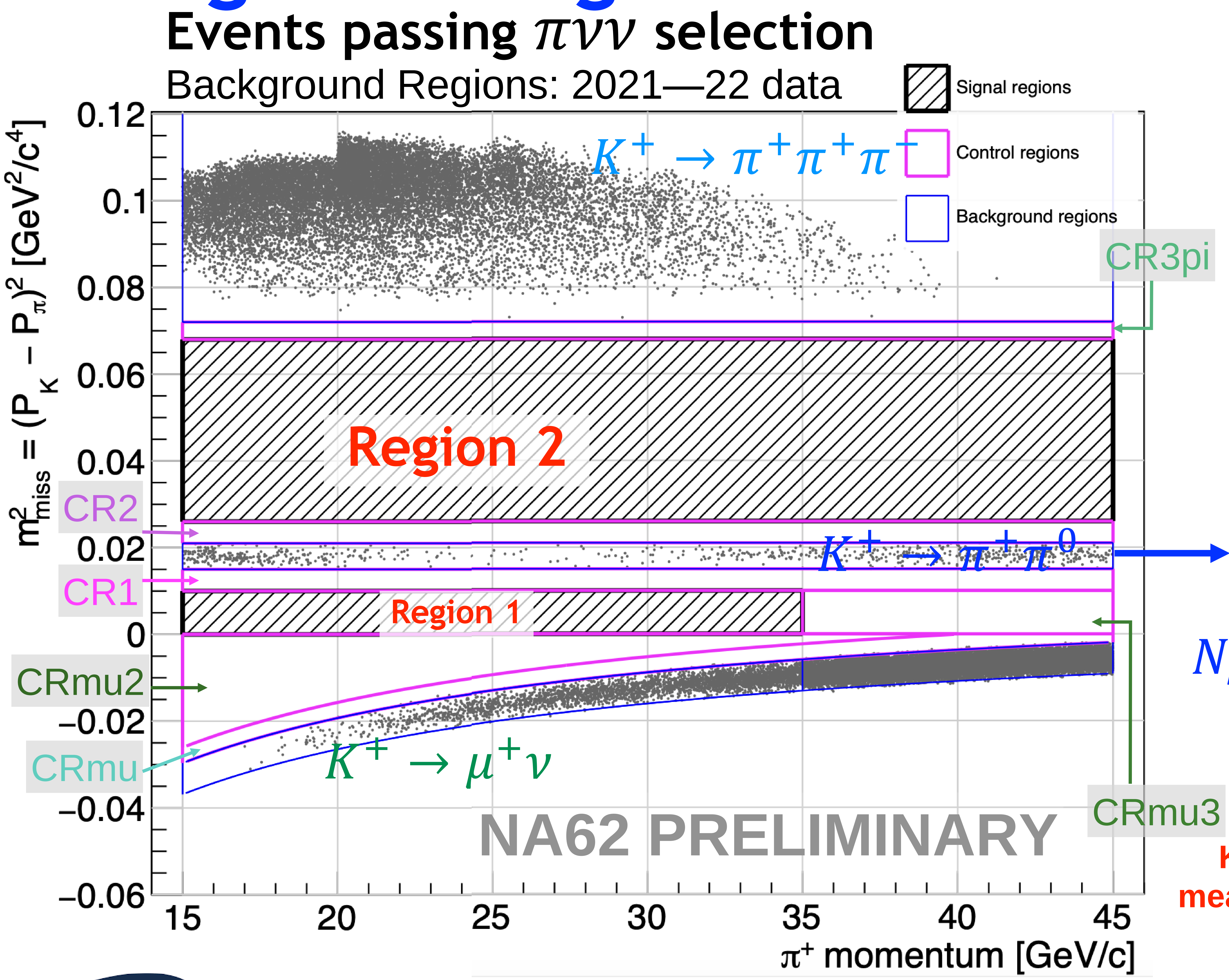
- Saturation of expected signal yield with intensity. Mainly due to:
  - Paralyzable effects from TDAQ dead time and trigger veto windows.
  - Offline selection, due to veto conditions.
- Main sources of uncertainty for model:
  - Online time-dependent mis-calibrations.
  - Fit uncertainty.
- **From 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

$K^+ \to \pi^+ \nu\bar{\nu}$: Analysis of new data

2021—2022 data : Background Evaluation

Background regions & estimations



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

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

Number of events passing signal selection in background region

Kinematic tail fraction: measured in control sample

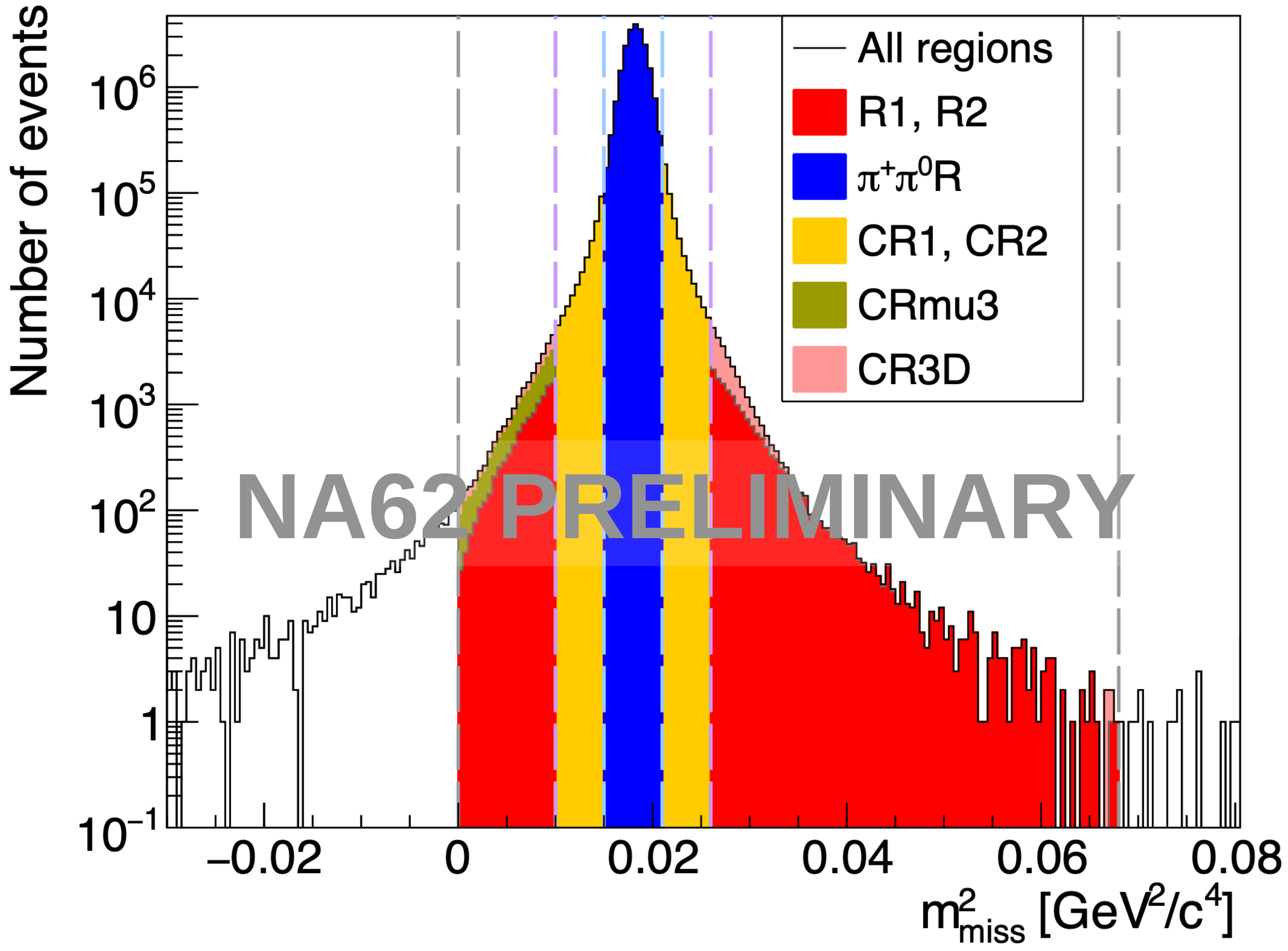
Control sample events in Signal Regions

Control sample events in Background Region

Backgrounds from kinematic tails

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

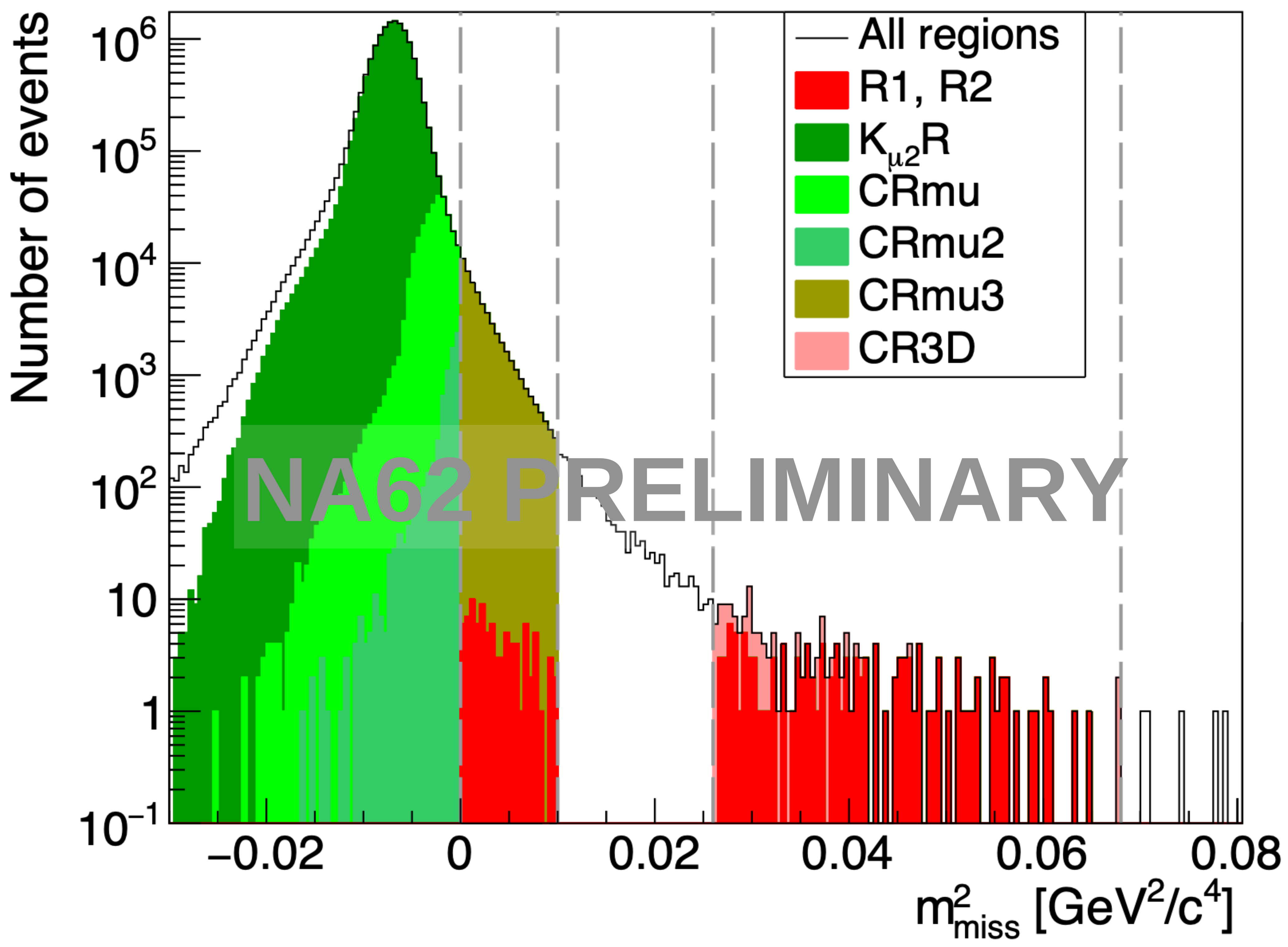
control sample of $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ and 2 photons detected in LKr:



$$N_{bg}(K^+ \to \pi^+\pi^0(\gamma)) = 0.83 \pm 0.05$$

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

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 $\mu^+ \to e^+\nu\nu$

$$N_{bg}(K^+ \to \mu^+\nu) = 0.9 \pm 0.2$$

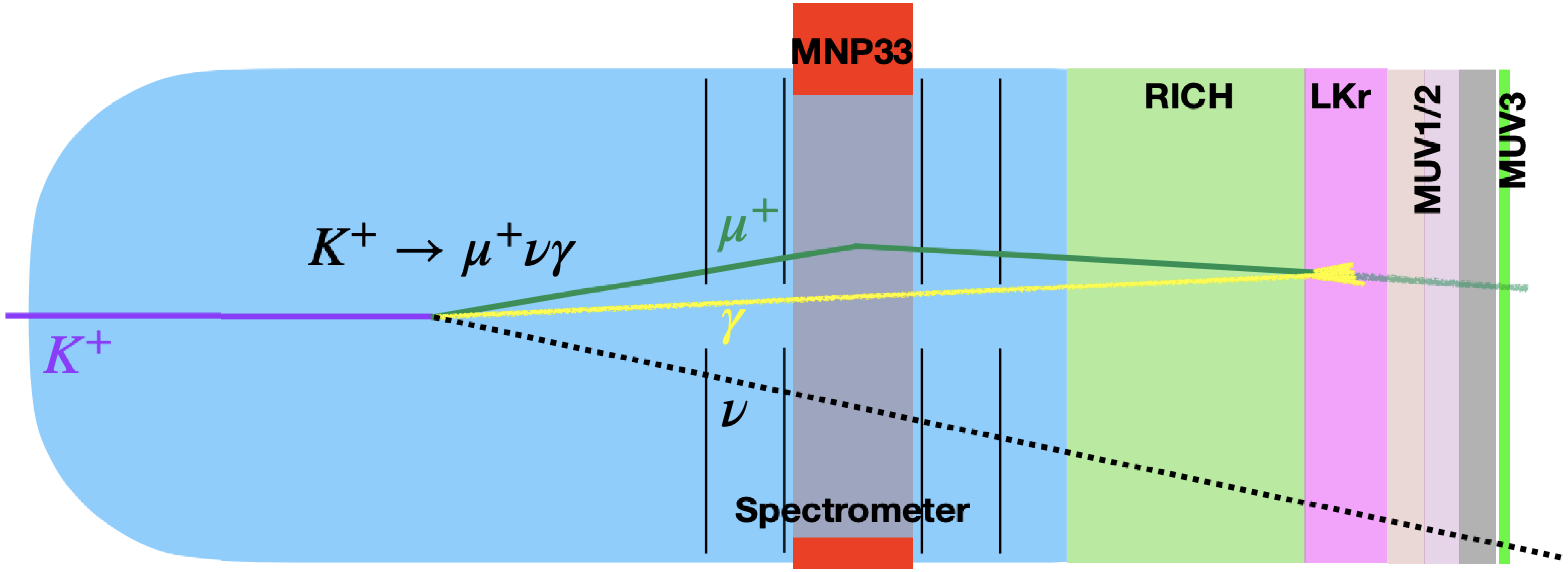
$K^+ \to \pi^+\pi^+\pi^-$

- Use MC to measure f_{tail}:

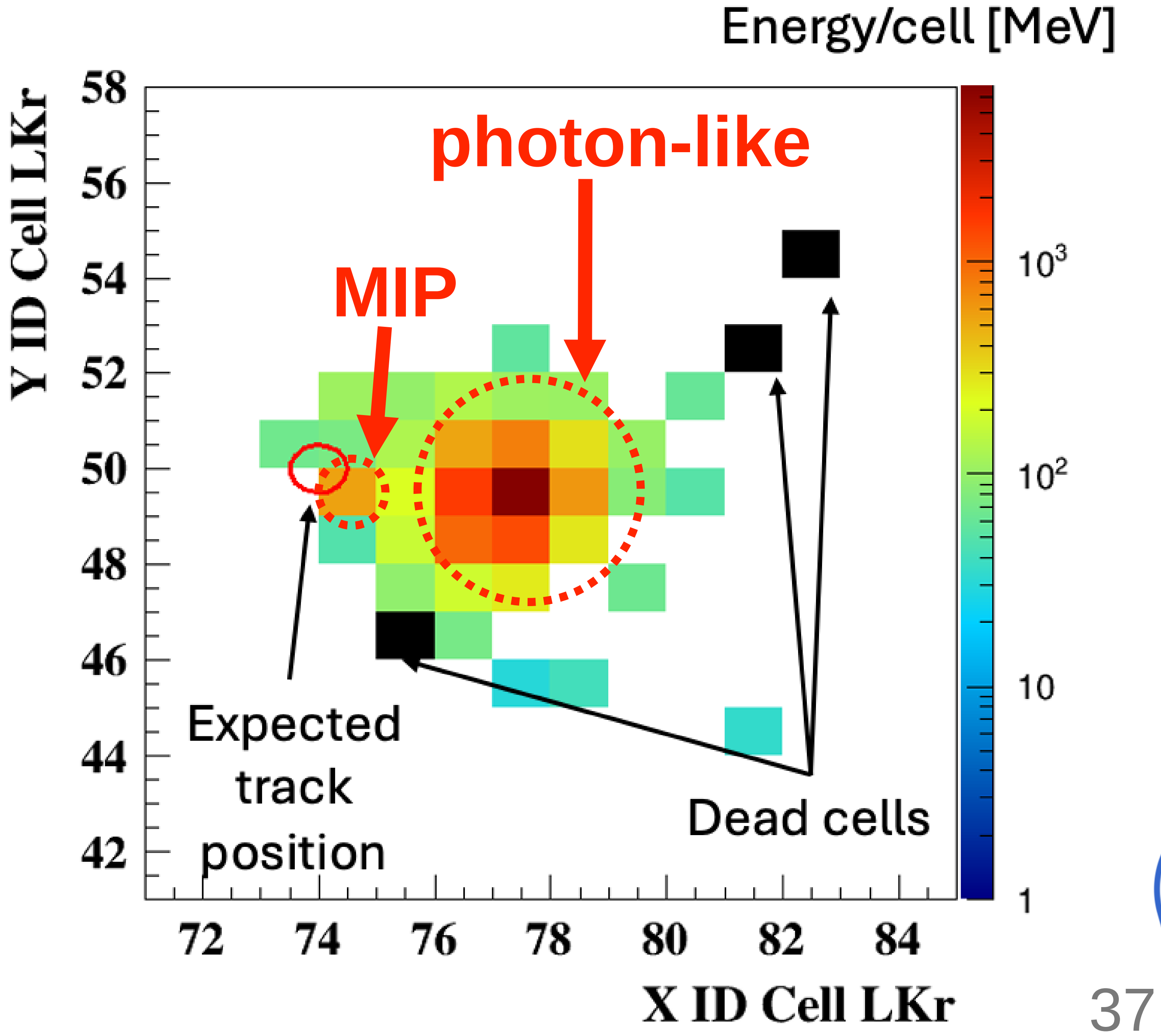
$$N_{bg}(K^+ \to \pi^+\pi^+\pi^-) = 0.11 \pm 0.03$$

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

- $K^+ \to \pi^+\pi^0\gamma$ **: included with "kinematic tails" estimation.**
  - Suppression: photon vetos, rejection with additional γ is 30x stronger.
  - Estimation: 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 - see later)
- $K^+ \to \mu^+\nu\gamma$ **: 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 : $N_{bg}(K^+ \to \mu^+\nu\gamma) = 0.8 \pm 0.4$
  - Validation: data sample without $K^+ \to \mu^+\nu\gamma$ veto and PID = "less pion-like" (Calo BDT bins below π^+ bin).



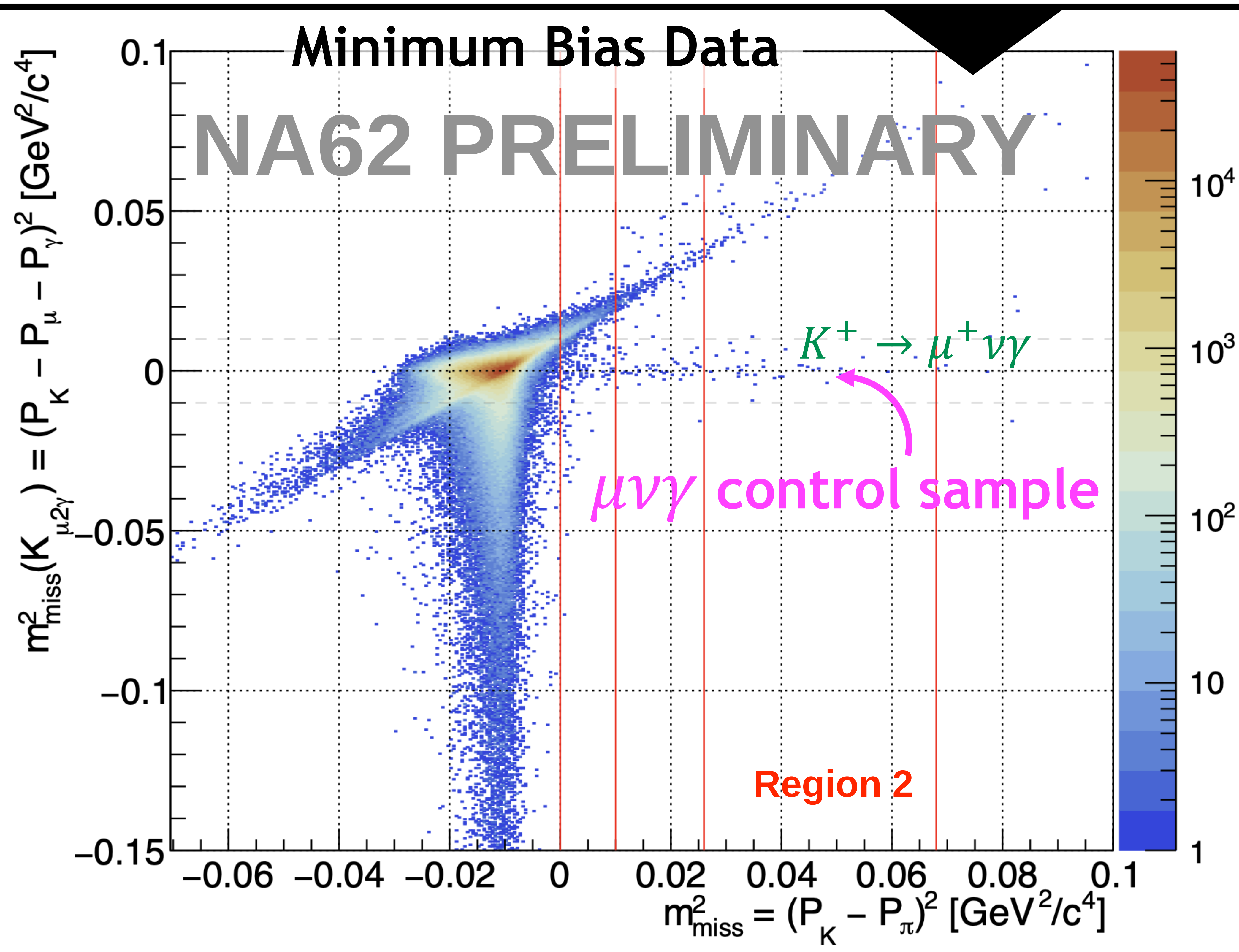
Sketch only



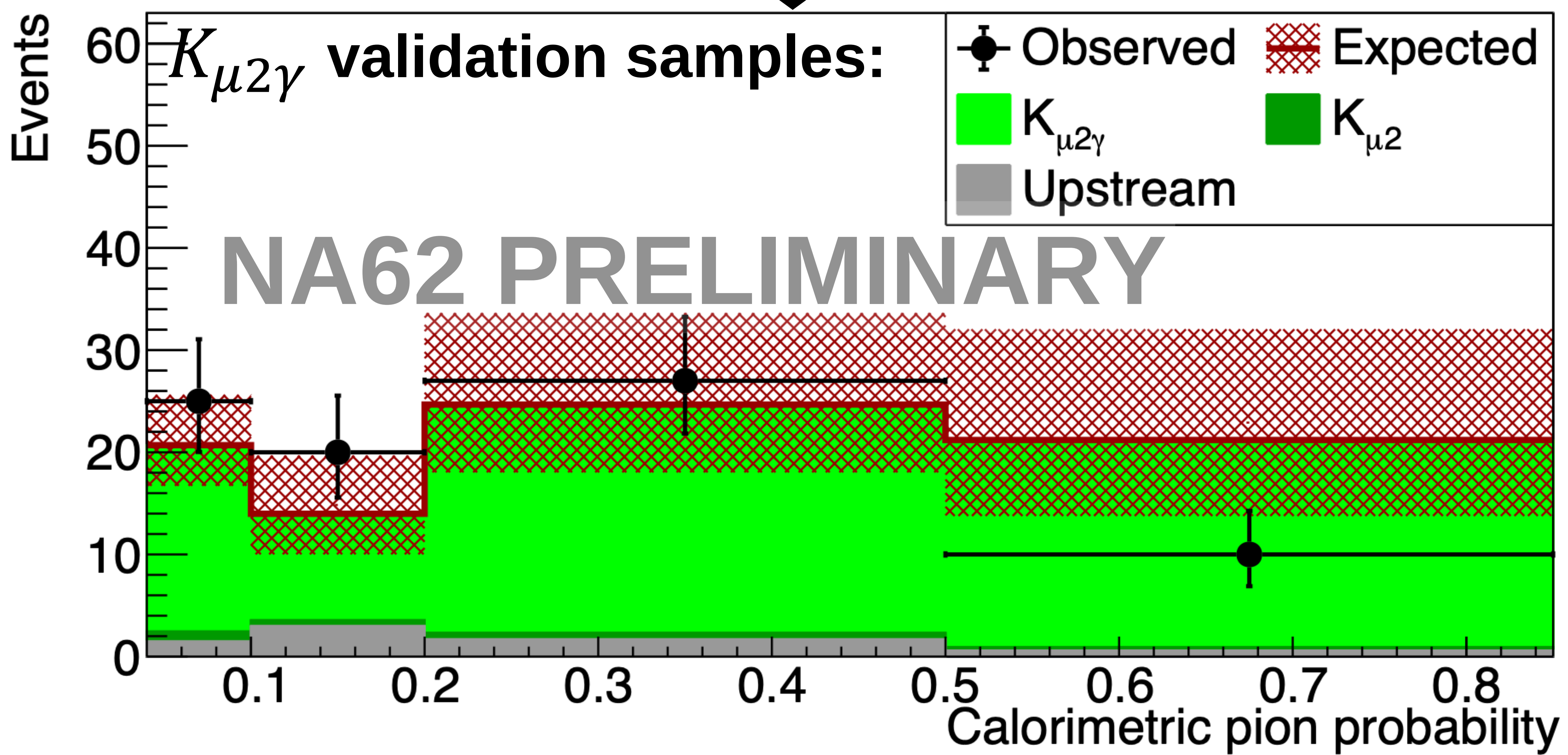
$K^+ \rightarrow \mu^+\nu\gamma$ Background

- Kinematically select $K^+ \rightarrow \mu^+\nu\gamma$ events: $m^2_{miss}(K_{\mu2\gamma}) = (P_K - P_\mu - P_\gamma)^2$
  - 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:



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



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

Other backgrounds

- $K^+ \to \pi^+\pi^-e^+\nu$ (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 : $A_{K_{e4}} = \frac{N_{MC}^{sel}}{N_{MC}^{gen}} = (1.3 \pm 0.3_{stat}) \times 10^{-8}$

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

Branching ratio of K_{e4} (from PDG)

$$N_{bg}(K^+ \to \pi^+\pi^-e^+\nu) = 0.89^{+0.34}_{-0.28}$$

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

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

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

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

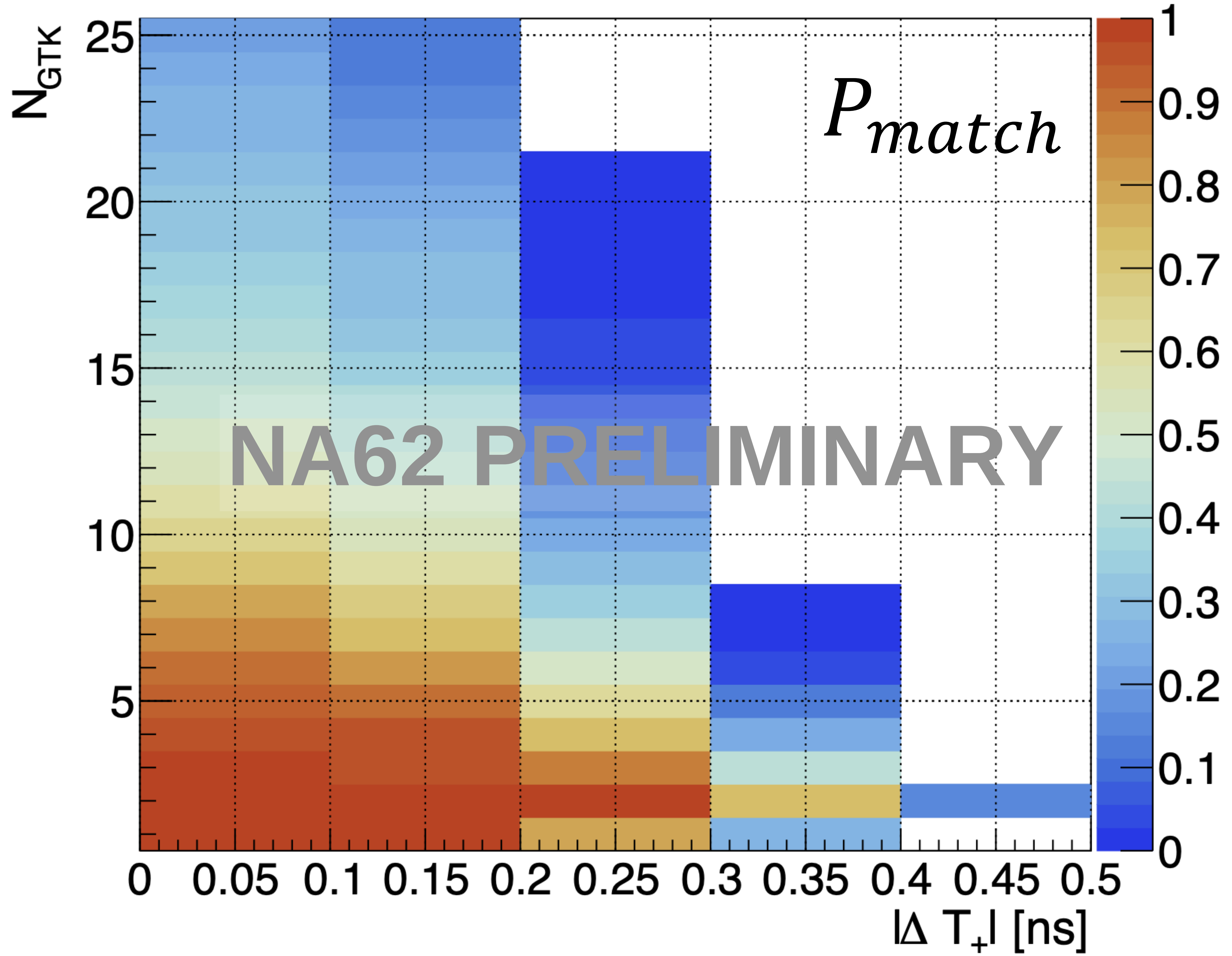
P_{match} — Probability to pass $K^+ - \pi^+$ matching

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

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

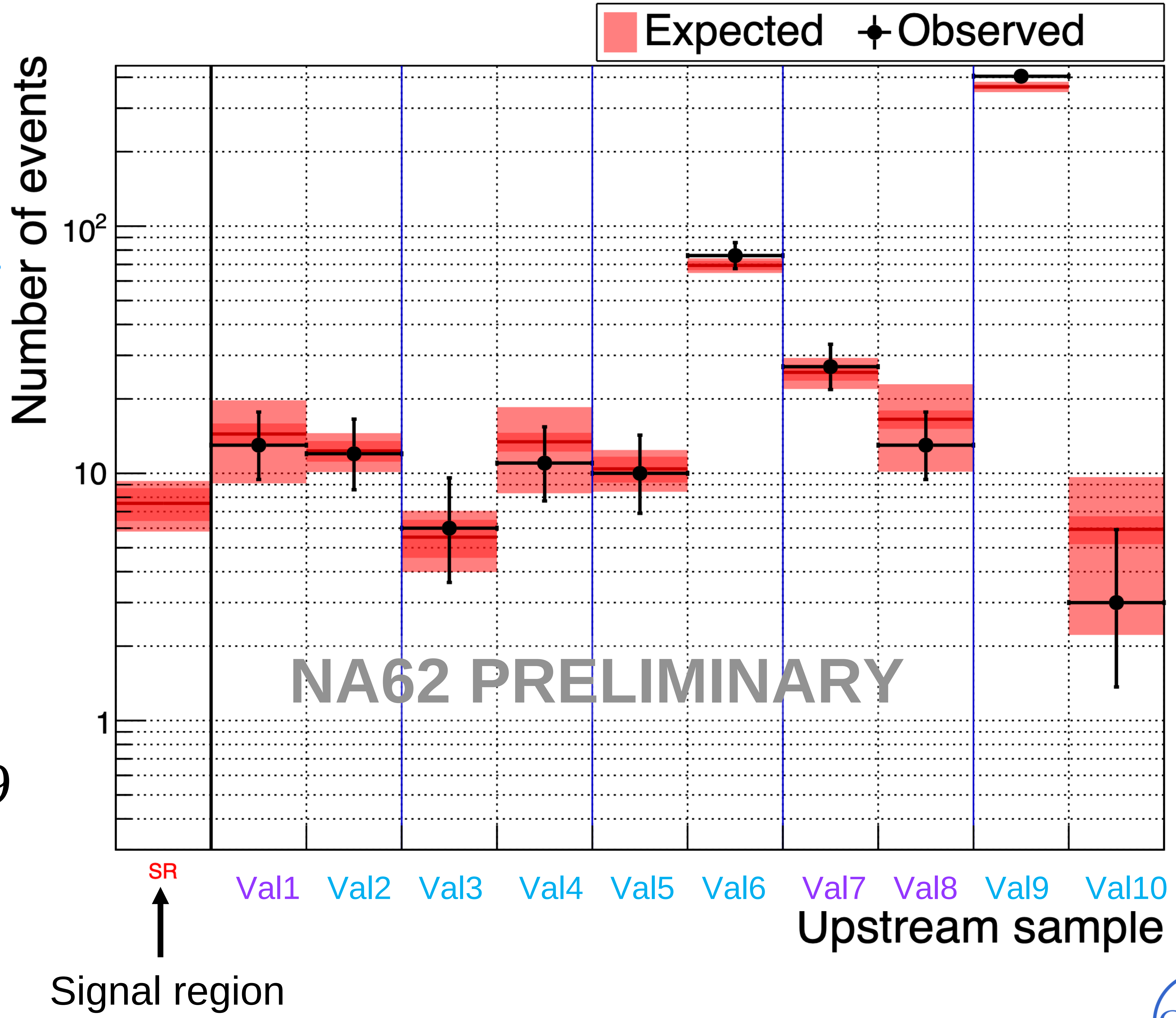
$$N_{bg}(Upstream) = 7.4^{+2.1}_{-1.8}$$

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



Upstream background validation

- **Invert & loosen upstream vetos to enrich with different mechanisms:**
  - Interaction-enriched: Val1,2,7,8
  - Accidental-enriched: Val3,4,5,6,9,10.
  - **All independent.**
- Expectations and observations are in good agreement.
- Number of events rejected by VetoCounter:
  - (i.e. events in signal region with associated VC signal)
  - $N_{exp}^{VCrej.} = 6.9 \pm 1.4$, $N_{obs}^{VCrej.} = 9$
- **VetoCounter is essential to control upstream background.**



Summary of expectations

NA62

Backgrounds

$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \pi^+\pi^0$	0.76 ± 0.04
$K^+ \to \pi^+\pi^0\gamma$	0.07 ± 0.01
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \mu^+\nu$	0.87 ± 0.19
$K^+ \to \mu^+\nu\gamma$	0.82 ± 0.43
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89^{+0.34}_{-0.28}$
$K^+ \to \pi^0\ell^+\nu$	< 0.001
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.0^{+2.1}_{-1.9}$

Signal Sensitivity

$$\mathcal{B}_{SES} = (0.84 \pm 0.03) \times 10^{-11}$$

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

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

2021–22: $N_{\pi\nu\bar{\nu}} = 10.00 \pm 0.34$

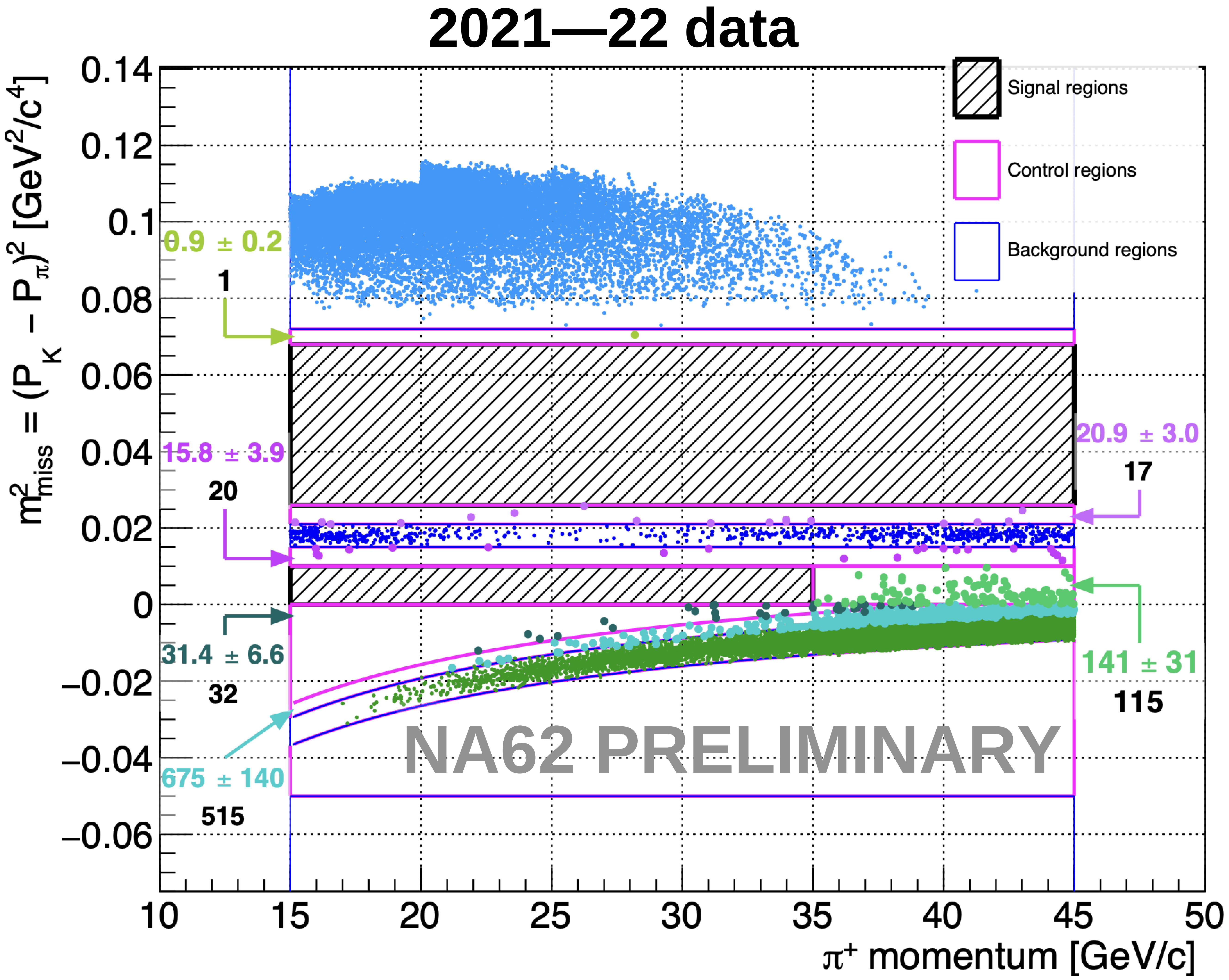
c.f. 2016–18 : $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

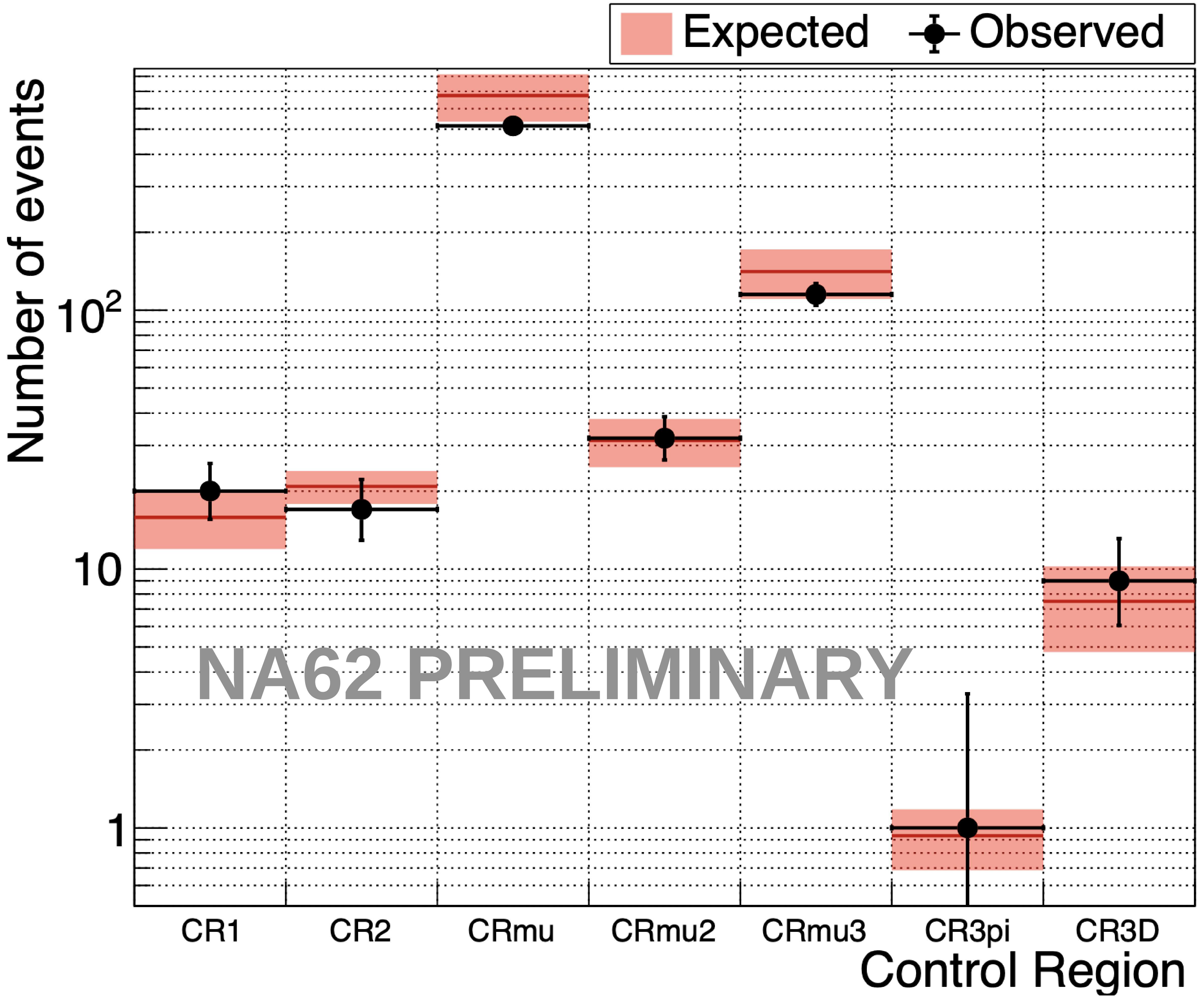
→ **Expected signal doubled by including 2021–22 data**

- $N^{SM}_{\pi\nu\bar{\nu}}$ 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

INFN CERN

Control regions: 2021—22 Data



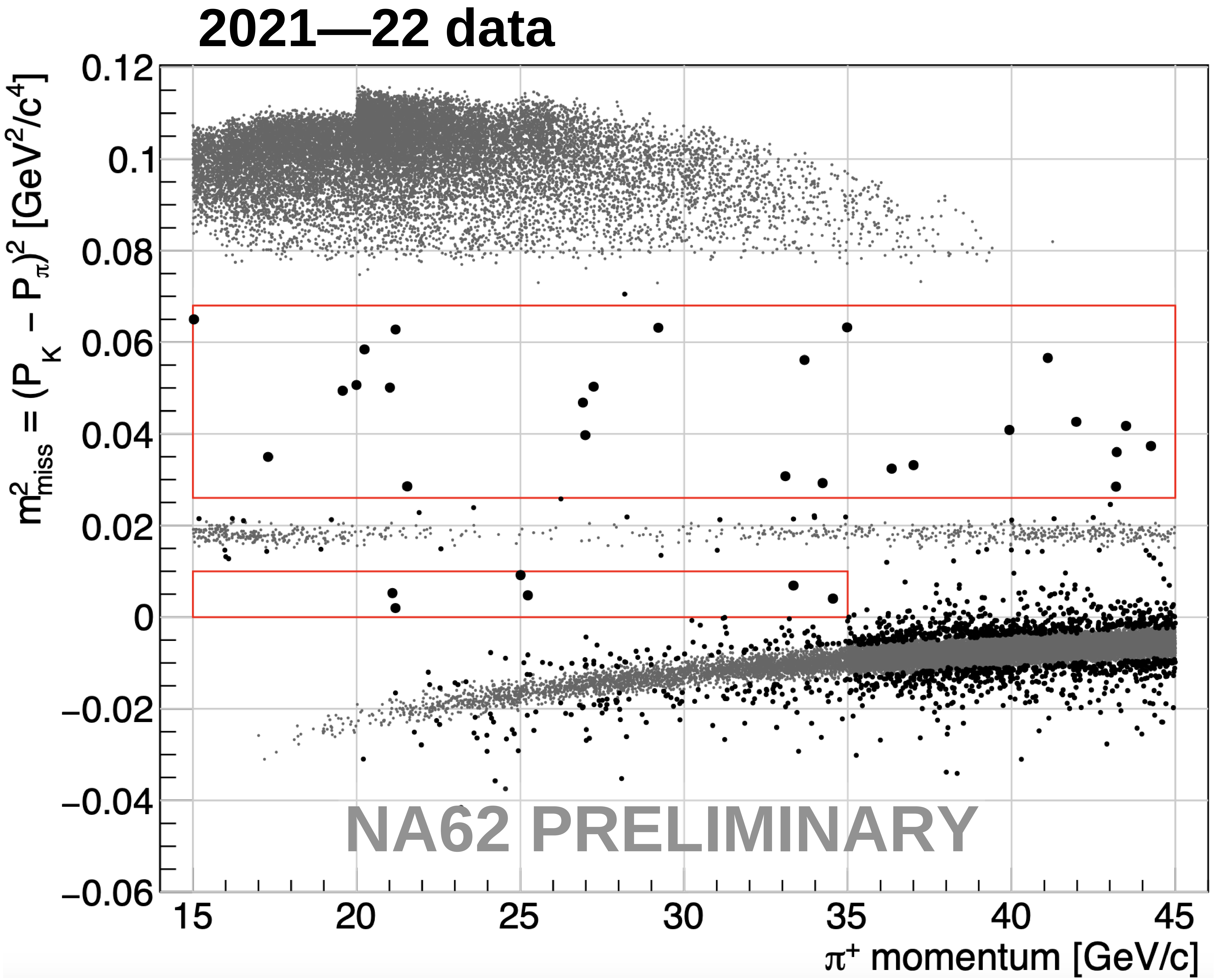


- Good agreement in control regions validates background expectations.

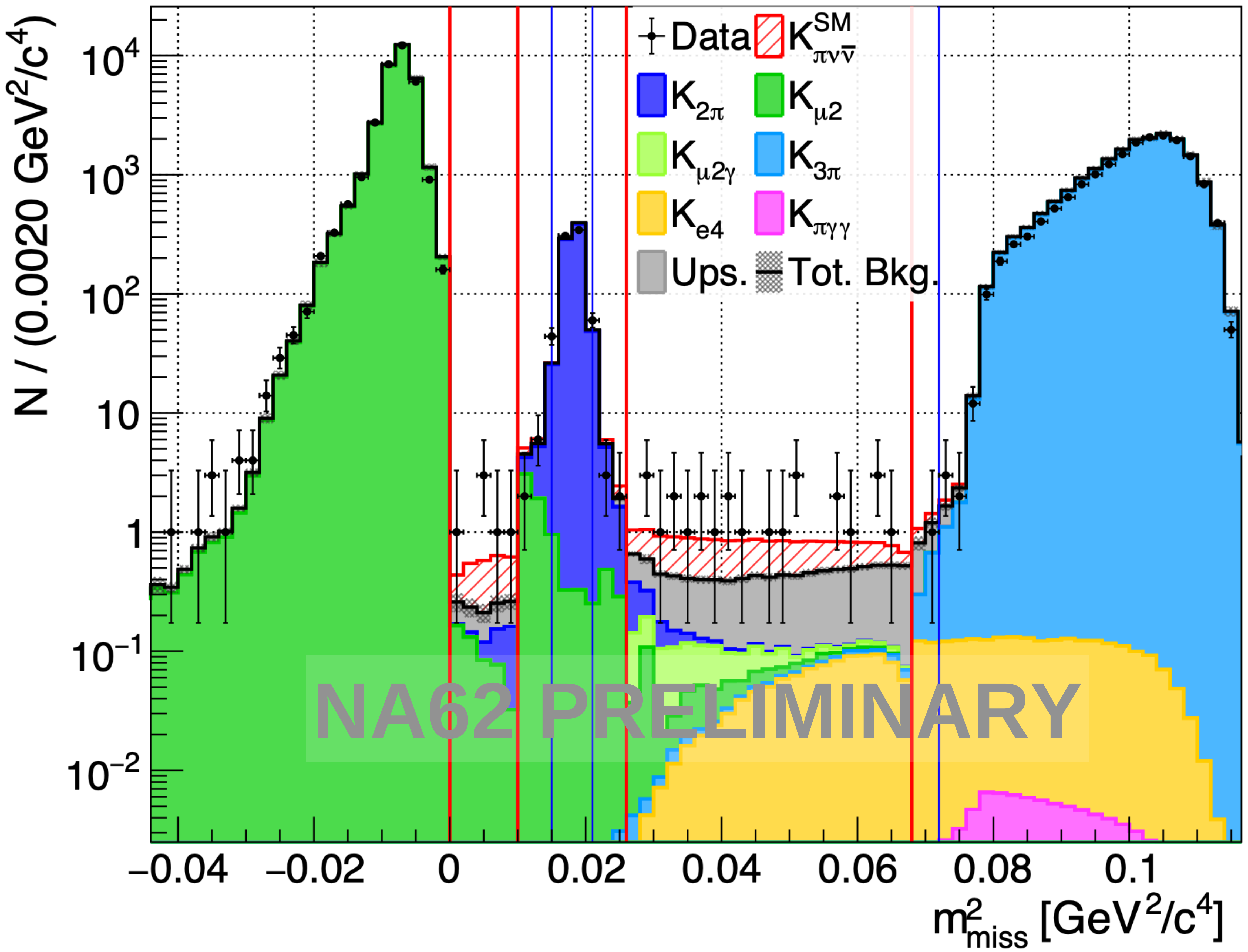
$K^+ \to \pi^+ \nu\bar{\nu}$: New NA62 Results

2021—22 data
and combined 2016—22 data

Signal regions: 2021—22 Data



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



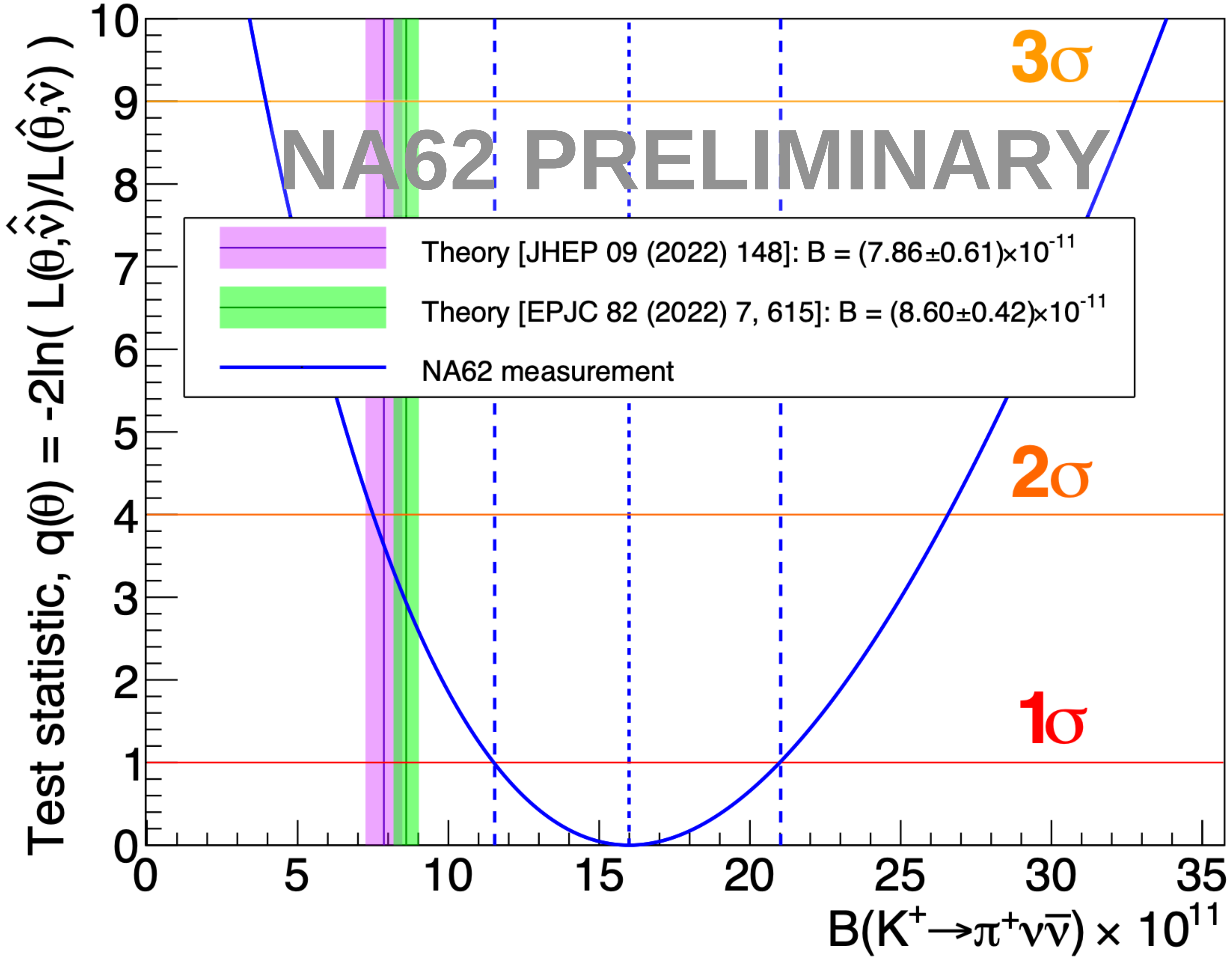
Expected SM signal: $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

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

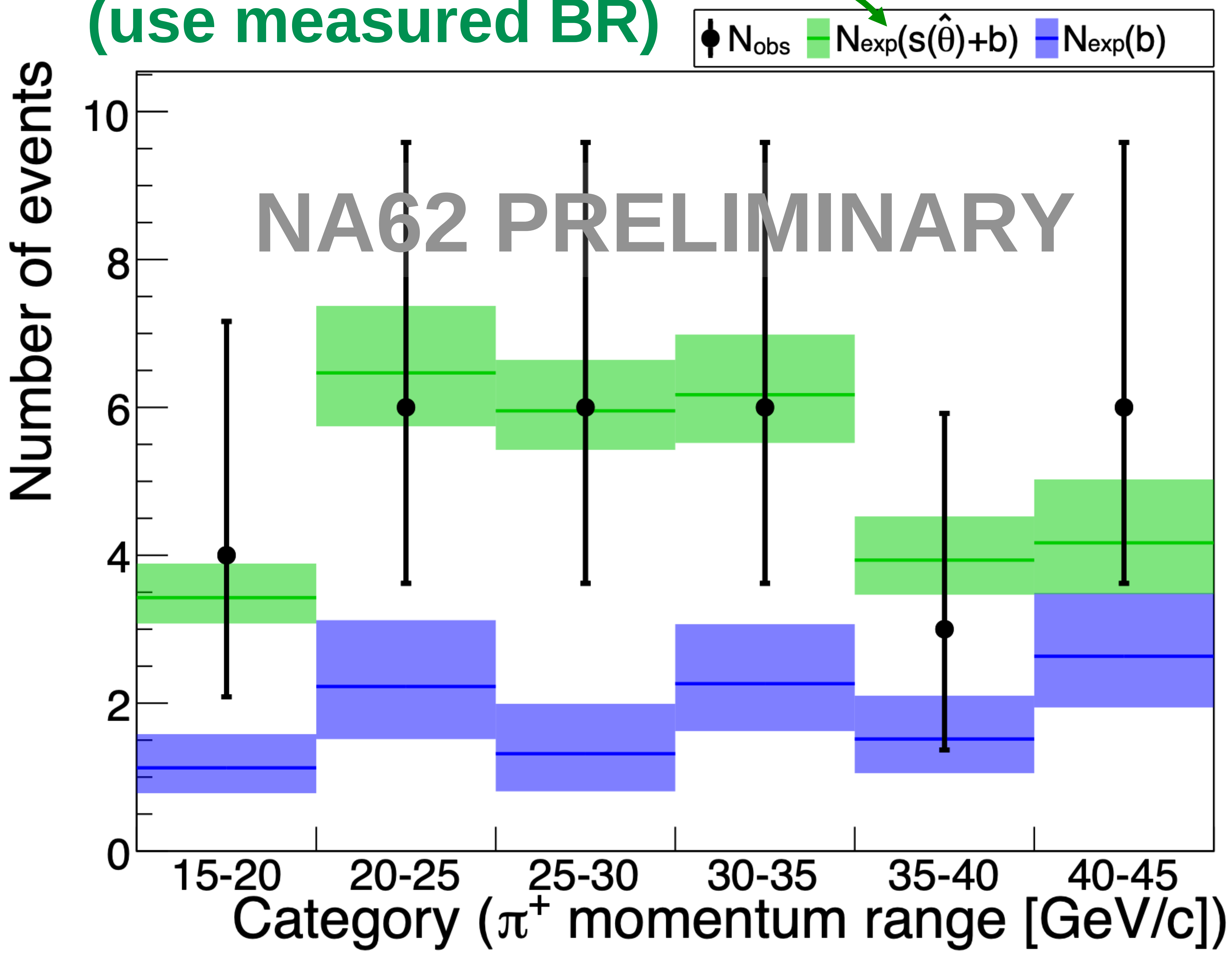
Observed: $N_{obs} = 31$

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

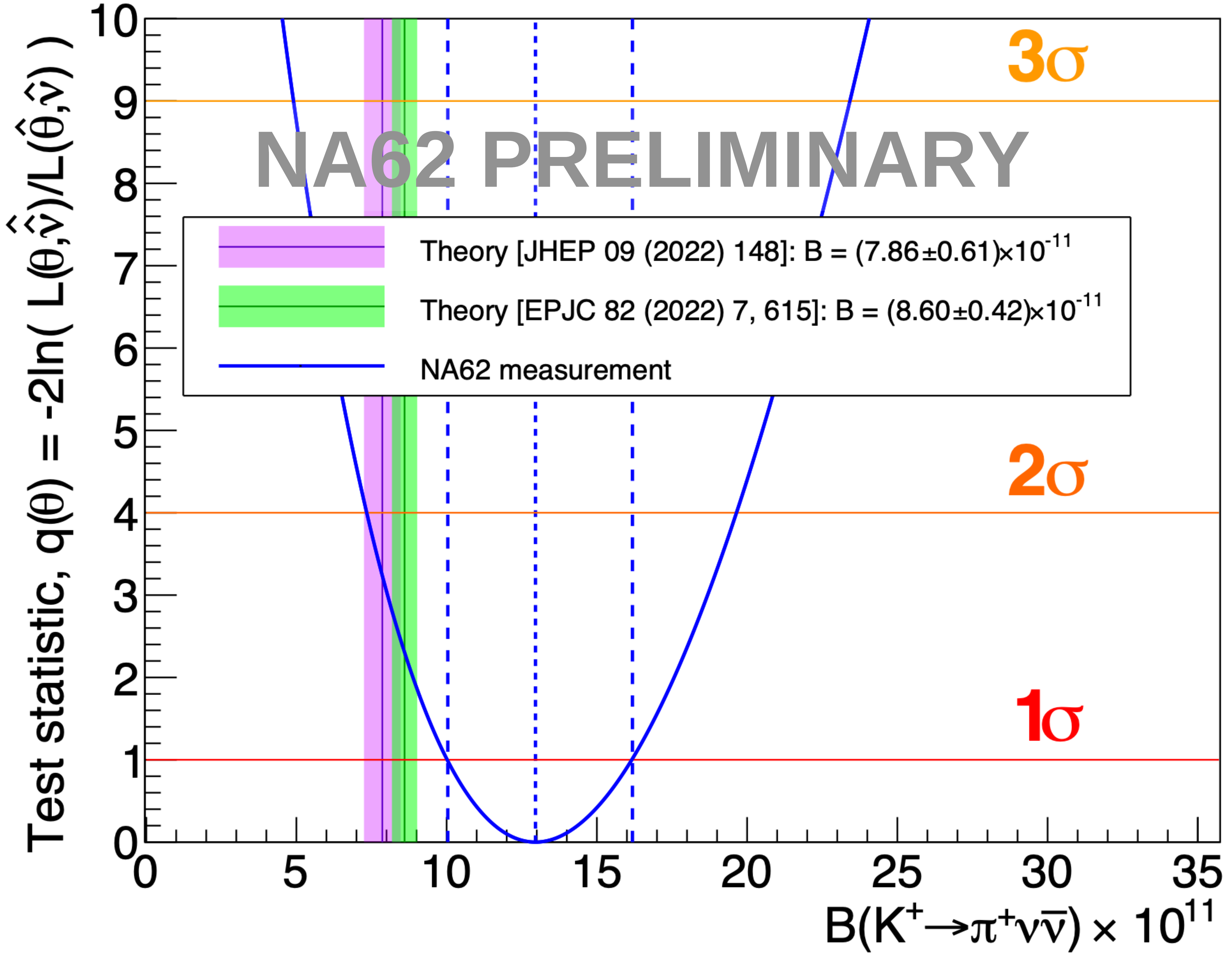


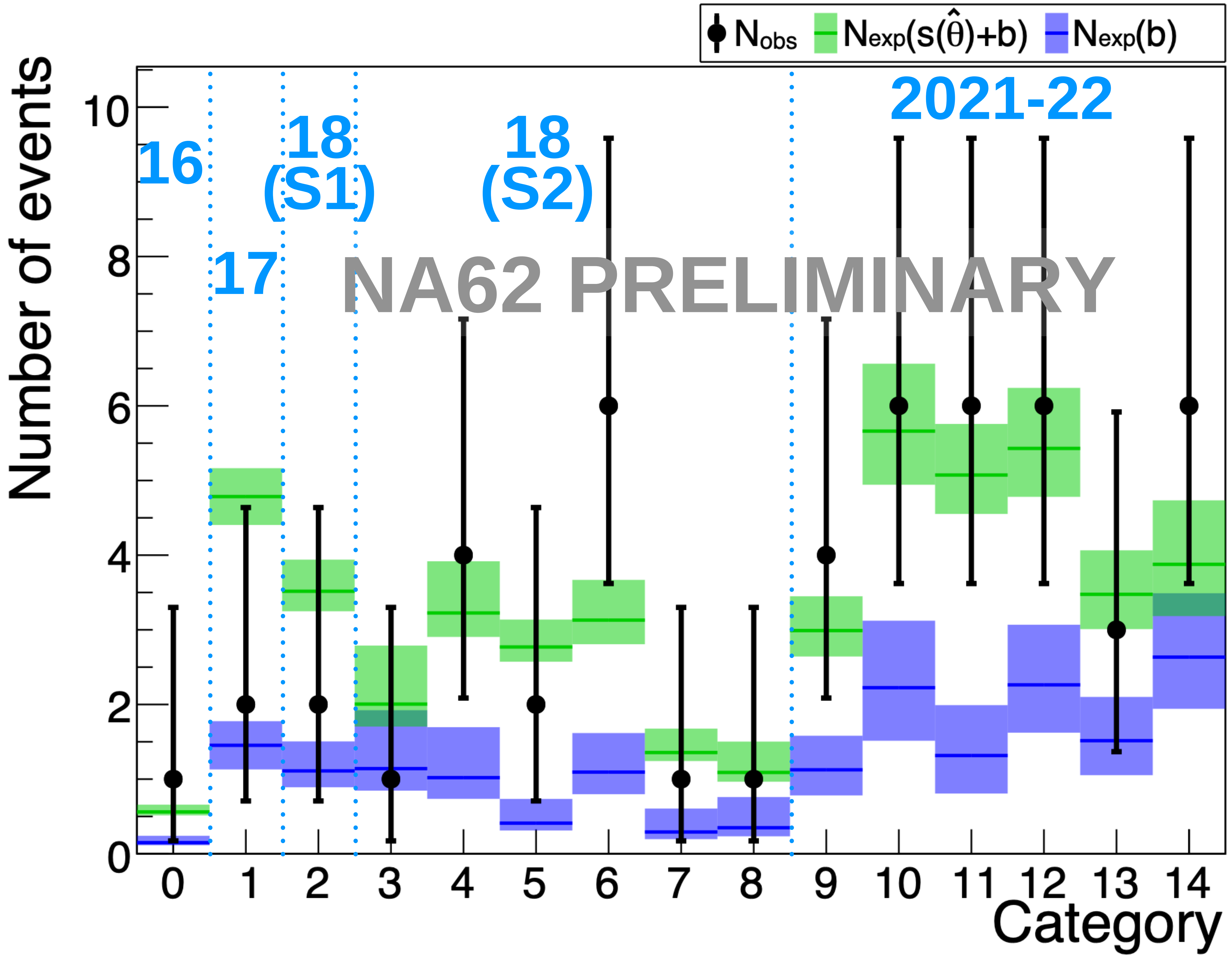
$$\mathcal{B}_{21-22}(K^+ \to \pi^+\nu\bar{\nu}) = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11} = \left(16.0\ \left(^{+4.8}_{-4.2}\right)_{stat}\ \left(^{+1.4}_{-1.3}\right)_{syst}\right) \times 10^{-11}$$

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 $Z > 5$**





$$\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-2.9}) \times 10^{-11} = (13.0\ (^{+3.0}_{-2.7})_{stat}\ (^{+1.3}_{-1.2})_{syst}) \times 10^{-11}$$

Results in context

BNL E787/E949 experiment
[Phys.Rev.D 79 (2009) 092004]

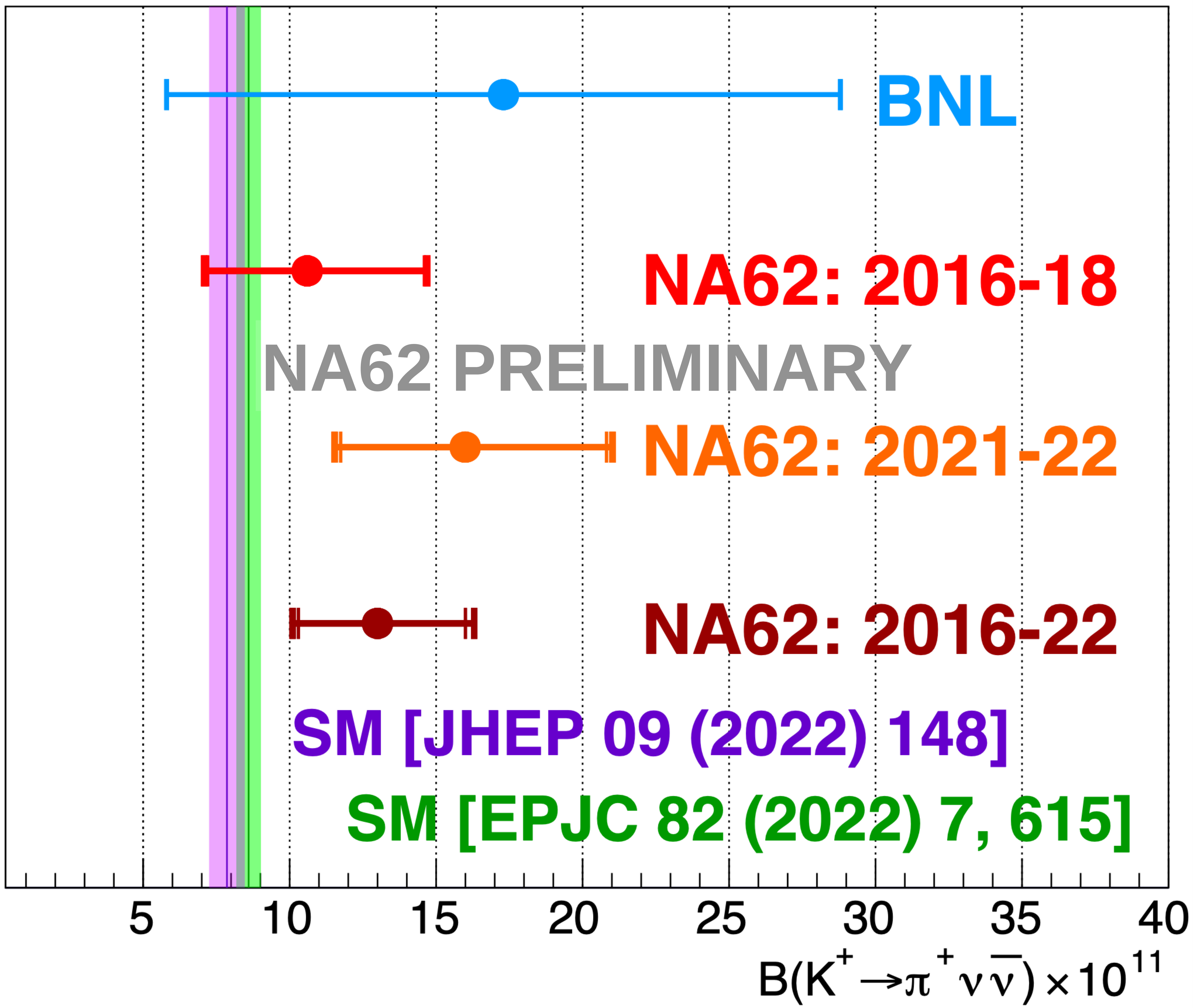
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$$

[JHEP 06 (2021) 093]

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

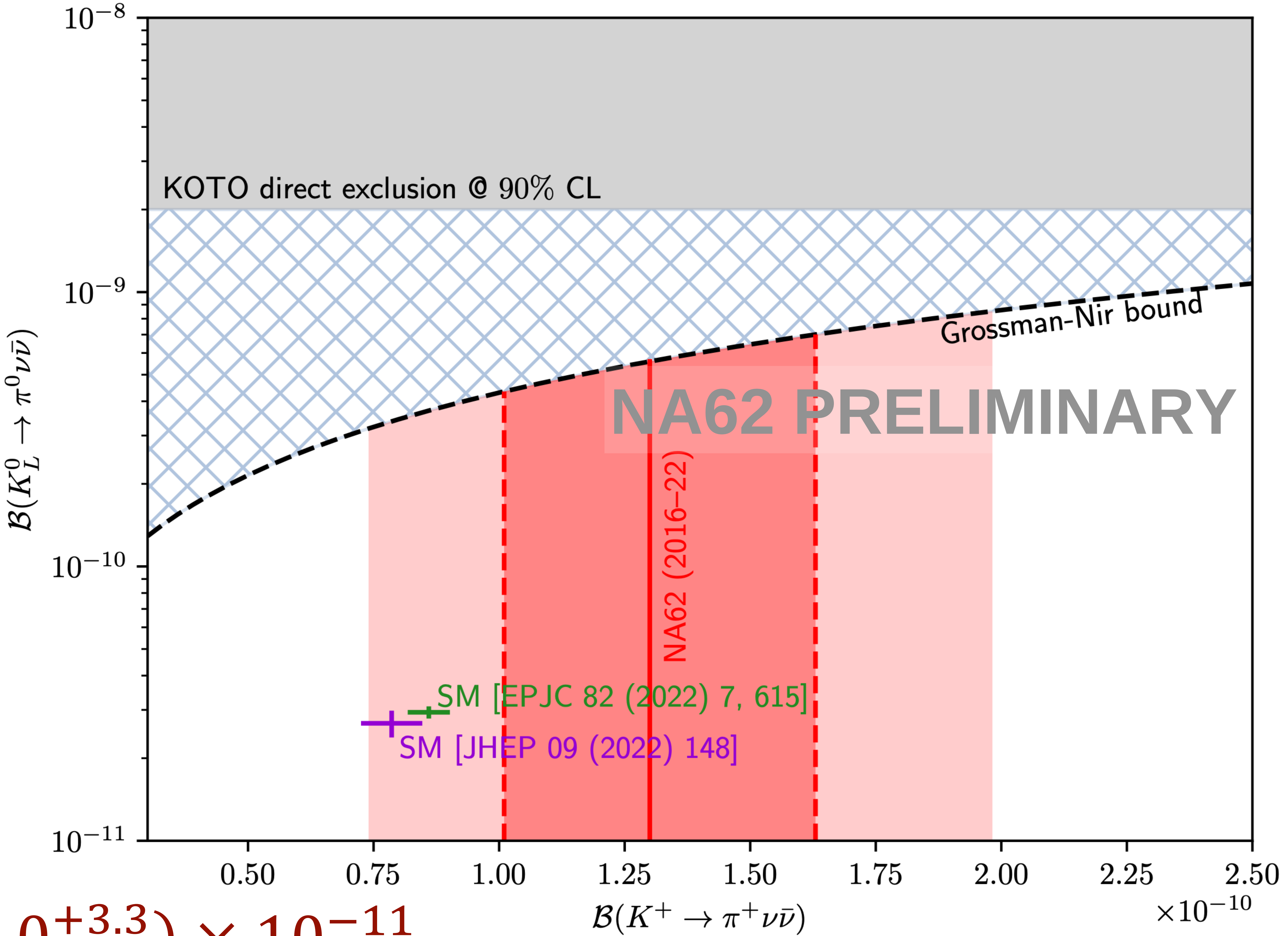
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

- 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**



$$\mathcal{B}^{16-22}_{\pi\nu\bar{\nu}} = (13.0^{+3.3}_{-2.9}) \times 10^{-11}$$

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

Conclusions

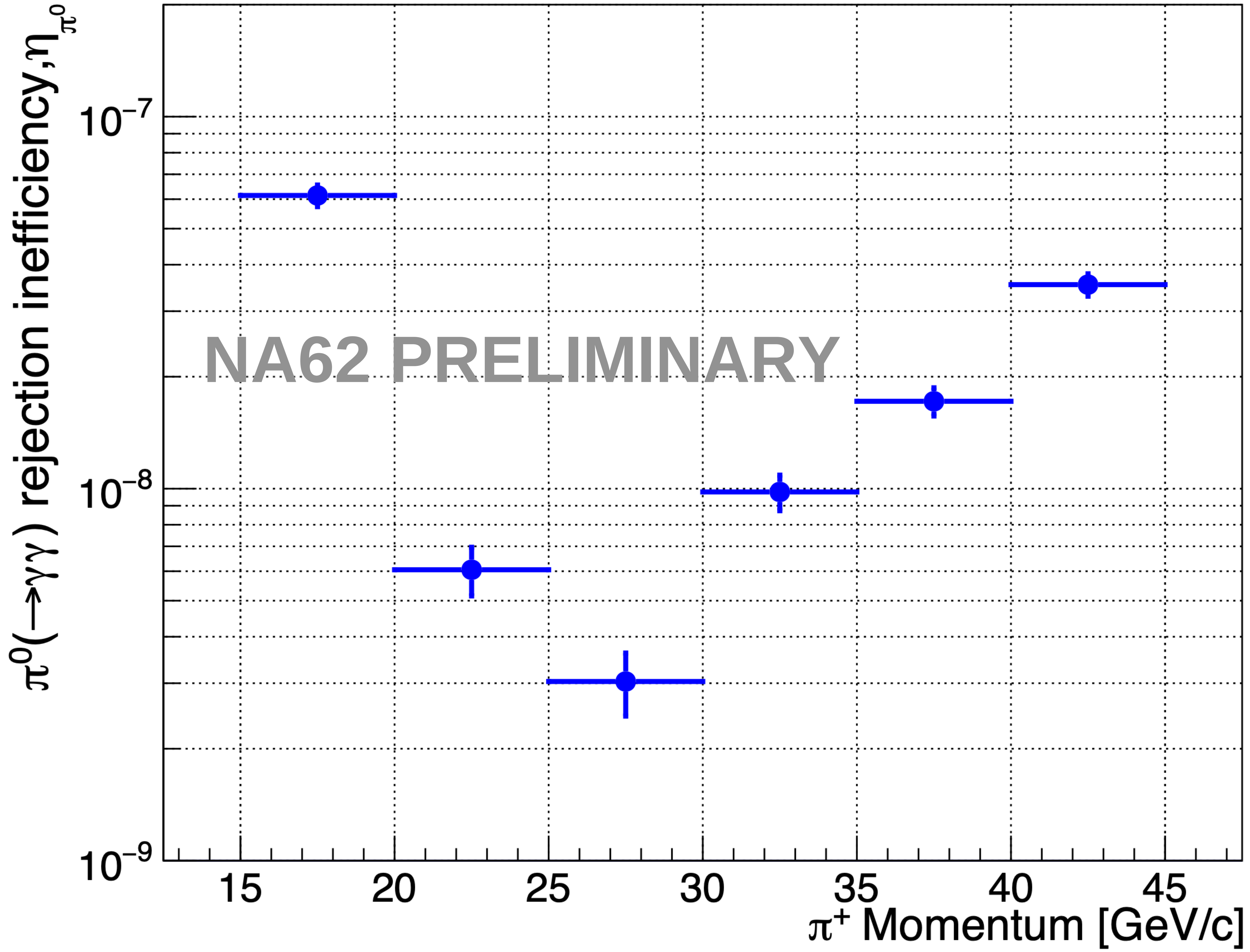
- New study of $K^+ \to \pi^+ \nu\bar{\nu}$ decay using NA62 2021—22 dataset:
  - Improved signal yield per SPS spill by 50%.
  - $N_{bg} = 11.0^{+2.1}_{-1.9}$, $N_{obs} = 31$
  - $\mathcal{B}_{21-22}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11} = \left(16.0\ (^{+4.8}_{-4.2})_{stat}\ (^{+1.4}_{-1.3})_{syst}\right) \times 10^{-11}$

- Combining with 2016—18 data for full 2016—22 results:
  - $N_{bg} = 18^{+3}_{-2}$, $N_{obs} = 51$ (using 9+6 categories for BR extraction)
  - $\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-2.9}) \times 10^{-11} = (13.0\ (^{+3.0}_{-2.7})_{stat}\ (^{+1.3}_{-1.2})_{syst}) \times 10^{-11}$
  - Background-only hypothesis rejected with significance Z>5.
- **First observation of $K^+ \to \pi^+ \nu\bar{\nu}$ decay: BR consistent with SM prediction within 1.7σ**
  - **Need full NA62 data-set to clarify SM agreement or tension.**

2023—LS3 data-set collection & analysis in progress…

Supplemental

Photon veto performance



- Probability of $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ passing full photon vetos:

$$\eta_{\pi^0} = \frac{N_{sel.}^{\pi^+\pi^0 R}}{N_{\pi\pi} D_0 \varepsilon_{trig} \varepsilon_{RV}}$$

Number of events passing full $\pi^+\nu\bar{\nu}$ selection in $\pi^+\pi^0$ region

Number of selected normalisation events

Normalisation trigger downscaling and efficiency

Random veto efficiency

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

- **Combined γ/π^0 rejection of $\mathcal{O}(10^8)$.**

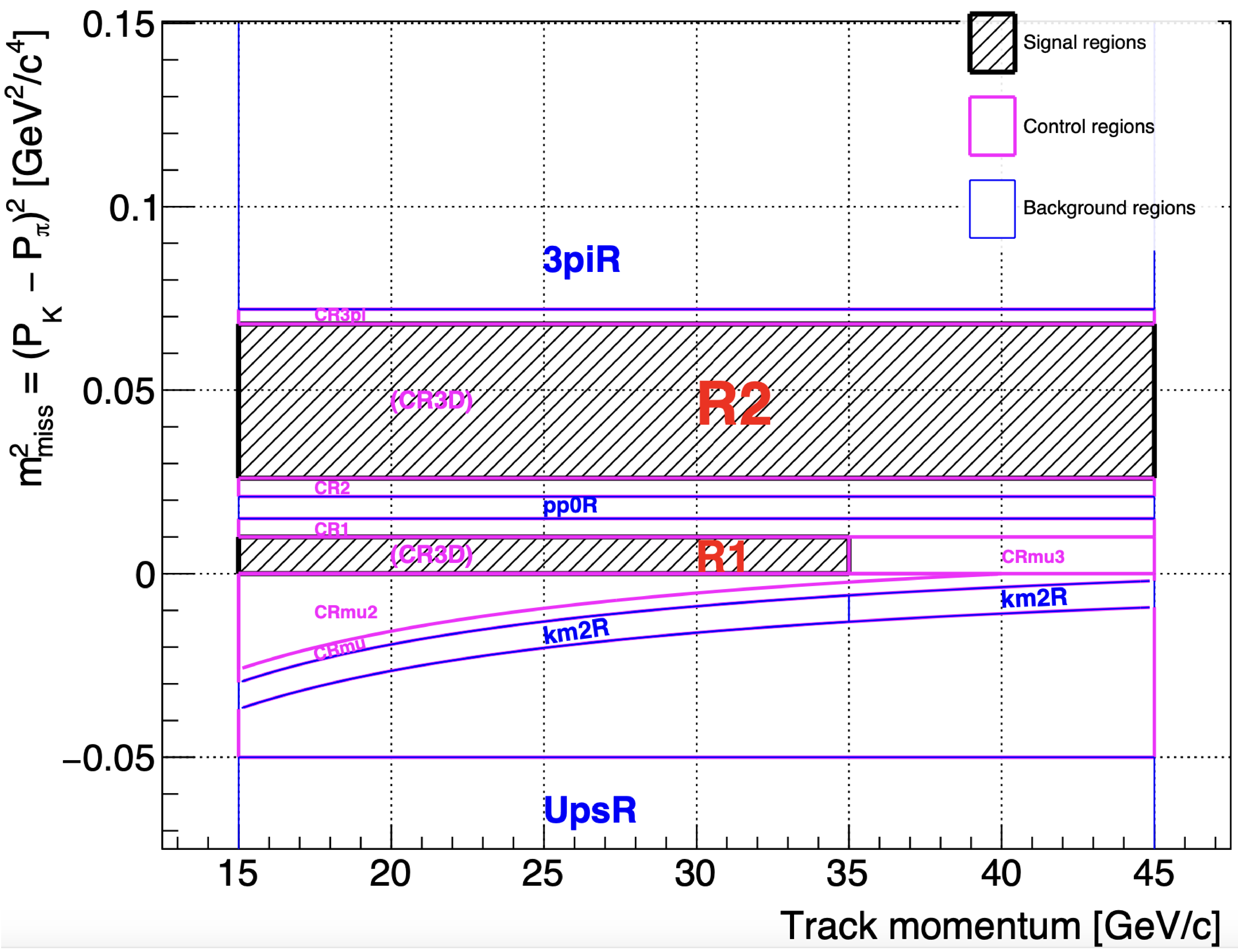
Bayesian classifier for $K^+ - \pi^+$ matching

- **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

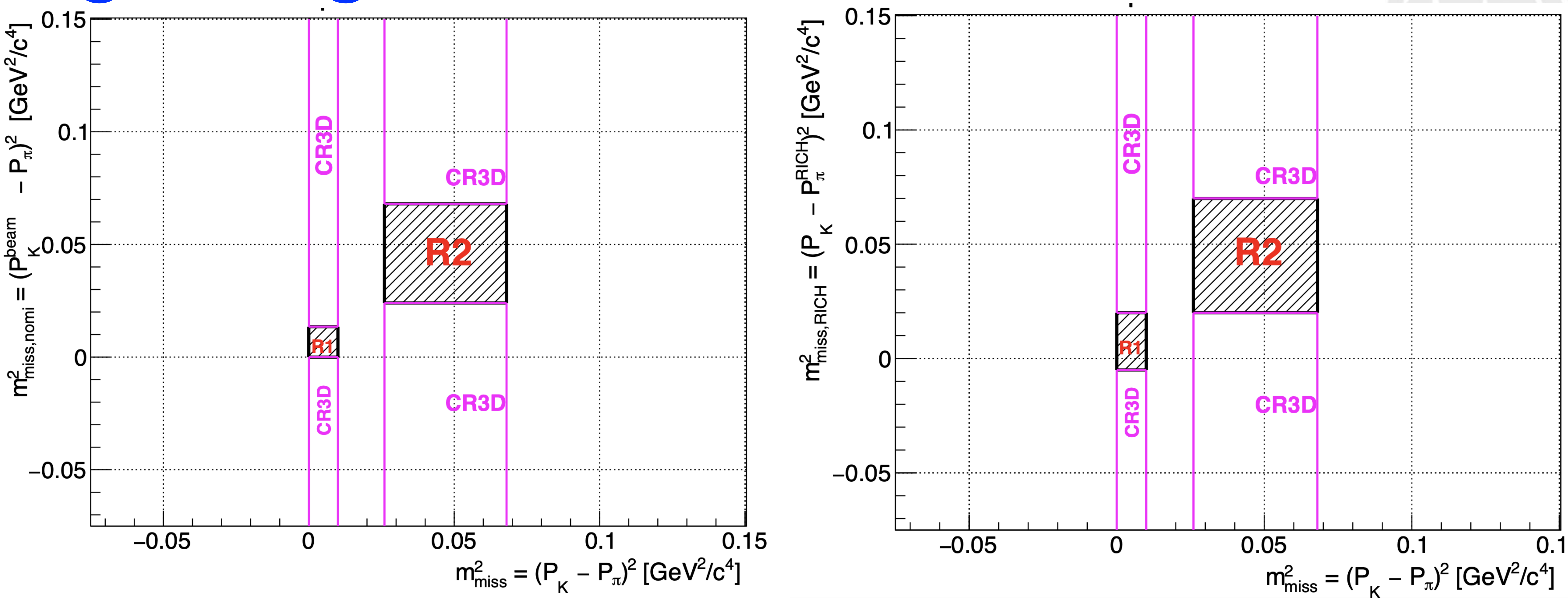
- **Output:** posterior probability of GTK track = true K^+
  - Use likelihoods of kaons (K) and pileup (P)
  - Likelihood ratio used to select true match when $N_{GTK} > 1$
- Efficiency improved (+10%) and mistagging probability maintained.

Kinematic regions



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

3D signal regions definition



CR3D: control region for events in SR in 2 out of 3 dimensions.

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

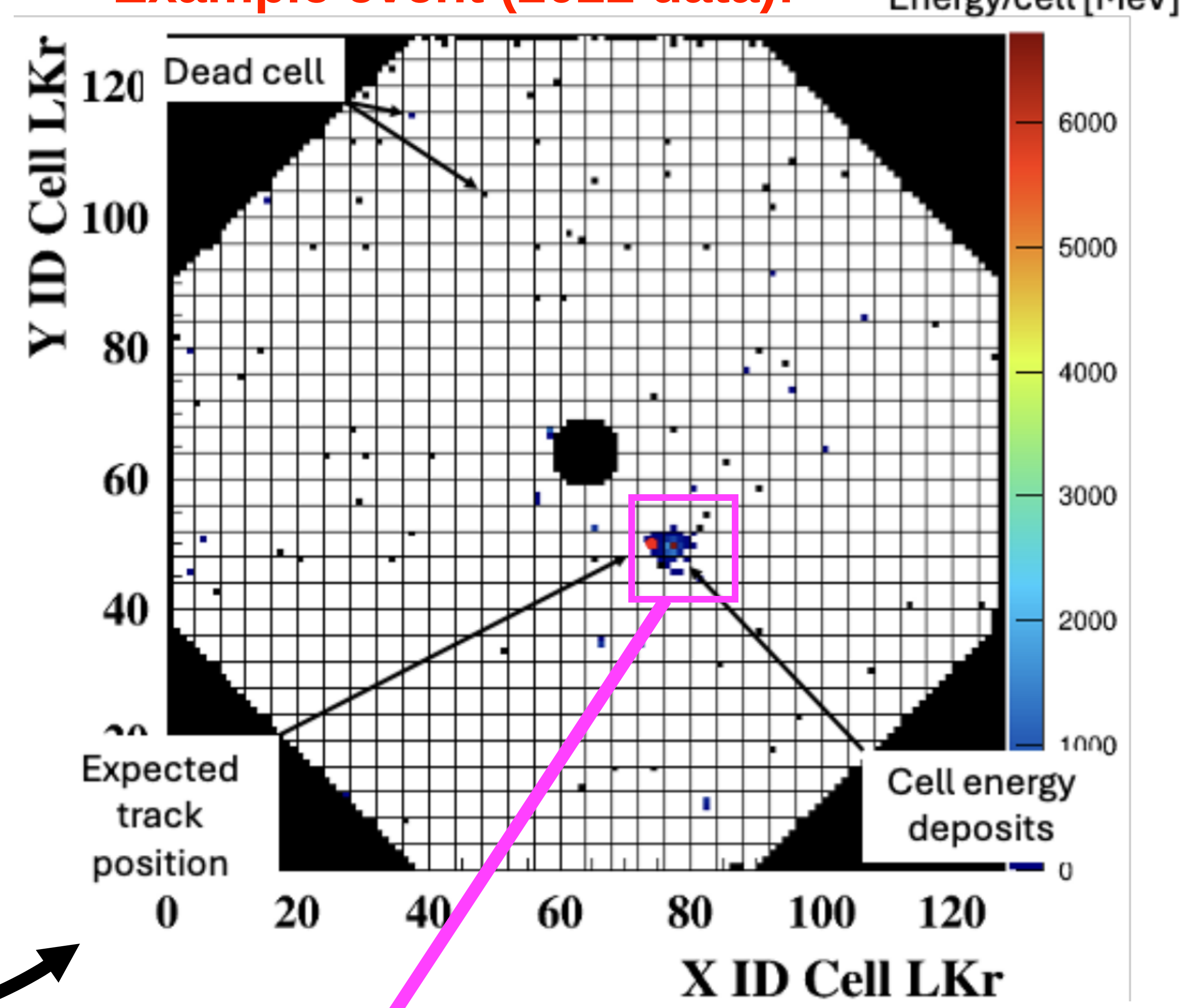
Default: GTK
Alternative: Nominal beam = $m^2_{miss,nom}$

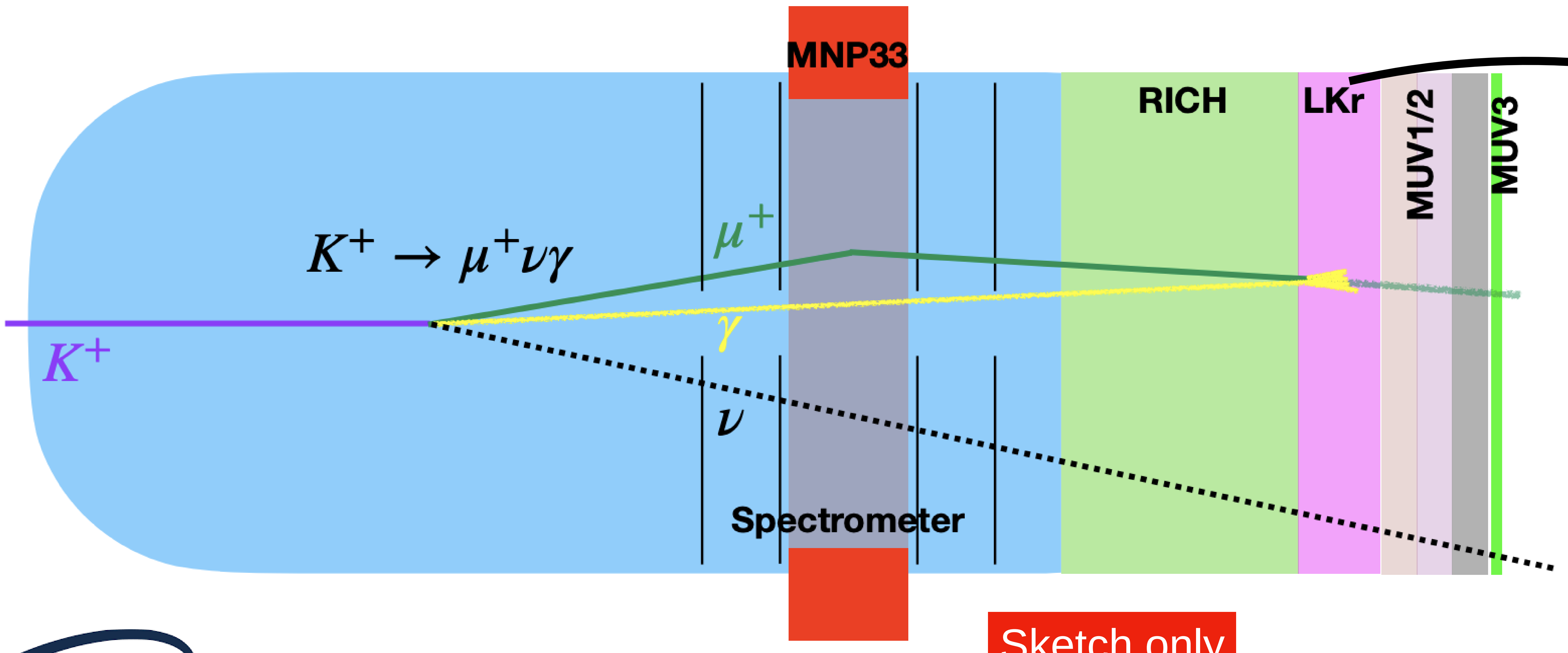
Default: STRAW
Alternative: $|p|$ **from RICH (use as a velocity spectrometer) =** $m^2_{miss,RICH}$

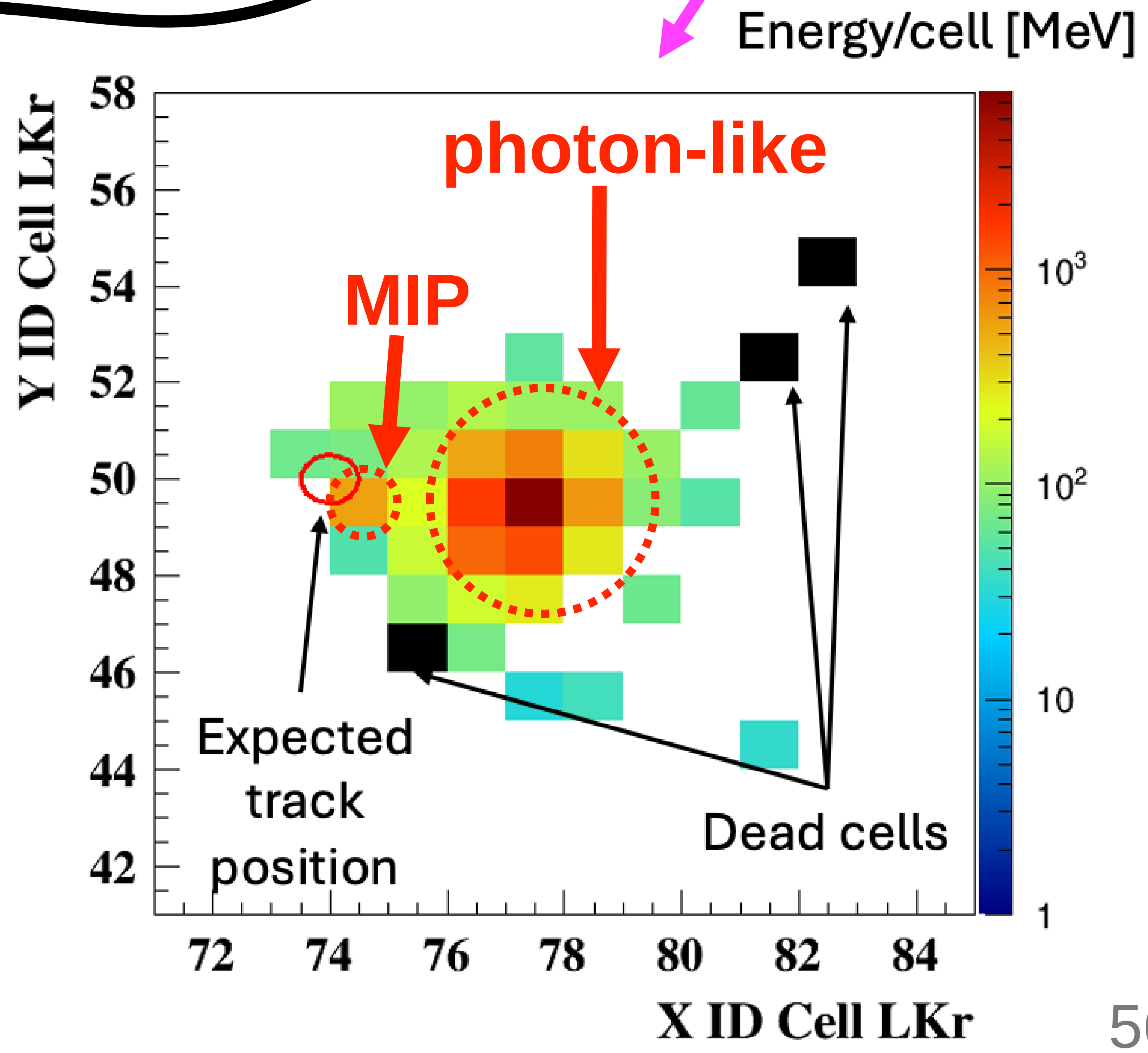
Background mechanism: $K^+ \rightarrow \mu^+\nu\gamma$

- $K^+ \rightarrow \mu^+\nu\gamma$ 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):

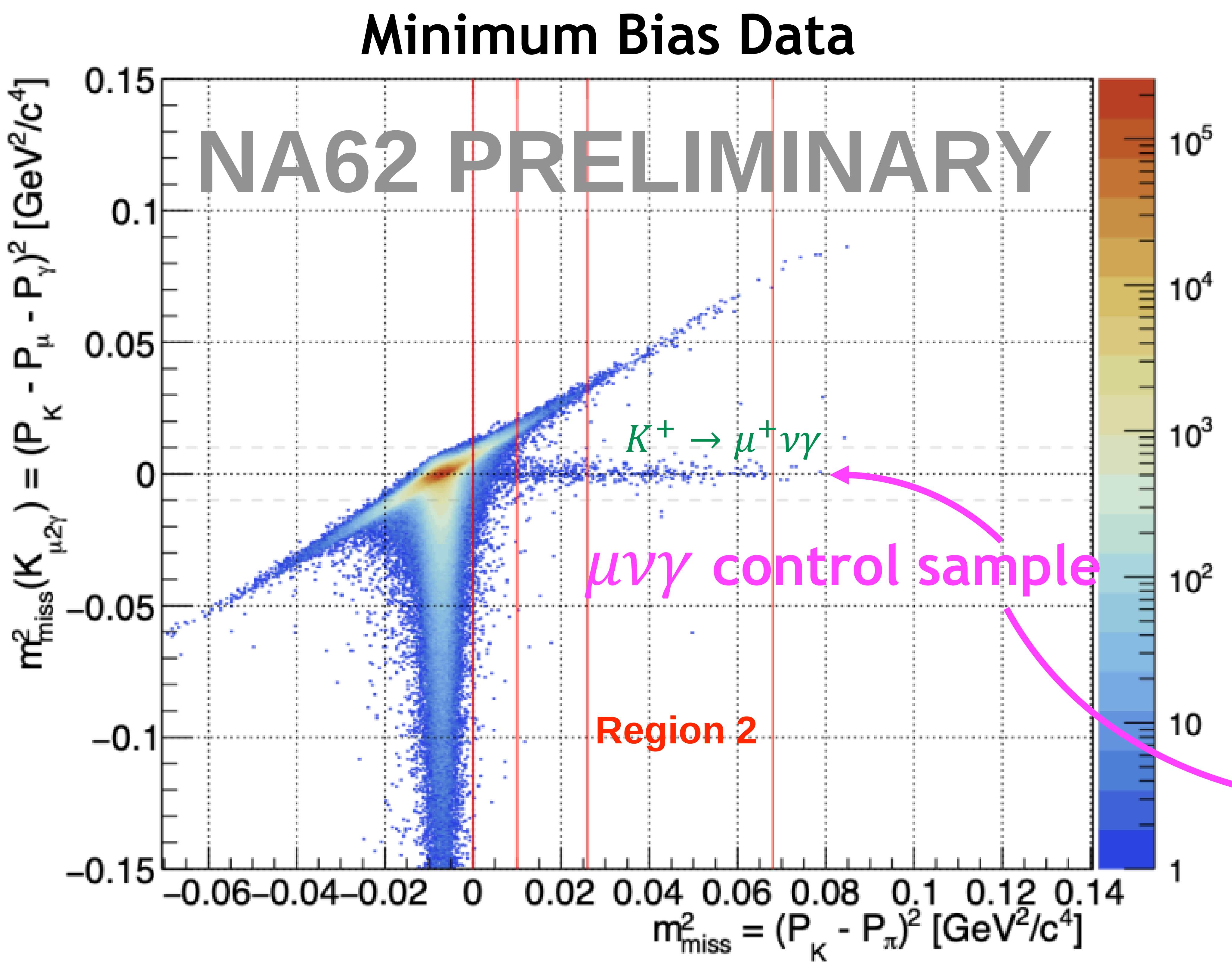






Background evaluation: $K^+ \to \mu^+\nu\gamma$

- Evaluate background expectation using $\mu\nu\gamma$ control sample from MinimumBias (MB) trigger.
  - Not applying Calorimetric BDT classifier and a signal in MUV3.



- Kinematically select $K^+ \to \mu^+\nu\gamma$ events: $m^2_{miss}(K_{\mu2\gamma}) = (P_K - P_\mu - P_\gamma)^2$
  - 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 (subtracting MIP energy deposit) and position of LKr cluster (and position of K^+-μ^+ vertex).

$$N_{bg}(K^+ \to \mu^+\nu\gamma) = N^{MB}_{\mu\nu\gamma} D_{MB} \frac{\varepsilon_{signal}}{\varepsilon_{MB}} P_{misID}$$

Downscaling of MB trigger

Ratio of $\pi^+\nu\bar{\nu}$ and MB trigger efficiencies

probability of γ+μ^+ being misidentified as a π^+

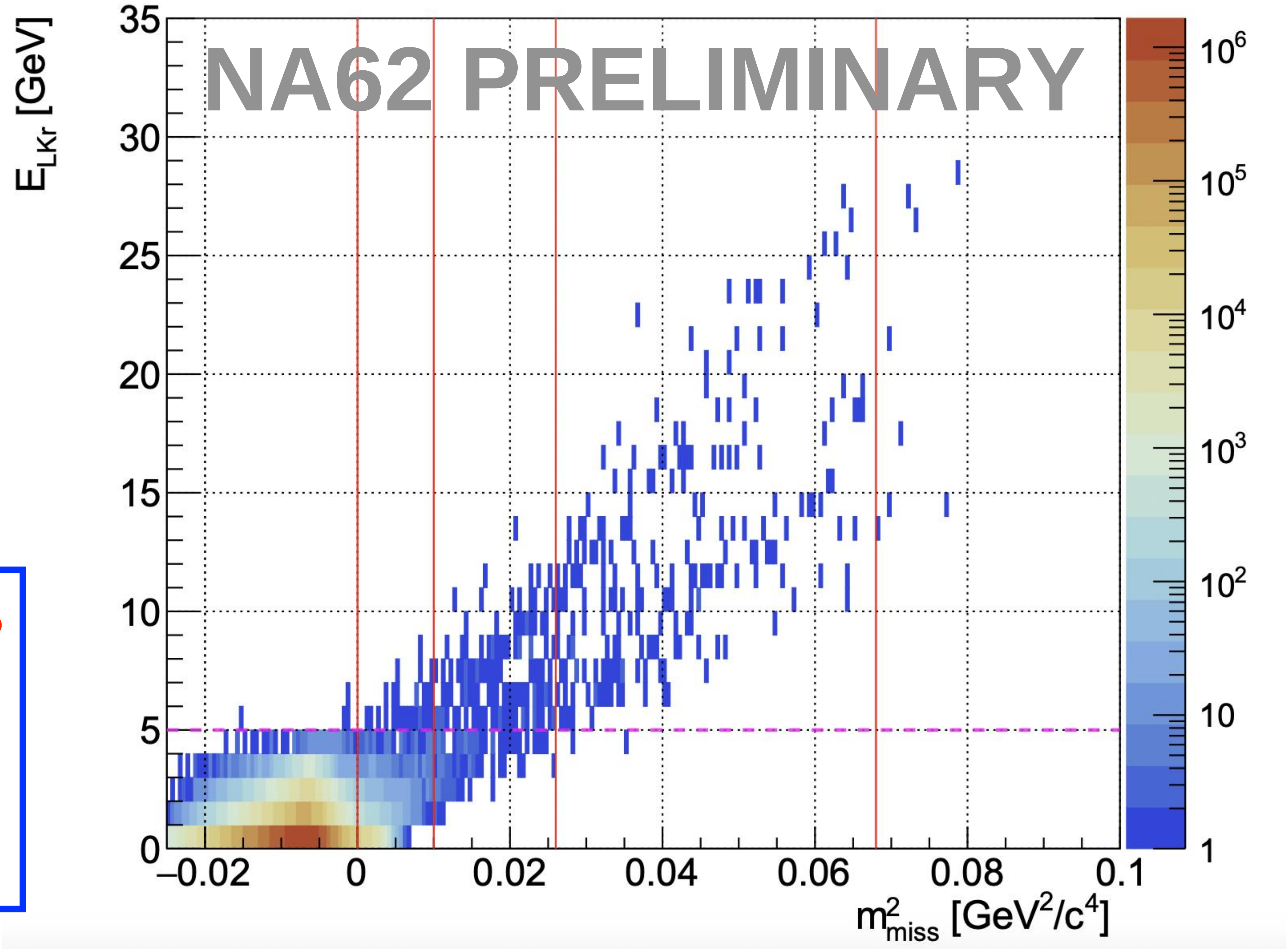
Not included in kinematic tails calculation because the tails sample imposes Calorimetric PID=μ^+, while here there is misID of $\mu^+\gamma \Rightarrow \pi^+$.

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

veto $K^+ \rightarrow \mu^+ \nu\gamma$ events with:

- $|m^2_{miss}(K_{\mu 2\gamma})|^2 < 0.01 GeV^2/c^4$ → c.f. resolution $\sim 0.0025 GeV^2/c^4$
- $E_\gamma > 5 GeV$
- μ^+-like RICH PID.

Minimum Bias Data
Events with MUV3 association and
$|m^2_{miss}(K_{\mu 2\gamma})|^2 < 0.01 GeV^2/c^4$



- **Veto conditions established using data control samples and MC.**
- $K^+ \rightarrow \mu^+ \nu\gamma$ Veto ⇒ 20x background suppression with 0.4% signal loss.

- **Why different to 2016—18 analysis?**
  - Calorimetric PID degraded:
    - Higher intensity in 2021—22 data (in particular, affects MUV1,2).
      - Training of BDT classifier.

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

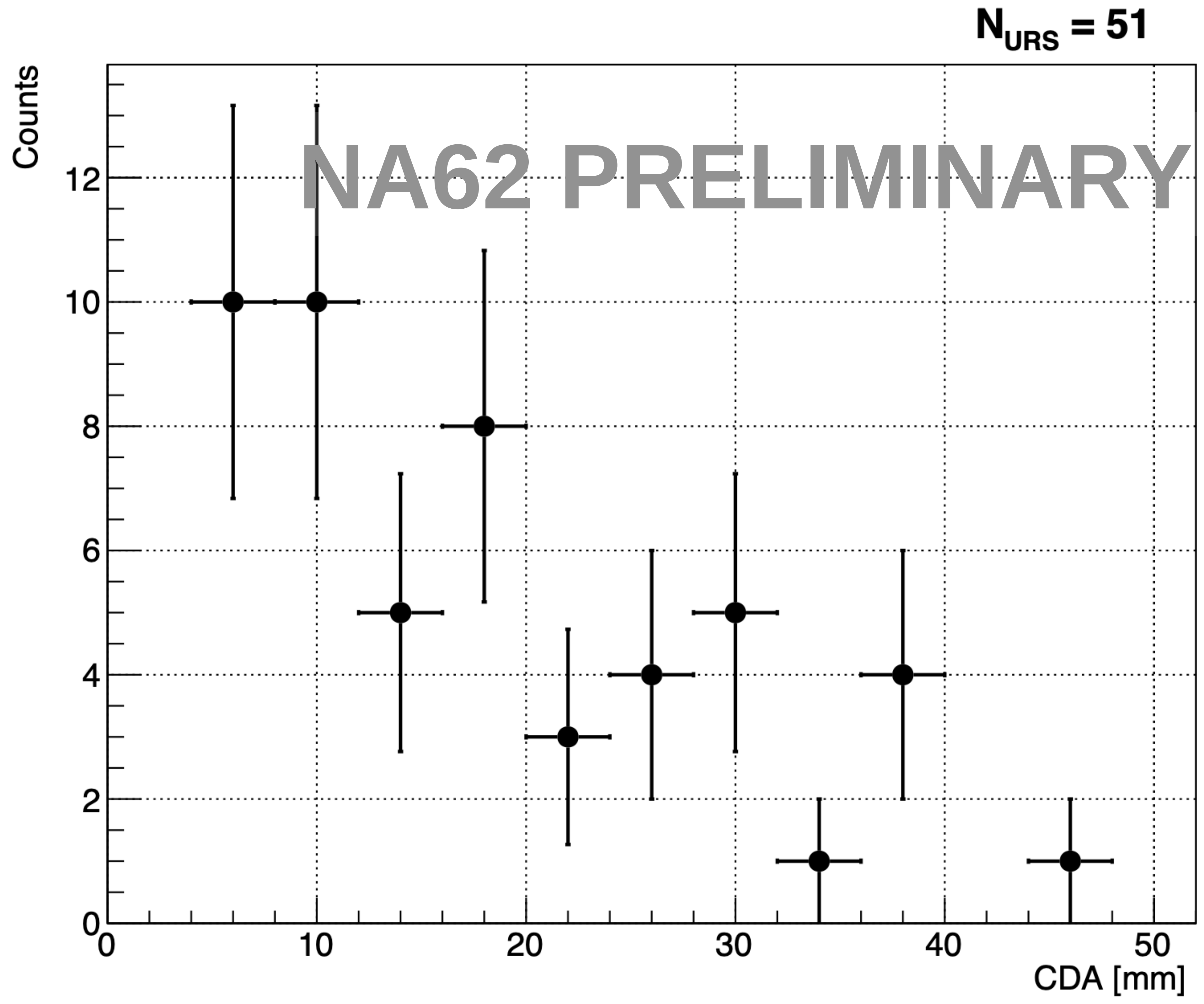
Calculate using bins (i) of $(\Delta T_+, N_{GTK})$

[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** $(\Delta T_+, N_{GTK})$.



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 : this result.
- 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]