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

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BLOIS

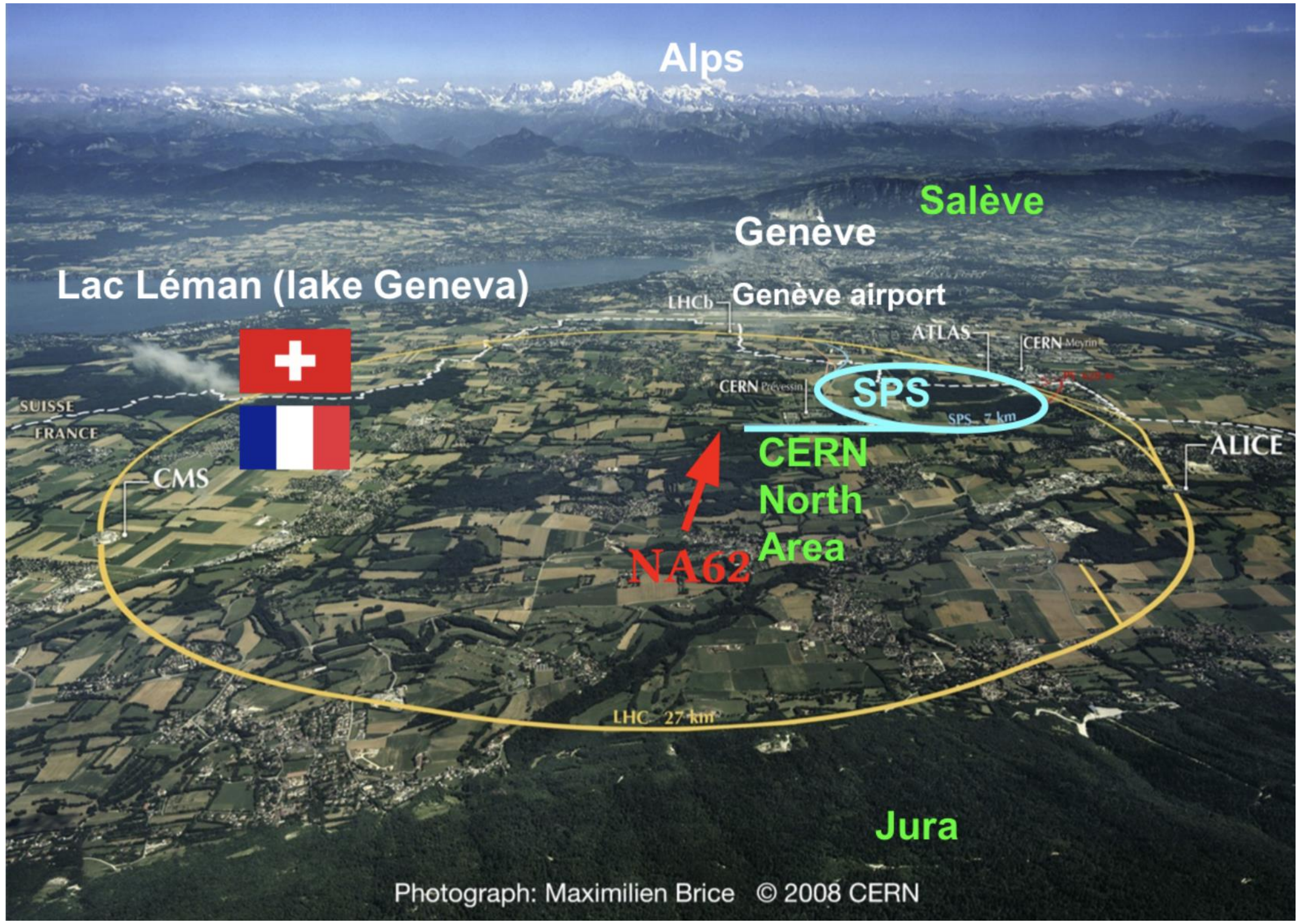
PARTICLE PHYSICS AND COSMOLOGY

2024

Blois (France), October 23rd, 2024

The NA62 Experiment at CERN

~200 collaborators from ~30 institutions.



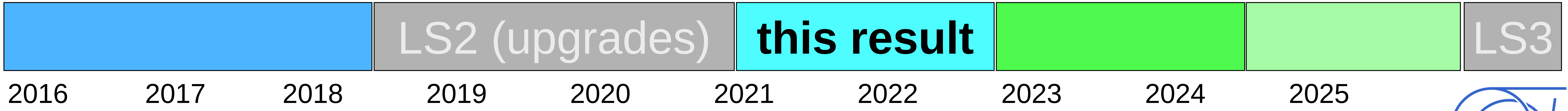
Photograph: Maximilien Brice © 2008 CERN

- **Primary goal: measurement of** $\boldsymbol{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})}$
- **New Technique:** K^+ decay-in-flight
- **Results:** [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
- **Broader physics programme:**
  - **Precision measurements of kaon and pion decays**
  - **HNL and LNV/LFV searches in kaon decays**
  - **Hidden Sector searches with kaons and in dump mode**

See L. Peruzzo's talk later today, Flavour parallel session

- **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 …

This result



LS2 (upgrades)

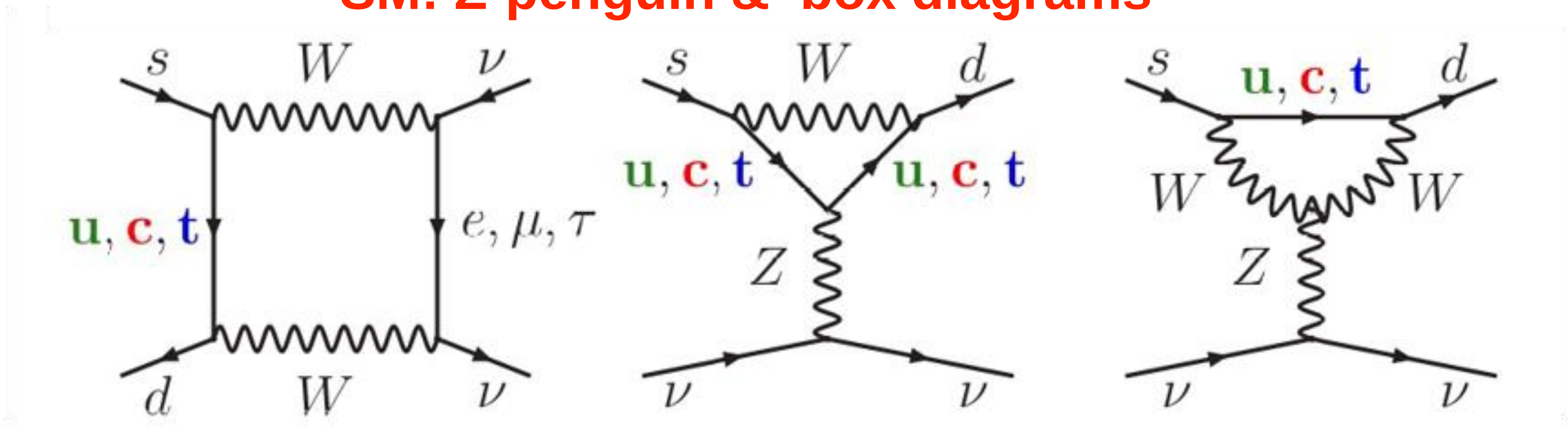
this result

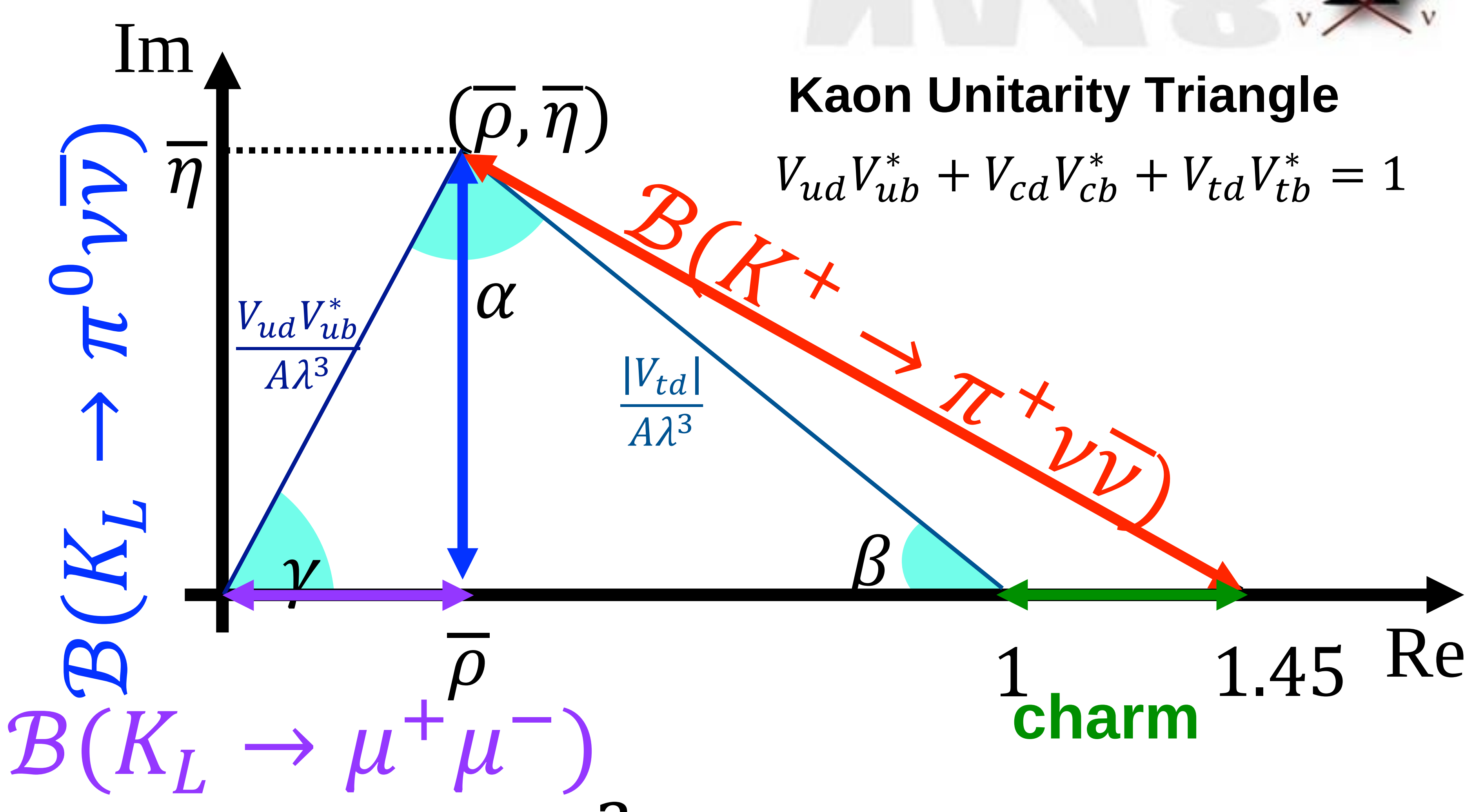
LS3

2016 2017 2018 2019 2020 2021 2022 2023 2024 2025

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

SM: Z-penguin & box diagrams





- $\mathcal{B}(K \to \pi\nu\bar{\nu})$ **highly suppressed** in SM
  - GIM mechanism & maximum CKM suppression $s \to d$ transition: $\sim \frac{m_t^2}{m_W^2}|V_{ts}^*V_{td}|$
- Theoretically clean ⇒ high precision SM predictions
  - Dominated by short distance contributions.
  - Hadronic matrix element extracted from $\mathcal{B}(K \to \pi l \nu)$ decays via isospin rotation.

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

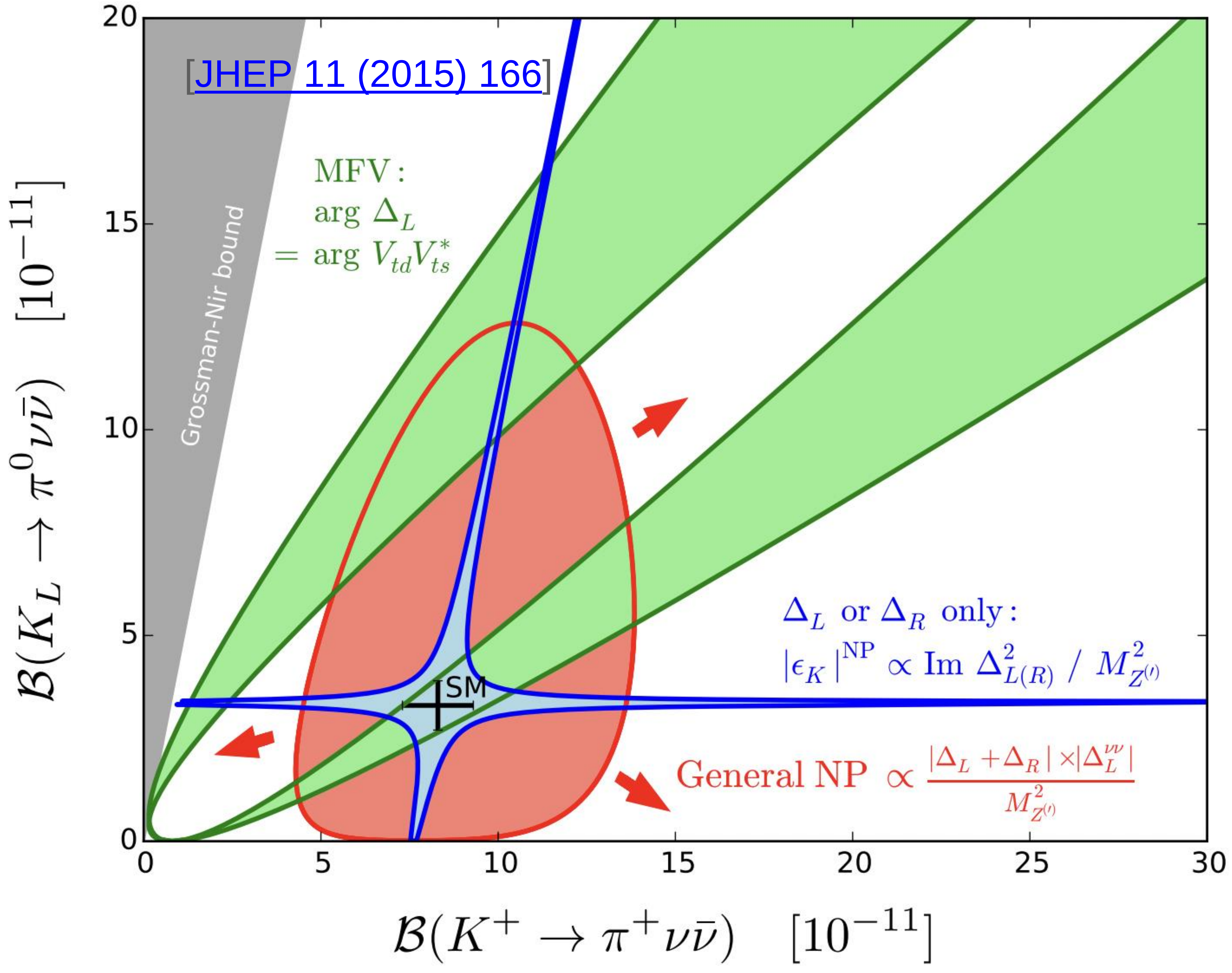
- Correlations between BSM contributions to BRs of K^+ and K_L modes [JHEP 11 (2015) 166].
  - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ε'/ε, ΔM_B, B-decays) [JHEP 12 (2020) 097][PLB 809 (2020) 135769].
- Leptoquarks [EPJ.C 82 (2022) 4, 320], Interplay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

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

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



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

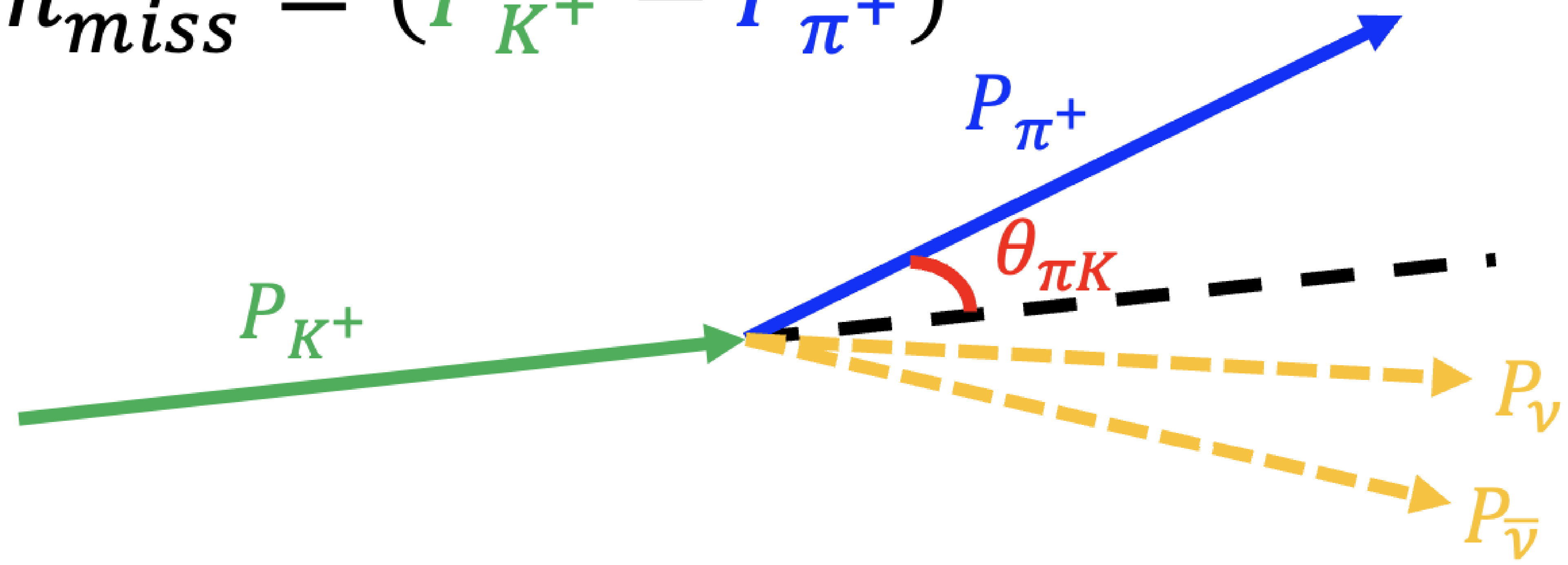
NA62 Strategy:

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

NA62 Performance Keystones:

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

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



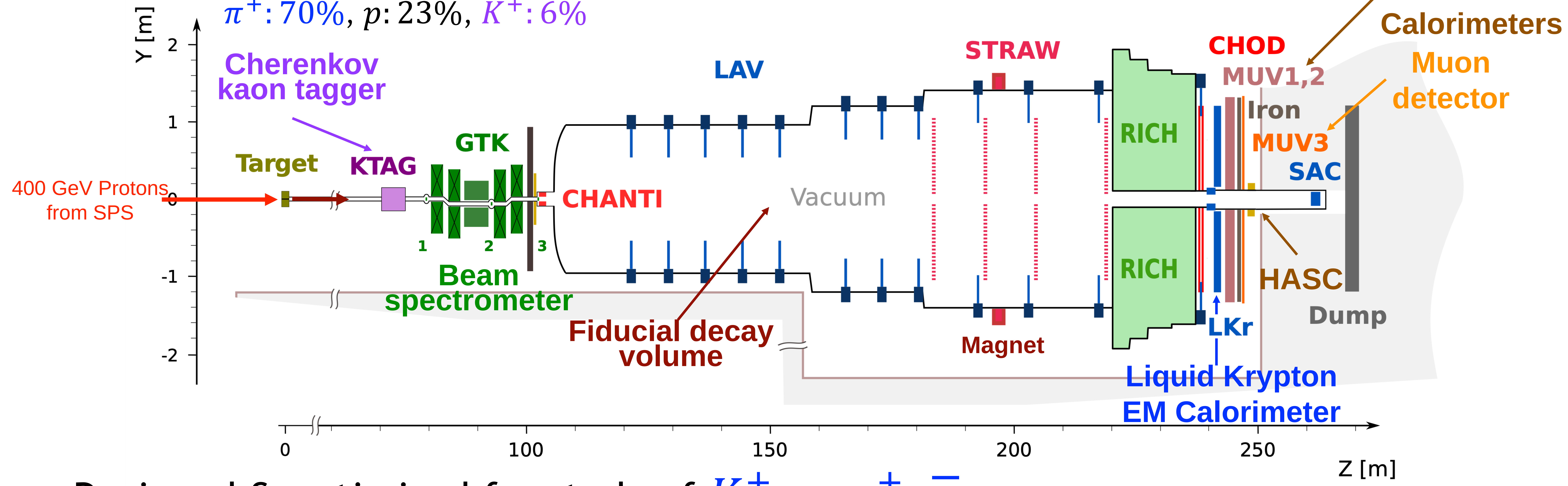
Decay mode	Branching Ratio [PDG]
$K^+ \to \mu^+\nu_\mu$	$(63.56 \pm 0.11)\%$
$K^+ \to \pi^+\pi^0$	$(20.67 \pm 0.08)\%$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024)\%$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$
$K^+ \to \pi^+\nu\bar{\nu}$	$\approx 10^{-10}$

NA62 beamline & detector

[JINST 12 (2017) 05, P05025]

Secondary $75\,GeV/c$ beam:

$\pi^+: 70\%,\ p: 23\%,\ K^+: 6\%$

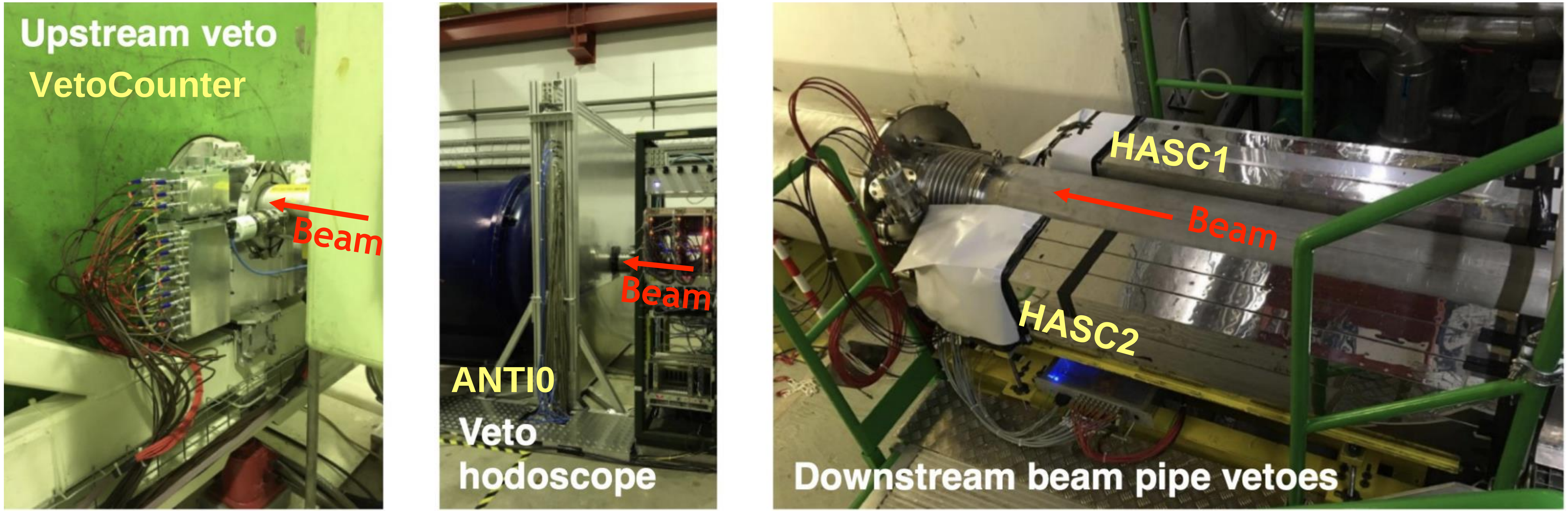


- Designed & optimised for study of $K^+ \to \pi^+ \nu \bar{\nu}$:
  - **Particle tracking:** beam particle (GTK) & downstream tracks (STRAW)
  - **PID:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
  - **Comprehensive veto systems:** CHANTI (beam interactions), LAV,LKr,IRC,SAC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

NA62 upgrades for 2021-22 data taking

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

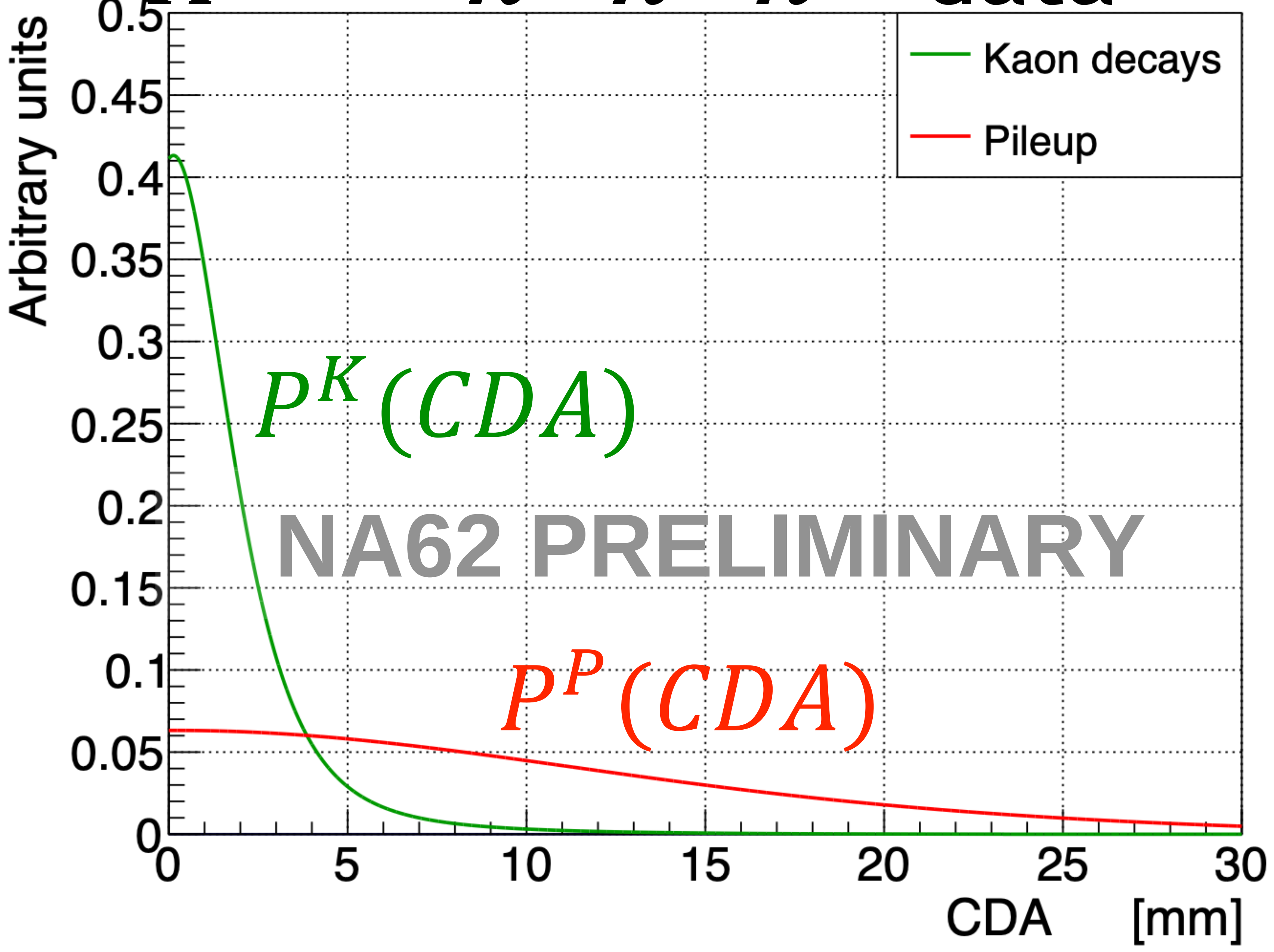
New detectors installed in 2021:



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

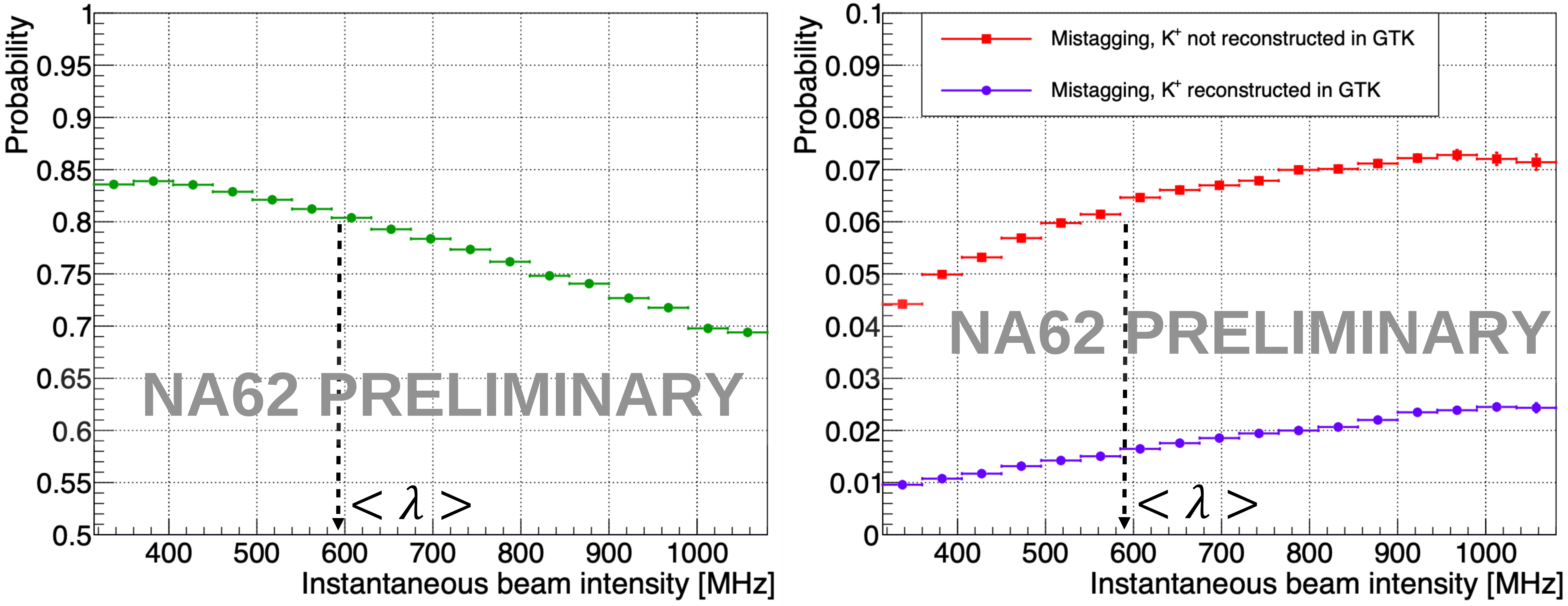
Example of selection update

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



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

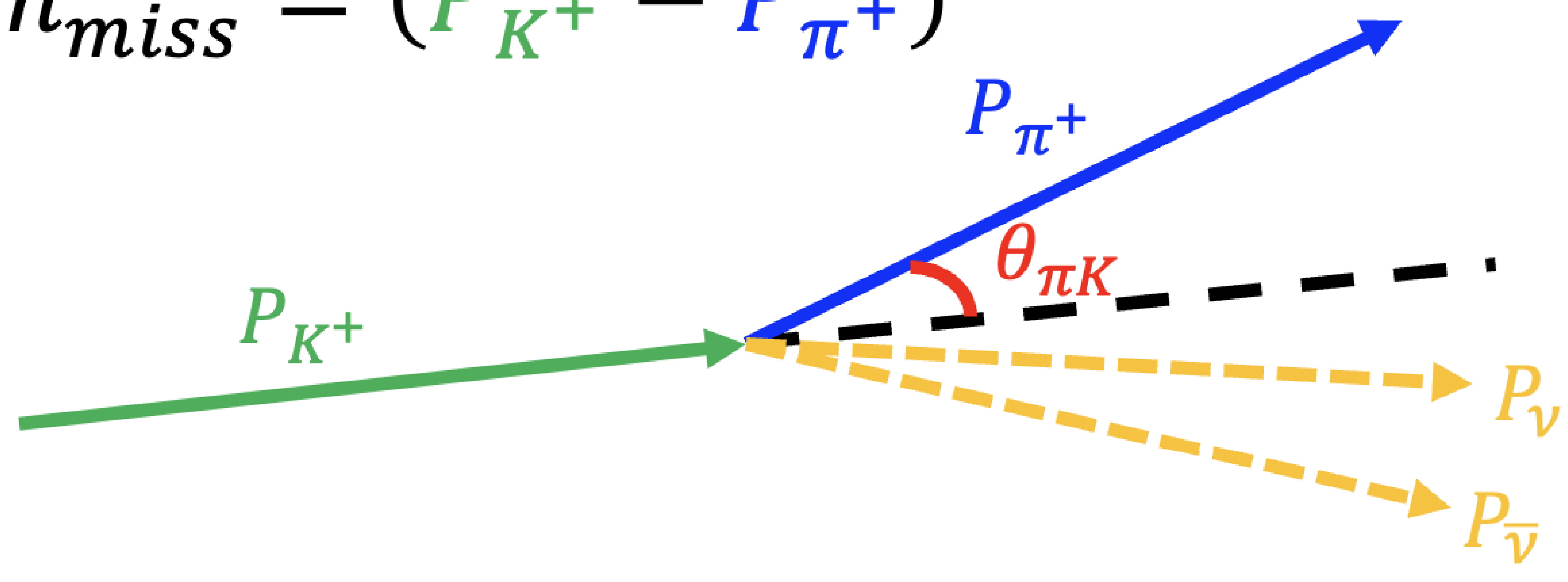
$\varepsilon = 80\%$ $P^P_{mistag} = 6\%$ $P^K_{mistag} = 2\%$

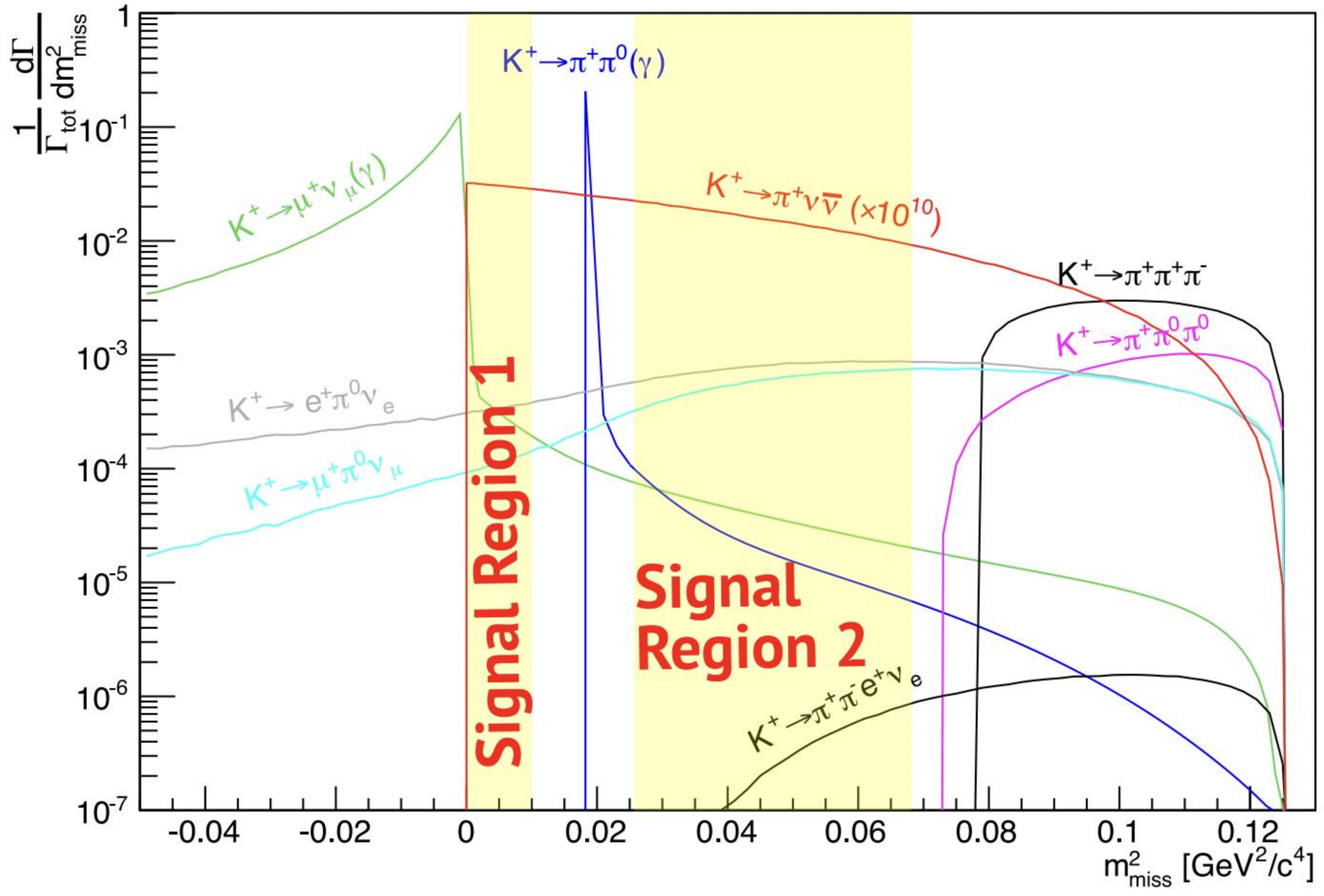


- Efficiency improved (+10%) and mistagging probability maintained.

Kinematic constraints & signal regions

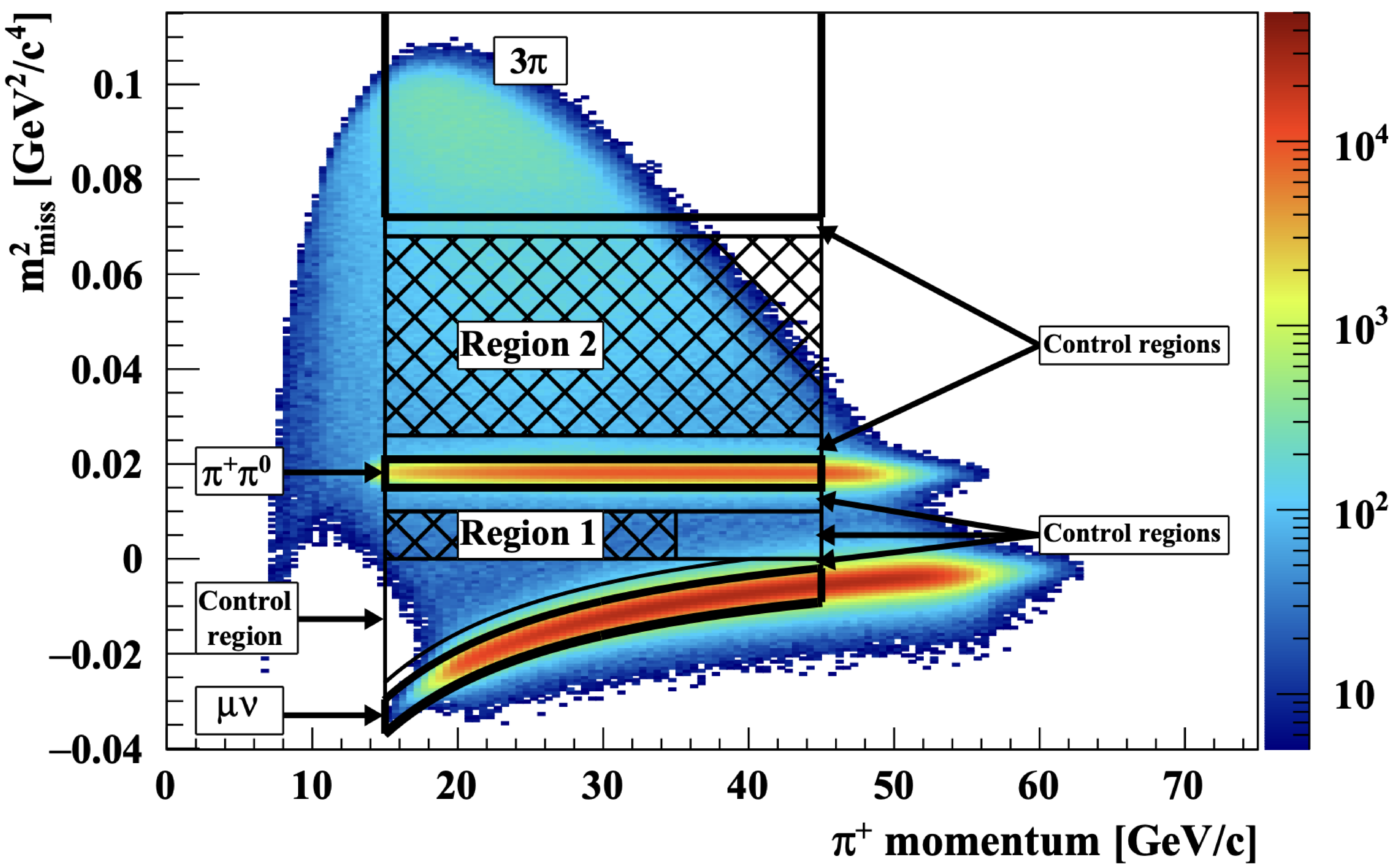
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$





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

[JHEP 06 (2021) 093]



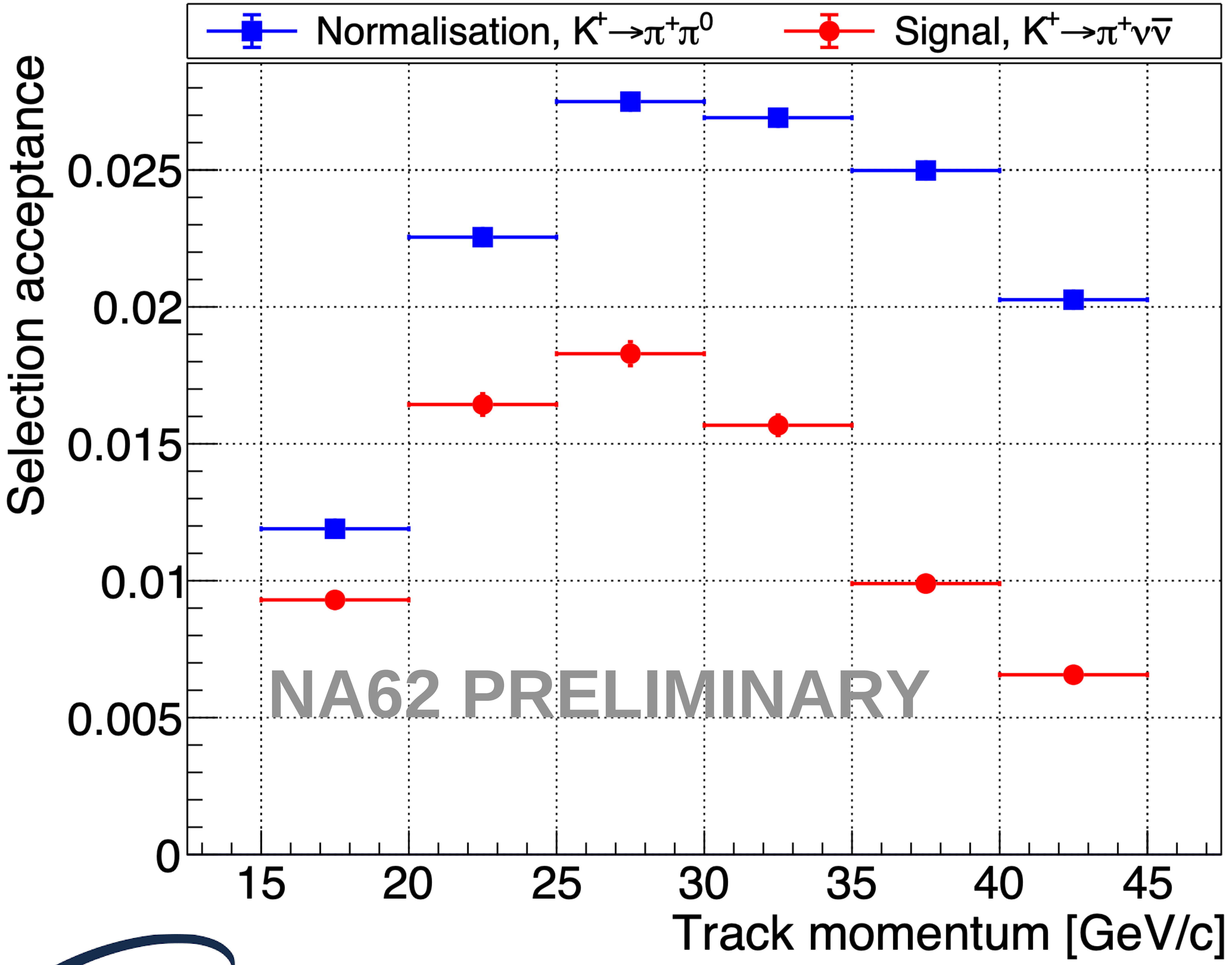
π^+ momentum range: 15—45 GeV/c

Signal sensitivity: acceptances

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

Acceptances

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



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

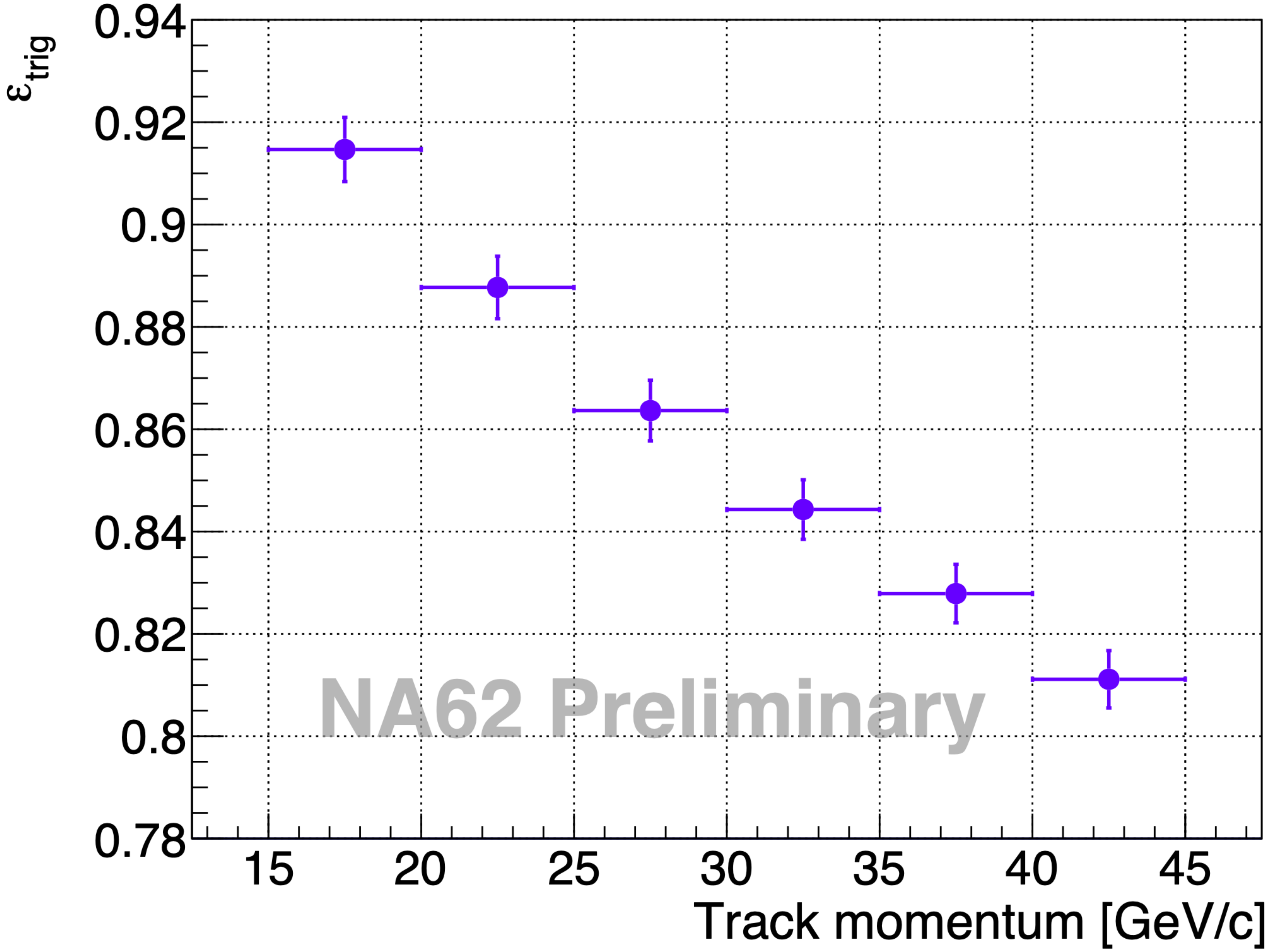
Case	**OLD** 2018 (S2)	**NEW** 2021-22	
Norm.	11.8%	13.4%	**+15%**
Signal	(6.37±0.64)%	(7.61±0.18)%	**+20%**

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

Signal sensitivity: trigger efficiencies

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

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



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

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

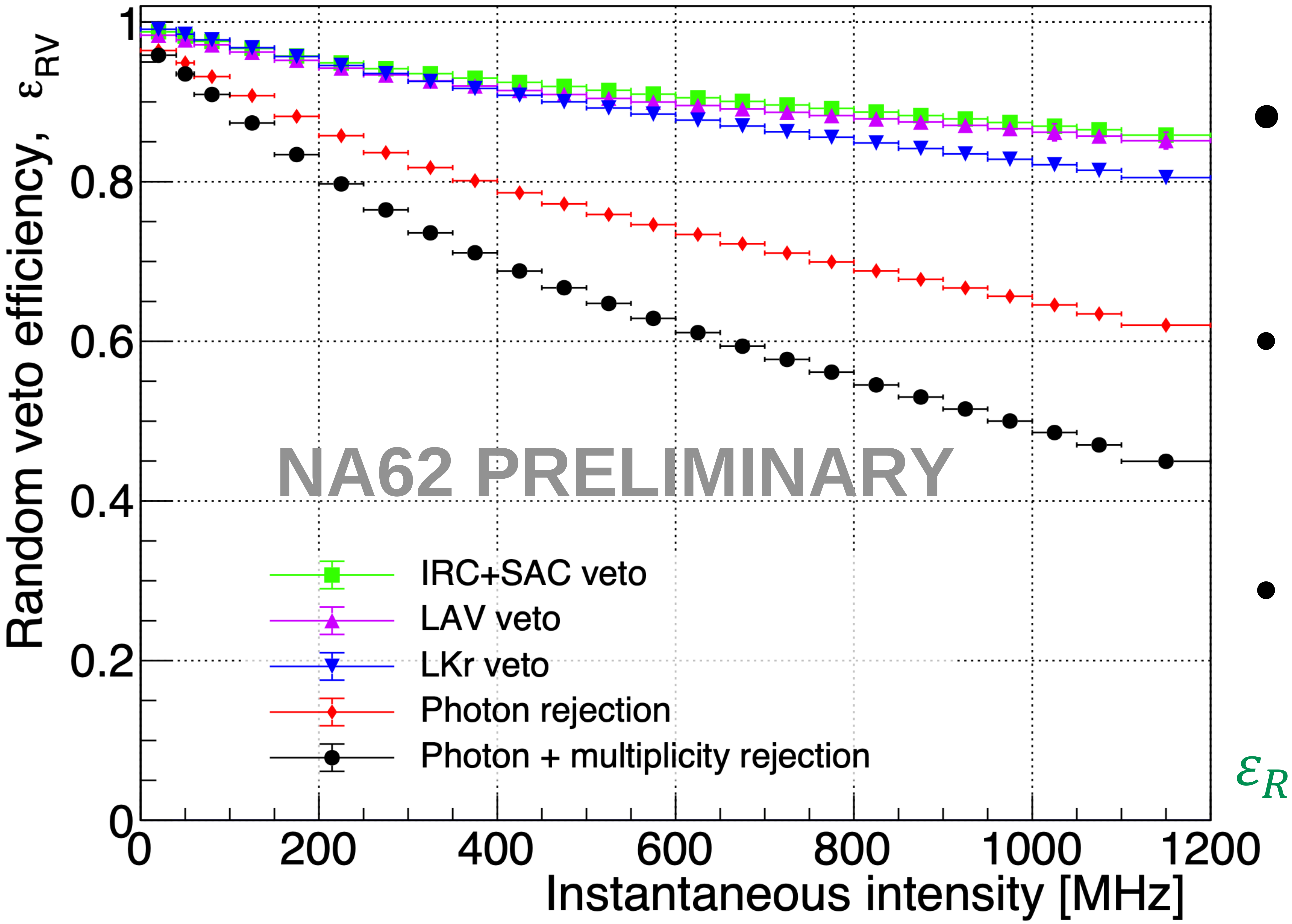
$$\varepsilon_{trig}(2018) = (89 \pm 5)\%$$

- 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.

Signal sensitivity: random veto

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

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



- 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 : $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

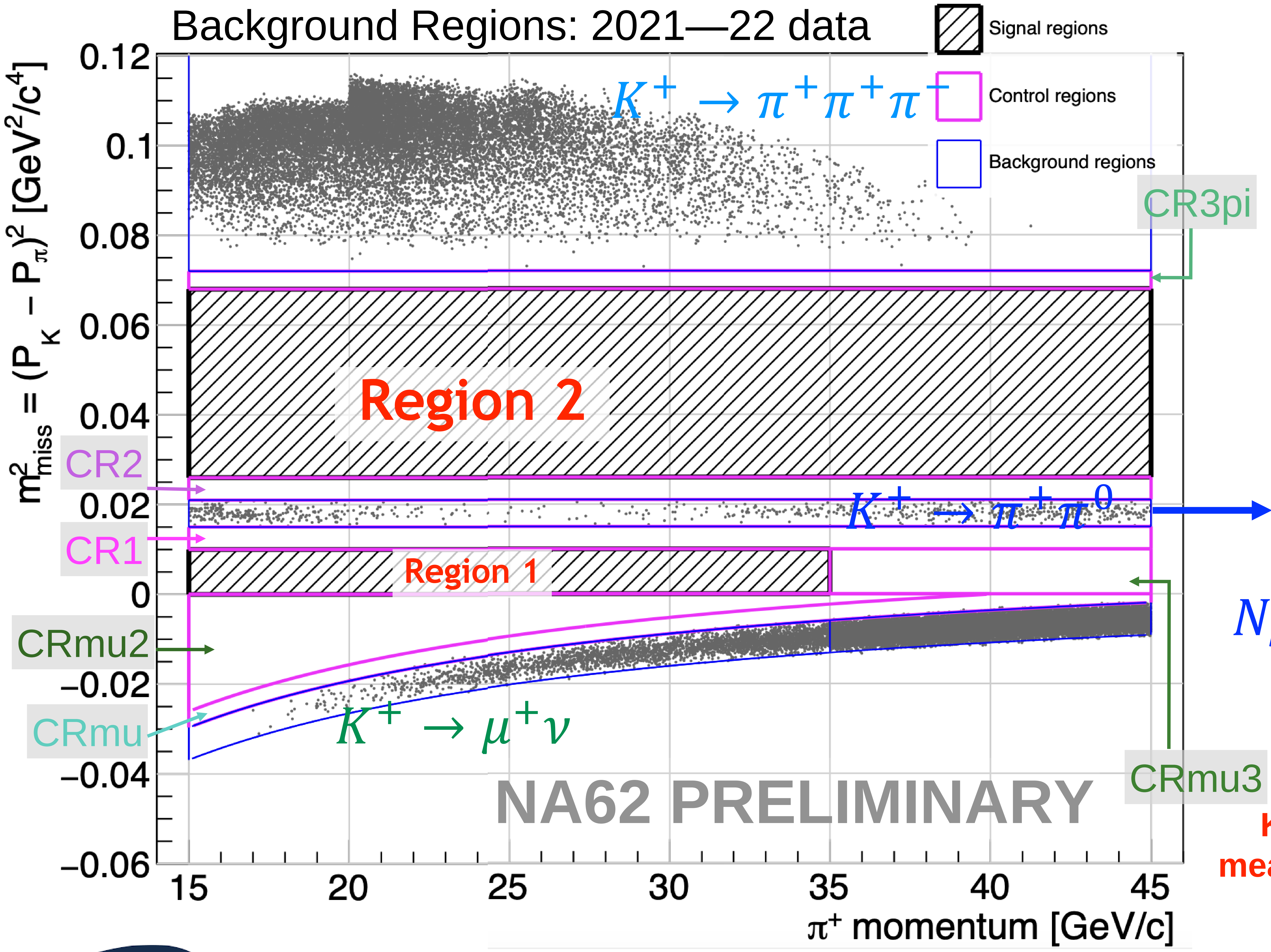
↓

Double expected signal by including 2021—22 data.

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

Background regions & estimations

Events passing $\pi\nu\nu$ selection



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

Number of events passing signal selection in background region

Control sample events in Signal Regions

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

Kinematic tail fraction: measured in control sample

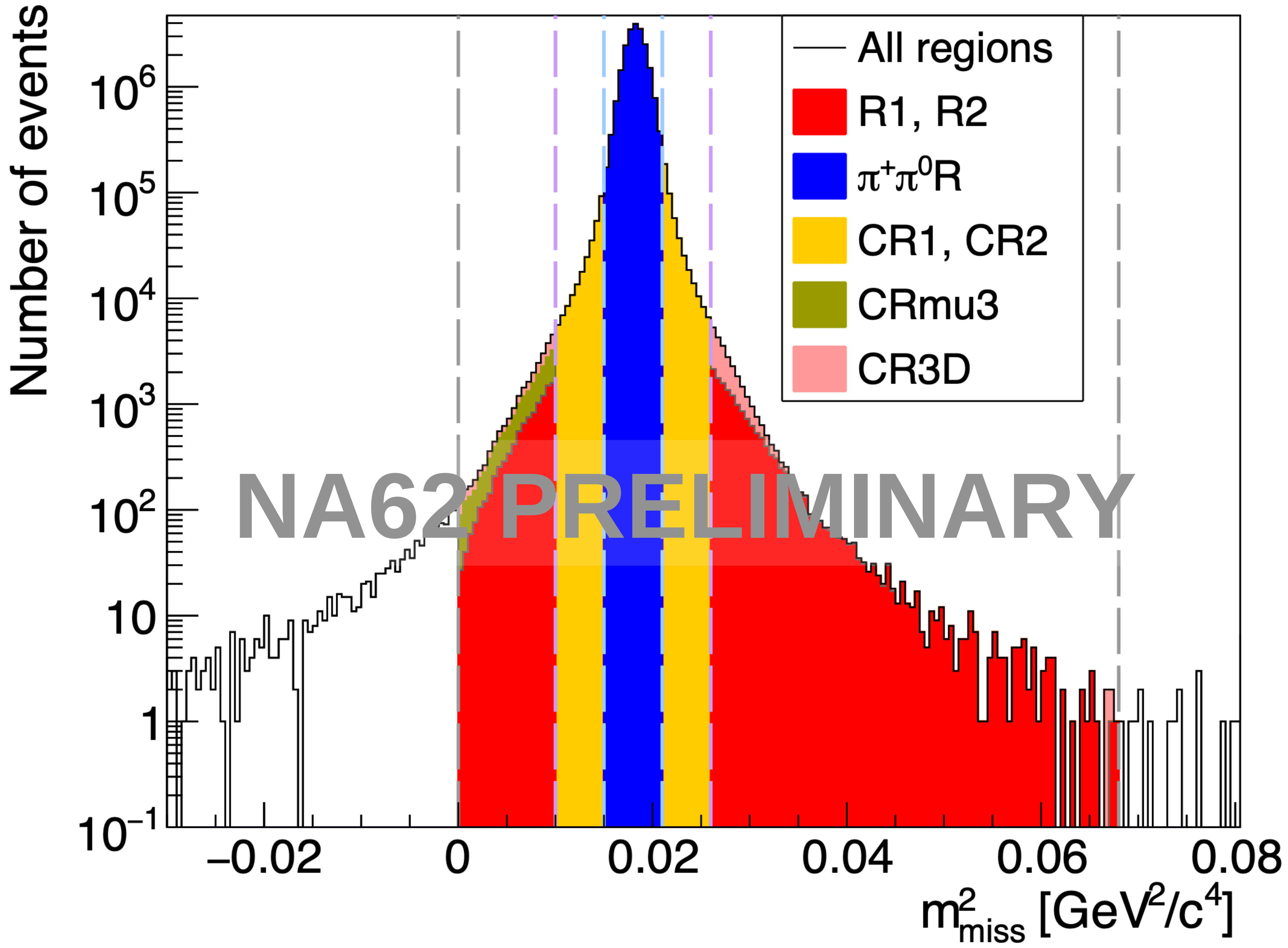
Control sample events in Background Region

Background estimations in signal regions validated with control regions

Backgrounds from kinematic tails

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

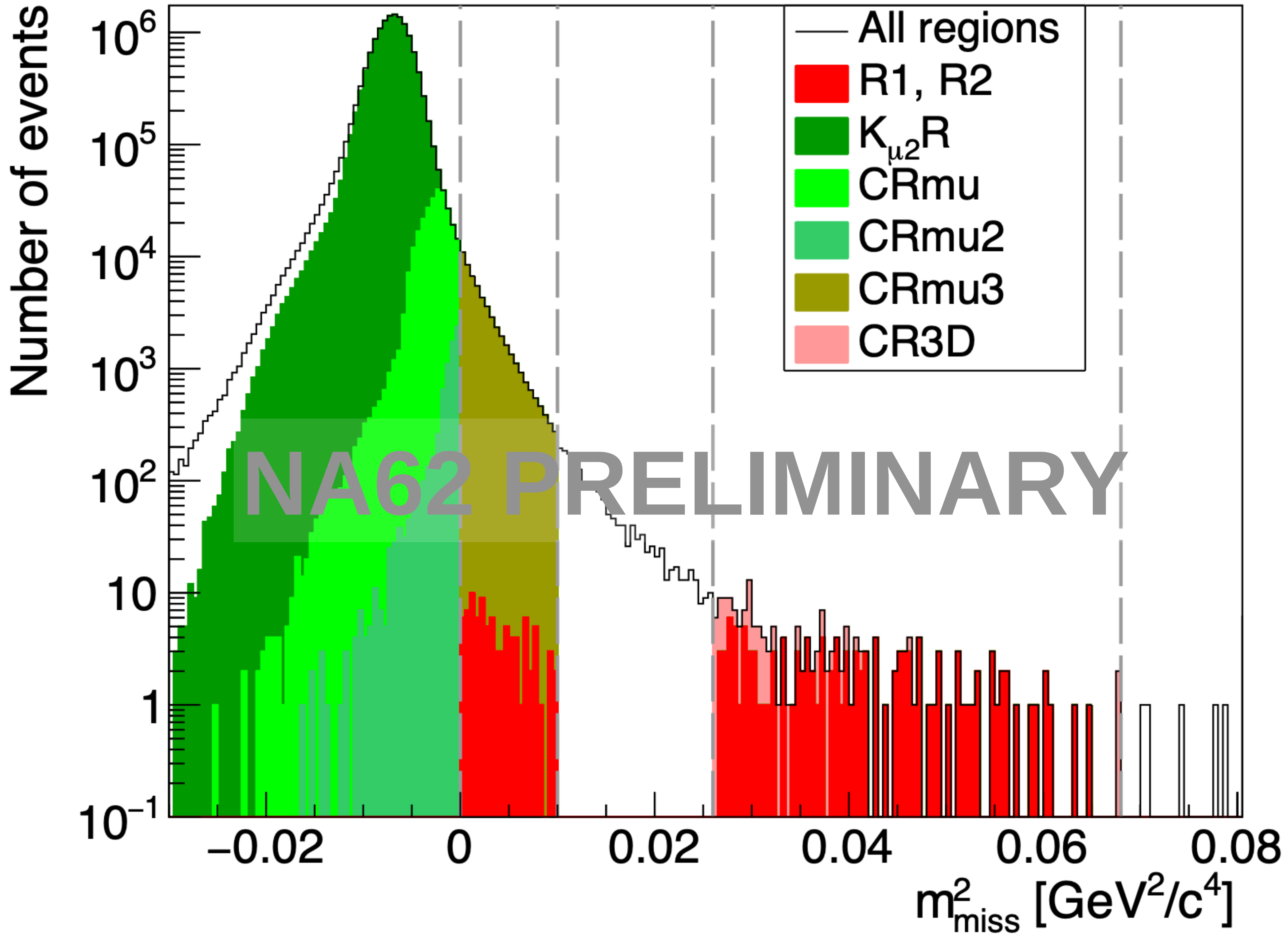
control sample of $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ and 2 photons detected in LKr:



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

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

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

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

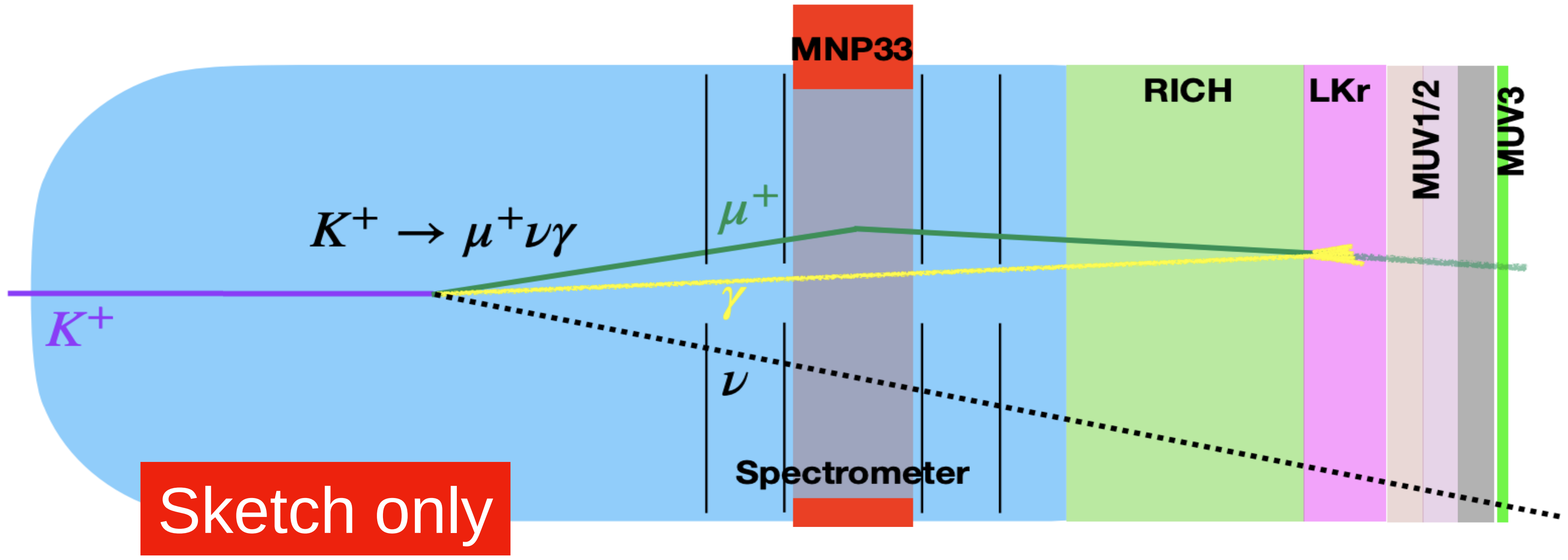
$K^+ \to \pi^+\pi^+\pi^-$

- Use MC to measure f_{tail}:

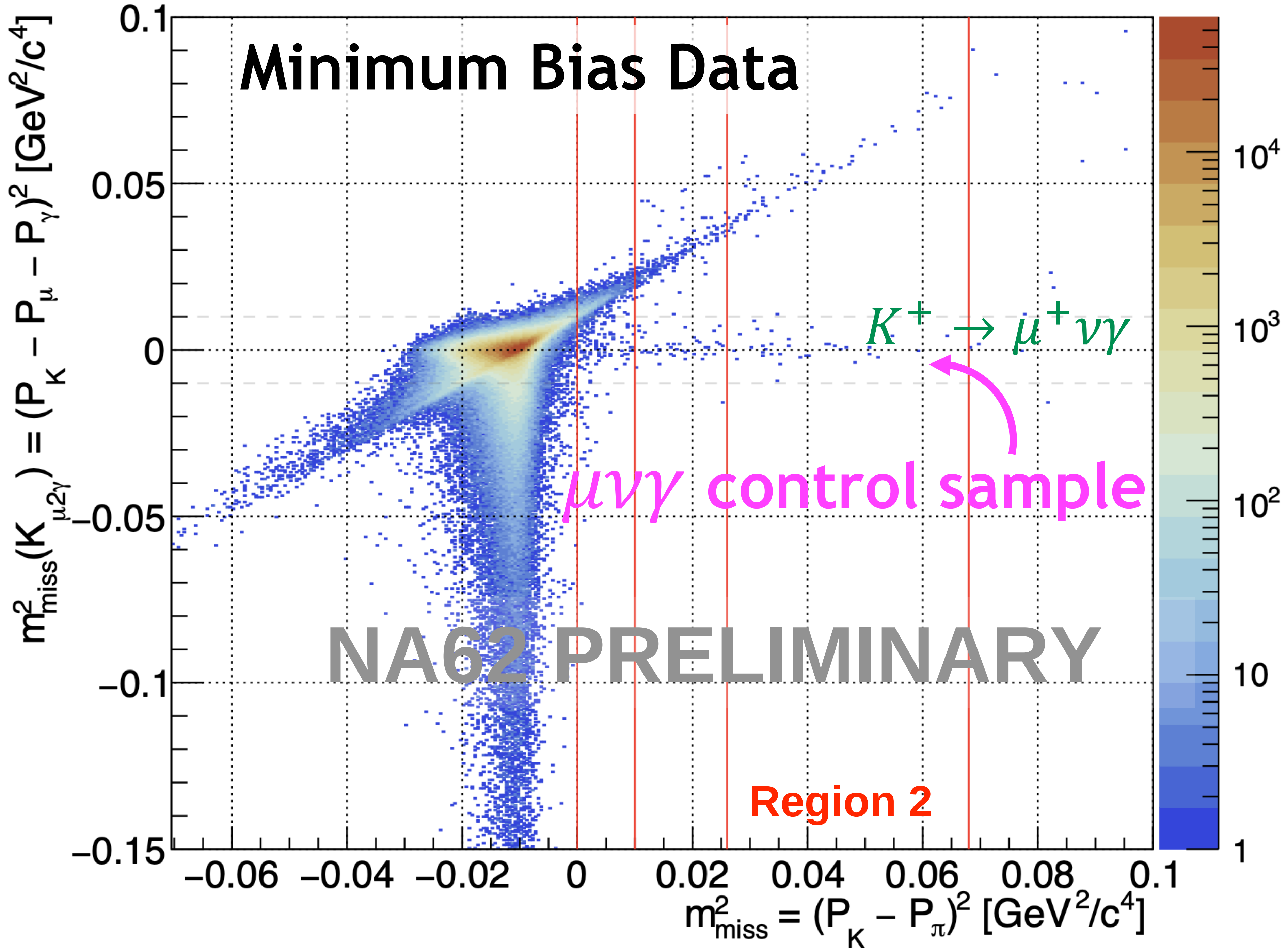
$$N_{bg}(K^+ \to \pi^+\pi^+\pi^-) = 0.11 \pm 0.03$$

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).

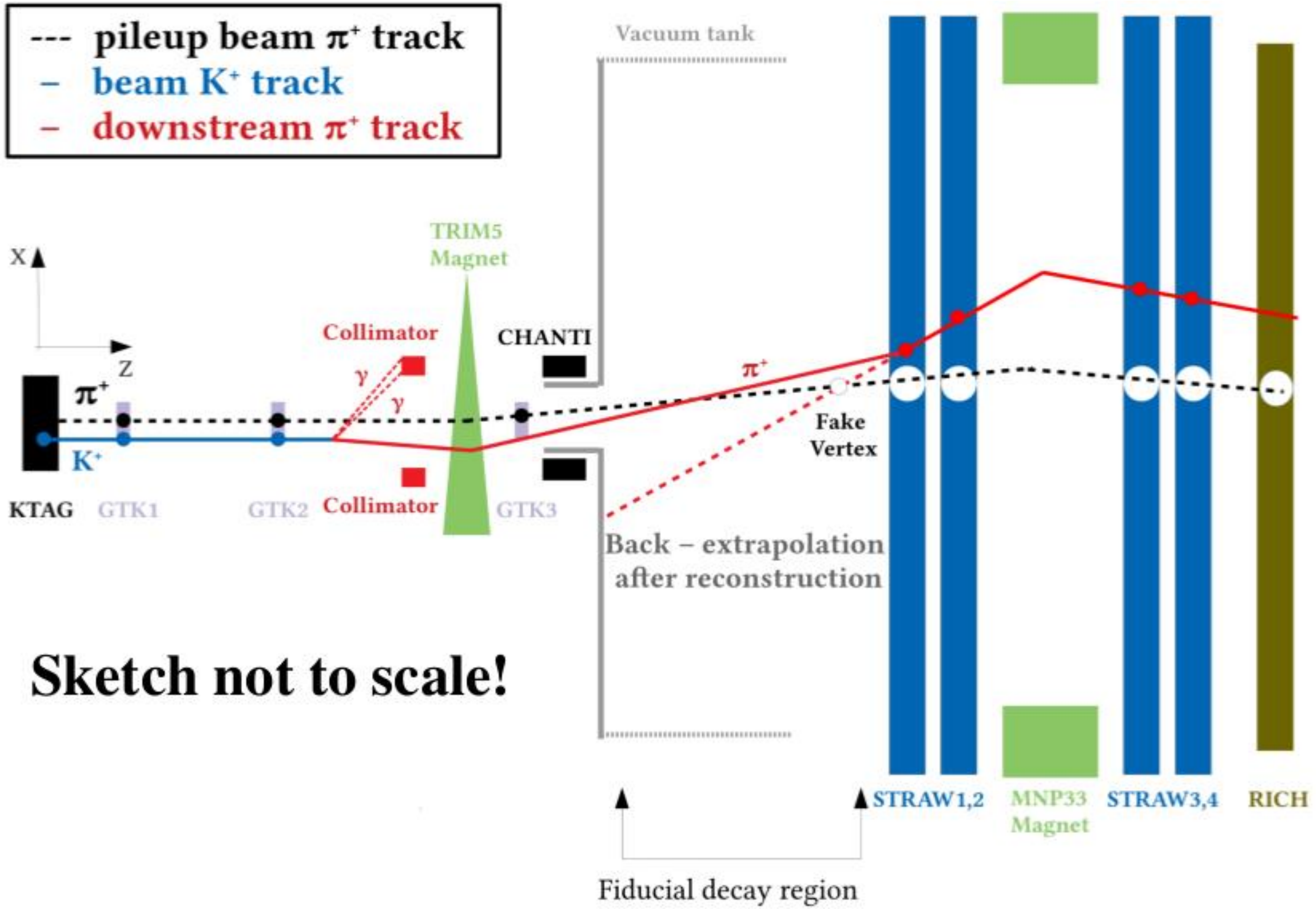


- Before $K^+ \to \mu^+\nu\gamma$ veto: found excess of events at $p > 35\,GeV/c$ in Region 2 relative to 2016—18 data.
- Additional background identified and studied in data control samples & MC.
- $K^+ \to \mu^+\nu\gamma$ veto added to selection criteria for final analysis.



Upstream background mechanism

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



Upstream background evaluation

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

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

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

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

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

[Updated to fully data-driven procedure]

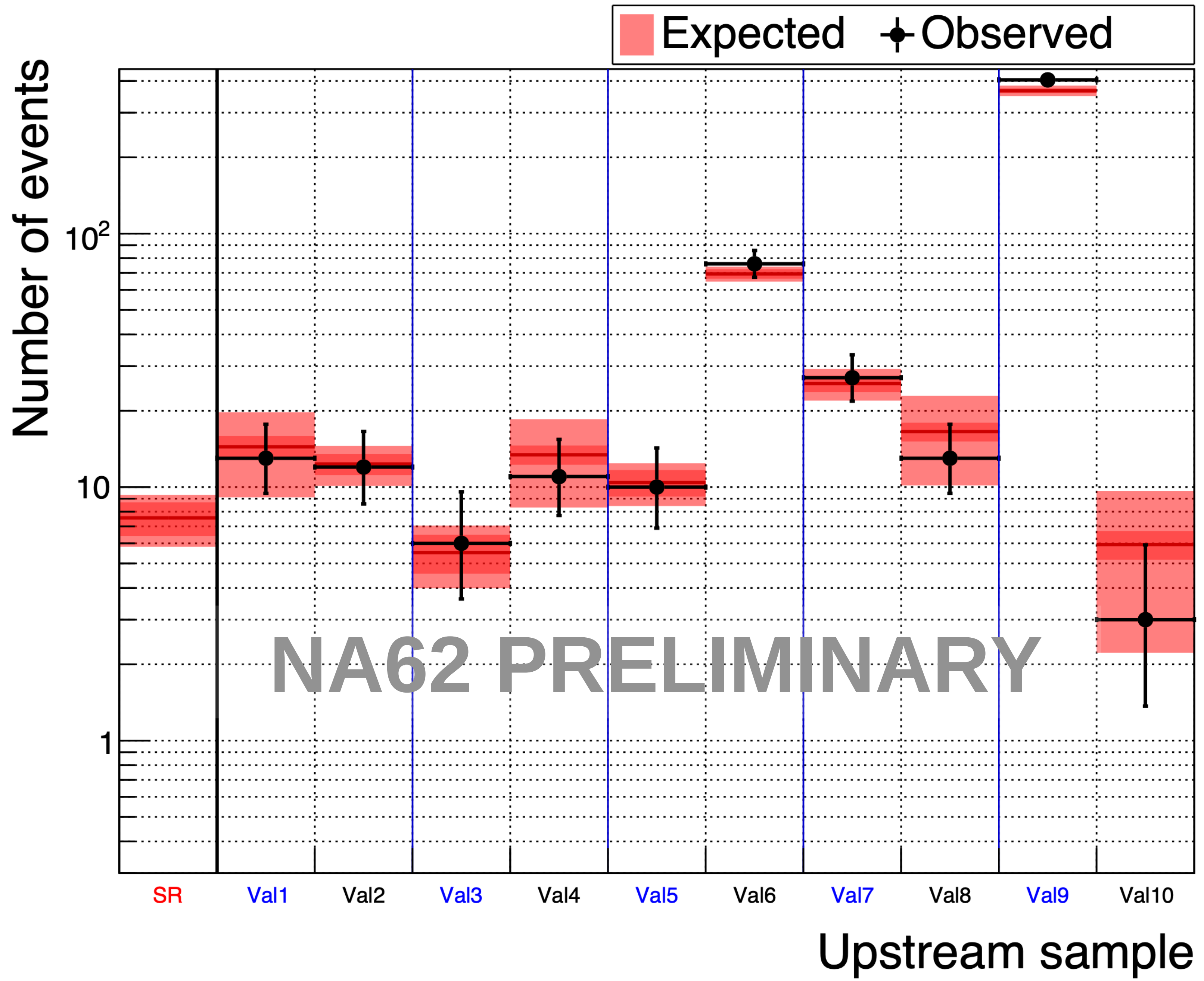
$N = 51 \quad f_{CDA} = 0.20 \pm 0.03 \quad < P_{match} > = 73\%$

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

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

VALIDATION SAMPLES:

invert & loosen upstream vetos to enrich with different mechanisms



Summary of expectations

Backgrounds

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

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

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

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

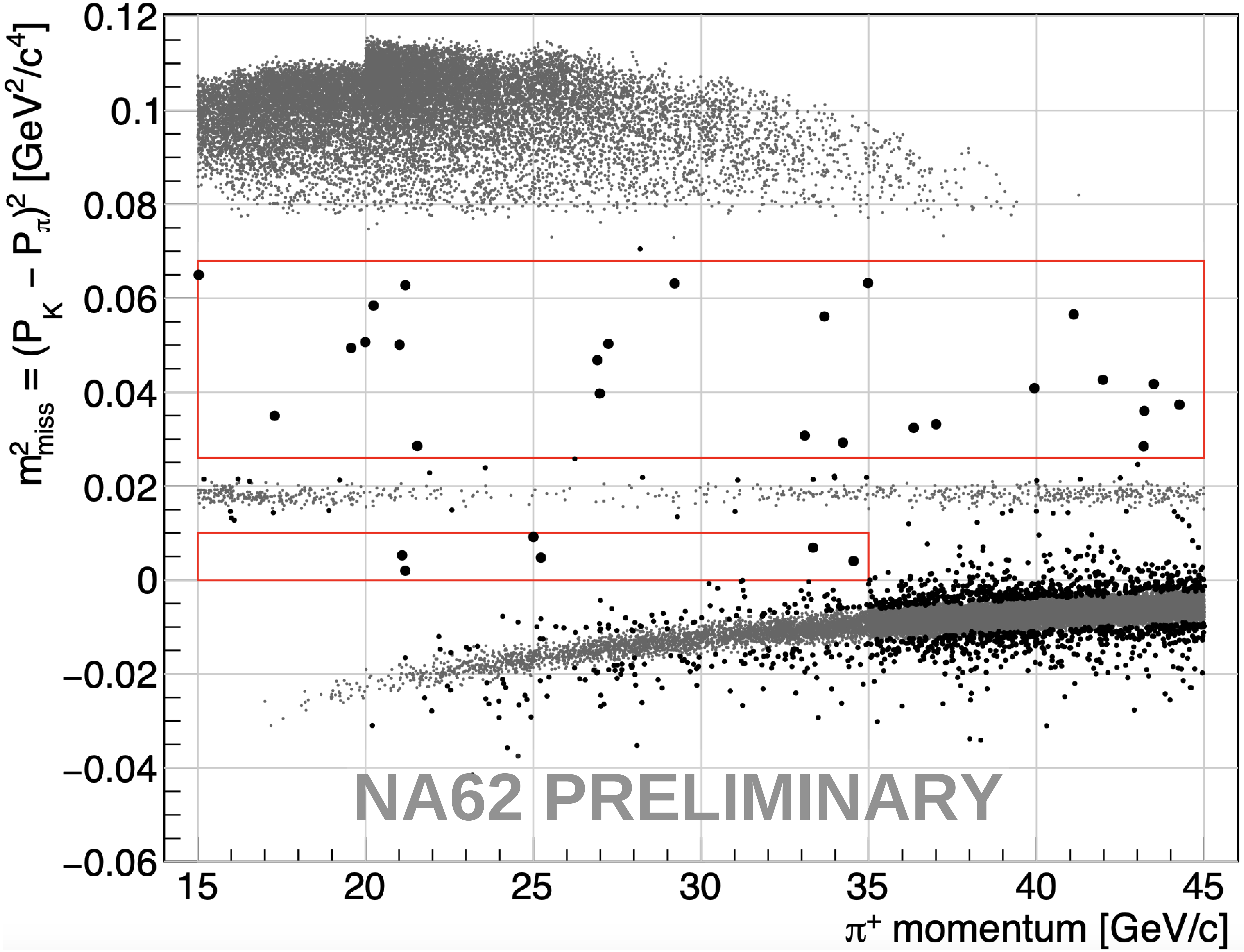
2021–22: $N_{\pi\nu\bar{\nu}} = 10.00 \pm 0.34$

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

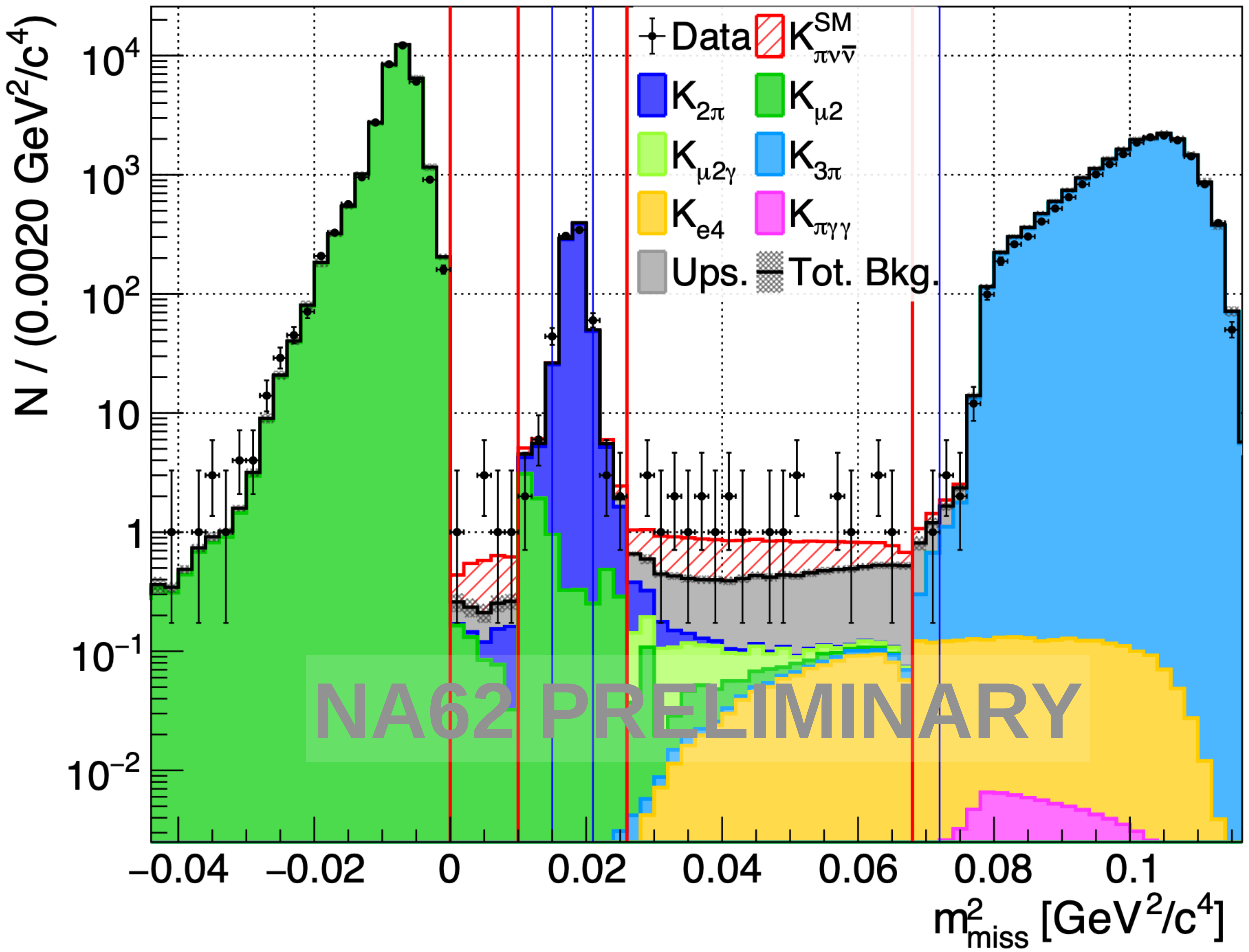
→ **Expected signal doubled by including 2021–22 data**

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

Signal regions: 2021—22 Data


2021—22 data

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



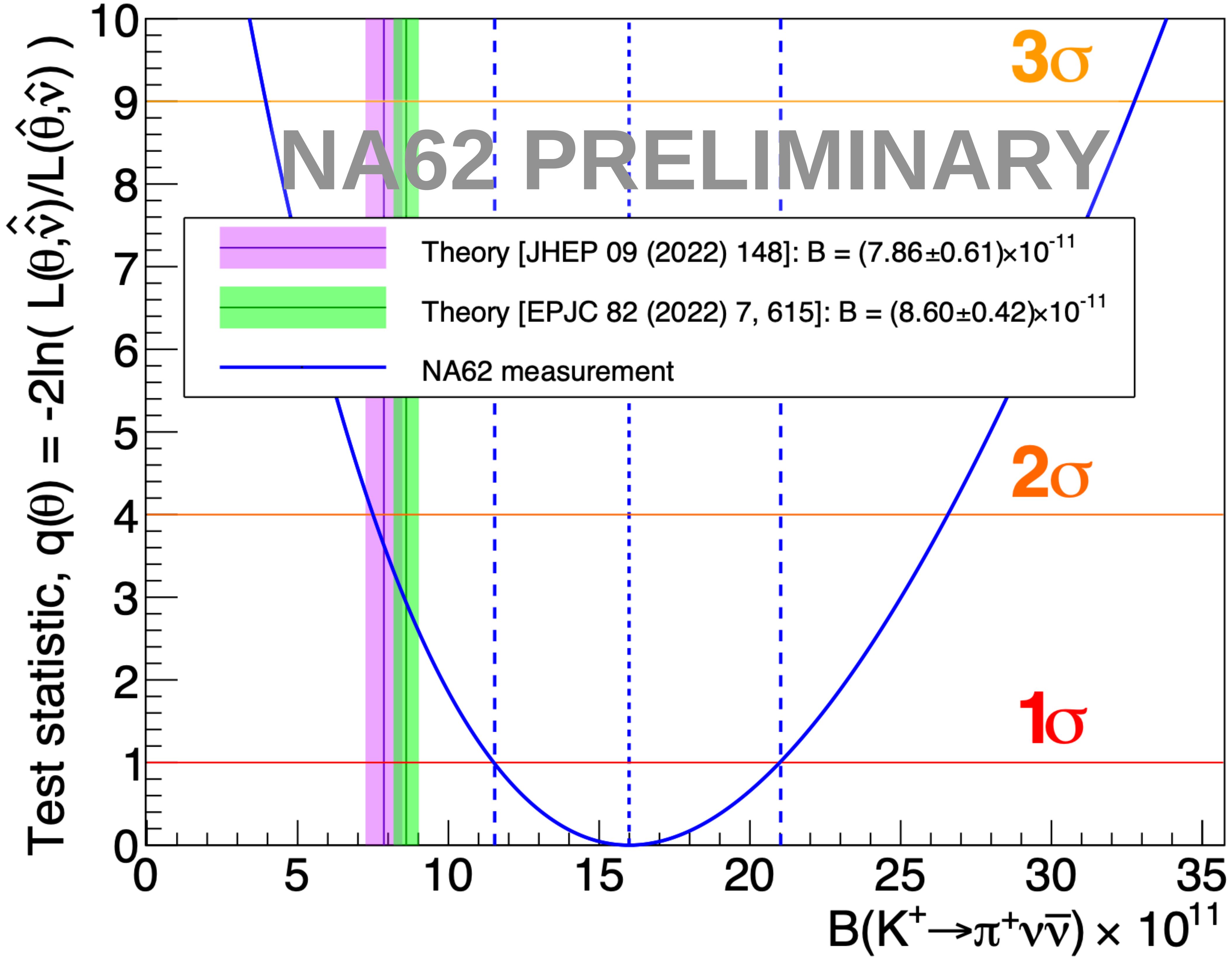
Expected SM signal: $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

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

Observed: $N_{obs} = 31$

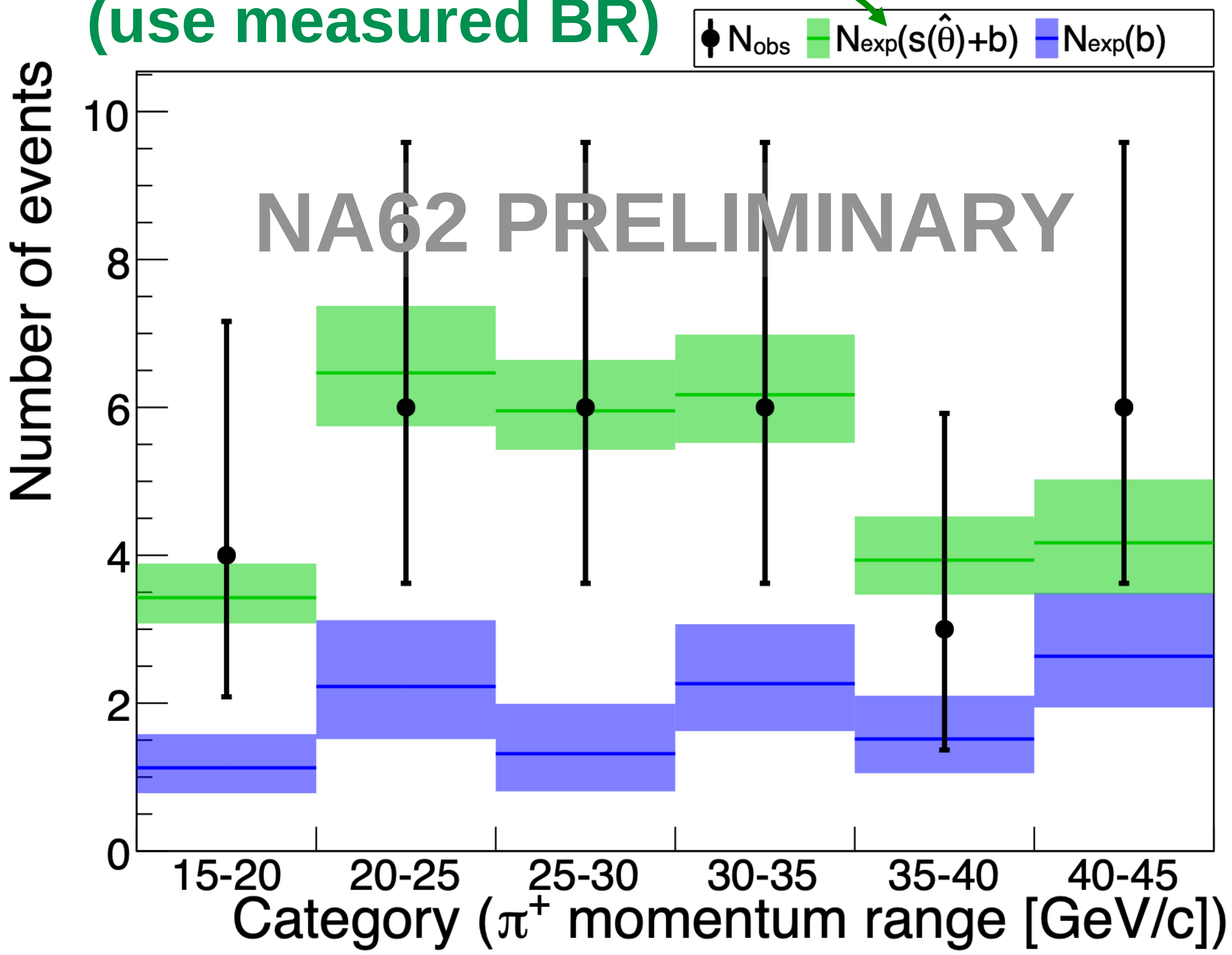
Results: 2021—22 Data

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



- Use 6 (momentum bin) categories

After fit (use measured BR)

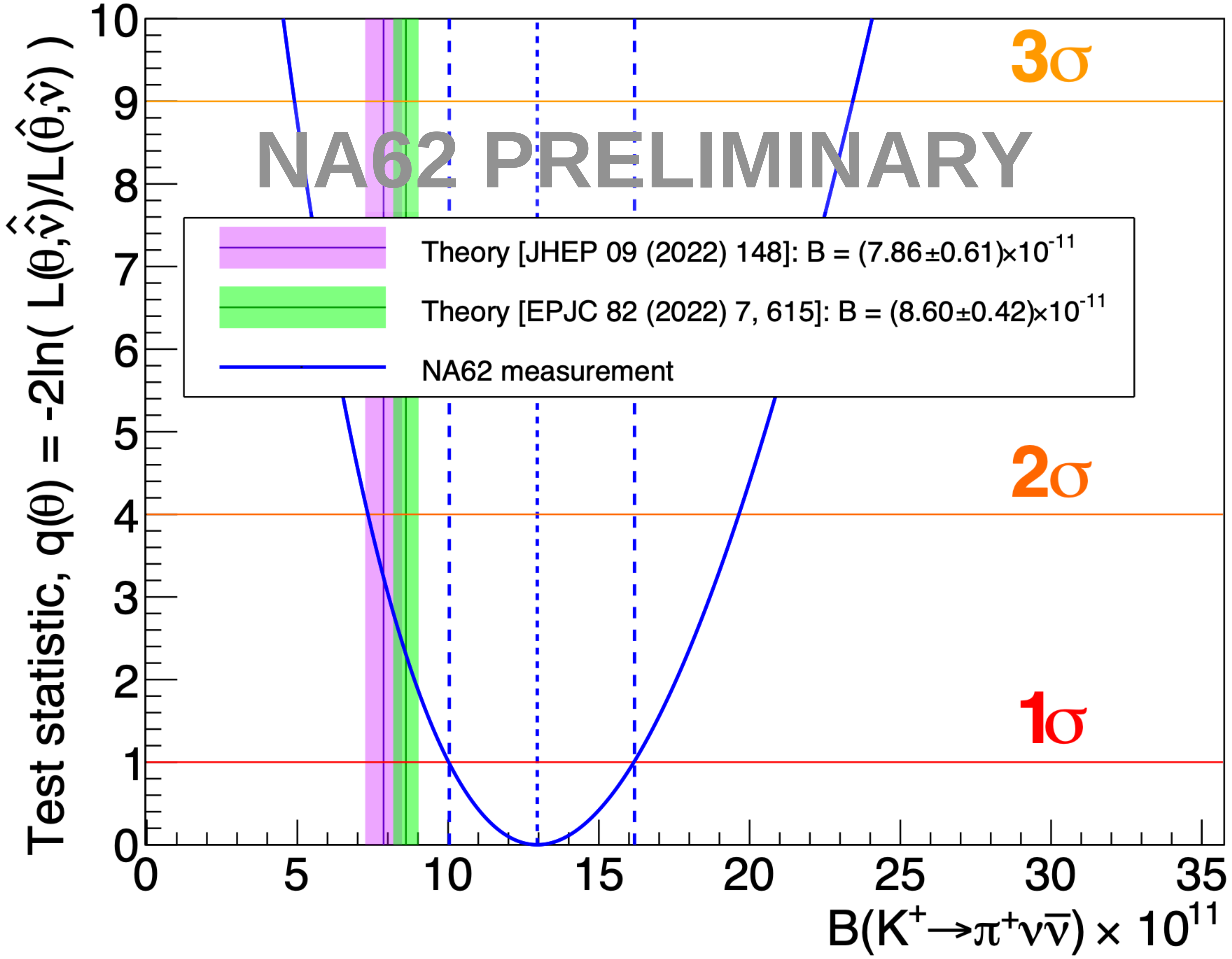


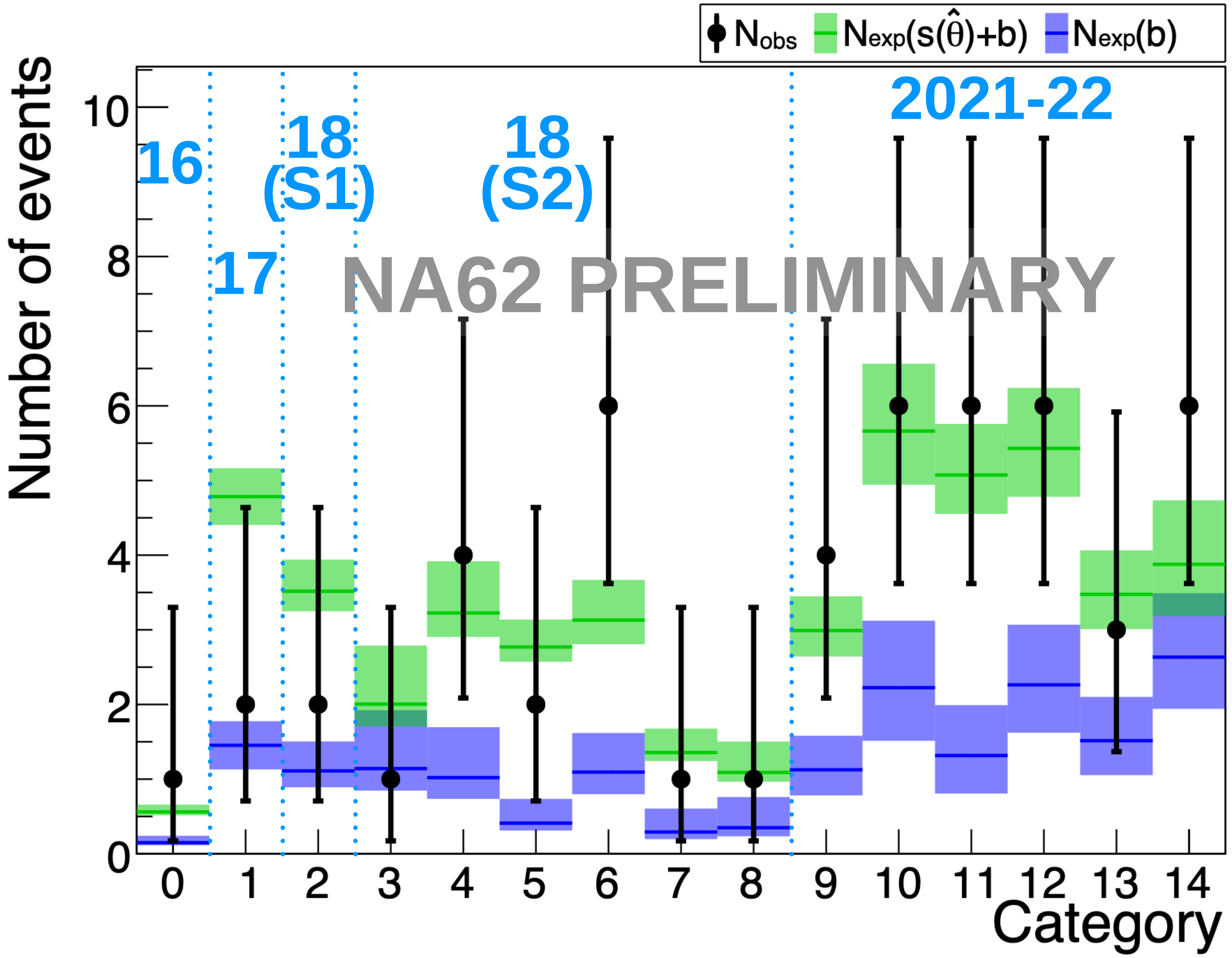
$$\mathcal{B}_{21-22}(K^+ \to \pi^+\nu\bar{\nu}) = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11} = \left(16.0\ \left({}^{+4.8}_{-4.2}\right)_{stat}\ \left({}^{+1.4}_{-1.3}\right)_{syst}\right) \times 10^{-11}$$

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]

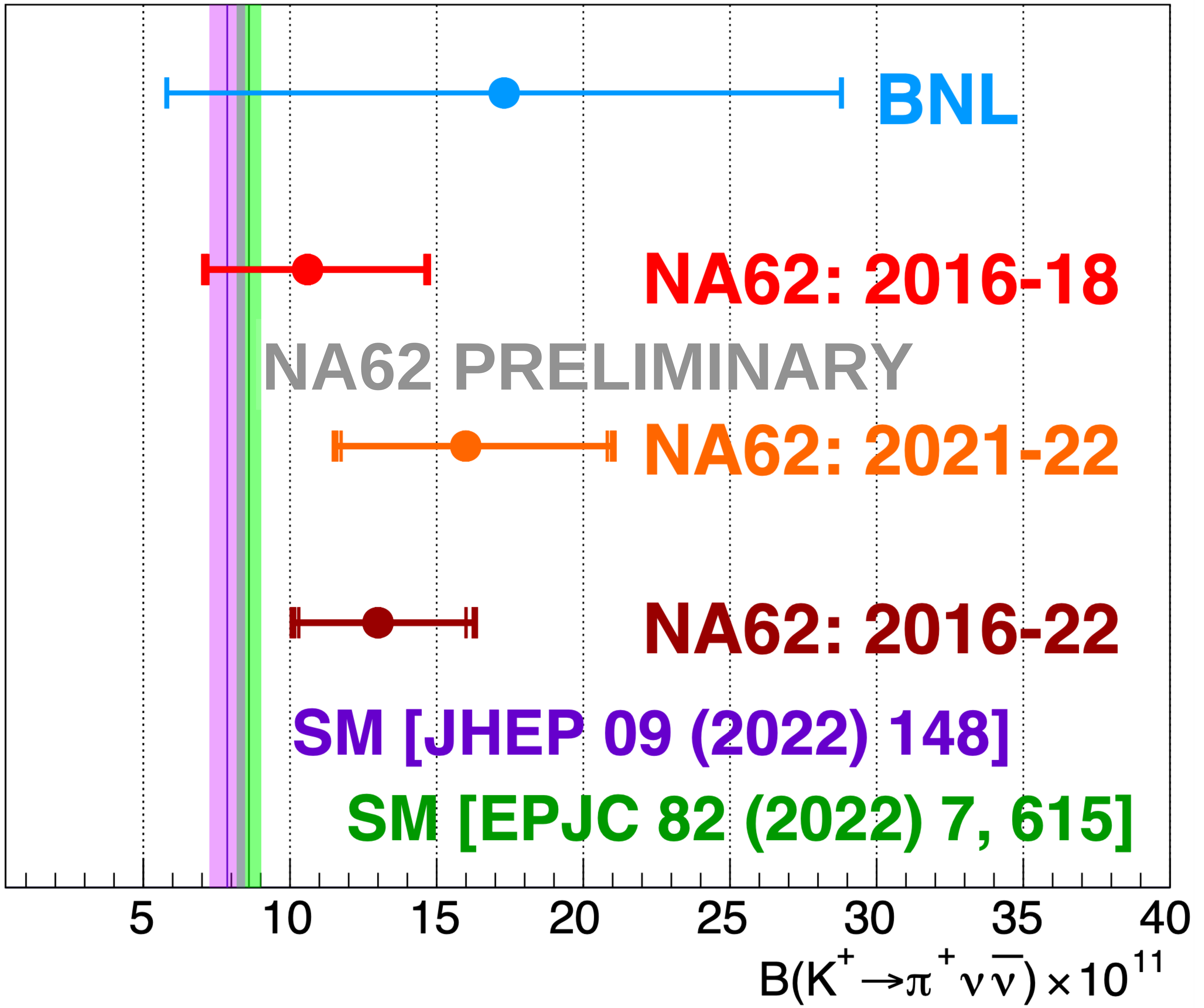
$$\mathcal{B}^{16-18}_{\pi\nu\bar{\nu}} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$$

[JHEP 06 (2021) 093]

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

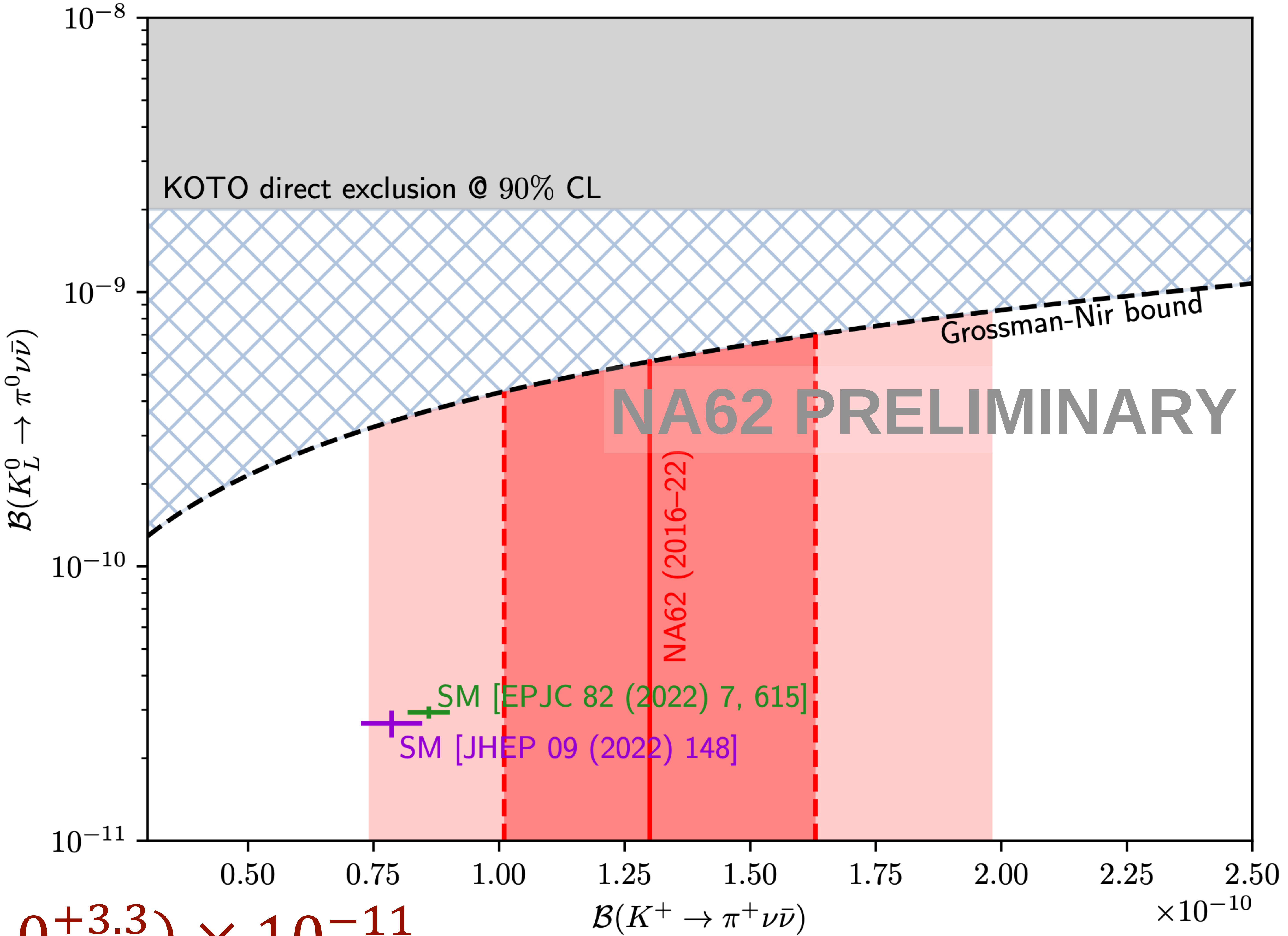
$$\mathcal{B}^{16-22}_{\pi\nu\bar{\nu}} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

- 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] × 10^{-11}

Conclusions

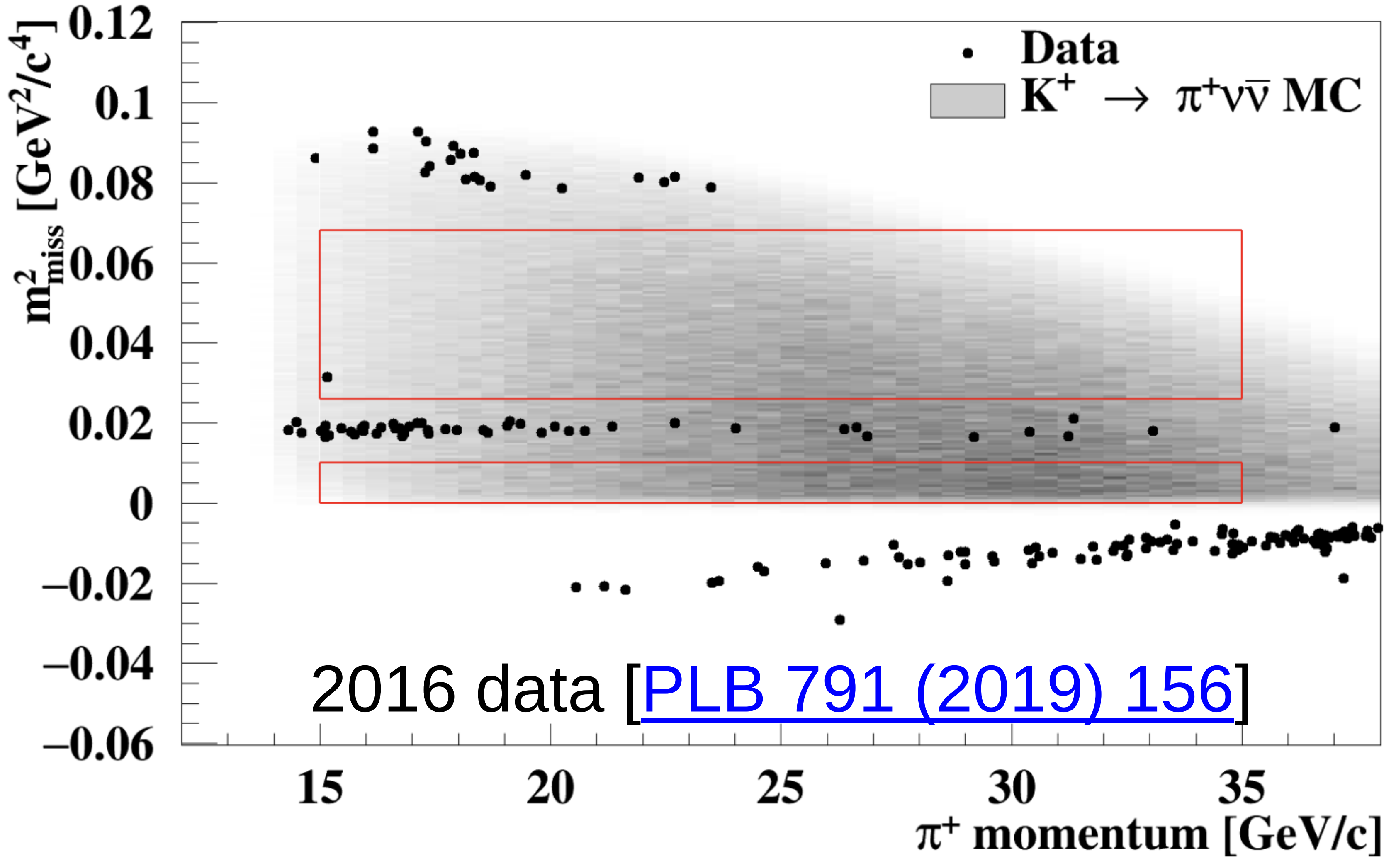
- New study of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay using NA62 2021—22 dataset:
  - Improved signal yield per SPS spill by 50%.
  - $N_{bg} = 11.0^{+2.1}_{-1.9}$, $N_{obs} = 31$
  - $\mathcal{B}_{21-22}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11} = \left(16.0\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

- 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)
  - $\mathcal{B}_{16-22}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11} = \left(13.0\ \left(^{+3.0}_{-2.7}\right)_{stat}\ \left(^{+1.3}_{-1.2}\right)_{syst}\right) \times 10^{-11}$
  - Background-only hypothesis rejected with significance Z>5.
- **First observation of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay: BR consistent with SM prediction within 1.7σ**
  - **Need full NA62 data-set to clarify SM agreement or tension.**

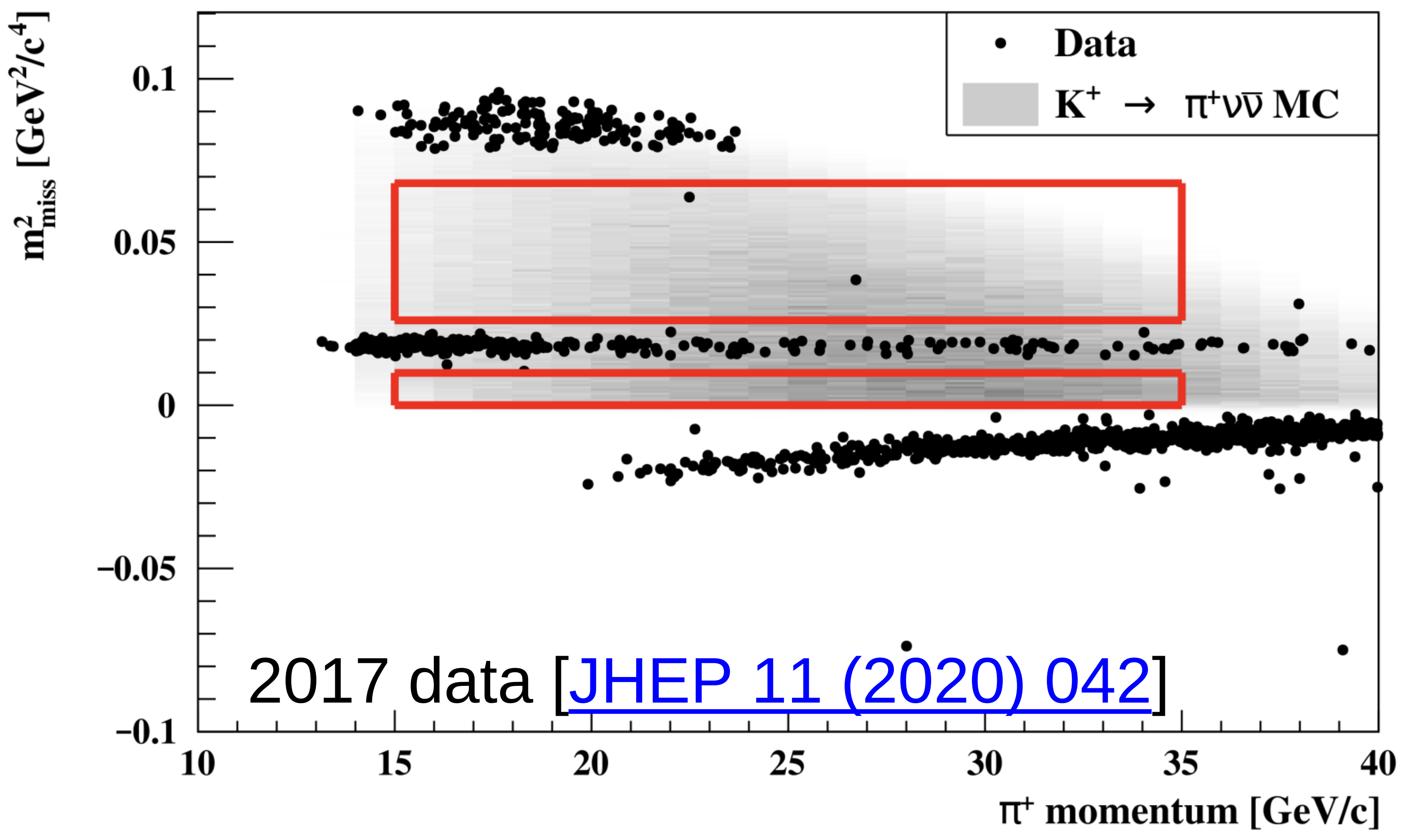
2023—LS3 data-set collection & analysis in progress…

Supplemental

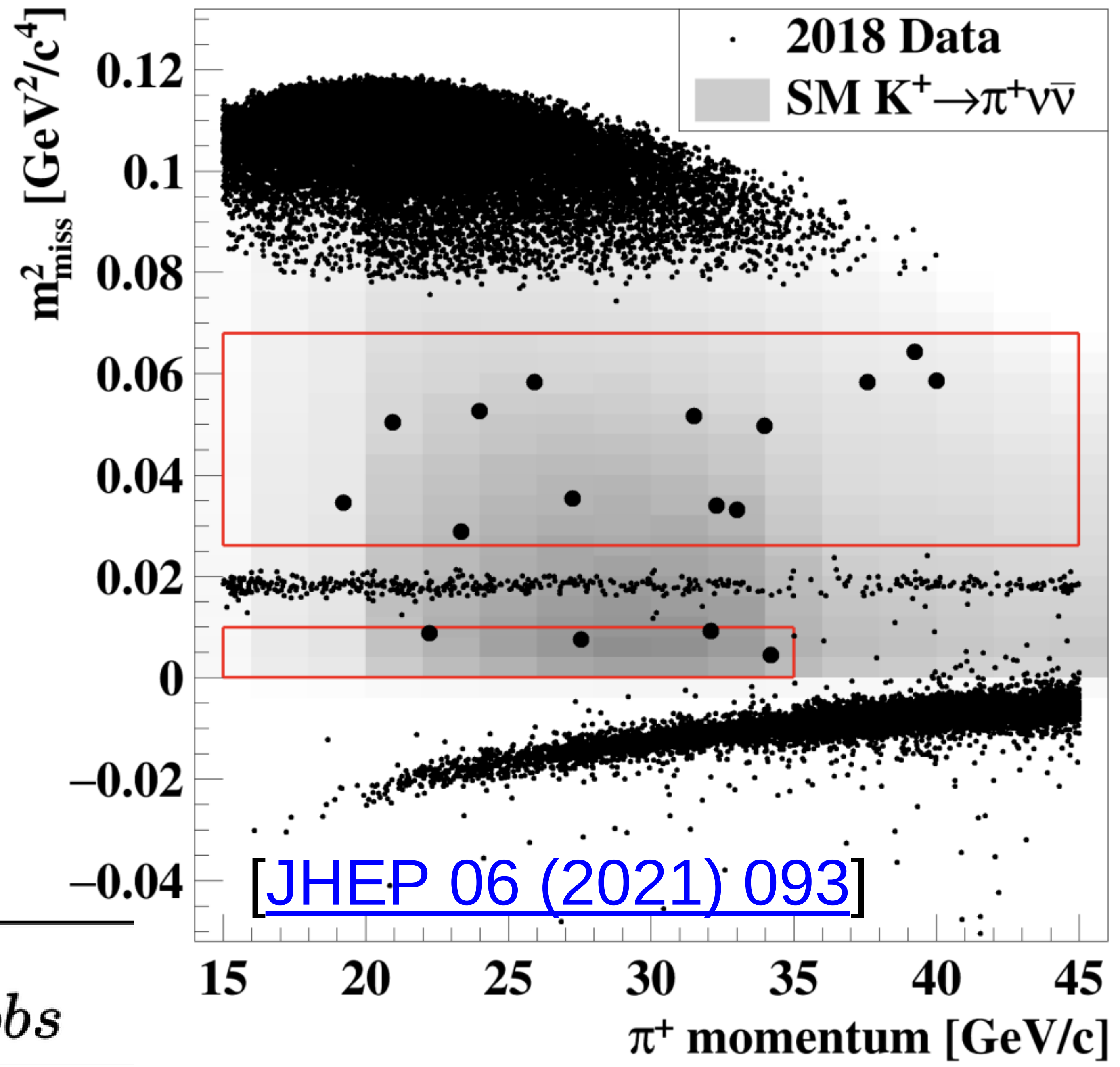
The story so far: $K^+ \to \pi^+\nu\bar{\nu}$ with 2016—18 data



2016 data [PLB 791 (2019) 156]



2017 data [JHEP 11 (2020) 042]



[JHEP 06 (2021) 093]

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:

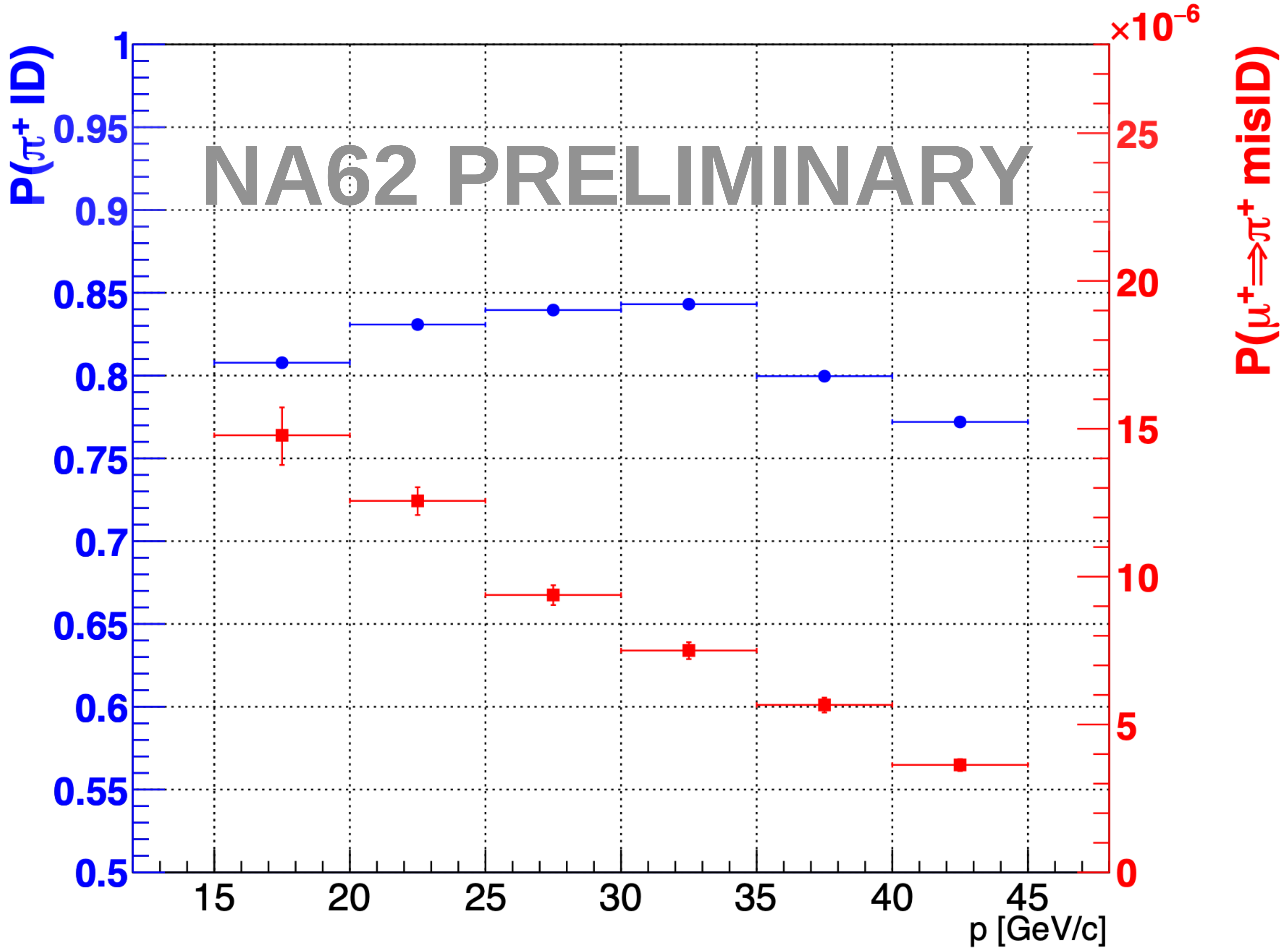
$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}\big|_{stat} \pm 0.9_{syst}) \times 10^{-11} @ 68\%\ CL$$

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

Particle ID performance : 2021—22 data

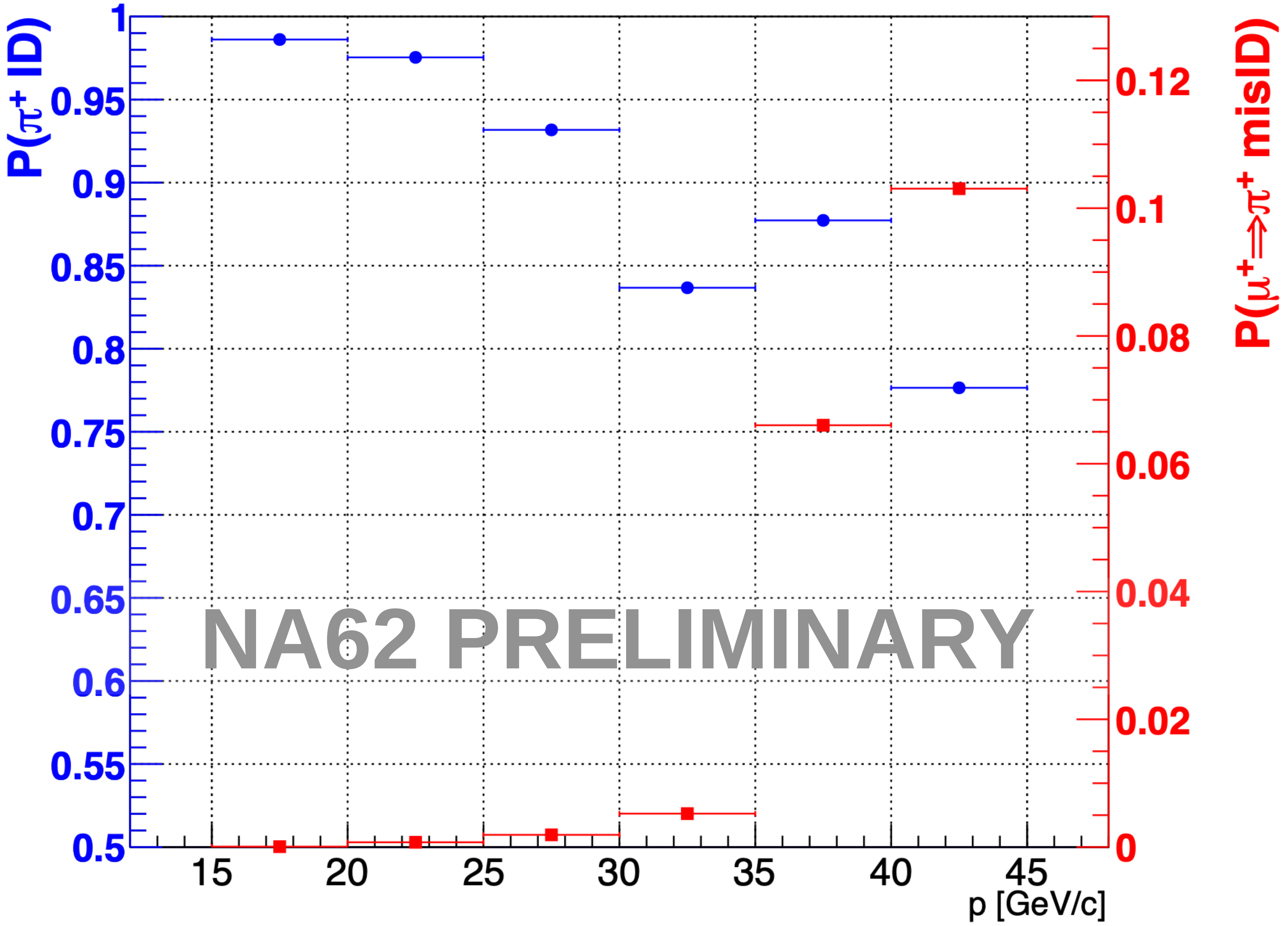
Calorimeters

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



RICH

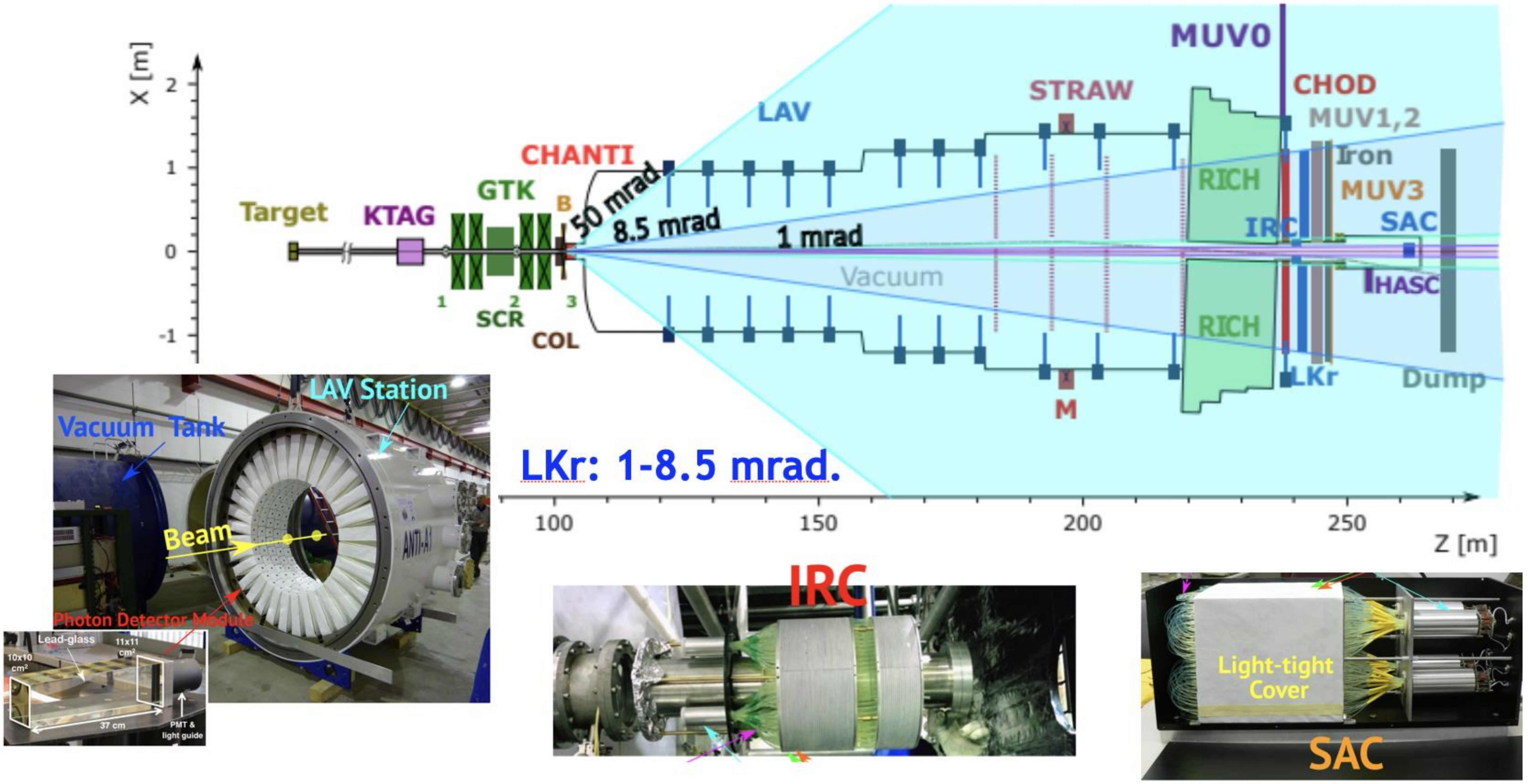
Designed to distinguish between π^+/μ^+ with $15 - 35\,GeV/c$



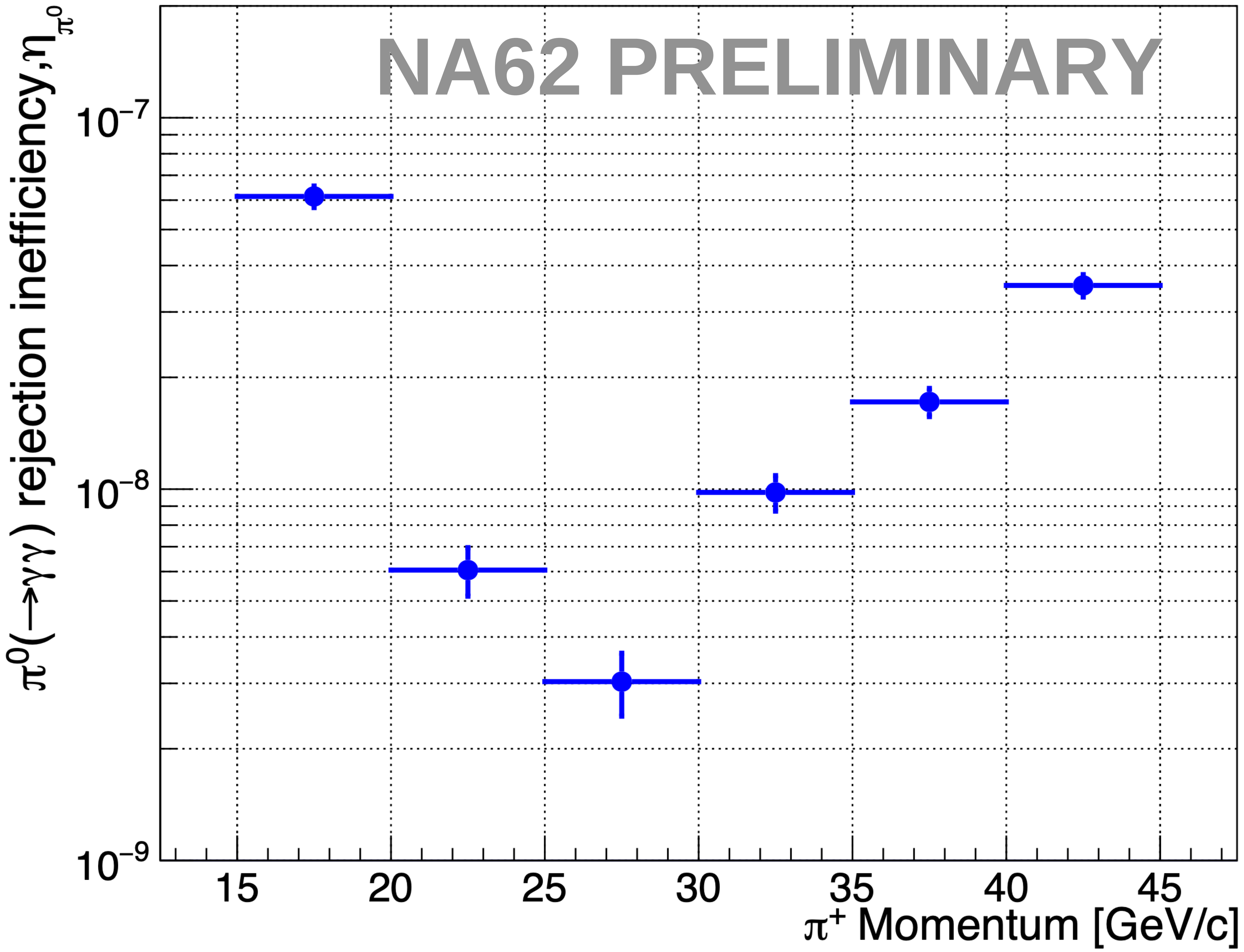
$$\mathrm{P}(\pi^+) = 73\ \%$$

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

Comprehensive photon veto system: 21—22



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

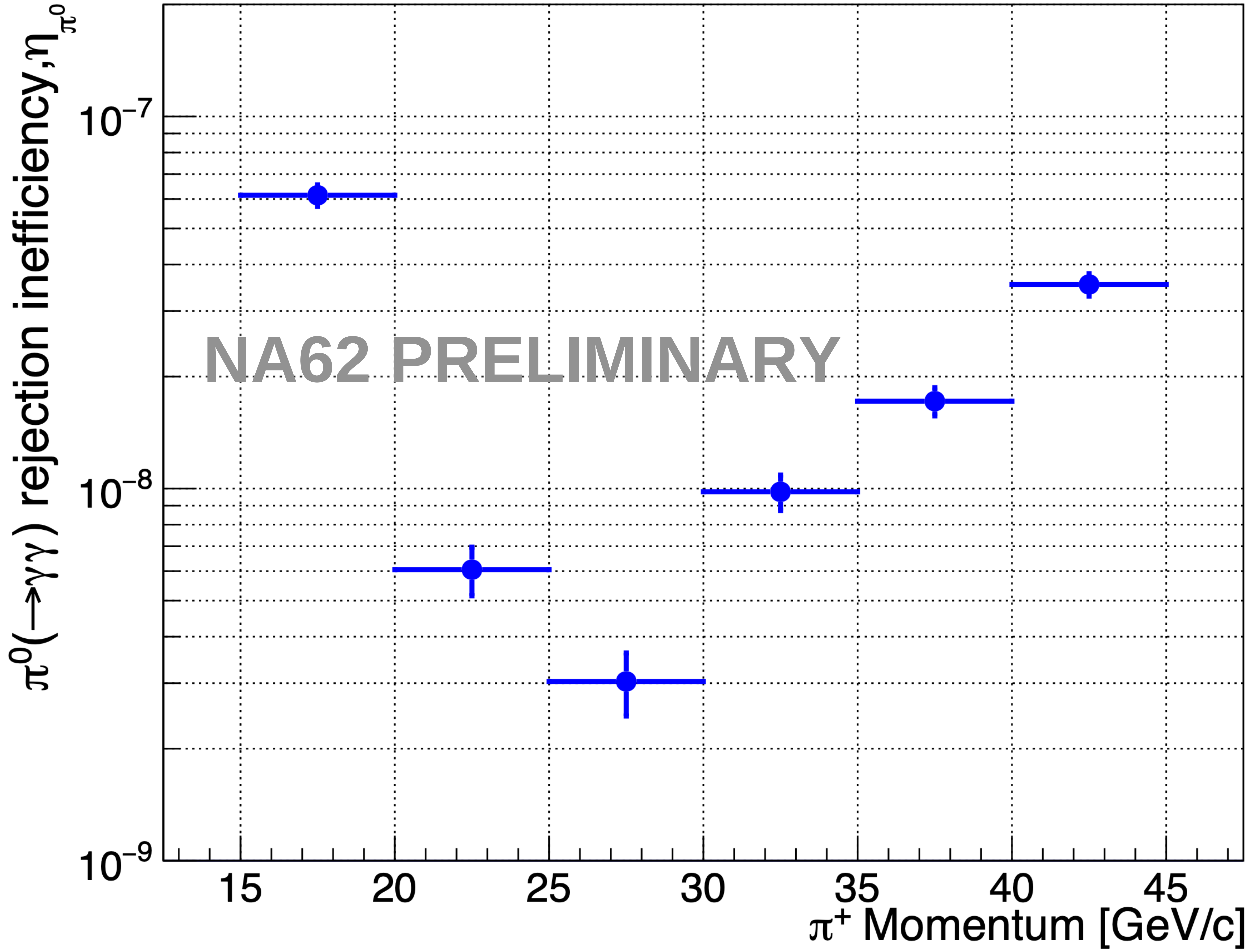


- Probability of $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$ events passing all photon veto conditions:

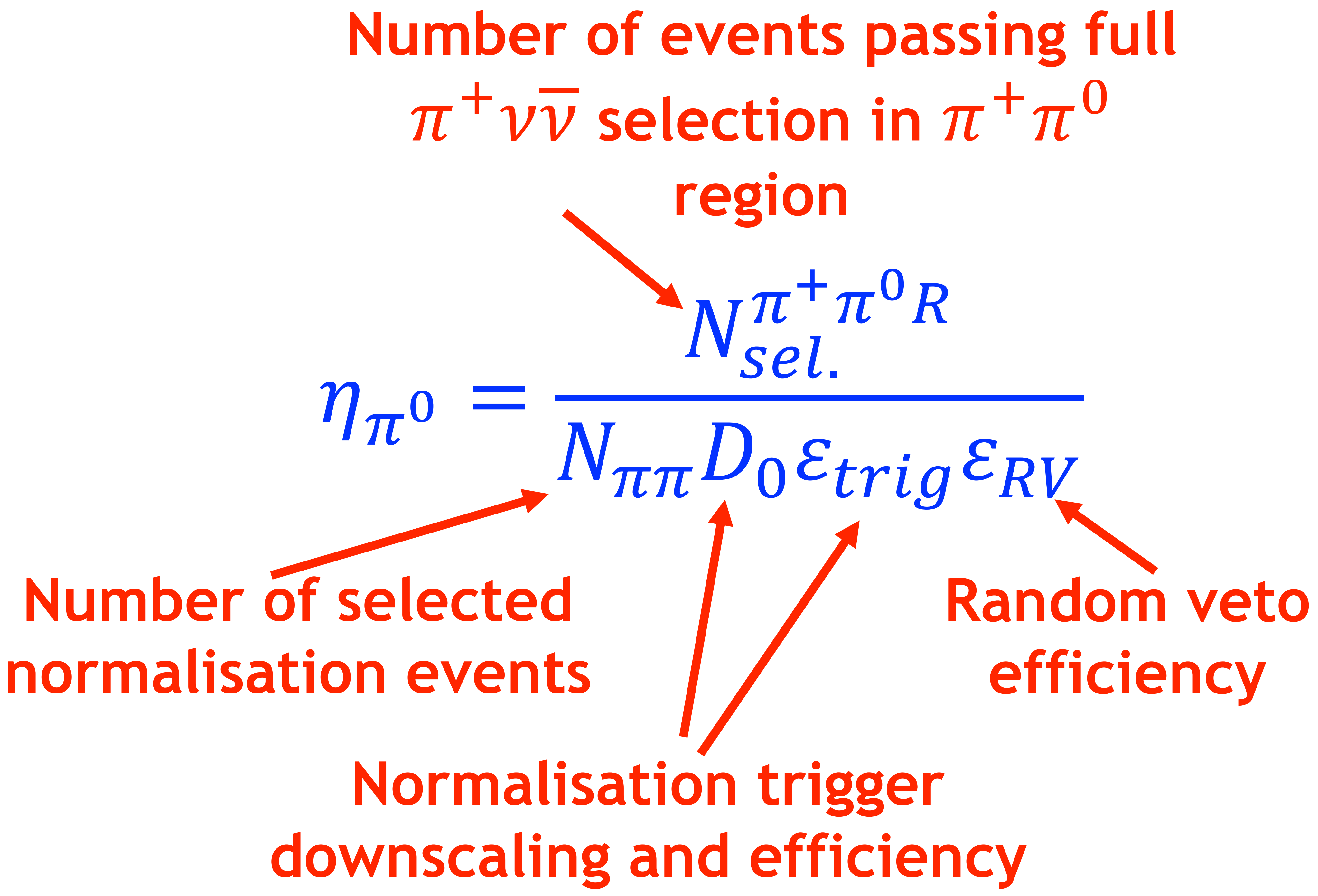
$$\eta_{\pi^0} = (1.72 \pm 0.07) \times 10^{-8}$$

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

Photon veto performance



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



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

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

Number of selected normalisation events

Random veto efficiency

Normalisation trigger downscaling and efficiency

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

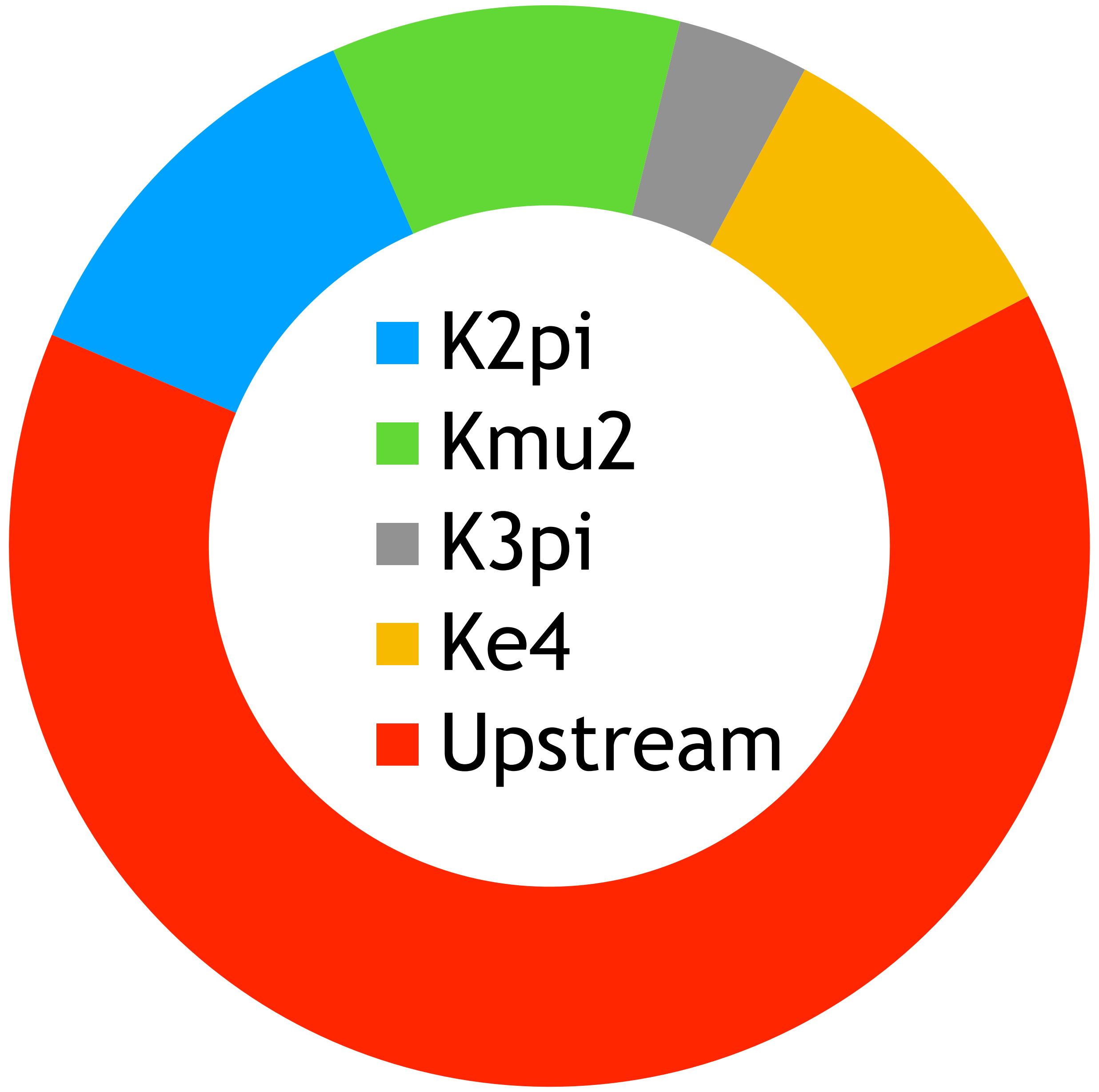
- **Combined γ/π^0 rejection of $\mathcal{O}(10^8)$.**

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.

Sketch only

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

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

2021 - addition of VetoCounter

Upstream decays can be detected and actively vetoed.

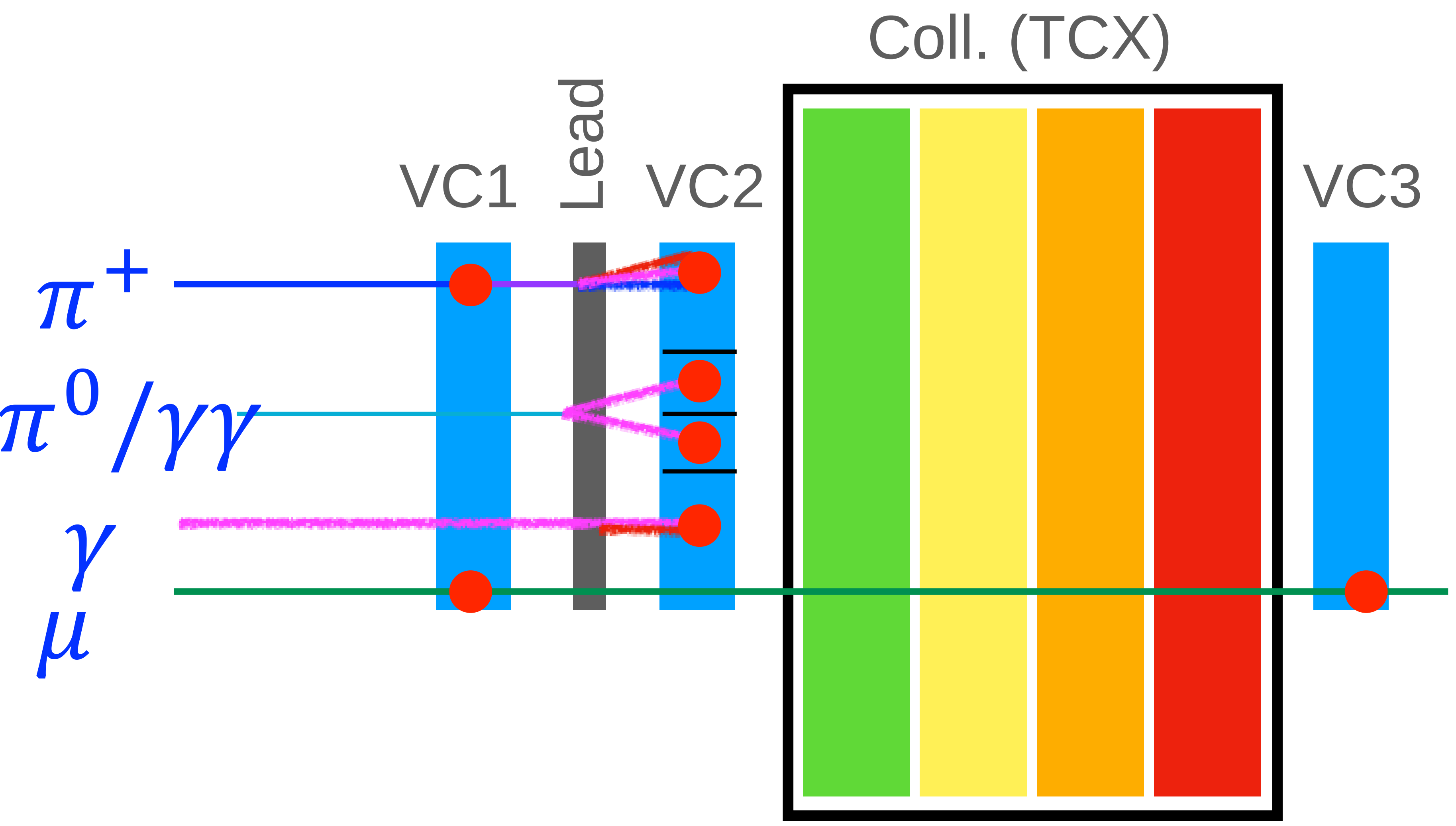
Sketch only

● 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]

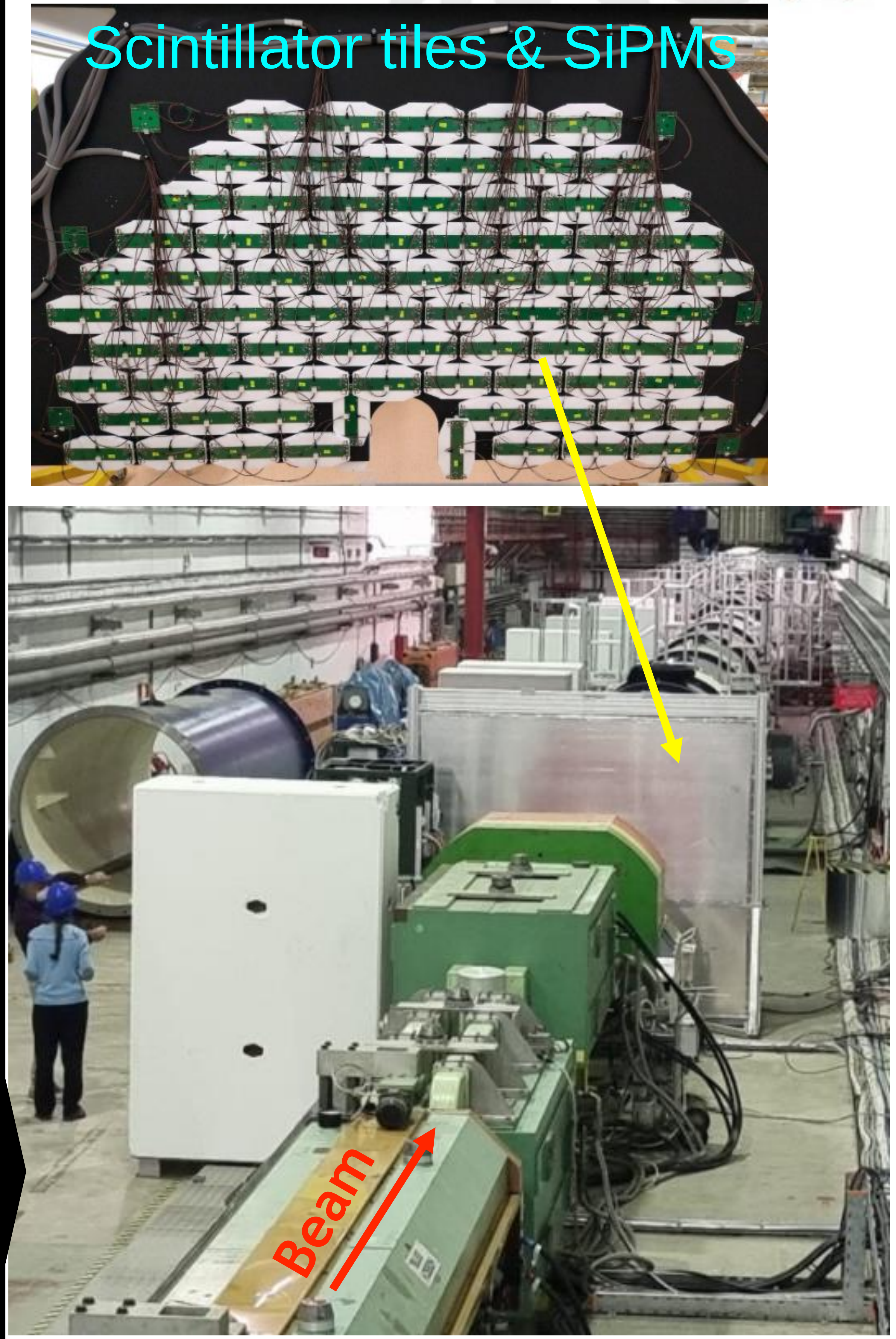


VetoCounter

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

ANTI0

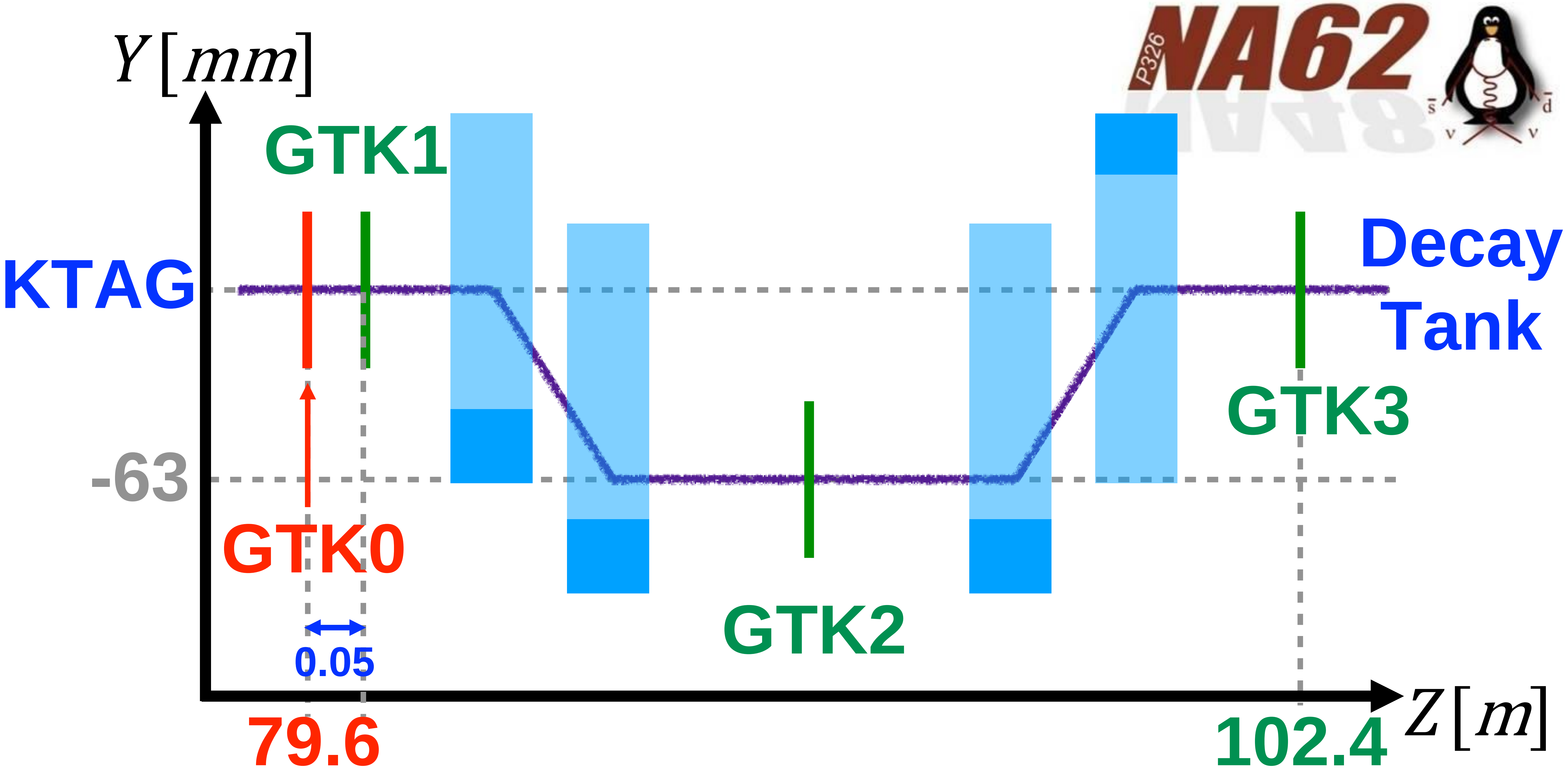
- Detect particles up to ~1 m from beam line.
- **Reject ~20% of upstream background** with <1% signal loss.

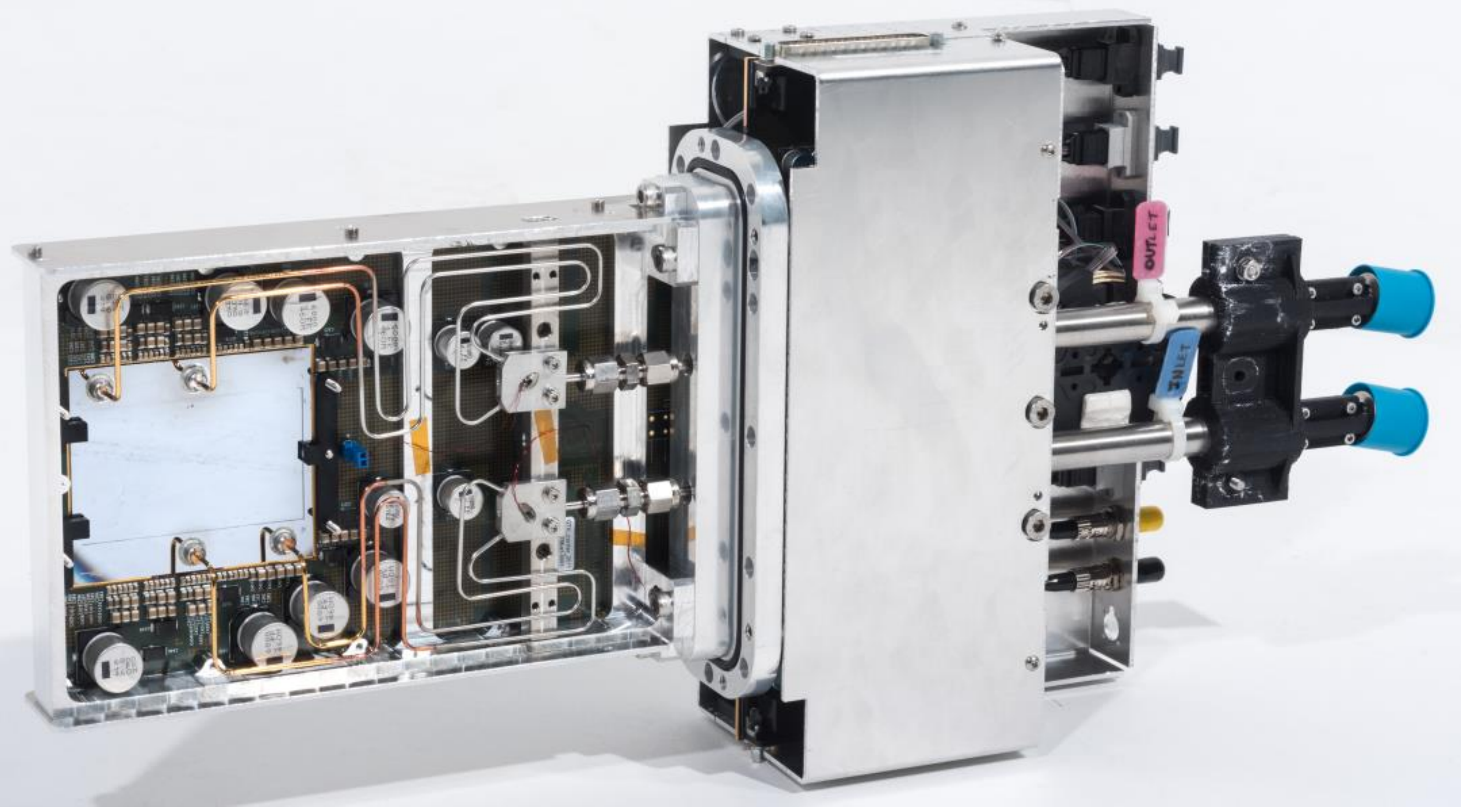


[SPSC report 2023][EP Newsletter, Dec21]

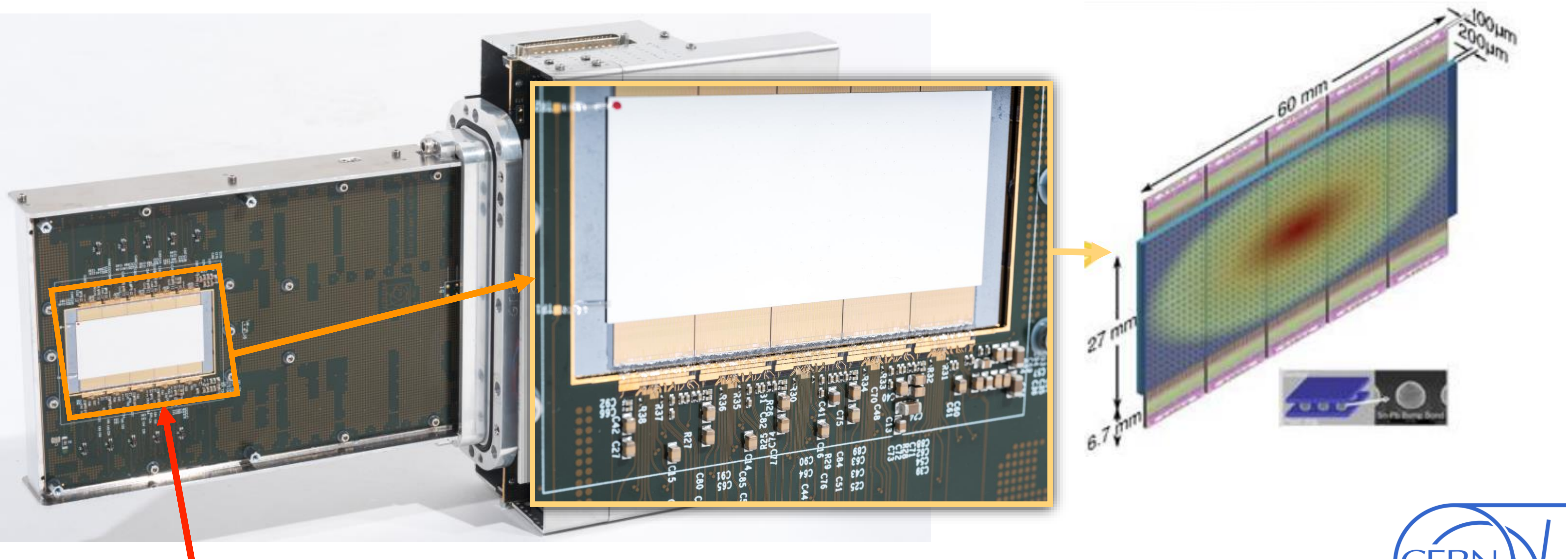
4th GTK station

- 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

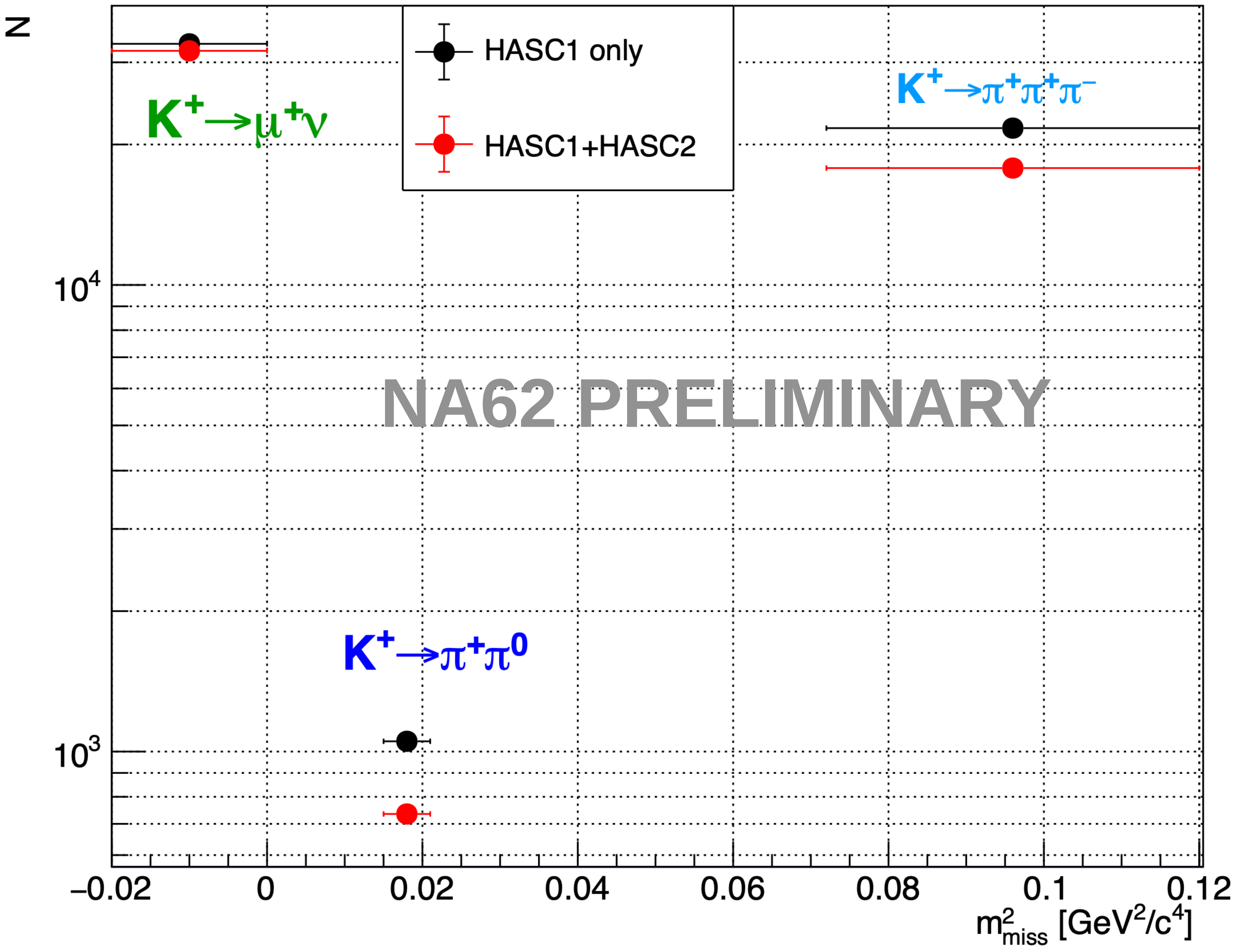
2021 - add HASC2

Additional downstream particles can be vetoed.

HASC2 veto

- $K^+ \rightarrow \pi^+\pi^0$ **was 2nd largest background for 2018 analysis.**

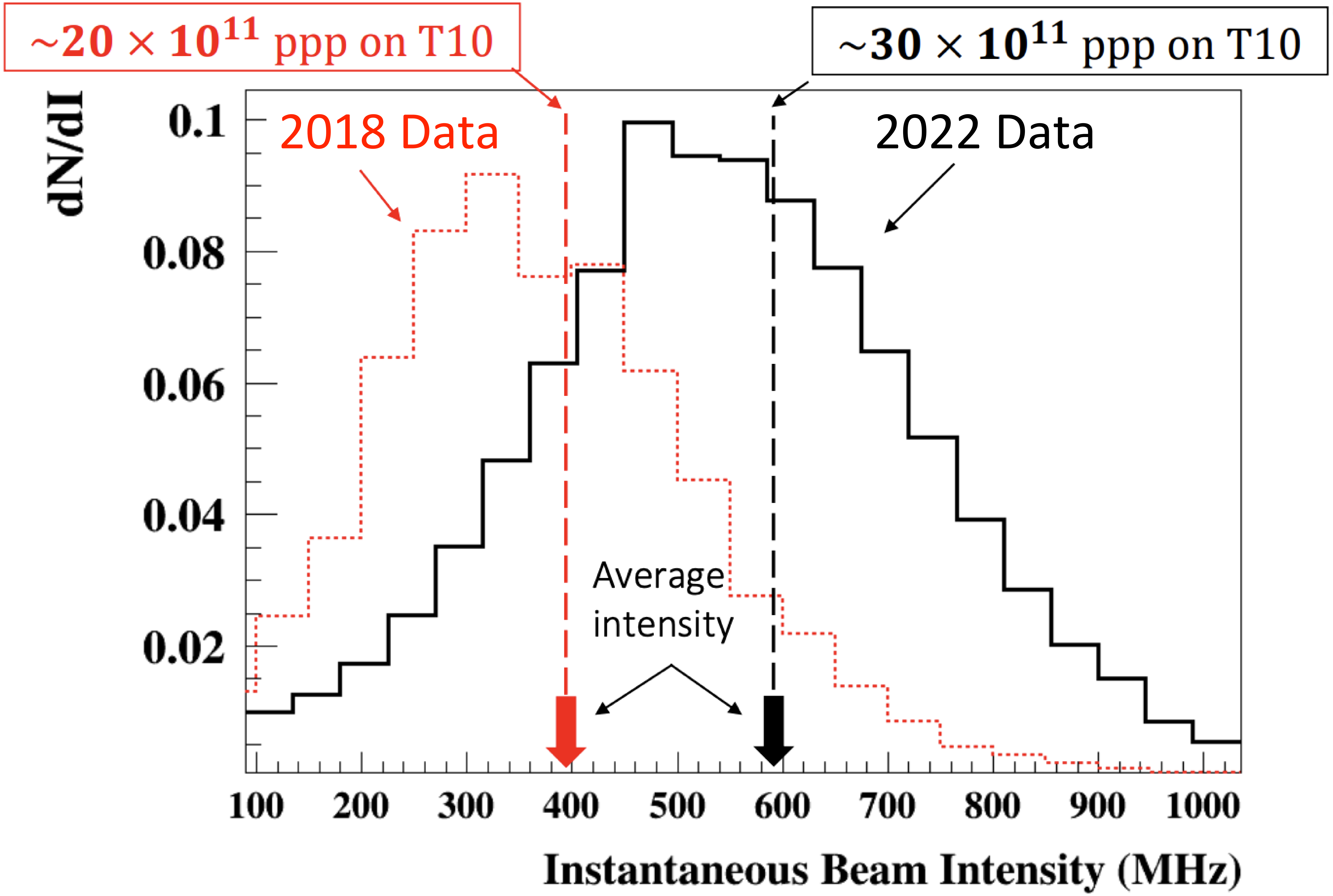
- Addition of HASC2:
  - **30% less** $K^+ \rightarrow \pi^+\pi^0$
  - 18% less $K^+ \rightarrow \pi^+\pi^+\pi^-$
  - 3.5% less $K^+ \rightarrow \mu^+\nu$
  - with only 1.5% signal loss



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

(modifying HASC veto: study integral of background regions)

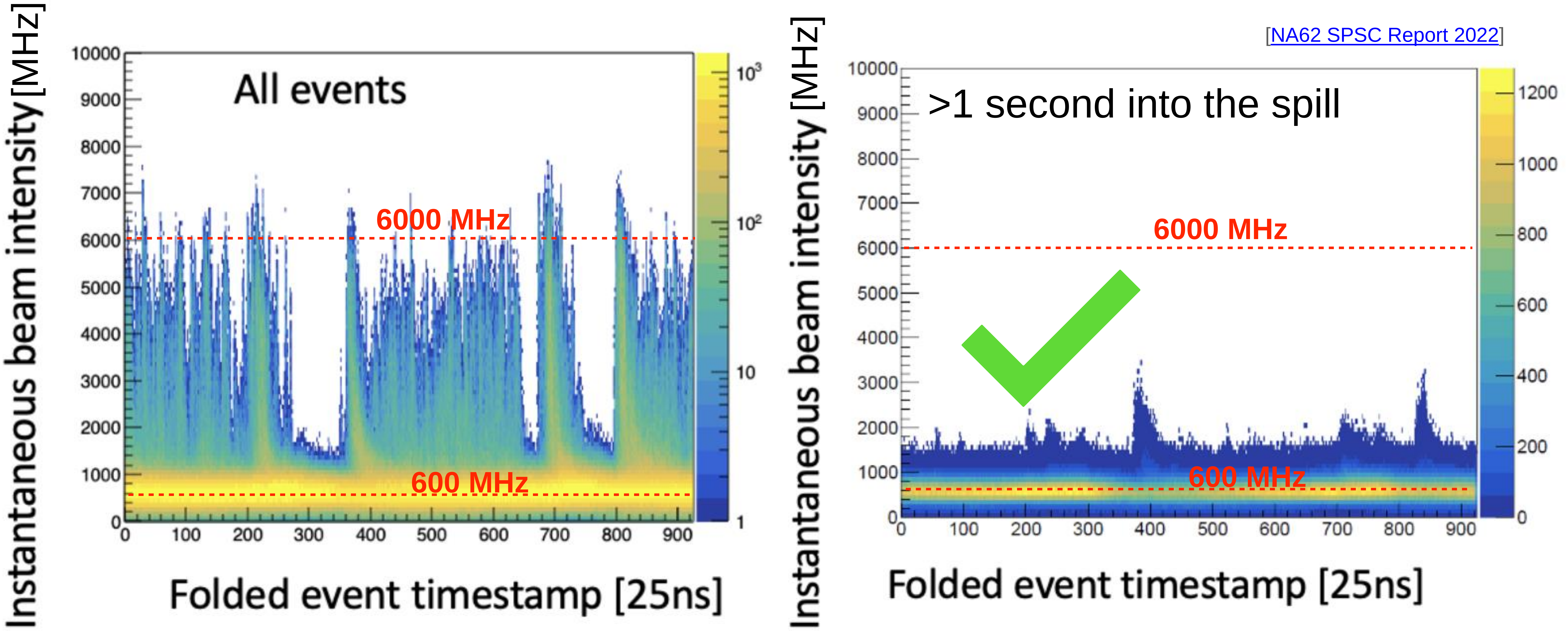
Beam intensity: 2018 vs 2022



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

2021 instantaneous beam intensity

[NA62 SPSC Report 2022]



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

Analysis strategy

Triggers:

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

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

Common conditions

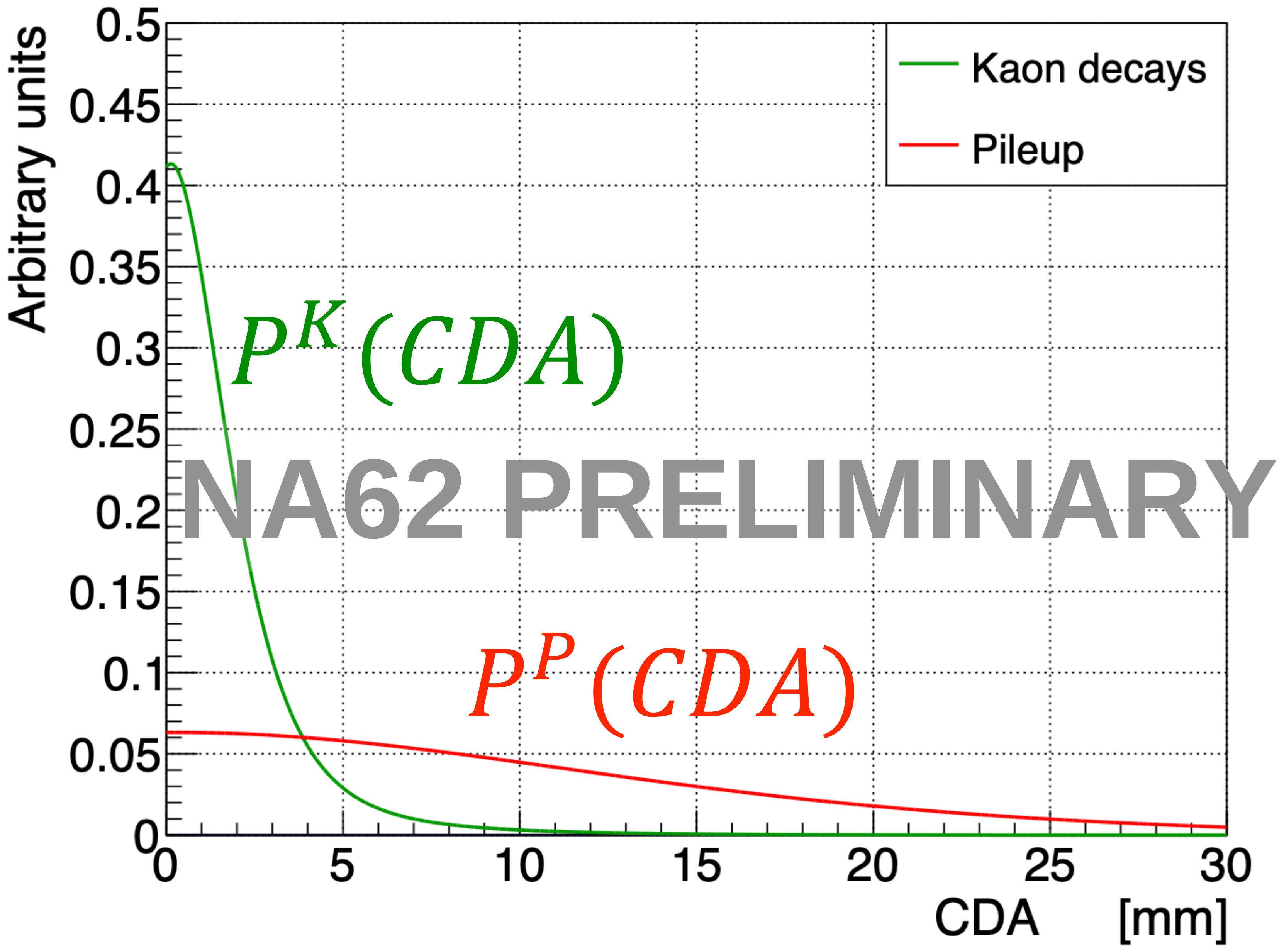
+ add more conditions

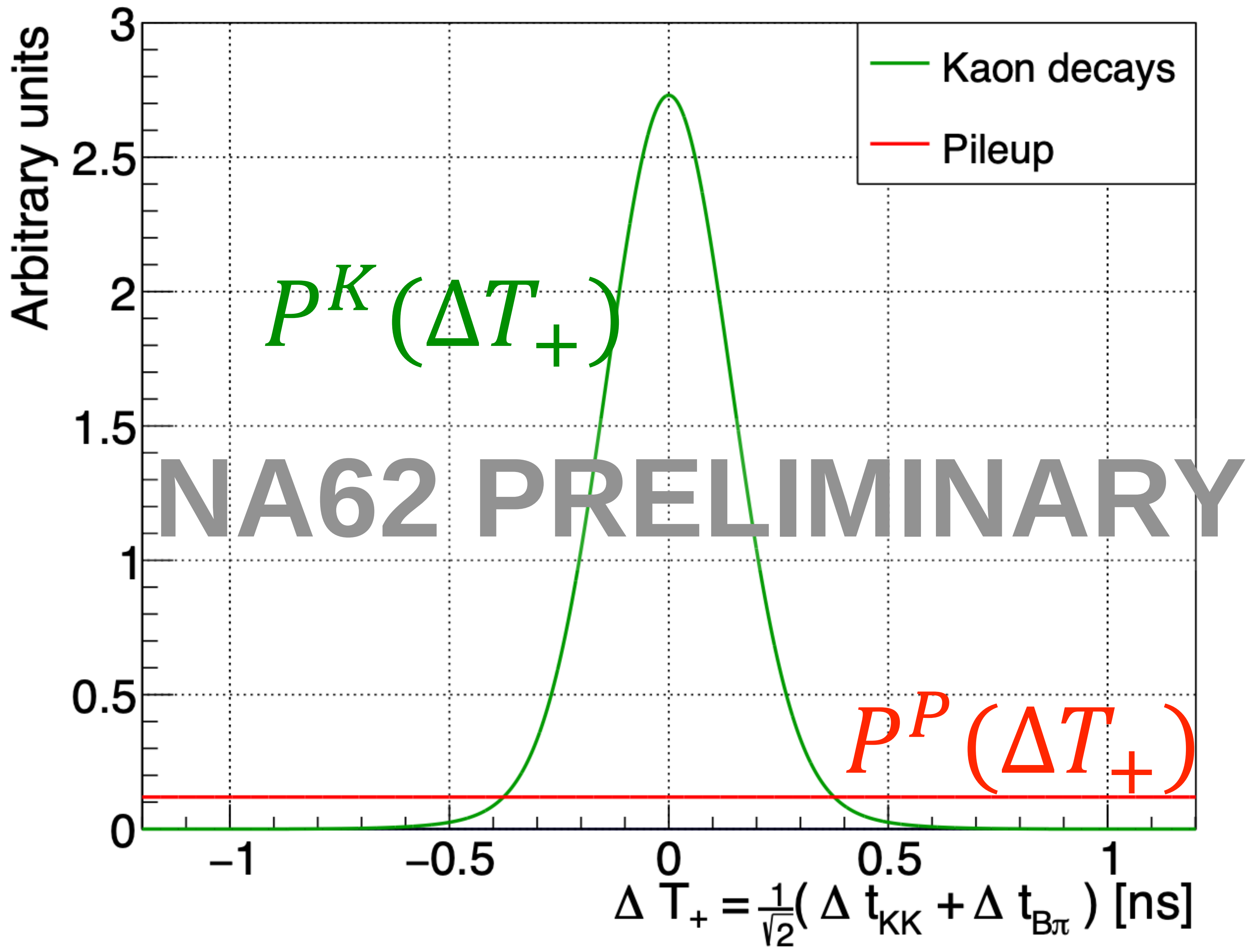
Selection:

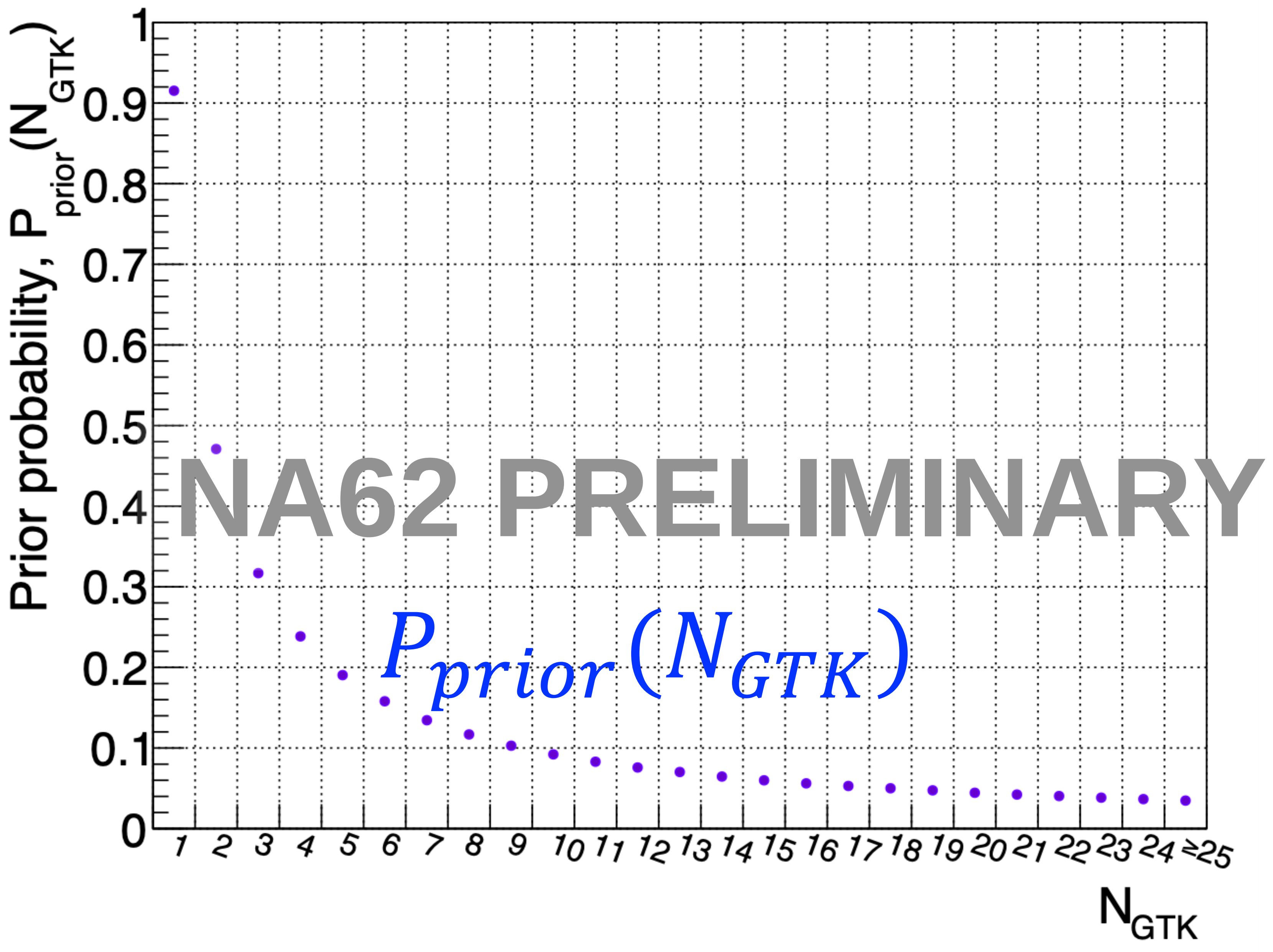
- **Normalisation** $K^+ \to \pi^+\pi^0$: 1 downstream track (only); identified as π^+; $K^+ - \pi^+$ matching (space & time); upstream vetos.
- **Signal** $K^+ \to \pi^+\nu\bar{\nu}$ candidates: same as normalisation selection + full photon and detector multiplicity cuts (reject all extra activity).

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

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







Example of selection update

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

Signal sensitivity

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

Effective number of K^+ decays, N_K:

Number of normalisation events

Downscaling factor of normalisation trigger (generally 400)

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

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

Acceptance of normalisation selection

Single event sensitivity:

(Branching ratio corresponding to expectation of 1 event)

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

Random veto efficiency

Trigger efficiency (ratio)

Signal selection acceptance

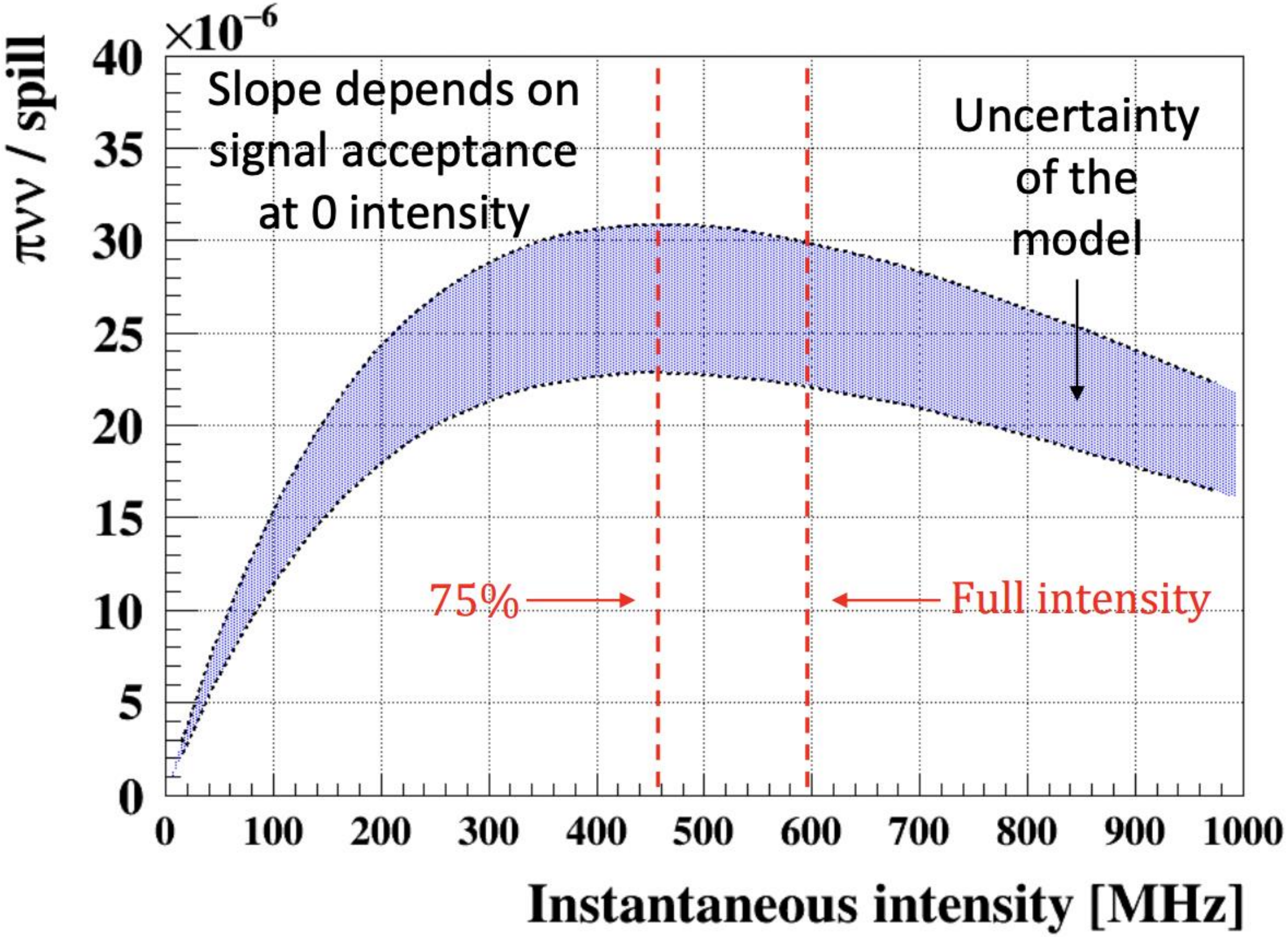
Number of expected SM events:

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

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

Optimum NA62 intensity

Selected signal yield vs intensity



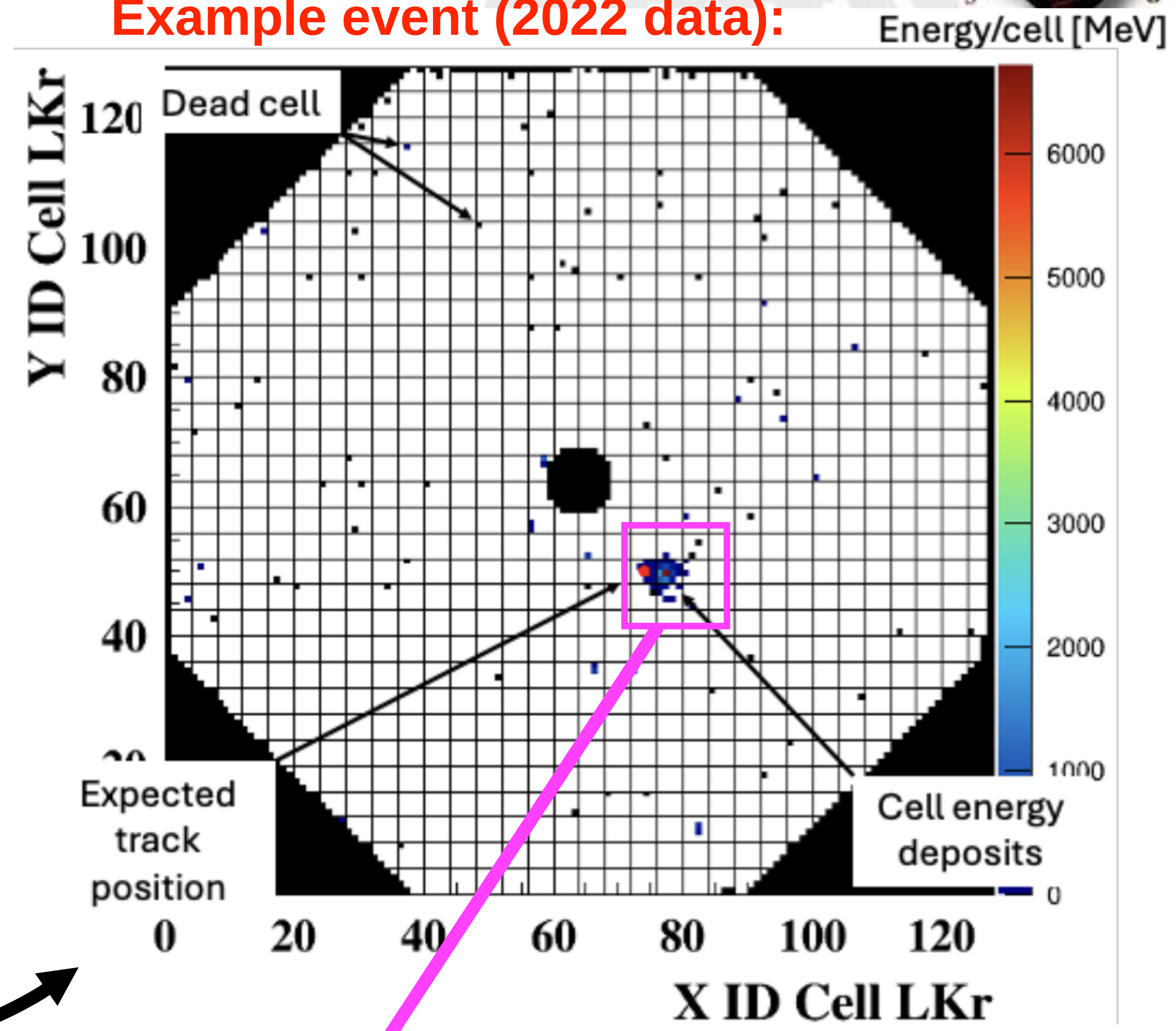
- Saturation of expected signal yield with intensity. Mainly due to:
  - Paralyzable effects from TDAQ dead time and trigger veto windows.
  - Offline selection, due to veto conditions.
- Main sources of uncertainty for model:
  - Online time-dependent mis-calibrations.
  - Fit uncertainty.
- **From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

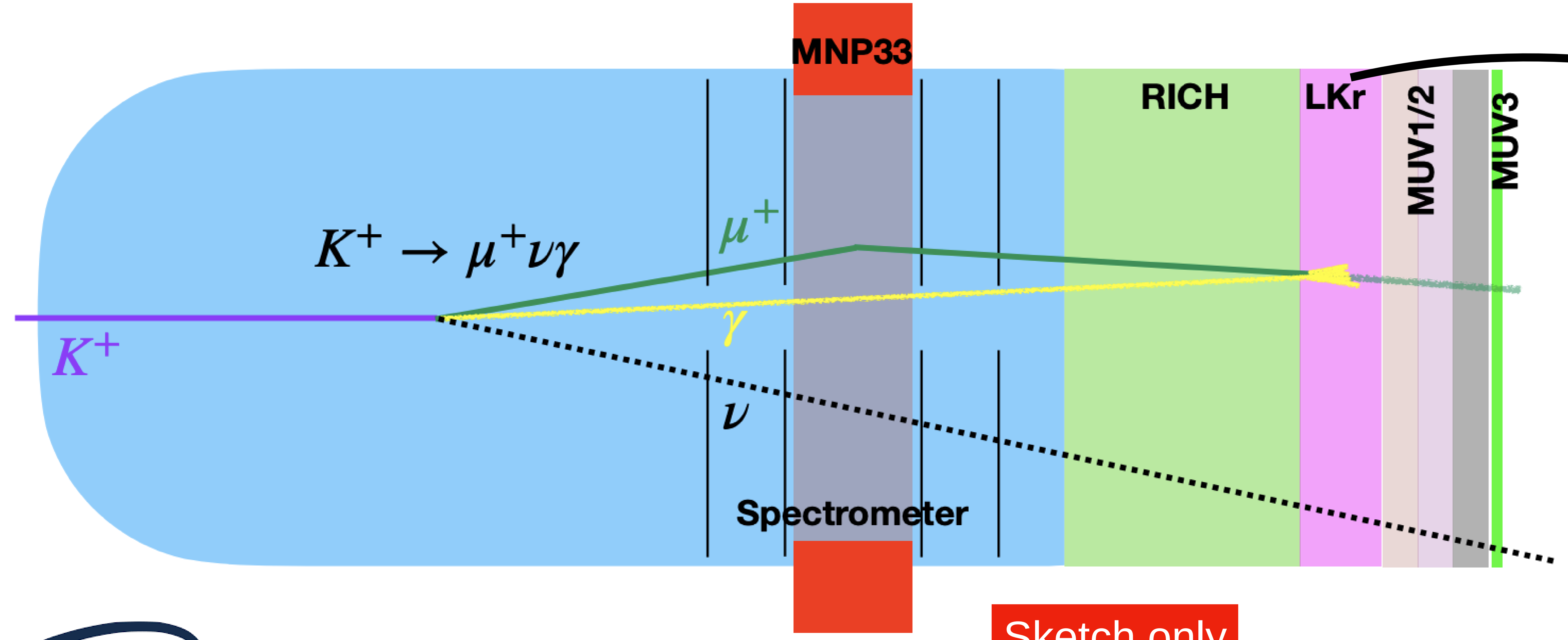
Studies of **2021—22 data** at high intensity **were crucial** to establish optimal intensity

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

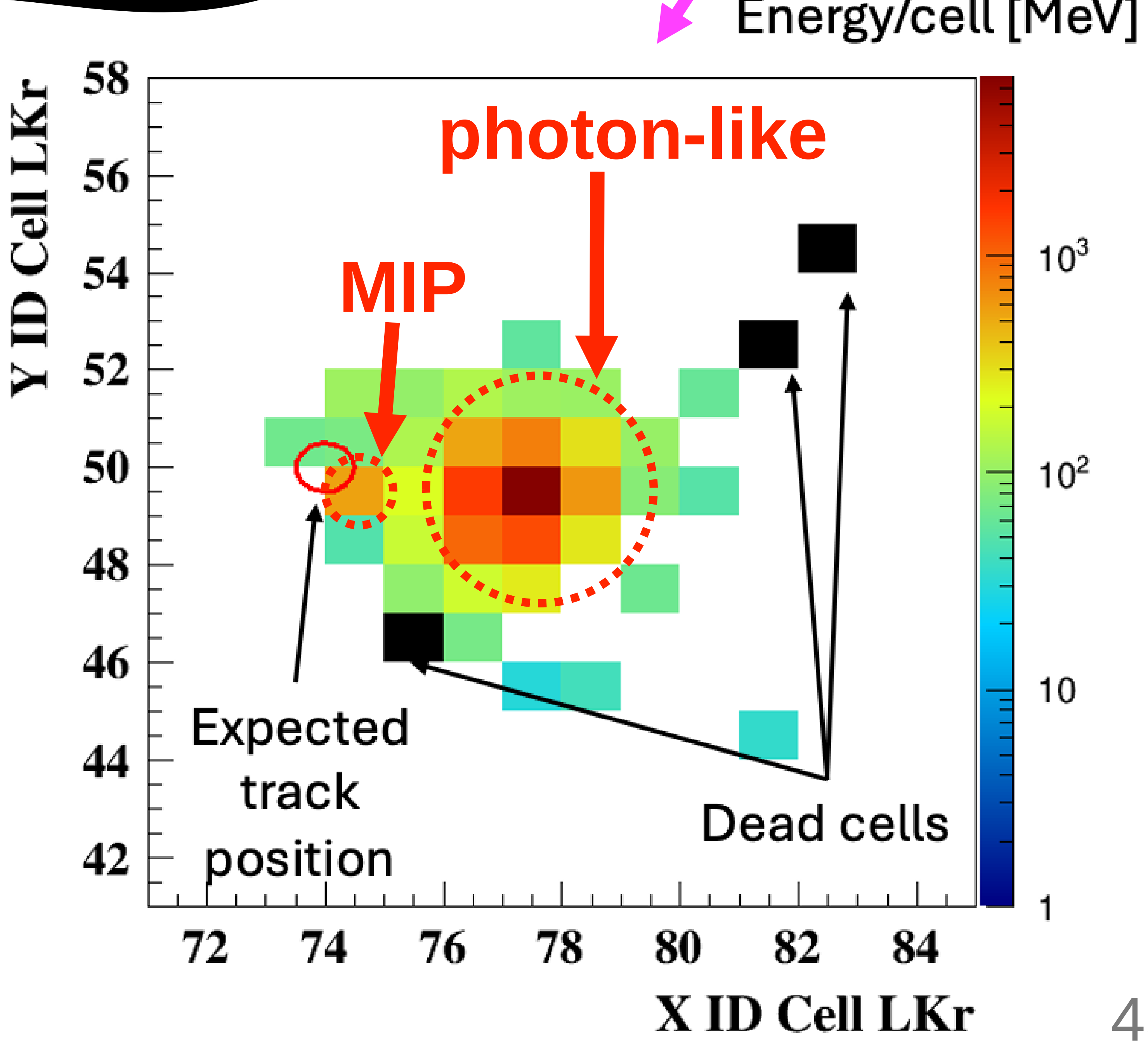
- $K^+ \to \mu^+\nu\gamma$ decay with fairly energetic photon ($E_\gamma > 5\,GeV$) and high momentum μ^+ ($p \gtrsim 35\,GeV/c$).
- γ and μ^+ hit LKr together and are misidentified as a π^+.
- No rejection power from photon vetos (LKr γ cluster associated to track).
- Additional γ naturally shifts $m^2_{miss}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

Example event (2022 data):





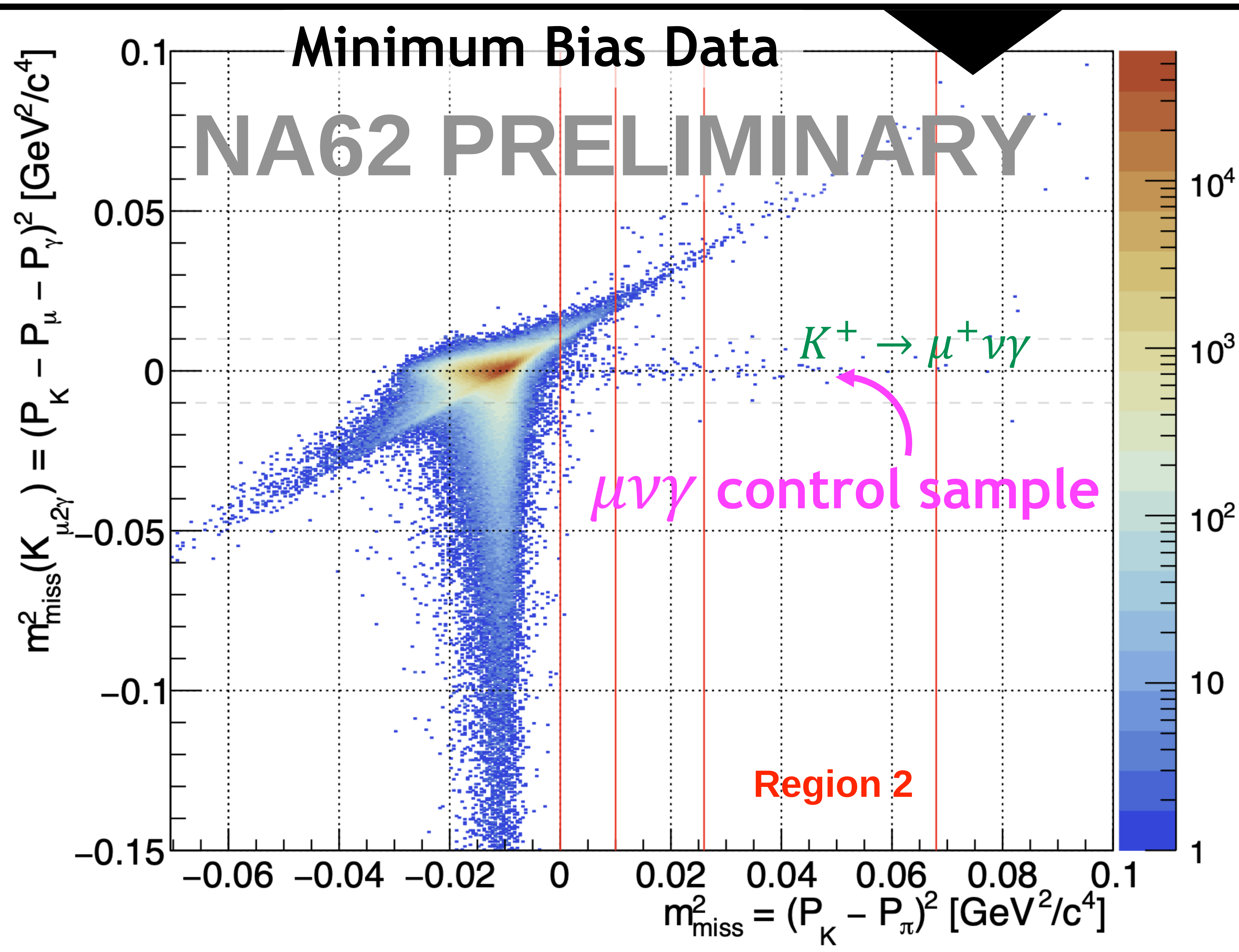
Sketch only



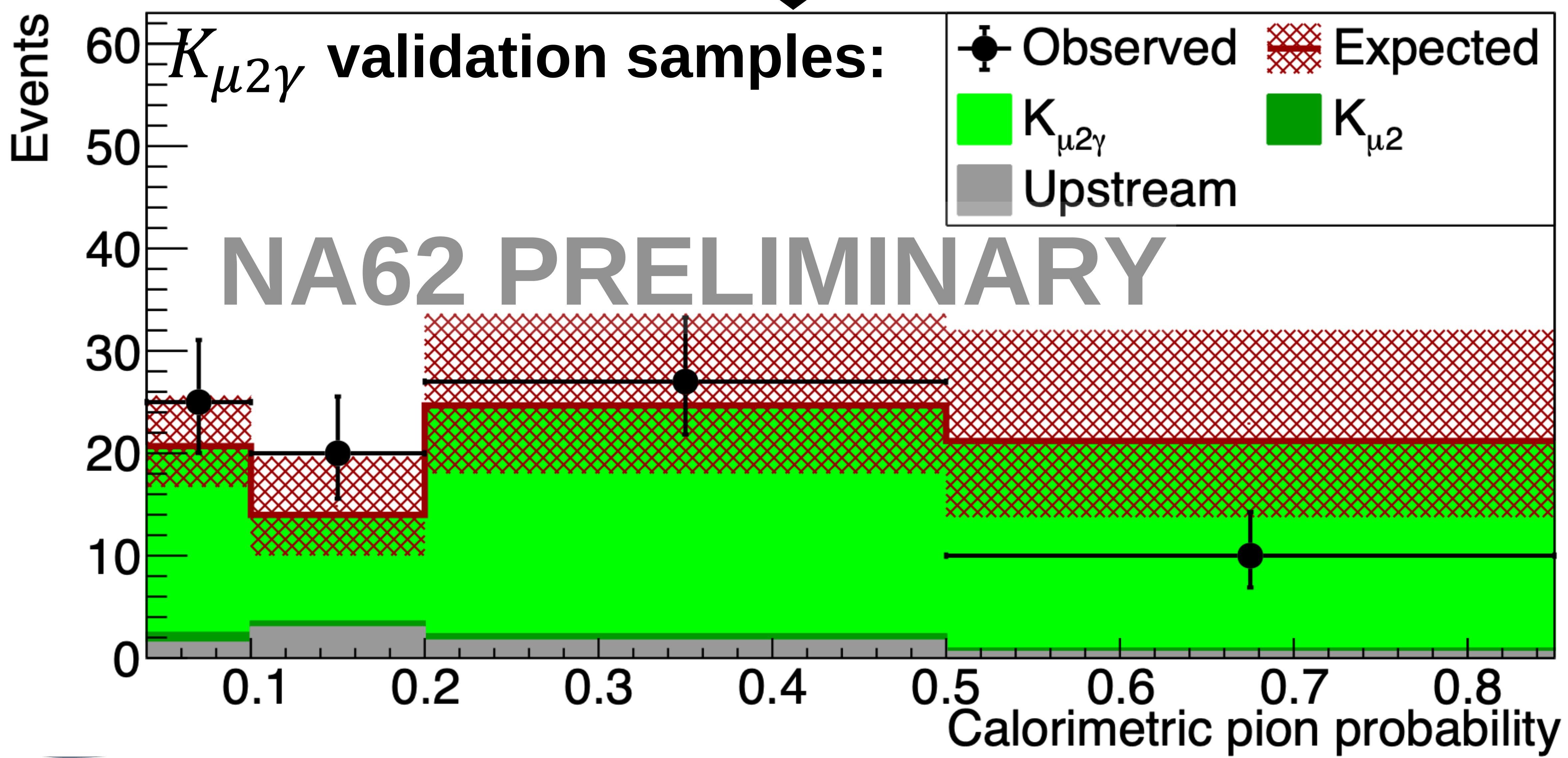
$K^+ \to \mu^+\nu\gamma$ Background

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

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



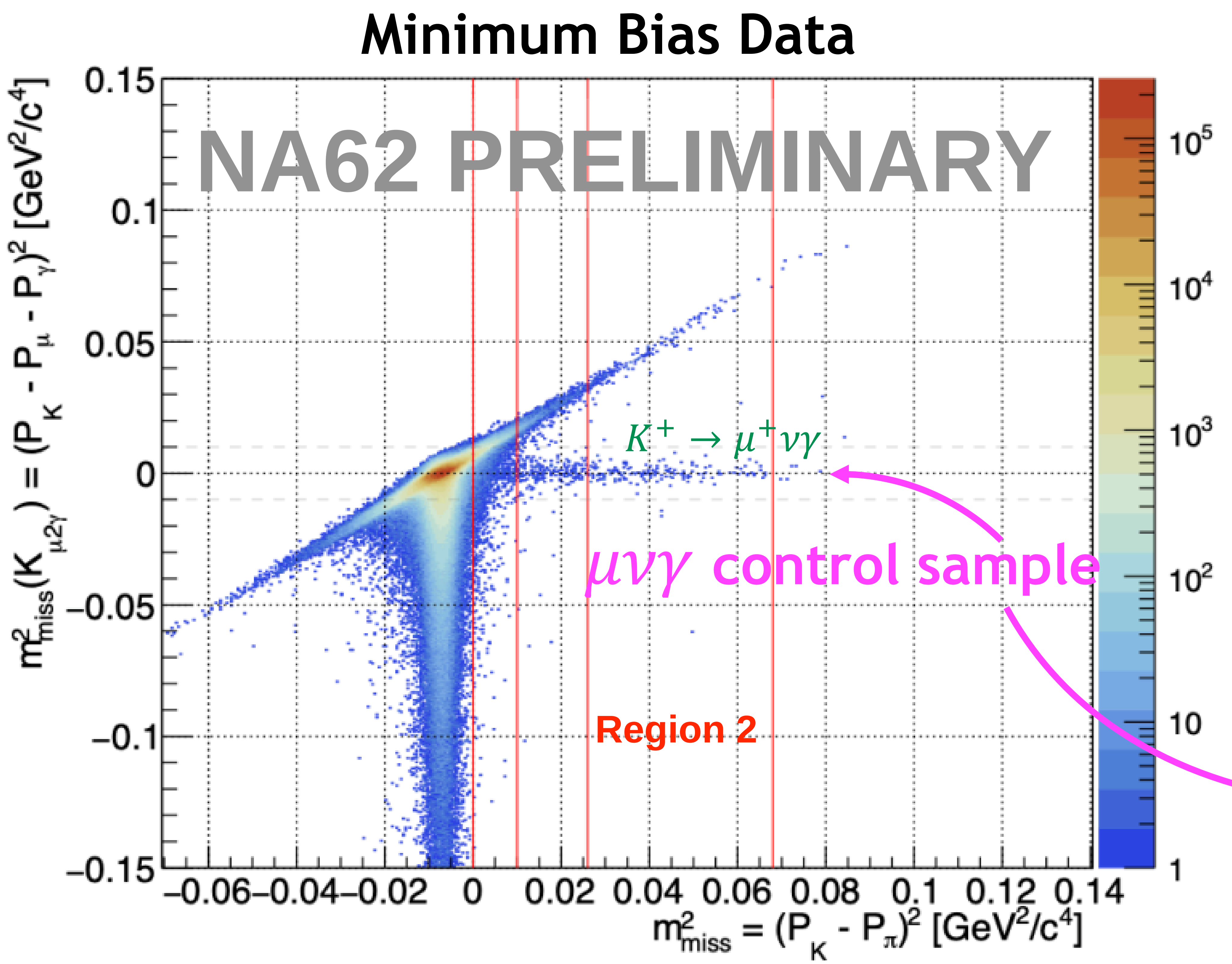
Validation: data sample with PID = “less pion-like” (Calo BDT bins below π^+ bin).



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

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

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

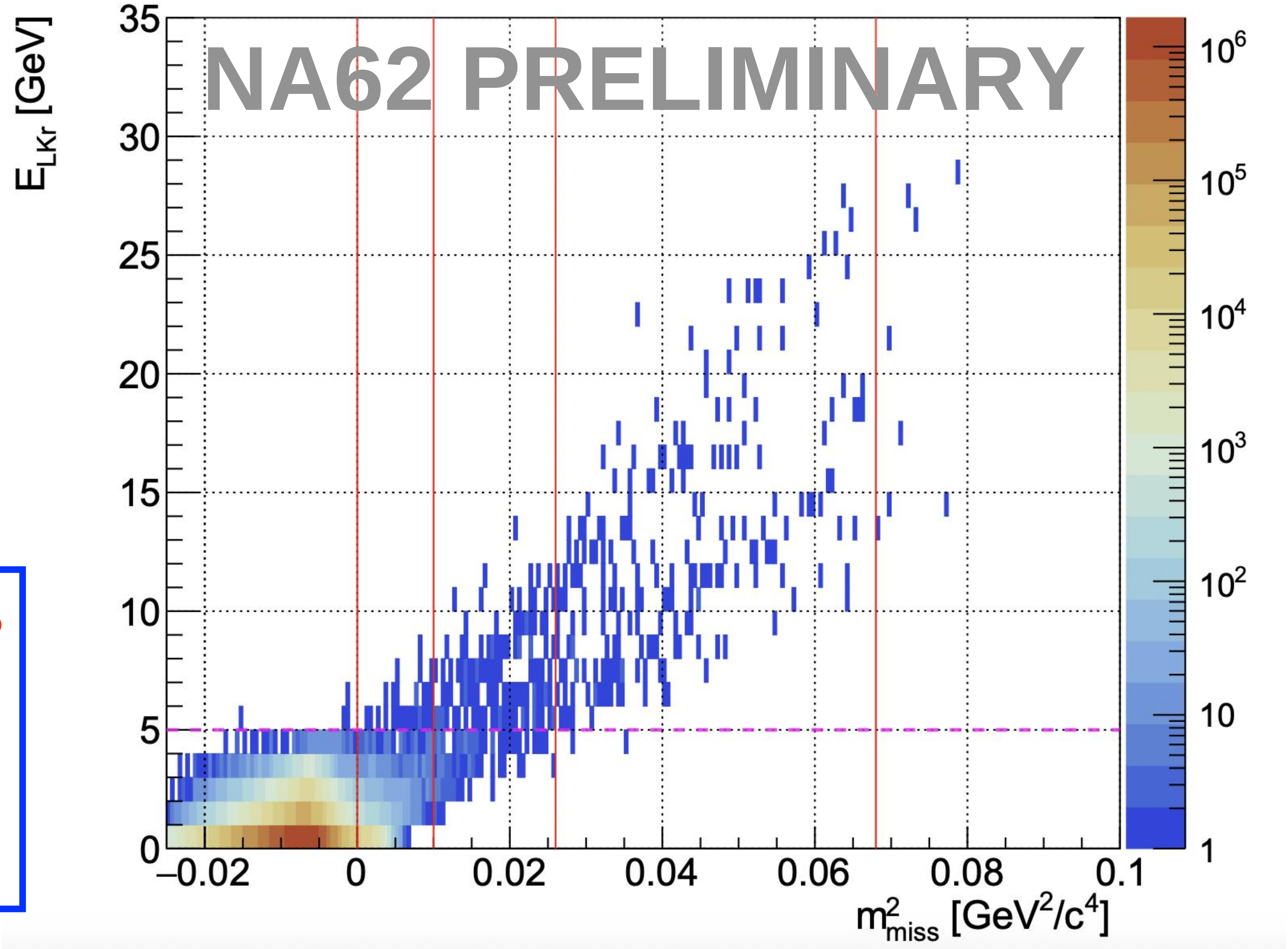
- $|m^2_{miss}(K_{\mu 2\gamma})|^2 < 0.01\,GeV^2/c^4$ → c.f. resolution $\sim 0.0025\,GeV^2/c^4$
- $E_\gamma > 5\,GeV$
- μ^+-like RICH PID.

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

Minimum Bias Data

Events with MUV3 association and

$|m^2_{miss}(K_{\mu 2\gamma})|^2 < 0.01\,\boldsymbol{GeV}^2/c^4$



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

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)

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

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

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

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

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

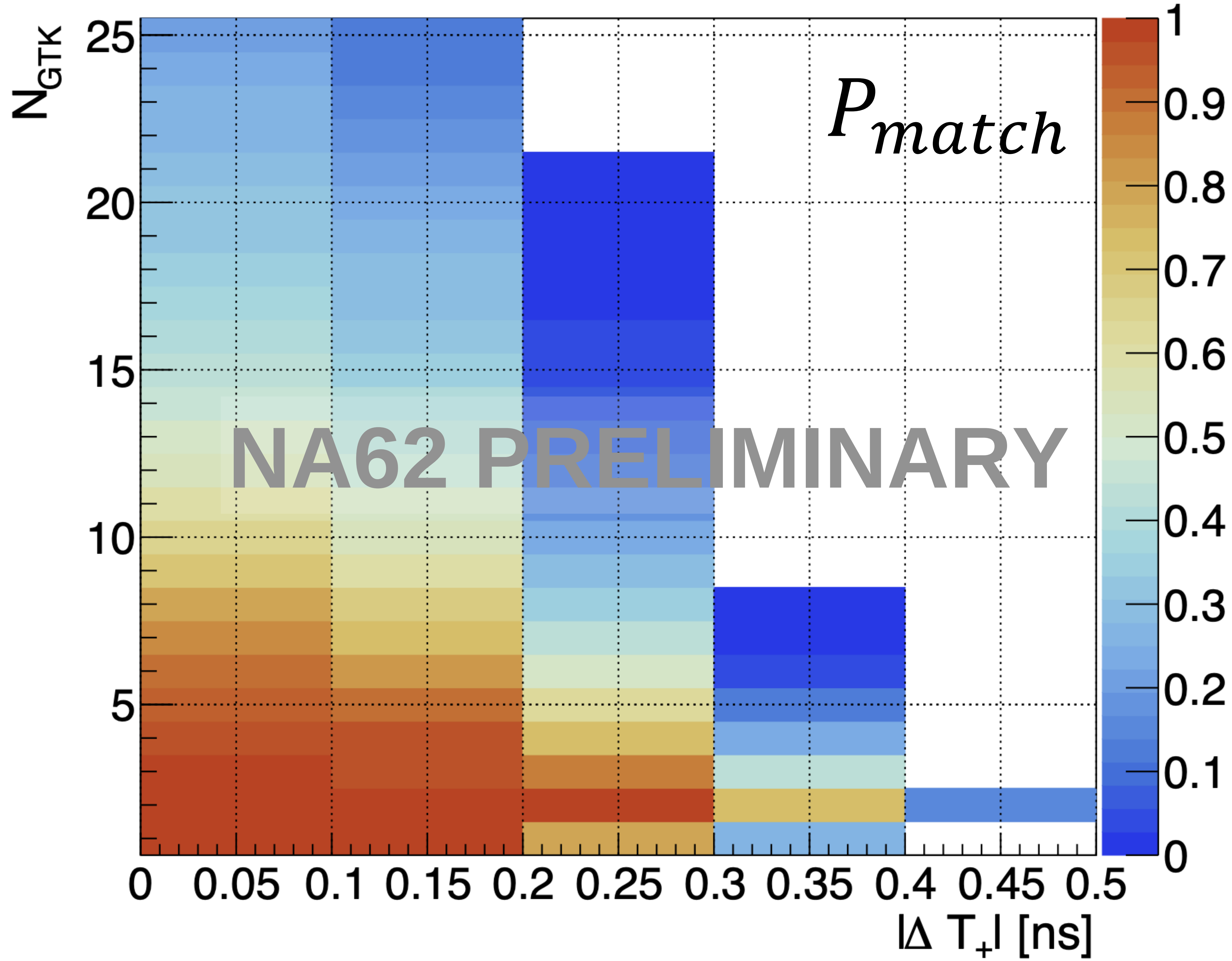
P_{match} Probability to pass $K^+ - \pi^+$ matching

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

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

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

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



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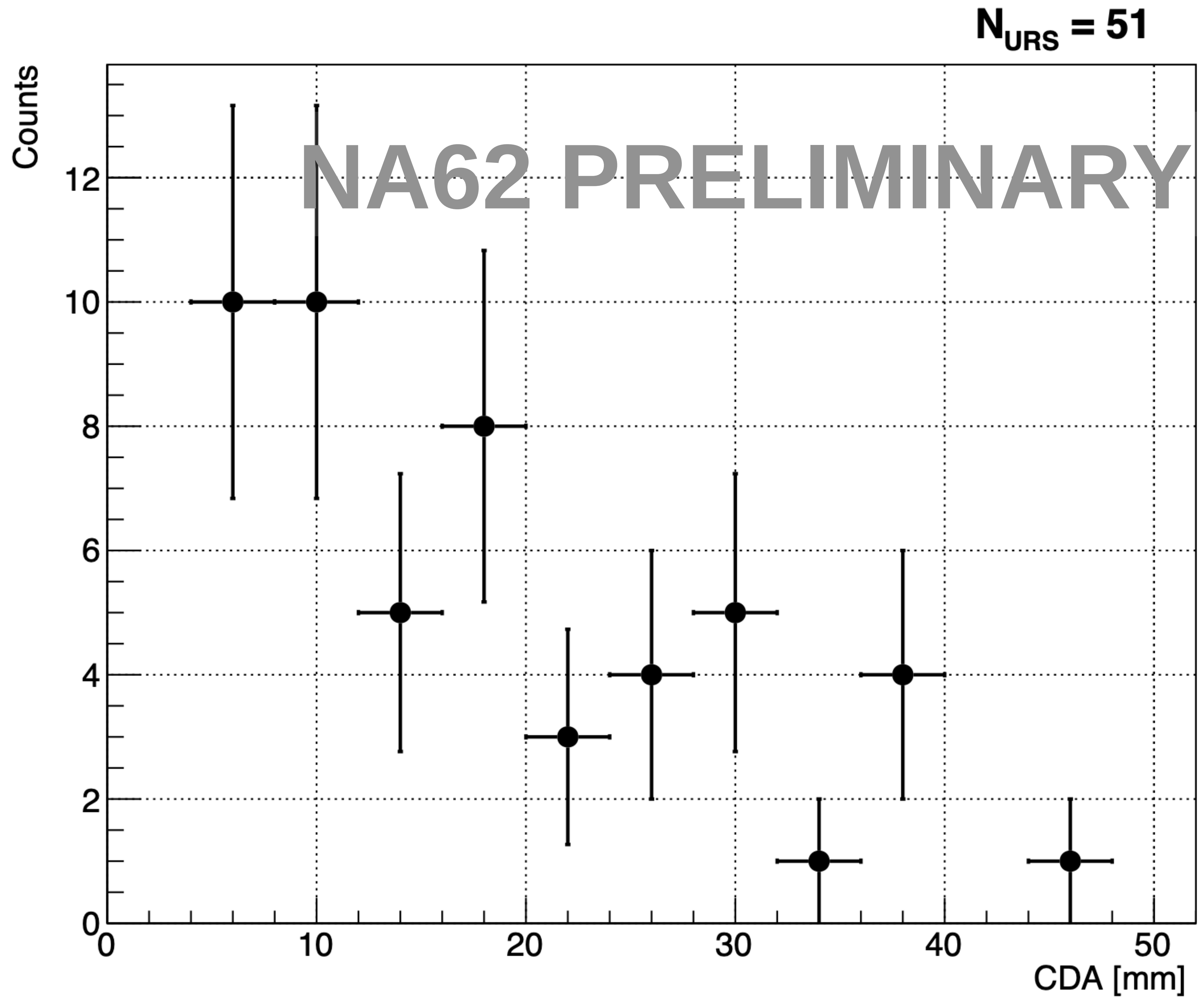
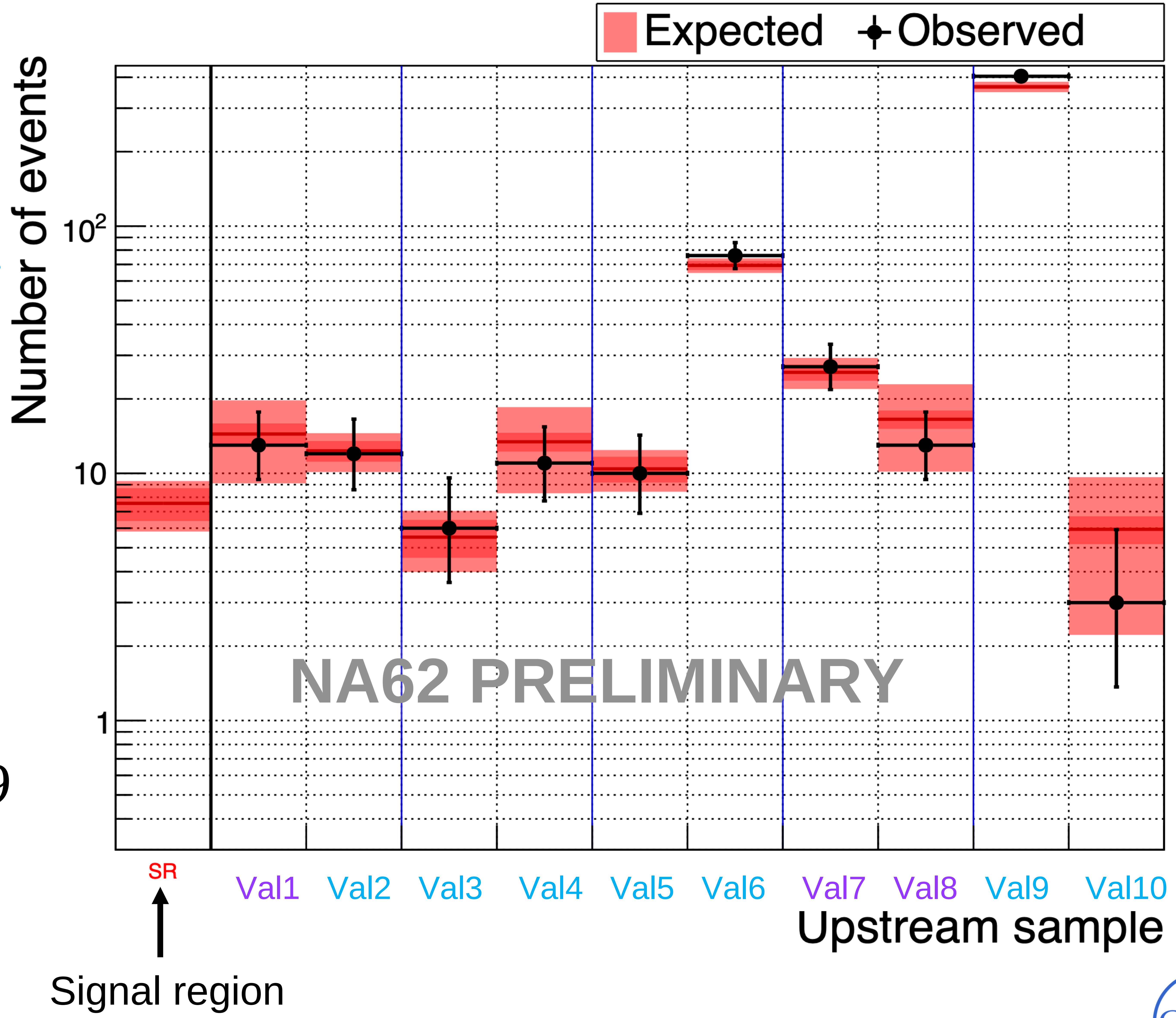
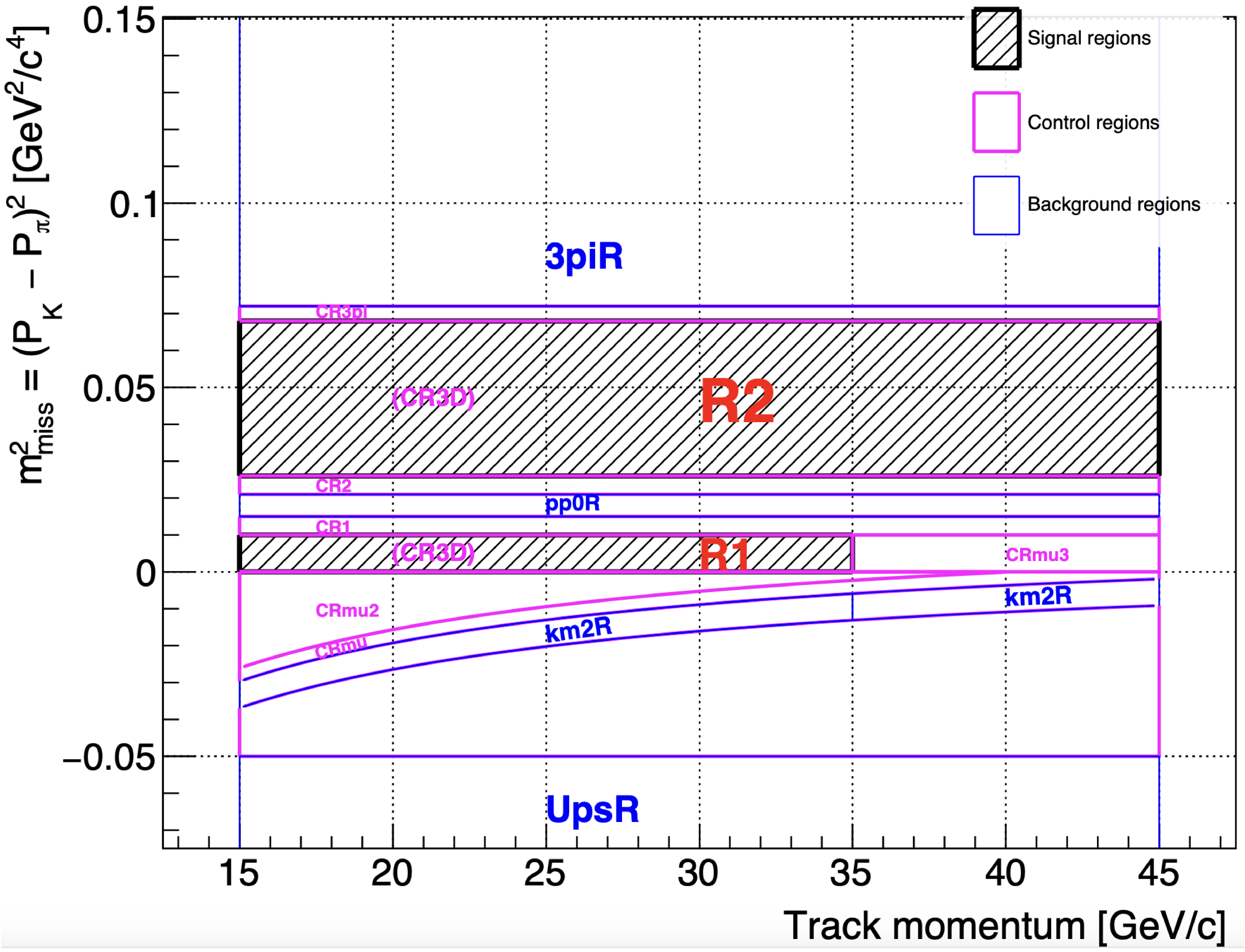


Upstream background validation

- **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.**

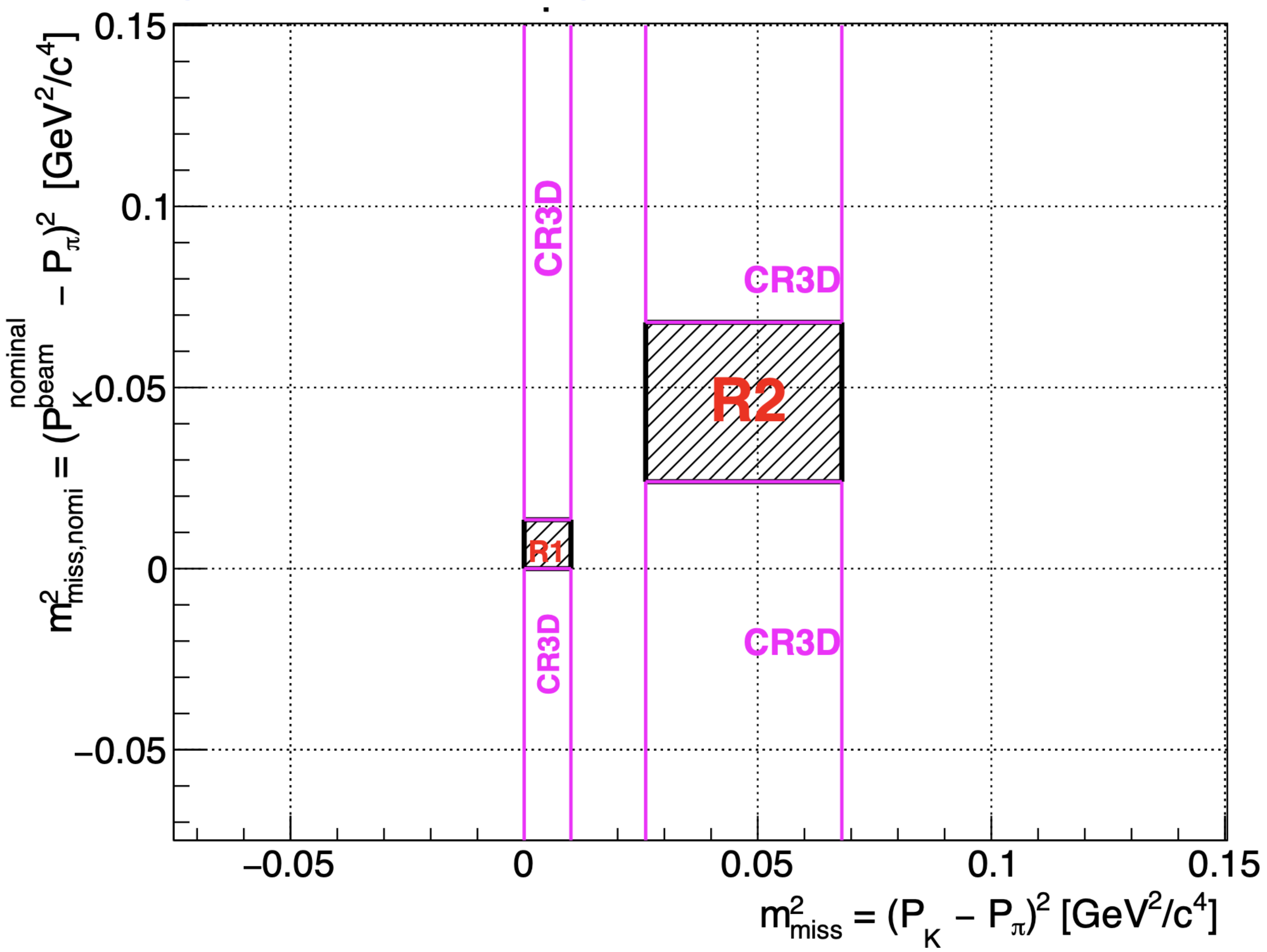


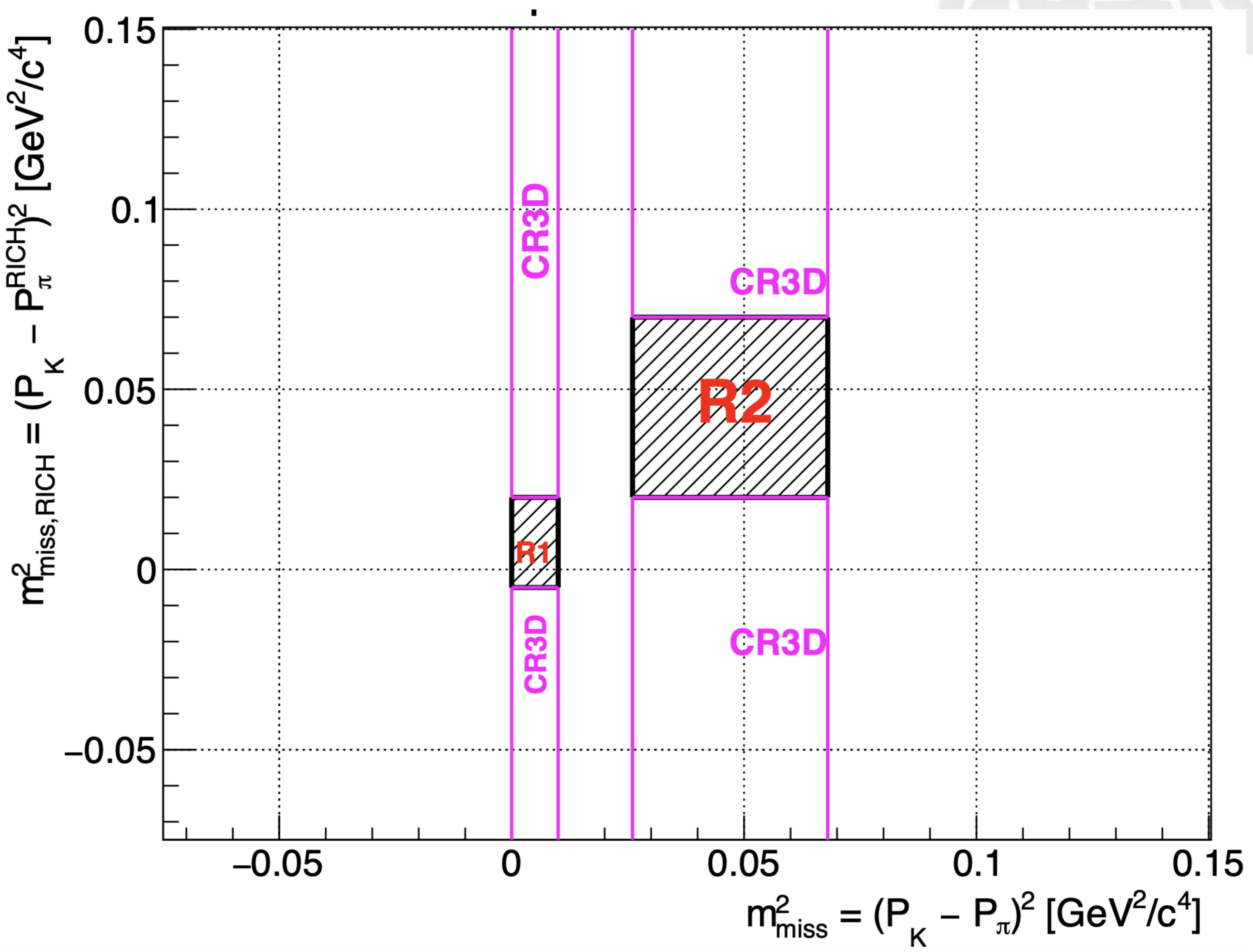
Kinematic regions



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

3D signal regions definition





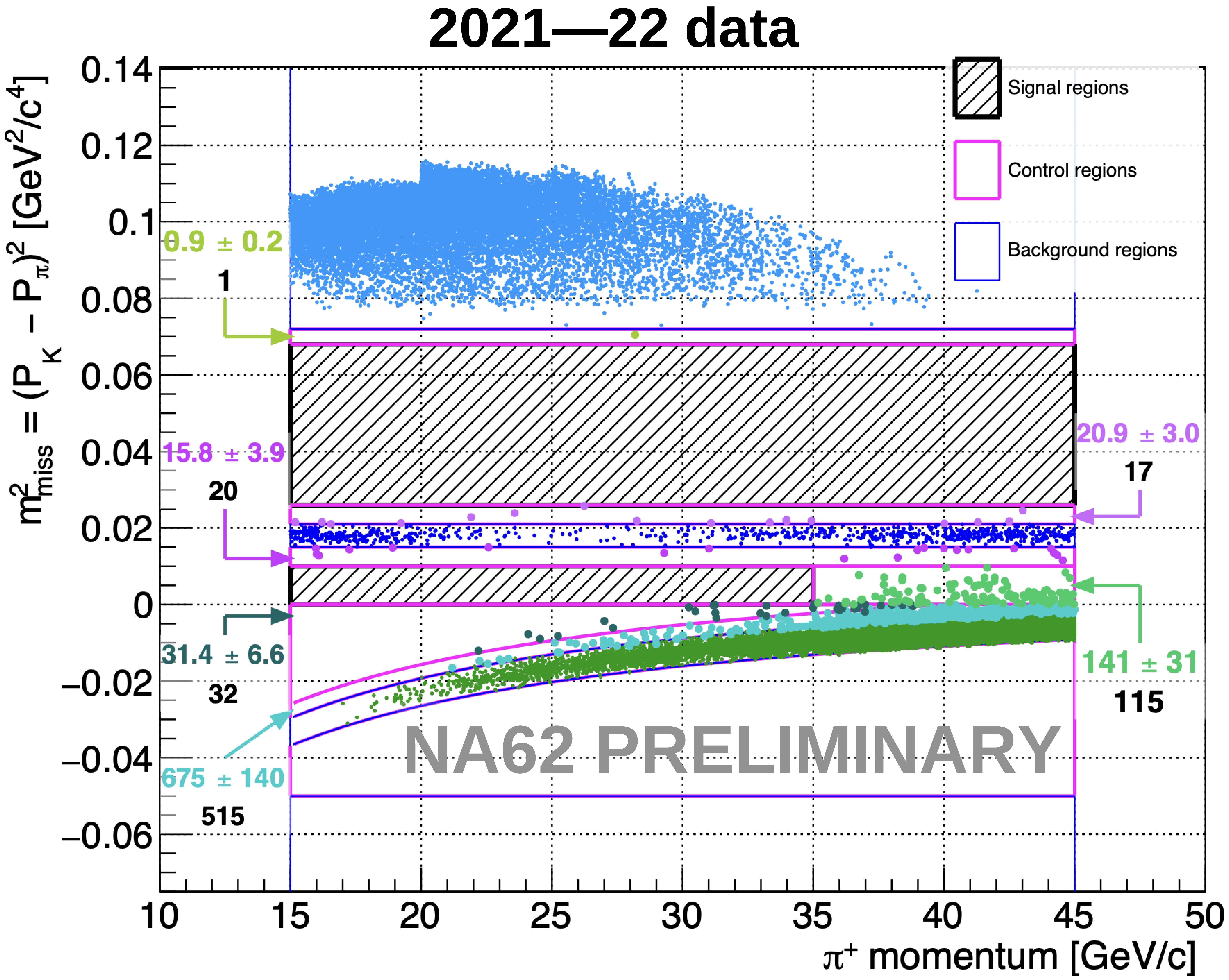
CR3D: control region for events in SR in 2 out of 3 dimensions.

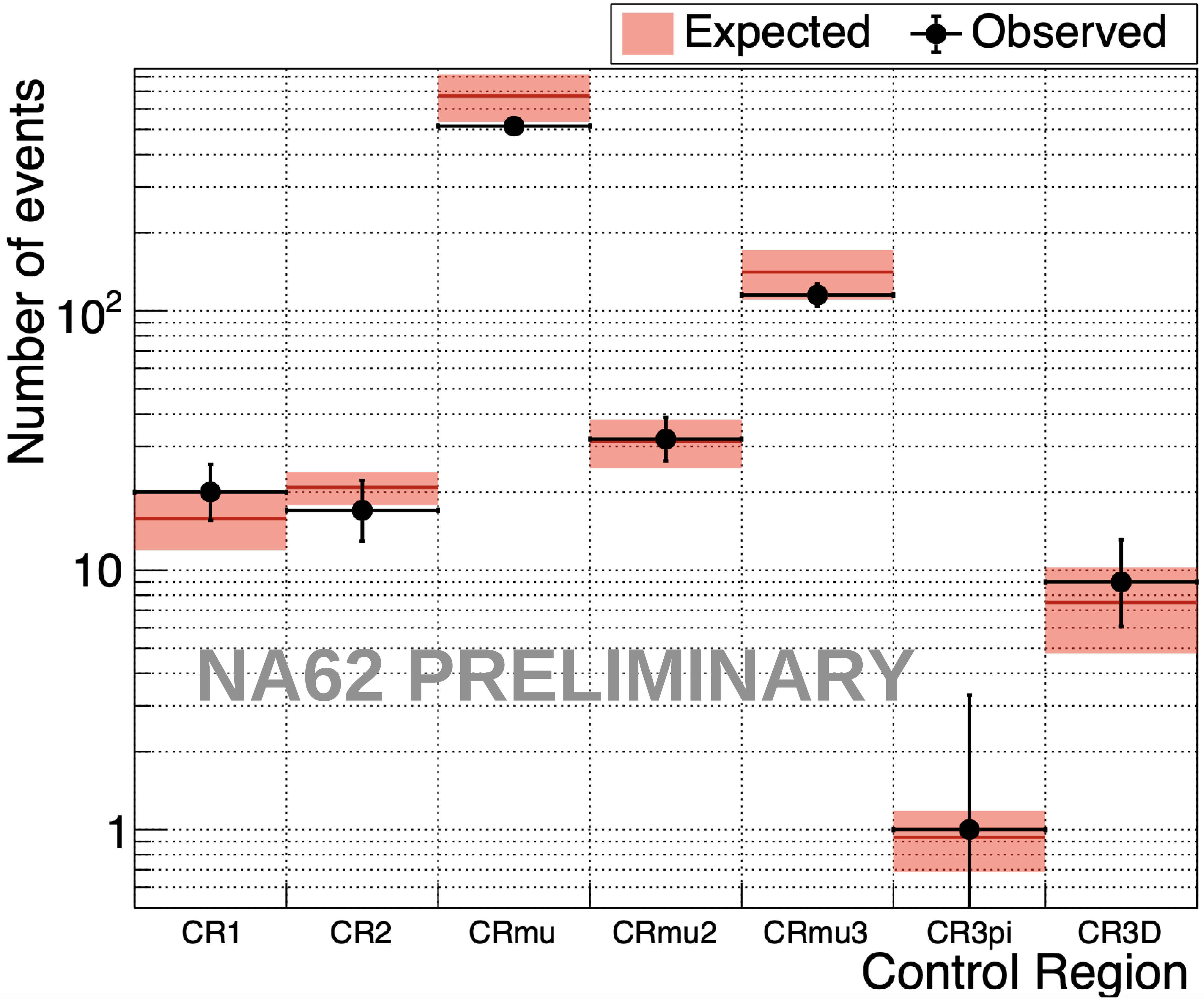
$$m^2_{miss} = (P_K - P_\pi)^2$$

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

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

Control regions: 2021—22 Data

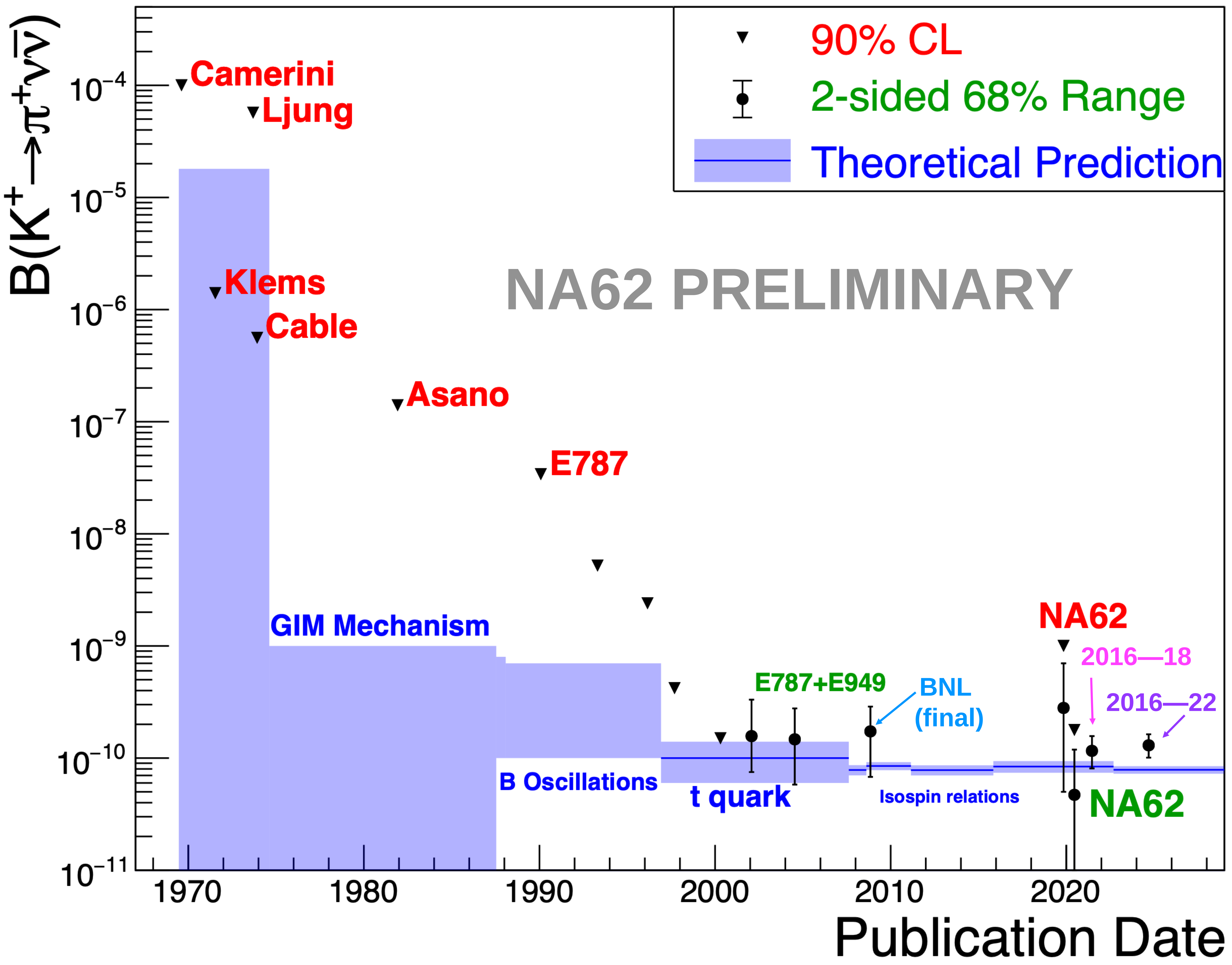




- Good agreement in control regions validates background expectations.

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]



The NA62 published results

1. First search for K+→π0πμe decays, arXiv: 2409.12981 [hep-ex], submitted to Phys. Lett. B.
2. Search for leptonic decays of the dark photon at NA62, Phys. Rev. Lett. 133 (2024) 111802.
3. Measurement of the K+ → π+γγ decay, Phys. Lett. B 850 (2024) 138513.
4. Search for K+ decays into the π+e+e−e+e− final state, Phys. Lett. B 846 (2023) 138193.
5. A study of the K+ → π0e+νγ decay, JHEP 09 (2023) 040.
6. Search for dark photon decays to μ+μ− at NA62, JHEP 09 (2023) 035.
7. A search for the K+ → μ−νe+e+ decay, Phys. Lett. B 838 (2023) 137679.
8. A measurement of the K+ → π+μ+μ− decay, JHEP 11 (2022) 011.
9. Searches for lepton number violating K+ → π−(π0) e+e+ decays, Phys. Lett. B 830 (2022) 137172.
10. Search for Lepton Number and Flavor Violation in K+ and π0 Decays, Phys. Rev. Lett. 127 (2021) 131802.
11. Measurement of the very rare K+ → π+ν ¯ν decay, JHEP 06 (2021) 093.
12. Search for K+ decays to a muon and invisible particles, Phys. Lett. B 816 (2021) 136259.
13. Search for a feebly interacting particle X in the decay K+ → π+X, JHEP 03, (2021) 058.
14. Search for π0 decays to invisible particles, JHEP 02, (2021) 201.
15. An investigation of the very rare K+ → π+ν ¯ν decay, JHEP 11 (2020) 042.
16. Search for heavy neutral lepton production in K+ decays to positrons, Phys. Lett. B 807 (2020) 135599.
17. Searches for lepton number violating K+ decays, Phys. Lett. B 797 (2019) 134794.
18. Search for production of an invisible dark photon in π0 decays, JHEP 1905 (2019) 182.
19. First search of K+ → π+ν ¯ν using the decay-in-flight technique, Phys. Lett. B 791 (2019) 156.
20. Search for heavy neutral lepton production in K+ decays, Phys. Lett. B 778 (2018) 137.