FACULTY
OF MATHEMATICS
AND PHYSICS
Charles University

# New results from the NA62 experiment

Michal Koval
IPNP

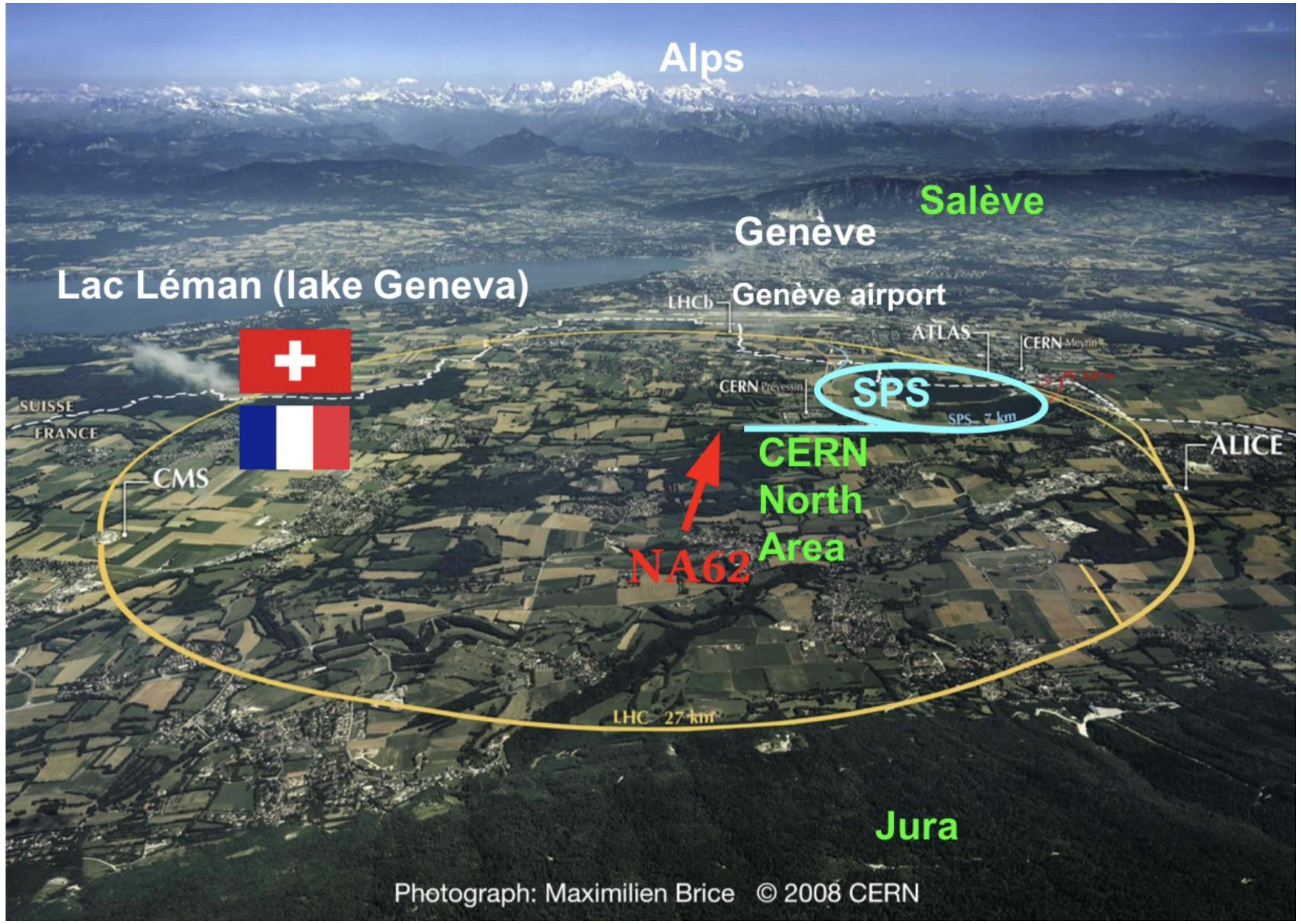
Contents:

- **Measurement of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$**
- Measurement of $\mathcal{B}(\pi^0 \to e^+ e^-)$

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

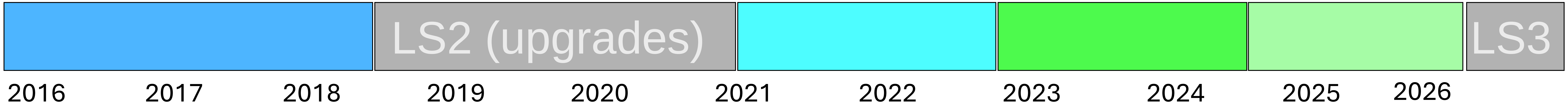
# The NA62 Experiment at CERN

~200 collaborators from ~30 institutions.



Photograph: Maximilien Brice © 2008 CERN

- **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 program:**
  - 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 ...

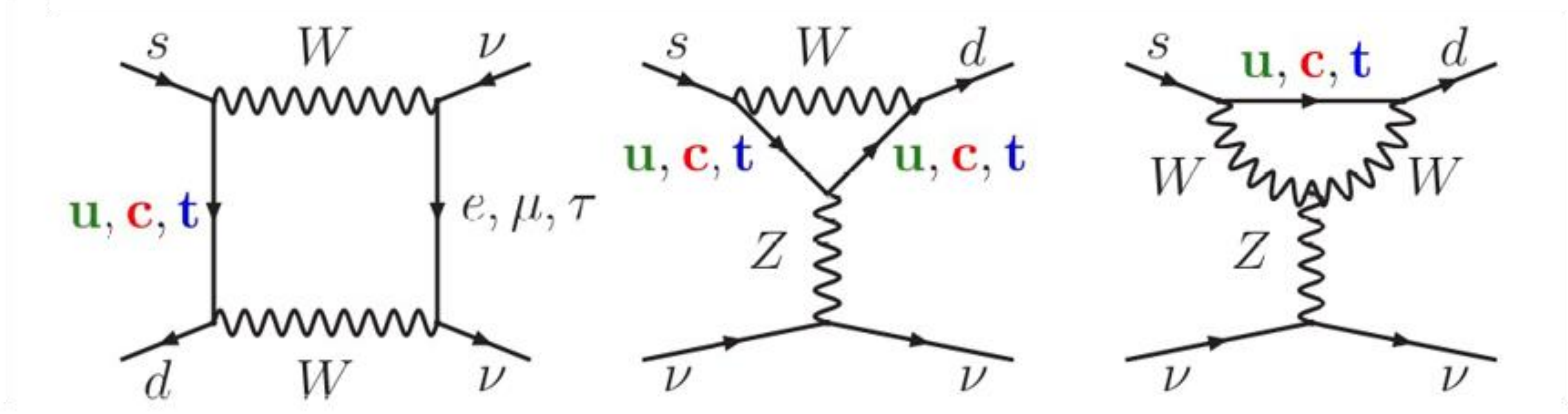


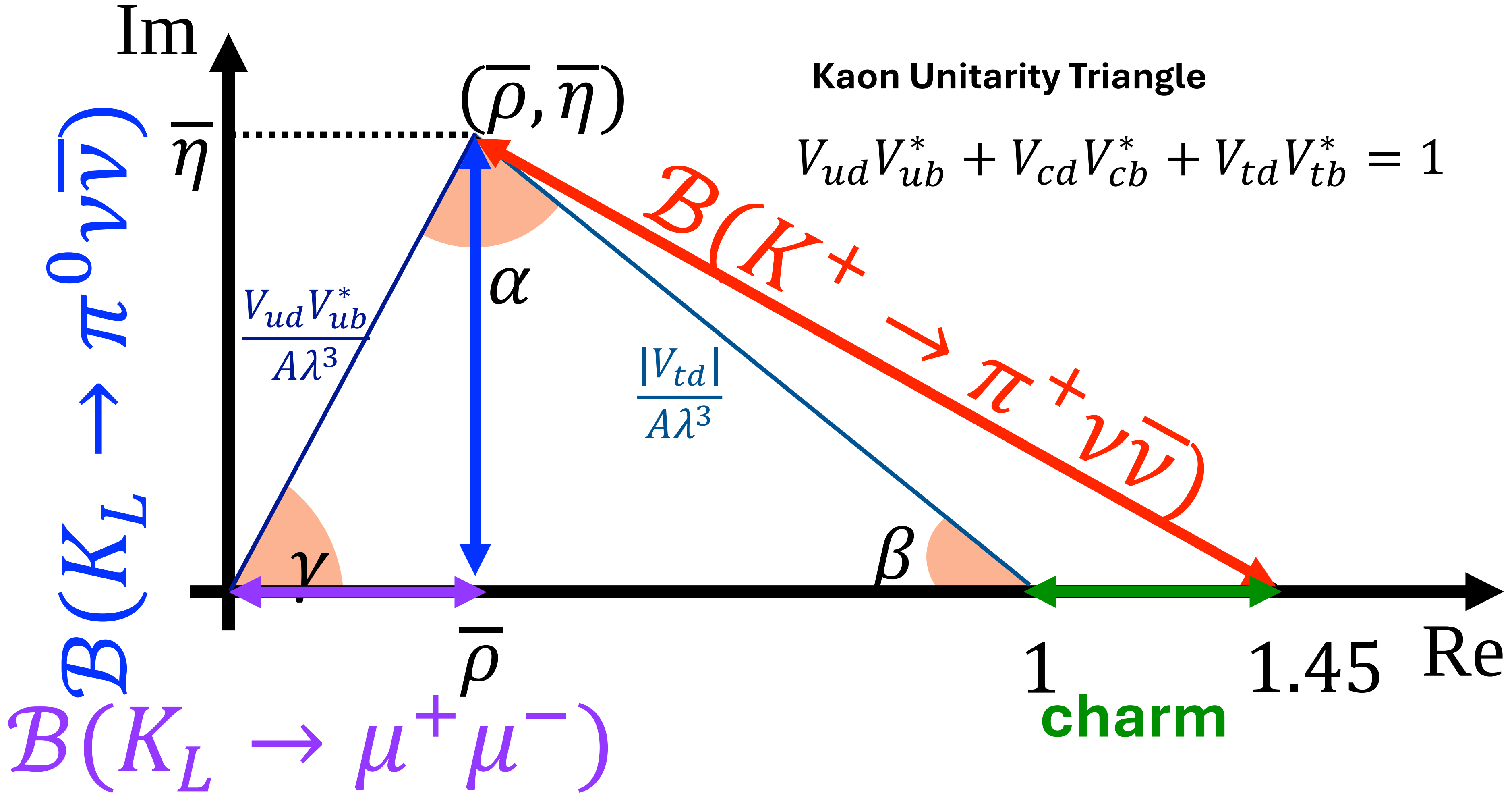
# The NA62 Collaboration

NA62 Collaboration meeting
Birmingham, UK, 2024

# $K \to \pi\nu\bar{\nu}$ : 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

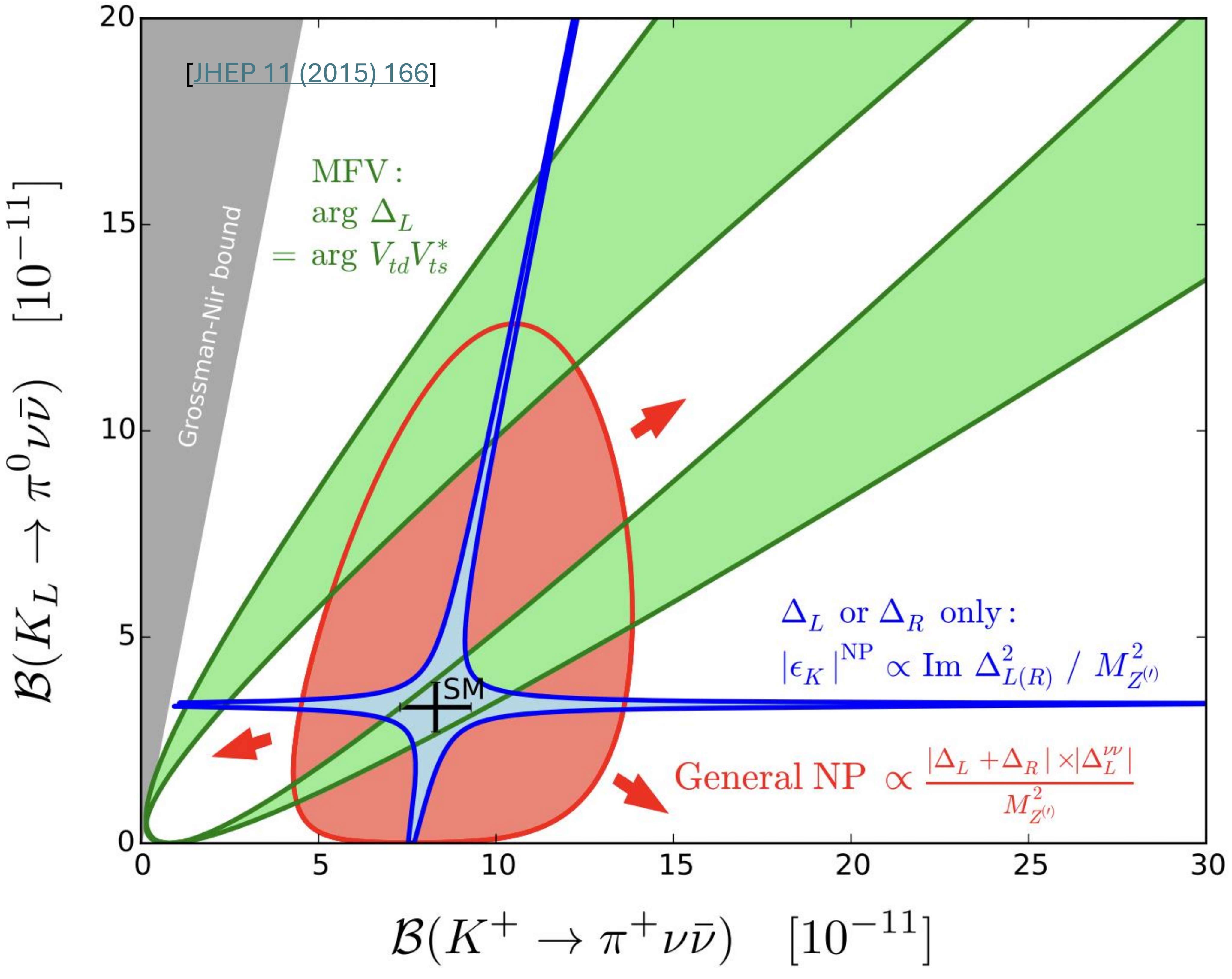
- Correlations between BSM contributions to BRs of $K^+$ and $K_L$ modes [JHEP 11 (2015) 166].
  - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables ($\varepsilon'/\varepsilon, \Delta M_B$, B-decays) [JHEP 12 (2020) 097][PLB 809 (2020) 135769].
- Leptoquarks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

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

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


[JHEP 11 (2015) 166]

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

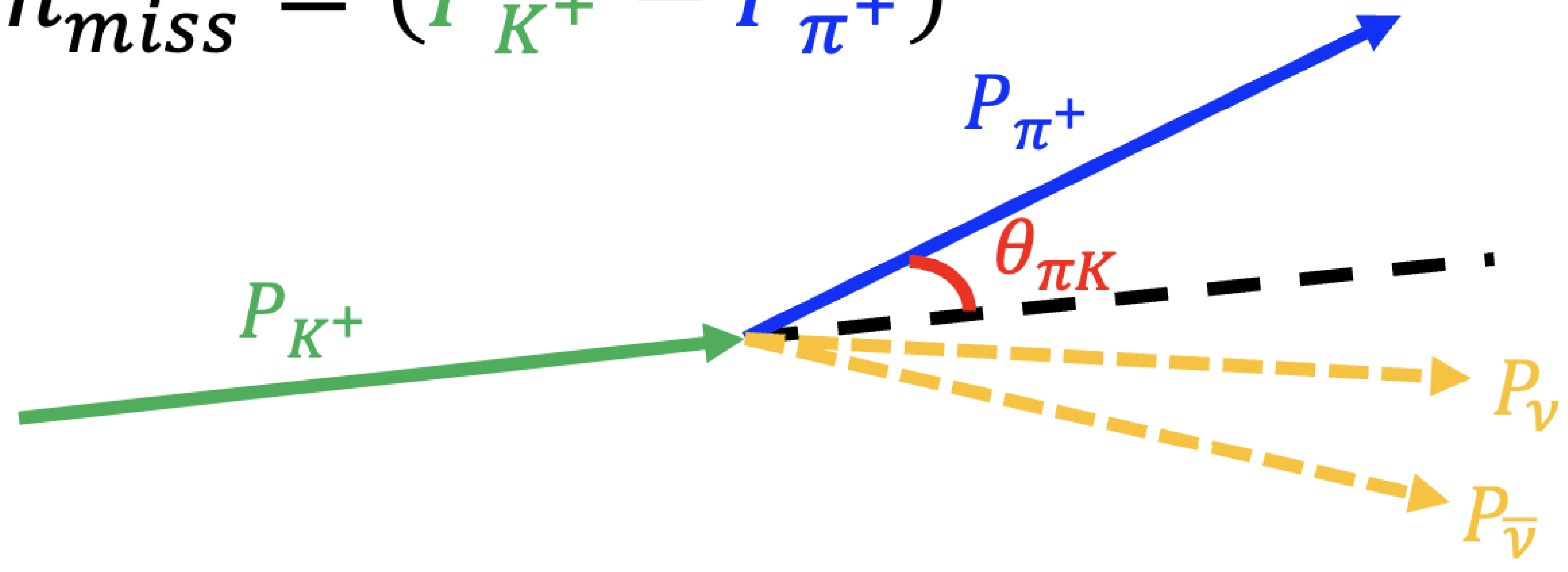
**NA62 Strategy:**

- Tag $K^+$ and measure momentum.
- Identify $\pi^+$ and measure momentum.
- Match $K^+$ and $\pi^+$ 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 $\pi^0$ from $K^+ \to \pi^+\pi^0$ decays

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



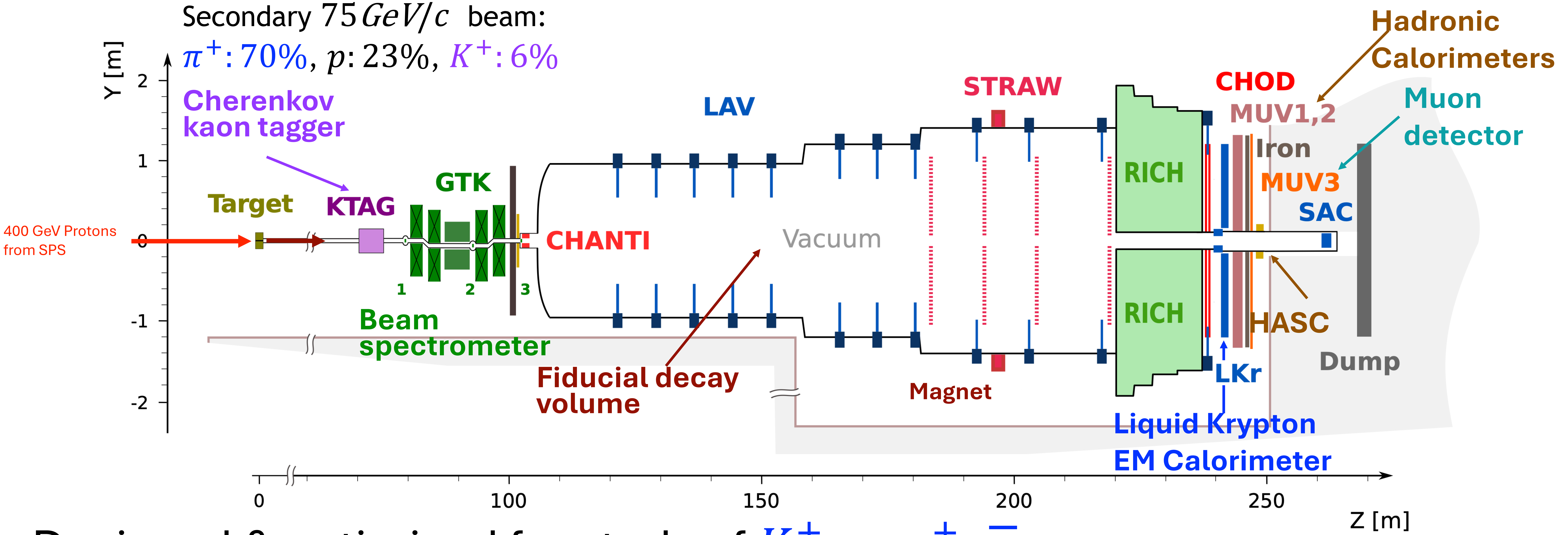
| Decay mode | Branching Ratio [PDG] |
|---|---|
| $K^+ \to \mu^+\nu_\mu$ | $(63.56 \pm 0.11)\%$ |
| $K^+ \to \pi^+\pi^0$ | $(20.67 \pm 0.08)\%$ |
| $K^+ \to \pi^+\pi^+\pi^-$ | $(5.583 \pm 0.024)\%$ |
| $K^+ \to \pi^+\pi^-e^+\nu_e$ | $(4.247 \pm 0.024) \times 10^{-5}$ |
| $K^+ \to \pi^+\nu\bar{\nu}$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

# NA62 beamline & detector

[JINST 12 (2017) 05, P05025]

Secondary $75\,GeV/c$ beam:

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

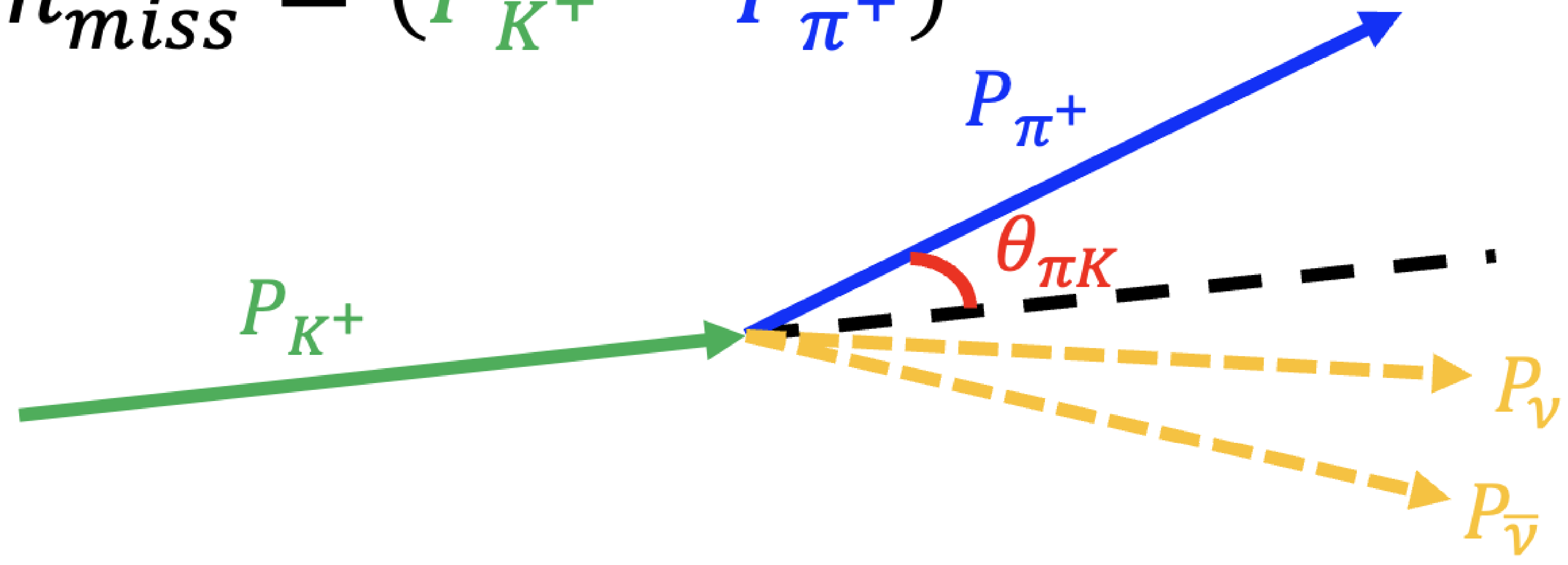


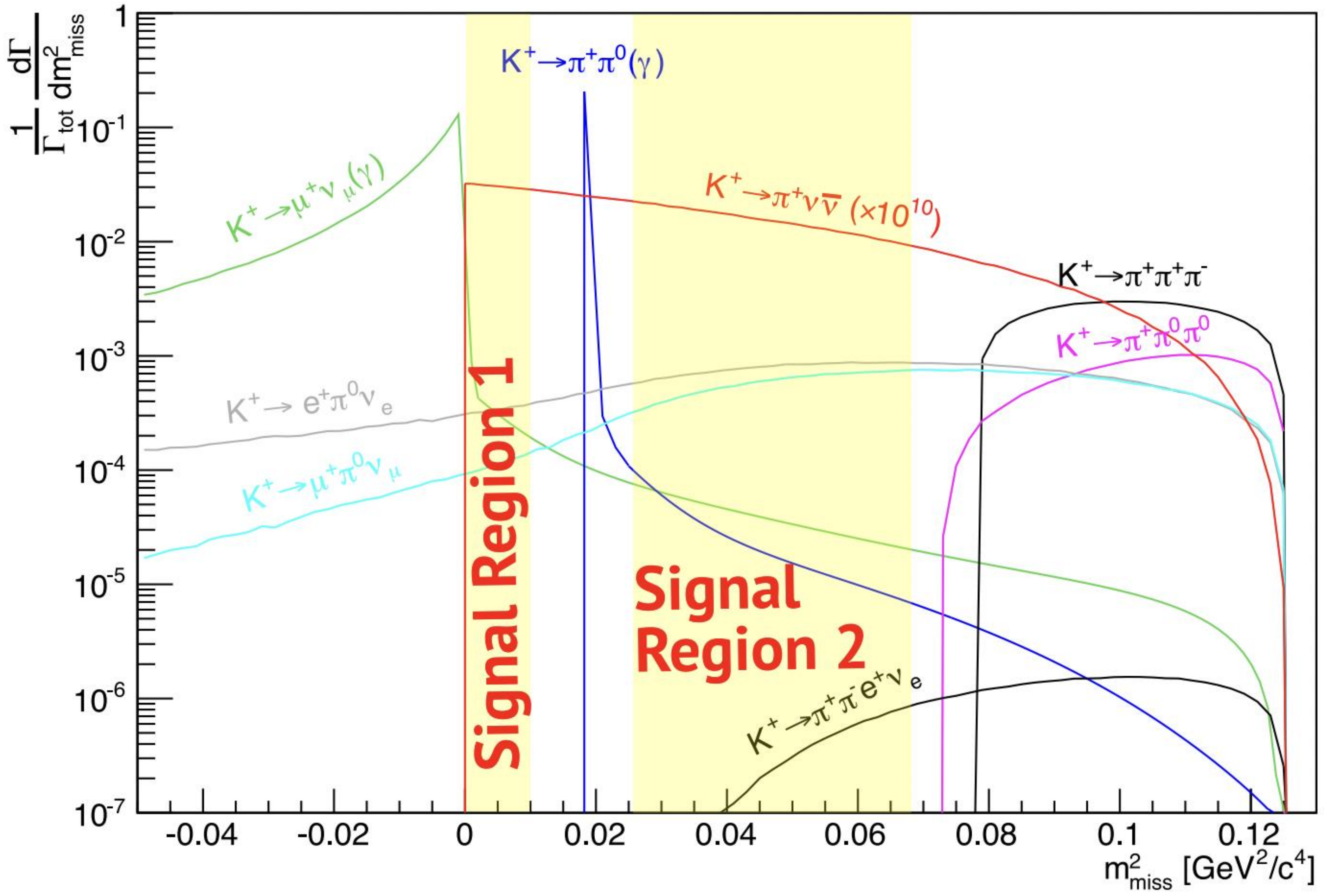
- Designed & optimised for study of $K^+ \to \pi^+ \nu \bar{\nu}$ :
  - **Particle tracking:** beam particle (GTK) & downstream tracks (STRAW)
  - **PID:** $K^+$ - KTAG, $\pi^+$ - RICH, Calorimeters (LKr, MUV1,2), MUV3 ($\mu$ detector)
  - **Comprehensive veto systems:** CHANTI (beam interactions), LAV,LKr,IRC,SAC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

# NA62 beamline & detector

# Kinematic constraints & signal regions

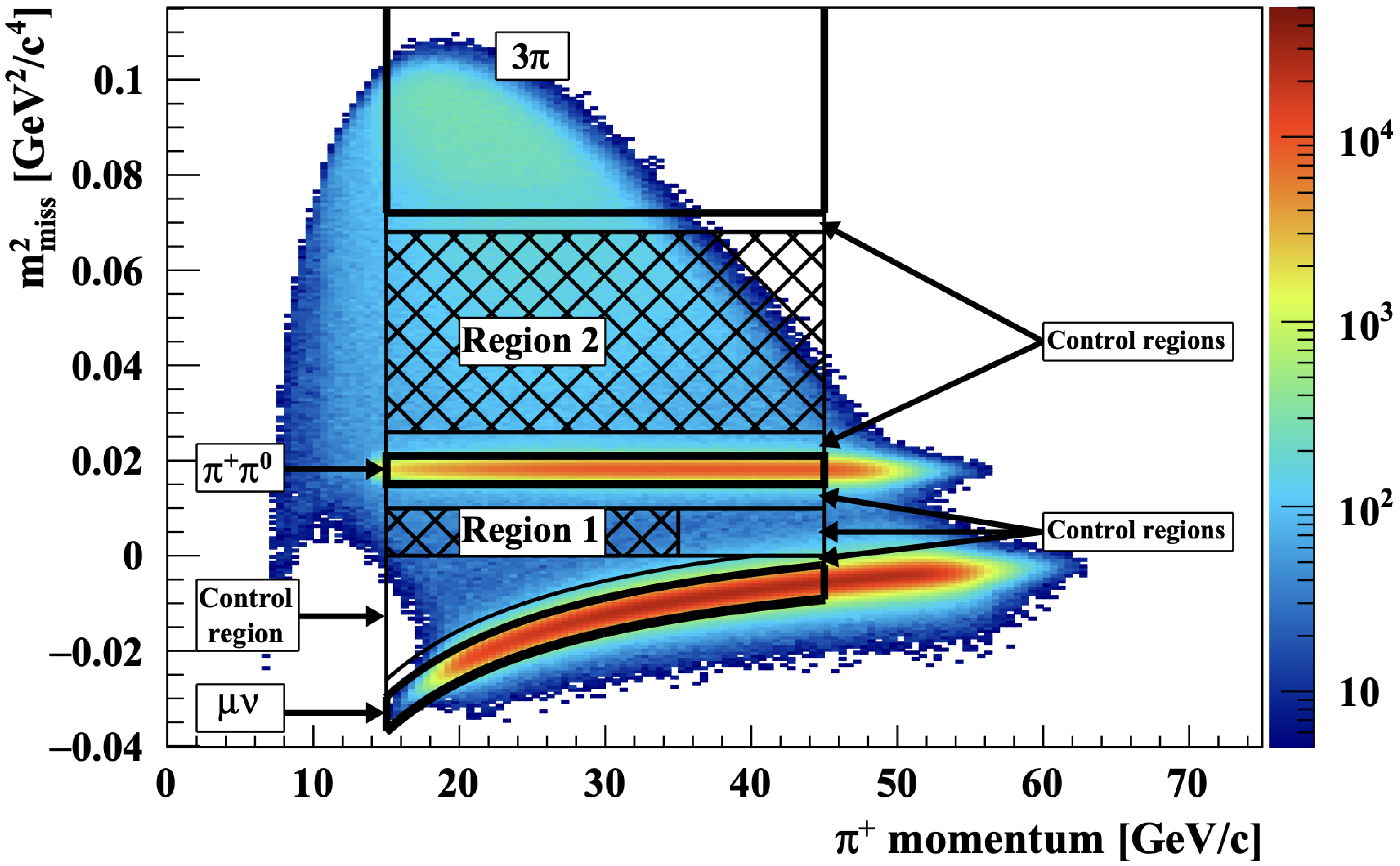
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$





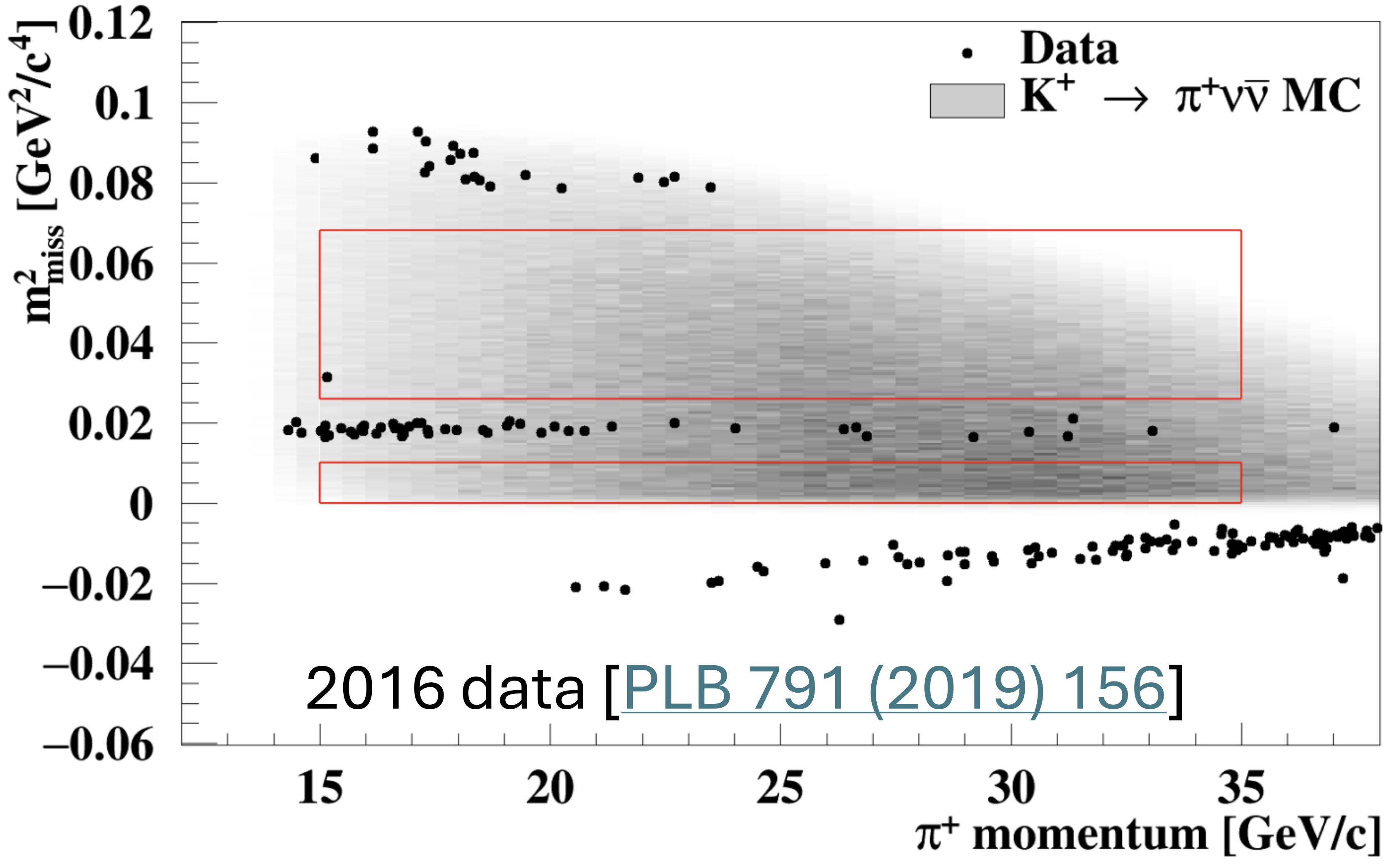
$\mathcal{O}(10^4)$ background suppression from kinematics

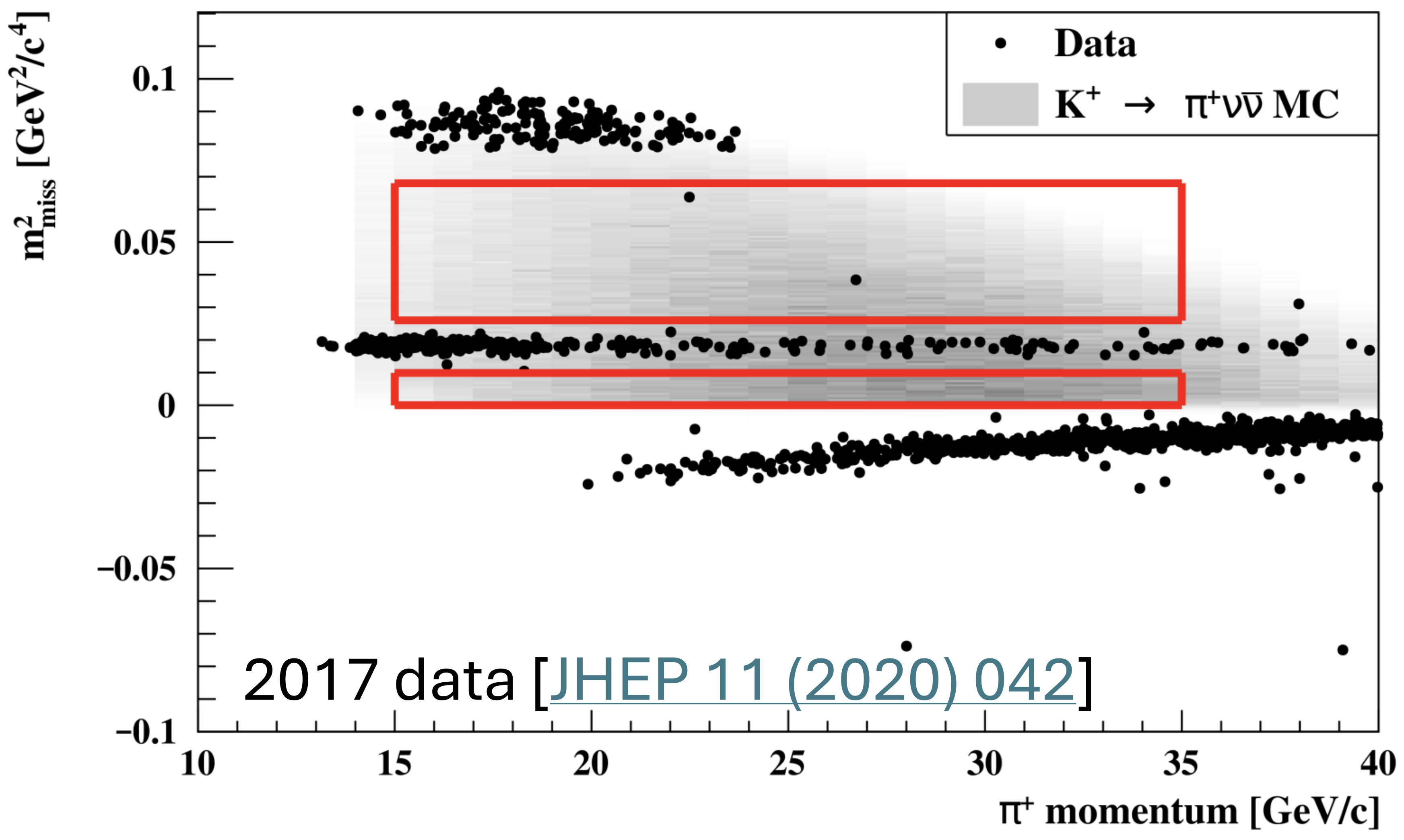
[JHEP 06 (2021) 093]

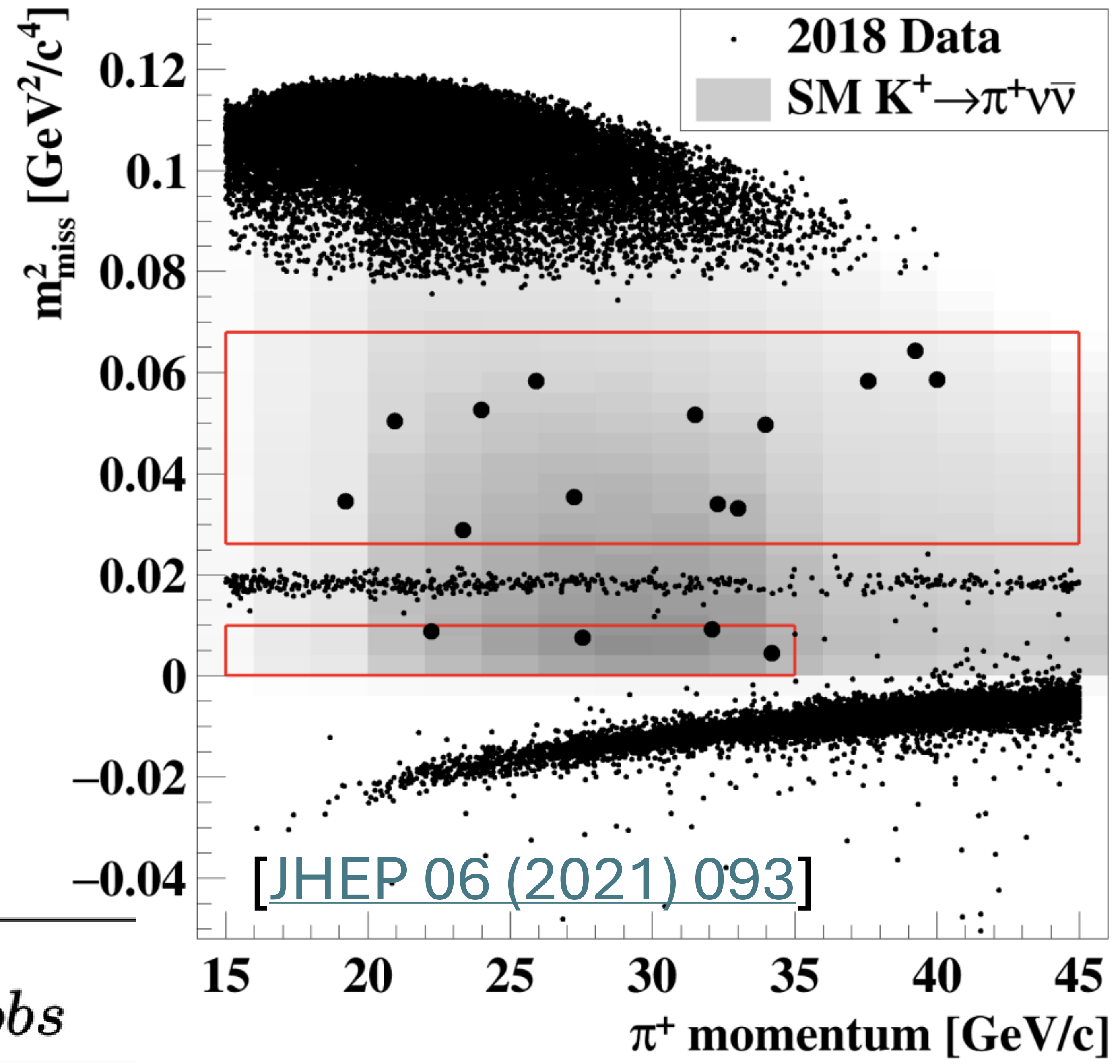


$\pi^+$ momentum range: 15—45 GeV/c

# The NA62 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] | $0.152^{+0.093}_{-0.035}$ | $0.267 \pm 0.020$ | 1 |
| 2017 | [JHEP 11 (2020) 042] | $1.46 \pm 0.33$ | $2.16 \pm 0.13$ | 2 |
| 2018 | [JHEP 06 (2021) 093] | $5.42^{+0.99}_{-0.75}$ | $7.58 \pm 0.40$ | 17 |
| 2016–18 | [JHEP 06 (2021) 093] | $7.03^{+1.05}_{-0.82}$ | $10.01 \pm 0.42$ | 20 |

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

**Statistical combination:**

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

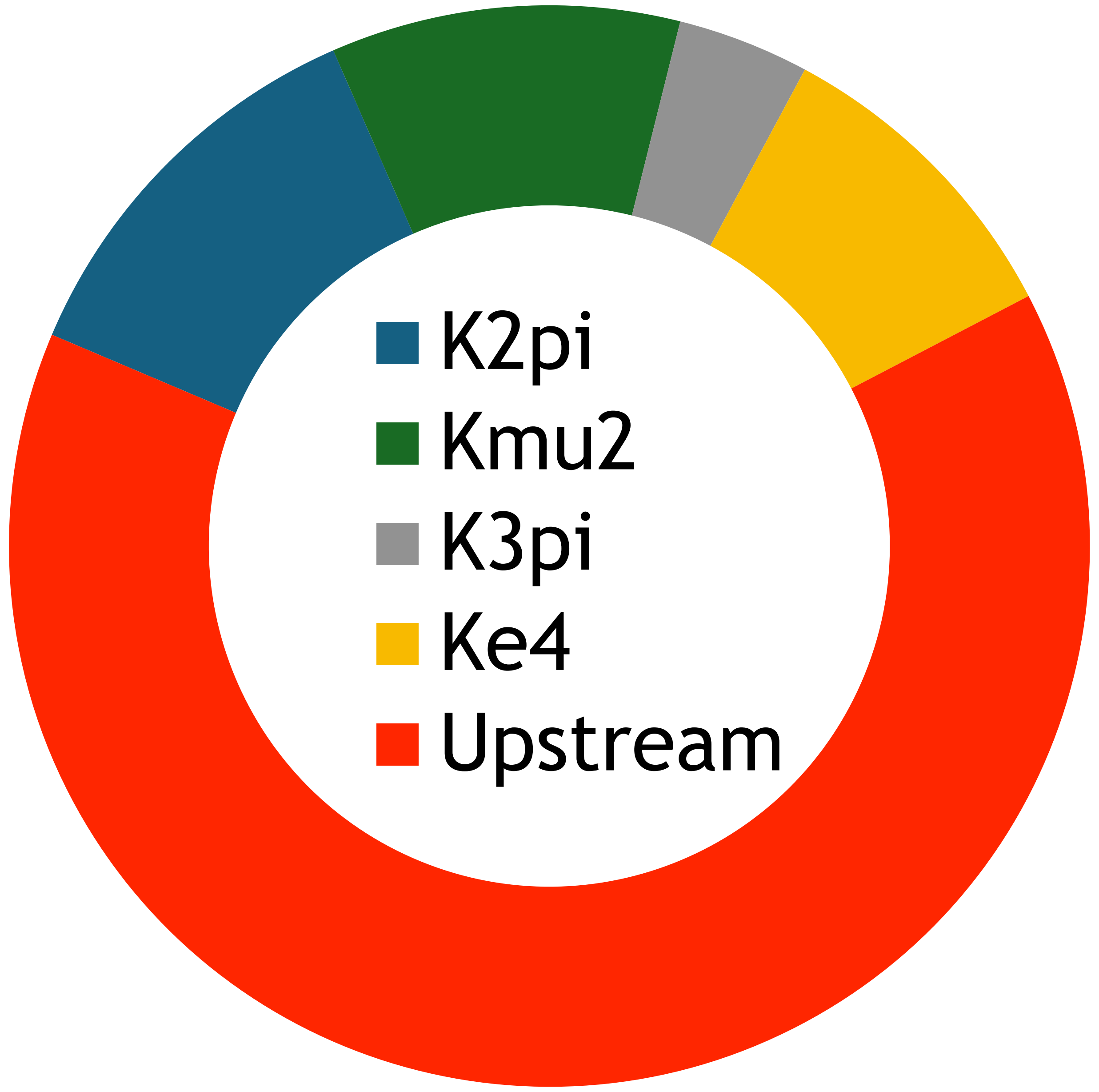
Background-only hypothesis: $p = 3.4 \times 10^{-4}$ ⇒ significance = $3.4\sigma$

# 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)<br>2018 (S2)** |
|---|---|
| Upstream | $2.76^{+0.90}_{-0.70}$ |
| $K^+ \to \pi^+\pi^0$ | $0.52 \pm 0.05$ |
| $K^+ \to \mu^+\nu$ | $0.45 \pm 0.06$ |
| $K^+ \to \pi^+\pi^-e^+\nu$ | $0.41 \pm 0.10$ |
| $K^+ \to \pi^+\pi^+\pi^-$ | $0.17 \pm 0.08$ |
| **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 ($\pi^+$) which does not leave beam pipe

## 2021 - addition of VetoCounter

Upstream decays can be detected and actively vetoed.

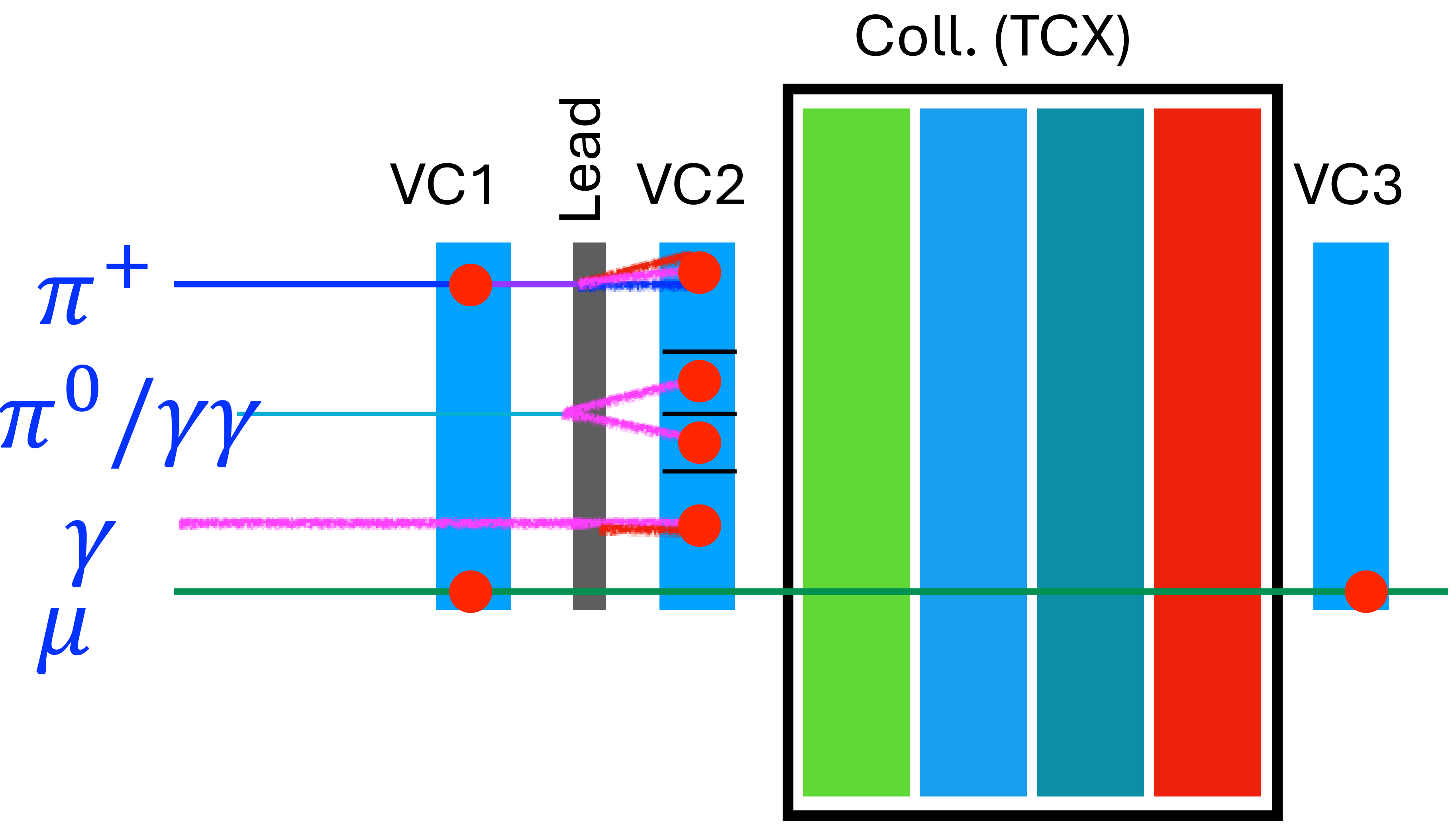
Sketch only

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

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

# New upstream vetos: VetoCounter & ANTI0

[FELIX readout: Streaming Readout Workshop talk 2021]



VetoCounter

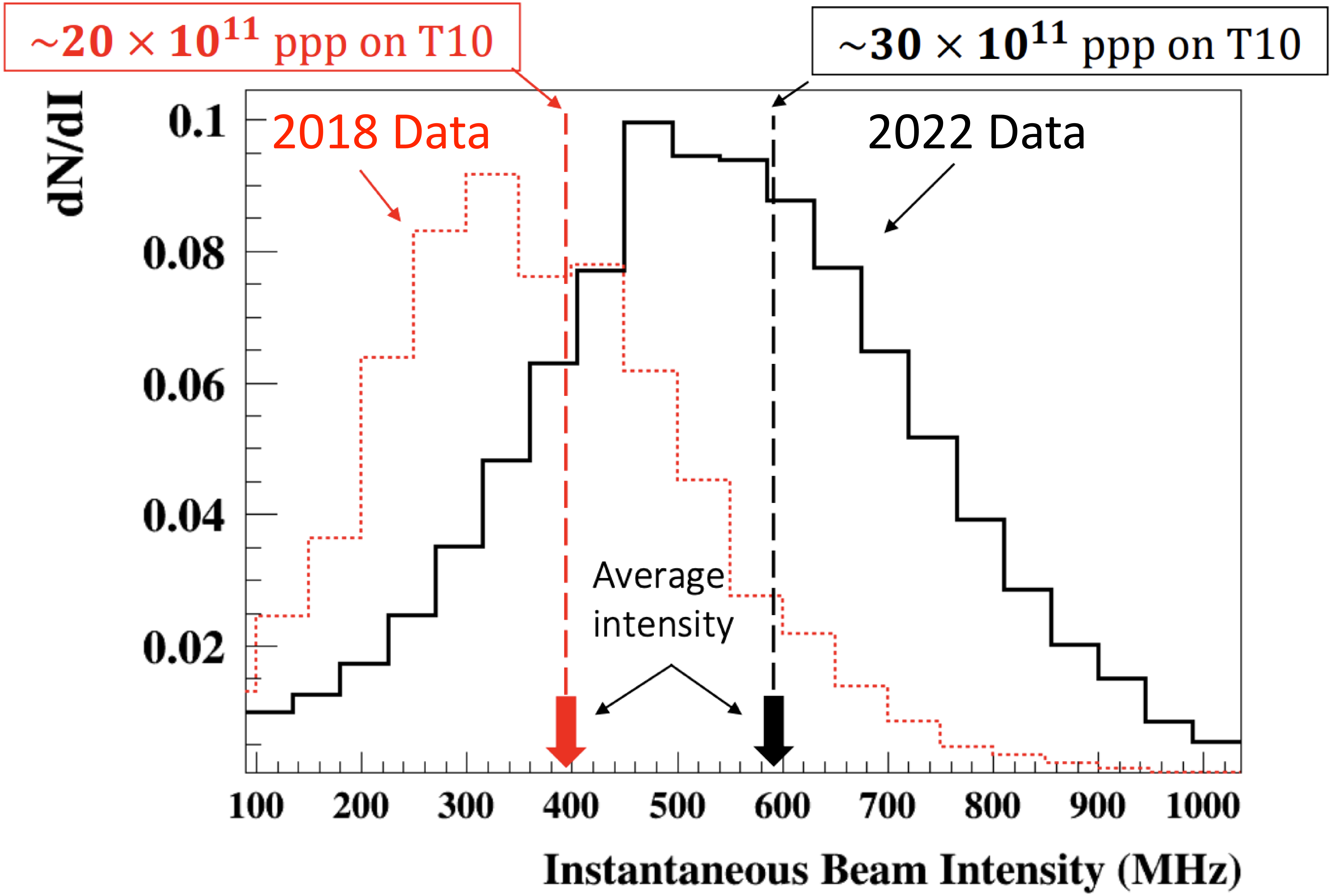
- Detect particles from decays upstream of final collimator.
- **Factor ~3 rejection** with ~2% accidental veto.

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]

# Beam intensity: 2018 vs 2022

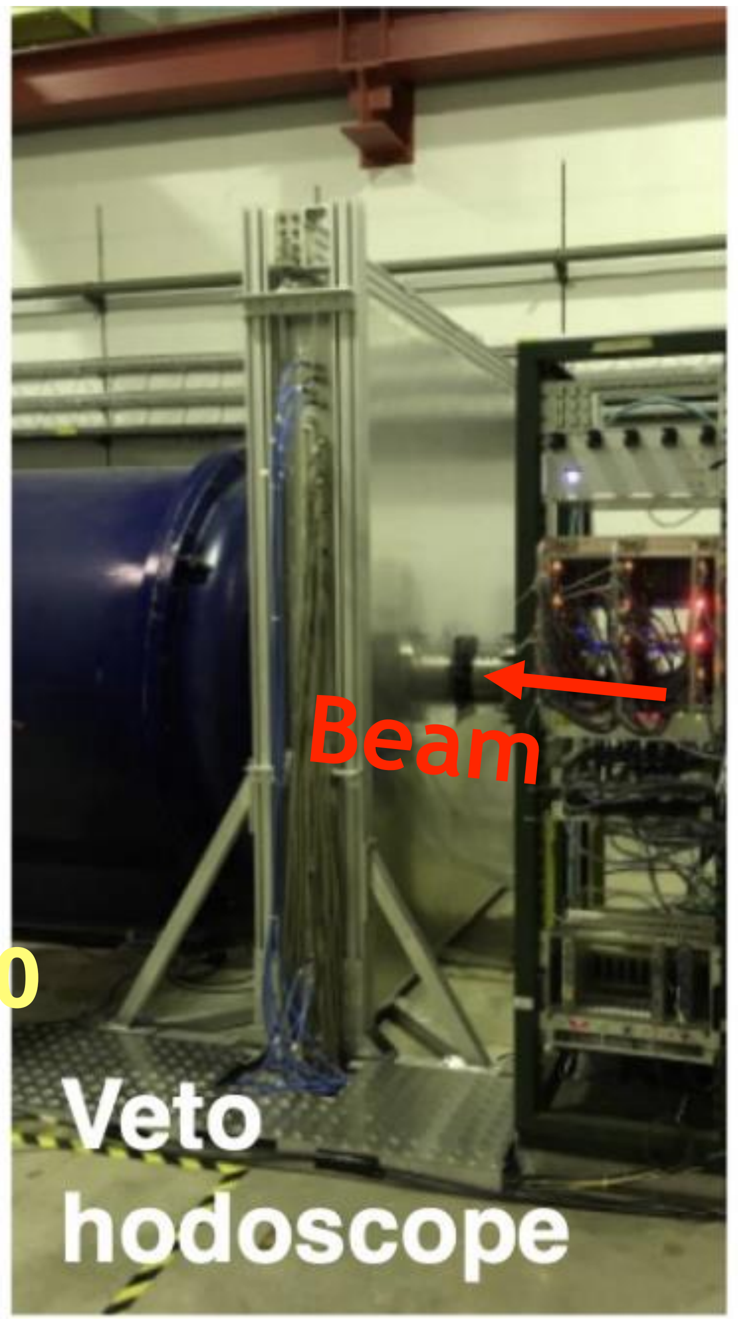


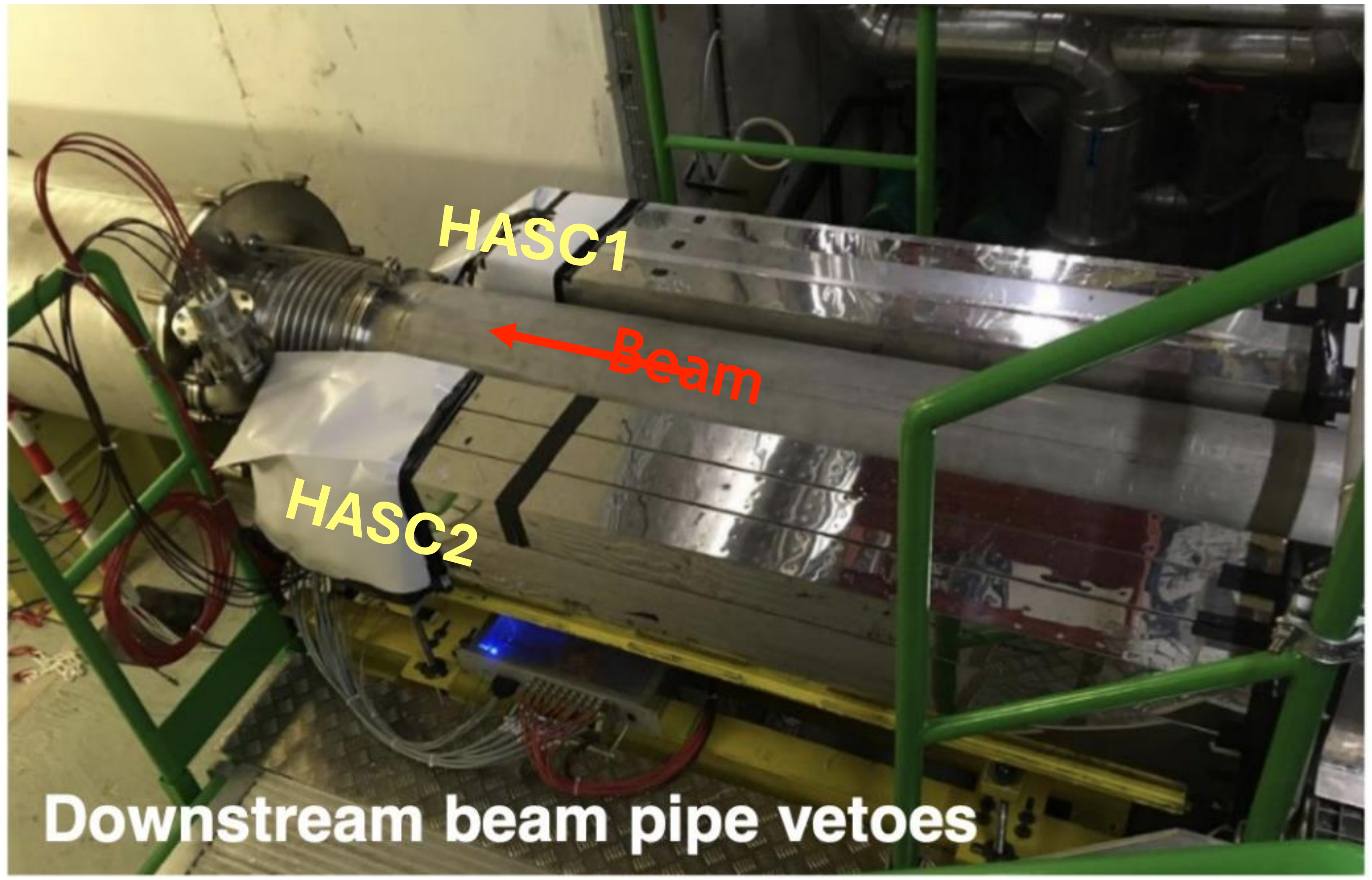
- Average beam intensity increased.
- NA62 “Full intensity” with 4.8s spill = 600 MHz

# 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:**





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

## 2021–2022 data : Signal Sensitivity

# 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($\mu$ 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

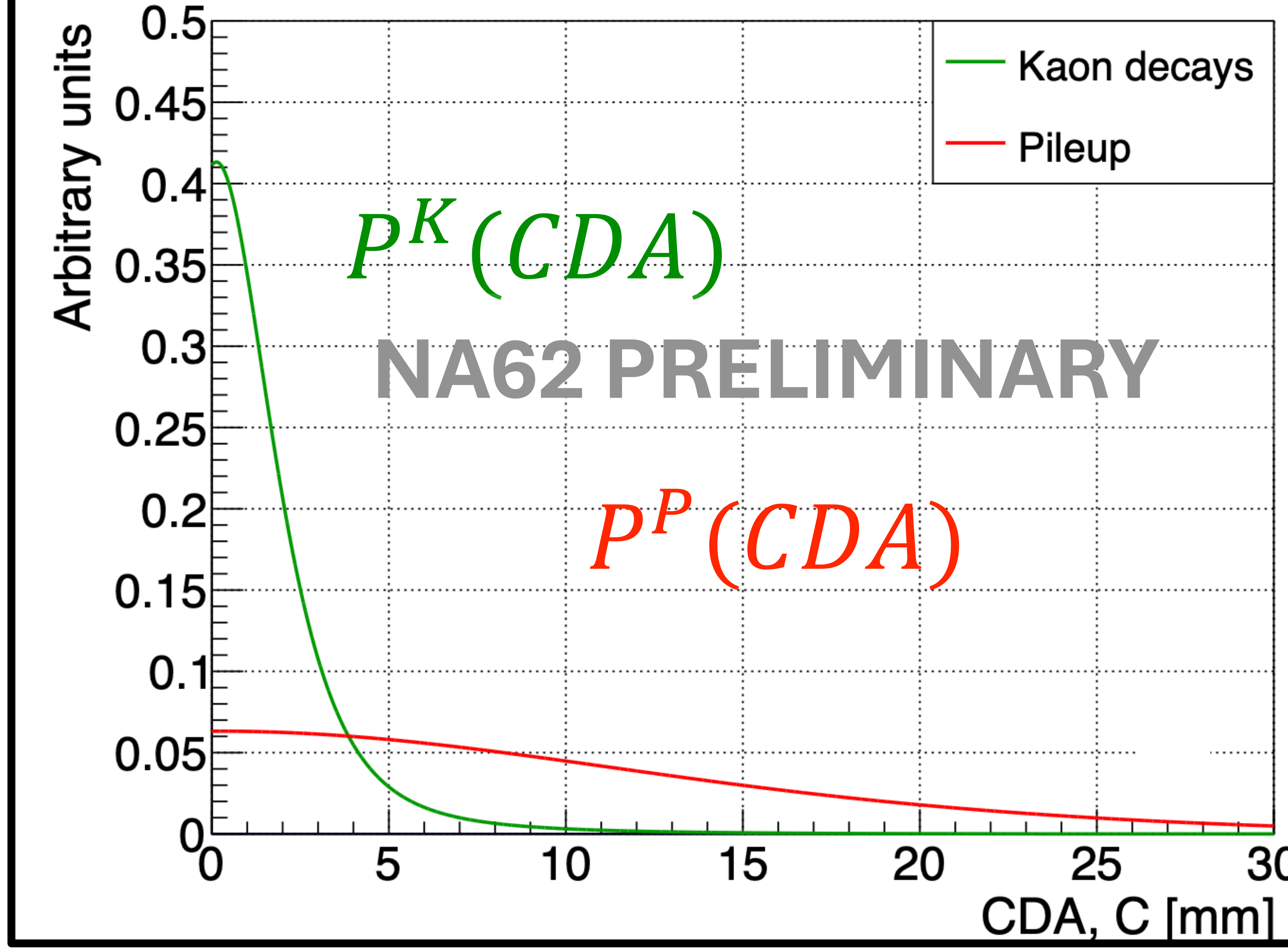
Selection:

- **Normalisation** $K^+ \to \pi^+\pi^0$: 1 downstream track (only); identified as $\pi^+$; $K^+ - \pi^+$ 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

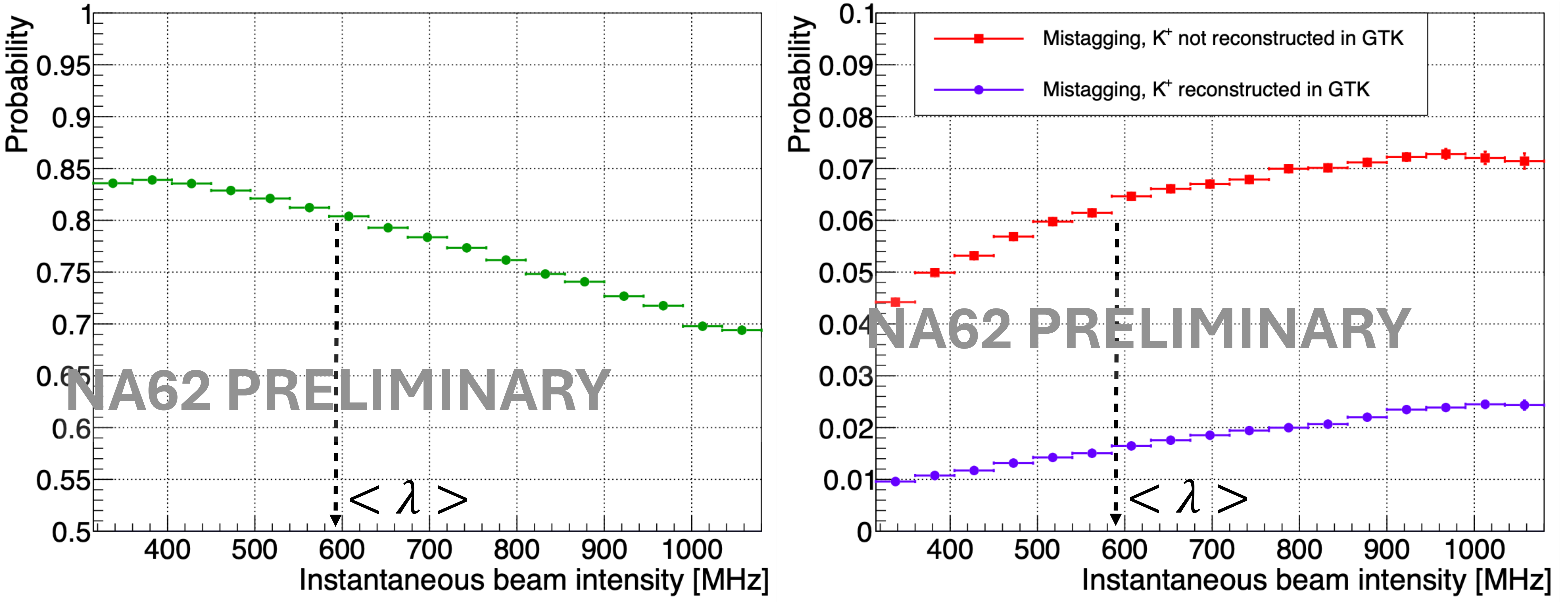
Example of selection update

- **Inputs:** spatial (CDA) & time ($\Delta T_+$) 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 $N_{GTK} > 1$

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



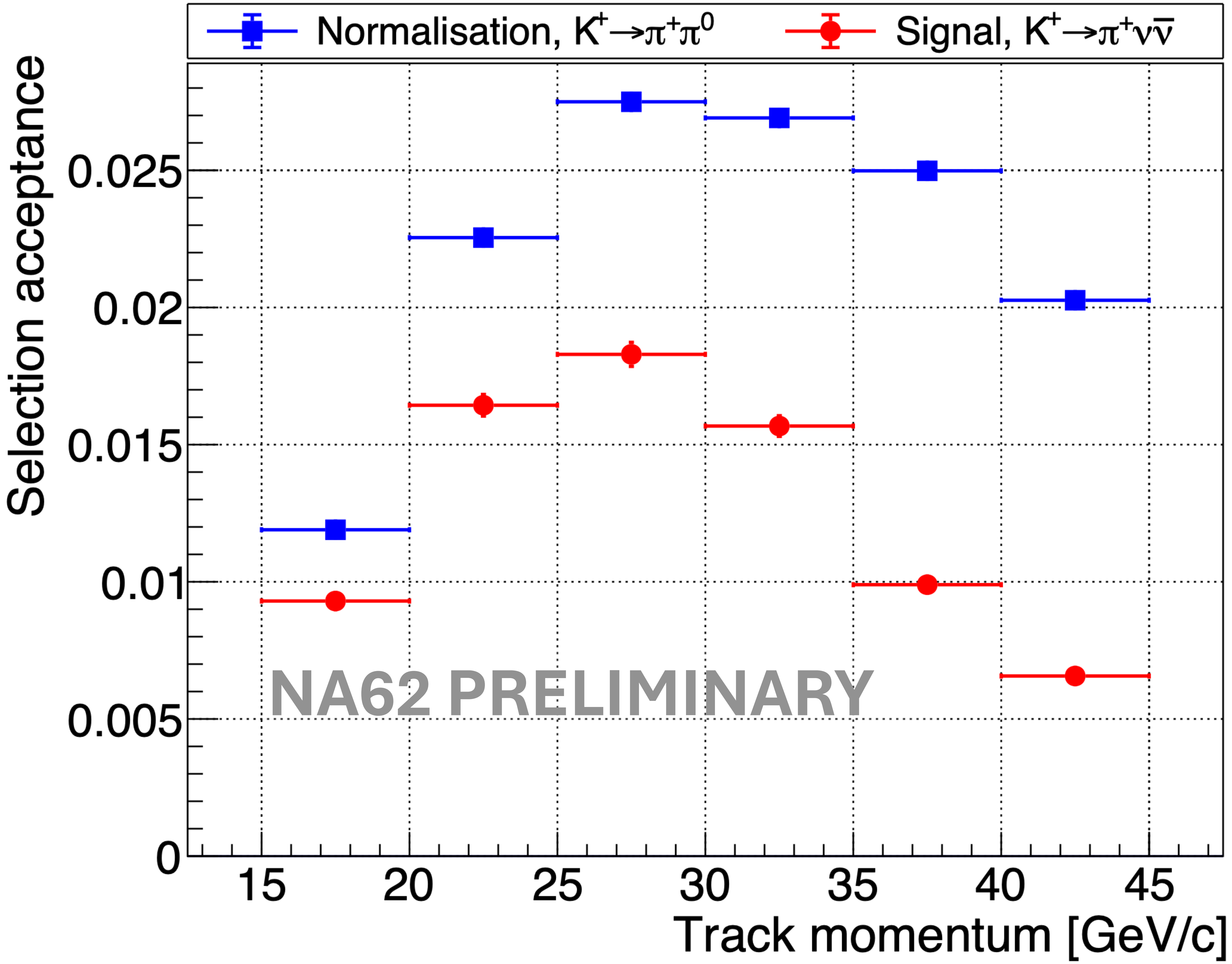
- Efficiency improved (+10%) and mistagging probability maintained.

# 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 $\varepsilon_{RV}$

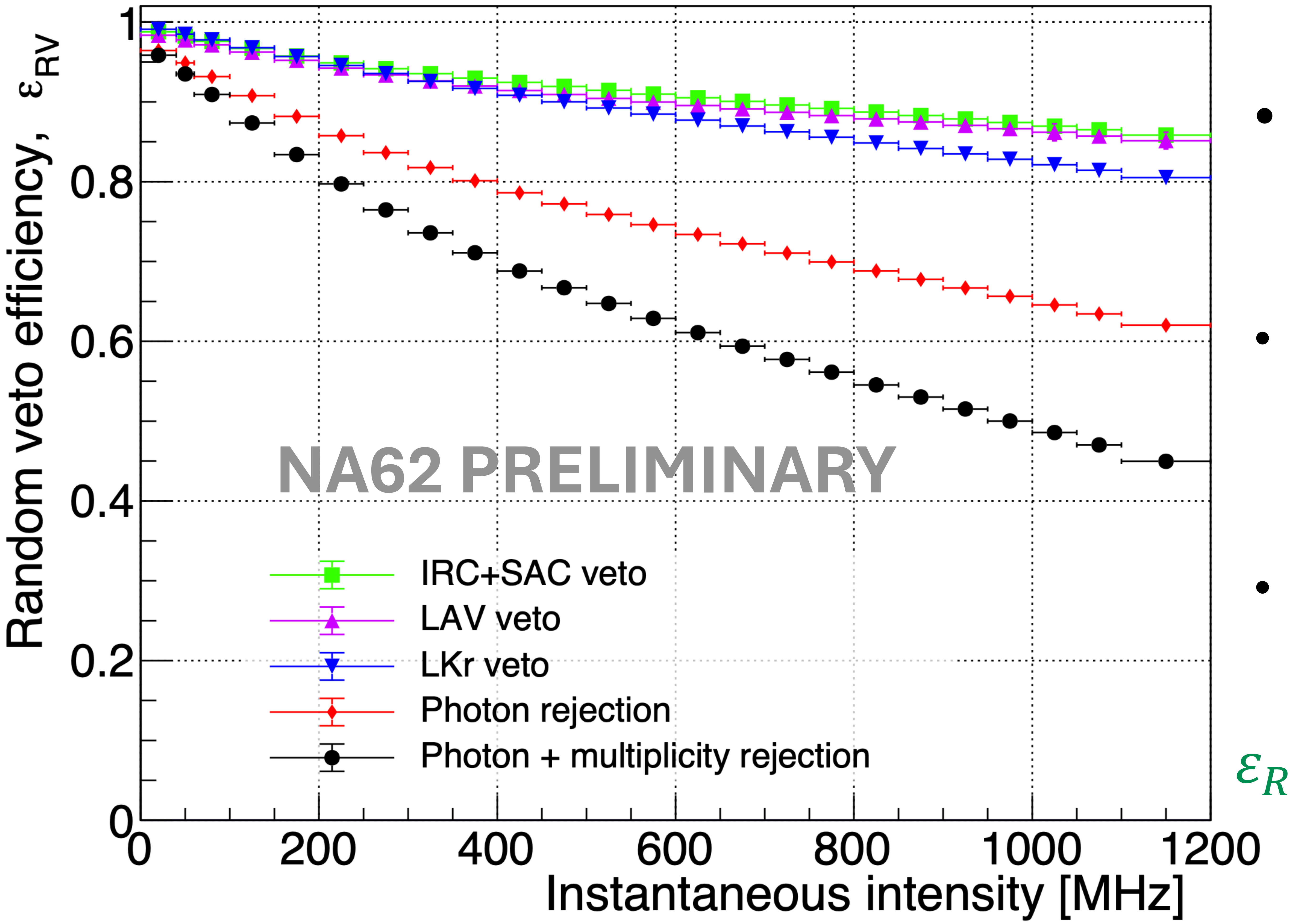
| **Case** | OLD<br>2018 (S2) | NEW<br>2021-22 | |
|---|---|---|---|
| **Norm.** | 11.8% | 13.4% | **+15%** |
| **Signal** | (6.37±0.64)% | (7.61±0.18)% | **+20%** |

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

# Random veto

$\varepsilon_{RV}$ **is independent of track momentum (related to additional activity only)**

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



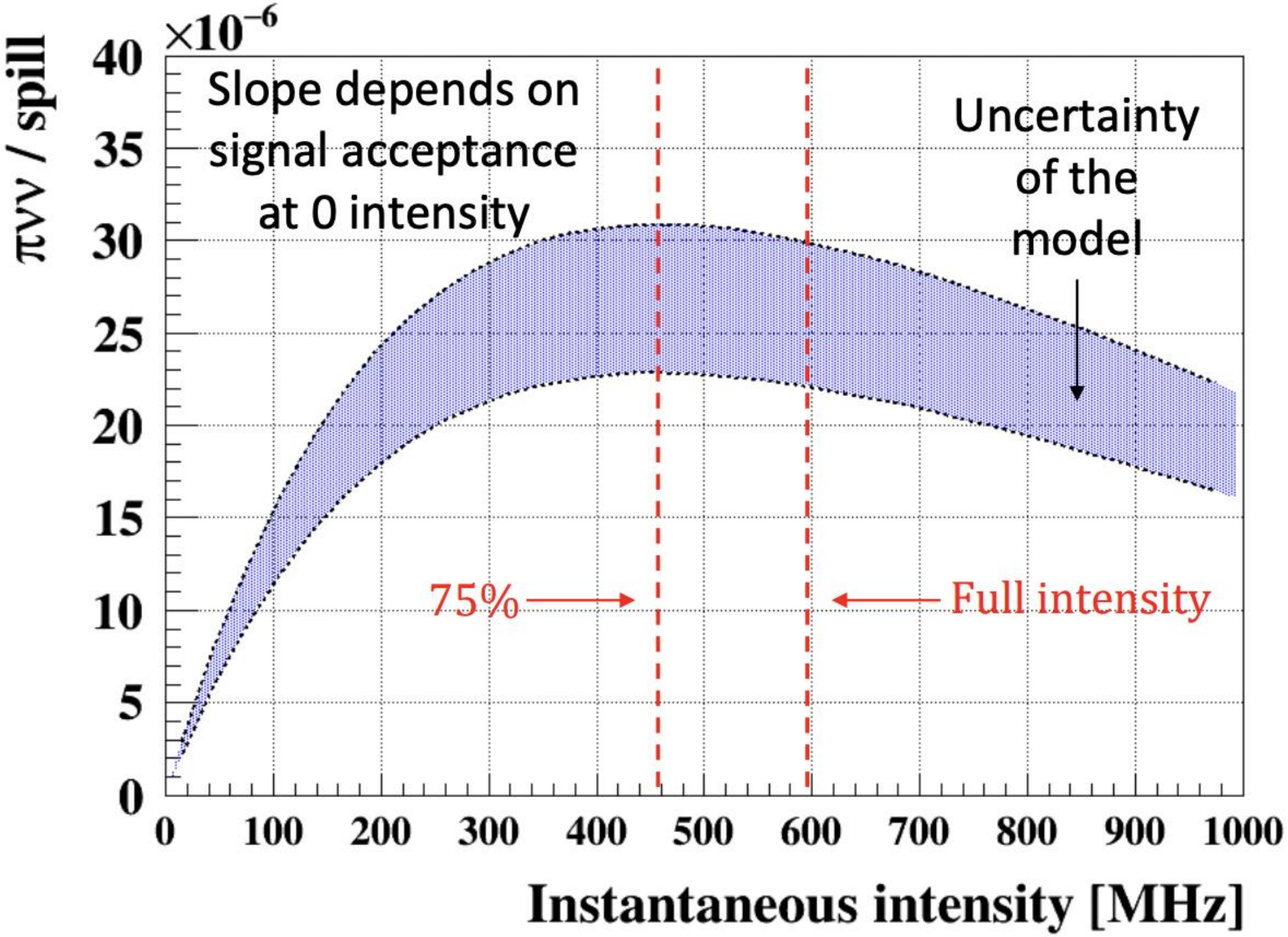
- $\varepsilon_{RV}$ **= Random Veto Efficiency:**
  - $1 - \varepsilon_{RV}$ **= Probability of rejecting a signal event due to additional activity.**
- Balance:
  - Strict vetos ⇒ lower efficiency
  - Loose vetos ⇒ higher background
- **Operational intensity higher** but re-tuning vetos means $\varepsilon_{RV}$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

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

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

# 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

# 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 $K^+ \to \pi^+\pi^0$ | $2.0 \times 10^8$ |
| $A_{\pi\pi}$ | Normalisation acceptance | $(13.410 \pm 0.005)\%$ |
| $N_K$ | Effective $K^+$ decays | $2.9 \times 10^{12}$ |
| $A_{\pi\nu\bar{\nu}}$ | Signal acceptance | $(7.6 \pm 0.2)\%$ |
| $\varepsilon_{trig}$ | Trigger efficiency | $(85.9 \pm 1.4)\%$ |
| $\varepsilon_{RV}$ | 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 :** $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

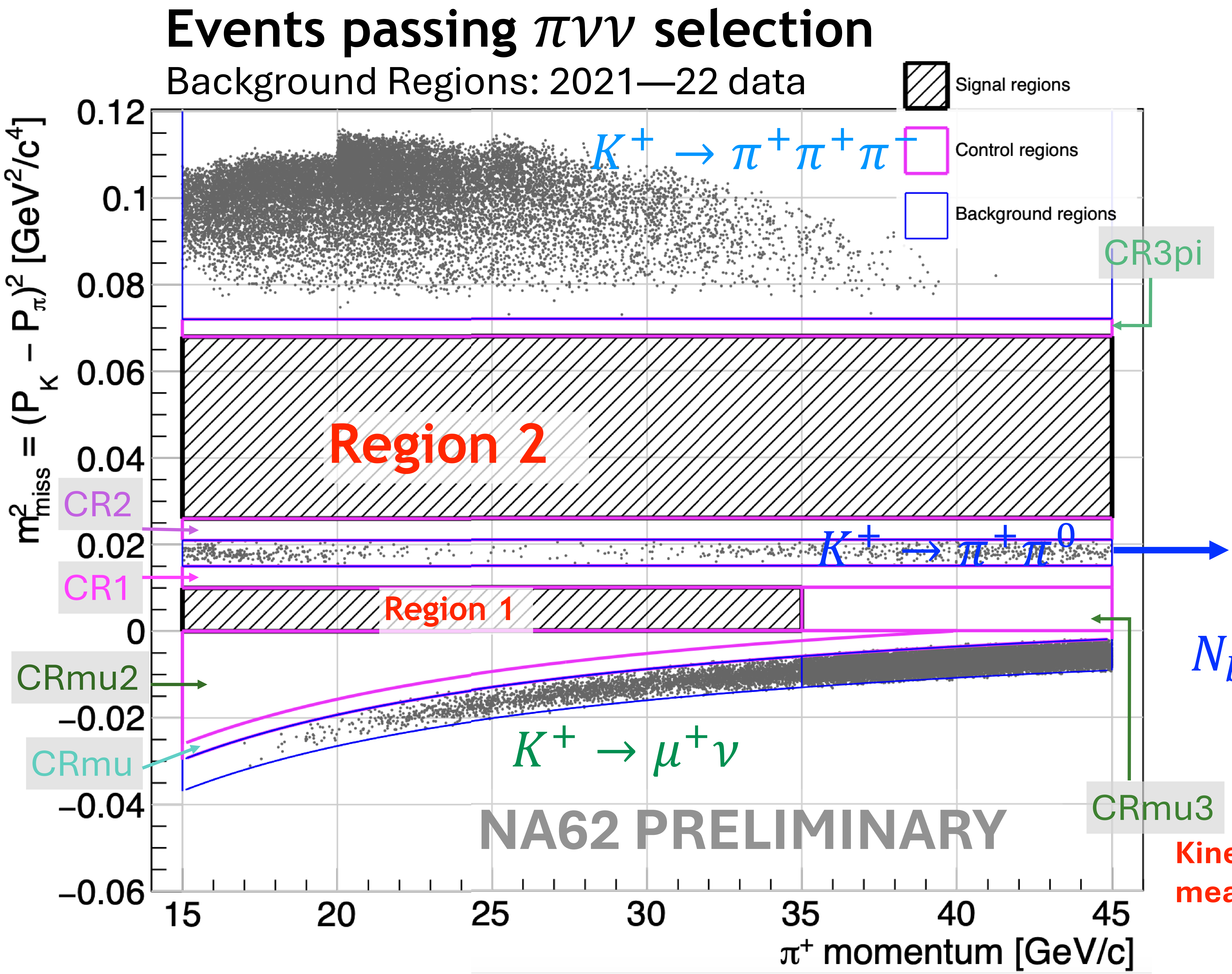
**Double expected signal by including 21—22 data.**

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

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

## 2021—2022 data : Background Evaluation

# Background regions & estimations



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

**Number of events passing signal selection in background region**

**Control sample events in Signal Regions**

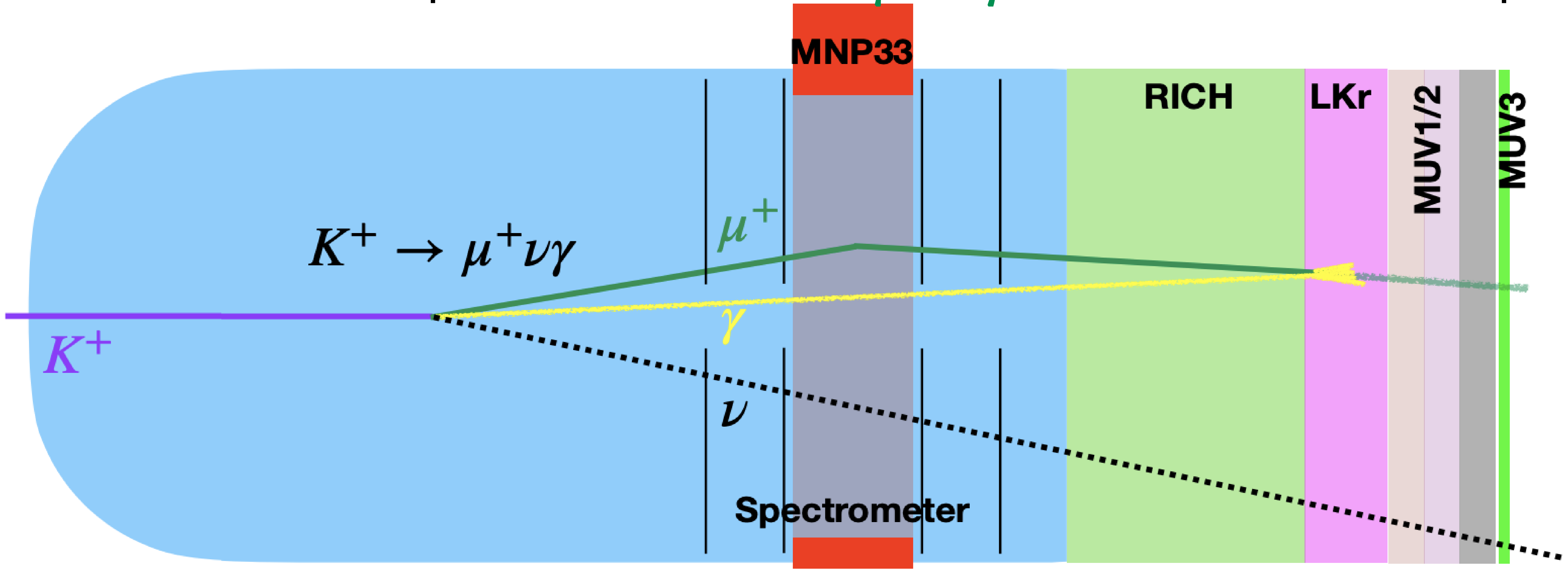
$$N_{bg} = N_{bkgR} \cdot f_{tail} = N_{bkgR} \cdot \frac{N^{CS}_{SR}}{N^{CS}_{bkgR}}$$

**Kinematic tail fraction: measured in control sample**

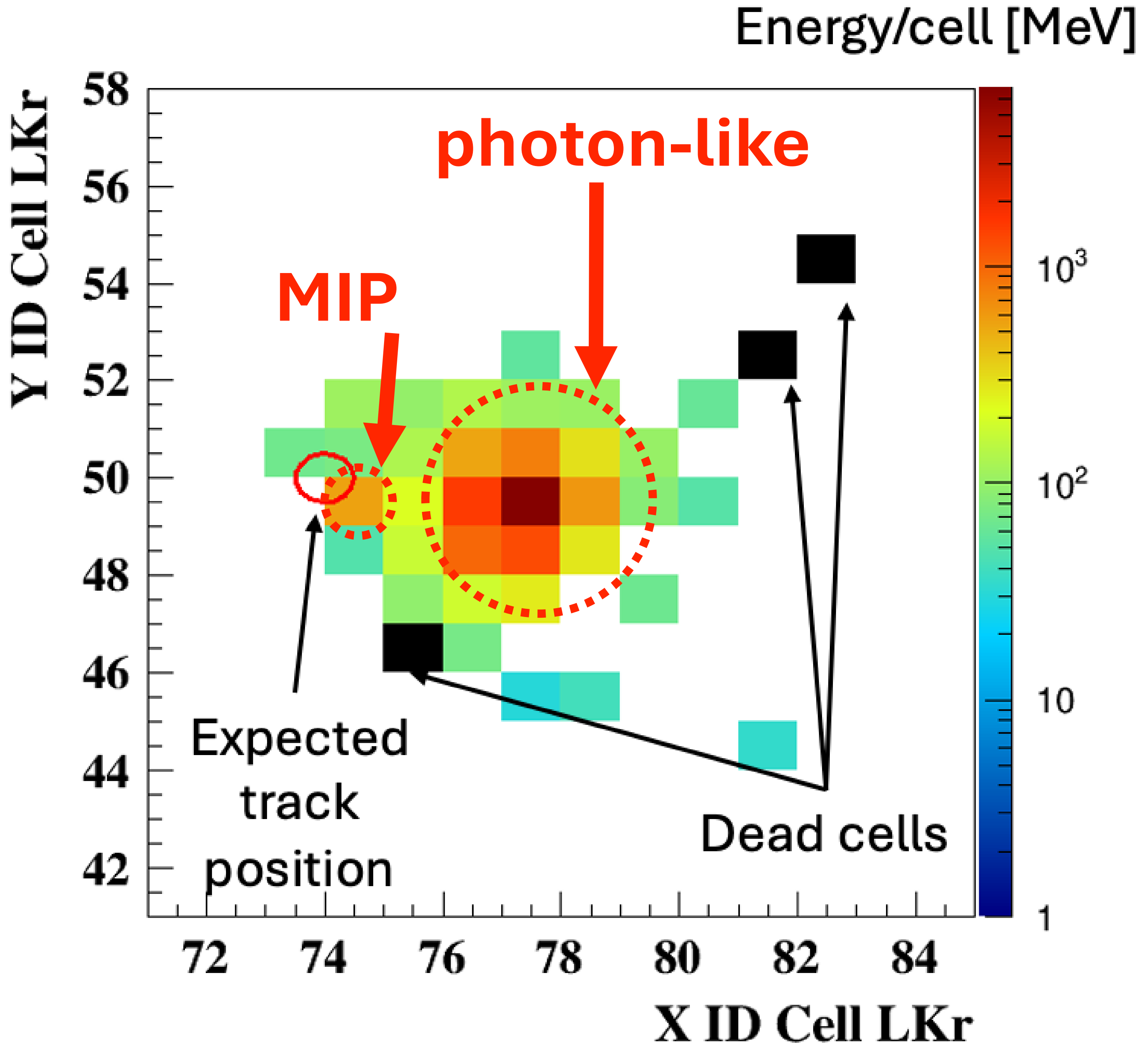
**Control sample events in Background Region**

# 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 $\gamma$ 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 $\gamma$ overlaps $\mu^+$ at LKr (leading to misID as $\pi^+$)**
  - Suppression: based on $(P_K - P_\mu - P_\gamma)^2$ and $E_\gamma$ with $\gamma$ = 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 $\pi^+$ bin).



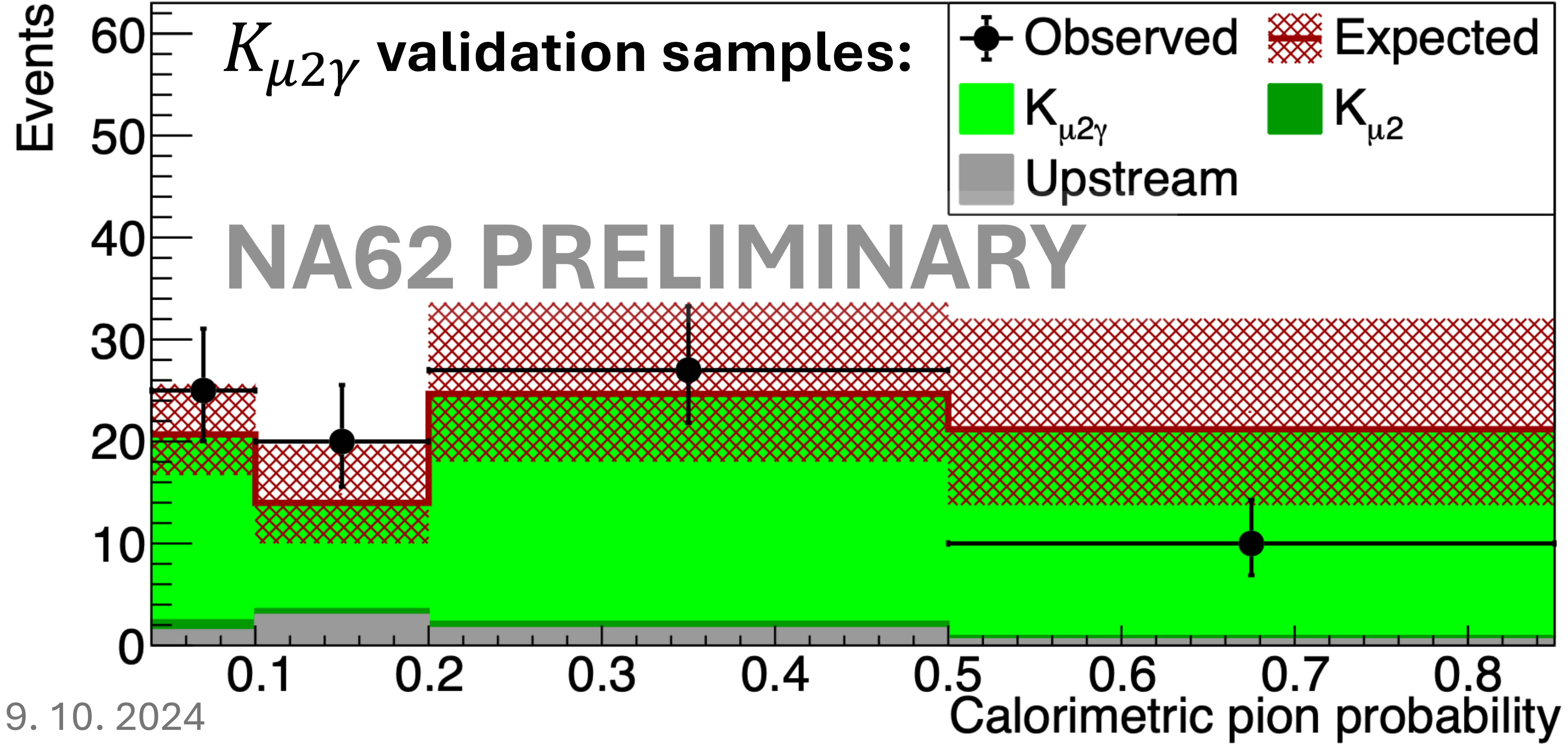
Sketch only



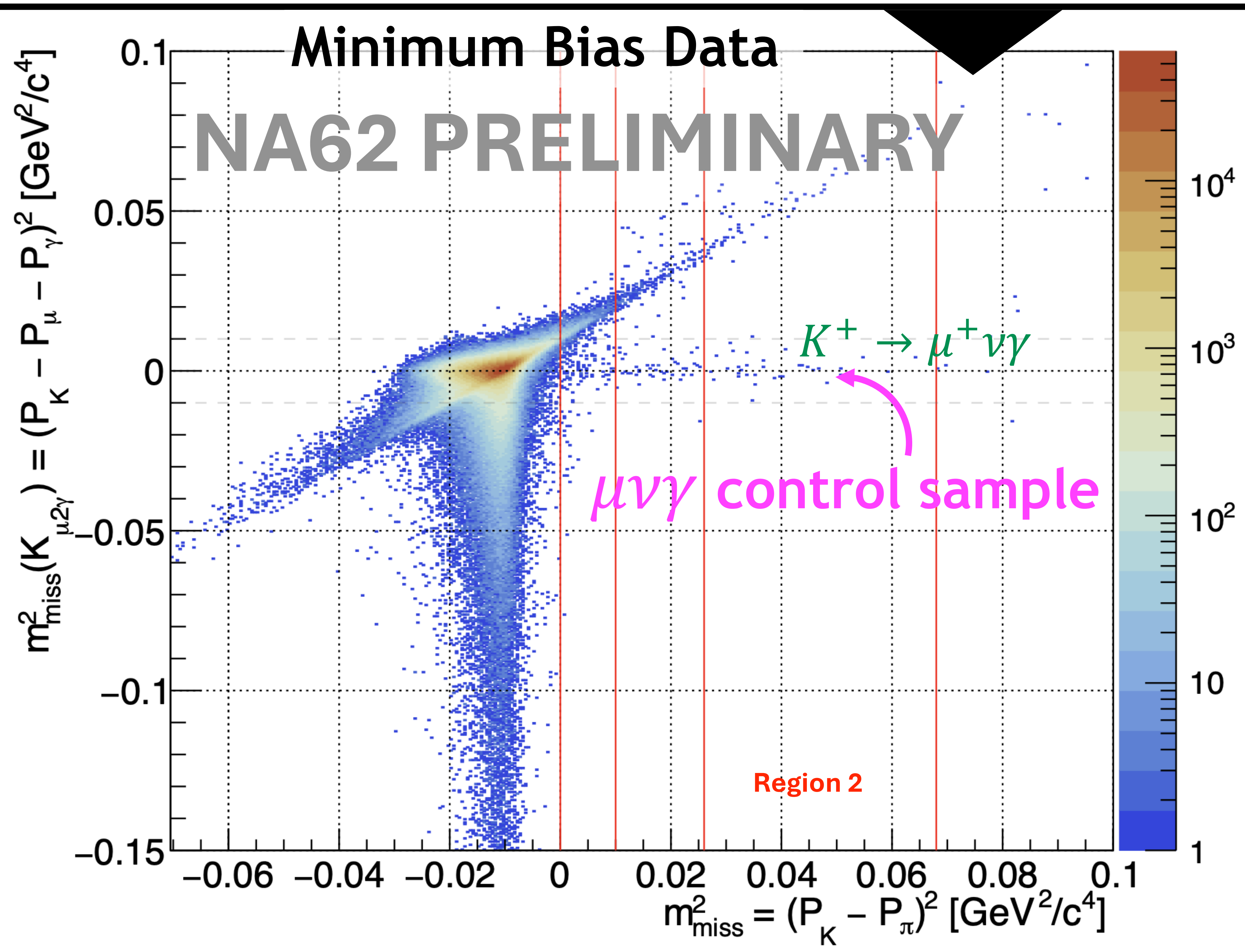
# $K^+ \to \mu^+ \nu \gamma$ Background

- 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)
  - $P_\mu$ : 4-momentum of track with $\mu^+$ mass hypothesis.
  - $P_\gamma$ : reconstructed from energy and position of LKr cluster (and position of $K^+$-$\mu^+$ vertex).

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



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



- 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.

# Summary of expectations

**Backgrounds**

| | |
|---|---|
| $K^+ \to \pi^+\pi^0(\gamma)$ | $0.83 \pm 0.05$ |
| $K^+ \to \pi^+\pi^0$ | $0.76 \pm 0.04$ |
| $K^+ \to \pi^+\pi^0\gamma$ | $0.07 \pm 0.01$ |
| $K^+ \to \mu^+\nu(\gamma)$ | $1.70 \pm 0.47$ |
| $K^+ \to \mu^+\nu$ | $0.87 \pm 0.19$ |
| $K^+ \to \mu^+\nu\gamma$ | $0.82 \pm 0.43$ |
| $K^+ \to \pi^+\pi^+\pi^-$ | $0.11 \pm 0.03$ |
| $K^+ \to \pi^+\pi^-e^+\nu$ | $0.89^{+0.34}_{-0.28}$ |
| $K^+ \to \pi^0\ell^+\nu$ | $< 0.001$ |
| $K^+ \to \pi^+\gamma\gamma$ | $0.01 \pm 0.01$ |
| 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** $\mathcal{B}^{SM}_{\pi\nu\bar{\nu}} = 8.4 \times 10^{-11}$ **:**

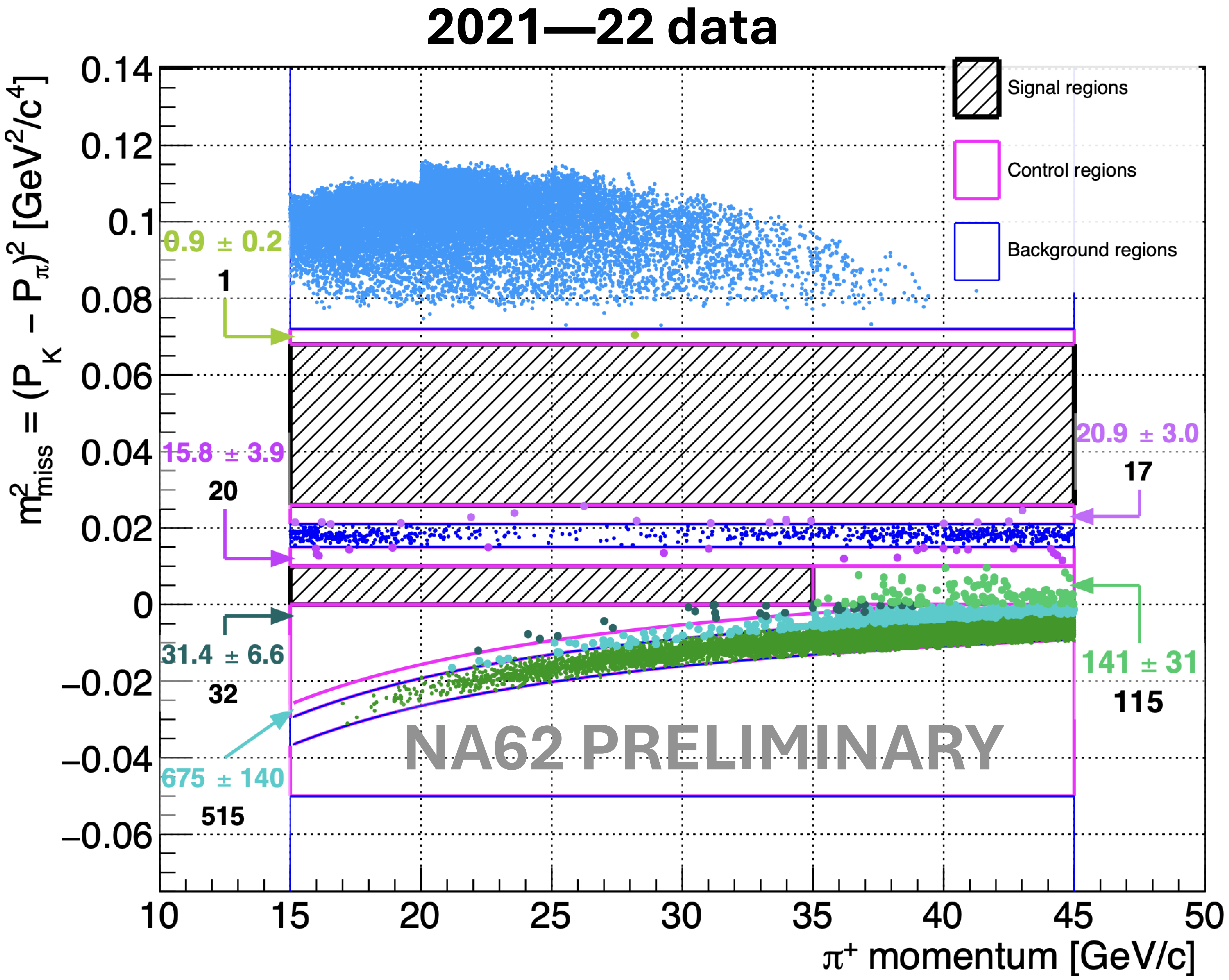
**2021–22:** $N_{\pi\nu\bar{\nu}} = 10.00 \pm 0.34$

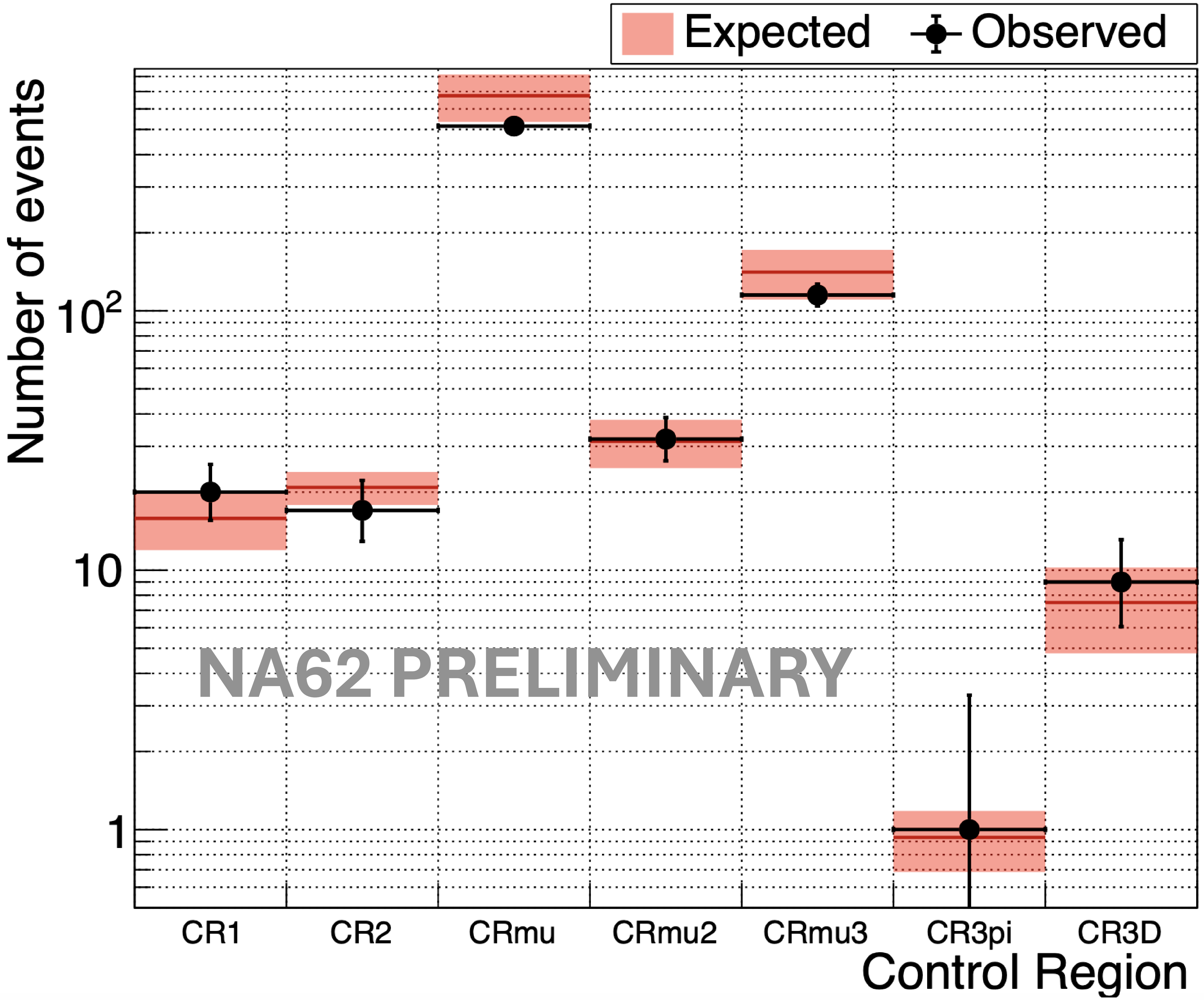
**c.f. 2016–18 :** $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

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

- $N^{SM}_{\pi\nu\bar{\nu}}$ per SPS burst: $2.5 \times 10^{-5}$ in 2022
  - c.f. $1.7 \times 10^{-5}$ in 2018. ⇒ **signal yield increased by 50%**
- Sensitivity for BR $\sim \sqrt{S + B}/S = 0.5$
  - **Similar but improved with respect to 2018 analysis for same amount of data**

# Control regions: 2021—22 Data



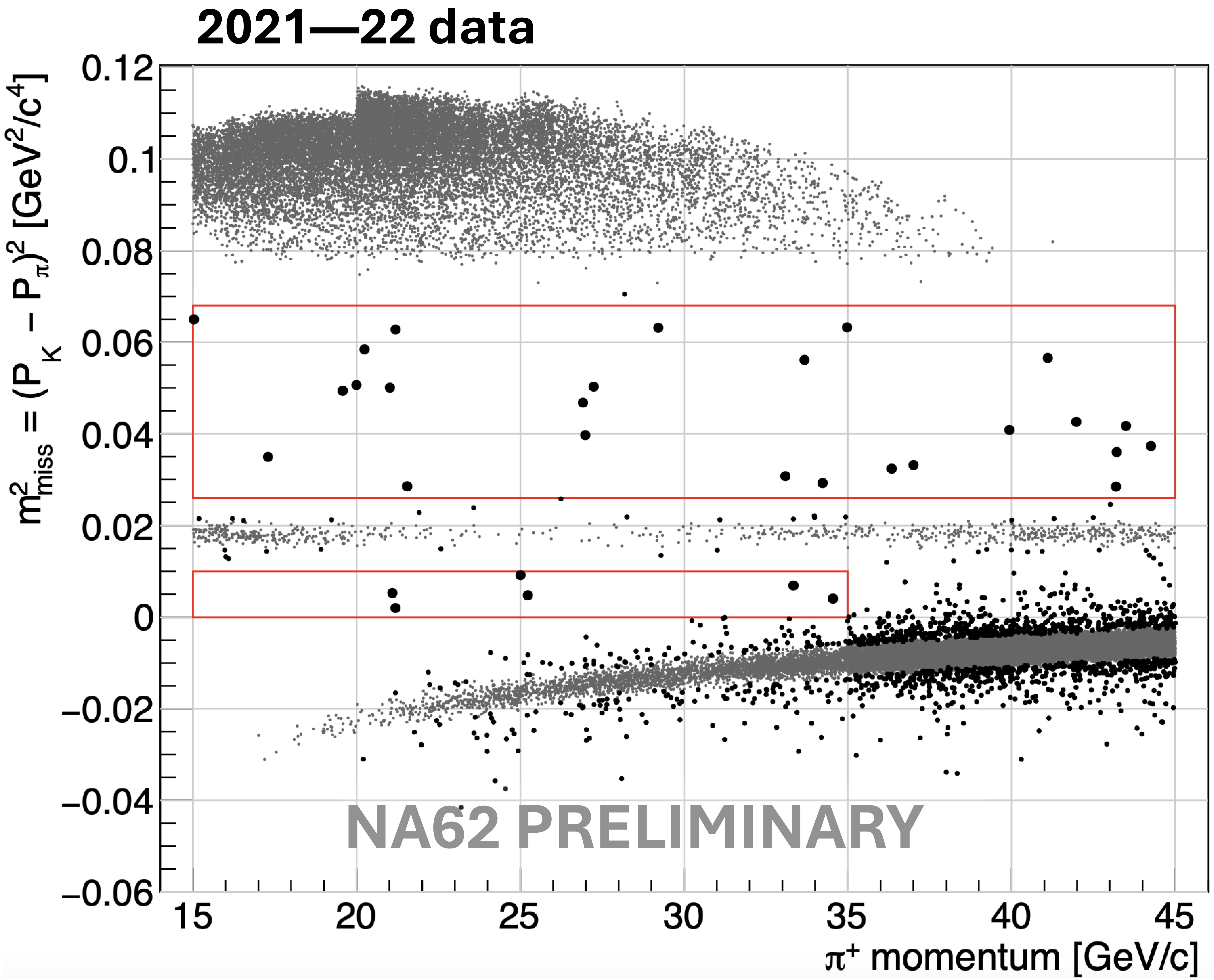


- Good agreement in control regions validates background expectations.

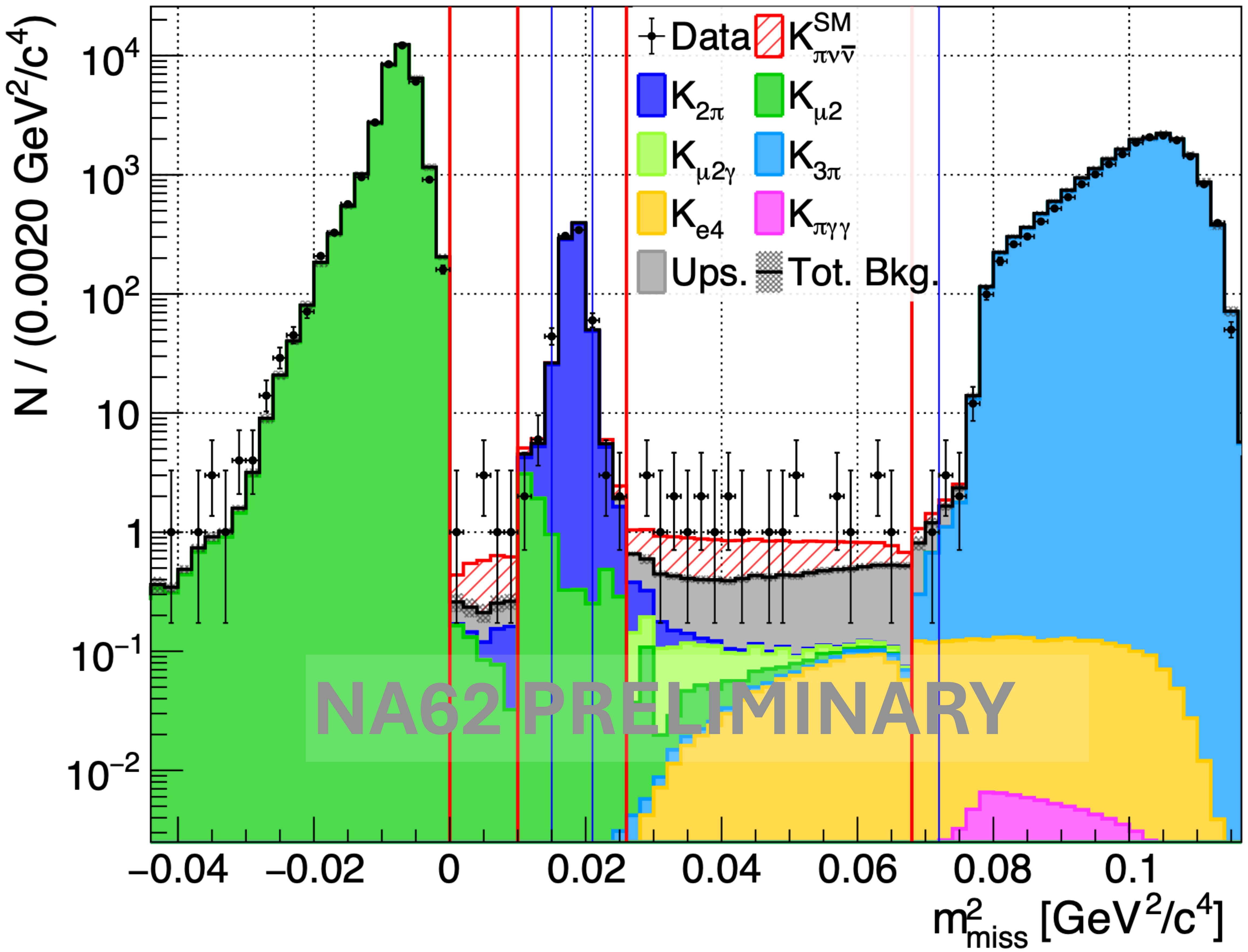
# $K^+ \to \pi^+ \nu \overline{\nu}$ : New NA62 Results

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]:



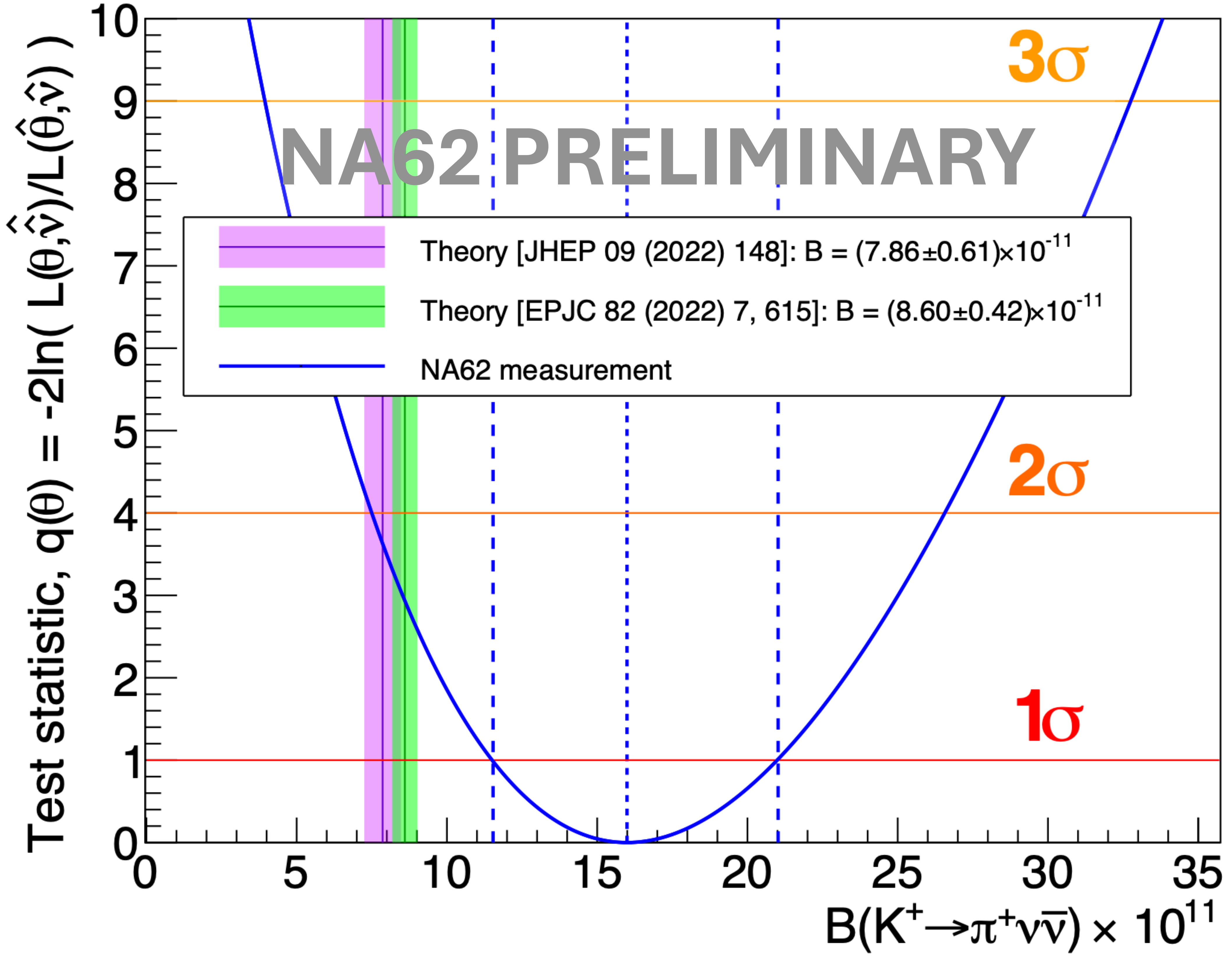
Expected SM signal: $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

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

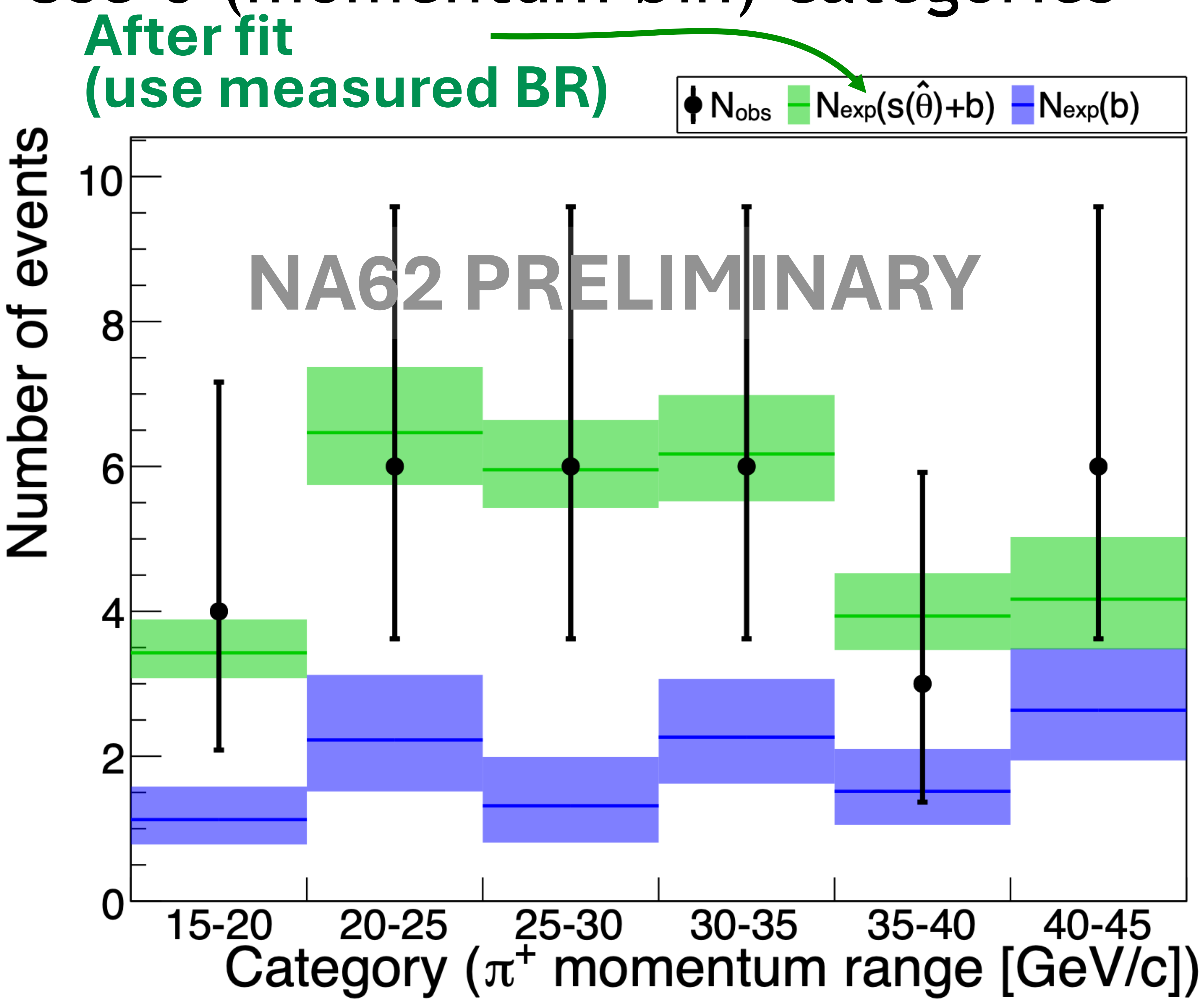
Observed: $N_{obs} = 31$

# Results: 2021—22 Data

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



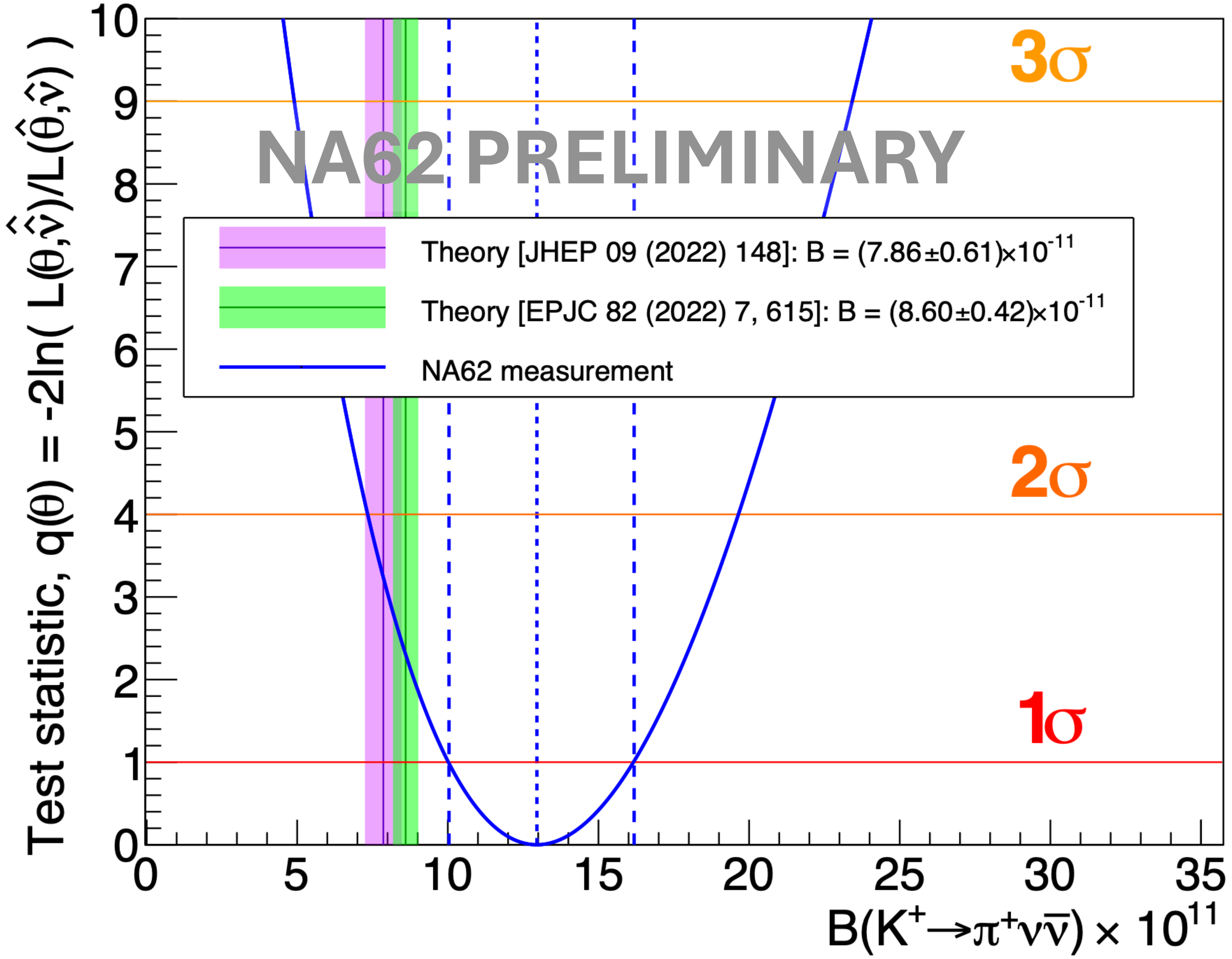
- Use 6 (momentum bin) categories

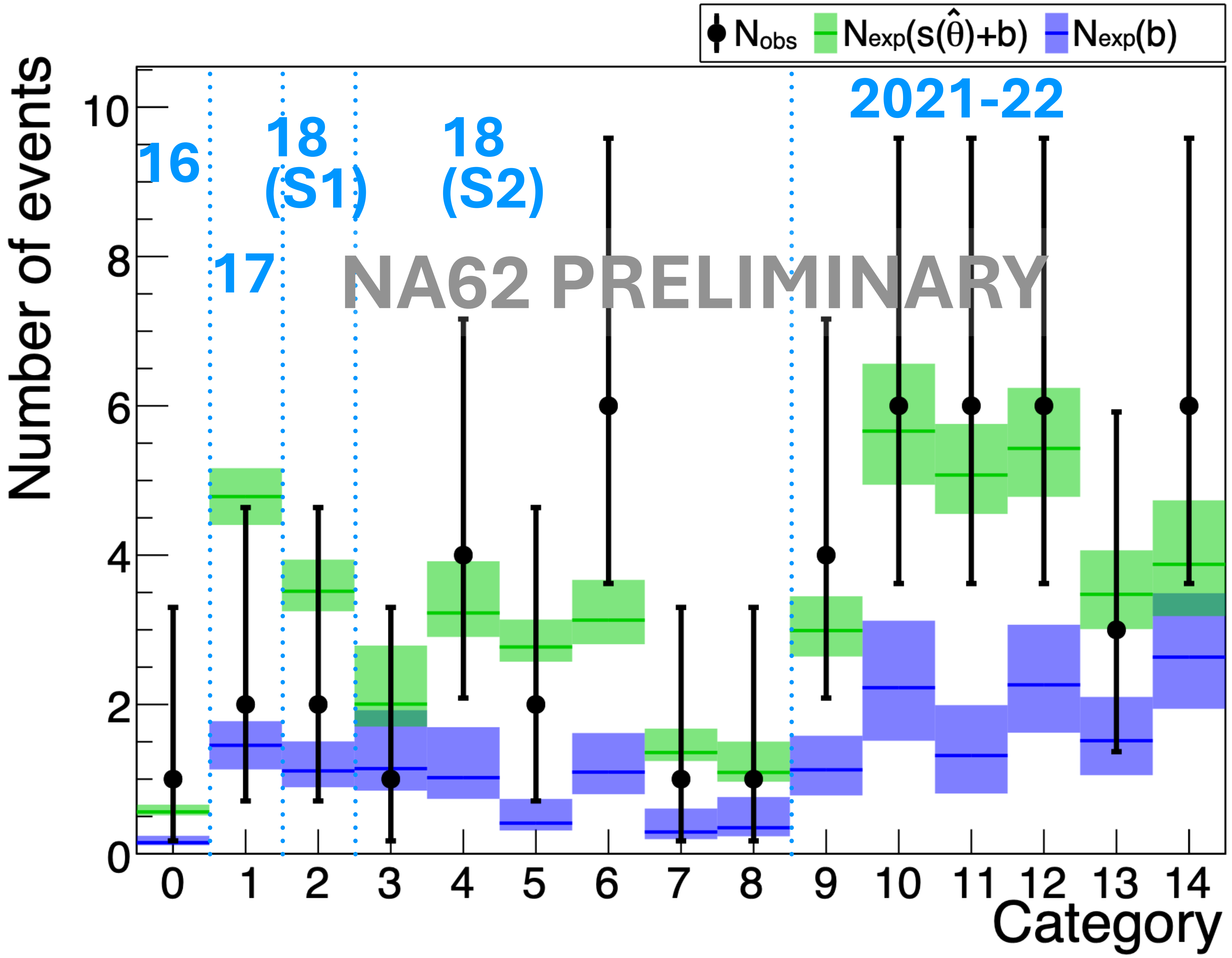


$$\mathcal{B}_{21-22}(K^+ \to \pi^+\nu\bar{\nu}) = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11} = \left(16.0\ \left(^{+4.8}_{-4.2}\right)_{stat}\ \left(^{+1.4}_{-1.3}\right)_{syst}\right) \times 10^{-11}$$

# Combining NA62 results: 2016—22

- Integrating 2016—22 data: $N_{bg} = 18^{+3}_{-2}\,, N_{obs} = 51.$
    - **Background-only hypothesis p-value =** $2 \times 10^{-7} \Rightarrow$ **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]

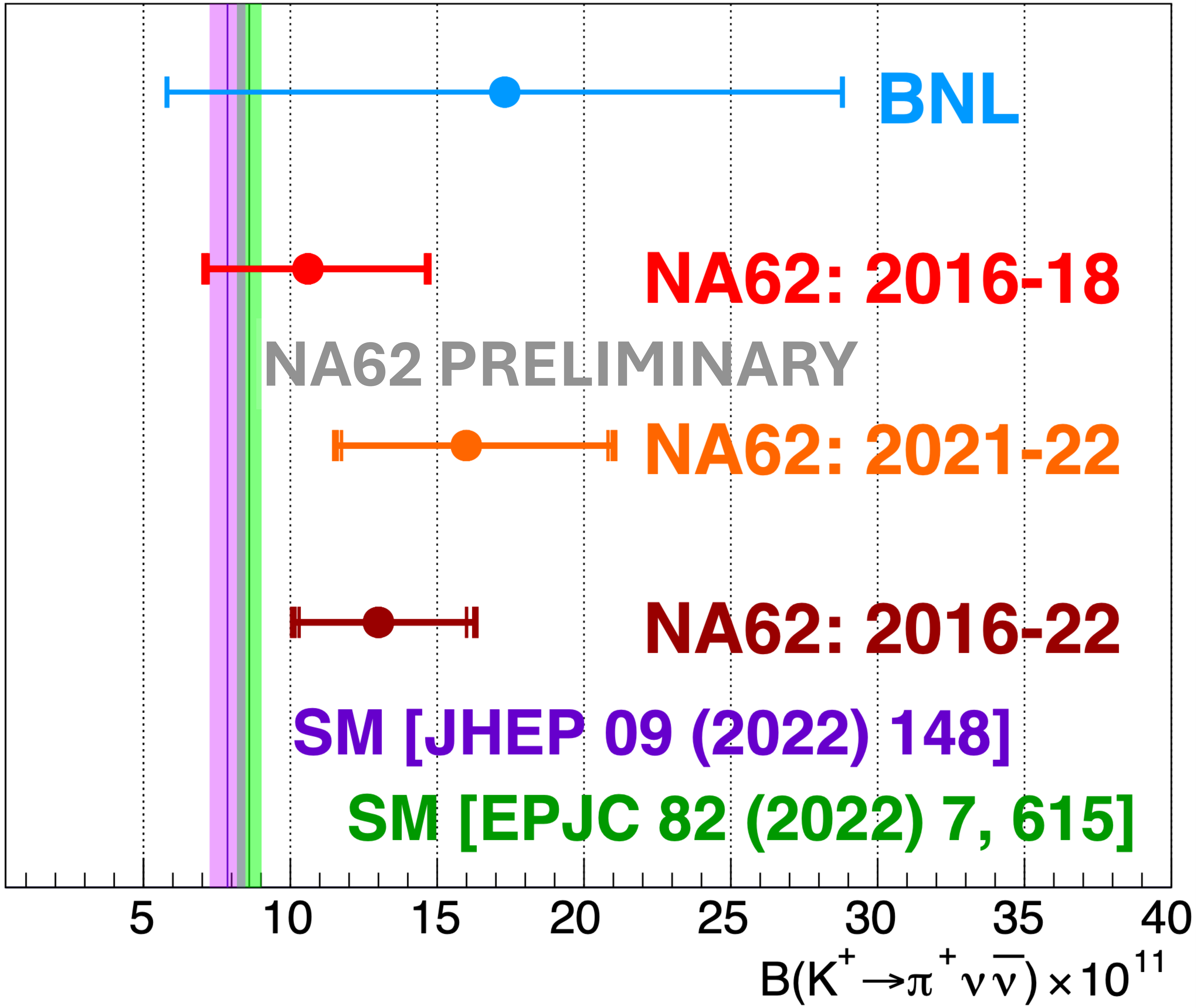
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6_{-3.5}^{+4.1}\right) \times 10^{-11}$$

[JHEP 06 (2021) 093]

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

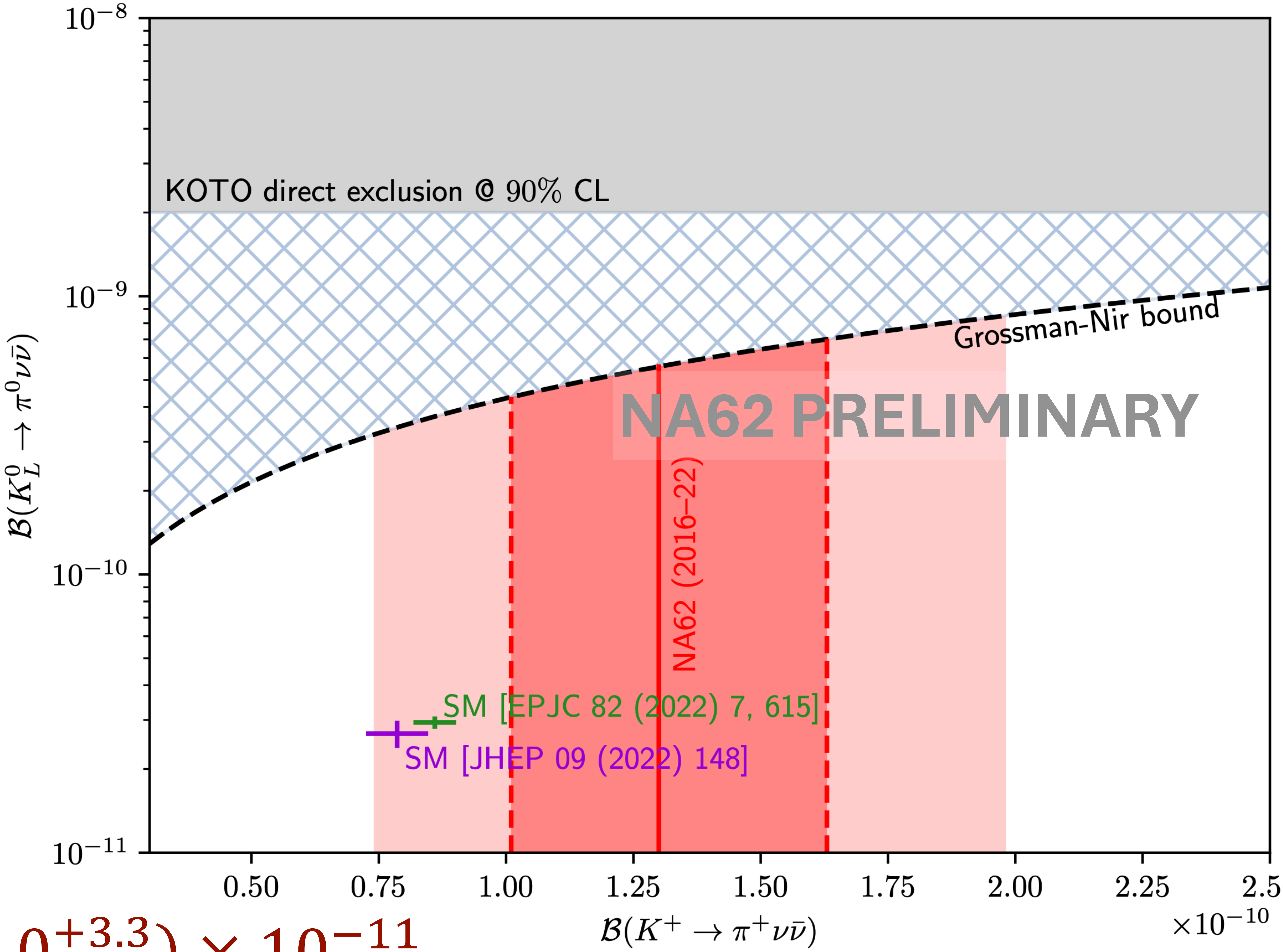
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0_{-2.9}^{+3.3}\right) \times 10^{-11}$$

- NA62 results are consistent
- Central value moved up (now 1.5—1.7$\sigma$ 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 1.7$\sigma$**
  - **Need full NA62 data-set to clarify SM agreement or tension**



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

$2\sigma$ 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%.
  - $N_{bg} = 11.0^{+2.1}_{-1.9}$ , $N_{obs} = 31$
  - $\mathcal{B}_{21-22}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11} = \left(16.0\ (^{+4.8}_{-4.2})_{stat}\ (^{+1.4}_{-1.3})_{syst}\right) \times 10^{-11}$

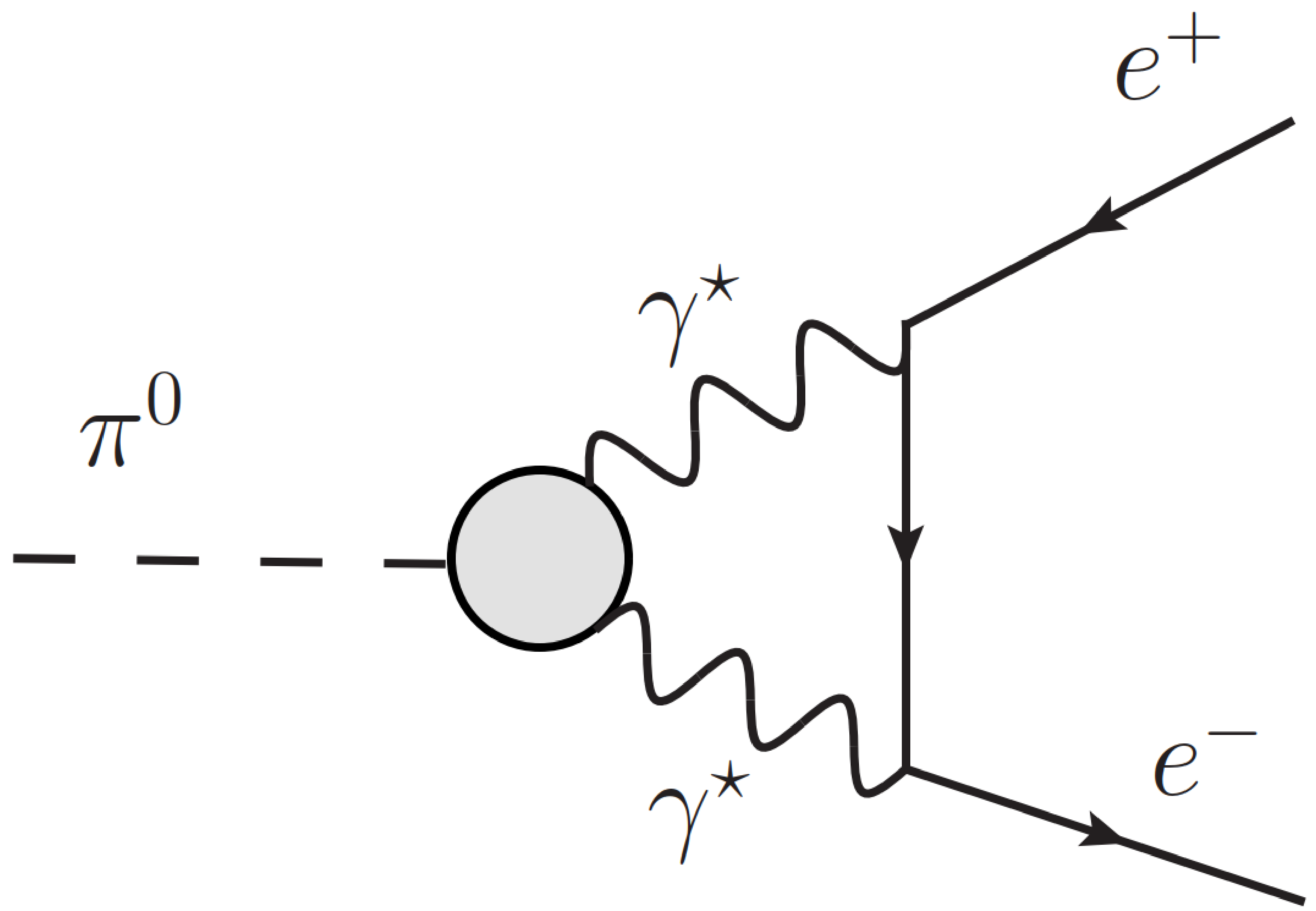
- Combining with 2016—18 data for full 2016—22 results:
  - $N_{bg} = 18^{+3}_{-2}$ , $N_{obs} = 51$ (using 9+6 categories for BR extraction)
  - $\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-2.9}) \times 10^{-11} = (13.0\ (^{+3.0}_{-2.7})_{stat}\ (^{+1.3}_{-1.2})_{syst}) \times 10^{-11}$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

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

# $\pi^0 \to e^+e^-$ at NA62: new results

## 2017—18 data

# $\pi^0 \to e^+e^-$: Introduction



- Diagram considered in theoretical predictions
- Various $\pi^0 \to \gamma^\star\gamma^\star$ transition form factors lead to $\mathcal{B}(\pi^0 \to e^+e^-, \text{no-rad})$

Experimentally observable:

$$\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > x_{\text{cut}}), \quad x = m_{ee}^2/m_{\pi^0}^2$$

- Dalitz decay $\pi^0 \to \gamma\, e^+e^-$: dominant in low-$x$ region
- For $x > x_{\text{cut}} = 0.95$, Dalitz decay $\approx 3.3\%$ of $\mathcal{B}(\pi^0 \to e^+e^-(\gamma))$

# $\pi^0 \to e^+e^-$ : Previous measurement

- Experimentally observable:

$$\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > x_{\text{cut}}), \quad x = m_{ee}^2/m_{\pi^0}^2$$

- Previous best measurement by KTeV [PRD 75 (2007) 012004]

$$\mathcal{B}_{\text{KTeV}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$$

- Using latest radiative corrections in [JHEP 10 (2011) 122], [EPJC 74 (2014) 8, 3010], [PRD 110 (2024), 033004], the result can be extrapolated and compared with theory:

| | $\mathcal{B}(\pi^0 \to e^+e^-, \text{no-rad}) \times 10^8$ |
|---|---|
| KTeV, PRD 75 (2007) | 6.84(35) |
| Knecht et al., PRL 83 (1999) | 6.2(3) |
| Dorokhov and Ivanov, PRD 75 (2007) | 6.23(9) |
| Husek and Leupold, EPJC 75 (2015) | 6.12(6) |
| Hoferichter et al., PRL 128 (2022) | 6.25(3) |

# $\pi^0 \to e^+e^-$ : Data sample and trigger

- Data sample collected by NA62 in 2017 and 2018
- Signal decay mode: $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^- \equiv K^+ \to \pi^+\pi^0_{ee}$
  - Latest radiative corrections included in the simulation
- Normalization decay mode: $K^+ \to \pi^+e^+e^-$
  - Identical final state as the signal, common selection criteria → cancellation of systematics
  - Selecting almost background-free region $m_{ee} > 140\,\mathrm{MeV}$
- *Multi-track electron* trigger line used to collect both $K^+ \to \pi^+\pi^0_{ee}$ and $K^+ \to \pi^+e^+e^-$
  - Downscaling factor $D_{eMT} = 8$
  - Level-0: RICH, CHOD, LKr
  - Level-1: KTAG, Straw
  - Total trigger efficiency $\approx 90\%$ for both signal and normalization

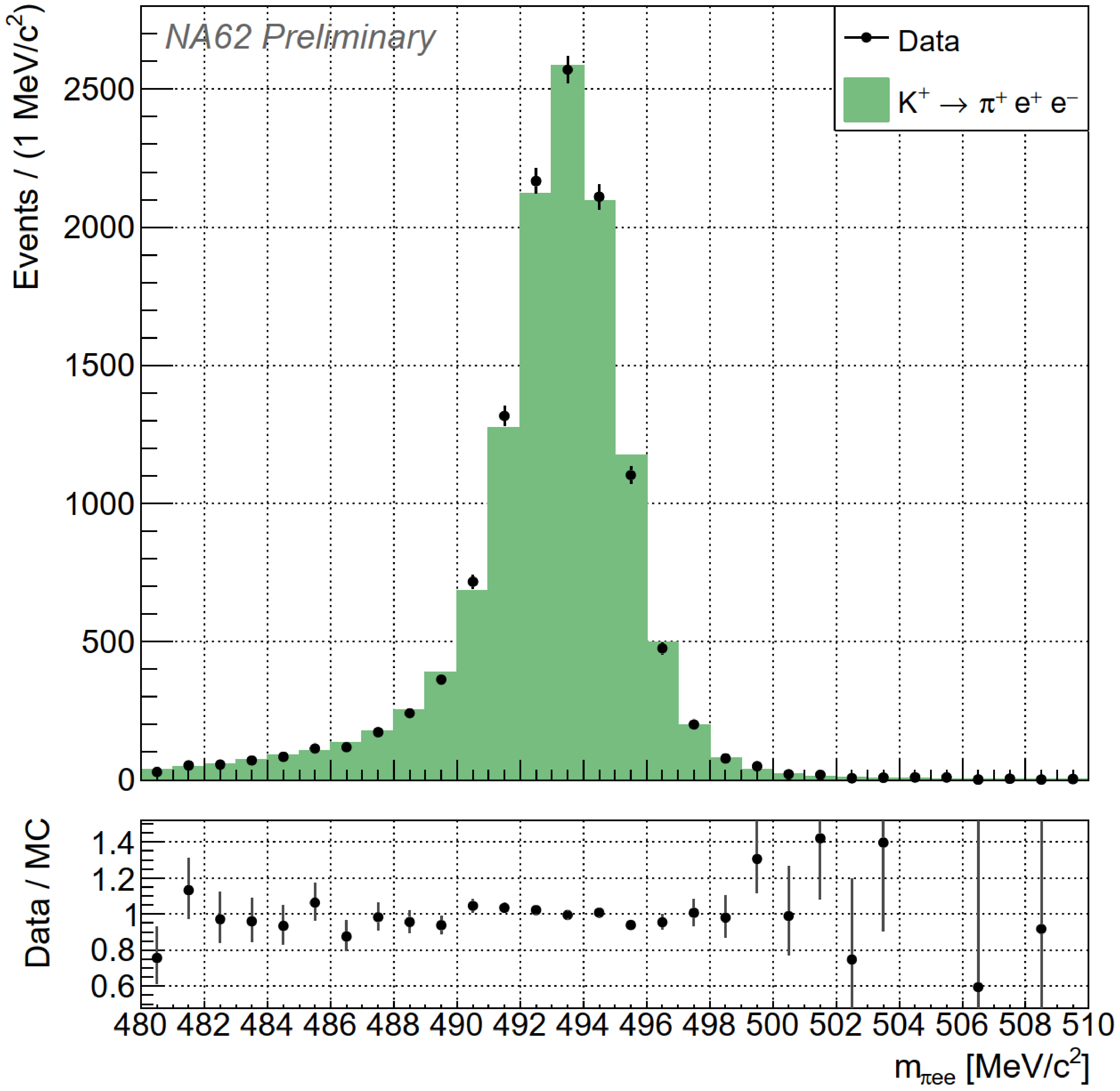
# $\pi^0 \to e^+e^-$ : Backgrounds

Backgrounds for the signal decay mode:

- $K^+ \to \pi^+ e^+ e^-$: irreducible, flat in the signal region close to the $\pi^0$ mass
- $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\, e^+ e^- \equiv K^+ \to \pi^+\pi^0_D$
  a) Large-$x$ tail of the $\pi^0$ Dalitz decay distribution
  b) Photon conversion in STRAW + selection of a $e^\pm$ track from the conversion
- $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+ e^- e^+ e^- \equiv K^+ \to \pi^+\pi^0_{DD}$
  $\pi^0$ double Dalitz decay with two undetected $e^\pm$

# $\pi^0 \to e^+e^-$ : Common selection criteria

- Three track vertex topology (STRAW)
- Timing cuts (CHOD, KTAG)
- Kinematic constraints on total and transverse momenta of the vertex
- Particle ID using LKr + STRAW and decay kinematics
  - $\pi^+$: $E/p < 0.9$
  - $e^\pm$: $E/p \in (0.9, 1.1)$
  - Total invariant mass: $m_{\pi ee} \in (480, 510)\,\text{MeV}$
  - Di-electron invariant mass: $m_{ee} > 130\,\text{MeV}$
- Background suppression:
  - Using STRAW hit information to reject $e^\pm$ tracks from $\gamma$ conversions
  - Reject events with a track segment reconstructed in the first two STRAW chambers compatible with the vertex



# $K^+ \to \pi^+ e^+ e^-$: Normalization sample

- Common selection applied
- Normalization region:

$$m_{ee} \in (140, 360)\,\mathrm{MeV}$$

- Number of observed events: 12160
- Acceptance:

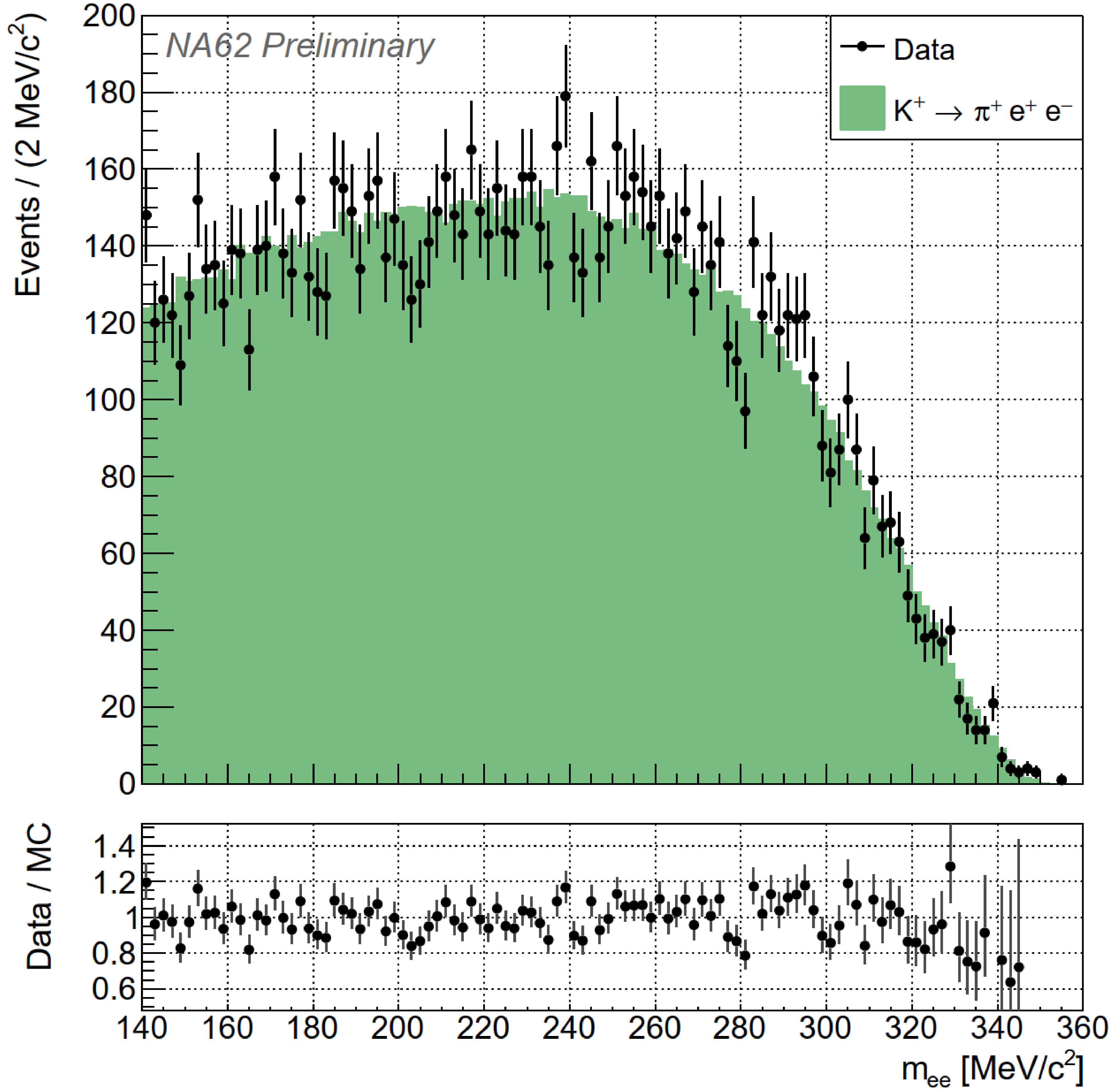
$$A(K^+ \to \pi^+ e^+ e^-) = (4.70 \pm 0.01_{\mathrm{stat}})\%$$

- Sample purity $> 99.9\%$
- Effective number of kaon decays:

$$N_K = (8.62 \pm 0.08_{\mathrm{stat}} \pm 0.26_{\mathrm{ext}}) \times 10^{11}$$

  - External uncertainty from

$$\mathcal{B}_{\mathrm{PDG}}(K^+ \to \pi^+ e^+ e^-) = (3.00 \pm 0.09) \times 10^{-7}$$



# $\pi^0 \to e^+e^-$: Signal sample

- Common selection applied
- Fit region:

$$m_{ee} \in (130, 140)\,\mathrm{MeV}$$

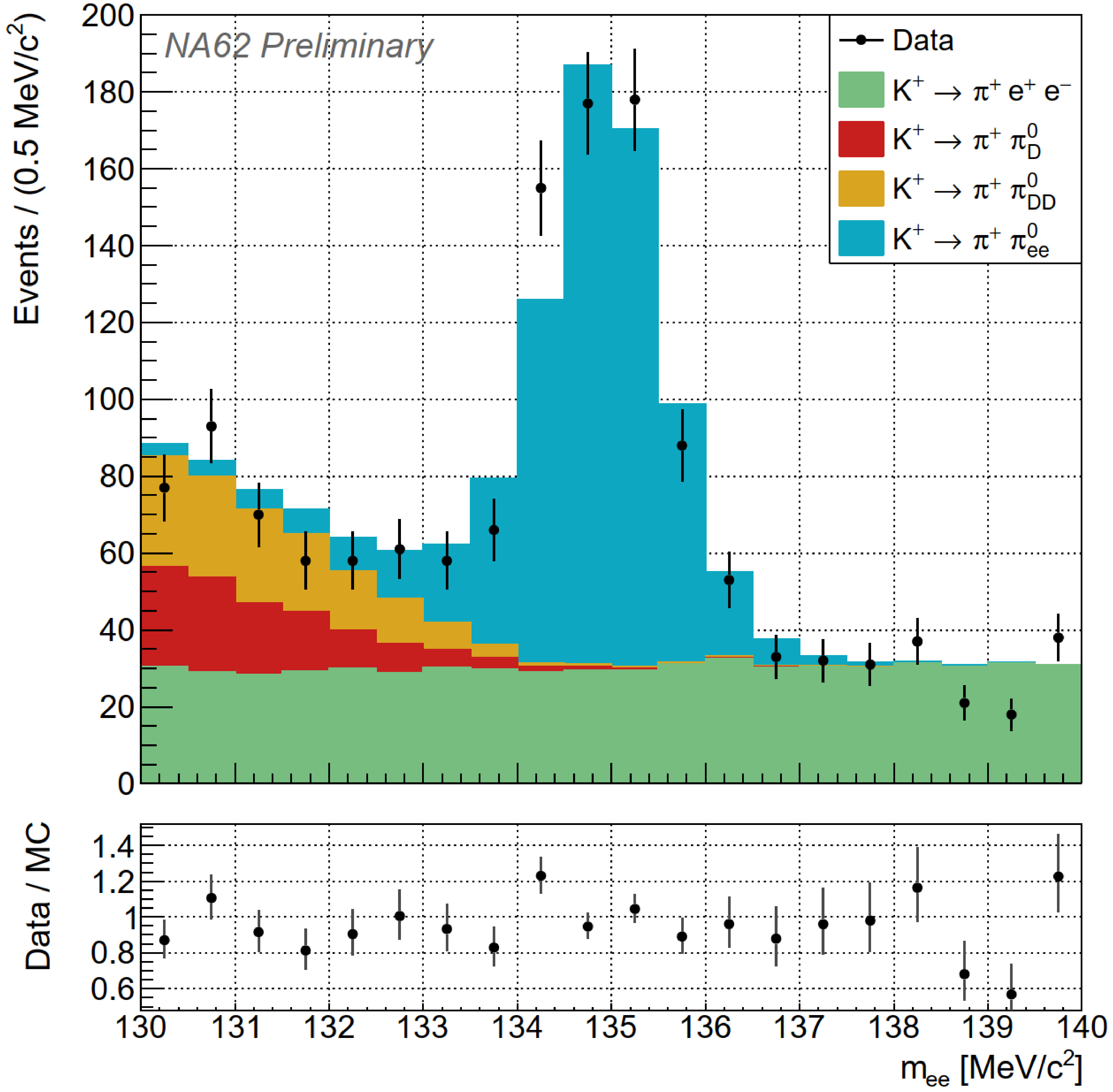
- Signal acceptance ($x_{\mathrm{true}} > 0.95$):

$$A(K^+ \to \pi^+\pi^0_{ee}) = (5.72 \pm 0.02_{\mathrm{stat}})\%$$

- Branching fraction of $\pi^0 \to e^+e^-$ obtained by performing maximum likelihood fit of simulated samples to data

$$\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (5.86 \pm 0.30_{\mathrm{stat}}) \times 10^{-8}$$

  - Branching fractions of other decays: external input from PDG 2023
  - Fitted signal event yield: $597 \pm 29$
  - $\chi^2$ test: $\chi^2/\mathrm{ndf} = 25.3/19$, $p$-value: 0.152



# $\pi^0 \to e^+e^-$: Preliminary result and uncertainties

$$\begin{aligned}\mathcal{B}_{\mathrm{NA62}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) &= (5.86 \pm 0.30_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}} \pm 0.19_{\mathrm{ext}}) \times 10^{-8} \\ &= (5.86 \pm 0.37) \times 10^{-8}\end{aligned}$$

| | $\delta\mathcal{B}$ $[10^{-8}]$ | $\delta\mathcal{B}/\mathcal{B}$ [%] |
|---|---|---|
| *Statistical uncertainty* | 0.30 | 5.1 |
| *Total external uncertainty* | 0.19 | 3.2 |
| *Total systematic uncertainty* | 0.11 | 1.9 |
| Trigger efficiency | 0.07 | 1.2 |
| Radiative corrections for $\pi^0 \to e^+e^-$ | 0.05 | 0.9 |
| Background | 0.04 | 0.7 |
| Reconstruction and particle identification | 0.04 | 0.7 |
| Beam simulation | 0.03 | 0.5 |

# $\pi^0 \to e^+e^-$: Summary and outlook

- New preliminary result based on data collected by NA62 in 2017 – 2018:

$$\begin{aligned}\mathcal{B}_{\mathrm{NA62}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) &= (5.86 \pm 0.30_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}} \pm 0.19_{\mathrm{ext}}) \times 10^{-8} \\ &= (5.86 \pm 0.37) \times 10^{-8}\end{aligned}$$

- Lower central value than in KTeV measurement, but results are compatible:

$$\mathcal{B}_{\mathrm{KTeV}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (6.44 \pm 0.33) \times 10^{-8}$$

- Result in agreement with theory when extrapolated using radiative corrections:

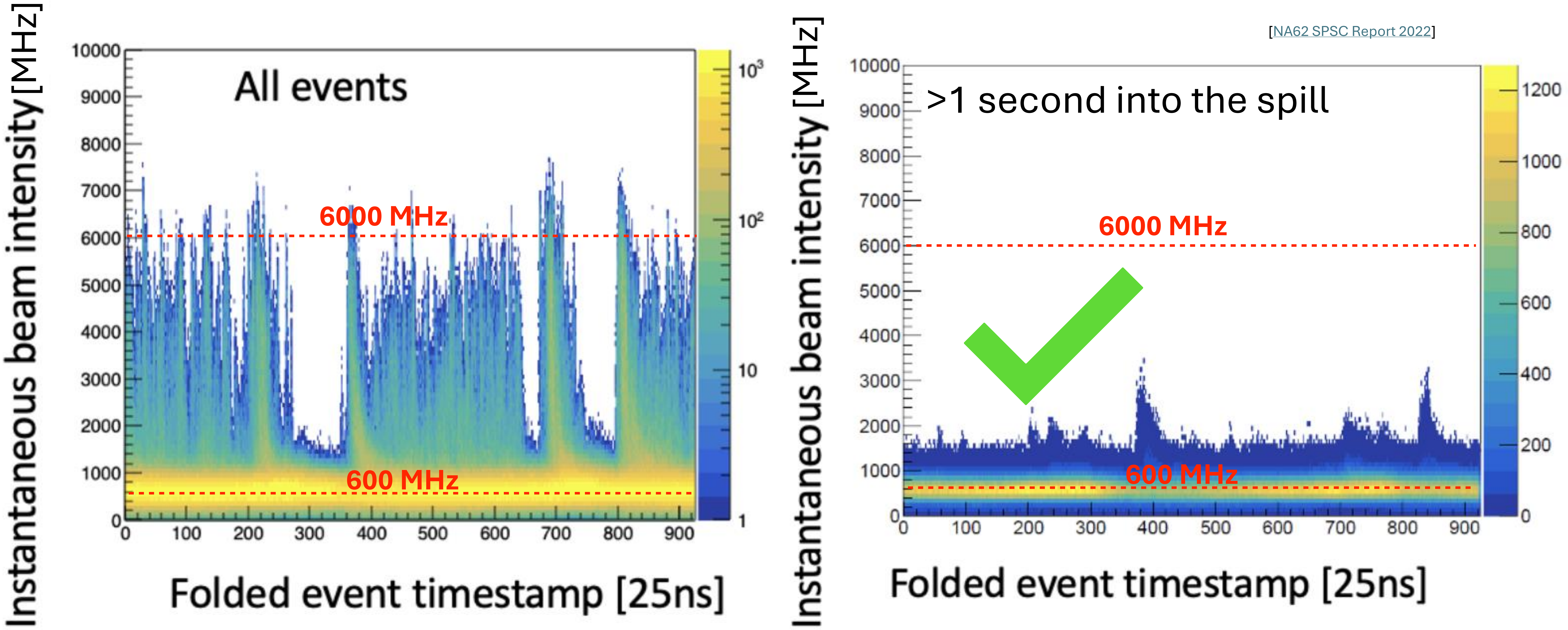
$$\mathcal{B}_{\mathrm{NA62}}\left(\pi^0 \to e^+e^-, \text{no-rad}\right) = (6.22 \pm 0.39) \times 10^{-8}$$

$$\mathcal{B}_{\mathrm{theory\ (2022)}}\left(\pi^0 \to e^+e^-, \text{no-rad}\right) = (6.25 \pm 0.03) \times 10^{-8}$$

- External uncertainty from $\mathcal{B}(K^+ \to \pi^+e^+e^-)$, measured by NA48/2 and E865
    - New analysis of $K^+ \to \pi^+e^+e^-$ is planned at NA62
- Ongoing NA62 data taking (2021 – LS3)
    - Optimized multi-track electron trigger line with reduced downscaling
    - Collecting large samples of decays with di-electron final states

# Supplemental

# 2021 instantaneous beam intensity



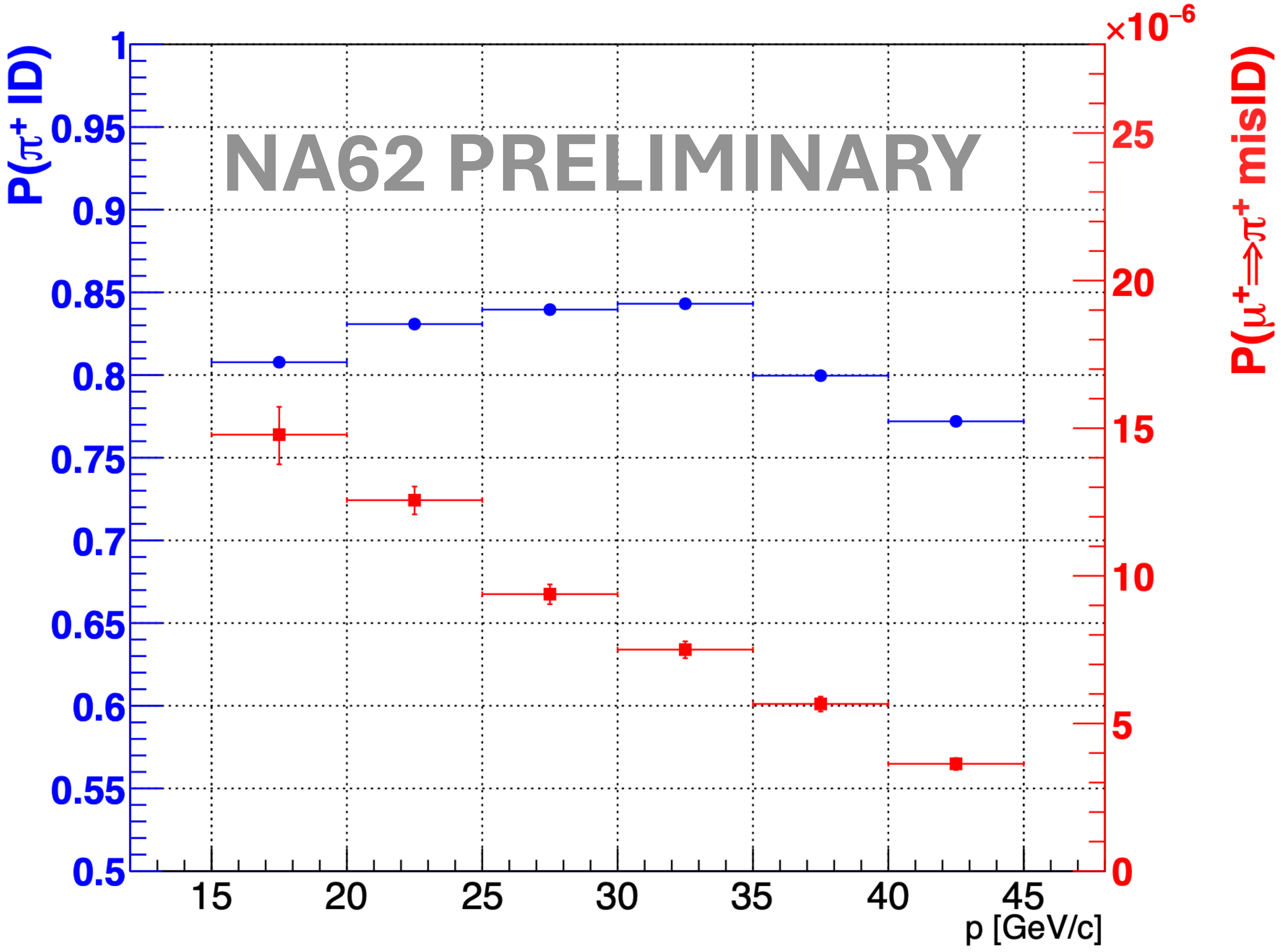
[NA62 SPSC Report 2022]

- **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.

# Particle ID performance : 2021—22 data

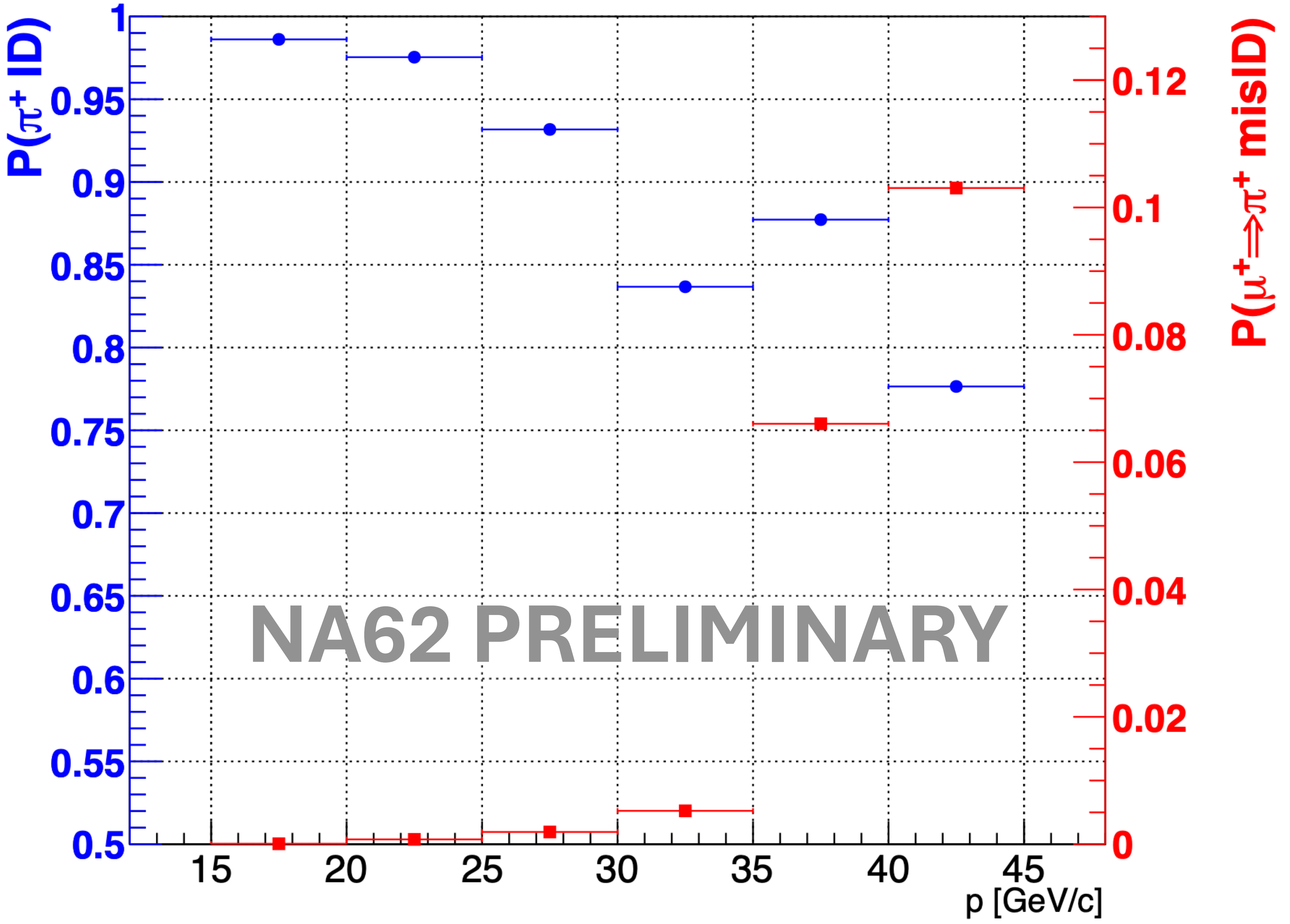
## Calorimeters

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



## RICH

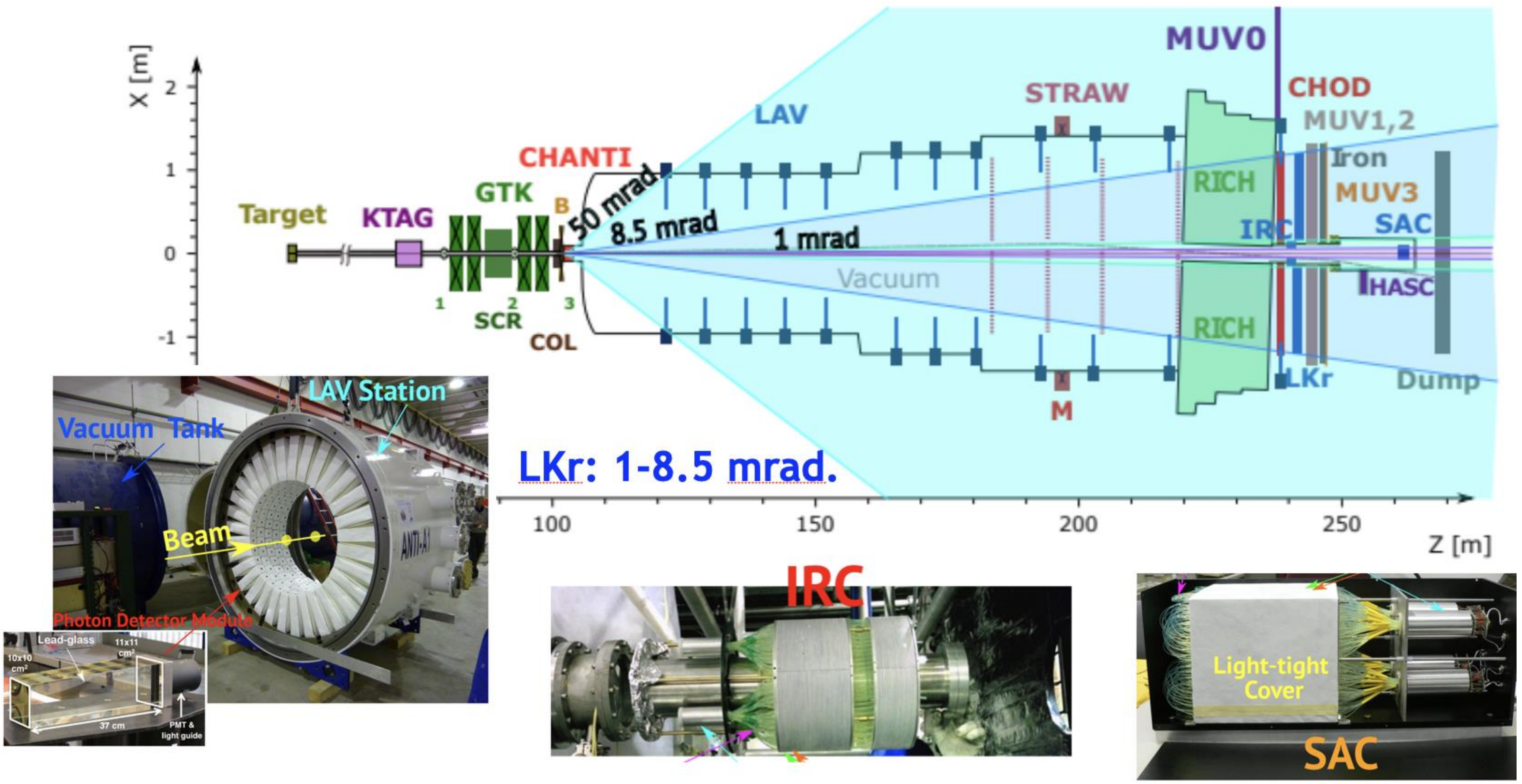
Designed to distinguish between $\pi^+/\mu^+$ with $15-35\,GeV/c$



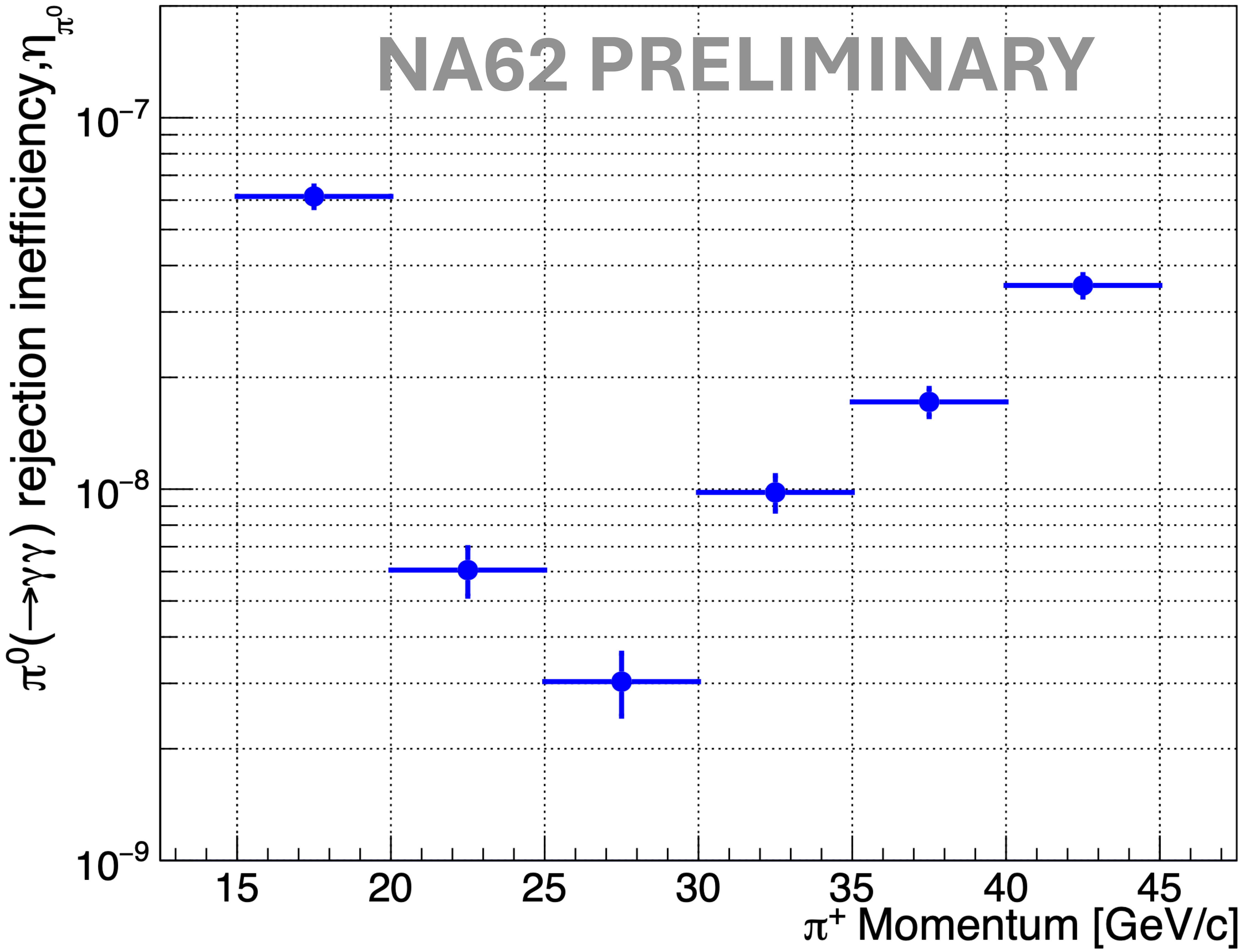
$$P(\pi^+) = (73.00 \pm 0.01)\%$$

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

# Comprehensive photon veto system: 21—22



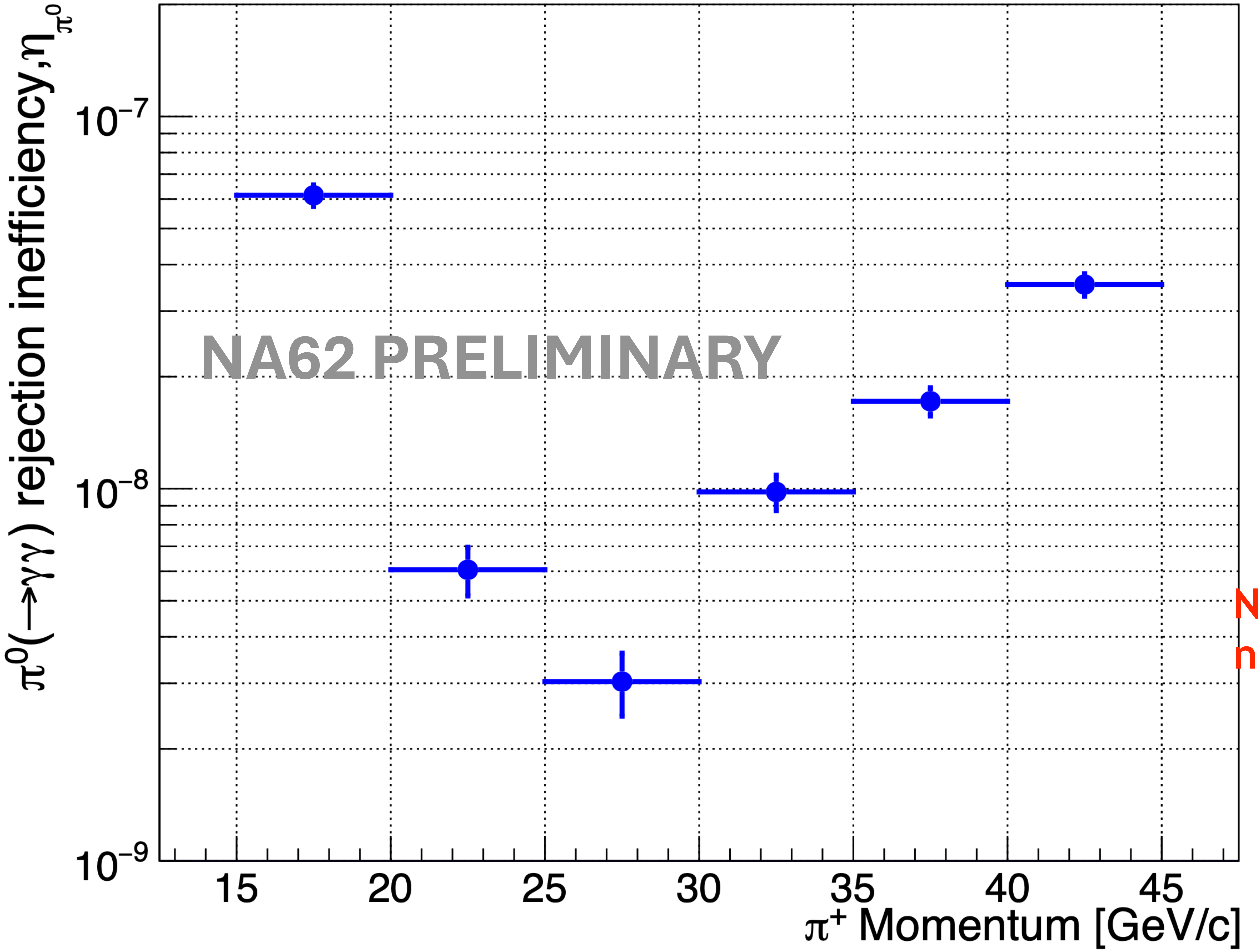
Control sample of $K^+ \to \pi^+\pi^0$



- 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 $\gamma/\pi^0$ rejection of $\mathcal{O}(10^8)$**

# Photon veto performance



- Probability of $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ 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**

**Normalisation trigger downscaling and efficiency**

**Random veto efficiency**

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

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

# 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

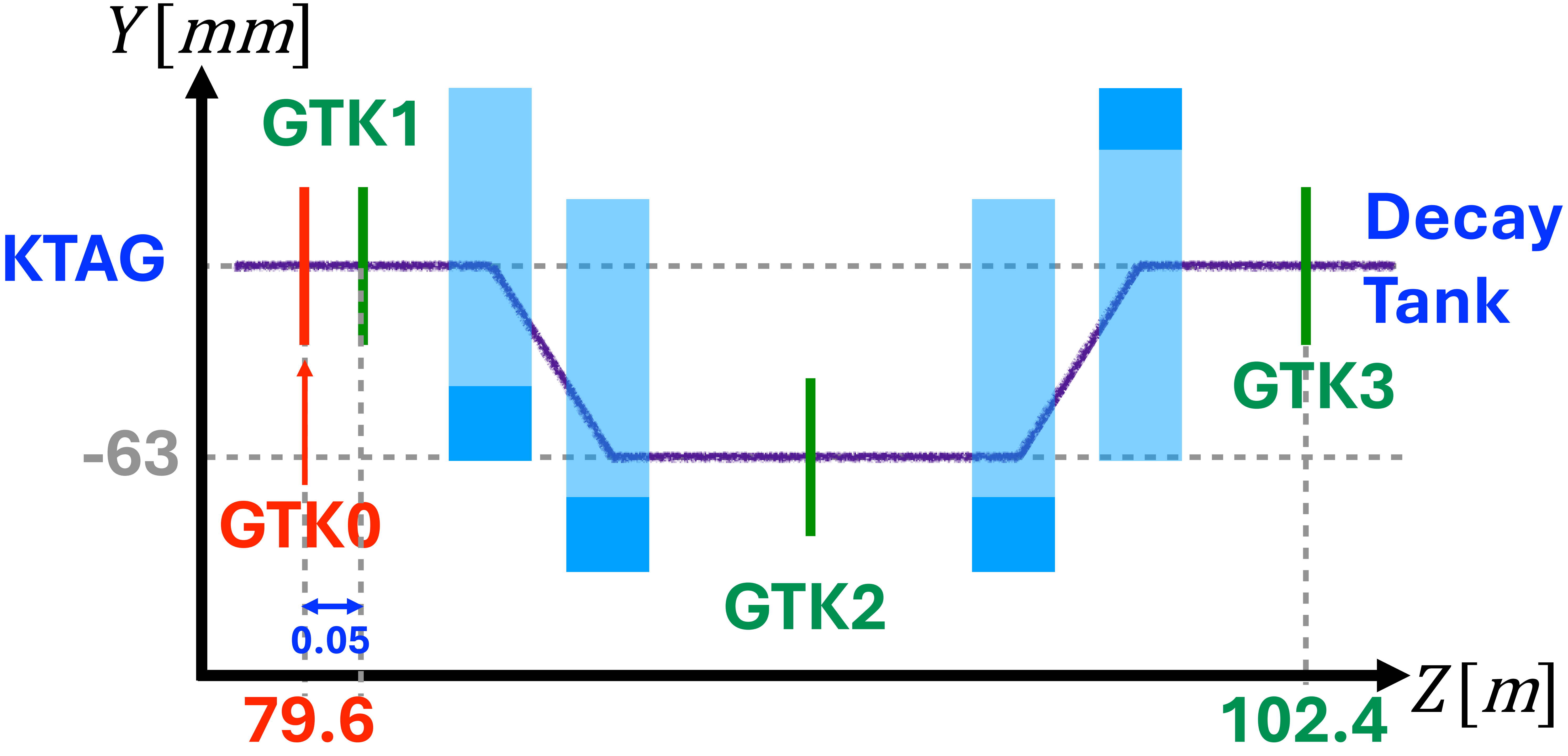
## Number of expected SM events:

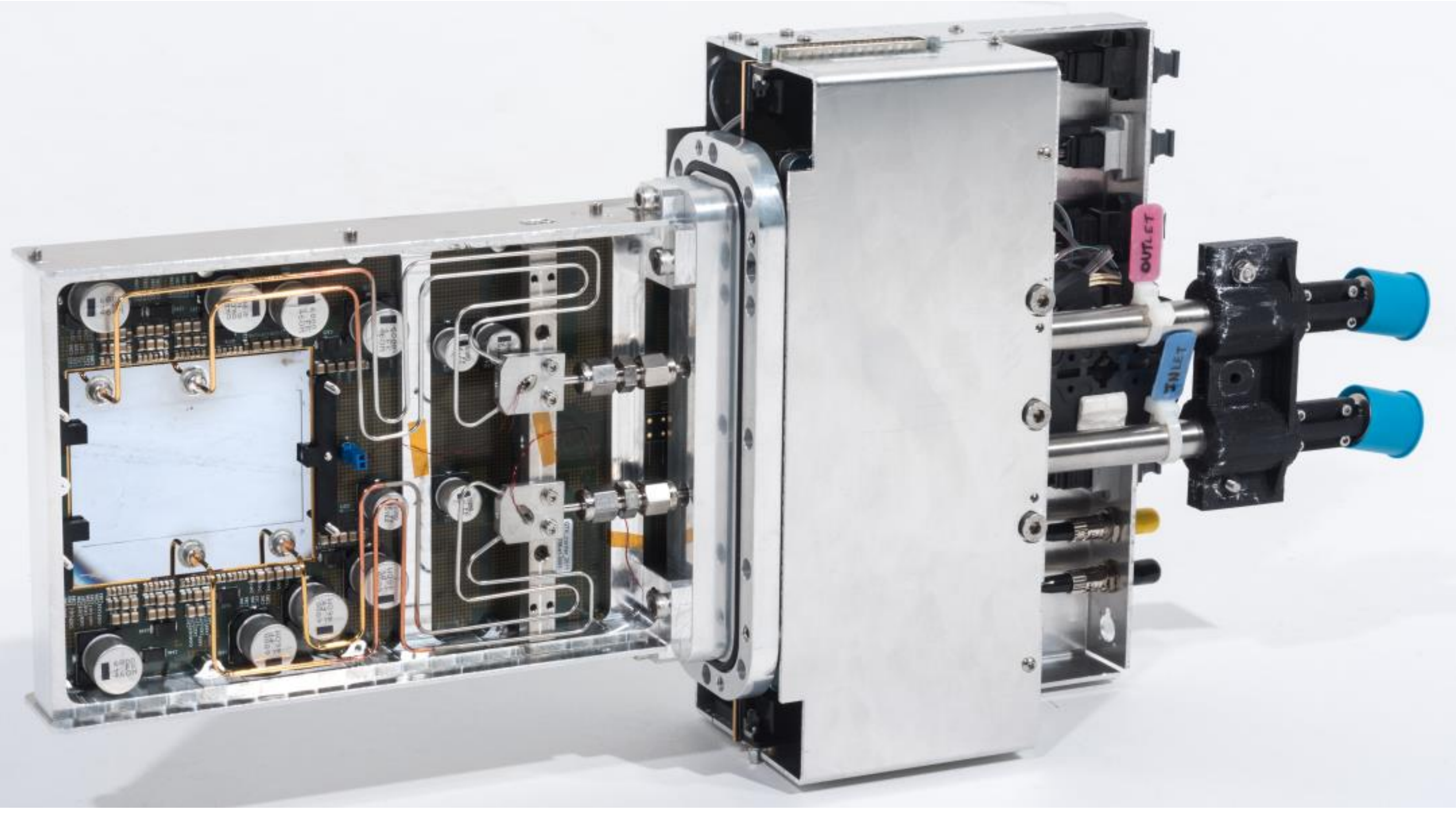
(For comparison to previous results use $\mathcal{B}^{SM}_{\pi\nu\bar{\nu}} = 8.4 \times 10^{-11}$ but results are independent of this choice)

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

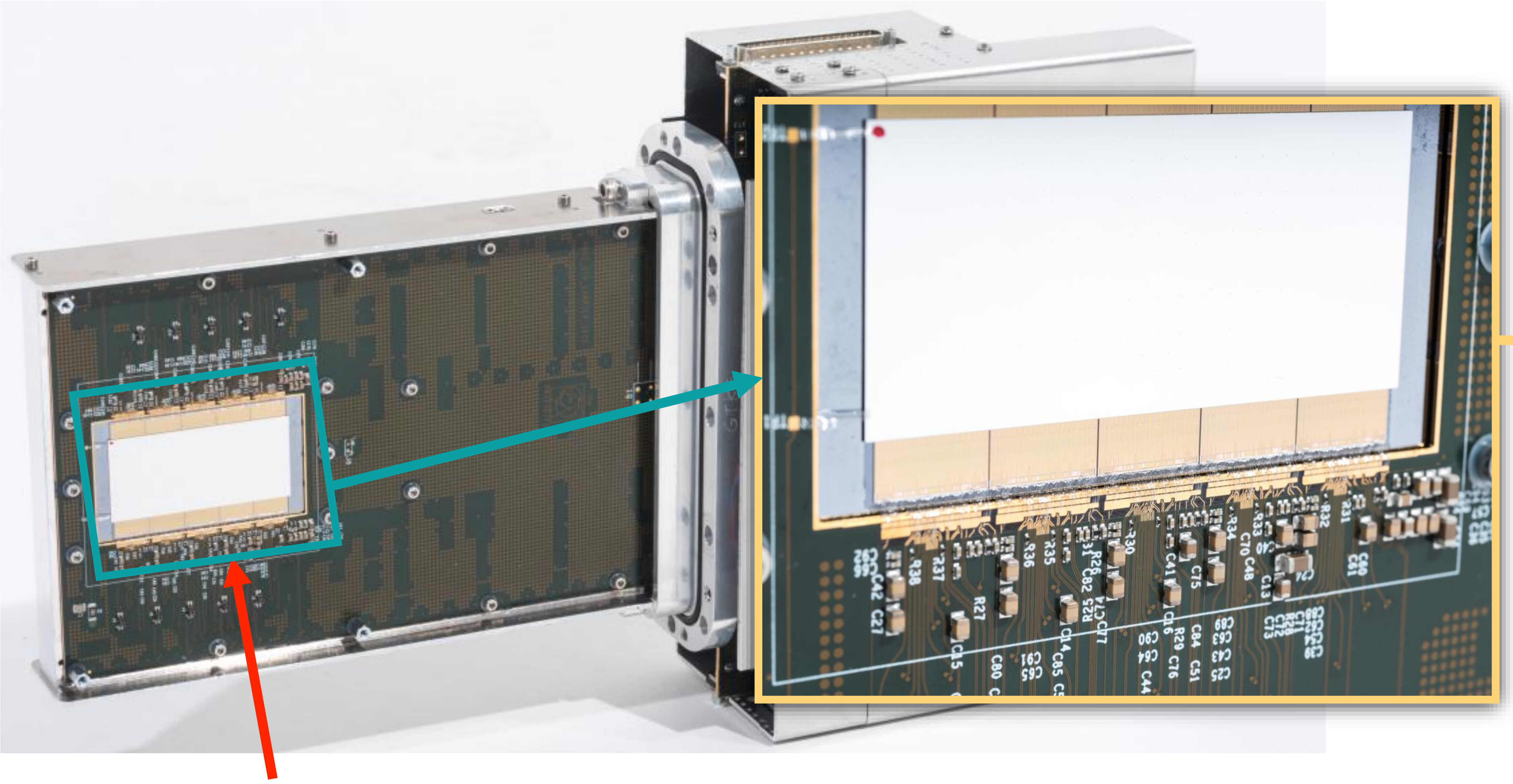
# 4th GTK station

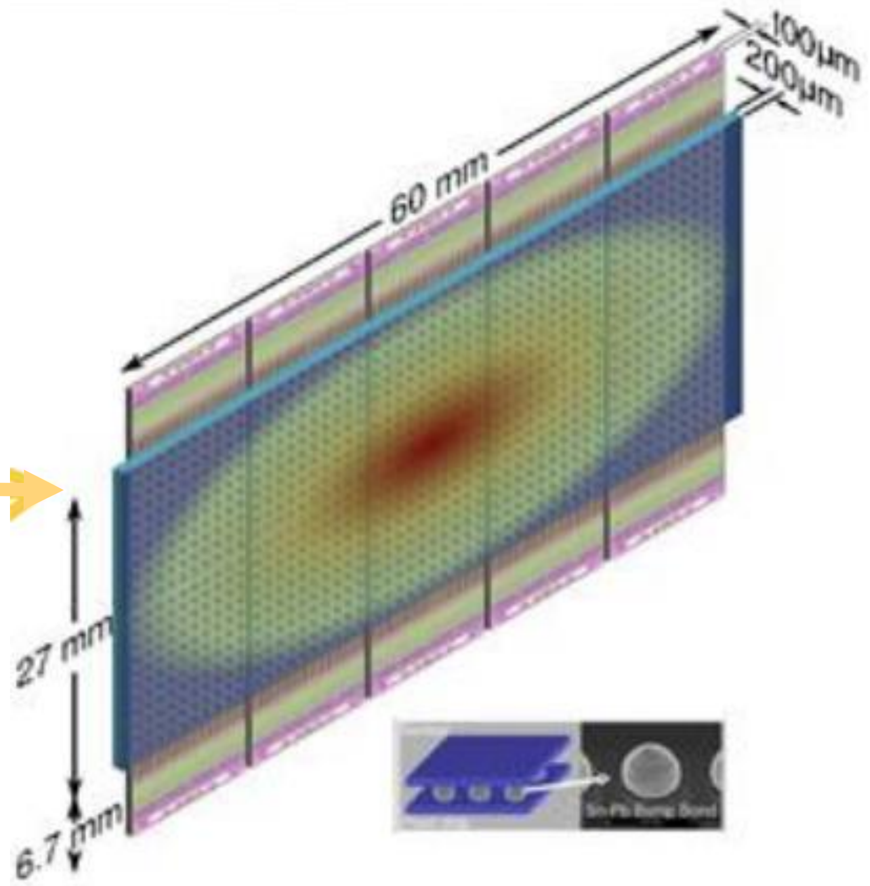
- Si Pixel detector exposed to ~1GHz beam.
- Essential for $K^+ - \pi^+$ matching.
    - Measures $K^+$ 3-mom. & time
- 4th GTK station improves efficiency & pileup resilience.





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.

Sketch only

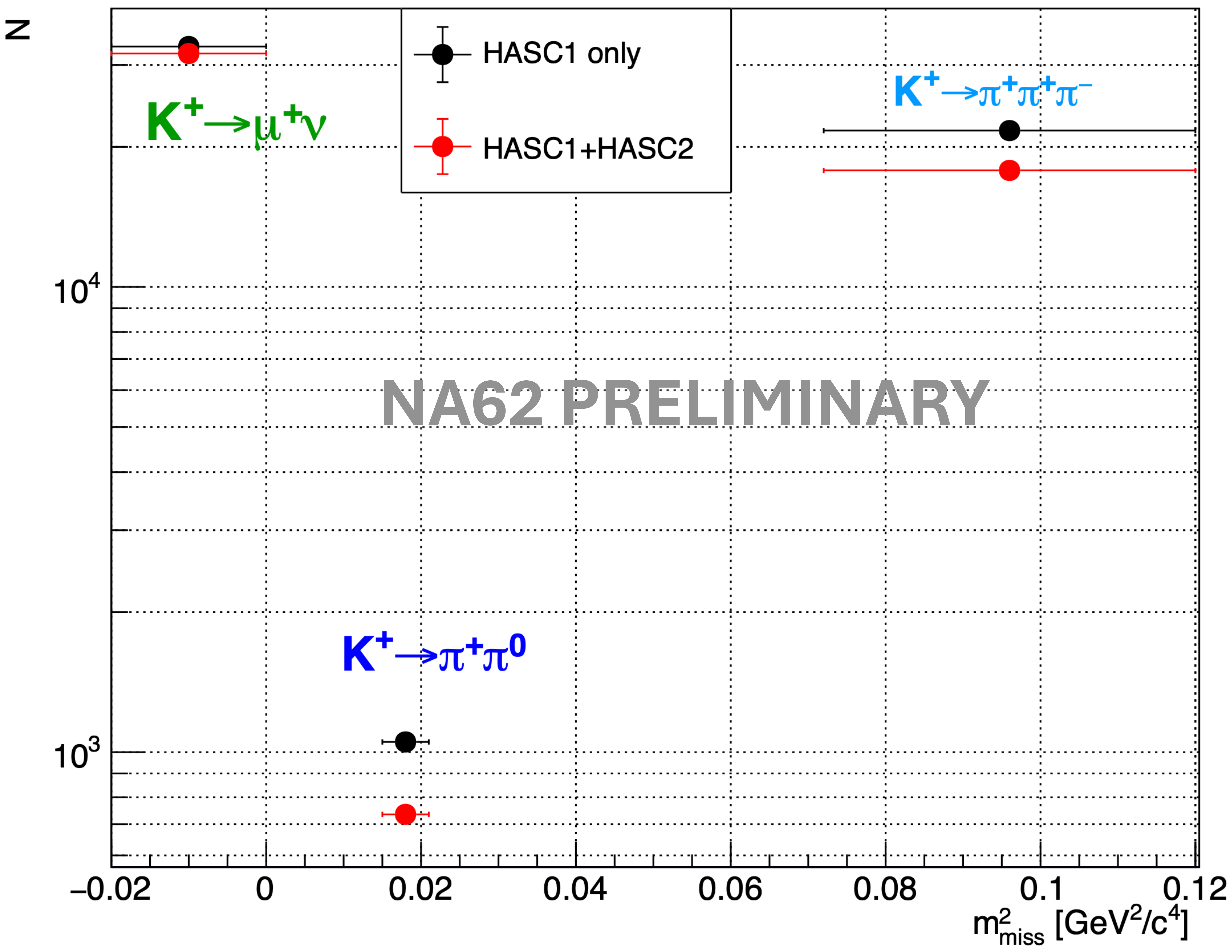
# HASC2 veto

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

- 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

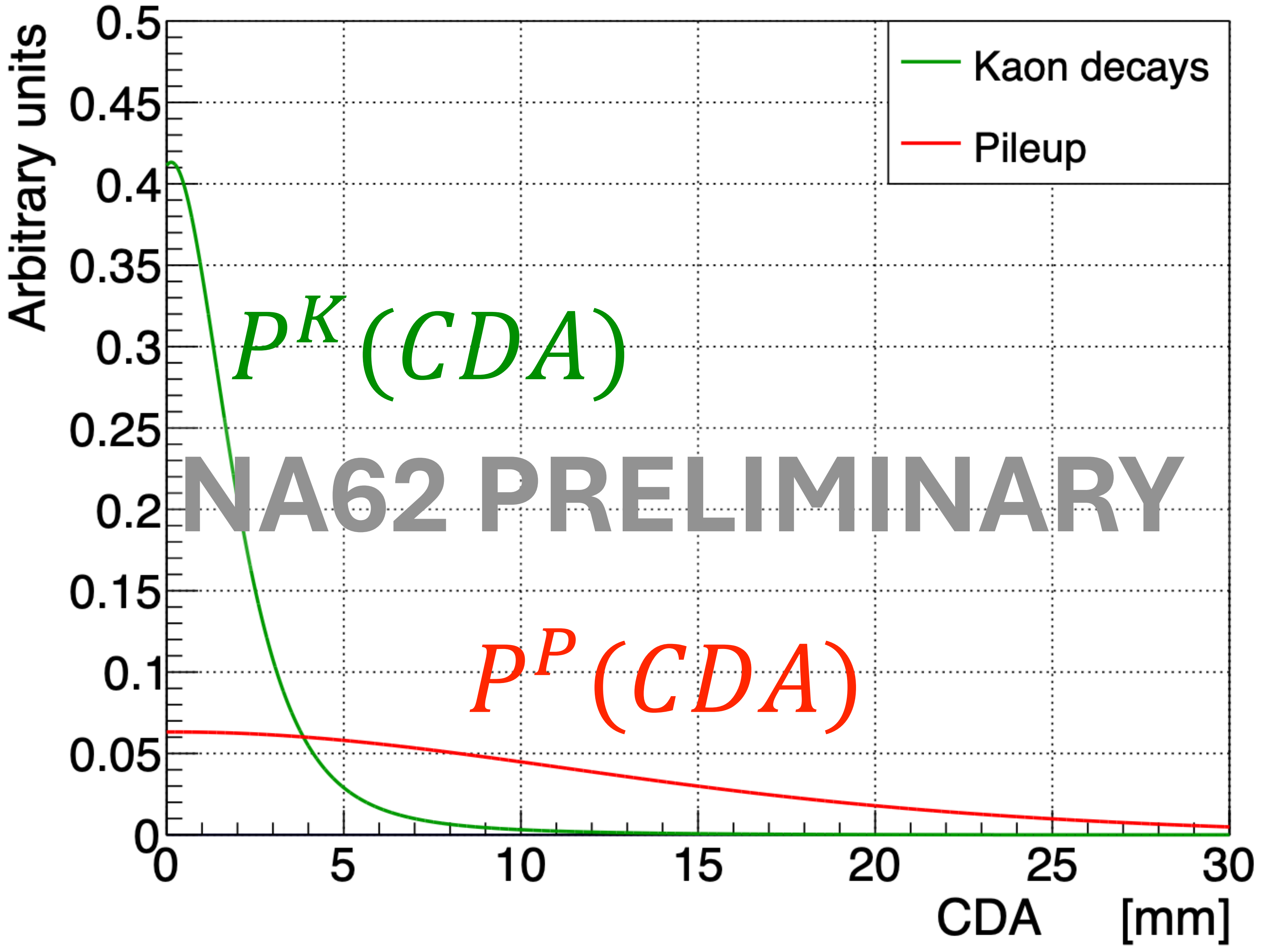
**Events passing $\pi^+\nu\bar{\nu}$ selection**

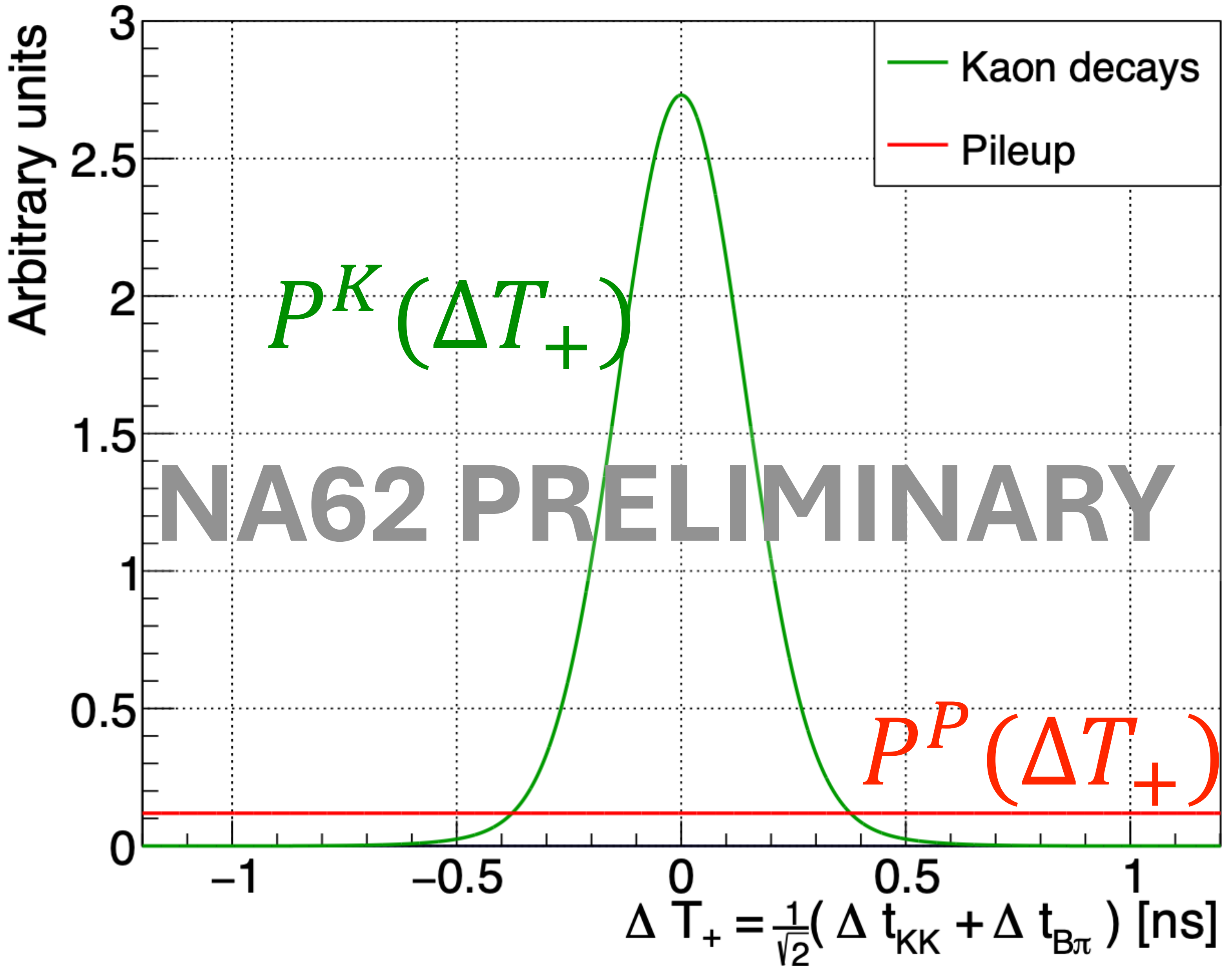
(modifying HASC veto: study integral of background regions)

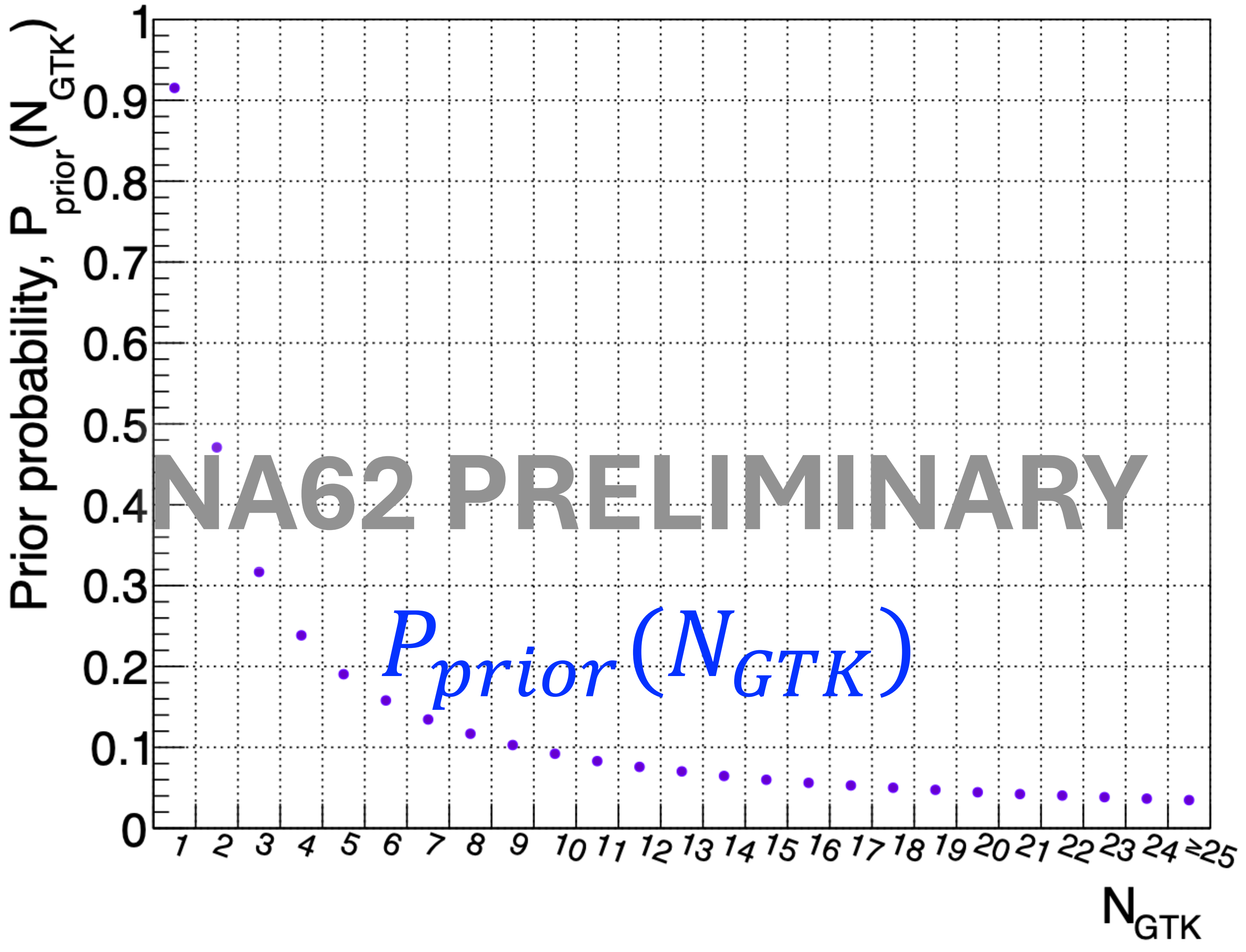


# Bayesian classifier for $K^+ - \pi^+$ matching

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







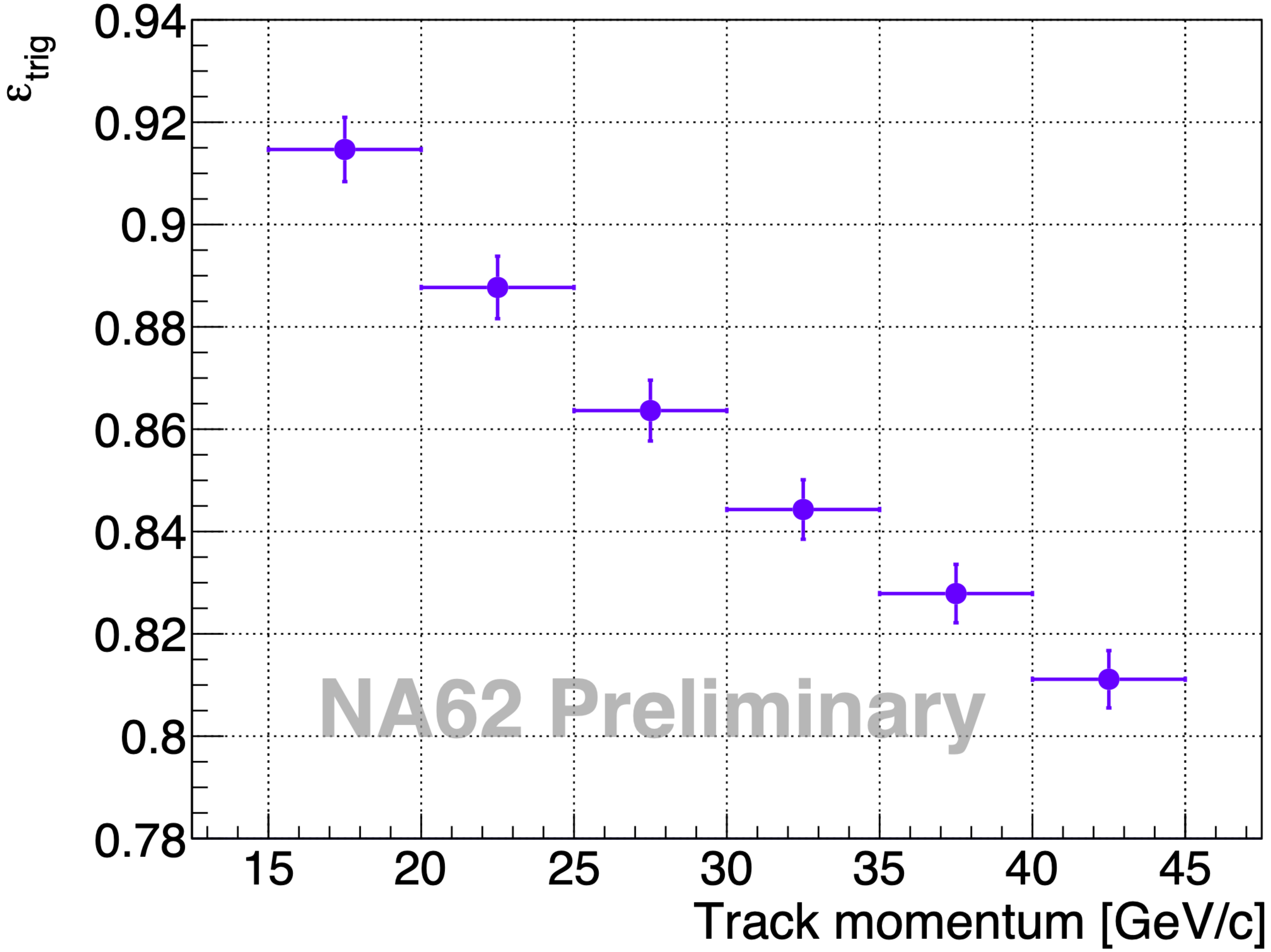
Example of selection update

- **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.

# Trigger efficiencies

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

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



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

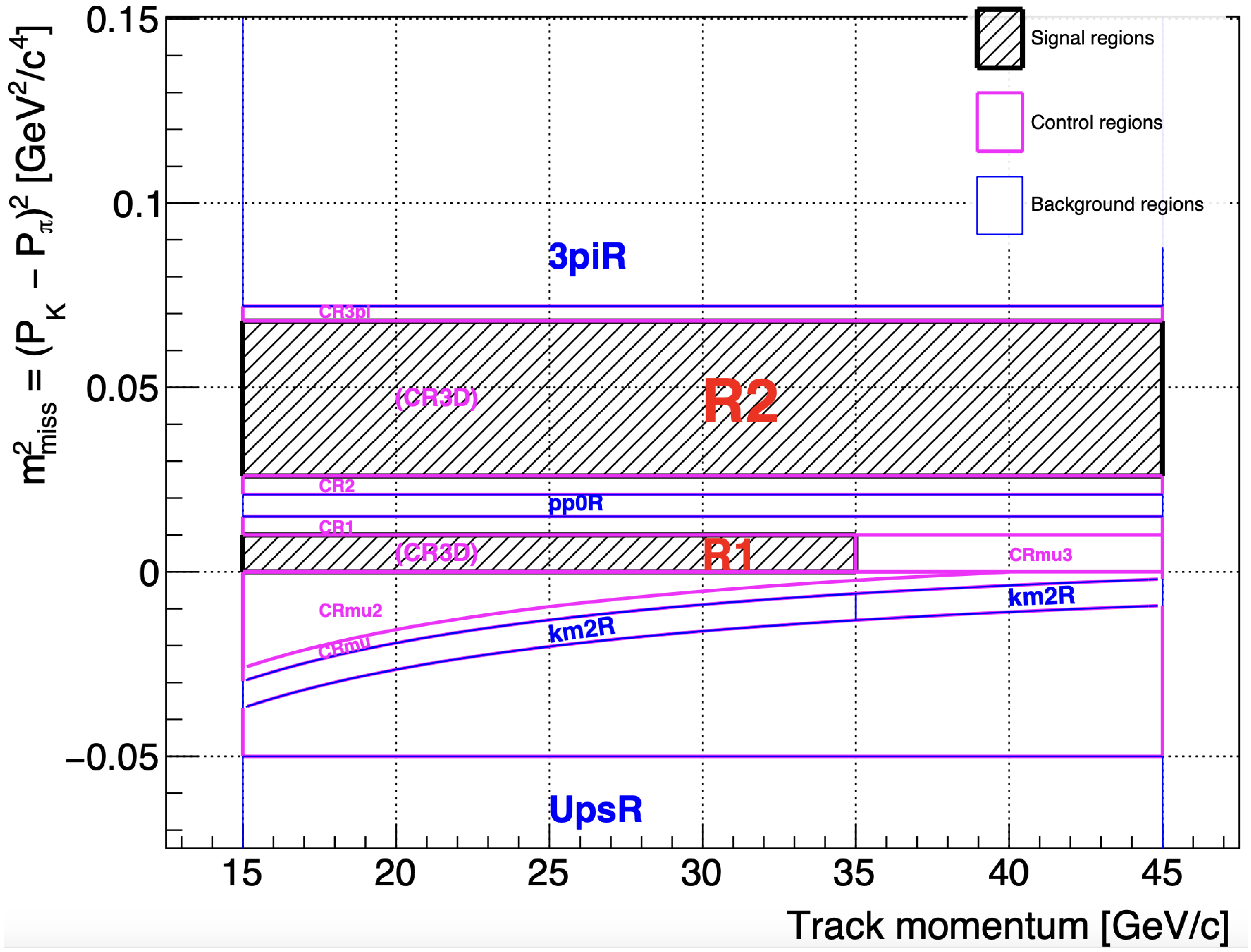
$$\varepsilon_{trig}(new) = (85.9 \pm 1.4)\%$$

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

- 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**).

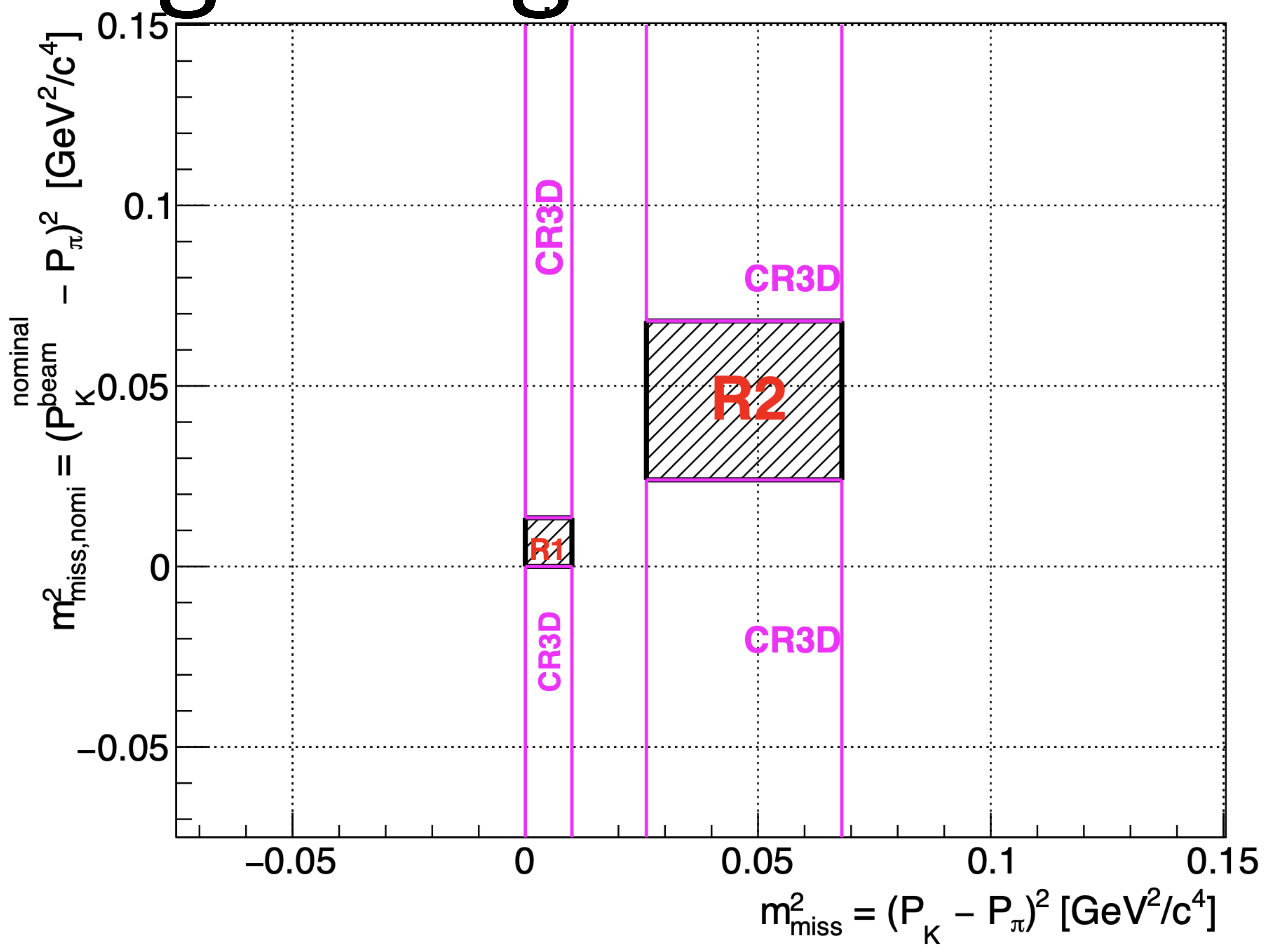
- Improved precision by factor 3 with reduced systematic uncertainty.

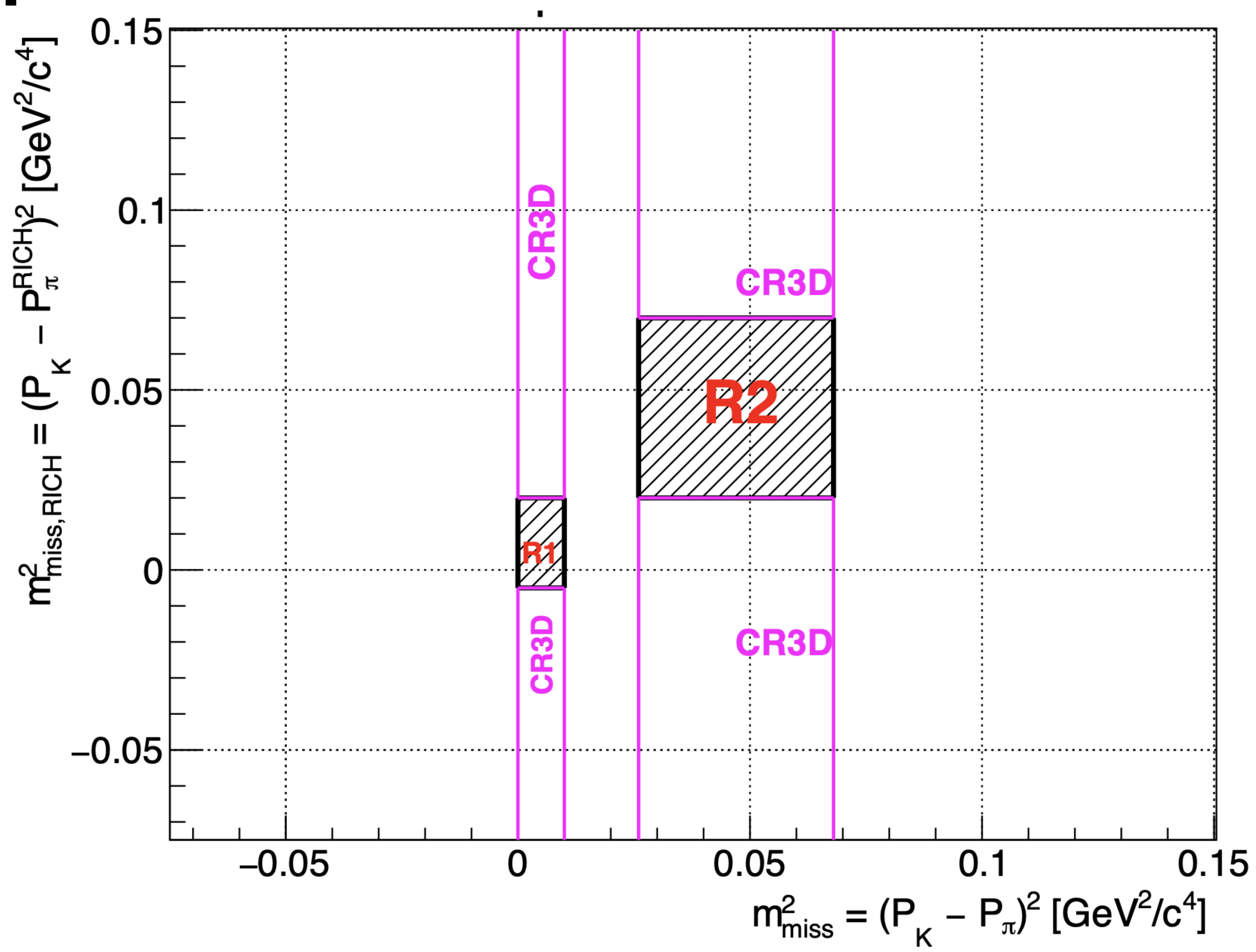
# Kinematic regions



- **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.

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

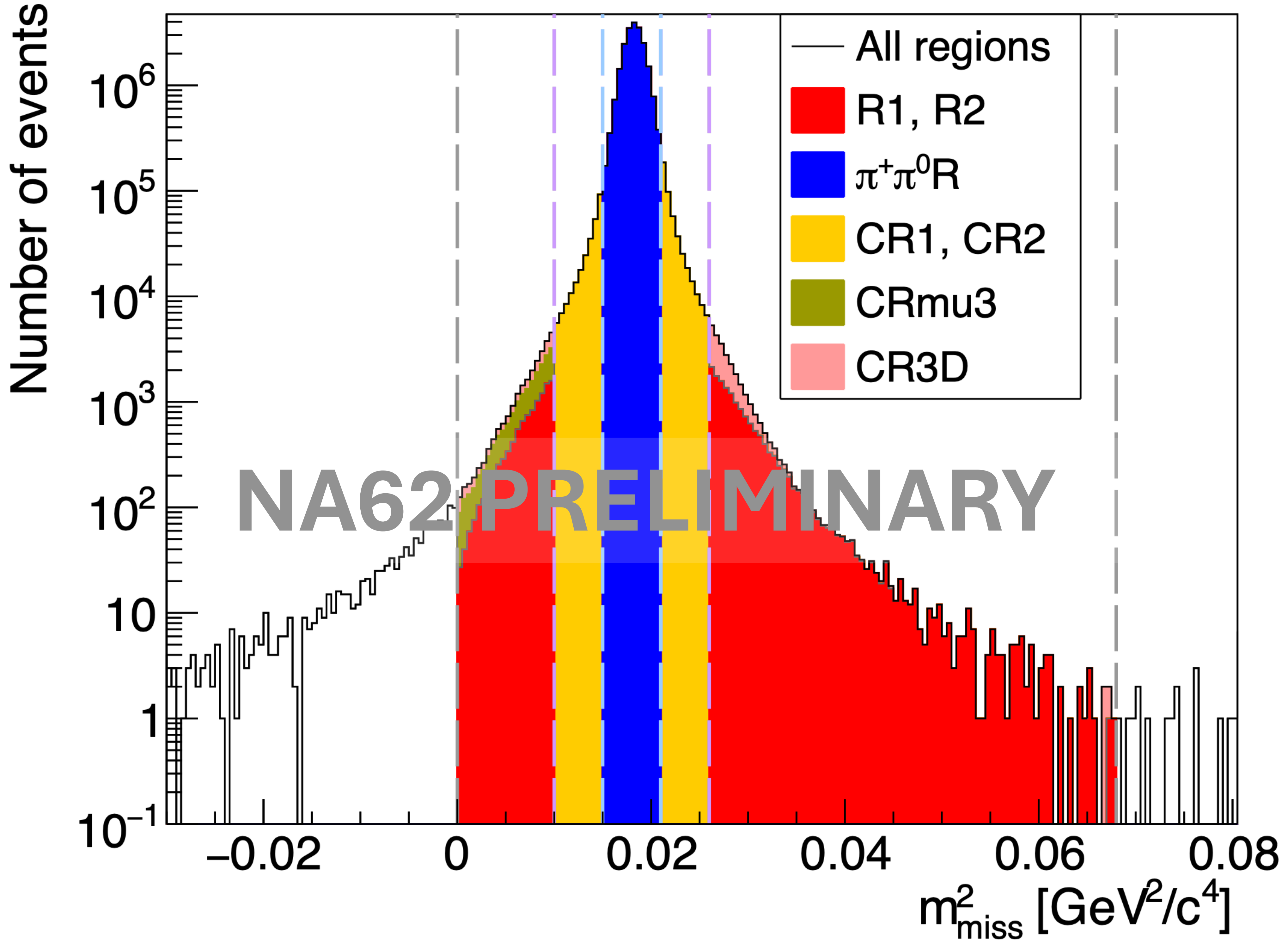
**Default: GTK**
**Alternative: Nominal beam = $m^2_{miss,nom}$**

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

# Backgrounds from kinematic tails

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

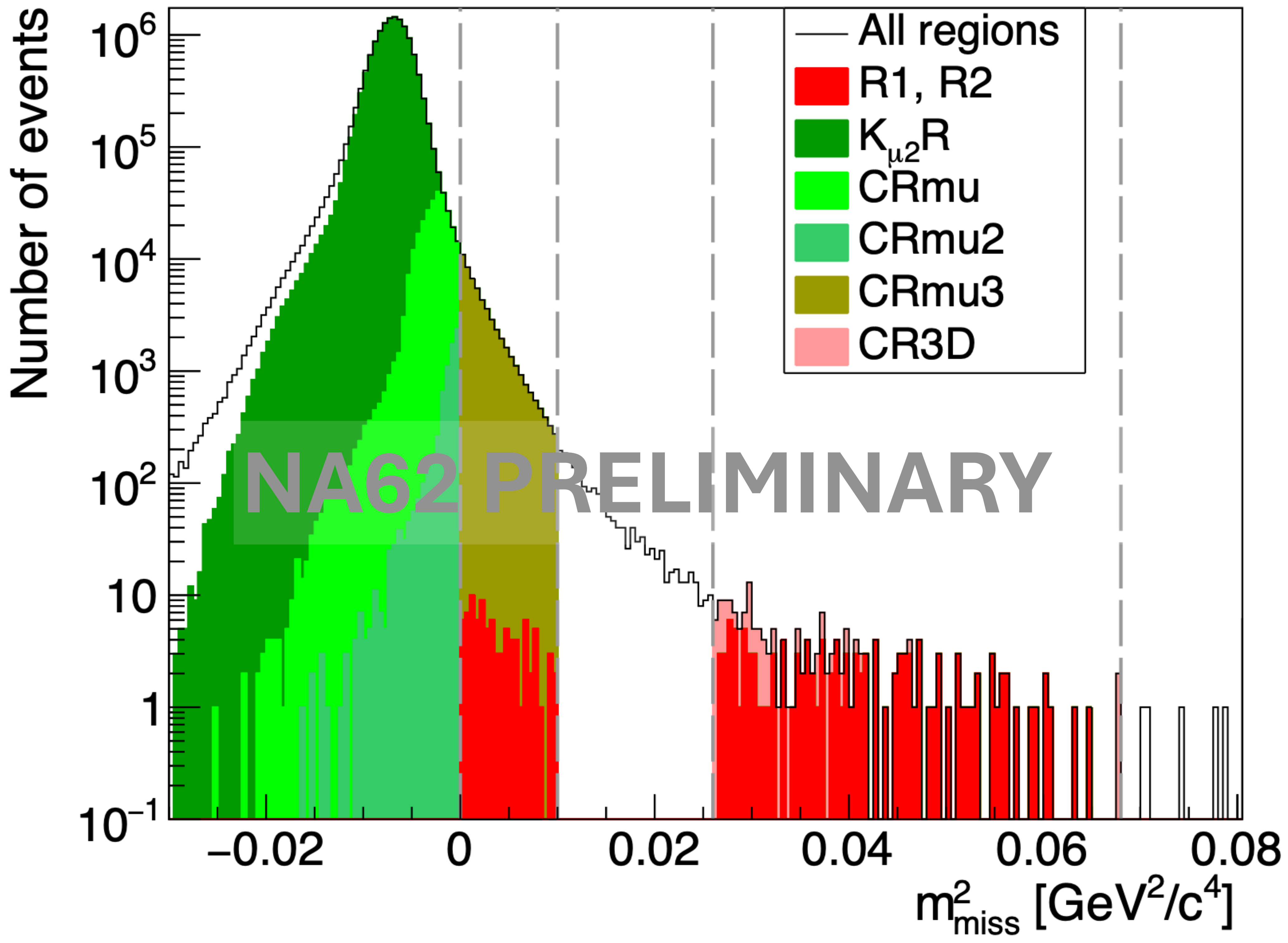
**control sample of $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ and 2 photons detected in LKr:**



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

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

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



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

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

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

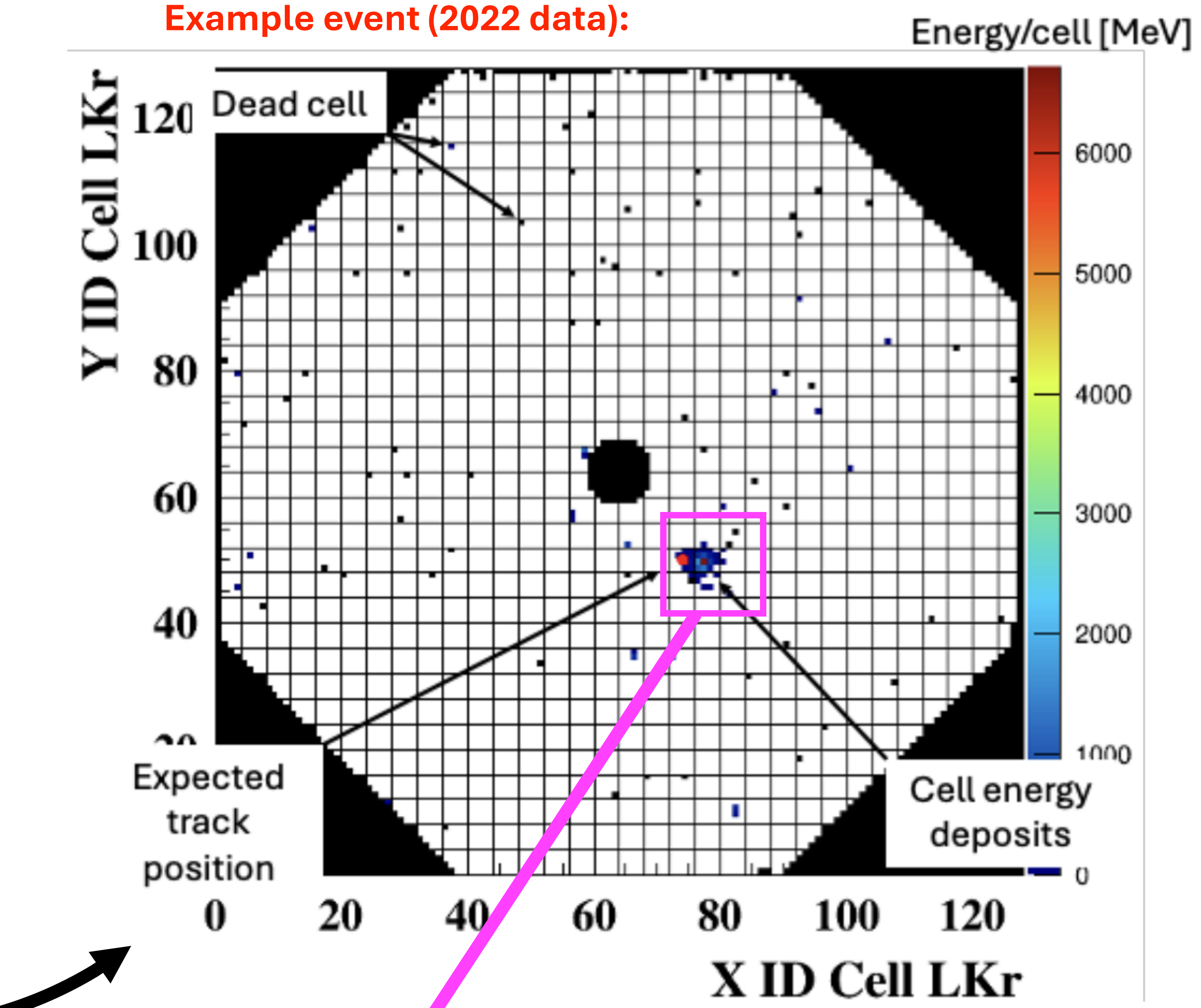
- Use MC to measure $f_{tail}$:

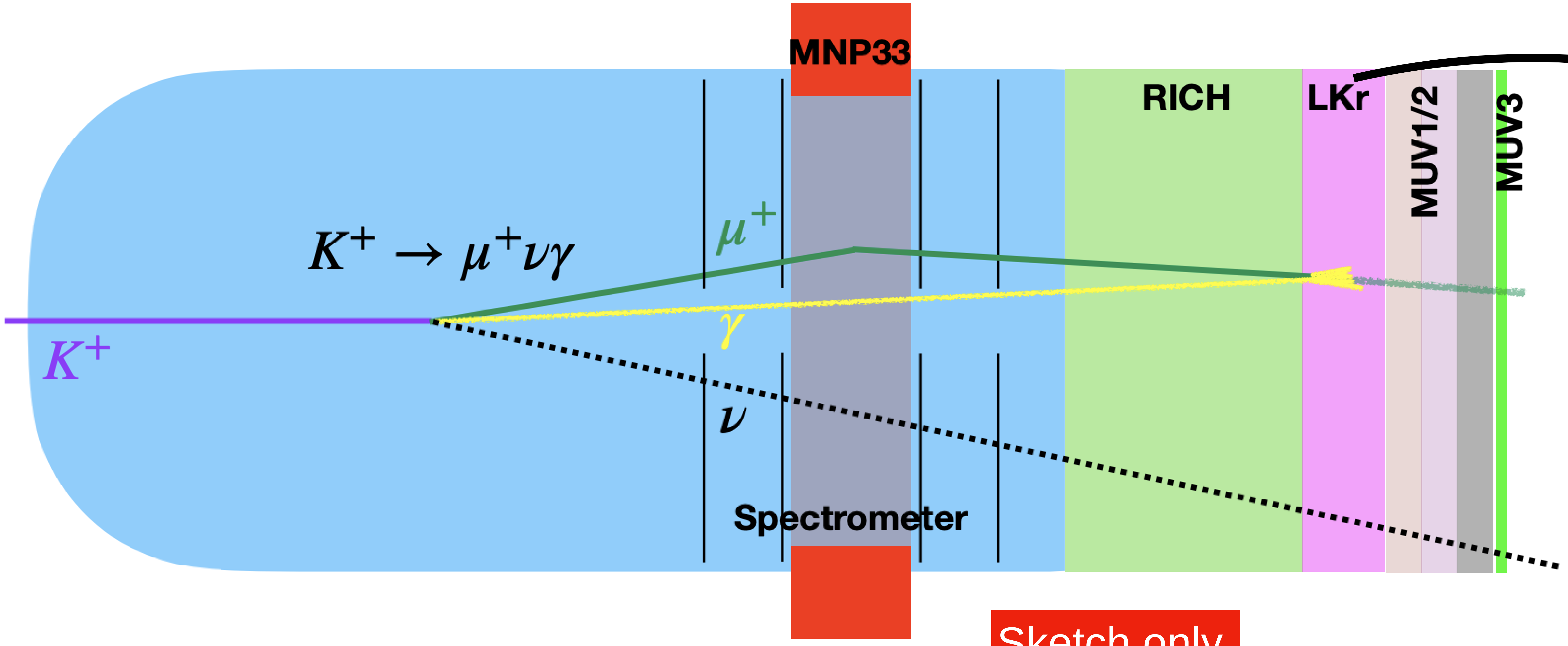
$$N_{bg}(K^+ \to \pi^+\pi^+\pi^-) = 0.11 \pm 0.03$$

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

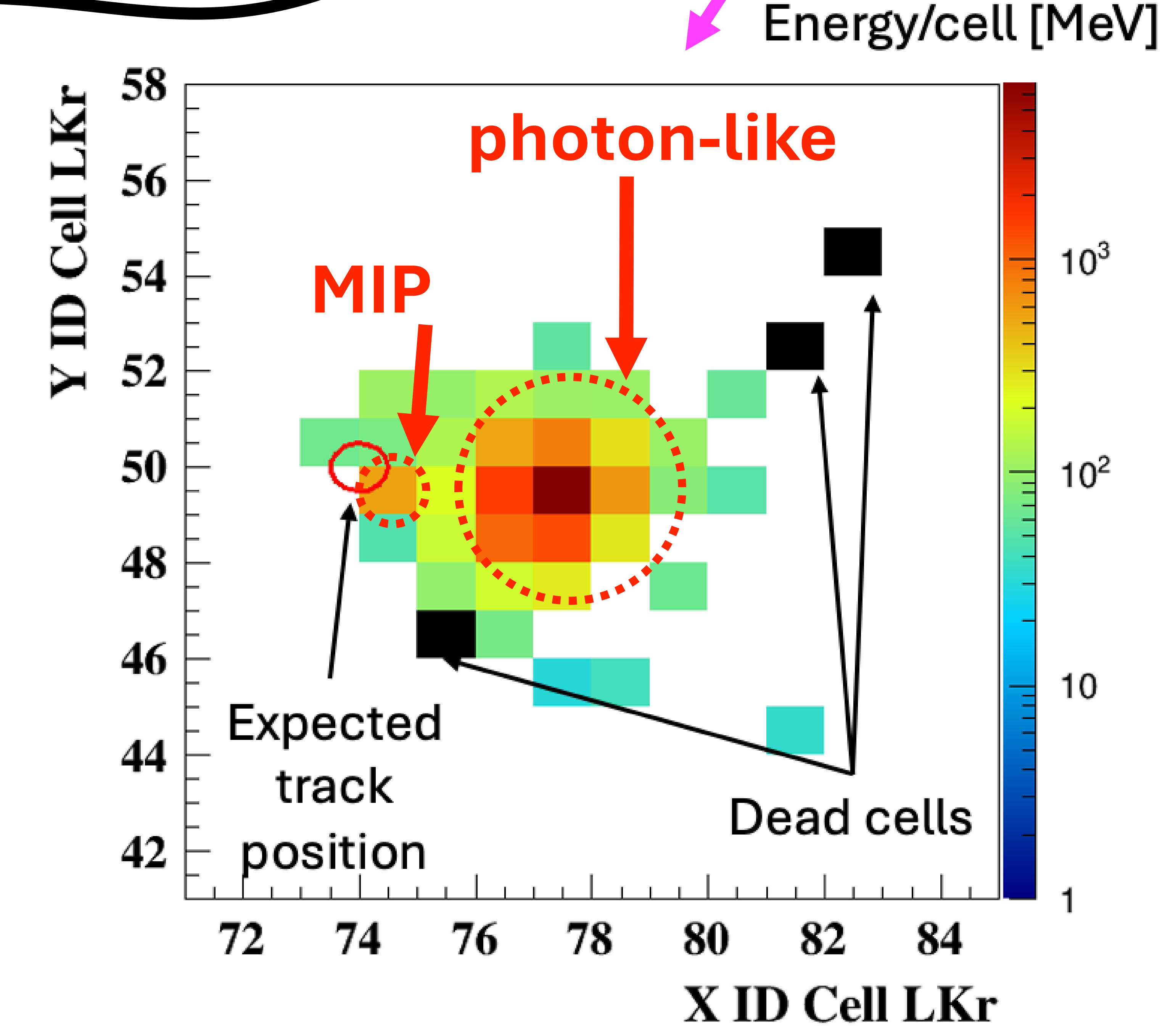
- $K^+ \to \mu^+\nu\gamma$ decay with fairly energetic photon $(E_\gamma > 5\,GeV)$ and high momentum $\mu^+$ $(p \gtrsim 35\,GeV/c)$.
- $\gamma$ and $\mu^+$ hit LKr together and are misidentified as a $\pi^+$.
- No rejection power from photon vetos (LKr $\gamma$ cluster associated to track).
- Additional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

Example event (2022 data):



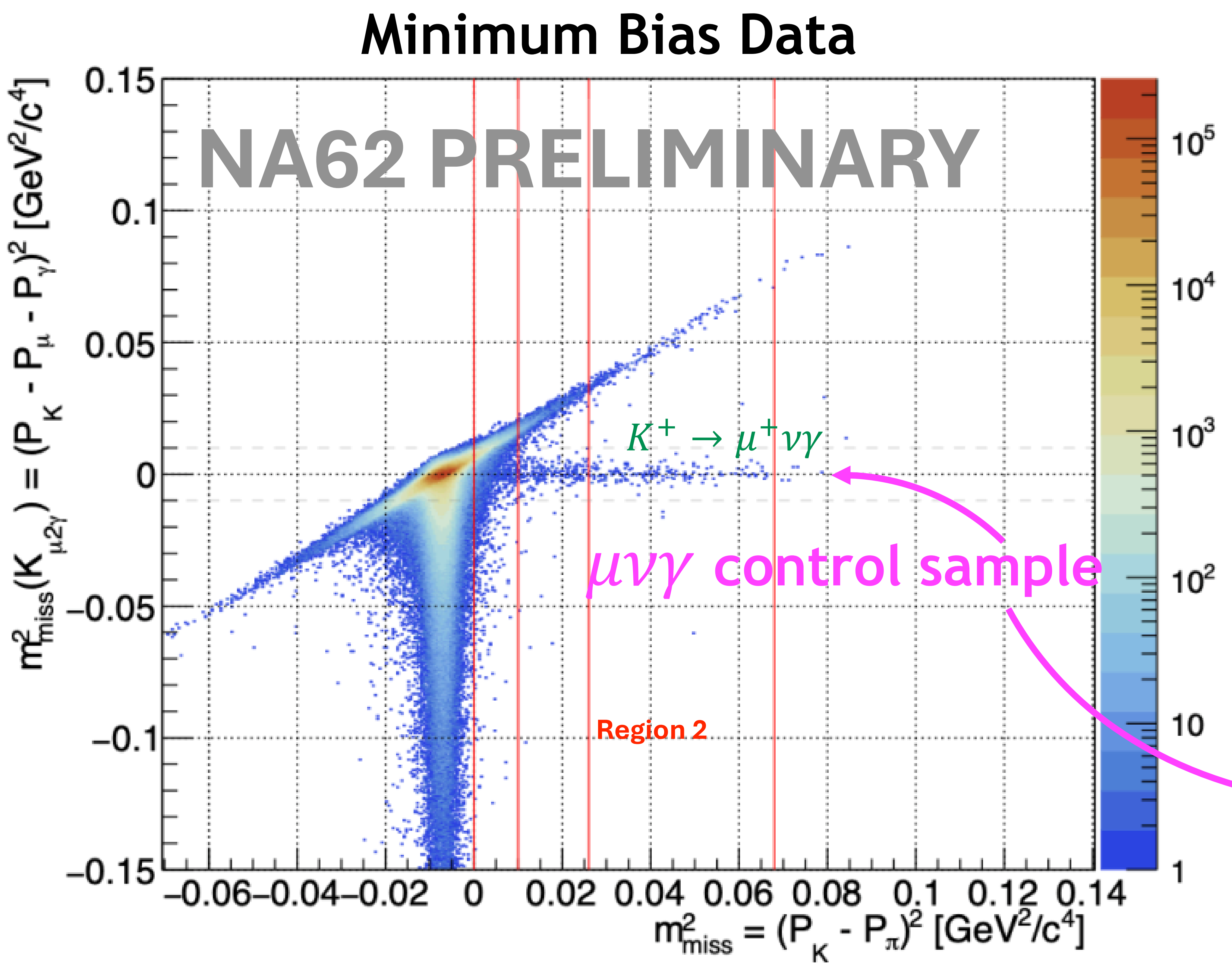


Sketch only



# Background evaluation: $K^+ \rightarrow \mu^+\nu\gamma$

- 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 $K^+ \rightarrow \mu^+\nu\gamma$ events: $m^2_{miss}(K_{\mu2\gamma}) = (P_K - P_\mu - P_\gamma)^2$
  - $P_K$ : 4-momentum of $K^+$ from GTK (as normal)
  - $P_\mu$ : 4-momentum of track with $\mu^+$ mass hypothesis.
  - $P_\gamma$ : reconstructed from energy (subtracting MIP energy deposit) and position of LKr cluster (and position of $K^+$-$\mu^+$ vertex).

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

Downscaling of MB trigger

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

probability of $\gamma$+$\mu^+$ being misidentifie as a $\pi^+$

Not included in kinematic tails calculation because the tails sample imposes Calorimetric PID=$\mu^+$, 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:**

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

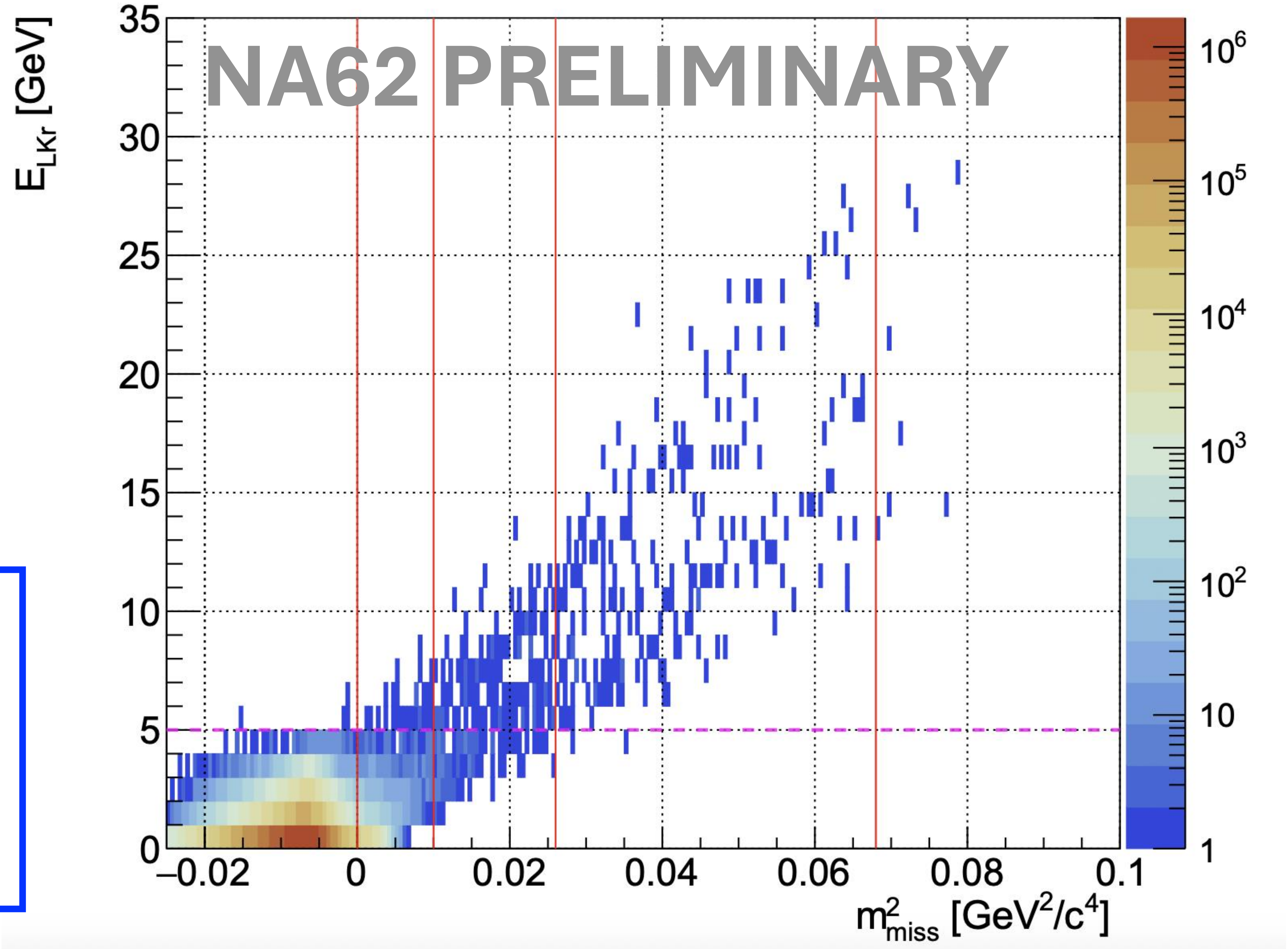
c.f. resolution $\sim 0.0025\,GeV^2/c^4$

- **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.

# 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

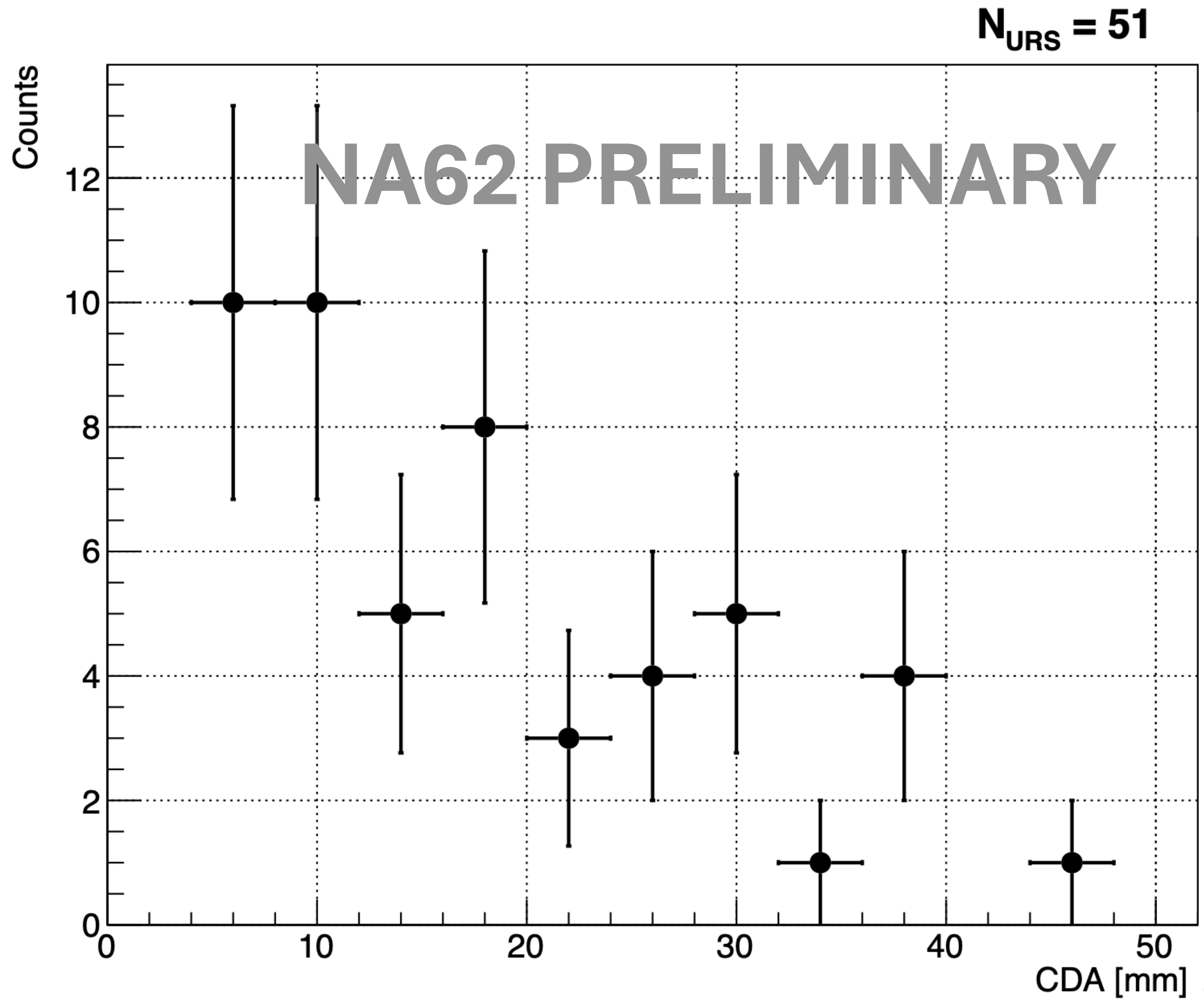
$P_{match}$ Probability to pass $K^+ - \pi^+$ matching

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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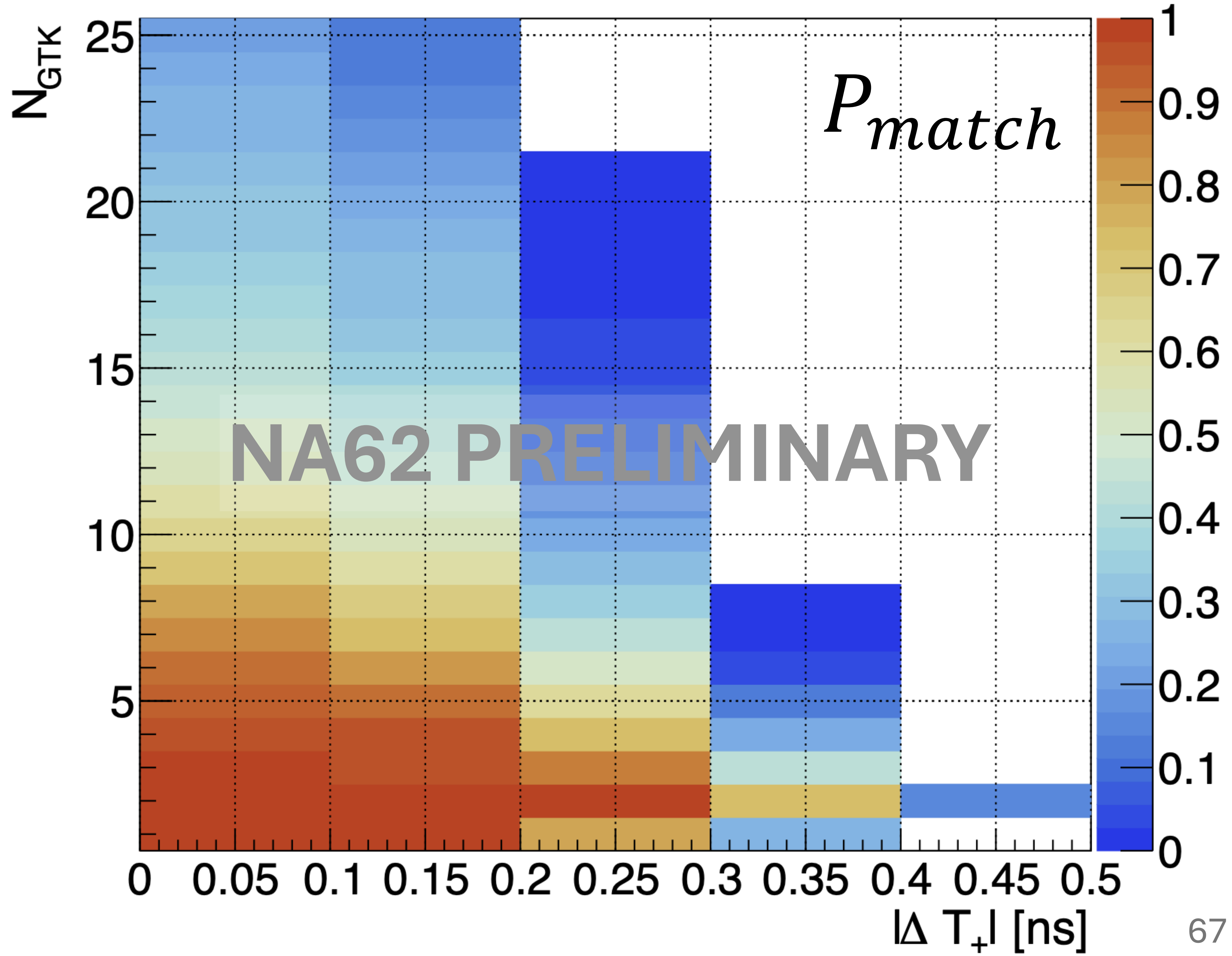
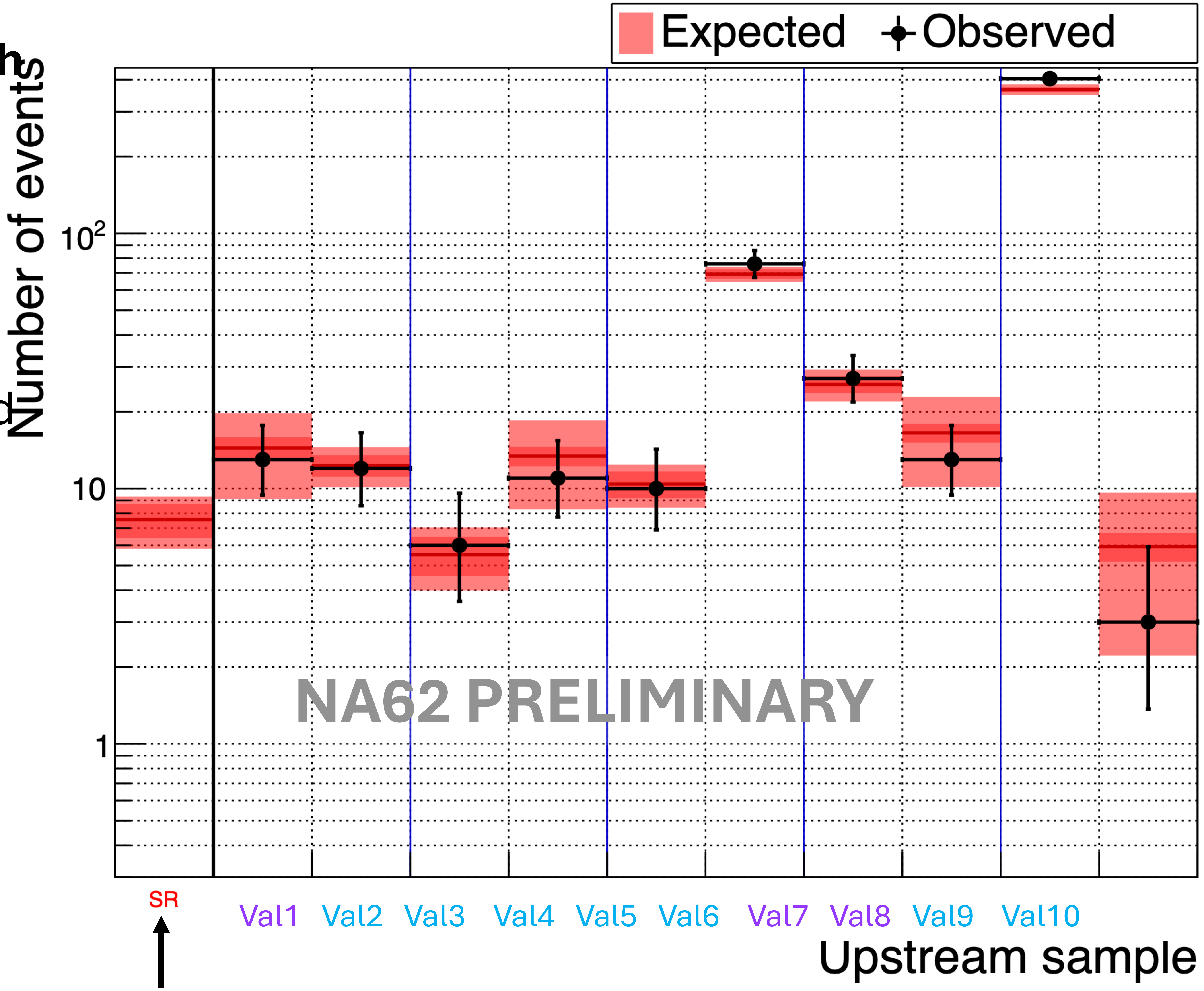


# Upstream background validation

- **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.**



Signal region

# Other backgrounds

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

Effective # of K+

Random veto & trigger efficiencies

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

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

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

Branching ratio of $K_{e4}$
(from PDG)

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

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

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

# 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]