Status and prospects of rare decay searches at NA62

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on behalf of the **NA62 Collaboration**

INFN Laboratori Nazionali di Frascati

WIFAI 2024

See Ilaria Rosa's talk on Tuesday

See Ilaria Panichi's talk tomorrow

Flavour Physics

Search for New Physics at the EW scale with sizeable coupling to SM particles via indirect effects in loops:

Experiment main goal:

$$BR(K^+ \to \pi^+ \nu \bar{\nu})$$

Search for lepton flavour and number violation, rare and forbidden decays:

e.g.:

$$K^+ \to \pi^+ \gamma\gamma$$

(PLB 850 (2024) 138513)

$$K^+ \to \pi^-(\pi^0) e^+ e^+$$

(PLB 830 (2022) 137172)

Hidden sector Physics

Search for New Physics below the EW scale (MeV-GeV) feebly-coupled to SM particles via direct detection of long-lived particles:

Dark Photon(**DP**), Axion Like Particle (**ALPs**), Dark Scalar (**S**), Heavy neutral Lepton(**N**)

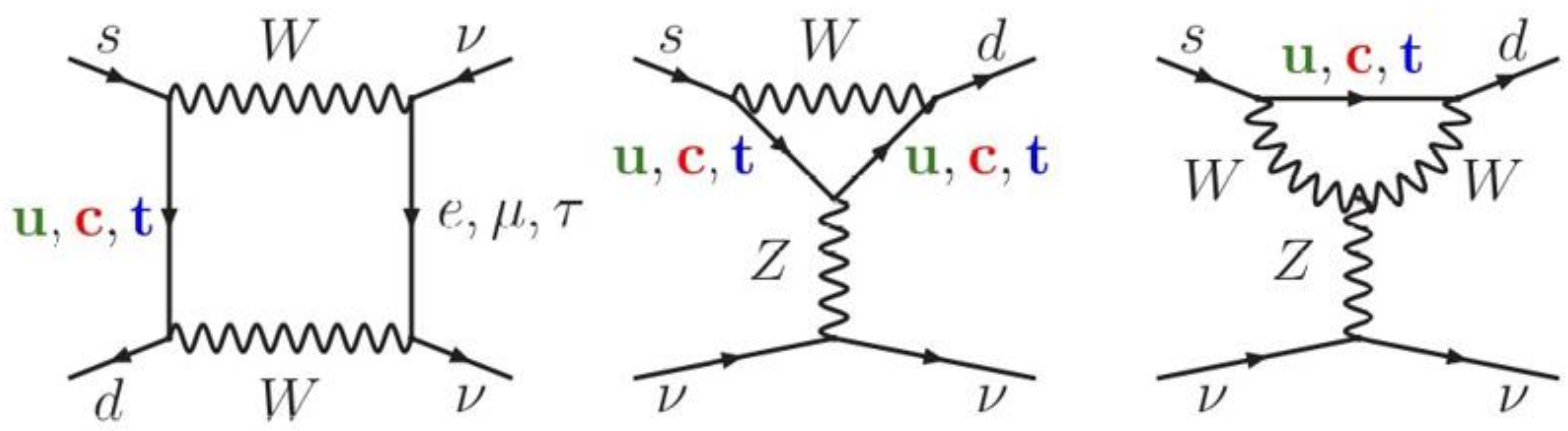
(PRL 133 (2024) 11, 111802)

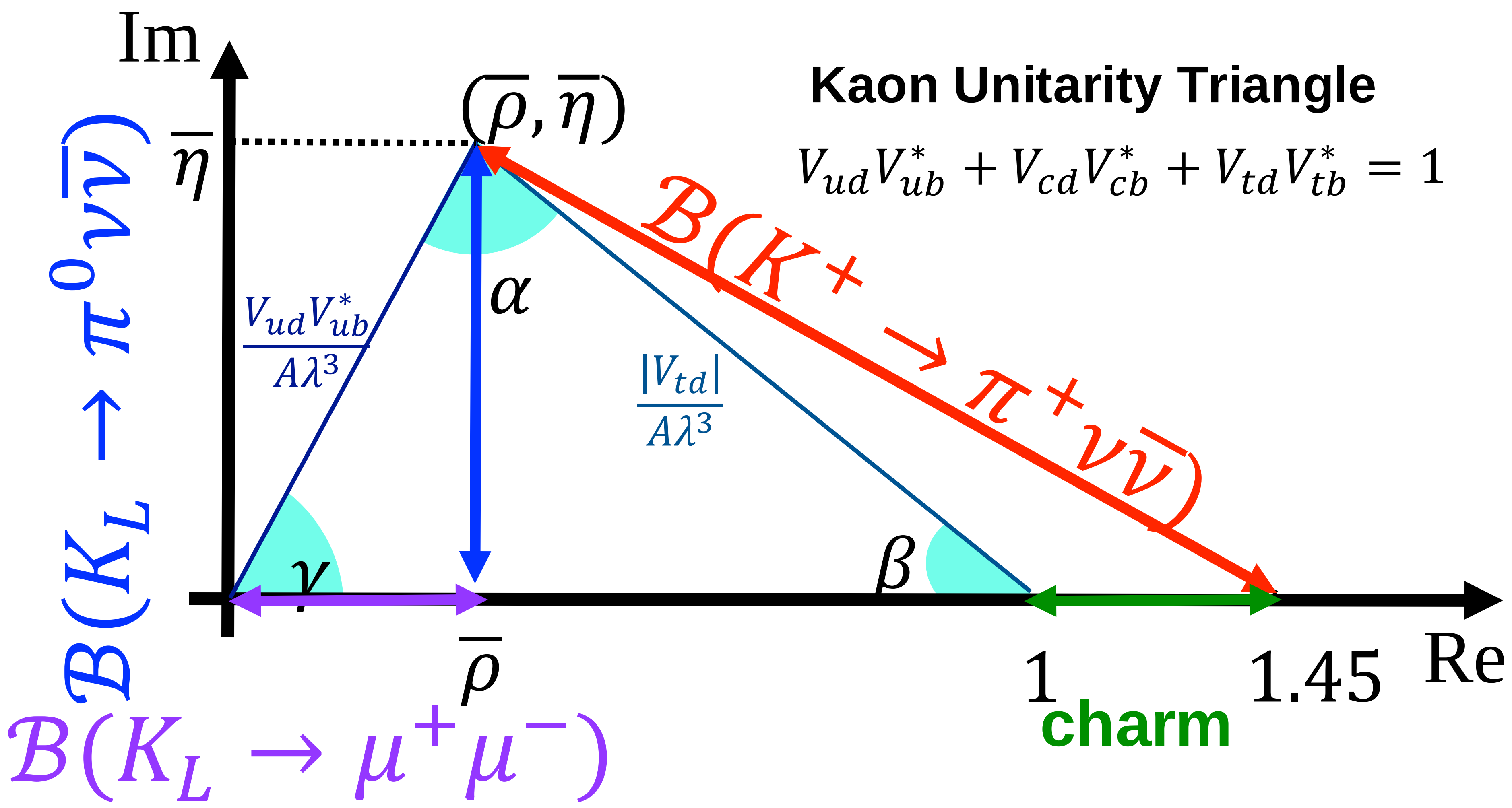
Rare Kaon Decays:
SM and Beyond

The golden mode $K^+ \to \pi^+ \nu\bar{\nu}$

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

SM: Z-penguin & box diagrams





- $\mathcal{B}(K \to \pi\nu\bar{\nu})$ **highly suppressed** in SM
  - GIM mechanism & maximum CKM suppression $s \to d$ transition: $\sim \frac{m_t^2}{m_W^2}|V_{ts}^* V_{td}|$
- 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]

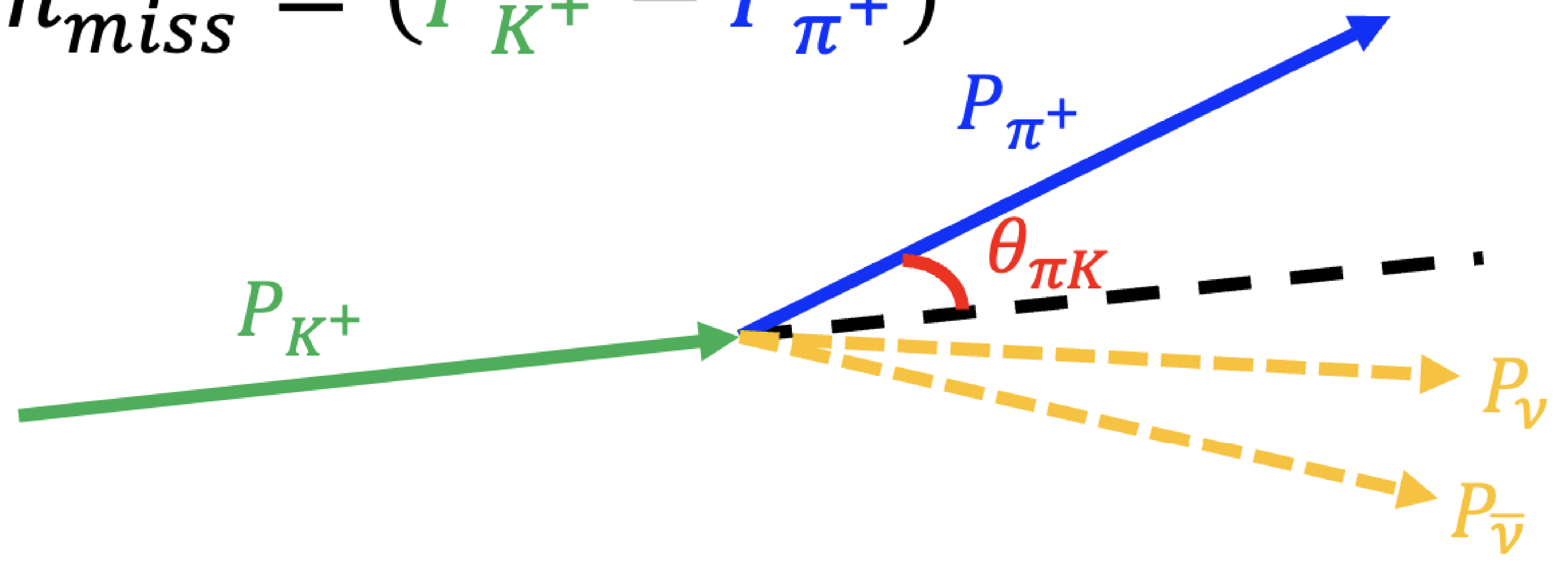
NA62 (2016–18 data): [JHEP 06 (2021) 093]
KOTO (2021 data):
[Eur.Phys.J.C 84 (2024) 4, 377]

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

NA62 Strategy: K^+ decay in flight

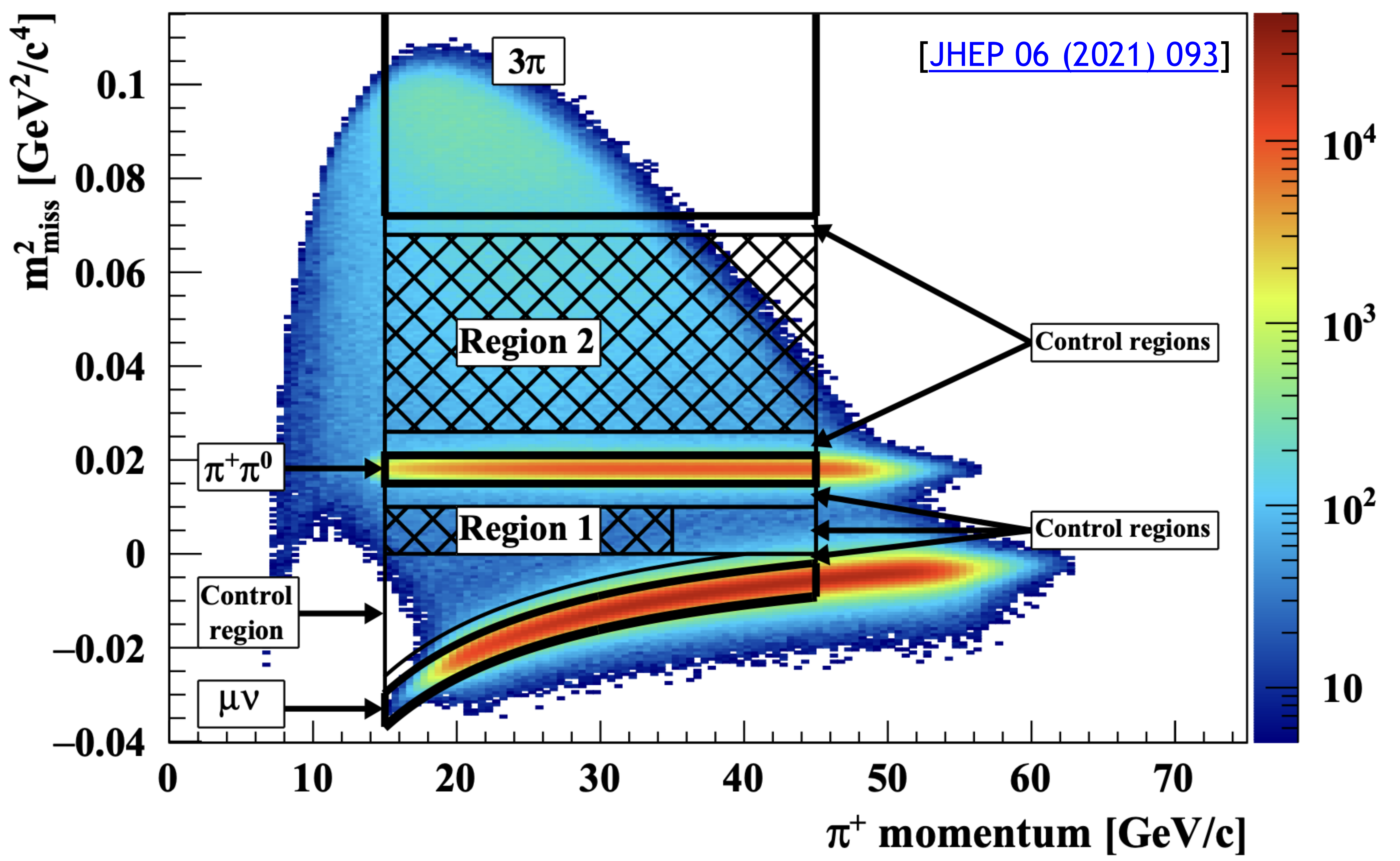
- Tag K^+ and measure momentum.
- Identify π^+ and measure momentum.
- Match K^+ and π^+ in time & form vertex.
  - Determine $m^2_{miss} = (P_K - P_\pi)^2$
- Reject **any** additional activity.

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



NA62 Performance Keystones:

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



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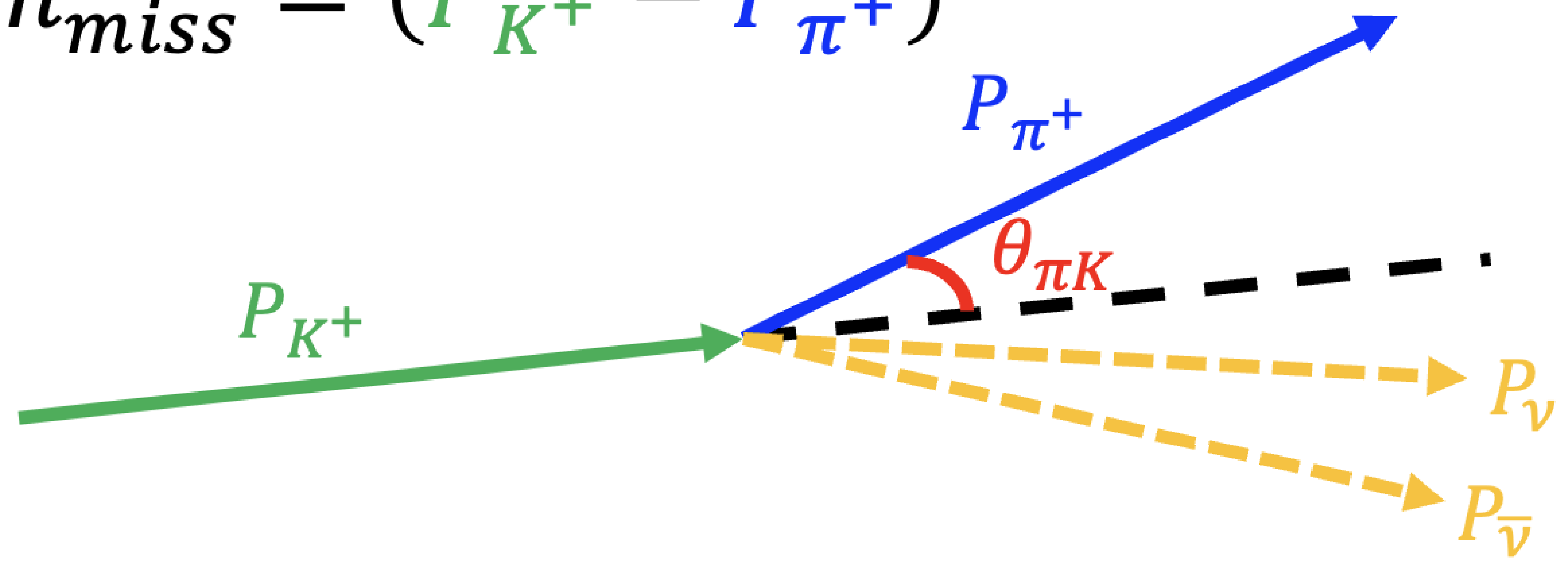

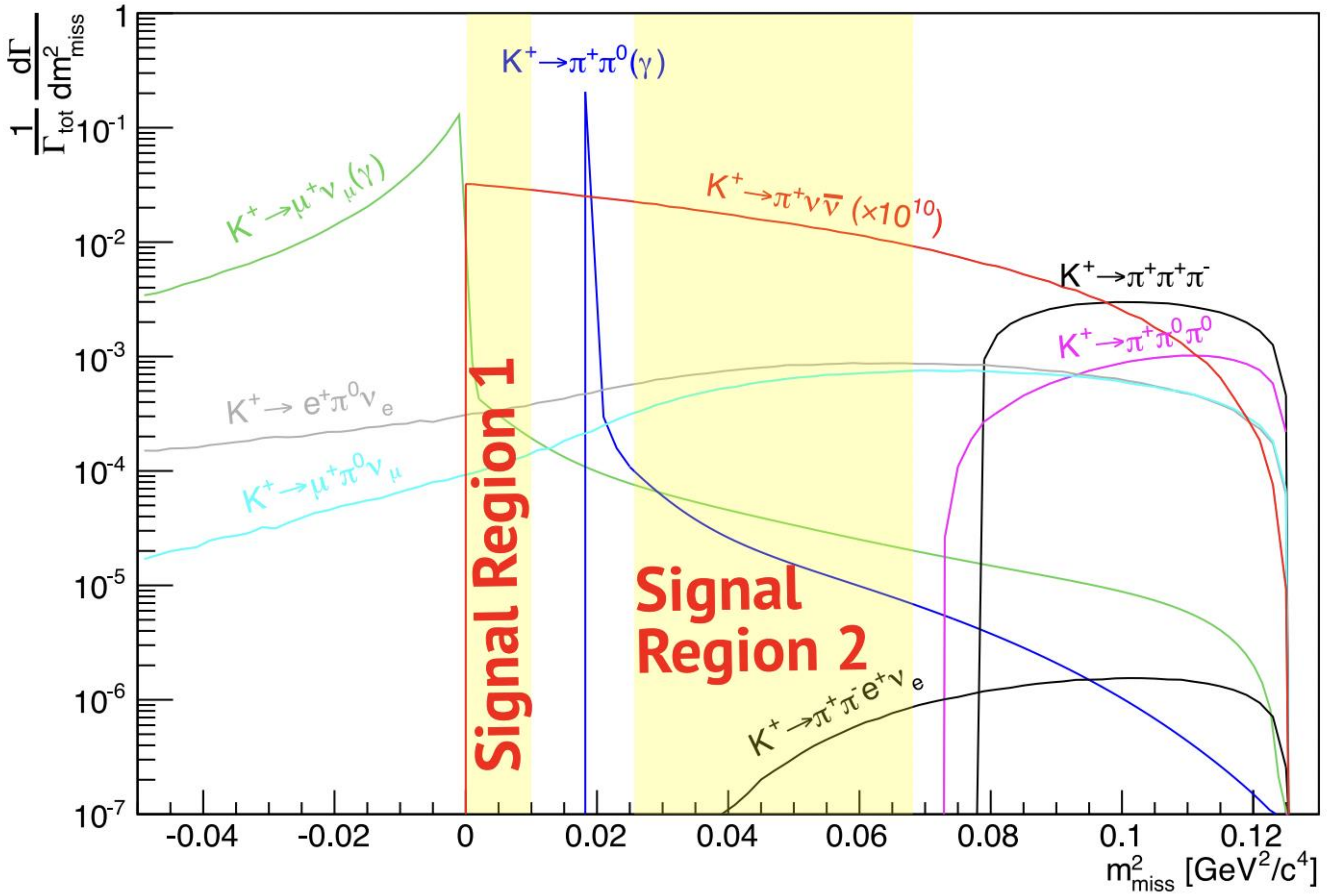

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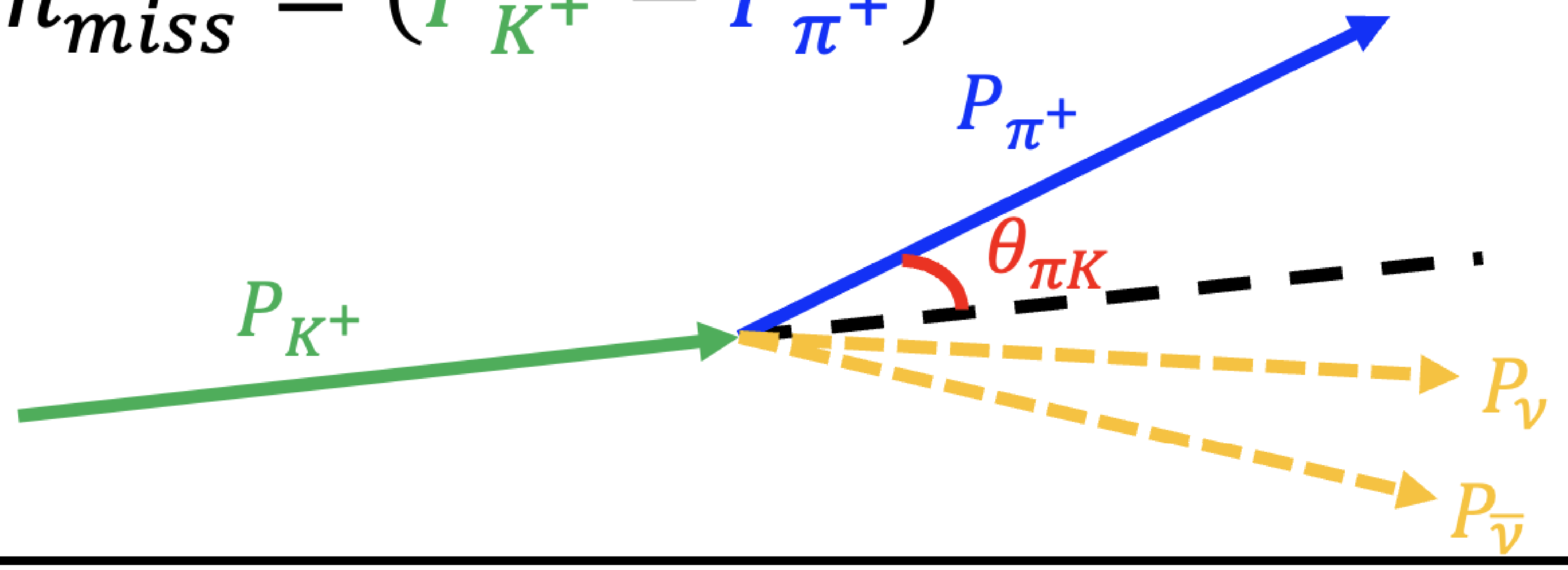

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Triggers & selection:

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

Common conditions

+ add more conditions

- **Normalisation** $K^+ \to \pi^+\pi^0$: 1 downstream track (only); identified as π^+; $K^+ - \pi^+$ matching (space & time); upstream vetos.

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

NA62 Strategy: K^+ decay in flight

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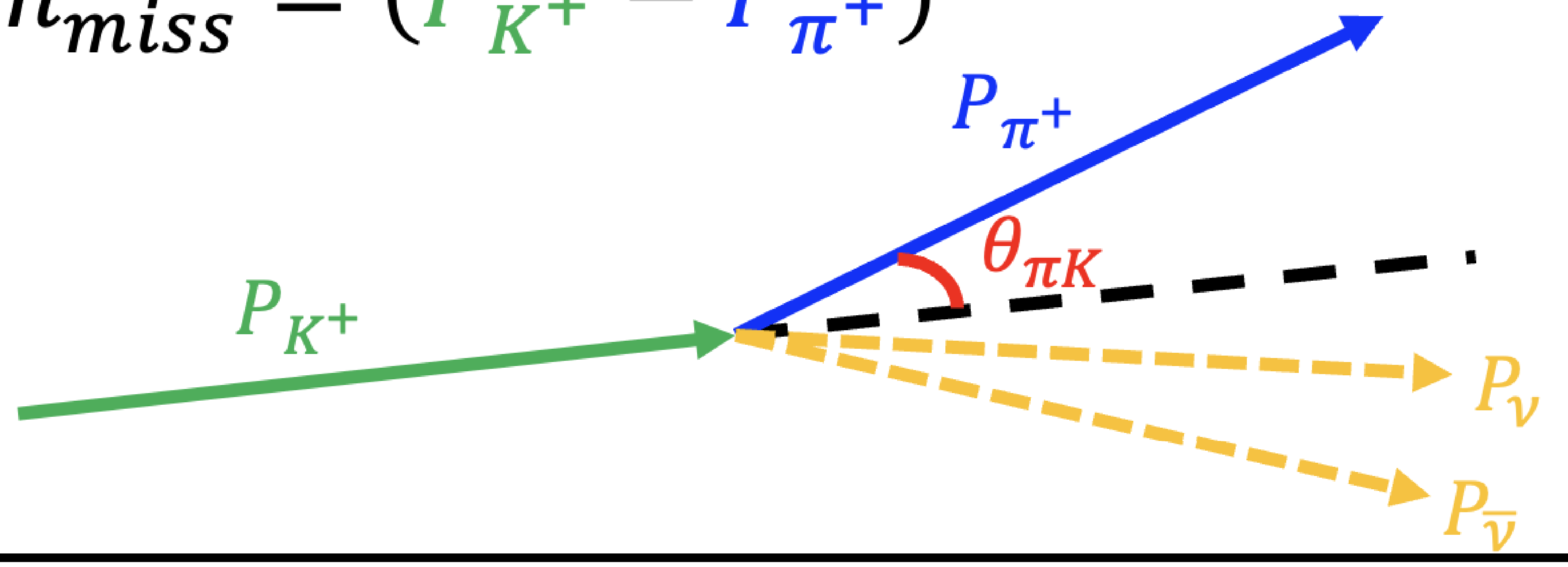

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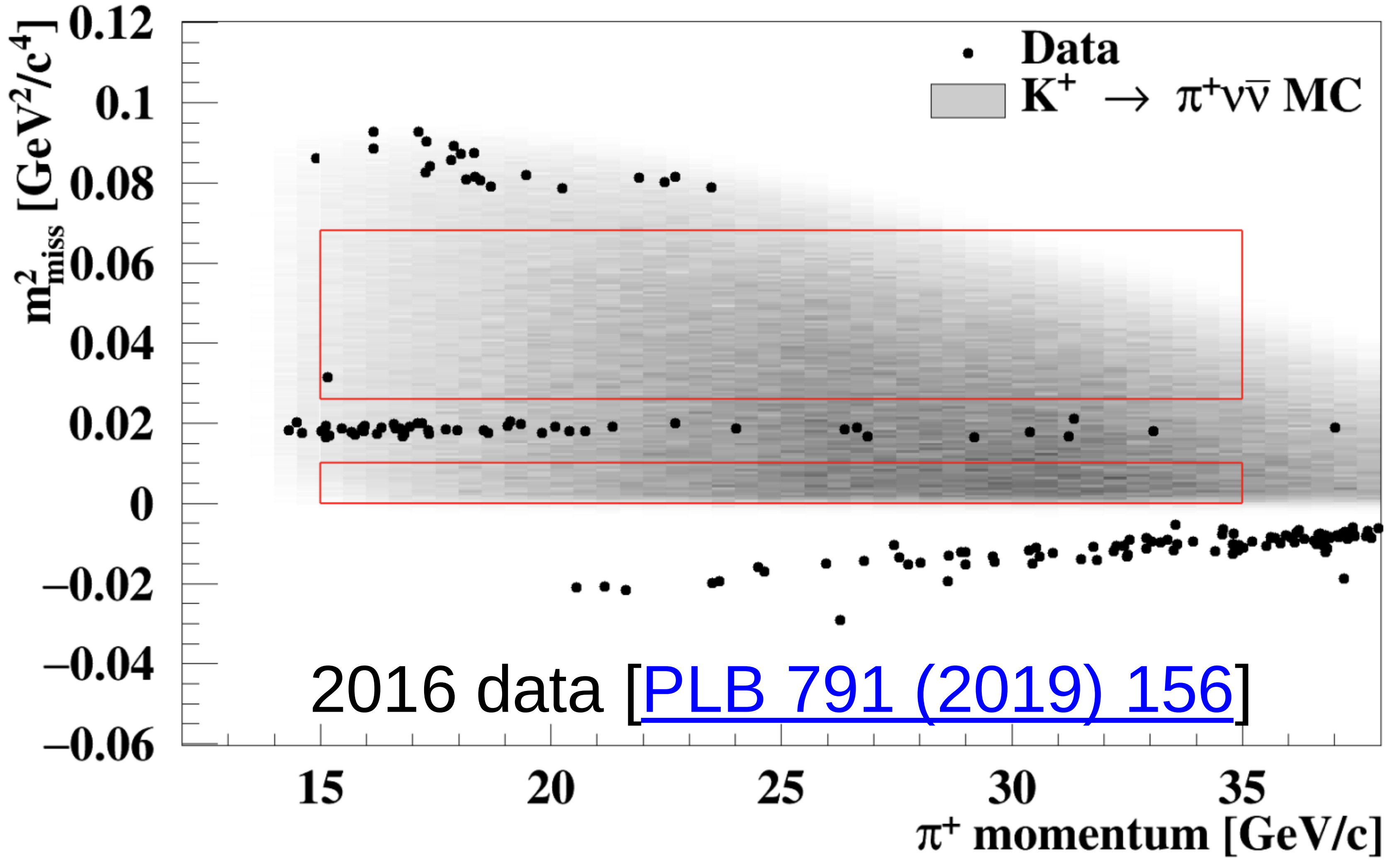
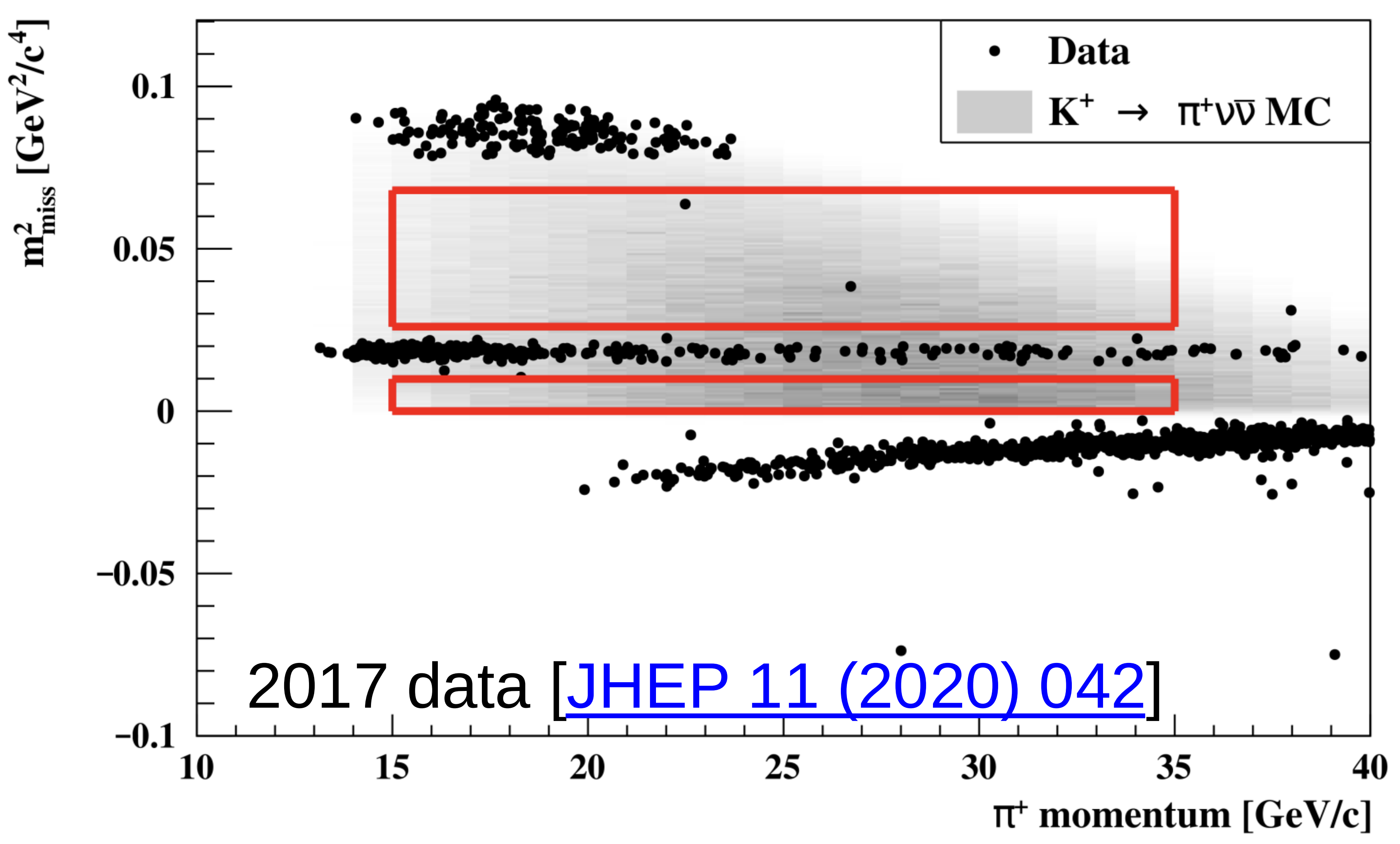
Common conditions

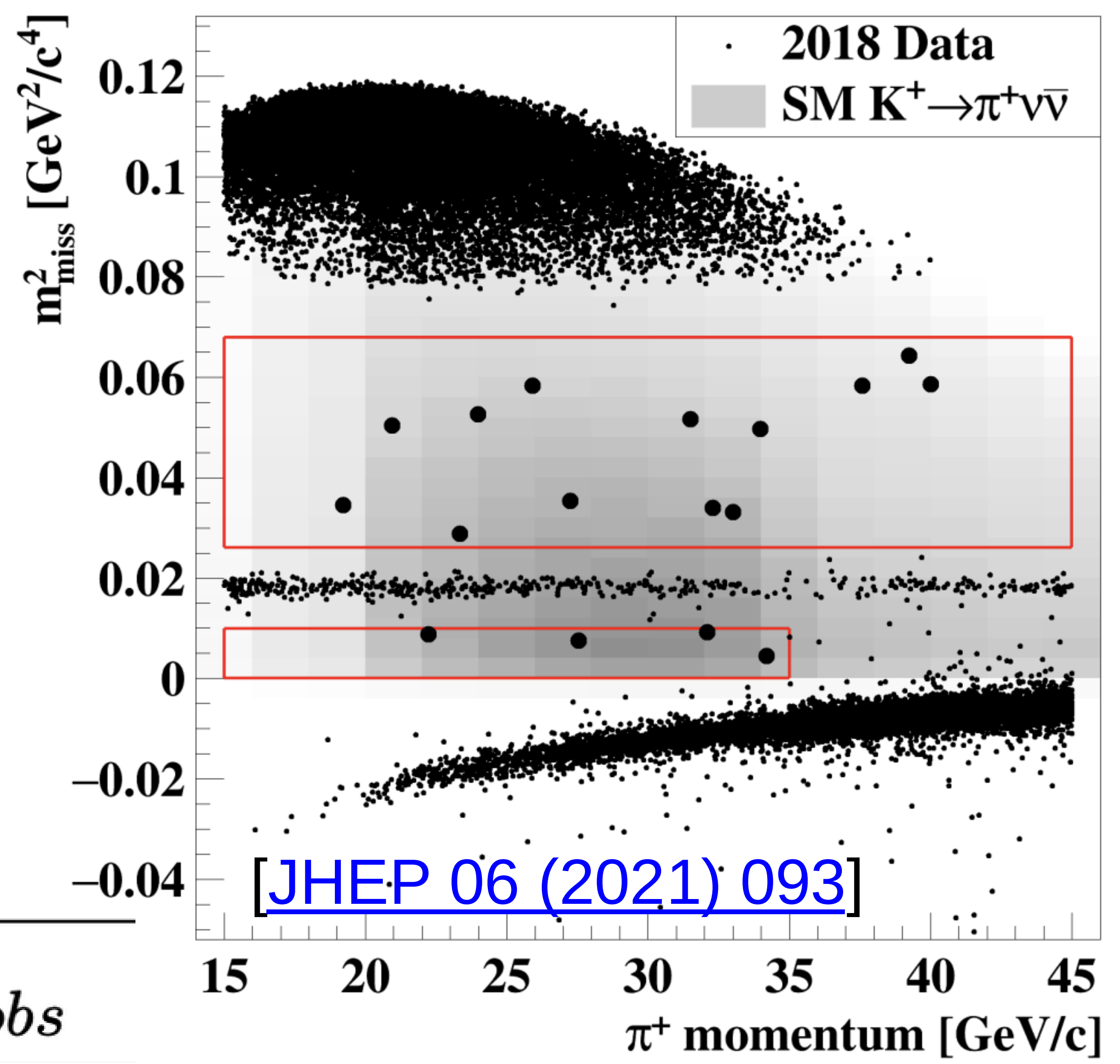
+ add more conditions

- **Signal** $K^+ \to \pi^+\nu\bar{\nu}$ candidates: same as normalisation selection + full photon and detector multiplicity cuts (reject all extra activity).

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







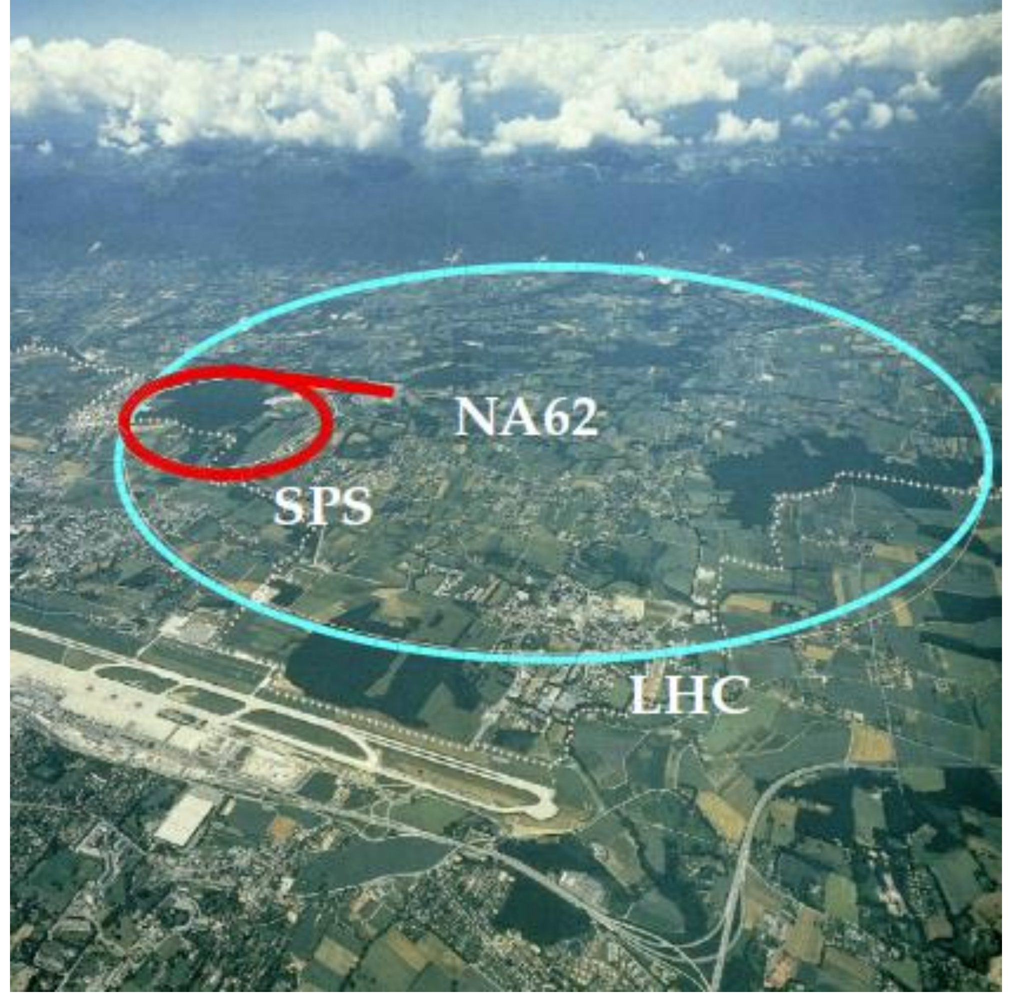
Data-taking year	[Reference]	N_{bg}	$N_{\pi\nu\bar{\nu}}^{SM,exp}$	N_{obs}
2016	[PLB 791 (2019) 156]	$0.152^{+0.093}_{-0.035}$	0.267 ± 0.020	1
2017	[JHEP 11 (2020) 042]	1.46 ± 0.33	2.16 ± 0.13	2
2018	[JHEP 06 (2021) 093]	$5.42^{+0.99}_{-0.75}$	7.58 ± 0.40	17
2016–18	[JHEP 06 (2021) 093]	$7.03^{+1.05}_{-0.82}$	10.01 ± 0.42	20

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

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



The NA62 K^+ factory at the CERN

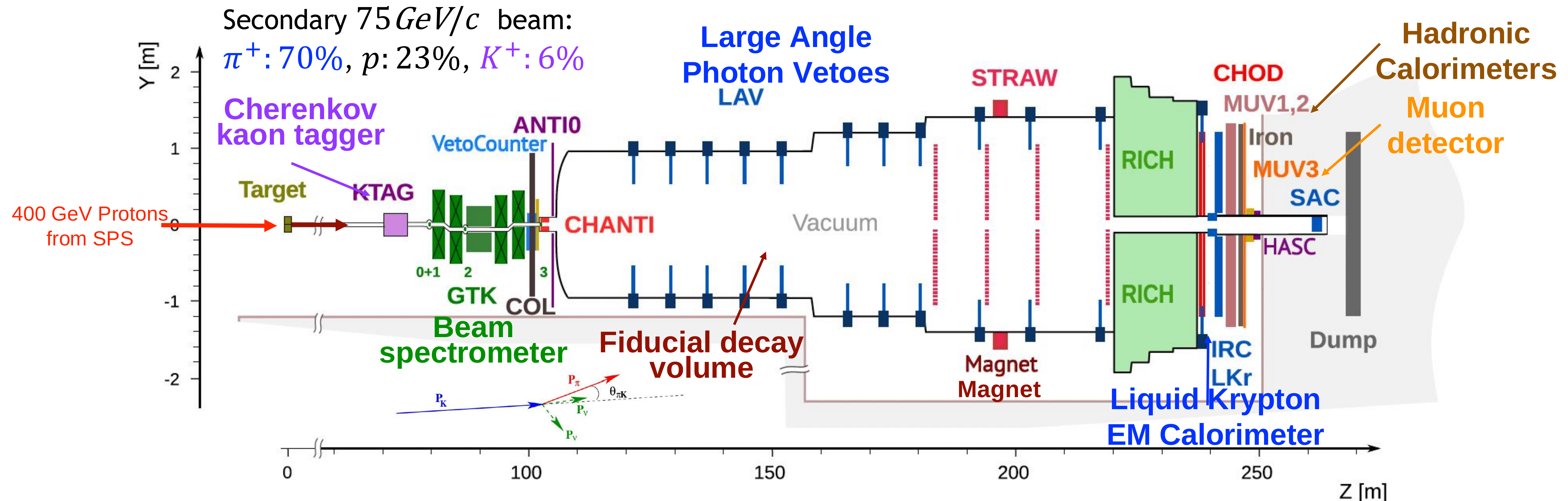
NA62 @ CERN North Area, exploits a 400 GeV/c primary proton beam from the SPS: 75 GeV/c unseparated secondary hadron beam: π^+(70%), K^+ (6%), p (24%)

2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	
			LS2 (upgrades)		this result					LS3

[JINST 12 (2017) 05, P05025]

NA62 beamline & detector

See Adam's talk yesterday on the KTAG



Intensity in 2021-2022 increased by~ 35% with respect to 2018 [450 → 600 MHz]

Upstream particle

KTAG: Differential Cherenkov for K⁺ ID
GTK: Si pixel tracker
CHANTI: Anti-counter for inelastic Interactions

+ new additions since LS2:
VetoCounter, ANTI0

Decay region detectors (π^+)

STRAW: Track momentum spectrometer
CHOD: Scintillator hodoscope
RICH: For $\pi/\mu/e$ ID
LKR/MUV1/2: Calorimetric systems

Downstream Vetos

LAV/IRC/SAC: photons
MUV3: muons
HASC


Mid 2018 - installed TCX Collimator
Much improved shielding - blocking almost all upstream decay paths.
Sketch only
TCX Collimator
MNP33
RICH
Bend6
Bend4A
Bend4
Bend5
TRIM5
GTK3
Vacuum Tank
Fake vertex
GTK2
π^+
γ
K^+
γ
KTAG
GTK1
Scraper
CHANTI
Scattering at STRAW1
STRAWs
y
z
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
VC gives a factor 2
rejection on the
upstream bkg
TCX Collimator
MNP33
RICH
Bend6
Bend4A
Bend4
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TRIM5
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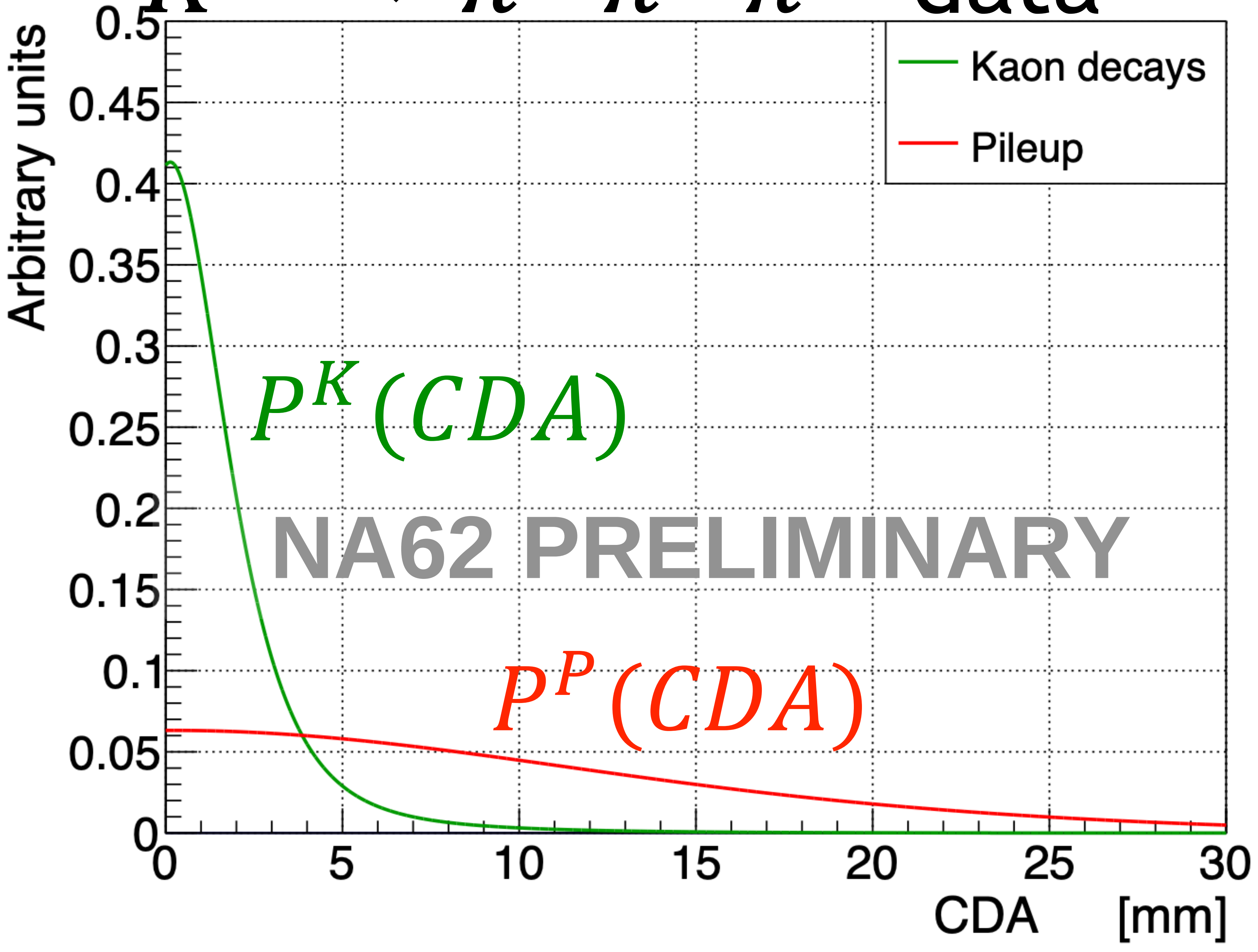
Bayesian classifier for $K^+ - \pi^+$ matching

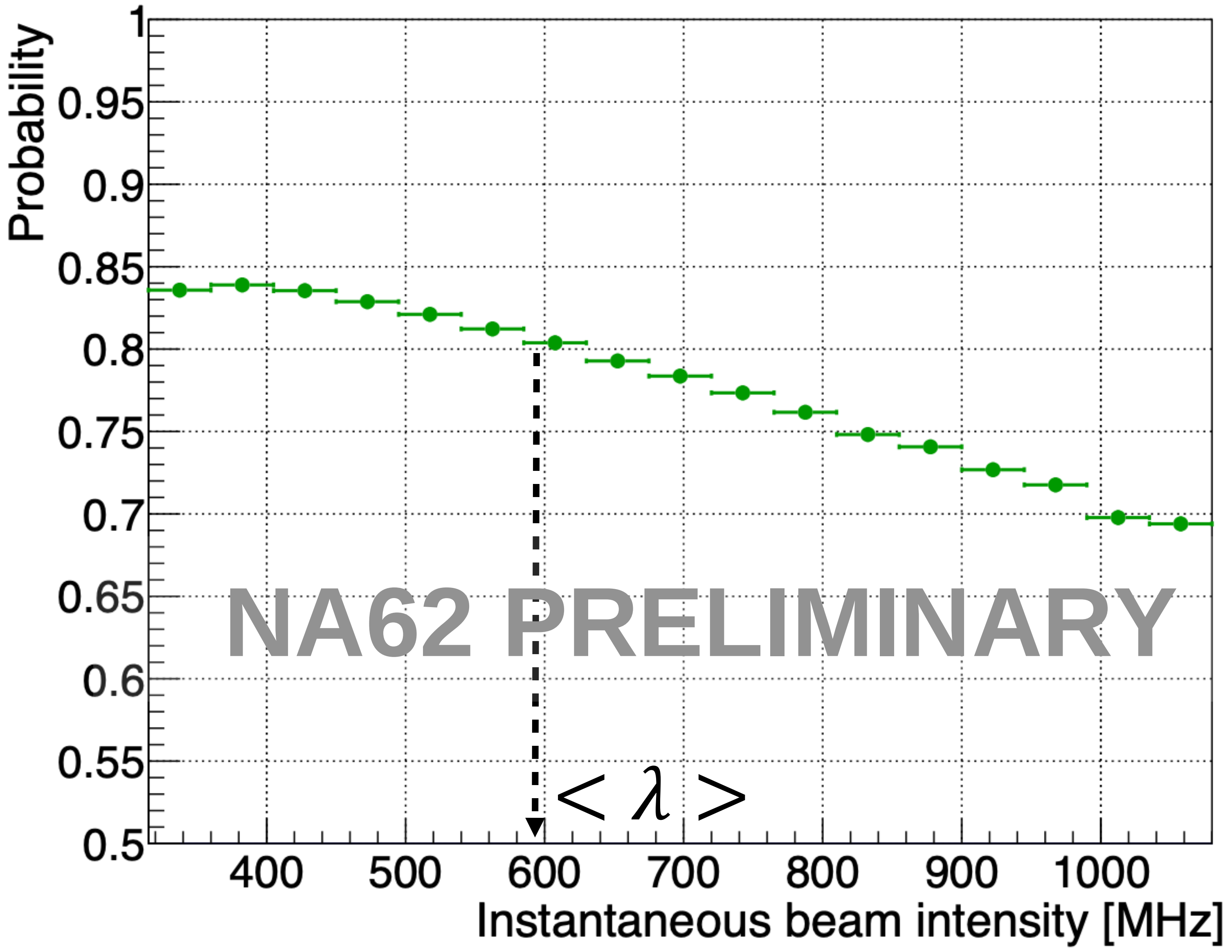
Example of selection update

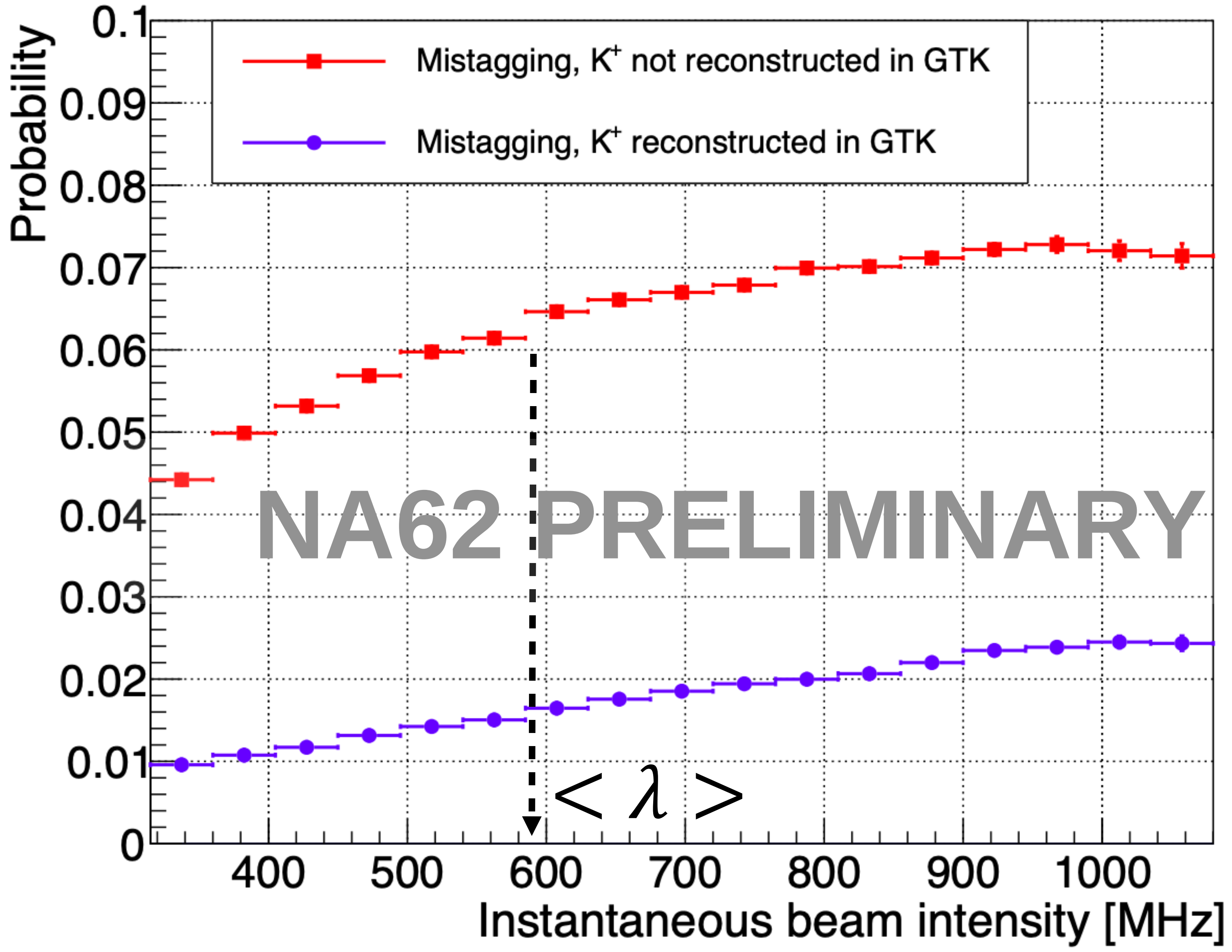
- **Inputs:** spatial (CDA) & time (ΔT_+) matching, intensity/pileup (N_{GTK}) [prior]
  - Models for PDFs/Prior from $K^+ \to \pi^+\pi^+\pi^-$ data



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

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





- Efficiency improved (+10%) for the same mistagging probabilities

Signal sensitivity results

- momentum range $p \in [15{,}45]\, GeV/c$
- (5 GeV/c) bins of momentum p_i

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

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

$N_{\pi\pi}$	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	$(0.84 \pm 0.03) \times 10^{-11}$

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

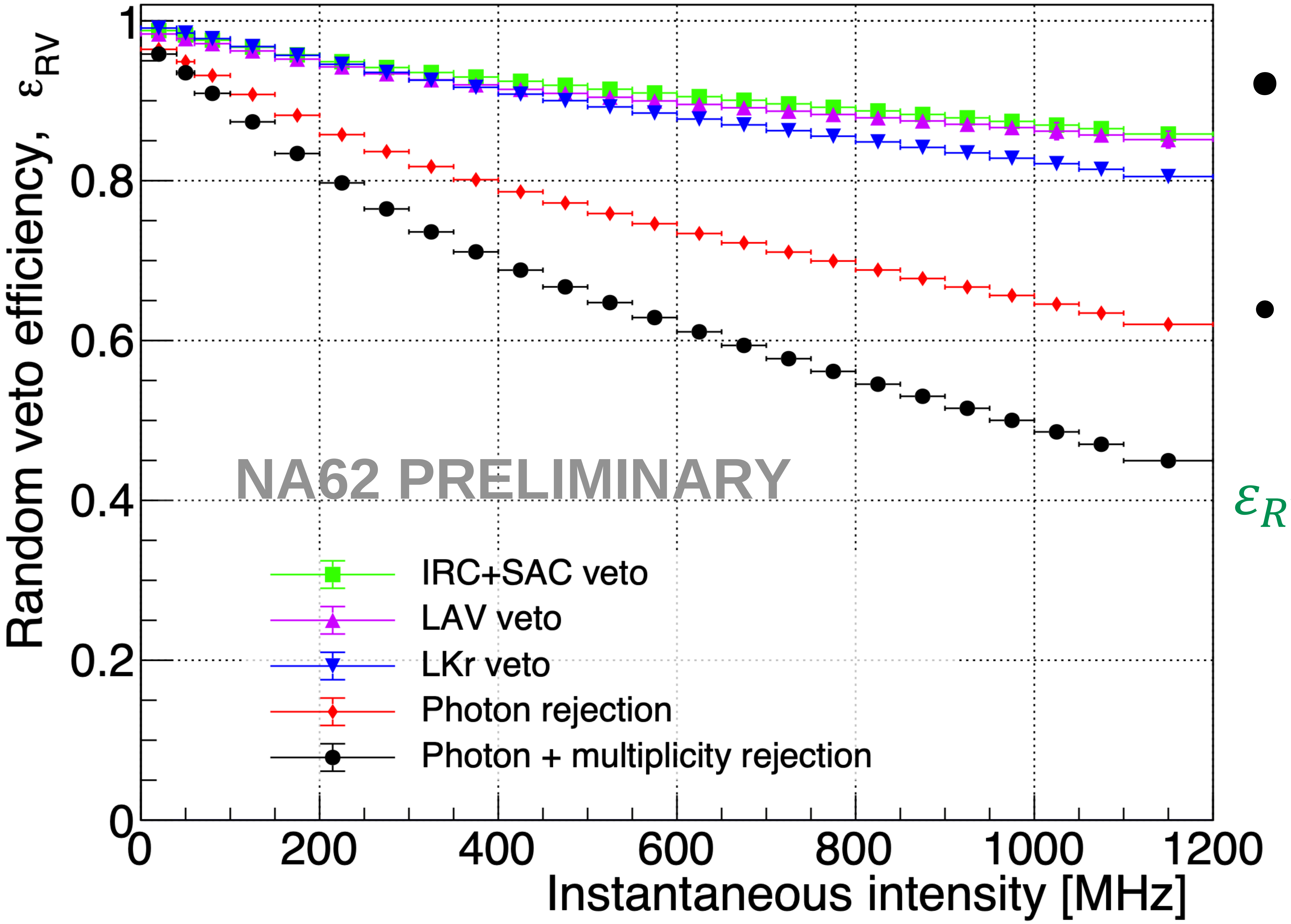
Double expected signal by including 21–22 data.

- $\mathcal{B}_{SES}$: Branching ratio corresponding to expectation of 1 event
- Significant improvement in SES uncertainty: old: 6.3% —> new: 3.5%
- Due to trigger efficiency cancellations and improved procedures for evaluation of acceptances and ε_{RV}

Signal sensitivity results

- momentum range $p \in [15,45]\,GeV/c$
- (5 GeV/c) bins of momentum p_i

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



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

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

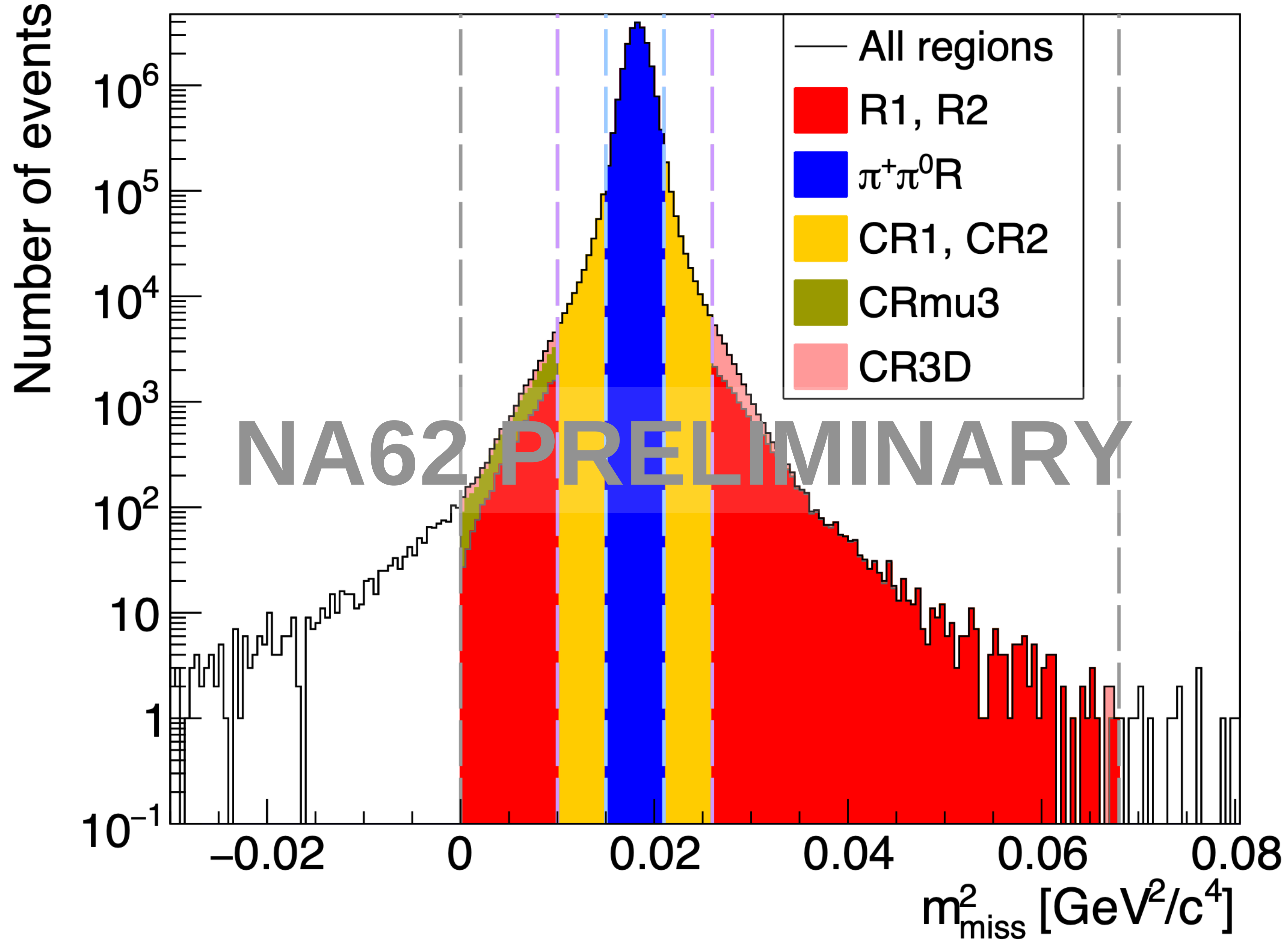
$$\varepsilon_{RV}(old, \overline{\lambda_{2018}} \approx 400\,MHz) = (66 \pm 1)\%$$

Backgrounds from kinematic tails

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

$K^+ \to \pi^+\pi^0$

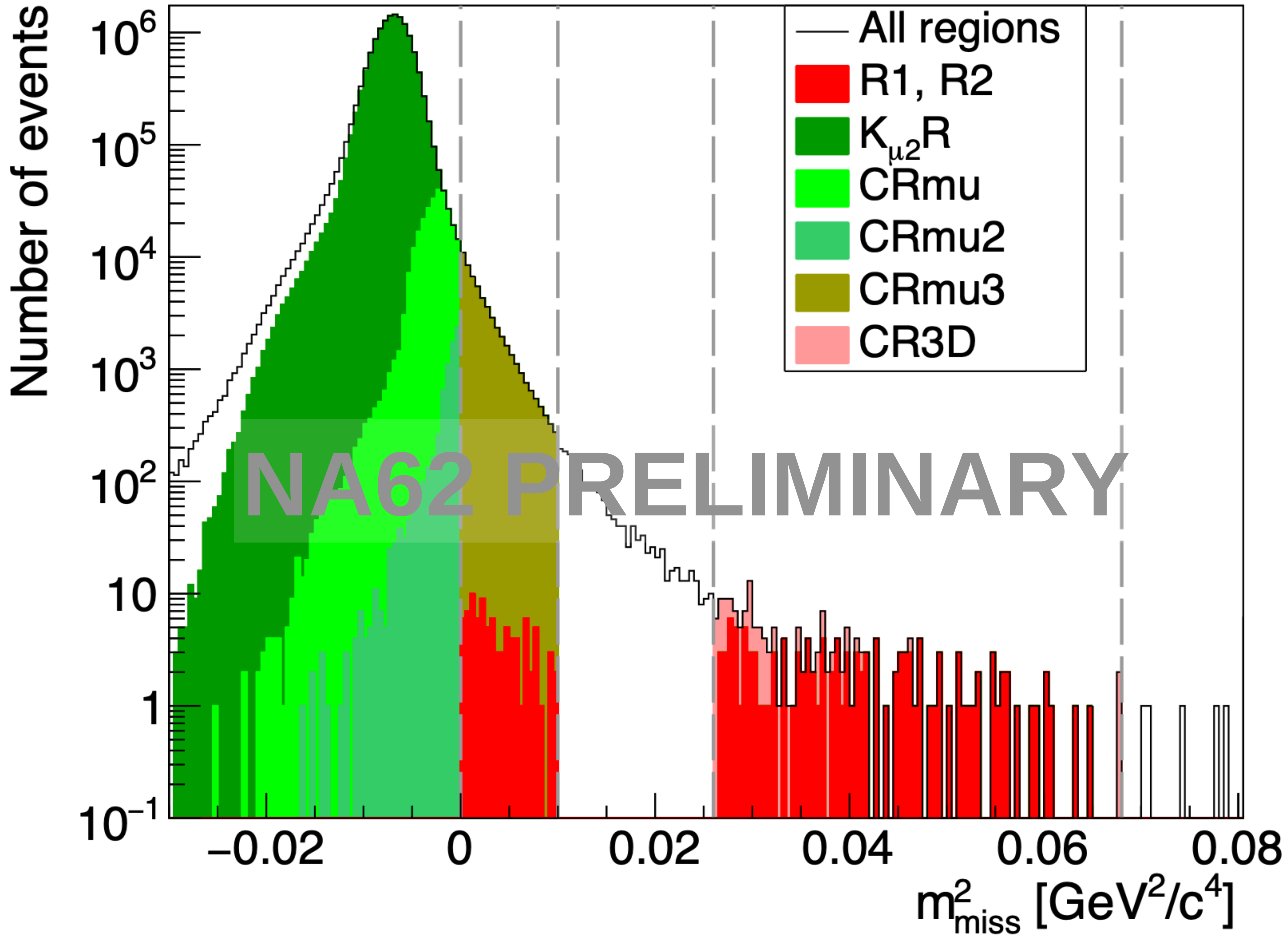
control sample of $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ and 2 photons detected in LKr:



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

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

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

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

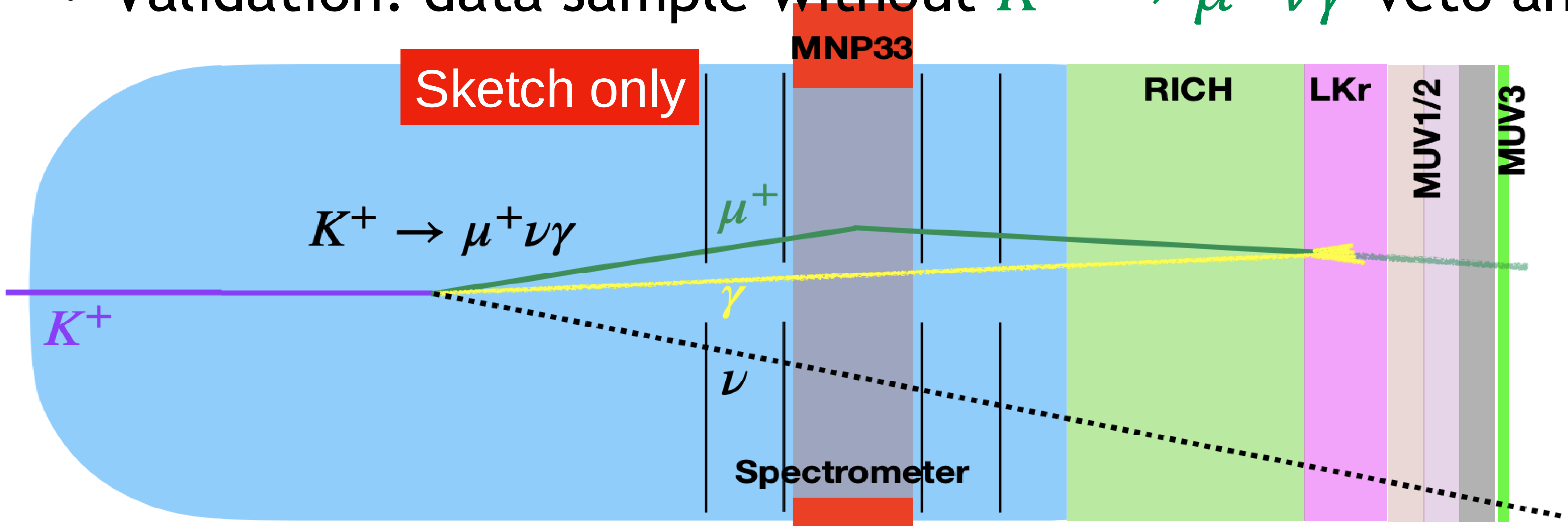
$K^+ \to \pi^+\pi^+\pi^-$

- Use MC to measure f_{tail}:

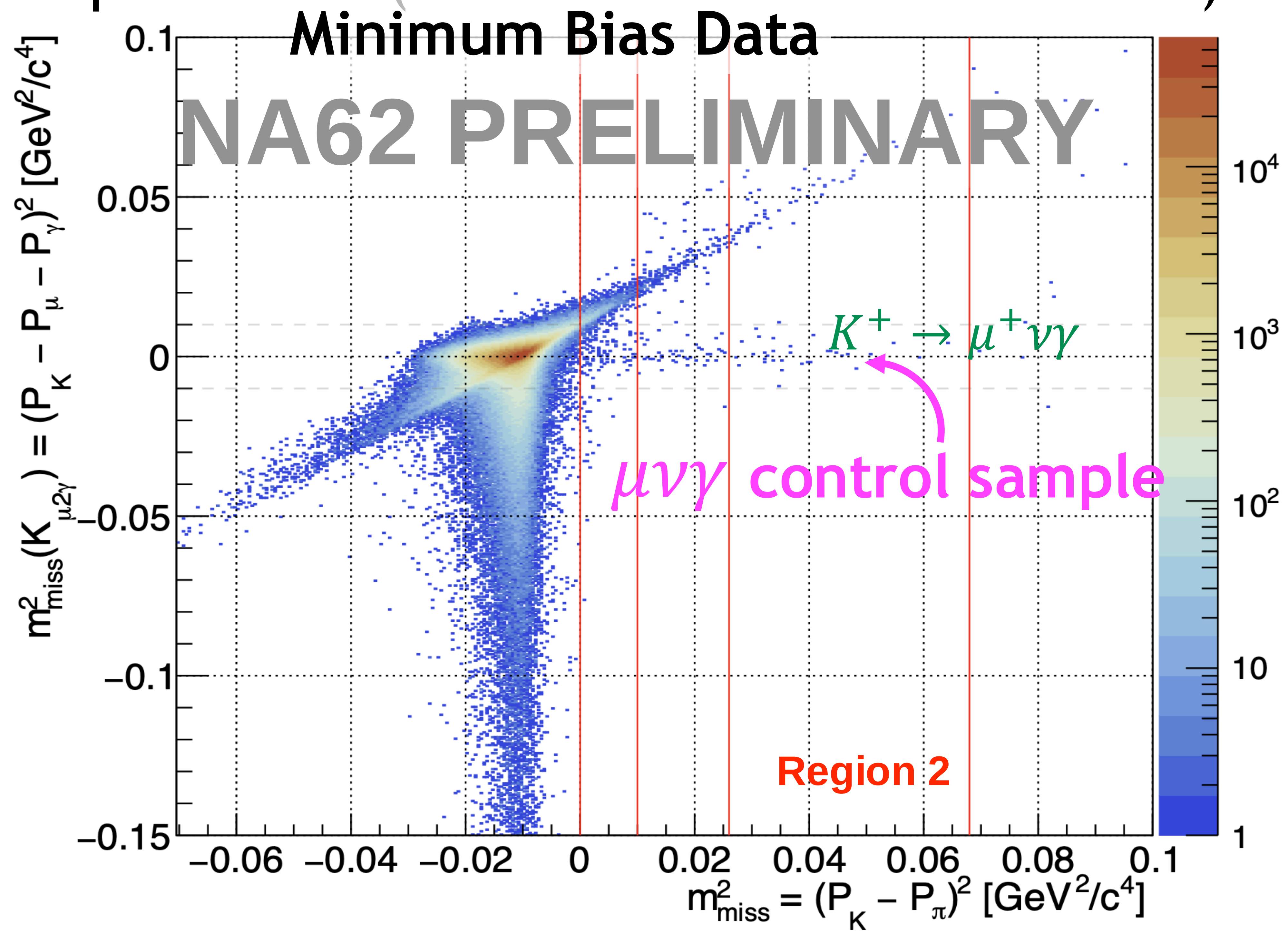
$N_{bg}(K^+ \to \pi^+\pi^+\pi^-) = 0.11 \pm 0.03$

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

- $K^+ \to \pi^+\pi^0\gamma$: **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.



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	$11.0^{+2.1}_{-1.9}$

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

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

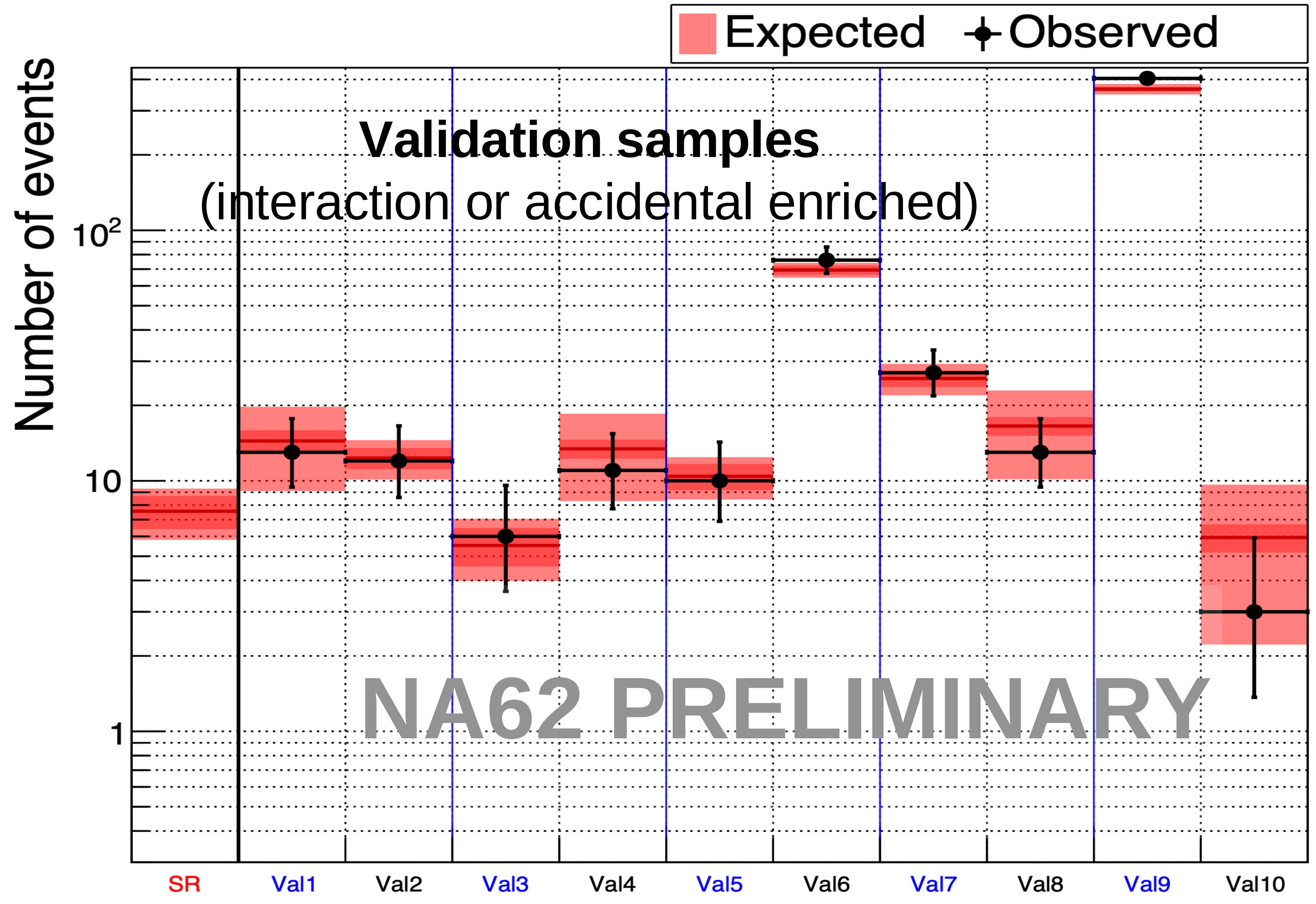
Upstream background calculation:

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

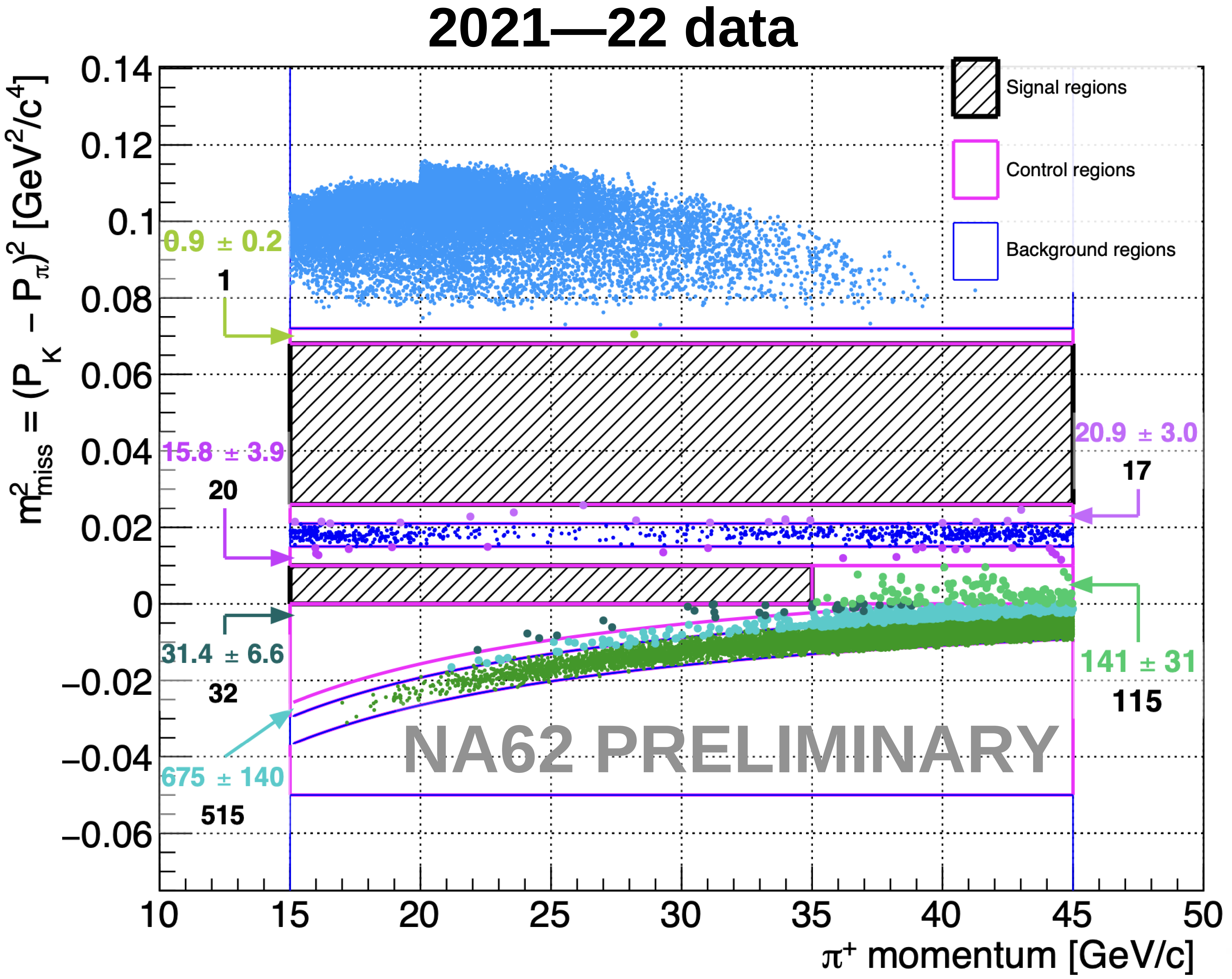
N Upstream Reference Sample: signal selection but invert CDA cut (CDA>4mm)

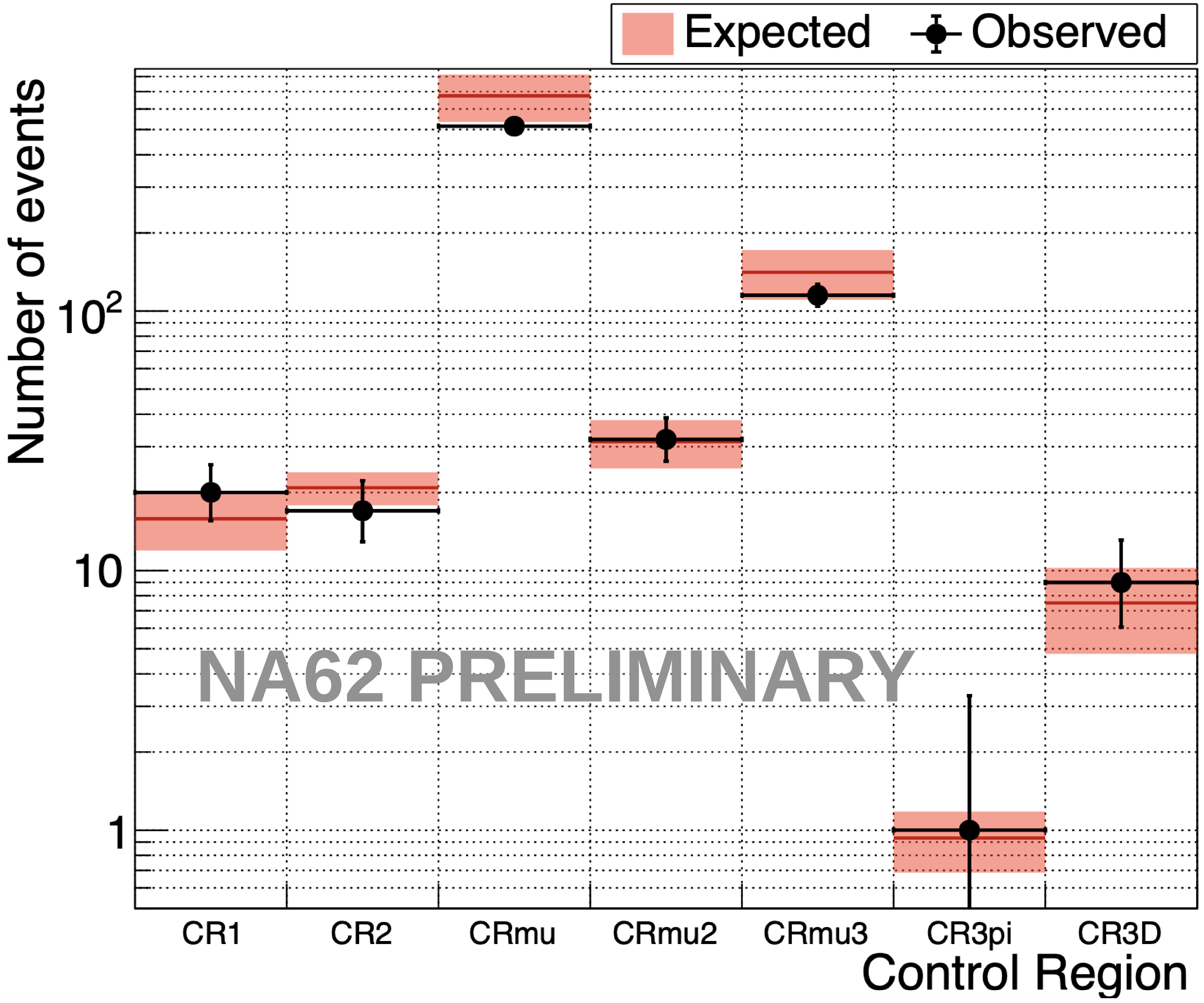
f_{cda} Scaling factor : bad cda —> good cda

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



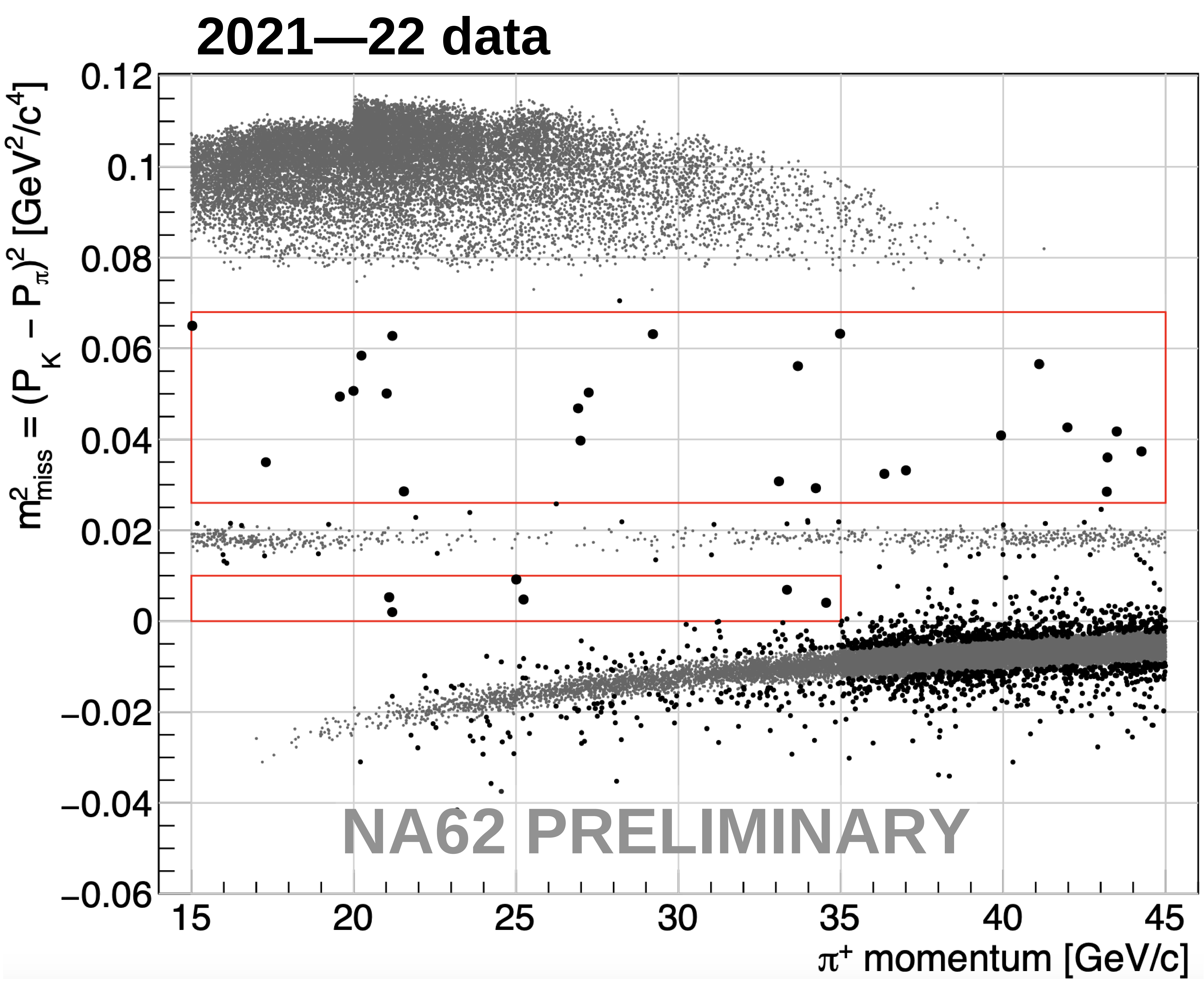
Control regions: 2021—22 Data



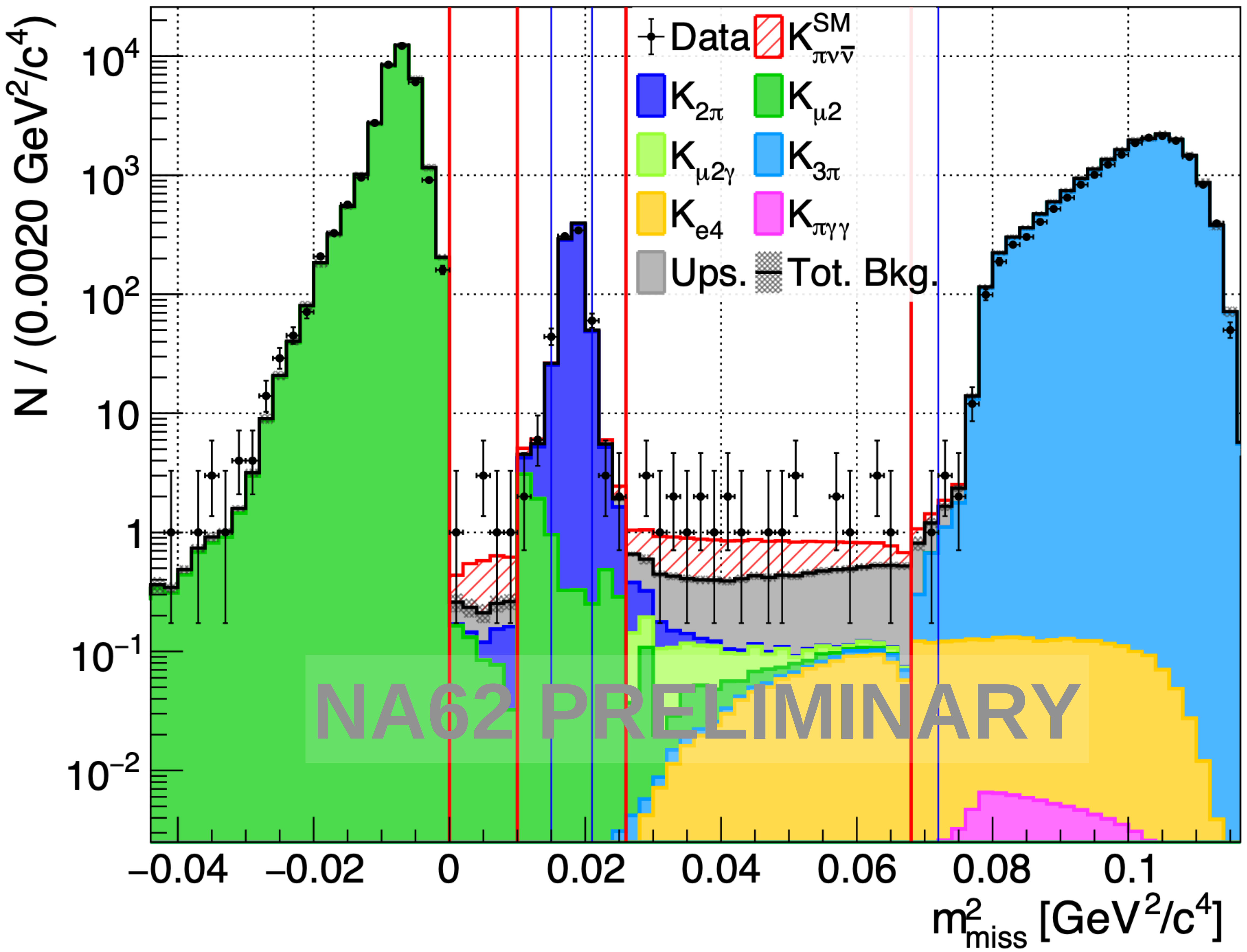


- Good agreement in control regions validates background expectations.

Signal regions: 2021—22 Data



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



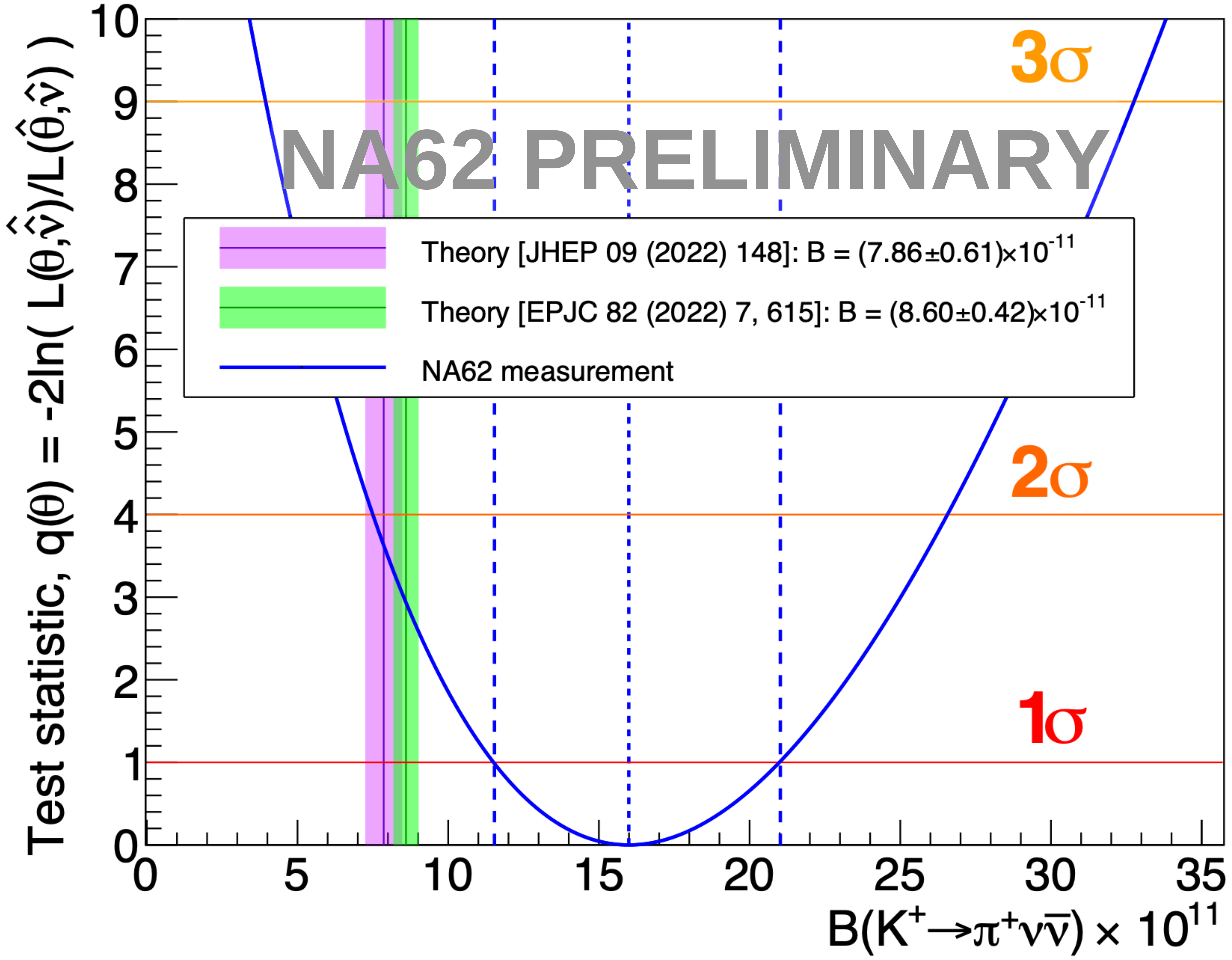
Expected SM signal: $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

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

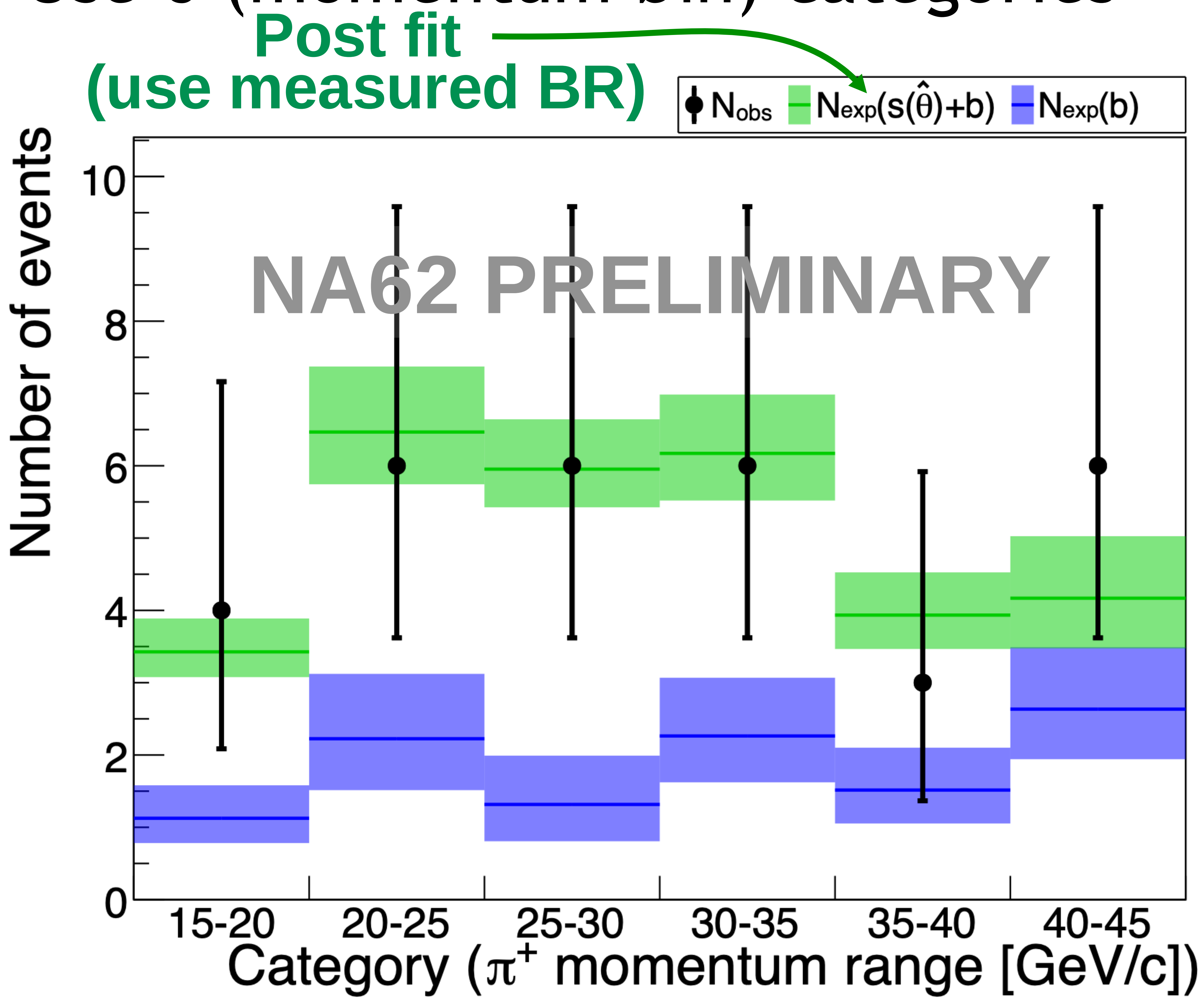
Observed: $N_{obs} = 31$

Results: 2021—22 Data

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



- Use 6 (momentum bin) categories

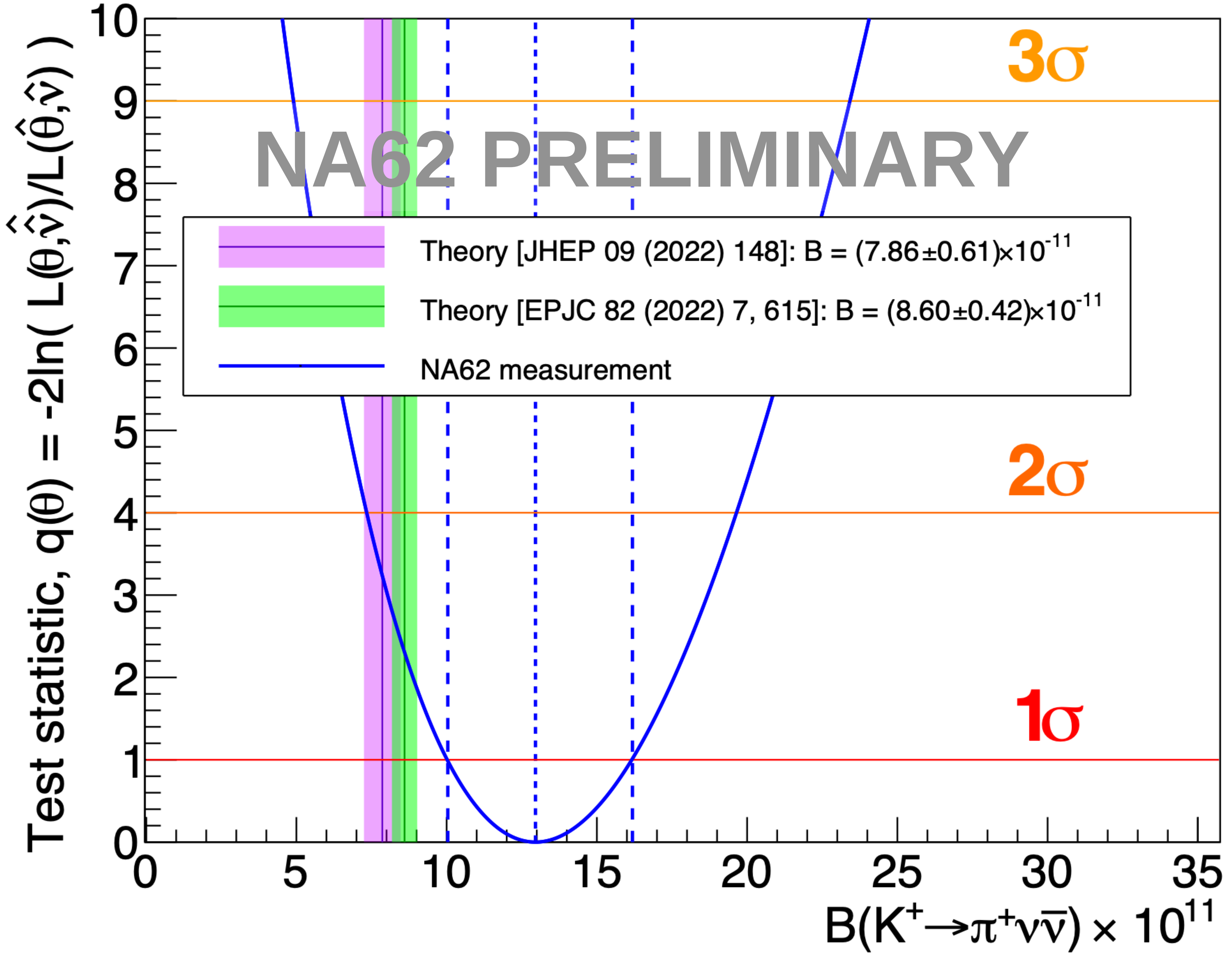


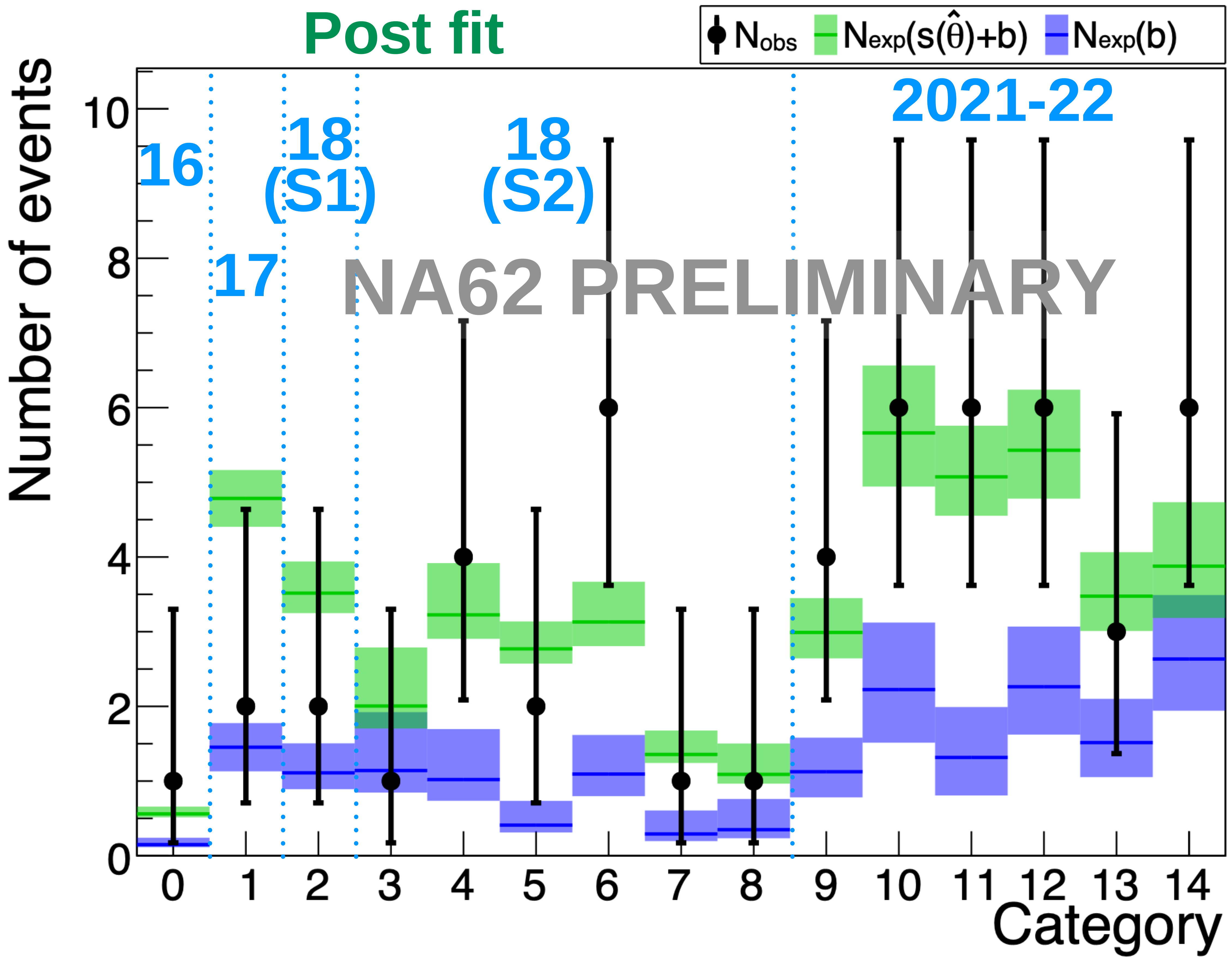
$$\mathcal{B}_{21-22}(K^+ \to \pi^+\nu\bar{\nu}) = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11} = \left(16.0\ (^{+4.8}_{-4.2})_{stat}\ (^{+1.4}_{-1.3})_{syst}\right) \times 10^{-11}$$

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 $Z > 5$**





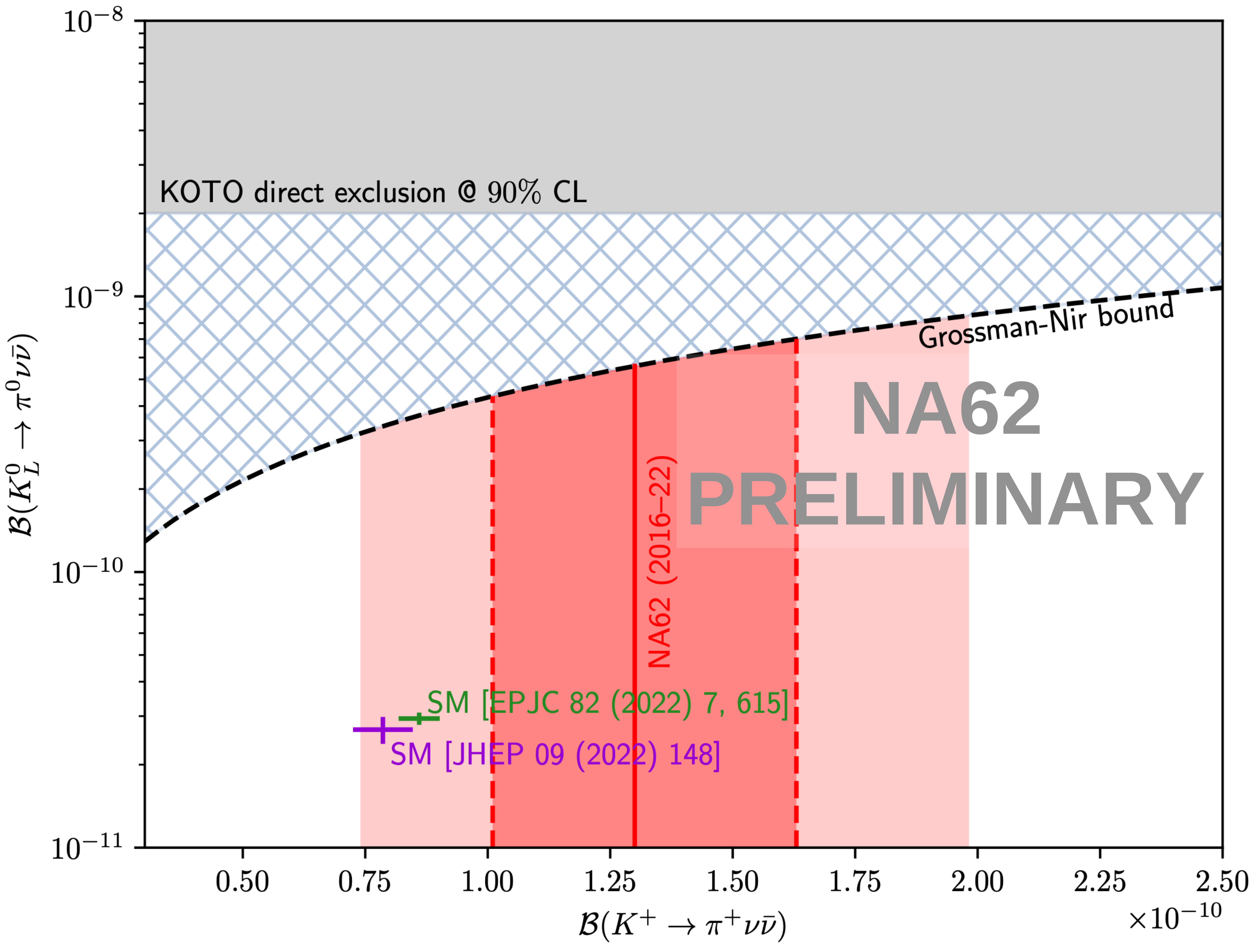
$$\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-2.9}) \times 10^{-11} = (13.0\ (^{+3.0}_{-2.7})_{stat}\ (^{+1.3}_{-1.2})_{syst}) \times 10^{-11}$$

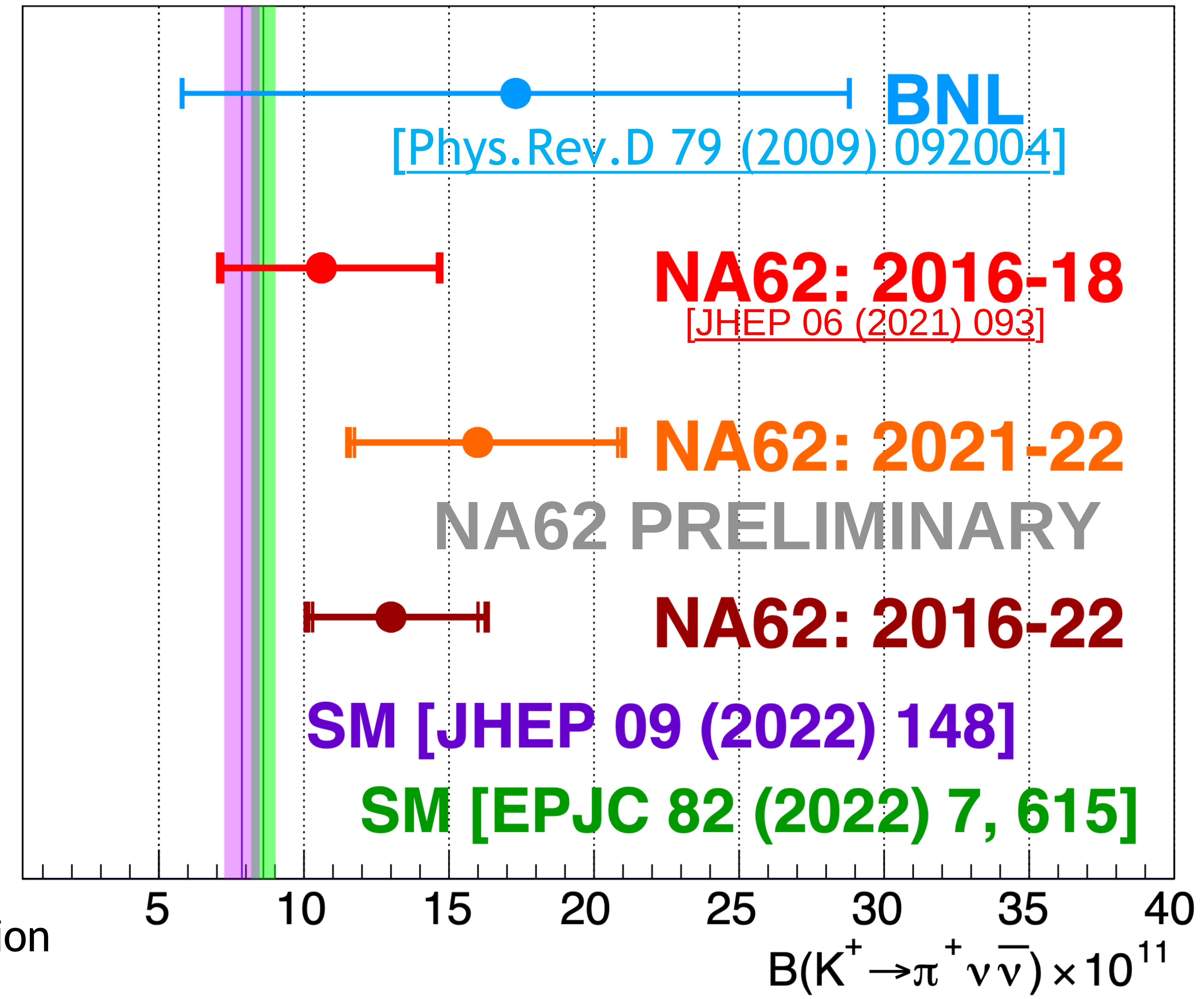
Results in context

$$\mathcal{B}^{16-18}_{\pi\nu\bar{\nu}} = \left(10.6^{+4.1}_{-3.5}\right)\times10^{-11}$$

$$\mathcal{B}^{21-22}_{\pi\nu\bar{\nu}} = \left(16.0^{+5.0}_{-4.5}\right)\times10^{-11}$$

$$\mathcal{B}^{16-22}_{\pi\nu\bar{\nu}} = \left(13.0^{+3.3}_{-2.9}\right)\times10^{-11}$$





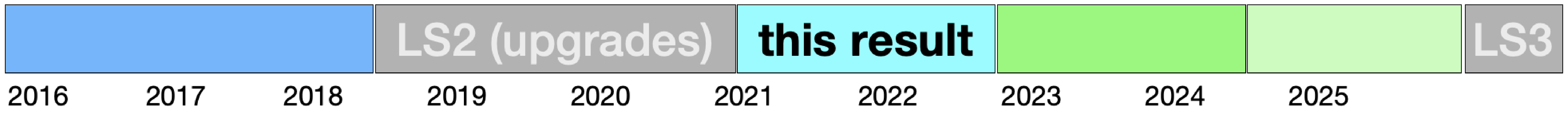
- NA62 results are consistent
- Central value moved up (now 1.5—1.7σ above SM)
- Fractional uncertainty decreased: 40% to 25%
- Bkg-only hypothesis rejected with significance Z>5
- Need full NA62 data-set to clarify SM agreement or tension

Conclusions

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

- 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)
  - $\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-2.9}) \times 10^{-11} = (13.0\ (^{+3.0}_{-2.7})_{stat}\ (^{+1.3}_{-1.2})_{syst}) \times 10^{-11}$
  - Background-only hypothesis rejected with significance Z>5.

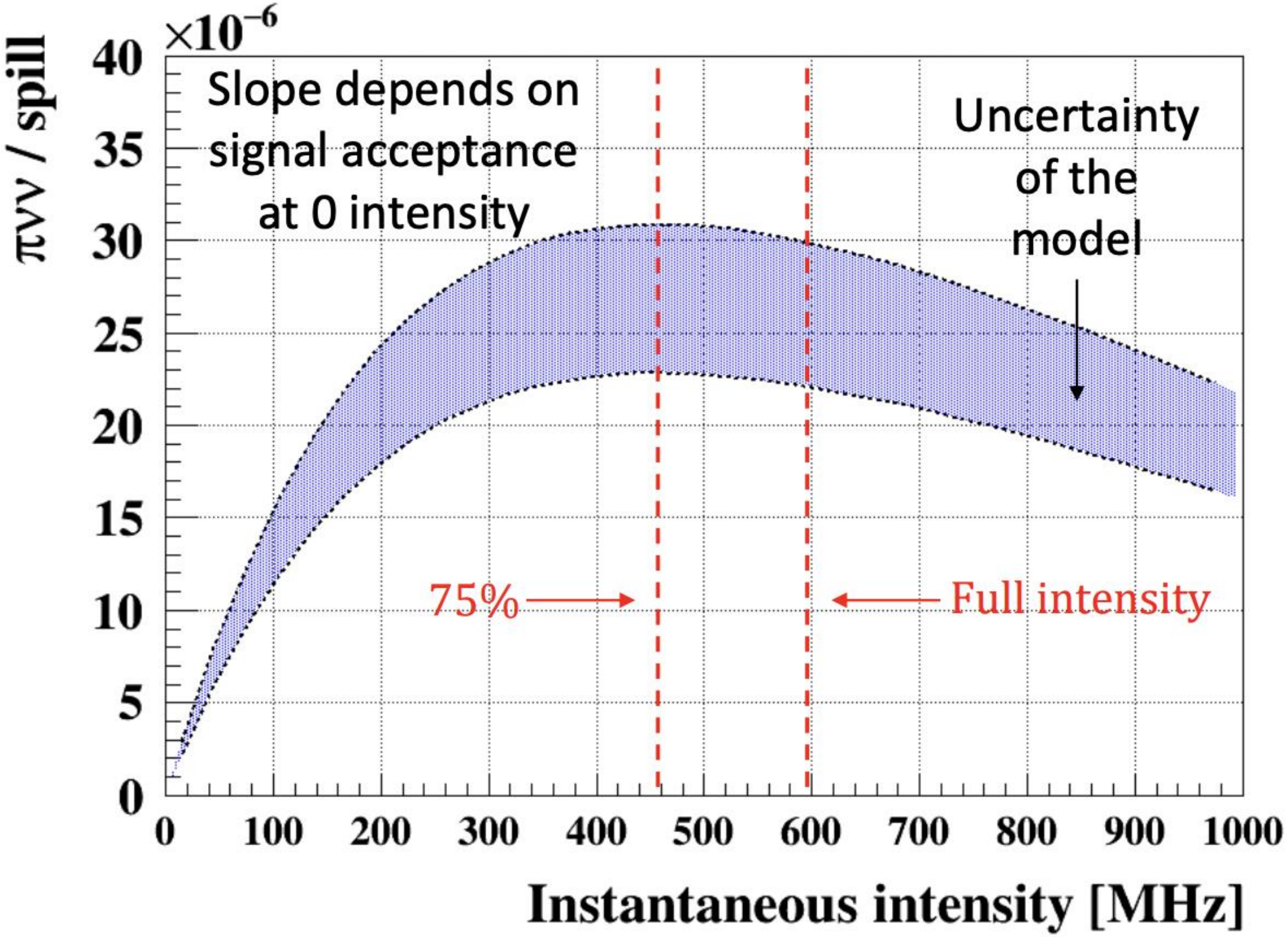
- **First observation of $K^+ \to \pi^+ \nu\bar{\nu}$ decay: BR consistent with SM prediction within 1.7σ**
  - **Need full NA62 data-set to clarify SM agreement or tension.**



2023- LS3 dataset collection & analysis in progress…

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

Supplemental

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

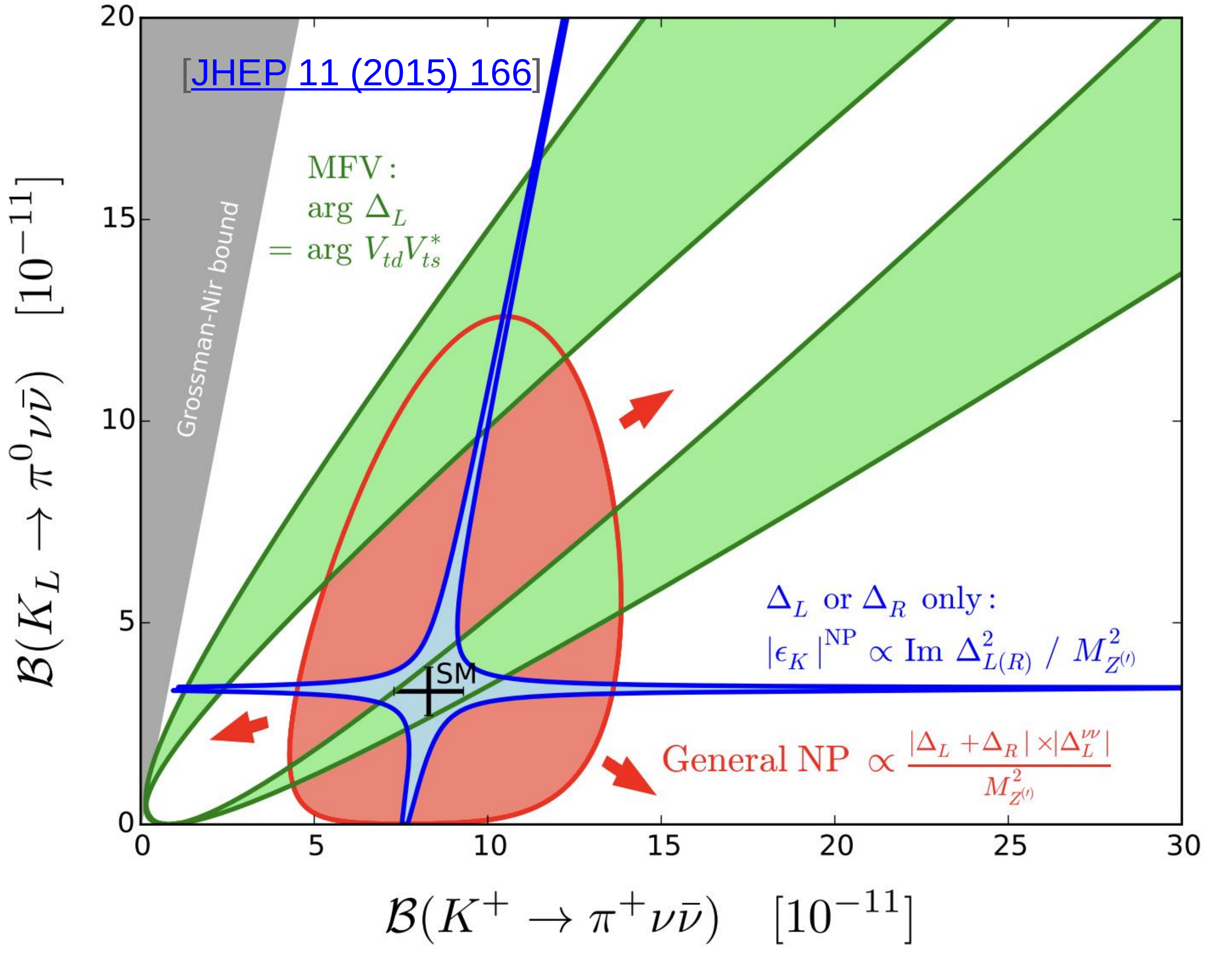
- Correlations between BSM contributions to BRs of K^+ and K_L modes [JHEP 11 (2015) 166].
  - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ε'/ε, ΔM_B, B-decays) [JHEP 12 (2020) 097][PLB 809 (2020) 135769].
- Leptoquarks [EPJ.C 82 (2022) 4, 320], Interplay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

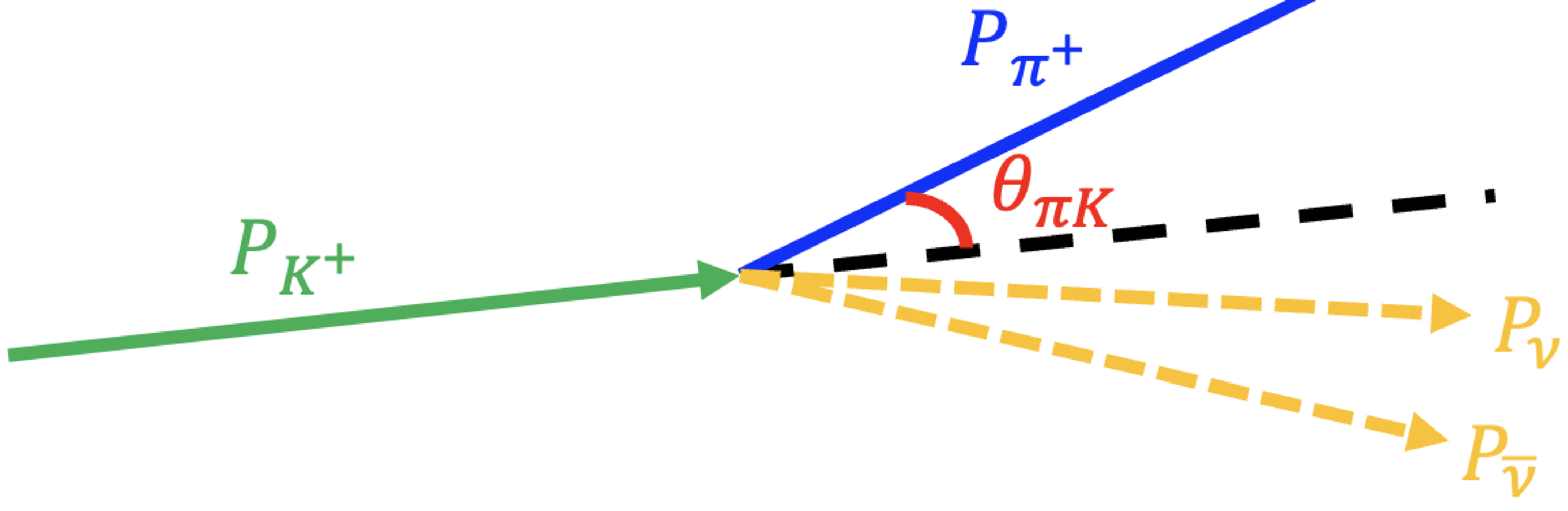
NA62 Strategy:

- 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

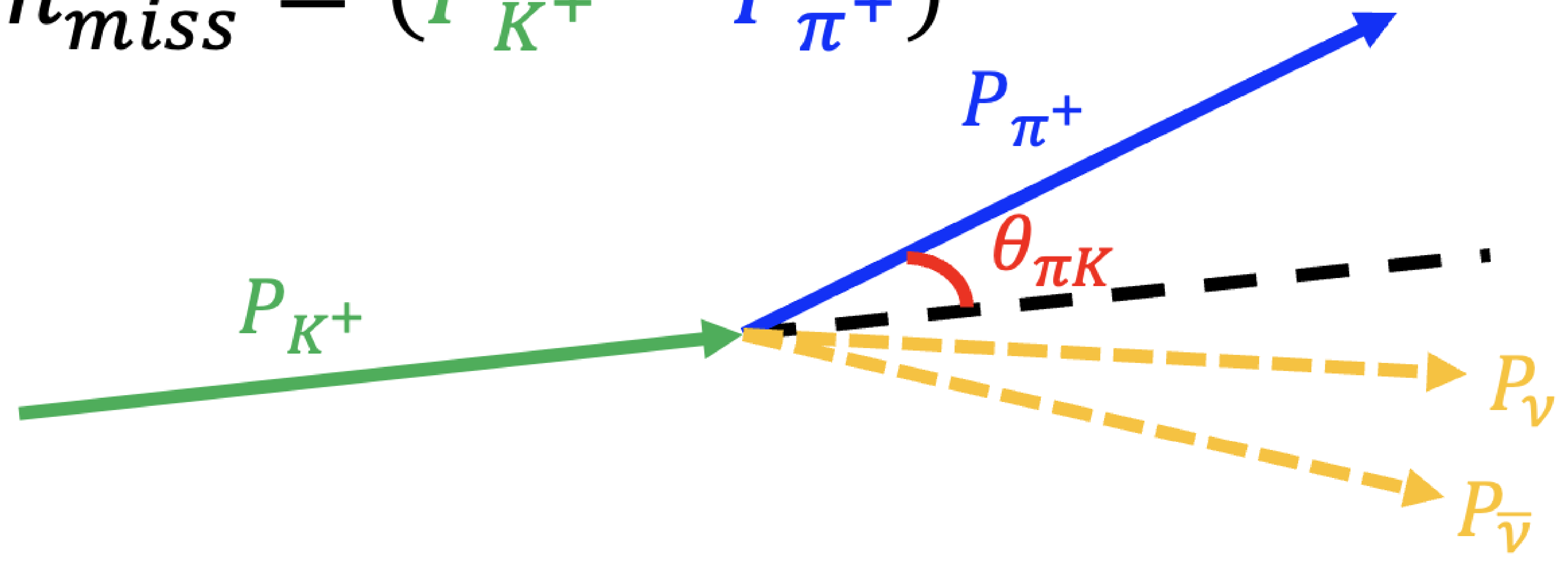
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$

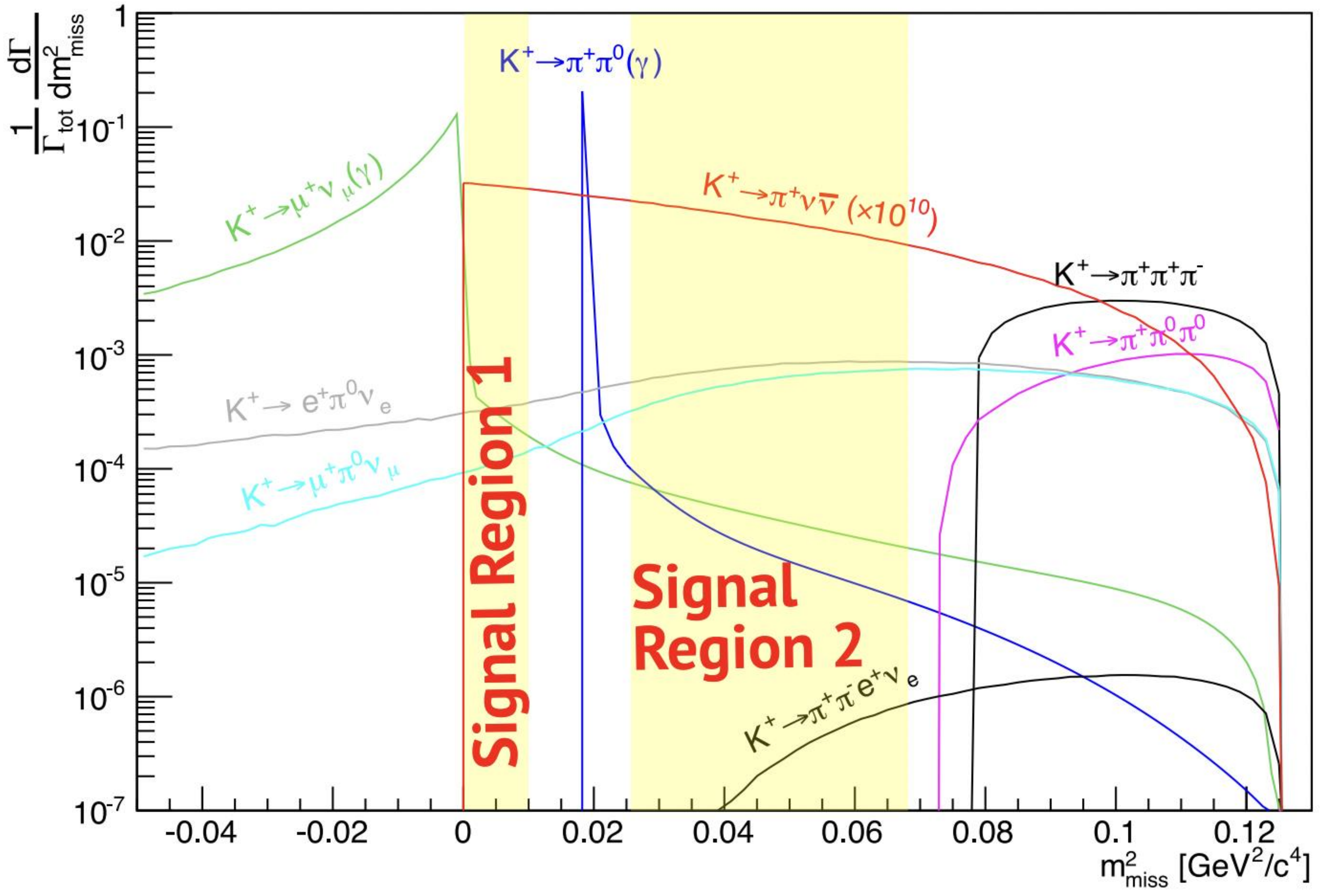


Decay mode	Branching Ratio [PDG]
$K^+ \to \mu^+\nu_\mu$	$(63.56 \pm 0.11)\%$
$K^+ \to \pi^+\pi^0$	$(20.67 \pm 0.08)\%$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024)\%$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$
$K^+ \to \pi^+\nu\bar{\nu}$	$\approx 10^{-10}$

Kinematic constraints & signal regions

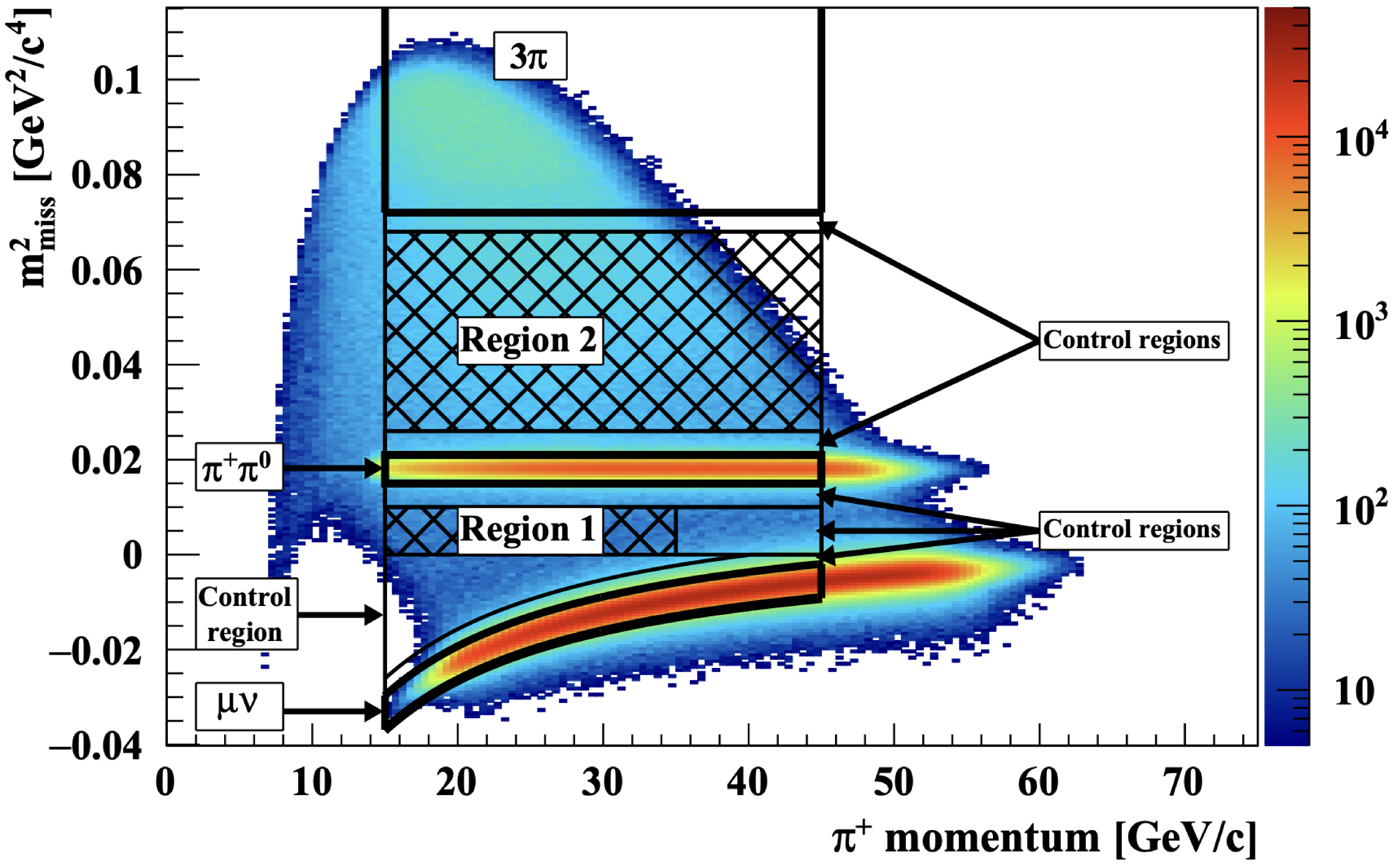
$$m_{miss}^2 = (P_{K^+} - P_{\pi^+})^2$$





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

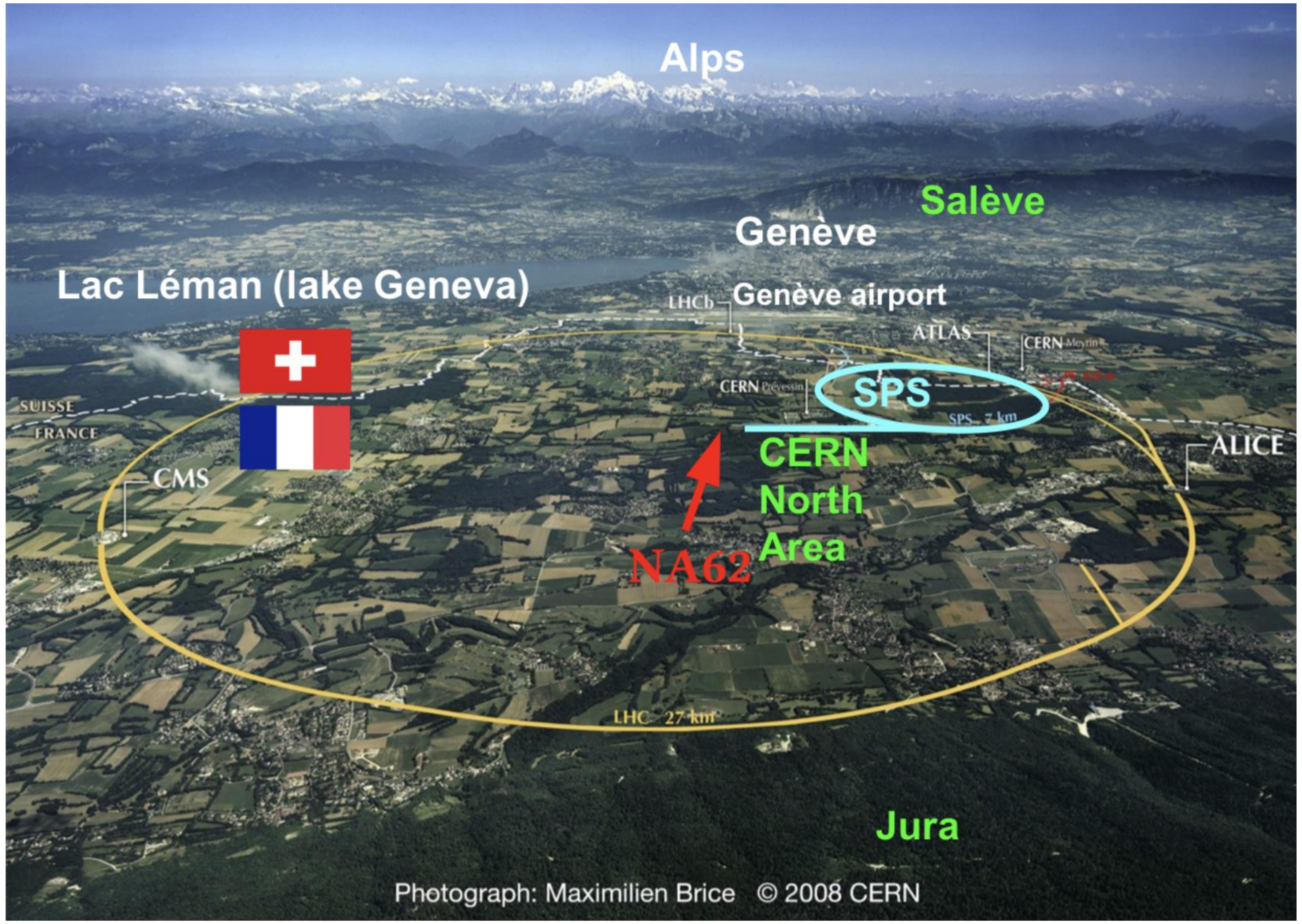
[JHEP 06 (2021) 093]



π^+ momentum range: 15—45 GeV/c

The NA62 Experiment at CERN

~200 collaborators from ~30 institutions.



- **Primary goal:** measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$
- **New Technique:** K^+ decay-in-flight
- **Results:** [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
- **Broader physics programme:**
  - Rare K^+ decays (e.g. $K^+ \rightarrow \pi^+\gamma\gamma$ [PLB 850 (2024) 138513])
  - LNV/LFV decays (e.g. $K^+ \rightarrow \pi^-(\pi^0)e^+e^+$ [PLB 830 (2022) 137172])
  - Exotics (e.g. Dark photon [PRL 133 (2024) 11, 111802])
- **Data taking**
  - 2016 Commissioning + Physics run (45 days).
  - 2017 Physics run (160 days).
  - 2018 Physics run (217 days).
  - 2021 Physics run (85 days [10 beam dump]).
  - 2022 Physics run (215 days).
  - 2023 Physics run (150 days [10 beam dump]).
  - 2024 Physics run ongoing …

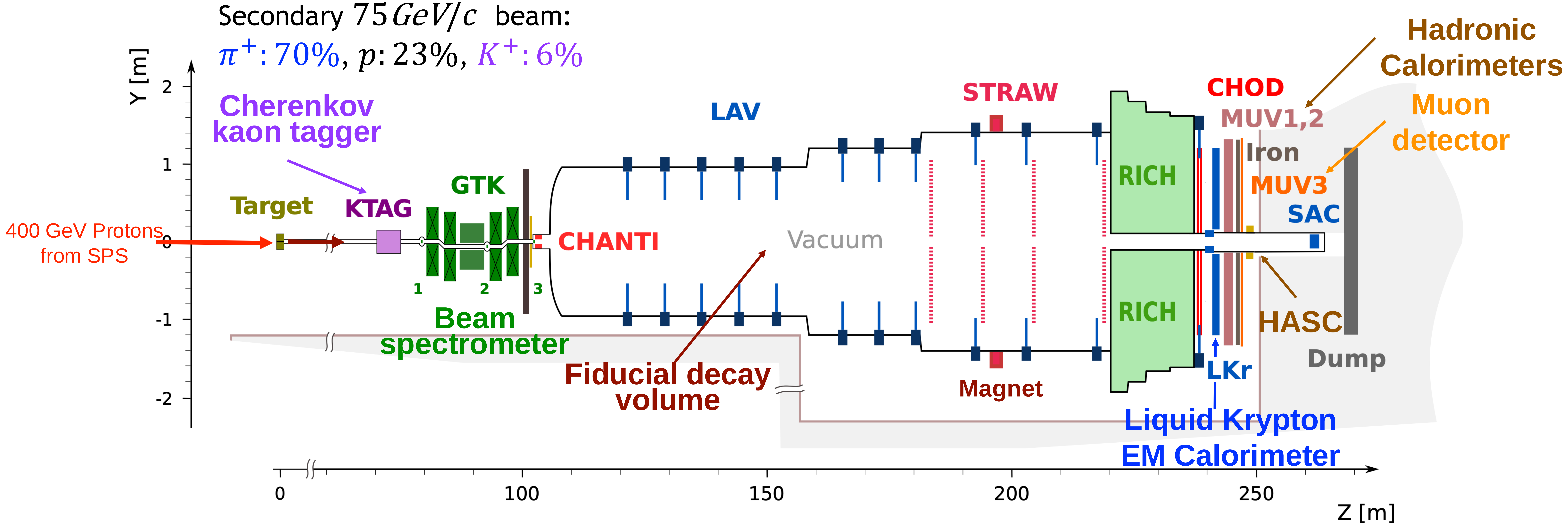
LS2 (upgrades) | this result | LS3

2016 2017 2018 2019 2020 2021 2022 2023 2024 2025

NA62 beamline & detector

[JINST 12 (2017) 05, P05025]

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



Upstream particle:
KTAG: Differential Cherenkov for K^+ ID
GTK: Si pixel tracker
CHANTI: Anti-counter for inelastic interactions

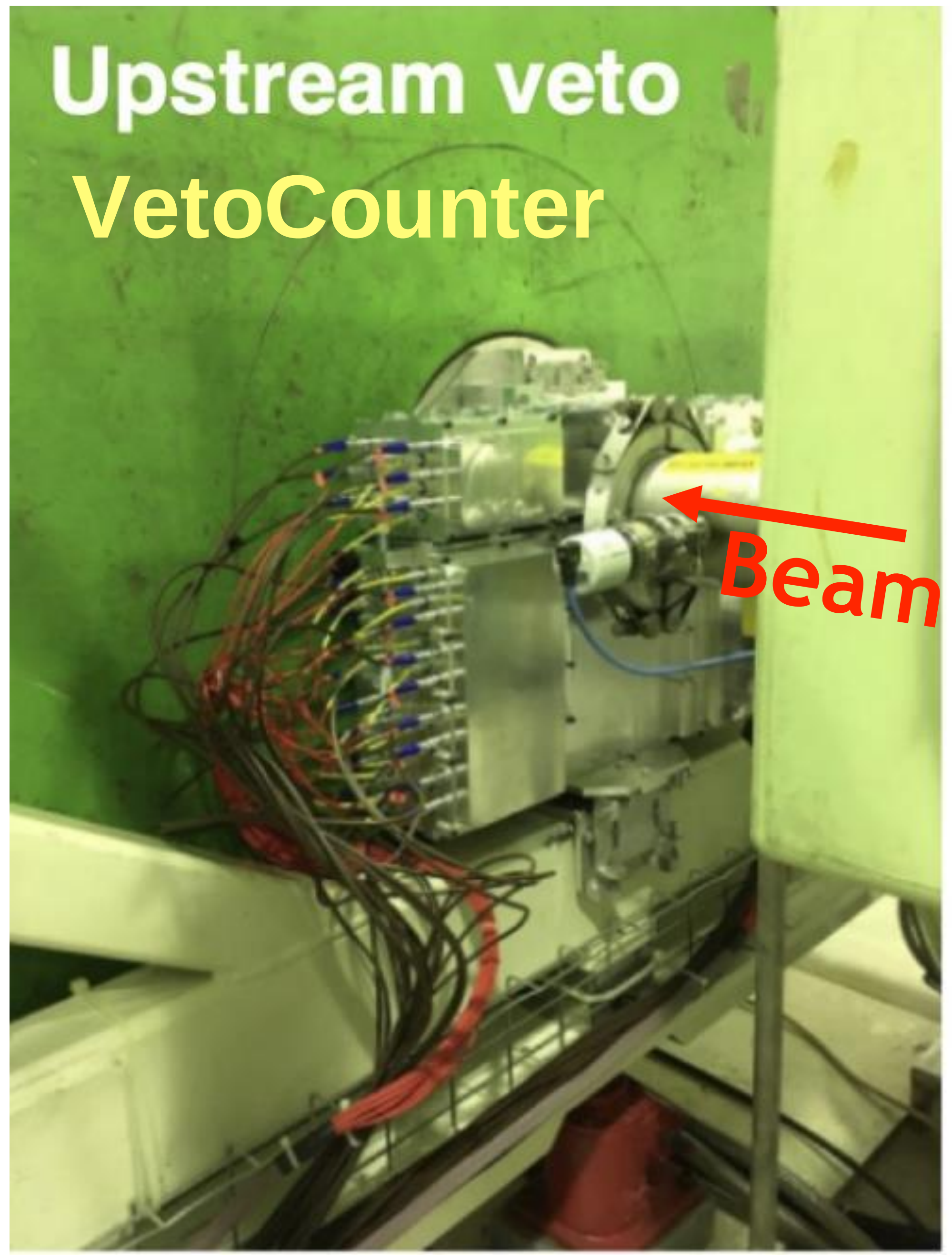
Decay region detectors (π^+):
STRAW: Track momentum spectrometer
CHOD: Scintillator hodoscope
RICH: For π/μ/e ID
LKR/MUV1/2: Calorimetric systems

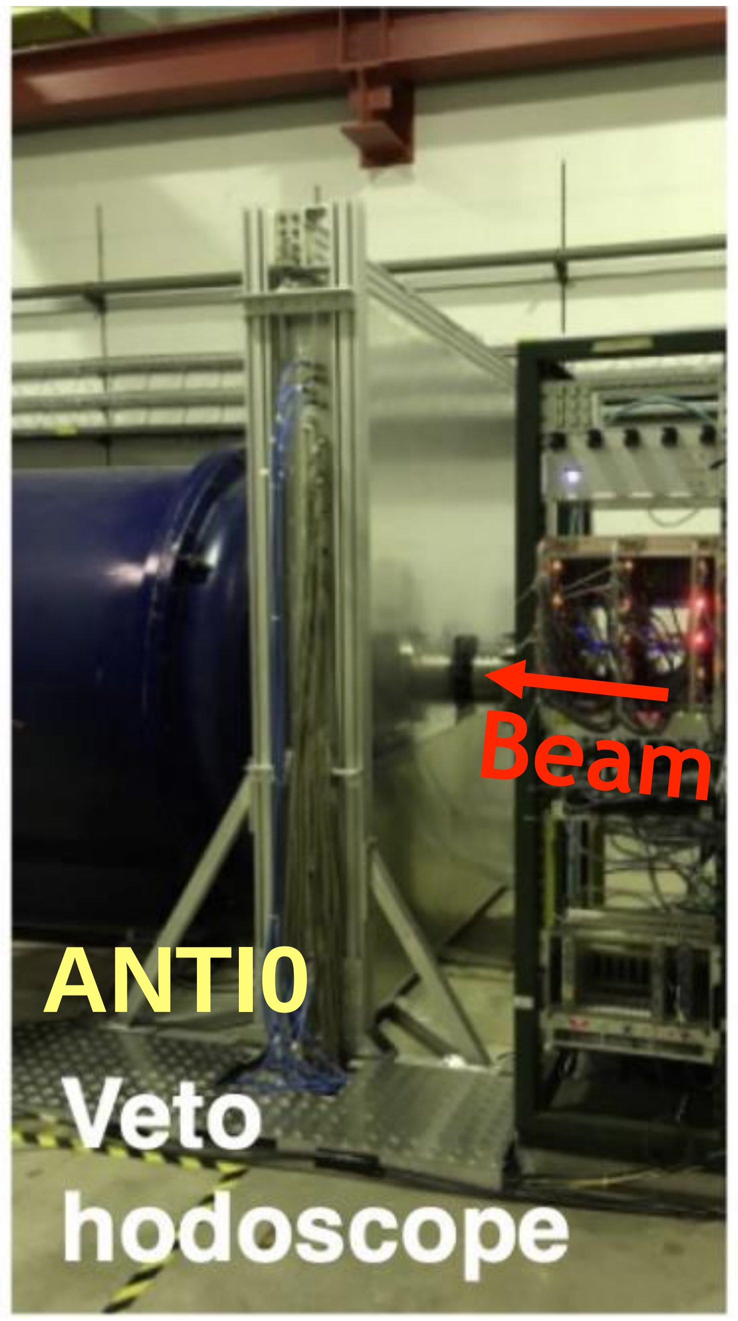
Vetos:
LAV/IRC/SAC: photons
MUV3: muons

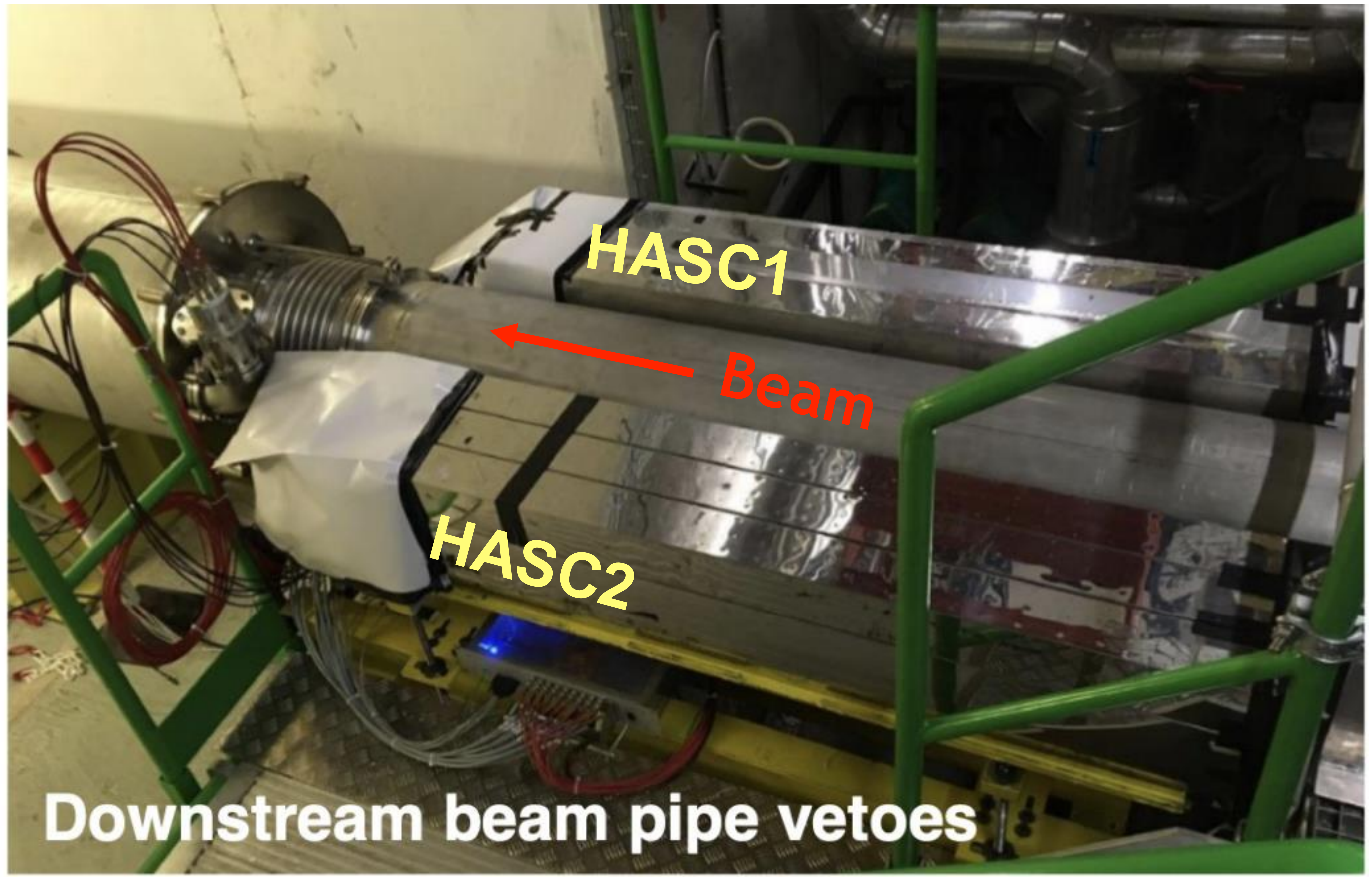
Summary of NA62 Run2 upgrades

- 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:







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

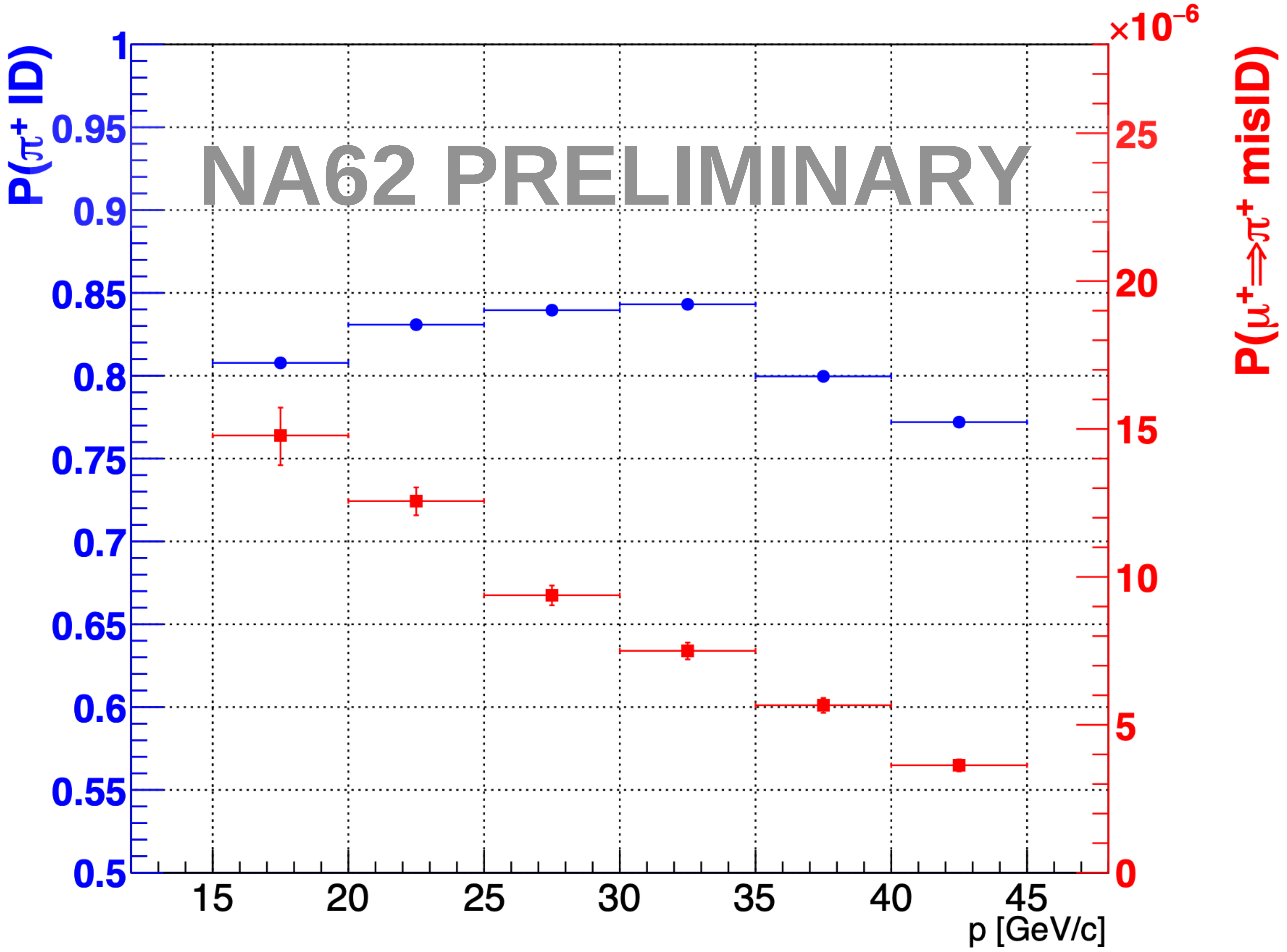
Selection:

- **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).

Particle ID performance : 2021—22 data

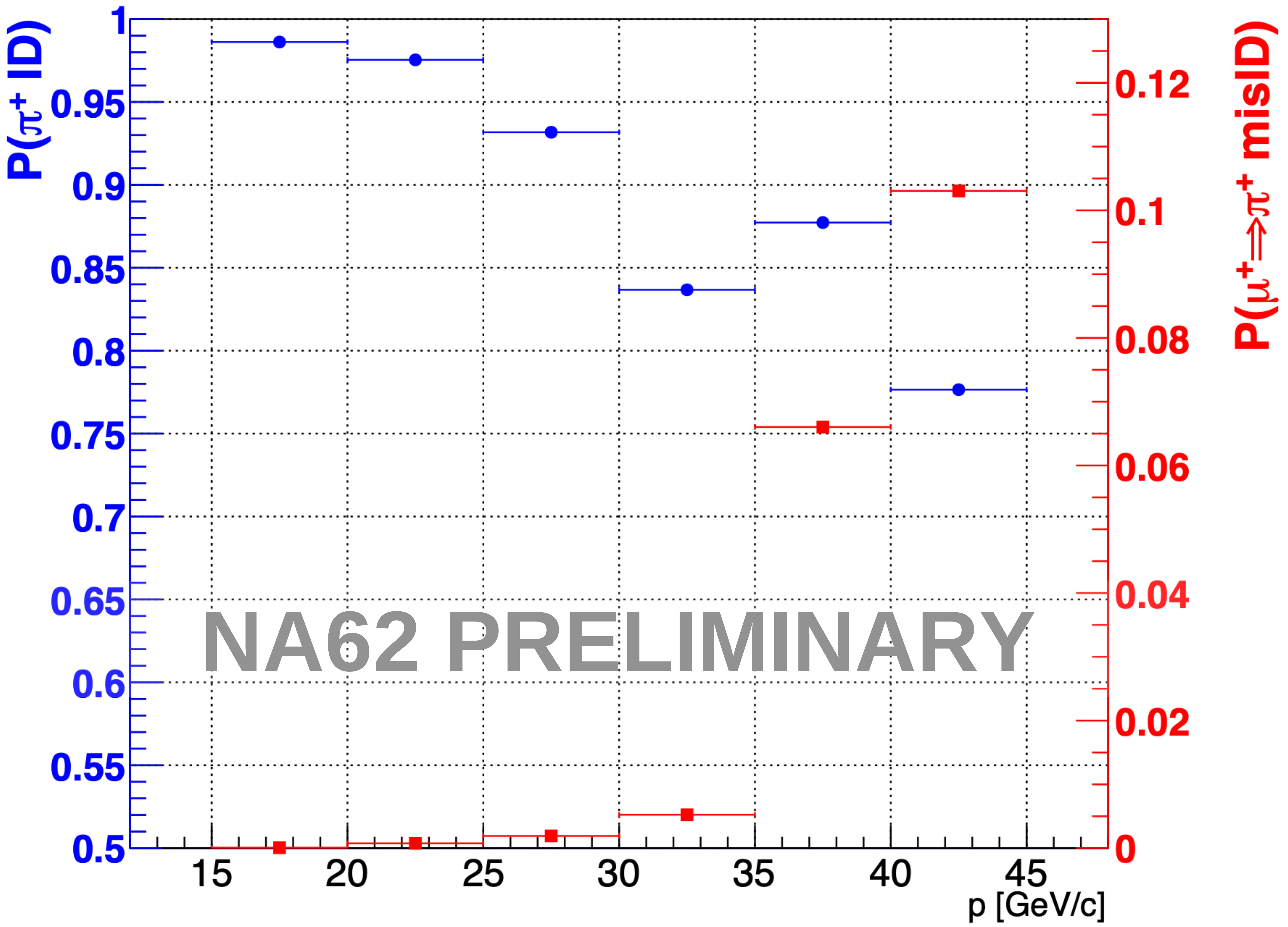
Calorimeters

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



RICH

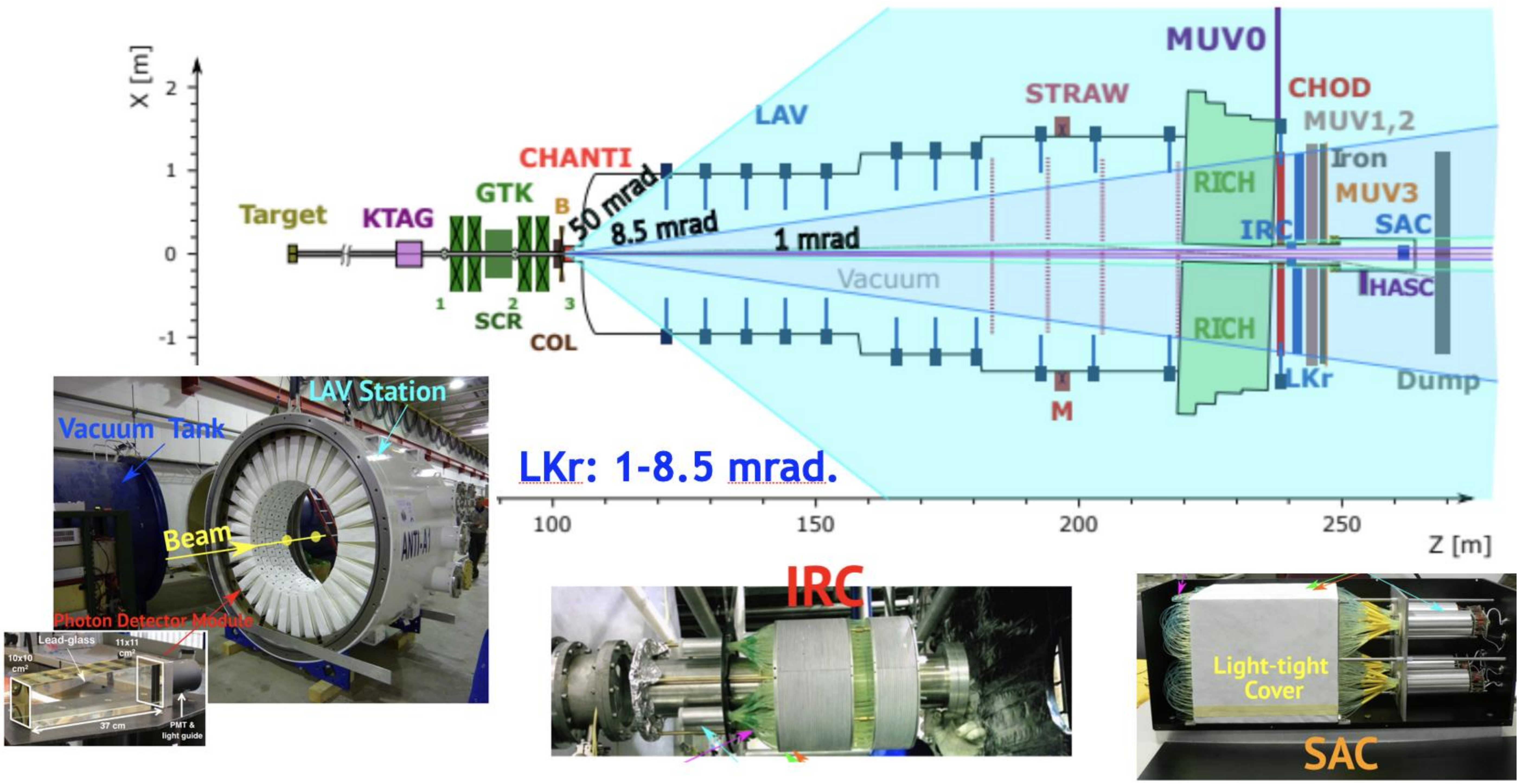
Designed to distinguish between π^+/μ^+ with $15 - 35\,GeV/c$



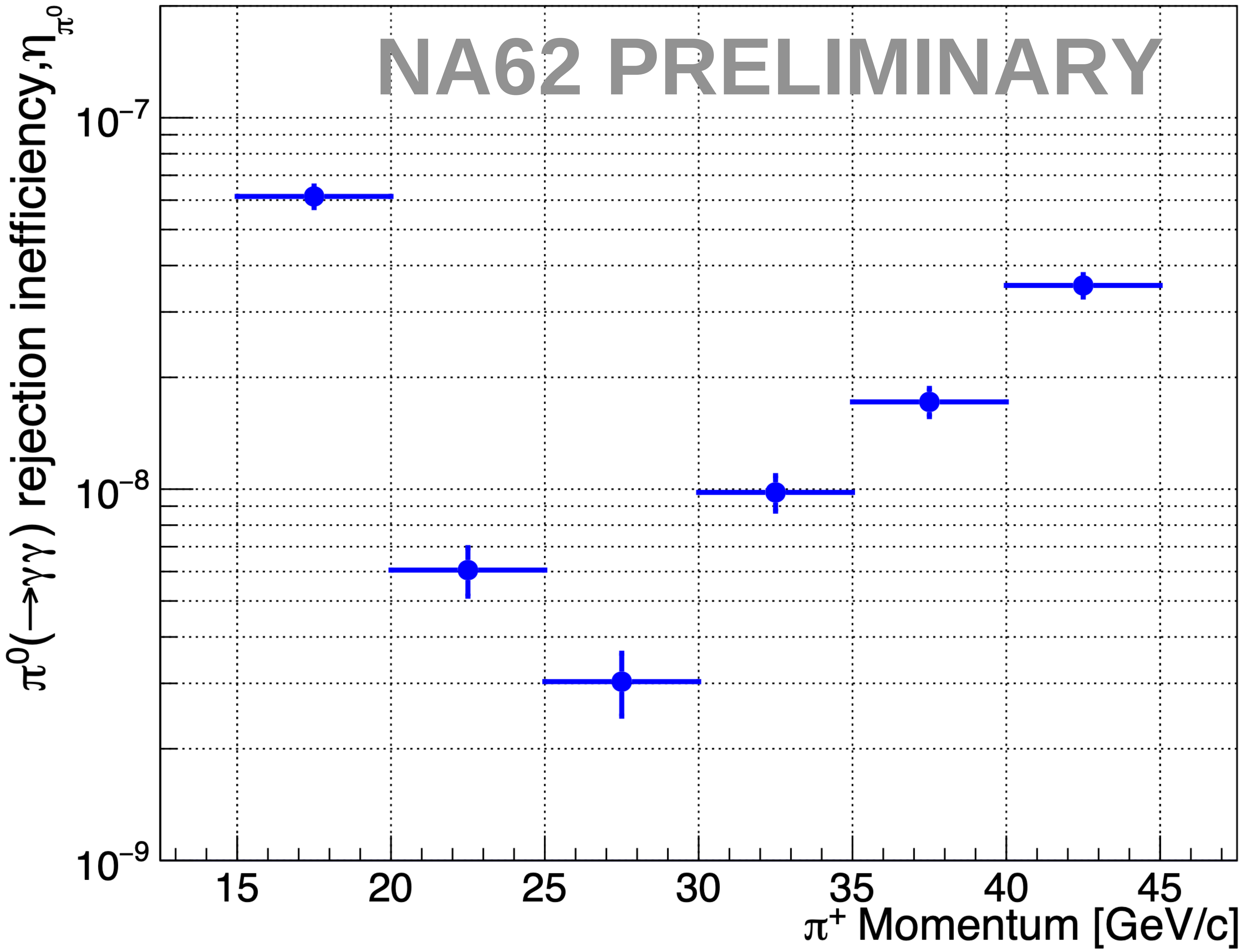
$\mathrm{P}(\pi^+) = 73\ \%$

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

Comprehensive photon veto system: 21—22



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

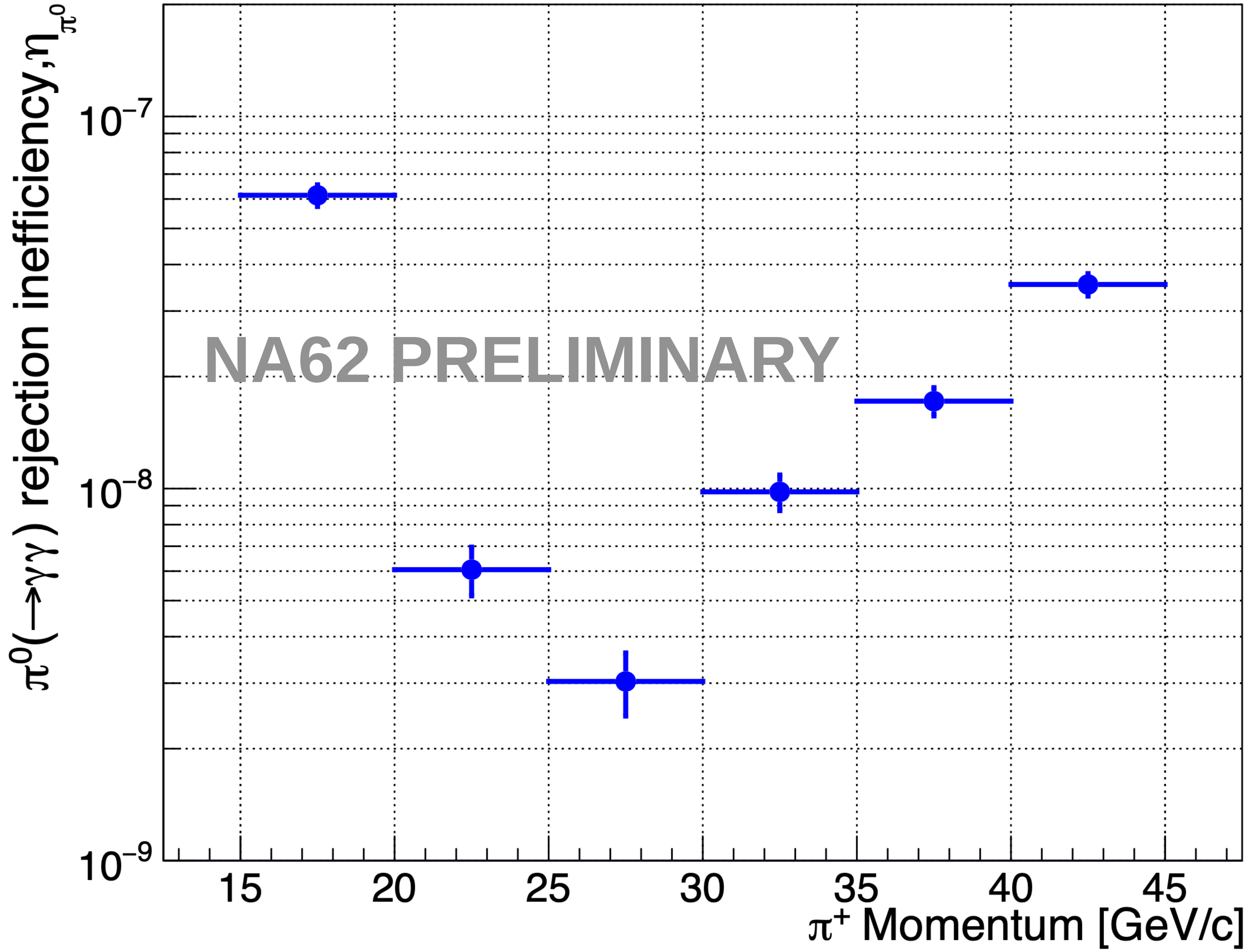


- Probability of $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma\gamma$ events passing all photon veto conditions:

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

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

Photon veto performance



- Probability of $K^+ \to \pi^+\pi^0$ 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

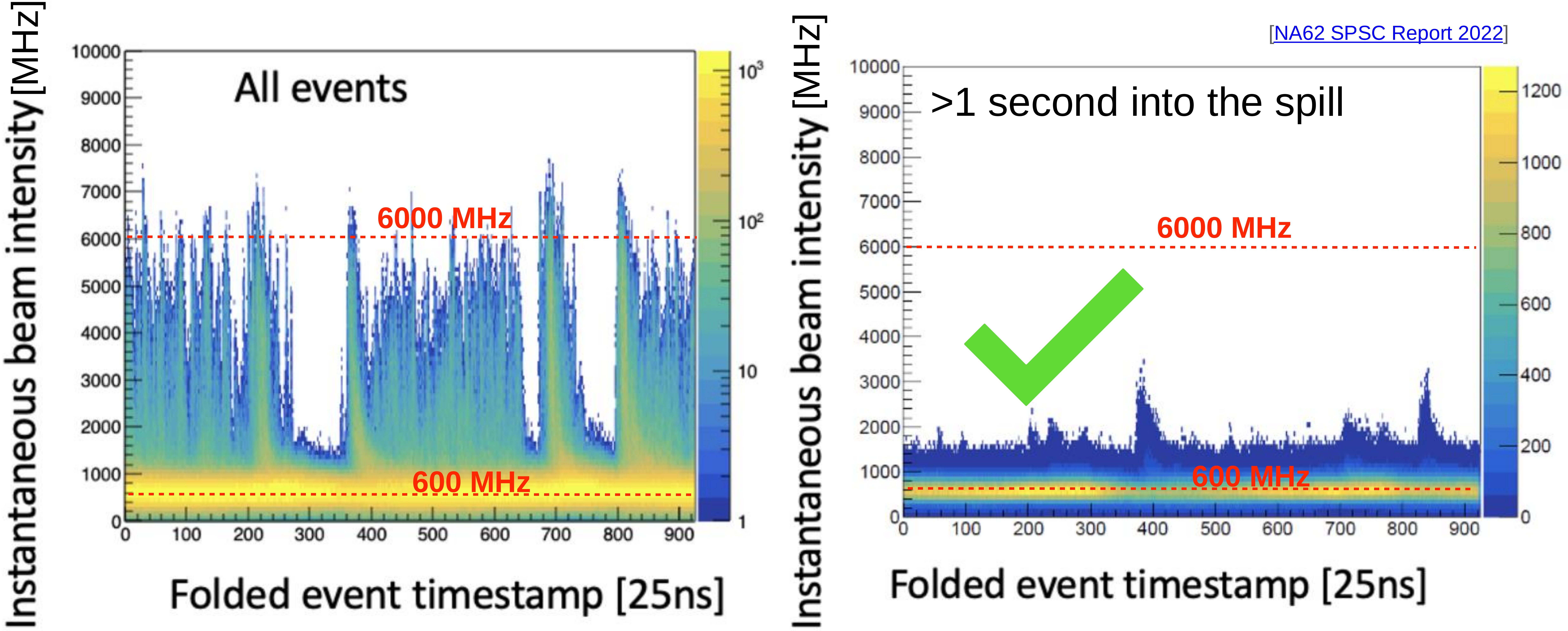
Normalisation trigger downscaling and efficiency

Random veto efficiency

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

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

2021 instantaneous beam intensity



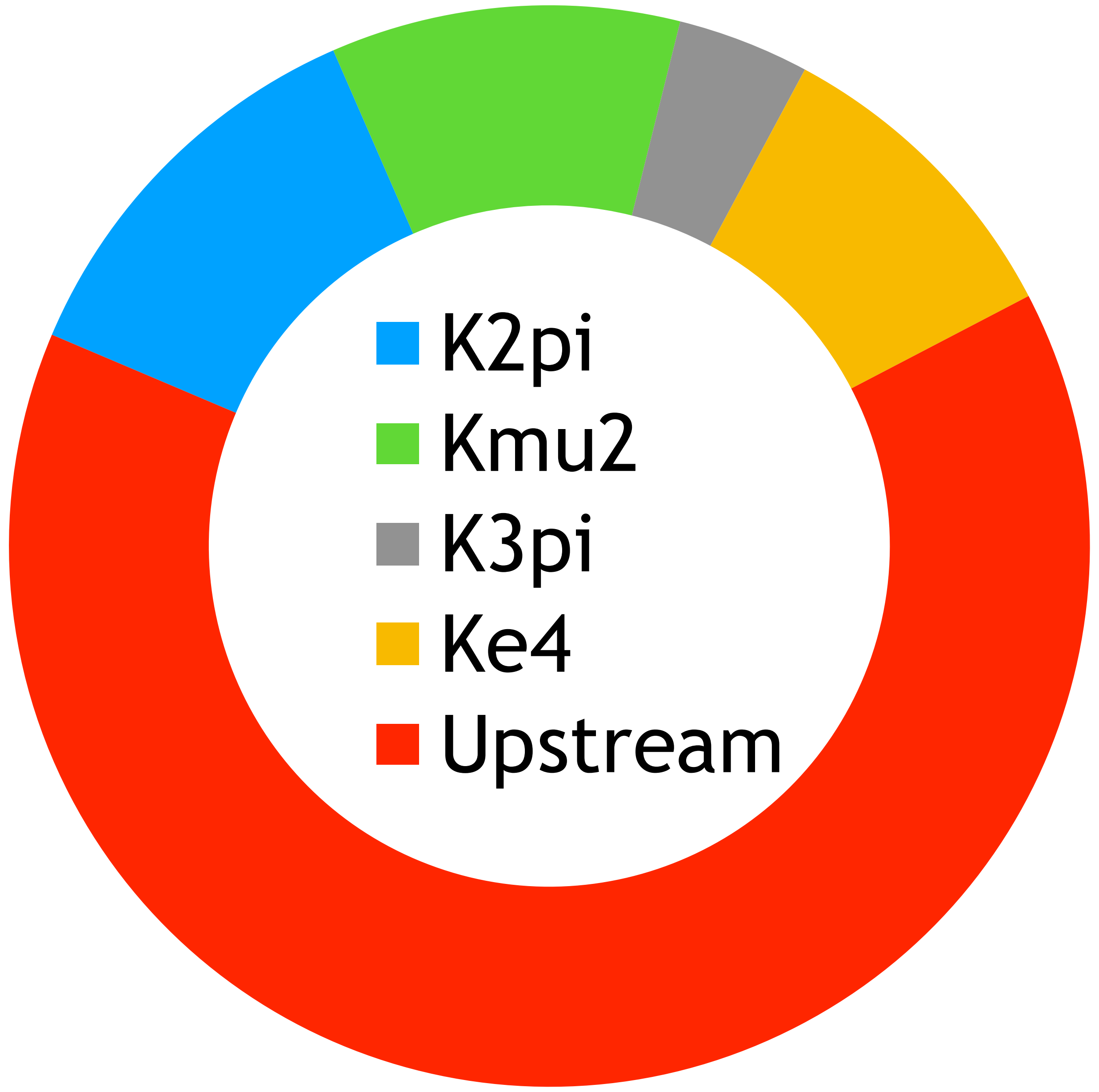
- Remove events in first 1s of 4.8s spill for <u>2021 data only</u>.
  - DAQ overwhelmed by instantaneous rates up to 10x higher than design.

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

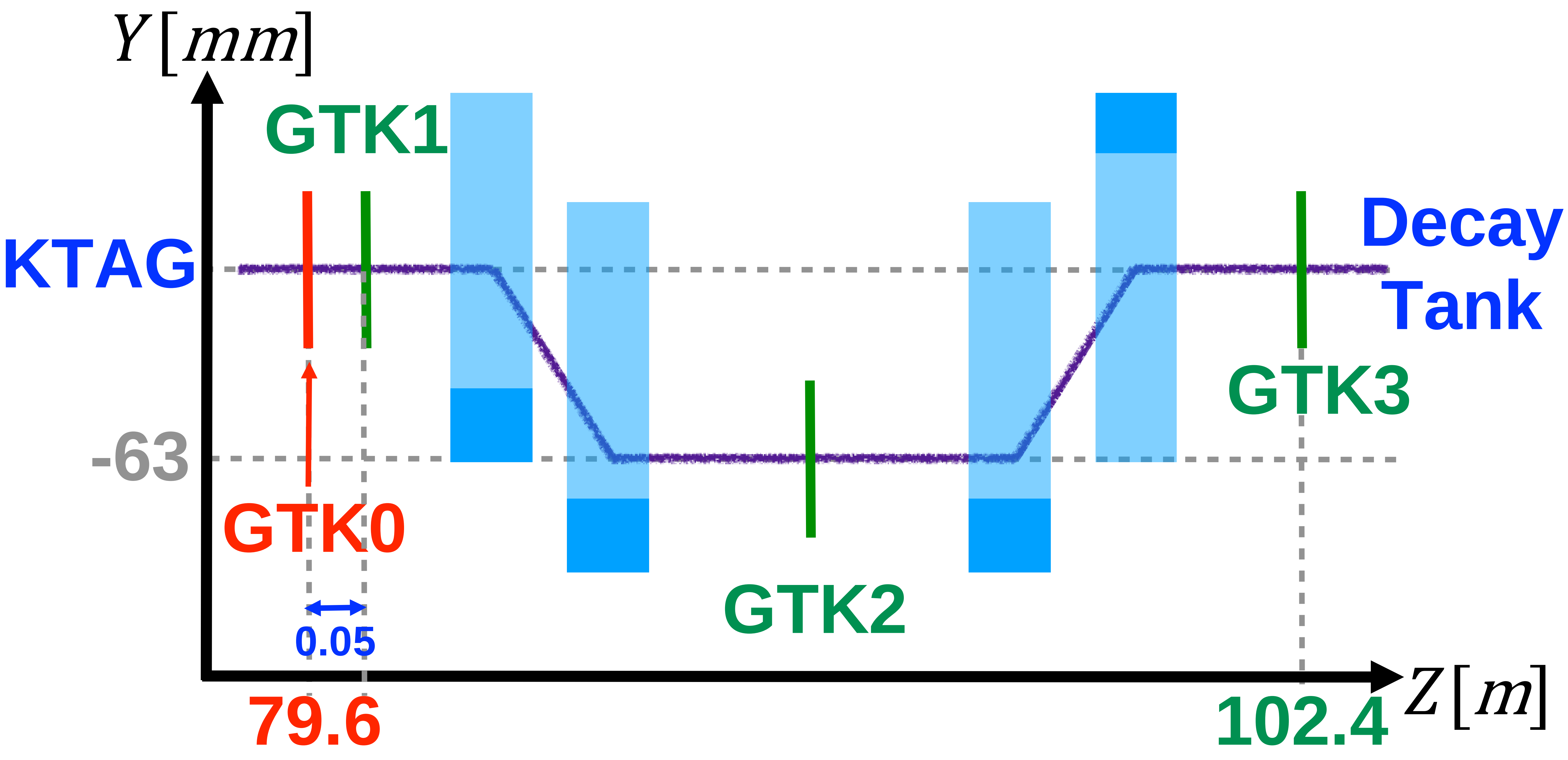
Largest backgrounds:

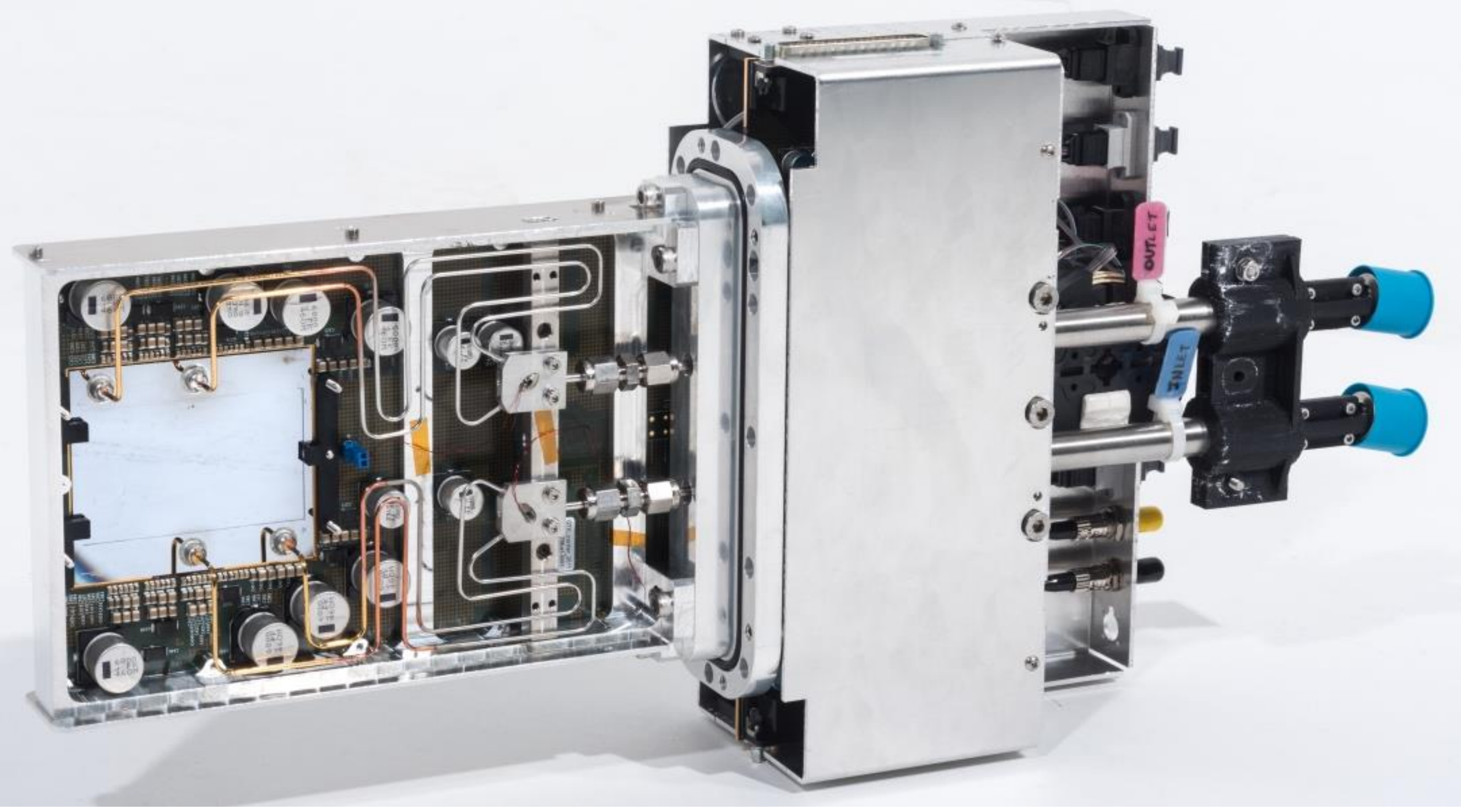
1. Upstream
2. $K^+ \to \pi^+\pi^0$

Veto by detecting previously missed particles…

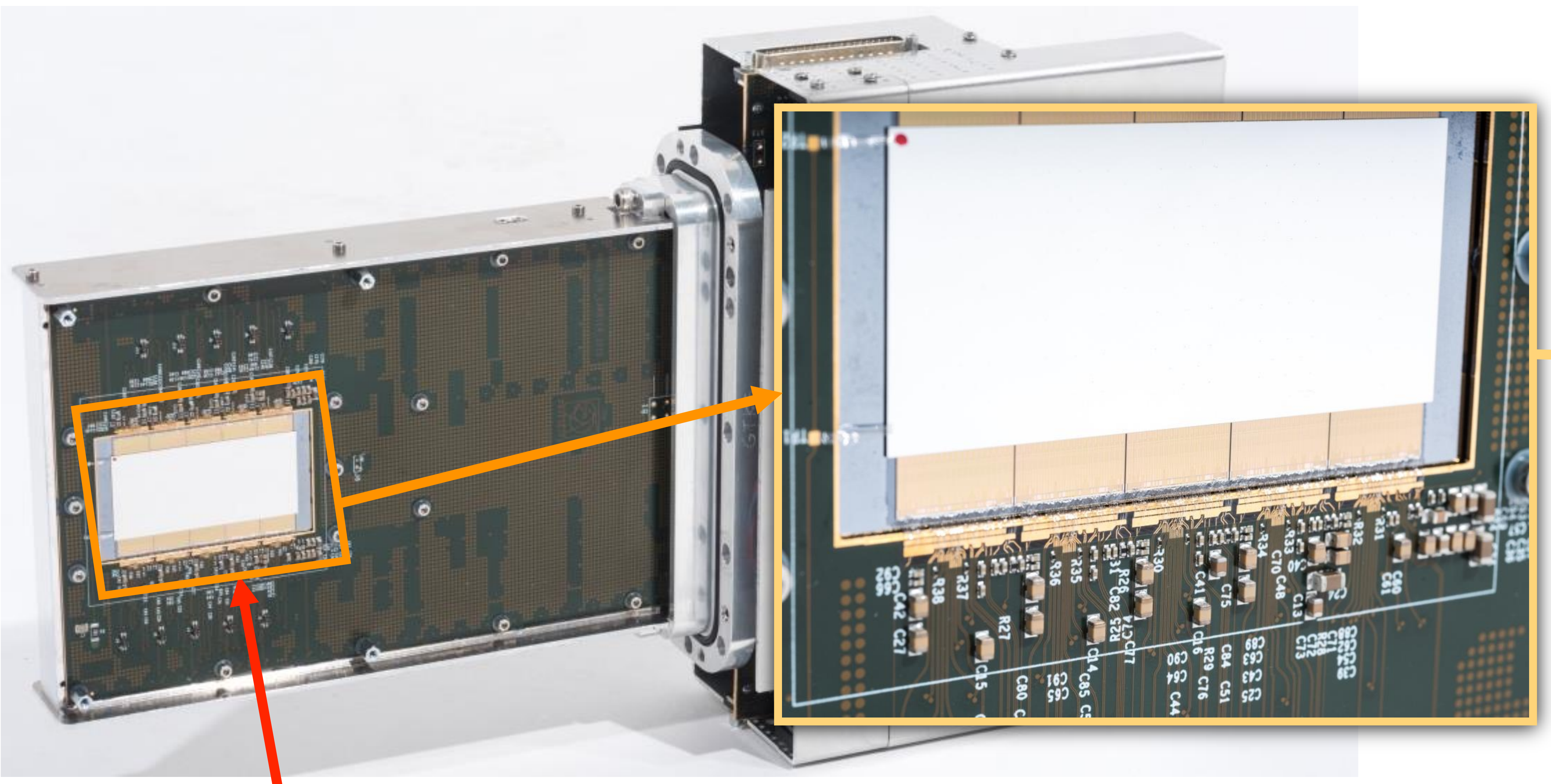
4th GTK station

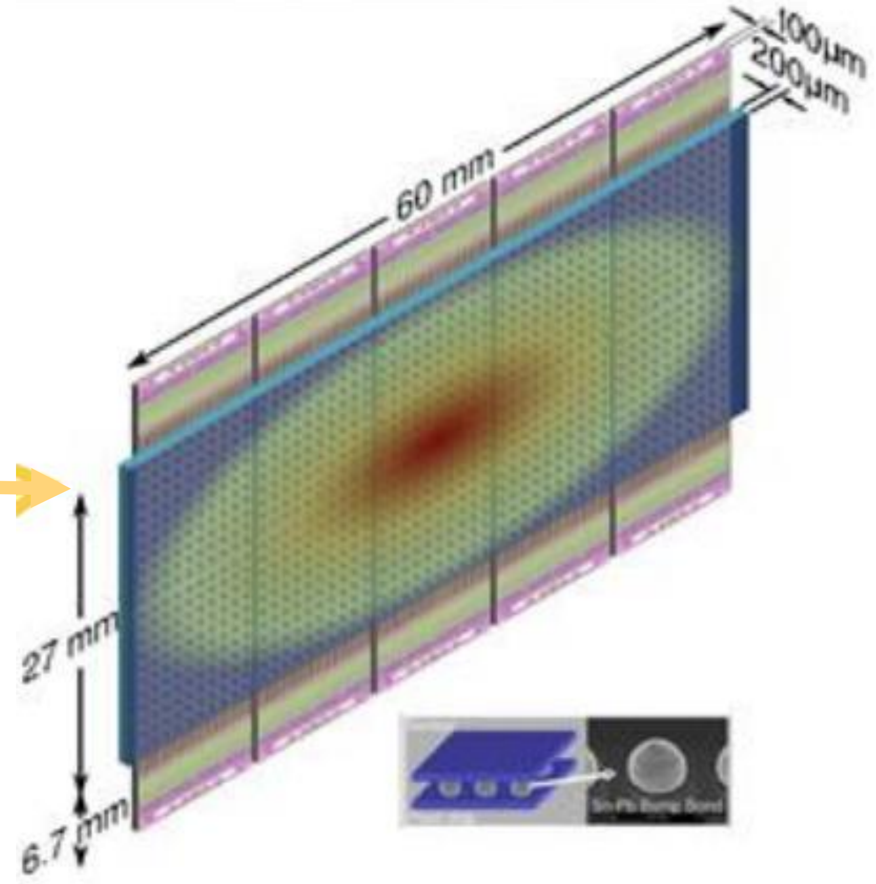
- Si Pixel detector exposed to ~1GHz beam.
- Essential for $K^+ - \pi^+$ matching.
    - Measures K^+ 3-mom. & time
- 4th GTK station improves efficiency & pileup resilience.





Cooling plate





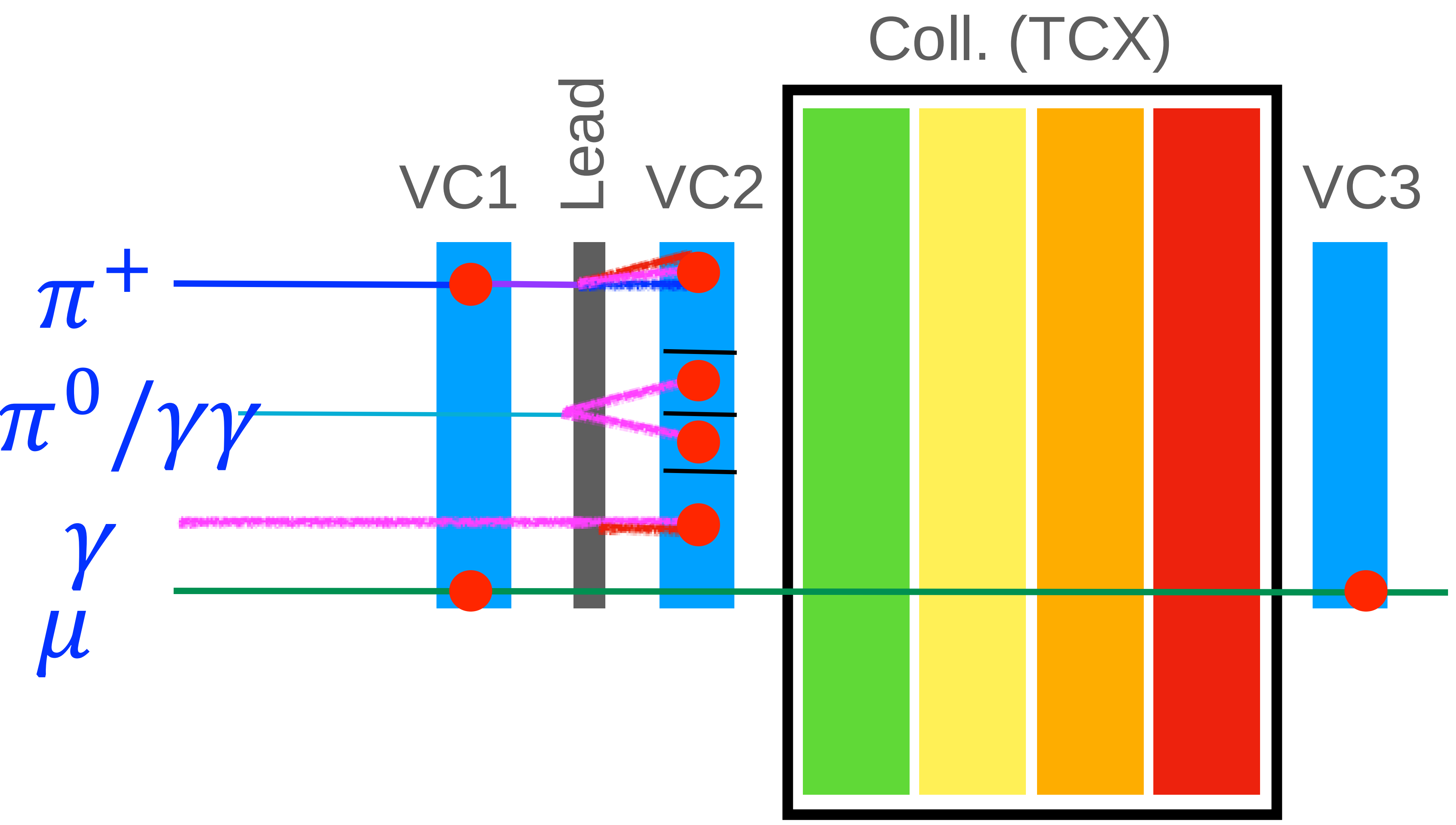
Si Pixels ~(30x60 mm active area)

Example $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma\gamma$ event
Not detected due to inefficiencies and/or missed interaction products
Sketch only
MNP33 Dipole Magnet
MUV0
LAV12
RICH
LKr
MUV1,2
MUV3
Iron wall
Dipole Magnet
Photon interaction with RICH flange
IRC
Beam pipe
SAC
Dump
HASC1
CHODs
STRAW
STRAW
γ
γ
π^+
e^-
e^+
x
z


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

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]

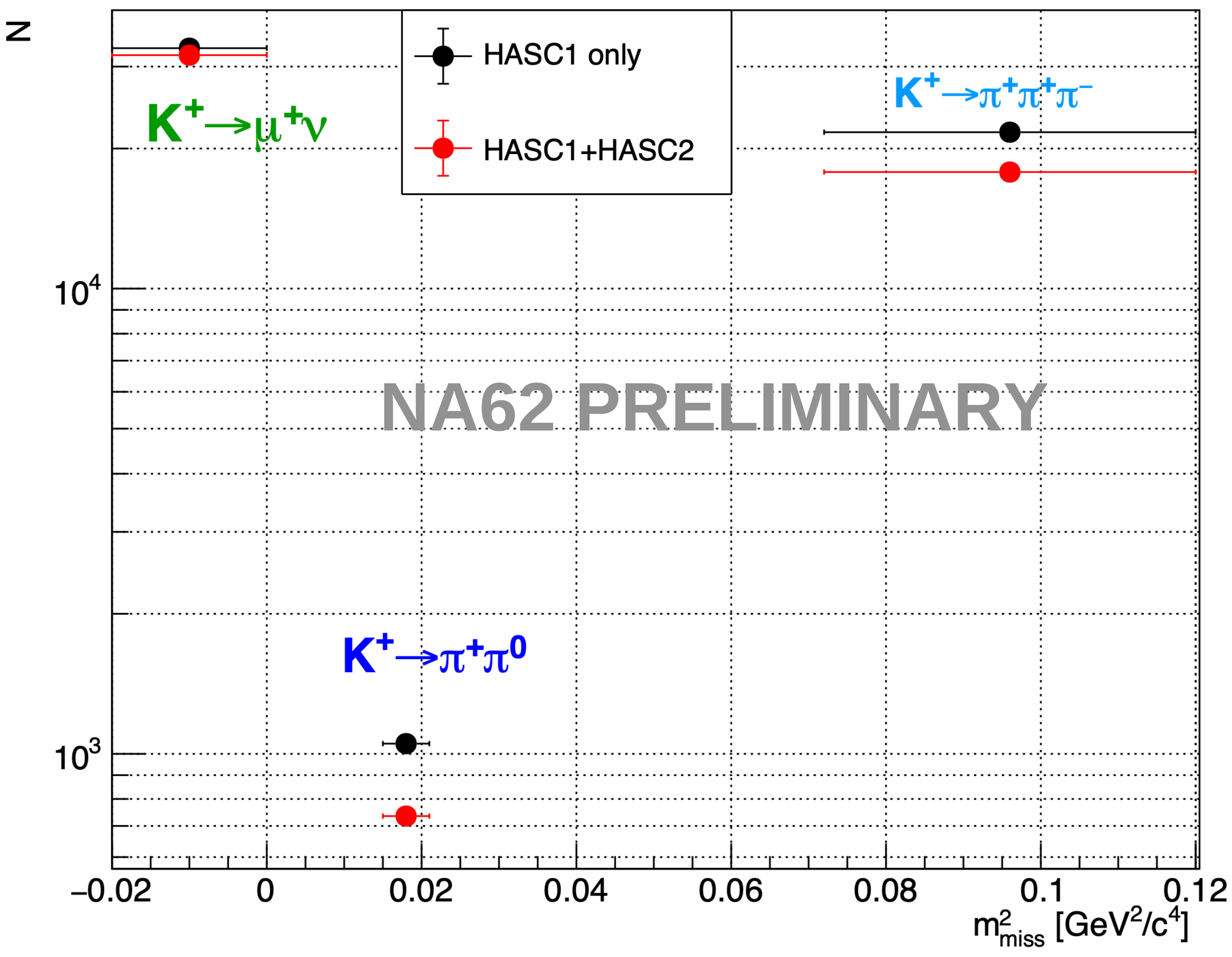
HASC2 veto

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

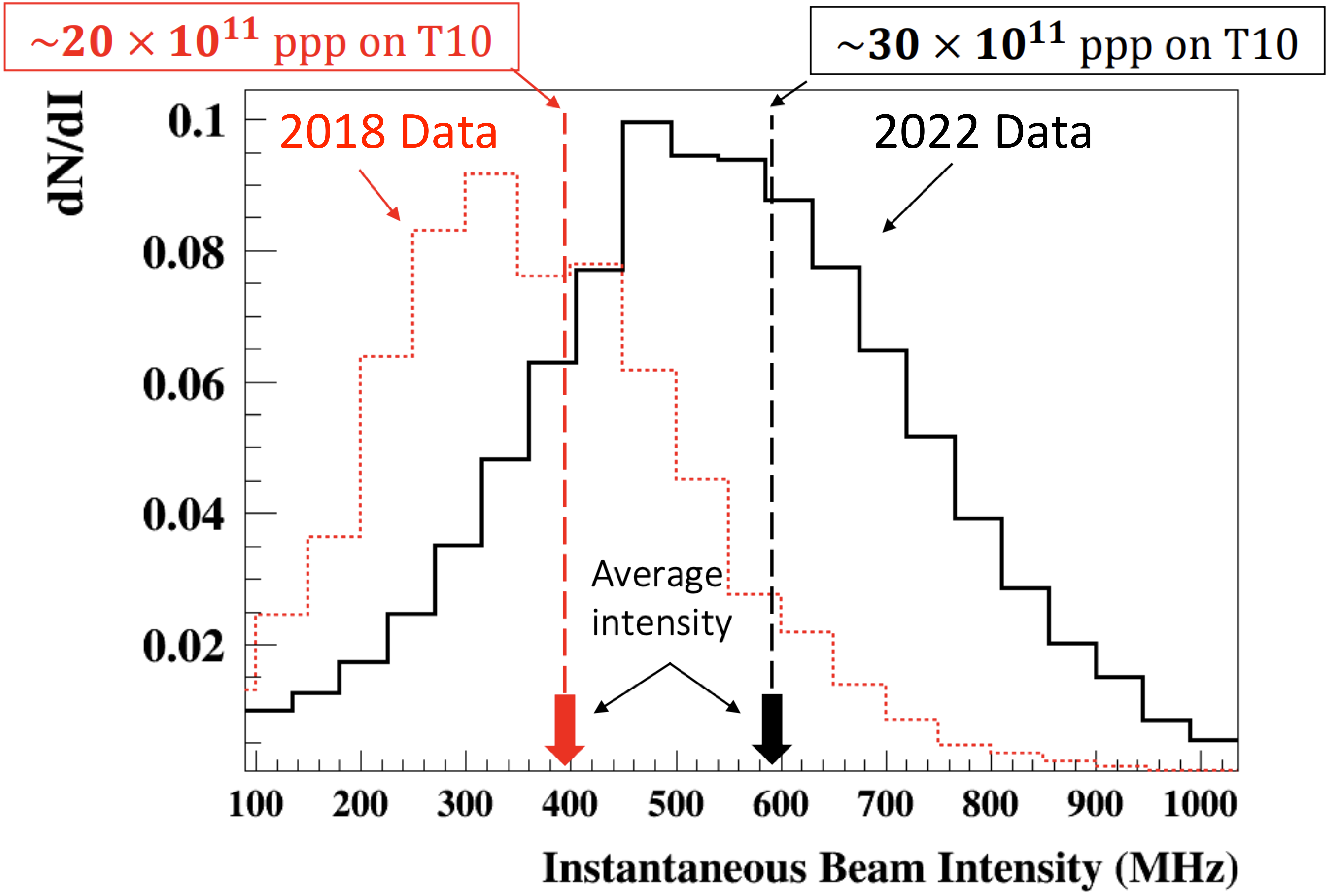
- Addition of HASC2:
  - **30% less** $K^+ \to \pi^+\pi^0$
  - 18% less $K^+ \to \pi^+\pi^+\pi^-$
  - 3.5% less $K^+ \to \mu^+\nu$
  - with only 1.5% signal loss

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

Single Event Sensitivity

- Normalisation channel: $K^+ \to \pi^+\pi^0$, momentum range $p \in [15,45]\, GeV/c$
- Analysis is performed in (5 GeV/c) bins of momentum p_i

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

SES

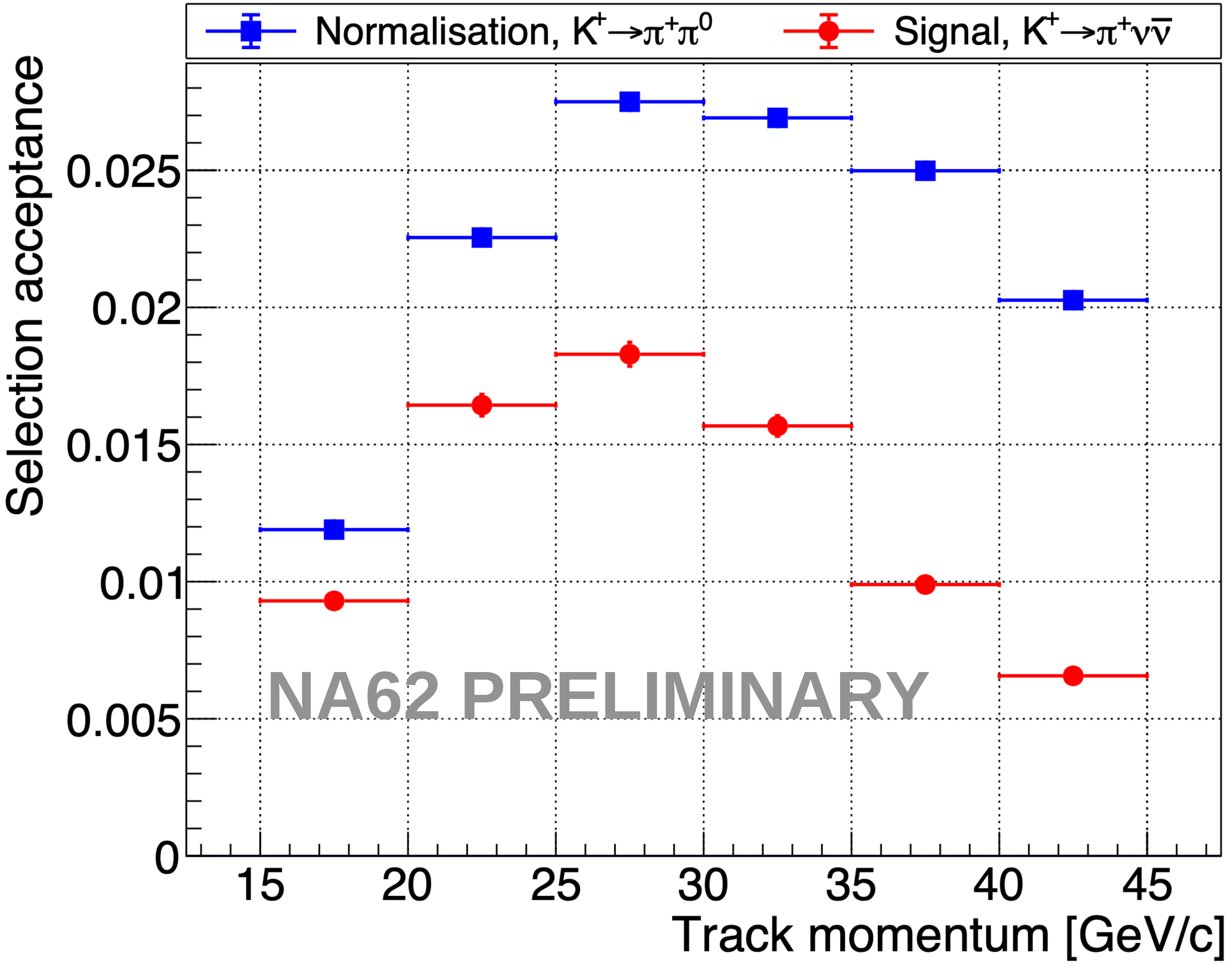
(SES: Branching ratio corresponding to expectation of 1 event)

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

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

Acceptances

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



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

Acceptances

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

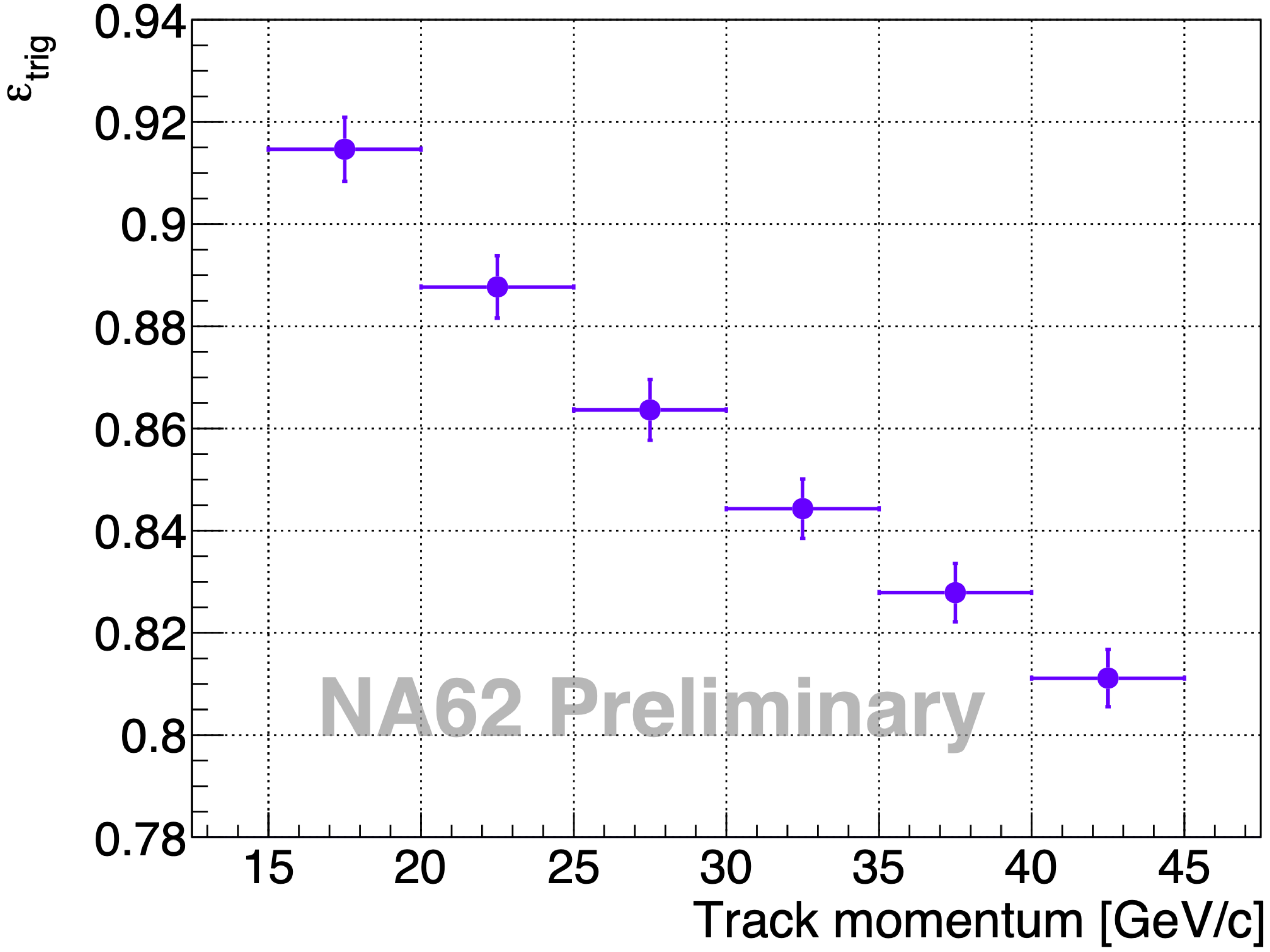
Case	OLD 2018 (S2)	NEW 2021-22	
Norm.	11.8%	13.4%	+15%
Signal	(6.37±0.64)%	(7.61±0.18)%	+20%

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

Trigger efficiencies

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

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



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

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

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

- 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 results

- momentum range $p \in [15,45]\, GeV/c$
- (5 GeV/c) bins of momentum p_i

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

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

$N_{\pi\pi}$	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	$(0.84 \pm 0.03) \times 10^{-11}$

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

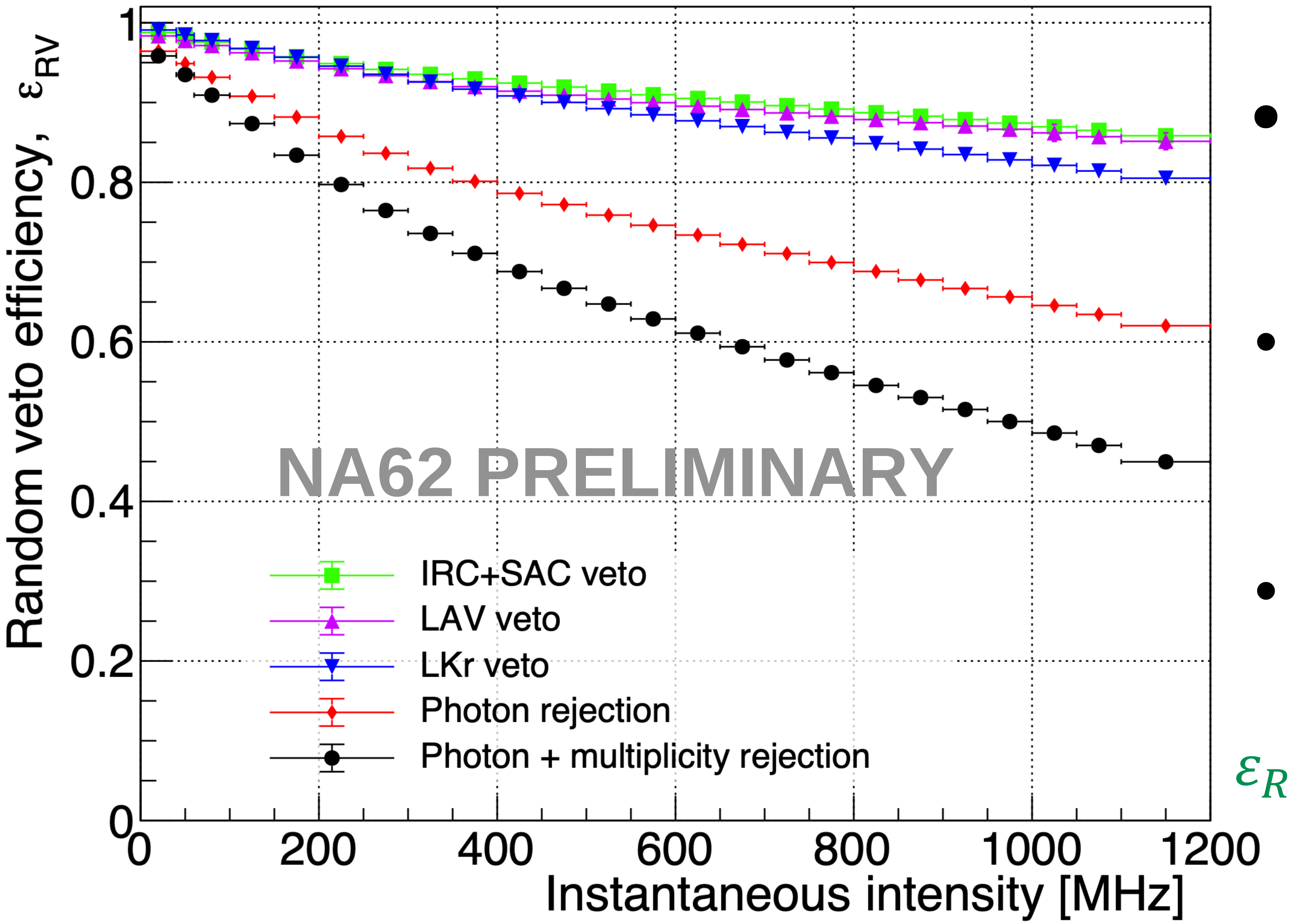
Double expected signal by including 21–22 data.

- **SES: Branching ratio corresponding to expectation of 1 event**
- **Significant improvement in SES uncertainty: old: 6.3% —> new: 3.5%**
- **Due to trigger efficiency cancellations and improved procedures for evaluation of acceptances and ε_{RV}**

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:**

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

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

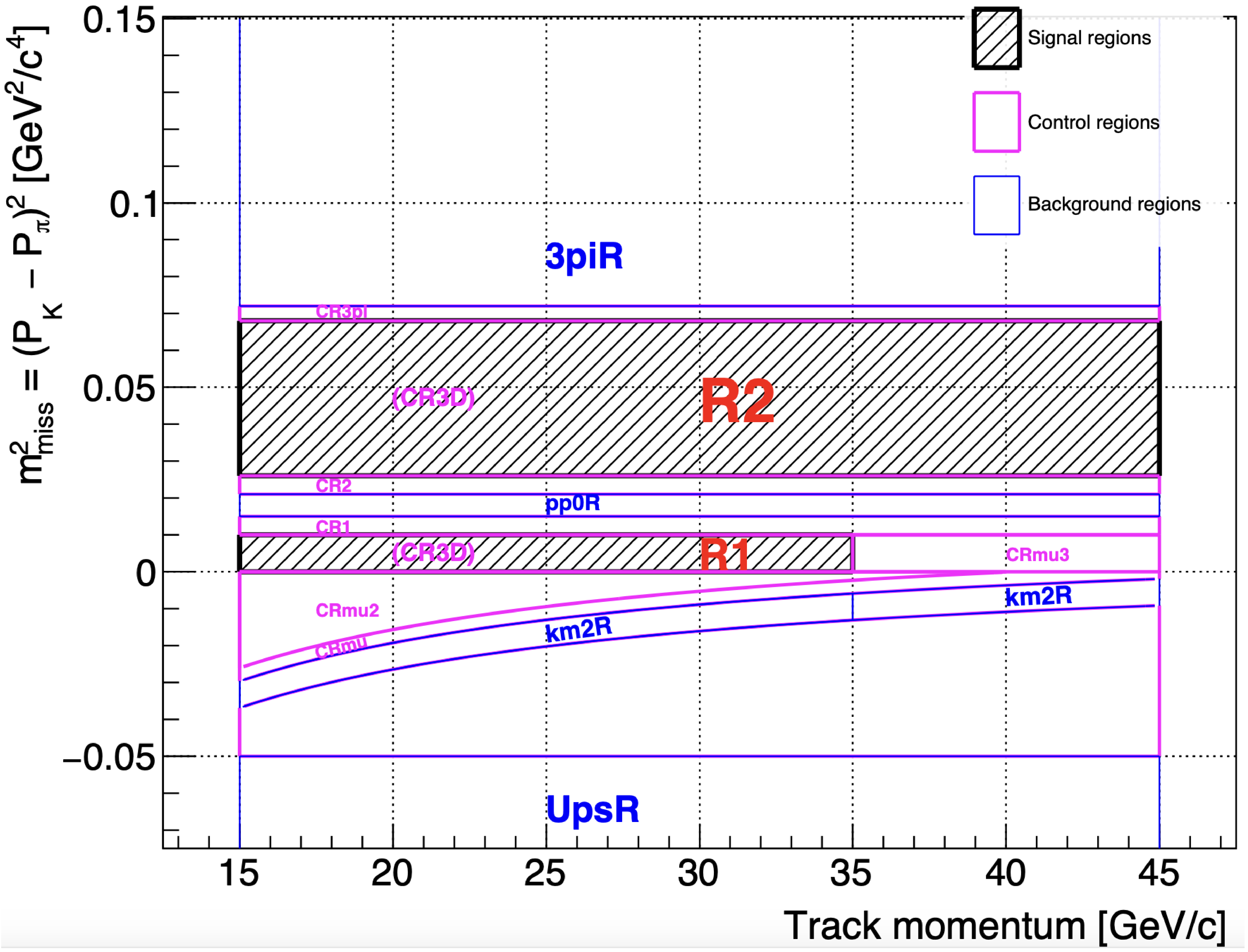
Bayesian classifier for $K^+ - \pi^+$ matching

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

Example of selection update

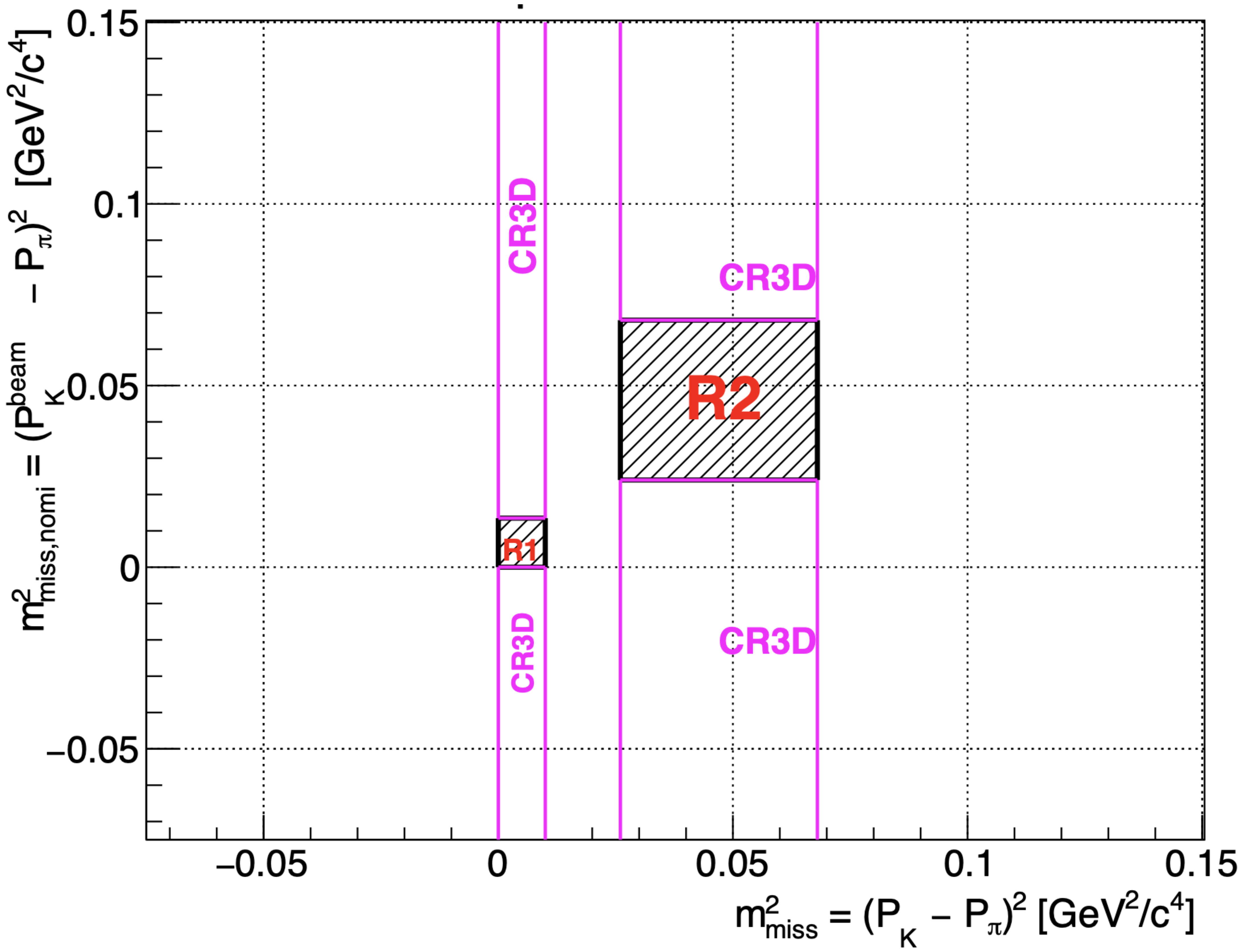
- **Output:** posterior probability of GTK track = true K^+
  - Use likelihoods of kaons (K) and pileup (P)
  - Likelihood ratio used to select true match when $N_{GTK} > 1$
- Efficiency improved (+10%) and mistagging probability maintained.

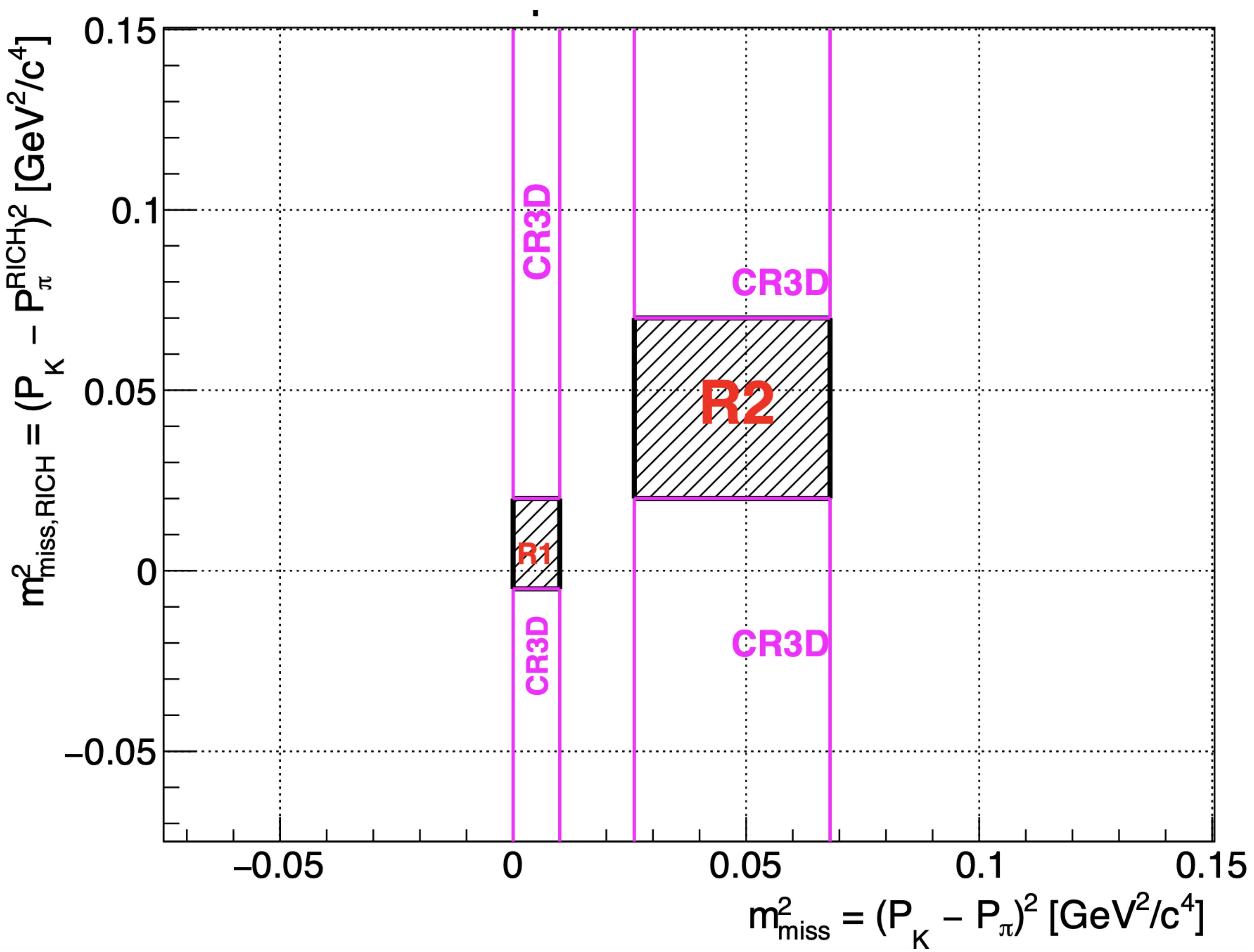
Kinematic regions



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

3D signal regions definition





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

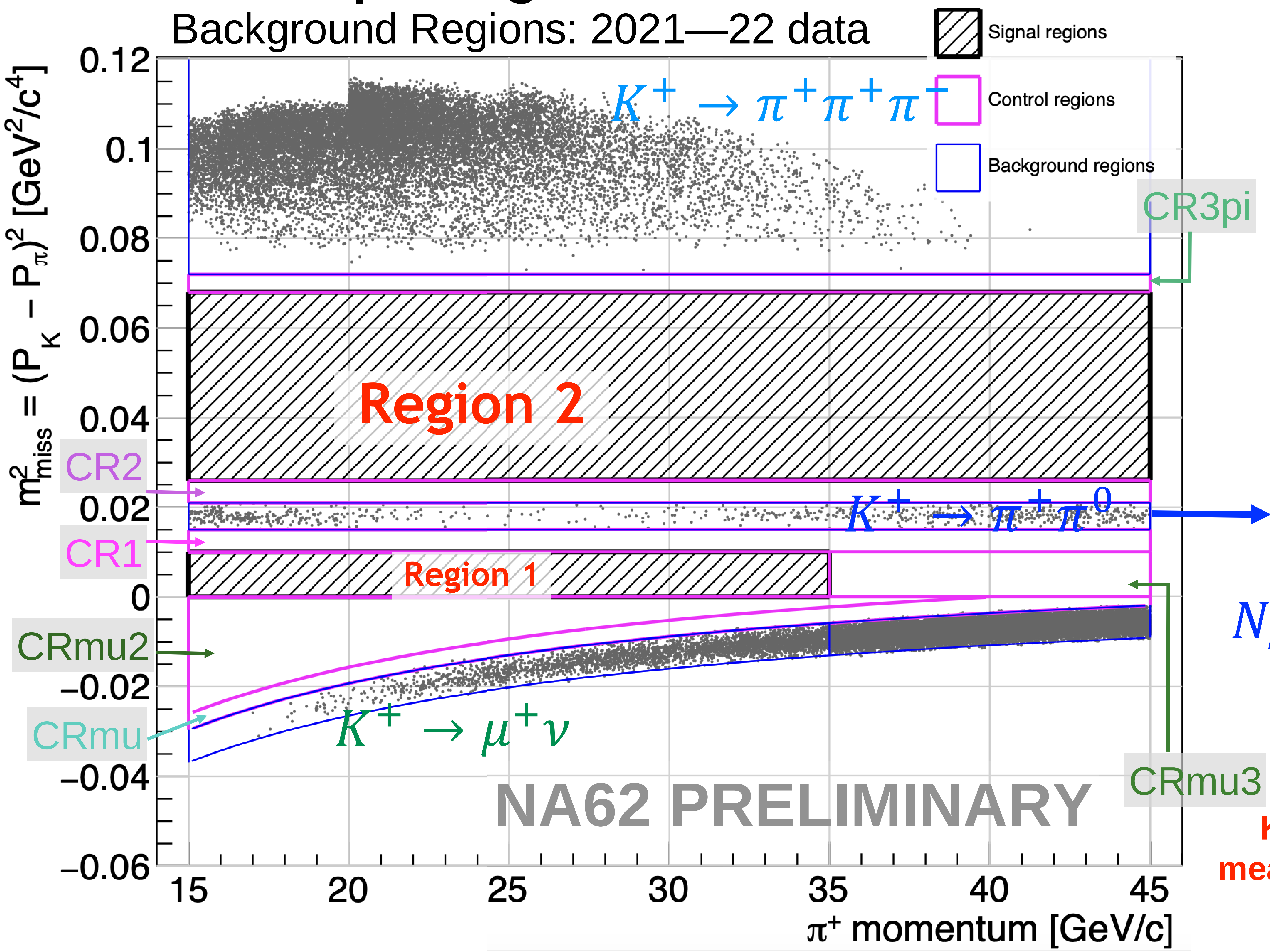
$$m^2_{miss} = (P_K - P_\pi)^2$$

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

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

Background 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

Other backgrounds

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

Effective # of K+

Random veto & trigger efficiencies

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

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

Branching ratio of K_{e4}
(from PDG)

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

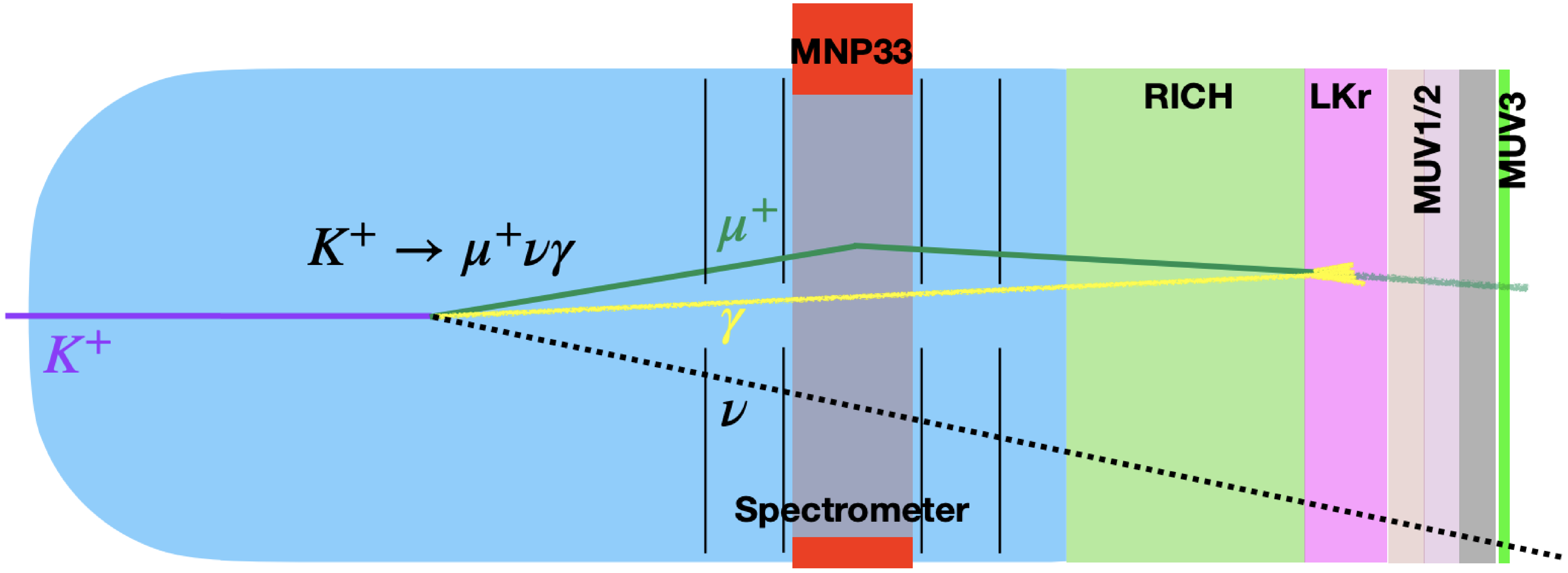
- $K^+ \to \pi^0\ell^+\nu$ and $K^+ \to \pi^+\gamma\gamma$:
  - Evaluated with simulations.
  - **Negligible contributions to total background.**

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

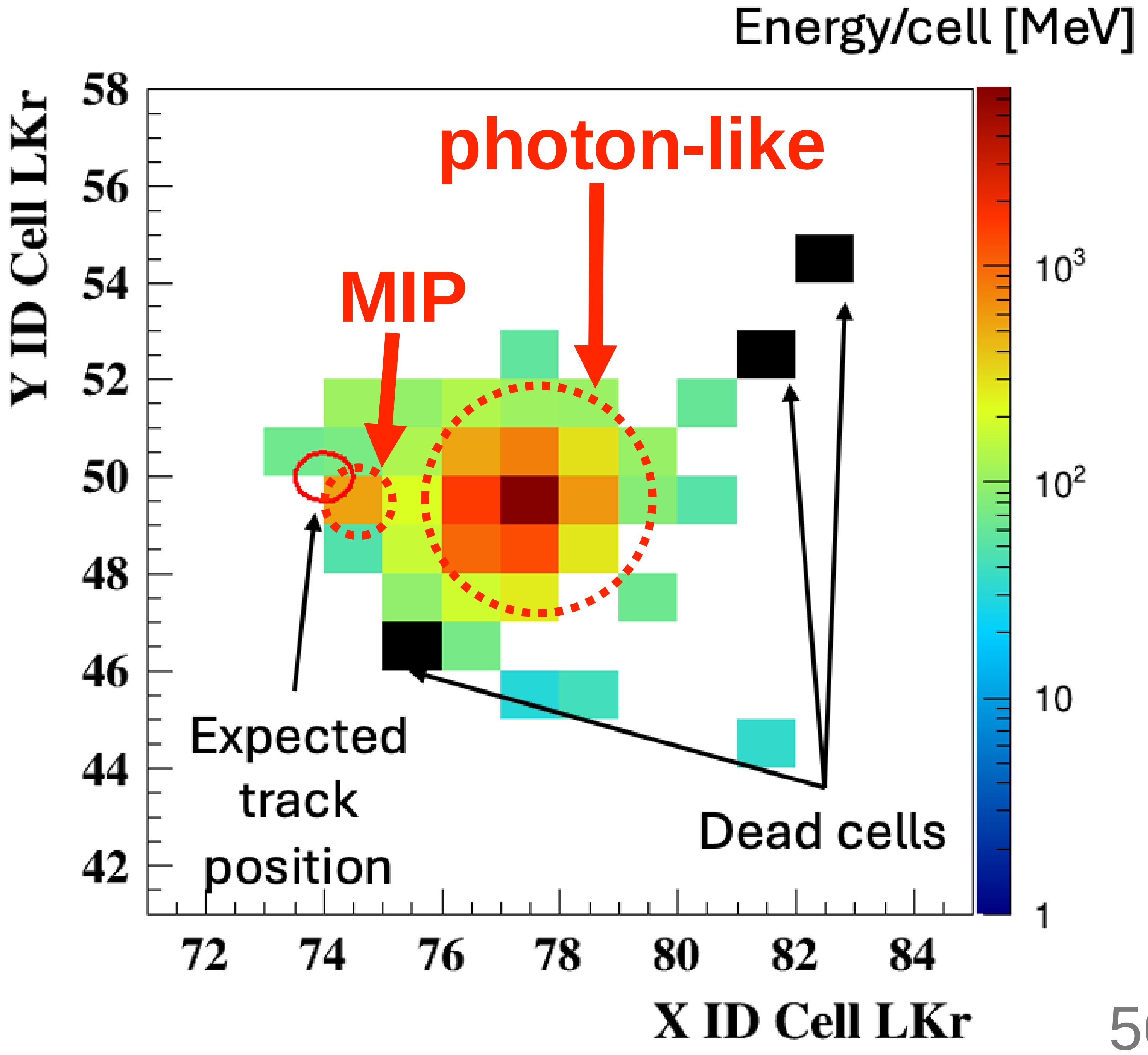
$$N_{bg}(K^+ \to \pi^+\gamma\gamma) = 0.01 \pm 0.01$$

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

- $K^+ \to \pi^+\pi^0\gamma$ **: included with “kinematic tails” estimation.**
  - Suppression: photon vetos, rejection with additional γ is 30x stronger.
  - Estimation: MC + measured single photon rejection efficiency : $N_{bg}(K^+ \to \pi^+\pi^0\gamma) = 0.07 \pm 0.01$
  - Validation: m^2_{miss} control regions (CR1,2 - see later)
- $K^+ \to \mu^+\nu\gamma$ **: not included in “kinematic tails” estimation if γ overlaps μ^+ at LKr (leading to misID as π^+)**
  - Suppression: based on $(P_K - P_\mu - P_\gamma)^2$ and E_γ with γ = LKr cluster (mis)associated to muon.
    - Necessary for 2021—22 data, since Calorimetric PID degraded at higher intensities.
  - Estimation: min. Bias data control sample with signal in MUV3 : $N_{bg}(K^+ \to \mu^+\nu\gamma) = 0.8 \pm 0.4$
  - Validation: data sample without $K^+ \to \mu^+\nu\gamma$ veto and PID = “less pion-like” (Calo BDT bins below π^+ bin).



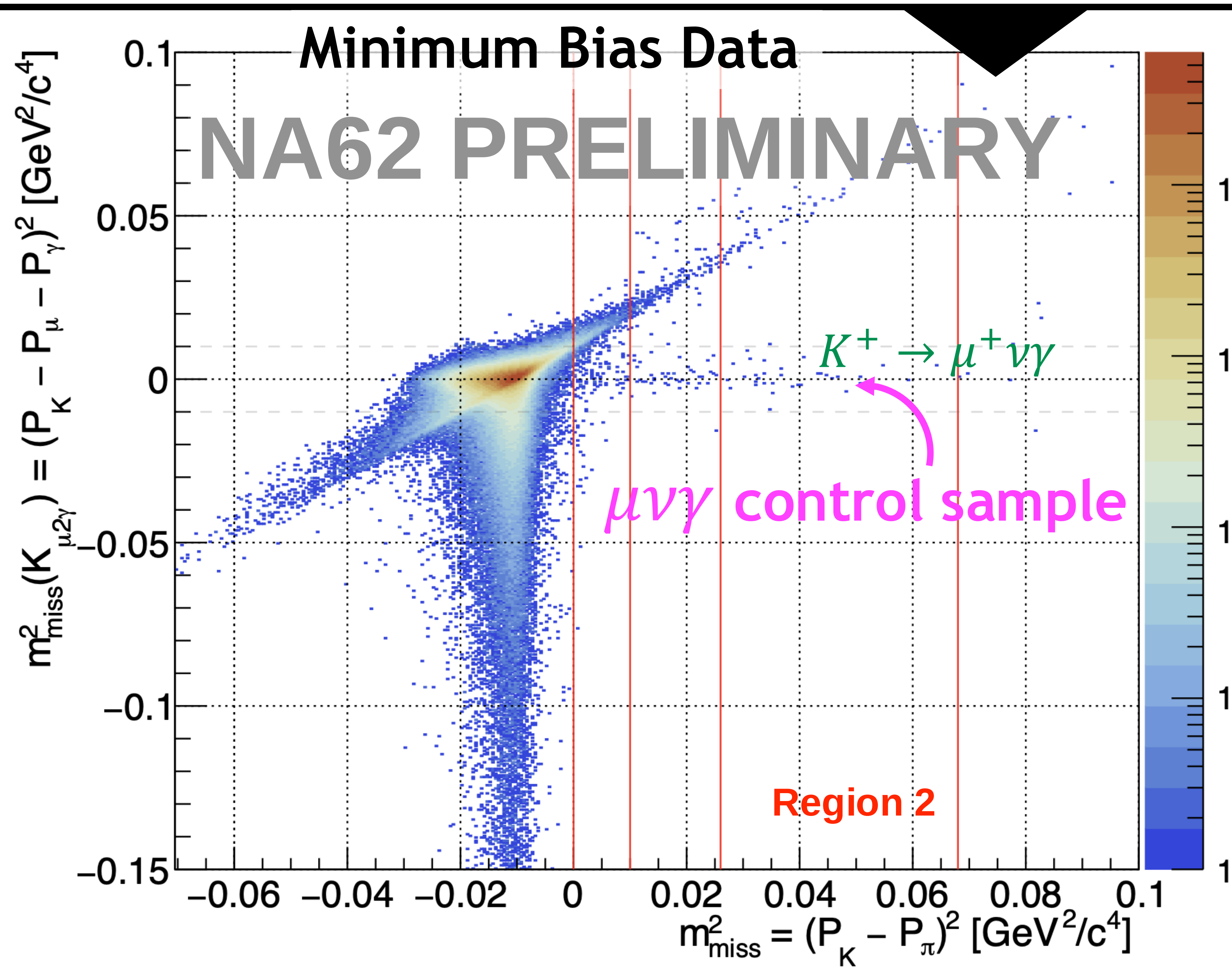
Sketch only



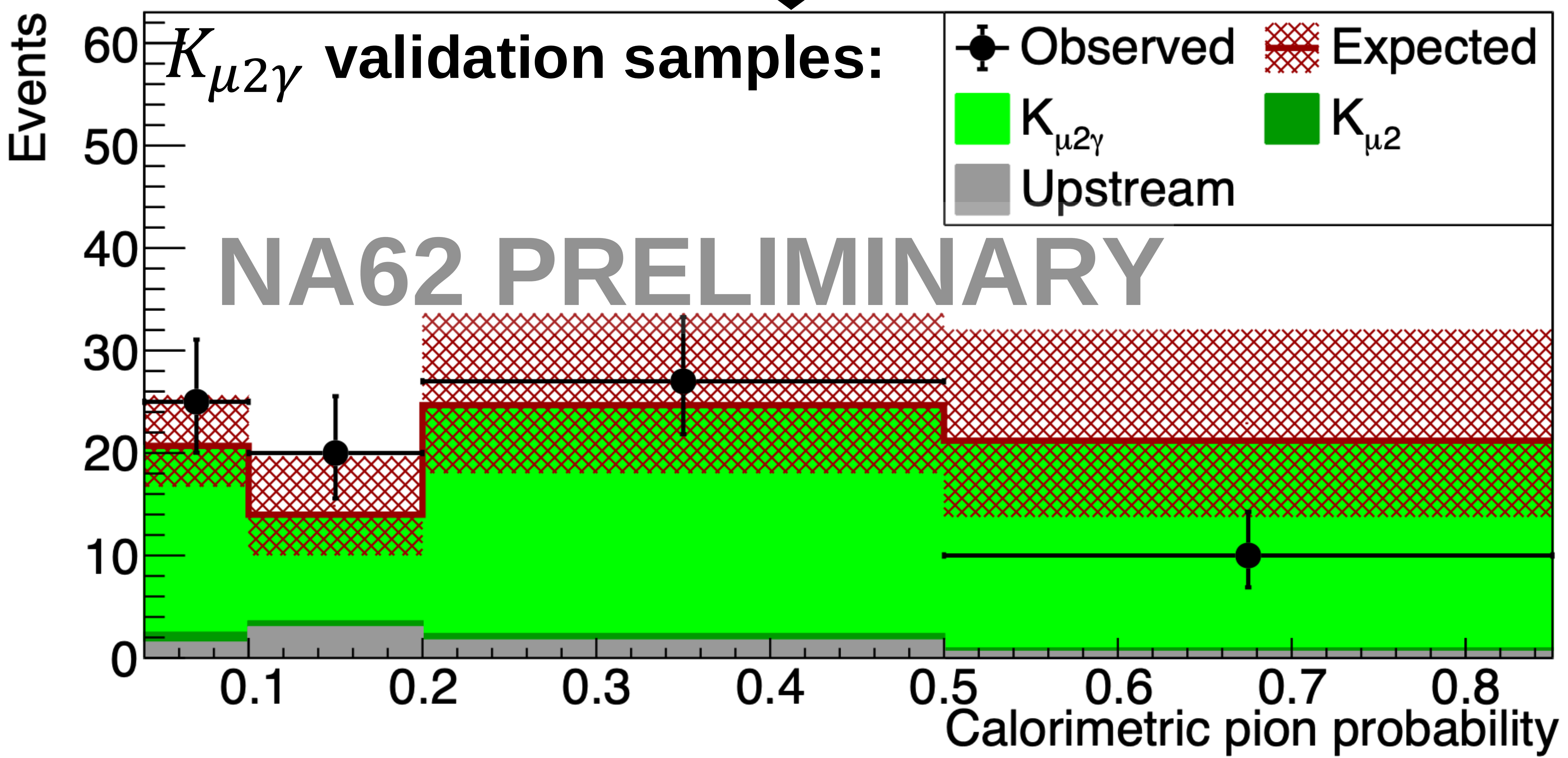
$K^+ \to \mu^+\nu\gamma$ Background

- 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 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:



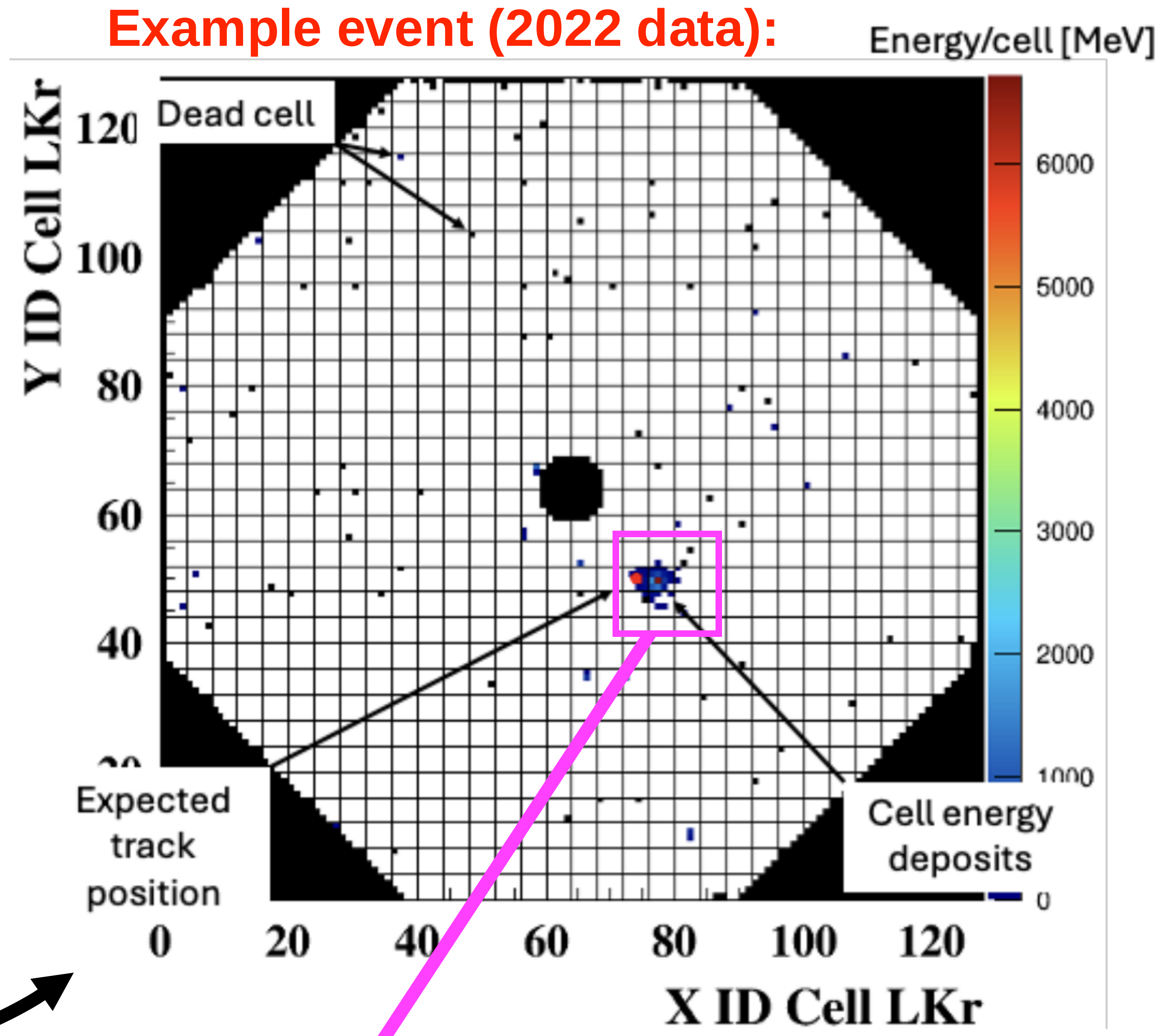
Validation: data sample with PID = "less pion-like" (Calo BDT bins below π^+ bin).

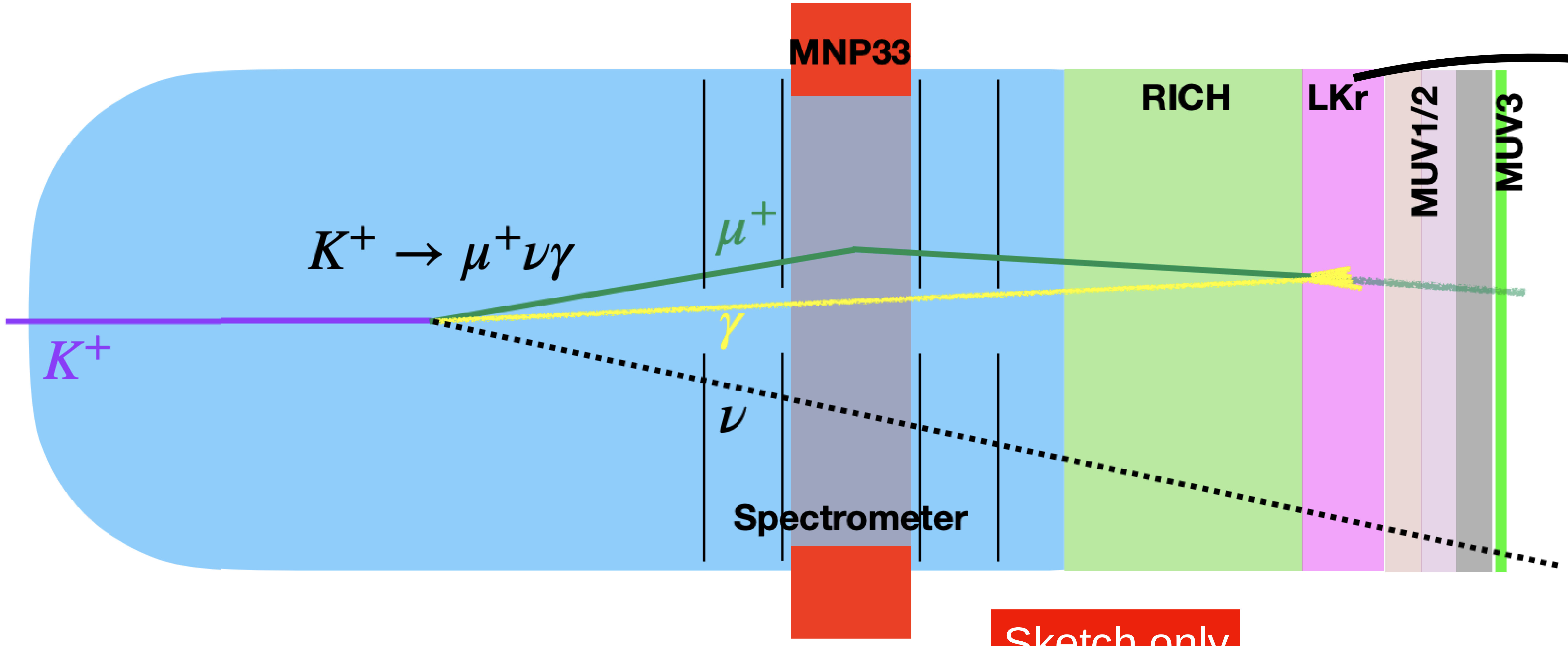


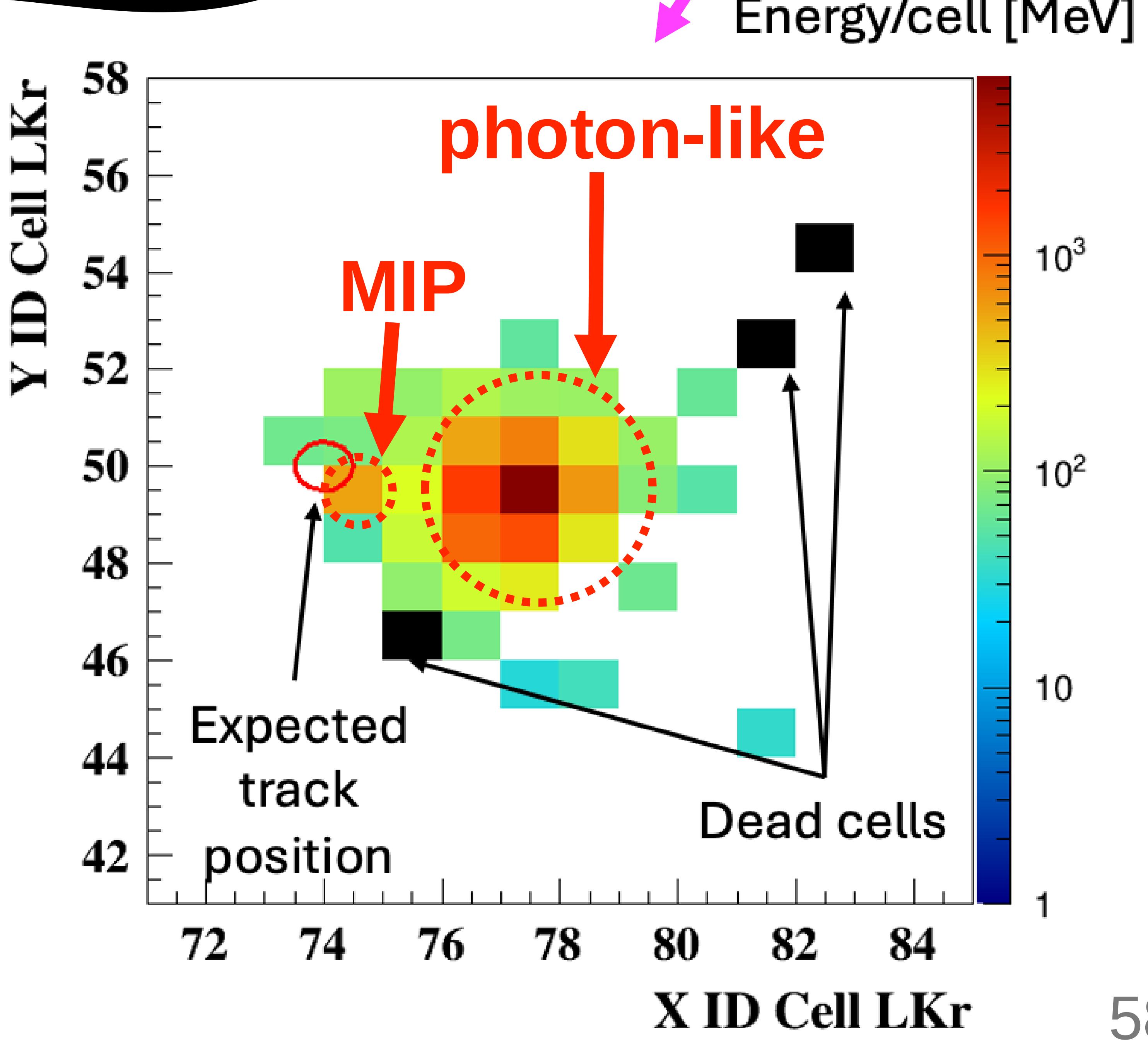
- Before $K^+ \to \mu^+\nu\gamma$ veto: found excess of events at $p > 35\,GeV/c$ in Region 2 relative to 2016−18 data.
- Additional background identified and studied in data control samples & MC.
- $K^+ \to \mu^+\nu\gamma$ veto added to selection criteria for final analysis.

Background 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).

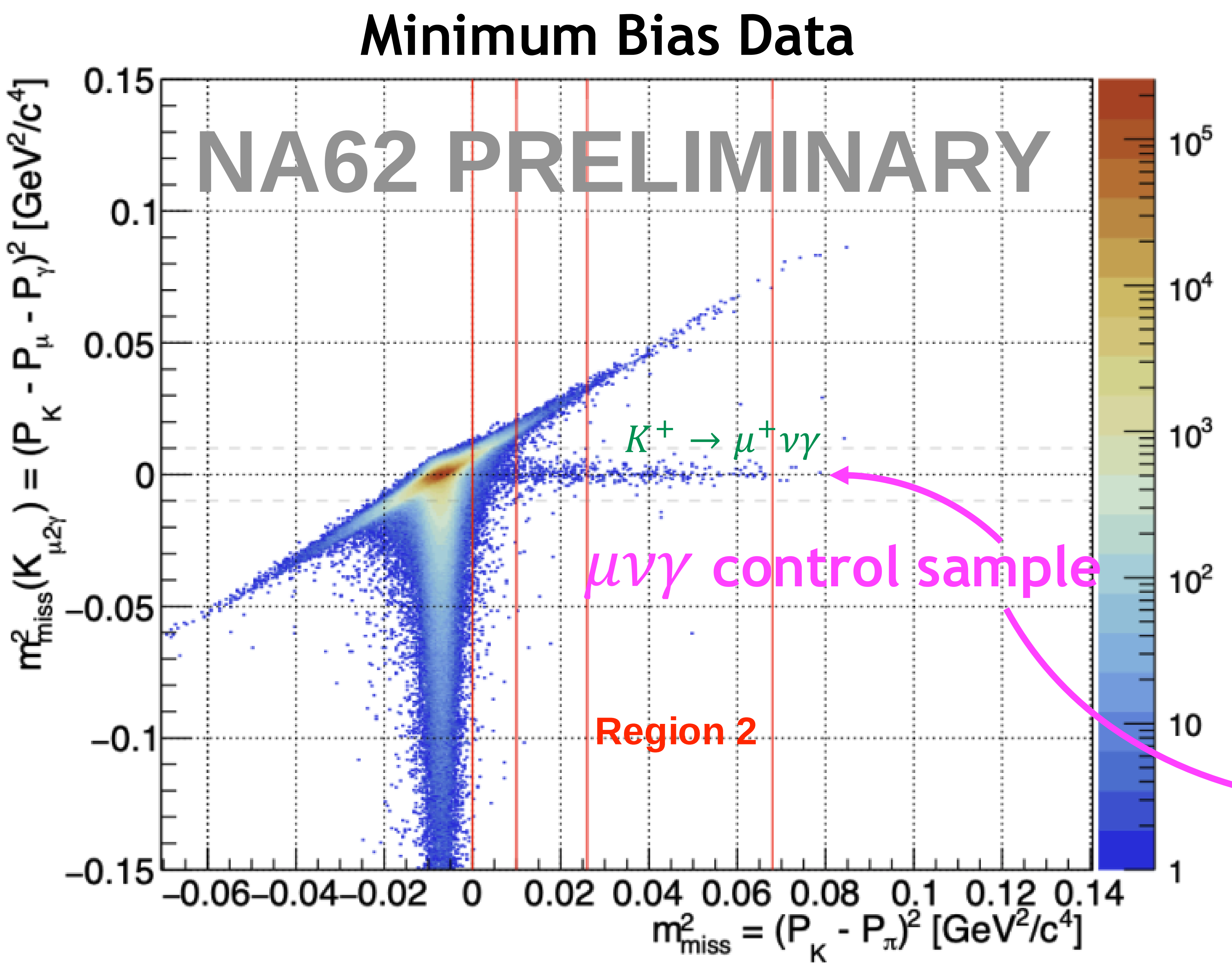






Background evaluation: $K^+ \to \mu^+\nu\gamma$

- 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).

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

- D_{MB}: Downscaling of MB trigger
- $\frac{\varepsilon_{signal}}{\varepsilon_{MB}}$: Ratio of $\pi^+\nu\bar{\nu}$ and MB trigger efficiencies
- P_{misID}: probability of γ+μ^+ being misidentified as a π^+

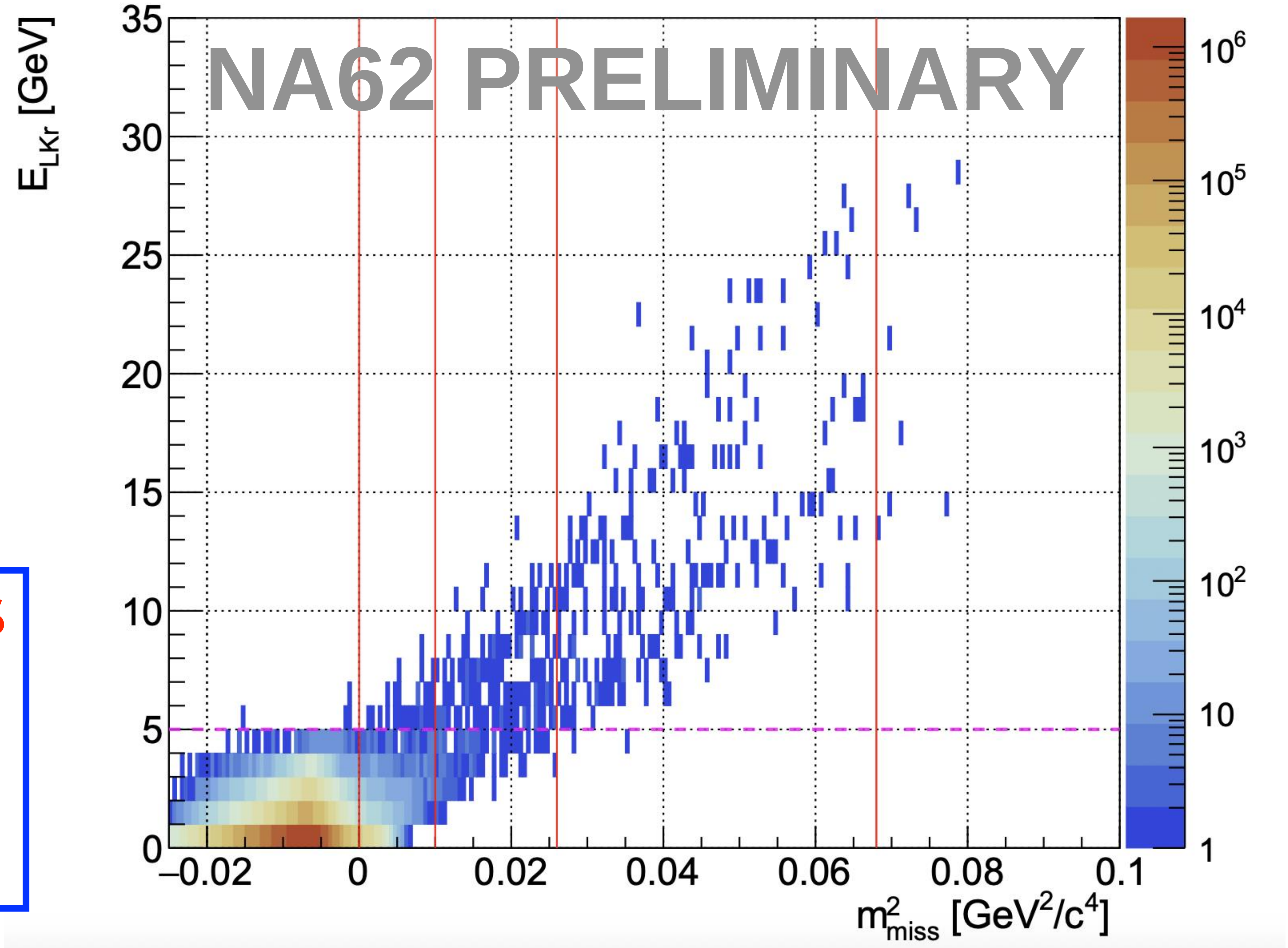
Not included in kinematic tails calculation because the tails sample imposes Calorimetric PID=μ^+, while here there is misID of $\mu^+\gamma \Rightarrow \pi^+$.

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.

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



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

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

Upstream background evaluation

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

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

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

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

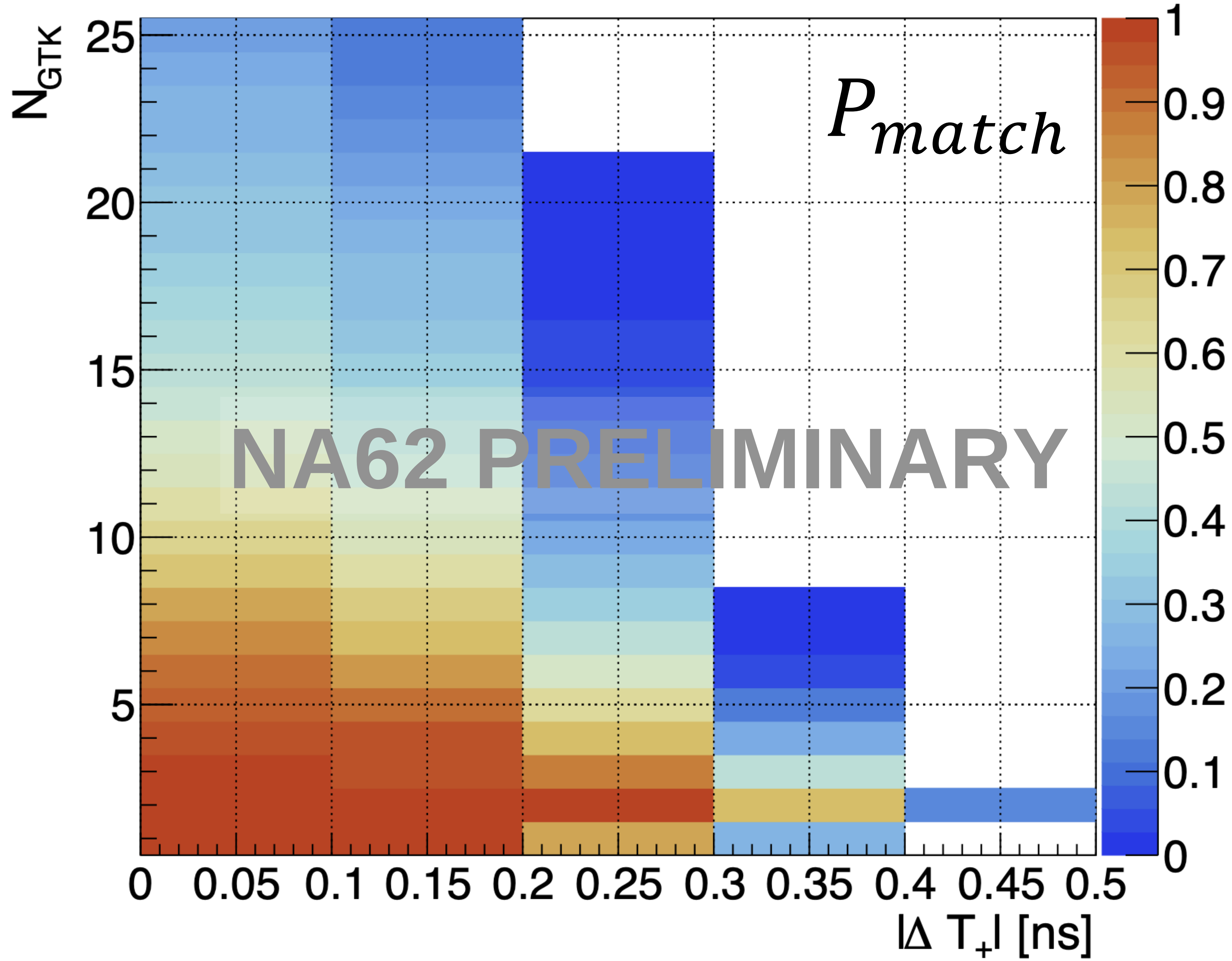
Calculate using bins (i) of $(\Delta T_+, N_{GTK})$

[Updated to fully data-driven procedure]

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

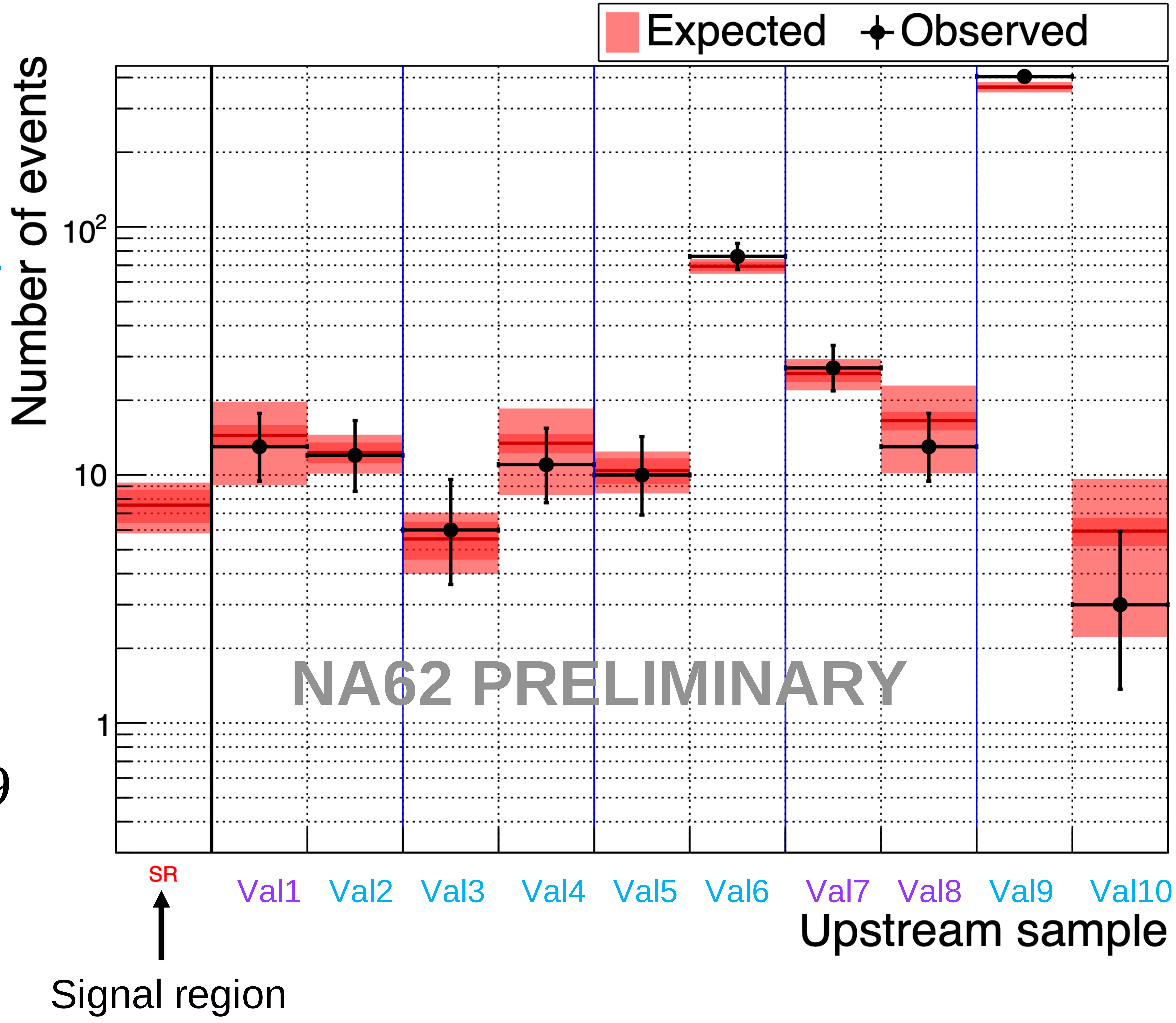
$$N_{bg}(Upstream) = 7.4^{+2.1}_{-1.8}$$

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



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.**



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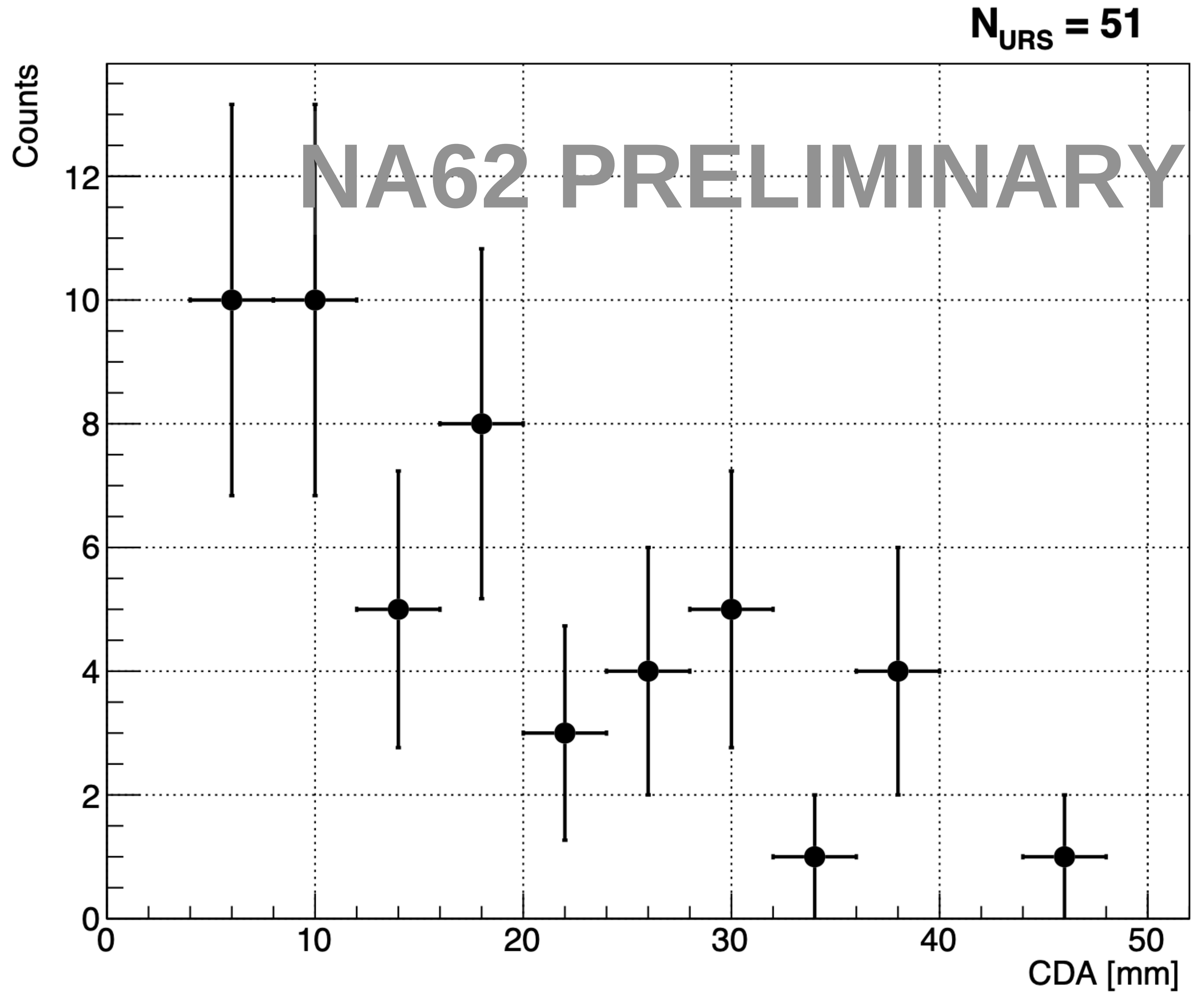

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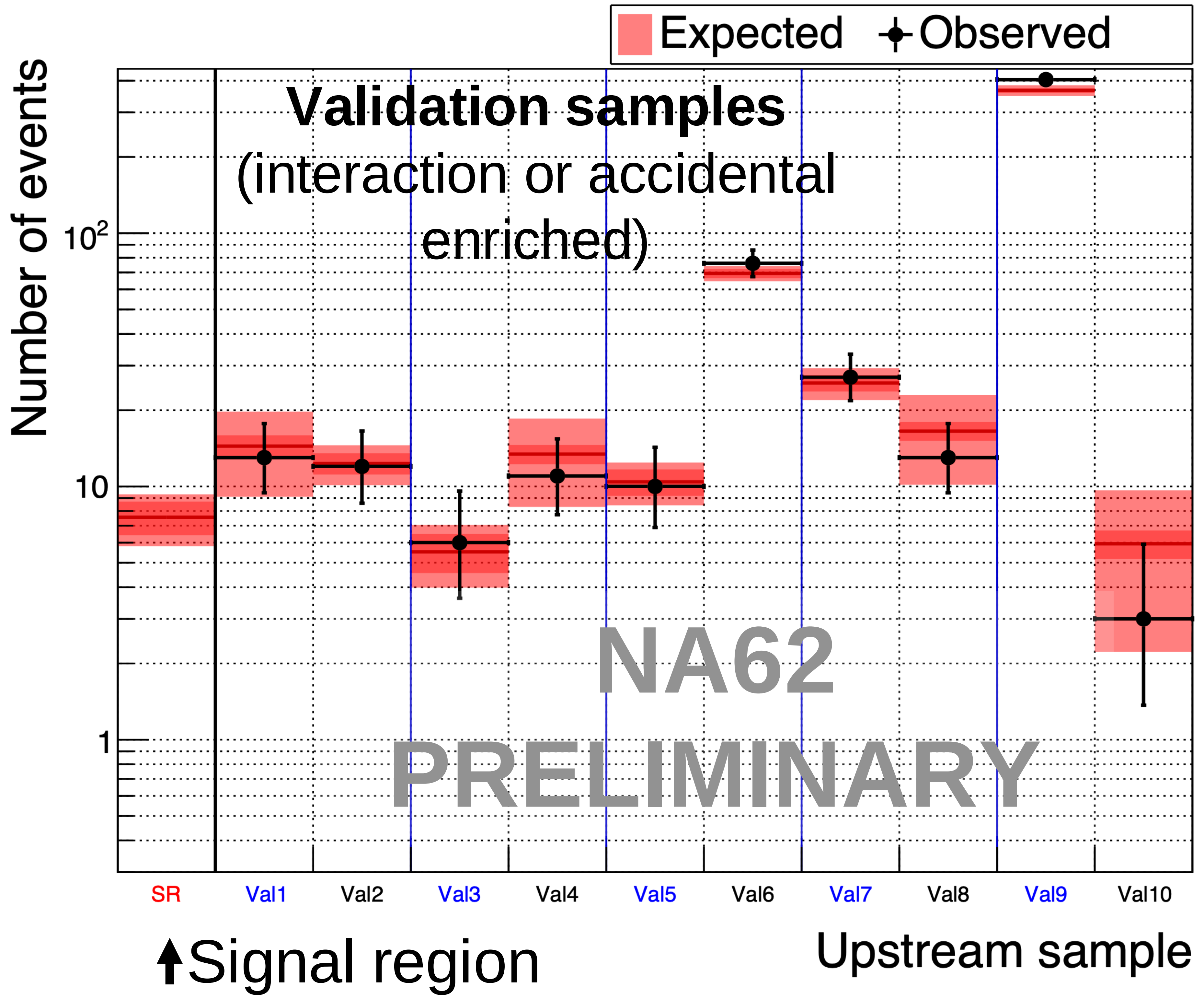


Summary of expectations

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

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

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

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

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

- $N^{SM}_{\pi\nu\bar{\nu}}$ per SPS burst: 2.5×10^{-5} in 2022
  - c.f. 1.7×10^{-5} in 2018. $\Rightarrow$ **signal yield increased by 50%**
- Sensitivity for BR $\sim \frac{\sqrt{S+B}}{S}$ slightly improved

Results in context

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

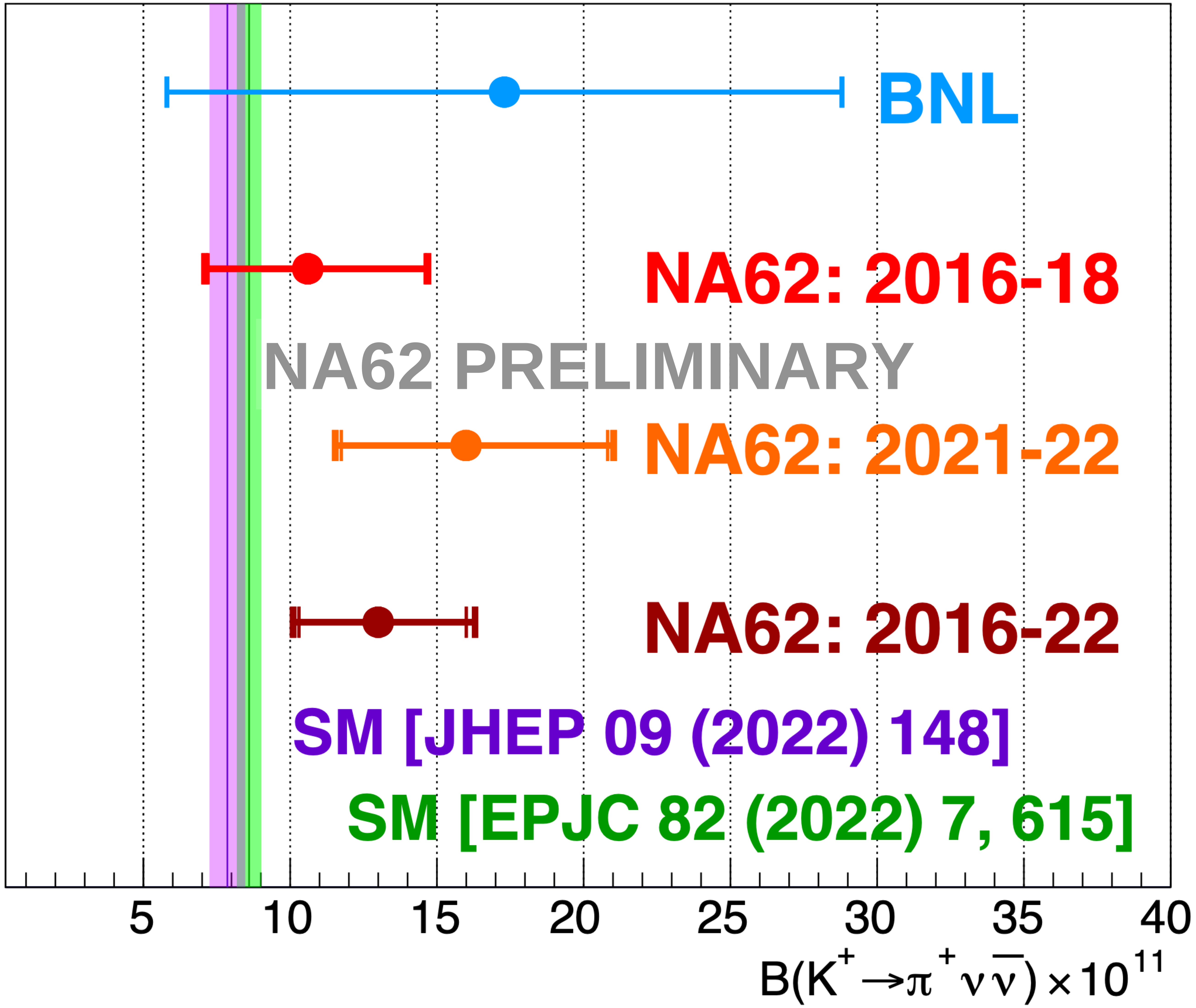
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$$

[JHEP 06 (2021) 093]

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

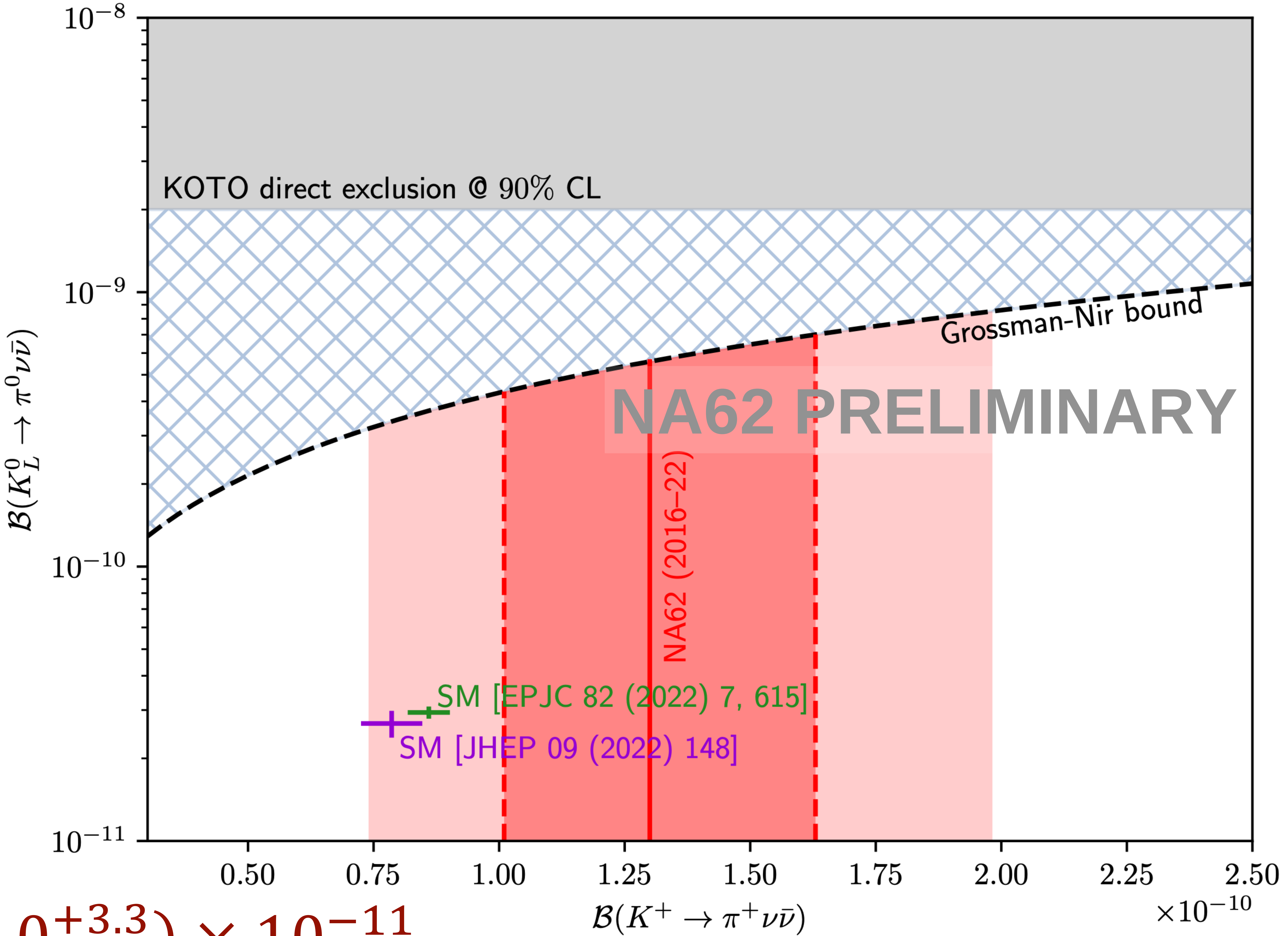
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

- NA62 results are consistent
- Central value moved up (now 1.5—1.7σ above SM)
- Fractional uncertainty decreased: 40% to 25%
- Bkg-only hypothesis rejected with significance Z>5



Results in context

- Fractional uncertainty: 25%
- Bkg-only hypothesis rejected with significance Z>5
- **Observation of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay with BR consistent with SM prediction, within 1.7σ**
  - **Need full NA62 data-set to clarify SM agreement or tension**

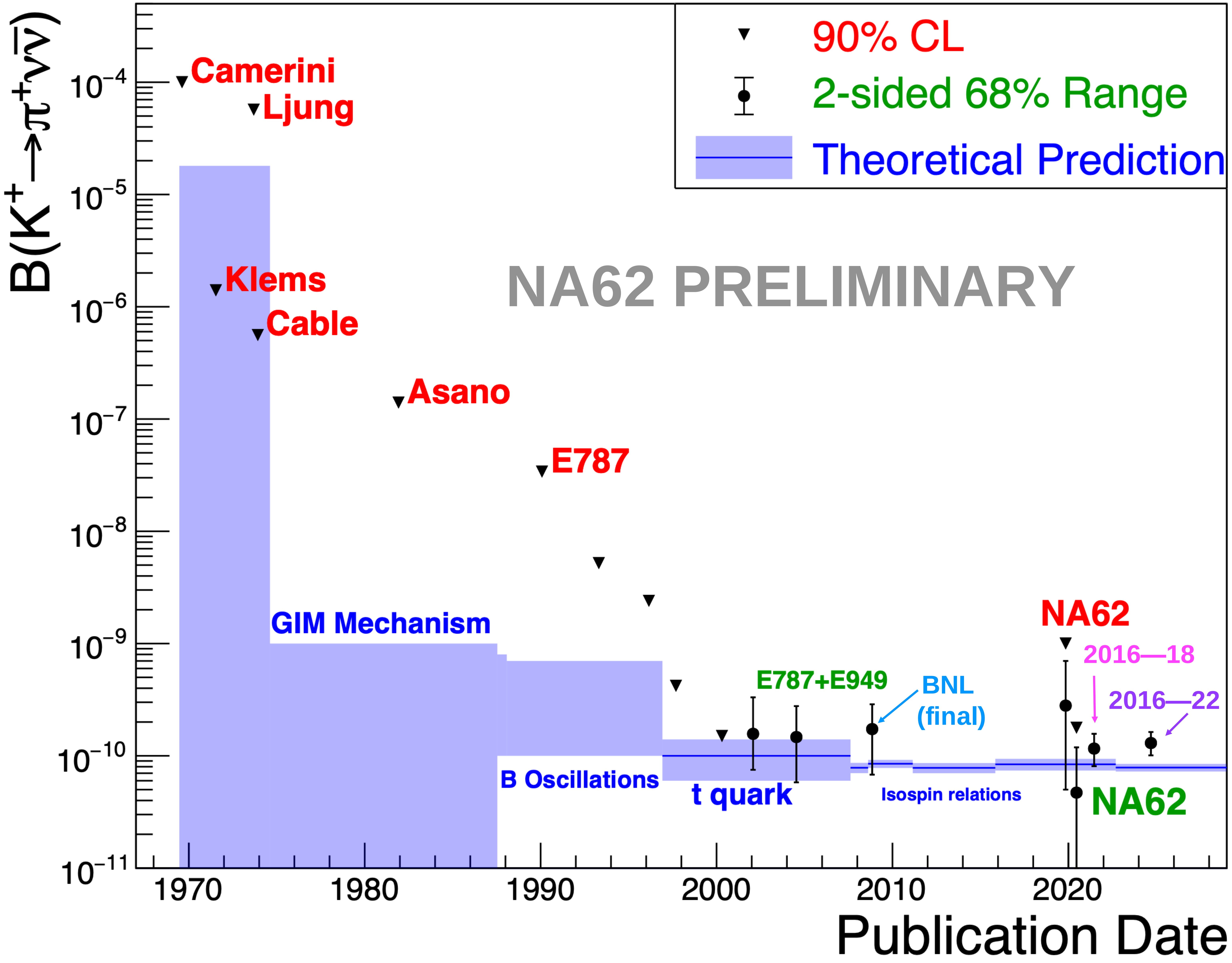


$$\mathcal{B}^{16-22}_{\pi\nu\bar{\nu}} = (13.0^{+3.3}_{-2.9}) \times 10^{-11}$$

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

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]

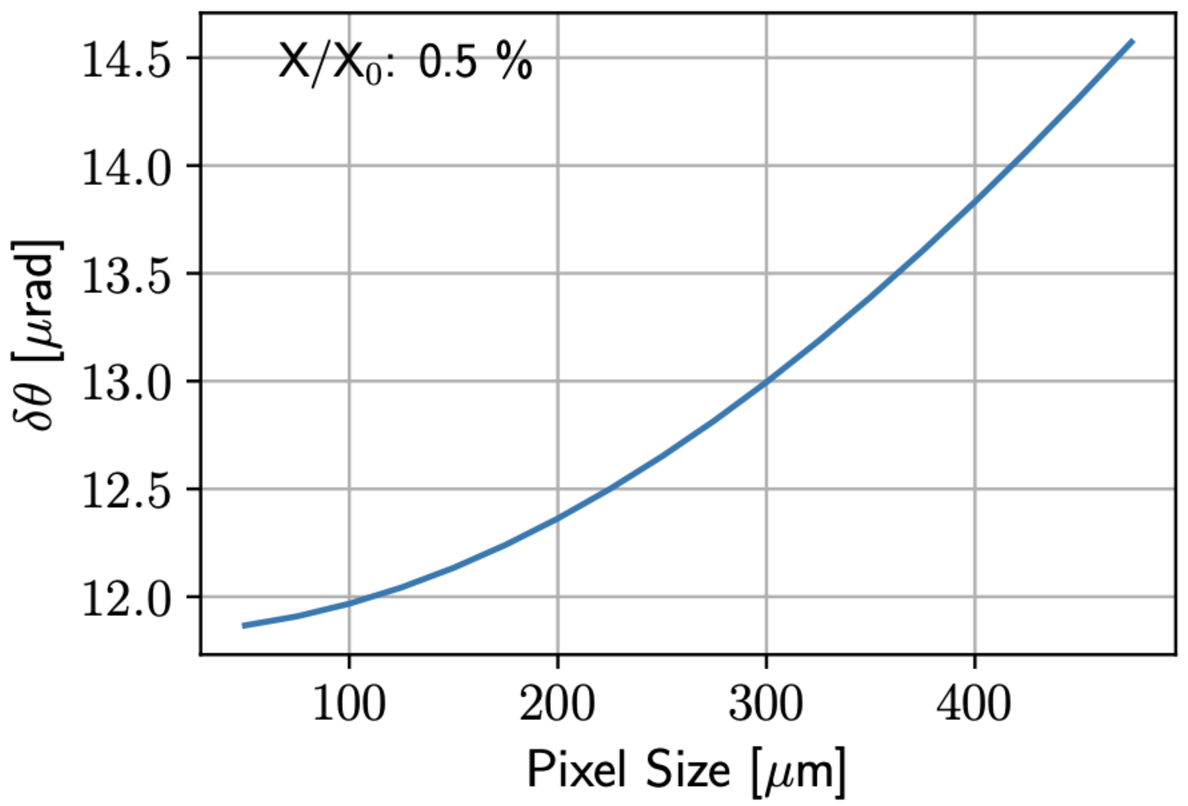


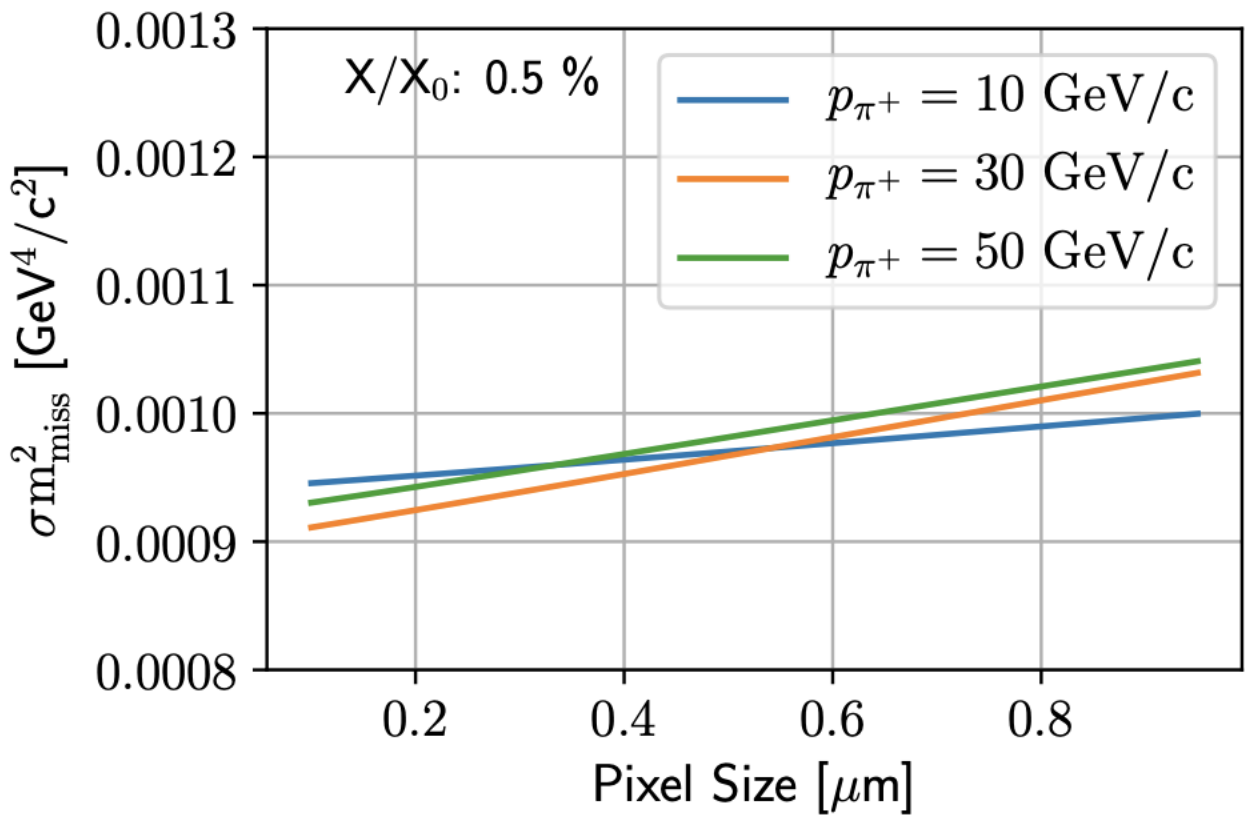
NA62 Si pixels

300 um pixel pitch, 150 um sensor thickness, 500 um total station thickness

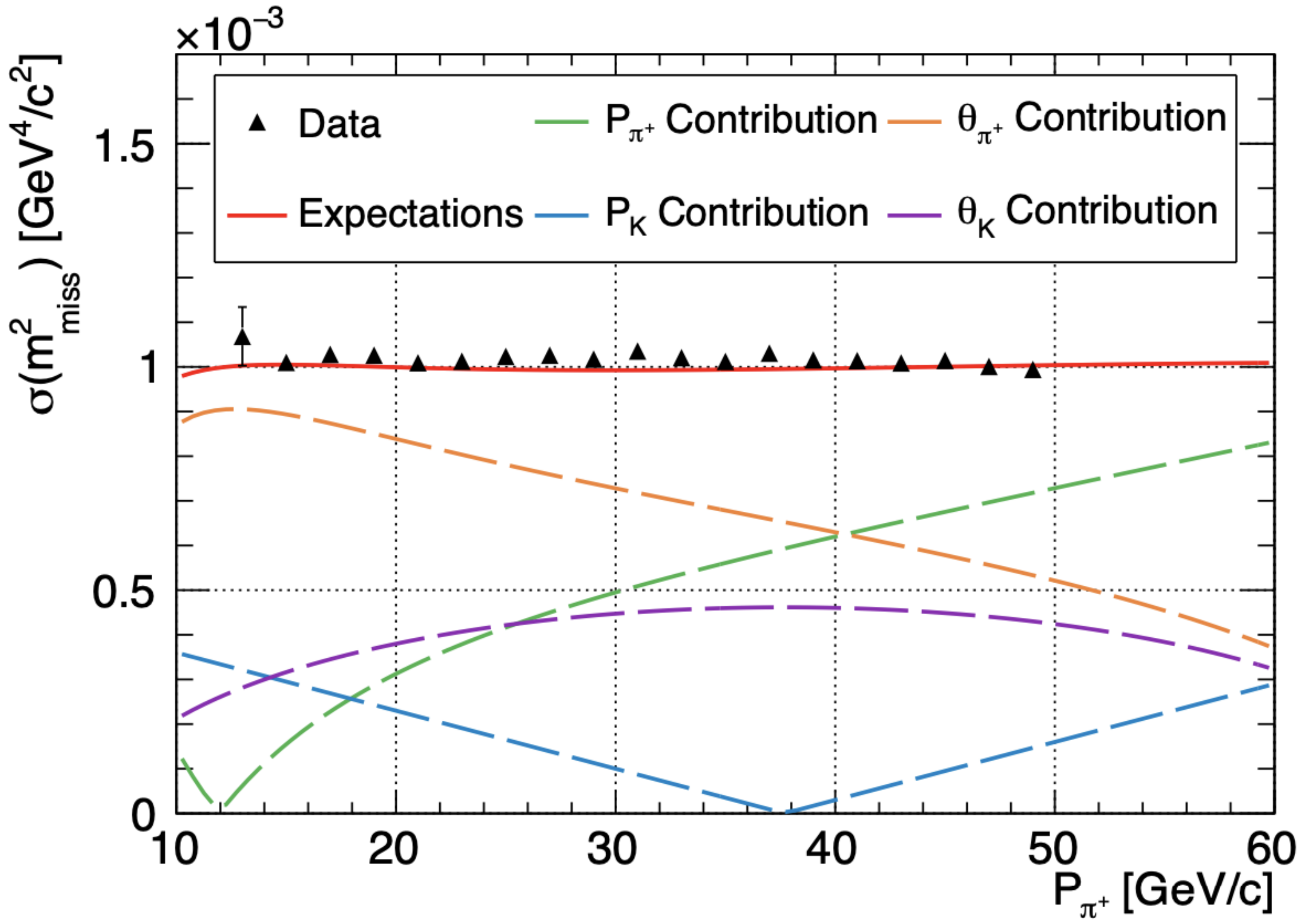
Single hit time resolution:

$$\sigma_t = \sigma_{\text{elec}} \oplus \sigma_{\text{TDC}} \oplus \sigma_{\text{field}} \oplus \sigma_{\text{straggling}}$$
$$= 28\text{ ps} \oplus 75\text{ ps} \oplus 85\text{ ps} \oplus 100\text{ ps}$$





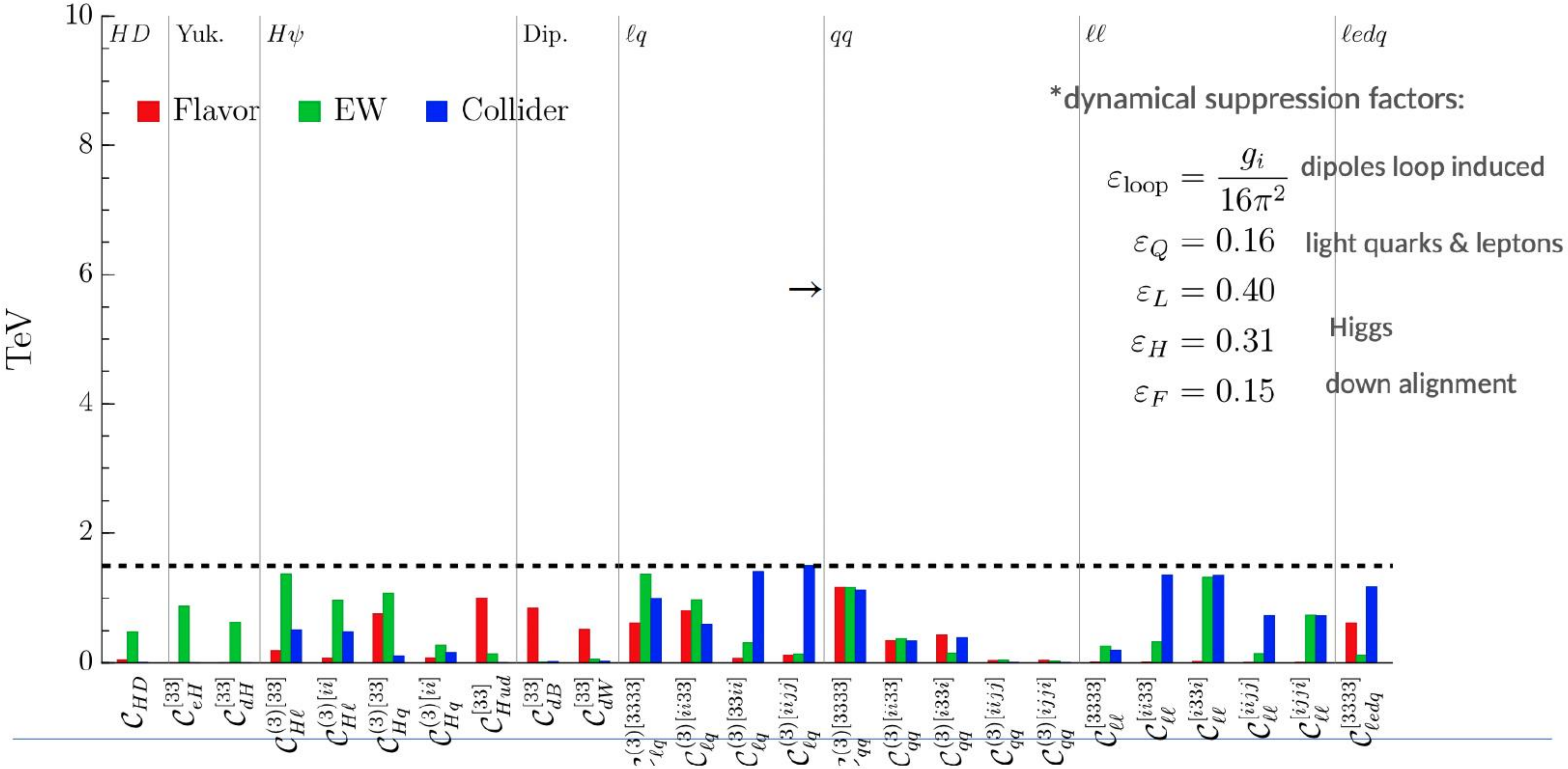
Smaller pixel pitch can improve only the angular component on the K direction, not on the momentum resolution. It improves the timing resolution.



Looking for NP with flavour observables

Assuming different NP couplings for light families makes it possible to suppress couplings to valence quarks and relax direct search bounds to 1 TeV

U(2)-symmetric SMETF, non-universal: bounds



arXiv:2311.00020

With current data, NP mainly coupled to the 3rd family can exist at scales as low as 1-2 TeV under conditions* that are radiatively stable and simple to realise
→ large room for improvement for the experiments