

A new measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ by the NA62 experiment

Joel Swallow (INFN-LNF)
on behalf of the NA62 collaboration

Contents:

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

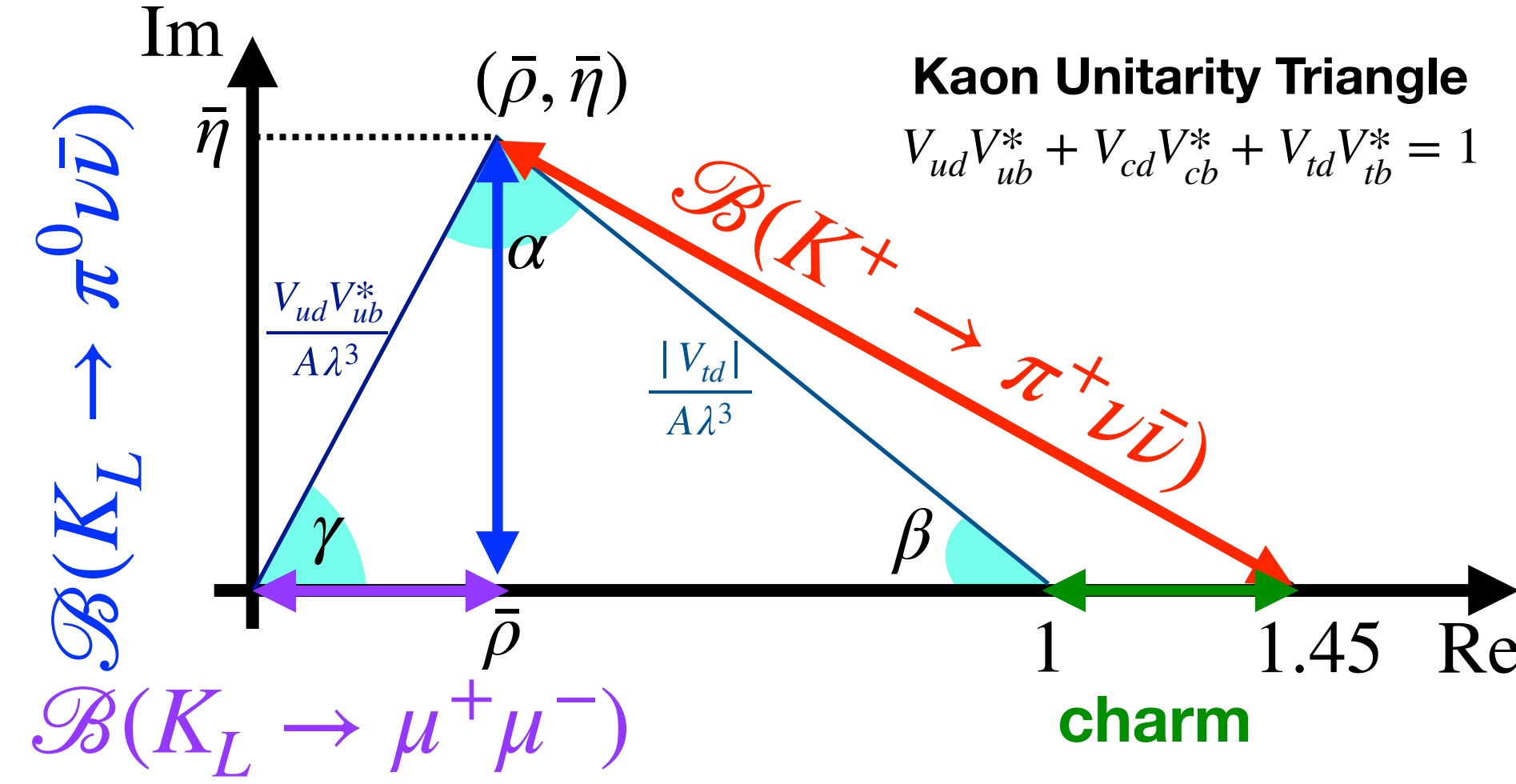
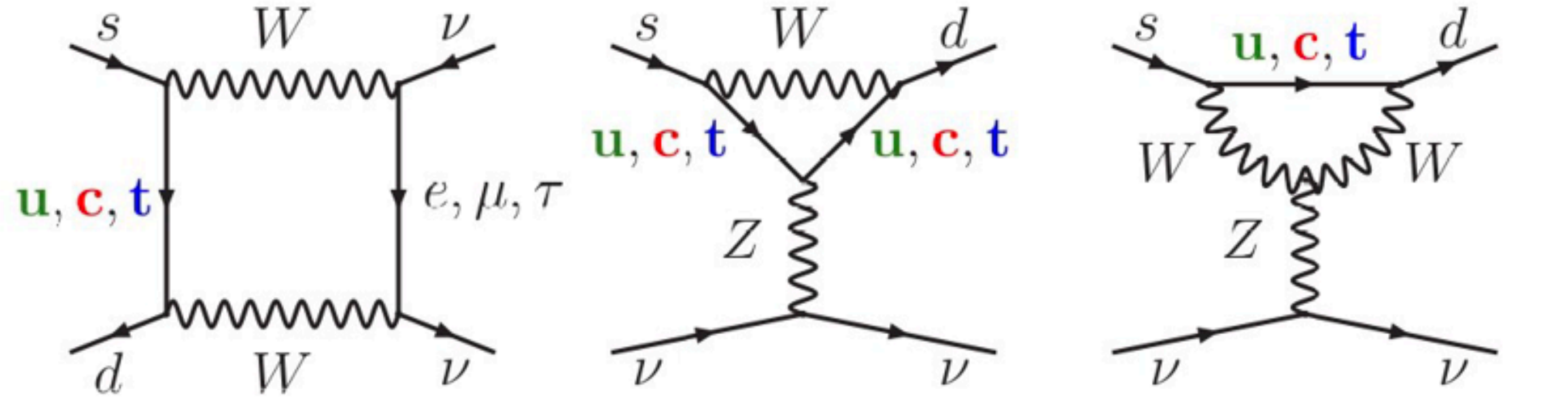
Rare Kaon Decays: SM and Beyond

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

$K \rightarrow \pi \nu \bar{\nu}$: Precision test of the Standard Model



SM: Z-penguin & box diagrams



• $\mathcal{B}(K \rightarrow \pi \nu \bar{\nu})$ highly suppressed in SM

• GIM mechanism & maximum CKM suppression $s \rightarrow d$ transition: $\sim \frac{m_t}{m_W} \left| V_{ts}^* V_{td} \right|$

• Theoretically clean \Rightarrow high precision SM predictions

• Dominated by short distance contributions.

• Hadronic matrix element extracted from $\mathcal{B}(K \rightarrow \pi^0 \ell^+ \nu_\ell)$ decays via isospin rotation.

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



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



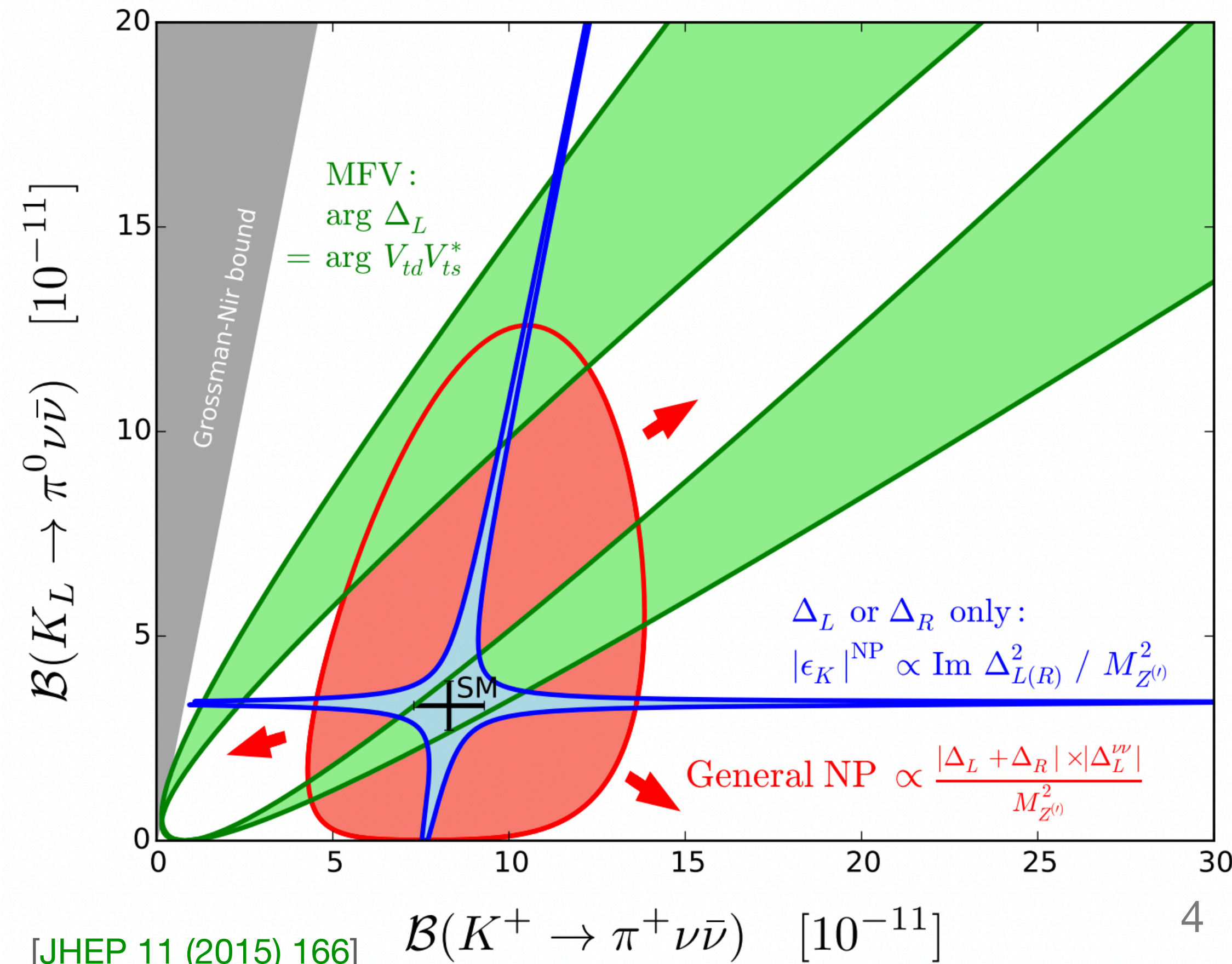
- Correlations between BSM contributions to BRs of K^+ and K_L modes [[JHEP 11 \(2015\) 166](#)].
 - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ϵ'/ϵ , ΔM_B , B-decays) [[JHEP 12 \(2020\) 097](#)][[PLB 809 \(2020\) 135769](#)].
- Leptoquarks [[EPJ.C 82 \(2022\) 4, 320](#)], Interplay between CC and FCNC [[JHEP 07 \(2023\) 029](#)], NP in neutrino sector [[EPJ.C 84 \(2024\) 7, 680](#)] and additional scalar/tensor contributions [[JHEP 12 \(2020\) 186](#)][[arXiv:2405.06742](#)] ...

- **Green:** CKM-like flavour structure
 - Models with Minimal Flavour Violation
- **Blue:** new flavour-violating interactions where LH or RH currents dominate
 - Z' models with pure LH/RH couplings
- **Red:** general NP models without above constraints
- **Grossman-Nir Bound:** model-independent relation

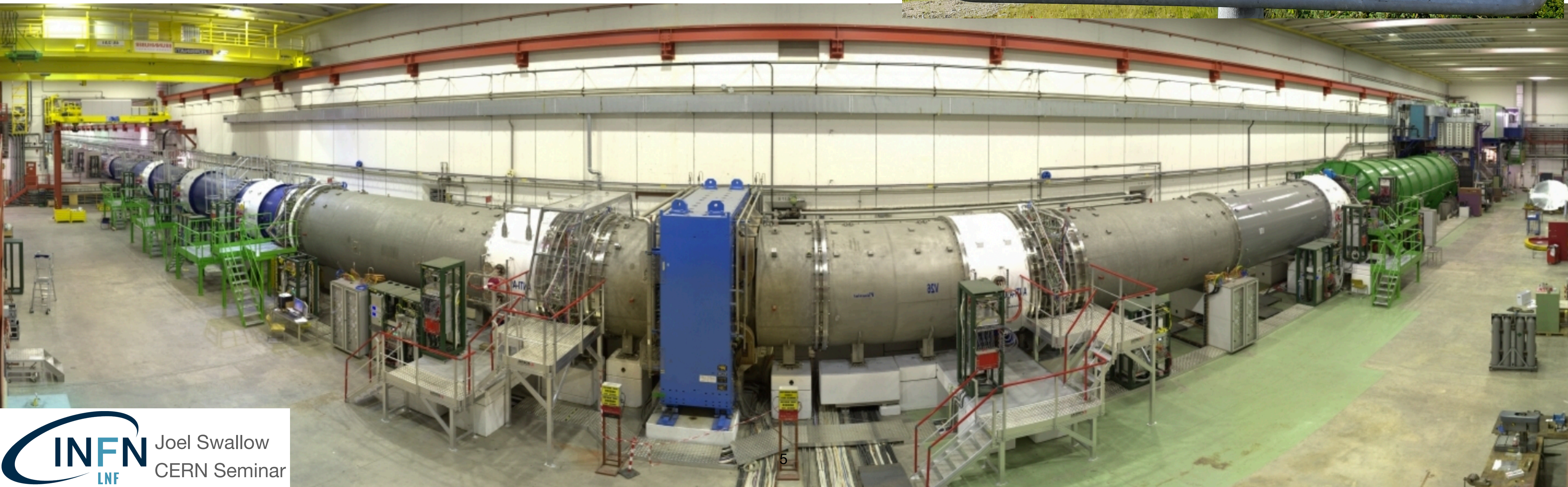
[[PLB 398 \(1997\) 163-168](#)]

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

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



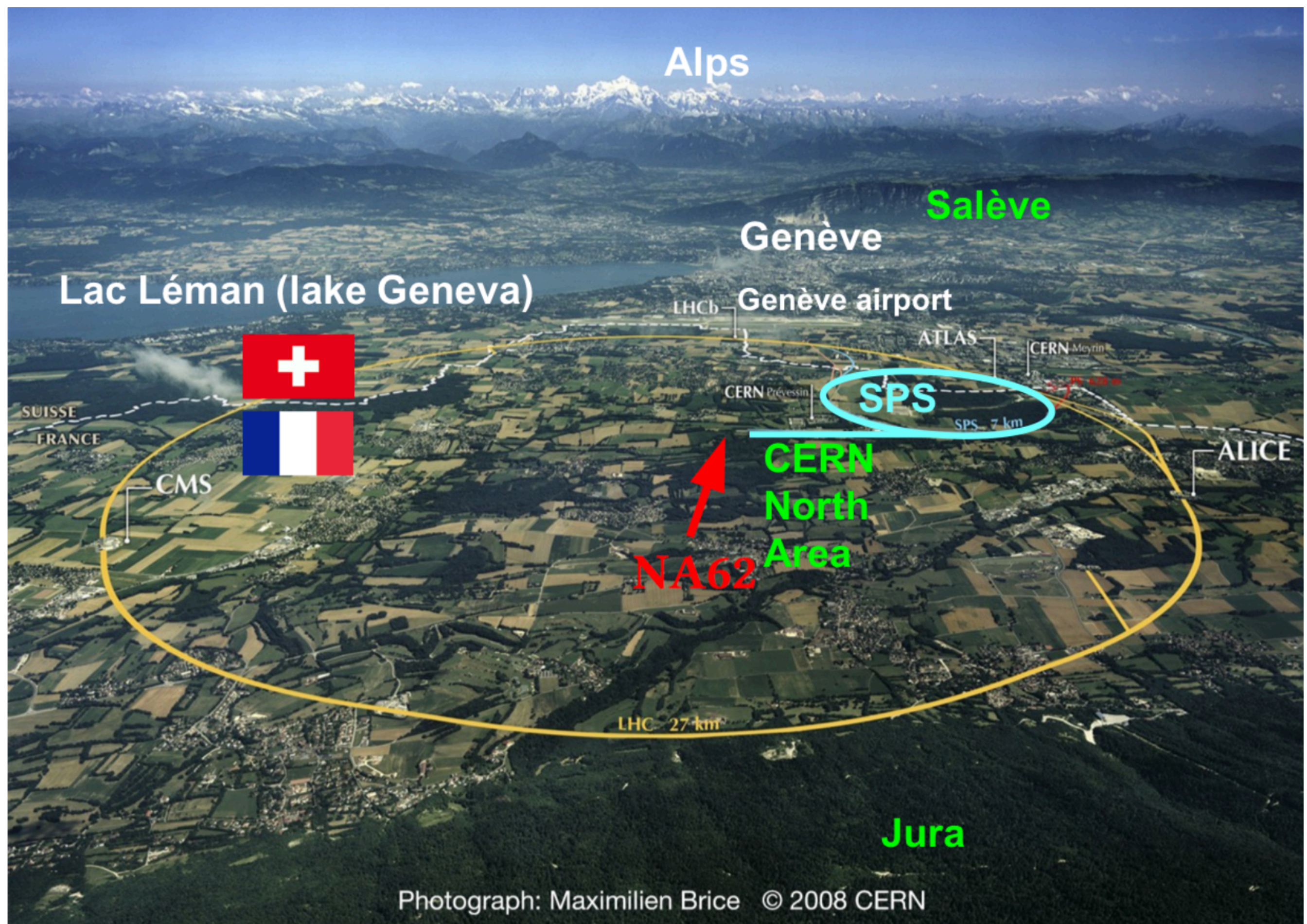
NA62: The K^+ factory at the CERN north area



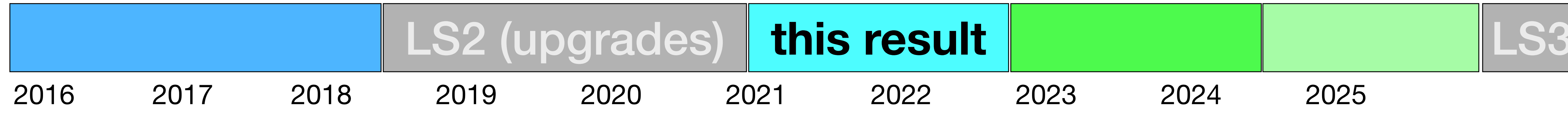
The NA62 Experiment at CERN



~200 collaborators from ~30 institutions.



- Primary goal: measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
- 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 ...



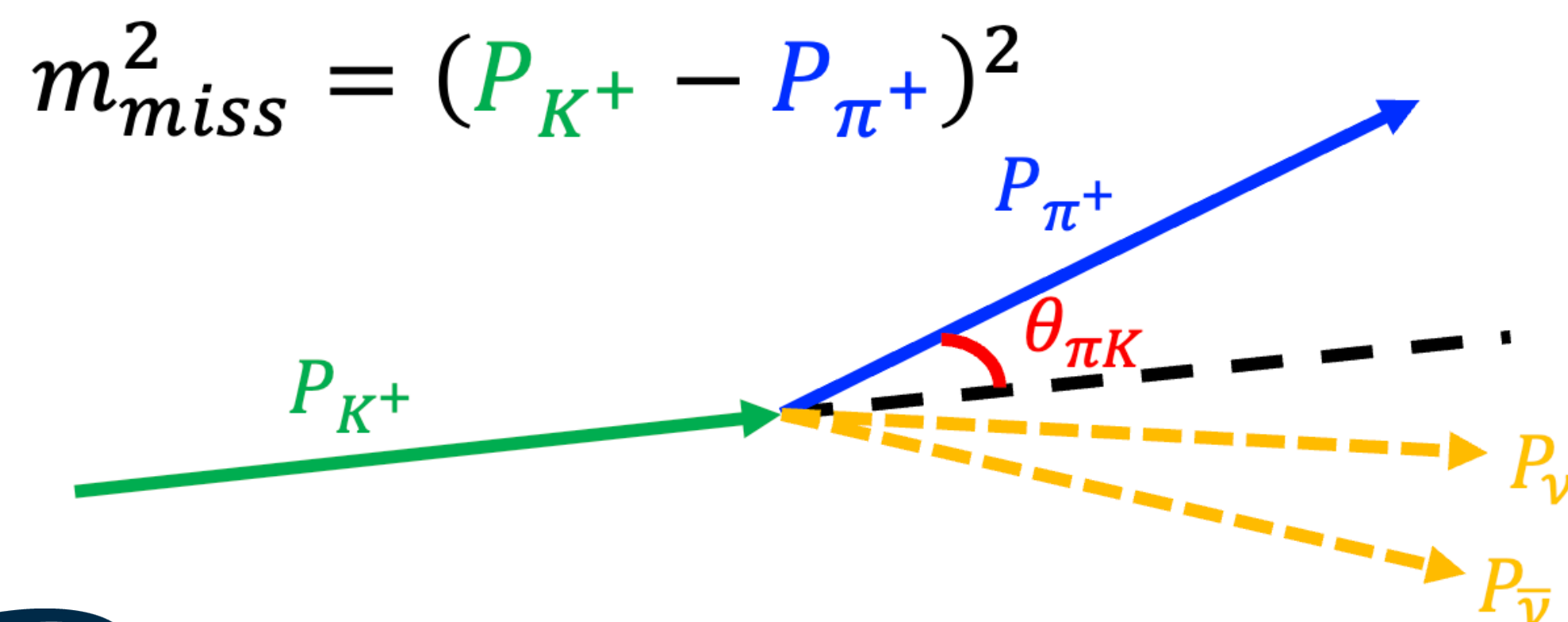
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at NA62

NA62 Strategy:

- Tag K^+ and measure momentum.
- Identify π^+ and measure momentum.
- Match K^+ and π^+ in time & form vertex.
 - Determine $m_{miss}^2 = (P_K - P_\pi)^2$
- 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 $K^+ \rightarrow \pi^+ \pi^0$ decays



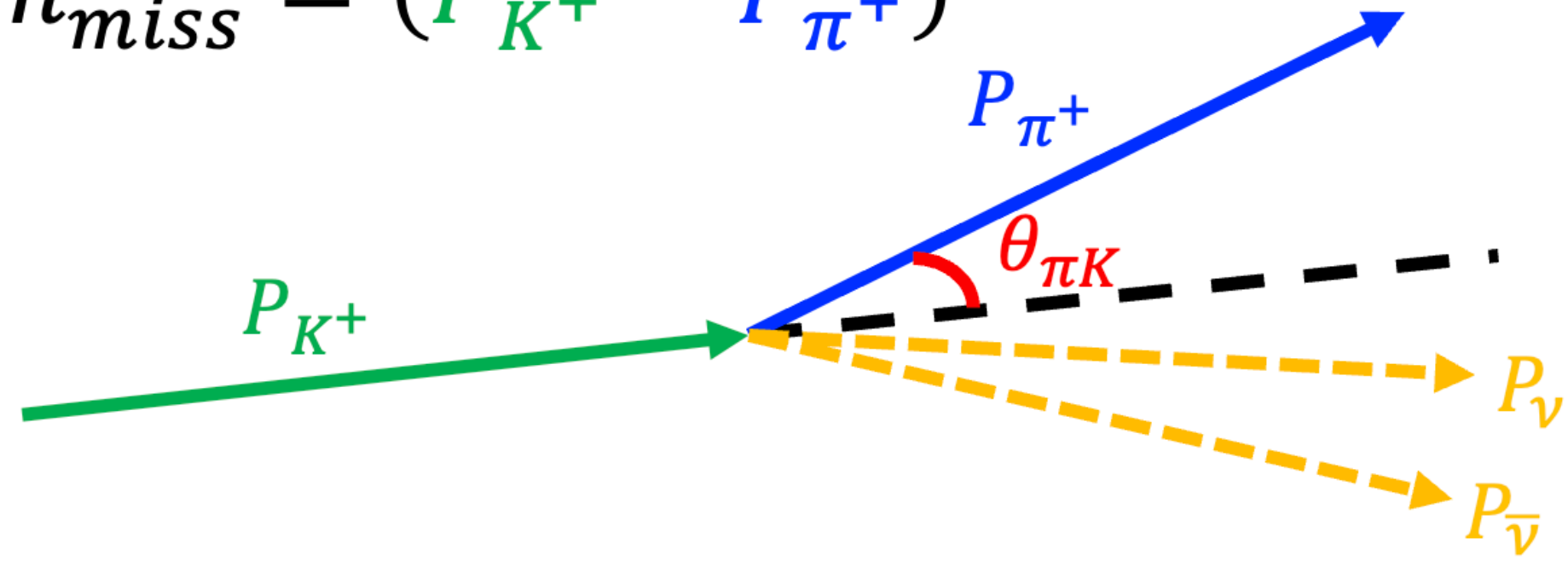
Decay mode	Branching Ratio [PDG]
$K^+ \rightarrow \mu^+ \nu_\mu$	$(63.56 \pm 0.11) \%$
$K^+ \rightarrow \pi^+ \pi^0$	$(20.67 \pm 0.08) \%$
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	$(5.583 \pm 0.024) \%$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$

$K^+ \rightarrow \pi^+ \nu \bar{\nu} \quad (8.60 \pm 0.42) \times 10^{-11} \text{ [SM]}$

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

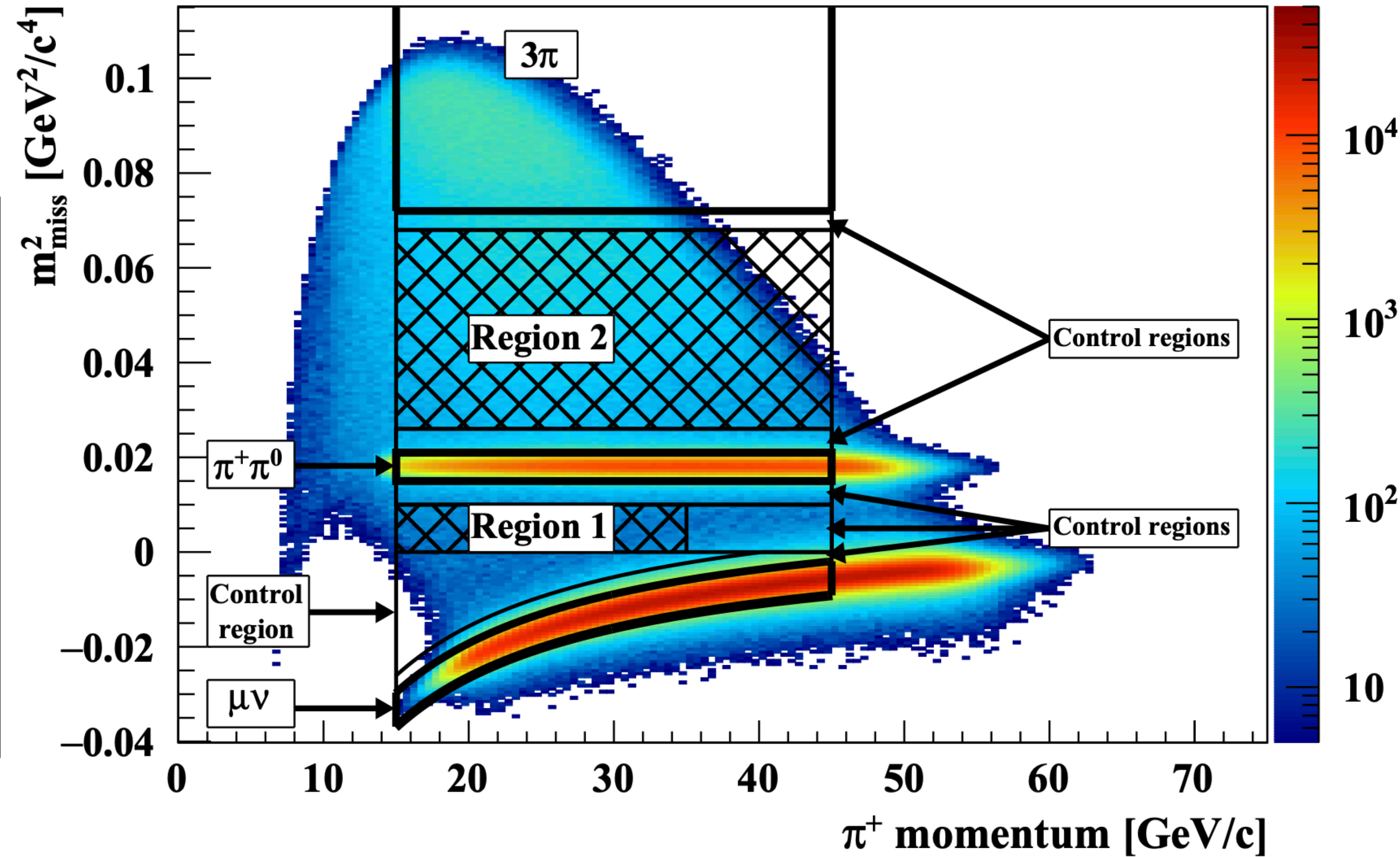
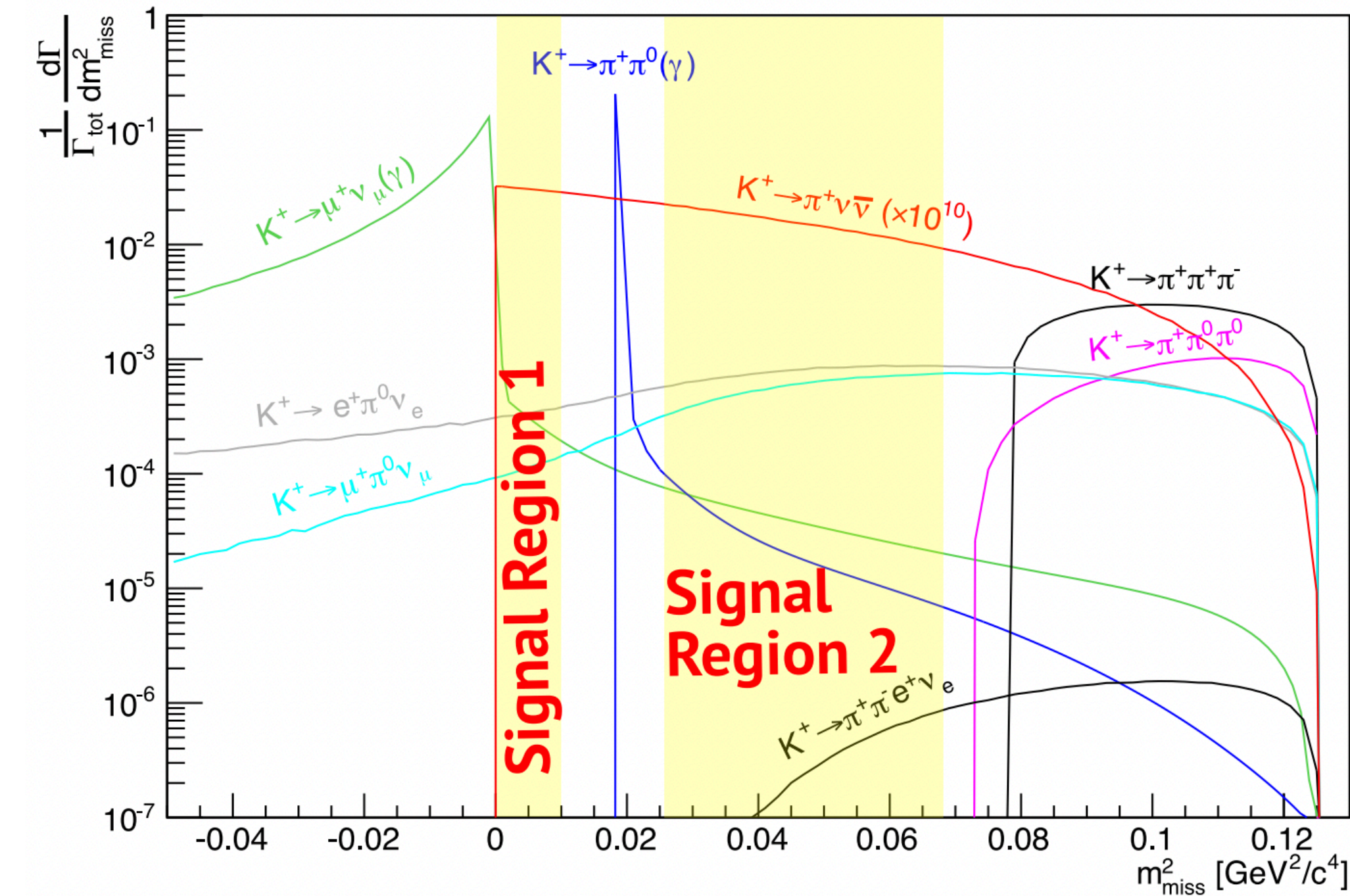
Kinematic constraints & signal regions

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



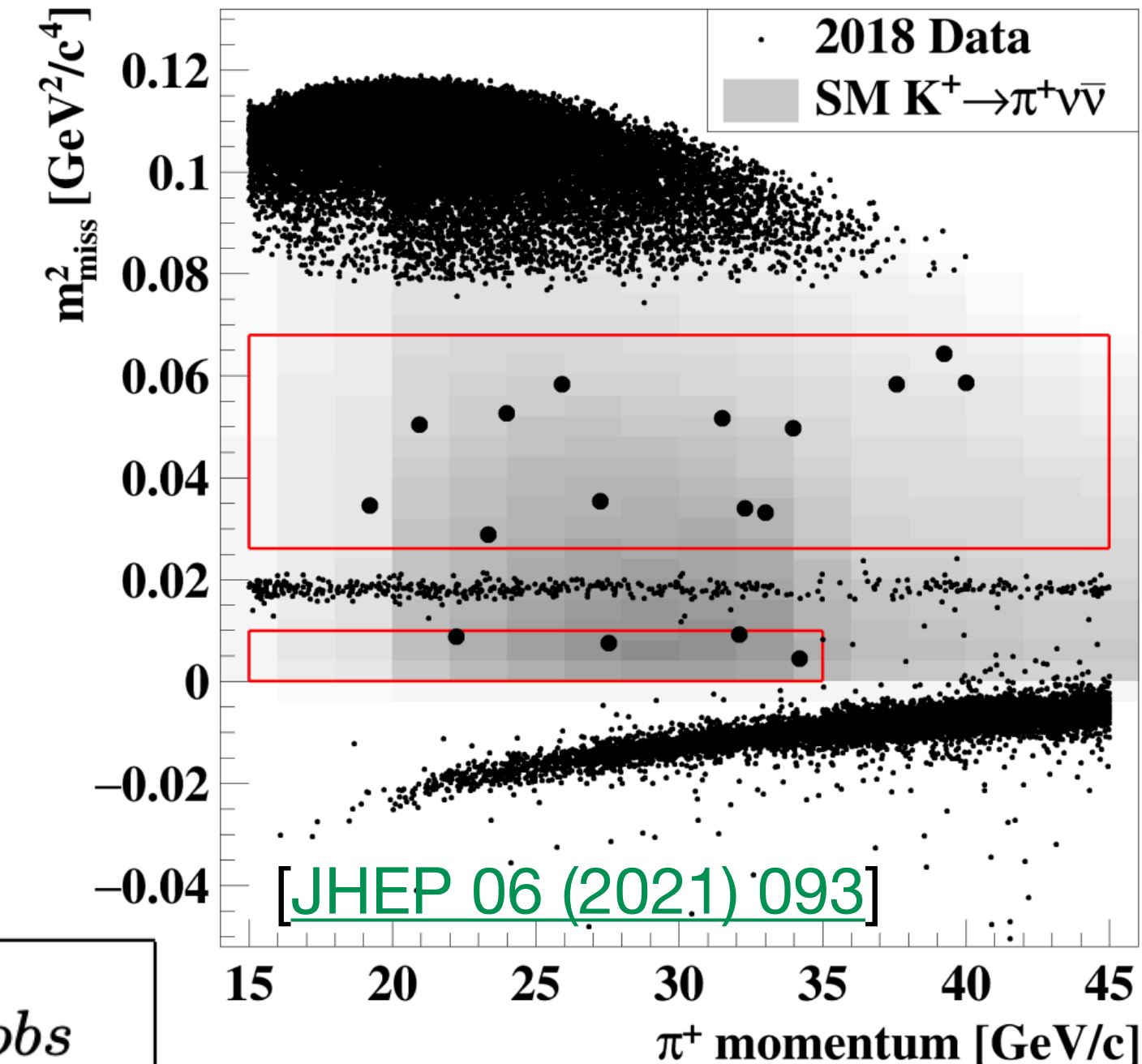
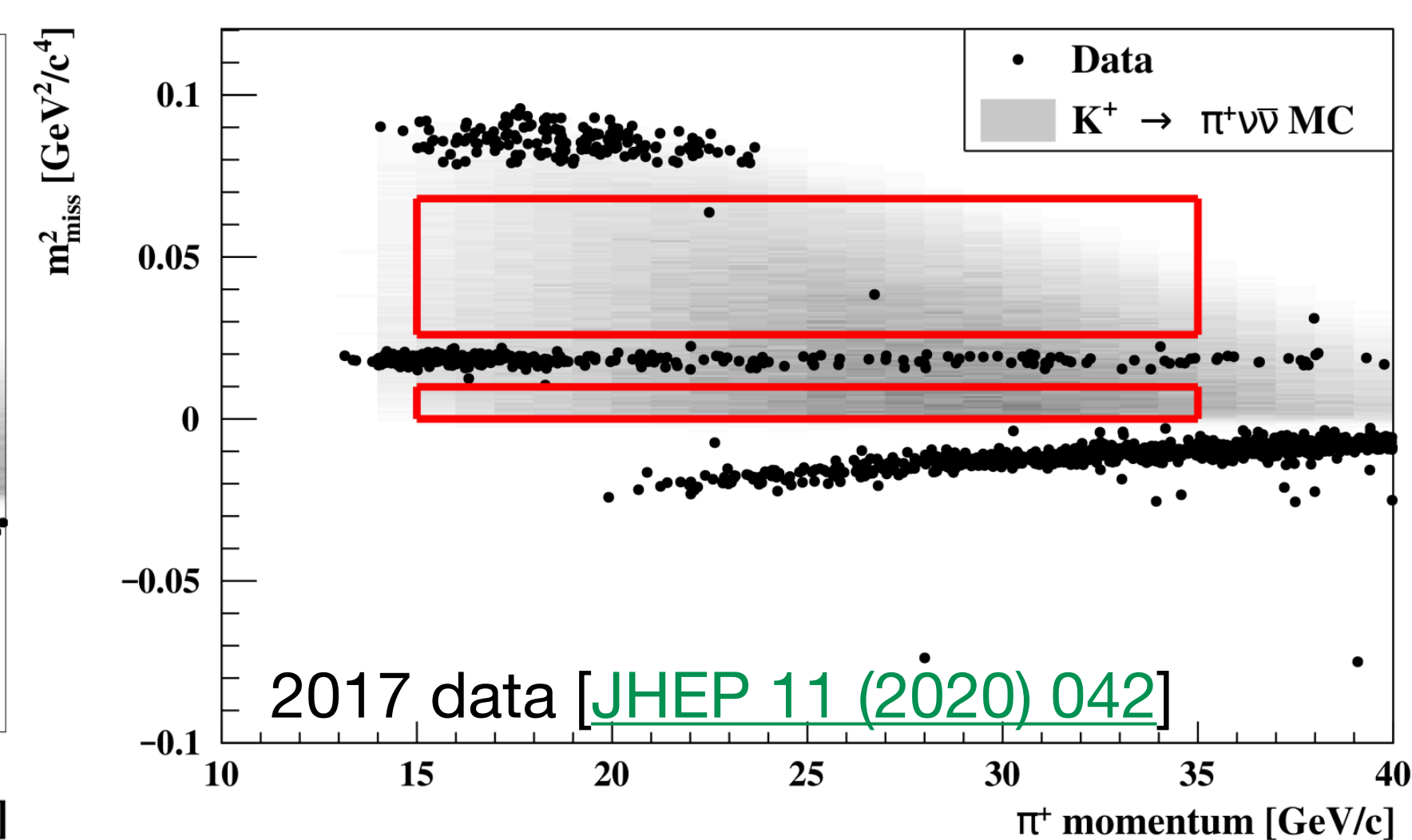
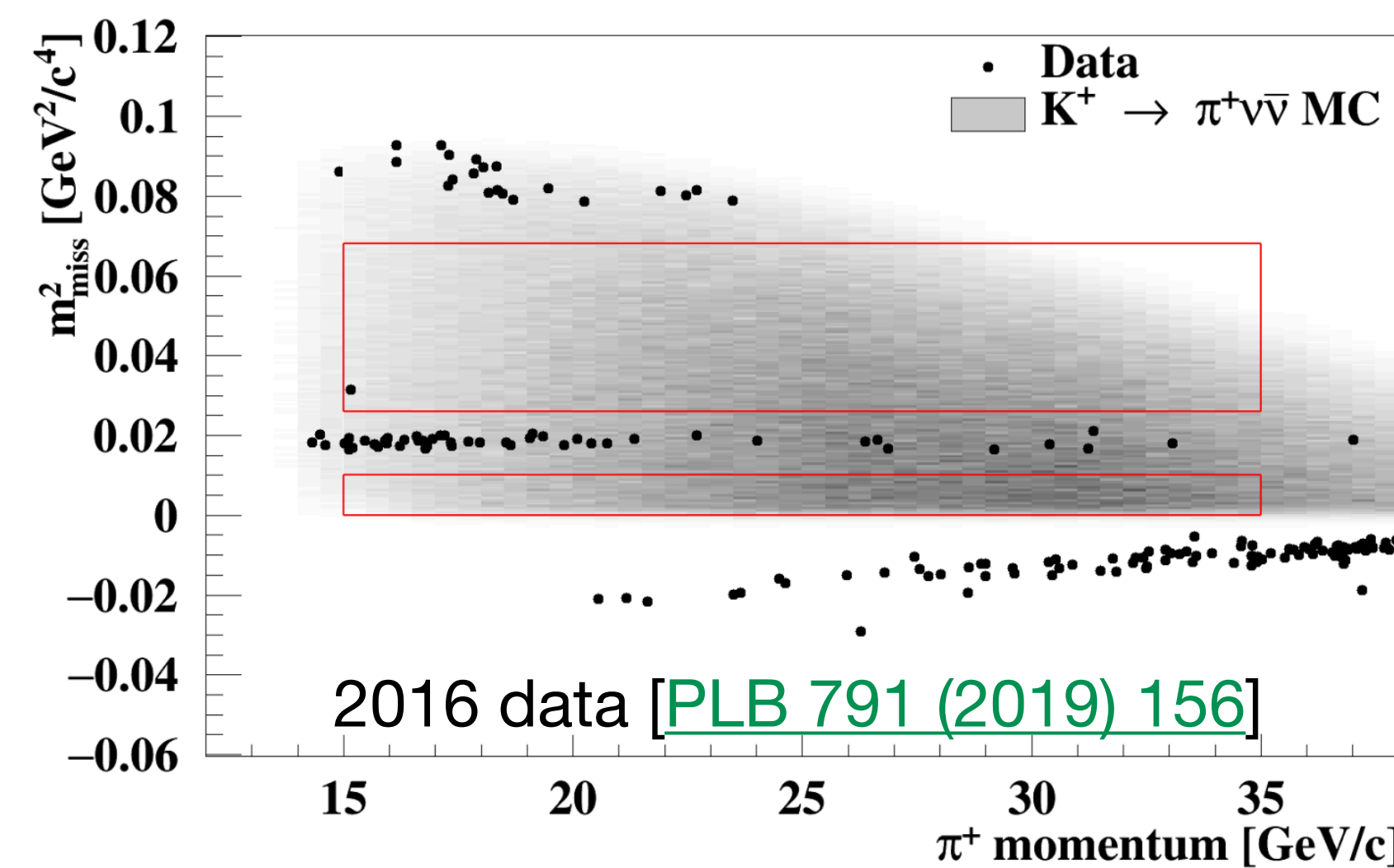
$\mathcal{O}(10^4)$ background suppression from kinematics

[JHEP 06 (2021) 093]



π^+ momentum range: 15–45 GeV/c

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



(* $N_{\pi\nu\bar{\nu}}^{SM,exp}$ assumes SM BR from [JHEP 11 (2015) 166])

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

Statistical combination:

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \left(10.6^{+4.0}_{-3.4} \Big|_{\text{stat}} \pm 0.9_{\text{syst}} \right) \times 10^{-11} \quad \text{at } 68\% \text{ CL}$$

$$\text{In background-only hypothesis: } p = 3.4 \times 10^{-4} \Rightarrow \text{significance} = 3.4\sigma.$$

NA62 Detector, Upgrades & Performance

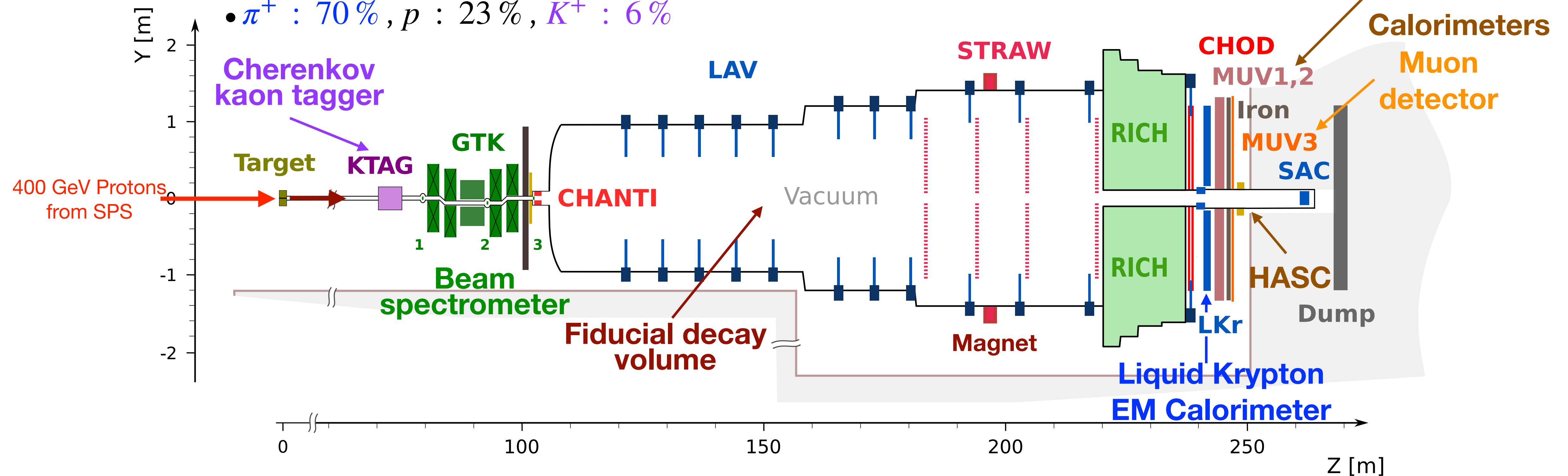
NA62 beamline & detector

[JINST 12 (2017) 05, P05025]



Secondary 75 GeV/c beam:

- π^+ : 70% , p : 23% , K^+ : 6%



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

Particle ID performance : 2021–22 data

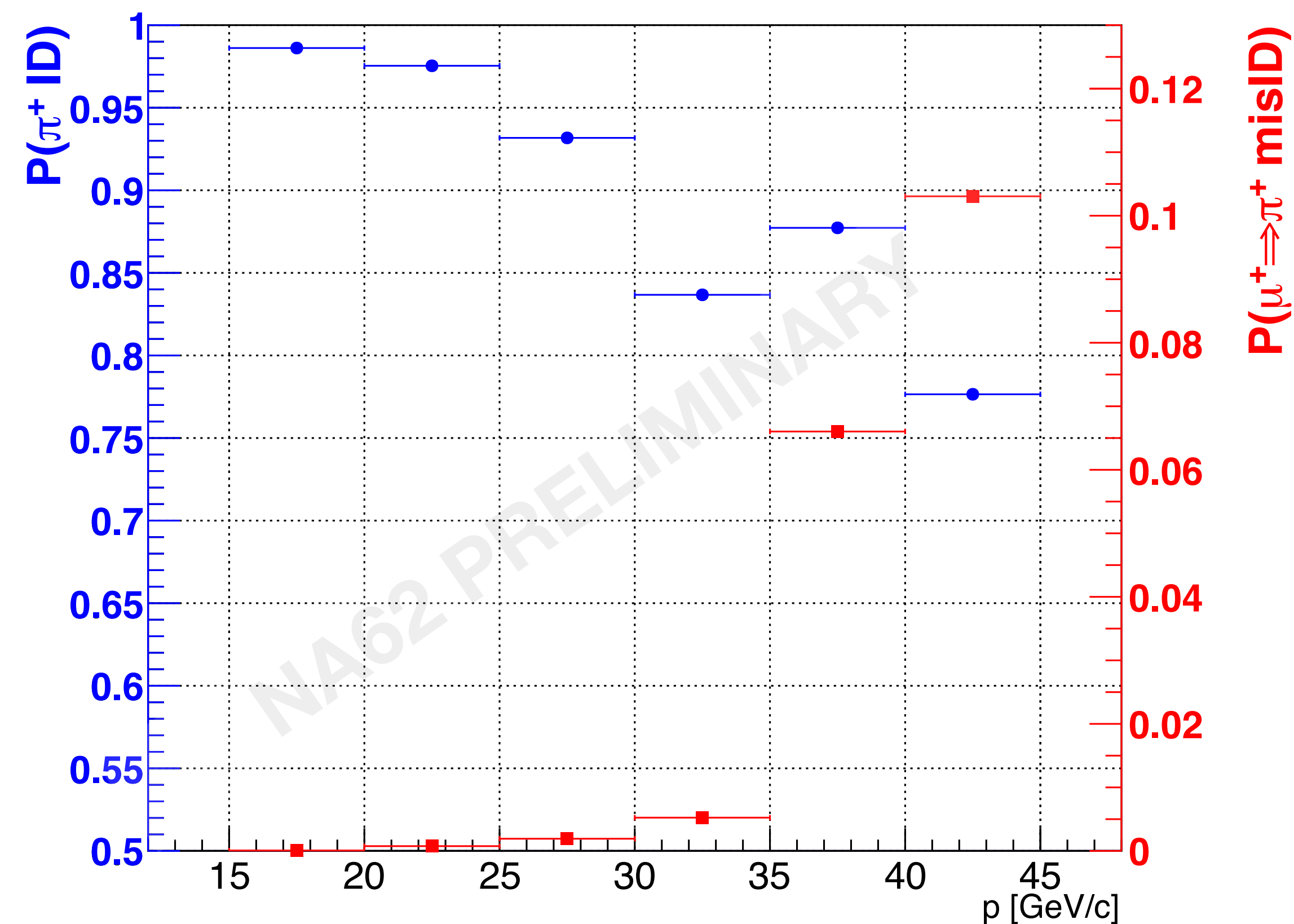
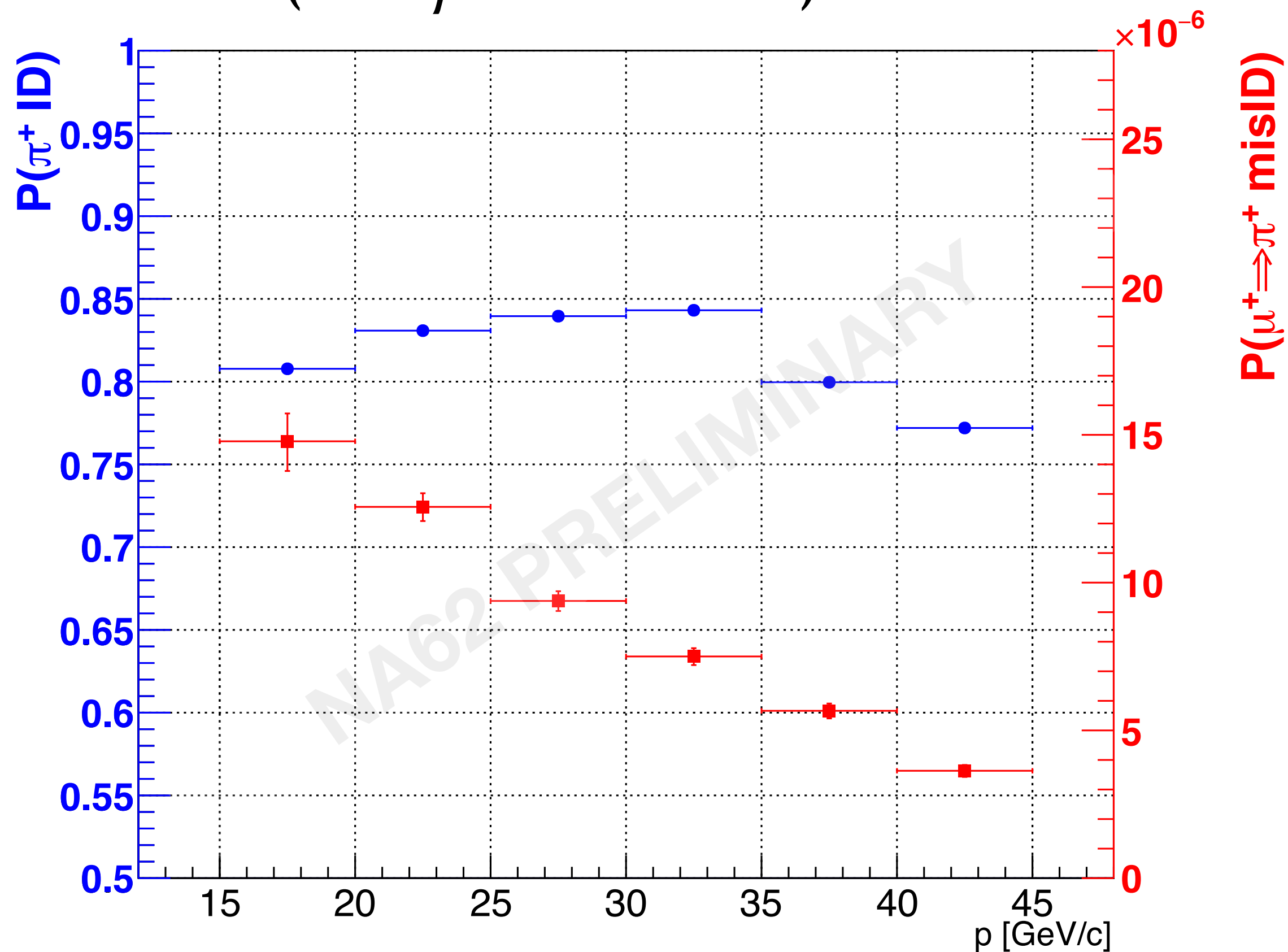


Calorimeters

RICH

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

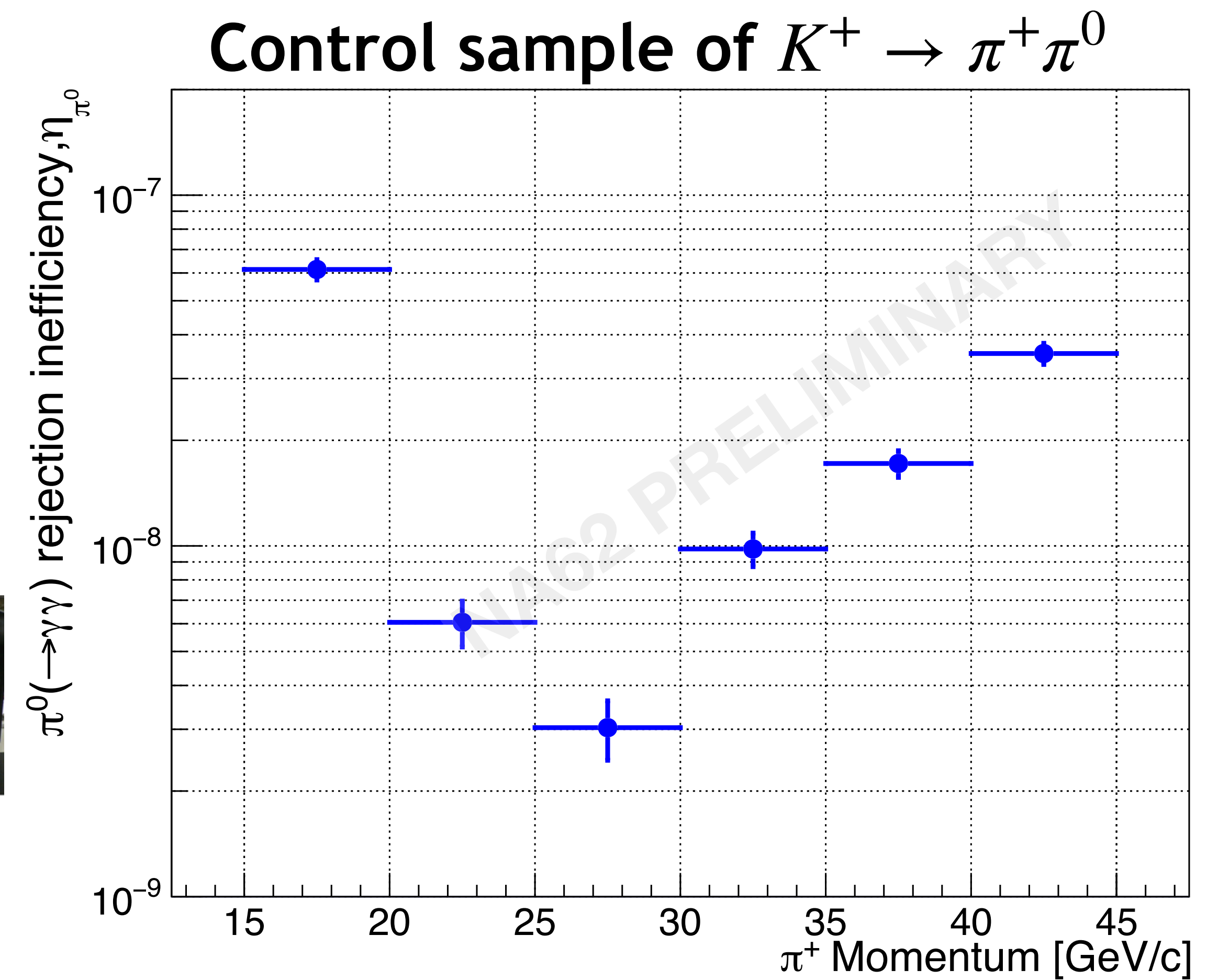
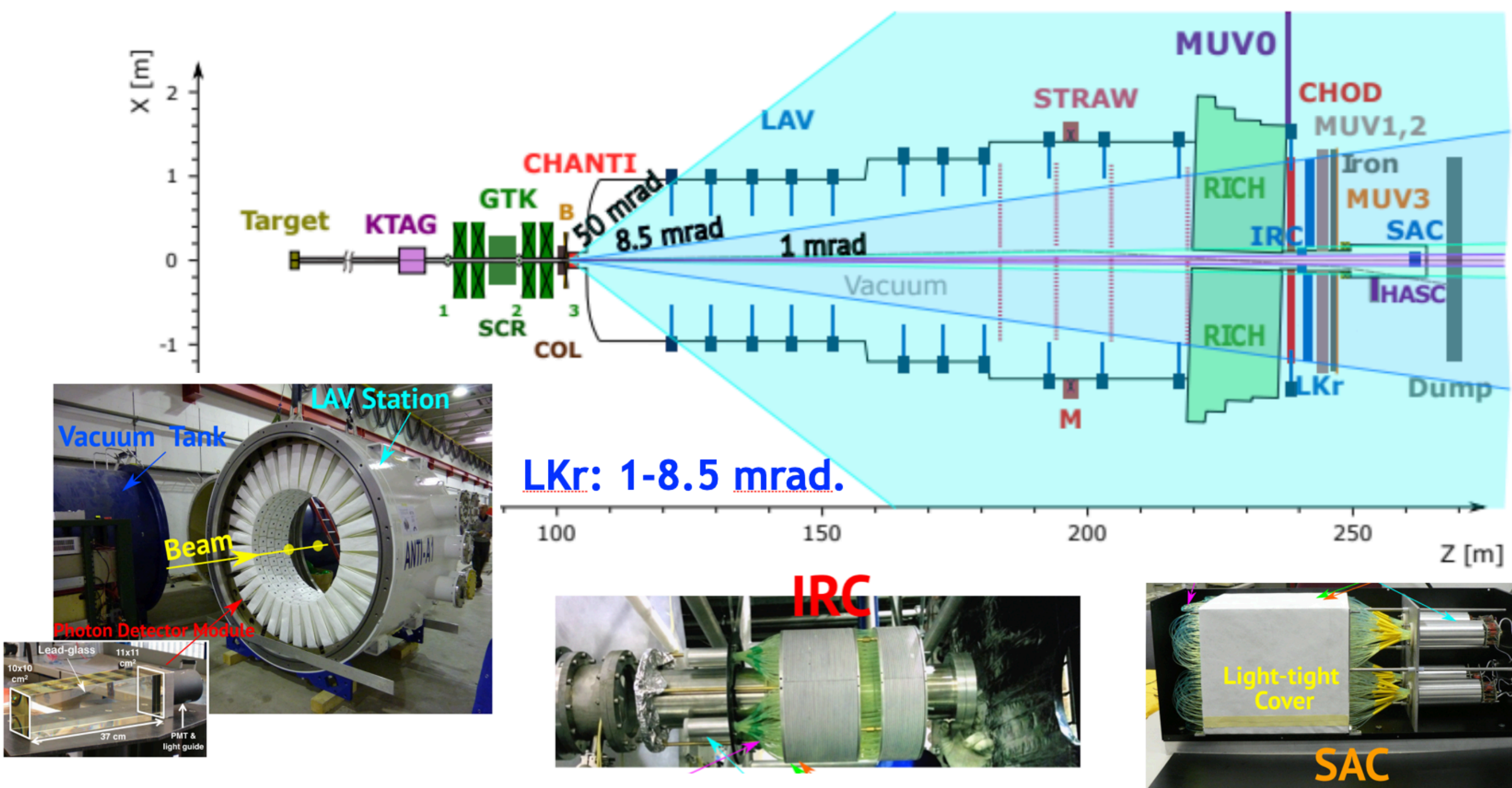
Designed to distinguish between π^+/μ^+ with 15 – 35 GeV/c.



$$\varepsilon(\pi \text{ ID}) = (73.00 \pm 0.01) \%$$

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

Comprehensive photon veto system: 2021–22



• Probability of $K^+ \rightarrow \pi^+ \pi^0$, $\pi^0 \rightarrow \gamma\gamma$ events passing all photon veto conditions: $\eta_{\pi^0} = (1.72 \pm 0.07) \times 10^{-8}$

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

Upgrading NA62



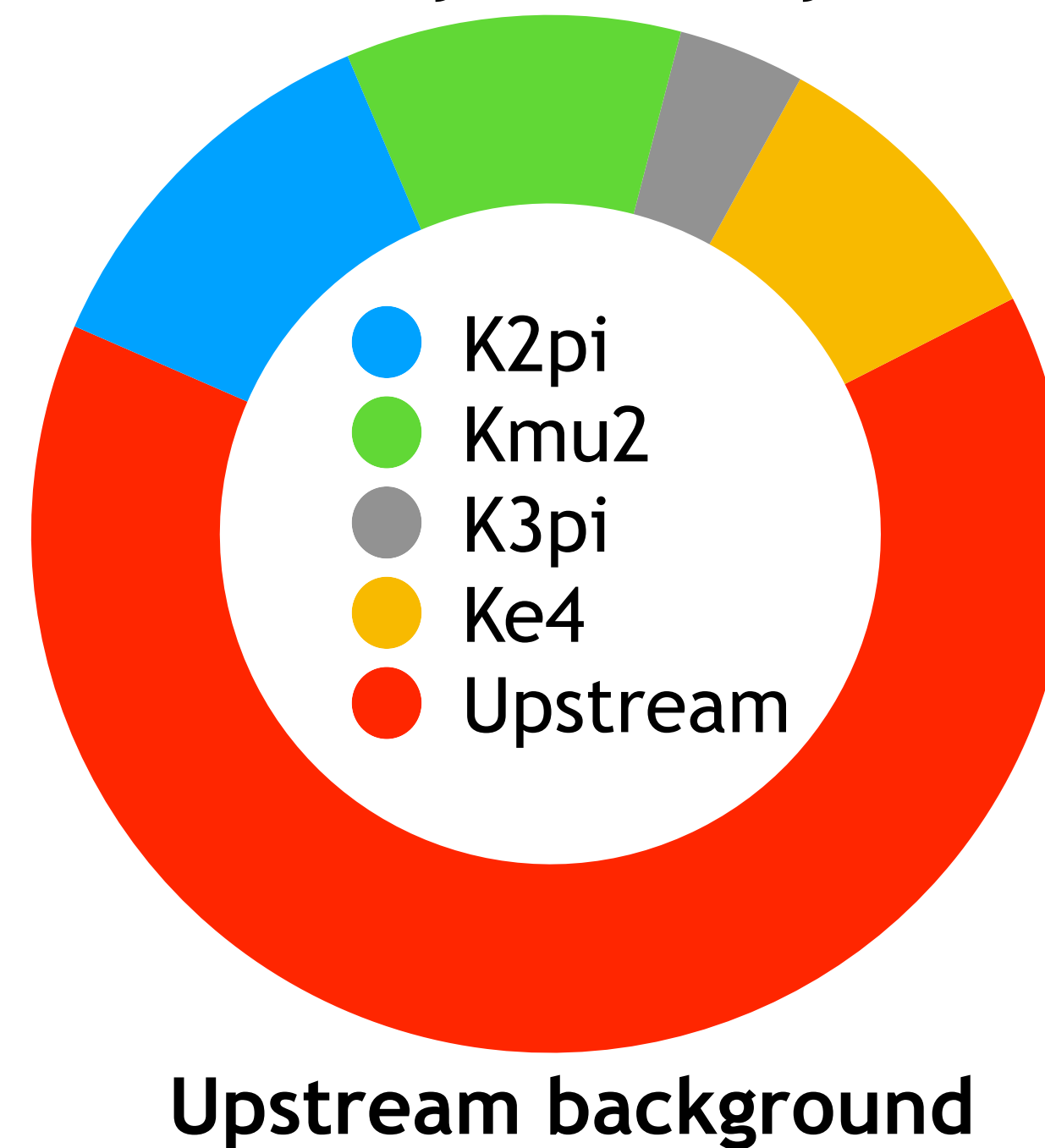
- 2016–18 analysis proved NA62 technique.
- Limitation: tight cuts to reject backgrounds \Rightarrow reduces signal efficiency.
- To improve: need new tools to control background.

Upgrading NA62

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

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

K^+ decays in decay tank



Largest backgrounds:

1. **Upstream**
2. $K^+ \rightarrow \pi^+ \pi^0$

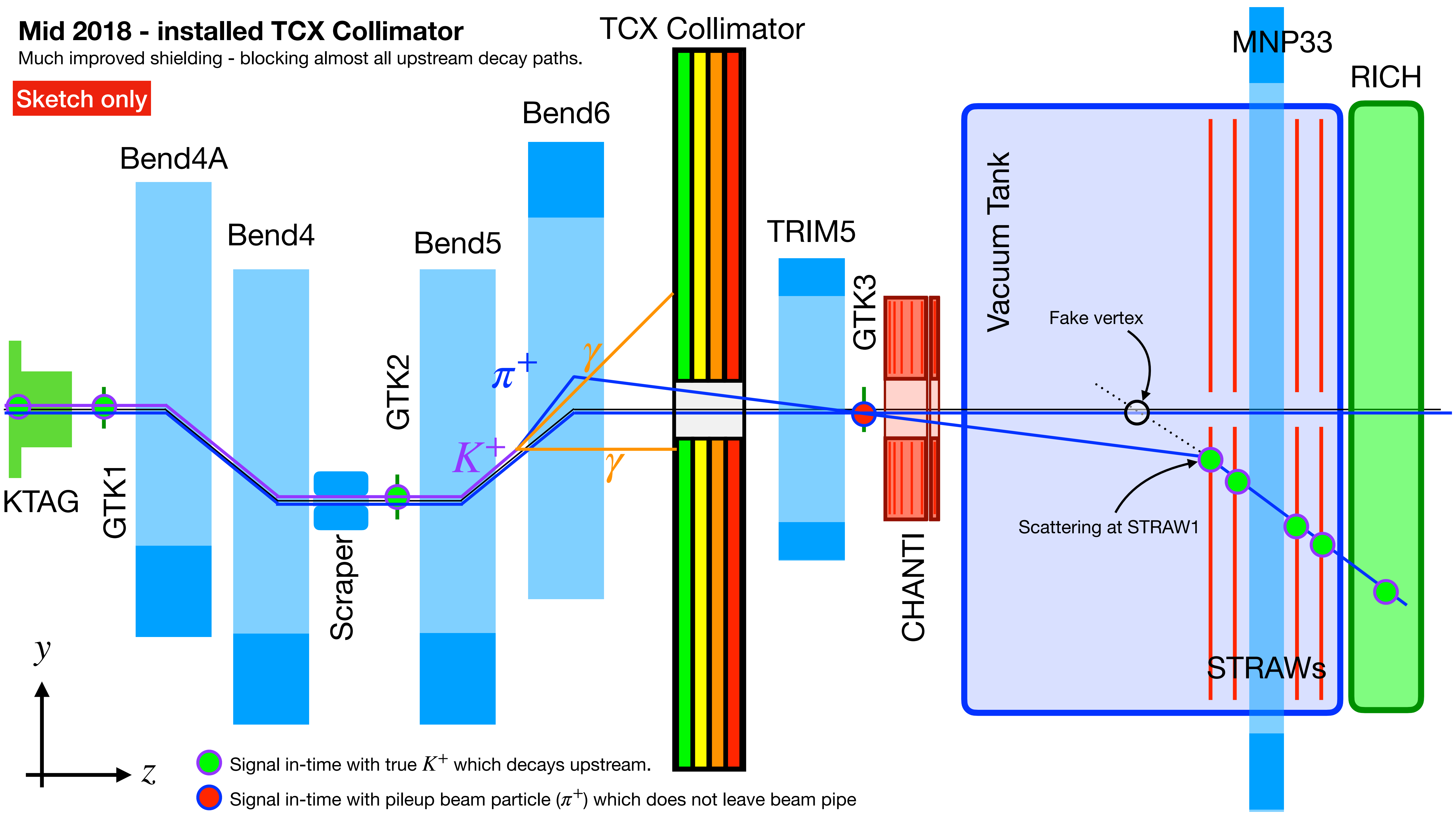
Veto by detecting previously missed particles...

Mid 2018 - installed TCX Collimator

Much improved shielding - blocking almost all upstream decay paths.

Sketch only

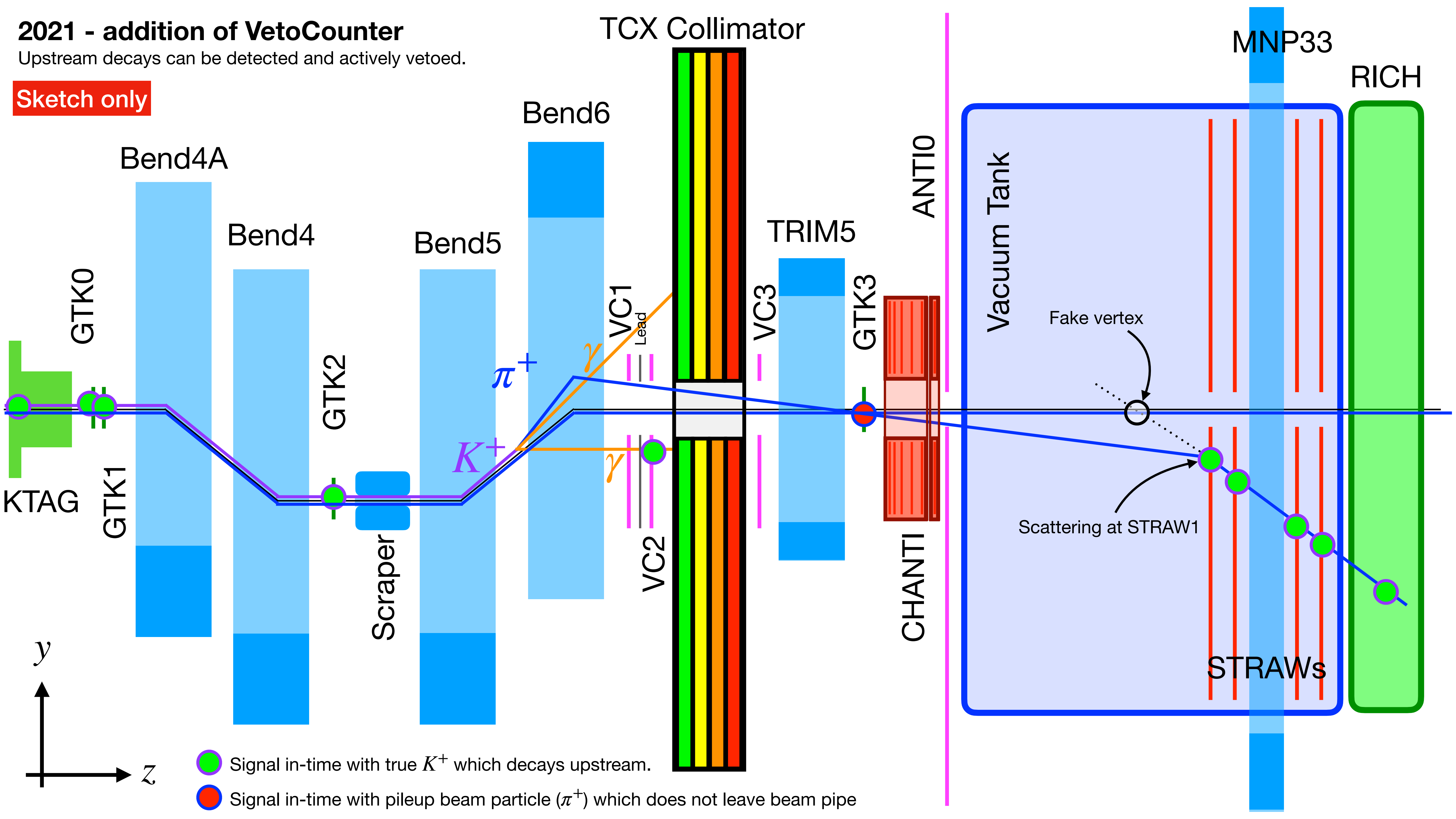
TCX Collimator



2021 - addition of VetoCounter

Upstream decays can be detected and actively vetoed.

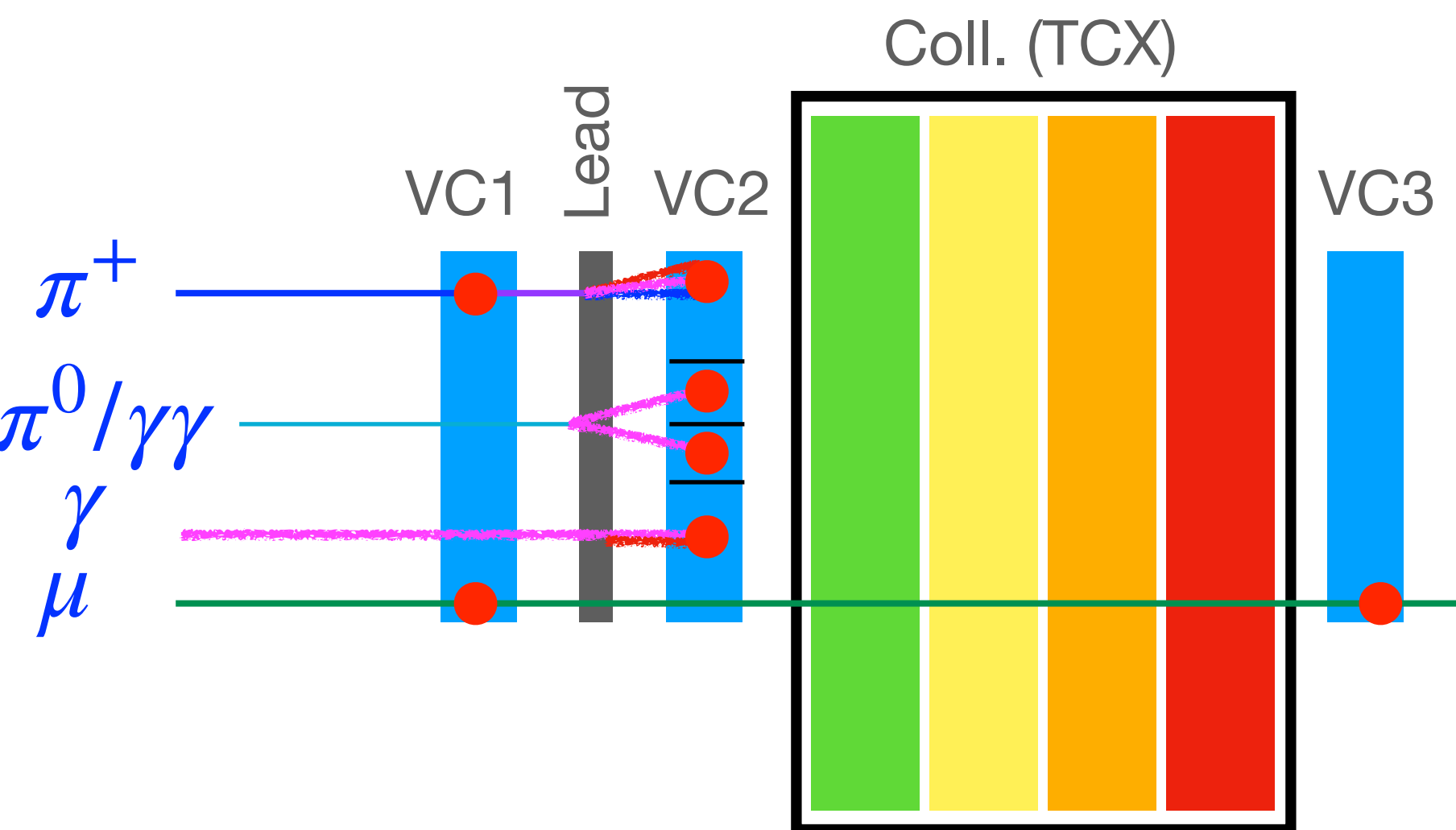
Sketch only



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.

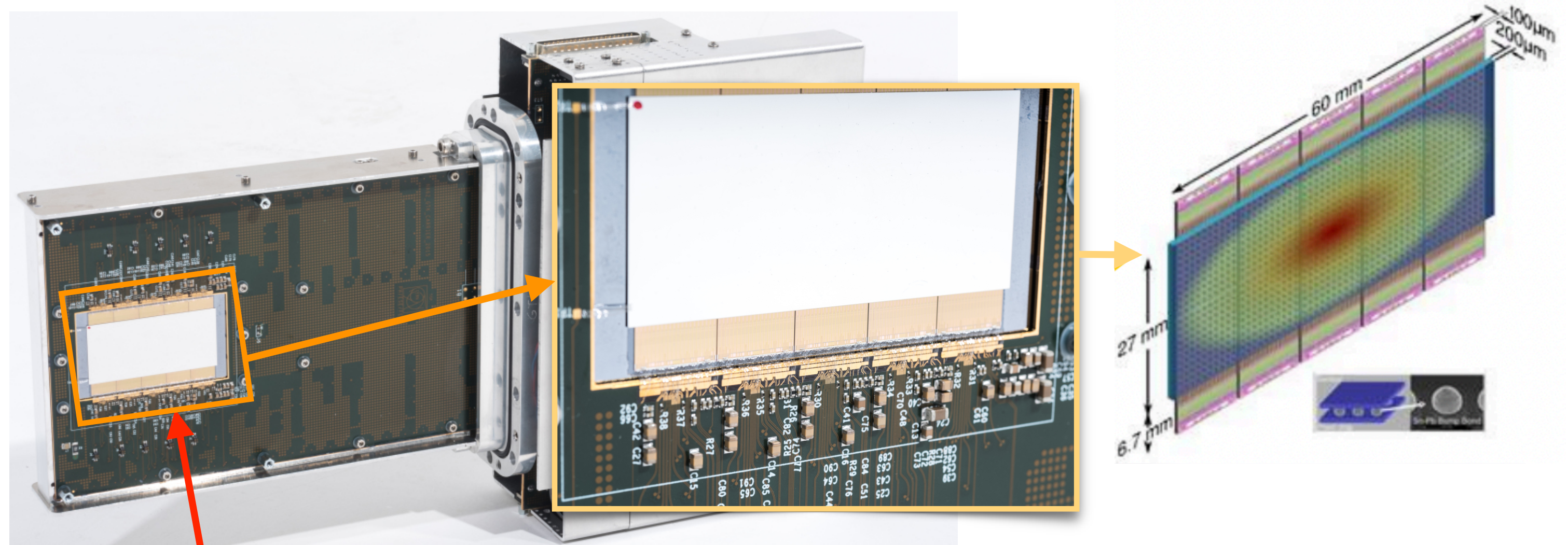
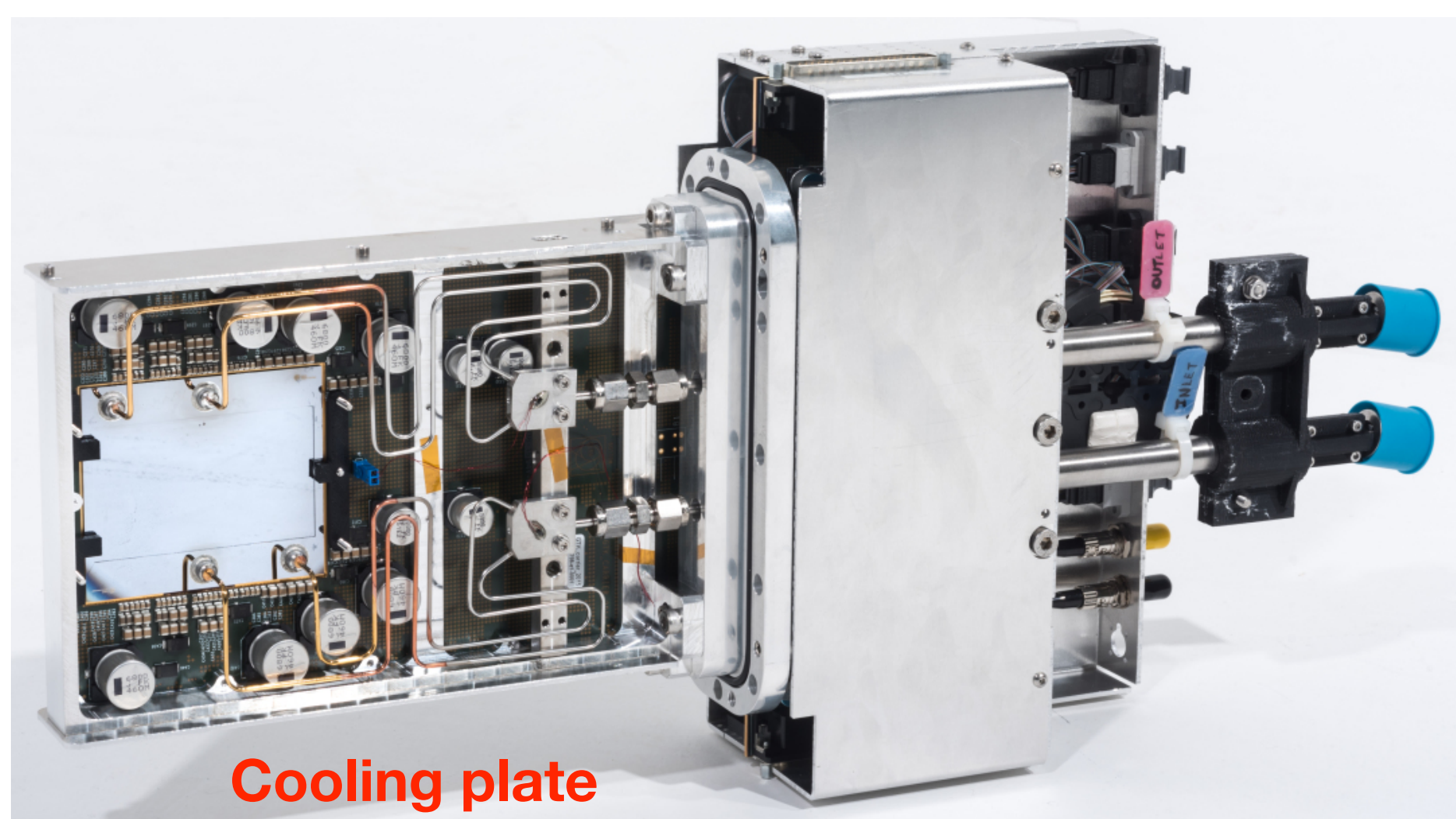
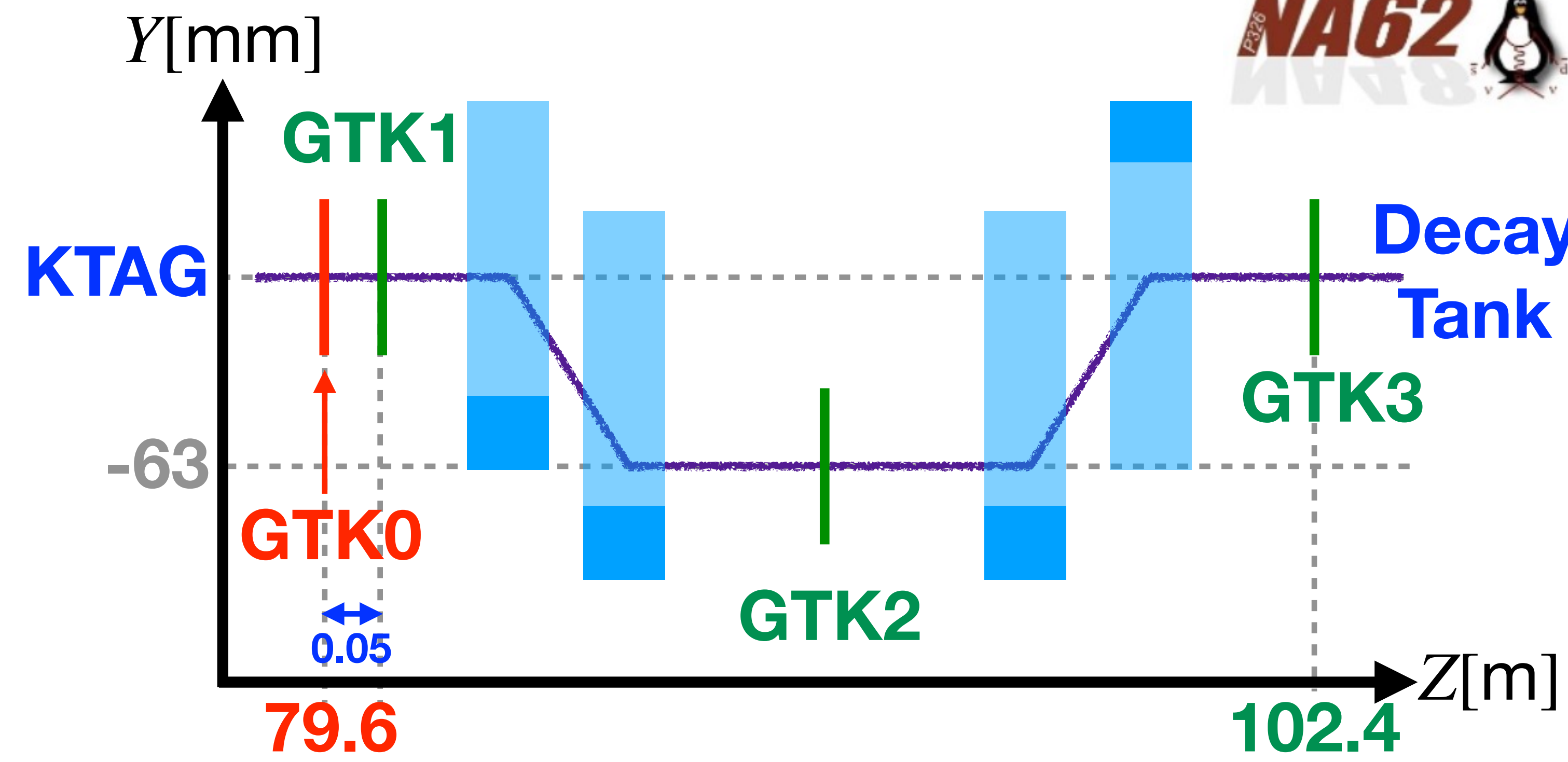
ANTI0

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

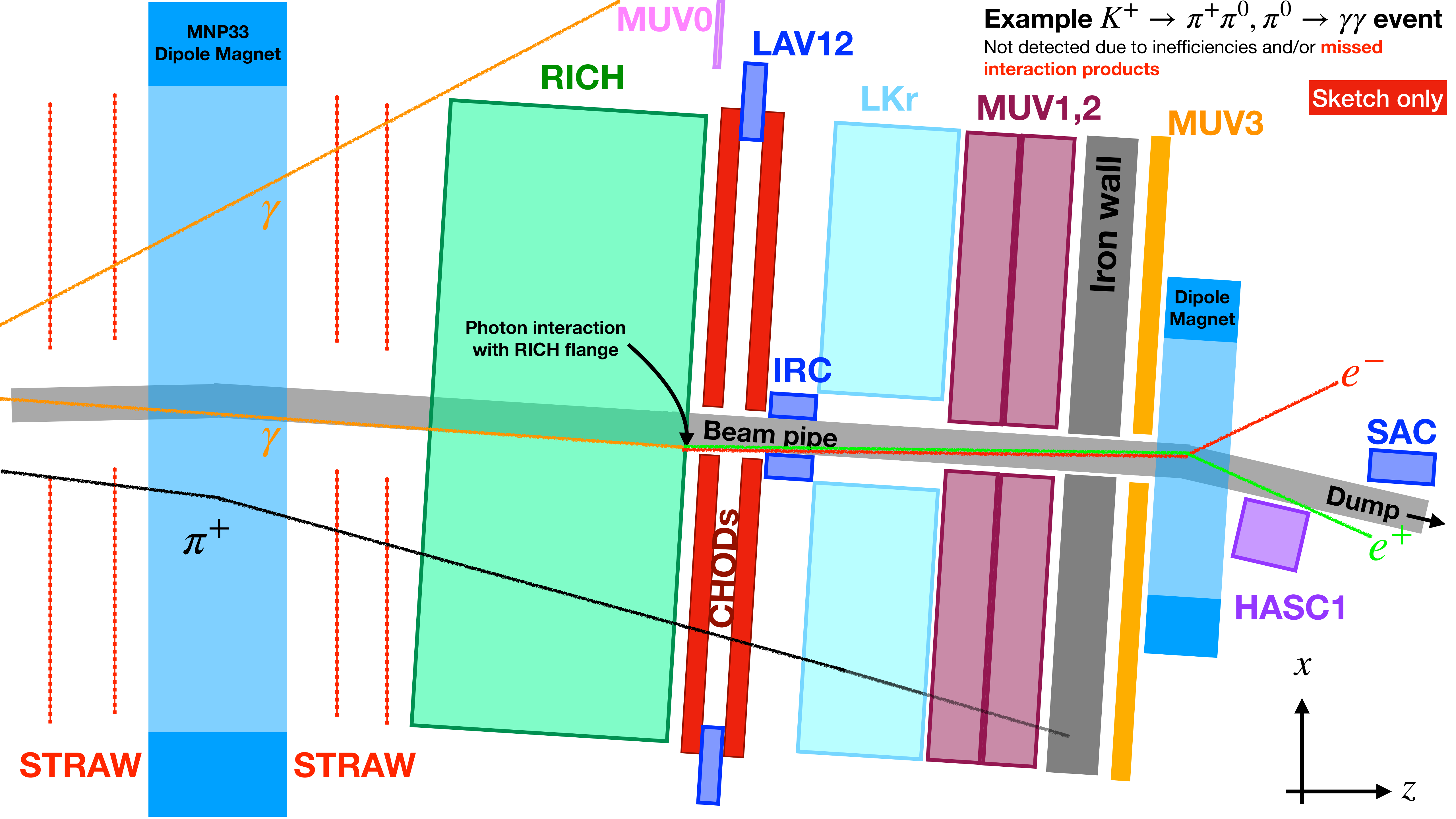


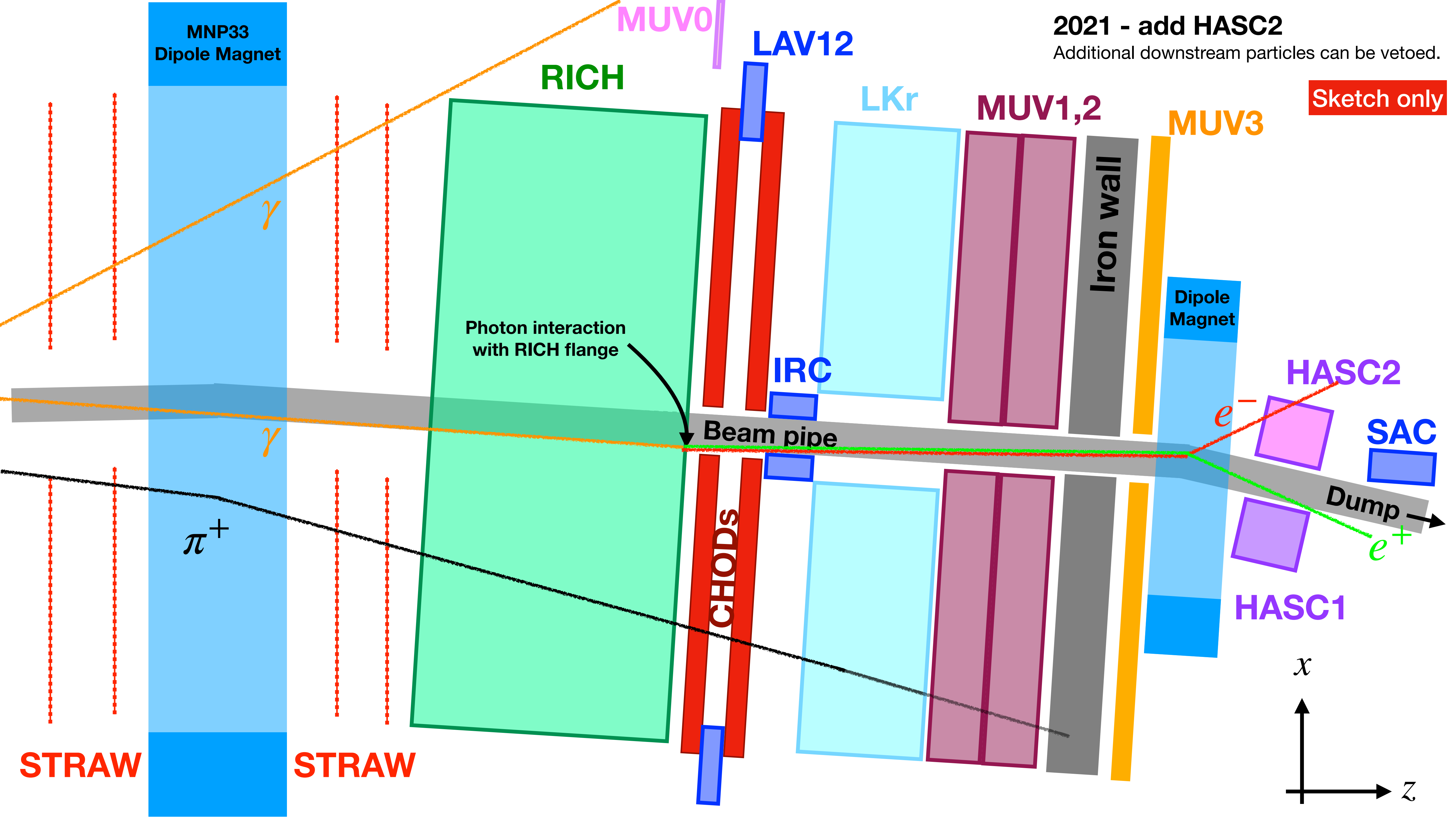
4th GTK station

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



Si Pixels ~(30x60 mm active area)

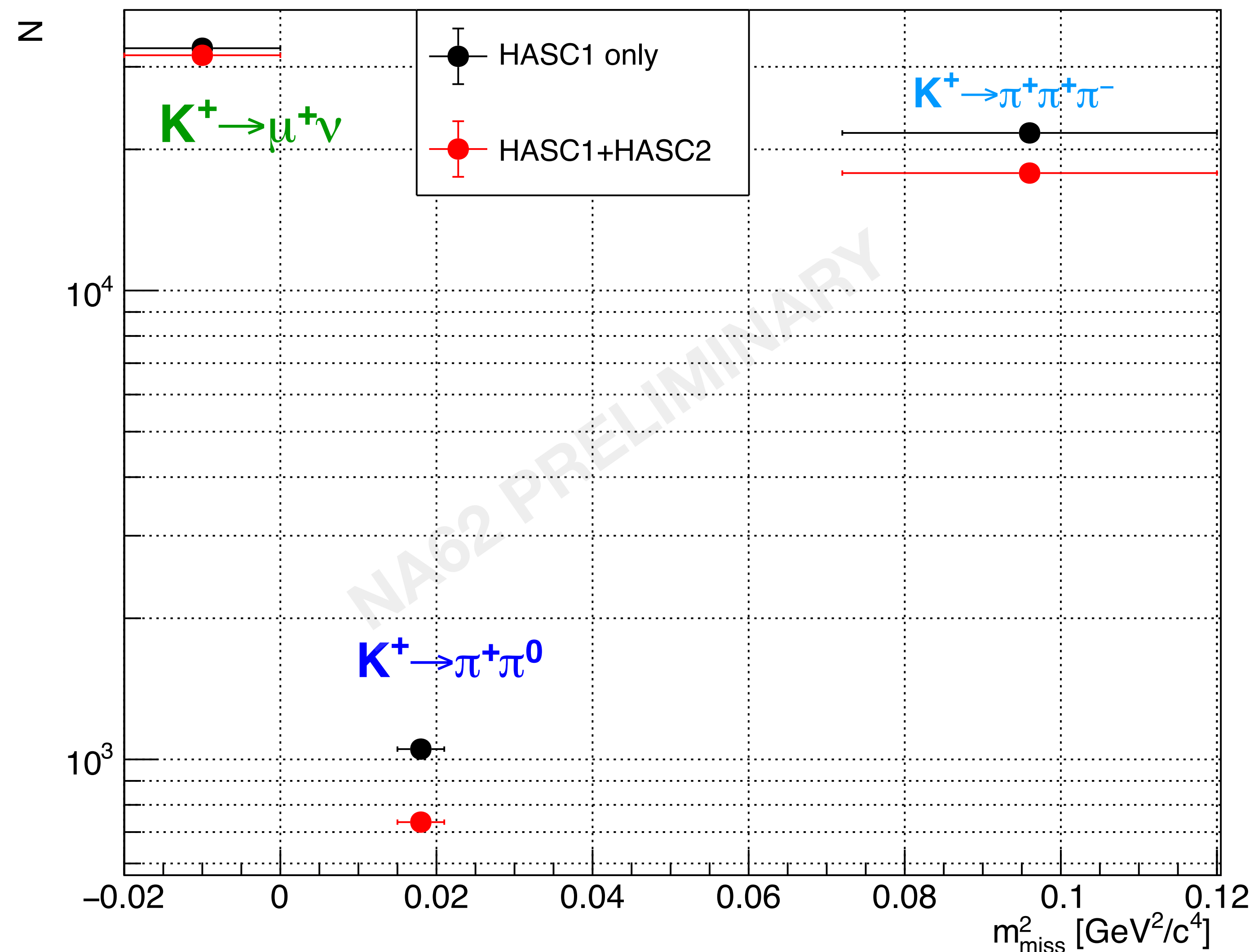




HASC2 veto

- $K^+ \rightarrow \pi^+ \pi^0$ was 2nd largest background for 2018 analysis.
- Addition of HASC2:
 - 30% less $K^+ \rightarrow \pi^+ \pi^0$
 - 18% less $K^+ \rightarrow \pi^+ \pi^+ \pi^-$
 - 3.5% less $K^+ \rightarrow \mu^+ \nu$
- with only 1.5% signal loss.

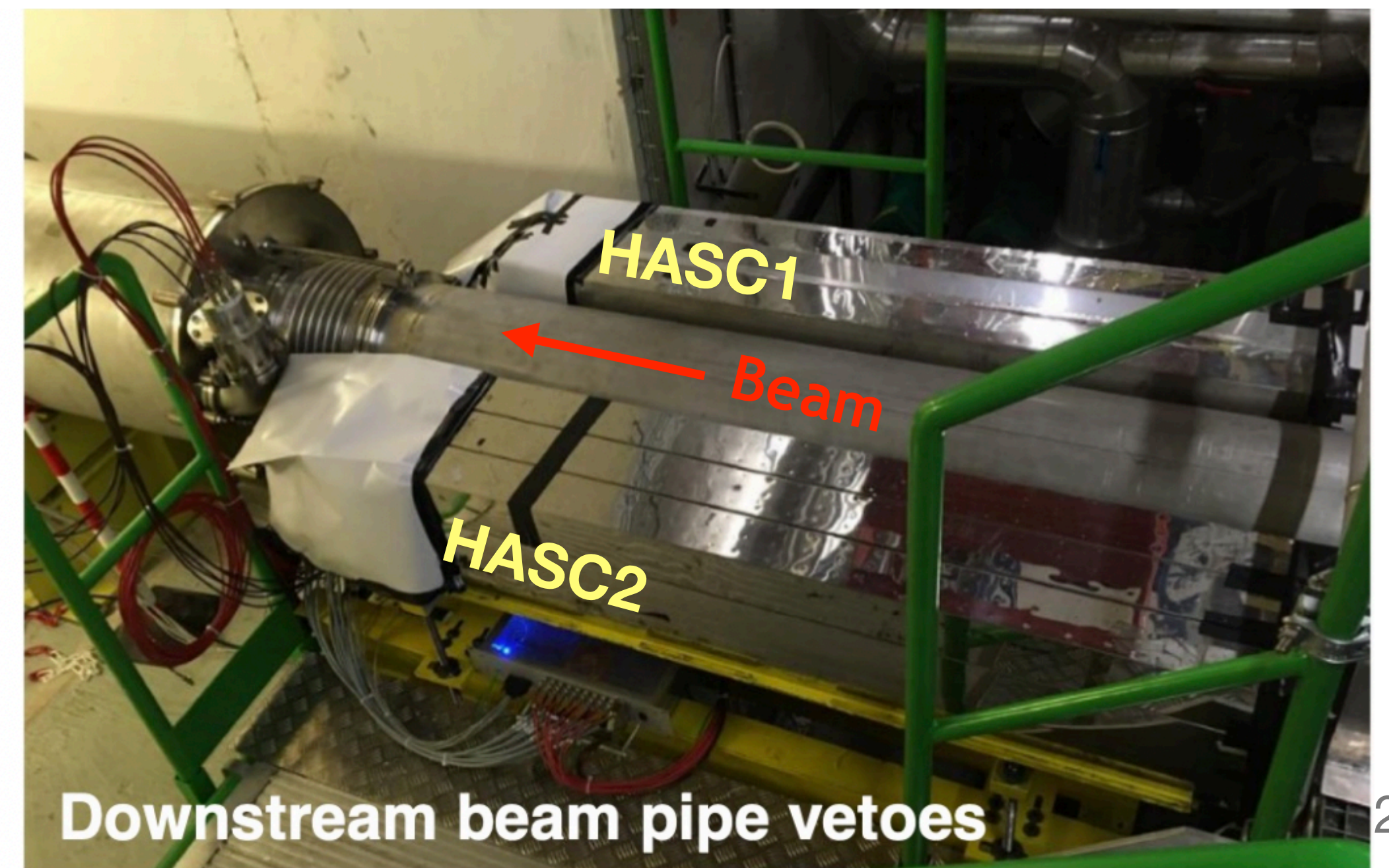
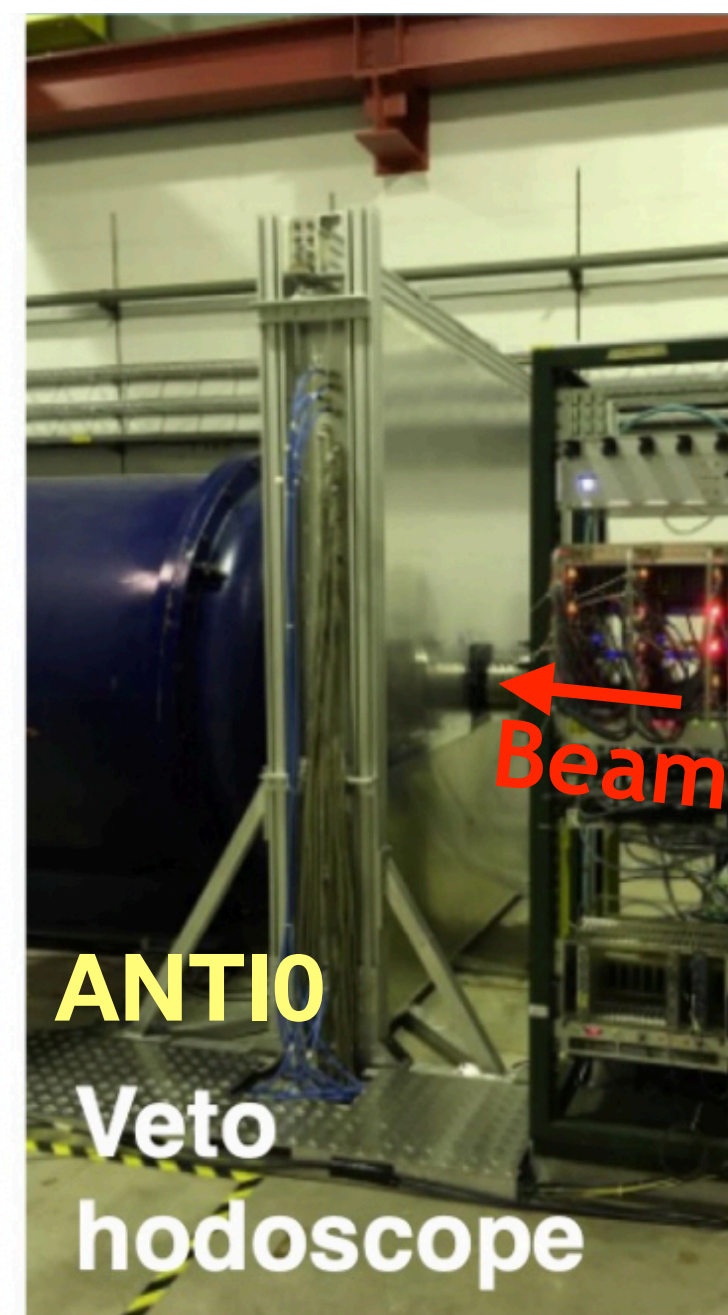
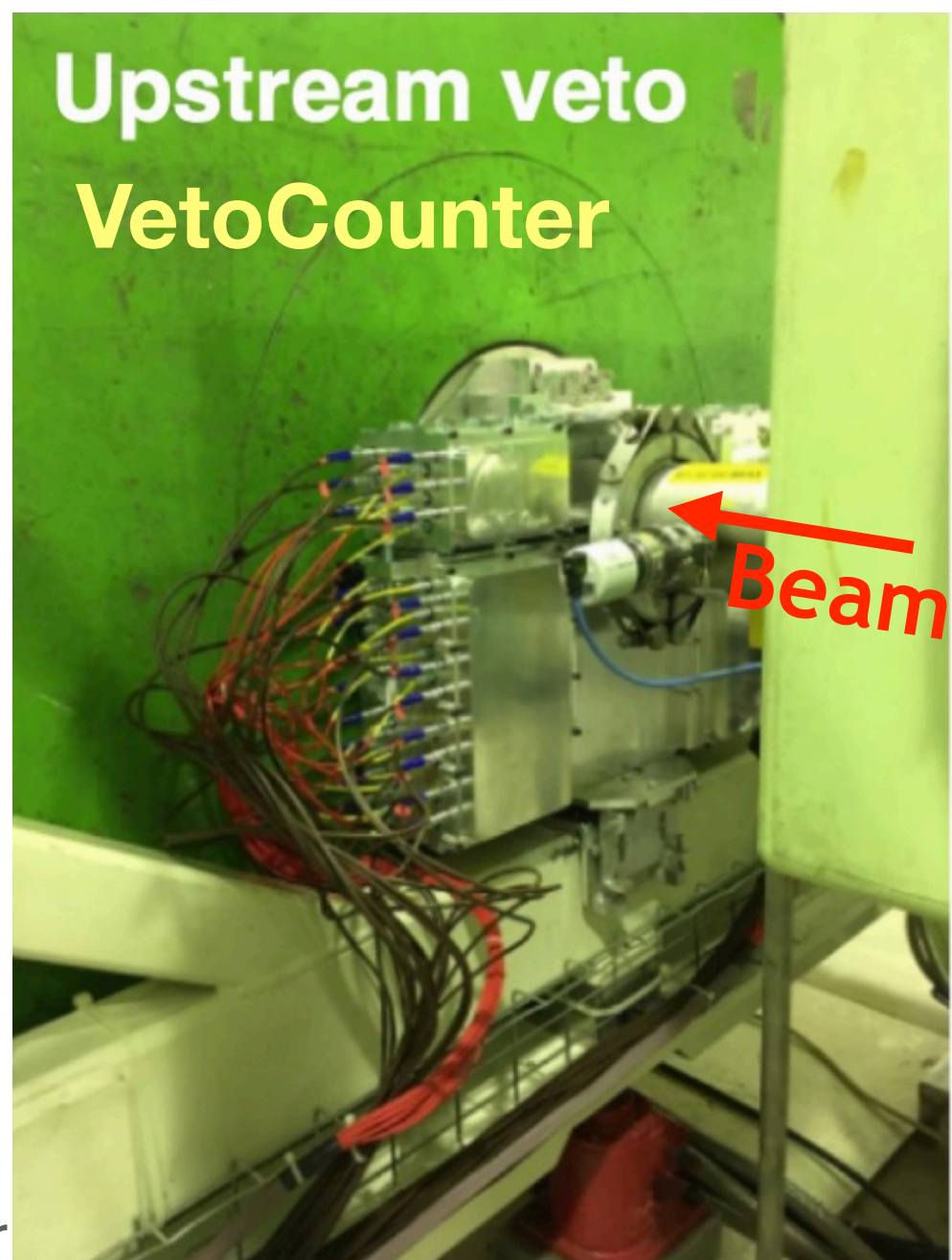
Events passing $\pi^+ \nu \bar{\nu}$ selection
 (modifying HASC veto: study integral of background regions)



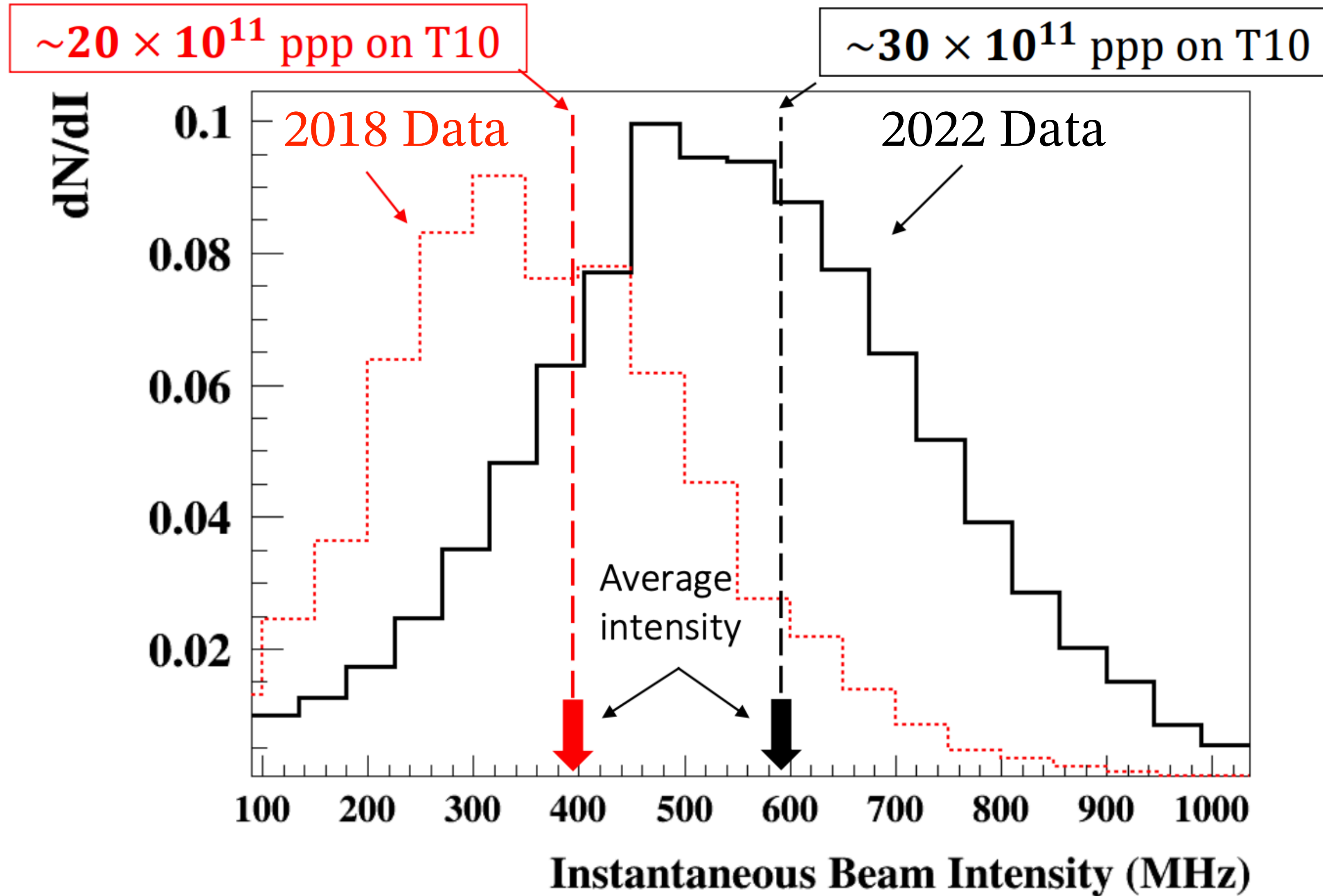
Summary of NA62 upgrades

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

New detectors
installed in 2021:



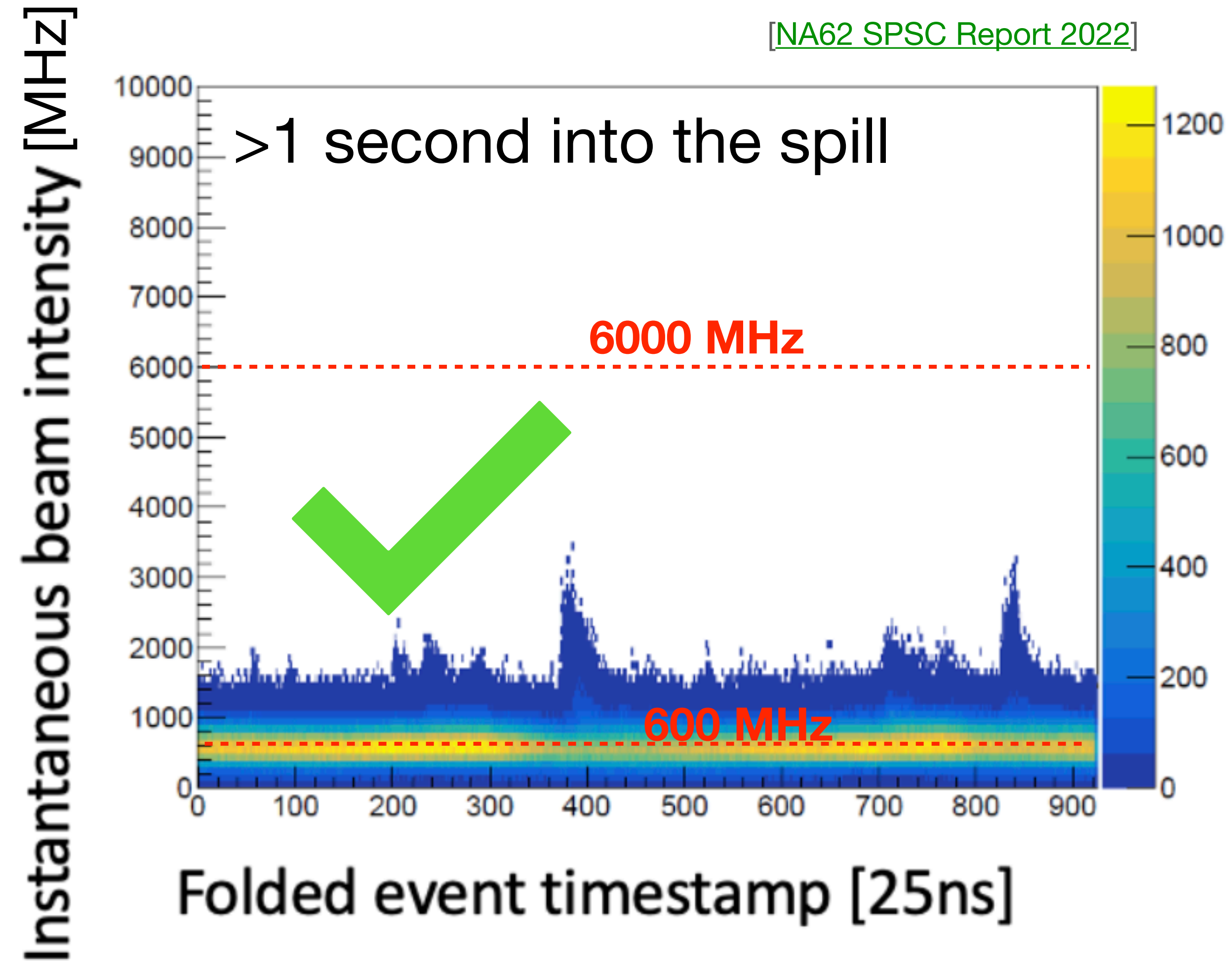
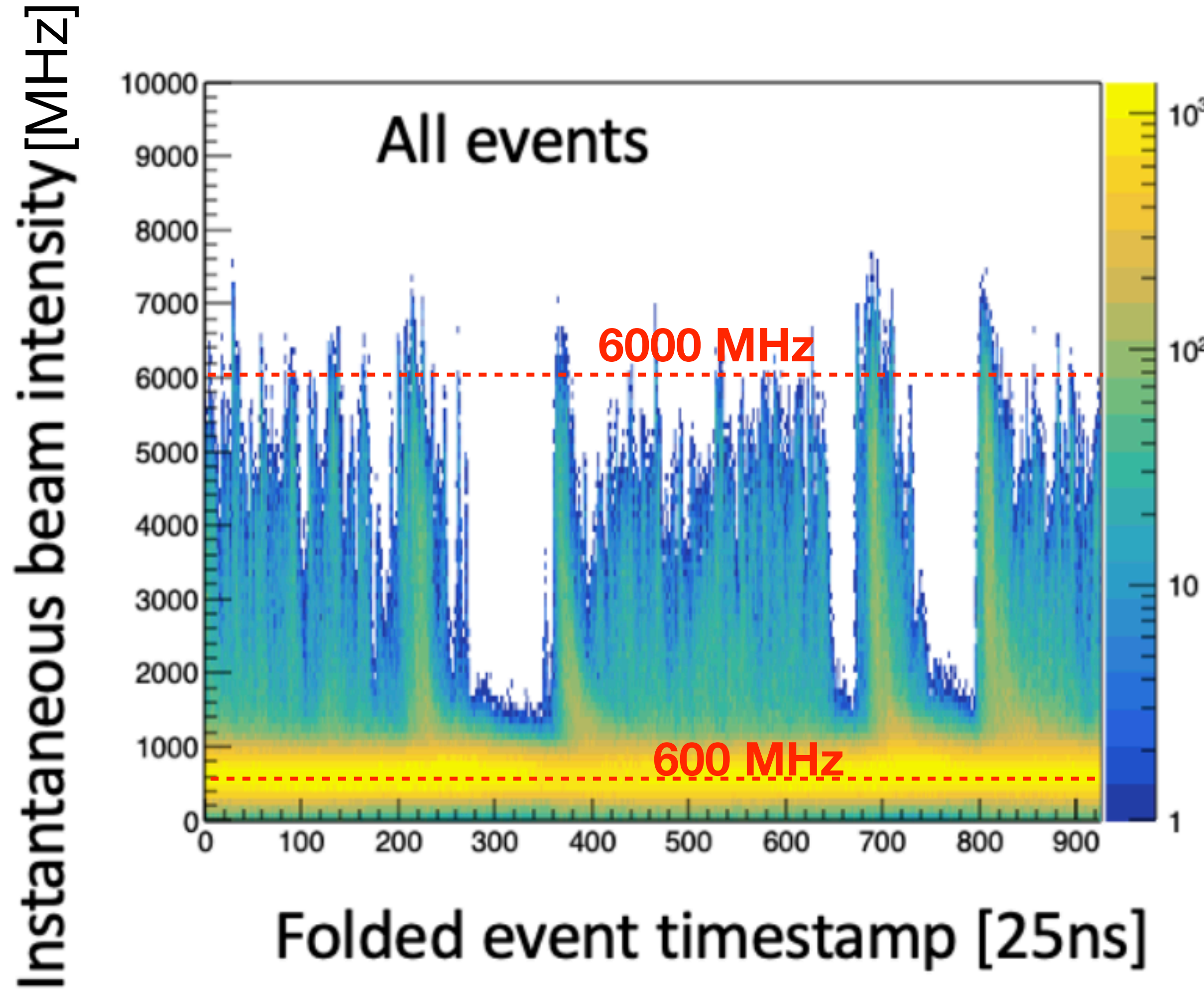
Beam intensity: 2018 vs 2022



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

2021 instantaneous beam intensity

[NA62 SPSC Report 2022]



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

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

2021–2022 data : Signal Sensitivity

Triggers:

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

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

Common conditions

+ add more conditions

Selection:

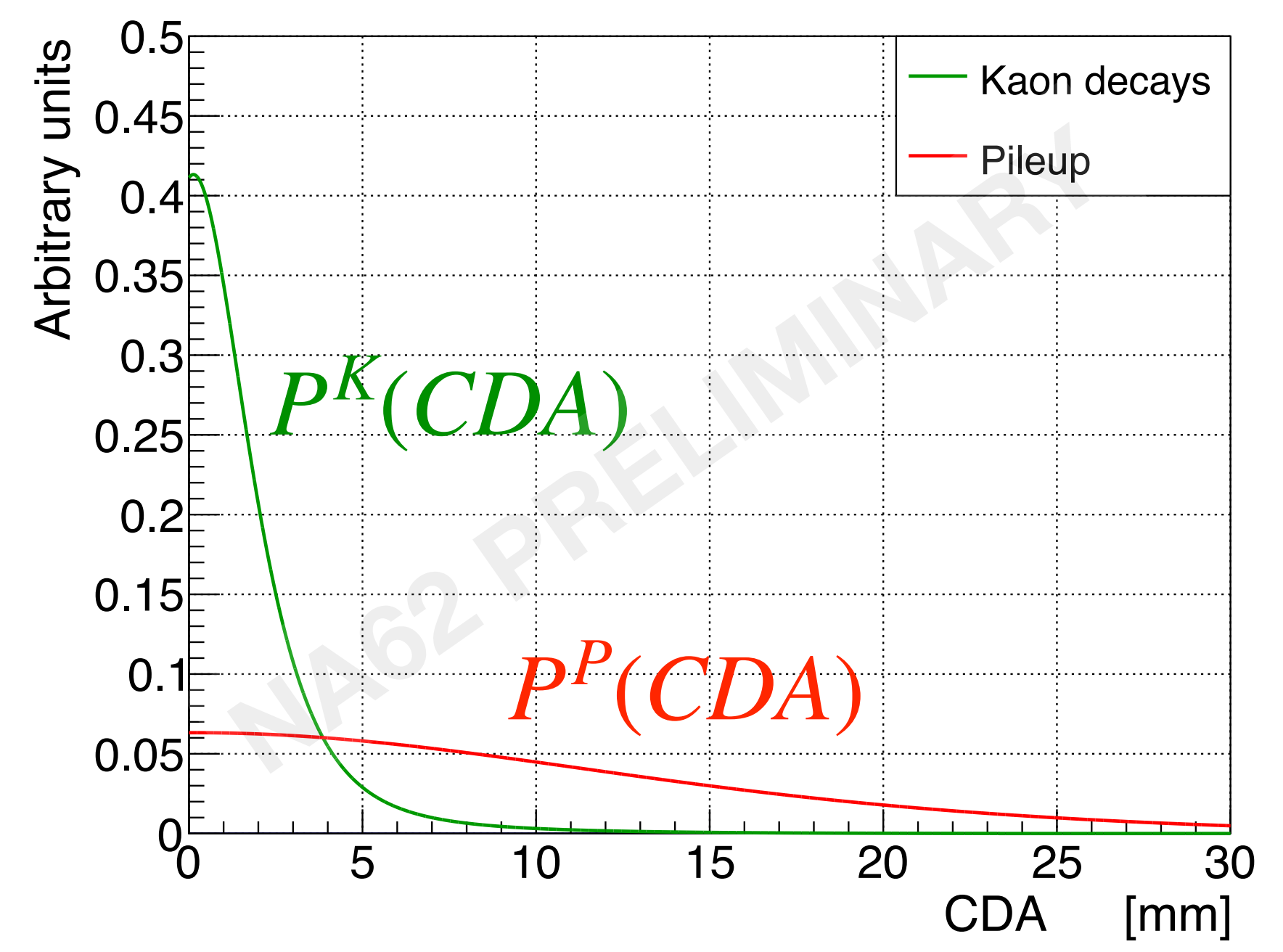
- **Normalisation** $K^+ \rightarrow \pi^+ \pi^0$: 1 downstream track (only); identified as π^+ ; $K^+ - \pi^+$ matching (space & time); upstream vetos.
- **Signal** $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ candidates: same as normalisation selection + full photon and detector multiplicity cuts (reject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

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

Example of selection update

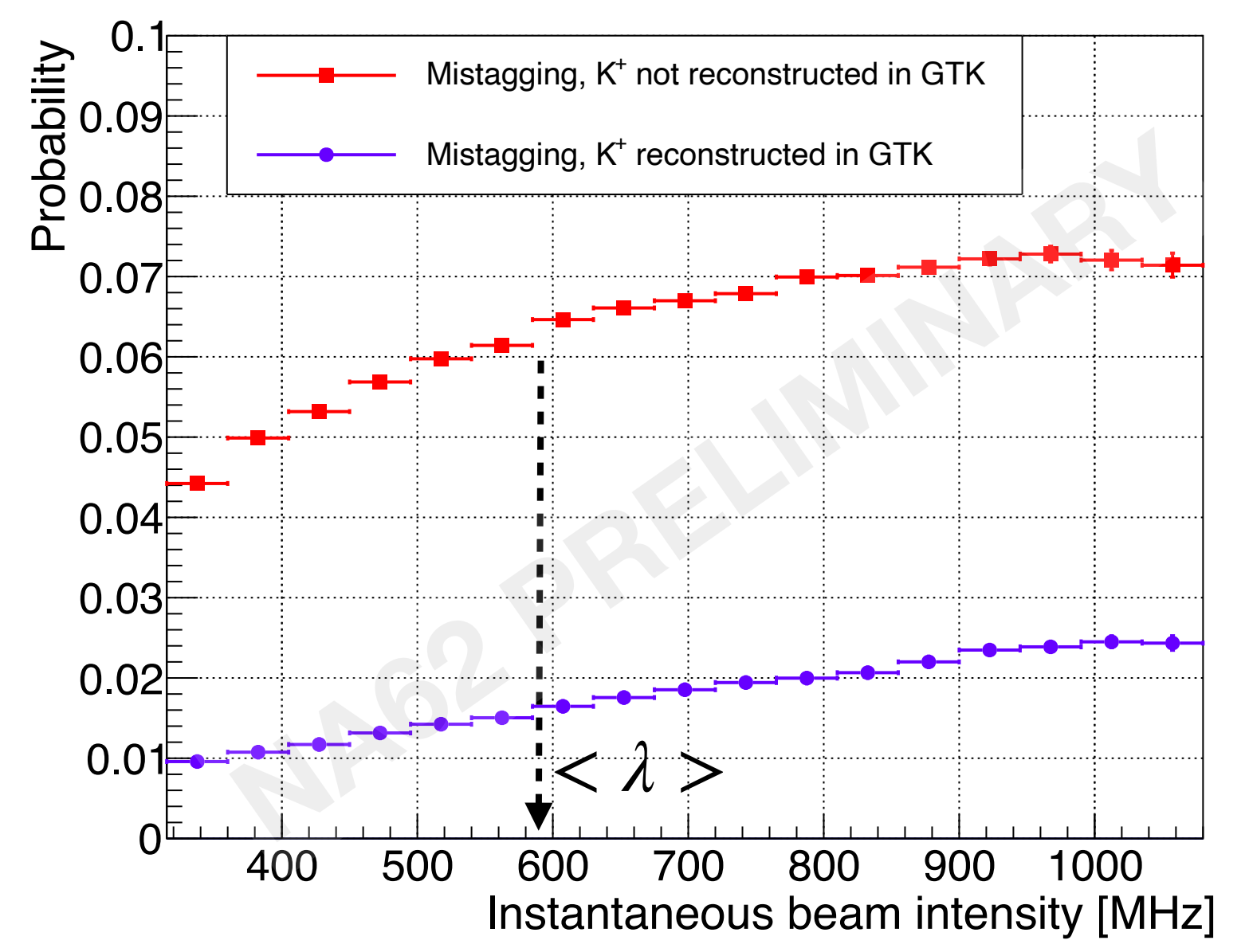
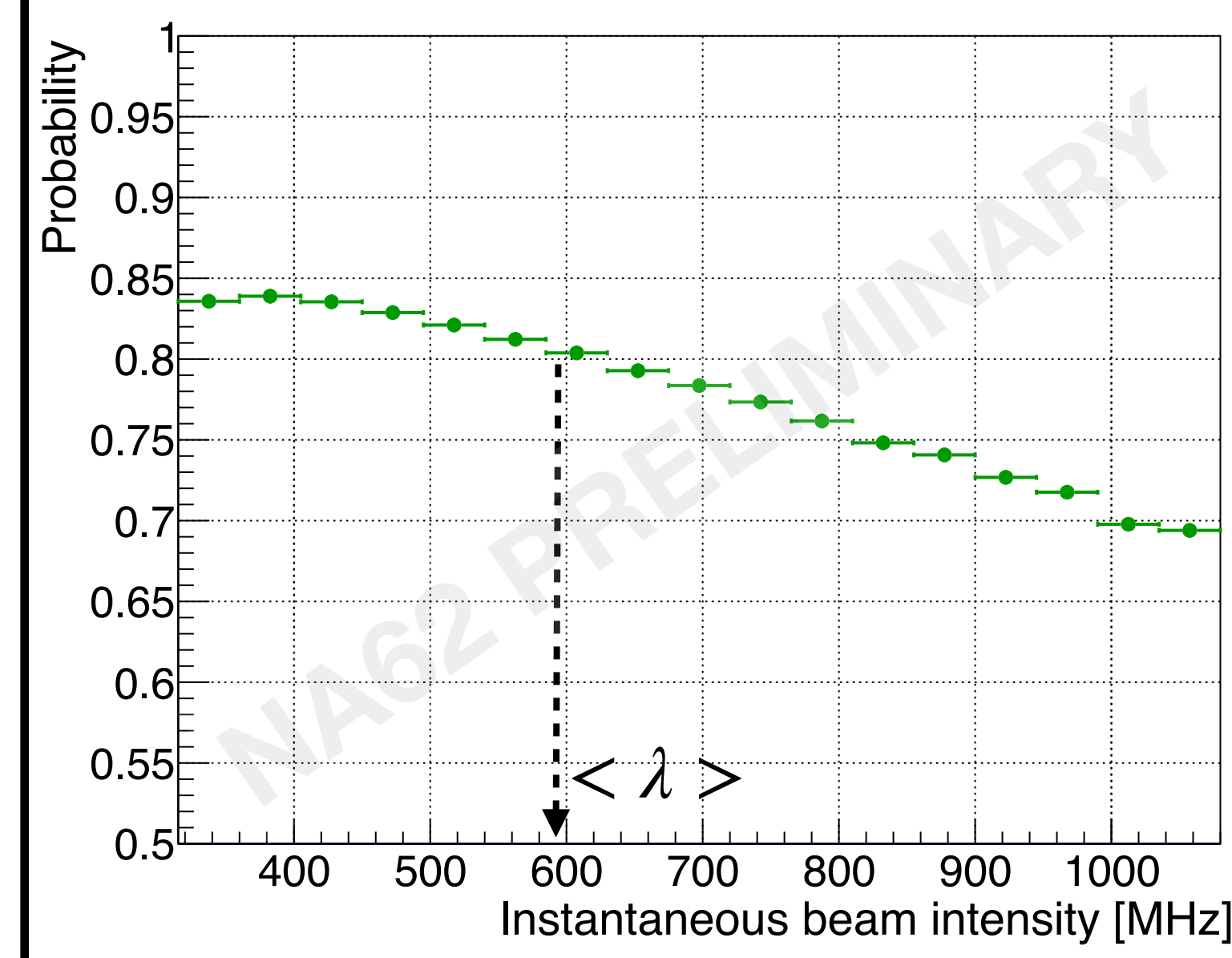


- **Inputs:** spatial (CDA) & time (ΔT_+) matching, intensity/pileup (N_{GTK}) [prior]
- Models for PDFs/Prior from $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ data.



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

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



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

Signal sensitivity

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

Effective number of K^+ decays, N_K :

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

Number of normalisation events $\rightarrow N_{\pi\pi} D_0$
 Downscaling factor of normalisation trigger (generally 400) $\rightarrow D_0$
 Branching ratio of $K^+ \rightarrow \pi^+\pi^0$ decay $\rightarrow \mathcal{B}_{\pi\pi}$
 Acceptance of normalisation selection $\rightarrow A_{\pi\pi}$

Single event sensitivity:

(Branching ratio corresponding to expectation of 1 event)

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

Random veto efficiency $\rightarrow \epsilon_{RV}$

Trigger efficiency (ratio) $\rightarrow \epsilon_{trig}$

Signal selection acceptance $\rightarrow A_{\pi\nu\bar{\nu}}$

Number of expected SM events:

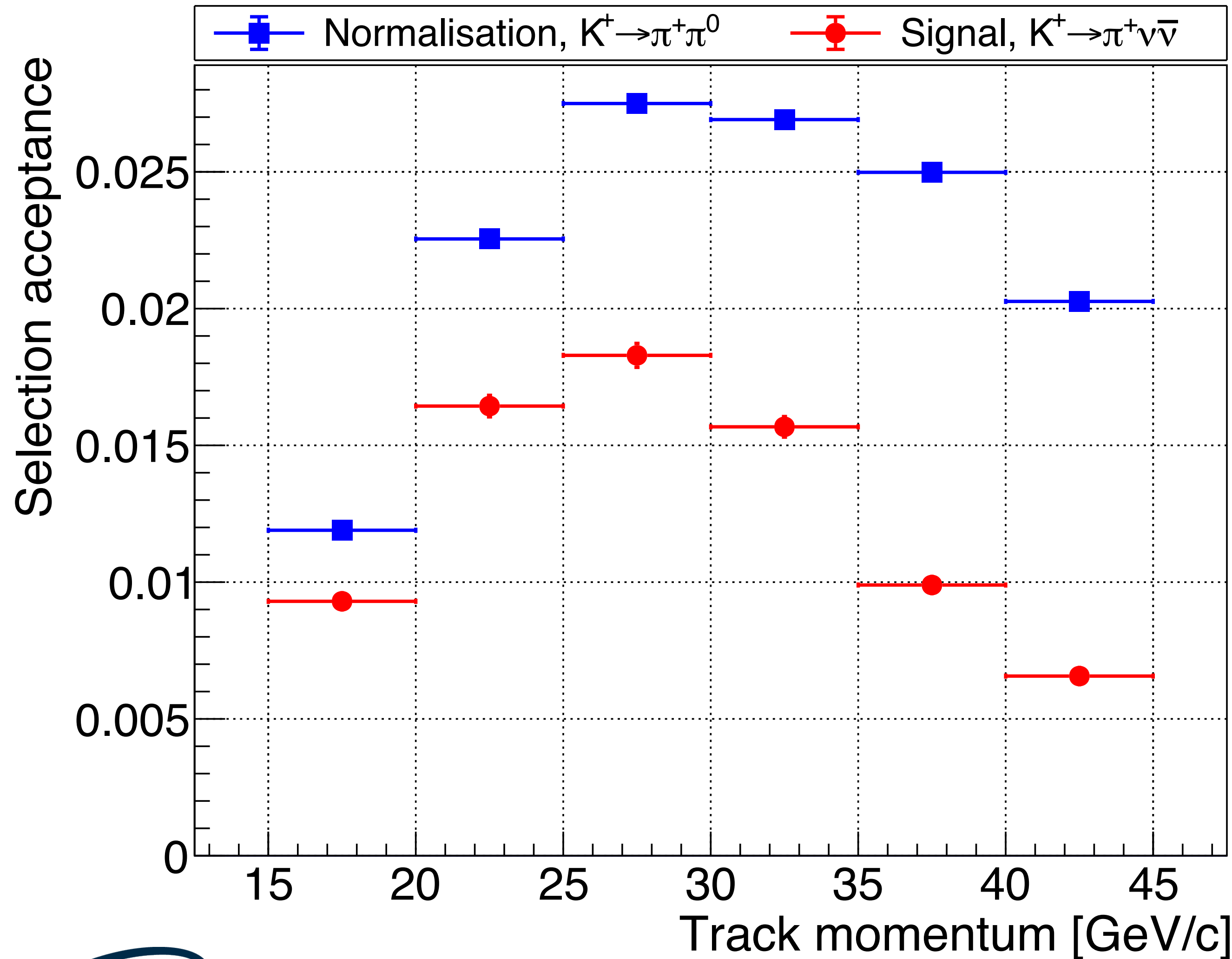
(For comparison to previous results use $\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$ [[JHEP 11 \(2015\) 166](#)], but results are independent of this choice)

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

Acceptances

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

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



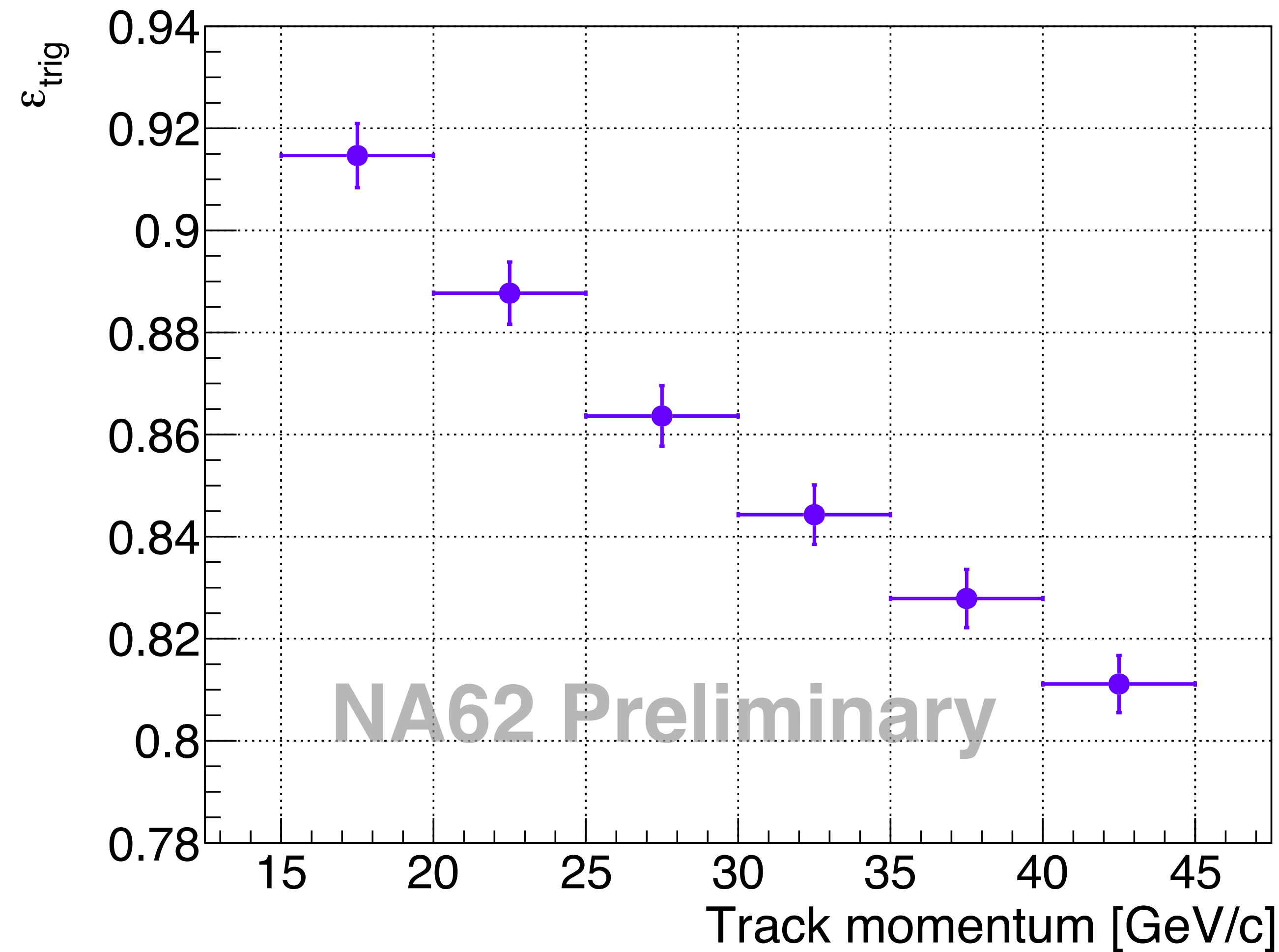
Case	OLD 2018 (S2)	NEW 2021-22	
Norm.	11.8%	13.4%	+15%
Signal	$(6.37 \pm 0.64)\%$	$(7.61 \pm 0.18)\%$	+20%

- 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:

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



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

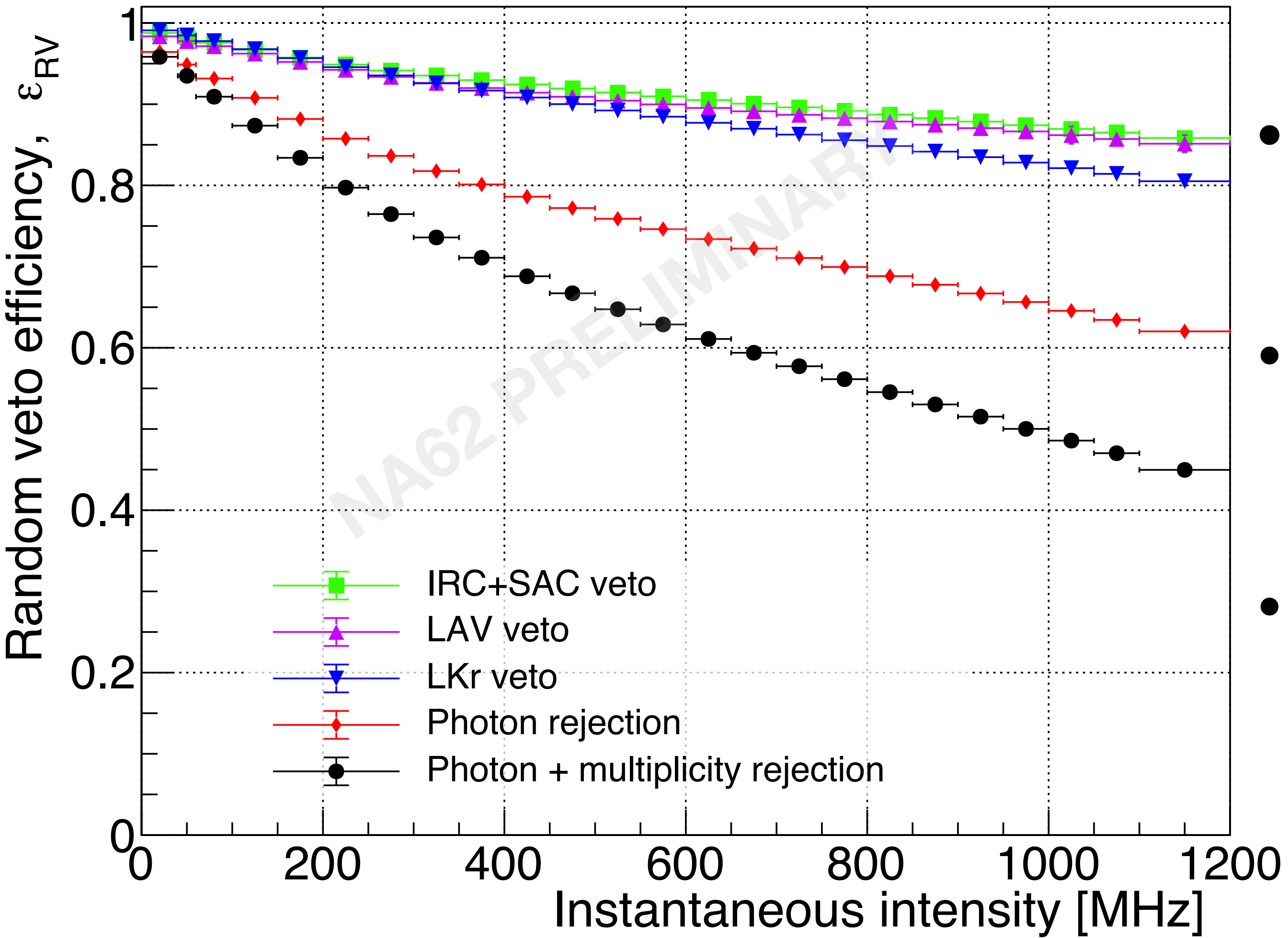
$\epsilon_{trig}(new) = (85.9 \pm 1.4) \%$
 $\epsilon_{trig}(2018) = (89 \pm 5) \%$

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

Random veto

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

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



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

$$\epsilon_{RV}(\text{new}, \overline{\lambda}_{21-22} \approx 600 \text{ MHz}) = (63.6 \pm 0.6) \%$$

$$\epsilon_{RV}(\text{old}, \overline{\lambda}_{2018} \approx 400 \text{ MHz}) = (66 \pm 1) \%$$

Signal sensitivity results

$$N_K = \frac{N_{\pi\pi} D_0}{\mathcal{B}_{\pi\pi} A_{\pi\pi}} \quad \mathcal{B}_{SES} = \frac{1}{N_K \epsilon_{RV} \epsilon_{trig} A_{\pi\nu\bar{\nu}}}$$

- Display integrals (15–45 GeV/c, 2021+22) for summary tables.
- * Acceptances evaluated at 0 intensity.

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

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

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

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

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

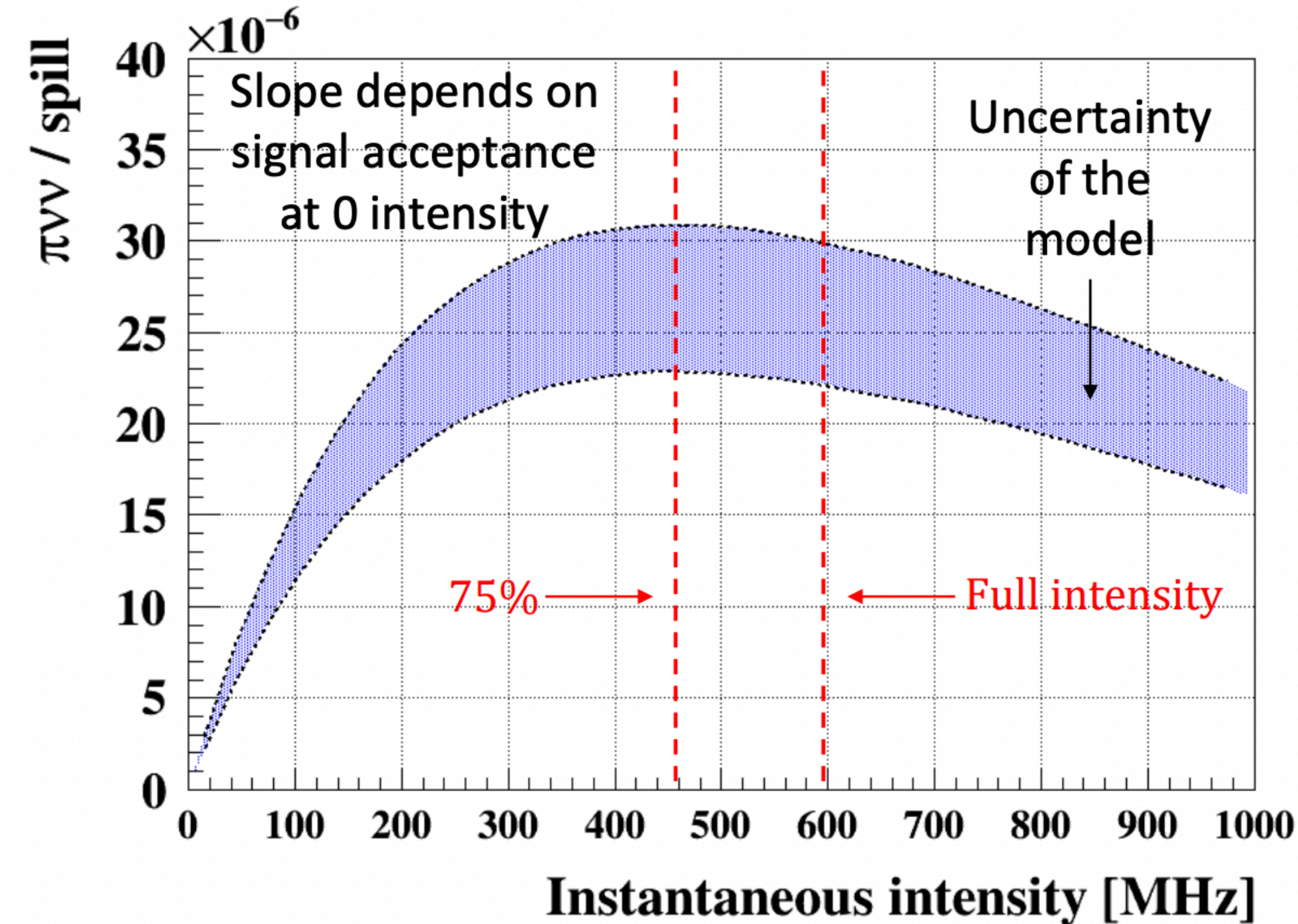


Double expected signal
by including 21–22 data.

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

Optimum NA62 intensity

Selected signal yield vs intensity



- Saturation of expected signal yield with intensity. Mainly due to:
 - Paralyzable effects from TDAQ dead time and trigger veto windows.
 - Offline selection, due to veto conditions.
- Main sources of uncertainty for model:
 - Online time-dependent mis-calibrations.
 - Fit uncertainty.
- **From August 2023 operate at optimal intensity (~75% of full) to maximise $\pi V V$ sensitivity**
 - Maximise signal yield
 - lower expected background
 - Higher DAQ efficiency
- **Studies of 2021–22 data at high intensity were crucial to establish optimal intensity.**

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

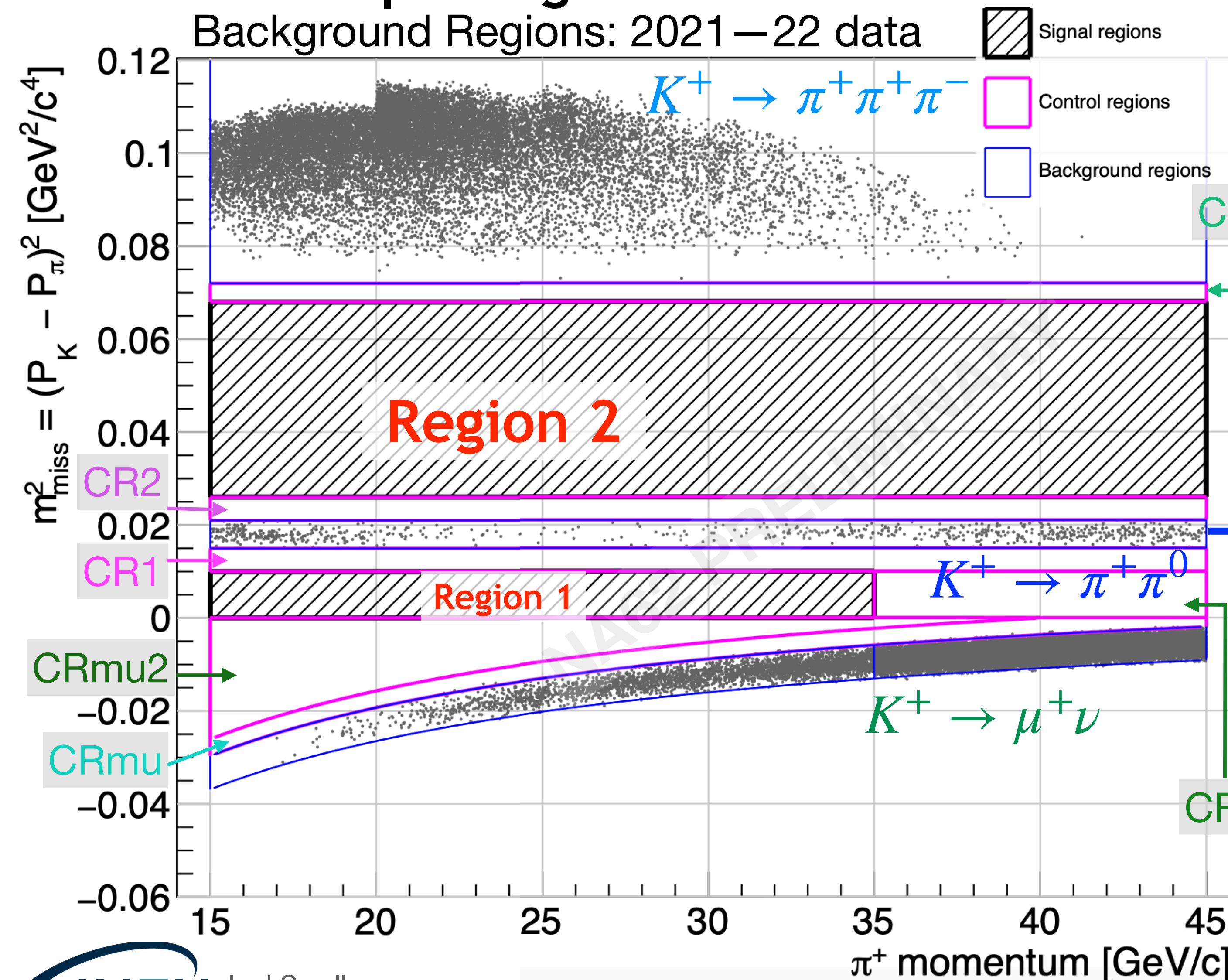
2021 – 2022 data : Background Evaluation

Background regions & background estimations



Events passing $\pi\nu\nu$ selection

Background Regions: 2021 – 22 data



- Backgrounds from kinematic misconstruction tails in m_{miss}^2

Number of events passing signal selection in background region

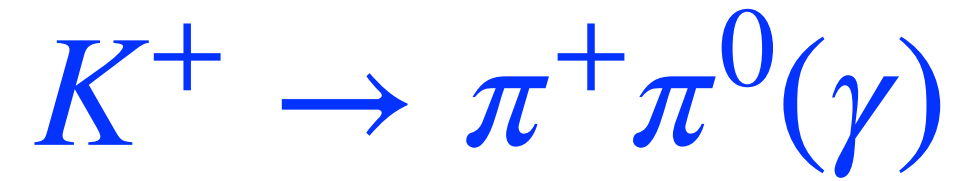
$$N_{bg} = N_{bkgR} \cdot f_{tail} = N_{bkgR} \cdot \frac{N_{SR}^{CS}}{N_{bkgR}^{CS}}$$

Kinematic tail fraction: measured in control sample

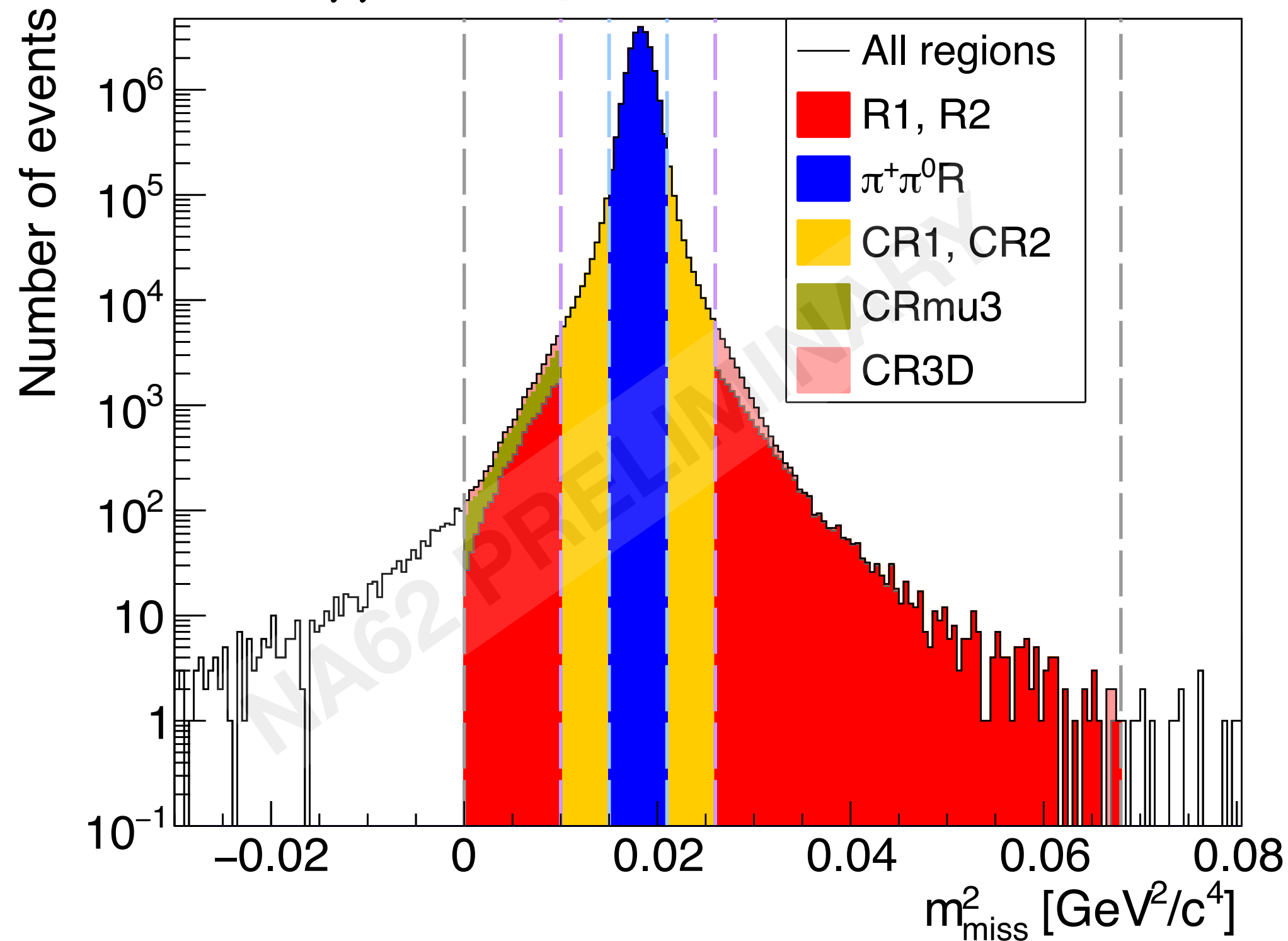
Control sample events in Signal Regions

Control sample events in Background Region

Backgrounds from kinematic tails



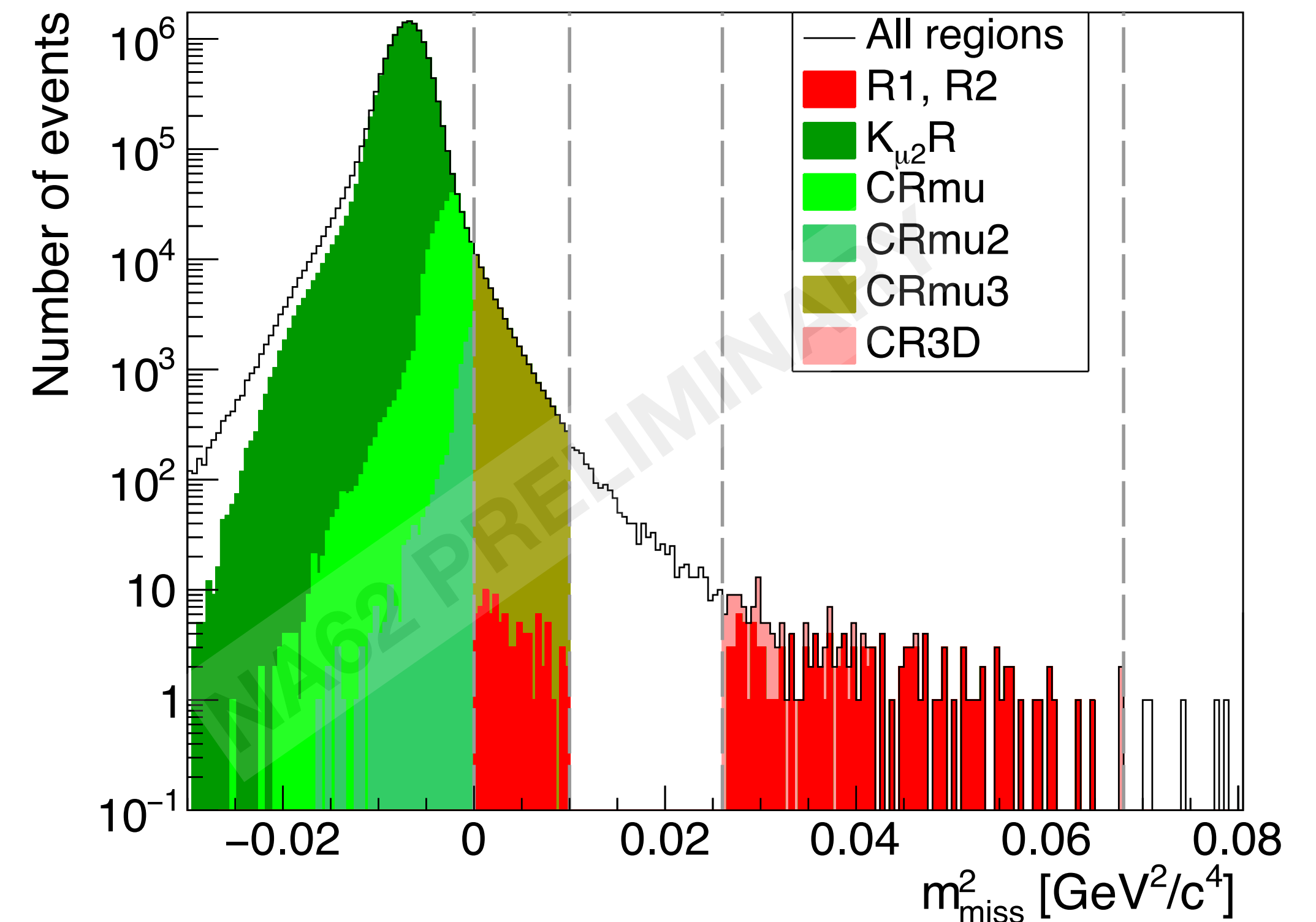
control sample of $K^+ \rightarrow \pi^+ \pi^0$ events with $\pi^0 \rightarrow \gamma\gamma$ and 2 photons detected in LKr:



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

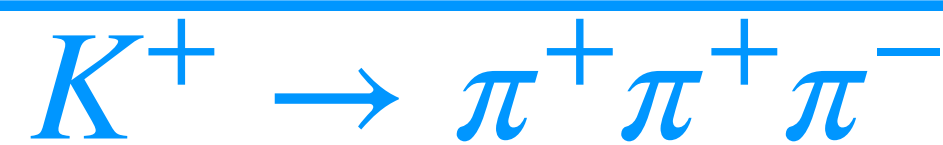


control sample of $K^+ \rightarrow \mu^+ \nu$ events with RICH PID= π^+ and Calo PID= μ^+ :



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

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

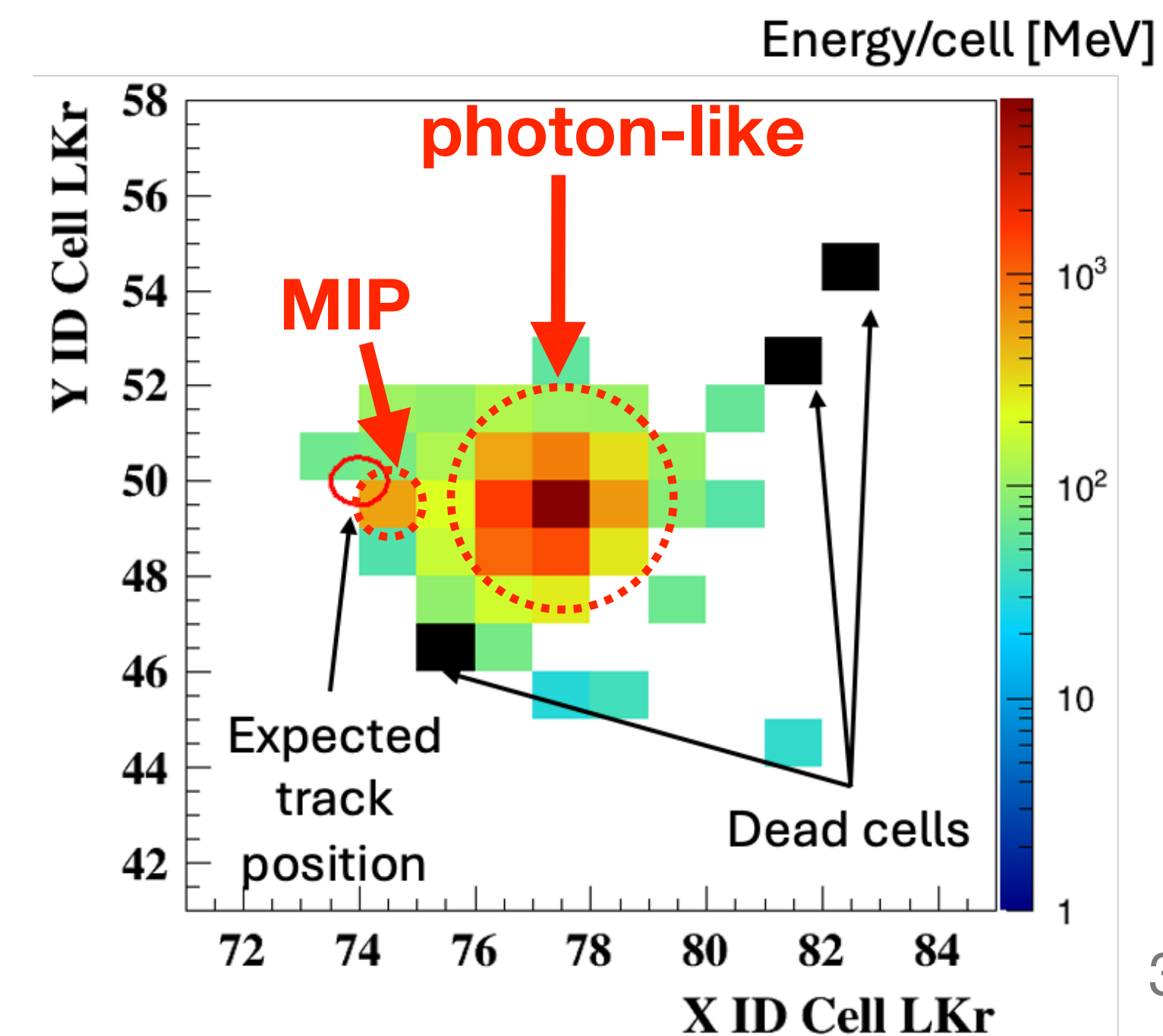
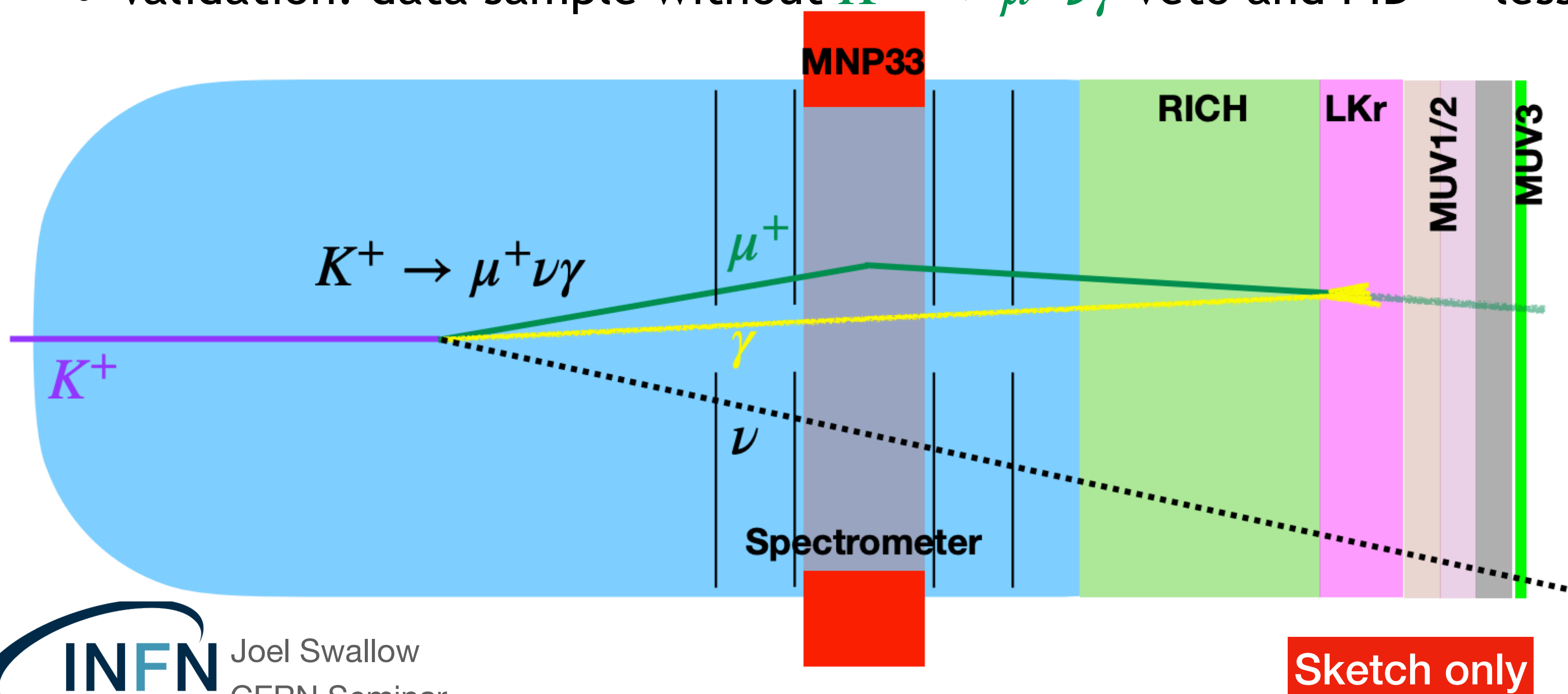


- Use MC to measure f_{tail} :

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

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

- $K^+ \rightarrow \pi^+ \pi^0 \gamma$: included with “kinematic tails” estimation.
 - Suppression: photon vetos, rejection with additional γ is 30x stronger.
 - Estimation: MC + measured single photon rejection efficiency : $N_{bg}(K^+ \rightarrow \pi^+ \pi^0 \gamma) = 0.07 \pm 0.01$
 - Validation: m_{miss}^2 control regions (CR1,2 - see later)
- $K^+ \rightarrow \mu^+ \nu \gamma$: 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 $\gamma =$ 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 : $N_{bg}(K^+ \rightarrow \mu^+ \nu \gamma) = 0.8 \pm 0.4$
 - Validation: data sample without $K^+ \rightarrow \mu^+ \nu \gamma$ veto and PID = “less pion-like” (Calo BDT bins below π^+ bin).

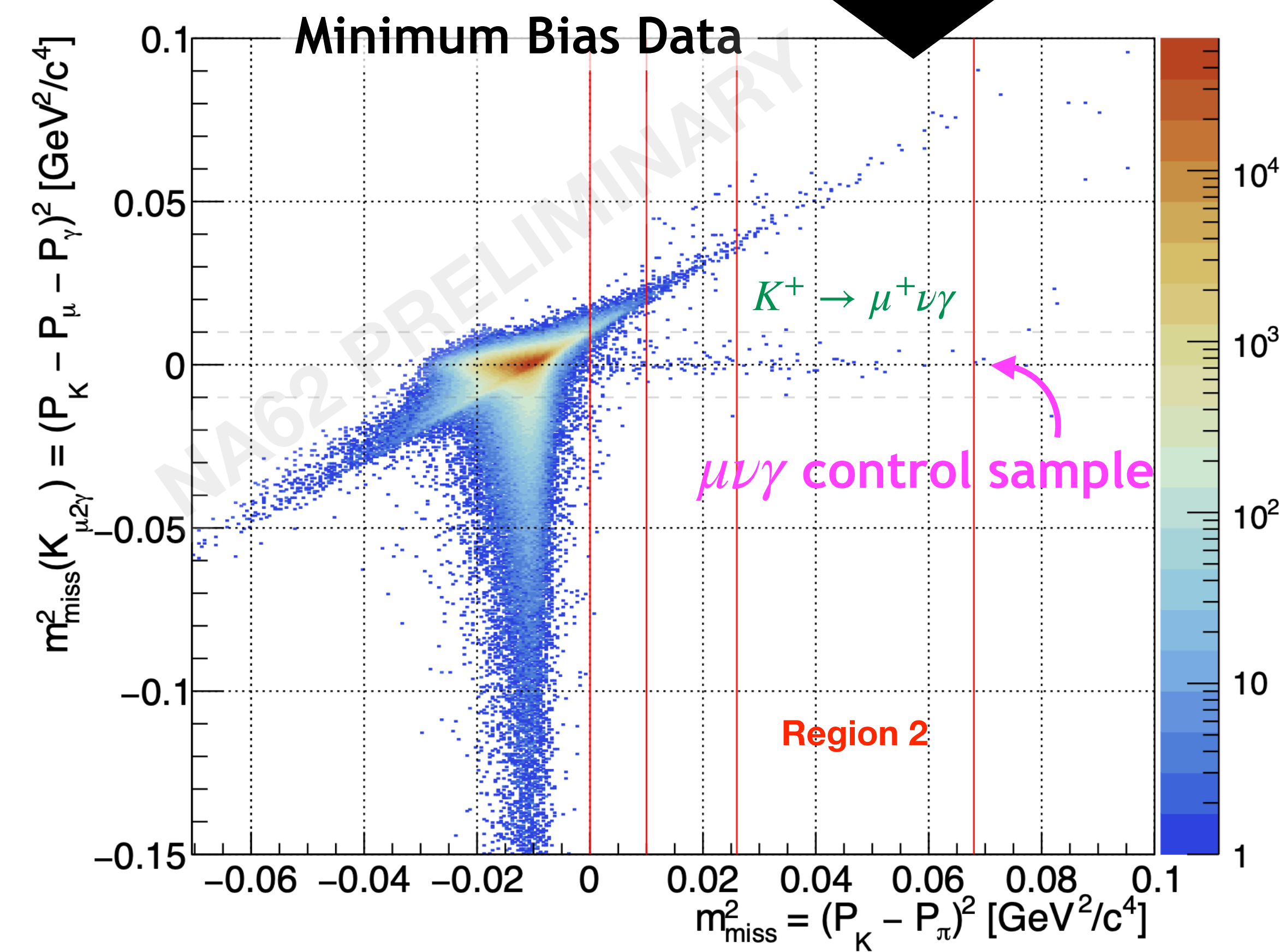


$K^+ \rightarrow \mu^+ \nu \gamma$ Background

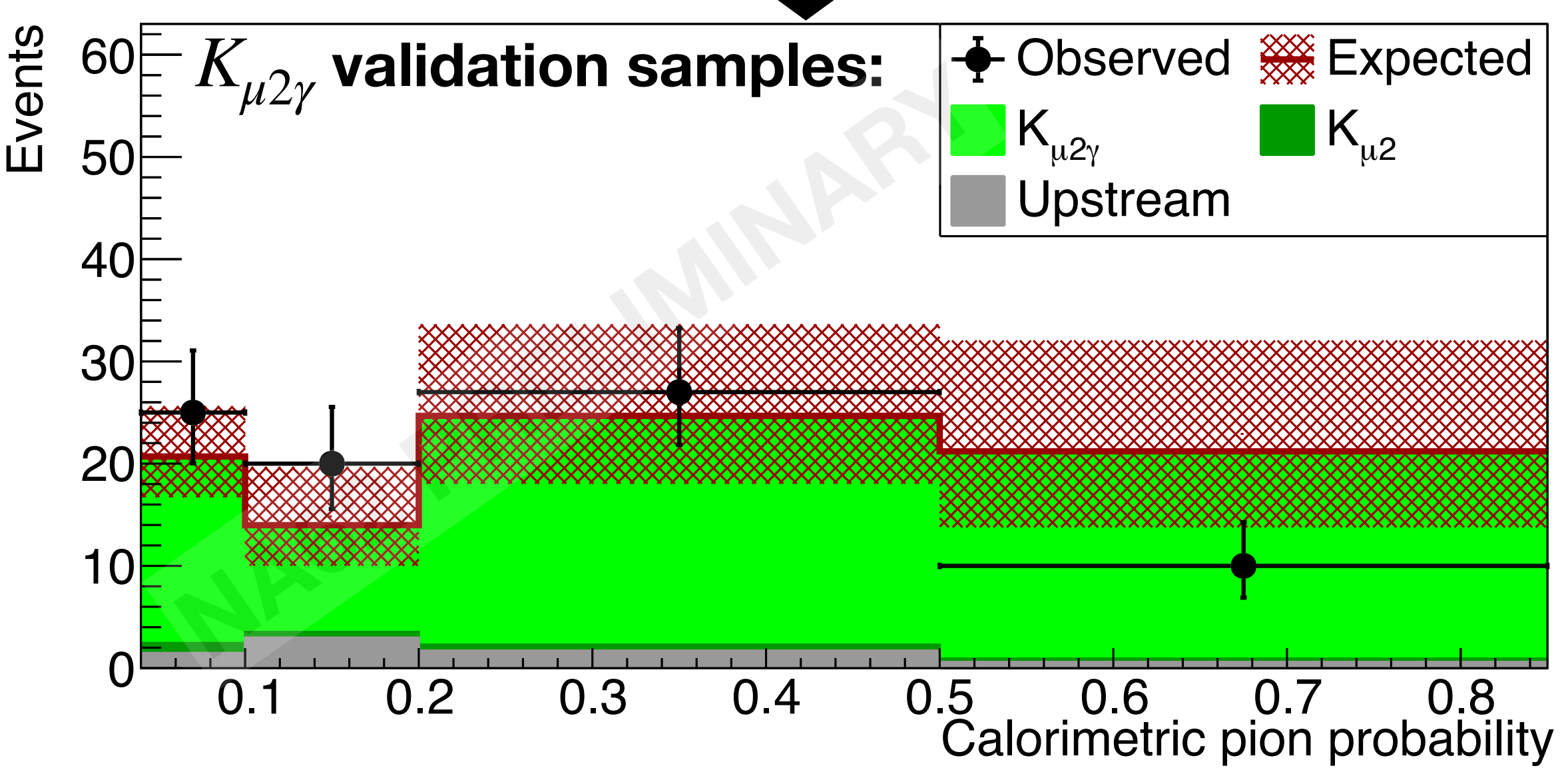
- Kinematically select $K^+ \rightarrow \mu^+ \nu \gamma$ events:

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

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

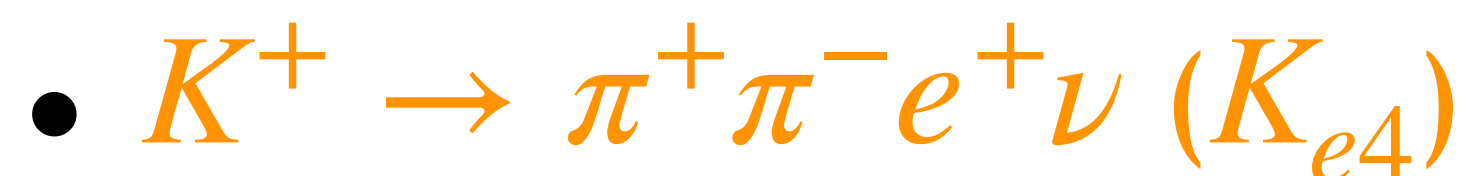


Validation: data sample with PID = “less pion-like” (Calo BDT bins below π^+ bin).



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

Other backgrounds



- No clean control samples for K_{e4} in data: use 2×10^9 simulated decays.

Effective # of K^+ Random veto & trigger efficiencies Acceptance : $A_{K_{e4}} = \frac{N_{MC}^{sel}}{N_{MC}^{gen}} = (1.3 \pm 0.3_{stat}) \times 10^{-8}$

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

Branching ratio of K_{e4} (from PDG)

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



- Evaluated with simulations.
- Negligible contributions to total background.

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

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

Upstream background evaluation

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

N
 f_{cda}
 P_{match}

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

Scaling factor : bad cda \rightarrow good cda

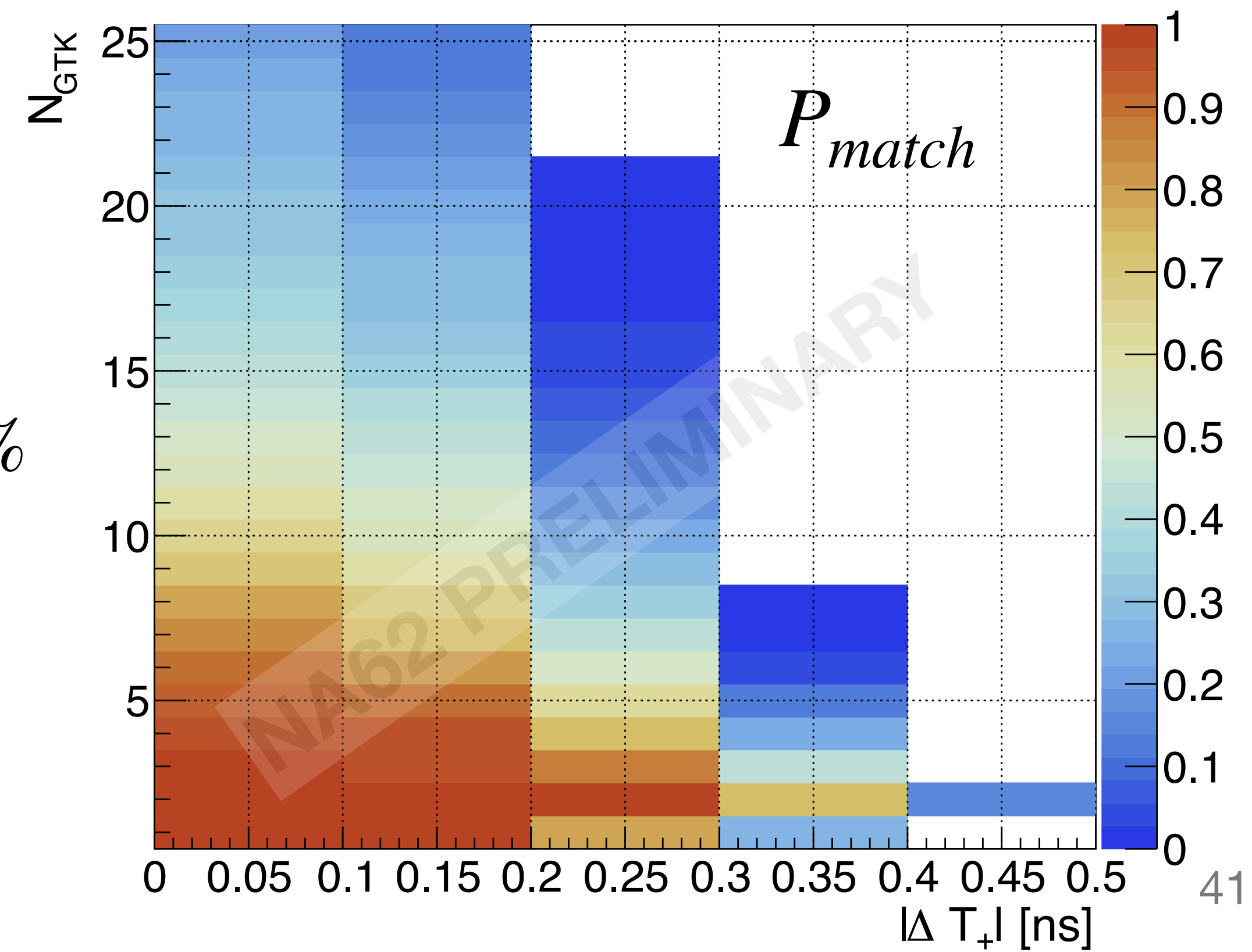
Probability to pass $K^+ - \pi^+$ matching

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

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

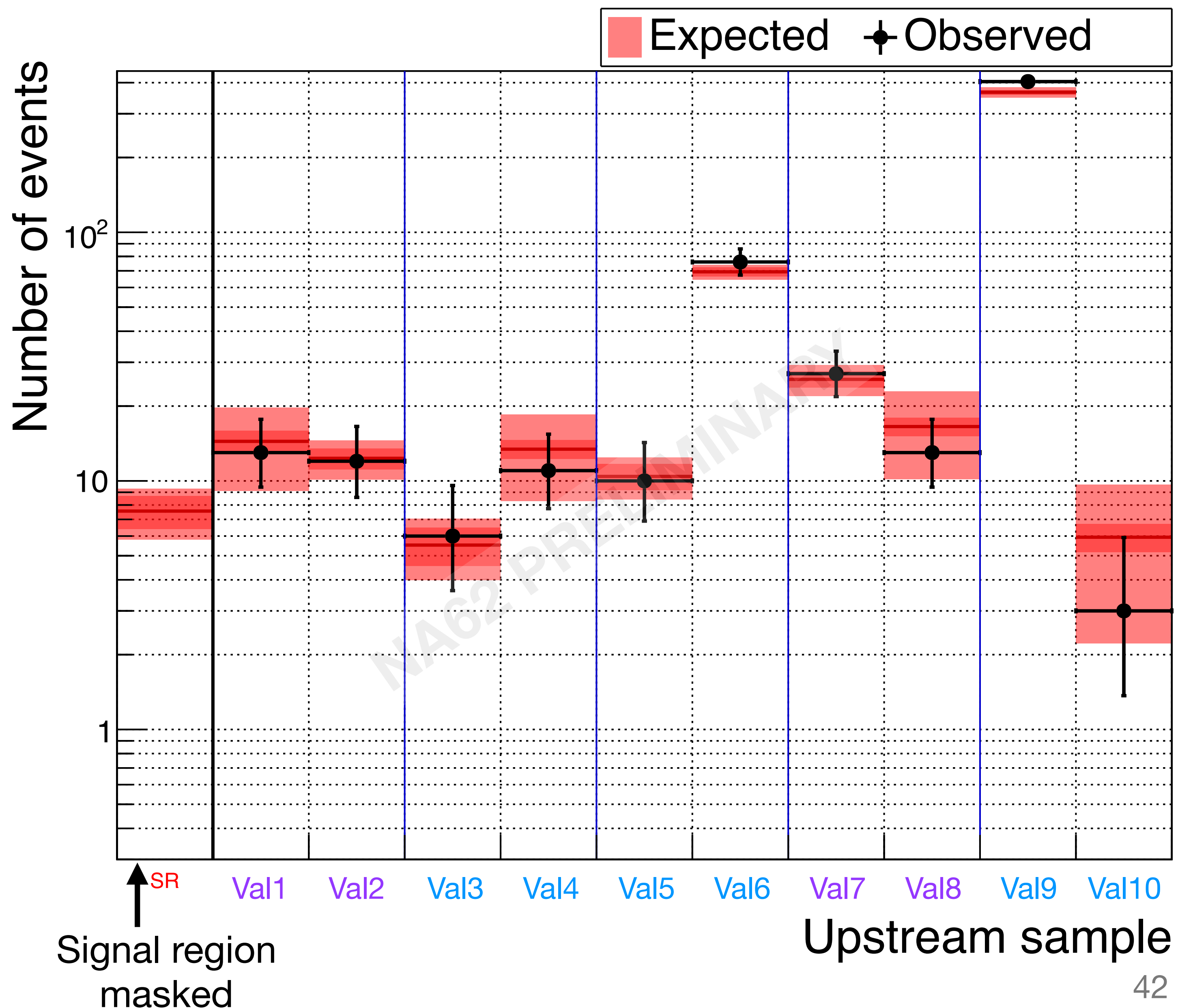
$$N = 51 \quad f_{CDA} = 0.20 \pm 0.03 \quad \langle P_{match} \rangle = 73 \%$$

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



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)
 - $N_{exp}^{VC rej.} = 6.9 \pm 1.4$, $N_{obs}^{VC rej.} = 9$
- VetoCounter is essential to control upstream background.



Summary of expectations

Backgrounds

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

Signal Sensitivity

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

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

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

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

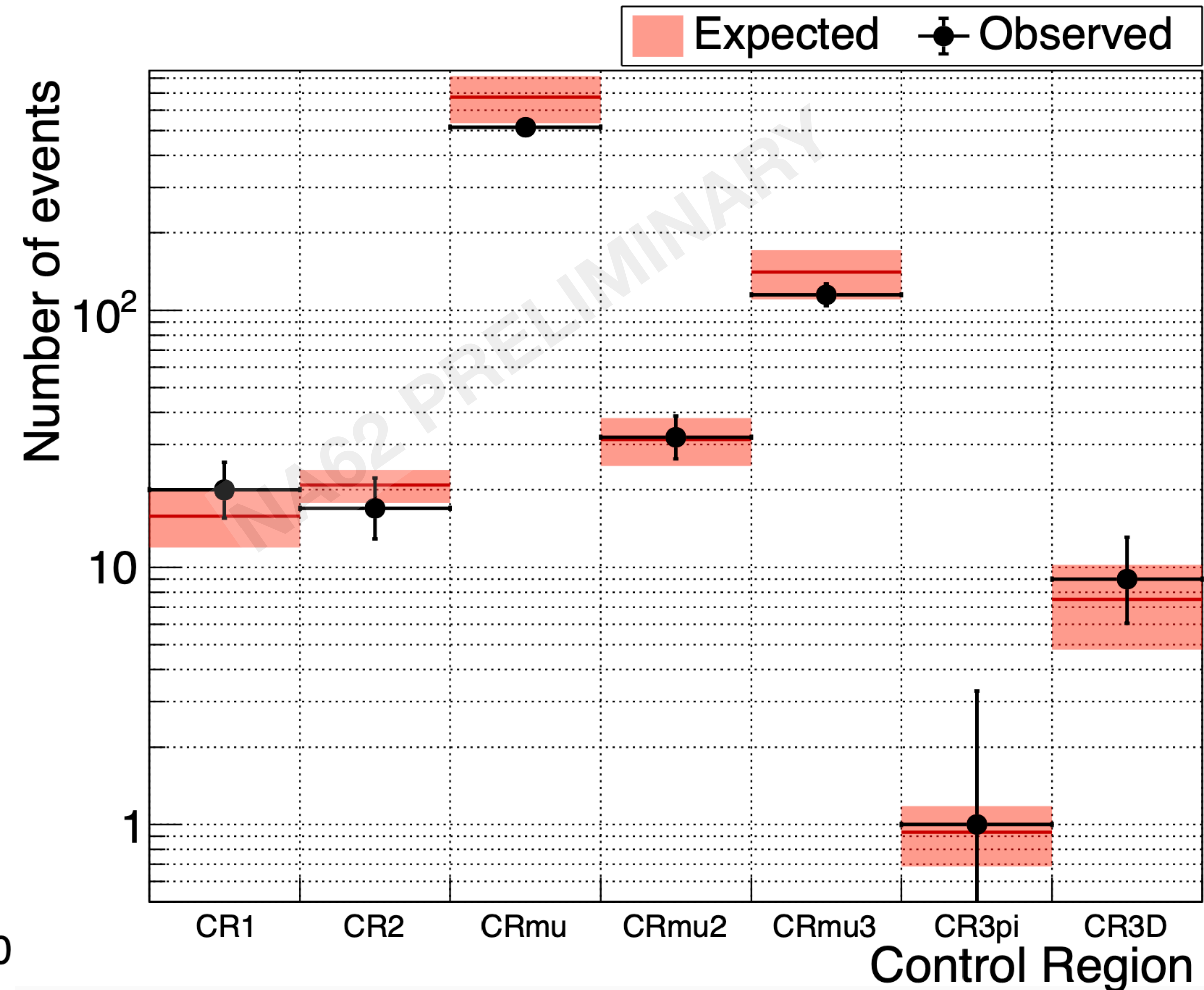
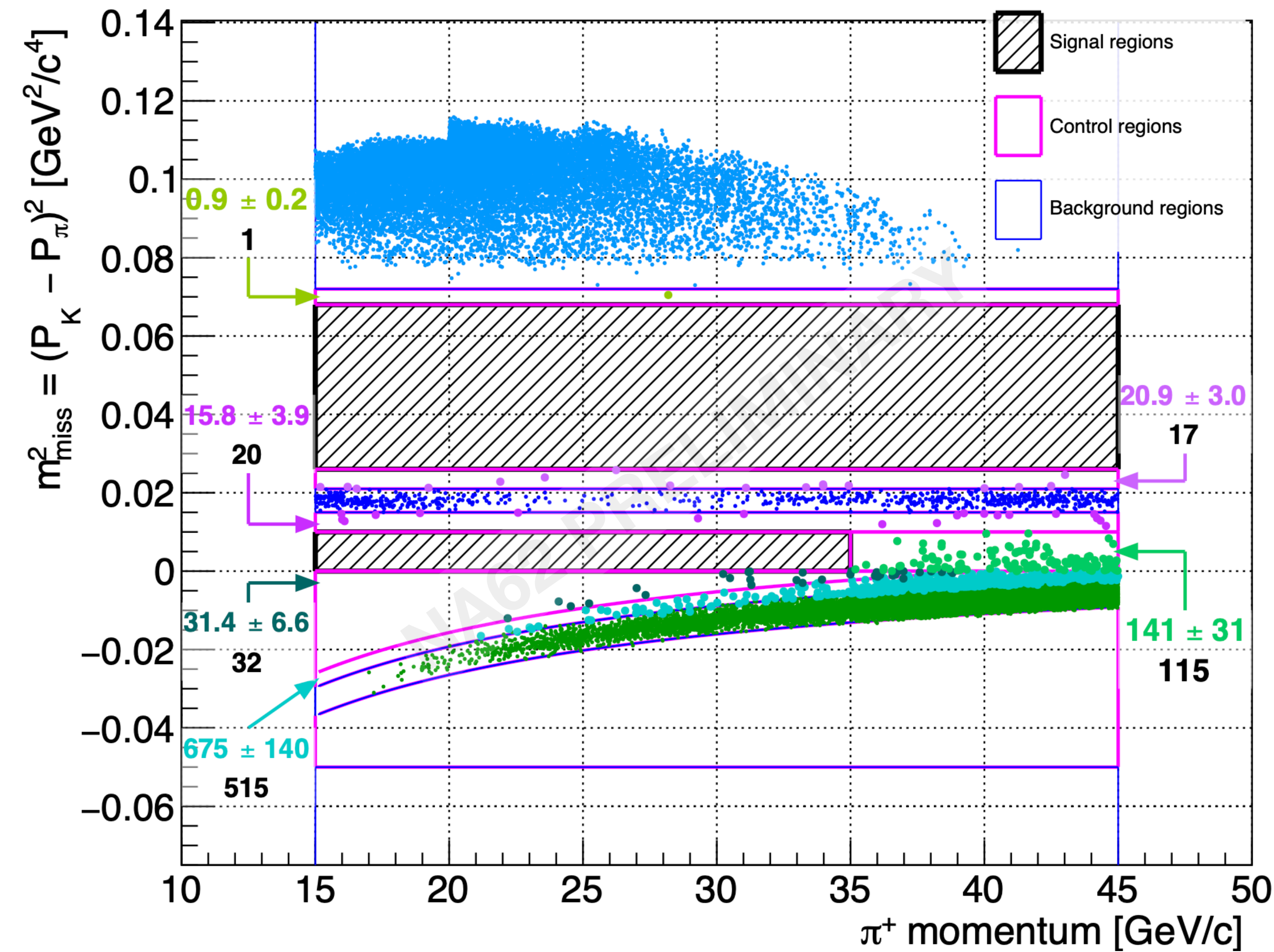
c.f. 2016–18 : $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

Expected signal doubled by including 2021–22 data

- $N_{\pi\nu\bar{\nu}}^{SM}$ per SPS spill: 2.5×10^{-5} in 2022
 - c.f. 1.7×10^{-5} in 2018. \Rightarrow 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



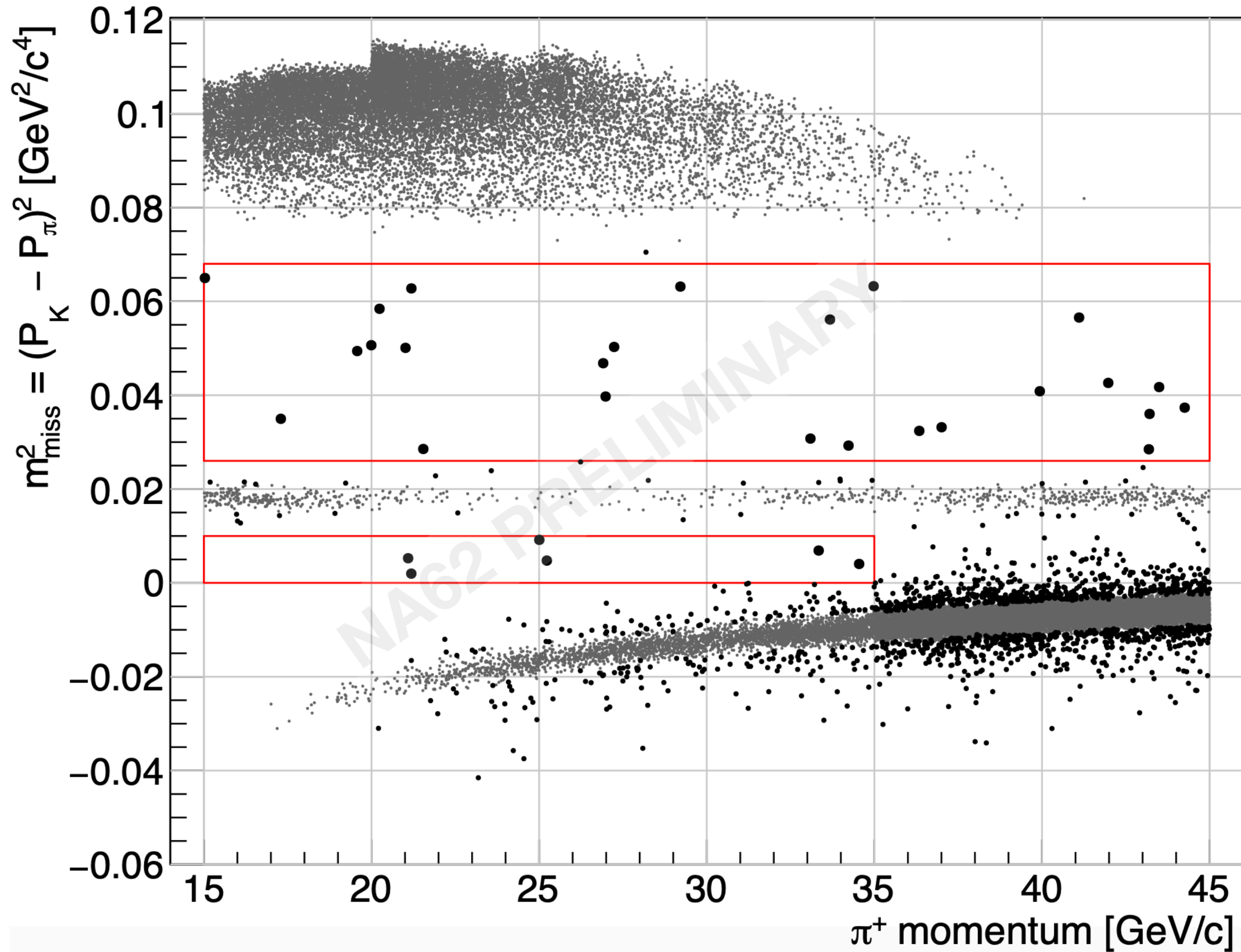
- Good agreement in control regions validates background expectations.

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

2021 – 2022 data

Signal regions

2021 – 22 data

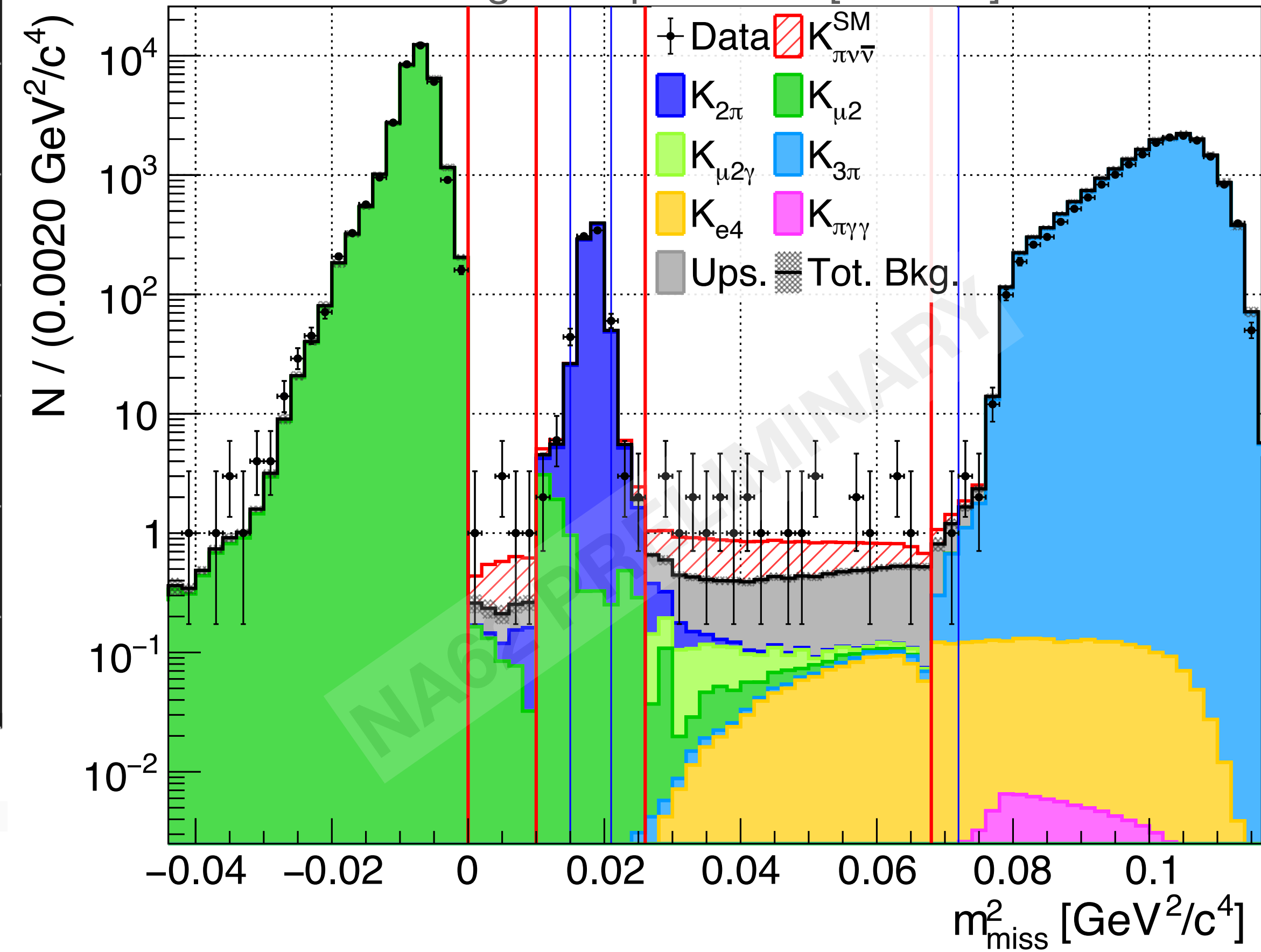


Expected SM signal, $N_{\pi\nu\bar{\nu}}^{SM} \approx 10$

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

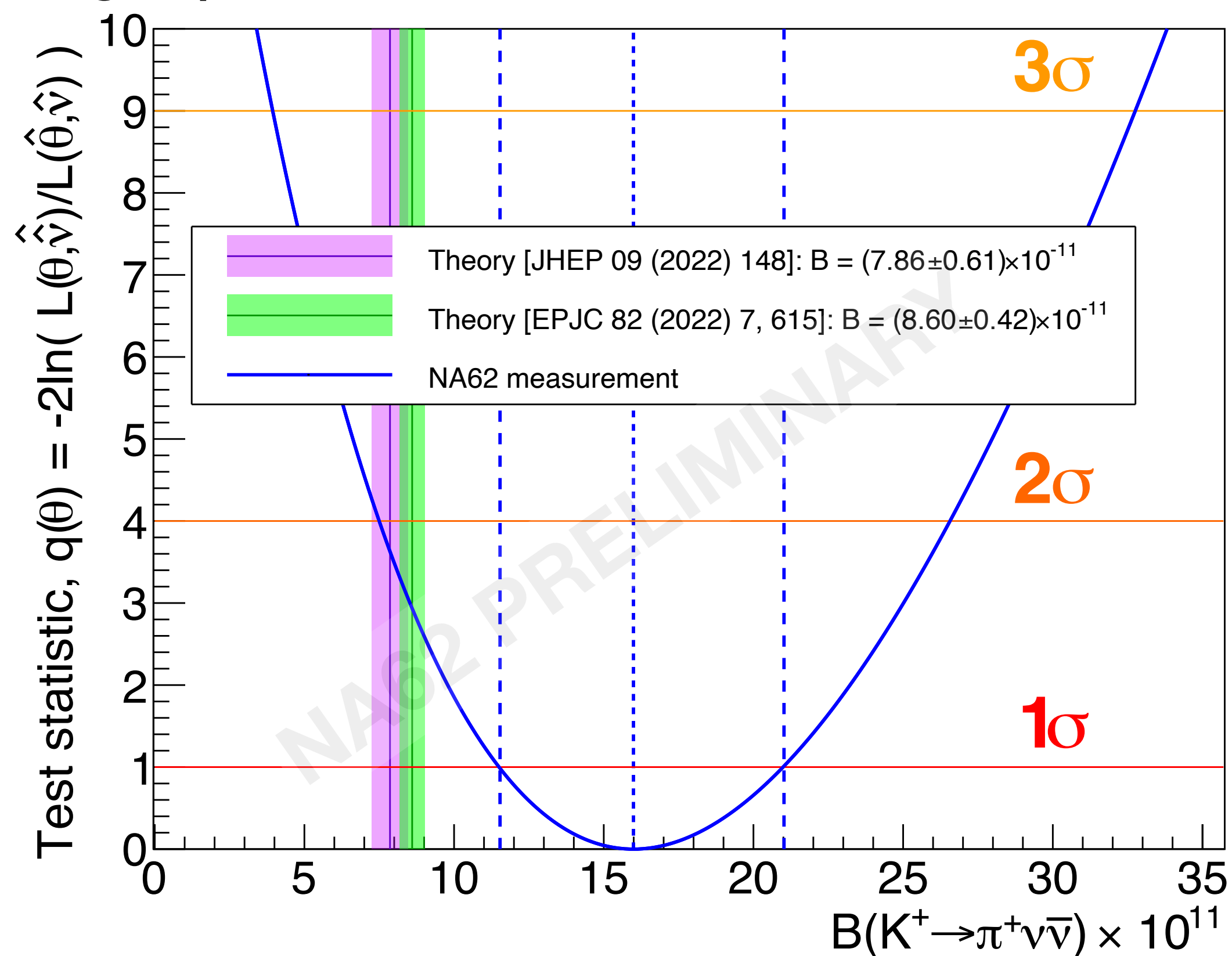
Observed, $N_{obs} = 31$

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

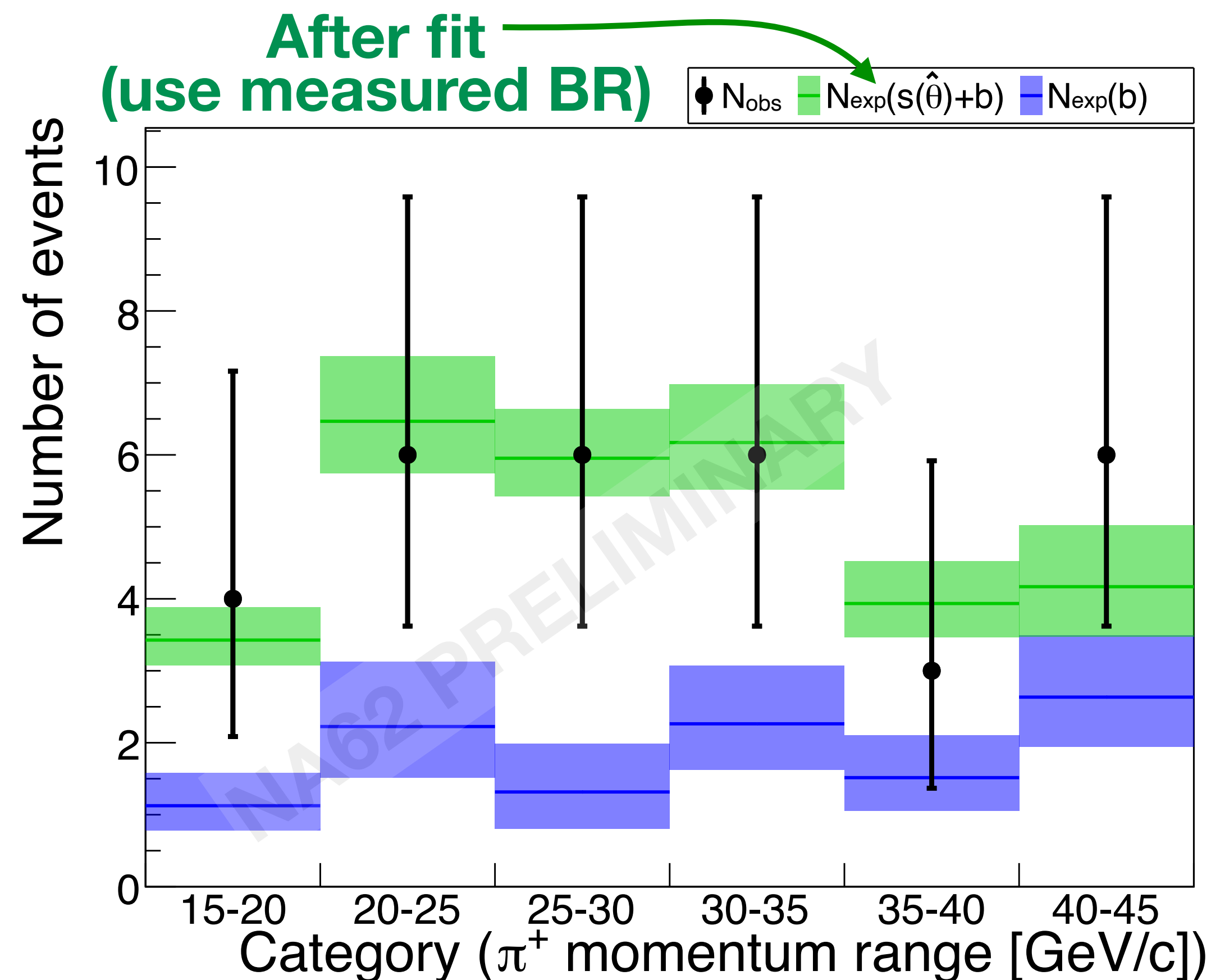


Results: 2021–22 Data

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



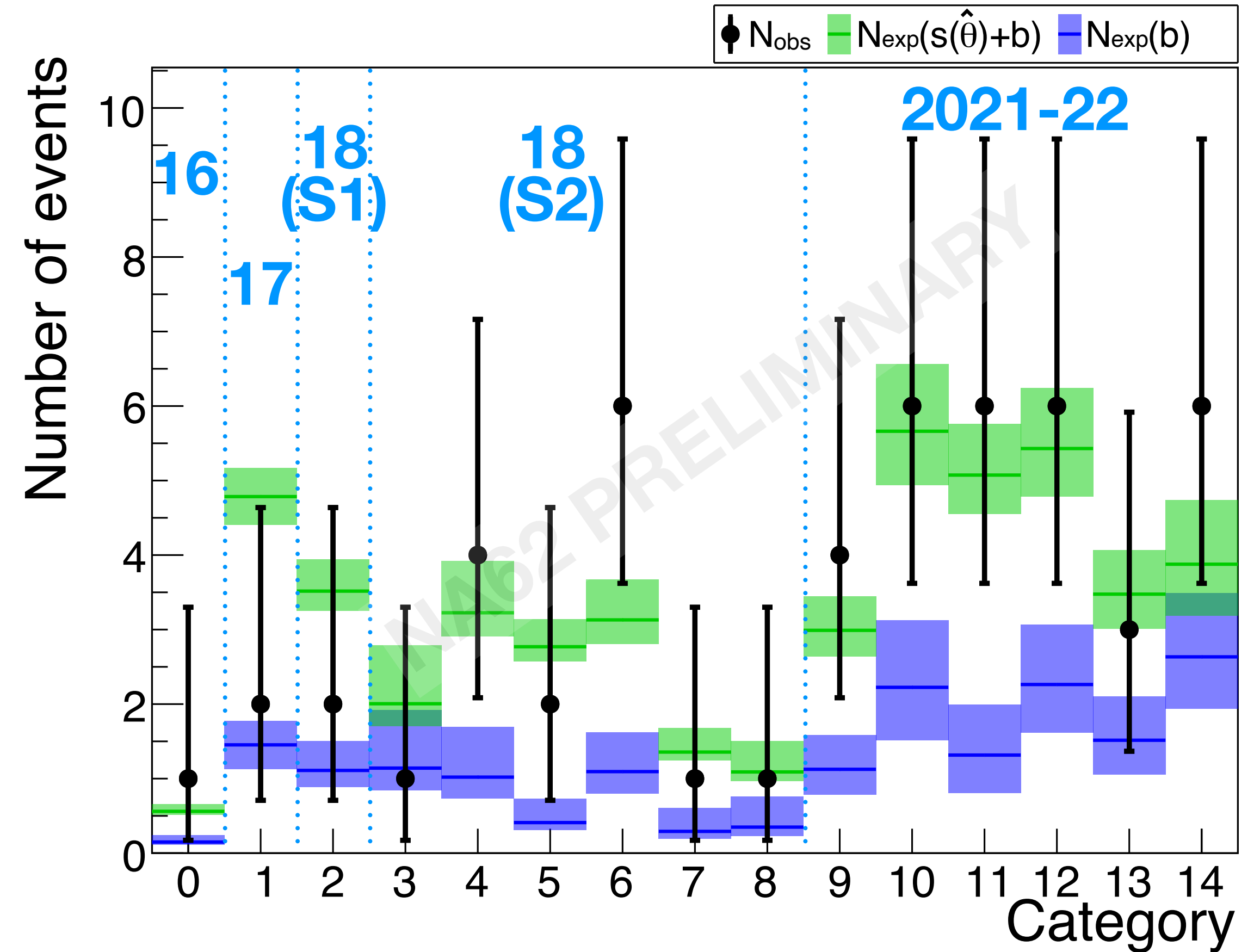
- Use 6 (momentum bin) categories



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

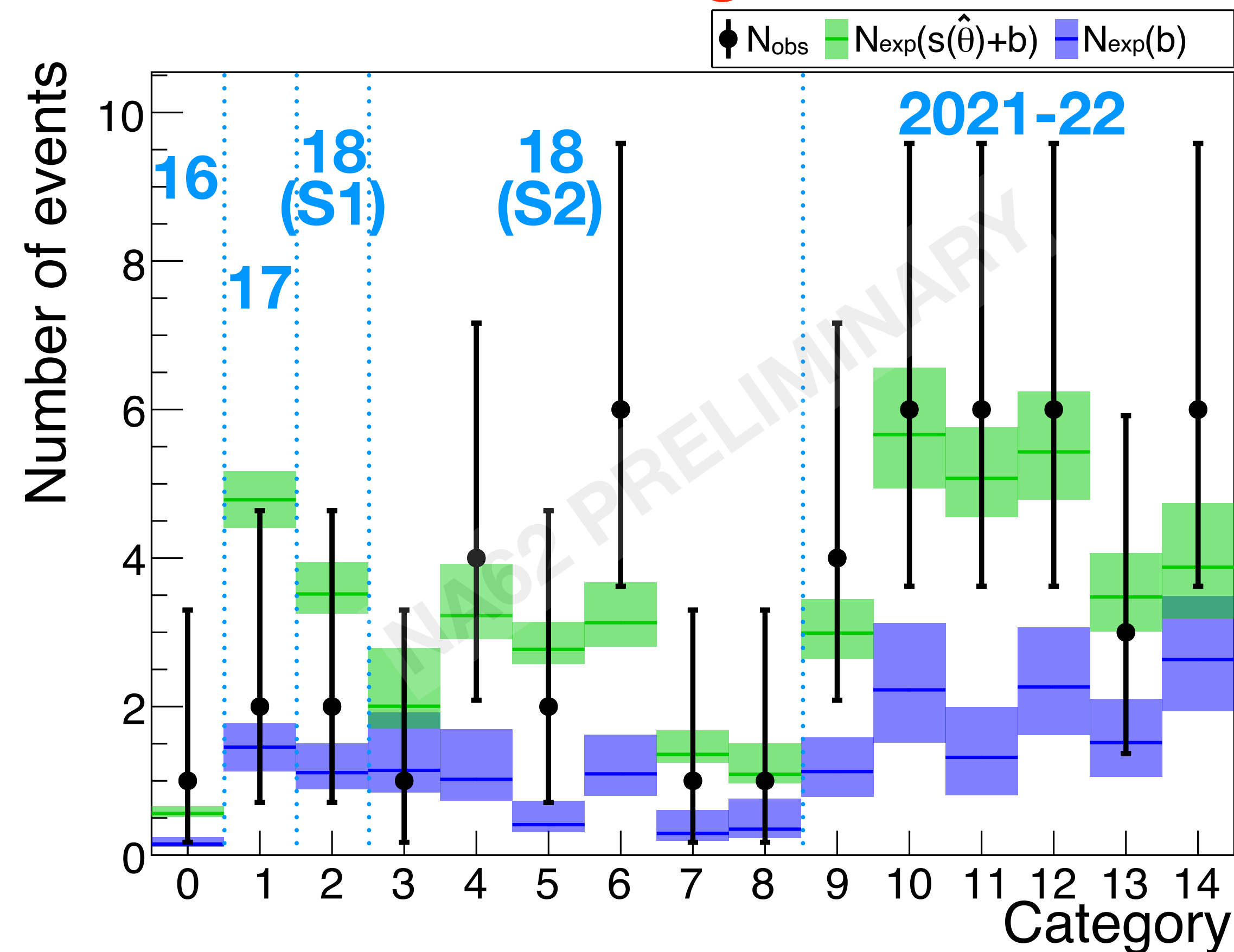
Combining NA62 results: 2016–22

- Integrating 2016–22 data: $N_{bg} = 18_{-2}^{+3}$, $N_{obs} = 51$.



Combining NA62 results: 2016–22

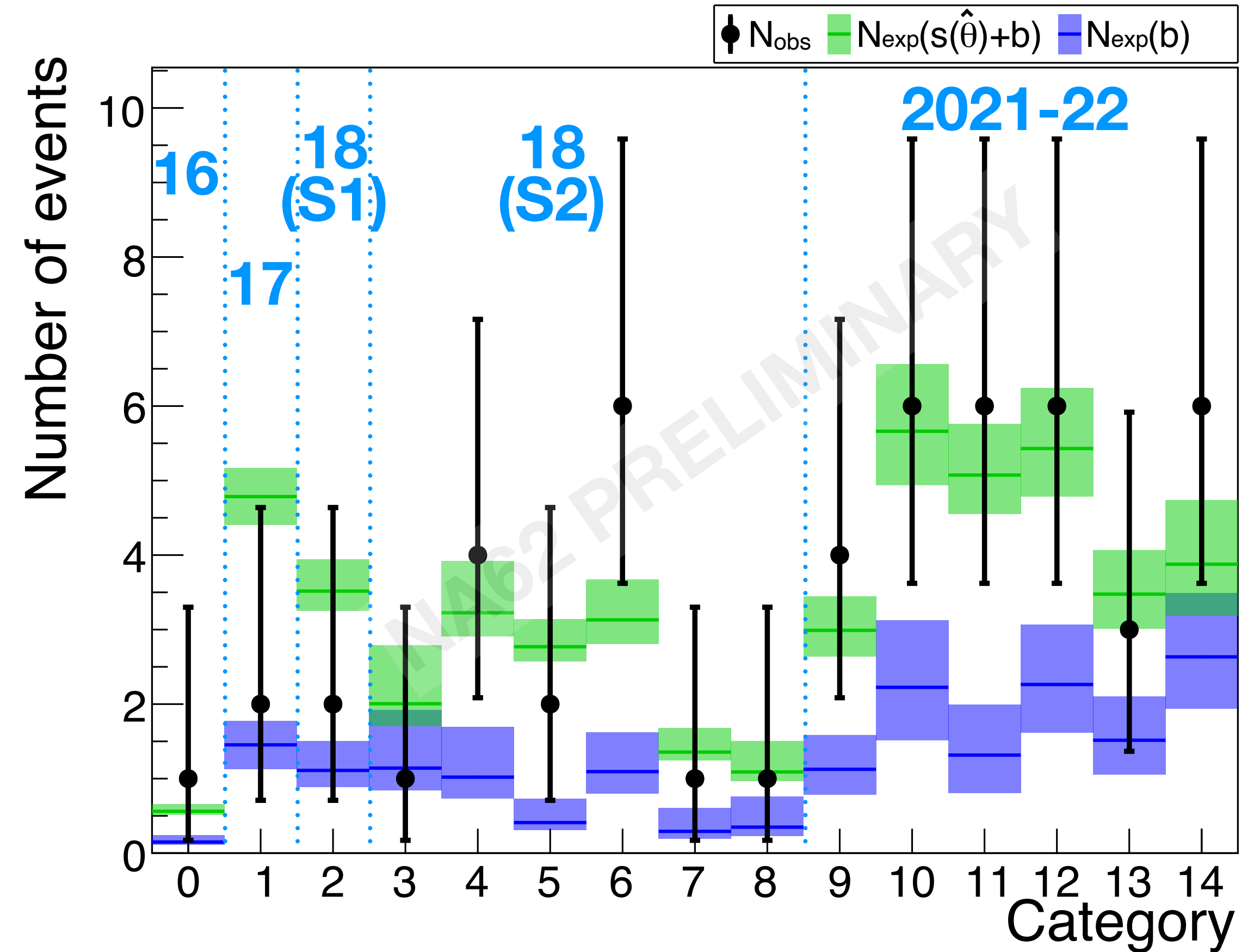
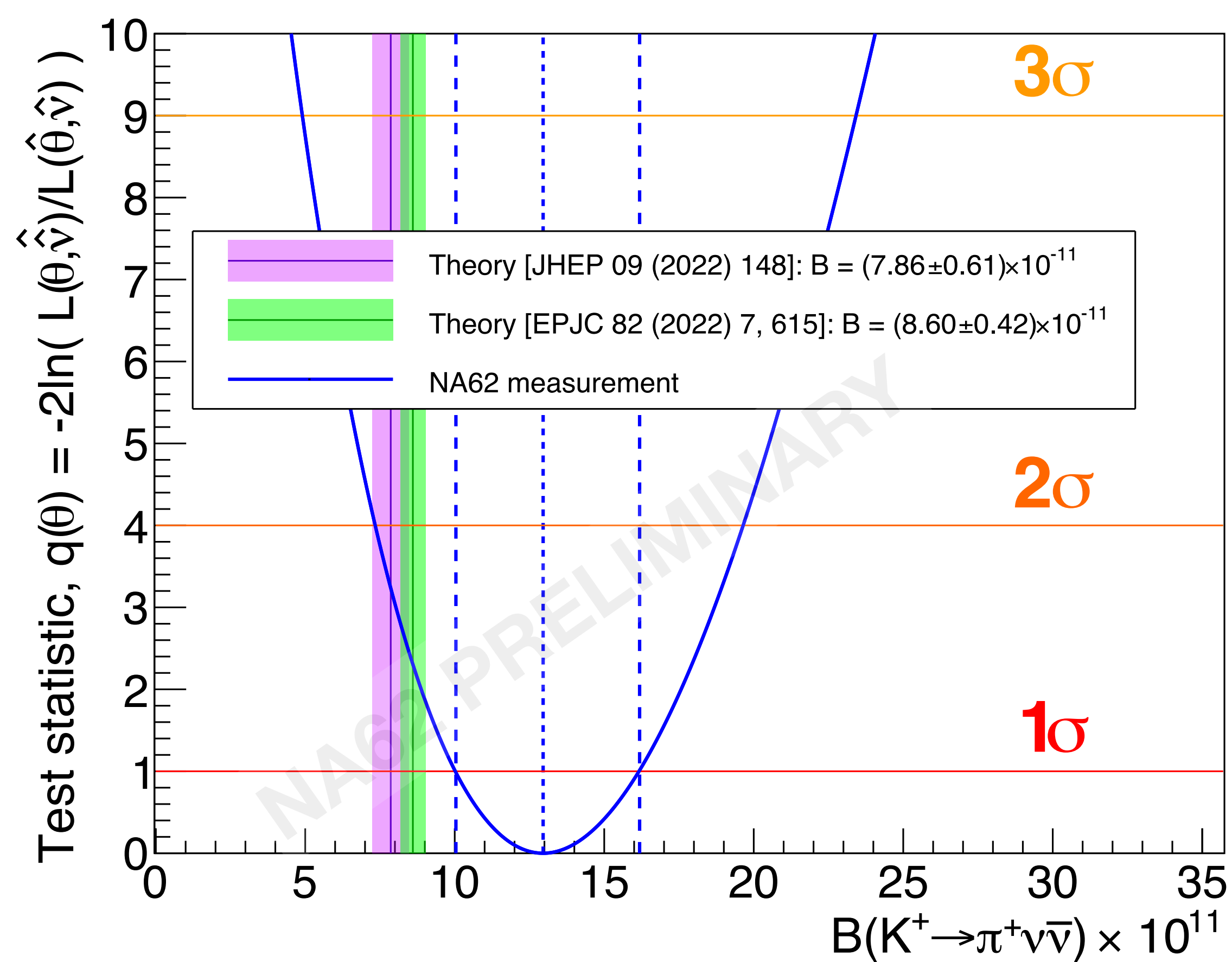
- Integrating 2016–22 data: $N_{bg} = 18_{-2}^{+3}$, $N_{obs} = 51$.
- Background-only hypothesis **p-value** = $2 \times 10^{-7} \Rightarrow$ **significance** $Z > 5$



Combining NA62 results: 2016–22

- Integrating 2016–22 data: $N_{bg} = 18_{-2}^{+3}$, $N_{obs} = 51$.

- Background-only hypothesis p-value = $2 \times 10^{-7} \Rightarrow$ significance $Z > 5$**



$$\mathcal{B}_{16-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0_{-2.9}^{+3.3}) \times 10^{-11} = \left(13.0 \left(\begin{matrix} +3.0 \\ -2.7 \end{matrix} \right)_{\text{stat}} \left[\begin{matrix} +1.3 \\ -1.2 \end{matrix} \right]_{\text{syst}} \right) \times 10^{-11}$$

Results in context

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

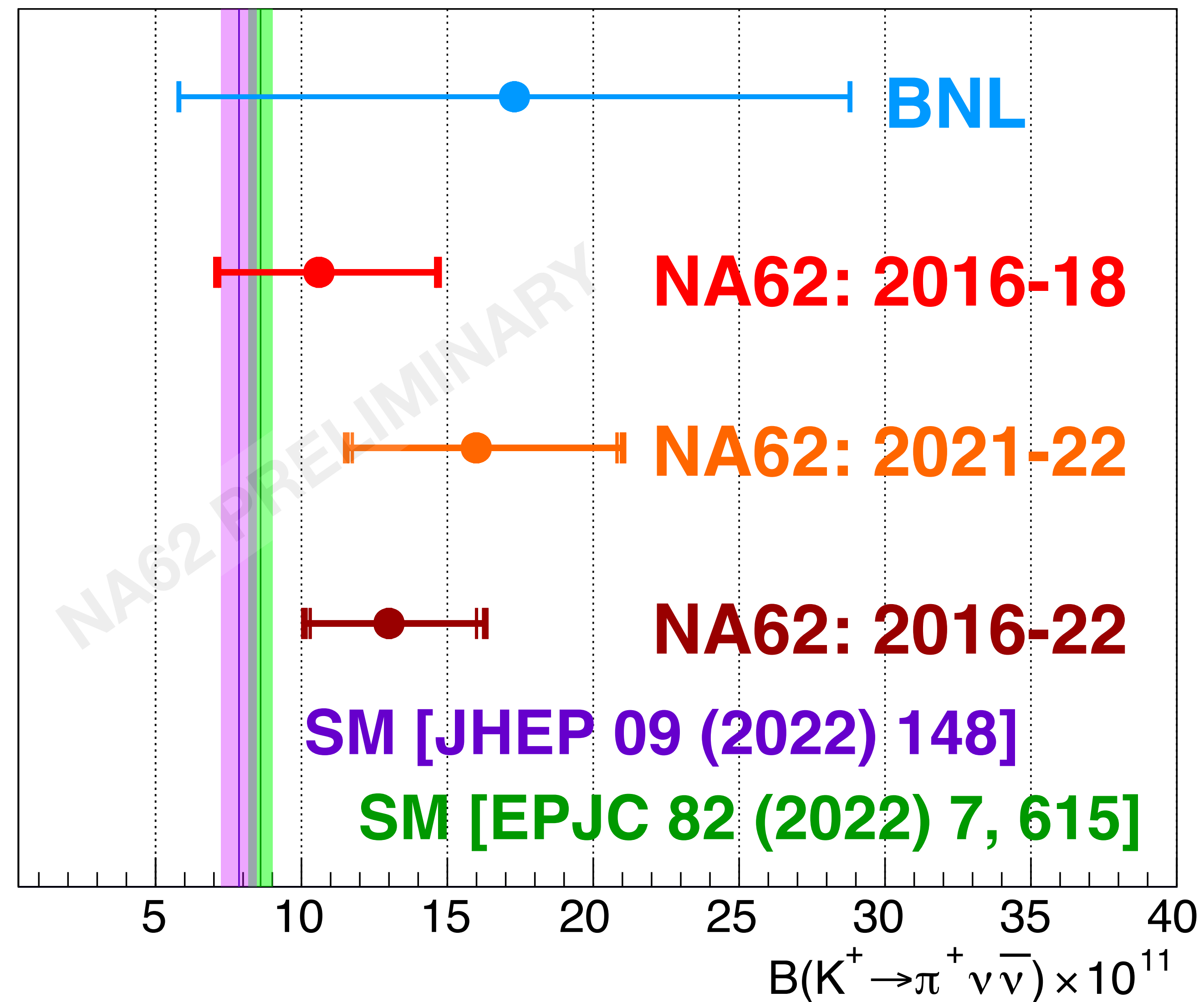
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$$

[JHEP 06 (2021) 093]

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

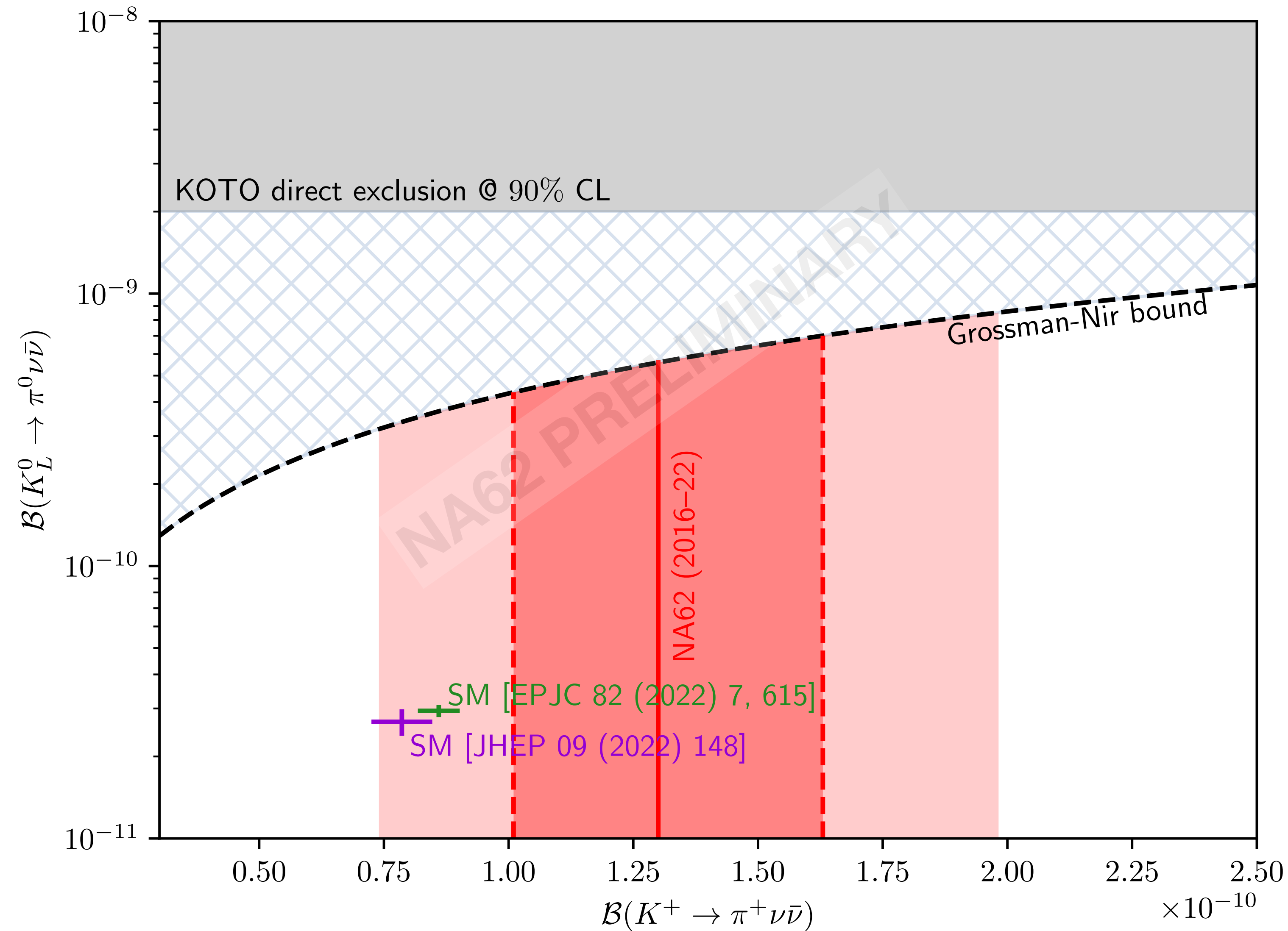
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

- NA62 results are consistent
- Central value moved up (now 1.5–1.7 σ 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 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay with BR consistent with SM prediction, within 1.7σ**
 - Need full NA62 data-set to clarify SM agreement or tension



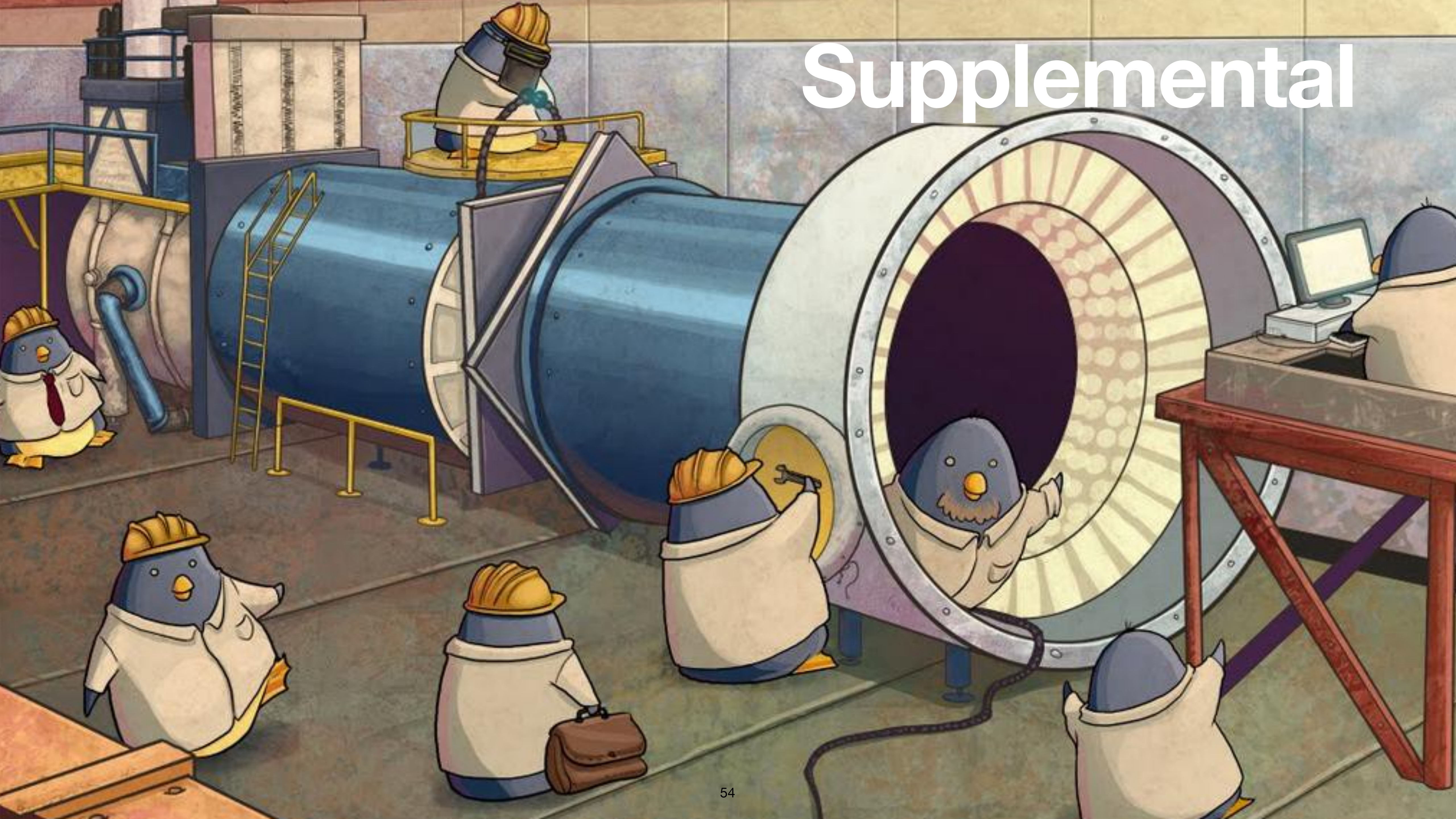
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

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

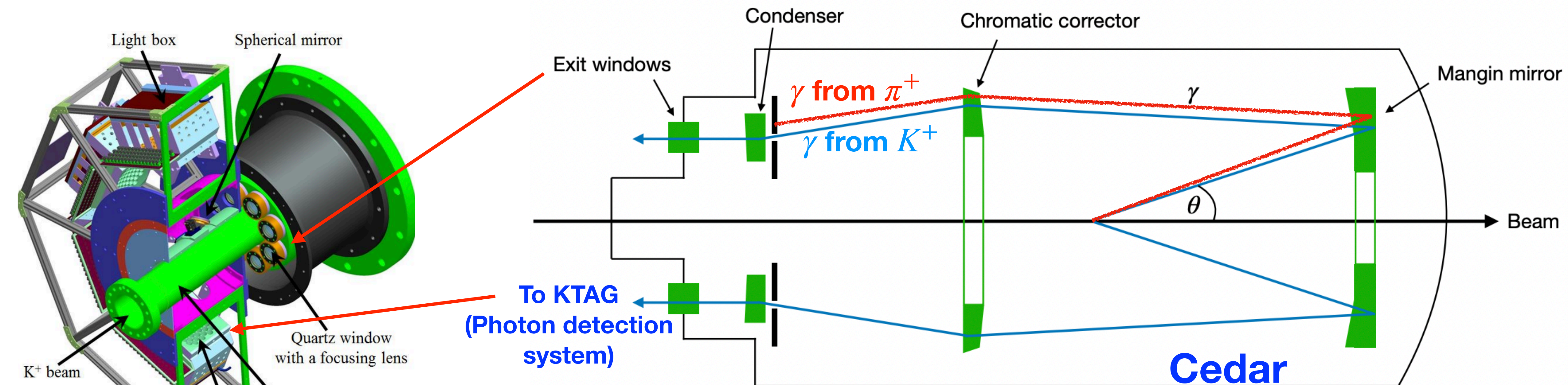
Conclusions

- New study of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay using NA62 2021–22 dataset:
 - Improved signal yield per SPS spill by 50%.
 - $N_{bg} = 11.0^{+2.1}_{-1.9}$, $N_{obs} = 31$
 - $\mathcal{B}_{21-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (16.0^{+5.0}_{-4.5}) \times 10^{-11} = \left(16.0 \left(\begin{smallmatrix} +4.8 \\ -4.2 \end{smallmatrix} \right)_{\text{stat}} \left[\begin{smallmatrix} +1.4 \\ -1.3 \end{smallmatrix} \right]_{\text{syst}} \right) \times 10^{-11}$
- Combining with 2016–18 data for full 2016–22 results:
 - $N_{bg} = 18^{+3}_{-2}$, $N_{obs} = 51$ (using 9+6 categories for BR extraction)
 - $\mathcal{B}_{16-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0^{+3.3}_{-2.9}) \times 10^{-11} = \left(13.0 \left(\begin{smallmatrix} +3.0 \\ -2.7 \end{smallmatrix} \right)_{\text{stat}} \left[\begin{smallmatrix} +1.3 \\ -1.2 \end{smallmatrix} \right]_{\text{syst}} \right) \times 10^{-11}$
 - Background-only hypothesis rejected with significance $Z > 5$.
- **First observation of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay: BR consistent with SM prediction within 1.7σ**
 - Need full NA62 data-set to clarify SM agreement or tension.

Supplemental

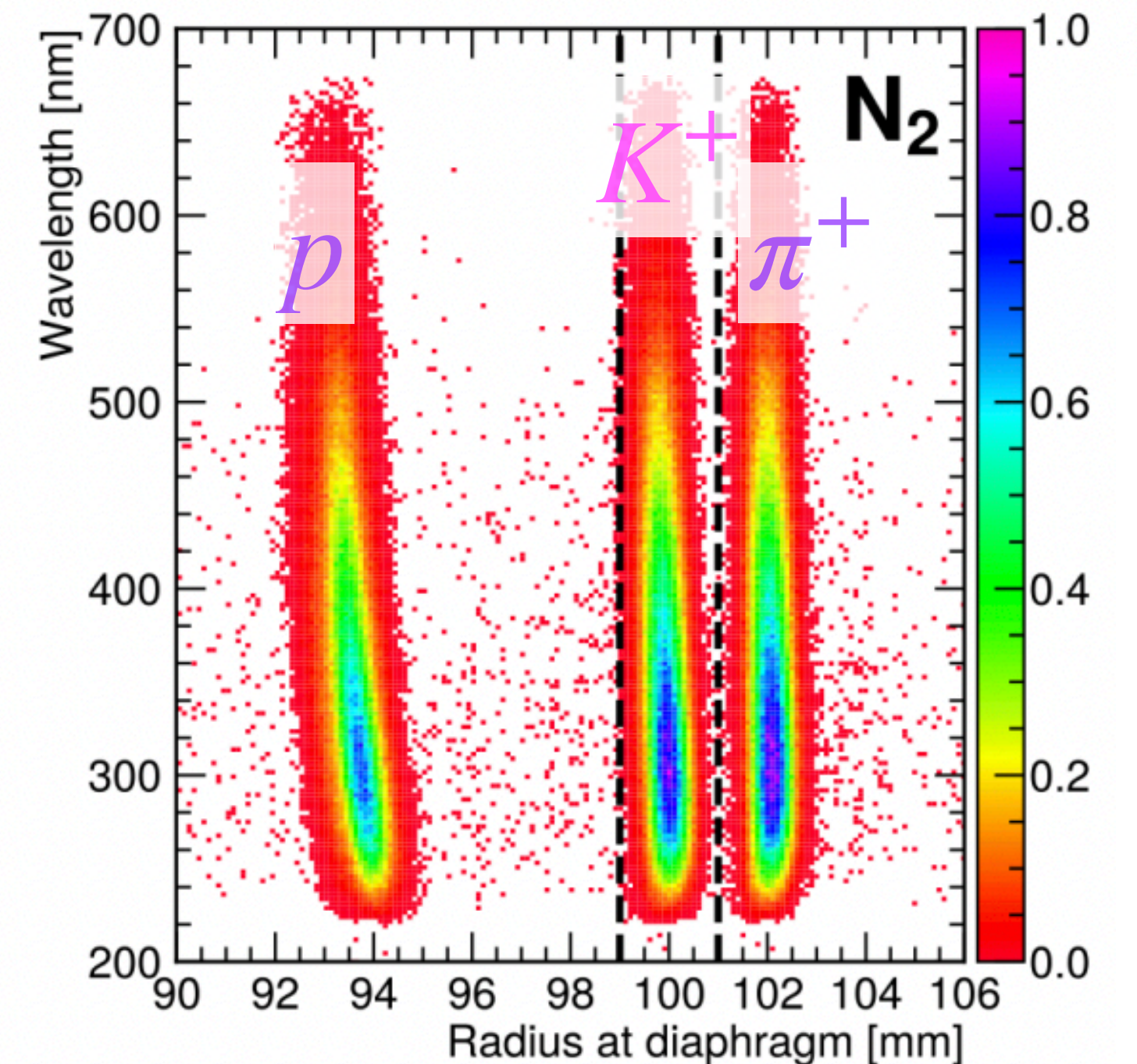


Cedar & KTAG : K^+ tagging with threshold Cherenkov counter



- 75 GeV Unseparated hadron beam
 $\pi^+ : 70\%$, $p : 23\%$, $K^+ : 6\%$.

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

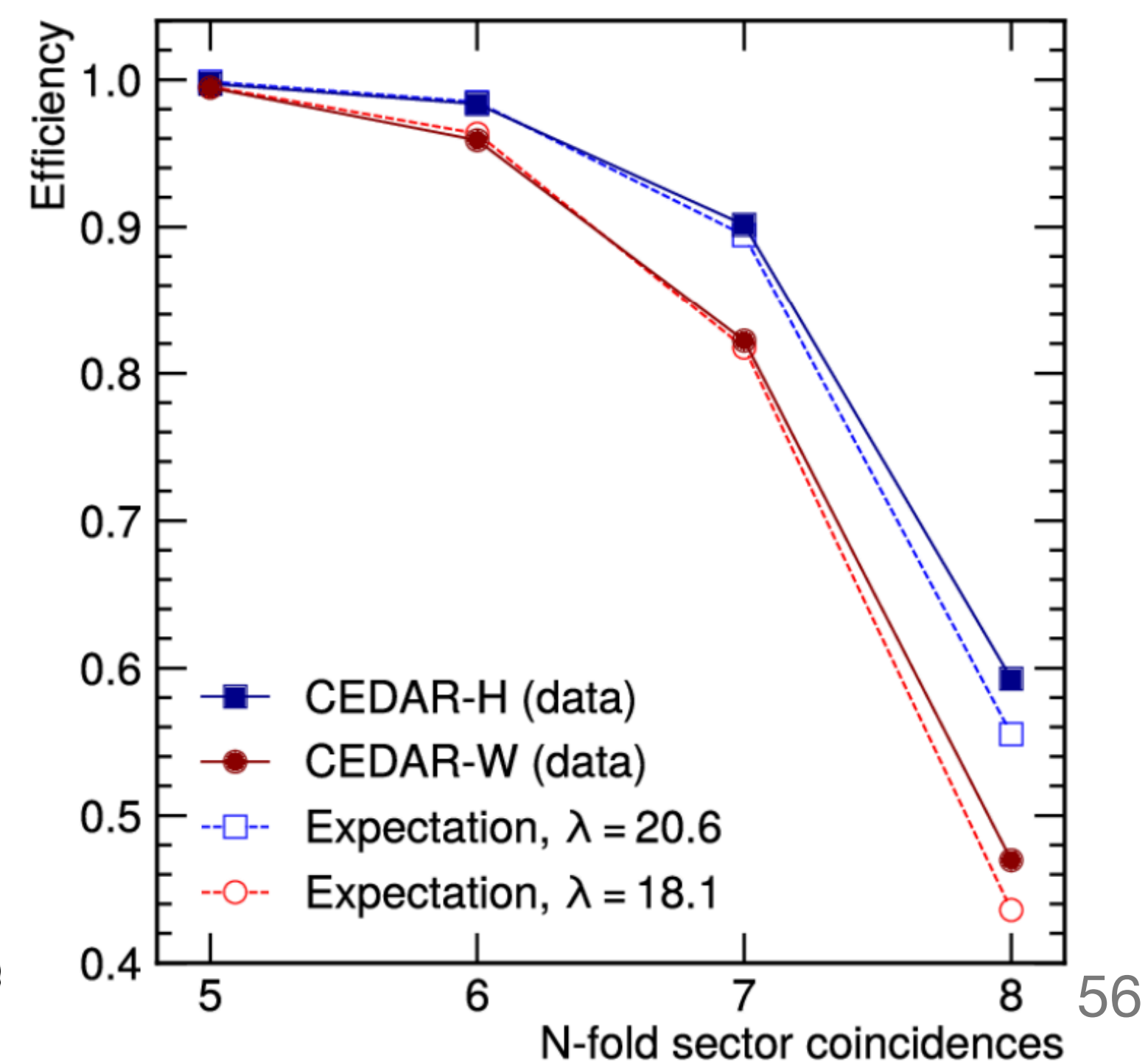
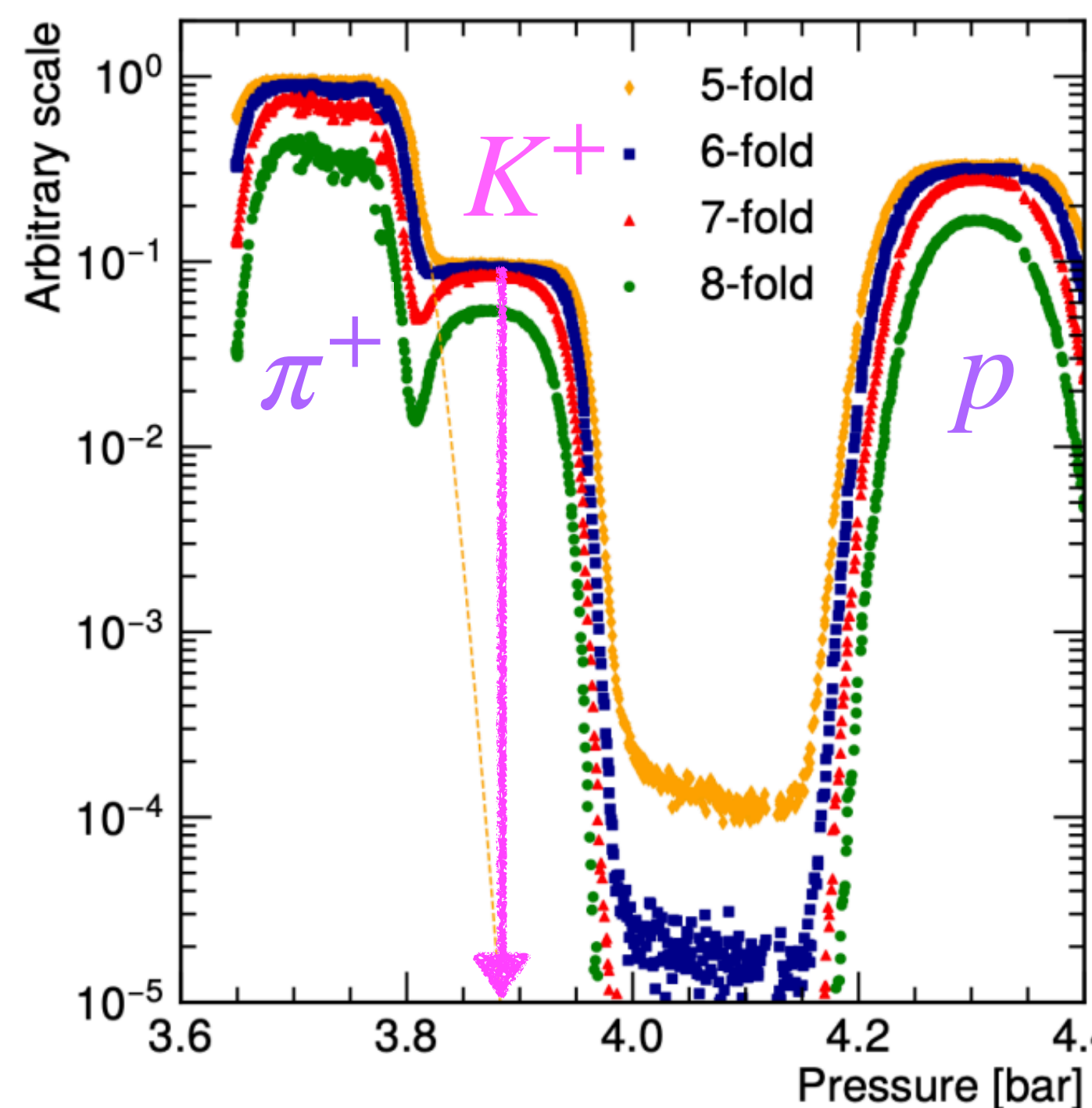


New Cedar-H : installed in 2023

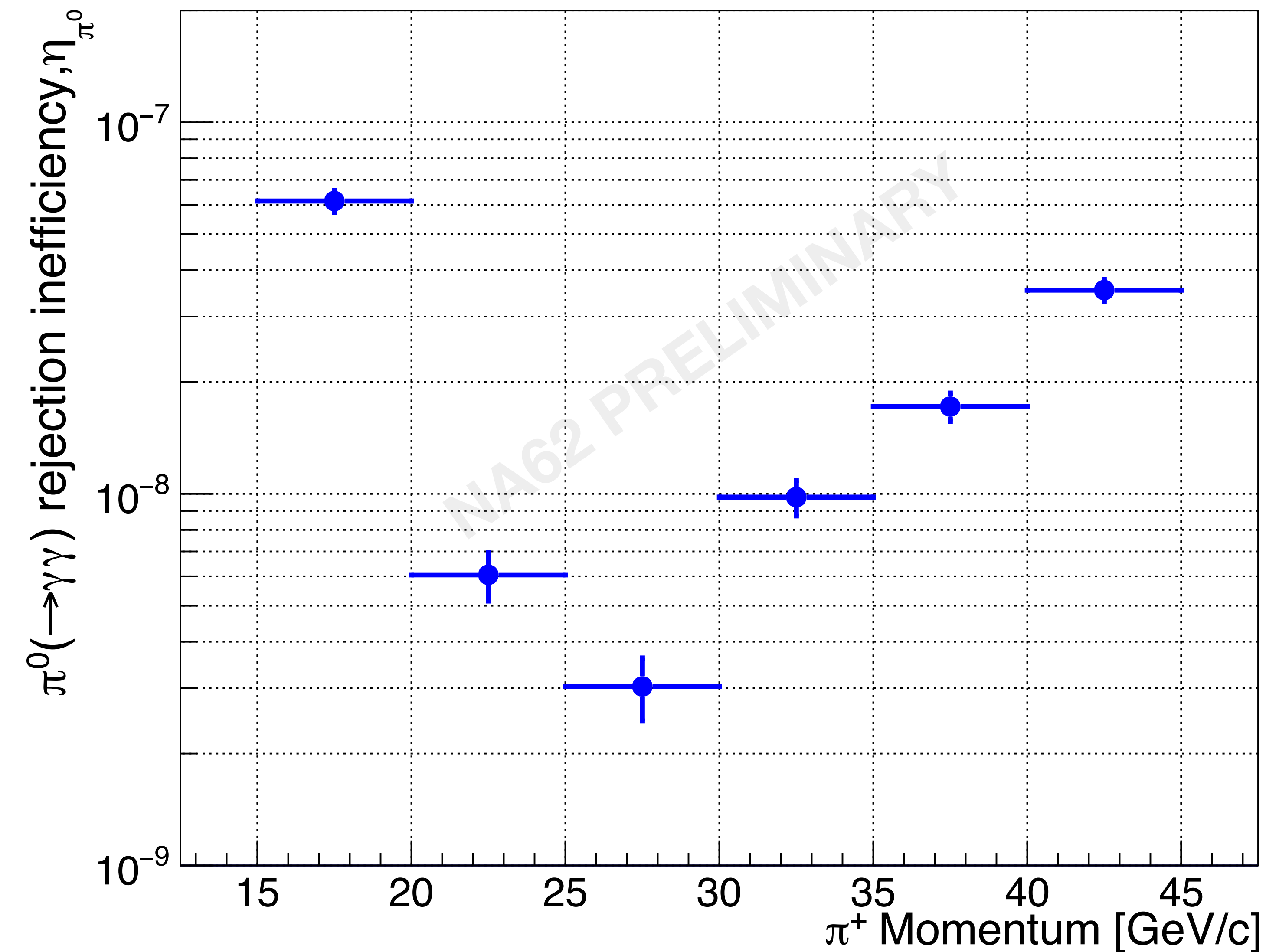
- CEDAR-W filled with N_2 at 1.7 bar was biggest contributor to material in beam line ($39 \times 10^{-3} X_0$).
- New CEDAR-H filled with H_2 at 3.8 bar:
 - Reduces material to $7.3 \times 10^{-3} X_0$: reducing multiple scattering.
 - But new optics required to account for different optical properties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

Cedar-H Performance at NA62:

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



Photon veto performance



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

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

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

Number of selected normalisation events

Random veto efficiency

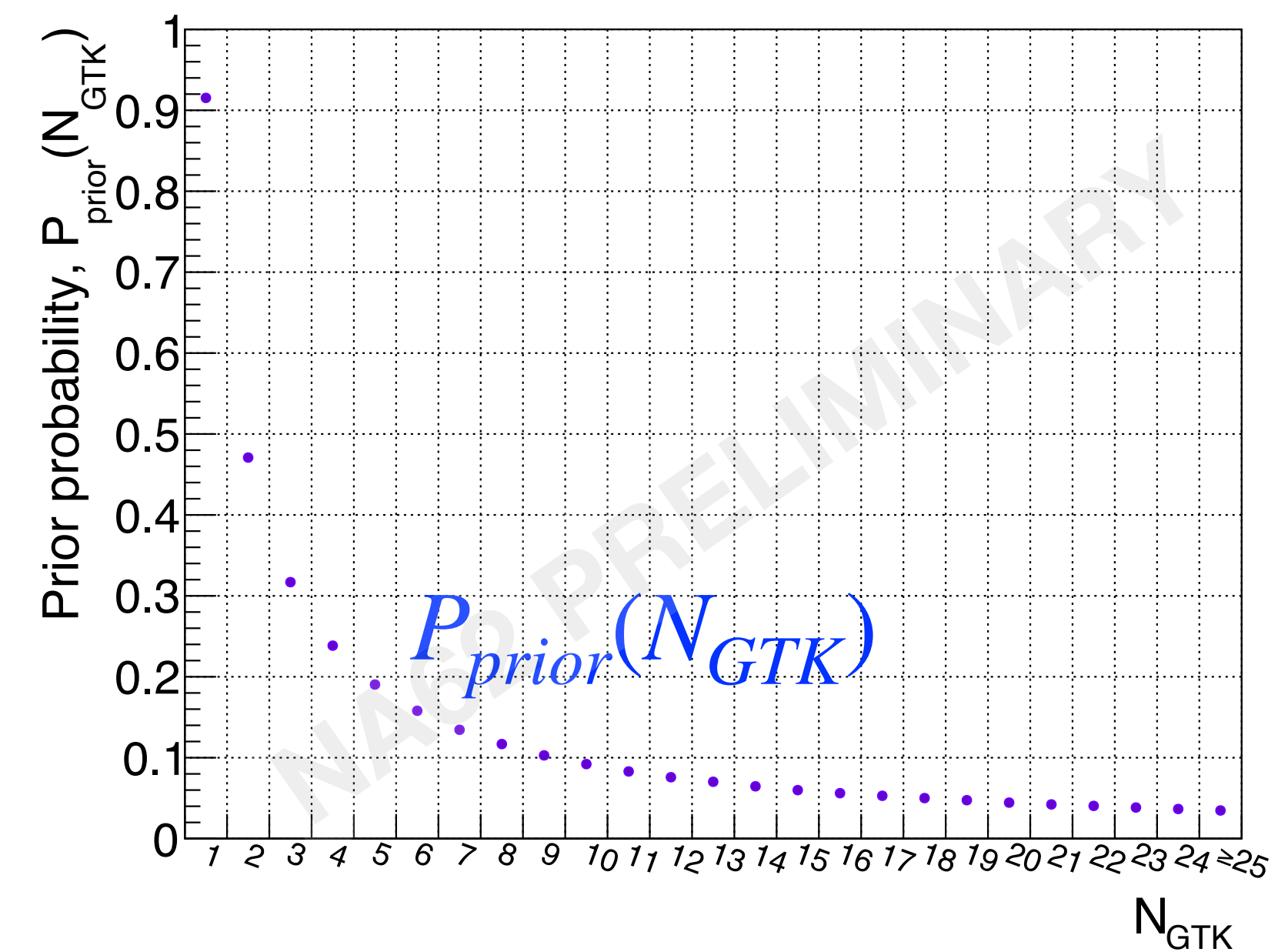
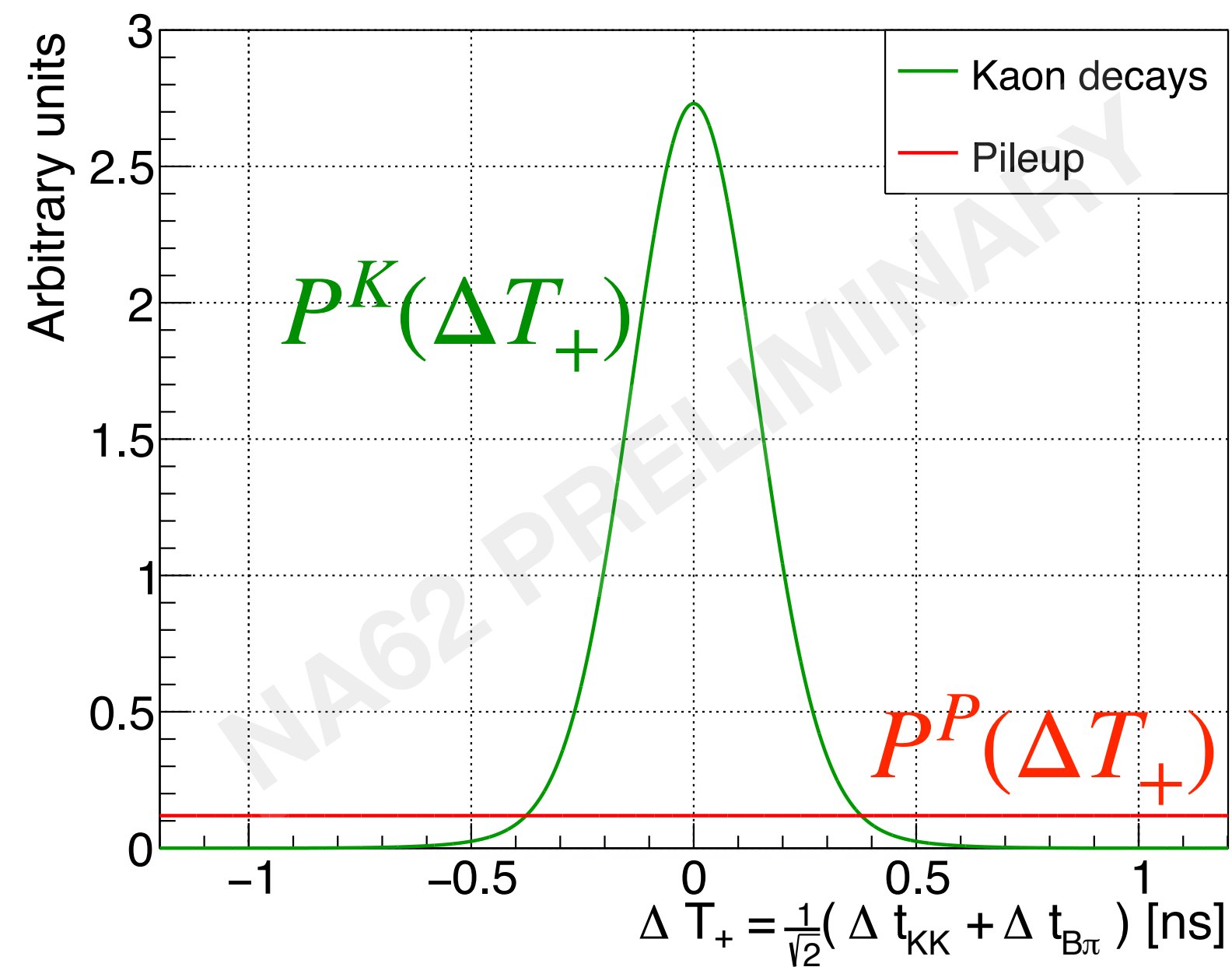
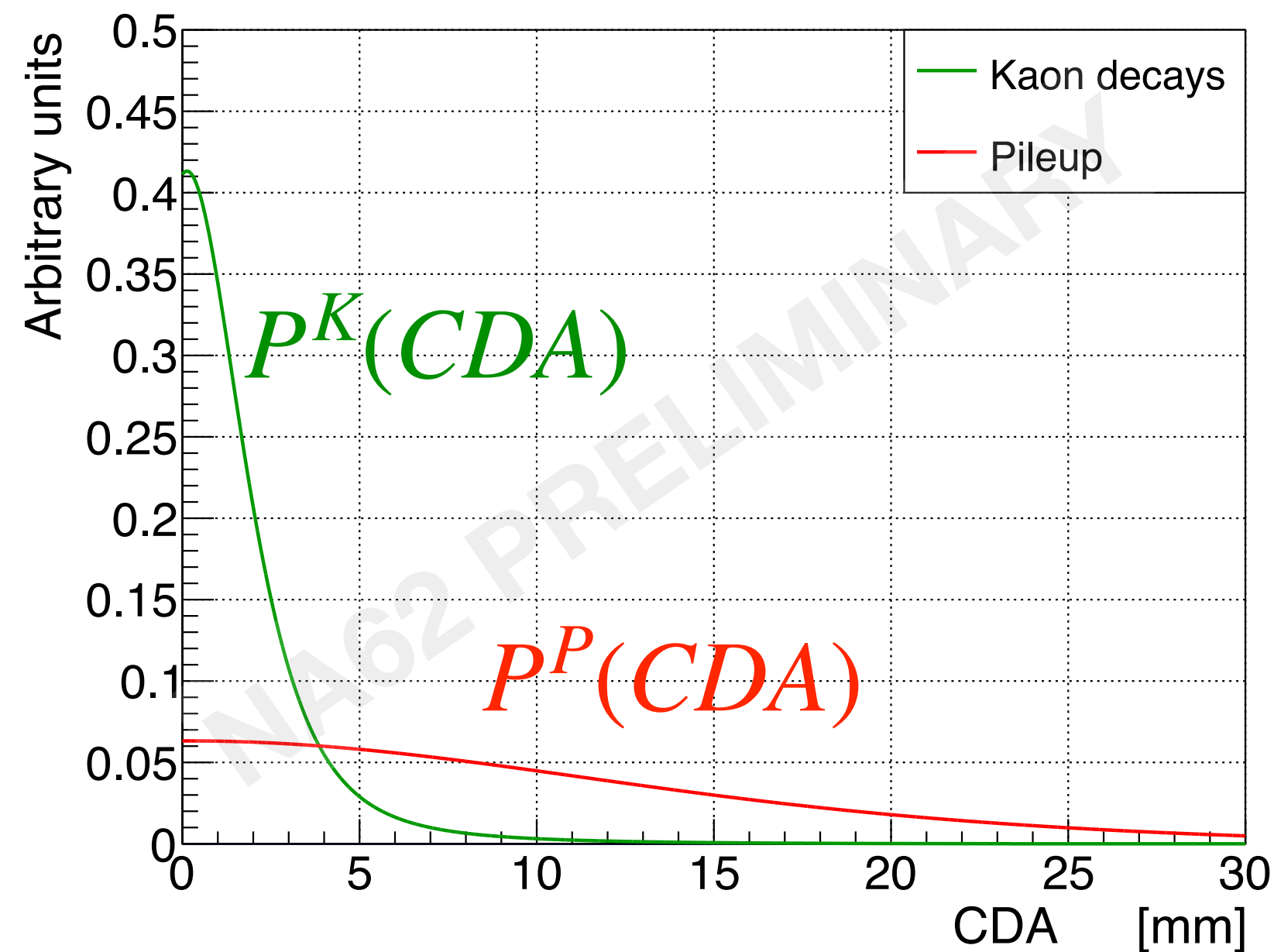
Normalisation trigger downscaling and efficiency

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

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

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

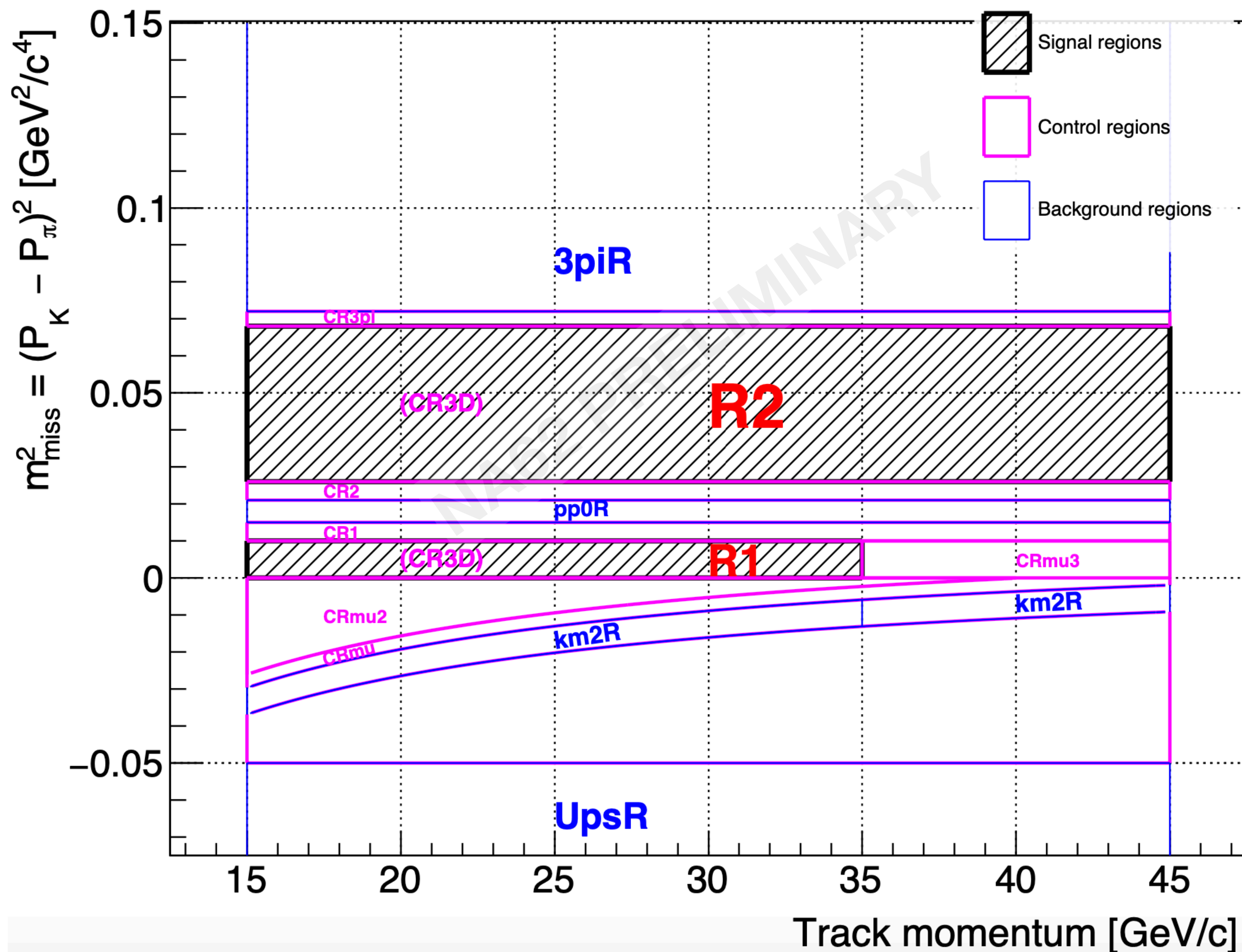
- **Inputs:** spatial (CDA) & time (ΔT_+) matching, intensity/pileup (N_{GTK}) [prior]
 - Models for PDFs/Prior from $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ data.



Example of selection update

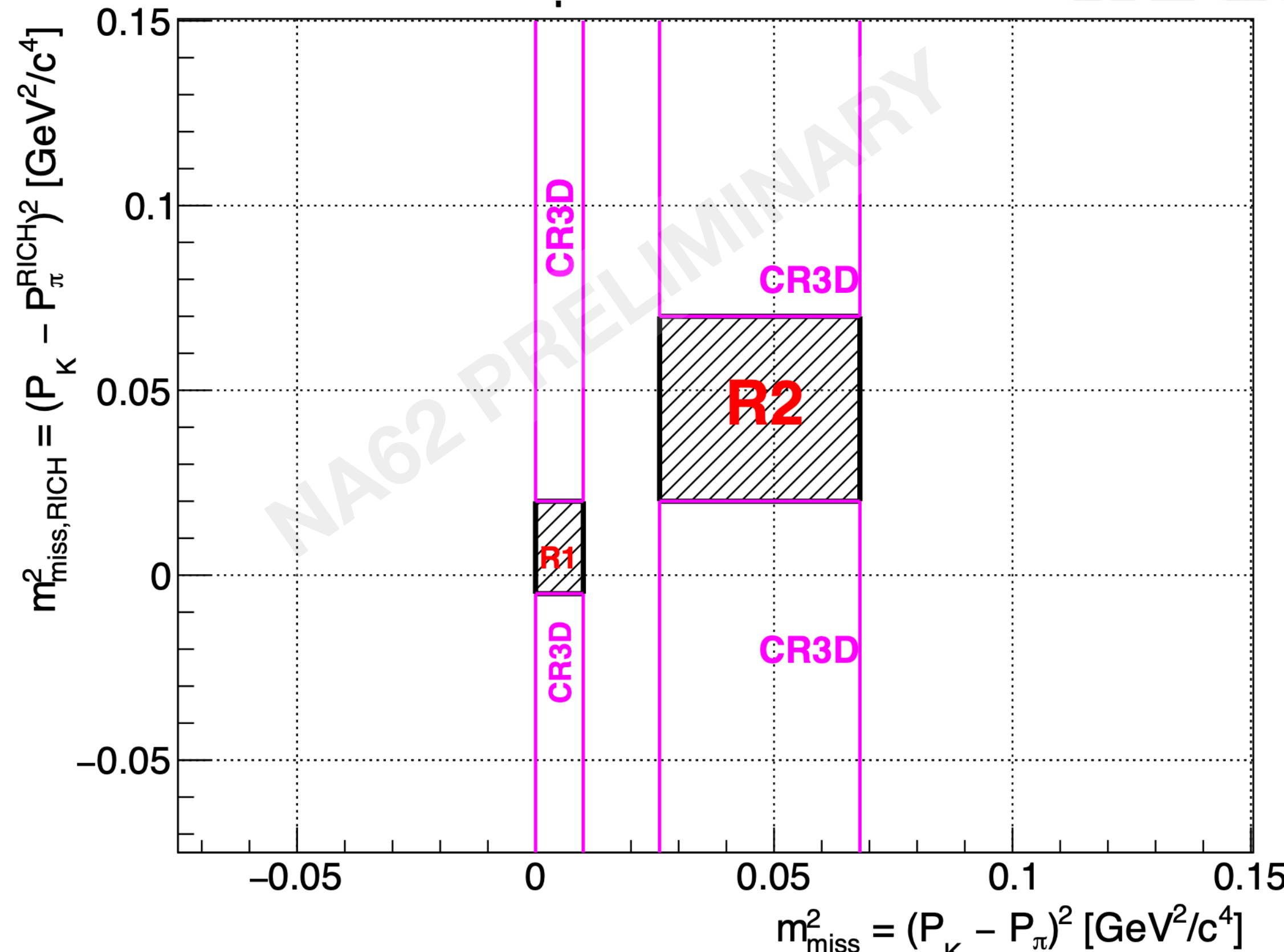
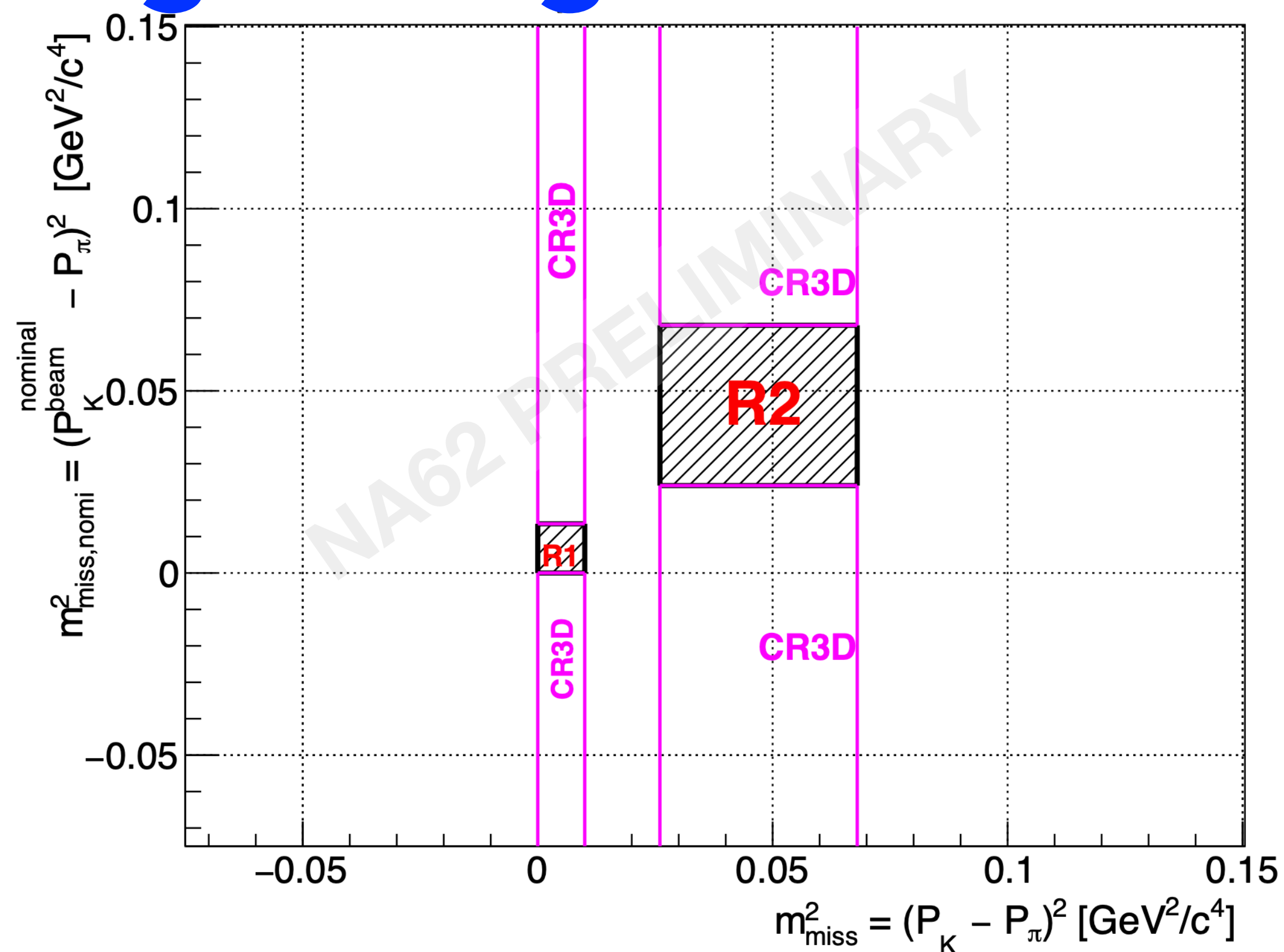
- **Output:** posterior probability of GTK track = true K^+
 - Use likelihoods of kaons (K) and pileup (P)
 - Likelihood ratio used to select true match when $N_{GTK} > 1$
- Efficiency improved (+10%) and mistagging probability maintained.

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.

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

Default: GTK

Alternative: Nominal beam = $m_{miss,nom}^2$

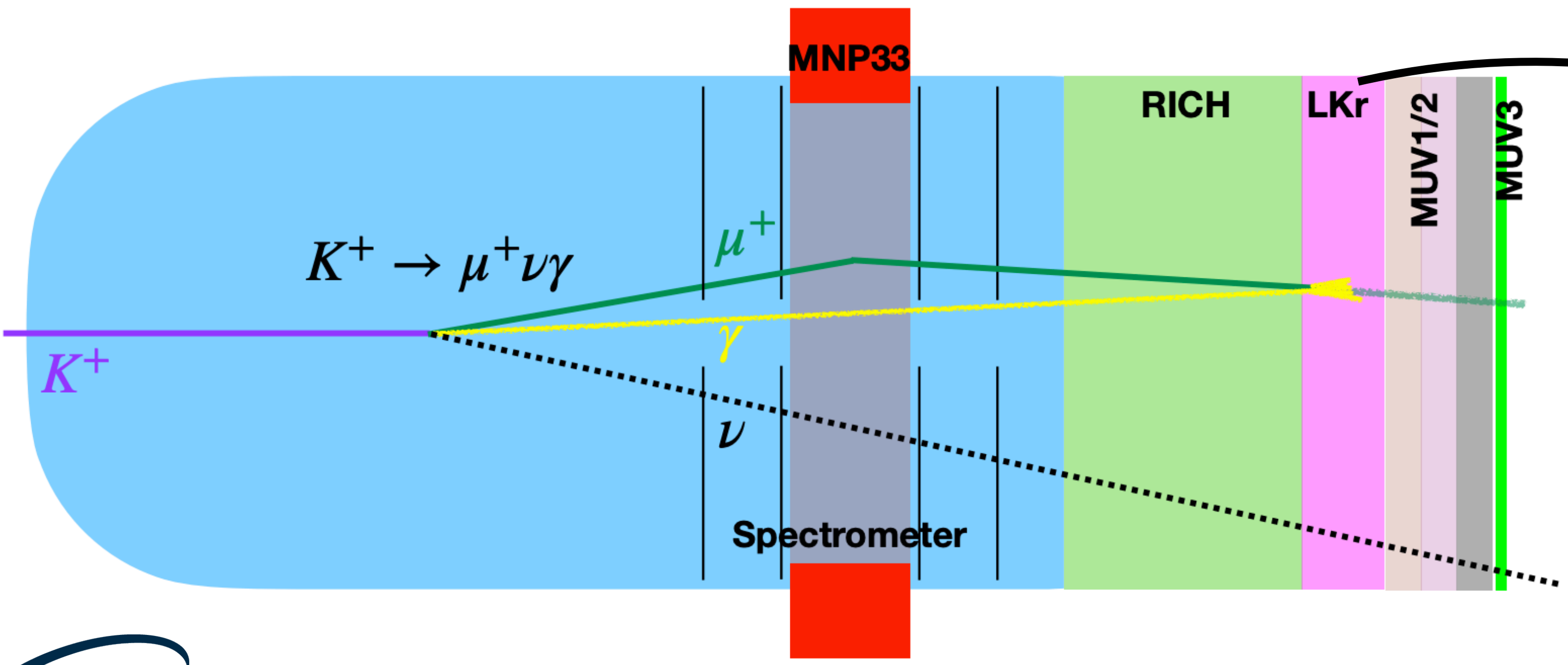
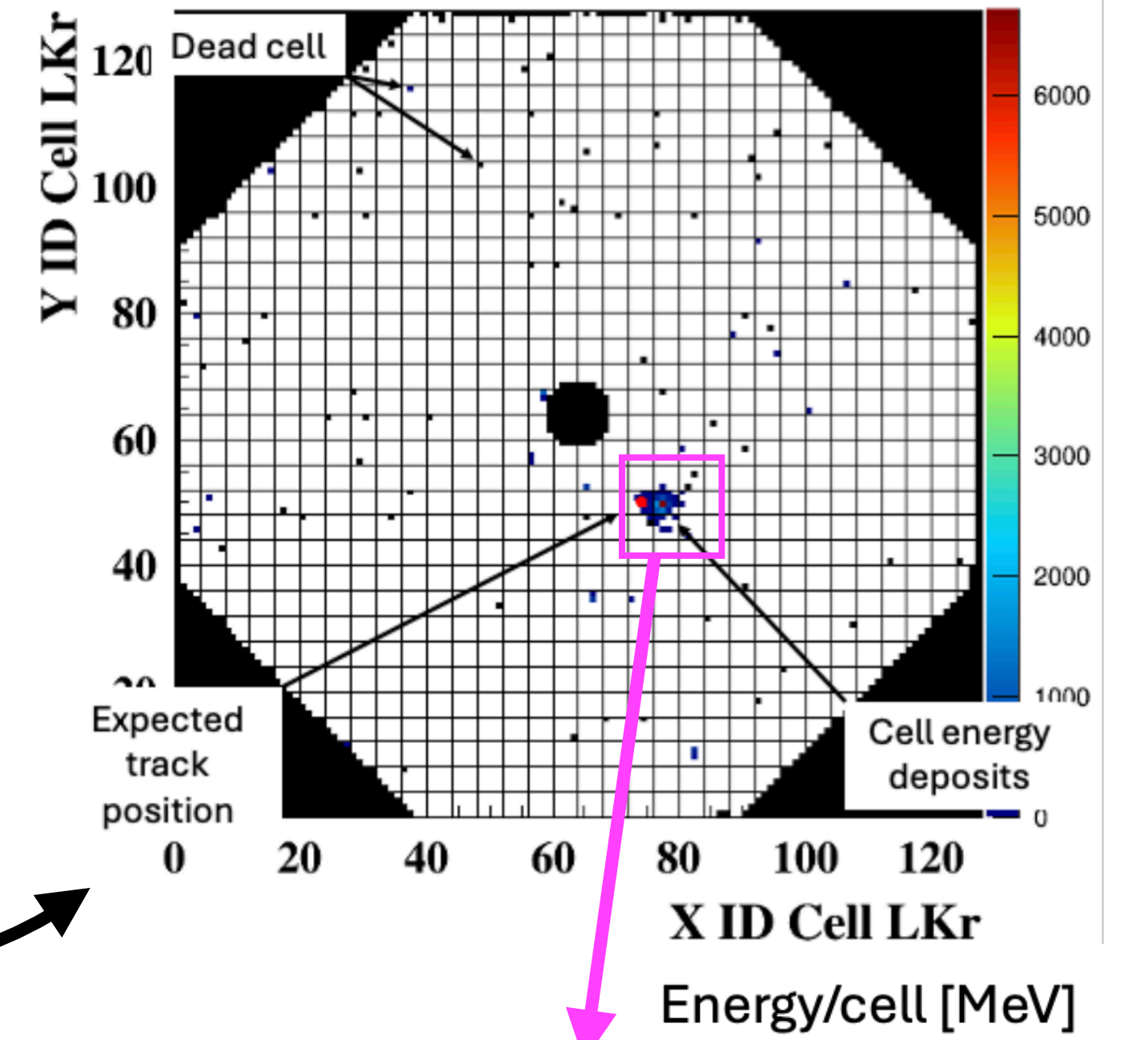
Default: STRAW

Alternative: $|p|$ from RICH (use as a velocity spectrometer) = $m_{miss,RICH}^2$

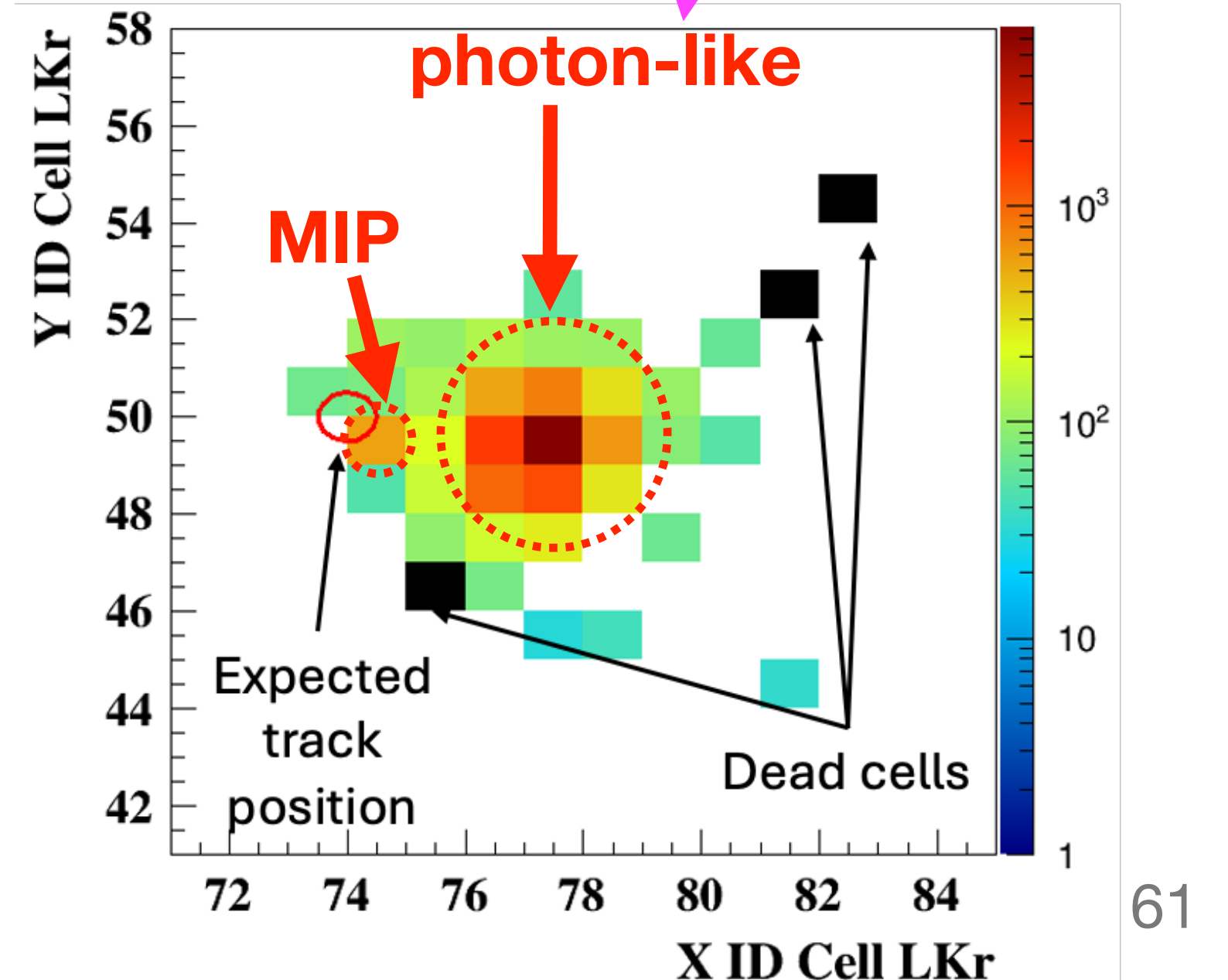
Background mechanism: $K^+ \rightarrow \mu^+ \nu \gamma$

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

Example event (2022 data):



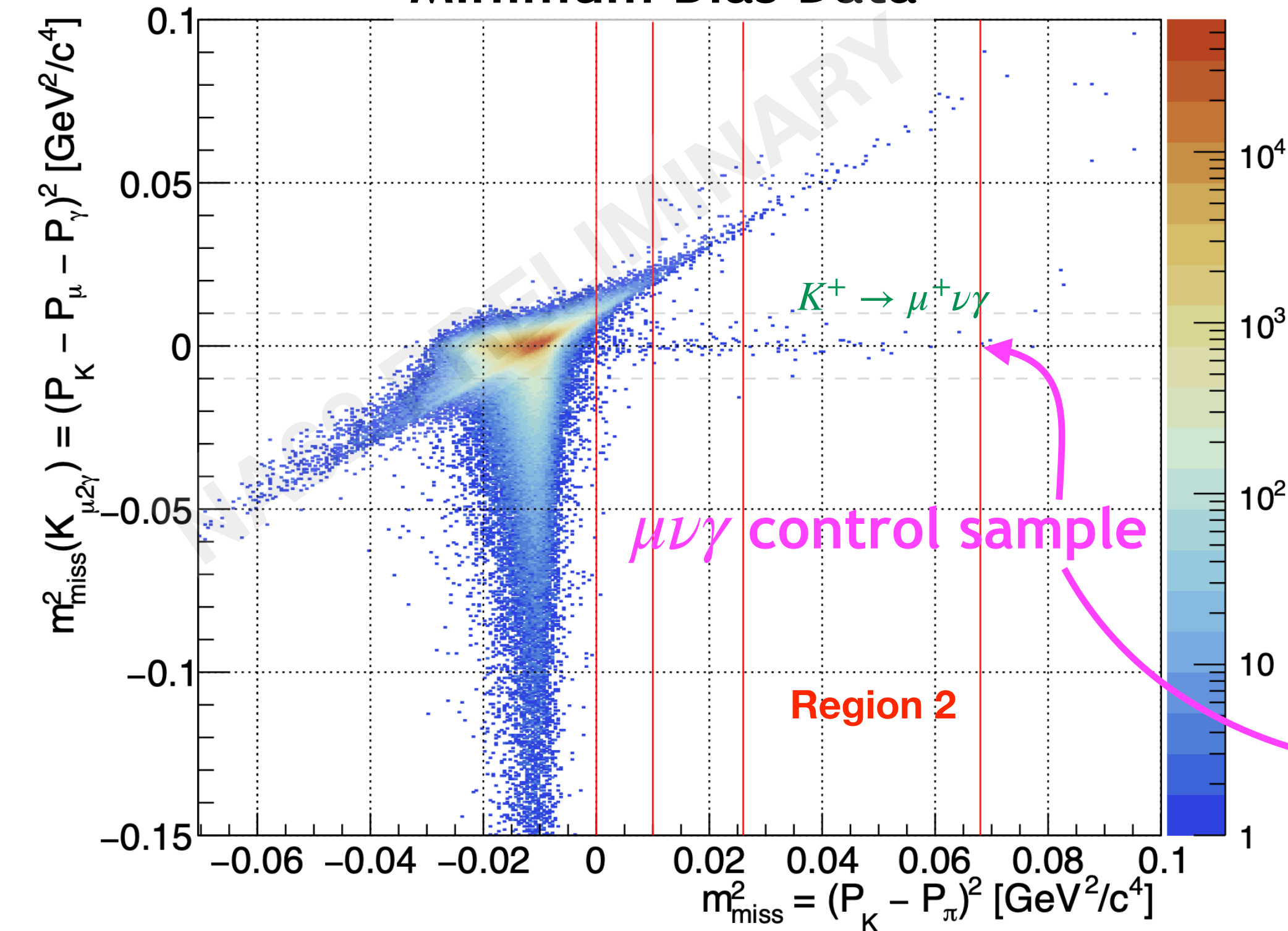
Sketch only



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.

Minimum Bias Data



- Kinematically select $K^+ \rightarrow \mu^+ \nu \gamma$ events:

$$m_{miss}^2(K_{\mu 2\gamma}) = (P_K - P_\mu - P_\gamma)^2$$

- P_K : 4-momentum of K^+ from GTK (as normal)
- P_μ : 4-momentum of track with μ^+ mass hypothesis.
- P_γ : reconstructed from energy (subtracting MIP energy deposit) and position of LKr cluster (and position of $K^+ - \mu^+$ vertex).

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

Downscaling of MB trigger

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

probability of $\gamma + \mu^+$ being misidentified as a π^+

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

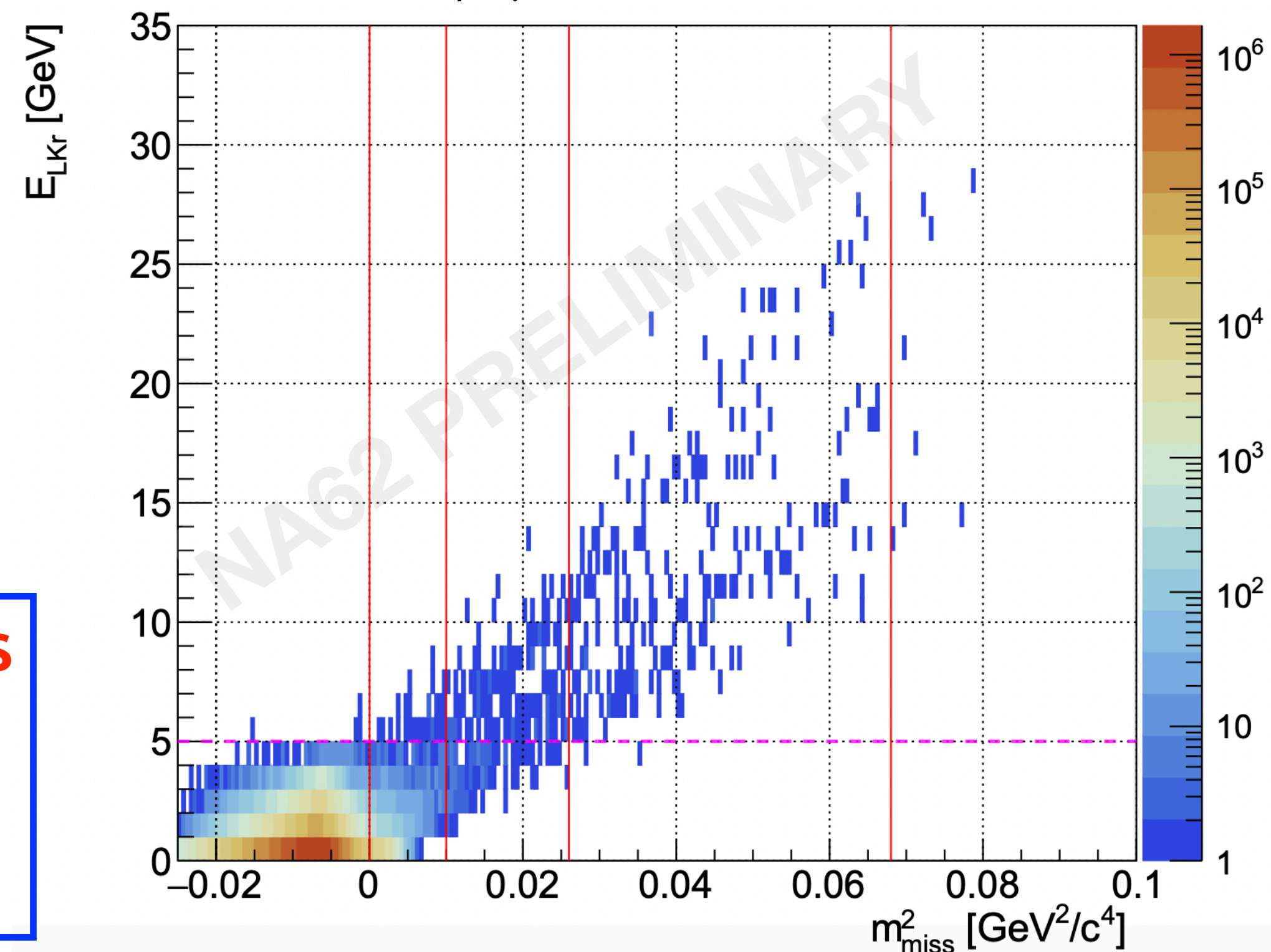
Background rejection: $K^+ \rightarrow \mu^+ \nu \gamma$

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

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

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

c.f. resolution
 $\sim 0.0025 \text{ GeV}^2/c^4$



- Veto conditions established using data control samples and MC.
- $K^+ \rightarrow \mu^+ \nu \gamma$ Veto \Rightarrow 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
 f_{cda}
 P_{match}

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

Scaling factor : bad cda \rightarrow good cda

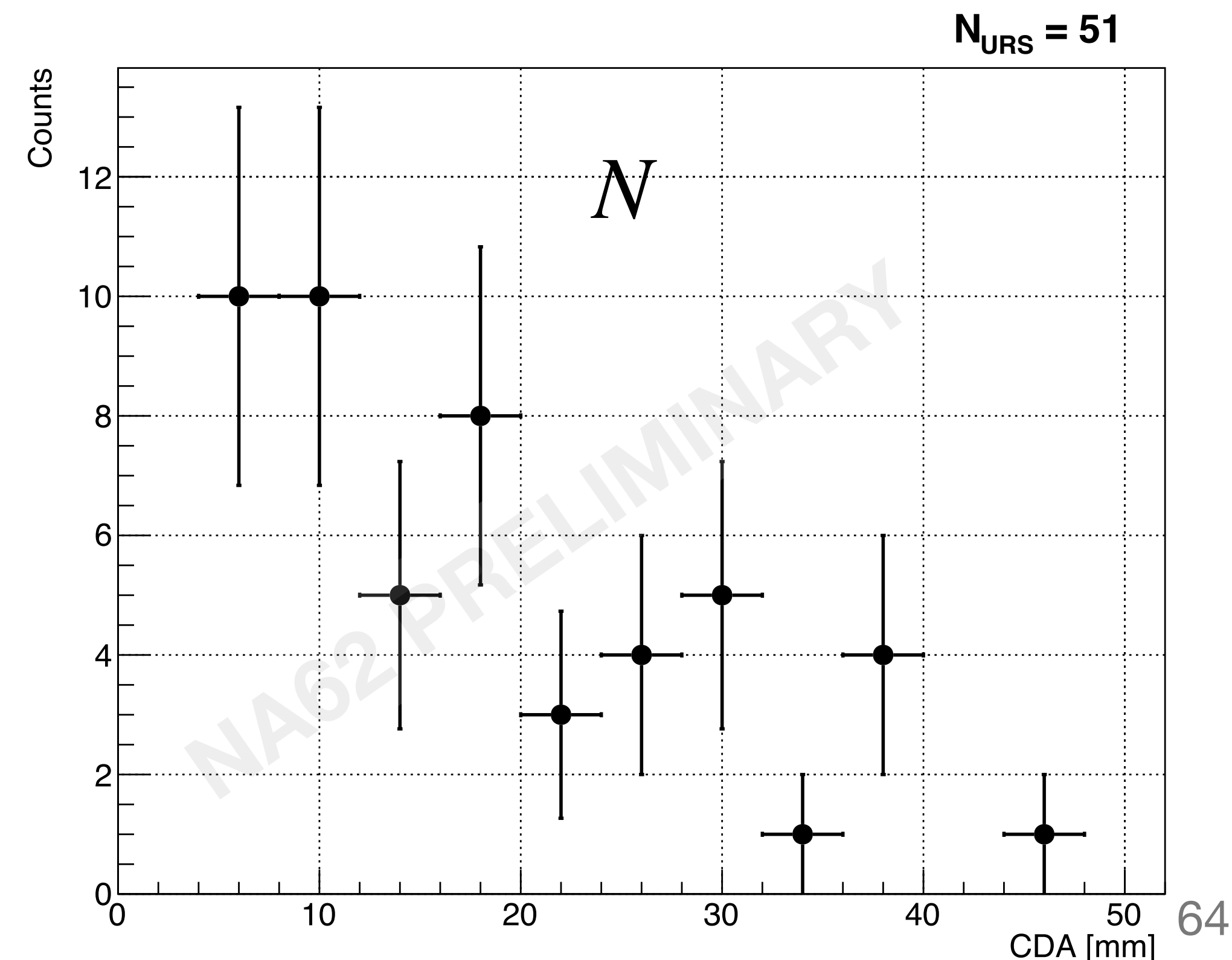
Probability to pass $K^+ - \pi^+$ matching

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

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

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

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



Results in context: the long story of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

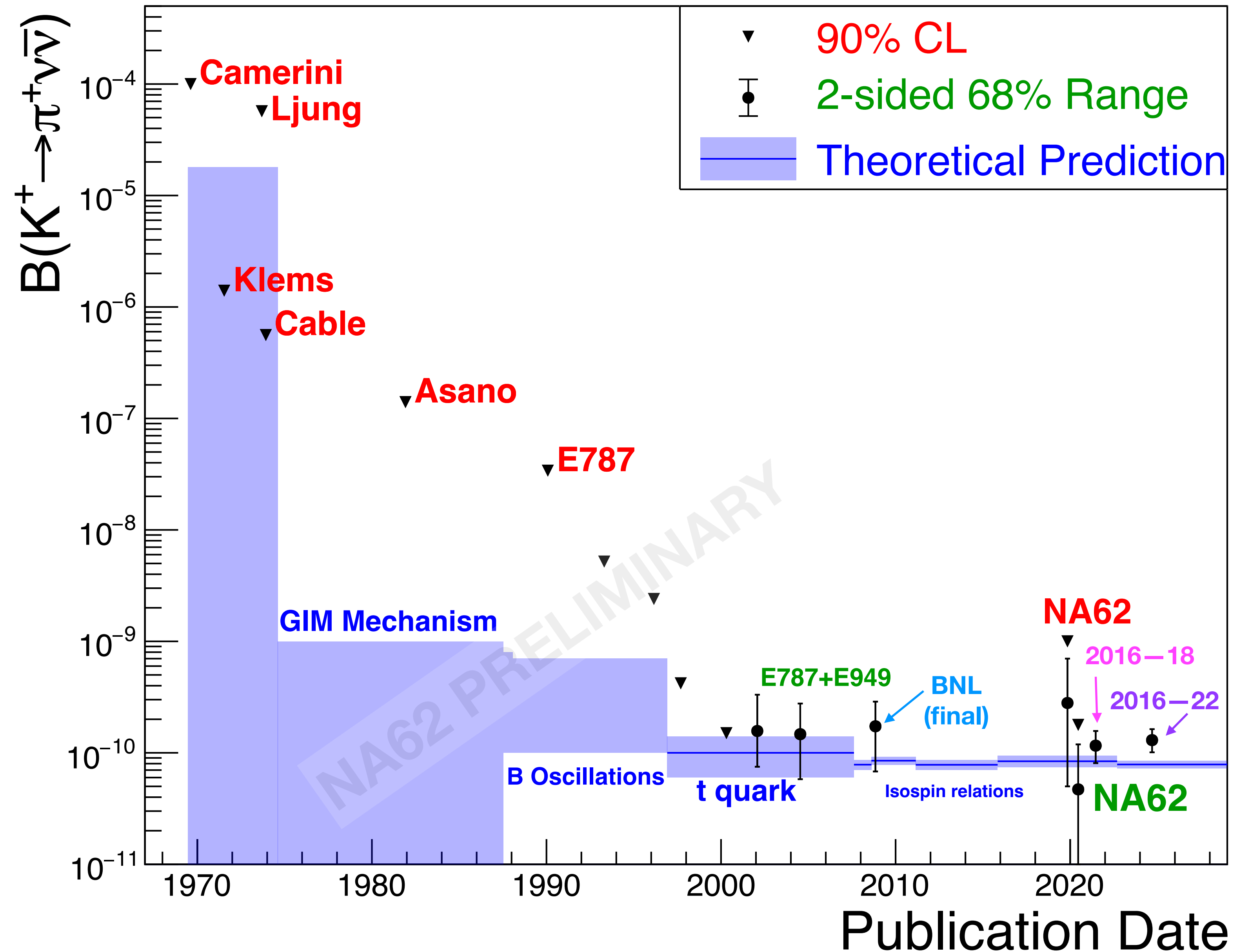


Experimental measurements:

- 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](#)]



$K_L \rightarrow \pi^0 \nu \bar{\nu}$ at KOTO

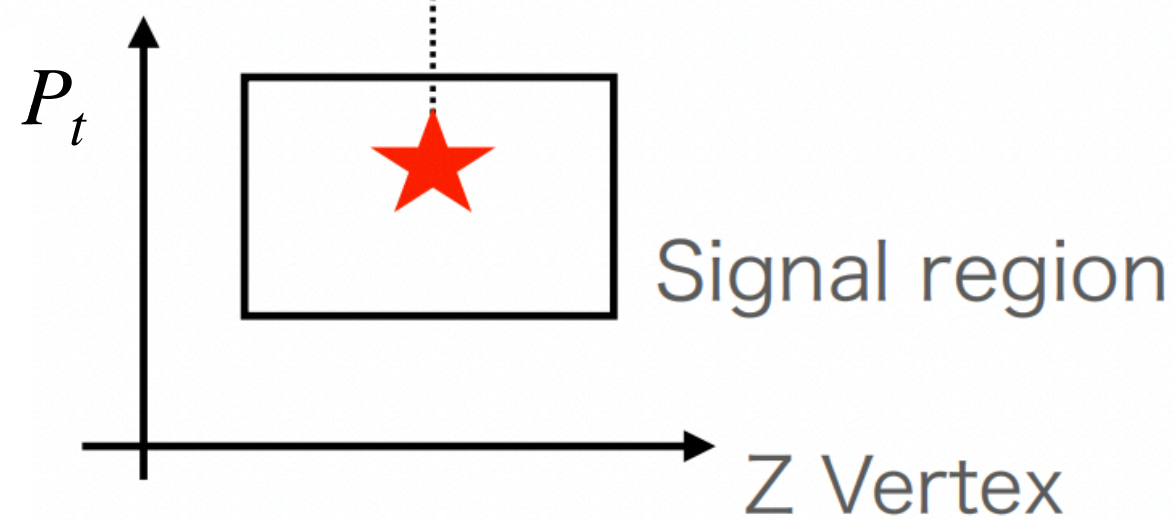
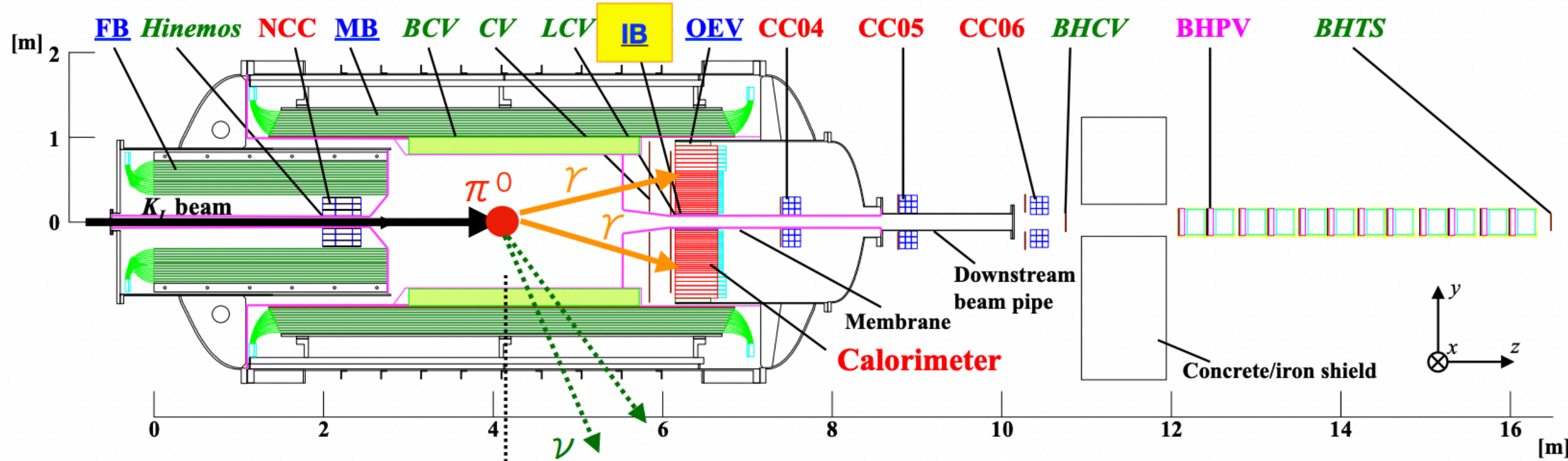
[K. shiomi : Kaons @ CERN 2023]

[T. Nomura : Kaons @ J-PARC 2024]

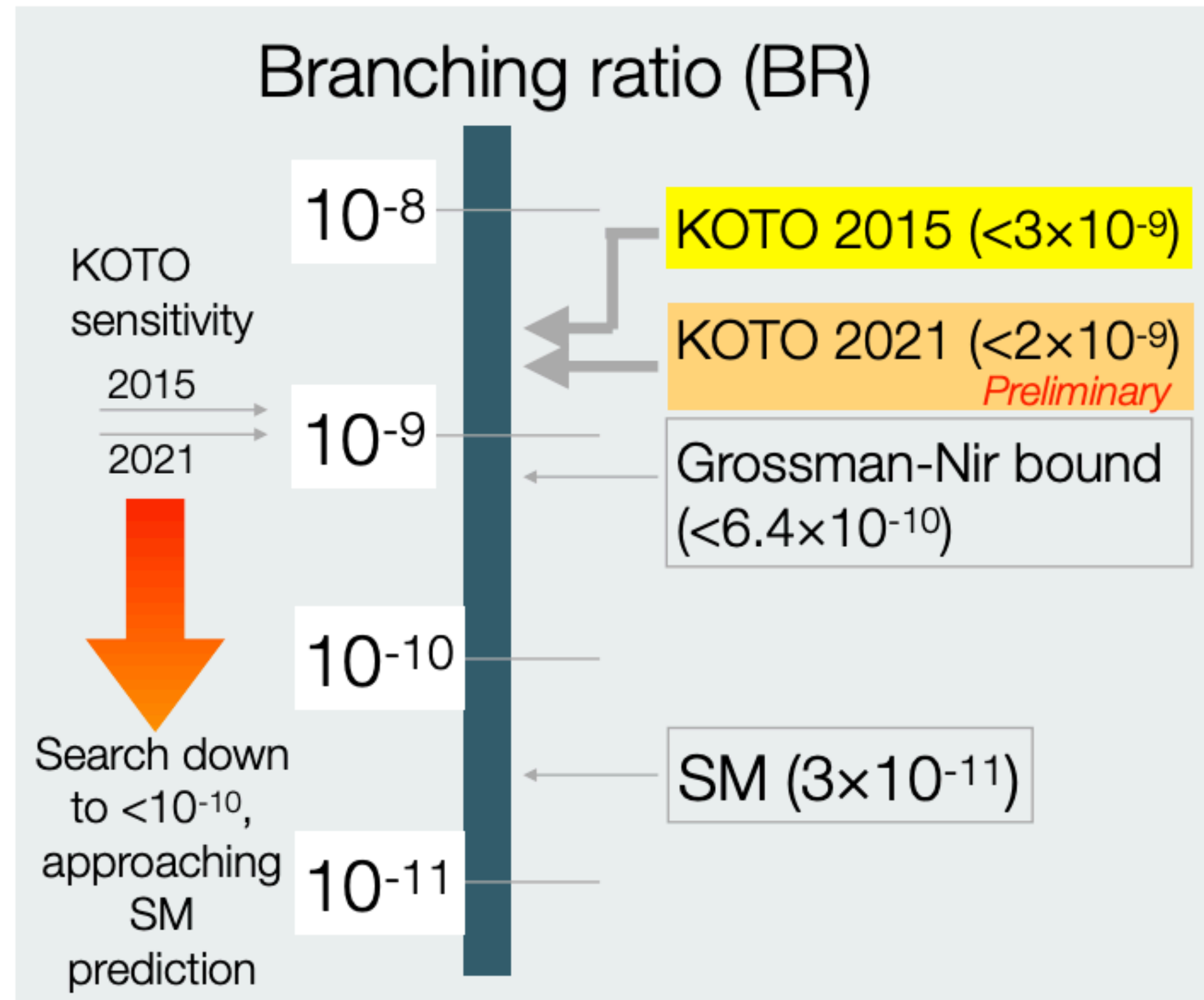


- Located at J-Park 30 GeV main ring.
- KOTO continues data-taking to reach sensitivity $<10^{-10}$
- Planned future program (KOTO-2) key part of high priority hadron hall extension plans at J-PARC.

Signature of $K_L \rightarrow \pi^0 \nu \bar{\nu} = "2 \gamma + \text{Nothing} + P_t"$



Assuming 2γ from π^0 ,
 Calculate z vertex on the beam axis
 $M^2(\pi^0) = 2E_1 E_2 (1 - \cos \theta)$
 Calculate π^0 transverse momentum



Grossman-Nir bound:
 indirect limit from relation to $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$;
 Calc'd from NA62 results (2021) with 1σ region

Latest results:

Results of the 2021 data analysis

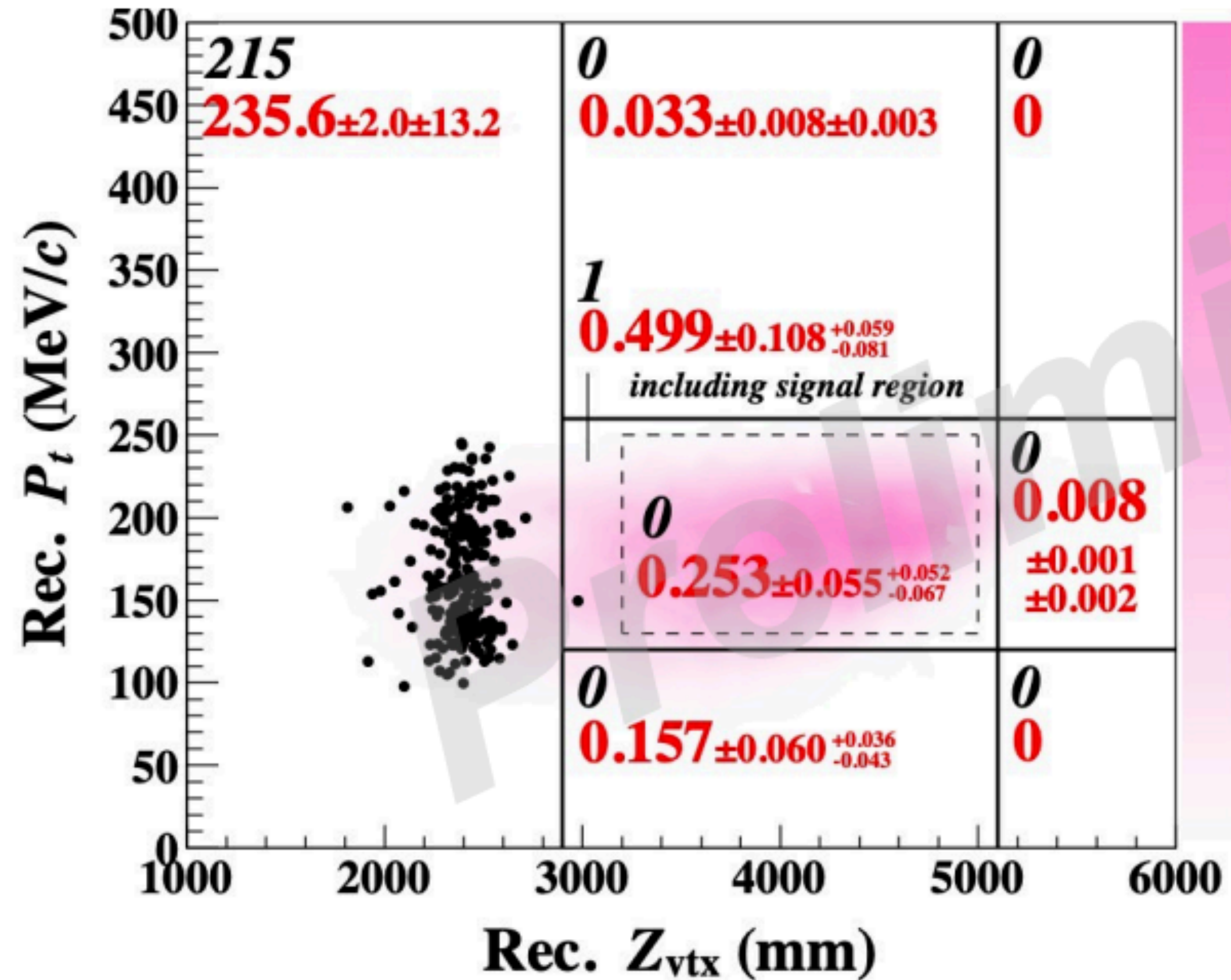


T. Nomura : Kaons @ J-PARC 2024

Final PT vs Z plot

Black: observed
Red: expected BG
Contour: signal MC

Single Event Sensitivity =
 $(9.26 \pm 0.03_{\text{stat}} \pm 0.75_{\text{syst}}) \times 10^{-10}$



$N_{\text{observed}} = 0$

$BR(K_L \rightarrow \pi^0 \nu \nu) < 2.1 \times 10^{-9}$ (90% C.L.)

Obtained the world best limit.

We will submit the paper on this result soon.



physics programme

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

Rare Decays

Forbidden Decays

Exotics

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$: [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093][this talk]
- $K^+ \rightarrow \pi^+ X$: [JHEP 03 (2021) 058] [JHEP 06 (2021) 093]
- $(K^+ \rightarrow \pi^+ \pi^0,) \pi^0 \rightarrow$ invisible [JHEP 02 (2021) 201]

- $K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow e^+ e^-$ [prelim. Spring 2024]
- $K^+ \rightarrow \pi^+ \gamma \gamma$ [PLB 850 (2024) 138513]
- Tagged neutrino [prelim. 2023]

- $K^+ \rightarrow \pi^0 \pi \mu e$ [prelim. Spring 2024]
- $K^+ \rightarrow (\pi^0) \pi^- e^+ e^+$ [PLB 830 (2022) 137172]
- $K^+ \rightarrow \mu^- \nu e^+ e^+$ [PLB838 (2023) 137679]
- $K^+ \rightarrow \pi \mu e, \pi^0 \rightarrow \mu^- e^+$ [PRL 127 (2021) 13, 131802]

- Beam dump dark photon searches:
 - $A' \rightarrow \ell^+ \ell^-$ [PRL 133 (2024) 11, 111802] [JHEP 09 (2023) 035]
 - $A' \rightarrow$ hadrons [prelim. Spring 2024]