Particle Physics Seminar :
University of Manchester - 31 January 2025

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

[New: arXiv:2412.12015: submitted to JHEP]

Joel Swallow (INFN-LNF)

Contents:

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

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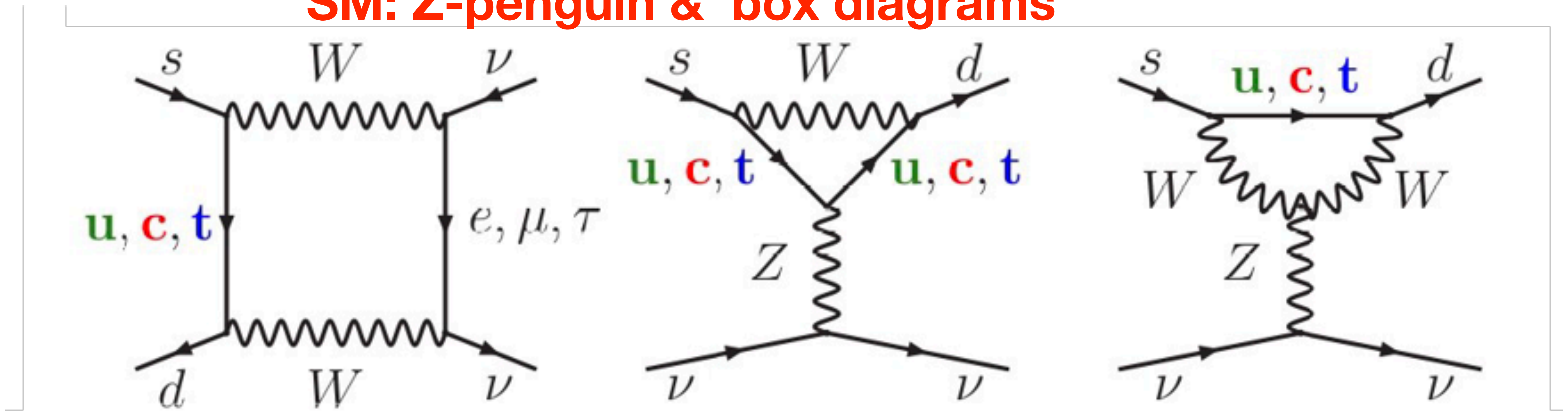
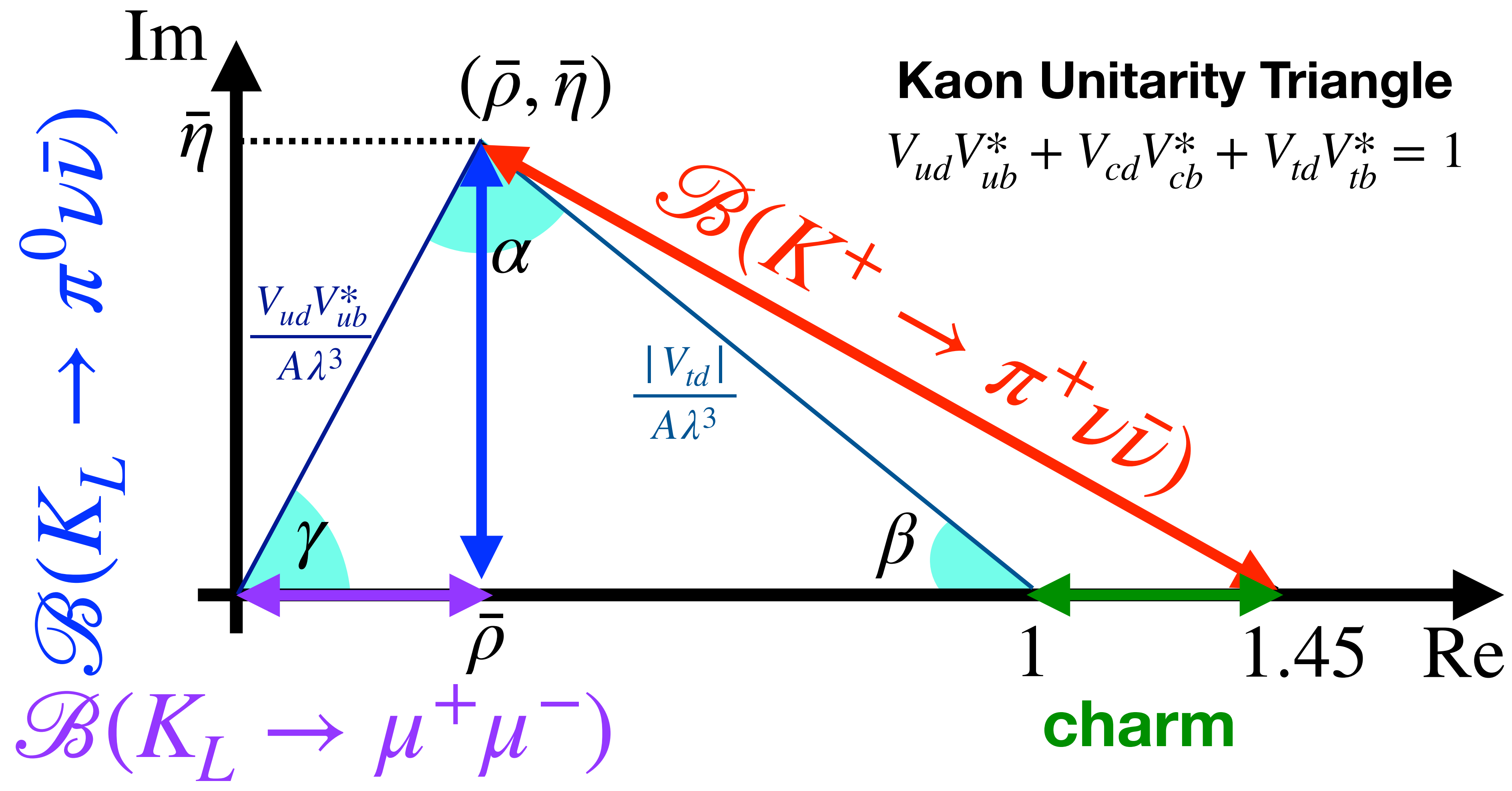
Rare Kaon Decays:
SM and Beyond

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

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





- $\mathcal{B}(K \to \pi\nu\bar{\nu})$ **highly suppressed** in SM
  - GIM mechanism & maximum CKM suppression $s \to d$ transition: $\sim \frac{m_t^2}{m_W^2} \left| V^*_{ts} V_{td} \right|$
- Theoretically clean ⇒ high precision SM predictions
  - Dominated by short distance contributions.
  - Hadronic matrix element extracted from $\mathcal{B}(K \to \pi^0 \ell^+ \nu_\ell)$ decays via isospin rotation.

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

^Recent SM calculations [1:Buras et al. EPJC 82 (2022) 7, 615][2:D'Ambrosio et al. JHEP 09 (2022) 148]
(Differences in SM calculations from choice of CKM parameters: see [Eur.Phys.J.C 84 (2024) 4, 377])

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

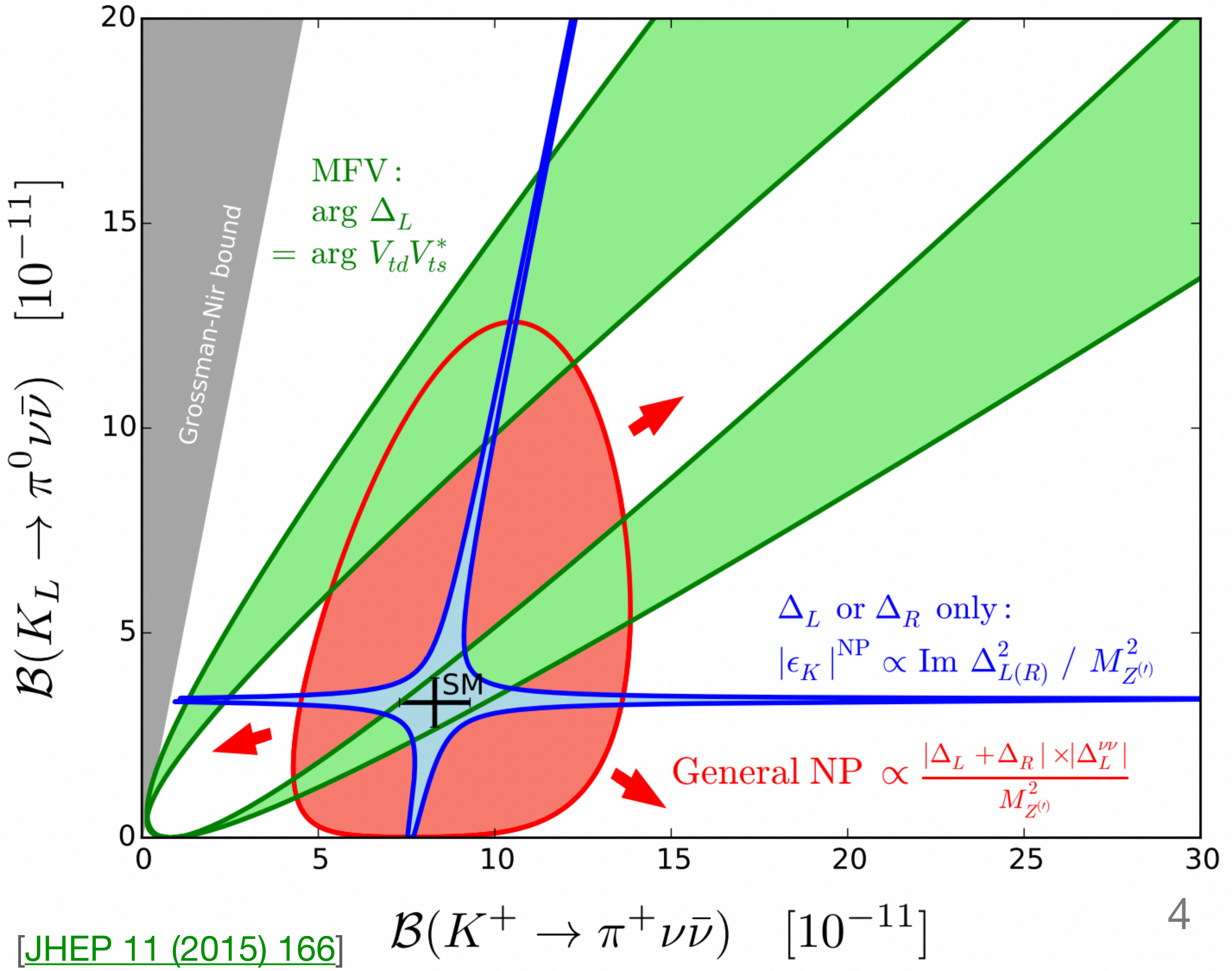
- Correlations between BSM contributions to BRs of K^+ and K_L modes [JHEP 11 (2015) 166].
  - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ε'/ε, ΔM_B, B-decays) [JHEP 12 (2020) 097][PLB 809 (2020) 135769].
- Leptoquarks [EPJ.C 82 (2022) 4, 320], Interplay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

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

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

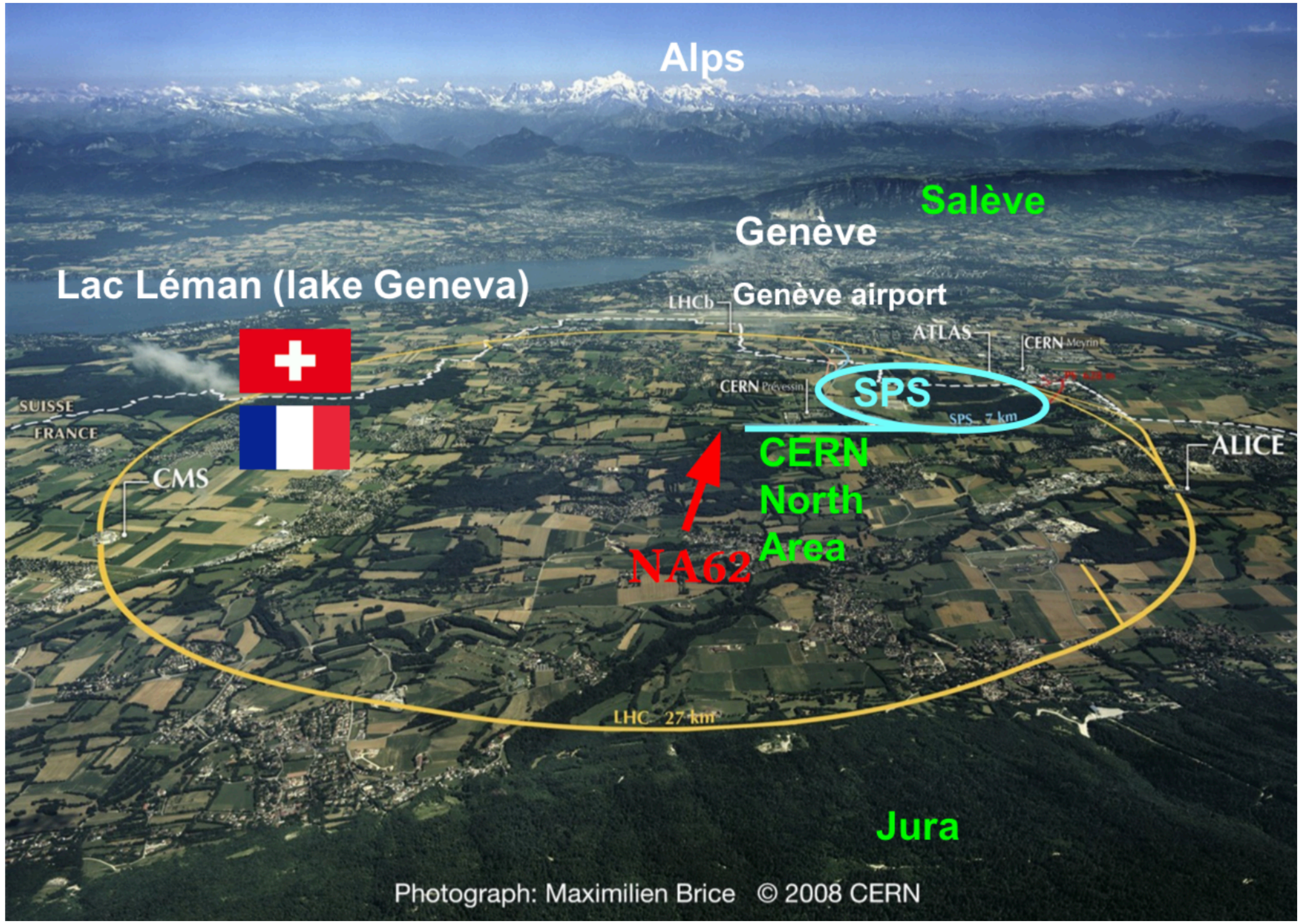


[JHEP 11 (2015) 166]

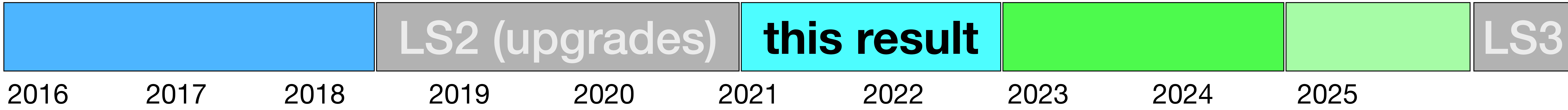
NA62:
The K^+ factory at the CERN north area

The NA62 Experiment at CERN

~200 collaborators from ~30 institutions.



- **Primary goal:** measurement of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$
- **New Technique:** K^+ decay-in-flight
- **Results:** [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
- **Broader physics programme:**
  - Rare K^+ decays (e.g. $K^+ \to \pi^+\gamma\gamma$ [PLB 850 (2024) 138513])
  - LNV/LFV decays (e.g. $K^+ \to \pi^-(\pi^0)e^+e^+$ [PLB 830 (2022) 137172])
  - Exotics (e.g. Dark photon [PRL 133 (2024) 11, 111802])
- **Data taking**
  - 2016 Commissioning + Physics run (45 days).
  - 2017 Physics run (160 days).
  - 2018 Physics run (217 days).
  - 2021 Physics run (85 days [10 beam dump]).
  - 2022 Physics run (215 days).
  - 2023 Physics run (150 days [10 beam dump]).
  - 2024 Physics run (204 days [12 dump] {5 low intensity}).



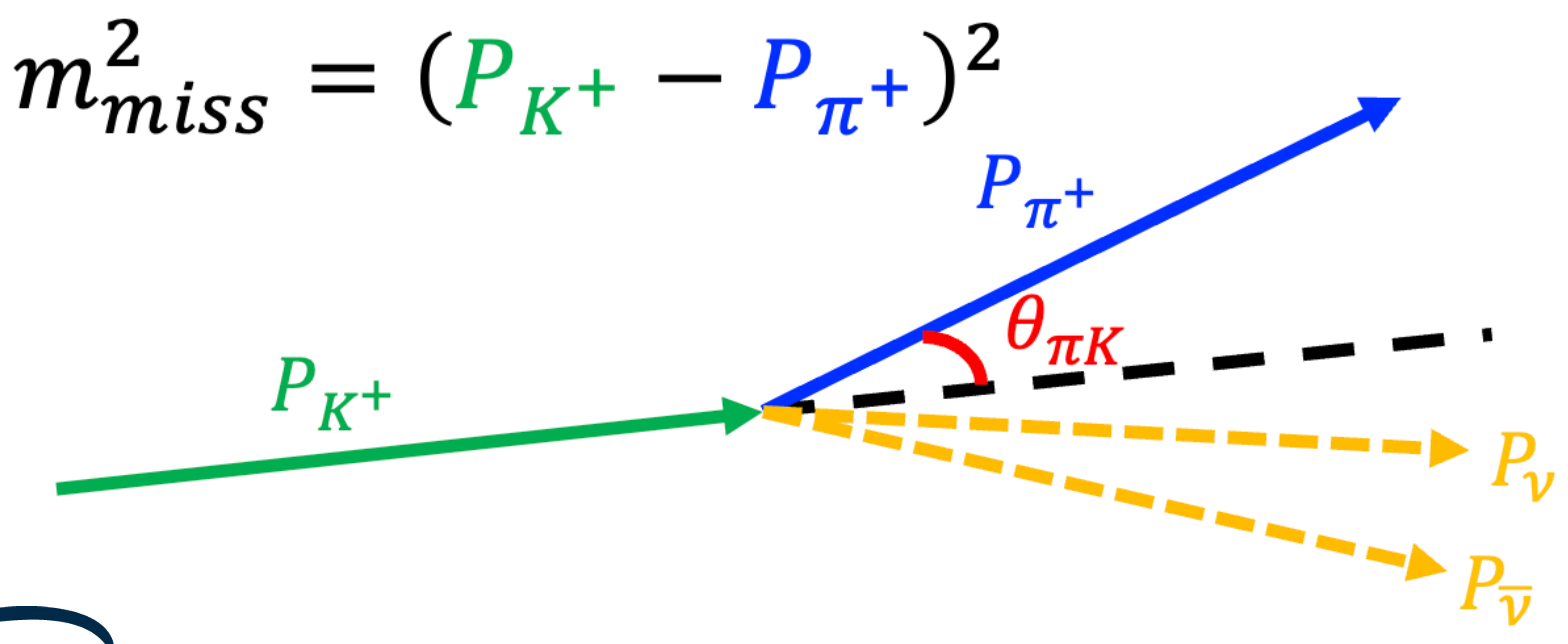
$K^+ \to \pi^+\nu\bar{\nu}$ at NA62

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

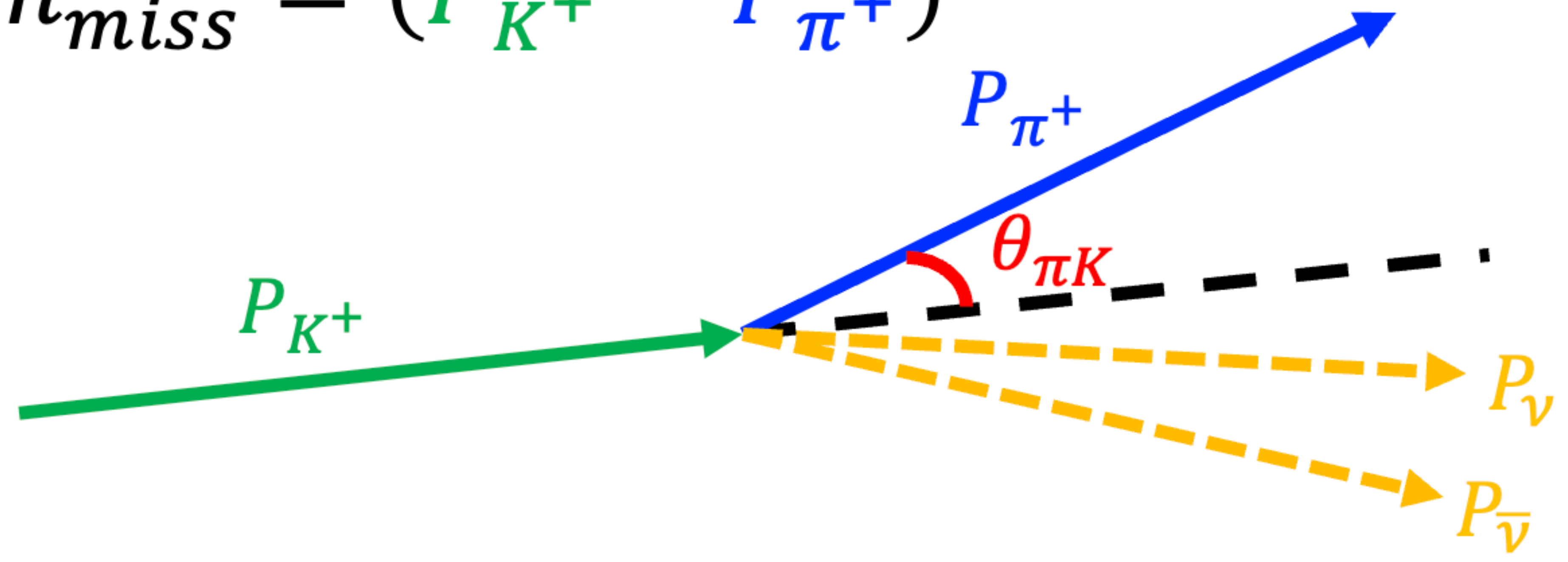


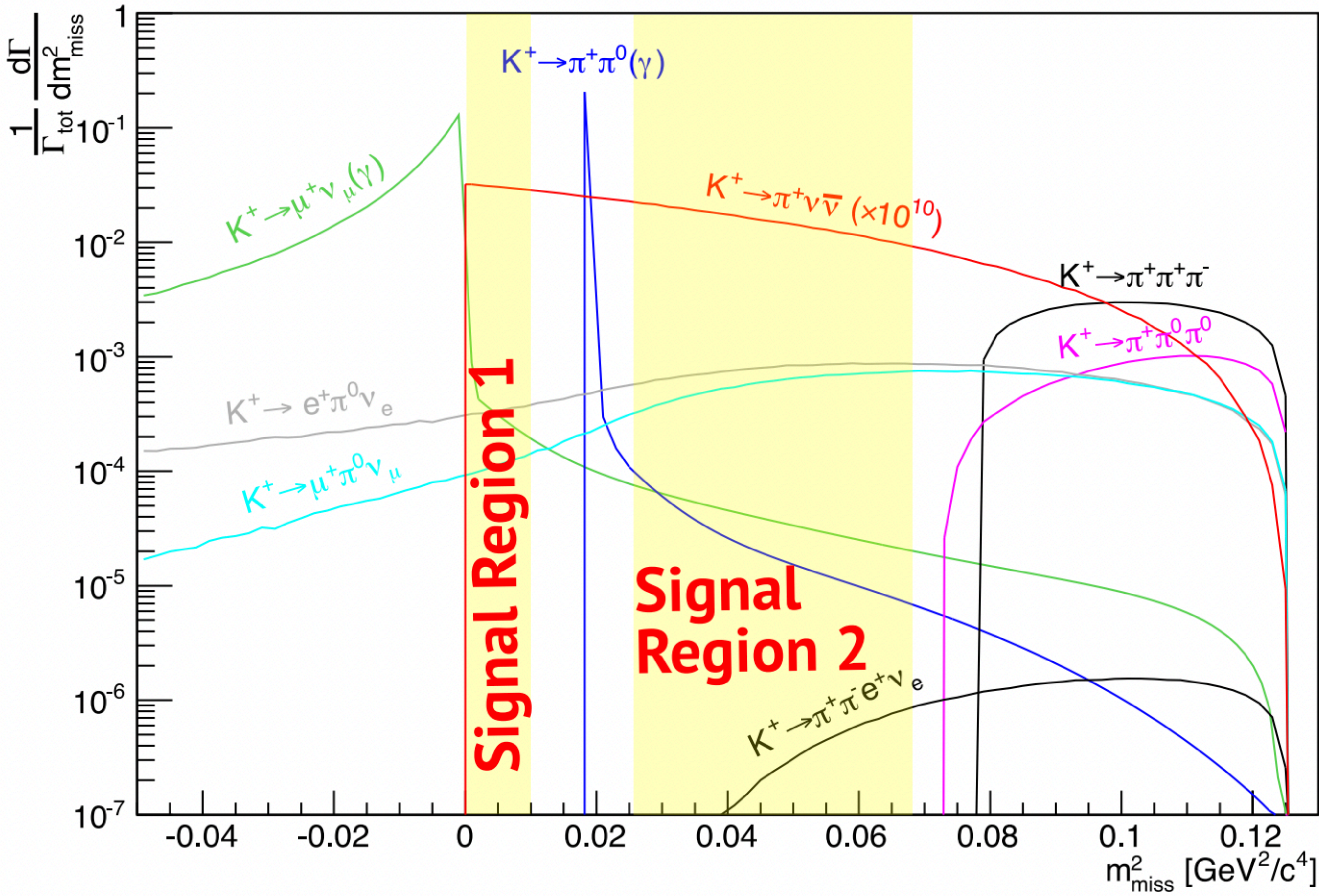
Decay mode	Branching Ratio [PDG]
$K^+ \to \mu^+\nu_\mu$	$(63.56 \pm 0.11)\,\%$
$K^+ \to \pi^+\pi^0$	$(20.67 \pm 0.08)\,\%$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024)\,\%$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$
$K^+ \to \pi^+\nu\bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$ [SM]

Buras et al. EPJC 82 (2022) 7, 615

Kinematic constraints & signal regions

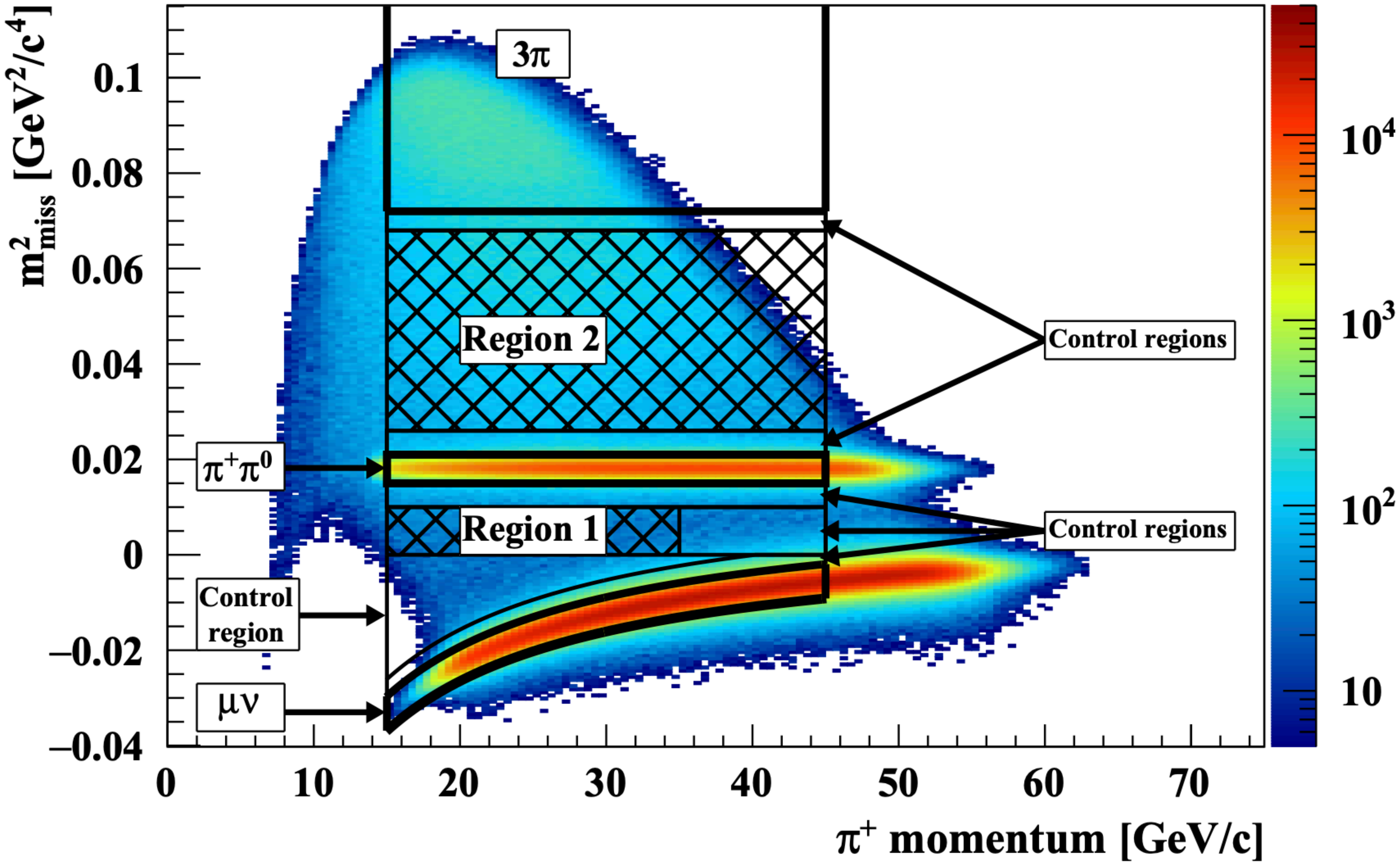
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$





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

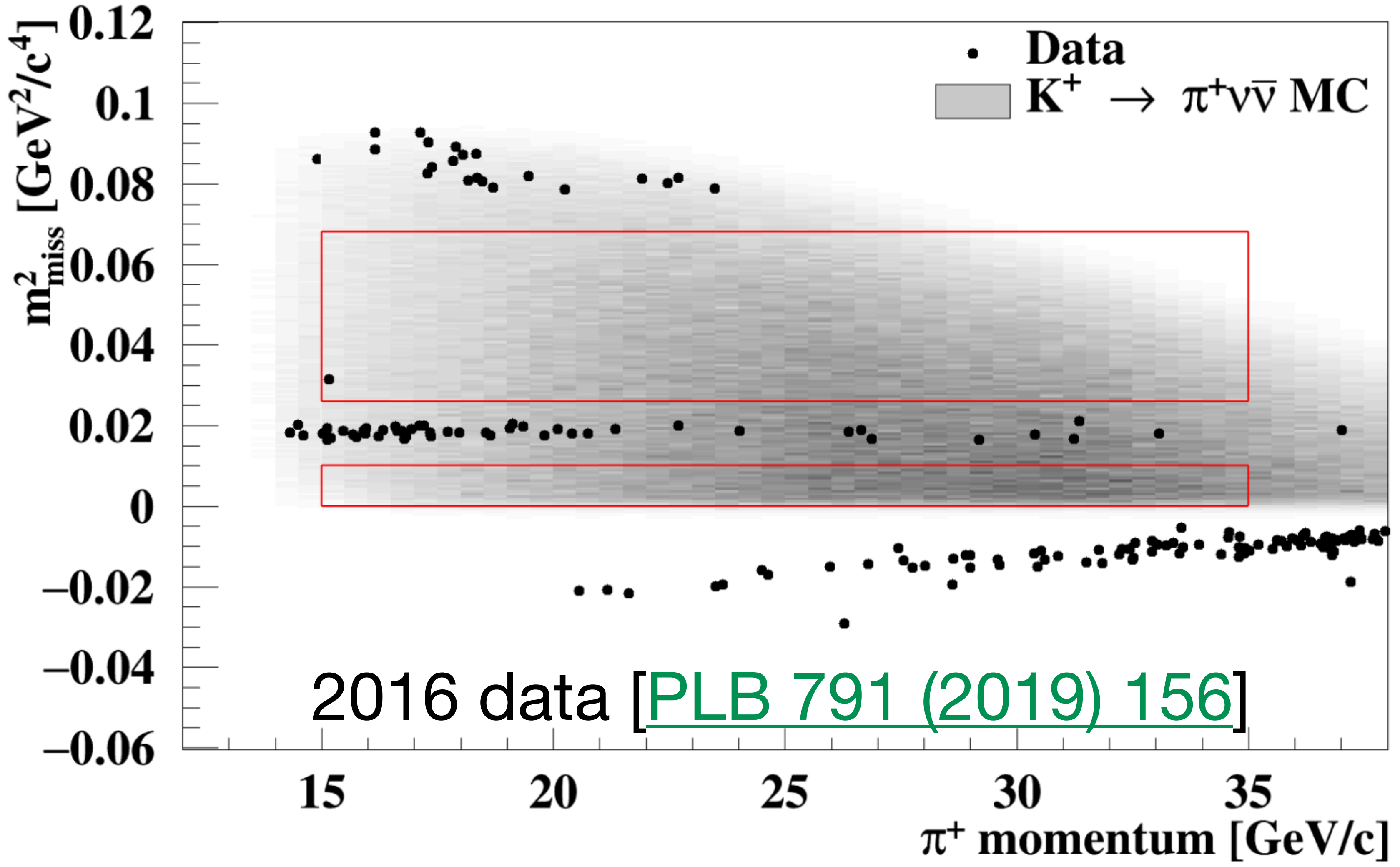
[JHEP 06 (2021) 093]

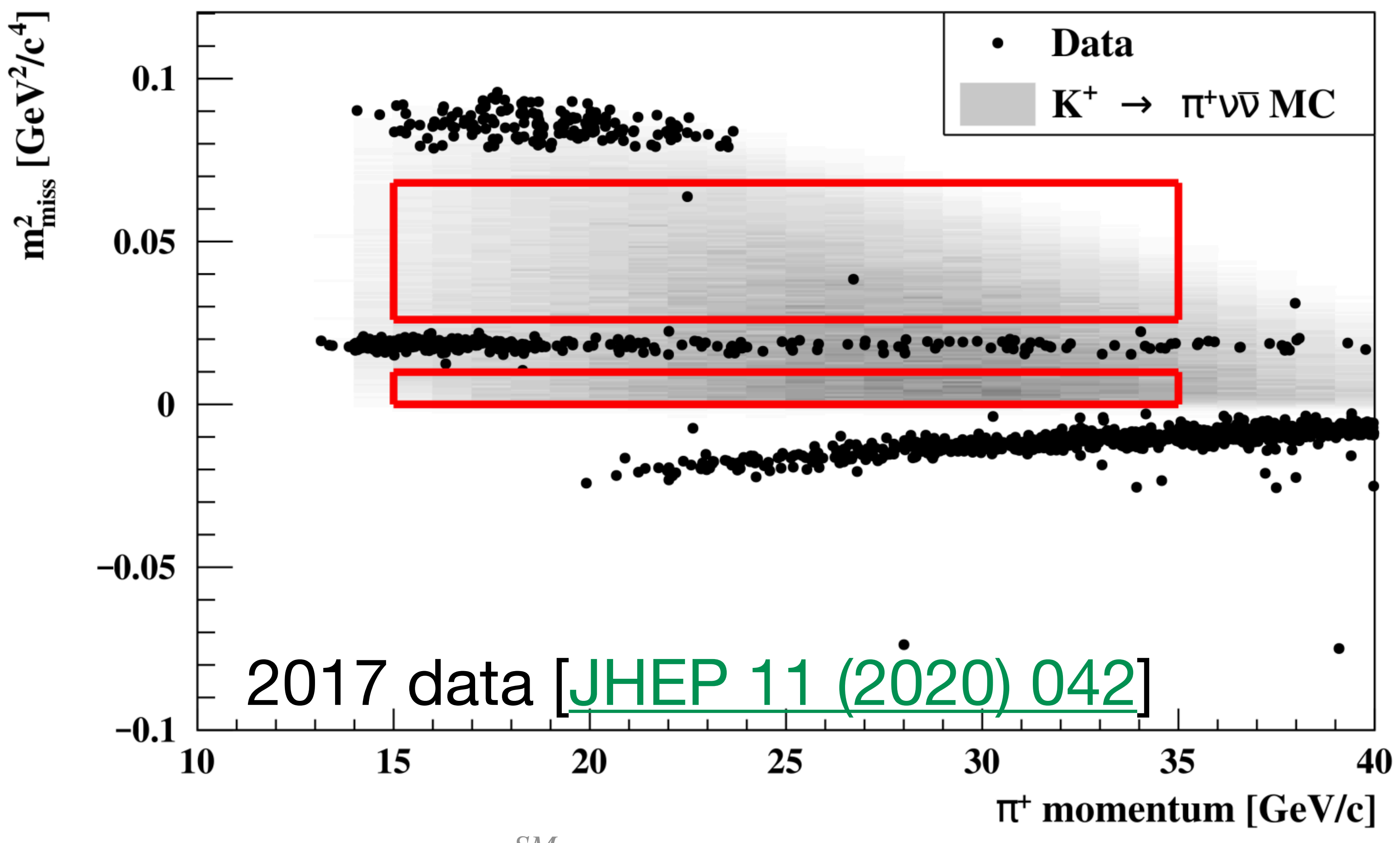


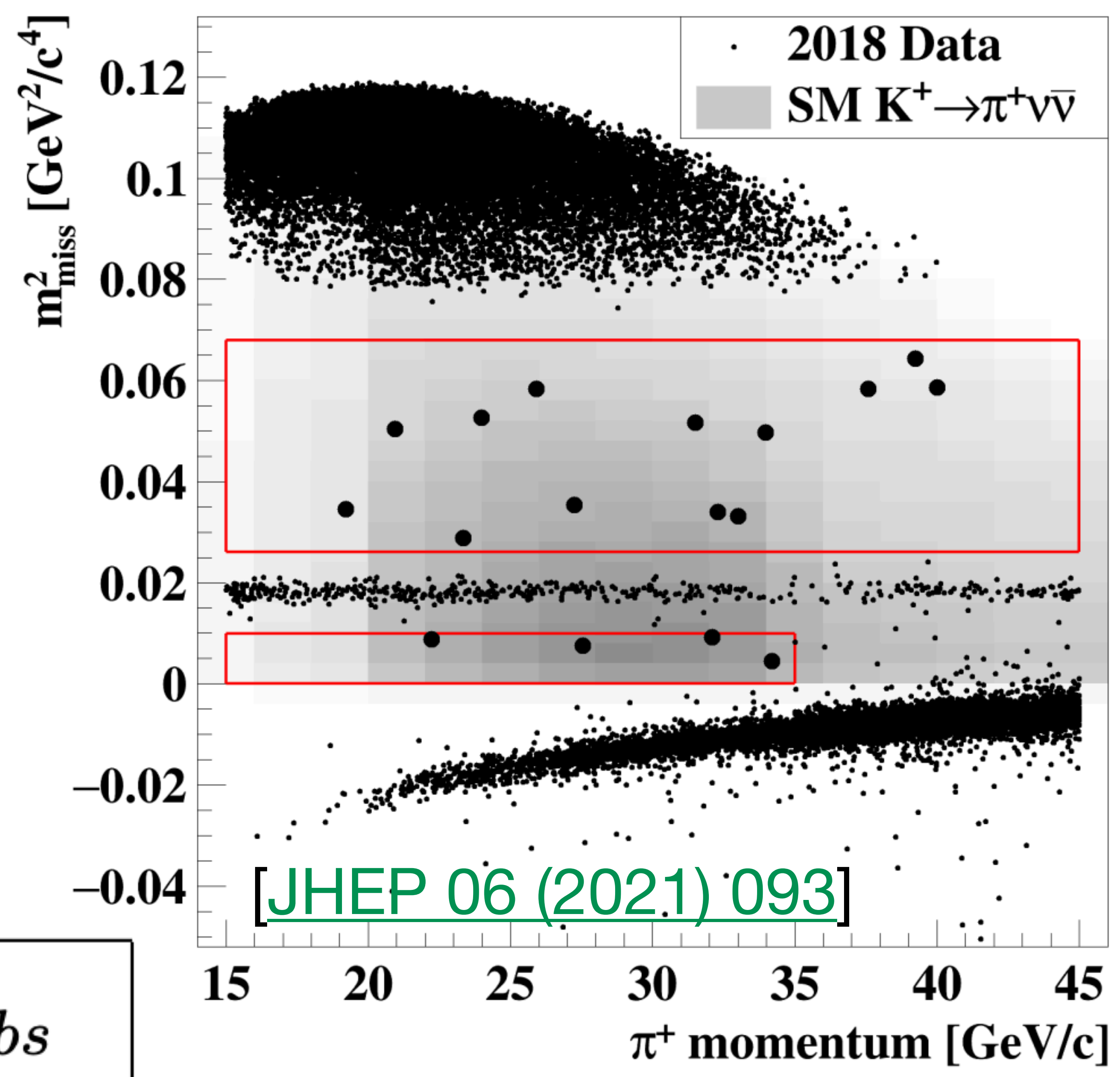
π^+ momentum range: 15—45 GeV/c

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

NA62







(*$N_{\pi\nu\bar{\nu}}^{SM,exp}$ 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:

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

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

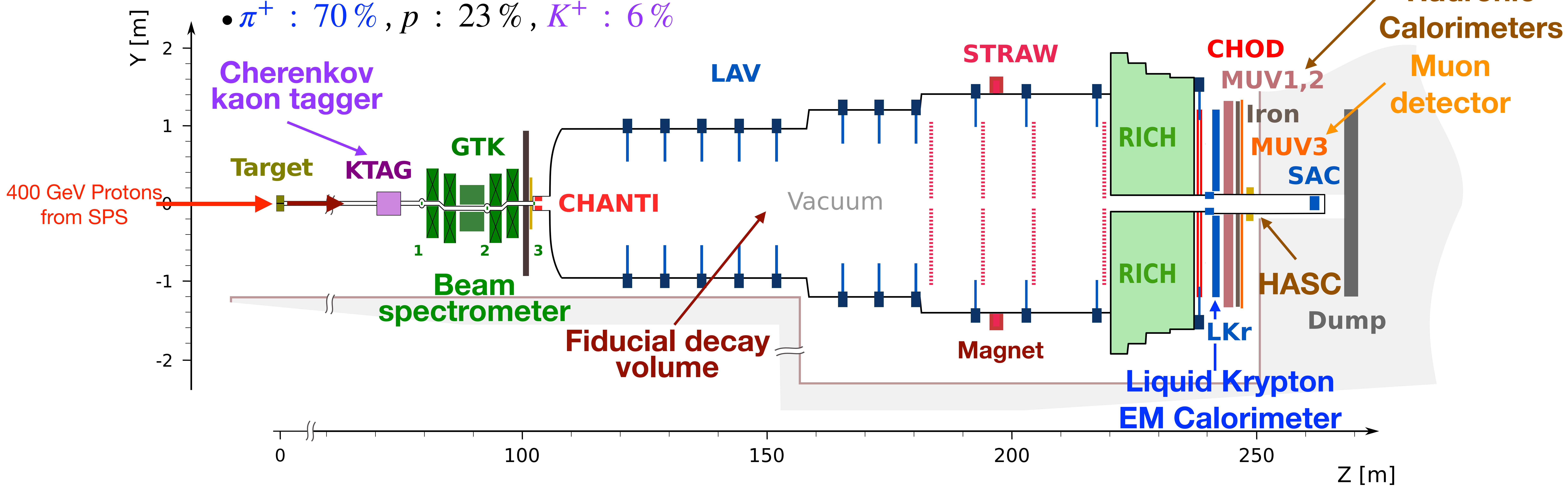
NA62 Detector, Upgrades & Performance

NA62 beamline & detector

[JINST 12 (2017) 05, P05025]

Secondary $75\,\text{GeV}/c$ beam:

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

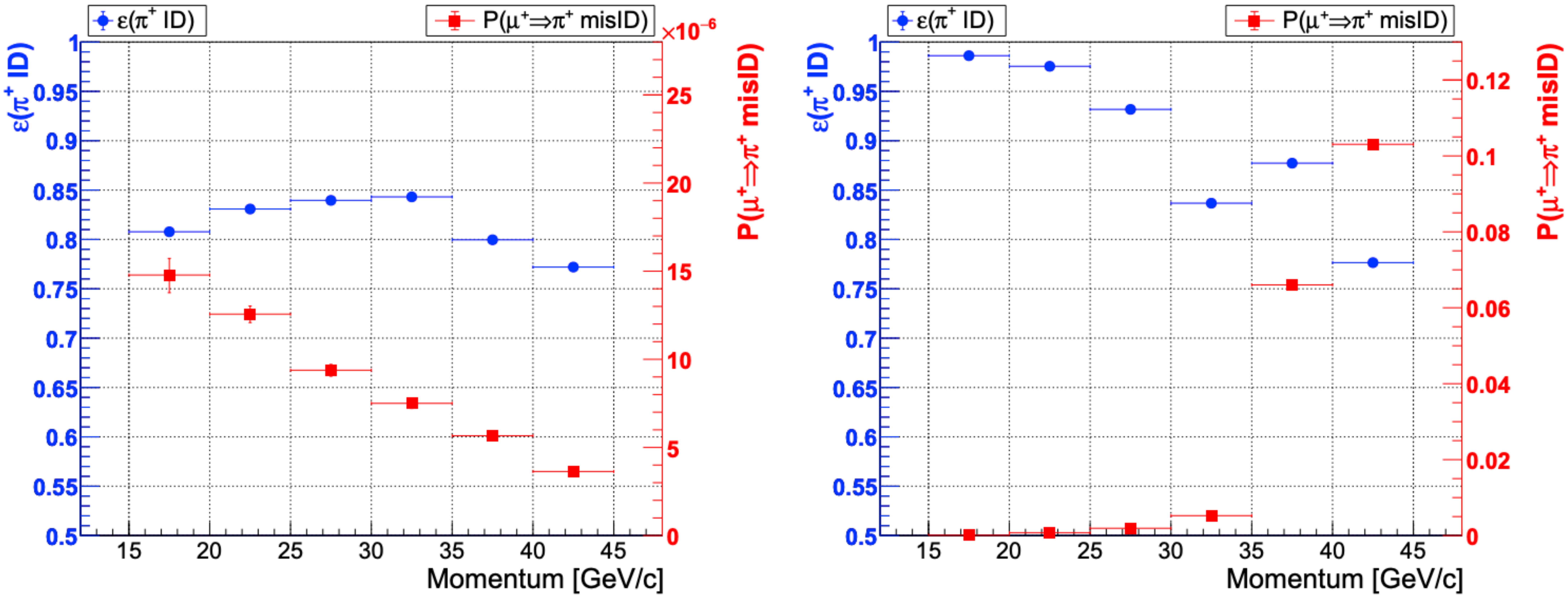


- Designed & optimised for study of $K^+ \to \pi^+ \nu \bar{\nu}$:
  - **Particle tracking:** beam particle (GTK) & downstream tracks (STRAW)
  - **PID:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
  - **Comprehensive veto systems:** CHANTI (beam interactions), LAV,LKr,IRC,SAC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

Particle ID performance : 2021—22 data

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

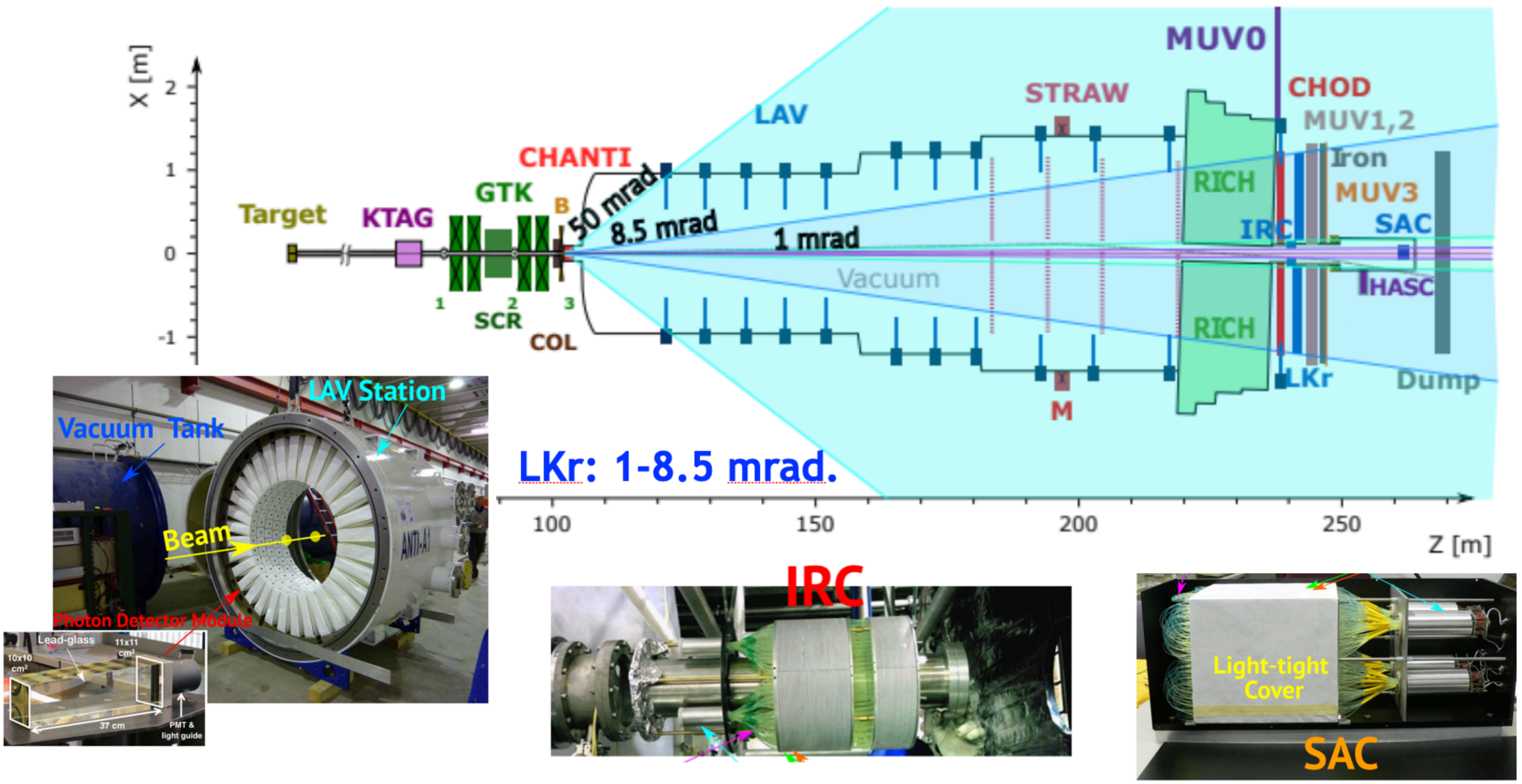
Designed to distinguish between π^+/μ^+ with $15 - 35$ GeV/c.



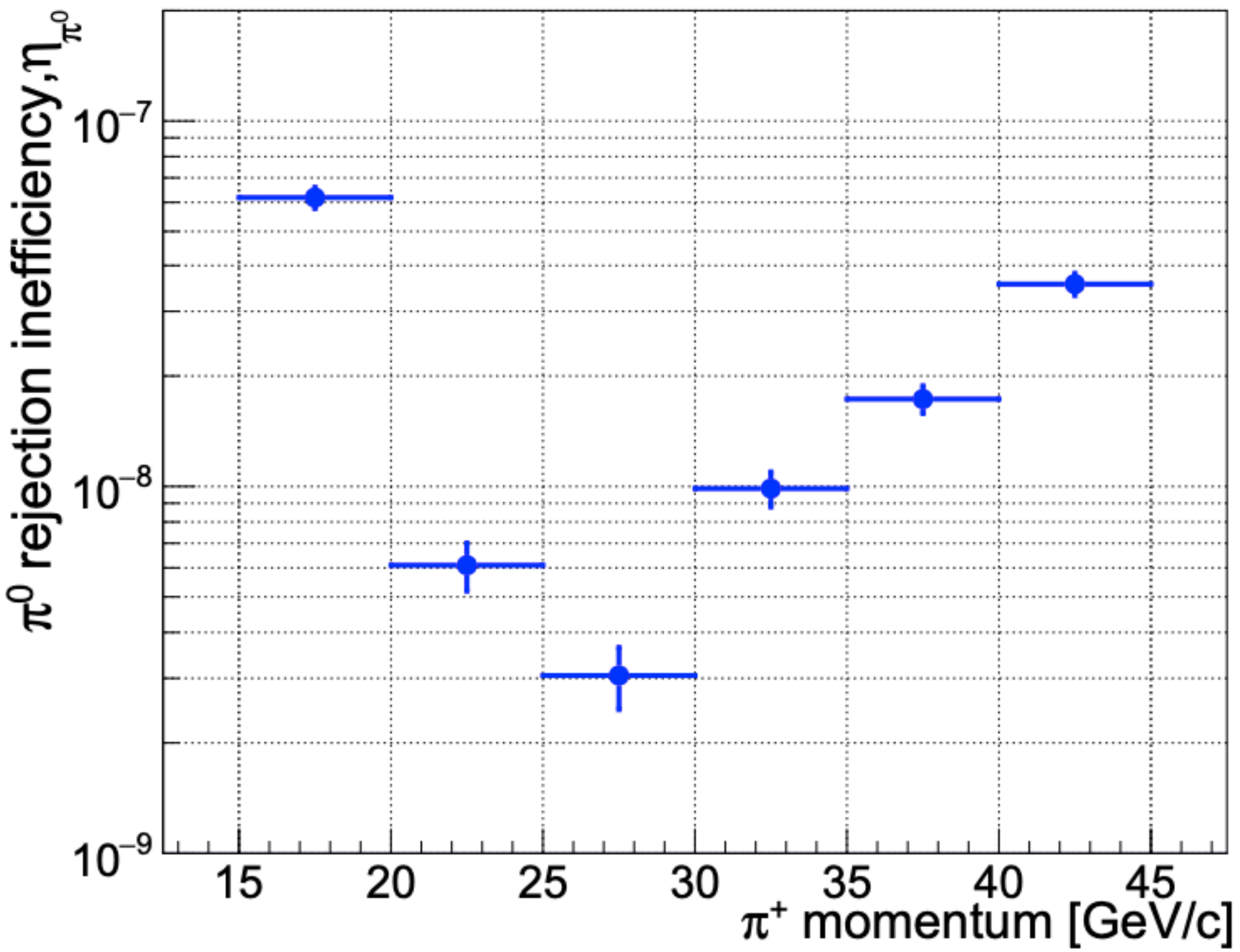
$\varepsilon(\pi\,\text{ID}) = (73.00 \pm 0.01)\,\%$

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

Comprehensive photon veto system: 2021—22



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 $\mathcal{O}(10^8)$.**

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.

Upgrading NA62

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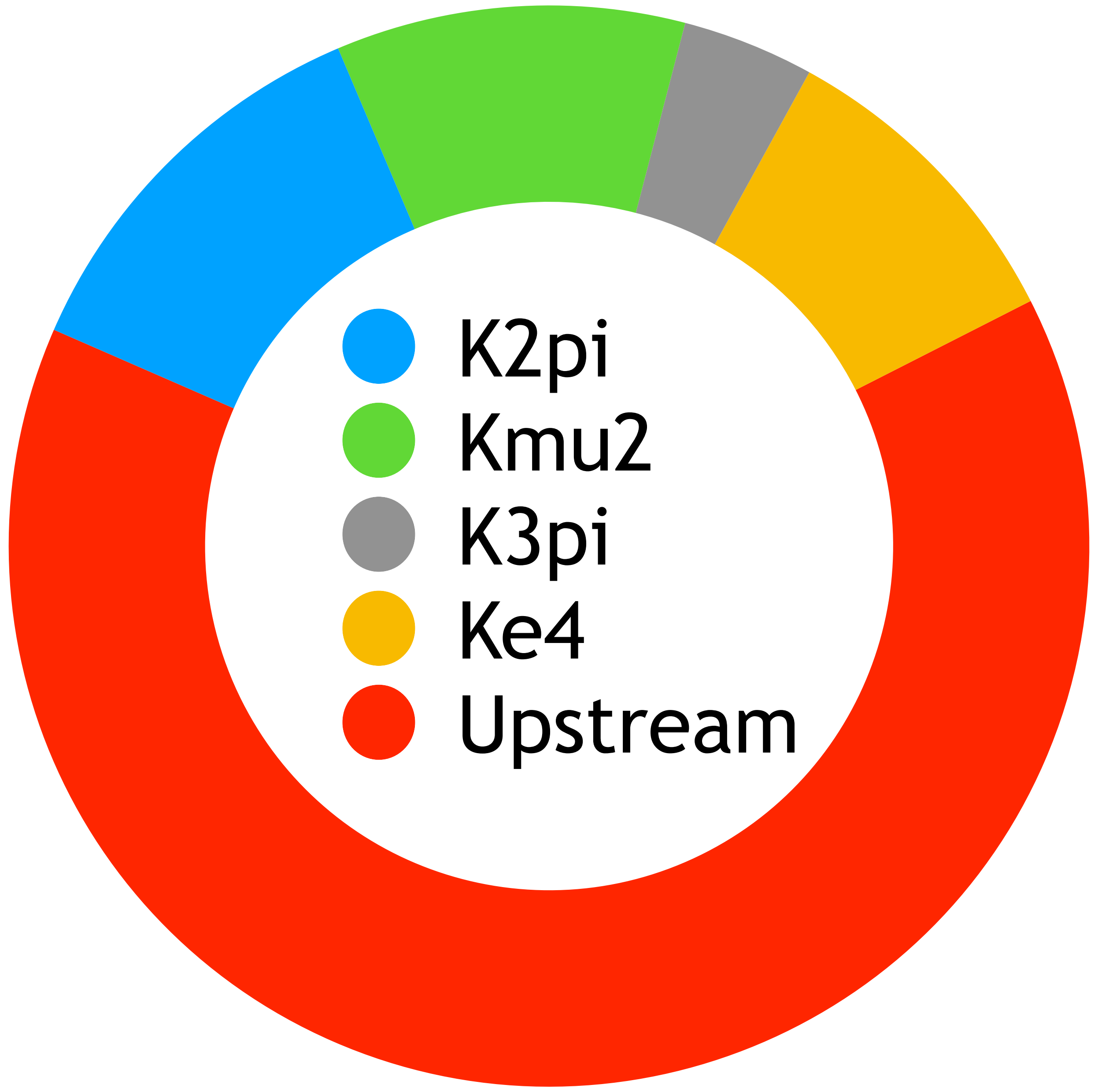
Background	**N(exp) 2018 (S2)**
Upstream	$2.76^{+0.90}_{-0.70}$
$K^+ \to \pi^+\pi^0$	0.52 ± 0.05
$K^+ \to \mu^+\nu$	0.45 ± 0.06
$K^+ \to \pi^+\pi^- e^+\nu$	0.41 ± 0.10
$K^+ \to \pi^+\pi^+\pi^-$	0.17 ± 0.08
Total	$4.31^{+0.91}_{-0.72}$

K^+ decays in decay tank



Upstream background

Largest backgrounds:

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

Veto by detecting previously missed particles…


Mid 2018 - installed TCX Collimator
Much improved shielding - blocking almost all upstream decay paths.
Sketch only
TCX Collimator
MNP33
RICH
Bend6
Bend4A
Bend4
Bend5
TRIM5
GTK3
GTK2
Vacuum Tank
Fake vertex
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
TCX Collimator
MNP33
RICH
Bend6
Bend4A
Bend4
Bend5
TRIM5
ANTI0
Vacuum Tank
GTK0
GTK2
VC1
Lead
VC3
GTK3
Fake vertex
π^+
γ
K^+
γ
KTAG
GTK1
Scraper
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Scattering at STRAW1
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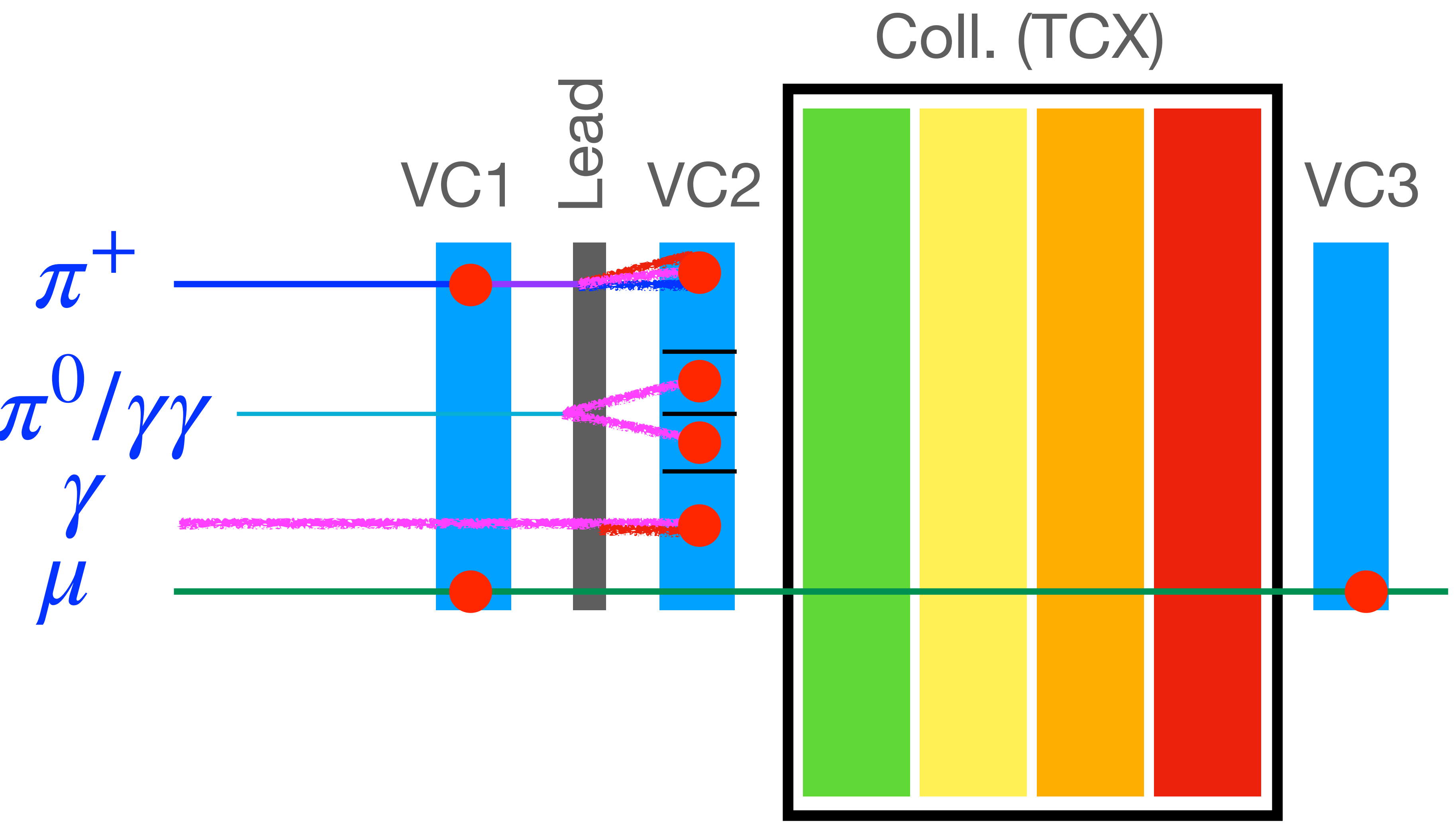
y
z
Signal in-time with true K^+ which decays upstream.
Signal in-time with pileup beam particle (π^+) which does not leave beam pipe

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.

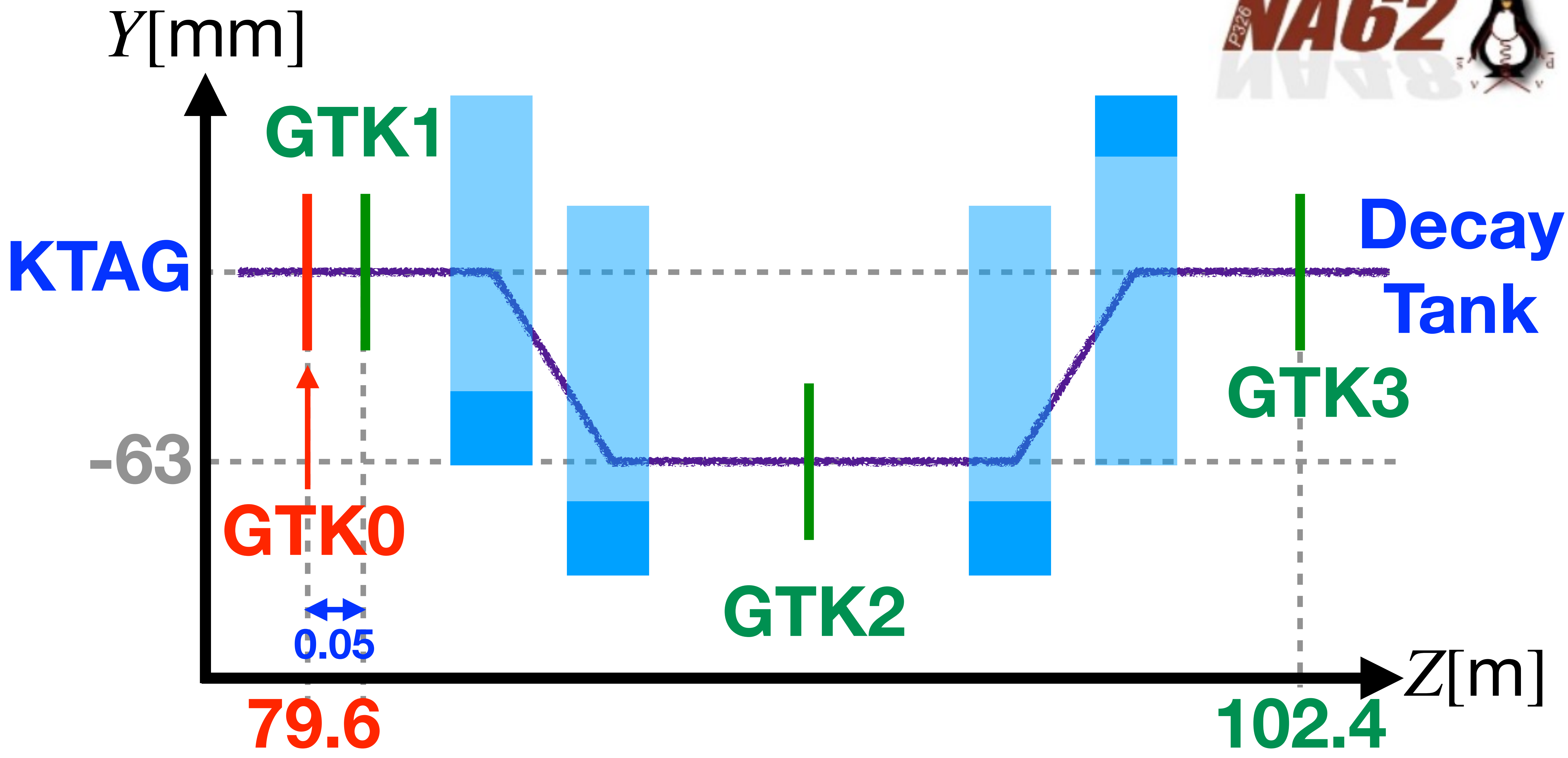
ANTI0

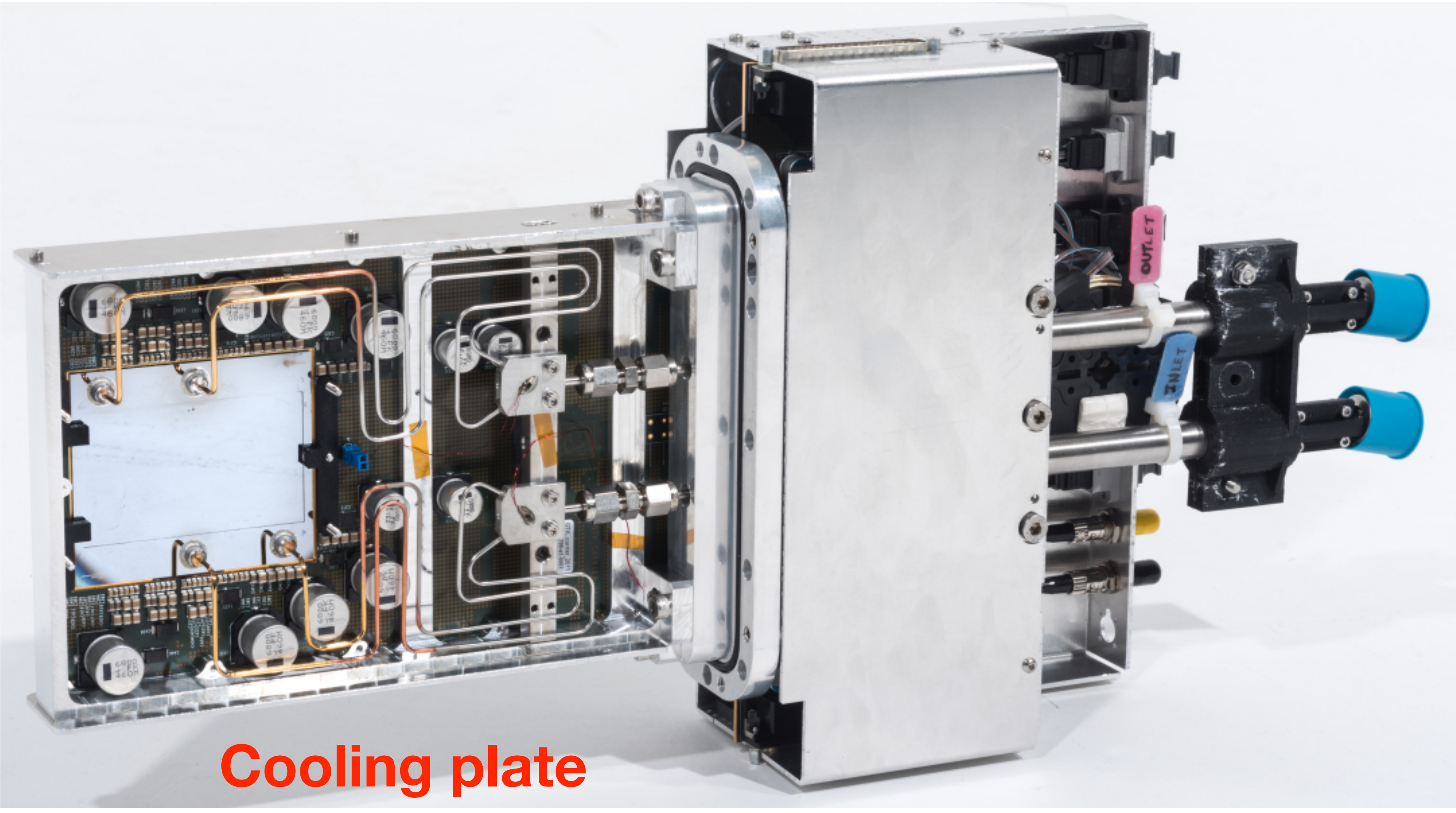
- Detect particles up to ~1 m from beam line.
- **Reject ~20% of upstream background** with <1% signal loss.

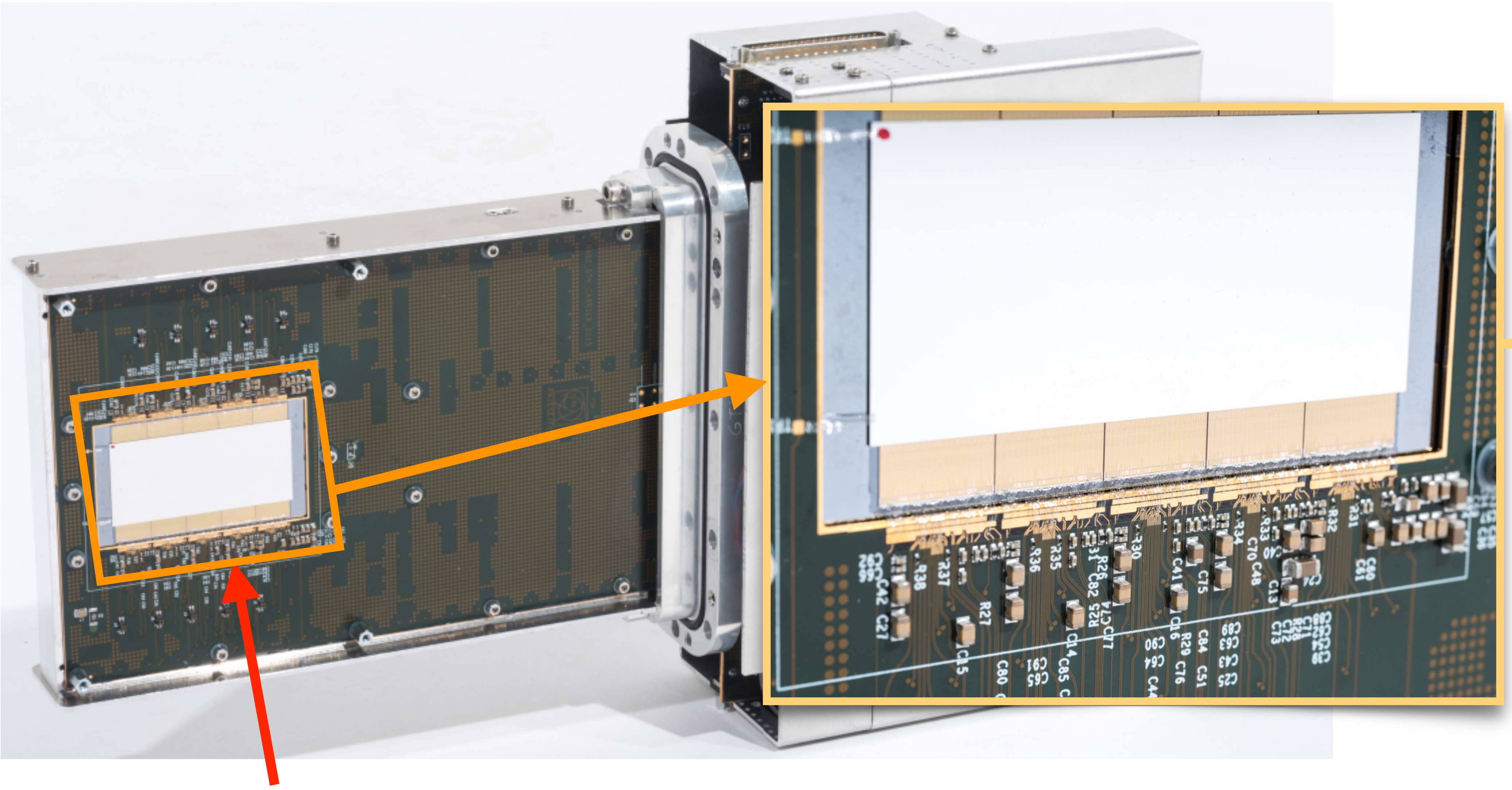
[JINST 15 (2020) C07007]
[SPSC report 2023][EP Newsletter, Dec21]

4th GTK station

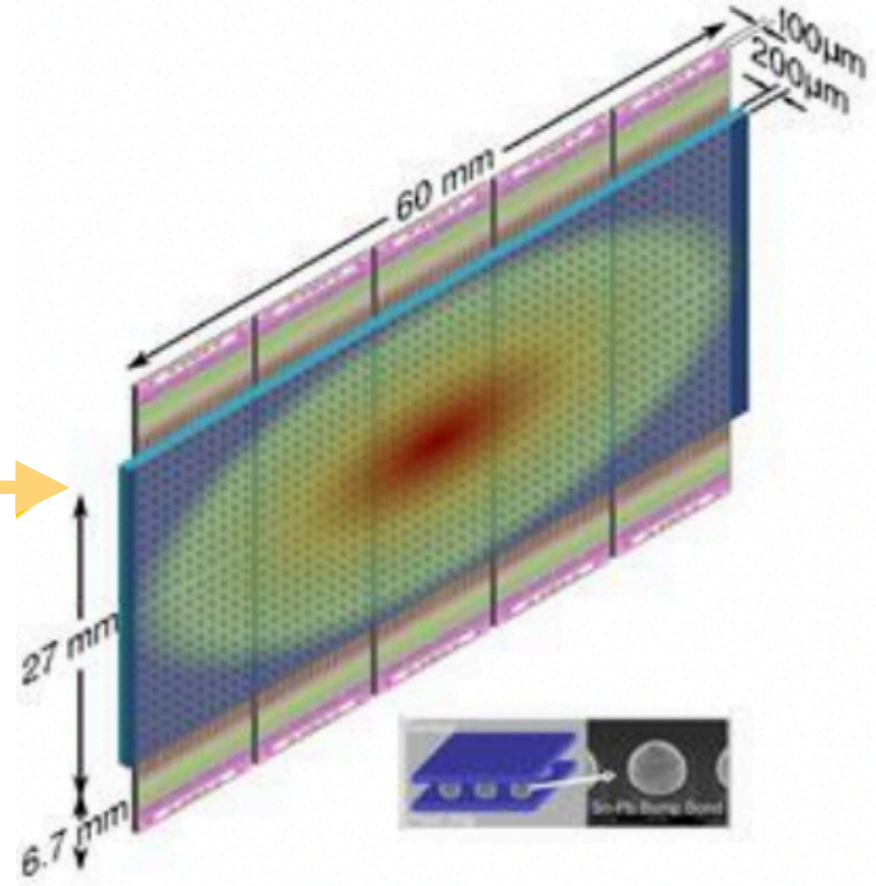
- Si Pixel detector exposed to ~1GHz beam.
- Essential for $K^+ - \pi^+$ matching.
  - Measures K^+ 3-mom. & time
- 4th GTK station improves efficiency & pileup resilience.







Si Pixels ~(30x60 mm active area)



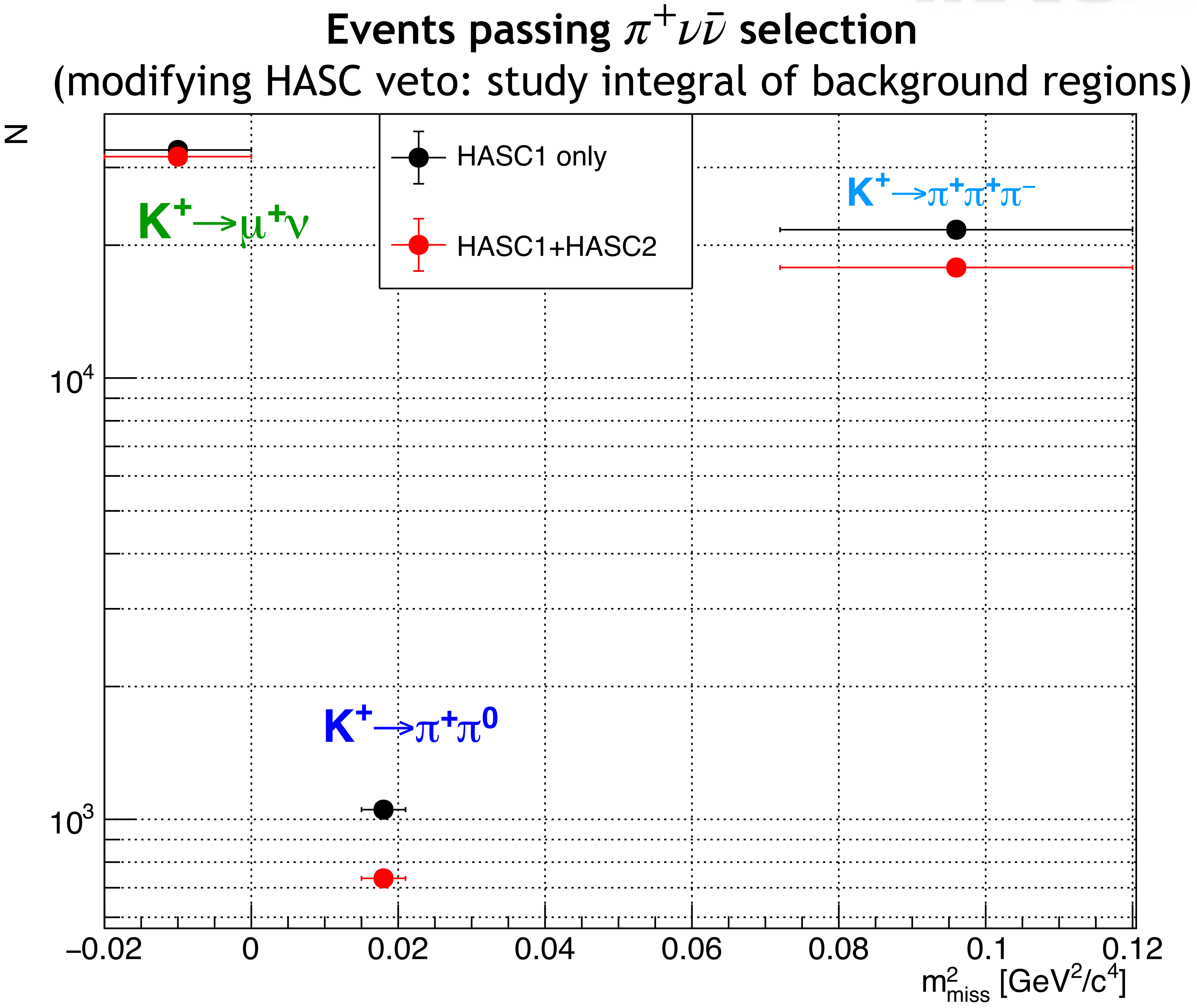
More info: [Kleimenova, VERTEX2023]

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
CHODs
SAC
Dump
HASC1
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

HASC2 veto

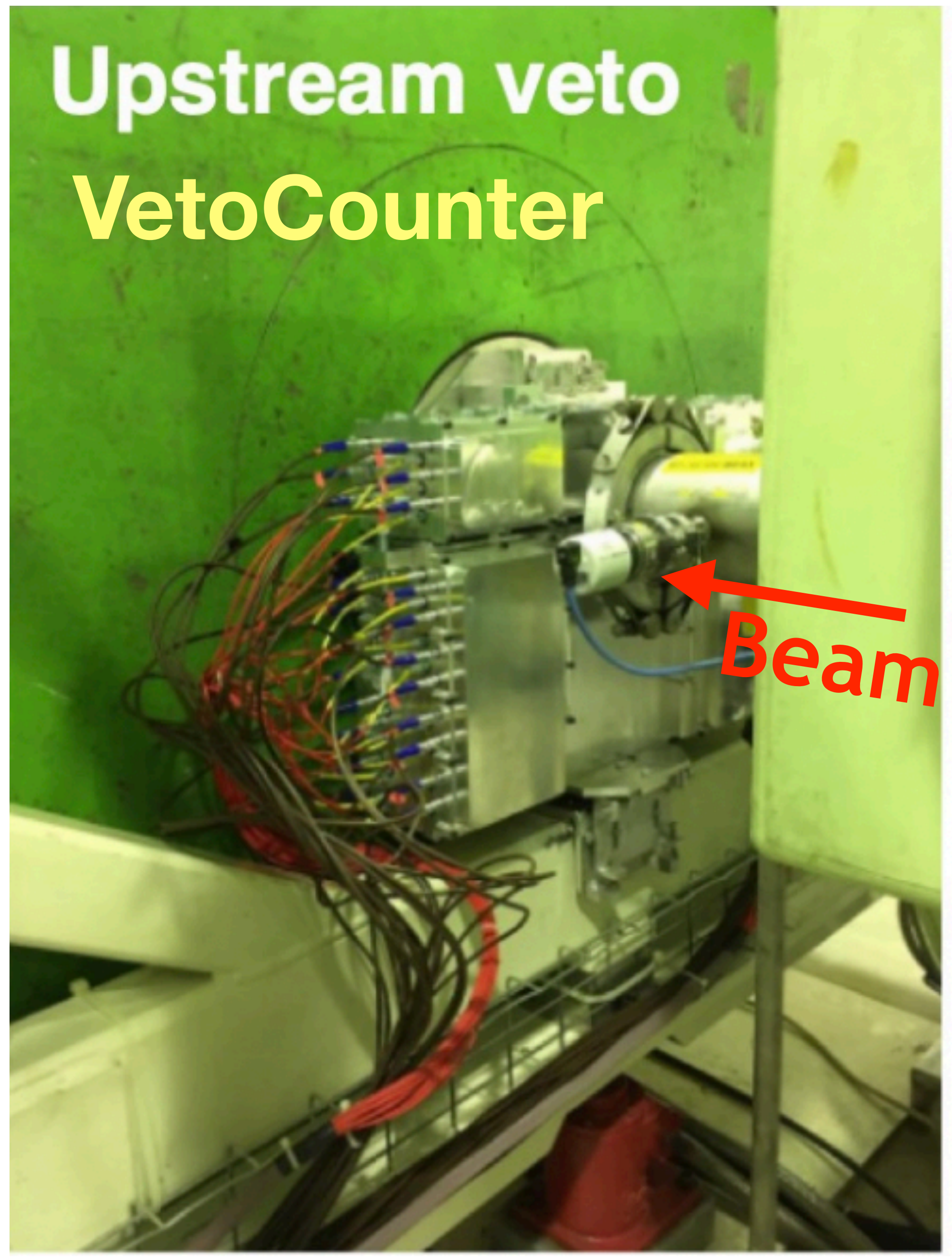
- $K^+ \to \pi^+\pi^0$ **was 2nd largest background for 2018 analysis.**
- Addition of HASC2:
  - **30% less** $K^+ \to \pi^+\pi^0$
  - 18% less $K^+ \to \pi^+\pi^+\pi^-$
  - 3.5% less $K^+ \to \mu^+\nu$
- with only 1.5% signal loss.

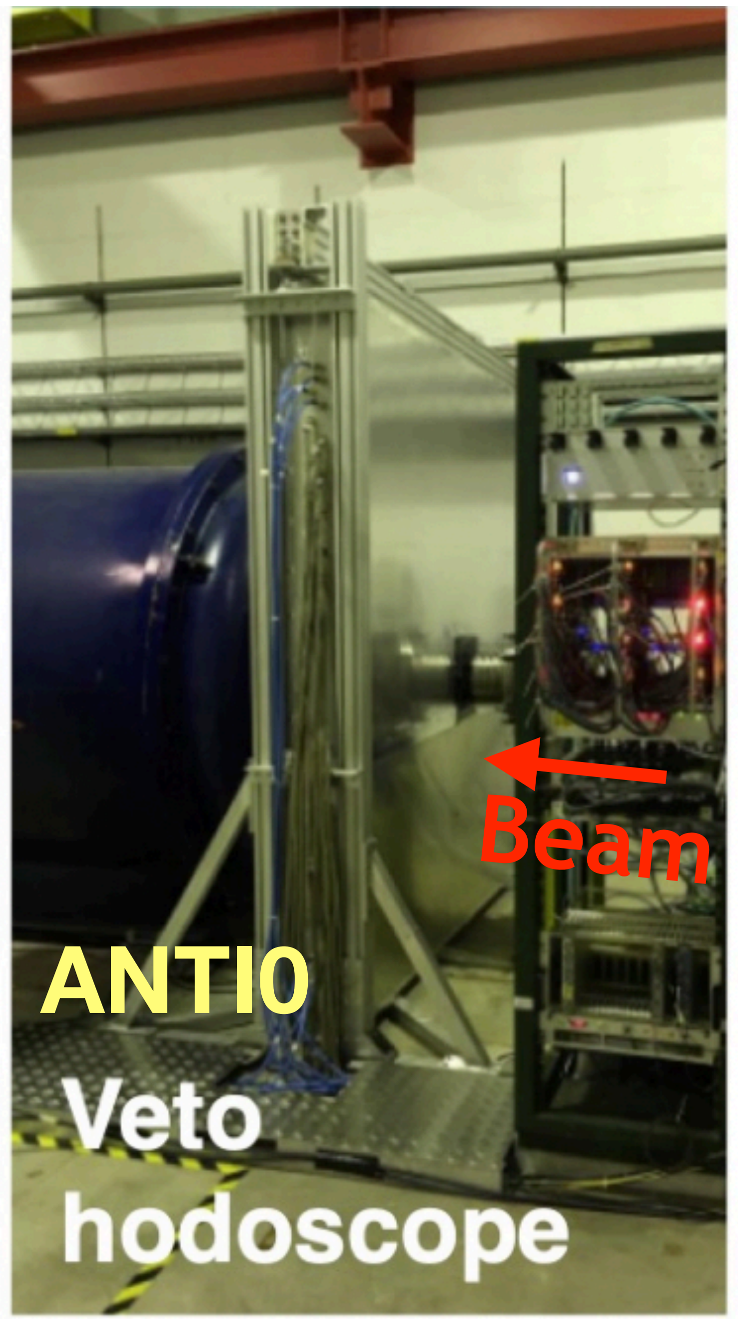


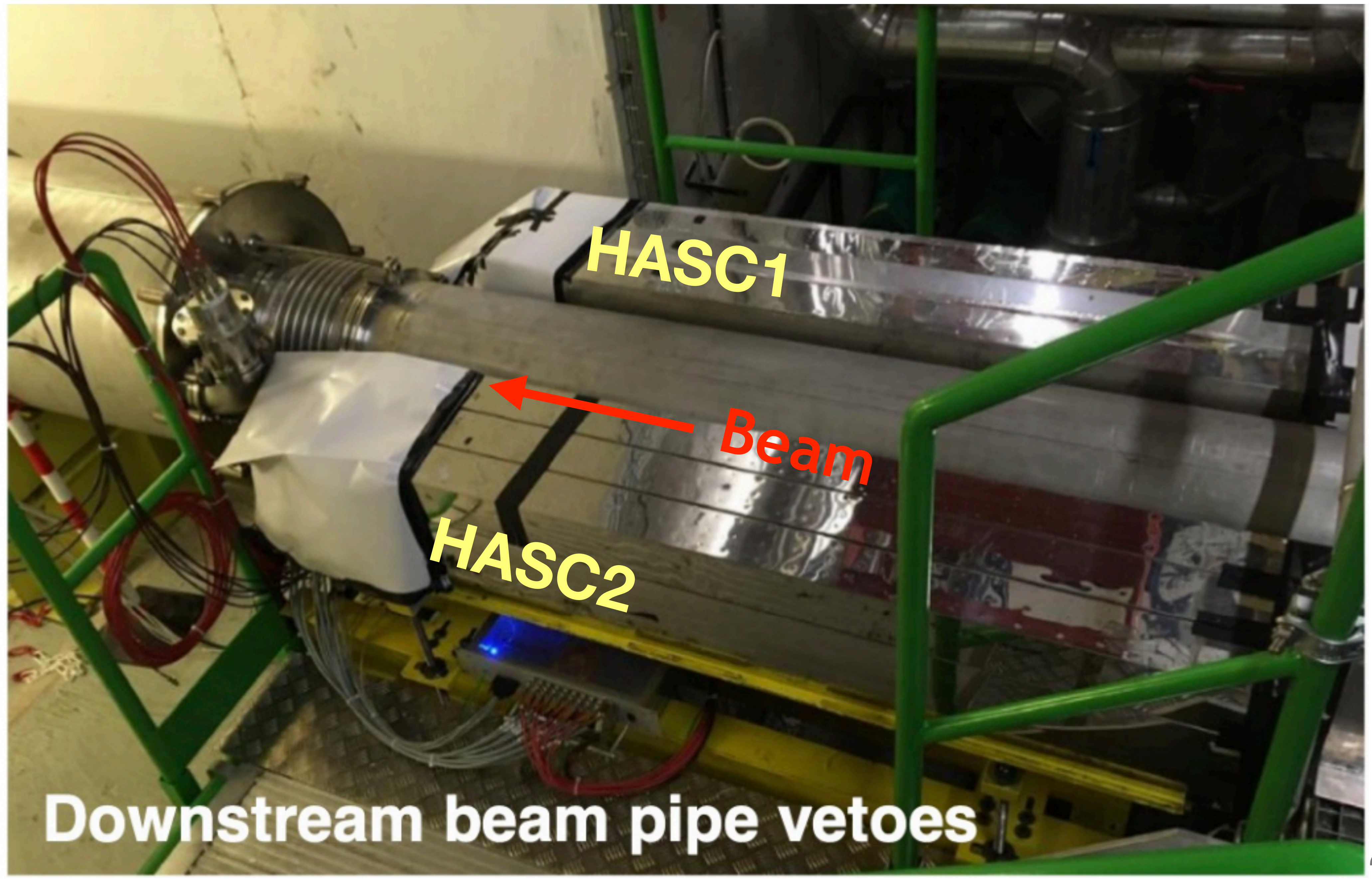
Summary of NA62 upgrades

- 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.**

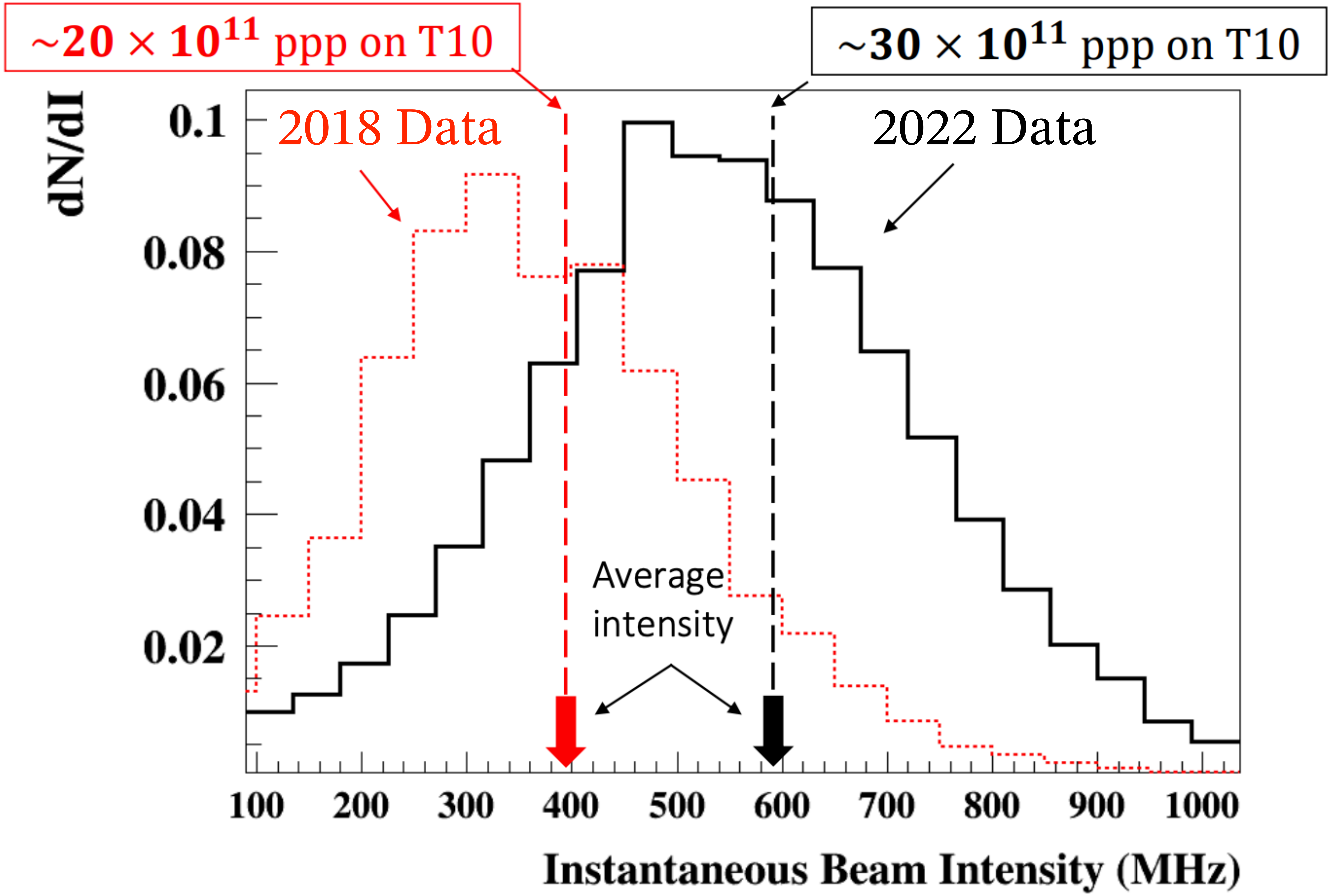
New detectors installed in 2021:







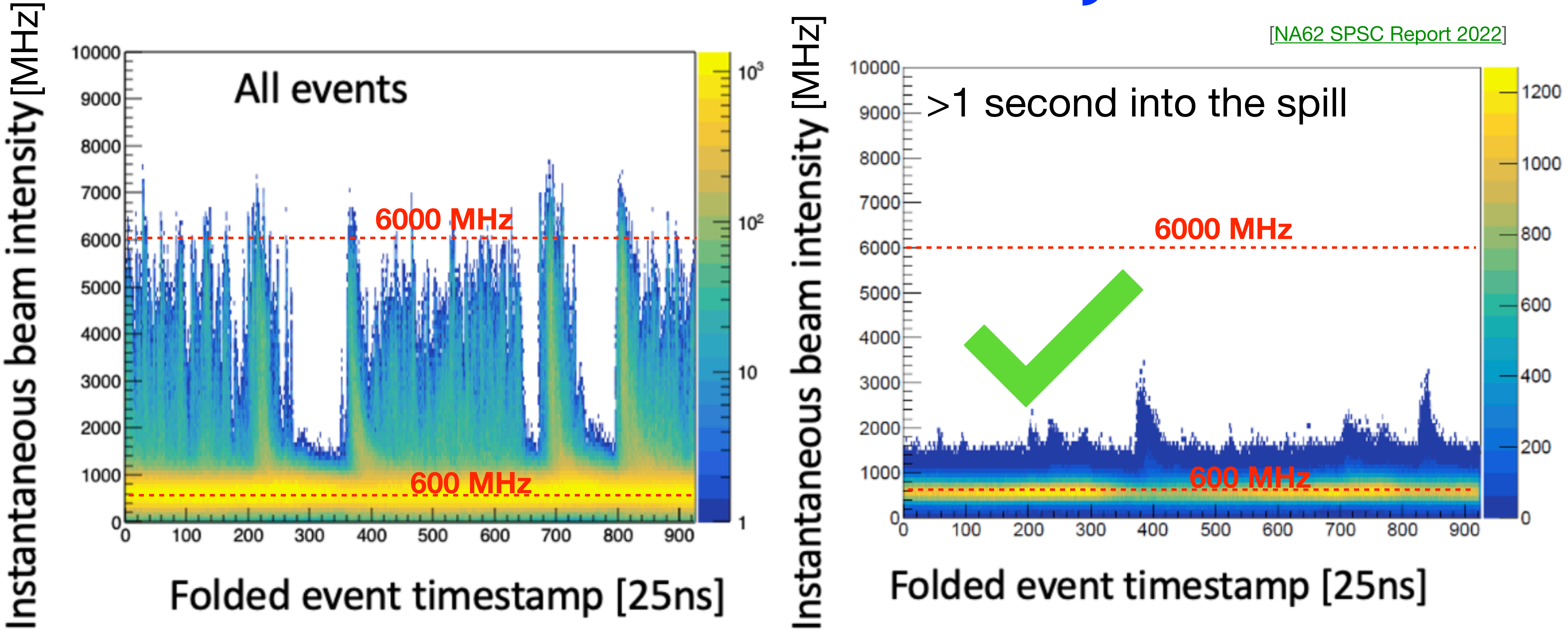
Beam intensity: 2018 vs 2022



- 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.

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

2021–2022 data : Signal Sensitivity

Analysis strategy

NA62

Triggers:

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

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

Common conditions

+ add more conditions

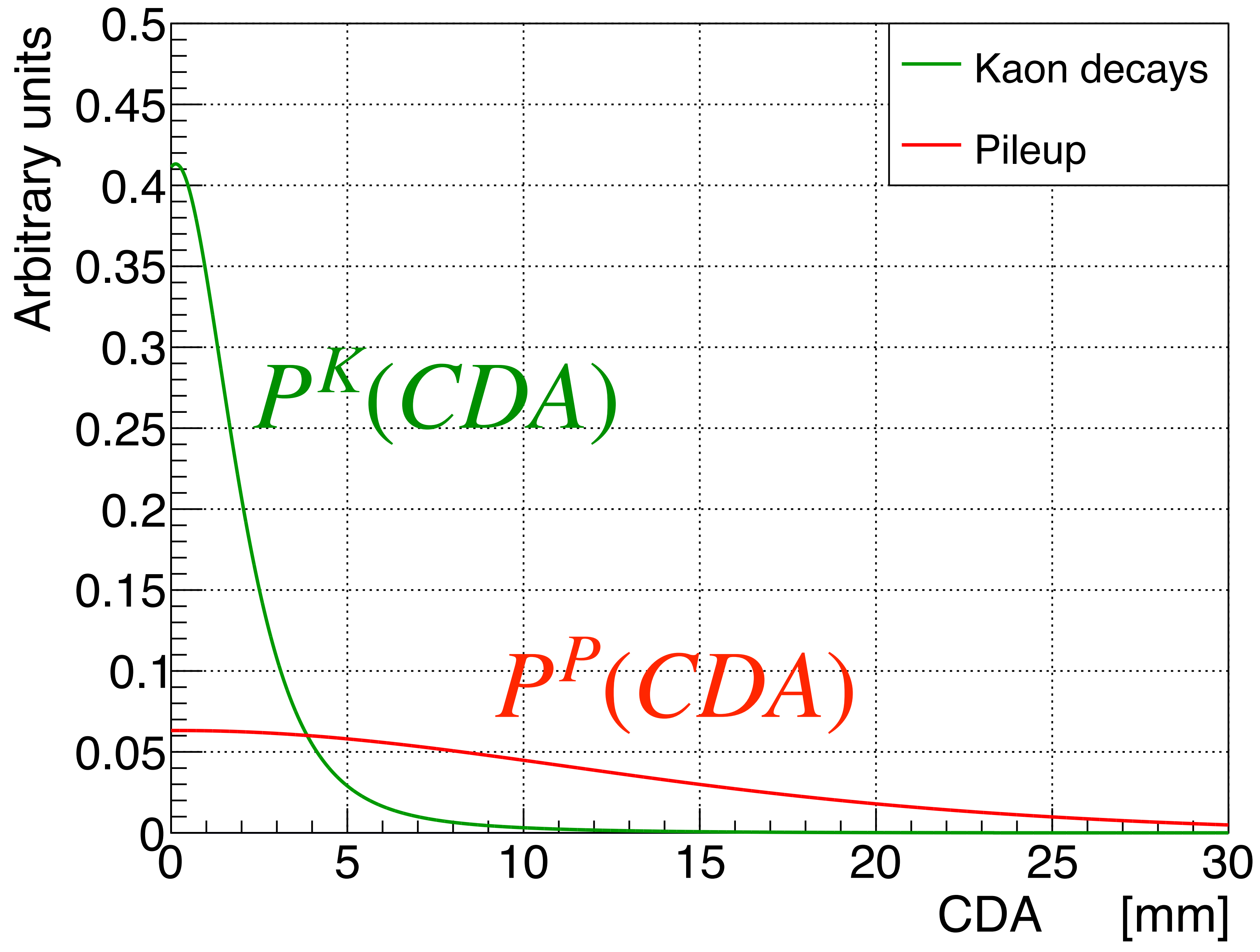
Selection:

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

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

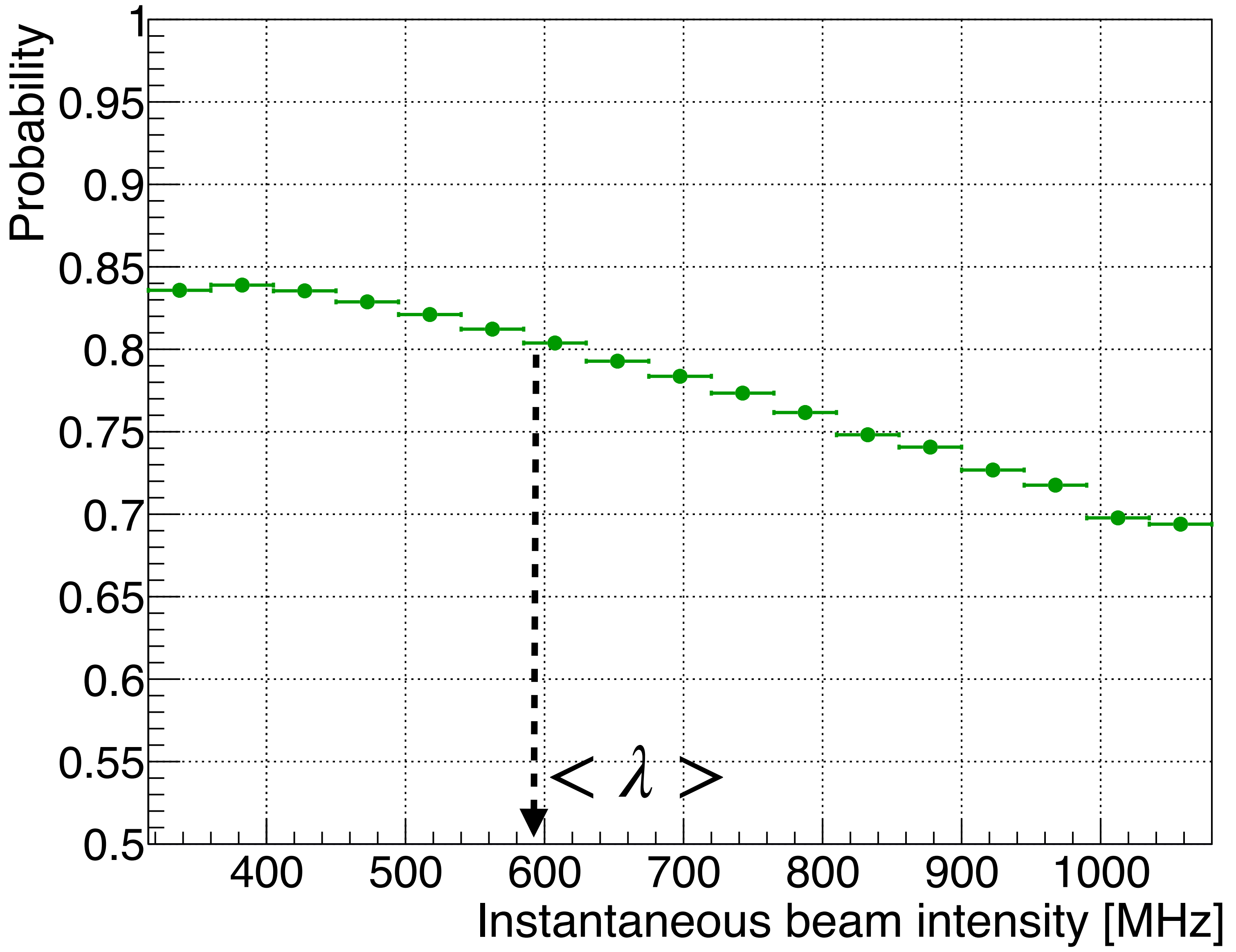
Example of selection update

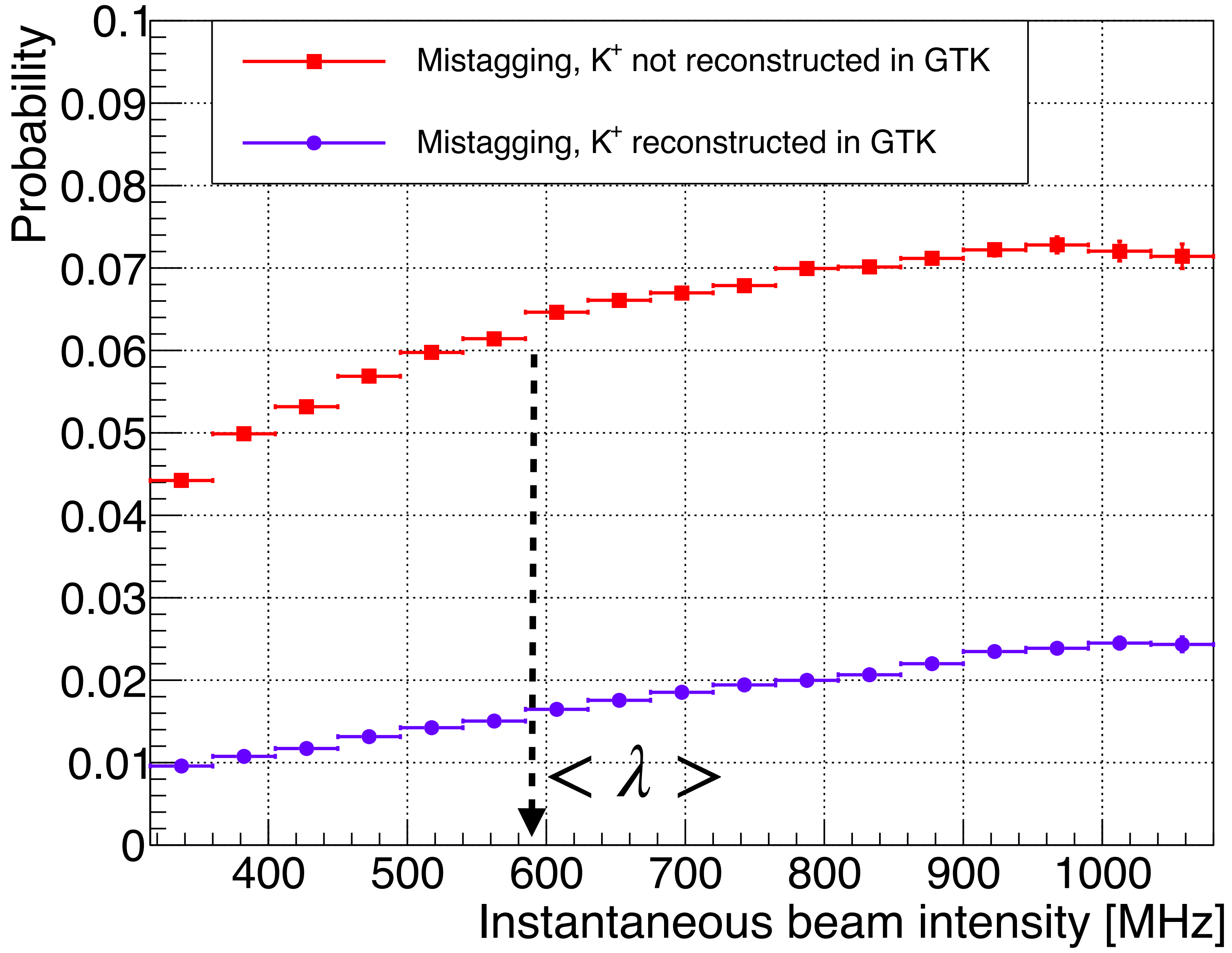
- **Inputs:** spatial (CDA) & time (ΔT_+) matching, intensity/pileup (N_{GTK}) [prior]
  - Models for PDFs/Prior from $K^+ \to \pi^+\pi^+\pi^-$ data.



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

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





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

Signal sensitivity

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

Effective number of K^+ decays, N_K:

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

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

Single event sensitivity:

(Branching ratio corresponding to expectation of 1 event)

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

- Random veto efficiency (ε_{RV})
- Trigger efficiency (ratio) (ε_{trig})
- Signal selection acceptance ($A_{\pi\nu\bar{\nu}}$)

Number of expected SM events:

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

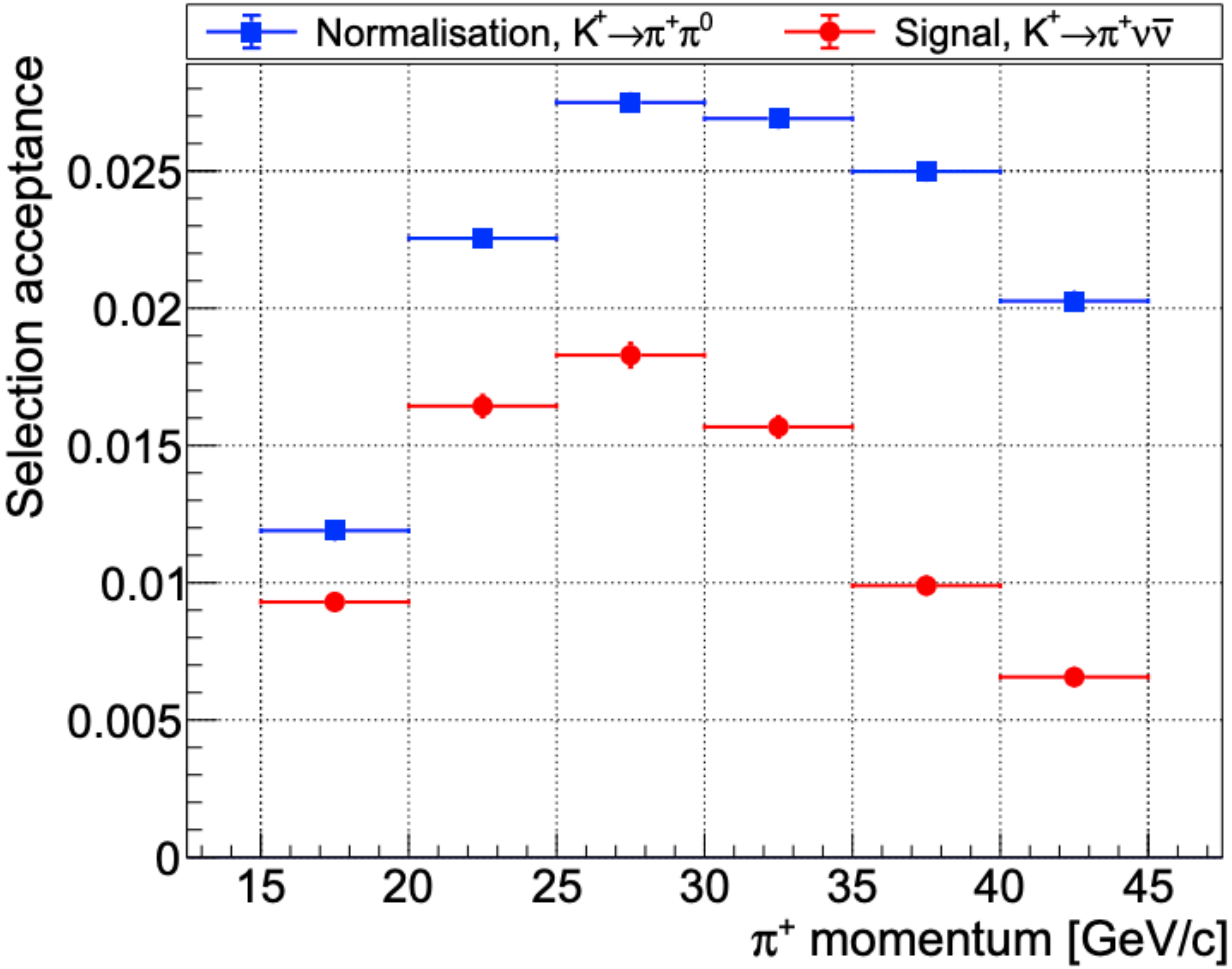
$$N^{SM}_{\pi\nu\bar{\nu}} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}}$$

Acceptances

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

Acceptances

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



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

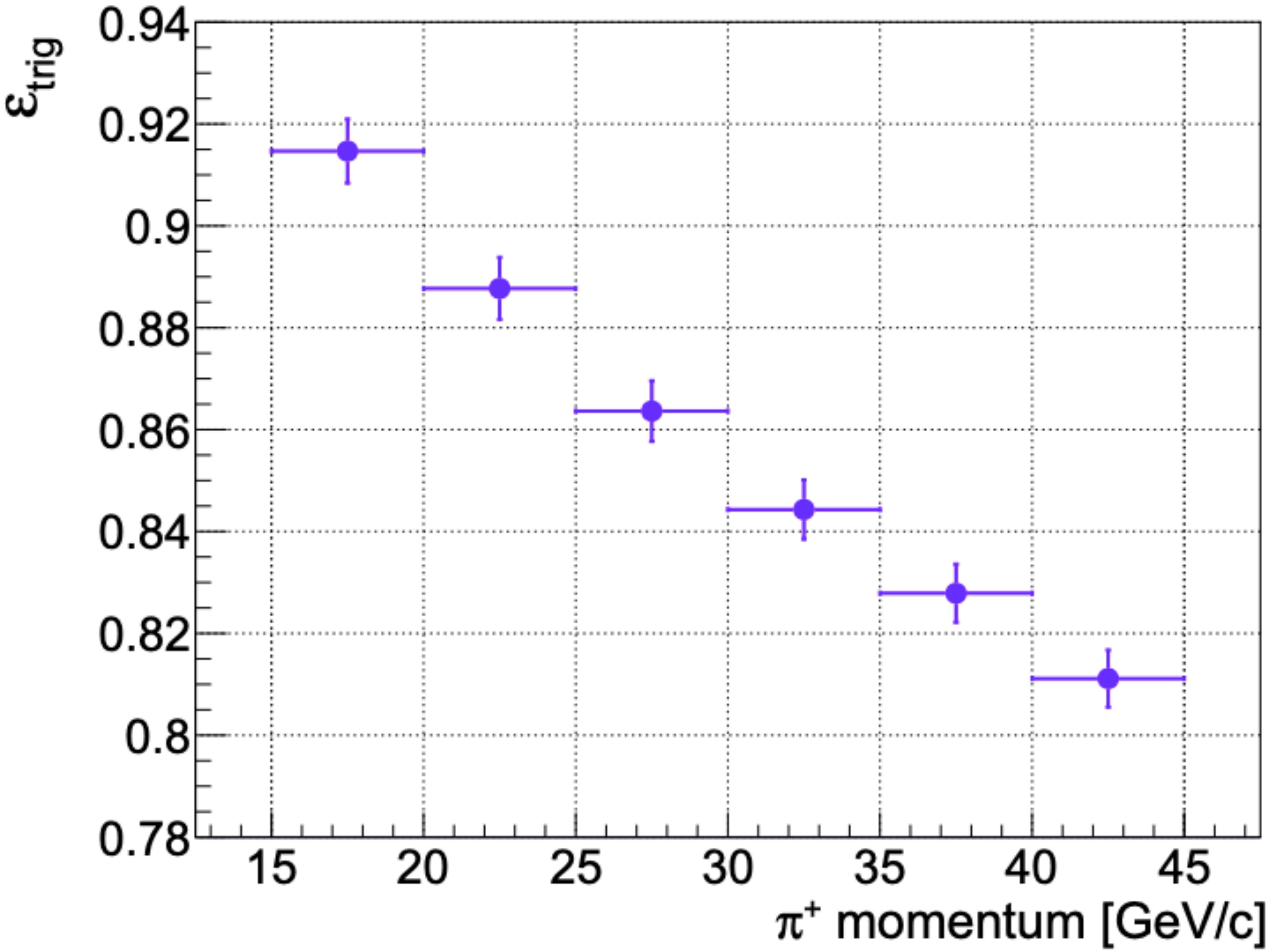
- Increased selection efficiencies.
  - New K-pi matching technique.
  - Re-tuned vertex conditions.
  - Relaxation of some vetos.
- Improved precision (plus improved systematic uncertainty evaluation).

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

Trigger efficiencies

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

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



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

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

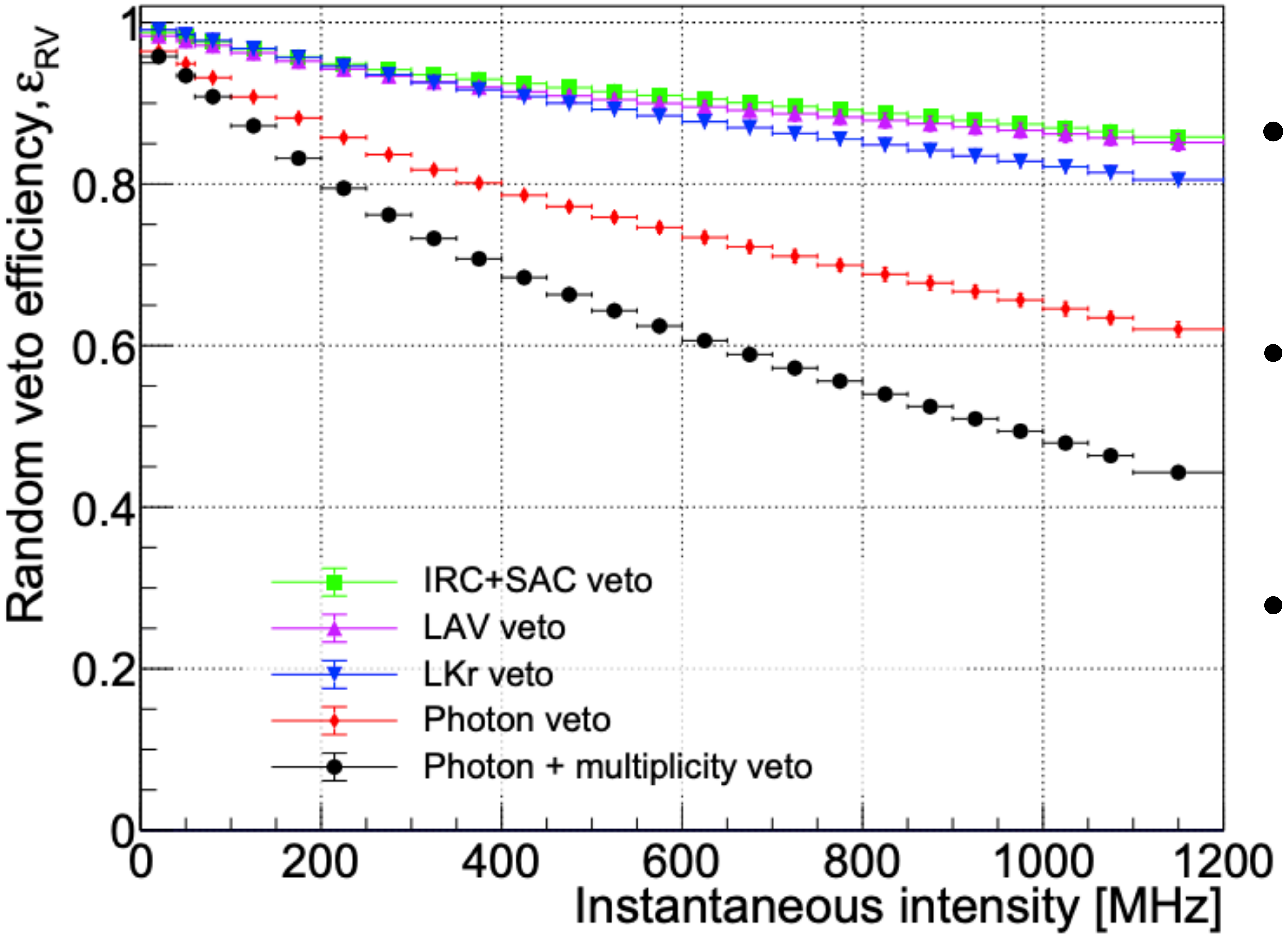
$\varepsilon_{trig}(2018) = (89 \pm 5)\,\%$

- 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.

Random veto

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

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



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

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

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

Signal sensitivity results

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

- Display integrals (15—45 GeV/c, 2021+22) for summary tables.

* Acceptances evaluated at 0 intensity.

	Factor	Value
$N_{\pi\pi}^{\rm eff}$	Effective number of normalisation events	$(1.953 \pm 0.005) \times 10^8$
$A_{\pi\pi}$	Normalisation acceptance	$(13.410 \pm 0.005)\%$
N_K	Effective number of K^+ decays	$(2.85 \pm 0.01) \times 10^{12}$
$A_{\pi\nu\bar{\nu}}$	Signal acceptance	$(7.62 \pm 0.22)\%$
$\varepsilon_{\rm trig}$	Trigger efficiency ratio	$(85.9 \pm 1.4)\%$
$\varepsilon_{\rm RV}$	Random veto efficiency	$(63.2 \pm 0.6)\%$
$\mathcal{B}_{\rm SES}$	Single event sensitivity	$(8.48 \pm 0.29) \times 10^{-12}$
$N_{\pi\nu\bar{\nu}}^{\rm SM}$	Number of expected SM $K^+ \to \pi^+\nu\bar{\nu}$ events	9.91 ± 0.34

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

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

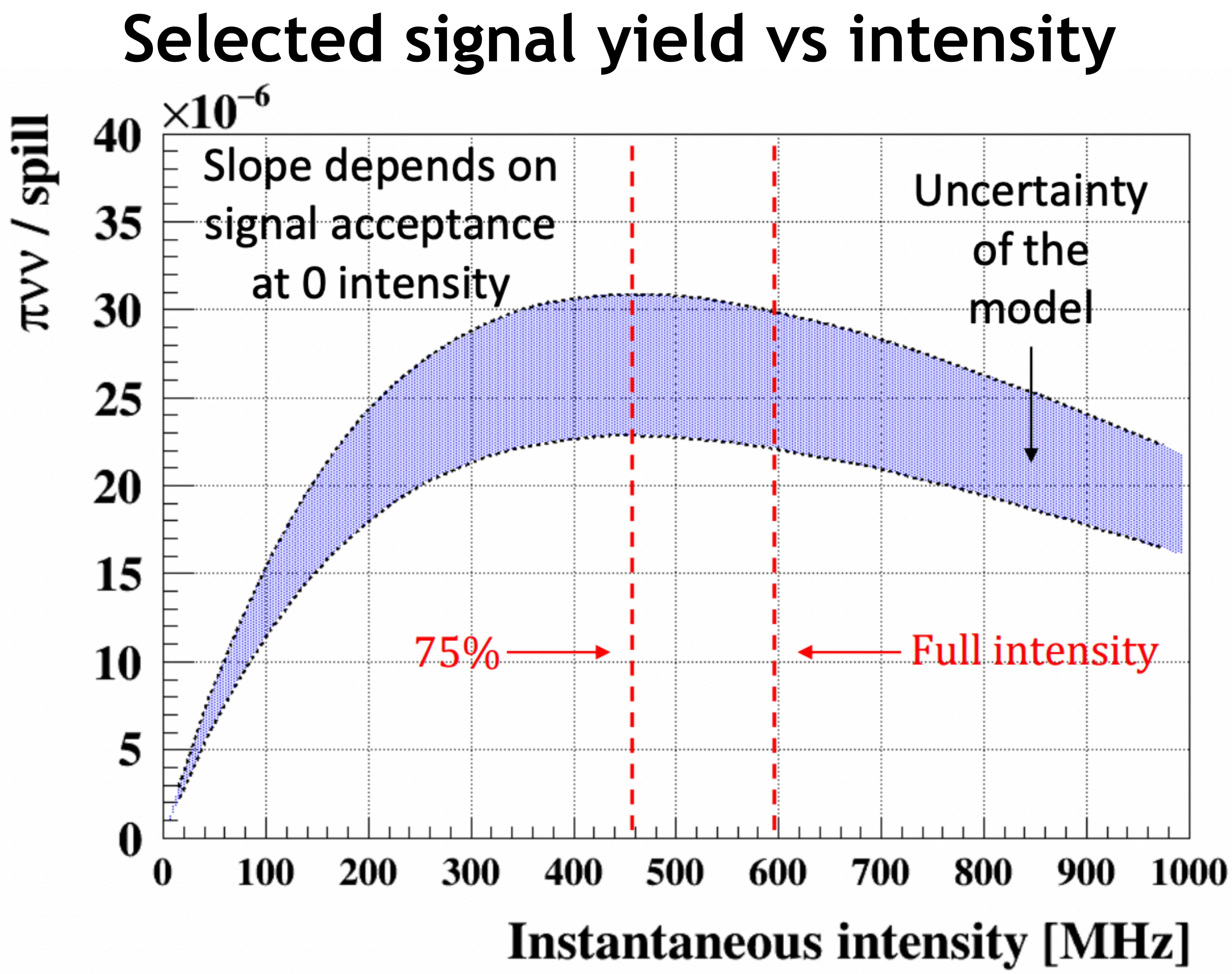
2021—22: $N_{\pi\nu\bar{\nu}} = 9.91 \pm 0.29$

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

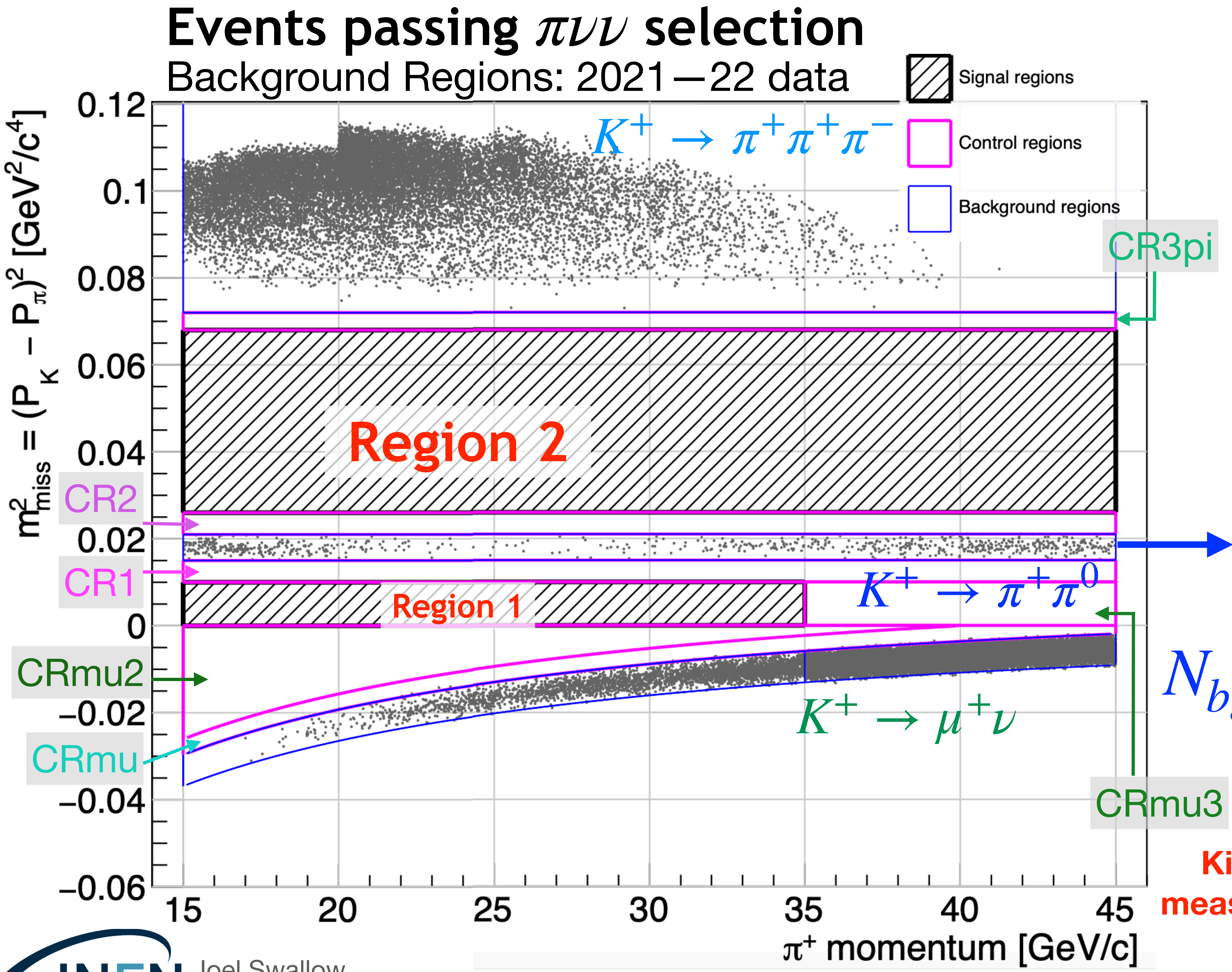


- Saturation of expected signal yield with intensity. Mainly due to:
  - Paralyzable effects from TDAQ dead time and trigger veto windows.
  - Offline selection, due to veto conditions.
- Main sources of uncertainty for model:
  - Online time-dependent mis-calibrations.
  - Fit uncertainty.
- **From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

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

2021—2022 data : Background Evaluation

Background regions & background estimations



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

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

Number of events passing signal selection in background region

Kinematic tail fraction: measured in control sample

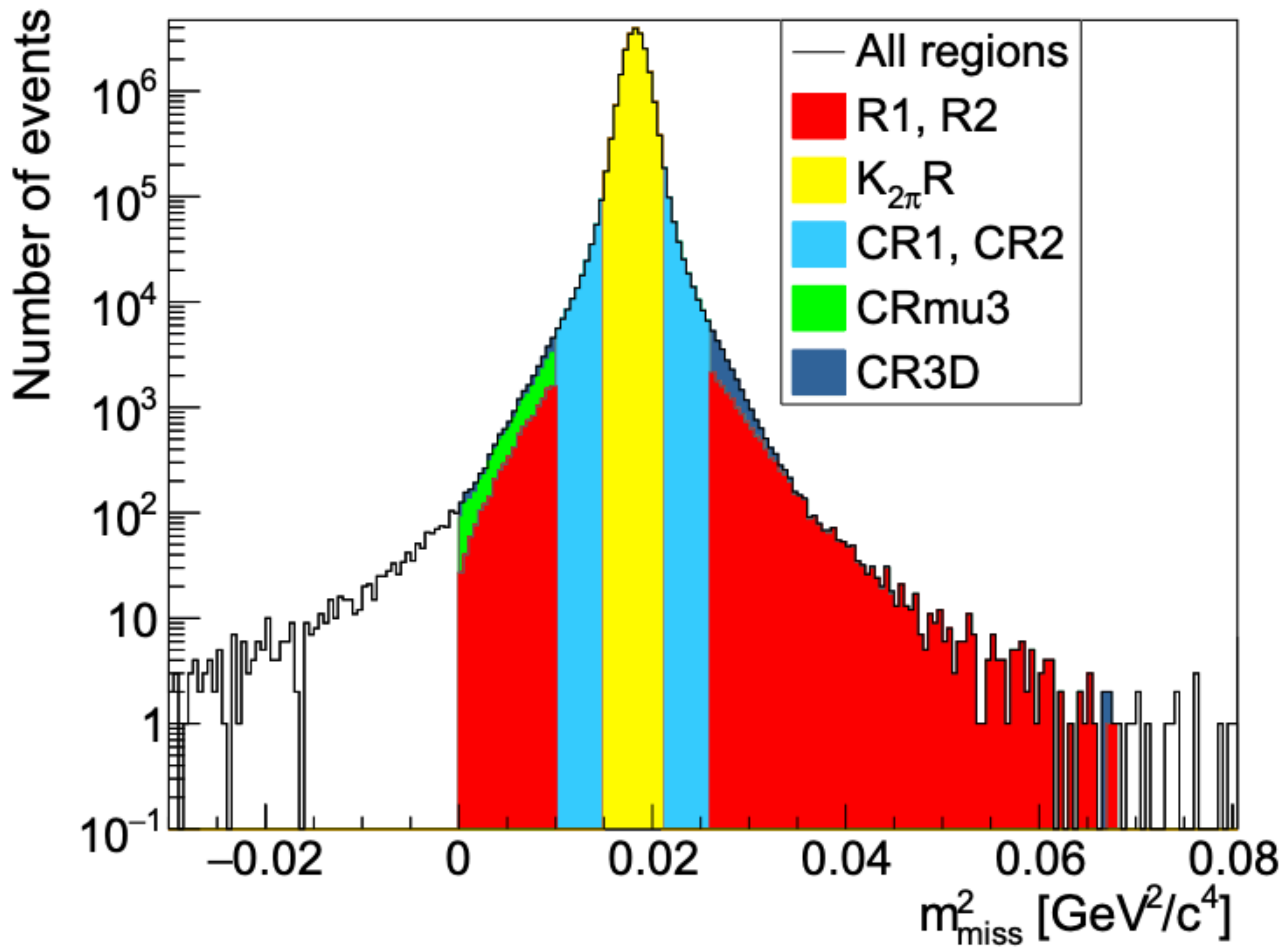
Control sample events in Signal Regions

Control sample events in Background Region

Backgrounds from kinematic tails

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

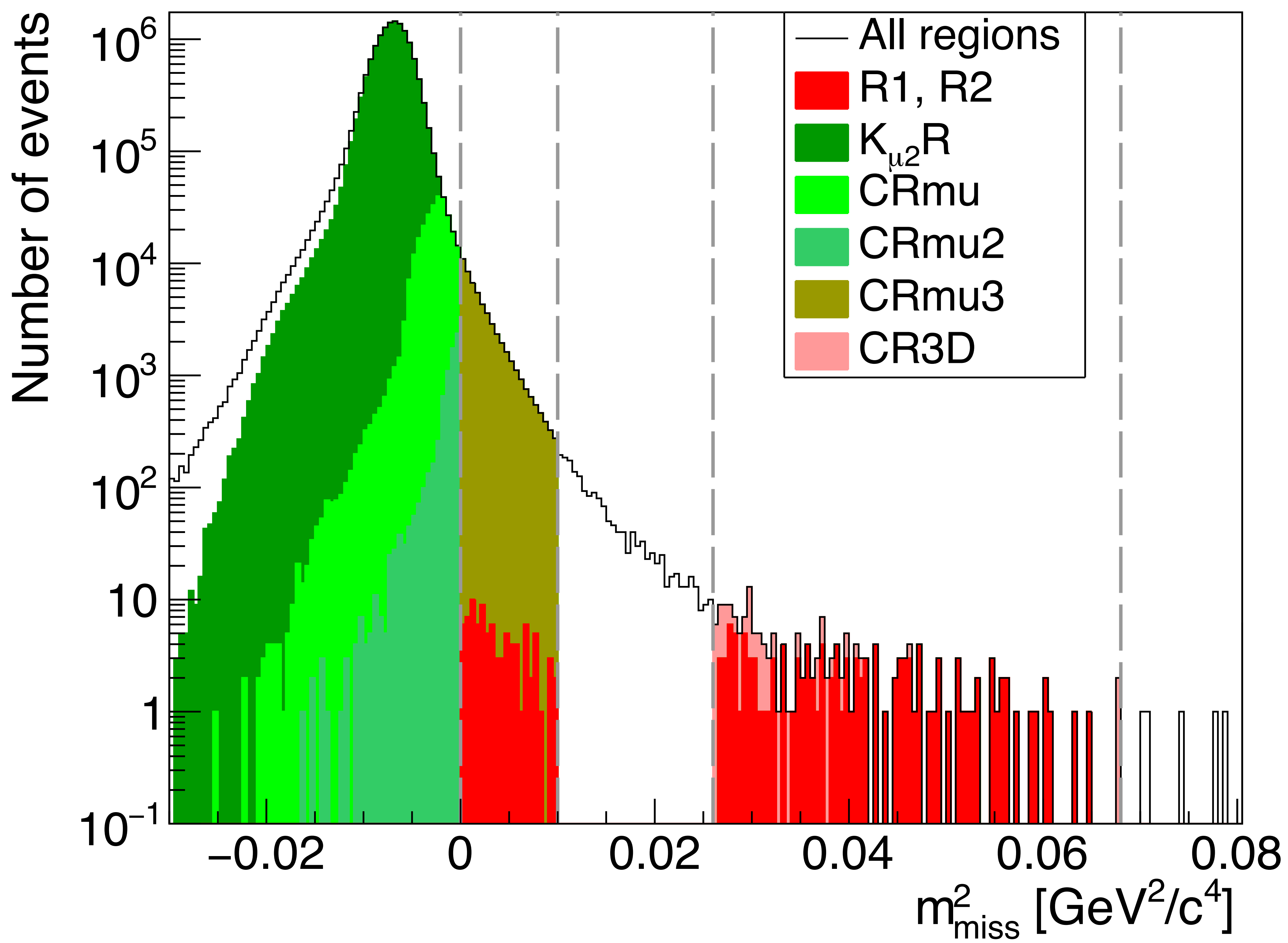
control sample of $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ and 2 photons detected in LKr:



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

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

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



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

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

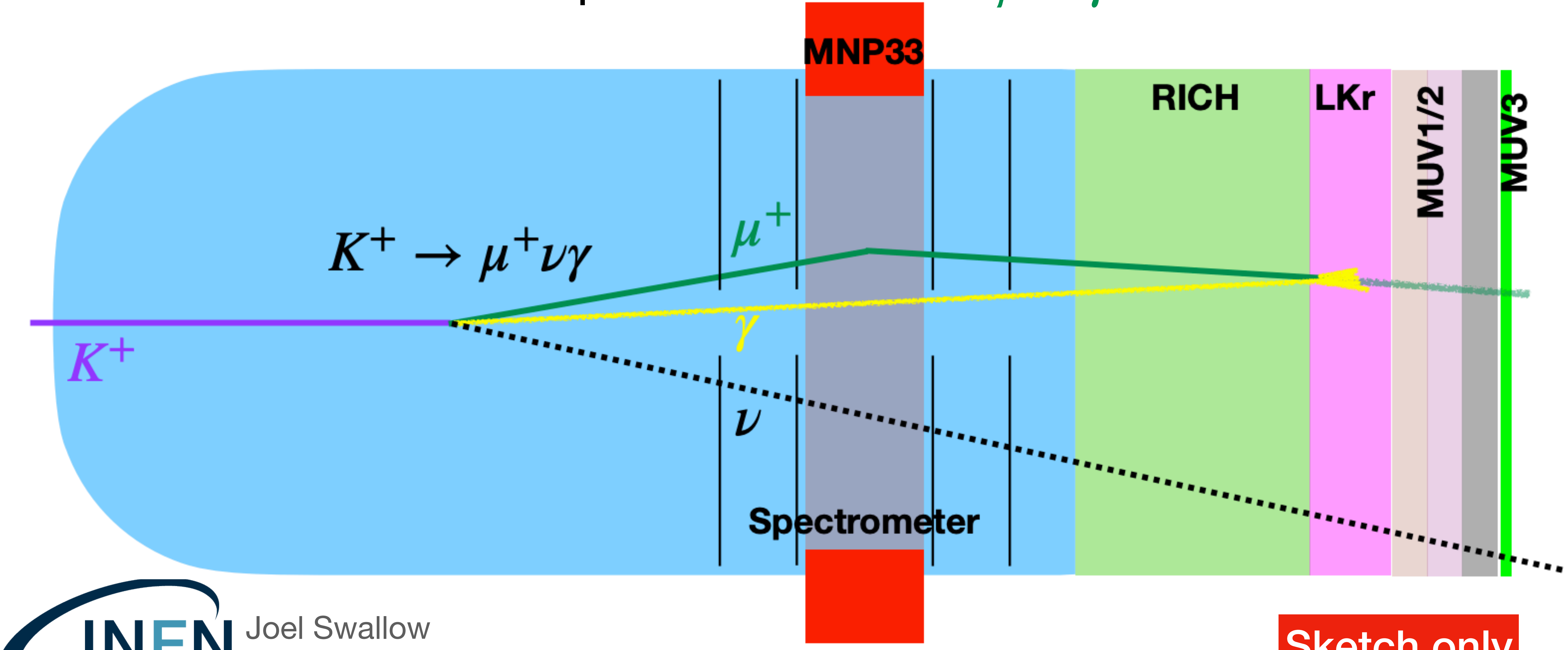
$K^+ \to \pi^+\pi^+\pi^-$

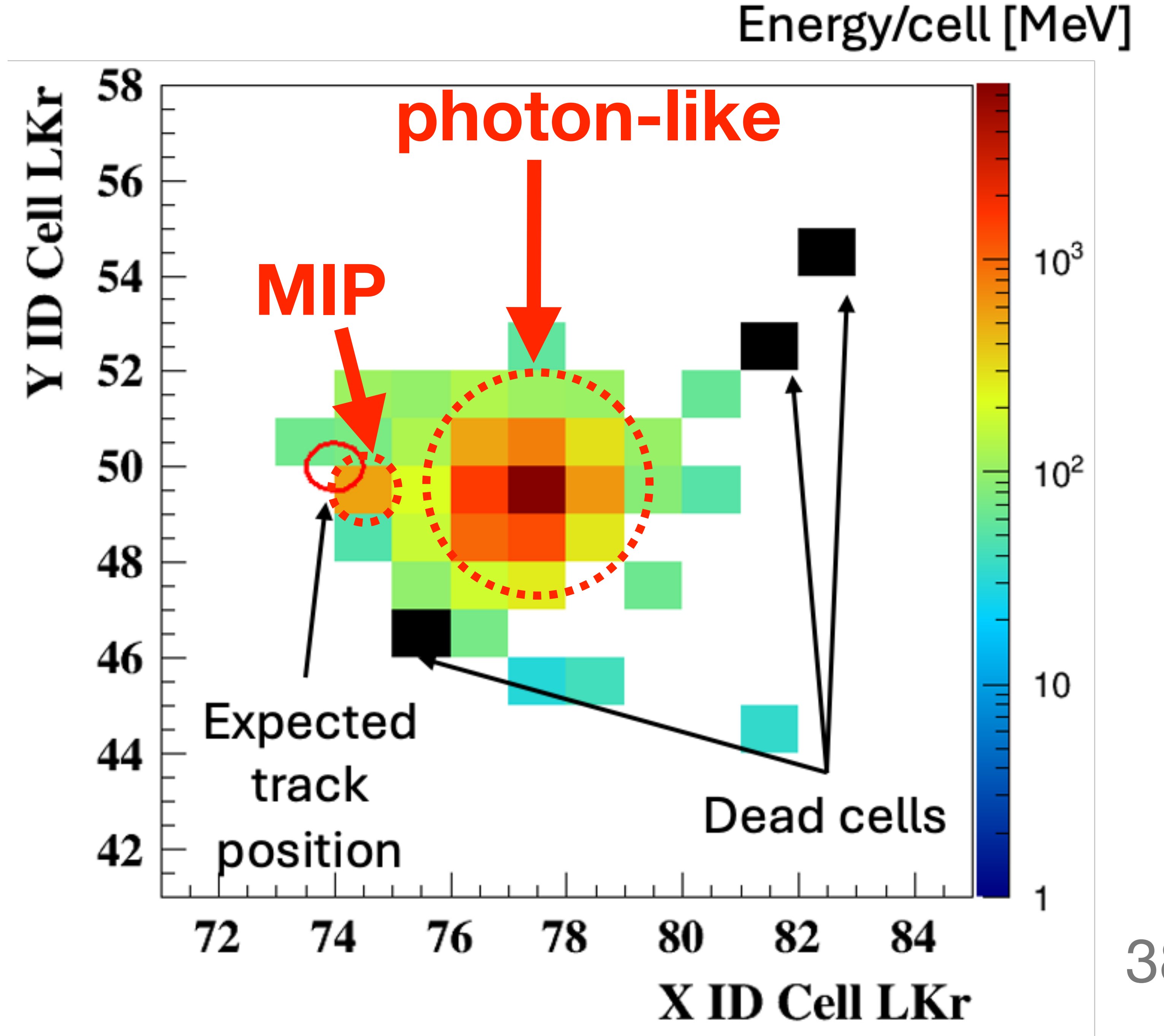
- Use MC to measure f_{tail}:

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

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

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

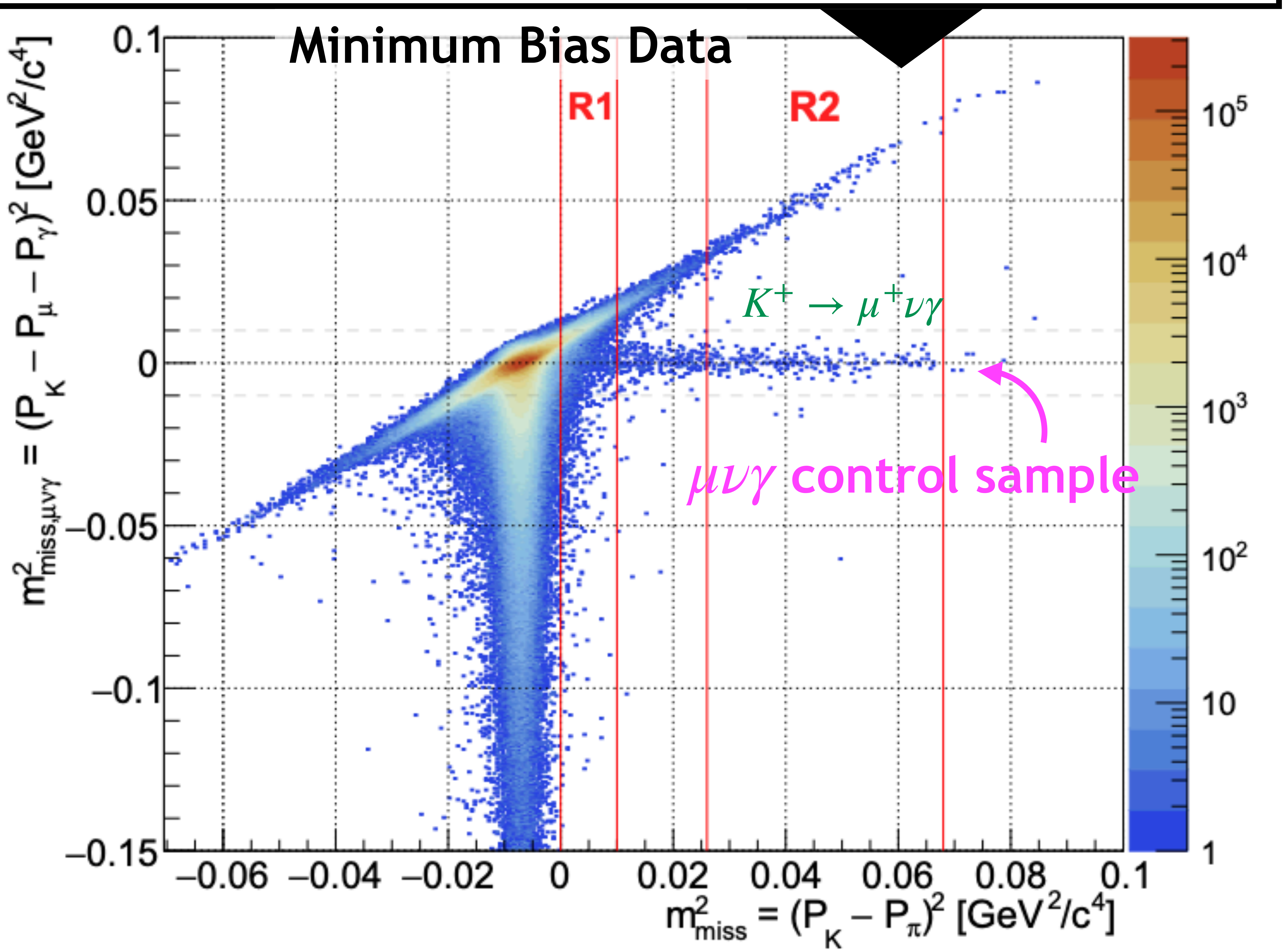




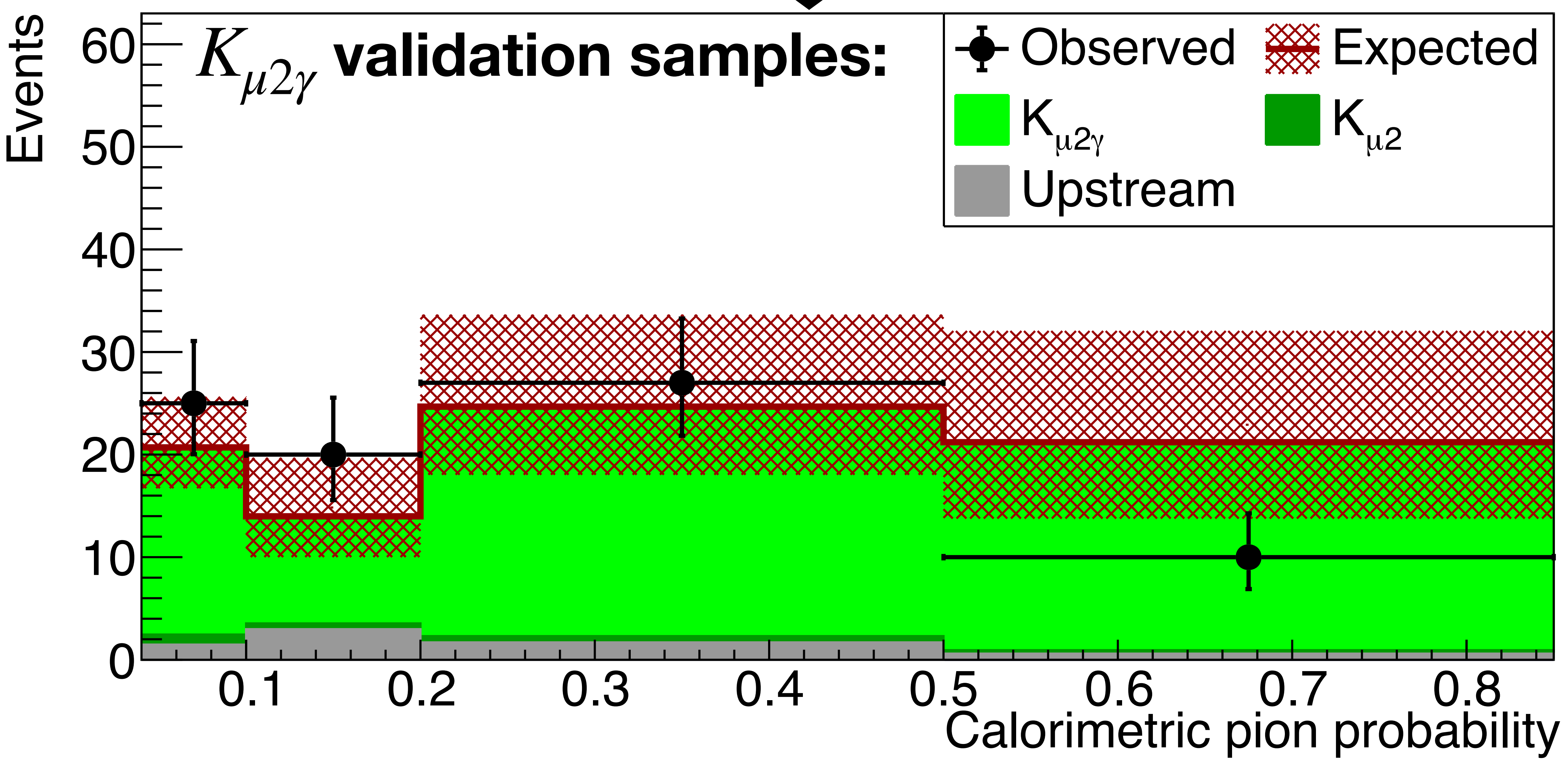
$K^+ \to \mu^+\nu\gamma$ Background

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

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



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



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

Other backgrounds

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

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

Branching ratio of K_{e4} (from PDG)

$$N_{bg}(K^+ \rightarrow \pi^+\pi^-e^+\nu) = 0.89^{+0.33}_{-0.27}$$

- $K^+ \rightarrow \pi^0\ell^+\nu$ and $K^+ \rightarrow \pi^+\gamma\gamma$:
  - 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 — 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

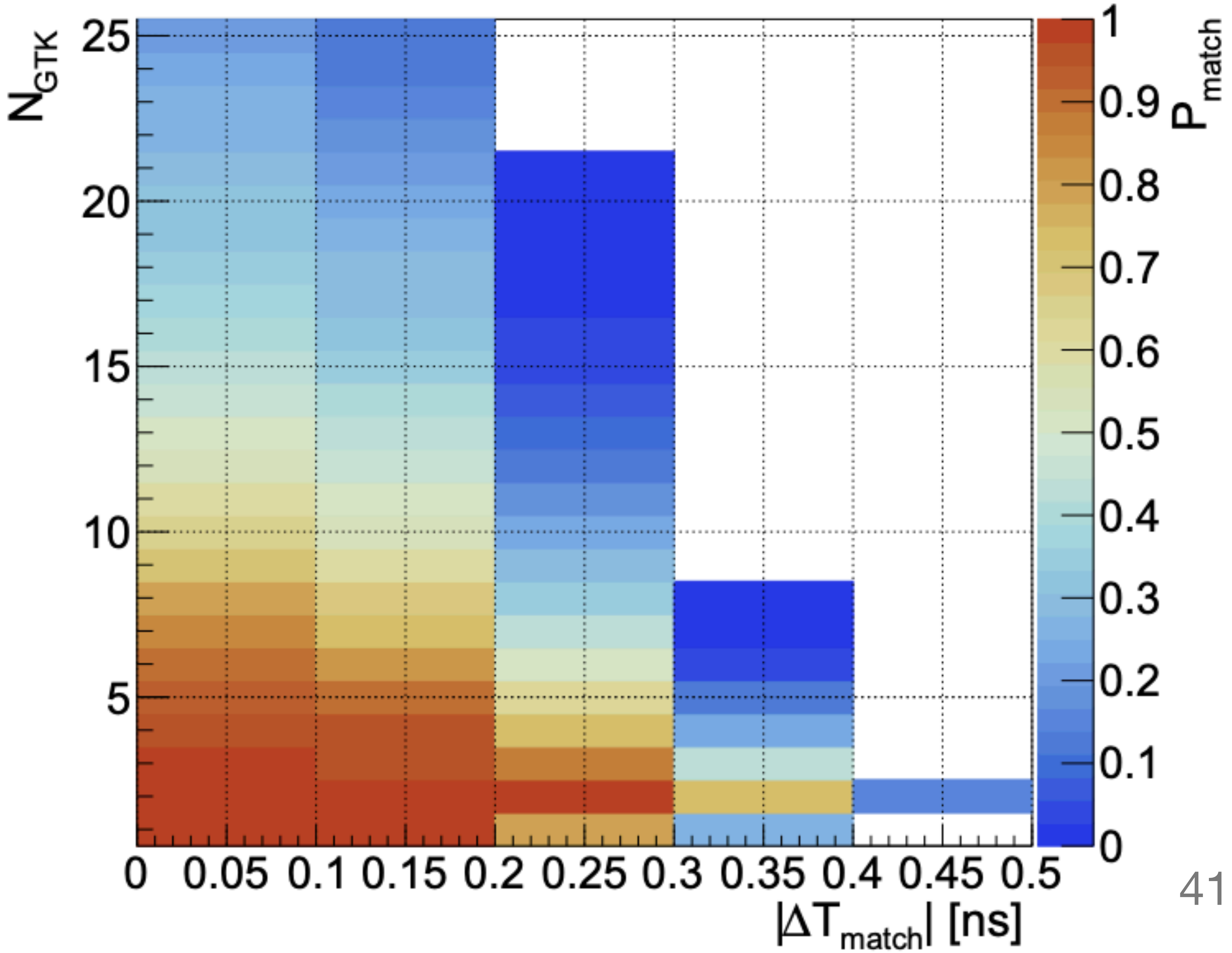
Calculate using bins (i) of $(\Delta T_+, N_{GTK})$

[Updated to fully data-driven procedure]

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

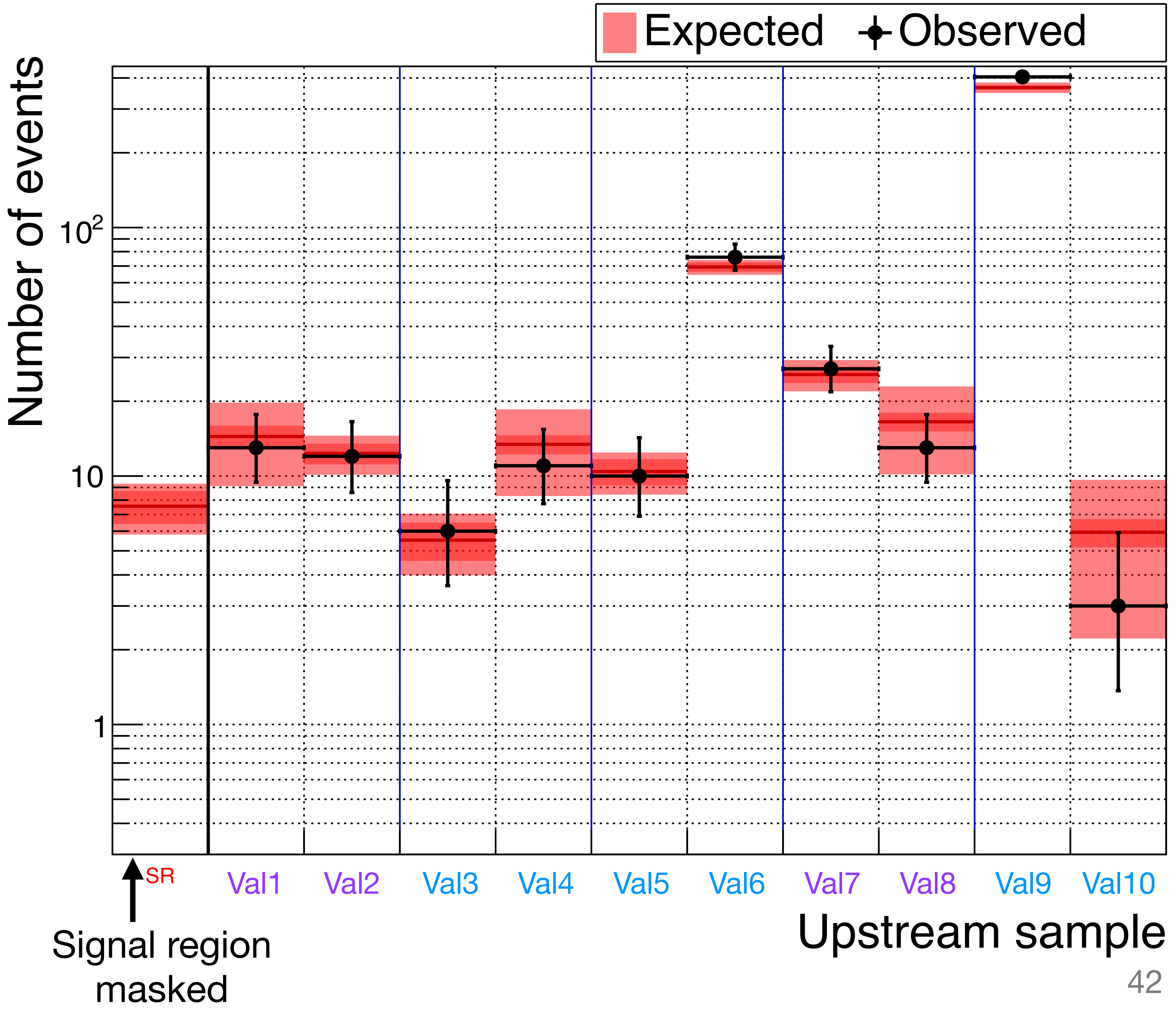
$$N_{bg}(\text{Upstream}) = 7.4^{+2.1}_{-1.8}$$

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



Summary of expectations

Backgrounds

Background	Events
$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89^{+0.33}_{-0.27}$
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
$K^+ \to \pi^0\ell^+\nu$	< 0.001
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.0^{+2.1}_{-1.9}$

Signal Sensitivity

$$\mathcal{B}_{SES} = (8.5 \pm 0.3) \times 10^{-12}$$

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

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

2021–22: $N_{\pi\nu\bar{\nu}} = 9.91 \pm 0.34$

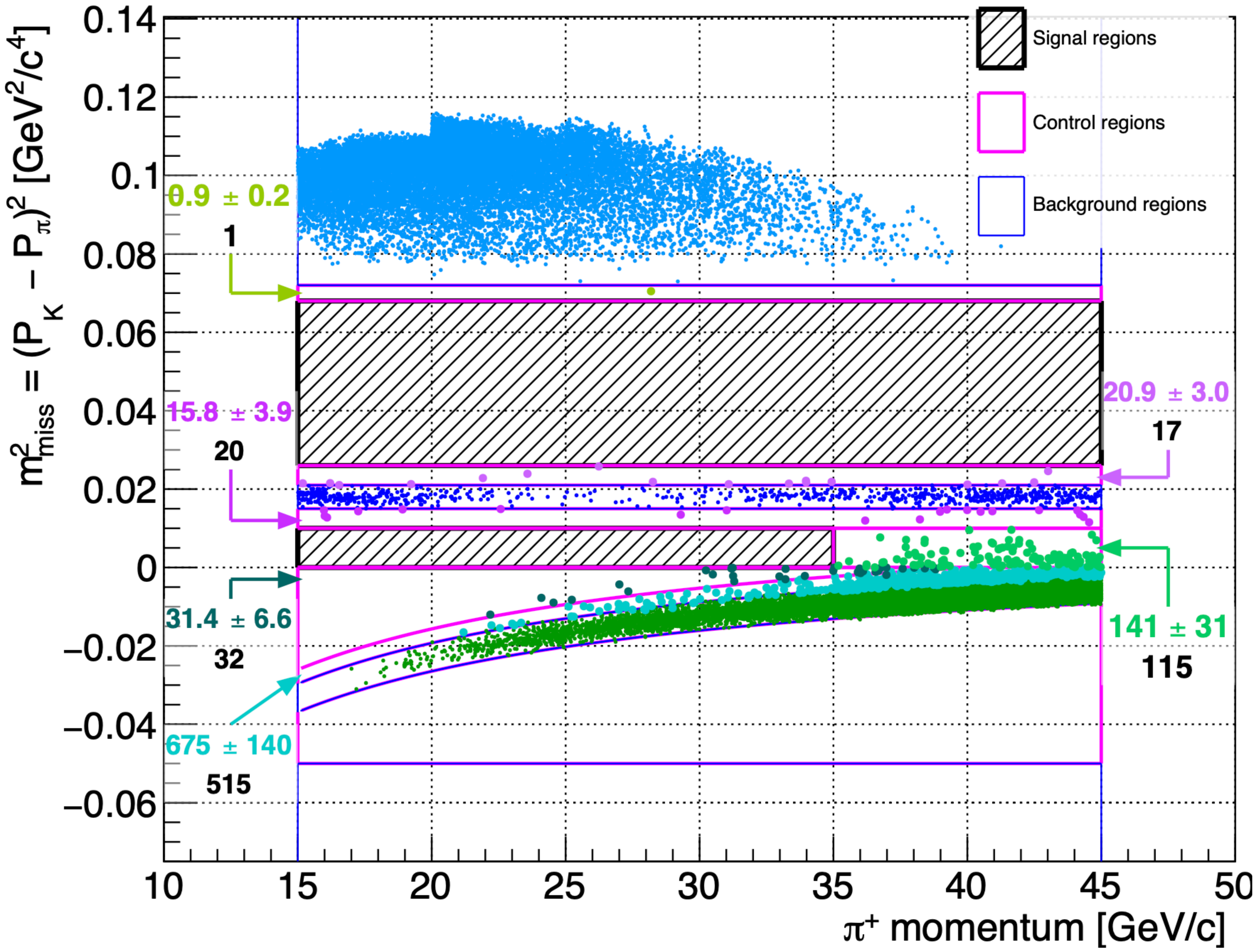
c.f. 2016–18 : $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

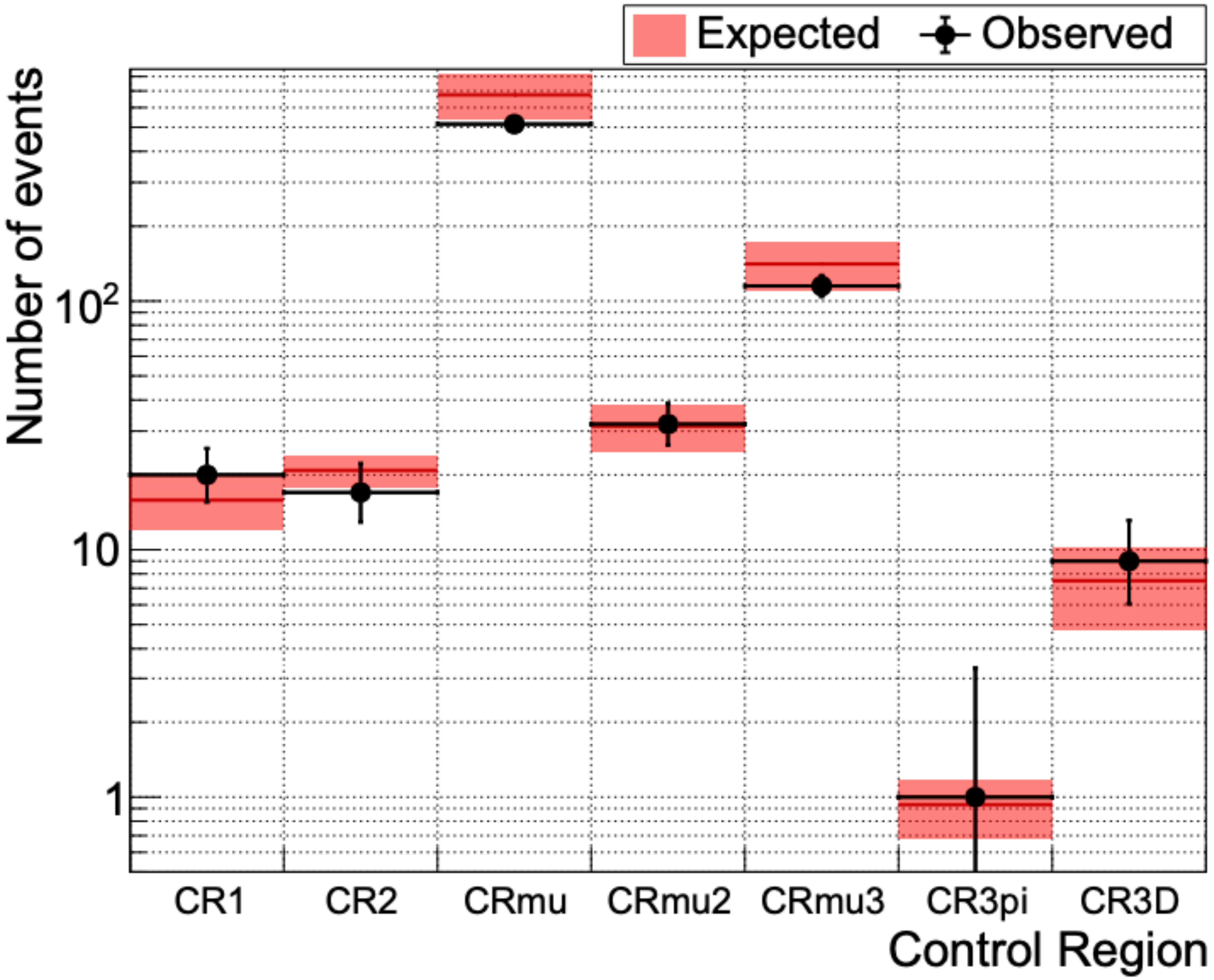
→ Expected signal doubled by including 2021–22 data

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

Control regions

2021—22 data



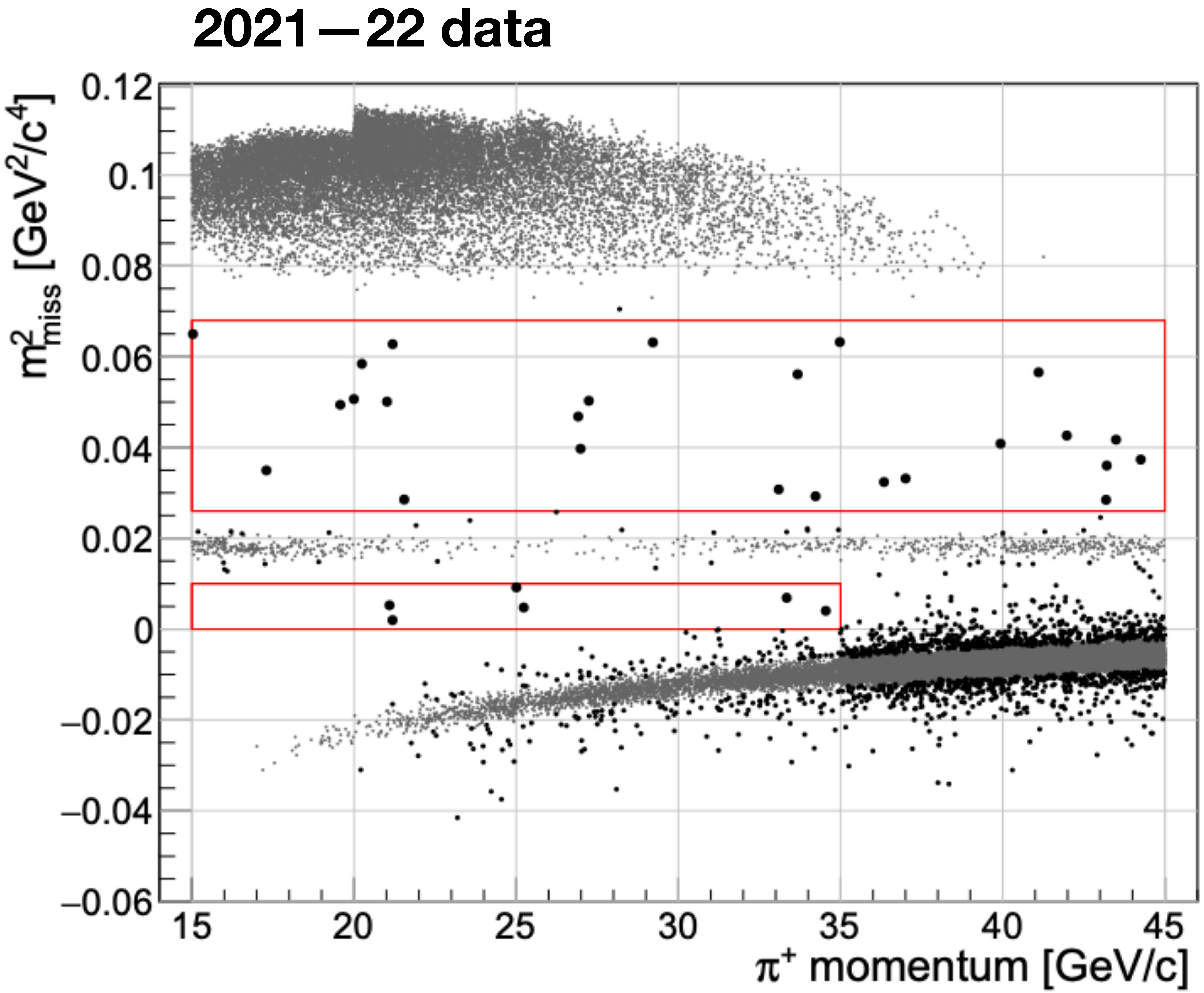


- Good agreement in control regions validates background expectations.

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

2021—2022 data

Signal regions

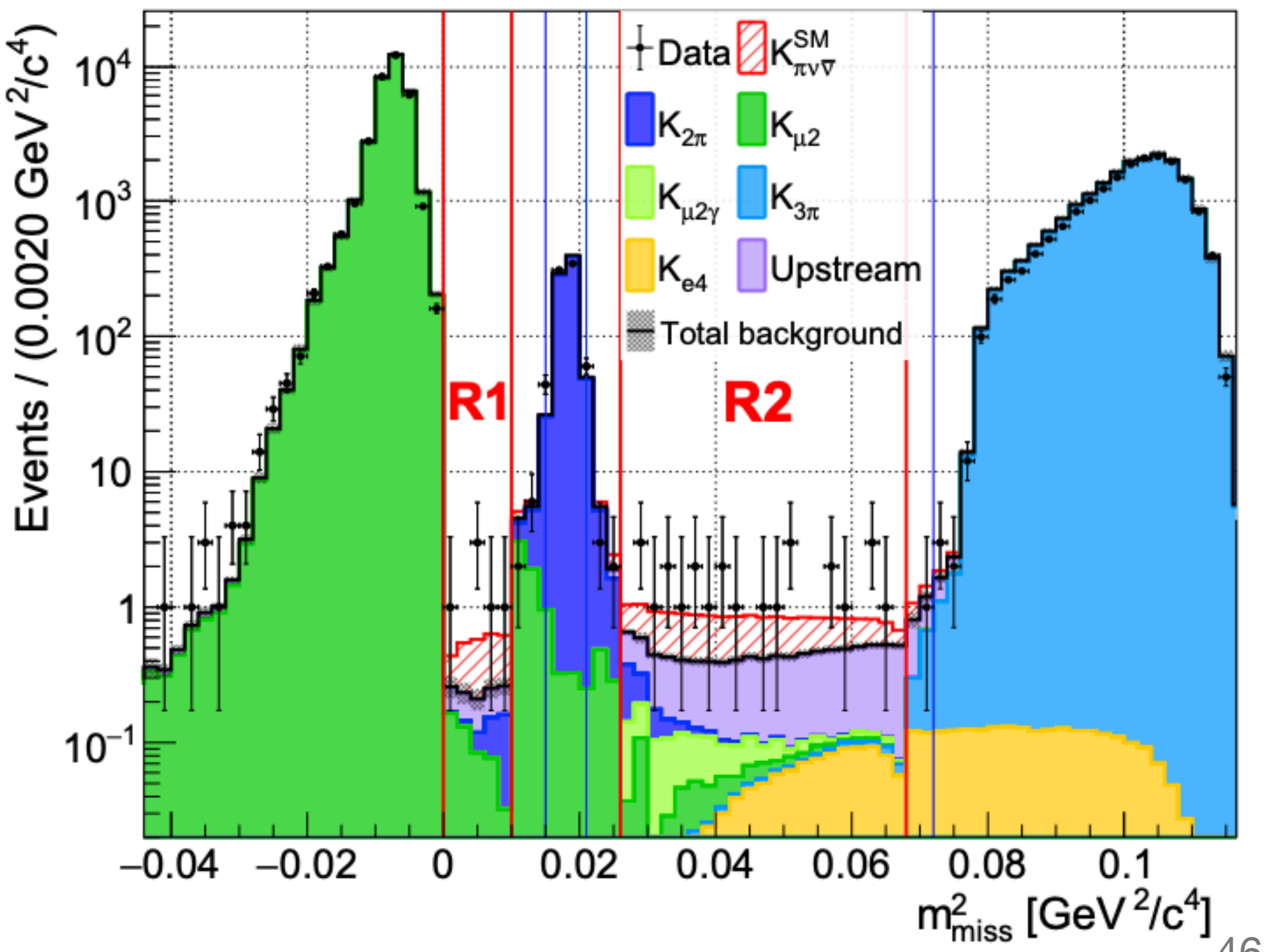


Expected SM signal, $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

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

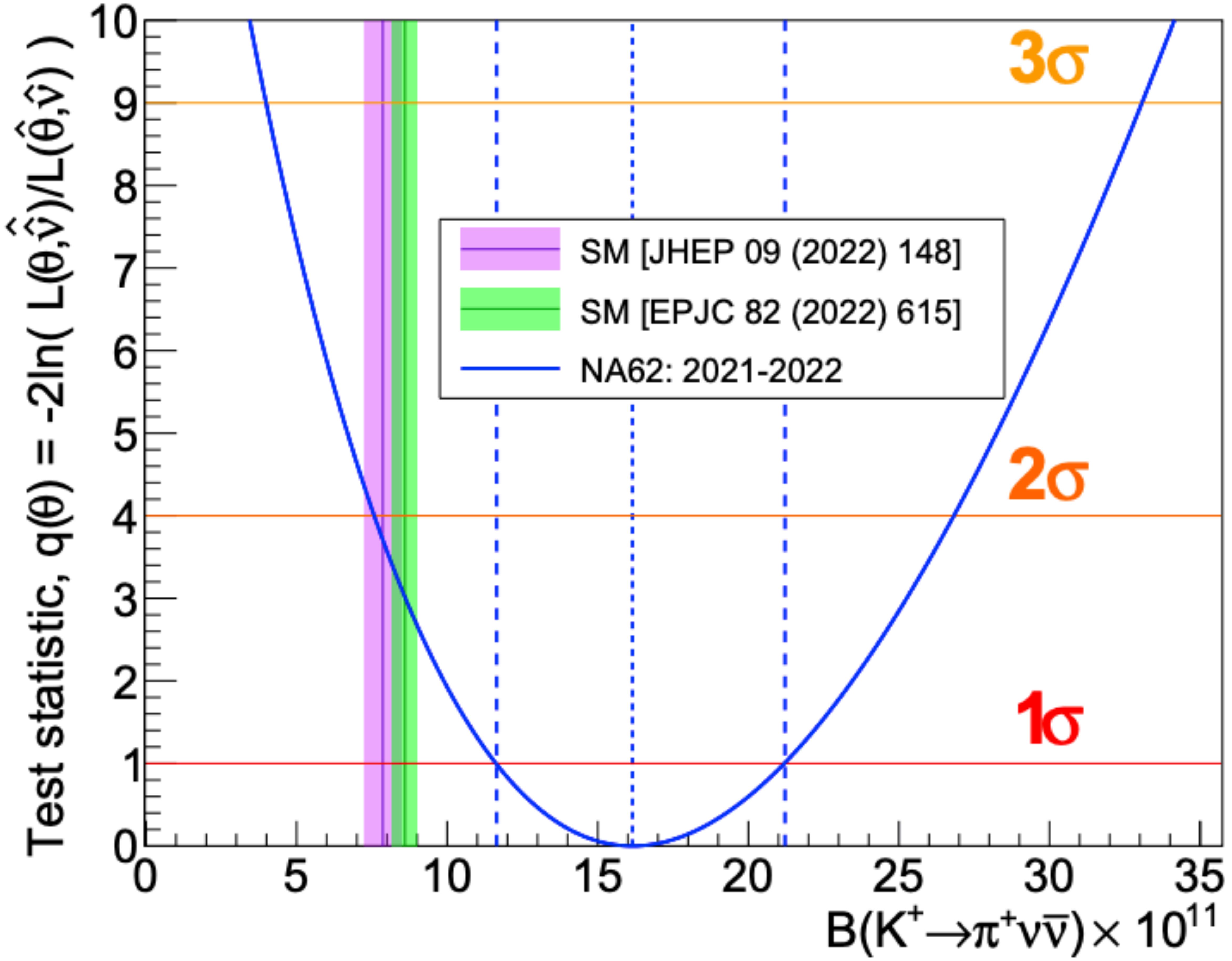
Observed, $N_{obs} = 31$

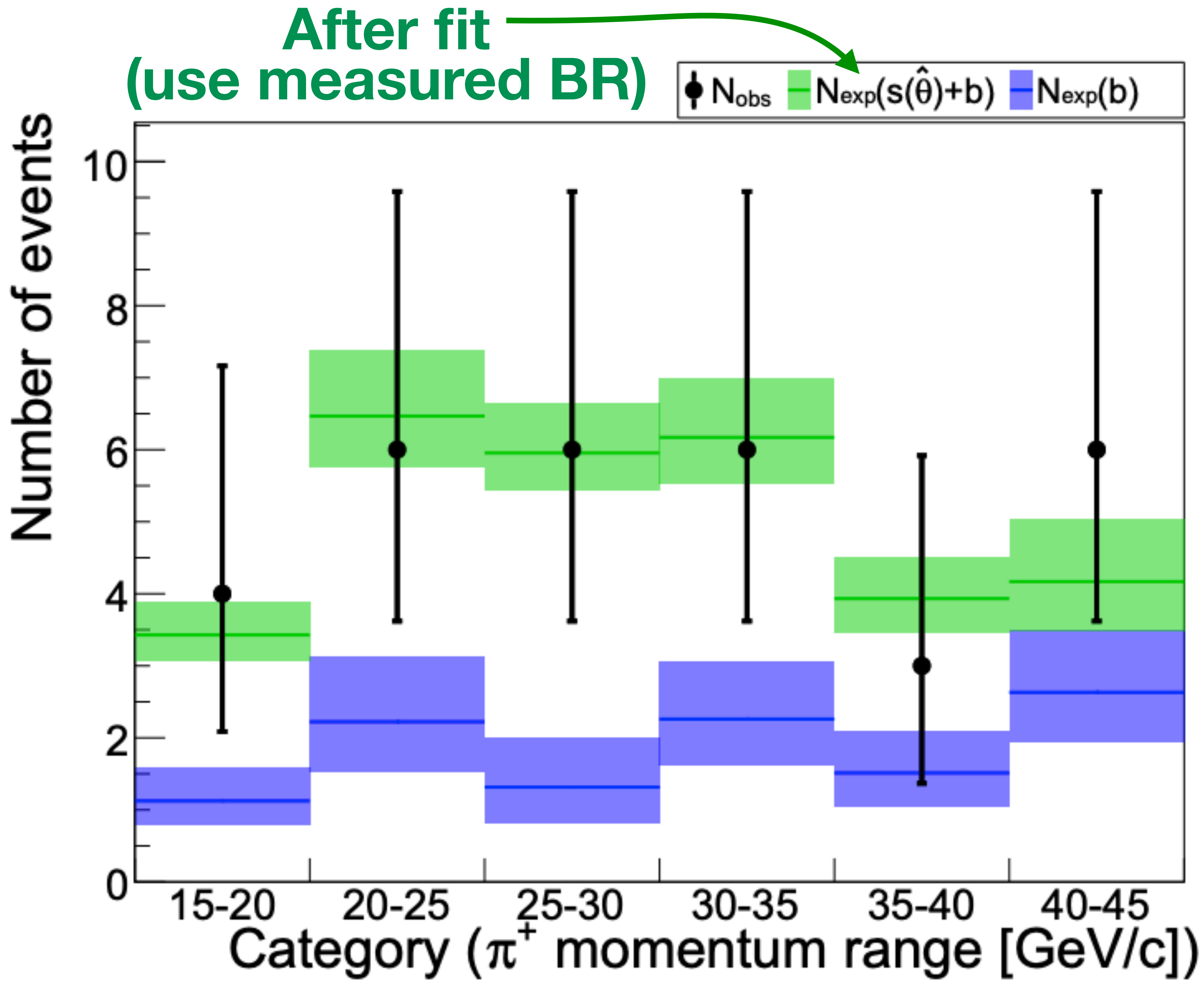
1D projection with differential background predictions & SM signal expectation [not a fit]:



Results: 2021—22 Data

- Measure $\mathscr{B}_{\pi\nu\bar{\nu}}$ and 68% (1σ) confidence interval using a profile likelihood ratio test statistic $q(\theta)$.
- Use 6 (momentum bin) categories



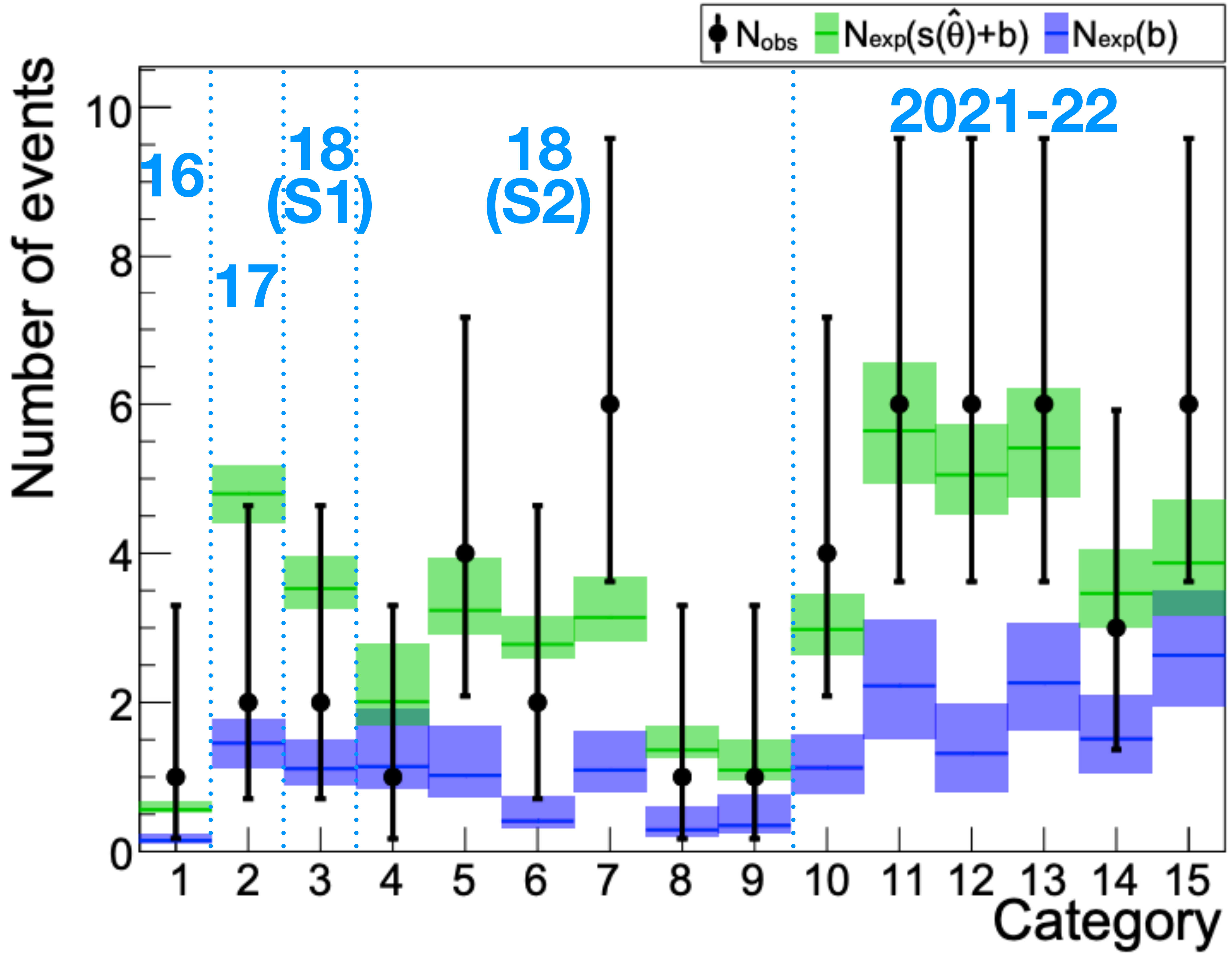


$$\mathscr{B}_{21-22}(K^+ \to \pi^+\nu\bar{\nu}) = \left(16.2^{+5.1}_{-4.5}\right) \times 10^{-11} = \left(16.2\left({}^{+4.9}_{-4.3}\right)_{\text{stat}}\left[{}^{+1.4}_{-1.4}\right]_{\text{syst}}\right) \times 10^{-11}$$

Evaluate statistical-only component by repeating procedure assuming exact knowledge of signal and background expectations.

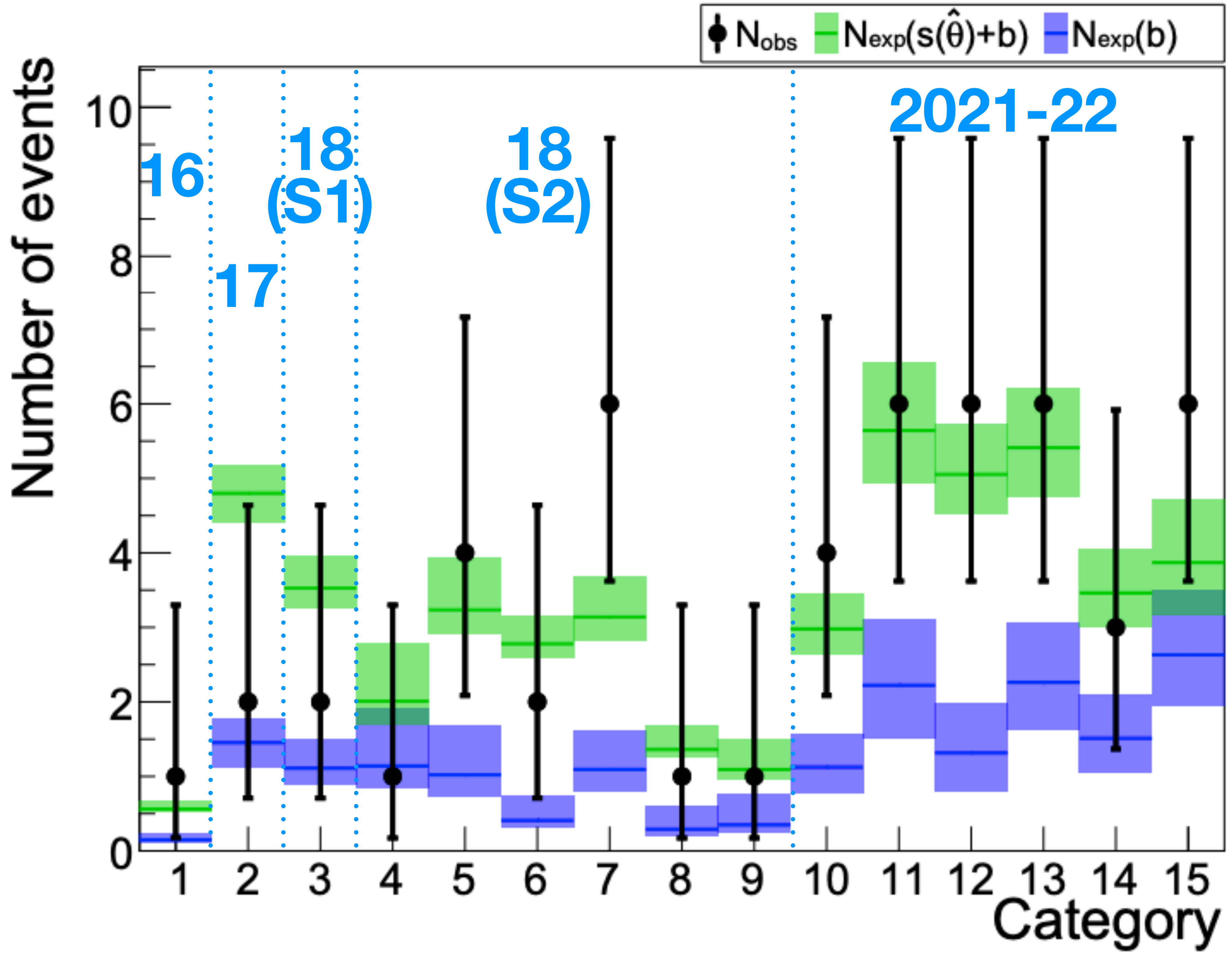
Combining NA62 results: 2016—22

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



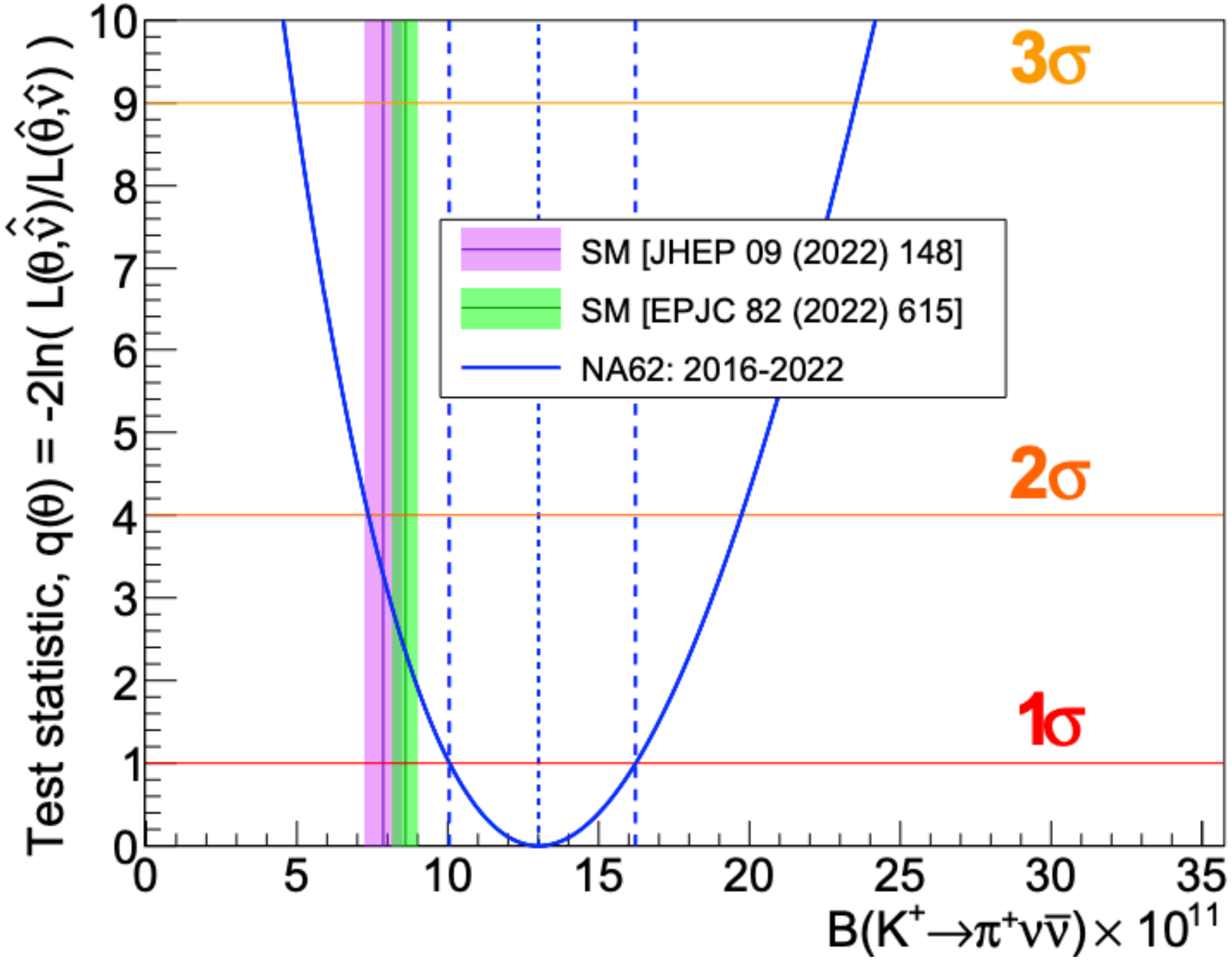
Combining NA62 results: 2016—22

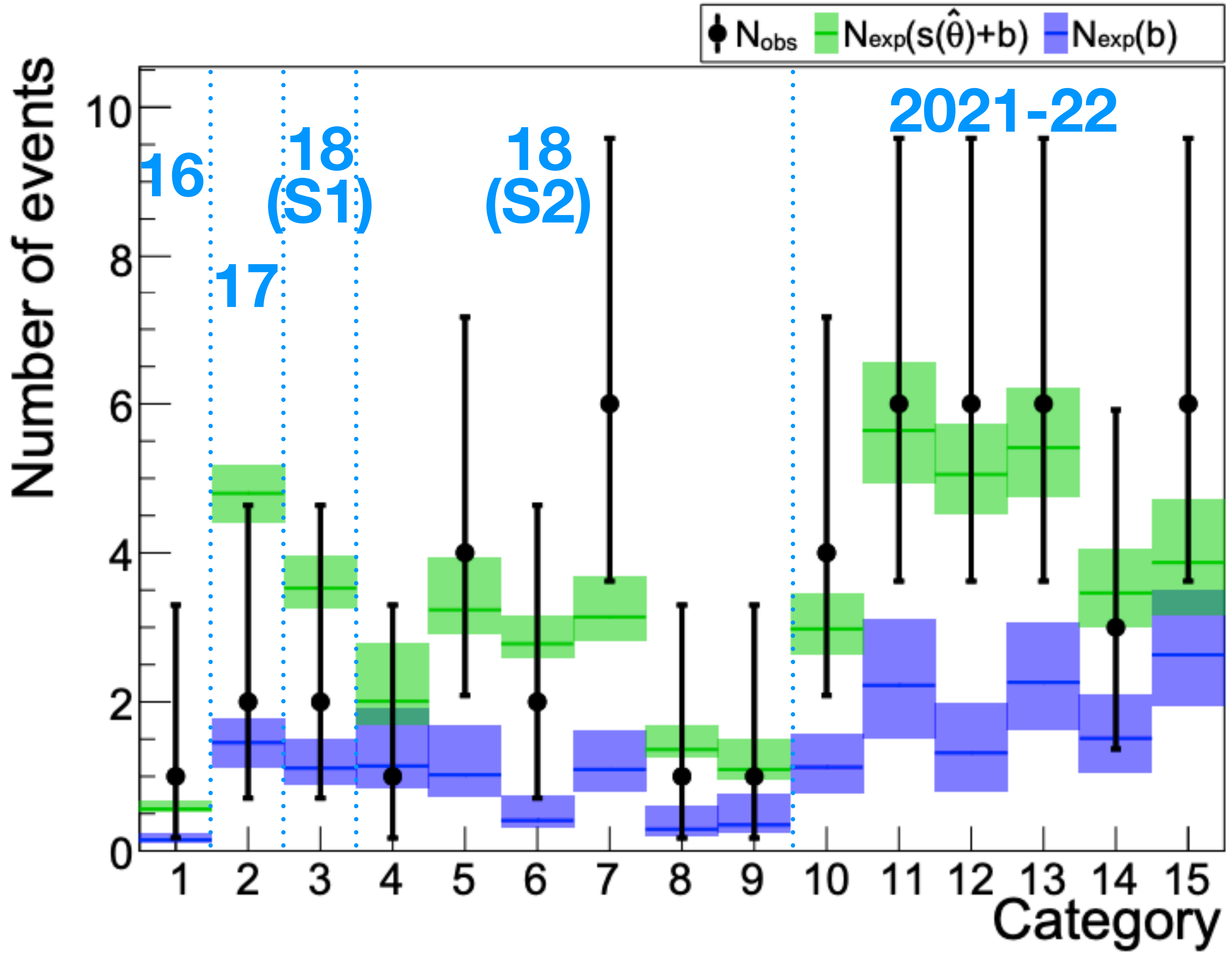
- Integrating 2016—22 data: $N_{bg} = 18^{+3}_{-2}$, $N_{obs} = 51$.
  - **Background-only hypothesis** p-value = 2×10^{-7} $\Rightarrow$ significance $Z > 5$



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 $Z > 5$





$$\mathscr{B}_{16-22}(K^+ \to \pi^+ \nu \bar{\nu}) = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11} = \left(13.0 \left(^{+3.0}_{-2.7}\right)_{\text{stat}} \left[^{+1.3}_{-1.3}\right]_{\text{syst}}\right) \times 10^{-11}$$

Results in context

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

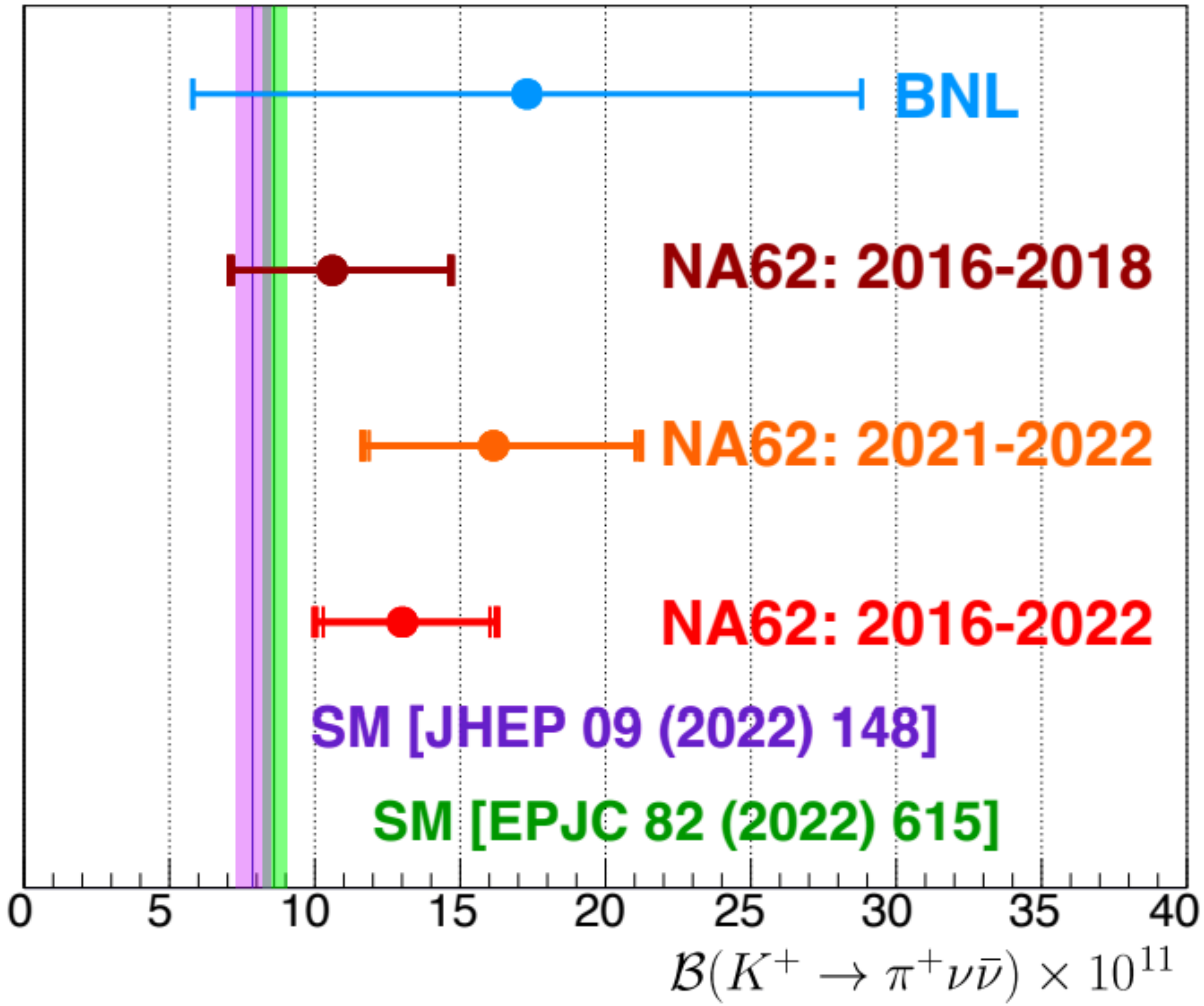
$$\mathcal{B}^{16-18}_{\pi\nu\bar{\nu}} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$$

[JHEP 06 (2021) 093]

$$\mathcal{B}^{21-22}_{\pi\nu\bar{\nu}} = \left(16.2^{+5.1}_{-4.5}\right) \times 10^{-11}$$

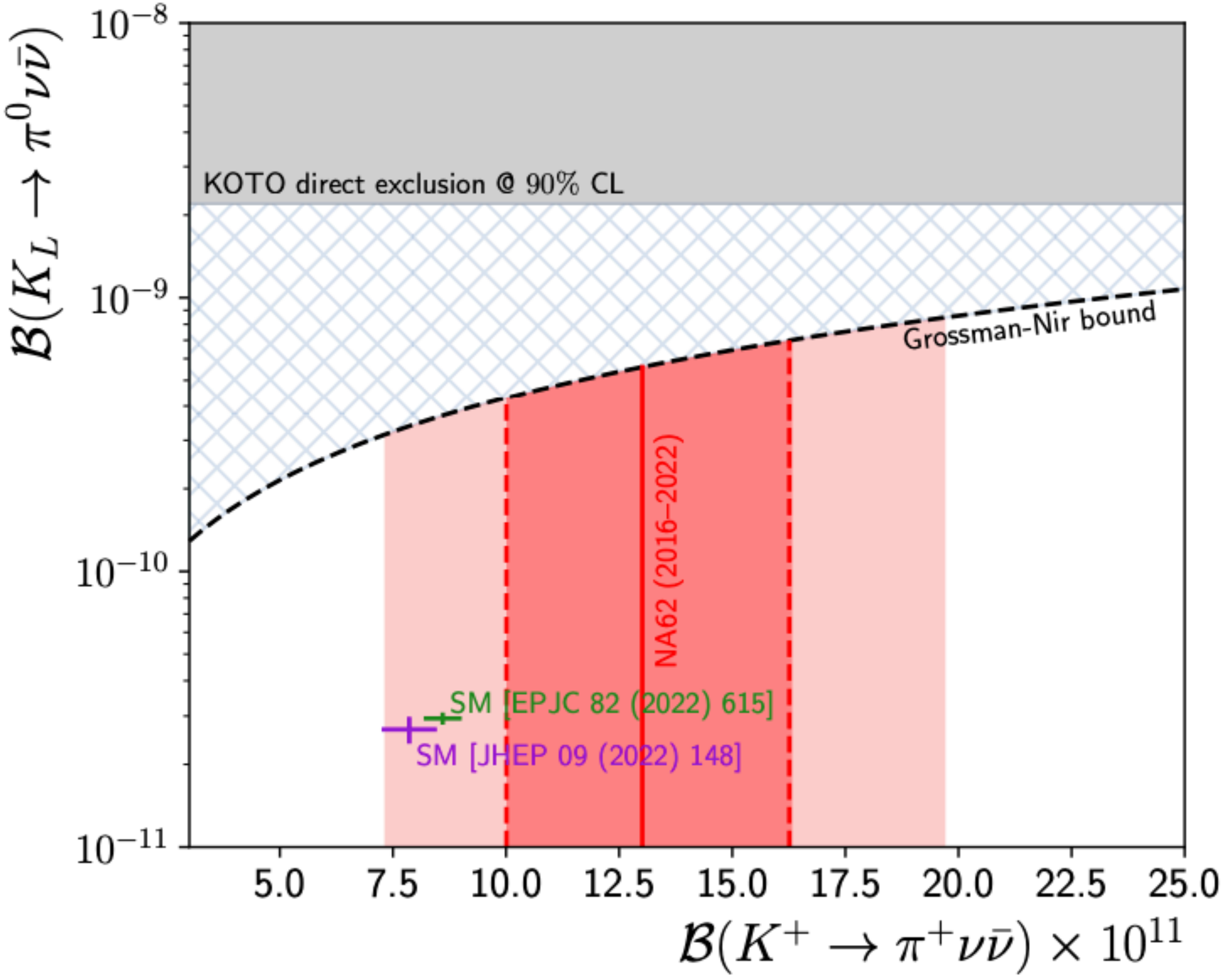
$$\mathcal{B}^{16-22}_{\pi\nu\bar{\nu}} = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$$

- 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**



$$\mathcal{B}^{16-22}_{\pi\nu\bar{\nu}} = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$$

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

Latest KOTO result: [arXiv:2411.11237]

Breaking news: [New: arXiv:2412.12015: submitted to JHEP]

NA62

CERN Press release :

CERN Accelerating science

NA62 experiment at CERN observes ultra-rare particle decay

In the Standard Model of particle physics, the odds of this decay occurring are less than one in 10 billion

25 SEPTEMBER, 2024

INFN Press release :

INFN Istituto Nazionale di Fisica Nucleare

25 SETTEMBRE 2024

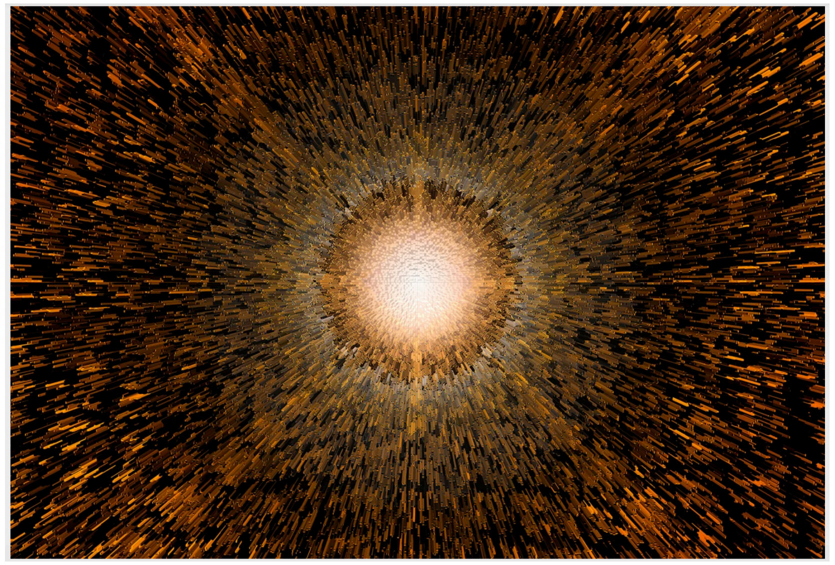
CERN: L'ESPERIMENTO NA62 OSSERVA UN PROCESSO RARISSIMO

UKRI Press release : UK Research and Innovation

CERN reports first observation of ultra-rare particle decay

Scientific American :

SCI AM



OCTOBER 1, 2024 | 5 MIN READ

A One-in-10-Billion Particle Decay Hints at Hidden Physics

Physicists have detected a long-sought particle process that may suggest new forces and particles exist in the universe

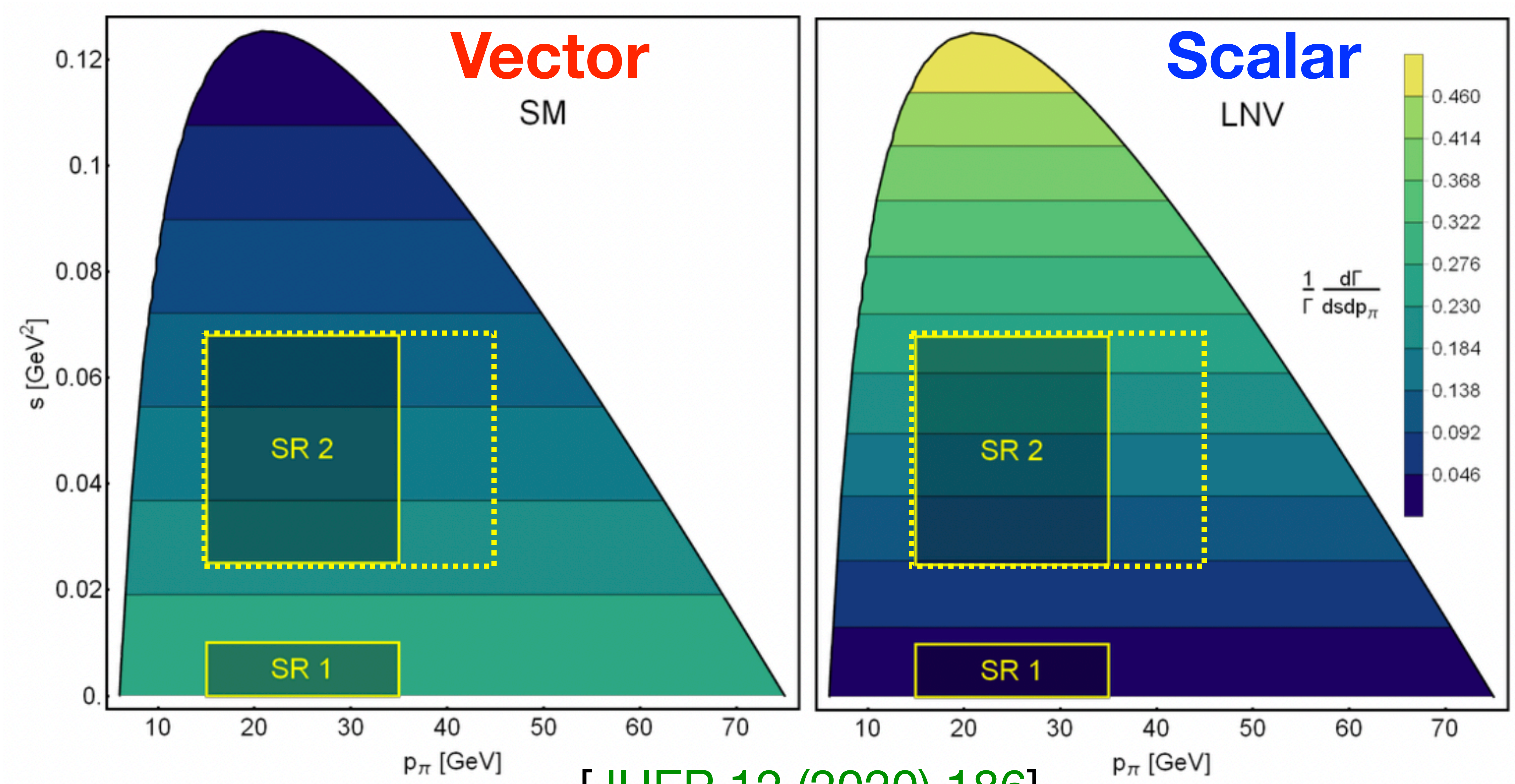
Conclusions

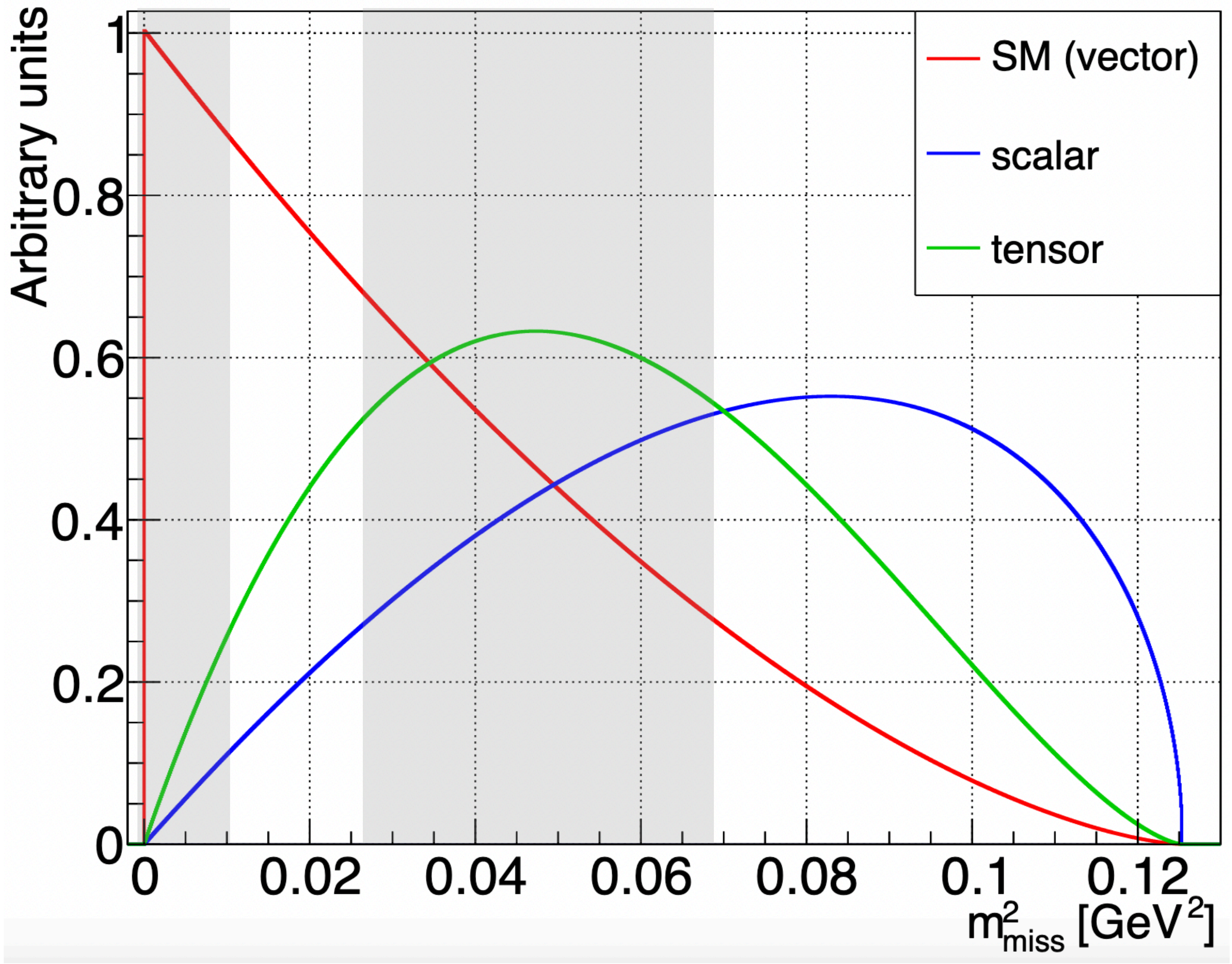
- New study of $K^+ \to \pi^+ \nu\bar{\nu}$ decay using NA62 2021—22 dataset:
  - Improved signal yield per SPS spill by 50%.
  - $N_{bg} = 11.0^{+2.1}_{-1.9}$, $N_{obs} = 31$
  - $\mathcal{B}_{21-22}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(16.2^{+5.1}_{-4.5}\right) \times 10^{-11} = \left(16.0 \left(^{+4.9}_{-4.3}\right)_{\text{stat}} \left[^{+1.4}_{-1.4}\right]_{\text{syst}}\right) \times 10^{-11}$
- 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)
  - $\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11} = \left(13.0 \left(^{+3.0}_{-2.7}\right)_{\text{stat}} \left[^{+1.3}_{-1.3}\right]_{\text{syst}}\right) \times 10^{-11}$
  - Background-only hypothesis rejected with significance Z>5.
- First observation of $K^+ \to \pi^+ \nu\bar{\nu}$ decay: BR consistent with SM prediction within 1.7σ
  - **Need full NA62 data-set to clarify SM agreement or tension.**

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

Supplemental

What is the nature of the $K \to \pi\nu\bar{\nu}$ decay?



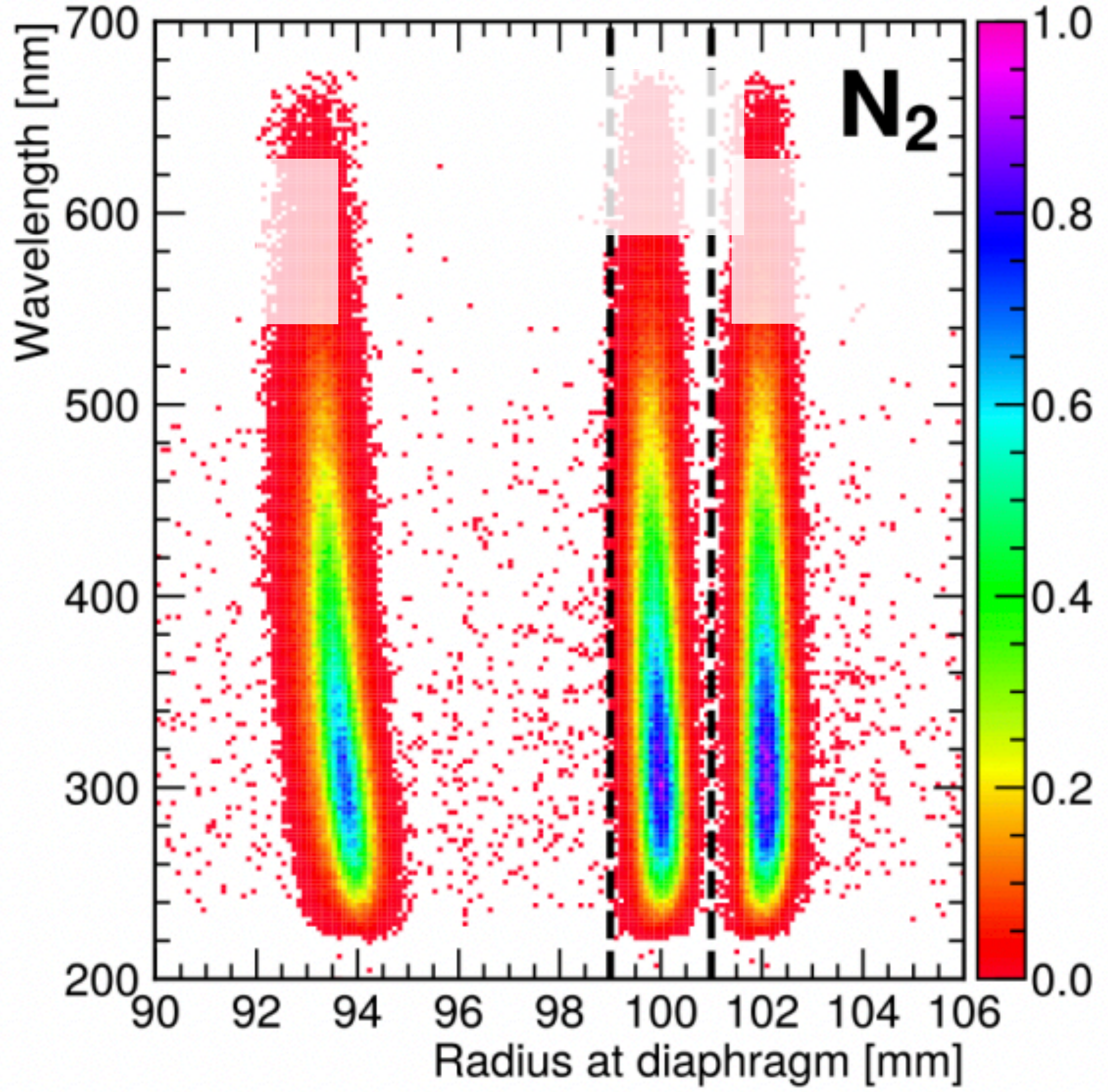


[JHEP 12 (2020) 186]

- In SM: vector form factor.
- BSM: possible vector, scalar, tensor contributions.
- Differential measurement could show presence of new physics.

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

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

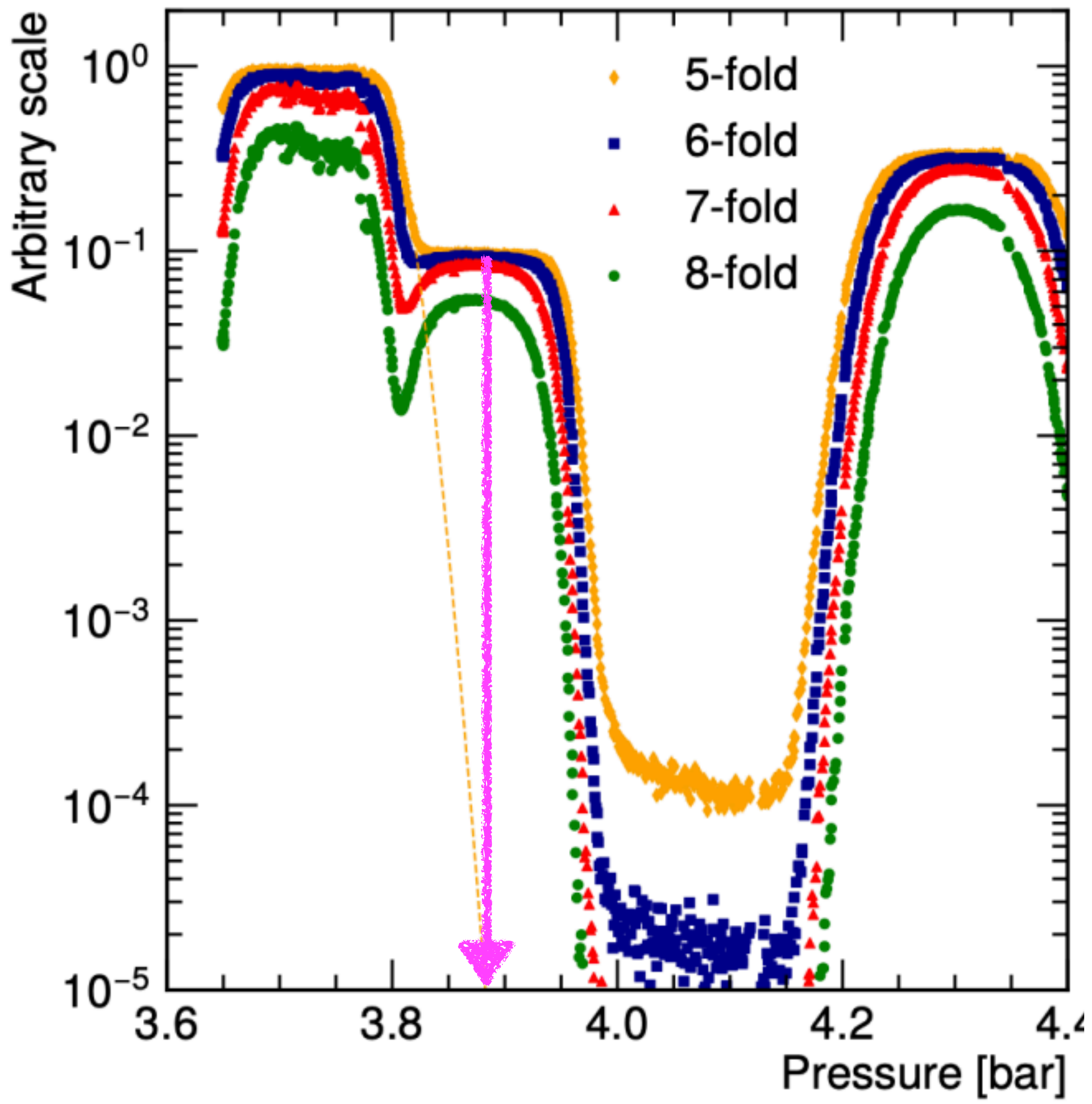


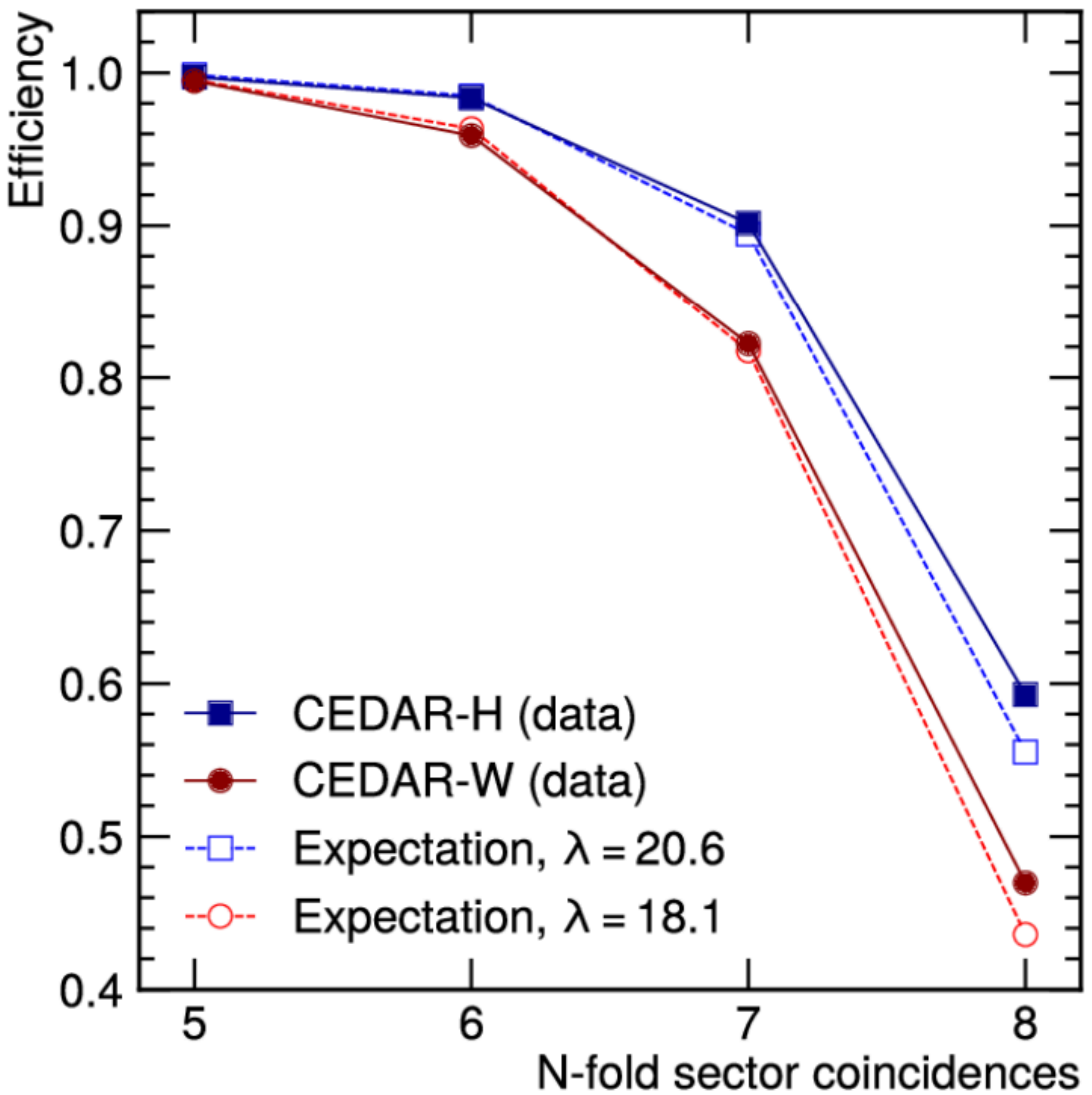
- Use fixed diaphragm to select ONLY Cherenkov light from K^+ (adjust diaphragm width and gas pressure in CEDAR to ensure powerful K^+/π^+ discrimination).

New Cedar-H : installed in 2023

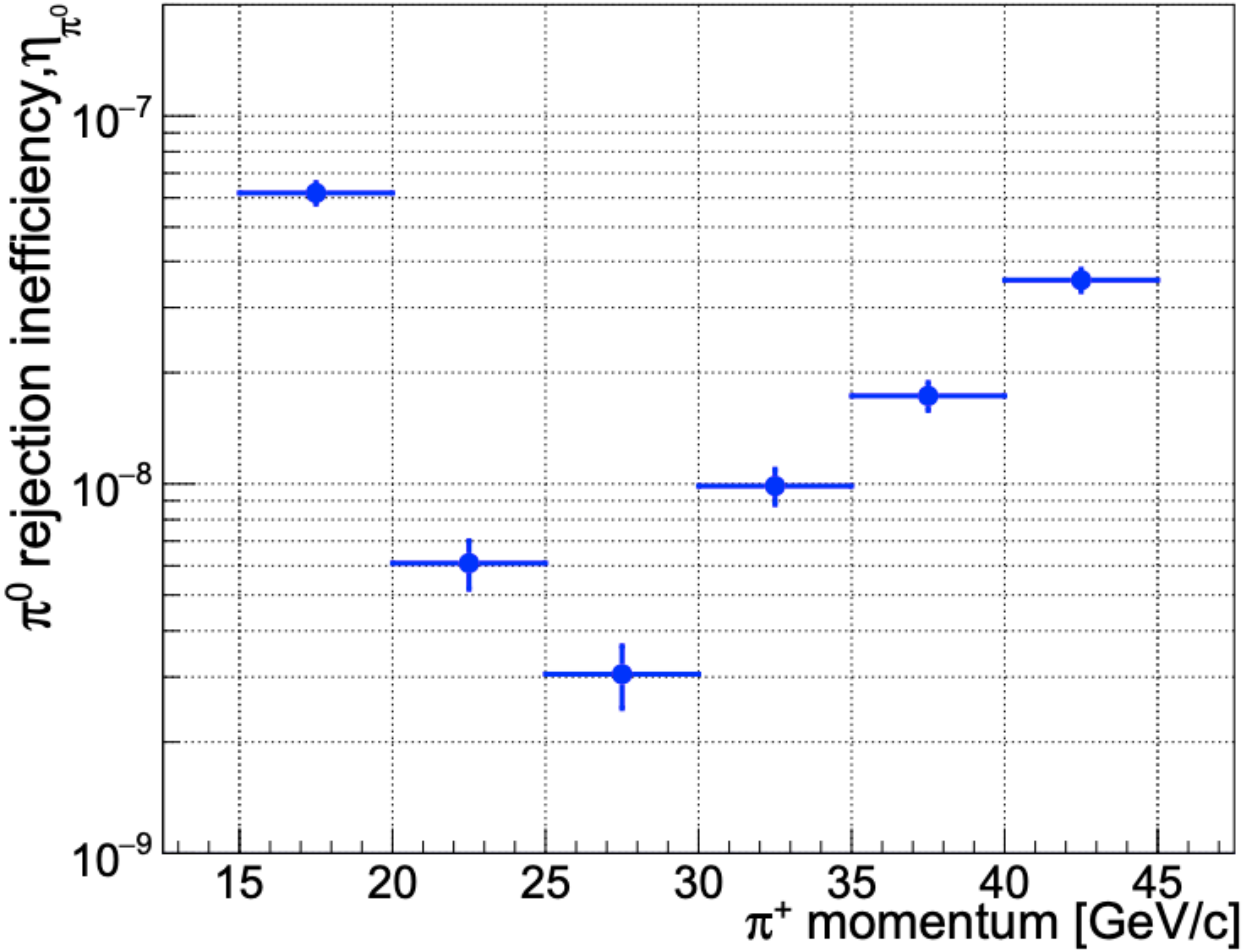
- CEDAR-W filled with N_2 at 1.7 bar was biggest contributor to material in beam line $(39 \times 10^{-3} X_0)$.
- New CEDAR-H filled with H_2 at 3.8 bar:
  - Reduces material to $7.3 \times 10^{-3} X_0$: reducing multiple scattering.
  - But new optics required to account for different optical properties 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 $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ passing full photon vetos:

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

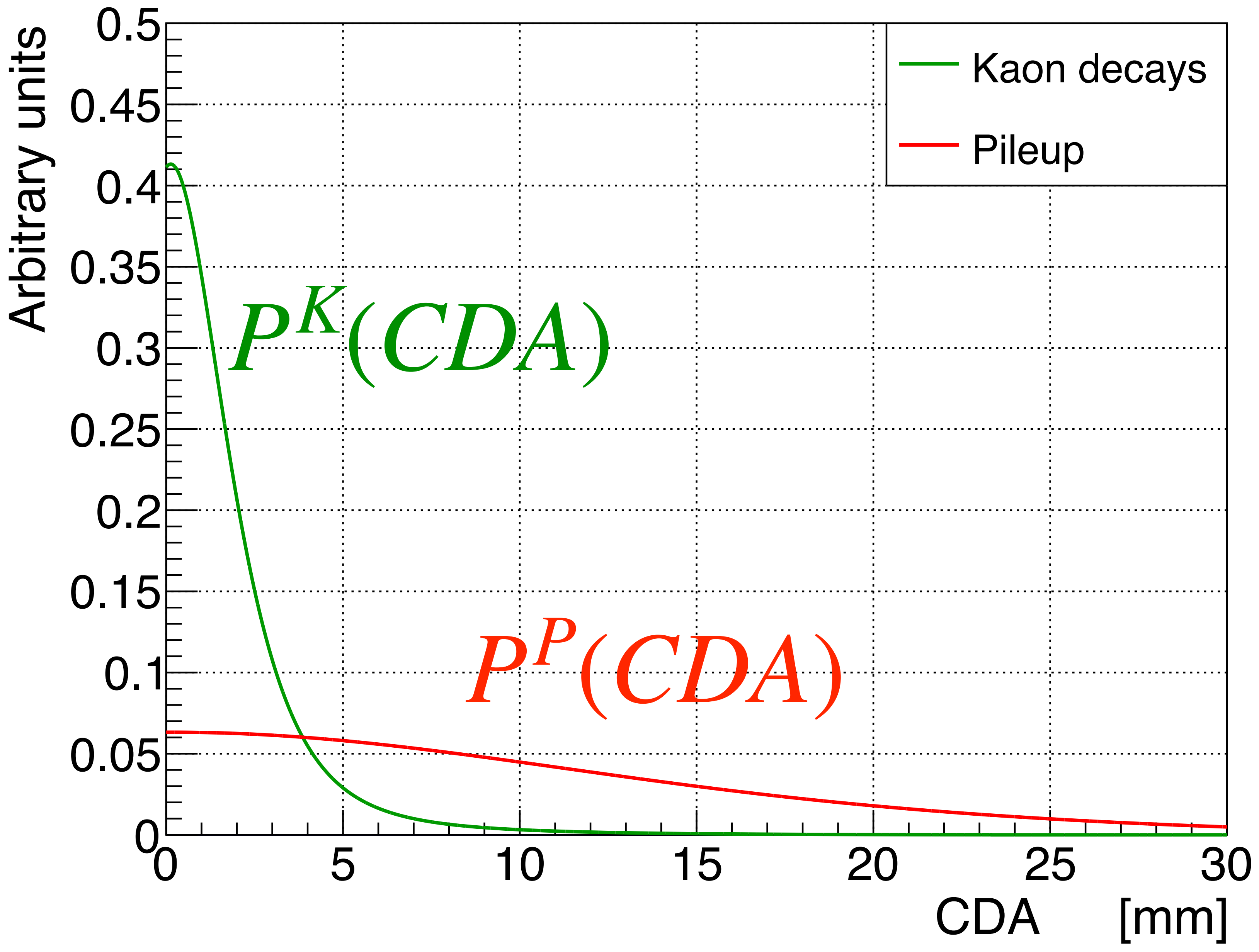
- $N_{sel.}^{\pi^+\pi^0 R}$: Number of events passing full $\pi^+\nu\bar{\nu}$ selection in $\pi^+\pi^0$ region
- $N_{\pi\pi}$: Number of selected normalisation events
- $D_0 \varepsilon_{trig}$: Normalisation trigger downscaling and efficiency
- ε_{RV}: Random veto efficiency

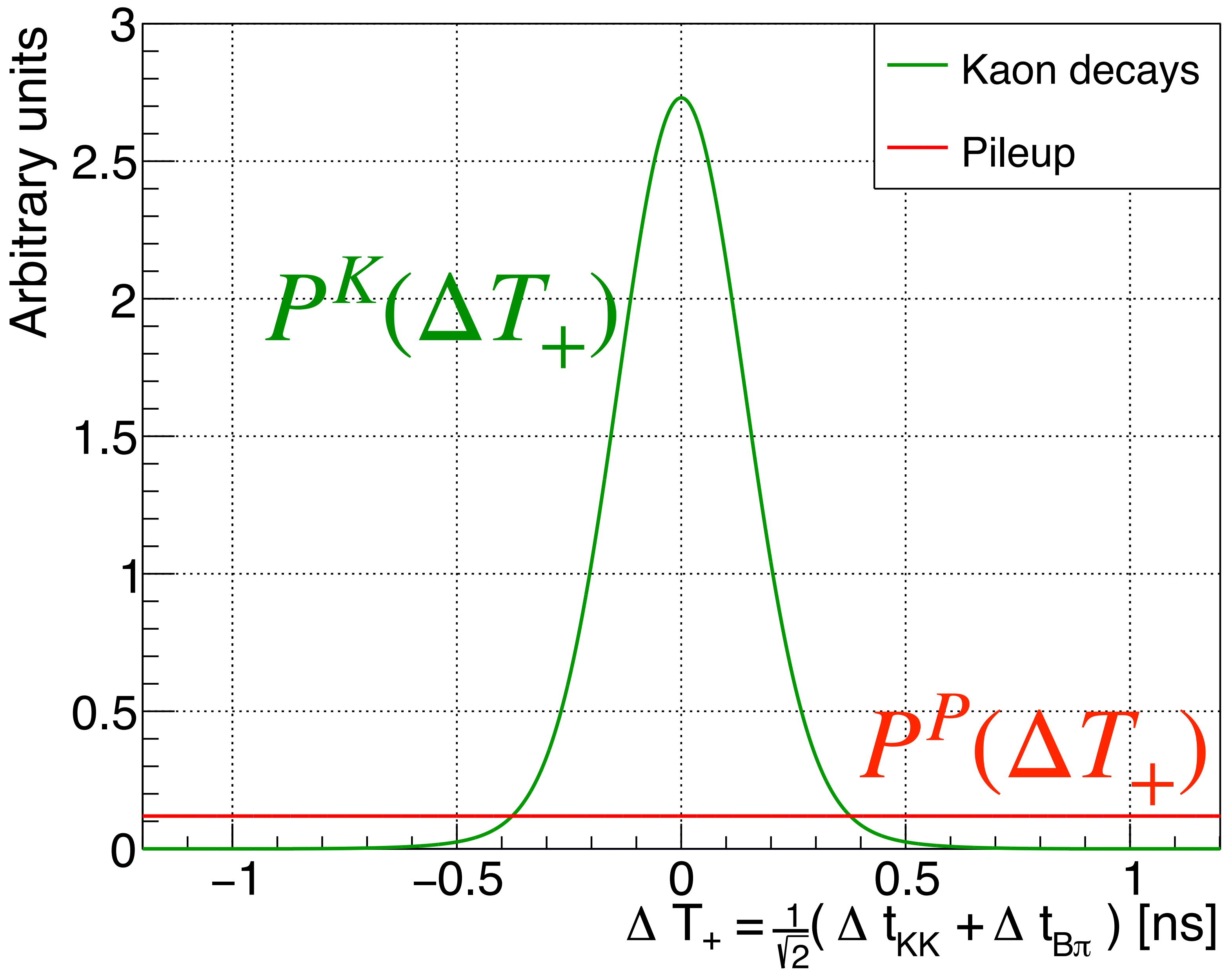
$$\eta_{\pi^0} = (1.72 \pm 0.07) \times 10^{-8}$$

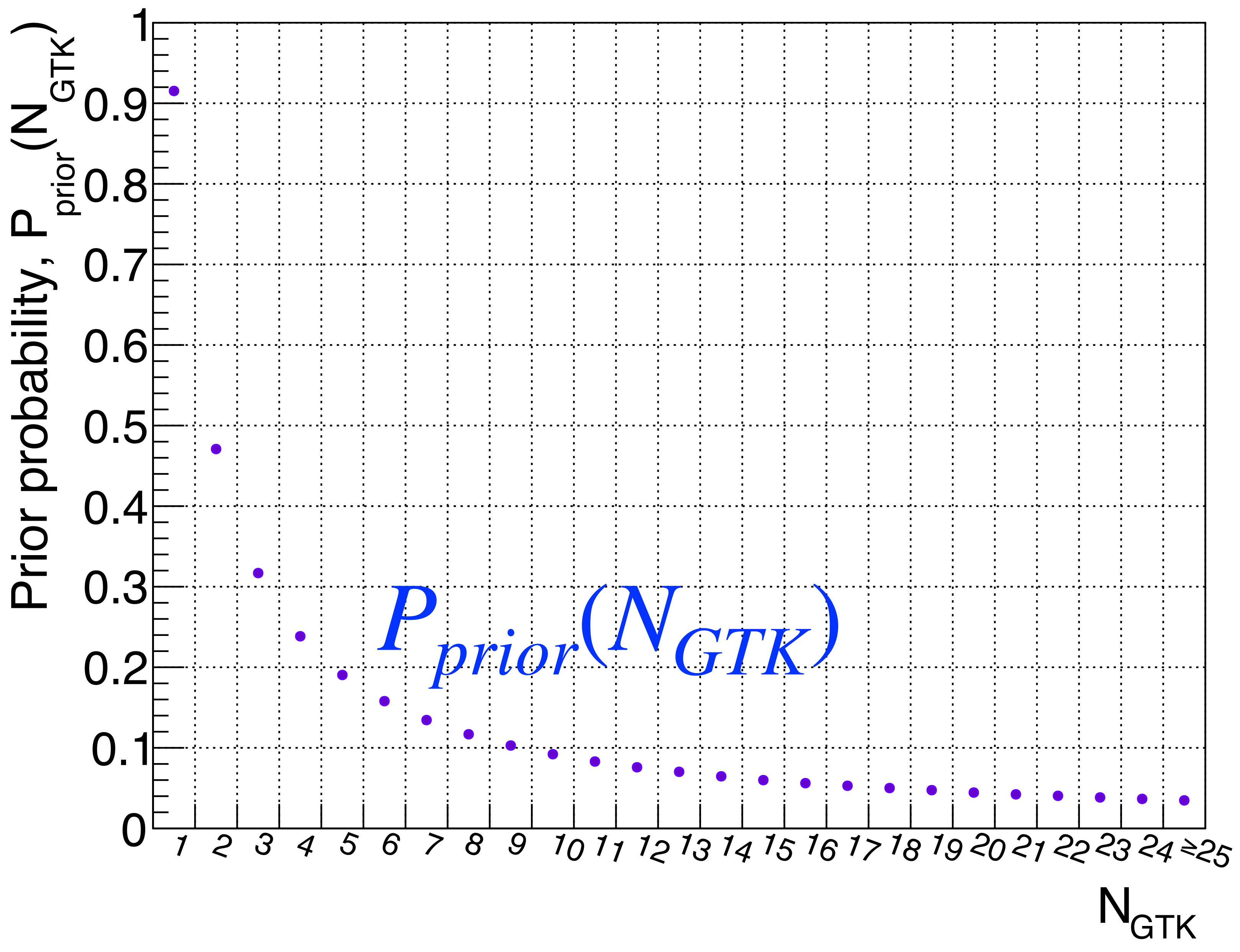
- **Combined γ/π^0 rejection of $\mathcal{O}(10^8)$.**

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

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



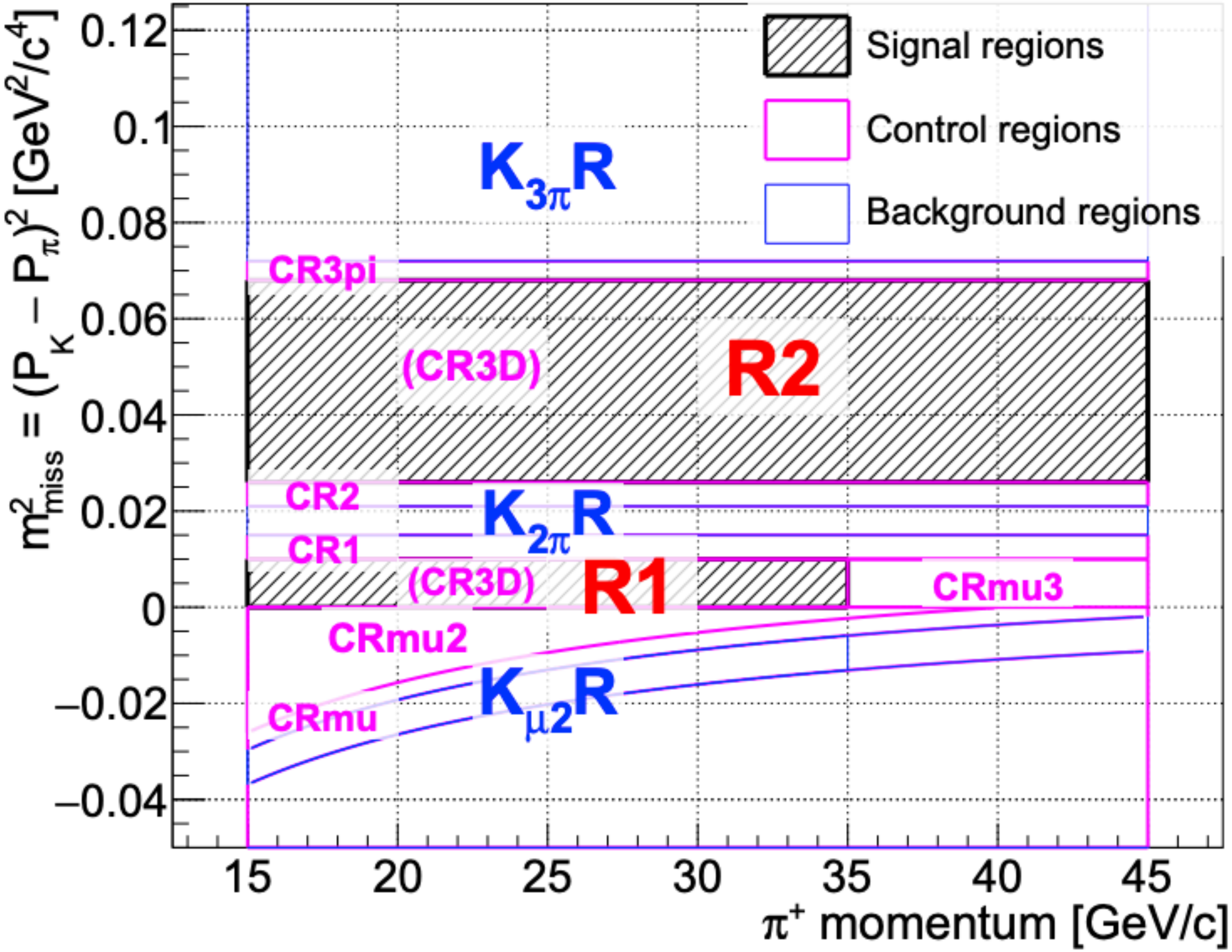




Example of selection update

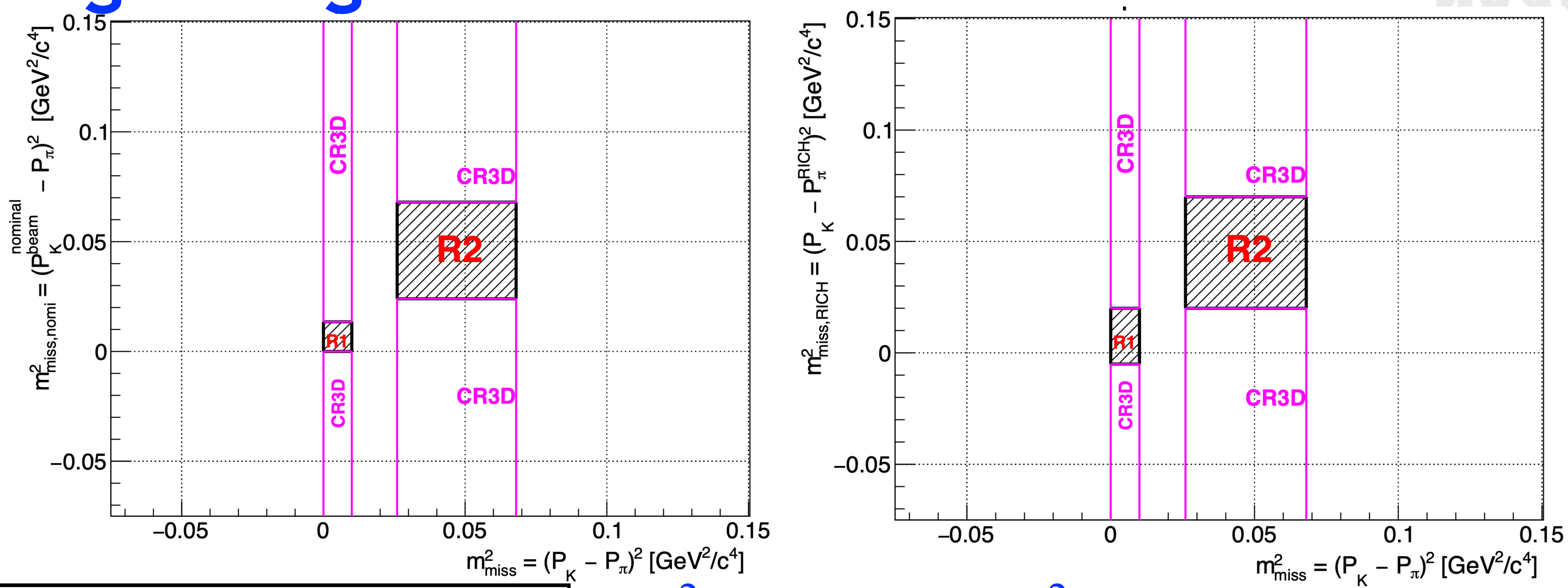
- **Output:** posterior probability of GTK track = true K^+
  - Use likelihoods of kaons (K) and pileup (P)
  - Likelihood ratio used to select true match when $N_{GTK} > 1$
- Efficiency improved (+10%) and mistagging probability maintained.

Kinematic regions



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

3D signal regions definition



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

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

Default: GTK

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

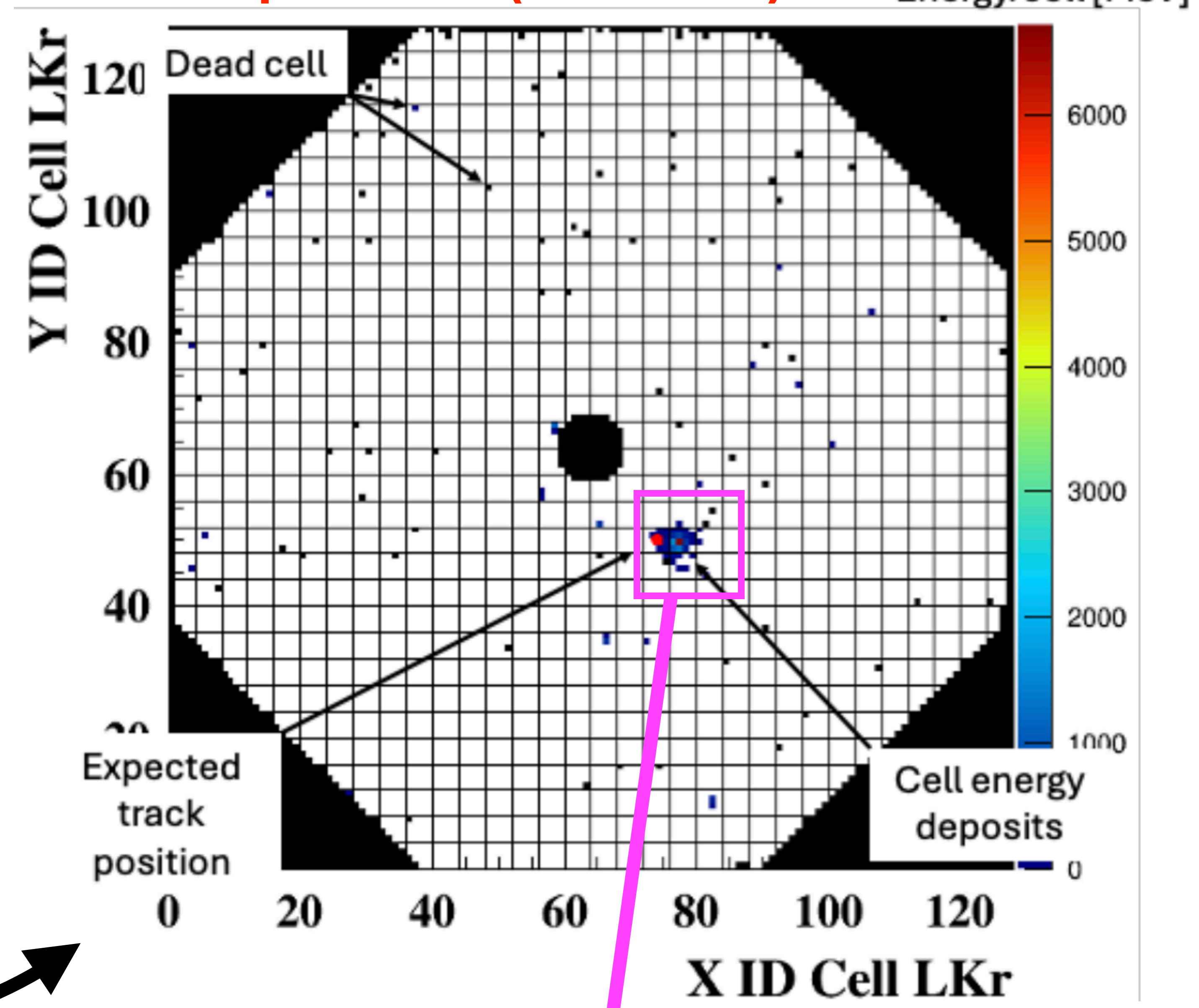
Default: STRAW

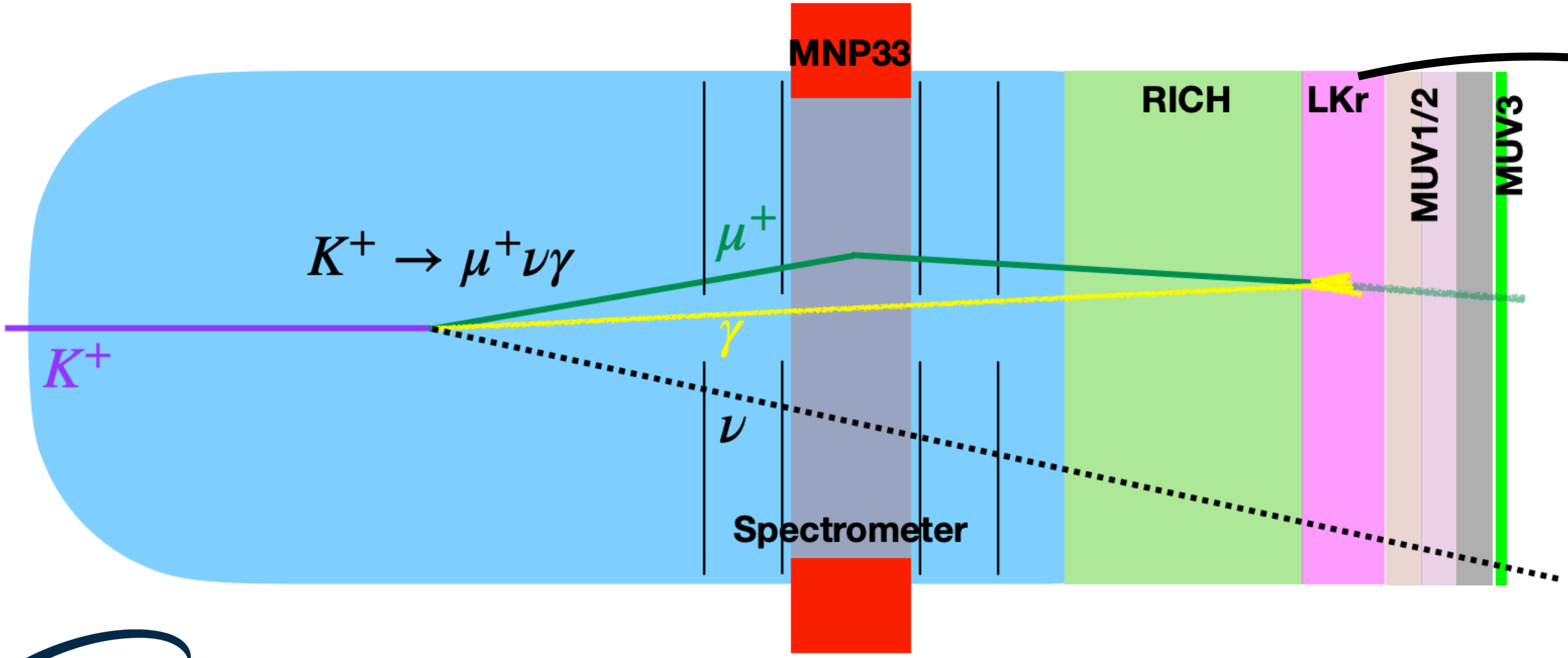
Alternative: $|p|$ **from RICH (use as a velocity spectrometer) =** $m^2_{miss,RICH}$

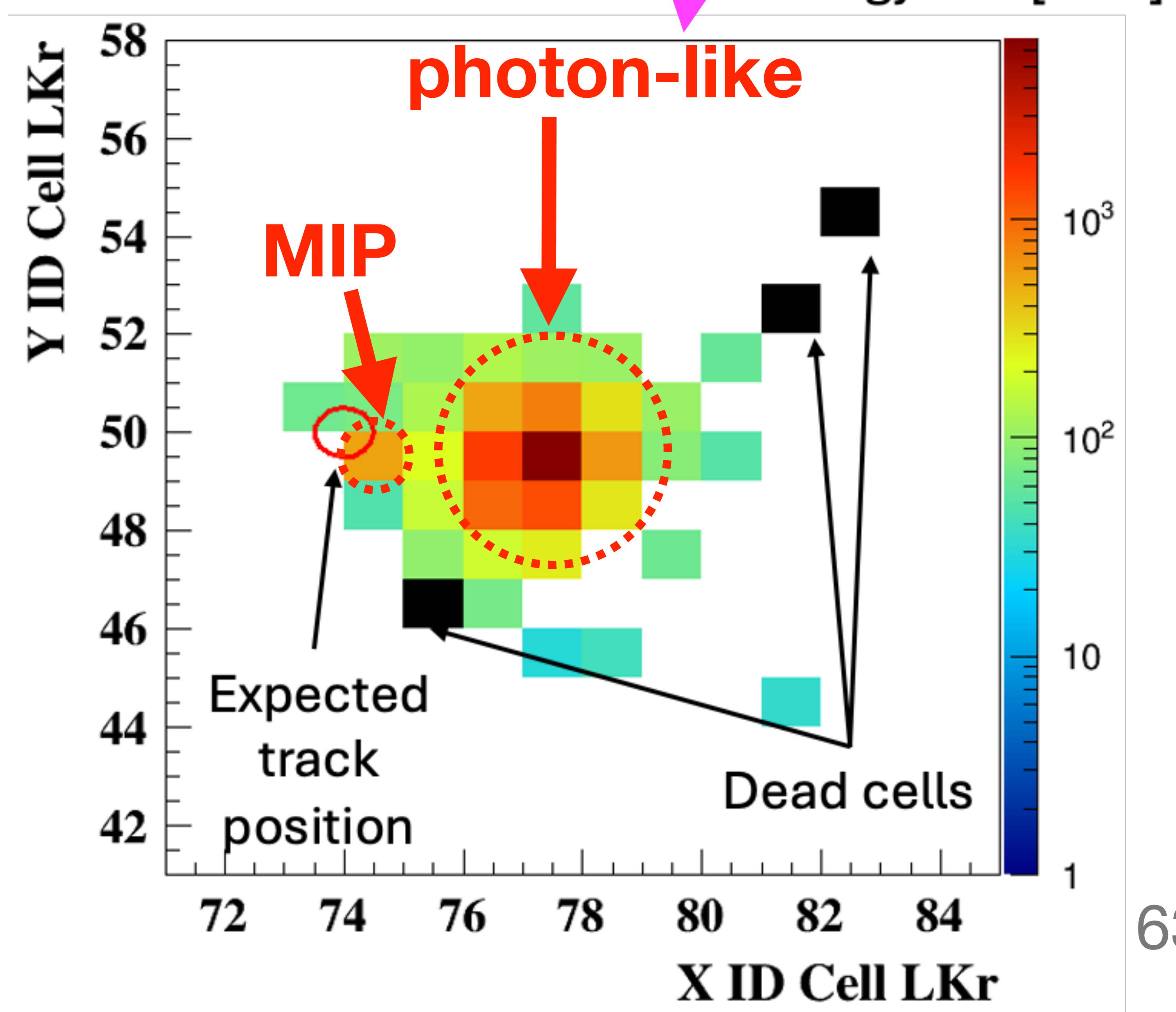
Background mechanism: $K^+ \to \mu^+\nu\gamma$

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

Example event (2022 data):



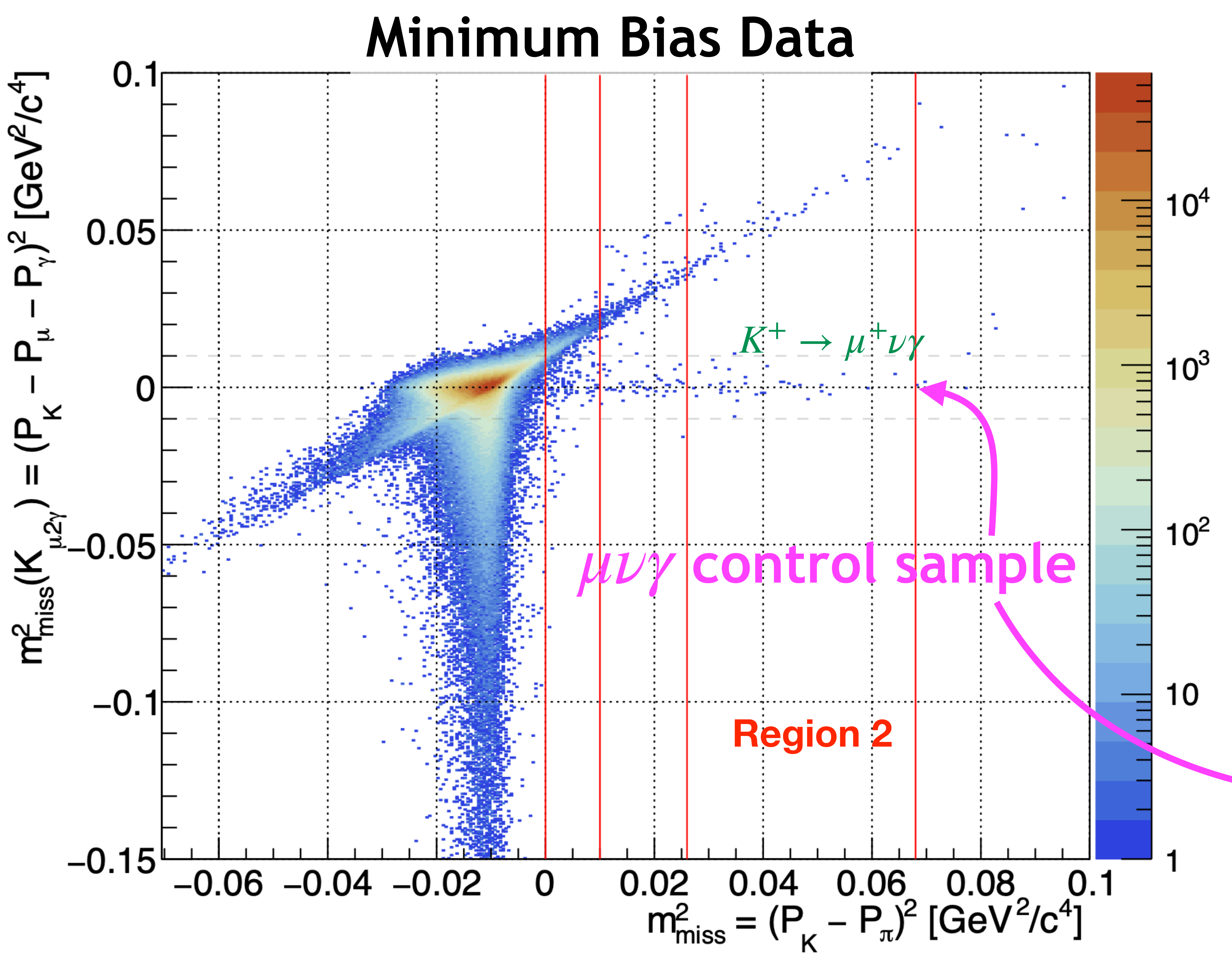




Sketch only

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:
  $m^2_{miss}(K_{\mu 2\gamma}) = (P_K - P_\mu - P_\gamma)^2$
    - 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^+-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
- $\varepsilon_{signal}/\varepsilon_{MB}$: 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 $\mu^+\gamma \Rightarrow \pi^+$.

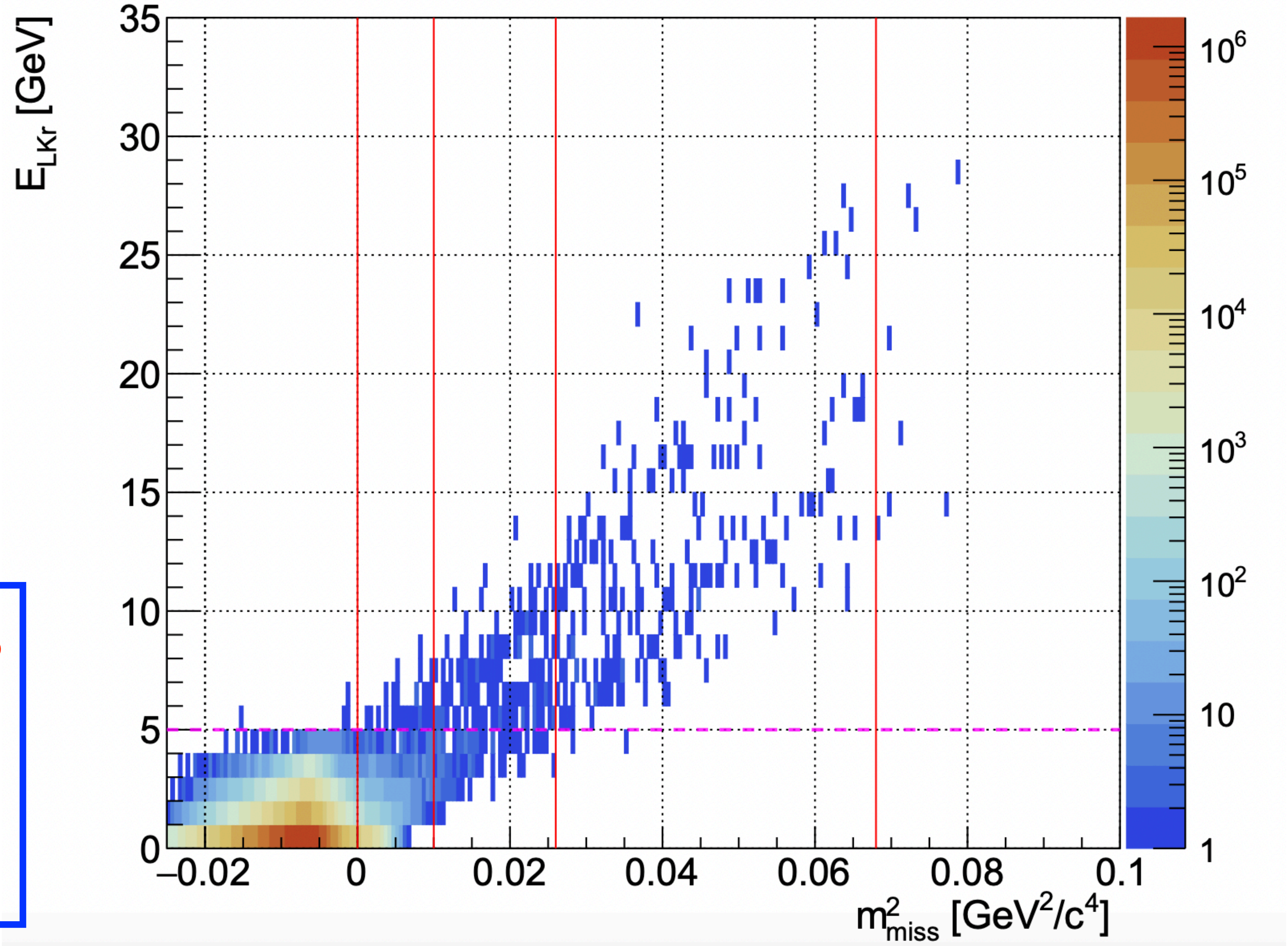
Background rejection: $K^+ \to \mu^+\nu\gamma$

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 ~ 0.0025 GeV$^2/c^4$
- $E_\gamma > 5$ GeV
- μ^+-like RICH PID.

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

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



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

Upstream background evaluation

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

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

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

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

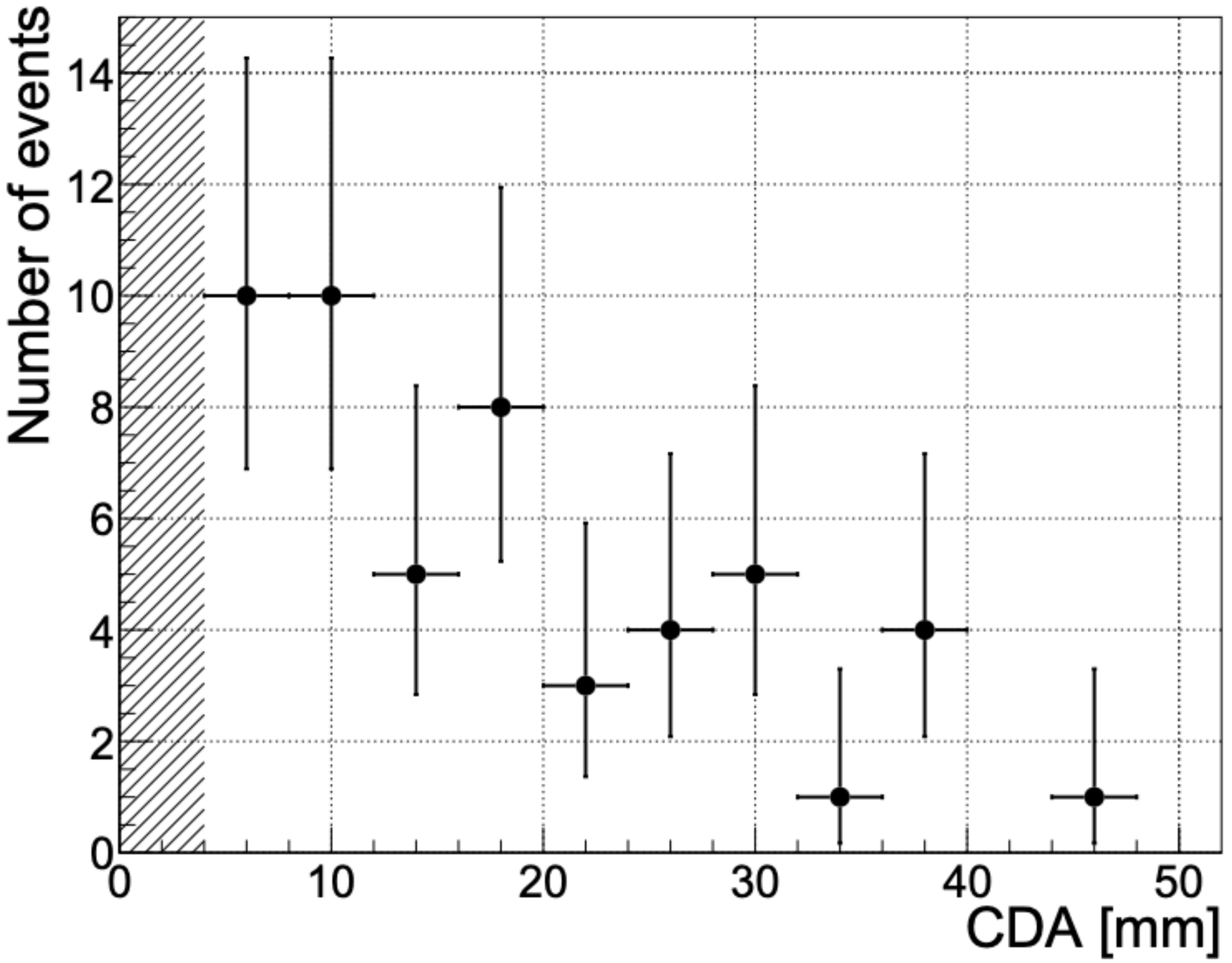
Calculate using bins (i) of $(\Delta T_+, N_{GTK})$

[Updated to fully data-driven procedure]

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

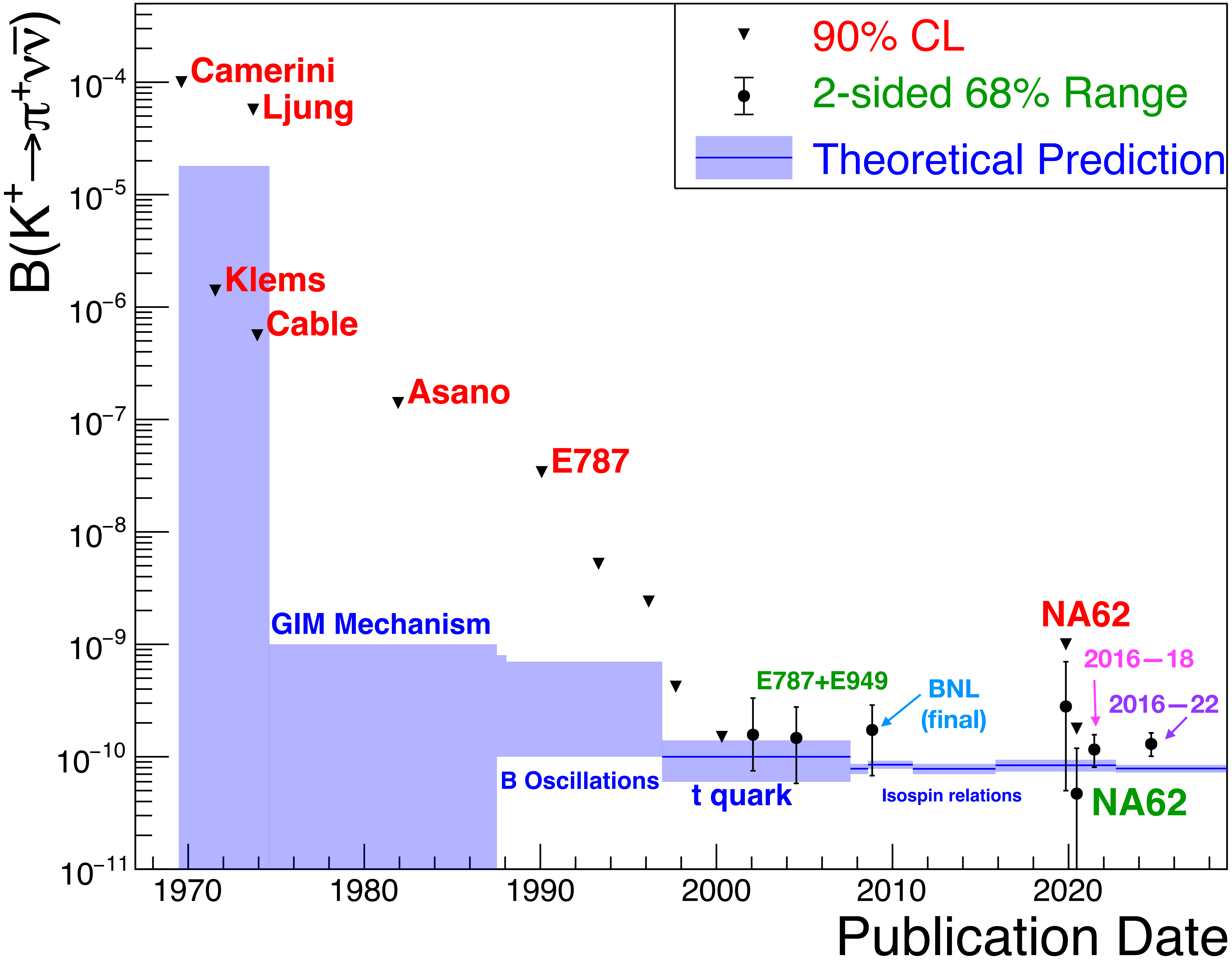
$$N_{bg}(\text{Upstream}) = 7.4^{+2.1}_{-1.8}$$

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



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

- Experimental measurements:
  - Camerini et al. [PRL 23 (1969) 326-329]
  - Klems et al. [PRD 4 (1971) 66-80]
  - Ljung et al. [PRD 8 (1973) 1307-1330]
  - Cable et al. [PRD 8 (1973) 3807-3812]
  - Asano et al. [PLB 107 (1981) 159]
  - E787 :
    - [PRL 64 (1990) 21-24]
    - [PRL 70 (1993) 2521-2524]
    - [PRL 76 (1996) 1421-1424]
    - [PRL 79 (1997) 2204-2207]
    - [PRL 84 (2000) 3768-3770]
    - [PRL 88 (2002) 041803]
  - E949 (+E787)
    - [PRL 93 (2004) 031801]
    - [PRL 101 (2008) 191802]
  - NA62:
    - 2016 data: [PLB 791 (2019) 156]
    - 2016+17 data: [JHEP 11 (2020) 042]
    - 2016—18 data: [JHEP 06 (2021) 093]
    - 2016—22 data : this result.
- Theory:
  - [Phys.Rev. 163 (1967) 1430-1440]
  - [PRD 10 (1974) 897]
  - [Prog.Theor.Phys. 65 (1981)]
  - [PLB 133 (1983) 443-448]
  - [PLB 192 (1987) 201-206]
  - [Nucl.Phys.B 304 (1988) 205-235]
  - [PRD 54 (1996) 6782-6789]
  - [PRD 76 (2007) 034017]
  - [PRD 78 (2008) 034006]
  - [PRD 83 (2011) 034030]
  - [JHEP 11 (2015) 033]
  - [JHEP 09 (2022) 148]



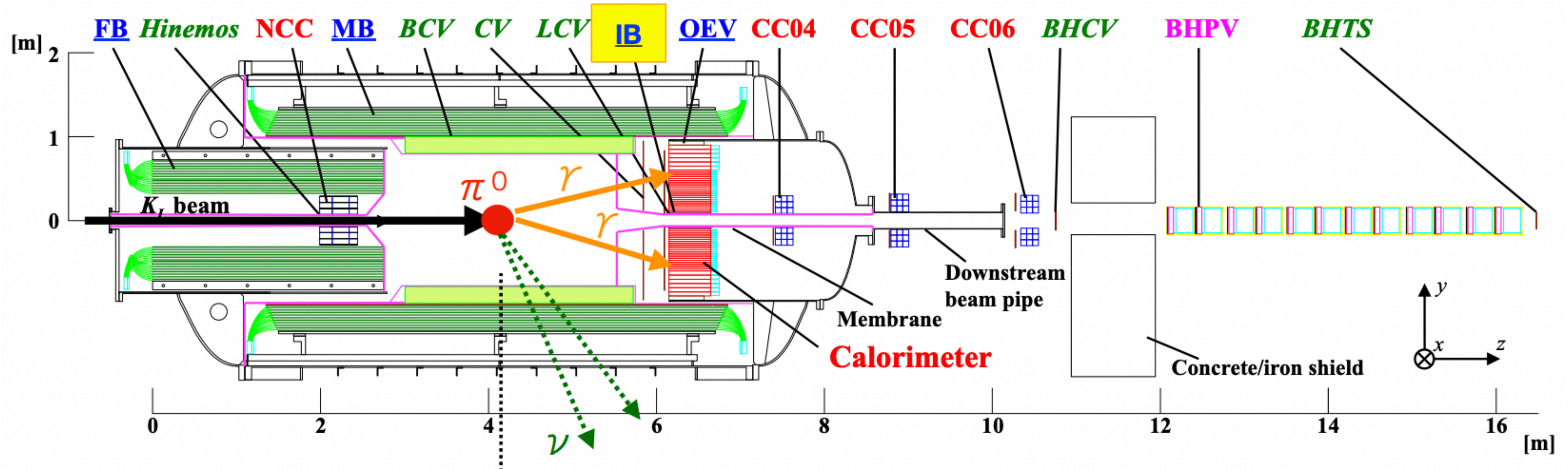
$K_L \to \pi^0 \nu\bar{\nu}$ at KOTO

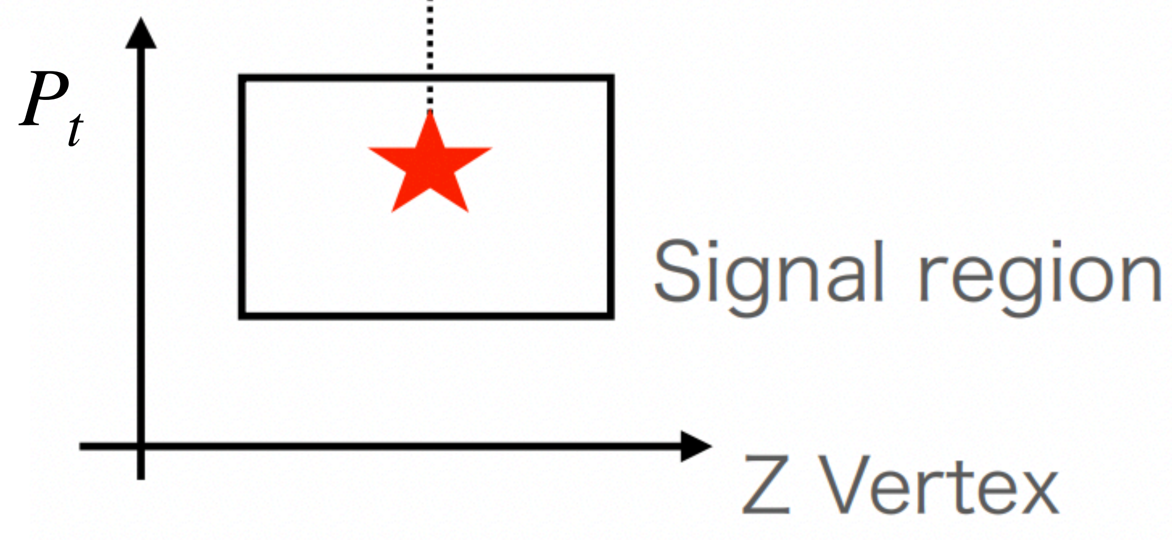
[K. shiomi : Kaons @ CERN 2023]

[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 $K_L \to \pi^0 \nu \nu$ = "2γ+Nothing+Pt"



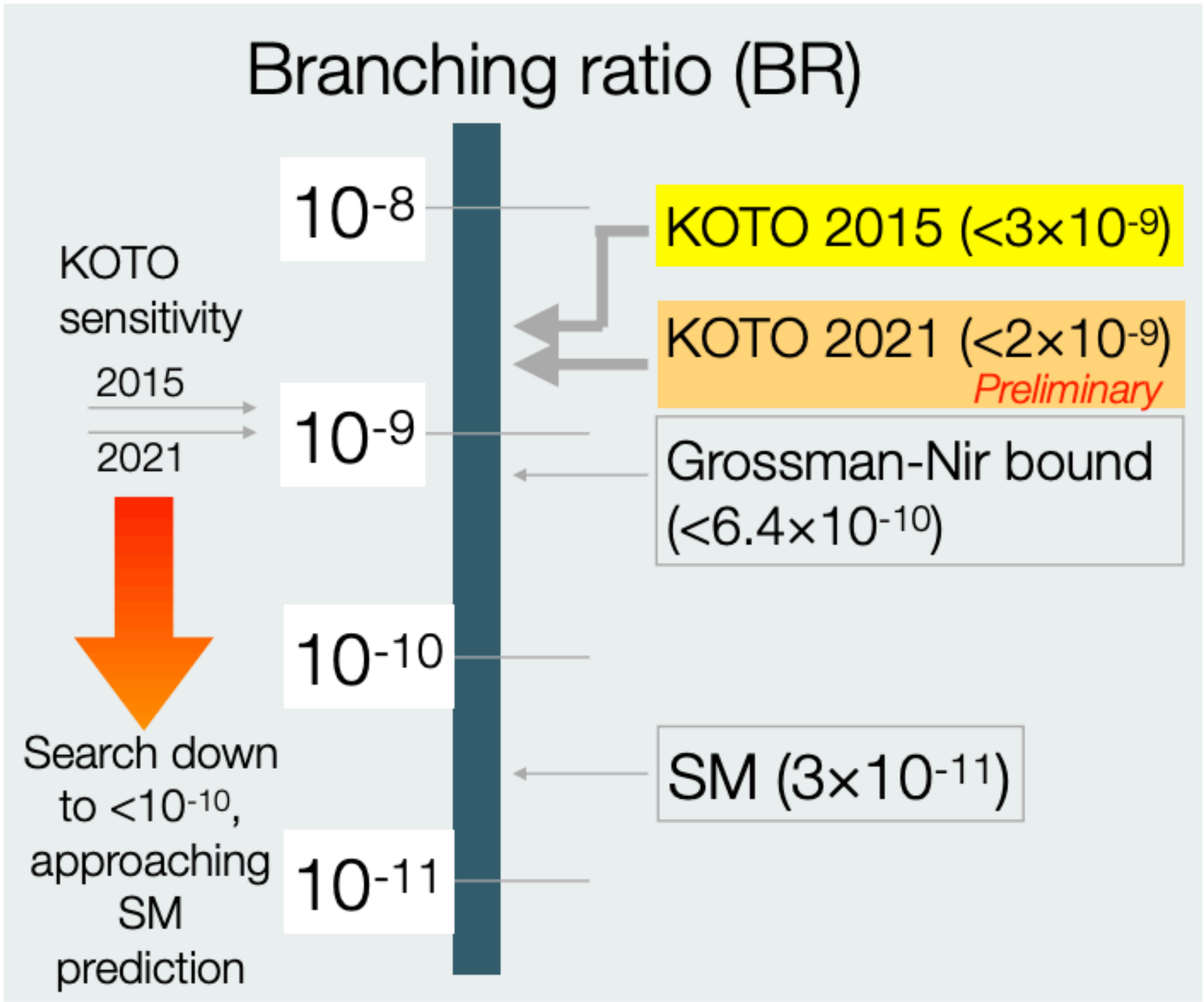


Assuming 2γ from π^0,

Calculate z vertex on the beam axis

$$M^2(\pi^0)=2E_1E_2(1-\cos\theta)$$

Calculate π^0 transverse momentum



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

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

[ArXiv:2411.11237, Nov2024]

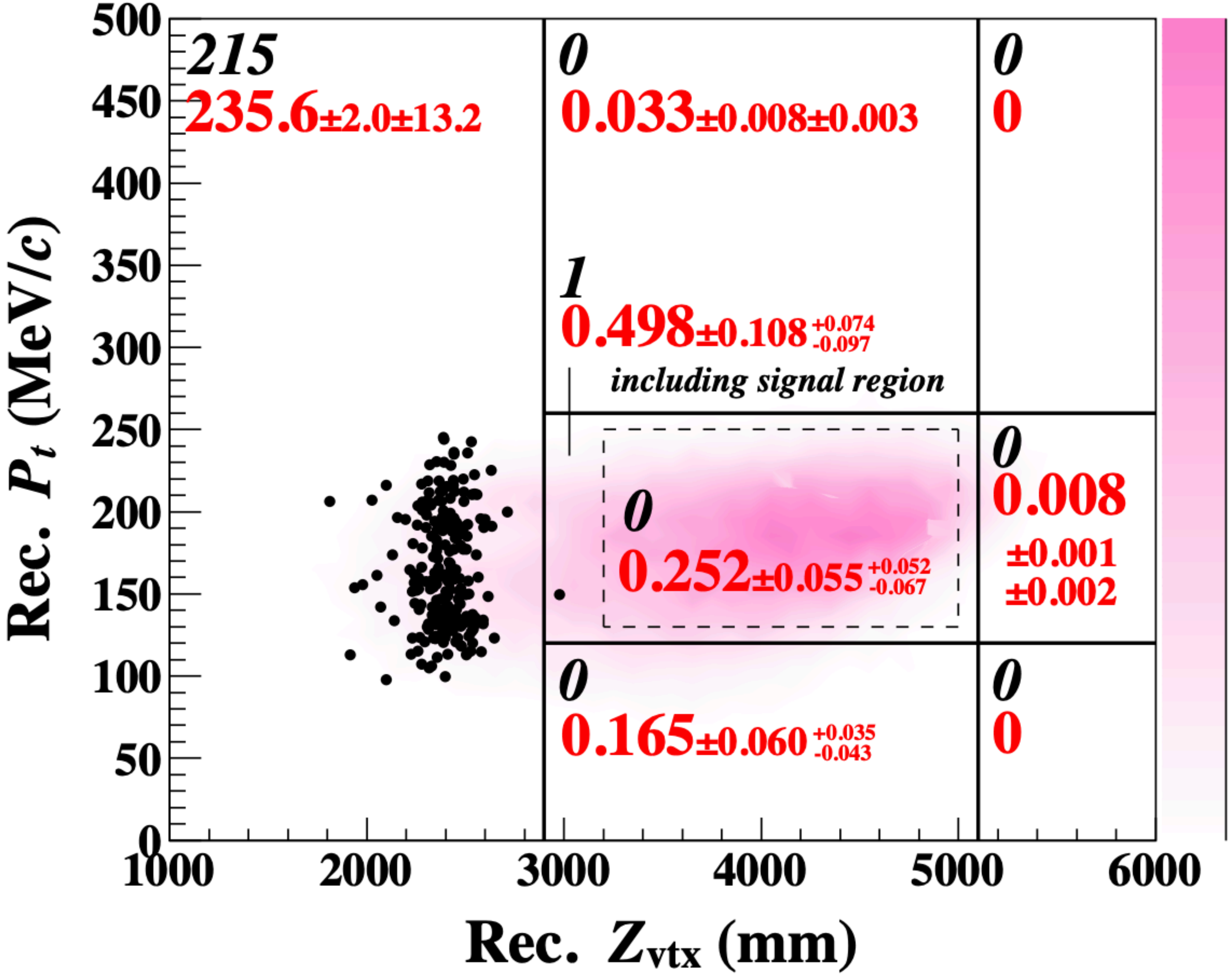


TABLE I. Summary of background estimation. The second (third) numbers represent the statistical uncertainties (systematic uncertainties).

Source		Number of events
$K^{\pm}$		$0.042 \pm 0.014\ ^{+0.004}_{-0.028}$
K_L	$K_L \to 2\gamma$ (beam-halo)	$0.045 \pm 0.010 \pm 0.006$
	$K_L \to 2\pi^0$	$0.059 \pm 0.022\ ^{+0.050}_{-0.059}$
Neutron	Hadron-cluster	$0.024 \pm 0.004 \pm 0.006$
	CV-η	$0.023 \pm 0.010 \pm 0.005$
	Upstream-π^0	$0.060 \pm 0.046 \pm 0.007$
Total		$0.252 \pm 0.055\ ^{+0.052}_{-0.067}$

$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) < 2.2 \times 10^{-9}$ @ 90 % CL

- Result uses data from 2021
- Includes new veto detectors against K^+ backgrounds

NA62 physics programme

with 2024 results

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

- $K^+ \to \pi^+ \nu \bar{\nu}$: [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
  - New: Prelim. 2024 [this talk]
- $K^+ \to \pi^+ X$: [JHEP 03 (2021) 058] [JHEP 06 (2021) 093]
- $(K^+ \to \pi^+ \pi^0,)\ \pi^0 \to$ invisible [JHEP 02 (2021) 201]

Rare Decays

- $K^+ \to \pi^+ \pi^0,\ \pi^0 \to e^+ e^-$ [prelim. Spring 2024]
- Tagged neutrino [prelim. 2023, arXiv:2412.04033 (Dec 2024)]
- $K^+ \to \pi^+ \gamma\gamma$ [PLB 850 (2024) 138513]

Forbidden Decays

- $K^+ \to \pi^0 \pi \mu e$ [PLB 859 (2024) 139122]
- $K^+ \to (\pi^0) \pi^- e^+ e^+$ [PLB 830 (2022) 137172]
- $K^+ \to \mu^- \nu e^+ e^+$ [PLB838 (2023) 137679]
- $K^+ \to \pi \mu e$ and $\pi^0 \to \mu^- e^+$ [PRL 127 (2021) 13, 131802]

Exotics

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

Rare Decays

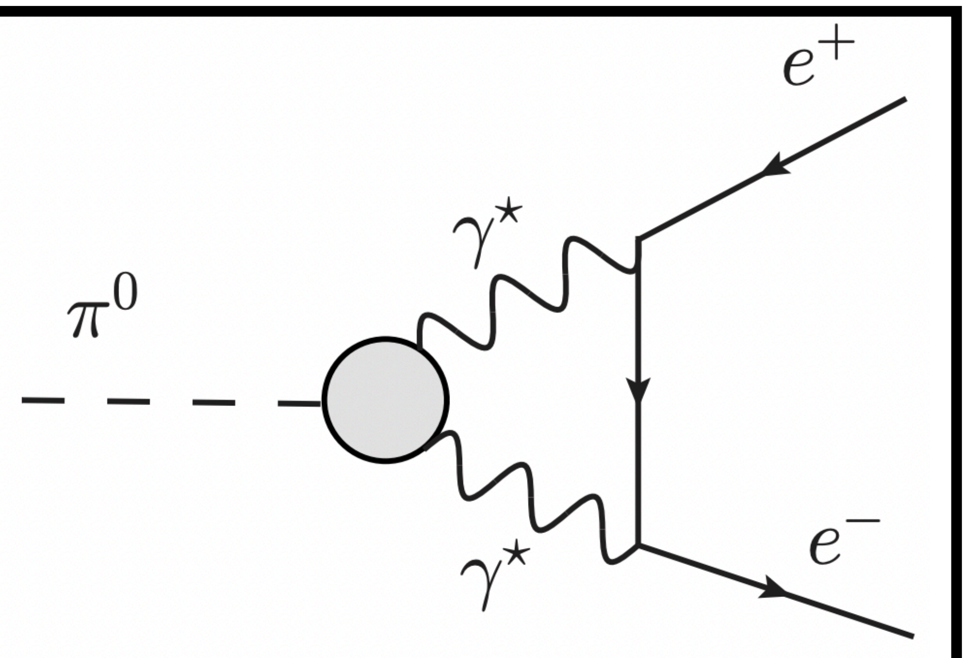
Study of $K^+ \to \pi^+\pi^0,\ \pi^0 \to e^+e^-$

[new: spring 2024]

- Experimentally observable BR:
  $\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > x_{cut})$ where $x = m_{ee}^2/m_{\pi^0}^2$
- Using latest radiative corrections [JHEP 10 (2011) 122], [Eur.Phys.J.C 74 (2014) 8, 3010] this result can be extrapolated to the full phase-space and compared to theory:

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

- Diagram for $\pi^0 \to e^+e^-$:
  - considered in theoretical predictions , with various $\pi^0 \to \gamma^*\gamma^*$ transition form factors

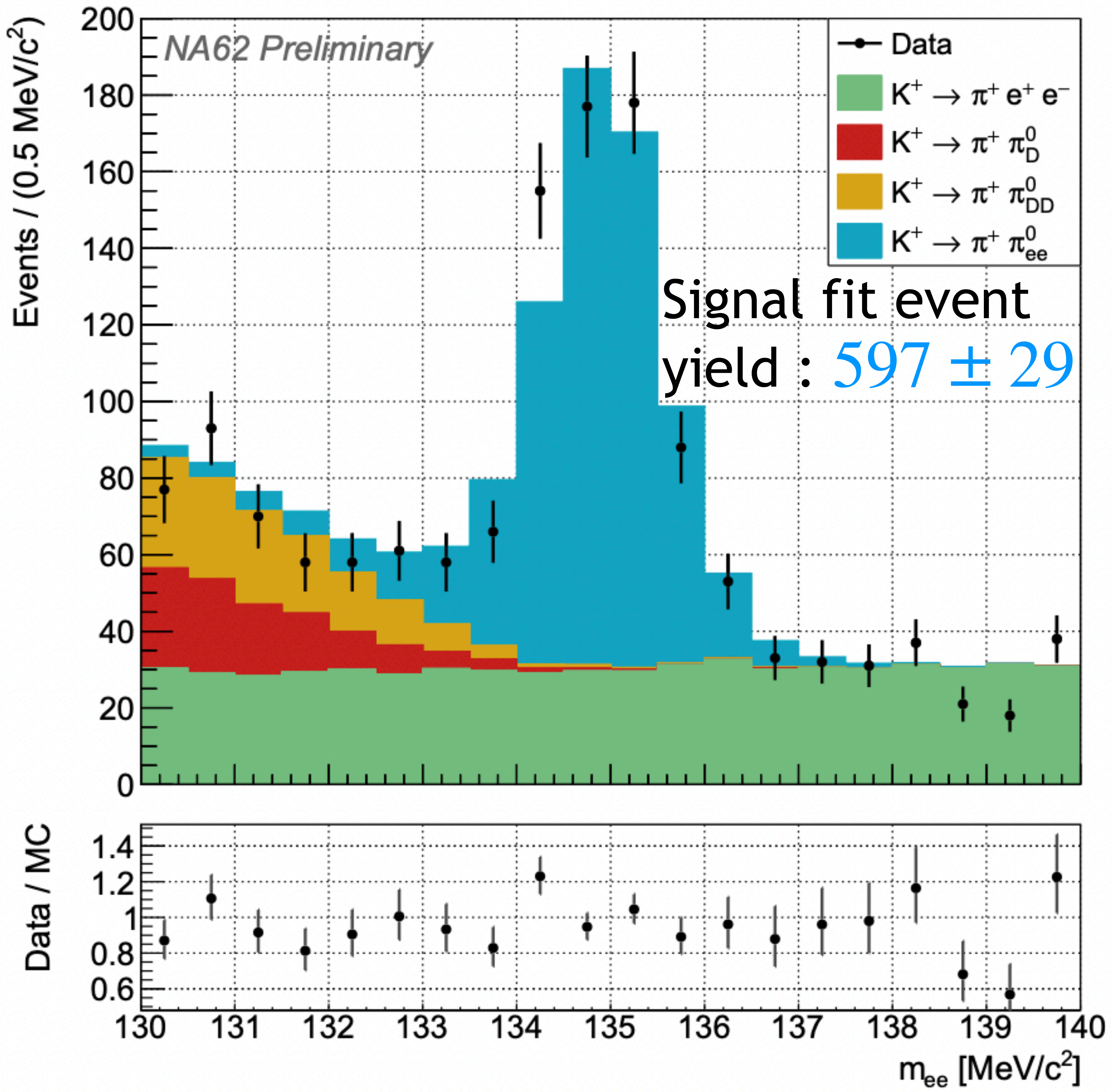


$$\mathcal{B}(\pi^0 \to e^+e^-) = (5.86 \pm 0.37) \times 10^{-8}$$

[New: NA62 for $x > 0.95$]

Using NA62 **2017+2018 Data:**

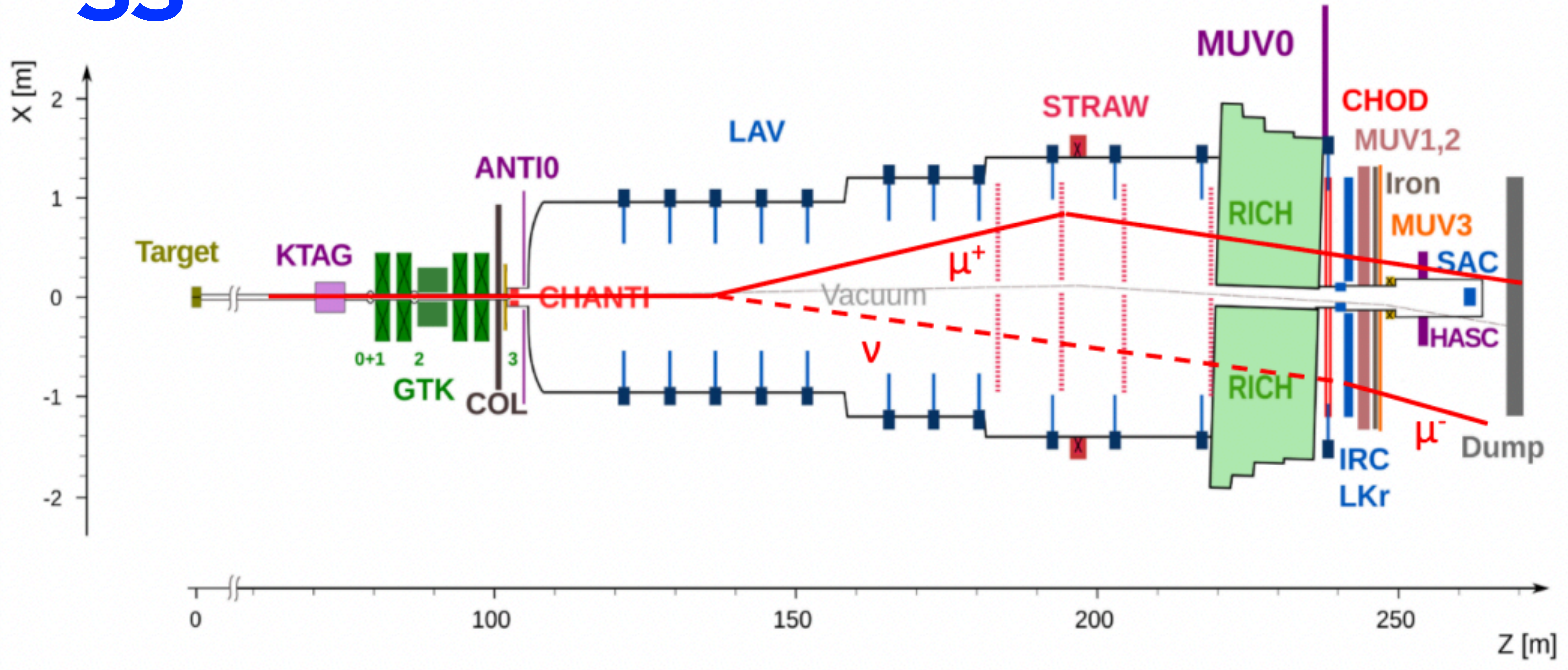
- Normalise to $K^+ \to \pi^+e^+e^-$ (almost all cuts identical)
- Trigger with downscaling ~8 and 90% efficiency

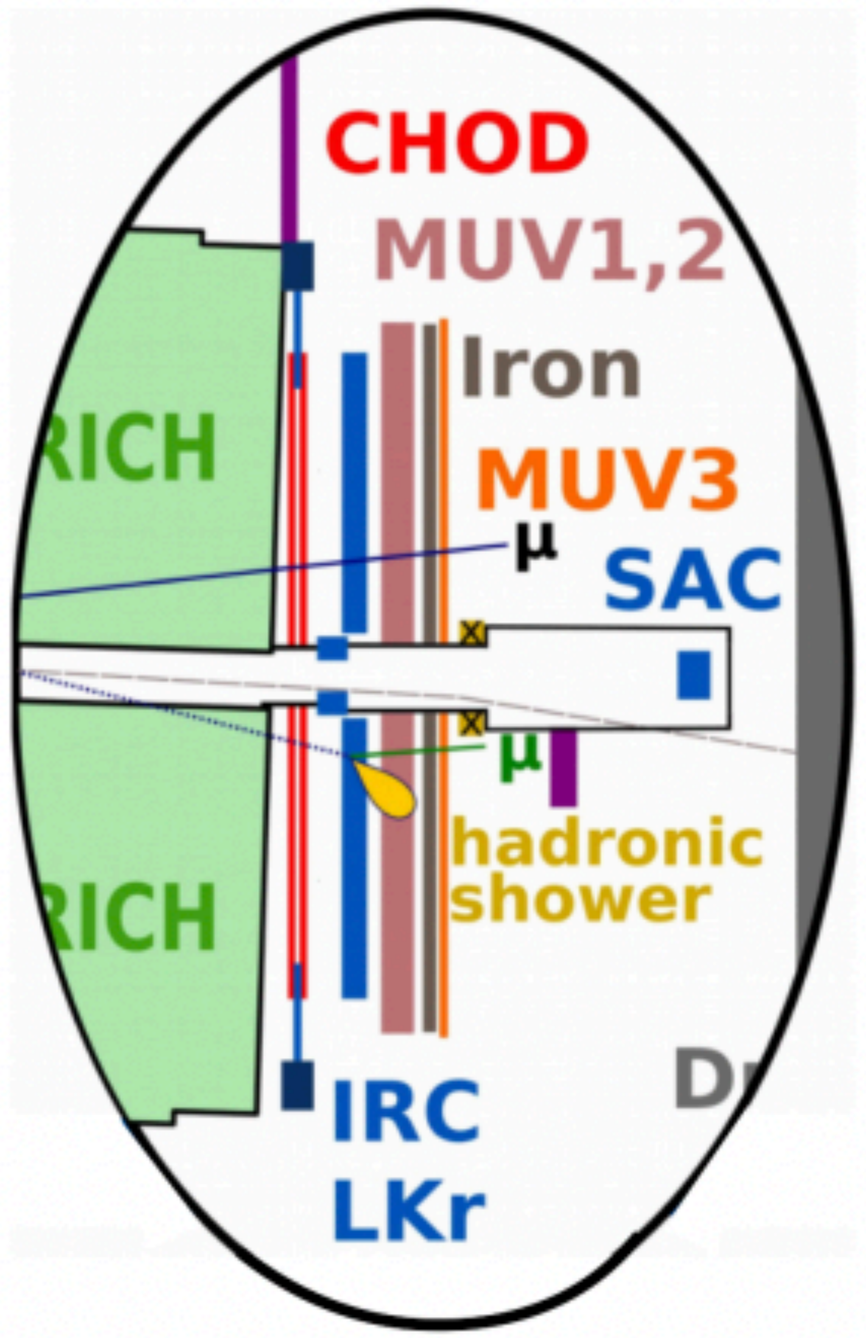


Signal fit event yield : 597 ± 29

Tagged neutrinos at NA62

[De Martino, NuFact23]





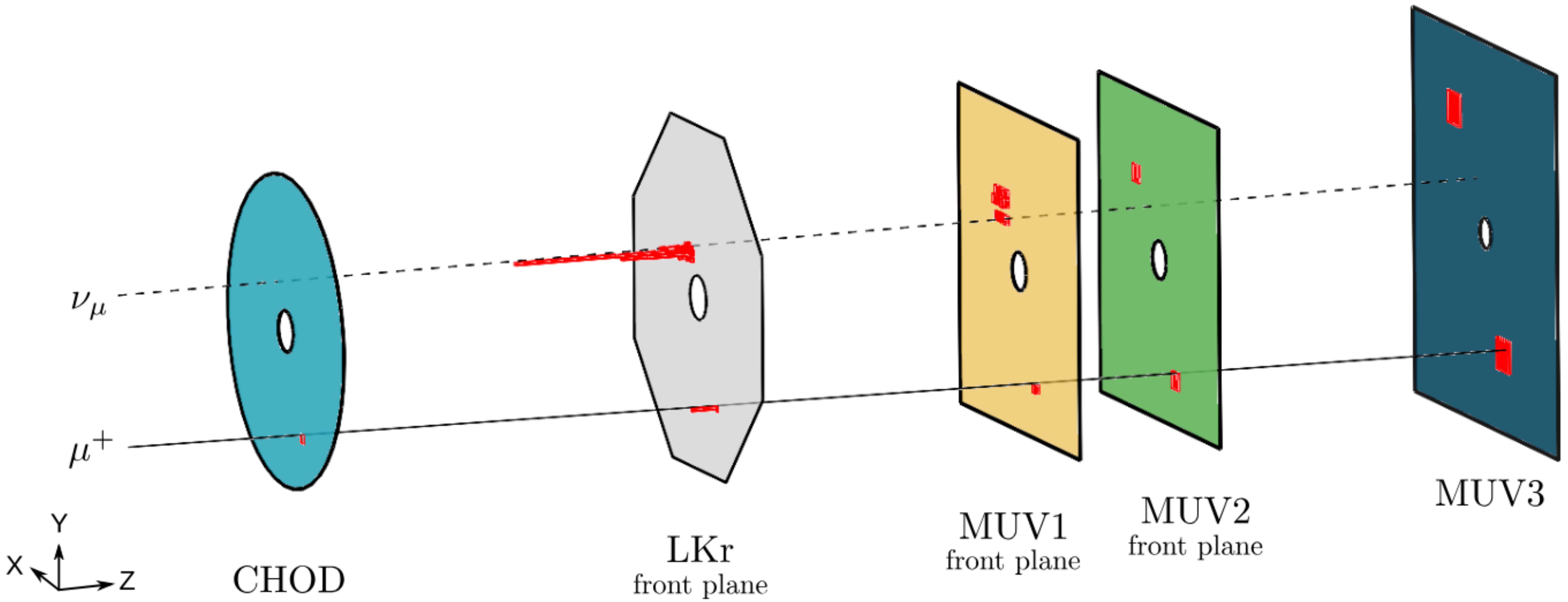
- Goal: search for $K^+ \to \mu^+ \nu_\mu$ with:
  - K^+ and μ^+ detected by GTK and STRAW trackers as usual.
  - ν_μ interacting in LKr calorimeter (20 tons of Liquid Kr, MUV12 66ton HCAL)
- ν_μ Interaction probability $\mathcal{O}(10^{-11})$: CC-DIS $\nu_\mu \to \mu^- +$ shower
  - Trigger based on μ^+, μ^- and shower activity.

Tagged neutrinos at NA62

[New: arXiv:2412.04033, Dec2024]

- Using **2022 NA62 data:**
- Expected signal:
  $N^{exp}_{signal} = 0.208 \pm 0.013_{\text{stat}} \pm 0.009_{\text{syst}}$
- Background (dominated by $K^+ \to \mu^+\nu$ + pileup):
  - $N^{exp}_{bg} = 0.034^{+0.041}_{-0.023}|_{\text{stat}} \pm 0.004_{\text{syst}}$

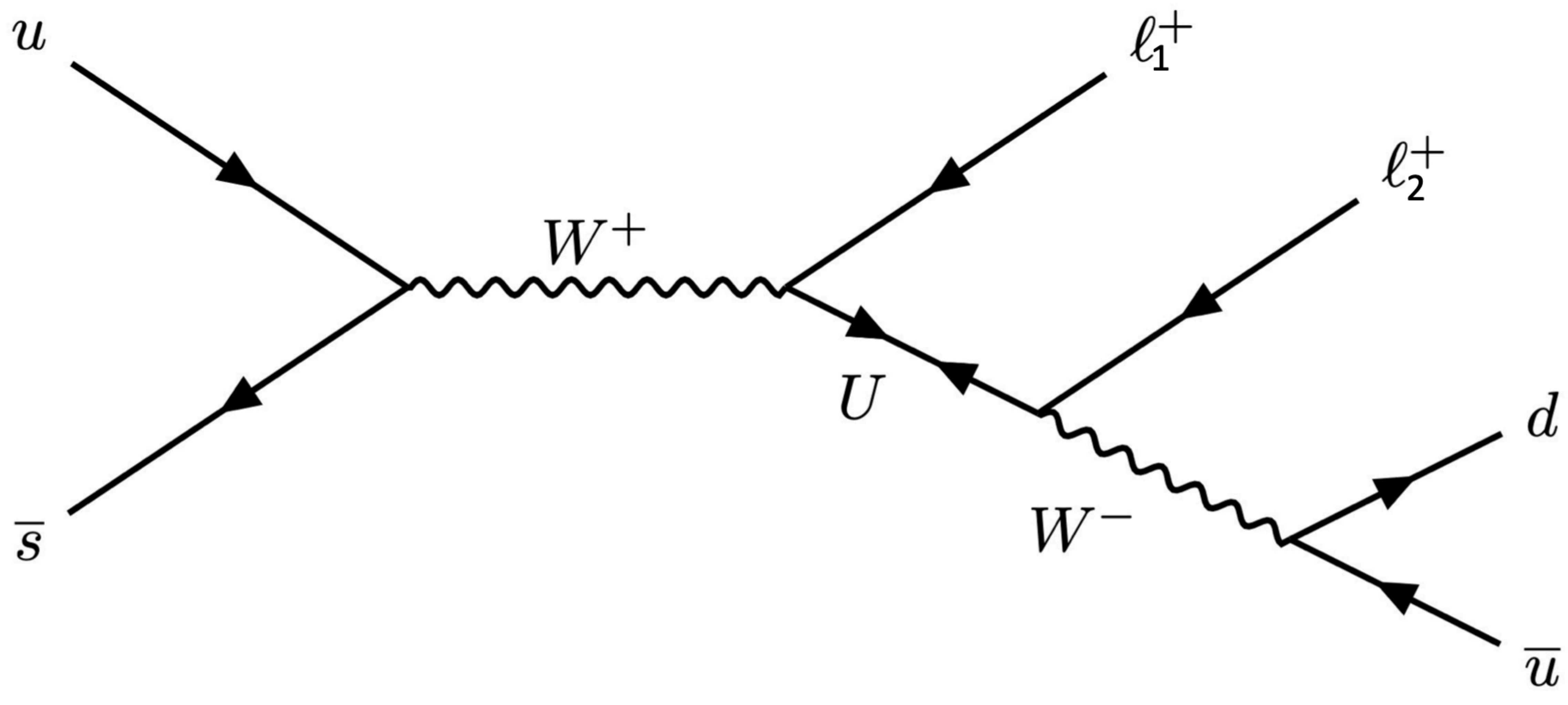
- **Detect 1 candidate $K^+ \to \mu^+\nu$ tagged ν event!**
- Demonstrates the feasibility of the neutrino tagging technique.



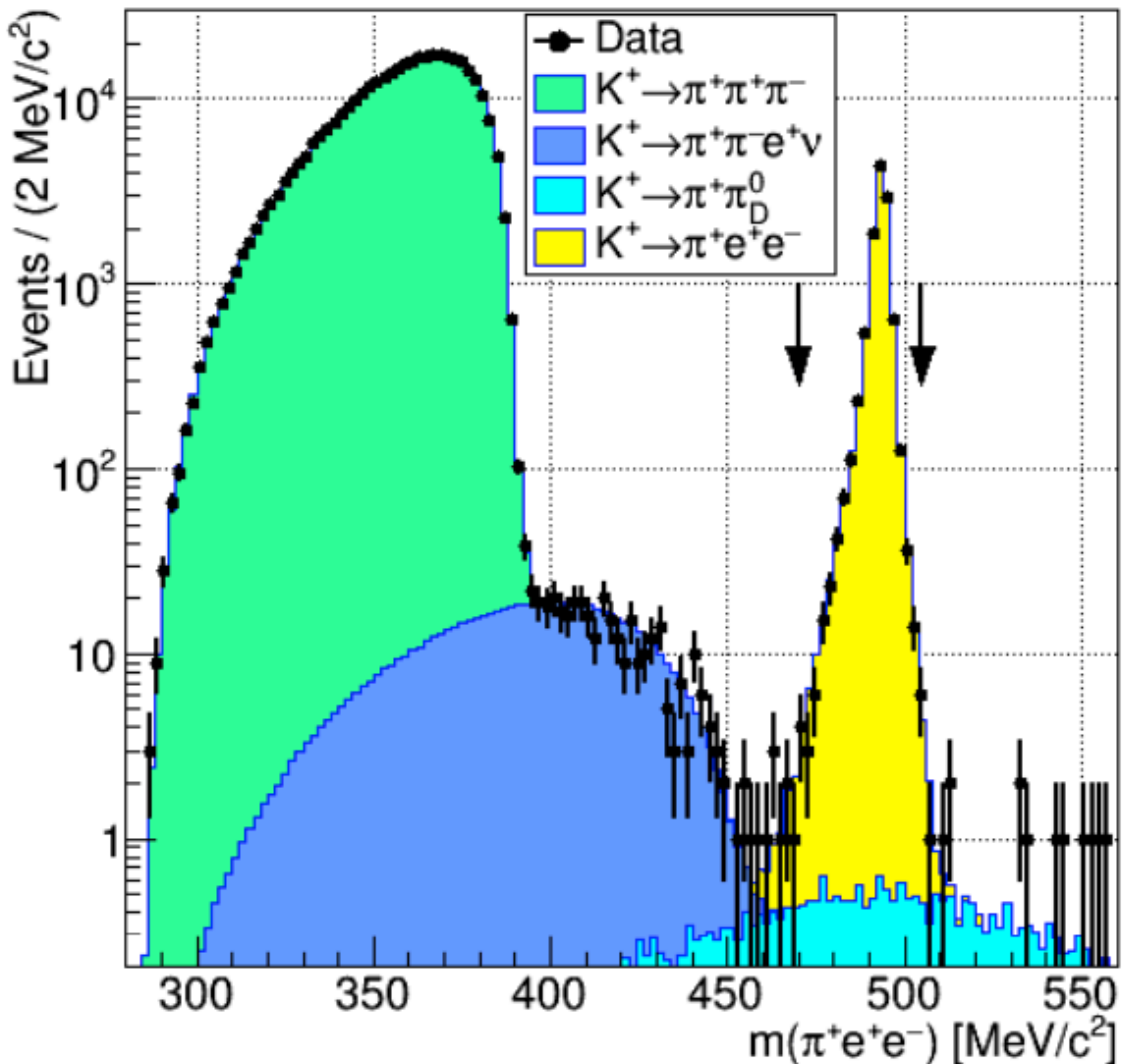
Forbidden K^+ Decays

Searches for CLFV/LNV Decays at NA62

- Observation of Lepton Number/Flavour Violating (LNV/CLFV) processes would be a clear indication of BSM physics.
- E.g. $K^+ \to \pi^- \ell_1^+ \ell_2^+$ via exchange of Majorana Neutrinos (analogue to $0\nu\beta\beta$ decays) [JHEP 05 (2009) 030] [PLB 491 (2000) 285].



- Use Run1 (2016—18) data set.
  - Use 3 Multi-track triggers (Downscaled by factors of $\mathcal{O}(10)$).
- Normalise to 'similar' SM decay, often $K^+ \to \pi^+ e^+ e^-$:

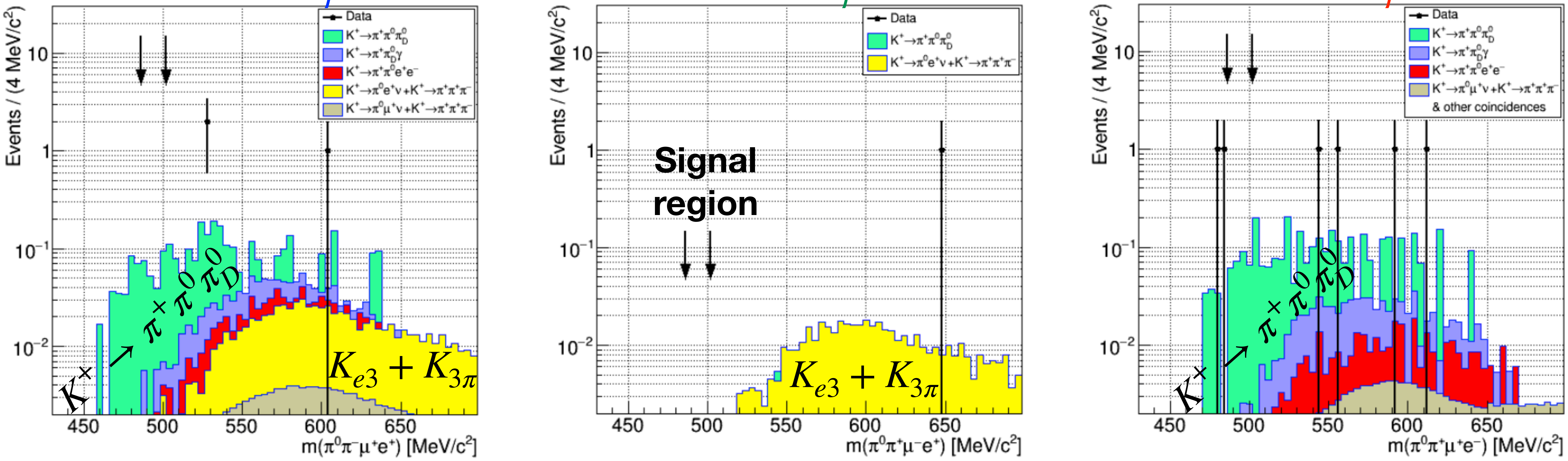


Search for $K^+ \to \pi^0 \pi \mu e$

PLB 859 (2024) 139122

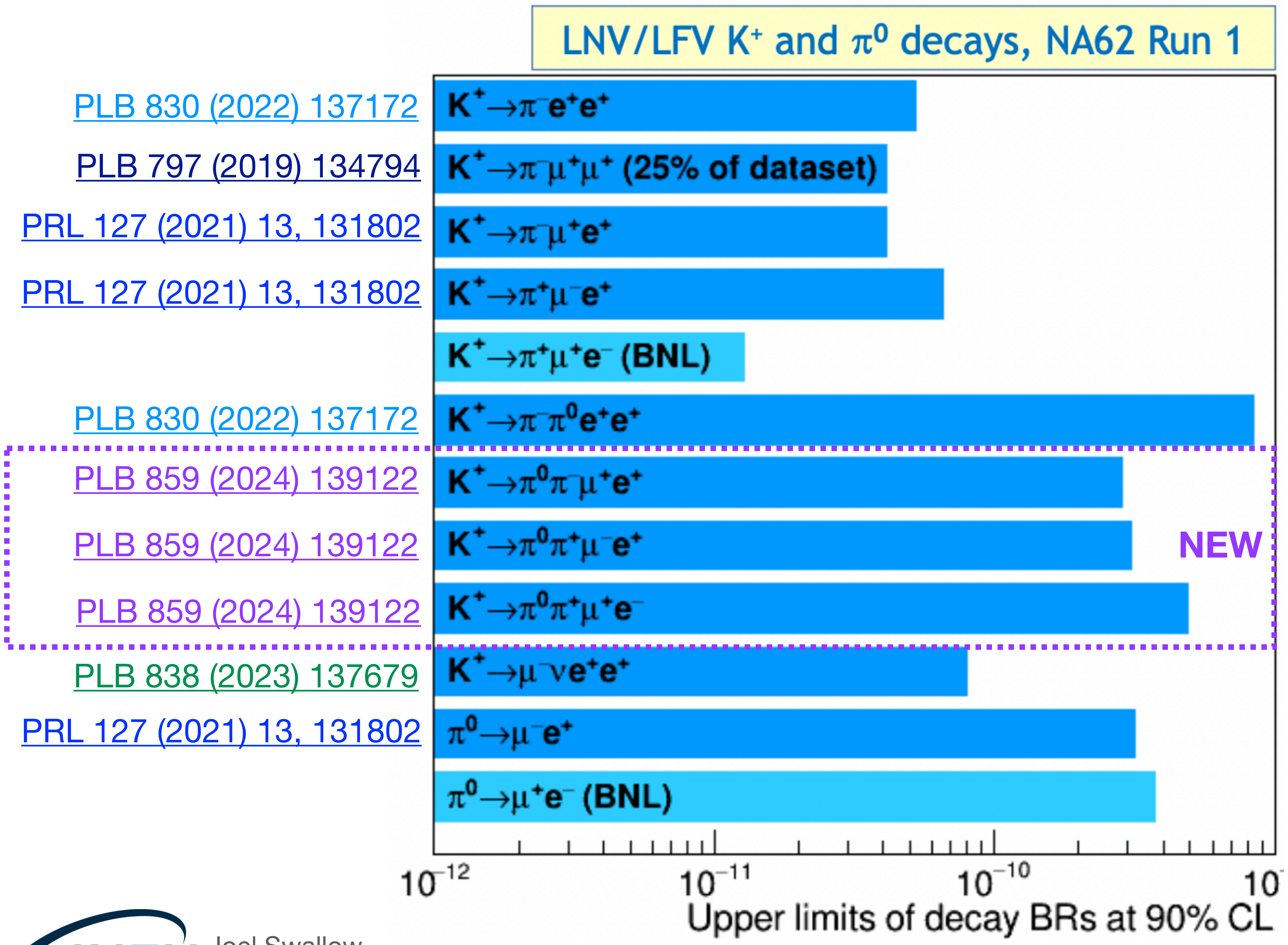
Mode	Expected background	Candidates observed	$\mathcal{B}$ Upper limit at 90% CL
$K^+\pi^0\pi^-\mu^+e^+$	0.33 ± 0.07	0	2.9×10^{-10}
$K^+\pi^0\pi^+\mu^-e^+$	0.004 ± 0.003	0	3.1×10^{-10}
$K^+\pi^0\pi^+\mu^+e^-$	0.29 ± 0.07	0	5.0×10^{-10}

$K^+ \to \pi^0\pi^-\mu^+e^+$ $K^+ \to \pi^0\pi^+\mu^-e^+$ $K^+ \to \pi^0\pi^+\mu^+e^-$



- Novel feature: backgrounds from pair of coincident K^+ decays.

Searches for CLFV/LNV Decays at NA62



- Comprehensive set of CLFV/LNV searches in K^+ decays.
- Strong prospects for further improvements due to:
  - 2021—LS3 data
  - updates to multi-track triggers and reduced downscaling.

Exotic Processes

NA62 in beam dump mode

- target removed and TAX closed, KTAG and GTK not used:

- Search for LLP produced in TAX (beam dump) flying into FV and decaying to visible SM particles detected downstream.

Search for LLP X (Dark photon, scalar, ALP)

- **Dark Photon: A'**
  - Bremsstrahlung production: $P \to A'\gamma$, $V \to A'P$ in TAX
  - Decay to di-lepton in FV: $A' \to e^+e^-$ [JHEP 09 (2023) 035] or $A' \to \mu^+\mu^-$ [arXiv.2312.12055].

- **Extensive search for hadronic final states: [new for spring 2024]**
  - $\Rightarrow$ numerous production and decay channels:

DP	DS	ALP
$\pi^+\pi^-$	$\pi^+\pi^-$	$\pi^+\pi^-\gamma$
$\pi^+\pi^-\pi^0$		$\pi^+\pi^-\pi^0$
$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$
		$\pi^+\pi^-\eta$
K^+K^-	K^+K^-	
$K^+K^-\pi^0$		$K^+K^-\pi^0$

  - ALP: Primakoff (on-, off-shell), mixing with $P = \{\pi^0,\eta,\eta'\}$, $B^{\pm,0} \to K^{\pm,0,(\star)}a$
  - DP: Bremsstrahlung, $P \to A'\gamma$, $V \to A'P$ $(V = \{\rho, \omega, \phi\})$
  - DS: $B^{\pm,0} \to K^{\pm,0,(\star)}S$
  - Altogether 36 combinations of production and decay channels studied

[Spadaro, Vulcano24]

Backgrounds

$A' \to e^+e^-$ [JHEP 09 (2023) 035]: $N_{\text{bkg}}^{\text{CR}} = 9.7^{+21.3}_{-7.3} \times 10^{-3}$, $N_{\text{bkg}}^{\text{SR}} = 9.4^{+20.6}_{-7.2} \times 10^{-3}$

$A' \to \mu^+\mu^-$[PRL 133 (2024) 11, 111802]:

Table 4: Summary of expected numbers of background events for the search of $A' \to \mu^+\mu^-$ with the related uncertainty. The limits reported are defined with a 90% CL.

Region	Combinatorial	Prompt	Upstream-prompt
VR	0.17 ± 0.02	< 0.004	< 0.069
SR	0.016 ± 0.002	< 0.0004	< 0.007

Hadronic final states:

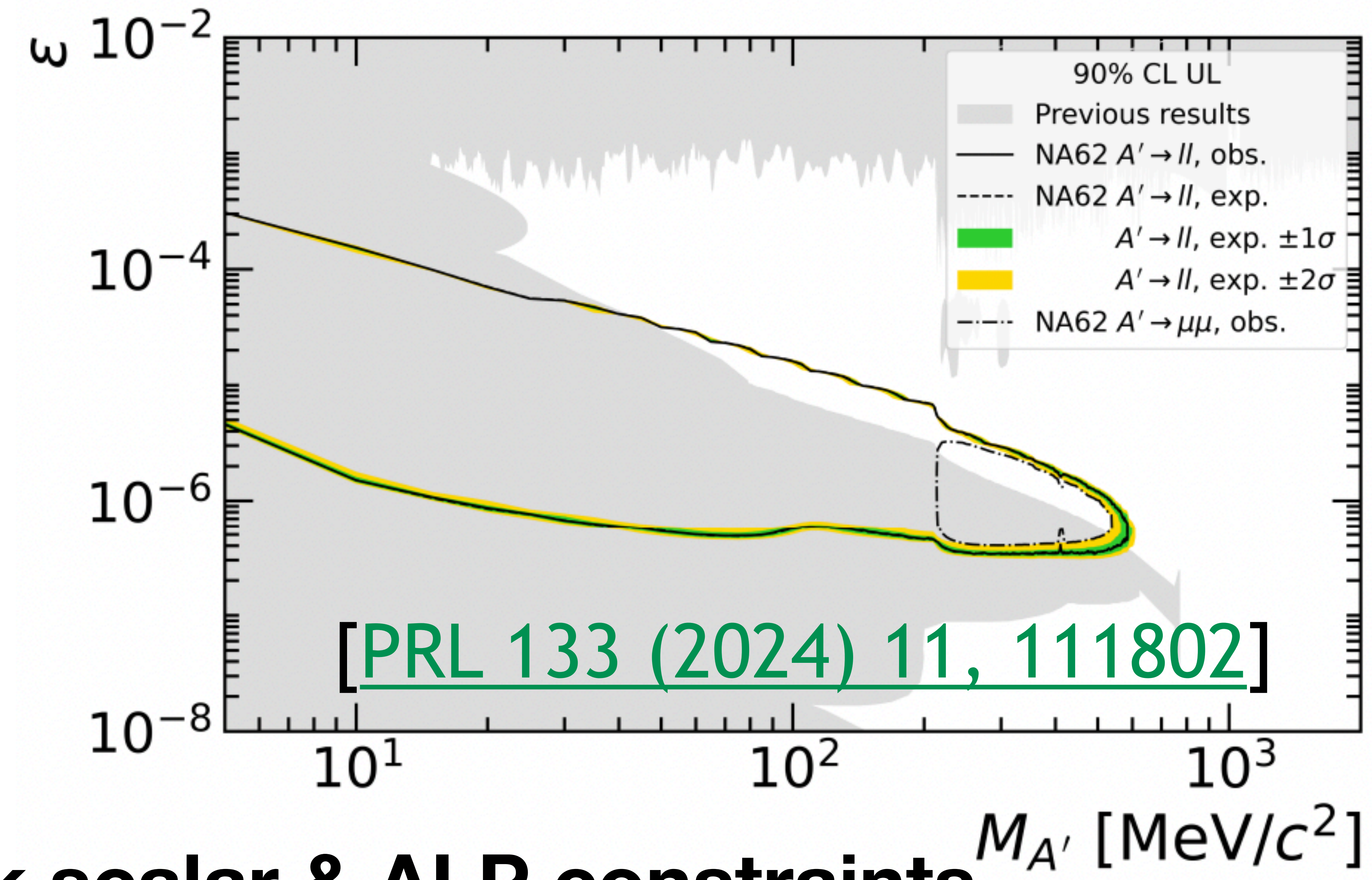
Channel	$N_{\text{exp,CR}} \pm \delta N_{\text{exp,CR}}$	$N_{\text{exp,SR}} \pm \delta N_{\text{exp,SR}}$	$N_{\text{obs,SR}}^{p>5\sigma}$	$N_{\text{obs,SR+CR}}^{p>5\sigma}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004	3	5
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$	1	1
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$	1	1
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$	1	1
K^+K^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$	1	2
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$	1	1

All final regions almost background-free, 5σ discovery for 1 event for some cases…

Results:

- e^+e^- : 0 observed
- $\mu^+\mu^-$: 1 observed (p=1.6%, 2.4σ global significance)
- 25 Hadronic channel signal regions: 0 events.
- Therefore set upper limits…

Dark photon mixing/coupling strength vs mass for $A' \to \ell^+\ell^-$ searches



Hadronic final states: dark scalar & ALP constraints