Status and prospects of Rare Kaon decay searches at NA62 and KOTO

WIFAI 2025

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on behalf of NA62 collaboration

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Outline

- NA62 last measurement of BR($K^+ \rightarrow \pi^+ \nu\nu$) with 2021-2022 data
- KOTO last upper limit on BR($K_L \rightarrow \pi^0 \nu\nu$) with 2021 data
- NA62 other physic results

K ⟶ πνν decay: precision test of the SM

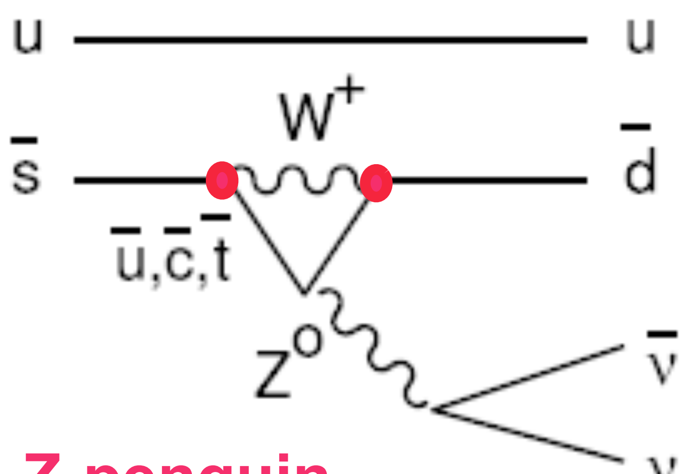
When a rare decay is useful as a New Physics probe?

- Process (strongly) suppressed in the SM
- Parameter to be measured precisely calculated in SM
- There are specific predictions for NP contributions

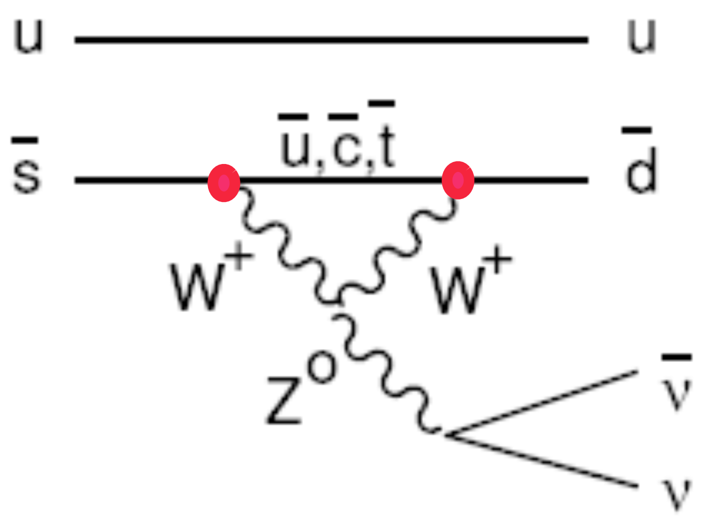
Kaon decay experiments are the quintessential precision frontier experiments

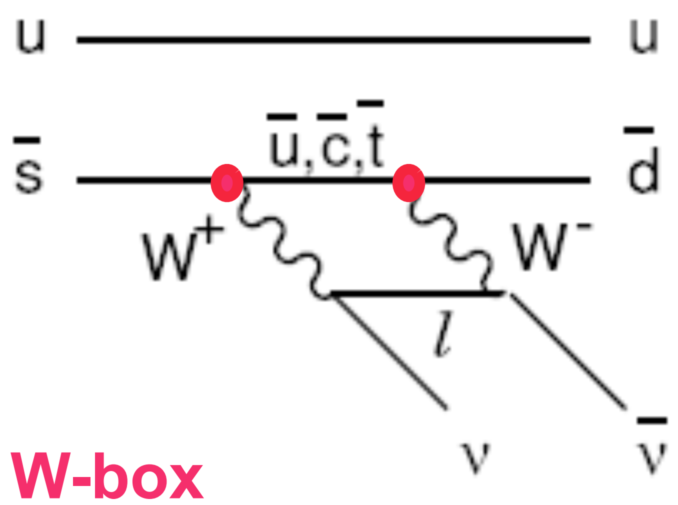
Large statistic ⟶ **Few decay modes** ⟶ **Simple final states**

The golden modes K ⟶ πνν (intrinsic theoretical uncertainty ~ 1%)



Z-penguin





W-box

- s ⟶ dνν FCNC transition extremely suppressed by GIM mechanism
- Forbidden at tree level, dominated by short distance contributions
- K-π form factor extracted from well known BR($K^+ \to \pi^0 e^+ \nu_e$)

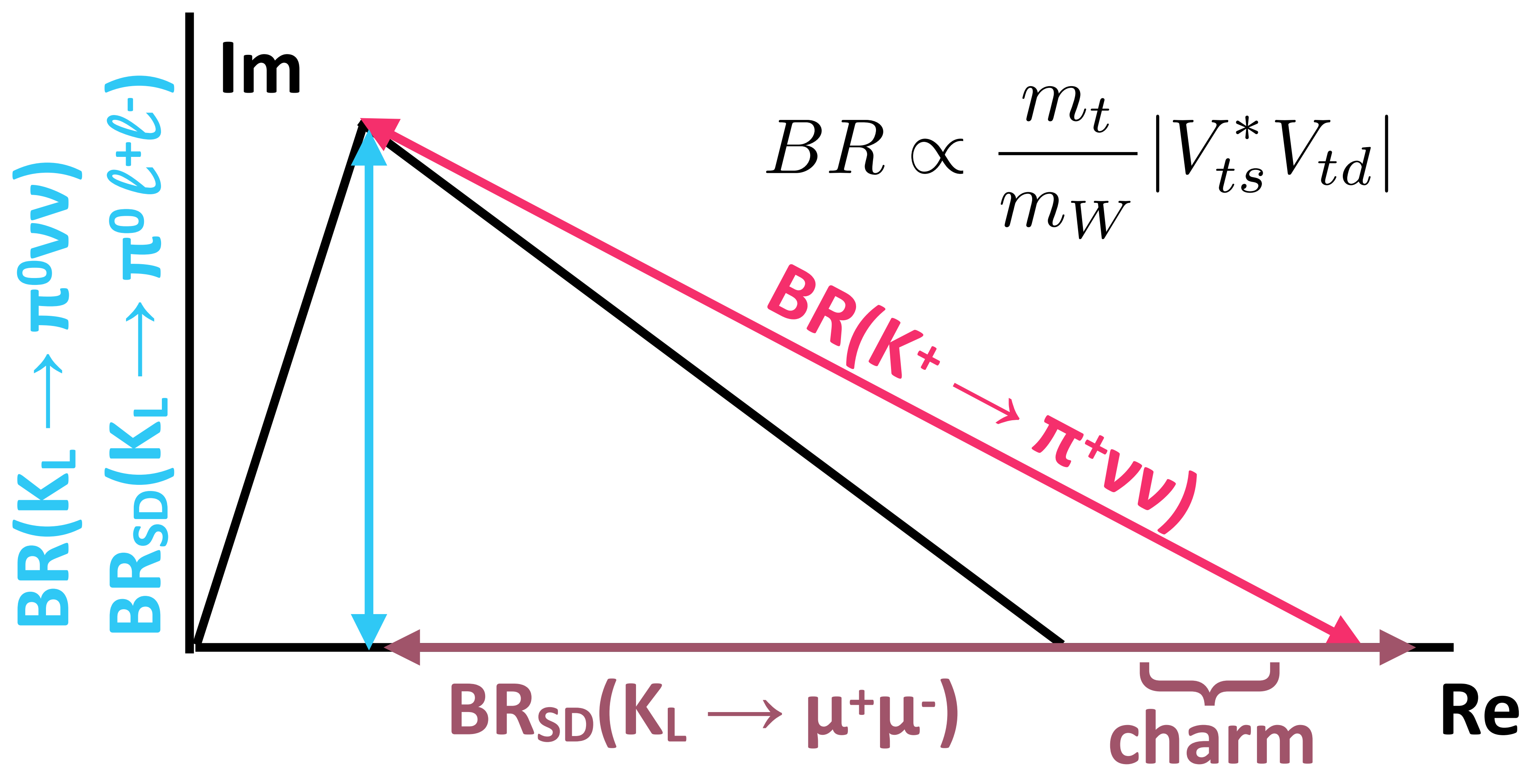
Mode	SM BR [1]	SM BR [2]
$K^+ \to \pi^+ \nu \bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$
$K_L \to \pi^0 \nu \bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$

Errors dominated by CKM input parameters

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

[2] D'Ambrosio et al. JHEP 09 (2022) 148

$K \to \pi\nu\nu$ decay: beyond the SM



BRs overconstraint CKM matrix

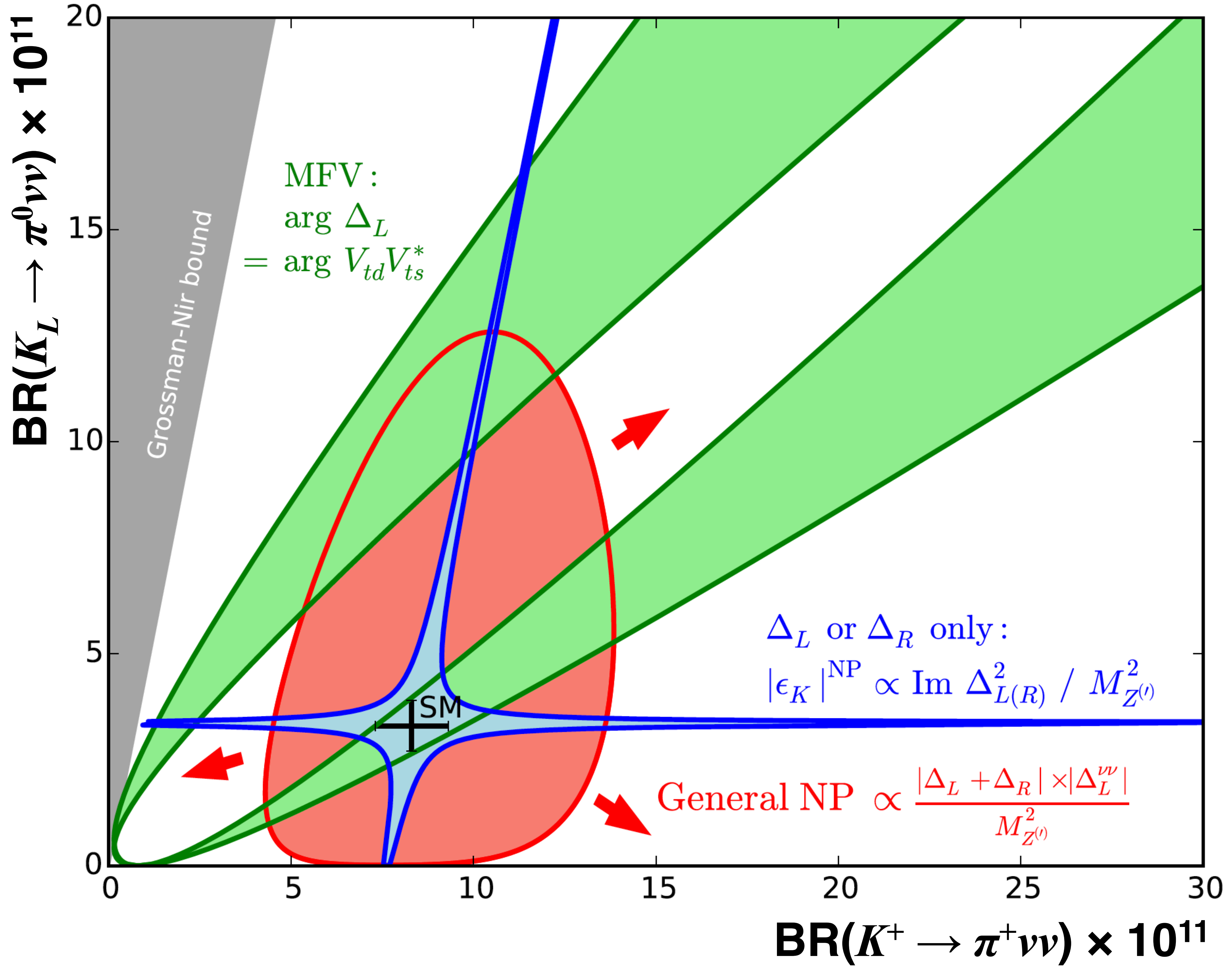
Measurement of BR($K^+ \to \pi^+\nu\nu$) and BR($K_L \to \pi^0\nu\nu$) can constrain the **unitarity triangle** independently from B inputs

Must measure both to discriminate between BSM scenarios.

High sensitivity to **new physics that affects both K^+ and K_L modes:**

- Models with **MFV** (CKM-like flavor structure)
- Flavor-violating interactions in which either LH or RH couplings dominate
  Z/Z′ models with pure LH/RH couplings, **Littlest Higgs with T parity**
- Models without above constraints: **Randall-Sundrum**

Correlations with other observables (ε'/ε, ΔM_B, B-decays) [2] [3] [4]



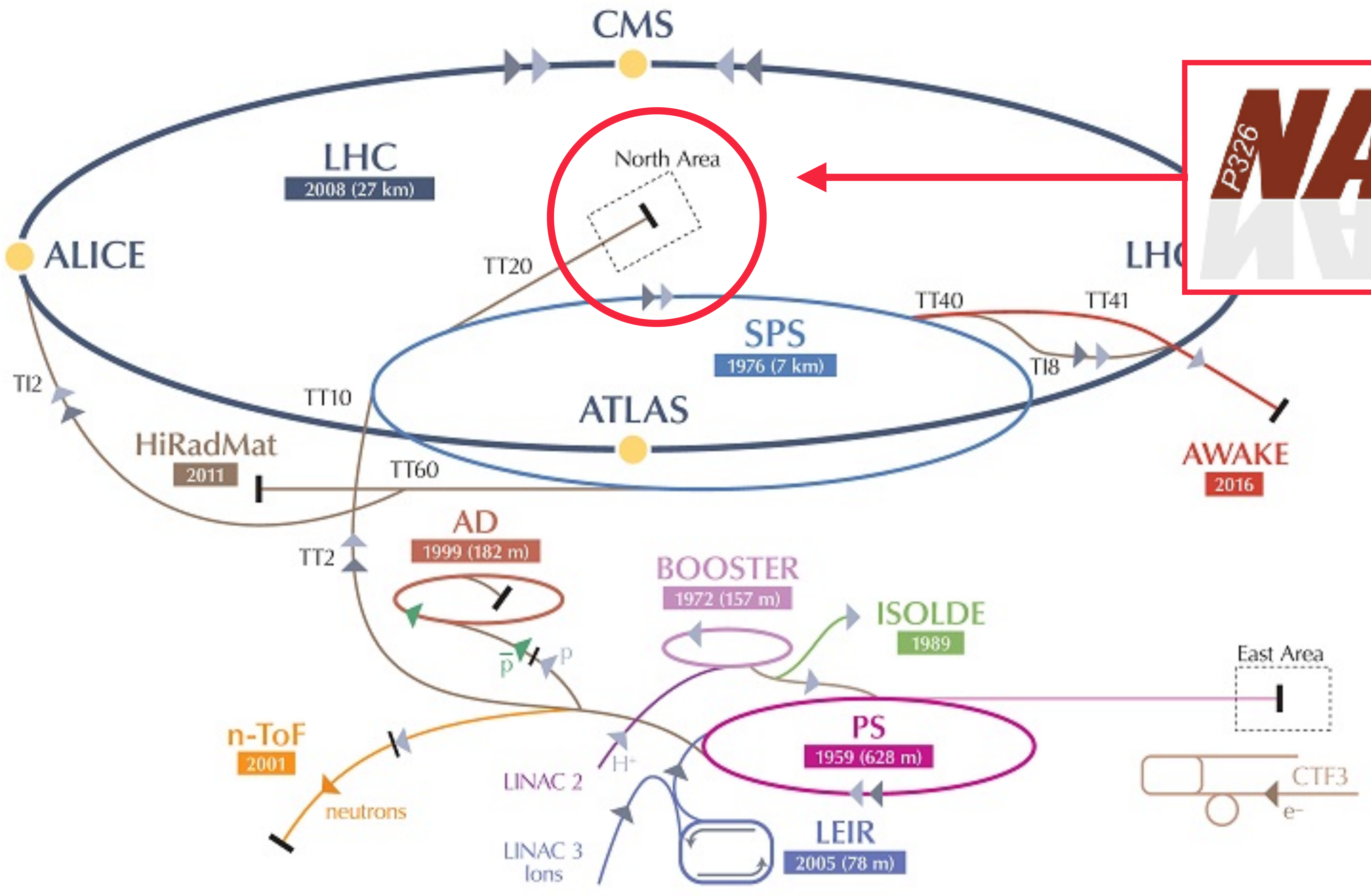
NA62 experiment at CERN: the K^+ factory

In the CERN SPS North Area the K12 extraction line provides an extremely intense Kaon beam

400 GeV/c **primary protons**
(3×10^{12} p/pulse, 4.8 s spills)

40 cm
Be target

75 GeV/c secondary **hadrons beam:**
π^+, p, K^+ . ($\Delta p/p \pm 1\%$).
~600 MHz beam particle rate ⇒ **36 MHz of K^+ (6%)**



NA62 has been designed for the measurement of the **BR($K^+ \to \pi^+\nu\nu$)**

Collaboration: ~ **200 participants** ~ **30 institutions**

History

- Commissioning: 2014-2016
- **RUN 1: 2016-2018**
- LS2
- **RUN 2: 2021-2026 (… ongoing)**
- LS3

NA62 experiment at CERN: the K^+ factory

- 270 m long downstream of the target
- Cylindrical shape around the beam axis for the main detectors
- Detector diameters from 20 cm to 4 m

NA62 detector

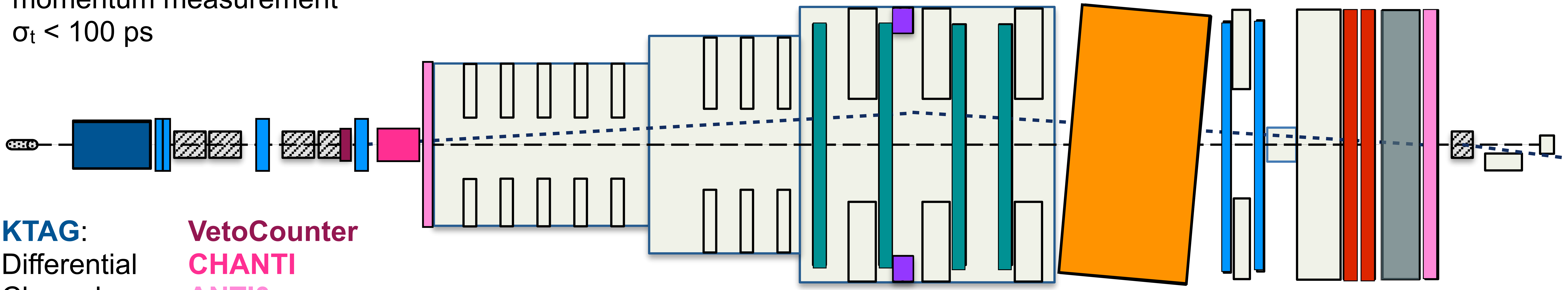
Hadron Beam →

GTK (GigaTracker): Silicon pixel spectrometer for momentum measurement
$\sigma_t < 100$ ps

STRAW tubes spectrometer:
$\sigma_p/p = (0.3 \oplus 0.005 \cdot p)\%$ [GeV/c]

RICH
Neon (1 atm)
Cherenkov $\sigma_t \sim 70$ ps
for particle ID ($\pi/\mu/e$)

CHODs scintillator hodoscopes for trigger and timing.
$\sigma_t = 200$ ps



KTAG:
Differential Cherenkov for Kaon Identification
$\sigma_t = 70$ ps

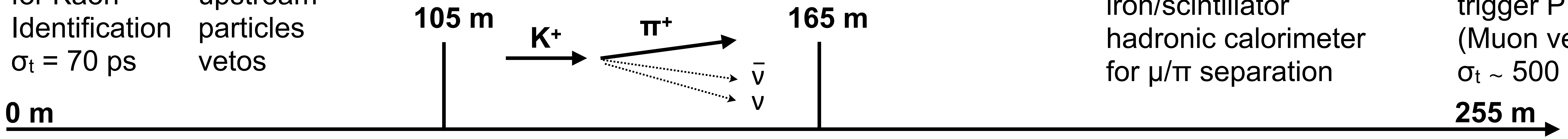
VetoCounter
CHANTI
ANTI0
upstream particles vetos

MAGNET

MUV1 & MUV2
iron/scintillator hadronic calorimeter for μ/π separation

IRON

MUV3
trigger PID (Muon veto)
$\sigma_t \sim 500$ ps



K⁺ identification in the beam and tracking

Fiducial decay region

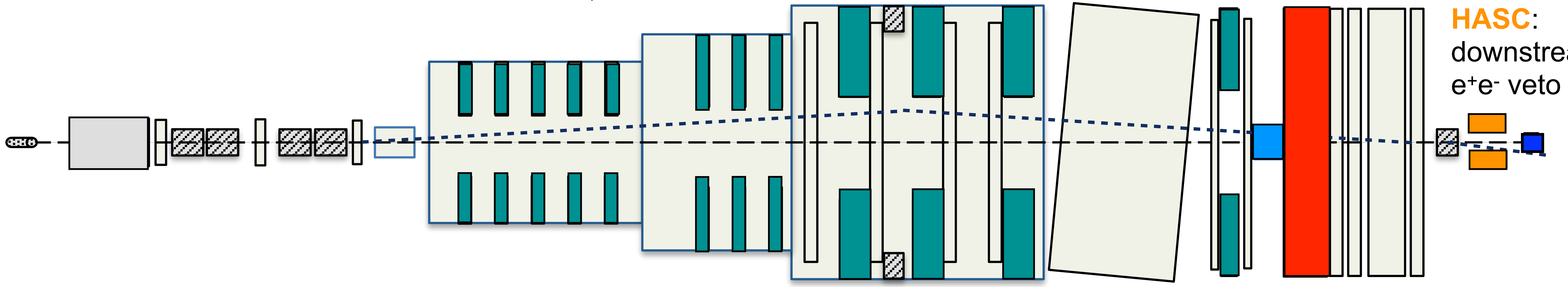
Secondary particles identification and tracking

NA62 detector

LAVs Large Angle Veto. 12 stations (lead glass blocks) to veto γ with $8.5 < \theta\gamma < 50$ mrad

LKr Calorimeter: to veto γ with $1 < \theta\gamma < 8.5$ mrad and for PID & energy reconstruction

HASC: downstream e^+e^- veto



IRC Inner Ring Calorimeter: shashlik

SAC Small Angle Calorimeter: shashlik

To veto γ with $\theta\gamma < 1$ mrad

Hermetic photon veto system to reject the main background: $K^+ \rightarrow \pi^+\pi^0 (\gamma\gamma)$

BR($K^+ \to \pi^+\nu\nu$): NA62 analysis strategy

Selection:

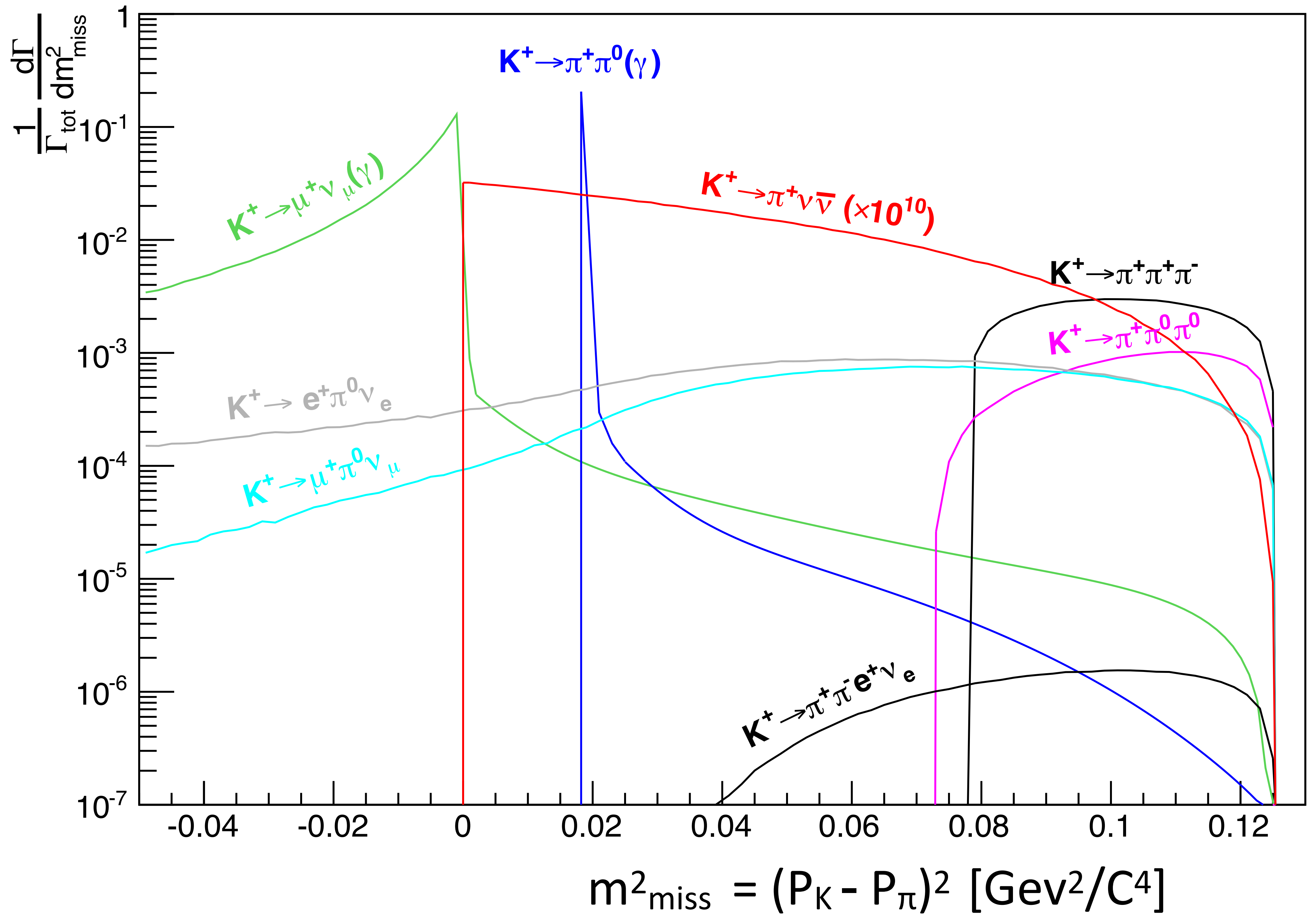
- K^+-ID and measure P_K
- π^+-ID and measure P_π
- K-π matching in time
- K-π vertex reconstruction in FV
- Reject ANY additional activity

Background sources:

- $K^+ \to \mu^+ \nu$ (63% of BR)
- $K^+ \to \pi^+\pi^0$ (21% of BR)
- $K^+ \to \pi^+\pi^+\pi^-$ non gaussian resolution tails
- Upstream interactions and decays

Performance:

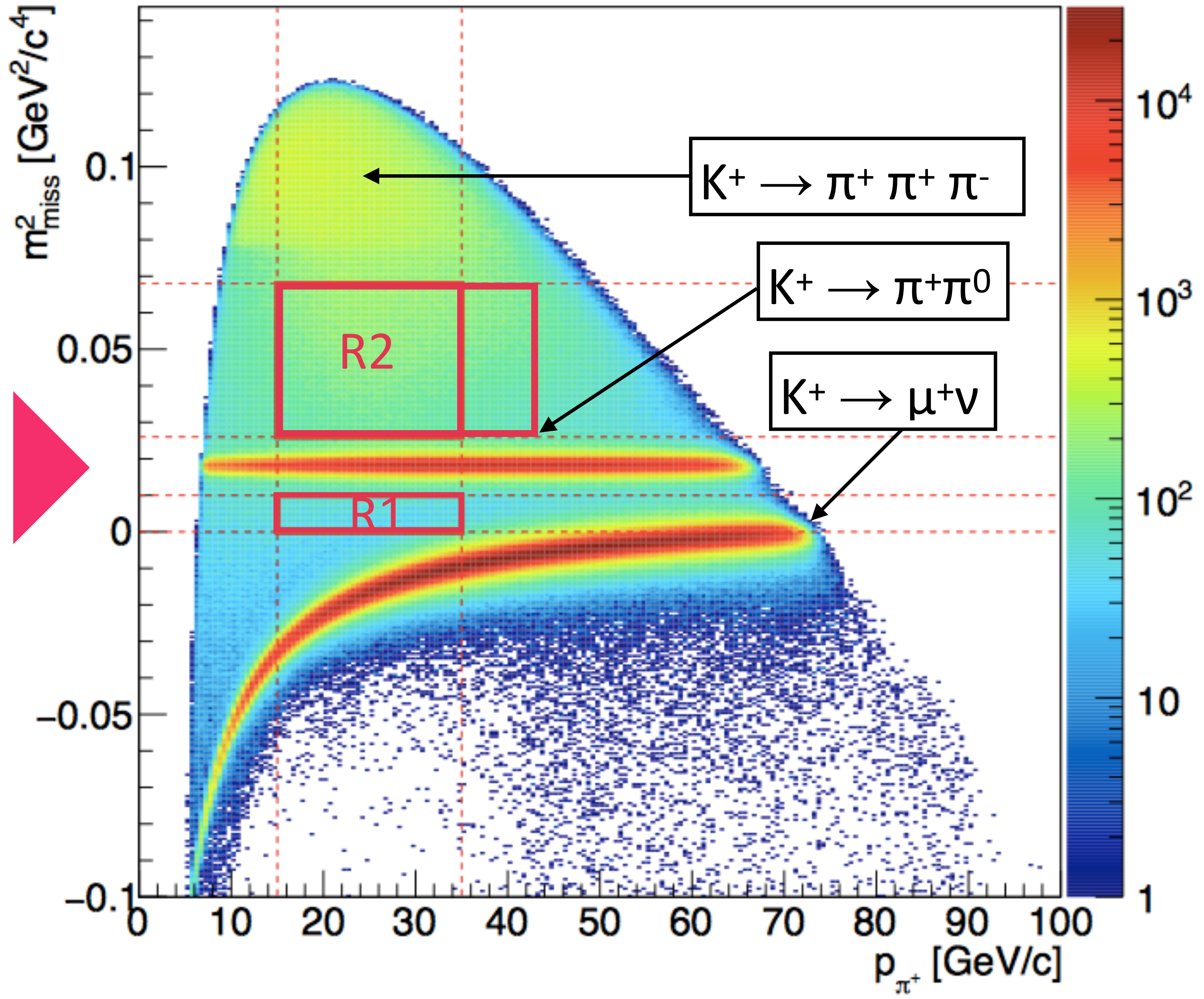
- $\sigma_T \sim O(100ps)$
- $\sim 10^4$ kinematic rejection
- $> 10^7$ μ^+ rejection (from $K^+ \to \mu^+ \nu$)
- $> 10^7$ π^0 rejection (from $K^+ \to \pi^+\pi^0$)



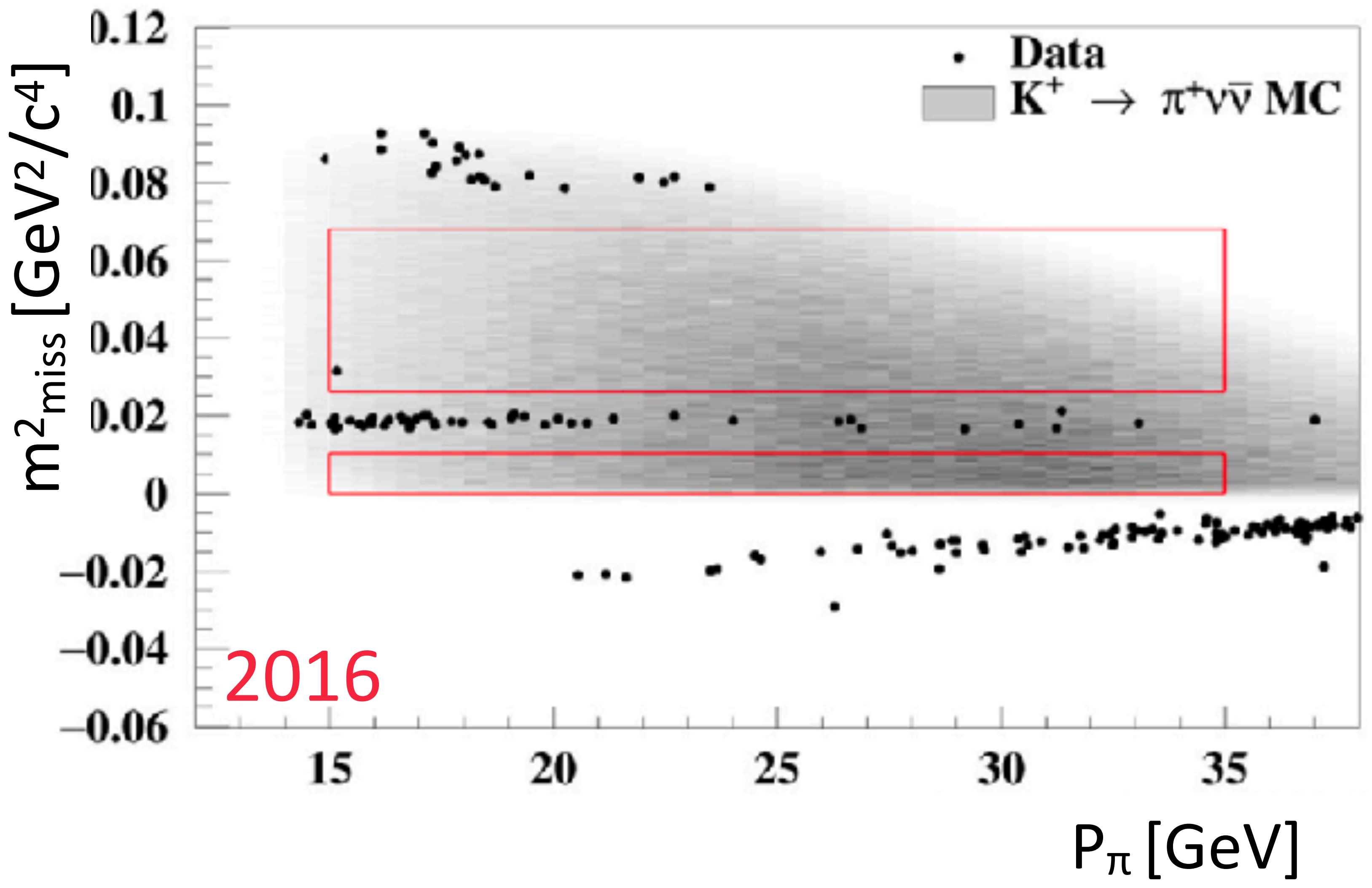
Most discriminating variable:
$m^2_{miss} = (P_{K+} - P_{\pi+})^2$

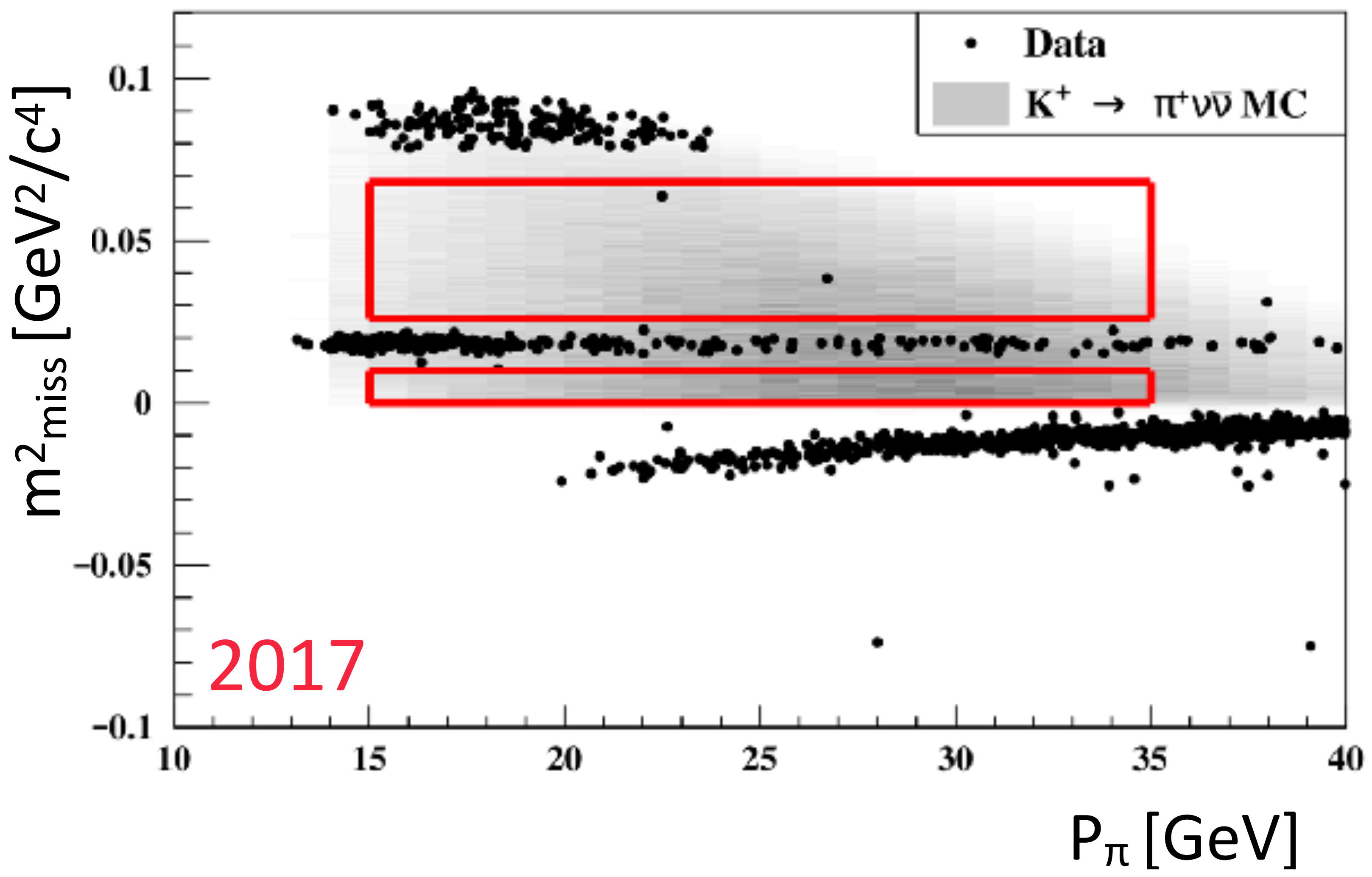
Control data with 1 single secondary track selection

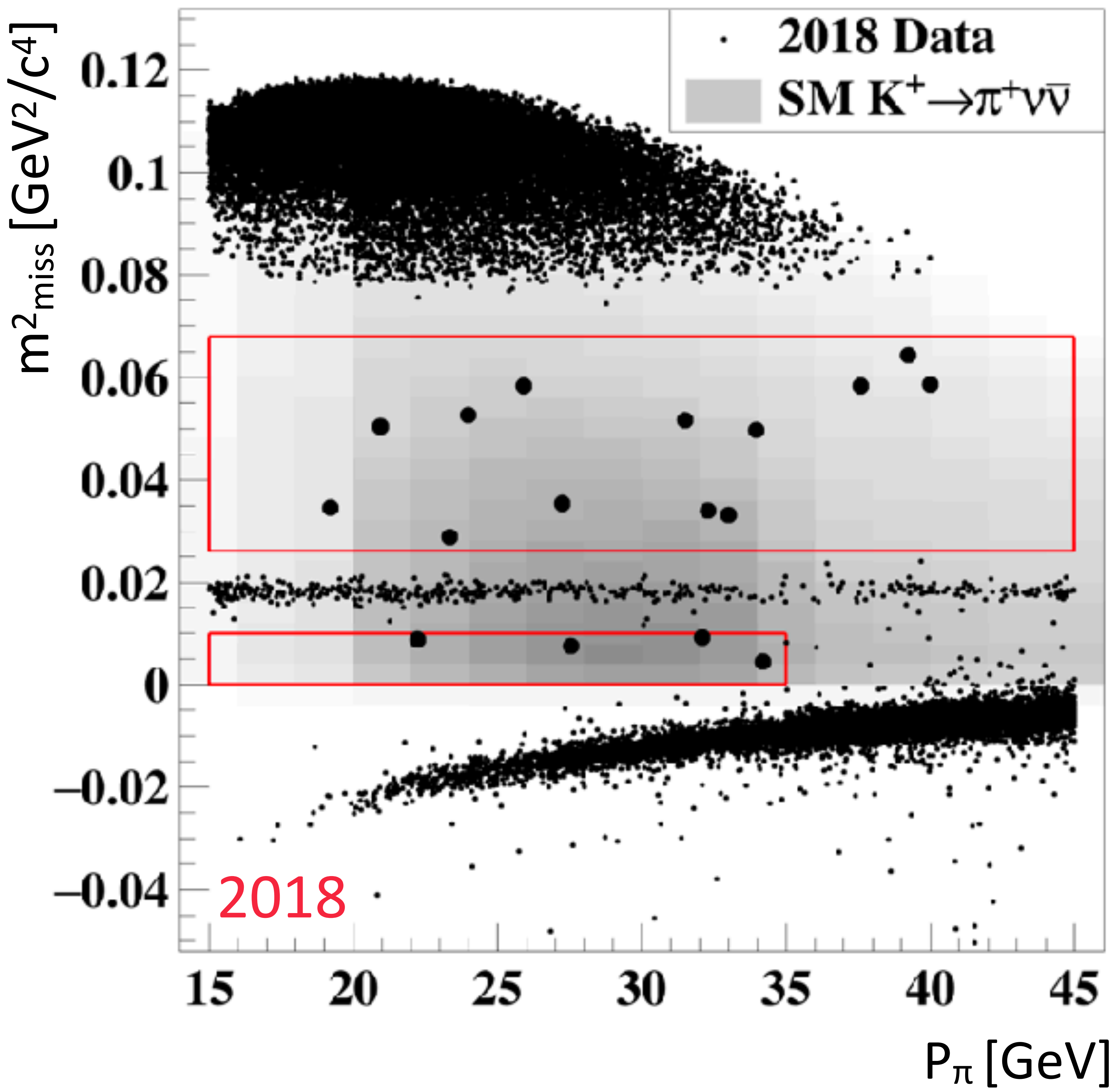
2 signal regions: on each side of $K^+ \to \pi^+\pi^0$ peak



BR($K^+ \longrightarrow \pi^+\nu\nu$): result from Run1 (2016-2018)







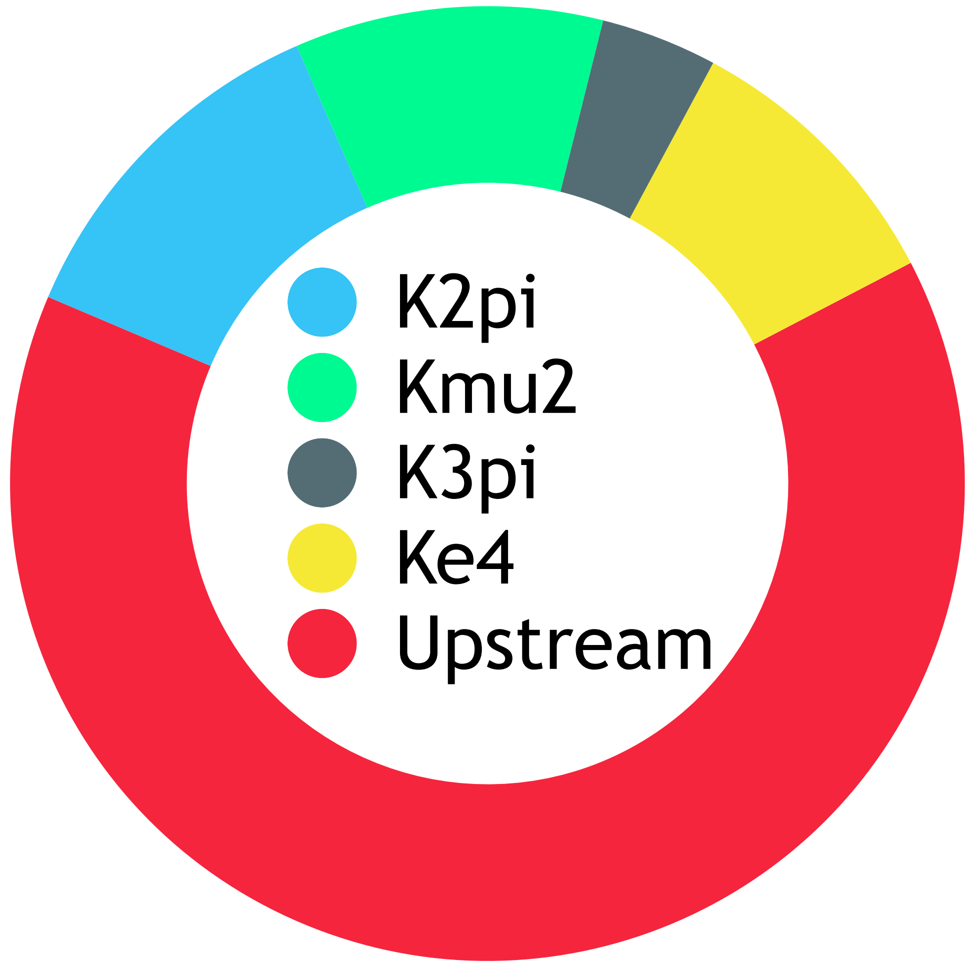
Data taking	Reference	N_{bg}^{exp}	$N_{\pi\nu\nu}^{exp(SM)}$	N_{obs}
2016	PBL 791 (2019) 156	$0.152^{+0.093}_{-0.035}$	0.267 ± 0.020	1
2017	JHEP 11 (2020) 042	1.46 ± 0.33	2.16 ± 0.13	2
2018	JHEP 06 (2021) 093	$5.43^{+0.99}_{-0.075}$	7.58 ± 0.40	17
2016-2018	JHEP 06 (2021) 093	$7.03^{+1.05}_{-0.82}$	10.01 ± 0.42	20

Background-only hypothesis:
p = 3.4 × 10^{-4} ⇒ **significance = 3.4 σ**

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}{}_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

NA62 upgrades in view of Run 2

Background contributions



Run 1 analysis proved NA62 technique

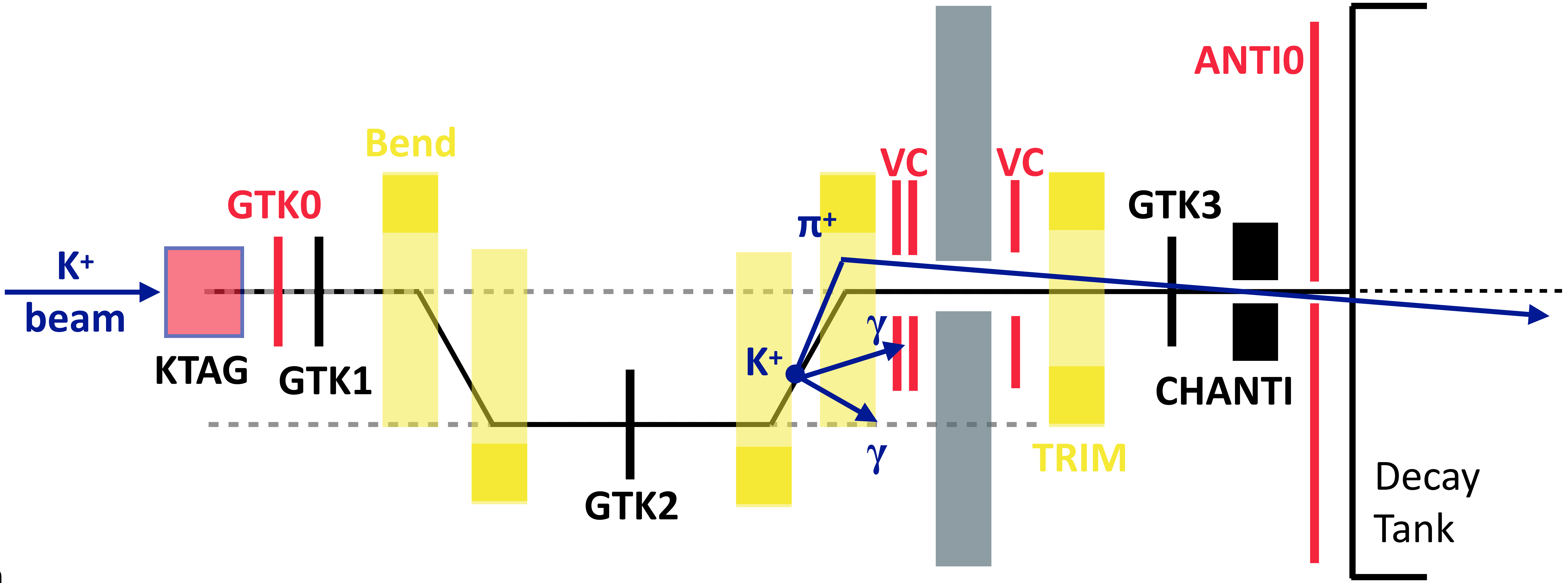
- Limitations: tight cuts to reject background $\Longrightarrow$ signal efficiency reduced
- To improve: new tools for background suppression

Main backgrounds:

- **Beam interaction and K^+ decays upstream of fiducial volume**
- **$K^+ \longrightarrow \pi^+\pi^0$**

Hardware improvements after LS2:

- A **4^{th} GTK** station for the K^+ tracking
- **VetoCounter(VC)** to reduce upstream background
- **ANTI0** to reduce muon halo
- **Cedar-H (KTAG)**: Cherenkov for K^+-ID with Hydrogen in place of Nitrogen
- **HASC** calorimeter **downstream** to intercept e^+e^- from γ (of π^0) conversion



Single event sensitivity 2021-2022

Branching ratio corresponding to expectation of 1 event:

$$B_{SES} = \frac{BR(K^+ \to \pi^+ \nu\bar{\nu})}{N^{SM}_{\pi\nu\nu}} = \frac{1}{N_K \cdot A_{\pi\nu\nu} \cdot \varepsilon_{trig} \cdot \varepsilon_{RV}}$$

$N^{SM}_{\pi\nu\nu}$ = expected number of SM events

$K^+ \to \pi^+\pi^0$ used as normalization channel:

$$N_K = \frac{N_{\pi\pi} \cdot D}{A_{\pi\pi} \cdot BR(K^+ \to \pi^+\pi^0)}$$

Effective number of K^+ decays

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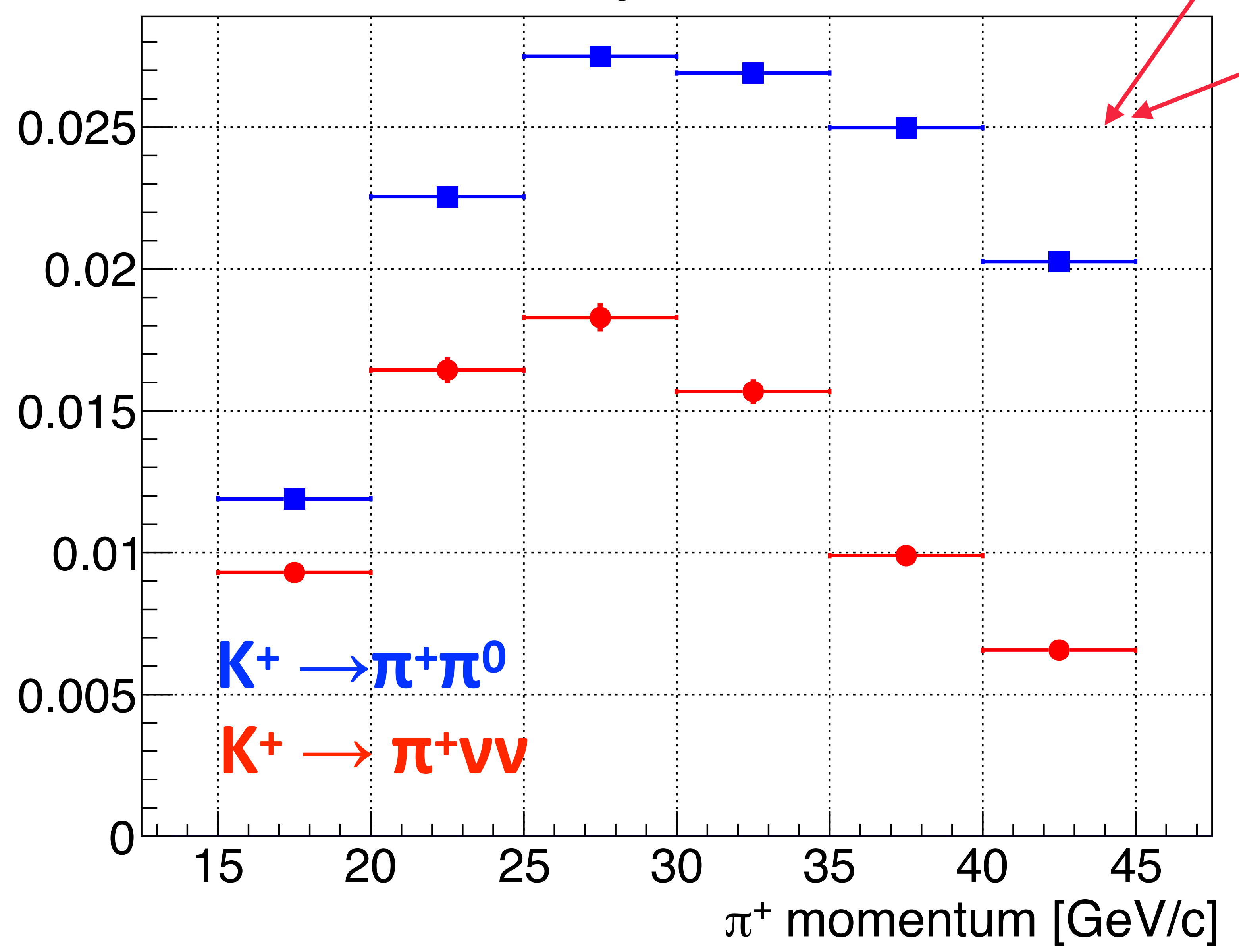
Effective number of K^+ decays

Selection Acceptances



Increased selection efficiencies

	2018	2021-22
Norm $K^+ \to \pi^+\pi^0$	11.8%	13.4%
Signal $K^+ \to \pi^+\nu\nu$	(6.37±0.64) %	(7.61±0.18) %

Increased selection efficiencies

- New K-π matching technique
- Re-tuned vertex conditions
- Relaxation of some vetoes

Improved precision and better systematic uncertainty evaluation

Single event sensitivity 2021-2022

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$$B_{SES} = \frac{BR(K^+ \to \pi^+ \nu \bar{\nu})}{N_{\pi\nu\nu}^{SM}} = \frac{1}{N_K \cdot A_{\pi\nu\nu} \cdot \varepsilon_{trig} \cdot \varepsilon_{RV}}$$

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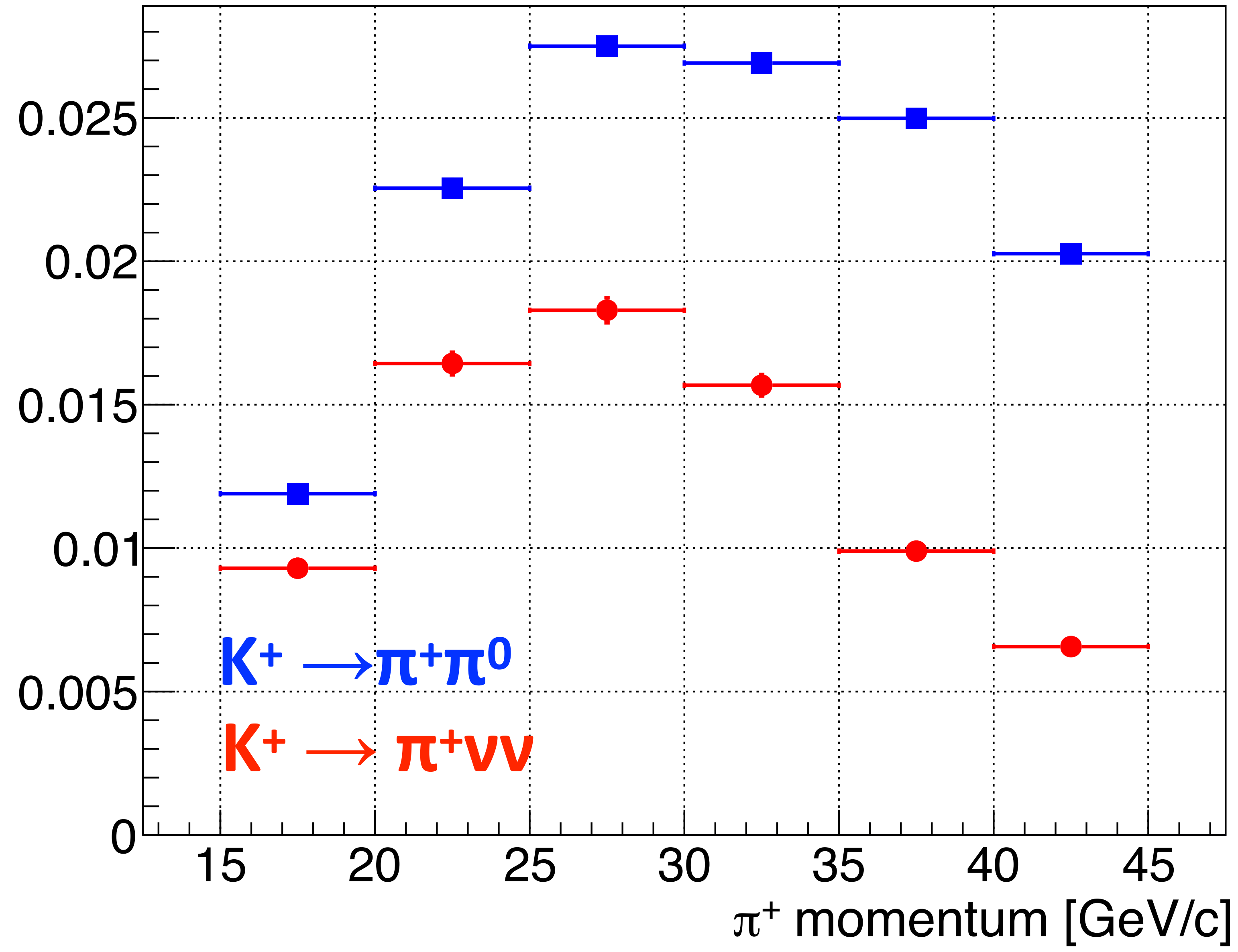
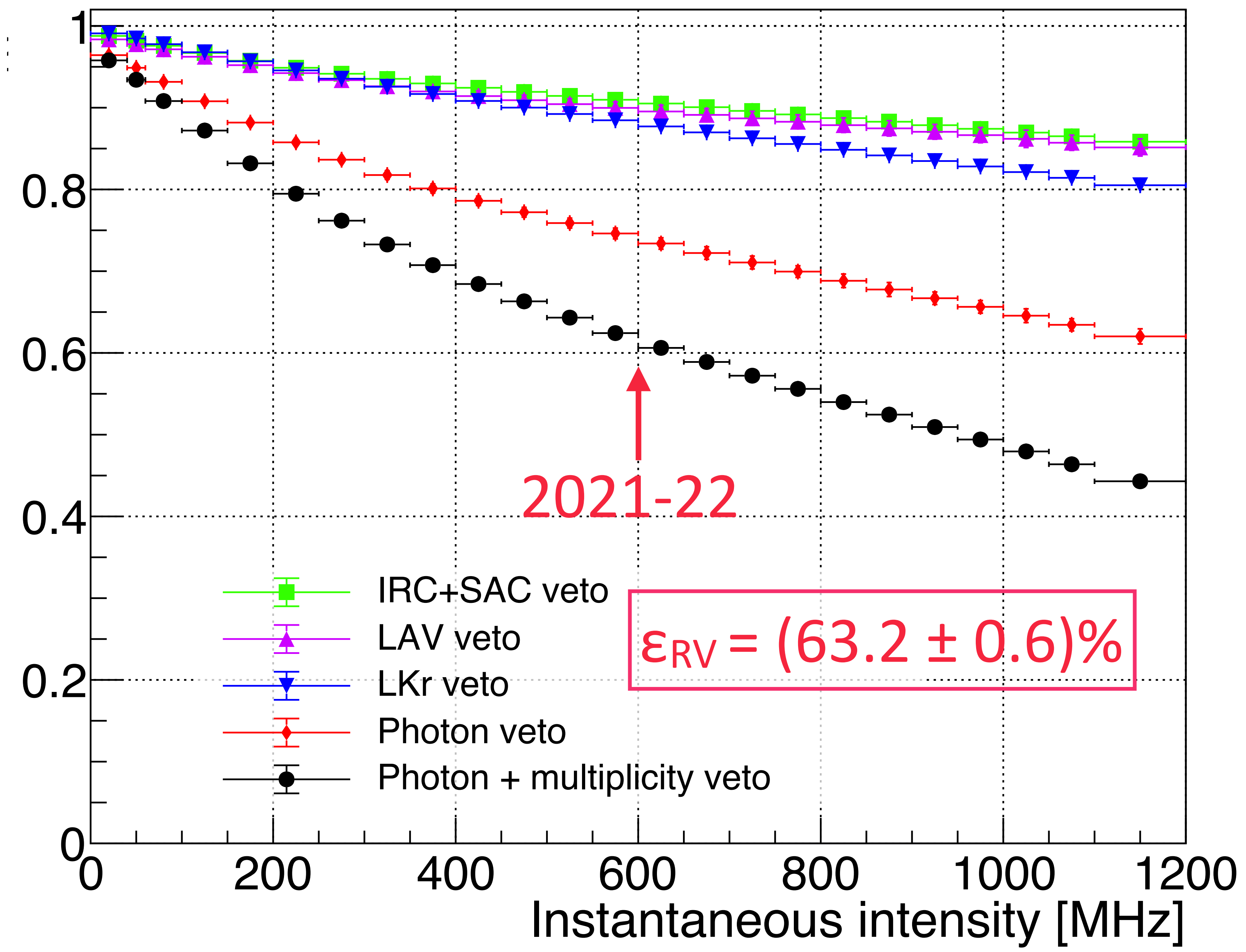


$1 - \varepsilon_{RV}$ = probability of rejecting a signal due to accidental coincidence in the veto detectors

Estimated with data using a $K^+ \to \mu^+ \nu$ sample

Random veto efficiency ε_{RV}



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Branching ratio corresponding to expectation of 1 event:

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$N^{SM}_{\pi\nu\nu}$ = expected number of SM events

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

$K^+ \to \pi^+\pi^0$ used as normalization channel:

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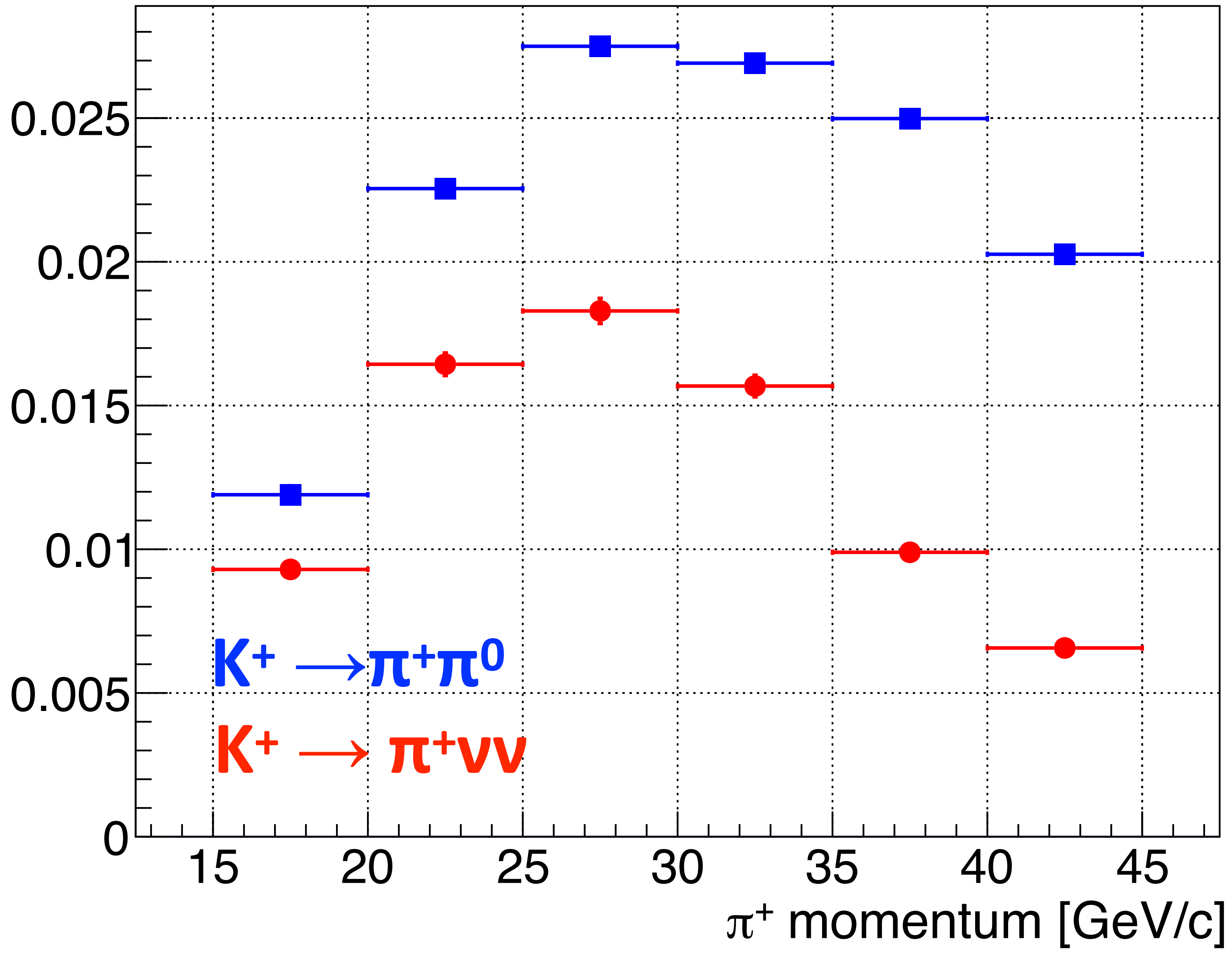
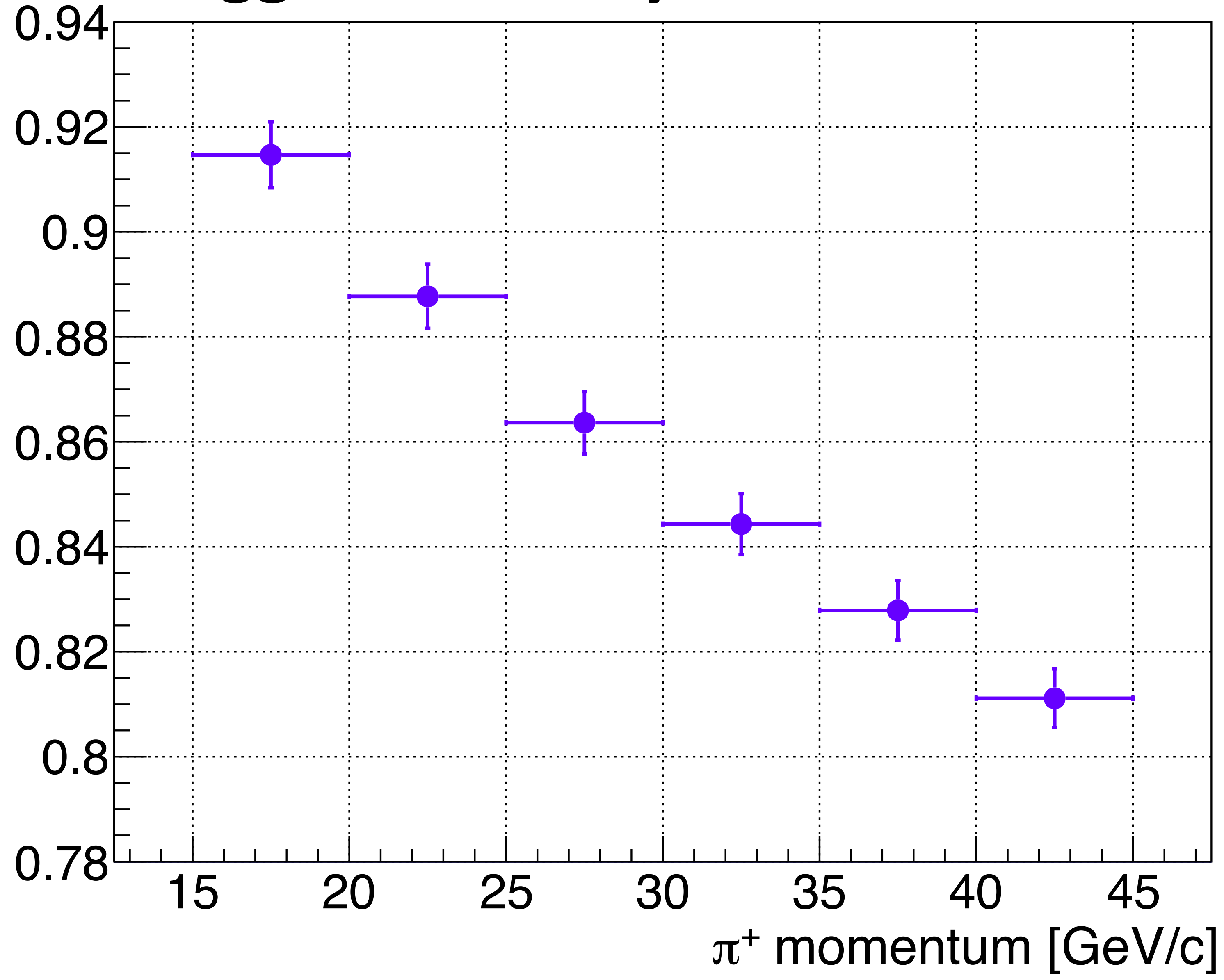
Effective number of K^+ decays

Selection Acceptances



Trigger efficiency



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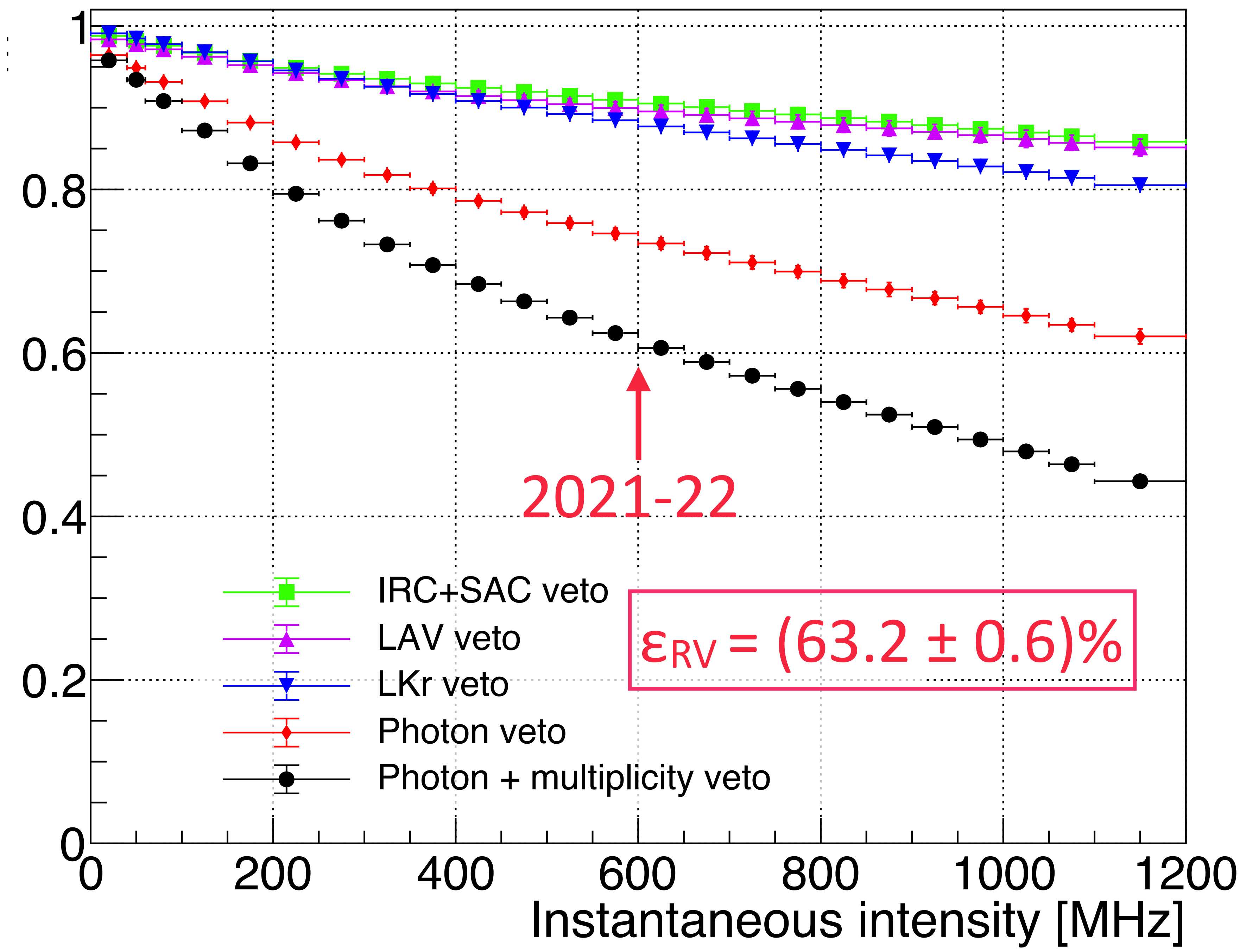

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$$N^{SM}_{\pi\nu\nu} = 9.91 \pm 0.34$$

$K^+ \to \pi^+\pi^0$ used as normalization channel:

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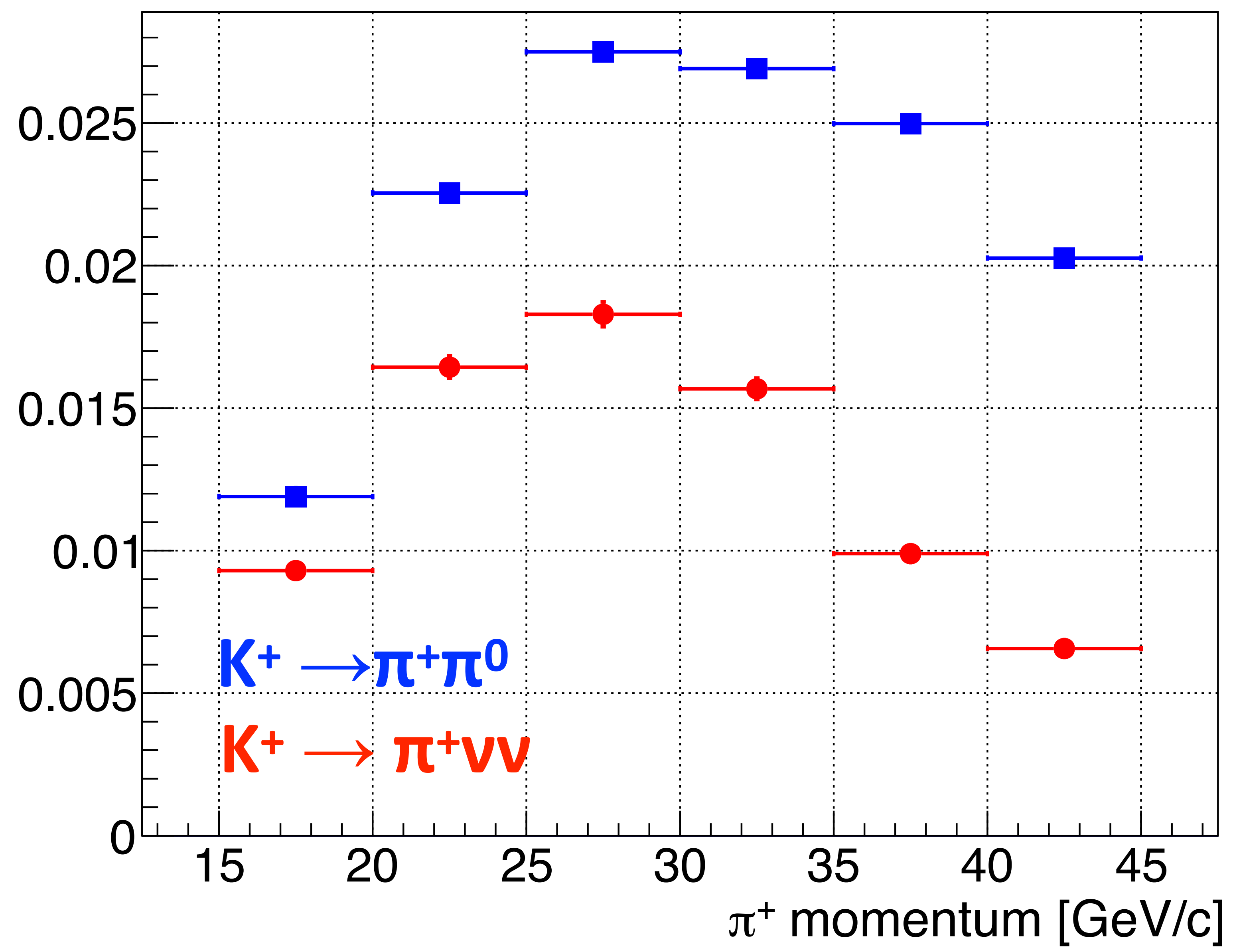
Effective number of K^+ decays

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

Selection Acceptances



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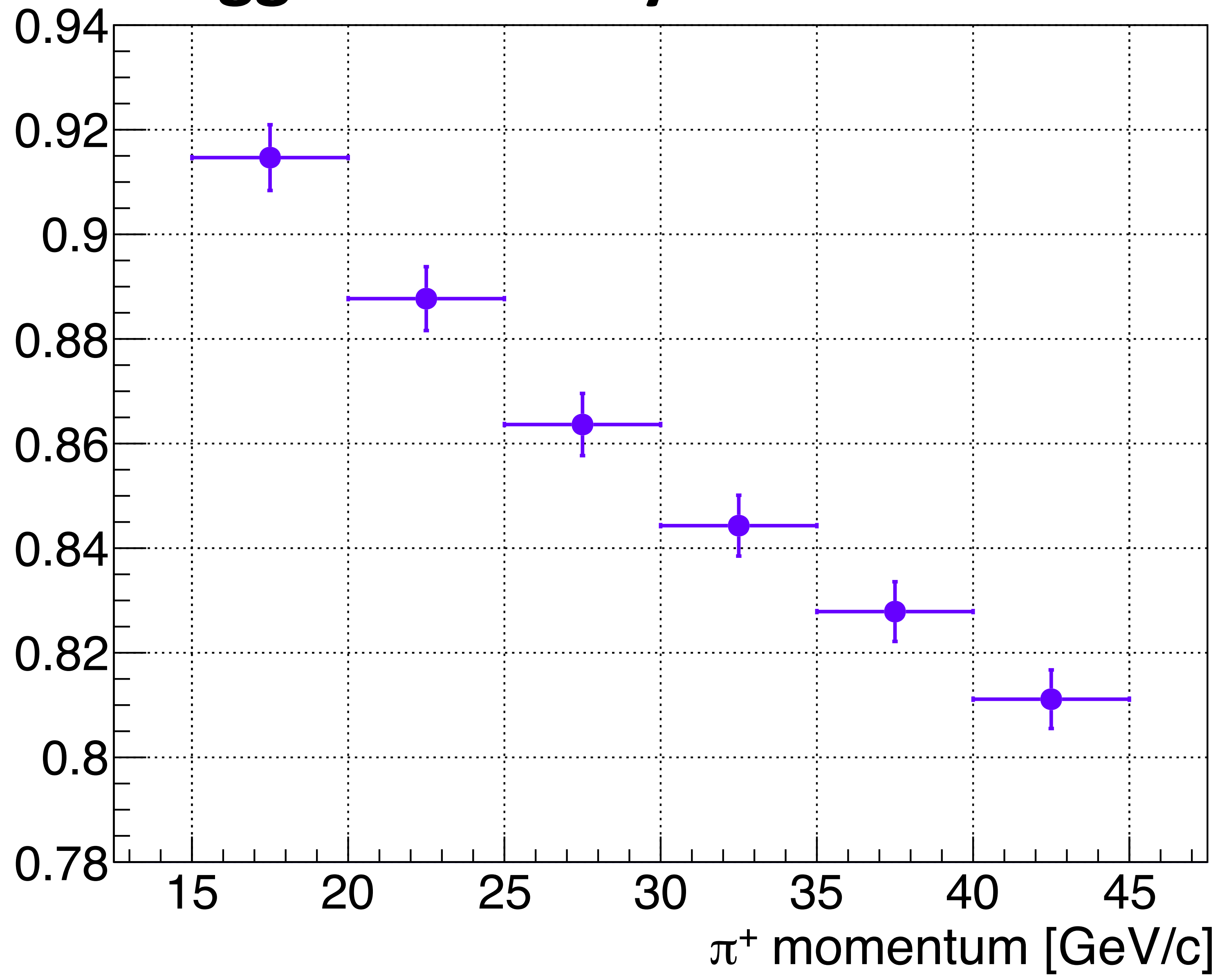

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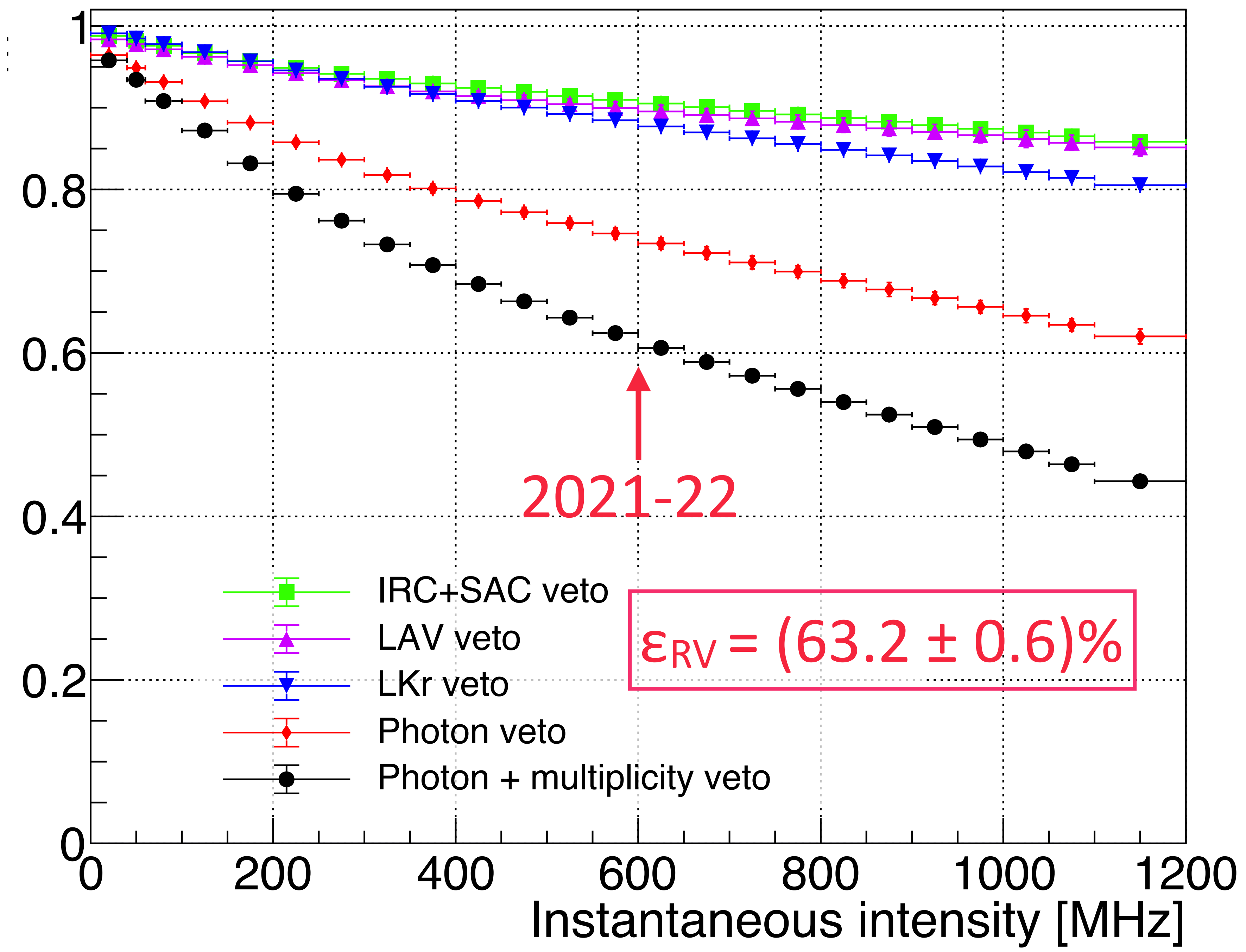


Background evaluation

Upstream background:
Decays and interactions upstream of the FV

$$N_{bkg} = f_{CDA} \cdot \sum_i N_i \cdot P_i^{match}$$

- f_{CDA}: Scaling factor from bad CDA to good CDA (geometry dependent only)
- N_i: Upstream reference sample:
  - full signal selection
  - no K+- π+ matching
  - CDA > 4 mm (instead of < 4 mm)

  contains all known upstream mechanisms and provides normalization in bins
- P_i^{match}: Probability to pass K+- π+ matching

Upstream: fully data driven procedure

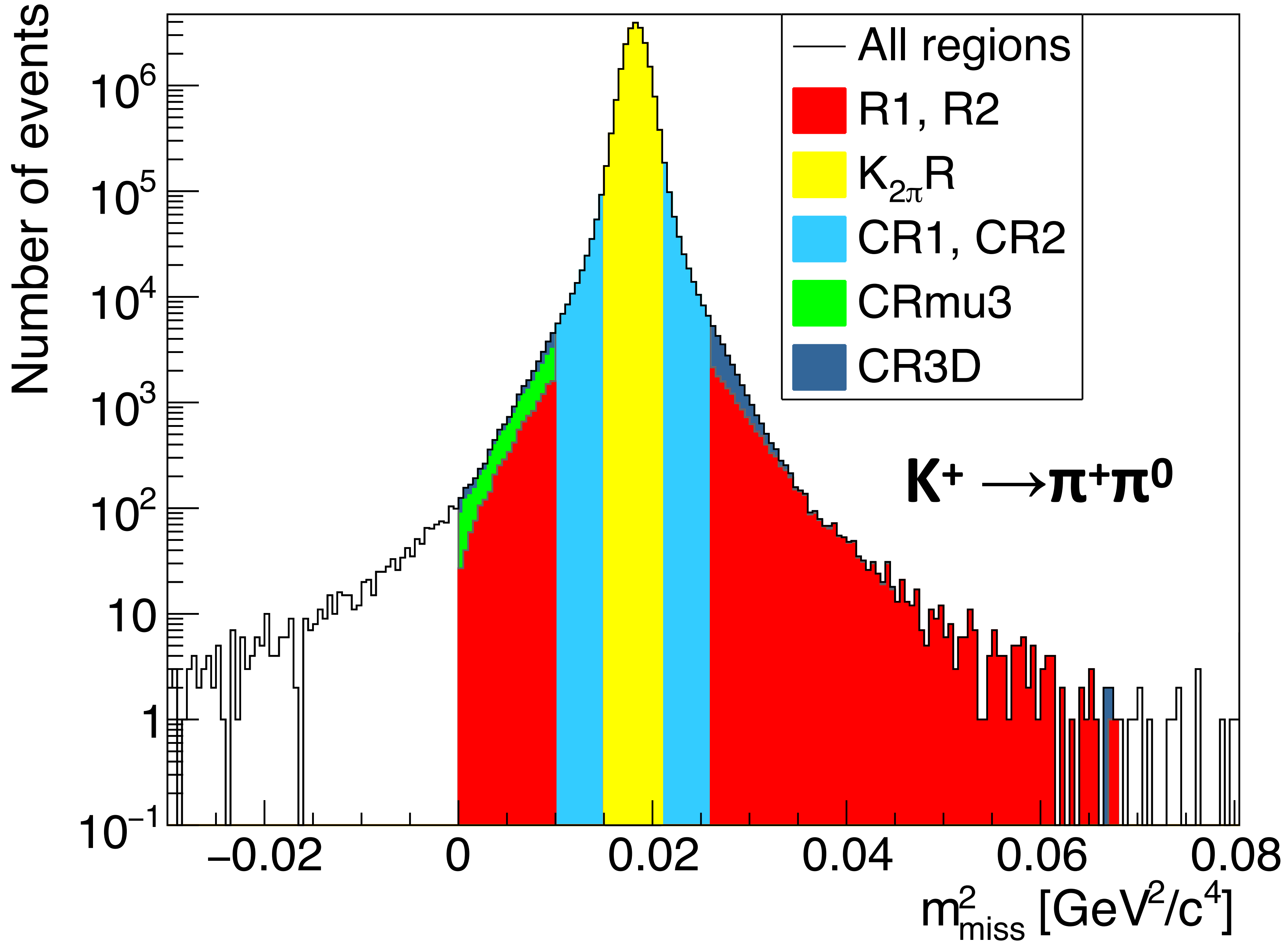
Background from other K^+ decays
Kinematic misconstruction tails in m^2_{miss}

$$N_{bkg} = N_{bkgR} \cdot f_{tail}$$

- N_{bkgR}: Number of events passing signal selection in background region
- f_{tail}: Kinematic tail fraction measured in control sample

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

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



$K^+ \to \pi^-\pi^+\pi^-$ (MC for f_{tail} ev.)

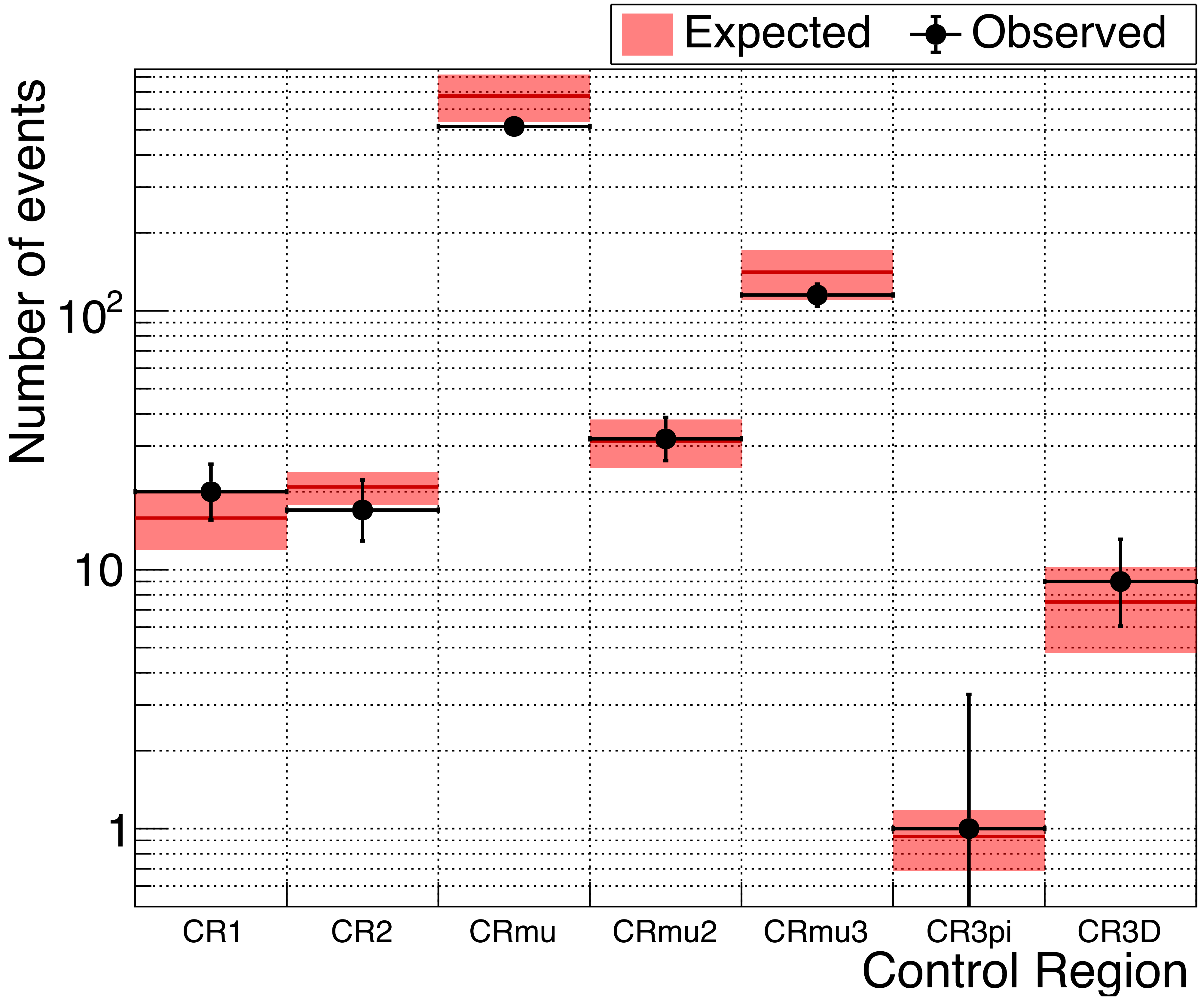
$K^+ \to \pi^+\pi^- e^+\nu$ (MC)

$K^+ \to \pi^0\ell^+\nu$ (MC)

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

Expected events 2021-2022 data

Background evaluation methods are tested on control regions: **a good agreement is found that validates background expectations**



Expected events in R1 + R2

Process	Events
$K^+ \to \pi^+ \nu\bar{\nu}$	$\mathbf{9.91 \pm 0.34}$
$K^+ \to \pi^+ \pi^0 (\gamma)$	0.83 ± 0.05
$K^+ \to \mu^+ \nu (\gamma)$	1.70 ± 0.47
$K^+ \to \pi^+ \pi^- e^+ \nu$	$0.89^{+0.33}_{-0.27}$
$K^+ \to \pi^+ \pi^+ \pi^-$	0.11 ± 0.03
$K^+ \to \pi^+ \gamma\gamma$	0.01 ± 0.01
$K^+ \to \pi^0 l^+ \nu$	< 0.001
Upstream	$7.4^{+2.1}_{-1.8}$
Total background	$\mathbf{11.0^{+2.1}_{-1.9}}$

2021-2022 ~ Run1 expected signal events

Improvements in B_{SES} uncertainty:

6.5% → 3.5%

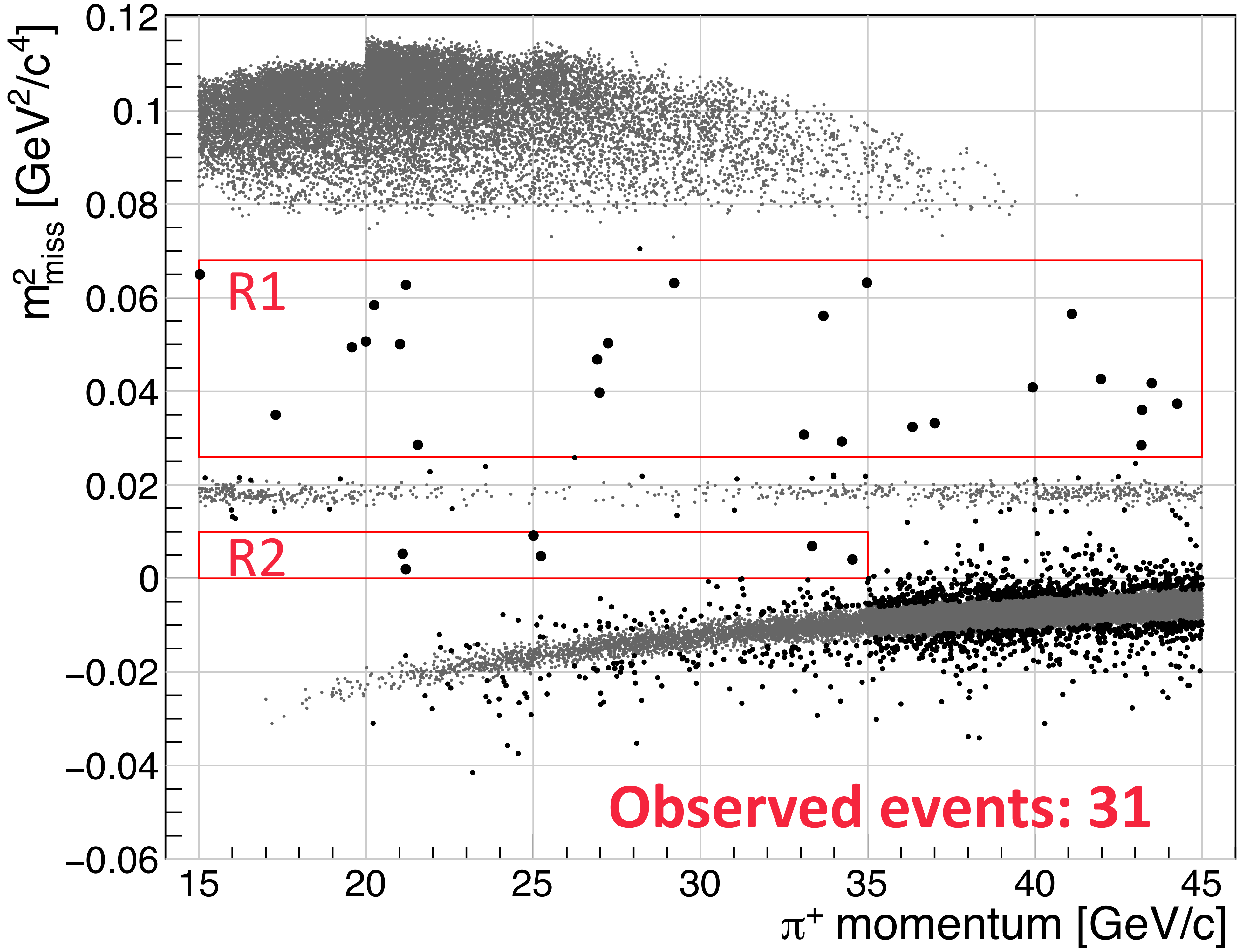
- trigger efficiency cancellation
- better evaluation of acceptances and ε_{RV}

Signal yield 50% increase

- $N_{\pi\nu\nu}$ per spill = 1.7×10^{-5} in 2018
- $N_{\pi\nu\nu}$ per spill = 2.5×10^{-5} in 2022

NA62 result with 2021-2022 data

$K^+ \to \pi^+ \nu\bar{\nu}$ (SM)	$\mathbf{9.91} \pm 0.34$
Total background	$\mathbf{11.0}^{+2.1}_{-1.9}$



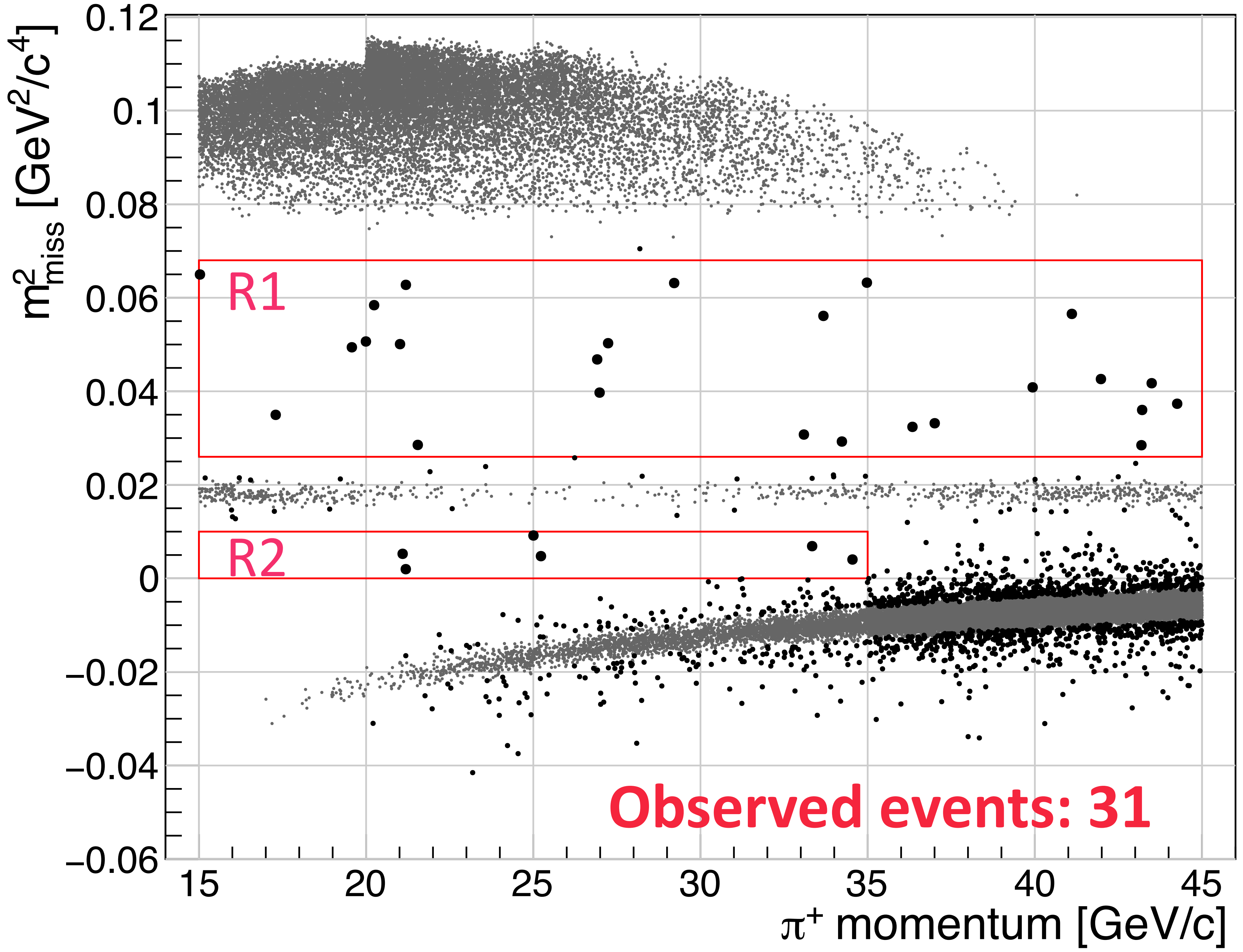
Integrating 2016—22 data: N_{sig} = 20, N_{bkg} = 18, N_{obs} = 51

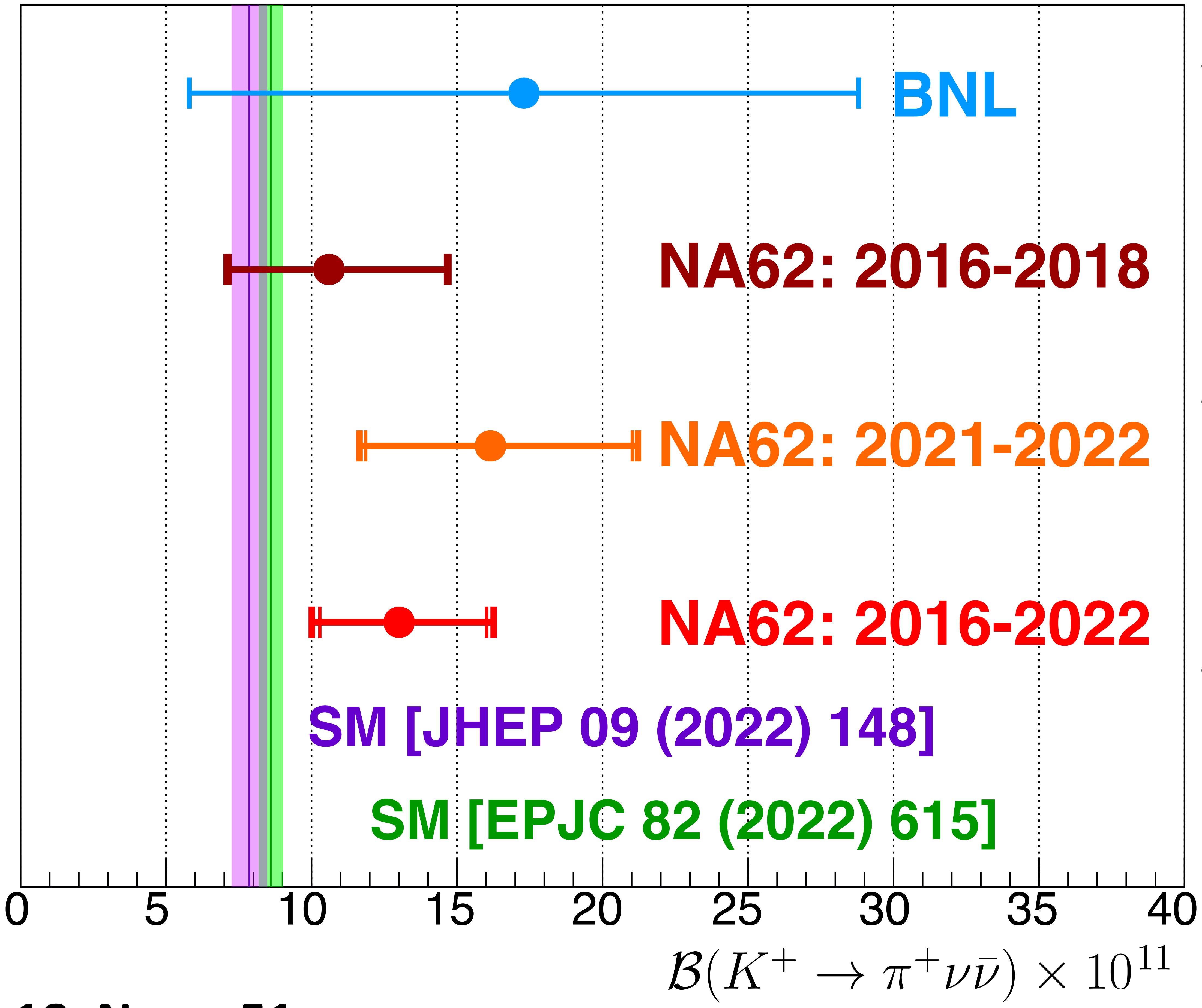
- Background-only hypothesis p-value = 2×10^{7} ⇒ **significance Z > 5 σ ⇒** **First observation of $K^+ \to \pi^+ \nu\nu$**

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

NA62 result to date

$K^+ \to \pi^+ \nu \bar{\nu}$ (SM)	$\mathbf{9.91} \pm 0.34$
Total background	$\mathbf{11.0}^{+2.1}_{-1.9}$





- Central value moved up (1.5-1.7σ above SM)
- Fractional uncertainty decreased: 40% to 25%
- Bkg-only hypothesis rejected

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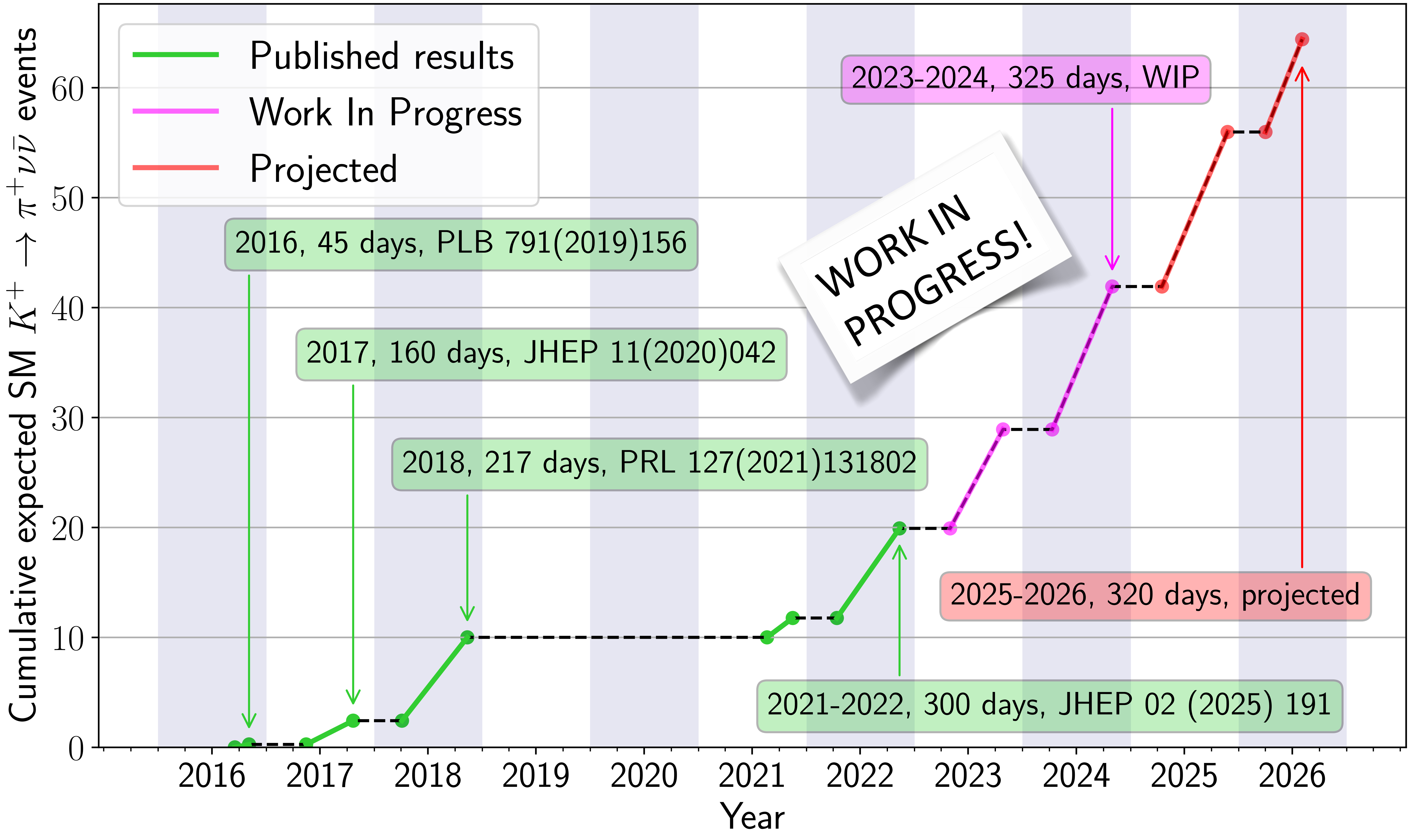
Future prospects for BR($K^+ \longrightarrow \pi^+\nu\nu$) measurement

Dataset	2022	2023	2024
Number of spills $[10^3]$	326	363	519
$<$ Beam intensity $>$ [GHz]	0.57	0.48	0.41
$< N_{\pi\pi}/\text{spill} >$ $[10^2]$	4.9	4.7	4.4
N_K $[10^{12}]$	2.3	2.5	3.3
ε_{RV}	0.63	0.68	0.73
$N_{\pi\nu\nu}$	8	9	13
$N_{\pi\nu\nu}/\text{spill}$ $[10^{-5}]$	2.5	2.5	2.6
$B_{\text{total}}/N_{\pi\nu\nu}$	1.1	1.1	1.0

WORK IN PROGRESS!

- **Optimal intensity established with 2021-2023 data:**
  Improved signal yield and data collection efficiency
- **Full NA62 $K^+ \rightarrow \pi^+\nu\nu$ sample expected next year (2026)**

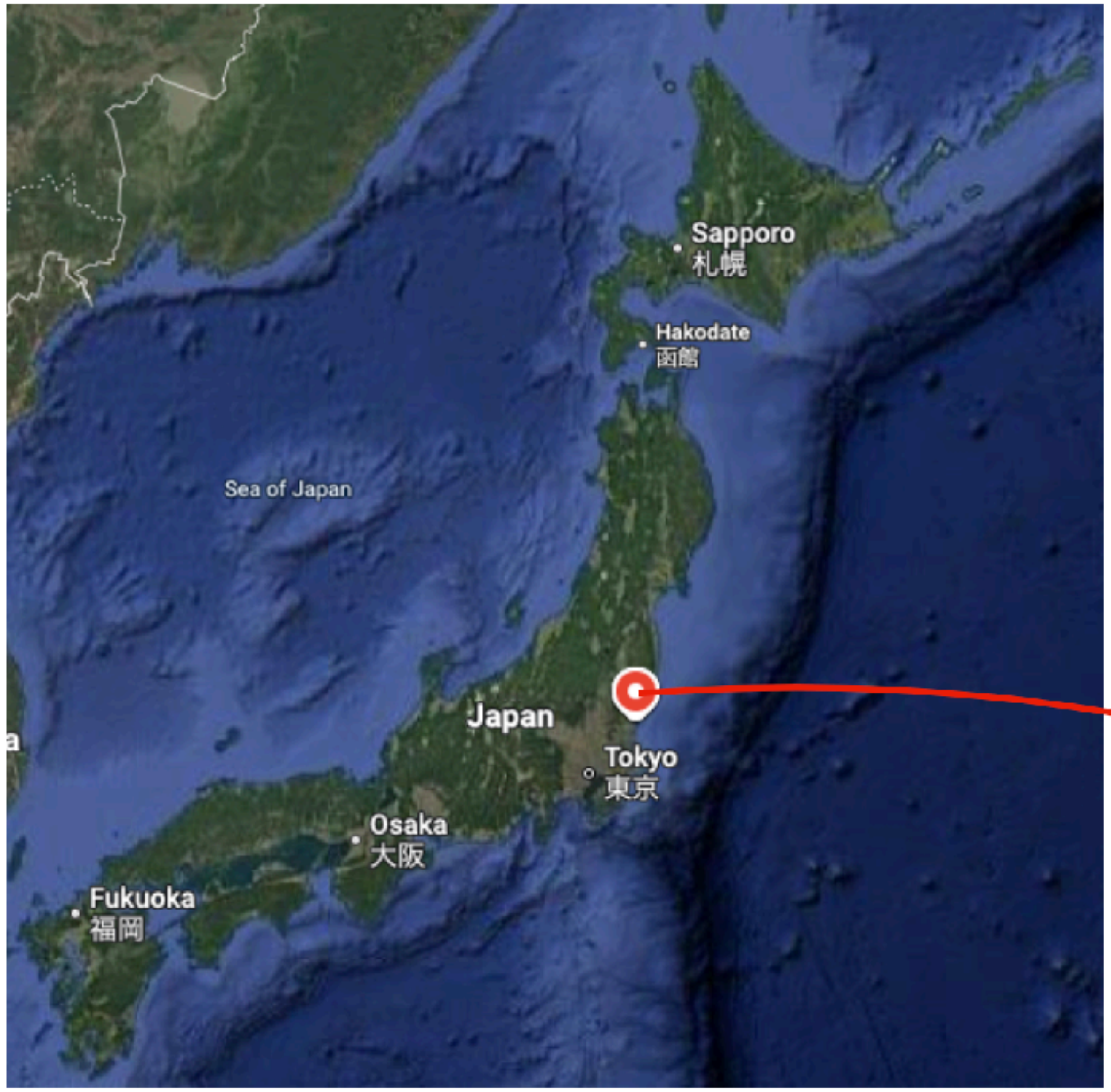


- **<u>Preliminary</u> projection:**
  Assuming $N_{\pi\nu\nu}$/day is the same as for 2024
  N_{sig} ~ 65 (3x published result 2016-2022)
- **BR($K^+ \rightarrow \pi^+\nu\nu$) uncertainty target 15-20%**
  More statistics and analysis improvements

..... Stay tuned!

Search for $K_L \longrightarrow \pi^0 \nu\nu$ at J-PARC

J-PARC KOTO experiment

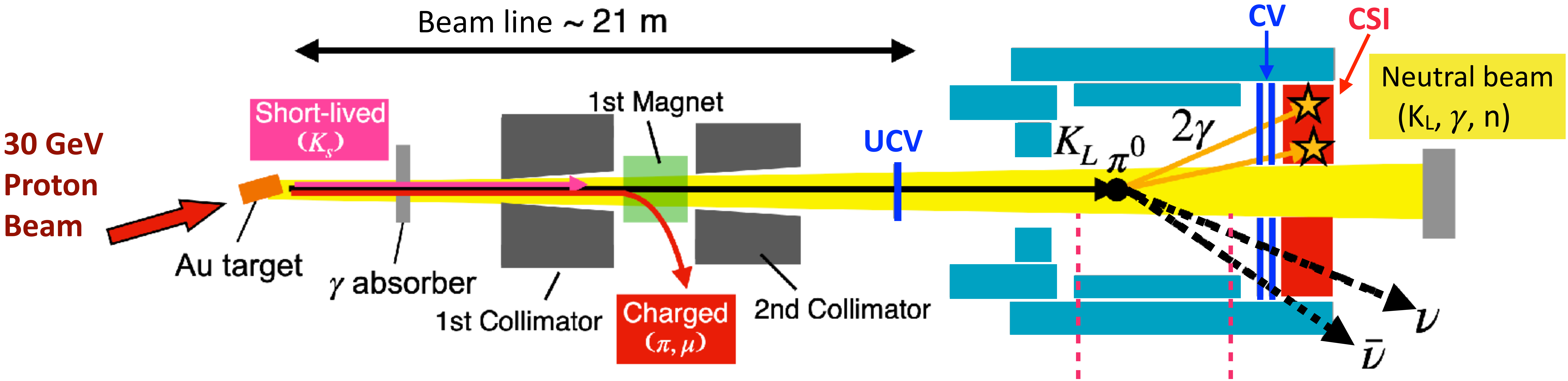


~ **50 collaborators**

Photo@Collaboration meeting on June 2025

From Keita Ono talk at KAON2025, Maintz September 8th

KOTO detector

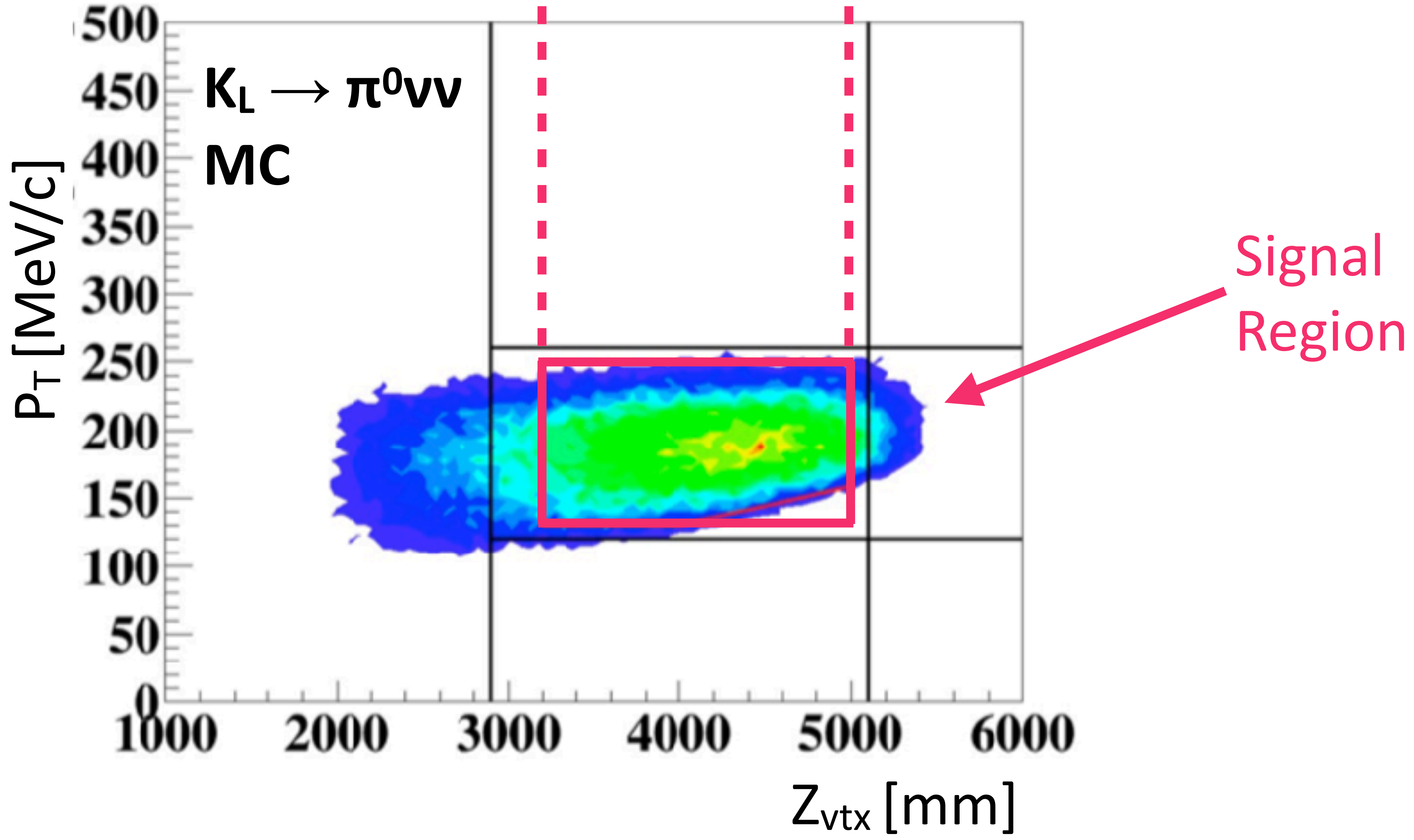


$K_L \to \pi^0\nu\nu$ **decay-in-flight signature (E_{peak} = 1.4 GeV)**

- **2 photons from π^0** in electromagnetic calorimeter (**CSI** - undoped-CsI crystal)
- Nothing else in VETO DETECTORS (**Comprehensive Photon vetos & Charged-Particle veto**)

Signal region

- π^0 reconstructed vertex position (Z_{vtx}) inside fiducial volume (assuming the 2 γ from π^0)
- High π^0 transverse momentum (P_T) - to account for missing neutrino momentum (and reject $K_L \to \pi^+\pi^-\pi^0$)



KOTO Results with 2021 data

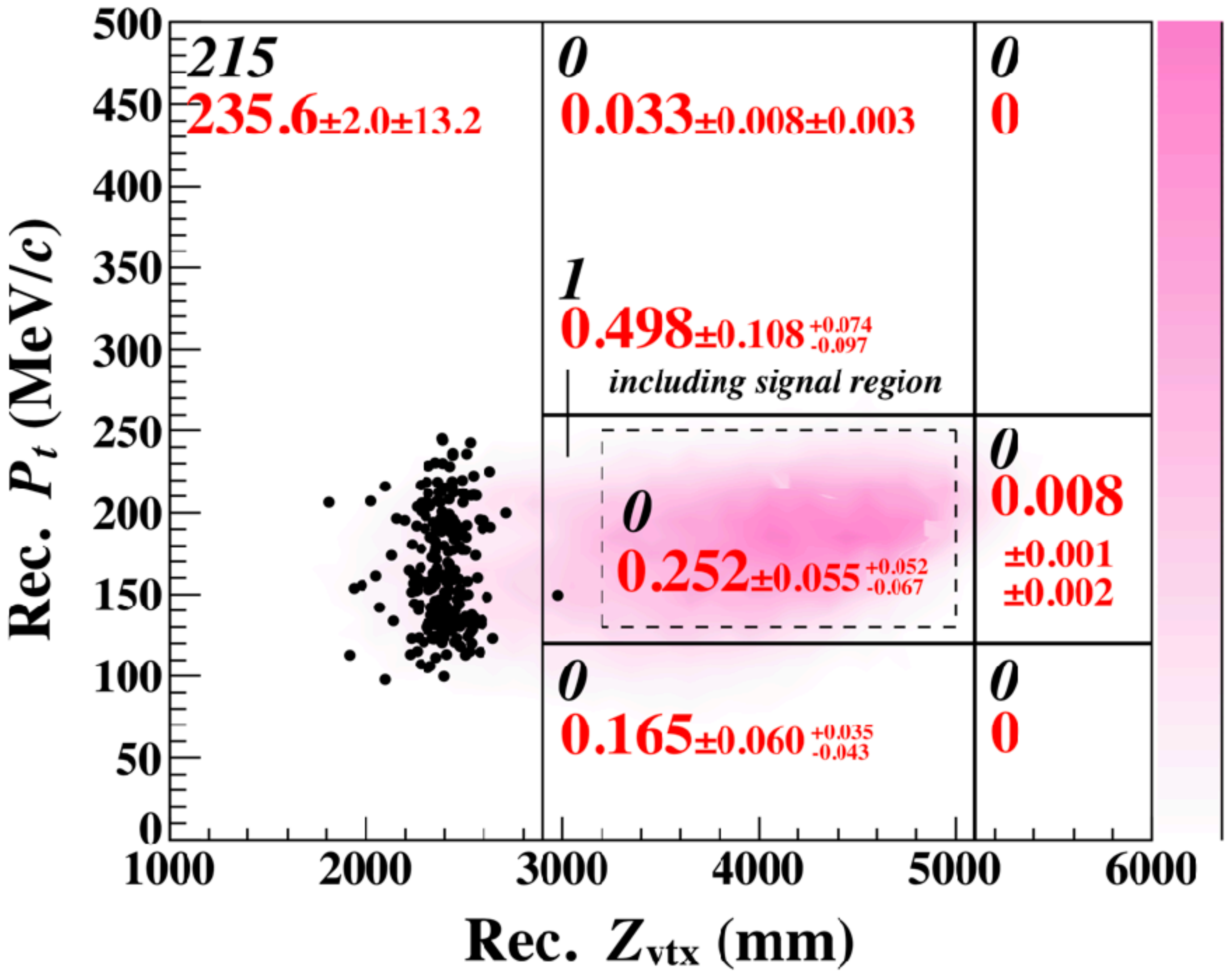
$$SES = \frac{1}{A_{\pi^0\nu\nu}} \frac{A_{\pi^0\pi^0} \cdot BR(K_L \to 2\pi^0)}{N_{\pi^0\pi^0}}$$

Single event sensitivity

$N_{\pi^0\pi^0} = 6.25 \times 10^5,\ A_{\pi^0\pi^0} = 0.334\%,\ A_{\pi^0\nu\nu} = 0.475\%$

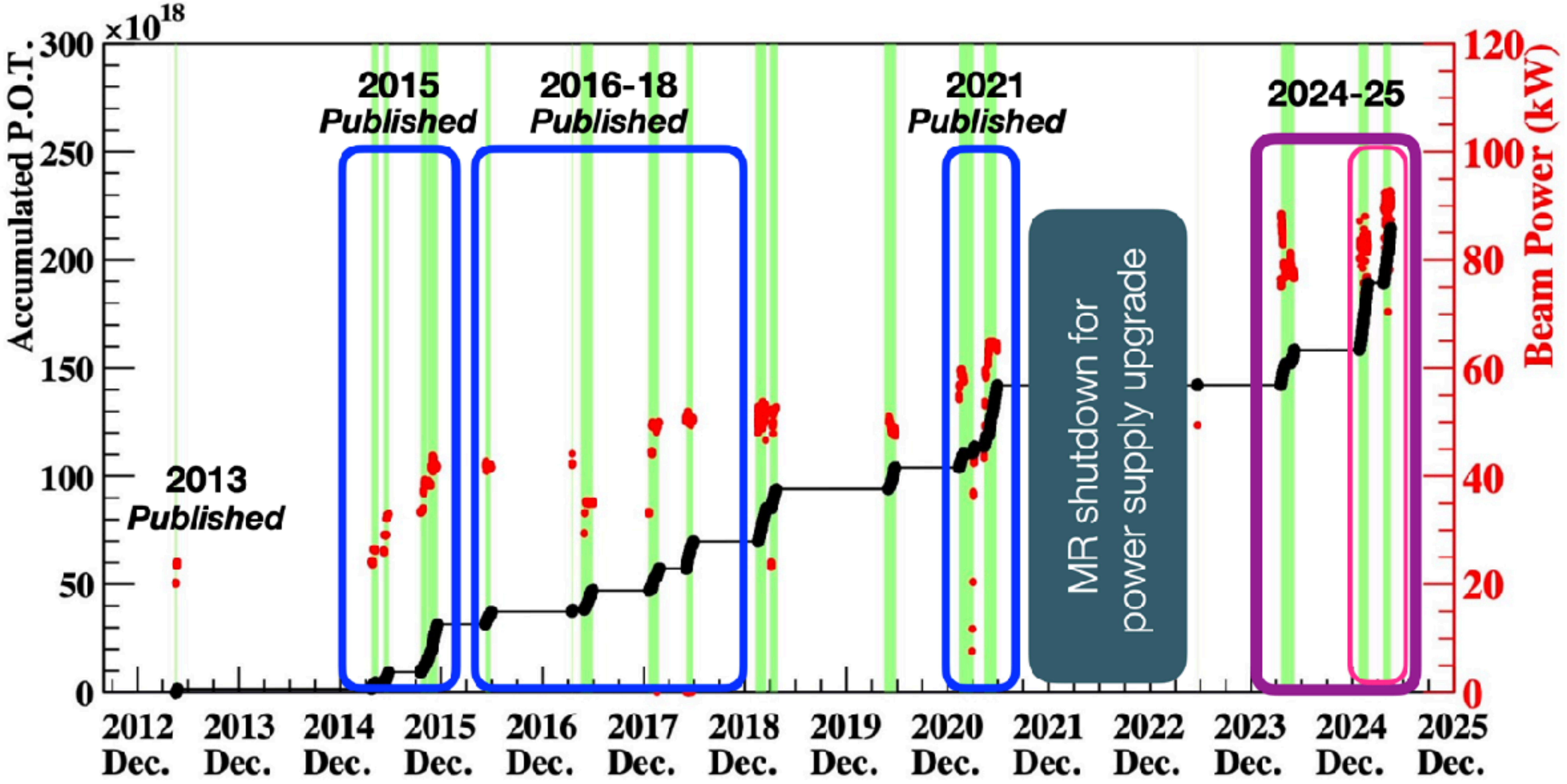
$\mathbf{SES = (9.33 \pm 0.06_{stat} \pm 0.84_{syst}) \times 10^{-10}}$

SM signal	Expected events in signal region
$K_L \to \pi^0\nu\bar{\nu}$	$\simeq 0.03$
Background sources	**Expected events in signal region**
$K^{\pm}$	$0.042 \pm 0.014^{+0.004}_{-0.028}$
$K_L \to 2\gamma$ (beam-halo)	$0.045 \pm 0.010 \pm 0.006$
$K_L \to 2\pi^0$	$0.059 \pm 0.022^{+0.050}_{-0.059}$
hadron-clusters (neutron halo)	$0.024 \pm 0.004 \pm 0.006$
CV-η (neutron halo)	$0.023 \pm 0.010 \pm 0.005$
Upstream-π^0 (neutron halo)	$0.060 \pm 0.046 \pm 0.007$
Total background	$0.252 \pm 0.055^{+0.052}_{-0.067}$



$BR(K_L \to \pi^0\nu\bar{\nu}) < 2.2 \times 10^{-9}$ @ 90%C.L.

KOTO prospects



- **Sys. error of $K_L \rightarrow 2\pi^0$ background could potentially be reduced to 10%**
- **Reduced statistical uncertainty of photon inefficiency (calculated from $K_L \rightarrow 3\pi^0$) by ~10%**

2024-2025 data analysis ongoing ….

Beam power gradually increased

2024+2025 ~ twice 2021 statistic

KOTO upgrades after 2021

- Upstream Charged Veto with thinner scintillating fibers
- Additional magnet at the end of the KOTO beam-line

$K^{\pm}$ reduced by a factor > 15

Halo K_L 16% reduction

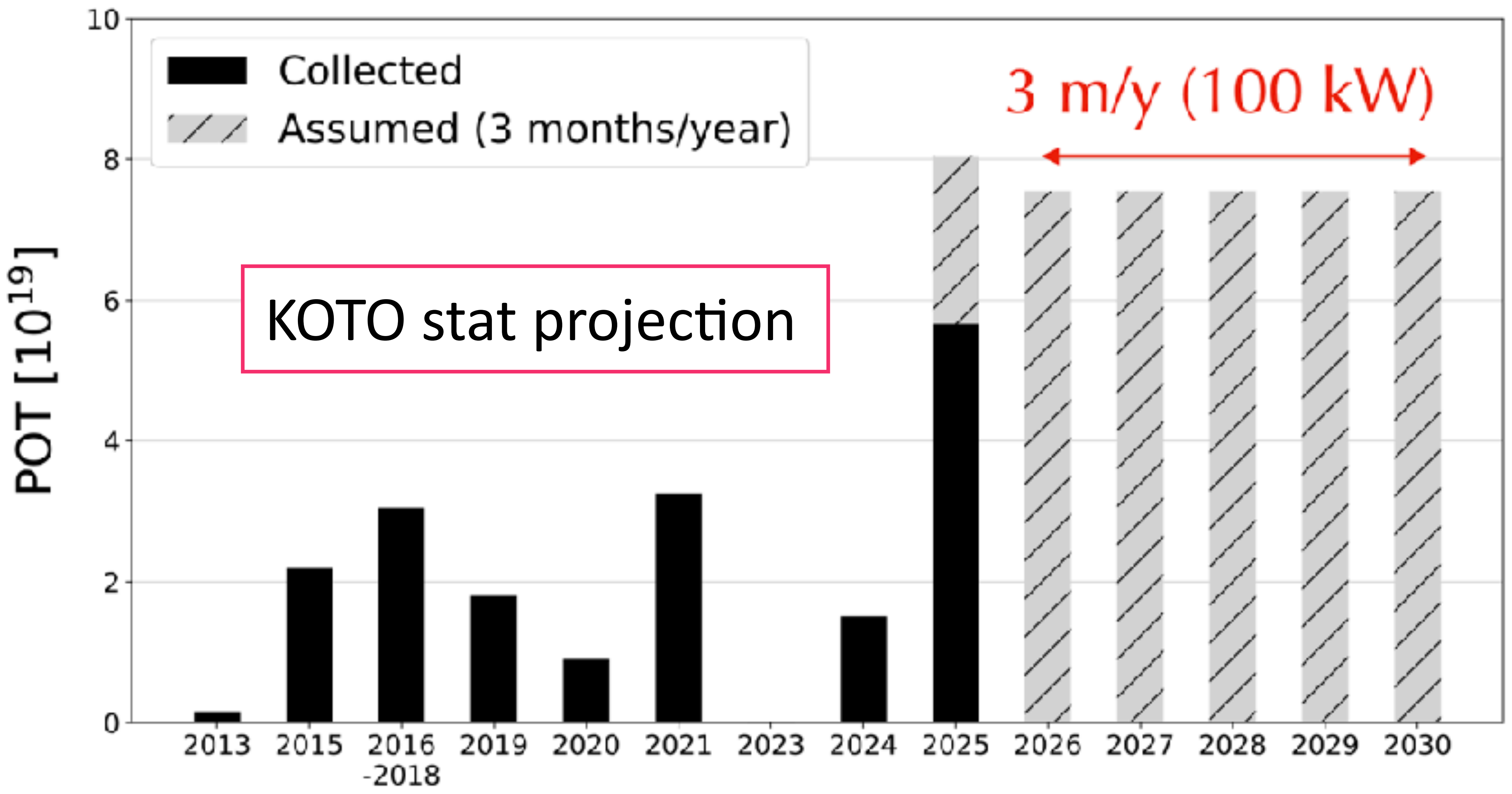
Neutron 20% reduction

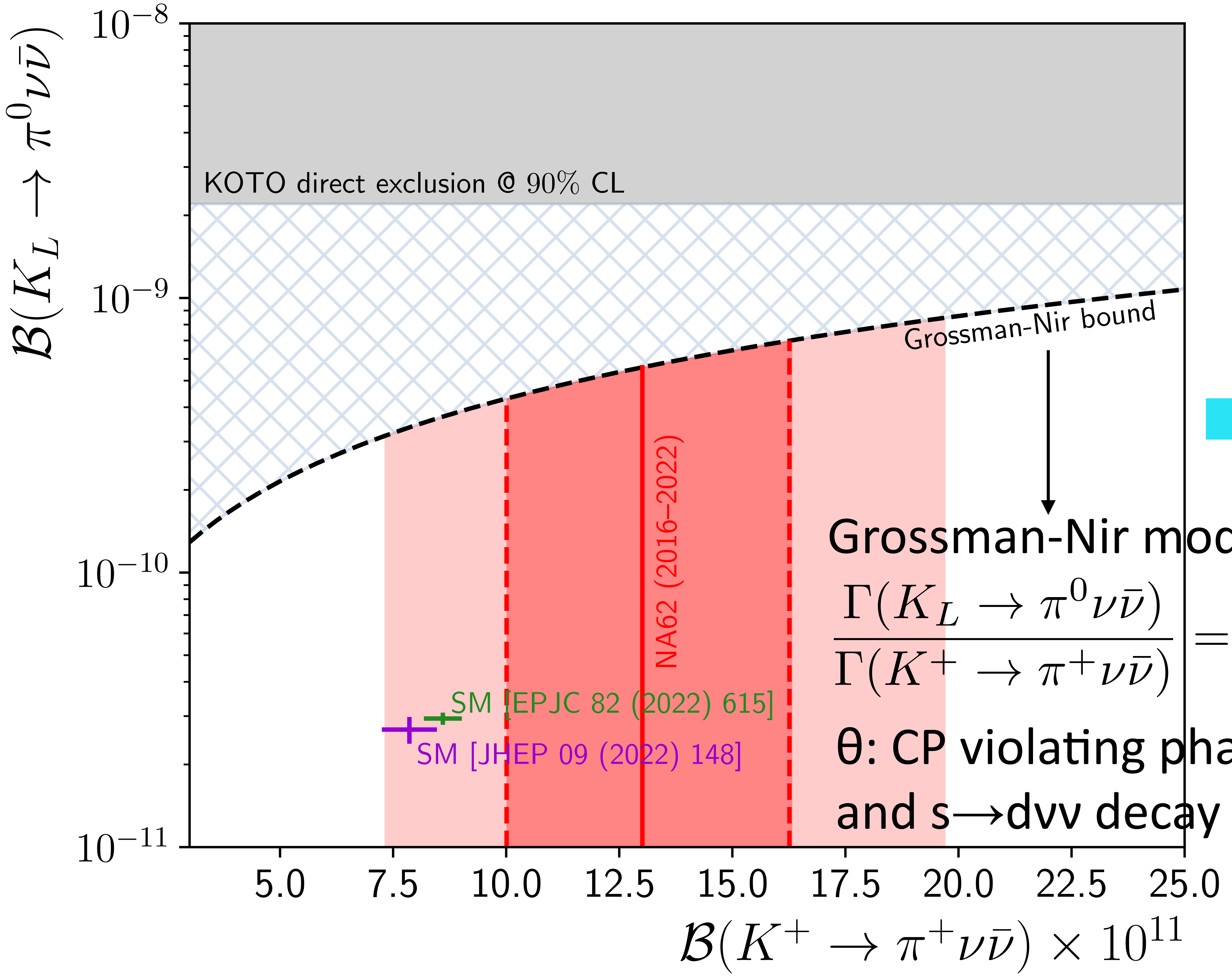
- New DAQ for more rate capability

Total background can be reduced to 75%

Results in context

- **KOTO:** sequential upper limit improvements (10^{-9}) - **towards SES of 10^{-10} by the end of 2028 (10 x 2021 stat)**
- **NAG2:** Observation of the $K^+ \to \pi^+\nu\nu$ decay with BR measurement at 25% precision and consistent with SM prediction, within 1.7σ - **towards 20-15 % precision**

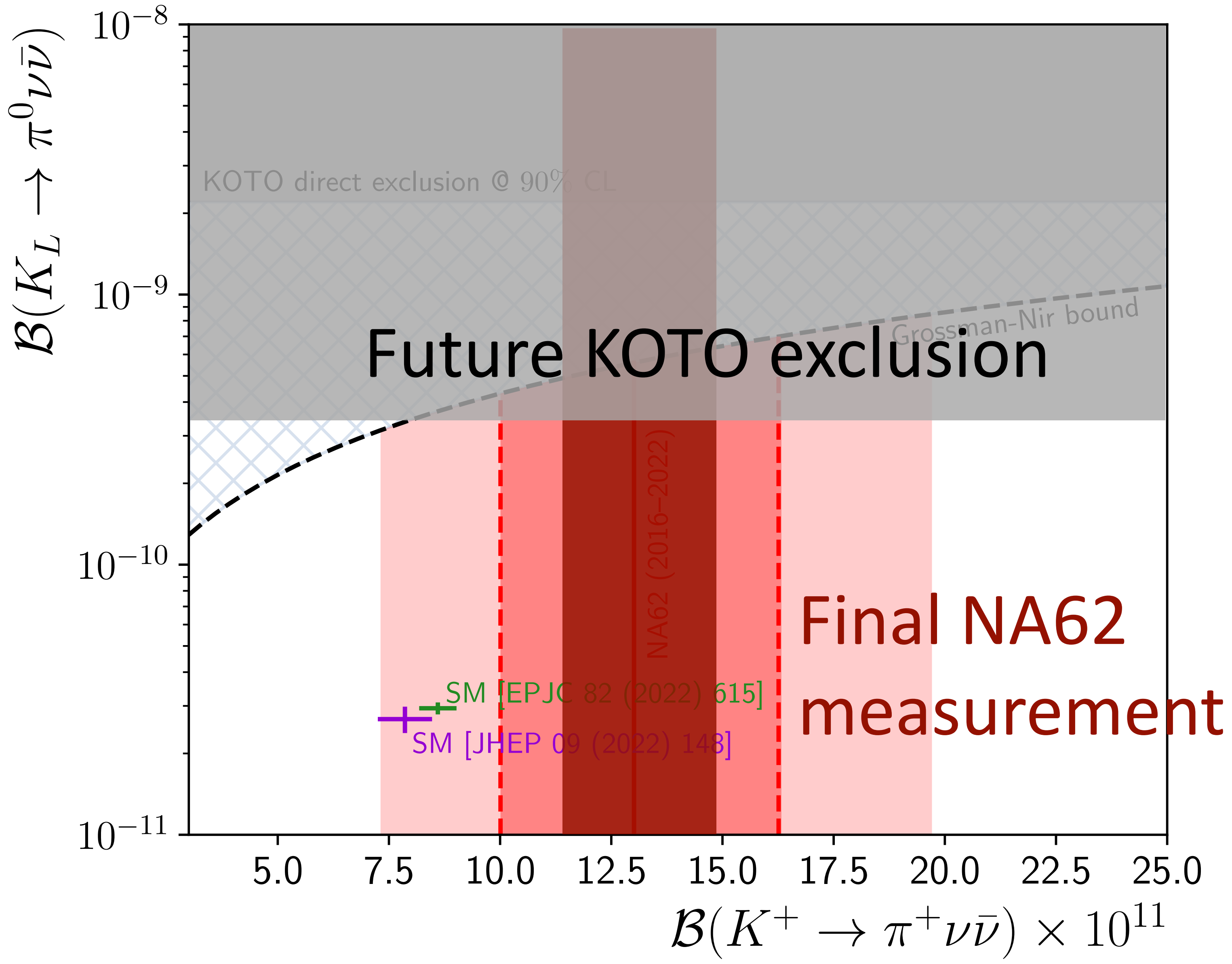




Grossman-Nir model independent bound:

$$\frac{\Gamma(K_L \to \pi^0\nu\bar{\nu})}{\Gamma(K^+ \to \pi^+\nu\bar{\nu})} = sin^2\theta < 4.4$$

θ: CP violating phase between K-K mixing and s→dνν decay

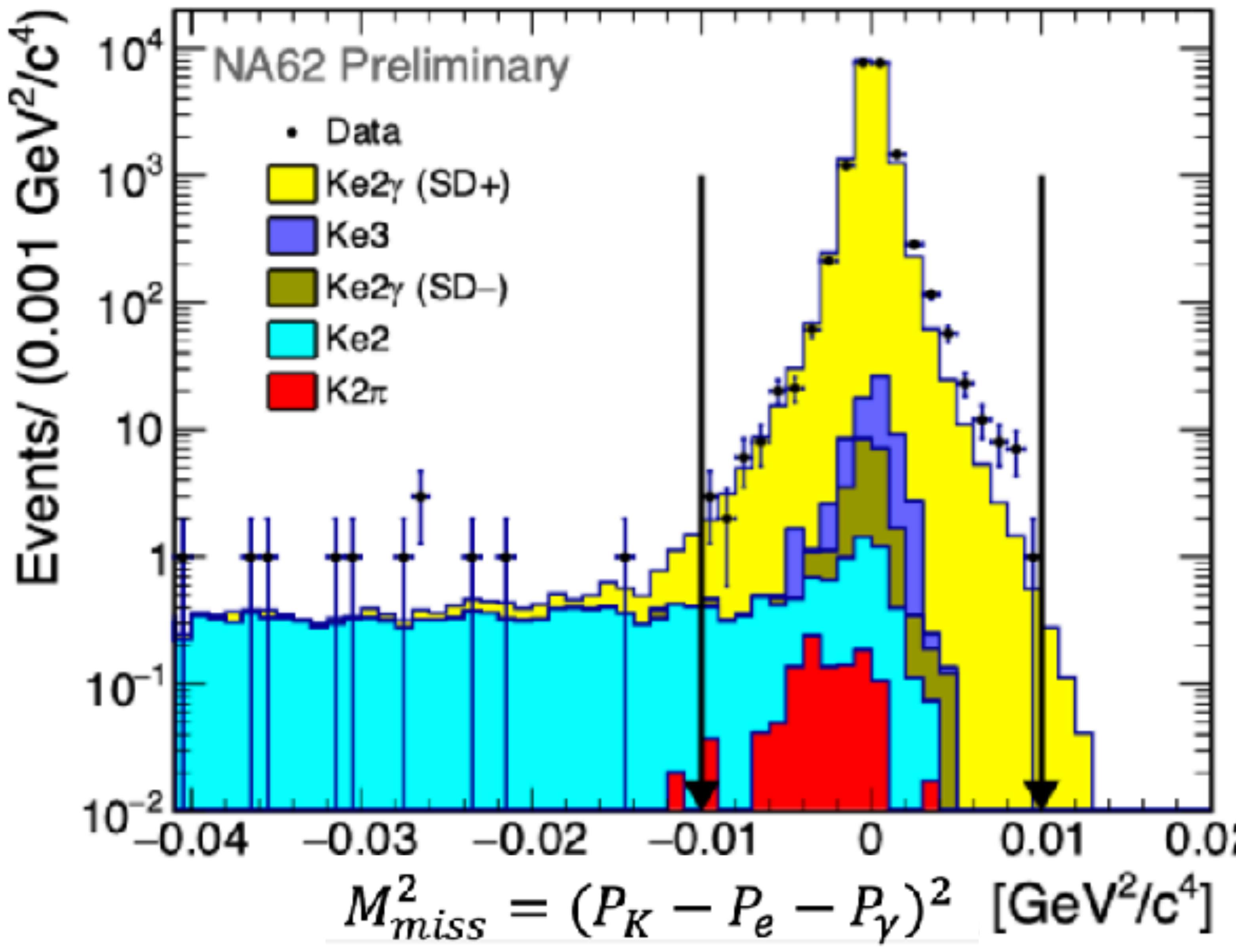


NA62 as a multi purpose experiment

Trigger system flexibility and detector performances make NA62 ideal for many other interesting measurements

Recent results of precision measurement to test standard model

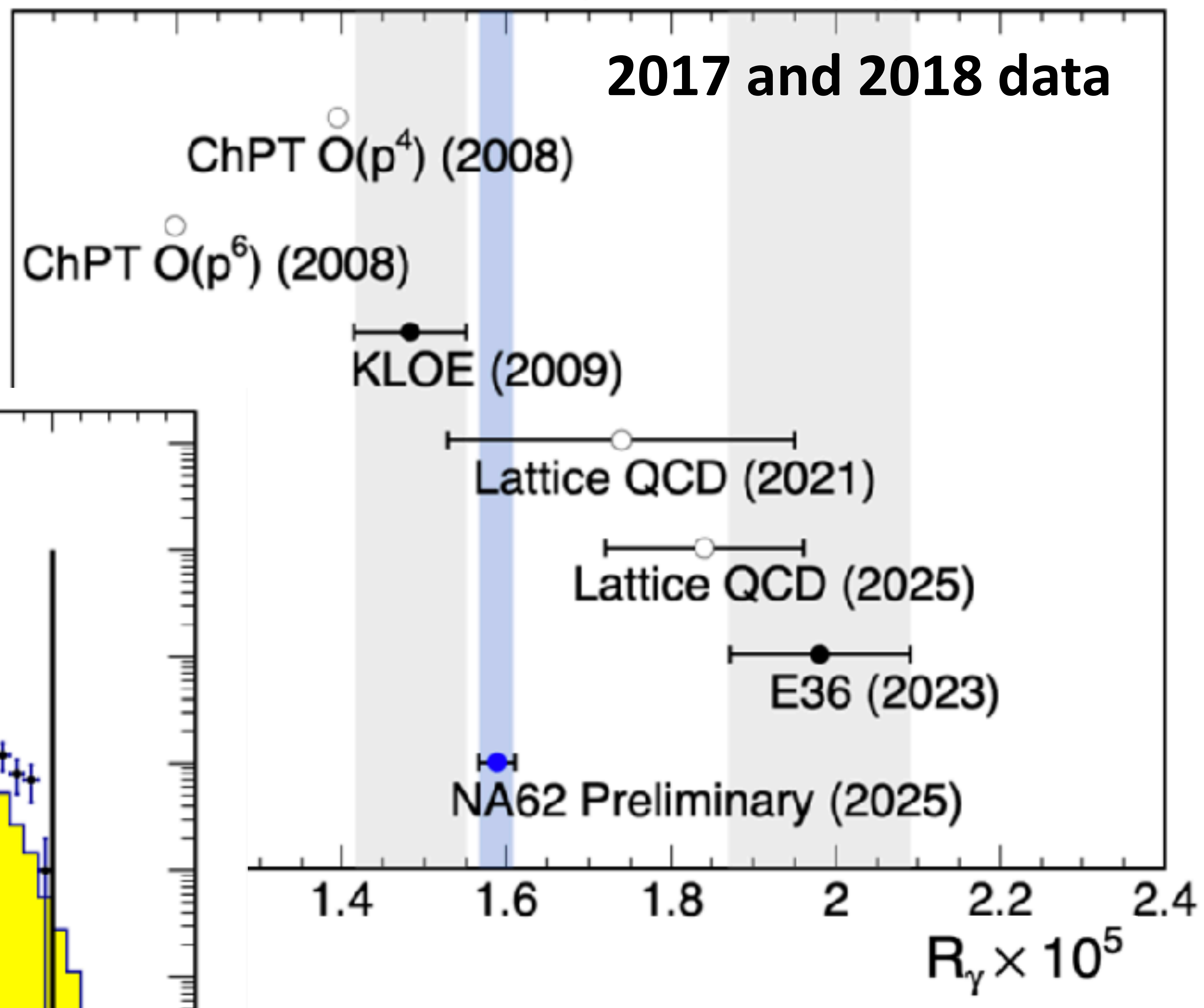
$N^{obs}_{Ke2\gamma}$	18929
$Acc_{Ke2\gamma}$	14.2 %
B/S	0.4 %



Improved precision by factor ~ 4 on

BR($K^+ \to e^+\nu\gamma$ (SD+)) = (0.466 ± 0.006)x10^-5

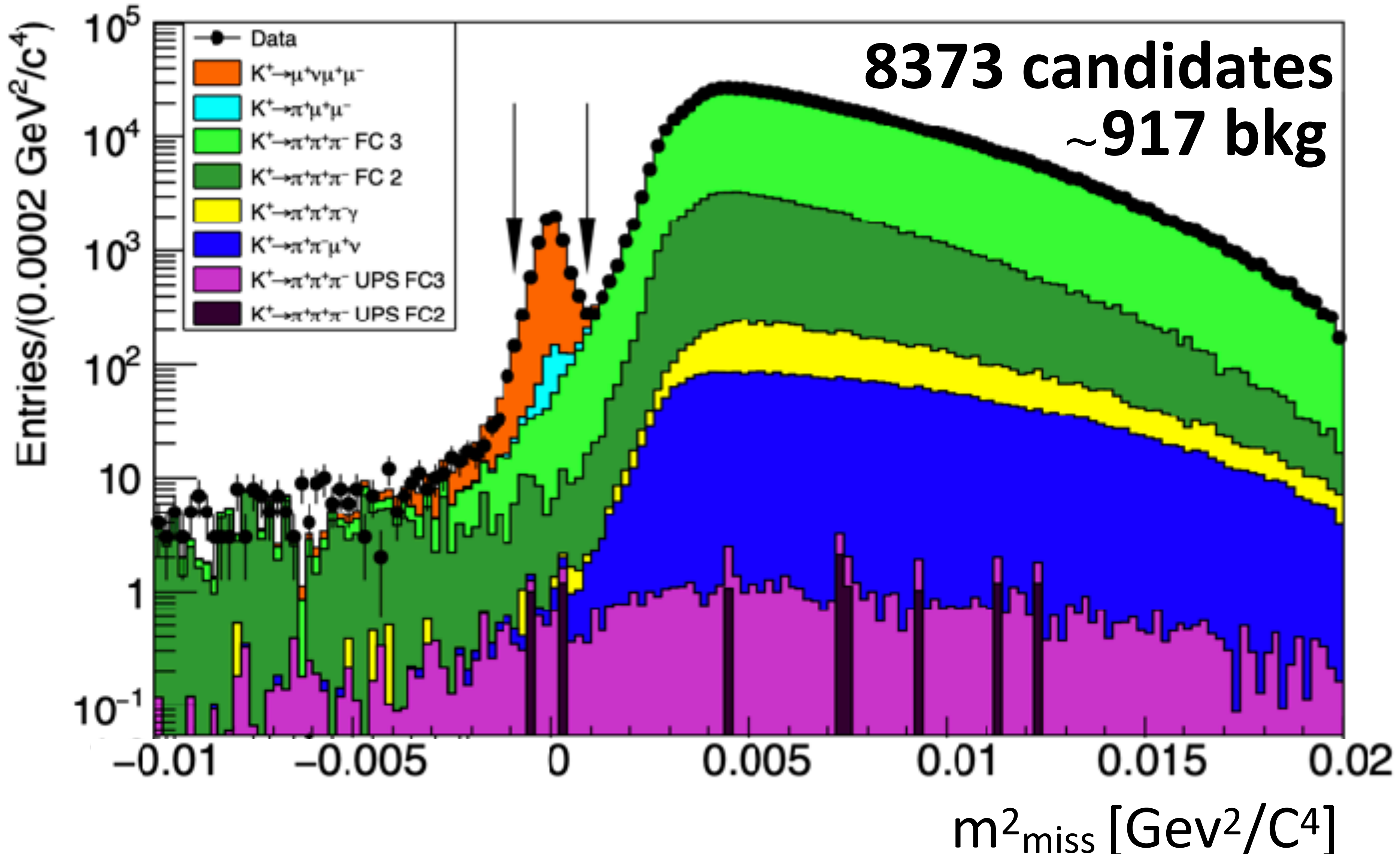
$$R_\gamma = \Gamma(K_{e2\gamma}\ SD+)/\Gamma(K_{\mu 2})$$

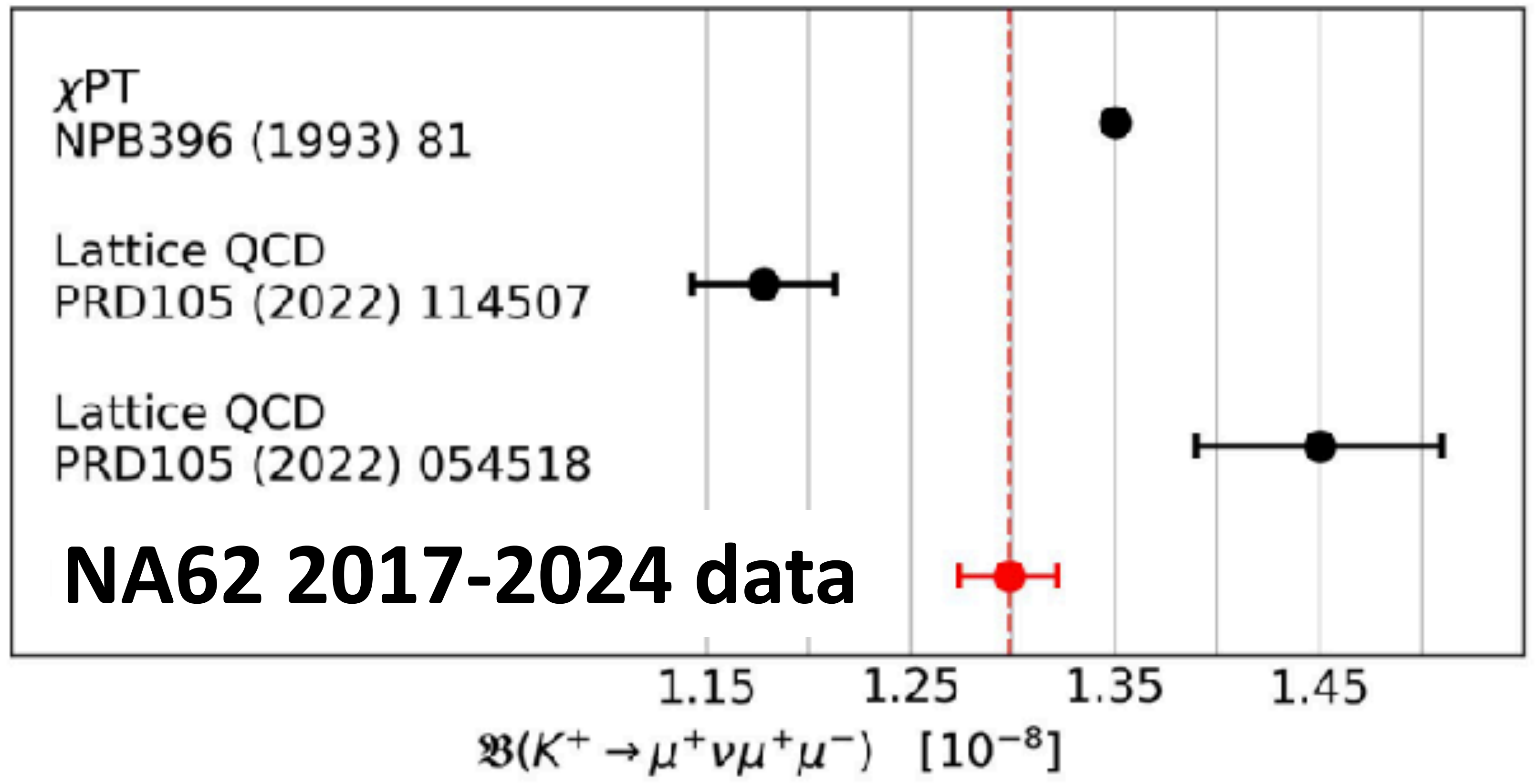


See Romano's talk at KAON2025

First measurement of

BR($K^+ \to \mu^+\nu\mu^+\mu^-$) = (1.298 ± 0.024)x10^-8





Conclusions

$K^+ \to \pi^+ \nu\bar{\nu}$		JHEP 02 (2025) 191
$K^+ \to \pi^0 \pi \mu e$	NA62 Run 1	PLB 859 (2024) 139122
$A' \to e^+ e^-$	NA62 2021	PRL 133 (2024) 111802
$K^+ \to \pi^+ \gamma\gamma$	NA62 Run 1	PLB 850 (2024) 138513
$K^+ \to \pi^+ e^+ e^- e^+ e^-$	NA62 Run 1	PLB 846 (2023) 138193
$K^+ \to \mu^- \nu e^+ e^+$	NA62 Run 1	PLB 838 (2023) 137679
$K^+ \to \pi^0 e^+ \nu \gamma$	NA62 Run 1	JHEP 09 (2023) 040
$A' \to \mu^+ \mu^-$	NA62 2021	JHEP 09 (2023) 035
$K^+ \to \mu^- \nu e^+ e^+$	NA62 Run 1	PLB 838 (2023) 137679
$K^+ \to \pi^- (\pi^0) e^+ e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \pi^+ \mu^+ \mu^-$	NA62 Run 1	JHEP 11 (2022) 011
$\pi^0 \to \mu^- e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^+ \mu^- e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^- \mu^+ e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^+ \nu\bar{\nu}$	NA62 Run 1	JHEP 06 (2021) 093
$K^+ \to \pi^- \mu^+ \mu^+$	NA62 Run 1	PBL 797 (2019) 134794
....		

- Several new physics results obtained by the NA62 collaboration
- Multiple analyses are ongoing

Flavour Physics: search for **lepton flavor & lepton number violation,** rare & forbidden decays

Panichi's talk tomorrow

- End of data taking: 2026

… further results will be obtained and new searches developed with the full statistic

Thank you for your attention from the NA62 collaboration