Recent Results from the NA62 Experiment

Joel Swallow (INFN-LNF)

Contents:

- **New headline measurement of $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ [NEW: arXiv:2412.12015]**
  - Golden modes $K \to \pi \nu \bar{\nu}$ in the SM and beyond, NA62 detector upgrades & performance
- **Other 2024 physics results:**
  - New measurement of $K^+ \to \pi^+ \pi^0, \pi^0 \to e^+ e^-$ [preliminary: Spring 2024]
  - Search for $K^+ \to \pi^0 \pi \mu e$ LNV/LFV decays [PLB 859 (2024) 139122]
  - Beam dump search for dark photon decays to hadrons [preliminary: Spring 2024]

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New measurement of $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu})$

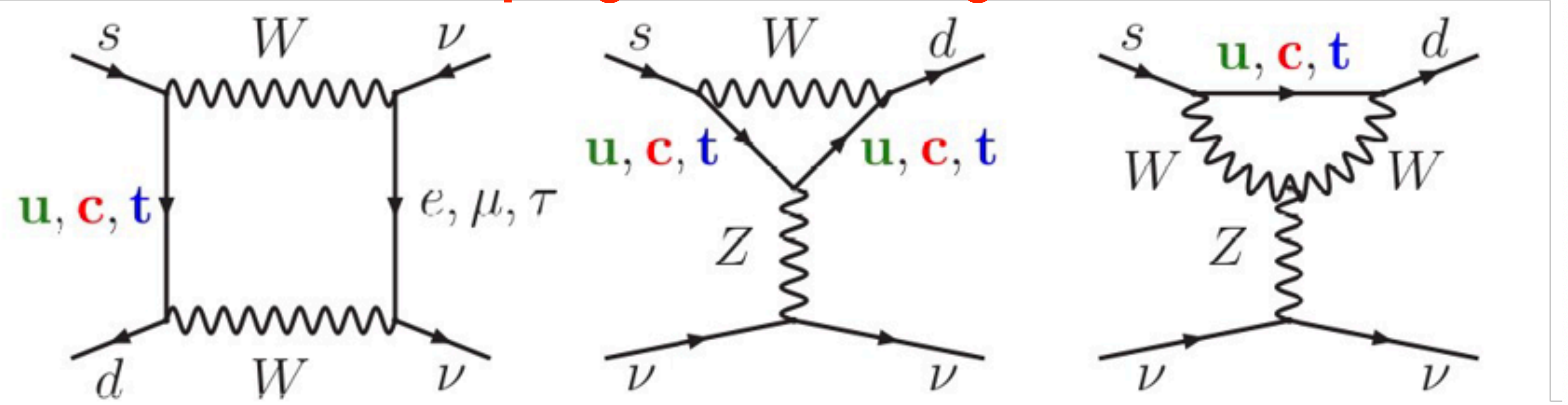
NEW: arXiv:2412.12015

Hot off the press! (Available since Tuesday)

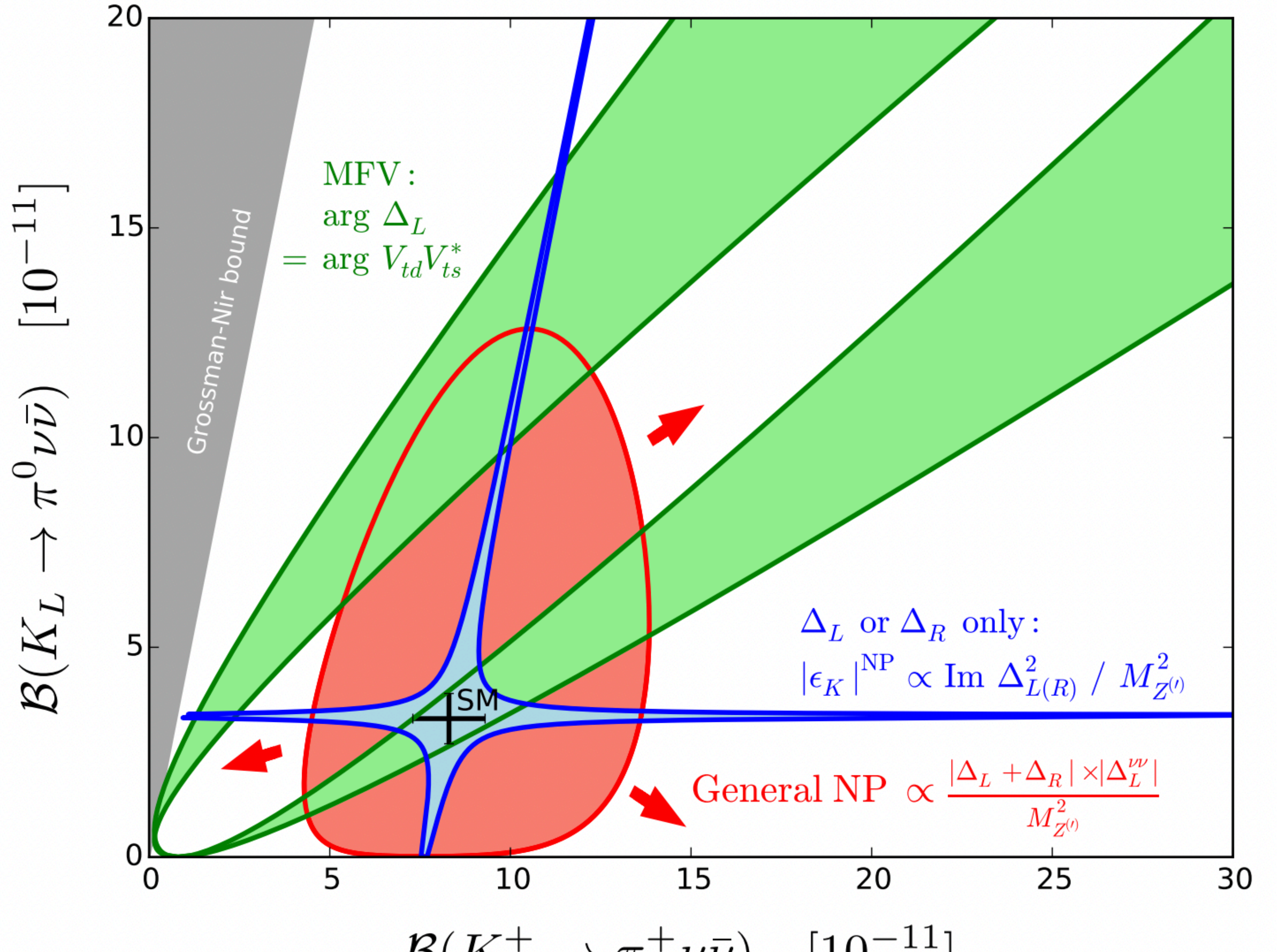
Golden modes $K \to \pi\nu\bar{\nu}$: SM and beyond

NA62

SM: Z-penguin & box diagrams



- $\mathscr{B}(K \to \pi\nu\bar{\nu})$ **highly suppressed** in SM
  - GIM mechanism & maximum CKM suppression.
- Theoretically clean ⇒ high precision SM predictions
- High sensitivity to New Physics up to $\mathcal{O}(100)$ TeV



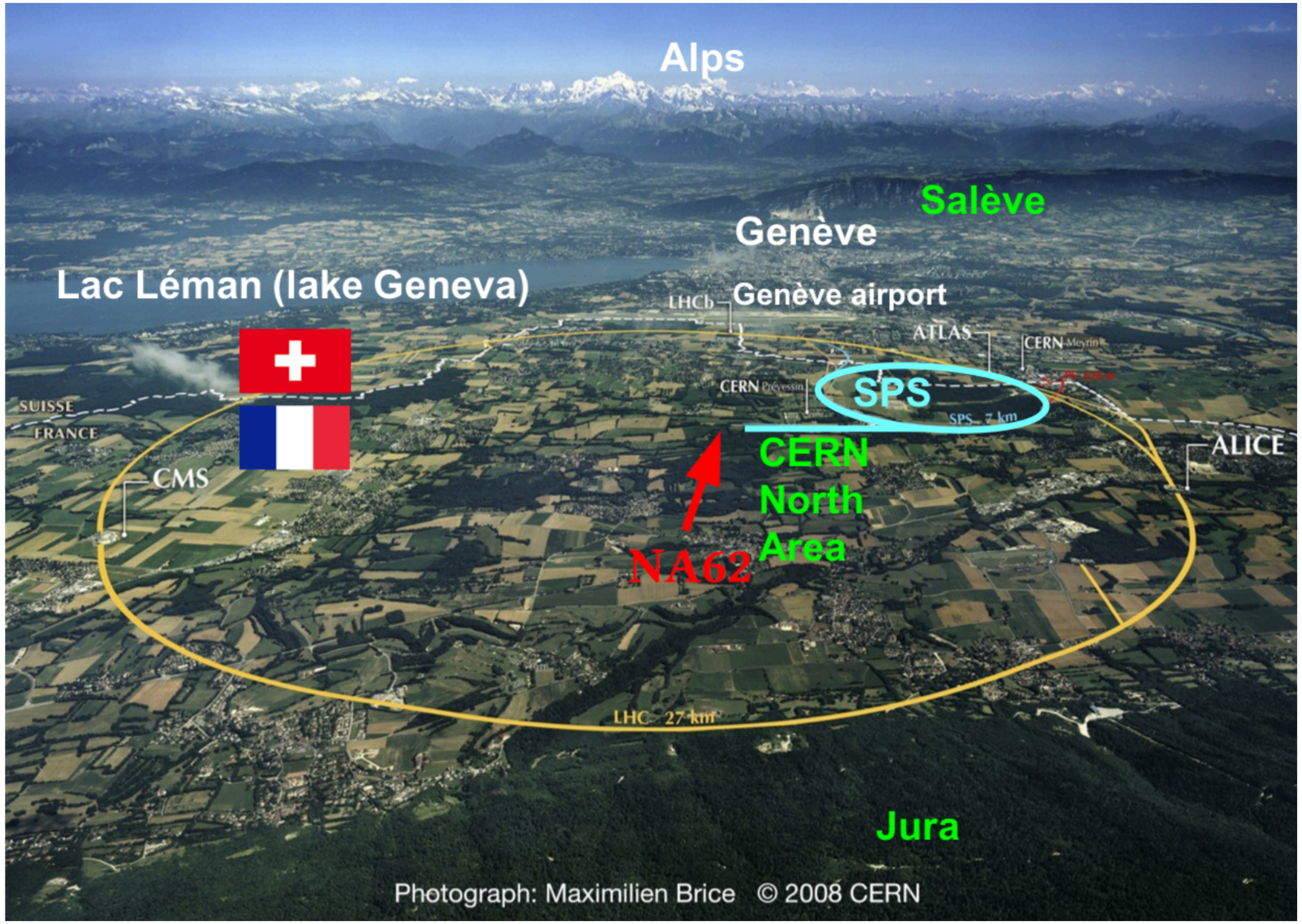
[JHEP 11 (2015) 166]

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])

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, 7 low Intensity]).

LS2 (upgrades) | this result | LS3

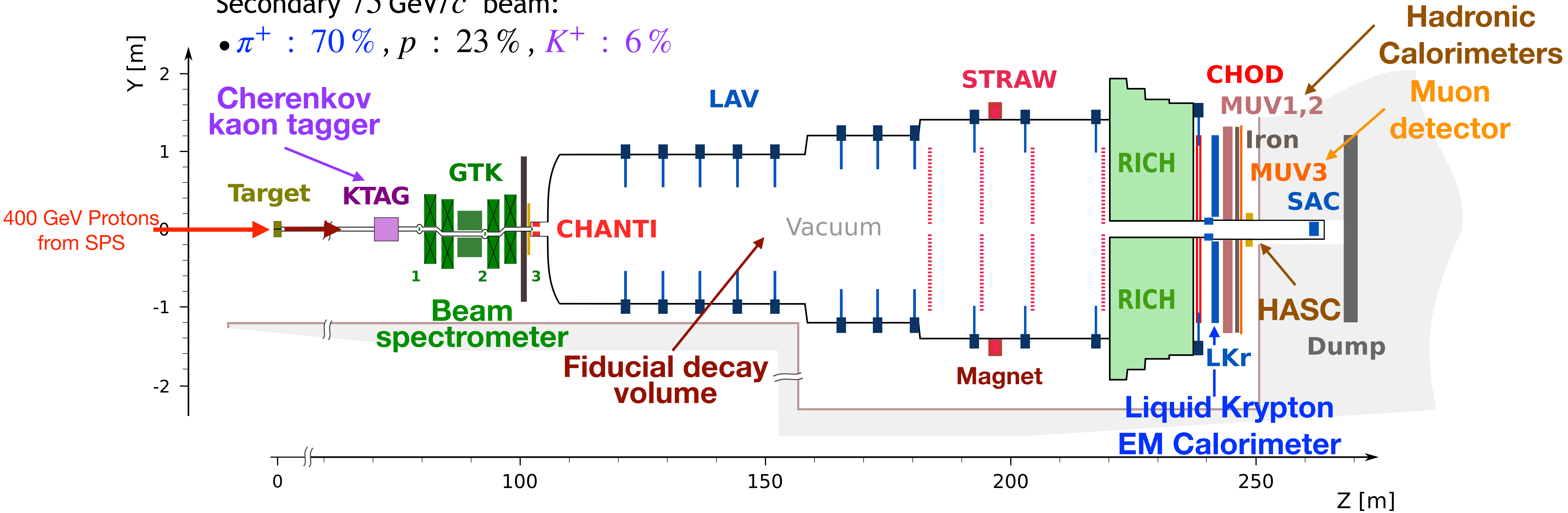
2016 2017 2018 2019 2020 2021 2022 2023 2024 2025

NA62 beamline & detector

[JINST 12 (2017) 05, P05025]

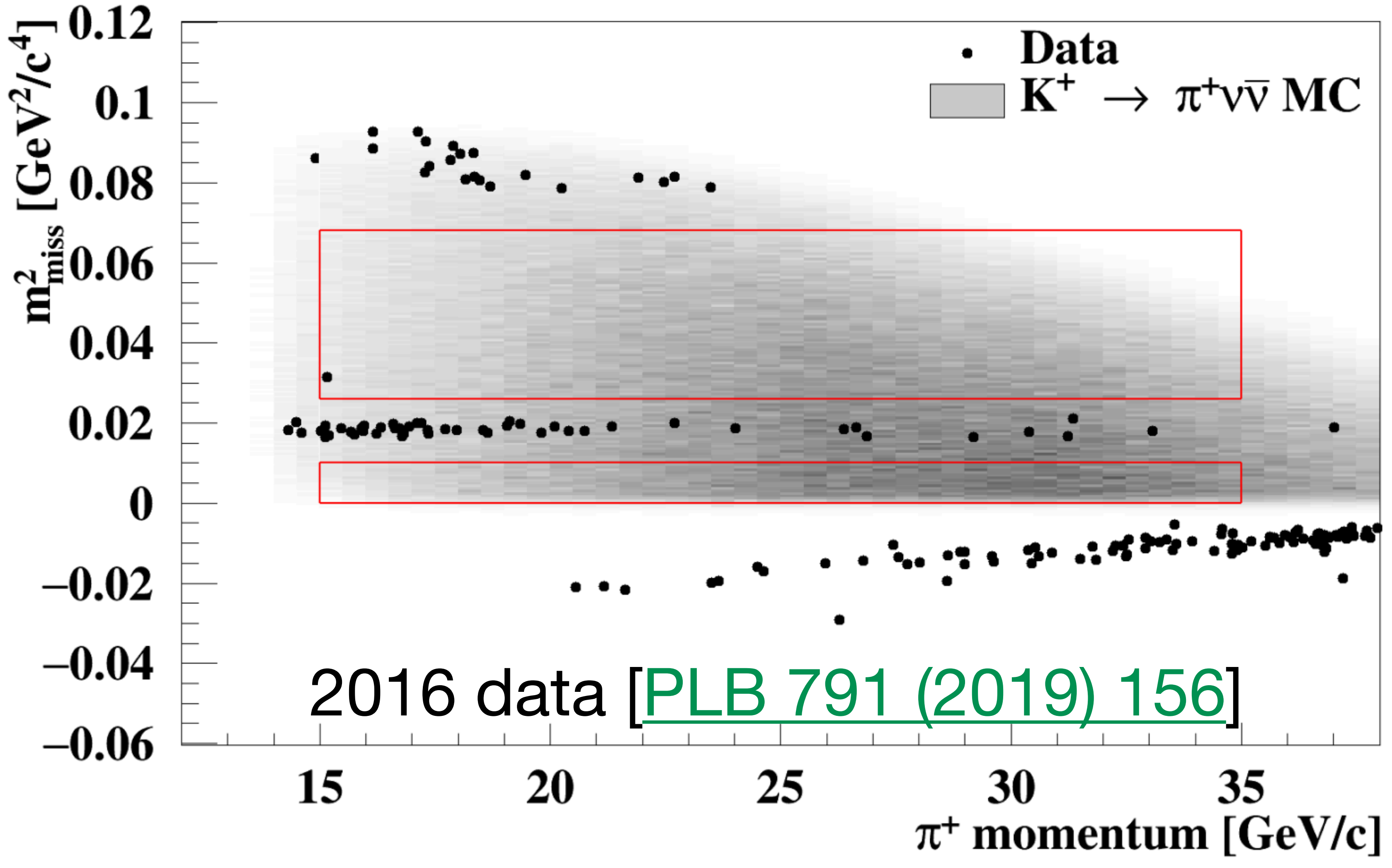
Secondary $75\,\mathrm{GeV}/c$ beam:

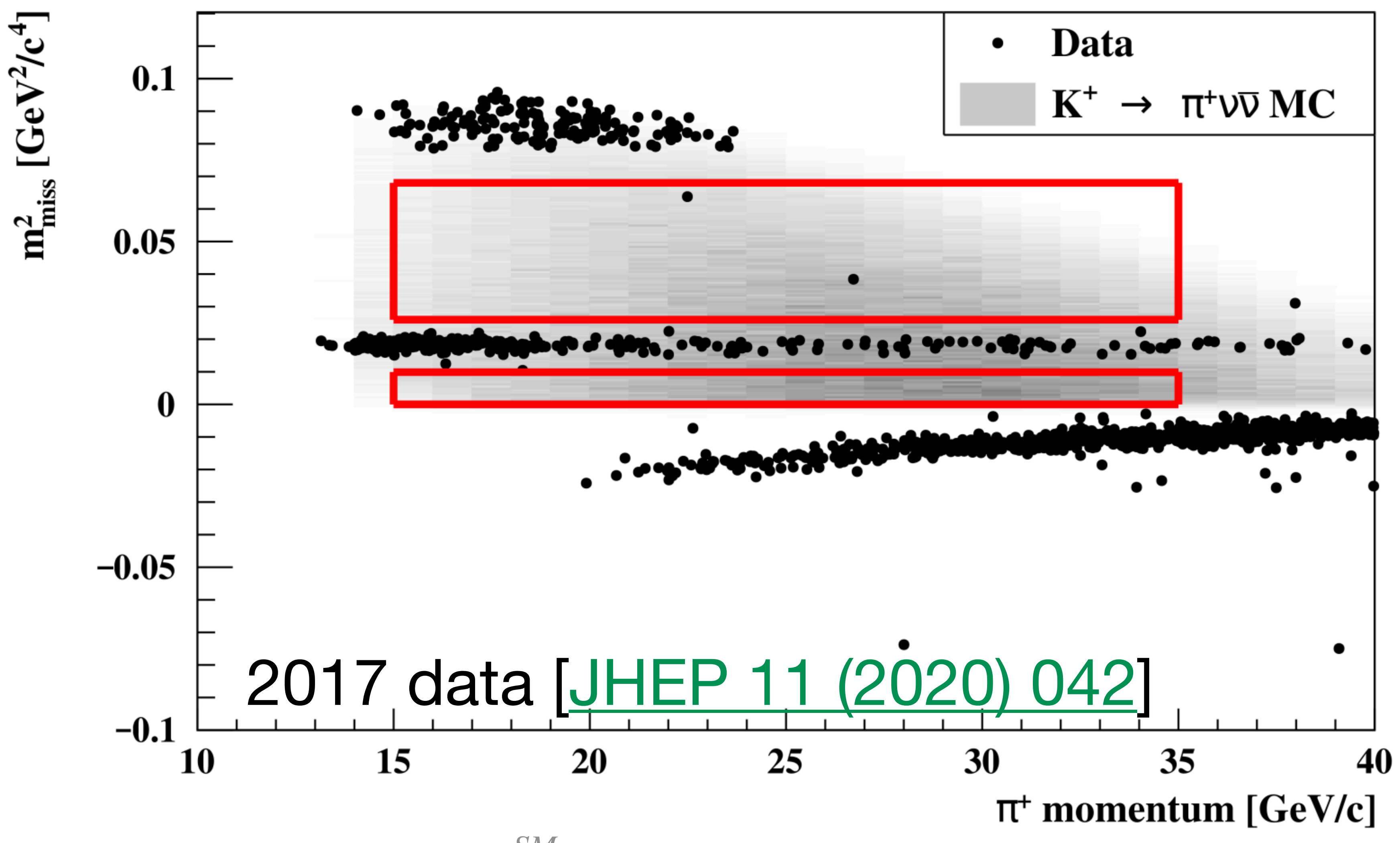
- $\pi^+ : 70\,\%$, $p : 23\,\%$, $K^+ : 6\,\%$

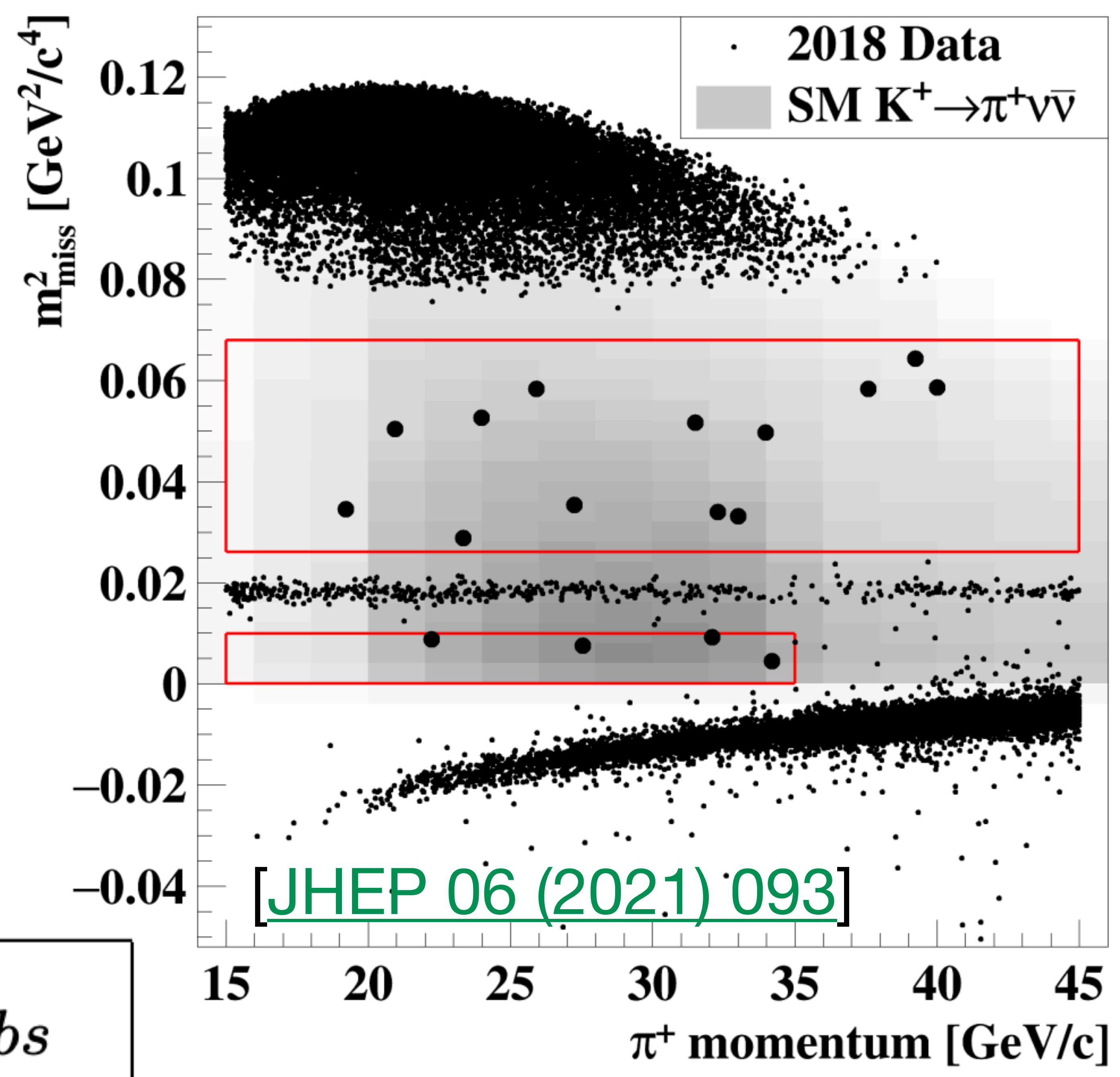


- Designed & optimised for study of $K^+ \to \pi^+ \nu \bar{\nu}$:
  - **Particle tracking:** beam particle (GTK) & downstream tracks (STRAW)
  - **PID:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
  - **Comprehensive veto systems:** CHANTI (beam interactions), LAV,LKr,IRC,SAC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

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







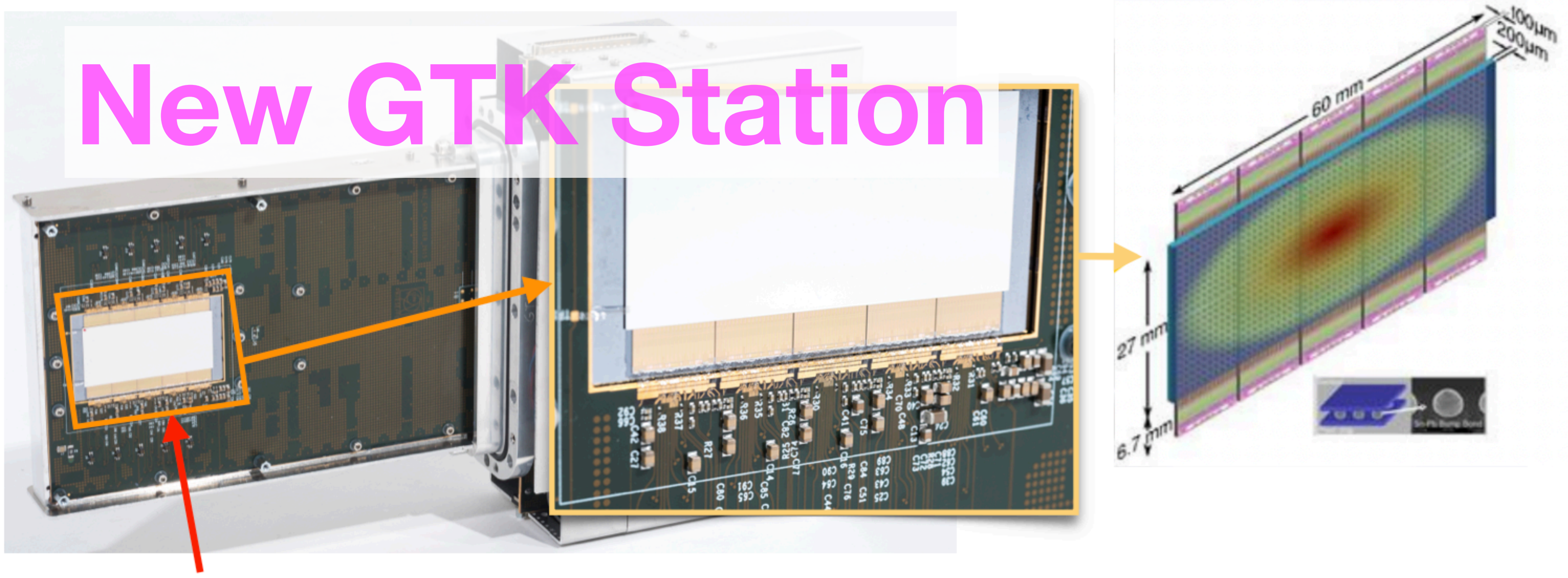
(* $N_{\pi\nu\bar{\nu}}^{SM,exp}$ assumes SM BR from [JHEP 11 (2015) 166])

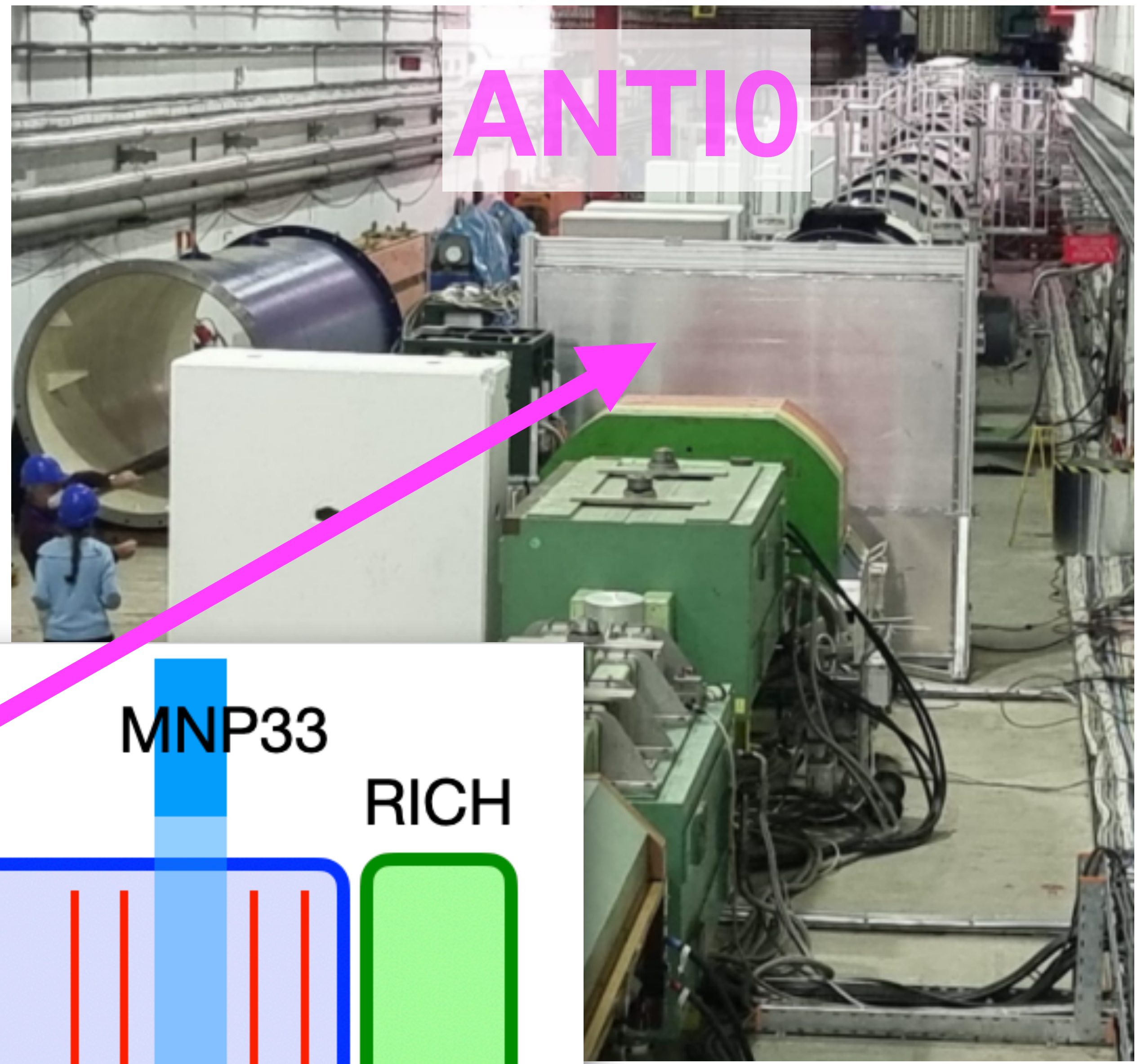
Data-taking year	[Reference]	N_{bg}	$N_{\pi\nu\bar{\nu}}^{SM,exp}$	N_{obs}
2016	[PLB 791 (2019) 156]	$0.152^{+0.093}_{-0.035}$	0.267 ± 0.020	1
2017	[JHEP 11 (2020) 042]	1.46 ± 0.33	2.16 ± 0.13	2
2018	[JHEP 06 (2021) 093]	$5.42^{+0.99}_{-0.75}$	7.58 ± 0.40	17
2016–18	[JHEP 06 (2021) 093]	$7.03^{+1.05}_{-0.82}$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

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

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

Upgrading NA62: against upstream background



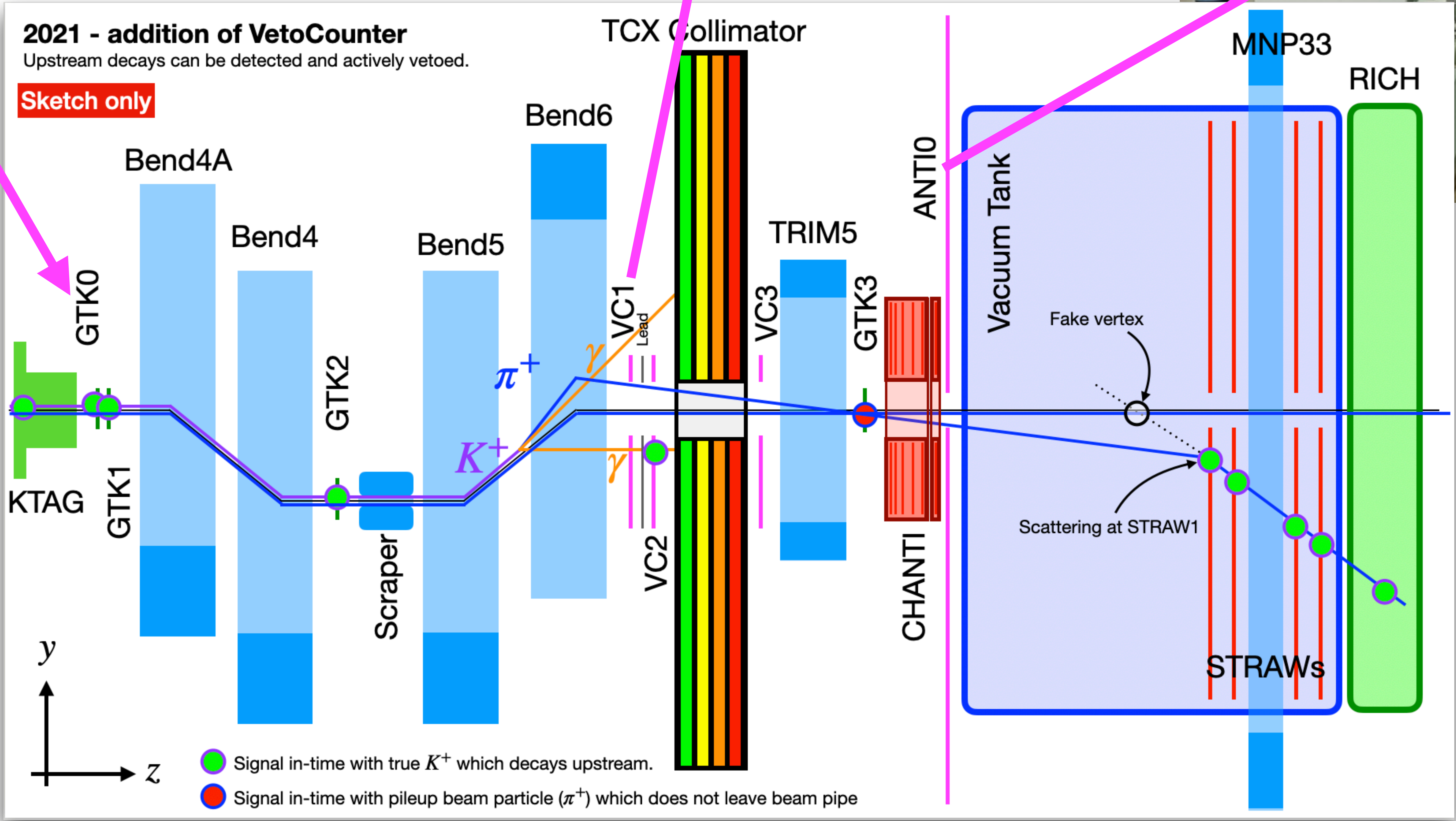


4th GTK station improves efficiency & pileup resilience.

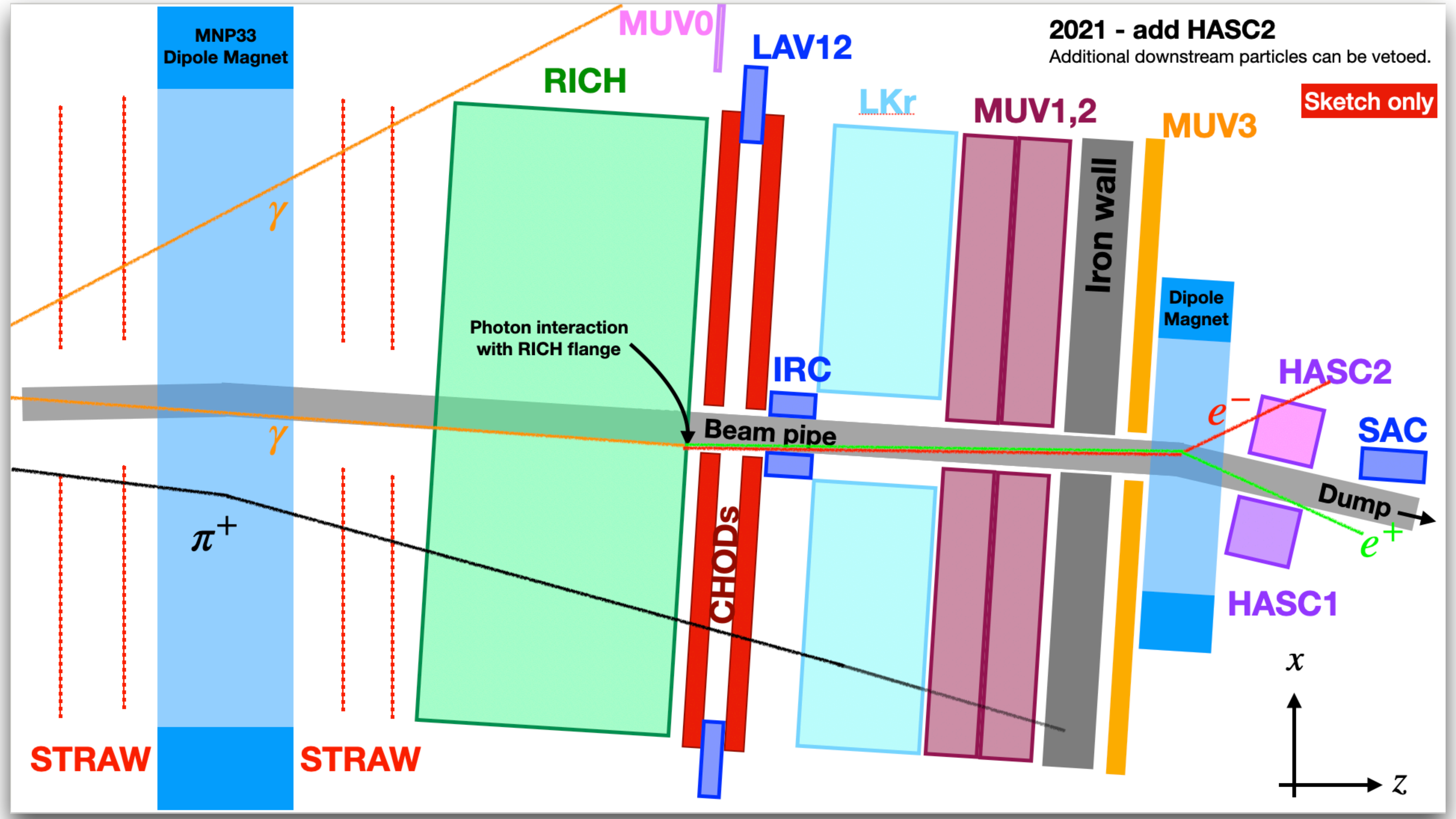
VetoCounter:

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

ANTI0 **reject ~20% of upstream background.**

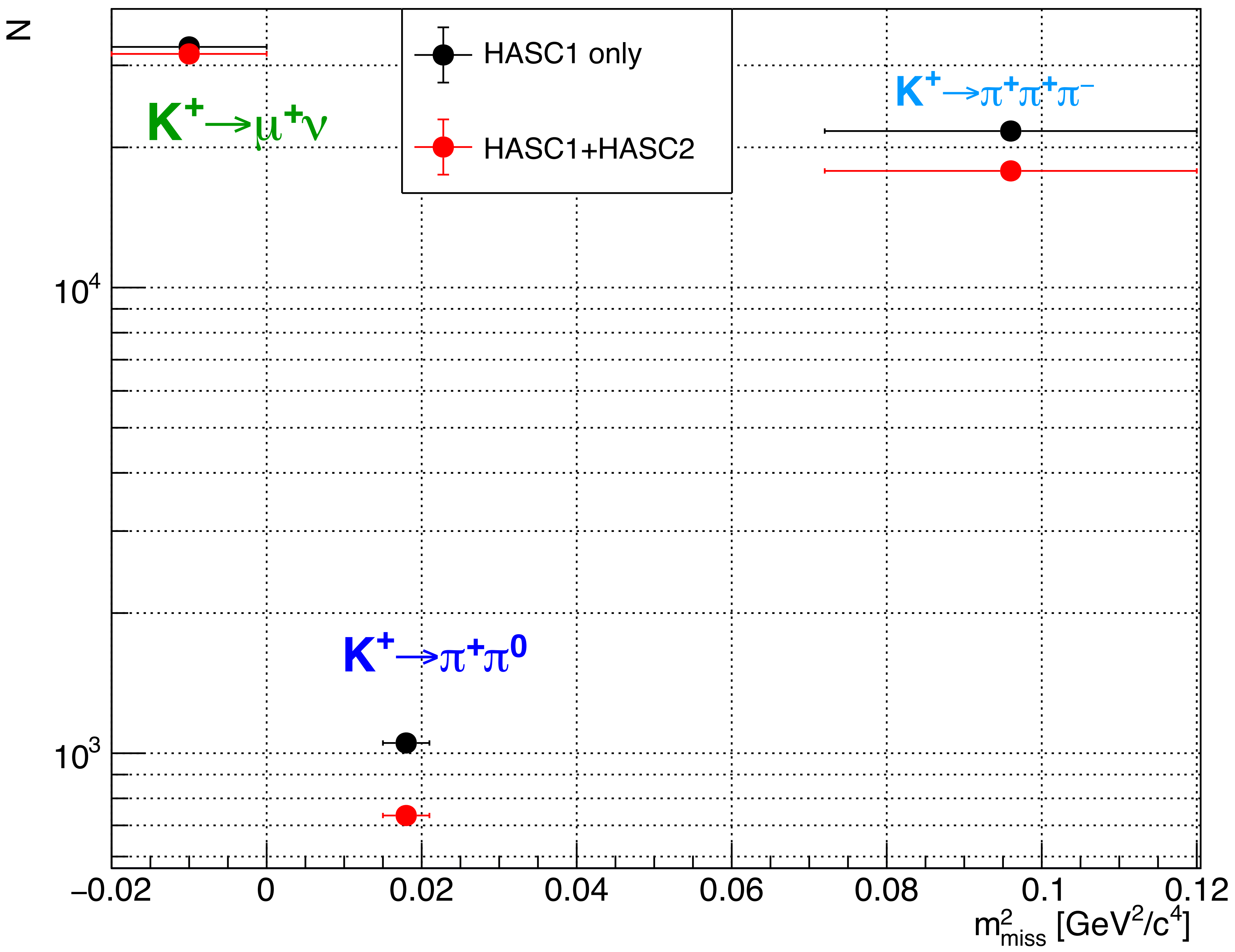


Upgrading NA62: against $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma\gamma$



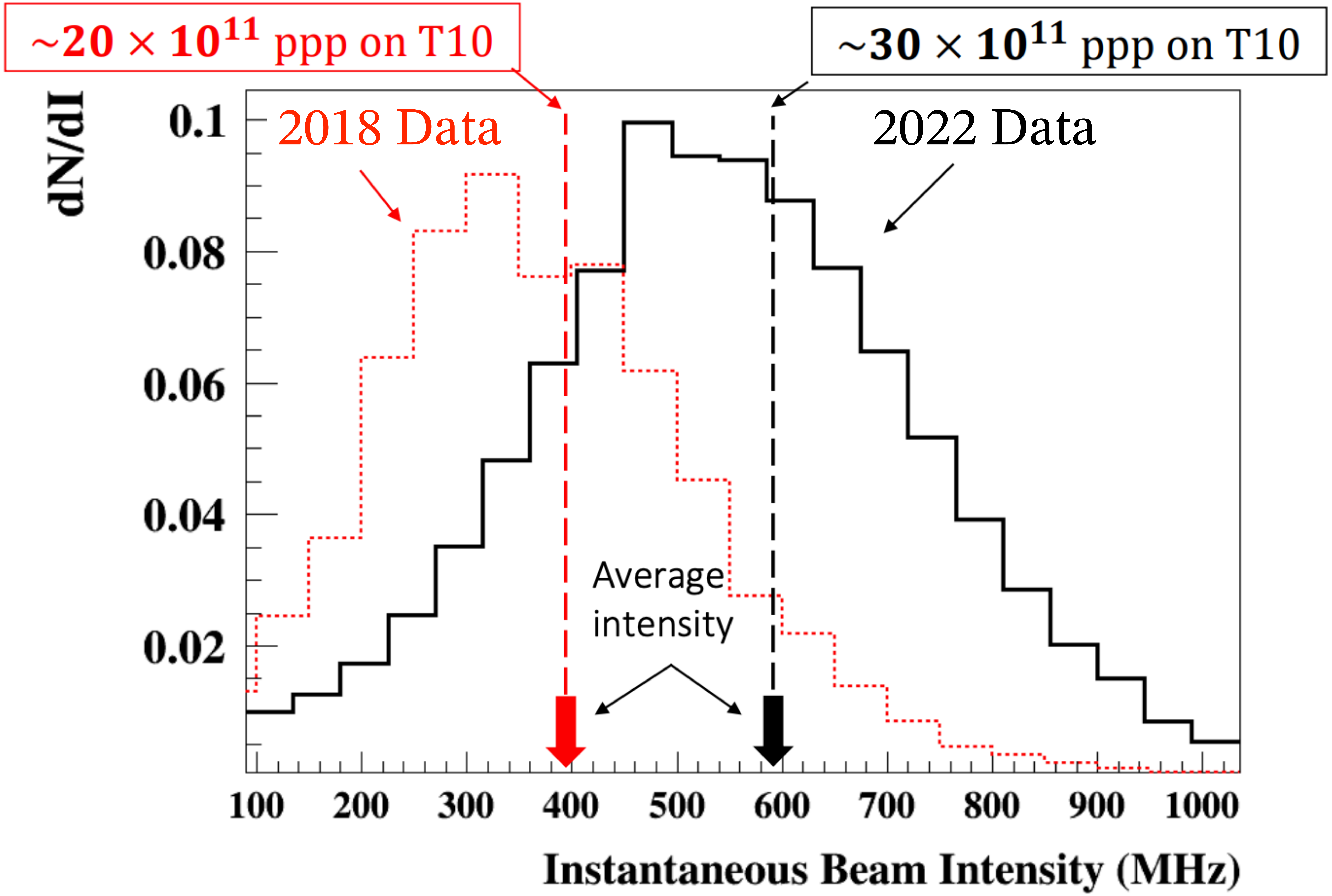
Events passing $\pi^+\nu\bar{\nu}$ selection

(modifying HASC veto: study integral of background regions)



- 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.

Beam intensity: 2018 vs 2022

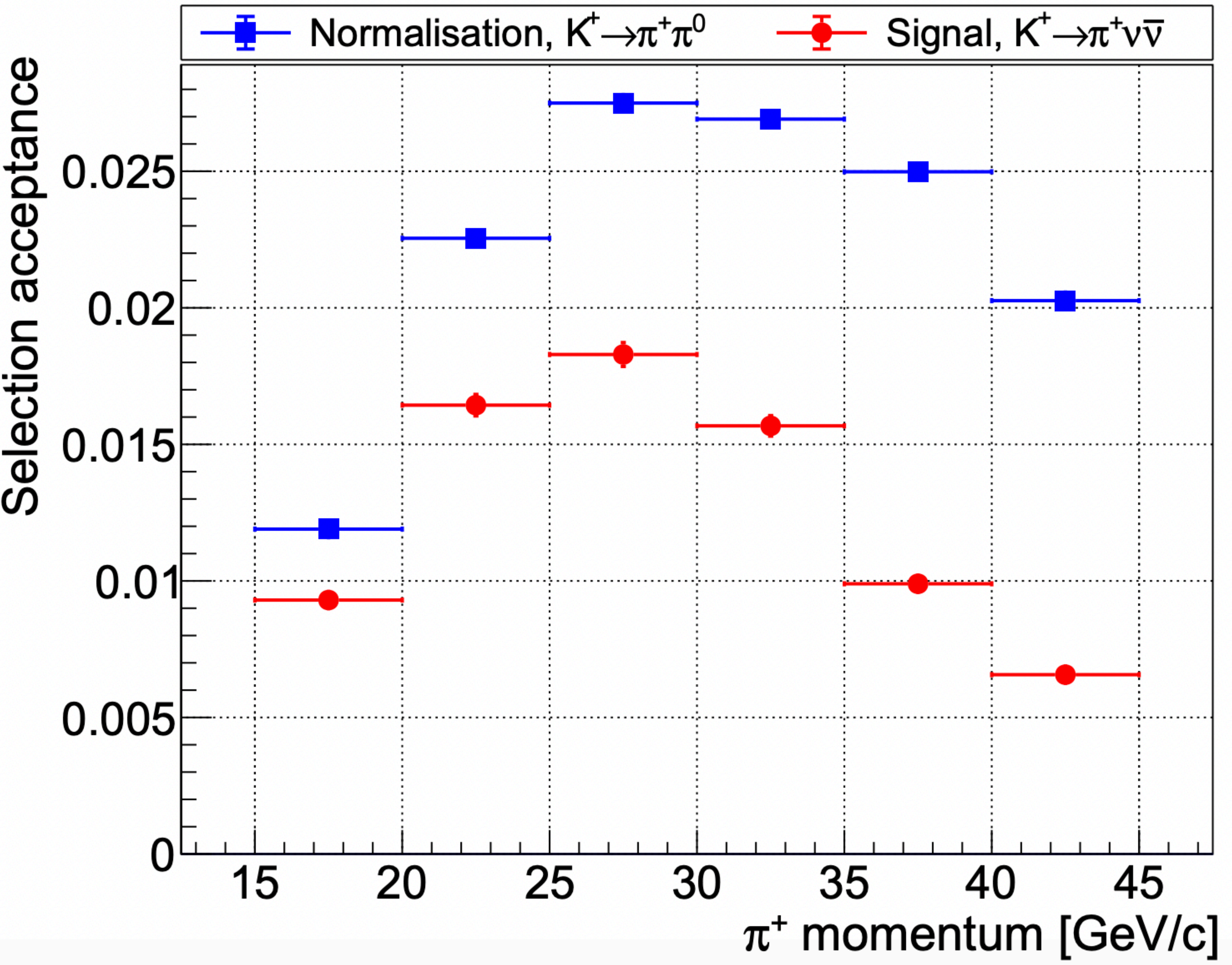


- Average beam intensity increased.
- NA62 “Full intensity” with 4.8s spill = 600 MHz

Signal Sensitivity

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

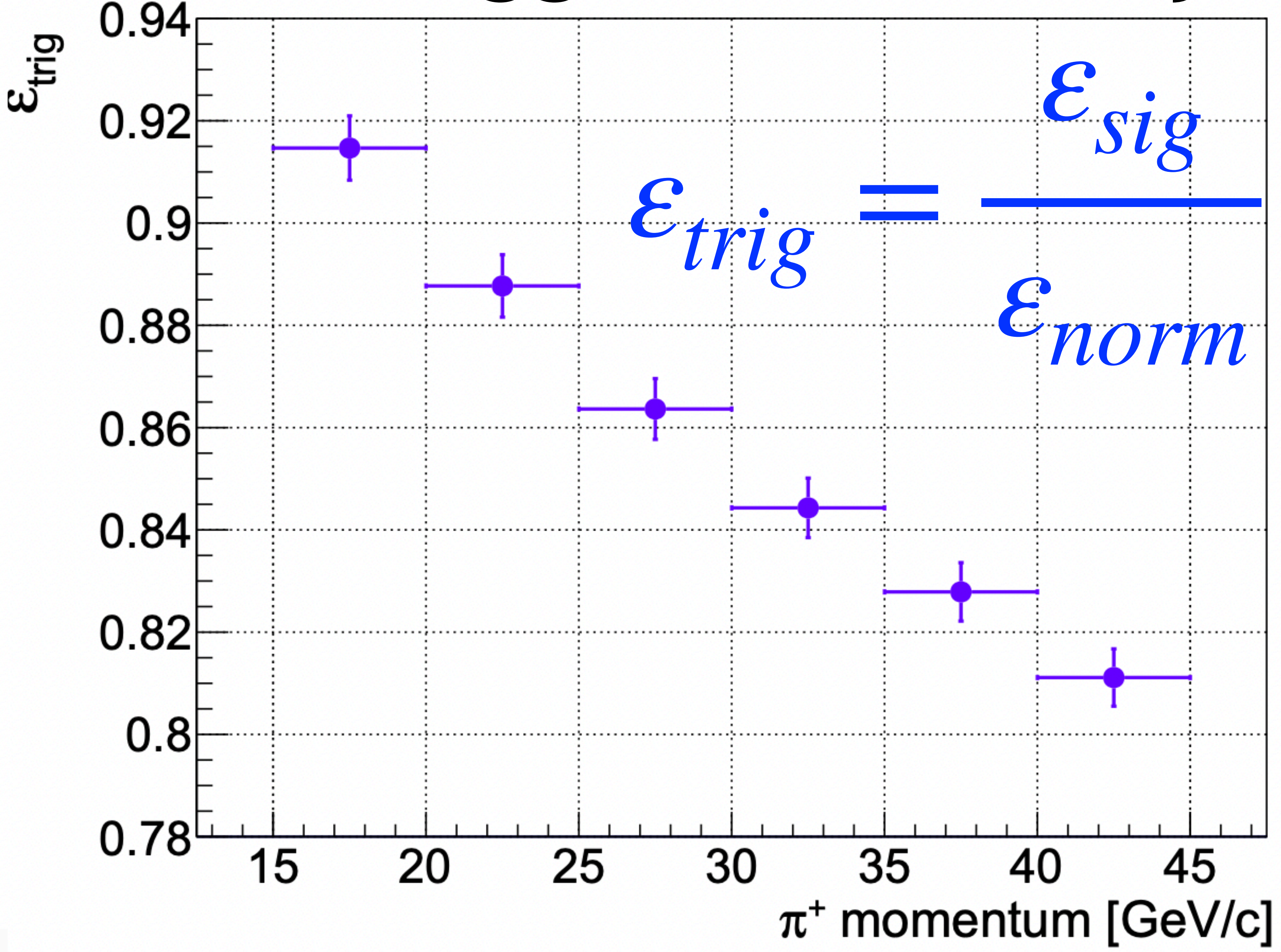
Selection Acceptances



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

+20% signal acceptance (Wrt. 2018 analysis)

Trigger efficiency



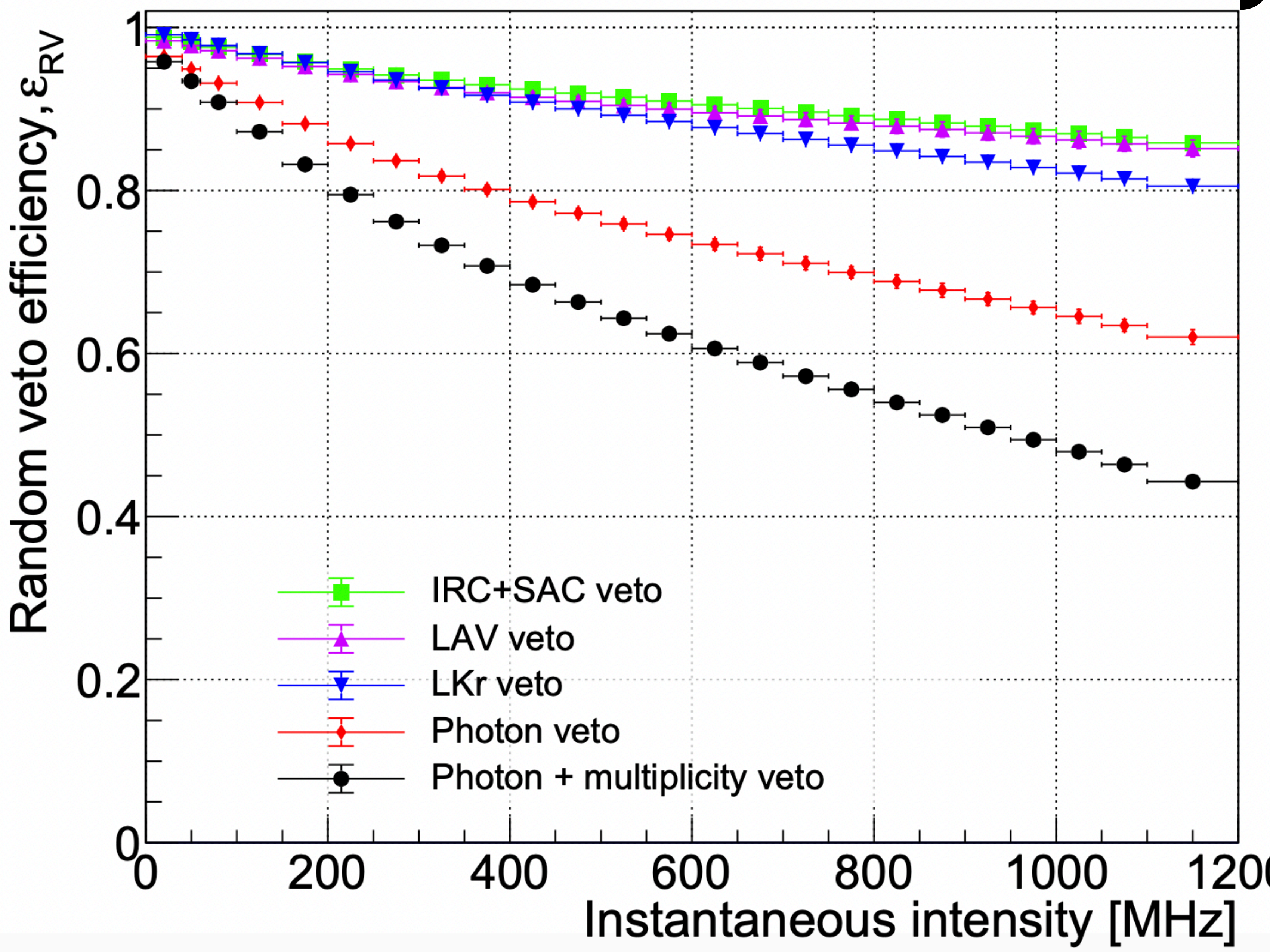
$$\varepsilon_{trig} = \frac{\varepsilon_{sig}}{\varepsilon_{norm}}$$

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

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

- **Improved precision by factor 3** with reduced systematic uncertainty.
  - Due to cancellations in ratio.

Random Veto efficiency



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

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

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

Signal sensitivity results

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

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

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

* Acceptances evaluated at 0 intensity.

	Factor	Value
$N_{\pi\pi}^{\text{eff}}$	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	$(7.62 \pm 0.22)\%$
$\varepsilon_{\text{trig}}$	Trigger efficiency ratio	$(85.9 \pm 1.4)\%$
ε_{RV}	Random veto efficiency	$(63.2 \pm 0.6)\%$
$\mathcal{B}_{\text{SES}}$	Single event sensitivity	$(8.48 \pm 0.29) \times 10^{-12}$
$N_{\pi\nu\bar{\nu}}^{\text{SM}}$	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 $\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$:

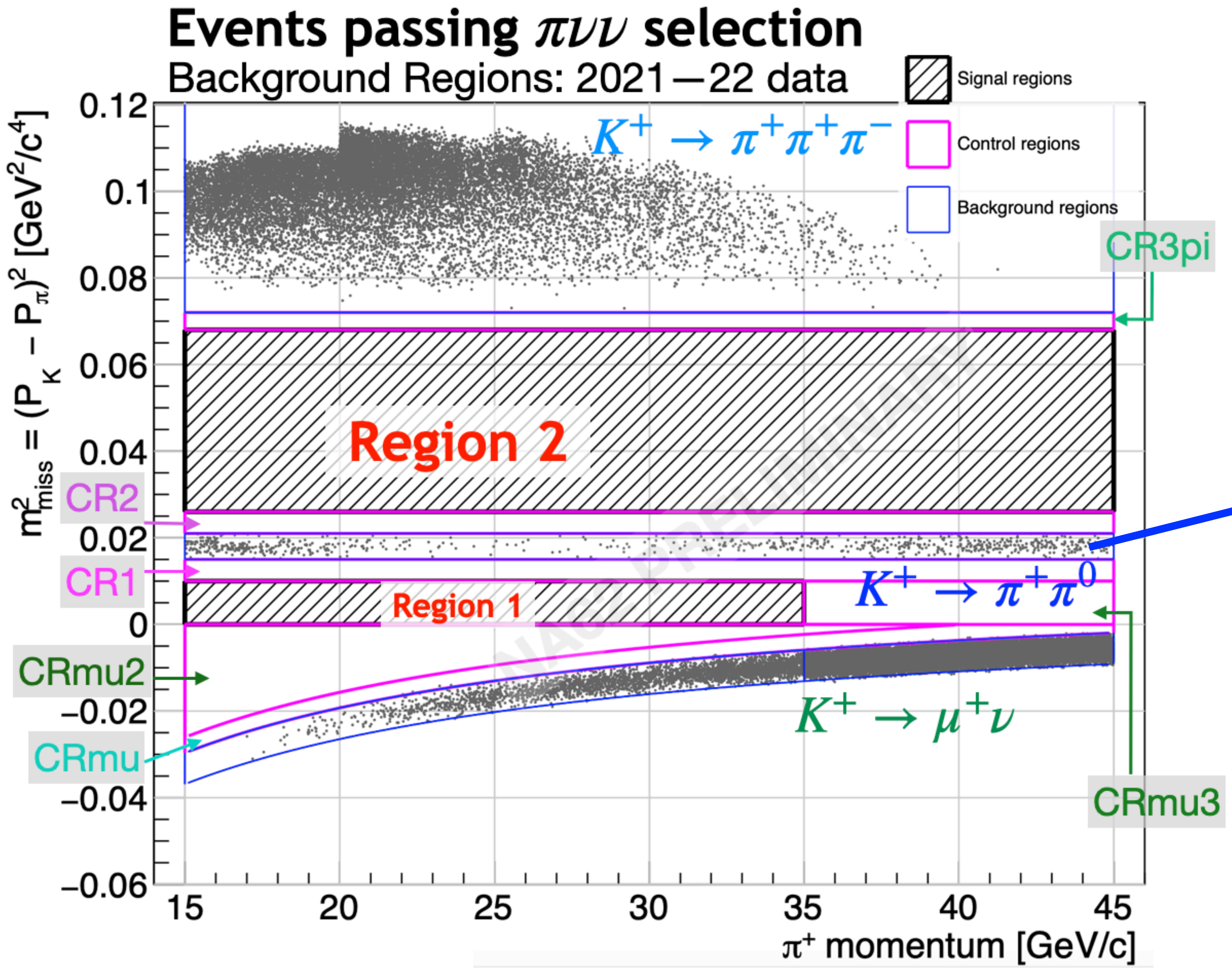
2021—22: $N_{\pi\nu\bar{\nu}} = 9.91 \pm 0.34$

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}

Background regions & background estimations



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

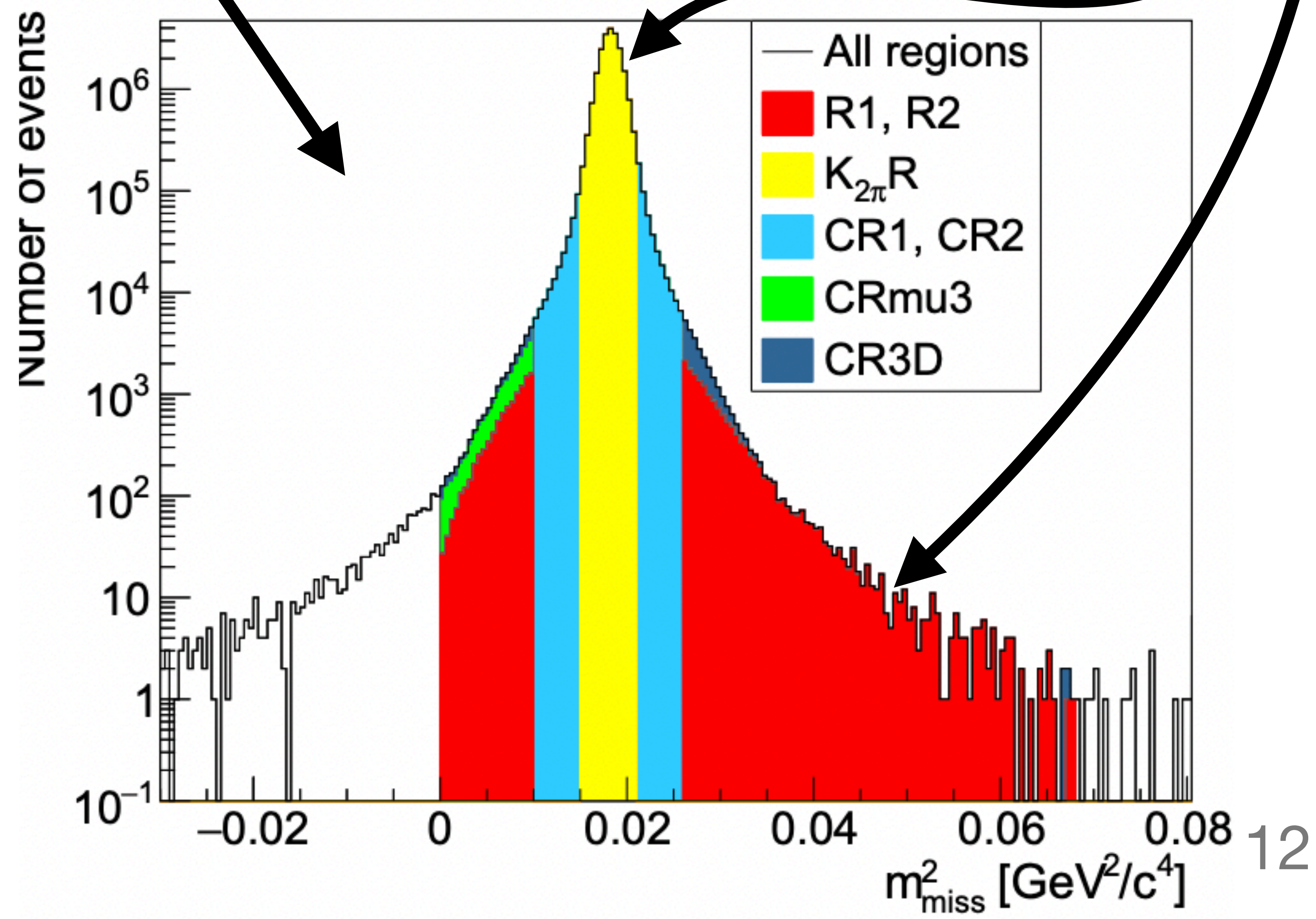
$$N_{bg} = N_{bkgR} \cdot f_{tail} = N_{bkgR} \cdot \frac{N^{CS}_{SR}}{N^{CS}_{bkgR}}$$

Number of events passing signal selection in background region

Control sample events in Signal Regions

Kinematic tail fraction: measured in control sample

Control sample events in Background Region



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

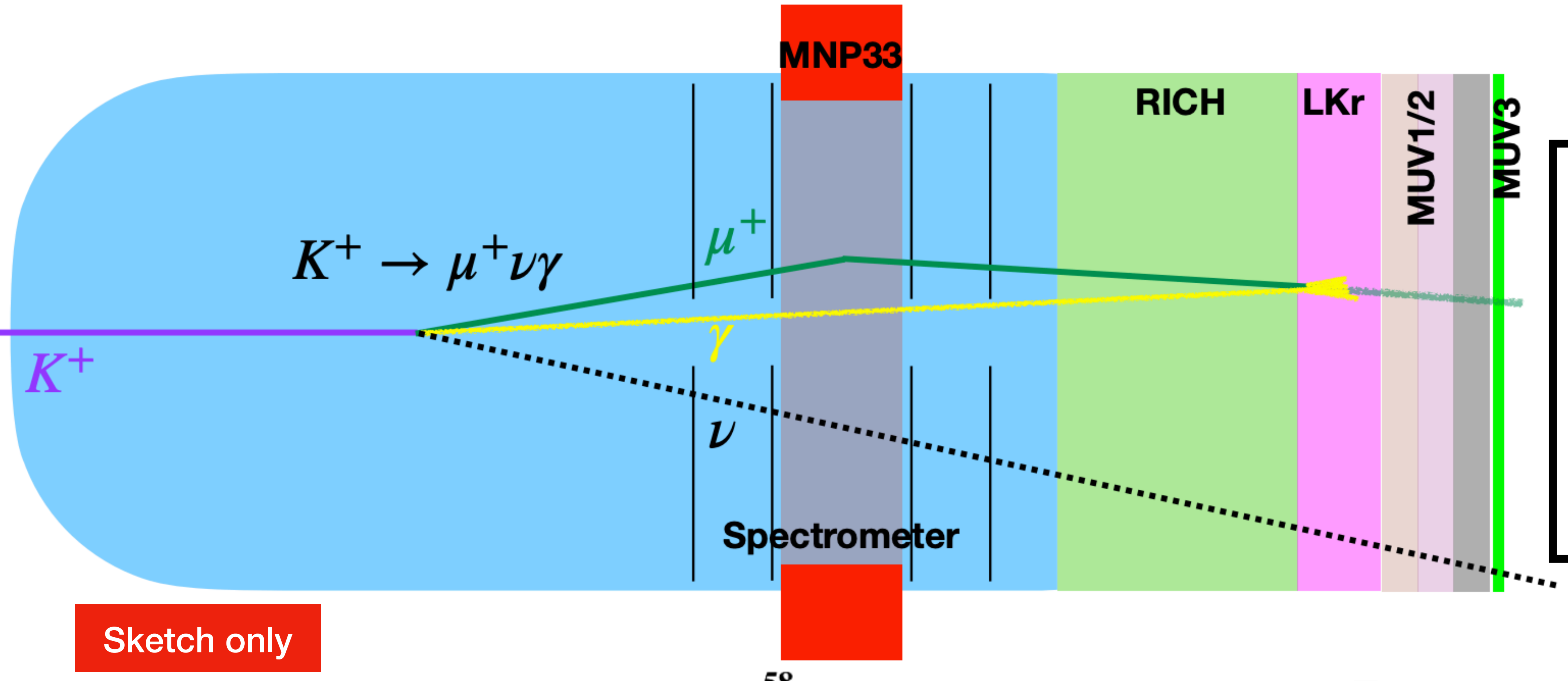
$$N_{bg}(K^+ \to \mu^+\nu) = 0.9 \pm 0.2$$

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

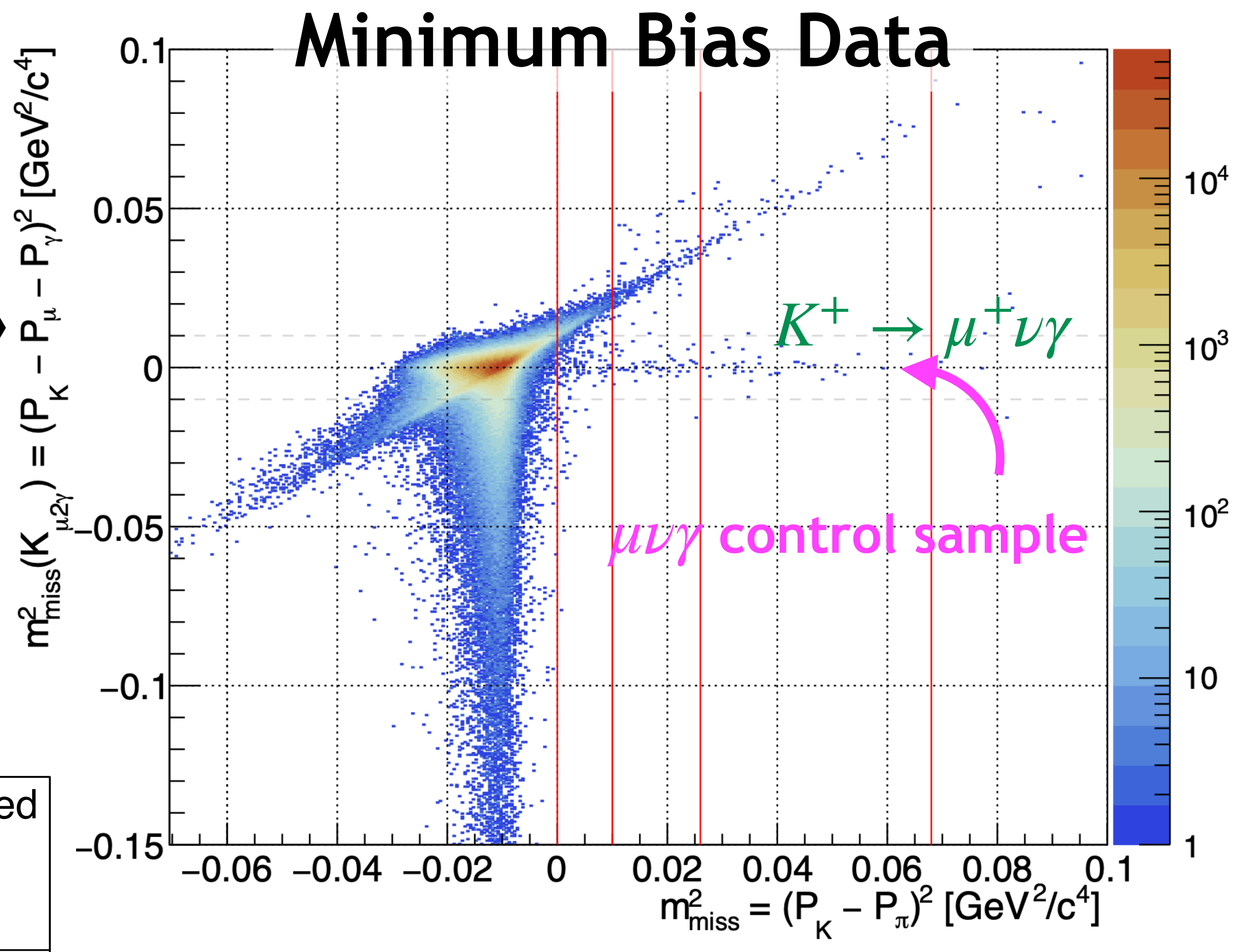
Radiative decays: $K^+ \to \pi^+\pi^0\gamma$ & $K^+ \to \mu^+\nu\gamma$

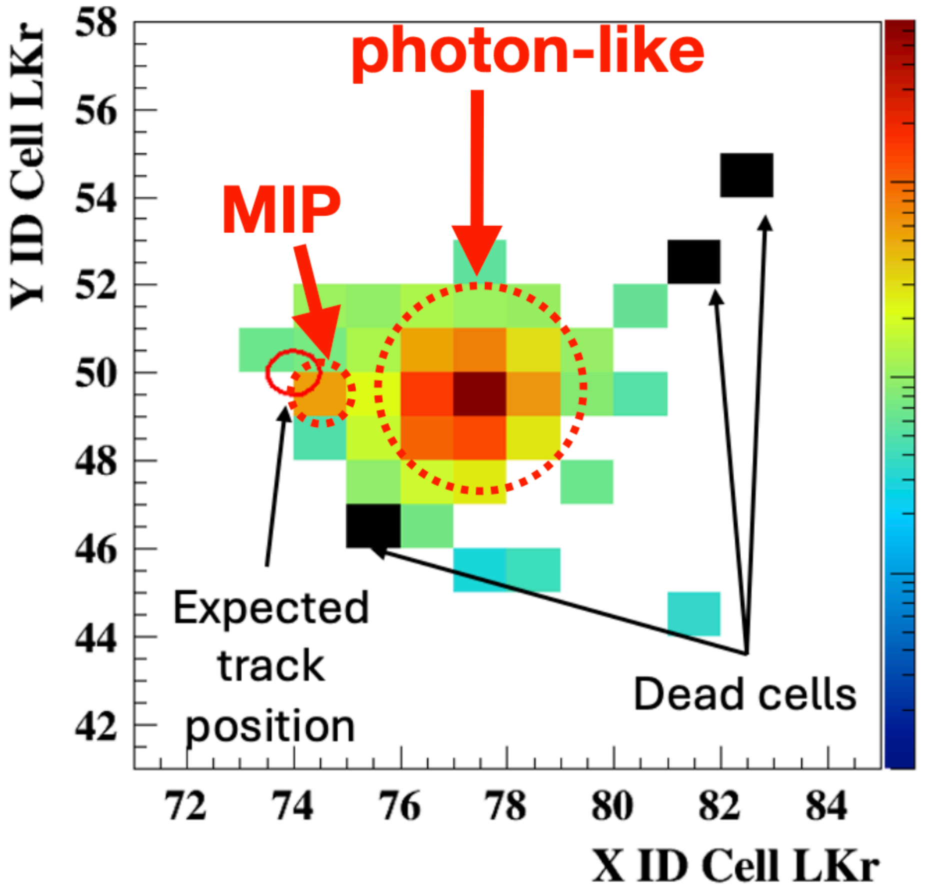
NA62

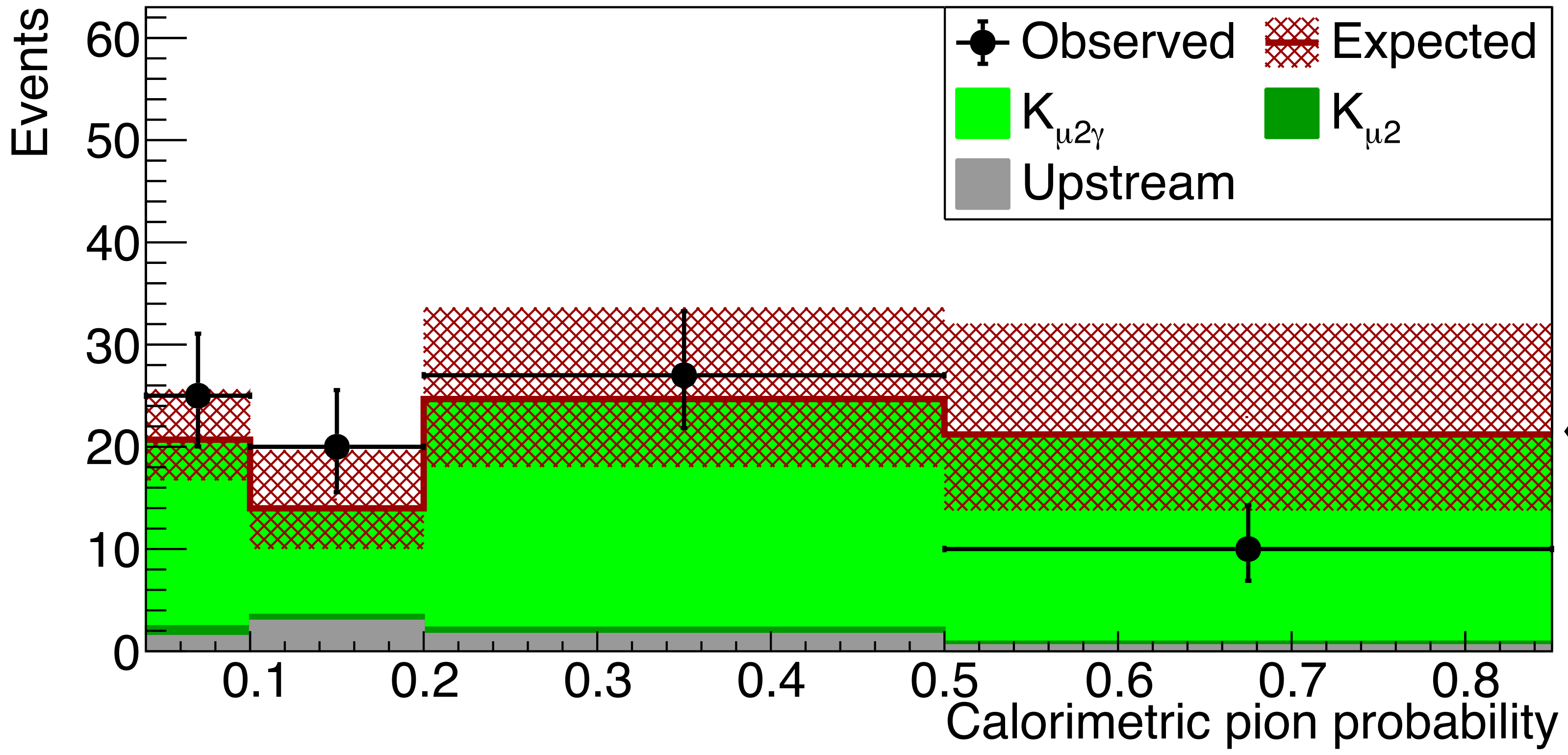
- $K^+ \to \pi^+\pi^0\gamma$: extra photon = 30x stronger rejection: $N_{bg}(K^+ \to \pi^+\pi^0\gamma) = 0.07 \pm 0.01$
- $K^+ \to \mu^+\nu\gamma$: **not included in "kinematic tails" estimation if γ overlaps μ^+ at LKr (leading to misID as π^+)**
  - Suppression: based on $(P_K - P_\mu - P_\gamma)^2$ 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).



- 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).





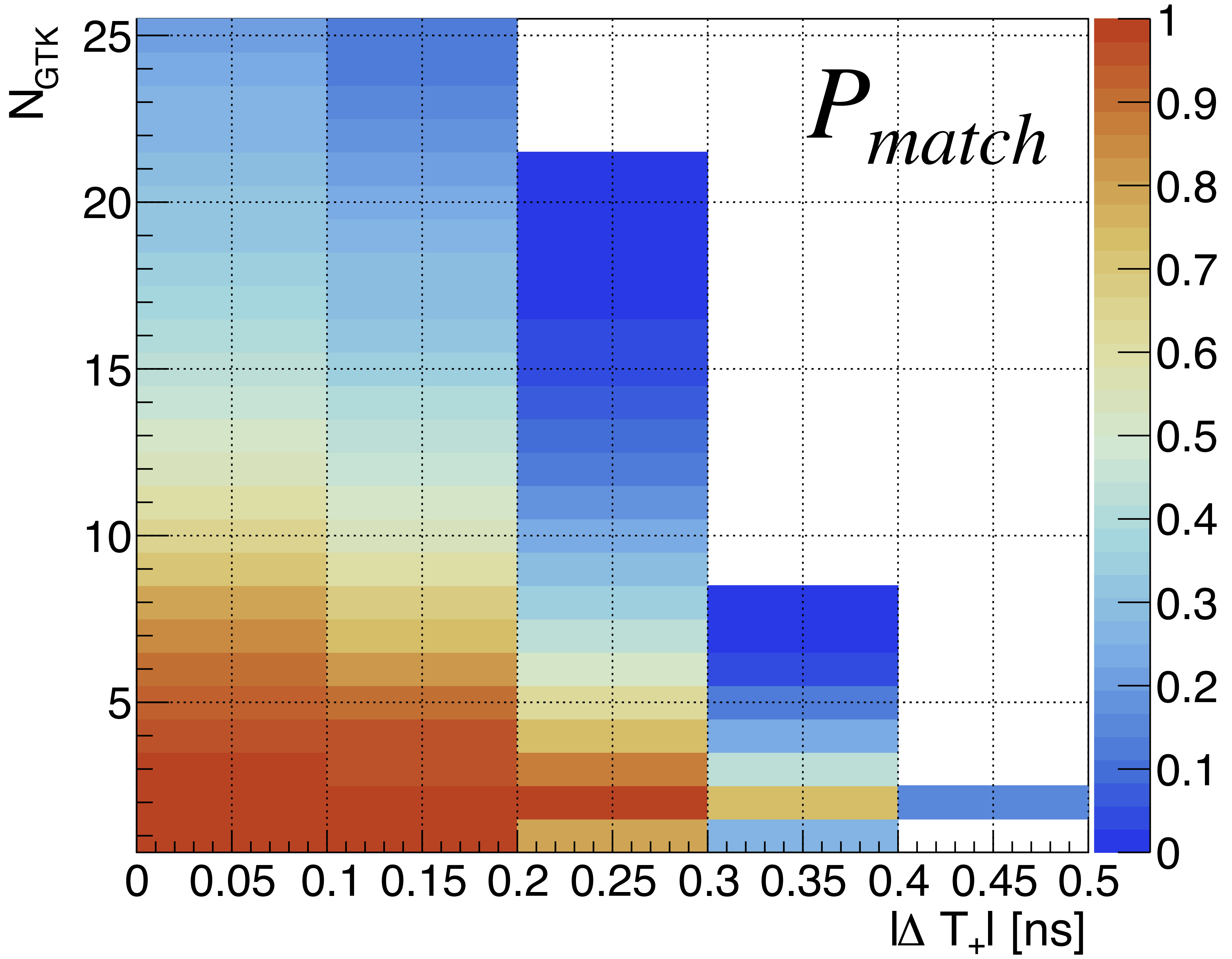


Validation: data sample with PID = "less pion-like" (Calo BDT bins below π^+ bin).

Upstream background evaluation & Validation

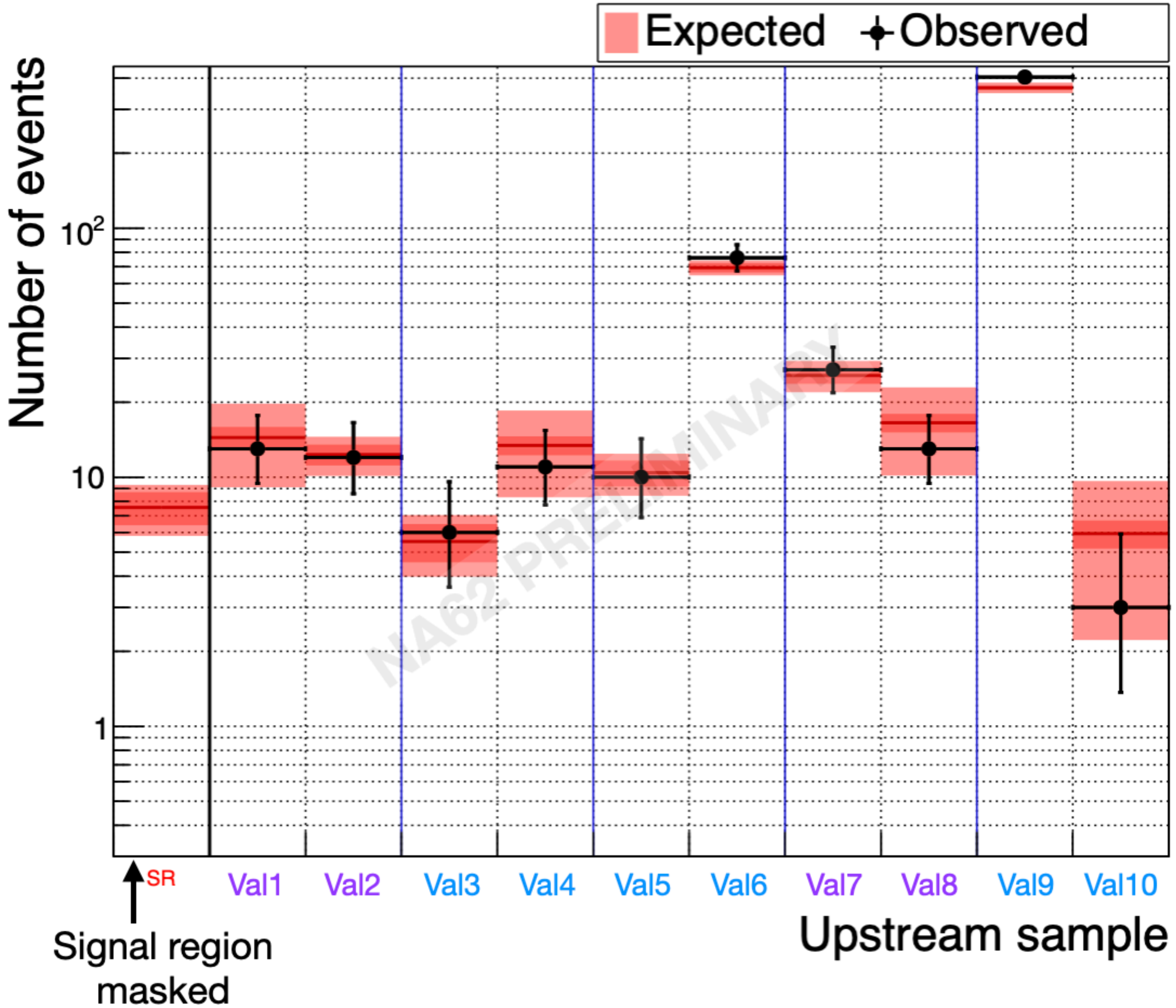
$$N_{bg} = \sum_i N_i^{URS} f_{cda} P_i^{match} = 7.4^{+2.1}_{-1.8}$$

- Updated to fully data-driven procedure
- Upstream reference sample (URS) contains all known upstream mechanisms.
- f_{CDA} depends only on geometry.
- P_{match} depends on $(\Delta T_+, N_{GTK})$.



Validate precistions:

- Invert & loosen upstream vetos to enrich with different mechanisms: interactions or accidentals. All independent.
- VetoCounter is essential: $N_{exp}^{VC\,rej.} = 6.9 \pm 1.4$, $N_{obs}^{VC\,rej.} = 9$



Summary of expectations

NA62

Backgrounds

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

Signal Sensitivity

$$\mathscr{B}_{SES} = (0.85 \pm 0.03) \times 10^{-11}$$

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

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

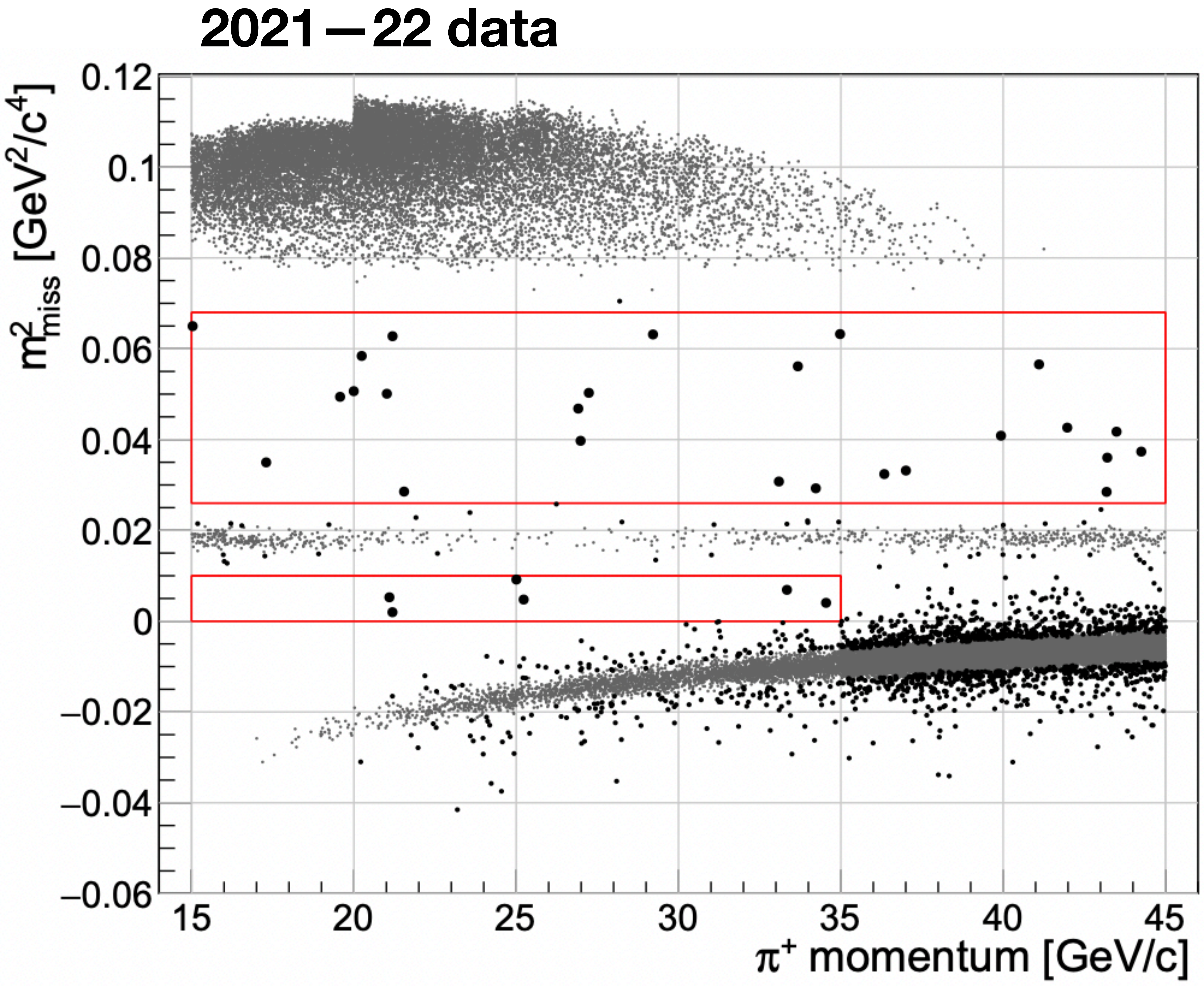
2021–22: $N_{\pi\nu\bar{\nu}} = 9.91 \pm 0.34$

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.**

Signal regions

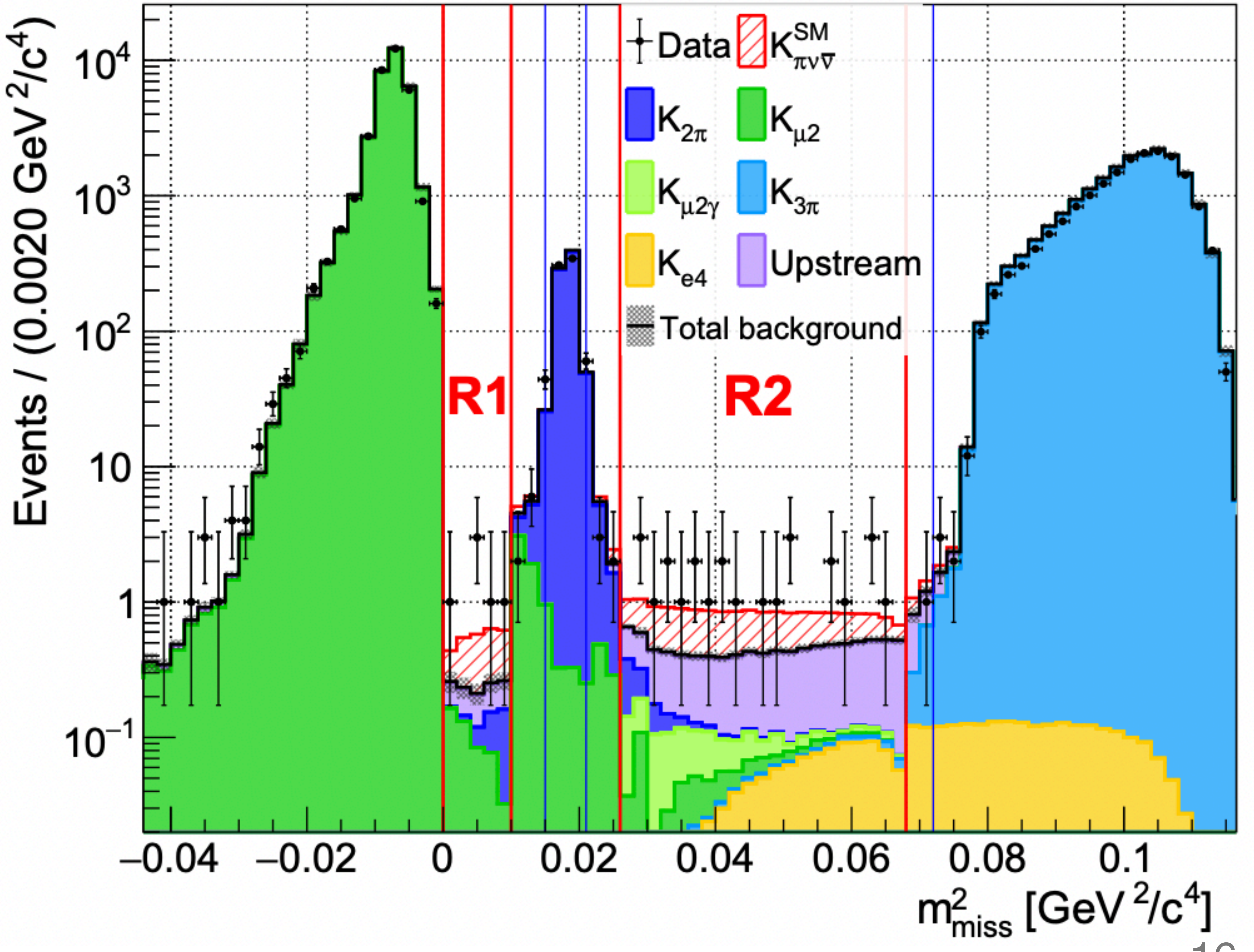


Expected SM signal, $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

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

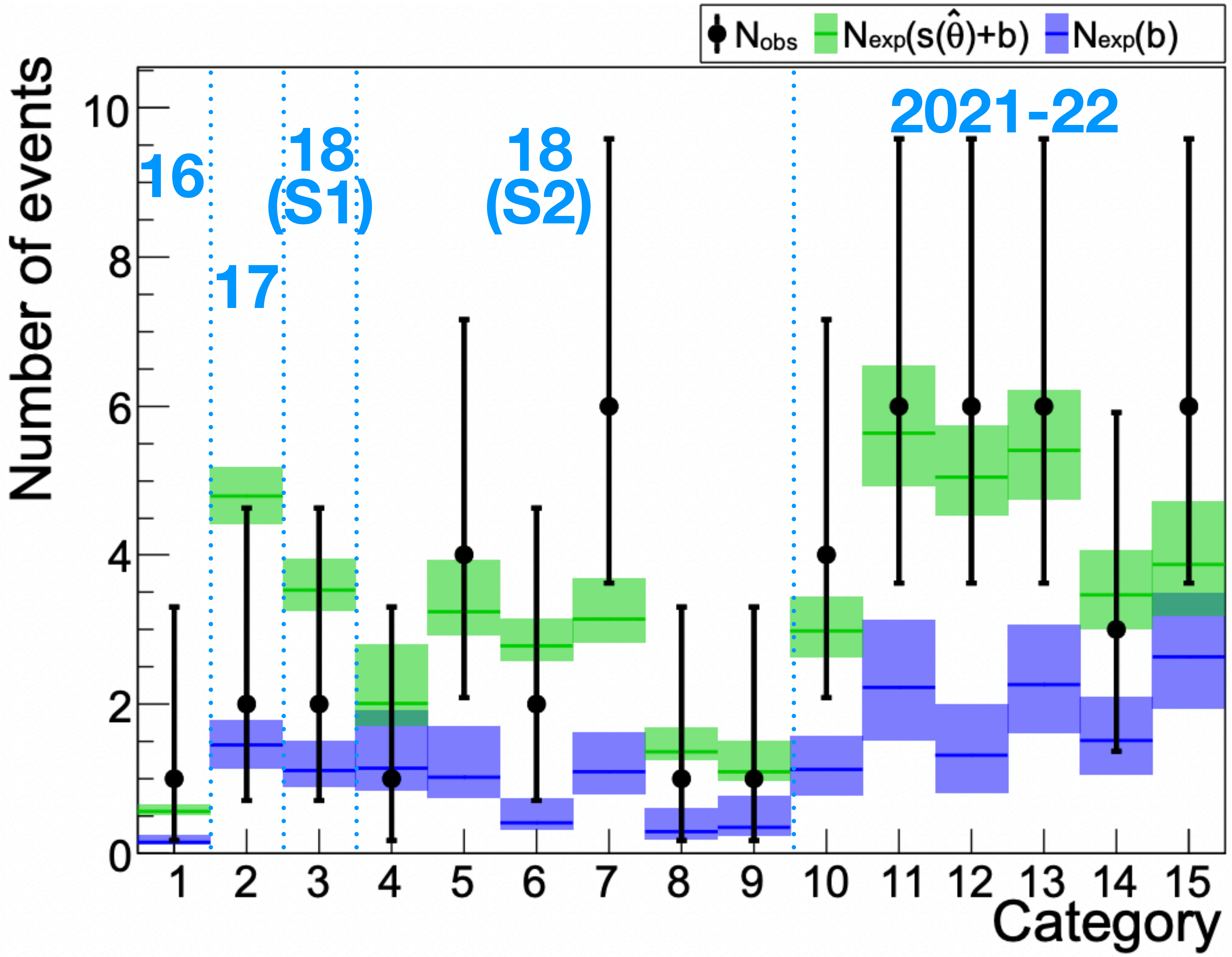
Observed, $N_{obs} = 31$

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



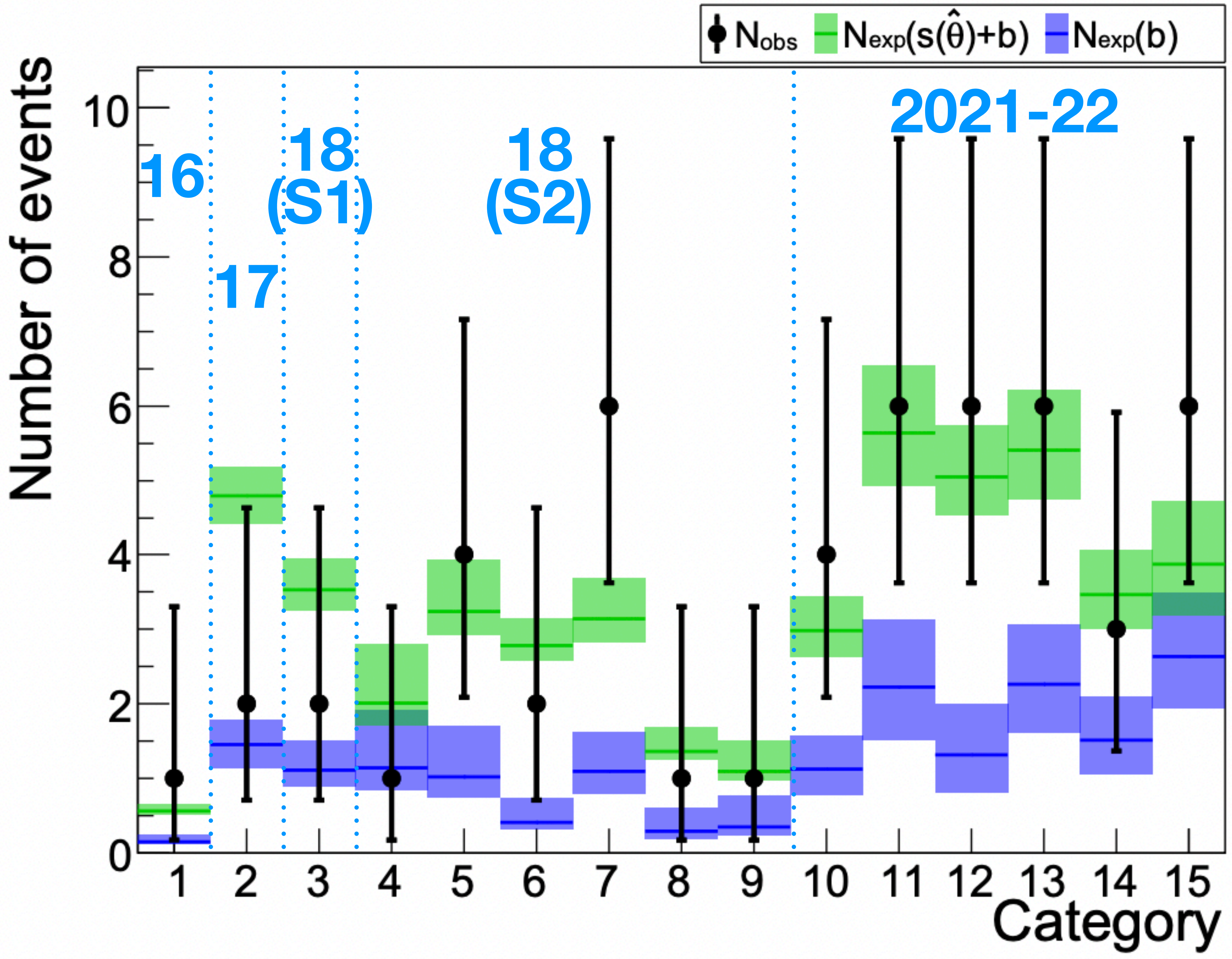
Combining NA62 results: 2016—22

- 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 $Z > 5$



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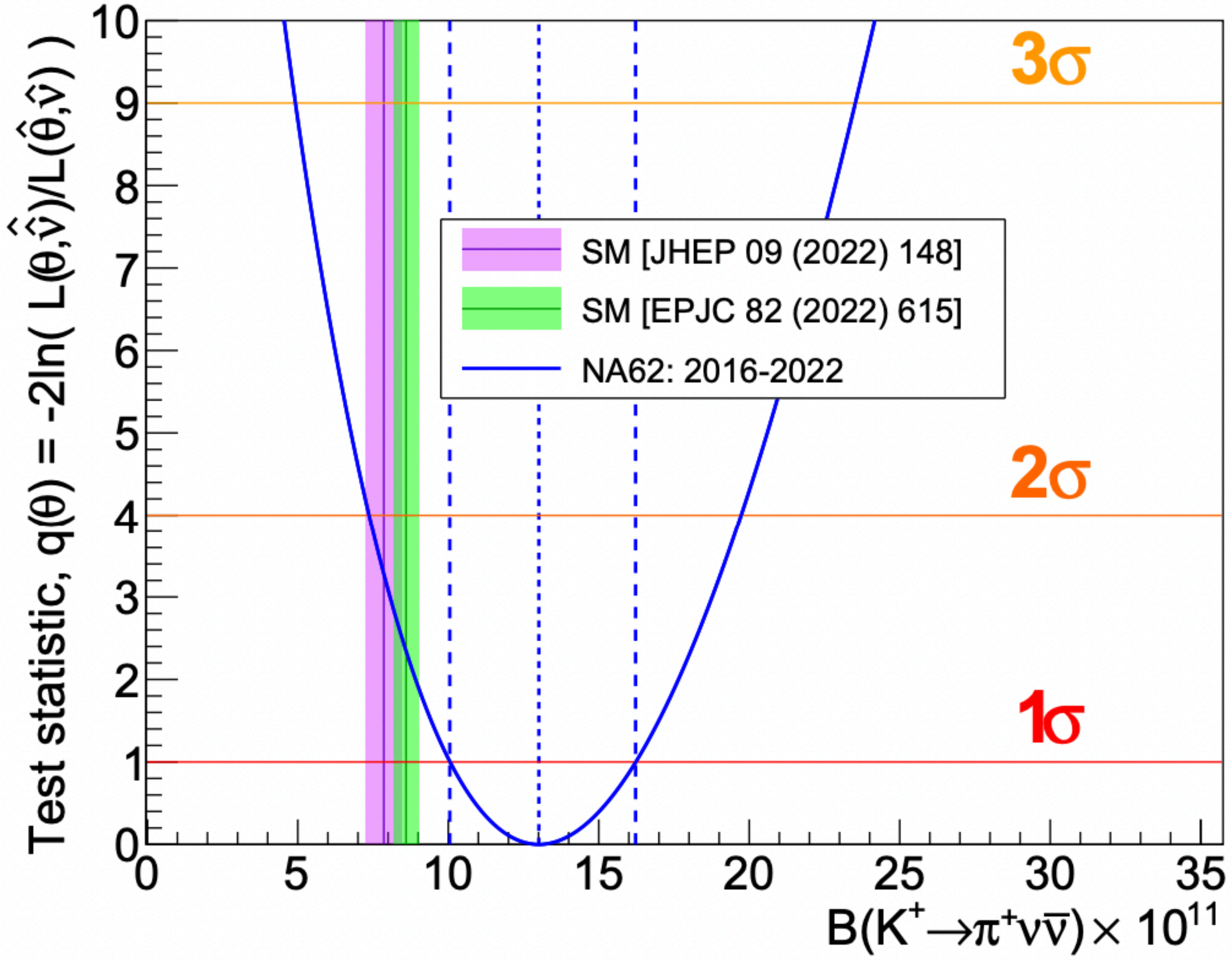
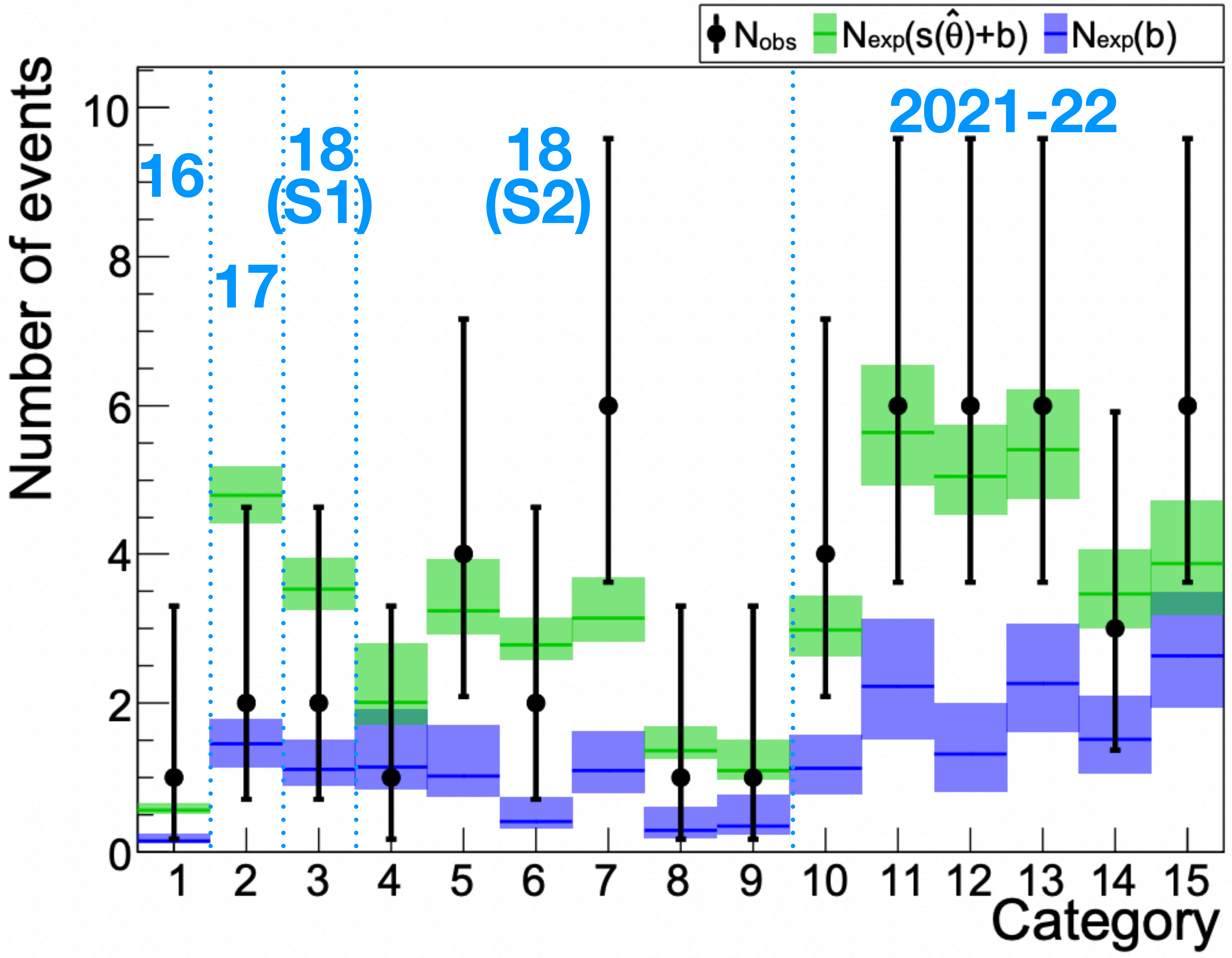
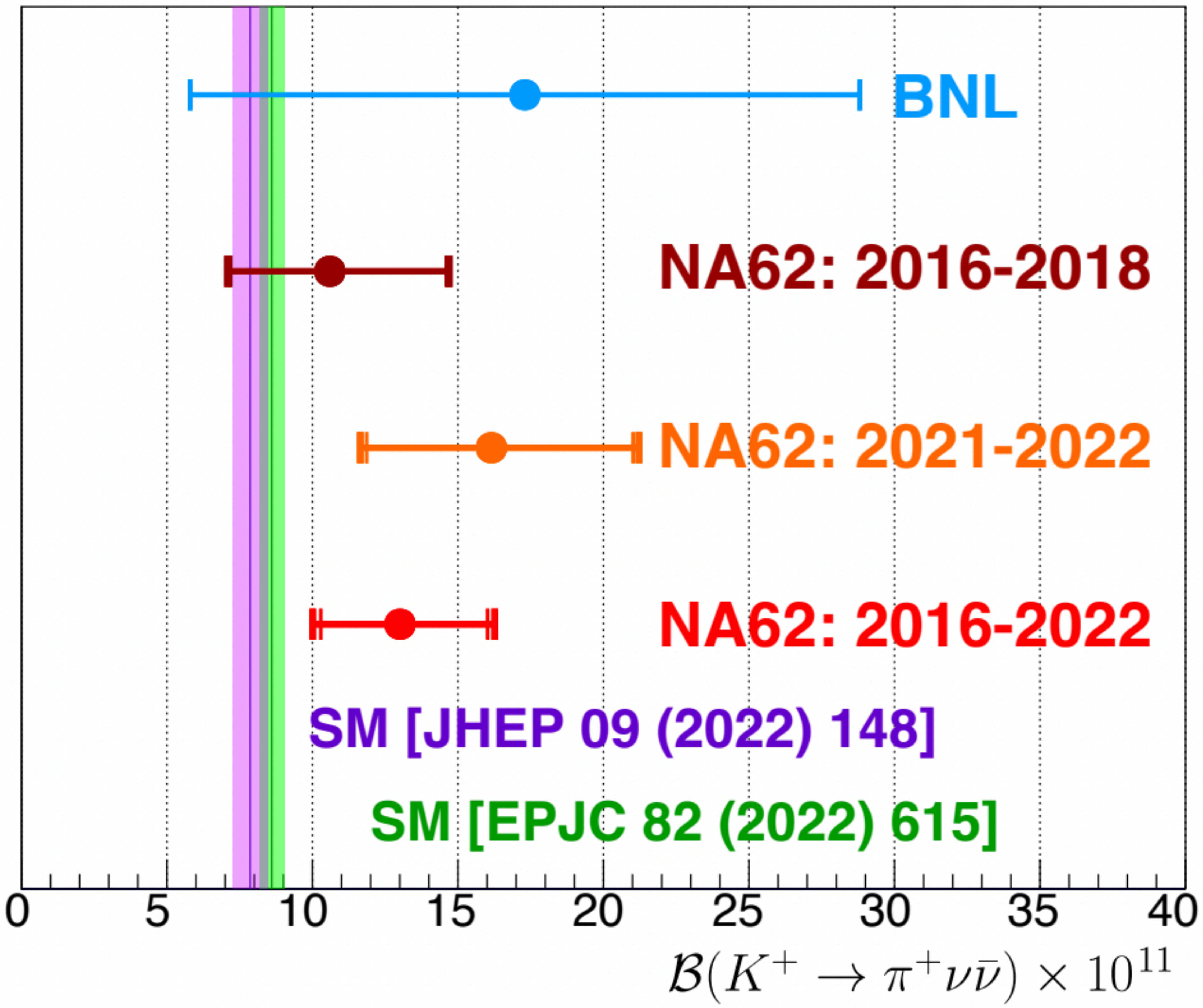
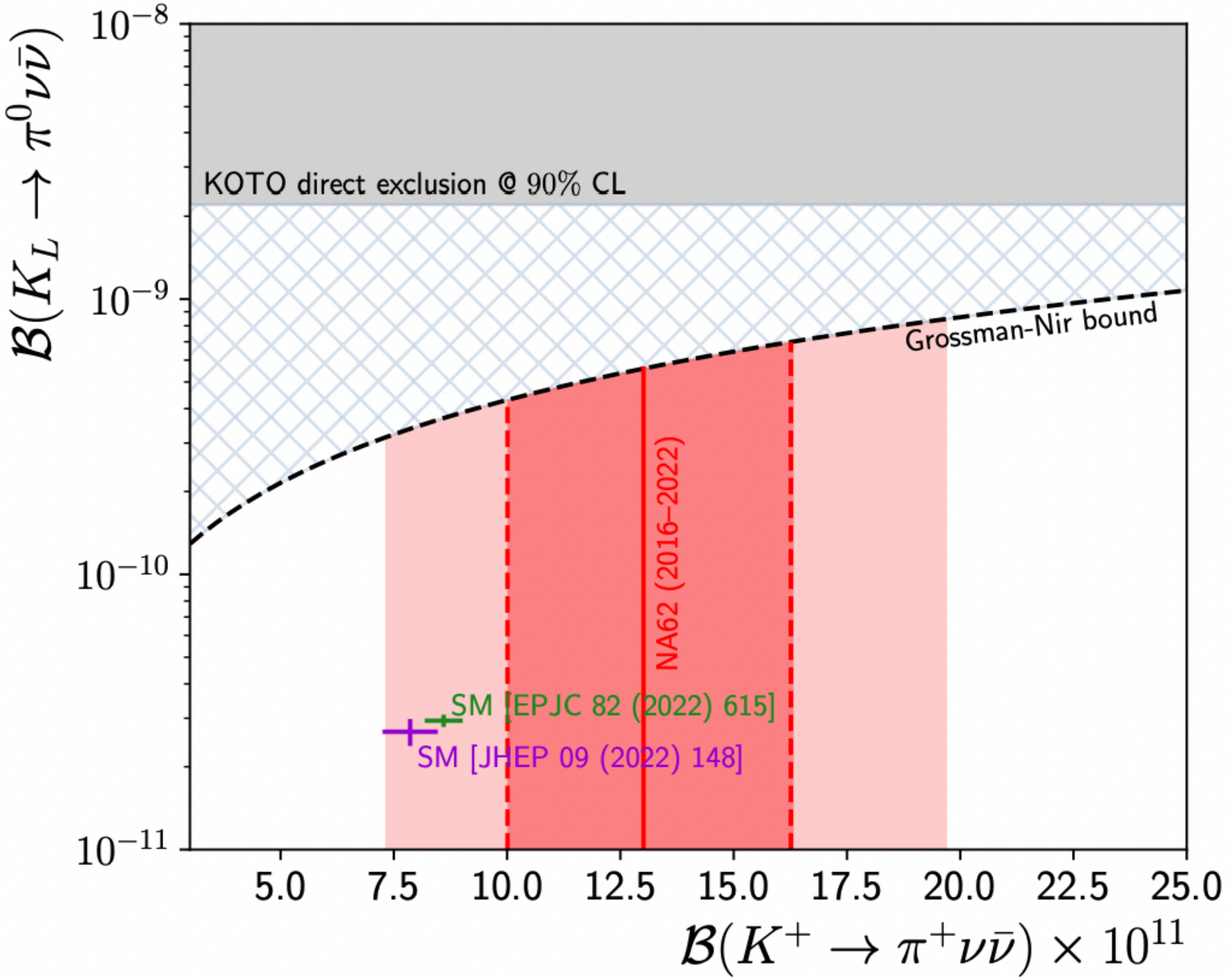




$$\mathscr{B}_{16-22}(K^+ \to \pi^+ \nu \bar{\nu}) = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11} = \left(13.0\,\left(^{+3.0}_{-2.7}\right)_{\text{stat}}\left[^{+1.3}_{-1.3}\right]_{\text{syst}}\right) \times 10^{-11}$$

Results in context





- NA62 results are consistent. Fractional uncertainty decreased: 40% to 25%
- Central value moved up (now 1.5—1.7σ above SM)
- 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**

NA62 physics programme

with 2024 results

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

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$: [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
  - New: Prelim. 2024 [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]

Rare Decays

Forbidden Decays

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

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

Exotics

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

Rare Decays

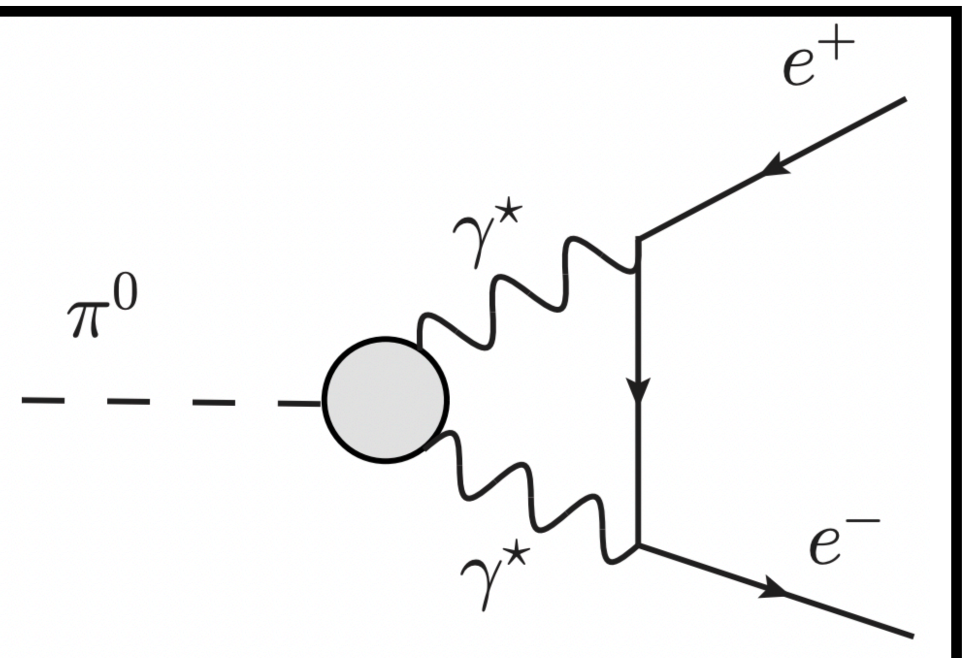
Study of $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-$

[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

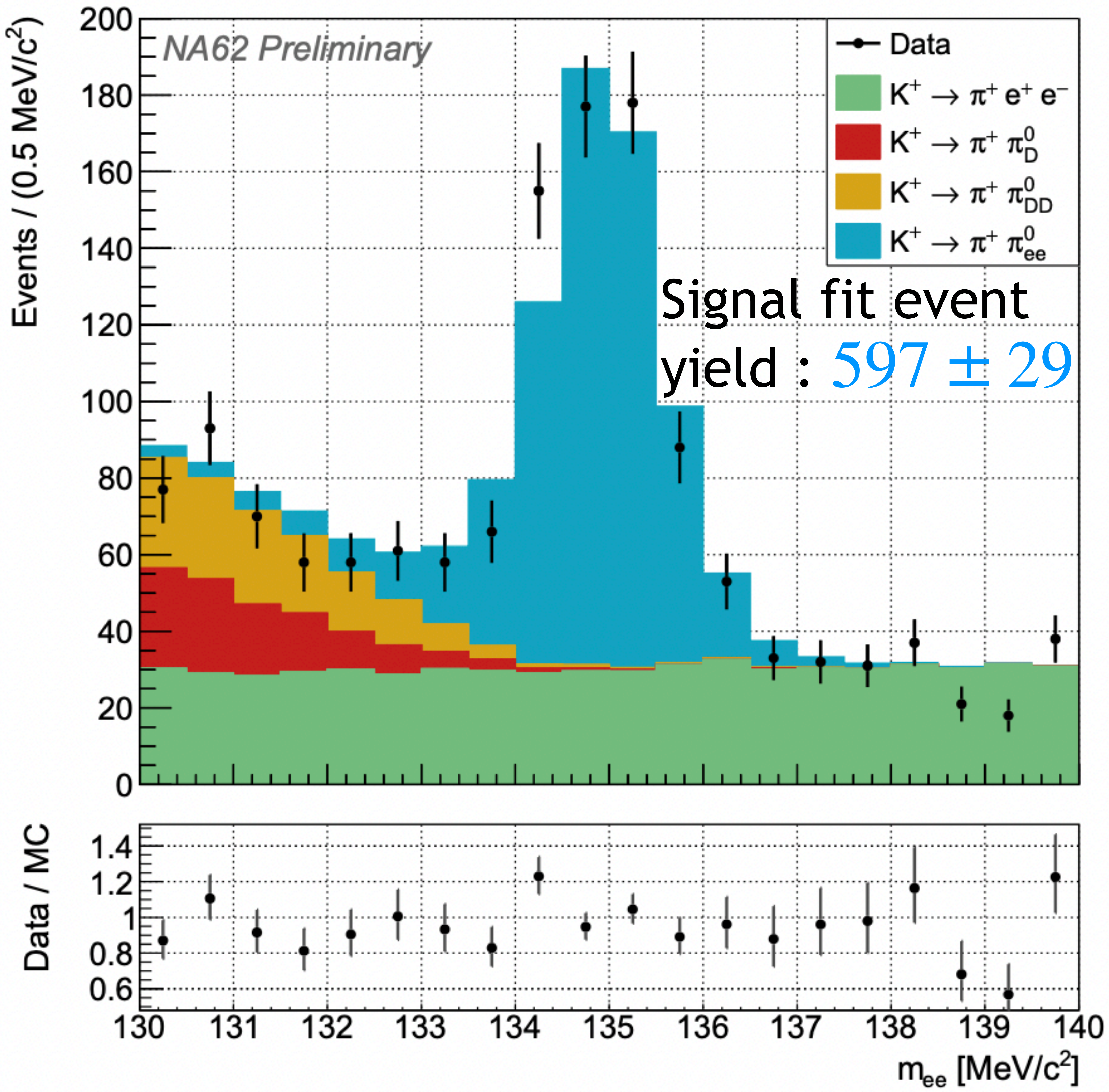


$$\mathcal{B}(\pi^0 \to e^+e^-) = (5.86 \pm 0.37) \times 10^{-8}$$

[New: NA62 for $x > 0.95$]

Using NA62 **2017+2018 Data:**

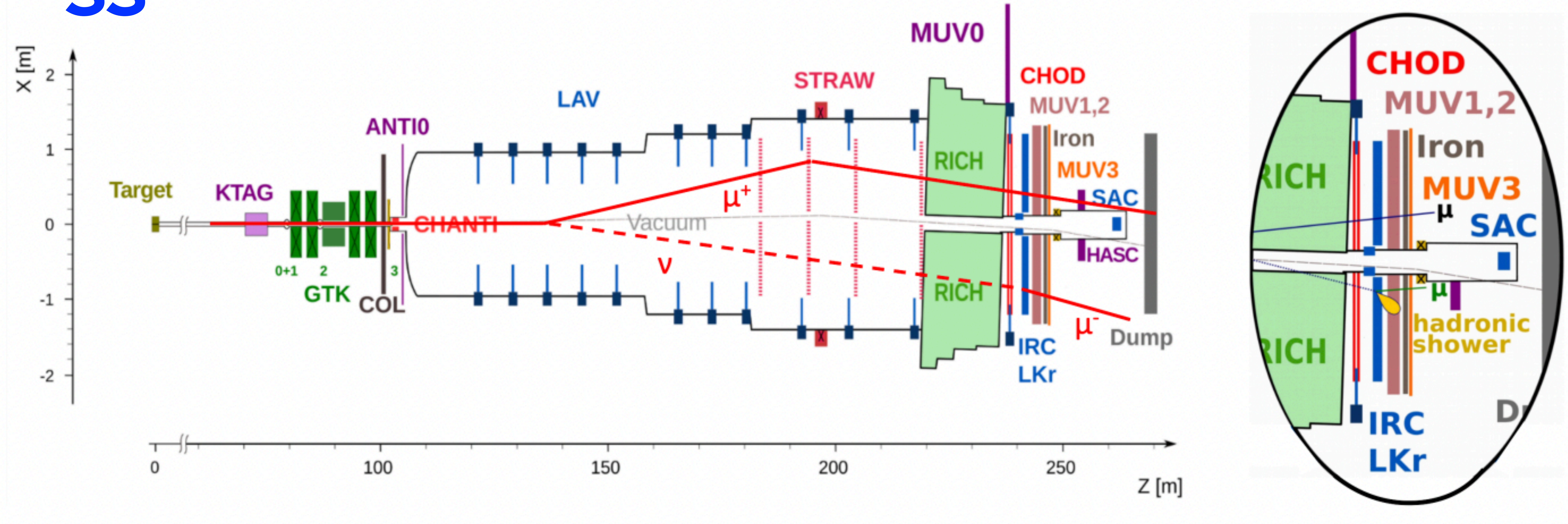
- Normalise to $K^+ \to \pi^+e^+e^-$ (almost all cuts identical)
- Trigger with downscaling ~8 and 90% efficiency



Signal fit event yield : 597 ± 29

Tagged neutrinos at NA62

[De Martino, NuFact23]



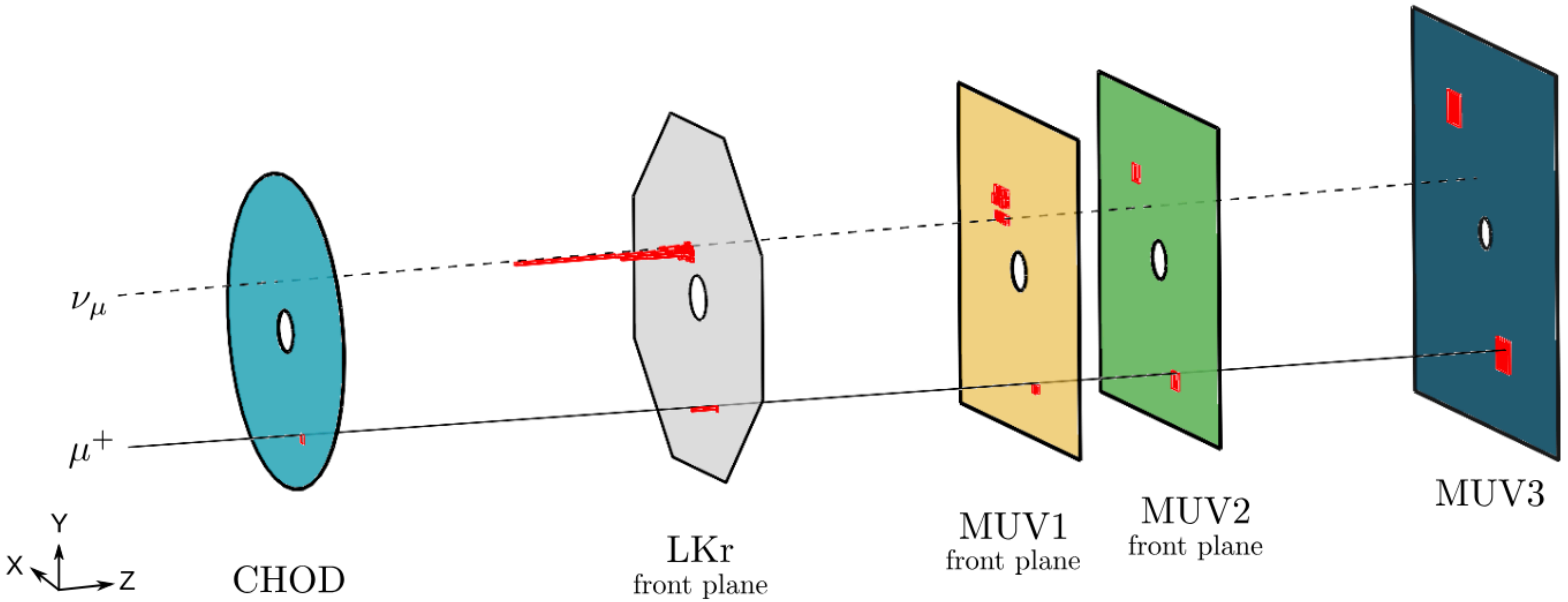
- Goal: search for $K^+ \to \mu^+\nu_\mu$ with:
  - K^+ and μ^+ detected by GTK and STRAW trackers as usual.
  - ν_μ interacting in LKr calorimeter (20 tons of Liquid Kr, MUV12 66ton HCAL)
- ν_μ Interaction probability $\mathcal{O}(10^{-11})$: CC-DIS $\nu_\mu \to \mu^- +$ shower
  - Trigger based on 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):
  - $N^{exp}_{bg} = 0.034^{+0.041}_{-0.023}|_{\text{stat}} \pm 0.004_{\text{syst}}$

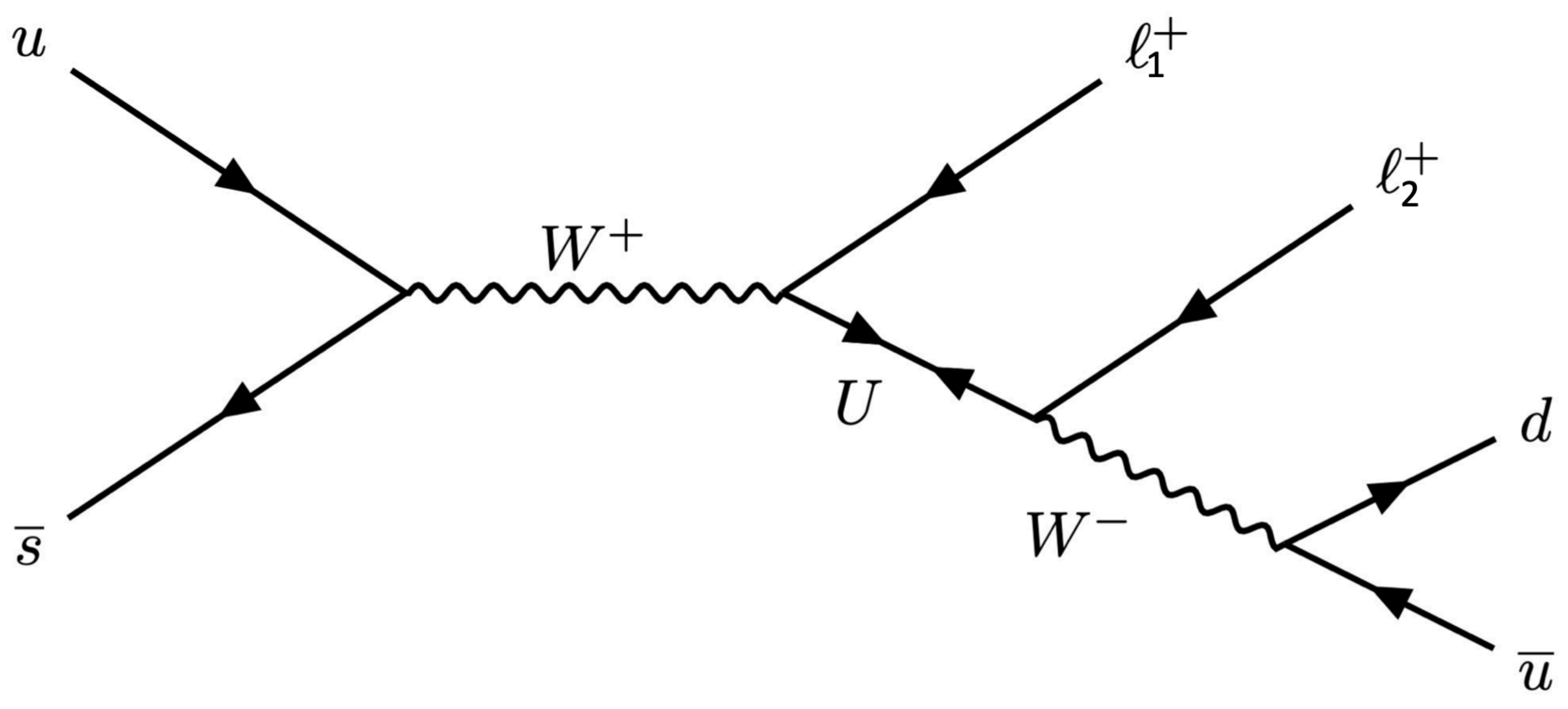
- **Detect 1 candidate $K^+ \to \mu^+\nu$ tagged ν event!**
- Demonstrates the neutrino tagging technique.



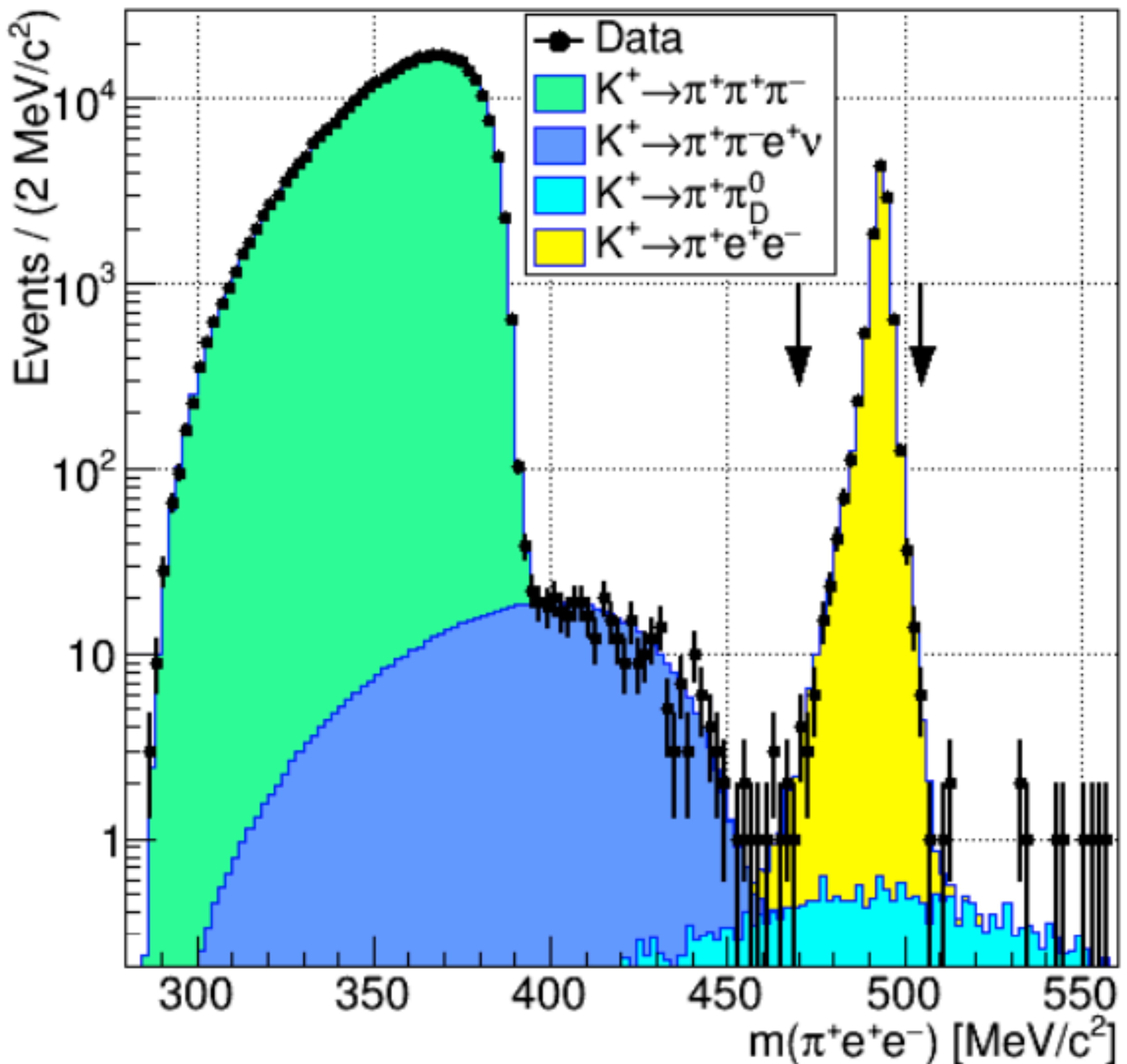
Forbidden K^+ Decays

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

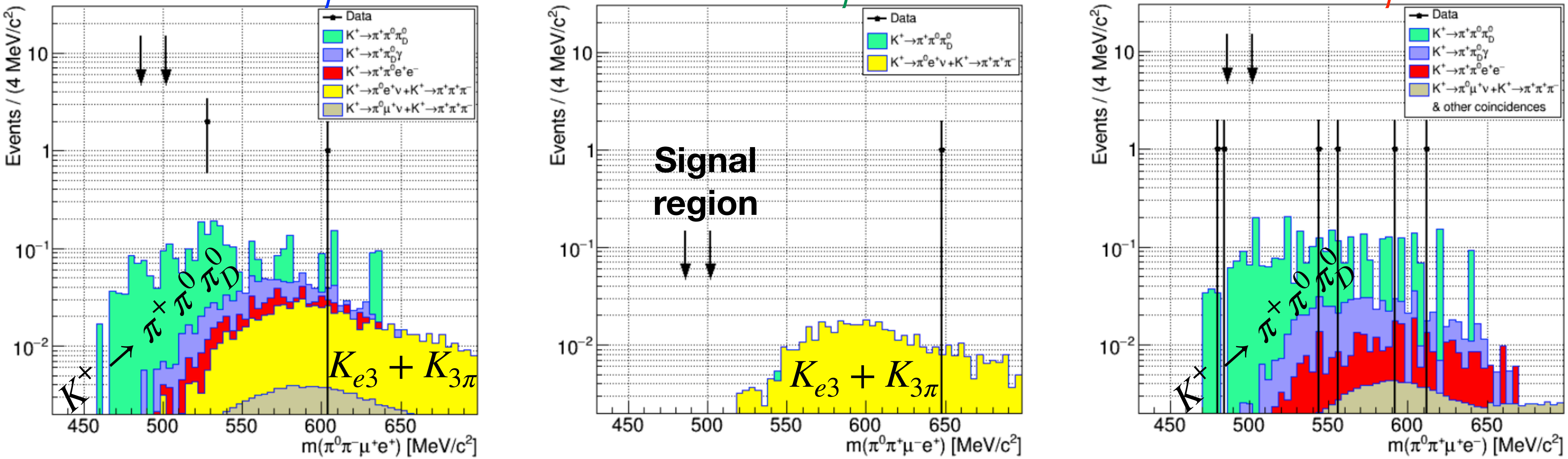


Search for $K^+ \to \pi^0\pi\mu e$

[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}

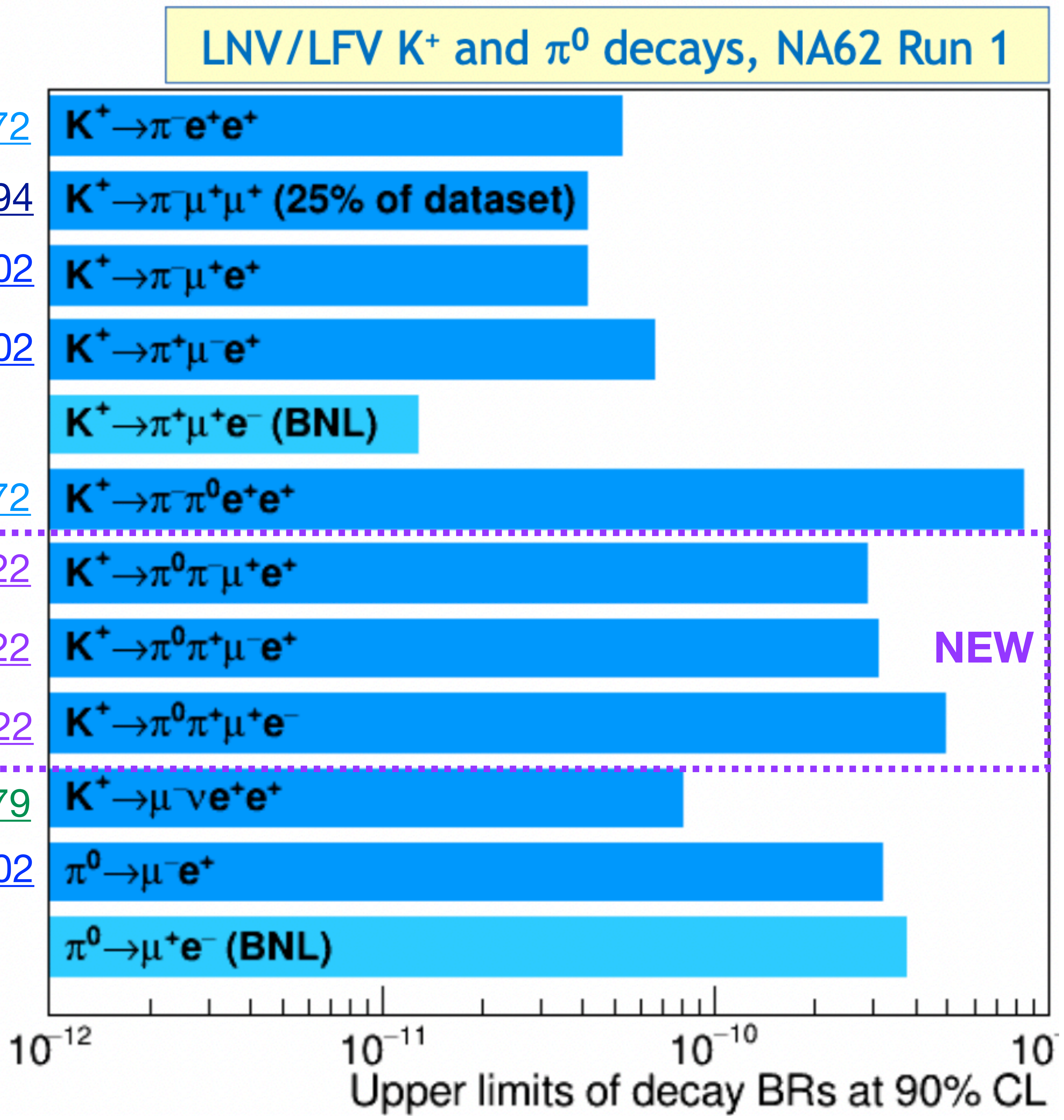
$K^+ \to \pi^0\pi^-\mu^+e^+$ $K^+ \to \pi^0\pi^+\mu^-e^+$ $K^+ \to \pi^0\pi^+\mu^+e^-$



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

Searches for CLFV/LNV Decays at NA62

PLB 830 (2022) 137172
PLB 797 (2019) 134794
PRL 127 (2021) 13, 131802
PRL 127 (2021) 13, 131802
PLB 830 (2022) 137172
PLB 859 (2024) 139122
PLB 859 (2024) 139122
PLB 859 (2024) 139122
PLB 838 (2023) 137679
PRL 127 (2021) 13, 131802



- 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]: $N_{\rm bkg}^{\rm CR} = 9.7^{+21.3}_{-7.3} \times 10^{-3}$, $N_{\rm bkg}^{\rm SR} = 9.4^{+20.6}_{-7.2} \times 10^{-3}$

$A' \to \mu^+\mu^-$ [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:

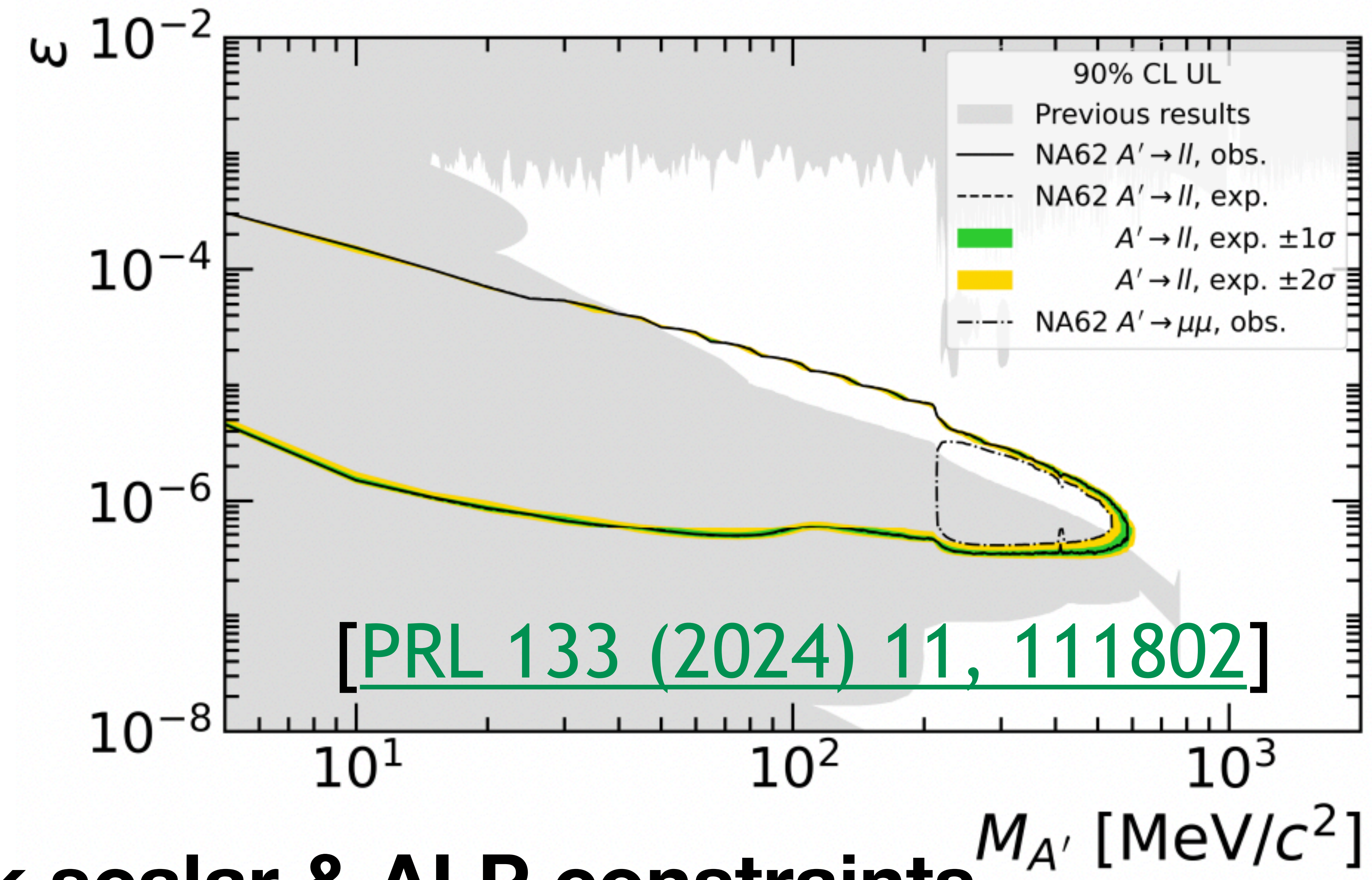
Channel	$N_{\rm exp,CR} \pm \delta N_{\rm exp,CR}$	$N_{\rm exp,SR} \pm \delta N_{\rm exp,SR}$	$N^{p>5\sigma}_{\rm obs,SR}$	$N^{p>5\sigma}_{\rm obs,SR+CR}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004	3	5
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$	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…

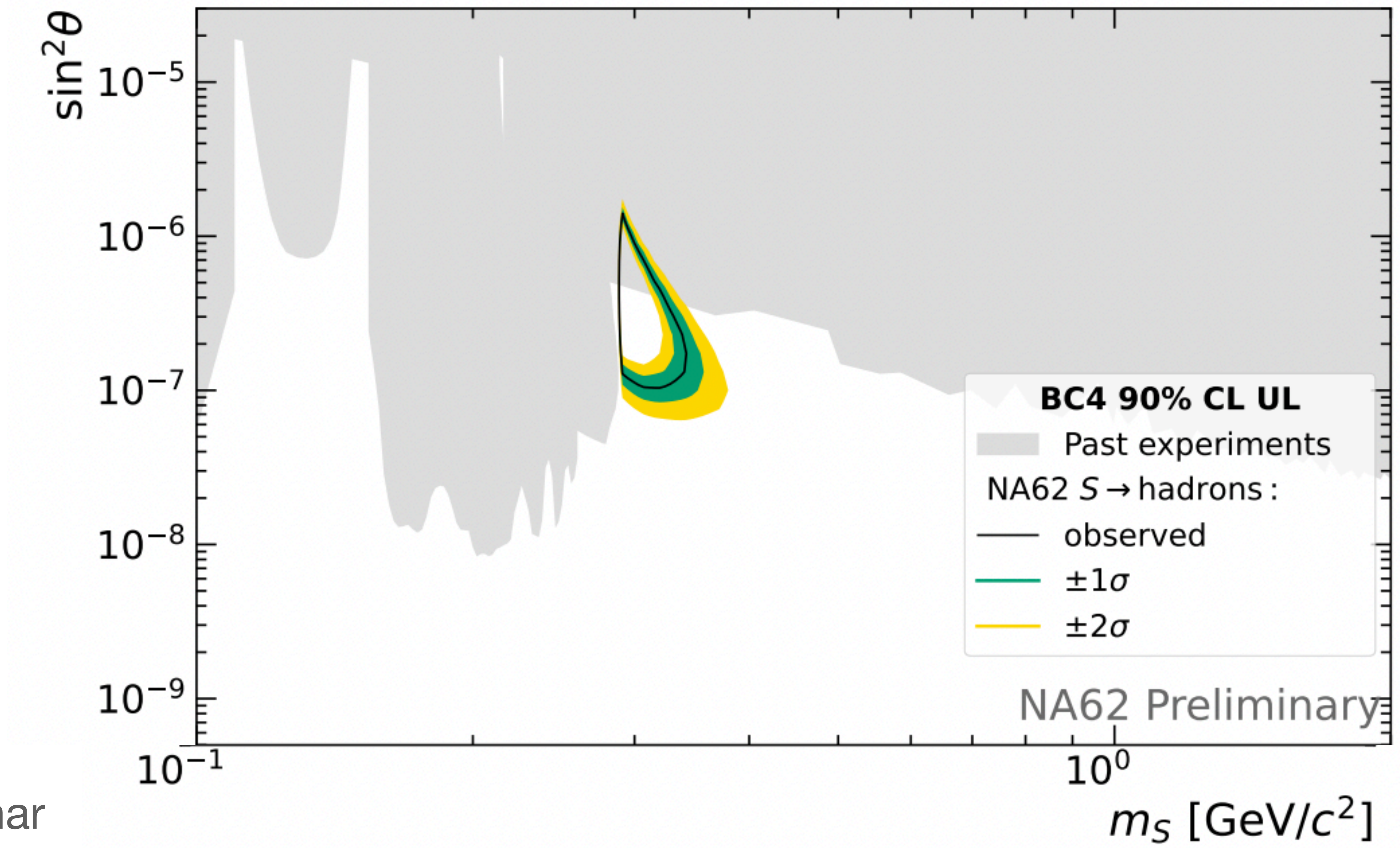
Results:

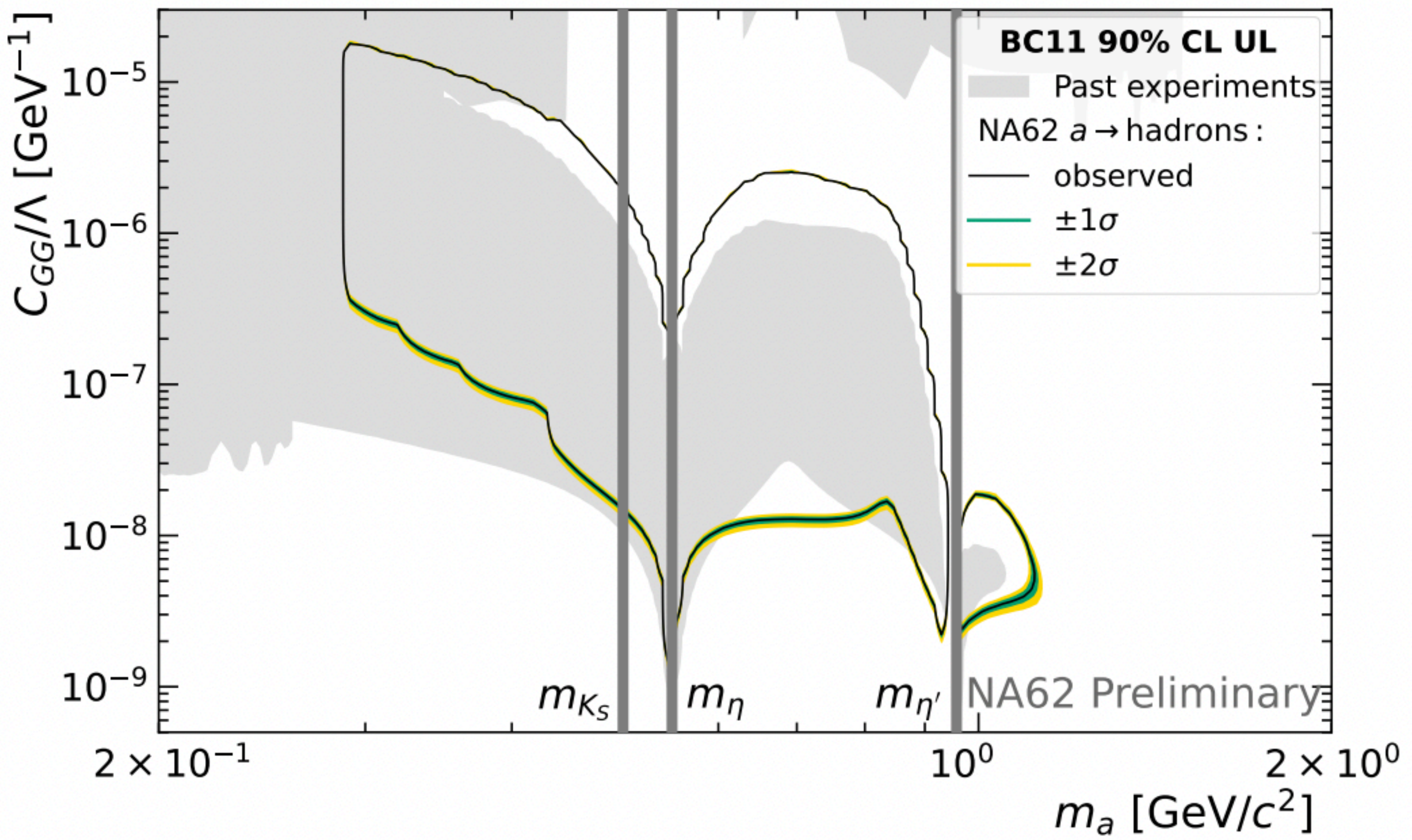
- e^+e^- : 0 observed
- $\mu^+\mu^-$: 1 observed (p=1.6%, 2.4σ global significance)
- 25 Hadronic channel signal regions: 0 events.
- Therefore set upper limits…

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



Hadronic final states: dark scalar & ALP constraints





Conclusions

[NEW: arXiv:2412.12015]

- New study of $K^+ \to \pi^+ \nu \bar{\nu}$ decay using NA62 2016—22 data:
  - $N_{bg} = 18^{+3}_{-2}$, $N_{obs} = 51$ (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.**

- Many other results in 2024 from broad physics programme:
  - Rare decays: study of $K^+ \to \pi^+ \pi^0$, $\pi^0 \to e^+ e^-$ provides new measurement $\mathcal{B}_{NA62}(\pi^0 \to e^+ e^- (\gamma), x > 0.95) = (5.86 \pm 0.37) \times 10^{-8}$
  - Forbidden decays: CLFV/LNF searches for $K^+ \to \pi^0 \pi \mu e$ setting limits at $< 5 \times 10^{-10}$
  - Exotic processes: beam-dump searches for dark photons to leptons or hadrons.

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

Supplemental

Breaking news:

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

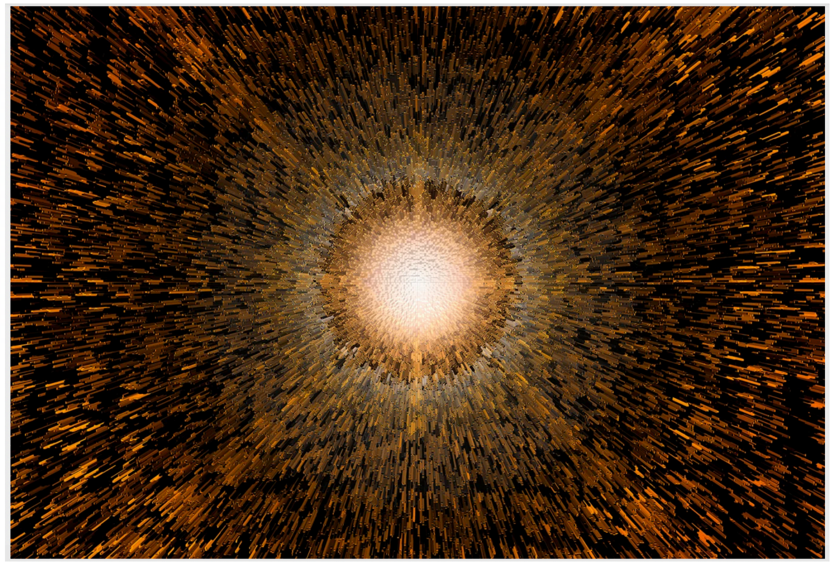
CERN: L'ESPERIMENTO NA62 OSSERVA UN PROCESSO RARISSIMO

UKRI Press release : UK Research and Innovation

CERN reports first observation of ultra-rare particle decay

Scientific American :

SCI AM

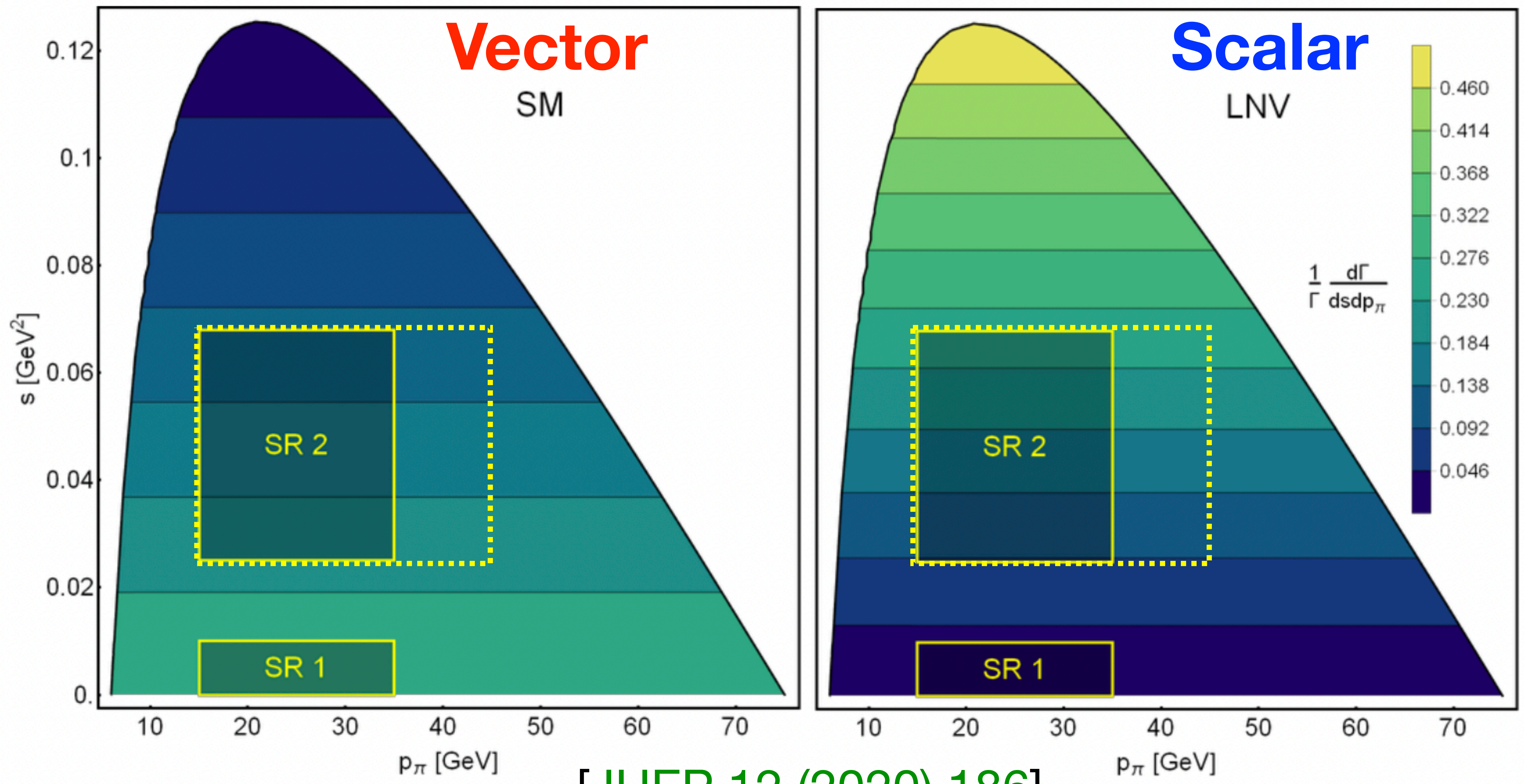


OCTOBER 1, 2024 | 5 MIN READ

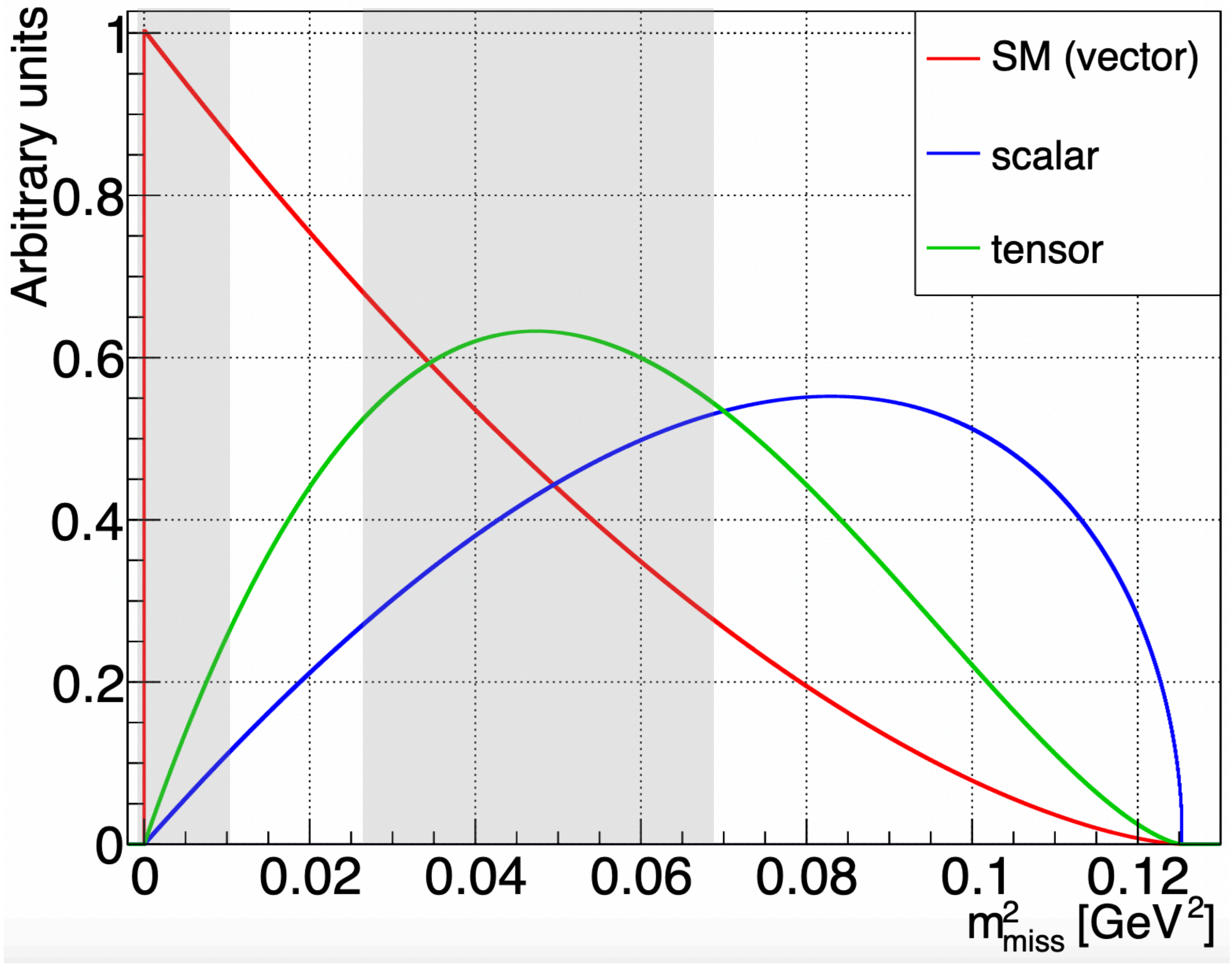
A One-in-10-Billion Particle Decay Hints at Hidden Physics

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

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



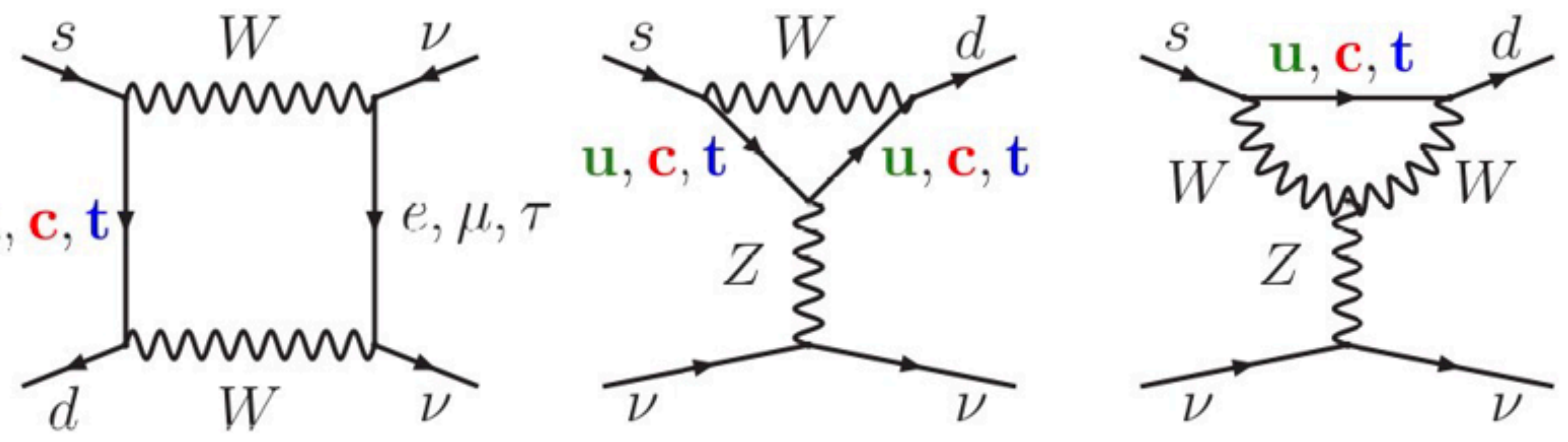
[JHEP 12 (2020) 186]

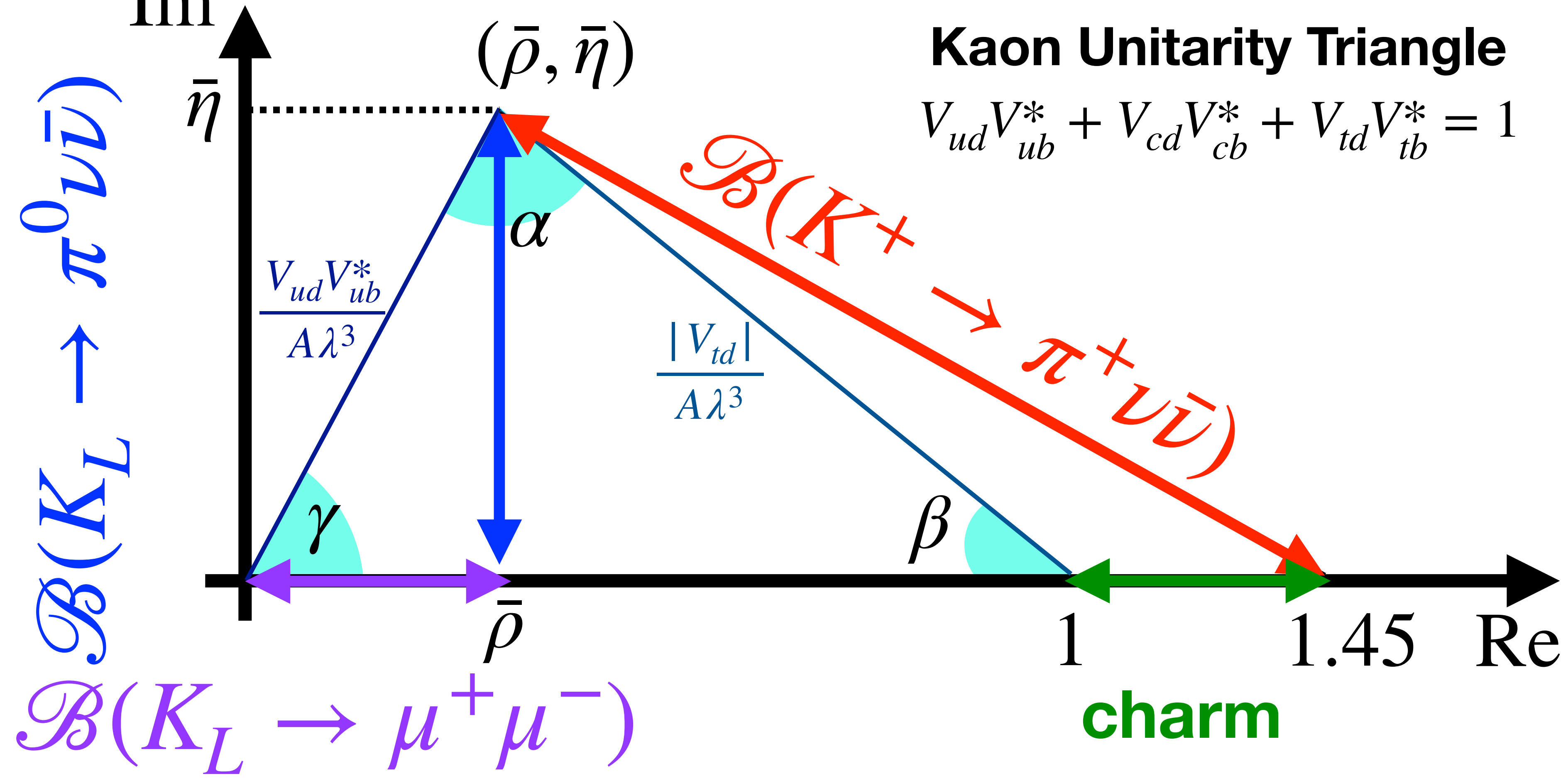


- In SM: vector form factor.
- BSM: possible vector, scalar, tensor contributions.
- Differential measurement could show presence of new physics.

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

SM: Z-penguin & box diagrams





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

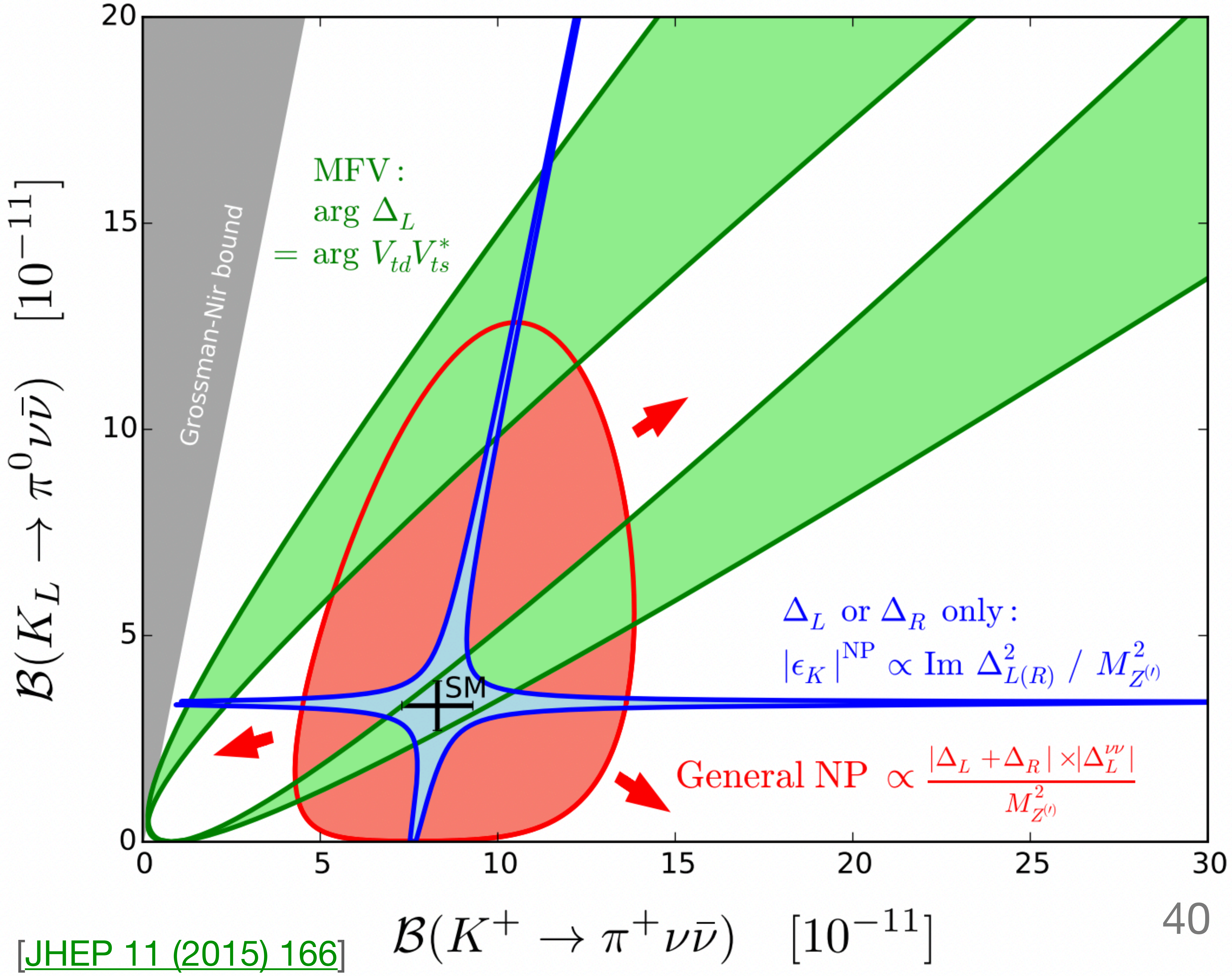
- Correlations between BSM contributions to BRs of K^+ and K_L modes [JHEP 11 (2015) 166].
  - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ε'/ε, ΔM_B, B-decays) [JHEP 12 (2020) 097][PLB 809 (2020) 135769].
- Leptoquarks [EPJ.C 82 (2022) 4, 320], Interplay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

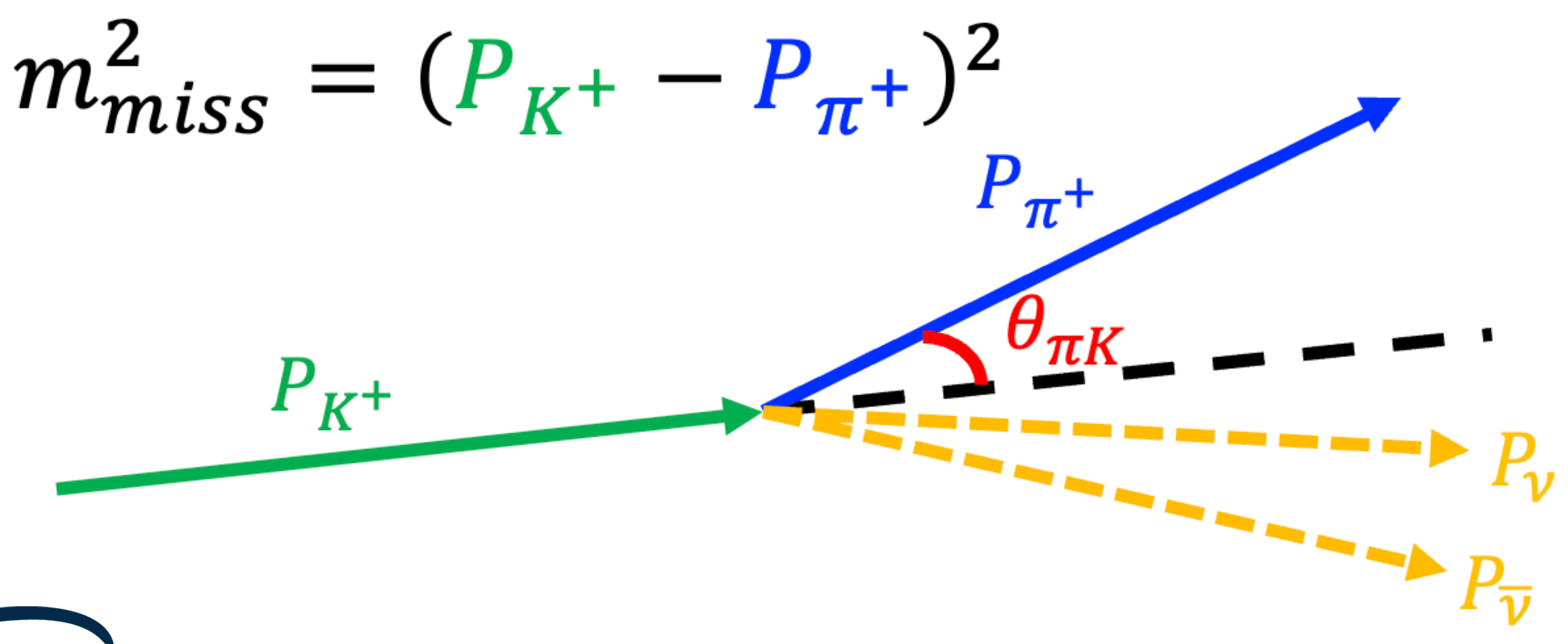
$K^+ \to \pi^+ \nu \bar{\nu}$ at NA62

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:

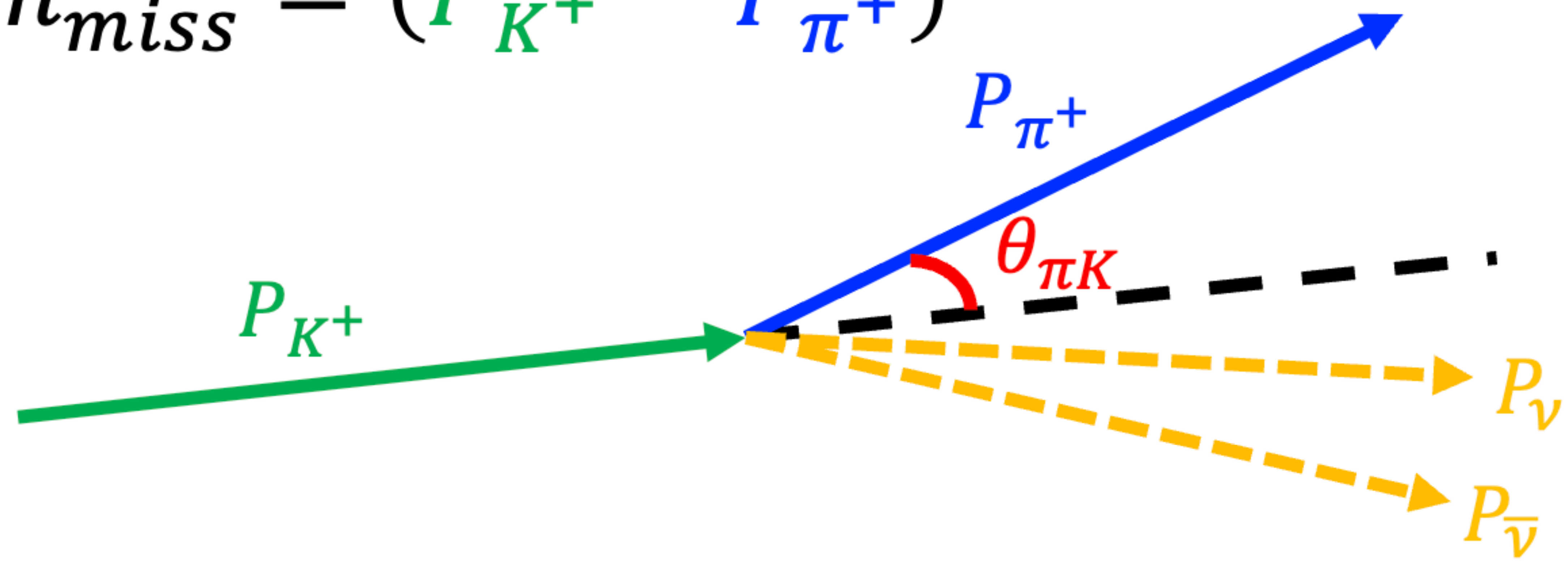
- $\mathcal{O}(100)\, ps$ timing between detectors
- $\mathcal{O}(10^4)$ background suppression from kinematics
- $> 10^7$ muon rejection
- $> 10^7$ rejection of π^0 from $K^+ \to \pi^+ \pi^0$ decays



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

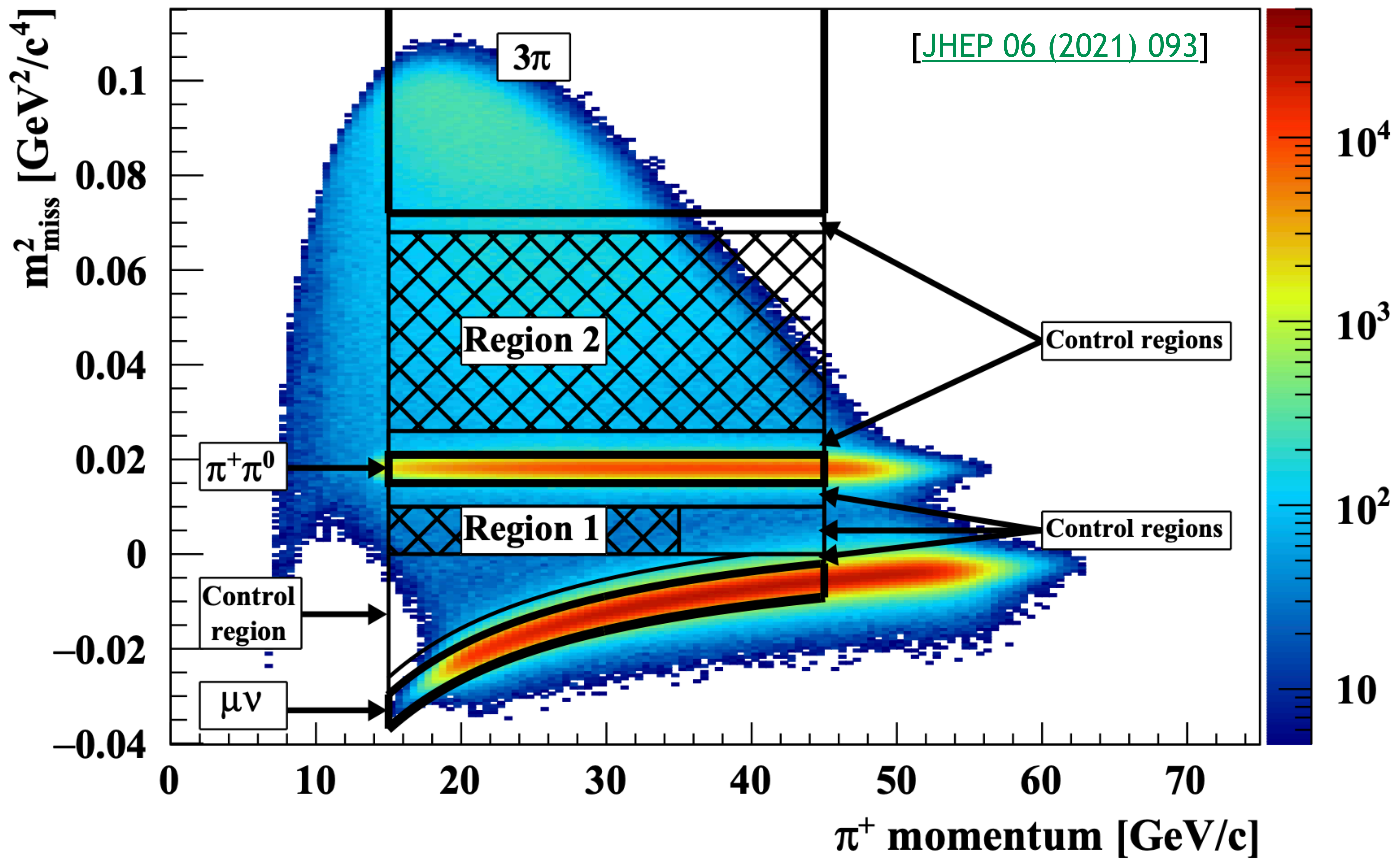
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$



Kinematics

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

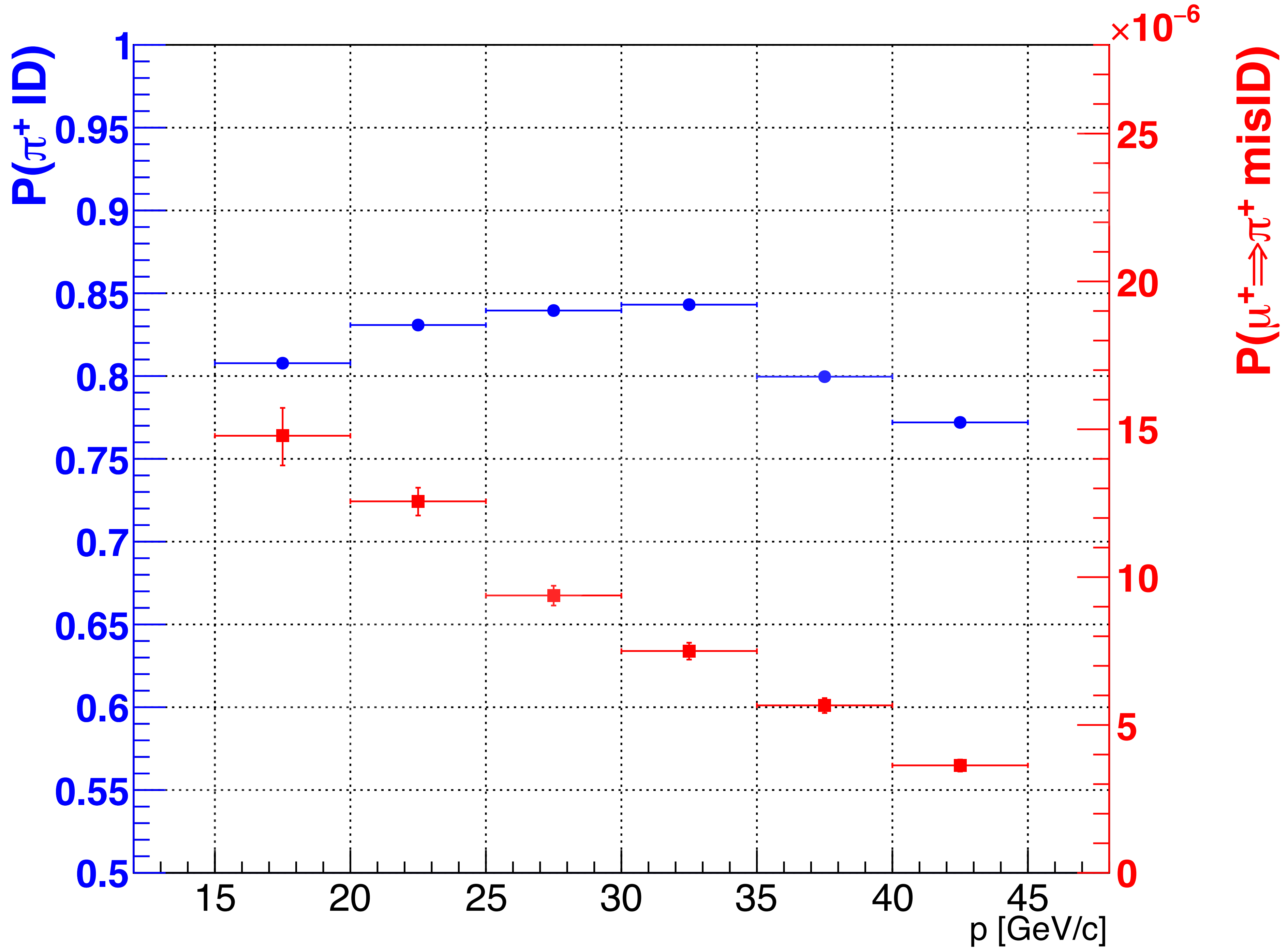


π^+ momentum range: 15—45 GeV/c

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



Particle ID

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

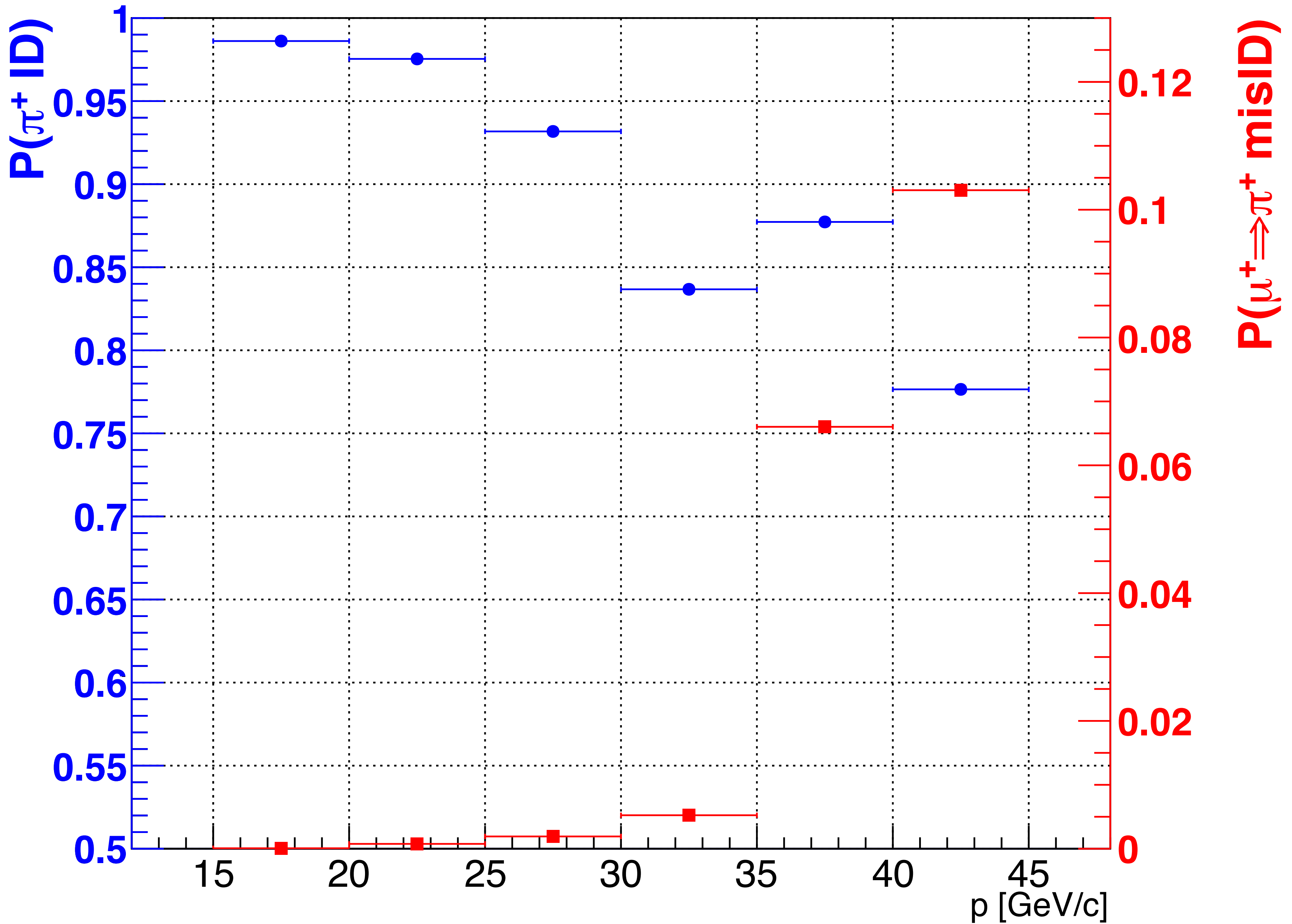
$$\varepsilon(\pi\,\text{ID}) = (73.00 \pm 0.01)\,\%$$

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

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

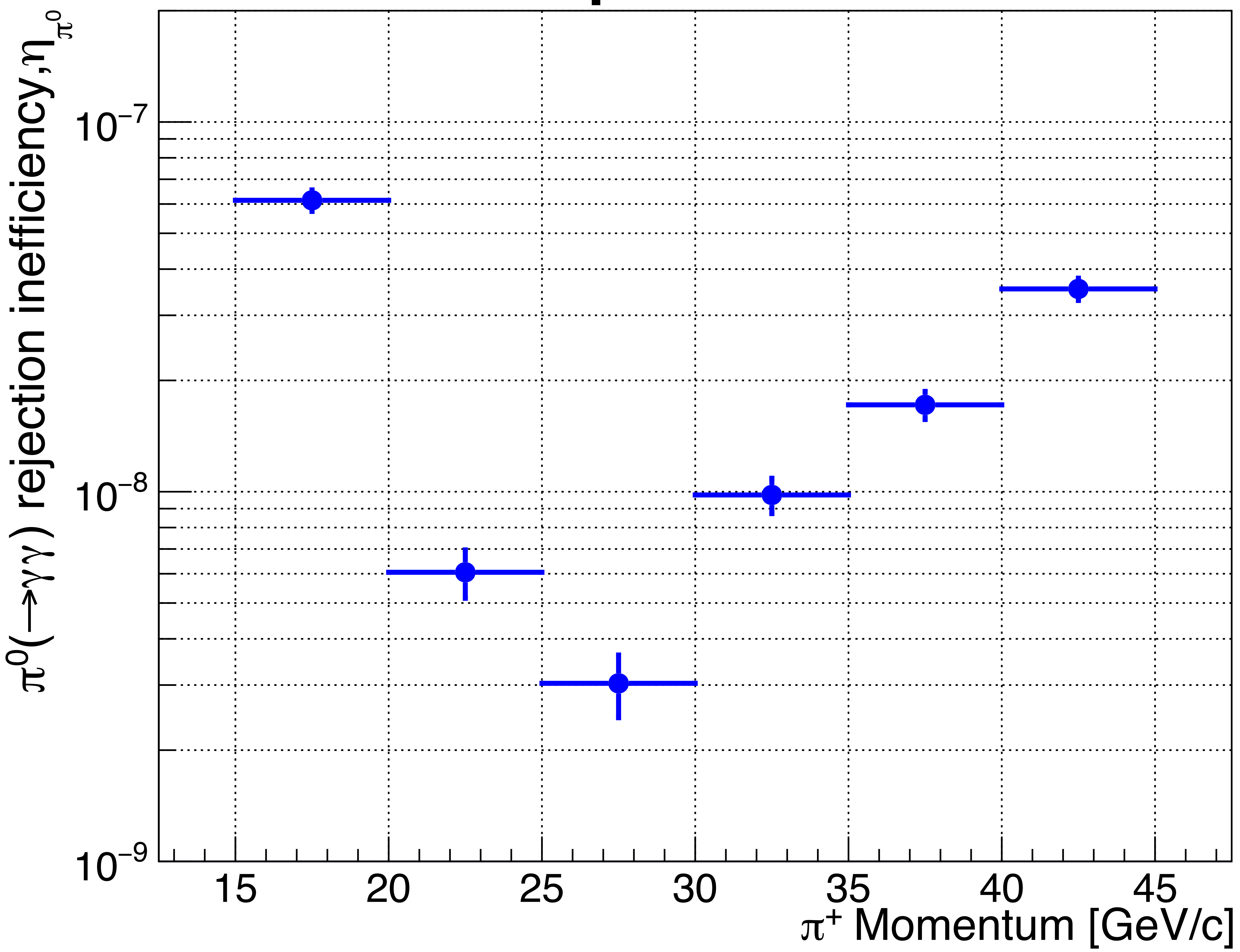


Photon Rejection

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

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



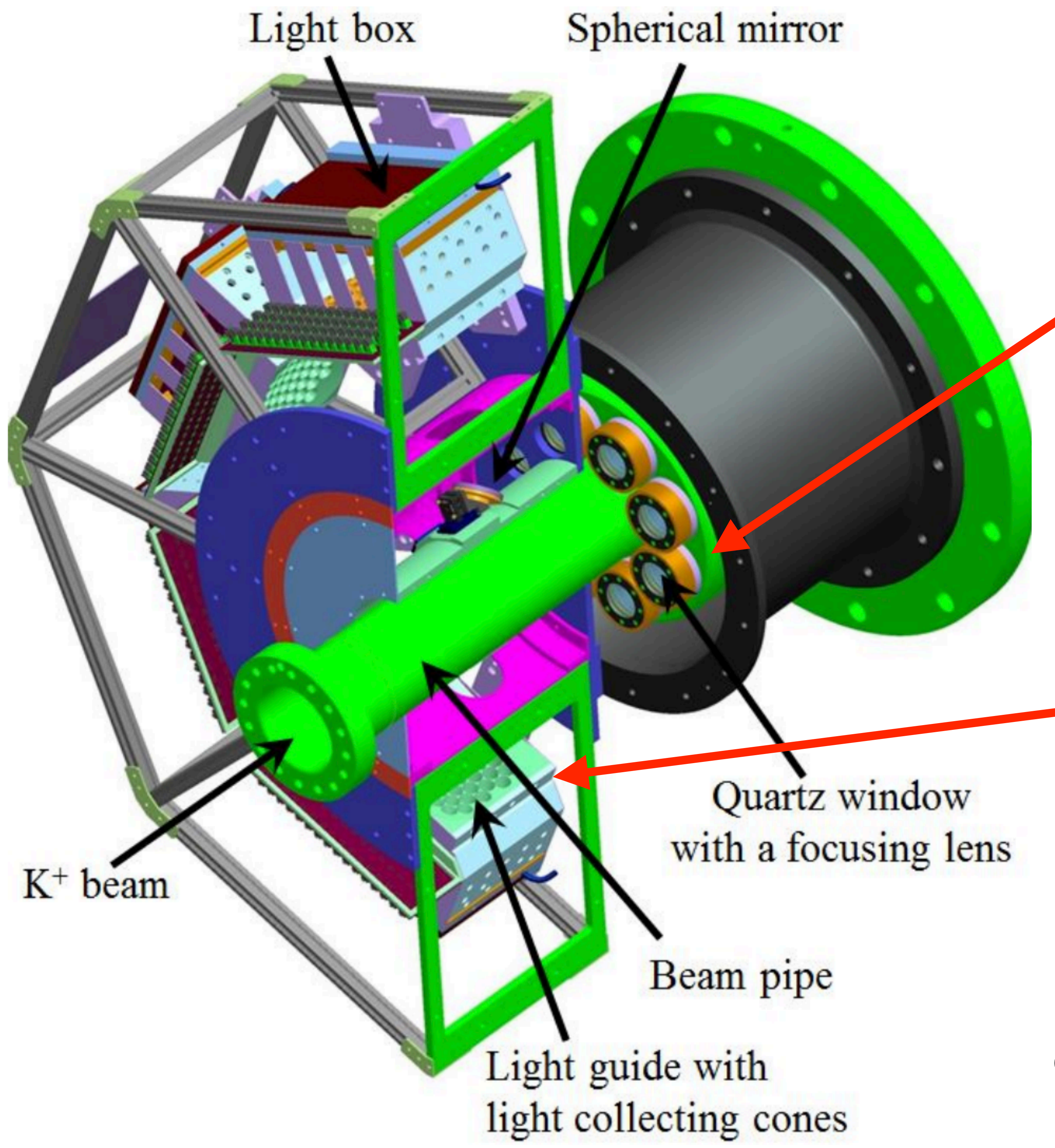
- Probability of $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$ events passing all photon veto conditions:

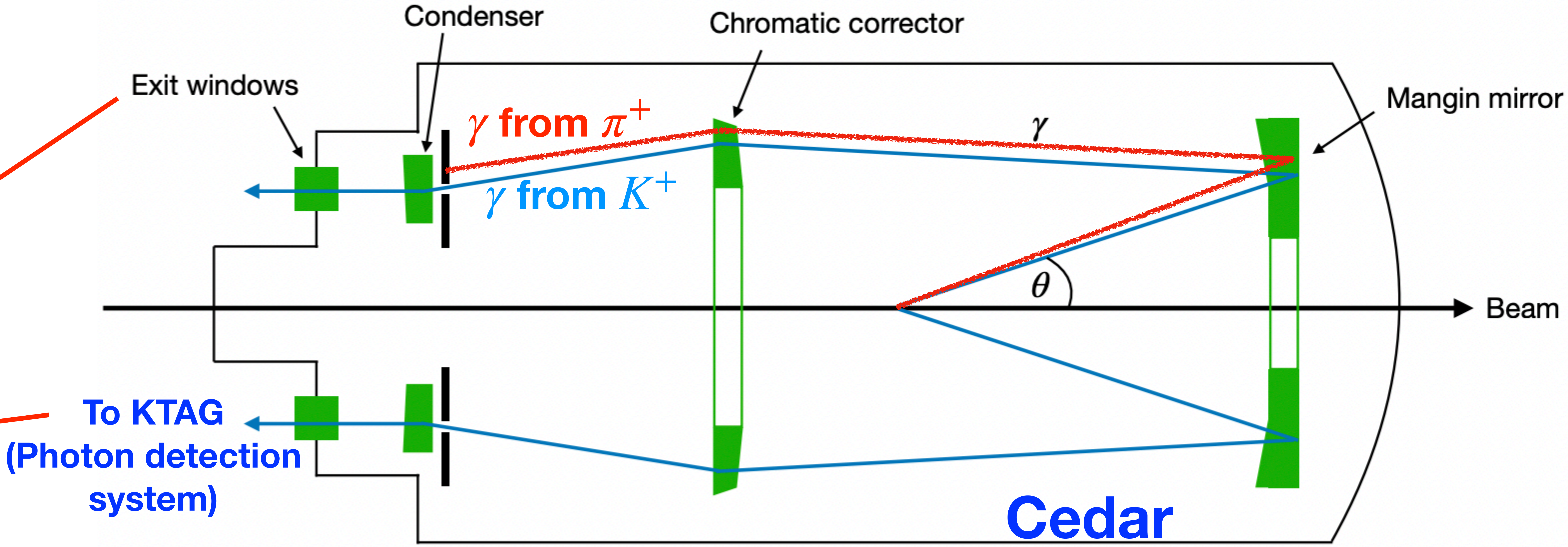
$$\eta_{\pi^0} = (1.72 \pm 0.07) \times 10^{-8}$$

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

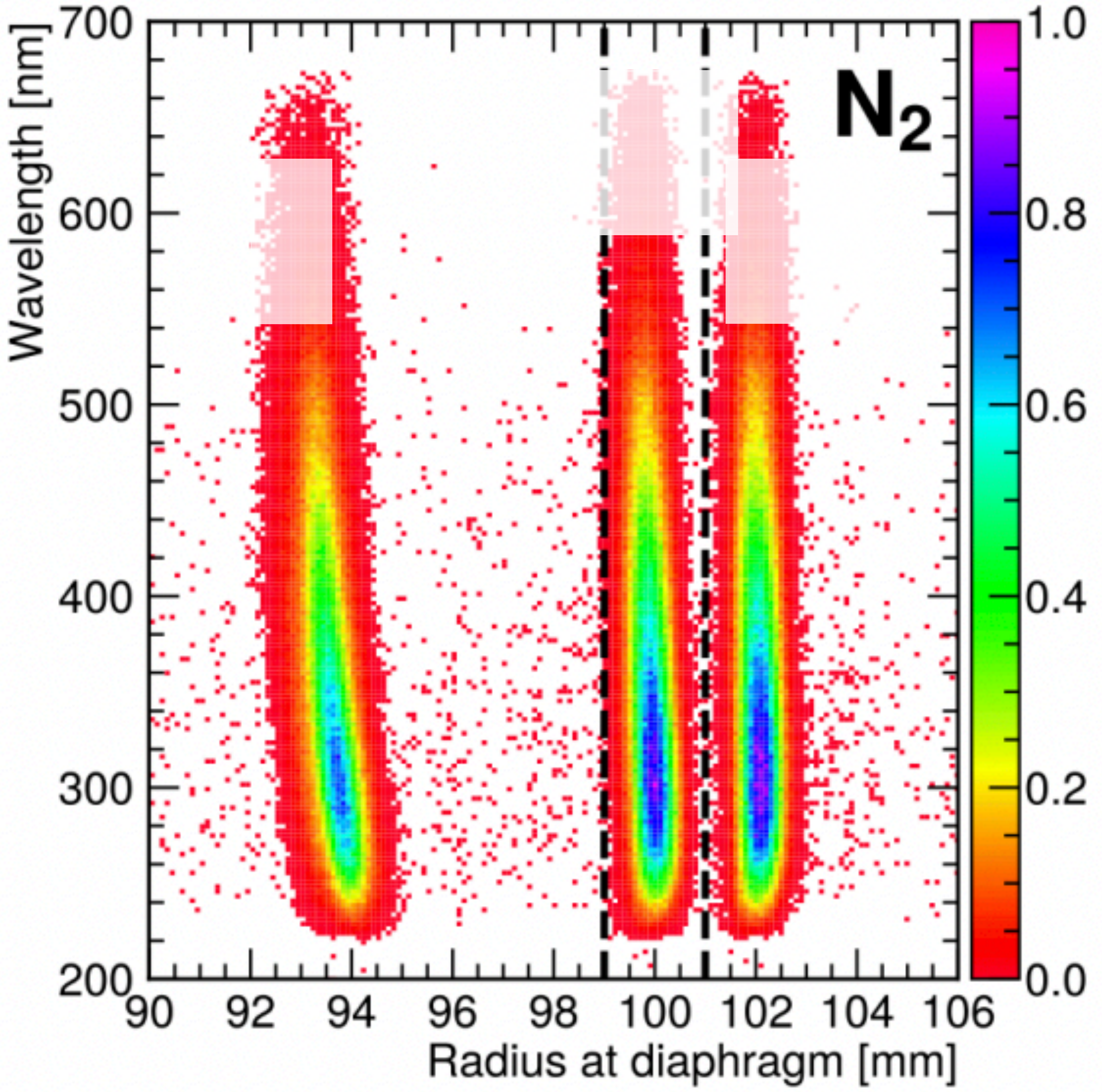
Cedar & KTAG : K^+ tagging with threshold Cherenkov counter





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

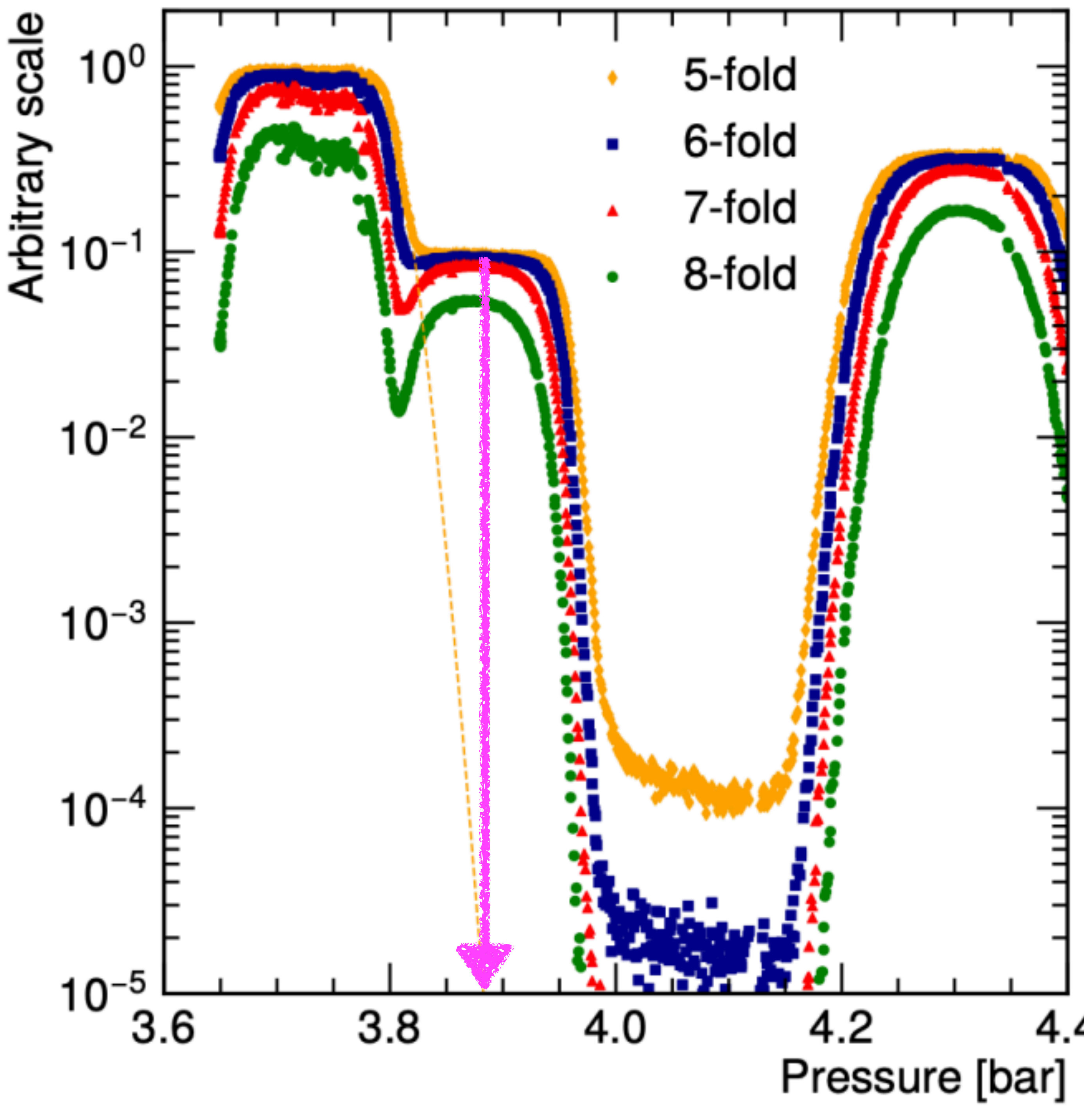
- Use fixed diaphragm to select ONLY Cherenkov light from K^+ (adjust diaphragm width and gas pressure in CEDAR to ensure powerful K^+/π^+ discrimination).

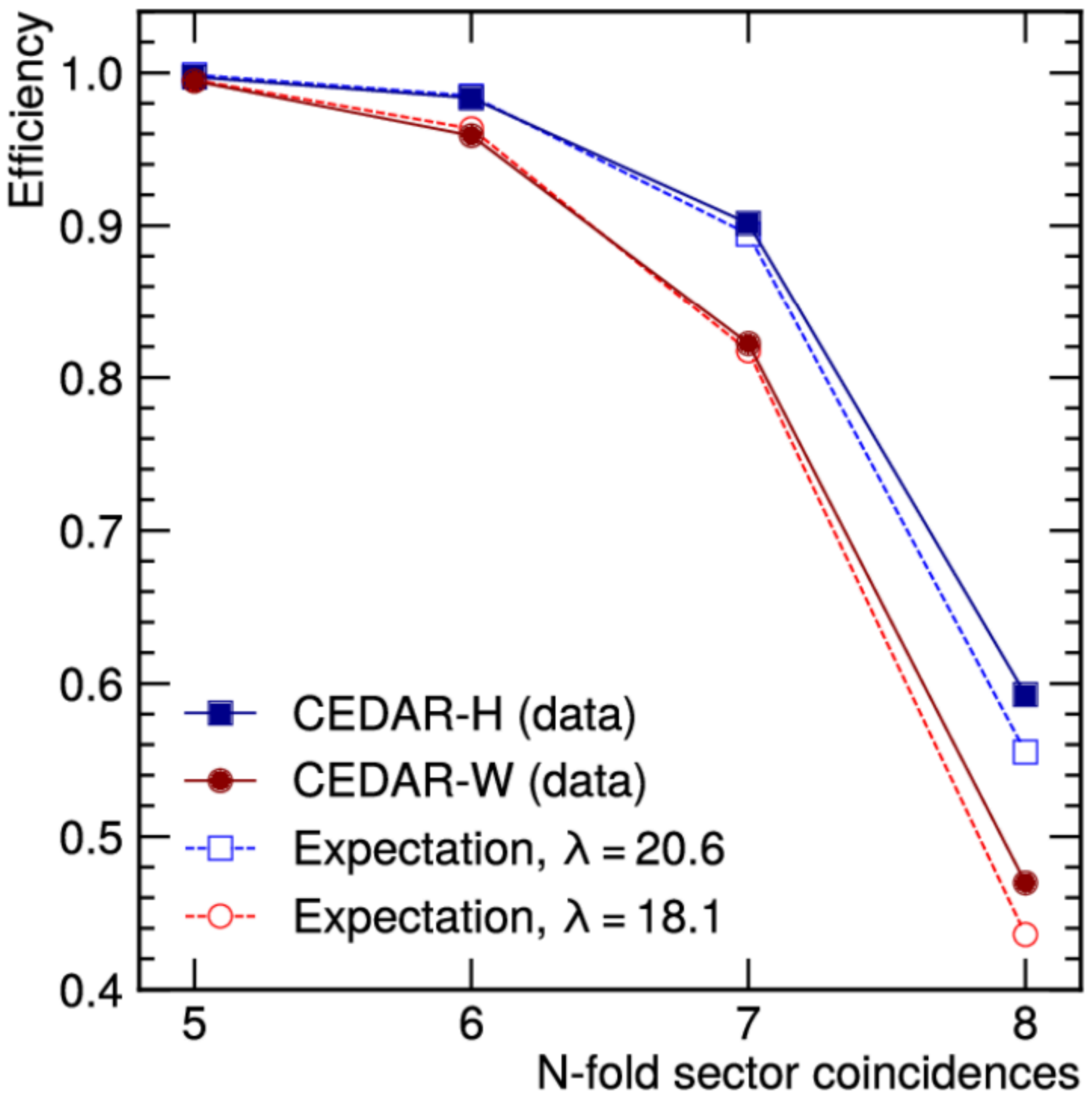


New Cedar-H : installed in 2023

- 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.

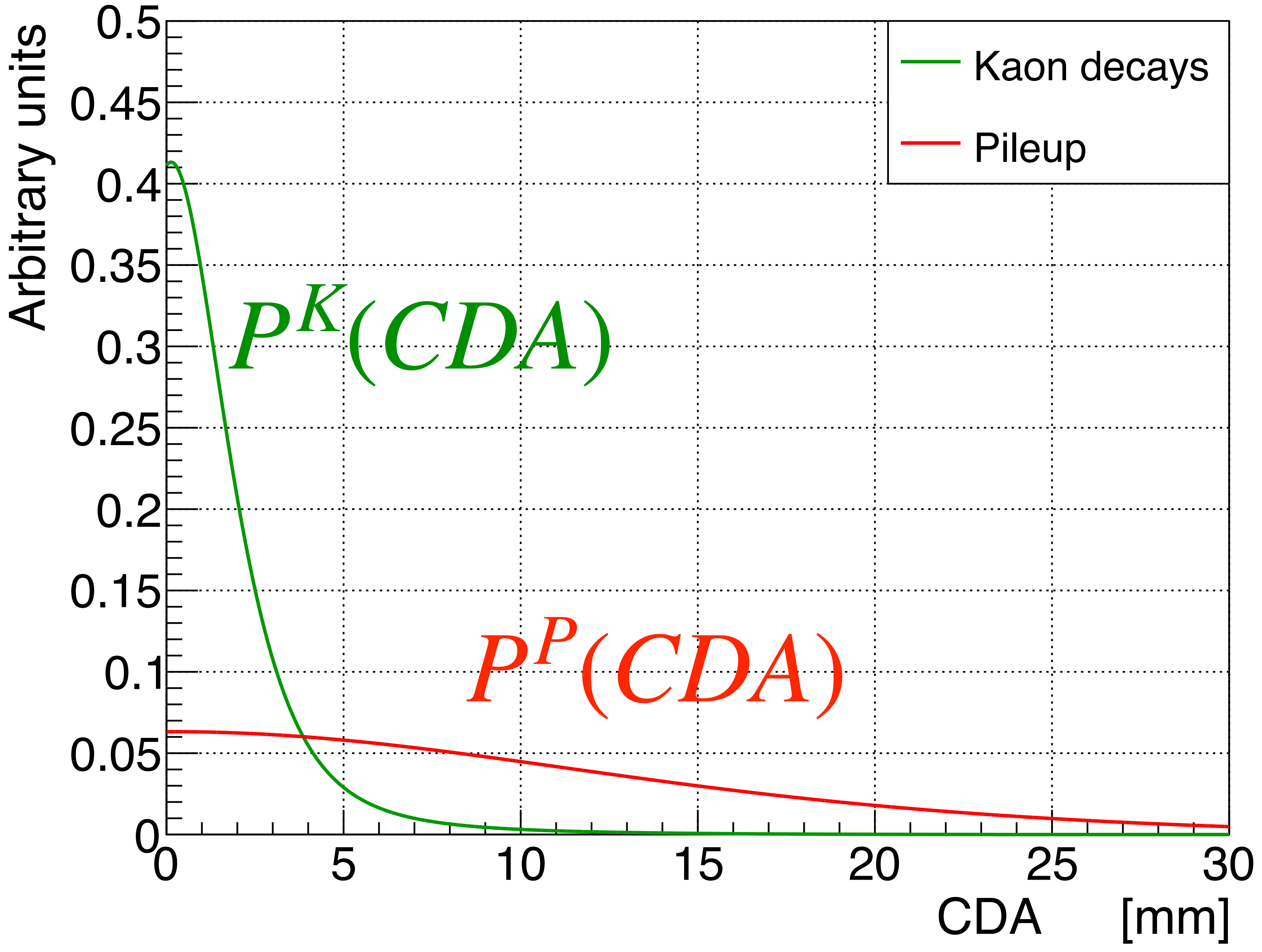


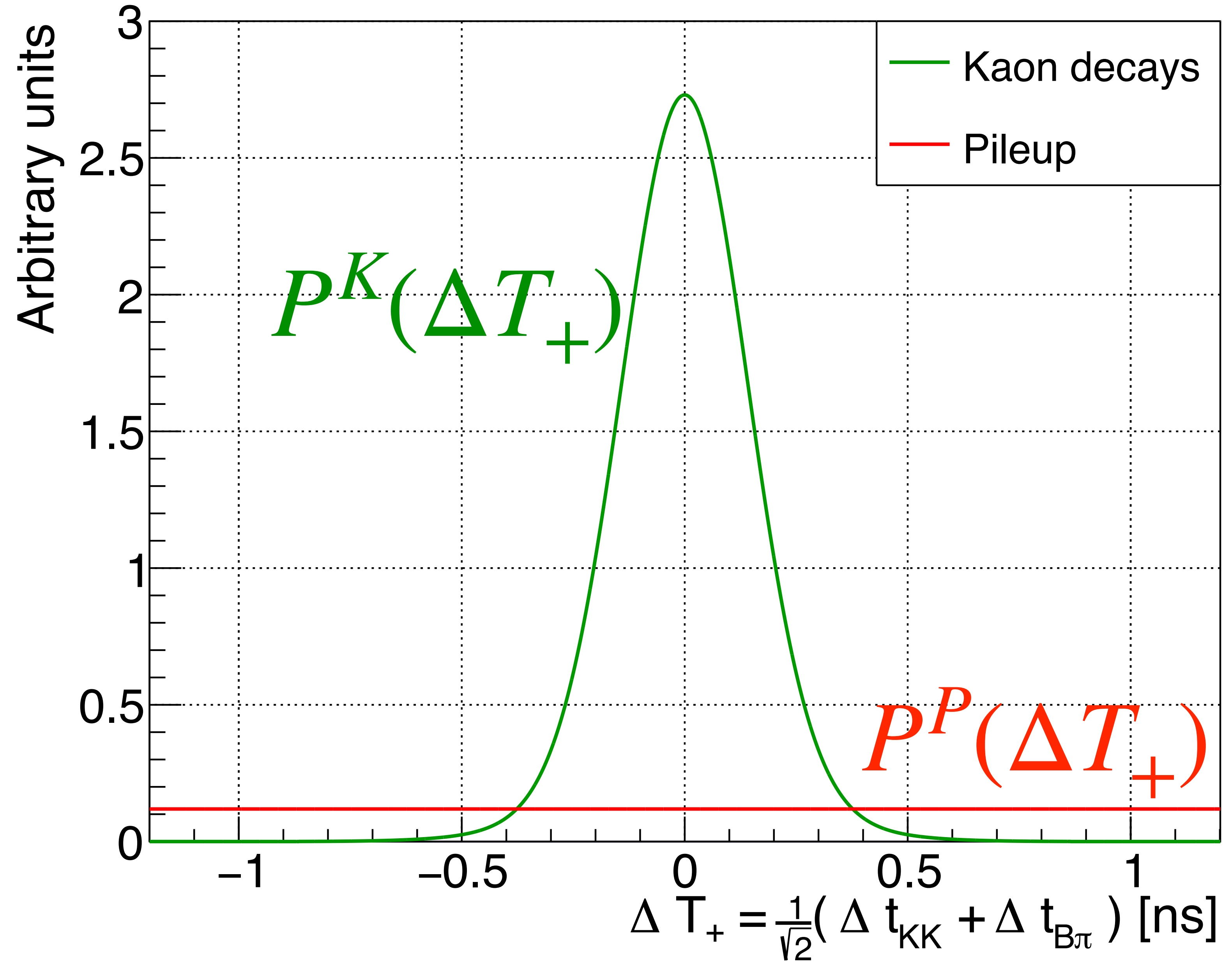


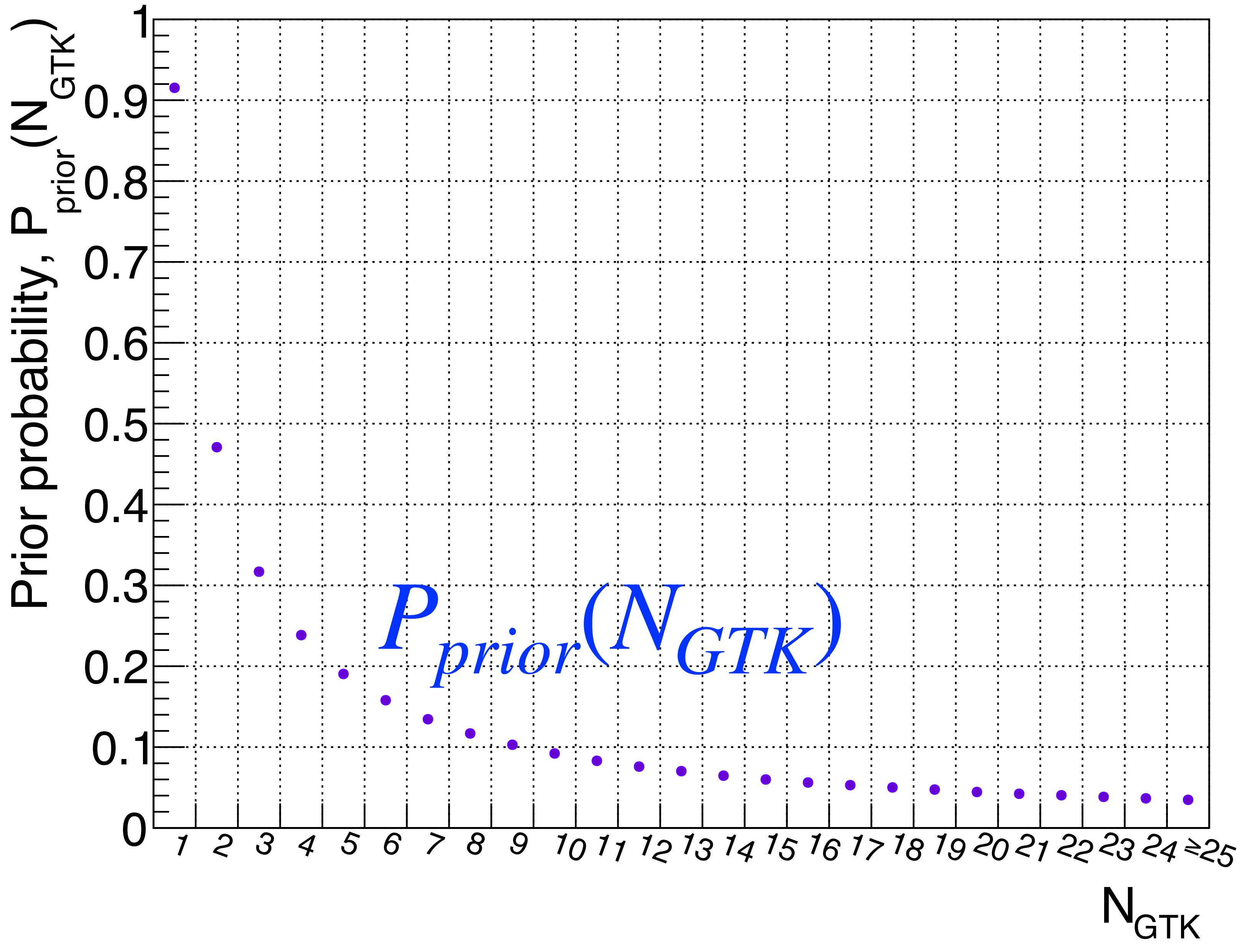
[JINST 19 (2024) 05, P05005]
More info: [Kenworthy, PM2024]

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.



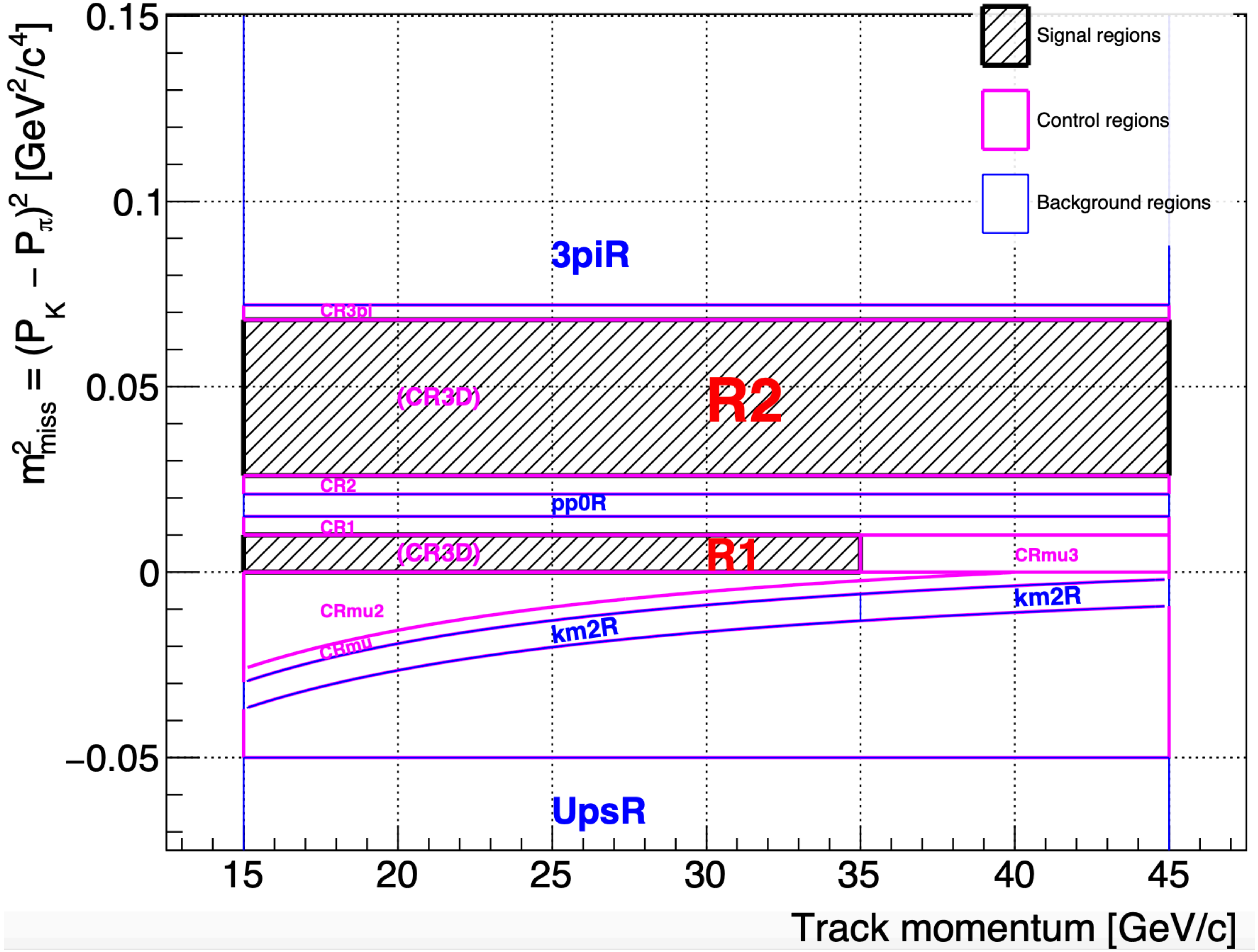




Example of selection update

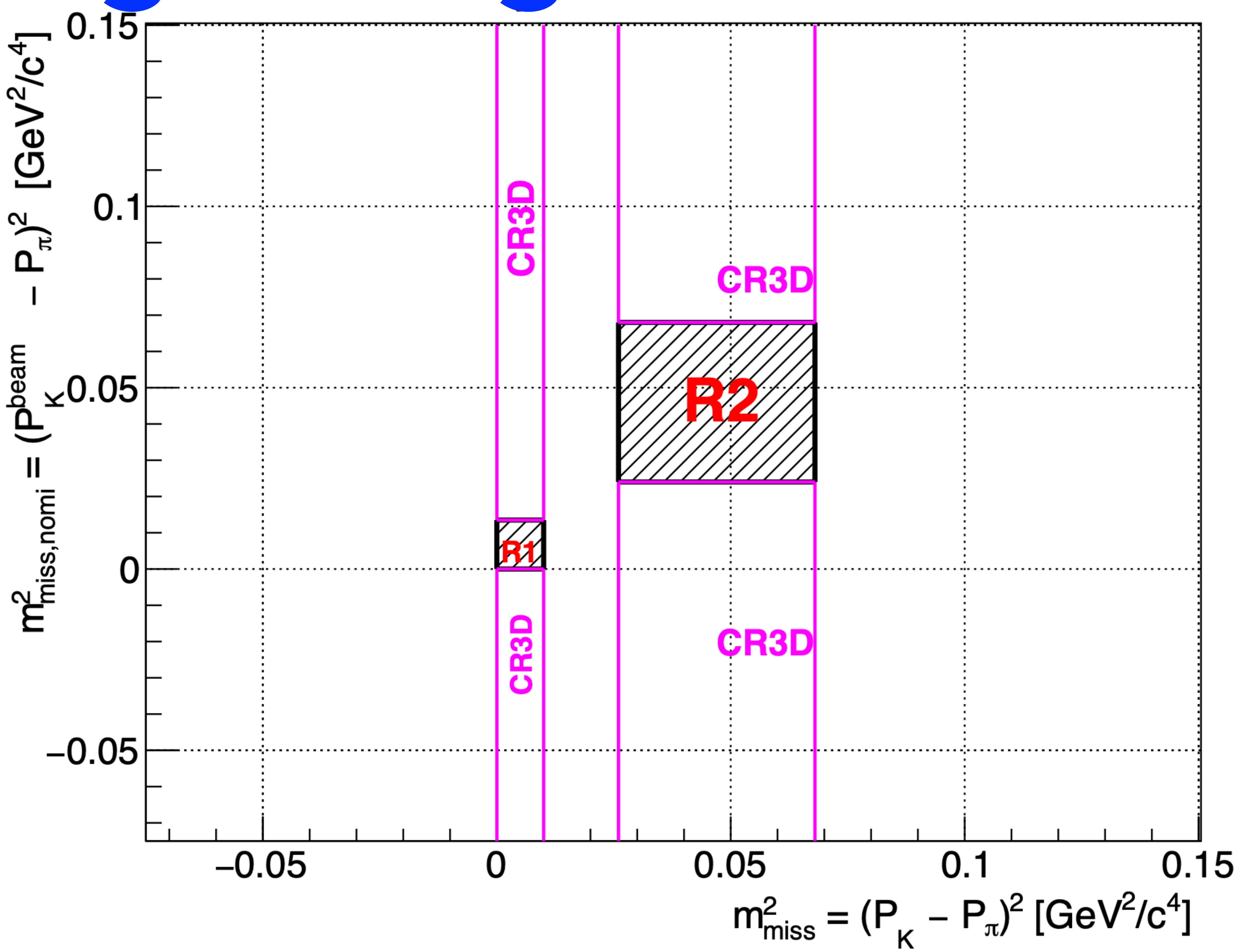
- **Output:** posterior probability of GTK track = true K^+
  - Use likelihoods of kaons (K) and pileup (P)
  - Likelihood ratio used to select true match when $N_{GTK} > 1$
- Efficiency improved (+10%) and mistagging probability maintained.

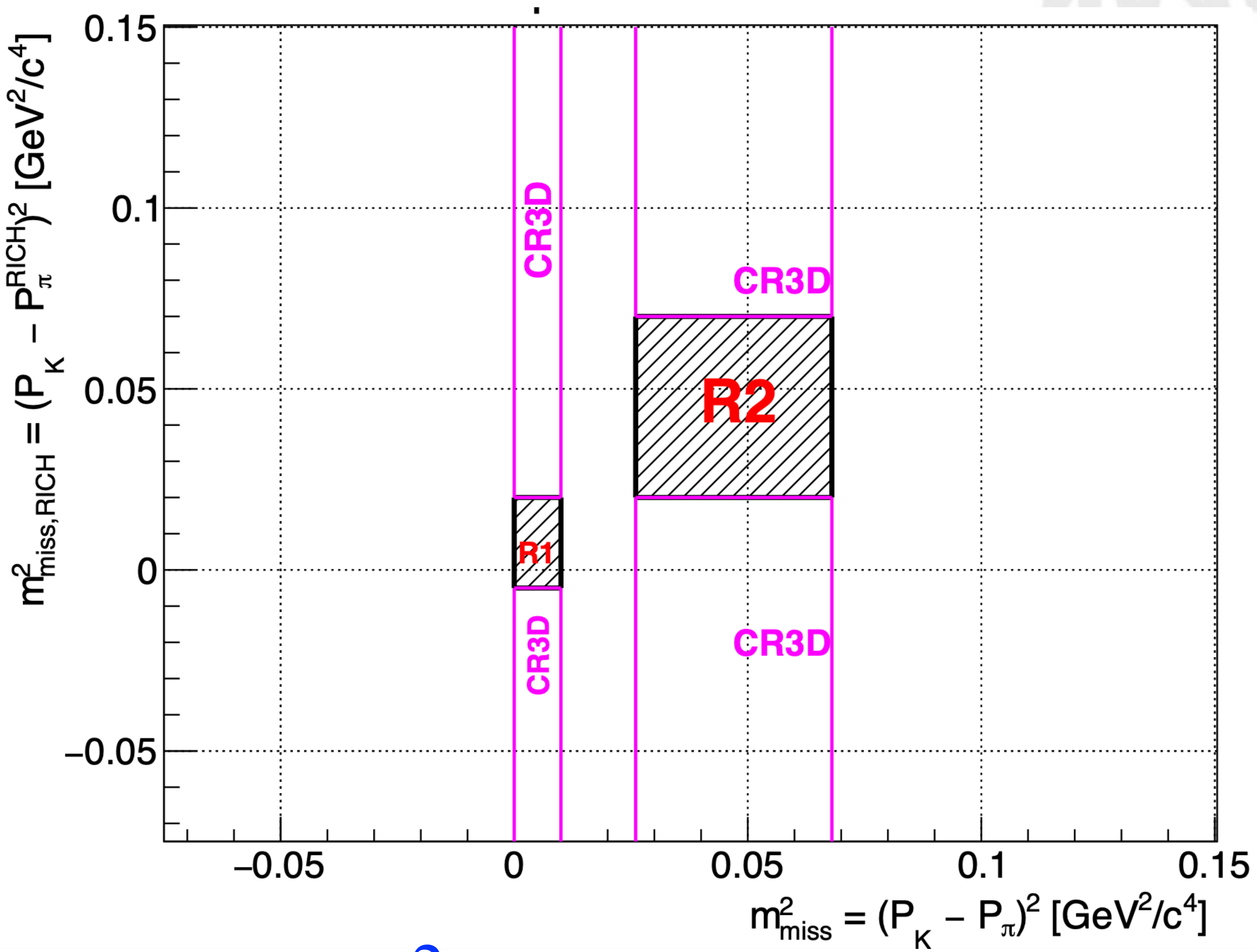
Kinematic regions



- **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) =** $m^2_{miss,RICH}$

Other backgrounds

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

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

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

Branching ratio of K_{e4} (from PDG)

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

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

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

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

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

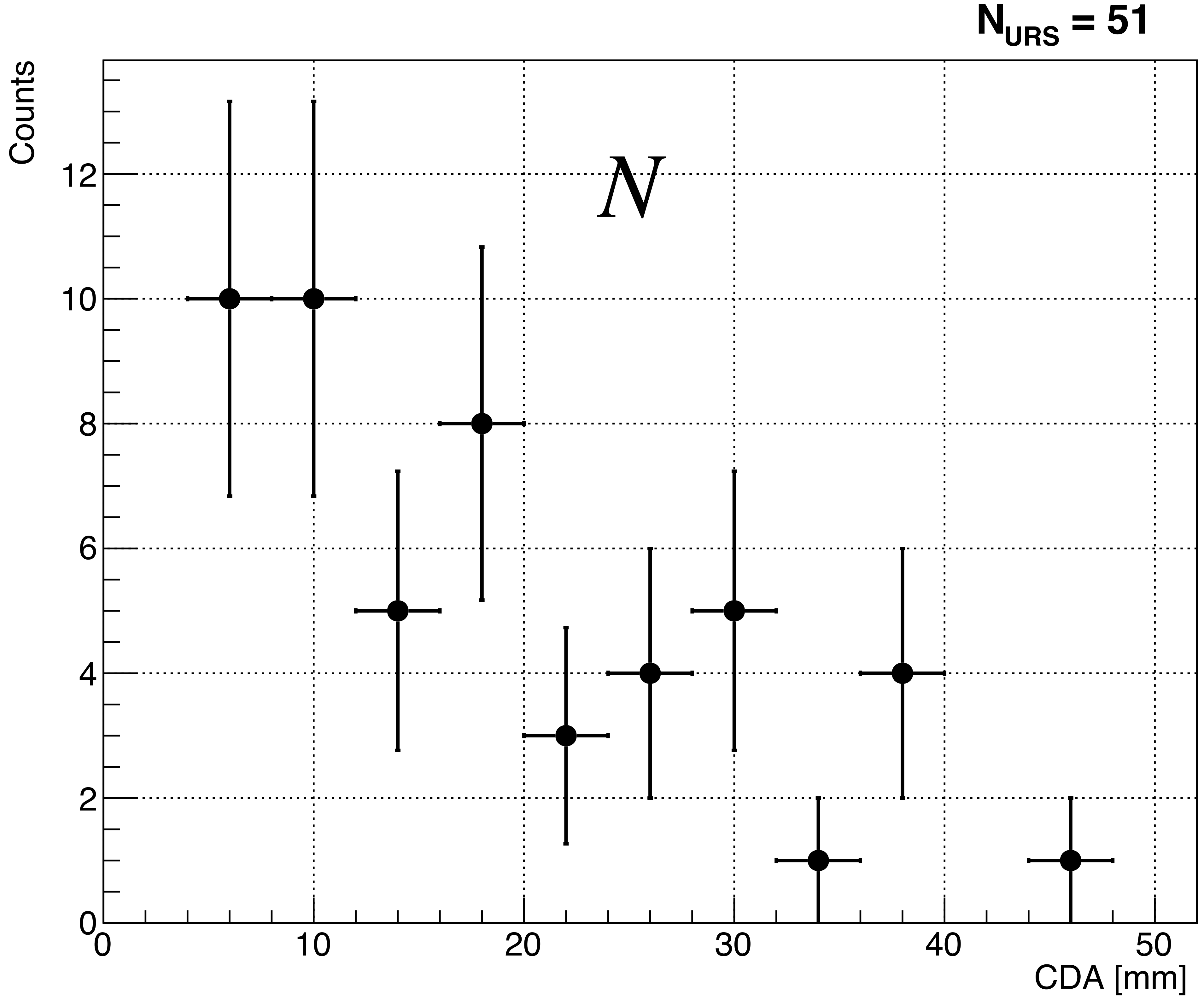
Calculate using bins (i) of $(\Delta T_+, N_{GTK})$

[Updated to fully data-driven procedure]

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

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

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



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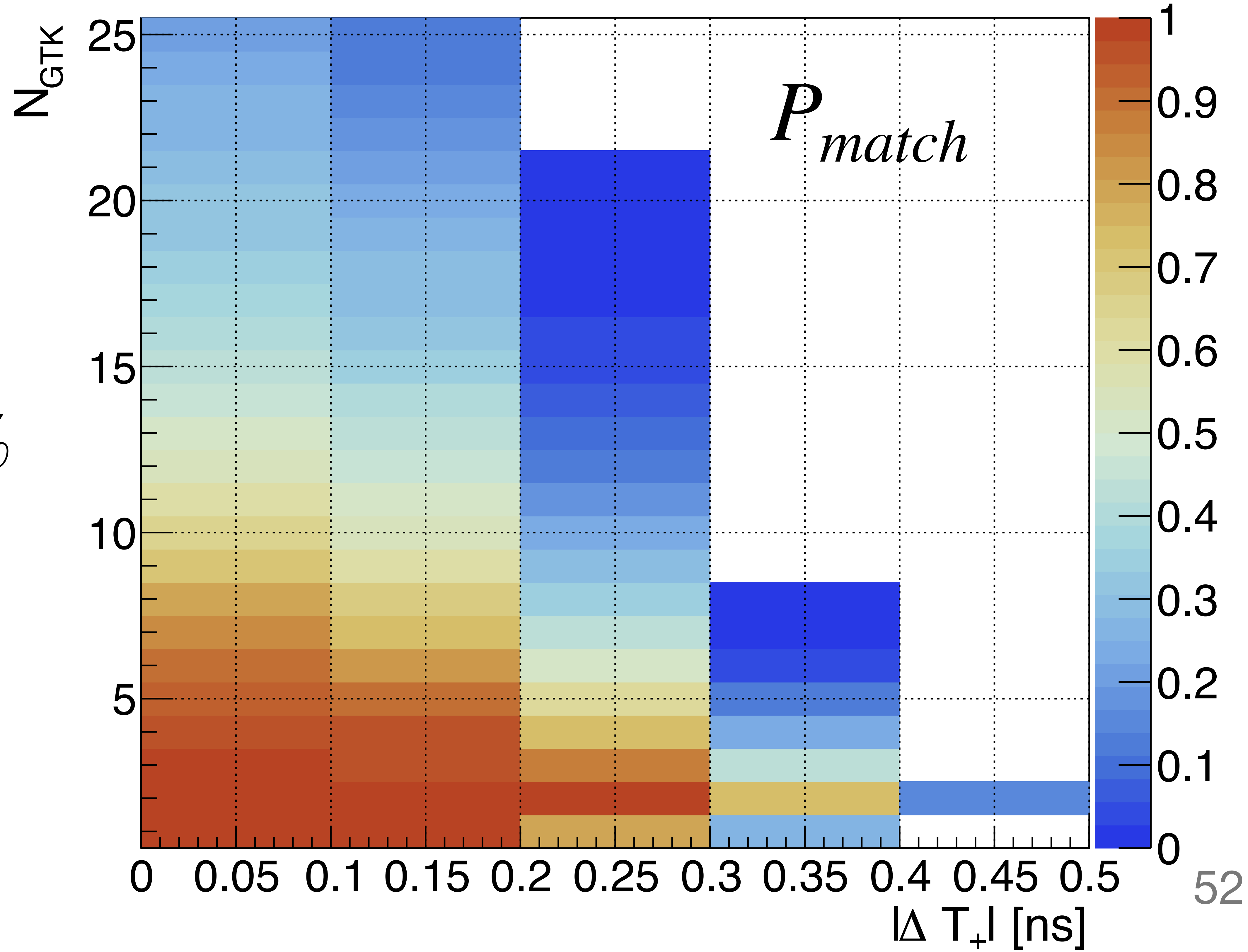
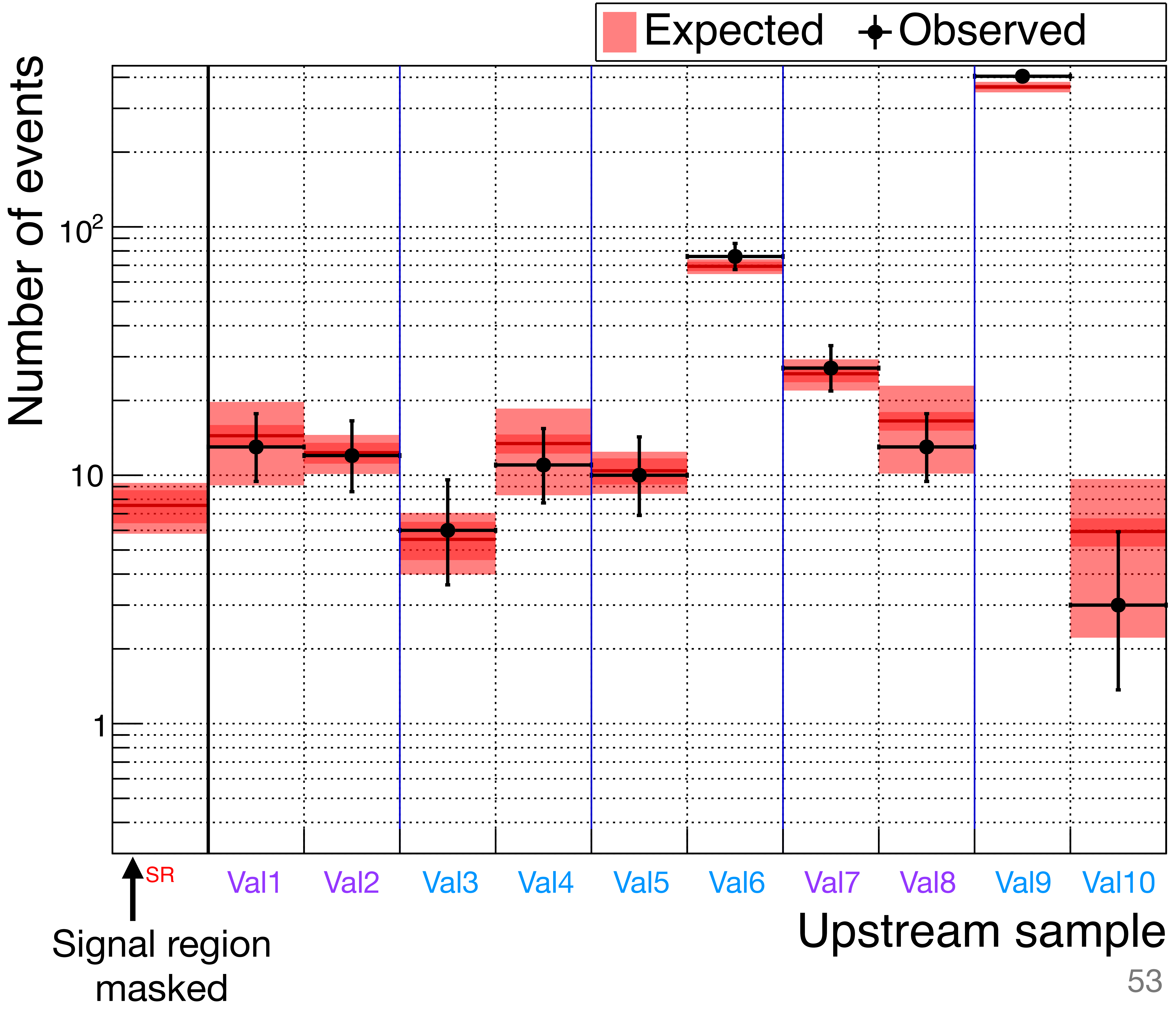


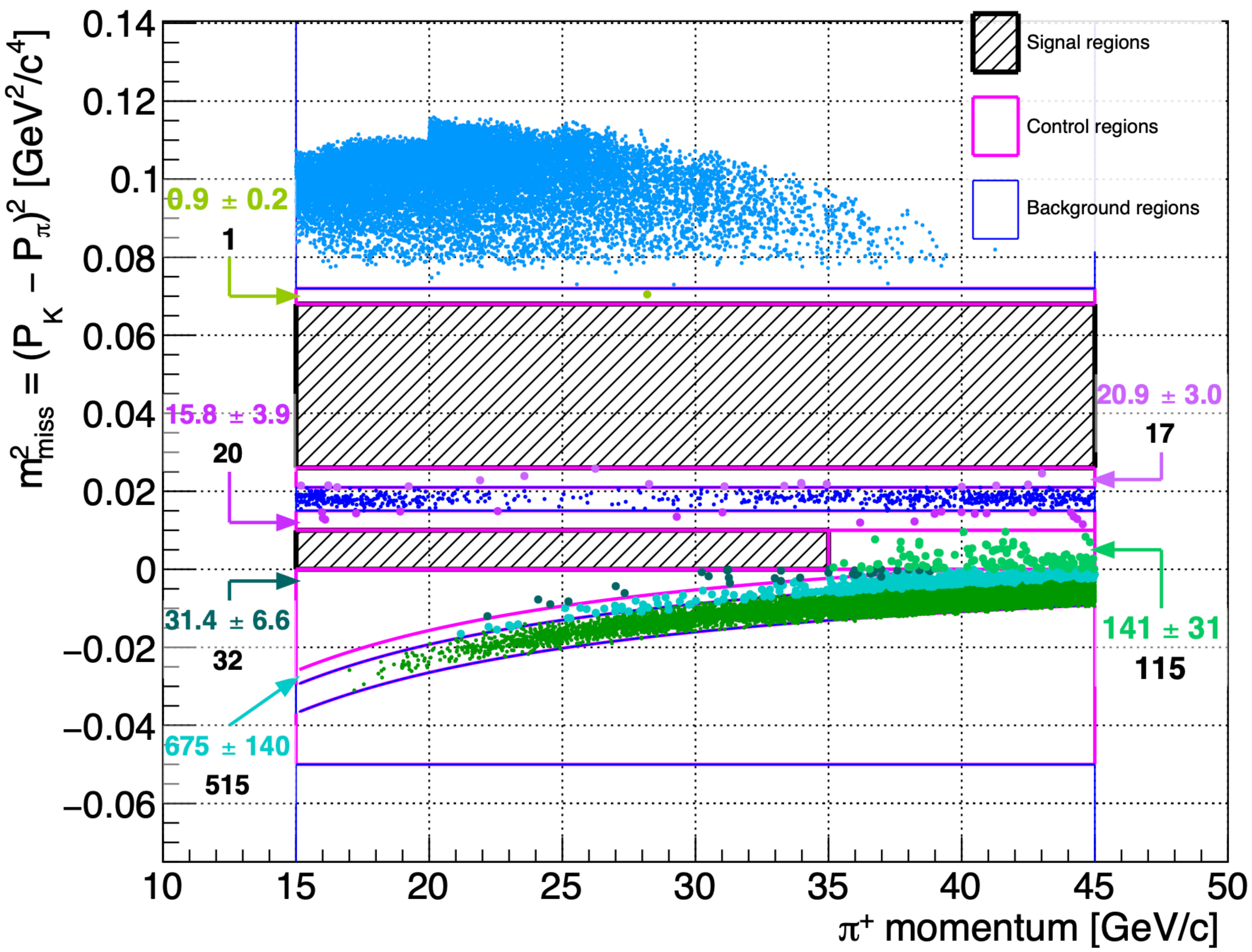
Upstream background validation

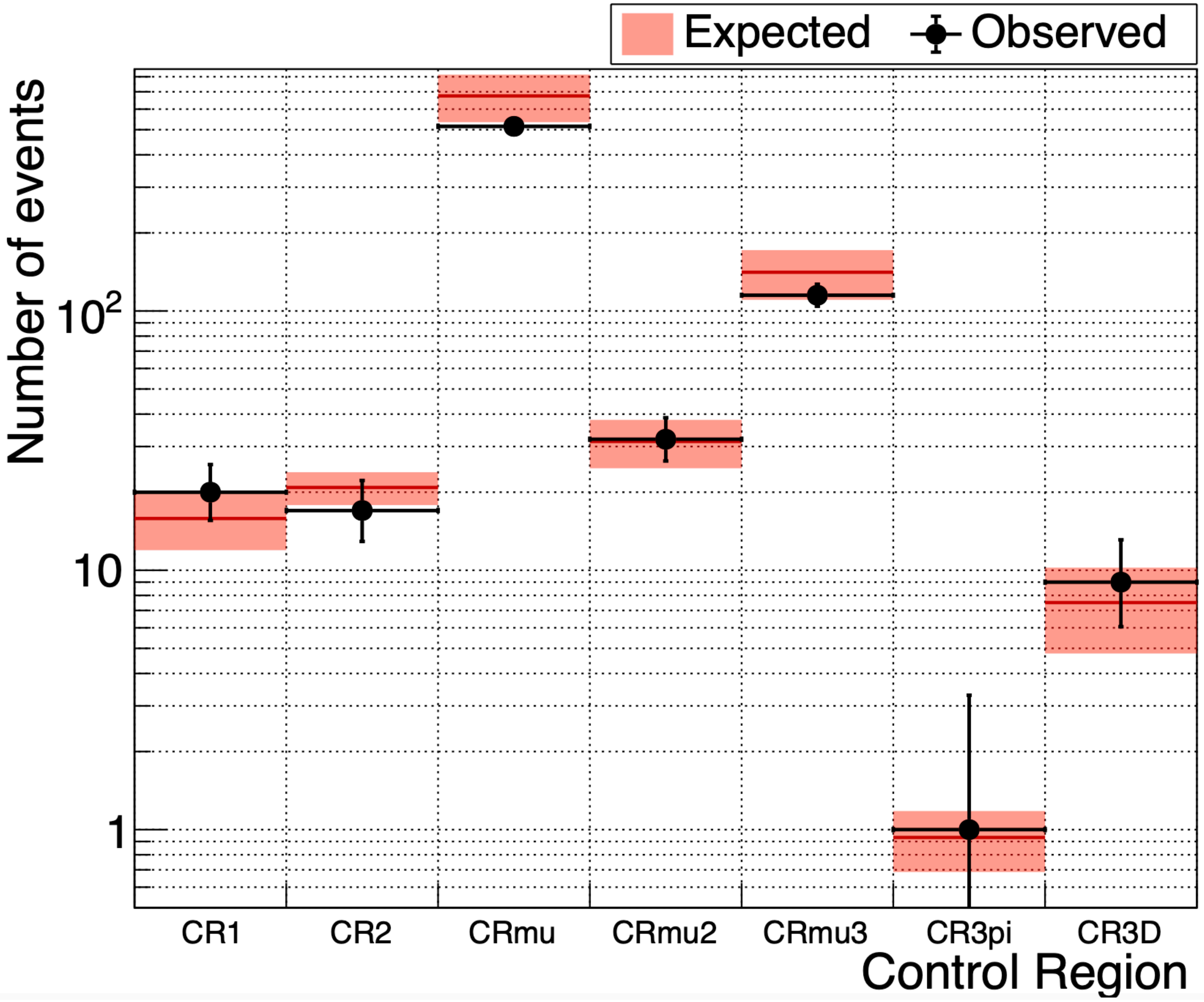
- **Invert & loosen upstream vetos to enrich with different mechanisms:**
  - Interaction-enriched: Val1,2,7,8
  - Accidental-enriched: Val3,4,5,6,9,10.
  - **All independent.**
- Expectations and observations are in good agreement.
- Number of events rejected by VetoCounter:
  - (i.e. events in signal region with associated VC signal)
  - $N_{exp}^{VC\,rej.} = 6.9 \pm 1.4$, $N_{obs}^{VC\,rej.} = 9$
- **VetoCounter is essential to control upstream background.**



Control regions

2021—22 data

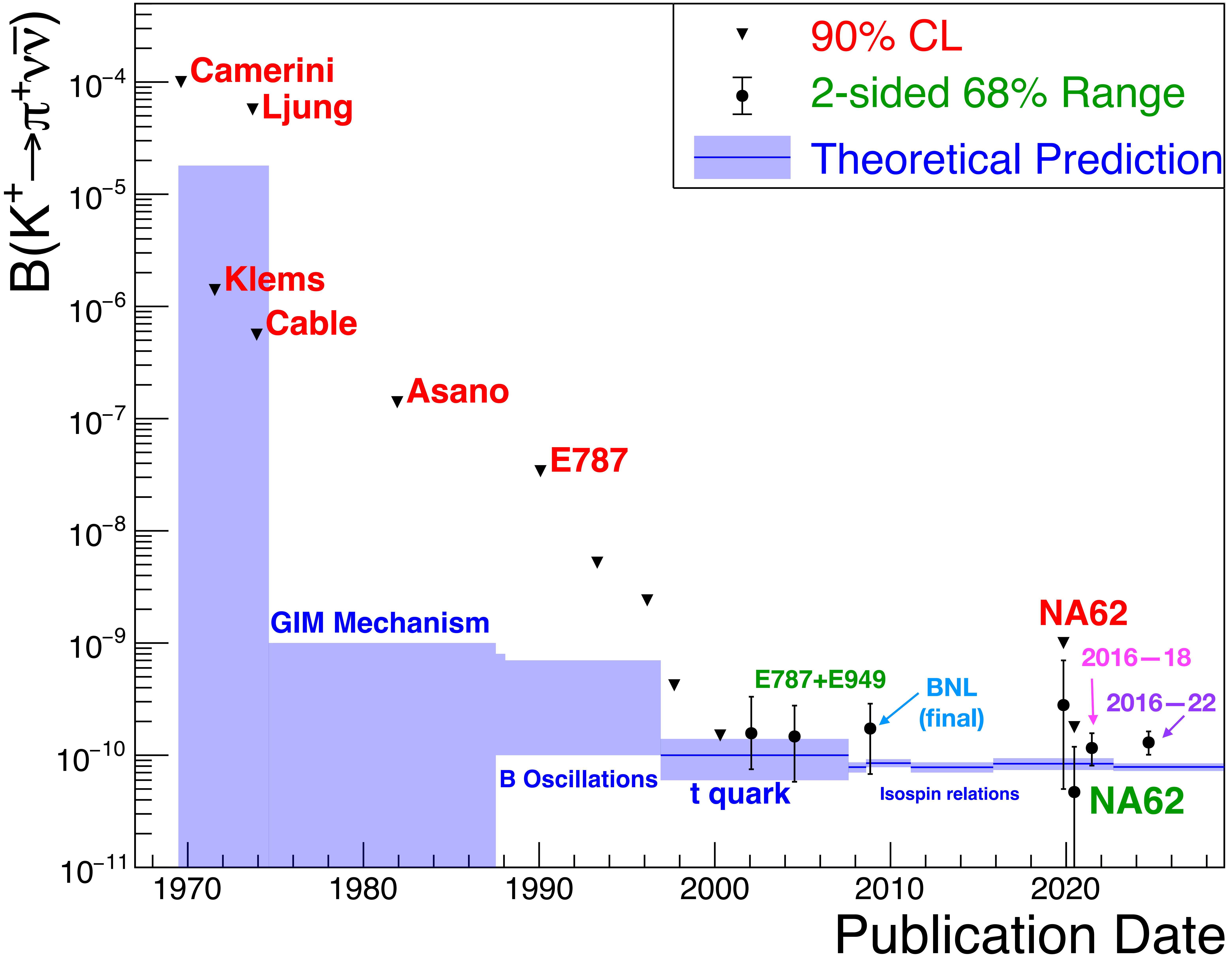




- Good agreement in control regions validates background expectations.

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]



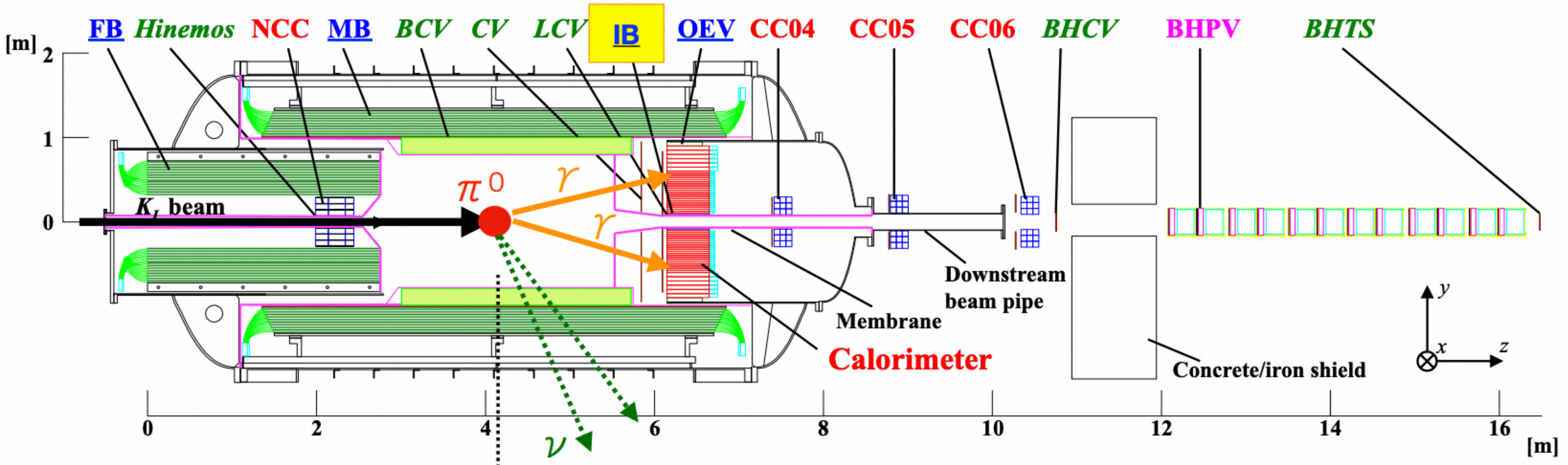
$K_L \to \pi^0 \nu \bar{\nu}$ at KOTO

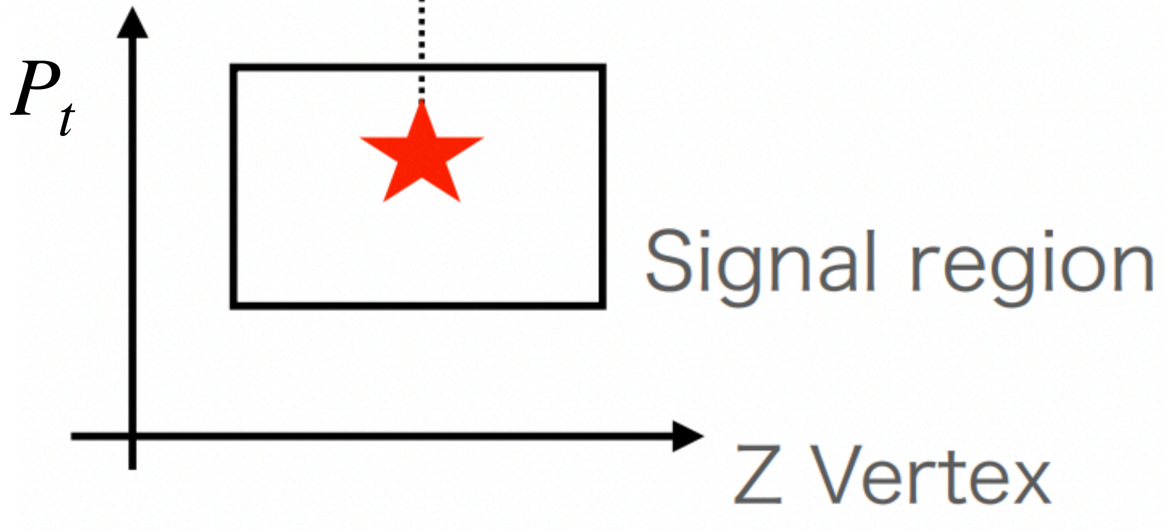
[K. shiomi : Kaons @ CERN 2023]

[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"



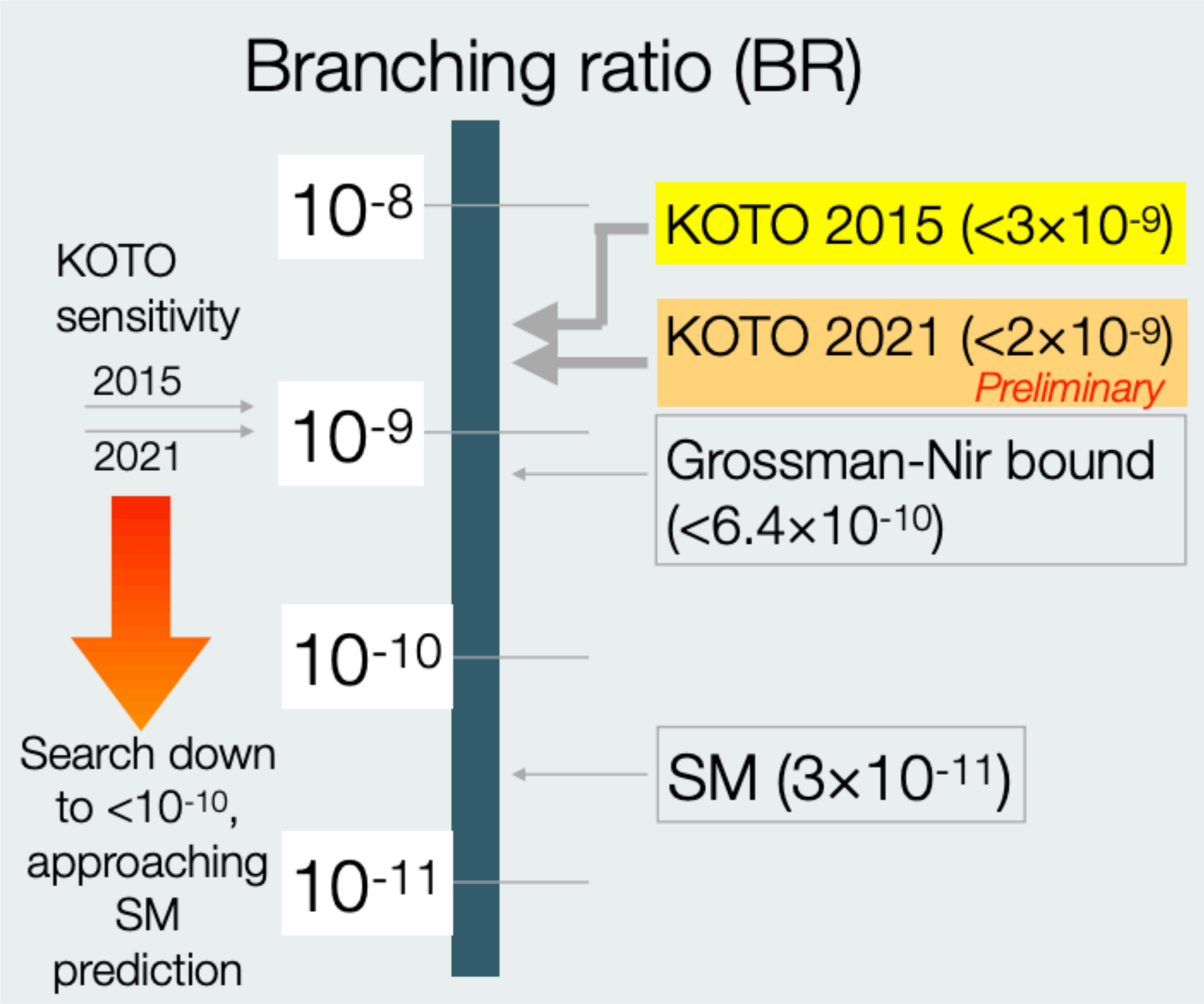


Assuming 2γ from π^0,

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]

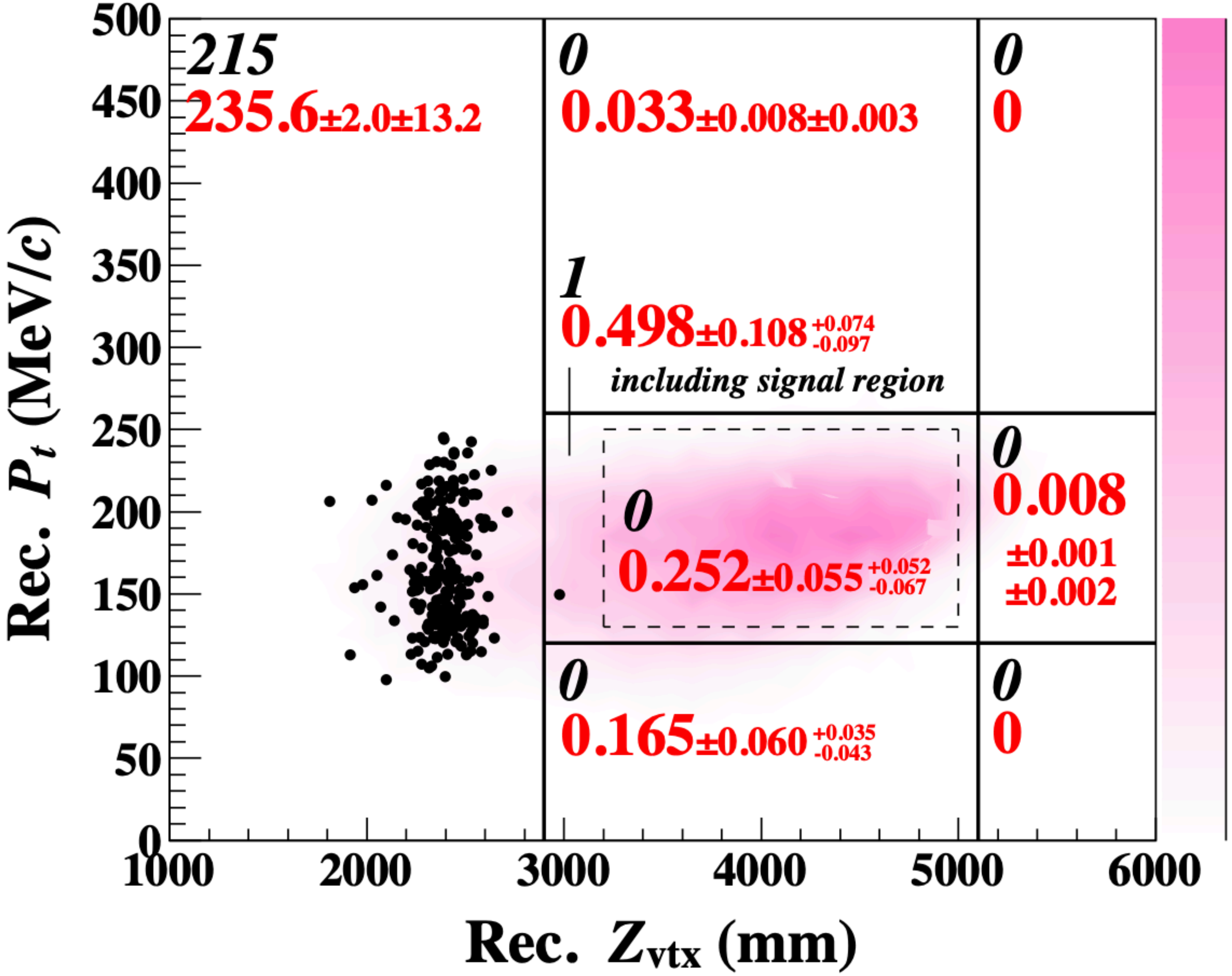


TABLE I. Summary of background estimation. The second (third) numbers represent the statistical uncertainties (systematic uncertainties).

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]

Preliminary Results: $K^+ \to \pi^+\pi^0,\ \pi^0 \to e^+e^-$

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

[new preliminary result for spring 2024]

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

- Strong prospects for the future with optimised trigger with reduced downscaling ($\approx 8 \to \approx 1$).
- Large external uncertainty from $\mathscr{B}(K^+ \to \pi^+e^+e^-)$. New analysis for this mode planned at NA62.

- Lower central value than KTeV measurement, but results are compatible:
  - $\mathscr{B}_{KTeV}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (6.44 \pm 0.33) \times 10^{-8}$
- Result in agreement with theoretical expectations when extrapolated using radiative corrections:
  - $\mathscr{B}_{\text{theory2022}}(\pi^0 \to e^+e^-(\gamma), \text{no rad}) = (6.25 \pm 0.03) \times 10^{-8}$

Backgrounds and PID studies

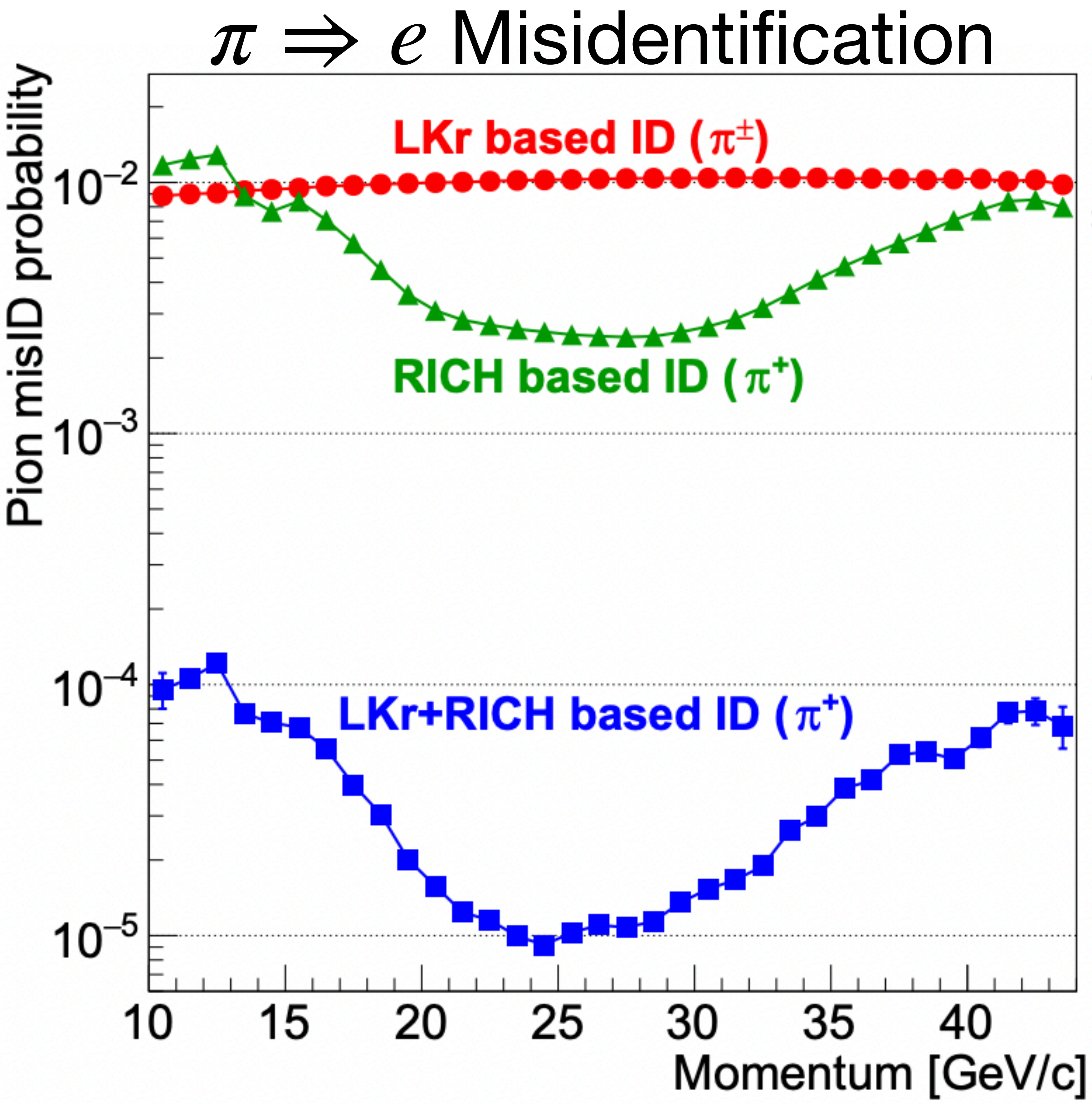
e.g. for $K^+ \to \pi^-(\pi^0)e^+e^+$ searches [PLB 830 (2022) 137172]

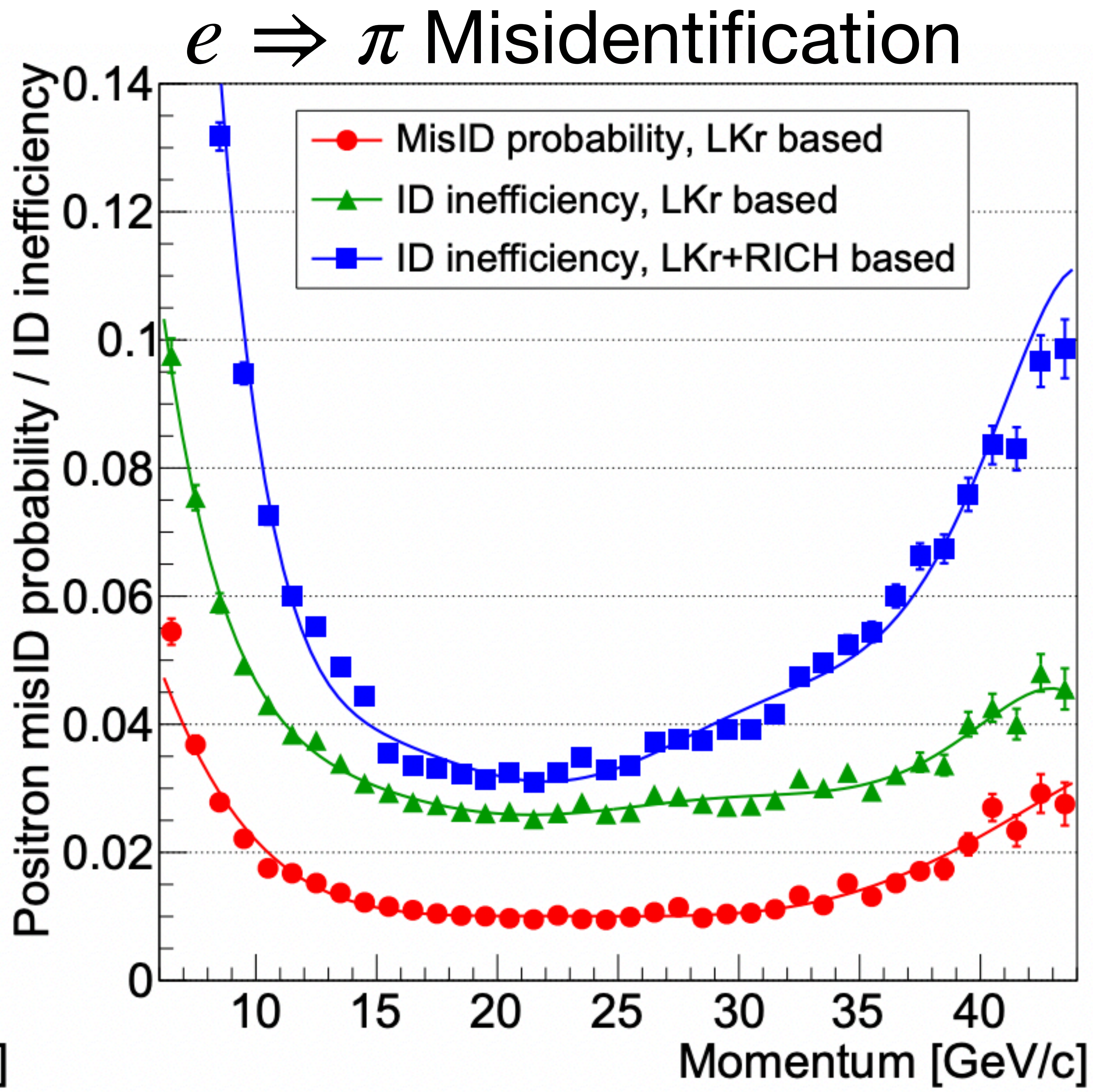
PID conditions:

$\pi^\pm$: E/p<0.8, No MUV3 association.

$e^\pm$: 1 LKr cluster 0.9<E/p<1.1.

+ for $K^+ \to \pi^- e^+ e^+$ search : require RICH PID for e^+.





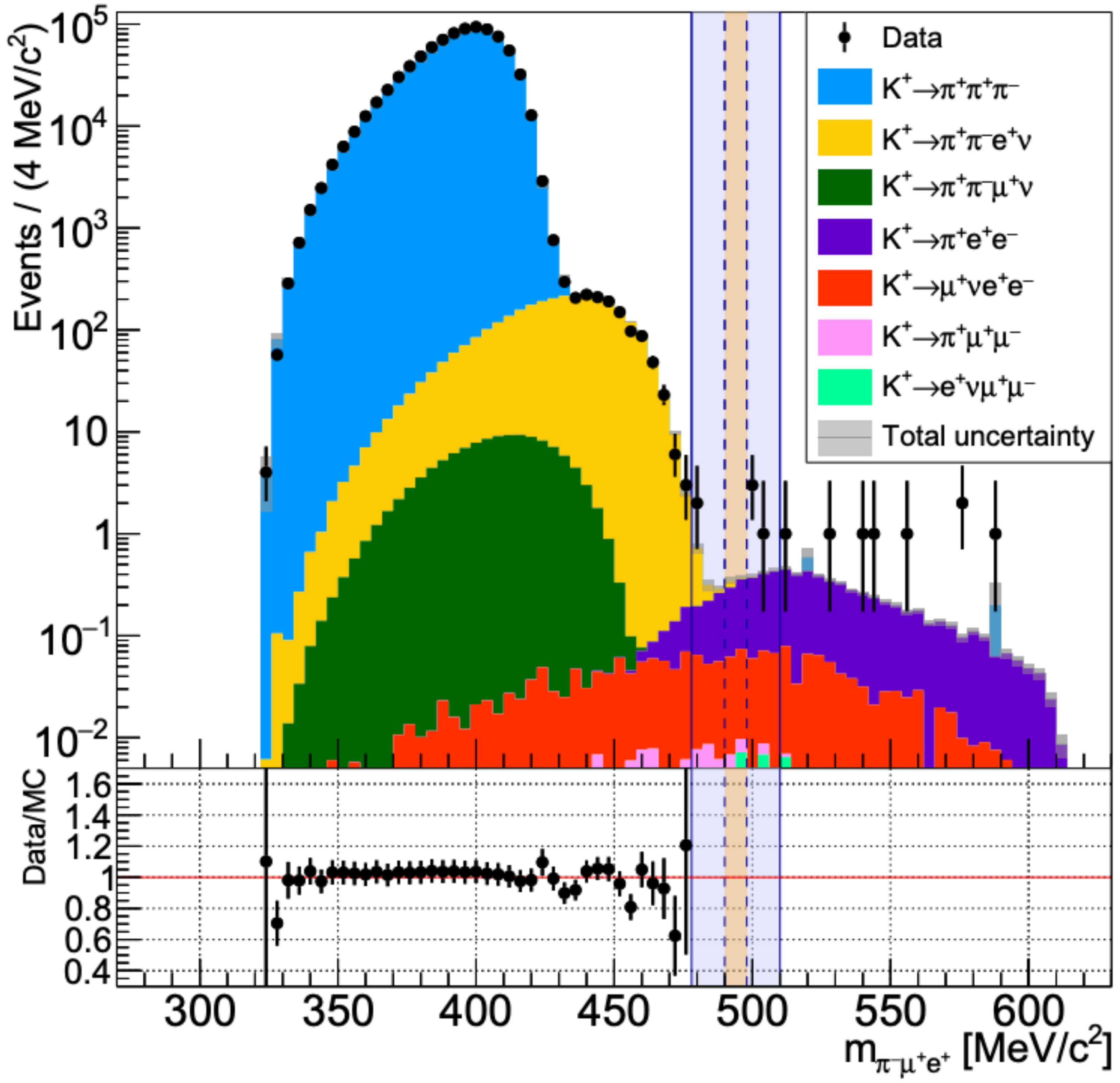
- Primary background mechanisms from misidentification.
- Models from data applied in simulations to describe misID.
- Validated using control samples [without RICH, with missing momentum].

Searches for $K^+ \to \pi\mu e$ decays

[PRL 127 (2021) 131802]

- Normalise to $K^+ \to \pi^+\pi^+\pi^-$.
- Use 3 trigger streams, 2017+18 data : $N_K = (1.33 \pm 0.02) \times 10^{12}$
  - Special care needed for eMT trigger with LKr-energy dependence.
- Signal acceptances:
  - $A(K^+ \to \pi^-\mu^+e^+) = (4.90 \pm 0.02)\,\%$
  - $A(K^+ \to \pi^+\mu^-e^+) = (6.21 \pm 0.02)\,\%$
  - For π^-channel only: $m(\pi^-e^+) < 140\,\text{MeV}/c^2$ to reject backgrounds involving $\pi^0 \to e^+e^-\gamma$ + misID.

LNV/LFV : $K^+ \to \pi^-\mu^+e^+$

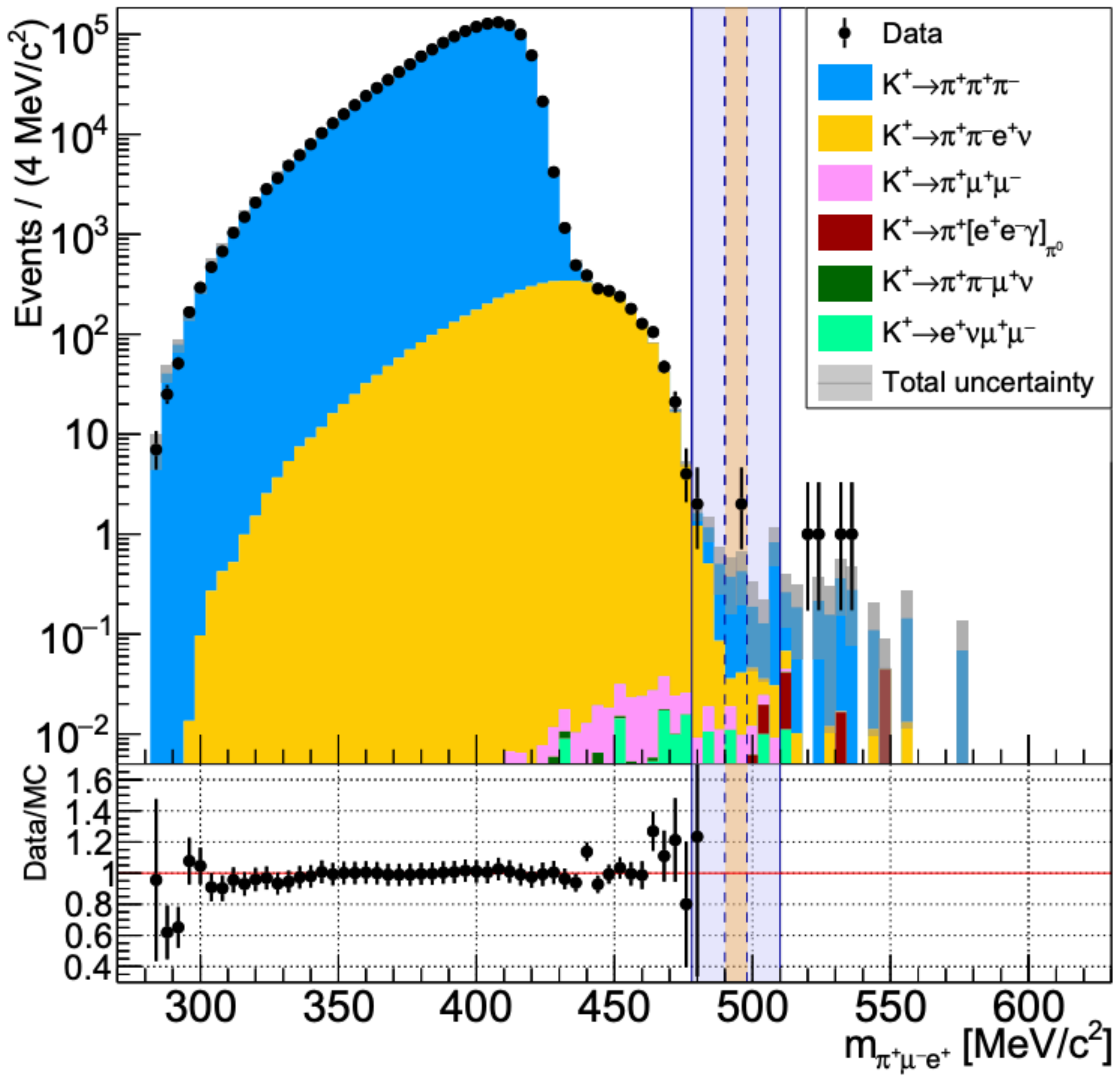


Expected background: 1.07 ± 0.20

Candidates observed: 0

$\mathcal{B}(K^+ \to \pi^-\mu^+e^+) < 4.2 \times 10^{-11}$ @ 90 % CL

LFV : $K^+ \to \pi^+\mu^-e^+$



Expected background: 0.92 ± 0.34

Candidates observed: 2

$\mathcal{B}(K^+ \to \pi^-\mu^+e^+) < 6.6 \times 10^{-11}$ @ 90 % CL

From $K^+ \to \pi^+\pi^0$, $\pi^0 \to \mu^-e^+$ search:

$\mathcal{B}(\pi^0 \to \mu^-e^+) < 3.2 \times 10^{-10}$ @ 90 % CL

Improve by approximately 1 order of magnitude on previous BNL E865 results [PRL 85 (2000) 2877].