Latest Rare Kaon Decay Results

Joel Swallow (INFN-LNF) [NA62]

Contents:

- Latest results from NA62: $K^+ \to \pi^+\gamma\gamma$, $[K^+ \to \pi^+\pi^0]\pi^0 \to e^+e^-$, tagged ν
- Status of golden modes $K \to \pi\nu\bar{\nu}$

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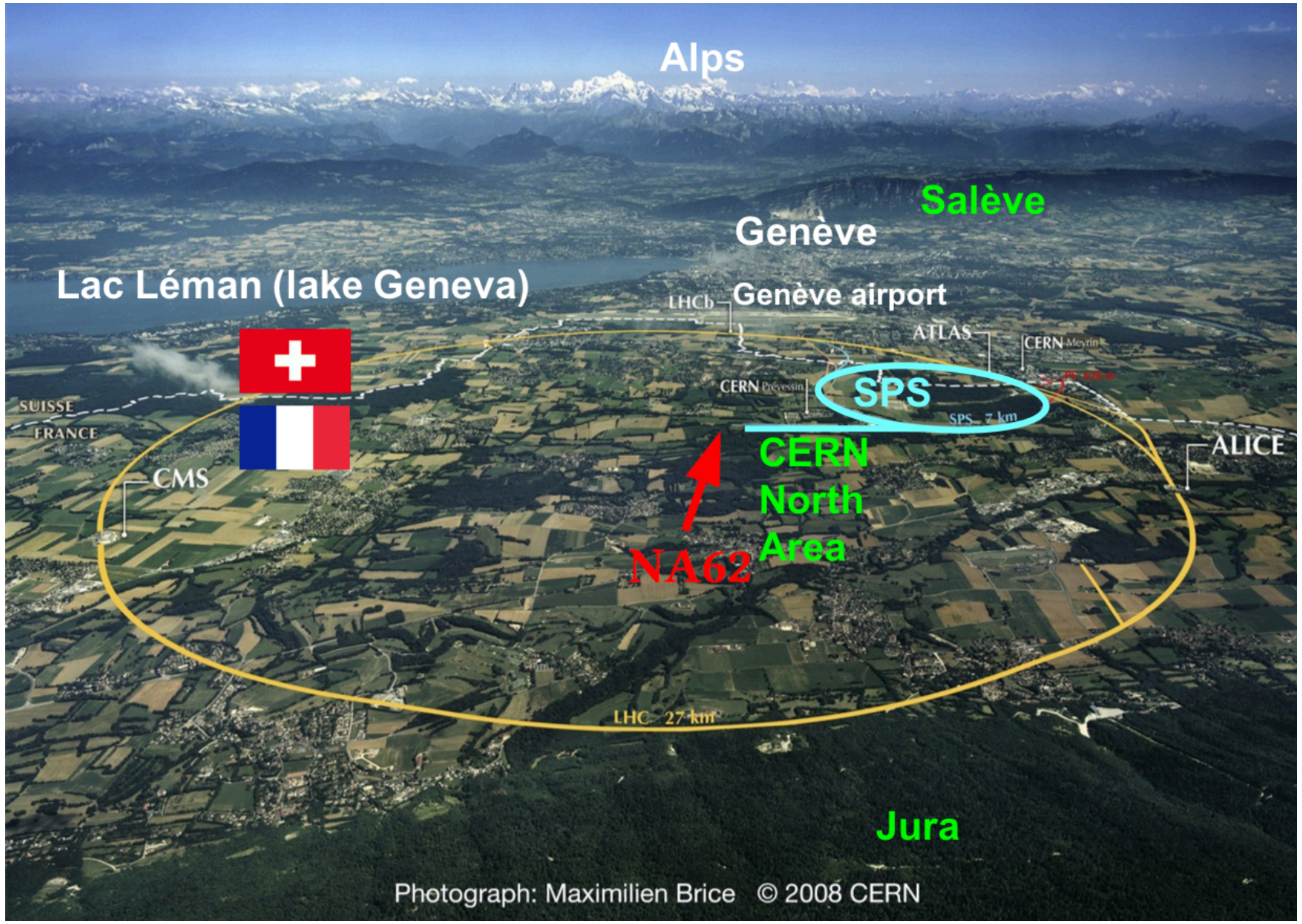
Studies of rare K^+ decays at NA62

The NA62 Experiment at CERN: K^+

~300 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 (this talk)
  - LNV/LFV decays (e.g. $K^+ \to \mu^+ \nu e^+ e^+$ [JHEP 09 (2023) 040])
  - Exotics (e.g. Dark photon [arXiv.2312.12055], talk by T. Spadaro)
- **Data taking**
  - 2016 Commissioning + Physics run (45 days).
  - 2017 Physics run (160 days).
  - 2018 Physics run (217 days).
  - 2021 Physics run (85 days [10 beam dump]).
  - 2022 Physics run (215 days).
  - 2023 Physics run (150 days [10 beam dump]).
  - 2024 Physics run ongoing …

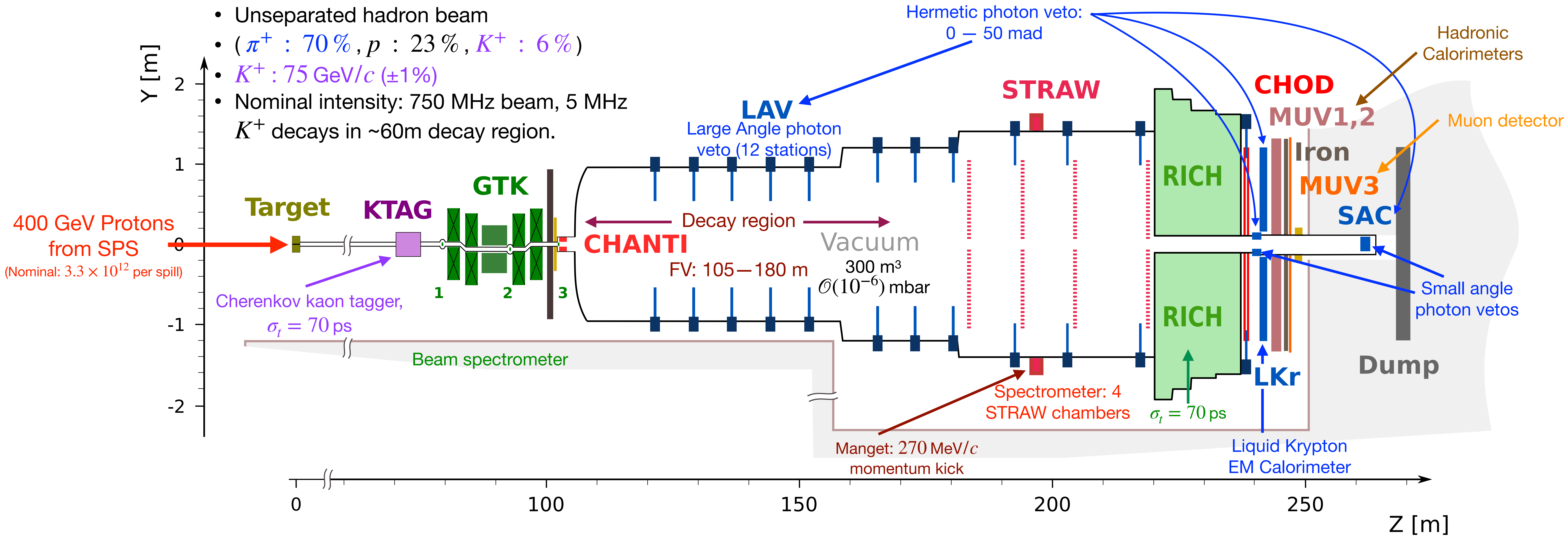
Continues long history of Kaon physics at CERN :

NA31	NA48	NA48/1	NA48/2	NA62-R_K	NA62 Run1	NA62 Run2
1986-98	1977—2001	2002	2003-4	2007-8	2016-18	2021—LS3
	Discovery of direct CVP					

NA62 Beamline & Detector

[JINST 12 (2017) 05, P05025]

- Unseparated hadron beam
- ($\pi^+ : 70\,\%$, $p : 23\,\%$, $K^+ : 6\,\%$)
- K^+ : 75 GeV/c (±1%)
- Nominal intensity: 750 MHz beam, 5 MHz K^+ decays in ~60m decay region.



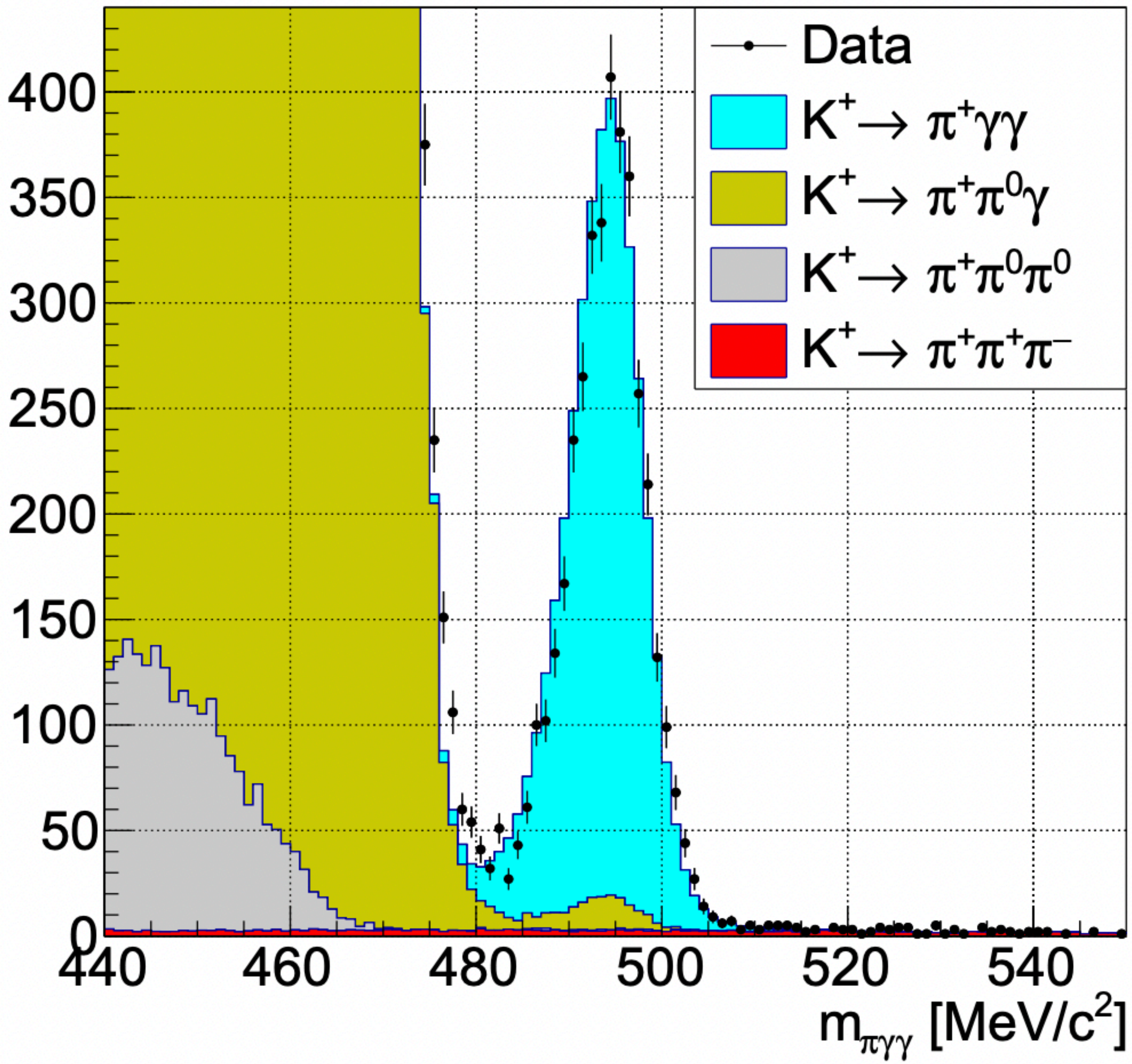
- Designed & optimised for study of $K^+ \to \pi^+ \nu \bar{\nu}$:
  - **Particle tracking:** beam particle (GTK) & downstream tracks (STRAW)
  - **PID:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
  - **Comprehensive veto systems:** CHANTI (beam interactions), LAV, IRC, SAC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

Precision study of $K^+ \to \pi^+\gamma\gamma$

[PLB 850 (2024) 138513]

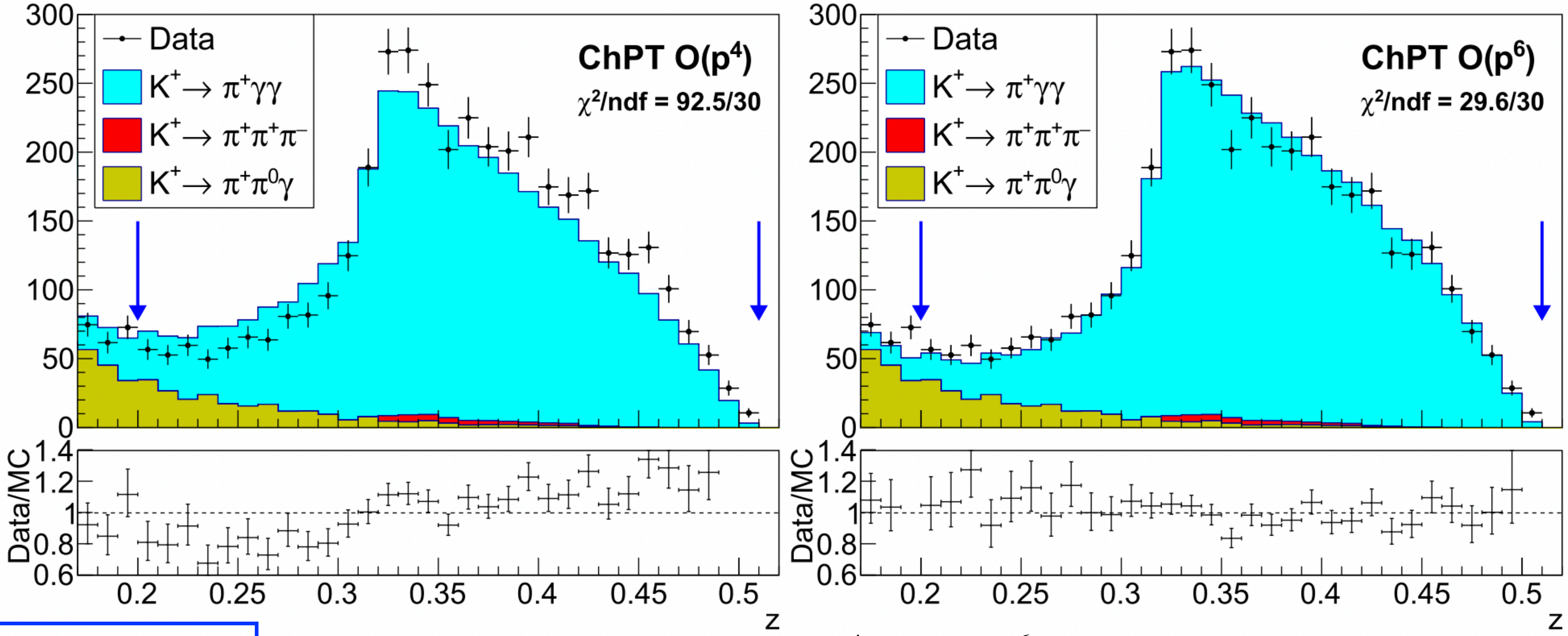
- Crucial test of **chiral perturbation theory (ChPT)**.
- Branching ratio $\mathscr{B}(K^+ \to \pi^+\gamma\gamma)$ is parameterised in ChPT by an **unknown real parameter** $\hat{c}$.
  - External inputs [PLB 835 (2022) 137594] for $\mathcal{O}(p^6)$.
- Signal selection:
  - positive track identified as π^+, match with K^+ and 2γ in LKr.
  - Kinematic constraints on **invariant mass** $m_{\pi\gamma\gamma}$ and **total momentum** $p_{\pi\gamma\gamma}$.
  - **Main kinematic variable:** $z = \dfrac{(P_K - P_\pi)^2}{m_K^2} = \dfrac{m_{\gamma\gamma}^2}{m_K^2}$.

    Select range $0.20 < z < 0.51$ signal $(0.04 < z < 0.12$ norm.$)$.
- Main background: $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma\gamma$ with photon cluster margining in LKr.



$K^+ \to \pi^+\gamma\gamma$ ChPT $\hat{c}$ results

[PLB 850 (2024) 138513]



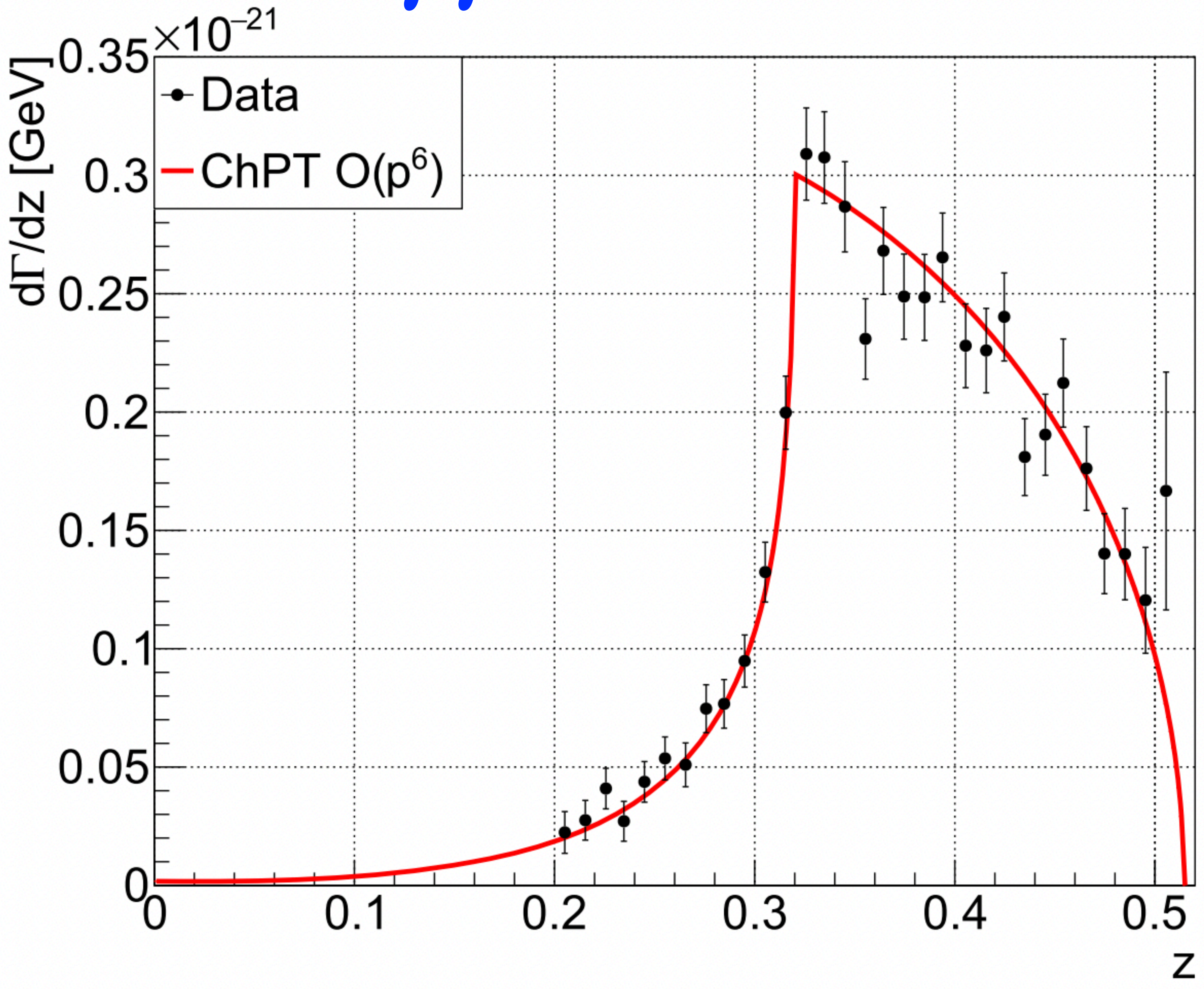
$N_{obs} = 3984$

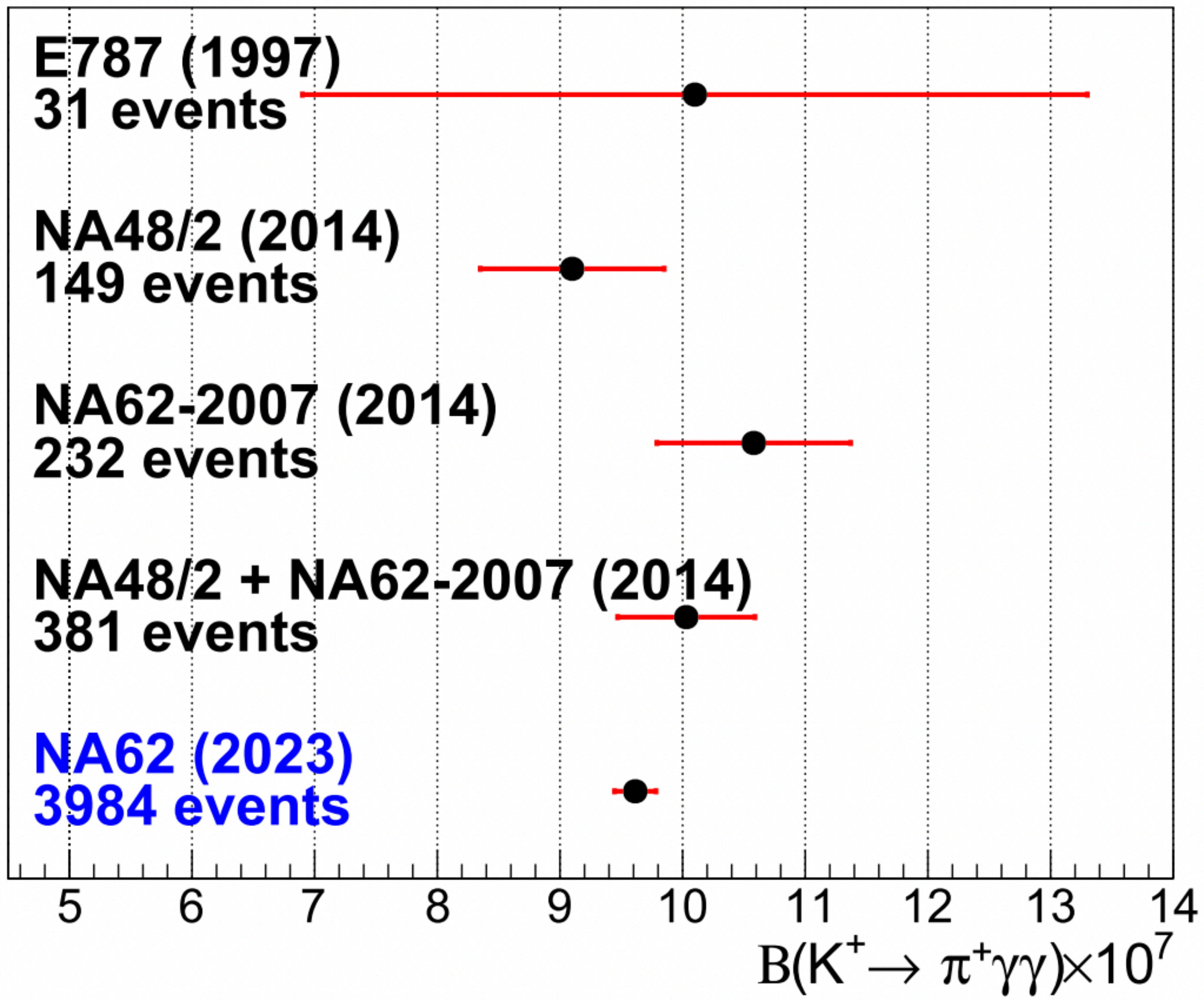
$N_{bg}^{exp} = 291 \pm 14$

- Parameter $\hat{c}$ measured in ChPT $\mathcal{O}(p^4)$ and $\mathcal{O}(p^6)$ descriptions by reweighing $K^+ \to \pi^+\gamma\gamma$ MC and performing a minimum-χ^2 fit:
  - ChiPT $\mathcal{O}(p^4)$ p-value = 2.7×10^{-8} : cannot describe di-photon mass (z) distribution.
  - ChiPT $\mathcal{O}(p^6)$ p-value = 0.49 : $\hat{c} = 1.144 \pm 0.069_{\text{stat}} \pm 0.034_{\text{syst}}$

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

[PLB 850 (2024) 138513]





$N_{obs} = 3984$

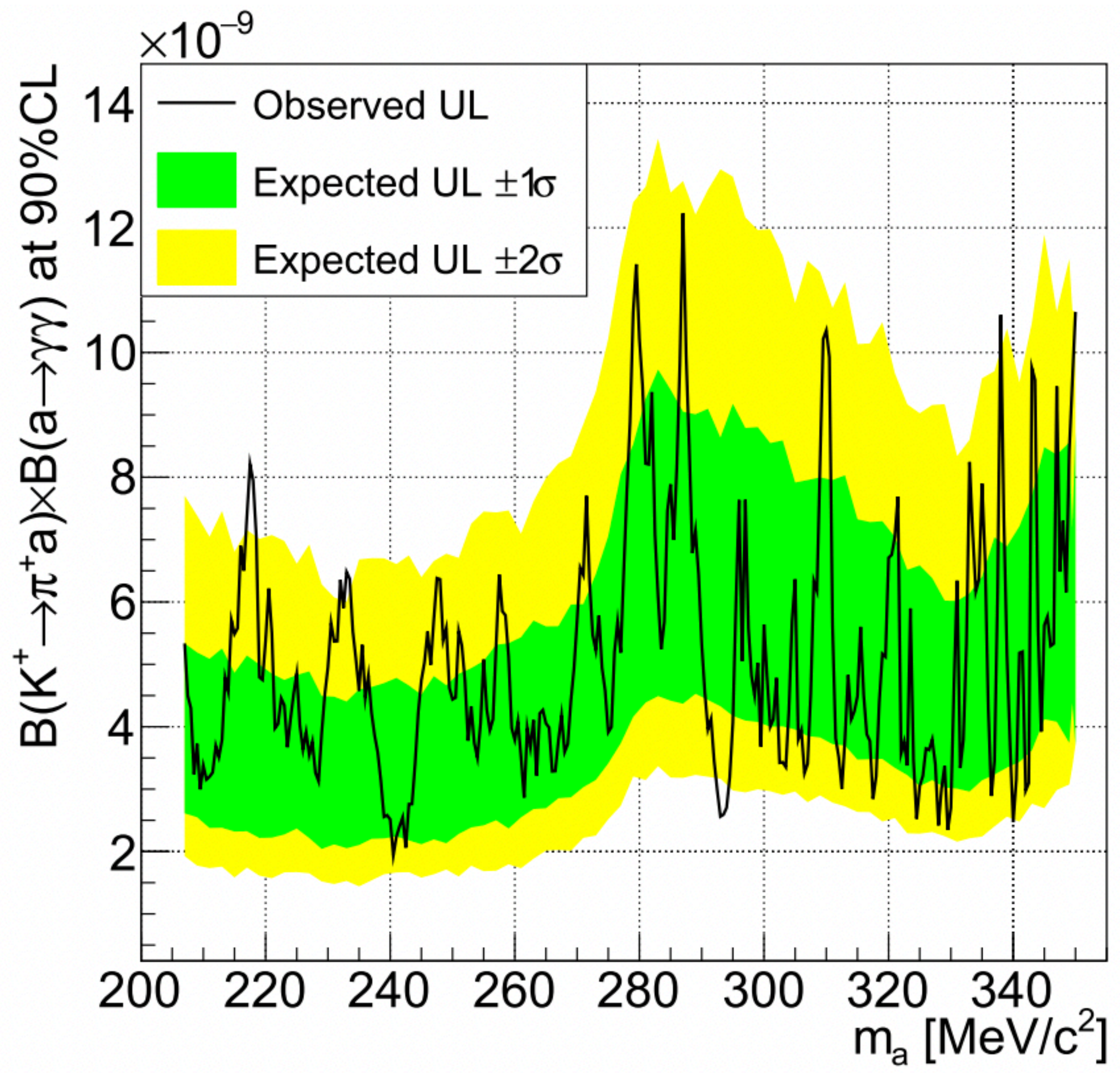
$N_{bg}^{exp} = 291 \pm 14$

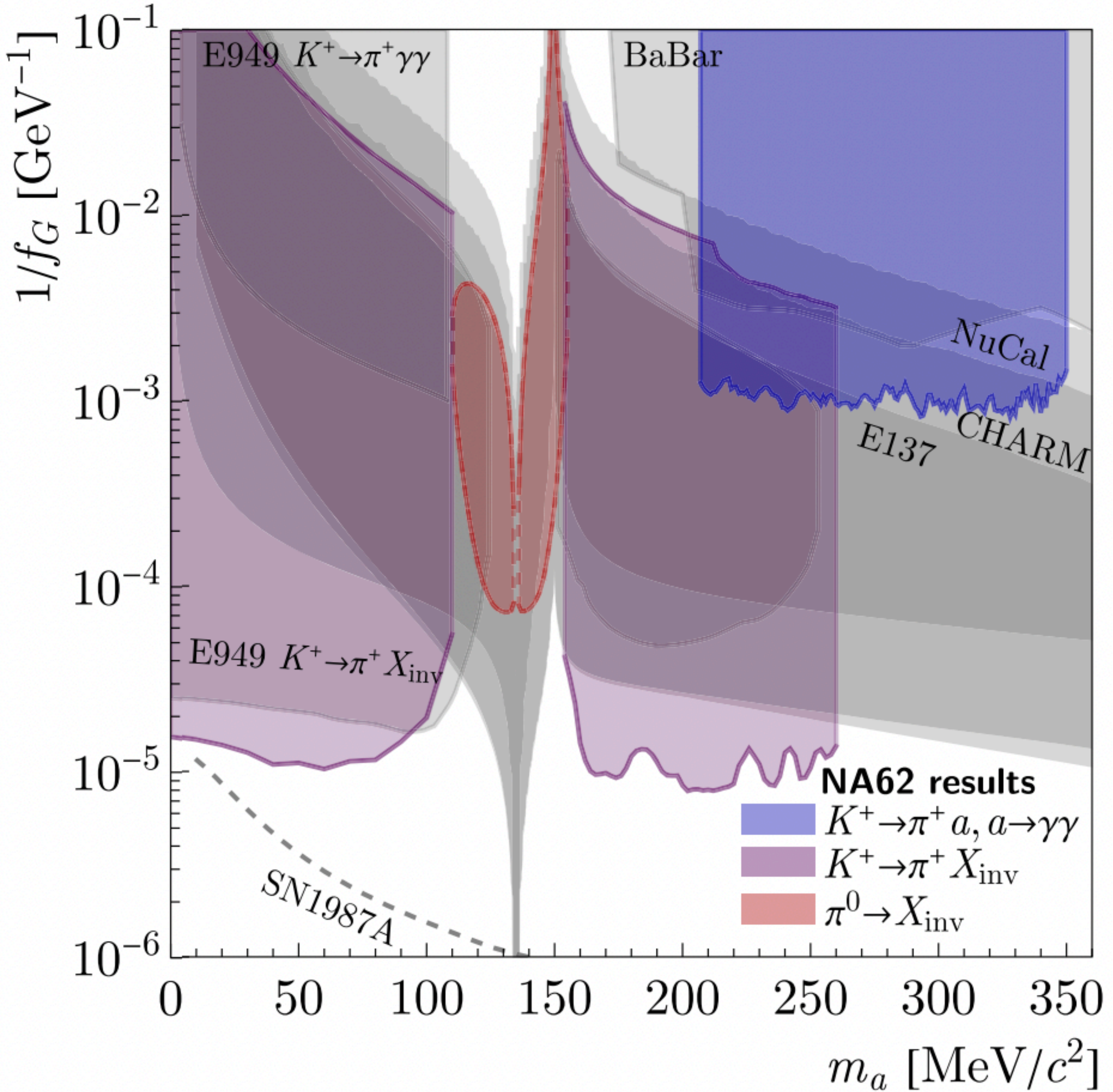
- ChiPT $\mathcal{O}(p^6)$ description: Fit p-value = 0.49 : $\hat{c} = 1.144 \pm 0.069_{\text{stat}} \pm 0.034_{\text{syst}}$
  - $\mathcal{B}(K^+ \to \pi^+\gamma\gamma, \text{ChPT}\,\mathcal{O}(p^6)) = (9.61 \pm 0.15_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-7}$
- Model independent BR measurement:
  - $\mathcal{B}(K^+ \to \pi^+\gamma\gamma, z > 0.2) = (9.46 \pm 0.19_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-7}$

Search for ALP in $K^+ \to \pi^+ a, a \to \gamma\gamma$ decays

[PLB 850 (2024) 138513]

- Peak search in $m_a = \sqrt{(P_K - P_\pi)^2}$ $(207 - 350\,\text{MeV}/c^2)$ in steps of $0.5\,\text{MeV}/c^2$ [m_a resolution from $2.0 - 0.2\,\text{MeV}/c^2$ across search range].
- For each m_a hypothesis background estimated with simulation and UL on number of signal events established with CL_S method.
- Gives first limits on $\mathscr{B}(K^+ \to \pi^+ a)$ for ALP decaying promptly as $a \to \gamma\gamma$, and limits on coupling strength $f_G^{-1} \sim \tau_a^{-0.5}$ in the BC11 FIPs benchmark scenario.





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

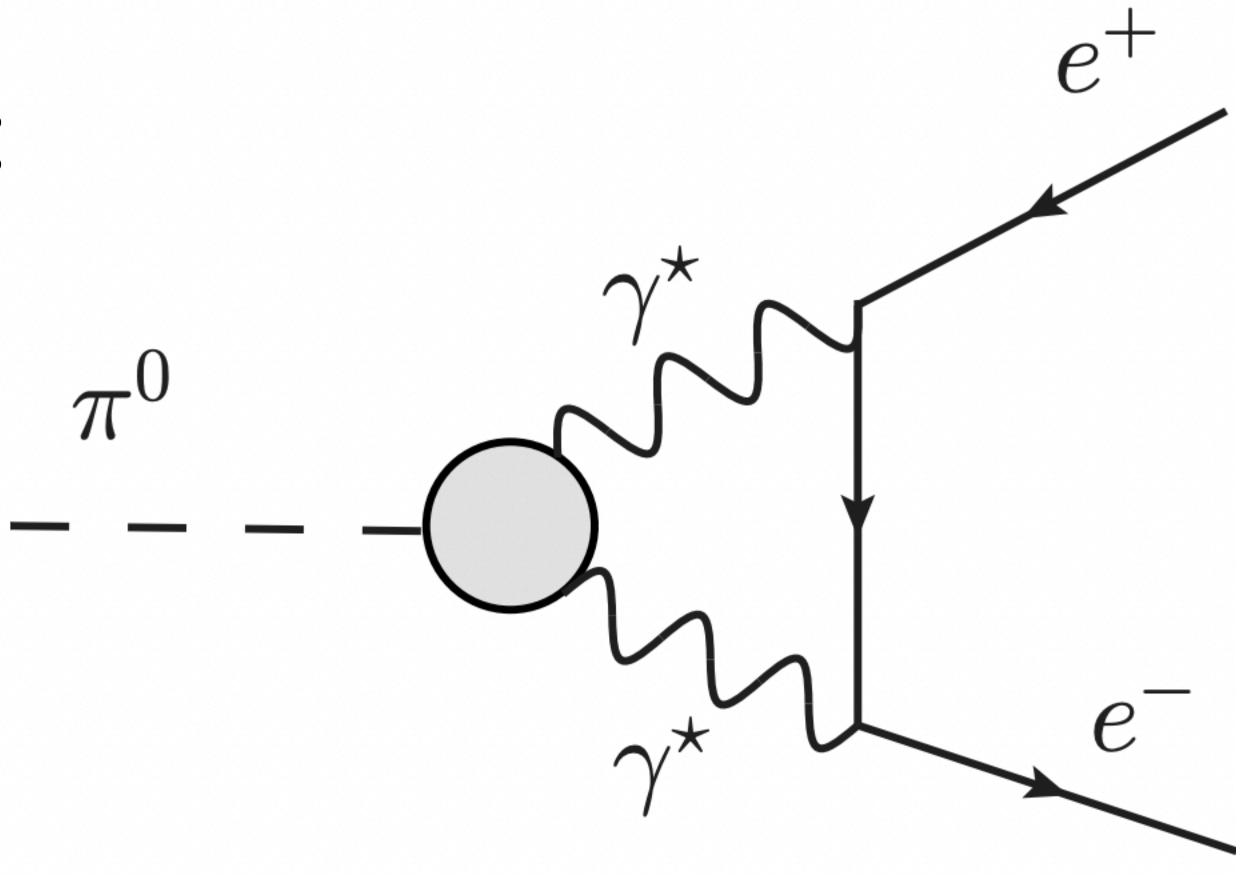
[new: spring 2024]

NA62

- Experimentally observable BR: $\mathscr{B}(\pi^0 \to e^+e^-(\gamma), x > x_{cut})$ where $x = m_{ee}^2/m_{\pi^0}^2$.
  - Dalitz decay $\pi^0 \to e^+e^-\gamma$ dominates for low x.
  - For $x > 0.95$, Dalitz Decay $\approx 3.3\,\%$ of decay rate.
- Previous best measurement from KTeV experiment [Phys.Rev.D 75 (2007) 012004] $\mathscr{B}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (6.44 \pm 0.25_{\text{stat}} \pm 0.22_{\text{syst}}) \times 10^{-8}$.
- 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)

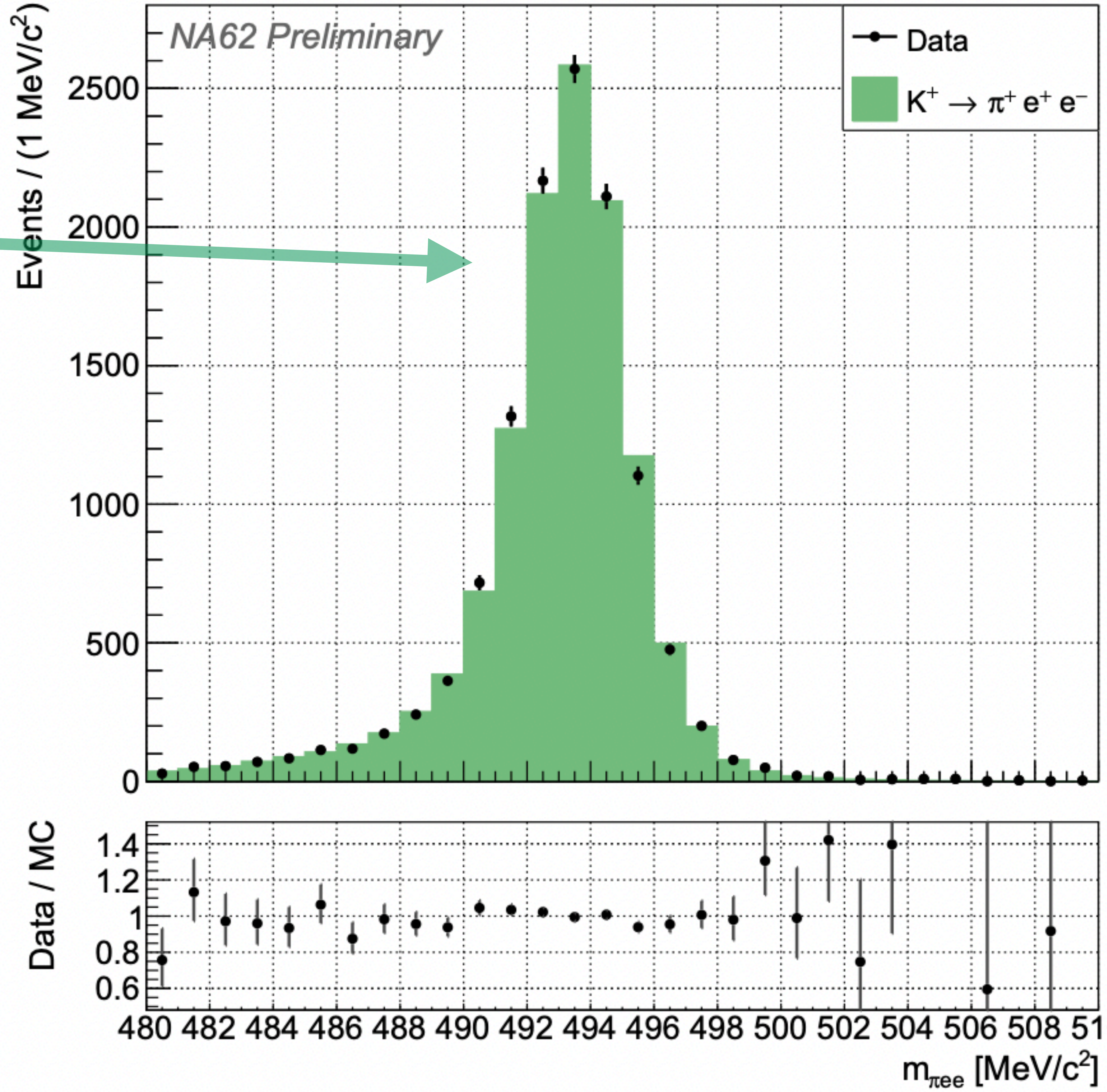
- Diagram for $\pi^0 \to e^+e^-$:
  - considered in theoretical predictions, with various $\pi^0 \to \gamma^*\gamma^*$ transition form factors



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

[new: spring 2024]

- NA62 **Data collected in 2017+2018** & using **simulations with the latest radiative corrections included.**
- **Normalisation:** $K^+ \to \pi^+ e^+ e^-$
  - [select ~background-free for $m_{ee} > 140\,\text{MeV}/c^2$]
  - Identical final state, common selection criteria → cancellation of systematics.
- **Multi-track electron trigger line** used to collect **both** signal & normalisation.
  - Level 0 (hardware) : RICH(timing), CHOD(>2 charged tracks), LKr(>30 GeV)
  - Level 1 (software) : KTAG(tag K+), STRAW(charged tracks forming vertex)
  - Downscaling factor $D_{eMT} = 8$.
  - Overall trigger efficiency $\approx 90\,\%$ for **both** signal & normalisation.



$A_{\pi ee} = (4.70 \pm 0.01_{\text{stat}})\,\%$

$N_{\pi ee} = 12160$ Purity $> 99.9\,\%$

Effective number of kaon decays: $N_K = (8.62 \pm 0.08_{\text{stat}} \pm 0.26_{\text{ext}}) \times 10^{11}$

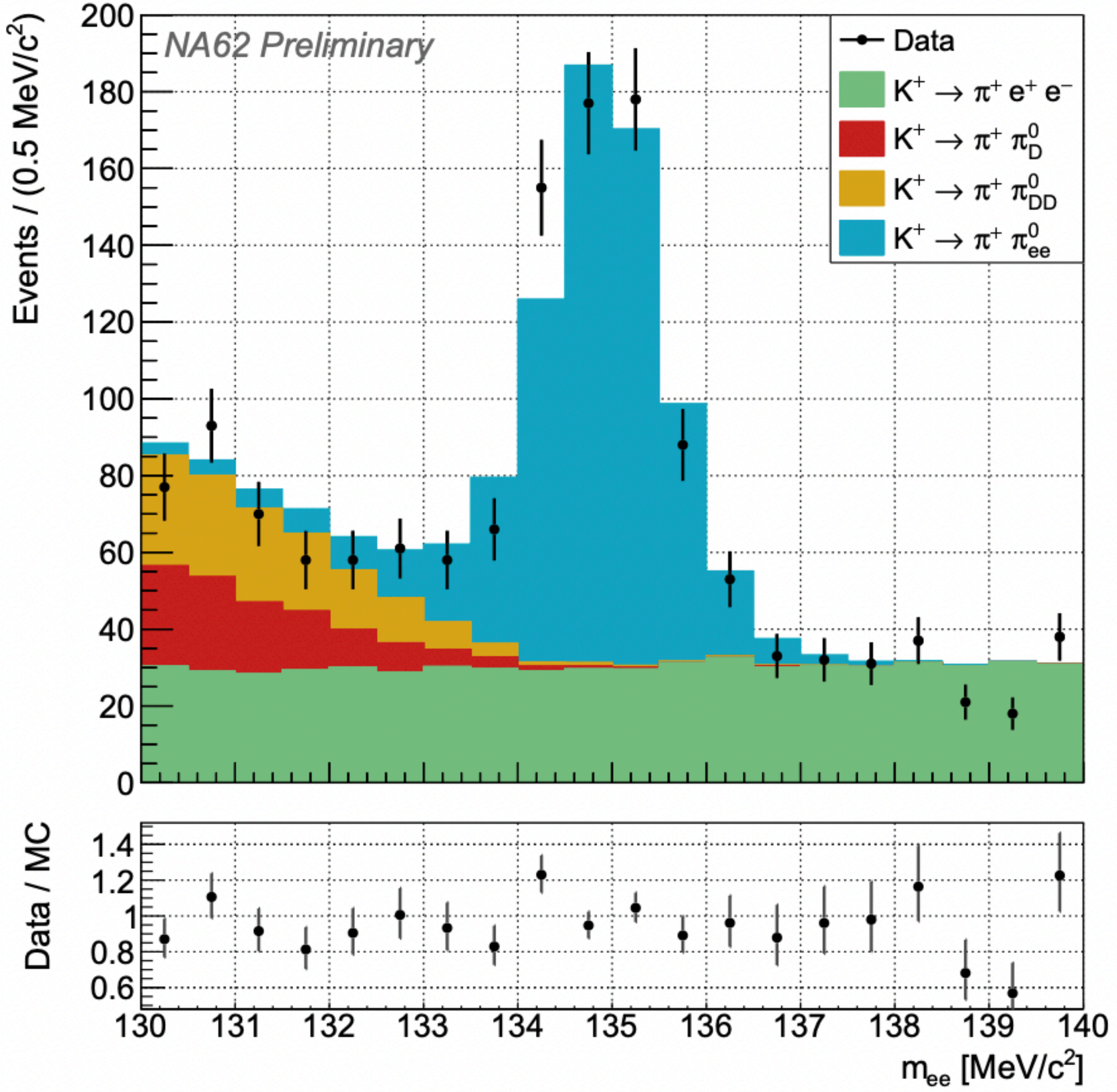
External uncertainty from norm. BR: $\mathscr{B}(K^+ \to \pi^+ e^+ e^-) = (3.00 \pm 0.09) \times 10^7$

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

[new: spring 2024]

Backgrounds:

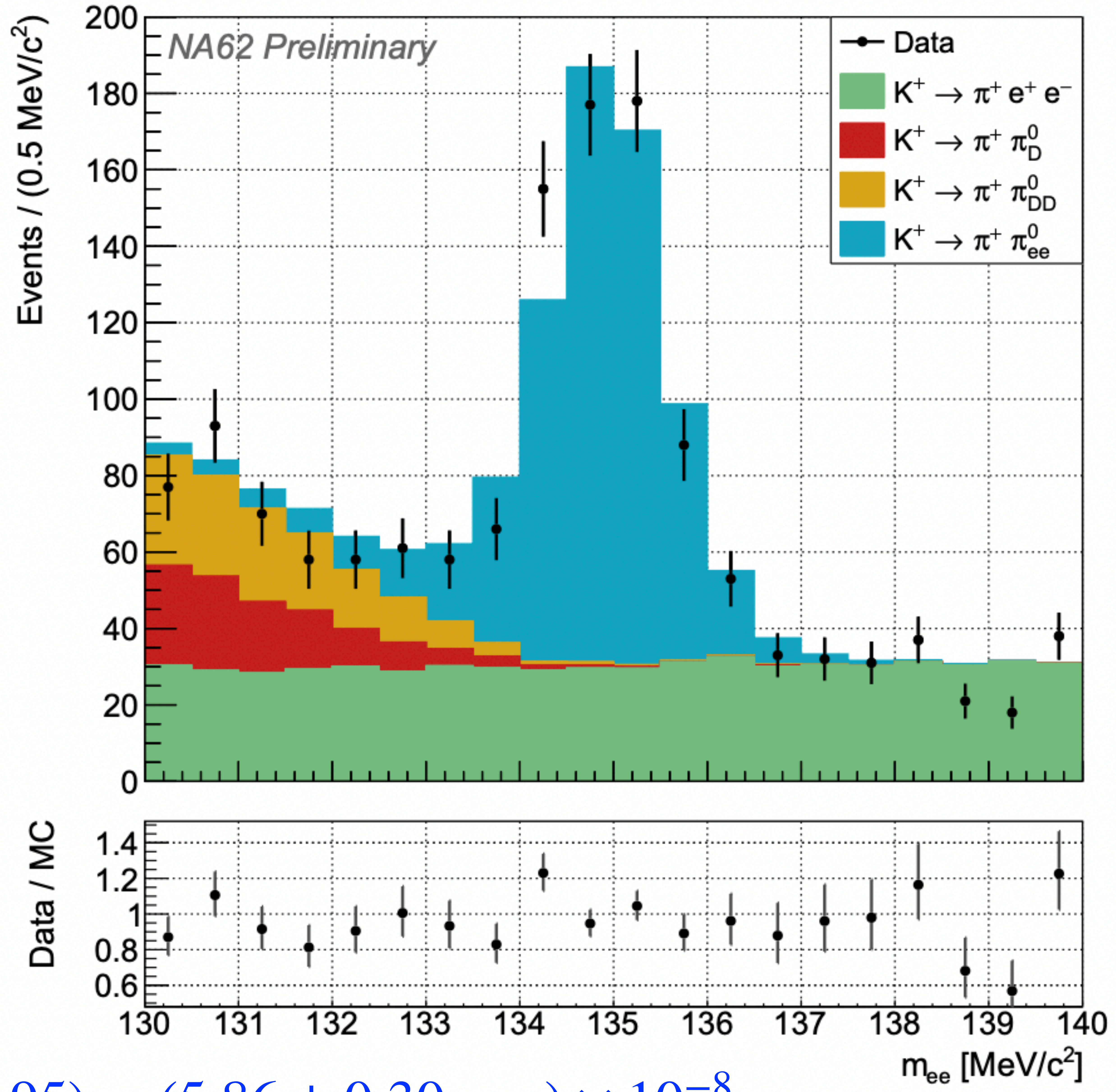
- $K^+ \to \pi^+e^+e^-$: irreducible, flat in signal region $m_{ee} \approx m_{\pi^0}$
- $K^+ \to \pi^+\pi^0,\ \pi^0 \to e^+e^-\gamma \equiv K^+ \to \pi^+\pi^0_D$:
  - a) π^0 Dalitz decay distribution with large-x tail.
  - b) Photon conversion in STRAW ($\gamma \to e^+e^-$) + selection of a produced $e^\pm$.
    - Suppress using STRAW hit information, building 'track segments' pointing to vertex
- $K^+ \to \pi^+\pi^0,\ \pi^0 \to e^+e^-e^+e^- \equiv K^+ \to \pi^+\pi^0_{DD}$: double Dalitz decay with an undetected e^+e^-.



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

[new: spring 2024]

- Fit for signal extraction: $m_{ee} \in (130,140)\text{MeV}/c^2$
- Signal acceptance (for $x_{\text{true}} > 0.95$) $A(K^+ \to \pi^+\pi^0_{ee}) = (5.72 \pm 0.02_{\text{stat}})\ \%$
- Perform maximum likelihood fit of simulated samples to data:
  - Fitted signal event yield : 597 ± 29
  - $\chi^2/\text{ndf} = 25.3/19$, p-value = 0.152.
  - {BR of other decays: external input from PDG}



BR from fit

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

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

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

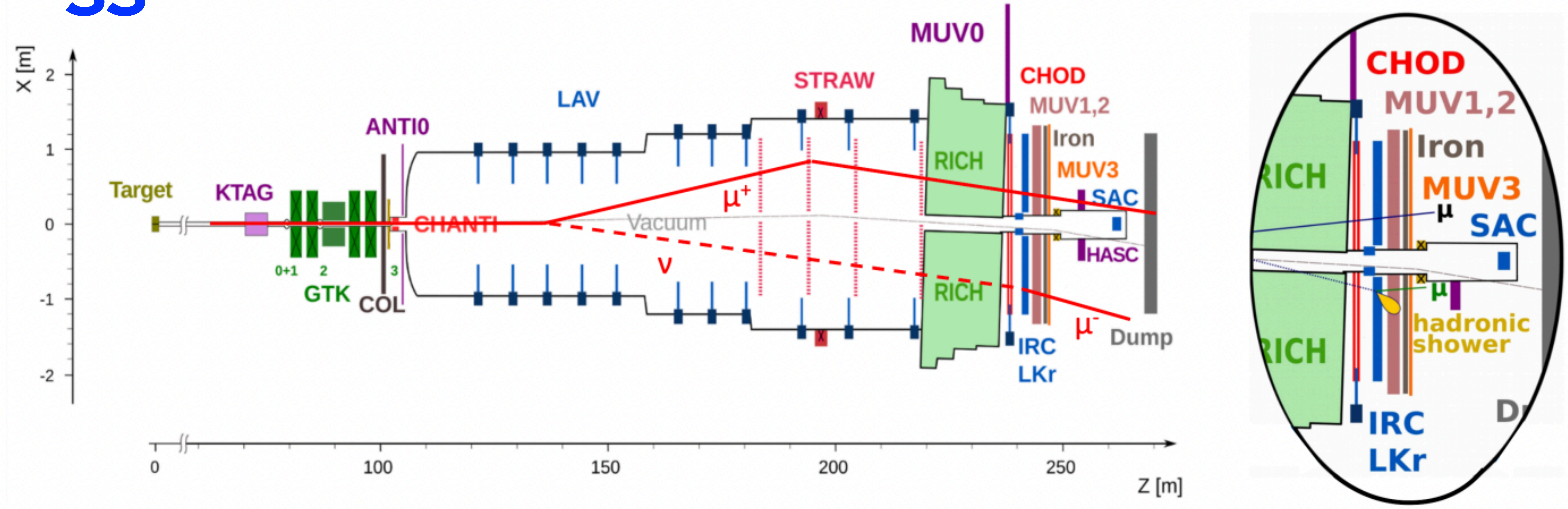
- Large external uncertainty from $\mathcal{B}(K^+ \to \pi^+e^+e^-)$, measured by NA48/2 and E865. New analysis for this mode planned at NA62.
- Strong prospects for the future with optimised multi-track electron trigger line with reduced downscaling, collecting a large di-electron final states sample.

	$\delta\mathcal{B}$ [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

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

Tagged neutrinos at NA62

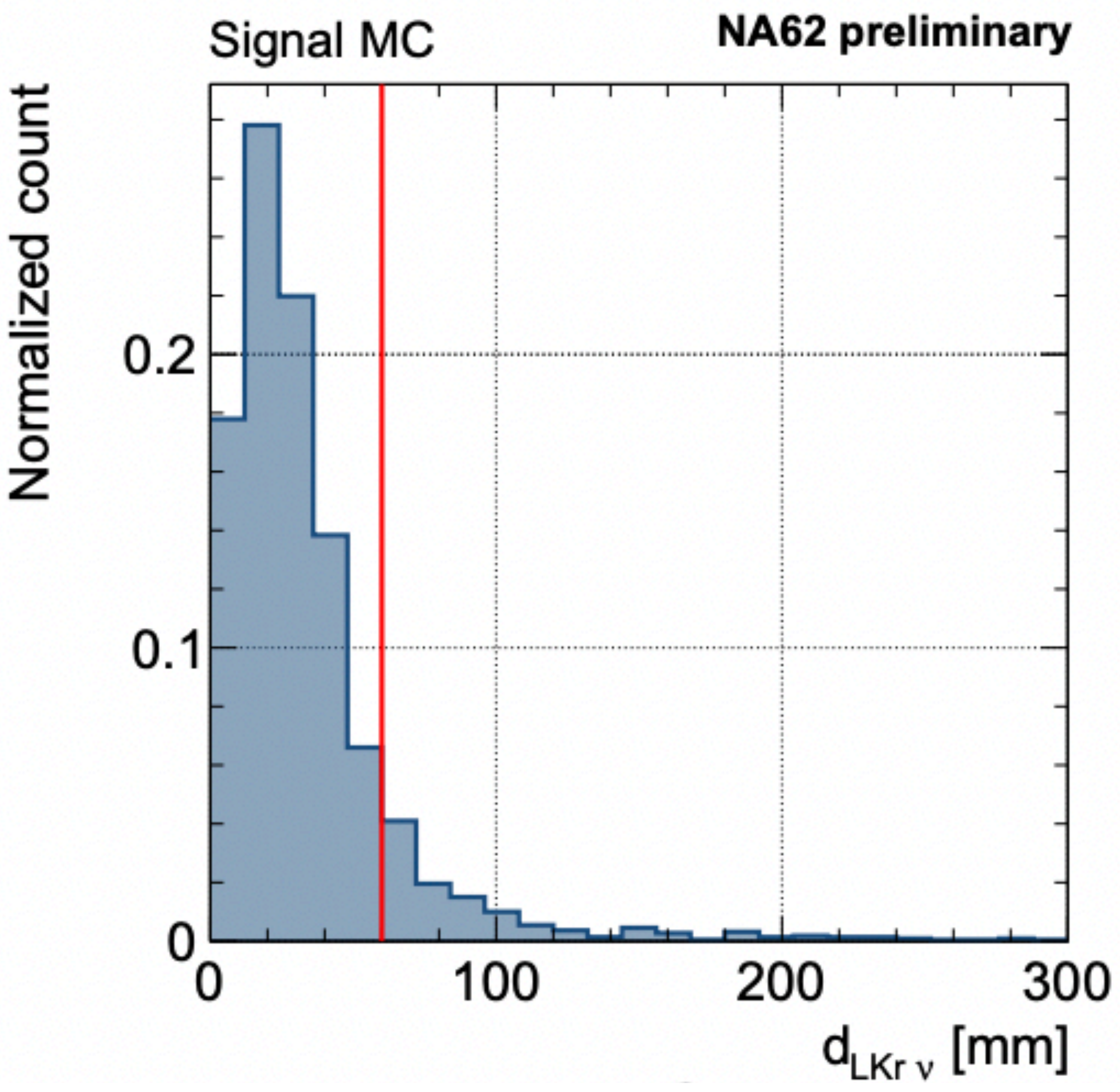
[De Martino, NuFact23]

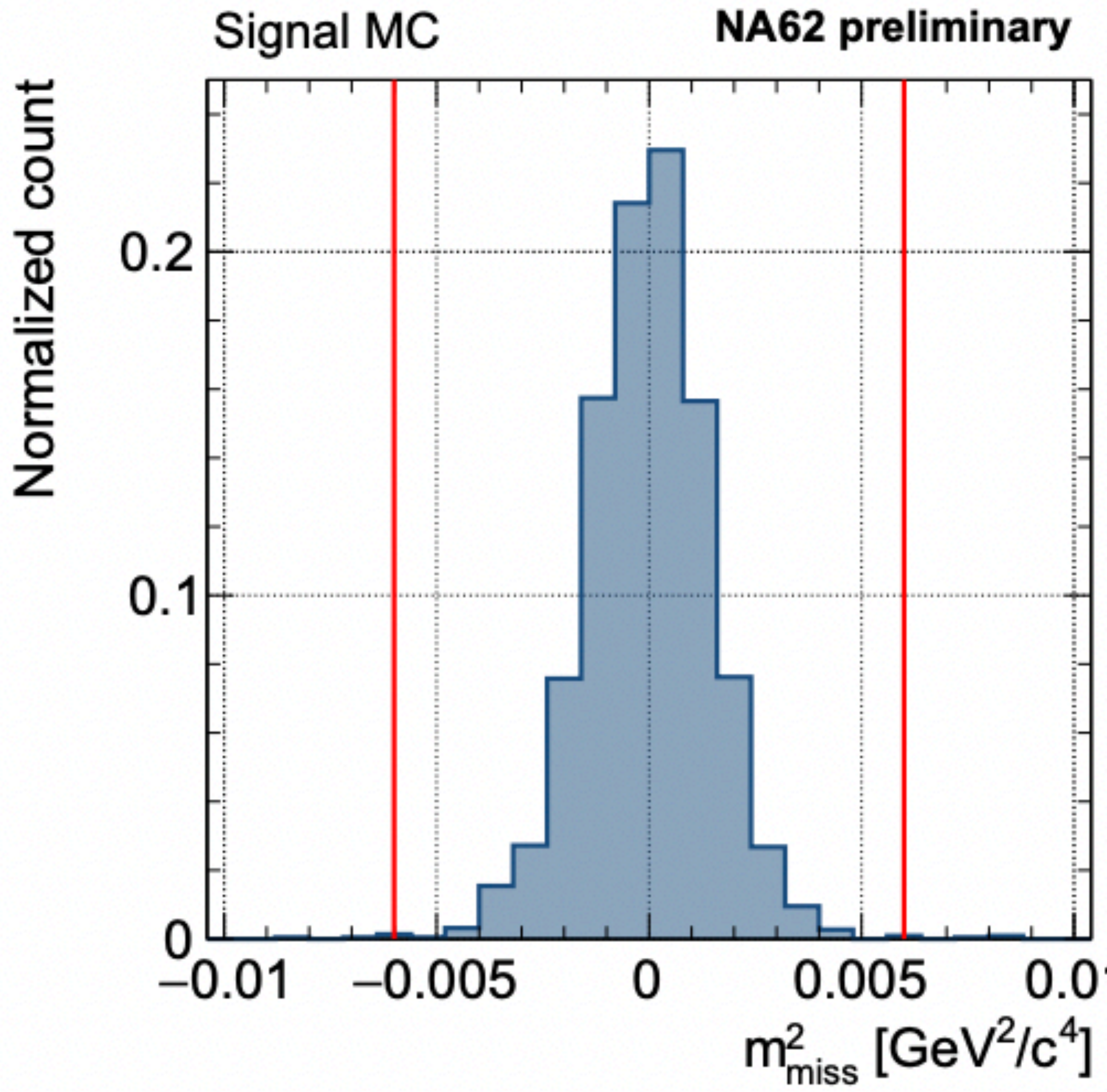


- Goal: search for $K^+ \to \mu^+ \nu_\mu$ with:
  - K^+ and μ^+ detected by GTK and STRAW trackers as usual.
  - ν_μ interacting in LKr calorimeter (20 tons of Liquid Kr, MUV12 66ton HCAL)
- ν_μ Interaction probability $\mathcal{O}(10^{-11})$: CC-DIS $\nu_\mu \to \mu^- +$ shower
  - Trigger based on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

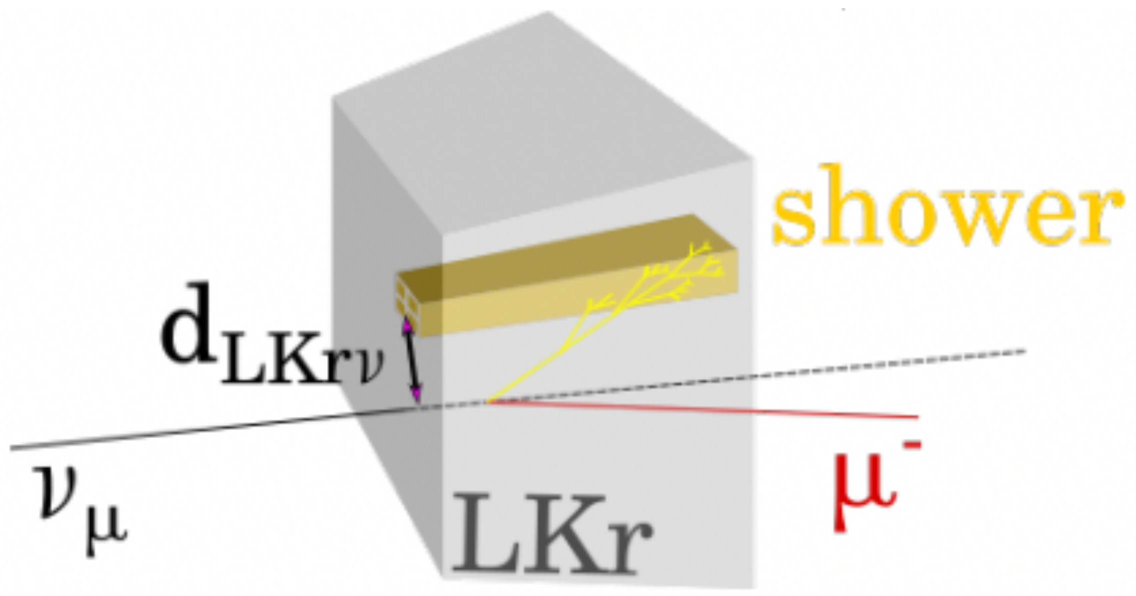
Tagged neutrinos at NA62: strategy

[De Martino, NuFact23]





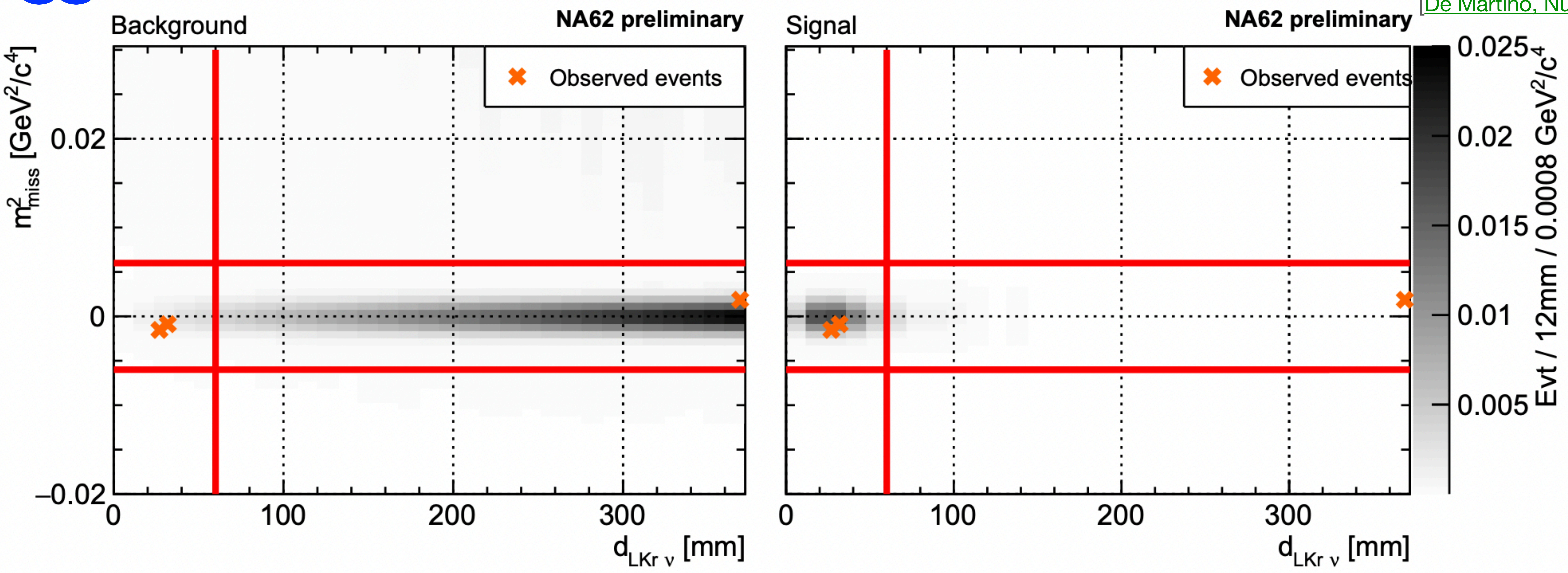
- Blind analysis, using **2022 data.**
- Signal region : $|d_{LKr}| < 60\,\text{mm}$, $|m^2_{miss}| = |(P_K - P_\mu)^2| < 0.006\,\text{GeV}^2/c^4$
- Sudy backgrounds using data-driven methods using side-bands:
  - $K^+ \to \mu^+\nu$ + extra in-time activity (side-bands of d_{LKr}).
  - Mis-reconstructed K^+ decays (sidebands of m^2_{miss}).



- Normalise to $K^+ \to \mu^+\nu$ (no interaction) : $N_K = \dfrac{N_{norm}}{\varepsilon_{norm}\mathscr{B}(K^+ \to \mu^+\nu)}$
- $N^{signal}_{exp} = N_K\mathscr{B}(K^+ \to \mu^+\nu)P_{int,Lkr}\varepsilon_{signal} = N_{norm}\dfrac{\varepsilon_{signal}}{\varepsilon_{norm}}P_{int,LKr}$
- Evaluate signal efficiency with MC (GENIE)
- Results: $P_{int,LKr} = (6.0 \pm 0.1_{syst}) \times 10^{-11}$, $\varepsilon_{signal} = (2.55 \pm 0.15_{stat} \pm 0.04_{syst})\,\%$: $N^{exp}_{signal} = 0.228 \pm 0.014_{stat} \pm 0.011_{syst}$

Tagged neutrinos at NA62: Results

[De Martino, NuFact23]

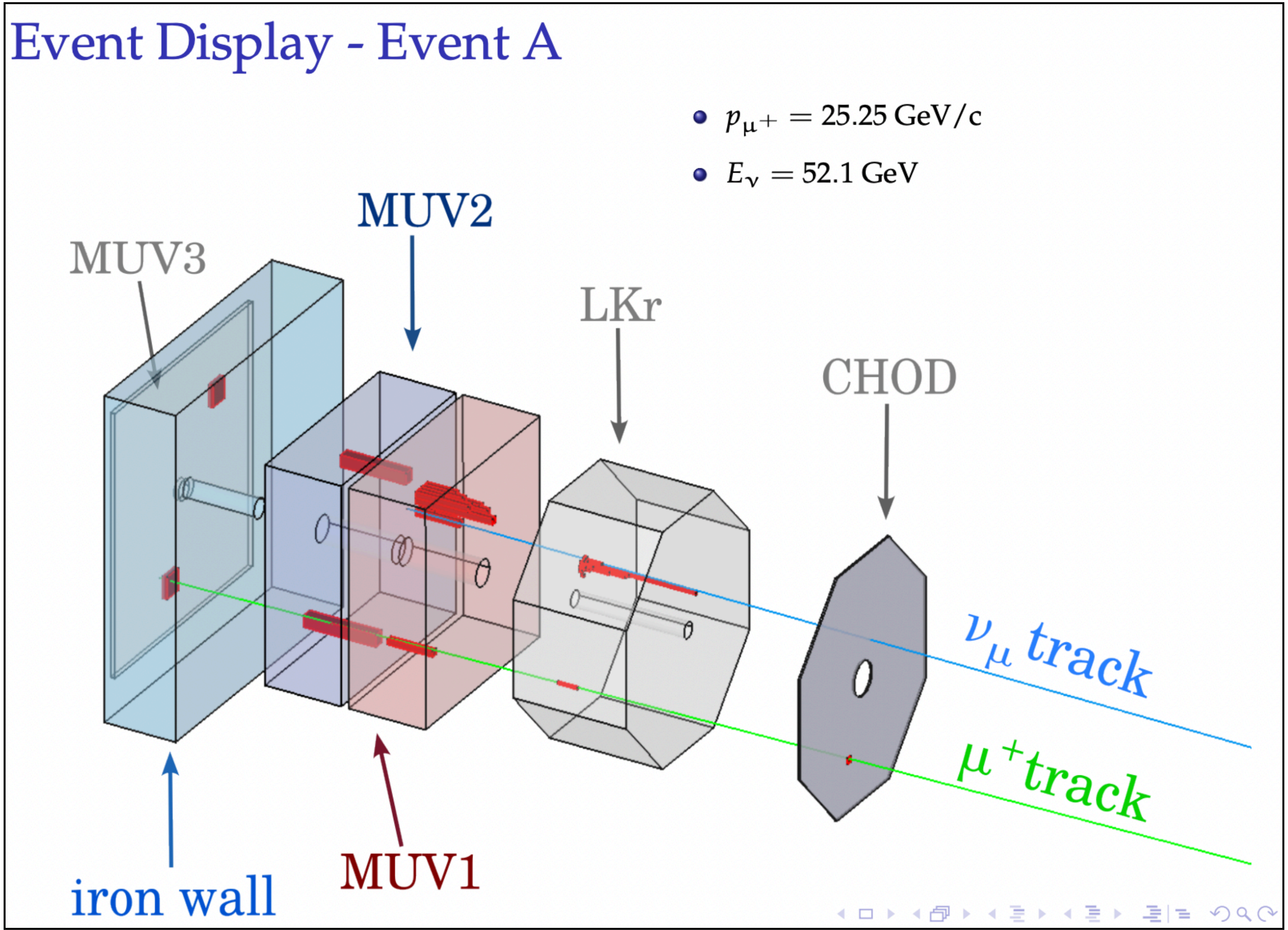


- $N^{exp}_{signal} = 0.228 \pm 0.014_{\text{stat}} \pm 0.011_{\text{syst}}$
- Backgrounds:
  - N^{exp}_{bg}(mis-reco K^+) $= 0.0014 \pm 0.0007_{\text{stat}} \pm 0.0002_{\text{syst}}$
  - N^{exp}_{bg}(pileup + $K^+ \to \mu^+\nu$) $= 0.04 \pm 0.02_{\text{stat}} \pm 0.01_{\text{syst}}$

- Observe 2 events in signal regions.
  - (+1 in background sideband)
- Detect full event : $K^+ \to \mu^+\nu$, tagging the neutrino!

Tagged neutrinos at NA62: Results

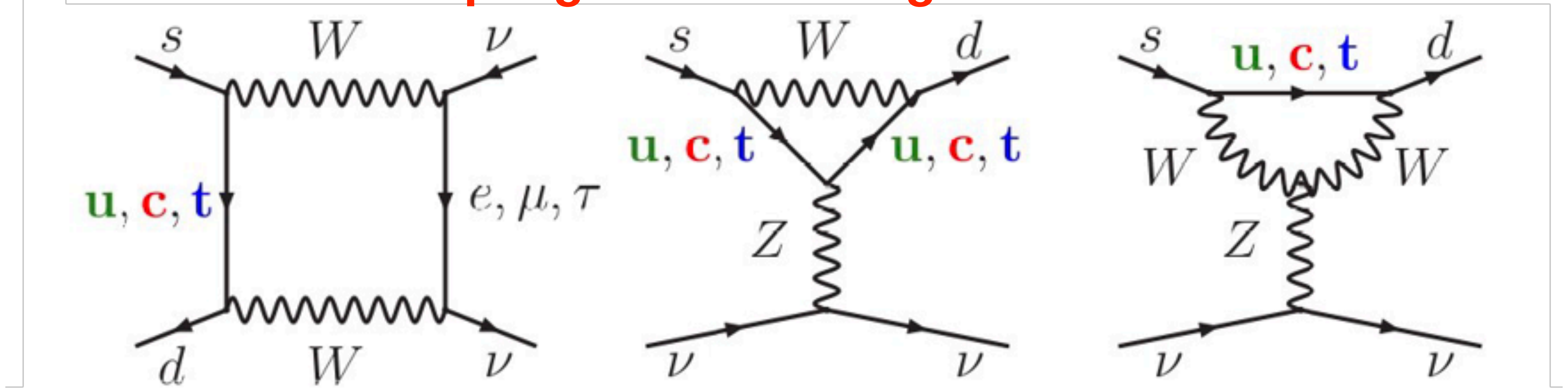
[De Martino, NuFact23]

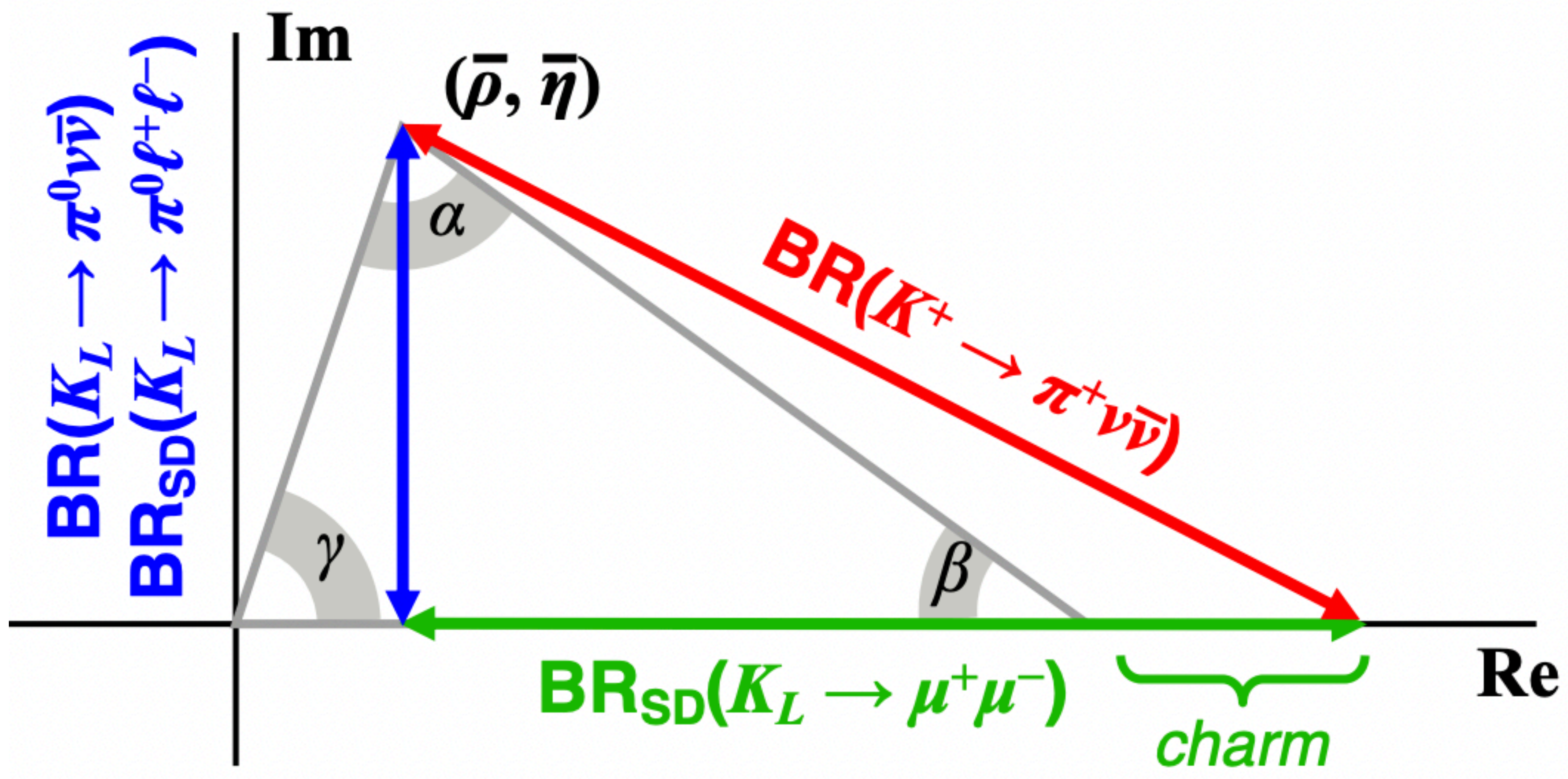


Golden Modes: $K \to \pi\nu\bar{\nu}$

$K \to \pi\nu\bar{\nu}$: 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: $\sim \frac{m_t}{m_W} \left| V_{ts}^* V_{td} \right|$
- 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.
- High sensitivity to new physics: unique flavour physics probe to reach a model independent $\mathcal{O}(100)$ TeV mass scale
  - BR predictions modified by $\mathcal{O}(50\%)$ in multiple BSM scenarios (Z', little higgs, Randall-Sundrum, non-MFV MSSM, LFUV leptoquark…)

Mode	SM Branching Ratio	Experimental Status
$K^+ \to \pi^+\nu\bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$	$(10.6 \pm 4.0) \times 10^{-11}$ NA62 Run1
$K_L \to \pi^0\nu\bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$	$< 300 \times 10^{-11}$ KOTO (2015 data)

^Recent SM calculations [Buras & Venurini, Acta Phys.Polon.B 53 6, A1][arXiv:2205.01118]

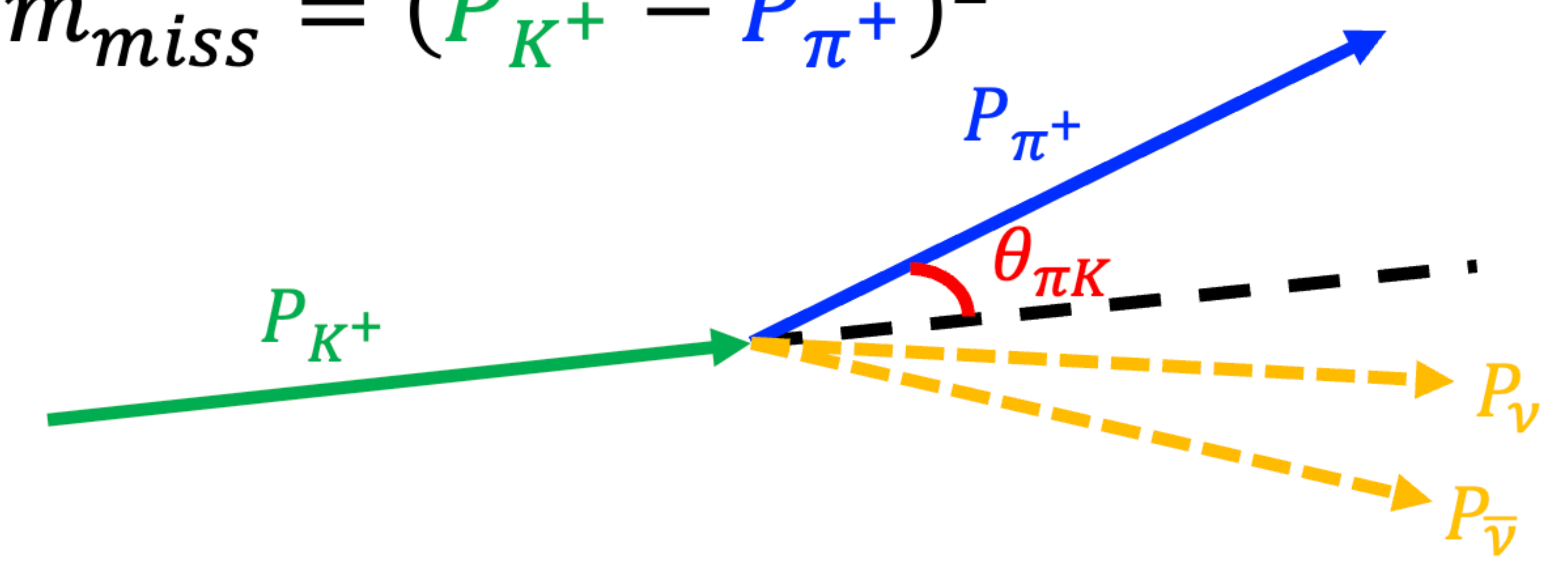
$K^+ \to \pi^+\nu\bar{\nu}$ at NA62

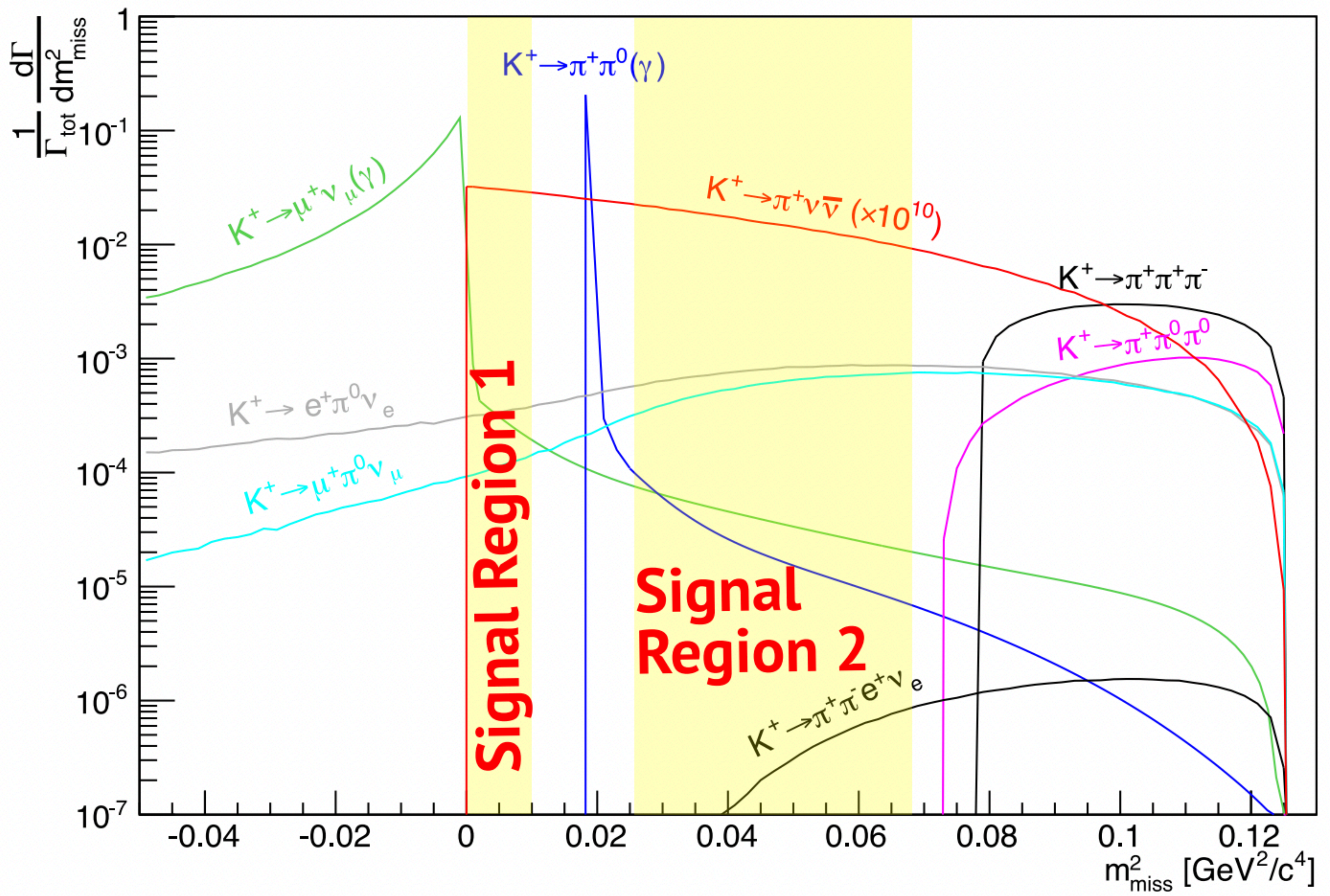
NA62 Performance Keystones:

- $\mathcal{O}(100)\,ps$ 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

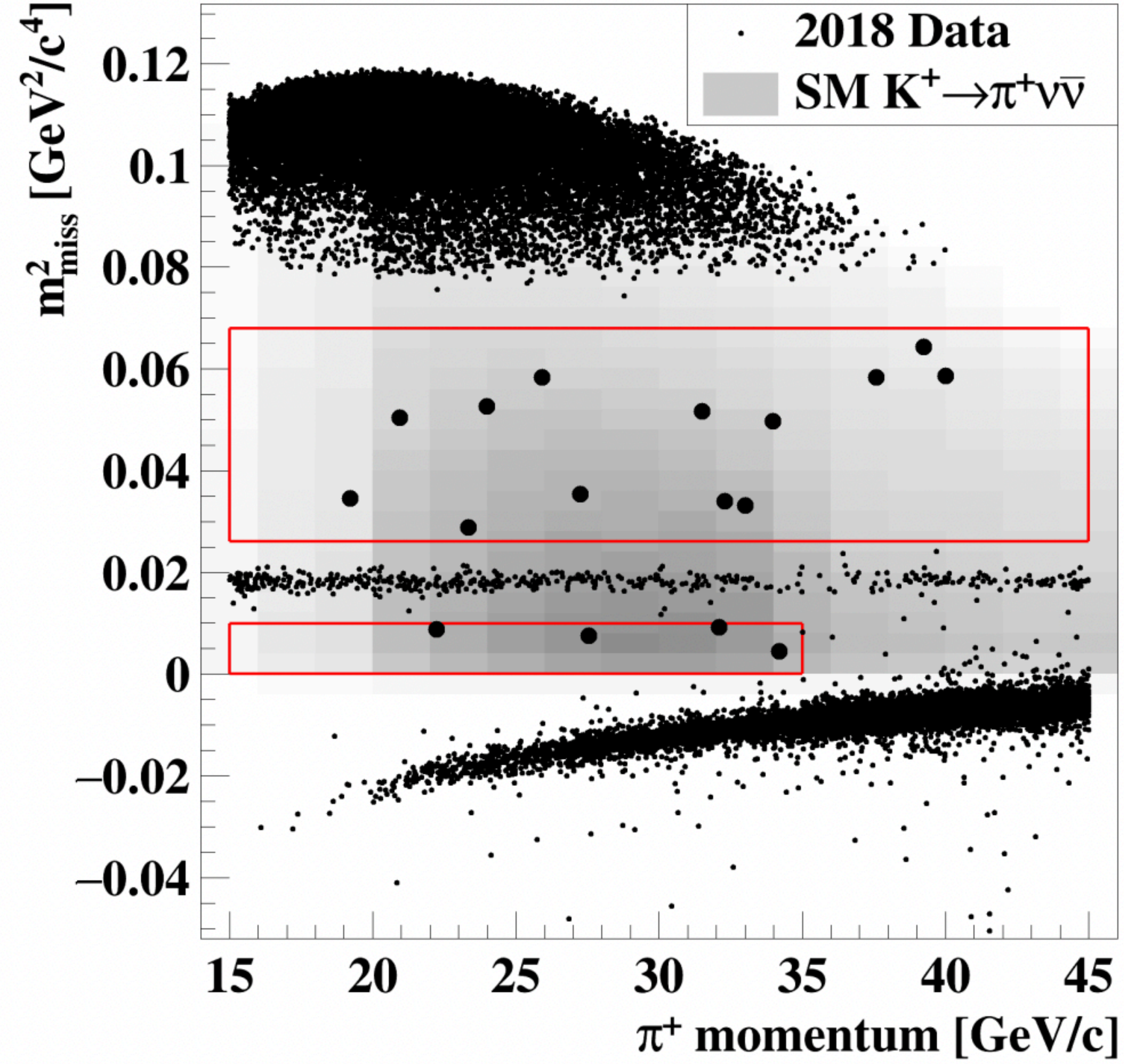
Process	Branching Ratio [PDG]
$K^+ \to \mu^+\nu_\mu$	$(63.56 \pm 0.11)\,\%$
$K^+ \to \pi^+\pi^0$	$(20.67 \pm 0.08)\,\%$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024)\,\%$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$
$K^+ \to \pi^+\nu\bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$ [SM]

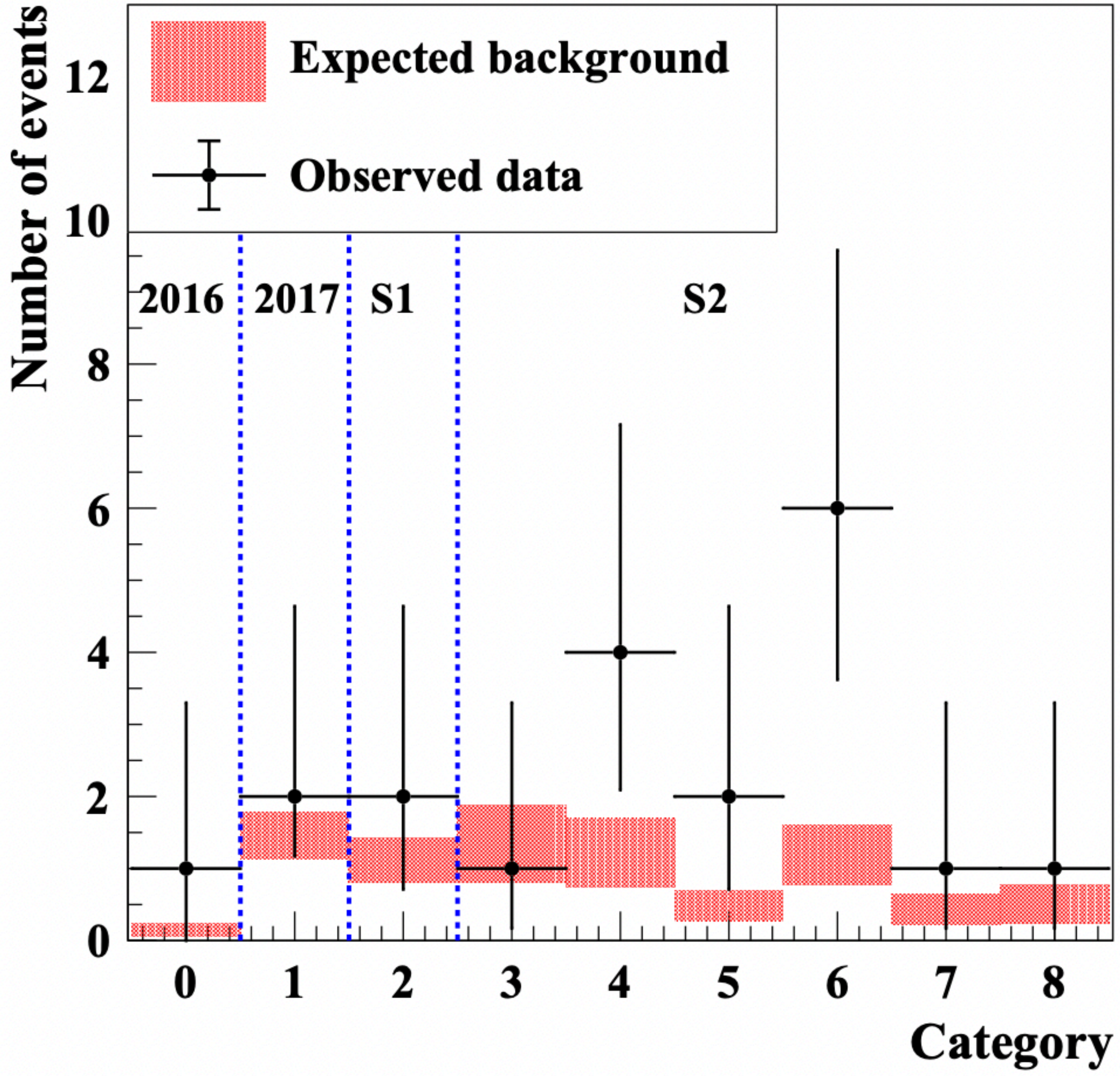
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$





Run1 (2016–18) $K^+ \to \pi^+ \nu \bar{\nu}$ Results:





- $N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$, $N^{exp}_{bkg.} = 7.03^{+1.05}_{-0.82}$: $n_{obs} = 20$
- In background-only hypothesis: $p = 3.4 \times 10^{-4}$ ⇒ signal significance: 3.4σ.
- $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-11}$ @ 68 % CL [JHEP 06 (2021) 093]

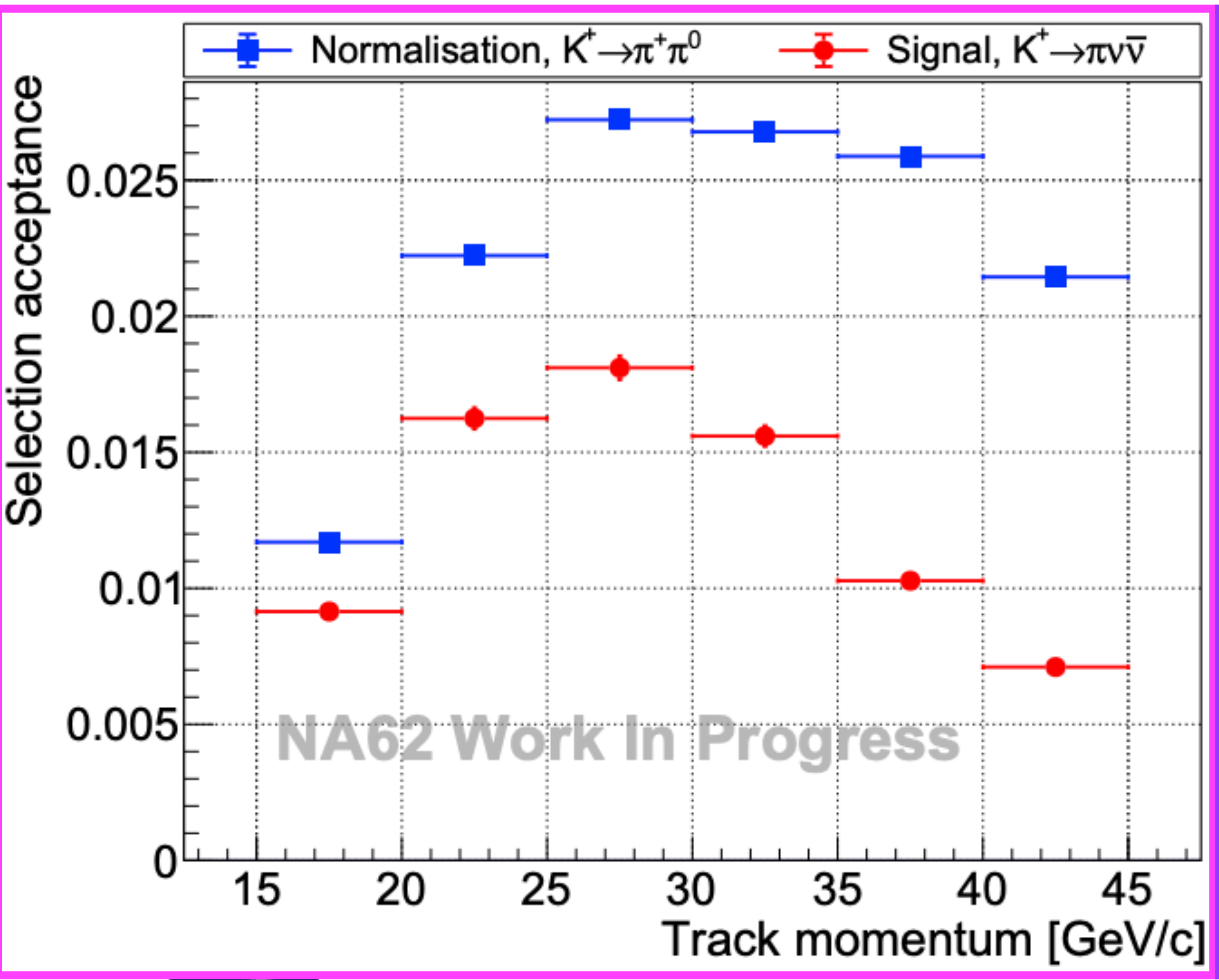
$K^+ \to \pi^+\nu\bar{\nu}$ with NA62 RUN2 data (2021+22)

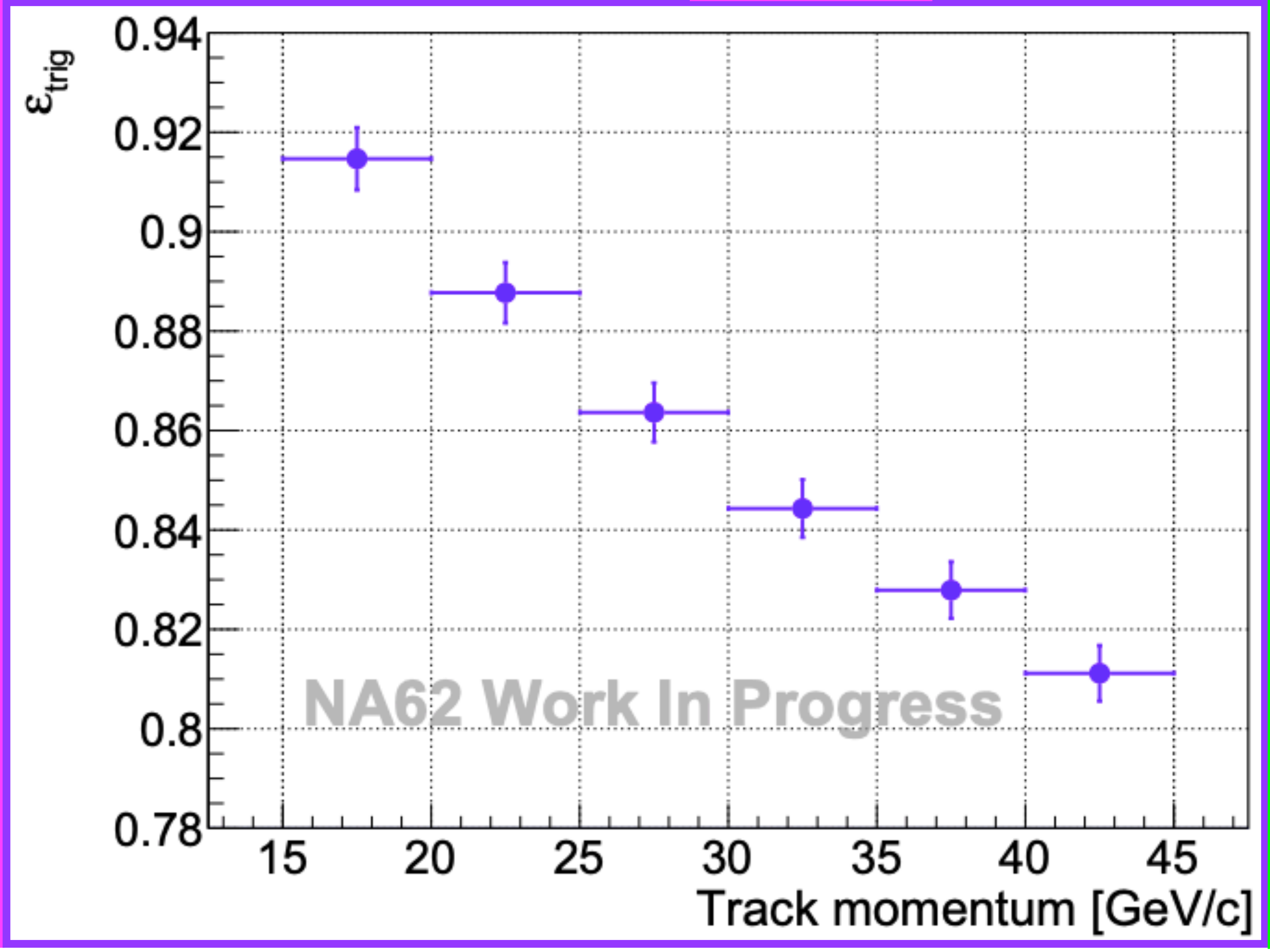
[NA62 SPSC report 2024

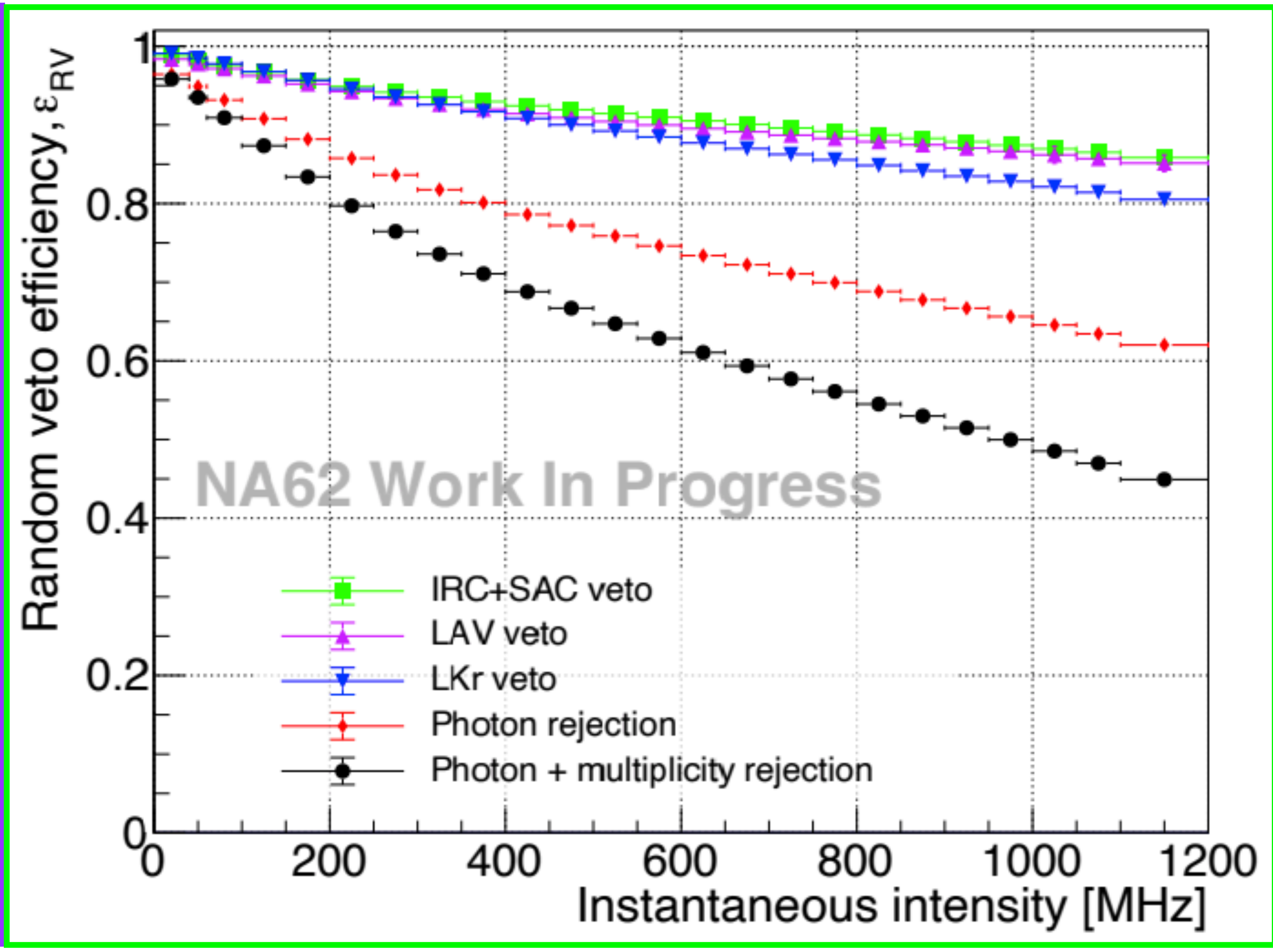
Work in progress

- Analysis overhauled and re-optimised for high intensity data.
- Improve signal yield by 50% and improving overall sensitivity.
  - Number of expected signal events per good SPS spill increased: $1.7 \times 10^{-5} \to 2.5 \times 10^{-5}$.

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





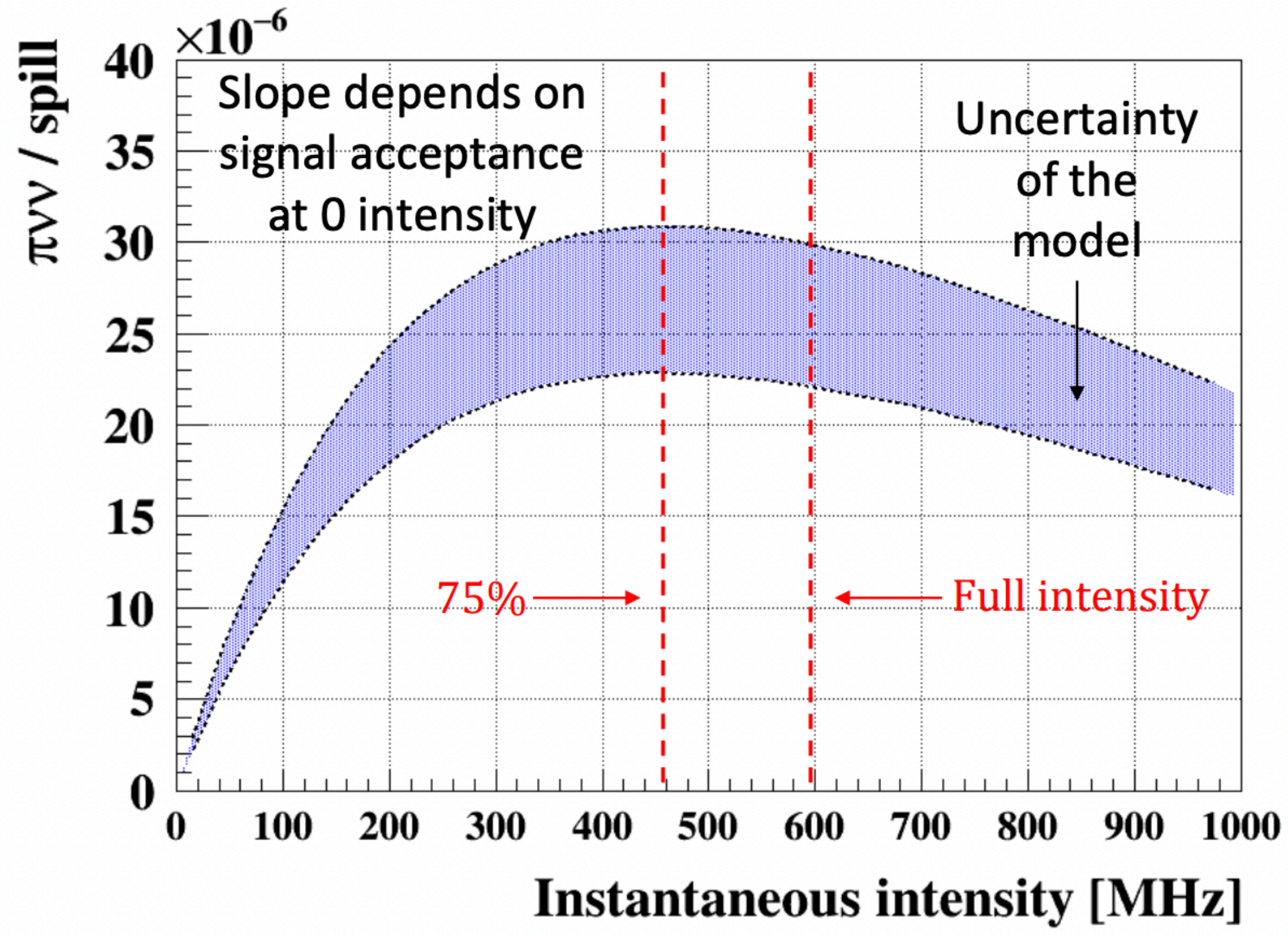


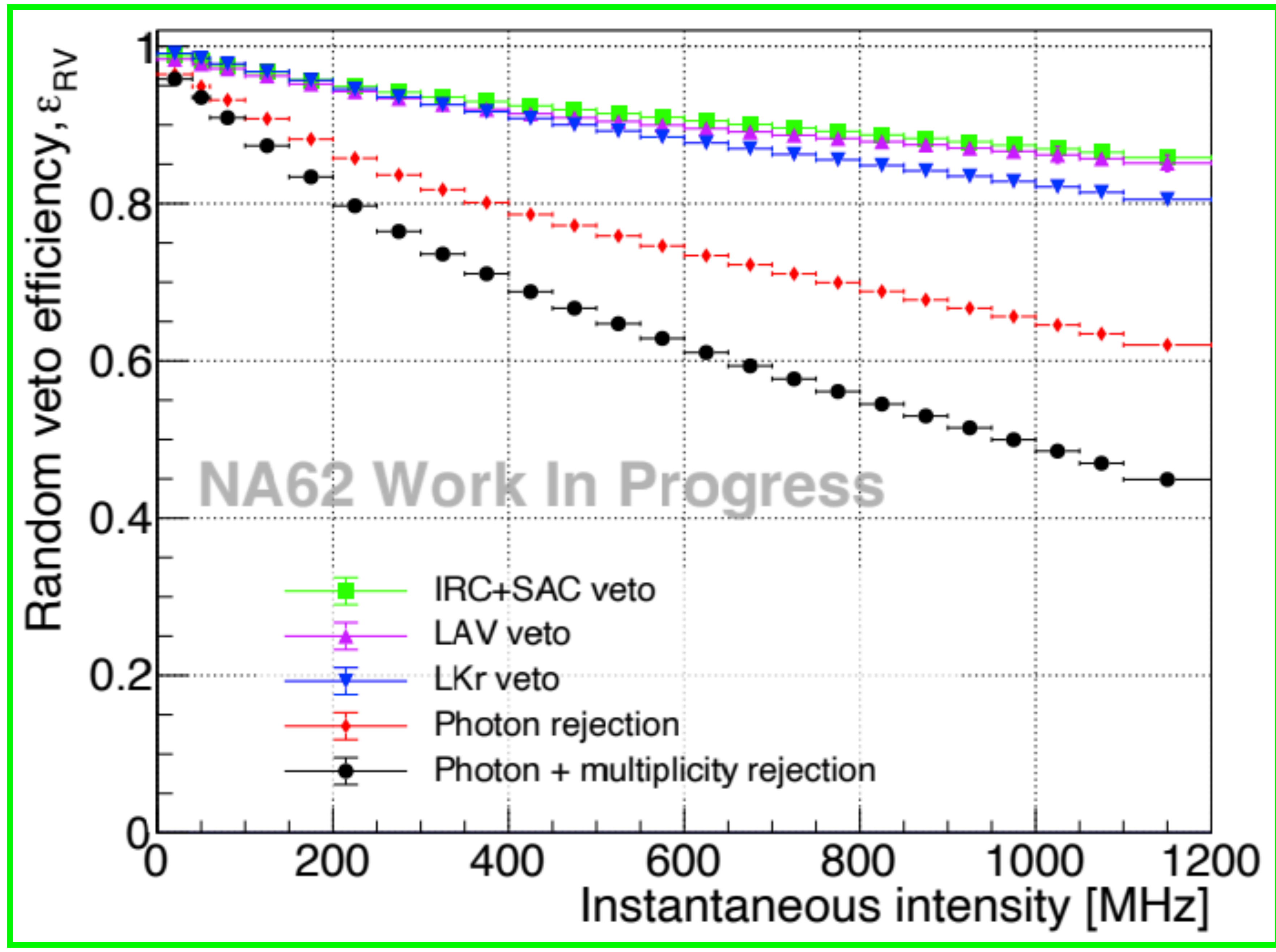
$K^+ \to \pi^+ \nu\bar{\nu}$ with NA62 RUN2 data (2021+22)

[NA62 SPSC report 2024

Work in progress

- Data was taken at the (hardware) high intensity limit.
- Studied these limits and understood how the yield of signal $K^+ \to \pi^+ \nu\bar{\nu}$ events evolves with intensity.
  - Determined an optimum operating condition, adopted starting from mid 2023.



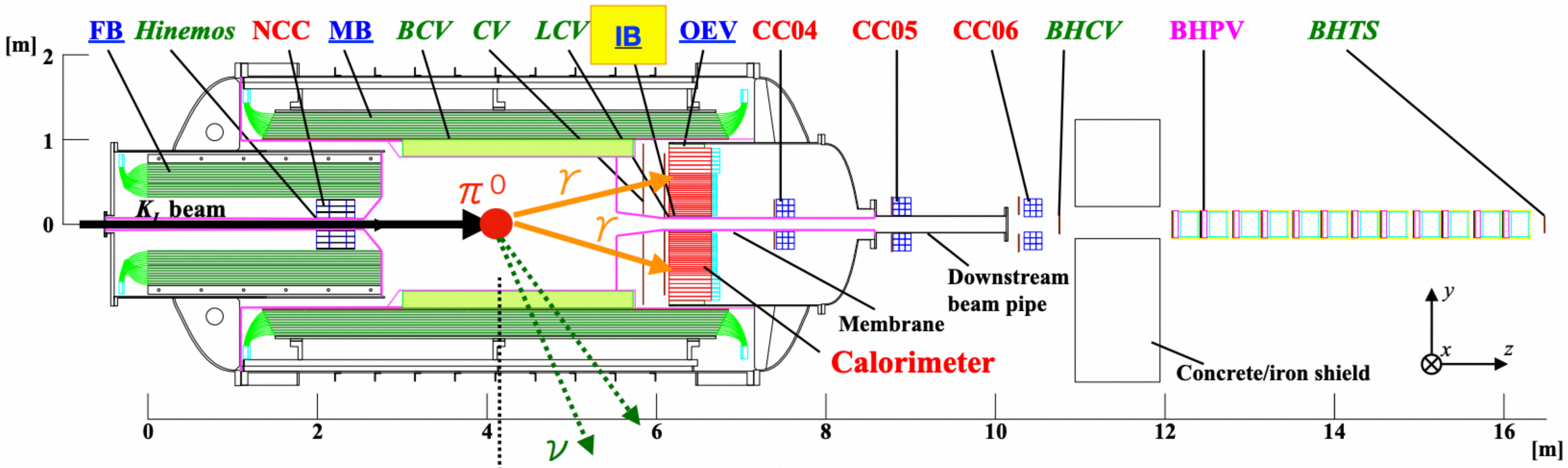


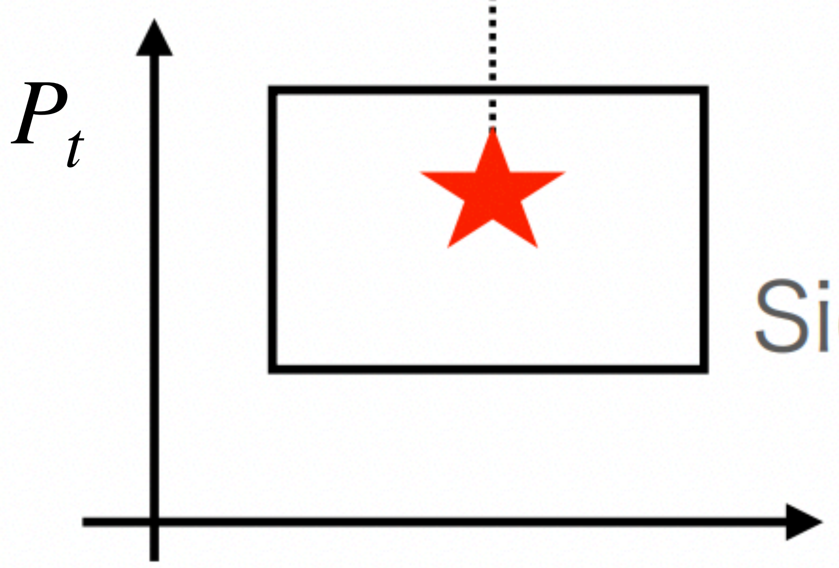
$K_L \to \pi^0 \nu \bar{\nu}$ at KOTO

[K. shiomi : Kaons @ CERN 2023]

- Located at J-Park 30 GeV main ring.

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



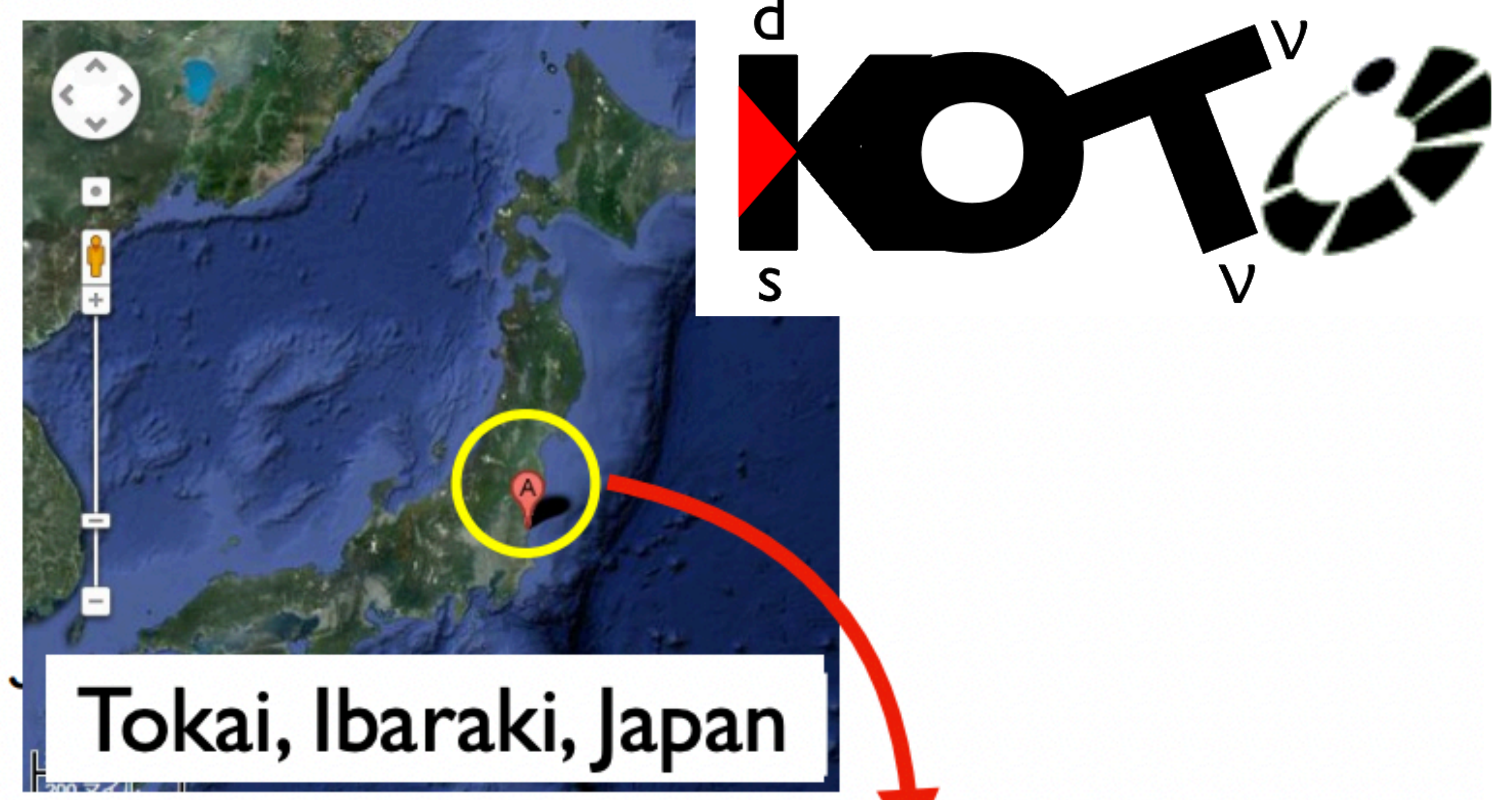


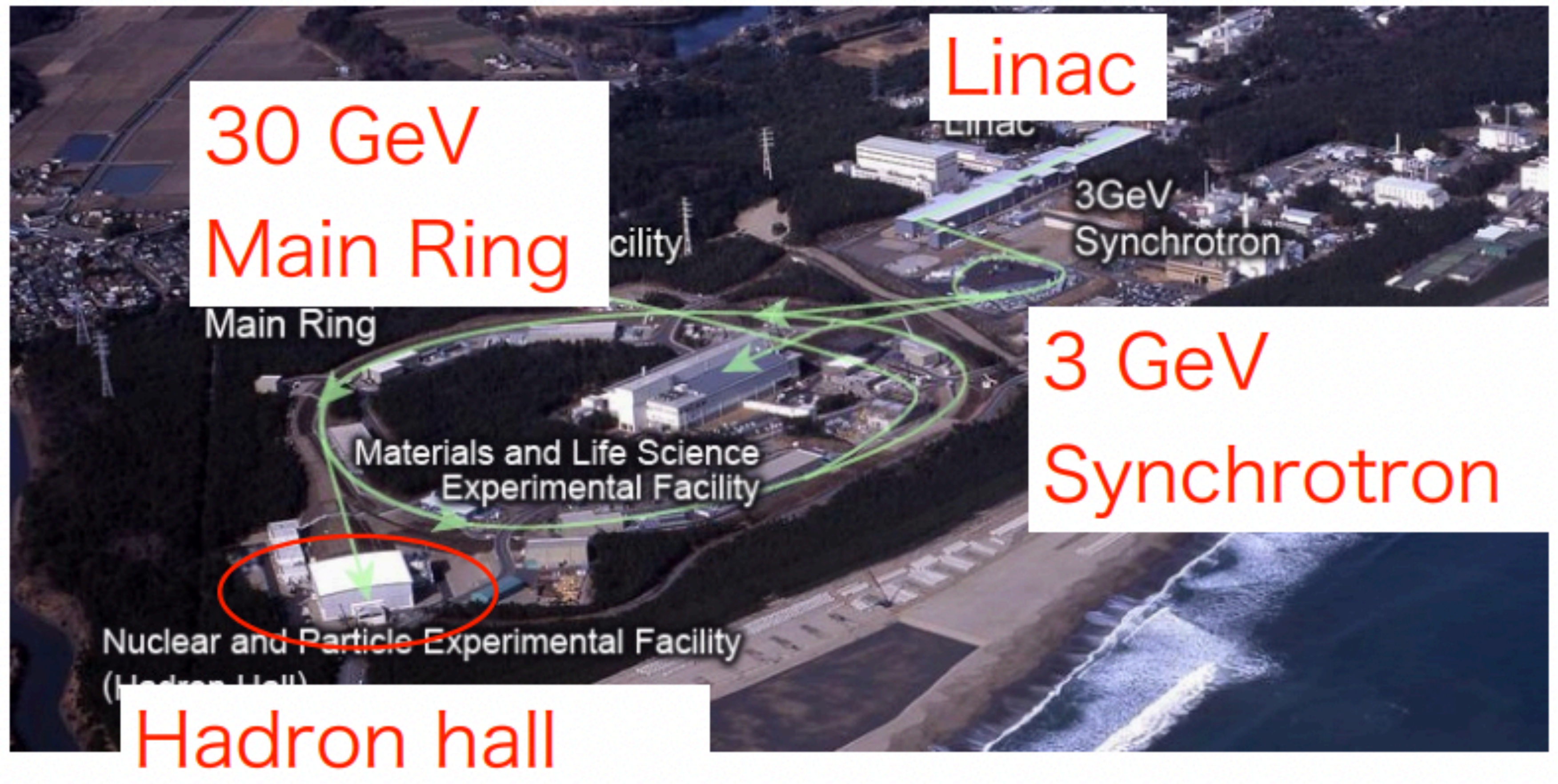
Assuming 2γ from π^0,

Calculate z vertex on the beam axis

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

Calculate π^0 transverse momentum

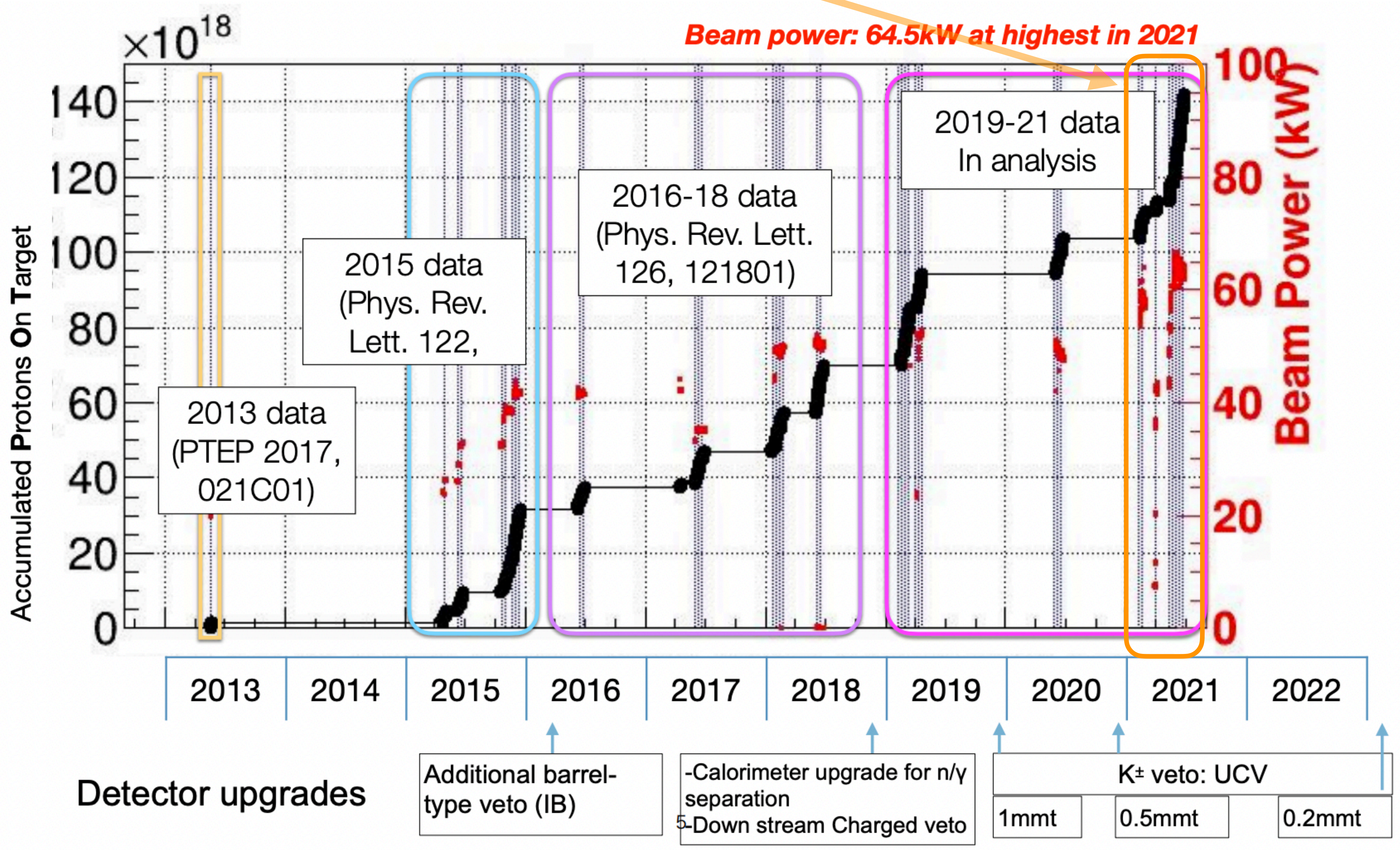




$K_L \to \pi^0 \nu \bar{\nu}$ at KOTO

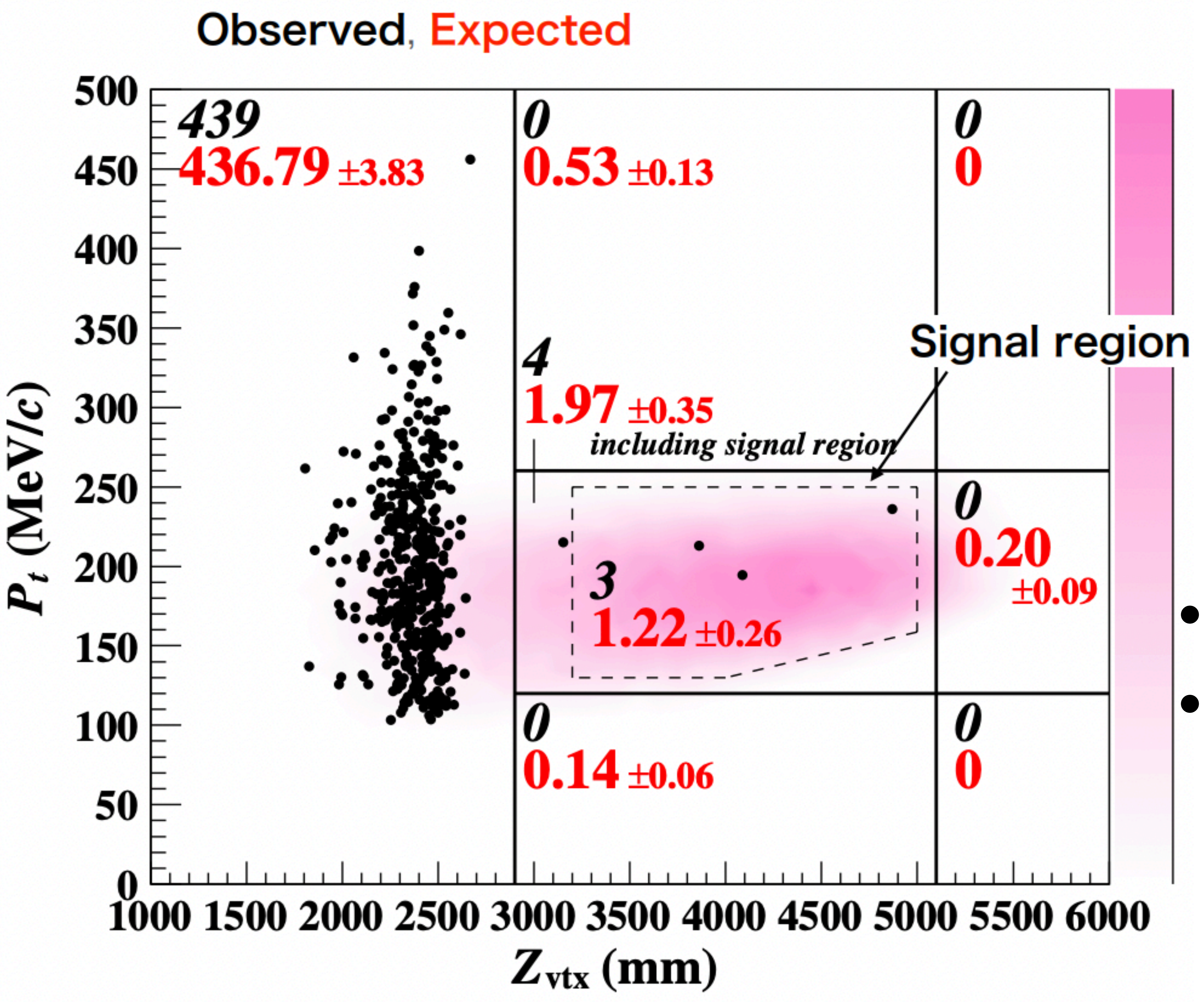
[K. shiomi : Kaons @ CERN 2023]

- Long-term data-taking campaign with 10x more data expected in 3-4 more years (60 days/year).
- Latest preliminary results based on **2021 data** where background is smallest due to Upstream Charged Veto newly installed in 2021.



$K_L \to \pi^0 \nu \bar{\nu}$ at KOTO : 2016—18 results

[K. shiomi : Kaons @ CERN 2023]

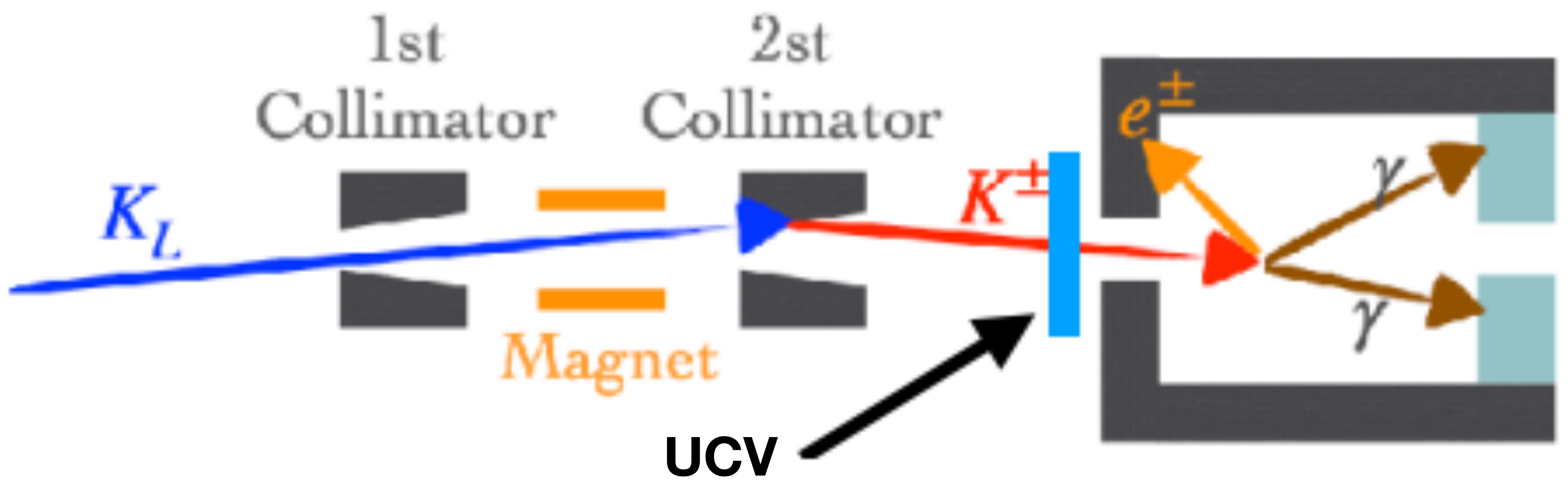


Background Table

	Number of events
$K_L \to 3\pi^0$	0.01 ± 0.01
$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07[a]
Other K_L decays	0.005 ± 0.005
$K^\pm$	0.87 ± 0.25[a]
Hadron cluster	0.017 ± 0.002
CV η	0.03 ± 0.01
Upstream π^0	0.03 ± 0.03
	1.22 ± 0.26

- Resut: $\mathscr{B}(K_L \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}$ @ 90 % CL
- Identified $K^\pm$ background and mitigated starting from 2021 with new upstream charged veto (UCV)
  - Reduce by factor 13 with 97% signal efficiency.

$K^\pm \to \pi^0 e^\pm \nu$ background:



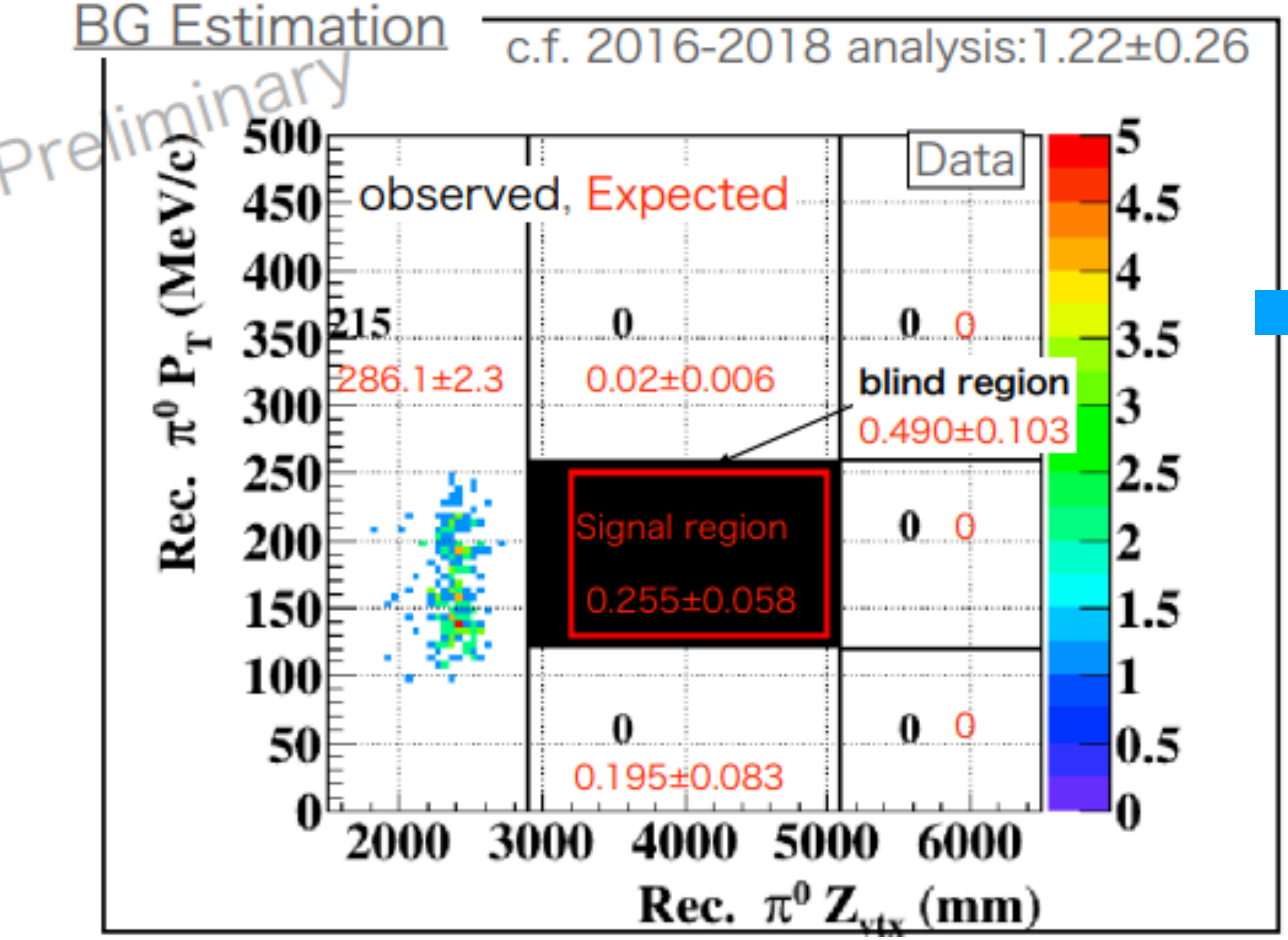
$K_L \to \pi^0 \nu \bar{\nu}$ at KOTO : PRELIMINARY 2021 analysis

[K. shiomi : Kaons @ CERN 2023]

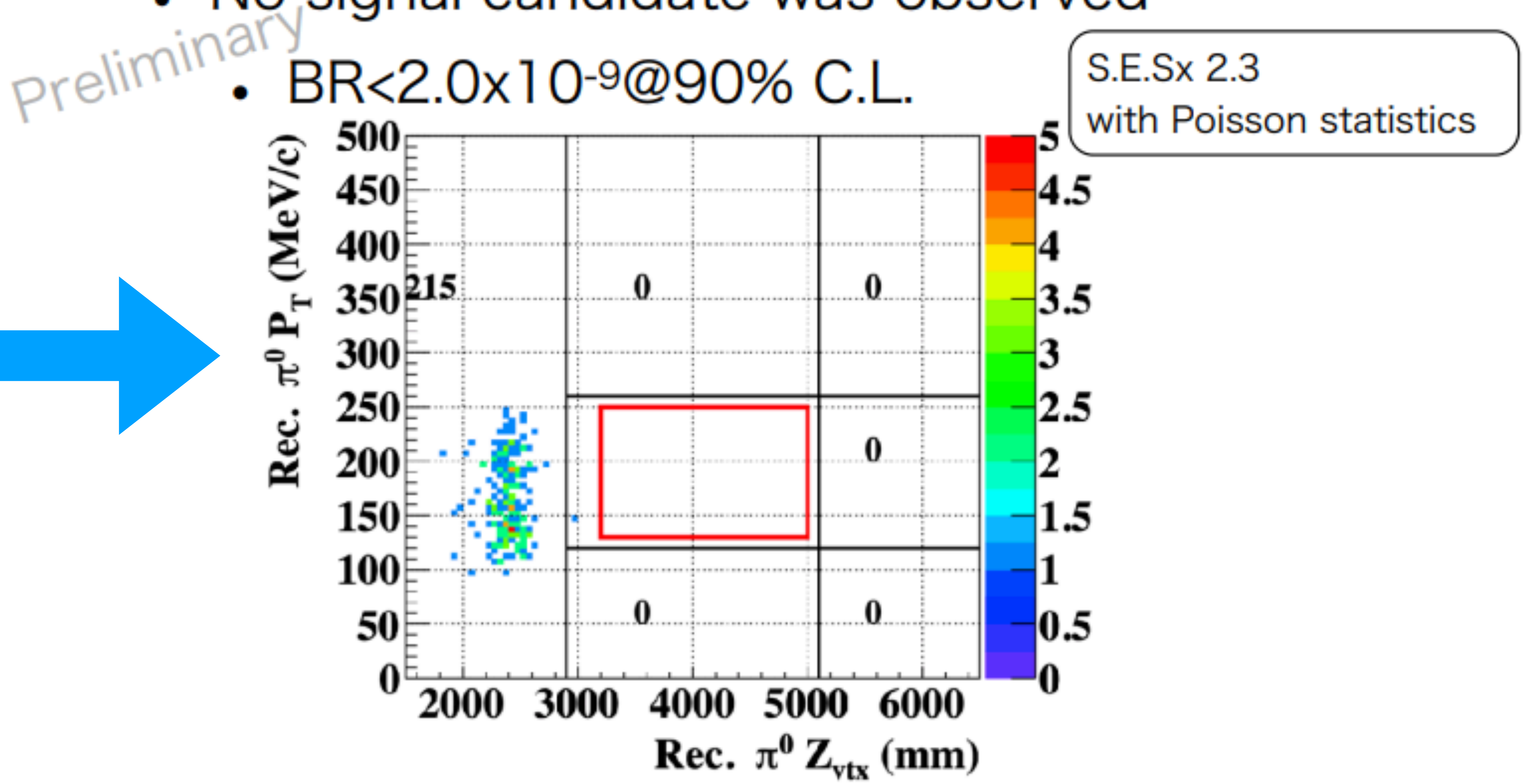
Single Event Sensitivity(S.E.S.):8.7×10-10

c.f. 2016-2018 analysis:7.2×10-10

BG Estimation



- No signal candidate was observed
  - BR<2.0x10-9@90% C.L.



- KOTO continues data-taking to reach sensitivity below 10^{-10}.
- Planned future program (KOTO-2) key part of high priority hadron hall extension plans at J-PARC.

Summary

Summary

NA62 studies of rare K^+ decays providing new precision measurements:

- Study of $K^+ \rightarrow \pi^+\gamma\gamma$: test of Chiral perturbation theory (ChPT) [PLB 850 (2024) 138513]
  - $\hat{c} = 1.144 \pm 0.069_{\text{stat}} \pm 0.034_{\text{syst}}$
  - $\mathscr{B}(K^+ \rightarrow \pi^+\gamma\gamma, \text{ChPT}\mathcal{O}(p^6)) = (9.61 \pm 0.15_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-7}$
  - Consistent with previous measurements with precision improved by factor 3, statistically dominated.
- Study of $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow e^+e^-$ [Preliminary result: spring 2024]
  - $\mathscr{B}_{NA62}(\pi^0 \rightarrow e^+e^-(\gamma), x > 0.95) = (5.86 \pm 0.37) \times 10^{-8}$
  - Precision comparable with previous measurement, statistically dominated
  - In agreement with latest theoretical expectations
- 2 candidate events with tagged ν in $K^+ \rightarrow \mu^+\nu$ decays

Status of Golden Modes $K \rightarrow \pi\nu\bar{\nu}$

- KOTO continuously improving sensitivity to $K_L \rightarrow \pi^0\nu\bar{\nu}$ with good prospects for future KOTO-2 programme.
- NA62: worlds best measurements of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ with RUN1 data. First RUN2 data result being finalised.
  - NA62 will provide the final measurements of rare K^+ decays for the foreseeable future.

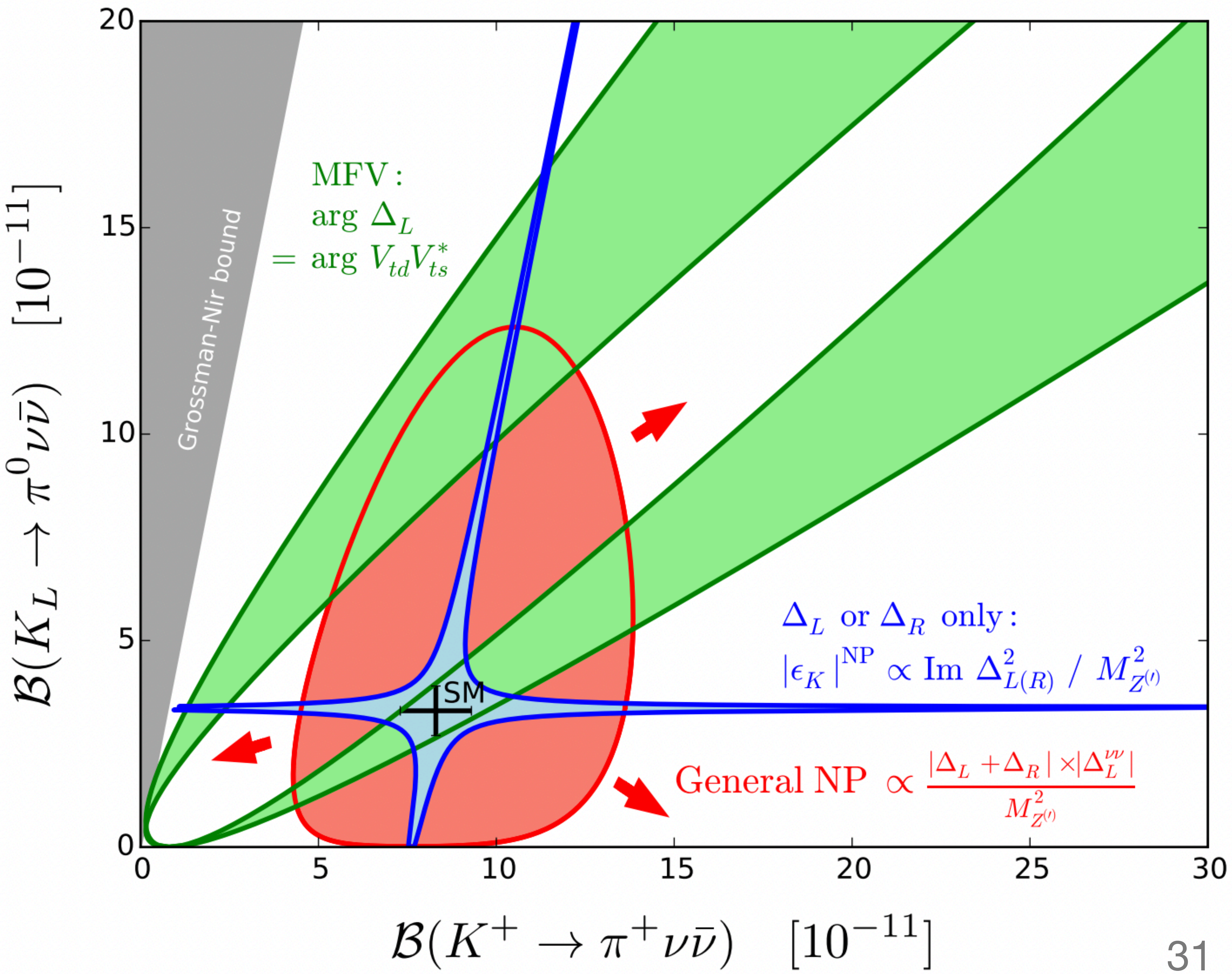
Supplemental

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

- Correlations between BSM contributions to BRs of K^+ and K_L modes [Buras et al. JHEP 11 (2015) 166].
- Must measure both to discriminate between BSM scenarios. (In SM get clean β measurement).
- Correlations with other observables (ε'/ε, ΔM_B, B-decays) [Aebischer et al. JHEP 12 (2020) 097]

- **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

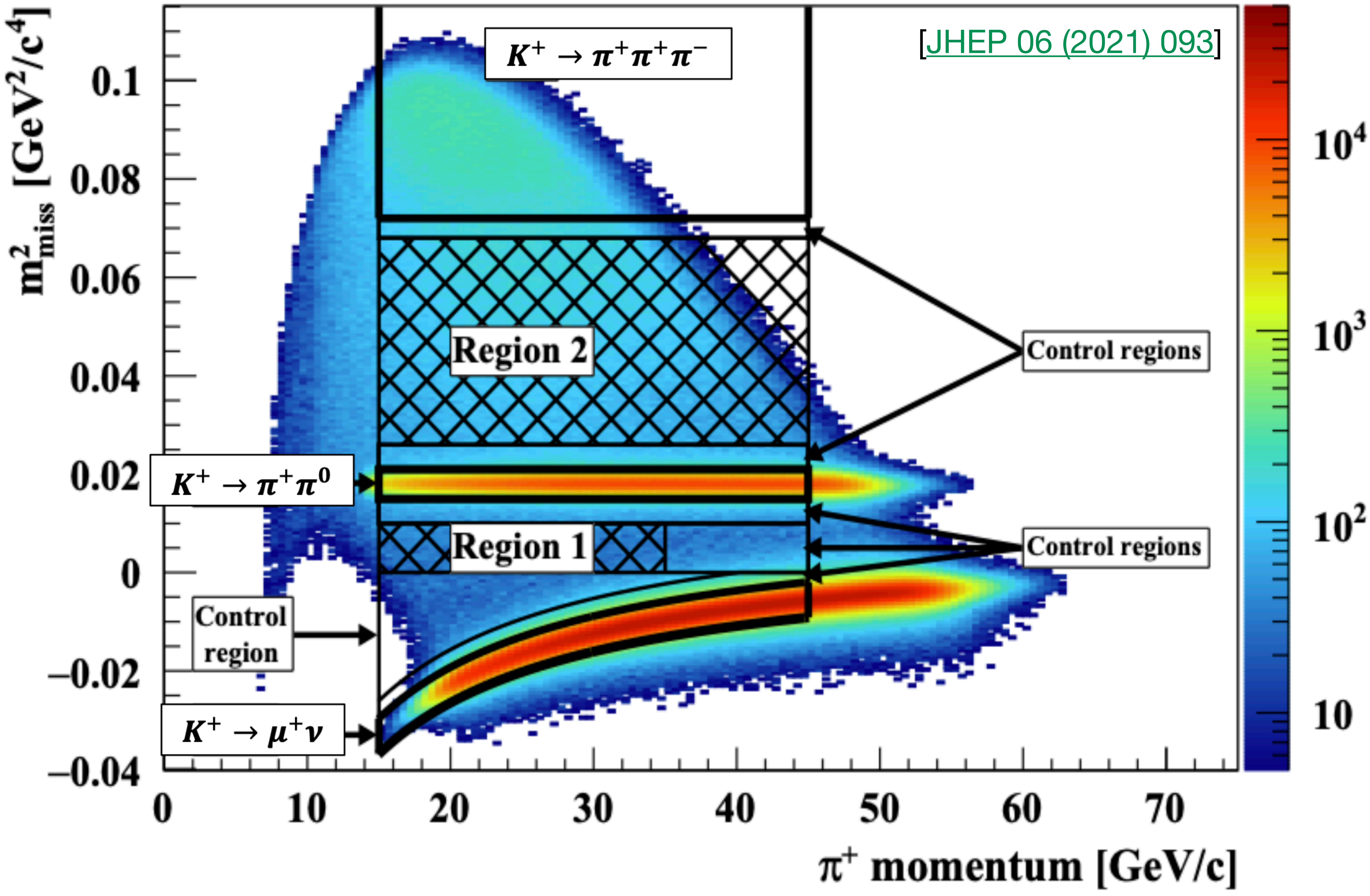
$$\frac{\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})}{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})}\frac{\tau_{K^+}}{\tau_{K_L}} \leq 1$$



[Buras et al. JHEP 11 (2015) 166]

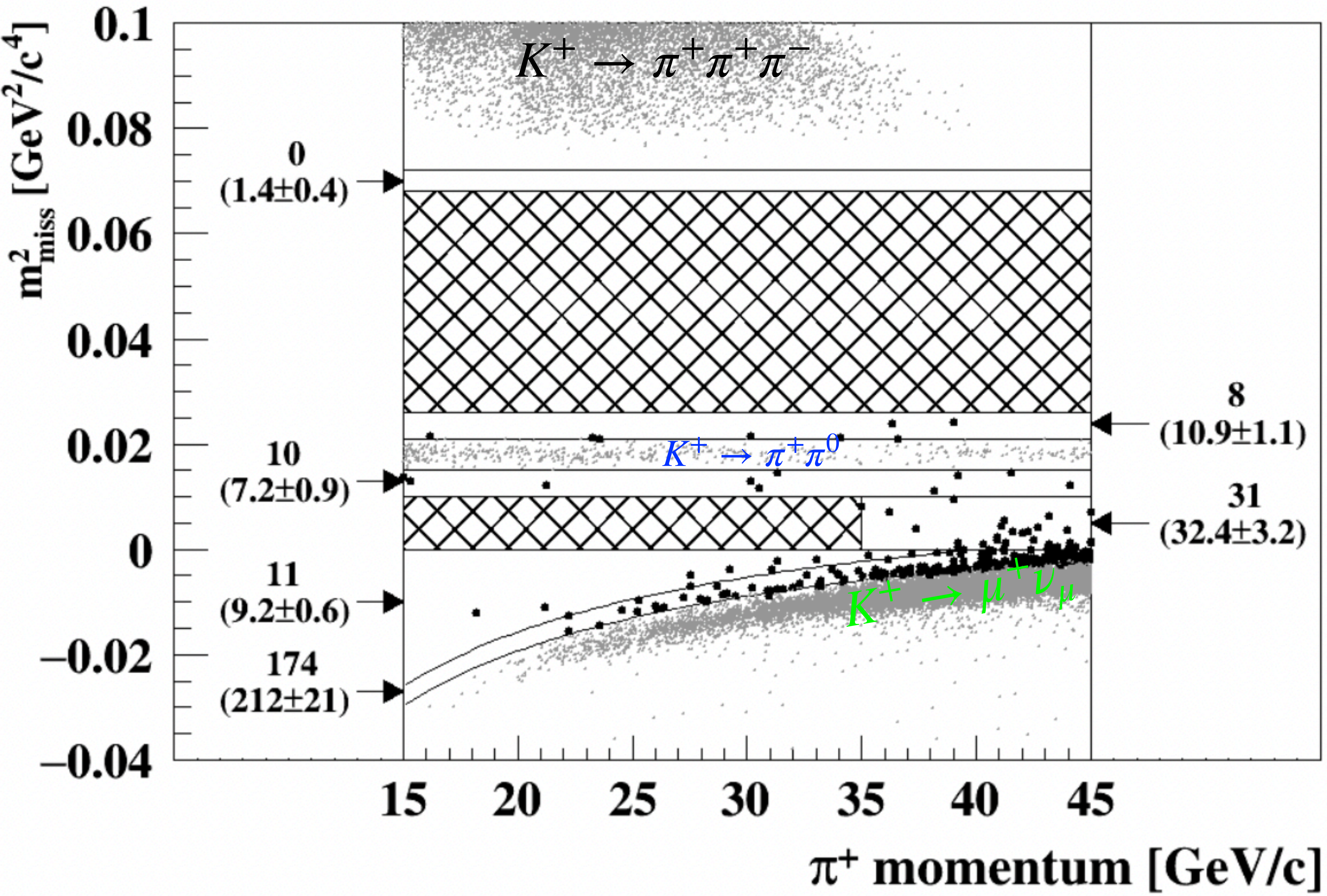
$K^+ \to \pi^+ \nu\bar{\nu}$ Signal Selection

- **Reconstruct K^+ and π^+**
- $K - \pi$ **matching** & reconstruct vertex
  - CDA, timing, vertex in FV
- π^+ **Identification (μ^+ rejection)**
  - RICH (Calorimeters) performance:
    - $\varepsilon(\pi^+ \text{ ID}) \approx 0.85(0.82)\,\%$
    - $P(\mu^+ \Rightarrow \pi^+ \text{ misID}) \approx 3 \times 10^{-3}(10^{-5})$
- **Photon vetos & Multi-track rejection**
  - $\pi^0(\to \gamma\gamma)$ rejection inefficiency $\sim 10^{-8}$



- **Kinematics:** m^2_{miss} vs p_{π^+} :
  - Selection optimised in bins of p_{π^+}

Background Studies [2018 data]



Before & after new final collimator in 2018

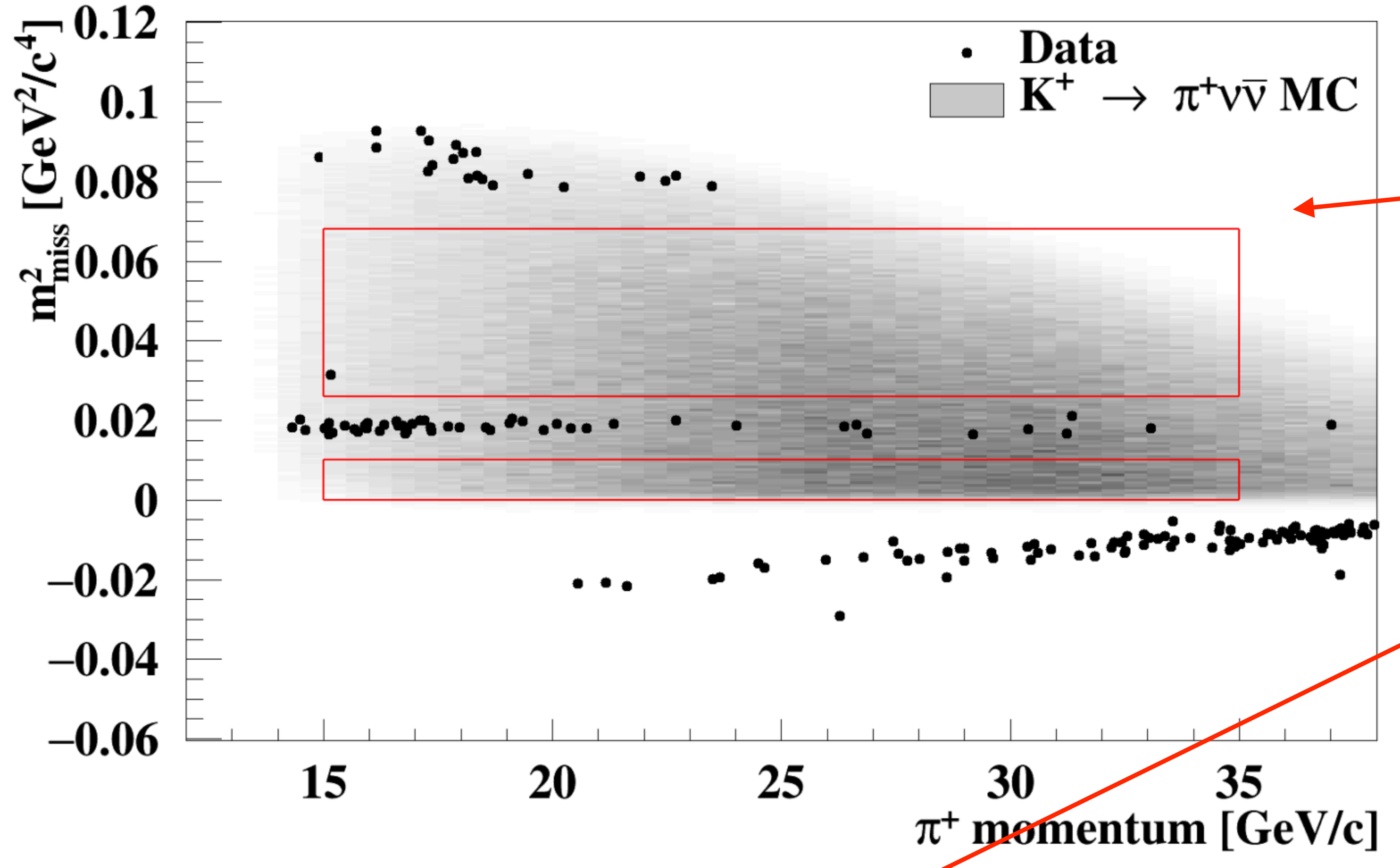
Background	Subset S1	Subset S2
K^+ decays in the FV:		
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

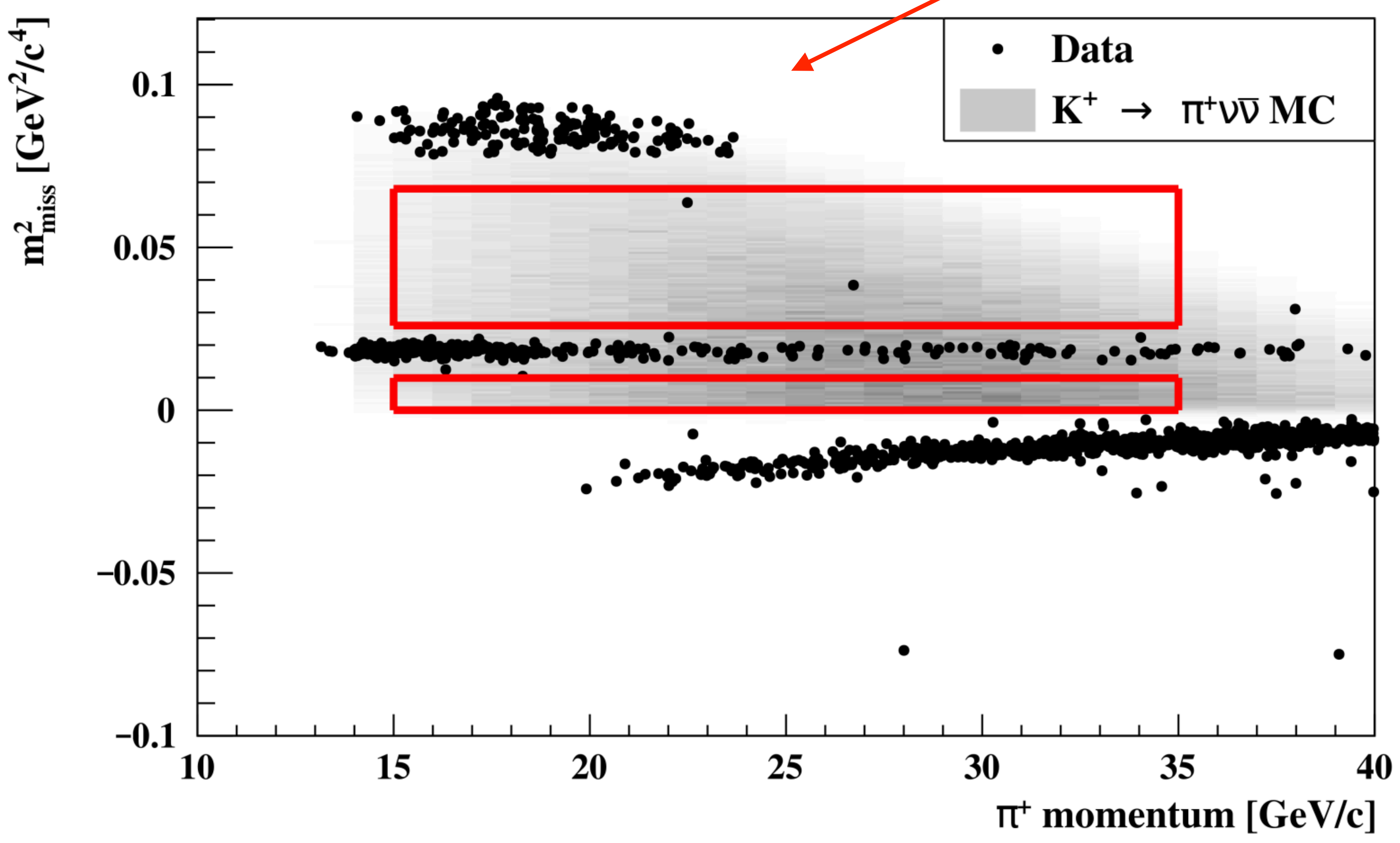
[Fraction of 2018 data sample: S1 = 20% , S2 = 80%]

- Primary backgrounds (from kinematic tails) evaluated with data-driven procedures.
- Upstream bkg. dominated by decays upstream of FV
  - New collimator installed (June 2018) blocks many upstream decays
  - Strict anti-upstream rejection loosened.

[JHEP 06 (2021) 093]

$K^+ \to \pi^+ \nu \bar{\nu}$: Run 1 data





2016 data [PLB 791 (2019) 156]

$n_{bg} = 0.152^{+0.093}_{-0.035}$, $n^{SM}_{\pi\nu\bar{\nu}} = 0.267 \pm 0.038$

$n_{obs} = 1$

2017 data [JHEP 11 (2020) 042]

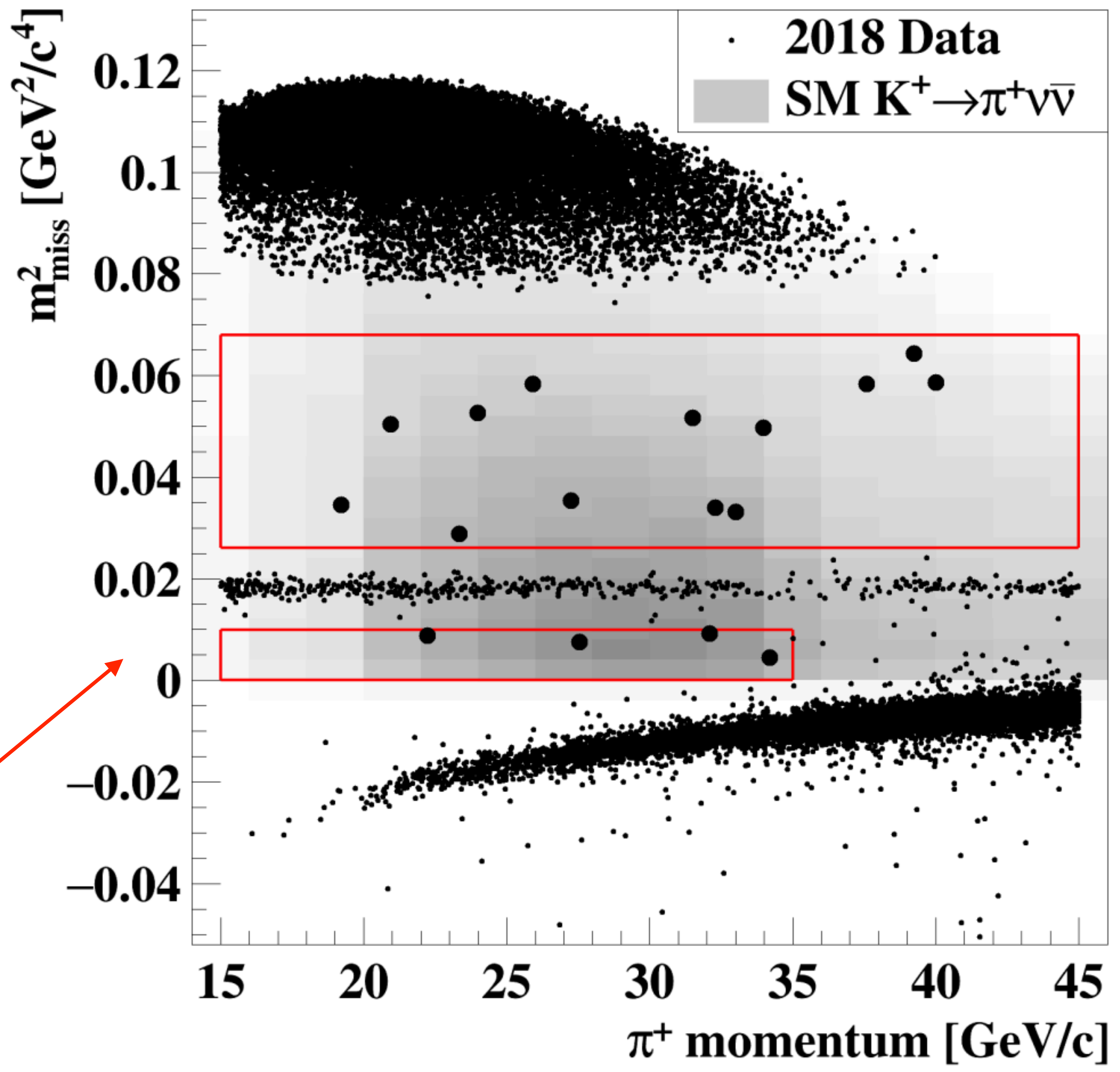
$n_{bg} = 1.46 \pm 0.33$, $n^{SM}_{\pi\nu\bar{\nu}} = 2.16 \pm 0.29$

$n_{obs} = 2$

2018 data [JHEP 06 (2021) 093]

$n_{bg} = 5.24^{+0.99}_{-0.75}$, $n^{SM}_{\pi\nu\bar{\nu}} = 7.58 \pm 0.85$

$n_{obs} = 17$

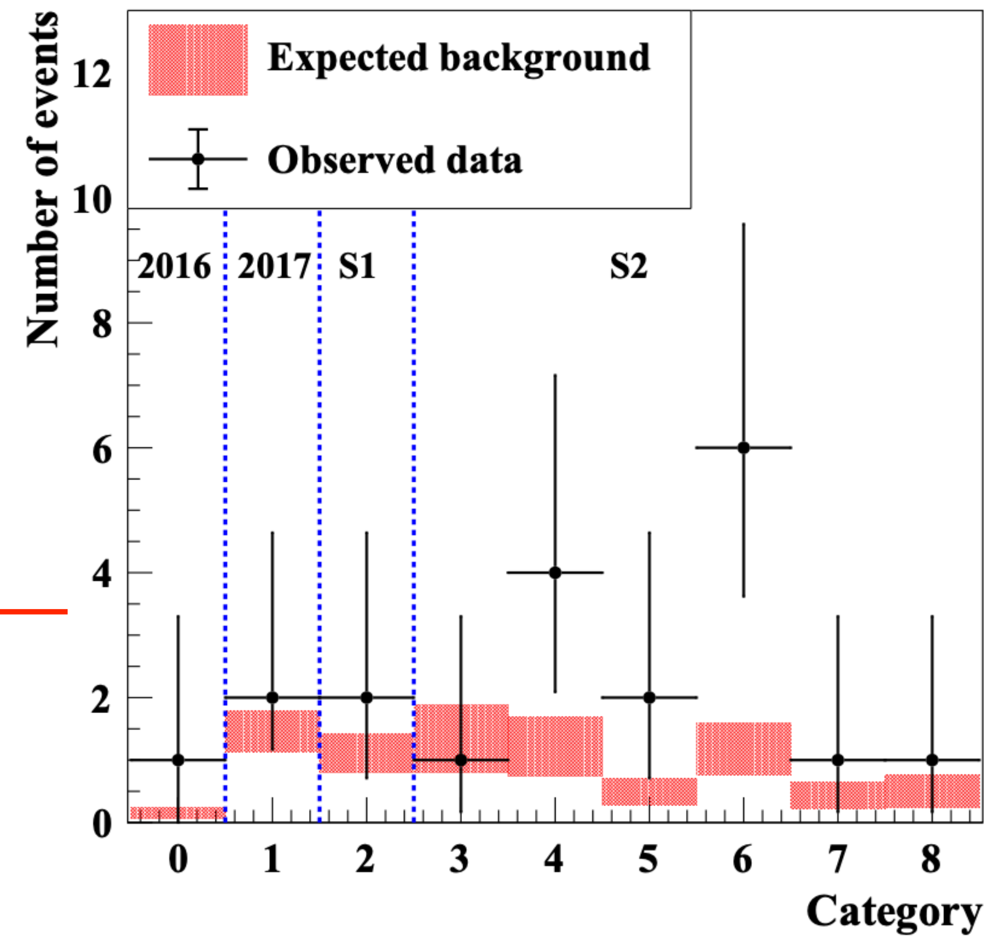


Run1 2016–18 data [JHEP 06 (2021) 093]

$n_{bg} = 6.85^{+1.05}_{-0.82}$, $n^{SM}_{\pi\nu\bar{\nu}} = 10.01 \pm 1.26$, $n_{obs} = 20$

Statistical combination:

$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = \left(10.6^{+4.0}_{-3.4}\Big|_{\text{stat}} \pm 0.09_{\text{syst}}\right) \times 10^{-11}$ at 68 % CL

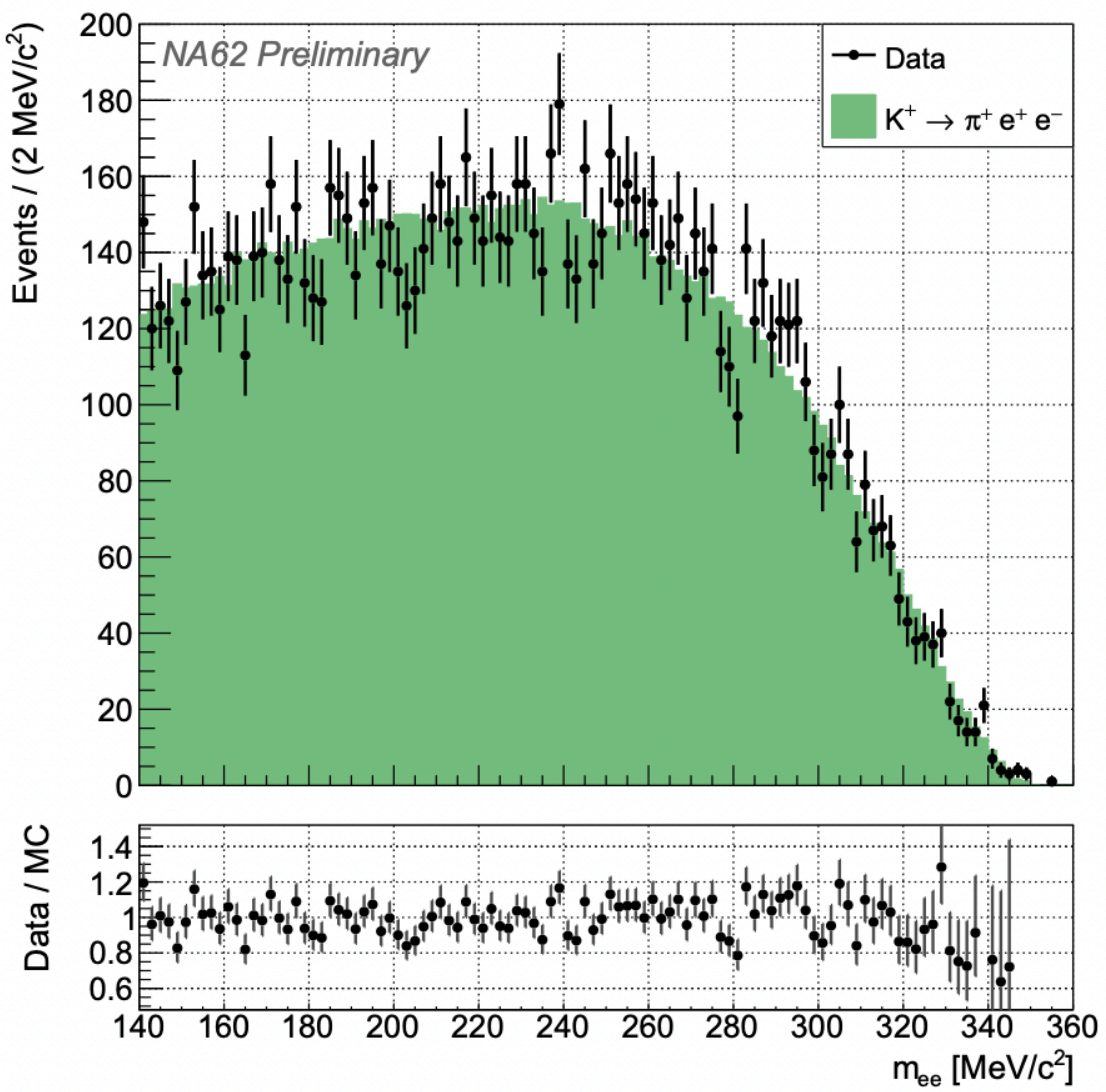


Study of $K^+ \to \pi^+\pi^0,\ \pi^0 \to e^+e^-$

[new: spring 2024]

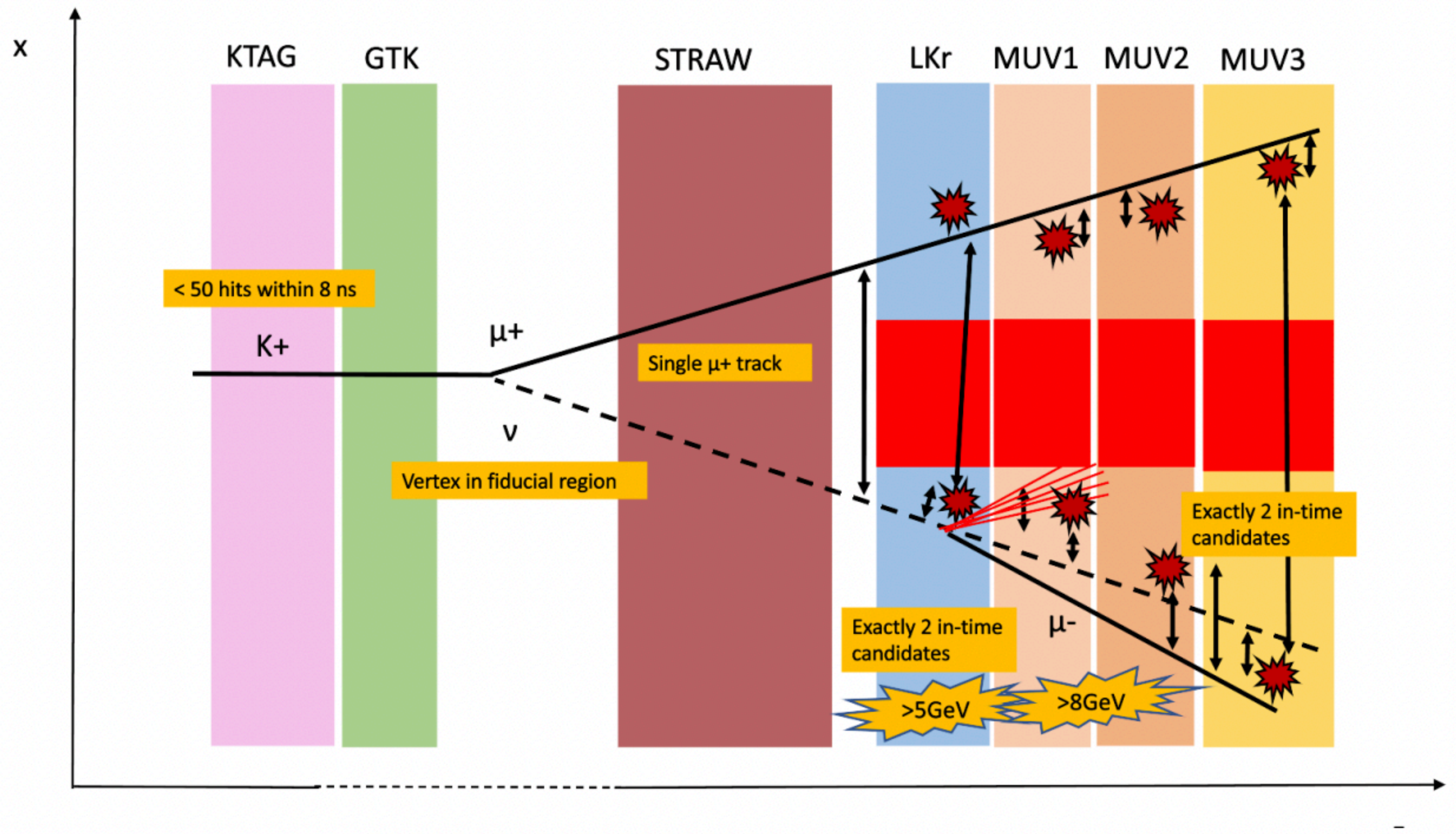
- Common Signal & Background Selection:
  - Vertex from 3 (in-time) charged tracks
  - Kinematics (momentum & vertex position)
  - PID: $\pi^+e^+e^-$ (using LKr E/p : <0.9 for π^+ vs 0.9-1.1 for e^+)
  - $m_{ee} > 130\,\text{MeV}/c^2$ (>140 for normalisation).

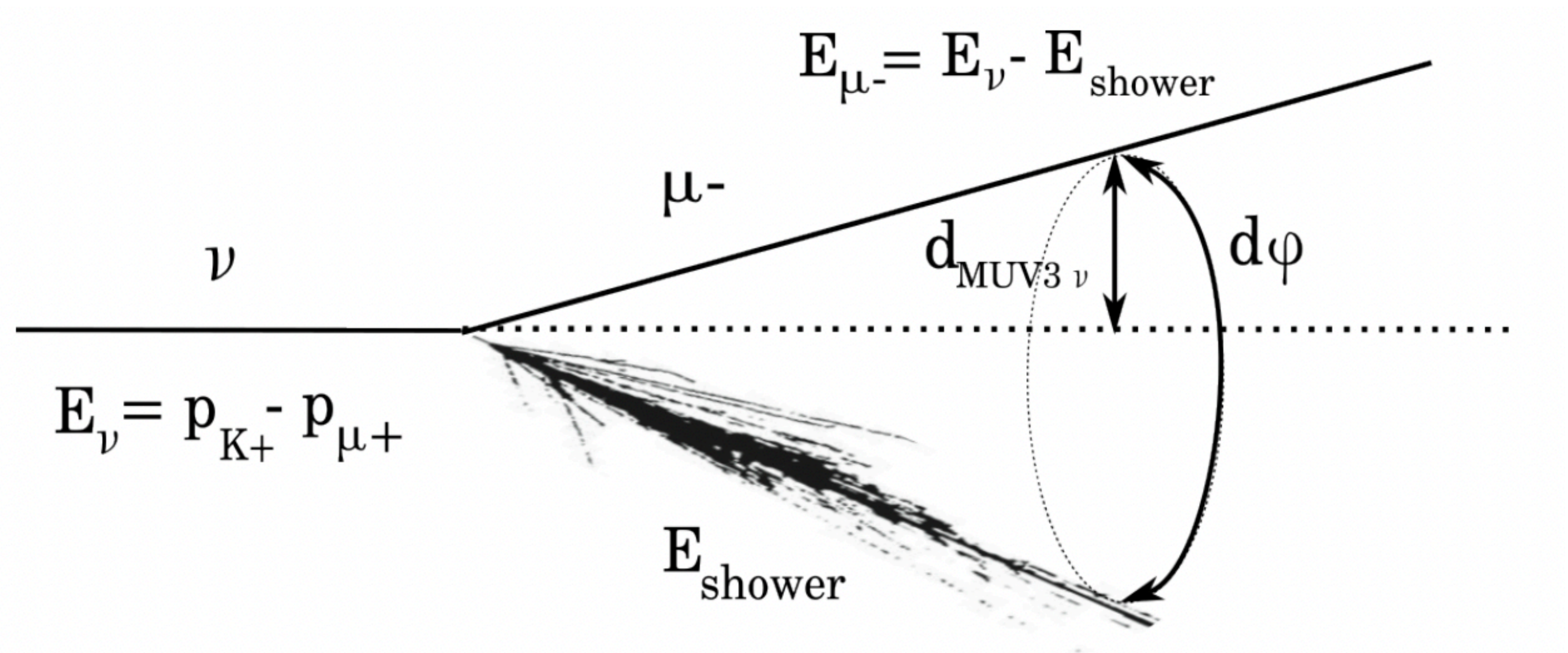
- **Normalisation:**
  - Acceptance: $A_{\pi ee} = (4.70 \pm 0.01_{\text{stat}})\,\%$
  - Selected events: $N_{\pi ee} = 12160$ (purity>99.9%)
  - Effective number of kaon decays:
    $N_K = (8.62 \pm 0.08_{\text{stat}} \pm 0.26_{\text{ext}}) \times 10^{11}$
    - With external uncertainty from norm. BR:
      $\mathcal{B}(K^+ \to \pi^+e^+e^-) = (3.00 \pm 0.09) \times 10^7$

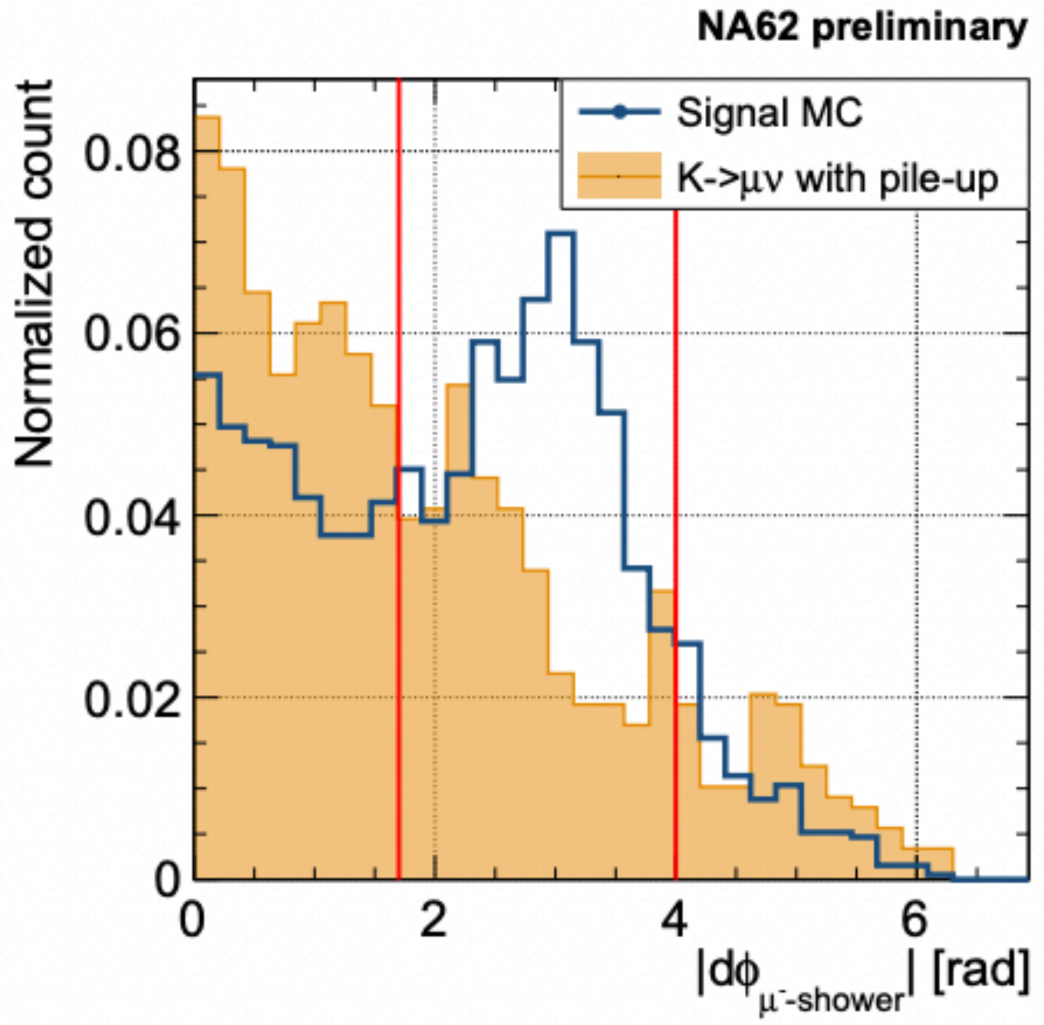


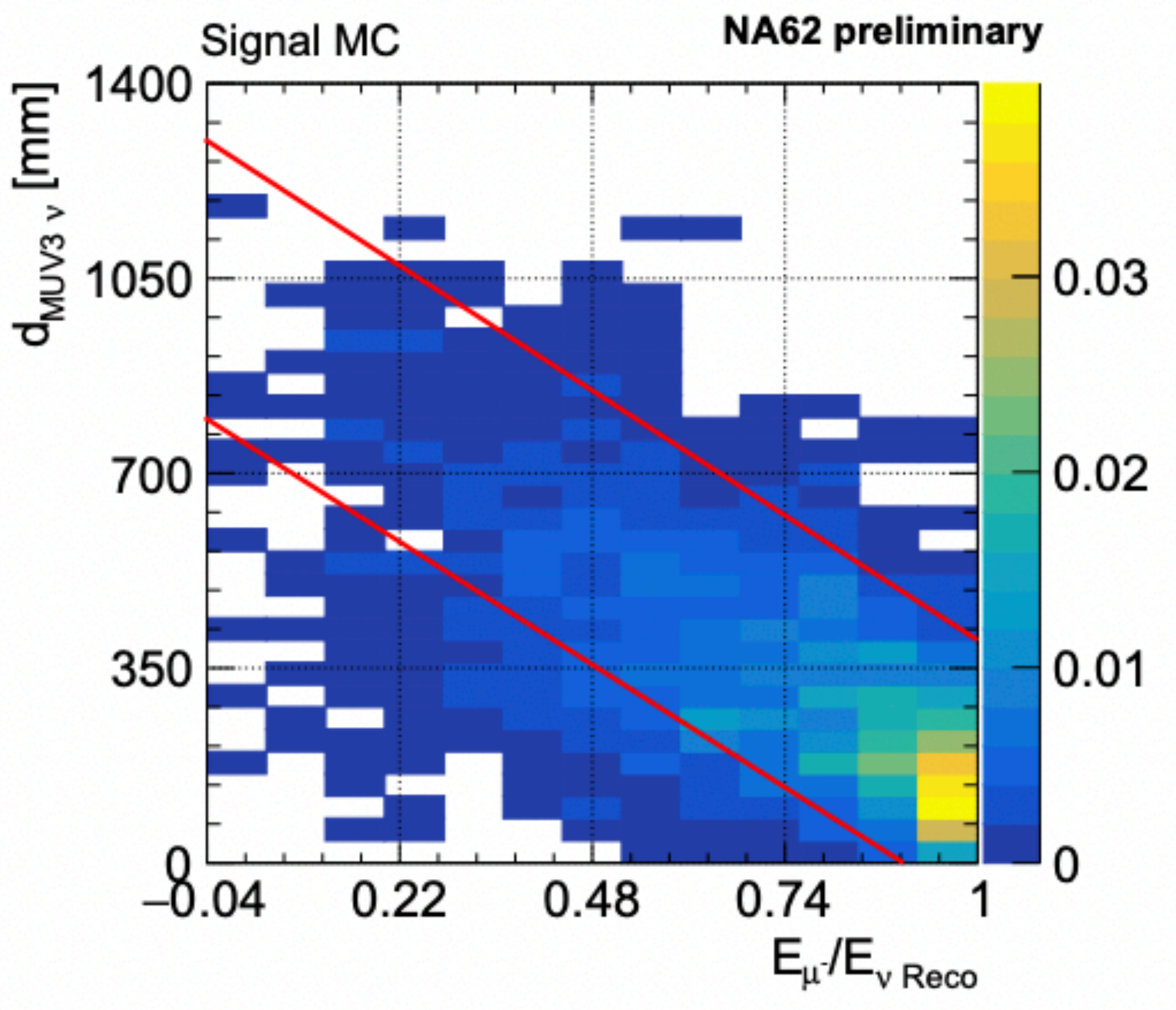
Tagged neutrinos at NA62: selection

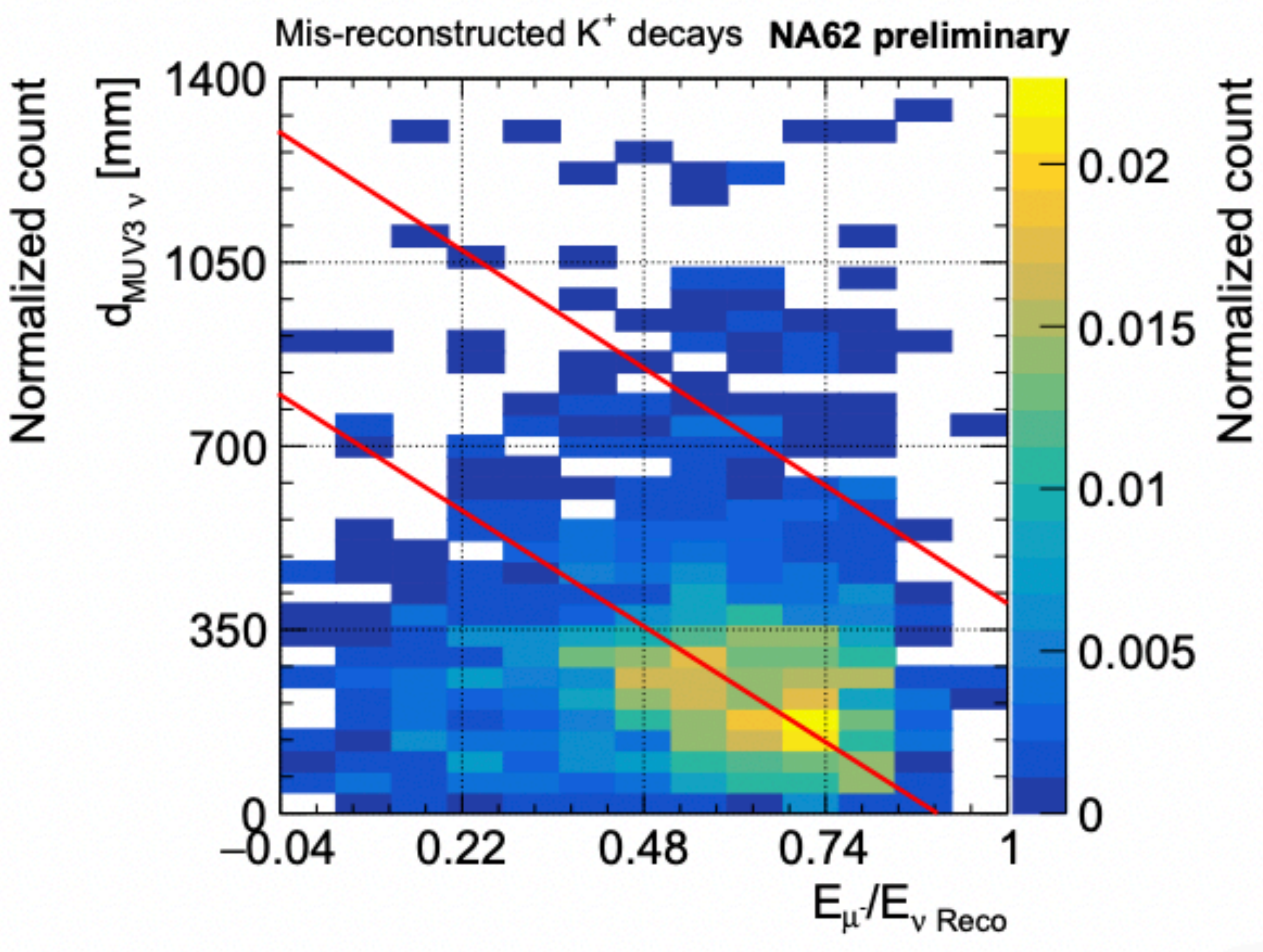
[De Martino, NuFact23]





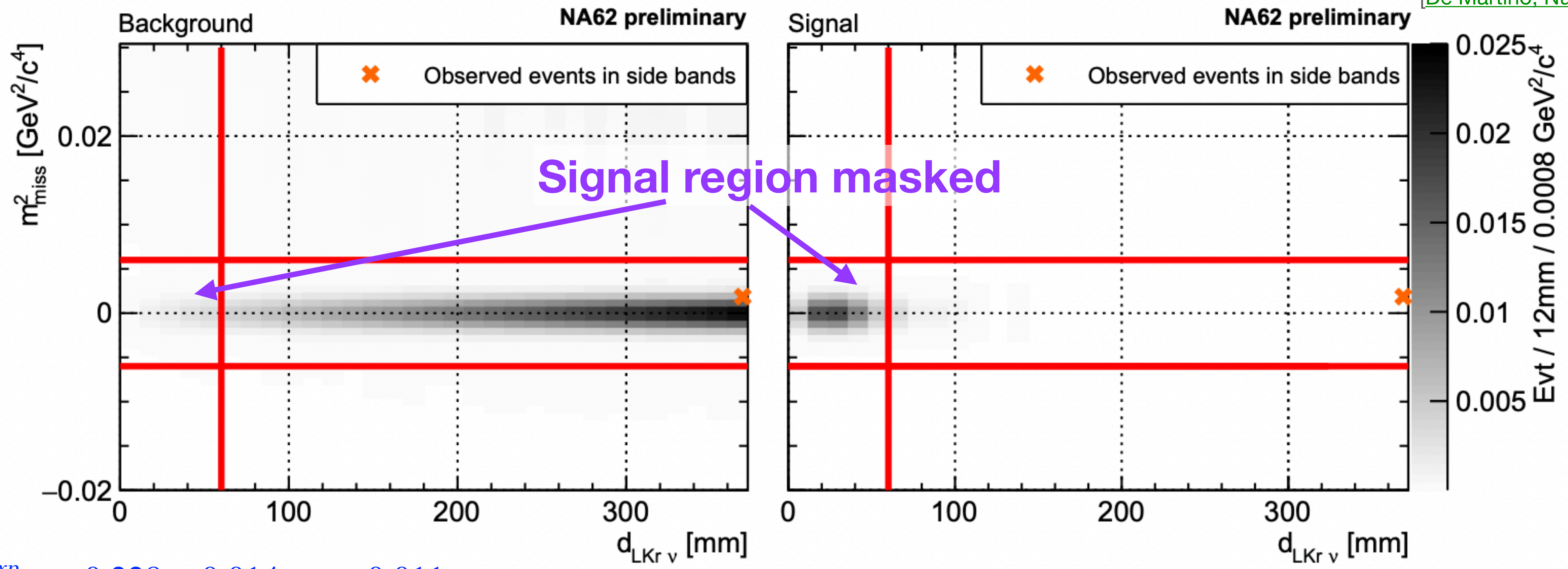






Tagged neutrinos at NA62: Expectations

[De Martino, NuFact23]



- $N^{exp}_{signal} = 0.228 \pm 0.014_{\text{stat}} \pm 0.011_{\text{syst}}$
- Backgrounds:
  - N^{exp}_{bg}(mis-reco K^+) $= 0.0014 \pm 0.0007_{\text{stat}} \pm 0.0002_{\text{syst}}$
  - N^{exp}_{bg}(pileup + $K^+ \to \mu^+\nu$) $= 0.04 \pm 0.02_{\text{stat}} \pm 0.01_{\text{syst}}$

Probability for total event yield $N^{exp}_{events} = 0.2694$

- for 0 data events p = 0.7638
- for 1 data event p = 0.2058
- for 2 data events p = 0.0277.

NA62 Run2

- NA62 technique is firmly established.
- Run2 - target $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ measurement: $\mathcal{O}(15)\,\%$ **precision**.
  - 4th GTK (Kaon beam tracker) & rearrange beam line elements around GTK achromat.
  - New upstream veto & veto hodoscope upstream of decay volume.
  - Additional veto detector at end of beam-line.
  - Intensity increased by $\sim 30\,\%$ with respect Run1. Matched by trigger updates.
- Improvements to the trigger have led to smaller trigger downscaling factors for multi-track triggers: more data available for rare decays and CLFV/LNV searches.

New detectors installed in 2021 for NA62 Run2: