Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Latest Results From the NA62 Experiment

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Contents:

- Introduction to Kaon physics and NA62
- Latest results from NA62: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, Rare decays, Exotic Decays (beam dump)
- Summary & Outlook for kaon physics

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Prologue: my story so far…

- 2013—17: MSci Physics degree at University of Birmingham (UK)
  - Specialising mostly in astro & particle physics.
  - Y3 group project on possible LHCb calorimeter upgrades, Y4 (dissertation) project on NA62 ($K^+ \to \pi^+ \nu \bar{\nu}$ backgrounds).
- 2017—21: PhD Particle Physics also at UoB
  - Joined NA62 in Oct. 2017.
  - First project: LNV/LFV decays $K^+ \to \pi \mu e$ (and $\pi^0 \to \mu e$)
  - Hardware responsibilities: KTAG & first simulations for upgrade (see later)
  - Joined $K^+ \to \pi^+ \nu \bar{\nu}$ team: re-interpretation as $K^+ \to \pi^+ X$

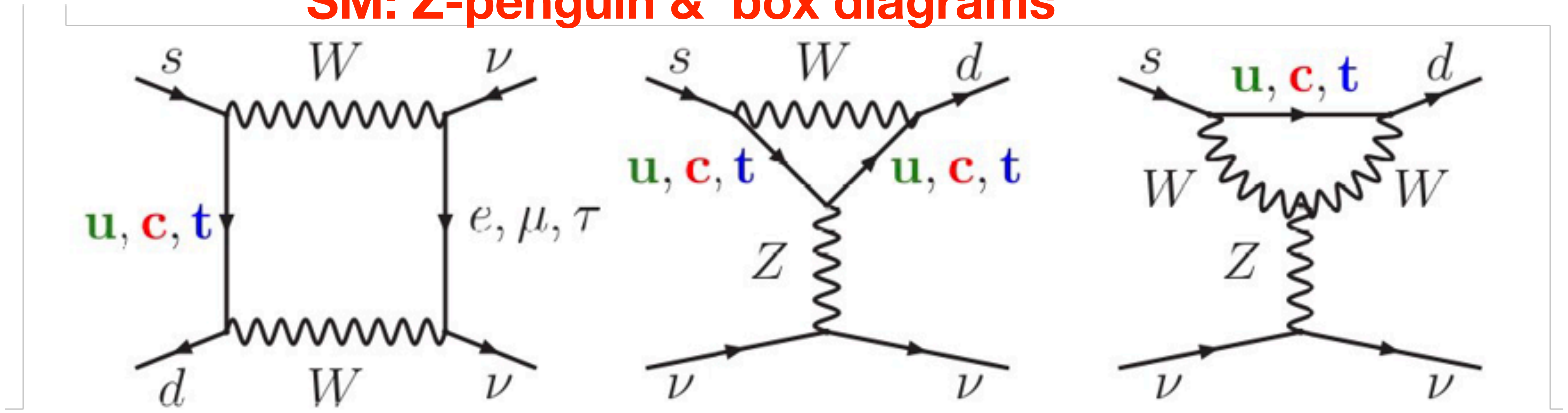
- 2021—23 : Senior Research Fellow @ CERN
  - Leading $K^+ \to \pi^+ \nu \bar{\nu}$ analysis
  - Data-taking/data-quality responsibilities with new upgrades
- 2023— : Research fellow @ INFN Frascati (Rome)
  - Work in progress…
  - co-convenor of $K^+ \to \pi^+ \nu \bar{\nu}$ analysis group

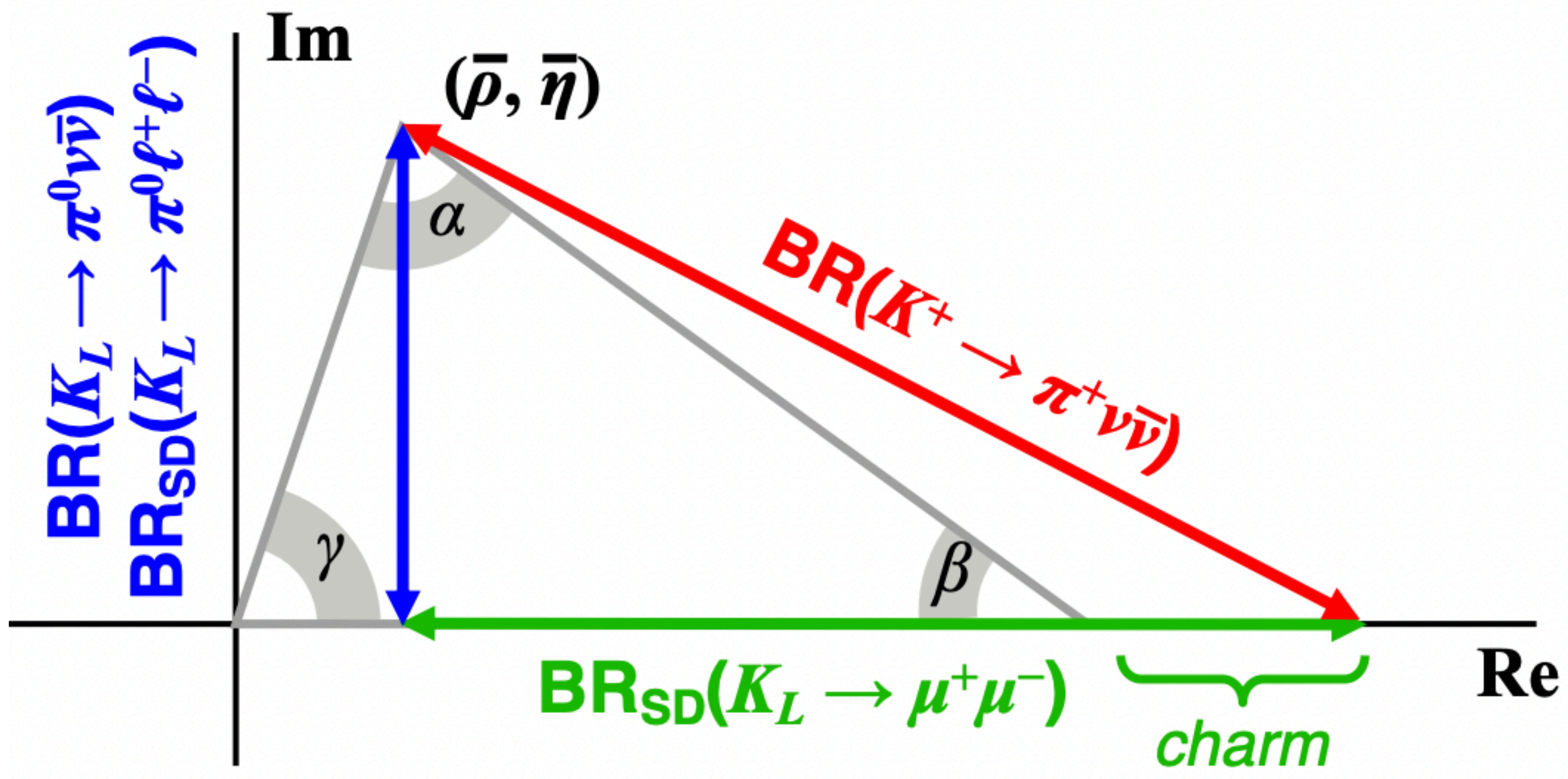
Rare Kaon Decays:
SM and Beyond

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

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

SM: Z-penguin & box diagrams





- $\mathscr{B}(K \to \pi\nu\bar{\nu})$ **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 $\mathscr{B}(K \to \pi^0\ell^+\nu_\ell)$ decays via isospin rotation.

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]

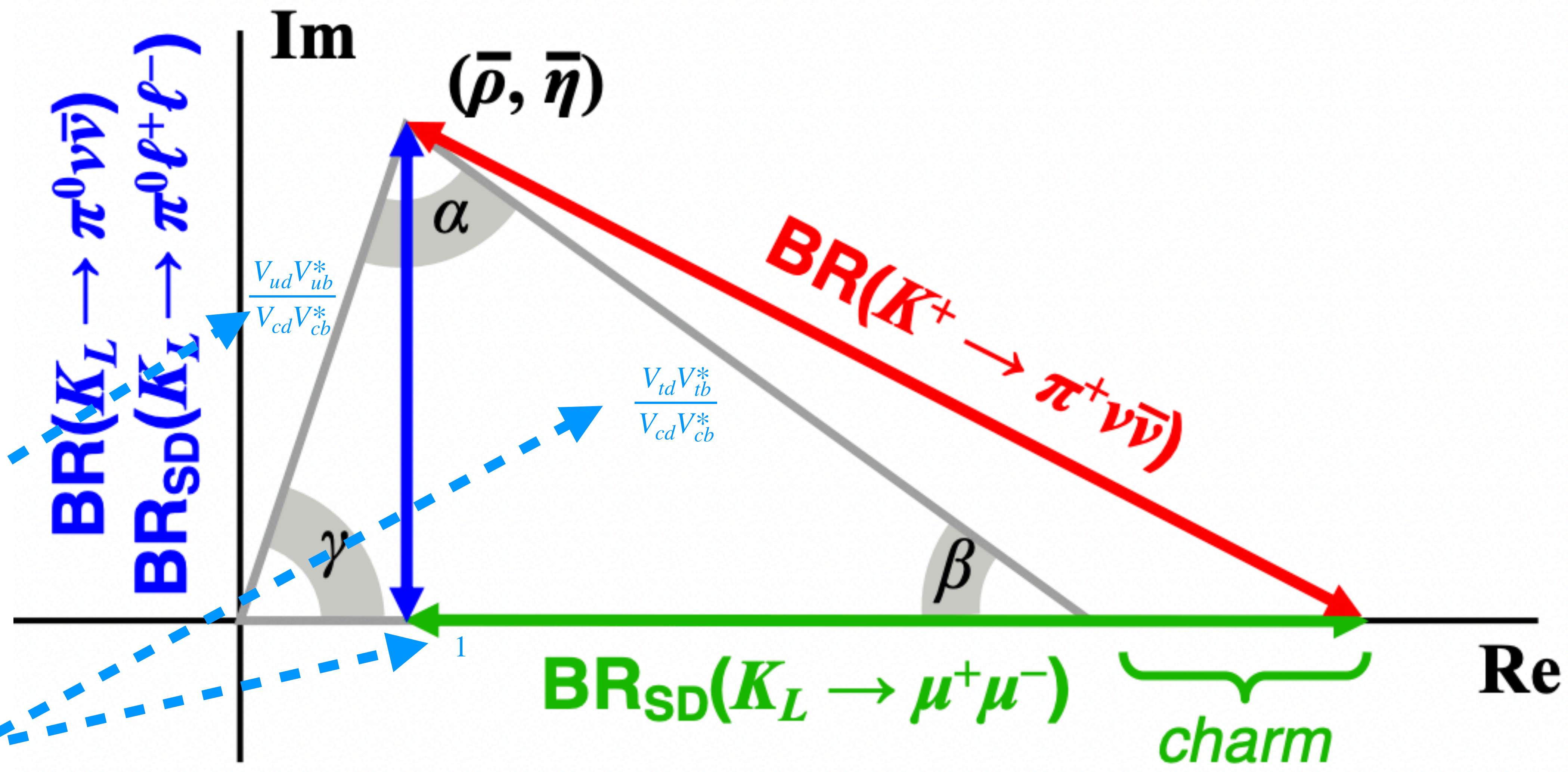
$K \to \pi\nu\bar{\nu}$: Precision test of the Standard Model

- Measurements of **both** charged and natural modes over-constrains CKM parameters:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ \lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)\,,$$

- Unitarity constraint —> unitarity triangle:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \qquad \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

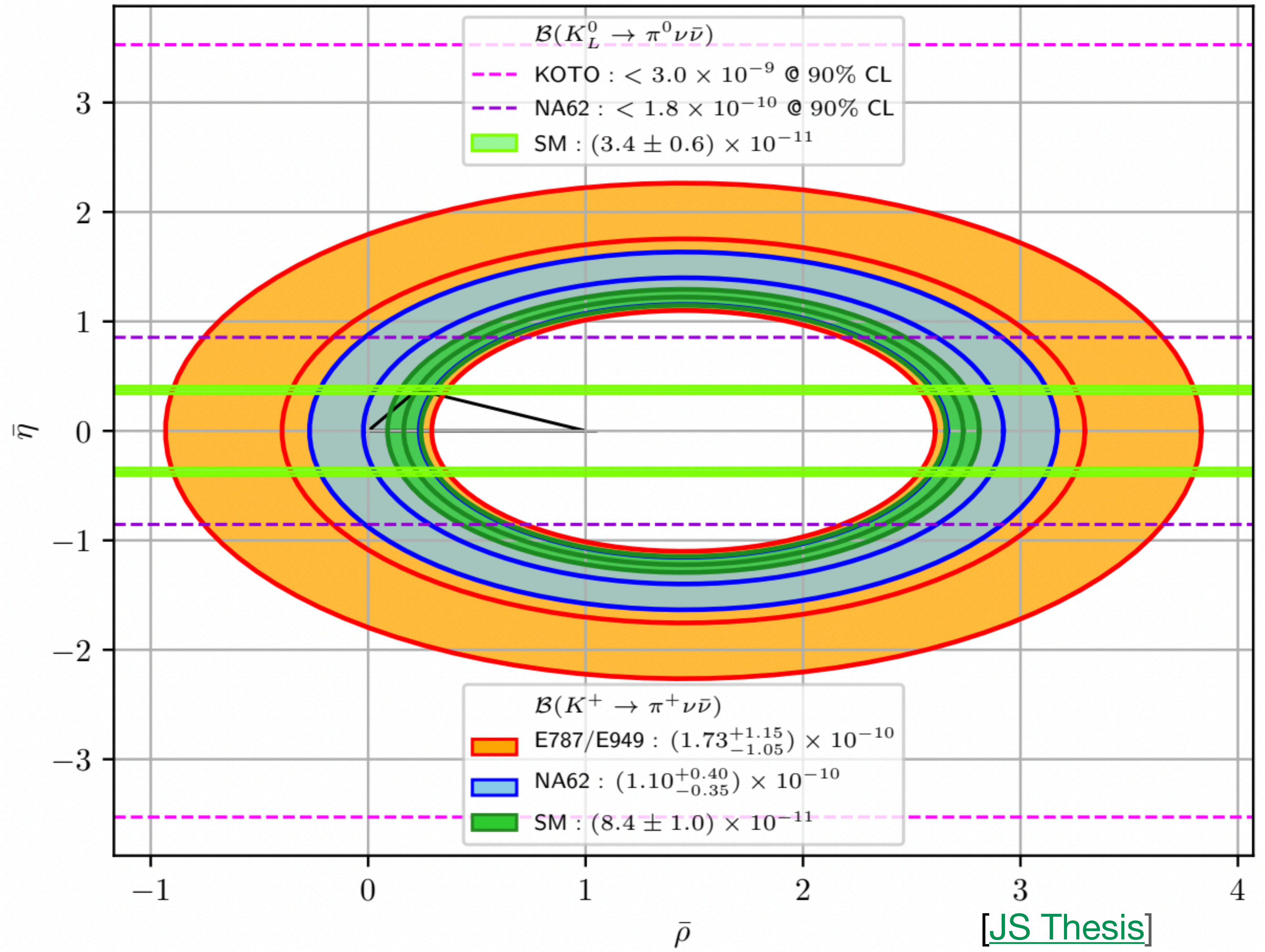


$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) \approx 1.6 \times 10^{-5} |V_{cb}|^4 (\sigma\bar{\eta}^2 + (\rho_c + \bar{\rho})^2)$$

- Charged mode : circular constraint

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \approx 7.6 \times 10^{-5} |V_{cb}|^4 \bar{\eta}^2$$

- Neutral mode : "y-axis" ($\bar{\eta}$) constraint



[JS Thesis]

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

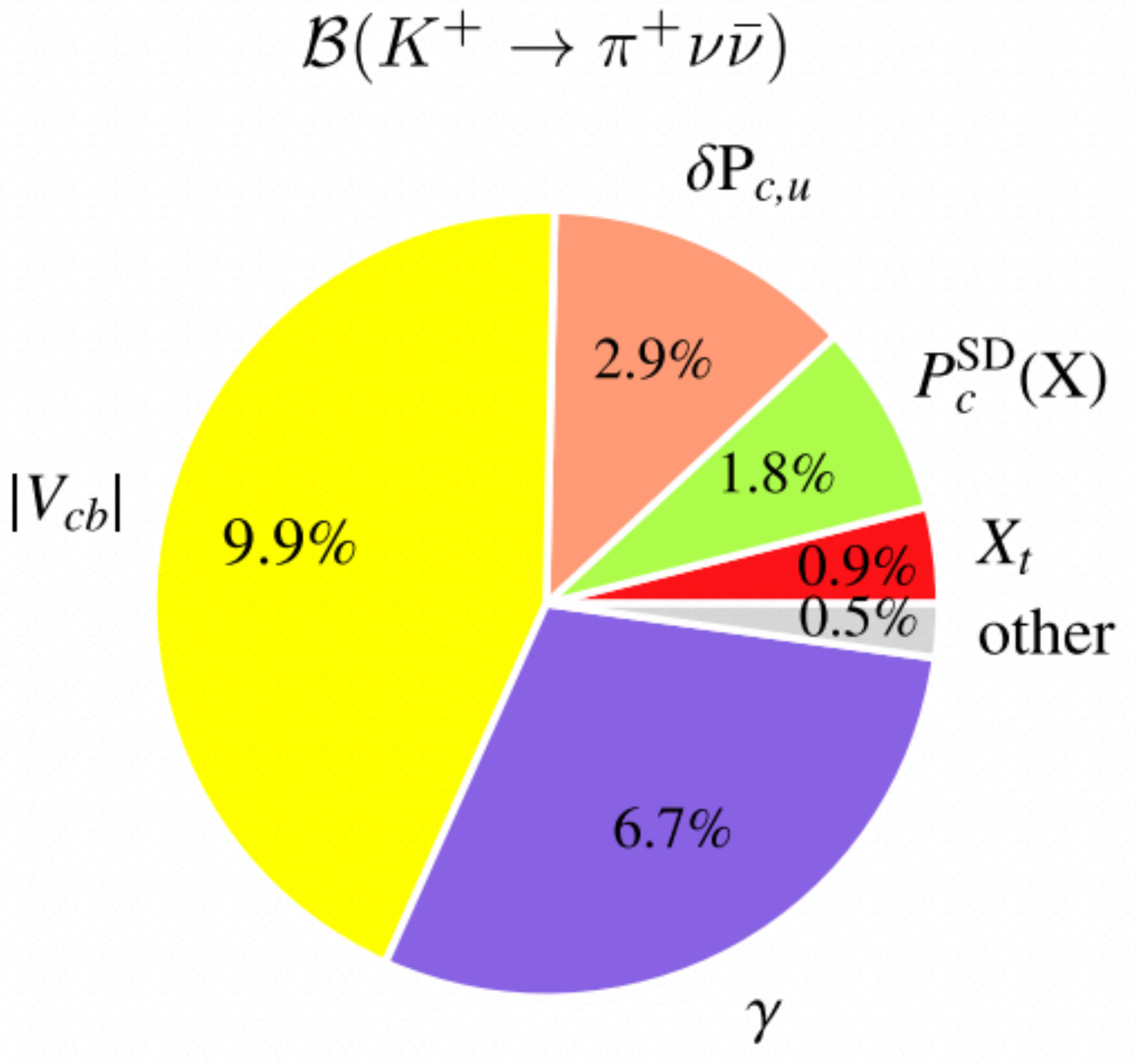
- Theoretically clean ⇒ high precision SM predictions
  - Dominated by short distance contributions.
  - Hadronic matrix element extracted from $\mathscr{B}(K \to \pi^0\ell^+\nu_\ell)$ decays via isospin rotation.

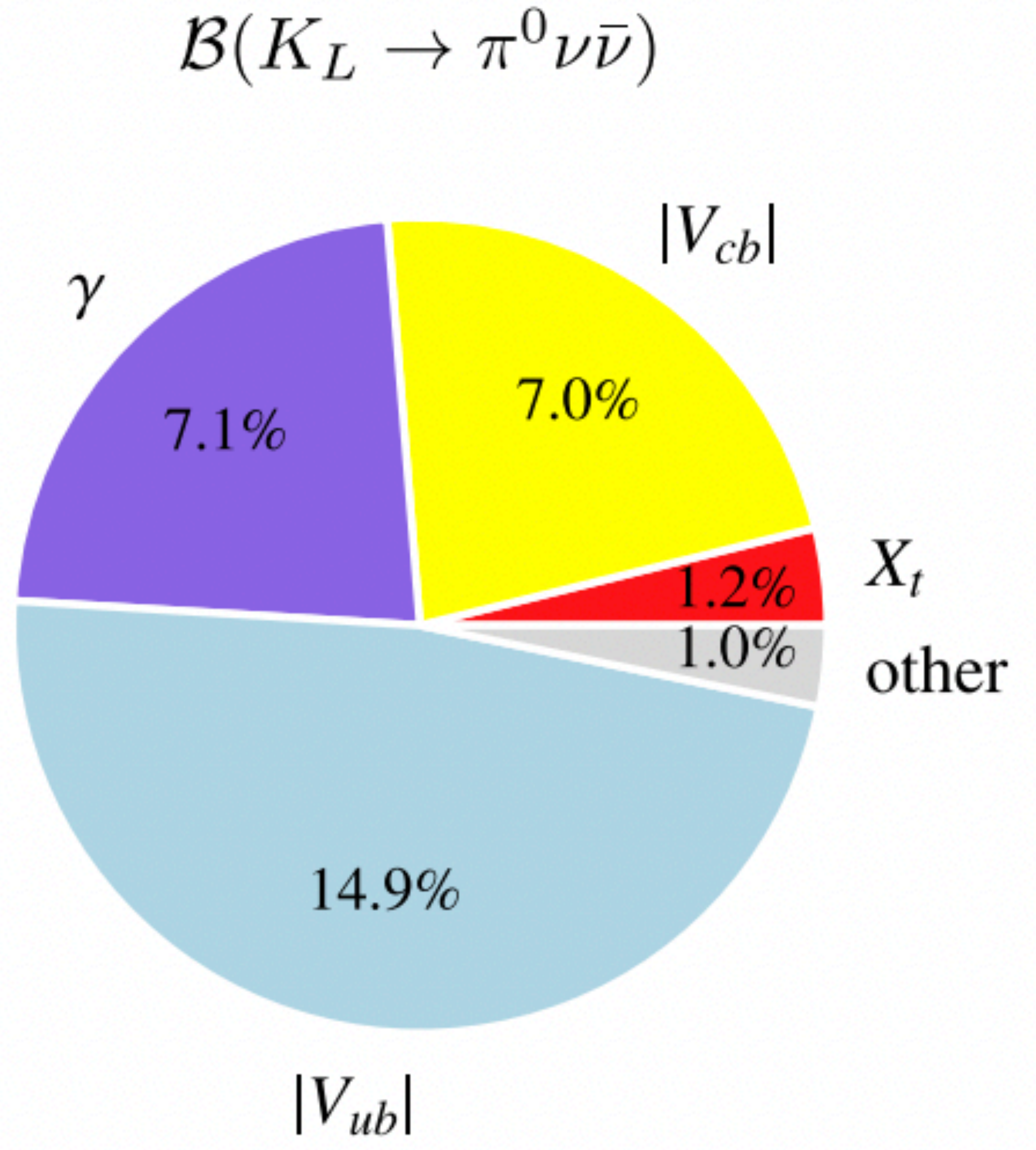
- Precision limited by knowledge of CKM parameters.
  - Improvements ongoing (e.g. γ angle from LHCb.)
- Theoretical precision on BRs can be at the level of $\mathcal{O}(5\%)$.
  - Precision test of SM: do measured BRs agree?
  - Sensitive to new physics: measured BRs do **not** agree…

$$\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

[JHEP 11 (2015) 033]

$$\mathscr{B}(K_L \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \left[\frac{|V_{ub}|}{3.88 \times 10^{-8}}\right]^{2} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2} \left[\frac{\sin(\gamma)}{\sin(73.2^\circ)}\right]^{2}$$



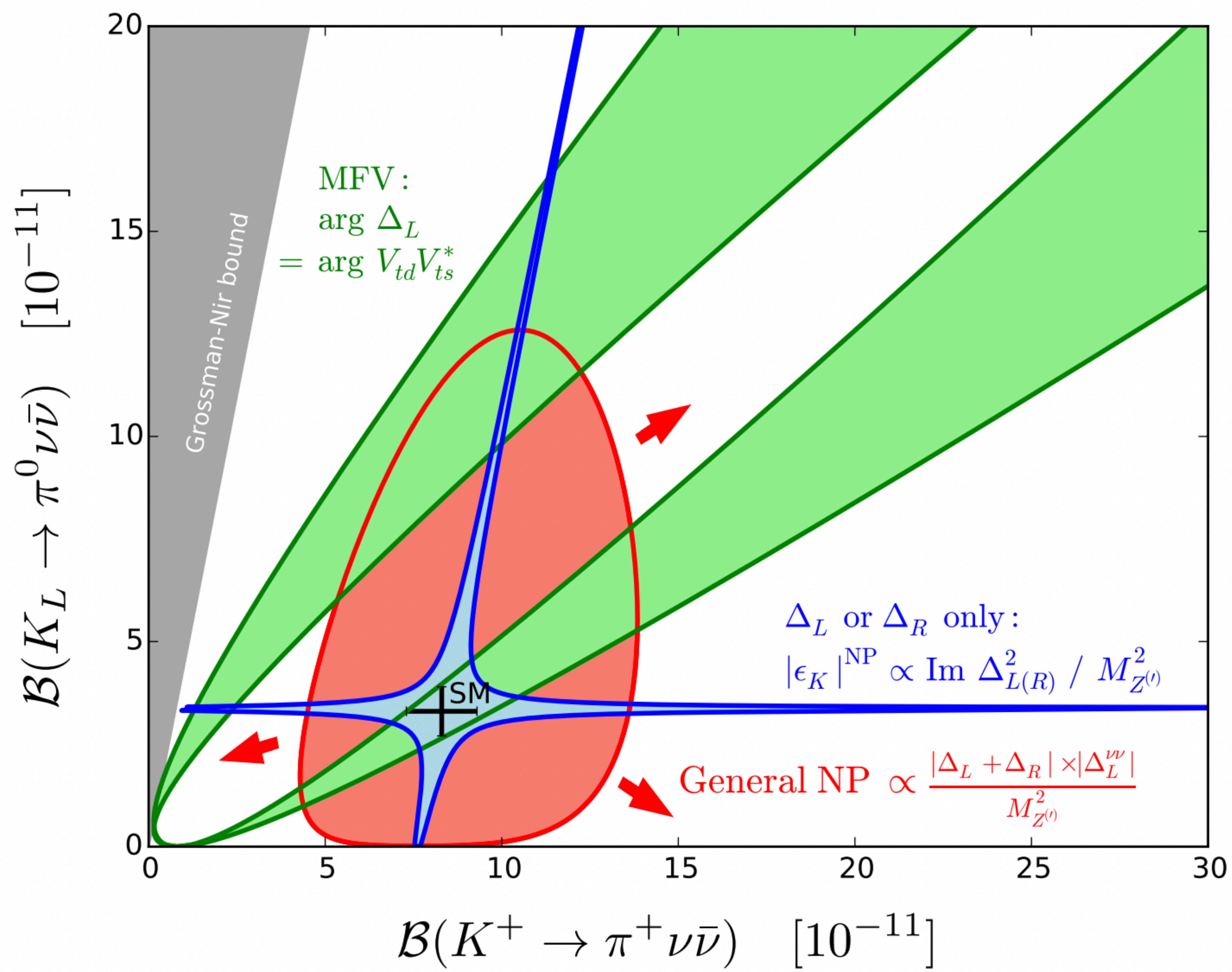


$K \to \pi\nu\bar{\nu}$: Beyond the Standard Model

- 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.
- 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

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

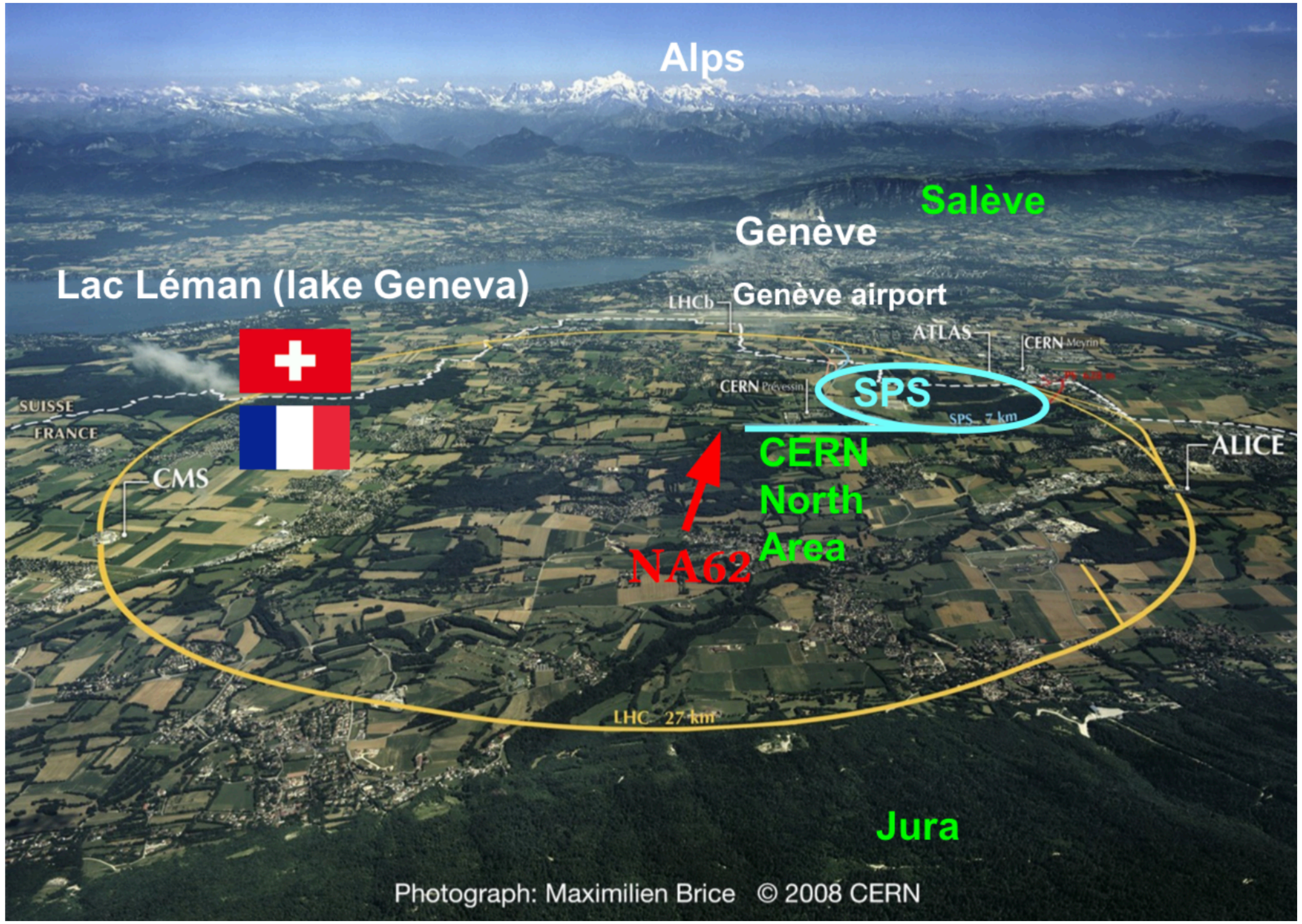


[Buras et al. JHEP 11 (2015) 166]

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

The NA62 Experiment at CERN

~300 collaborators from ~30 institutions.



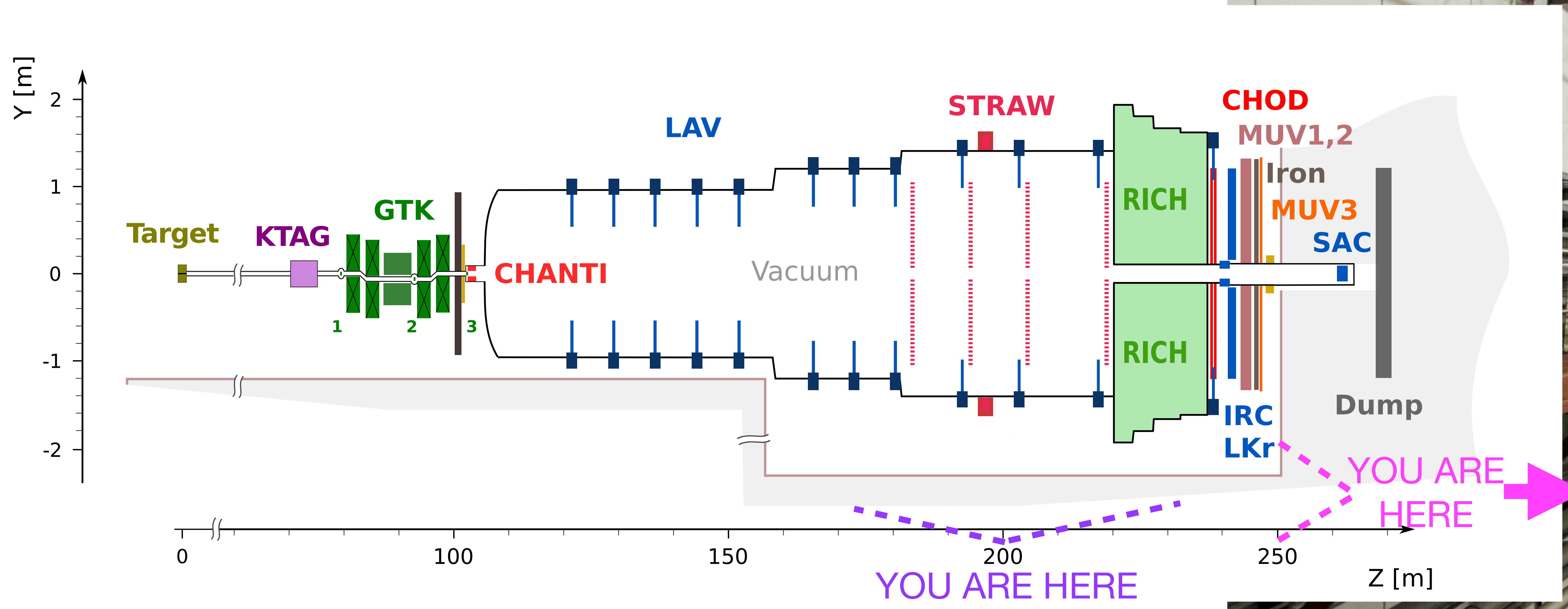
- **Primary goal:** measurement of $\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu})$
- **New Technique:** K^+ decay-in-flight
- **Results:** [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
- **Broader physics programme:**
  - Rare K^+ decays (e.g. $K^+ \to \pi^+\gamma\gamma$ [PLB 850 (2024) 138513])
  - LNV/LFV decays (e.g. $K^+ \to \mu^+\nu e^+ e^+$ [JHEP 09 (2023) 040])
  - Exotics (e.g. Dark photon [arXiv.2312.12055])
- **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 …

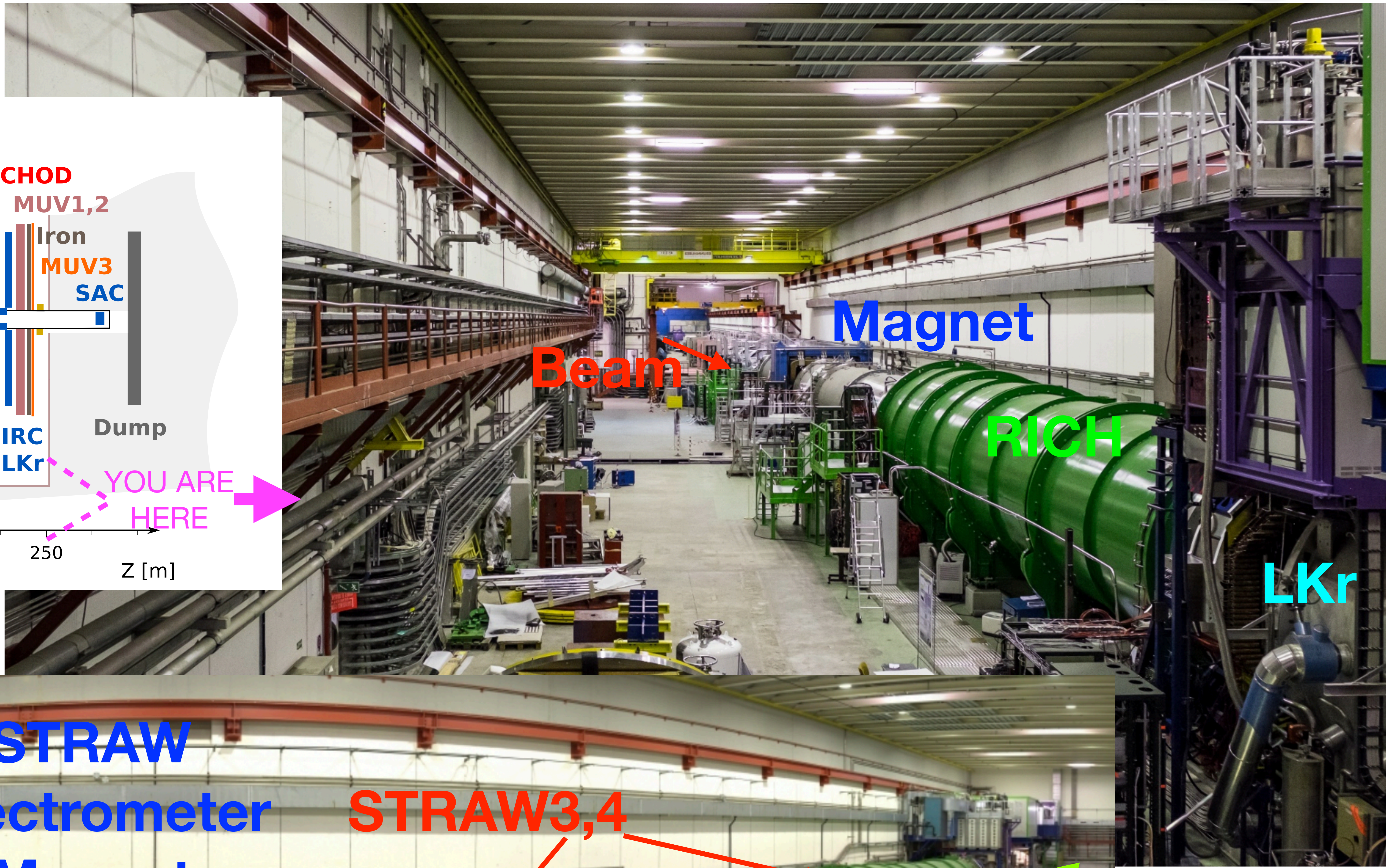
Continues long history of Kaon physics at CERN :

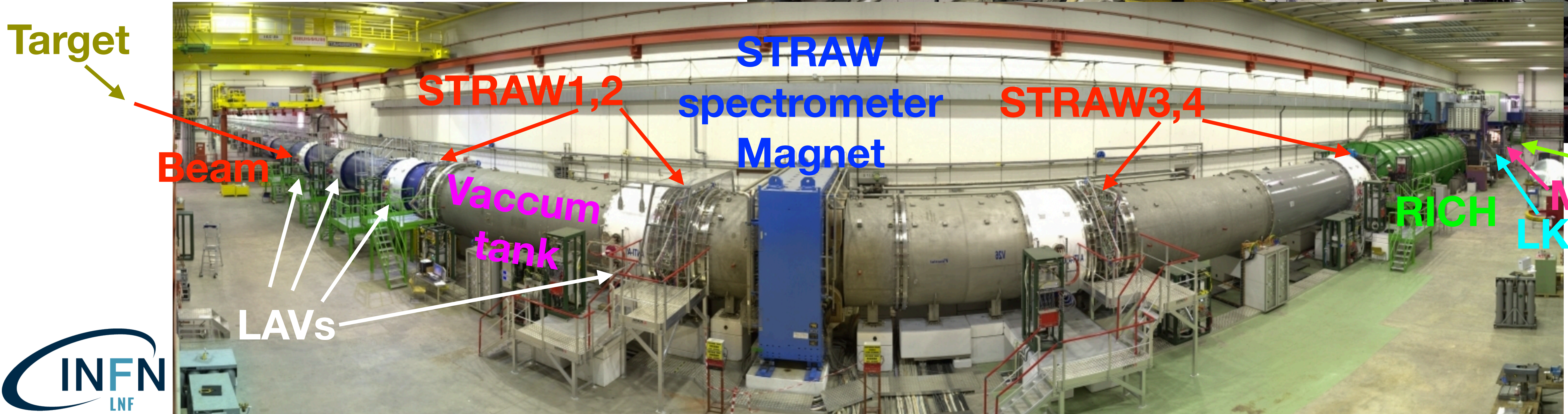
NA31	NA48	NA48/1	NA48/2	NA62-R_K	NA62 Run1	NA62 Run2
1986-98	1977—2001 Discovery of direct CVP	2002	2003-4	2007-8	2016-18	2021—LS3

NA62 Beamline & Detector

$\bar{x}(75\,\mathrm{GeV}/c\,K^+) = \beta\gamma c\tau = 560\,\mathrm{m}$



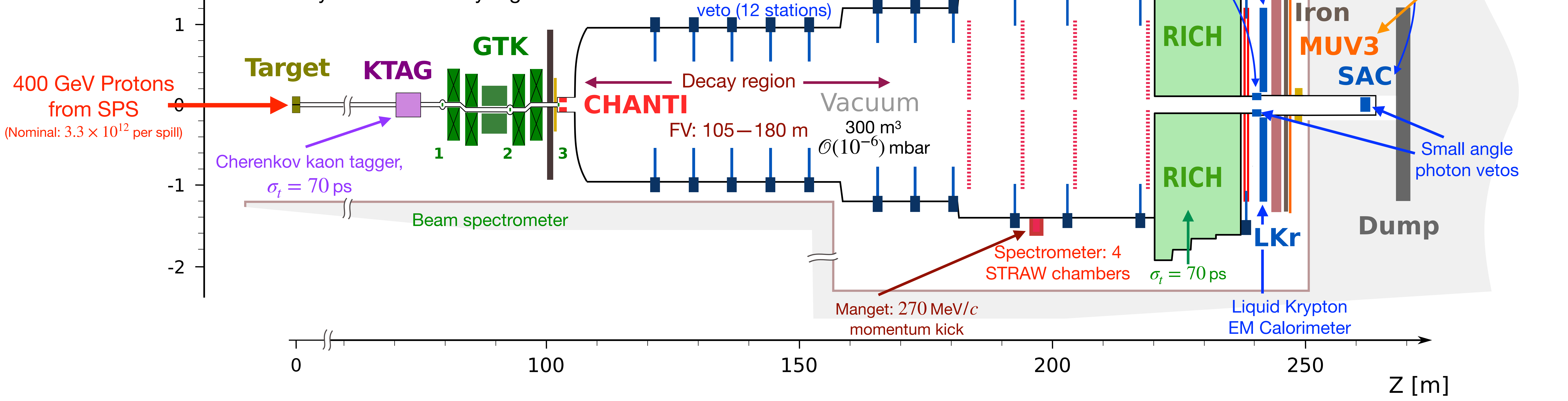




NA62 Beamline & Detector

[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)

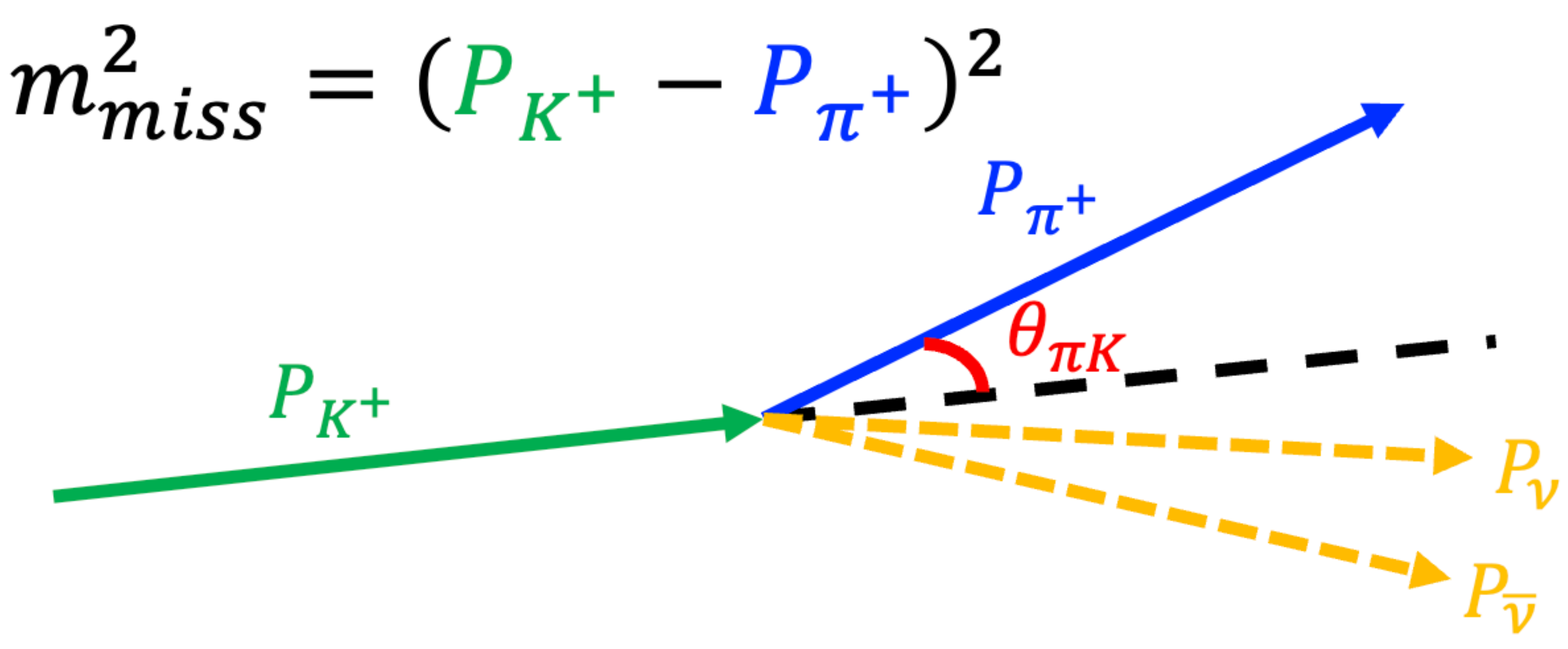
$K^+ \to \pi^+ \nu \bar{\nu}$ at NA62

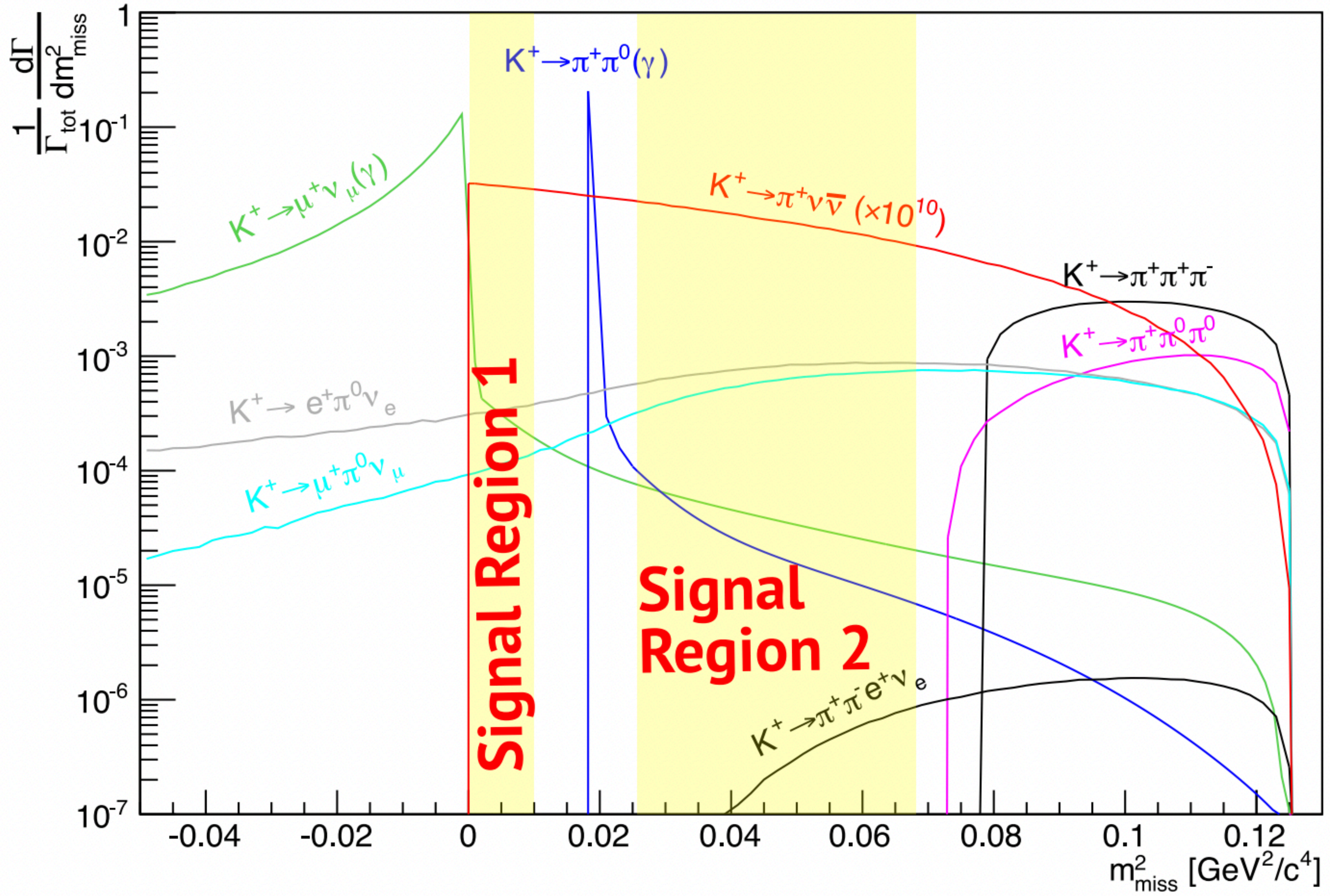
NA62 Performance Keystones:

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

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

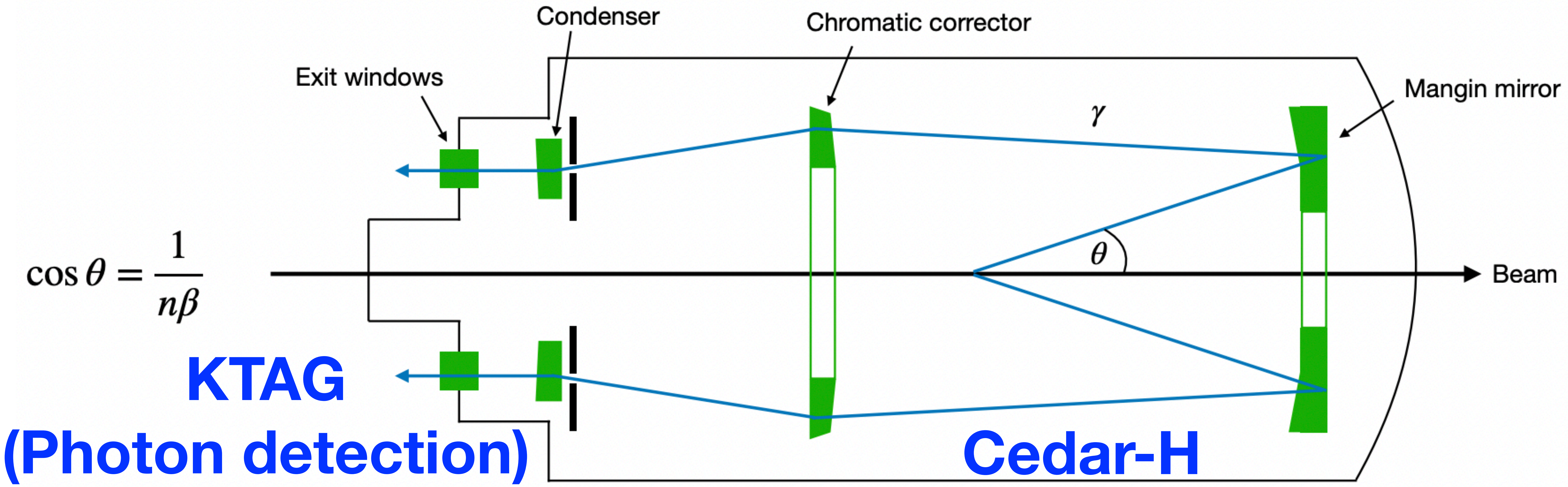


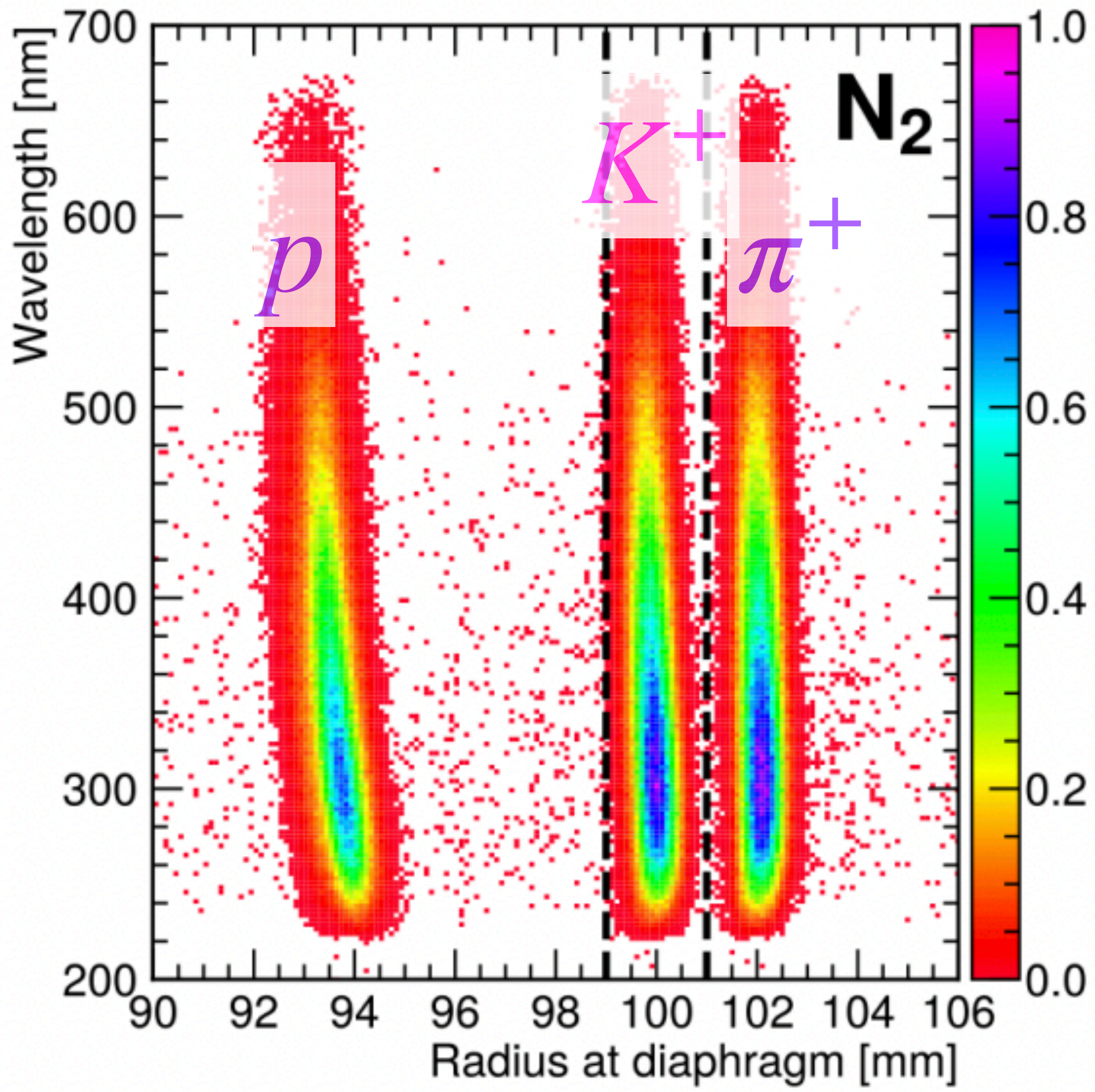


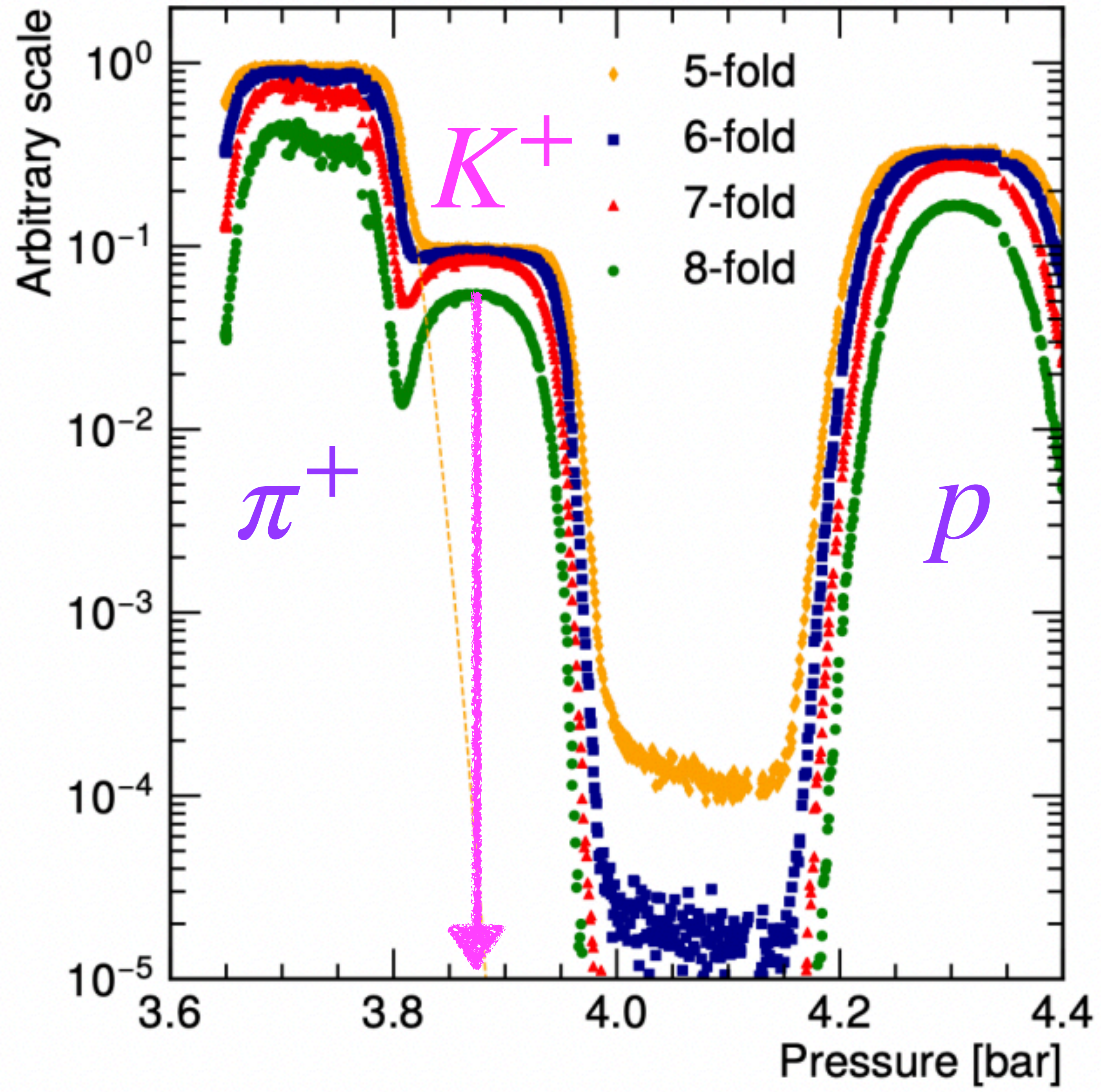
Cedar-H & KTAG : K^+ tagging with threshold Cherenkov counter

- Only 6% of 75GeV/c secondary beam is K^+.
  - (70% p, 23% π^+)
- Set diaphragm aperture so only photons from K^+ reach photon detectors.
- **New for 2023**: redesigned Cedar (new optics) for operation with H_2.
  - Reduce inelastic scattering: $(39 \rightarrow 7) \times 10^{-3} X_0$.
- $\varepsilon_K > 99.5\,\%$, $\eta_\pi \leq 10^{-4}$
- **~65ps time resolution.**

More info: [Kenworthy, PM2024]

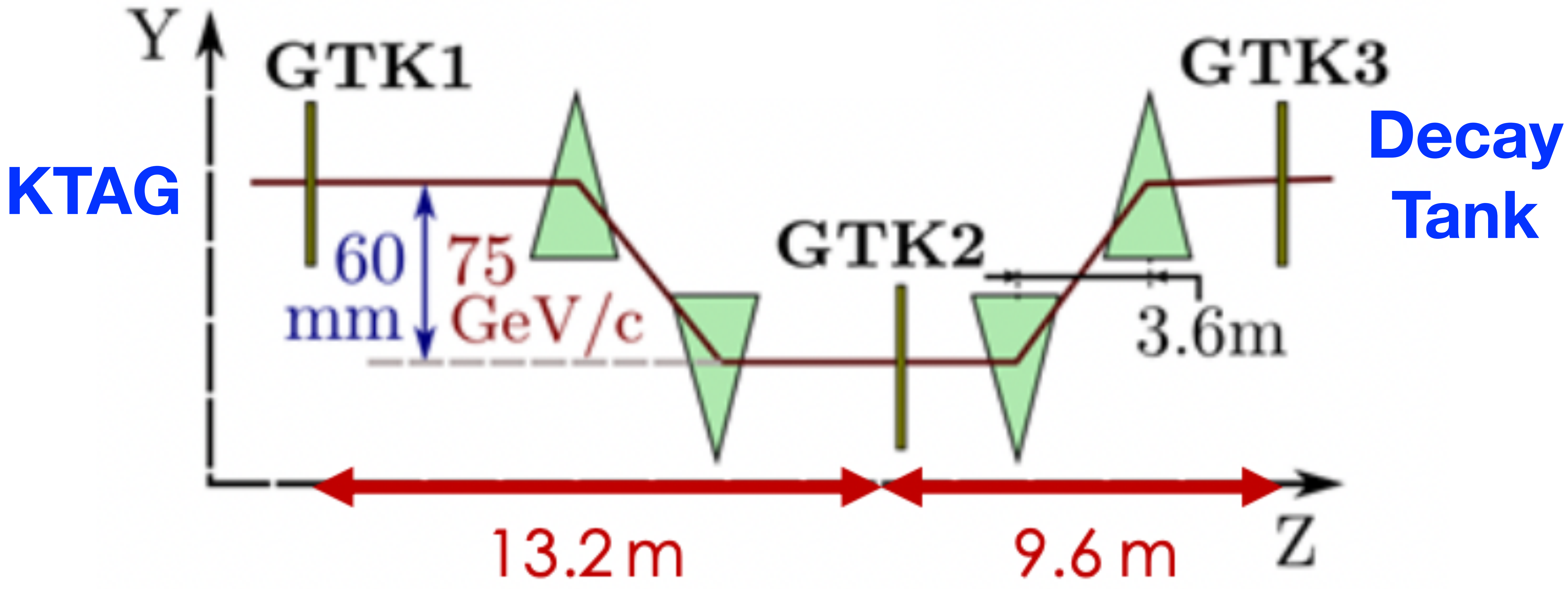


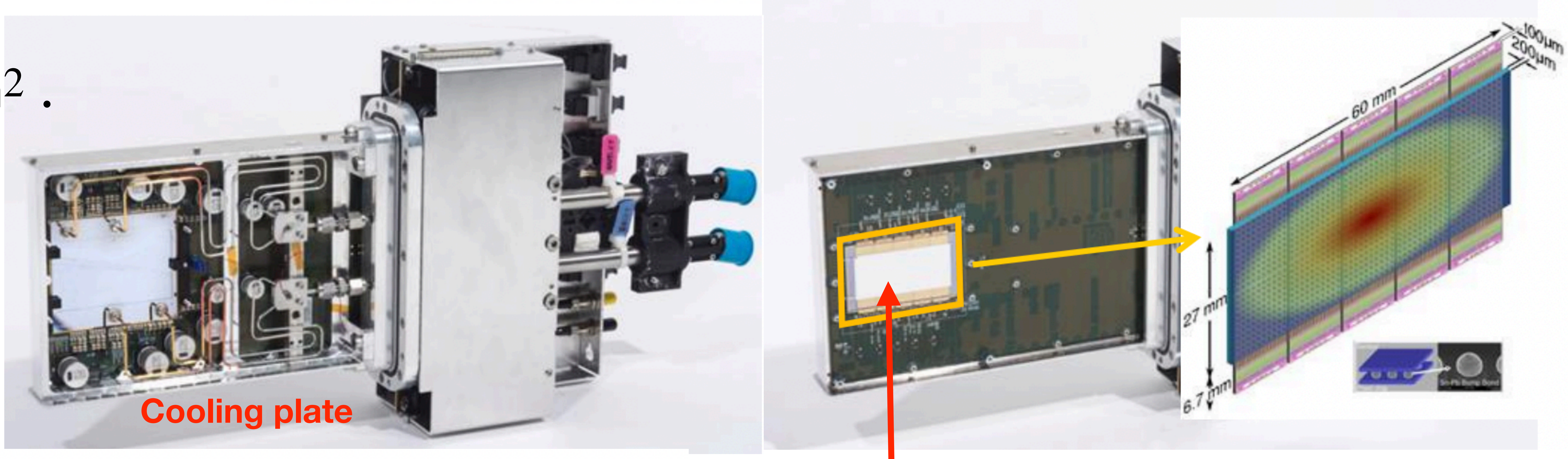




GTK: Si Pixel Detector exposed to ~1GHz beam

- Upstream spectrometer with Hybrid si pixel detectors.
  - Key for $K^+ - \pi^+$ matching.
- 4D beam tracker:
  - Measures momentum & angle ($\sigma_\theta = 16\,\mu$rad) of **all beam particles**, with **~100ps time resolution**.
- Most irradiated modules with peak(average) fluence of $2.5(0.8) \times 10^{14}$ 1MeVn_{eq}/cm² .
- 4th GTK station installed in 2021 to improve tagging and rejection of 'upstream background' related to pileup beam particles.





Si Pixels ~(30x60 mm active area)

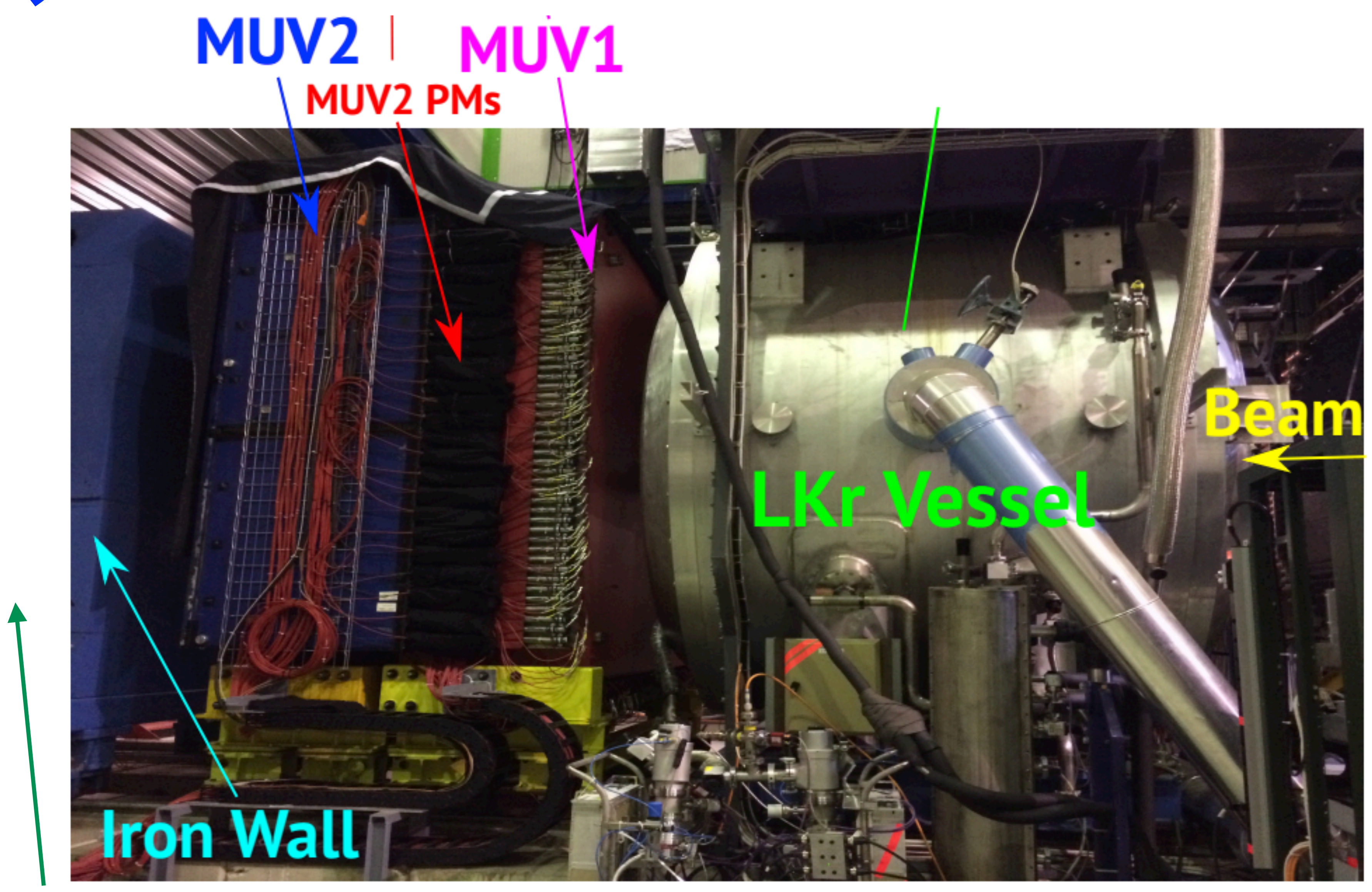
More info: [Kleimenova, VERTEX2023]

Particle ID: RICH, Calorimeters. MUV3

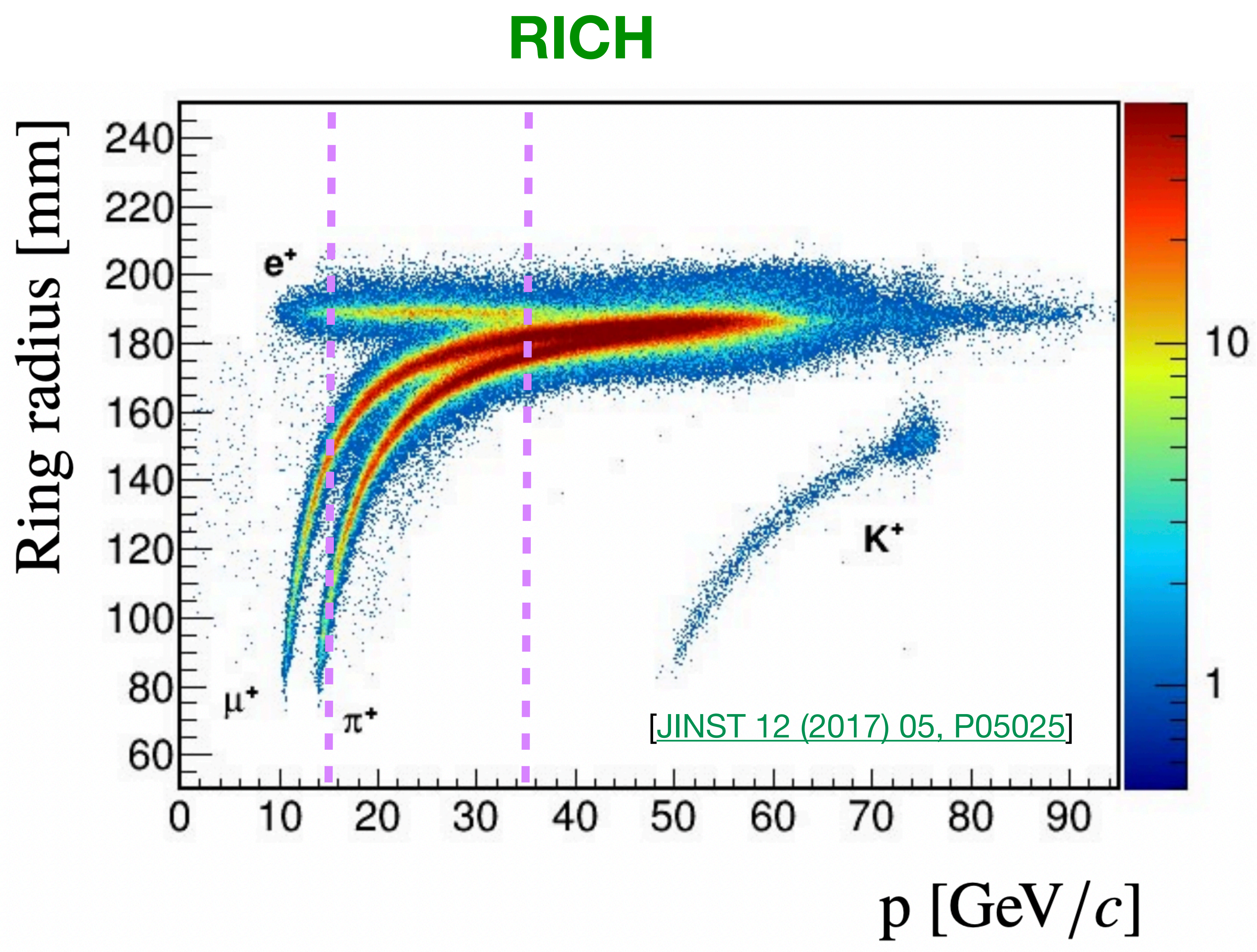
- RICH: 17.5m long filled with Neon gas.
- Designed to distinguish between $15 - 35\,\text{GeV}/c$ π^+/μ^+.
- Calorimeters:
  - LKr ~ ECAL
  - MUV1,2 ~ HCAL
- + MUV3 (fast mu detector, used for trigger)

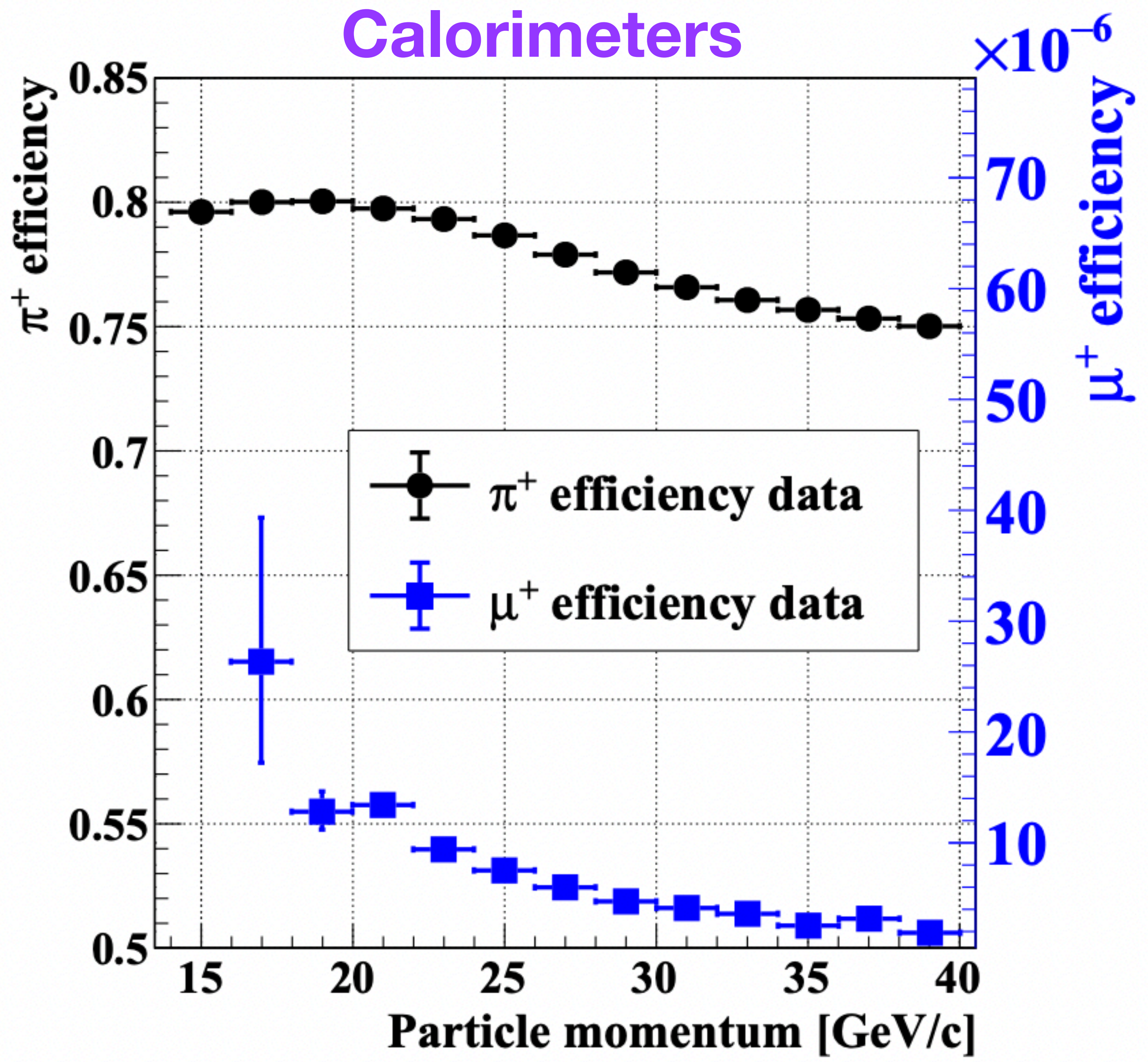
- **Combined μ^+ rejection of $> 10^7$.**

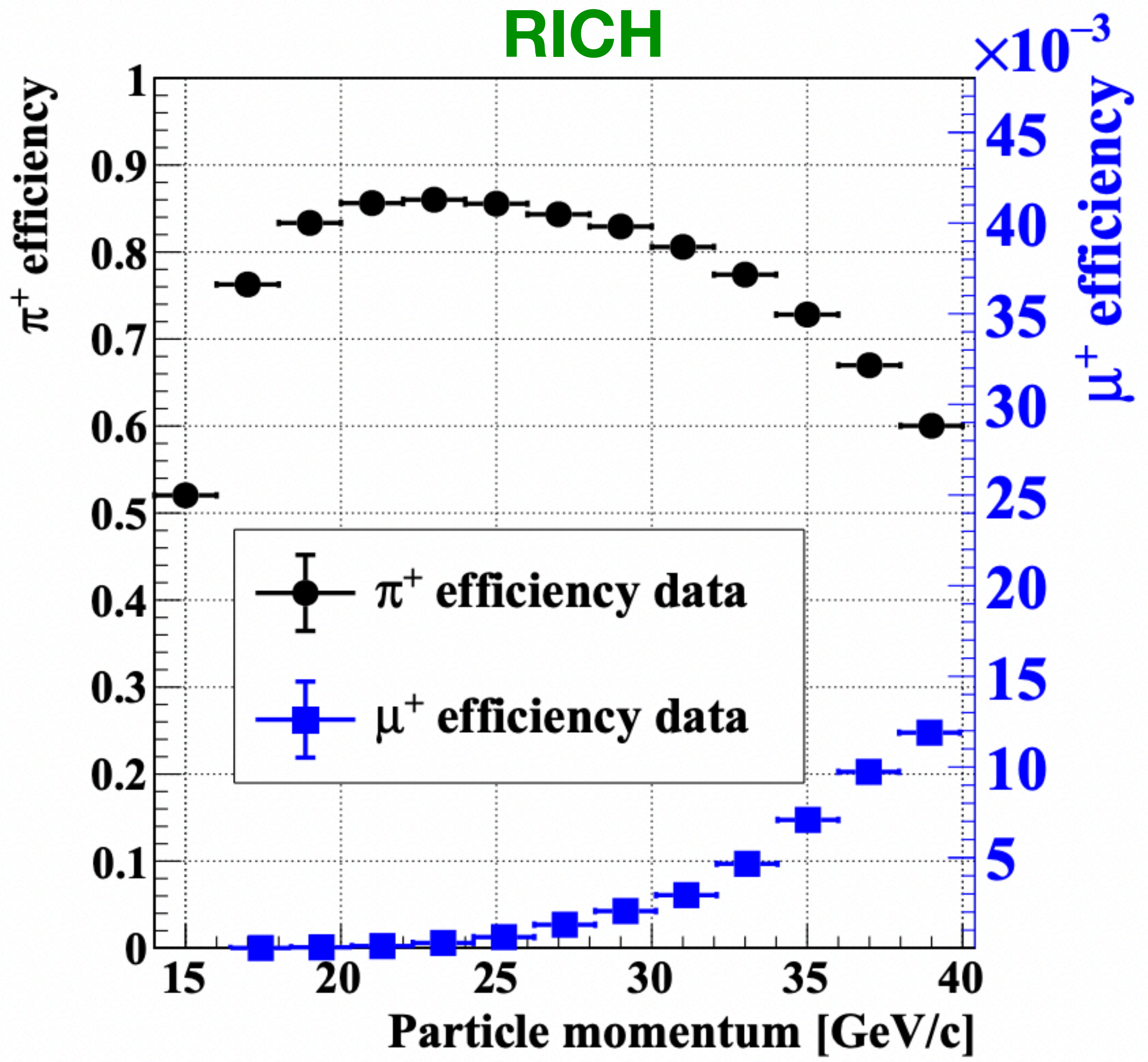
[JHEP 11 (2020) 042]



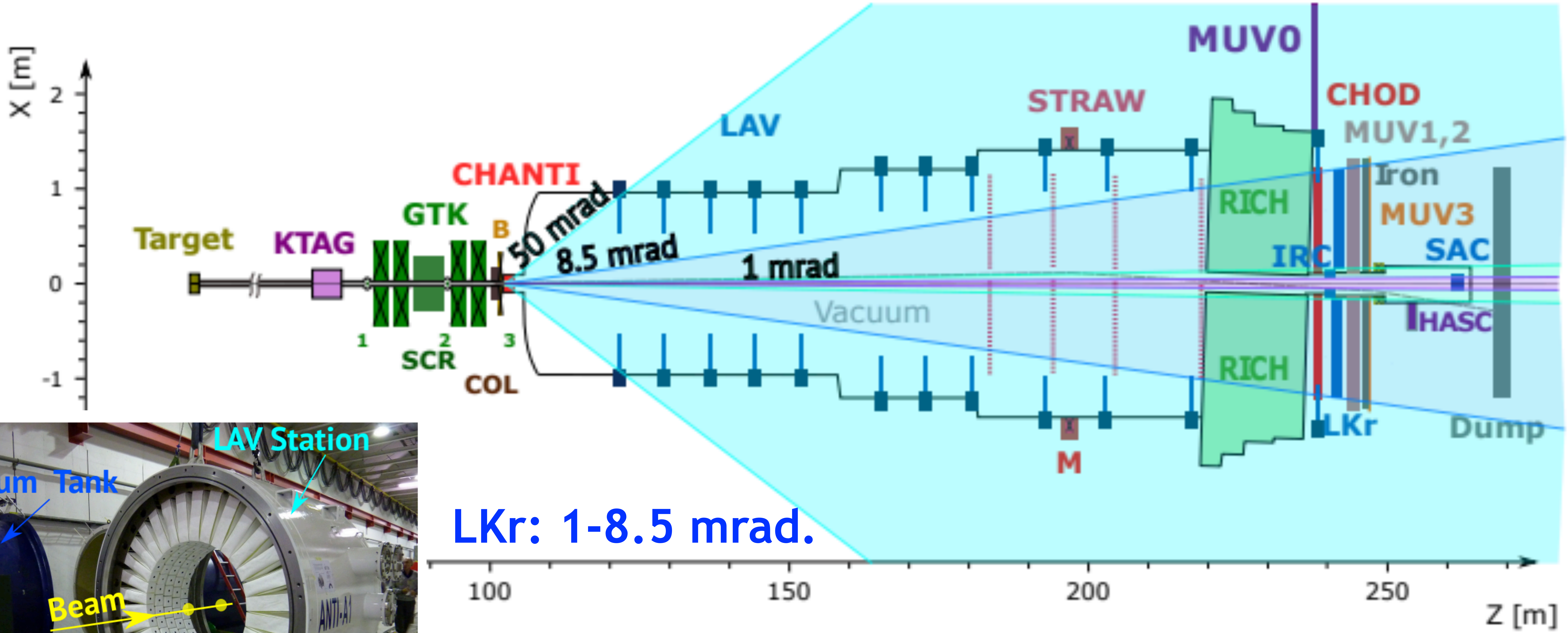
MUV3: fast muon scintillator detector

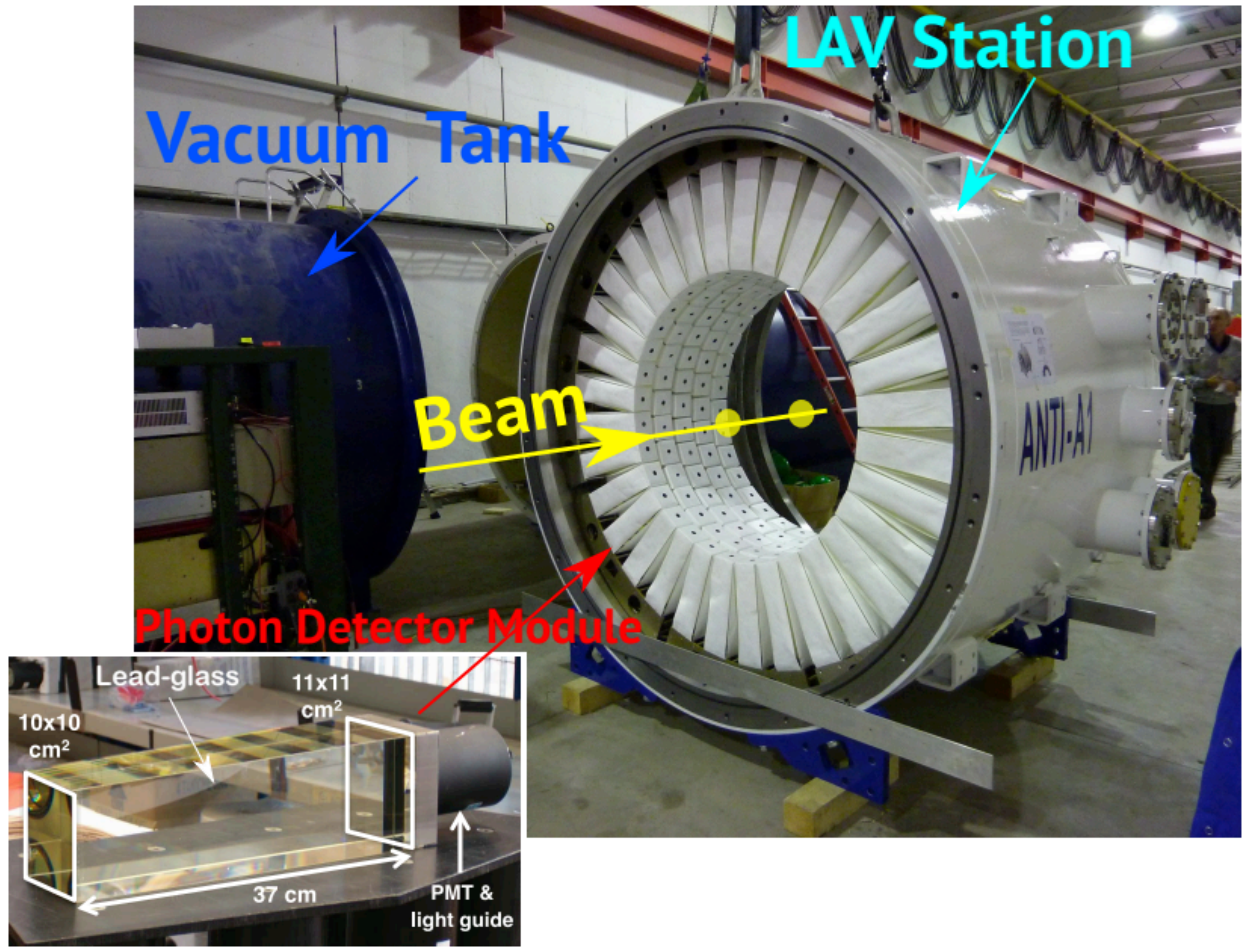


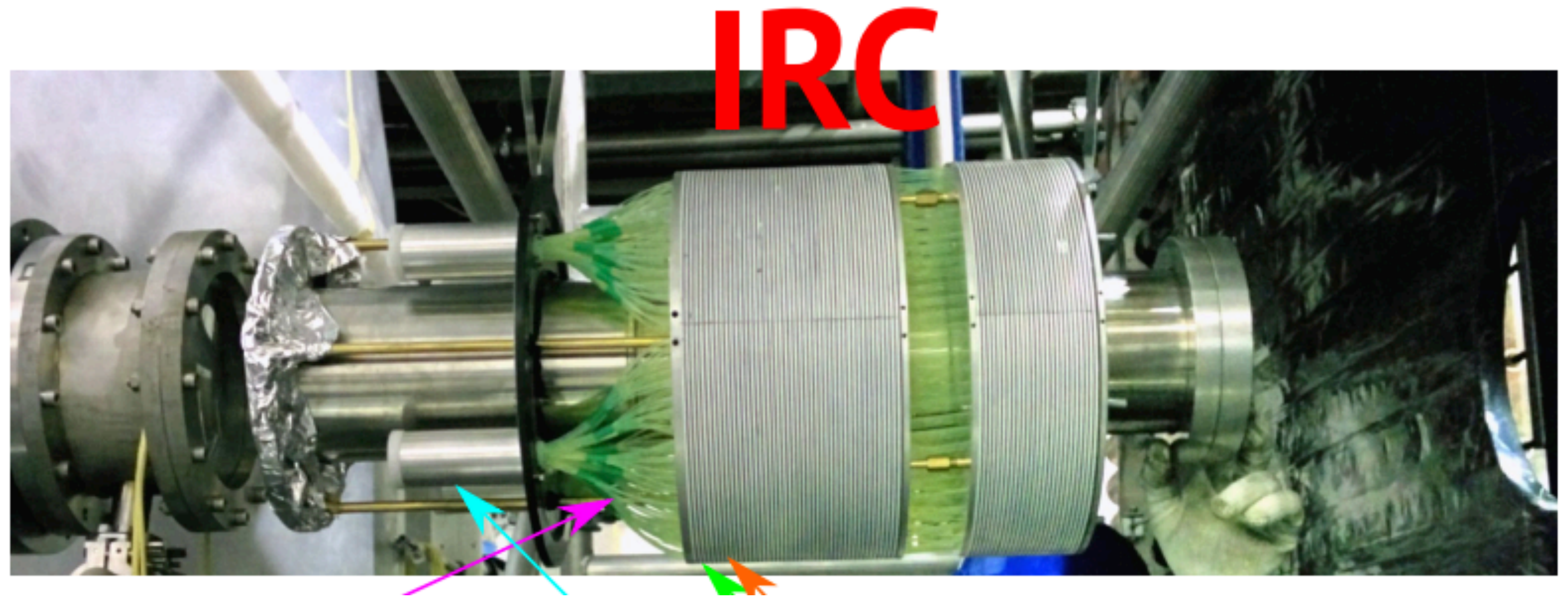


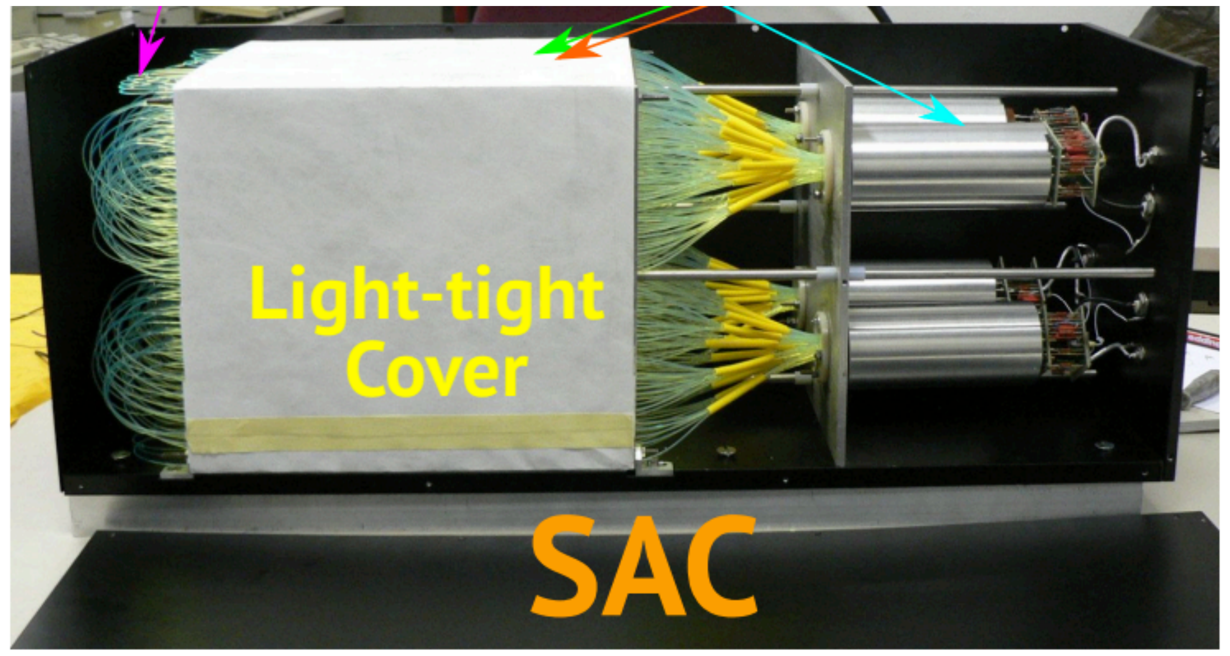


Comprehensive photon veto system









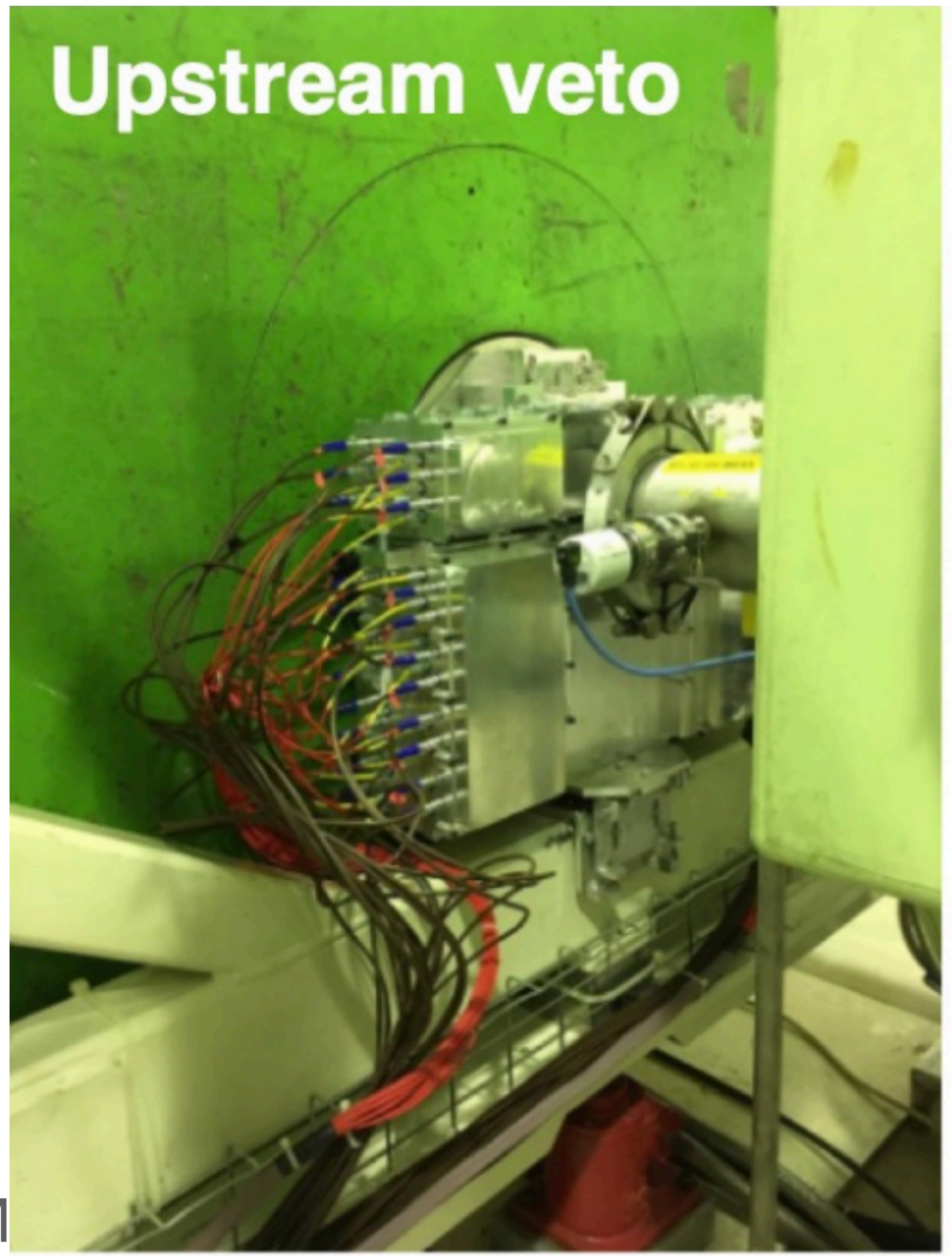
- Combined γ/π^0 rejection of $> 10^8$.

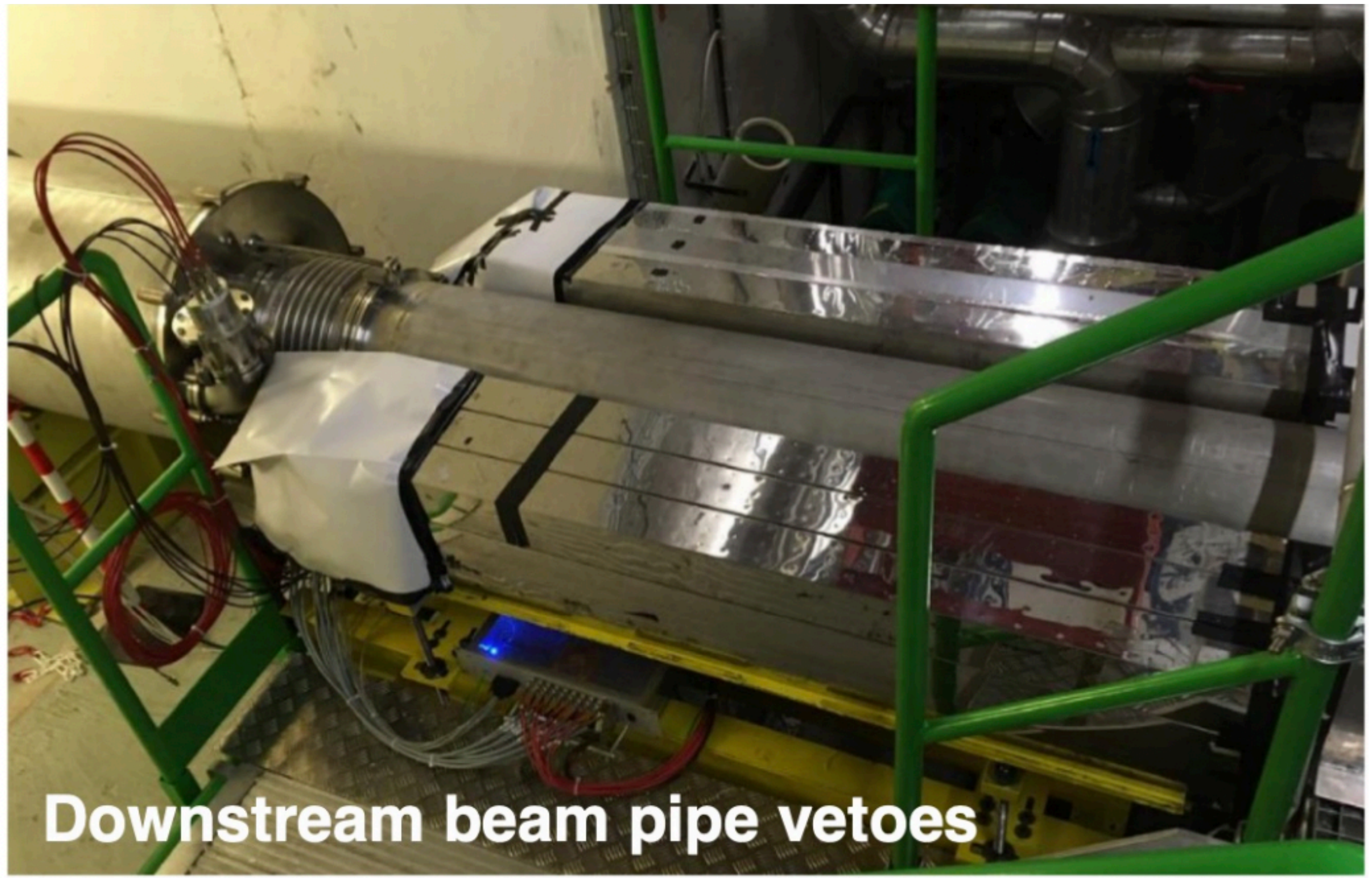
[JHEP 11 (2020) 042]

NA62 Run2 Upgrades

- New detectors:
  - Cedar-H (2023)
  - 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 to end of Run1 [$450 \rightarrow 600$ MHz].
- **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.

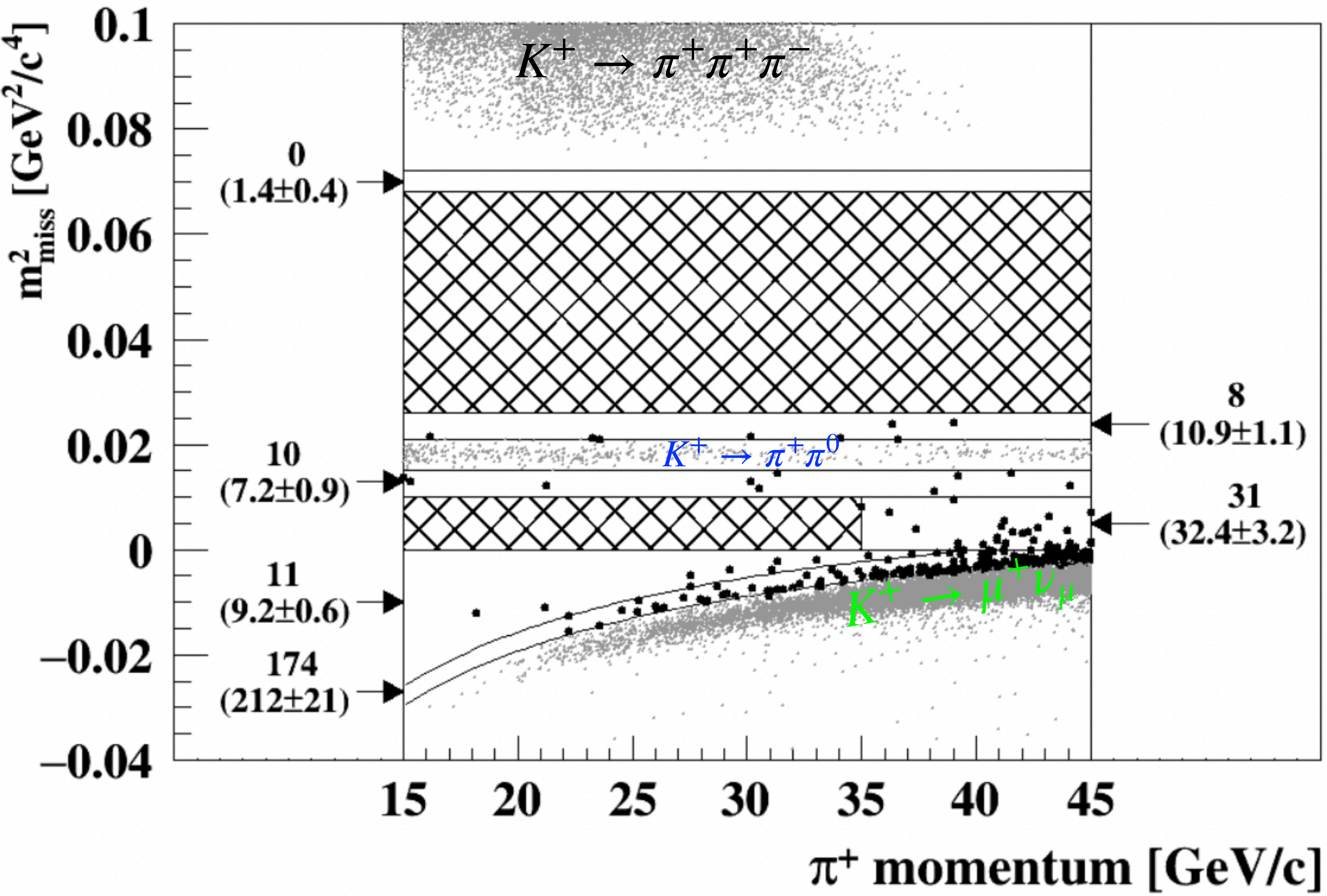
New detectors installed in 2021 for NA62 Run2:





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

Background Studies [2018 data]



Before & after new final collimator in 2018

K^+ decays in the FV

Background	Subset S1	Subset S2
$\pi^+\pi^0$	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%]

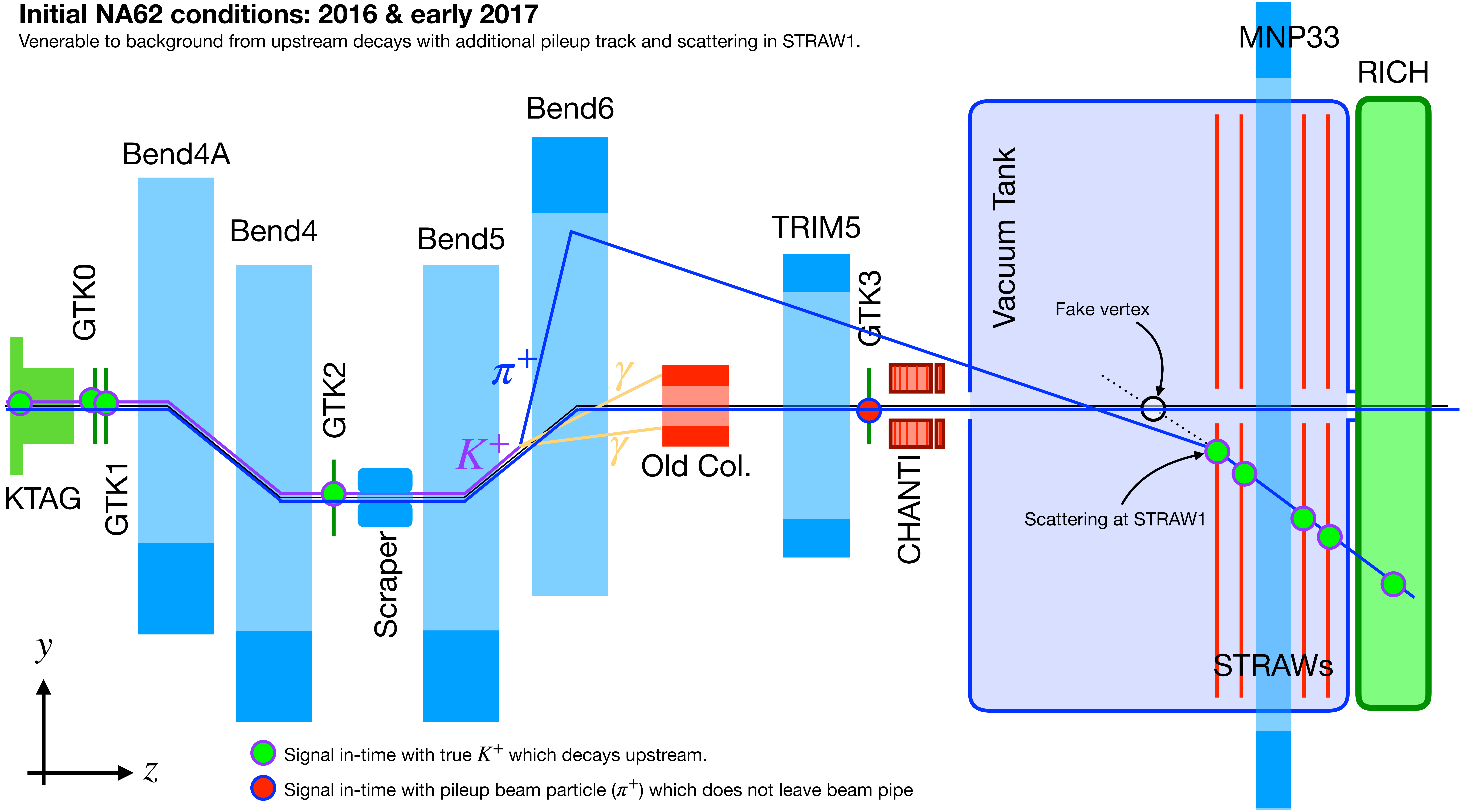
- Primary backgrounds (from kinematic tails) evaluated with data-driven procedures.
- Upstream bkg. dominated by decays upstream of FV
  - New collimator installed (June 2018) blocks many upstream decays
  - Strict anti-upstream rejection loosened.

[JHEP 06 (2021) 093]

Upstream Background & new VetoCounter

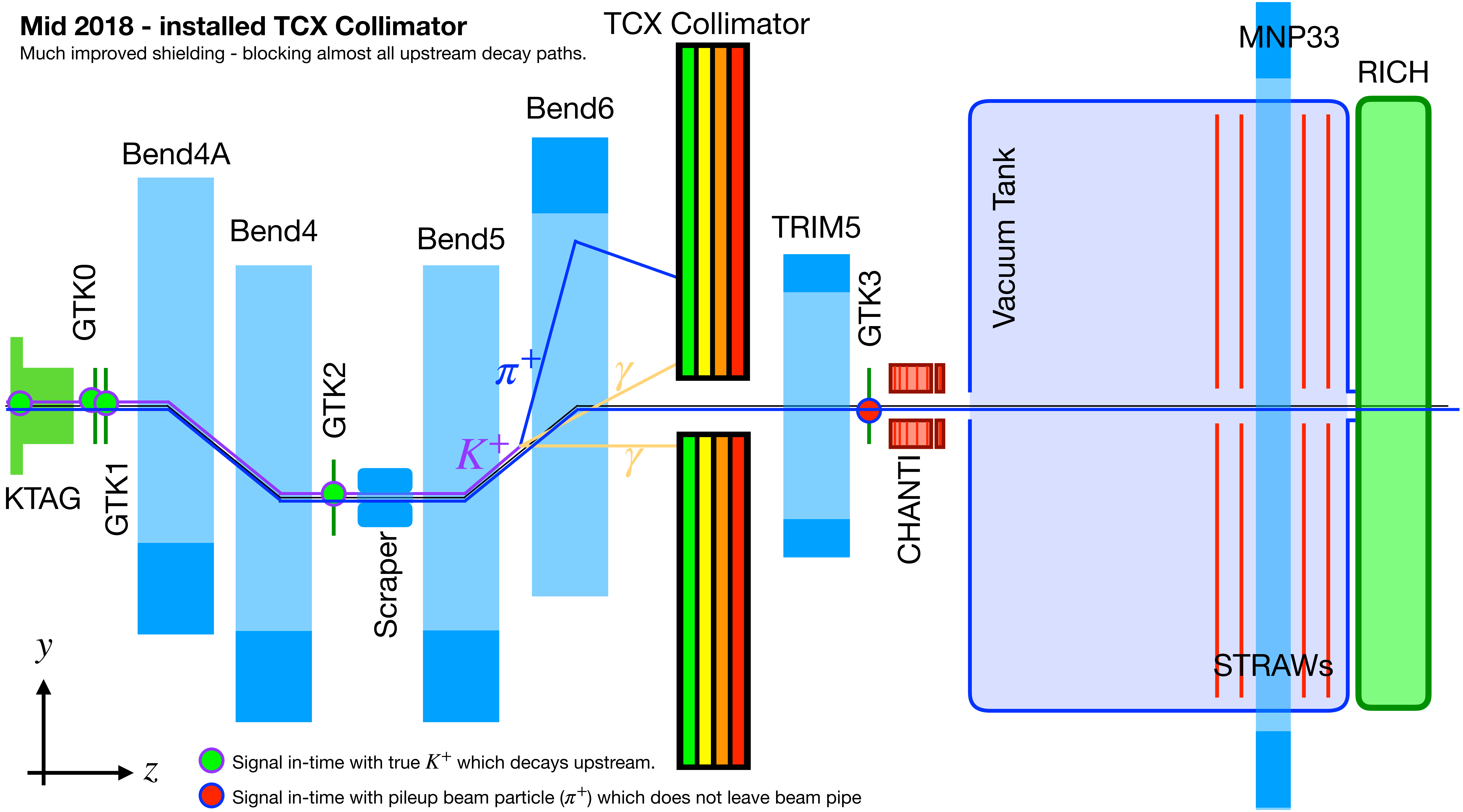
Initial NA62 conditions: 2016 & early 2017

Venerable to background from upstream decays with additional pileup track and scattering in STRAW1.

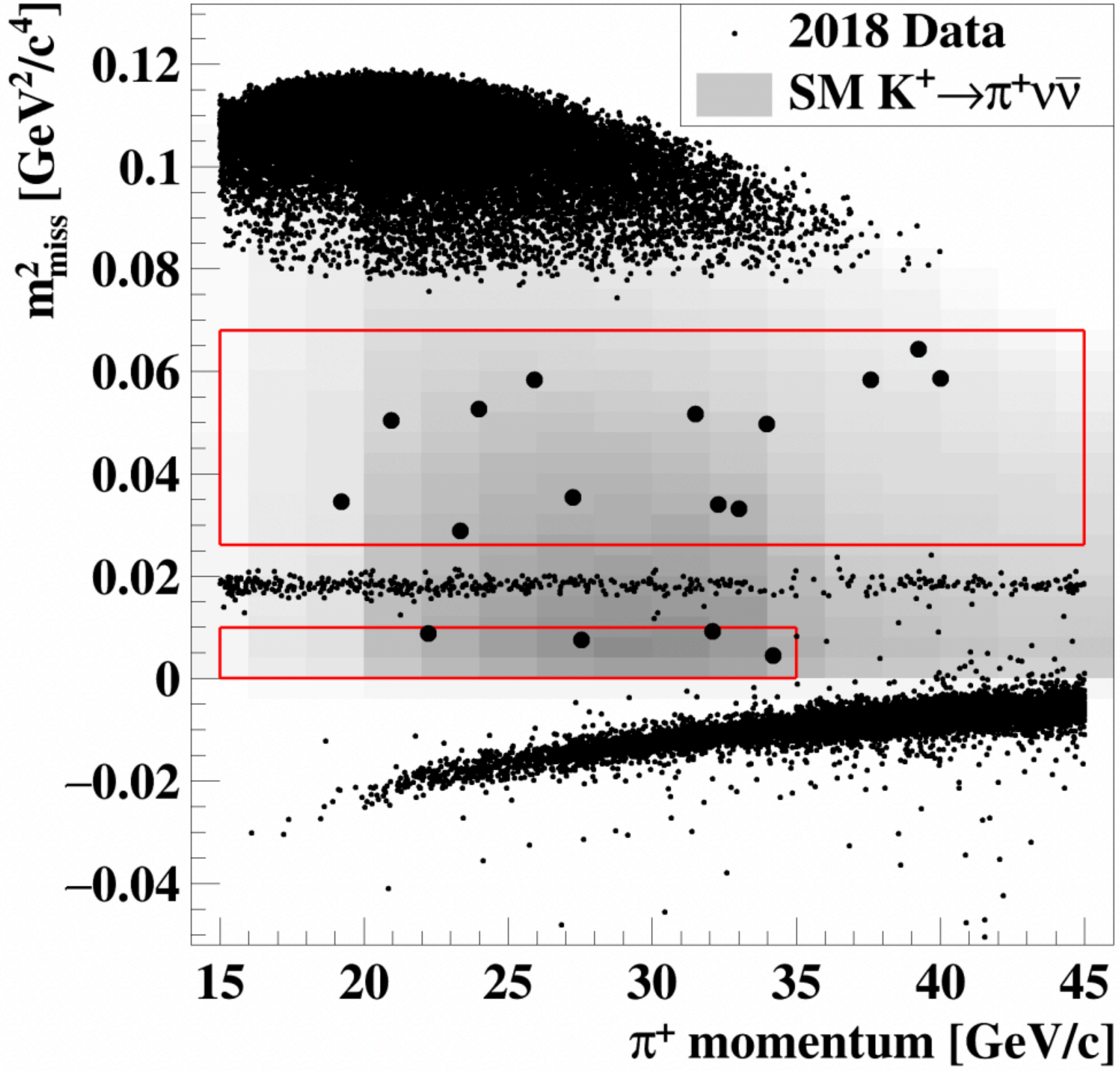


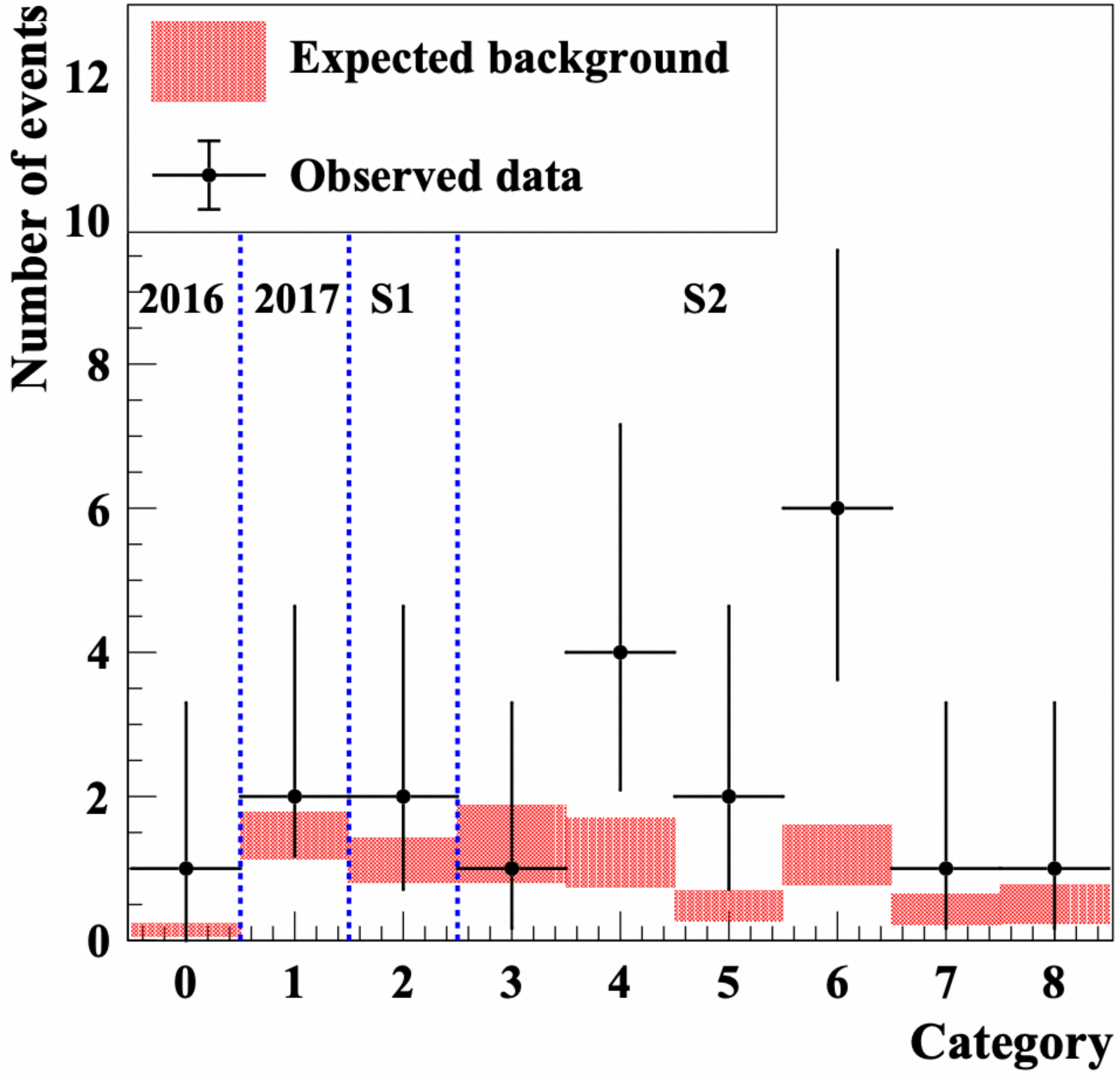
Upstream Background & new VetoCounter

Mid 2018 - installed TCX Collimator
Much improved shielding - blocking almost all upstream decay paths.



Run1 (2016–18) $K^+ \rightarrow \pi^+\nu\bar{\nu}$ 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: $p = 3.4 \times 10^{-4}$ $\Rightarrow$ signal significance: 3.4σ.
- $\mathscr{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$ @ 68 % CL [JHEP 06 (2021) 093]

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

Work in progress

[NA62 SPSC report 2024]

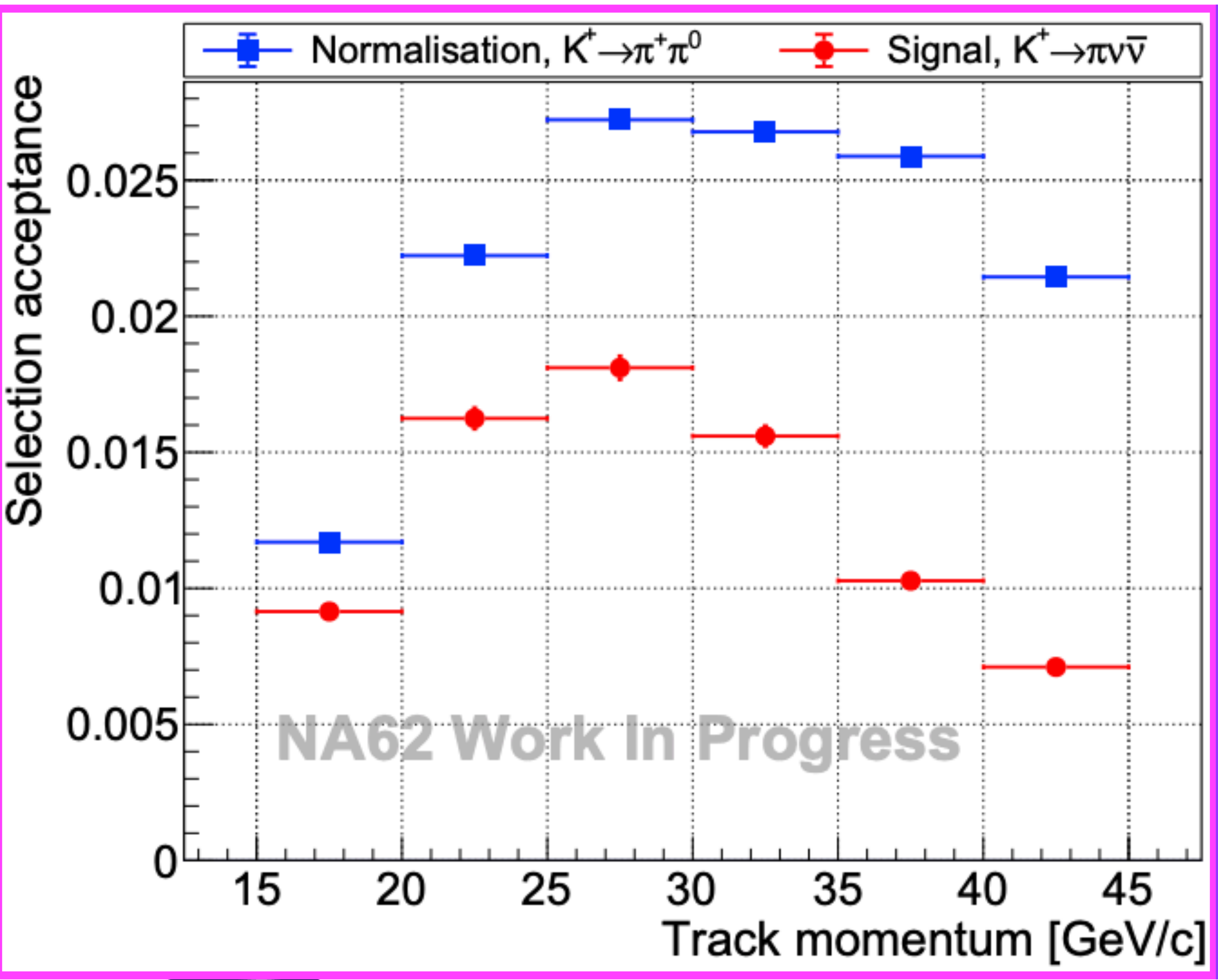
$K^+ \to \pi^+\nu\bar{\nu}$ with NA62 RUN2 data (2021+22)

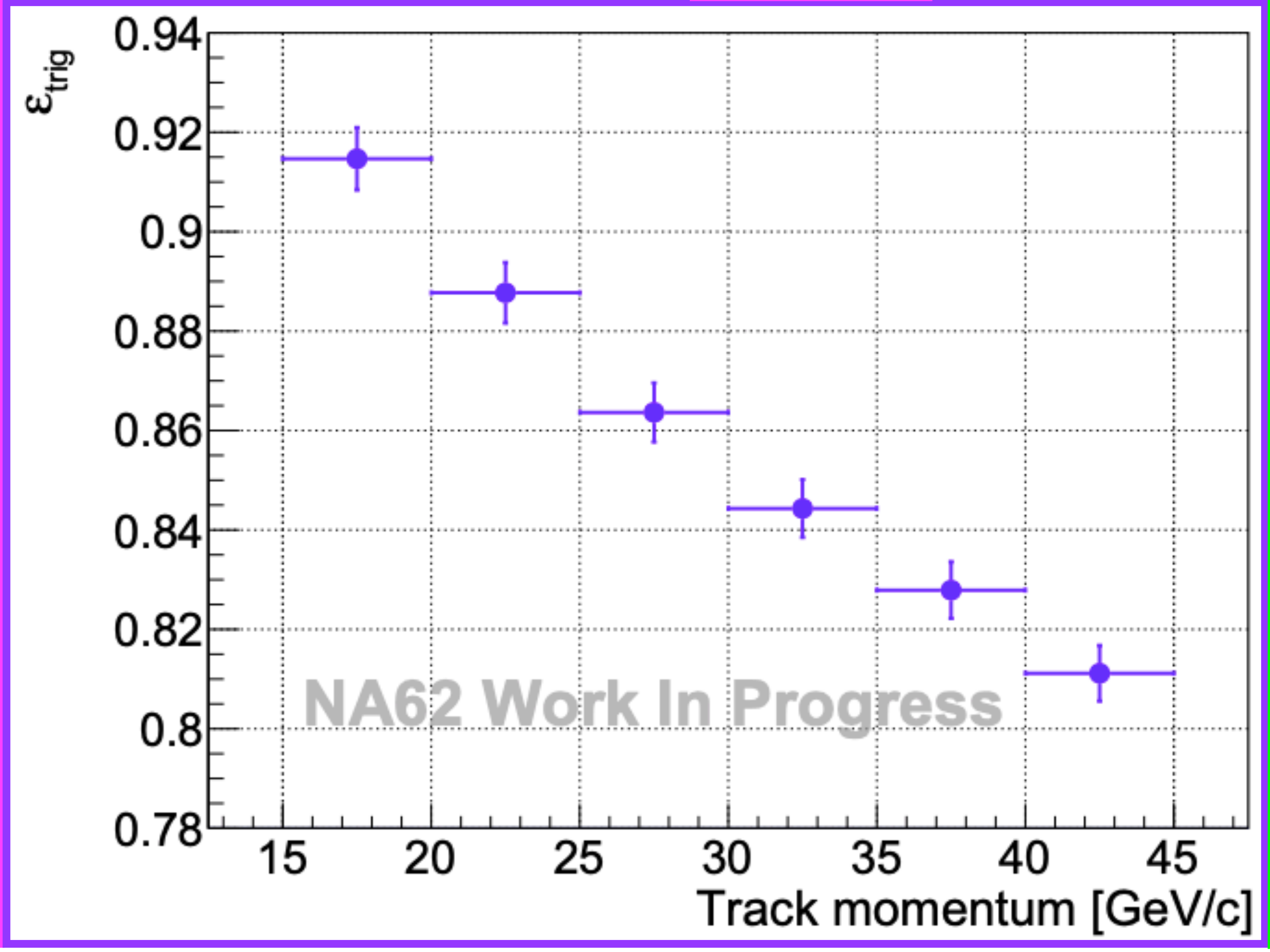
[NA62 SPSC report 2024

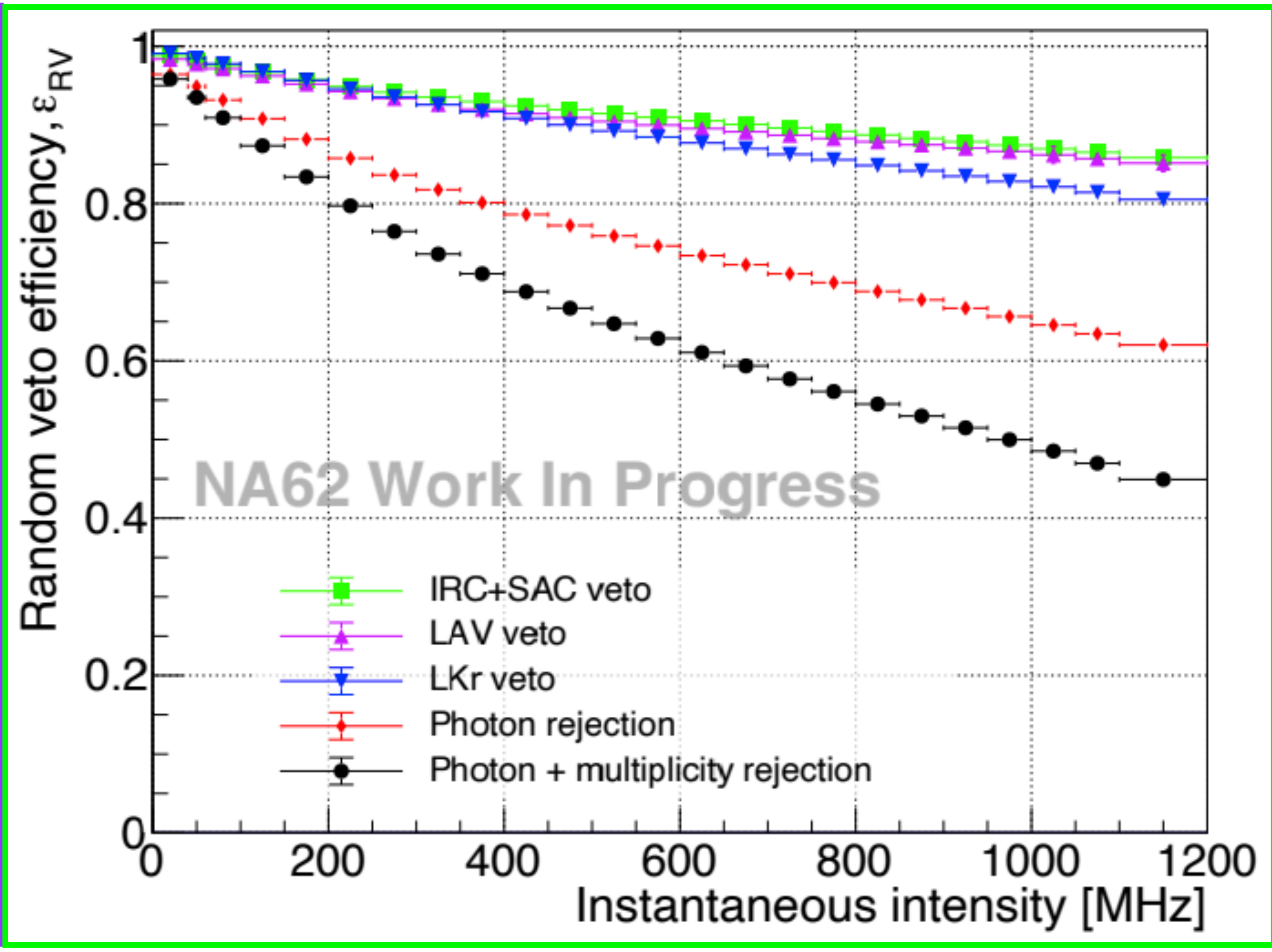
Work in progress

- 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: $1.7\times10^{-5} \to 2.5\times10^{-5}$.

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







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

[NA62 SPSC report 2024]

Work in progress

- 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: $1.7 \times 10^{-5} \to 2.5 \times 10^{-5}$.

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

Table 2: Preliminary signal sensitivity for the combined 2021+22 dataset.

Work in progress

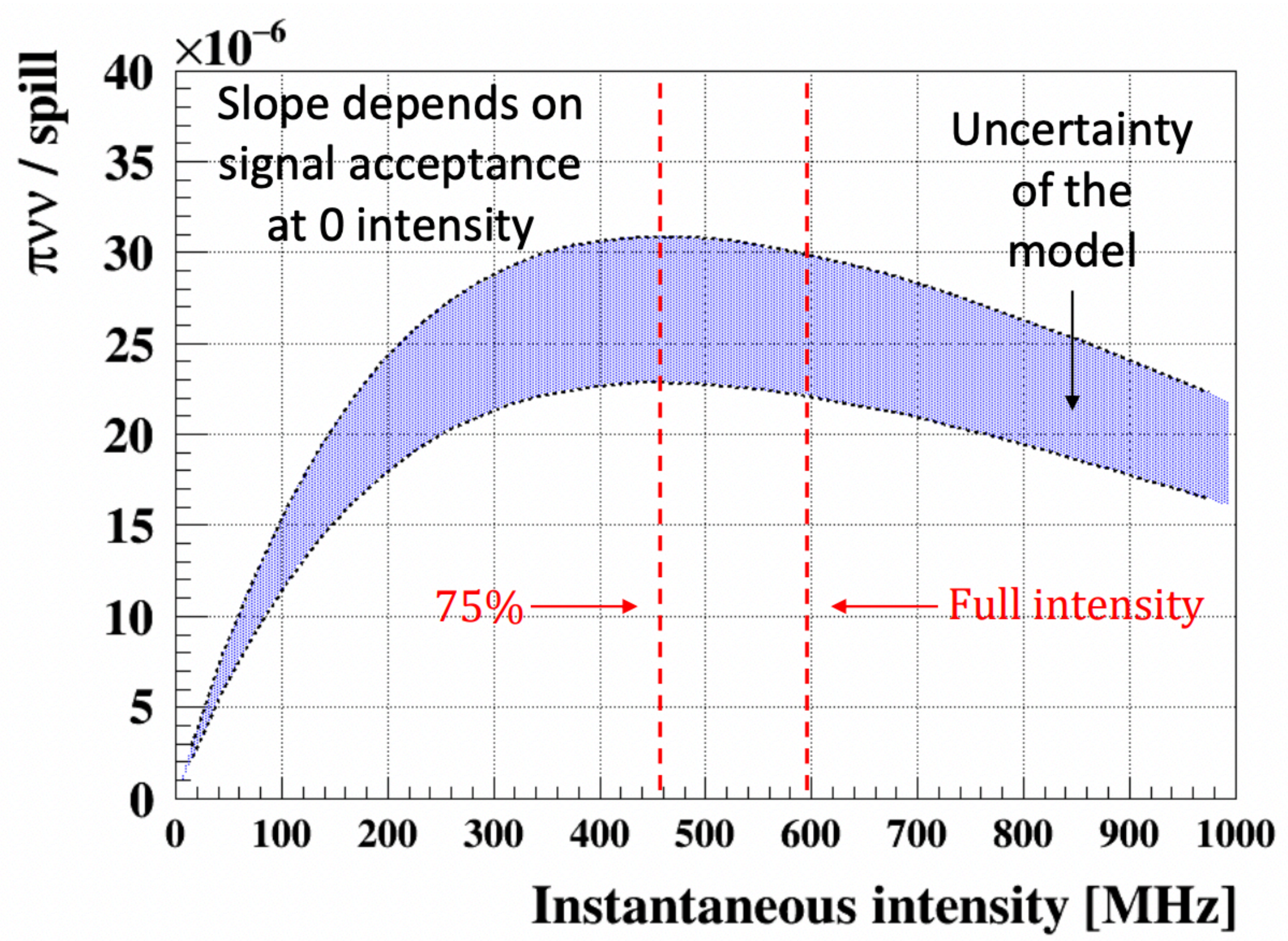
Variable	2021 ($t > 2$ s)	2022	21+22
$(N_{\pi\pi}D_0)/400$ [$\times 10^7$]	3.713	16.374	20.087
ε_{trig}	$(83.5 \pm 1.3)\%$	$(86.3 \pm 1.5)\%$	$(85.8 \pm 1.4)\%$
ε_{RV}	$(63.0 \pm 0.5)\%$	$(63.8 \pm 0.5)\%$	$(63.6 \pm 0.5)\%$
$A_{\pi\pi}$	$13.525 \pm 0.005\%$		
$A_{\pi\nu\bar{\nu}}$	$7.7 \pm 0.2\%$		
$\mathcal{B}_{SES}[\times 10^{-11}]$	4.68 ± 0.17	1.01 ± 0.03	0.83 ± 0.03
$N_{\pi\nu\bar{\nu}}^{\mathrm{SM,exp}}$	1.80 ± 0.06	8.28 ± 0.24	10.07 ± 0.31
$N_{\pi\nu\bar{\nu}}^{\mathrm{SM,exp}}$ per burst	1.7×10^{-5}	2.5×10^{-5}	2.3×10^{-5}

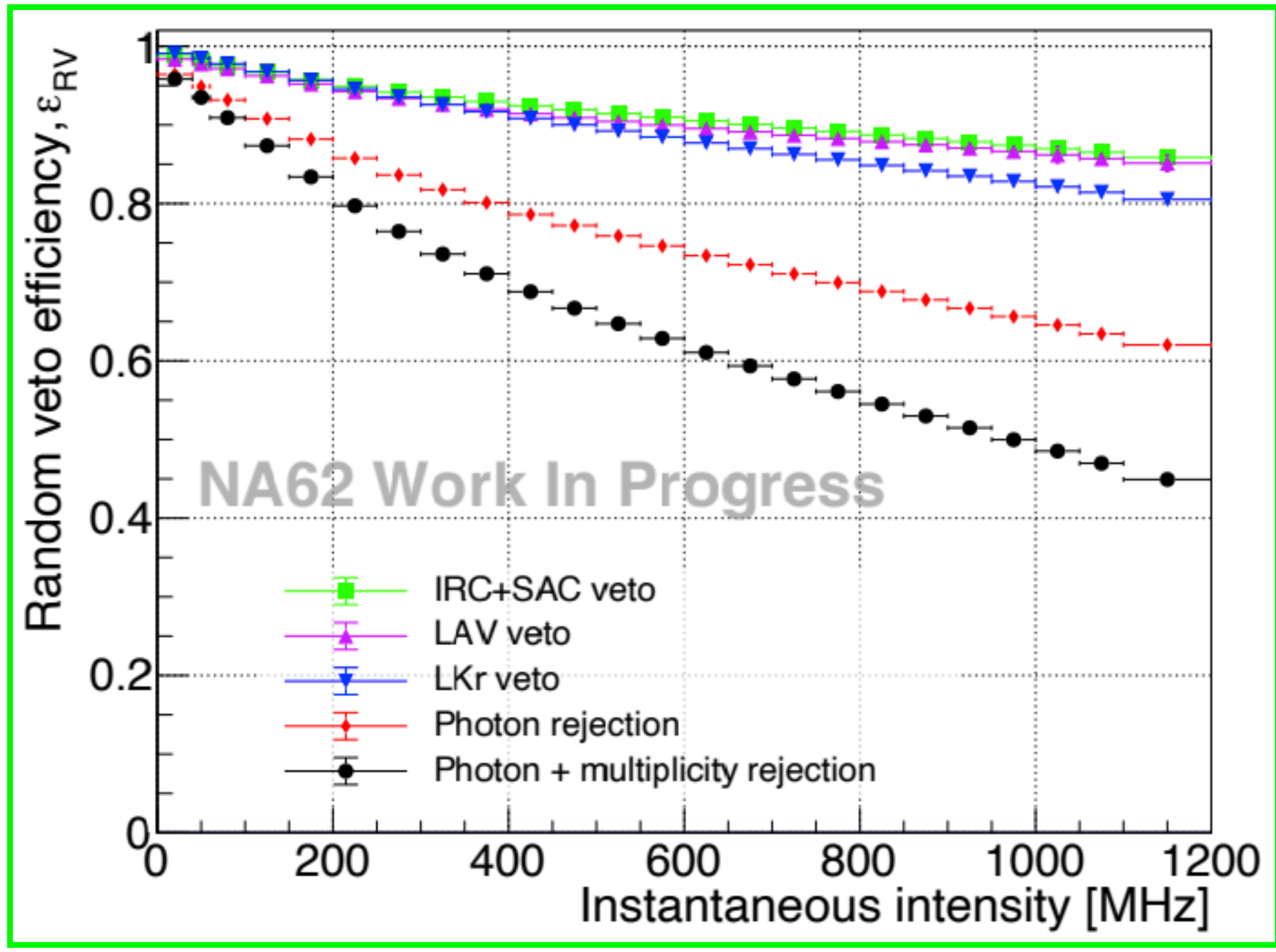
$K^+ \to \pi^+\nu\bar{\nu}$ with NA62 RUN2 data (2021+22)

[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.

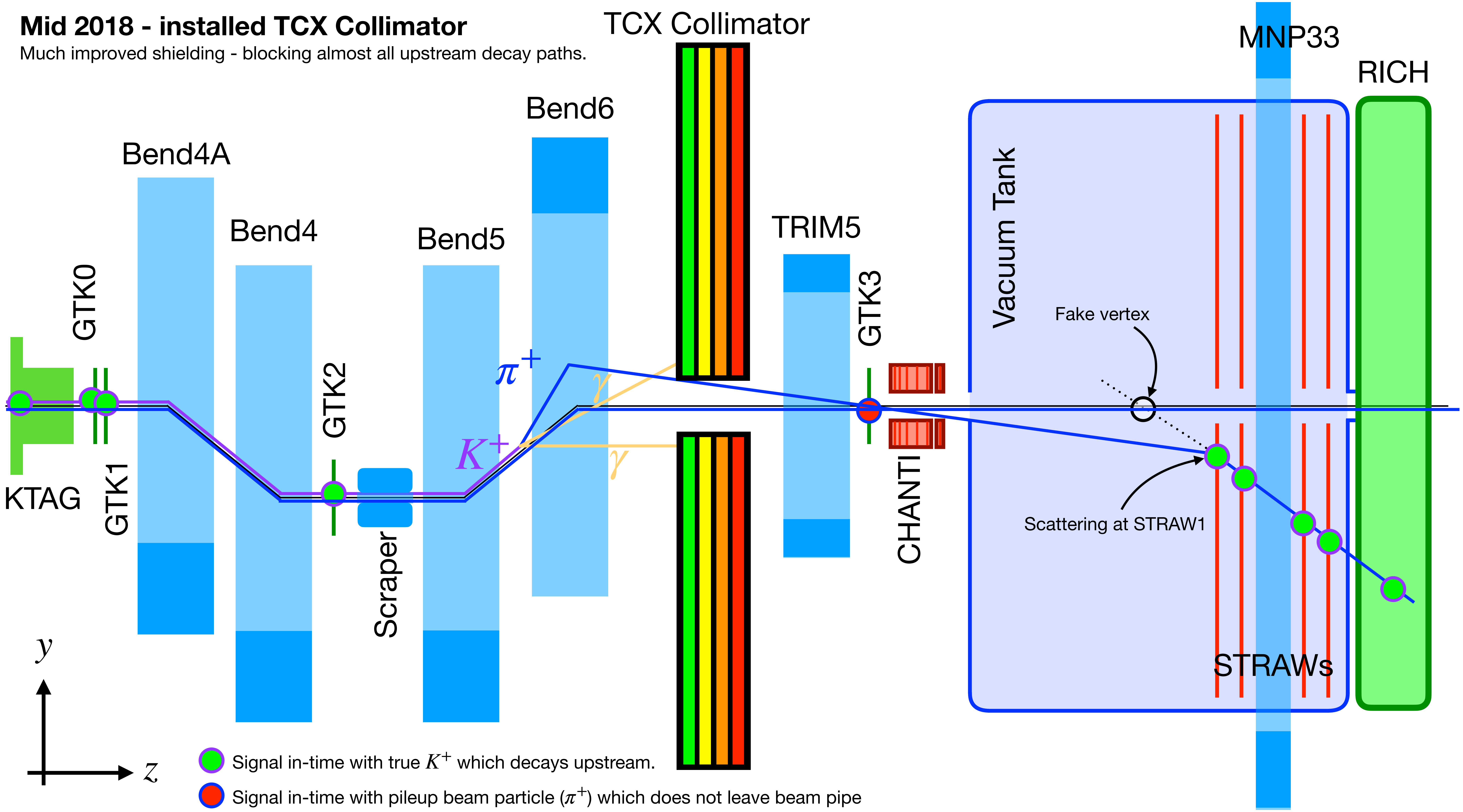




Upstream Background & new VetoCounter

Mid 2018 - installed TCX Collimator

Much improved shielding - blocking almost all upstream decay paths.

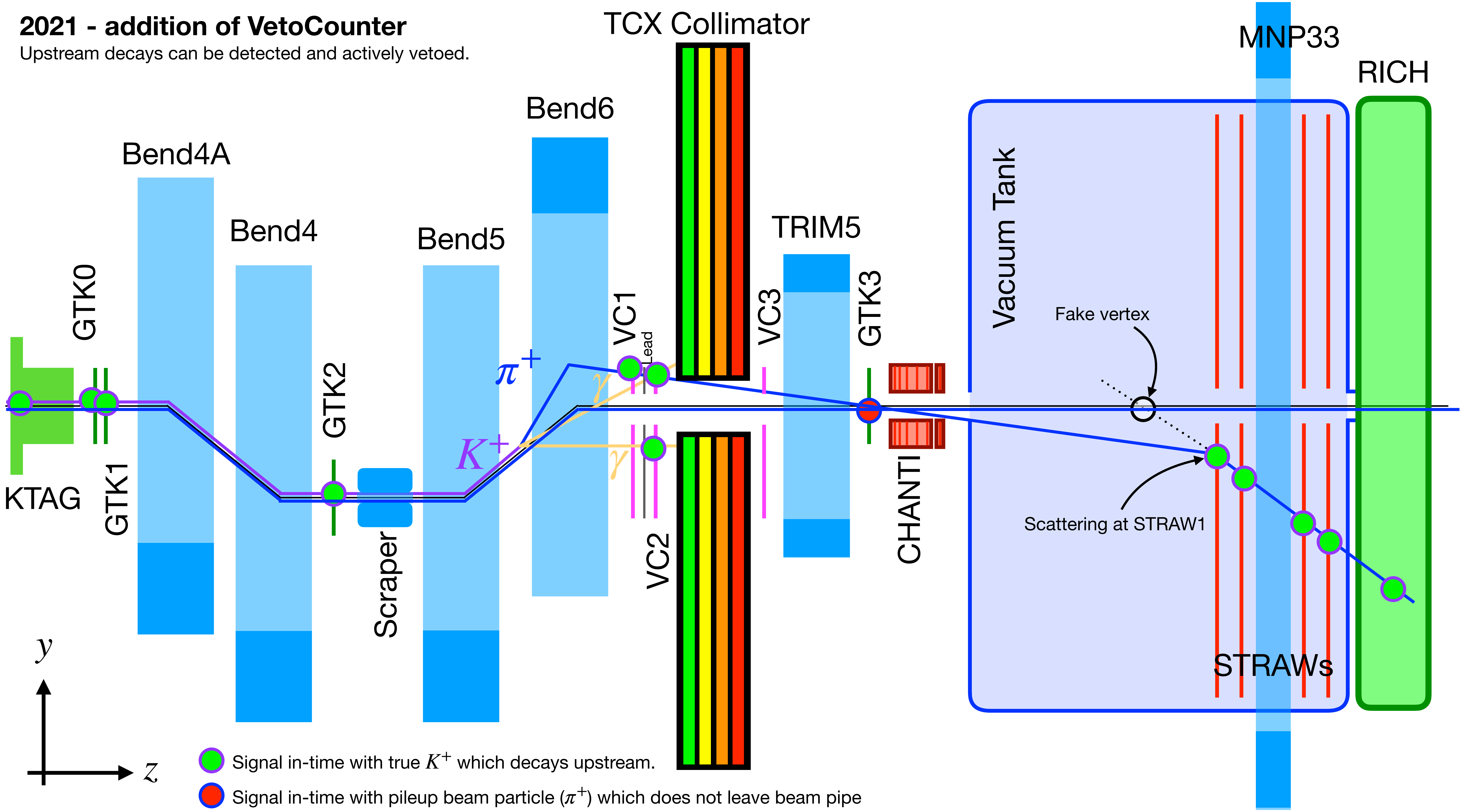


Signal in-time with true K^+ which decays upstream.

Signal in-time with pileup beam particle (π^+) which does not leave beam pipe

Upstream Background & new VetoCounter

2021 - addition of VetoCounter
Upstream decays can be detected and actively vetoed.

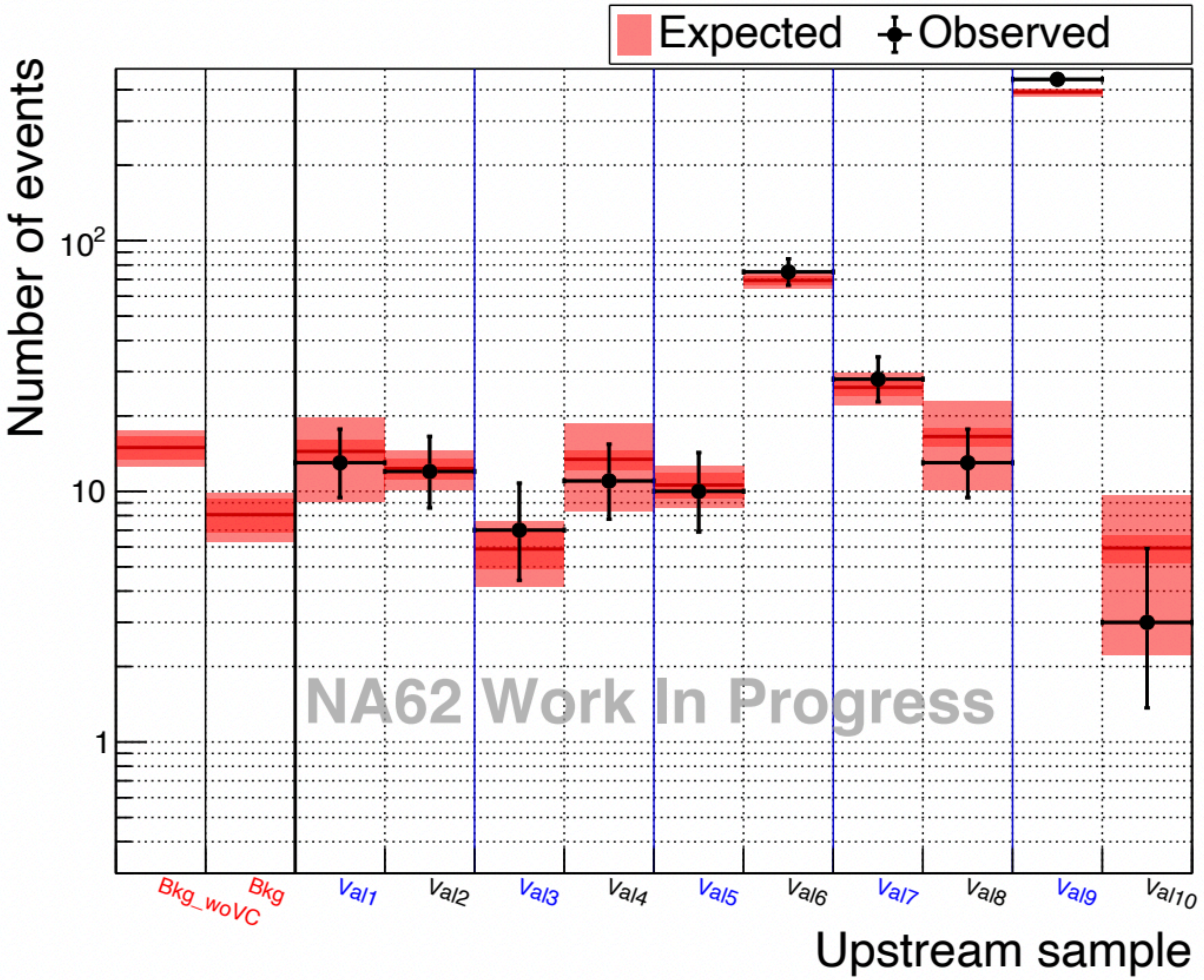


$K^+ \to \pi^+\nu\bar{\nu}$ with NA62 RUN2 data (2021+22)

[NA62 SPSC report 2024

Work in progress

- Upstream background studied in detail and new detectors applied to reduce it.
- e.g. VetoCounter provides at least 50% rejection.



Work in progress

Process	N_{bg}
$K^+ \to \pi^+\pi^0(\gamma)$	0.86 ± 0.06
$K^+ \to \mu^+\nu(\gamma)$	0.93 ± 0.20
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.84^{+0.35}_{-0.28}$
$K^+ \to \pi^0\ell^+\nu$	$< 10^{-3}$
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
Upstream	$8.0^{+2.2}_{-1.8}$
Total background	$10.8^{+2.2}_{-1.9}$

- Sensitivity ~as RUN1, doubling total expected number of signal events.

More news ASAP…

Full NA62 Physics Programme

NA62

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

Rare Decays

Forbidden Decays

Exotics

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

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

- $K^+ \rightarrow \pi^0 \pi \mu e$ [new: prelim. Spring 2024]
- $K^+ \rightarrow (\pi^0) \pi^- e^+ e^+$ [PLB 830 (2022) 137172]
- $K^+ \rightarrow \mu^- \nu e^+ e^+$ [PLB838 (2023) 137679]
- $K^+ \rightarrow \pi \mu e\ ,\ \pi^0 \rightarrow \mu^- e^+$ [PRL 127 (2021) 13, 131802]
- $K^+ \rightarrow \pi^- \mu^+ \mu^+$ [PLB 797 (2019) 134794]

- Beam dump dark photon searches:
  - $A' \rightarrow \ell^+ \ell^-$ [arXiv.2312.12055] [JHEP 09 (2023) 035]
  - $A' \rightarrow$ hadrons [prelim. Spring 2024]

Analysis Overview [K^+ data-taking mode]

- Trigger: L0 hardware —> L1 Software.
- Trigger Menu:
  - Main trigger = PNN
  - Other triggers: Multi-track (MT), MTμ, MTe … Downscaled by factors ~2—100.
- Measure BR of signal mode by counting candidates and normalising to a well-known "normalisation mode":
  - Effective number of K+ in FV = $N_K = \dfrac{N_n}{\mathscr{B}_n A_n \varepsilon_n} \dfrac{D_n}{D_s}$, then $\mathscr{B}_s = \dfrac{N_s}{N_K A_s \varepsilon_s}$ Where:
    - $N_{n,s}$ is the number of observed norm(signal) [candidate] events
    - $A_{n,s}$ is the acceptance (from MC)
    - $\varepsilon_{n,s}$ and $D_{n,s}$ are the efficiency and downscaling factors of triggers for norm(signal)
    - $\mathscr{B}_{n,s}$ are the branching ratios of the norm(signal) processes.
- Detailed background evaluations (MC and/or data-driven) to isolate signal candidates.
  - For all searches **blind analysis strategy** is adopted.

Rare K^+ decays at NA62

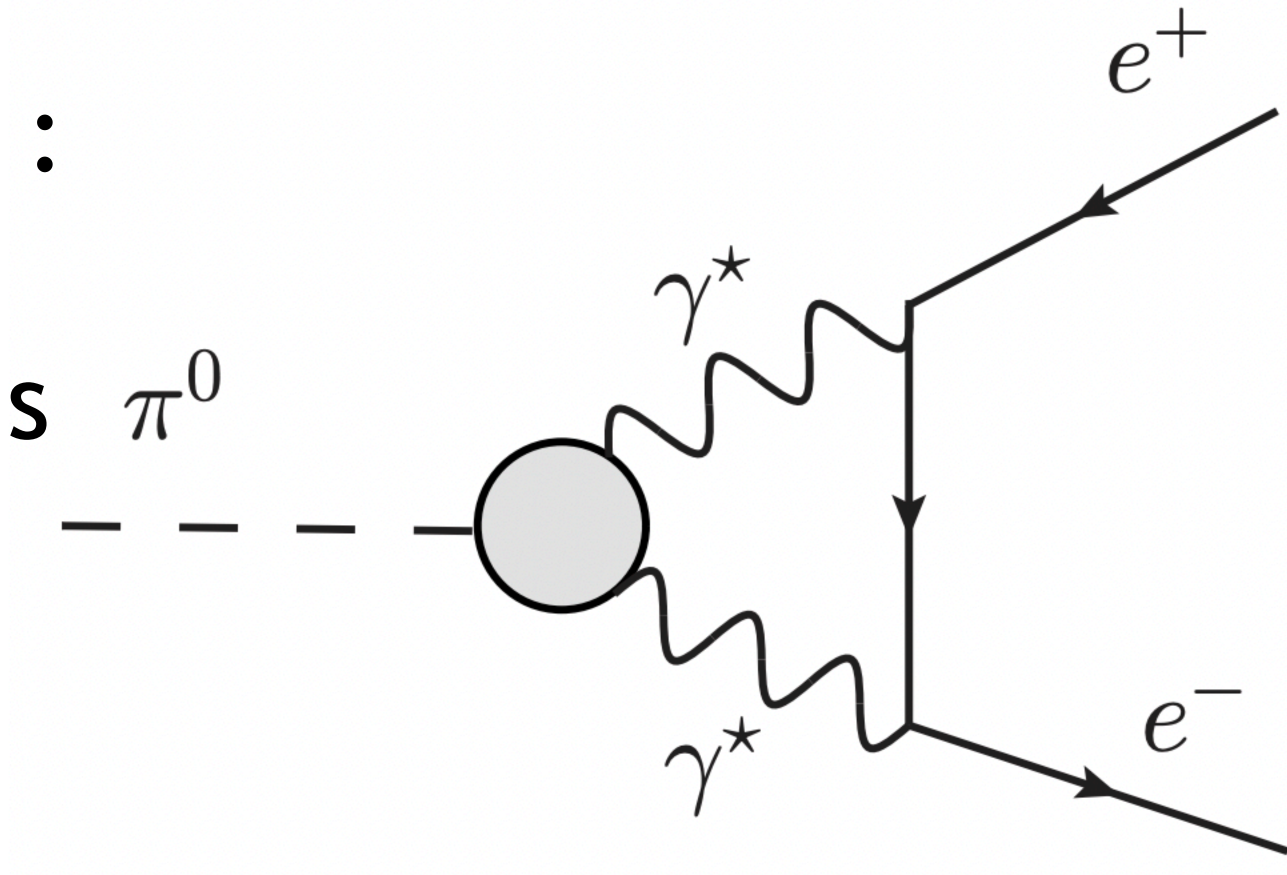
Study of $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-$

[new: spring 2024]

- 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)

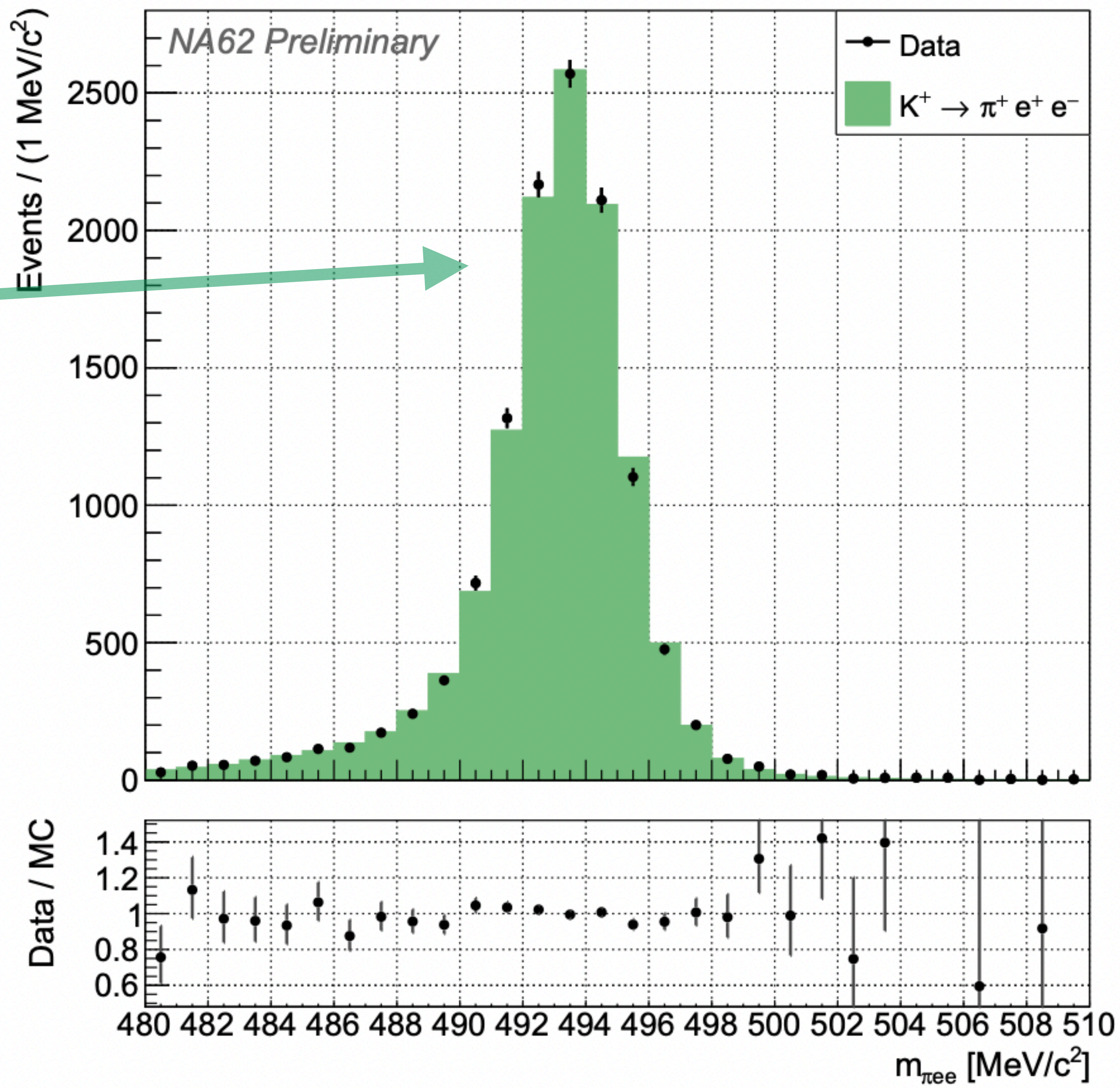
- Diagram for $\pi^0 \to e^+e^-$:
  - considered in theoretical predictions, with various $\pi^0 \to \gamma^*\gamma^*$ transition form factors



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.
  - 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: $N_K = (8.62 \pm 0.08_{\text{stat}} \pm 0.26_{\text{ext}}) \times 10^{11}$

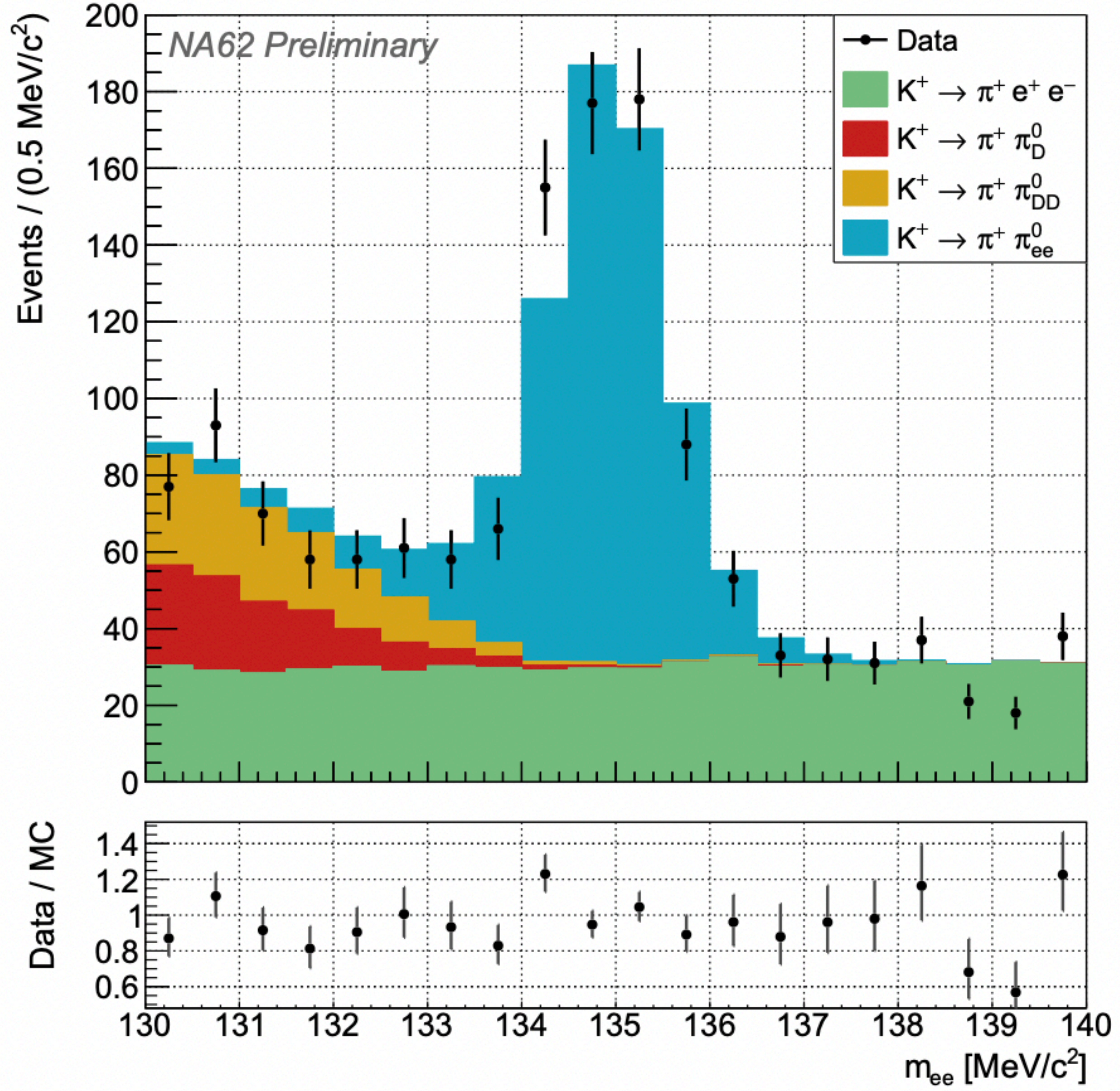
External uncertainty from norm. BR: $\mathscr{B}(K^+ \to \pi^+ e^+ e^-) = (3.00 \pm 0.09) \times 10^7$

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

[new: spring 2024]

Backgrounds:

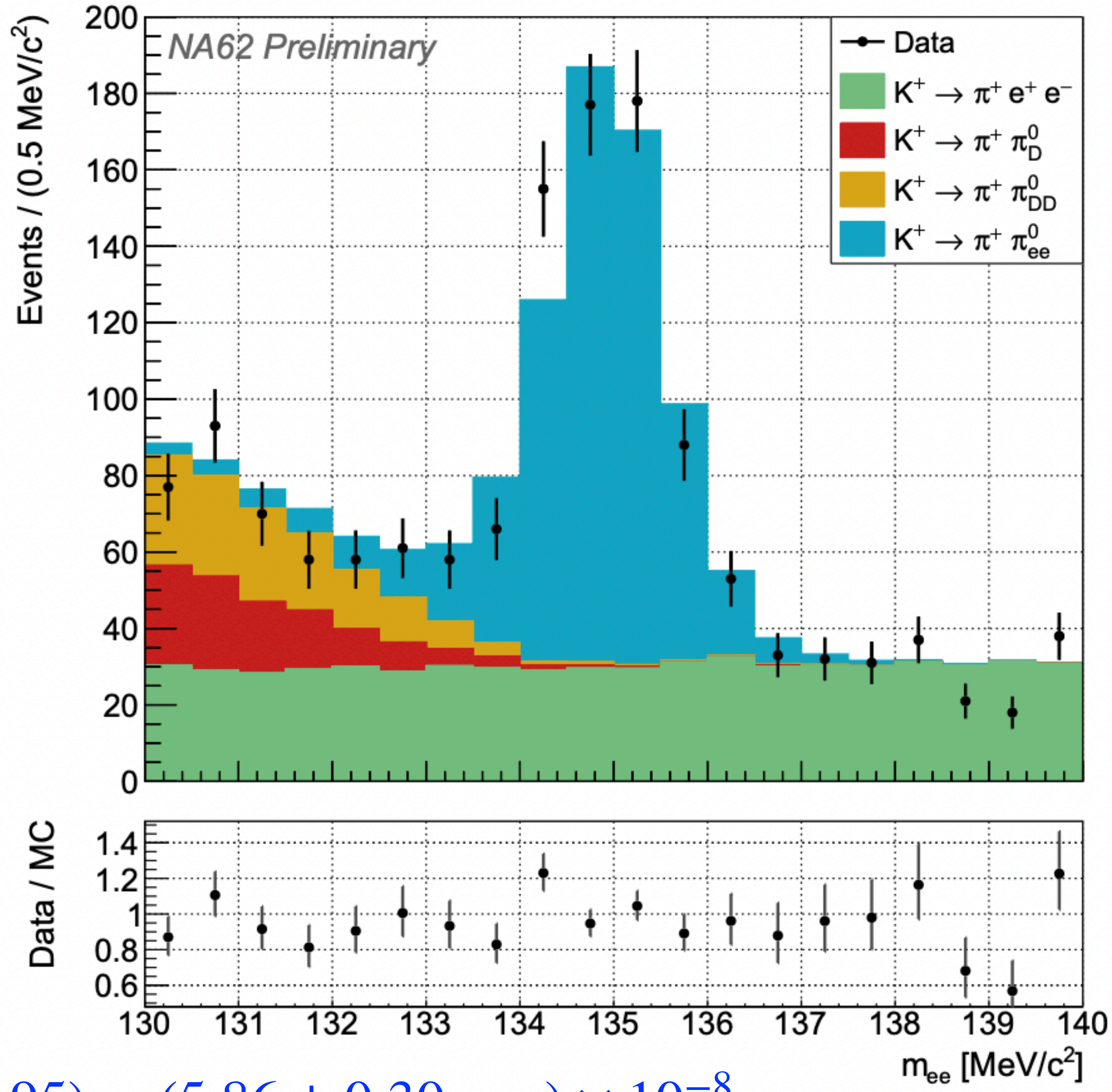
- $K^+ \to \pi^+ e^+ e^-$: irreducible, flat in signal region $m_{ee} \approx m_{\pi^0}$
- $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-\gamma \equiv K^+ \to \pi^+\pi^0_D$:
  - a) π^0 Dalitz decay distribution with large-x tail.
  - b) Photon conversion in STRAW ($\gamma \to e^+e^-$) + selection of a produced $e^\pm$.
    - 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: $m_{ee} \in (130,140)\,\mathrm{MeV}/c^2$
- Signal acceptance (for $x_{\mathrm{true}} > 0.95$) $A(K^+ \to \pi^+\pi^0_{ee}) = (5.72 \pm 0.02_{\mathrm{stat}})\,\%$
- Perform maximum likelihood fit of simulated samples to data:
  - Fitted signal event yield : 597 ± 29
  - $\chi^2/\mathrm{ndf} = 25.3/19$, p-value = 0.152.
  - {BR of other decays: external input from PDG}



BR from fit

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

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]

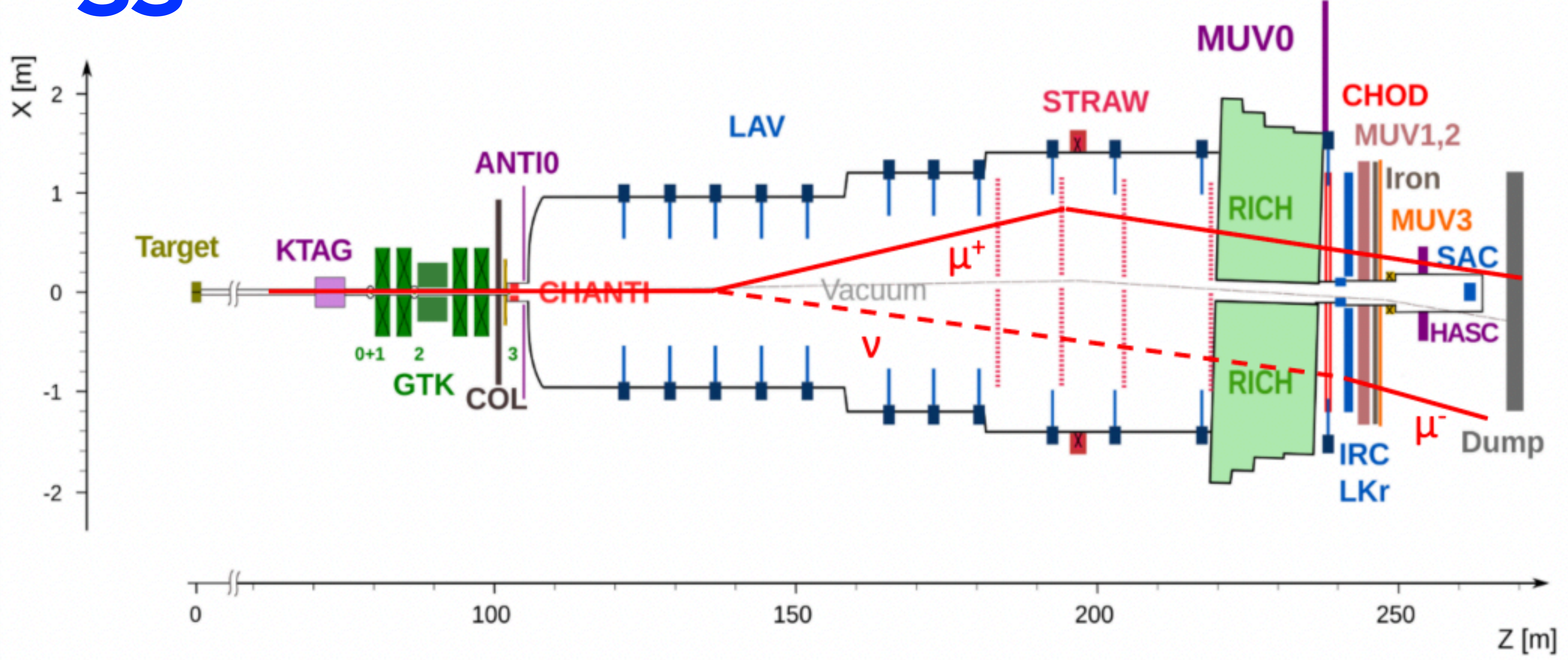
	$\delta\mathcal{B}$ $[10^{-8}]$	$\delta\mathcal{B}/\mathcal{B}$ [%]
Statistical uncertainty	0.30	5.1
Total external uncertainty	0.19	3.2
Total systematic uncertainty	0.11	1.9
Trigger efficiency	0.07	1.2
Radiative corrections for $\pi^0 \to e^+e^-$	0.05	0.9
Background	0.04	0.7
Reconstruction and particle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

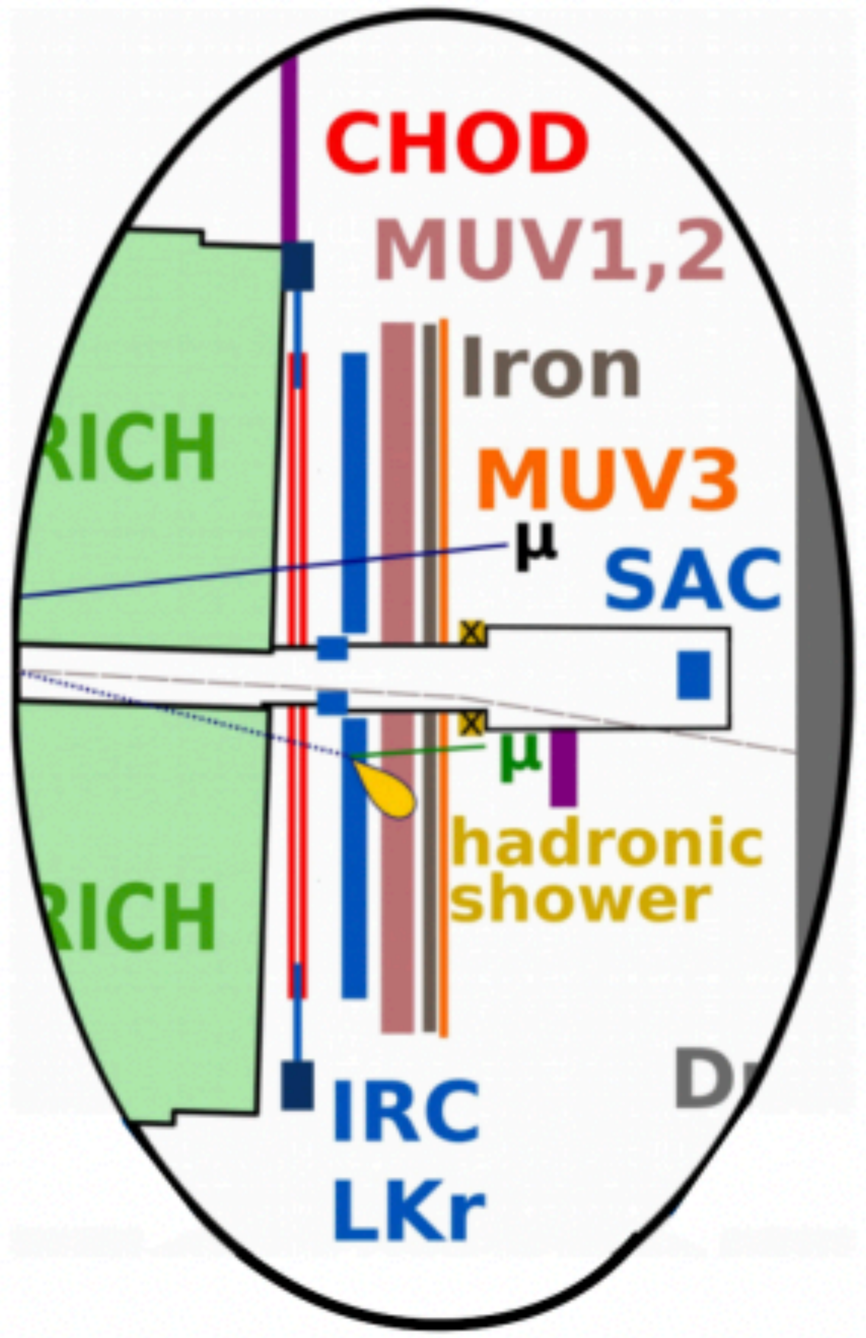
- Large external uncertainty from $\mathscr{B}(K^+ \to \pi^+e^+e^-)$, measured by NA48/2 and E865. New analysis for this mode planned at NA62.
- Strong prospects for the future with optimised multi-track electron trigger line with reduced downscaling, collecting a large di-electron final states sample.

- 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:
  - $\mathscr{B}_{\text{theory2022}}(\pi^0 \to e^+e^-(\gamma), \text{no rad}) = (6.25 \pm 0.03) \times 10^{-8}$

Tagged neutrinos at NA62

[De Martino, NuFact23]

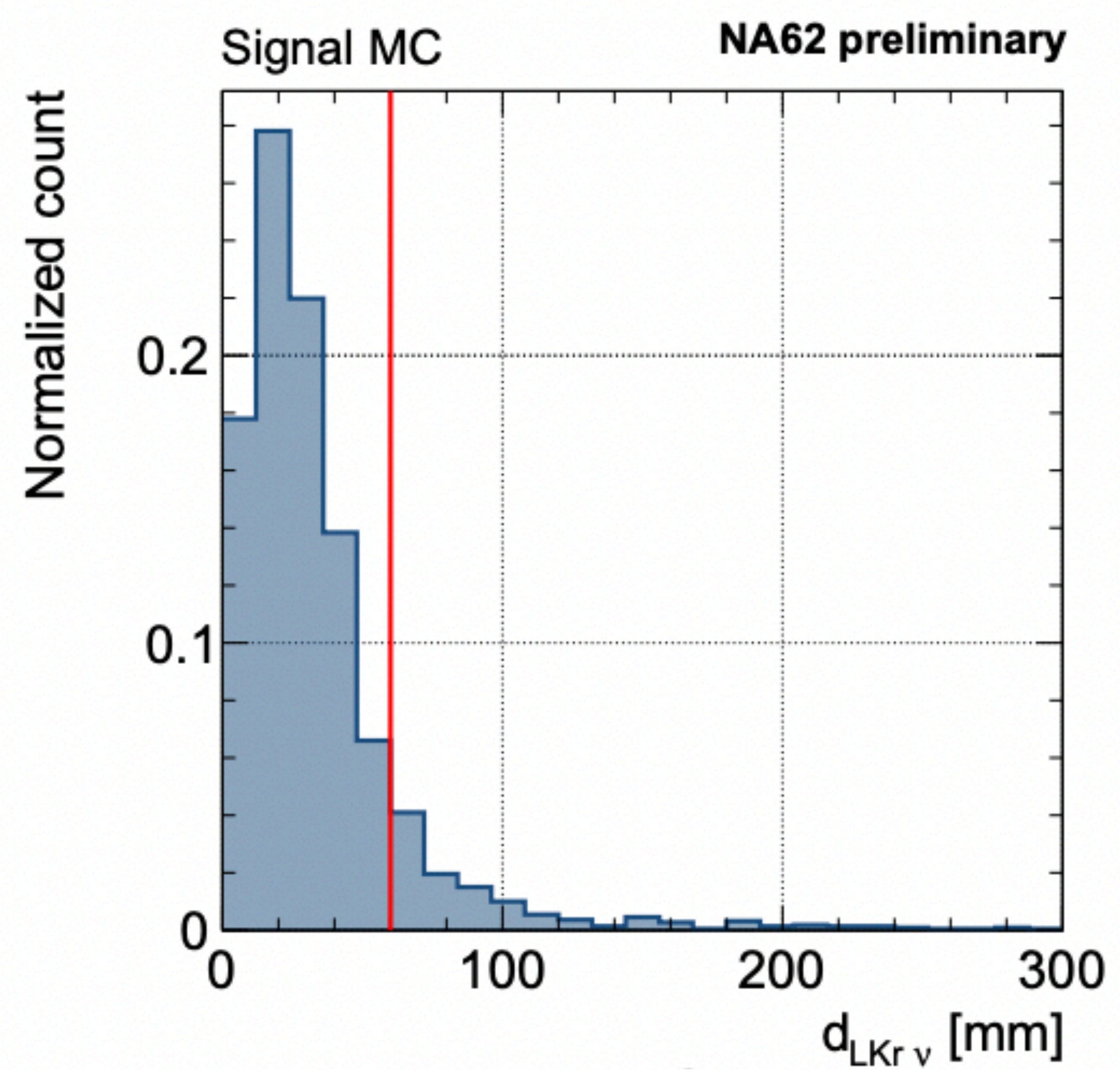


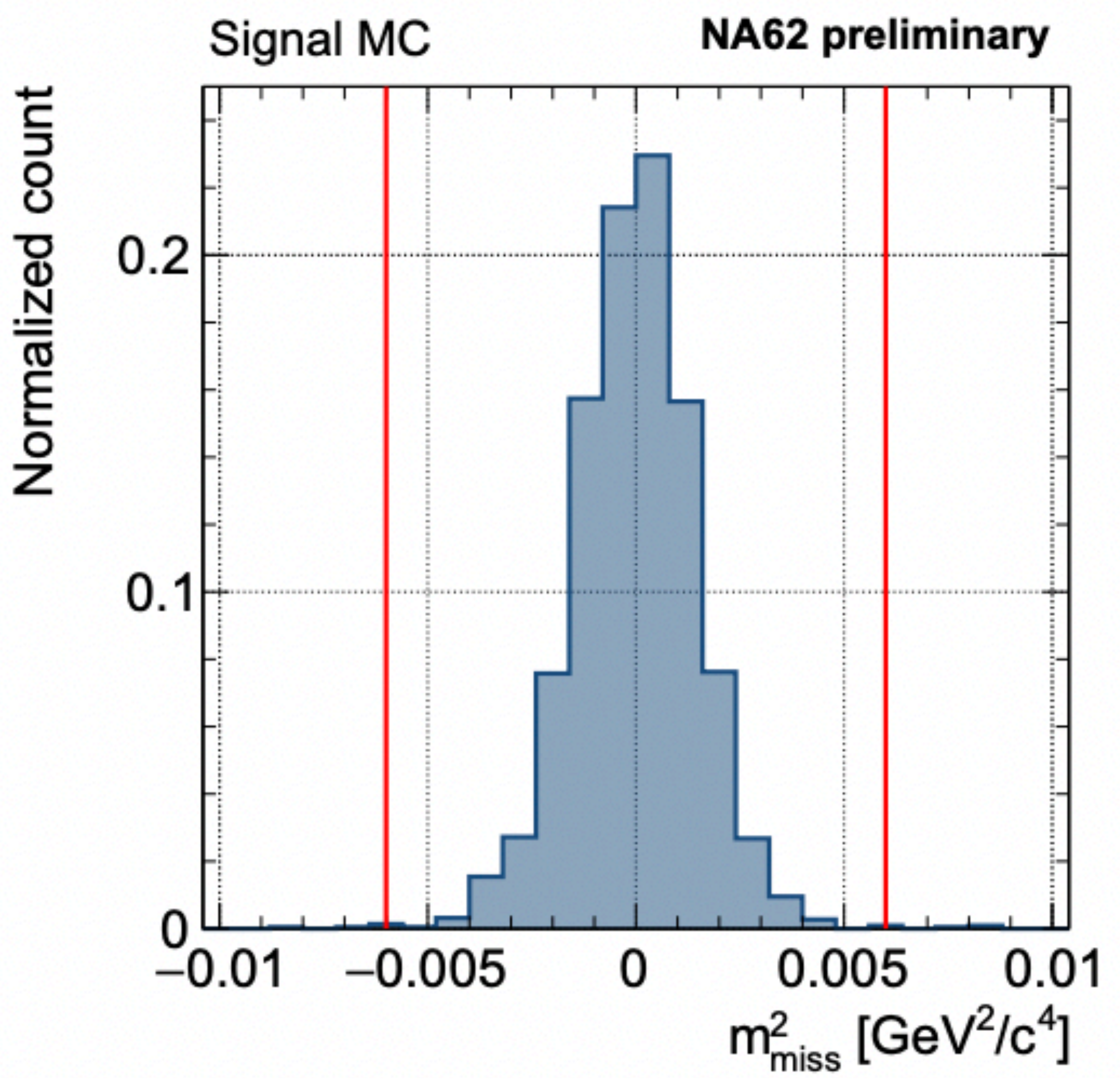


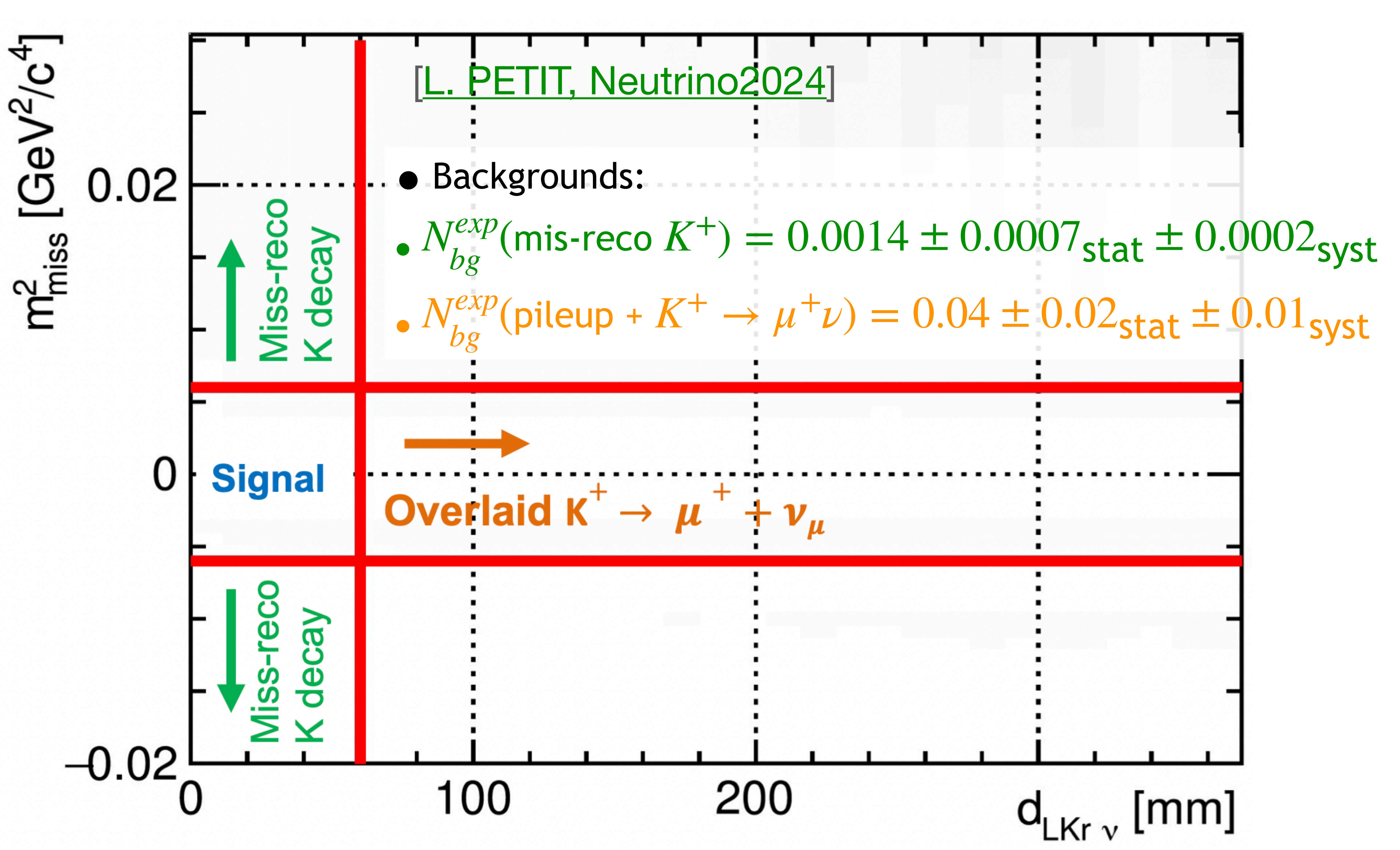
- Goal: search for $K^+ \to \mu^+ \nu_\mu$ with:
  - K^+ and μ^+ detected by GTK and STRAW trackers as usual.
  - ν_μ interacting in LKr calorimeter (20 tons of Liquid Kr, MUV12 66ton HCAL)
- ν_μ Interaction probability $\mathcal{O}(10^{-11})$: CC-DIS $\nu_\mu \to \mu^- + \text{shower}$
  - Trigger based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

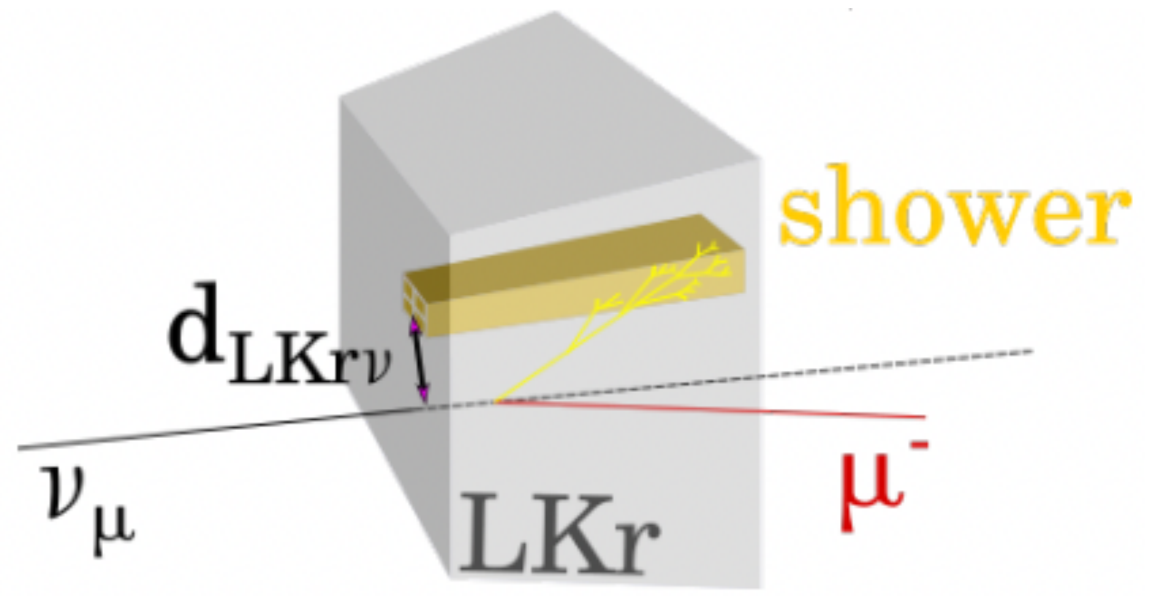
Tagged neutrinos at NA62: strategy

[De Martino, NuFact23]





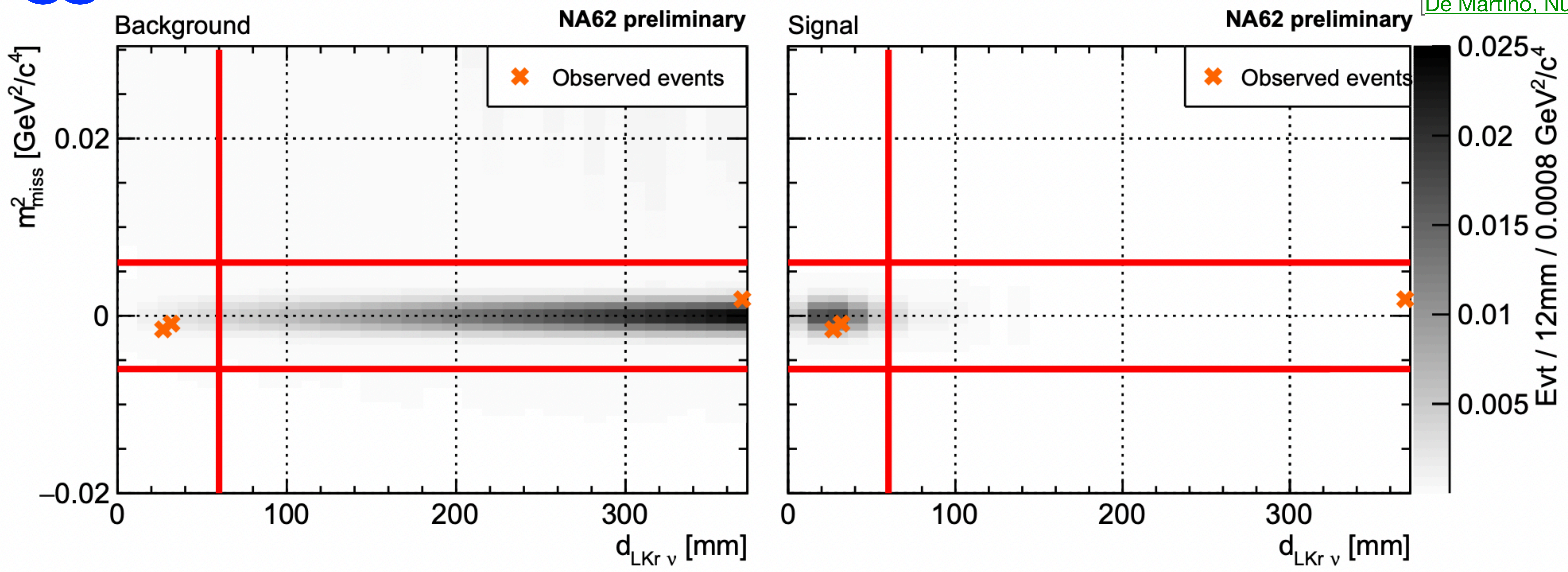




- Normalise to $K^+ \to \mu^+\nu$ (no interaction) :
  - $N^{sigmal}_{exp} = N_K \mathscr{B}(K^+ \to \mu^+\nu) P_{int,Lkr} \varepsilon_{signal} = N_{norm} \dfrac{\varepsilon_{signal}}{\varepsilon_{norm}} P_{int,LKr}$
- Evaluate signal efficiency with MC (GENIE) : $P_{int,LKr} = (6.0 \pm 0.1_{syst}) \times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

Tagged neutrinos at NA62: Results

[De Martino, NuFact23]

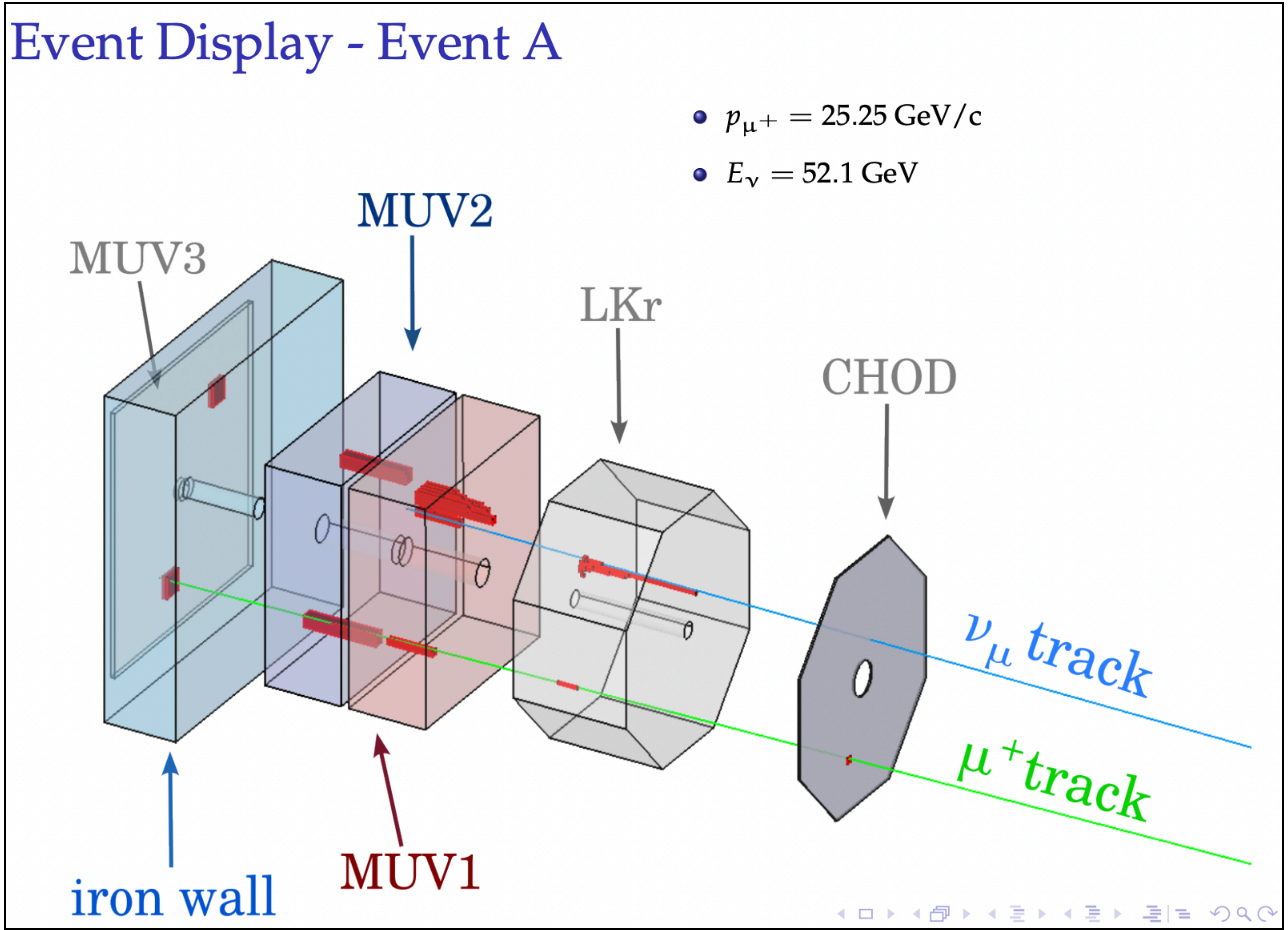


- $N^{exp}_{signal} = 0.228 \pm 0.014_{\text{stat}} \pm 0.011_{\text{syst}}$
- Backgrounds:
  - N^{exp}_{bg}(mis-reco K^+) $= 0.0014 \pm 0.0007_{\text{stat}} \pm 0.0002_{\text{syst}}$
  - N^{exp}_{bg}(pileup + $K^+ \to \mu^+\nu$) $= 0.04 \pm 0.02_{\text{stat}} \pm 0.01_{\text{syst}}$

- 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]

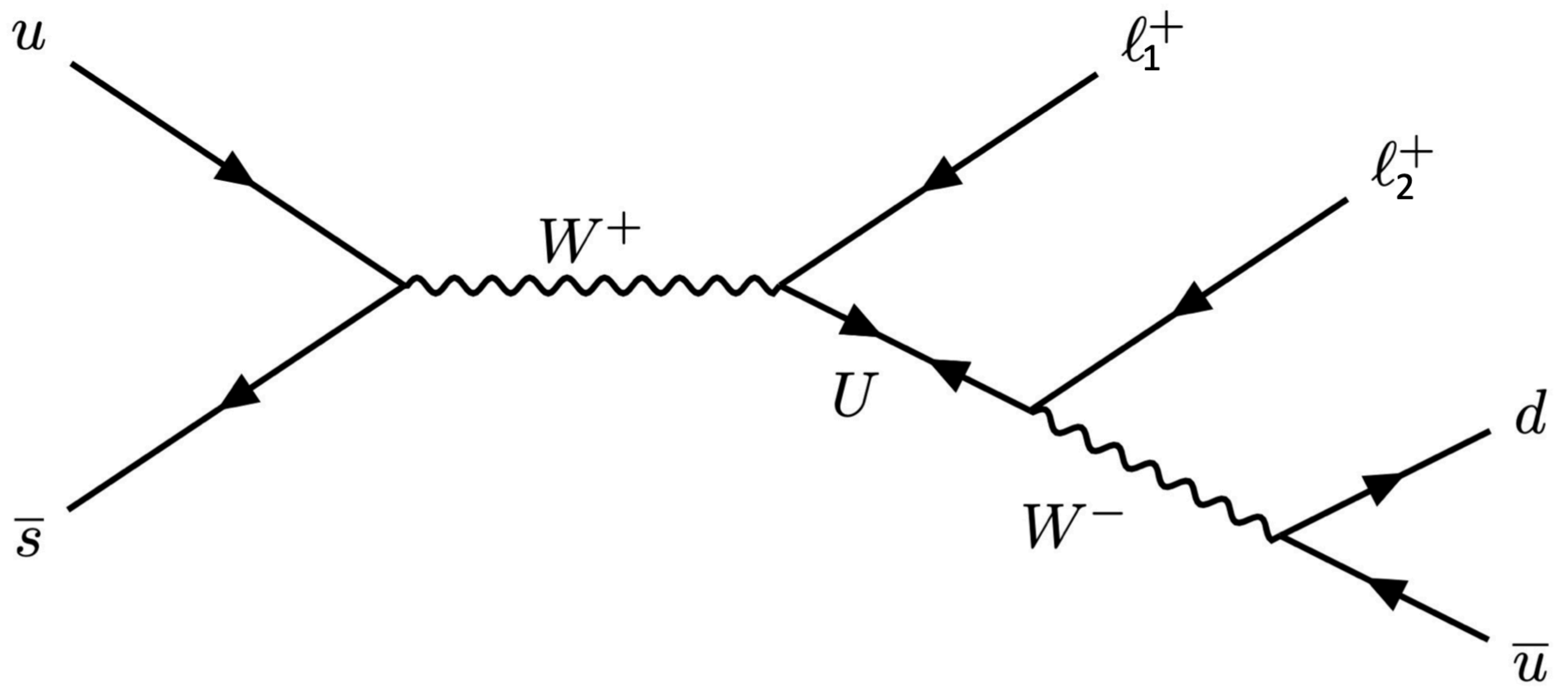


Forbidden K^+ decays at NA62

Searches for CLFV/LNV Decays at NA62

- Observation of Lepton Number/Flavour Violating (LNV/CLFV) processes would be a clear indication of BSM physics.

- E.g. $K^+ \to \pi^- \ell_1^+ \ell_2^+$ via exchange of Majorana Neutrinos (analogue to $0\nu\beta\beta$ decays) [JHEP 05 (2009) 030] [PLB 491 (2000) 285].



- Use Run1 (2016—18) data set, search for:

$K^+ \to \pi^0 \pi^- \mu^+ e^+$ $K^+ \to \pi^0 \pi^+ \mu^- e^+$ $K^+ \to \pi^0 \pi^+ \mu^+ e^-$	[New: Prelim. 2024]
$K^+ \to \mu^+ \nu e^+ e^+$	[PLB 838 (2023) 137679]
$K^+ \to \pi^- e^+ e^+$ $K^+ \to \pi^0 \pi^- e^+ e^+$	[PLB 830 (2022) 137172]
$K^+ \to \pi^- \mu^+ e^+$ $K^+ \to \pi^+ \mu^- e^+$ $\pi^0 \to \mu^- e^+$	[PRL 127 (2021) 13, 131802]
$K^+ \to \pi^- \mu^+ \mu^+$	(Sub-set of data) [PLB 797 (2019) 134794]

Backgrounds and PID studies

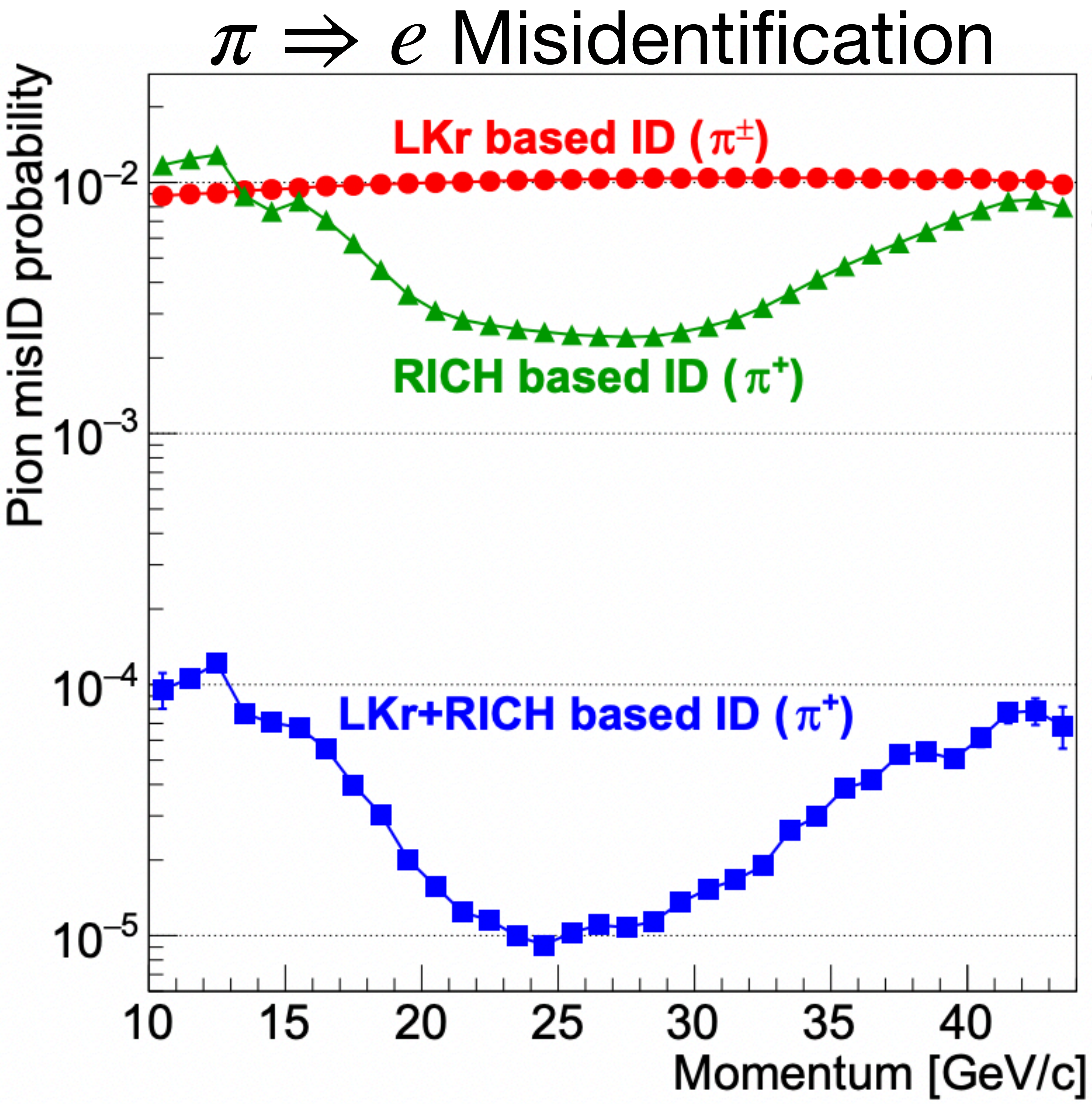
e.g. for $K^+ \to \pi^-(\pi^0)e^+e^+$ searches [PLB 830 (2022) 137172]

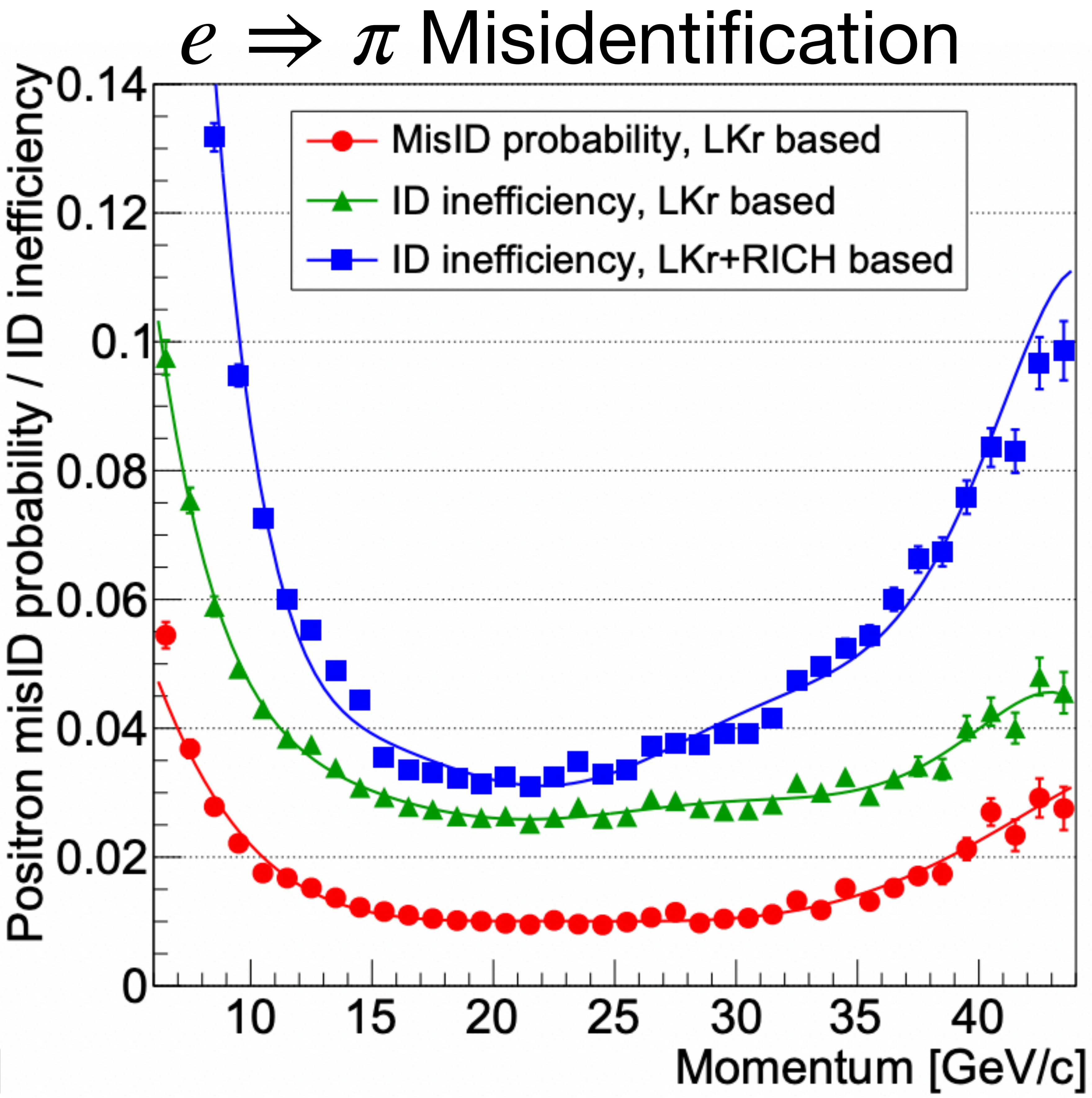
PID conditions:

$\pi^\pm$: 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^+.

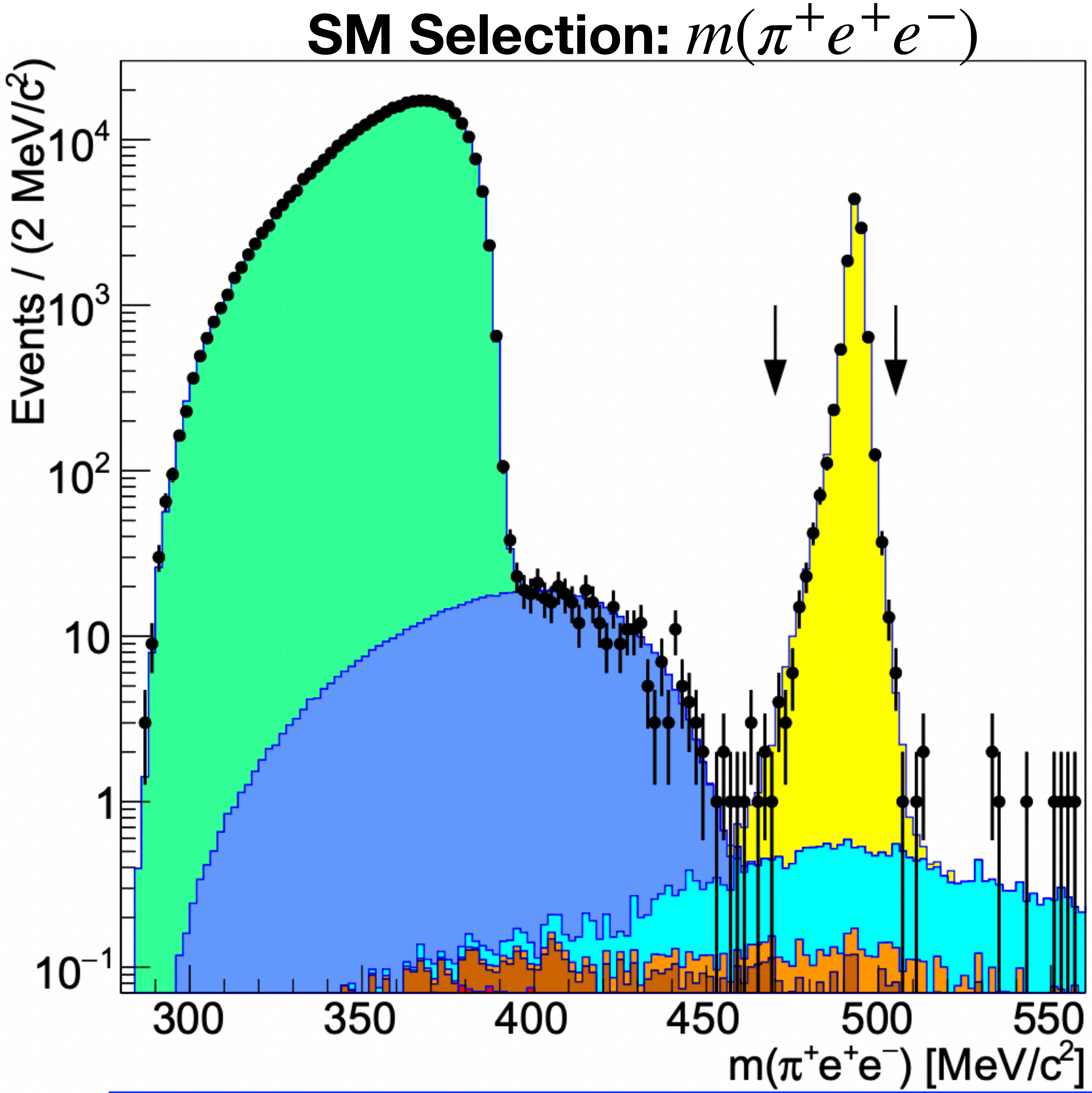


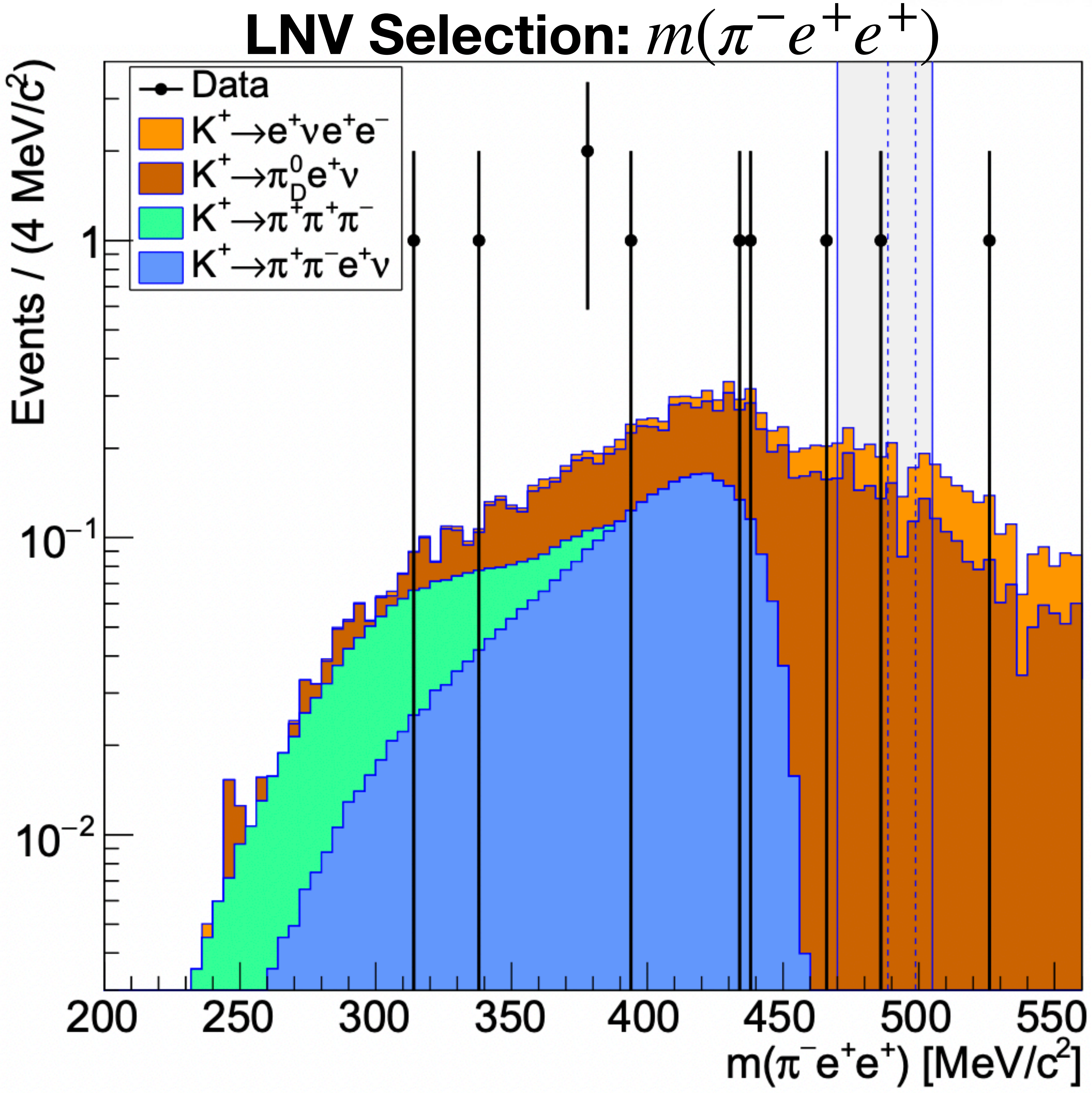


- Primary background mechanisms from misidentification.
- Models from data applied in simulations to describe misID.
- Validated using control samples [without RICH, with missing momentum].

Search for $K^+ \to \pi^- e^+ e^+$

[PLB 830 (2022) 137172]





- 11041 candidates
- $\mathscr{B}(K^+ \to \pi^+ e^+ e^-) = (3.00 \pm 0.09) \times 10^{-7}$
- Effective # of K^+ decays in FV = $(1.015 \pm 0.031) \times 10^{12}$

- Expected background = 0.43 ± 0.09
- Candidates observed: 0
- $\mathscr{B}(K^+ \to \pi^- e^+ e^-) < 5.3 \times 10^{-11}$ at 90 % CL

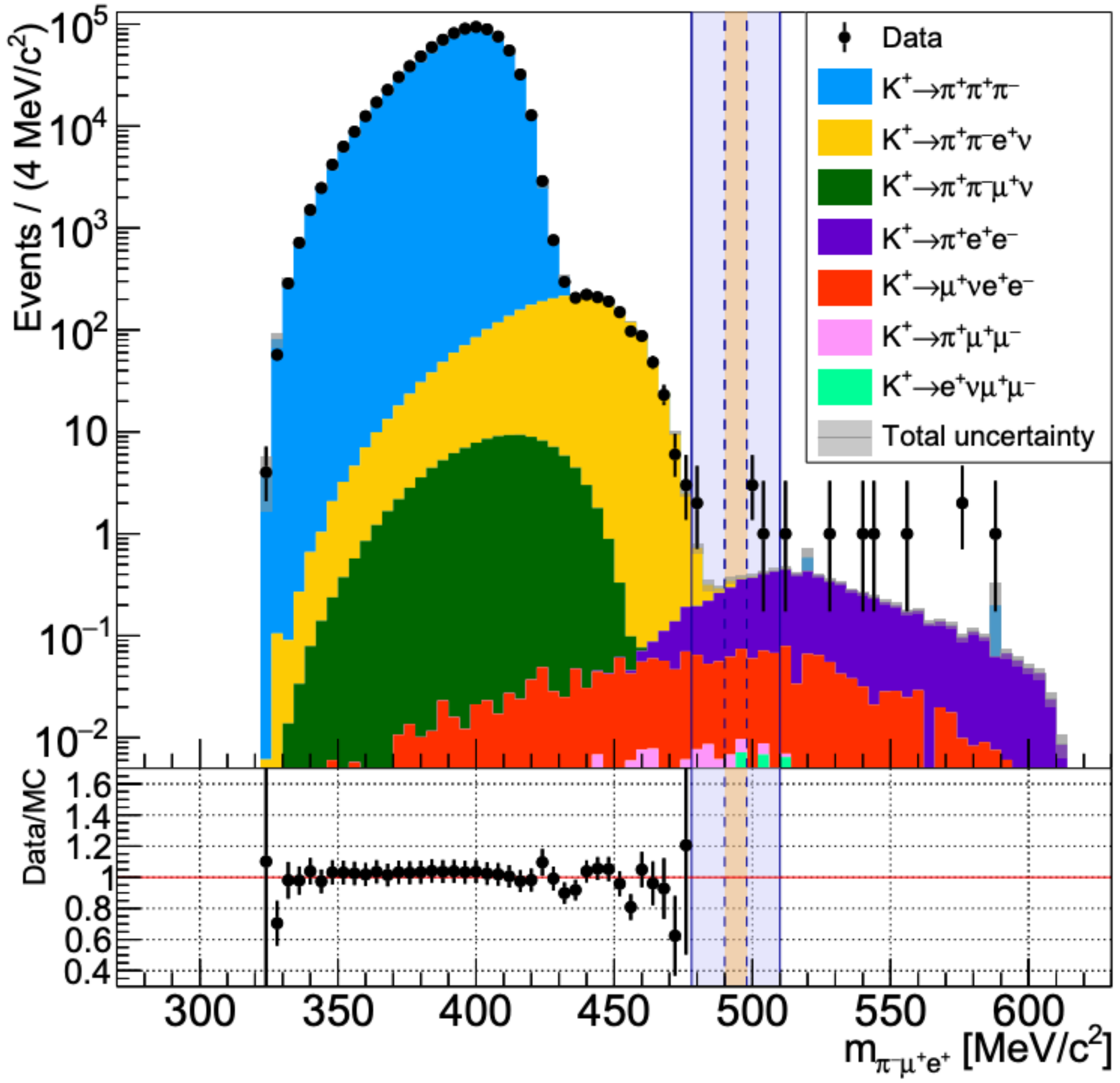
Searches for $K^+ \to \pi\mu e$ decays

[PRL 127 (2021) 131802]

NA62

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

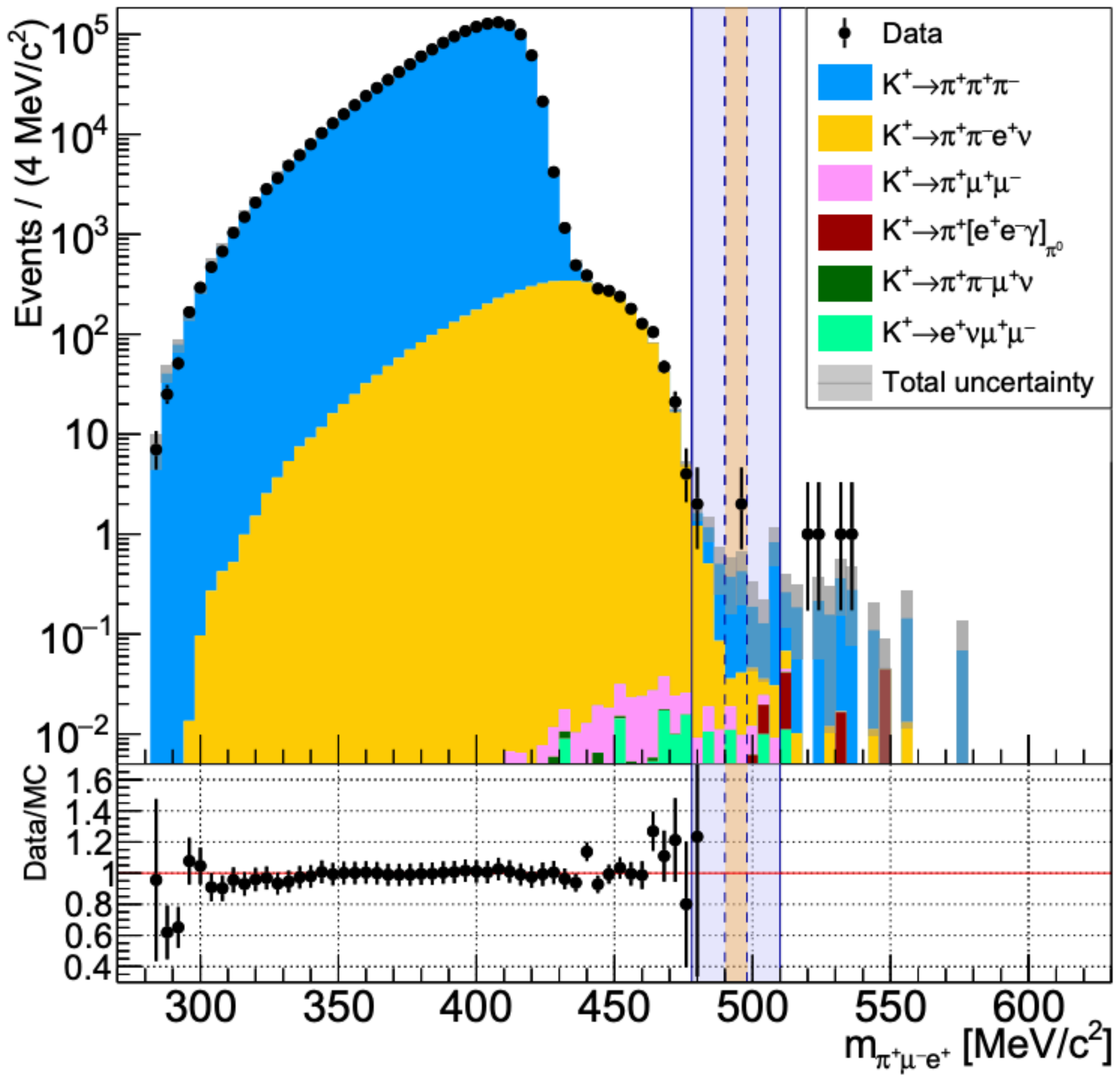


Expected background: 1.07 ± 0.20

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

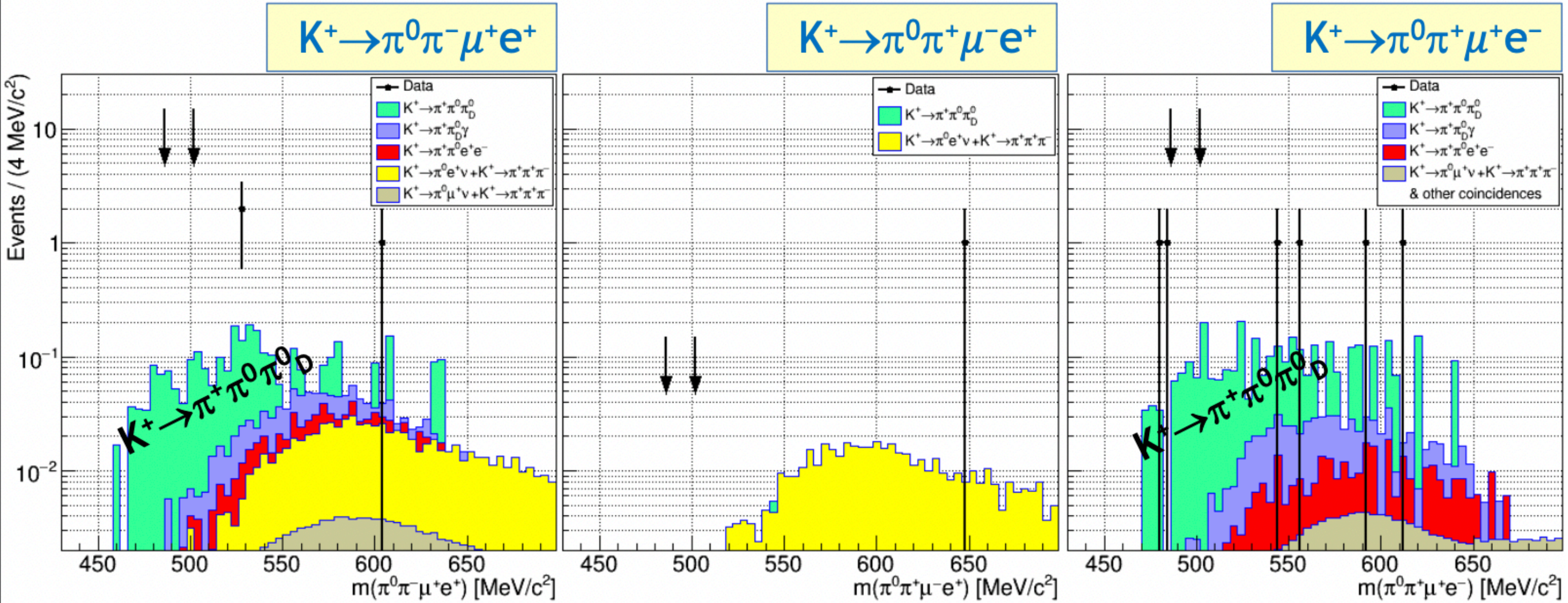
From $K^+ \to \pi^+\pi^0$, $\pi^0 \to \mu^-e^+$ search:

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

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

Hot off the press:

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



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

[First presented at BEACH 2024, to be published]

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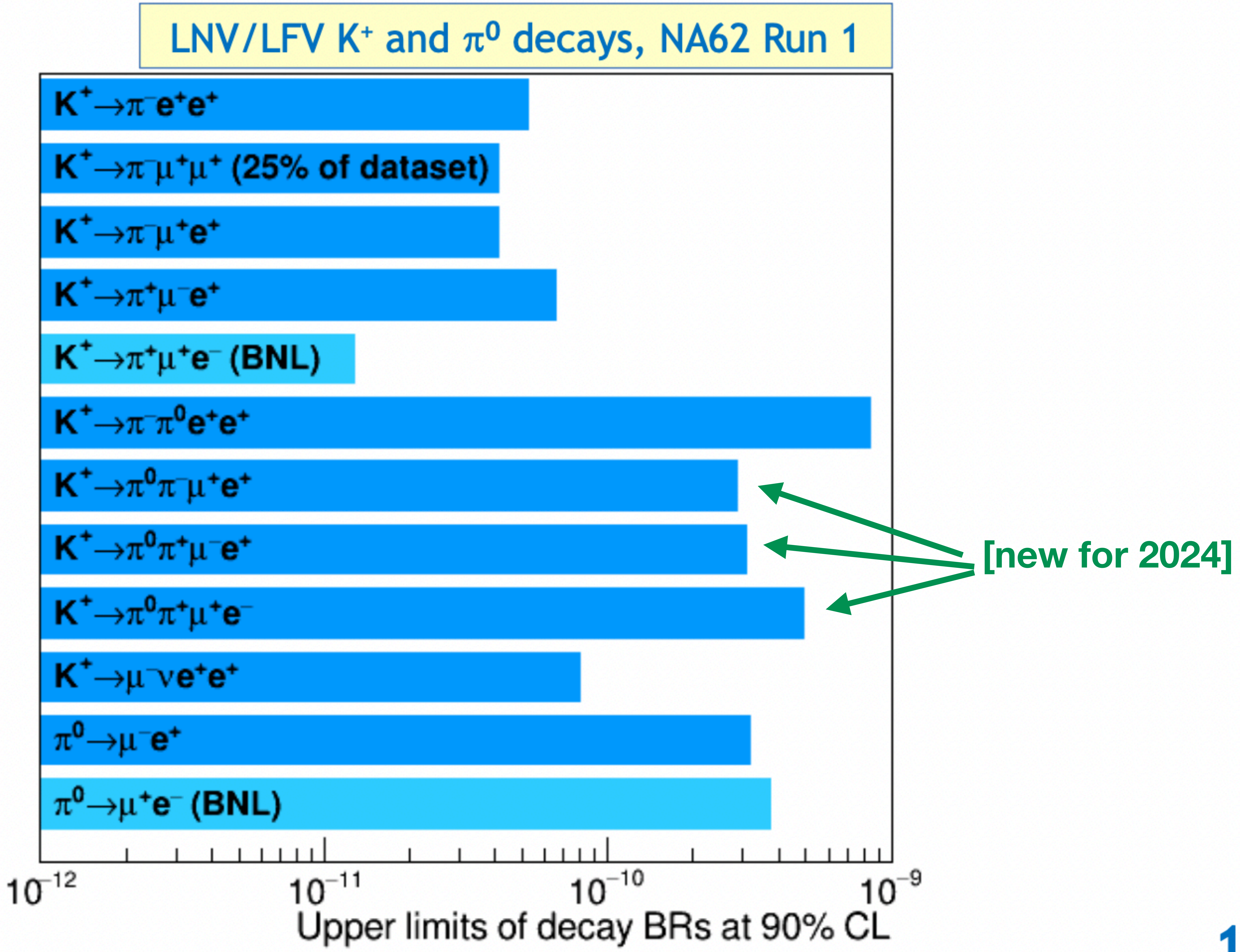
E. Goudzovski / BEACH 2024, Charleston, 4 June 2024

Hot off the press:

LFV/LNV K^+ decays: state of the art



E. Goudzovski / BEACH 2024, Charleston, 4 June 2024

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Exotic processes at NA62

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.

Joel Swallow

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]

Analysis Strategy

- Selection of 2 charged particles:
  - Tracks in coincidence with each other and trigger.
  - PID leptons (LKr, MUV3) or hadrons (LKr, MUV1,2,3, RICH)
  - LAV, SAV, ANTI0 vetos
  - Vertex in FV (r vs z), pointing back to TAX (CDA vs z).

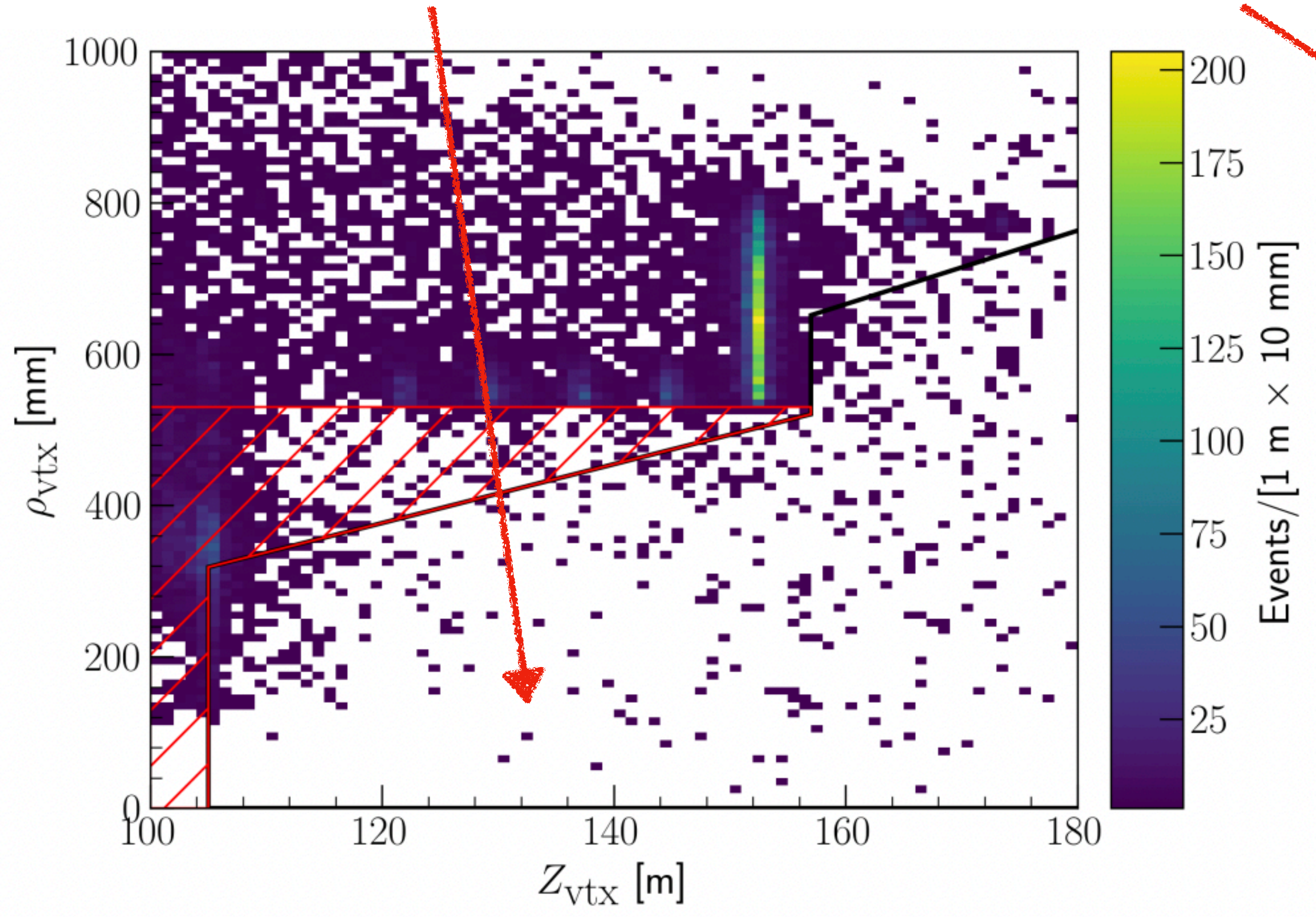


Figure: Two-track vertices (no PID) and definition of fiducial volume and upstream region (red hatched area).

- For hadronic channels with neutral particles reconstruct γ, π^0, η from LKr clusters, opening angle & timing.

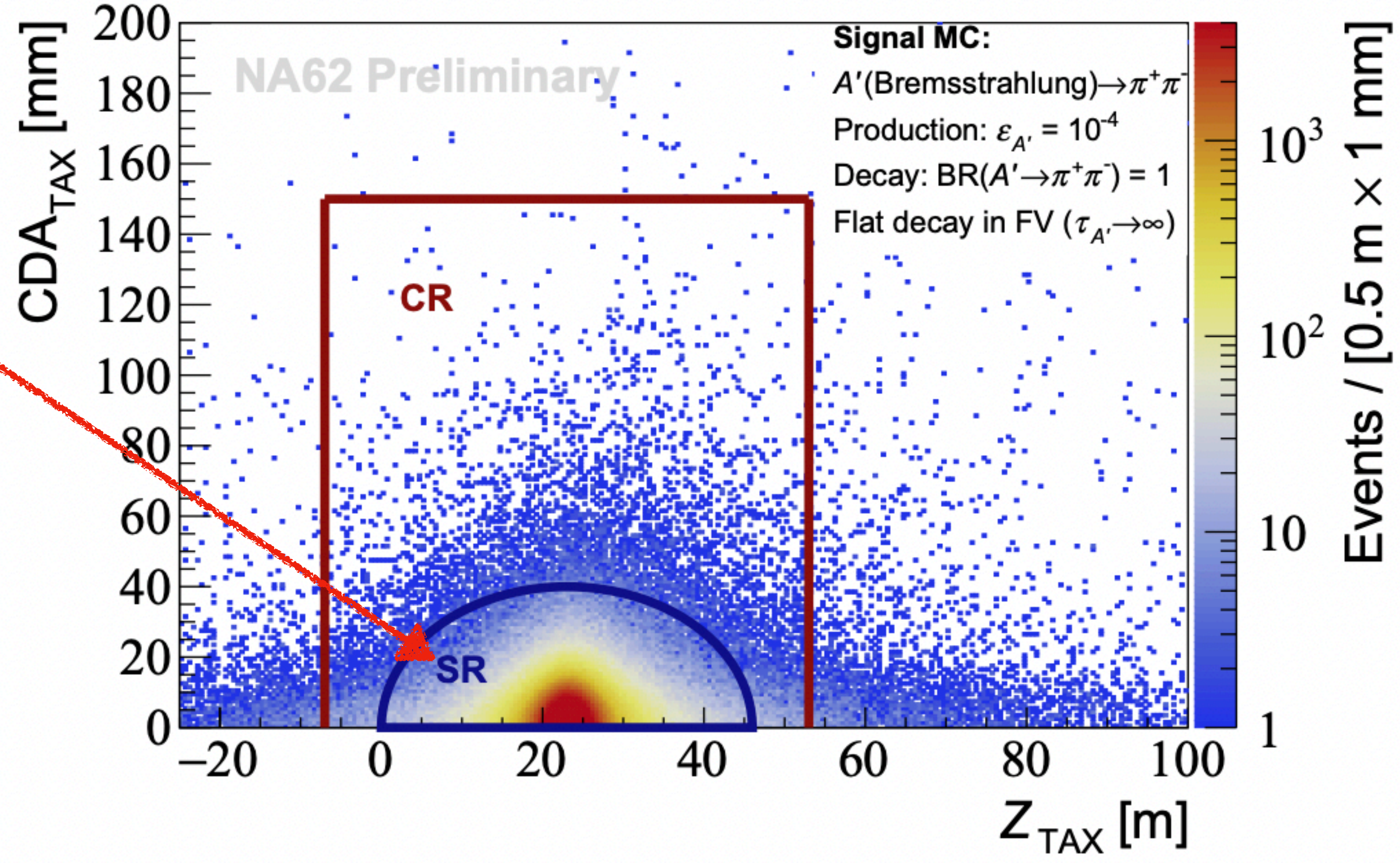


Figure: $A' \to \pi^+\pi^-$ MC: control (CR) and signal (SR) regions.

- SR: ellipse center $\{Z_{\mathrm{TAX}}, \mathrm{CDA}_{\mathrm{TAX}}\} = \{23\,\mathrm{m}, 0\,\mathrm{mm}\}$, semi-axes of 23 m and 40 mm
- CR: $\mathrm{CDA}_{\mathrm{TAX}} < 150\,\mathrm{mm}$ and $-7\,\mathrm{m} < Z_{\mathrm{TAX}} < 53\,\mathrm{m}$
- **both SR and CR kept masked during the analysis**

[Spadaro, Vulcano24]

Backgrounds

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

$A' \to \mu^+\mu^-$[arXiv.2312.12055]:

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:

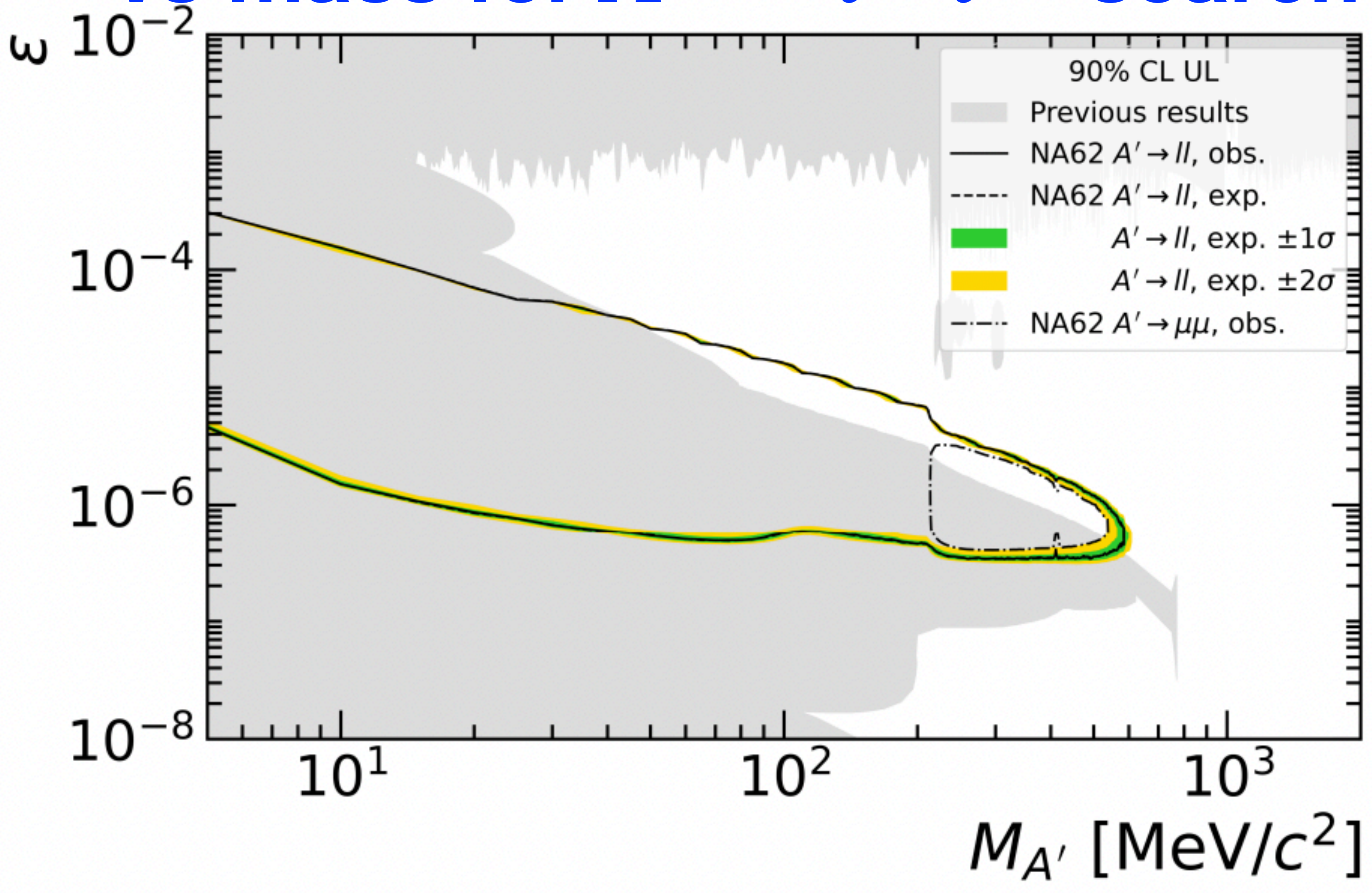
Channel	$N_{\rm exp,CR} \pm \delta N_{\rm exp,CR}$	$N_{\rm exp,SR} \pm \delta N_{\rm exp,SR}$	$N_{\rm obs,SR}^{p>5\sigma}$	$N_{\rm obs,SR+CR}^{p>5\sigma}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004	3	5
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$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

All almost background-free, 5σ discovery for 1 event for some hadronic channels…

Results:

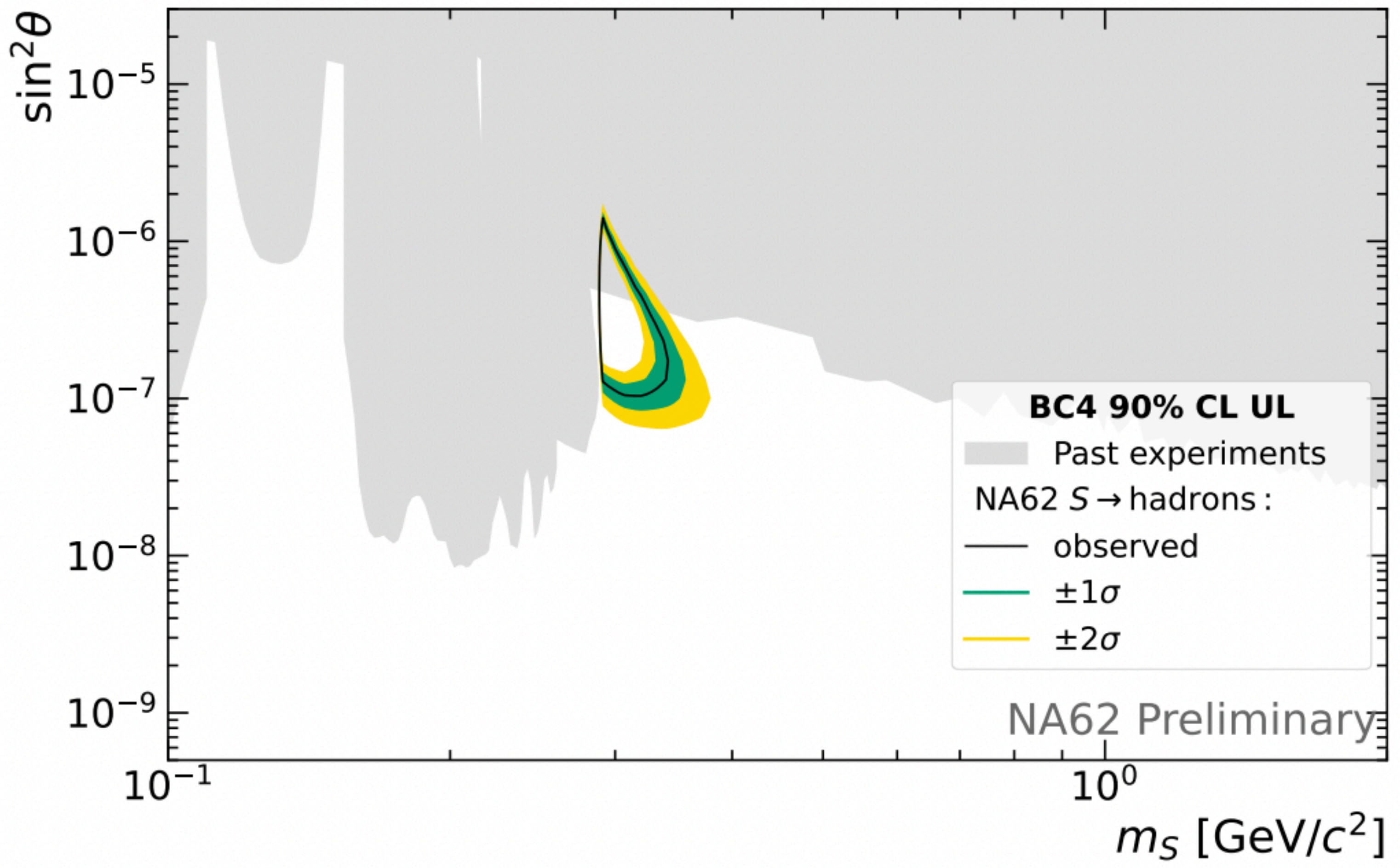
- e^+e^- : 0 observed
- $\mu^+\mu^-$: 1 observed (p=1.6%, 2.4σ global significance)
- 25 Hadronic channel signal regions: 0 events.
- Therefore set upper limits…

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



[arXiv.2312.12055]

Hadronic final states: dark scalar & ALP constraints



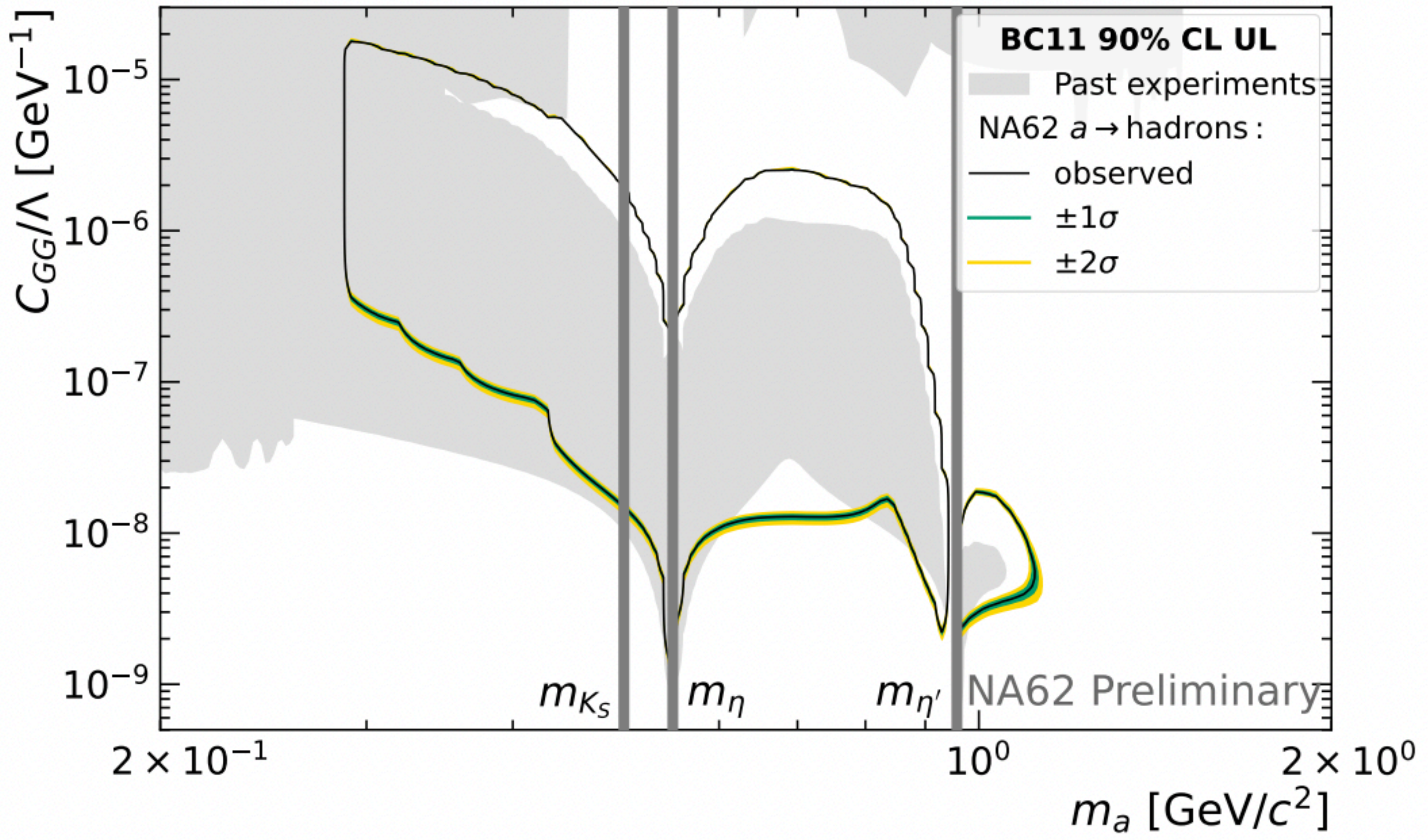


Figure: The observed 90% CL exclusion contours in BC4 (left) and BC11 (right) benchmarks together with the expected $\pm1\sigma$ and $\pm2\sigma$ bands (theory uncertainty not included). Public tool ALPINIST[5] used for the combination of the results from the individual production and decay channels. No standalone 90% CL exclusion for BC1 (dark photon).

[5] ALPINIST: Axion-Like Particles In Numerous Interactions Simulated and Tabulated. *JHEP* 07 (2022) 094, [2201.05170

[Spadaro, Vulcano24]

Outlook

The future of kaon physics

Charged Kaons

- Only possible to produce vast data-sets at high intensity @ CERN: HIKE proposal:
  - comprehensive project: $\mathcal{O}(5\%)$ precision of $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ along with full spectrum of K^+ physics, with K_L physics in phase2.
- CERN strategic decision: choose BDF/SHiP, HIKE not approved.
- **Therefore NA62 will mark the end of K+ physics @ CERN for the foreseeable future.**
  - Both a challenge & opportunity: must extract all we can from our data.

Neutral Kaons

- Ongoing **KOTO project for $K_L \to \pi^0 \nu \bar{\nu}$ at J-PARC**, **KOTO-II project towards SM sensitivity**:
  - On track but funding to be approved - part of high priority hadron hall extension.
  - Possibilities to extend physics reach, e.g. adding tracking, under discussion in community.
- Some contributions from LHCb on K_S are possible, exploiting new fully-software trigger.

[Kaons @ CERN23 : Eur.Phys.J.C 84 (2024) 4, 377]

Summary

Summary

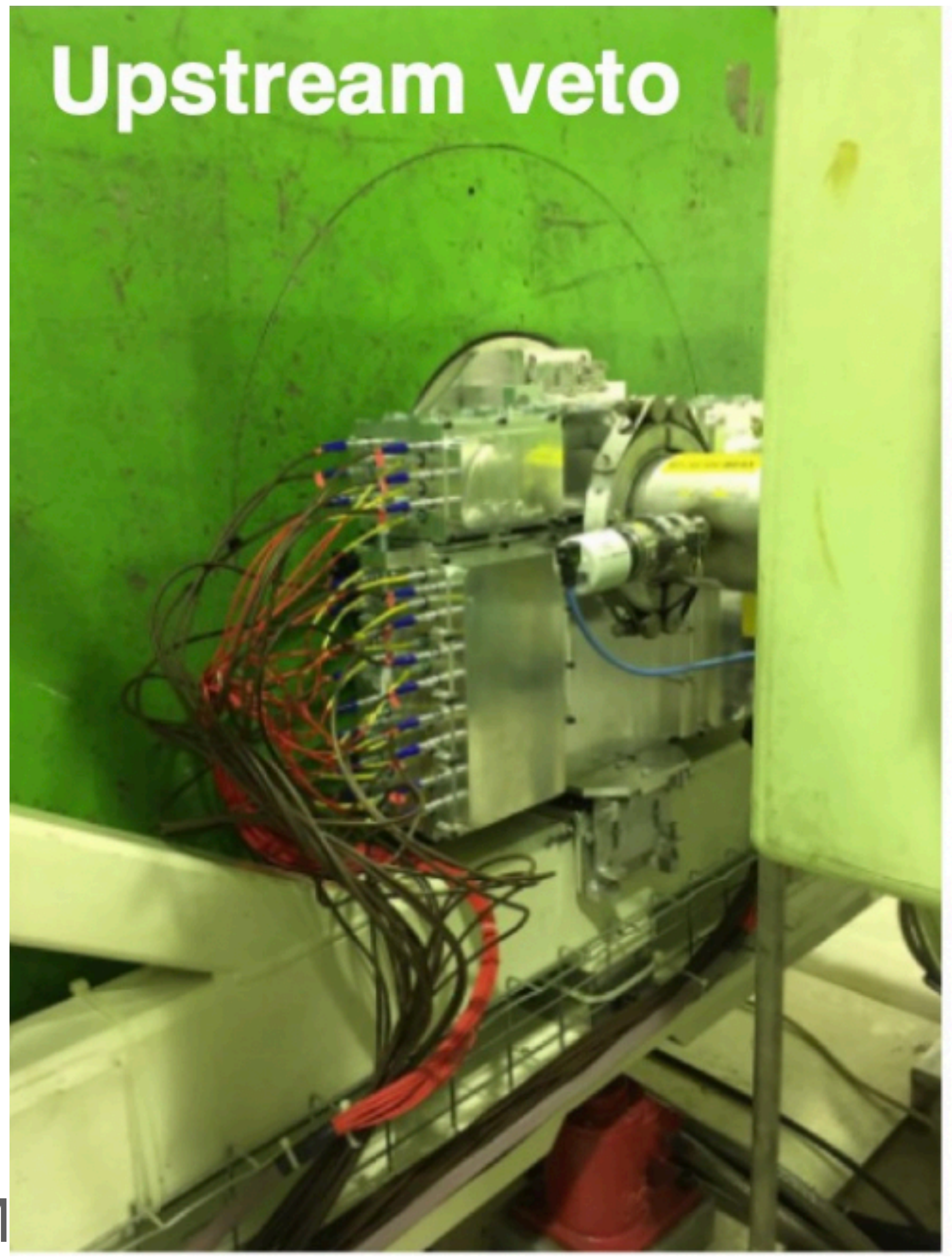
- $K^+ \to \pi^+ \nu \bar{\nu}$, NA62's primary objective: worlds best measurements with RUN1 data.
  - First RUN2 data result being finalised.
- Comprehensive set of rare and forbidden decays studied:
  - Precision ~1% for rare decays.
  - Sensitivity to LNV/LFV BR of $\mathcal{O}(10^{-11})$.
  - Significant improvements possible with RUN2 data (improved triggers).
- Searches for exotic particles with beam dump mode:
  - world-leading sensitivity below K+ mass.
- NA62 will provide final measurements of rare K^+ decays for the foreseeable future.
  - Challenge & opportunity: working hard to extract all we can from our data.
  - The best data may be arriving right now - plenty more physics results to come!

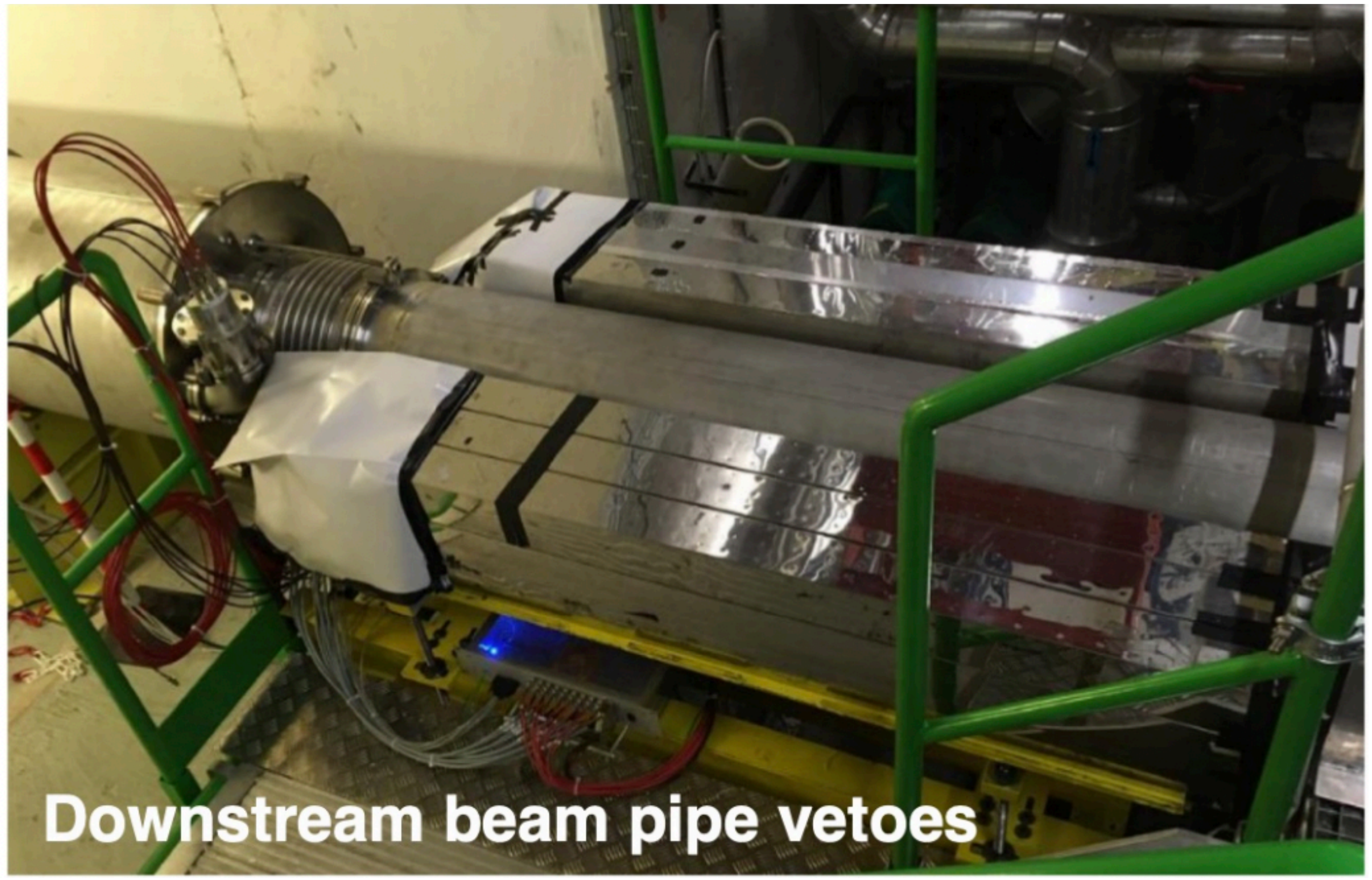
Supplemental

NA62 Run2

- NA62 technique is firmly established.
- Run2 - target $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu})$ 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:





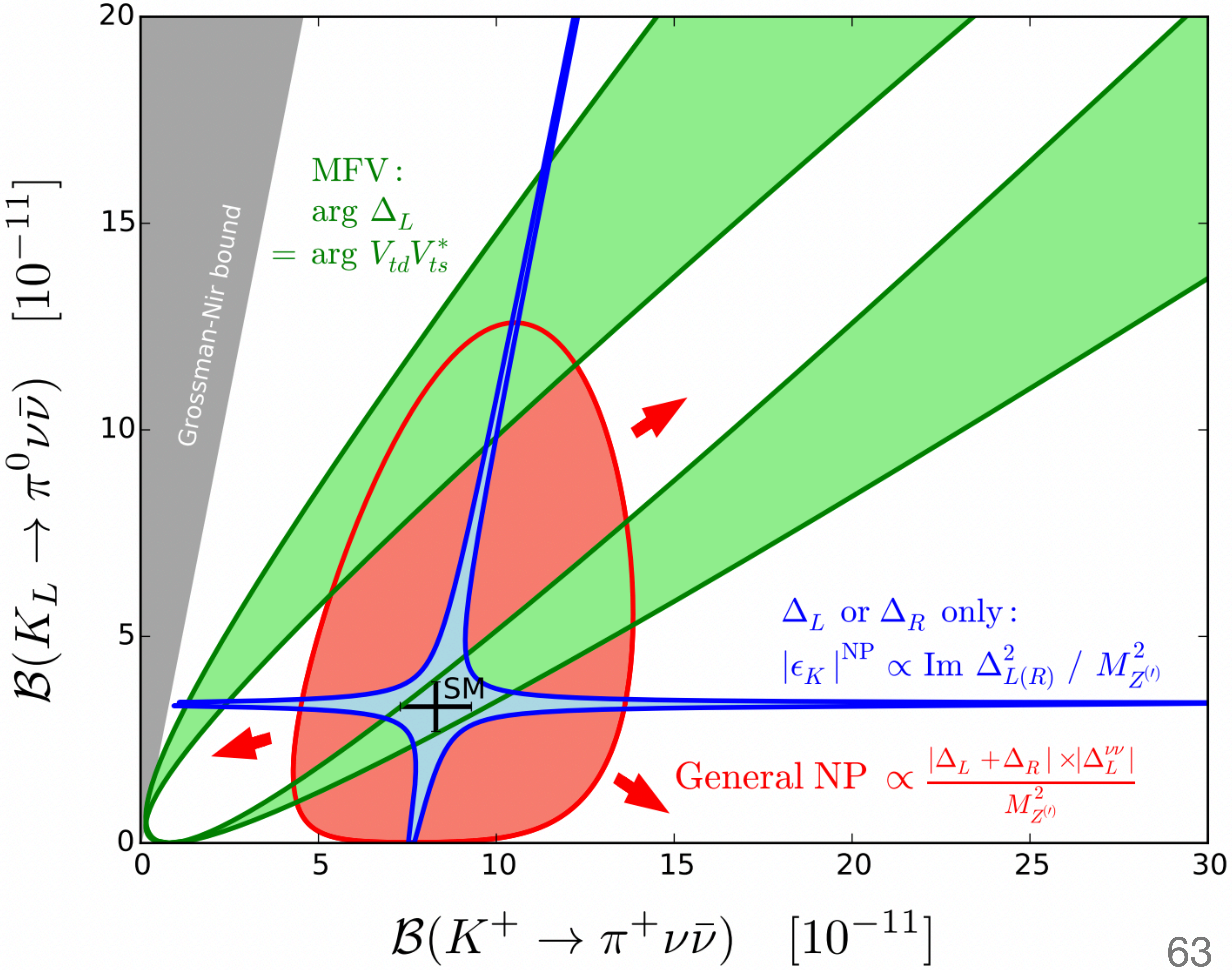
Golden Modes: $K \to \pi\nu\bar{\nu}$

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

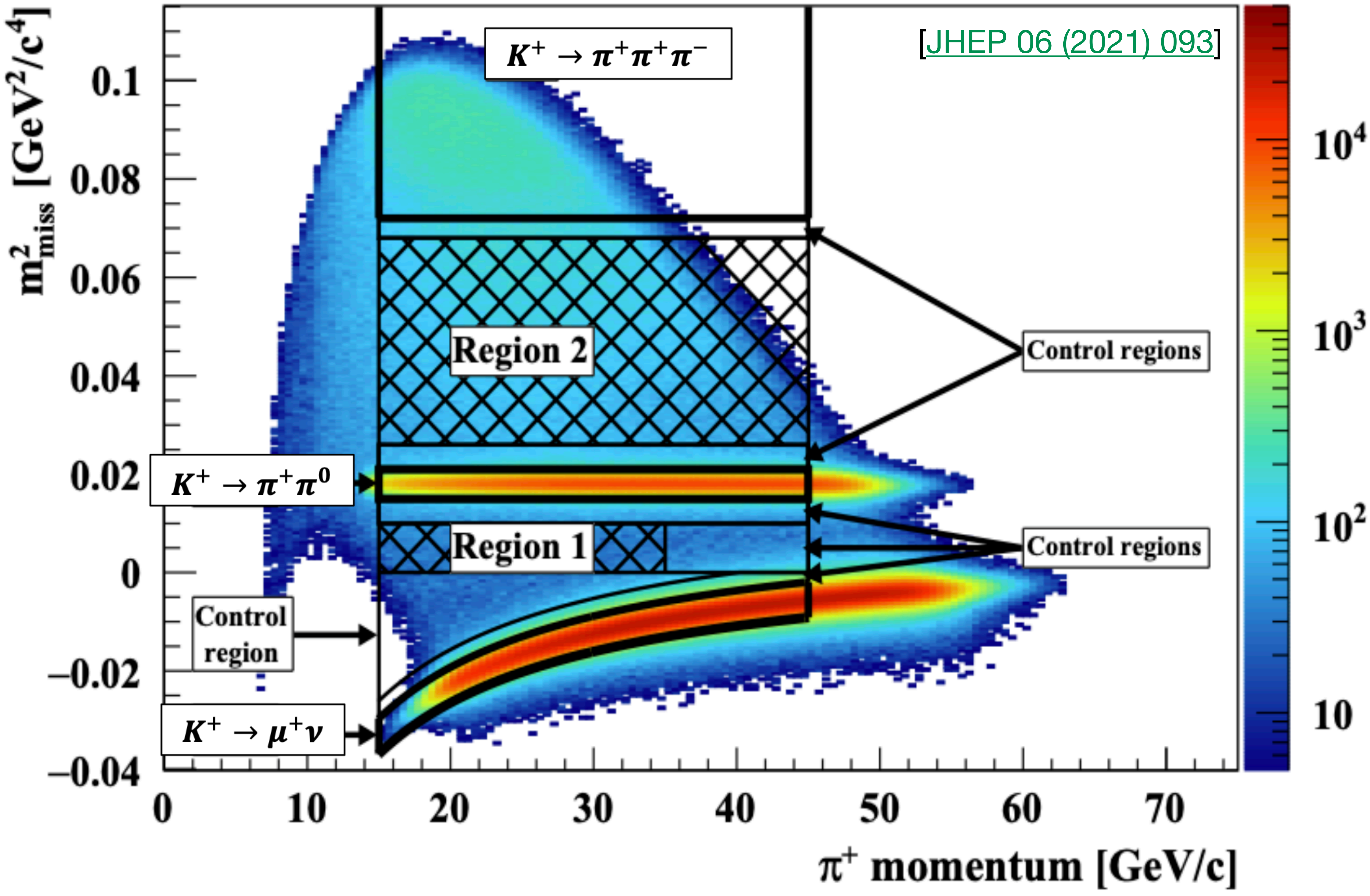
$$\frac{\mathscr{B}(K_L \to \pi^0\nu\bar{\nu})}{\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu})}\frac{\tau_{K^+}}{\tau_{K_L}} \leq 1$$



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

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

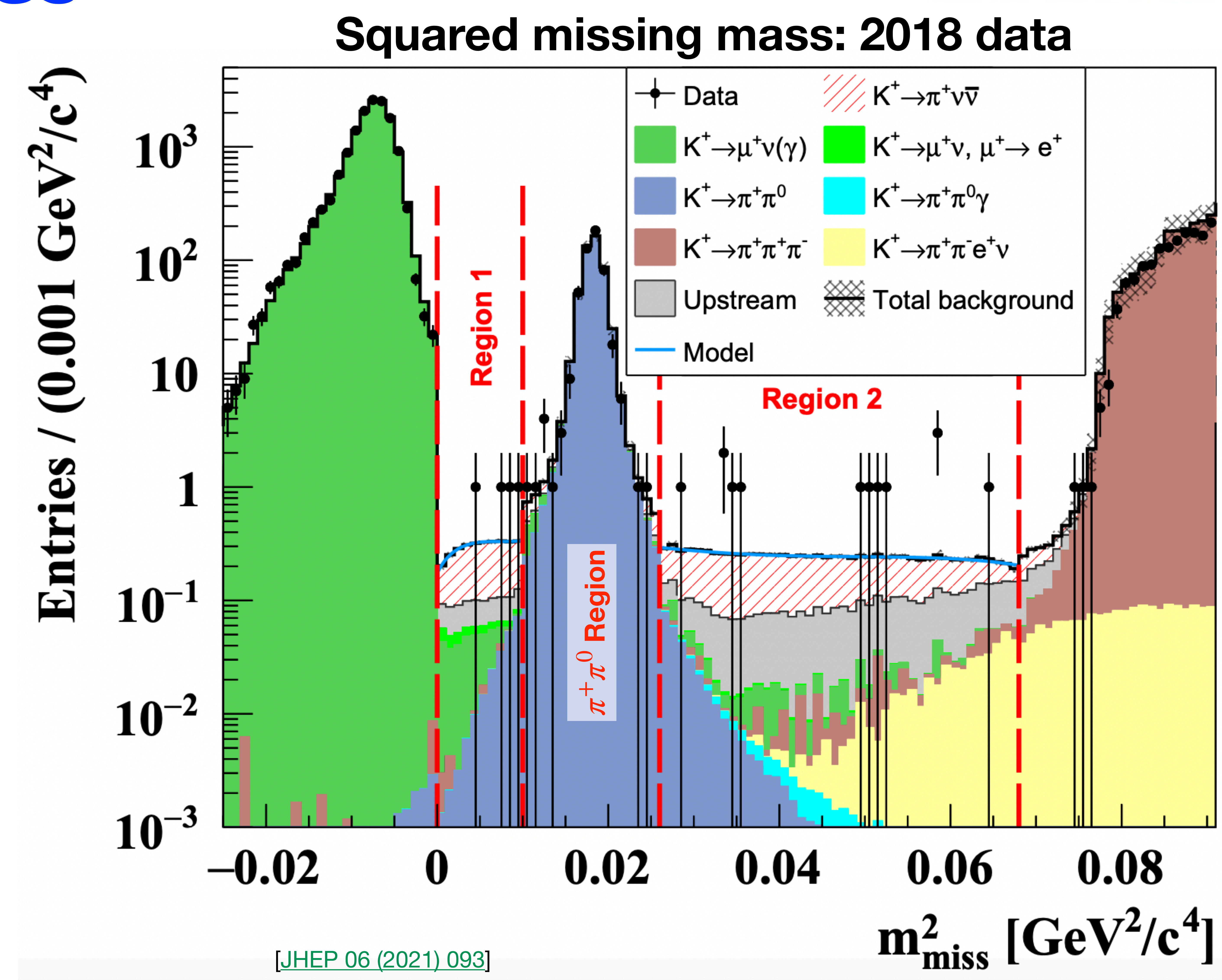
- **Reconstruct K^+ and π^+**
- $K - \pi$ **matching** & reconstruct vertex
  - CDA, timing, vertex in FV
- π^+ **Identification (**μ^+ **rejection)**
  - RICH (Calorimeters) performance:
    - $\varepsilon(\pi^+ \text{ID}) \approx 0.85(0.82)\,\%$
    - $P(\mu^+ \Rightarrow \pi^+ \text{misID}) \approx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

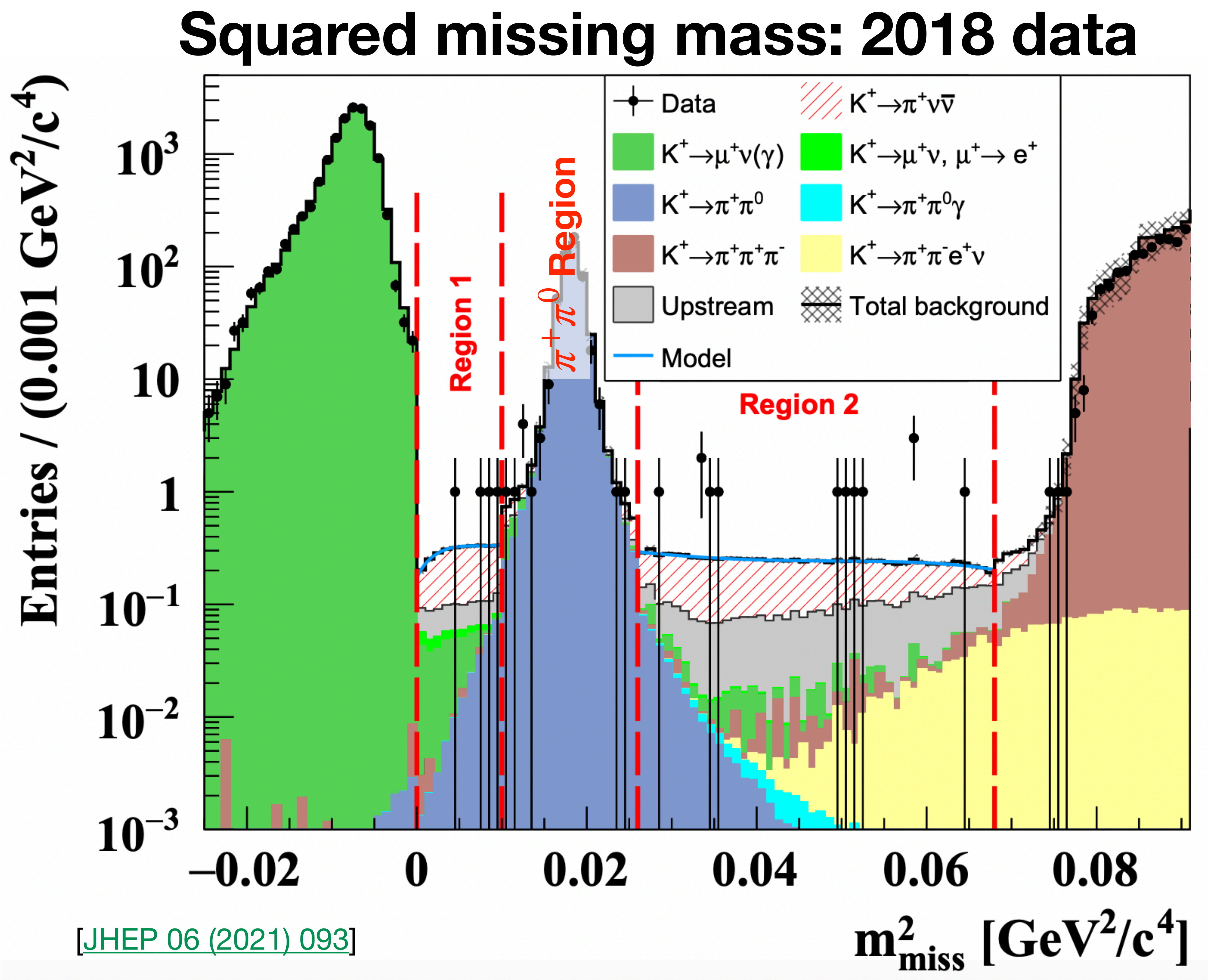
Hidden sector searches

- Search for $K^+ \to \pi^+ X$ in signal regions 1&2: $0 < m_X < 110\,\text{MeV}/c^2$, $154 < m_X < 260\,\text{MeV}/c^2$
  - X = invisible new particle
    - Dark scalar, ALP, QCD axion, axiflavon.
  - Main background = (SM) $K^+ \to \pi^+ \nu\bar{\nu}$
  - [2017: JHEP 03 (2021) 058, Run1: JHEP 06 (2021) 093]
- Search for $\pi^0 \to$ invisible in $\pi^+\pi^0$ region.
  - SM rate $\mathscr{B}(\pi^0 \to \nu\nu) \sim 10^{-24}$
  - observation = BSM
  - Reduced $\pi^0 \to \gamma\gamma$ background & optimised π^+ momentum range.
  - Interpret as $K^+ \to \pi^+ X$ with $m_X \sim m_{\pi^0}$.
  - [2017: JHEP 02 (2021) 201]

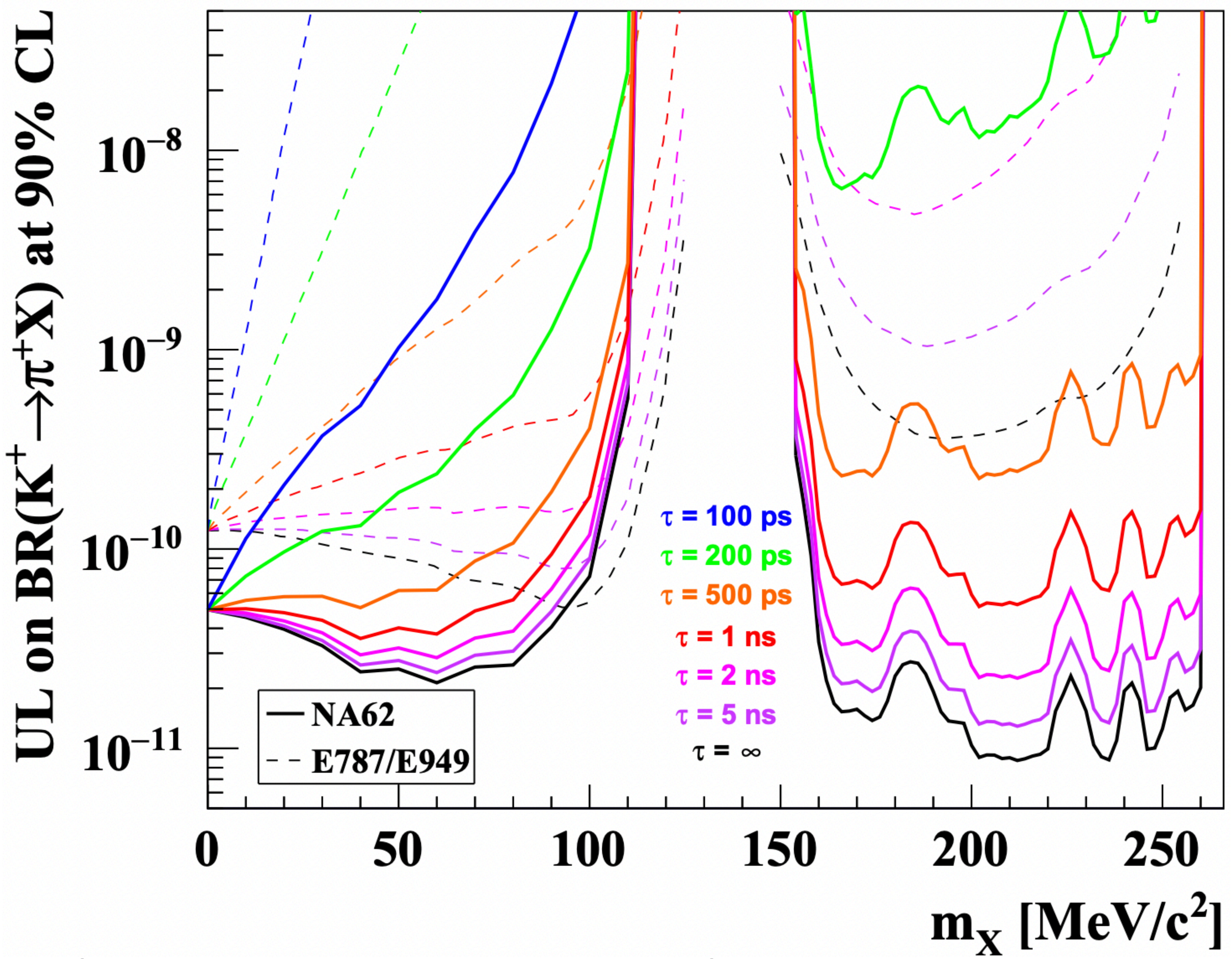


[JHEP 06 (2021) 093]

Hidden sector searches : $K^+ \to \pi^+ X$



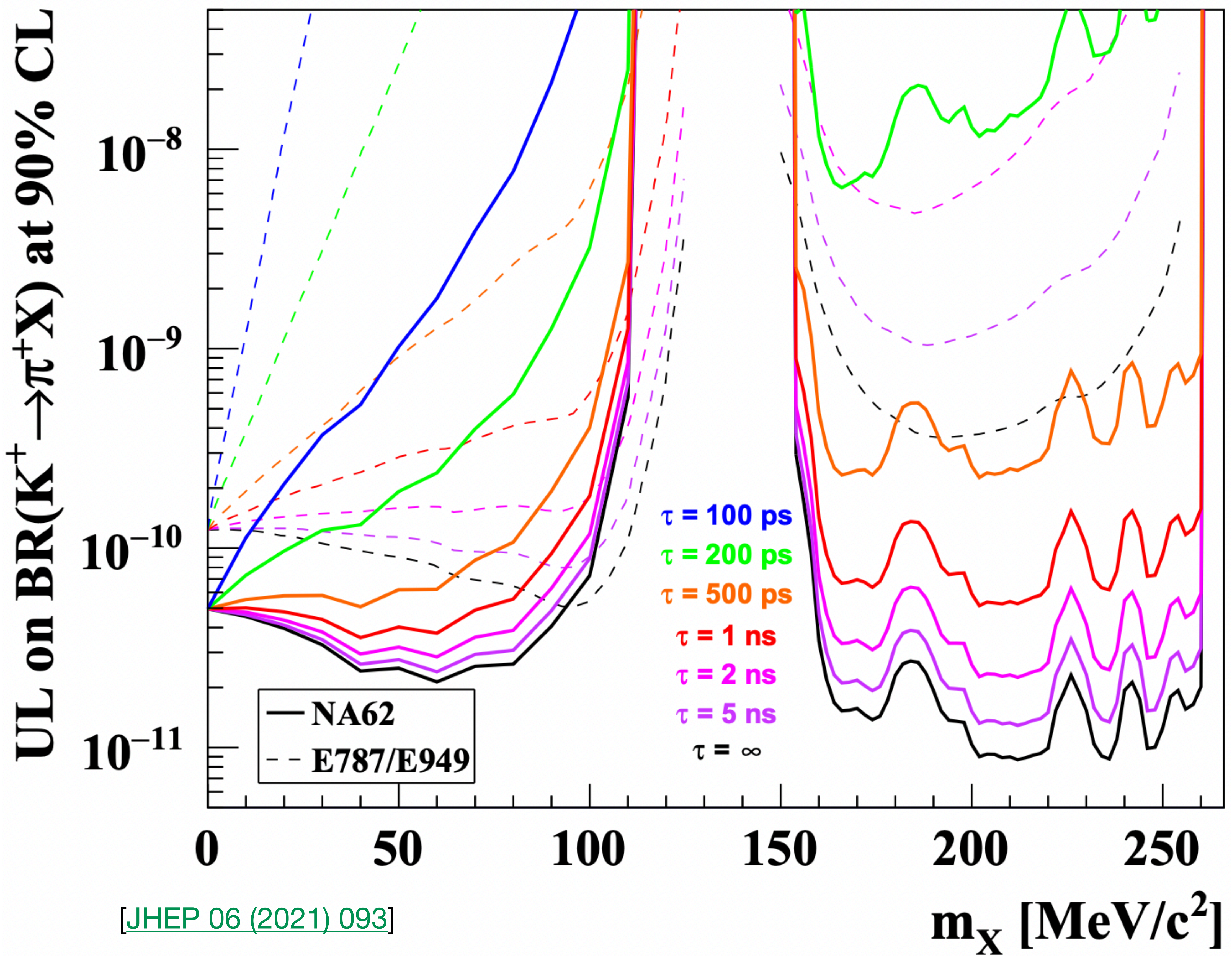
[JHEP 06 (2021) 093]



- Search for $K^+ \to \pi^+ X$ in signal regions 1&2: $0 < m_X < 110\,\text{MeV}/c^2$, $154 < m_X < 260\,\text{MeV}/c^2$
- X = invisible new particle: Dark scalar, ALP, QCD axion, axiflavon. [e.g. [EPJ C81 (2021) 1015; arXiv:2201.07805] (PBC: "BC4" & "BC10")]
- Main background = (SM) $K^+ \to \pi^+ \nu\bar{\nu}$.
- New upper limits [JHEP 03 (2021) 058][JHEP 06 (2021) 093], improve on BNL-E949 [PRD79 (2009) 092004] for most of m_X range.

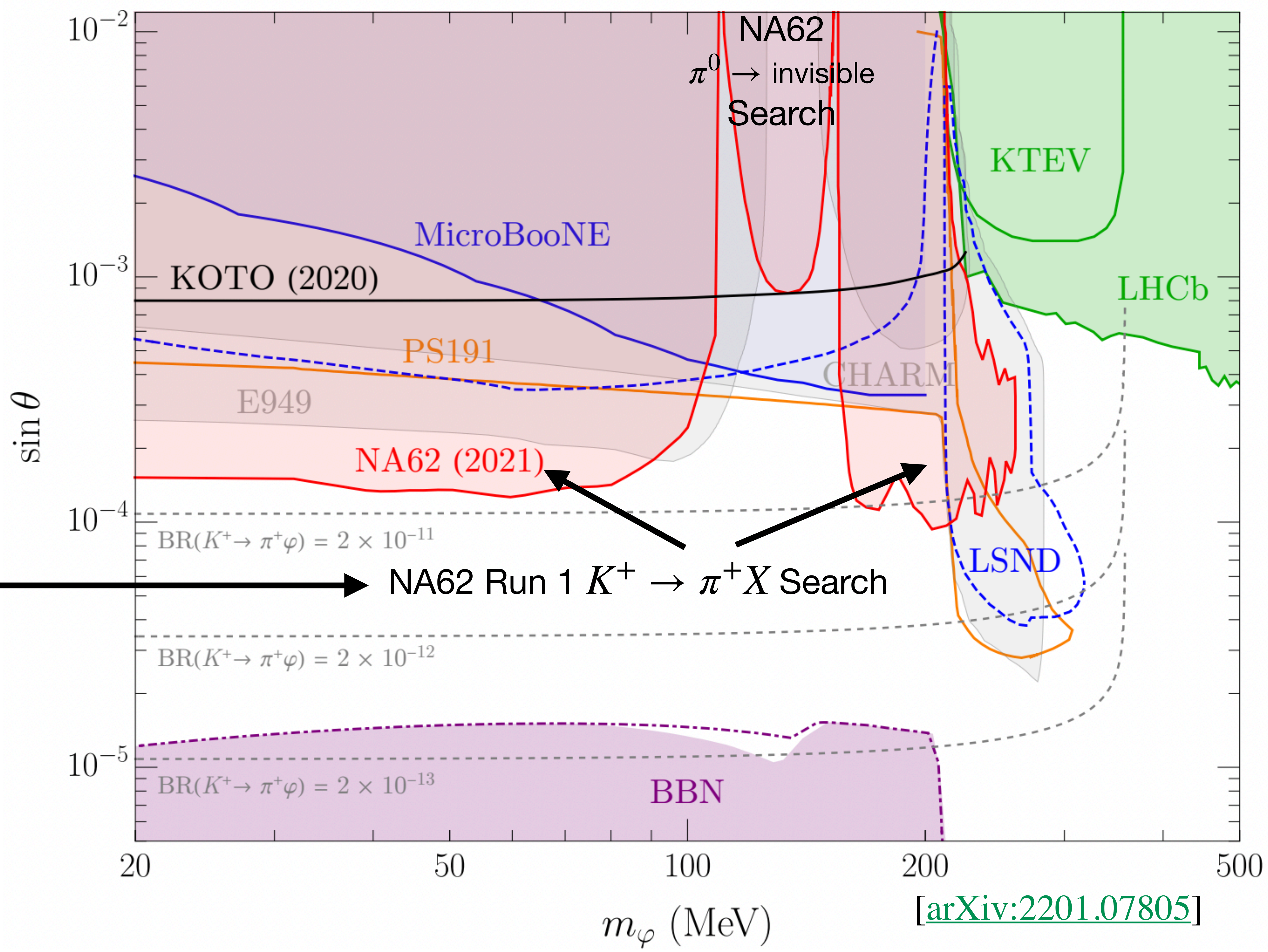
$K^+ \to \pi^+ X$ Search (Run1)

Upper Limits at 90% CL vs m_X for different lifetimes



[JHEP 06 (2021) 093]

Searches for dark scalar below kaon mass

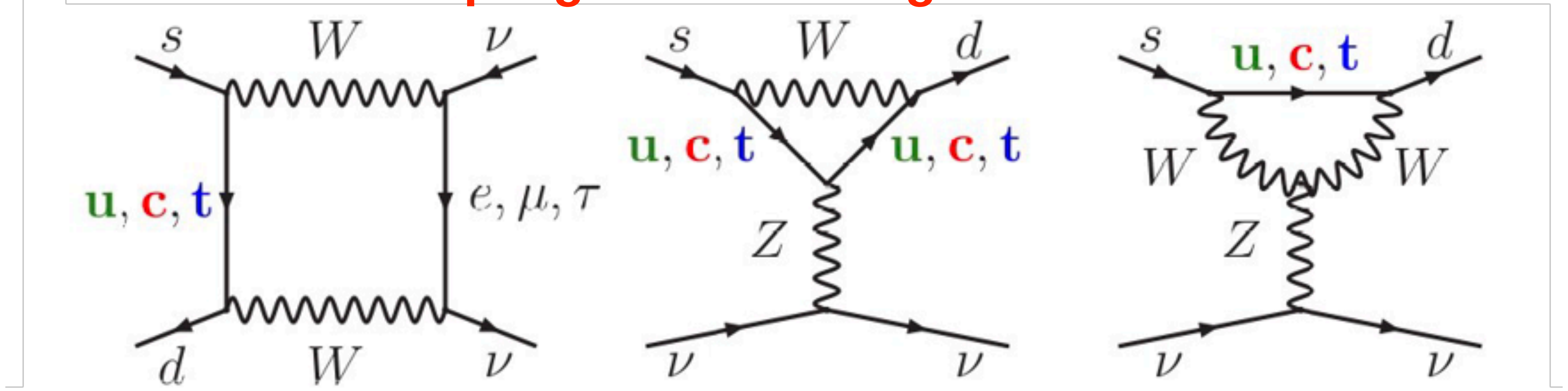


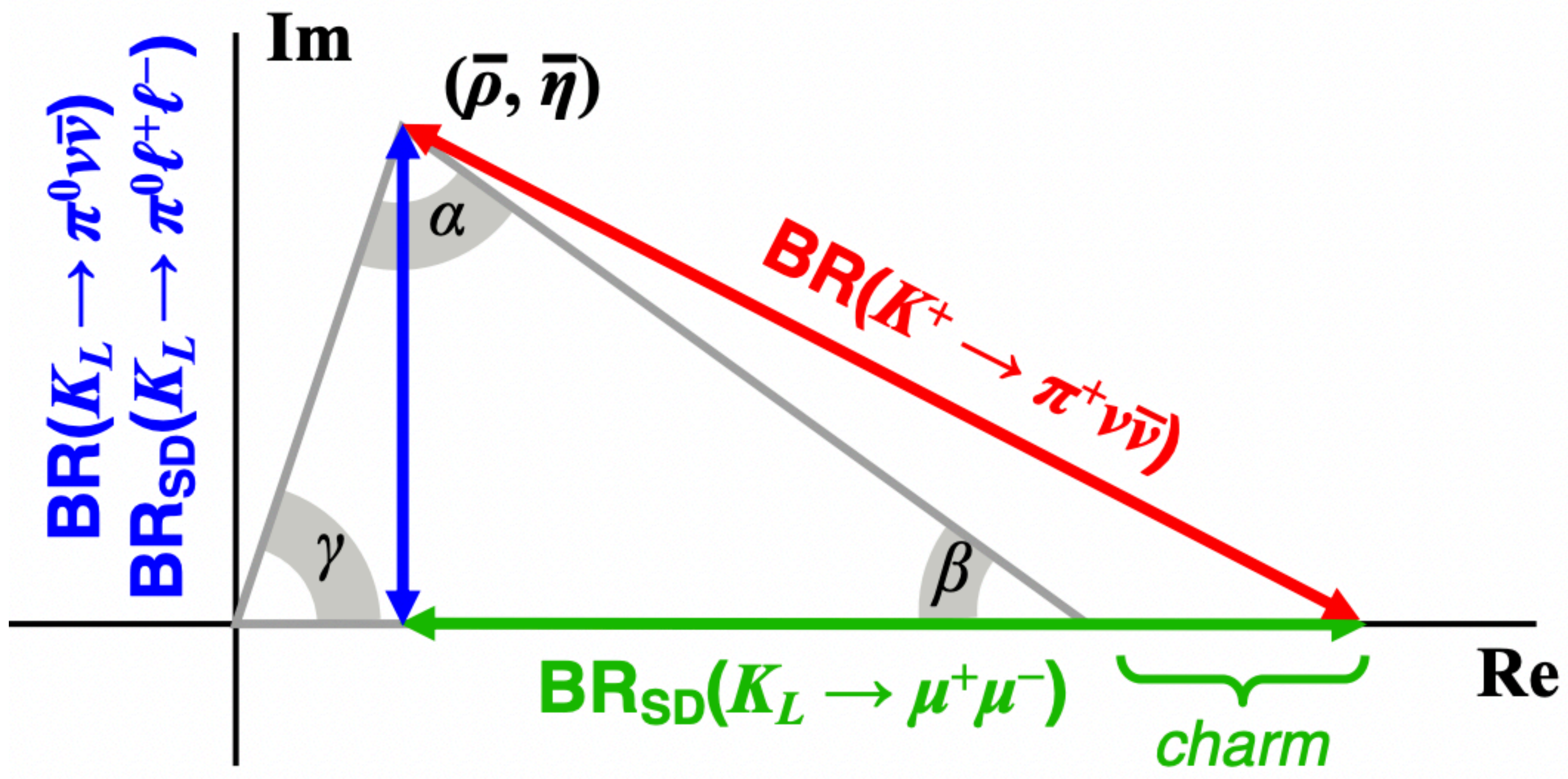
[arXiv:2201.07805]

- New upper limits improve on BNL-E949 [PRD79 (2009) 092004] over most of m_X range.
- Interpreted within the dark scalar and ALP (fermionic coupling) models [EPJ C81 (2021) 1015; arXiv:2201.07805] (PBC: "BC4" & "BC10").

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

SM: Z-penguin & box diagrams





- $\mathscr{B}(K \to \pi\nu\bar{\nu})$ 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 $\mathscr{B}(K \to \pi^0\ell^+\nu_\ell)$ 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…)

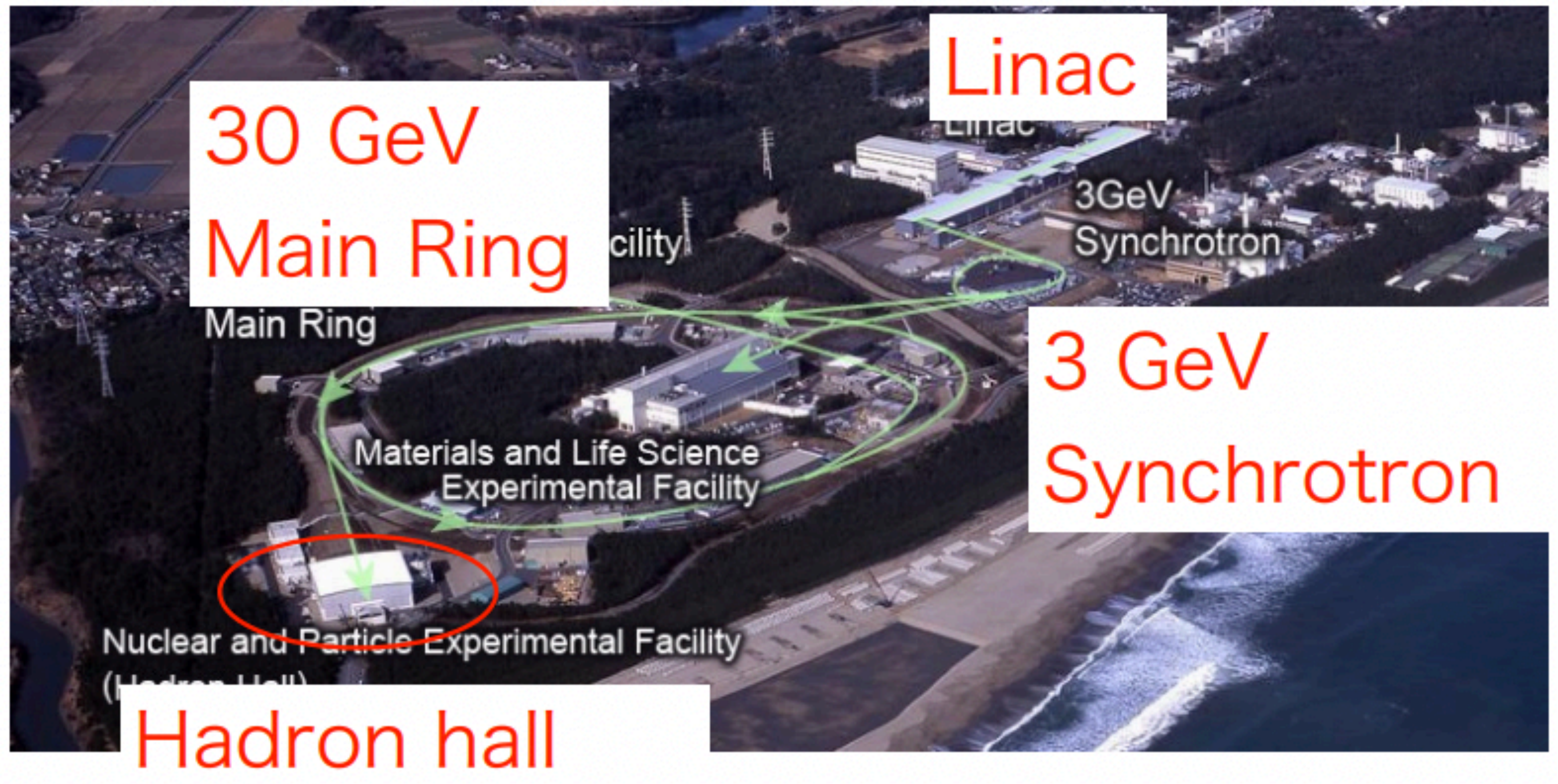
Mode	SM Branching Ratio	Experimental Status
$K^+ \to \pi^+\nu\bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$	$(10.6 \pm 4.0) \times 10^{-11}$ NA62 Run1
$K_L \to \pi^0\nu\bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$	$< 300 \times 10^{-11}$ KOTO (2015 data)

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

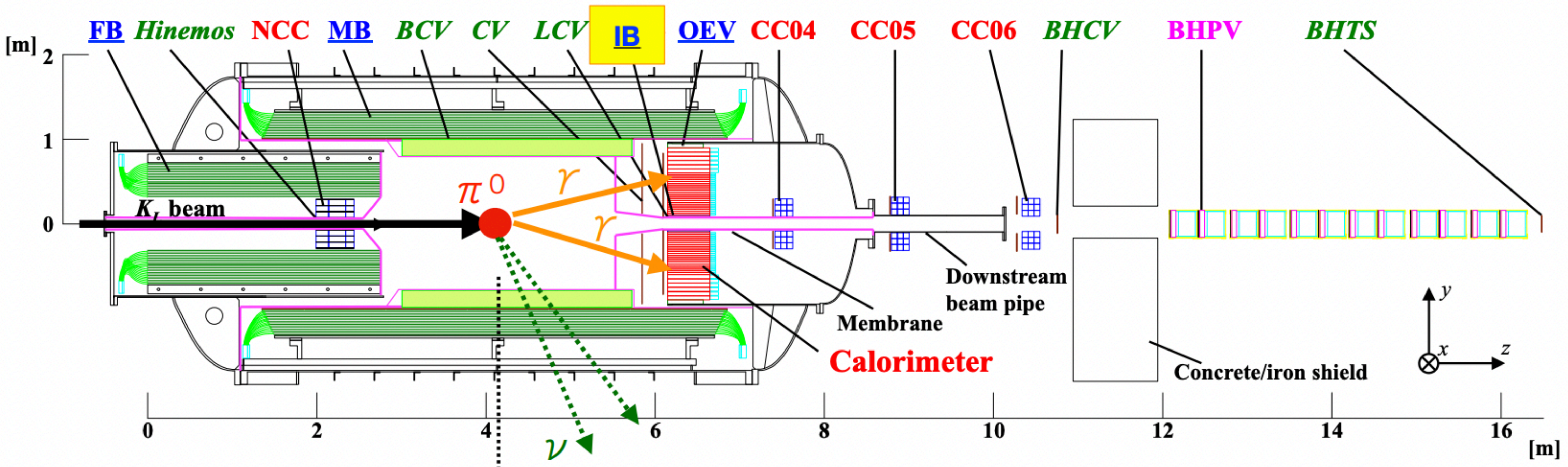
$K_L \to \pi^0 \nu \bar{\nu}$ at KOTO

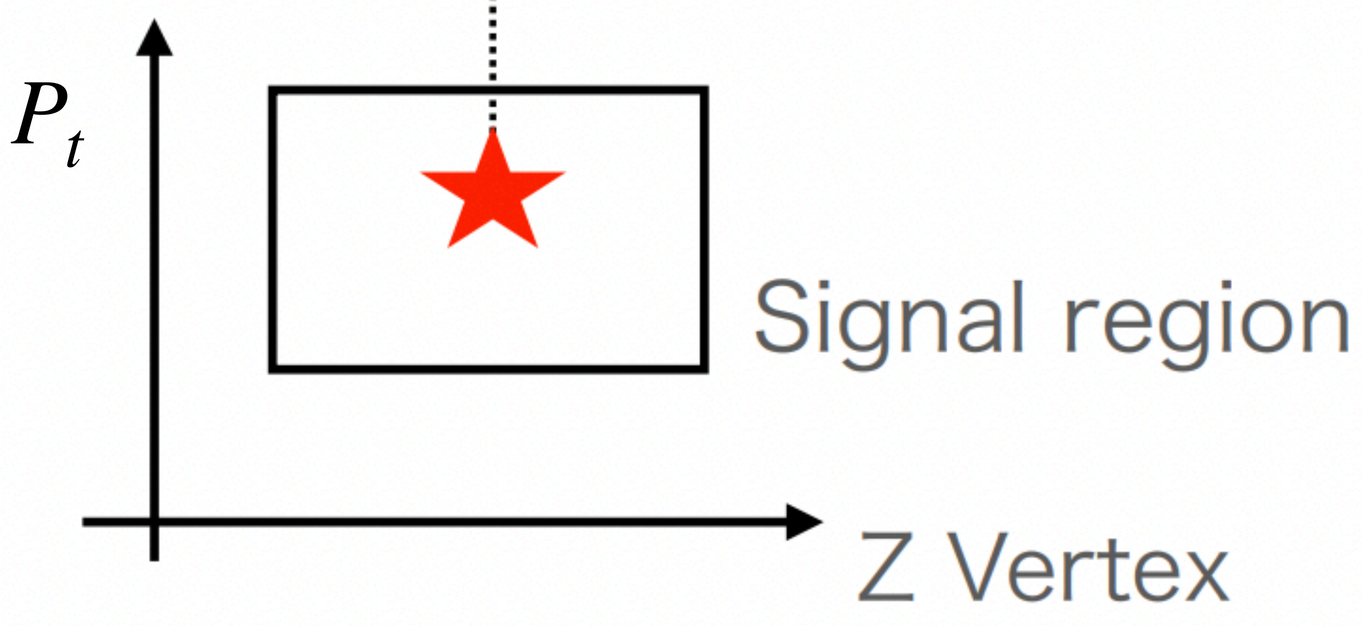
[K. shiomi : Kaons @ CERN 2023]

- 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

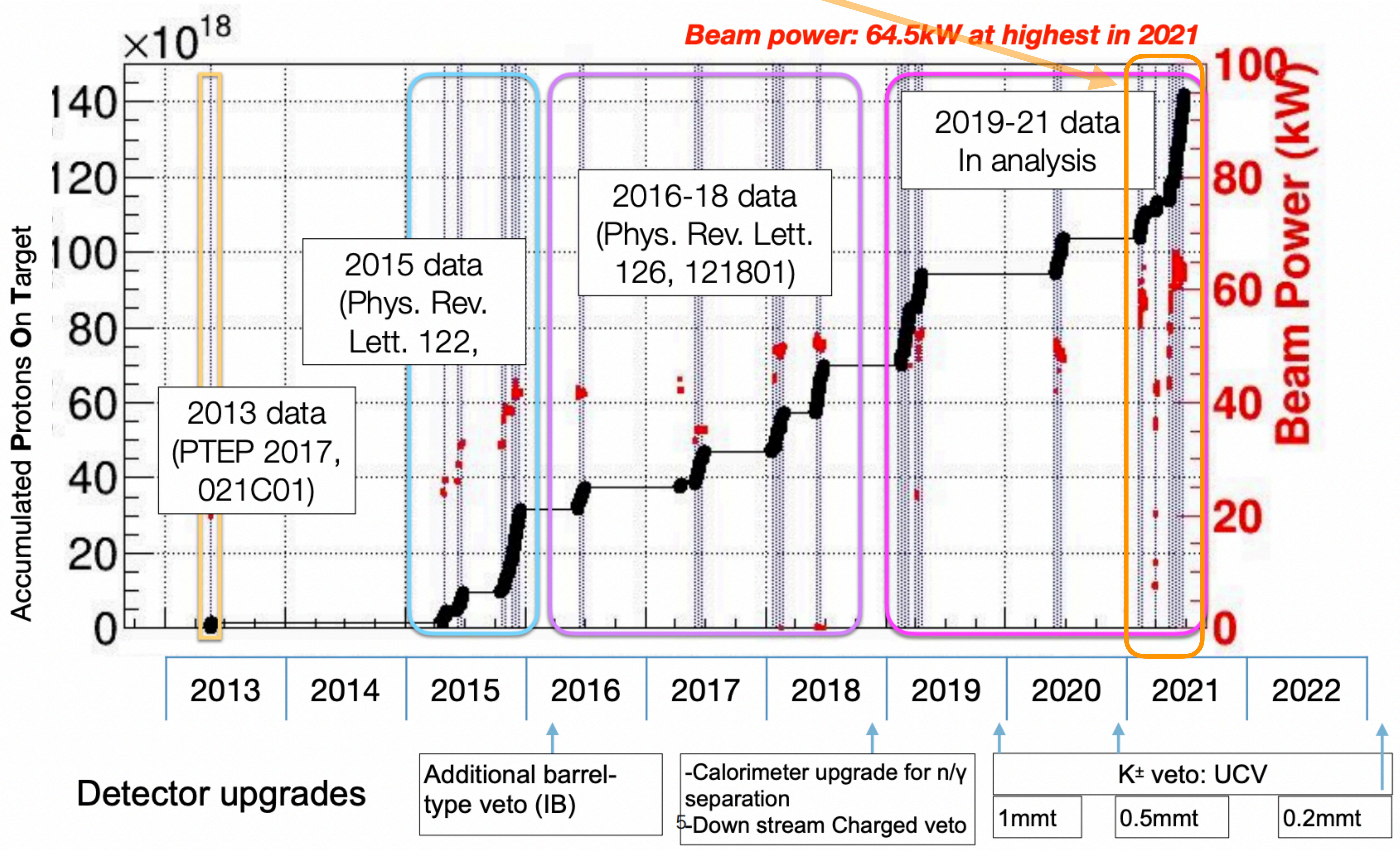
$$M^2(\pi^0)=2E_1E_2(1-\cos\theta)$$

Calculate π^0 transverse momentum

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

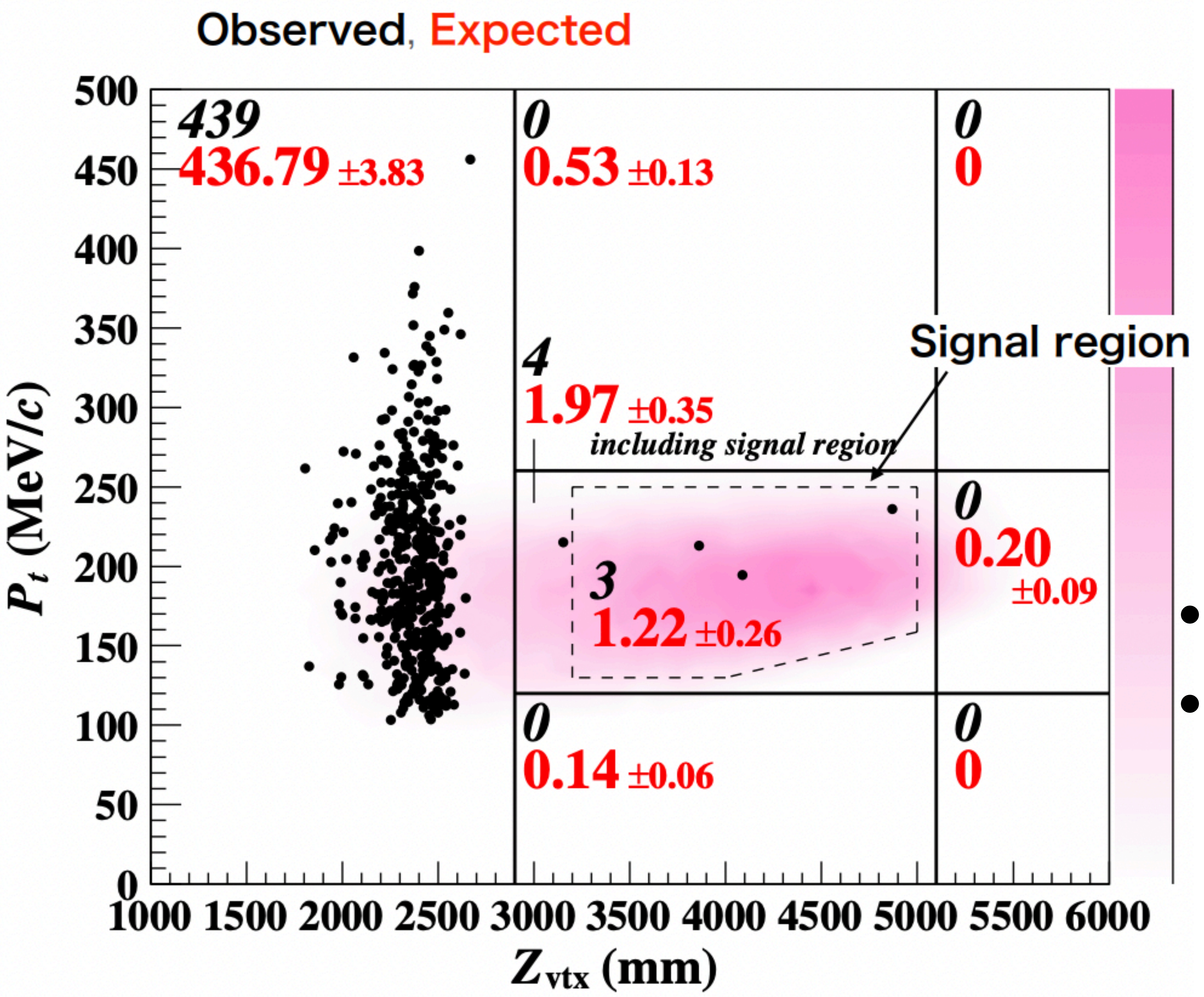
[K. shiomi : Kaons @ CERN 2023]

- 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]

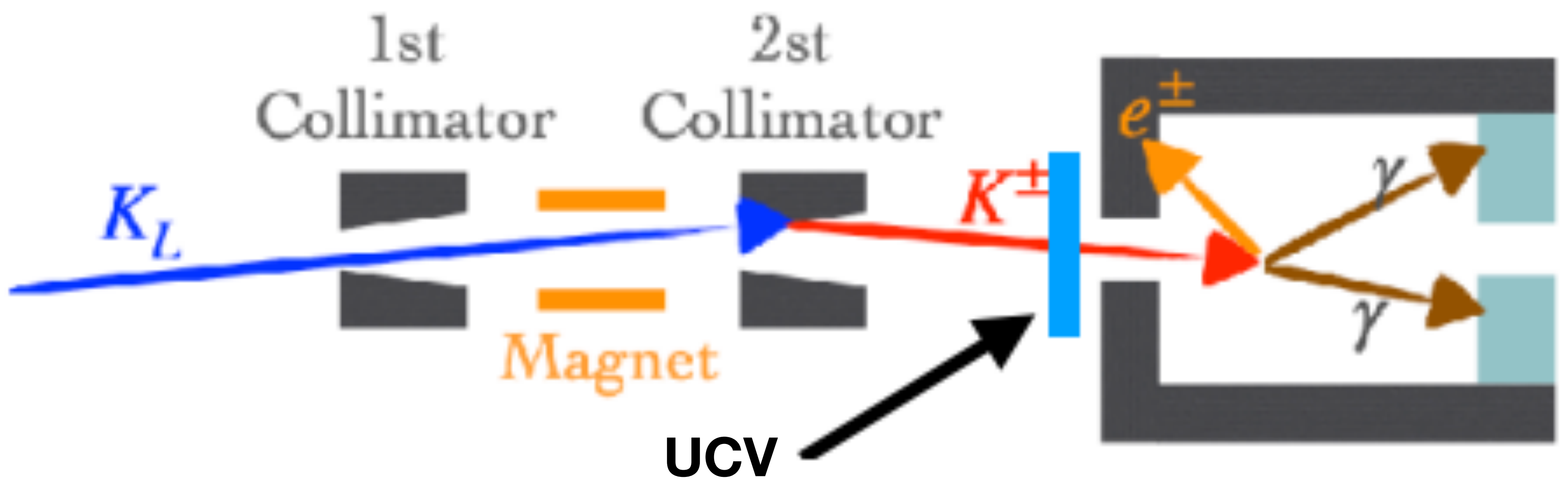


Background Table

	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

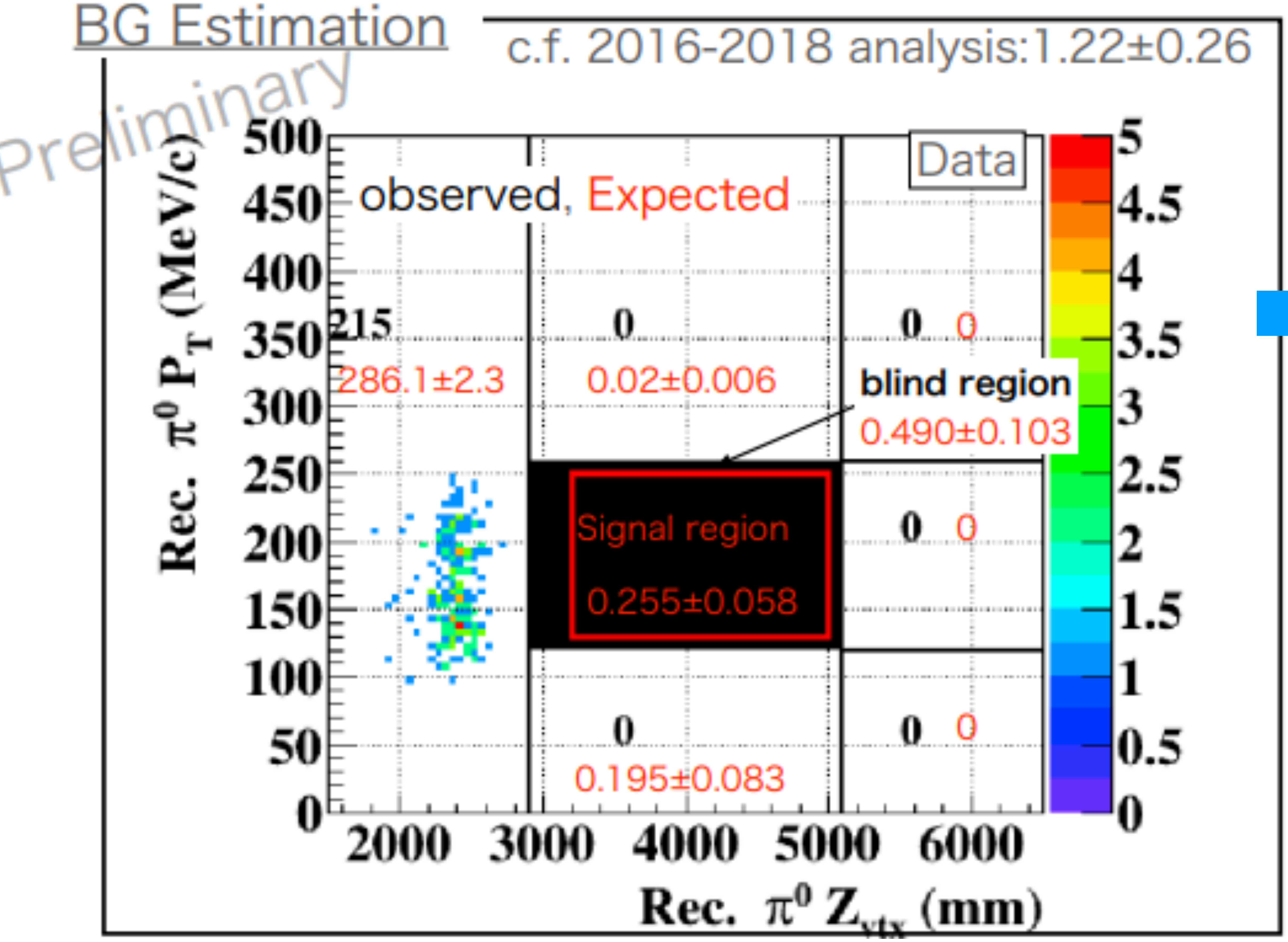
[K. shiomi : Kaons @ CERN 2023]

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

c.f. 2016-2018 analysis:7.2×10-10

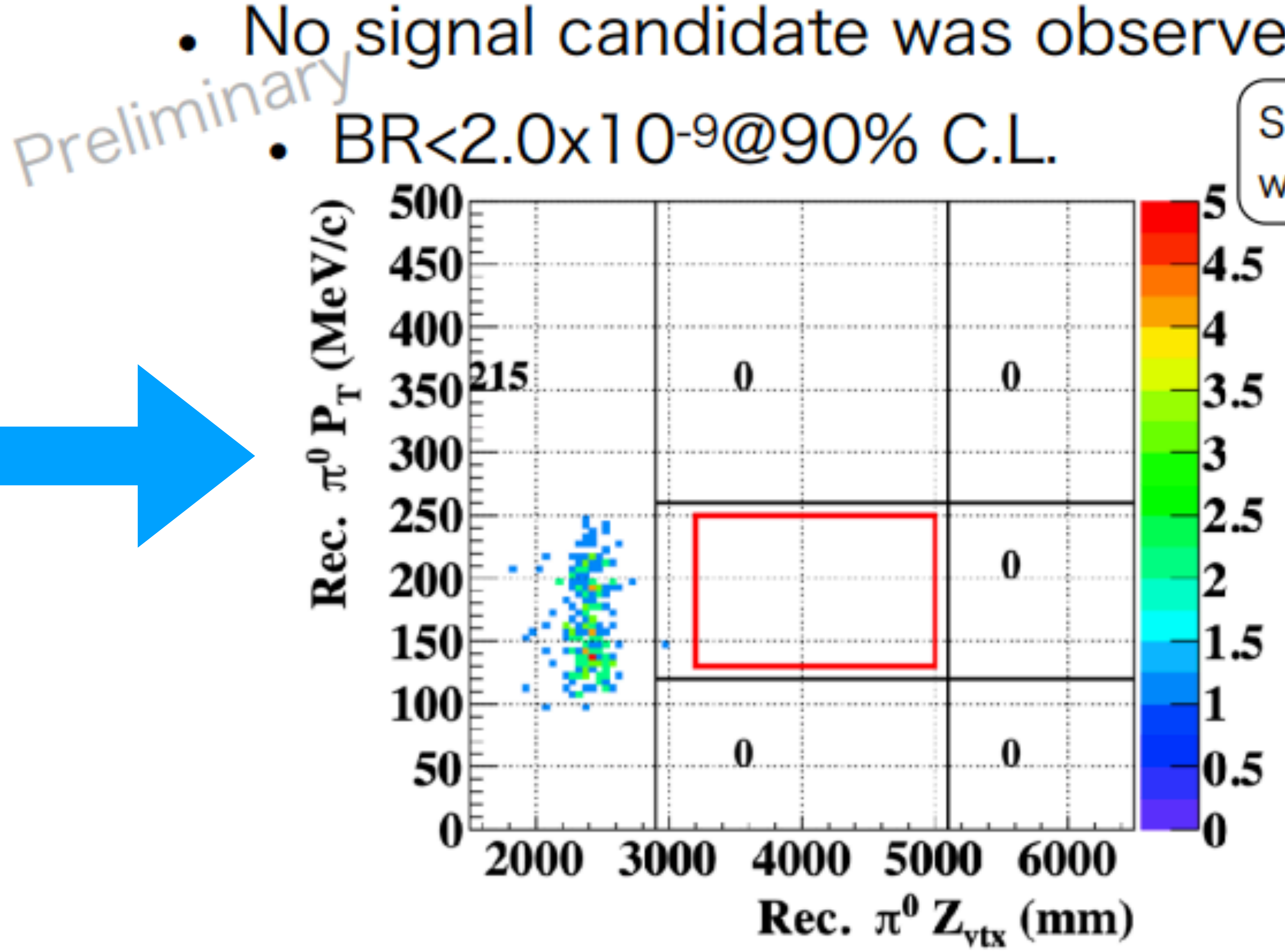
BG Estimation

c.f. 2016-2018 analysis:1.22±0.26



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

S.E.Sx 2.3
with Poisson statistics



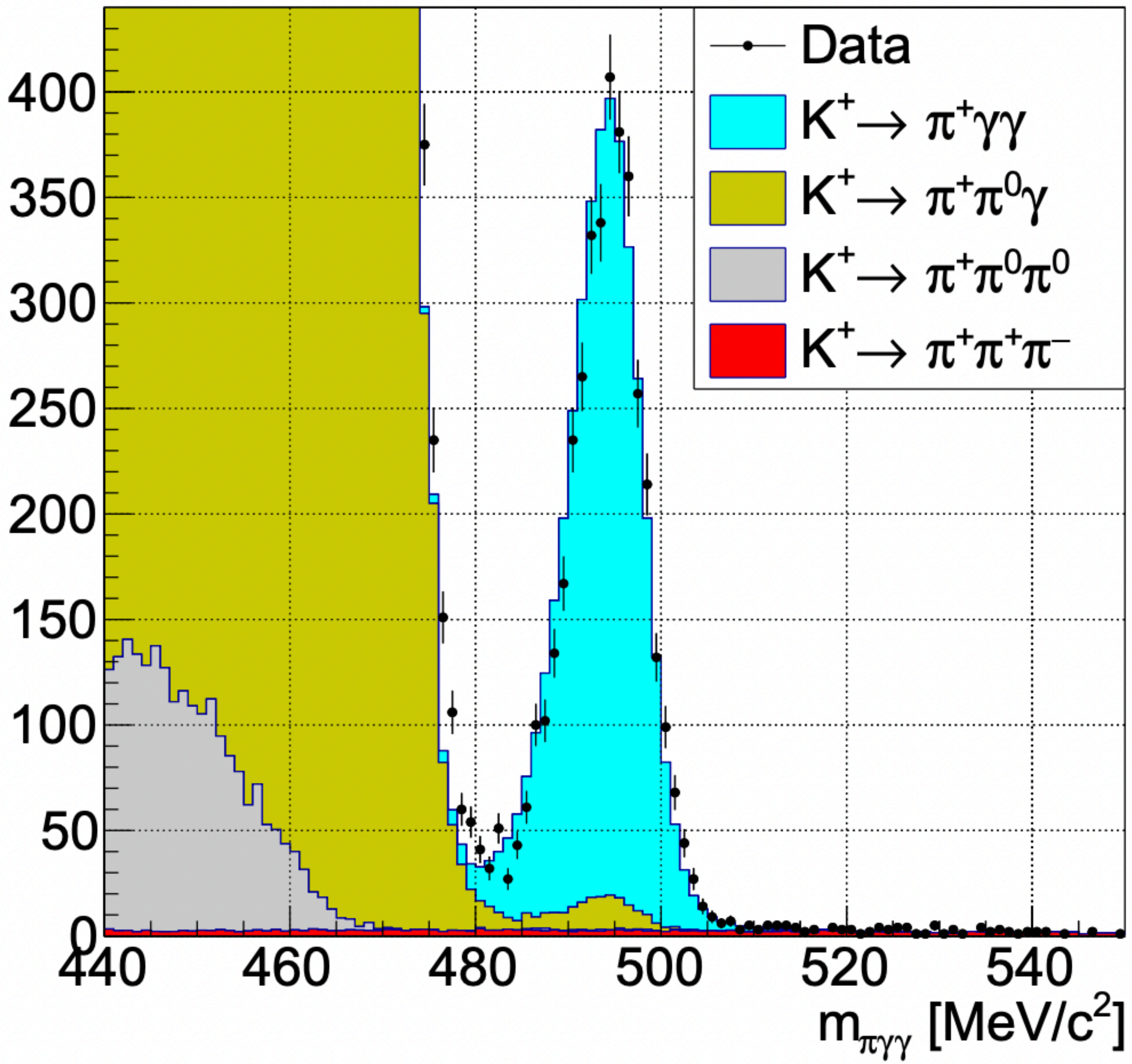
- KOTO continues data-taking to reach sensitivity below 10^{-10}.
- Planned future program (KOTO-2) key part of high priority hadron hall extension plans at J-PARC.

Rare K^+ decays at NA62

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

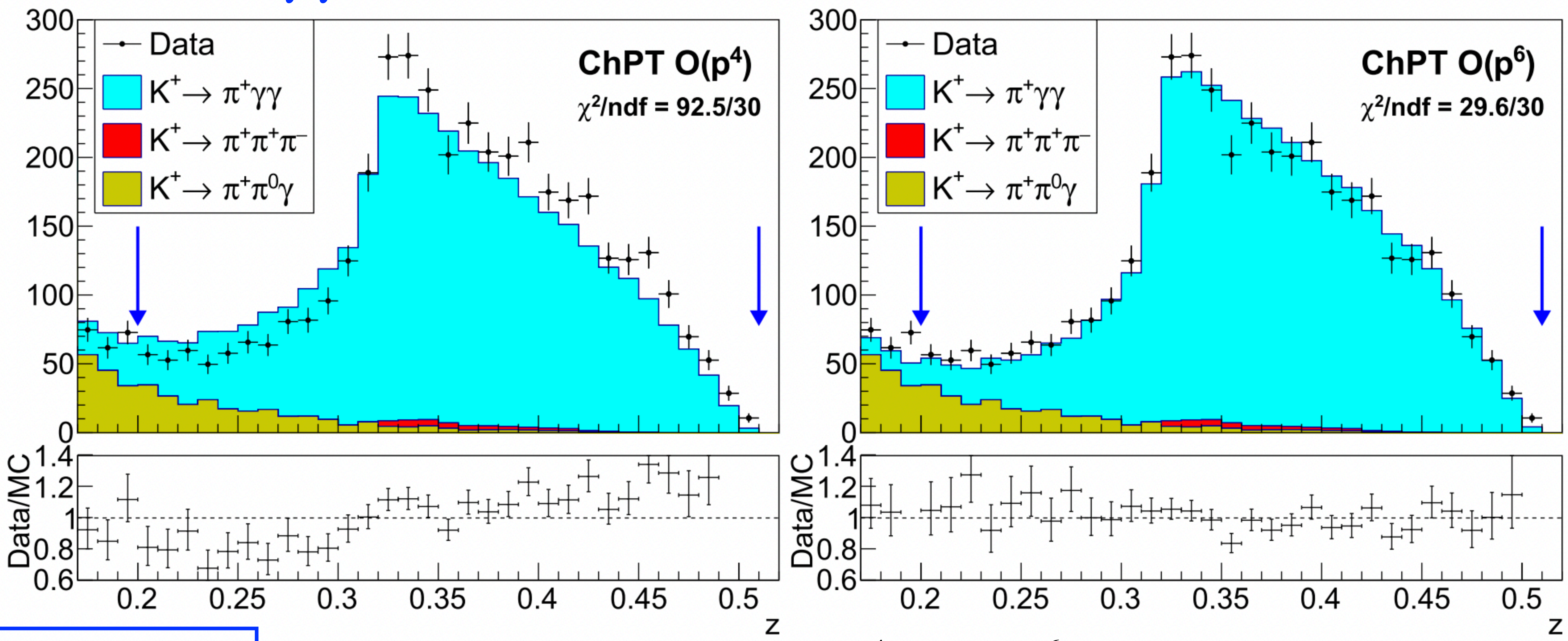
[PLB 850 (2024) 138513]

- 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:** $z = \frac{(P_K - P_\pi)^2}{m_K^2} = \frac{m_{\gamma\gamma}^2}{m_K^2}$.
    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]



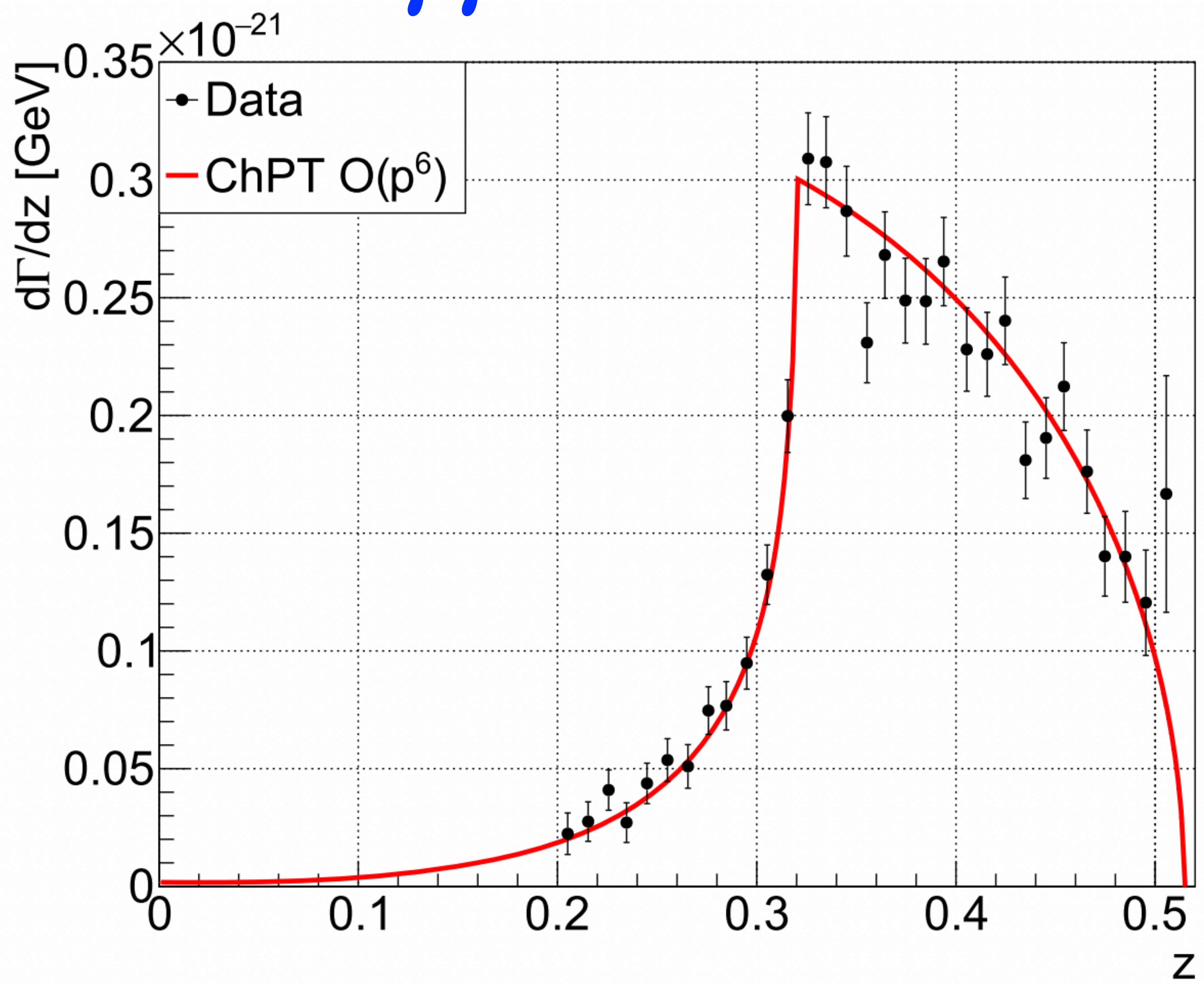
$N_{obs} = 3984$

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

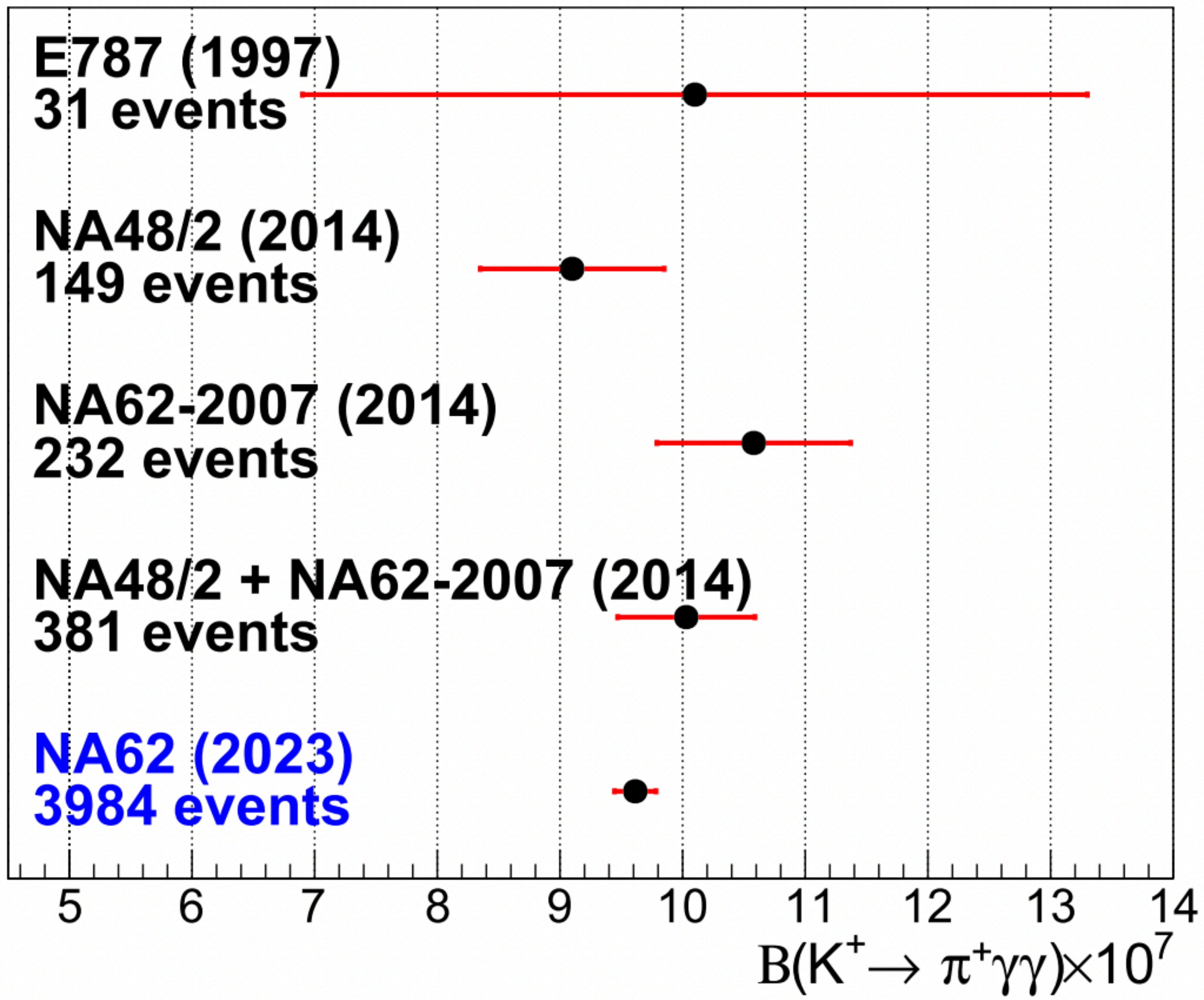
- Parameter $\hat{c}$ measured in ChPT $\mathcal{O}(p^4)$ and $\mathcal{O}(p^6)$ descriptions by reweighing $K^+ \to \pi^+\gamma\gamma$ MC and performing a minimum-χ^2 fit:
  - ChiPT $\mathcal{O}(p^4)$ low p-value: cannot describe di-photon mass (z) distribution.
  - ChiPT $\mathcal{O}(p^6)$ p-value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

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

[PLB 850 (2024) 138513]



BR results in ChPT framework



$N_{obs} = 3984$

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

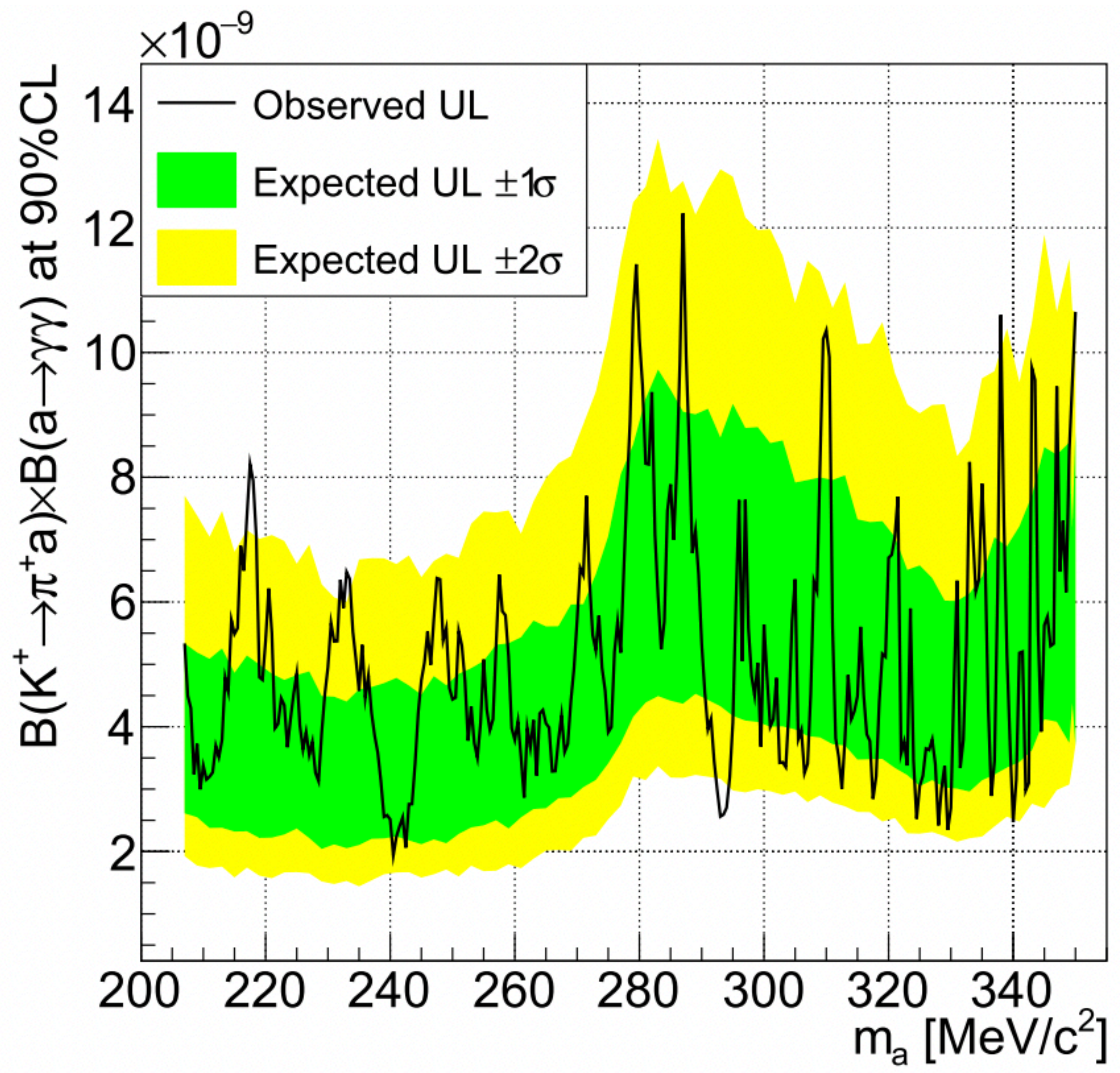
- ChiPT $\mathcal{O}(p^6)$ description: Fit p-value = 0.49 : $\hat{c} = 1.144 \pm 0.069_{\text{stat}} \pm 0.034_{\text{syst}}$
  - $\mathcal{B}(K^+ \to \pi^+\gamma\gamma, \text{ChPT}\,\mathcal{O}(p^6)) = (9.61 \pm 0.15_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-7}$
- Model independent BR measurement: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

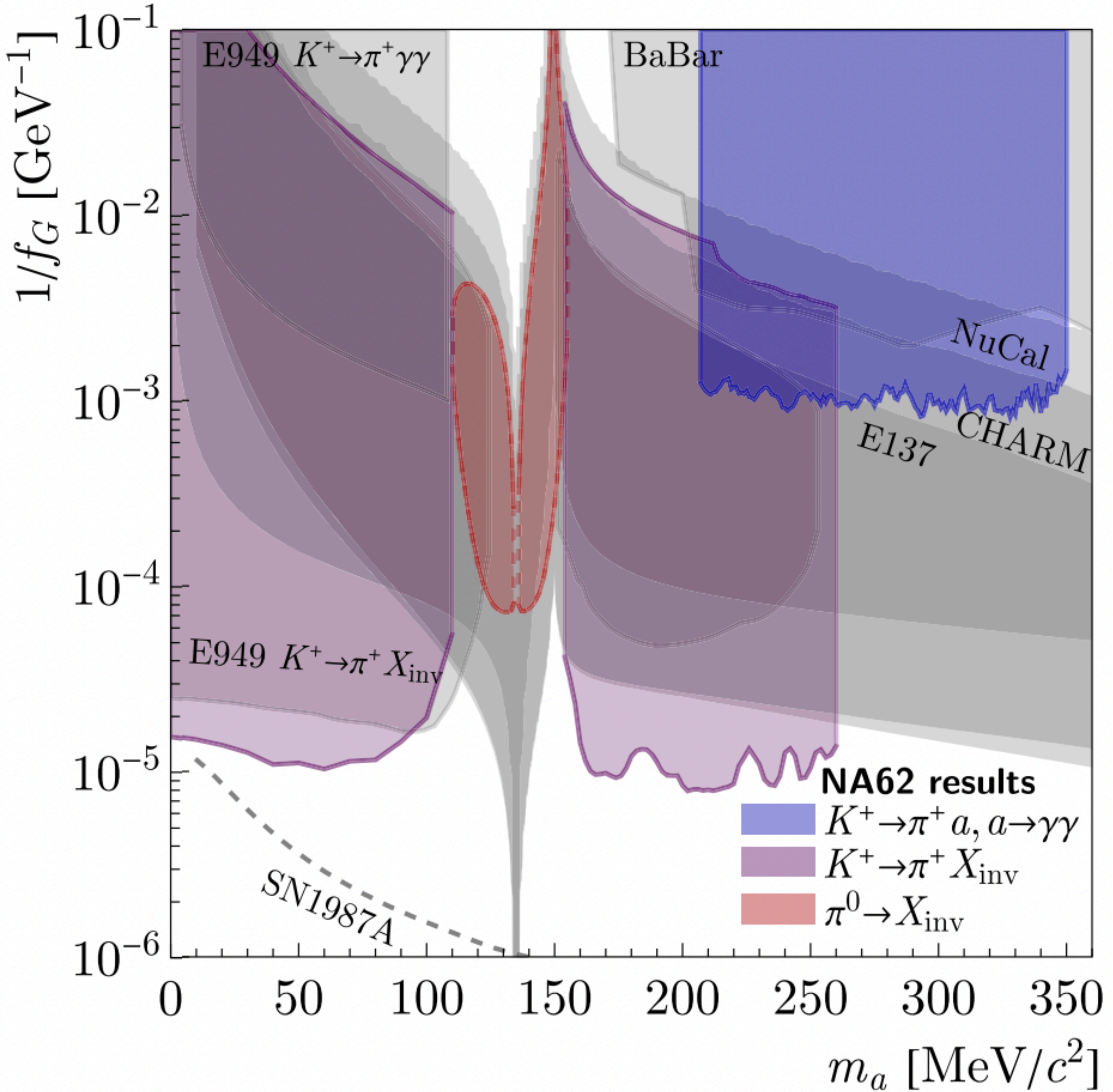
Search for ALP in $K^+ \to \pi^+ a, a \to \gamma\gamma$ decays

[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.

[Exotics search building on rare decays study!]



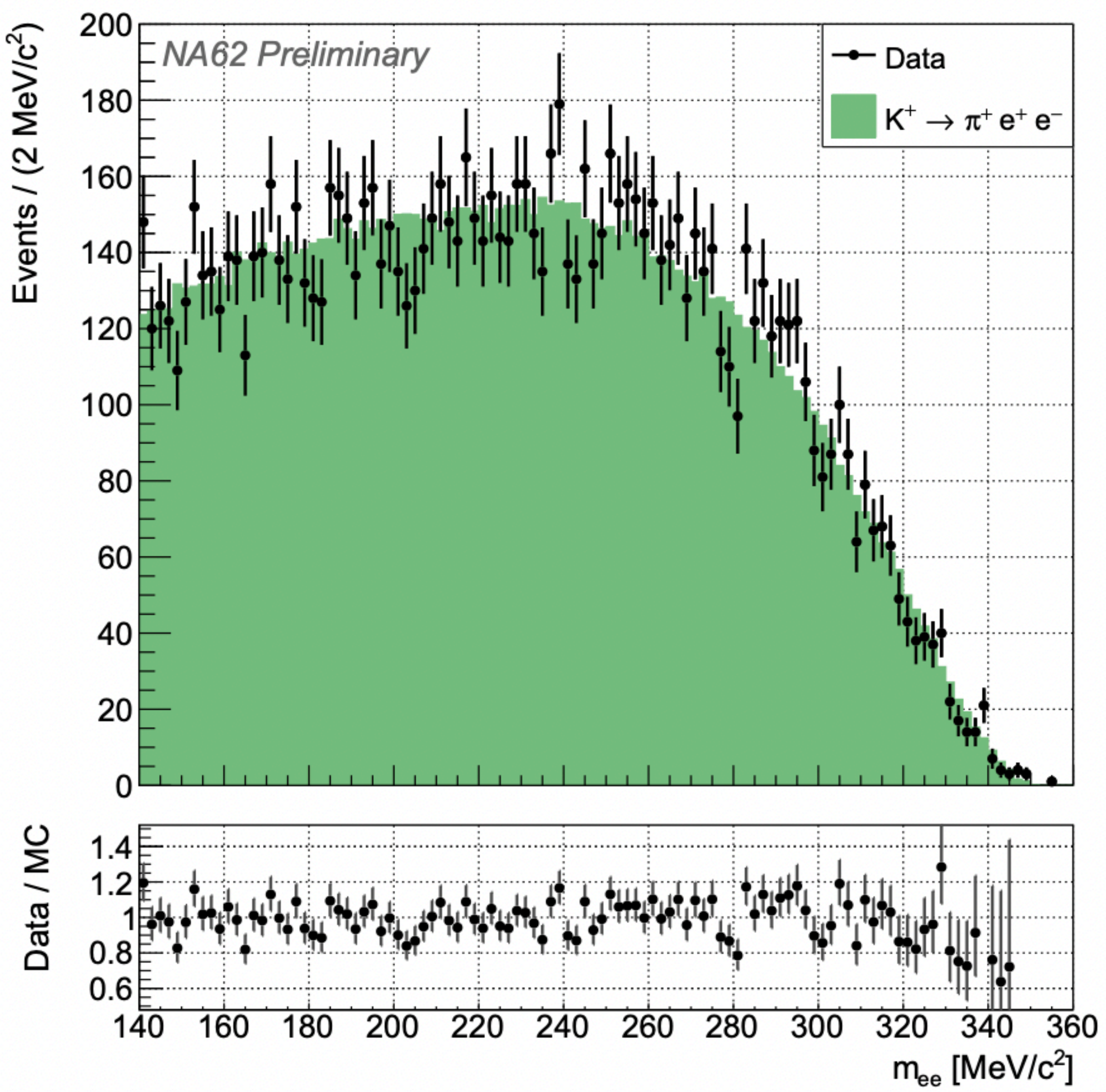


Study of $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-$

[new: spring 2024]

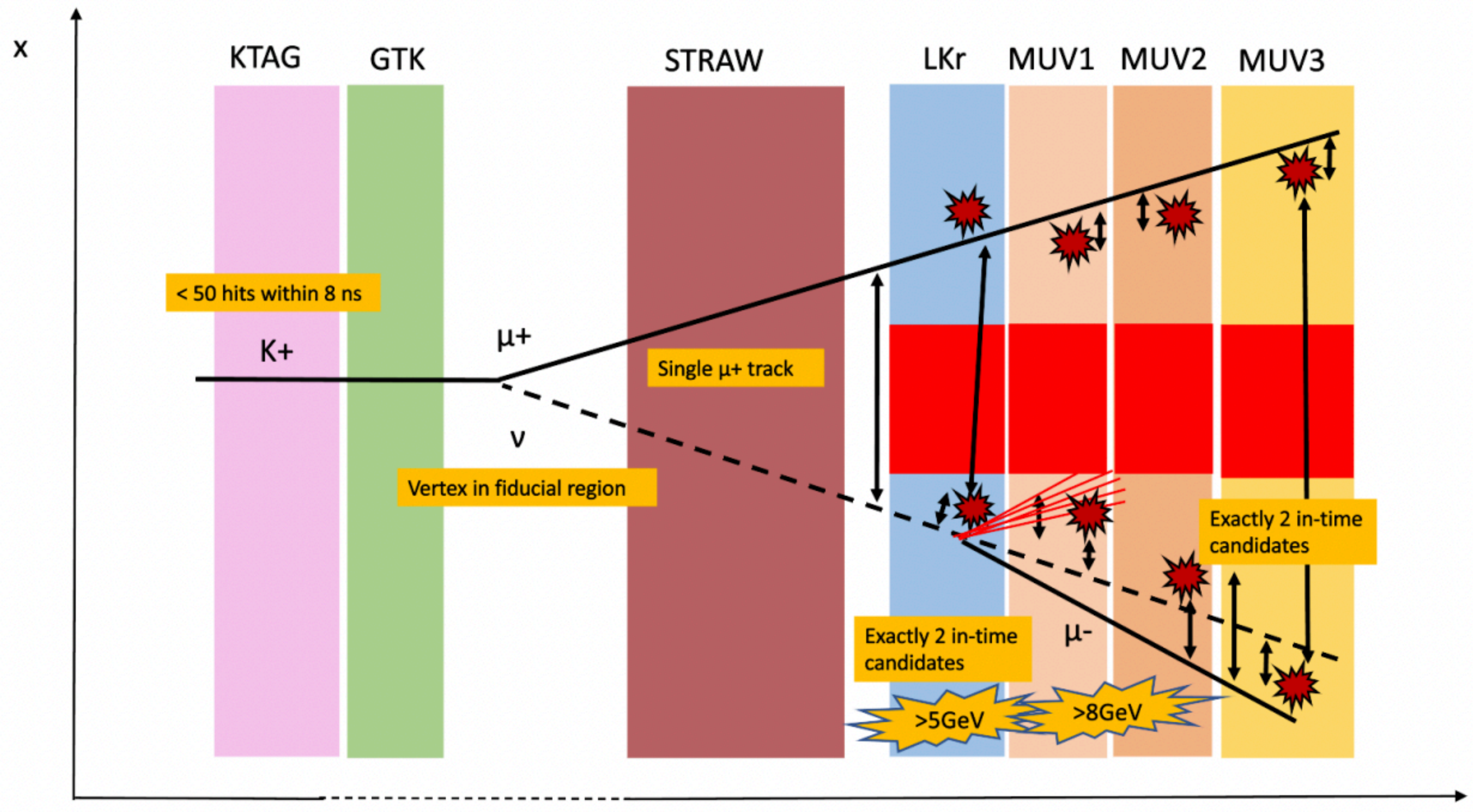
- Common Signal & Background Selection:
  - Vertex from 3 (in-time) charged tracks
  - Kinematics (momentum & vertex position)
  - PID: $\pi^+e^+e^-$ (using LKr E/p : <0.9 for π^+ vs 0.9-1.1 for e^+)
  - $m_{ee} > 130\,\mathrm{MeV}/c^2$ (>140 for normalisation).

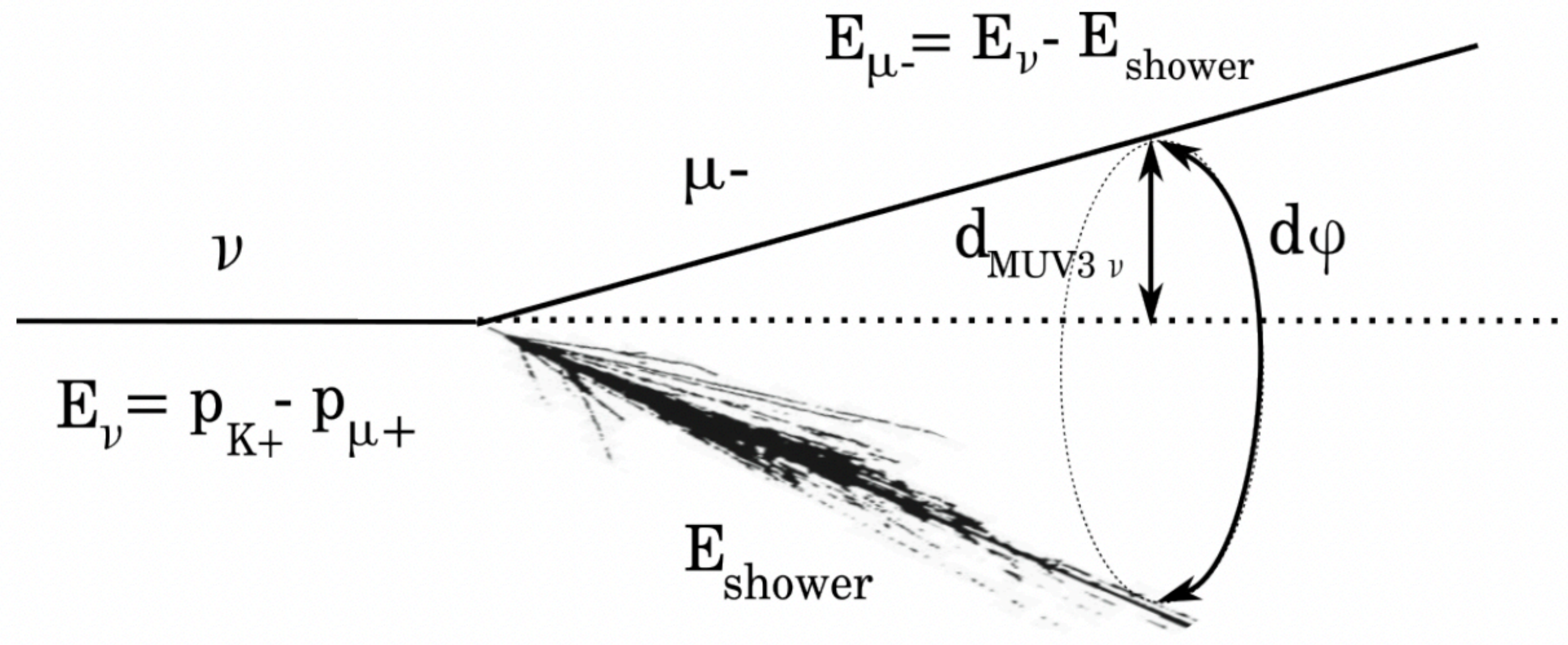
- **Normalisation:**
  - Acceptance: $A_{\pi ee} = (4.70 \pm 0.01_{\mathrm{stat}})\,\%$
  - Selected events: $N_{\pi ee} = 12160$ (purity>99.9%)
  - Effective number of kaon decays: $N_K = (8.62 \pm 0.08_{\mathrm{stat}} \pm 0.26_{\mathrm{ext}}) \times 10^{11}$
    - With external uncertainty from norm.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

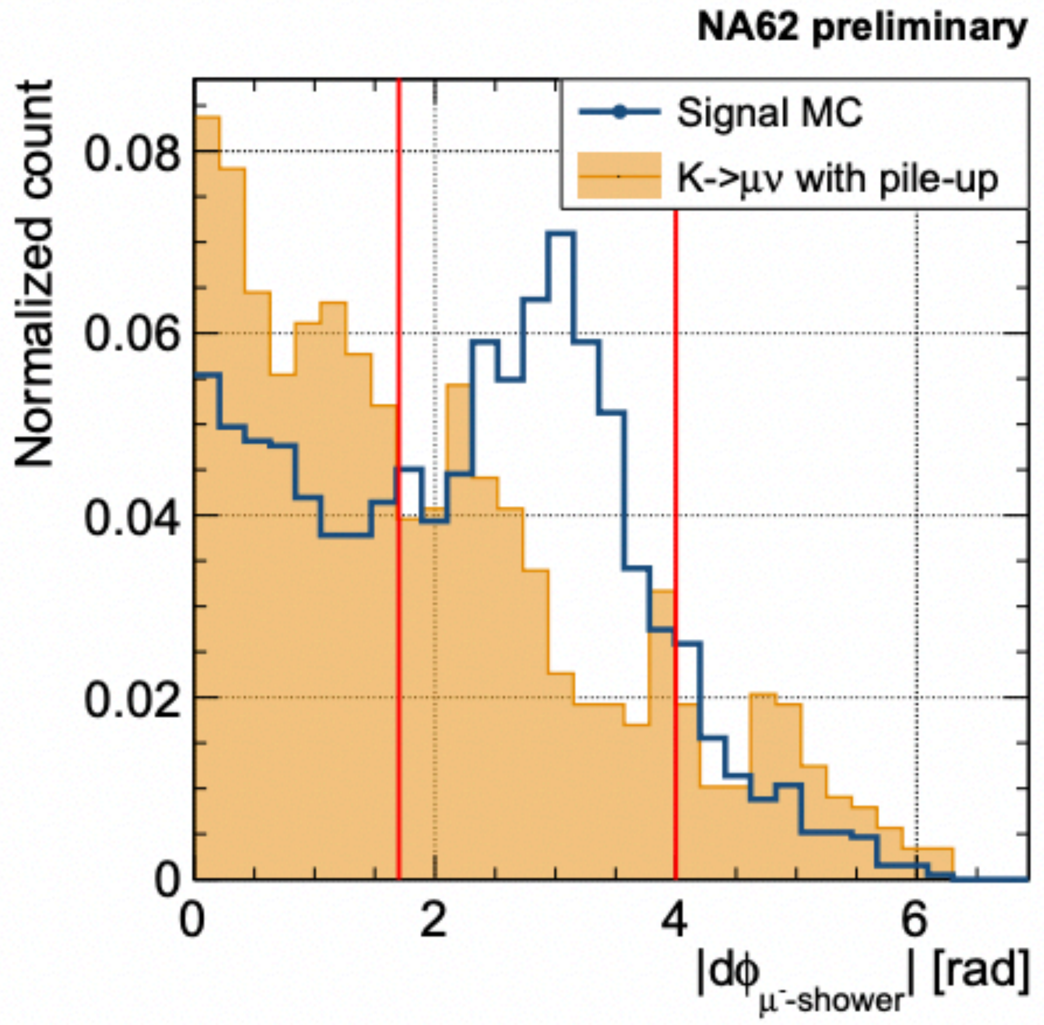


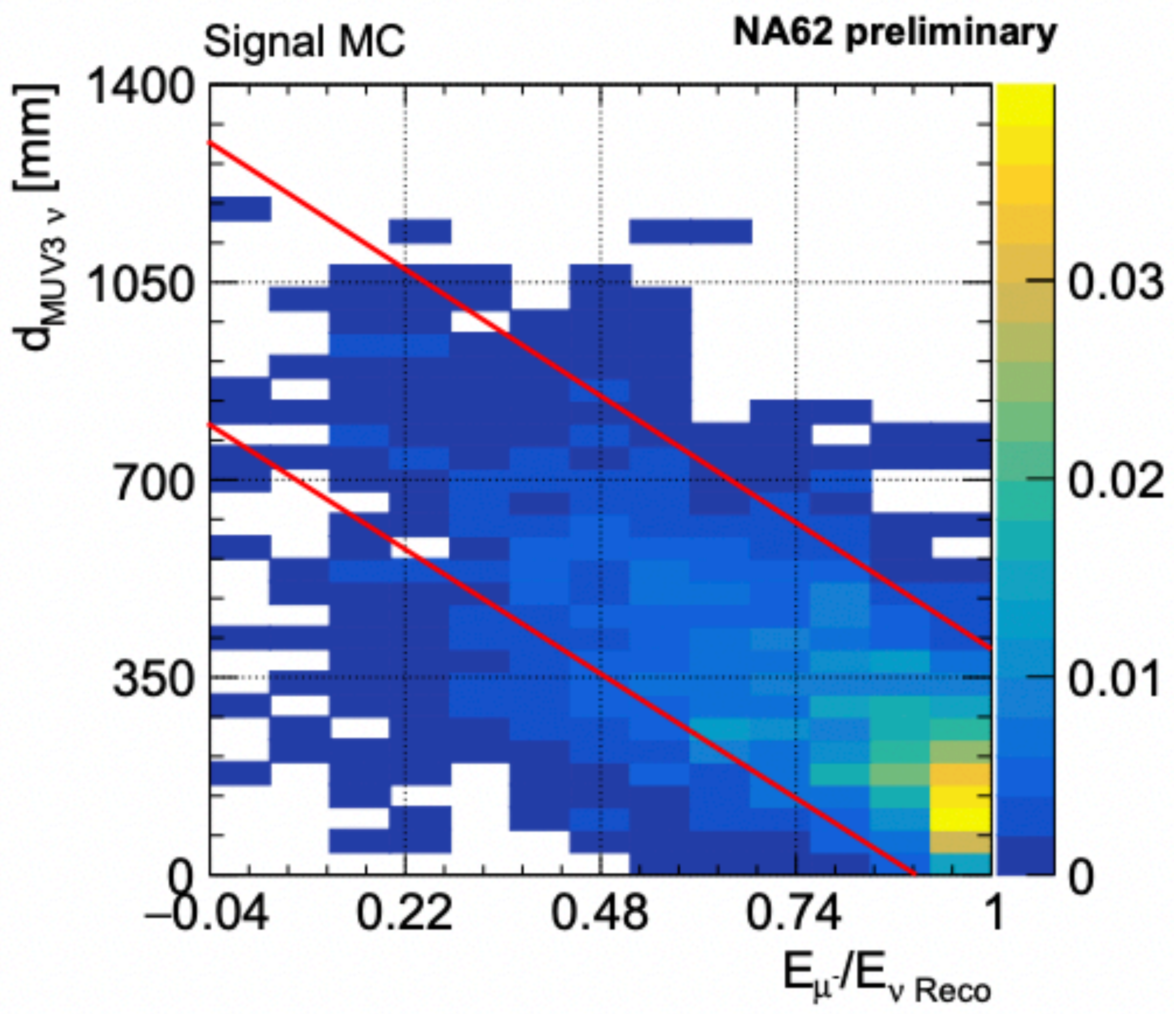
Tagged neutrinos at NA62: selection

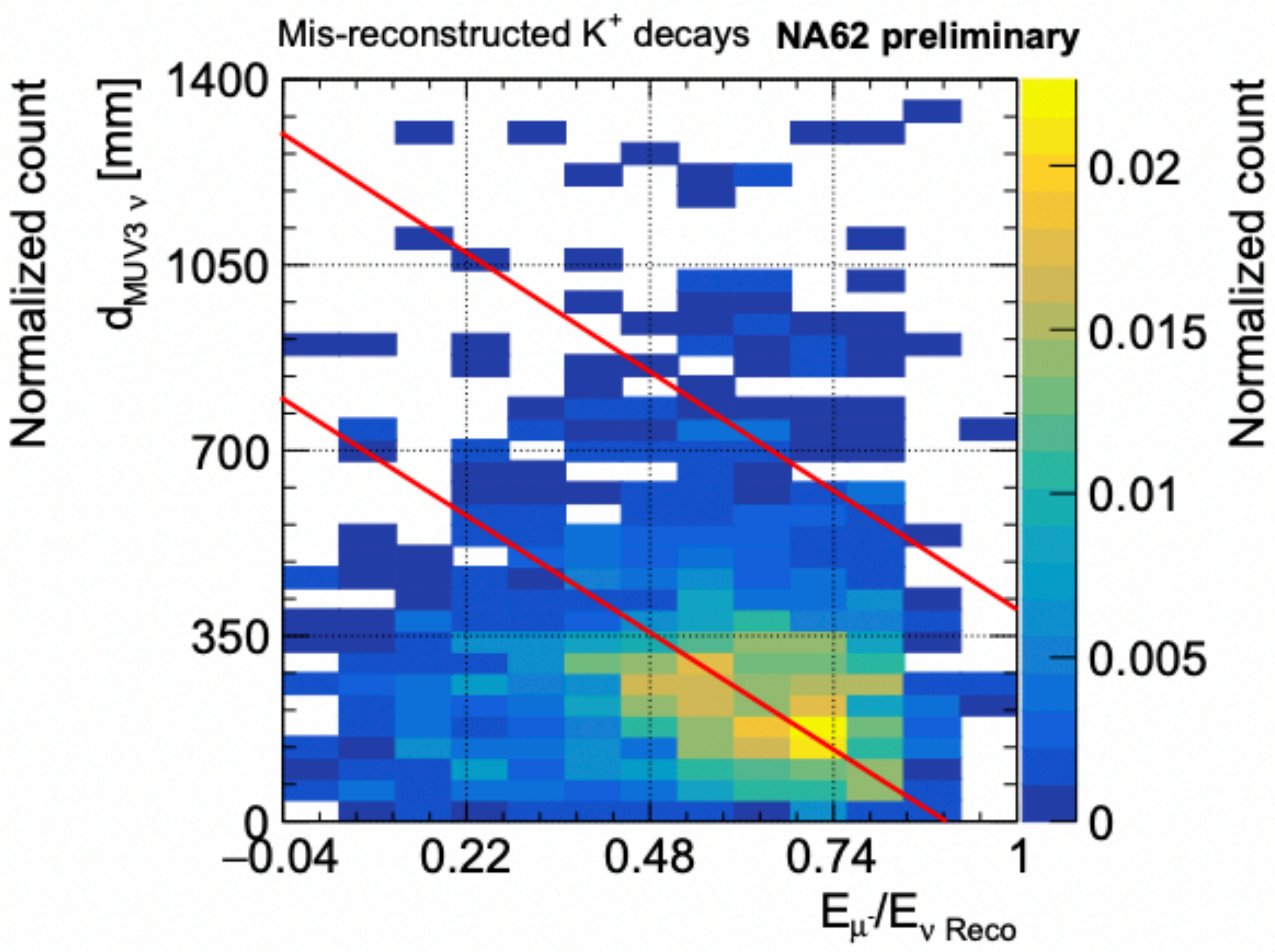
[De Martino, NuFact23]





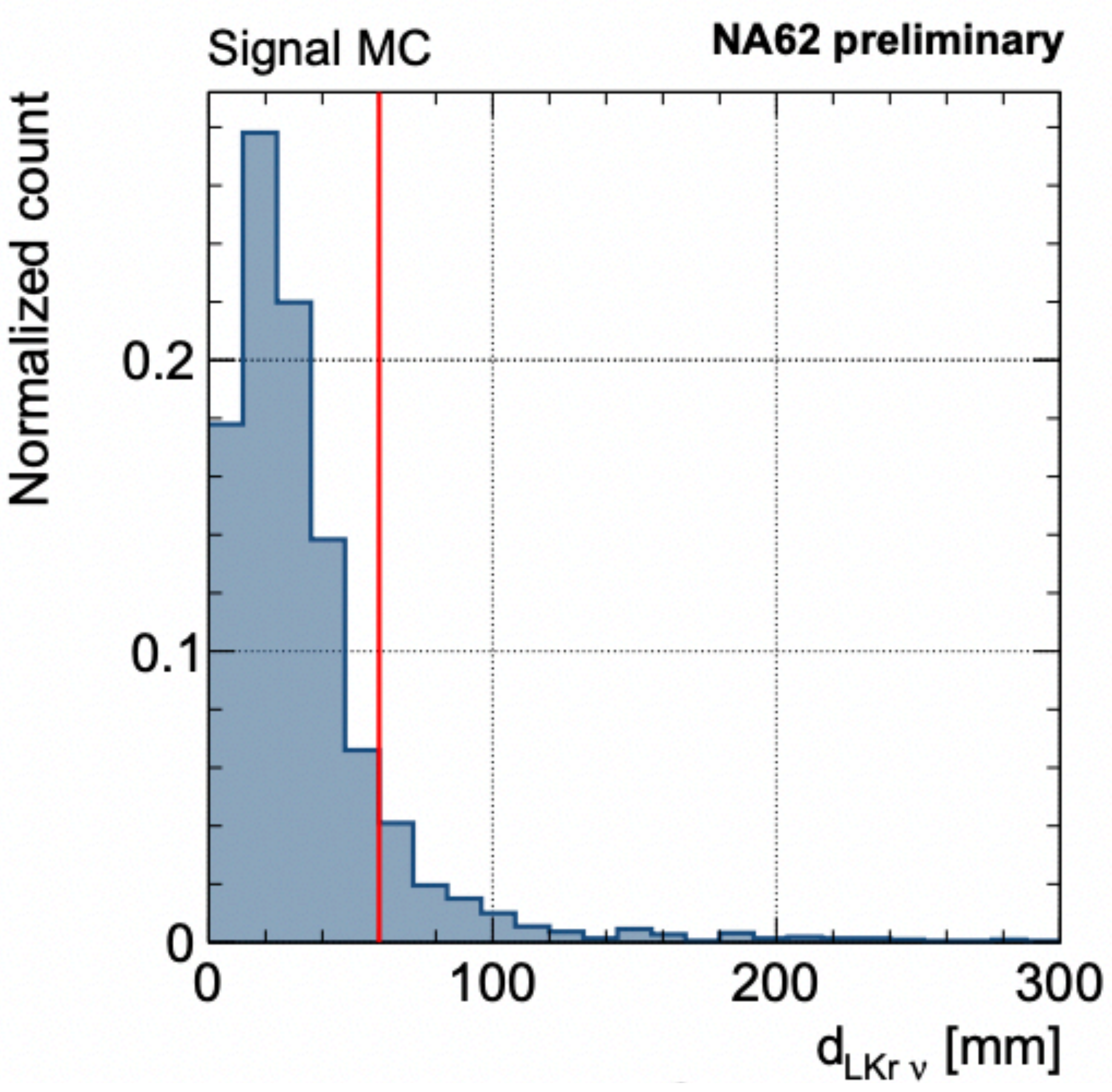


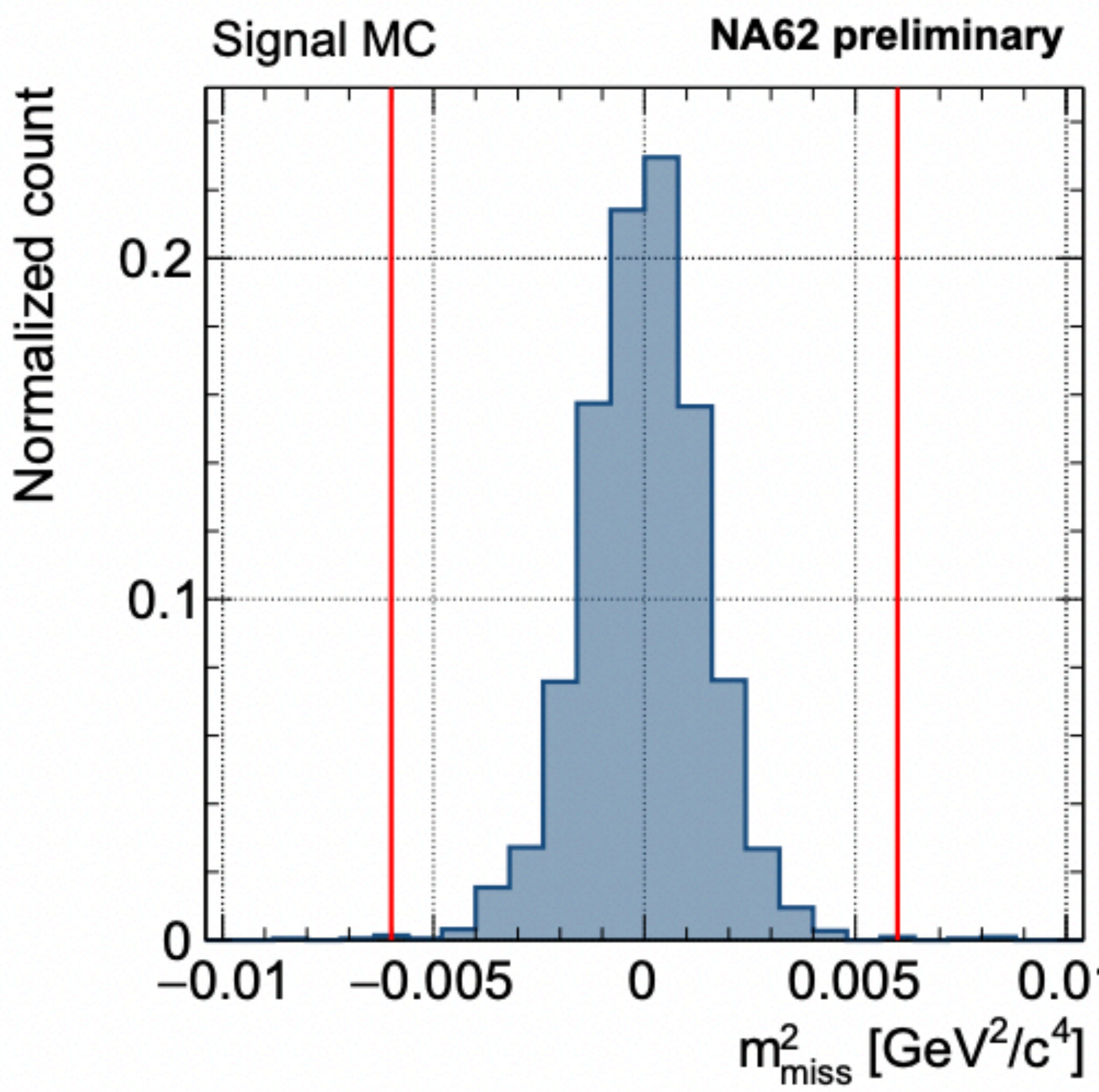




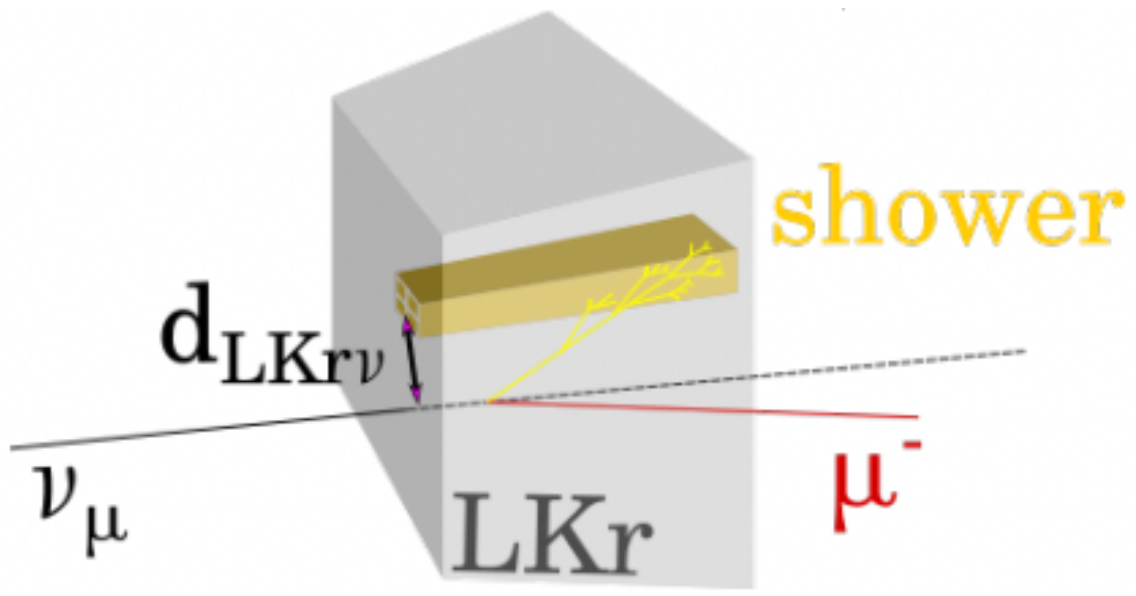
Tagged neutrinos at NA62: strategy

[De Martino, NuFact23]





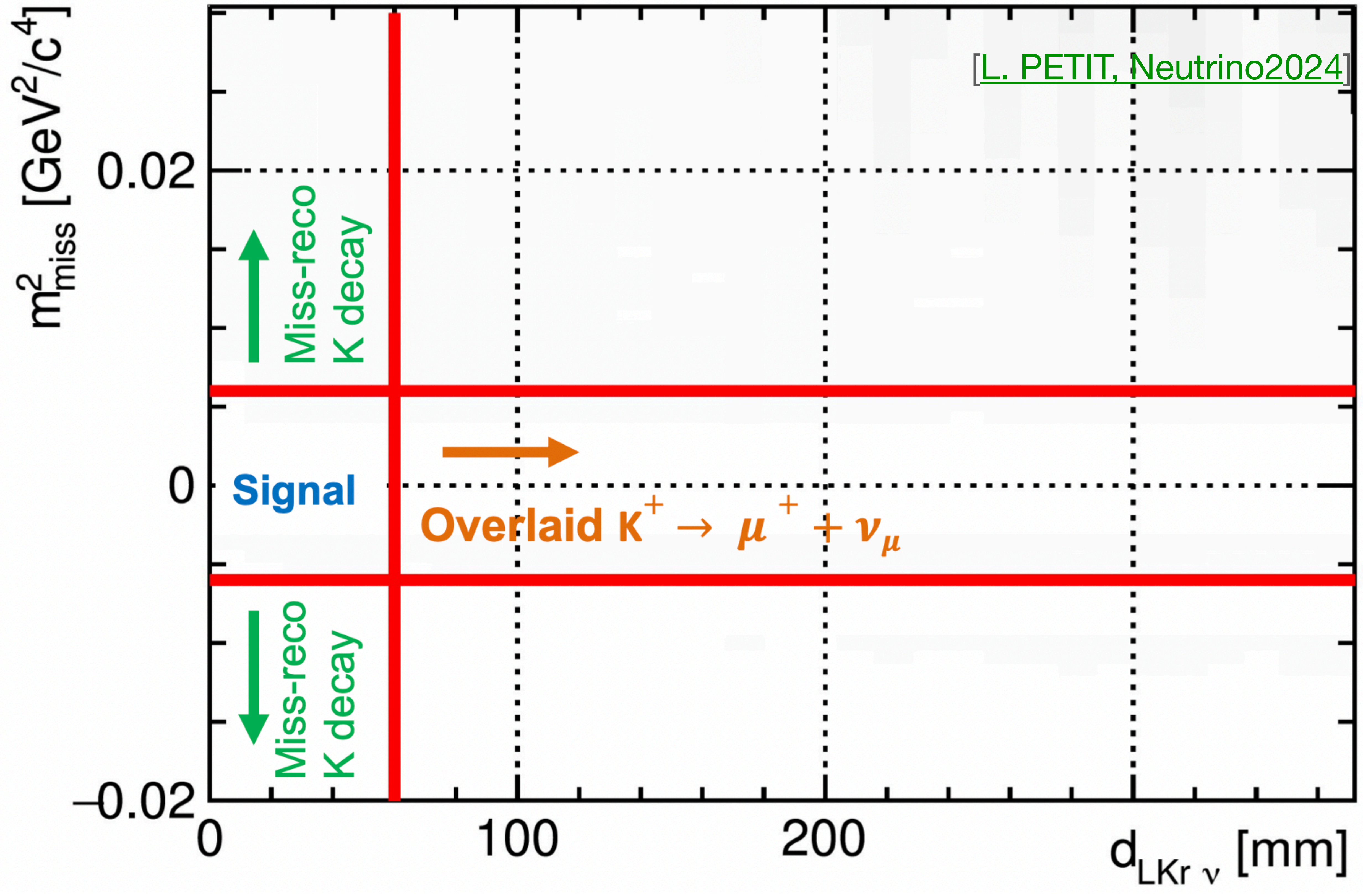
- Blind analysis, using **2022 data.**
- Signal region : $|d_{LKr}| < 60\,\text{mm}$, $|m^2_{miss}| = |(P_K - P_\mu)^2| < 0.006\,\text{GeV}^2/c^4$
- Sudy backgrounds using data-driven methods using side-bands:
  - $K^+ \to \mu^+\nu$ + extra in-time activity (side-bands of d_{LKr}).
  - Mis-reconstructed 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: $P_{int,LKr} = (6.0 \pm 0.1_{\text{syst}}) \times 10^{-11}$, $\varepsilon_{signal} = (2.55 \pm 0.15_{\text{stat}} \pm 0.04_{\text{syst}})\,\%$: $N^{exp}_{signal} = 0.228 \pm 0.014_{\text{stat}} \pm 0.011_{\text{syst}}$

Tagged neutrinos at NA62: Results

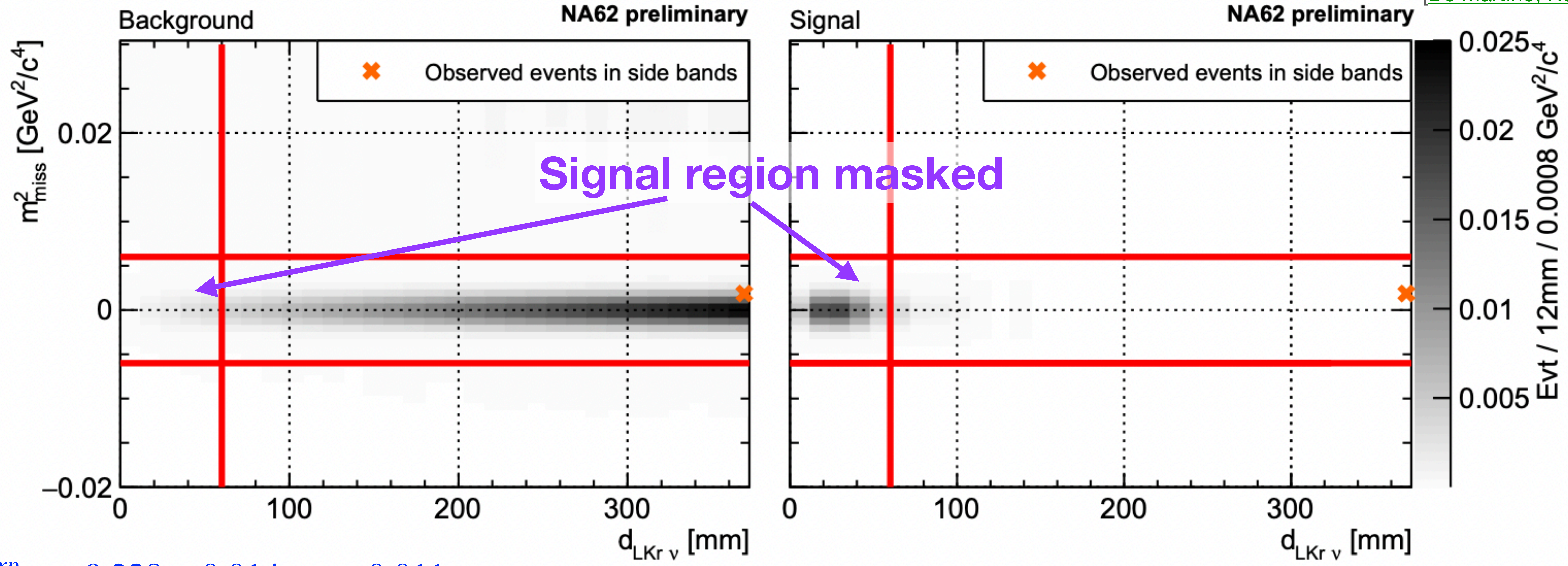
[De Martino, NuFact23]



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

Tagged neutrinos at NA62: Expectations

[De Martino, NuFact23]



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

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.

Forbidden K^+ decays at NA62

Search Strategy for CLFV/LNV Decays at NA62

- Use Run1 (2016—18) data set:
  - Search for $K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi(\pi^0)\ell\ell$, $K^+ \to \mu^- \nu e^+ e^+$, ($K^+ \to \pi^\mp \mu^\pm e^+$)
  - Normalise to SM rare decay $K^+ \to \pi^+ e^+ e^-$ (most common 3-track decay $K^+ \to \pi^+ \pi^+ \pi^-$).
- Triggers:
  - Hardware L0 + Software L1
  - "Rare+Exotics" triggers run simultaneously with $\pi\nu\bar{\nu}$ trigger and downscaled (by factors ~100, ~8, ~8)

Trigger Name	Description
Multi-Track	Minimum bias 3-track trigger
Multi-Track e	3-tracks + 20 GeV energy deposit in LKr
Multi-Track mu	3-tracks + MUV3 tagged mu (+10 GeV in LKr)

- Perform **blind analyses**

General selection strategy

- Select 3-track events forming a Q=+1 vertex in the FV.
- Kinematic constraints:
  - Each track has a momentum of approx. 10—40 GeV/c. (analysis-dependent)
  - Tracks >200mm apart at LKr.
  - Reconstructed kaon momentum consistent with beam average.
- Particle identification:
  - Use LKr, RICH and MUV3 detectors to distinguish between $\pi^\pm$, $\mu^\pm$ and $e^\pm$.
- Veto additional activity, e.g. LAV photon veto

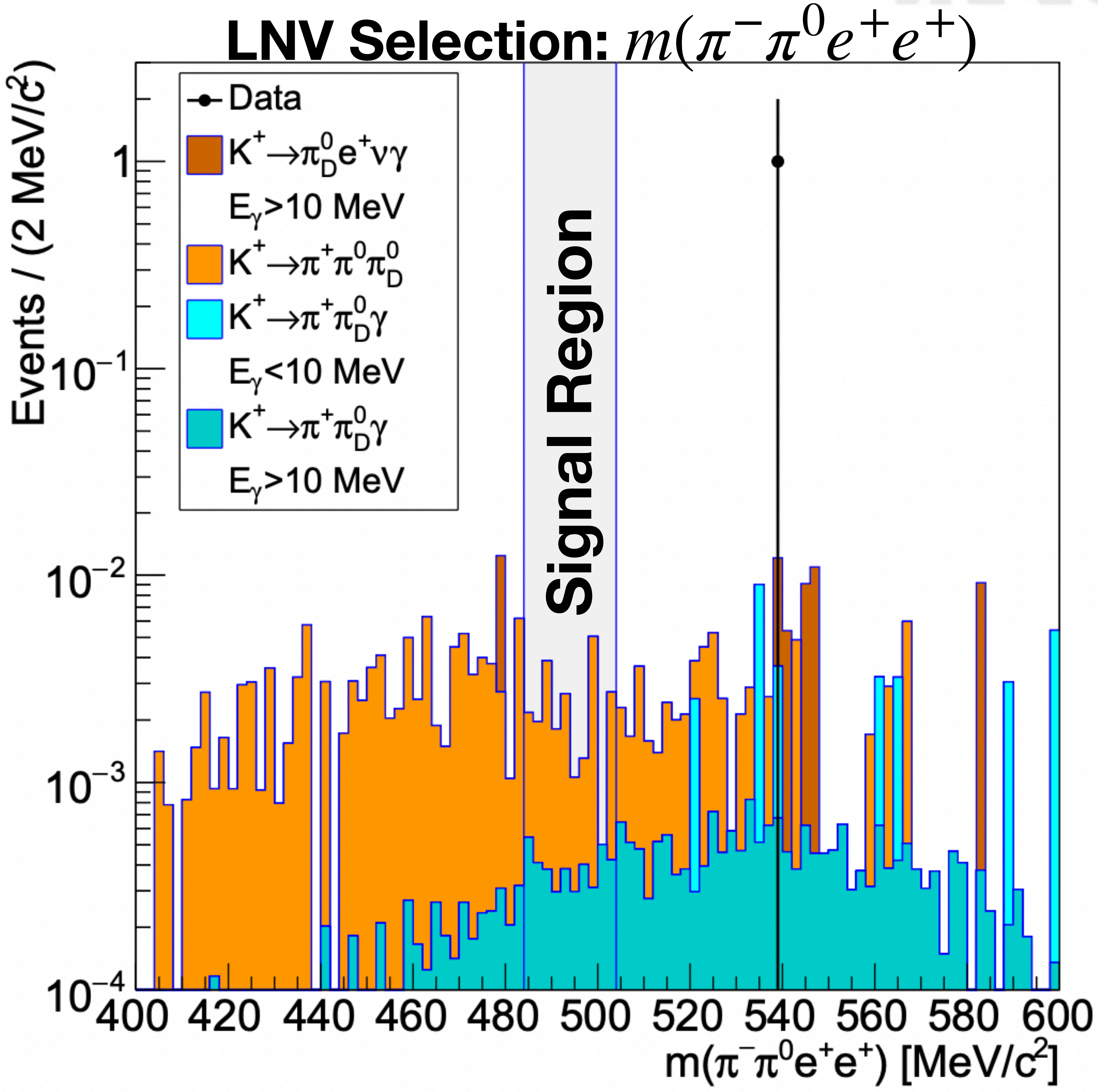
Search for $K^+ \to \pi^-\pi^0 e^+ e^+$

[PLB 830 (2022) 137172]

- Normalise to SM $K^+ \to \pi^+ e^+ e^-$.
- π^0 reconstructed in LKr calorimeter via $\pi^0 \to \gamma\gamma$ decay

Backgrounds:

Mode	Control region	Signal region
$K^+ \to \pi^+\pi^0\pi^0_D$	0.16 ± 0.01	0.019
$K^+ \to \pi^+\pi^0_D\gamma$	0.06 ± 0.01	0.004
$K^+ \to \pi^0_D e^+\nu\gamma$	0.05 ± 0.02	–
$K^+ \to \pi^+\pi^0 e^+ e^-$	0.01	0.001
Pileup	0.20 ± 0.20	0.020 ± 0.020
Total	0.48 ± 0.20	0.044 ± 0.020
Data	1	0



- Expected background = 0.044 ± 0.020
- Candidates observed: 0
- $\mathscr{B}(K^+ \to \pi^-\pi^0 e^+ e^-) < 8.5 \times 10^{-10}$ at 90 % CL

Search for $K^+ \to \mu^- \nu e^+ e^+$

[PLB 838 (2023) 137679]

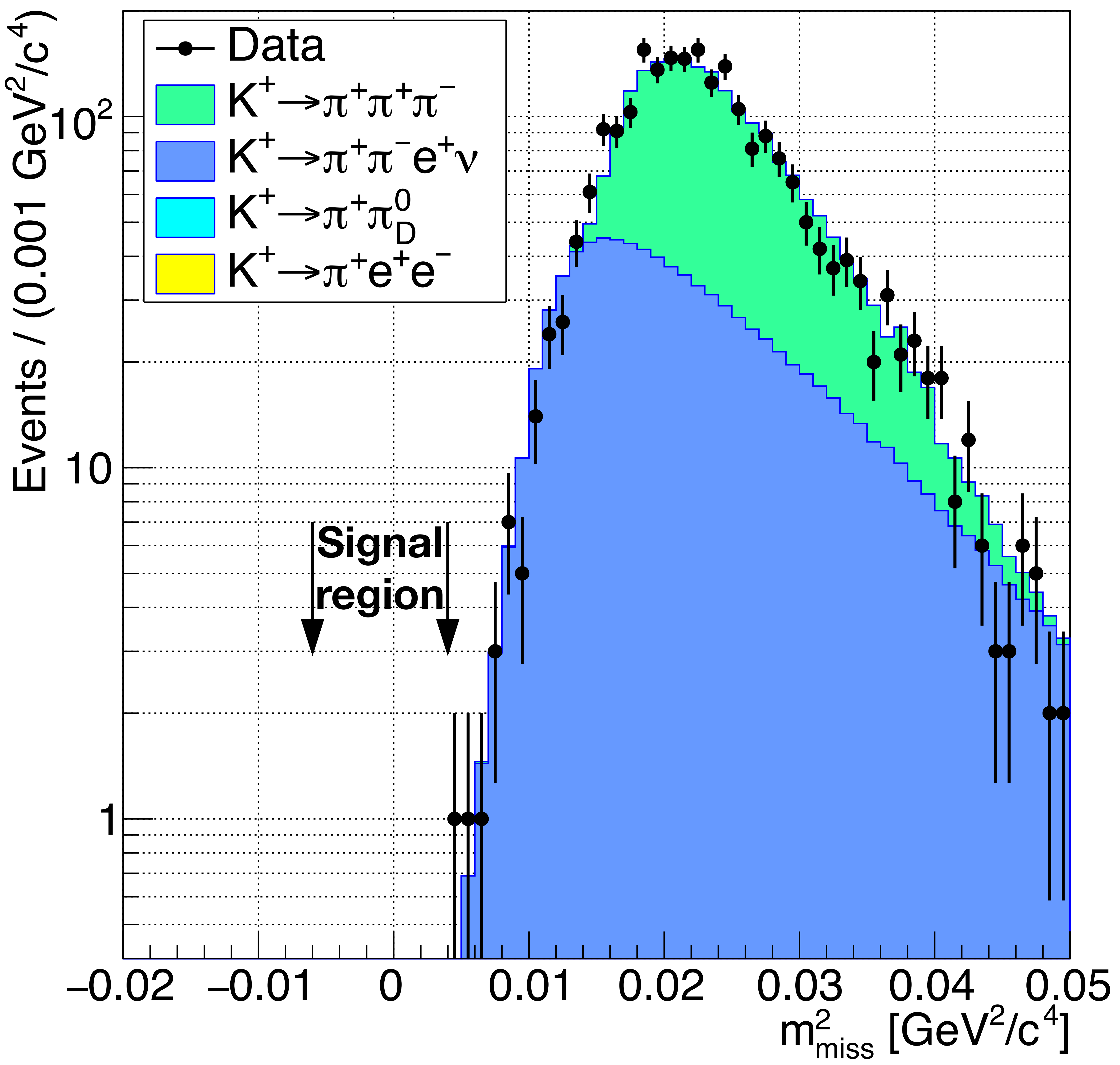
- LNV or LFV depending on neutrino flavour.
- Normalise to SM $K^+ \to \pi^+ e^+ e^-$.
- Use all three Multi-track triggers.
- Largest backgrounds from double misID (A) or misID + $\pi^- \to \mu^- \nu$ decays-in-flight (B).

Backgrounds:

	Mode / Region	Signal	Upper
(A)	$K^+ \to \pi^+\pi^+\pi^-$	< 0.07	1412 ± 11
	$K^+ \to \pi^+\pi^+\pi^-$ (upstream)	0.06 ± 0.03	1.5 ± 0.3
(B)	$K^+ \to \pi^+\pi^- e^+\nu$	0.16 ± 0.02	867 ± 1
	$K^+ \to \pi^+\pi^- e^+\nu$ (upstream)	0.01 ± 0.01	0.14 ± 0.03
	$K^+ \to \pi^0_D e^+\nu$	0.01 ± 0.01	0.02 ± 0.01
	$K^+ \to e^+\nu\mu^+\mu^-$	< 0.01	0.05 ± 0.02
	Total	0.26 ± 0.04	2281 ± 11
	Data	0	2271

- Expected background = 0.26 ± 0.04
- Candidates observed: 0
- $\mathcal{B}(K^+ \to \mu^- \nu e^+ e^-) < 8.1 \times 10^{-11}$ at 90 % CL

Squared missing mass $[P_K - (P_\mu + P_{e1} + P_{e2})]^2$

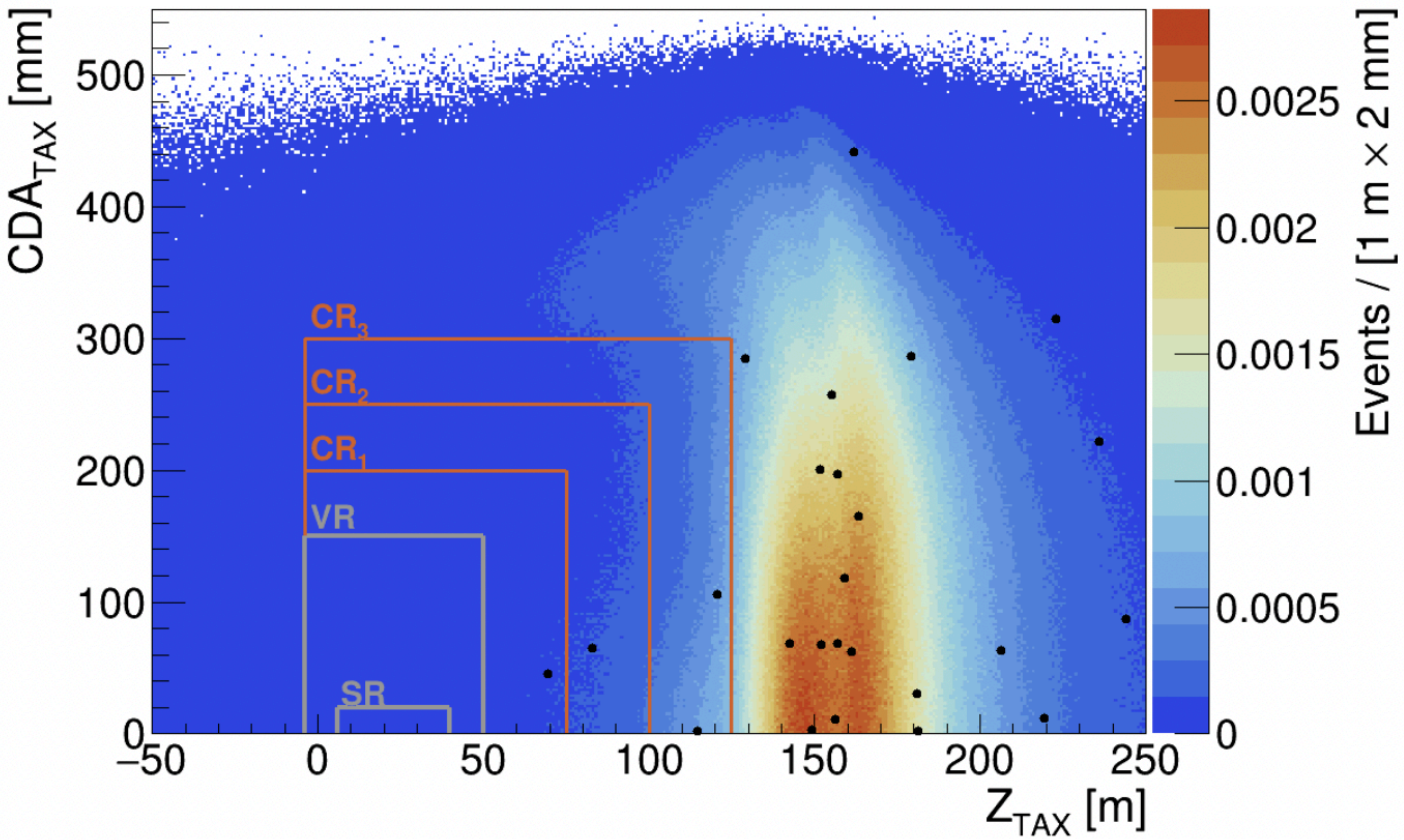


Exotic processes at NA62

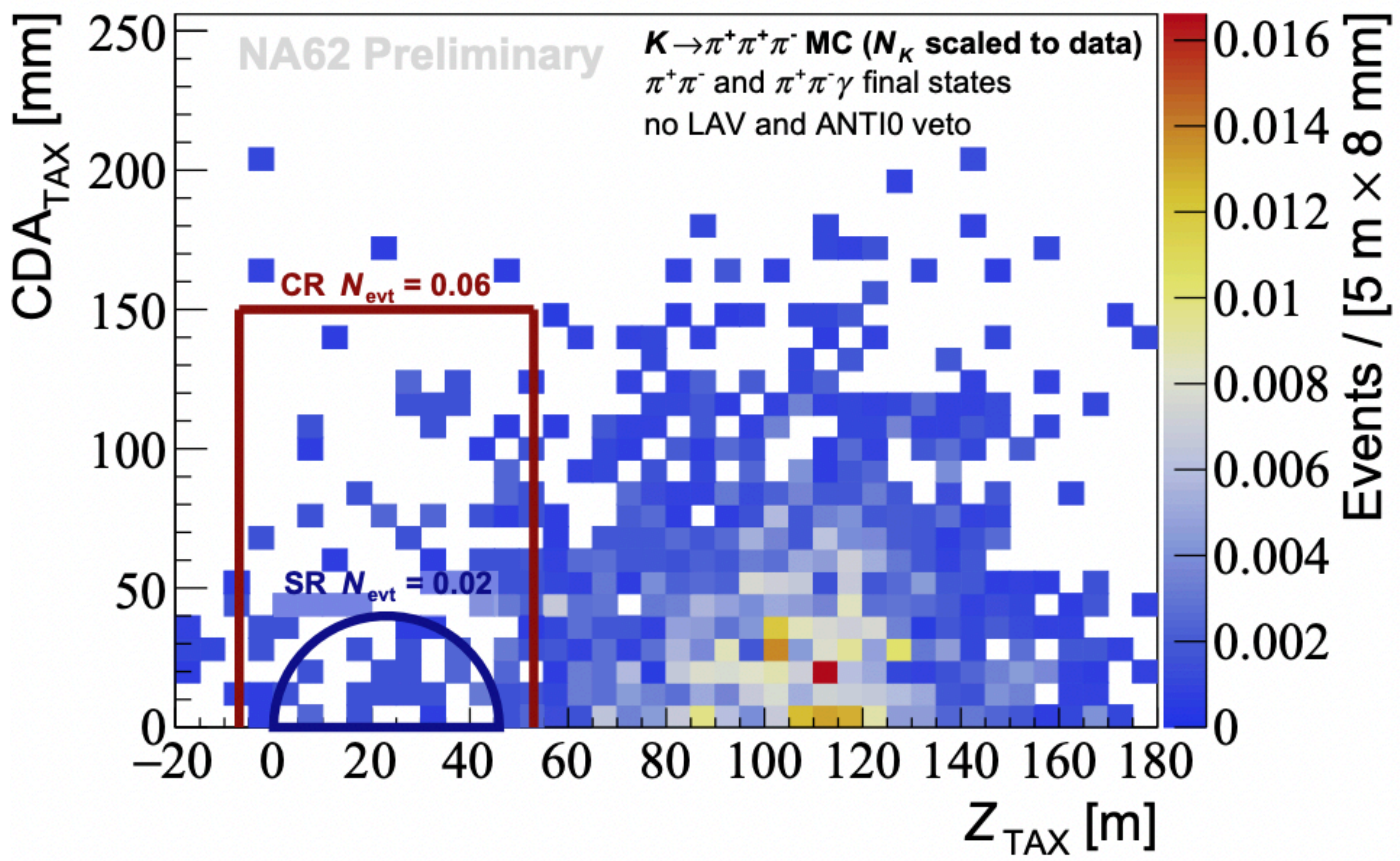
Backgrounds

- **Combinatorial:** Accidental coincidence with other tracks: data-driven event overlay —> negligible for hadronic.
- **Neutrino-induced:** MC GENIE + PYTHIA + GEANT4 —> negligible
- **Prompt:** Inelastic interaction of halo μ : data-driven + GEANT4.
  - use PUMAS MC to back-project and infer kinematics of accidentally associated halo μ
- **Upstream:** particles selected by the GTK achromat, ” data-driven + GEANT4

Combinatorial background for $A' \to \mu^+\mu^-$ search [arXiv.2312.12055]



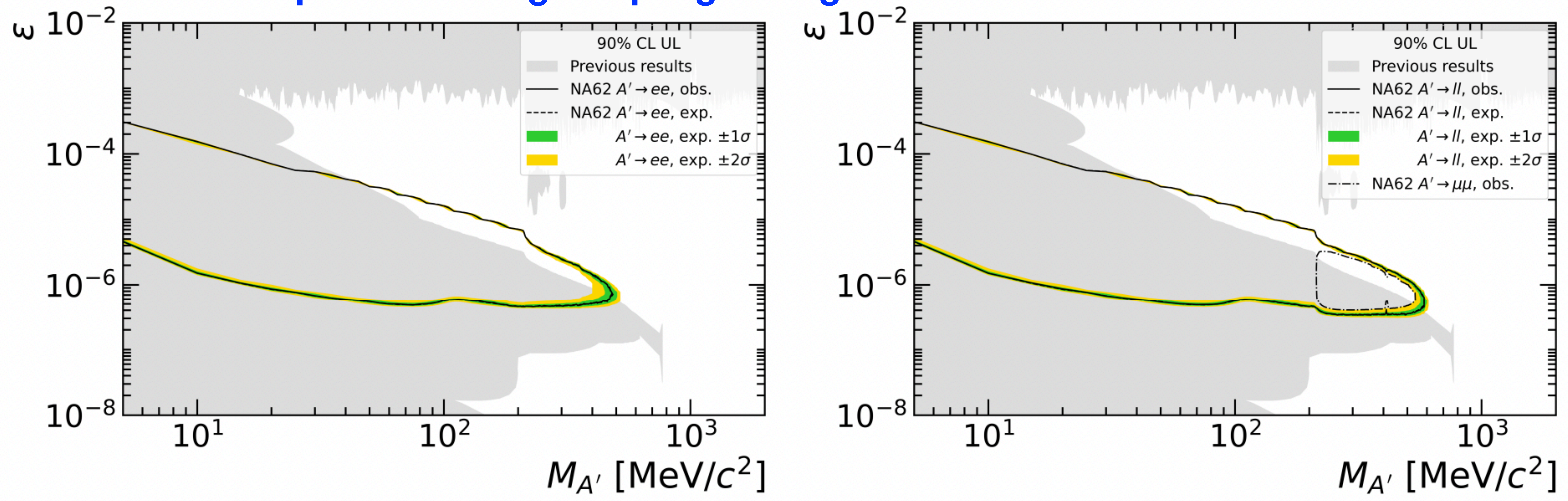
Upstream background for hadronic search [Spadaro, Vulcano24]



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



[arXiv.2312.12055]

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…

Hadronic final states: dark scalar & ALP constraints

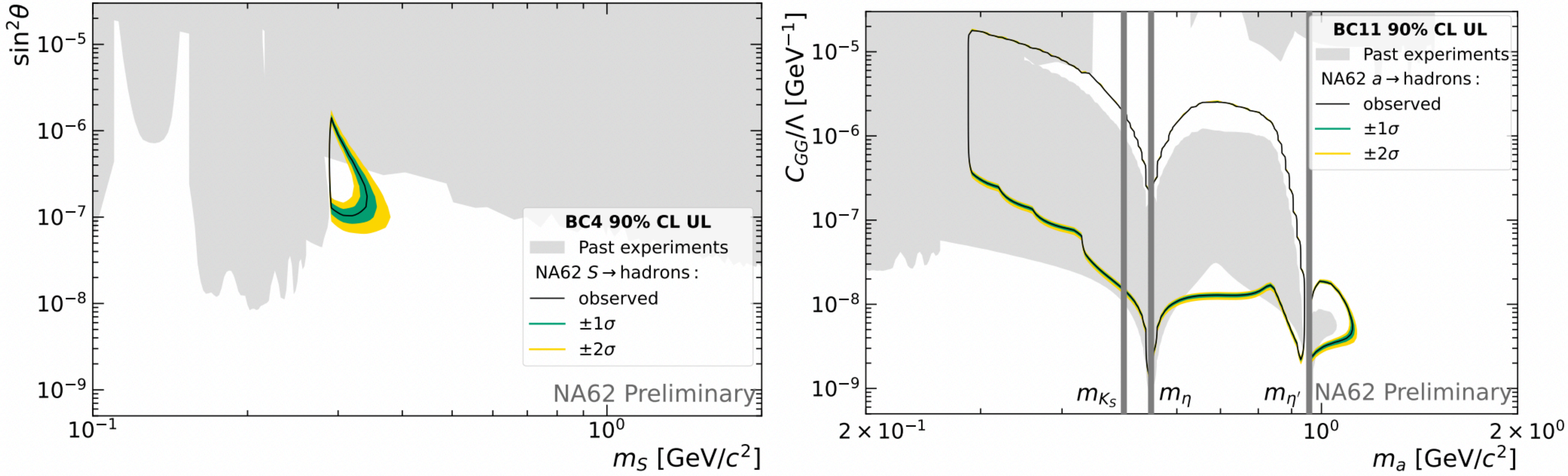


Figure: The observed 90% CL exclusion contours in BC4 (left) and BC11 (right) benchmarks together with the expected $\pm1\sigma$ and $\pm2\sigma$ bands (theory uncertainty not included). Public tool ALPINIST[5] used for the combination of the results from the individual production and decay channels. No standalone 90% CL exclusion for BC1 (dark photon).

[5] ALPINIST: Axion-Like Particles In Numerous Interactions Simulated and Tabulated. *JHEP* 07 (2022) 094, [2201.05170]