QNP2022

Florida State University (virtual)

Recent Results from the NA62 Experiment at CERN

Joel Swallow (CERN)

On behalf of the NA62 Collaboration

Contents:

- **The NA62 Experiment**
- $K^+ \to \pi^+ \nu \bar{\nu}$, $K^+ \to \pi^+ X$
- **LNV/LFV searches:** $K^+ \to \mu^- \nu e^+ e^+$, $K^+ \to \pi^-(\pi^0) e^+ e^+$, $K^+ \to \pi^\mp \mu^\pm e^+$, $\pi^0 \to \mu^- e^+$
- **Precision measurements:** $K^+ \to \pi^+ \mu^+ \mu^-$, $K^+ \to \pi^0 e^+ \nu \gamma$
- **Exotics: HNLs** $K^+ \to \ell^+ N$, **Beam Dump - Dark Photon** $A' \to \mu^+ \mu^-$.

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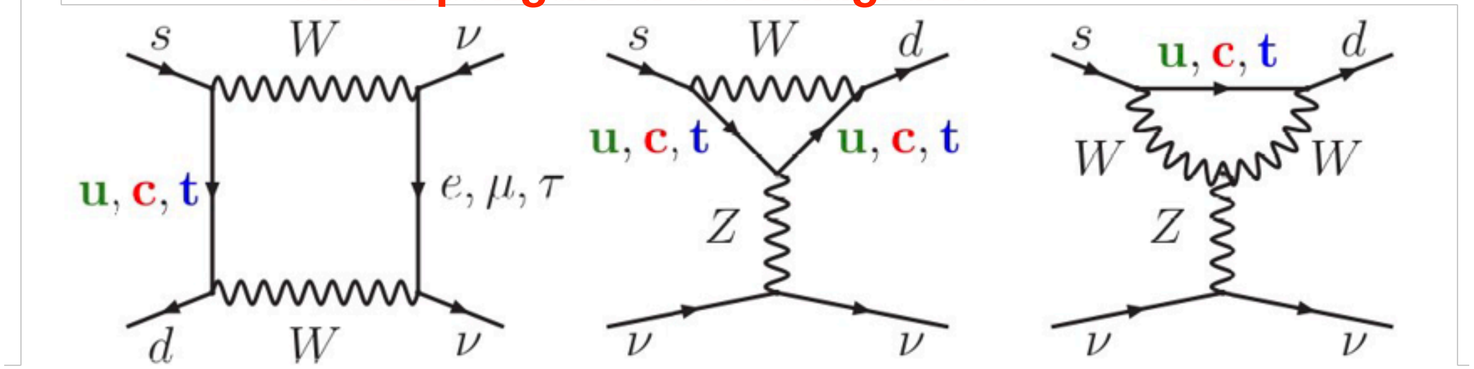
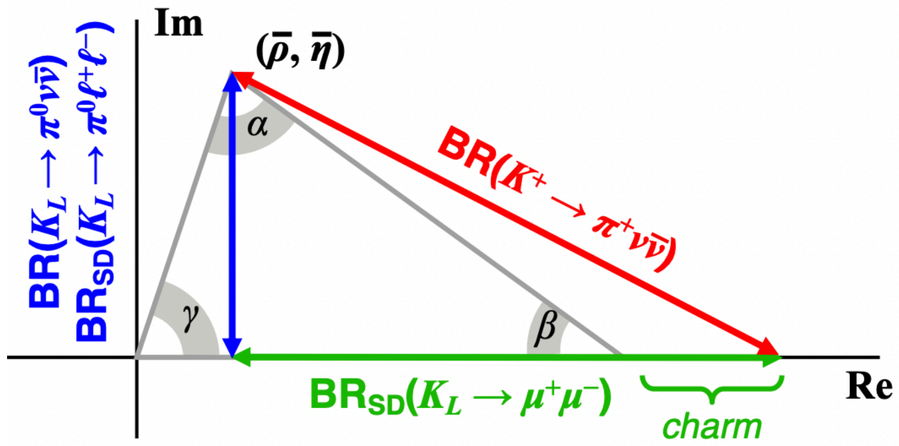
$K \to \pi\nu\bar{\nu}$: Precision test of the Standard Model

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)

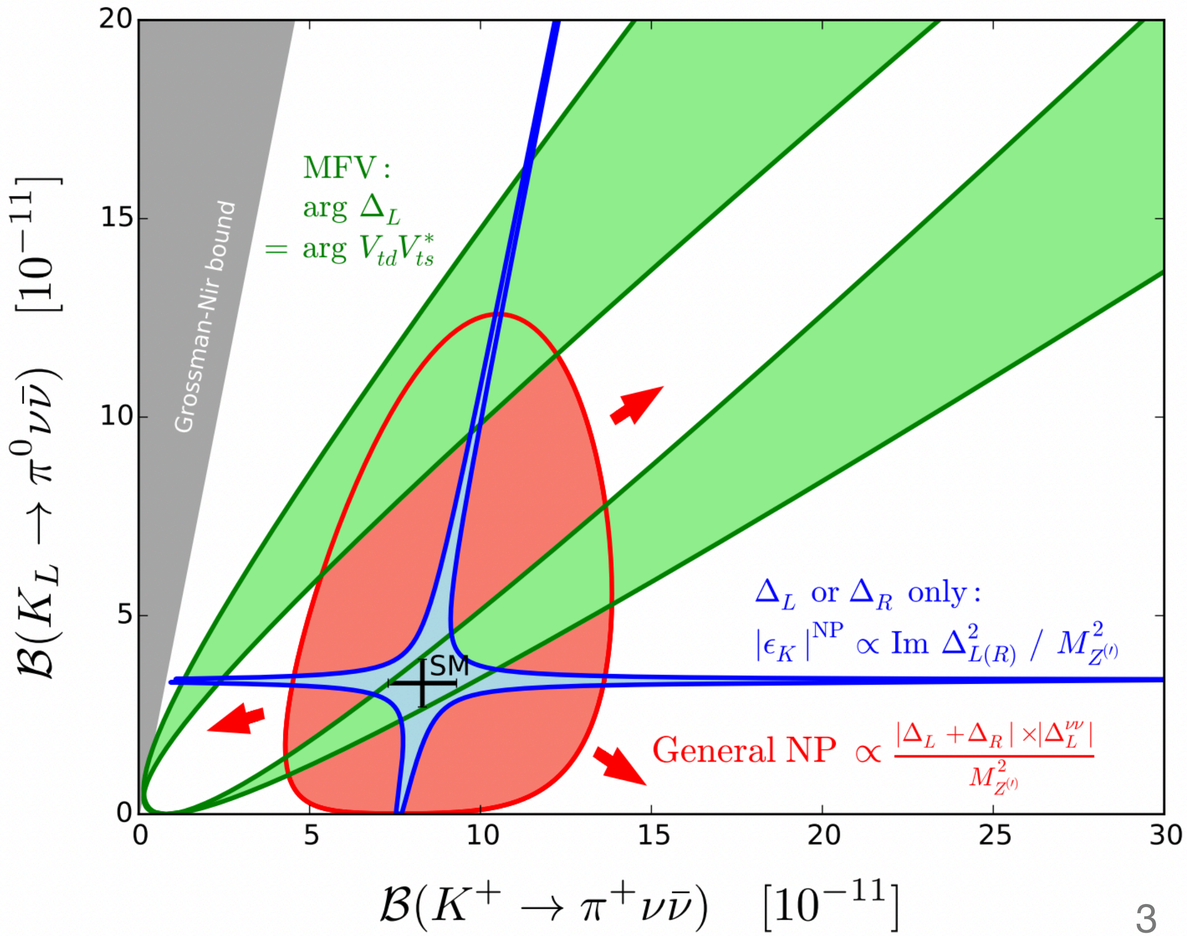
^Recent SM calculations [Buras & Venurini, Acta Phys.Polon.B 53 6, A1]: new parametric uncertainty treatment

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

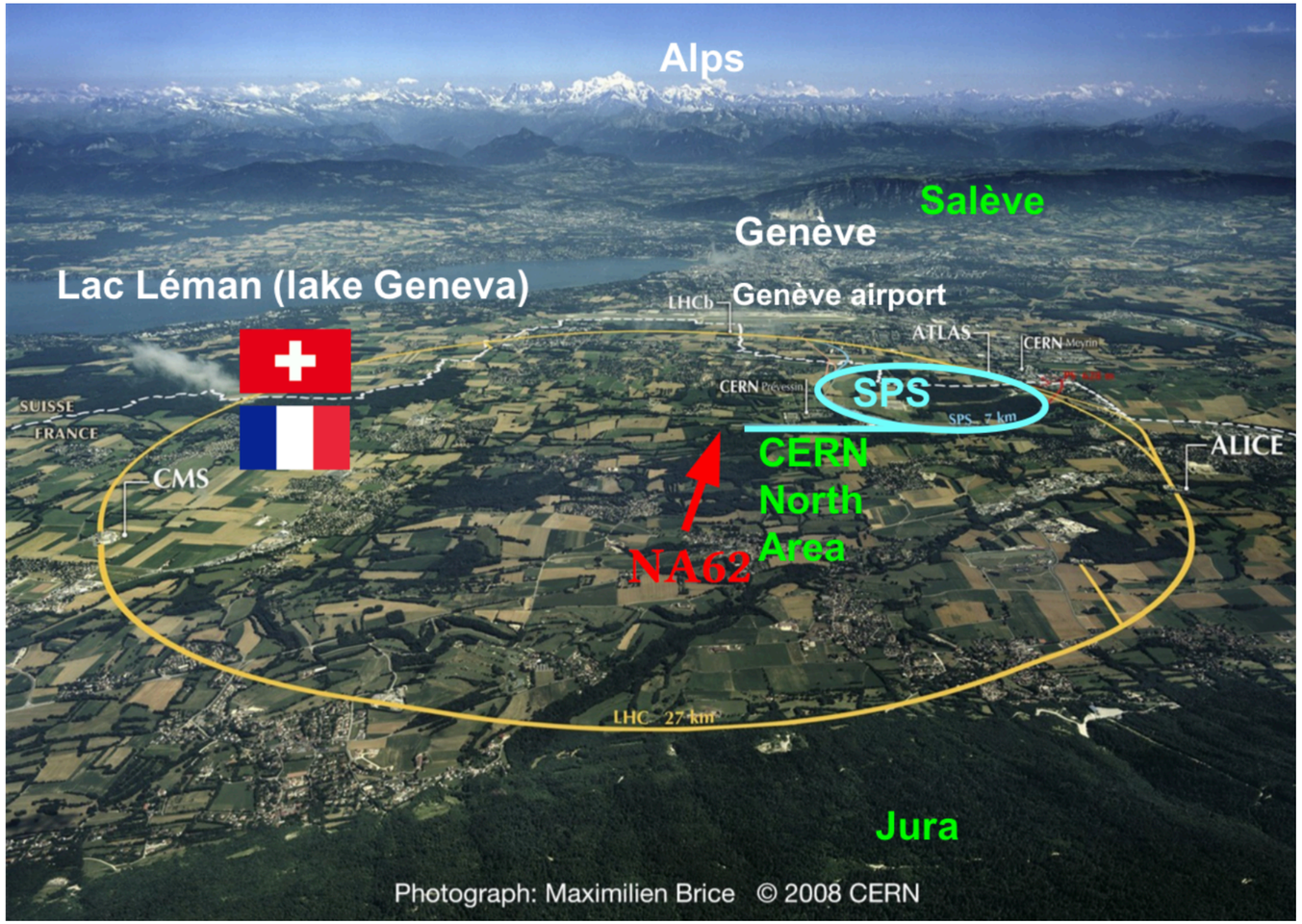
$$\frac{\mathscr{B}(K_L \to \pi^0\nu\bar{\nu})}{\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu})}\frac{\tau_{K^+}}{\tau_{K_L}} \leq 1$$



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

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. $K^+ \to \pi^+\mu^+\mu^-$ [ICHEP20])
  - LNV/LFV decays [PLB 830 (2022) 137172][PRL 127 (2021) 13, 131802]
  - Exotics (e.g. HNL [PLB 807 (2020) 135599] [PLB 816 (2021) 136259])
- **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 ongoing…

Continues long history of Kaon physics at CERN :

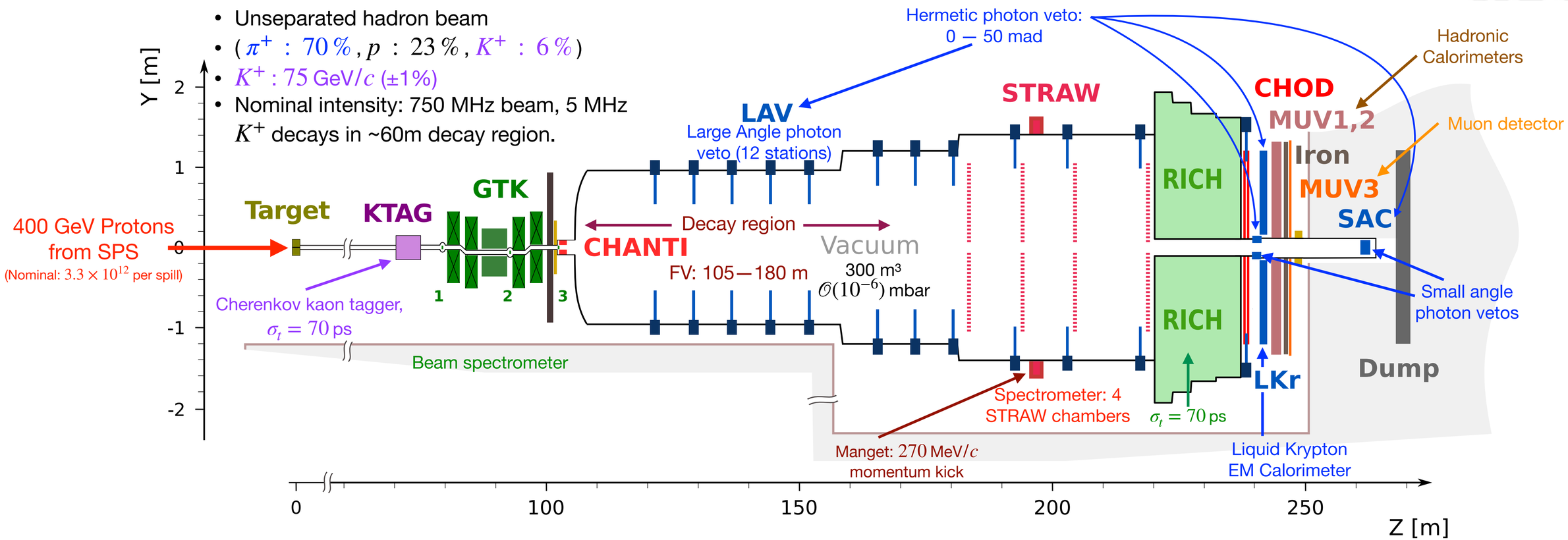
1986-98 | 1977—2001 | 2002 | 2003-4 | 2007-8 | 2016-18 | 2021…

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)

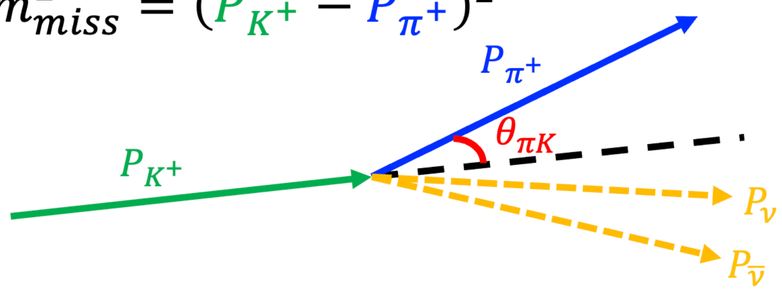
$K^+ \to \pi^+ \nu\bar{\nu}$ analysis strategy at NA62

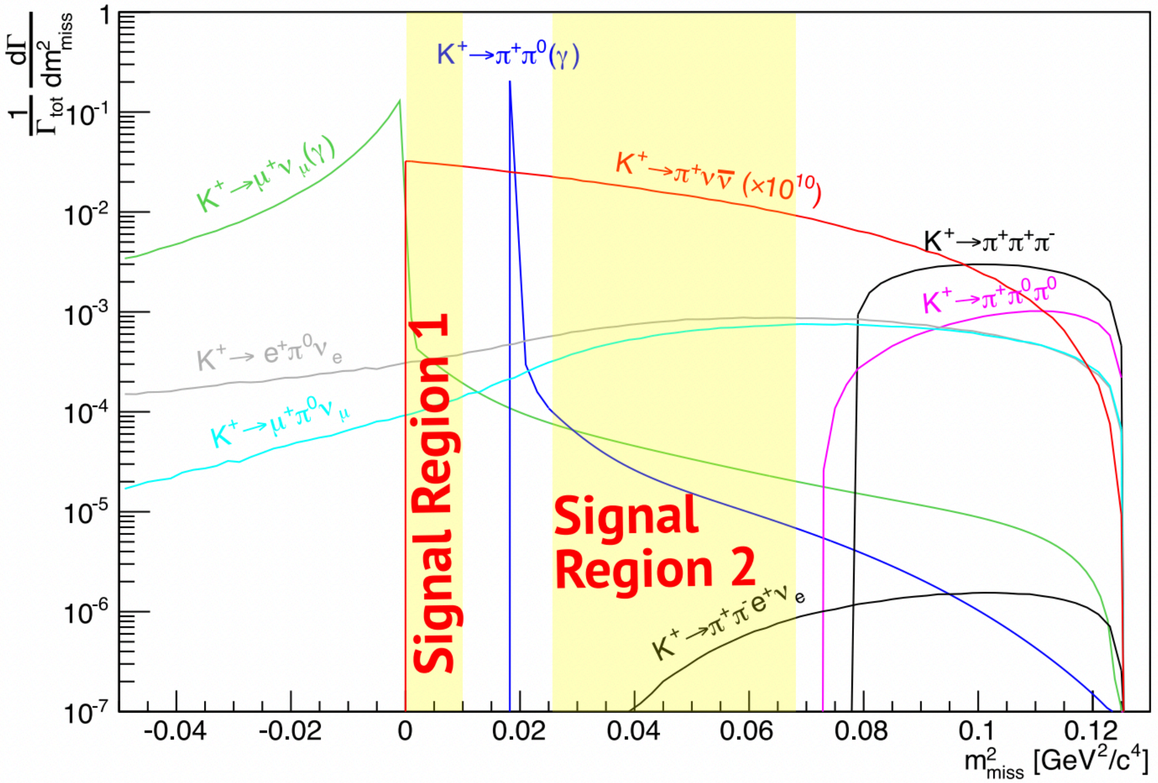
NA62 Performance Keystones:

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

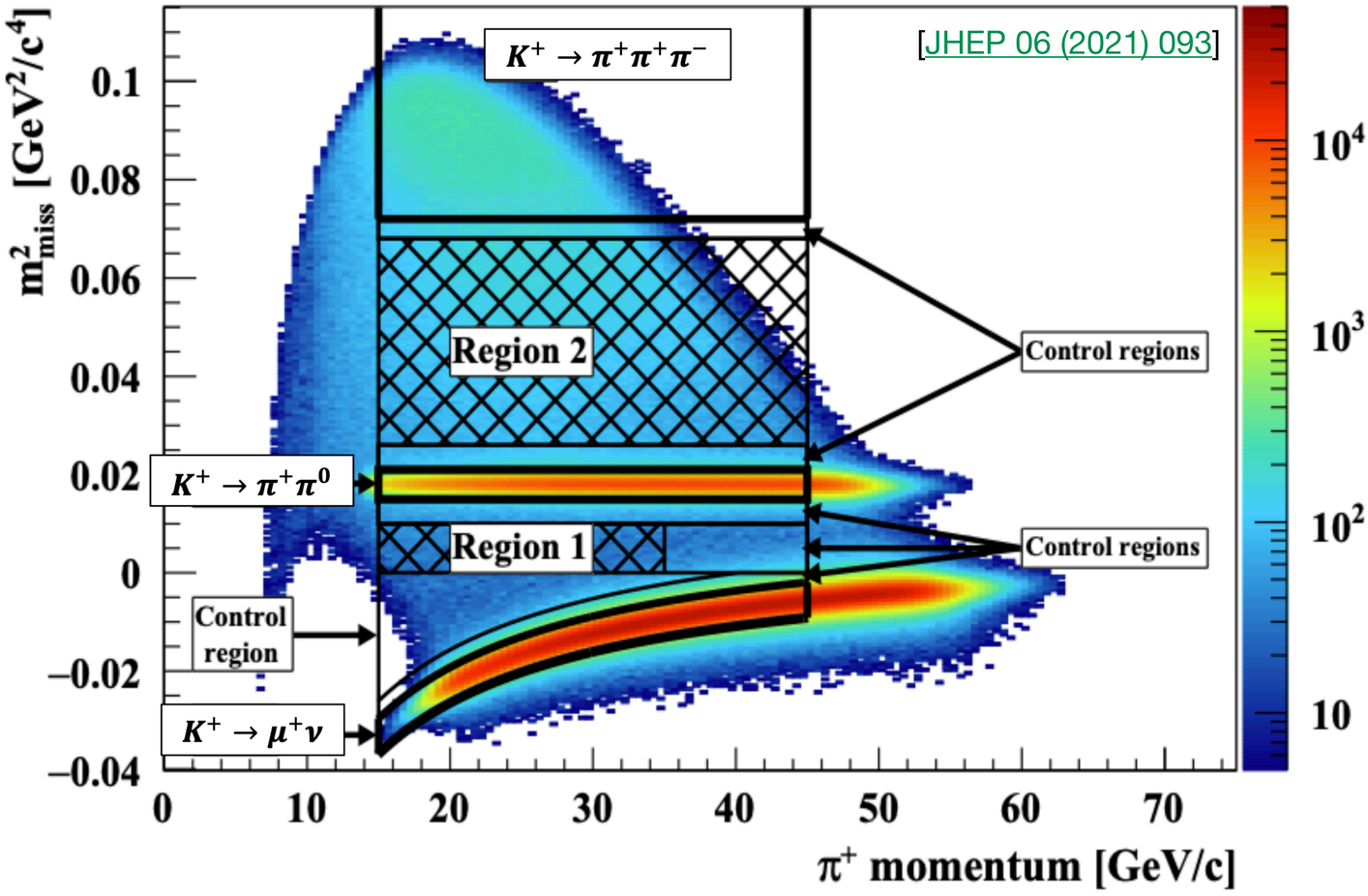
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$





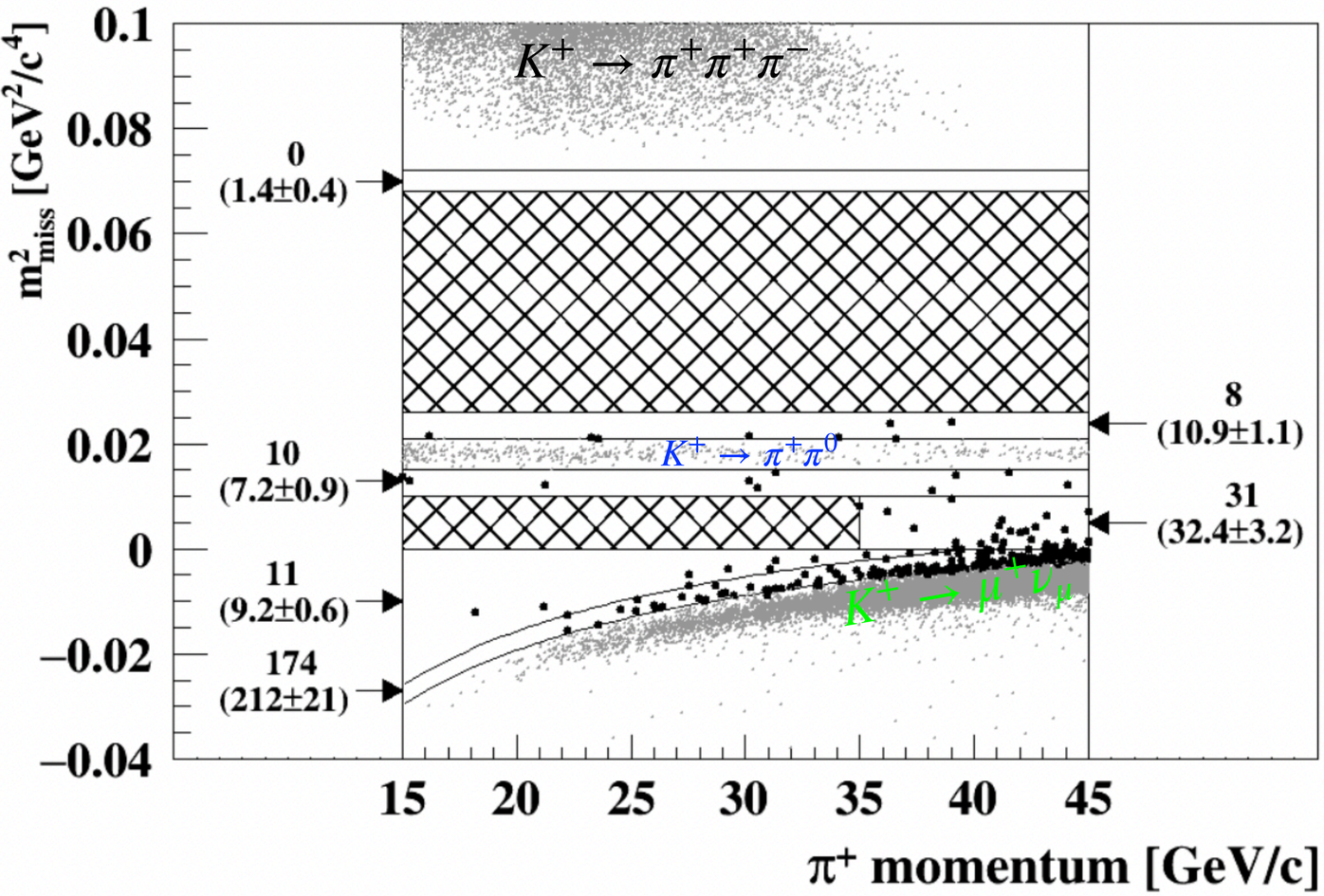
$K^+ \to \pi^+ \nu\bar{\nu}$ Signal Selection

- **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]



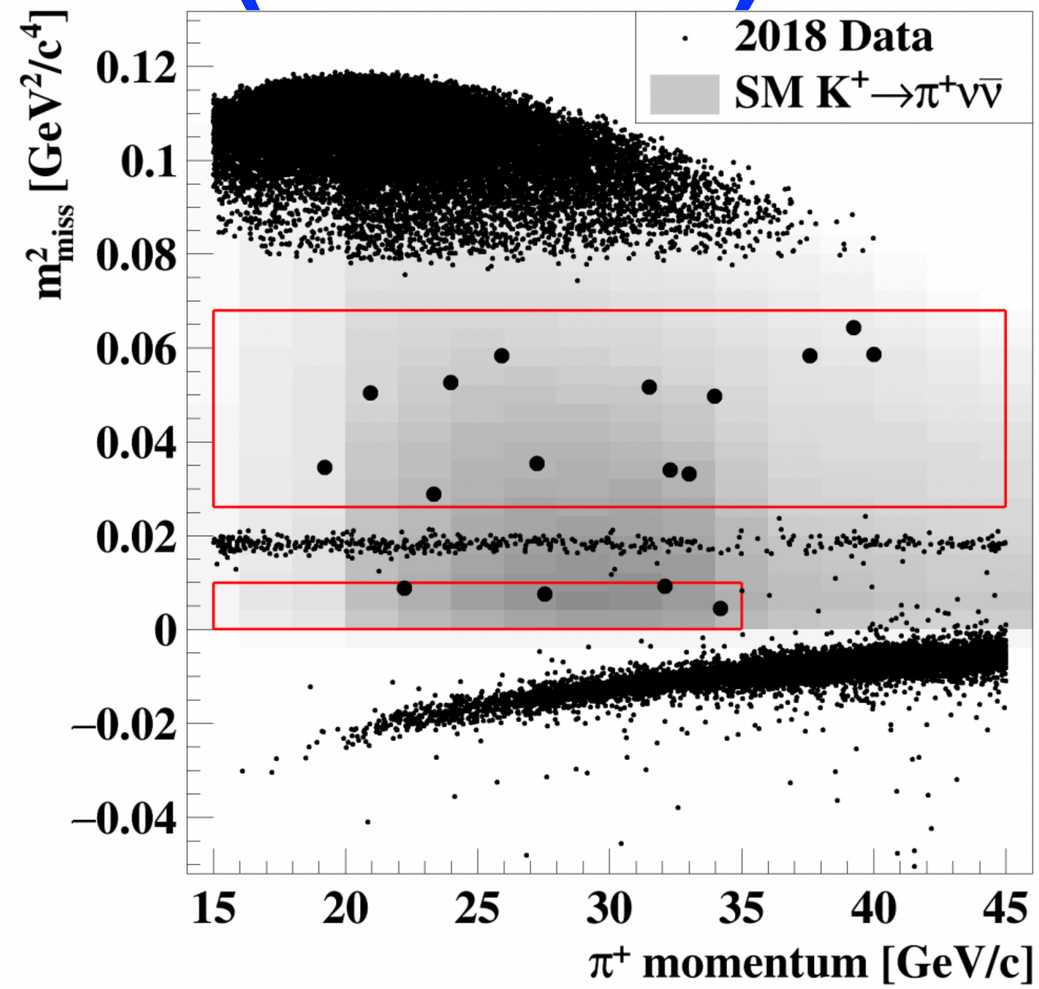
Before & after new final collimator in 2018

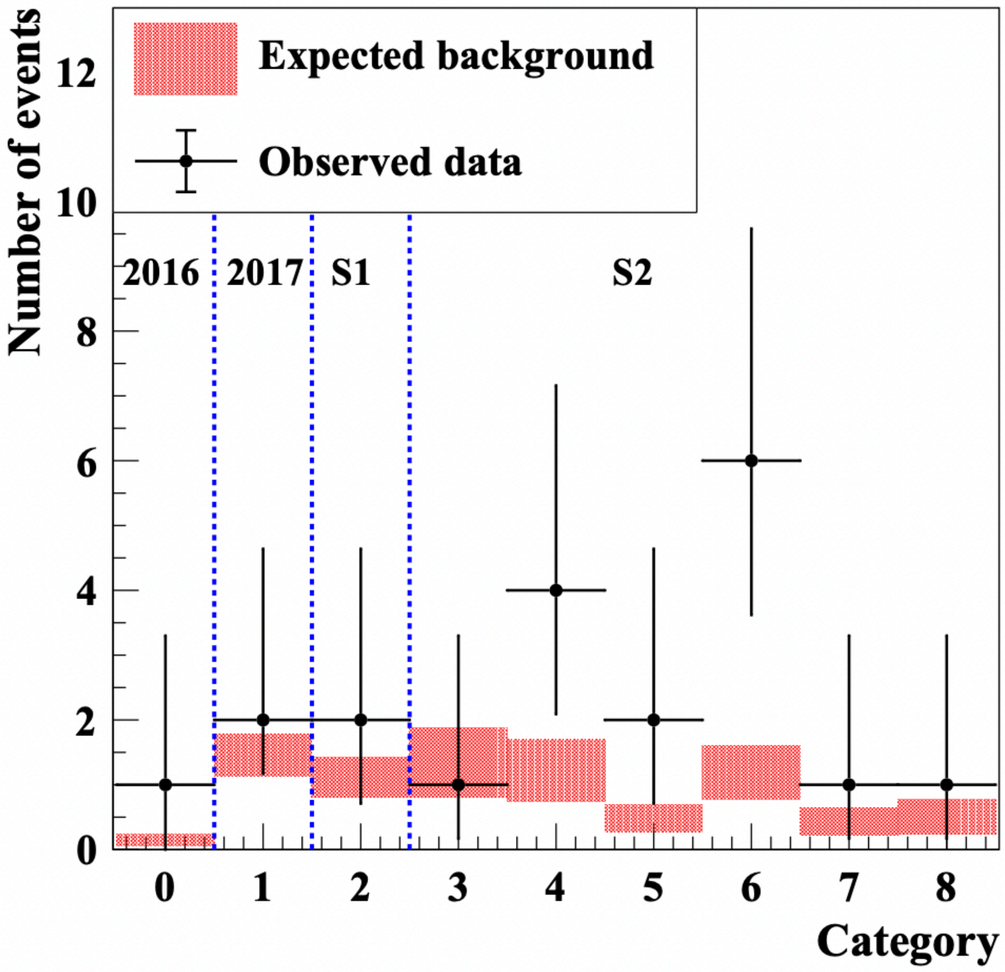
Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$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

K^+ decays in the FV

- 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.

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

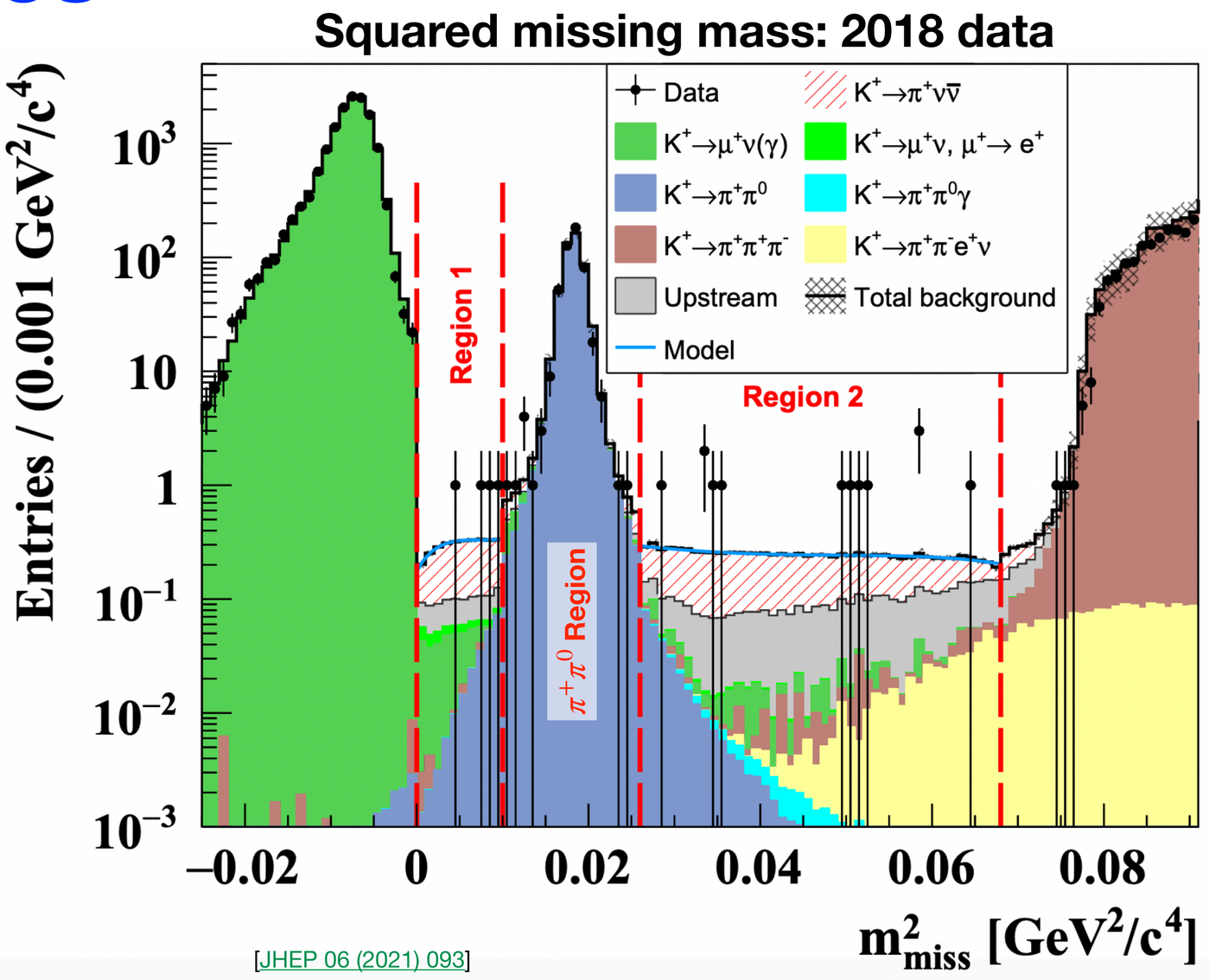




- $N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$, $N^{exp}_{bkg.} = 7.03^{+1.05}_{-0.82}$: $n_{obs} = 20$
- In background-only hypothesis: $p = 3.4 \times 10^{-4}$ ⇒ signal significance: 3.4σ.
- $\boxed{\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\text{stat}} \pm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

Hidden sector searches

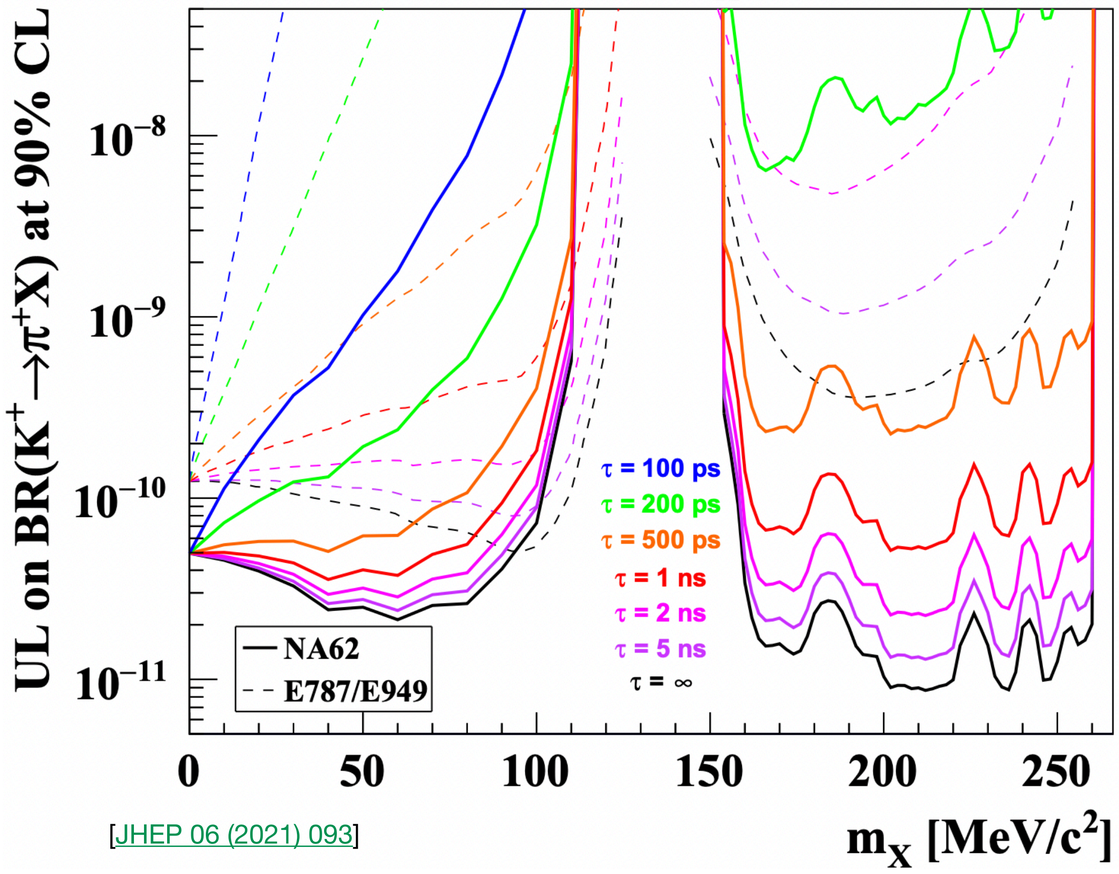
- Search for $K^+ \to \pi^+ X$ in signal regions 1&2: $0 < m_X < 110\,\text{MeV}/c^2$, $154 < m_X < 260\,\text{MeV}/c^2$
  - X = invisible new particle
    - Dark scalar, ALP, QCD axion, axiflavon.
  - Main background = (SM) $K^+ \to \pi^+ \nu\bar{\nu}$
  - [2017: JHEP 03 (2021) 058, Run1: JHEP 06 (2021) 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]

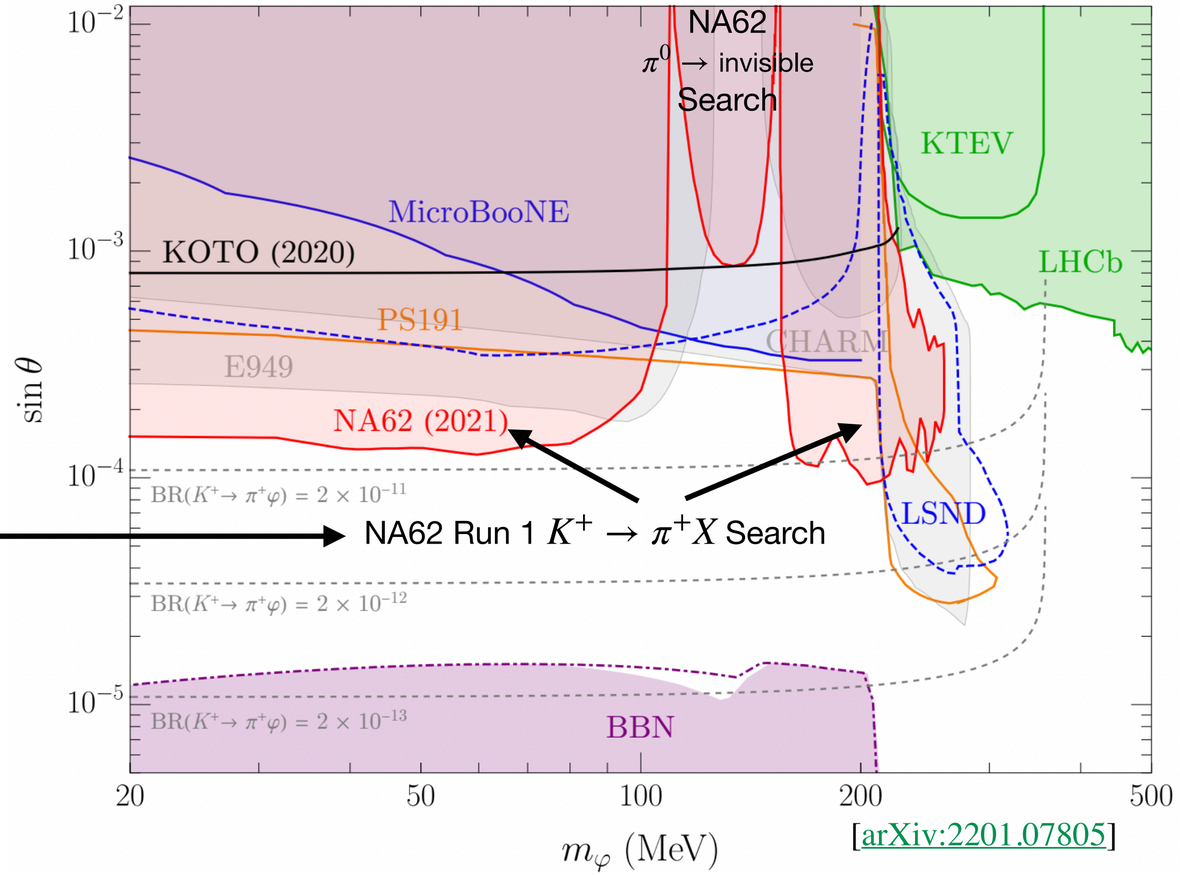
$K^+ \to \pi^+ X$ Search (Run1)

Upper Limits at 90% CL vs m_X for different lifetimes



[JHEP 06 (2021) 093]

Searches for dark scalar below kaon mass

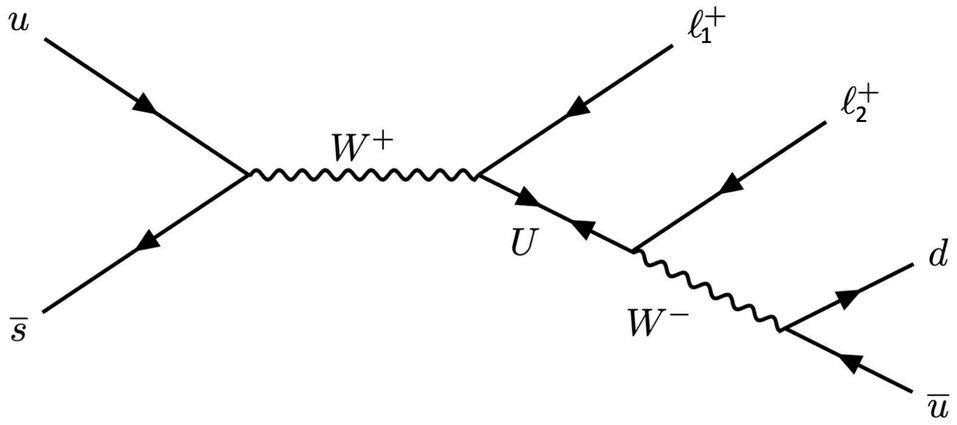


[arXiv:2201.07805]

- 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”).

Searches for LNV/LFV Decays at NA62

- Observation of Lepton Number/Flavour Violating (LNV/LFV) 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].



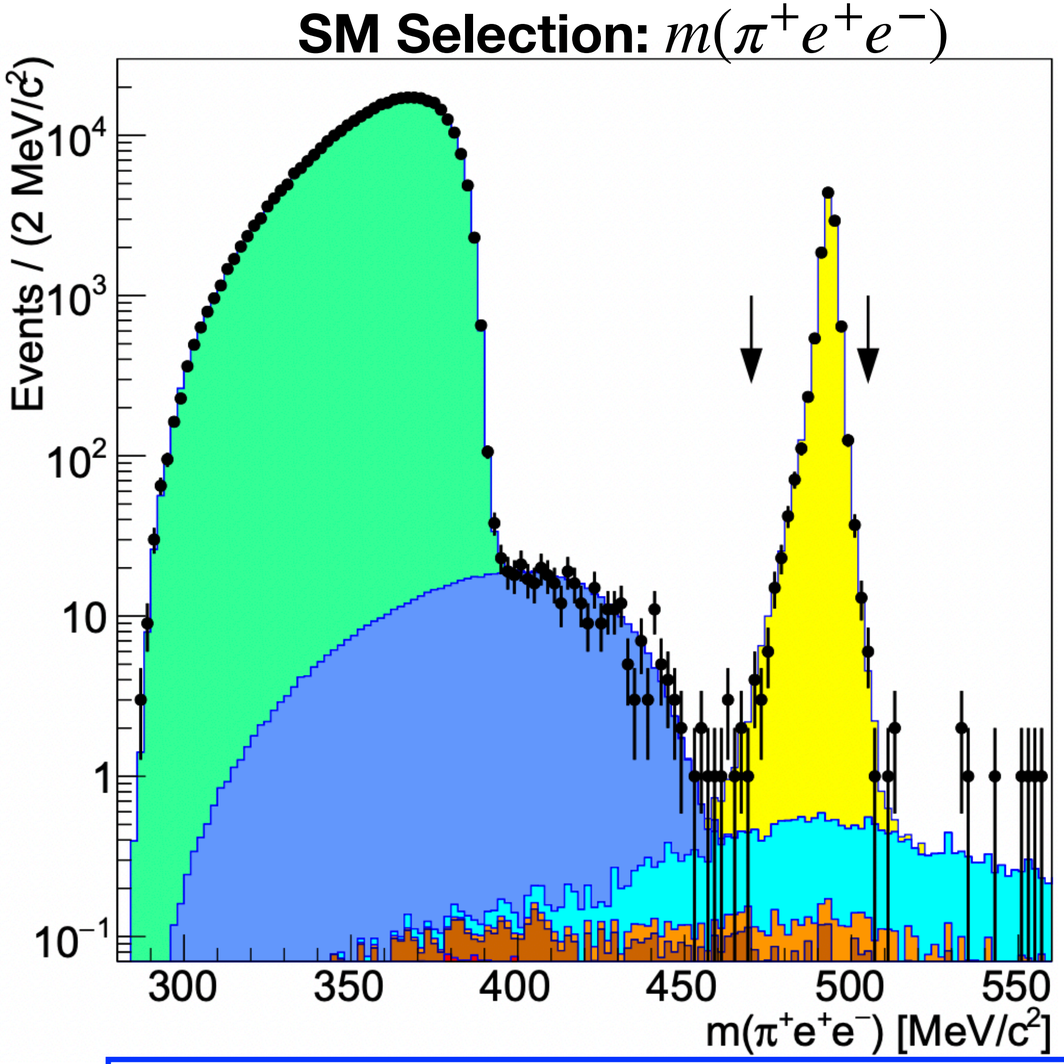
- Use Run1 (2016—18) data set:
  - Search for $K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^- \pi^0 e^+ e^+$, $K^+ \to \mu^- \nu e^+ e^+$, $(K^+ \to \pi^\mp \mu^\pm e^+)$
  - Normalise to SM rare decay $K^+ \to \pi^+ e^+ e^-$ (most common 3-track decay $K^+ \to \pi^+ \pi^+ \pi^-$).
- Triggers:
  - Hardware L0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

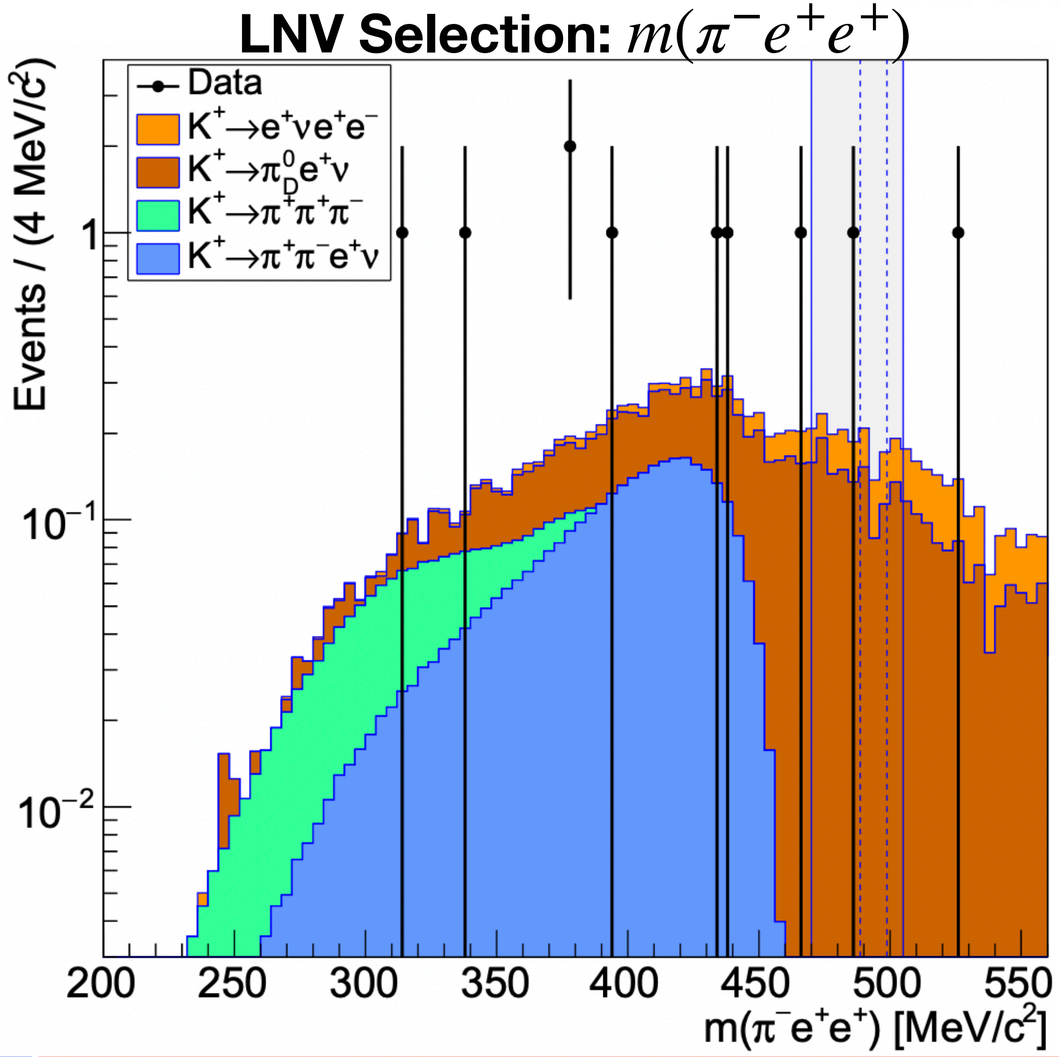
Trigger Name	Description
Multi-Track	Minimum bias 3-track trigger
Multi-Track e	3-tracks + 20 GeV energy deposit in LKr
Multi-Track mu	3-tracks + MUV3 tagged mu (+10 GeV in LKr)

- Perform **blind analyses**

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

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

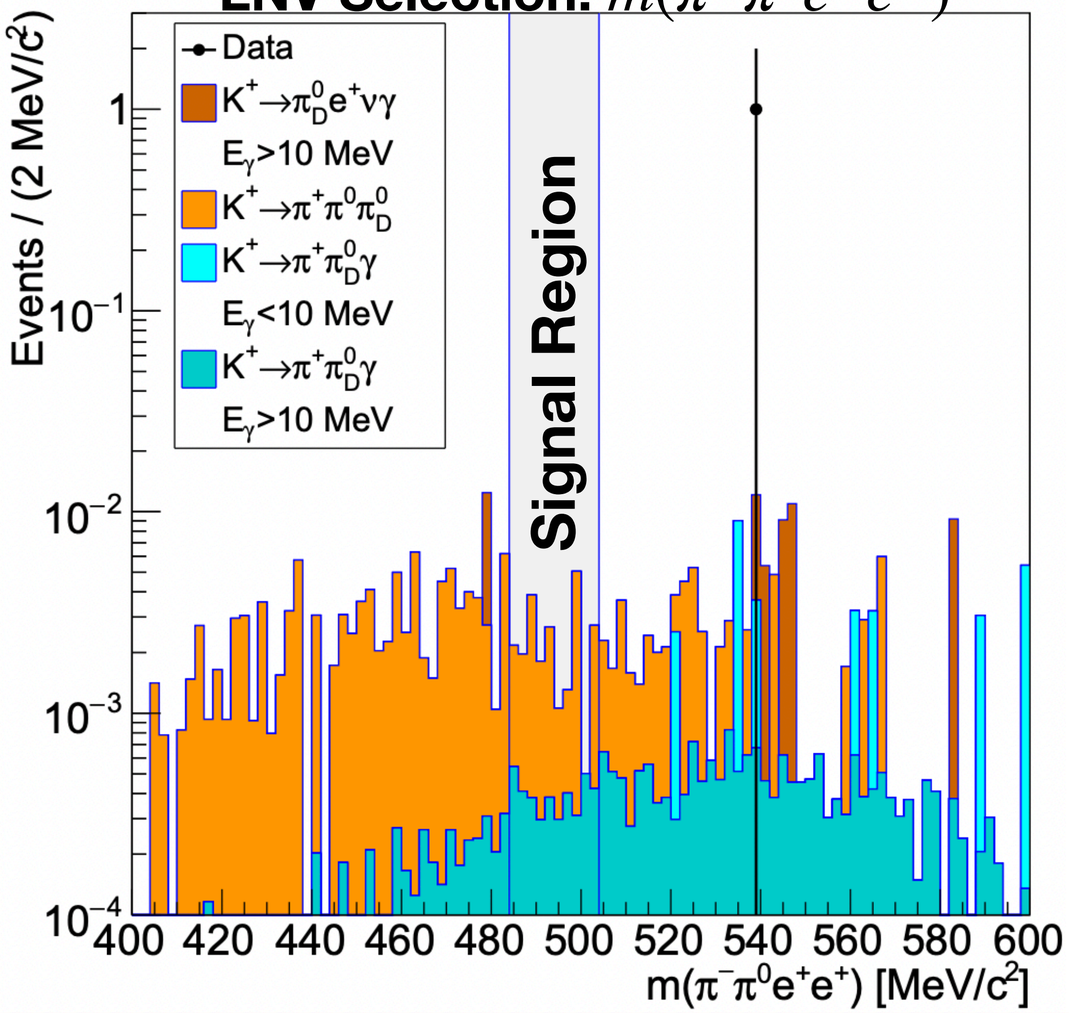
[PLB 830 (2022) 137172]

- 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

LNV Selection: $m(\pi^-\pi^0 e^+ e^+)$



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

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

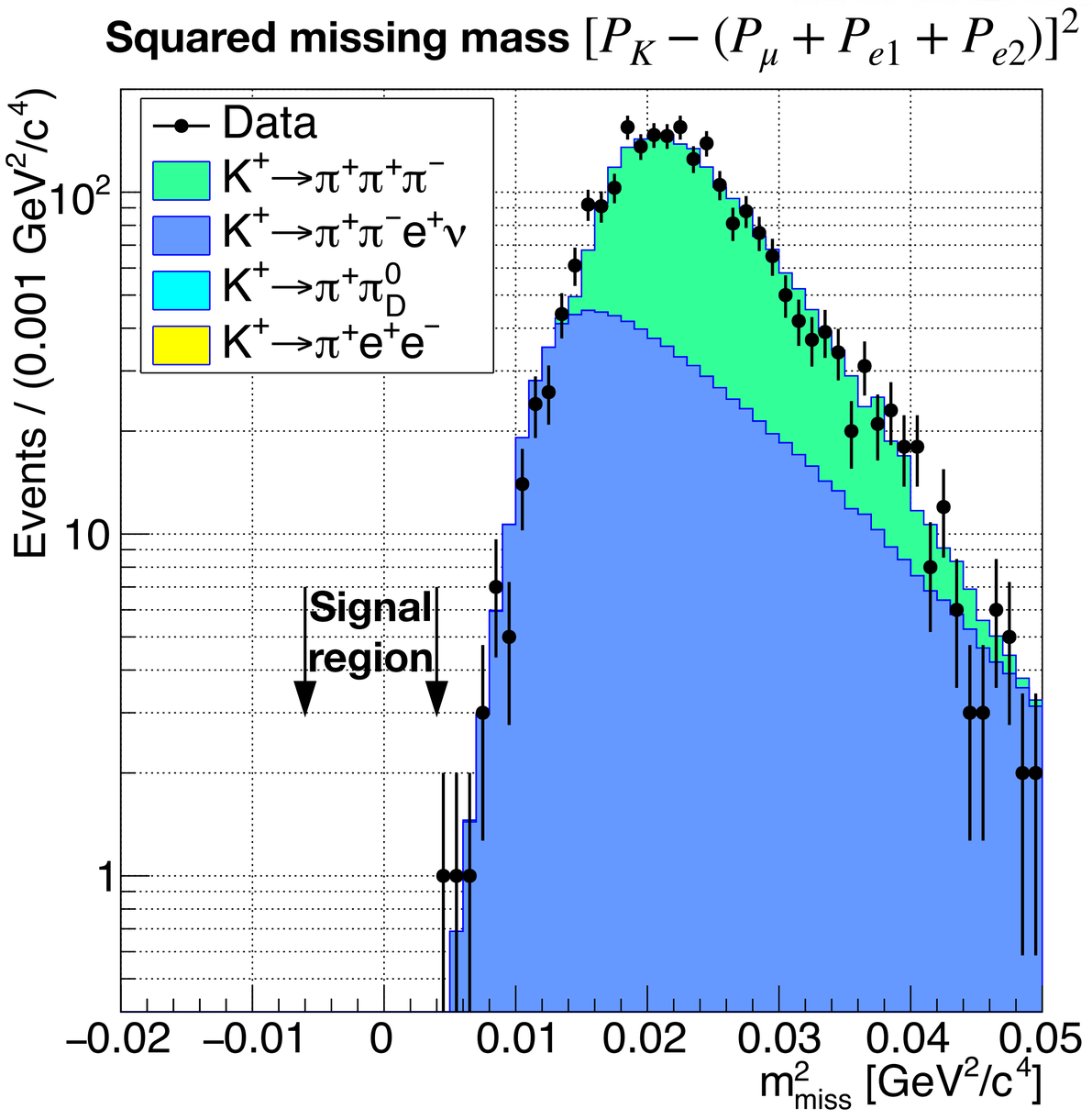
[Preliminary: arXiv publication imminent]

- LNV or LFV depending on neutrino flavour.
- Normalise to SM $K^+ \to \pi^+ e^+ e^-$.

Backgrounds:

Mode / Region	Signal	Upper
$K^+ \to \pi^+\pi^+\pi^-$	< 0.07	1412 ± 11
$K^+ \to \pi^+\pi^+\pi^-$ (upstream)	0.06 ± 0.03	1.5 ± 0.3
$K^+ \to \pi^+\pi^- e^+\nu$	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

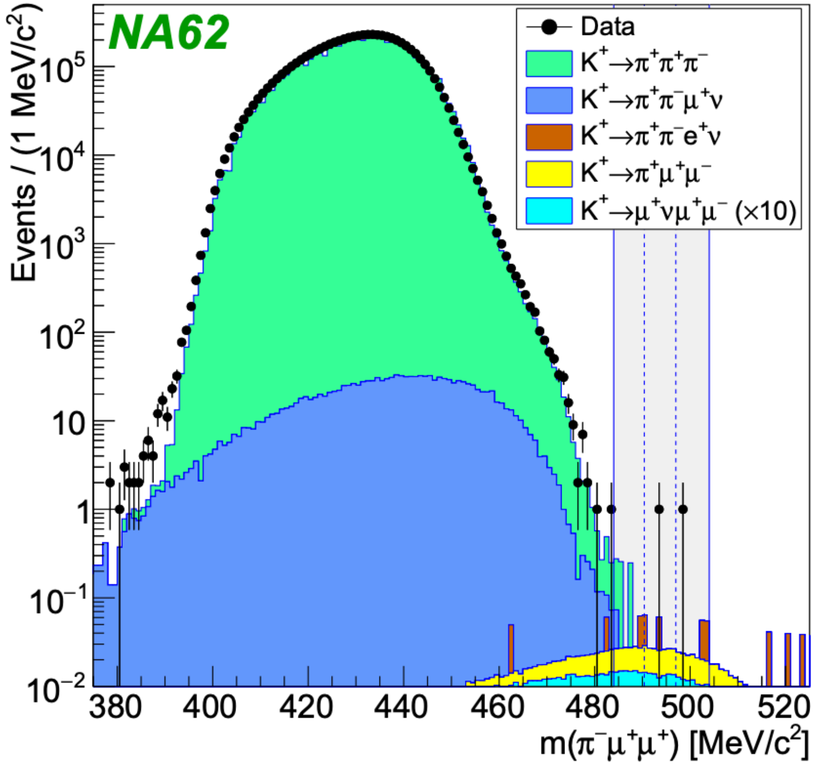
- Expected background = 0.26 ± 0.04
- Candidates observed: 0
- $\mathcal{B}(K^+ \to \mu^- \nu e^+ e^-) < 8.1 \times 10^{-11}$ at 90 % CL



Summary of other NA62 LNV/LFV Searches

- These results add to programme of searches for LNV/LFV with 2016-18 dataset:

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



2017 data : $N_K = (7.94 \pm 0.23) \times 10^{11}$ (di-muon trigger)

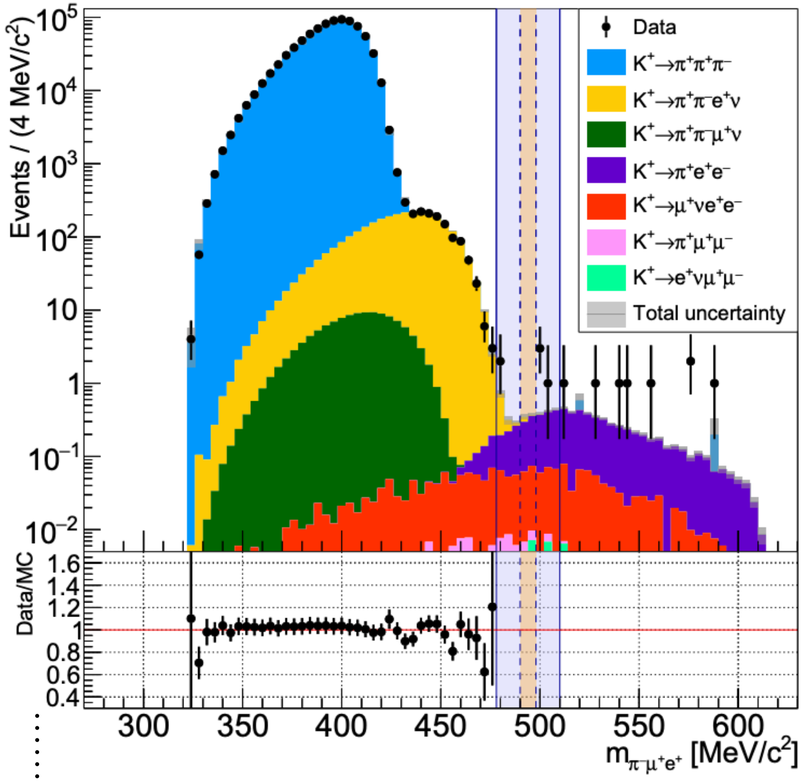
Expected background: 0.91 ± 0.41 Candidates observed: 1

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

[PLB 797 (2019) 134794]

Factor 2 improvement on NA48/2 limit [PLB 769 (2017) 67]

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



2017+18 data : $N_K = (1.33 \pm 0.02) \times 10^{12}$ (combine 3 triggers)

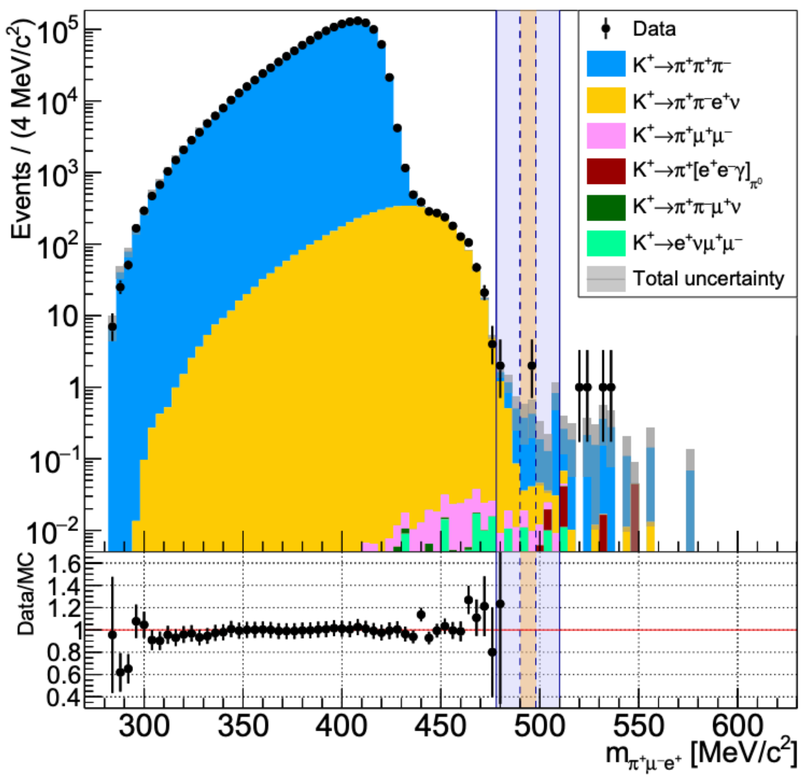
Expected background: 1.07 ± 0.20

Candidates observed: 0

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

[PRL 127 (2021) 131802]

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

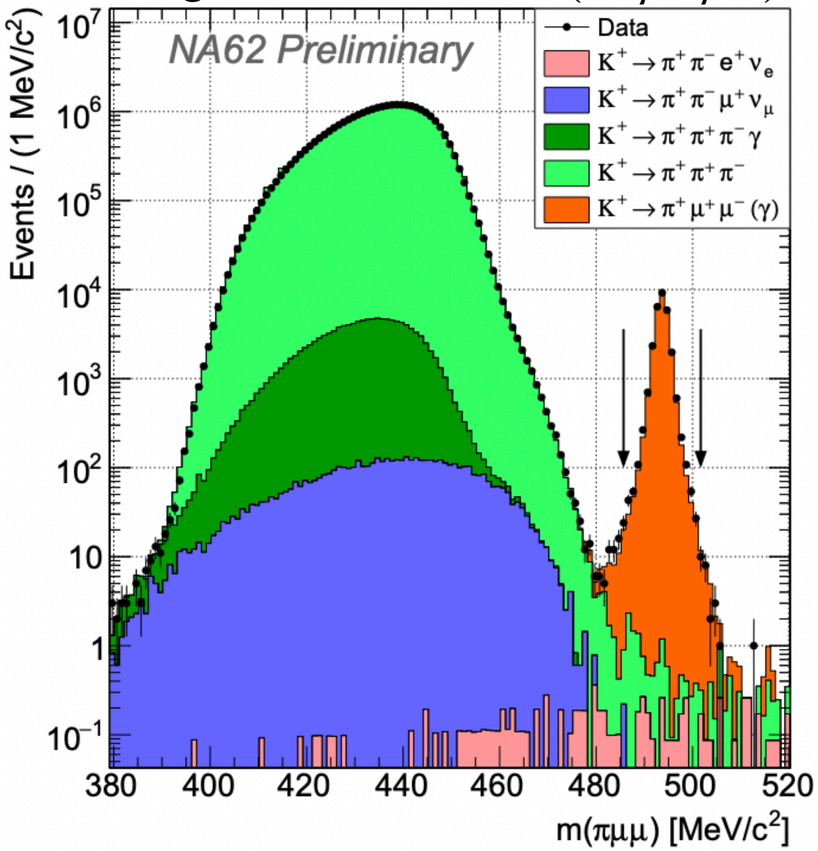
From $K^+ \to \pi^+\pi^0$, $\pi^0 \to \mu^-e^+$ search:

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

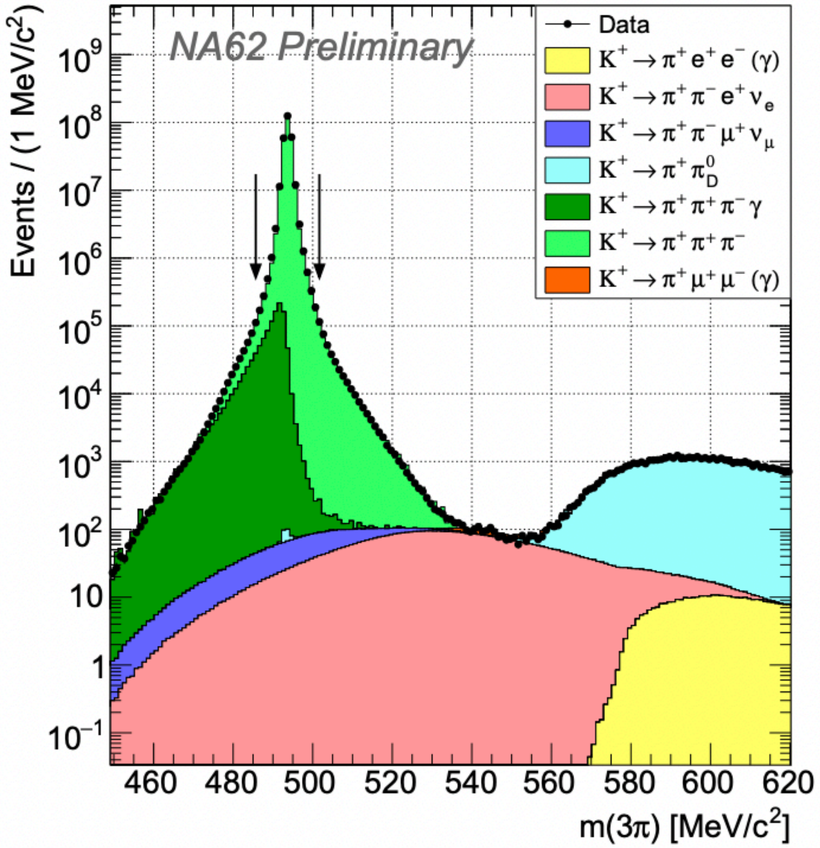
Improve by approximately 1 order of magnitude on previous BNL E865 results [PRL 85 (2000) 2877].

Precision Measurement: $K^+ \to \pi^+\mu^+\mu^-$

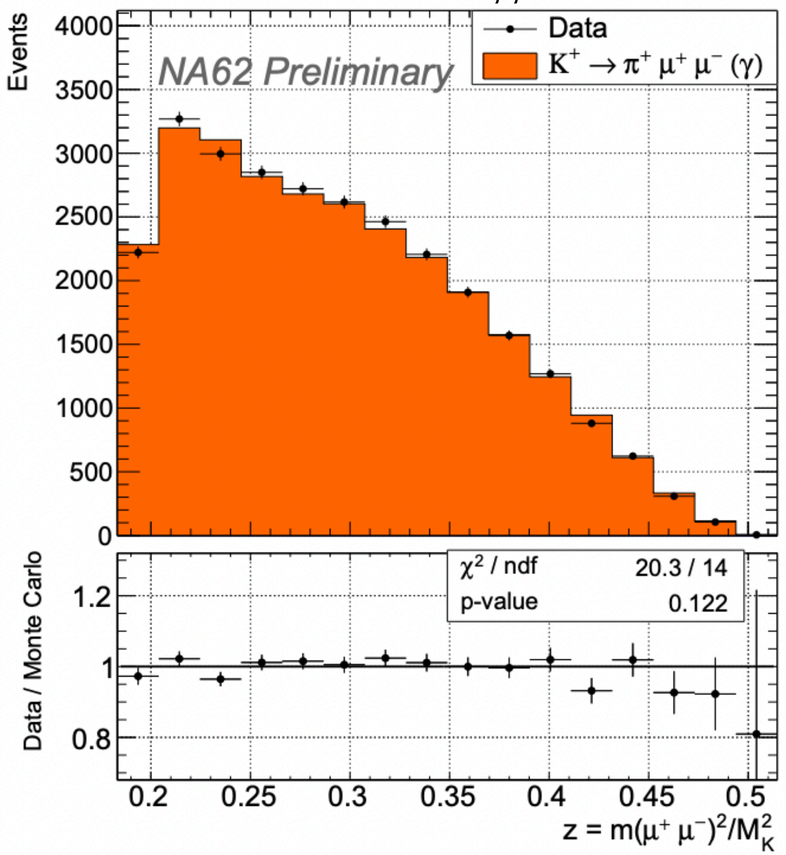
Signal Selection: $m(\pi^+\mu^+\mu^-)$



Normalisation Selection: $m(\pi^+\pi^+\pi^-)$



Bkg.-subtracted $z = m_{\mu\mu}/m_K$ **spectrum**

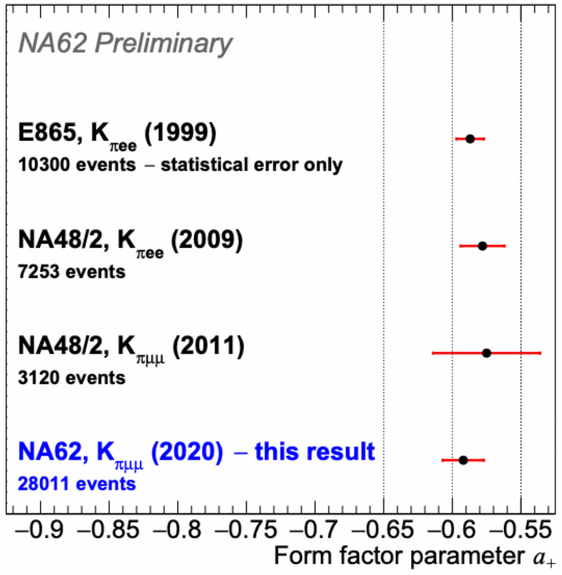


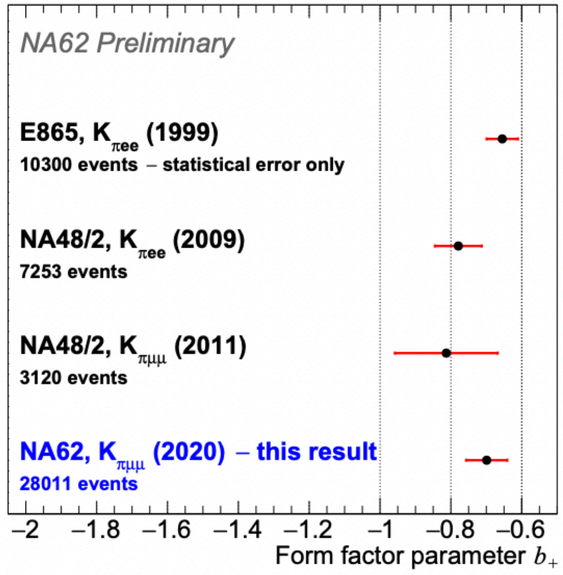
- 28011 events in $K^+ \to \pi^+\mu^+\mu^-$ signal region, bkg = $12.5 \pm 1.7_{\text{stat}} \pm 12.5_{\text{syst}}$
- Normalise to $K^+ \to \pi^+\pi^+\pi^-$ decay, subtract bkg., perform fit to $z = m_{\mu\mu}/m_K$ spectrum…

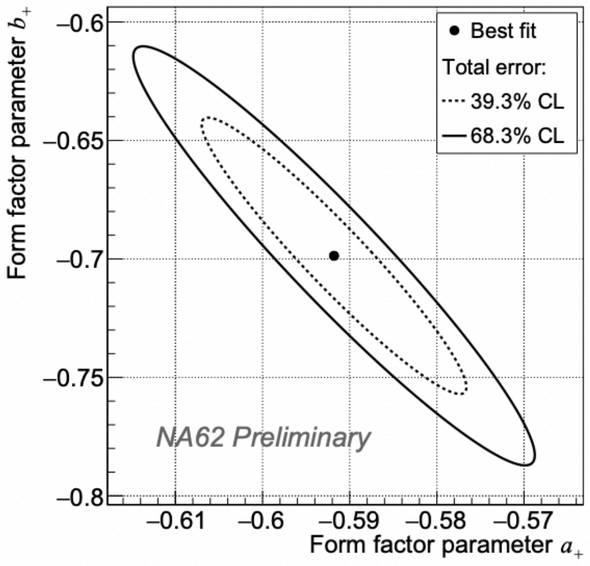
Precision Measurement: $K^+ \to \pi^+\mu^+\mu^-$

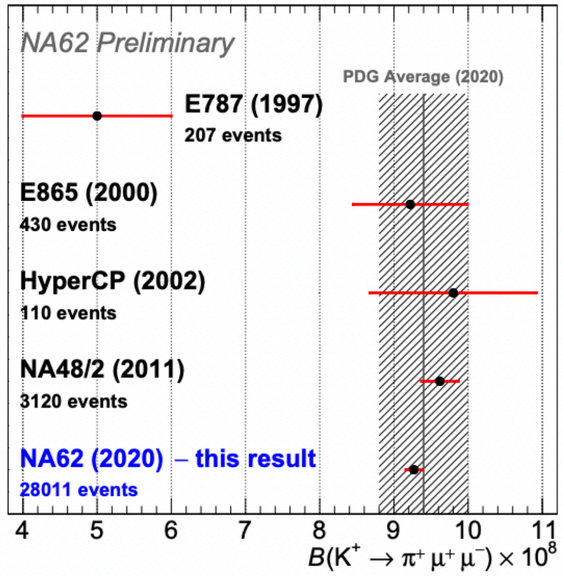
	a_+	b_+	$\mathcal{B}(K_{\pi\mu\mu}) \times 10^8$
Best fit	−0.592	−0.699	9.27
Errors	δa_+	δb_+	$\delta\mathcal{B}(K_{\pi\mu\mu}) \times 10^8$
Statistical	0.013	0.046	0.07
Systematic			
Reconstruction efficiency	0.005	0.026	0.06
Beam and pileup simulation	0.005	0.024	0.05
Trigger efficiency	0.001	0.005	0.04
Background	—	0.001	0.01
Total systematic	0.007	0.035	0.08
External			
PDG error in $\mathcal{B}(K_{3\pi})$	0.001	0.003	0.04
Total	0.015	0.058	0.11
Precision:	2.5%	8.3%	1.2%

- Form factor parameters a_+, b_+ extracted
- Comparison of a_+, b_+ between $\pi\mu\mu$ and πee
  $\Rightarrow$ LFU holds



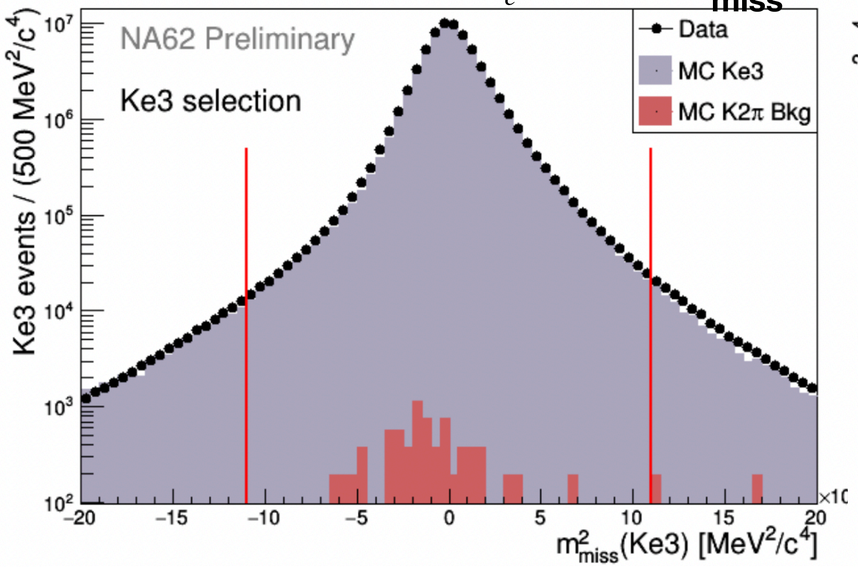




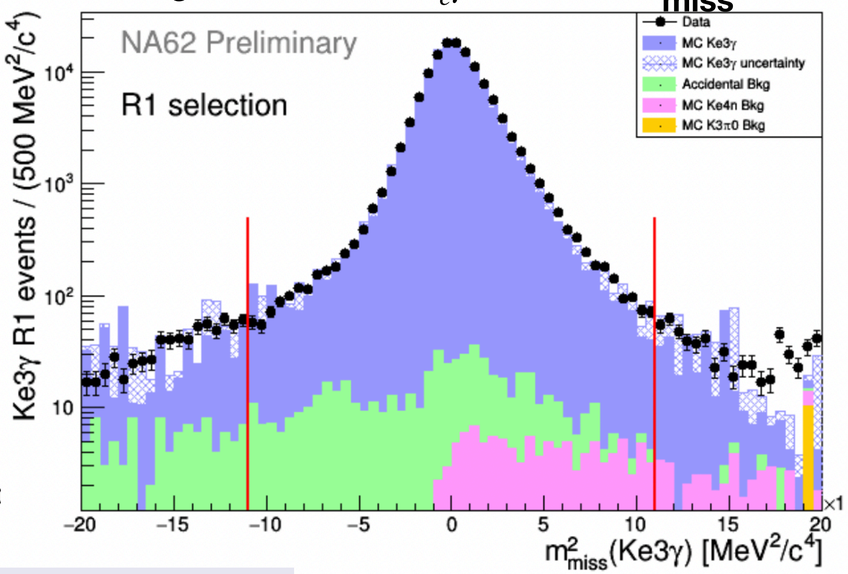


Precision Measurement: $K^+ \to \pi^0 e^+ \nu_e \gamma$

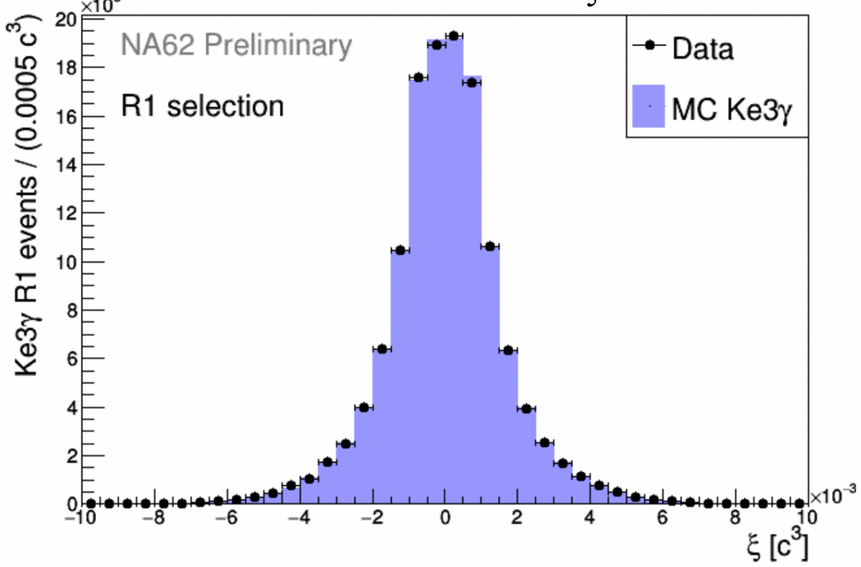
Normalisation $K^+ \to \pi^0 e^+ \nu_e$ selection: m^2_{miss}



Signal $K^+ \to \pi^0 e^+ \nu_e \gamma$ selection: m^2_{miss}



T-odd observable ξ



$$R_j = \frac{\mathcal{B}(Ke3\gamma^j)}{\mathcal{B}(Ke3)} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma \mid E^j_\gamma, \theta^j_{e,\gamma})}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu(\gamma))}$$

- 3 phase-space definitions (j=1,2,3).
- **<1% Precision measurement of R**: improved by factor between 2.0 and 3.6
- 6-7% relative discrepancy with ChPT $\mathcal{O}(p^6)$

	E_γ cut (*)	$\theta_{e,\gamma}$ cut (*)	$O(p^6)$ ChPT [EPJ C 50, 557]	ISTRA+	OKA	**NA62 preliminary**
R_1 $(\times 10^2)$	$E_\gamma > 10$ MeV	$\theta_{e,\gamma} > 10^\circ$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.684 \pm 0.005 \pm 0.010$
R_2 $(\times 10^2)$	$E_\gamma > 30$ MeV	$\theta_{e,\gamma} > 20^\circ$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.599 \pm 0.003 \pm 0.005$
R_3 $(\times 10^2)$	$E_\gamma > 10$ MeV	$0.6 < \cos\theta_{e,\gamma} < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.523 \pm 0.003 \pm 0.003$

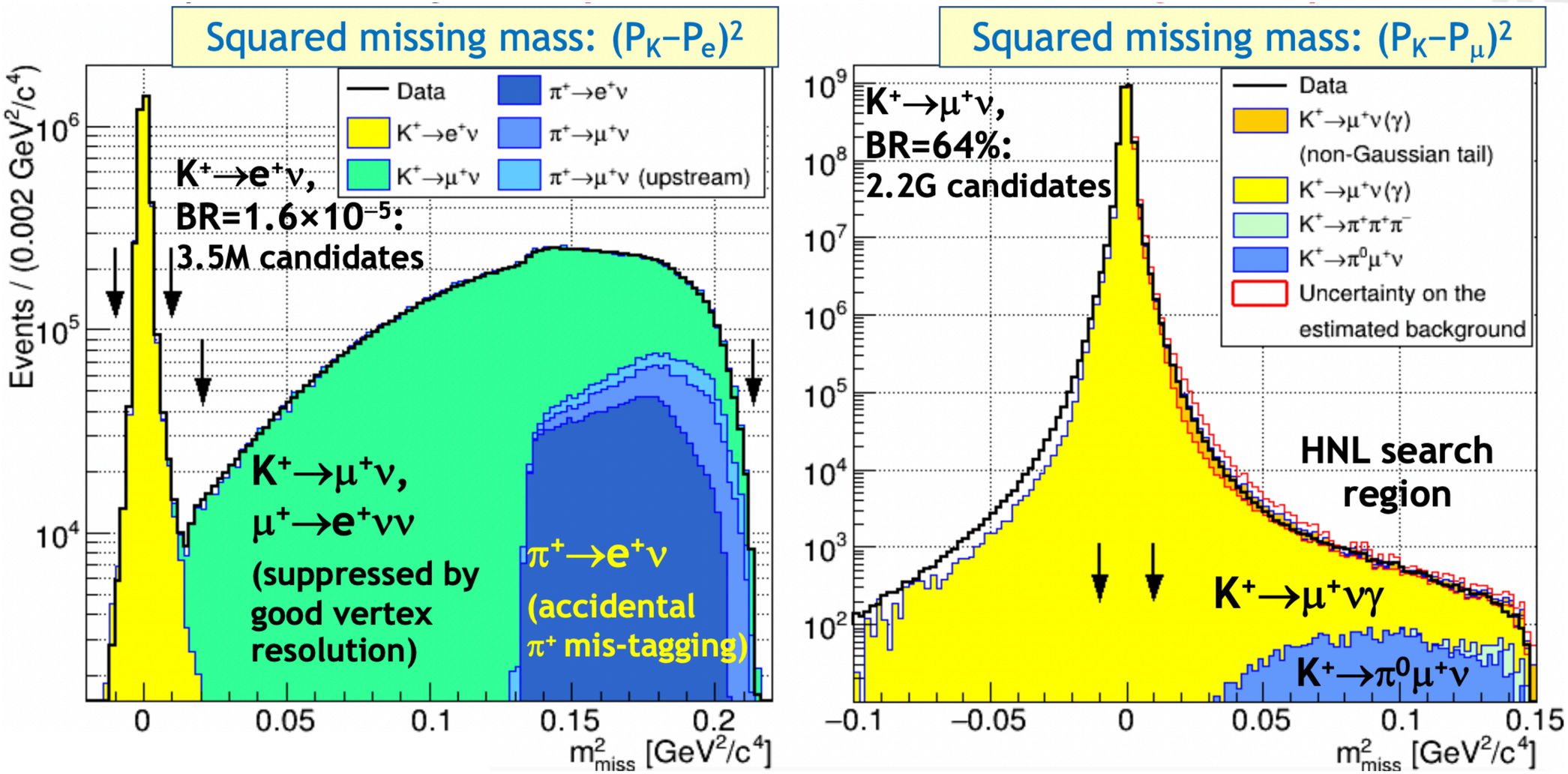
T-odd observable ξ (in the kaon rest frame):

$$\xi = \frac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{m_K^3} \; ; \; A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

Non-zero A_ξ values due to NLO (one-loop) electromagnetic corrections

	R1	R2	R3
A_ξ $(\times 10^2)$	$-0.1 \pm 0.3_{stat} \pm 0.2_{MC}$	$-0.3 \pm 0.4_{stat} \pm 0.3_{MC}$	$-0.9 \pm 0.5_{stat} \pm 0.4_{MC}$

Exotics: HNL Production Searches



- Look for HNL production: **spike above continuous missing mass spectrum**

$K^+ \to e^+N$

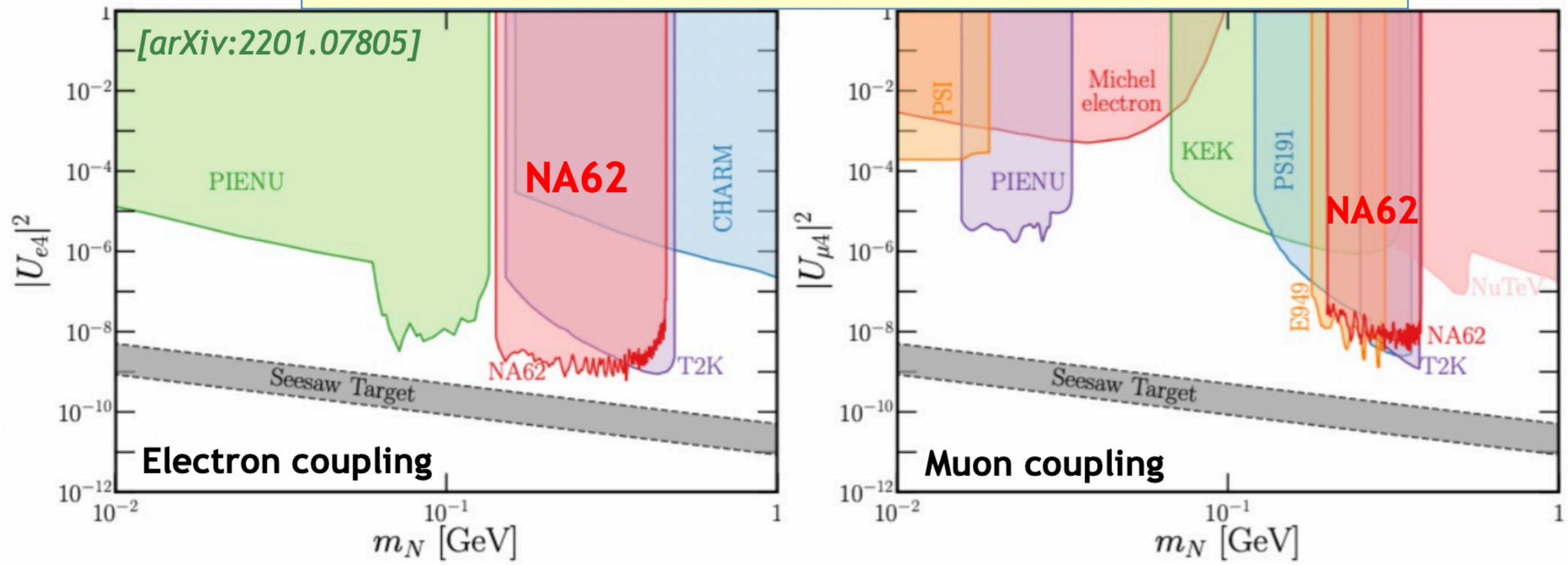
- Trigger = PNN (no downscale)
- $N_K^{eff}(K_{eN}) = (3.52 \pm 0.02) \times 10^{12}$

$K^+ \to \mu^+N$

- Trigger = Control , Downscale = 400
- $N_K^{eff}(K_{\mu N}) = (4.29 \pm 0.02) \times 10^{9}$

Exotics: HNL Production Searches

$|U_{\ell 4}|^2$ limits vs m_{HNL} from production & decay searches



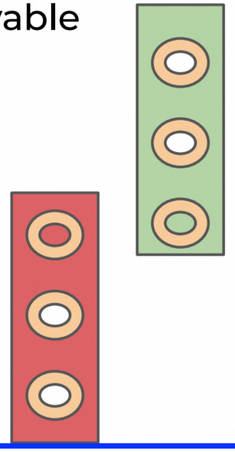
- For $|U_{e4}|^2$: complimentary to search for $\pi^+ \to e^+ N$ at PIENU
- For $|U_{\mu 4}|^2$: complimentary to search for $\pi^+ \to \mu^+ N$ at BNL-E949
- Both cases: complimentary to HNL decay searches at T2K.
- An upper limit at 90% CL $\mathscr{B}(K^+ \to \mu^+ \nu\nu\nu) < 1.0 \times 10^{-6}$ and similar limits on $\mathscr{B}(K^+ \to \mu^+ X)$, where X = invisible.

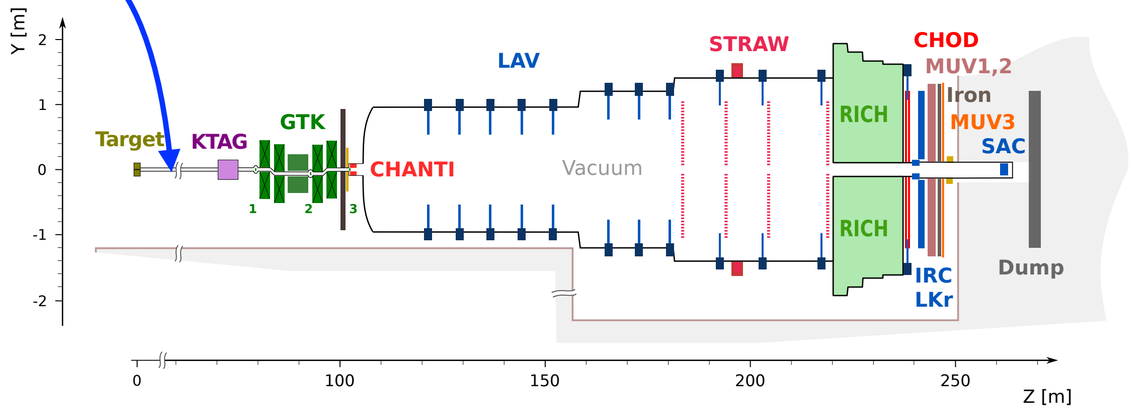
[PLB 807 (2020) 135599][PLB 816 (2021) 136259]

Exotics: Beam Dump Mode & $A' \to \mu^+\mu^-$

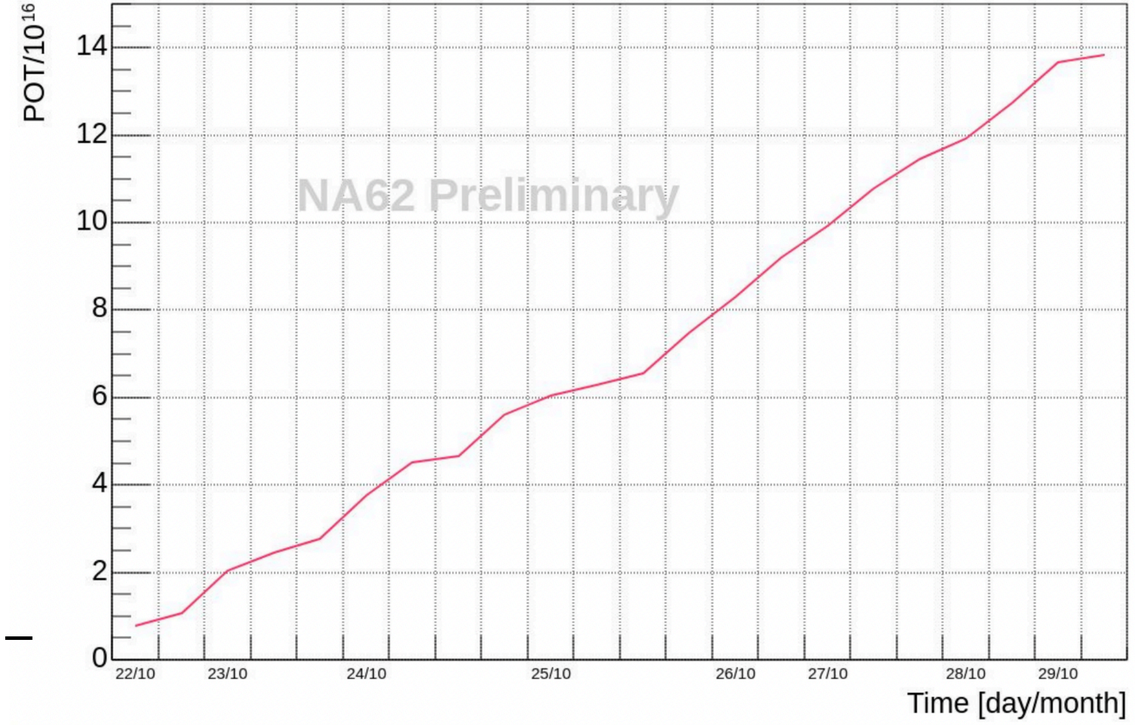
TAXes are movable collimators

400 GeV/c protons





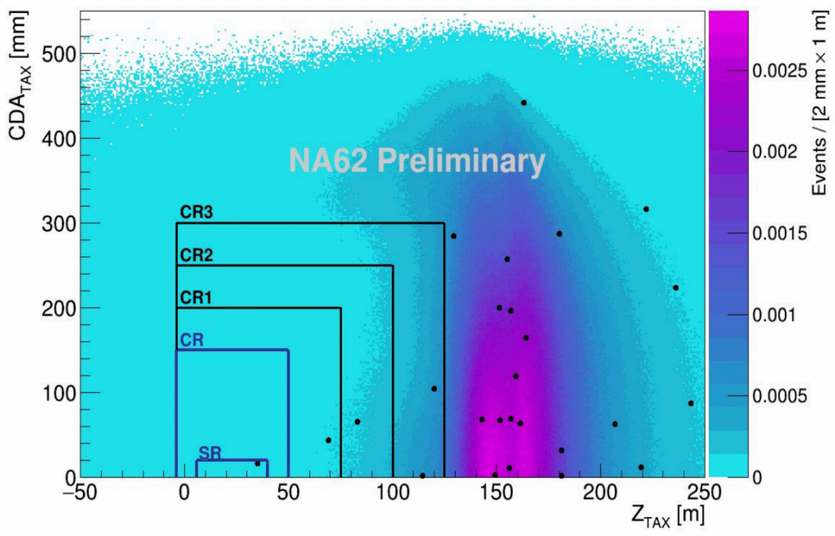
Collected $(1.40 \pm 0.28) \times 10^{17}$ POT in ~10 days of beam-dump data-taking in 2021



POT measured by beam secondary emission monitor

- Beam-line optimised in 2021: Improved sweeping & higher intensity
- Single & 2-track triggers.
- Search for Dark photon decays: $A' \to \mu^+\mu^-$

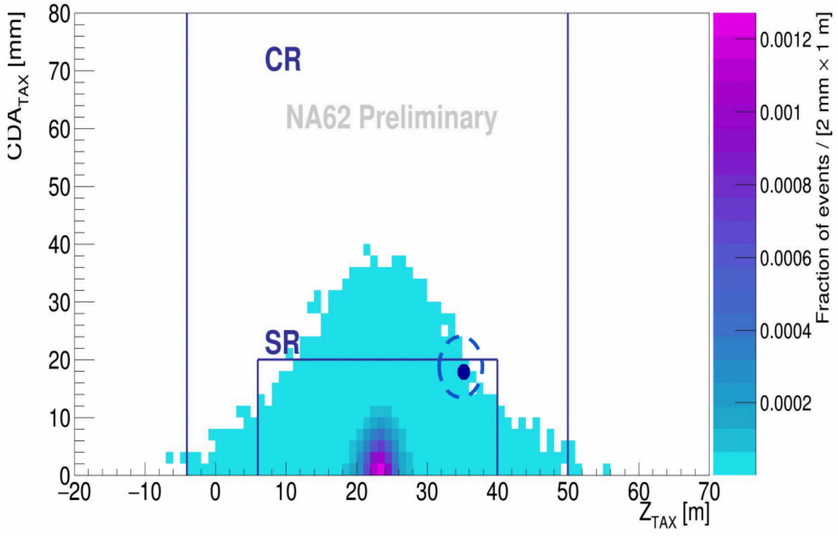
Exotics: Beam Dump Mode & $A' \to \mu^+\mu^-$



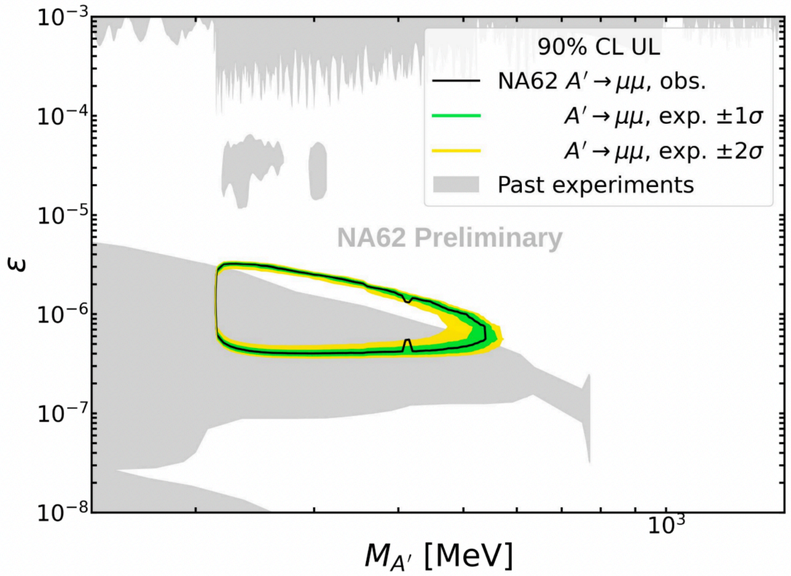
1 event observed

Counting experiment with 2.4σ global significance

Signal MC



Signal shape not taken into account for the significance



The region enclosed by the contour shown is excluded

	$N_{exp} \pm \delta N_{exp}$	N_{obs}	$p\ (N \geq N_{obs})$	$p\ (L \leq L_{obs})$
Outside CR	26.3 ± 3.4	28	0.41	0.74
CR1	0.29 ± 0.04	1	0.25	0.25
CR2	0.58 ± 0.07	1	0.44	0.44
CR3	1.70 ± 0.22	2	0.50	0.68
CR1+2+3	2.57 ± 0.33	4	0.26	0.24
CR	0.17 ± 0.02	0	1.0	1.0

Probability to observe 1 or more events in the SR is 1.59%

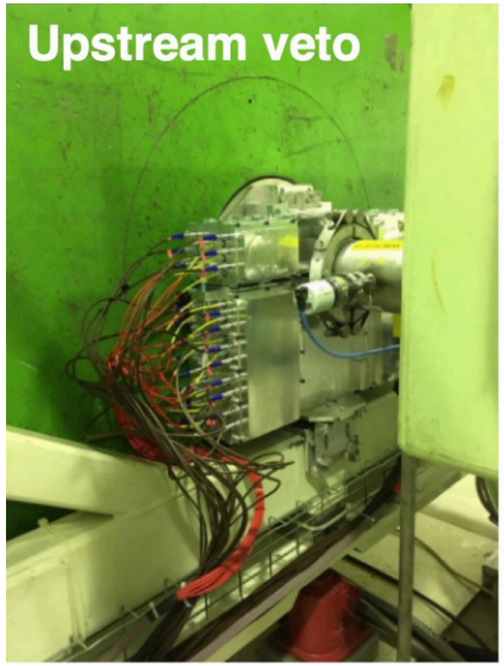
- **Expected background (SR) = 0.016±0.002**
- **Observed: 1**

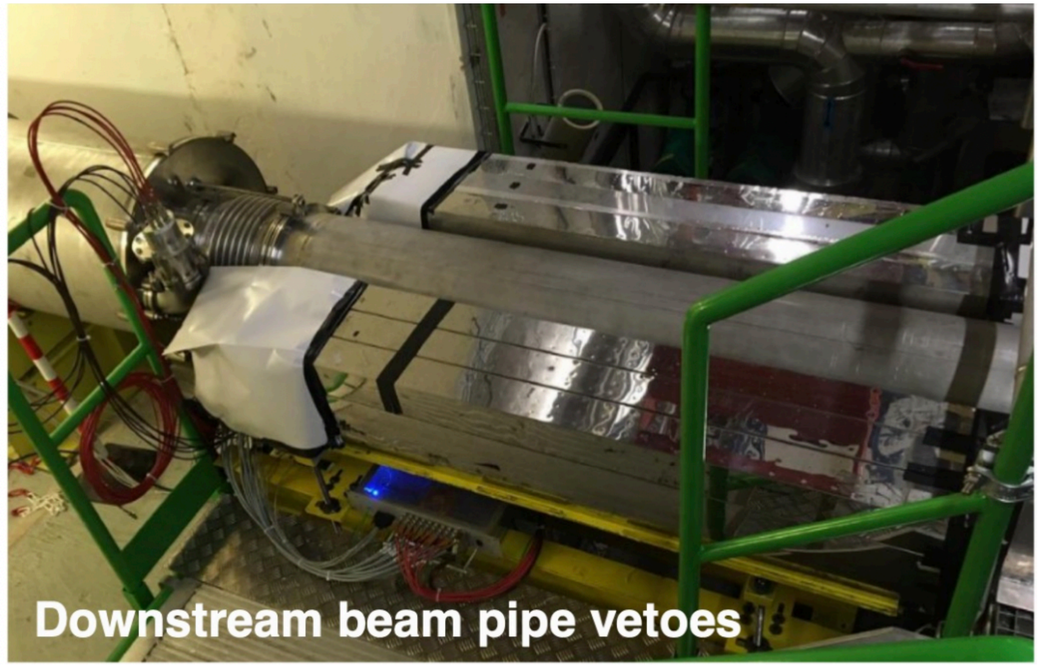
Searches for decays of exotic particles to $e^+e^-, \gamma\gamma, \pi^+\pi^-\gamma$ final states ongoing with 2021 data.

NA62 Run2 & The Future

- NA62 technique is firmly established.
- Run2 - target $\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu})$ measurement: $\mathcal{O}(10)\,\%$ **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.
- Beyond LS3: High Intensity Kaon Experiment (HIKE) program under development at CERN SPS. [arXiv:2204.13394]

New detectors installed in 2021 for NA62 Run2:



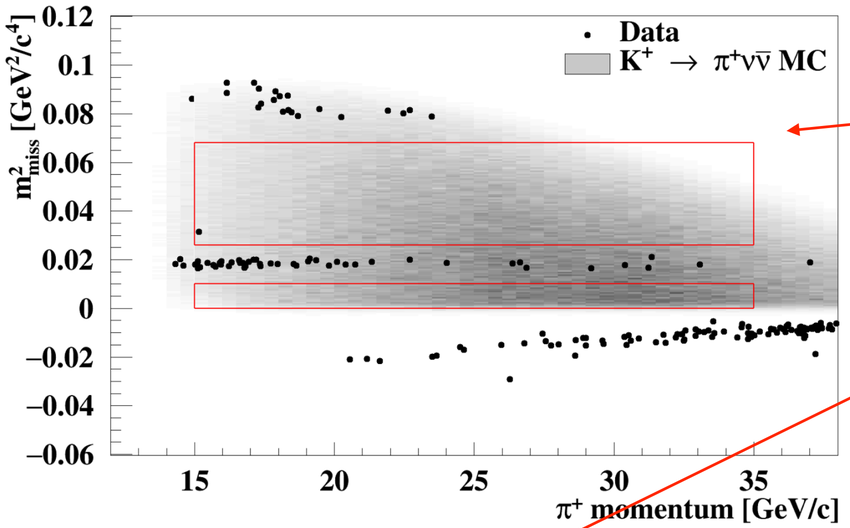


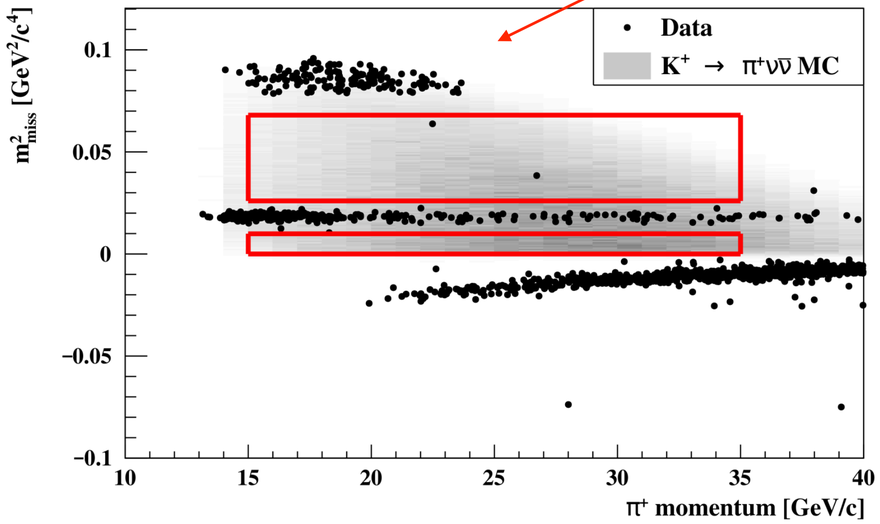
Summary & Outlook

- Studies of rare kaon decays ("golden modes" $K \to \pi\nu\bar{\nu}$) are unique tests of heavy new physics up to $\mathcal{O}(100\text{TeV})$ mass scale, and for light hidden sector.
- Presented recent results from NA62:
  - $K^+ \to \pi^+\nu\bar{\nu}$, $K^+ \to \pi^+ X$
  - LNV/LFV searches: $K^+ \to \mu^-\nu e^+e^+$, $K^+ \to \pi^-(\pi^0)e^+e^+$, $K^+ \to \pi^\mp\mu^\pm e^+$, $\pi^0 \to \mu^- e^+$
  - Precision measurements: $K^+ \to \pi^+\mu^+\mu^-$, $K^+ \to \pi^0 e^+\nu\gamma$
  - Exotics: HNLs $K^+ \to \ell^+ N$, Beam Dump - Dark Photon $A' \to \mu^+\mu^-$.
- NA62 Run2 is ongoing (2021 — CERN LS3).
  - Higher intensity & experimental setup improvements ⇒ towards $\mathcal{O}(10)\,\%$ precision measurement of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$.
- Future kaon program at CERN SPS (HIKE) is taking shape…

Supplemental

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

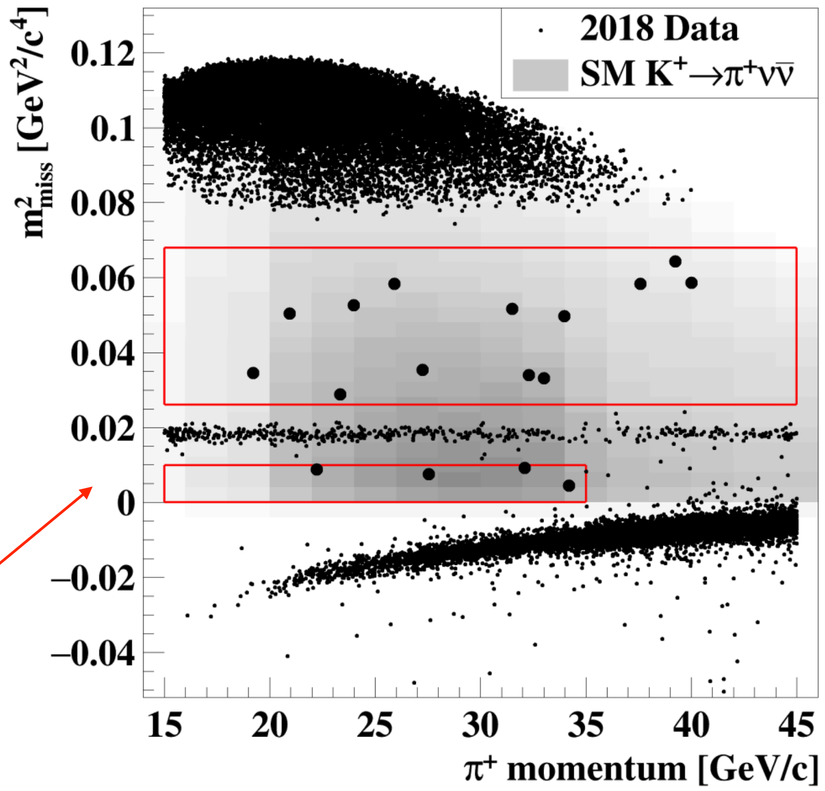
$n_{bg} = 1.46 \pm 0.33$, $n^{SM}_{\pi\nu\bar{\nu}} = 2.16 \pm 0.29$

$n_{obs} = 2$

2018 data [JHEP 06 (2021) 093]

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

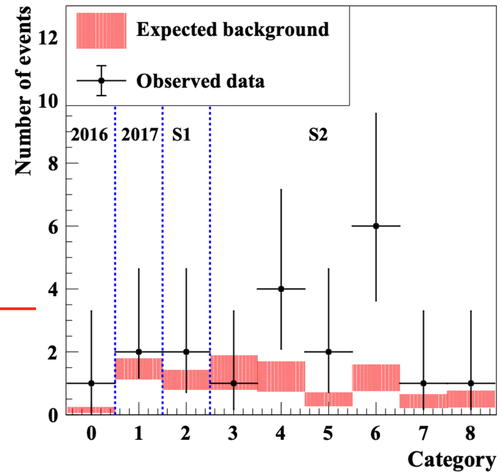
$n_{obs} = 17$



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:



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