Physics Beyond the Standard Model with the NA62 experiment at CERN

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on behalf of the NA62 collaboration

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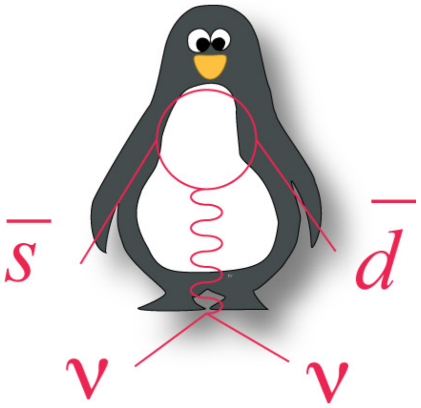
Outline

- The NA62 experiment
- Experimental setup
- NA62 main goal: $K^+ \rightarrow \pi^+ \nu\bar{\nu}$
- Hidden sector
  - $K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-$
  - $A' \rightarrow l^+ l^-$
- LFV
  - $K^+ \rightarrow \mu^- \nu e^+ e^+$
- Conclusions



NA62 experiment at CERN

NA62 is located in the North Area at CERN:

- ✓ Fixed target experiment with kaon decay-in-flight
- ✓ Main goal: **BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$) with 10% precision** [PLB791 (2019) 156-166, JHEP11 (2020), JHEP06 (2021)]
- ✓ Primary beam: **400 GeV/c protons** from SPS
- ✓ Secondary baem: **75 GeV/c** positive charged particle **(6% K^+)**

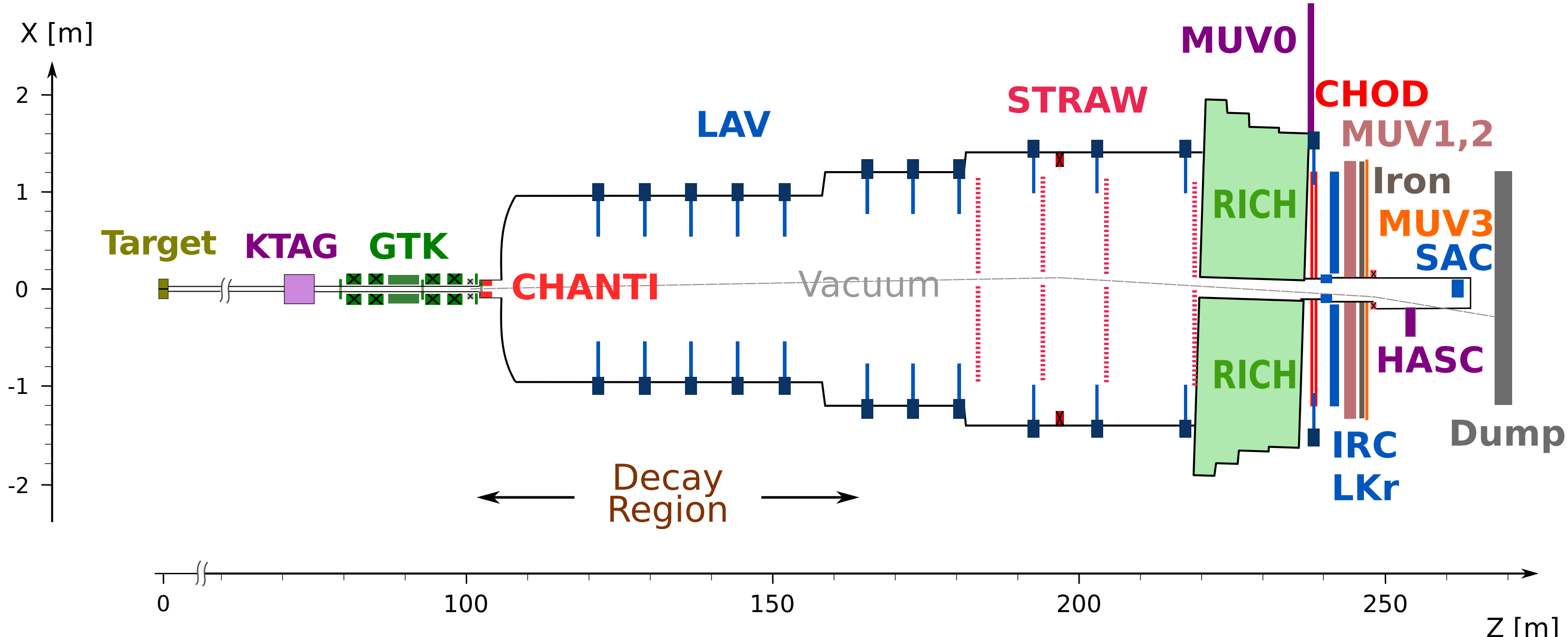
NA62 collaboration: ~ 200 participants from ~ 30 institution:

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

Timeline

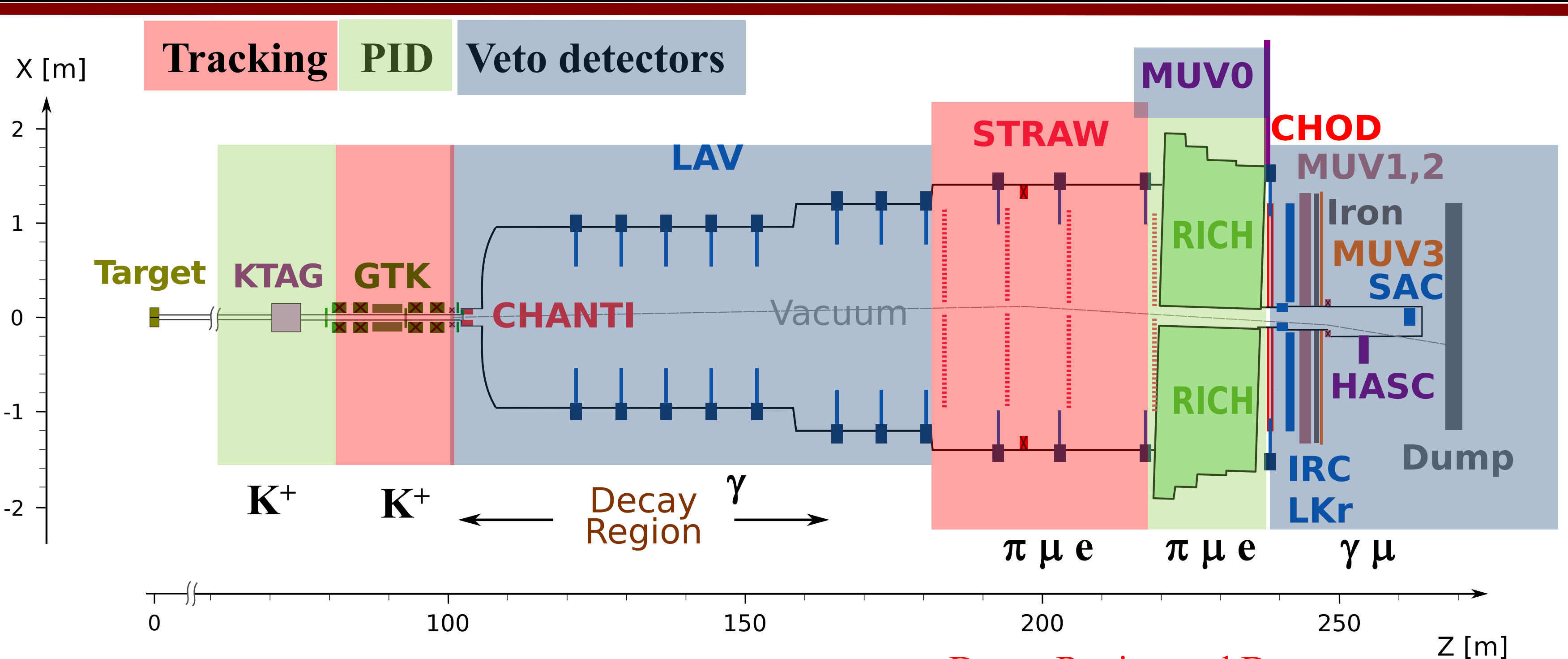
2009 – 2014	2014 – 2015	2016 – 2018	2021 – 2023
Construction and installation	Technical runs	Physics runs	Physics runs

NA62 beam and detector



SPS Beam	Secondary positive beam	Decay Region and Detectors
400 GeV/c protons 3.5s spill	75 GeV/c momentum, 1% bite 100 μrad divergence (RMS) 60x30 mm^2 transverse size K^+(6%)/π^+(70%)/p(24%) 750 MHz at GTK3	Fiducial region 60 m K^+ decay rate ~ 5 MHz Vacuum $\mathcal{O}$ 10^{-6} mbar Si pixel beam tracker + Straw tracker LKr Calorimeter from NA48 Cerenkov counter for K id RICH for π/μ id

NA62 beam and detector



SPS Beam

400 GeV/c protons

3.5s spill

Secondary positive beam

75 GeV/c momentum, 1% bite

100 μrad divergence (RMS)

60x30 mm^2 transverse size

K^+(6%)/π^+(70%)/p(24%)

750 MHz at GTK3

Decay Region and Detectors

Fiducial region 60 m

K^+ decay rate ~ 5 MHz

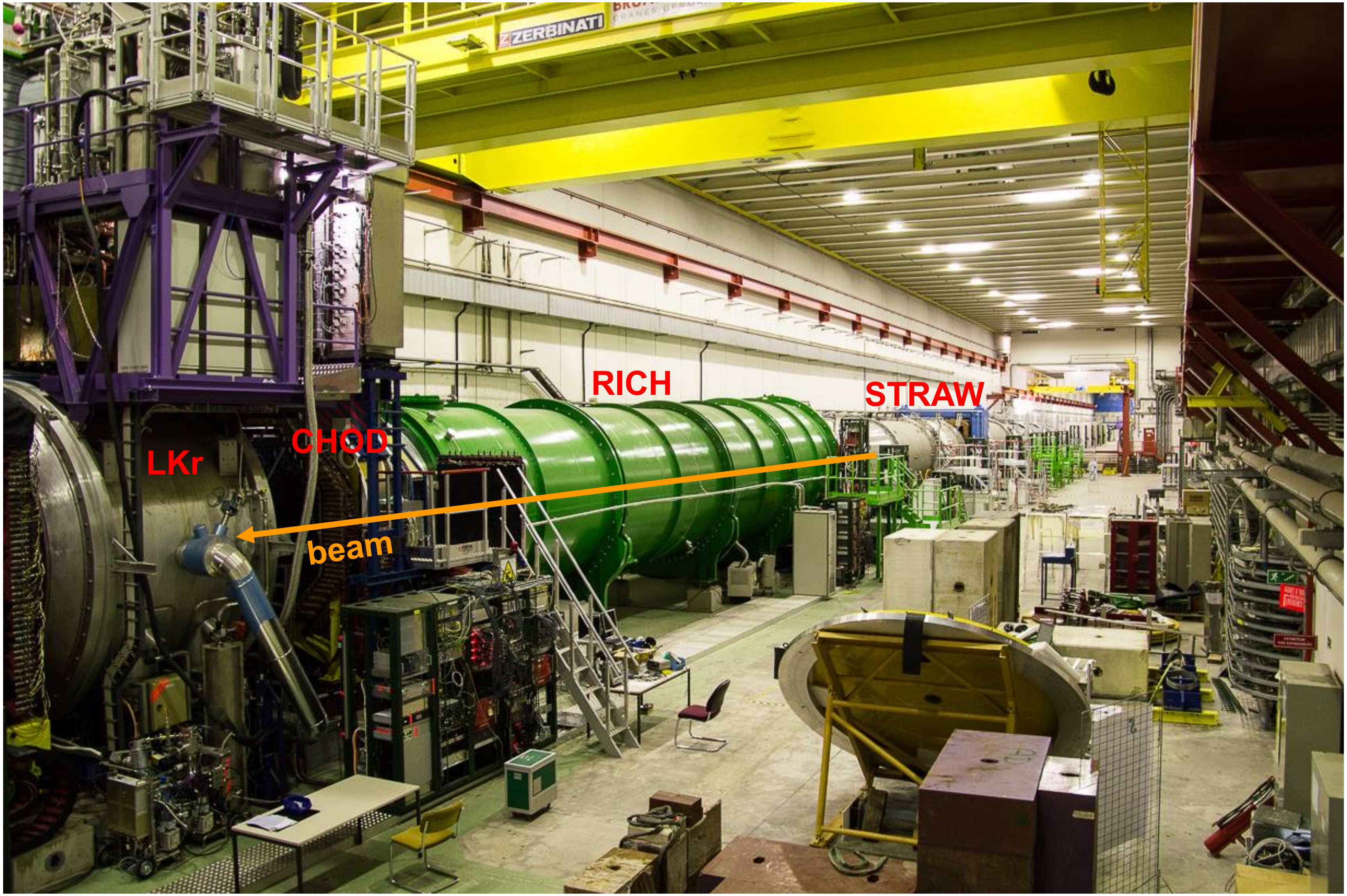
Vacuum $\mathcal{O}$ 10^{-6} mbar

Si pixel beam tracker + Straw tracker

LKr Calorimeter from NA48

Cerenkov counter for K id RICH for π/μ id

NA62 Detector



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

$K^+ \to \pi^+ \nu\bar{\nu}$ Beyond SM

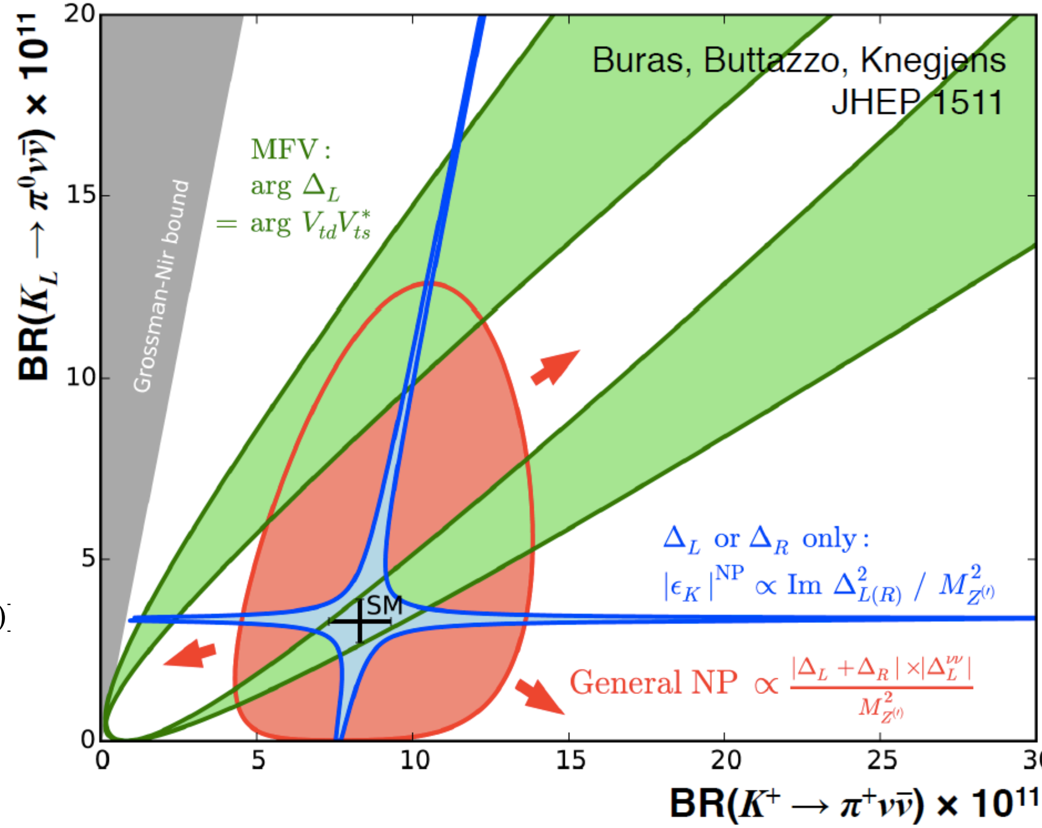
Precise SM predictions: [Buras. et. al., JHEP11(2015)033]

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

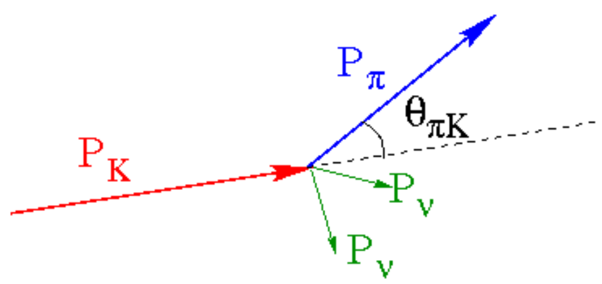
$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$

$BR(K^+ \to \pi^+ \nu\bar{\nu})$ and **$BR(K_L \to \pi^0 \nu\bar{\nu})$** can **discriminate among different NP scenarios**

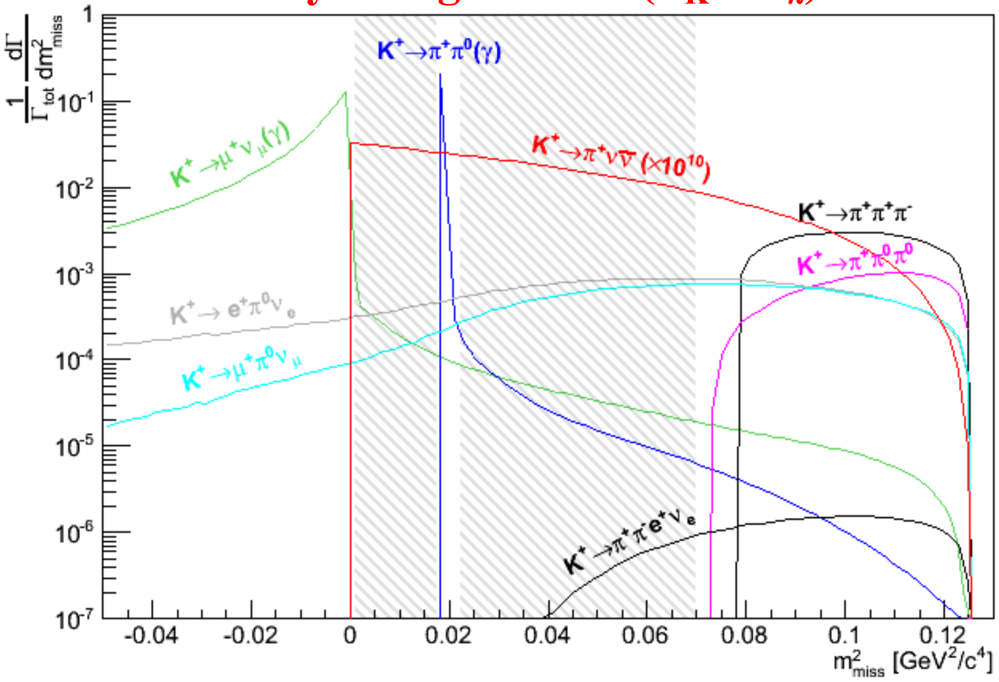
- ✓ **Models with CKM-like flavour structure**
  [Buras , Buttazzo, knegjens, JHEP11(2015) 166]
- ✓ **Custodial Randall-Sundrum**
  [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- ✓ **MSSM analyses**
  [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],
  [Isidori et al. JHEP 0608 (2006) 064]
- ✓ **LFU violation models**
  [Isidori et al., Eur. Phys. J. C (2017) 77: 618]
- ✓ **Leptoquarks**
  [S. Fajfer, N. Kosnik, L. Vale Silva, arXiv: 1802.00786v1 (2018)]
- ✓ **Simplified Z, Z' models**
  [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- ✓ **Littlest Higgs with T-parity**
  [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]



Experimental Strategy



K decay in flight: $m^2 = (P_K - P_\pi)^2$



Performances

- Kinematic suppression $O(10^4)$
- Muon suppression $O(10^7)$
- π^0 suppression $O(10^7)$
- Timing between sub-detectors O(100 ps)

Selection

- K^+, π^+ track reconstruction
- Track matching, vertex reconstruction
- π^+ identification, μ^+ rejection
- Multi-track rejection, photon veto
- Kinematics (m^2_{miss}, p_π)

Analysis

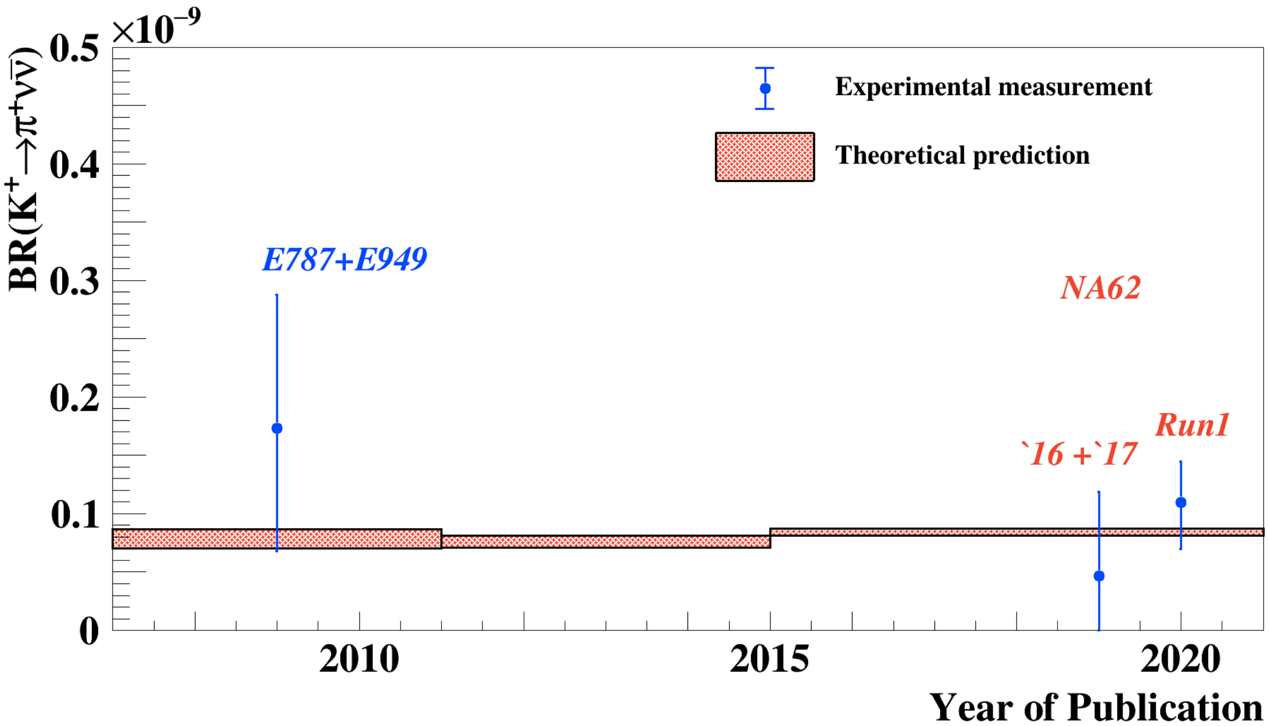
- Momentum range: $15 < p_\pi < 45$ GeV/c
- Signal regions blinded during the analysis
- Data-driven background estimate
- 7 categories depending on hardware and momentum

RUN1 summary

$$N_{\pi\nu\nu}^{exp} \approx N_{\pi\pi}\epsilon_{trigger}\epsilon_{RV}\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\frac{Br(\pi\nu\nu)}{Br(\pi\pi)} \Longrightarrow \text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}}$$

	2016 data	2017 data	2018 S1 data	2018 S2 data
$SES \times 10^{10}$	3.15 ± 0.24	0.39 ± 0.02	0.54 ± 0.04	0.14 ± 0.01
$A_{\pi\nu\nu} \times 10^{2}$	4 ± 0.4	3 ± 0.3	4 ± 0.4	6.4 ± 0.6
Expected SM signal	0.27 ± 0.04	2.16 ± 0.13	1.56 ± 0.10	6.02 ± 0.39
Expected background	0.15 ± 0.090	1.46 ± 0.30	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$
Observed events	1	2	2	15
	[PLB 791 (2019) 156-166]	[JHEP 11 (2020) 042]	[JHEP 06 (2021) 093]	

RUN1 summary



Single Event Sensitivity: $(0.839 \pm 0.053_{syst}) \times 10^{-11}$

Expected SM signal events: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

Expected background events: $7.03^{+1.05}_{-0.82}$

Observed events: 20

Significance: 3.4σ

$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.5}\,_{stat} \pm 0.9\,_{syst}) \cdot 10^{-11}$ (3.4 σ significance)

$$K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-$$

$K^+ \to \pi^+$ X X motivation

Searches for production of dark-sector in meson decays have been focused on the production of a single particle, which is either invisible or decays into lepton or photon pairs (not on the pair-production of dark states)

Two-fold interest in the context of dark sector:

- A short-lived QCD axion:
  - plausible explanation for the "17 MeV anomaly" in the mass spectra of the e^+e^- pairs produced in the de-excitation of 8Be, 4He and 12C nuclei
    [Phys. Rev. D105 (2022) 015017]
  - assuming $m_a = 17$ MeV/c^2, $B(K^+ \to \pi^+ aa) > 2 \times 10^{-8}$ is predicted
    [Phys. Rev. D 103(2021)055018), (Eur. Phys. J. C83 (2023) 230]

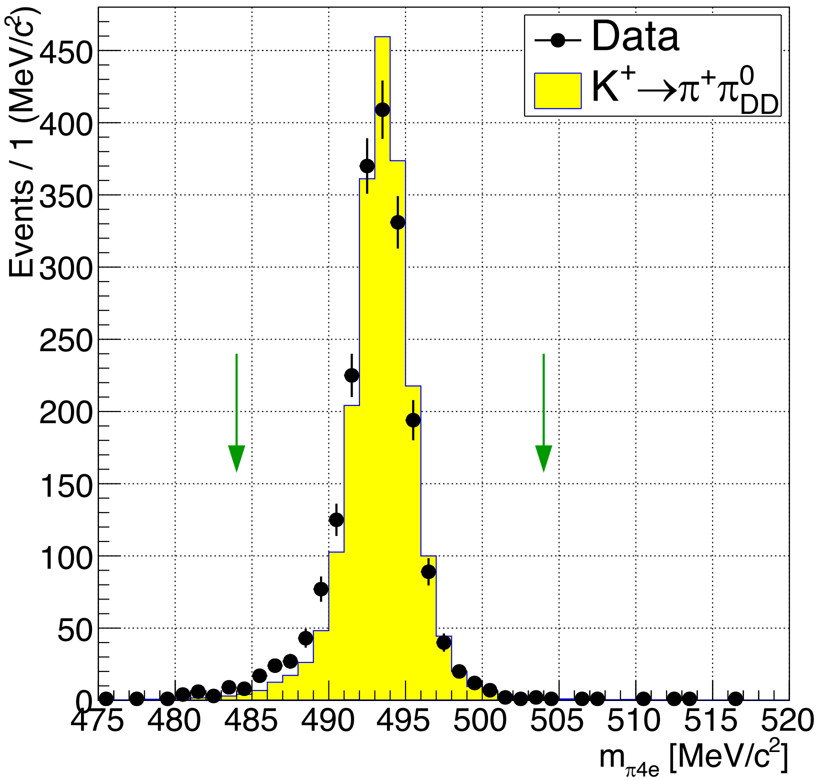
- Dark scalar S, and a dark photon A′ with masses satisfying the condition $m_S \geq 2m_{A'}$ and $K^+ \to \pi^+ S$, $S \to A'A'$, $A' \to e^+e^-$

[Phys. Rev. D105 (2022) 015017]

$K^+ \to \pi^+ X X$ selection (1)

The data sample analysed is obtained from 8.3 x 10^5 SPS spills recorded in 2017–2018; $K^+ \to \pi^+ e^+ e^- e^+ e^-$ ($K_{\pi 4e}$) rate is normalised to decay $K^+ \to \pi^+ \pi^0_{DD}$ ($K_{2\pi DD}$) which allows a first order cancellation of detector and trigger inefficiencies.

- **STRAW information only, to avoid loss in signal acceptance:**
  - vertices are reconstructed by extrapolating STRAW tracks backward
  - 5 tracks,
  - ptrack in the range 5–45 GeV/c.
  - each pair of tracks should be separated by at least 15 mm in each STRAW chamber plane, to suppress photon conversions and fake tracks
- **Invariant mass $m_{\pi 4e}$ used to distinguish between signal and bkg**
  - Three assignments of the π+ mass to one of the positively charged tracks are considered. The mass assignment corresponding to the minimal value of $|m_{\pi 4e} - m_K|^2$ is chosen



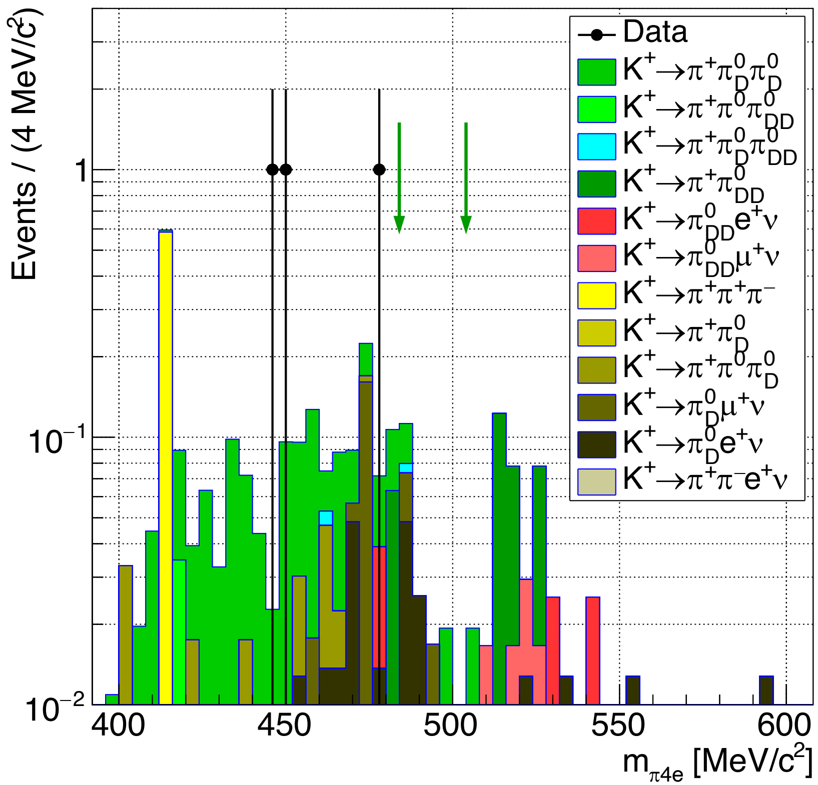
$K^+ \to \pi^+ X X$ selection (2)

The data sample analyzed is obtained from 8.3 x 10^5 SPS spills recorded in 2017–2018. $K^+ \to \pi^+ e^+ e^- e^+ e^-$ ($K_{\pi 4e}$) rate is normalised to decay $K^+ \to \pi^+ \pi^0_{DD}$ ($K_{2\pi DD}$) which allows a first order cancellation of detector and trigger inefficiencies.

- **Discriminating kinematic variable and blind analysis strategy**
  - Signal region kept masked until the completion and validation of the background evaluation

- **For $K_{\pi 4e}$**
  - $|m_{4e} - m_{\pi 0}|^2 > 10 MeV/c^2$
  - consistency of the two reconstructed e^+e^- mass for each X mass hypothesis $|m_{ee} - m_X| < 0.02 m_X$
  - $p_\pi > 10$ GeV/c.

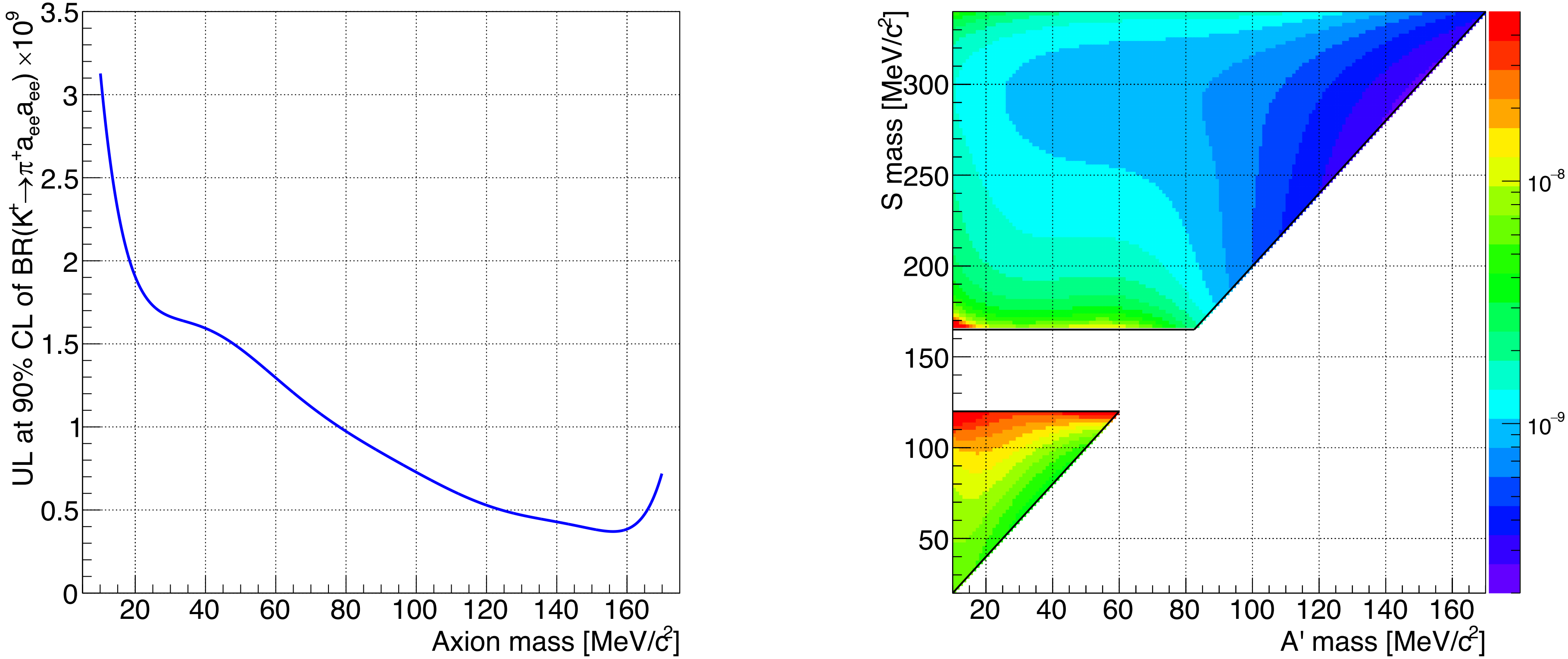
- **For $K_{2\pi DD}$ $|m_{4e} - m_{\pi 0}|^2 < 10 MeV/c^2$**



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

Uniform phase space assumed for K+ decays, isotropic decays of dark states

No data observed in the Signal Region



Upper limits at 90% CL at the level of 10^{-9} for the branching ratios of two prompt decay chains involving pair-production of hidden-sector mediators.

The QCD axion is excluded as a possible explanation of the 17 MeV anomaly

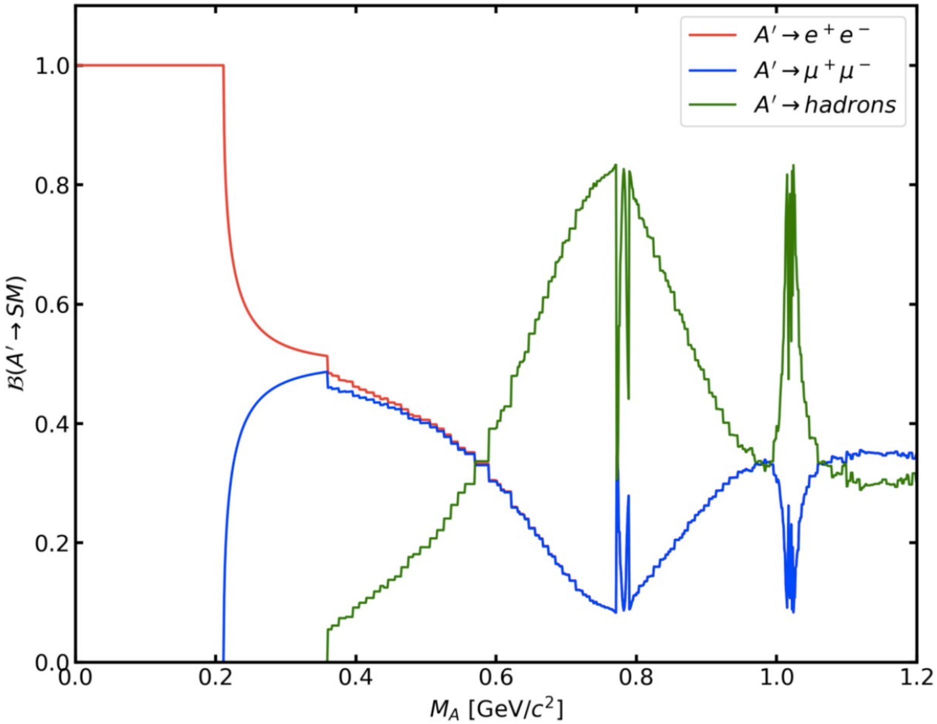
[Physics Letters B 846 (2023) 138193]

$$A' \rightarrow l^+ l^-$$

$A' \to l^+ l^-$ motivation

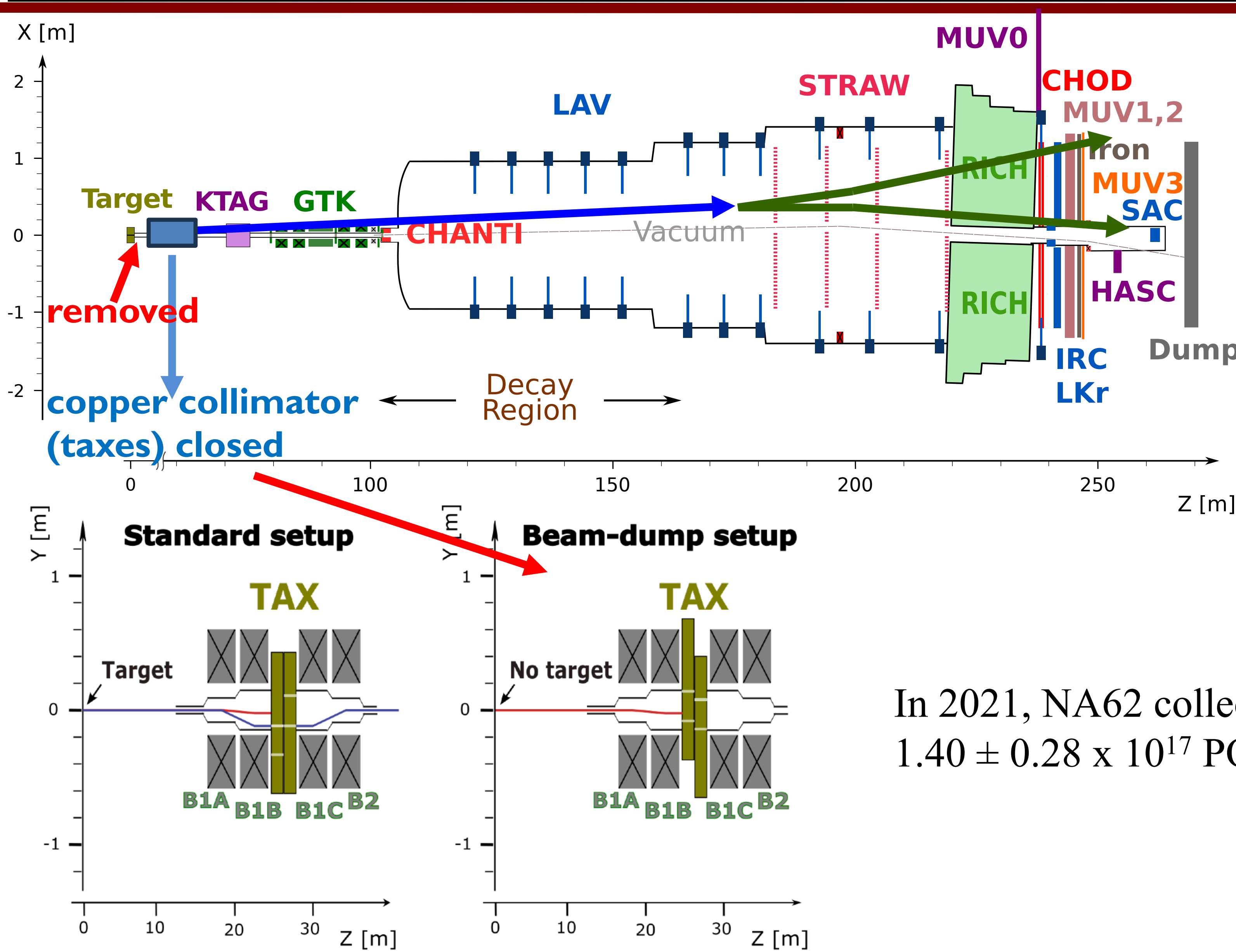
$$\mathcal{L} \propto -\epsilon \frac{1}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$

New U(1) gauge-simmetry
A' vector mediator field
interaction between A_μ'and the SM hypercharge $B_{\mu\nu}$ via kinetic-mixing



In the mass range < 700 MeV/c^2, DP decay width dominated by $l^+ l^-$ final states

NA62 beam dump configuration



In 2021, NA62 collected
$1.40 \pm 0.28 \times 10^{17}$ POT.

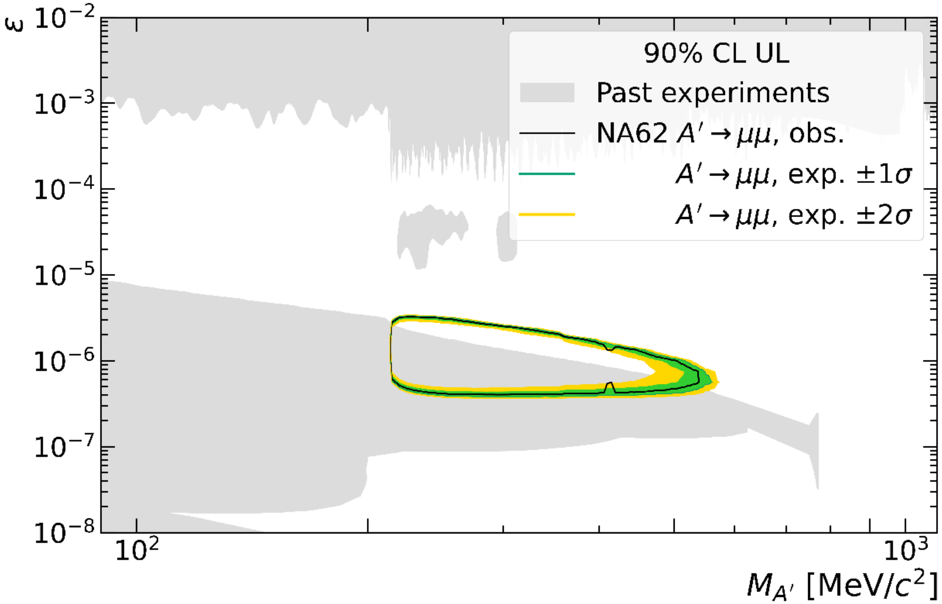
A'→l^+l^- selection

Signal selection

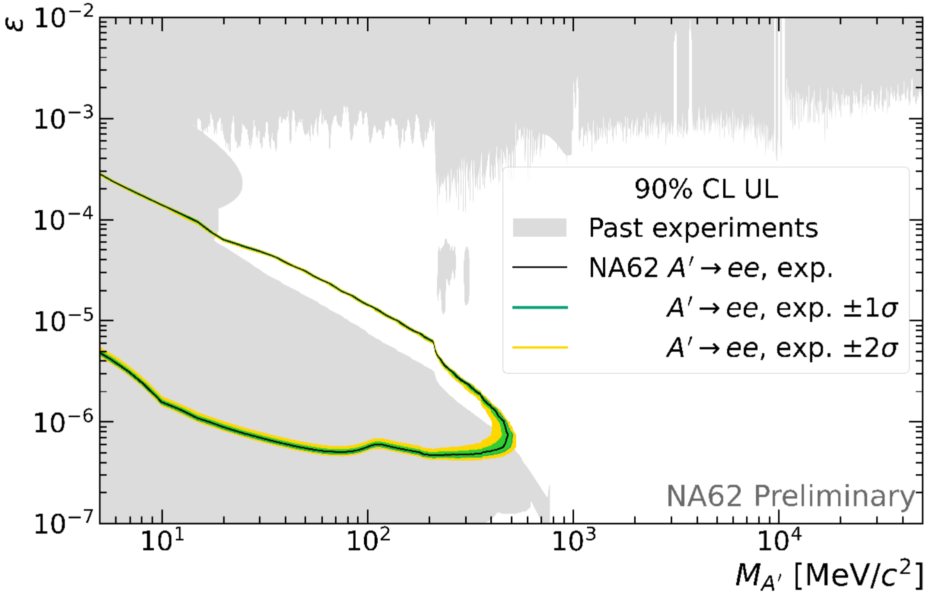
- l^+l^- vertex reconstructed within the NA62 decay region and pointing back to the proton beam interaction point at the TAXes
- CR and SR masked until the analysis strategy is frozen
- Bkg estimated selecting single tracks in a data sample orthogonal to the one used for the analysis
- $A' \rightarrow \mu^+\mu^-$ result also interpreted in terms of the emission of axion-like particles in a model-independent approach, improving on previous limits for masses below 280 MeV/c^2

A'→l^+l^- results

90% CL upper limits exploring new regions of the parameter space ϵ, $M_{A'}$



A'→$\mu^+\mu^-$



A'→e^+e^-

1 event observed in the SR
corresponing to 2.4σ global significance
[JHEP 09 (2023) 035]

0 event observed in both CR and SR

$$K^+ \rightarrow \mu^- \, \nu \, e^+ e^+$$

Search for LFV and LNV @ NA62

A large dataset of K^+ decays to lepton pairs in 2016–2018, using dedicated trigger.

- UL of the branching ratios of the LNV decays
  - $K^+ \to \pi^-(\pi^0)e^+e^+$ [Phys. Lett. B 830 (2022) 137172]
  - $K^+ \to \pi^- \mu^+\mu^+$ [Phys. Lett. B 797 (2019)134794]
  - $K^+ \to \pi^- \mu^+e^+$ [Phys. Rev. Lett. 127 (2021) 131802]

- UL of the branching ratios of the LFV decays
  - $K^+ \to \pi^+\mu^-e^+$ [Phys. Rev. Lett. 127 (2021) 131802]
  - $\pi^0 \to \mu^- e^+$ [Phys. Rev. Lett. 127 (2021) 131802]

$K^+ \to \mu^- \nu e^+e^+$ decay is forbidden in the SM by either lepton number (LN) or lepton flavour (LF) conservation, depending on the flavour of the emitted neutrino.

Current UL of the decay branching fraction is 2.1×10^{-8} at 90% CL
[Phys. Lett. B 62 (1976) 485. Prog. Theor. Exp. Phys. 2022 (2022) 083C01]

$K^+ \to \mu^- \nu e^+ e^+$ selection

$K^+ \to \mu^- \nu e^+ e^+$ rate ($K_{\mu\nu ee}$) is normalised to decay $K^+ \to \pi^+ e^+ e^-$ ($K_{\pi ee}$) which allows a first order cancellation of detector and trigger inefficiencies.

Common selection

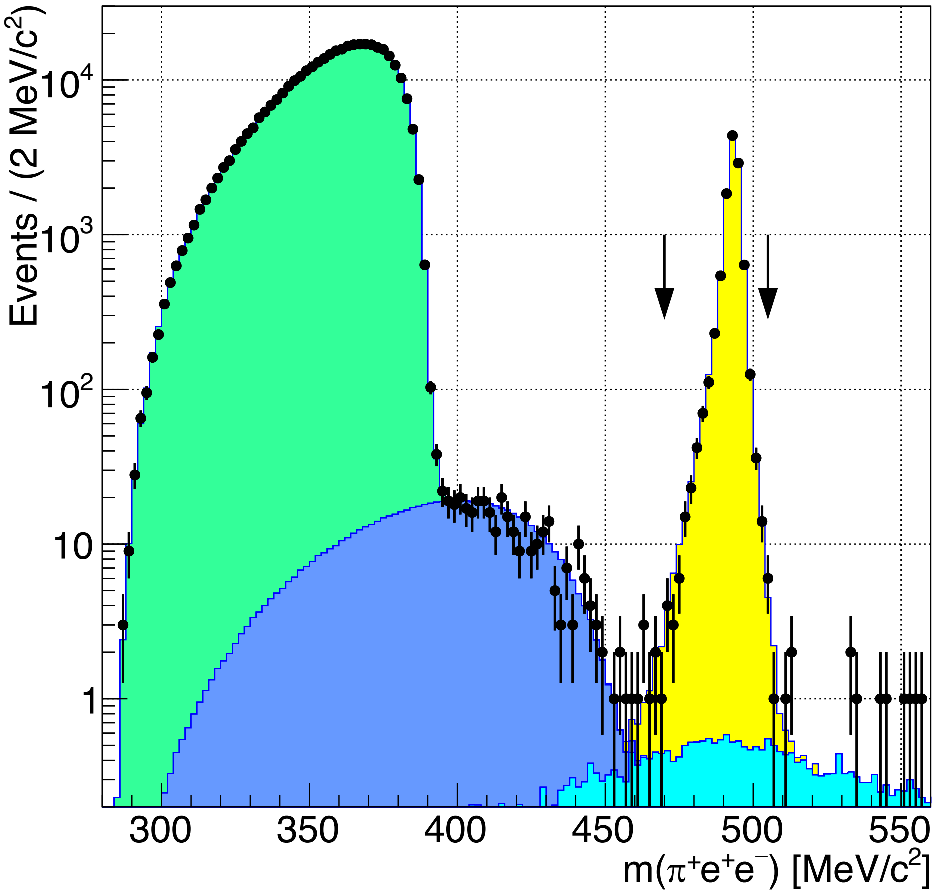
- **Three-track vertices extrapolating STRAW tracks into the FV with $6 < P < 44$ GeV/c**

- **PID is based on the ratio E/p**
  - π is identified by $E/p < 0.85$,
  - μ is identified by $E/p < 0.2$
  - e is identified by $0.9 < E/p < 1.1$

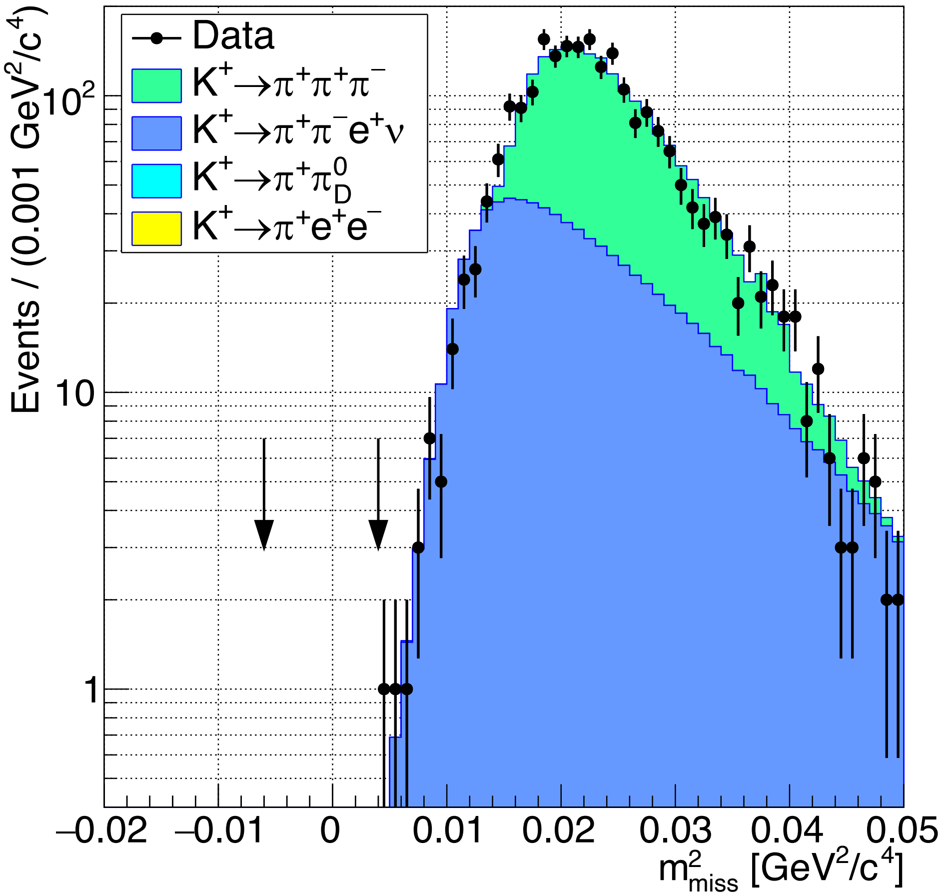
- **For $K_{\pi ee}$**
  - $|p_{vtx} - p_{beam}| < 2$ GeV/c,
  - $470 < m_{\pi ee} < 505$ MeV/c^2,

- **For $K_{\mu\nu ee}$**
  - $p_{beam} - p_{vtx} > 10$ GeV/c,
  - $-0.006\ \mathrm{GeV}^2/c^4 < m^2_{miss} < 0.004\ \mathrm{GeV}^2/c^4$

$K^+ \to \mu^- \nu e^+ e^+$ result



$K^+ \to \pi^+ e^+ e^-$ invariant mass



$K^+ \to \mu^- \nu e^+ e^+$ missing mass

$Br(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11}$ at 90% CL

[Physics Letters B 838 (2023) 137679]

Conclusions

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

- ✓ Run1 measurement compatible with the SM within one standard deviation
- ✓ The most precise measurement of the BR obtained so far

[JHEP 06 (2021) 093]

$\mathbf{K^+ \rightarrow \pi^+ aa,\ a \rightarrow e^+e^-}$ and $\mathbf{K^+ \rightarrow \pi^+ S,\ S \rightarrow A'A',\ A' \rightarrow e^+e^-}$ UL have been set

[Physics Letters B 846 (2023) 138193]

$\mathbf{A' \rightarrow \ell^+\ell^-}$ in beam-dump mode UL have been set, exploring new regions of the parameter space

[JHEP 09 (2023) 035]

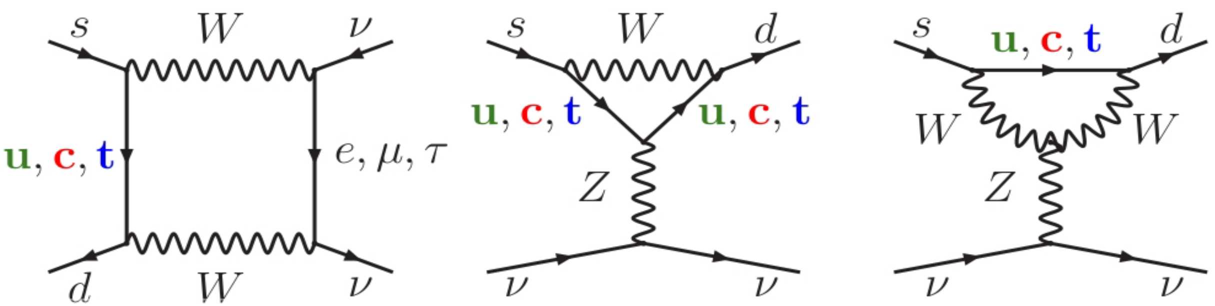
$\mathbf{K^+ \rightarrow \mu^- \nu e^+ e^+}$ UL have been set

[Physics Letters B 838 (2023) 137679]

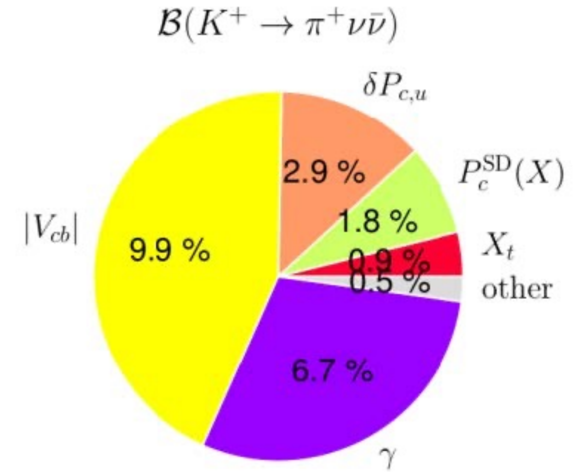
NA62 will take data until LS3. Stay tuned!!!!!

SPARE

$K^+ \to \pi^+ \nu\bar{\nu}$ decay in the SM



Theoretical error budget
[Buras. et. al., JHEP11(2015)033](#)



- FCNC loop processes: s→d coupling and highest CKM suppression
- Theoretically clean: Short distance contribution
- Hadronic matrix element measured with K_{l3} decays
- SM predictions: [Buras. et. al., JHEP11(2015)033]

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \left(\frac{|V_{cb}|}{0.0407} \right)^{2.8} \left(\frac{\gamma}{73.2^\circ} \right)^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$$

- Experimental result collecting 7 events: [Phys. Rev. D 79, 092004 (2009)]

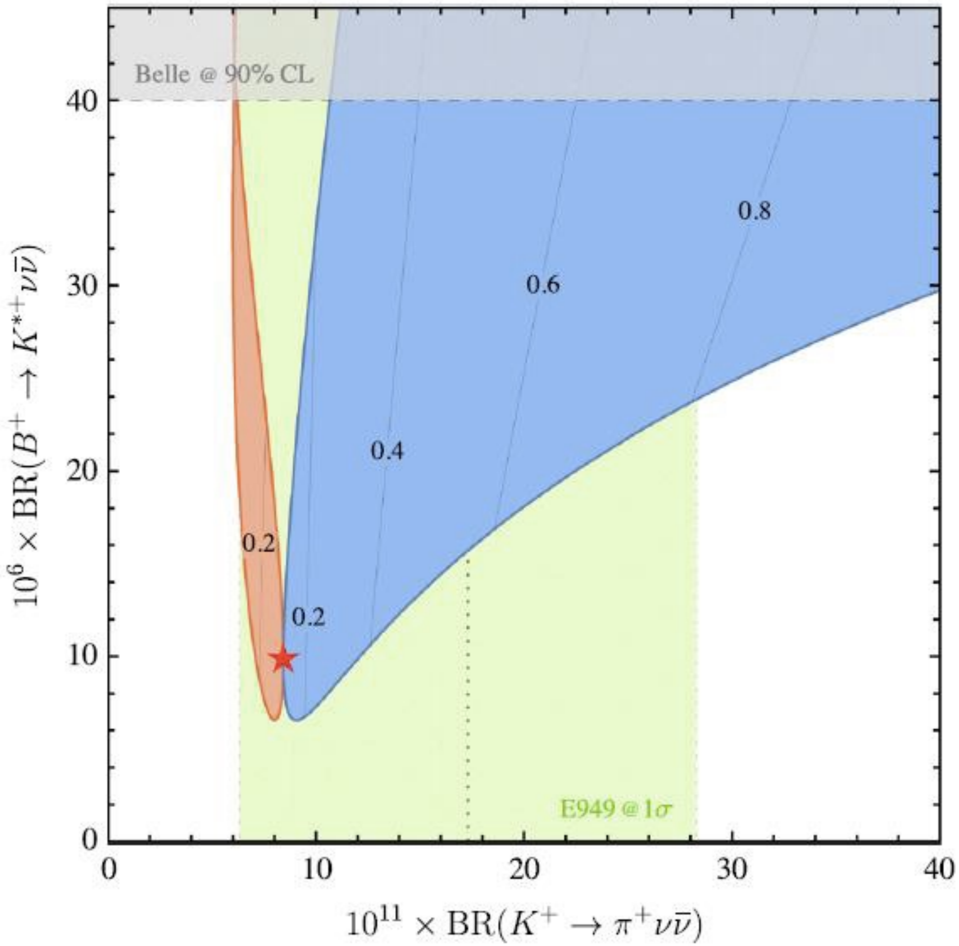
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

(BNL "kaon decays at rest)

$K^+ \to \pi^+\nu\bar{\nu}$ and the LFU violation

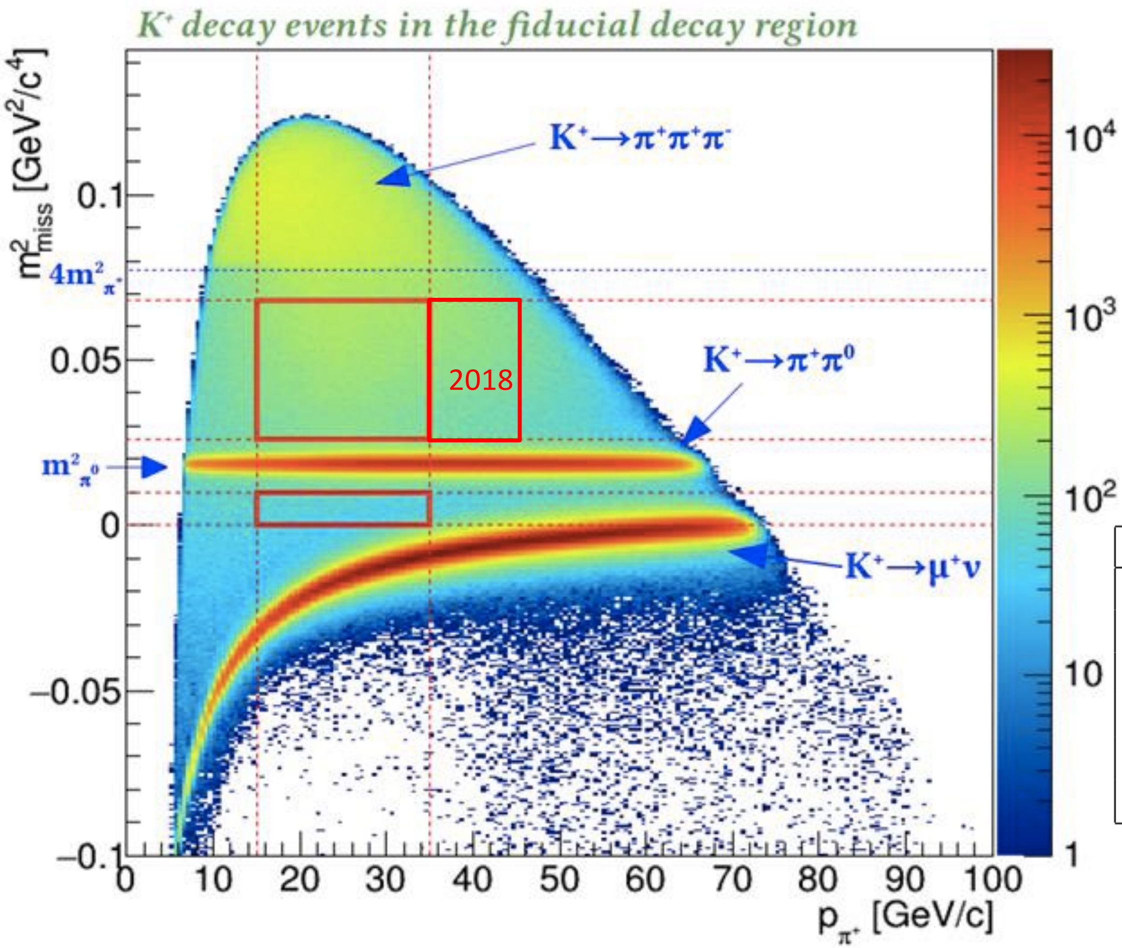
Measurement of $\mathbf{K^+ \to \pi^+\nu\bar{\nu}}$ together with $\mathbf{B^+ \to K^{*+}\nu\bar{\nu}}$ can probe the **Lepton-Flavour Universality**

- ✓ An interactions responsible for LFU violations can couple mainly to the third generation of left-handed fermions;
- ✓ $\mathbf{K^+ \to \pi^+\nu\bar{\nu}}$ is the only kaon decays with third-generation leptons (the τ neutrinos) in the final state;
- ✓ A deviations from the Standard Model predictions in $\mathbf{K^+ \to \pi^+\nu\bar{\nu}}$ branching ratios should be closely correlated to similar effects in $\mathbf{B^+ \to K^{*+}\nu\bar{\nu}}$.



Signal Selection

- Two signal regions kept blinded
- In order to evaluate the background from K decays, the tails of the distribution are extrapolated into the signal regions.
- The control regions are kept blinded too, to validate the procedure.



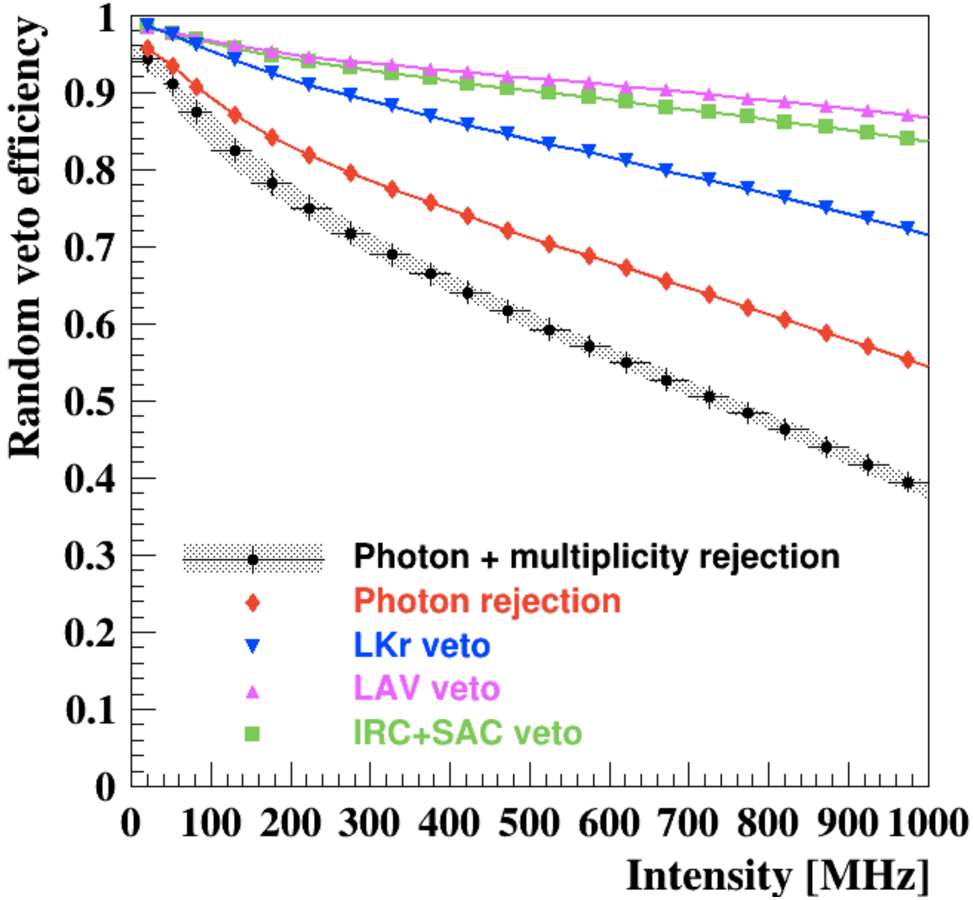
Selection criteria

- single track decay topology
- π^+ identification
- photon rejection
- multi-track rejection

Decay mode	BR	Main rejection tools
$K^+ \to \mu^+\nu(\gamma)$	63%	μ–ID + kinematics
$K^+ \to \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	multi + kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+\nu_e$	5%	e–ID + γ-veto
$K^+ \to \pi^0\mu^+\nu_\mu$	3%	μ–ID + γ-veto

Single Event Sensitivity (SES)

$$N_{\pi\nu\nu}^{exp} \approx N_{\pi\pi}\epsilon_{trigger}\epsilon_{RV}\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\frac{Br(\pi\nu\nu)}{Br(\pi\pi)} \Rightarrow \text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}}$$



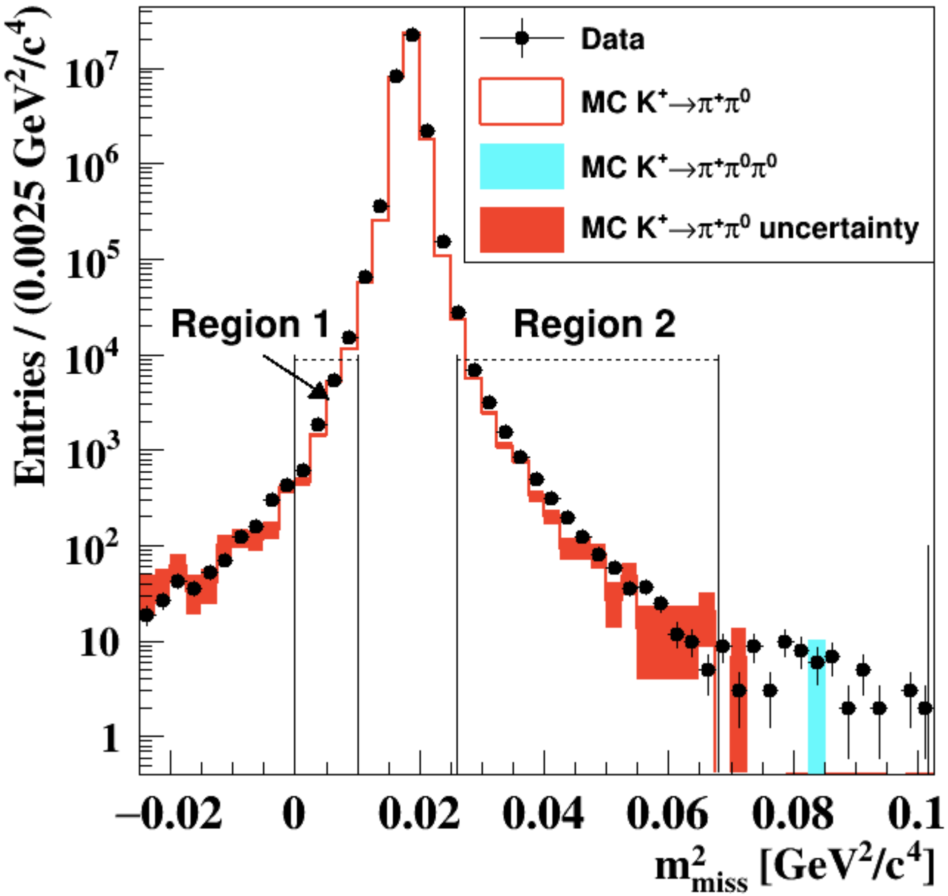
	Subset S1	Subset S2
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^{2}$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^{2}$	3.95 ± 0.40	6.37 ± 0.64
$\epsilon_{\text{trig}}^{\text{PNN}}$	0.89 ± 0.05	0.89 ± 0.05
ϵ_{RV}	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
$N_{\pi\nu\bar{\nu}}^{\text{exp}}$	$1.56 \pm 0.10 \pm 0.19_{\text{ext}}$	$6.02 \pm 0.39 \pm 0.72_{\text{ext}}$

- ✓ $K^+ \rightarrow \pi^+\pi^0$ normalization signal
- ✓ Cancellation of systematic effects
- ✓ Random Veto: efficiency loss due to beam activity

$SES_{Run1} = (0.839 \pm 0.054) \times 10^{-11}$

Background from Kaon Decay

Control $\pi^+ \pi^0$ data to study m^2_{miss} distribution



Expected $K^+ \to \pi^+\pi^0$ events in signal region

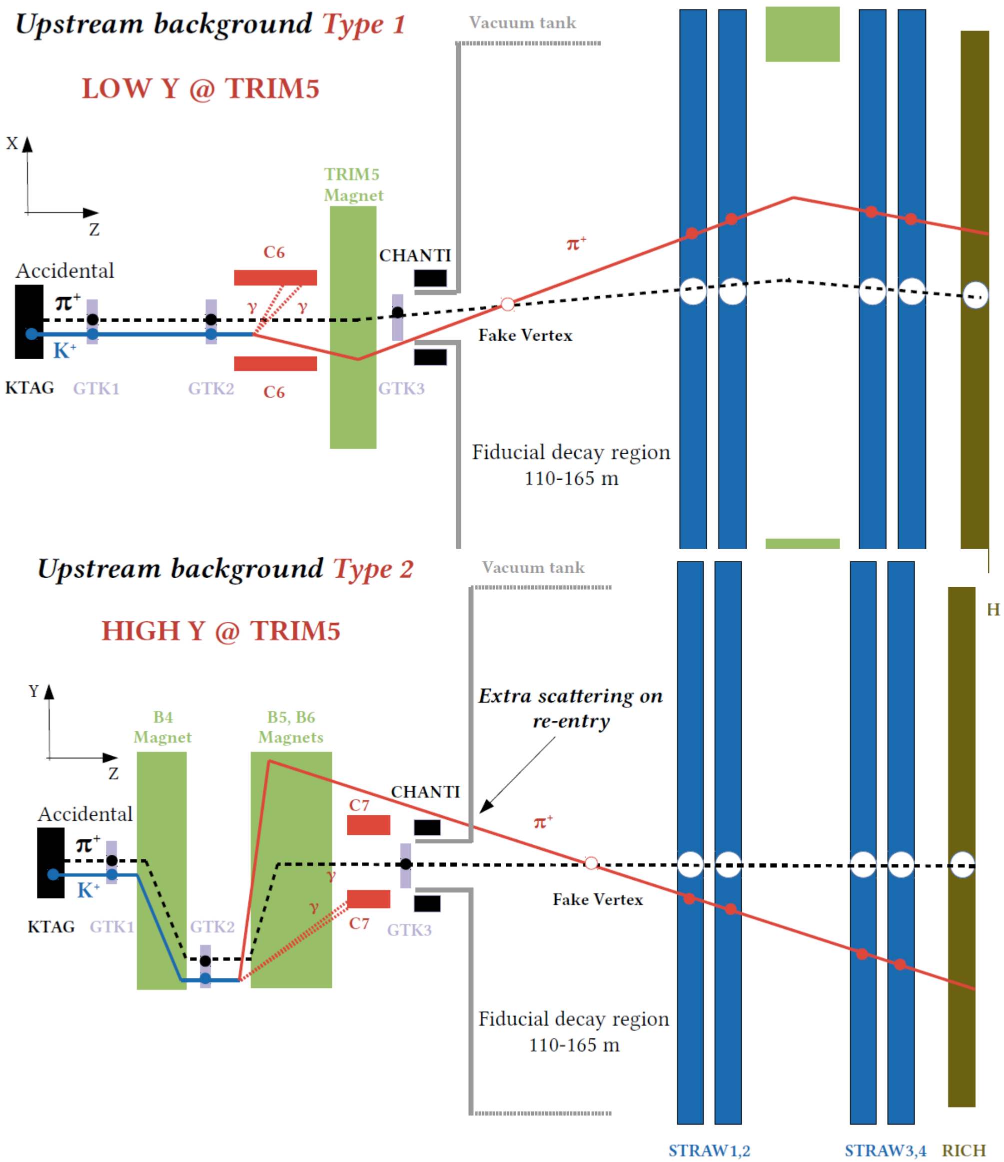
$$N^{exp}_{\pi\pi}(SR) = N_{\pi\pi}\, f_{kin}(SR)$$

Data in $\pi^+\pi^0$ region after $\pi^+\nu\bar{\nu}$ selection

Fraction of $\pi^+\pi^0$ in signal region, measured on control data

- $K^+ \to \mu^+ \nu_\mu$ and $K^+ \to \pi^+ \pi^+ \pi^-$ backgrounds: similar procedure
- $K^+ \to \pi^+\pi^- e^+ \nu_e$ evaluated with MC simulations

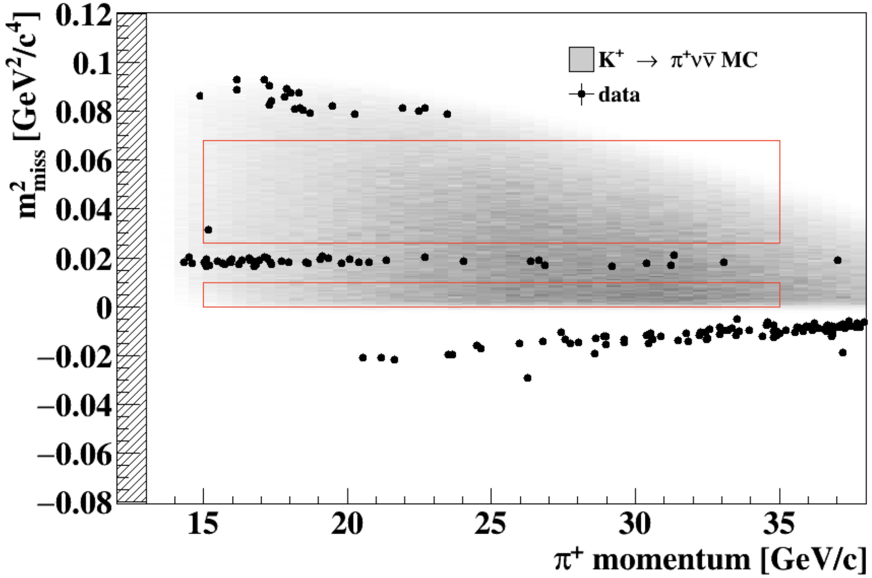
Upstream background

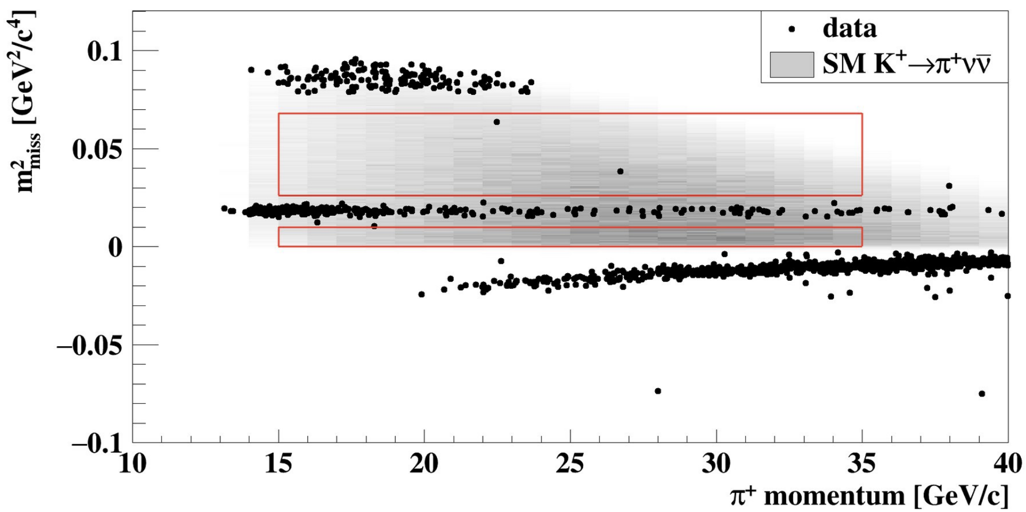


- Pions produced upstream the fiducial volume
  - ✓ Early K^+decay or interaction with the beam spectrometer material
  - ✓ only a π^+ enters the fiducial decay region
  - ✓ there is an in-time pileup beam particle (in GTK)
  - ✓ the upstream π^+ is scattered in the first STRAW chamber.

- Kaon-pion association and geometrical variables
- Data driven background estimation

2016 – 2017 data tacking results





2016

1 events observed

SES = 3.15 x 10^{-10}

Br($K^+ \rightarrow \pi^+\nu\bar{\nu}$) < 14x$10^{-10}$@ 90% CL

[Phys. Lett. B 791 (2019) 156-166]

2017

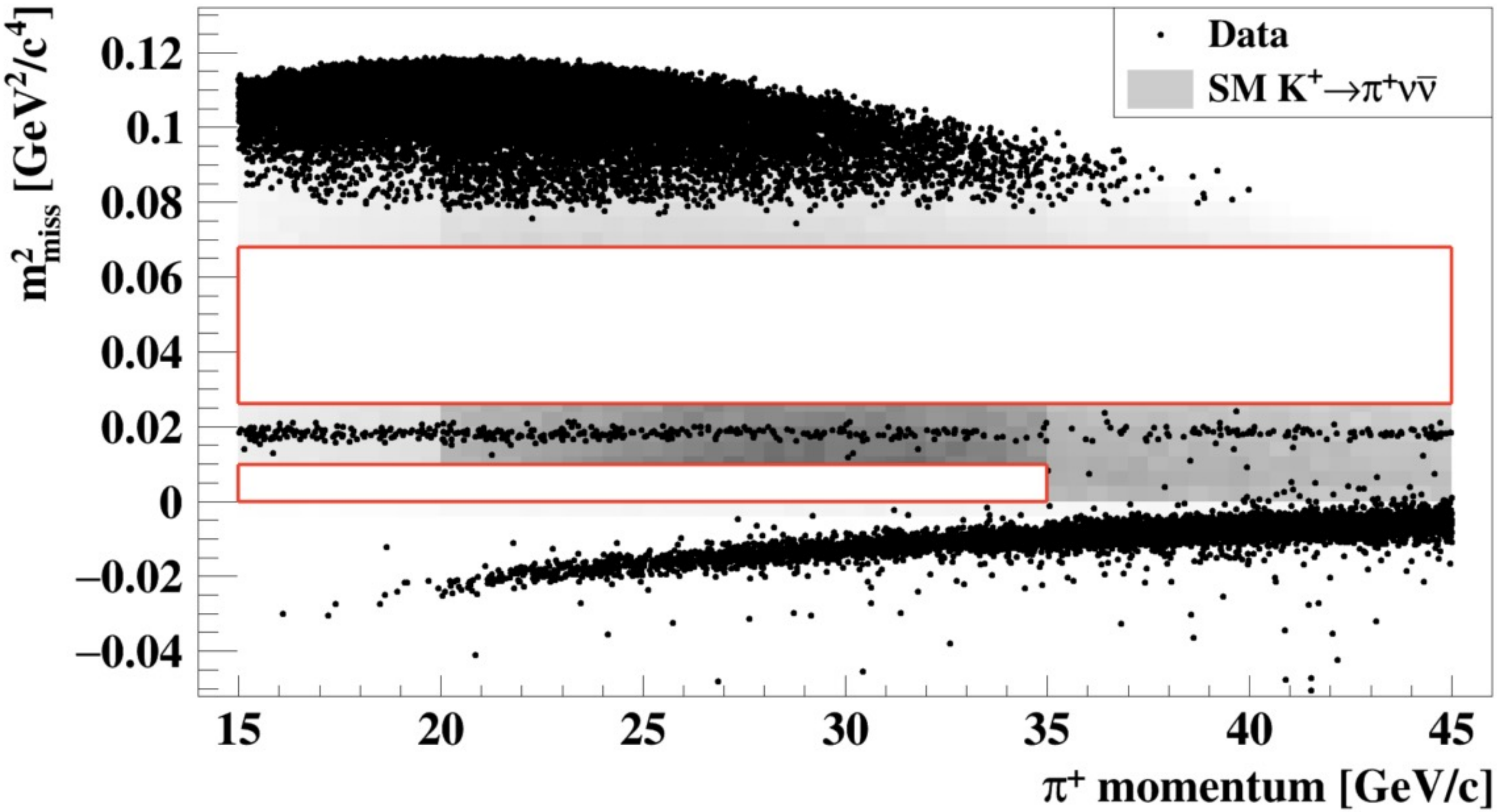
2 events observed

SES = 0.389 x 10^{-10}

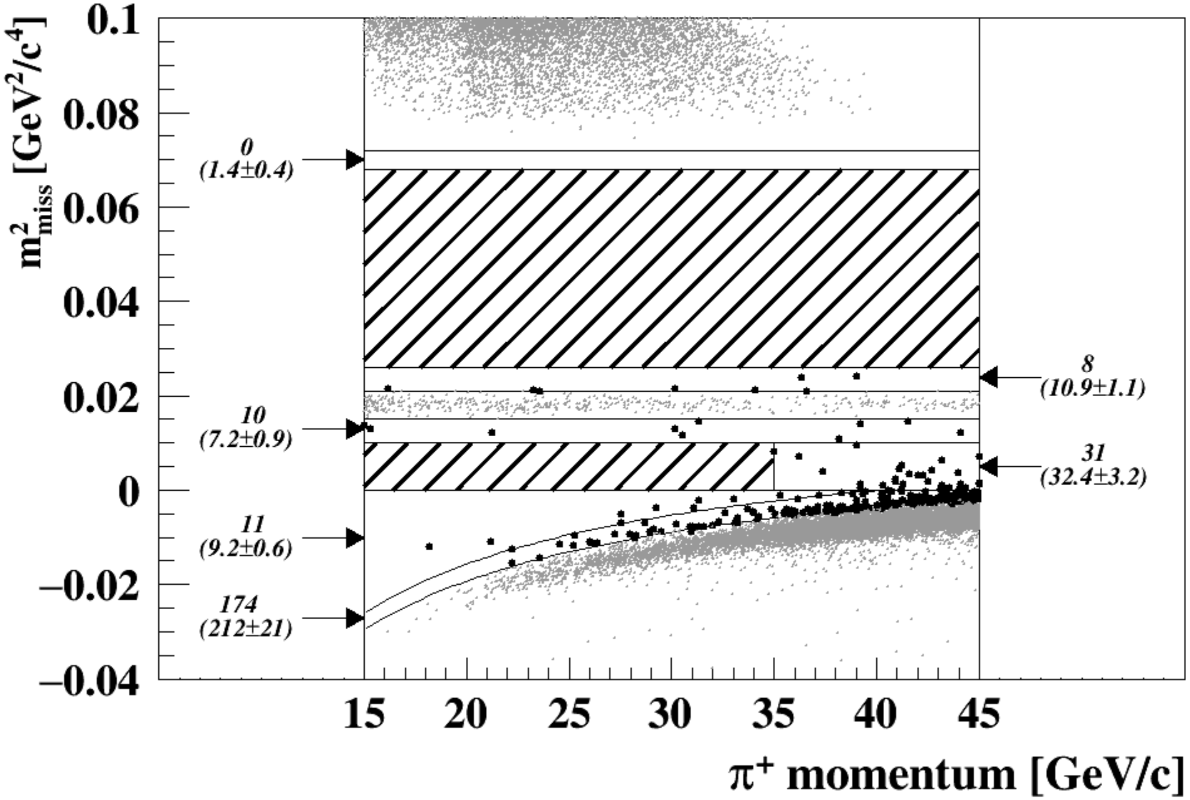
Br($K^+ \rightarrow \pi^+\nu\bar{\nu}$) < 1,7x$10^{-10}$@ 90% CL

[J. High Energ. Phys. 2020, 42 (2020)]

2018 data tacking results

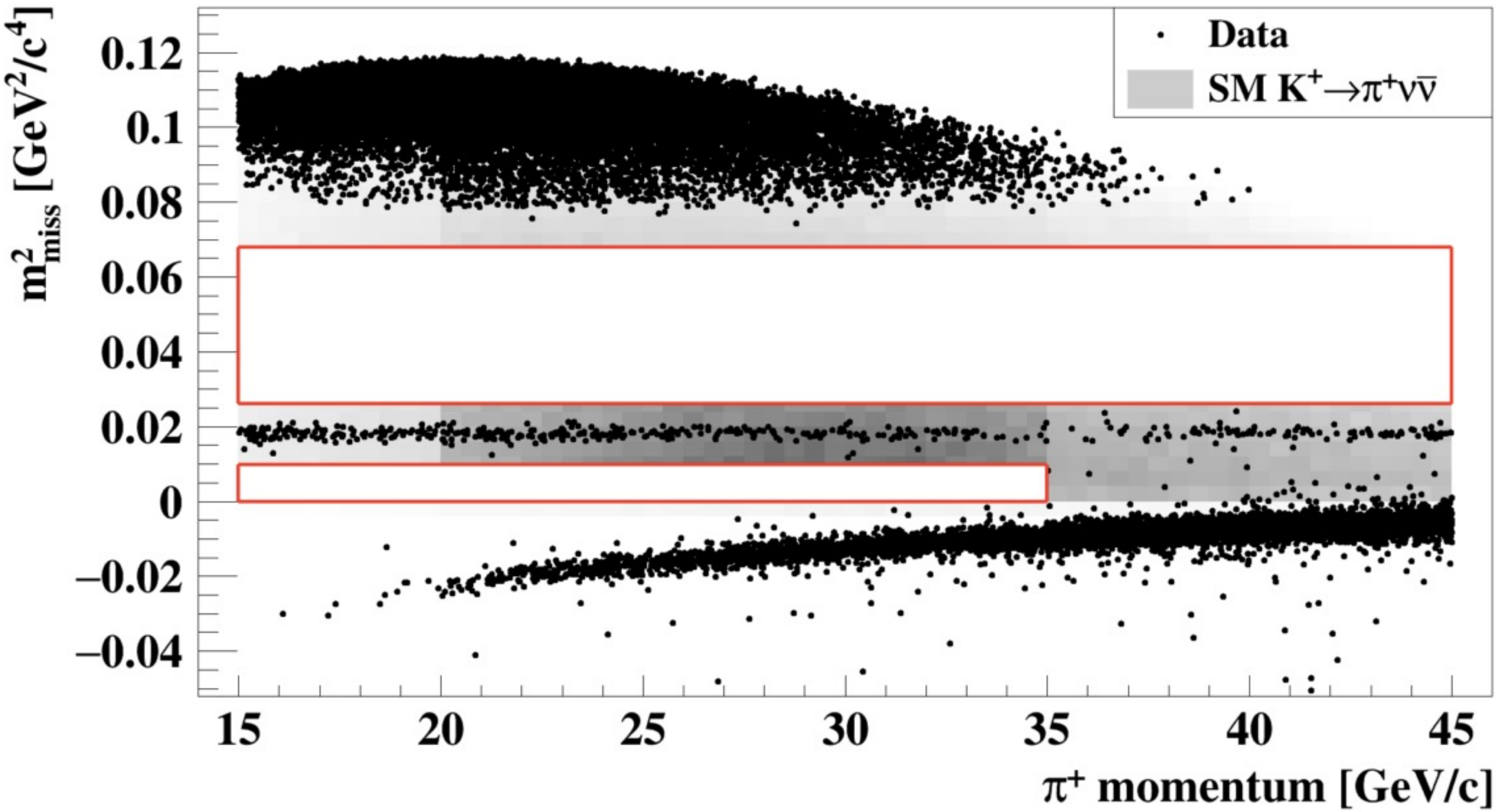


Control regions: main decays



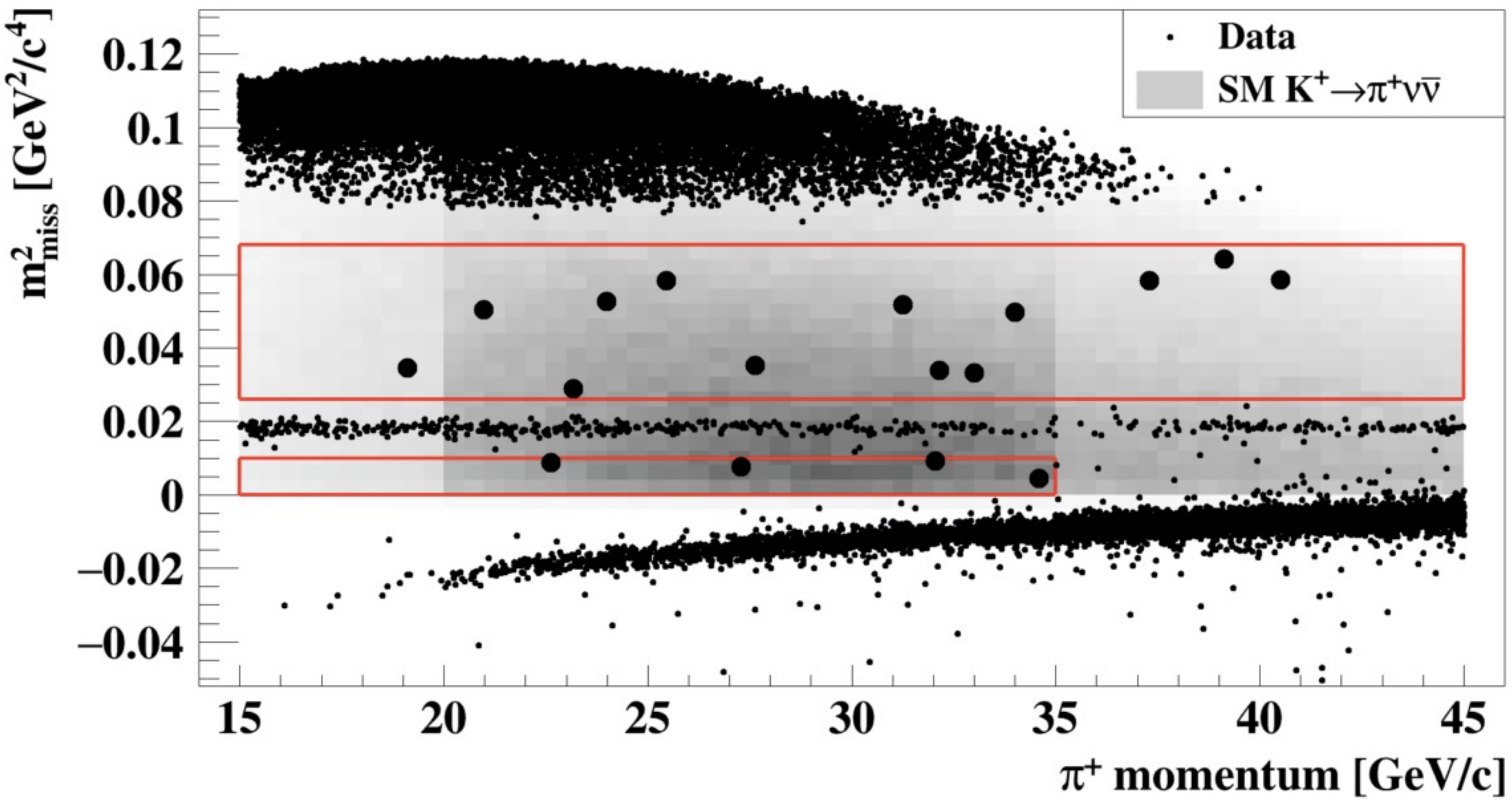
Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$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

2018 data tacking results



5.3 background + 7.6 SM signal events expected

2018 data tacking results



5.3 background + 7.6 SM signal events expected, **17 events** observed

Search for LNV and LNV @ NA62

	Previous UL @90% CL	NA62 UL @90% CL			
$K^+ \to \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}	2017 data	PLB 797 (2019) 134794	*Factor 2 improvement*
$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10}	5.3×10^{-11}	Run1 data	PLB 830 (2022) 137172	*Factor 12 improvement*
$K^+ \to \pi^- \pi^0 e^+ e^+$	no limit	8.5×10^{-10}	Run1 data	PLB 830 (2022) 137172	
$K^+ \to \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11}	2017+2018 data	PRL 127 (2021) 131802	*Factor 12 improvement*
$K^+ \to \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11}	2017+2018 data	PRL 127 (2021) 131802	*Factor 8 improvement*
$\pi^0 \to \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10}	2017+2018 data	PRL 127 (2021) 131802	*Factor 13 improvement*