Latest results from the NA62 experiment at CERN

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on behalf of the **NA62 Collaboration**

INFN Laboratori Nazionali di Frascati

Blois 2021: 32nd Rencontres de Blois on "Particle Physics and Cosmology"

Flavour Physics

Search for New Physics at the EW scale with sizeable coupling to SM particles via indirect effects in loops:

Experiment main goal:

$BR(K^+ \to \pi^+ \nu\bar{\nu})$

Search for lepton flavour and number violation, rare and forbidden decays:

$K^+ \to \pi^\pm \mu^\mp e^+$

$K^+ \to \pi^- l^+ l^+$

$K^+ \to \mu^+ \nu X$

$(K^+ \to \pi^+ \pi^0)\, \pi^0 \to \text{invisible}$

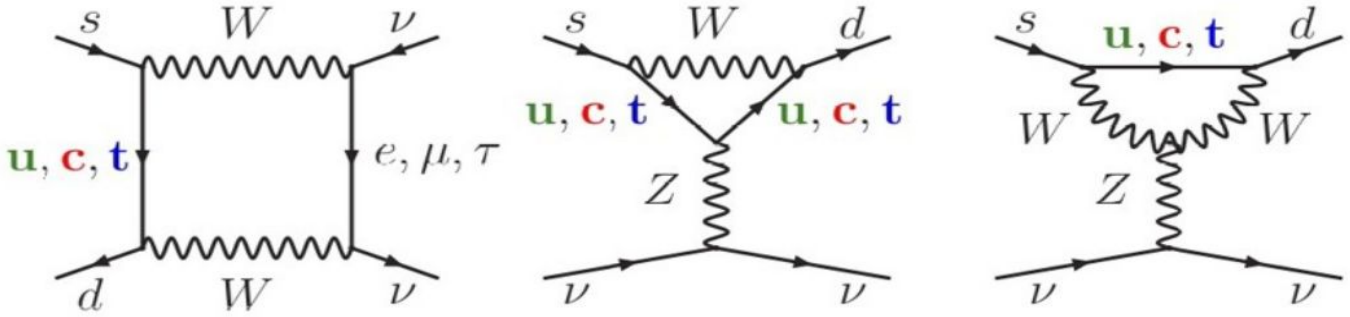
Hidden sector Physics

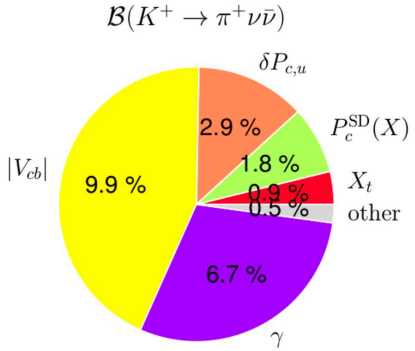
Search for New Physics below the EW scale (MeV-GeV) feebly-coupled to SM particles via direct detection of long-lived particles:

Dark Photon(**DP**), Axion Like Particle (**ALPs**), Dark Scalar (**S**), Heavy neutral Lepton(**N**)

$K^+ \to l^+ N$

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





Uncertainties

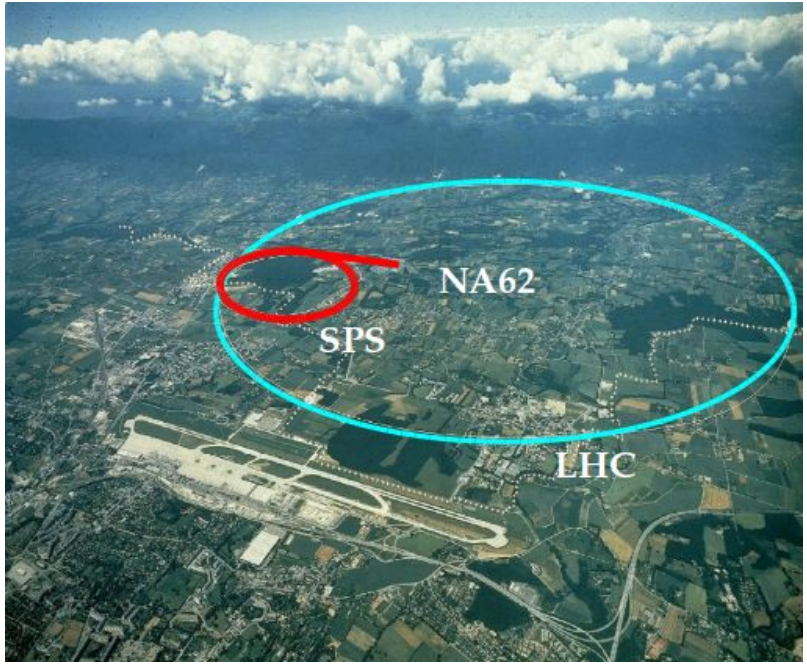
[Buras et al., JHEP11(2015)033]

- FCNC loop process s ⟶d coupling with high CKM suppression
- Clean theoretical prediction: short distance contributions
- Hadronic matrix elements: obtained from Kl3 measurements and SU(2) isospin symmetry

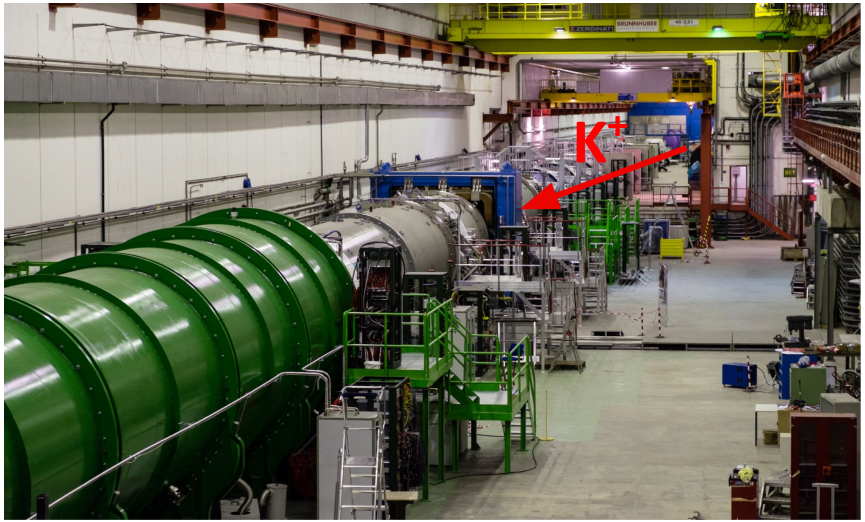
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.03) \times 10^{-10} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (0.84 \pm 0.10) \times 10^{-10}$$

- Channel sensitive to physics BSM

The NA62 experiment at the SPS



NA62 @ CERN North Area, exploits a 400 GeV/c primary proton beam from the SPS. 2 x 10^{12} protons/spill



p on 40 cm Be target.

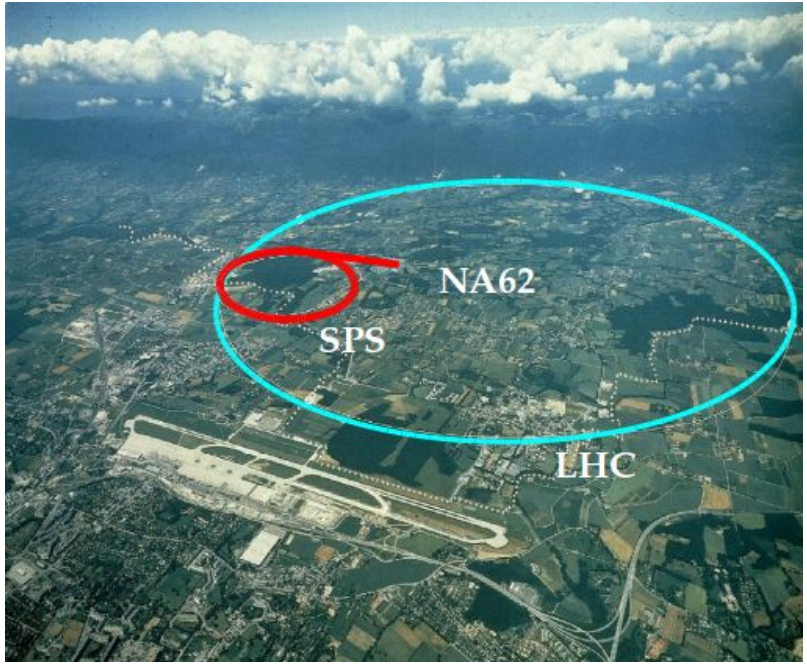
75 GeV/c unseparated hadrons beam:

π^+(70%), K^+ (6%), p(24%).

100 mrad divergence (RMS)

60x30 mm^2 transverse size.

The NA62 experiment at the SPS



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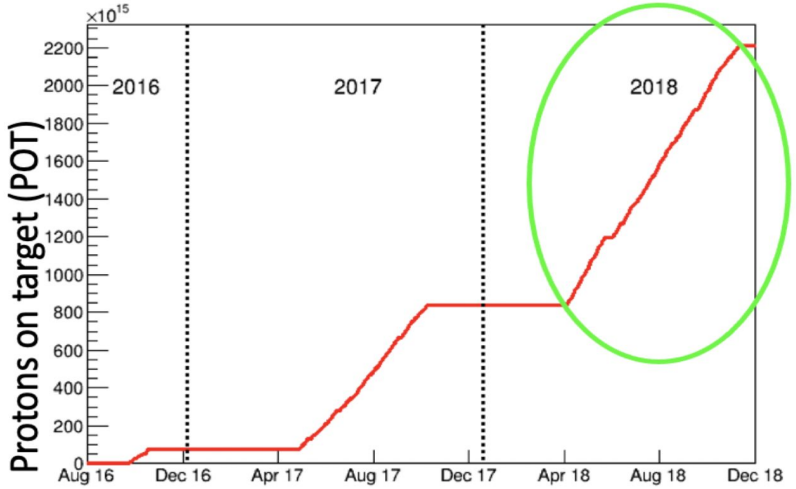
2.2 10^{18} POT



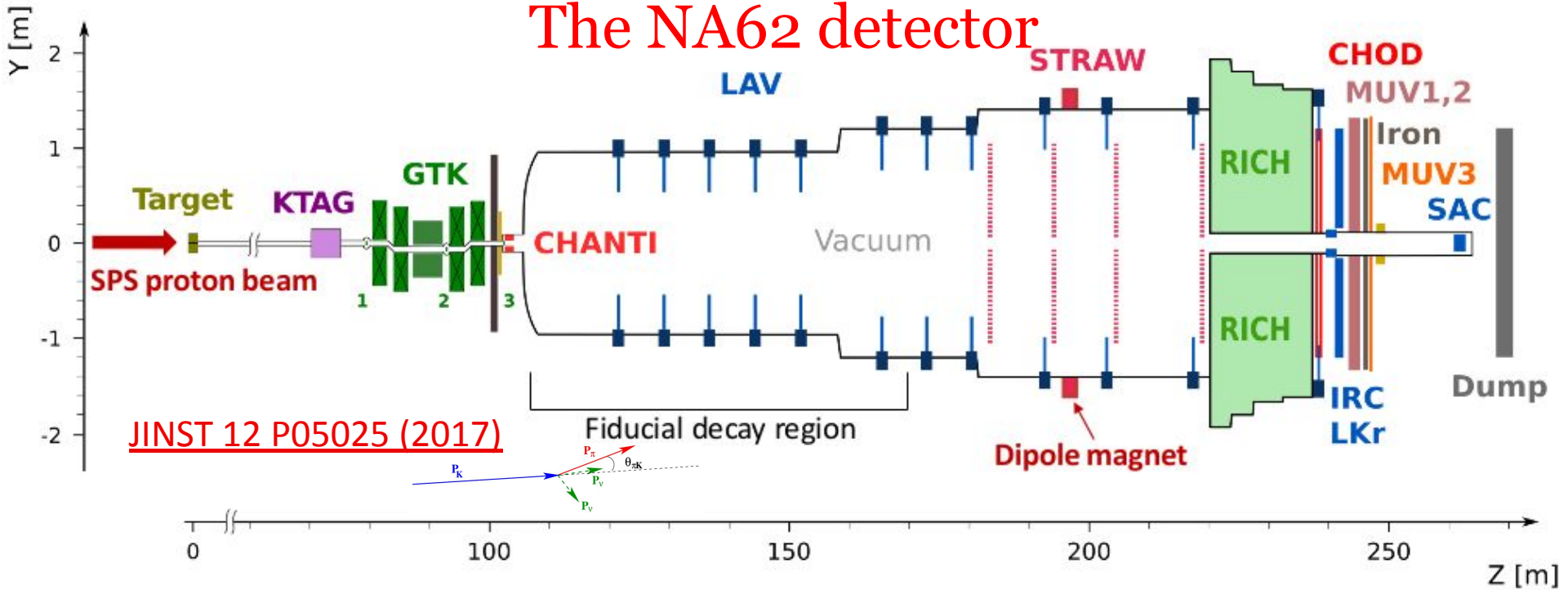
Intensity: 750 MHz (45 MHz K^+).

4.8 x 10^{12} K^+ decays/year, ~ 4 10^{12} K^+ in FV

Run I 2016 -2018:

2016/2017/2018 40%/60%/60-70% nominal intensity

The NA62 detector



Upstream particle:

KTAG: Differential Cherenkov for K^+ ID

GTK: Si pixel tracker

CHANTI: Anti-counter for inelastic interactions

Decay region detectors (π^+):

STRAW: Track momentum spectrometer

CHOD: Scintillator hodoscope

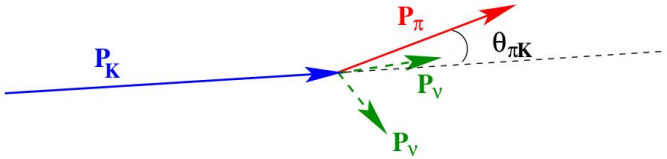
RICH: For $\pi/\mu/e$ ID

LKR/MUV1/2: Calorimetric systems

Vetos:

LAV/IRC/SAC: photons

MUV3: muons

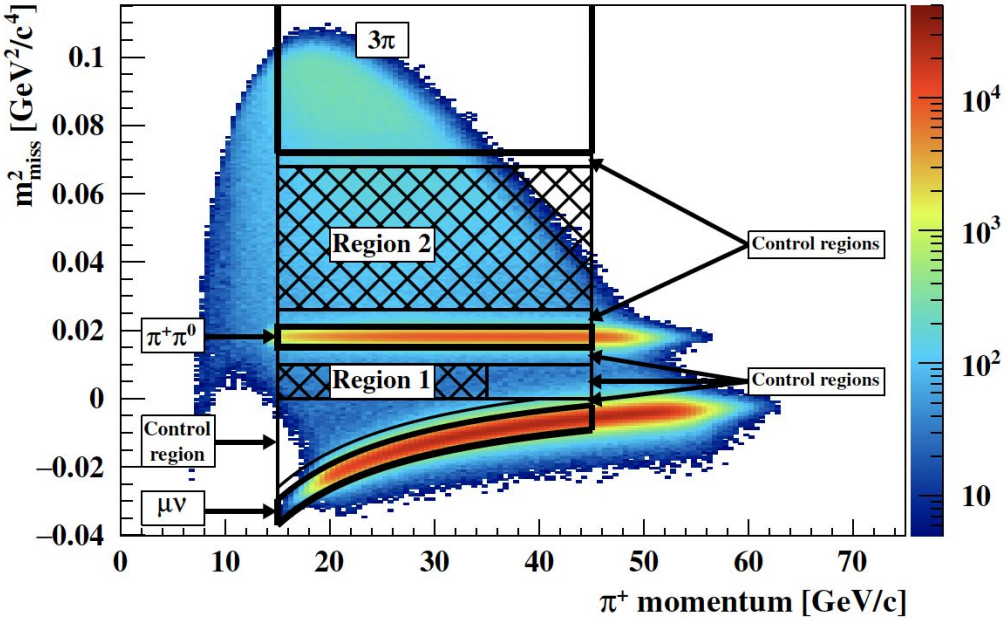


$K^+ \to \pi^+ \nu\bar{\nu}$ selection

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

Selection steps:

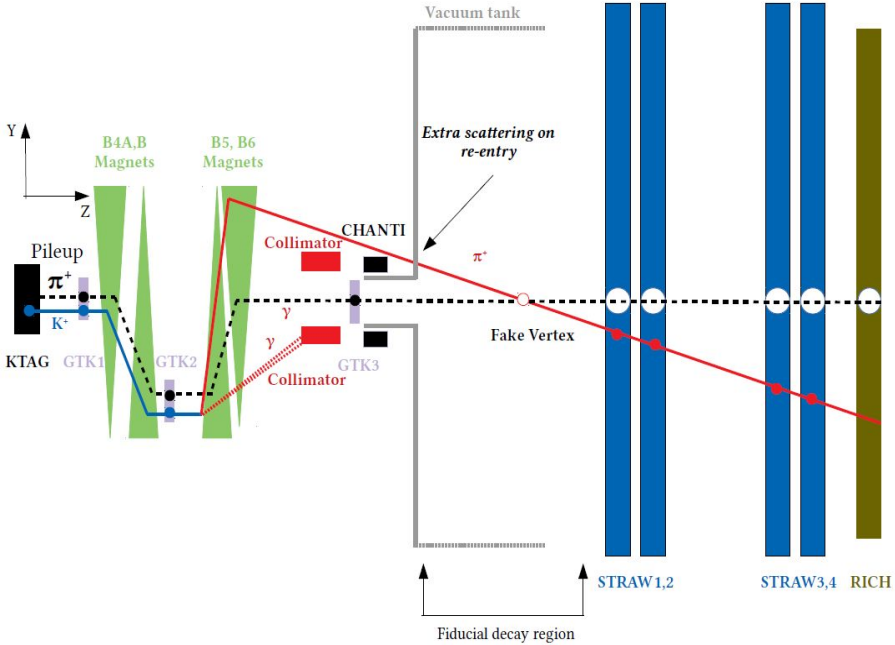
- K^+ and π^+ track reconstruction
  - L0: presence of charged particles and μ/γ veto
  - L1: K^+ ID+ photon veto
- K^+- π^+ matching
  - Excellent time resolution O(100ps)
- Decay vertex FV + other cuts
- π^+ ID (μ^+ rejection ~ 10^{-8})
- Photon rejection (~ 10^{-8})
- Kinematic cuts (m^2_{miss}, p_π):
  - Signal regions + control regions defined: blind analysis performed



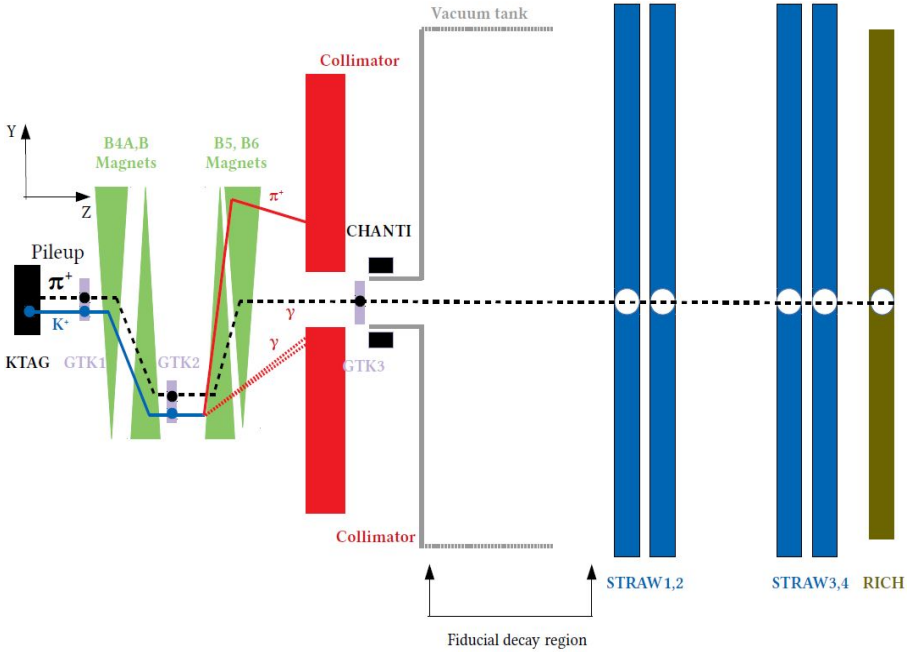
MINIMUM BIAS data shown

NORMALIZATION CHANNEL $\pi^+\pi^0$ in MIN BIAS

Upstream background



OLD collimator, “S1” sample early 2018

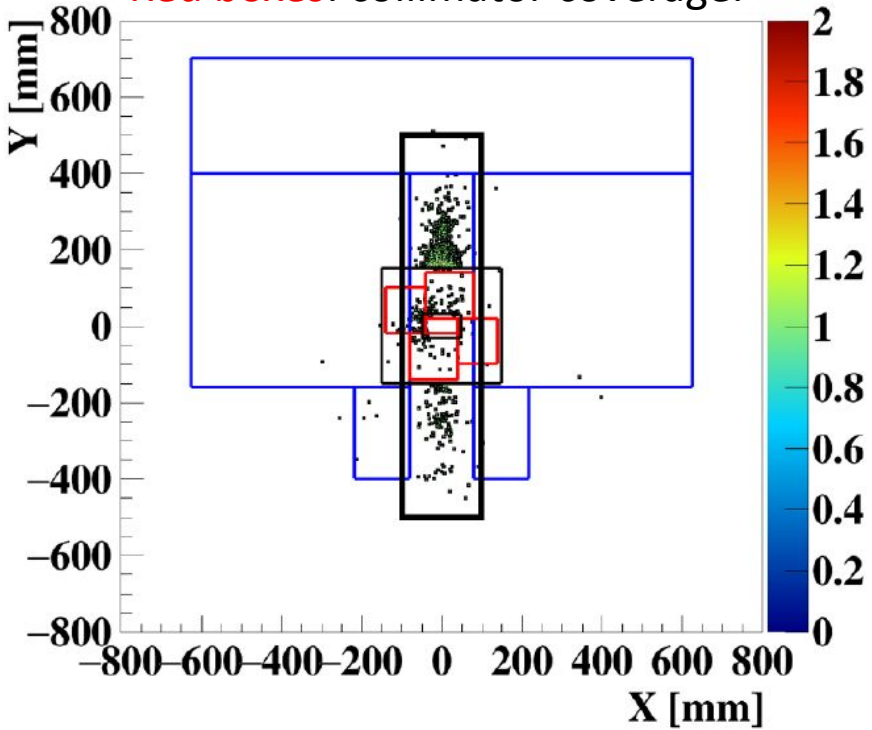


NEW collimator, “S2” majority of 2018

Upstream background

Track extrapolation at collimator in enriched sample of upstream events (data).

Red boxes: collimator coverage.



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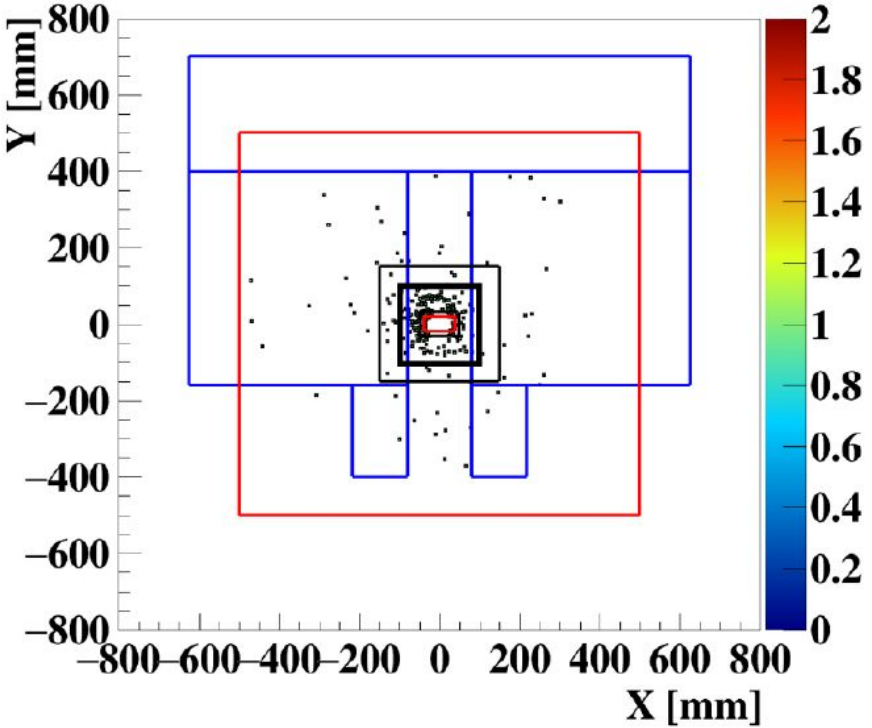
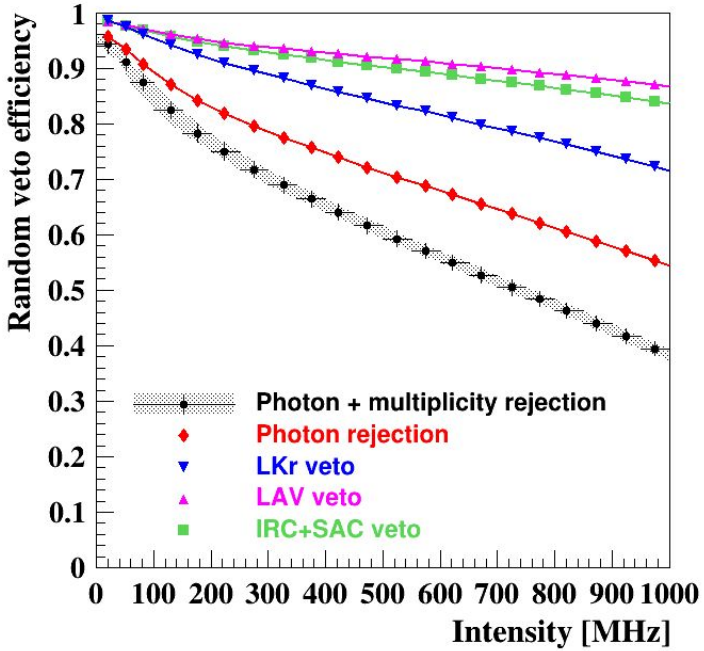


NEW collimator, “S2” majority of 2018

Single Event Sensitivity

SES

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \frac{N_{\pi\nu\nu} \cdot BR(K^+ \to \pi^+\pi^0) \cdot A_{\pi\pi} \cdot \epsilon_{trig}^{MB}}{D \cdot N_{\pi\pi} \cdot A_{\pi\nu\nu} \cdot \epsilon_{RV} \cdot \epsilon_{trig}^{\pi\nu\nu}}$$

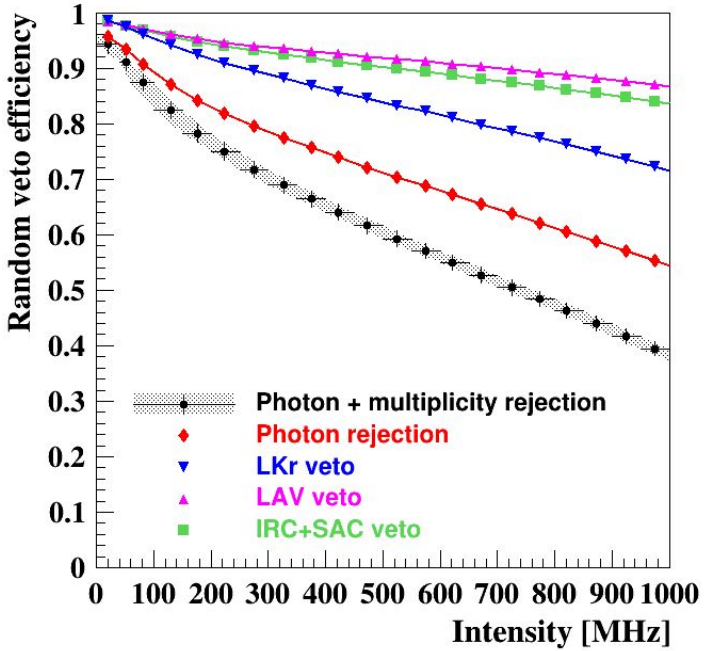


	Subset S1	Subset S2
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^2$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^2$	3.95 ± 0.40	6.37 ± 0.64
$\epsilon_{\rm trig}^{\rm PNN}$	0.89 ± 0.05	0.89 ± 0.05
$\epsilon_{\rm RV}$	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14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

Single Event Sensitivity

SES

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \frac{N_{\pi\nu\nu} \cdot BR(K^+ \to \pi^+\pi^0) \cdot A_{\pi\pi} \cdot \epsilon_{trig}^{MB}}{D \cdot N_{\pi\pi} \cdot A_{\pi\nu\nu} \cdot \epsilon_{RV} \cdot \epsilon_{trig}^{\pi\nu\nu}}$$



Cancellation of systematic effects (PID, detector efficiencies, Kaon ID, beam related acceptance loss)
Remaining systematic uncertainties:

Trigger efficiency	5%
MC acceptance	3.5%
Random Veto	2%
Background(normalization)	0.7%
Instantaneous intensity	0.7%
Total	**6.5%**

Background from Kaon decays

Data driven estimation of background in control and signal region:

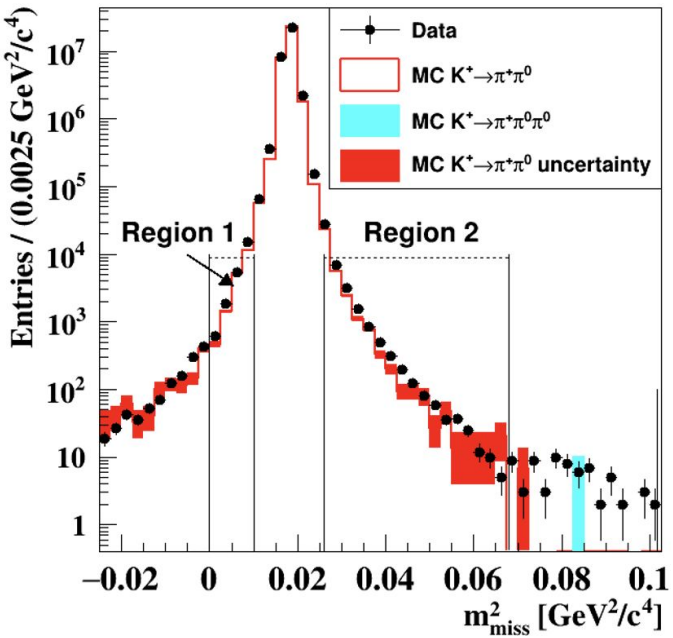
- $K^+ \to \pi^+\pi^0$
- $K^+ \to \mu^+\nu$
- $K^+ \to \pi^+\pi^+\pi^-$

$$N_{\text{decay}}^{\text{exp}} = N_{\text{bkg}} \cdot f_{\text{kin}}(\text{region})$$

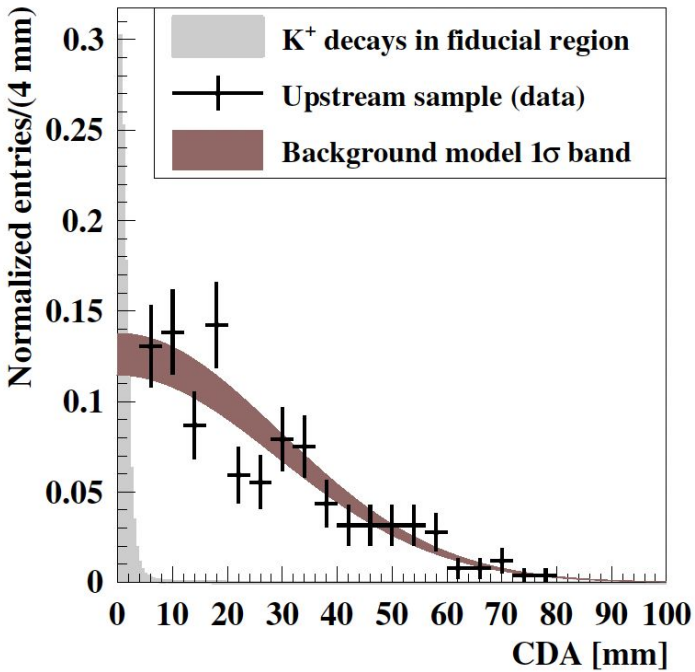
Fraction of events in signal region in MINIMUM BIAS sample

MC estimation:

- $K^+ \to \pi^+\pi^- e^+\nu$



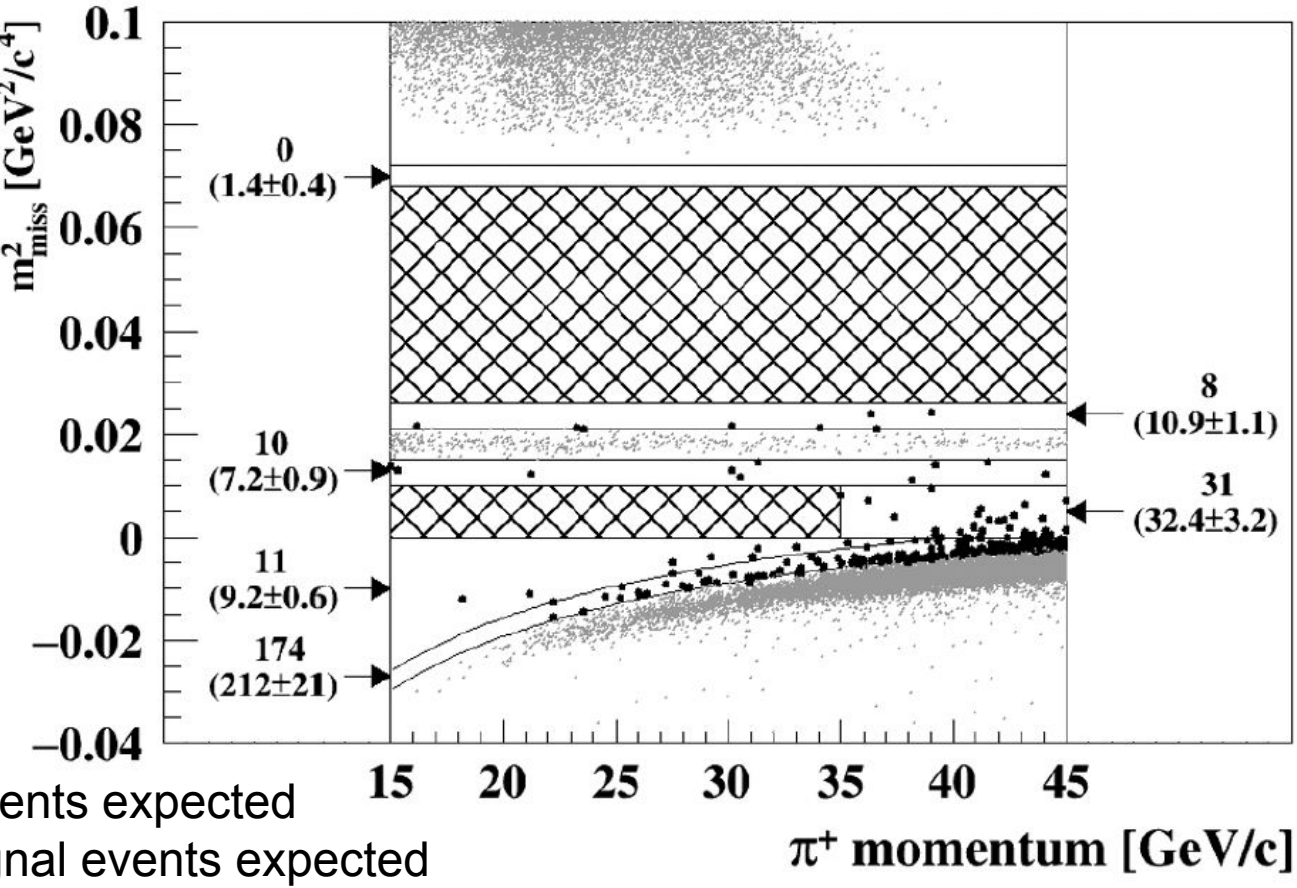
Upstream background



- Data-driven estimate
- Evaluation using an enriched sample:
  - Signal selection with inverted CDA condition
  - weighted by mistag probability evaluated in data

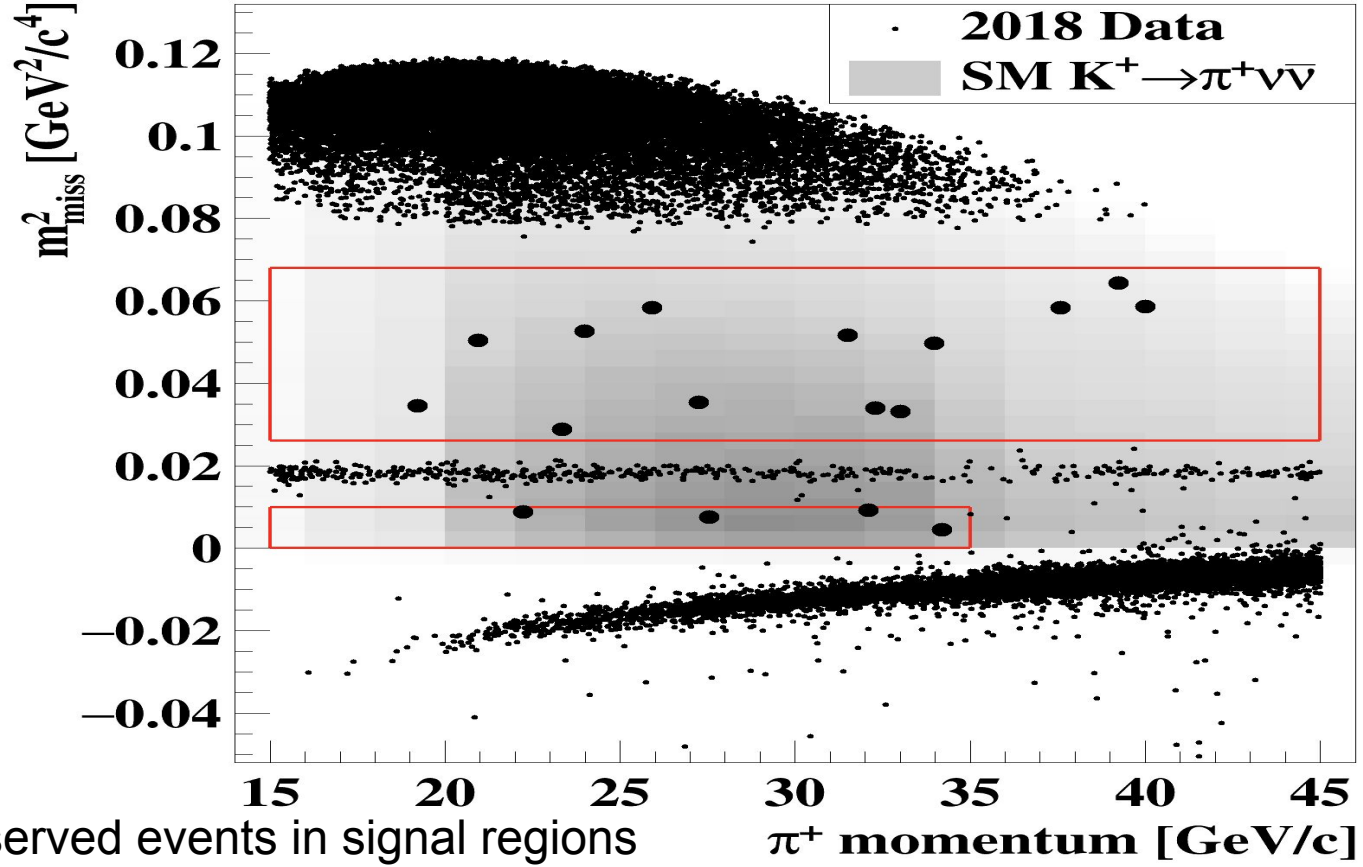
Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$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

Control regions and expectation



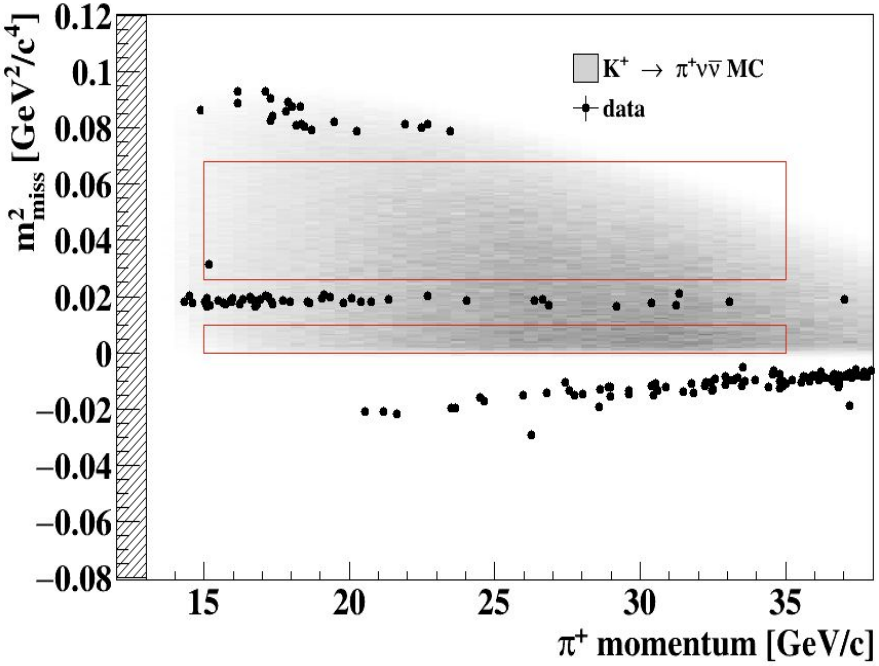
- 5.4 bkg events expected
- 7.6 SM signal events expected

Data selection 2018 unblinded



- 17 observed events in signal regions

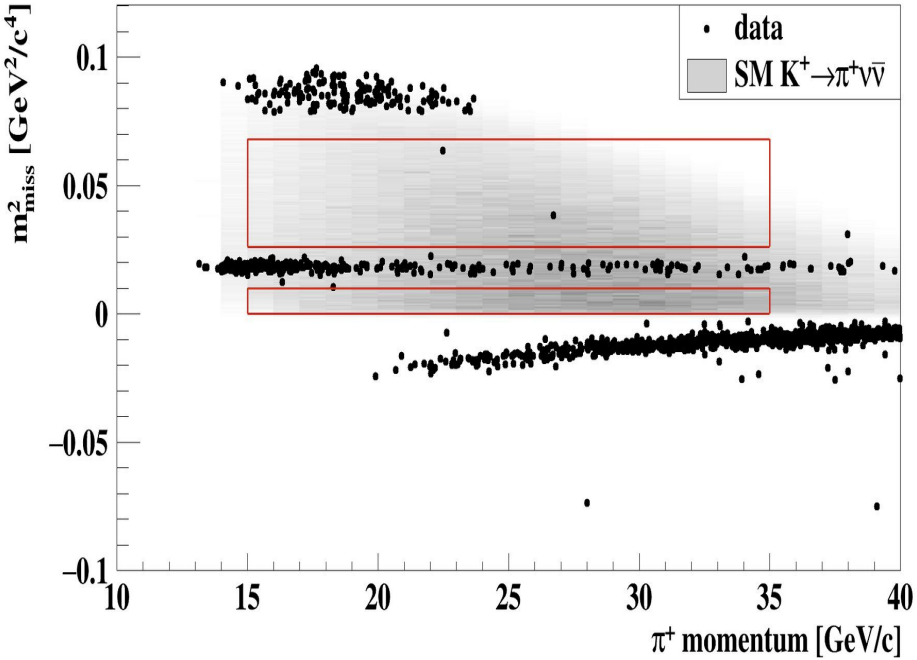
2016 and 2017 results



1 event observed

BR($K^+ \to \pi^+\nu\nu$)< 14 10^{-10} @90% CL

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

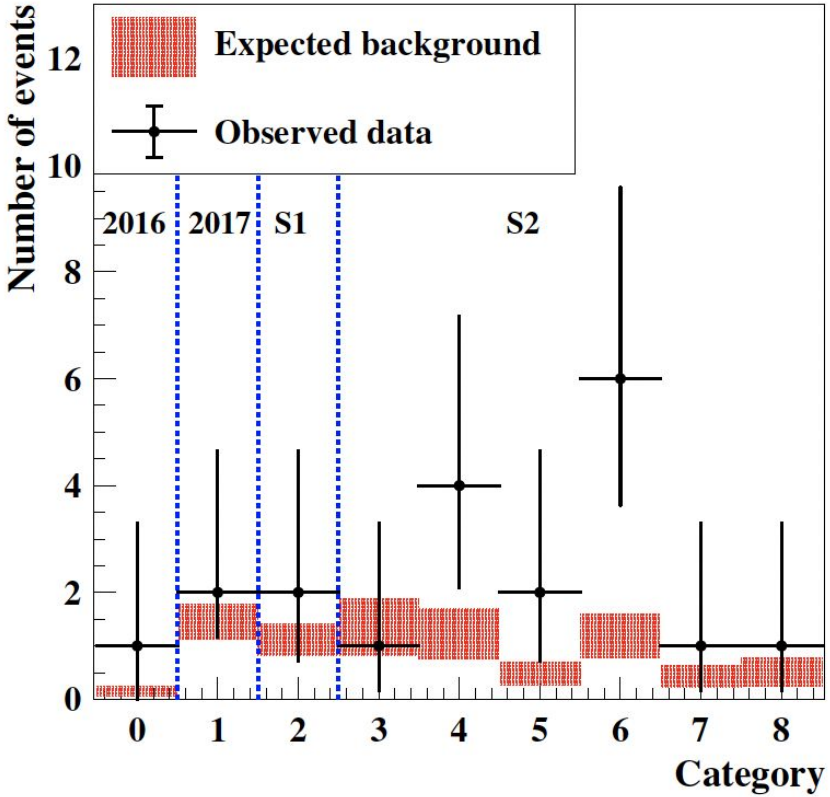


2 events observed

BR($K^+ \to \pi^+\nu\nu$)< 1.78 10^{-10} @90% CL

JHEP 11 (2020) 042

Br ($K^+ \to \pi^+ \nu\bar{\nu}$) results



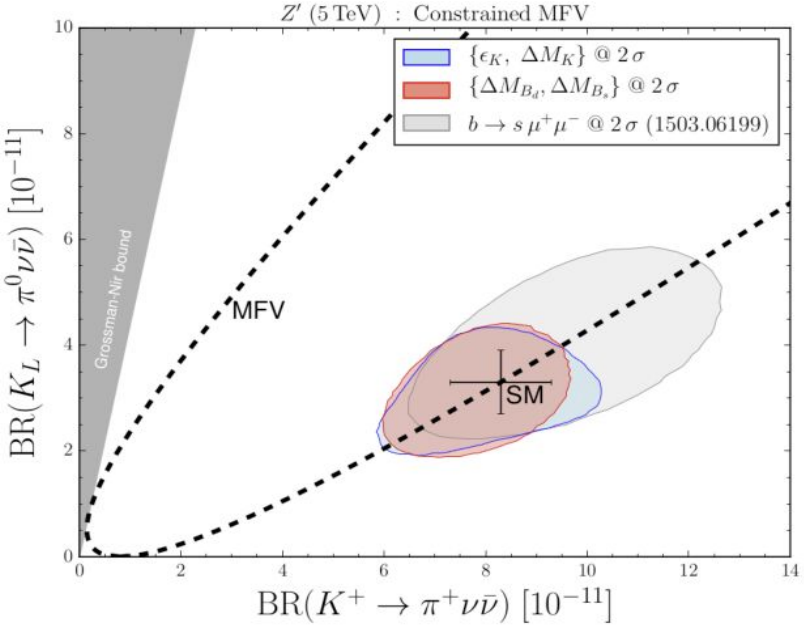
- Maximum likelihood fit using observed data and background expectations in each category
- 2016, 2017, 2018 with old collimator (S1) and 2018 with new collimator (S2)
- S2: sample split in 5 GeV/c wide bins from 15-45 GeV/c

JHEP 06 (2021) 093

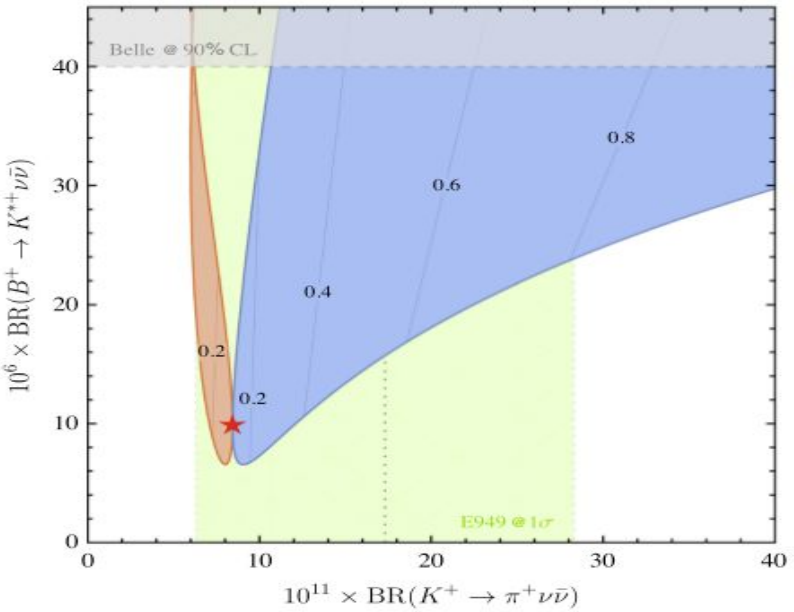
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4 stat.} \pm 0.9_{syst.}) \times 10^{-11} (3.4\sigma \text{ significance})$$

$K^+ \to \pi^+ \nu\bar{\nu}$ beyond the Standard Model

Buras et al.,JHEP11 (2015) 166



Isidori et al., Eur. Phys.J. C (2017) 77



New Physics: BR sensitive to the highest mass scale

New Physics Models: MFV; Simplified Z, Z'; LFU violation;MSSM; Leptoquarks..

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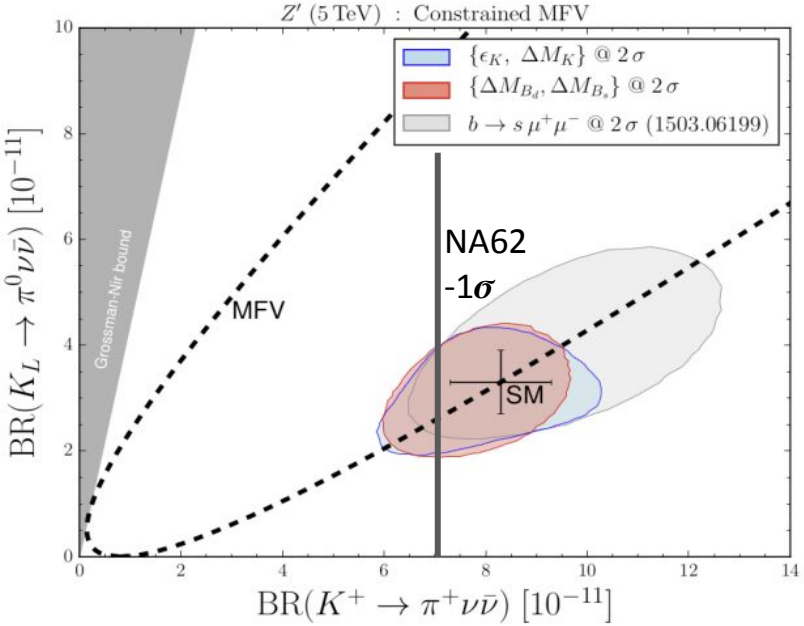

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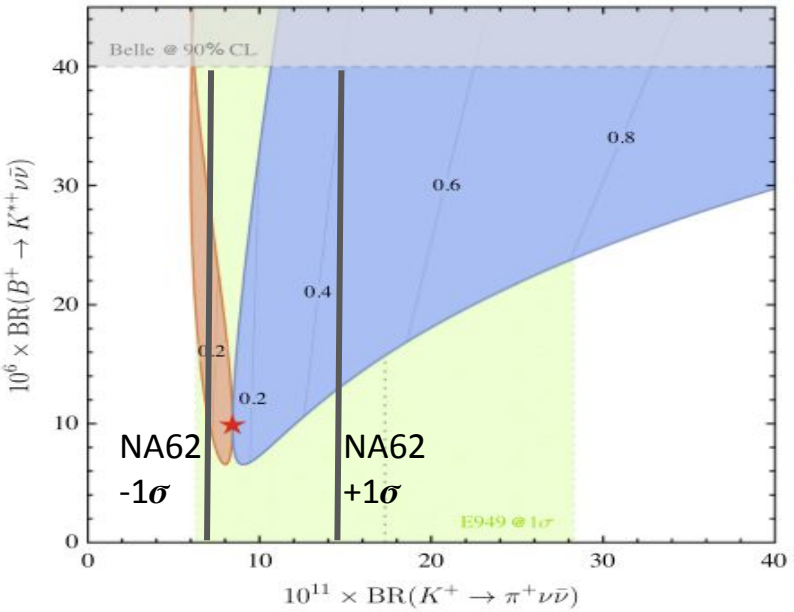

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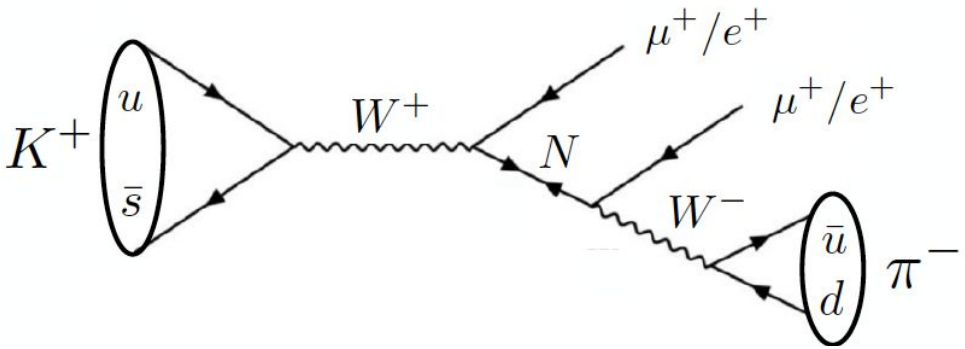
$K^+ \to l^+ N$

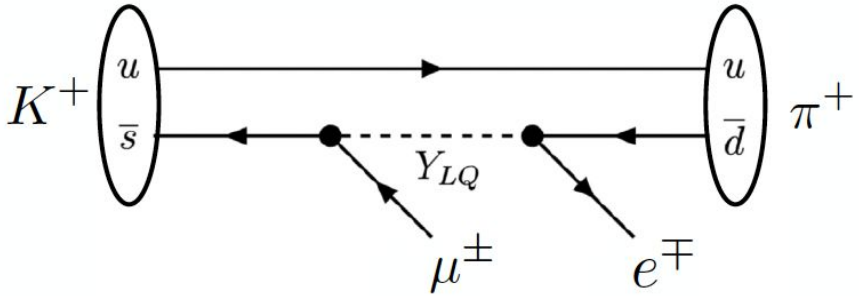
LFV and LNV in Kaon decays

- Lepton Number (**L**) and Lepton Flavour (L_e, L_μ, L_τ) are foreseen in some BSM theories: conservation laws in SM are not imposed by any local gauge symmetry
  - **Lepton number violation:**



eg: $K^+ \rightarrow \pi^- \mu^+ e^+$
$\Delta L=2$ via Majorana neutrinos

  - **Lepton flavour violation:**



eg: $K^+ \rightarrow \pi^+ \mu^- e^+$
$\Delta L_e=1$ and $\Delta L_\mu=1$
Via leptoquark, Z'..

$K^+ \to \pi^\pm \mu^\mp e^+$ ($\pi^0 \to \mu^- e^+$): analysis workflow and results

- Experimental signature: 3 charged tracks with $\pi^\pm \mu^\mp e^+$
- Consistent with closed kinematics K^+ decay
- The invariant mass $M_{\pi ve}$ of the three selected tracks build under the $\pi\mu e$ is used to distinguish between signal and background (σ_M~1.4 MeV)
- Normalized with $K^+ \to \pi^+\pi^+\pi^-$
- Main bkg π mis-ID and decay in flight

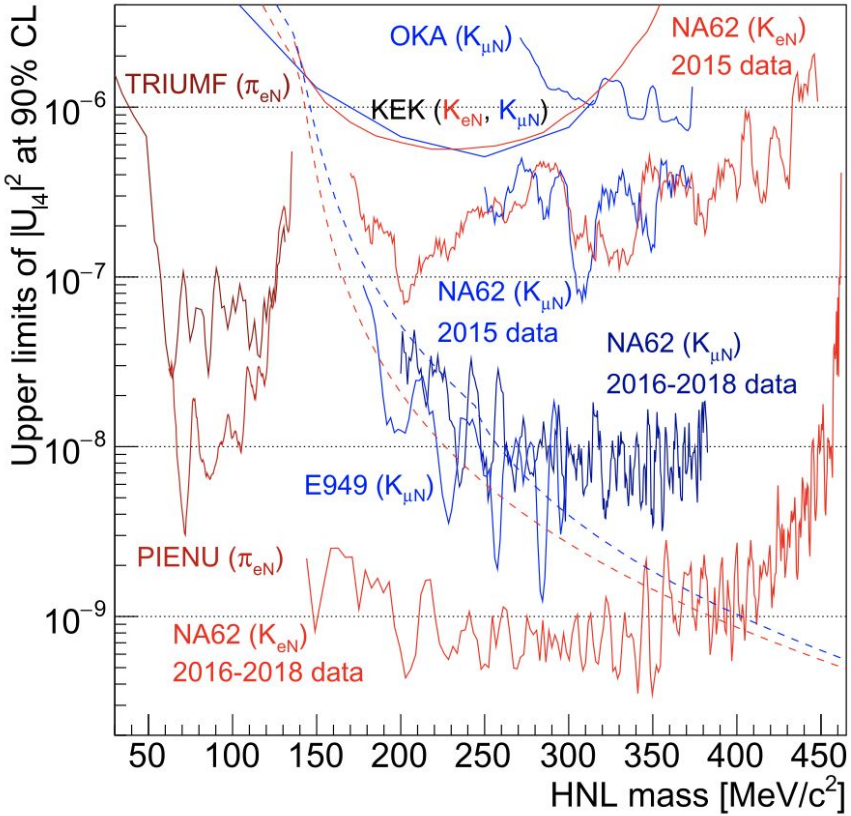
1 order of magnitude improvements compared to previous searches
Upper limits at 90% CL:

PRL 127 131802 (2021)

$$\mathcal{B}(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11};$$
$$\mathcal{B}(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11};$$
$$\mathcal{B}(\pi^0 \to \mu^- e^+) < 3.2 \times 10^{-10}.$$

Heavy neutral leptons

Right handed neutrinos or Heavy Neutral Leptons (HNL) are included in several extension of the Standard Model



- Search for HNL produced in K decays: $K^+ \to \mu^+ N$, $K^+ \to e^+ N$ due to mixing with standard model neutrinos
-

$$\mathcal{B}(K^+ \to \mu^+ N) = \mathcal{B}(K^+ \to \mu^+ \nu) \cdot \rho_\mu(m_N) \cdot |U_{\mu 4}|^2$$

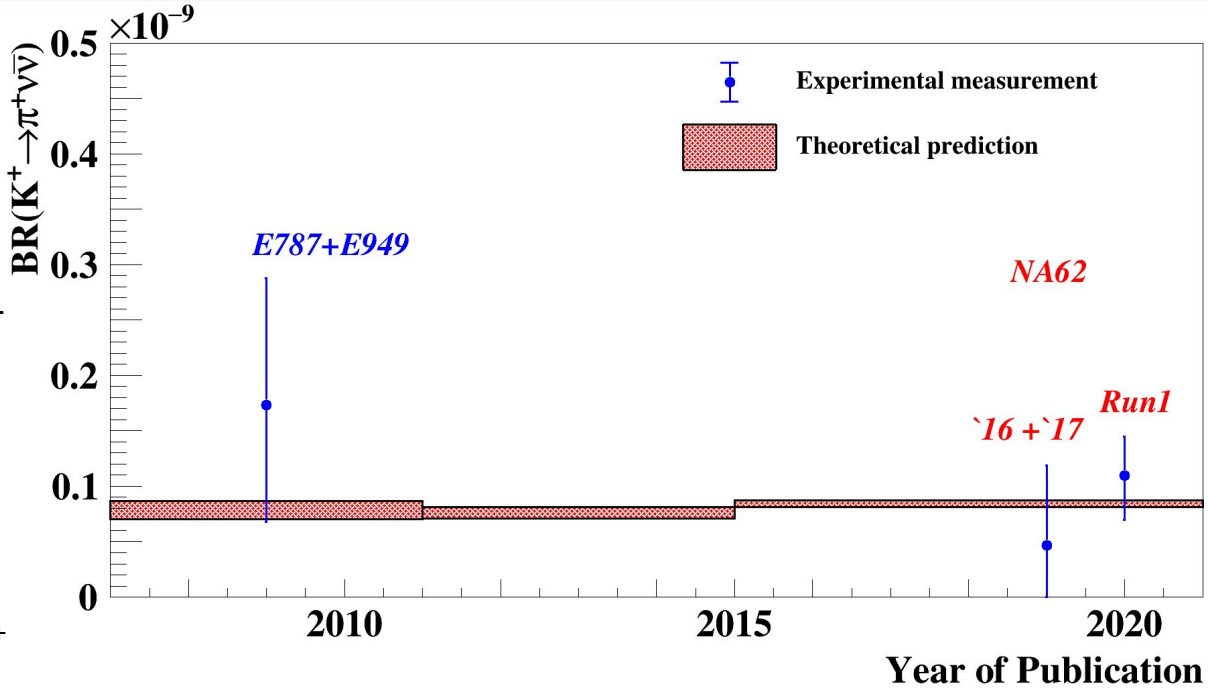
- **O(10^{-9}) limits on $|Ue4|^2$** Big Bang nucleosynthesis (BBN) allowed range (dashed lines) excluded up to 340 MeV/c^2
- **O(10^{-8}) limits on $|U\mu 4|^2$** over the HNL mass range of 200–384 MeV/c^2

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

Conclusions

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4 stat.} \pm 0.9_{syst.}) \times 10^{-11} (3.4\sigma \text{ significance})$$

- The most precise measurement of $K^+ \to \pi^+ \nu\nu$
- Compatible with the SM prediction within 1σ
- Run II started in August 2021 till 2024
- New K^+ tracker with extra station and veto counter to reduce upstream background
- New calorimeter to reject K^+ bkg decays
- 100% beam intensity



Run II just started: stay tuned!

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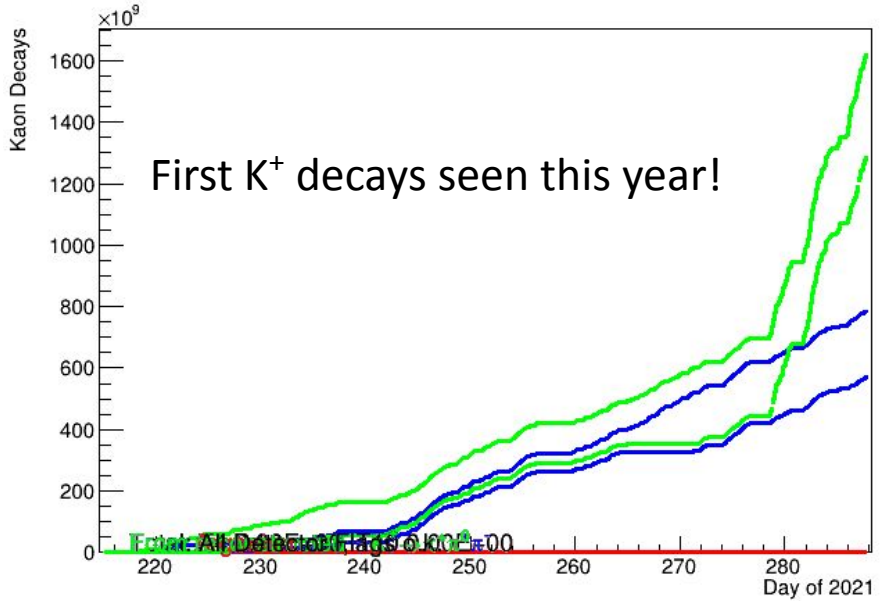

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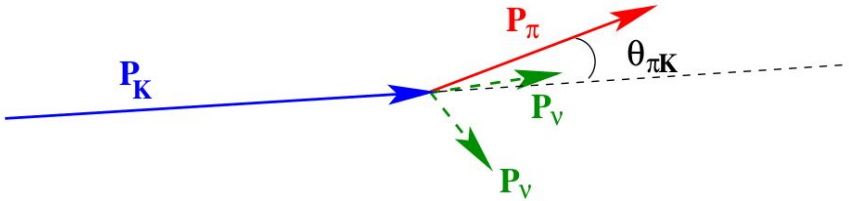
Analysis strategy



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

- Decay in flight technique
- Build missing invariant mass square

$$\delta p_K = 1.\% p_K$$

$$\delta p_\mu = 0.3\% p_\mu \oplus 0.005\% p_\mu^2$$

$$\delta\theta = 40 \mu rad$$

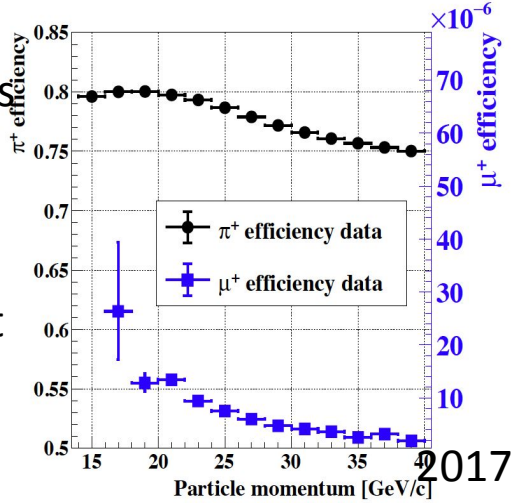
$$\delta M^2 = 0.00196 \text{ GeV}^2$$

$K^+ \to \pi^+ \nu\bar{\nu}$ selection

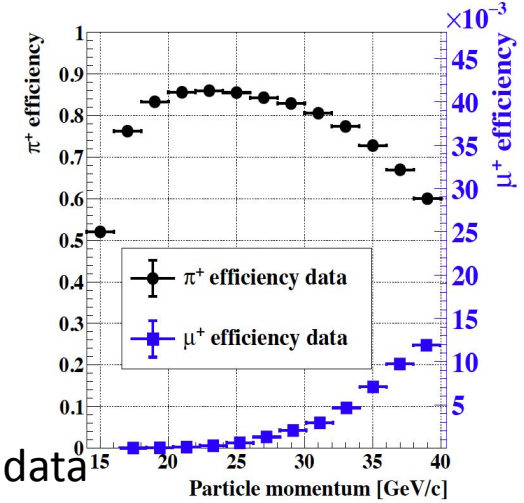
Selection steps:

- K^+ and π^+ track reconstruction
  - L0: presence of charged particles and μ/γ veto
  - L1: K^+ ID+ photon veto
- K^+- π^+ matching
  - dT(RICH,KTAG,GTK) and closest distance of approach
- Decay vertex reconstruction + cuts
- π^+ ID (μ^+ rejection)

LKr+MUV3



RICH



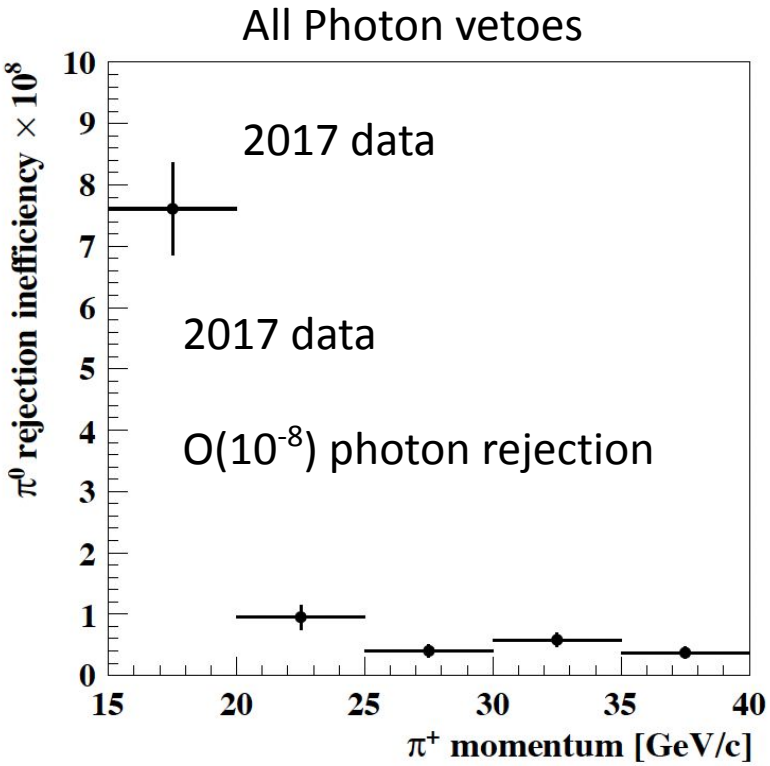
2017 data

O(10^{-8}) muon rejection

$K^+ \to \pi^+ \nu\bar{\nu}$ selection

Selection steps:

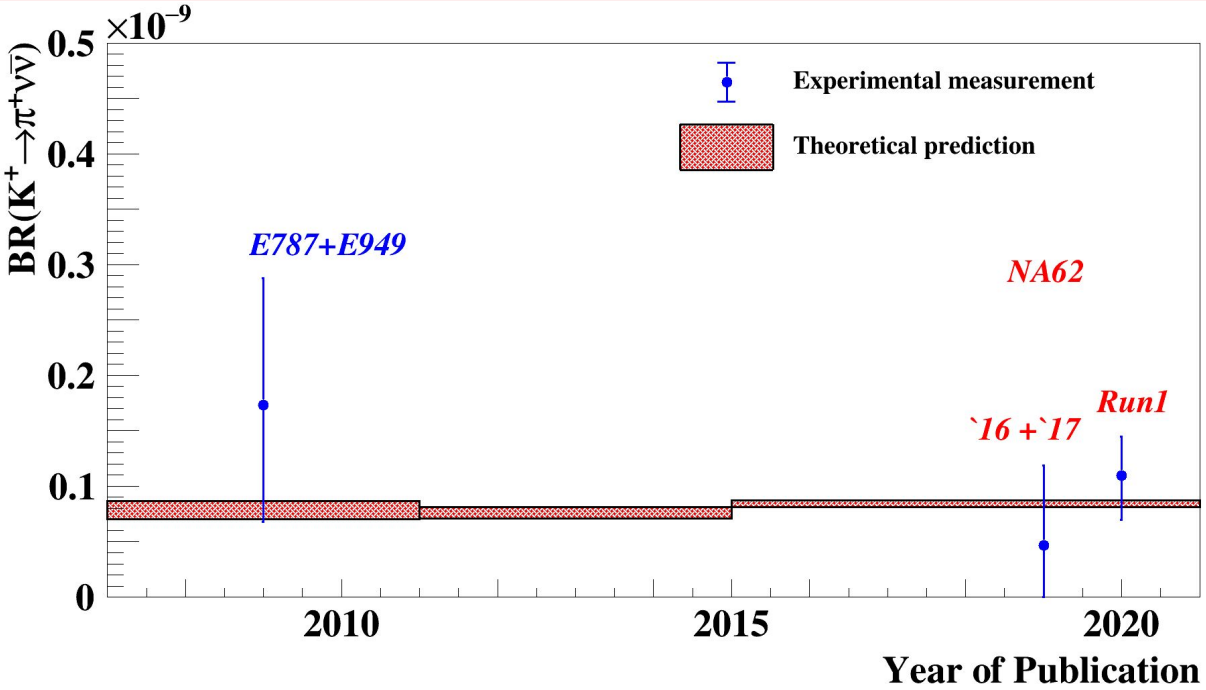
- K^+ and π^+ track reconstruction
  - L0: presence of charged particles and μ/γ veto
  - L1: K^+ ID+ photon veto
- K^+- π^+ matching
  - dT(RICH,KTAG,GTK) and closest distance of approach
- Decay vertex reconstruction + cuts
- π^+ ID (μ^+ rejection)
- Photon rejection



Conclusions

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4 stat.} \pm 0.9_{syst.}) \times 10^{-11} (3.4\sigma \text{ significance})$$

- The most precise measurement of $K^+ \to \pi^+ \nu\nu$
- Compatible with the SM prediction within 1σ
- Large improvements on most of the LFV and LNV K^+ decays: sensitivity up to $O(10^{-11})$
- Limits on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$: $O(10^{-9})$ and $O(10^{-8})$ mass range 144(200)–462(384) MeV/c^2



Run II just started: stay tuned!