Measurement of the rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay

Gemma Tinti
on behalf of the **NA62 Collaboration**

INFN Laboratori Nazionali di Frascati

Beach 2022

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**)

$K^+ \to l^+ N$

NA62

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

Hidden sector Physics

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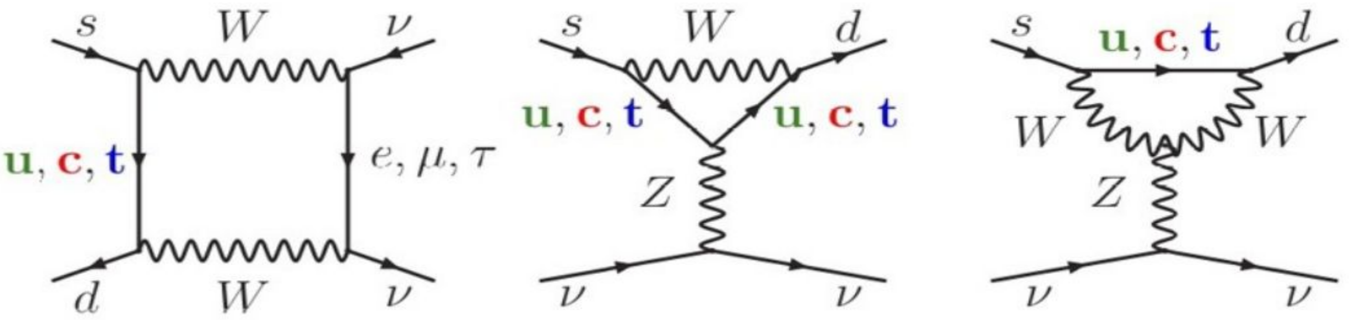
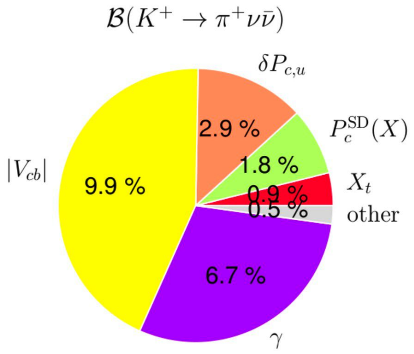
A. Kleimenova 06/06/2022, 15:15

C. Parkinson 07/06/2022, 13:55

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





Uncertainties

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

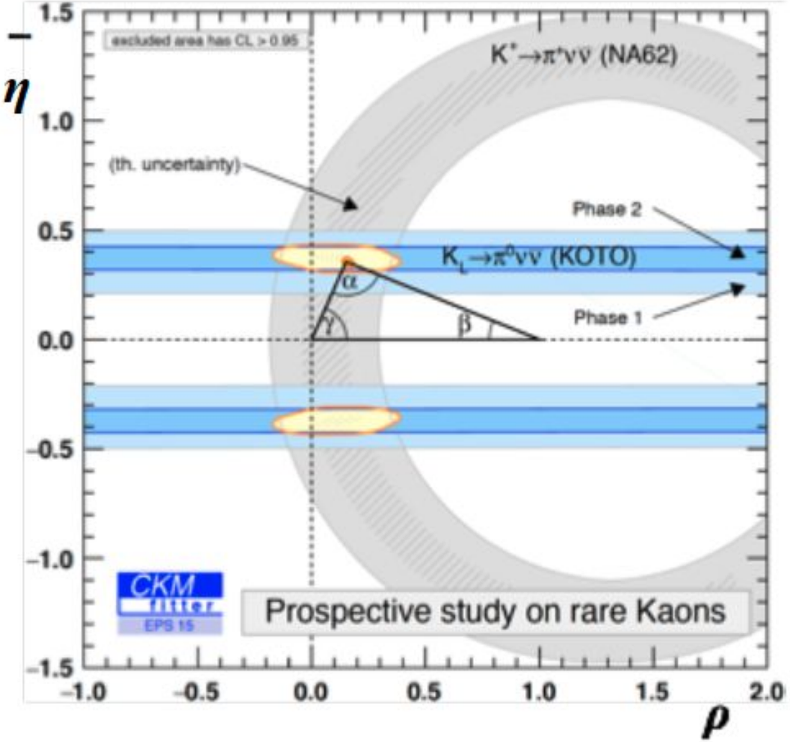
- FCNC loop process s →d coupling with high CKM suppression
- Clean theoretical prediction: short distance contributions
- Hadronic matrix elements: obtained from Kl3 measurements and SU(2) isospin symmetry

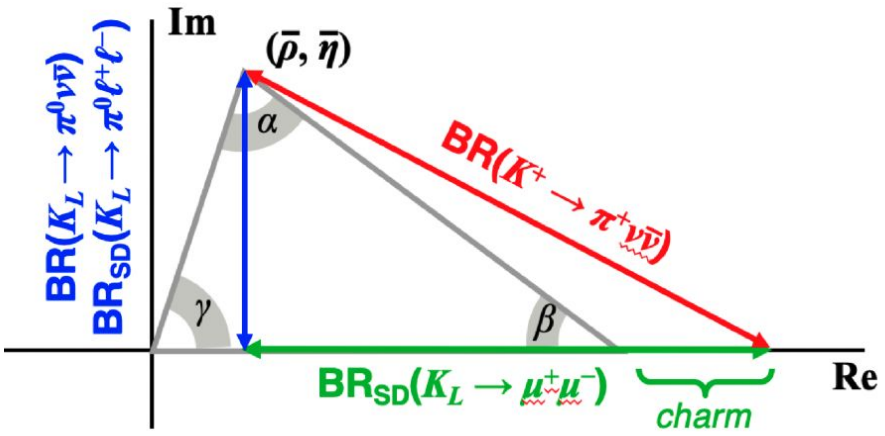
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.03) \times 10^{-10} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (0.84 \pm 0.10) \times 10^{-10}$$

- Channel sensitive to physics BSM

Complementarity to B flavour Physics

Measurement of BR of ($K^+ \to \boldsymbol{\pi}^+ \mathbf{vv}$) and ($K_L \to \boldsymbol{\pi}^0 \mathbf{vv}$) modes can determine the unitarity triangle independently from B inputs





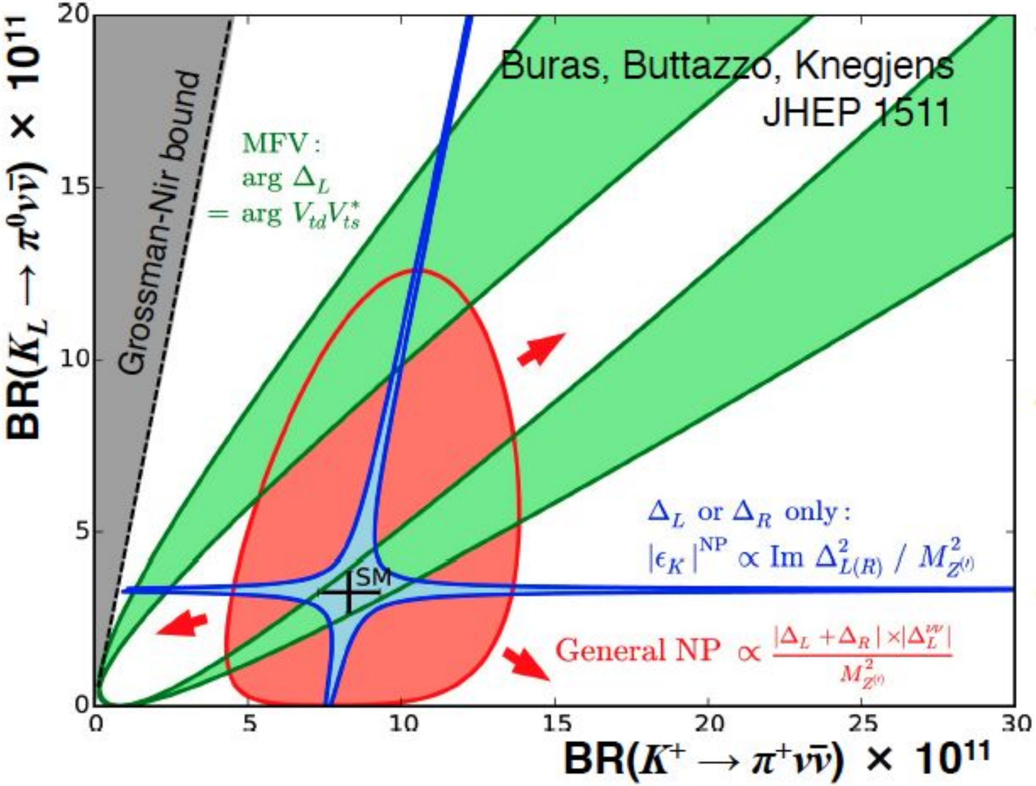
Example of CKM constraints:

- BR($K^+ \to \pi^+ \nu\nu$) to ±10%
- BR($K_L \to \pi^0 \nu\nu$) to 15%

- Complementarity to B physics
- Over-constraining CKM matrix can reveal new physics effects

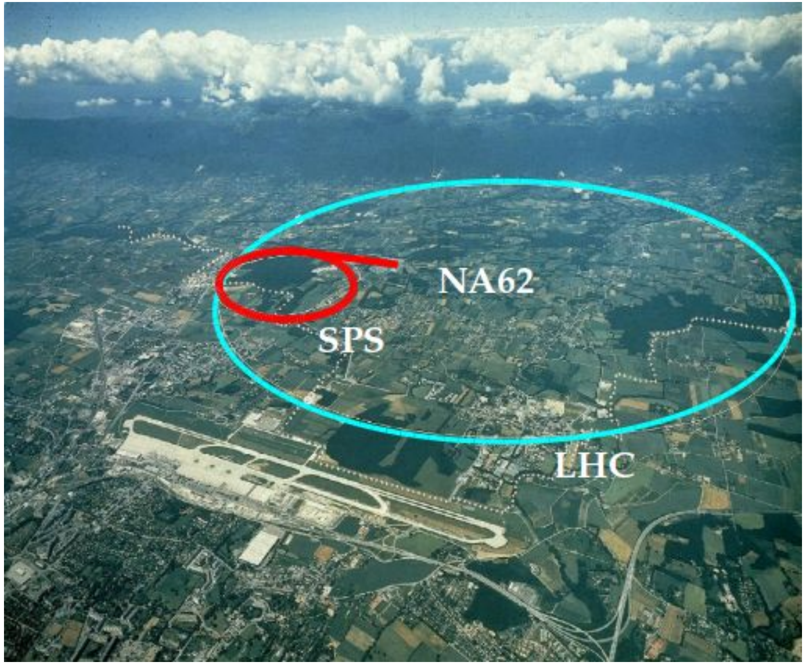
$K^+ \to \pi^+ \nu\bar{\nu}$ New Physics

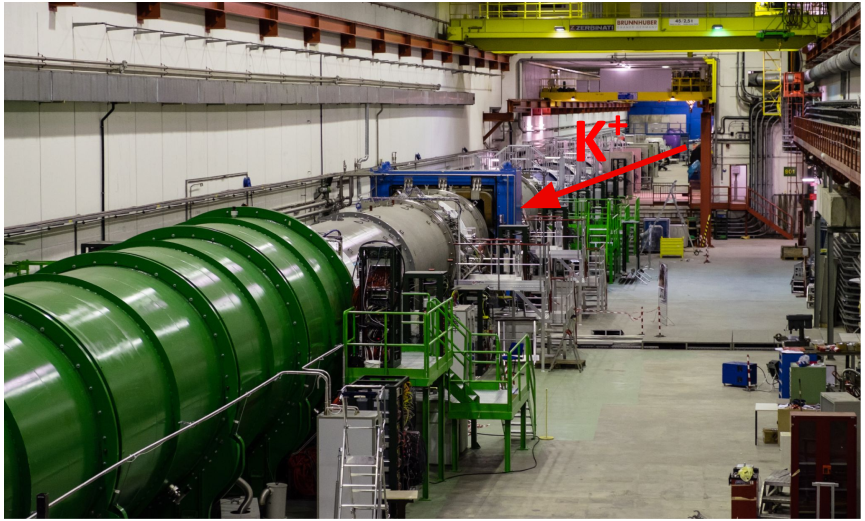
NP affects K^+ and K_L BRs differently: measure of both can discriminate among new physics scenarios



- Models with CKM-like flavour structure:
  - Models with MFV
- Models with new flavour-violating interactions in which either LH or RH couplings dominate:
  - Z/Z’ models with pure LH/RH couplings
  - Littlest Higgs with T parity
- Models without above constraints:
  - Randall-Sundrum
- Grossman-Nir bound:
  - Model independent relation
  - $$\frac{BR(K_L \to \pi^0 \nu\bar{\nu})}{BR(K^+ \to \pi^+ \nu\bar{\nu})} \times \frac{\tau_+}{\tau_L} \le 1$$

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.

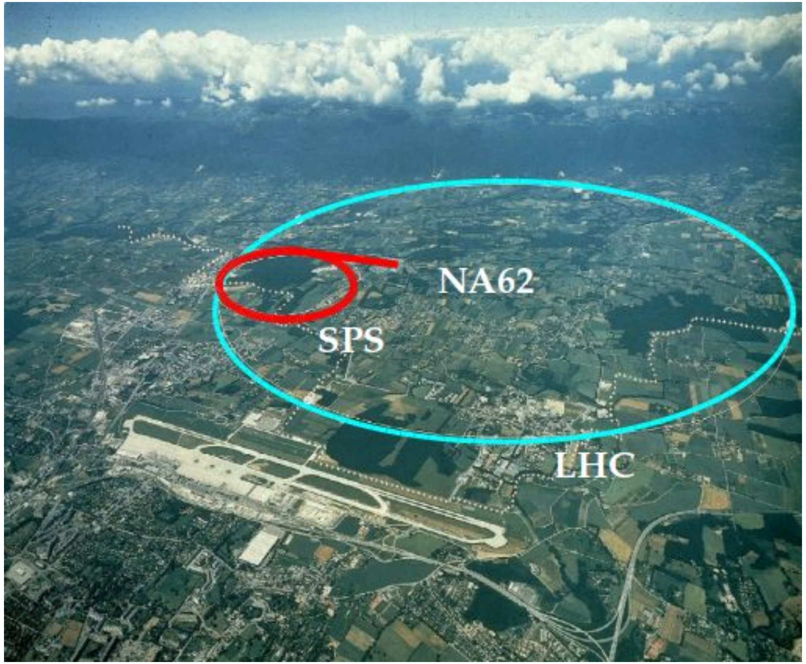
75 GeV/c unseparated hadrons beam:

π^+(70%), K^+ (6%), p(24%).

100 mrad divergence (RMS)

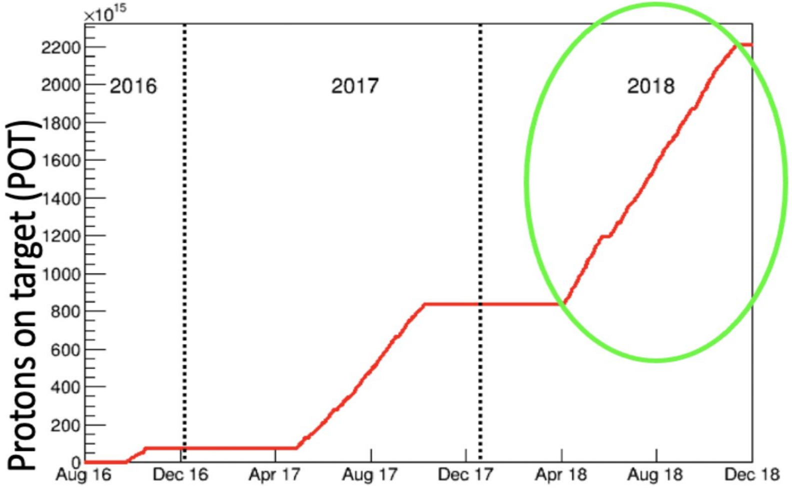
60x30 mm^2 transverse size.

The NA62 experiment at the SPS



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

2.2 10^{18} POT



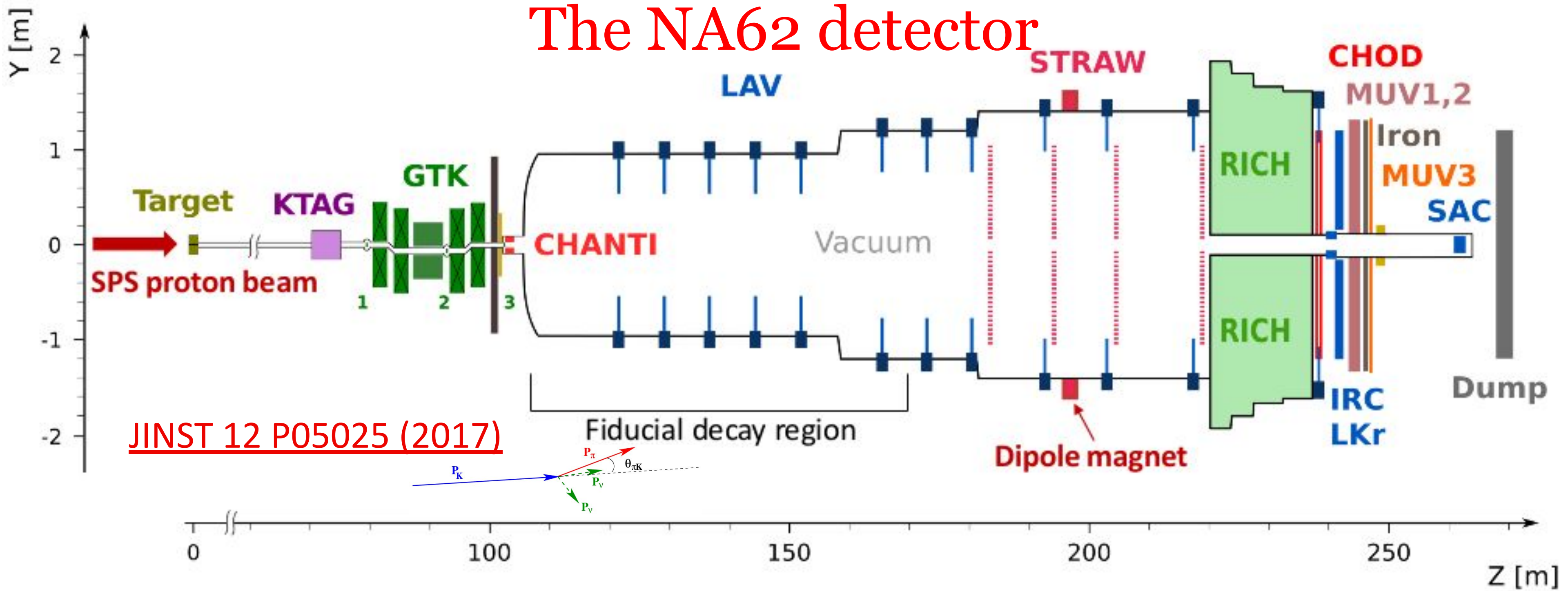
Intensity: 750 MHz (45 MHz K^+).

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



JINST 12 P05025 (2017)

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

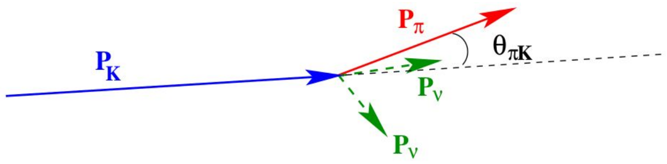
LKR/MUV1/2: Calorimetric systems

Vetos:

LAV/IRC/SAC: photons

MUV3: muons

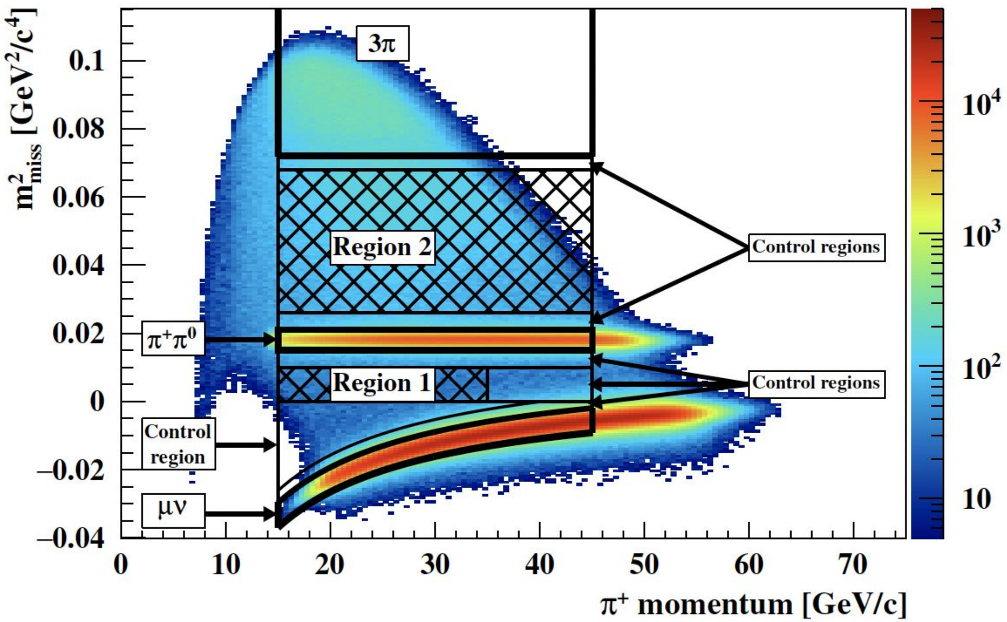
$K^+ \to \pi^+ \nu\bar{\nu}$ selection



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

Selection steps:

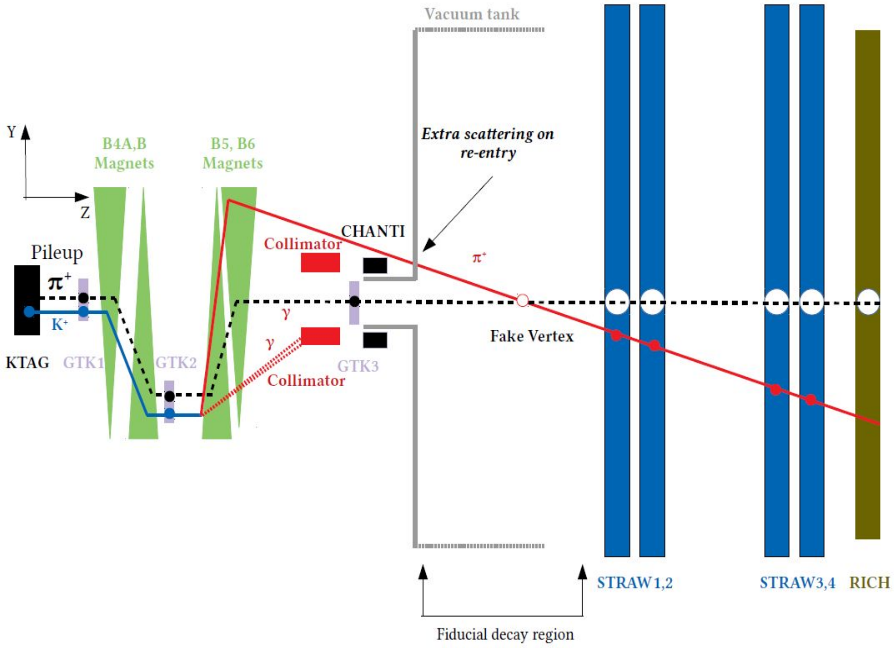
- K^+ and π^+ track reconstruction
  - L0: presence of charged particles and μ/γ veto
  - L1: K^+ ID+ photon veto
- K^+- π^+ matching
  - Excellent time resolution O(100ps)
- Decay vertex FV, CDA and other cuts
- π^+ ID (μ^+ rejection ~ 10^{-7})
- Photon rejection (~ 10^{-7})
- Kinematic cuts (m^2_{miss}, p_π):
  - Signal regions + control regions defined: blind analysis performed



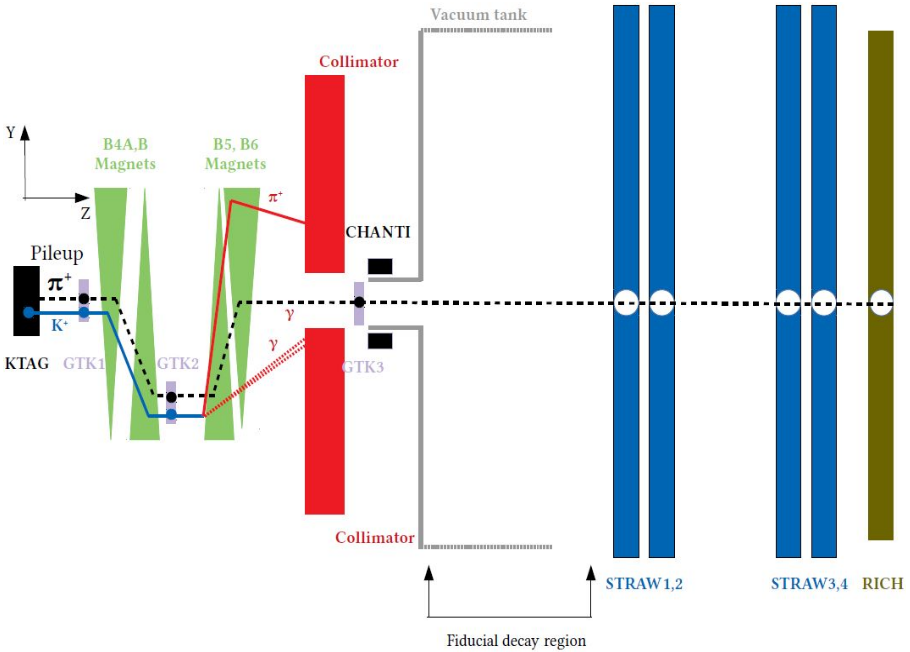
MINIMUM BIAS data shown

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

Upstream background



OLD collimator, "S1" sample early 2018

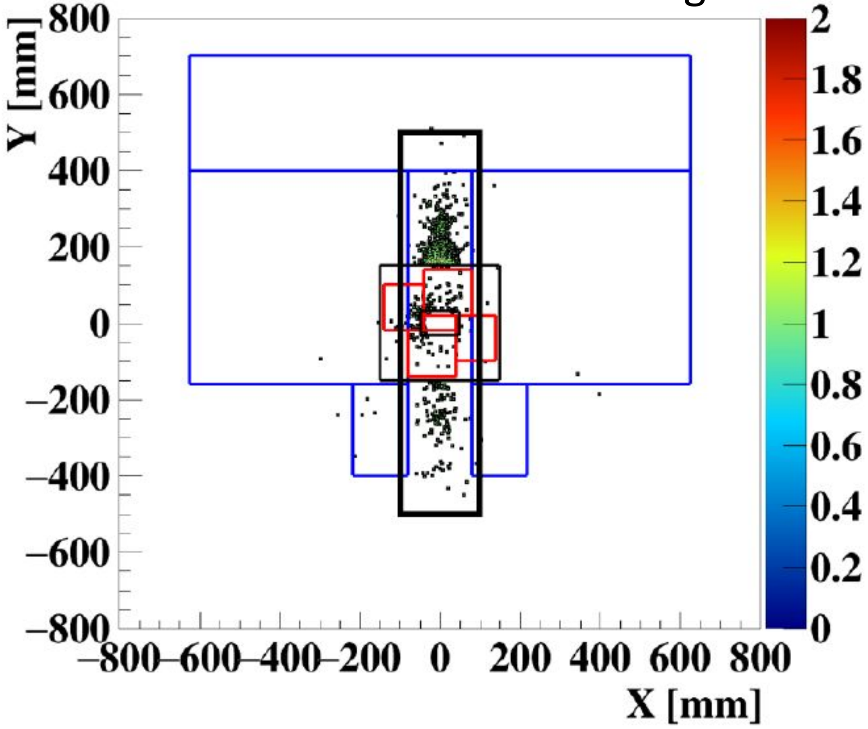


NEW collimator, "S2" majority of 2018

Upstream background

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

Red boxes: collimator coverage.



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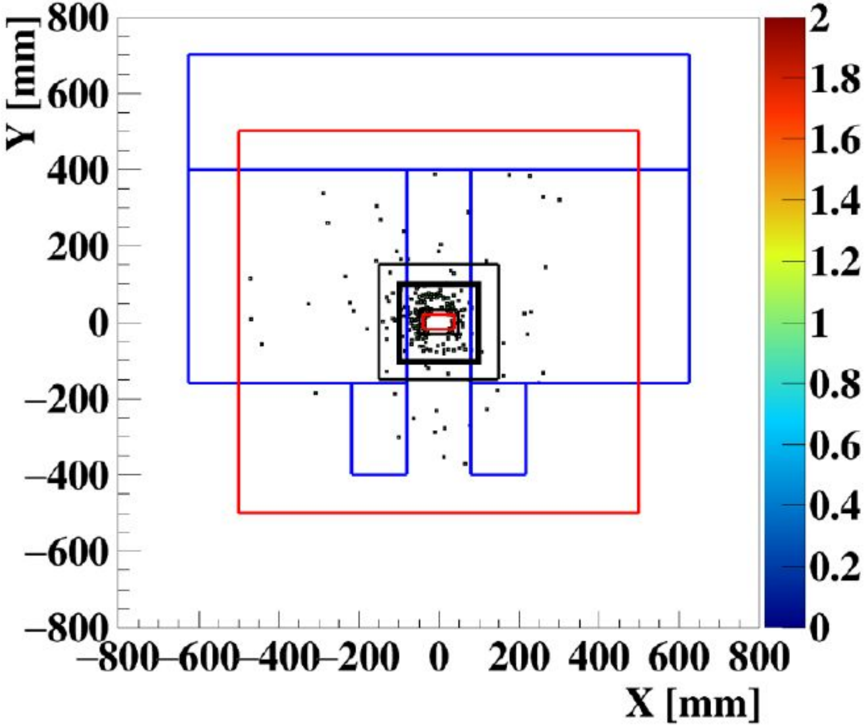
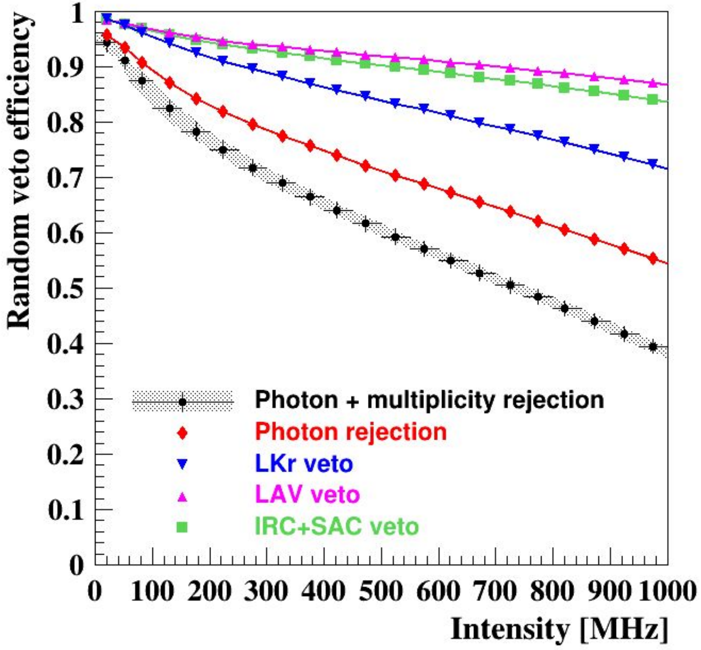


NEW collimator, "S2" majority of 2018

Single Event Sensitivity

SES

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

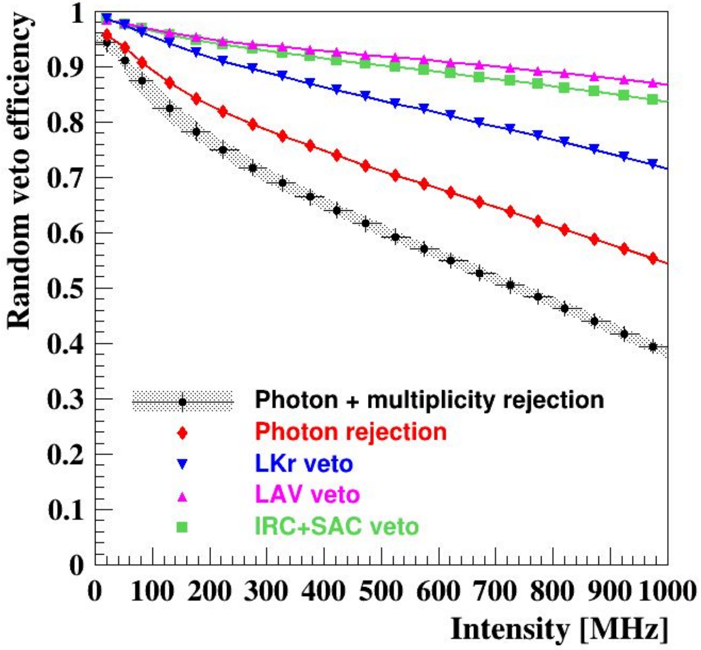


	Subset S1	Subset S2
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^2$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^2$	3.95 ± 0.40	6.37 ± 0.64
$\epsilon_{\rm trig}^{\rm PNN}$	0.89 ± 0.05	0.89 ± 0.05
$\epsilon_{\rm RV}$	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 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:

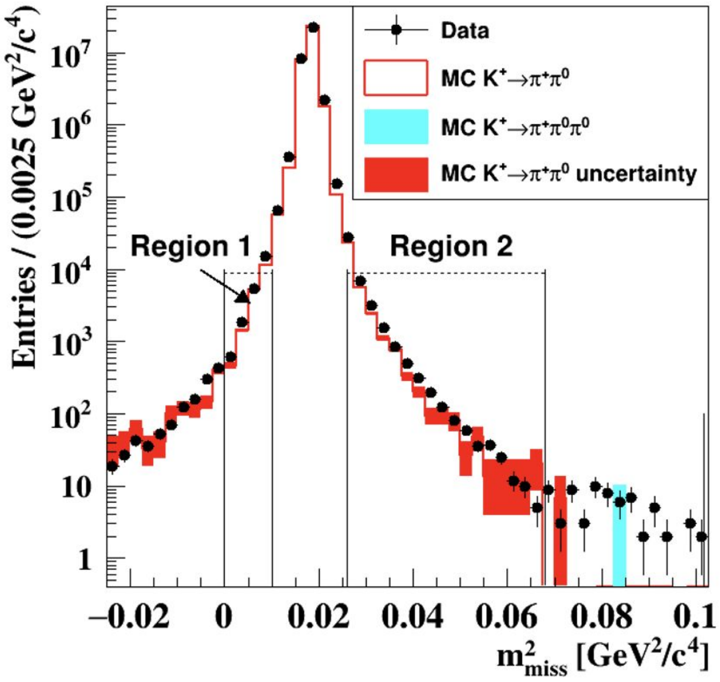
- $K^+ \to \pi^+\pi^0$
- $K^+ \to \mu^+\nu$
- $K^+ \to \pi^+\pi^+\pi^-$

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

Events expected in signal/control region after ***πνν*** selection

Events in $\pi^+\pi^0$ region after ***πνν*** selection

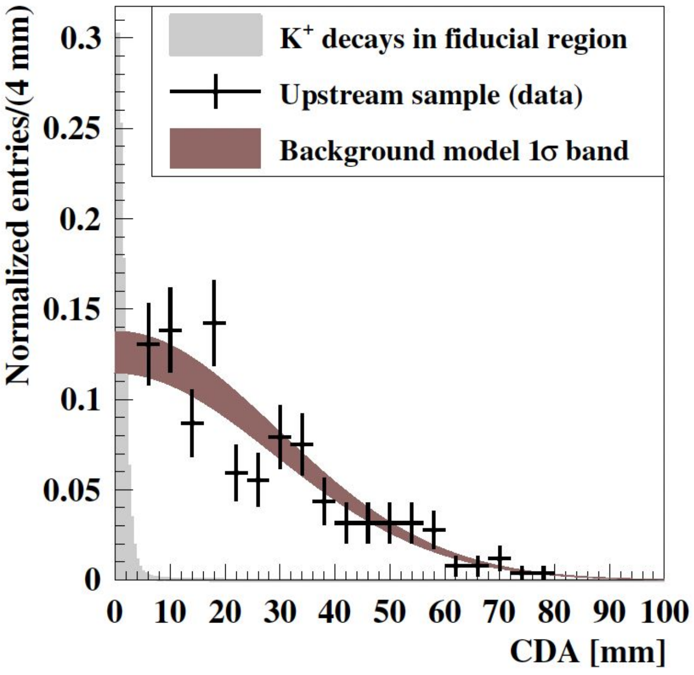
Fraction of events in signal/control region in MINIMUM BIAS sample



MC estimation (validated using minimum-bias samples) normalized:

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

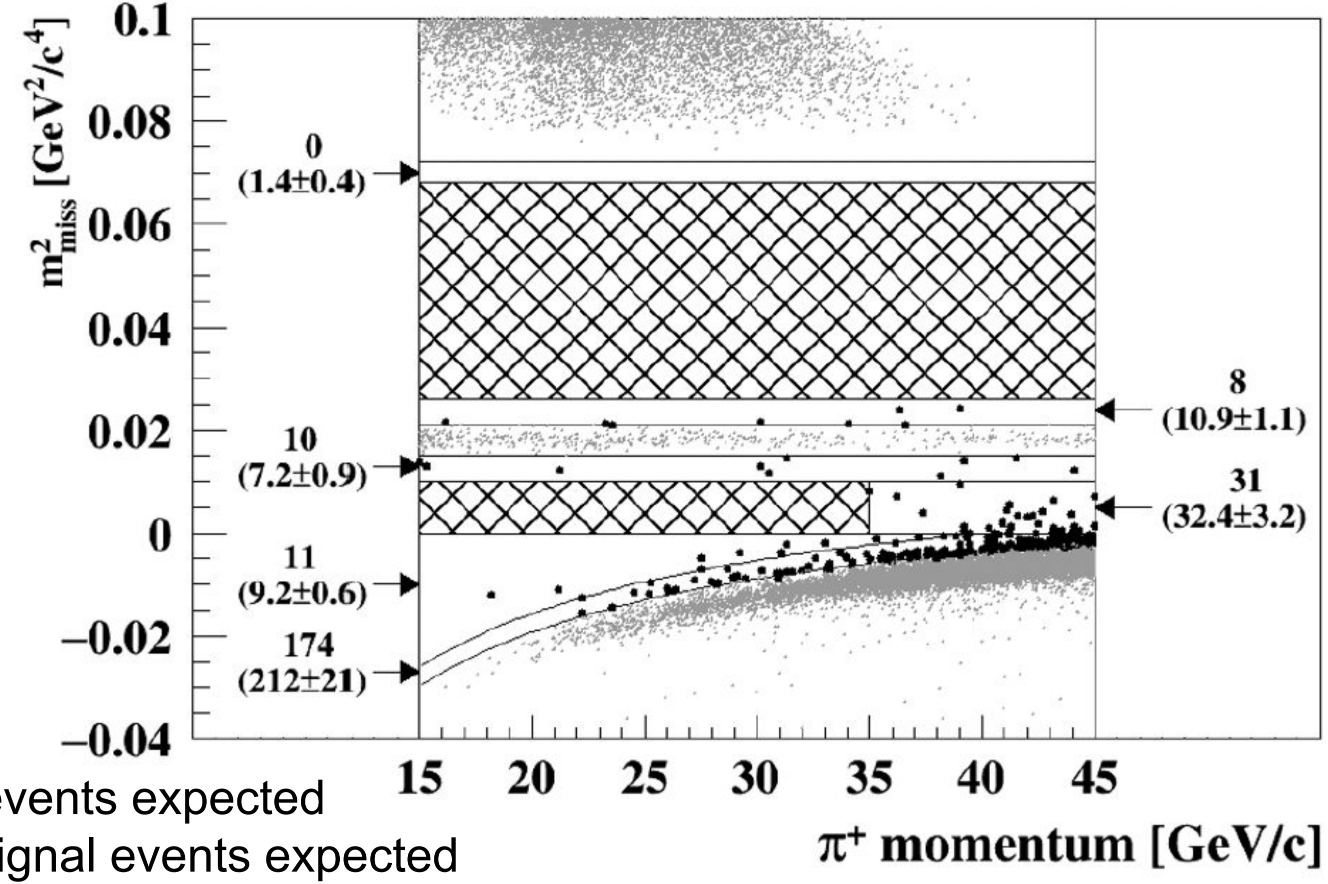
Upstream background



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

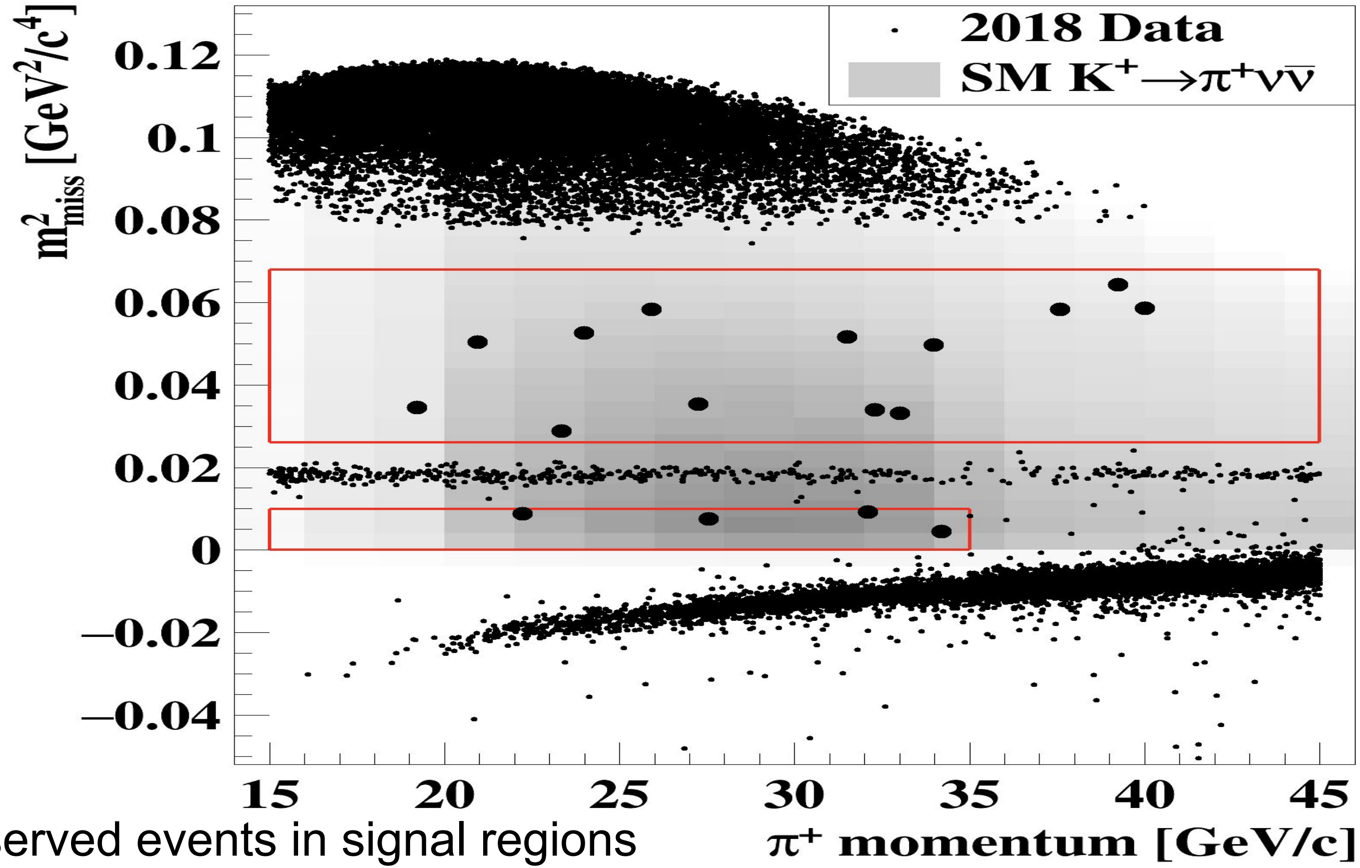
Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$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

Control regions and expectation



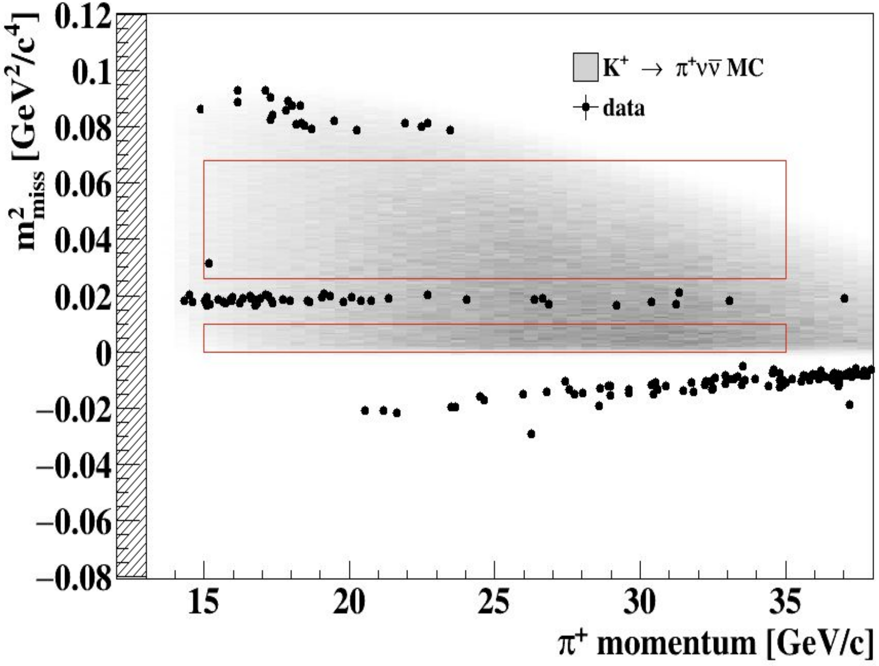
- 5.4 bkg events expected
- 7.6 SM signal events expected

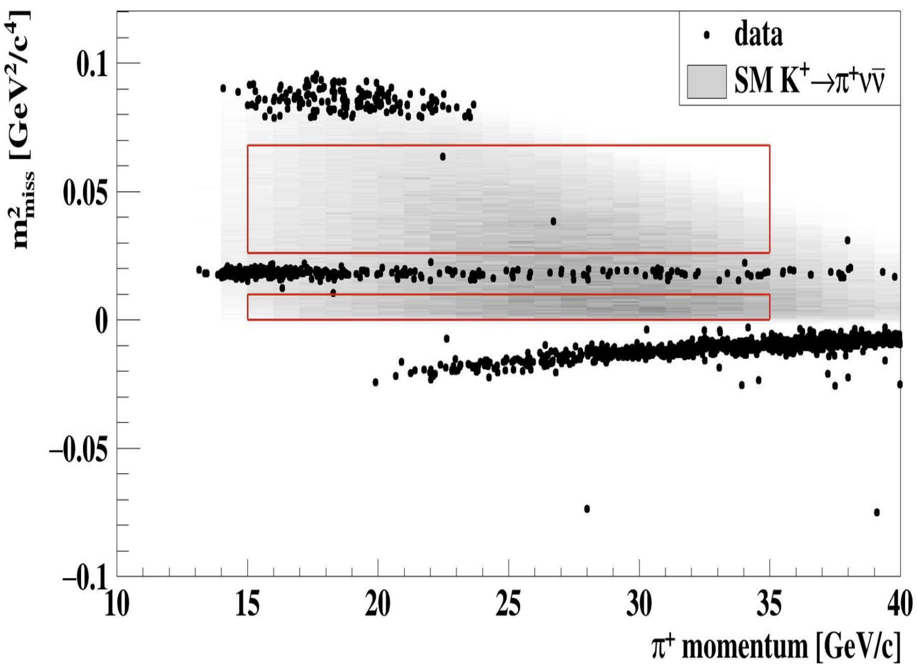
Data selection 2018 unblinded



- 17 observed events in signal regions

2016 and 2017 results

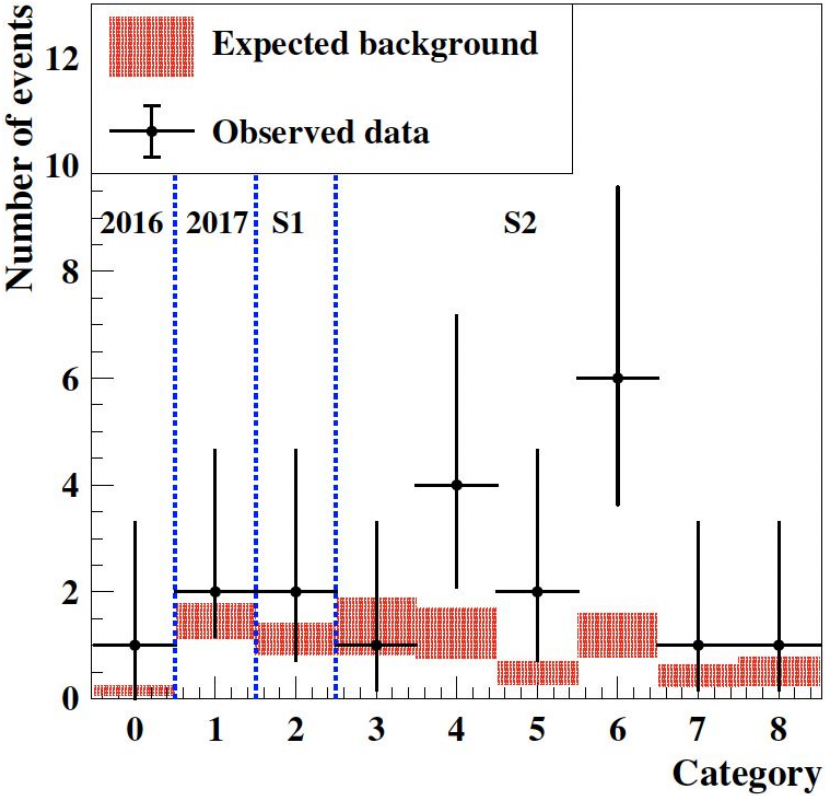




1 event observed
BR($K^+\to\pi^+\nu\nu$)< 14 10^{-10} @90% CL
Phys. Lett. B 791 (2019) 156-166

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

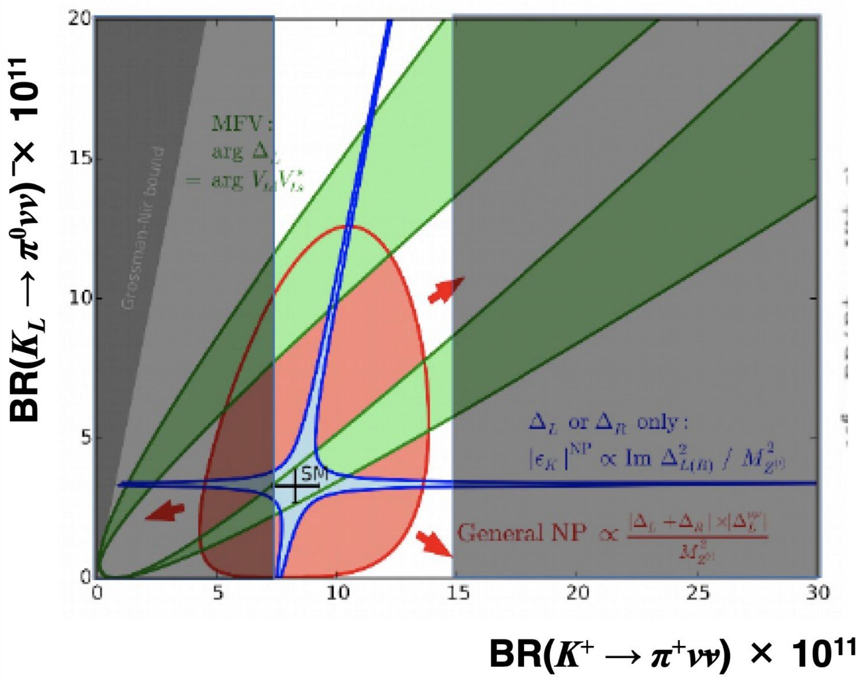


- Maximum likelihood fit using observed data and background expectations in each category
- 2016, 2017, 2018 with old collimator (S1) and 2018 with new collimator (S2)
- S2: sample split in 5 GeV/c wide bins from 15-45 GeV/c

JHEP 06 (2021) 093

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

$K^+ \to \pi^+ \nu\bar{\nu}$ and New Physics



- Large deviation from the SM expectation seems to be excluded
- A more precise measurement is needed

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

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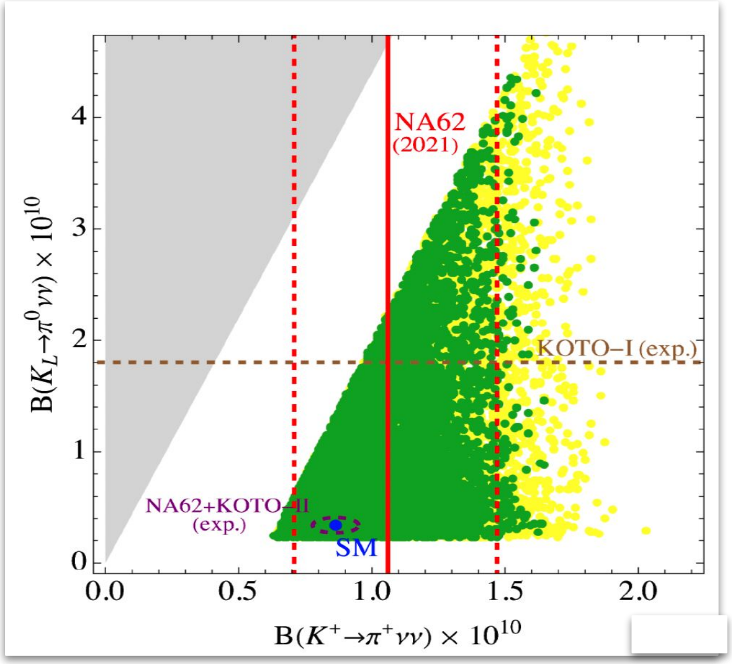
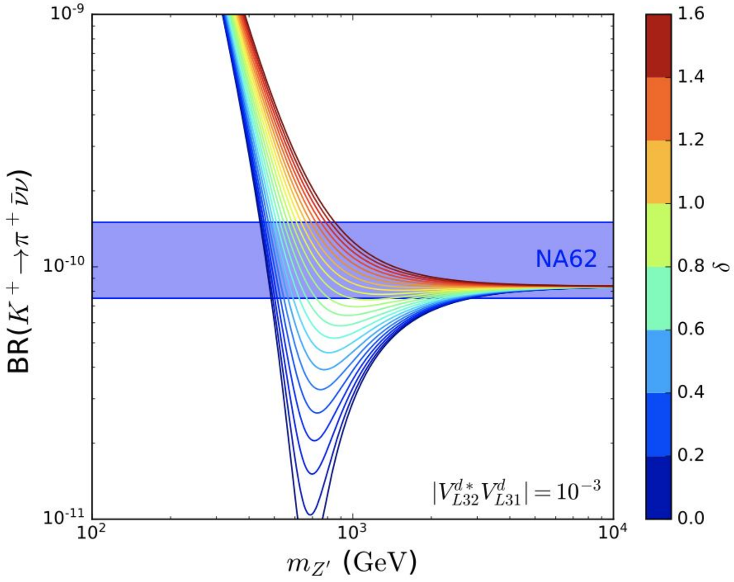




Marzocca et al., Eur. Phys. J. C (2022)

Generic scalar Leptoquark model addressing B anomalies

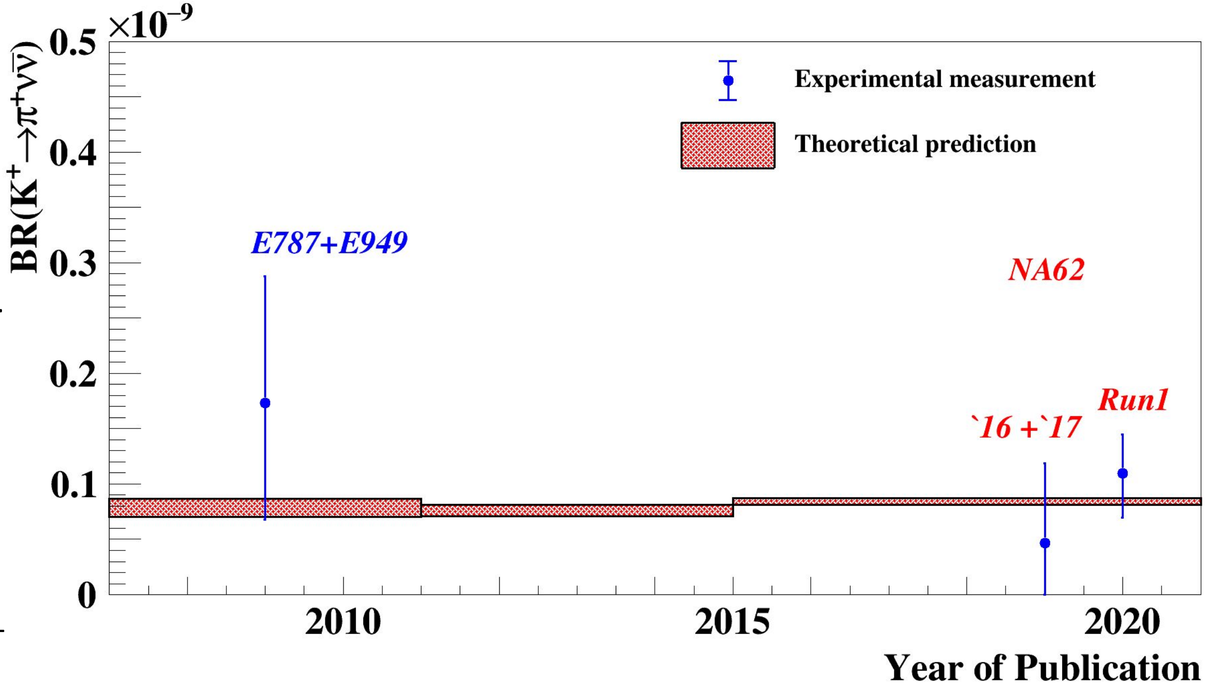
Tessio B. de Melo et al., *Phys.Rev.D* 103 (2021) 11

Z' mediated interactions, setting lower limits on the Z' mass mZ'~5TeV at $\boldsymbol{\delta}$=0

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 $K^+ \to \pi^+\nu\bar{\nu}$
- 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!

Conclusions

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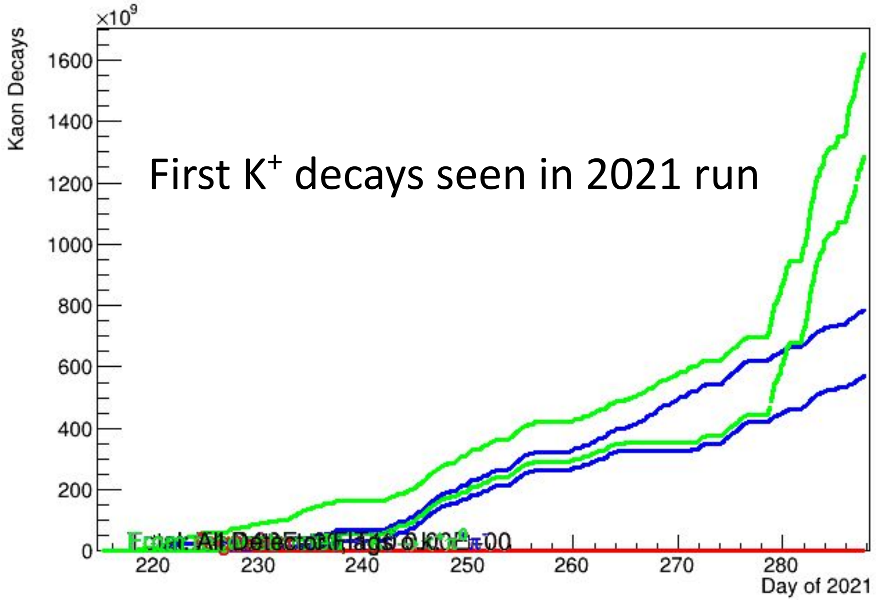
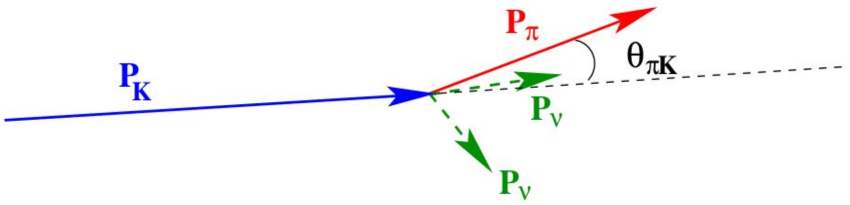


Run II just started: stay tuned!

Backup slides

Analysis strategy



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

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

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

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

$$\delta M^2 = 0.00196\ GeV^2$$

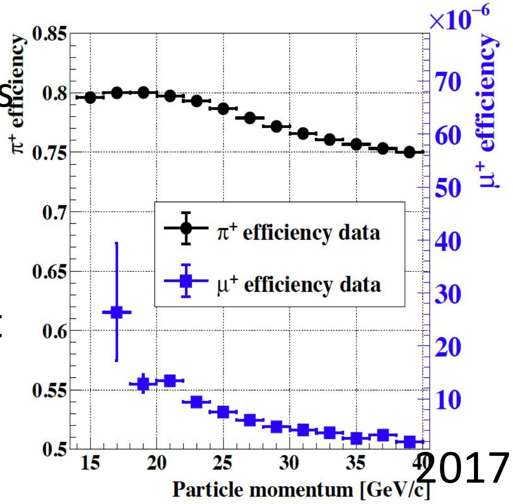
- Decay in flight technique
- Build missing invariant mass square

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

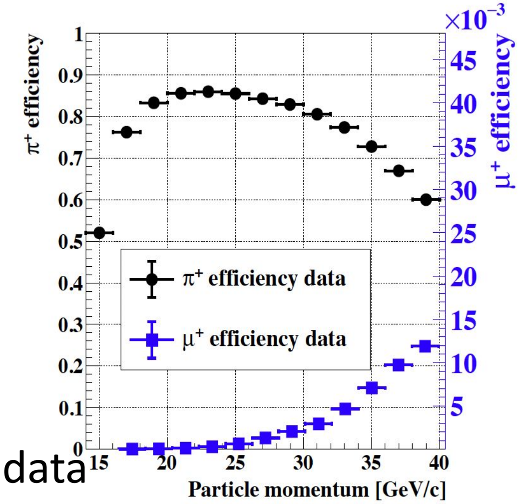
Selection steps:

- 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

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

Selection steps:

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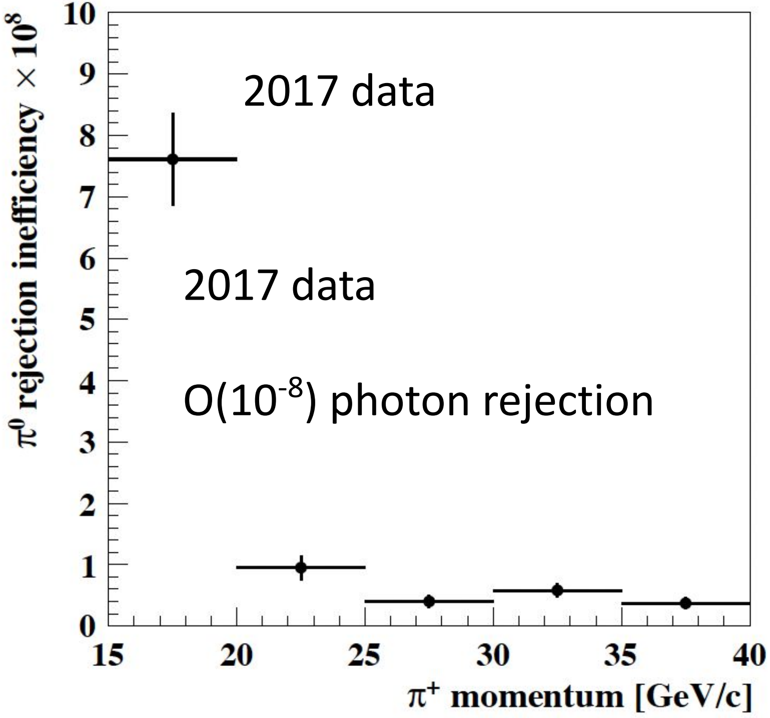
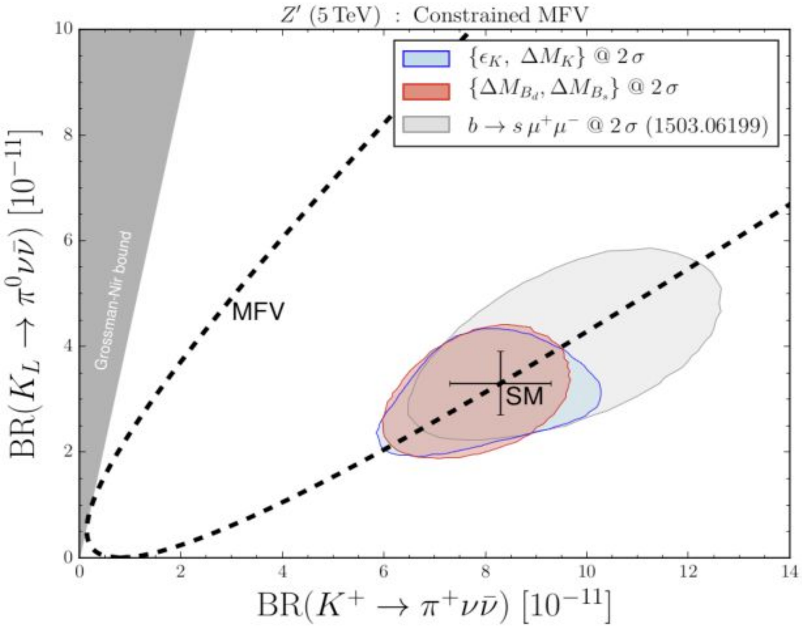
- K^+- π^+ matching
  - dT(RICH,KTAG,GTK) and closest distance of approach
- Decay vertex reconstruction + cuts
- π^+ ID (μ^+ rejection)
- Photon rejection

All Photon vetoes

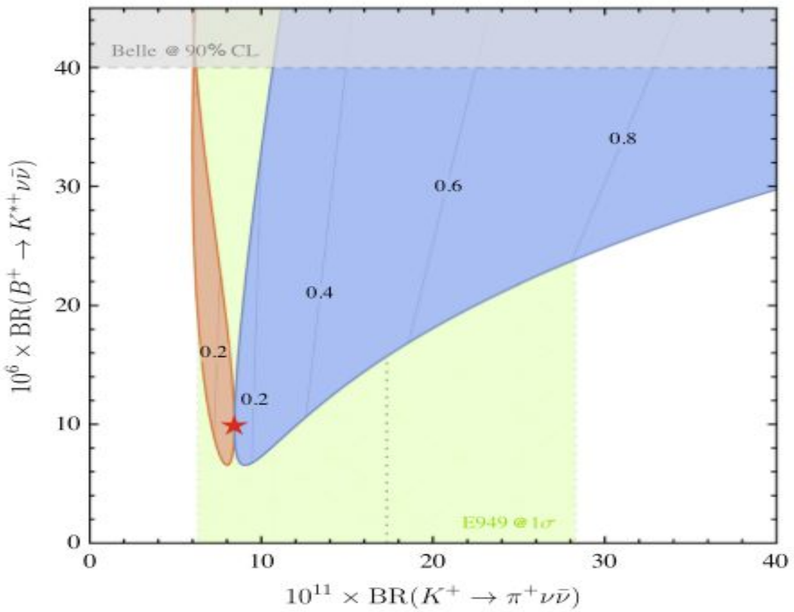


$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ beyond the Standard Model

Buras et al.,JHEP11 (2015) 166



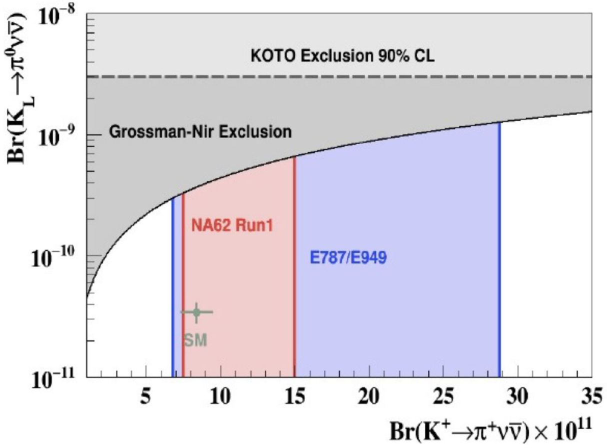
Isidori et al., Eur. Phys.J. C (2017) 77

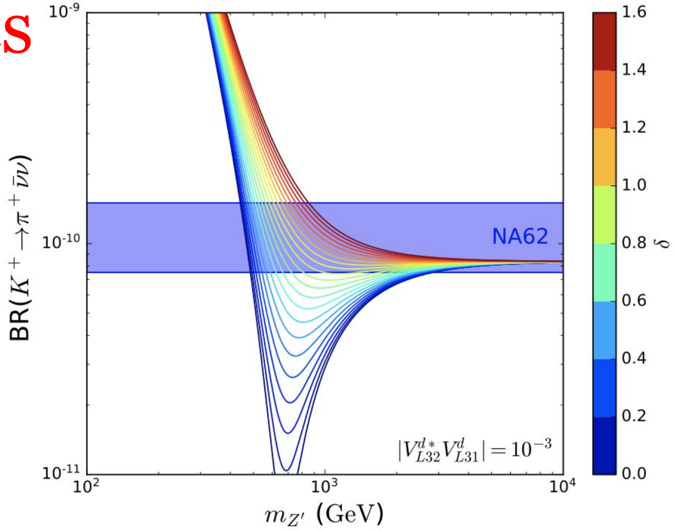


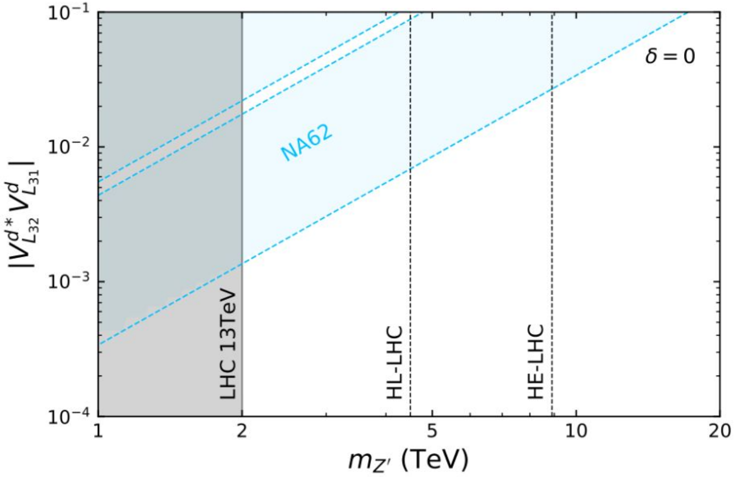
New Physics: BR sensitive to the highest mass scale

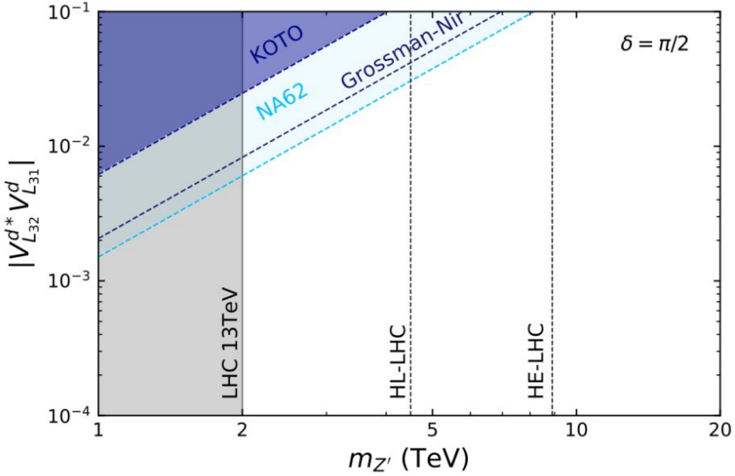
New Physics Models: MFV; Simplified Z, Z’; LFU violation;MSSM; Leptoquarks..

$K^+ \to \pi^+ \nu\bar{\nu}$ and New Physics

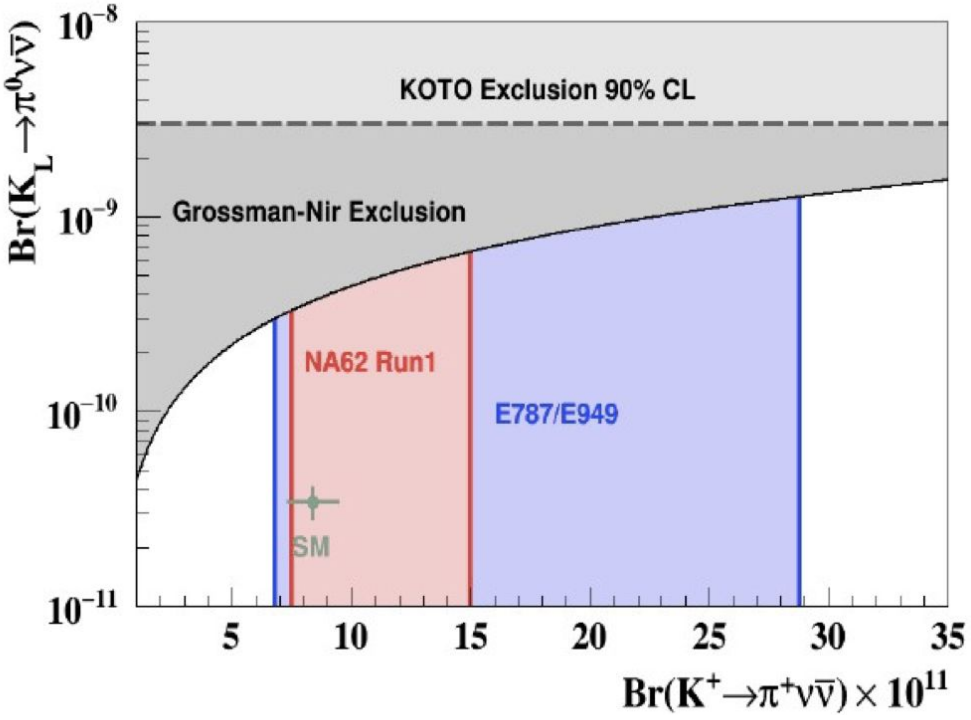








$K^+ \to \pi^+ \nu\bar{\nu}$ and New Physics



- Large deviation from the SM expectation seems to be excluded
- A more precise measurement is needed

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

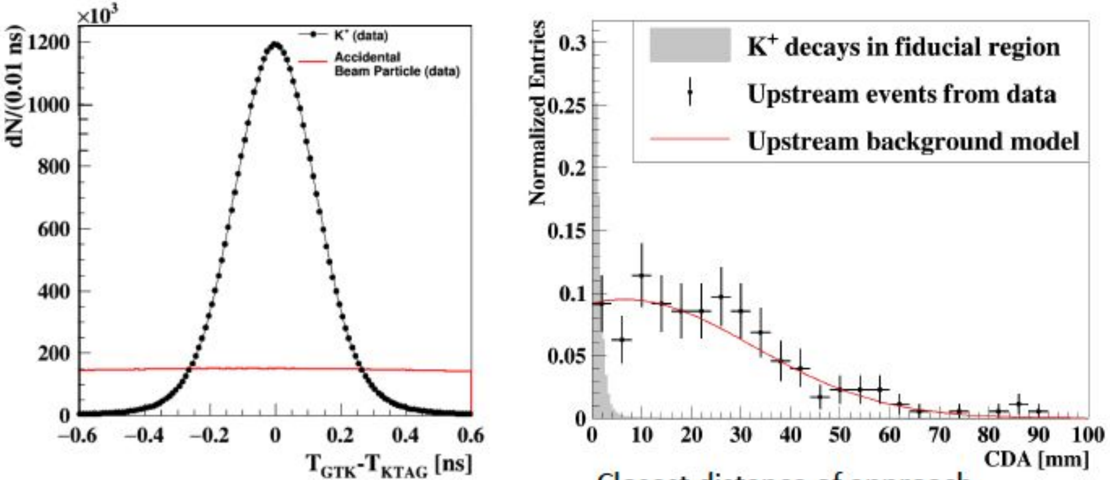
$$N^{bg}_{upstream} = N^{\pi^+}_{upstream} \cdot P^{reco}_{pileup} \cdot P^{matching}_{K-\pi}$$

Events with a downstream 15-35 GeV/c π^+ originating upstream of GTK3

Probability that a π^+ from the beam is reconstructed in the GTK

Probability that the downstream π^+ is matched to a GTK track

Number of events after πνν selection in a sample enriched of upstream background



Closest distance of approach

Probability to be on time · probability to have CDA < 4 mm (matching cut)