Kaon physics: recent results

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Introduction

Kaons: very clean environment, protagonists of many discoveries since 1947!

Current primary experimental focus: **“Golden modes”**

but also many results about..

Lepton Universality tests

BSM searches

this talk

(topic selection driven by recent results!)

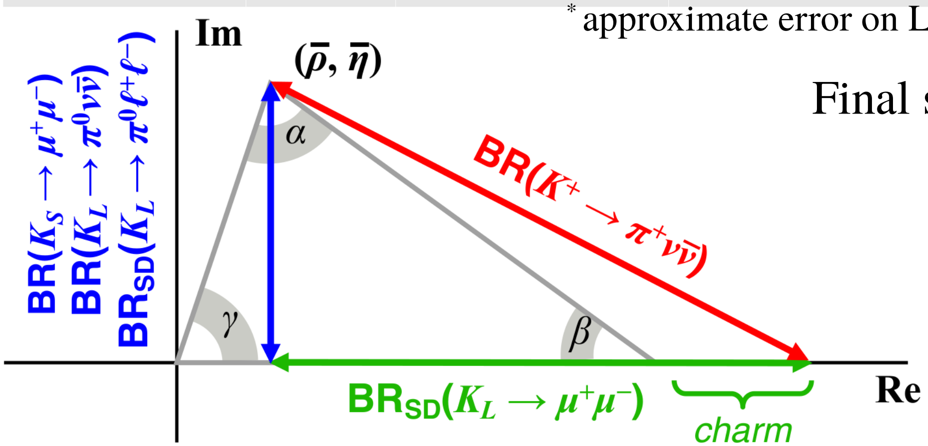
The golden modes

- FCNC forbidden at tree level: 1-loop contributions as leading order
- Highest CKM suppression: BR ~ $|V_{ts}{}^{*}V_{td}|^2 \sim \lambda^{10}$

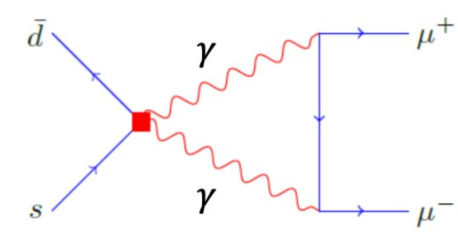
} high sensitivity to new physics

Decay	Γ_{SD}/Γ	Theory error*	SM BR × 10^{11}	Experimental BR × 10^{11} (before KAON19)	Experiment	Year
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	< 300	KOTO	2019
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.4 ± 1.0	$17.3^{+11.5}_{-10.5}$	BNL-787/949	2009
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28	KTeV	2004
$K_L \to \pi^0 \mu^+ \mu^-$	30%	15%	1.5 ± 0.3	< 38	KTeV	2000
$K_L \to \mu^+ \mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11	BNL-871	2000
$K_S \to \mu^+ \mu^-$	4%	>30%	0.52 ± 0.15	< 80	LHCb	2017

* approximate error on LD-subtracted rate excluding parametric contributions

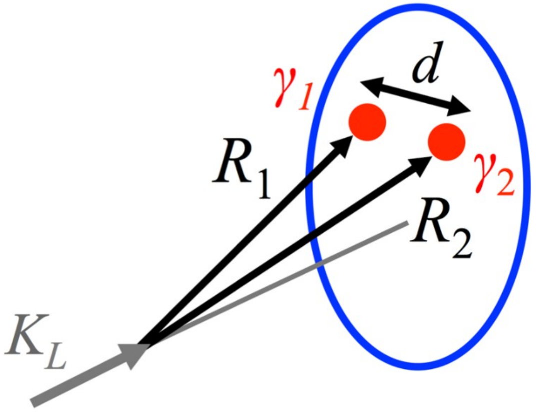


Final states with $\ell^+\ell^-$ pair polluted by non-perturbative QCD long distance (LD) contributions:



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

$K_L \to \pi^0 \nu\bar{\nu}$ signature: 2γs + missing p_T + nothing else!



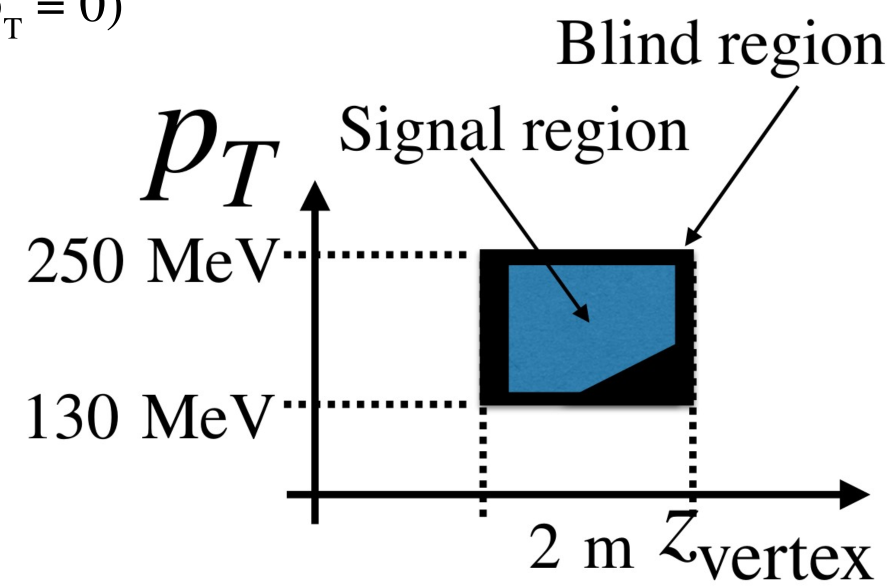
- K_L momentum not known → Kinematics with p_T
- Decay vertex reconstructed assuming $M(\gamma\gamma) = m(\pi^0)$

$$m_{\pi^0}^2 = 2E_1E_2\,(1-\cos\theta)$$

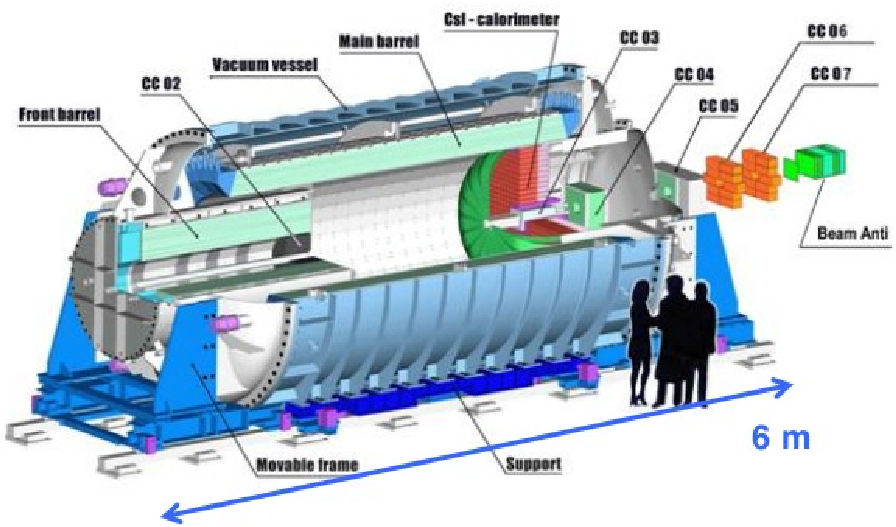
$$R_1 \approx R_2 \equiv R = \frac{d\sqrt{E_1E_2}}{m_{\pi^0}}$$

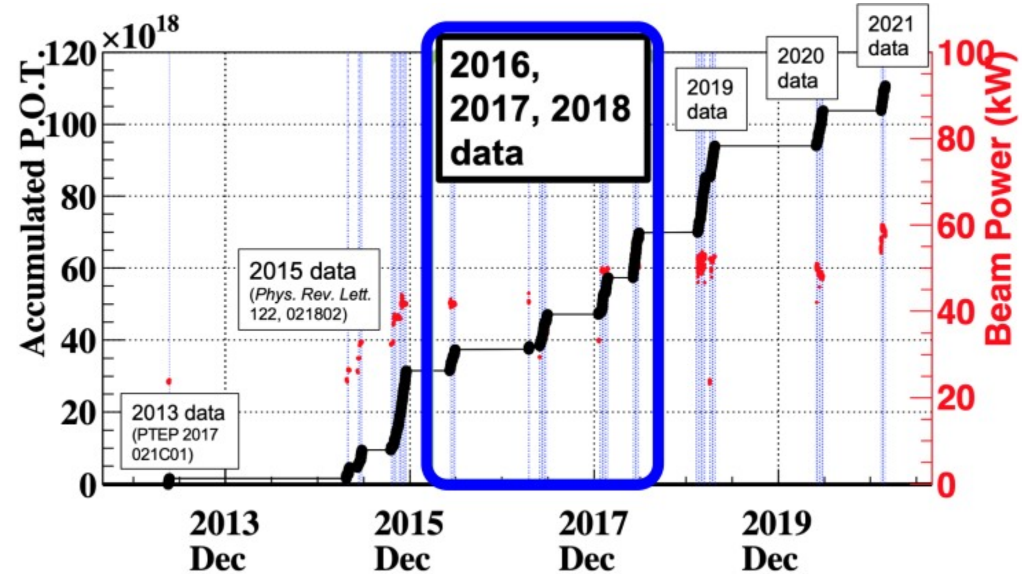
- Particle veto is essential:
  All other K_L decays have ≥ 2 extra γs or ≥ 2 tracks to veto,
  except $K_L \to \gamma\gamma$: 2γs + nothing else (but $p_T = 0$)

KOTO Keystones:
- Pencil neutral beam (precise p_T)
- Photon rejection
- Charged particle veto



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





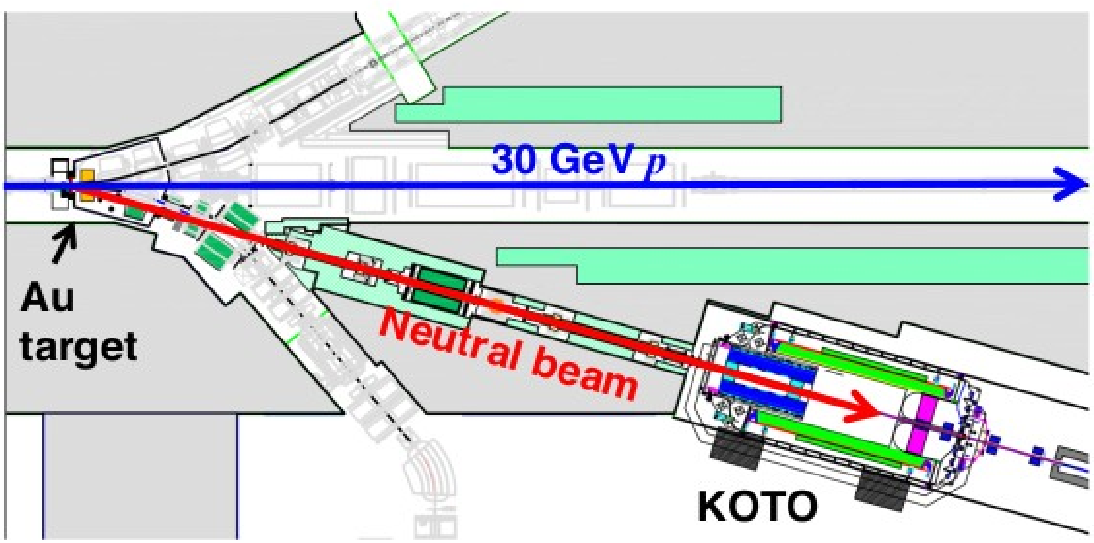
Primary beam: 30 GeV/c protons from J-PARC

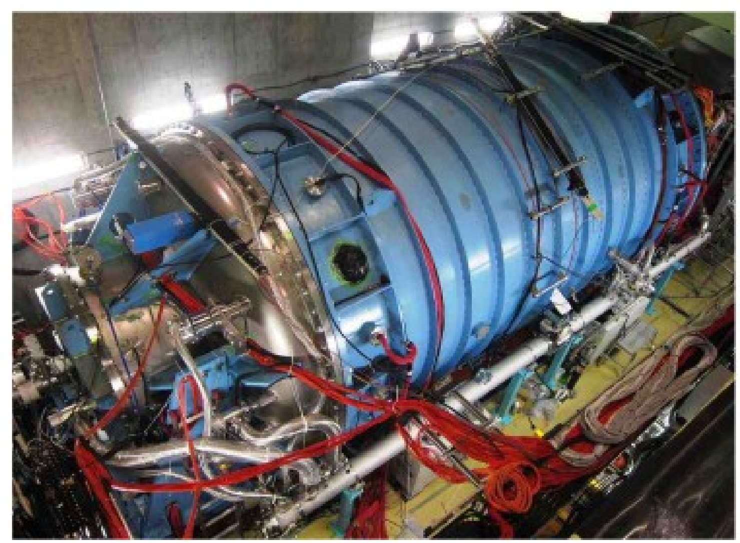
Neutral beam (16°), 8 μsr "pencil" beam

$<p(K_L)>$ = 2.1 GeV, 50% of K_L with p in [0.7-2.4] GeV

2016-2018 runs:

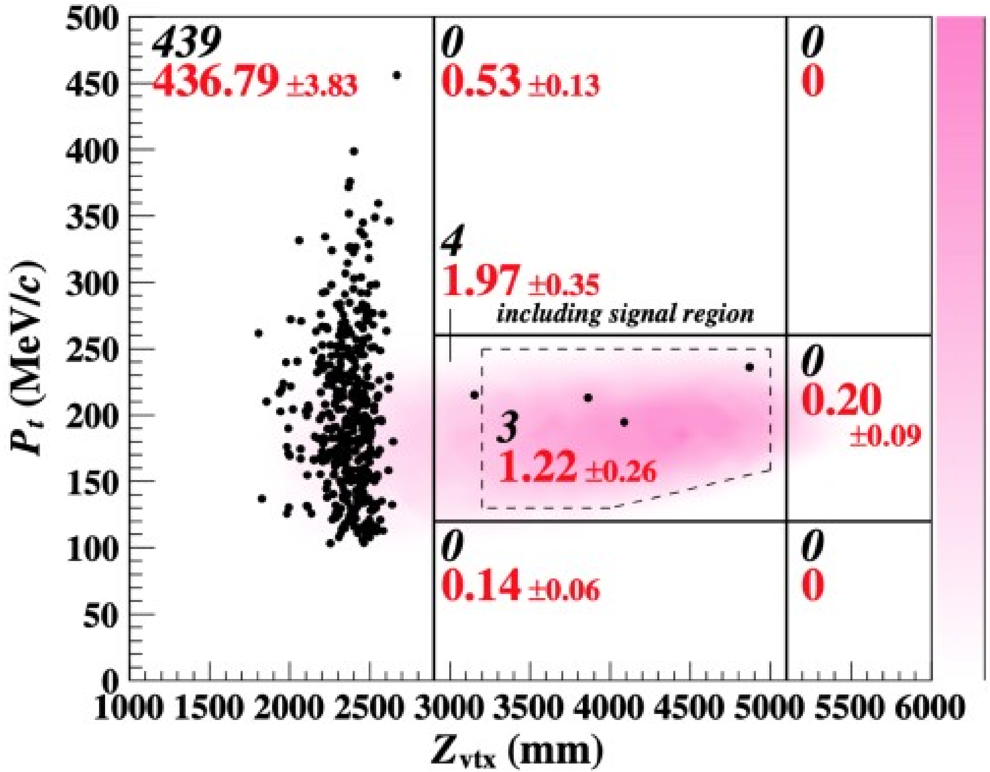
- Reached 50kW beam power
- 3.1×10^{19} POT collected





Final results: 2016-2018 data

PRL 126 (2021) 121801



Expected backgrounds

Source	Expected (68%CL)
$K_L \to \pi^0\pi^0\pi^0$	0.01 ± 0.01
$K_L \to \gamma\gamma$ halo	0.26 ± 0.07
Other K_L decays	0.005 ± 0.005
$K^{\pm}_{e3} + K^{\pm}_{\mu 3} + K^{\pm}_{\pi 2}$	0.87 ± 0.25
n interaction in CsI	0.017 ± 0.002
η from n in CV	0.03 ± 0.01
π^0 from upstream int.	0.03 ± 0.03
Total	**1.22 ± 0.26**

* Newly evaluated source after unblinding

Acceptance($K_L \to \pi^0 \nu \bar{\nu}$) from MC:
Decay in FV: 3.3%
Overall acceptance: 0.6%

K_L flux from $K_L \to \pi^0\pi^0 = 6.8 \times 10^{12}$

$$\mathrm{SES} = \frac{1}{A_{\mathrm{sig}} N_{K_L}} = (7.20 \pm 0.05_{\mathrm{stat}} \pm 0.66_{\mathrm{syst}}) \times 10^{-10}$$

→ **Expected:** 0.04 signal + 1.22 background events
Observed: 3 events in the signal box

$BR(K_L \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}$ (90% CL)

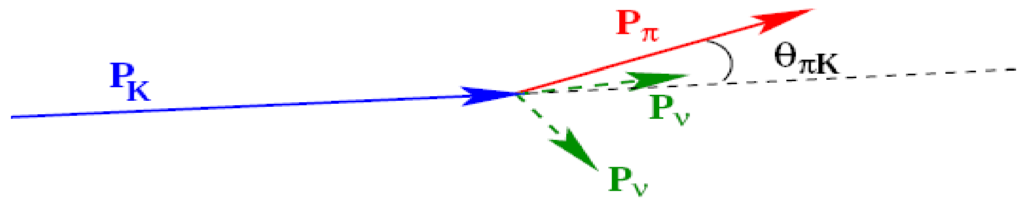
$K^+ \to \pi^+ \nu \bar{\nu}$ at NA62: strategy

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

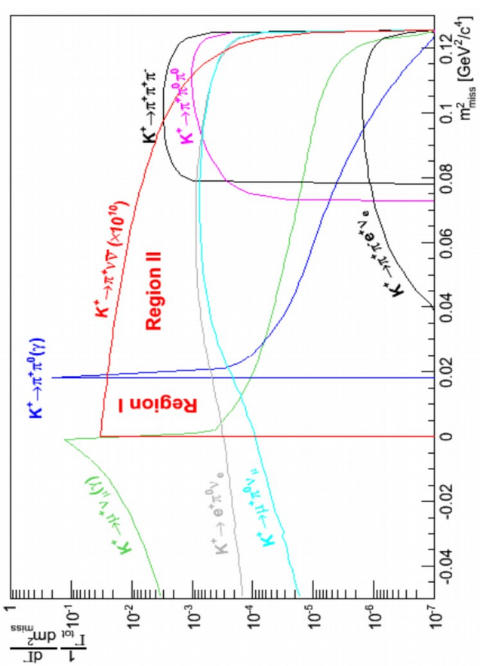
Kaon track +

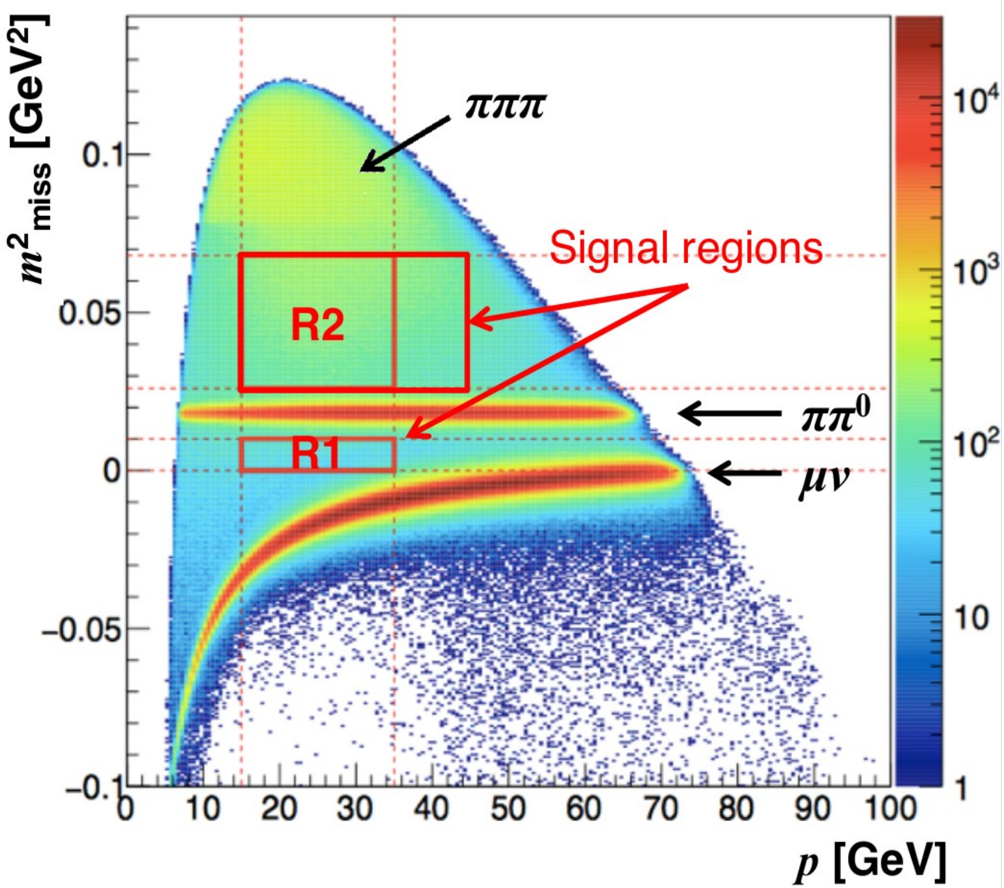
Pion track +

NOTHING ELSE



$$m^2_{miss} \approx m^2_K \left(1 - \frac{|p_\pi|}{|p_K|}\right) + m^2_\pi \left(1 - \frac{|p_K|}{|p_\pi|}\right) - |p_K||p_\pi|\theta^2_{\pi K}$$





Main backgrounds:

$BR(K^+ \to \mu^+ \nu) = 63.5\%$

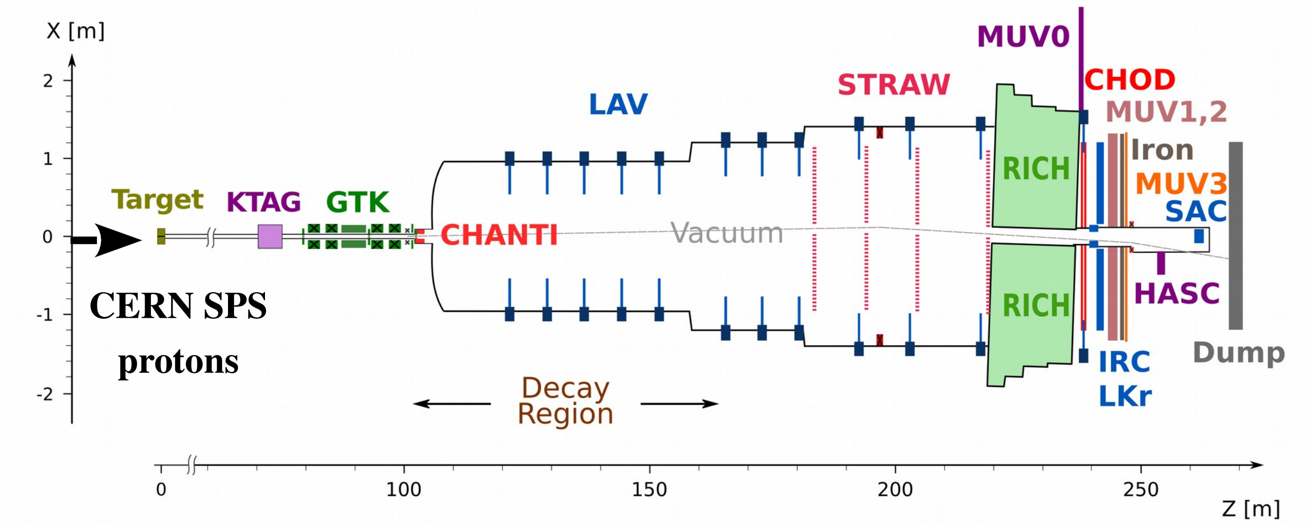
$BR(K^+ \to \pi^+ \pi^0) = 20.7\%$

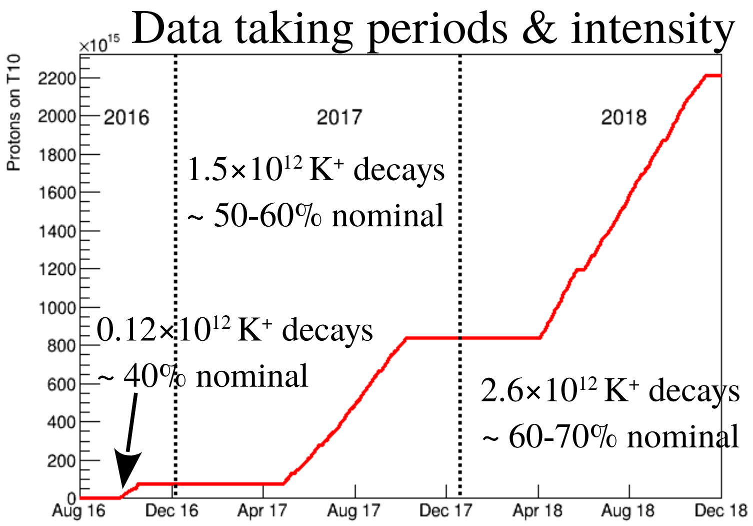
NA62 Keystones:

- Precise tracking
- PID (in particular π/μ)
- Photon rejection
- Precise timing: O(100 ps)

Background rejection at ~ 10^{11} level

The NA62 experiment





Primary beam:

- 400 GeV CERN SPS protons

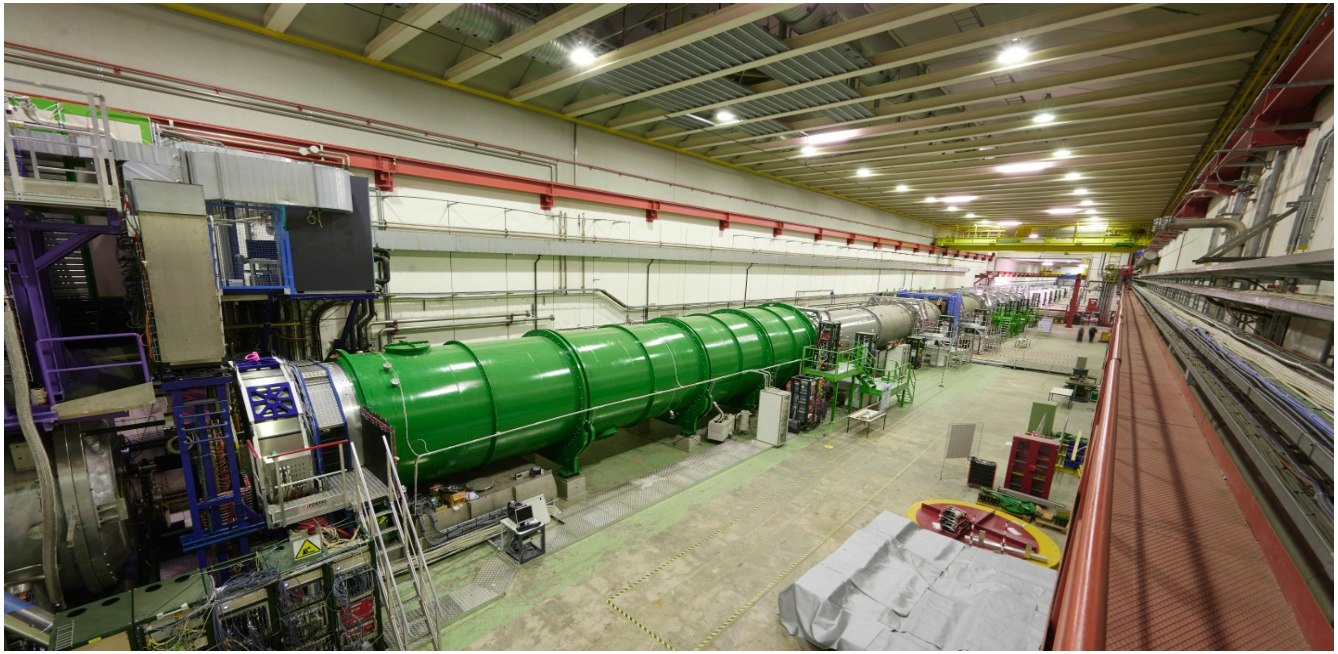
Secondary hadron beam:

- K^+ (6%) / π^+ (70%) / p (24%)
- p = 75 GeV, $\Delta p/p \sim 1\%$
- $60 \times 30\ mm^2$ transverse size

Decay region:

- 60 m long fiducial volume
- Vacuum ~ $O(10^{-6}$ mbar)
- ~ 5 MHz K^+ decay rate

Nominal intensity: ~ 3×10^{12} POT/spill → 750 MHz hadron beam



Final results: 2016-2018 data

2018 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	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

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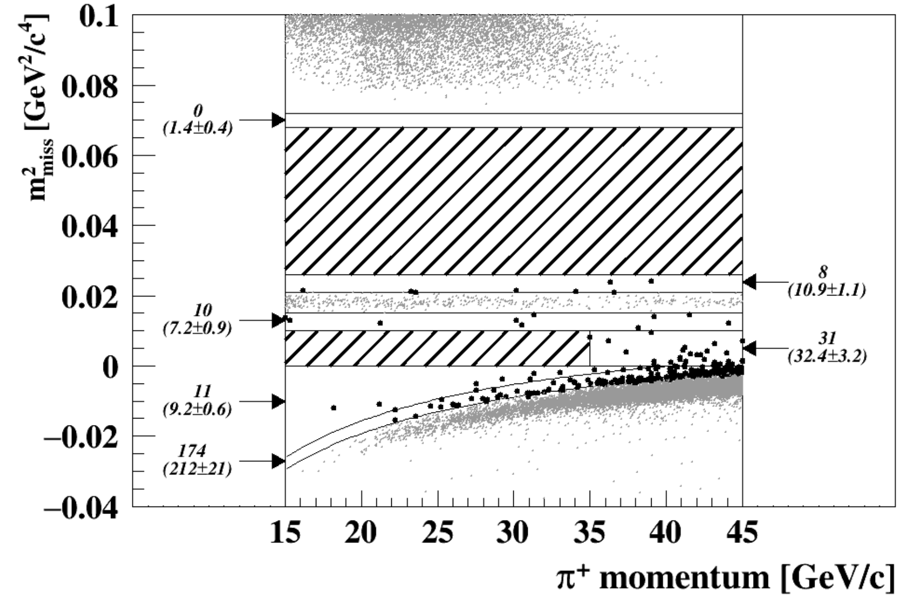
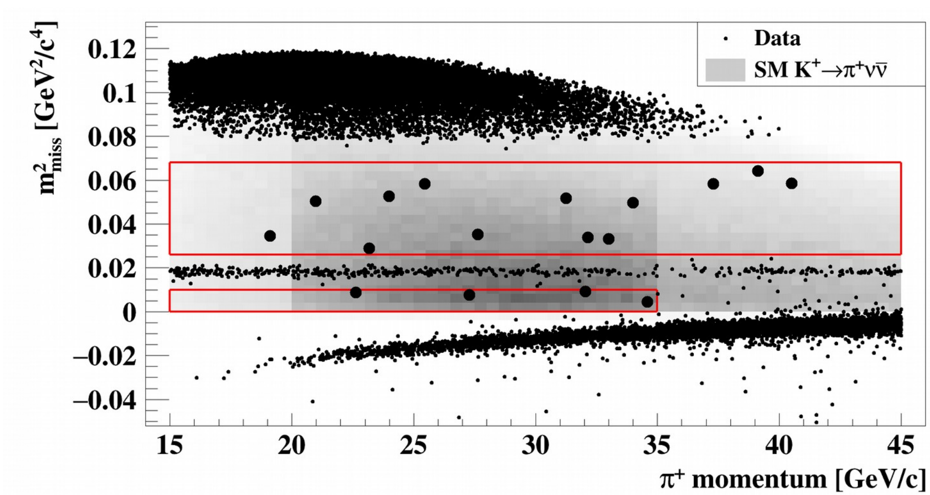


Expected: 7.6 signal + 5.4 background events

Observed: 17 $K^+ \rightarrow \pi^+\nu\bar{\nu}$ candidates!



Combined NA62 2016-2018 data

SES = $(8.39 \pm 0.53_{syst}) \times 10^{-12}$

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

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

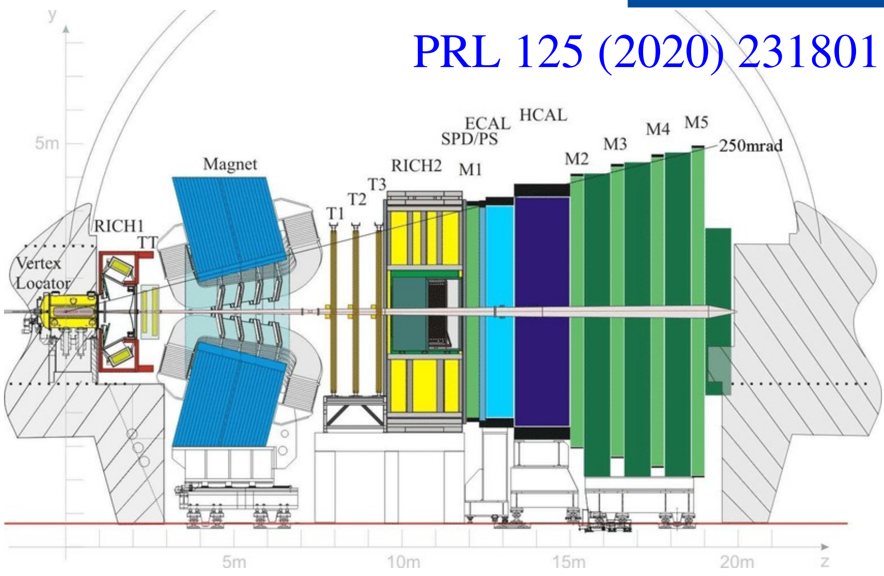
Observed: 20 (1+2+17) events

$$\mathbf{BR(K^+\rightarrow\pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}\ _{stat} \pm 0.9_{syst}) \times 10^{-11}}$$

3.5σ significance, most precise measurement to date!

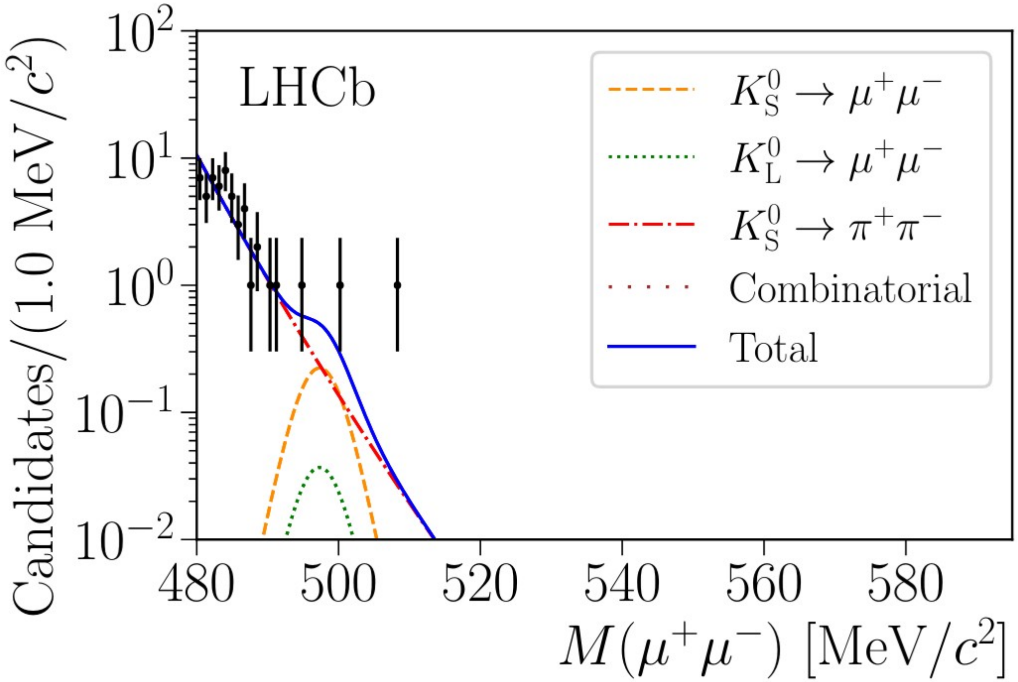
$K_S \to \mu^+\mu^-$ at LHCb

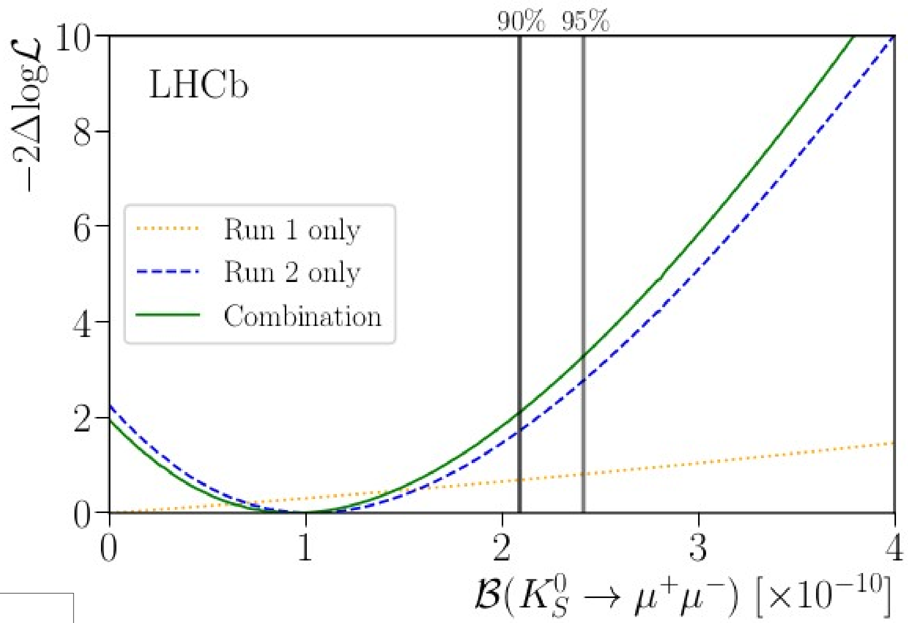
PRL 125 (2020) 231801



Data samples:

- **Run 1:** 3 fb $^{-1}$ (2011-2012 data) at 7-8 TeV
- **Run 2:** 5.6 fb^{-1} (2016-2018 data) at 13 TeV





Run1+Run2 result:

BR($K_S \to \mu^+\mu^-$) < 2.1 × 10^{-10} (90% CL)

Lepton Universality tests

Several stringent Lepton Universality tests with Kaons:

Neutral currents decays (FCNC, 1-loop level):

$K_{L,S} \rightarrow e^+e^-$ vs $K_{L,S} \rightarrow \mu^+\mu^-$

$K_{L,S} \rightarrow \pi^0 e^+e^-$ vs $K_{L,S} \rightarrow \pi^0 \mu^+\mu^-$

$K^+ \rightarrow \pi^+ e^+e^-$ vs $K^+ \rightarrow \pi^+ \mu^+\mu^-$ → NA62

Charged currents decays (Tree-level):

$R_K = BR(K^+ \rightarrow e^+\nu)/BR(K^+ \rightarrow \mu^+\nu)$

$K_{L,S} \rightarrow \pi^\pm e^\mp \nu$ vs $K_{L,S} \rightarrow \pi^\pm \mu^\mp \nu$ → KLOE

$K^+ \rightarrow \pi^0 e^+\nu$ vs $K^+ \rightarrow \pi^0 \mu^+\nu$

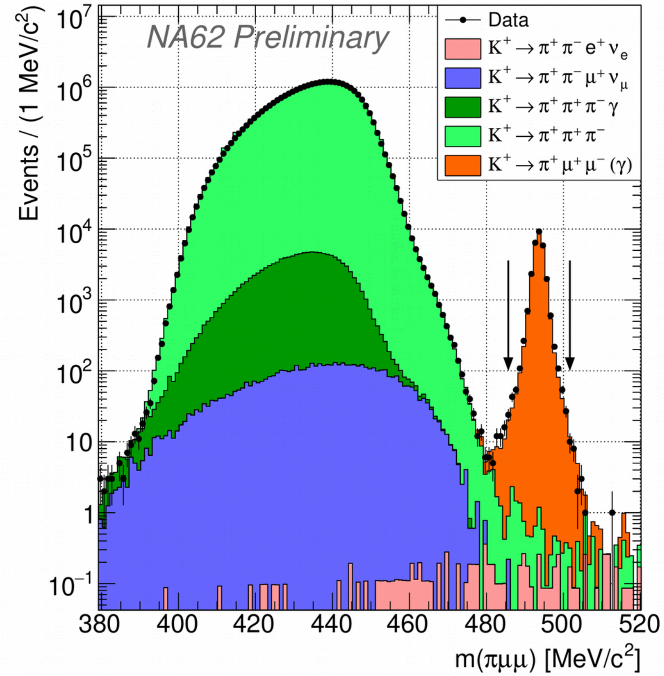
…

$K^+ \to \pi^+\mu^+\mu^-$ at NA62

LD-dominated, mediated by $K^+ \to \pi^+\gamma^*$:

$$d\Gamma/dz \sim G_F M_K^2(a+bz)+W^{\pi\pi}(z) \text{ [with } z = m(\ell^+\ell^-)^2/M_K^2\text{]}$$

Lepton Universality predicts same FF a,b for ℓ = e,μ

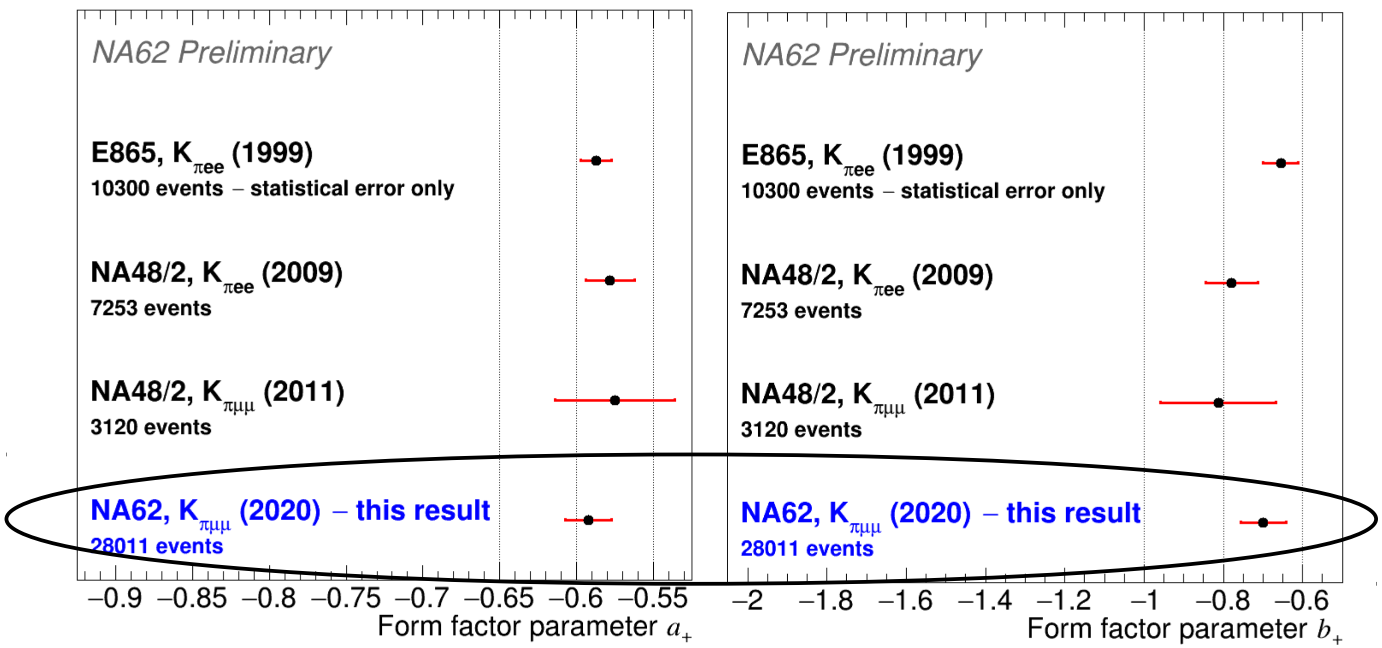


<u>Analysis strategy</u>:

Normalization to $K^+ \to \pi^+\pi^+\pi^-$, fit z spectrum to extract FF

Selected candidates:

$N(K^+ \to \pi^+\mu^+\mu^-) \sim 28\times10^3$, background < 0.1%



<u>Results from 2017-2018 data</u>:

a: 2% precision

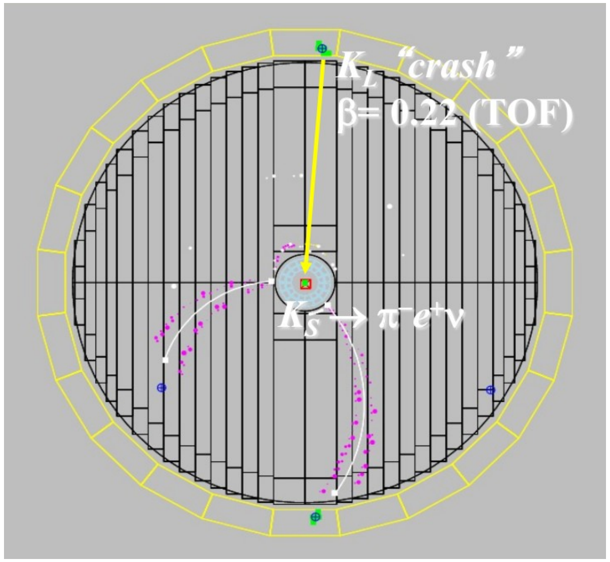
b: 8% precision

BR: $(9.27 \pm 0.11) \times 10^{-8}$

→ FF values in good agreement with Lepton Universality

$K_S \to \pi^{\pm}\mu^{\mp}\nu$ at KLOE

PLB 804 (2020) 135378



K_s tagged by K_L interaction in EM calorimeter

Efficiency ~ 30%

θ_{KS} resolution: ~1° (0.3° in φ)

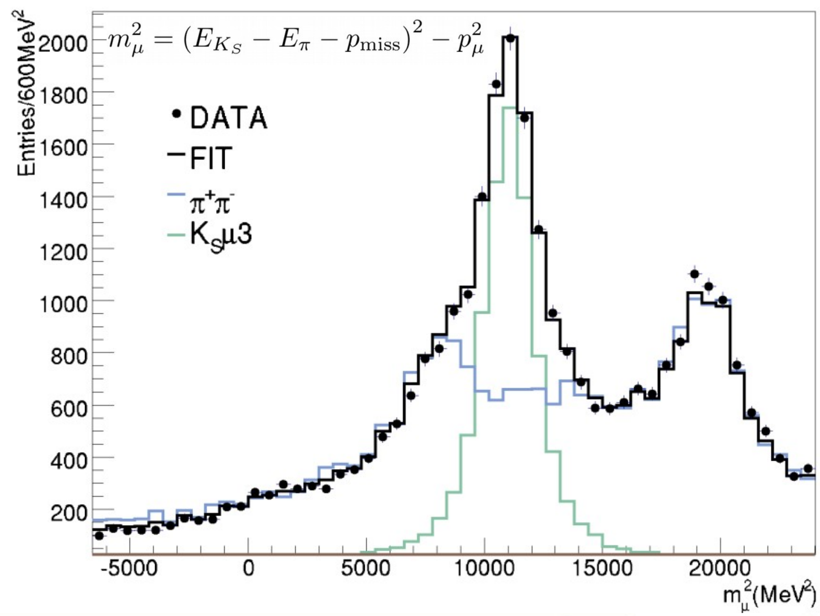
p_{KS} resolution: ~ 2 MeV

KLOE detector at the Frascati Φ-factory DAΦNE

300M K_sK_L pairs from 2001-2005 dataset

Selected candidates: $N(K_S \to \pi^{\pm}\mu^{\mp}\nu) = 7223 \pm 180$

Normalization: $K_s \to \pi^+\pi^-$



First ever measurement:

$BR(K_S \to \pi\mu\nu) = (4.56 \pm 0.11_{stat} \pm 0.17_{syst}) \times 10^{-4}$

in agreement with the expected value assuming lepton-flavour universality:

$BR(K_S \to \pi\mu\nu) = (4.69 \pm 0.06) \times 10^{-4}$

$\Gamma(\pi^{\pm}\mu^{\mp}\nu_\mu)/\Gamma_{total}$ **Γ_9/Γ**

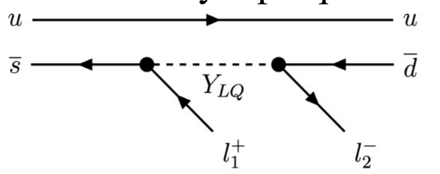
VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
4.56±0.20 OUR FIT				
4.56±0.11±0.17	7223	[1] BABUSCI 20	KLOE	direct measurement

[1] Value obtained by normalizing to the KLOE measurement $B(K_S^0 \to \pi^+\pi^-) = (69.196 \pm 0.051)\%$. Also comparison with the PDG 18 based derived value leads to a lepton flavor universality test $|V_{us}\, f_+(0)|^2_{K_S^0 \to \pi\mu\nu} / |V_{us}\, f_+(0)|^2_{K_S^0 \to \pi e\nu} = 0.975 \pm 0.044$.

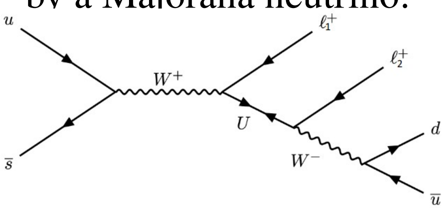
Direct BSM searches

<u>Lepton Number/Flavor Violation</u>: many decay modes, forbidden in SM:

LFV possibly mediated by leptoquark:



LNV possibly mediated by a Majorana neutrino:



Decay mode	UL (90% CL)	Experiment	Year	Type
$K^+\to\pi^+\mu^+e^-$	1.3×10^{-11}	BNL-777/865	2005	LFV
$K^+\to\pi^+\mu^-e^+$	5.2×10^{-10}	BNL-865	2000	LFV
$K^+\to\pi^-\mu^+e^+$	5.0×10^{-10}	BNL-865	2000	LNFV
$K^+\to\pi^-e^+e^+$	6.4×10^{-10}	BNL-865	2000	LNV
$K^+\to\pi^-\mu^+\mu^+$	8.6×10^{-11}	NA48/2	2017	LNV
$K_L\to\mu^\pm e^\mp$	4.7×10^{-12}	BNL-871	1998	LFV
$K_L\to\pi^0\mu^\pm e^\mp$	7.6×10^{-11}	KTeV	2008	LFV
$K_L\to\pi^0\pi^0\mu^\pm e^\mp$	1.7×10^{-10}	KTeV	2008	LFV
$K_L\to\mu^\pm e^\mp\mu^\pm e^\mp$	4.12×10^{-11}	KTeV	2003	LFV

NA62

<u>Production of on-shell BSM particles</u> in K decays:

$K^+\to\pi^+X$, $K^+\to\ell^+N$ → NA62

+ peak searches in states with $\ell^+\ell^-$ pair

$K^+\to\pi^+\ell^+\ell^-$, $K_{L,S}\to\pi^0\ell^+\ell^-$, $K^+\to\ell_1^+\nu\ell_2^+\ell_2^-$, $K_{L,S}\to\ell_1^+\ell_1^-\ell_2^+\ell_2^-$, …

$K^+ \to \pi\mu e$ (LFV) at NA62

arXiv:2105.06759

Normalization: $K \to \pi^+\pi^+\pi^-$

Background: mostly from double mis-ID ($e \leftrightarrow \pi$ & $\pi \leftrightarrow \mu$)

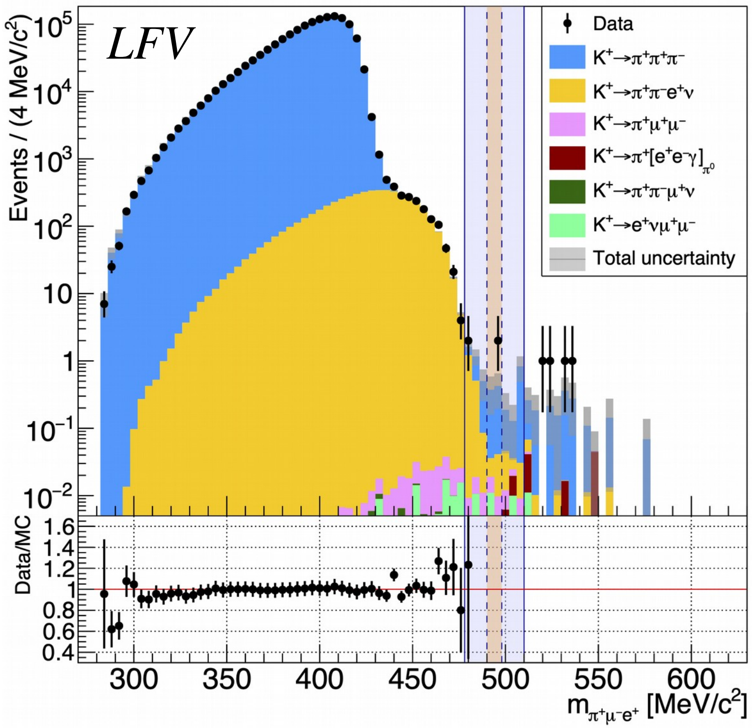
Data-driven mis-ID estimations

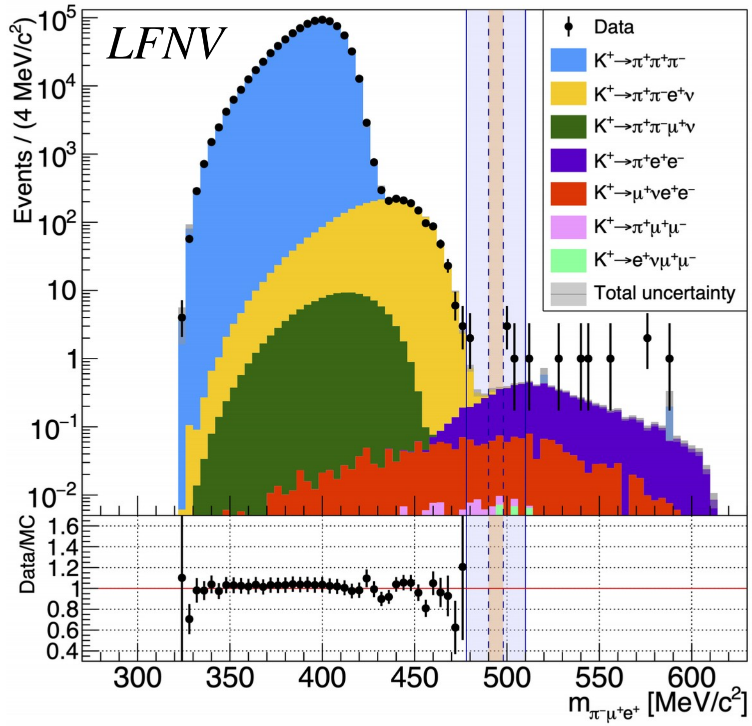
Expected: 0.92 ± 0.34 events

Observed: 2 events

Expected: 1.06 ± 0.20 events

Observed: 0 events





2017-2018 data

$BR(K^+ \to \pi^+\mu^-e^+) < 6.6 \times 10^{-11}$ (90% CL)

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

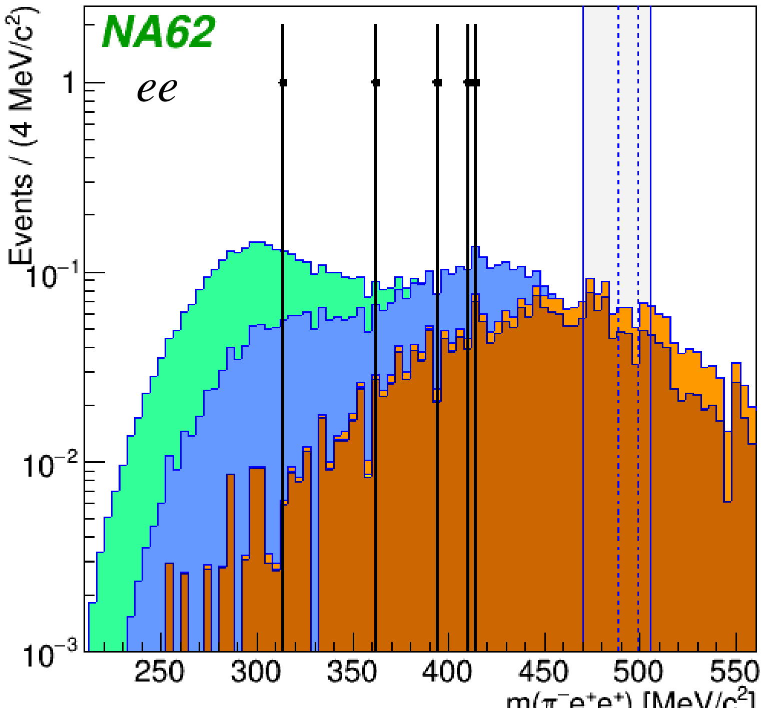
$K^+ \to \pi^- \ell^+ \ell^+$ (LNV) at NA62

PLB 797 (2019) 134794

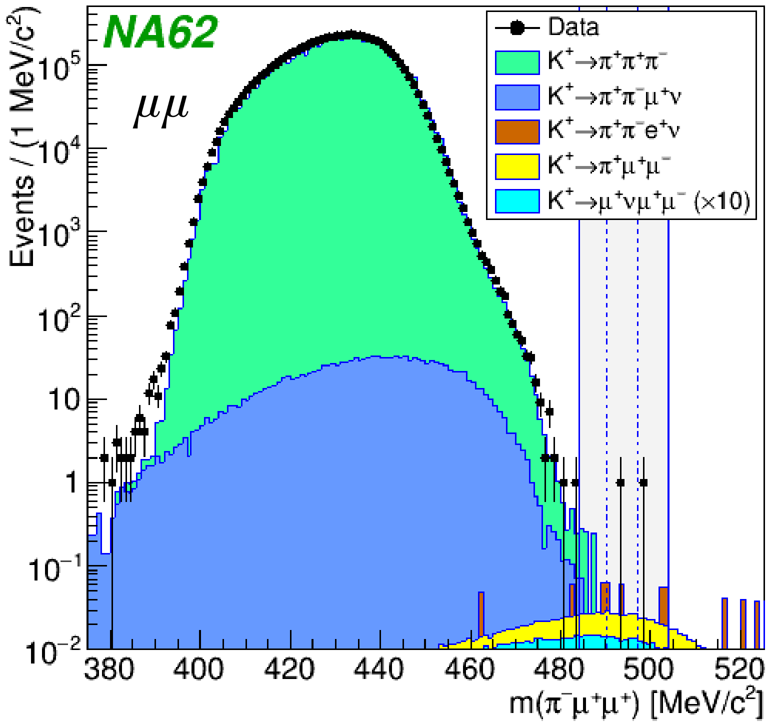
Normalization: $K \to \pi^+ \ell^+ \ell^-$

Background: mostly from double mis-ID ($\pi \leftrightarrow \ell$ & $\ell \leftrightarrow \pi$)
Data-driven mis-ID estimations

Expected: 0.16 ± 0.03 events
Observed: 0 events



Expected: 0.91 ± 0.41 events
Observed: 1 event



2017 data

$BR(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}$ (90% CL)

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

$K^+ \to \pi^+ X$ at NA62

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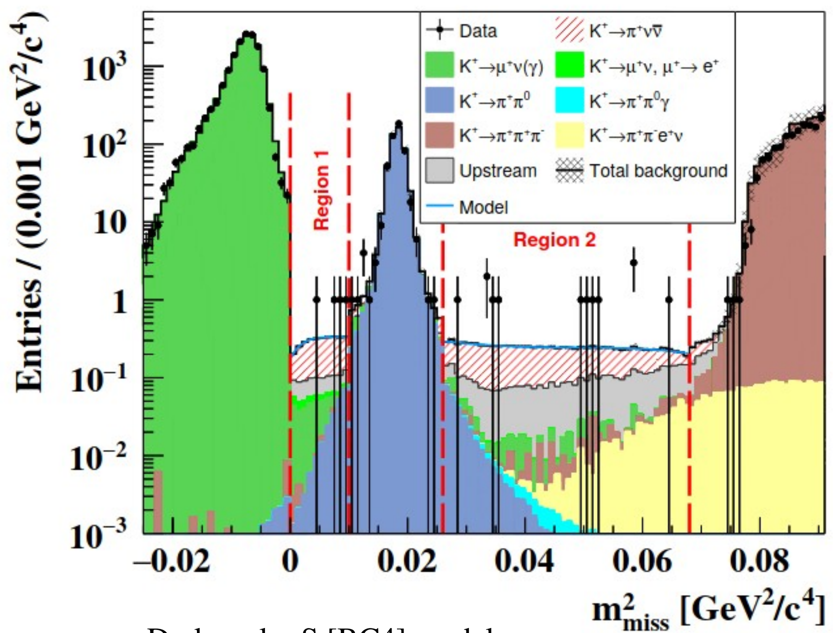
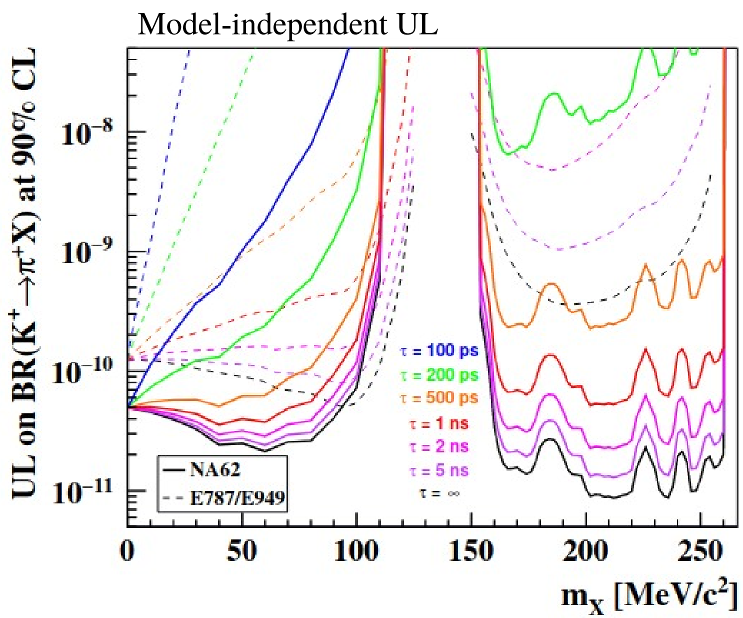
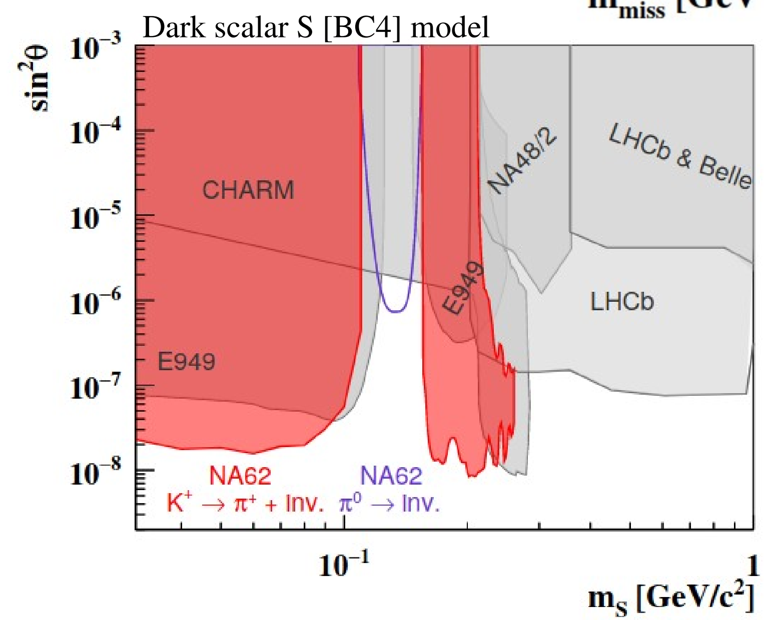
Spin-off of the $K^+ \to \pi^+ \nu\bar{\nu}$ analysis

Search for a peaking signal in the m^2_{miss} distribution

$K^+ \to \pi^+ \nu\bar{\nu}$ is now the main background!

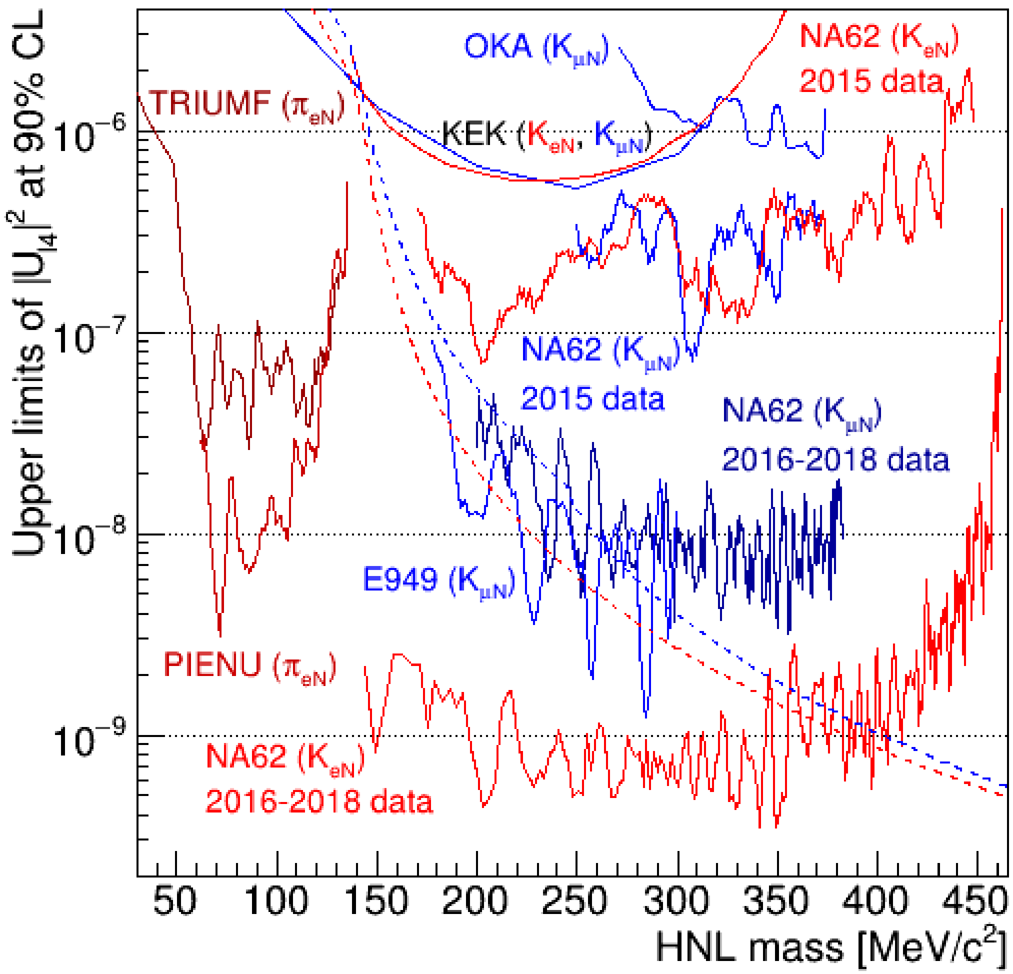




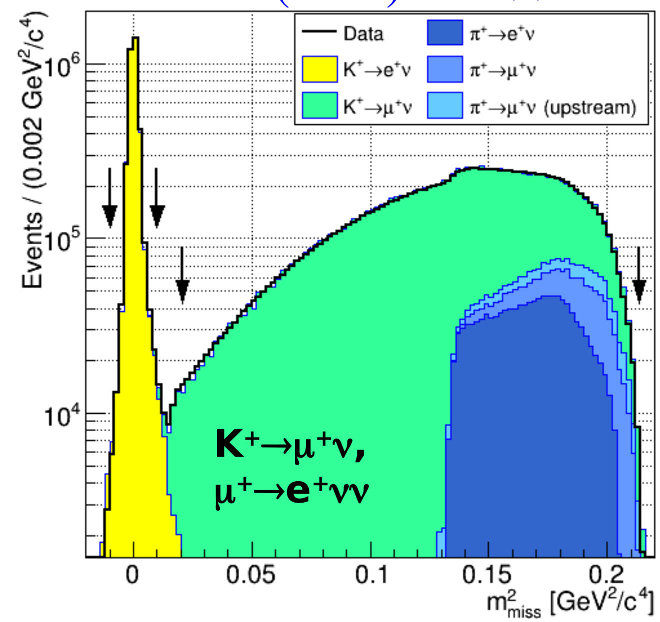


$K^+ \to \ell^+ N$ at NA62

HNL signal: **a spike above continuous missing mass spectrum**



PLB 807 (2020) 135599



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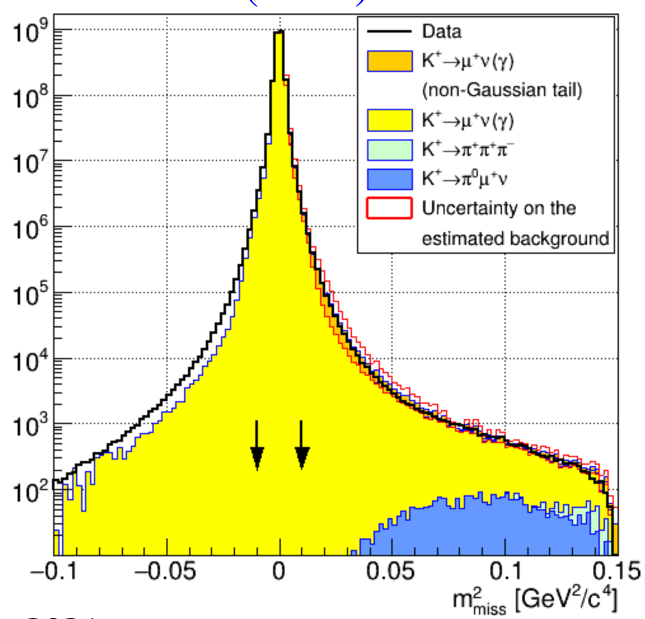
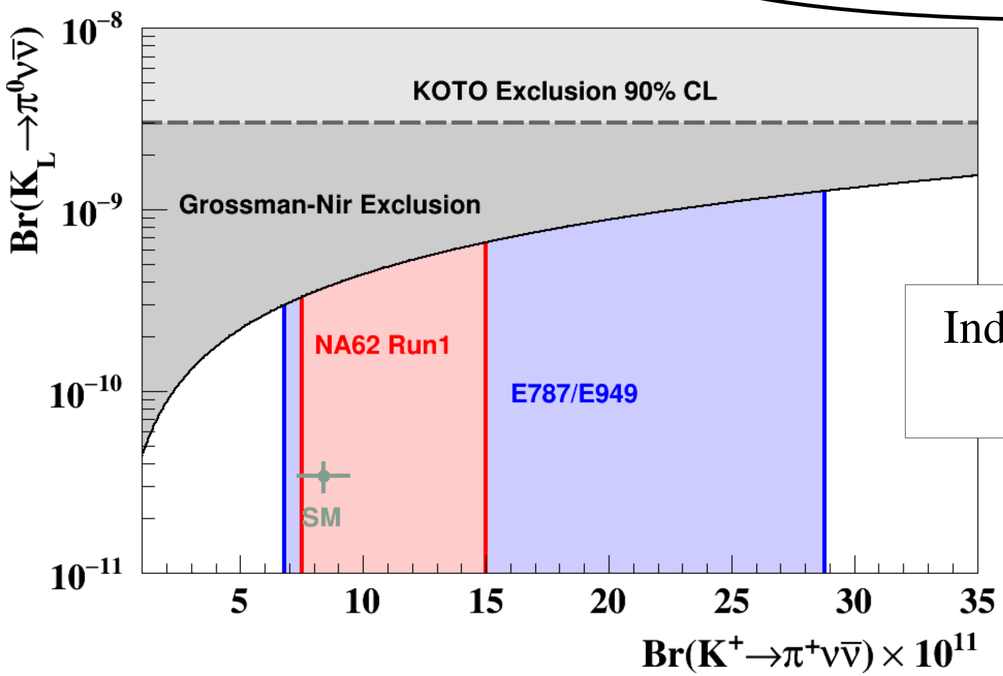


The golden modes – present

Decay	Γ_{SD}/Γ	Theory error*	SM BR × 10^{11}	Experimental BR × 10^{11}	Experiment	Year
$K_L \to \pi^0 \nu \bar{\nu}$	>99%	2%	3.4 ± 0.6	< 300	KOTO	2019
$K^+ \to \pi^+ \nu \bar{\nu}$	90%	4%	8.4 ± 1.0	**$10.6^{+4.0} \pm 0.9$**	**NA62**	**2021**
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28	KTeV	2004
$K_L \to \pi^0 \mu^+ \mu^-$	30%	15%	1.5 ± 0.3	< 38	KTeV	2000
$K_L \to \mu^+ \mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11	BNL-871	2000
$K_S \to \mu^+ \mu^-$	4%	>30%	0.52 ± 0.15	**< 21**	**LHCb**	**2020**



Indirect boundary by NA62 on $K_L \to \pi^0 \nu \bar{\nu}$

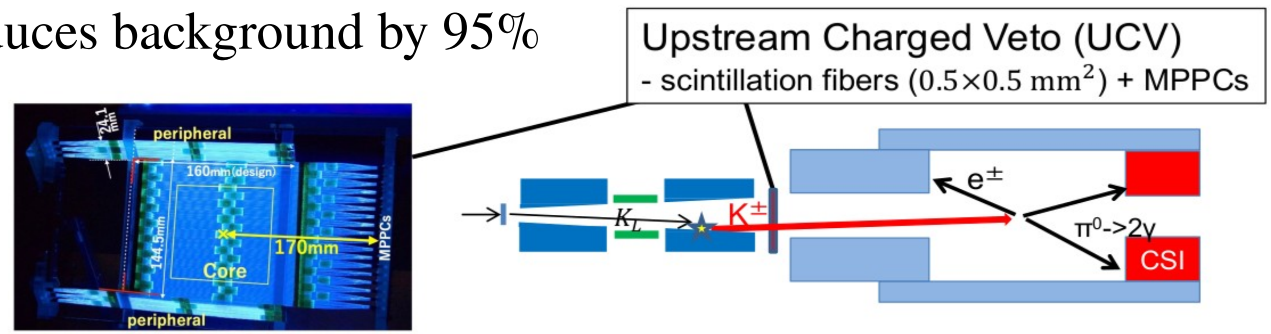
$K_L \to \pi^0 \nu \bar{\nu}$ at KOTO: prospects

Strategy for main backgrounds reduction:

- **$K^{\pm}$: Upstream charged-particle veto**

  Prototype installed for 2020 run, final version available in 2021

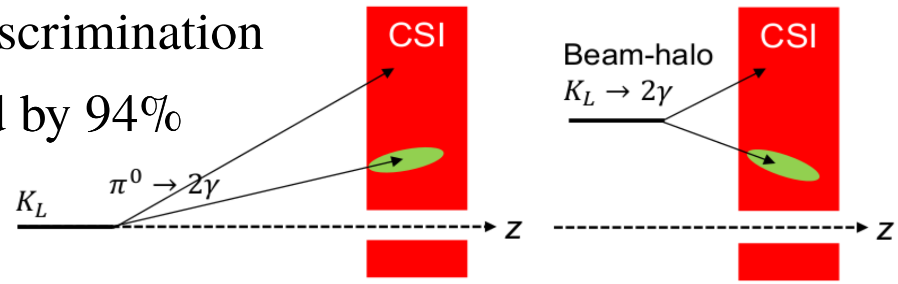
  Reduces background by 95%



- **Beam-halo $K_L \to \gamma\gamma$:**

  EM shower shape discrimination

  Reduces background by 94%



2019-2021 data set of comparable size to 2016-2018

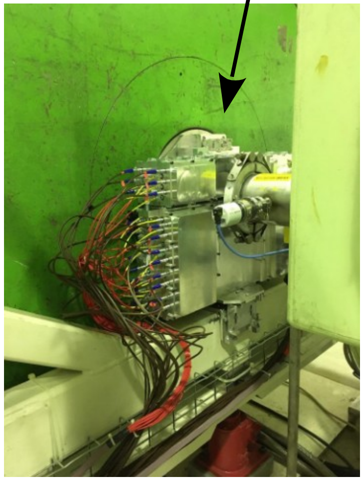
Beam power expected to increase from 50 → 80 kW in 2022 (later: 100 kW)

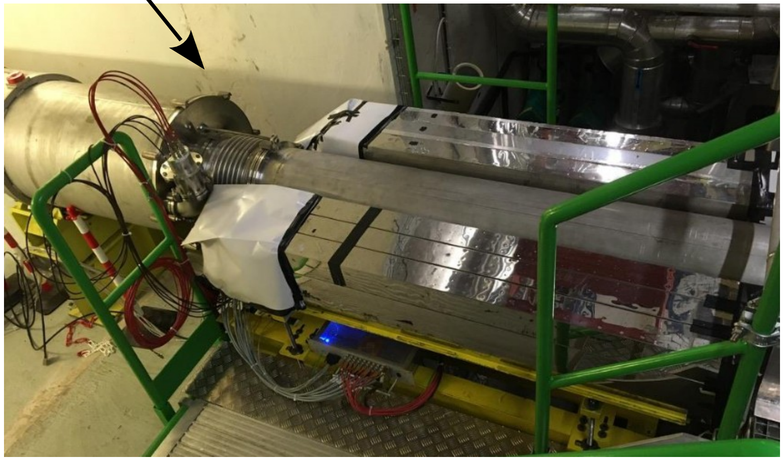
→ Expect to approach SM SES by mid-decade

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at NA62: prospects

Plans for NA62 Run 2 (from LS2 to LS3):

- Run at higher beam intensity (70% → 100%)
- Key modifications to reduce background from upstream decays and interactions:
  - Rearrangement of beamline elements around GTK achromat
  - Added 4th station to GTK beam tracker
  - New veto hodoscope upstream of decay volume
  - Additional veto counters around beam pipe (both upstream/downstream the FV)





NA62 data taking restarted (since July 2021)

→ Expect to measure $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ to O(10%) by LS3

$K_S \to \mu^+\mu^-$ at LHCb: prospects

LHCb Upgrade II TDR

7.6.1 Rare kaon decays

In the SM, the $K^0_S \to \mu^+\mu^-$ decay is long-distance dominated, with subdominant short-distance contributions. However, the long-distance contribution is still very small in absolute terms, and the decay rate is very suppressed. For example, the SM prediction [384–386] $\mathcal{B}(K^0_S \to \mu^+\mu^-)_{SM} = (5.18 \pm 1.50_{LD} \pm 0.02_{SD}) \times 10^{-12}$ can be compared with the current experimental upper limit [387] $\mathcal{B}(K^0_S \to \mu^+\mu^-)_{Exp} < 8 \times 10^{-10}$ at 90% CL. Therefore, even small BSM contributions and BSM–SM interferences can compete with the SM rate. This has been proven to be the case in leptoquark models [388, 389] as well as supersymmetric models [390]. In the latter, $\mathcal{B}(K^0_S \to \mu^+\mu^-)$ can have values anywhere in the range $[0.78 - 35] \times 10^{-12}$ (see Fig. 7.9, left) or even saturate the current experimental bound in certain narrow regions of the parameter space [390]. The *CP* asymmetry of the $K^0 \to \mu^+\mu^-$ decay is also sensitive to BSM contributions and experimentally accessible by means of a tagged analysis.

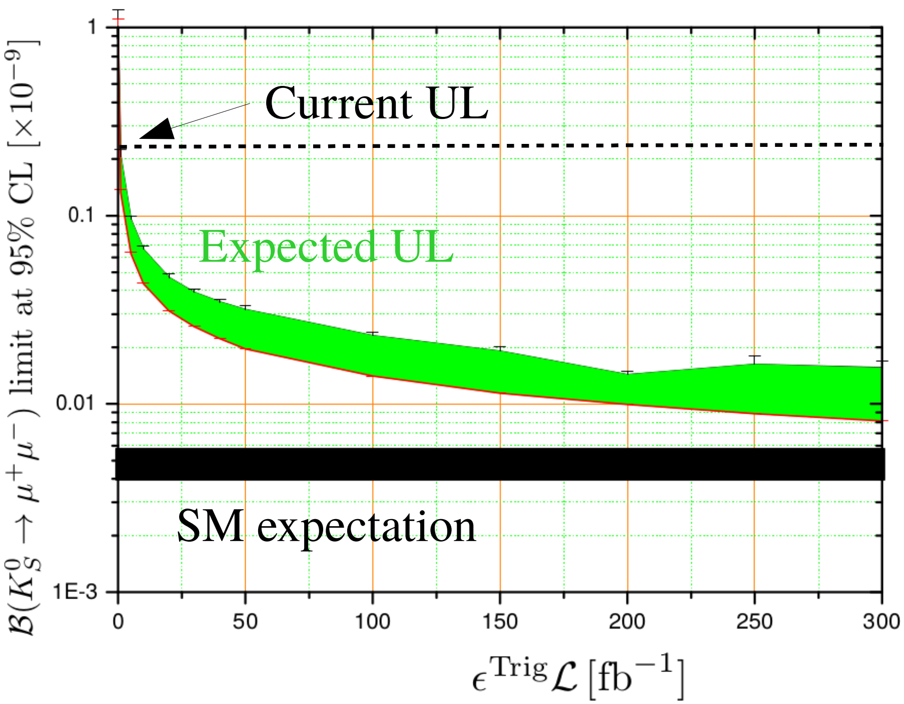
The LHCb prospects for the search for $K^0_S \to \mu^+\mu^-$ decays are excellent. With 2011 data the experiment overtook the previous world best upper limit by a factor of thirty [391], and has recently gained another order of magnitude [387]. The right hand side of Fig. 7.9 shows the expected upper limit for $\mathcal{B}(K^0_S \to \mu^+\mu^-)$ as a function of the integrated luminosity multiplied by the trigger efficiency. It can be seen that if the trigger efficiency is high, as expected from a full software trigger, LHCb can explore branching fractions down to near the SM prediction.

Currently, the only existing measurement of $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ comes from the NA48 experiment [392]

$$\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-) = (2.9^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}.$$

In the Upgrade II LHCb can achieve a statistical precision of 0.11×10^{-9} with $300\,\text{fb}^{-1}$ of integrated luminosity, assuming a trigger efficiency of 100% [393]. Assuming a trigger efficiency of 50% LHCb will still be able to significantly improve on the NA48 measurement. Apart from the branching fraction, the differential decay rate in the dimuon mass contains interesting information about the form factor parameters a_S and b_S [394]. The LHCb Upgrade II can reach a 10% statistical precision on the form factor term $|a_S|$ with free b_S [395].

Other kaon decays that can be studied at LHCb include $K^+ \to \pi\mu\mu$ (both with opposite-sign and same-sign muon pairs), $K^0_S \to 4\mu$, or decays involving electrons in order to test Lepton Universality [395]. The LHCb acceptance is such that it favours the sensitivity to K^0_S modes over K^0_L modes by about a factor 1000 due to the longer K^0_L lifetime.[3]



10^{13} K_S/fb^{-1} produced in LHCb acceptance

→ **~1 strange hadron/event!**

Vast K program for Run 3

Expected improvements on:

- $K_{S,L} \to \mu^+\mu^-$
- $K_S \to \pi^0\mu^+\mu^-$
- $K_S \to \mu^+\mu^-\mu^+\mu^-$
- …

Conclusions

Rich physics programme with Kaons

- Golden modes:
  - FCNC, very clean and suppressed in SM
  - Recent results from KOTO ($K_L \to \pi^0 \nu\bar{\nu}$), NA62 ($K^+ \to \pi^+ \nu\bar{\nu}$) and LHCb ($K_s \to \mu^+\mu^-$)
- Lepton Universality tests:
  - Both neutral and charged currents decays
  - Recent results from NA62 and KLOE presented: good agreement with SM
- BSM searches:
  - LFV/LNV modes → new results from NA62 presented
  - Production of on-shell BSM particles → new results from NA62 presented

Prospects:

Clear strategy defined for golden modes:
- Reduce current main sources of background
- Run at higher beam intensity

→ **Golden modes expected to be substantially probed further in near future**

→ Expect to improve further the presented LU/BSM results + many others