Rare kaon decays at NA62/LHCb

Riccardo Lollini

INFN – Perugia
(on behalf of the NA62 Collaboration)

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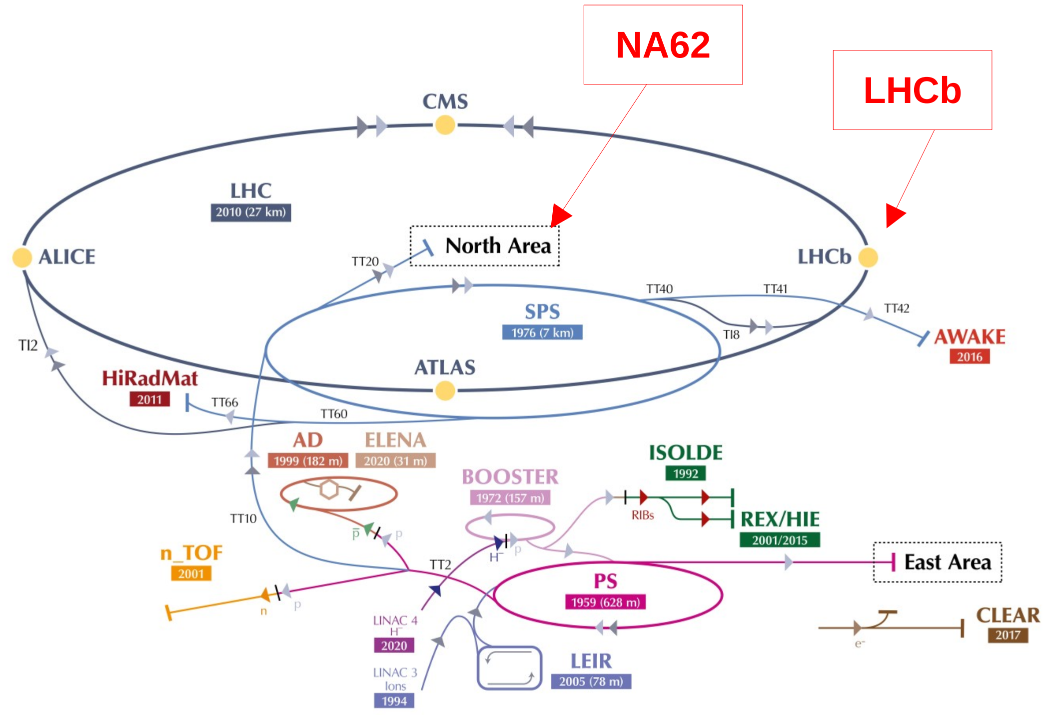
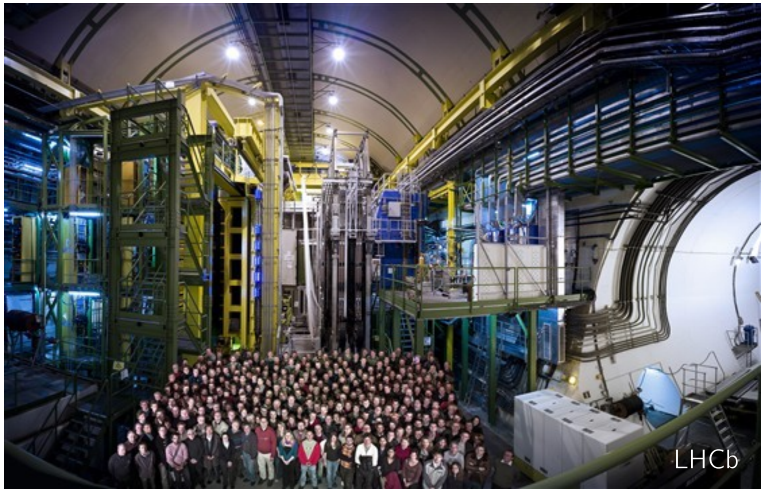
Overview

- $K^{+} \to \pi^{+} \nu\overline{\nu}$
- $K^{+} \to \pi^{+} X$
- $K^{+} \to \pi^{+} \mu^{+} \mu^{-}$
- $K^{0}_{S} \to \mu^{+} \mu^{-}$
- $K^{0}_{S} \to l^{+} l^{-} l^{+} l^{-}$
- $K^{0}_{S} \to \pi^{+} \pi^{-} e^{+} e^{-}$



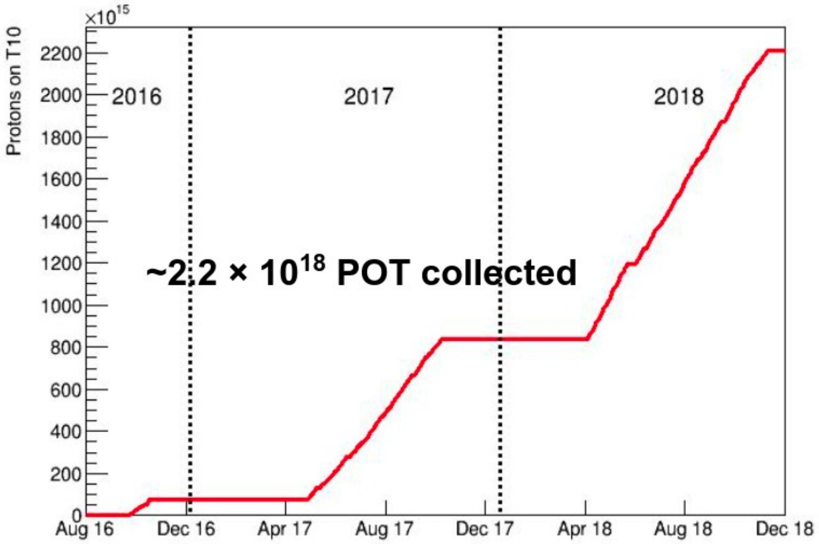


NA62

The NA62 experiment

- Fixed target experiment located in the North Area of the CERN SPS.
- Main goal: measurement of $Br(K^+ \to \pi^+ \nu \bar{\nu})$
- $Br_{SM} = (8.4 \pm 1.0) \times 10^{-11}$
- ~ 200 participants: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosi, TRIUMF, Turin, Vancouver UBC.

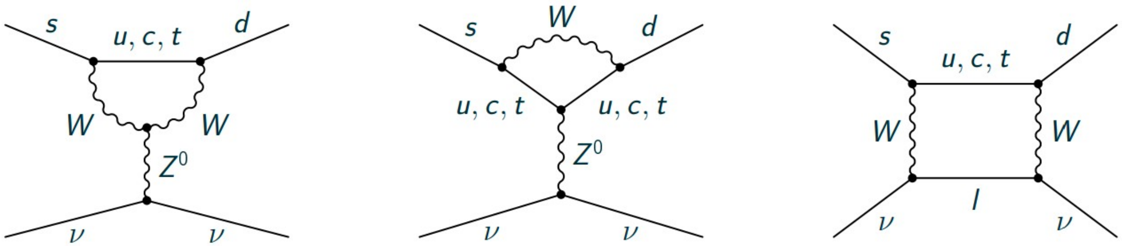
NA62 Timeline



- **2016**: 40% of nominal intensity
  ~0.12 x 10^{12} K^+ decays in fiducial volume
- **2017**: 60% of nominal intensity
  ~1.15 x 10^{12} K^+ decays in fiducial volume
- **2018**: 60–70% of nominal intensity
  ~2.6 x 10^{12} K^+ decays in fiducial volume
- **2021**: resume data taking after CERN LS2

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

- FCNC process dominated by Z-penguins and box amplitudes, main uncertainties from CKM matrix elements
- Theoretically clean, important test for the SM



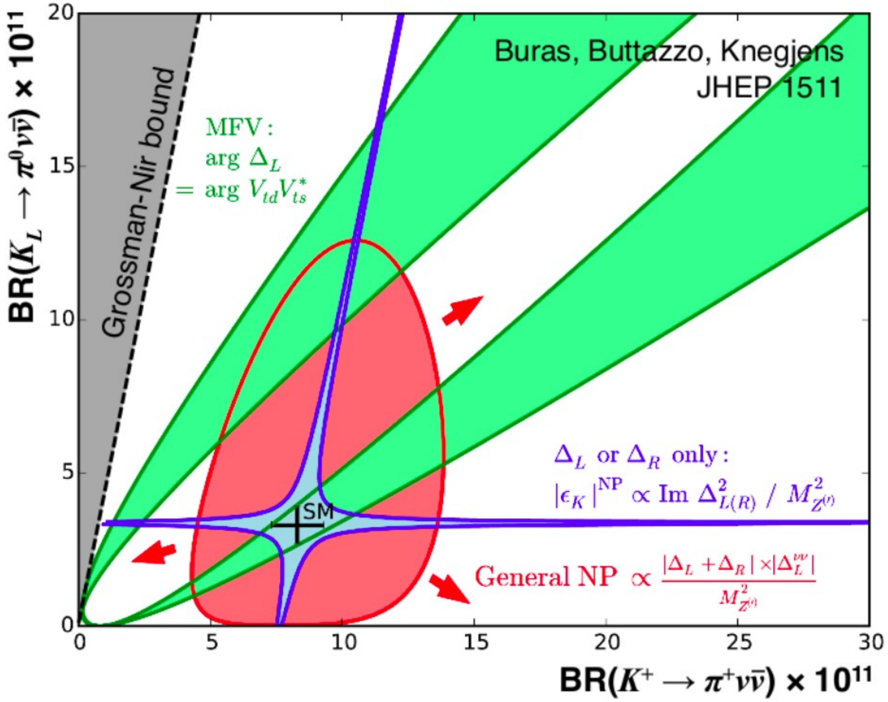
- $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2°}\right]^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$

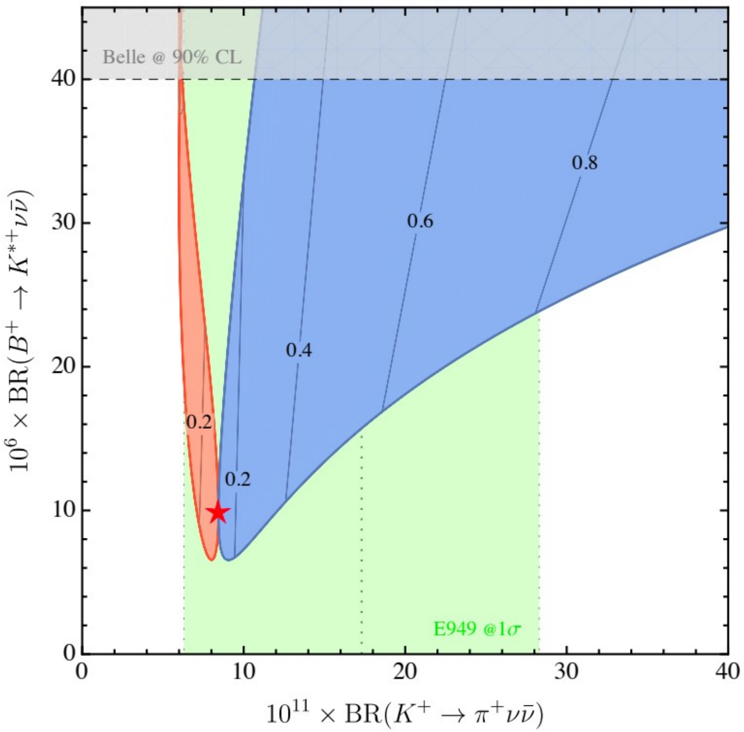
- CKM uncertainties: |Vcb| ~ 9.9%, γ ~ 6.7%

[Buras et al.. JHEP 1551]

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

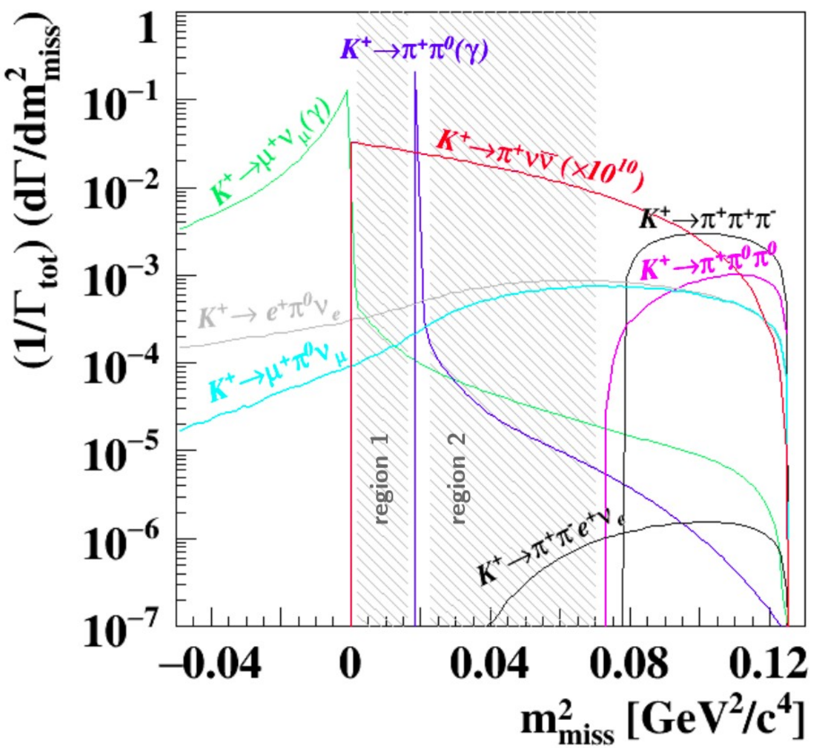
- $Br(K^+ \to \pi^+\nu\nu)$ interesting in several NP models
- Correlation patterns between $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ in many models



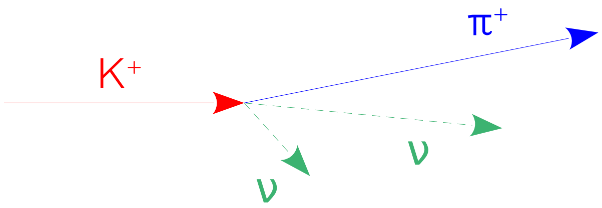


- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM Analysis [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27], [Isidori et al., JHEP 0608 (2006) 064]
- Simplified Z, Z' models [Buras, Buttazzo, Knegjens, JHEP 11 (2015) 166], [Aebischer, Buras, Kumar, JHEP 97 (2020)]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- LFU violation models [Isidori et al., Eur.Phys.J. C (2017) 77: 618]
- Leptoquark models [Bobeth, Buras, JHEP (2018) 101], [Fajfer, Kosnik, Vale Silva, Eur.Phys.J. C 78 (2018) 4]

Decay-in-flight technique at NA62



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

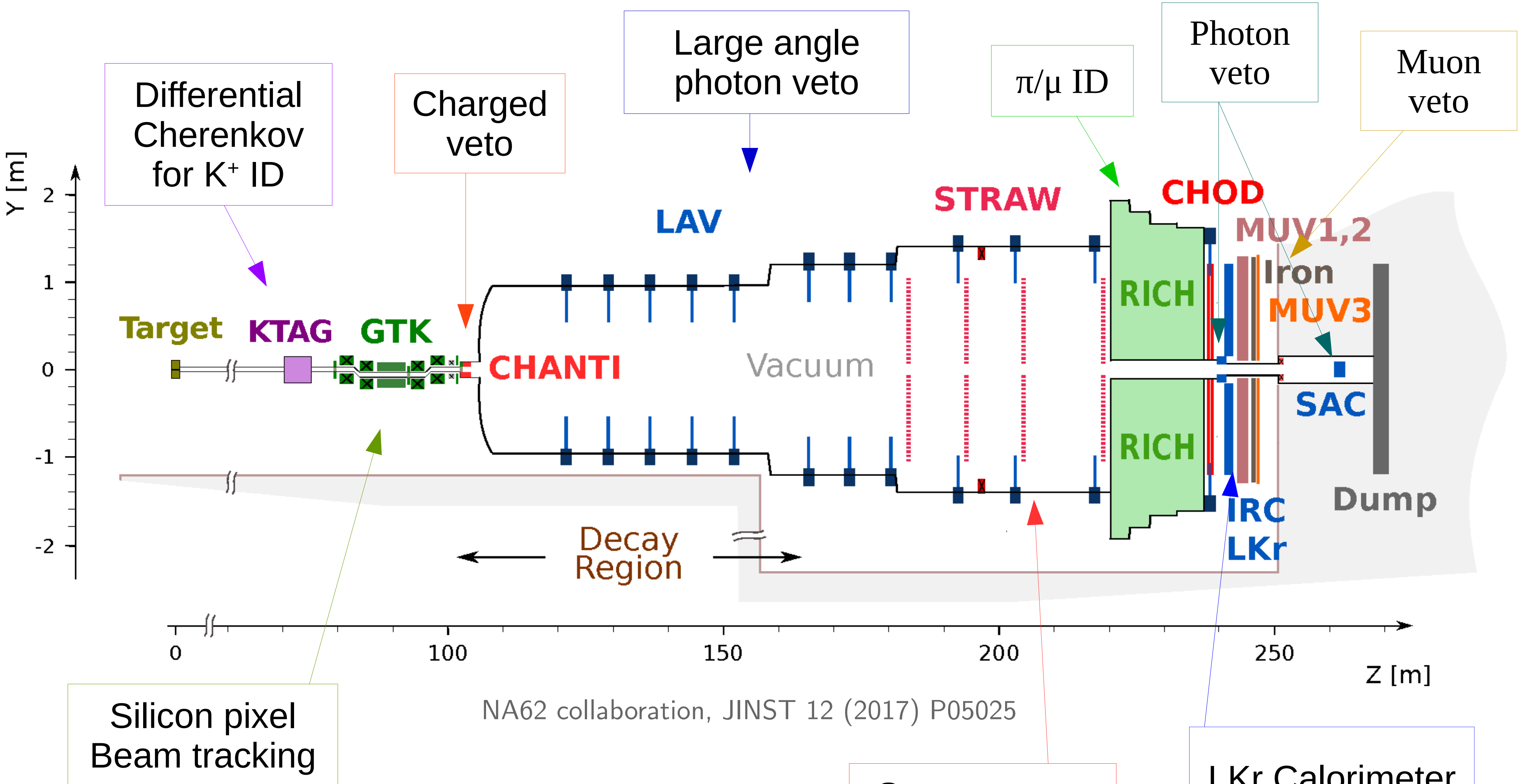


- The squared missing mass is the main kinematic variable used to kinematically separate the signal from the background:

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

- Two signal regions on each side of the $K^+\to\pi^+\pi^0$ peak
- Cut based analysis (mostly)
- Blind analysis procedure
- Requirements:
  - Very good kinematic reconstruction
  - Time measurements
  - Efficient PID
  - Hermetic photon veto

NA62 detector

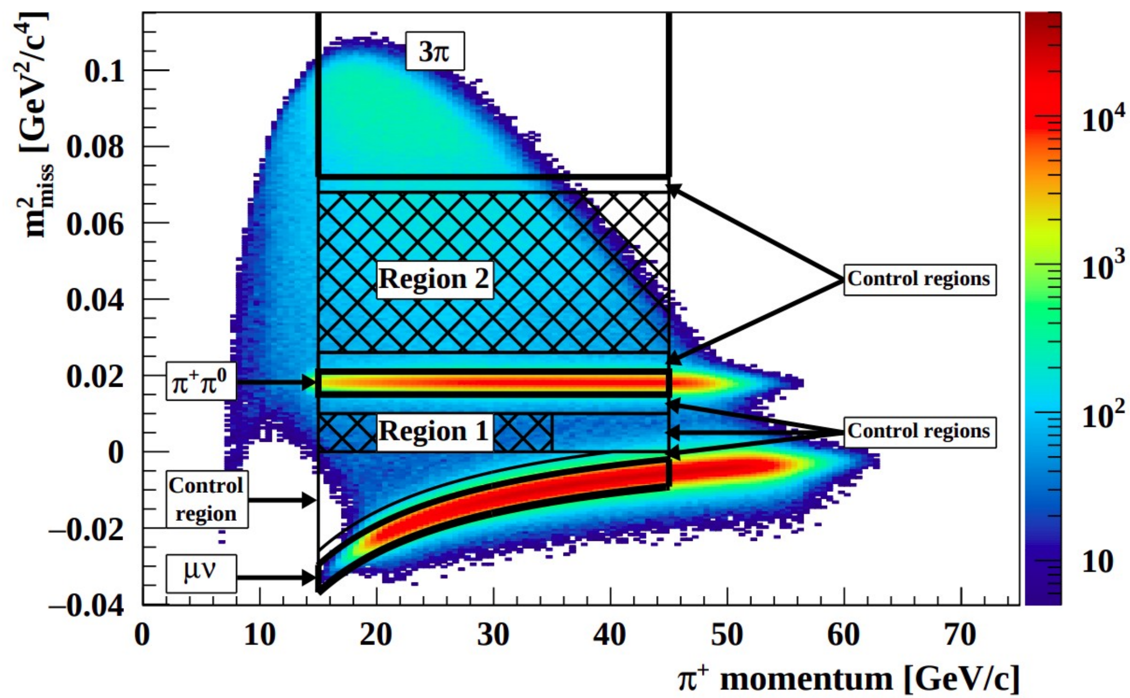


- Primary beam: 400 GeV/c protons from SPS
- Secondary beam: 75 GeV/c positively charged particles, 70% π^+, 23% p, 6% K^+

$K^+ \to \pi^+ \nu\bar{\nu}$ – Analysis strategy

- Two signal region kept blinded
- Control regions adjacent to the signal regions to validate the background estimation procedure
- The background from K decays is evaluated extrapolating the tails of the distributions inside the signal region
- Selection:
  - Single track in final state
  - π^+ identification
  - Photon rejection
  - Multiplicity rejection
  - Decay vertex inside the fiducial region
  - $15 < p_{\pi+} < 35$ GeV/c (region 1) and $15 < p_{\pi+} < 45$ GeV/c (region 2)

$\pi\nu\nu$ selection without PID and photon/multi-track rejection:



$K^+ \to \pi^+ \nu\bar{\nu}$ – Single Event Sensitivity

Normalization channel: $K^+ \to \pi^+ \pi^0$ from the control trigger

$$SES = \frac{Br(K^+ \to \pi^+ \pi^0) \cdot A_{\pi\pi}}{D \cdot N_{\pi\pi} \cdot A_{\pi\nu\nu} \cdot \epsilon_{RV} \cdot \epsilon_{trig}^{\pi\nu\nu}} \propto \frac{1}{N_K \cdot \epsilon_{\pi\nu\nu}}$$

$$N_{\pi\nu\nu}^{expected} = \frac{BR_{SM}(K^+ \to \pi^+ \nu\bar{\nu})}{SES}$$

- $A_{\pi\nu\nu}$: signal acceptance
- $A_{\pi\pi}$: normalization acceptance
- D: downscaling factor of the minimum bias trigger
- ϵ_{trig}: trigger efficiency
- $1-\epsilon_{RV}$: inefficiency due to random veto(accidental activity in the detector)
- N_K: number of kaon decays in the fiducial volume

	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
ϵ_{trig}^{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
$N_{\pi\nu\bar{\nu}}^{exp}$	$1.56 \pm 0.10 \pm 0.19_{ext}$	$6.02 \pm 0.39 \pm 0.72_{ext}$

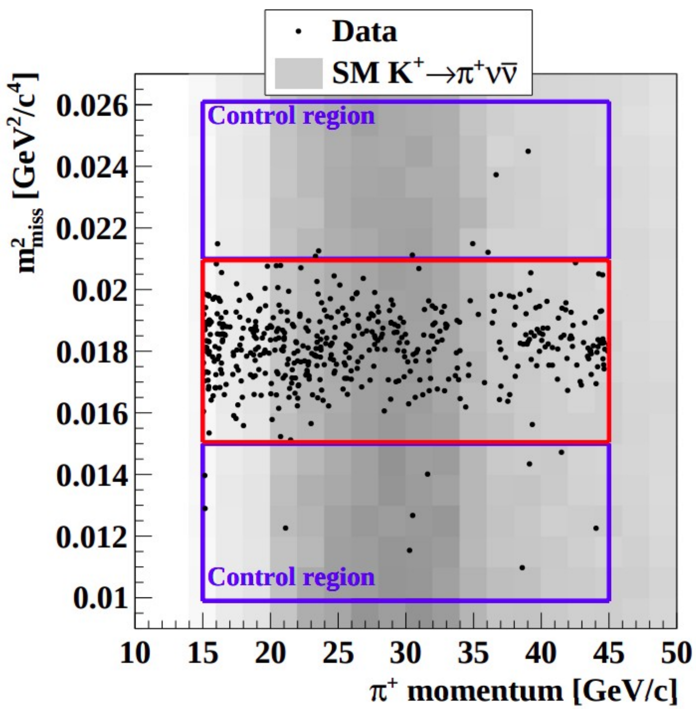
* The 2018 sample is divided into 2 subsamples (S1 and S2, before and after the installation of a new collimator, respectively)

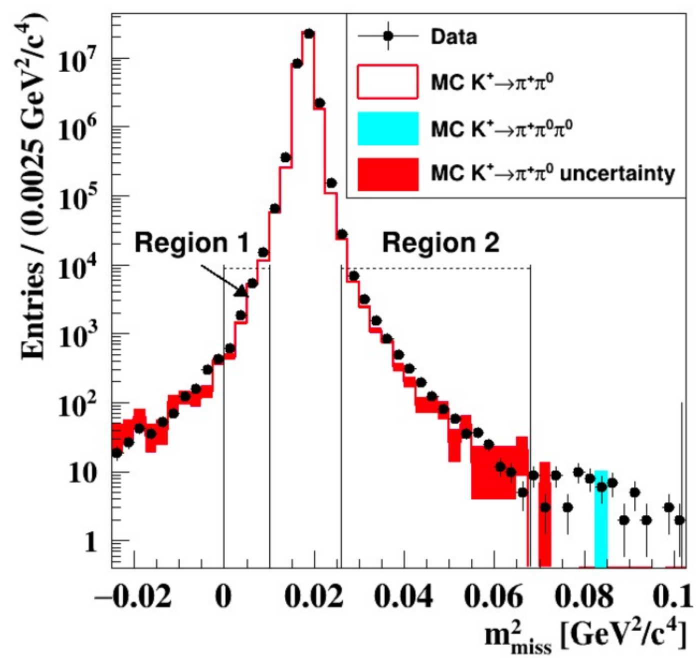
$K^+ \to \pi^+ \nu\bar{\nu}$ – Evaluation of background from K decays

- Data driven estimation

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

- N_{bkg} is the number of events in the corresponding background region at the end of the πνν selection, f_{kin} is the fraction of background events in the signal region (measured on control data)



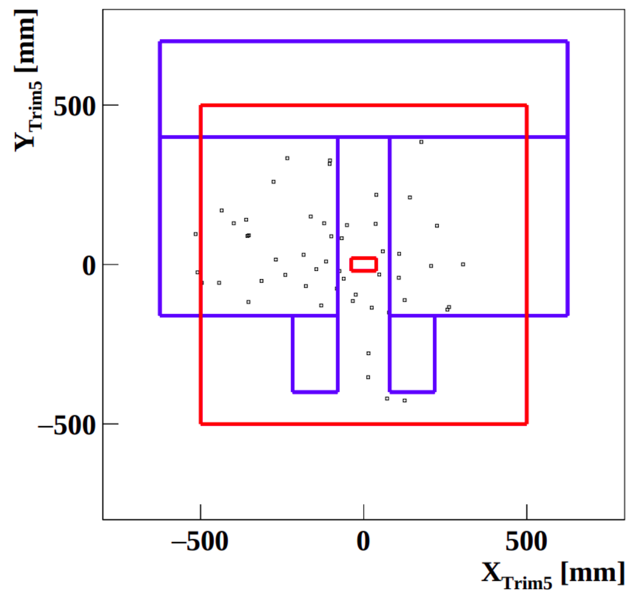


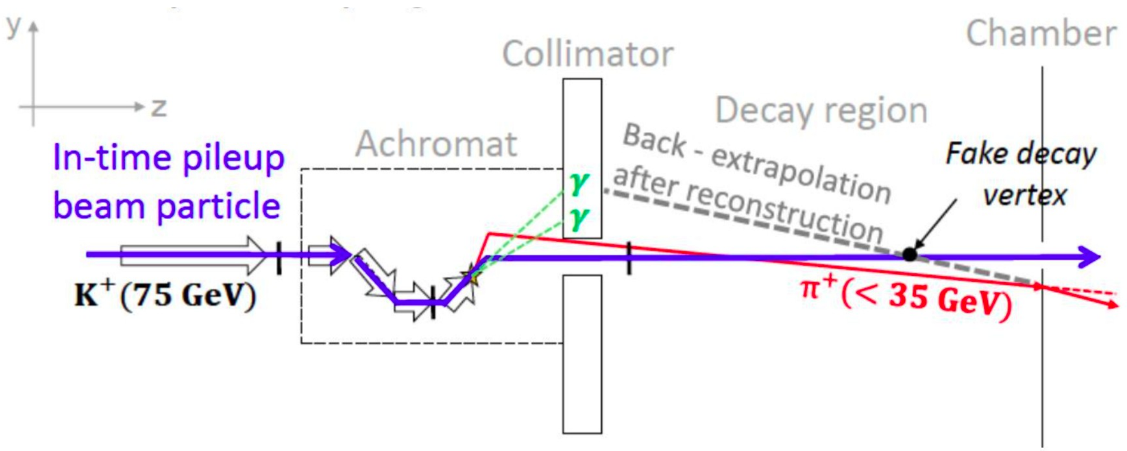
- The background is evaluated in this way for all the main decay channels: $K^+ \to \pi^+\pi^0$ (plots above), $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^+\pi^-$

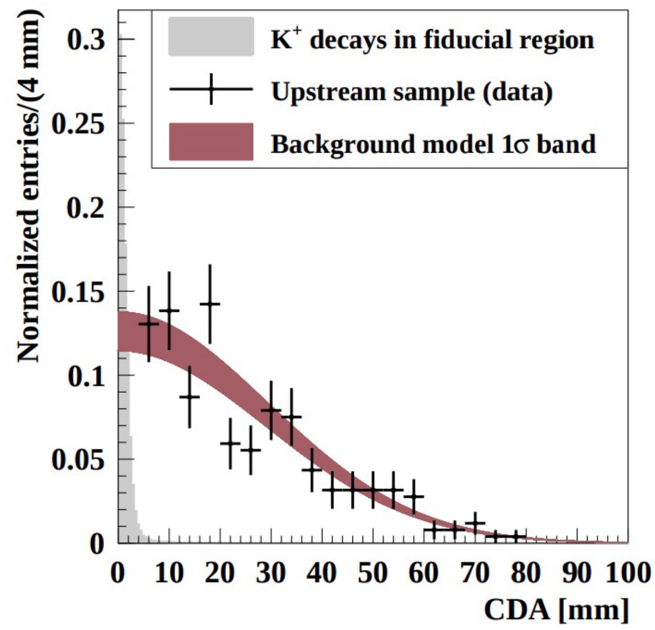
- Less abundant K^+ decays rely on MC simulations

$K^+ \to \pi^+ \nu\bar{\nu}$ – Upstream background

- π^+ produced upstream of the fiducial volume
  - Early K^+ decays
  - Interactions of beam particles with the detector
- These π^+ may be detected and associated to an accidental beam particle
- Dangerous when associated to scattering in the first Spectrometer (STRAW) chamber
- Rejected with K^+–π^+ association and geometrical cuts
- Data driven background estimation

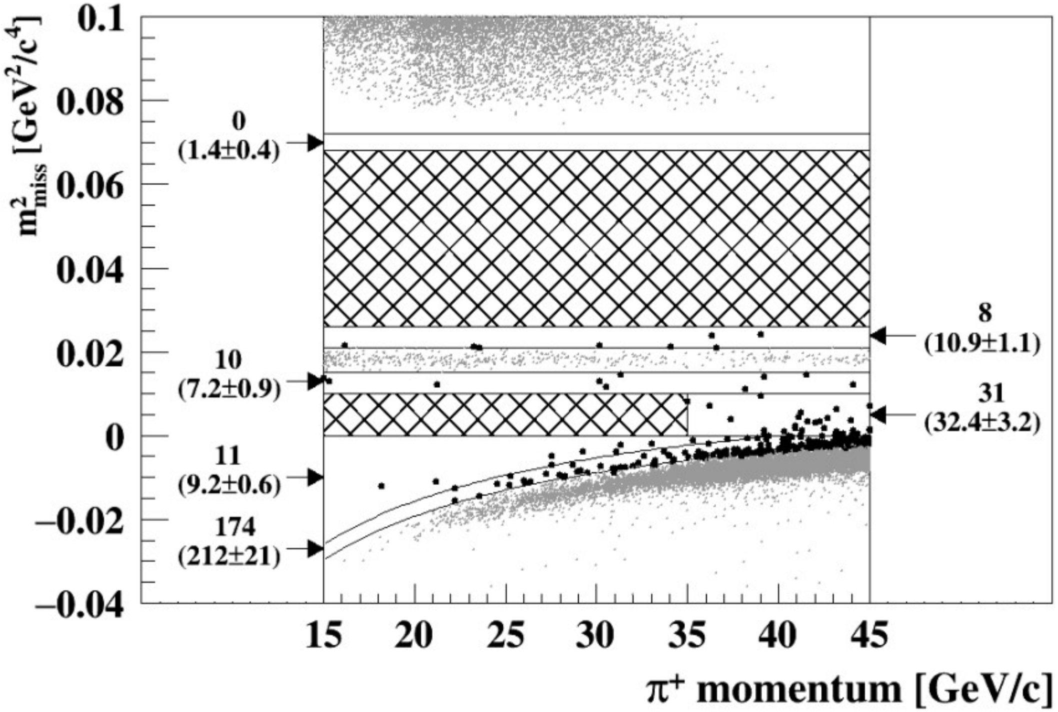






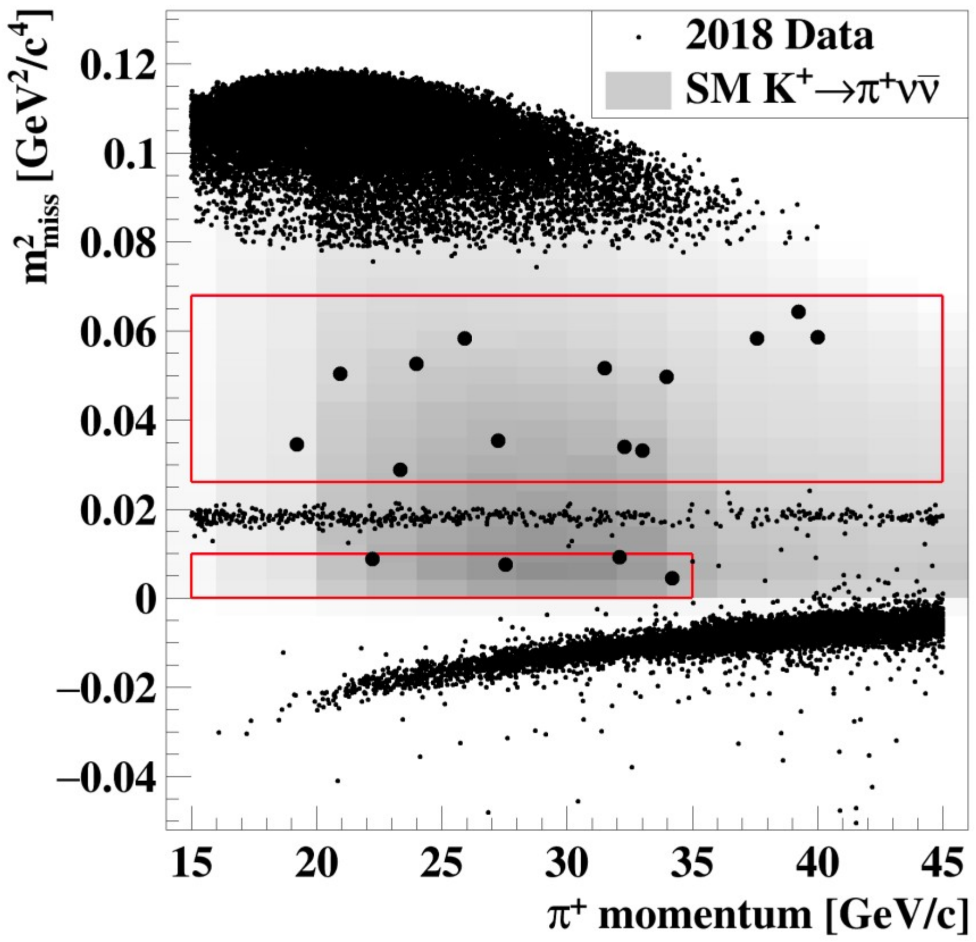
$K^+ \to \pi^+ \nu \bar{\nu}$ – Total expected background

- In the plot: expected and observed number of background events in the control regions after the signal selection
- Signal regions are masked



Process	Expected events in R1+R2 (2018 data)
$K^+ \to \pi^+ \nu \bar{\nu}$ (SM)	$7.58 \pm 0.40_{syst} \pm 0.75_{ext}$
Total Background	$5.28^{+0.99}_{-0.74}$
$K^+ \to \pi^+ \pi^0 (\gamma)$	0.75 ± 0.04
$K^+ \to \mu^+ \nu_\mu (\gamma)$	0.49 ± 0.05
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	0.50 ± 0.11
$K^+ \to \pi^+ \pi^+ \pi^-$	0.24 ± 0.08
$K^+ \to \pi^+ \gamma\gamma$	< 0.01
$K^+ \to \pi^0 l^+ \nu$	< 0.001
Upstream background	$3.3^{+0.98}_{-0.73}$

$K^+ \to \pi^+ \nu\bar{\nu}$ – Opening the box (2018 data)



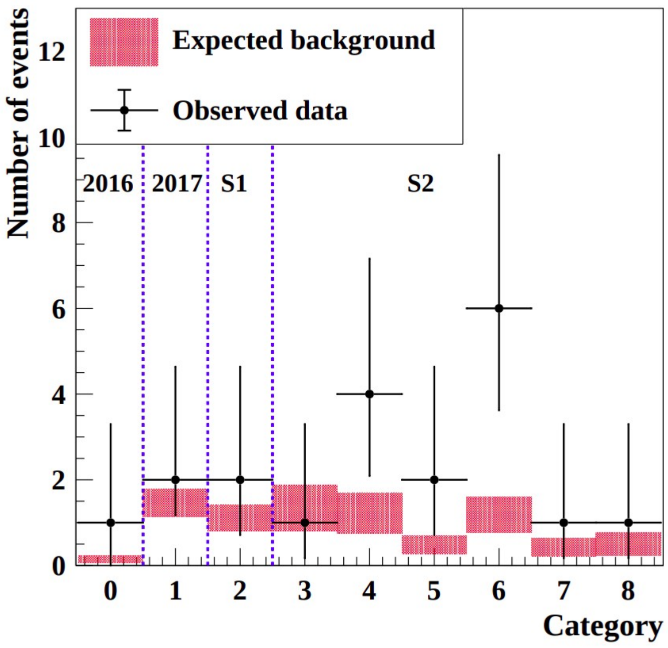
- 17 events observed in 2018 data
- Expected SM signal: 7.6
- Expected background: 5.3

$K^+ \to \pi^+ \nu\bar{\nu}$ – Combined results (2016+2017+2018)

- Combining data from 2016, 2017 and 2018, 20 events were found in the signal regions, consistent with the expectations

- Categories 3–8: 2018 data, 5 GeV/c momentum bins in the range 15–45 GeV/c
- Categories 0-2: integrated over momentum
- Maximum Likelihood fit to combine all categories

- Combined result:

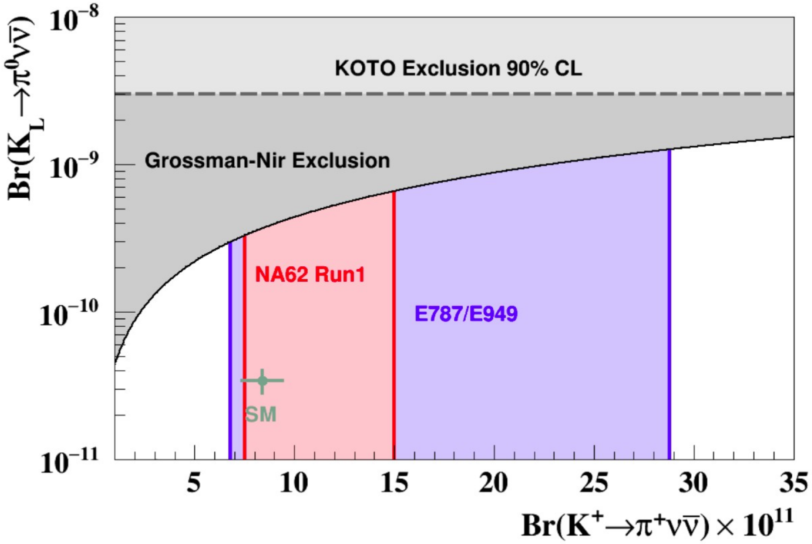


$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11} \quad @68\%\ \text{C.L.} \quad (3.4\,\sigma\ \text{significance})$$

- This is in agreement with the SM: $(8.4 \pm 1.0) \times 10^{-11}$

- Most precise measurement of this BR, so far

- Data taking will resume in July 2021, after important modifications to the beam line to suppress upstream events



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

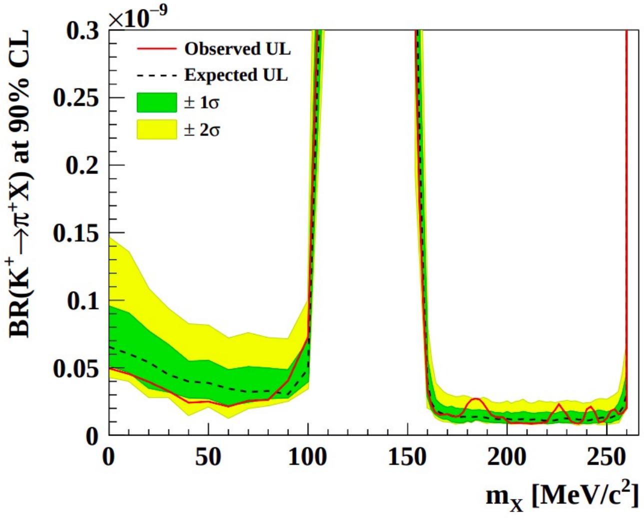
- X: feebly interacting new scalar or pseudo-scalar particle forseen in several BSM scenarios
  - [JHEP 05 (2010) 010], [JHEP 02 (2014) 123]
  - [JHEP 03 (2015) 171], [Phys.Rev.D16 (1977) 1791-1797], [Phys.Rev.D95 (2017) 095009]

- In the NA62 detector, the signature of $K^+ \to \pi^+ X$ is the same as for $K^+ \to \pi^+ \nu\bar{\nu}$: the results from the $\pi\nu\nu$ analysis can be interpreted in the framework of $K^+ \to \pi^+ X$

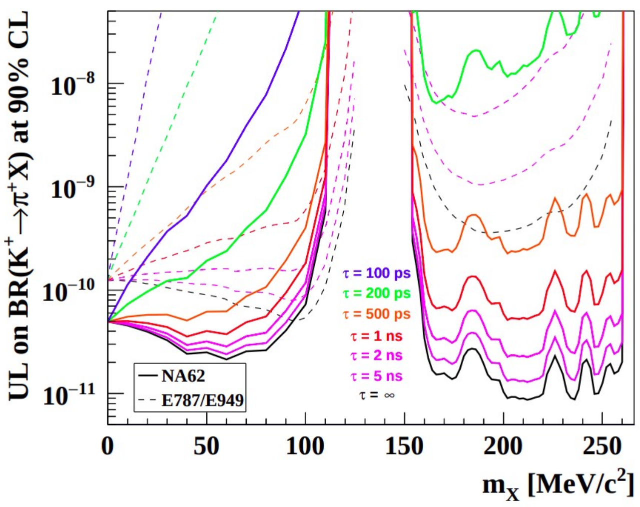
- Shape analysis of reconstructed m^2_{miss} to search for a peak centered at m^2_X

- Signal acceptance: generate MC samples for 200 m_X hypothesis

X invisible



X decays to SM particles



- Improved upper limit over the range [0,100] MeV and [160,260] MeV

- Comparison with BNL result: Artamonov et al., Phys.Rev.D 79, 092004

$K^+ \to \pi^+\mu^+\mu^-$ – Theoretical overview

- FCNC process described in ChPT, mediated by one photon exchange $K^+\to\pi^+\gamma^*$
- Together with $K^+\to\pi^+e^+e^-$ allows to test LFU
- Kinematical variables:

$$x = m(\pi^+\mu^-)^2/M_K^2\,, \quad z = m(\mu^+\mu^-)/M_K^2$$

- Differential decay width:

$$\frac{d^2\Gamma(x,z)}{dx\,dz} = \frac{d^2\Gamma_0(x,z)}{dx\,dz} \times (1+\delta(x,z))$$

Radiative corrections
[Eur.Phys.J. C70 (2010) 219-231]

$$\frac{d^2\Gamma_0(x,z)}{dx\,dz} = \frac{\alpha^2 M_K}{8\pi(4\pi)^4}\left[(2x+z-2-2r_\mu^2)(-2x-z+2r_\pi^2+2r_\mu^2)+z(z-2-2r_\pi^2)\right]|W(z)|^2$$

- Parametrization of form factor W(z) in NLO ChPT:

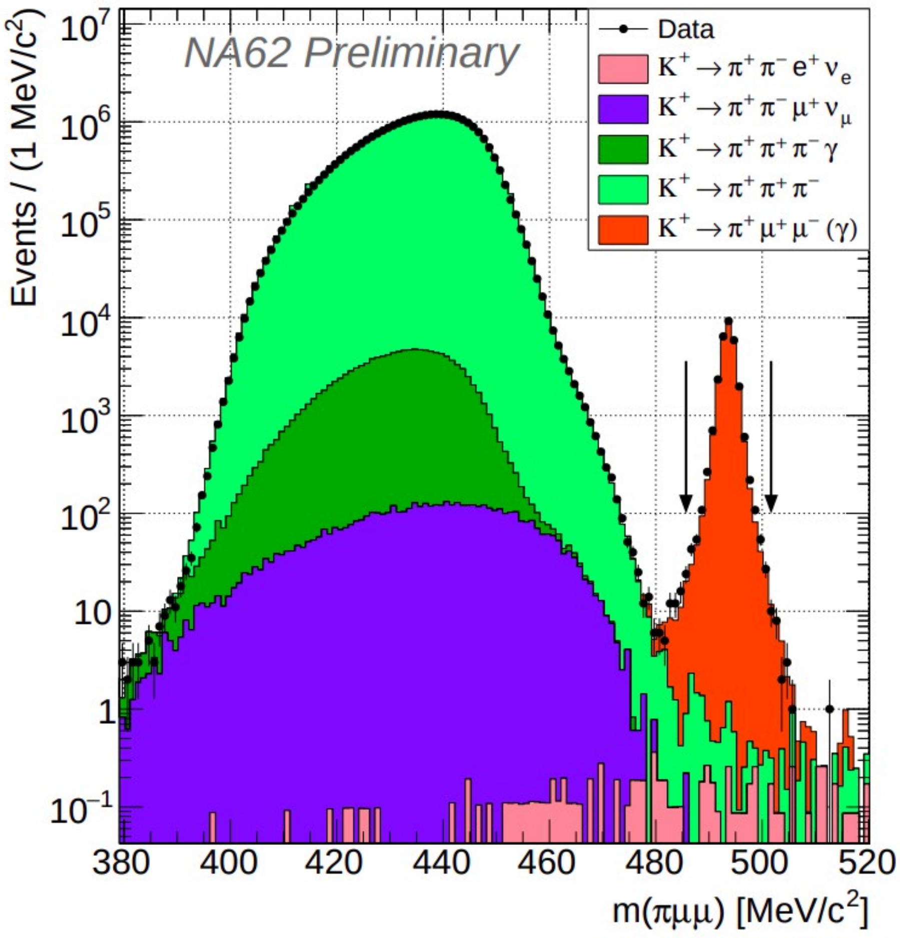
$$W(z) = G_F M_K^2(a+bz) + W^{\pi\pi}(z)$$

Pion loop term from $K^+\to\pi^+\pi^+\pi^-$

$K_{\pi\mu\mu}$ FF parameters

$K^+ \to \pi^+\mu^+\mu^-$ – Event selection

- Measurement of FF parameters (a,b) and model-dependent BR
- Normalization channel: $K^+ \to \pi^+\pi^+\pi^-$
- 2017+2018 data sample
- Event selection:
  - Generic 3-track event selection
  - Pion PID: $E/p < 0.9$, !MUV3
  - Muon PID: $E/p < 0.2$, MUV3
  - $|m(\pi\mu\mu) - M_K| < 8$ MeV/c^2
  - 28011 events selected
  - Expected background: $N_{bkg} = 12.5 \pm 1.7_{stat} \pm 12.5_{syst}$

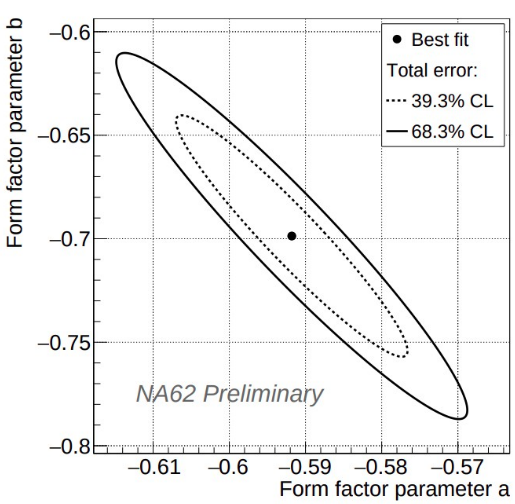


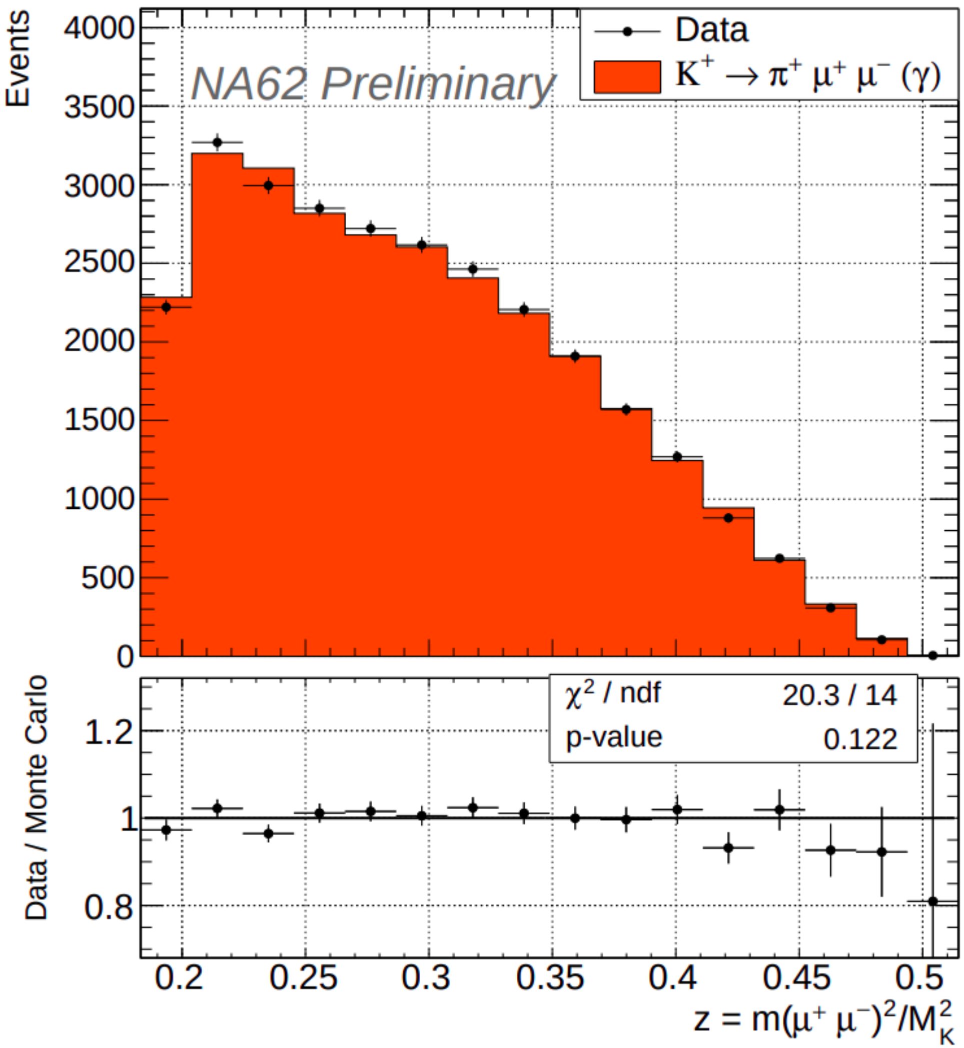
$K^+ \rightarrow \pi^+\mu^+\mu^-$ – Fit of form factor parameters

- z spectrum of $K_{\pi\mu\mu}$ reweighted to best fit the data, minimizing $\chi^2(a,b)$
- Best fit of FF parameters:

$$a = -0.592 \pm 0.013_{\text{stat}}$$
$$b = -0.699 \pm 0.046_{\text{stat}}$$

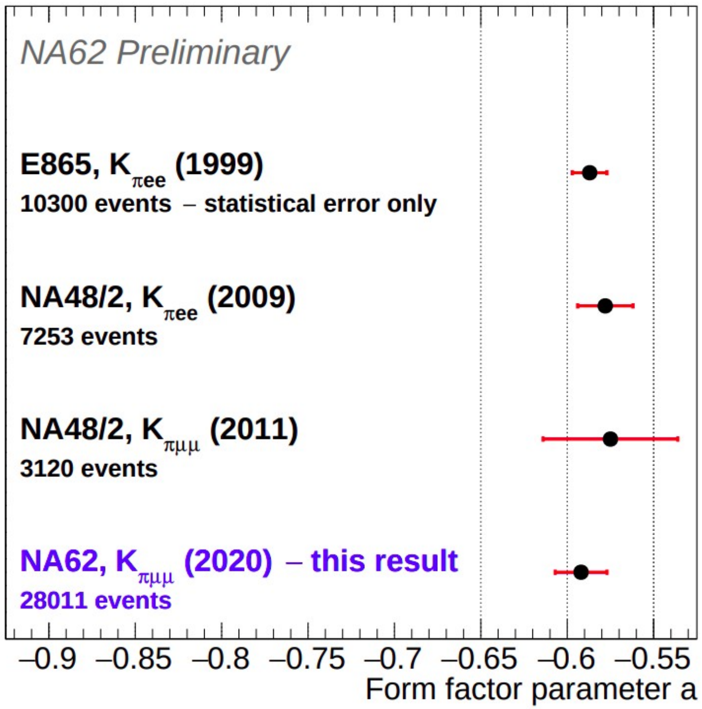
- $\chi^2/\text{ndf} = 20.3/14$
- p-value = 0.122
- Correlation coefficient: $\rho_{\text{stat}}(a,b) = -0.973$
- Model dependend $BR(K_{\pi\mu\mu})$: $(9.27 \pm 0.11)\times10^{-8}$

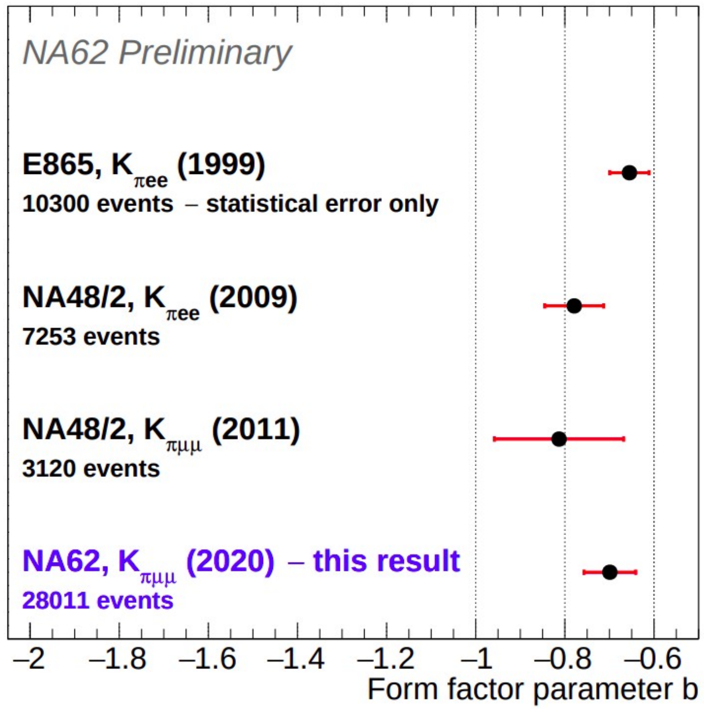




$K^+ \to \pi^+\mu^+\mu^-$ – Comparison with the world

- Preliminary $K_{\pi\mu\mu}$ result consistent with $K_{\pi ee}$ FF parameters
- No tension in LFU observed



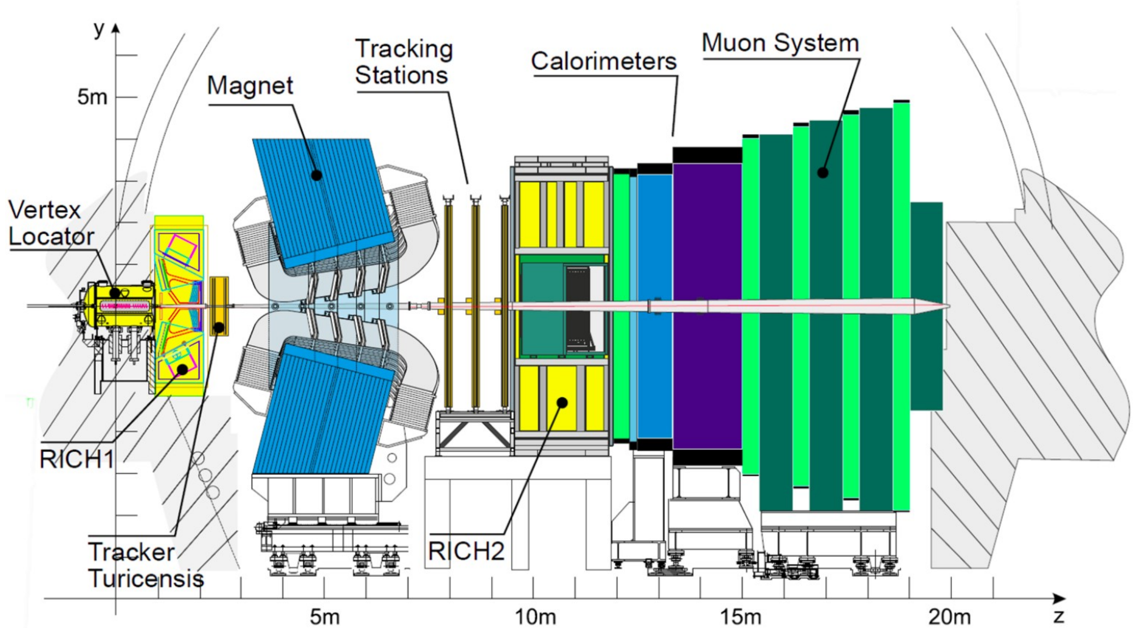


- E865 $K\pi ee$: Phys.Rev.Lett. 83 (1999) 4482-4485
- NA48/2 $K\pi ee$: Phys.Lett. B 677 (2009) 246-254
- NA48/2 $K\pi\mu\mu$: Phys. Lett. B 697 (2011) 107-115

LHCb

LHCb detector

- Forward spectrometer @LHC designed for the study of heavy flavour physics
- Pseudorapidity coverage $2 < \eta < 5$
- The weekly decaying b-particles fly ~O(cm) → displaced decay vertex to separate signal from background



- Abundant production of strange hadrons, but low efficiency in detecting kaon decays
- During Run 1, the total trigger efficiency for strangeness decays was < 1-2%
- During Run 2, dedicated software triggers for strange hadrons decaying into 2 μ: 1 order of magnitude improvement wrt Run 1

$K^0_S \to \mu^+\mu^-$

- $BR_{SM}(K^0_S \to \mu^+\mu^-) = (5.18 \pm 1.5_{LD} \pm 0.02_{SD}) \times 10^{-12}$ [D'Ambrosio et al., Phys. Rev. Lett. 119 (2017) 201802]
- FCNC process, highly suppressed in the SM
- Large deviations predicted by some BSM scenarios (e.g. SUSY, Leptoquarks)

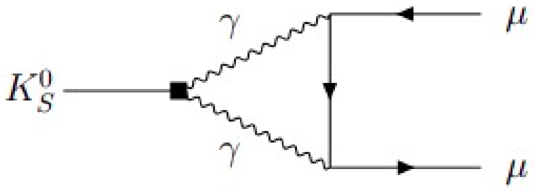
  [Chobanova et al., JHEP 05 (2018) 024],
  [Dorsner et al., JHEP 11 (2011) 002],
  [Bobeth and Buras, JHEP 02 (2018) 101]

- Run 1 limit:

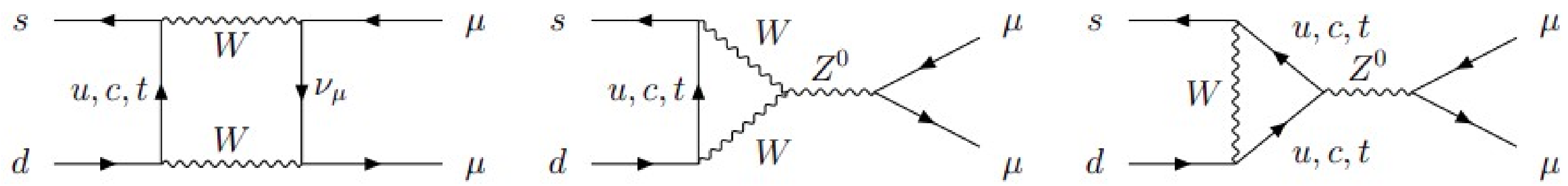
  $Br(K^0_S \to \mu^+\mu^-) < 0.8 \times 10^{-9}$ @90% C.L.

  [Eur. Phys. J. C77 (2017) 678]

Long distance contribution

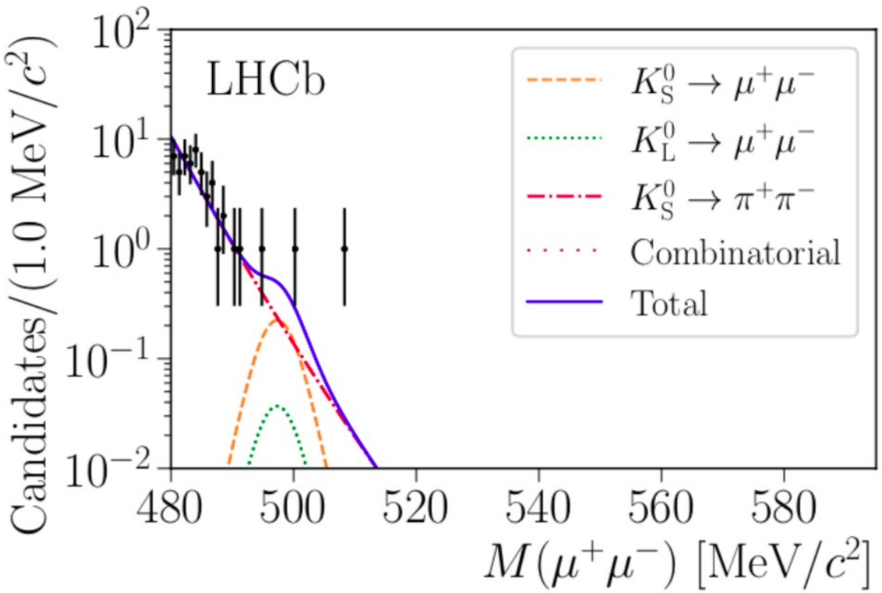


Short distance contributions



$K^0_S \to \mu^+\mu^-$

- Improved trigger strategy for Run 2
- Normalization channel: $K^0_S \to \pi^+\pi^-$
- Selection:
  - 2 tracks of opposite charge forming a vertex
  - Tracks identified as μ's
  - $400 < m(\mu\mu) < 600$ MeV/c^2
  - K decay vertex inside the VELO
  - K origin in PV, decay products origin in SV
- Main backgrounds:
  - $K^0_S \to \pi^+\pi^-$
  - $K^0_L \to \mu^+\mu^-$
- Signal yield consistent with zero



- New combined limit Run1+Run2:

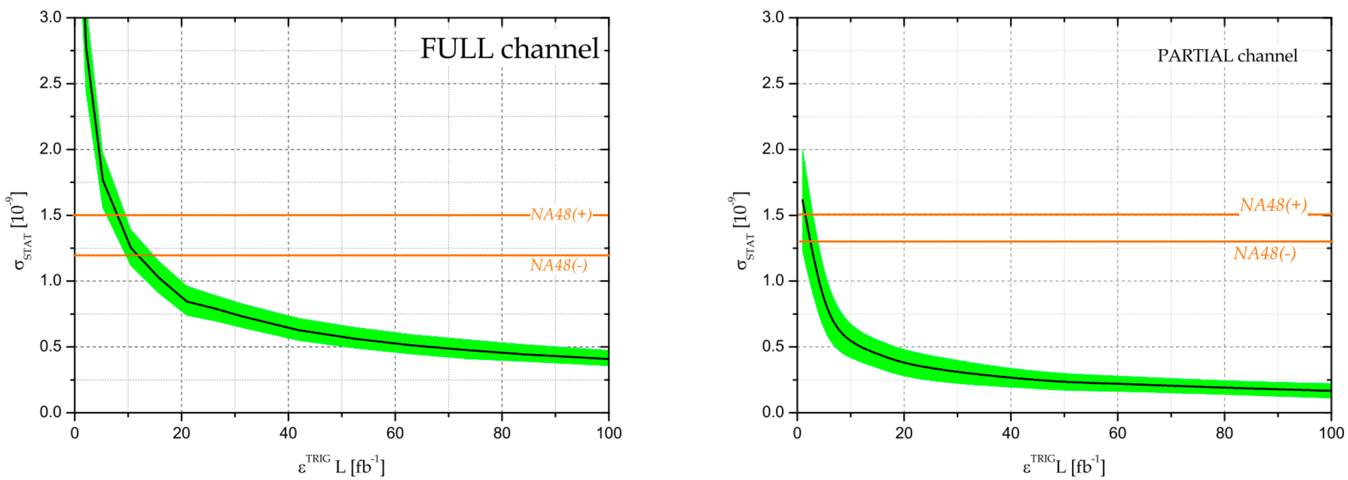
  $Br(K^0_S \to \mu^+\mu^-) < 2.1\times10^{-10}$ @ 90% C.L.

  [LHCb Collaboration, Phys.Rev.Lett. 125 (2020) 23, 231801

- After the upgrade, the hardware trigger will no longer be present, allowing for further efficiency improvements

$K_S^0 \to \pi^0 \mu^+ \mu^-$

- $Br(2.9^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$, by NA48 [Batley et al., PLB599 (2011) 197]
- $K_L^0 \to \pi^0 \mu^+ \mu^-$ very sensitive to models with extra dimensions, but currently there are large uncertainties on the SM prediction [Bauer et al., JHEP 09 (2010) 017]
- Theoretical precision on $K_L^0 \to \pi^0 \mu^+ \mu^-$ limited by knowledge of ChPT parameters $|a_S|$ extracted from $Br(K_S^0 \to \pi^0 \mu^+ \mu^-)$
- A precise measurement is crucial for a precise SM prediction of $Br(K_L^0 \to \pi^0 \mu^+ \mu^-)$
- Sensitivity studied for Run 2 and Upgrade scenarios [Chobanova et al., CERN-LHCb-PUB-2016-017]
- Soft π^0, but π^0 reconstruction not essential, being constrained by very low q-value
- Double strategy: with (“FULL”) and without (“PARTIAL”) π^0 reconstruction
- Combinatorial background studied from data
- Peaking background studied from MC, none found to contribute
- If LHCb can guarantee a trigger efficiency > 50%, it can improve on the NA48 result



Other K decays at LHCb

$$K_S^0 \to l^+ l^- l'^+ l'^- \qquad (l^{(\prime)} = e, \mu)$$

- $K_L^0 \to l^+ l^- l'^+ l'^-$ studied by different experiments, but no experimental limits available for $K_S^0 \to l^+ l^- l'^+ l'^-$
  - $Br(K_S^0 \to e^+ e^- e^+ e^-) \sim 10^{-10}$
  - $Br(K_S^0 \to \mu^+ \mu^- e^+ e^-) \sim 10^{-11}$
  - $Br(K_S^0 \to \mu^+ \mu^- \mu^+ \mu^-) \sim 10^{-14}$
- Short distance sensitive to NP, dominated by long distance contribution uncertainty
- Stringent CKM test from the interference between $A(K_S^0 \to l^+ l^- l'^+ l'^-)$ and $A(K_L^0 \to l^+ l^- l'^+ l'^-)$, that would allow the measurement of the sign of $A(K_L^0 \to \gamma\gamma)$ [D'Ambrosio et al., EPJC73 (2013) 2678], [Isidori, Unterdorfer, JHEP 0401 (2004) 009]

$K_S^0 \to \pi^+ \pi^- e^+ e^-$

- $K_S^0 \to \pi^+ \pi^- e^+ e^-$ is a proxy channel for $K_S^0 \to l^+ l^- l^+ l^-$
- Light dark matter states decaying into a pair of leptons (peak in m_{e+e-})
- State of the art: $Br(K_S^0 \to \pi^+ \pi^- e^+ e^-) = (4.79 \pm 0.15) \times 10^{-5}$ [NA48, PDG]
- Sensitivity study with MC: ε~0.2% limited by L0 trigger [Marin Benito et al., CERN-LHCb-PUB-2016-016]
- Expected signal yield per fb^{-1} at 8 TeV: $N_{\mathrm{Run1}}^{\mathrm{exp}} \sim 120^{+280}_{-100}$, on top of $3 \cdot 10^3$ background events
- Dedicated HLT trigger line in Run2, still limited by HLT1 and L0 trigger
- Upgrade on the trigger will improve the efficiency significantly
- After LHCb upgrade, in the ideal scenario of ε~100% wrt offline selection: $N_{\mathrm{Upgrade}}^{\mathrm{exp}} = (5.0 \pm 0.3) \times 10^4$
- Similar efficiencies are expected for related channels ($K_S^0 \to l^+ l^- l^+ l^-$)

Summary

- Kaon physics experiments have produced and are still producing important results

- **NA62**
  - $Br(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$ @ 68 % C.L.
  - Improved bounds on feebly interacting particle X, with signature $K^+ \to \pi^+ X$ in almost the full mass range ~[0, 250] MeV
  - Measured $K^+ \to \pi^+ \mu^+ \mu^-$ form factor parameters a and b, and model dependent $Br(K^+ \to \pi^+ \mu^+ \mu^-)$

- **LHCb**
  - $Br(K^0_S \to \mu^+ \mu^-) < 2.1 \times 10^{-10}$ @ 90 % C.L.
  - Promising prospects for measurements of $K^0_S \to \pi^0 \mu^+ \mu^-$, $K^0_S \to l^+ l^- l^+ l^-$ and $K^0_S \to \pi^+ \pi^- e^+ e^-$

- Both NA62 and LHCb will resume data taking soon, after the upgrades implemented during the LS2 → New and ongoing analyses will surely provide interesting information

- Many exciting experimental results in K physics could not be covered by this talk, so I invite you to have a look at the presentations by S. Martellotti and H. Nanjo:

  - Recent Kaon results at NA62: https://indico.ihep.ac.cn/event/12805/session/44/contribution/190
  - Rare Kaon decays in KOTO/KLOE2 experiment: https://indico.ihep.ac.cn/event/12805/session/40/contribution/236

Thank you for your attention!