The NA62 experiment: status and plans

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on behalf of the NA62 collaboration

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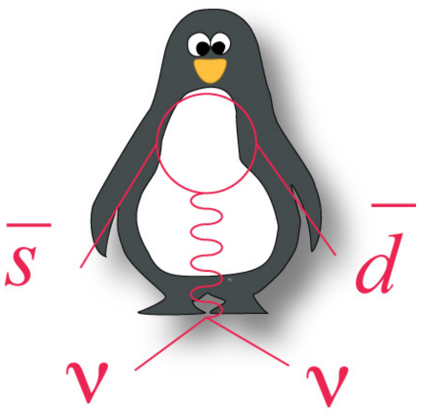
Outline

- The NA62 experiment
- Experimental setup
- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ analysis
- NA62 physics program:
  - ✓ LNV/LFV in kaon decays
  - ✓ Exotic searches
  - ✓ Rare kaon decays
- 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^+)**

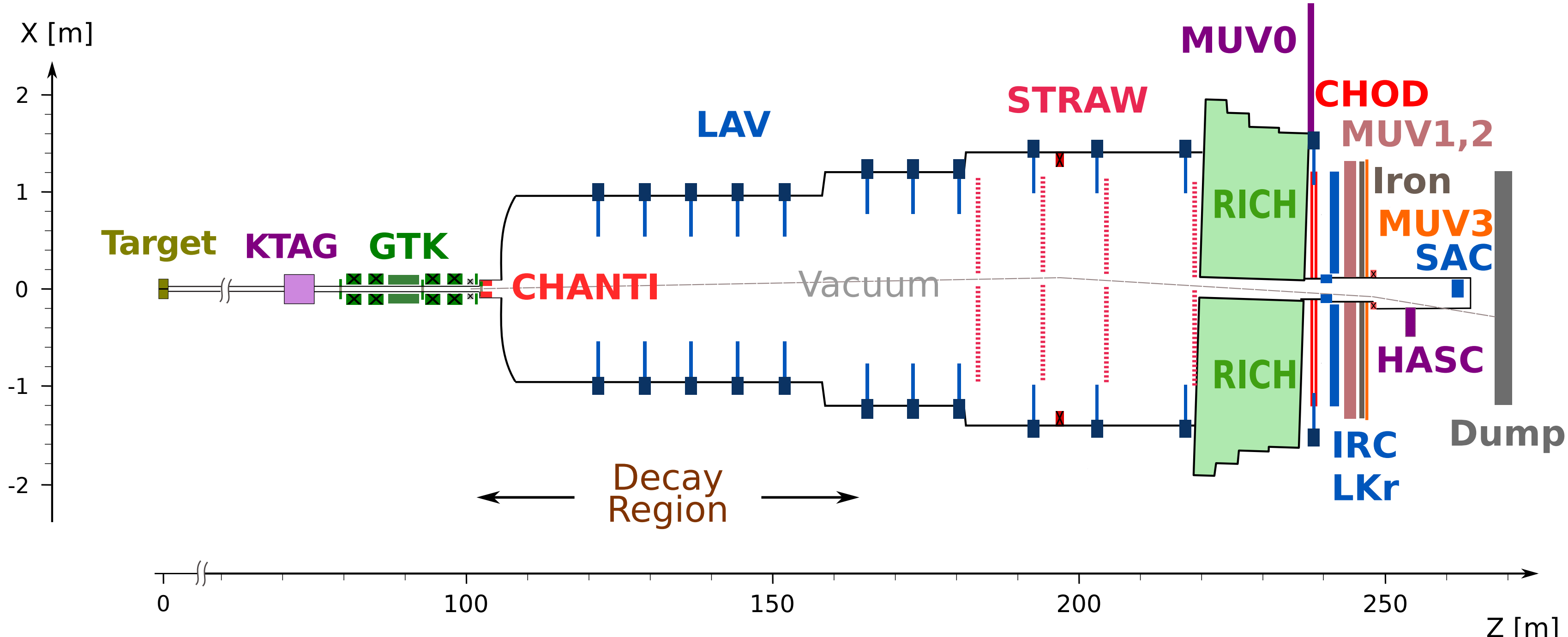
NA62 collaboration: ~ 200 participants from ~ 30 institution:

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

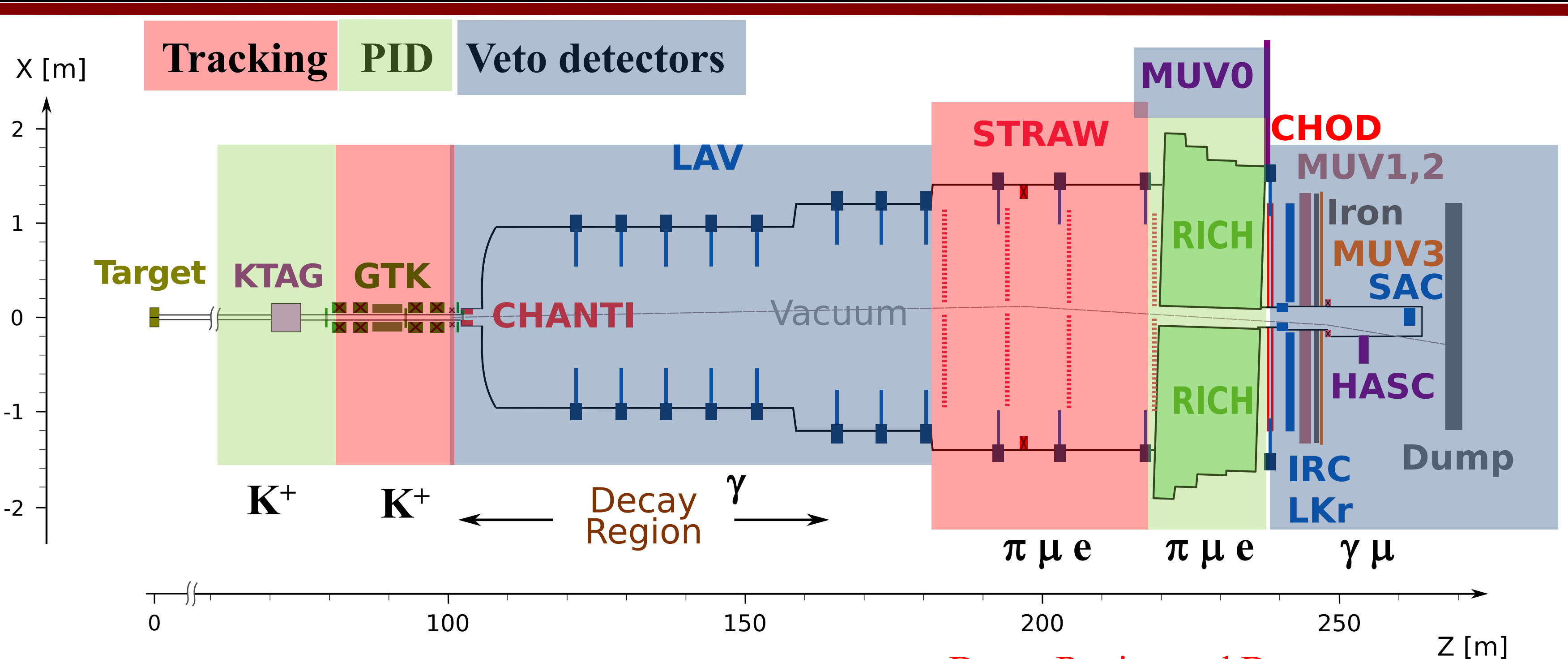
2009 – 2014	2014 – 2015	2016 – 2018	2021 – 2023
Construction and installation	Technical runs	Physics runs	Physics runs

NA62 beam and detector



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

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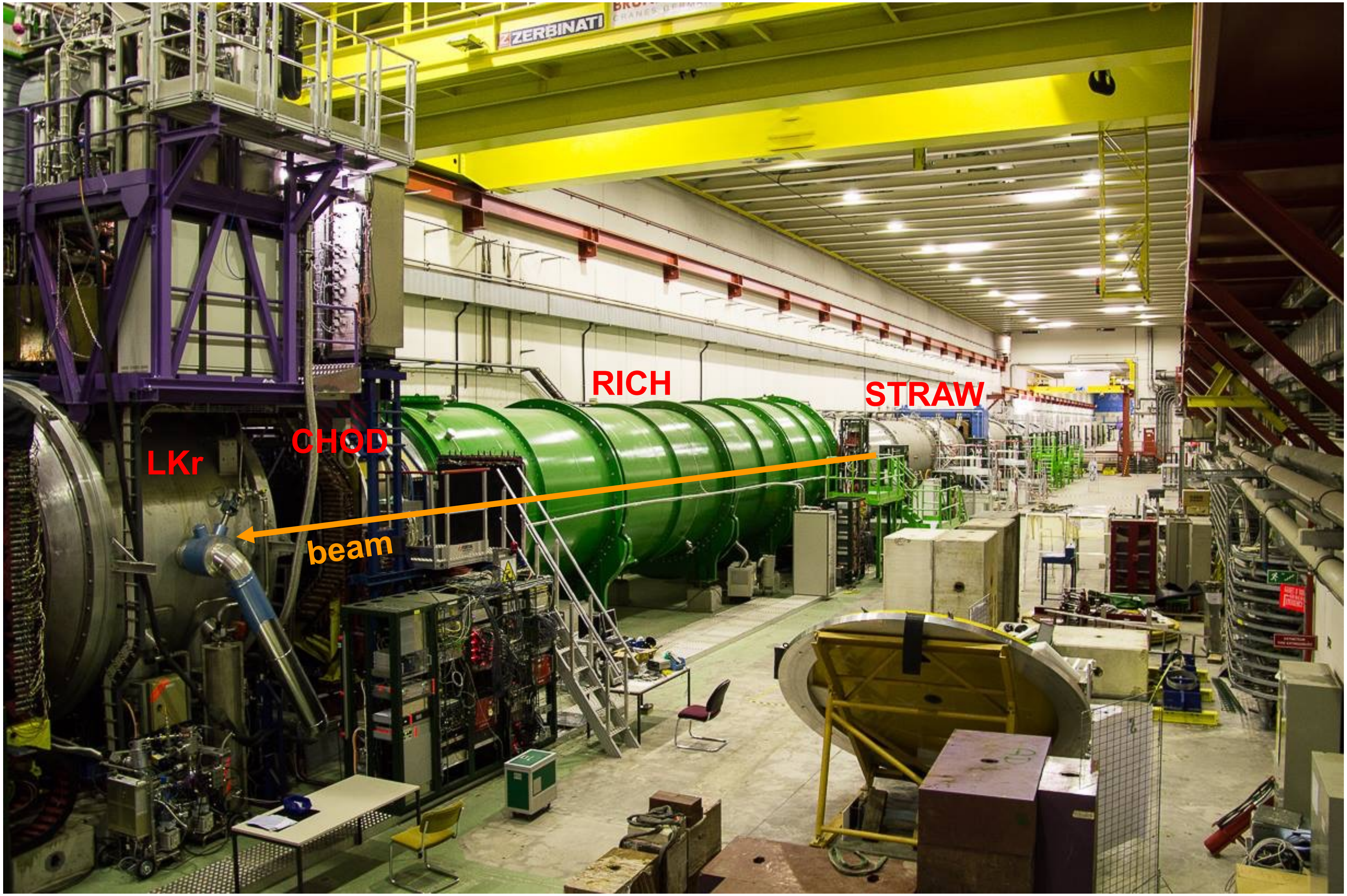
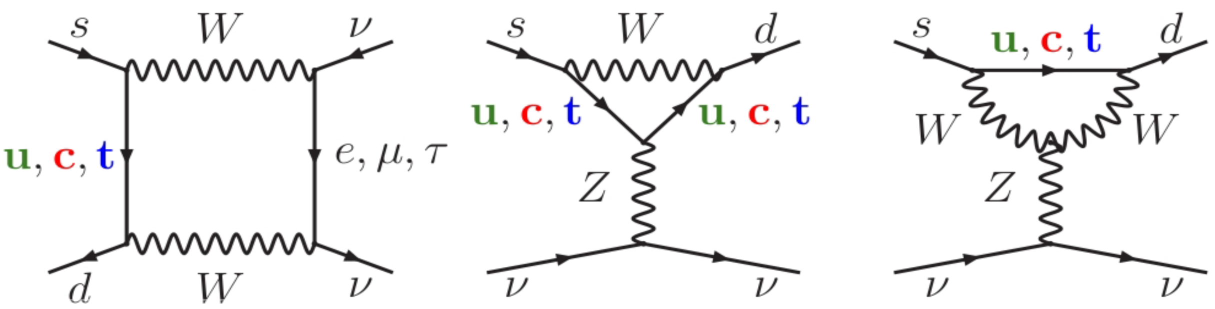
NA62 Detector

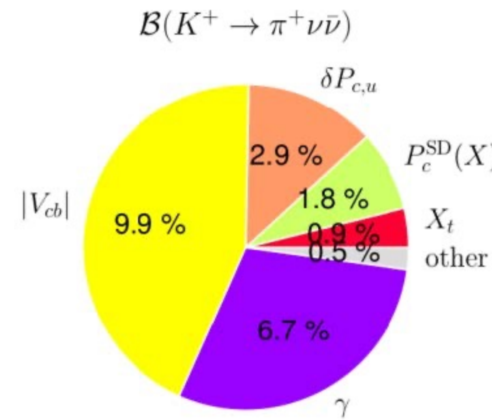


$$K^+ \rightarrow \pi^+ \nu\bar{\nu}$$

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



Theoretical error budget



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

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

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

- Experimental results:

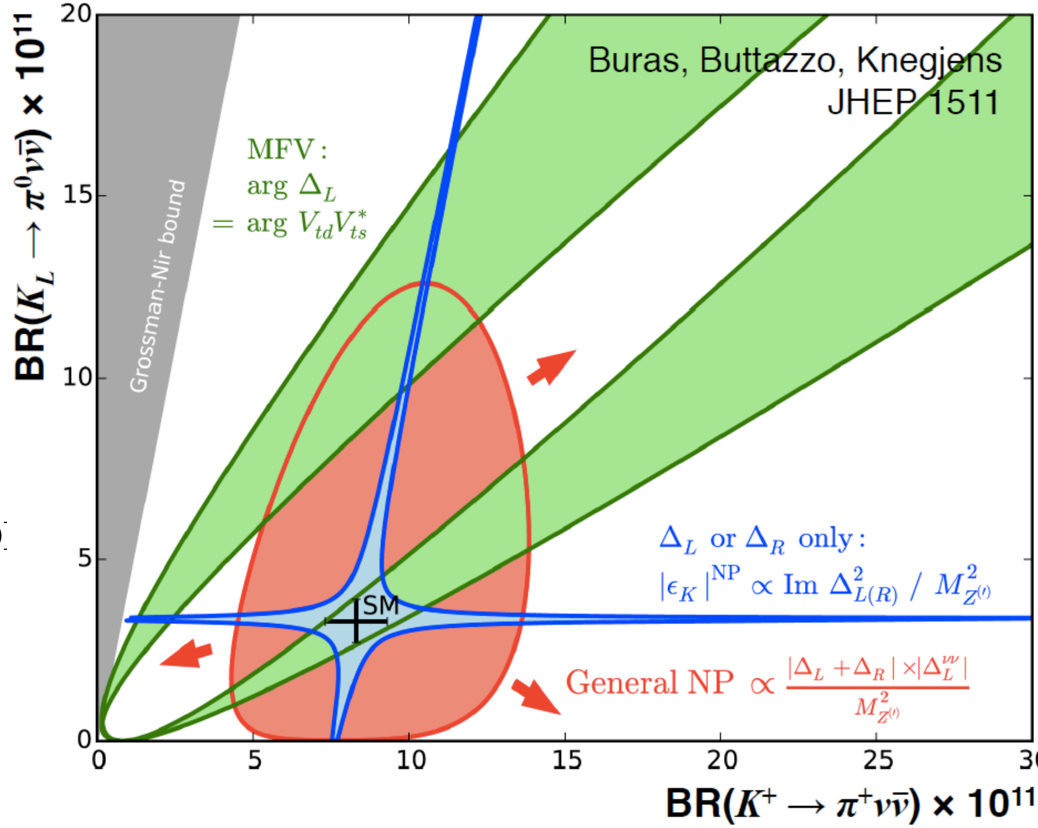
$$\mathbf{BR(K^+ \to \pi^+ \nu\bar{\nu})(E787\ E949) = (17.3\ ^{+11.5}_{-10.5}) \times 10^{-10}}$$ [Phys rev. D 79, 092004 (2009)]

$$\mathbf{BR(K_L \to \pi^0 \nu\bar{\nu})(391\ a) < 2.6 \times 10^{-8}\ (90\%\ CL)}$$ [Phys rev. D 81, 072004 (2010)]

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

Measurement of charged **($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)** and neutral (**$K_L \rightarrow \pi^0 \nu\bar{\nu}$**) modes can
discriminate among different NP scenarios

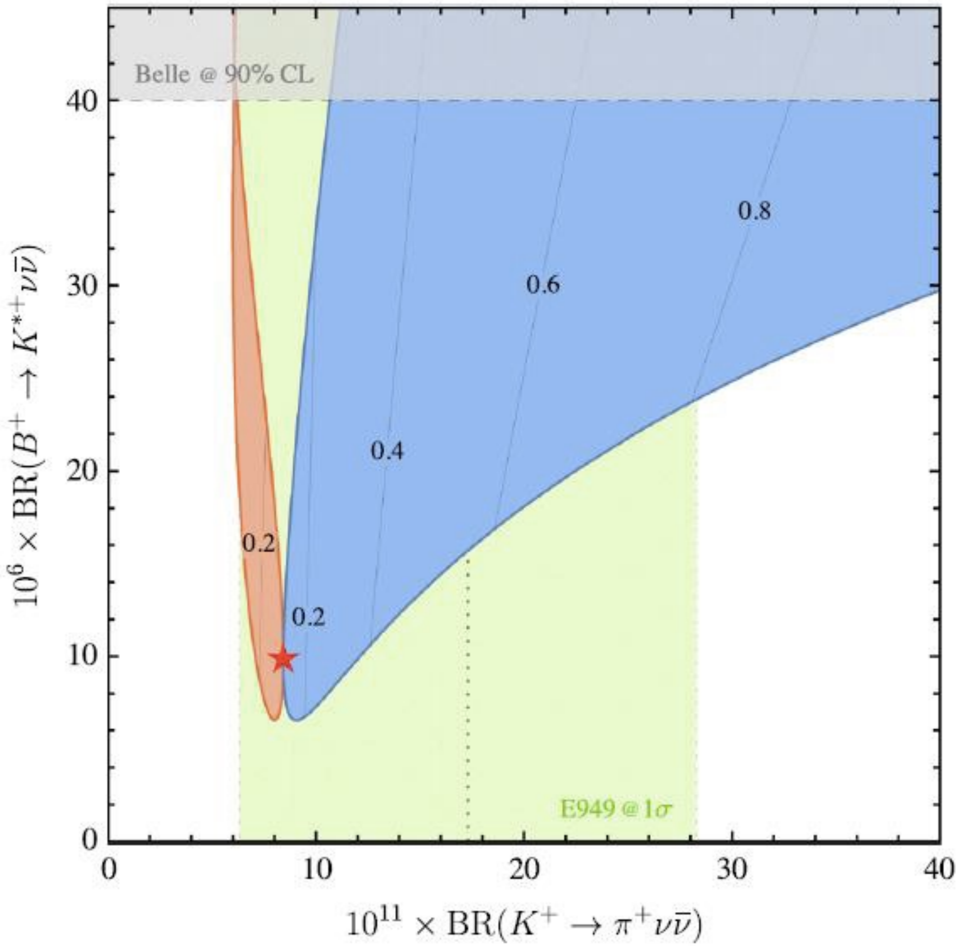
- ✓ **Models with CKM-like flavour structure**
  [Buras , Buttazzo, knegjens, JHEP11(2015) 166]
- ✓ **Custodial Randall-Sundrum**
  [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- ✓ **MSSM analyses**
  [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],
  [Isidori et al. JHEP 0608 (2006) 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]



$K^+ \to \pi^+ \nu\bar{\nu}$ 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 $\mathbf{B^+ \to K^{*+} \nu\bar{\nu}}$.

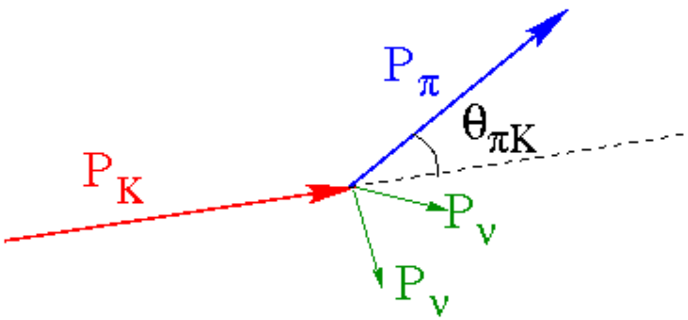


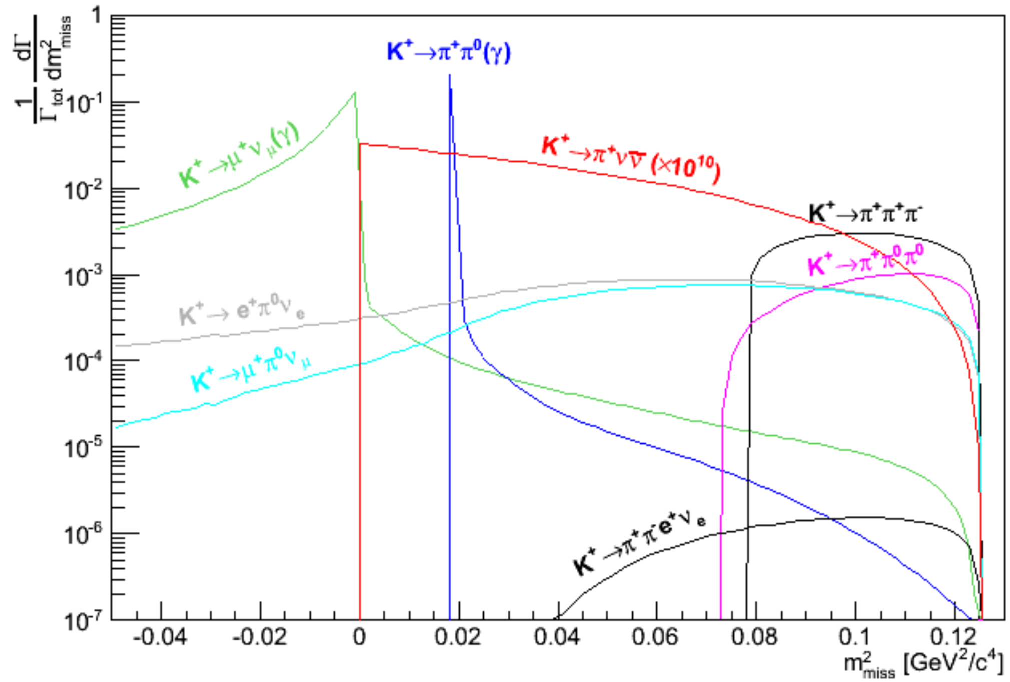
Experimental Strategy

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

15 GeV/c < $P\pi^+$ < 35 (45 in 2018) GeV/c
2 signal regions

- Particle ID(Cherenkov detectors)
- Particle ID(Calorimeters)
- Muon and Photon veto
- Signal and background control regions are kept blind throughout the analysis





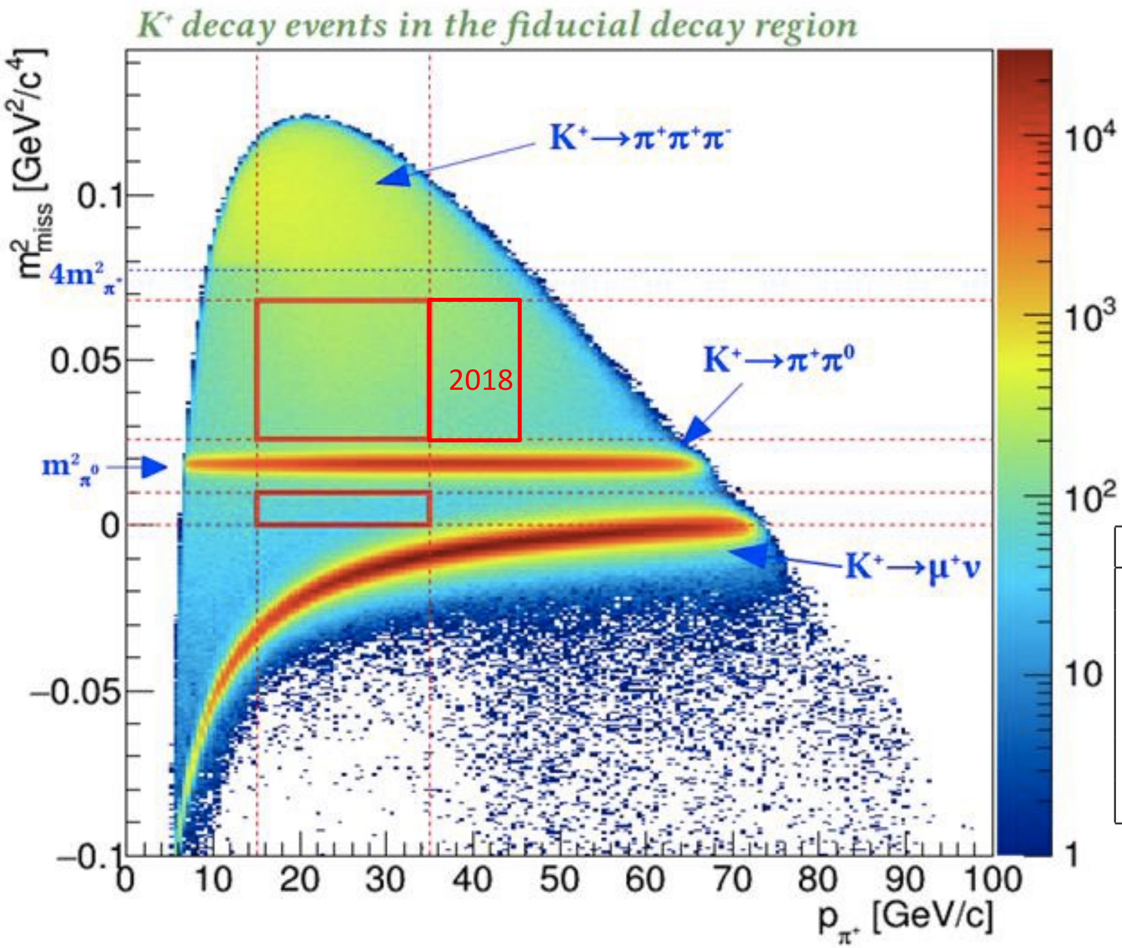
Decay mode	BR	Main rejection tools
$K^+ \to \mu^+\nu(\gamma)$	63%	μ–ID + kinematics
$K^+ \to \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	multi + kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+\nu_e$	5%	e–ID + γ-veto
$K^+ \to \pi^0\mu^+\nu_\mu$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

Required performances

O(100 ps) Timing between sub-detectors
O(10^4) Kinematic suppression
> 10^7 Muon suppression
> 10^7 π^0 (from $K^+\to\pi^+\pi^0$) suppression

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

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$K^+ \to \pi^0 e^+\nu_e$	5%	e−ID + γ-veto
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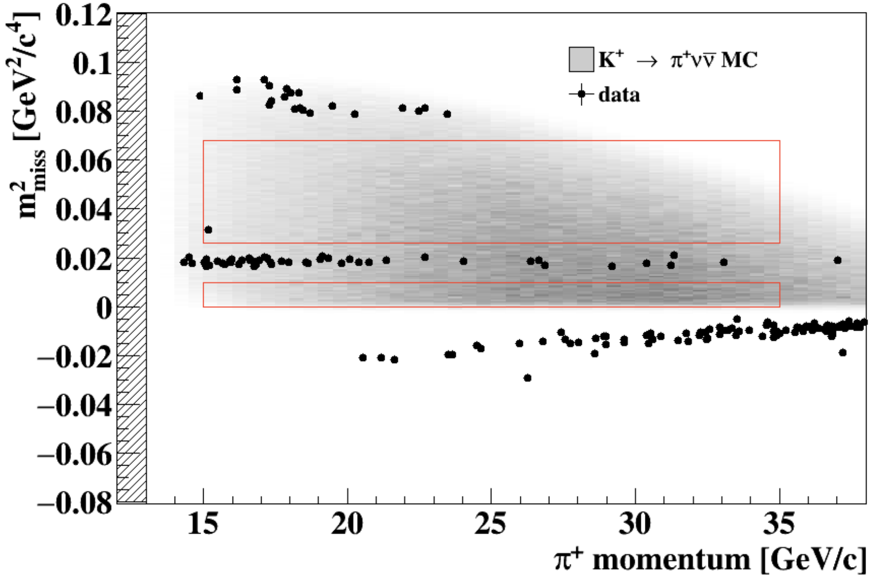
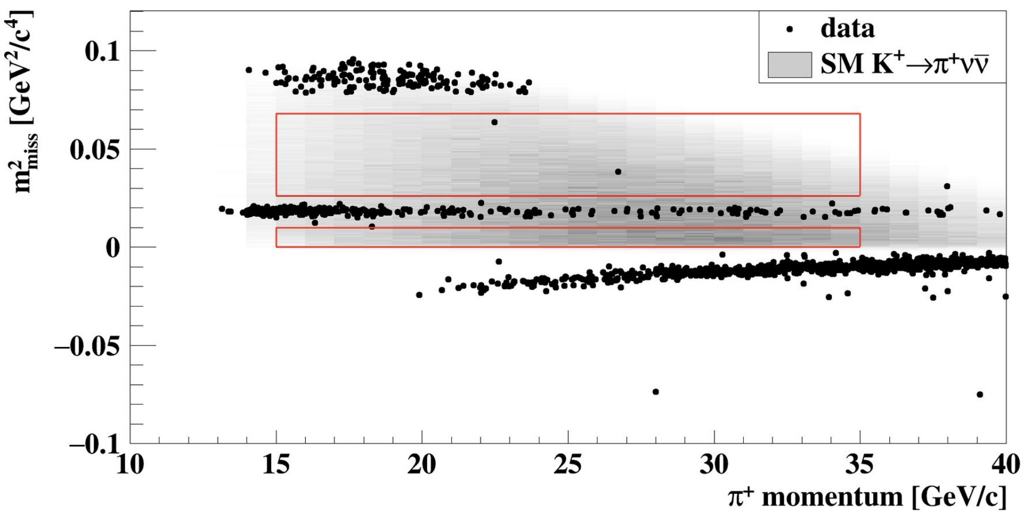
2016 – 2017 data tacking results





2016

2017

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]

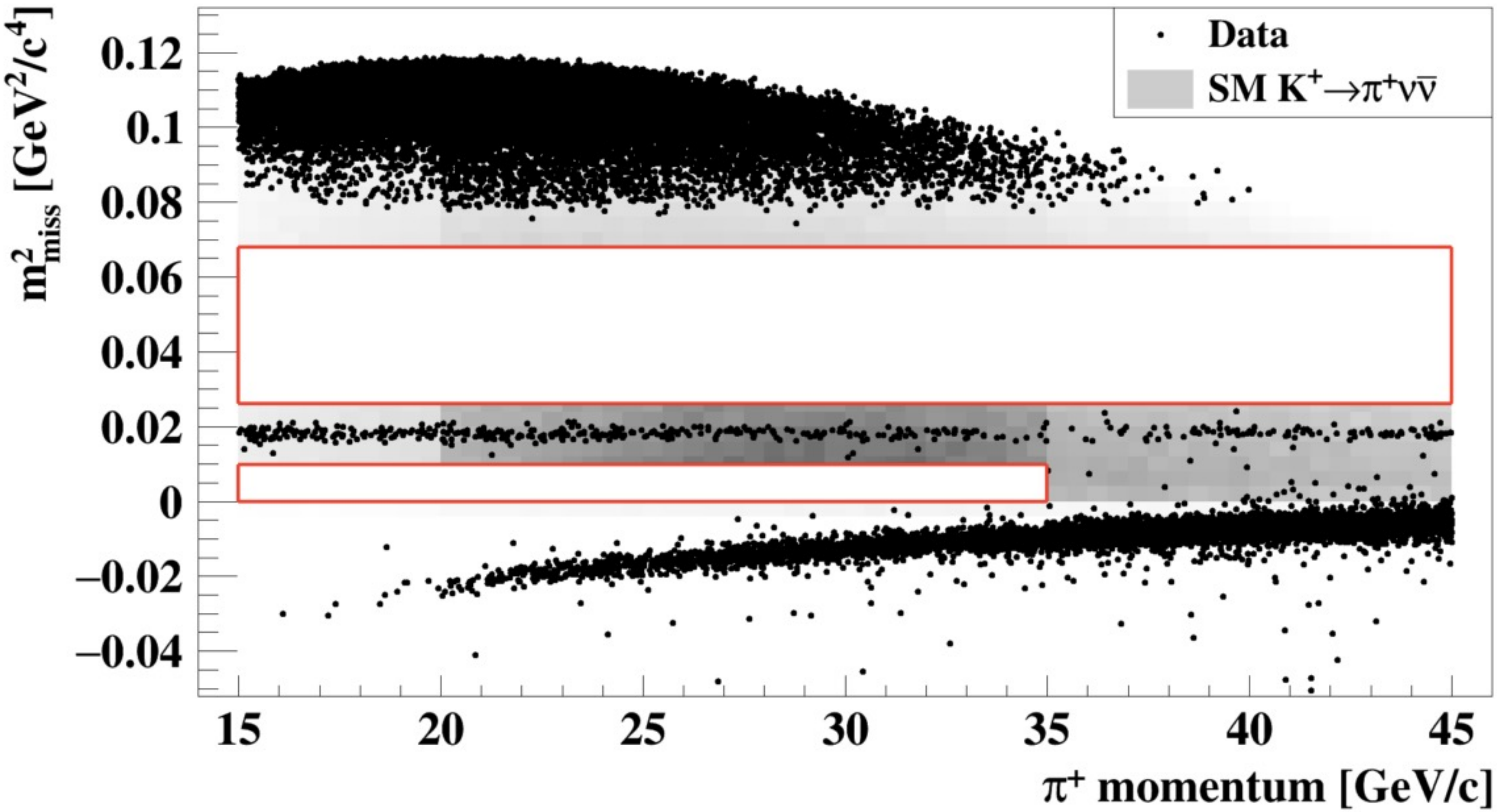
2 events observed

SES = 0.389 x 10^{-10}

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

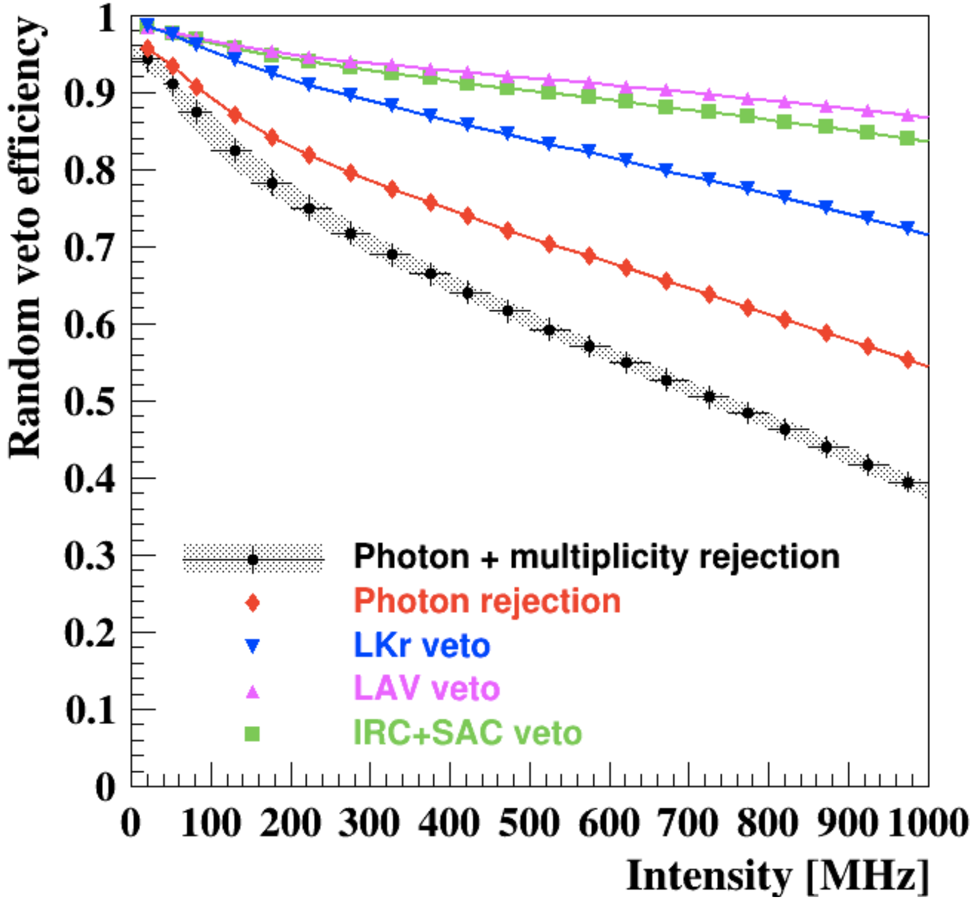
[J. High Energ. Phys. 2020, 42 (2020)]

2018 data tacking results



Single Event Sensitivity (SES)

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



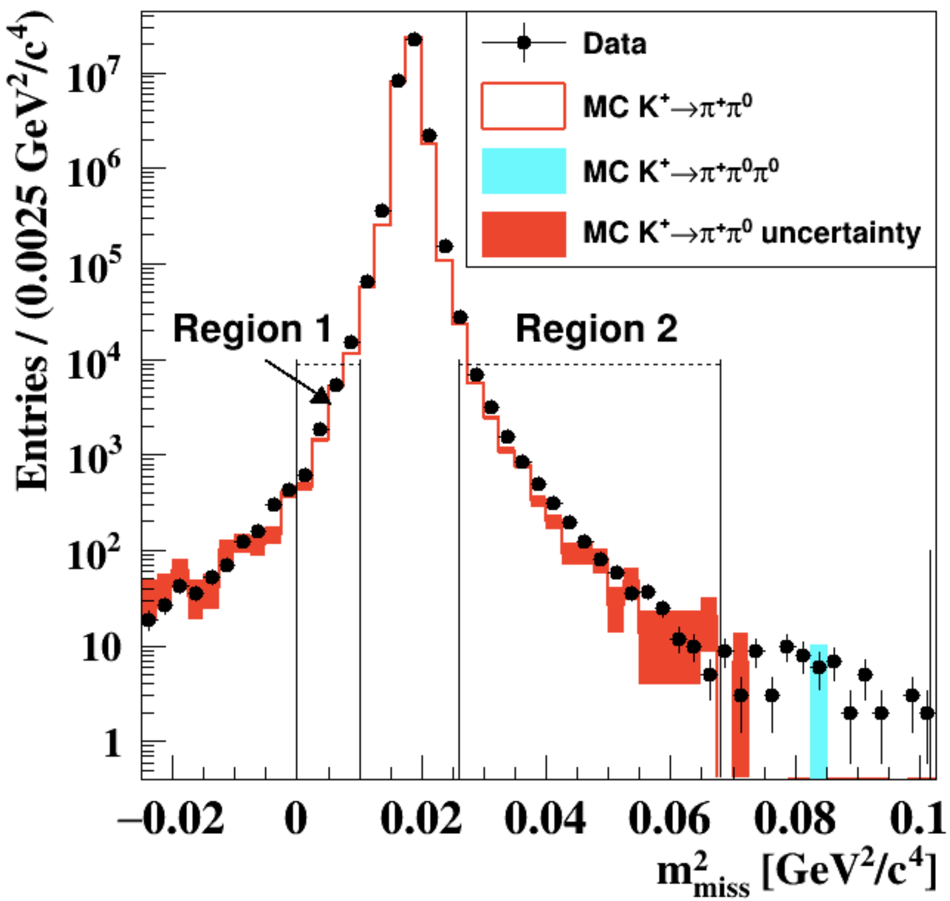
	Subset S1	Subset S2
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^{2}$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^{2}$	3.95 ± 0.40	6.37 ± 0.64
$\epsilon^{\text{PNN}}_{\text{trig}}$	0.89 ± 0.05	0.89 ± 0.05
ϵ_{RV}	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14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

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

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

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

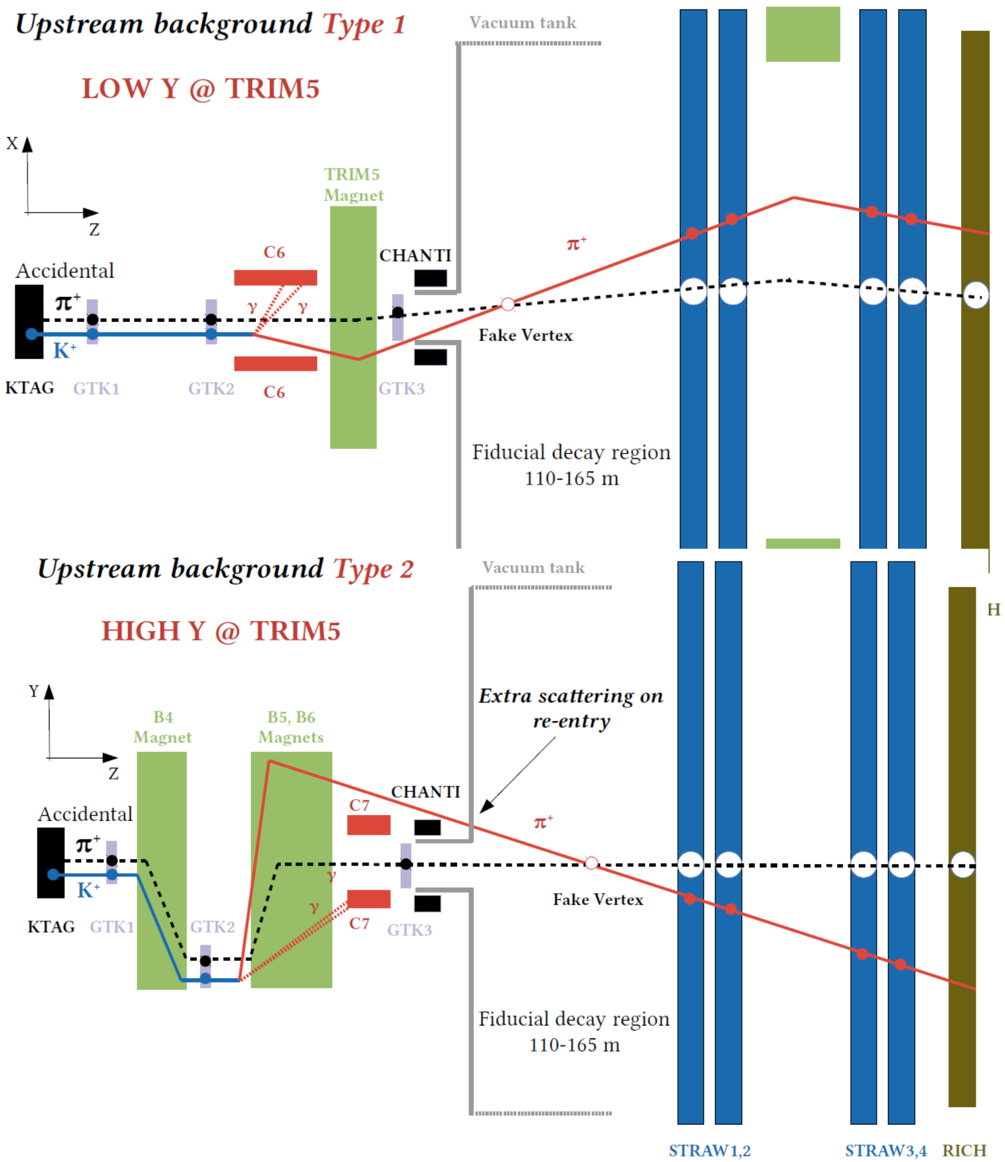
$$N^{exp}_{\pi\pi}(SR) = \mathbf{N_{\pi\pi}}\ \mathbf{f_{kin}(SR)}$$

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

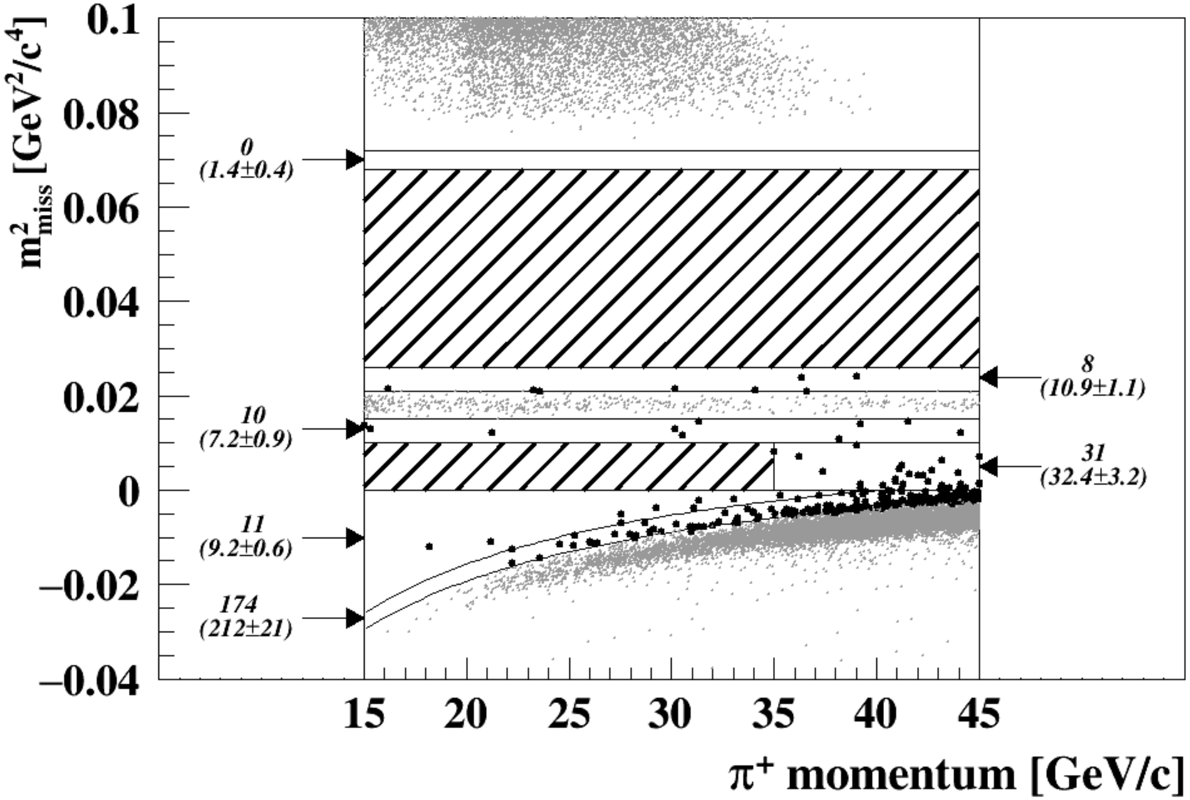
Upstream background



- 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.

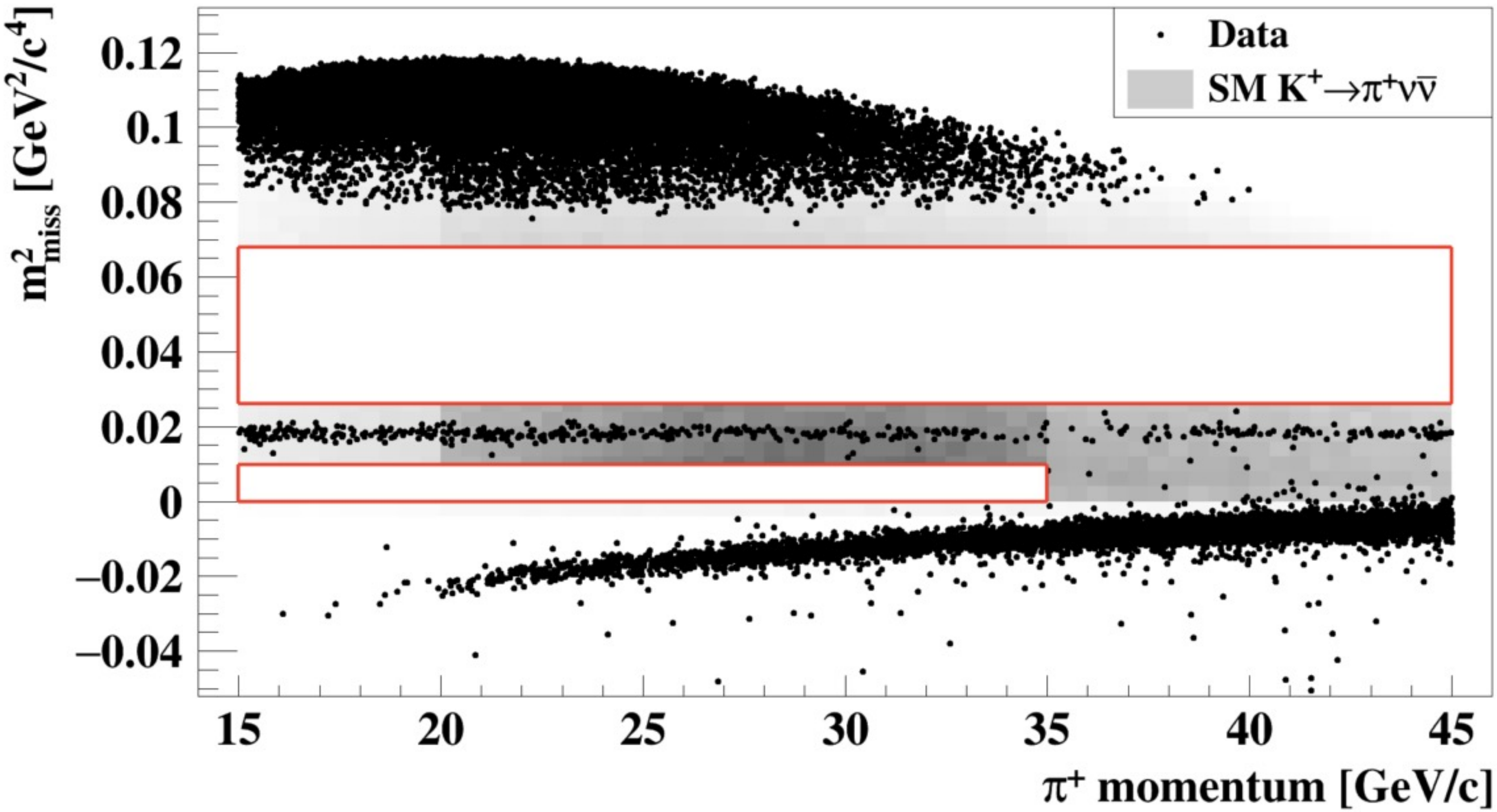
- Kaon-pion association and geometrical variables
- Data driven background estimation

Control regions: main decays



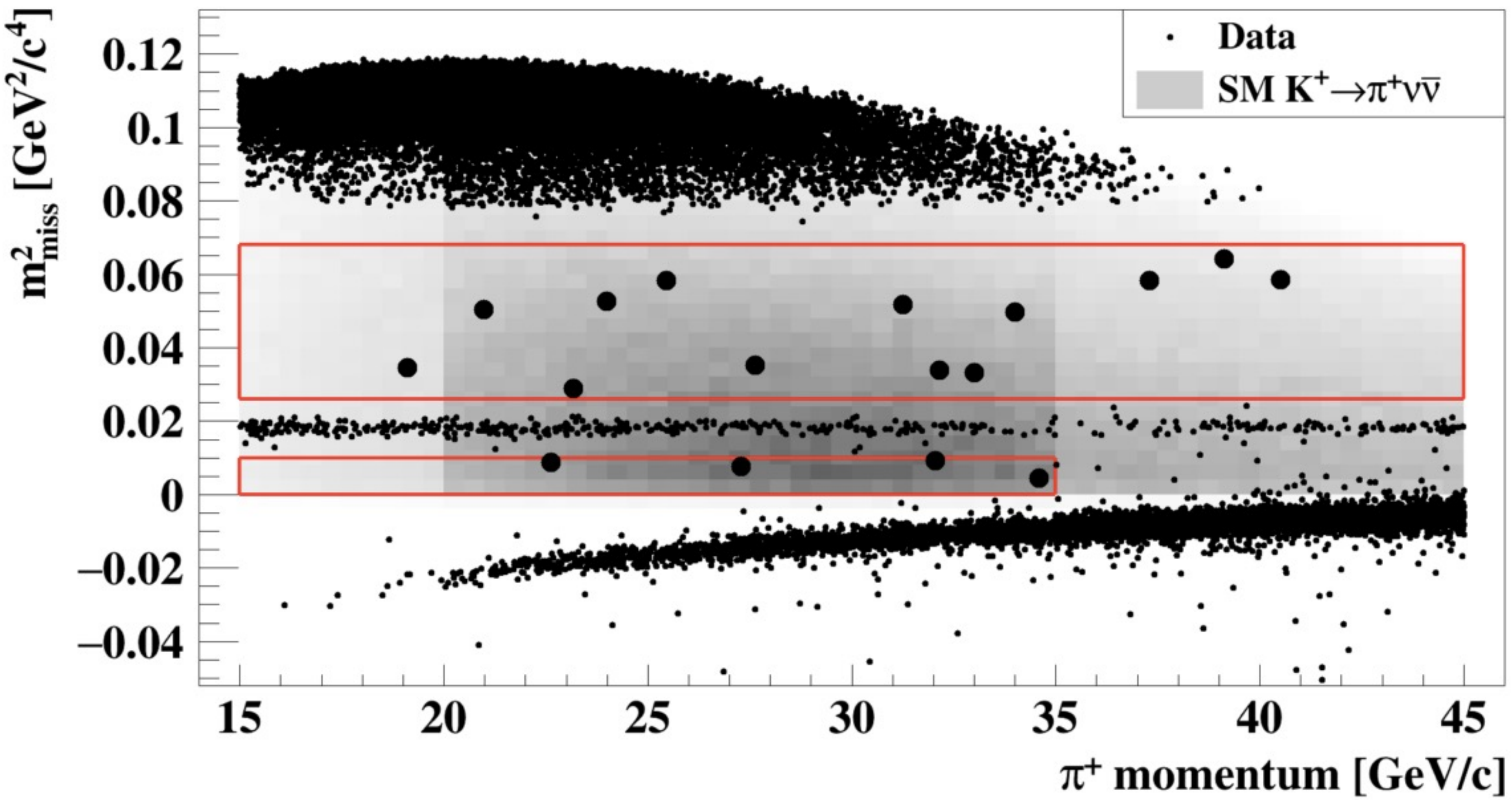
Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$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

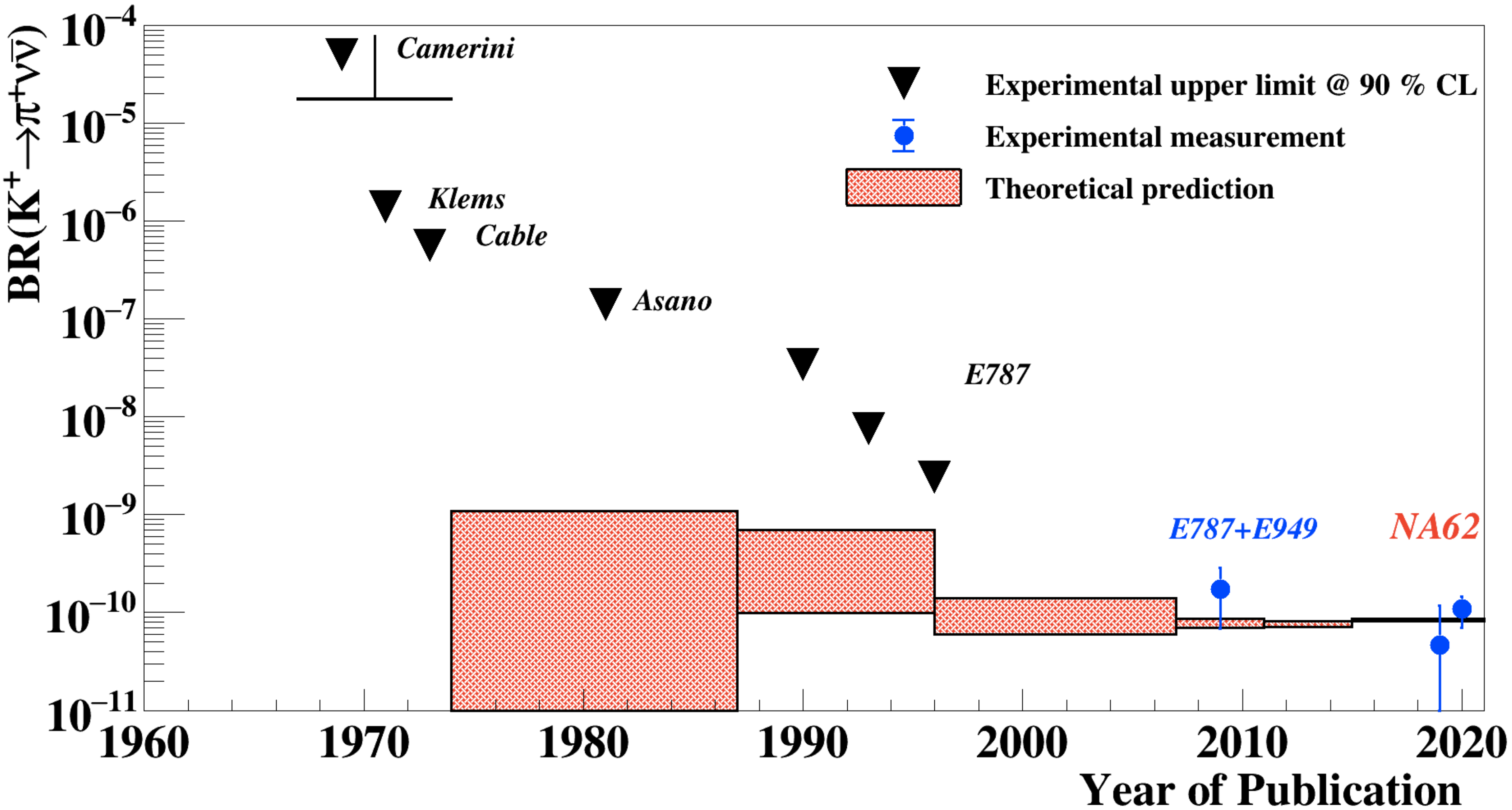


5.3 background + 7.6 SM signal events expected, **17 events** observed

RUN1 summary

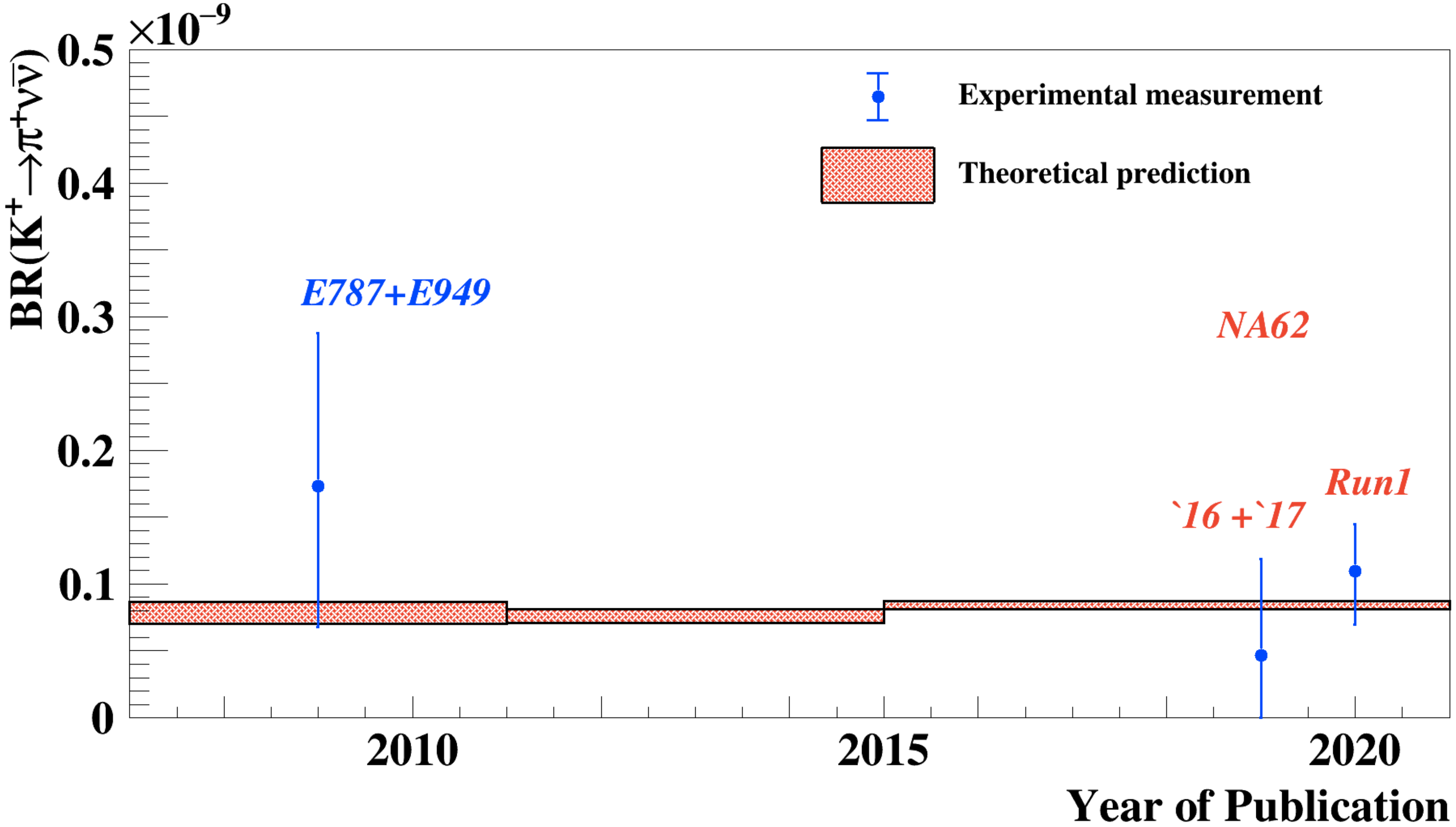
	2016 data	2017 data	2018 S1 data	2018 S2 data
$SES \times 10^{10}$	3.15 ± 0.24	0.39 ± 0.02	0.54 ± 0.04	0.14 ± 0.01
$A_{\pi\nu\nu} \times 10^{2}$	4 ± 0.4	3 ± 0.3	4 ± 0.4	6.4 ± 0.6
Expected SM signal	0.27 ± 0.04	2.16 ± 0.13	1.56 ± 0.10	6.02 ± 0.39
Expected background	0.15 ± 0.090	1.46 ± 0.30	$1.11^{+0.40}_{-0.22}$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

RUN1 summary



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

RUN1 summary



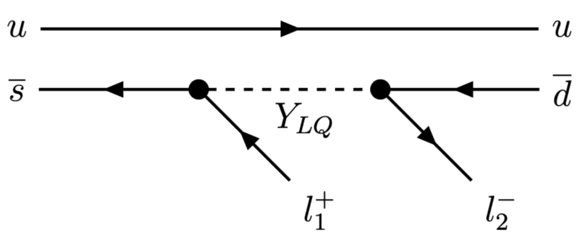
$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.5}\,_{stat} \pm 0.9\,_{syst}) \cdot 10^{-11}$ (3.4 σ significance)

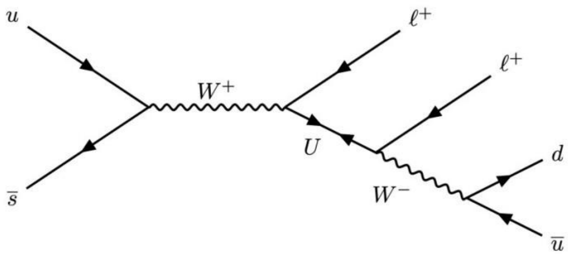
NA62 physics program:

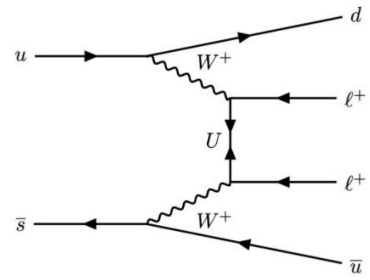
- LNV/LFV in kaon decays
- Exotic searches
- Rare kaon decays

Search for LNV and LFV @ NA62

Violation of these conservation laws predicted in BSM extentions (for example via Majorana neutrinos or leptoquark)







Previous experimental results:

✓ $BR(K^+ \to \pi^- e^+ e^+) < 6.4 \times 10^{-10}$ @ 90% CL
[BNL E865 : PRL 85 2877 (2000)]

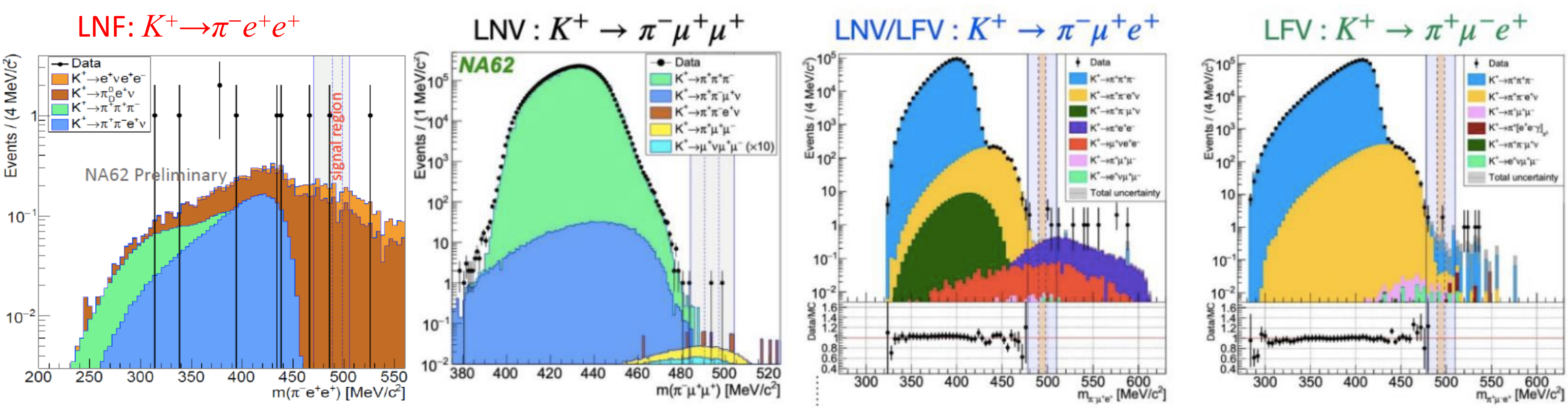
✓ $BR(K^+ \to \pi^- \mu^+ \mu^+) < 8.6 \times 10^{-11}$ @90%CL
[CERN NA48/2 : PL B769 67 (2017)]

LNV/LFV searches in NA62:

- 2017 + 2018 data
- Blind analysis
- Normalization to SM decays ($K^+ \to \pi^+ l^+ l^-$ and $K^+ \to \pi^+ \pi^+ \pi^-$)
- Main background is due to π mis-identification and π decays in flight

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*
$K^+ \to \pi^-\pi^0e^+e^+$	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*



Heavy Neutral Leptons (HNL)

- Heavy neutral leptons: three right-handed (sterile) neutrinos N_i are added to the SM, they mix with classical neutrinos:

$$\nu_\alpha = \sum_{i}^{3+k} U_{\alpha i} \nu_i \quad (\alpha = e, \mu, \tau); \;\; k = 3$$

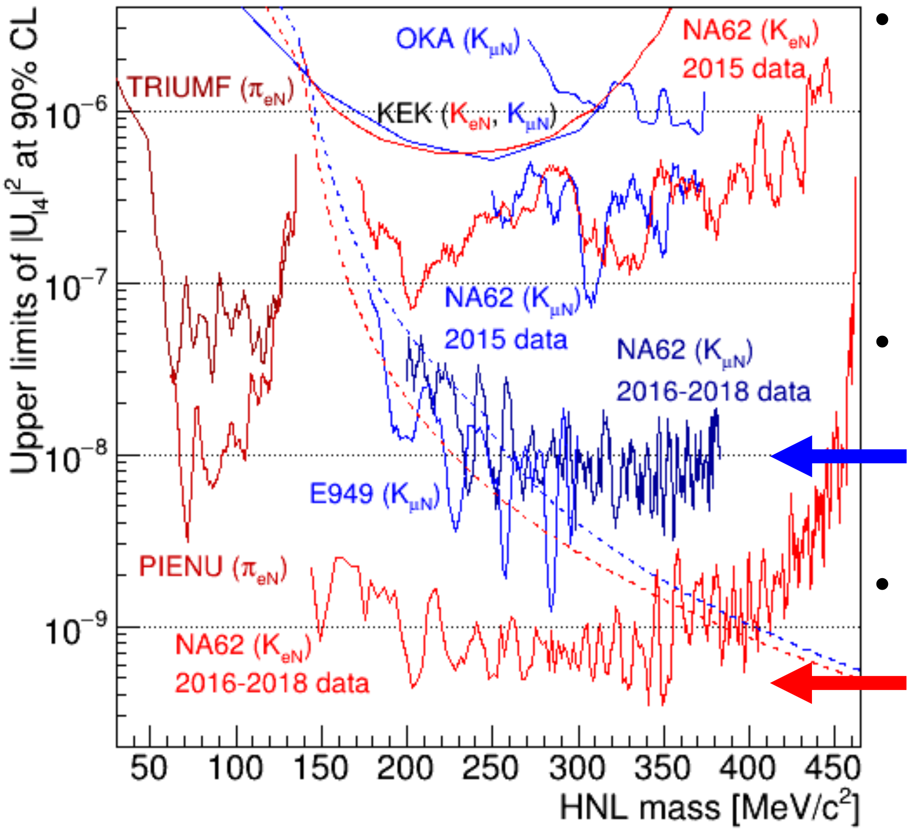
- to account for neutrino masses and oscillations, for the evidence of Dark Matter and for the baryon asymmetry of the universe.

- The neutrino minimal Standard Model extension (nMSM) considers mass ranges and couplings: **([Asaka, Blanchet, Shaposhnikov, PLB 631 (2005) 151])**
  - N_1: $m_1 \sim 10$ keV/c^2 — dark matter candidate
  - $N_{2,3}$: $m_{2,3} \sim 100$ MeV/c^2 — 100 GeV/c^2
  - Yukawa couplings in the range 10^{-11} to 10^{-6}

- If HNLs exist, they should be produced in every process containing active neutrinos with a branching fraction proportional to the mixing parameters $|U_{\ell 4}|^2$; here considering k = 1

At NA62, via Kaon decays, HNL production and decay searches.

Heavy Neutral Leptons: UL of $|U_{l4}|^2$ - Run1 data set

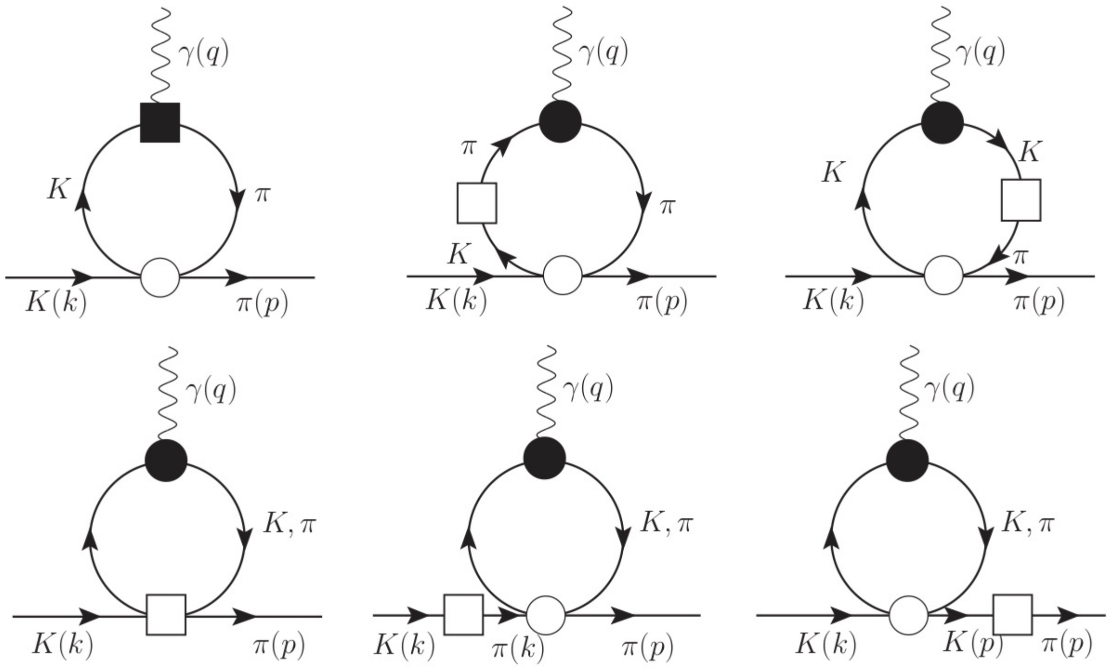


- $\mathcal{O}(10^{-9})$ limits on $|U_{e4}|^2$ and $\mathcal{O}(10^{-8})$ limits on $|U_{\mu4}|^2$
- More than **2**(**1**) orders of magnitude improvements from run 1 data for e^+(μ^+) with respect to previous results.
- For μ^+: NA62 consistent with the E949 result and extends UL to higher masses
- For e^+: values favored by the Big Bang Nucleosynthesis (BBN) constraint (dashed red line) are excluded for HNL masses up to 340 MeV/c^2

[PLB 807 (2020) 135599], [PLB 816 (2021) 136259]

$K^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay

- ✓ FCNC decay described in the scope of ChPT, mediated by one photon exchange $K^+ \rightarrow \pi^+ \Upsilon^*$
  [Nucl. Phys. B291 (1987) 692–719], [Phys. Part. Nucl. Lett. 5 (2008) 76–84]
- ✓ Together with $K^+ \rightarrow \pi^+ e^+ e^-$ allows for tests of Lepton Flavour Universality.
- ✓ A precise measurement of these decays could provide an evidence complementary to the B anomaly seen by LHCb
  [J. Phys. Conf. Ser. 800 (2017) 1, 012014]
- ✓ Form factor parametrized in NLO ChPT: $\mathbf{W(z) = G_F M^2_K (a + bz) + W^{\pi\pi}(z)}$
  [JHEP 08 (1998) 004]
- ✓ Goal: measurement of *a*, *b*, model-dependent BR



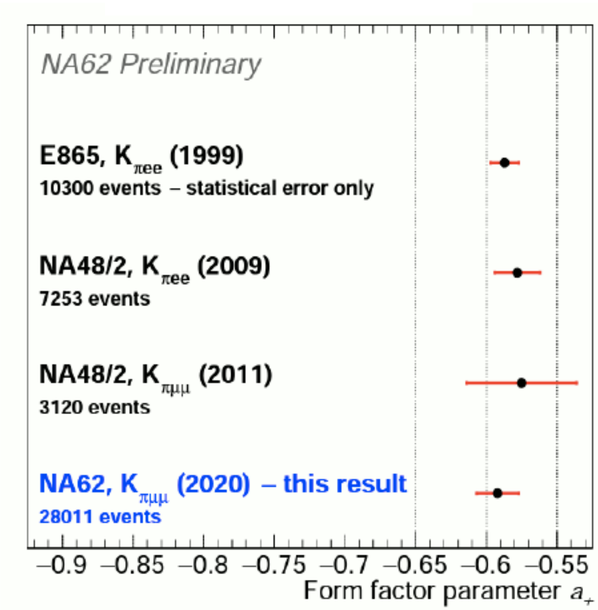
$K^+ \to \pi^+\mu^+\mu^-$ preliminary results

$N_K \approx 6.76 \times 10^{12}$ using the 2017+2018 data sample

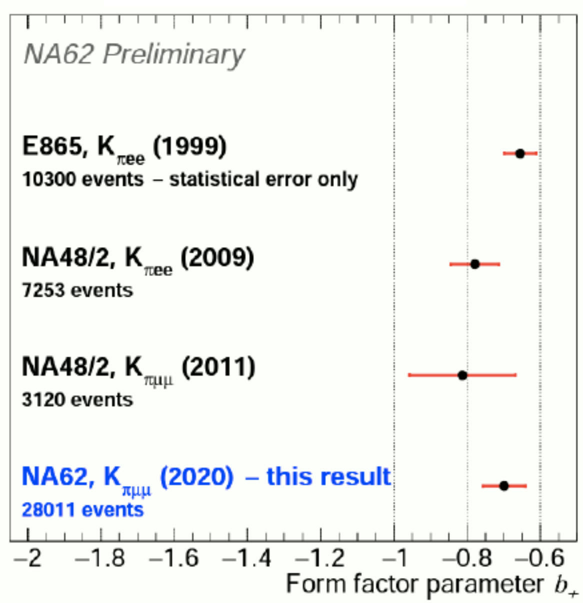
Preliminary $K_{\pi\mu\mu}$ result consistent with $K_{\pi ee}$ FF parameters: no tension in LFU observed

Paper in prepatation

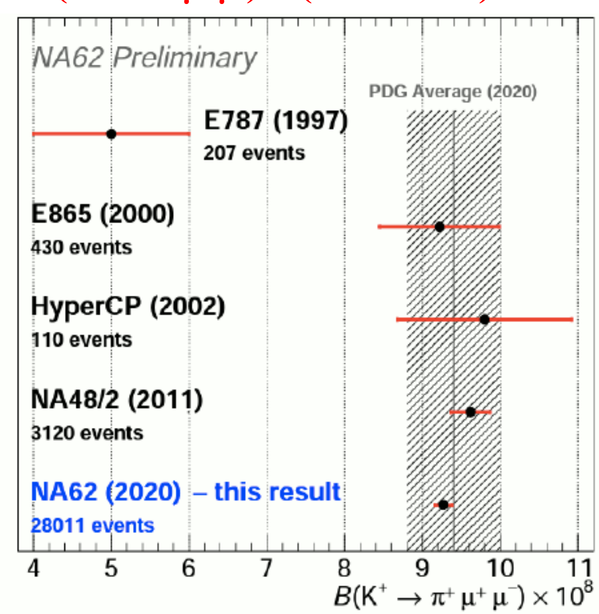
a = -0.592 ± 0.015



b = -0.699 ± 0.058



BR($K^+ \to \pi^+\mu^+\mu^-$) = (9.27 ± 0.11) x 10^{-8}



BR($K^+ \to \pi^+\mu^+\mu^-$) = (9.27 ± 0.11) x 10^{-8}

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]

Conclusions

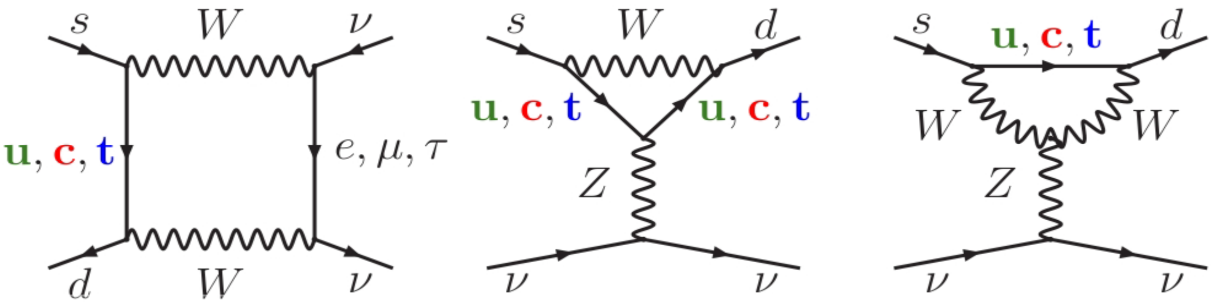
$K^+ \rightarrow \pi^+\nu\bar{\nu}$

- ✓ Run1 measurement compatible with the SM within one standard deviation
- ✓ **Br($K^+ \rightarrow \pi^+\nu\bar{\nu}$) = $(10.6^{+4.0}_{-3.5}\,_{stat} \pm 0.9\,_{syst}) \cdot 10^{-11}$ (3.4 σ significance)**
- ✓ The most precise measurement of the BR obtained so far

- ✓ Upper limit improved for LFV andLNV channels ($K^+ \rightarrow \pi^- l^+ l^+$, $K^+ \rightarrow \pi^+ e^+ \mu^-$,etc)
- ✓ $|U_{\mu 4}|^2$ and $|U_{e4}|^2$ limit improved for the HNL
- ✓ Measured $K_{\pi\mu\mu}$ form factor parameters, no LFU violation found

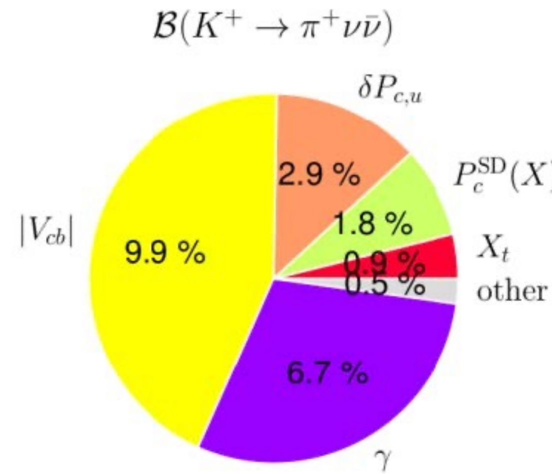
SPARE

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



- 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]

Theoretical error budget
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)