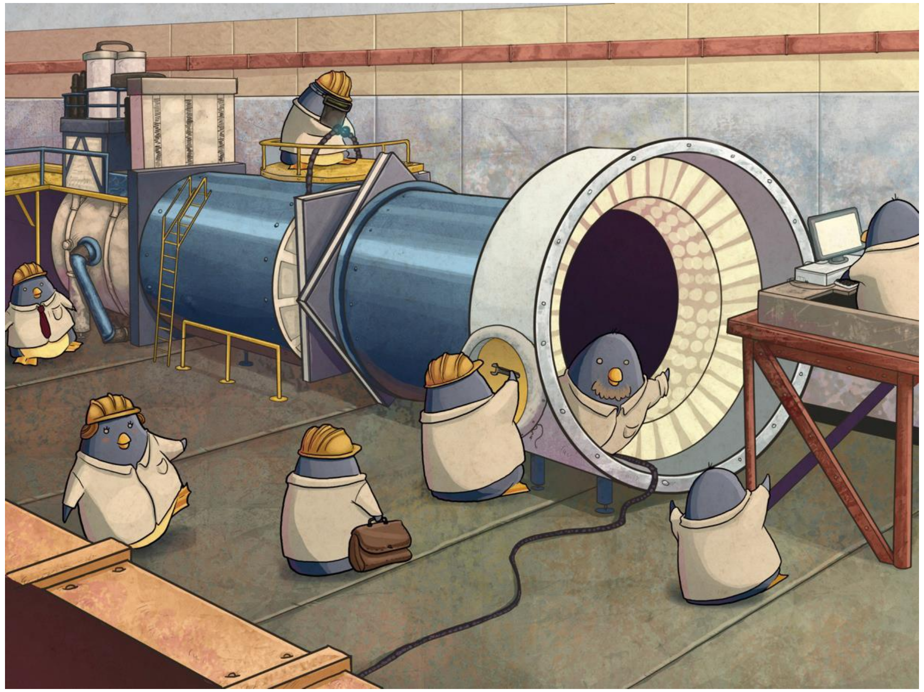
Status and results from the NA62 experiment at CERN

Jacopo Pinzino



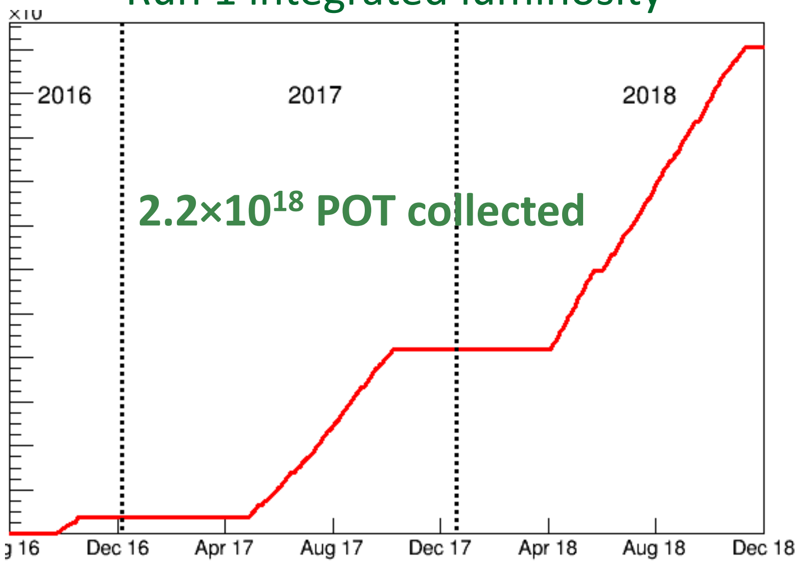
Vietnam Flavour Physics 2022
16/08/22

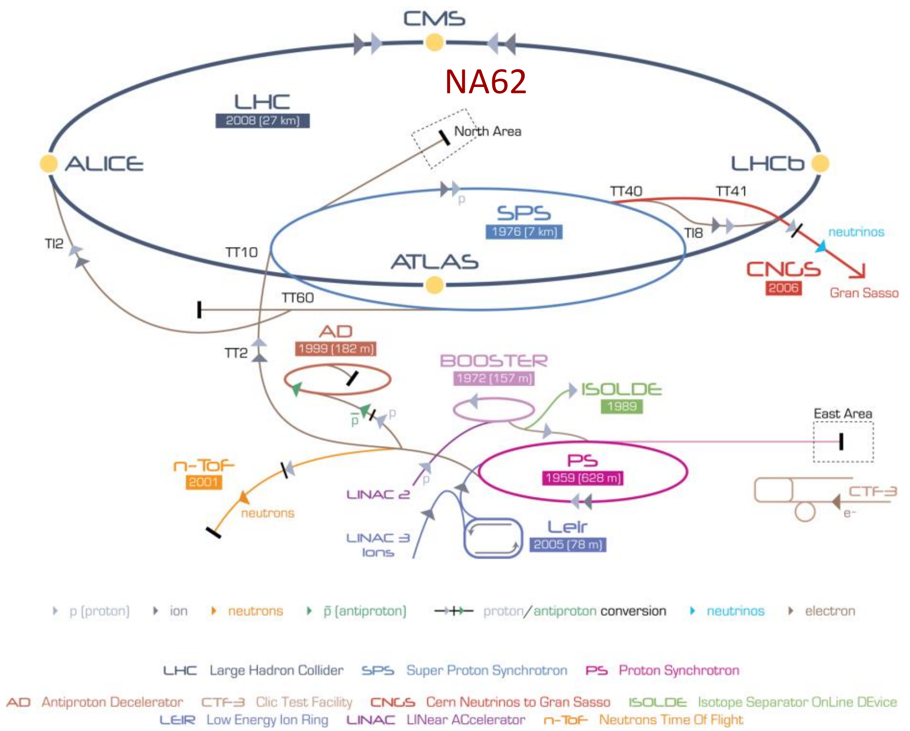
Fellini
Fellowship for Innovation at INFN
H2020 MSCA COFUND
G.A. 754496

The NA62 Experiment

- NA62: High precision fixed-target Kaon experiment at CERN SPS
- Main goal: measurement of $BR(K^+ \to \pi^+ \nu\bar{\nu})$
- Broader physics program: LFV / LNV in K^+ decays, hidden sector particles searches.

Run 1 integrated luminosity



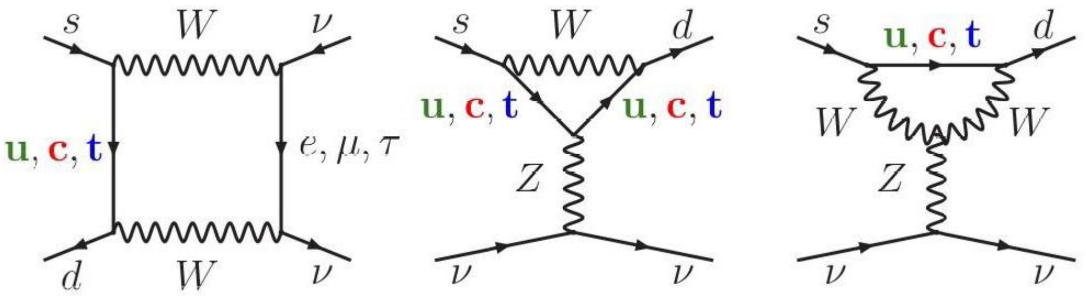


NA62 Timeline

- 2008: NA62 Approval
- 2014: NA62 Pilot Run (partial layout)
- 2015: Commissioning run
- Full detector installation completed in September 2016
- 2016 -2018 : First NA62-RUN
- data-taking was resumed in 2021 with improvements
- Continuous data-taking until LS3

~ 200 participants from: 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, Torino, TRIUMF, Vancouver UBC

The $K \to \pi\upsilon\bar{\upsilon}$ decay



- High sensitivity to New Physics
- FCNC process forbidden at tree level
- Highly CKM suppressed (BR ~ $|V_{ts} x V_{td}|^2$)

- Very clean theoretically: Short distance contribution
- hadronic matrix element extracted from precisely measured $BR(K^+ \to \pi^0 e^+ \upsilon)$
- Precise SM predictions: [Buras et al. JHEP 1511 (2015) 33]

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

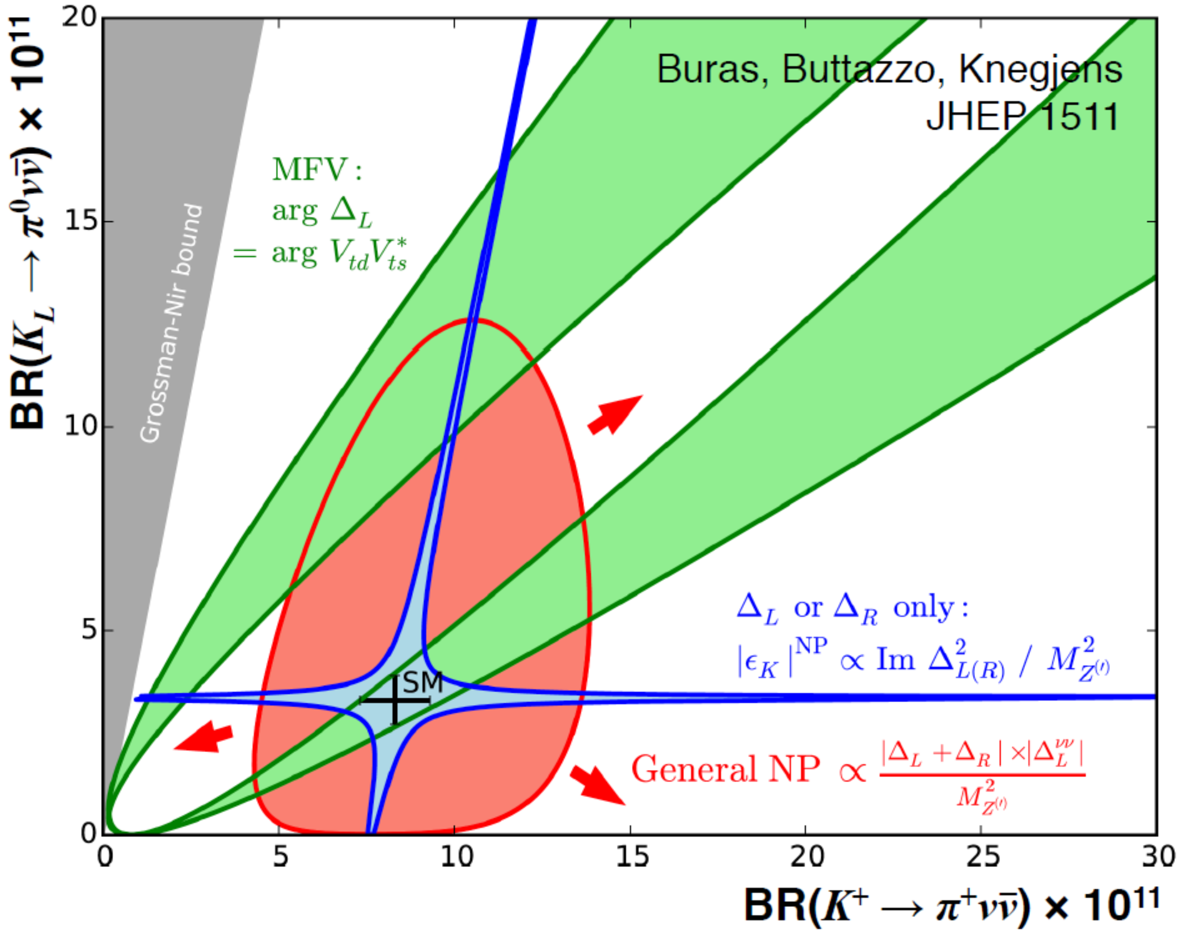
  $BR(K_L \to \pi^0 \upsilon\bar{\upsilon}) = (3.4 \pm 0.6) \times 10^{-11}$
- Previous Experimental Result:

  $BR(K^+ \to \pi^+ \upsilon\bar{\upsilon})$(E787/E949) $= (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ [Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)]

  $BR(K_L \to \pi^0 \upsilon\bar{\upsilon})$(E391a) $< 2.6 \times 10^{-8}$ (90% C.L) [Phys. Rev. D 81, 072004 (2010)]

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

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



- Models with CKM-like flavor structure (Models with MFV)
  [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Custodial Randall-Sundrum
  [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- Simplified Z, Z' models
  [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- 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]
- Leptoquarks
  [S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]
- MSSM analyses
  [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],[Isidori et al. JHEP 0608 (2006) 064]

$K \rightarrow \pi\upsilon\bar{\upsilon}$ and New Physics

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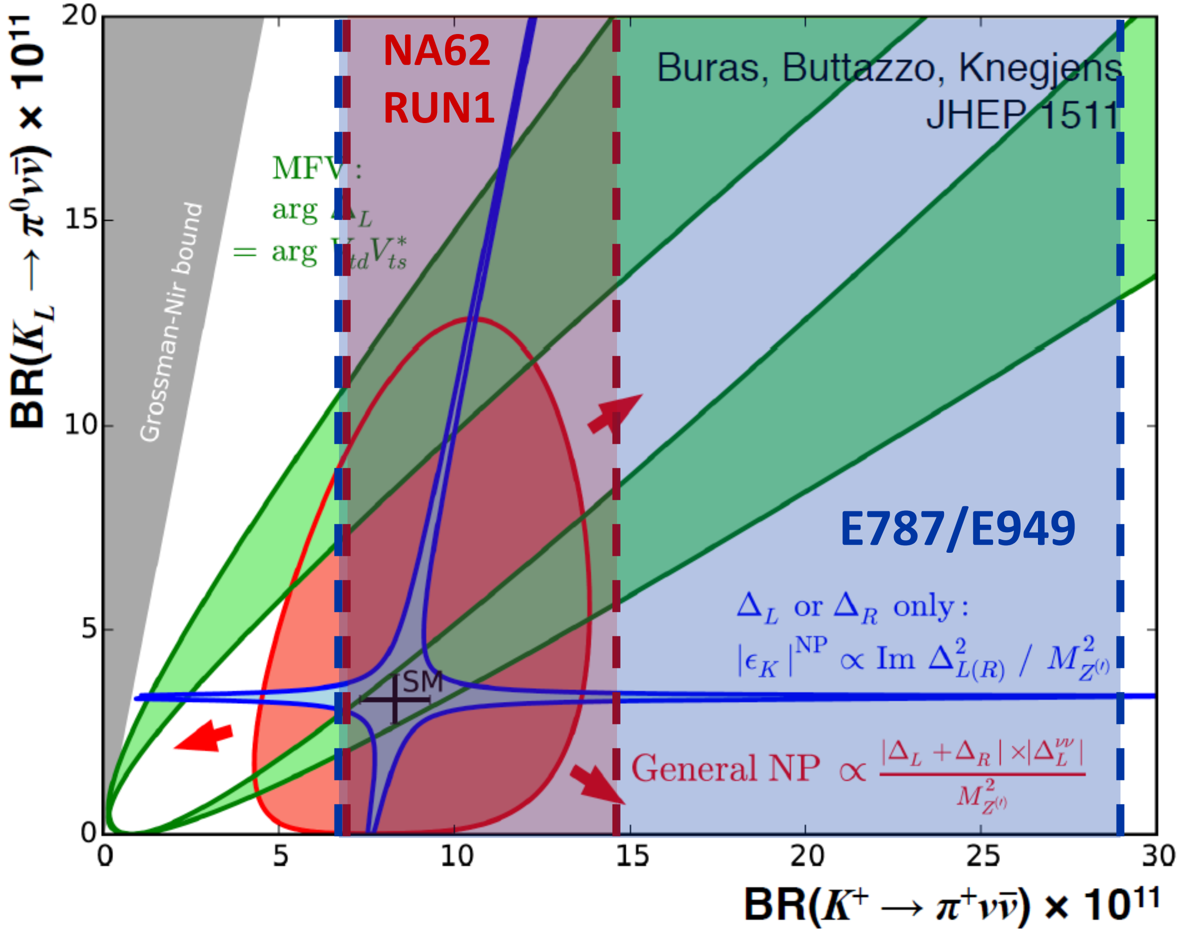

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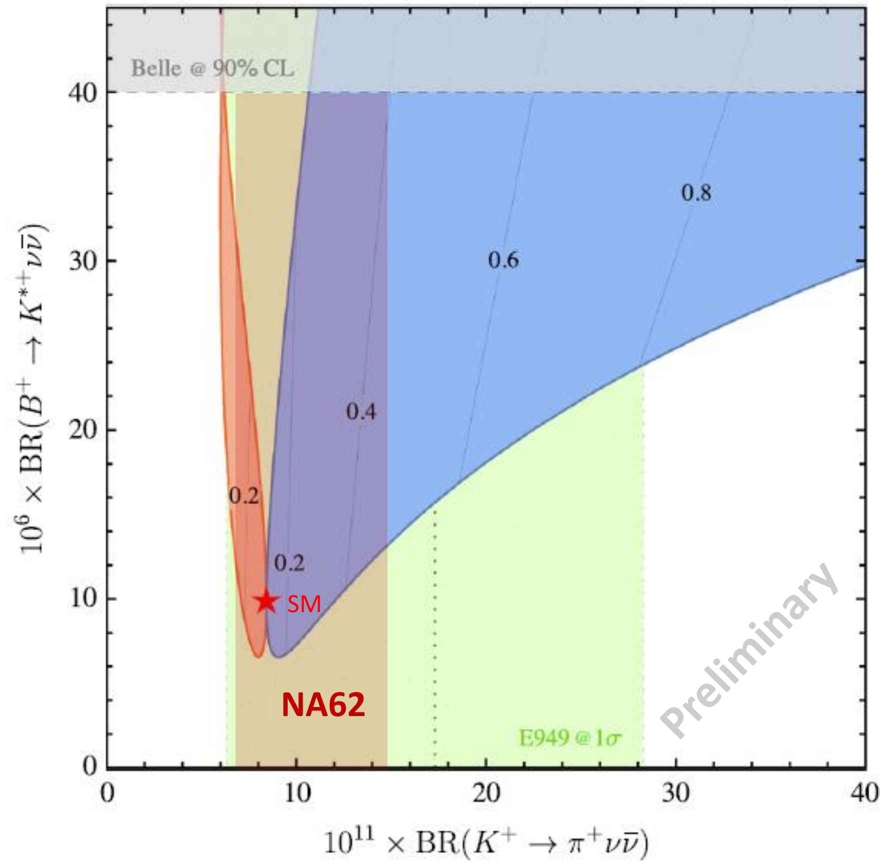
$K \rightarrow \pi\nu\bar{\nu}$ and the LFU violation

The Measurement of $K^{+} \rightarrow \pi^{+}\nu\bar{\nu}$ together with $B^{+} \rightarrow K^{*+}\nu\bar{\nu}$ can **can probe the Lepton-Flavour Universality**

- An interactions responsible for LFU violations can couple mainly to the third generation of left-handed fermions;
- $K \rightarrow \pi\nu\bar{\nu}$ is the only kaon decays with third-generation leptons (the τ neutrinos) in the final state;
- A deviations from the Standard Model predictions in $K \rightarrow \pi\nu\bar{\nu}$ branching ratios should be closely correlated to similar effects in $B \rightarrow K^{(*)}\nu\bar{\nu}$.



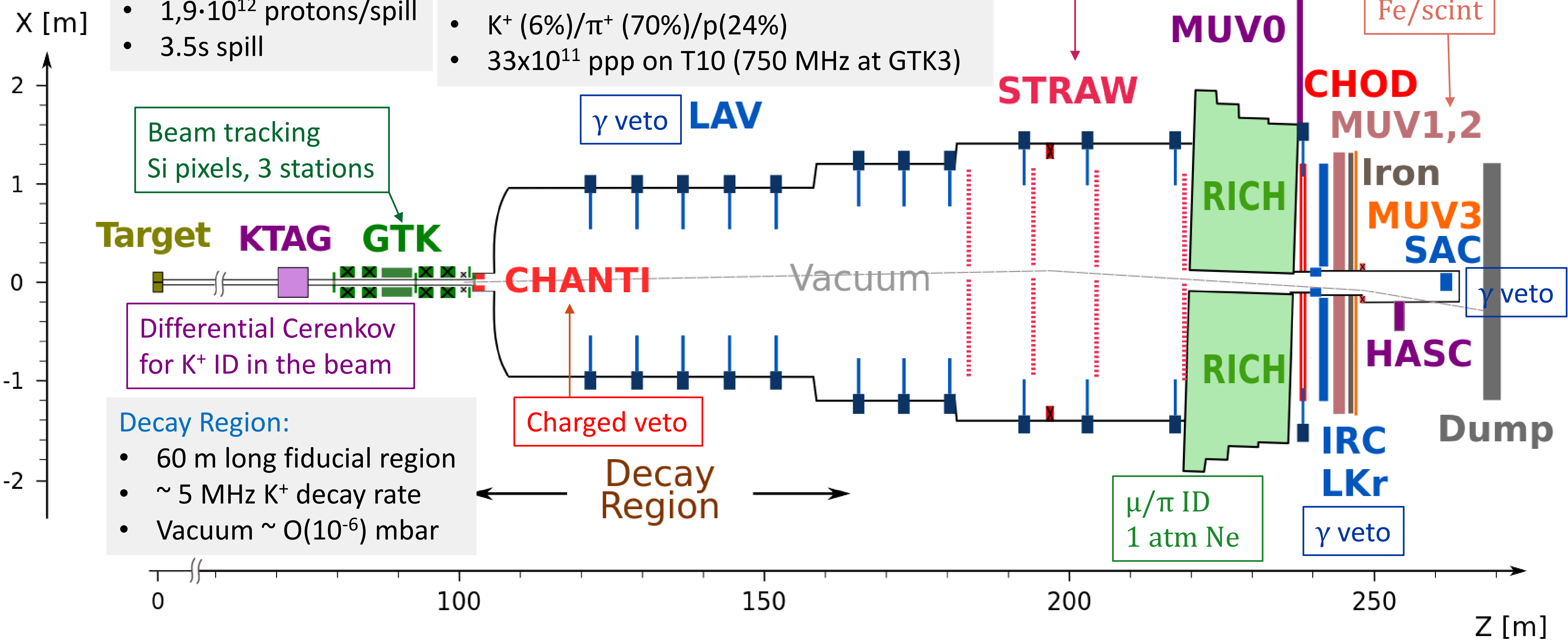
EPJ C (2017) 77: 618

NA62 Layout

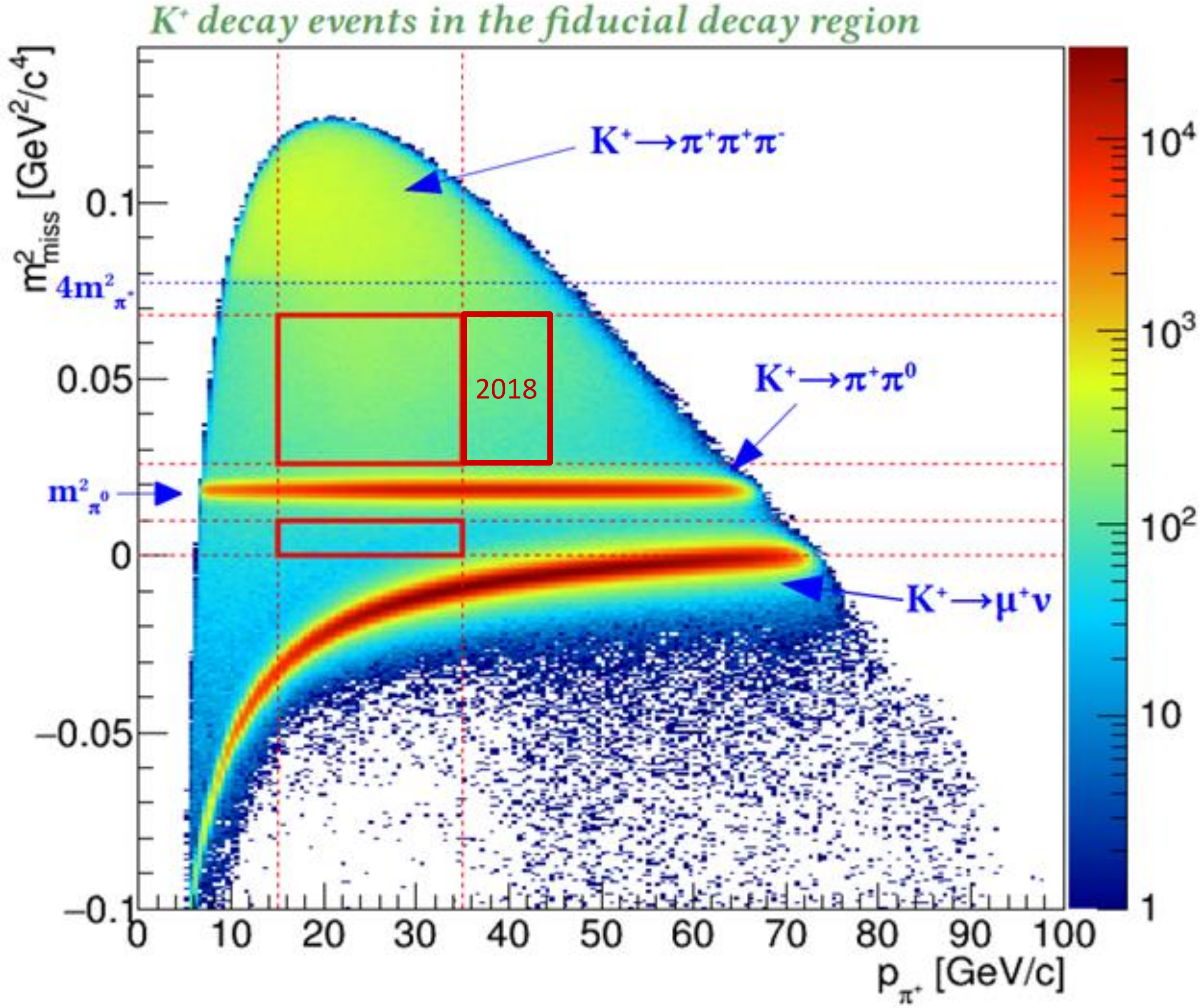
SPS Beam:
- 400 GeV/c protons
- $1{,}9\cdot10^{12}$ protons/spill
- 3.5s spill

Secondary positive Beam:
- 75 GeV/c momentum
- 1 % bite 100 mrad divergence (RMS)
- 60x30 mm2 transverse size
- K^+ (6%)/π^+ (70%)/p(24%)
- 33×10^{11} ppp on T10 (750 MHz at GTK3)

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



Signal region



Key analysis requirements:

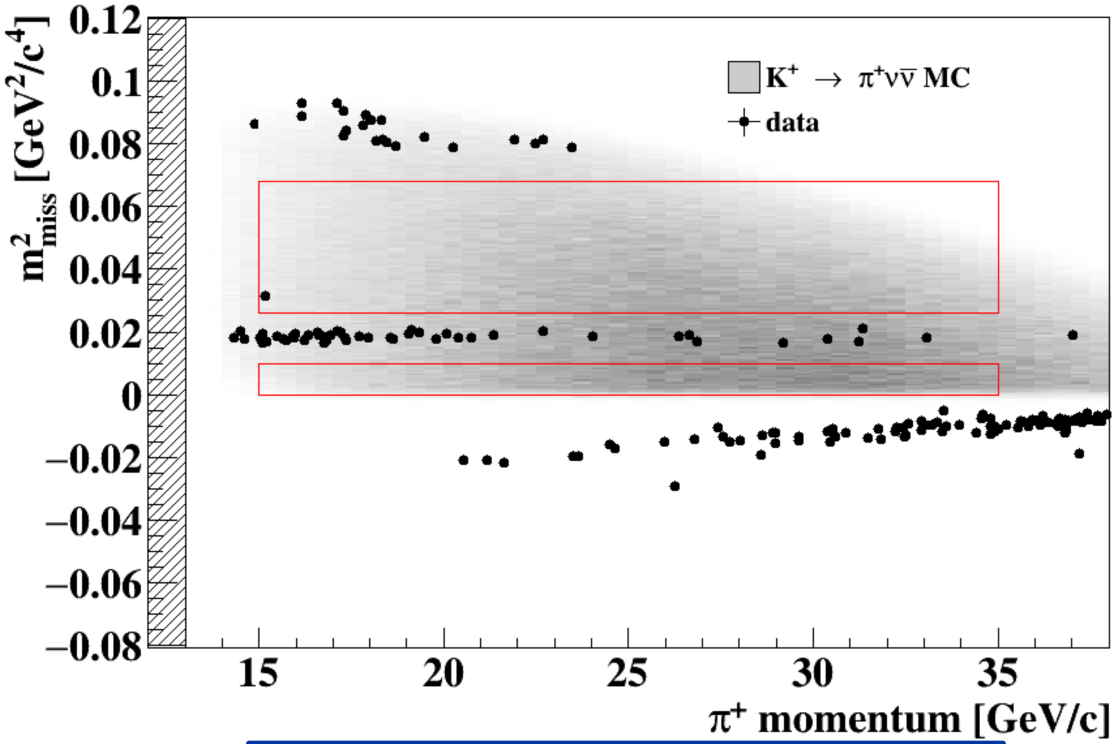
- 2 signal regions in m^2_{miss}
- $15 < P_{\pi^+} < 35$ (45 in 2018) GeV/c
- 60 m long decay region

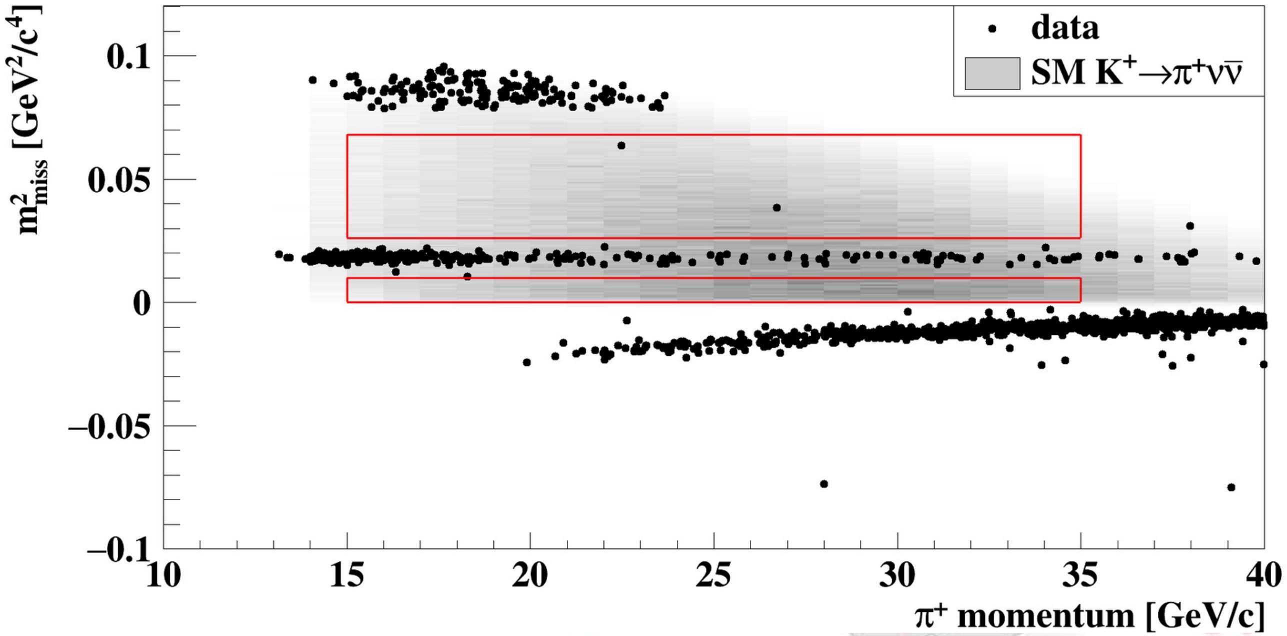
Performance:

- 10^{-3} GeV²/c⁴ m^2_{miss} resolution
- 1×10^{-3} $K^+\to\pi^+\pi^0$ kinematic background suppression
- 3×10^{-4} $K^+\to\mu^+\nu$ kinematic background suppression
- 10^{-8} Muon suppression
- 1.4×10^{-8} π^0 (from $K^+\to\pi^+\pi^0$) suppression
- 64% π^+ efficiency
- O(100 ps) timing between sub-detectors

Process	*Branching ratio*
$K^+\to\pi^+\pi^0(\gamma)$	0.2067
$K^+\to\mu^+\nu(\gamma)$	0.6356
$K^+\to\pi^+\pi^+\pi^-$	0.0558
$K^+\to\pi^+\pi^-e^+\nu$	$4.25\cdot10^{-5}$

Result of 2016 and 2017 data taking





2016

- 1 events observed
- SES = 3.15×10^{-10}
- $Br(K^+ \rightarrow \pi^+\nu\nu) < 14 \times 10^{-10}$ @ 90% CL

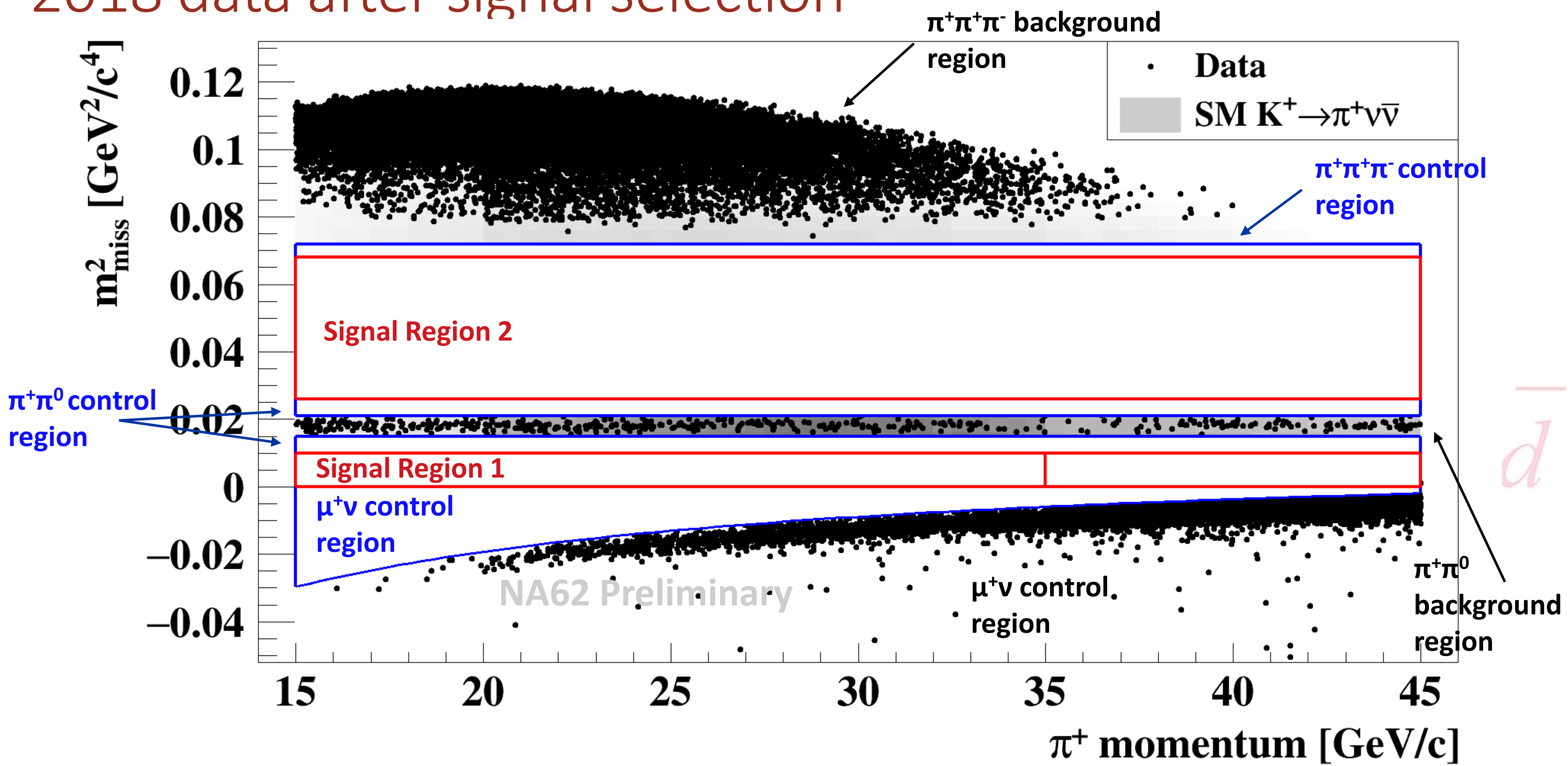
Phys. Lett. B 791 (2019) 156-166

2017

- 2 events observed
- SES = 0.389×10^{-10}
- $Br(K^+ \rightarrow \pi^+\nu\nu) < 1{,}7 \times 10^{-10}$ @ 90% CL

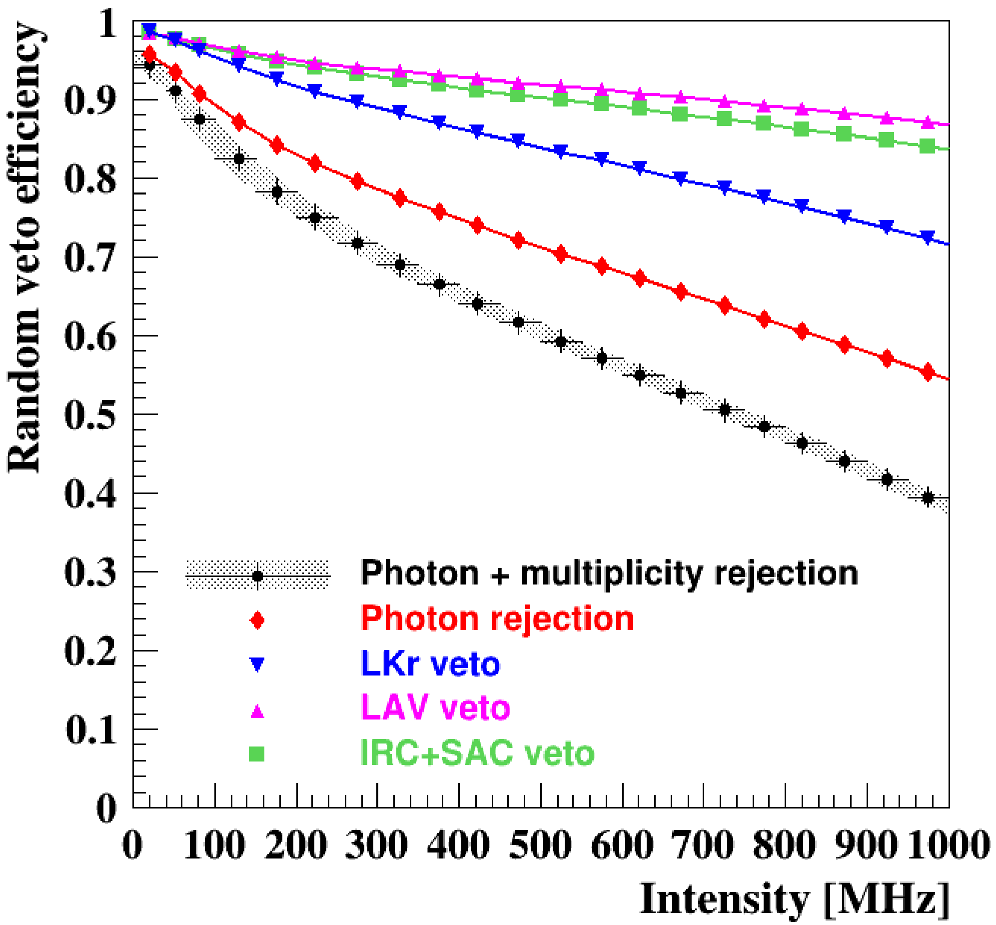
[J. High Energ. Phys. 2020, 42 (2020)]

2018 data after signal selection



Single Event Sensitivity (SES)

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



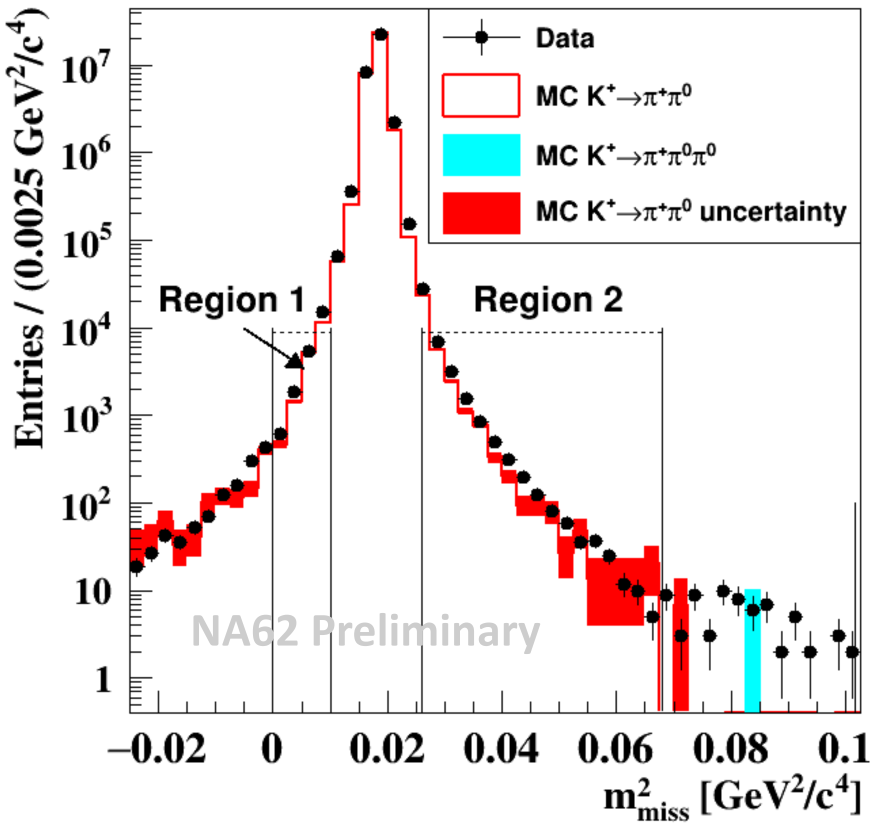
	Subset S1	Subset S2
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^{2}$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^{2}$	3.95 ± 0.40	6.37 ± 0.64
$\epsilon_{\text{trig}}^{\text{PNN}}$	0.89 ± 0.05	0.89 ± 0.05
ϵ_{RV}	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14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

- $K^+ \rightarrow \pi^+\pi^0$ decay used for normalization
- Cancellation of systematic effects (PID, Detector efficiencies, kaon ID and beam related acceptance loss)

$$SES_{Run1} = (0.839 \pm 0.054) \cdot 10^{-11}$$

Background from Kaon Decay Estimation

Control $K^+ \to \pi^+\pi^0$ data used to study the tails of the m^2_{miss} distribution



Data in $\pi^+\pi^0$ region after $\pi\nu\nu$ selection (including π^0 rejection)

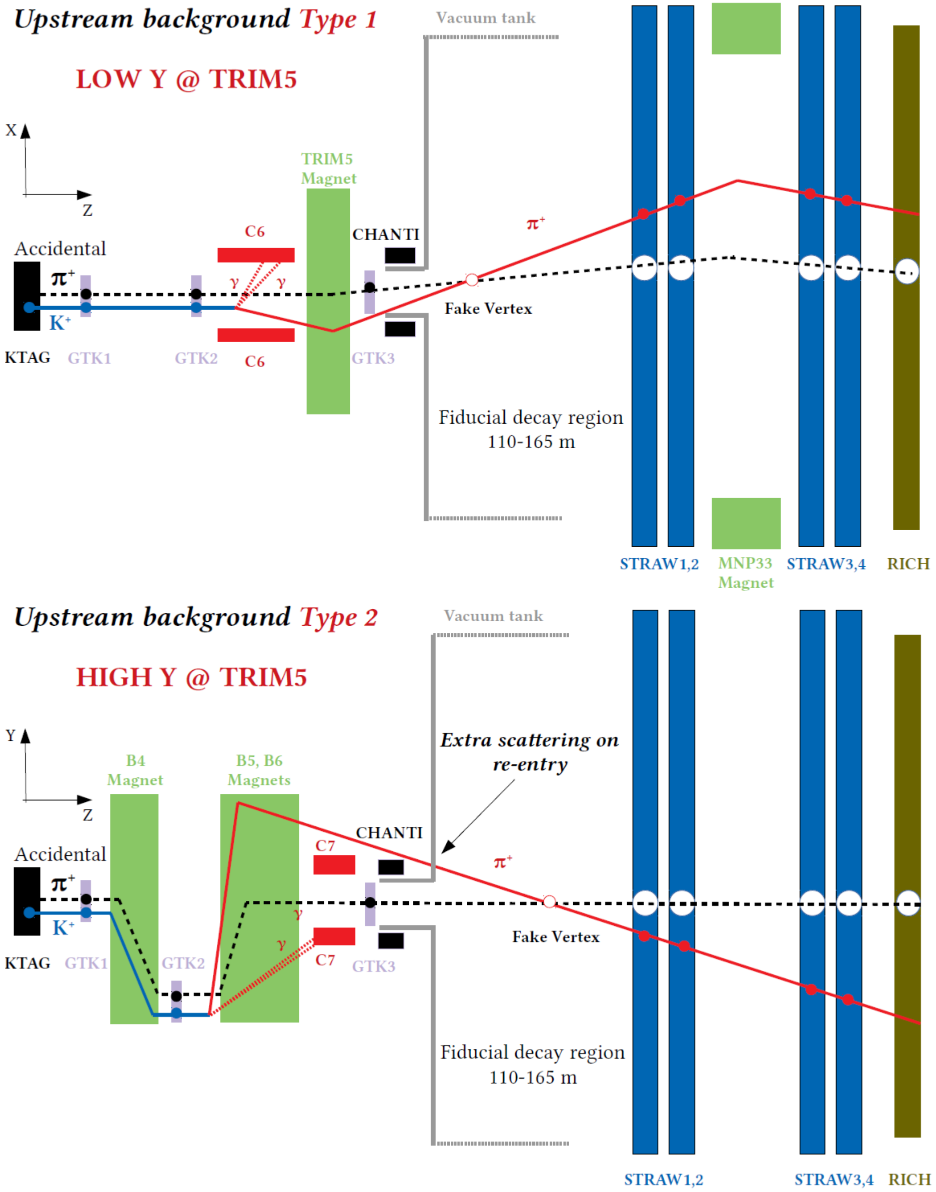
$$N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0) \cdot f_{kin}(region)$$

Expected $K^+ \to \pi^+\pi^0$ in signal regions after the $\pi\nu\nu$ selection

Fraction of $\pi^+\pi^0$ in signal region measured on control data

- The same procedure is used for $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^+\pi^-$
- $K^+ \to \pi^+\pi^- e^+\nu_e$ estimation entirely using MC simulations normalized to the S.E.S.

Upstream background



- Pions produced upstream the fiducial volume
  - Early K^+ decay
  - Interaction of beam particles with the beam spectrometer material
- Pions can be associated to an accidental particle of the beam line
- Dangerous if coupled with pion scattering in the first spectrometer chamber
- Kaon-pion association and geometrical cuts effective
- The geometrical origin of those events allow to define samples for backgrounds validation
- Data driven background estimation

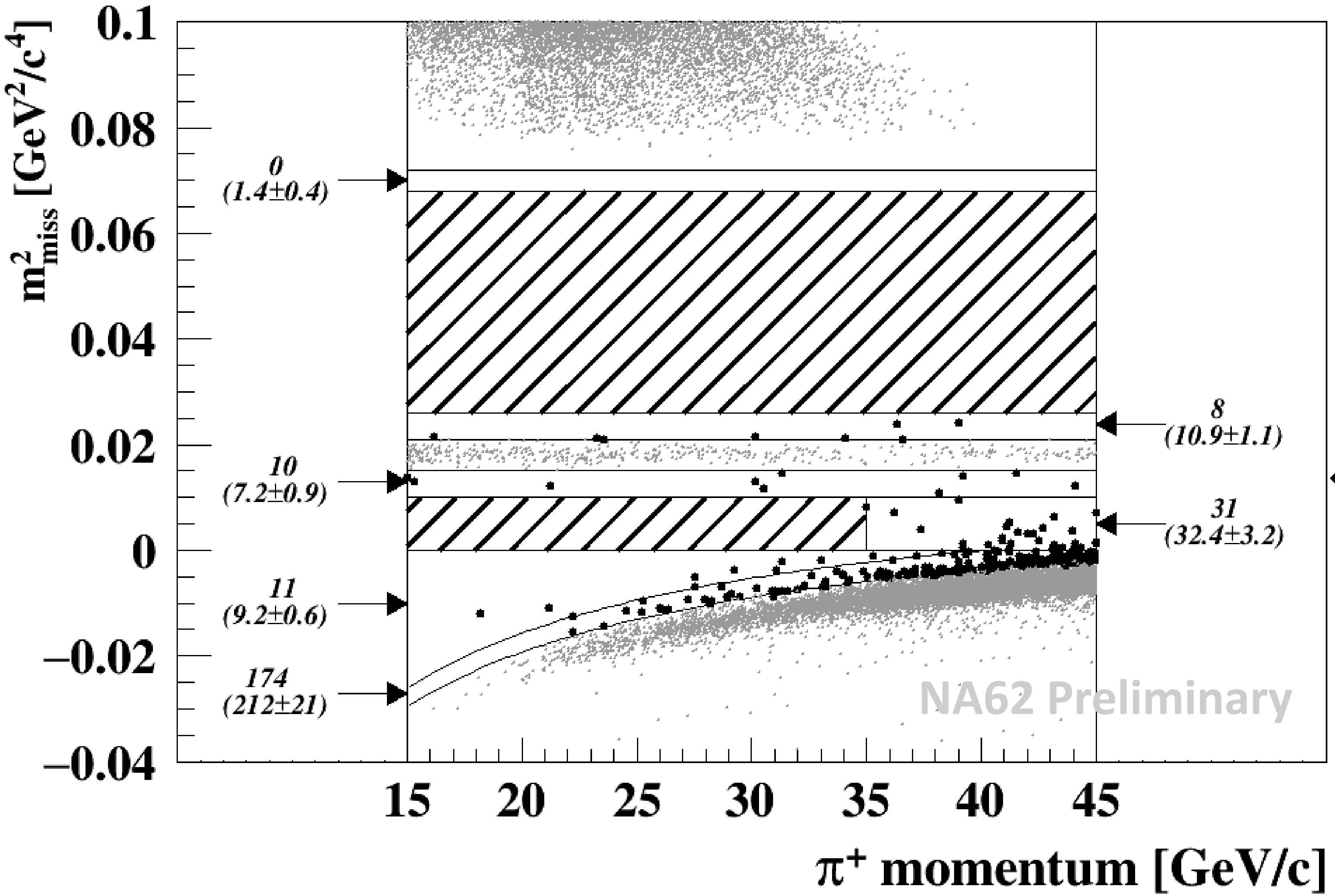
Background summary

- In 2018 collimator was replaced to reduce the upstream background
- data are split in 2 subsets: S1/S2 (20%/80% of 2018 data).
- It allows to relax some cuts for S2 to improve signal acceptance while keeping the S/B ratio same as for S1.

Background	Subset S1	Subset S2
$\mu^+\nu$	0.23 ± 0.02	0.52 ± 0.05
$\pi^+\pi^0$	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
$\pi^0\ell^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

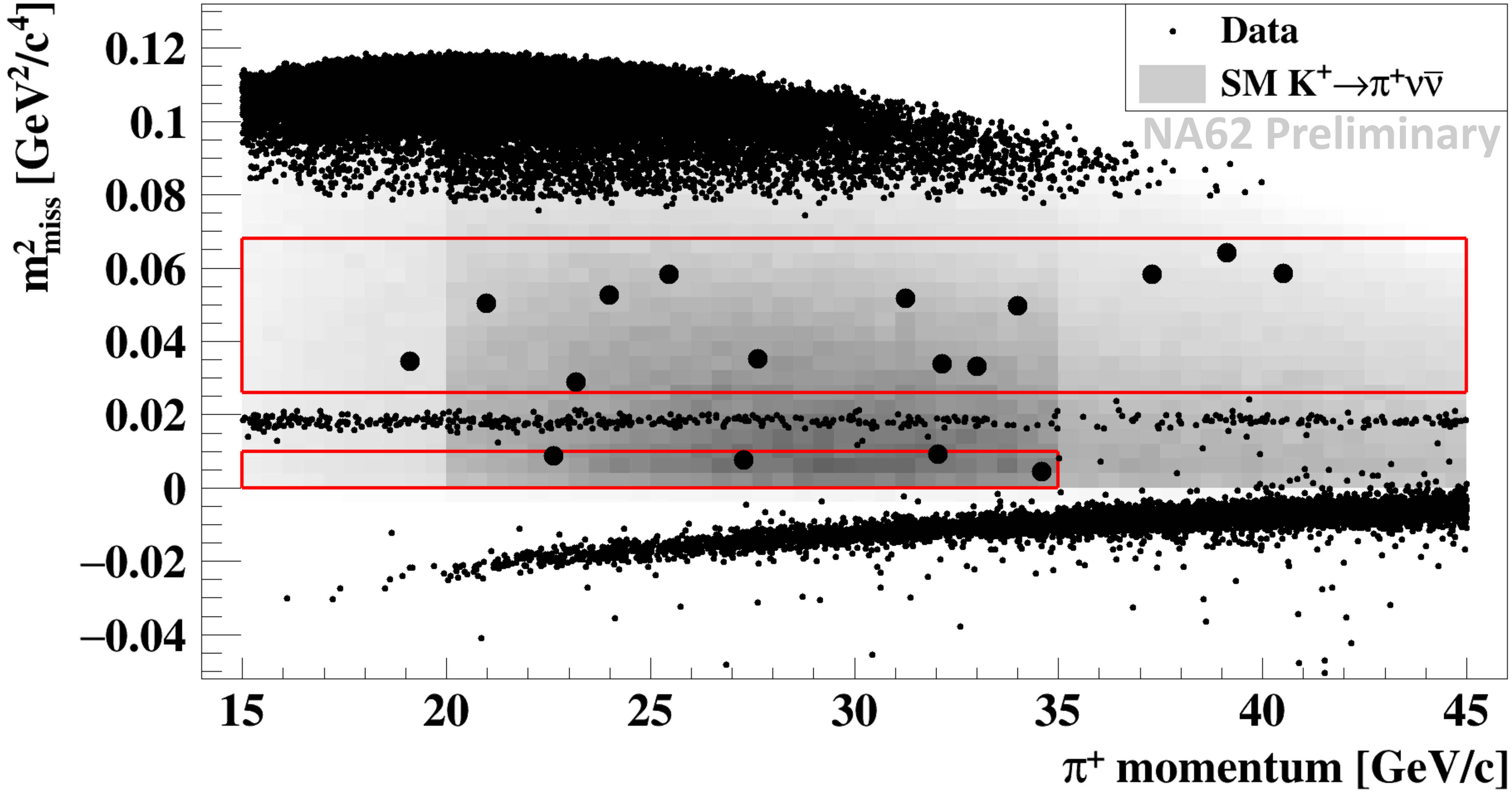
Background expectations validated in control regions using a blind procedure

Control regions: main decays



Measured
(expected)

Result 2018

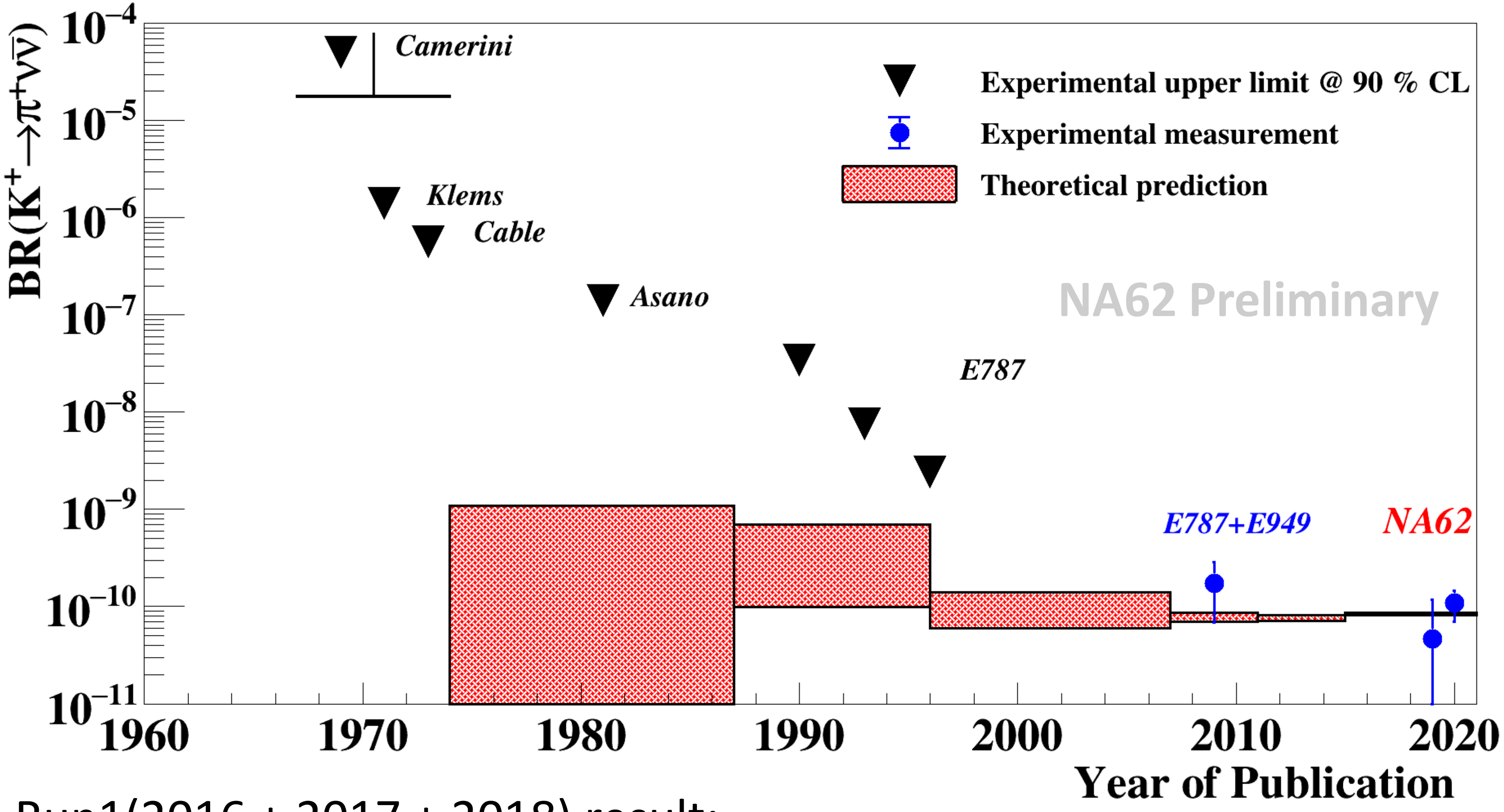


5.3 background + 7.6 SM signal events expected, 17 events observed

RUN1 resume

	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]	

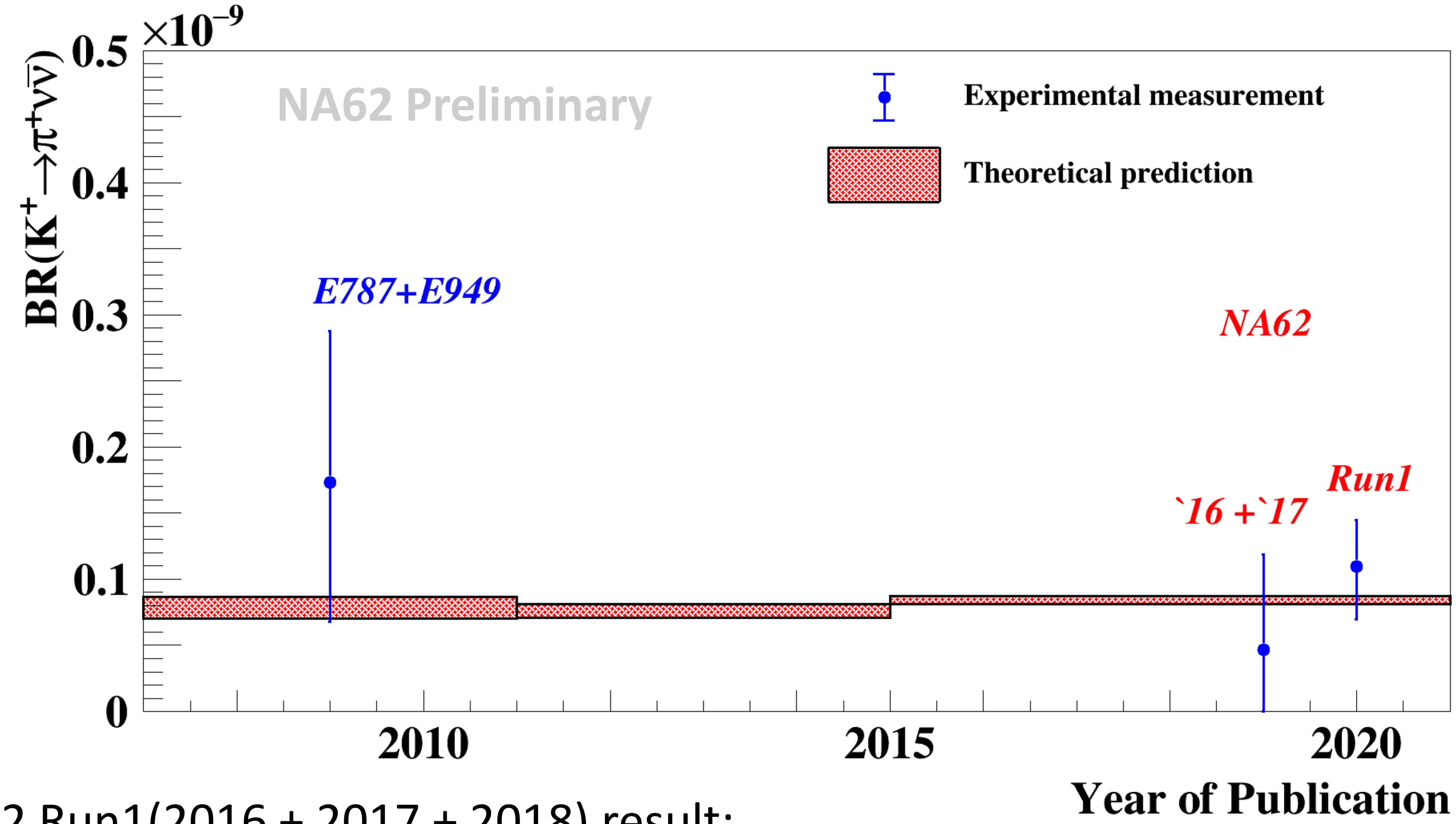
K → πνν̄ Result and historical context



NA62 Run1(2016 + 2017 + 2018) result:

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

$K \to \pi\nu\bar{\nu}$ Result and historical context



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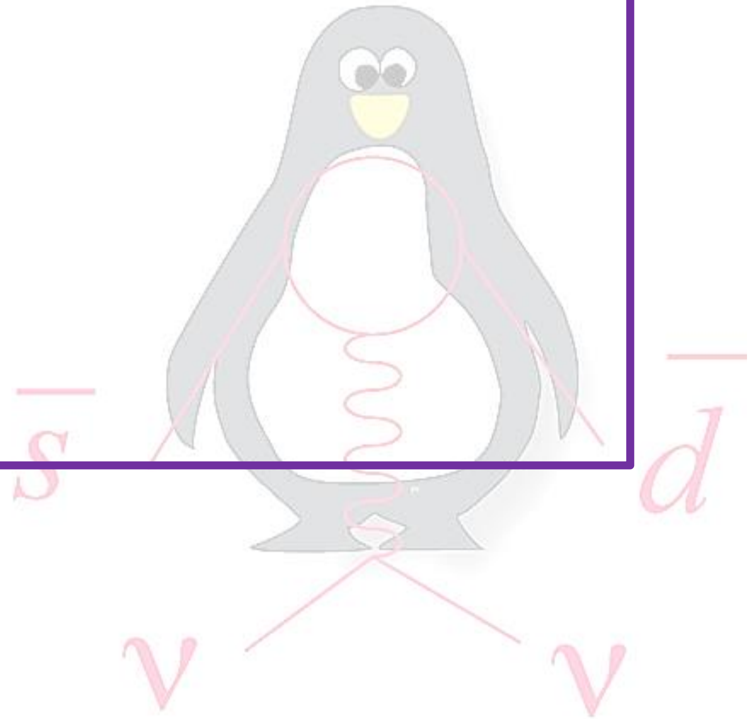
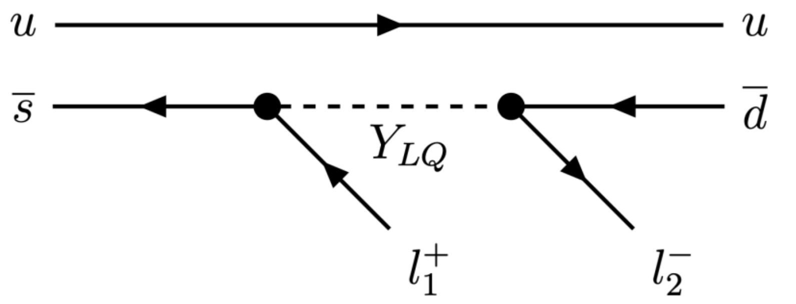
NA62: Broader physics program

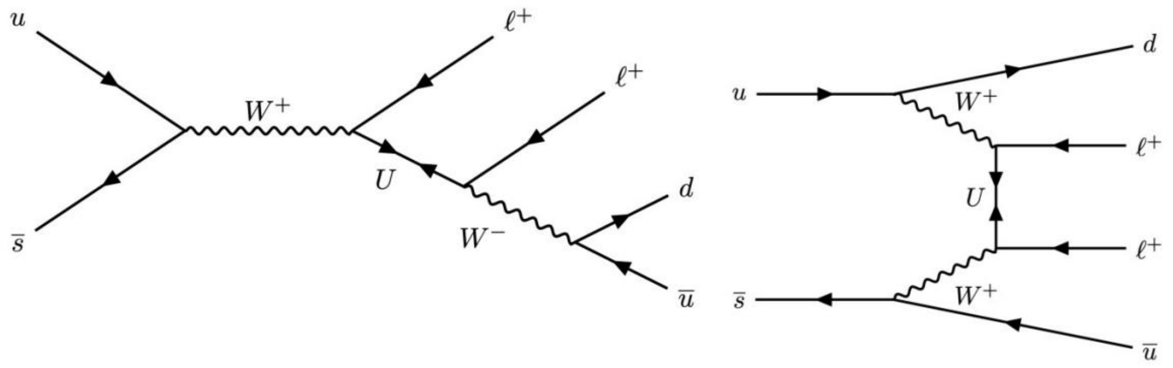
- Rare kaon decays
- LNV/LFV in kaon decays
- Exotic searches:
  - HNL searches [PLB 807 (2020) 135599]
  - Dark Photon [10.1007/JHEP05(2019)182]
  - Axion-like particle



LFV & LNV in Kaon Decays

Violation of LN and LF conservation laws predicted in BSM models (for example via Majorana neutrinos or leptoquark)





Previous experimental results:

- BR($K^+ \to \pi^- e^+ e^+$) < 6.4×10^{-10} @ 90% CL
  [BNL E865 : PRL 85 2877 (2000)]
- BR($K^+ \to \pi^- \mu^+ \mu^+$) < 8.6×10^{-11} @ 90% CL
  [CERN NA48/2 : PL B769 67 (2017)]

LNV/LFV searches in NA62:

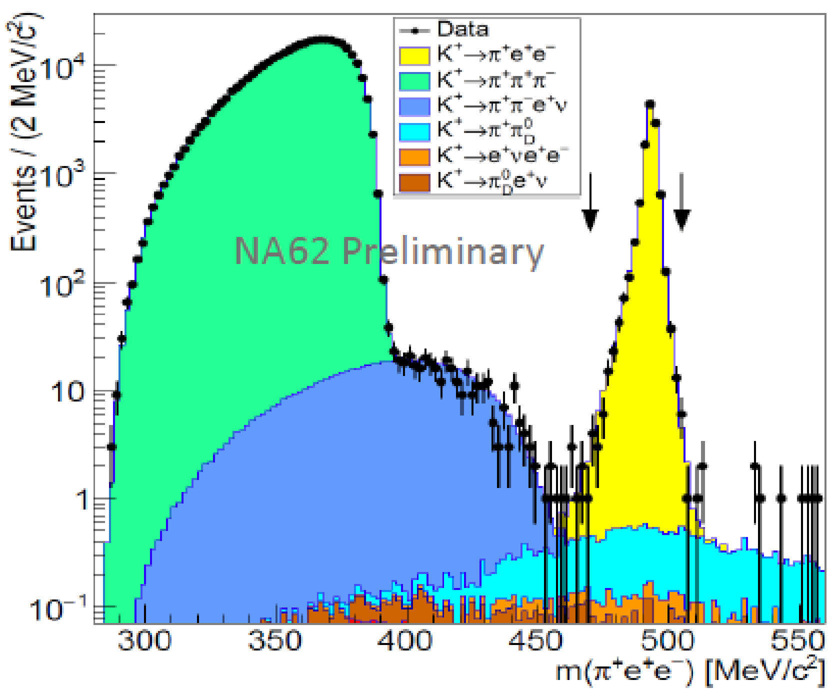
- 2017 + 2018 data
- Blind analysis
- Normalization to SM decays ($K^+ \to \pi^+ l^+ l^-$ and $K^+ \to \pi^+ \pi^+ \pi^-$)
- Acceptance:
  - ~5% for $K^+ \to \pi^- e^+ e^+$ and $K^+ \to \pi e \mu$
  - 10% for $K^+ \to \pi^- \mu^+ \mu^+$
- Main background is due to pion mis-identification and pion decays in flight

$K^+ \rightarrow \pi^- e^+ e^+$

[PLB830 (2022)137172]

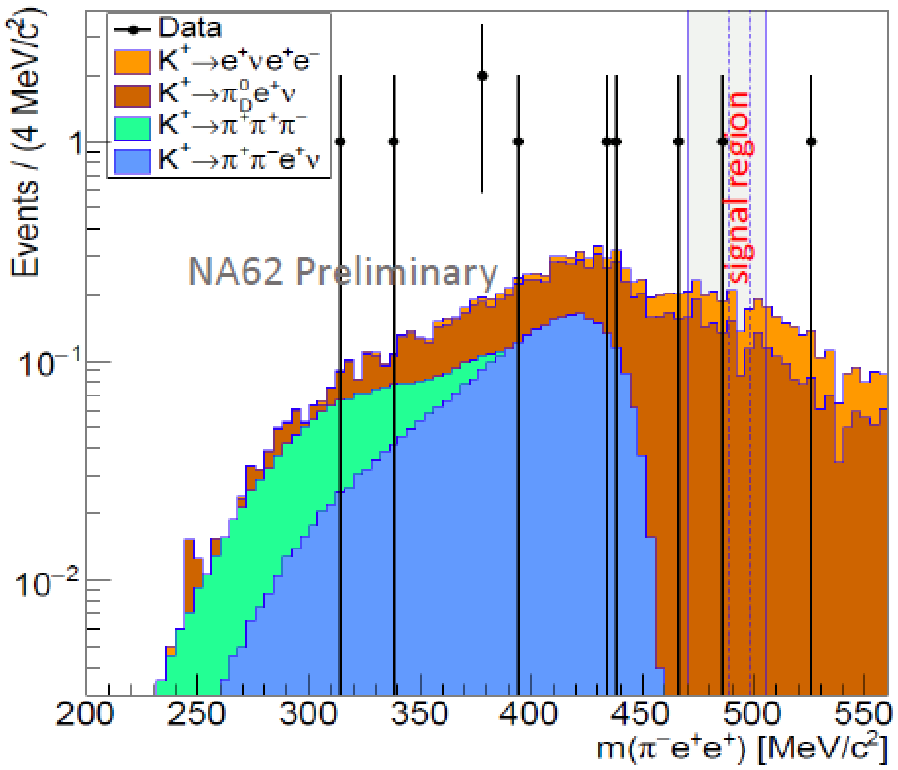
- Full RUN1 data set
- Expected background in the blinded region: 0.43 ± 0.09
- No candidate observed in the signal region
- $BR(K^+ \rightarrow \pi^- e^+ e^+) < 5.3 \cdot 10^{-11}$ @ *90% CL*

SM selection: $m(\pi^+ e^+ e^-)$



K^+ decays in FV: $(1.015 \pm 0.032) \times 10^{12}$

LNV selection: $m(\pi^- e^+ e^+)$

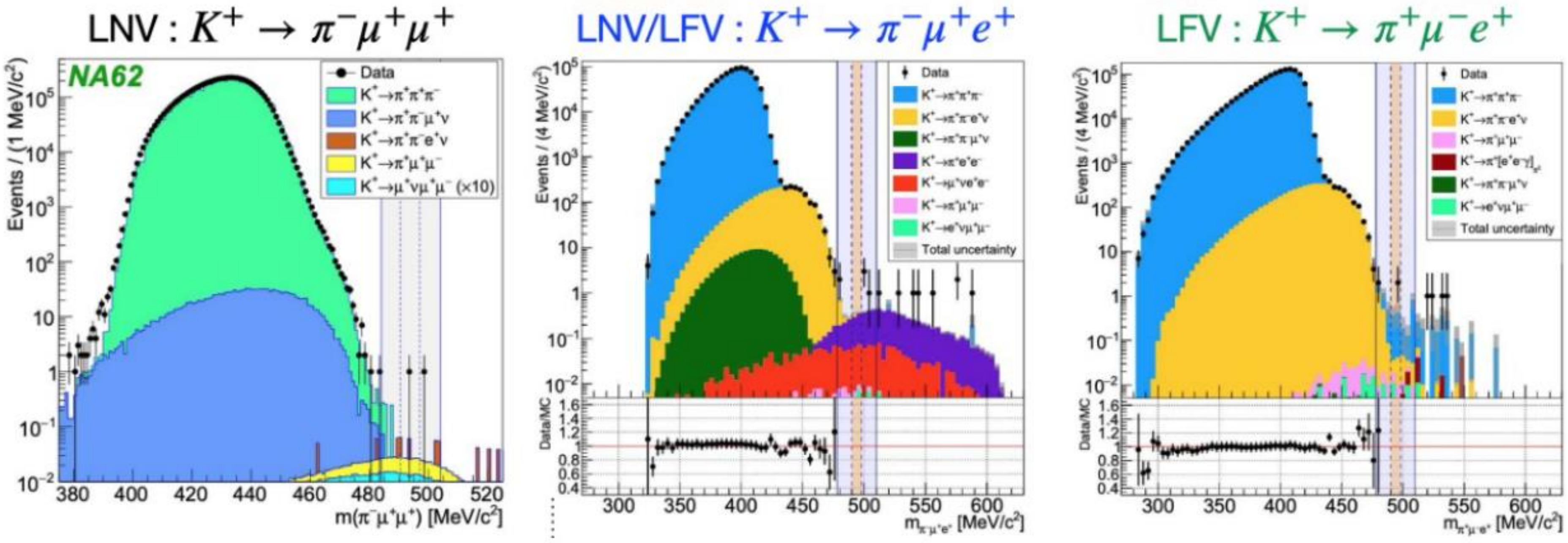


LFV & LNV results

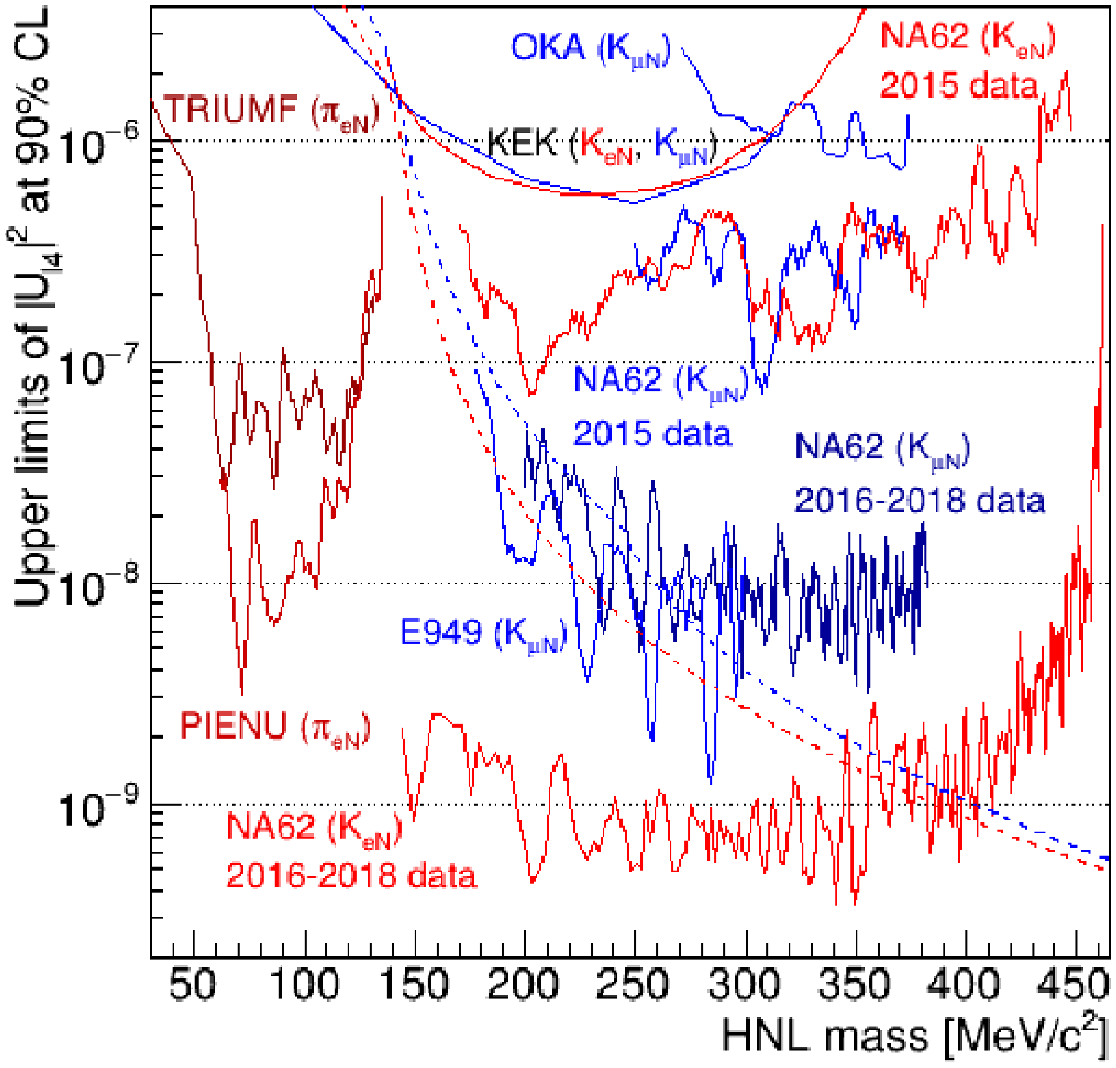
	Previous UL @90% CL	NA62 UL @90% CL		
$K^+ \to \pi^-\mu^+\mu^+$	8.6×10^{-11}	4.2×10^{-11}	2017 data	PLB 797 (2019) 134794
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	5.3×10^{-11}	Run1 data	PLB 830 (2022) 137172
$K^+ \to \pi^-\pi^0e^+e^+$	no limit	8.5×10^{-10}	Run1 data	PLB 830 (2022) 137172
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	4.2×10^{-11}	2017+2018 data	PRL 127 (2021) 131802
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	6.6×10^{-11}	2017+2018 data	PRL 127 (2021) 131802
$\pi^0 \to \mu^-e^+$	3.4×10^{-9}	3.2×10^{-10}	2017+2018 data	PRL 127 (2021) 131802

Factor 2 improvement
Factor 12 improvement

Factor 12 improvement
Factor 8 improvement
Factor 13 improvement



Search for Heavy Neutral Leptons



- Full RUN1 data set for $|U_{e4}|^2$ and $|U_{\mu4}|^2$.
- Improvement over earlier production searches by up to two orders of magnitude in terms of $|U_{\ell4}|^2$.
- For $|U_{e4}|^2$, the BBN-allowed range is excluded up to 340 MeV.

[PLB 807 (2020) 135599]

- For $|U_{\mu4}|^2$, the sensitivity approaches the E949 one; the search extends to 383 MeV.

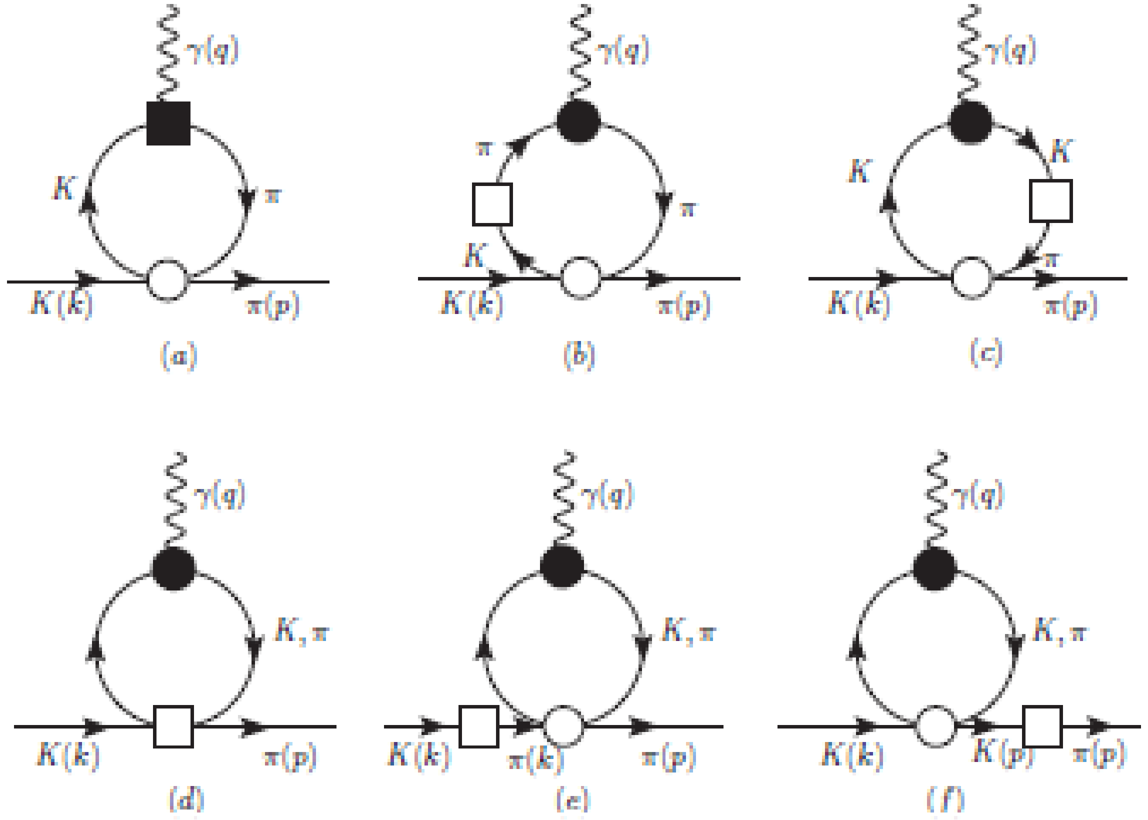
Rare Kaon Decay example: ($K^+ \to \pi^+ \mu^+ \mu^-$)

FCNC decay described in the scope of ChPT, mediated by one photon exchange $K^+ \to \pi^+ \gamma^*$

[Nucl. Phys. B291 (1987) 692–719], [Phys. Part. Nucl. Lett. 5 (2008) 76–84]

Together with $K^+ \to \pi^+ e^+ e^-$ allow to Test the Lepton Flavour Universality. A precise measurement of these decays could provide an evidence complementary to the B anomaly seen by LHCb.

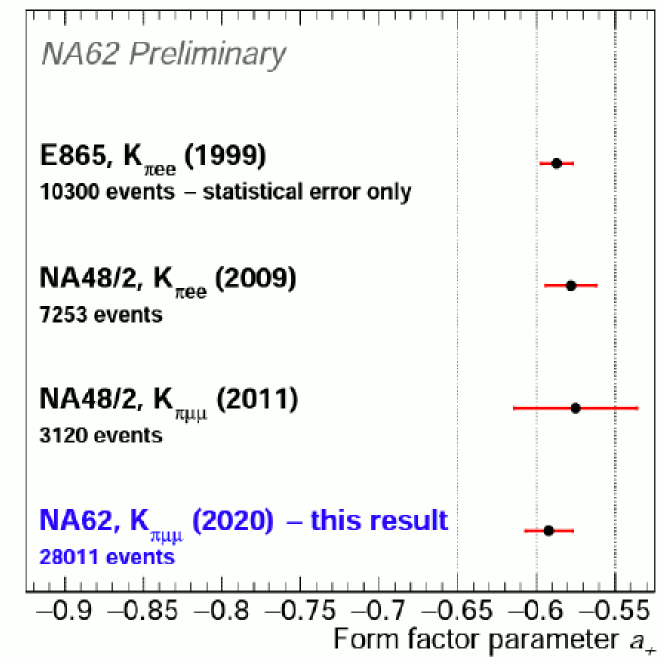
[Phys. Rev. Lett. 122, 191801 (2019)]
[JHEP 02, 049 (2019)]



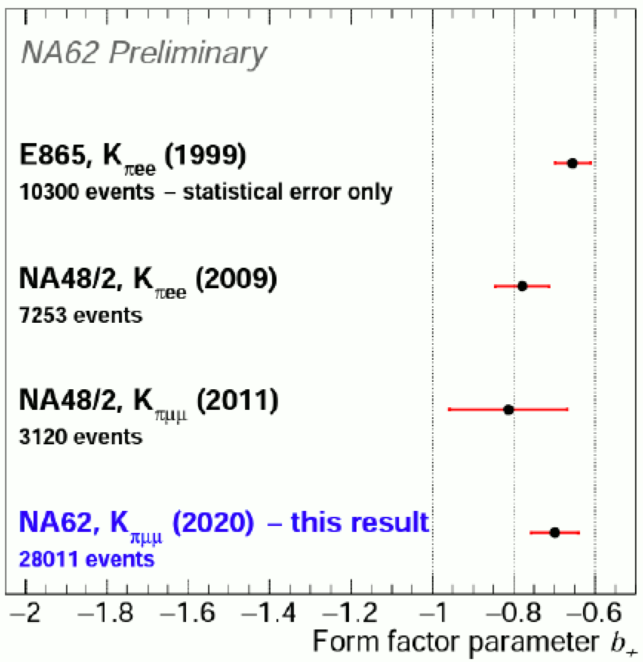
Preliminary result $K^+ \to \pi^+ \mu^+ \mu^-$

- $N_K \approx 6.76 \cdot 10^{12}$ 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

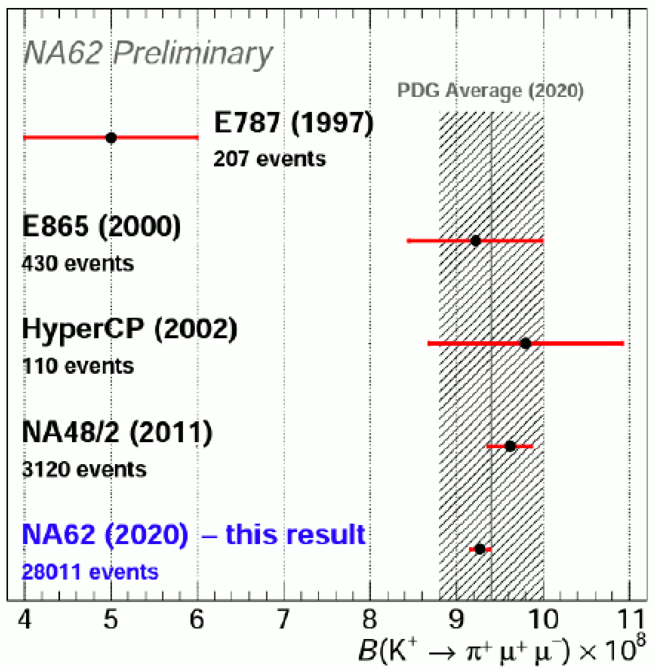
$a = -0.592 \pm 0.015$



$b = -0.699 \pm 0.058$



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

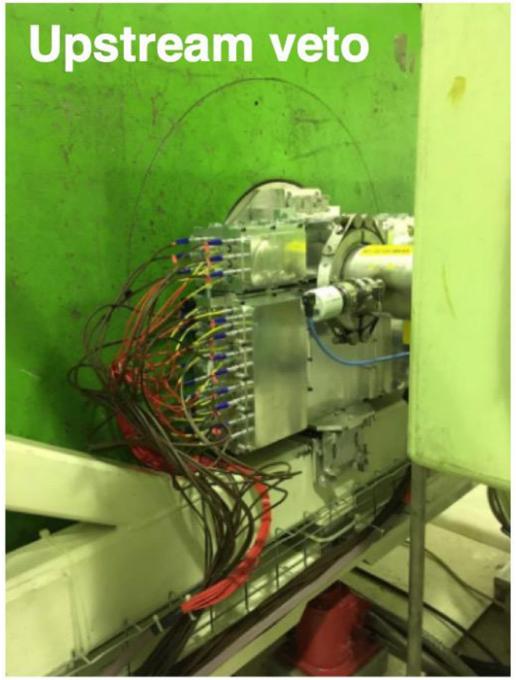


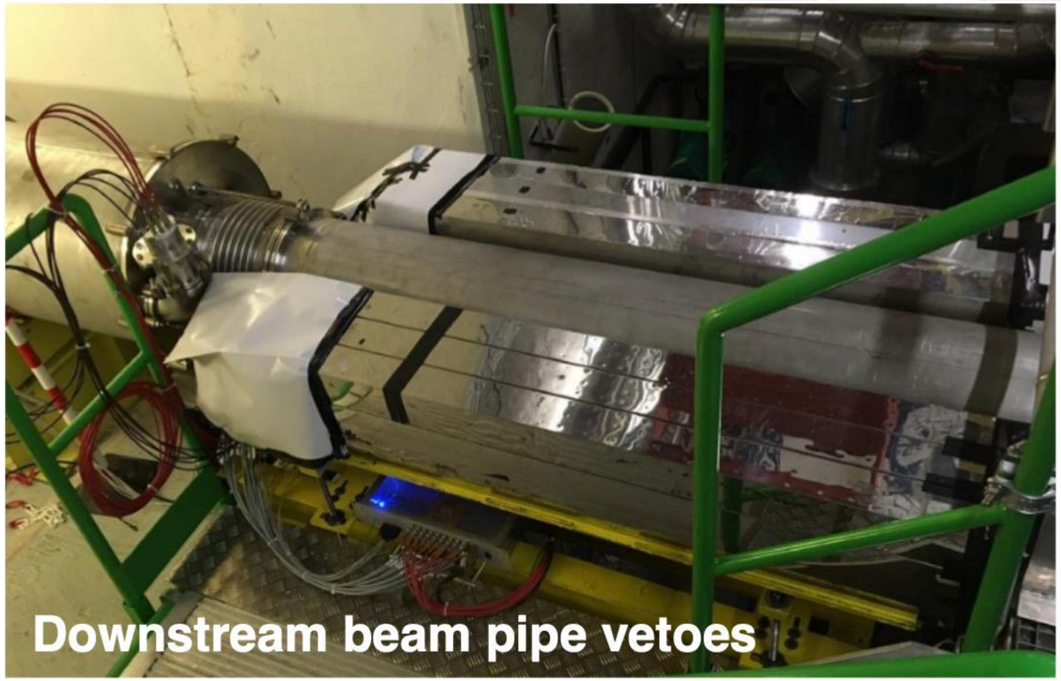
$$\mathrm{Br}(K^+ \to \pi^+ \mu^+ \mu) = (9.27 \pm 0.11) \cdot 10^{-8}$$

E865, Kee: **[Phys. Rev. Lett. 83 (1999) 4482-4485]**
NA48/2, Kee: **[Phys. Lett. B 677 (2009) 246-254]**
NA48/2, K: **[Phys. Lett. B 697 (2011) 107-115]**

NA62 Run 2: 2021–LS3

- The technique was firmly established during RUN1.
- Run 2: $K^+ \rightarrow \pi^+\nu\bar{\nu}$ measurement in a low-background and high-acceptance regime (O(10%) precision).
- Modifications of the setup for background reduction:
  - **fourth kaon beam tracker (GTK)** station added and rearrangement of beamline elements around the GTK;
  - **new veto hodoscopes** upstream of the decay volume;
  - an **additional veto counter** around downstream beam pipe.
- Improved TDAQ: **beam intensity increased by $\sim 30\%$** wrt Run 1.
- It is foreseen a **beam dump mode** to collect **10^{18} pot** in up to 90 days.

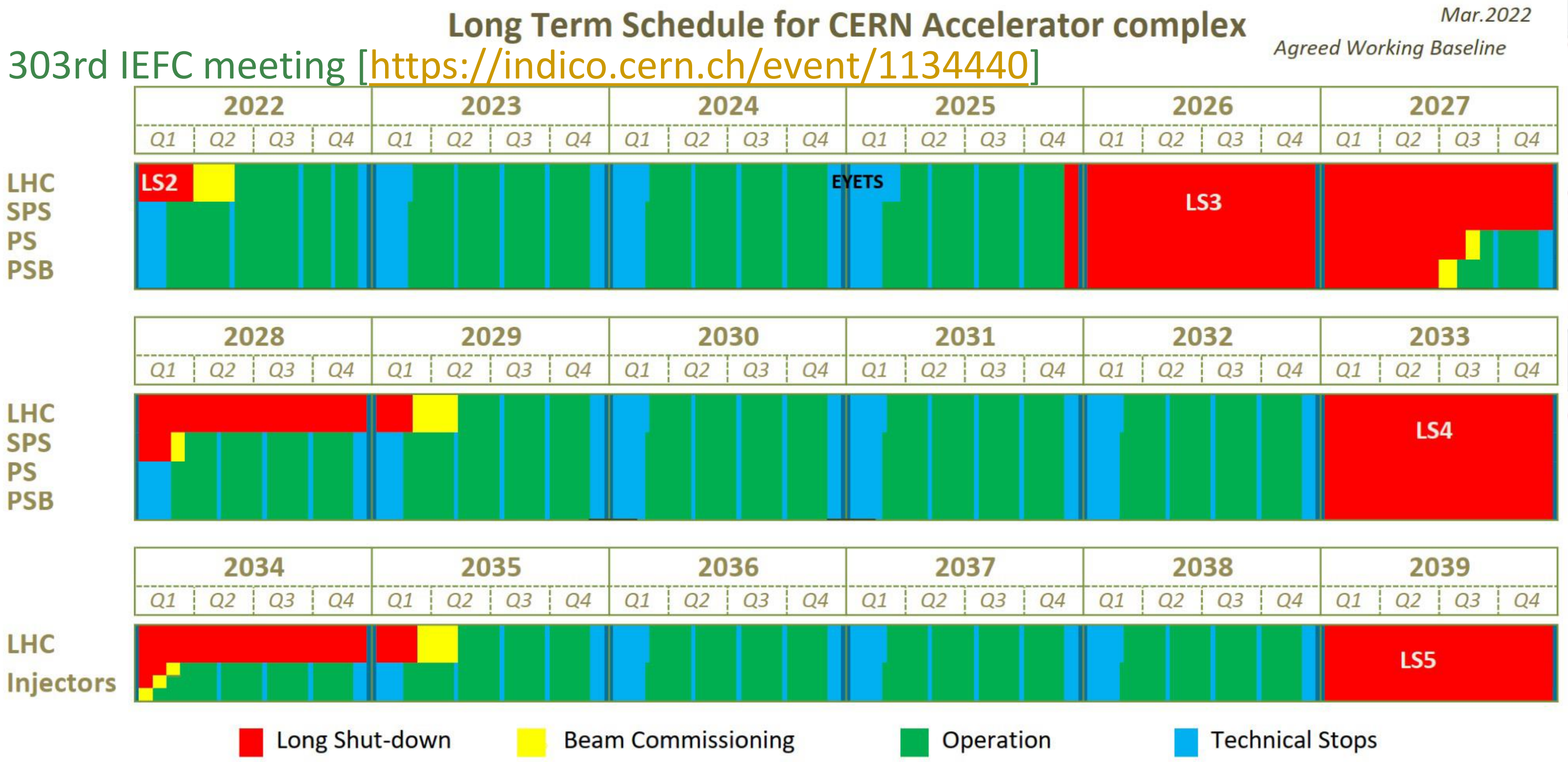




Fixed target program at CERN SPS

- SPS fixed target operation foreseen until at least 2038.
- **HIKE** ("High-Intensity Kaon experiment"): a long-term programme at the SPS proposed to search for new physics in kaon decays.
- Measurements of rare K^+ and K_L kaon decay modes: a clear insight into the flavour structure of new physics.
- Details in a Snowmass white paper: arXiv:2204.13394

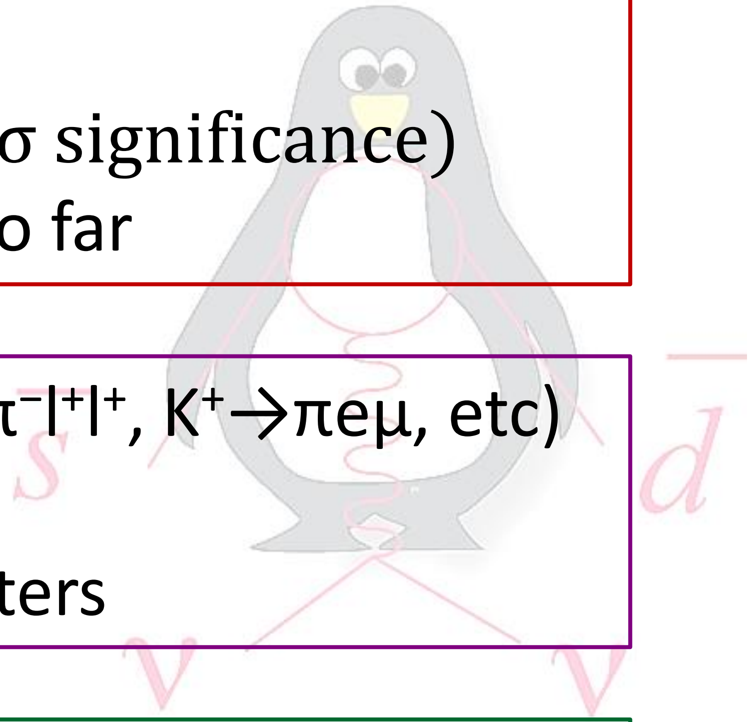
303rd IEFC meeting [https://indico.cern.ch/event/1134440]



Conclusion

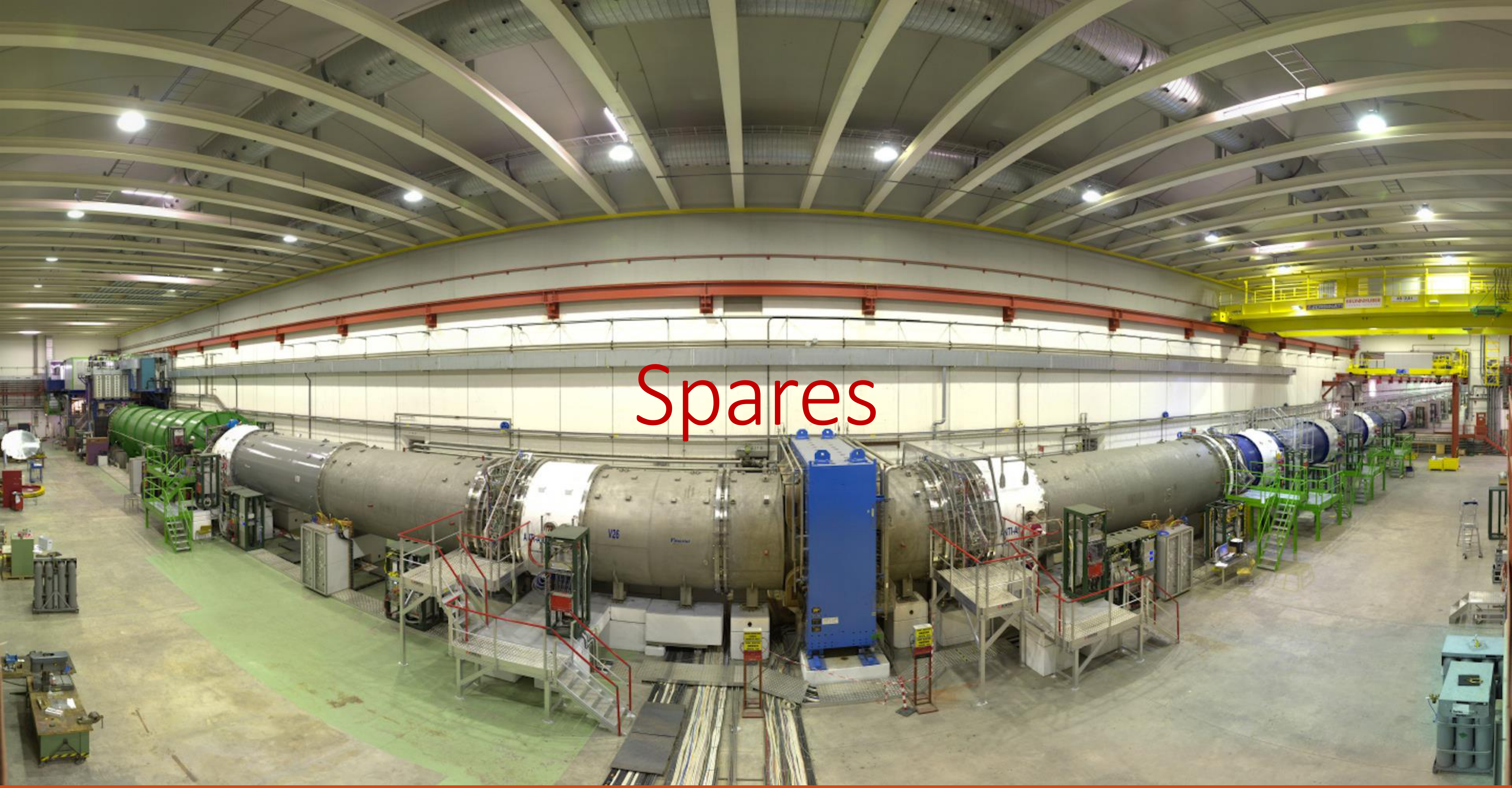
$K^+ \rightarrow \pi^+\nu\bar{\nu}$:

- Result from the complete Run 1(2016 + 2017 + 2018) compatible with the SM prediction within one standard deviation
- $Br(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.5}{}_{stat} \pm 0.9_{syst}) \cdot 10^{-11}$ (3.4σ significance)
- The most precise measurement of the BR obtained so far



- Upper limit improved for LFV and LNV 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
- Preliminary $K_{\pi\mu\mu}$ result consistent with $K_{\pi ee}$ FF parameters

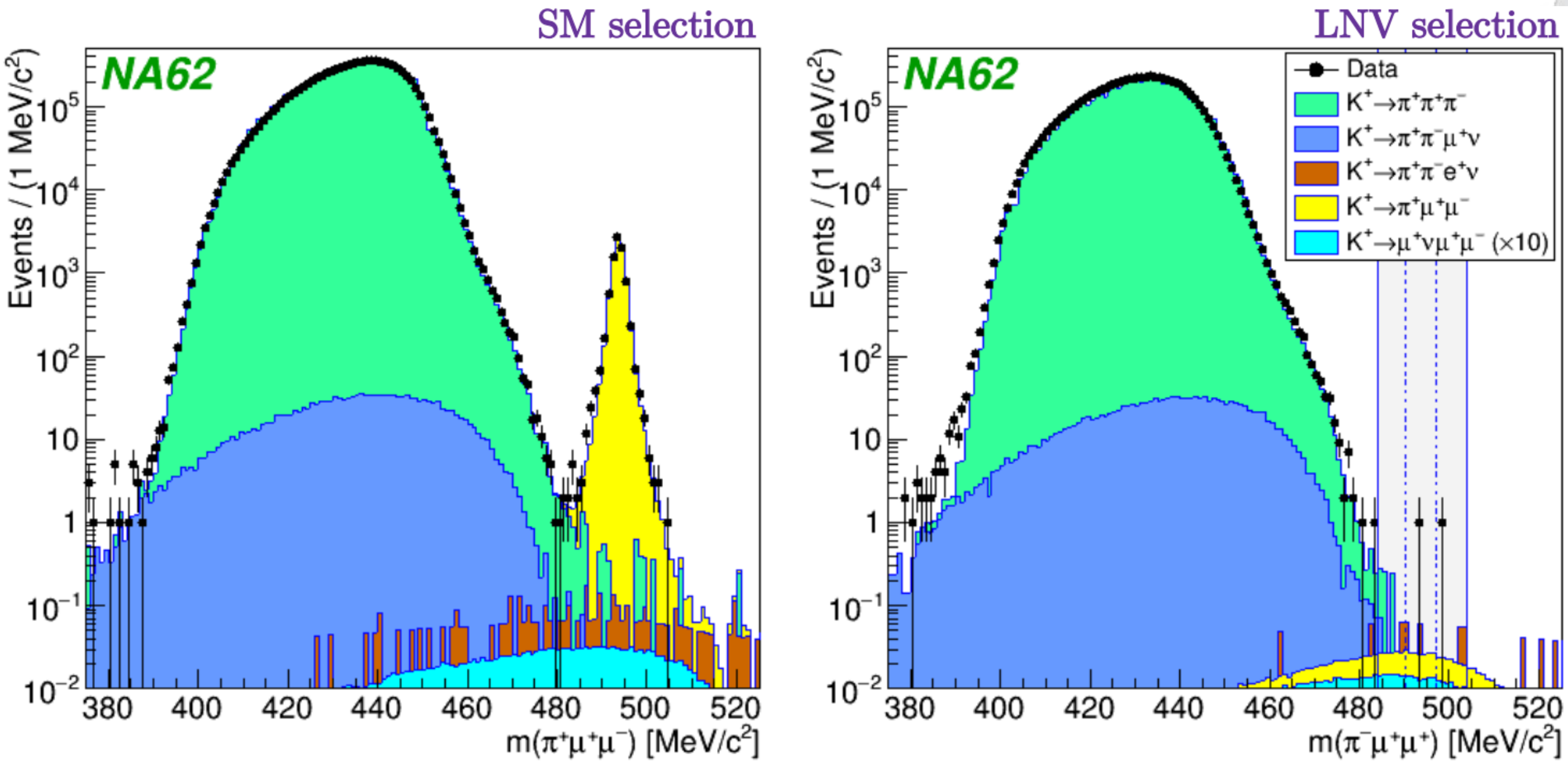
A long-term K^+ and K_L programme ("HIKE") is taking shape at CERN.



Spares

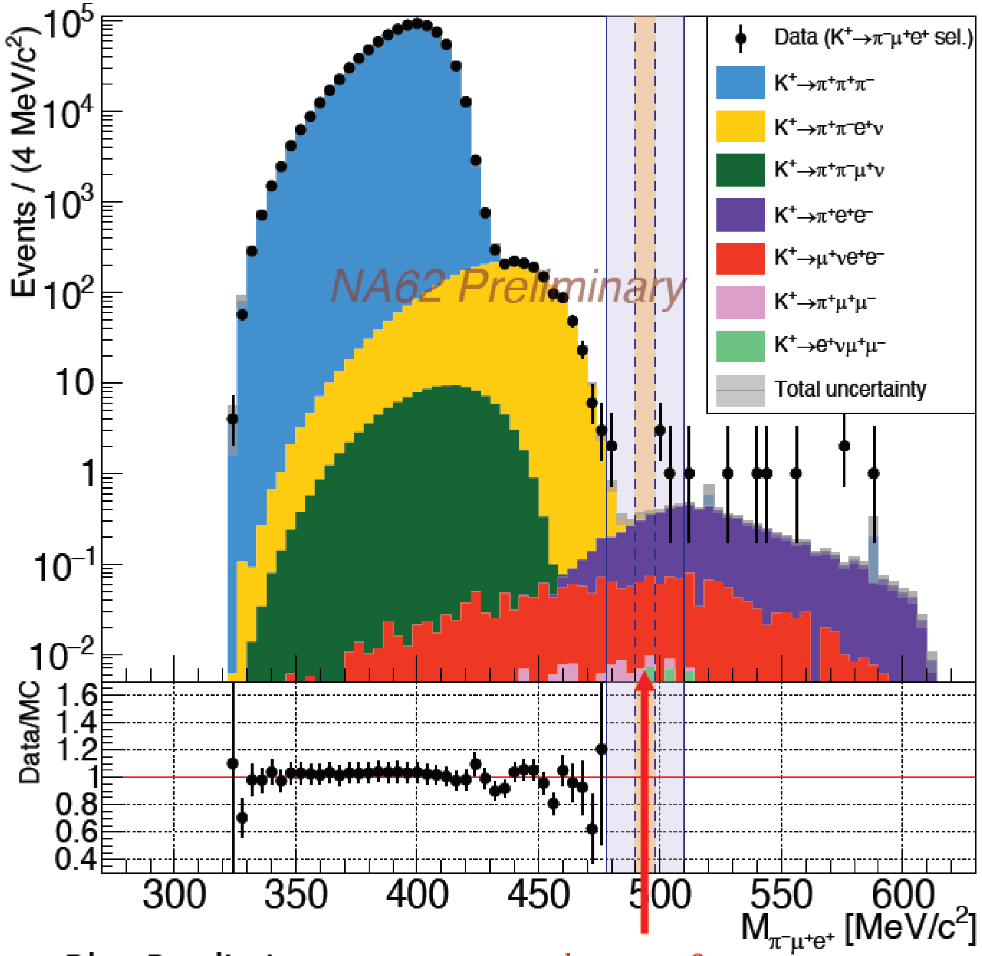
$K^+ \rightarrow \pi^- \mu^+ \mu^+$

- Expected background in the blinded region: 0.91 ± 0.41
- One candidate observed in the signal region
- $BR(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 4.2 \cdot 10^{-11}$ @ *90% CL*



$K^+ \to \pi^- \mu^+ e^+$ and $K^+ \to \pi^+ \mu^- e^+$

$BR(K^+ \to \pi^- \mu^+ e^+) < 4.2\times10^{-11}$ @ 90% CL

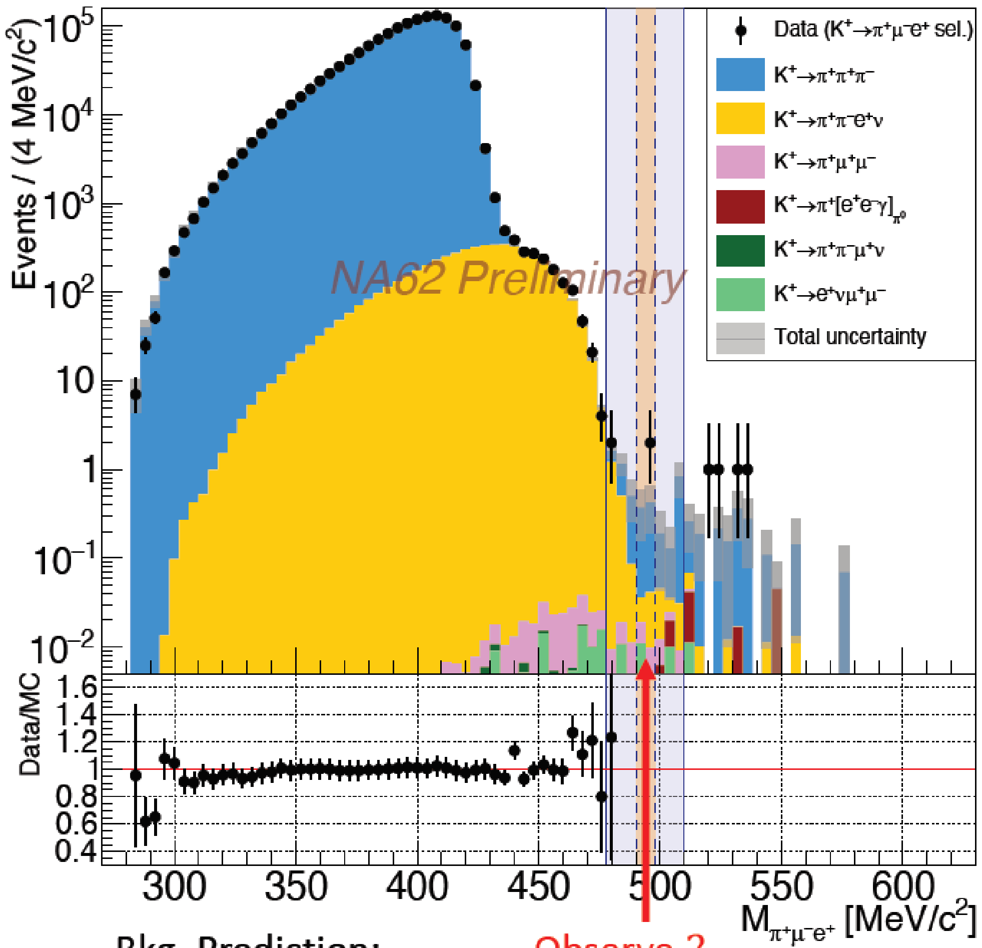


Bkg. Prediction:

$N_{SR}^{tot} = 1.06 \pm 0.20$

Observe 0 events in SR

$BR(K^+ \to \pi^+ \mu^- e^+) < 6.6\times10^{-11}$ @ 90% CL



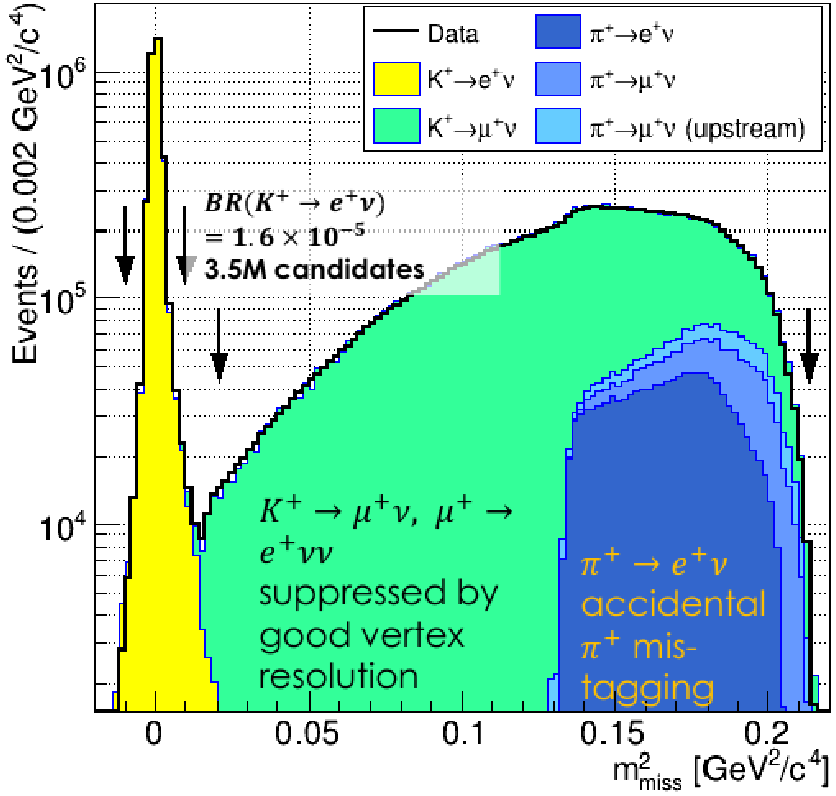
Bkg. Prediction:

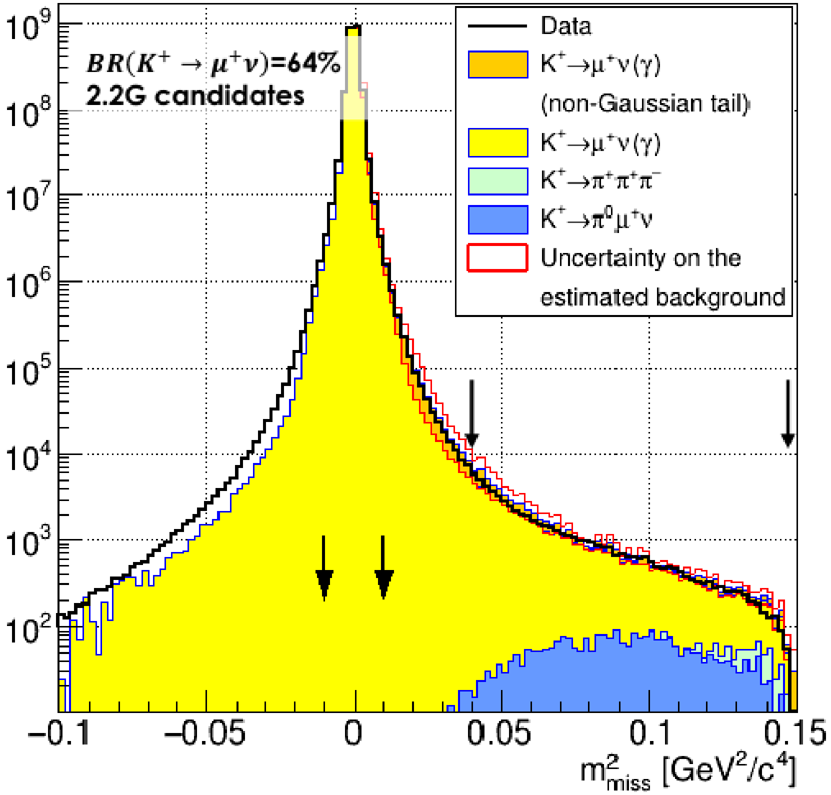
$N_{SR}^{tot} = 0.92 \pm 0.34$

Observe 2 events in SR

Data Sample

- Number of K⁺ in fiducial volume:
  - $(3.52 \pm 0.02) \cdot 10^{12}$ positron case
  - $(1.14 \pm 0.02) \cdot 10^{10}$ muon case
- A spike in the continuous m_{miss} spectrum is a HNL production signal





Long-term plan for the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

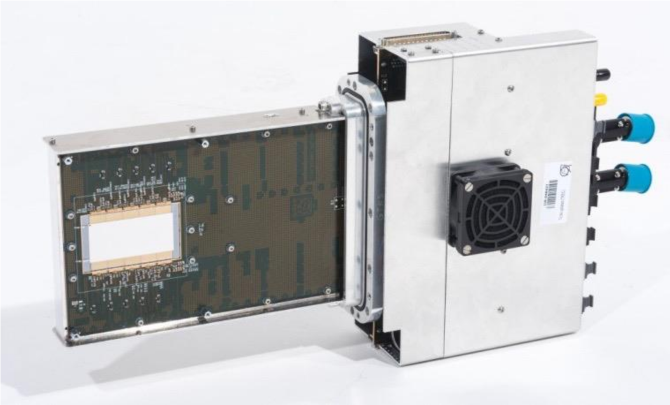
- An in-flight $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ experiment, up to **×6** the NA62 beam intensity, aiming at ~**5%** precision.
- Challenge: **20 ps** time resolution for key detectors to keep random veto under control, while maintaining all other NA62 specifications.
- Challenges aligned with HL-LHC projects and future flavour/dark matter exp.

New pixel beam tracker (GTK):

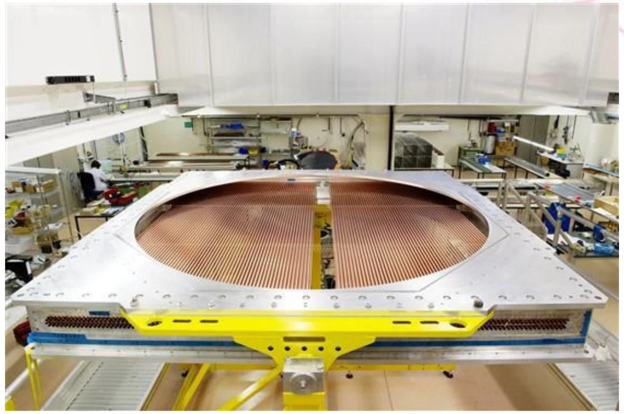
- time resolution: **<50 ps** per plane;
- pixel size: **<300×300 μm^2**;
- efficiency: **>99%** per plane (incl.fill factor);
- material budget : **0.3–0.5% X0**;
- beam intensity: **>3 GHz** on **30×60 mm^2**;
- peak intensity: **>8.0 MHz/mm^2**.

New STRAW spectrometer:

- operation in vacuum;
- straw diameter/length: **5 mm/2.2 m**;
- trailing time resolution: ~**6 ns** per straw;
- maximum drift time: ~**80 ns**;
- layout: ~**21000** straws (4 chambers);
- total material budget: **1.4% X_0**.

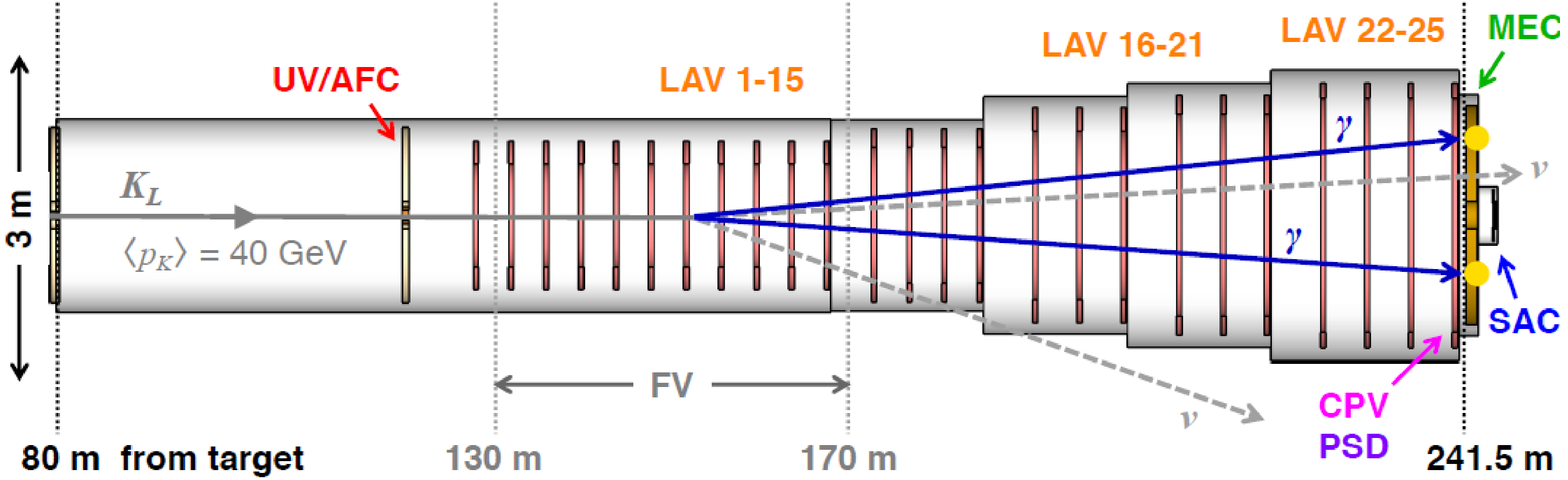


← current NA62 design →



Long-term plan for the $K_L \to \pi^0 \nu\bar{\nu}$

- **KLEVER**: a high-energy experiment (**10^{19}** pot/year) complementary to KOTO.
- Photons from **K_L** decays boosted forward: veto coverage only up to **100 mrad**.
- Vacuum tank layout and fiducial volume similar to NA62.
- A longer beamline is needed for $\boldsymbol{\Lambda \to n\pi^0}$ background suppression
- **60** SM $\boldsymbol{K_L \to \pi^0 \nu\bar{\nu}}$ events with **S/B ~ 1** and **~20%** precision in **5** years of operation;



Main detector/veto systems:

UV/AFC	Upstream veto/Active final collimator
LAV1-25	Large-angle vetoes (25 stations)
MEC	Main electromagnetic calorimeter
SAC	Small-angle vetoes
CPV	Charged particle veto
PSD	Pre-shower detector