New results and prospects in kaon physics from NA62 experiment

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on behalf of the NA62 collaboration

Outline:

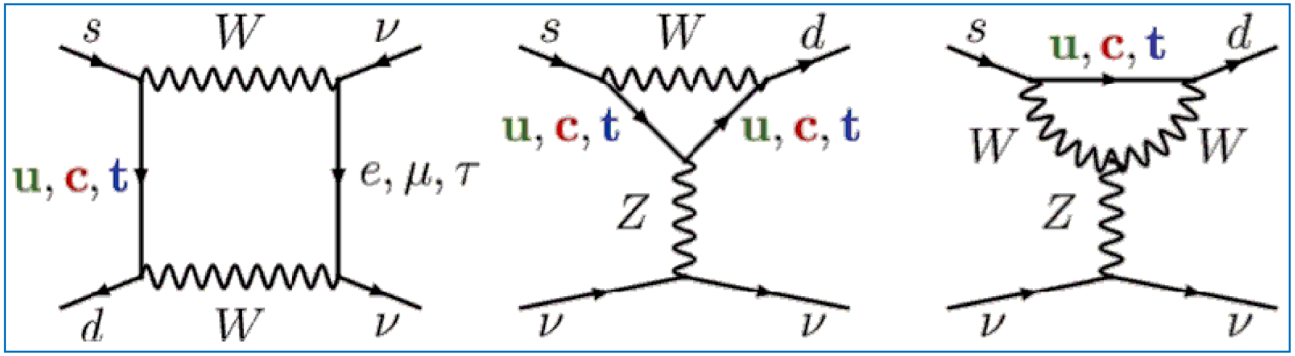
1) Rare kaon decays and the NA62 experiment at CERN
2) Status and prospects of $K^+ \to \pi^+ \nu\nu$ decay measurement
3) Search for heavy neutral lepton production in K^+ decays
4) Status of LF/LN conservation tests in 3-track K^+ decays
5) Summary

XIIIth Quark Confinement and Hadron Spectrum

Maynooth University • 1 August 2018

Rare kaon decays: $K\to\pi\nu\bar{\nu}$

SM: box and penguin diagrams



Ultra-rare decays with
the highest CKM suppression:

$$A \sim (m_t/m_W)^2 |V^*_{ts}V_{td}| \sim \lambda^5$$

- SM precision surpasses any other FCNC process involving quarks.
- Measurement of $|V_{td}|$ complementary to those from B–$\bar{B}$ mixing or $B^0\to\rho\gamma$.
- Main focus of kaon physics: measurement of both $K^+\to\pi^+\nu\nu$ and $K_L\to\pi^0\nu\nu$ decays.

SM branching ratios
Buras et al., JHEP 1511 (2015) 033

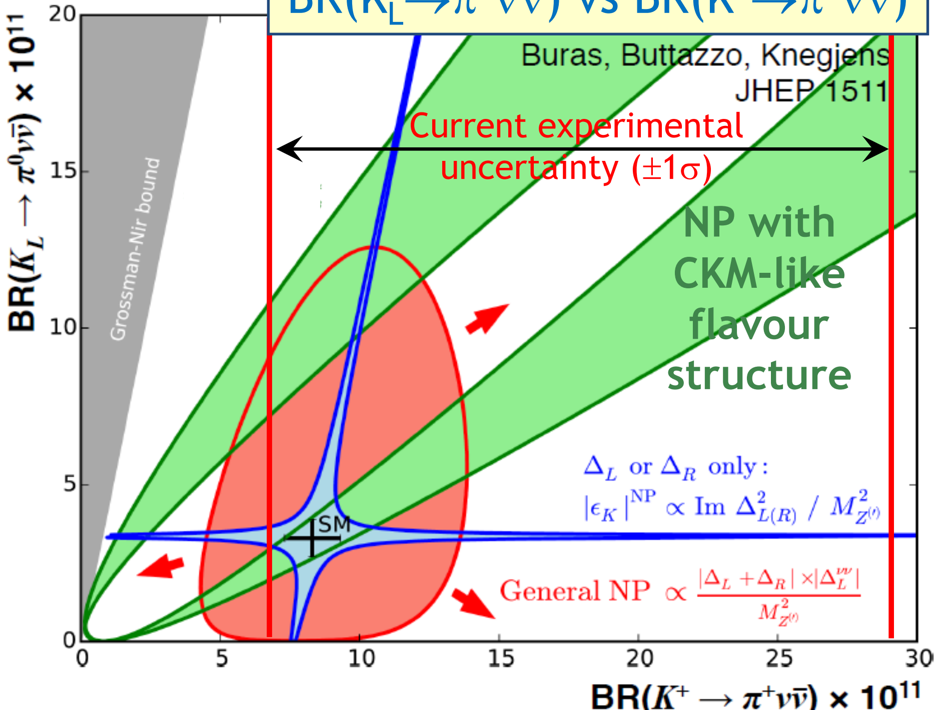
Mode	$BR_{SM}\times10^{11}$
$K^+\to\pi^+\nu\bar{\nu}(\gamma)$	8.4±1.0
$K_L\to\pi^0\nu\bar{\nu}$	3.4±0.6

The uncertainties are largely parametric (CKM)

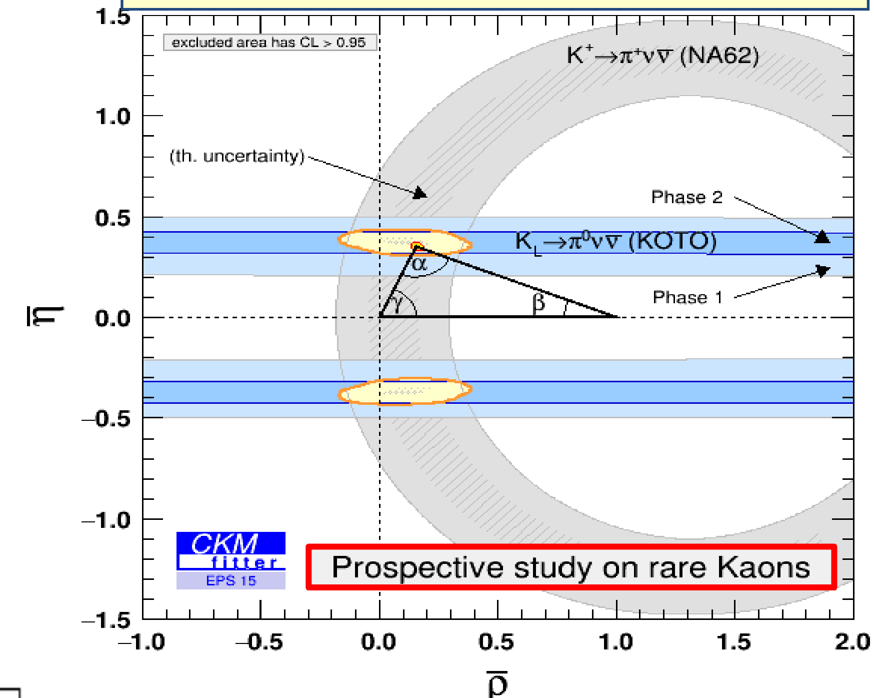
Theoretically clean,
sensitive to new physics,
almost unexplored

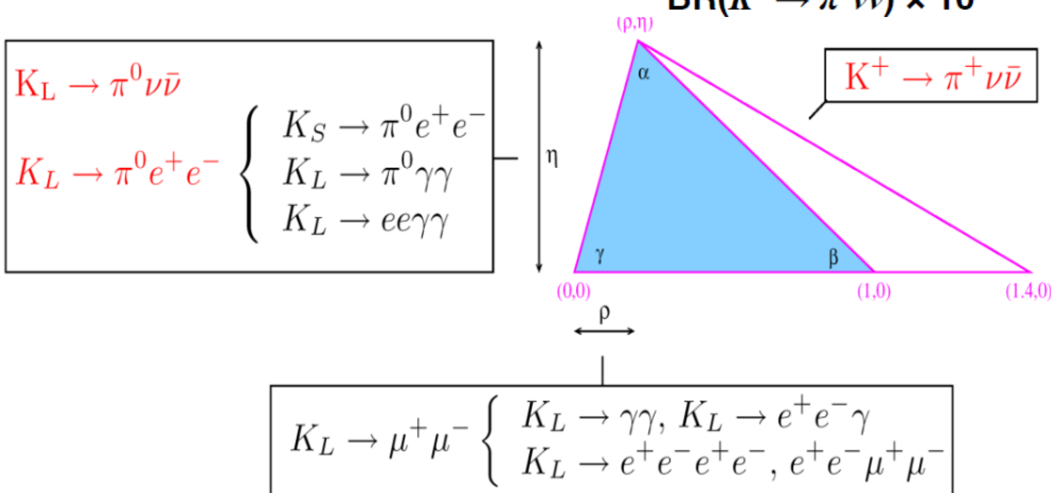
Status of theory and experiment

$BR(K_L \to \pi^0 \nu\bar{\nu})$ vs $BR(K^+ \to \pi^+ \nu\bar{\nu})$



CKM unitarity triangle with kaons

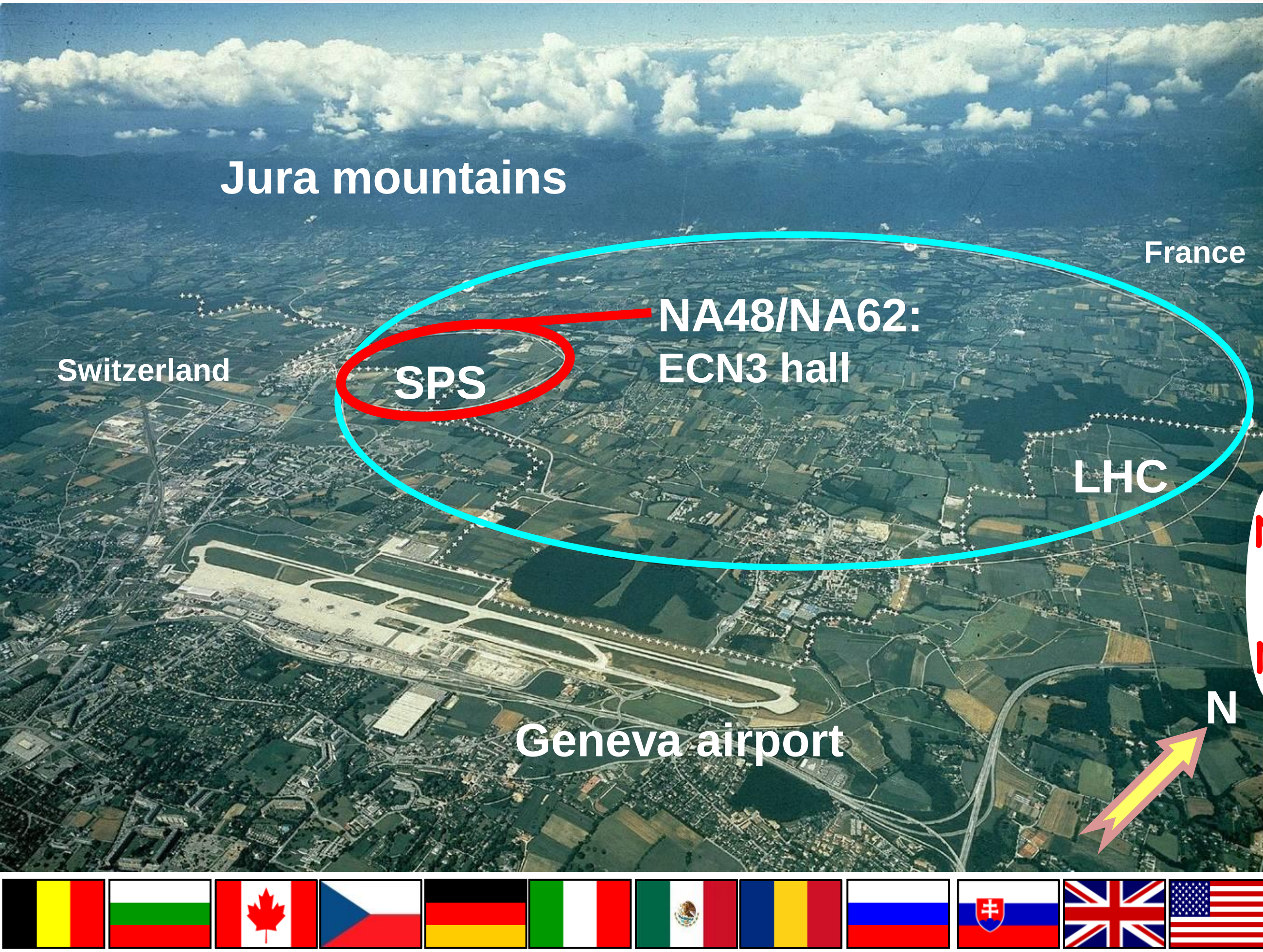




❖ Kaon measurements alone can fully constrain the unitarity triangle.

❖ Complementary to B physics in the description of NP flavour dynamics.

Kaon programme at CERN



Earlier: NA31

NA48 discovery of direct CPV	1997:	ε'/ε: K_L+K_S	
	1998:	K_L+K_S	
	1999:	K_L+K_S	K_S HI
	2000:	K_L only	K_S HI
	2001:	K_L+K_S	K_S HI
NA48/1	2002:	K_S/hyperons	
NA48/2	2003:	K^+/K^-	
	2004:	K^+/K^-	
NA62 R_K run	2007:	$K^\pm_{e2}/K^\pm_{\mu 2}$	tests
	2008:	$K^\pm_{e2}/K^\pm_{\mu 2}$	tests
NA62	2015:	commissioning	
	2016–18:	physics run	

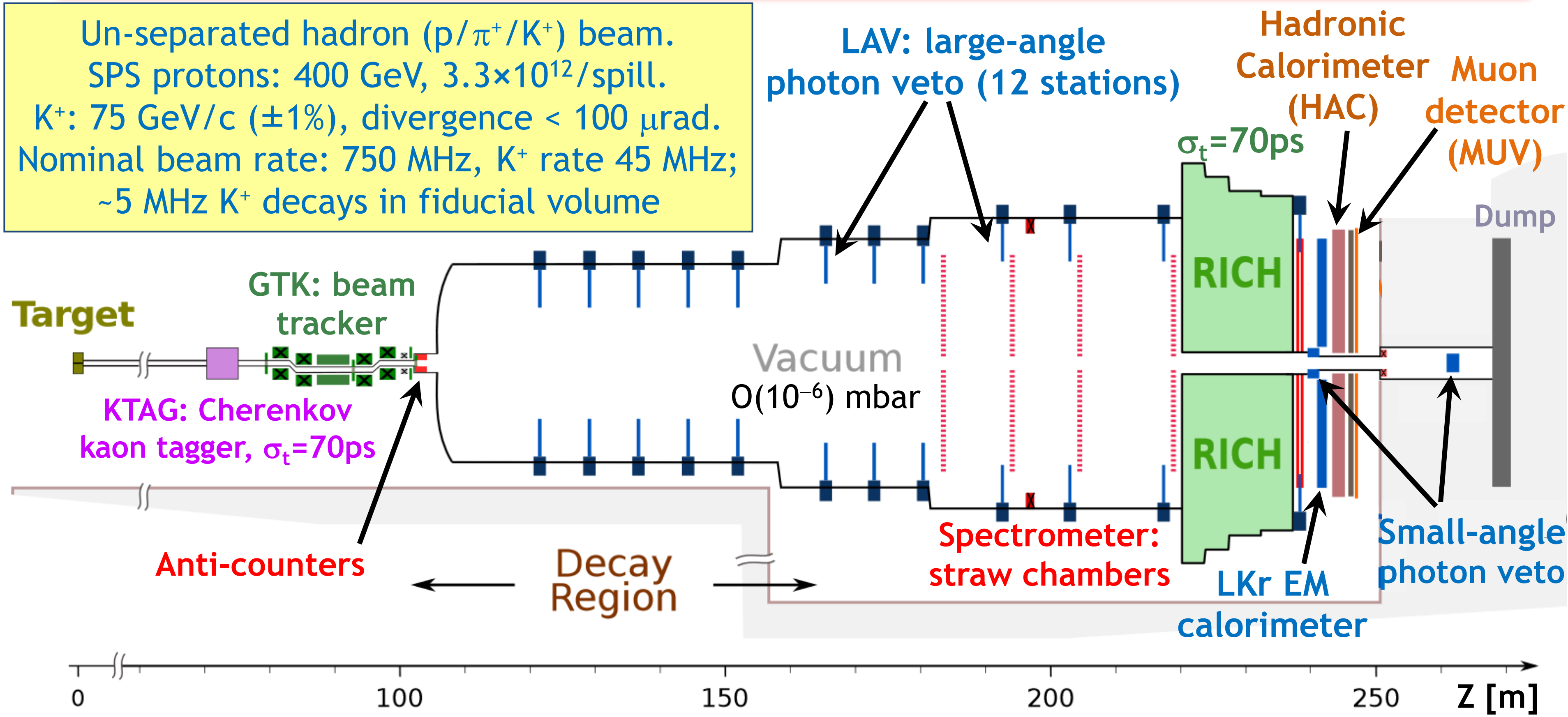
Main NA62 goal: an improved $K^+\to\pi^+\nu\nu$ measurement with a novel decay-in-flight technique.

Currently ~200 participants, ~30 institutions

NA62 collaboration, JINST 12 (2017) P05025

The NA62 detector

Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, 3.3×10^{12}/spill.
K^+: 75 GeV/c (±1%), divergence < 100 μrad.
Nominal beam rate: 750 MHz, K^+ rate 45 MHz;
~5 MHz K^+ decays in fiducial volume



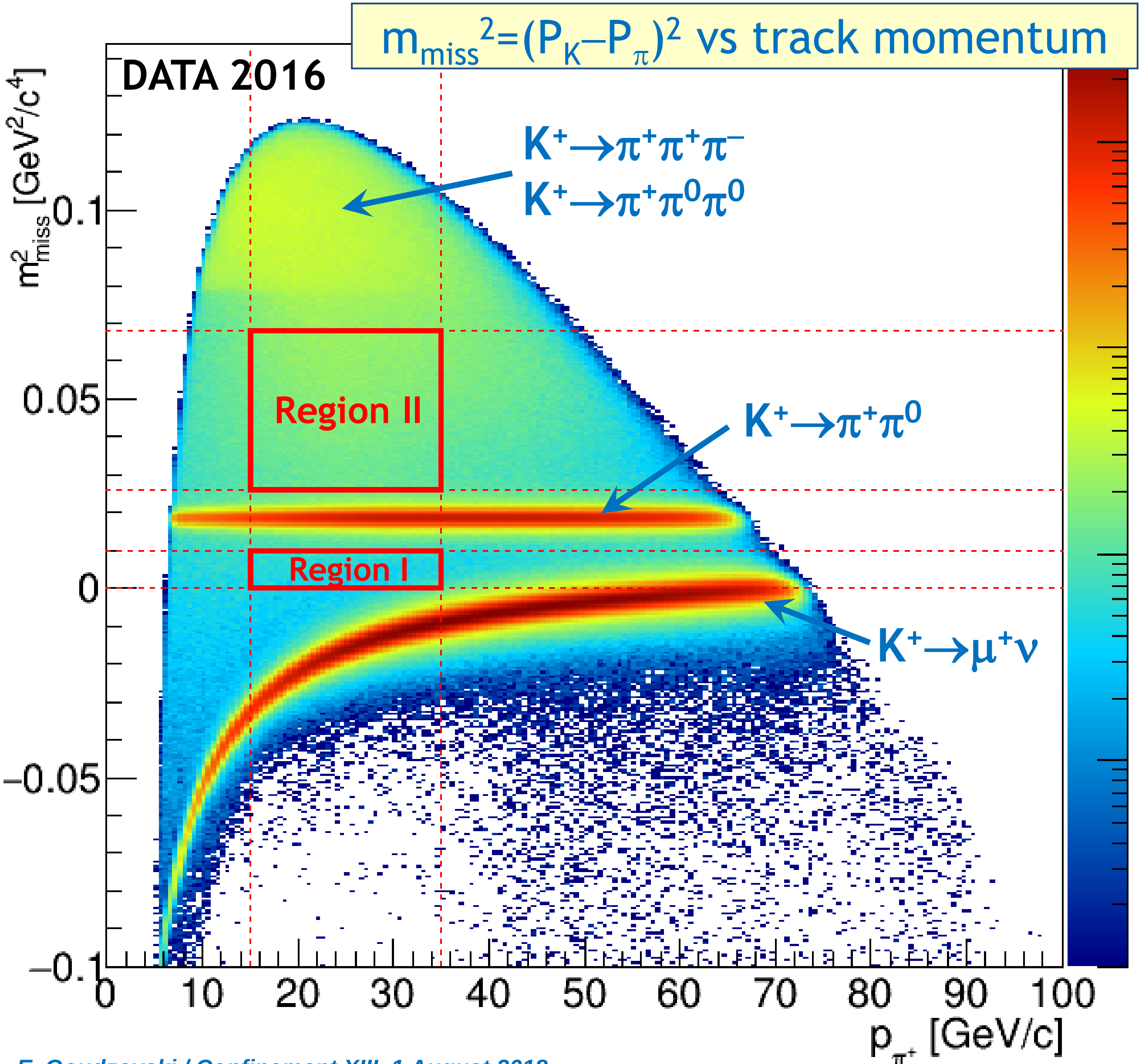
- ❖ Expected single event sensitivity for K^+ decays: **BR~10^{-12}**.
- ❖ Measured kinematic rejection factors (limited by beam pileup & MCS tails): 1×10^{-3} for $K^+\to\pi^+\pi^0$, 3×10^{-4} for $K\to\mu^+\nu$.
- ❖ Hermetic photon veto: $\pi^0\to\gamma\gamma$ decay suppression (for $E_{\pi0}$>40 GeV) = 3×10^{-8}.
- ❖ Particle ID (RICH+LKr+HAC+MUV): ~10^{-8} muon suppression.

NA62 data collection

- Commissioning run 2015: minimum bias (~1% of nominal beam intensity).
- Physics run 2016 (40% intensity, limited by beam quality): 1.2×10^{11} K^+ useful decays (1 month) for $K^+\to\pi^+\nu\nu$ analysis; analysis completed
- Physics run 2017 (65% intensity): $\sim3\times10^{12}$ useful K^+ decays.
- Physics run 2018 started in April, 218 days scheduled.

$K^+ \to \pi^+ \nu \nu$ measurement: results and prospects

NA62: $K_{\pi\nu\nu}$ signal region definition



Main K^+ decay modes (>90% of BR) rejected kinematically.

Design kinematical resolution on m_{miss}^2 has been achieved ($\sigma=1.0\times10^{-3}$ GeV^4/c^2).

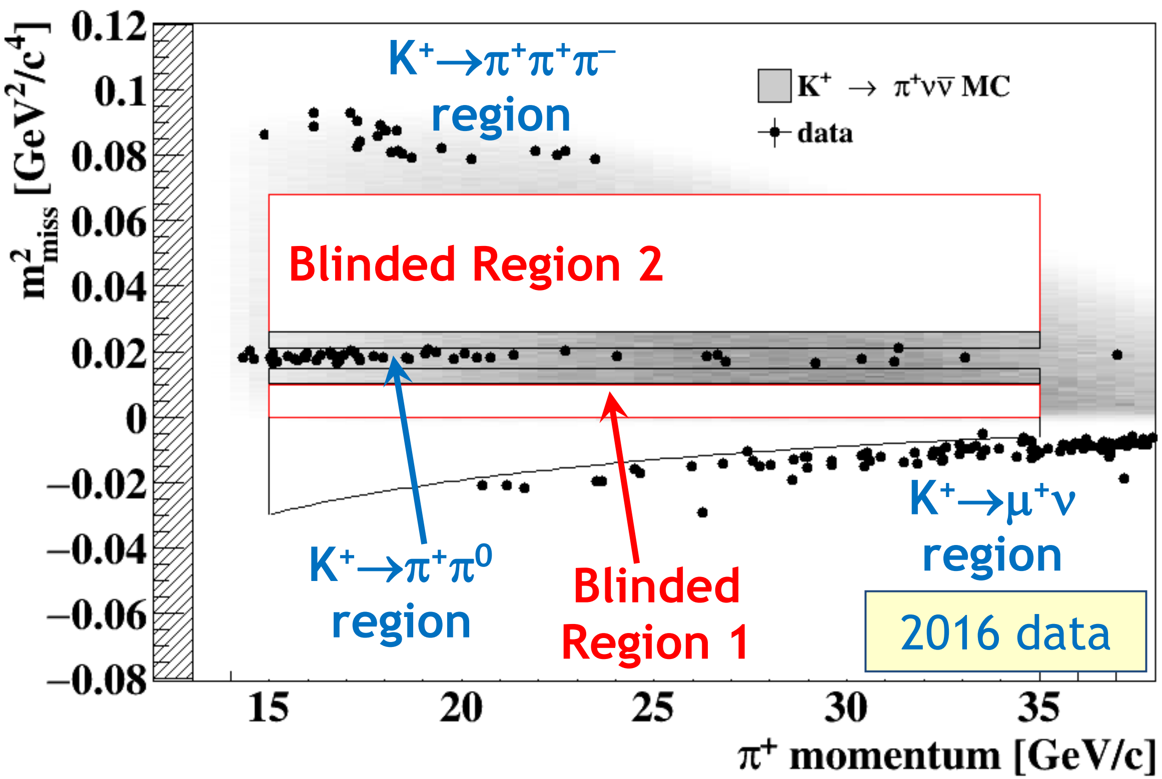
Measured kinematical background suppression:

- ✓ $K^+\to\pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+\to\mu^+\nu$: 3×10^{-4}.

Further background suppression:

- ✓ PID (calorimeters & Cherenkov detectors): μ suppression 10^{-8}.
- ✓ Hermetic photon veto: suppression of $\pi^0\to\gamma\gamma$ decays 3×10^{-8}.

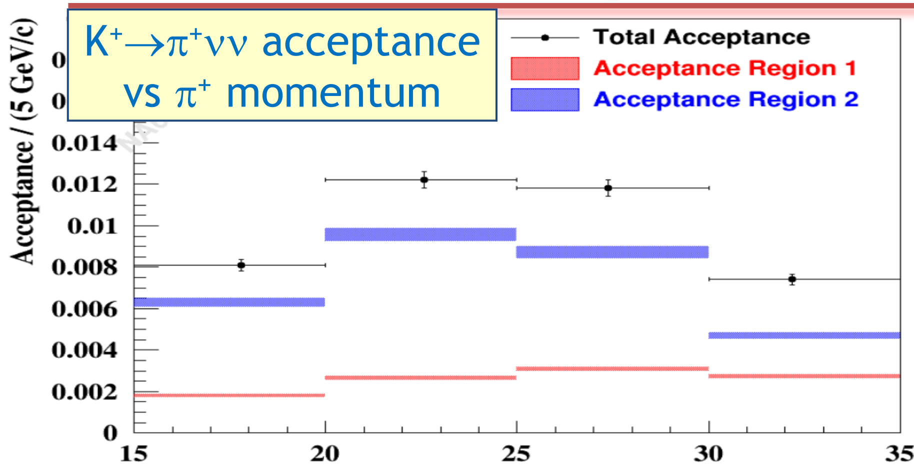
2016 data

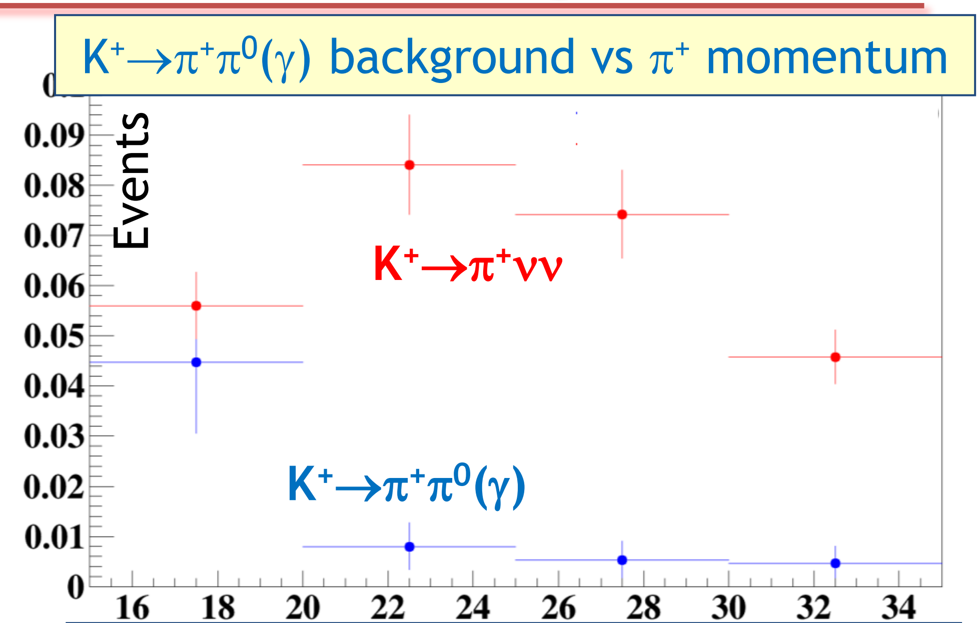


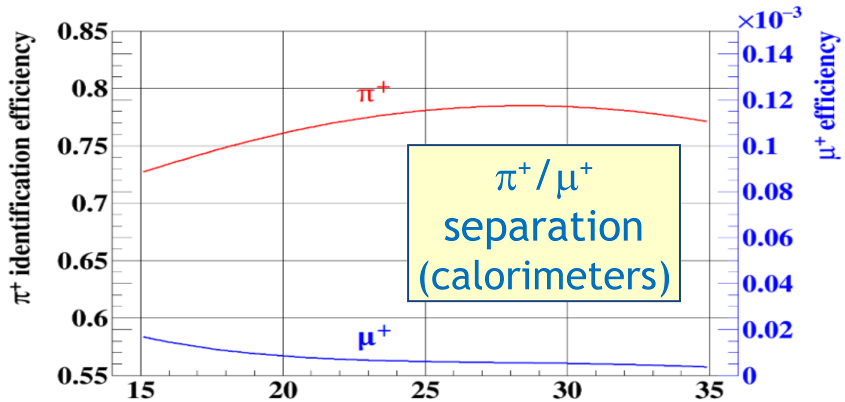
Process	Expected events in R1 + R2
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.029_{syst} \pm 0.032_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu_\mu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$0.018^{+0.024}_{-0.017}\|_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+\pi^-\pi^+$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream background	$0.050^{+0.090}_{-0.030}$
Total background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$

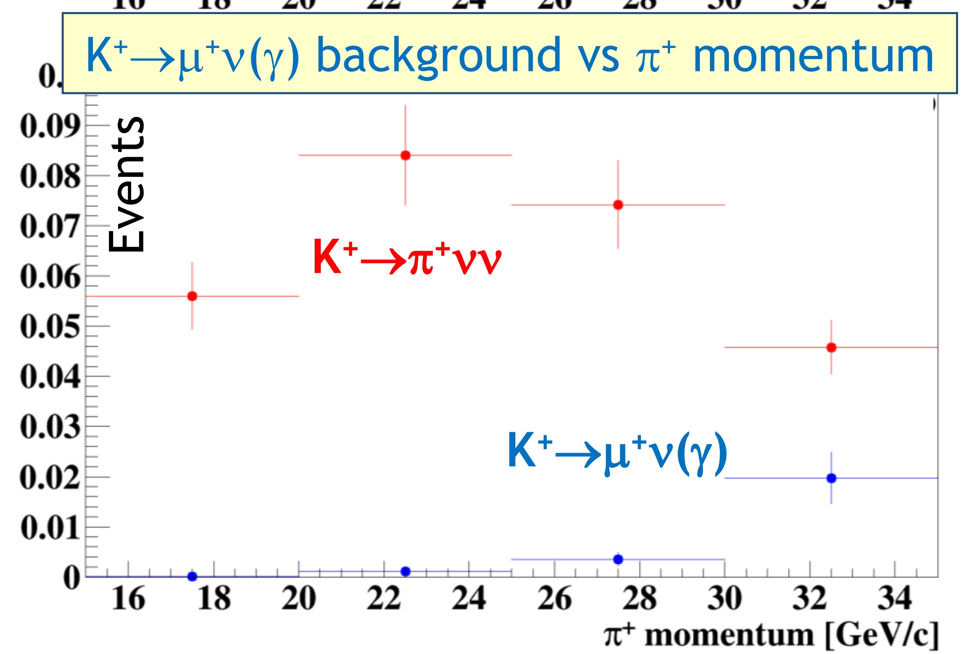
- Data sample: one month at **40%** of nominal intensity.
- Number of kaon decays: **$N_K=(1.21\pm0.02_{syst})\times10^{11}$**.
- The analysis procedure is fully established.
- Background estimates are mostly data-driven.
- Signal acceptance: **$A_{\pi\nu\nu}=(4.0\pm0.1)\%$**.
- Single-event sensitivity: **SES = $(3.15\pm0.24)\times10^{-10}$**.

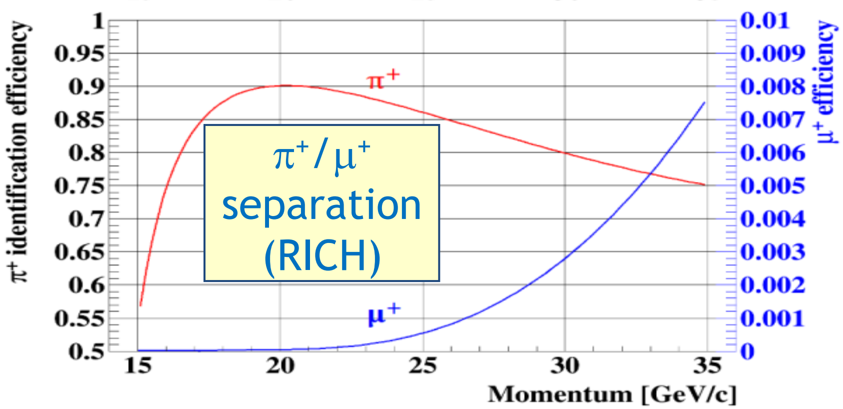
Acceptance and backgrounds



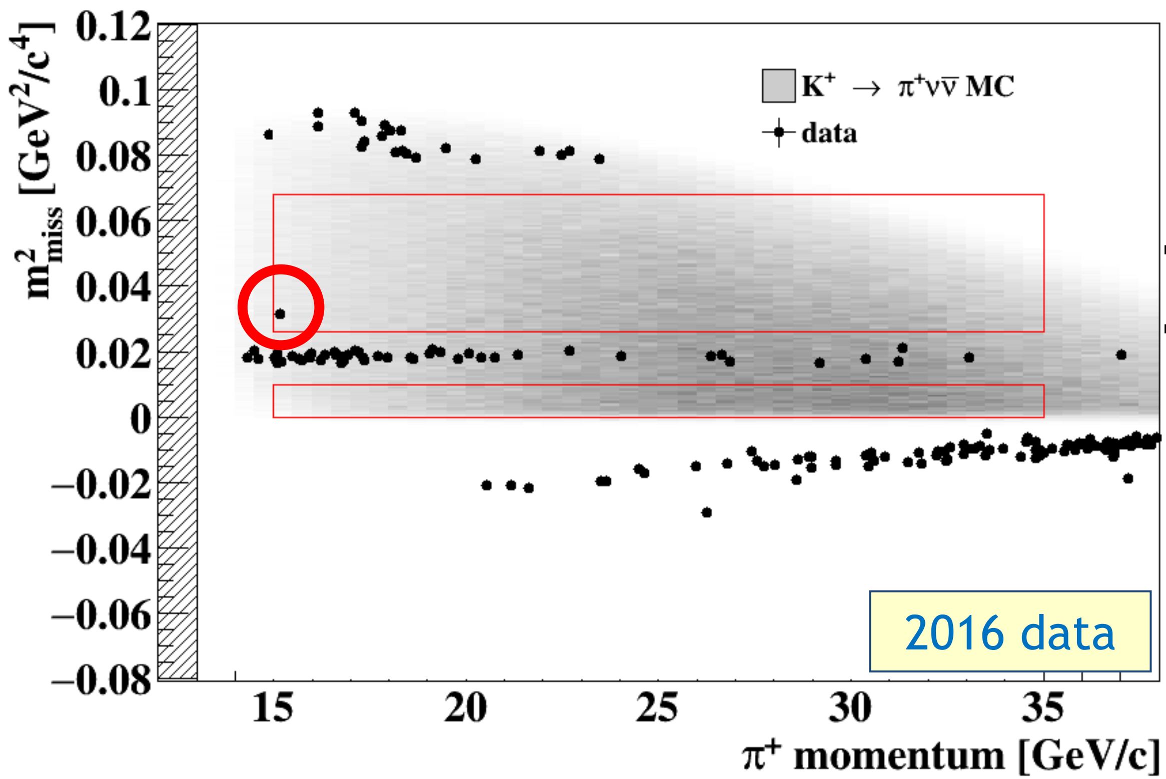


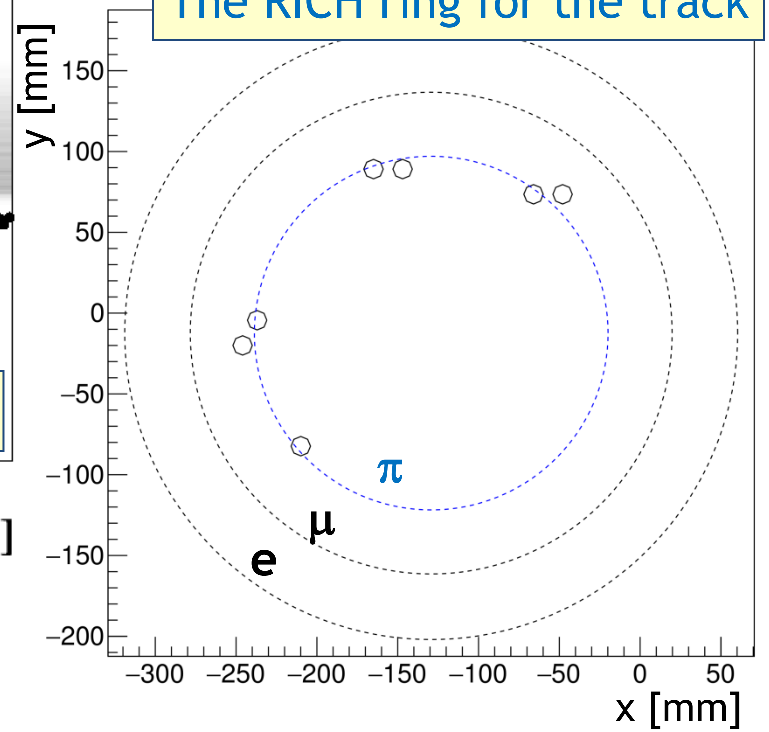






2016 result





One $K^+ \to \pi^+ \nu\nu$ candidate observed:
$BR(K^+ \to \pi^+ \nu\nu) < 11\times10^{-10}$ at 90% CL.

BNL 949 (K^+ decay at rest): $BR(K^+ \to \pi^+ \nu\nu) = (1.73^{+1.15}_{-1.05})\times10^{-10}$

SM prediction: $BR(K^+ \to \pi^+ \nu\nu) = (0.84\pm0.10)\times10^{-10}$

- ❖ The NA62 decay-in-flight technique works!
- ❖ Competitive sensitivity obtained with ~1% of the total expected statistics.

$K^+ \to \pi^+ \nu\nu$ analysis: prospects

Analysis of the 2017 data in progress:

- improvement in statistics by a factor of **20** wrt 2016;
- expect reduction of the upstream background;
- improving reconstruction and analysis to increase overall efficiency.

Data taking of 2018 is in progress:

- further mitigation of the upstream background is expected;
- processing in parallel with data-taking.

Expectation with the 2017+18 data sample: 20 SM events.

- Analysis will provide a solid extrapolation to the ultimate sensitivity achievable after LS2, and input to the European Strategy.

Plans for operation after LS2:

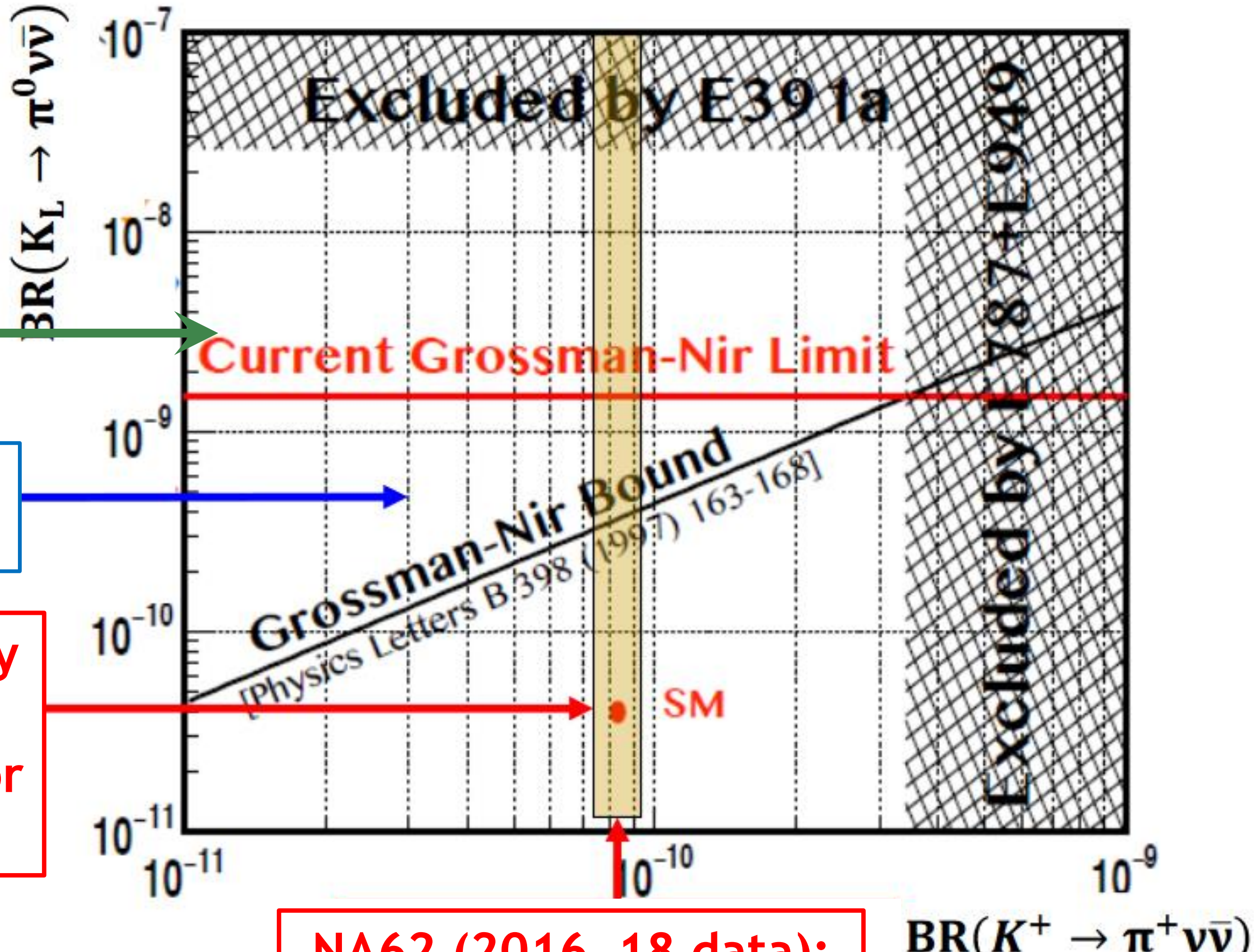
- SPSC has endorsed NA62 data taking for at least 2 years (**2021**, **2022**);
- addendum to proposal to be submitted to SPSC in September 2018;
- developing a strategy to collect **100 SM events**;
- possibly beam dump operation (**3** months of data taking = **10^{18} pot**): competitive searches for hidden sector (long-lived HNL, DP, ALP).

$K_L \to \pi^0 \nu\nu$ vs $K^+ \to \pi^+ \nu\nu$: prospects

New KOTO result, 2015 data (July 2018): $BR < 3.0 \times 10^{-9}$ @90% CL

KOTO sensitivity with 2015–18 data

KOTO sensitivity goal following beam & detector upgrades



NA62 (2016–18 data): ~20 SM events by 2020

~100 SM events by 2025

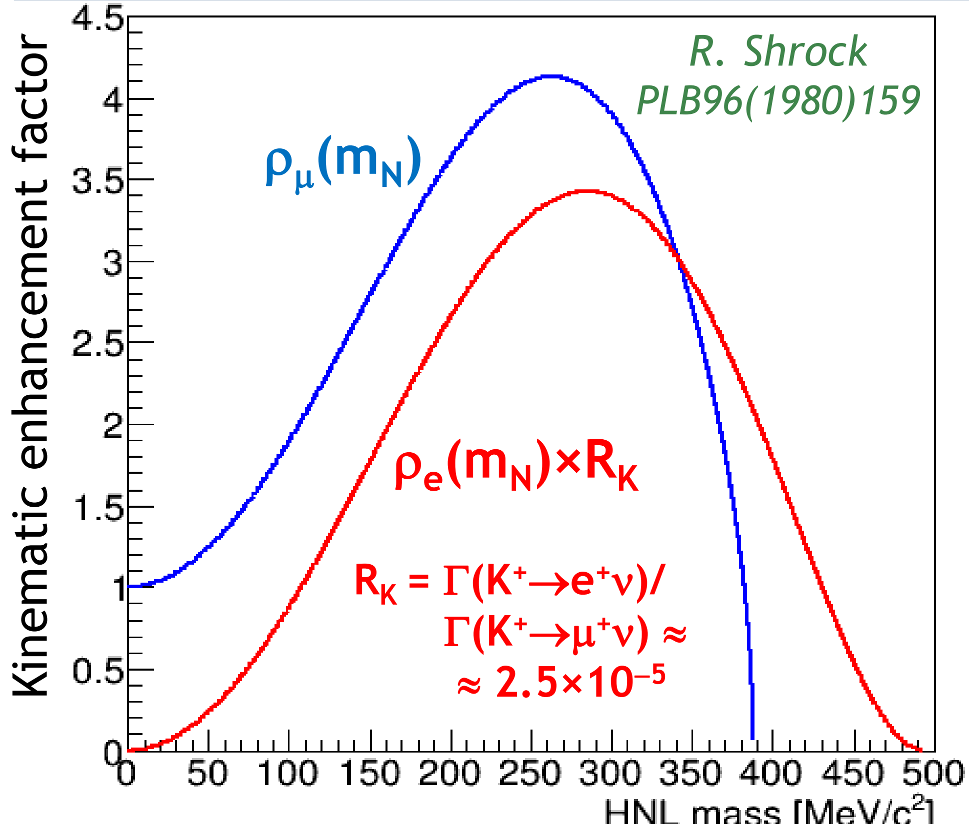
Searches for heavy neutral lepton production in K^+ decays

Result based on the 2015 data:
Phys. Lett. B778 (2018) 137

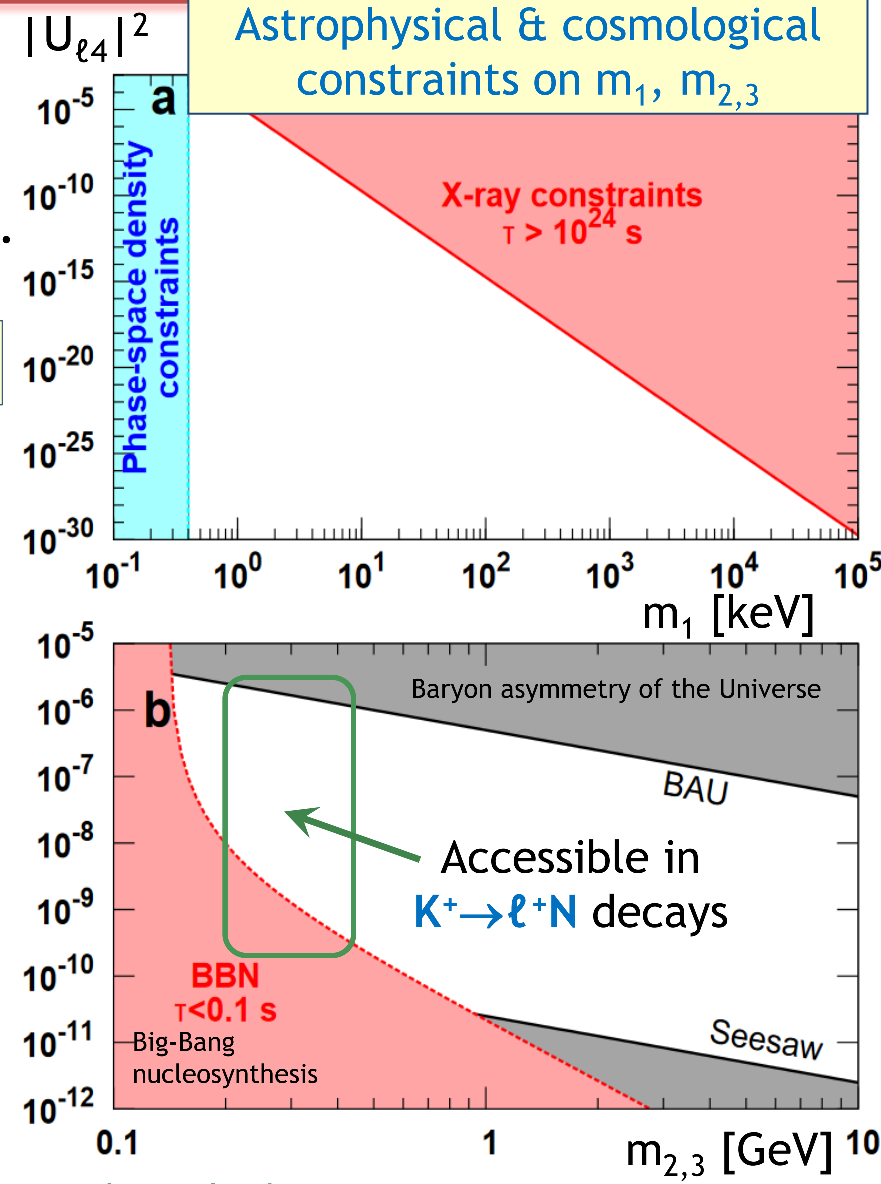
Heavy neutral leptons in νMSM

Neutrino minimal SM (νMSM) =
SM + 3 right-handed neutral heavy leptons.
[Asaka et al., PLB631 (2005) 151]
Masses: m_1~10 keV [DM candidate]; $m_{2,3}$~1 GeV.
HNLs observable via **production** and **decay**.

$$\Gamma(K^+\to\ell^+N) = \Gamma(K^+\to\ell^+\nu)\,\rho_\ell(m_N)\,|U_{\ell4}|^2$$



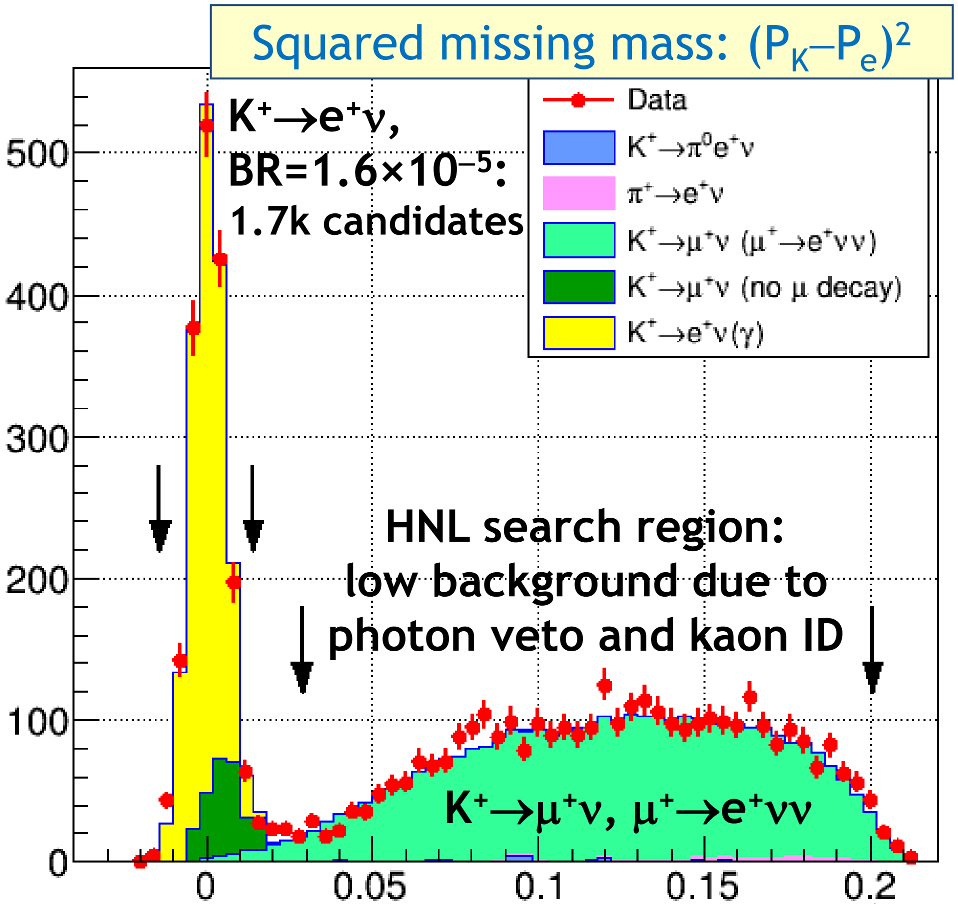
Astrophysical & cosmological constraints on m_1, $m_{2,3}$

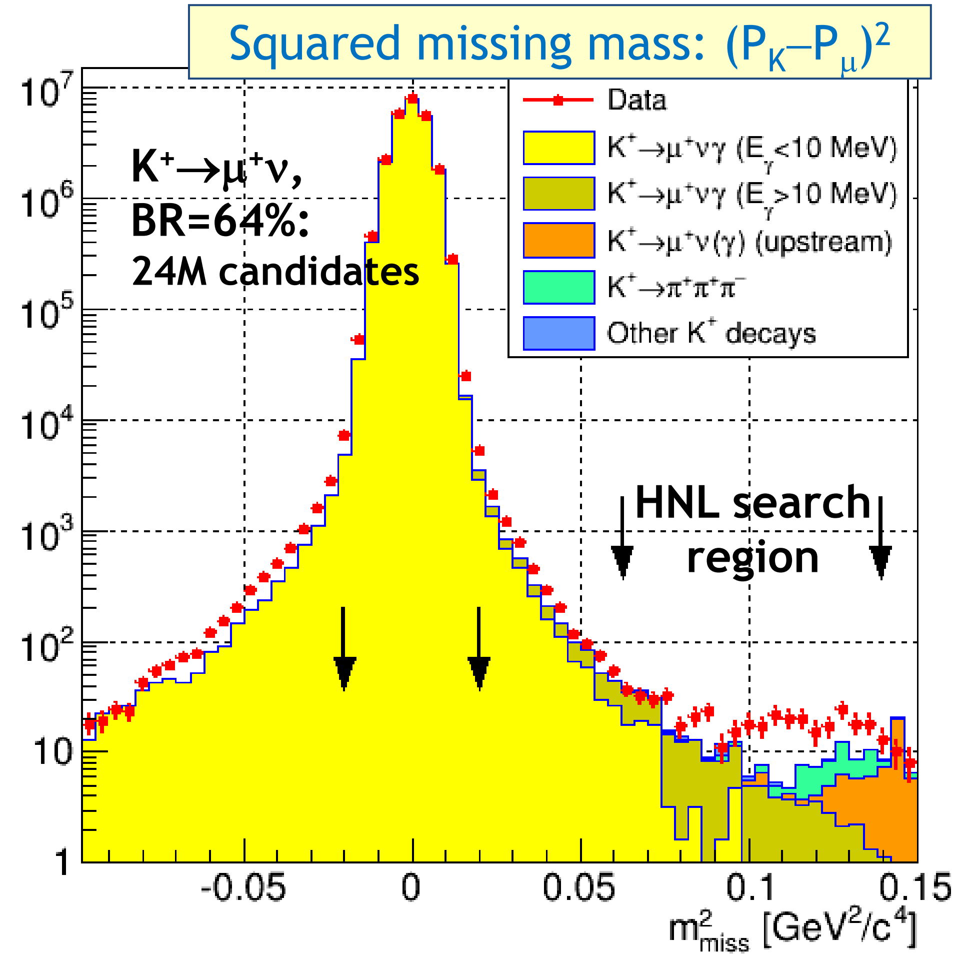


Shaposhnikov, JHEP 0808 (2008) 008
Boyarsky et al., Ann.Rev.Nucl.Part.Sci.59 (2009) 191

$K^+ \to \ell^+ N$ data samples

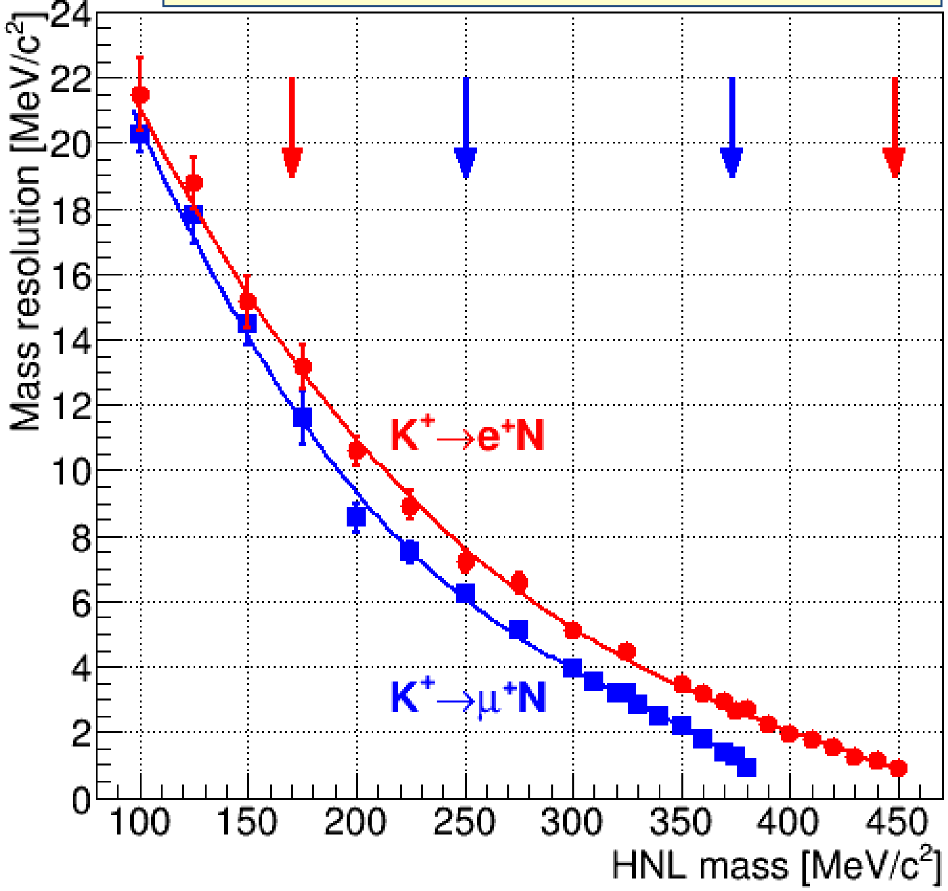
- Minimum bias data (**1%** intensity); **12k** SPS spills (=**5** days) in **2015**.
- Numbers of **K^+** decays in fiducial volume:
  $N_K=(3.01\pm0.11)\times10^8$ in positron case; **$N_K=(1.06\pm0.12)\times10^8$** in muon case.
- Beam tracker not available: beam average kaon momentum is used.
- HNL production signal: **a spike above continuous missing mass spectrum**.



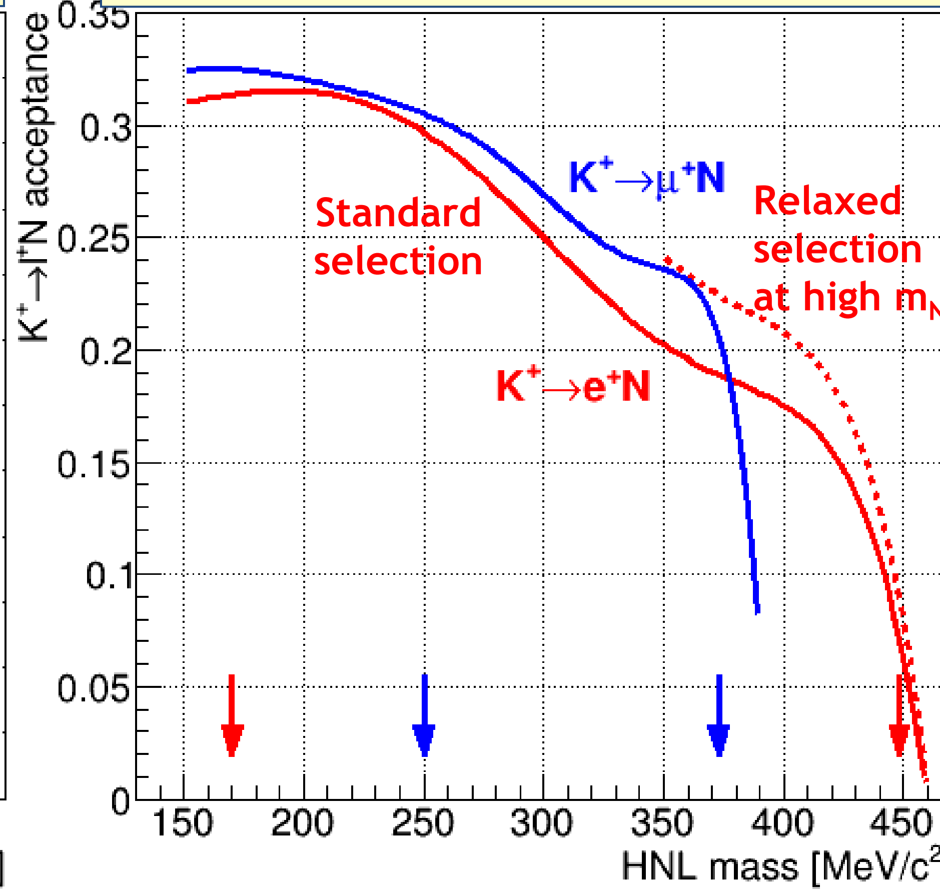


$K^+ \to \ell^+ N$: resolution & acceptance

HNL mass resolution σ_m vs mass



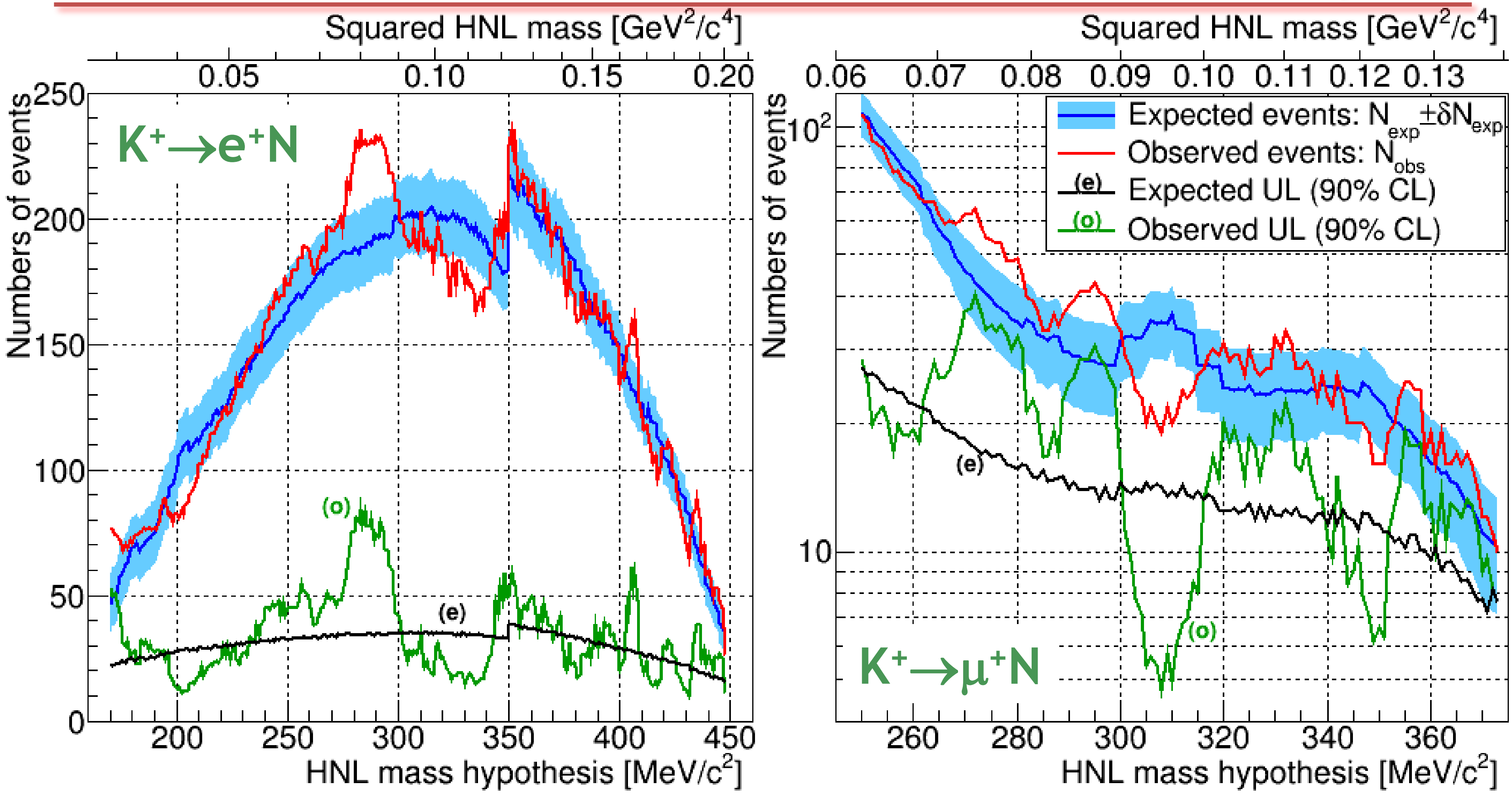
Signal selection acceptance vs mass



- Selection for each HNL mass hypothesis (m_{HNL}) includes the "mass window" condition: $|m - m_{HNL}| < 1.5\sigma_m$: background is proportional to mass resolution.
- Also, resolution is crucial to resolve possible HNL mass splitting.

[Baryogenesis: 2 quasi-degenerate mass states; Canetti et al., PRD87(2013)093006]

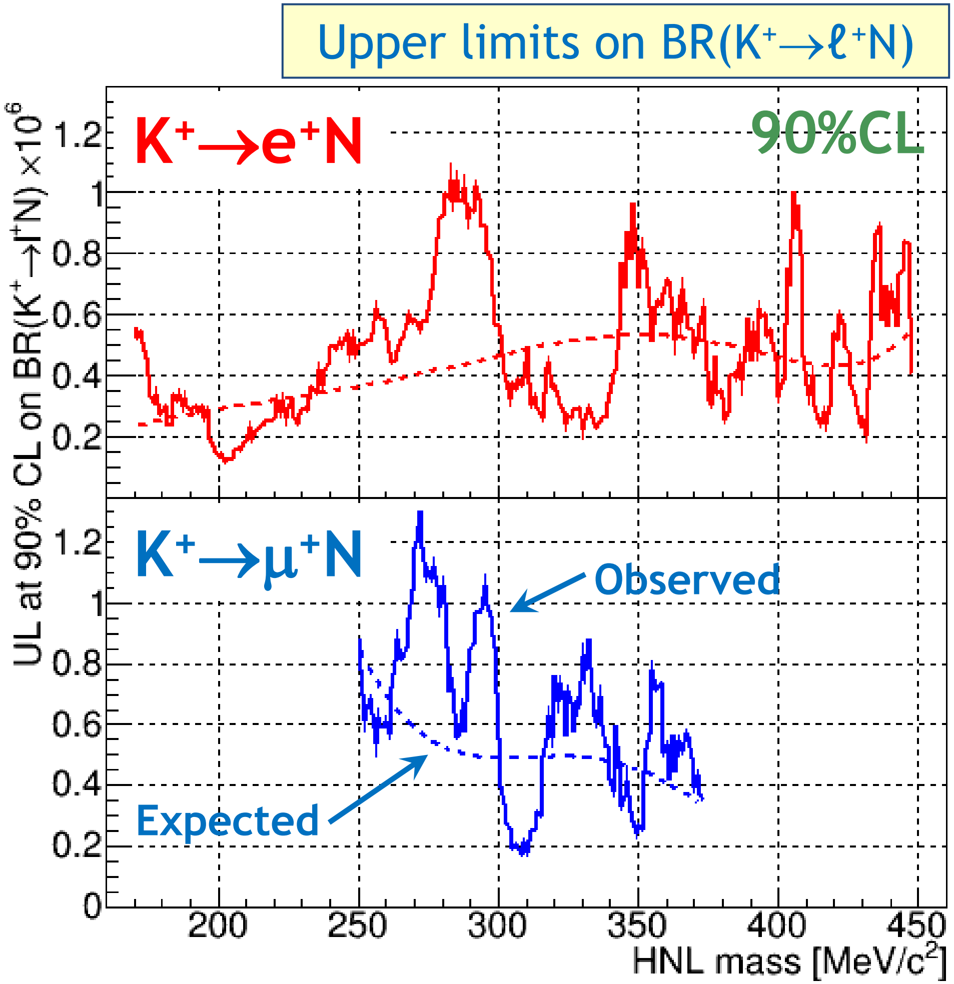
Statistical analysis

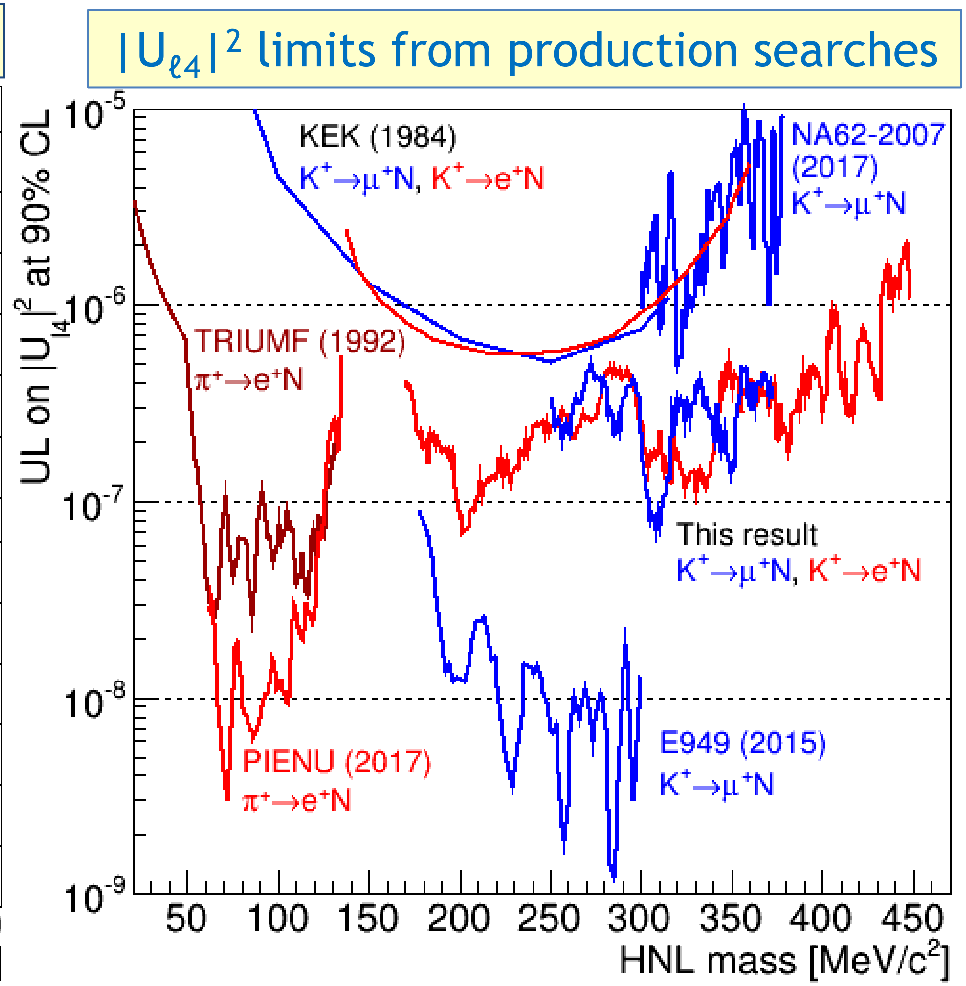


- ❖ Expected background (and stat.error) estimated from fits to the sidebands; numbers of observed and expected events converted into limits for the signal.
- ❖ Background simulations used to certify the absence of peaking structures.
- ❖ Full MC background estimate would allow **searches for $K^+ \to \ell^+\nu\nu\nu$, $K^+ \to \ell^+\nu X$**.

HNL production search: results

NA62 collaboration, Phys. Lett. B778 (2018) 137





- Local signal significance never exceeds **2.2σ**: **no HNL signal** is observed.
- Reached **10^{-6}–10^{-7}** limits for **$|U_{\ell 4}|^2$** in the **170–448 MeV/c^2** mass range.

HNLs: prospects with full dataset

Data sample 2016–18 in comparison to data sample 2015:

- Beam tracker (GTK) in operation:
  - ✓ a factor ~2 improved HNL mass resolution σ_m, therefore lower background and broader mass range accessible;
  - ✓ a factor ~3 lower background in the $K^+ \to e^+ N$ mode ($K^+ \to \mu^+ \nu$, $\mu^+ \to e^+ \nu\nu$: muon decays in flight rejected geometrically);
  - ✓ lower background from upstream decays in the $K^+ \to \mu^+ N$ mode.
- Much larger datasets:
  - ✓ In the $K^+ \to e^+ N$ mode, the main $K^+ \to \pi^+ \nu\nu$ trigger is used (with reduced signal acceptance: max calorimetric energy = 30 GeV): expect at $O(10^6)$ $K^+ \to e^+ \nu$ events, i.e. a factor ~1000 improvement.
  - ✓ In the $K^+ \to \mu^+ N$ mode, downscaled control trigger (D=400): expect $O(10^9)$ $K^+ \to \mu^+ \nu$ events, i.e. a factor ~100 improvement.

Expected sensitivities to $|U_{\ell 4}|^2$ with 2016–18 data:

better than 10^{-8} for both $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

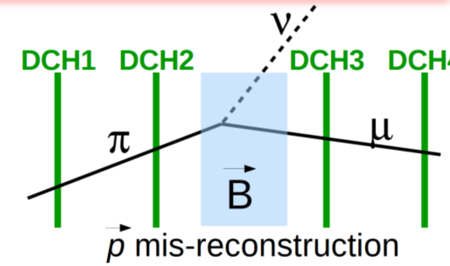
Large data sets already collected; analysis is in progress

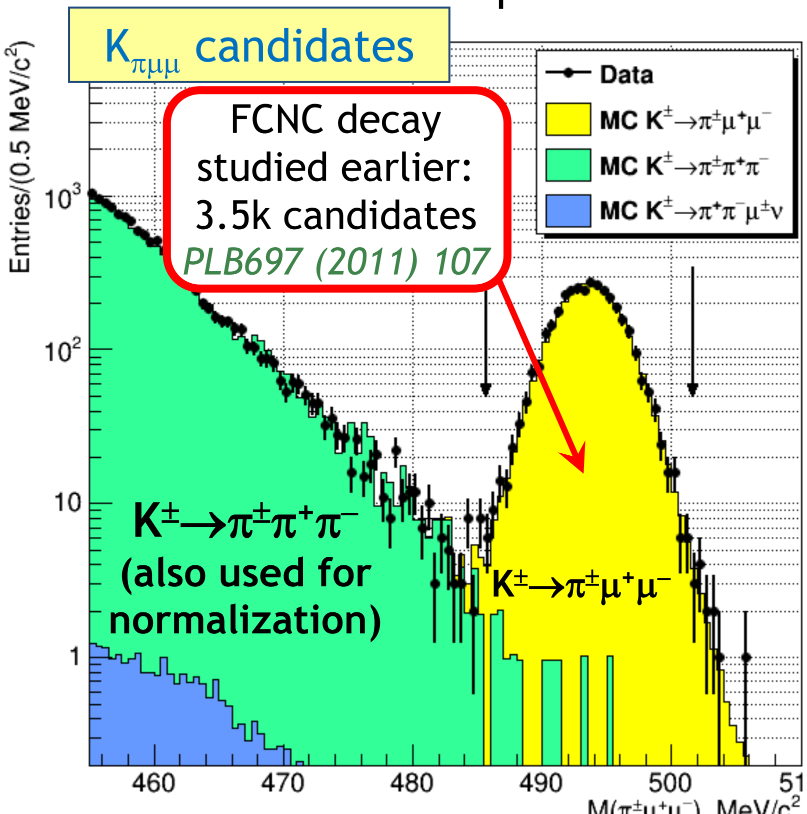
Searches lepton flavour and lepton number violation

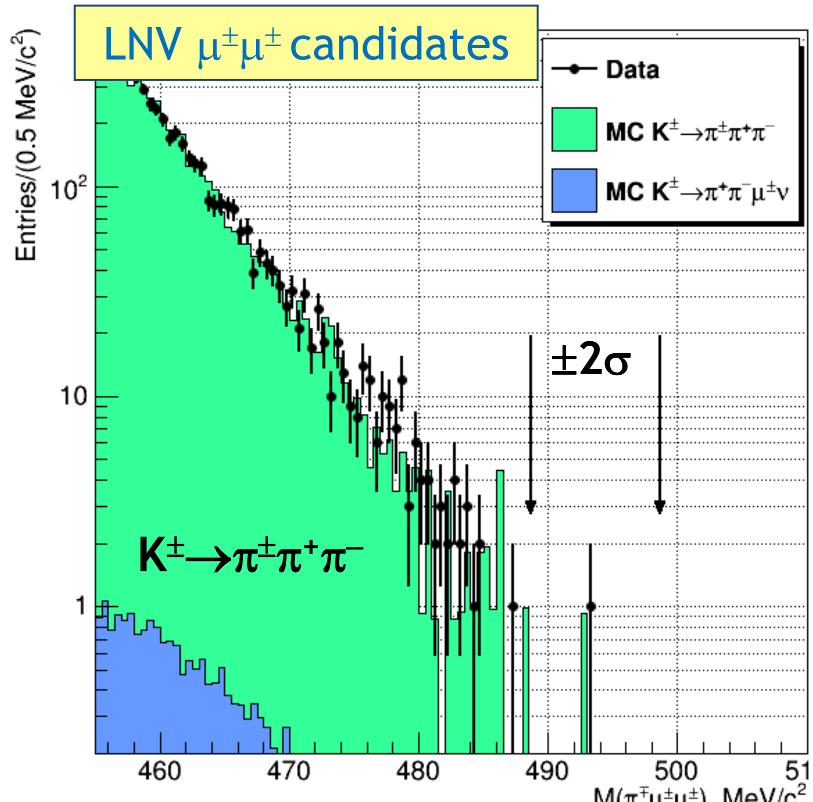
(work in progress: status report)

Search for $K^\pm \to \pi^\mp \mu^\pm \mu^\pm$ at NA48/2

- Data sample 2003–04. $K^\pm \to \pi\mu\mu$ selection: 3-track vertex; no missing momentum; muon ID (LKr, muon detector).
- Blind analysis: selection optimized with dedicated MC samples.
- Main background: $K^\pm \to 3\pi^\pm$ with $\pi^\pm \to \mu^\pm \nu$ decays in flight.
- Muon identification optimized for background reduction.







$N(\mu^\pm\mu^\pm) = 1$

$N_{bkg} = 1.16 \pm 0.87$

⇒ $BR(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 8.6 \times 10^{-11}$ [90% CL]

*[Factor 13 improvement; Phys. Lett. **B796** (2017) 67]*

Forbidden K^+ decays at NA62

Goal: improve over most existing limits (mainly from BNL E865, E777).

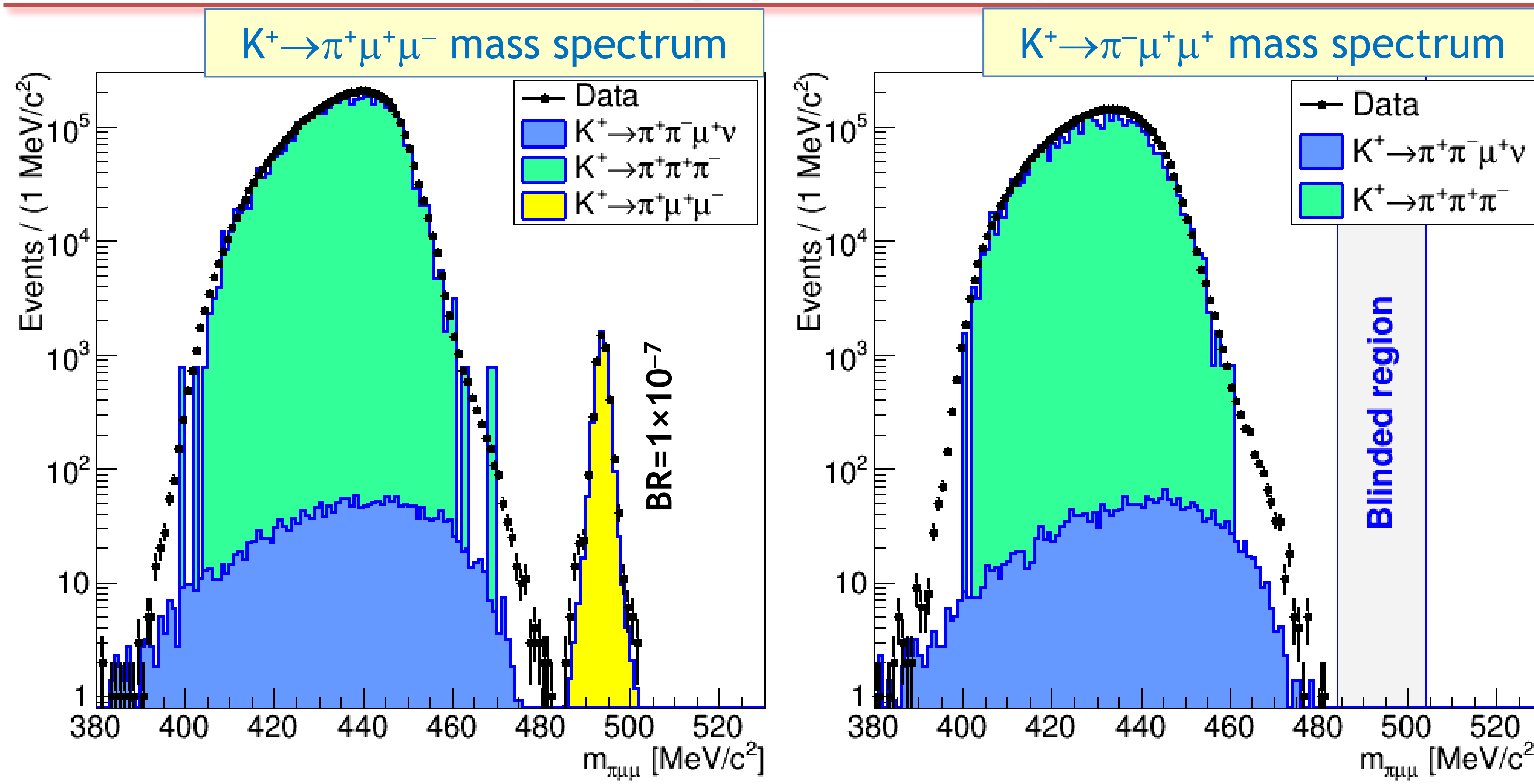
- Search for the LNV decay $K^+\to\pi^-\mu^+\mu^+$ [BR<8.6×10^{-11}, NA48/2@CERN]
- Search for the LNV decay $K^+\to\pi^-e^+e^+$ [BR<6.4×10^{-10}]
- Searches for LNV/LFV decays $K^+\to\pi\mu e$, including $\pi^0\to\mu e$.
  [BR($\pi^-\mu^+e^+$)<5.0×10^{-10}; BR($\pi^+\mu^-e^+$)<5.2×10^{-10}; BR($\pi^+\mu^+e^-$)<1.3×10^{-11}]
  [BR($\pi^0\to\mu^\pm e^\mp$)<3.6×10^{-10}, kTeV@FNAL]
- Searches for $K^+\to\mu^-\nu e^+e^+$ and $K^+\to e^-\nu\mu^+\mu^+$ decays.
  [BR($\mu^-\nu e^+e^+$)<1.9×10^{-8}: Geneva-Saclay, 1976]
- Searches for $\Delta S=\Delta Q$ violating decays $K^+\to\pi^+\pi^+e^-\nu$ and $K^+\to\pi^+\pi^+\mu^-\nu$.
  [BR($\pi^+\pi^+e^-\nu$)<1.3×10^{-8}; BR($\pi^+\pi^+\mu^-\nu$)<3.0×10^{-6}: ~50 years old]

Approximate statistical reach with the 2016–17 data sample:

- Di-muon trigger stream: ~2×10^{12} K^+ decays; SES~10^{-11};
- Decays to μe and ee pairs: ~5×10^{11} K^+ decays; SES~10^{-10};
- Other 3-track decays: ~5×10^{10} K^+ decays; SES~10^{-9}.

NA62 is competitive for most of these decay modes

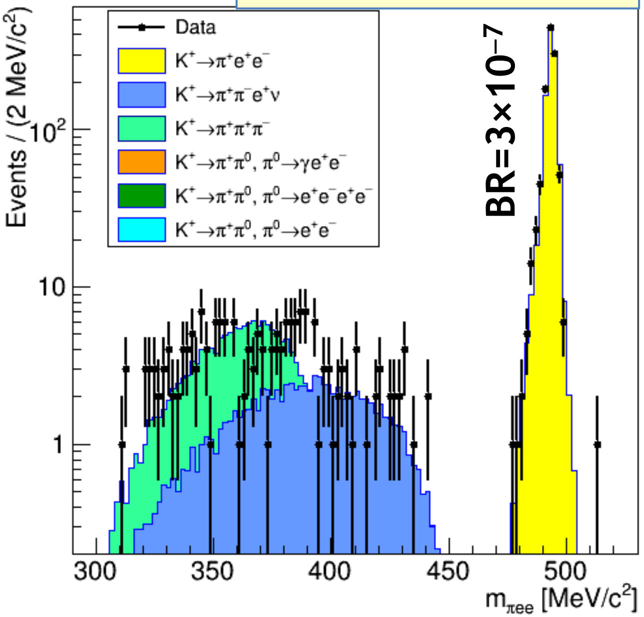
$K^+ \to \pi\mu\mu$ analysis at NA62



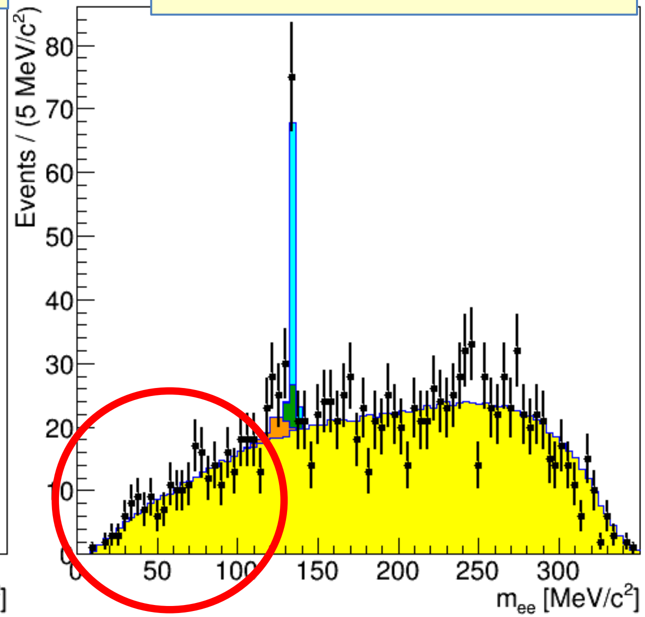
- World's largest $K^+ \to \pi^+\mu^+\mu^-$ sample: **4.6k** candidates in this partial data set; expect **~20k** candidates in total.
- Expect to make a competitive $K^+ \to \pi^+\mu^+\mu^-$ measurement.
- Search for new scalar: $K^+ \to \pi^+ S$, $S \to \mu^+\mu^-$: **SES~10^{-10}**, lifetimes up to **O(1 ns)**.
- Search for $K^+ \to \pi^-\mu^+\mu^+$: background-free, reached **SES~10^{-11}**.

$K^+ \to \pi ee$ analysis at NA62

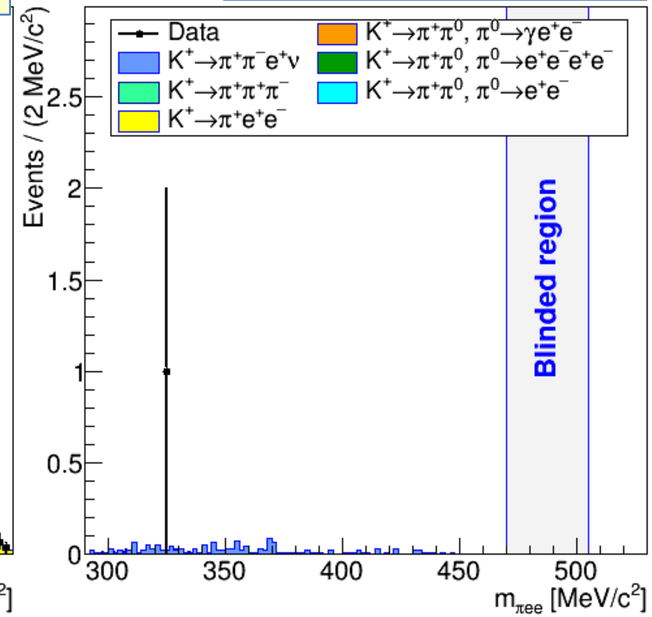
$K^+ \to \pi^+ e^+ e^-$ mass (m_{ee}>140 MeV/c^2)



e^+e^- mass for $K^+ \to \pi^+ e^+ e^-$ candidates



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



- A partial data set: background-free but not world's largest $K^+ \to \pi^+ e^+ e^-$ sample (1.1k events at m_{ee}>140 MeV/c^2).
- **First observation** of $K^+ \to \pi^+ e^+ e^-$ decay in the mass range m_{ee}<140 MeV/c^2.
- Observation of $\pi^0 \to e^+ e^-$ decay with an excellent m_{ee} resolution.
- Search for $K^+ \to \pi^+ X$, $X \to e^+ e^-$, 10<m_X<100 MeV/c^2: SES~10^{-9} for lifetime ≪1 ns.
- Search for $K^+ \to \pi^- e^+ e^+$: background-free, SES~10^{-10}.

Summary

- First NA62 physics run (**2016–18**) in progress until November 2018; a large **K^+** decay data sample collected already.
- Focused on **$K_{\pi\nu\nu}$** measurement (**SES~10^{-12}**). A programme of rare decay measurements, searches for hidden sector particles and LF/LN conservation tests is pursued.
- Analysis of the 2016 **$K_{\pi\nu\nu}$** data sample finished; the method is demonstrated to work. One **$K_{\pi\nu\nu}$** candidate observed, leading to **$BR(K^+\to\pi^+\nu\nu)<11\times10^{-10}$** at **90%** CL **[preliminary]**.
- HNL production search in **$K^+\to\ell^+N$** decays: sub-**10^{-6}** limits on **$|U_{\ell4}|^2$** with **5** days of low-intensity data. **[PLB778 (2018) 137]**
- LF/LN conservation tests in 3-track **K^+** decays: on track to reach **~10^{-11}** sensitivities, improving over the world limits.

Spares

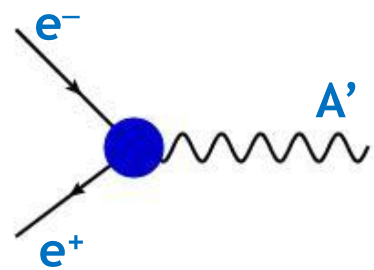
The dark photon

B.Holdom, Phys. Lett. B166 (1986) 196

The simplest hidden sector model introduces an extra **U(1)** gauge symmetry with its gauge boson: the dark photon (**A'**).

QED-like interaction with SM fermions:

$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$



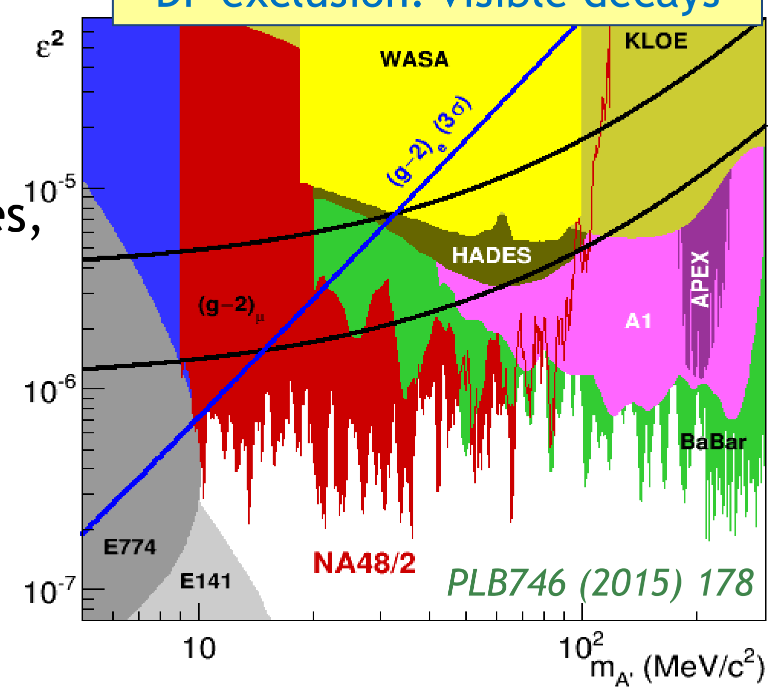
(not all SM fermions need to be charged under this new symmetry)

Considering SM decay modes only, DP lifetime below the di-muon threshold is

$$c\tau_{A'} \approx 0.8\ \mu\mathrm{m} \times \left(\frac{10^{-6}}{\varepsilon^2}\right) \times \left(\frac{100\ \mathrm{MeV}}{m_{A'}}\right)$$

- Multiple limits assuming decays into SM particles, including ($K^\pm \to \pi^\pm \pi^0$, $\pi^0 \to \gamma A'$, $A' \to e^+e^-$) from NA48/2 *[Phys.Lett. B746 (2015) 178]*
- DP decaying into SM fermions ruled out as explanation for the muon **g–2** anomaly.
- At low ε^2, limits from beam dump experiments.
- The invisible DP is much less constrained.

DP exclusion: visible decays



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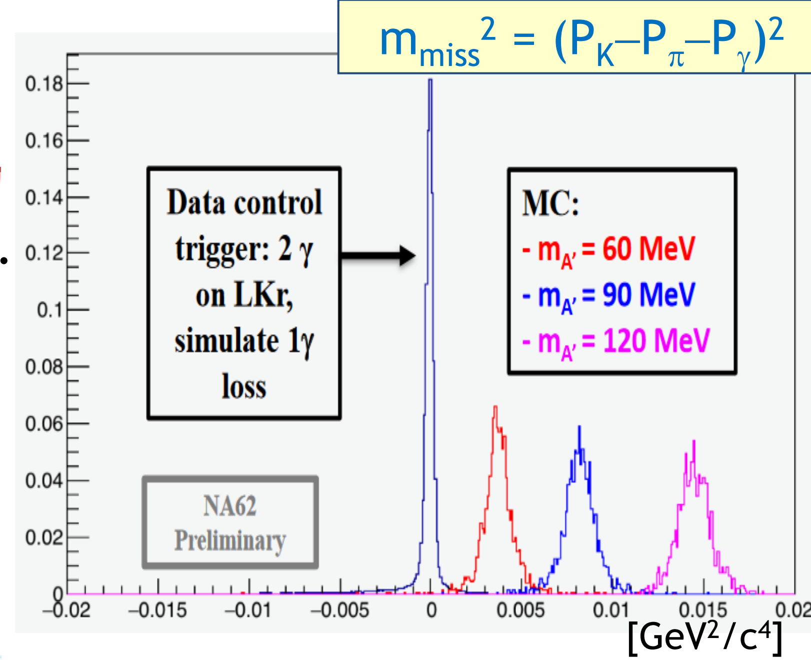
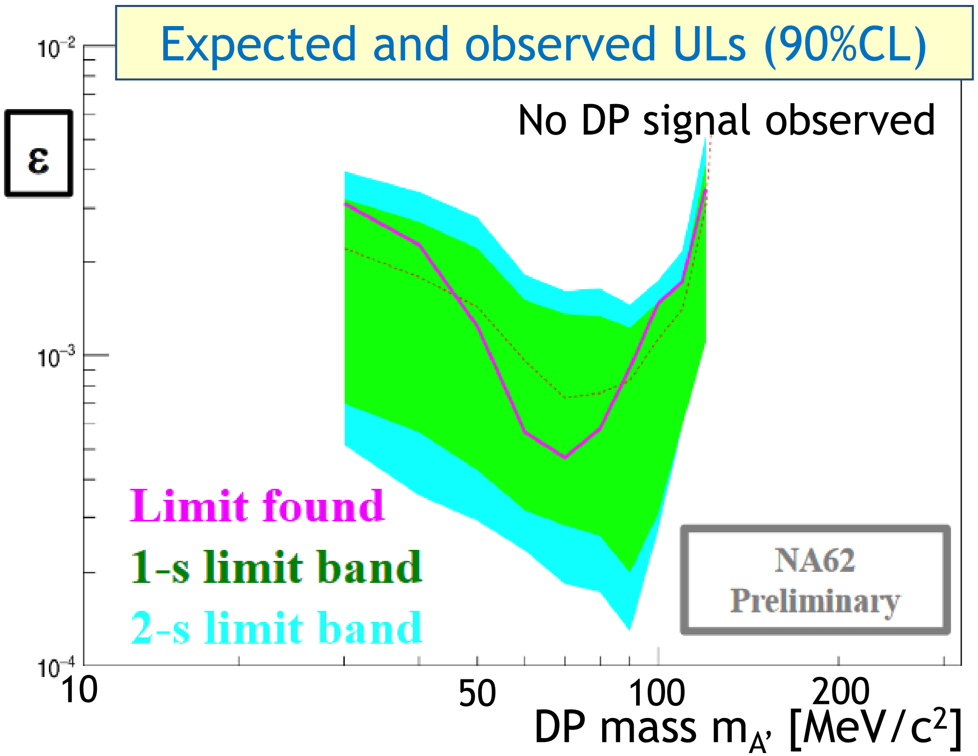
DP search at NA62

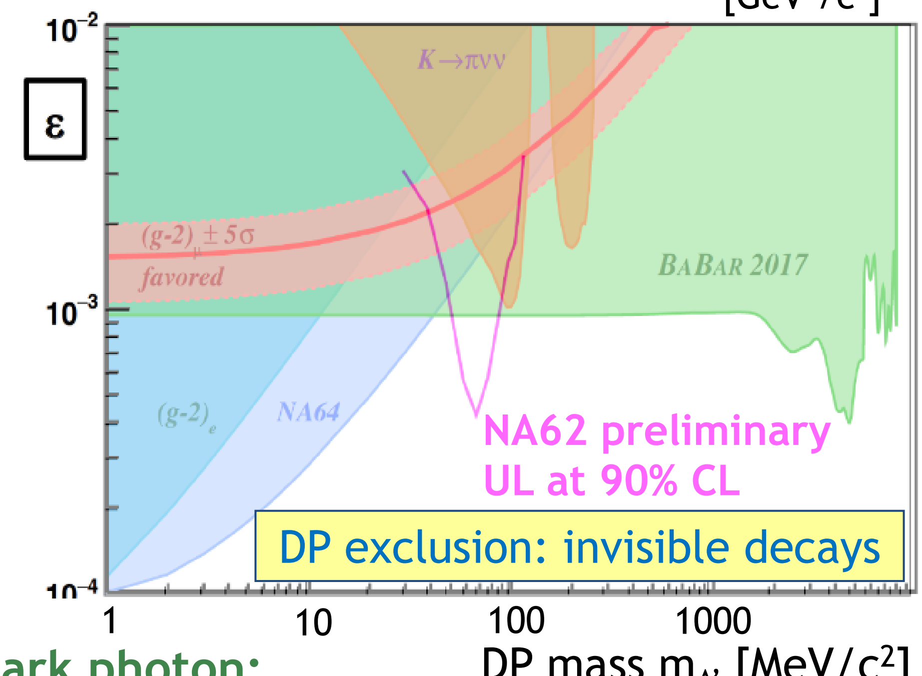
Decay chain: $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma A'$, $A' \to$ invisible.

Data: 4% of 2016 sample (~10^{10} K^+ decays).

Excellent photon veto: low background.







Further NA62 prospects for the invisible dark photon:

improved sensitivity to $K^+ \to \pi^+ A'$ over BNL E949, by-product of $K^+ \to \pi^+\nu\nu$ analysis.