# NA62 status and prospects

**Evgueni Goudzovski**

*(University of Birmingham, eg@hep.ph.bham.ac.uk)*

on behalf of the NA62UK collaboration

## Outline:

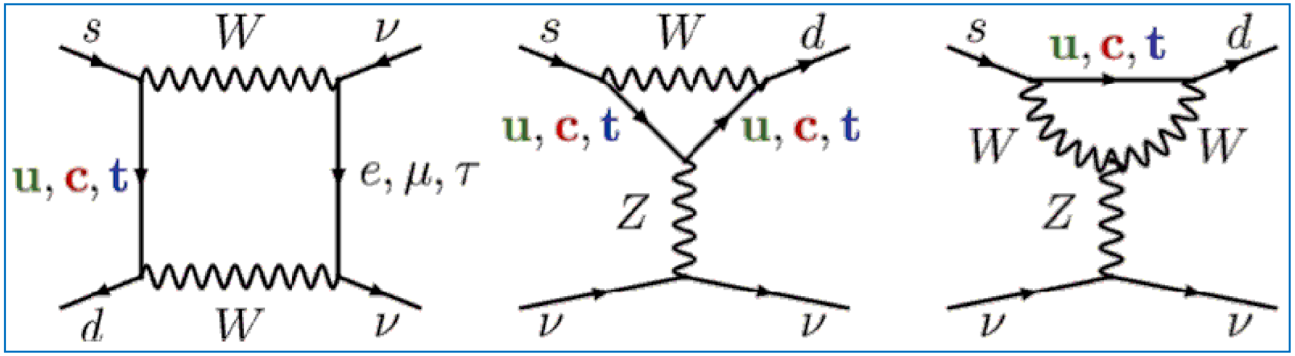
1) Physics at kaon experiments: $K\to\pi\nu\bar{\nu}$ decays and beyond
2) NA62 status, performance, UK involvement.
3) Prospects for CERN kaon experiments beyond 2018.
4) Overview of the recent results.
5) Summary

*PPAP community meeting*

*Birmingham • 26 July 2016*

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

## SM: box and penguin diagrams




Ultra-rare decays with the highest CKM suppression:

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

- Hadronic matrix element related to a measured quantity ($K^+ \to \pi^0 e^+ \nu$).
- SM precision surpasses any other FCNC process involving quarks.
- Measurement of $|V_{td}|$ complementary to those from $B$–$\bar{B}$ mixing or $B^0 \to \rho\gamma$.

SM branching ratios

*Buras et al., JHEP 1511 (2015) 033*

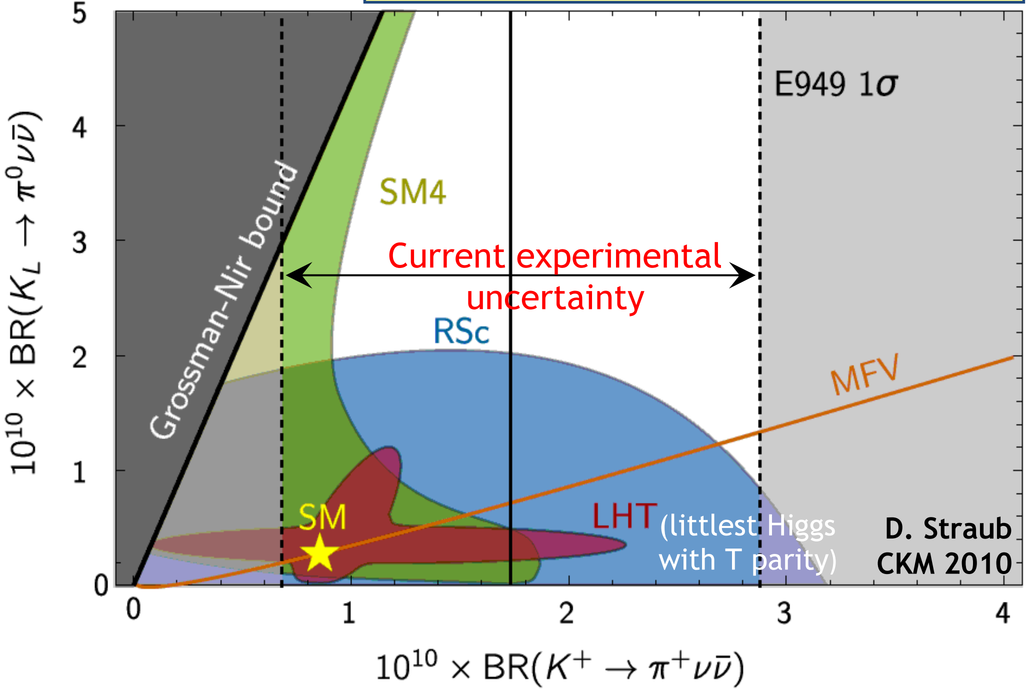
| Mode | $BR_{SM} \times 10^{11}$ |
|---|---|
| $K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$ | $9.11 \pm 0.72$ |
| $K_L \to \pi^0 \nu\bar{\nu}$ | $3.00 \pm 0.31$ |

The uncertainties are largely parametric (CKM)

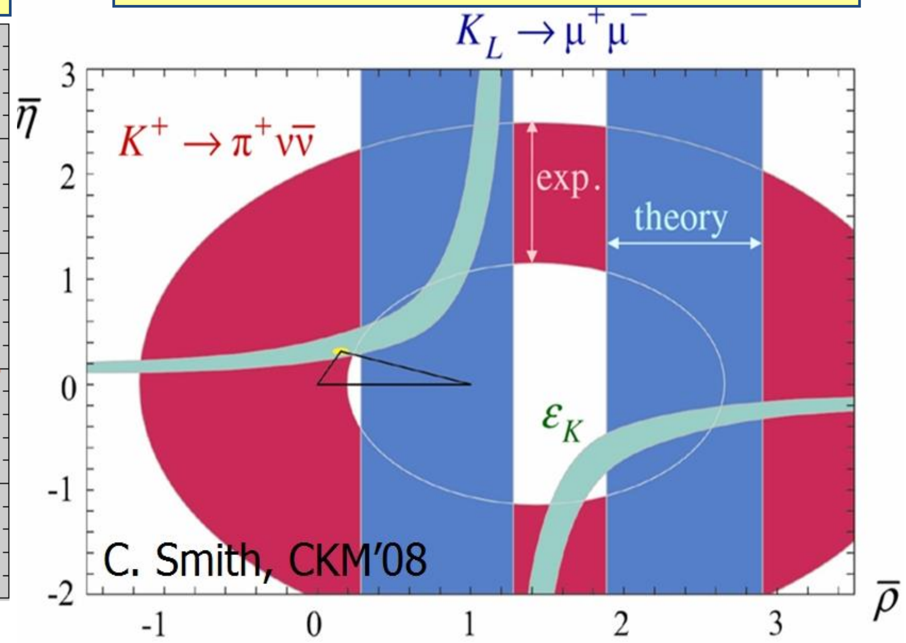
Theoretically clean, almost unexplored, sensitive to new physics.

# K→πνν̄: experiment vs theory

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




CKM unitarity triangle with kaons




NA62 aim: collect O(100) SM $K^+ \to \pi^+ \nu\bar{\nu}$ decays with <20% background in 3 years of data taking using a novel decay-in-flight technique.

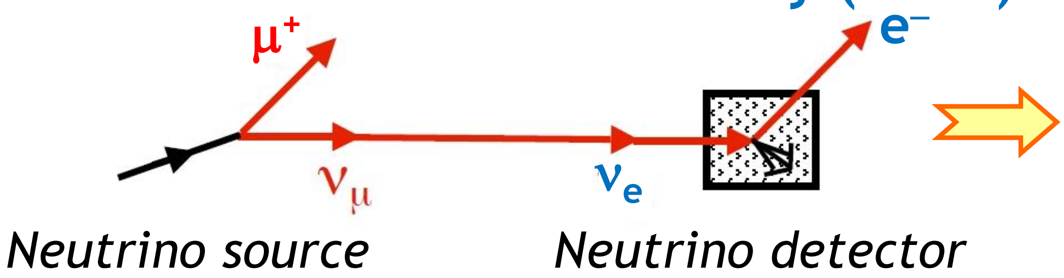
**Signature:** high momentum $K^+$ (75GeV/c) → low momentum $\pi^+$ (15–35 GeV/c).

**Advantages:** max detected $K^+$ decays/proton ($p_K/p_0 \approx 0.2$);
efficient photon veto (>40 GeV missing energy)

Un-separated beam (6% kaons) → higher rates, additional background sources.

# Broader programme (1)

## Neutrino oscillations discovery (1998)




*First non-SM phenomenon:*

*1) Lepton Flavour Violation;*
*2) non-zero neutrino mass.*

**New physics** scenarios involving **LFV**:

- ✓ Neutrino is a **Majorana fermion** (identical to antineutrino)
- ✓ Heavy (possibly sterile) neutrino states
- ✓ **Supersymmetry** with R-parity violation or RH neutrinos

Astrophysical consequences:

- ✓ Dark matter, nucleosynthesis, Supernova evolution, …

❖ Search for forbidden states with lepton pair (**ee**, **μμ**, **μe**):

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

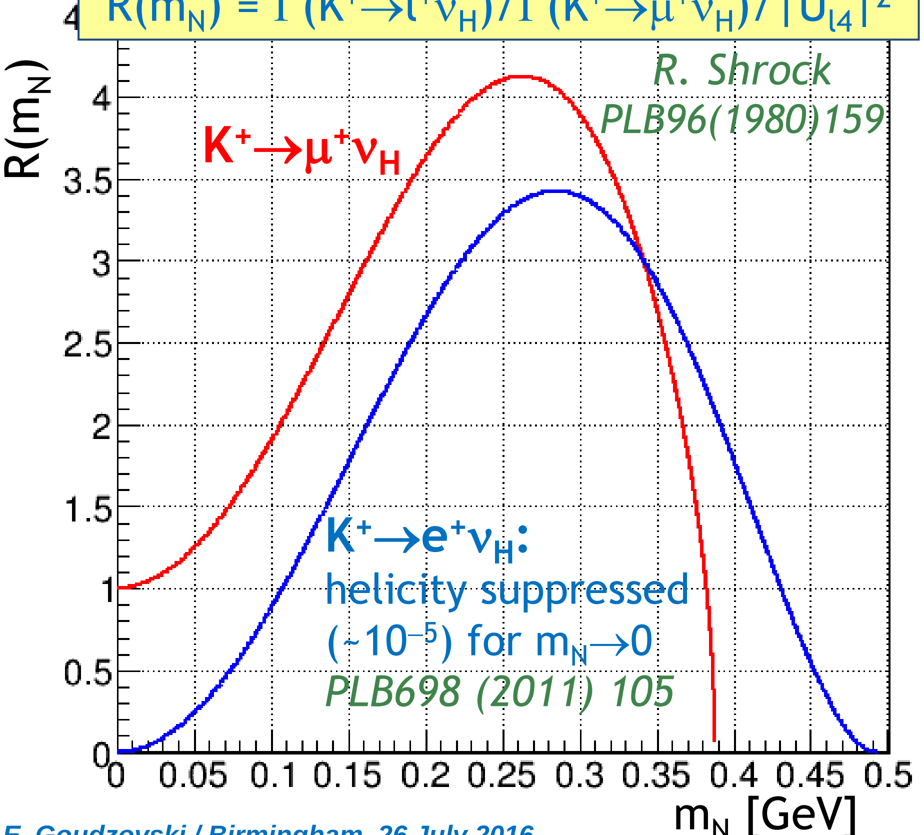
$$K^+ \to \mu^-\nu e^+e^+$$
$$K^+ \to e^-\nu\mu^+\mu^+$$

$$K^+ \to \pi^+\pi^0,\quad \pi^0 \to \mu^+e^-$$
$$K^+ \to \pi^+\pi^0,\quad \pi^0 \to \mu^-e^+$$

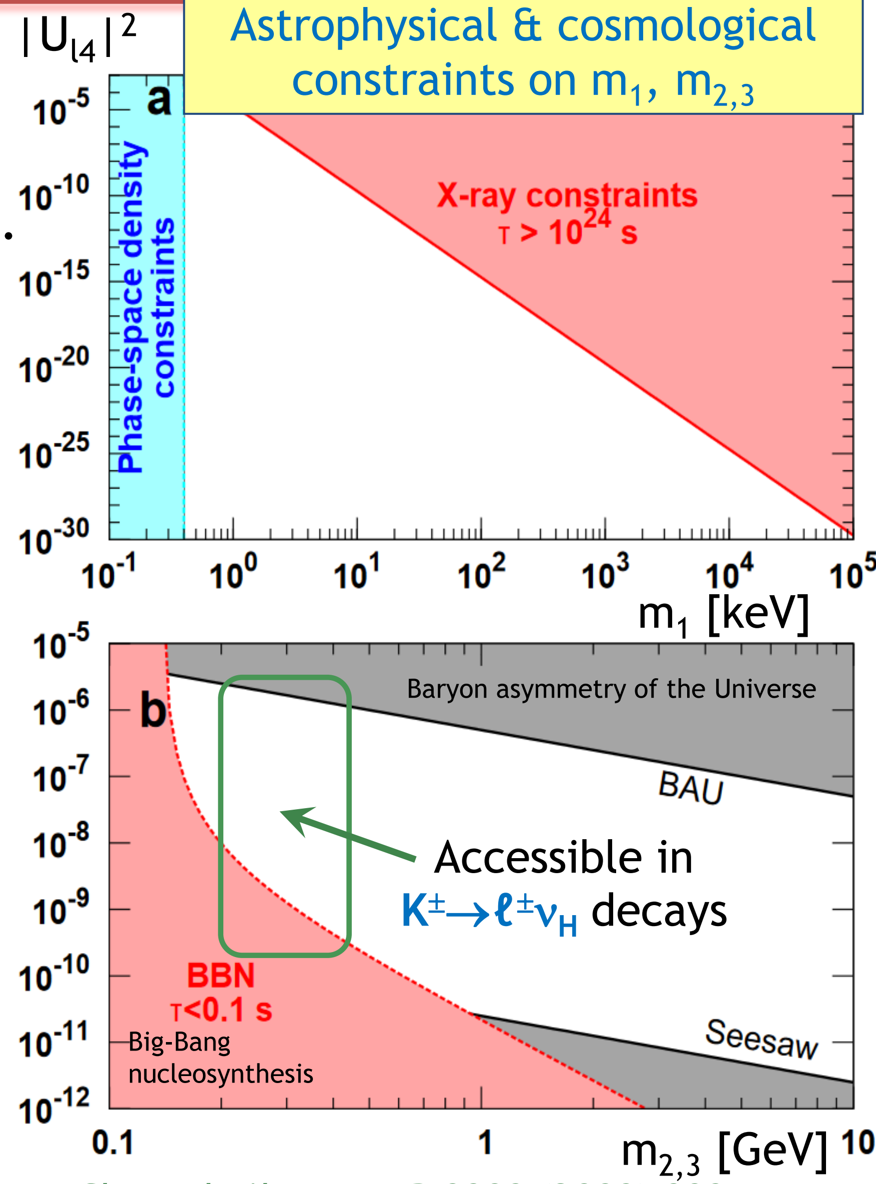
# Broader programme (2)

Neutrino minimal SM (**νMSM**) =
**SM** + 3 right-handed neutral heavy leptons.
*[Asaka et al., PLB 631 (2005) 151]*
Masses: **$m_1$~10 keV** [DM candidate]; **$m_{2,3}$~1 GeV**.
HNLs observable via **production** and **decay**.

HNL production, kinematic factor:
$R(m_N) = \Gamma(K^+\to l^+\nu_H)/\Gamma(K^+\to \mu^+\nu_H)/|U_{l4}|^2$



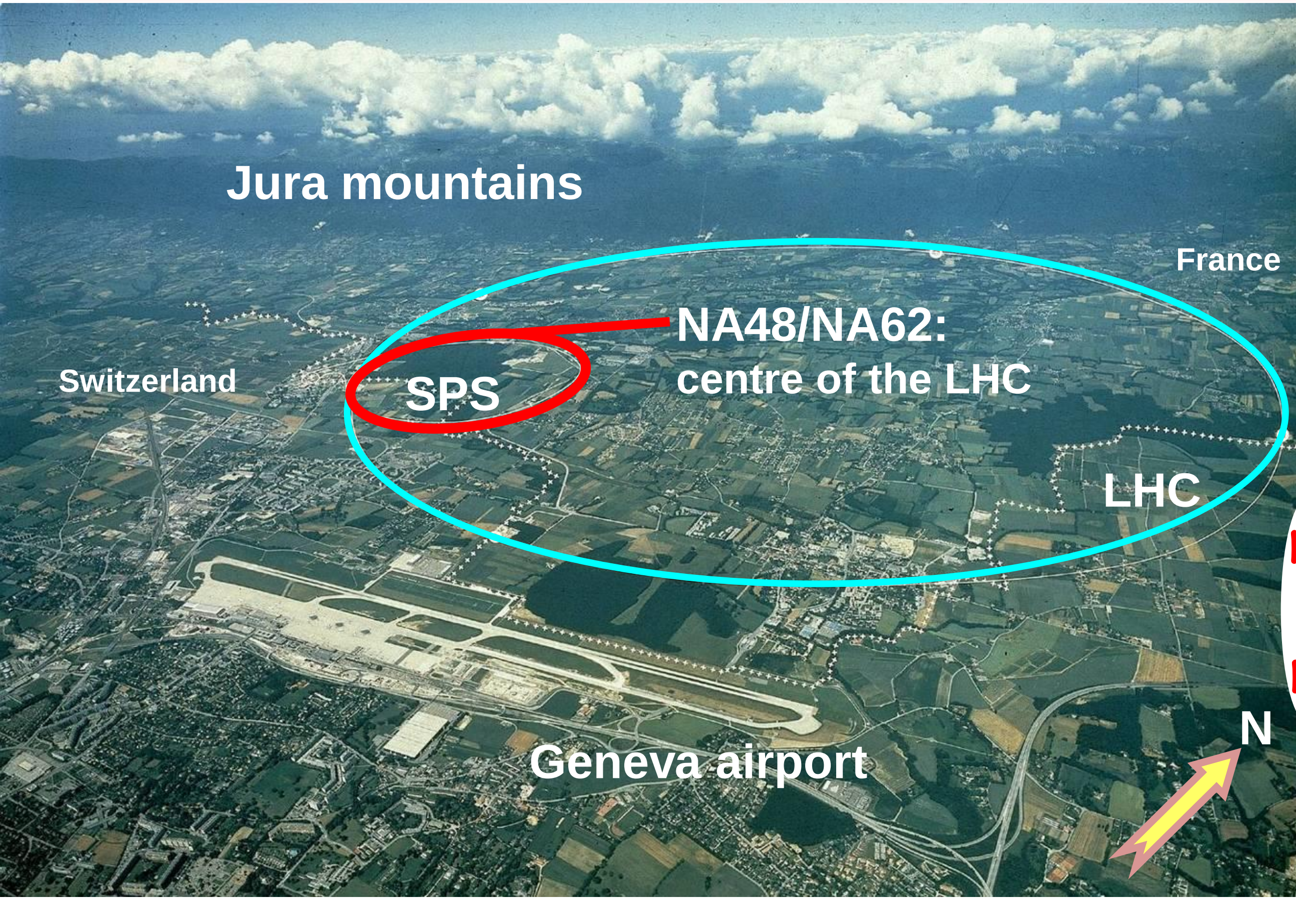

Astrophysical & cosmological constraints on $m_1$, $m_{2,3}$




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

# NA62 status and UK involvement

# CERN NA48/NA62 experiments




Kaon decay in flight experiments.

**NA62**: currently ~200 participants, ~30 institutions.

**NA62UK**: Birmingham, Bristol, Glasgow, Liverpool (12% of participants).

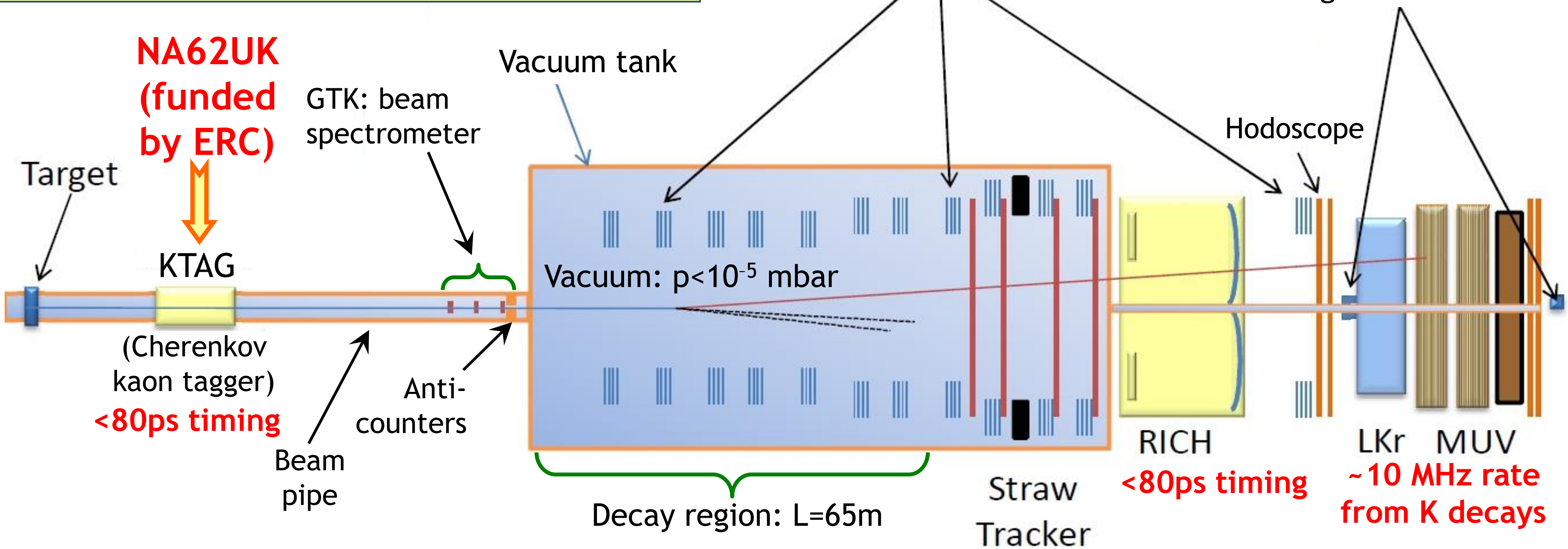
**Earlier: NA31**

| | | | |
|---|---|---|---|
| NA48 (discovery of direct CPV) | 1997 | $\varepsilon'/\varepsilon$: $K_L+K_S$ | |
| | 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 ($R_K$ phase) | 2007 | $K^\pm_{e2}/K^\pm_{\mu2}$ | tests |
| | 2008 | $K^\pm_{e2}/K^\pm_{\mu2}$ | tests |
| NA62 | 2014 | pilot run | |
| | 2015– | data taking | |

# The NA62 experiment

Un-separated hadron ($p/\pi^+/K^+$) beam:
400GeV SPS protons → 75GeV (±1%) kaons;
800MHz → 45MHz kaons →
5MHz decays in fiducial volume

Total length: ~270m




- Expected single event sensitivities (**SES**): **~$10^{-12}$** (**~$10^{-11}$**) for $K^\pm$ ($\pi^0$) decays.
- Kinematic rejection factors (limited by beam pileup and tails of MCS): **$5\times10^3$** for $K^+\to\pi^+\pi^0$, **$1.5\times10^4$** for $K\to\mu^+\nu$.
- Hermetic photon veto: **~$10^8$** suppression of $\pi^0\to\gamma\gamma$.
- Particle ID (RICH+LKr+MUV): **~$10^7$** muon suppression.

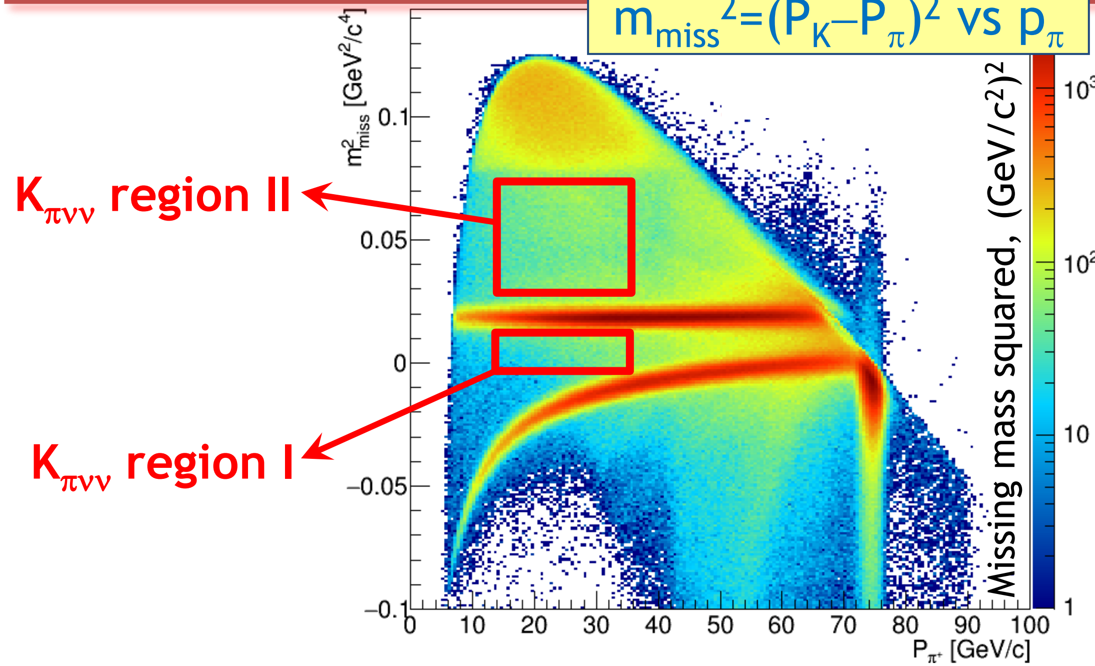
# NA62 status

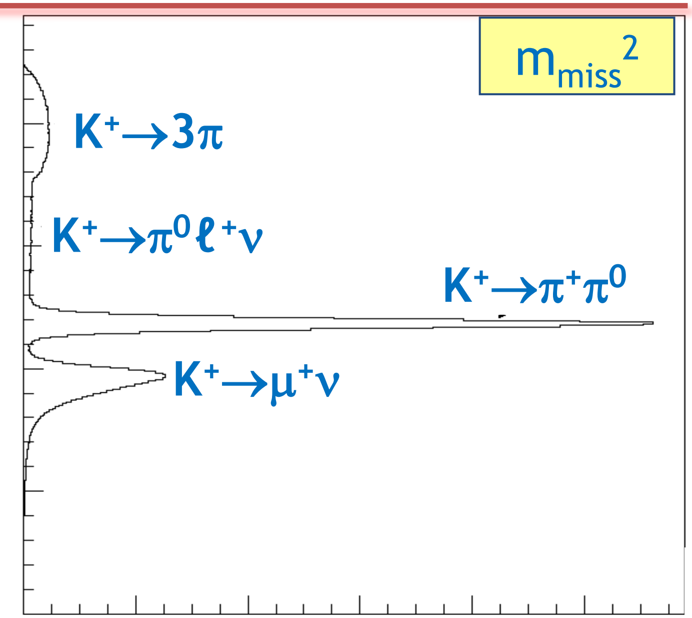
**Minimum bias** (~1% intensity) and $K_{\pi\nu\nu}$ **test** runs taken in **2015**.
Most systems commissioned and meet the design requirements.

Running at **20%** intensity now, planning **~50%** intensity later in **2016**
(max intensity is currently limited by SPS capabilities)

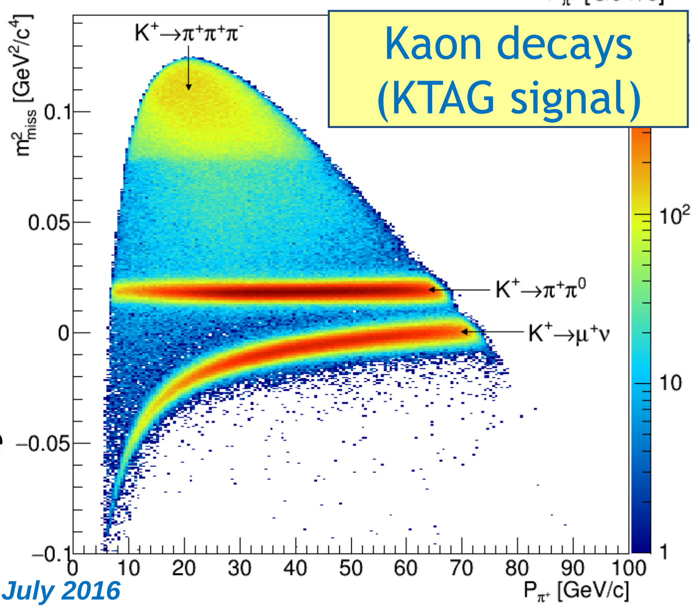
Expect to reach a few SM $K_{\pi\nu\nu}$ events sensitivity by the end of **2016**

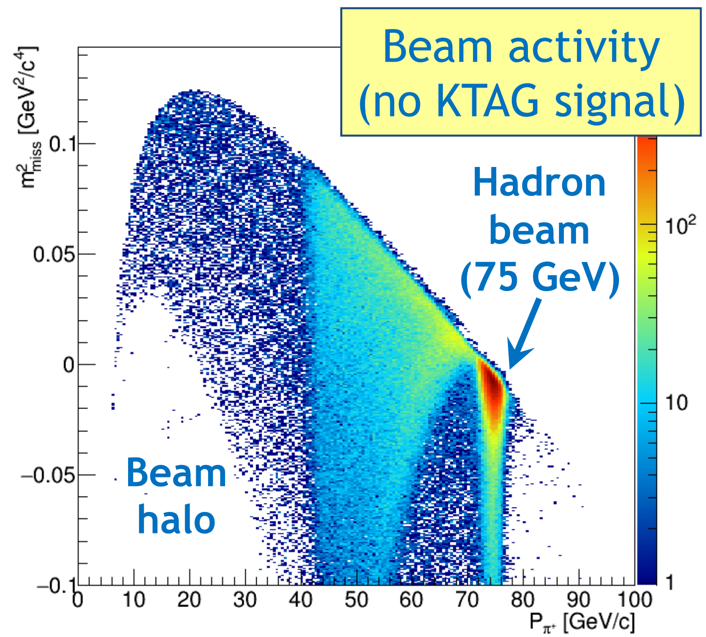
# NA62 performance in 2015



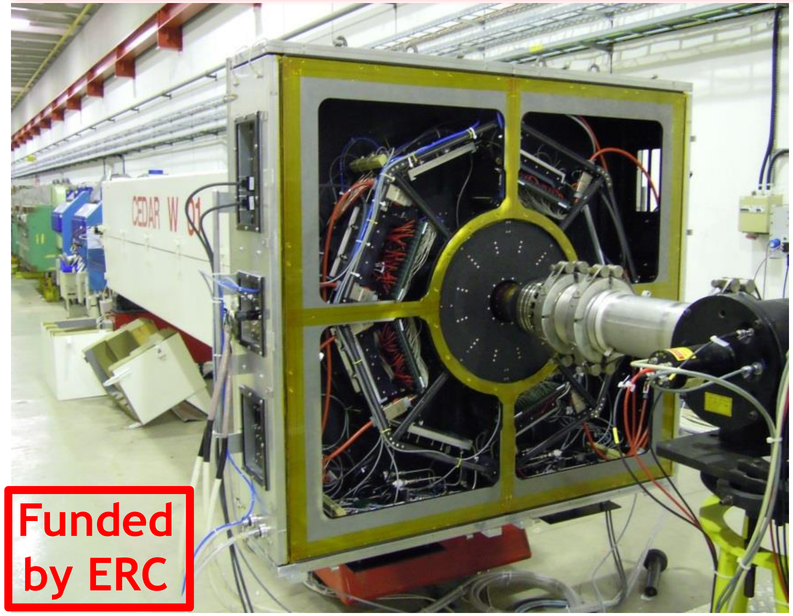

- ❖ Gigatracker information not used in this study.
- ❖ Photon veto criteria not applied on purpose.
- ❖ Kinematic & time resolutions are close to the design.

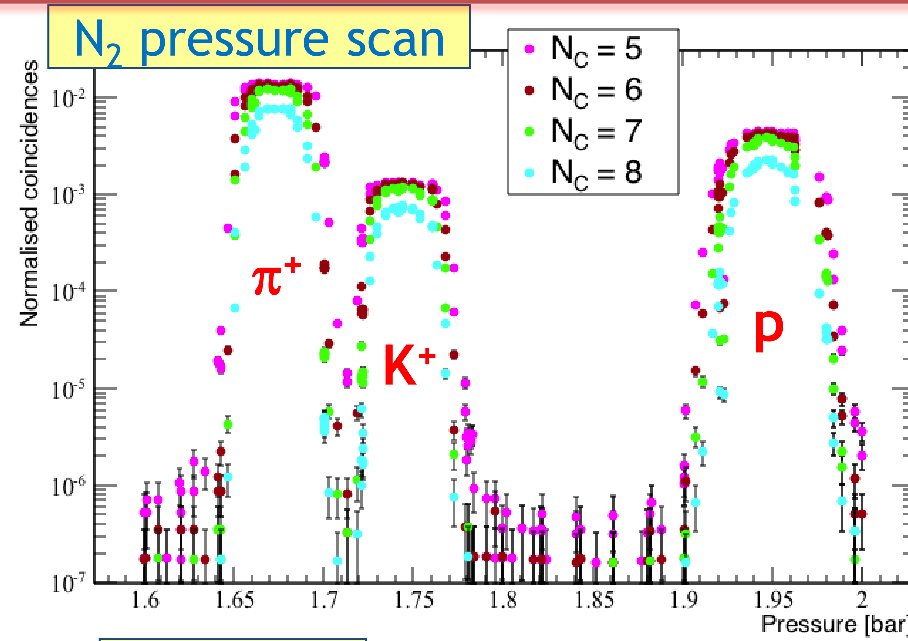


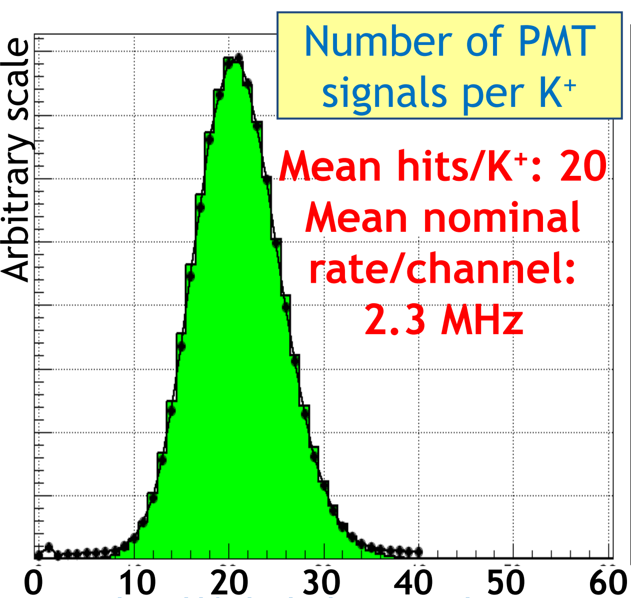



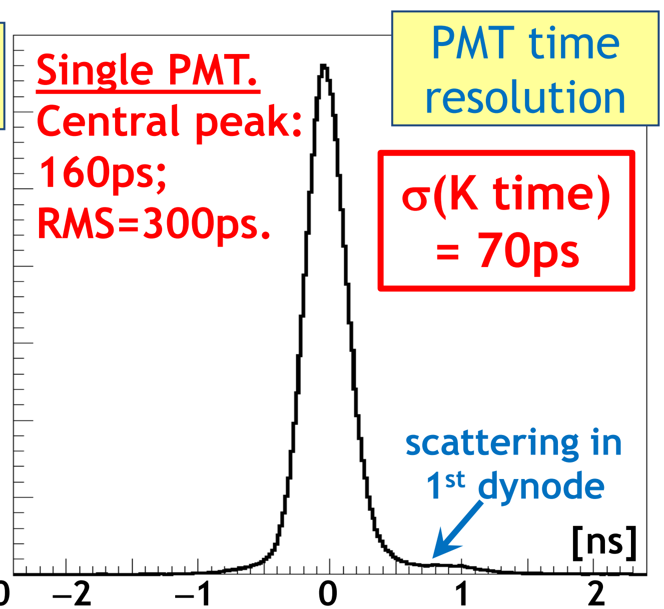
# KTAG operation in 2015

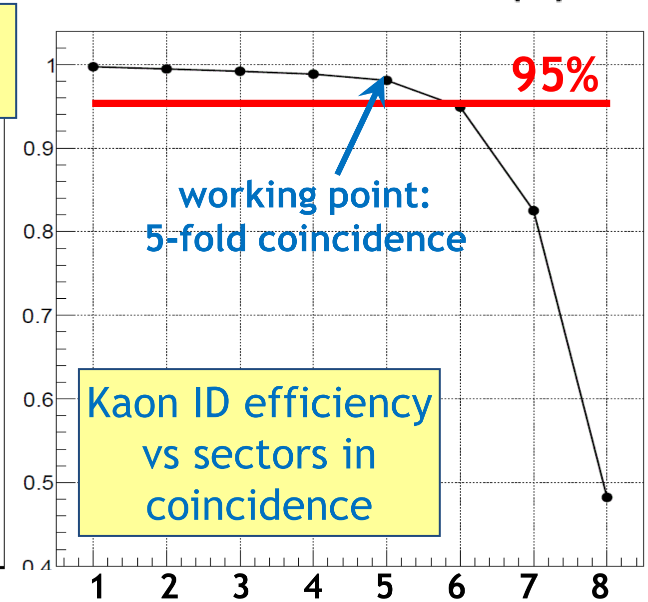
## The first NA62 detector to be commissioned; performance exceeds specifications



# NA62: UK contributions

## Hardware and trigger:

- full responsibility for the KTAG subdetector;
- full responsibility for the Run Control system;
- development and operation of L0 muon+hodoscope★+RICH★ trigger;
- development and operation of the high-level software trigger;
- GRID infrastructure, software, data processing, DCS system.

## Leadership in the physics exploitation:

- Flagship analysis: $K^+ \to \pi^+ \nu\nu$ ;
- Detector performance & rare decay studies with 2015+2016 data.
- Analyses of "old" NA48/NA62 data.

## Major leadership roles:

- Physics coordination;★
- Software coordination;
- 2007 data analysis coordination;
- high-level trigger coordination;★
- Run coordinators: 4 out of 15 (in 2016);★
- Editorial Board membership: 3 out of 10;
- Conference Committee chair.

★ = new responsibilities

# Run 2 and Run 3 programme

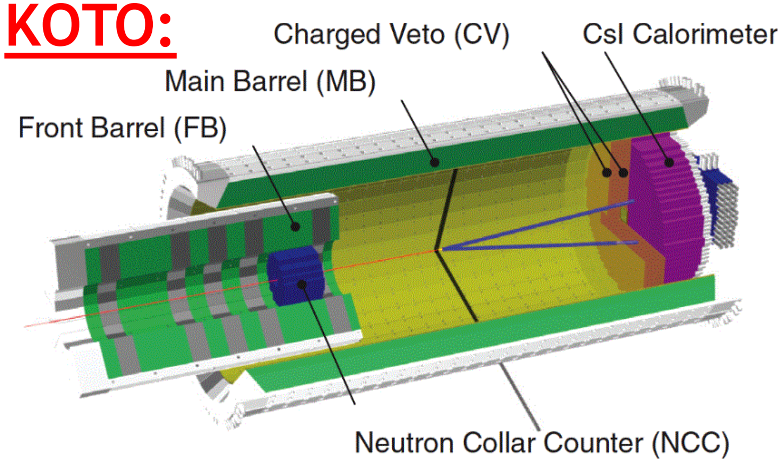
- **NA62 Run 2 (2015–2018)** is focused on $K^+ \to \pi^+ \nu\nu$.
  - ✓ Trigger bandwidth for other physics is limited.
  - ✓ Several measurements at nominal SES~$10^{-12}$: $K^+ \to \pi^+ A'$, $\pi^0 \to \nu\nu$.
  - ✓ A few measurements do not require extreme SES: $K^+ \to \ell^+ \nu_H$, …
  - ✓ In general, limited sensitivities to rare/forbidden decays (SES~$10^{-10}$ to ~$10^{-11}$, similar to NA48/2 and BNL-E865).
  - ✓ A proof of principle for the broad rare/forbidden decay programme.

- **NA62 Run 3 (2021–2024)** programme is under discussion.
  *[will be presented at "Physics Beyond Colliders" workshop, CERN, Sep 2016]*
  - ✓ Existing apparatus, different trigger logic: **no capital investment**.
  - ✓ Rare/forbidden $K^+$ and $\pi^0$ decays at SES~$10^{-12}$:
    $K^+$ physics: $K^+ \to \pi^+ \ell^+ \ell^-$, $K^+ \to \pi^+ \gamma \ell^+ \ell^-$, $K^+ \to \ell^+ \nu\gamma$, $K^+ \to \pi^+ \gamma\gamma$, …
    $\pi^0$ physics: $\pi^0 \to e^+e^-$, $\pi^0 \to e^+e^-e^+e^-$, $\pi^0 \to 3\gamma$, $\pi^0 \to 4\gamma$, …
    Searches for LFV/LNV: $K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \pi^+ \mu e$, $\pi^0 \to \mu e$, …
  - ✓ Possibly $K_L$ rare decays (SES~$10^{-11}$), including $K_L \to \pi^0 \ell^+ \ell^-$ [CPV].
  - ✓ Dump mode: hidden sector searches (long-lived HNL, DP, ALP).

# Beyond 2024

- Need to measure both $BR(K^+ \to \pi^+ \nu\nu)$ vs $BR(K_L \to \pi^0 \nu\nu)$: affected differently by NP.
- In the next few years, we expect:
  - ✓ NA62 @ CERN to measure $BR(K^+ \to \pi^+ \nu\nu)$ to 10%;
  - ✓ KOTO @ J-PARC to observe a few $K_L \to \pi^0 \nu\nu$ events.
- A new, possibly multi-purpose, $K_L$ experiment at CERN focussed on $K_L \to \pi^0 \nu\nu$, with $SES \sim 0.5 \times 10^{-12}$ is under consideration for Run 4 (2026–2029).

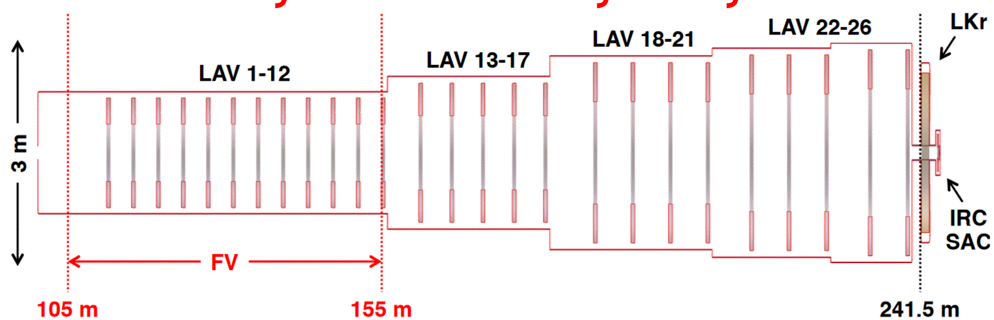
## KOTO:




- 30 GeV protons (300 kW); $\langle p_{KL} \rangle = 2$ GeV/c;
- Proposal: $SES = 8 \times 10^{-12}$ (~4 SM evts) with $S/B = 1.4$ in three years.
- Short (100h) run in 2013: $SES = 1.3 \times 10^{-8}$;
- Observed 1 event, expected 0.36; *[CKM2014]*
- Collected ×20 more data in 2015;
- Intention (no proposal): upgrade to 100 SM evts.

## KLEVER @ CERN:

**feasibility and sensitivity study**




- 400 GeV protons; $\langle p_{KL} \rangle \sim 100$ GeV/c: complementary approach to KOTO.
- 60 SM events in 5 years with $S/B \approx 1$.
- Protons required: $5 \times 10^{19}$ (NA62×10): target area & transfer line upgrade.
- Re-use NA62 infrastructure and parts of detector (LKr calorimeter; muon system).

# Recent & upcoming results: 2003-2007 data samples

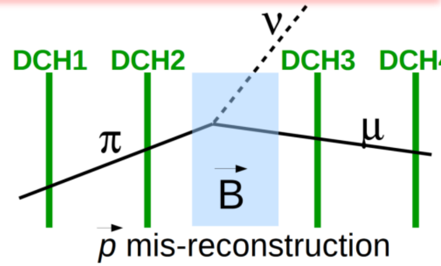
UK groups have been consistently responsible for
>50% of the physics output of the "old" CERN kaon experiments

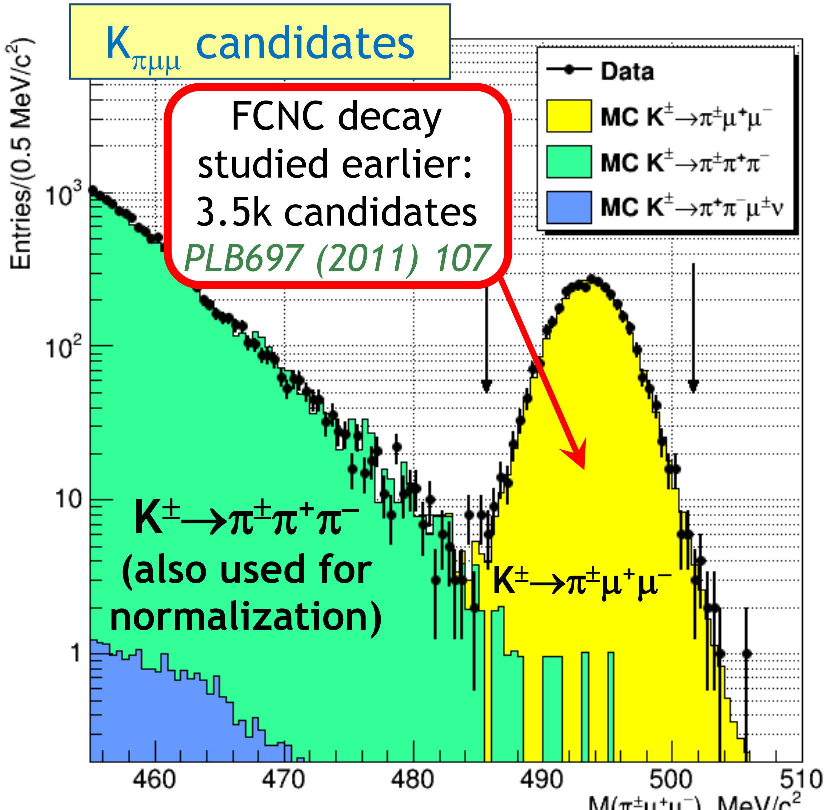
Recent results:

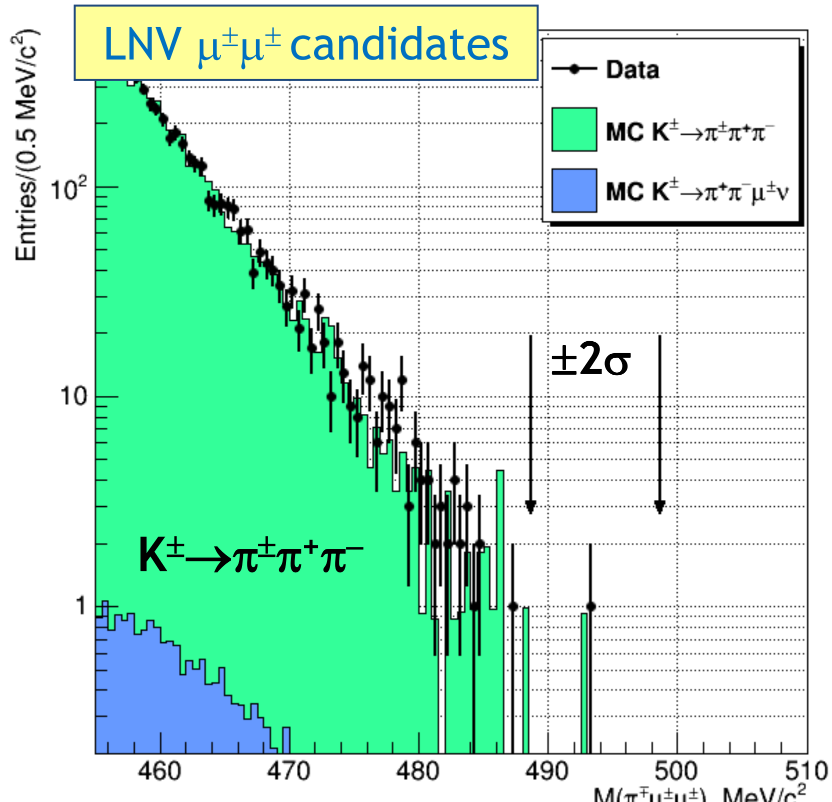
- ❖ Search for lepton number violation and resonances in $K^{\pm}\to\pi\mu\mu$ decays [Birmingham & Liverpool]
- ❖ Search for dark photon production: $\pi^0\to\gamma A'$ [Birmingham]
- ❖ $\pi^0$ transition form factor measurement [Birmingham & Bratislava]
- ❖ Searches for heavy neutral leptons: $K^+\to\ell^+\nu$ [Birmingham]

# $K^\pm \to \pi^\mp \mu^\pm \mu^\pm$: lepton number violation

- NA48/2 three-track data sample is analyzed.
- Main background: $K^\pm \to 3\pi^\pm$ with $\pi^\pm \to \mu^\pm \nu$ decays in flight.
- Upper limit on LNV decay + searches for 2-body resonances.
- Proof of principle for NA62 analysis at SES~$10^{-12}$.



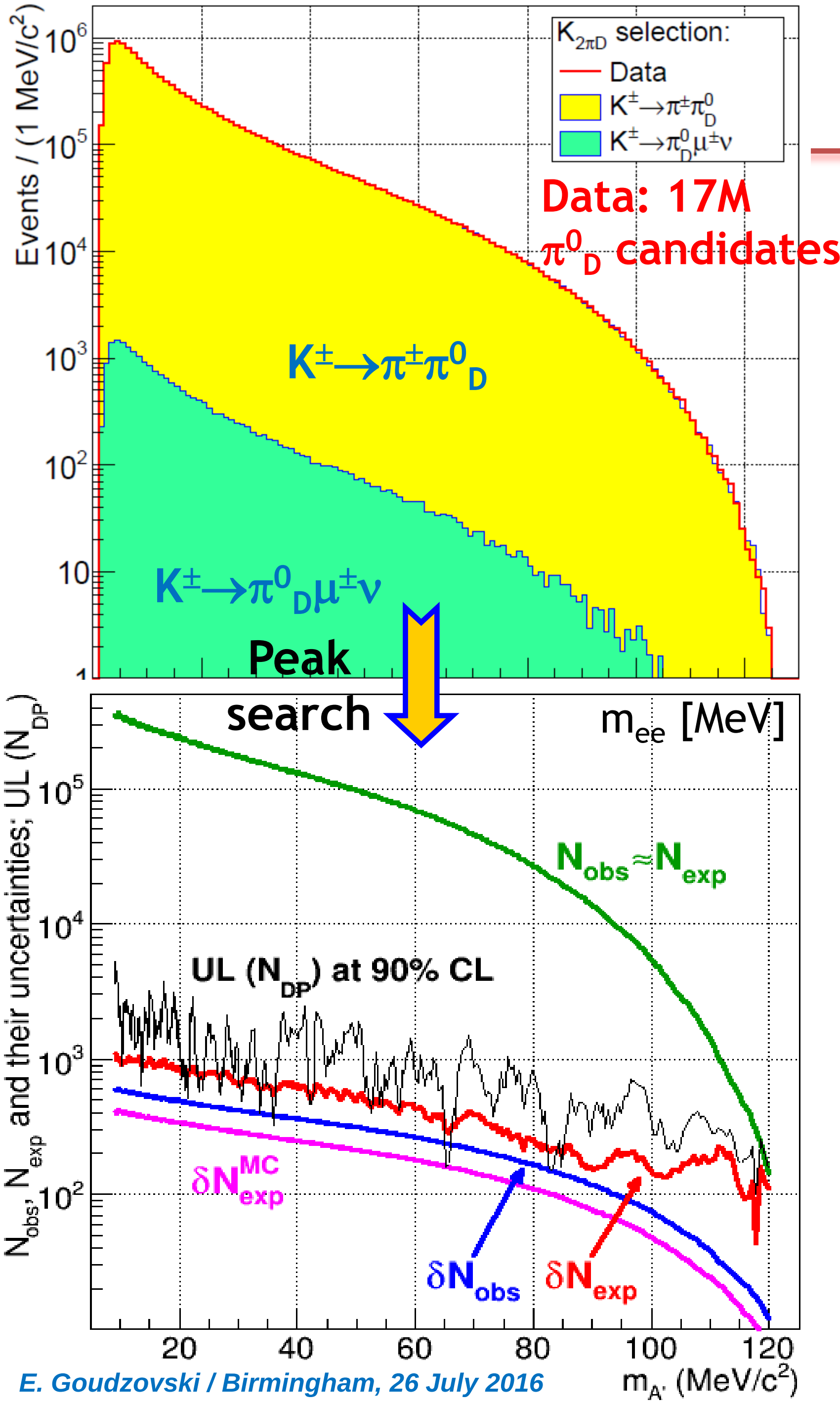



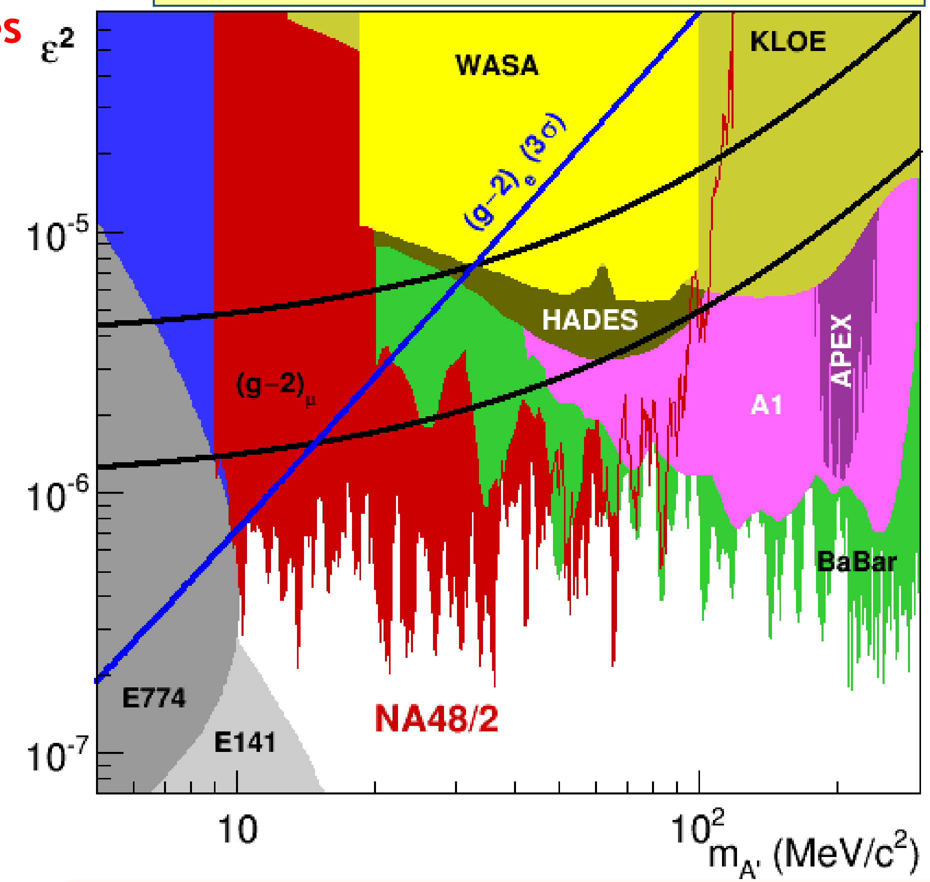

$N(\mu^\pm\mu^\pm) = 1$
$N_{bkg} = 1.16 \pm 0.87$ ⇒ $BR(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 8.6\times10^{-11}$ [90% CL]

*[Factor 13 improvement; final result; paper in preparation]*

# $\pi^0 \to \gamma A'$, $A \to e^+e^-$




DP exclusion summary (up to 2015)

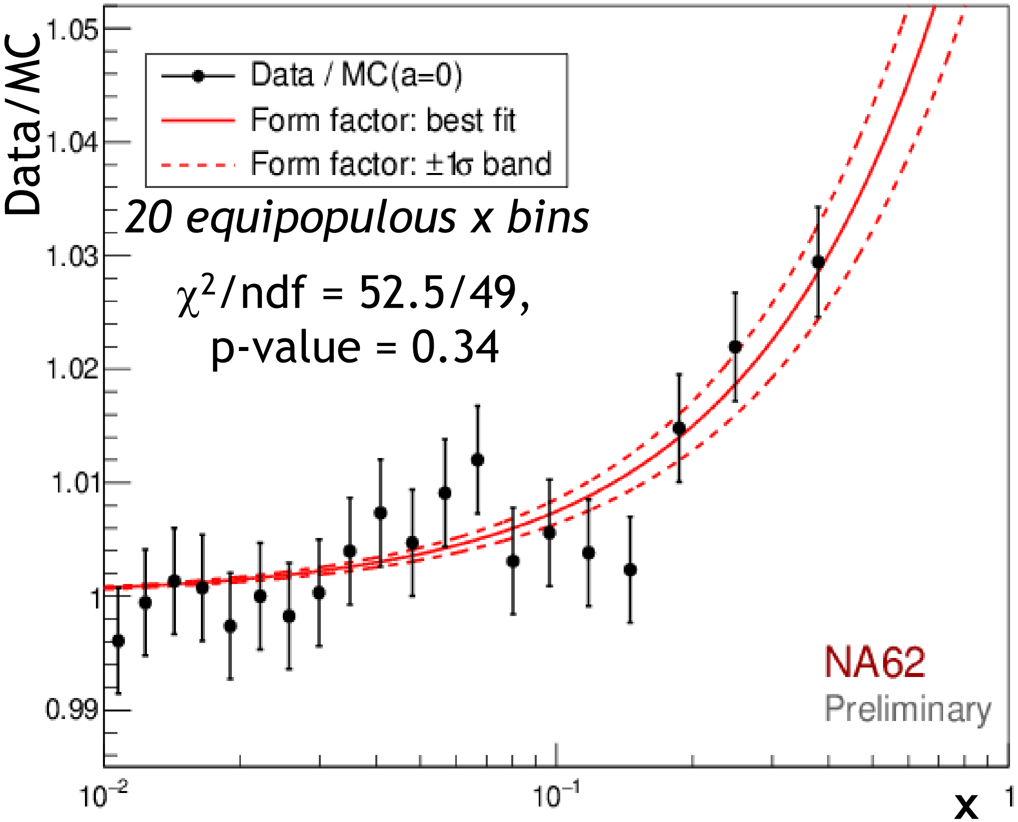



If the dark photon (**A'**) couples to quarks and decays mainly to SM fermions, it is **ruled out** as the explanation for the anomalous **$(g-2)_\mu$**.

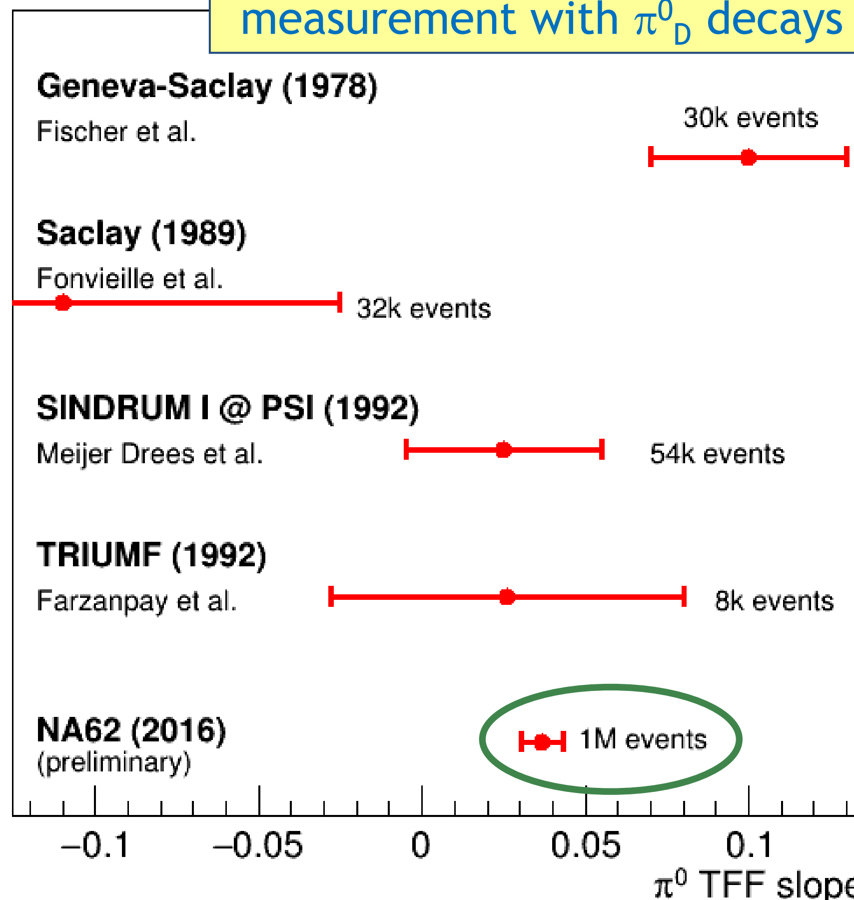
*[NA48/2 collaboration, PLB746 (2015) 178]*

# $\pi^0$ form factor (2007 data)

Fit illustration: Data/MC(a=0)




World data: $\pi^0$ TFF slope measurement with $\pi^0_D$ decays



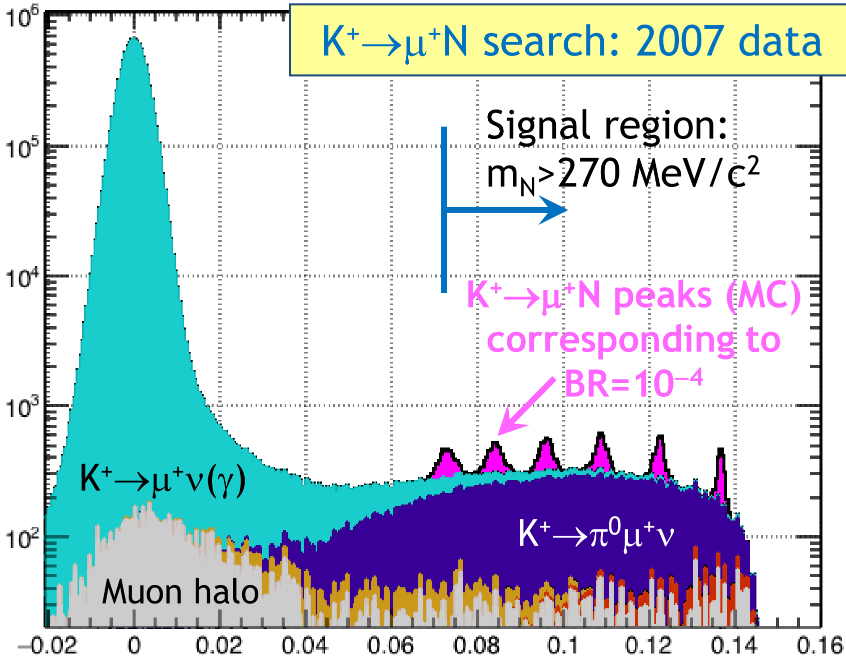

Preliminary result (2016):

$a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst}) \times 10^{-2}$

*[final result & paper in preparation]*

*First observation* (**5.8σ**) of *non-zero TFF slope* in the time-like momentum transfer region.

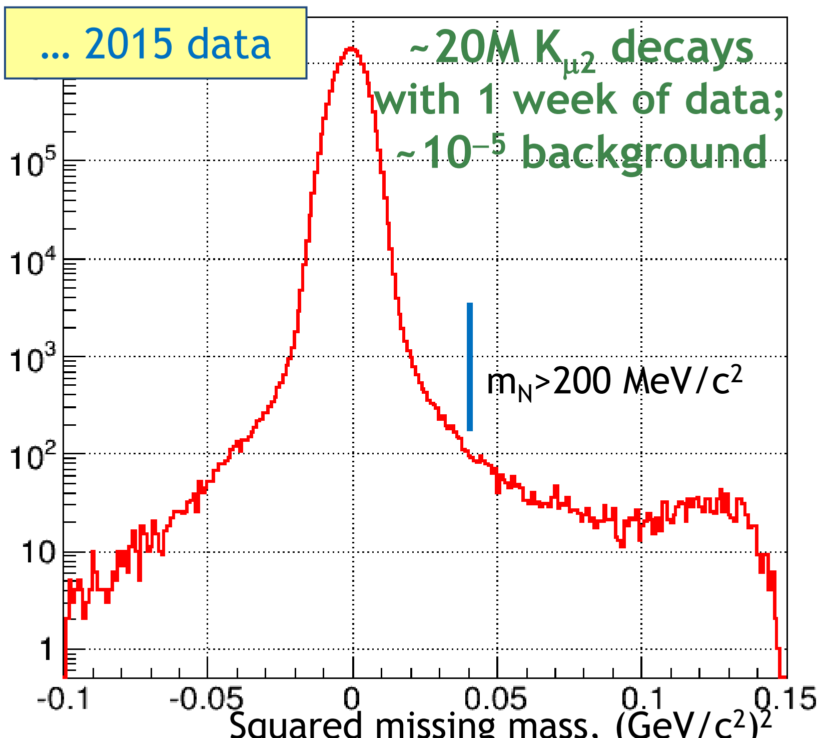
# HNL searches

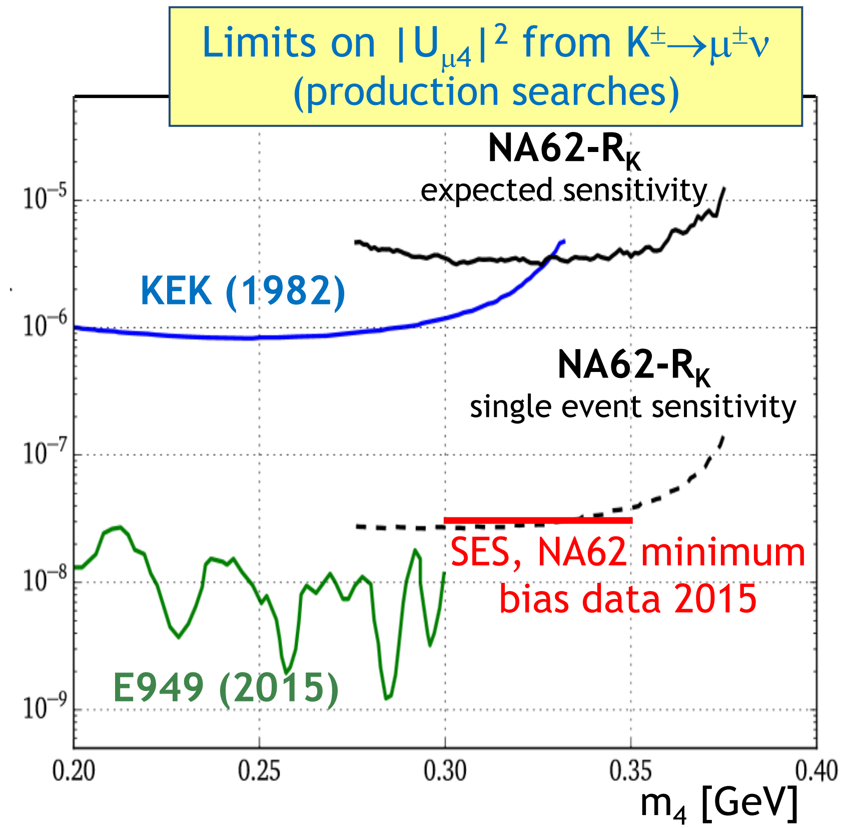



**2007 data**: background-limited; sensitive above **300 MeV/$c^2$** unlike BNL E949 (decay at rest)

**2015 data**: a wider programme including **$K^+\to\ell^+\nu_H$, $K^+\to\ell^+\nu\nu\nu$** and **$K^+\to\ell^+\nu A'$**.

- ✓ The $K^+$ flux of 2007 matched in one week;
- ✓ ~10 times lower background; wider $m_N$ range.



# Summary

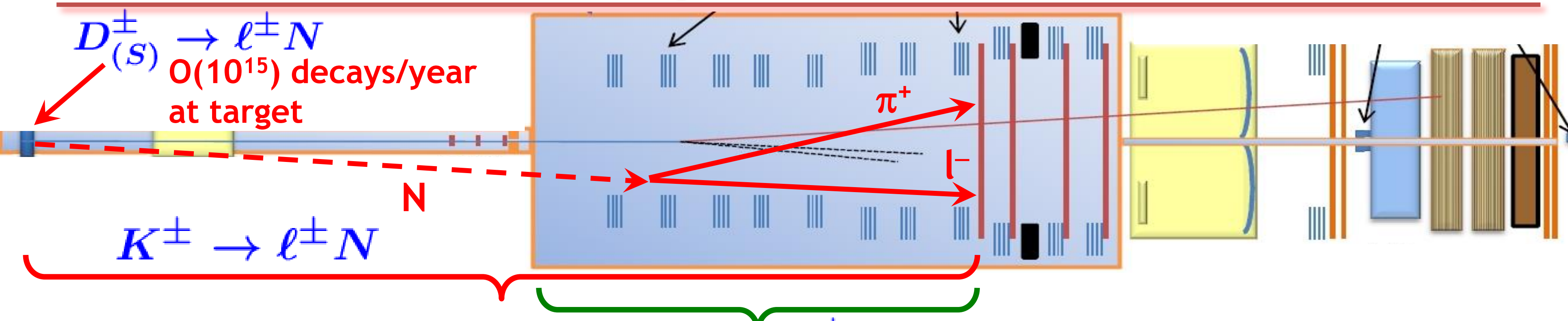
- **UK participation in NA62 from 2011:**
  - ✓ Capital funding and manpower for detector construction and operation from ERC Advanced and Royal Society Grants.
  - ✓ Soon after, STFC contribution with M&O costs.
  - ✓ KTAG detector delivered on time and exceeds specifications.
  - ✓ Now in exploitation mode: supported by STFC Particle Grant.
  - ✓ Extremely **good value for STFC investment** (M&O, **1** postdoc, **2** Rutherford fellows, travel, some academic time).
  - ✓ Strong UK leadership **in physics analysis**: both NA62 and "old" data. Recently, UK-led best limits on $K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$, $\pi^0\to\gamma A'$, **HNL**; $\pi^0$ TFF.

- **NA62 run 2015–2018:**
  - ✓ Running at **20%** intensity now, and going to **50%** soon.
  - ✓ Expect a few SM $K_{\pi\nu\nu}$ events sensitivity by the end of **2016**.
  - ✓ Focused on the $K_{\pi\nu\nu}$ measurement (**SES~$10^{-12}$**).

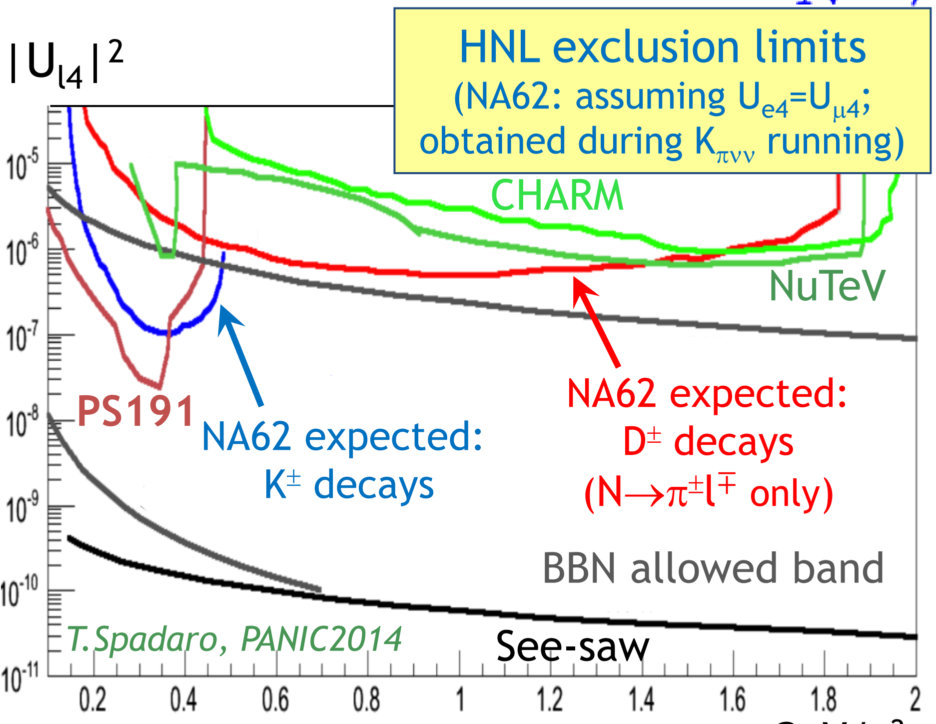
- **NA62 run 2021–2024:**
  - ✓ An extensive $K^+/K_L/\pi^0$ rare decay and beam dump programme with existing detector is being developed.
  - ✓ A new $K_L$ experiment afterwards is under consideration.

# Backup

# Beam dump mode: HNL decays




Search for decays:
$N \to \pi^{\pm}\ell^{\mp}$ (0.14 GeV/c² < $m_N$ < 1.9 GeV/c²)
$N \to \rho^{\pm}\ell^{\mp}$ (0.8 GeV/c² < $m_N$ < 1.9 GeV/c²)




The expected sensitivity is evaluated assuming **zero background**.

Backgrounds to be considered: scattering of halo muons ($\mu^{\pm}N\to K^0X$), charge exchange in KTAG/GTK ($K^+n\to K^0p$), accidentals ($K^+$ decays, halo muons).

Improvements over the world data are possible also for dark photon and axion production on Be target.

Proof-of-principle: the **2016 data**.

# NA62 & SHiP design parameters

Primary beam for both NA62 and SHiP: 400 GeV/c SPS protons

| | NA62 (running experiment) | SHiP (proposal) |
|---|---|---|
| Years of operation | 3 | 5 |
| POT per SPS spill | $3\times10^{12}$ | $4\times10^{13}$ |
| POT total | $5\times10^{18}$ | $2\times10^{20}$ |
| Decay volume ($m^3$) | 260 $m^3$ | 1780 $m^3$ |
| Decay volume distance to target | 104–183 m | 64–124 m |
| Decay volume pressure (bar) | $10^{-9}$ bar | $10^{-6}$ bar |
| Halo muon rate in spectrometer | 6 MHz | few kHz |
| Straw chamber area | 0.06m<R<1.05m | $R_1$=5m, $R_2$=10m |

… but a crucial aspect is the background rejection capability!

# LFV in $K^{\pm}$ and $\pi^0$ decays

| Mode | UL at 90% CL | Experiment | Reference |
|---|---|---|---|
| $K^+ \to \pi^+\mu^+e^-$ | $1.3 \times 10^{-11}$ | BNL E777/E865 | PRD 72 (2005) 012005 |
| $K^+ \to \pi^+\mu^-e^+$ | $5.2 \times 10^{-10}$ | BNL E865* | PRL 85 (2000) 2877 |
| $K^+ \to \pi^-\mu^+e^+$ | $5.0 \times 10^{-10}$ | BNL E865* | PRL 85 (2000) 2877 |
| $K^+ \to \pi^-e^+e^+$ | $6.4 \times 10^{-10}$ | BNL E865* | PRL 85 (2000) 2877 |
| $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ | $1.1 \times 10^{-9}$ | CERN NA48/2 | PLB 697 (2011) 107 |
| $K^+ \to \mu^-\nu e^+e^+$ | $2.0 \times 10^{-8}$ | Geneva-Saclay | PL 62B (1976) 485 |
| $K^+ \to e^-\nu\mu^+\mu^+$ | no data | | |
| $\pi^0 \to \mu^+e^-$ | $3.6 \times 10^{-10}$ | FNAL KTeV | PRL 100 (2008) 131803 |
| $\pi^0 \to \mu^-e^+$ | $3.6 \times 10^{-10}$ | FNAL KTeV | PRL 100 (2008) 131803 |

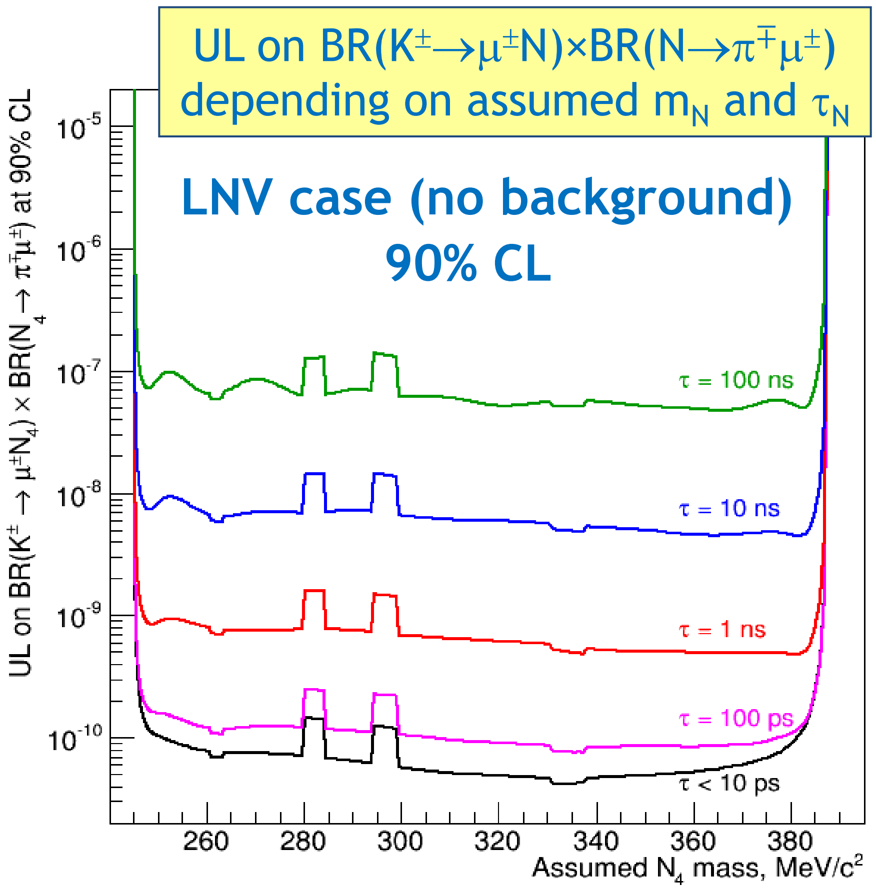
* CERN NA48/2 sensitivities for these three modes are similar to those of BNL E865

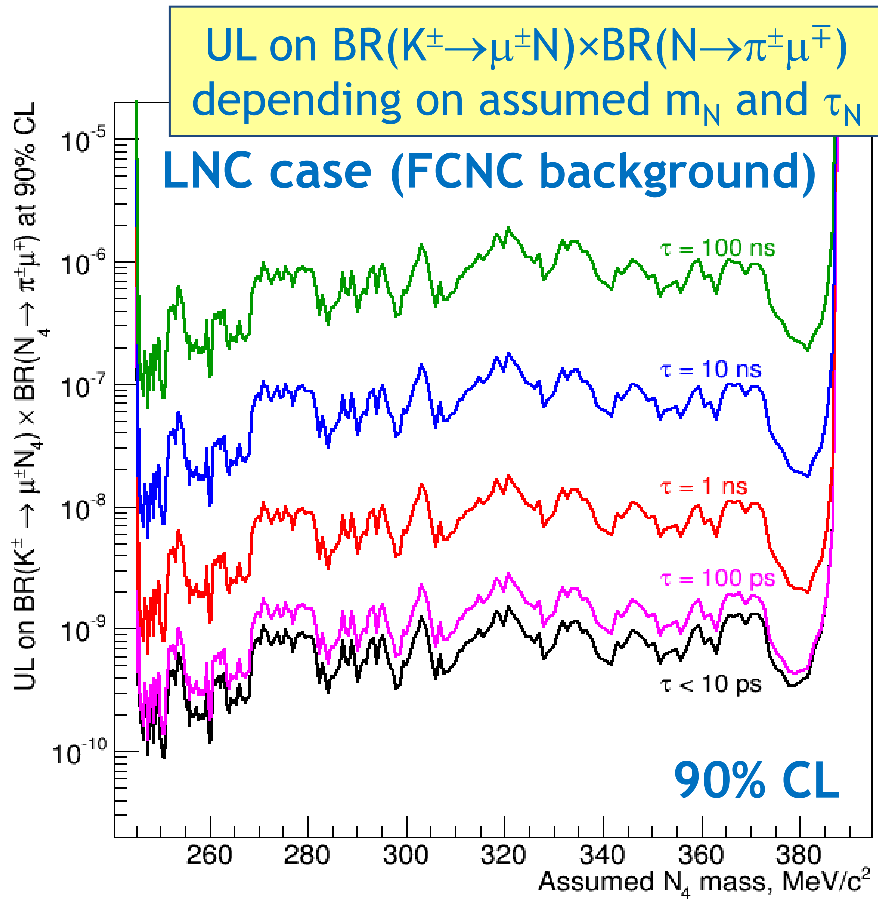
Expected NA62 single event sensitivities:
**~$10^{-12}$** for $K^{\pm}$ decays, **~$10^{-11}$** for $\pi^0$ decays.

- ❖ NA62 is capable of improving on all these decay modes.
- ❖ Sensitivity will depend on the trigger selectivity.

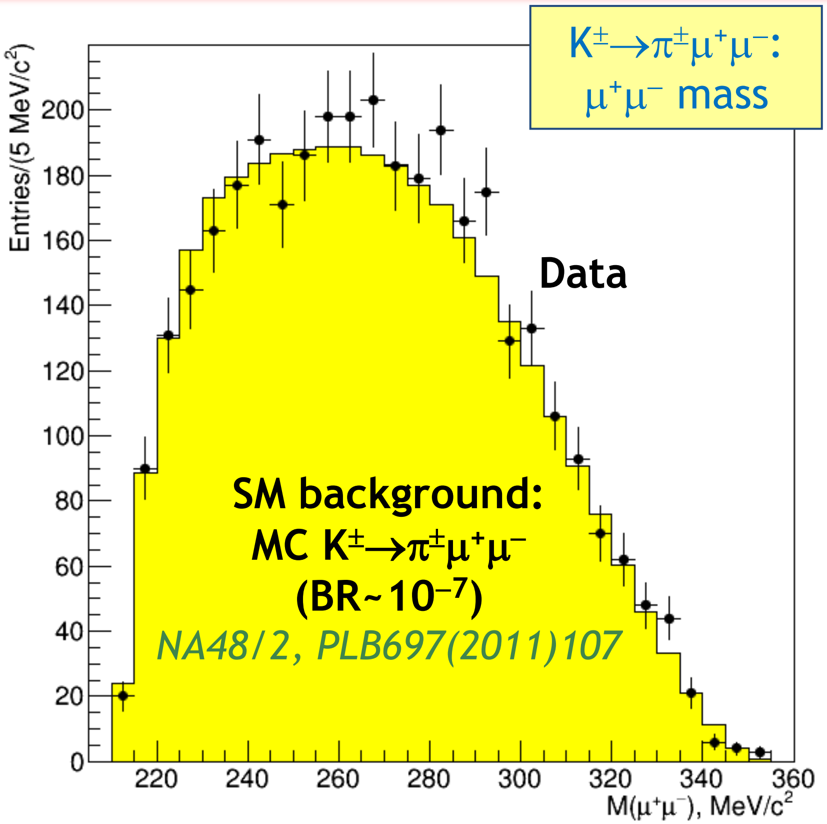
# Search for $K^{\pm}\to\mu^{\pm}N$, $N\to\pi^{\pm}\mu^{\mp}$

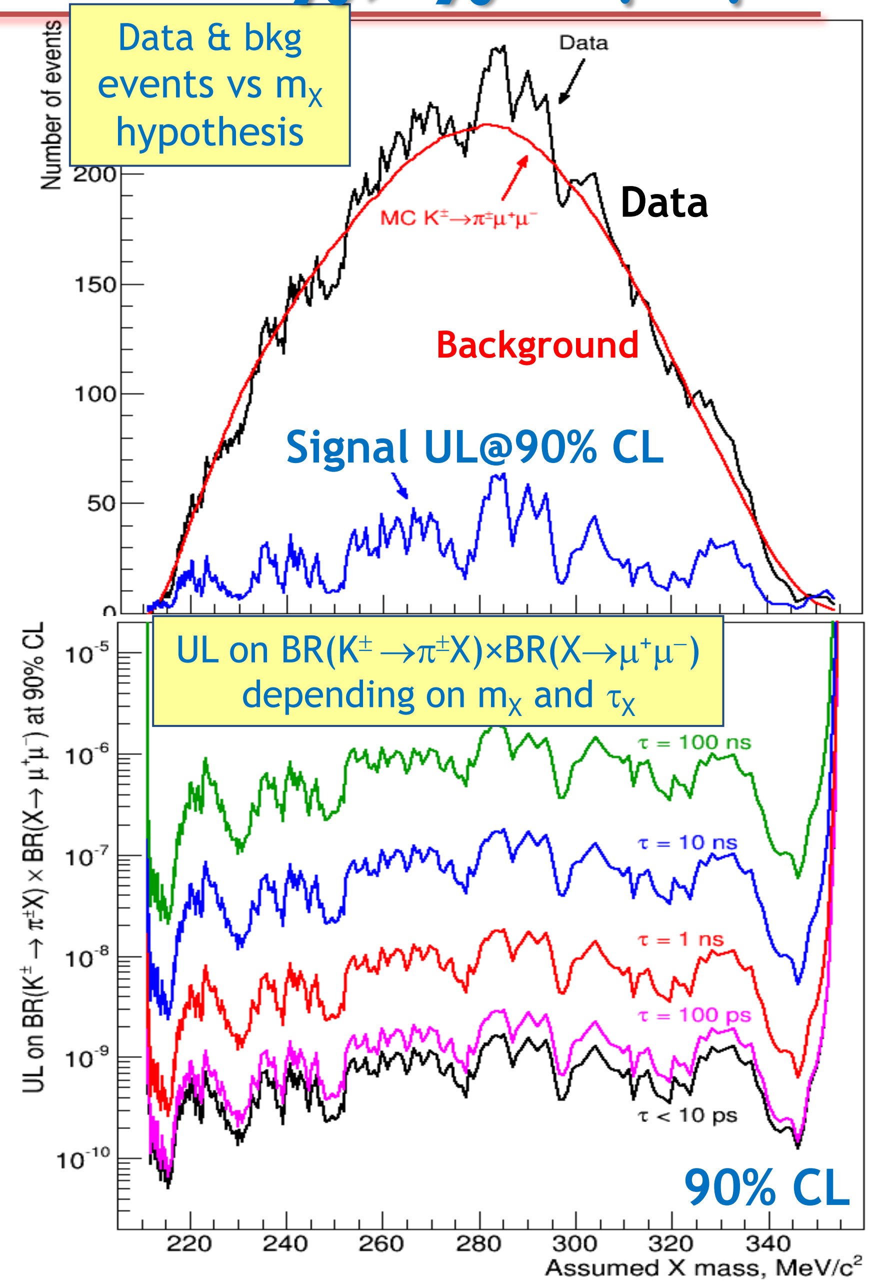
- Interpretation in terms of production and decay of either **Majorana neutrino** (**N**) or **LN conserving heavy neutrino**.
- A scan in the parameter space: $m_N$ and $\tau_N$.
- Limits of **~$10^{-10}$** (**~$10^{-9}$**) set for **$\tau_N$<100 ps** for LNV (LNC) case.



# Search for $K^{\pm}\to\pi^{\pm}\chi$, $\chi\to\mu^{+}\mu^{-}$




- ❖ Also background limited; **UL~$10^{-9}$**.
- ❖ This leads to non-trivial limitations on the inflation ($\chi$) phase space: $\chi\to\mu^{+}\mu^{-}$ decay dominates at **$m_{\chi}$~300 MeV/c²**.

*Shaposhnikov, Tkachev, PLB 639 (2006) 414;*
*Bezrukov, Gorbunov, PLB736 (2014) 494*