NA62: recent results and prospects

Cristina Lazzeroni

University of Birmingham

Outline:

1) Ultra-rare $K \rightarrow \pi \nu \nu$ decays.
2) UK responsibilities within NA62.
3) NA62 programme beyond the flagship mode.
4) The long-term future.

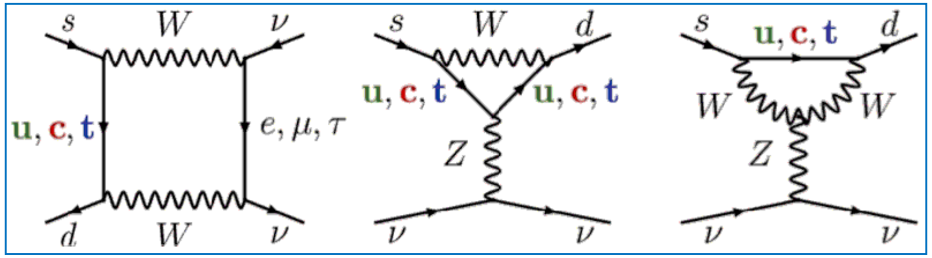
European Research Council
Established by the European Commission

PPAP Community Meeting
ICL • 25 September 2015

UNIVERSITY OF BIRMINGHAM

Flagship measurement: $K \to \pi\nu\bar{\nu}$

SM: box and penguin diagrams



Hadronic matrix element related to a measured quantity ($K^+ \to \pi^0 e^+ \nu$).

SM precision surpasses any other FCNC process involving quarks.

Theoretically clean, almost unexplored, sensitive to new physics.

Ultra-rare decays with the highest CKM suppression:

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

SM branching ratios

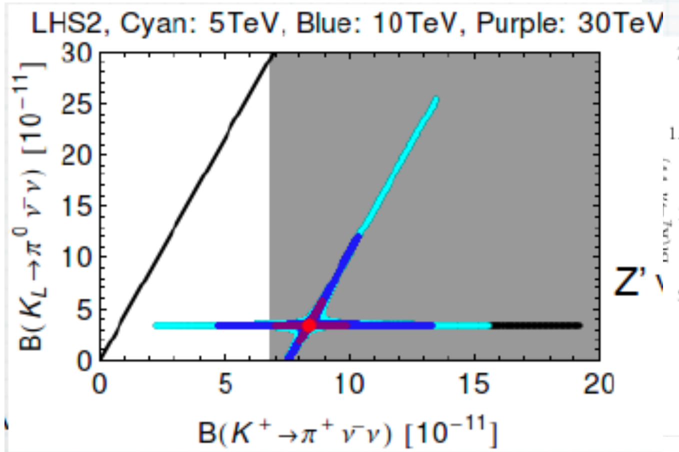
Buras et al., arXiv:1503.02693

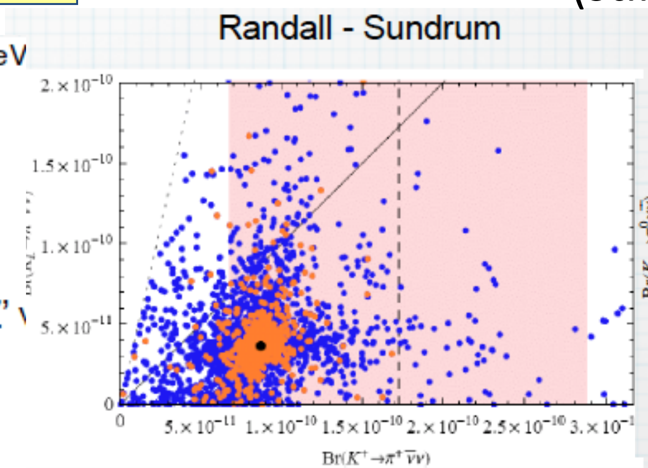
Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\nu(\gamma)$	9.11±0.72
$K_L \to \pi^0 \nu\nu$	3.00±0.30

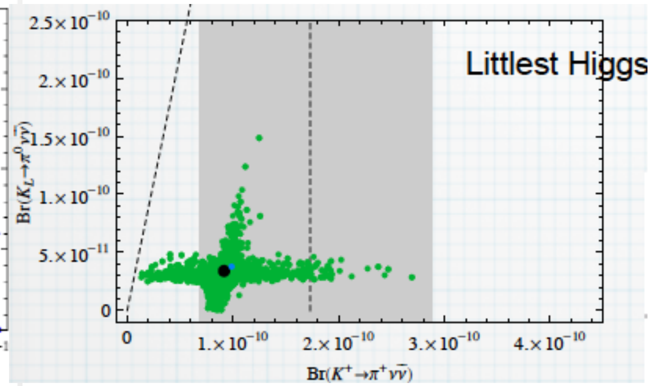
Best probe of MSSM non-MFV

(still not excluded by LHC)

[G. Isidori et al., JHEP 0608 (2006) 088]

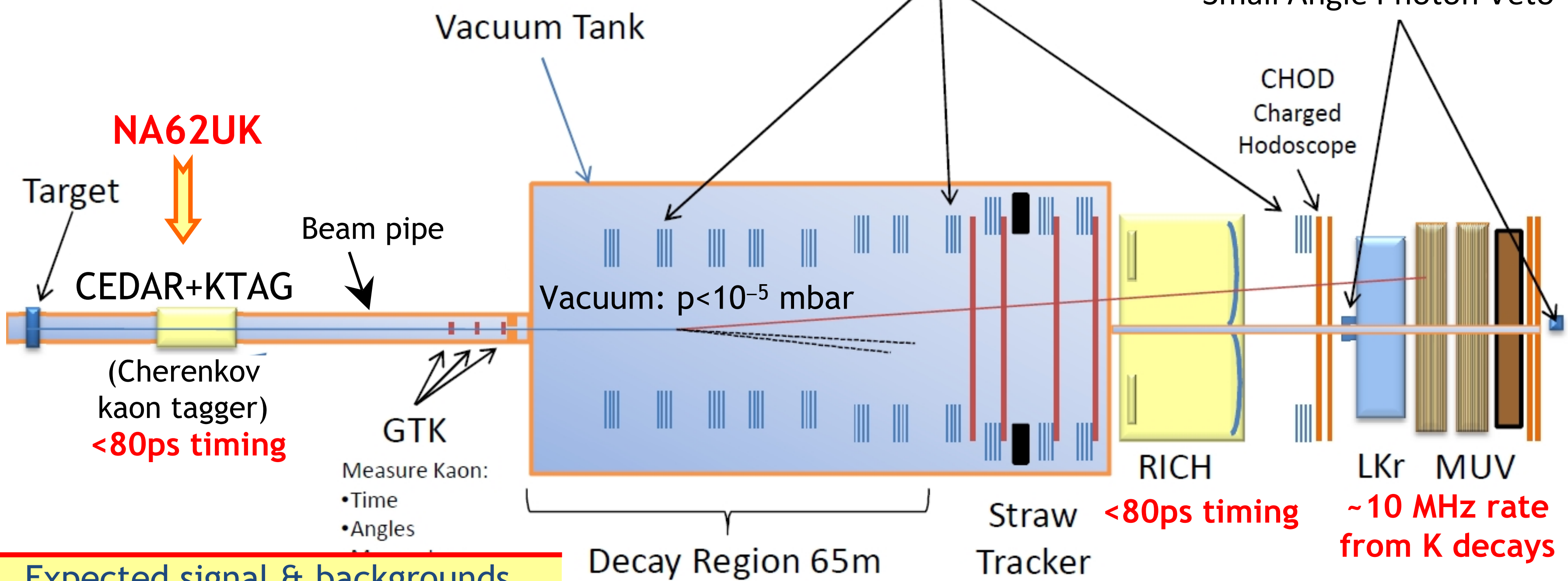






NA62 experiment at CERN SPS

UK: Birmingham, Bristol, Liverpool, Glasgow
Un-separated hadron ($p/\pi^+/K^+$) beam:
400GeV SPS protons → 75GeV (±1%) kaons



Expected signal & backgrounds	
Signal	45 evt/year
$K^+ \to \pi^+\pi^0$	4.3%
$K^+ \to \mu^+\nu$	2.2%
$K^+ \to$ 3 charged tracks	<4.5%
$K^+ \to \pi^+\pi^0\gamma$	~2%
$K^+ \to \mu^+\nu\gamma$	~0.7%
Total background	<13.5%

- High momentum K^+, low momentum π^+ (15–35 GeV/c).
- 5×10^{12} K^+ decays/year: record $\sim10^{-12}$ sensitivity.
- Hermetic photon veto: $\sim5\times10^{-8}$ $\pi^0 \to \gamma\gamma$ suppression.
- Kinematics: $\sim10^{-4}$ suppression of $K^+ \to \pi^+\pi^0$.
- Commissioning run 2014, Data taking 2015-2018.
- Efficient photon veto, good π^+/μ^+ identification.

NA62: UK responsibilities

Hardware and trigger:

- **full responsibility** for the **KTAG subdetector**;
- development and operation of the **L0 muon trigger**;
- development and operation of the **L1 trigger**;

Physics programme:

- **$K^+ \to \pi^+ \nu \nu$ analysis**
- lepton flavour and number conservation tests in **$K^+ \to \pi \ell \ell$** decays;
- lepton universality tests in **$K^+ \to \ell^+ \nu$** decays;
- **peak searches**: heavy neutral leptons, the dark photon.

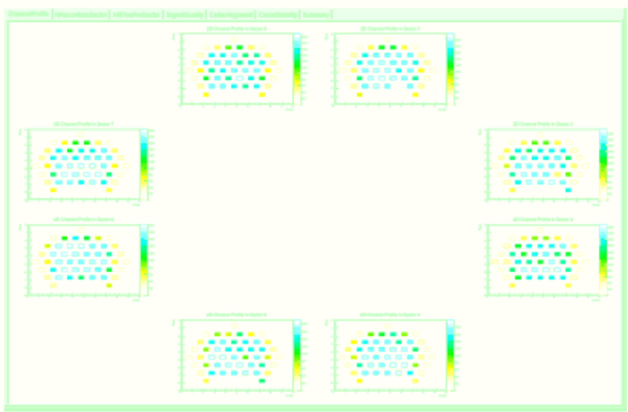
Coordination:

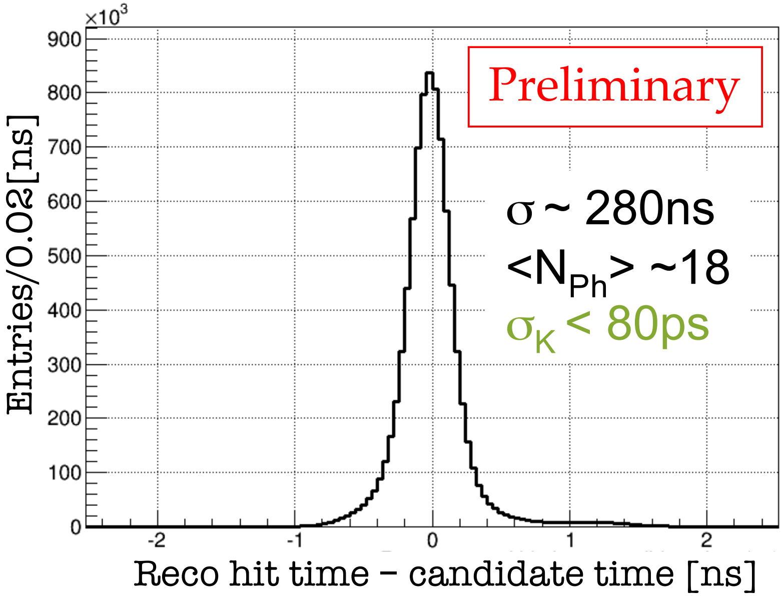
- co-convener of the **lepton flavour working group**;
- NA62 **analysis coordinator**;
- **software coordinator**;
- chair of the **Conference Committee**;
- members of the **Editorial Board** (3 out of 10)
- **Run Coordinators** (2 out of 8)

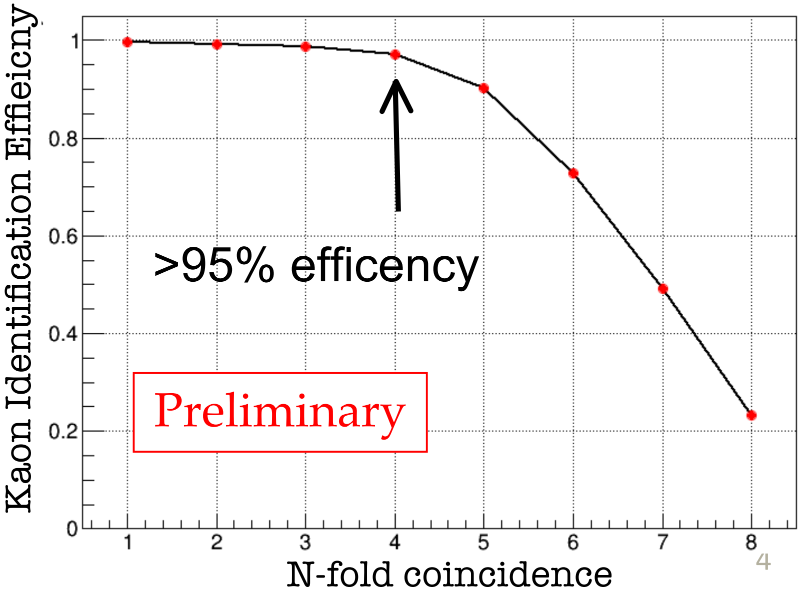
Kaon Identification KTAG

UK responsibility

PMTs illumination

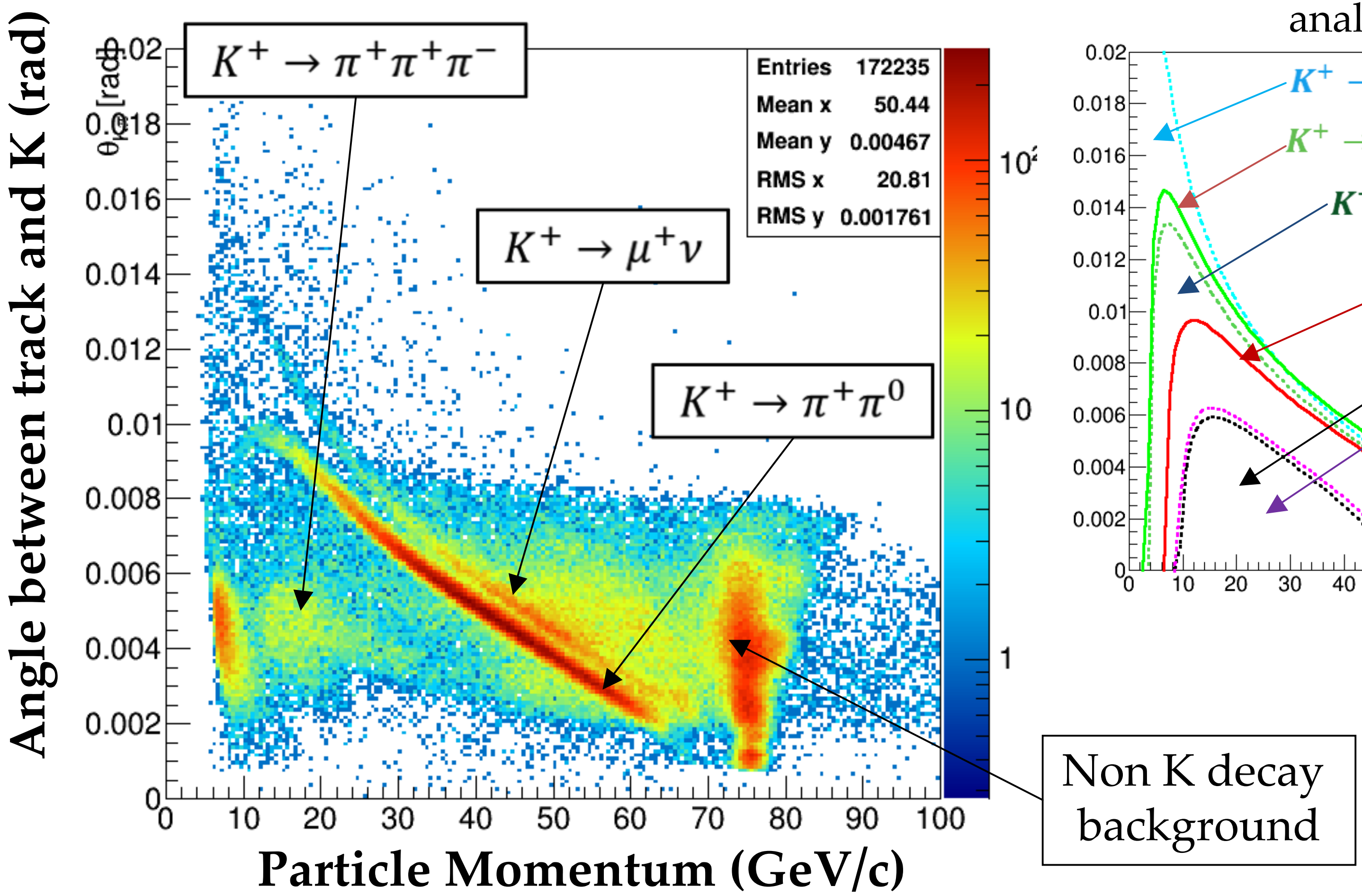




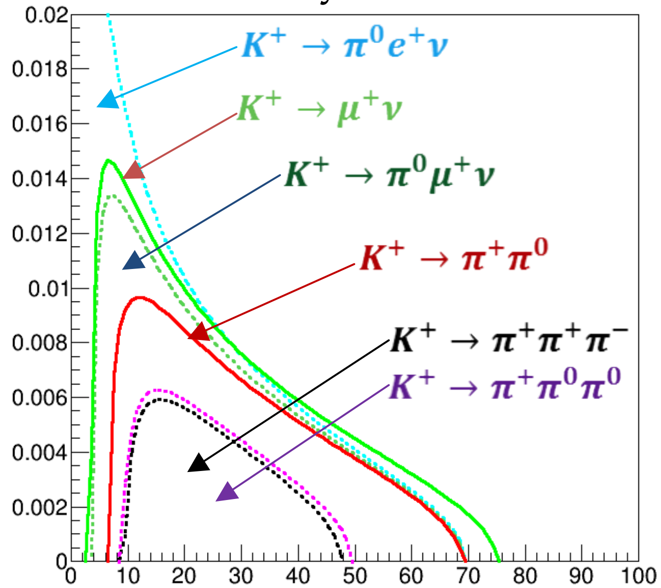


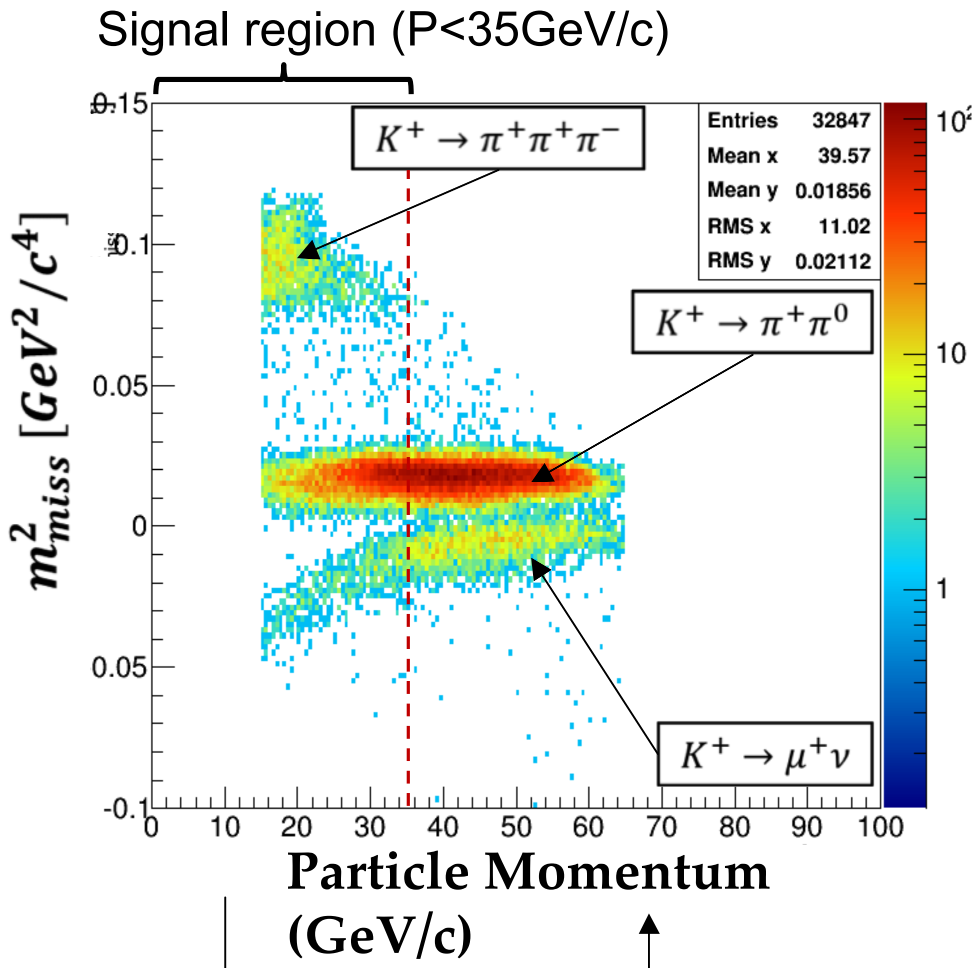
First Look at 2014 Data Quality

- Events with only 1 track in the spectrometer reconstructed (40 ns time window)
- 10^2 muon rejection at trigger level.

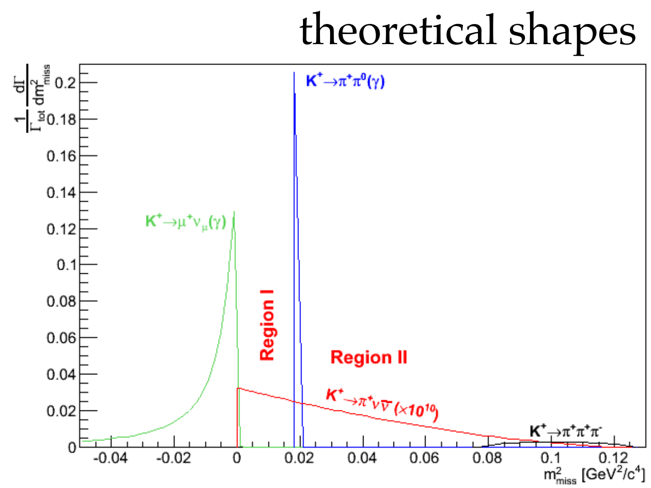


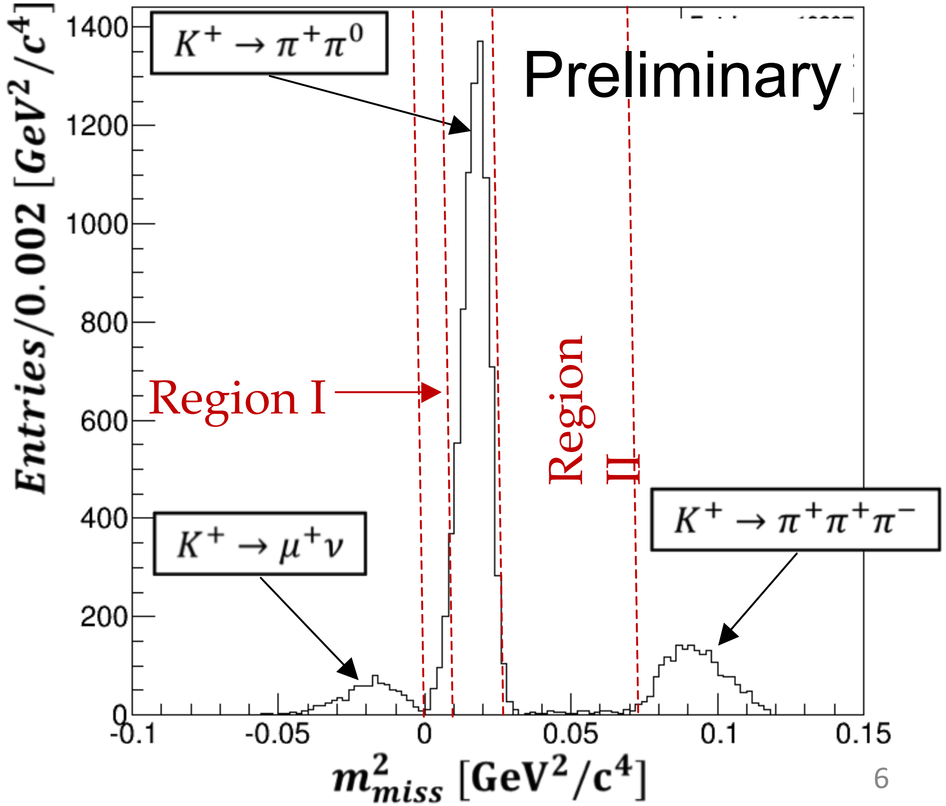
analytical contours





Kaon ID, mom cut, Vtx cut





Further NA62 K Physics Program

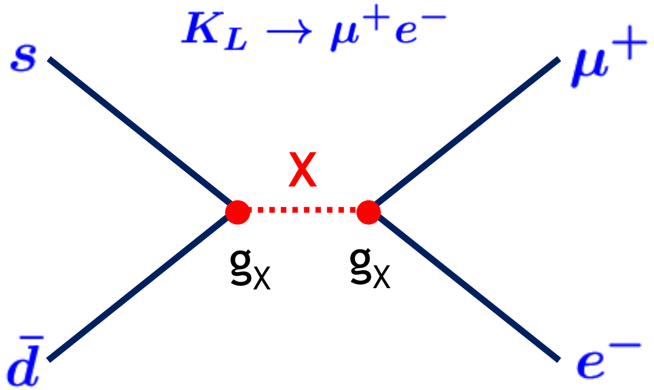
Decay	Physics	Present limit (90% C.L.) / Result	NA62 **Potential**
$\pi^+\mu^+e^-$	LFV	1.3×10^{-11}	
$\pi^+\mu^-e^+$	LFV	5.2×10^{-10}	
$\pi^-\mu^+e^+$	LNV	5.0×10^{-10}	
$\pi^-e^+e^+$	LNV	6.4×10^{-10}	10^{-12}
$\pi^-\mu^+\mu^+$	LNV	1.1×10^{-9}	
$\mu^-\nu e^+e^+$	LNV/LFV	2.0×10^{-8}	
$e^-\nu\mu^+\mu^+$	LNV	No data	
π^+X^0	New Particle	$5.9\times10^{-11}\ m_{X^0}=0$	10^{-12}
$\pi^+\chi\chi$	New Particle	–	10^{-12}
$\pi^+\pi^+e^-\nu$	$\Delta S\neq\Delta Q$	1.2×10^{-8}	10^{-11}
$\pi^+\pi^+\mu^-\nu$	$\Delta S\neq\Delta Q$	3.0×10^{-6}	10^{-11}
$\pi^+\gamma$	Angular Mom.	2.3×10^{-9}	10^{-12}
$\mu^+\nu_h, \nu_h\to\nu\gamma$	Heavy neutrino	Limits up to $m_{\nu_h}=350\ MeV$	
R_K	LU	$(2.488\pm0.010)\times10^{-5}$	>×2 better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^6 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$O(10^7)$
$\pi^0\pi^0\mu^+\nu$	χPT	-	$O(10^6)$

LFNV in $K^{\pm}$ and π^0 decays

NA62 single event sensitivities: **~10^{-12}** for $K^{\pm}$ decays, **~10^{-11}** for π^0 decays.
(modest L0 downscaling factors might be required for di-leptons)

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

* CERN NA48/2 sensitivities for these 3 modes are similar to those of BNL E865



Dimensional argument:

$$\frac{\Gamma_X}{\Gamma_{SM}} \sim \left(\frac{g_X}{g_W}\cdot\frac{M_W}{M_X}\right)^4$$

$g_X \approx g_W \quad \mathcal{B} \sim 10^{-12}$

$M_X \sim 100$ TeV

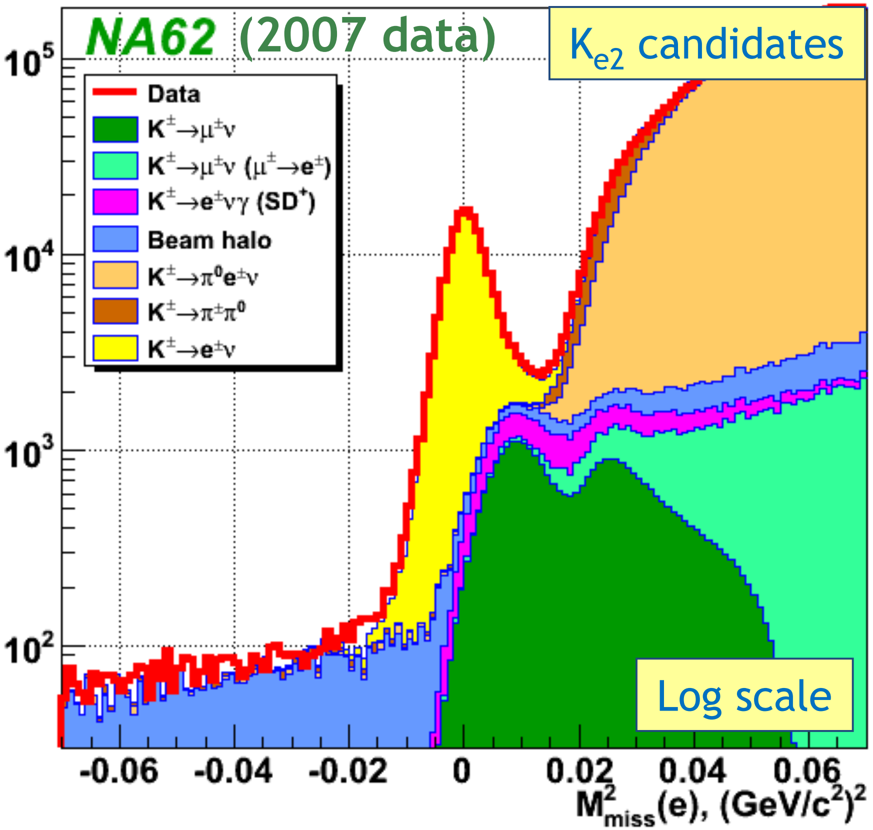
NA62-R_K: lepton universality

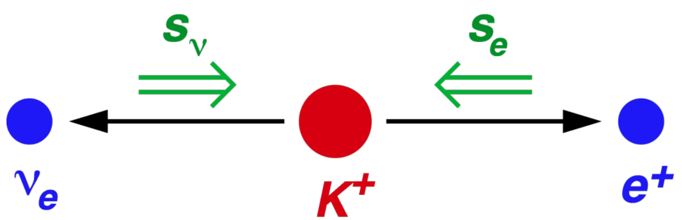
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{\mathrm{rad.corr.}})$$

Radiative correction (well known, few %)

$R_K = (2.488 \pm 0.010) \times 10^{-5}$

PLB719 (2013) 326





$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

Cirigliano and Rosell, PRL99 (2007) 231801

O(1%) effects due to sterile neutrinos or LFV

Lacker and Menzel, JHEP 1007 (2010) 006;
Abada et al., JHEP 1302 (2013) 048;
Girrbach and Nierste, arXiv:1202.4906

NA62 prospects:

improve precision by a factor ~2.
Competitor: **TREK@J-PARC**
(stopped K^+; similar precision).

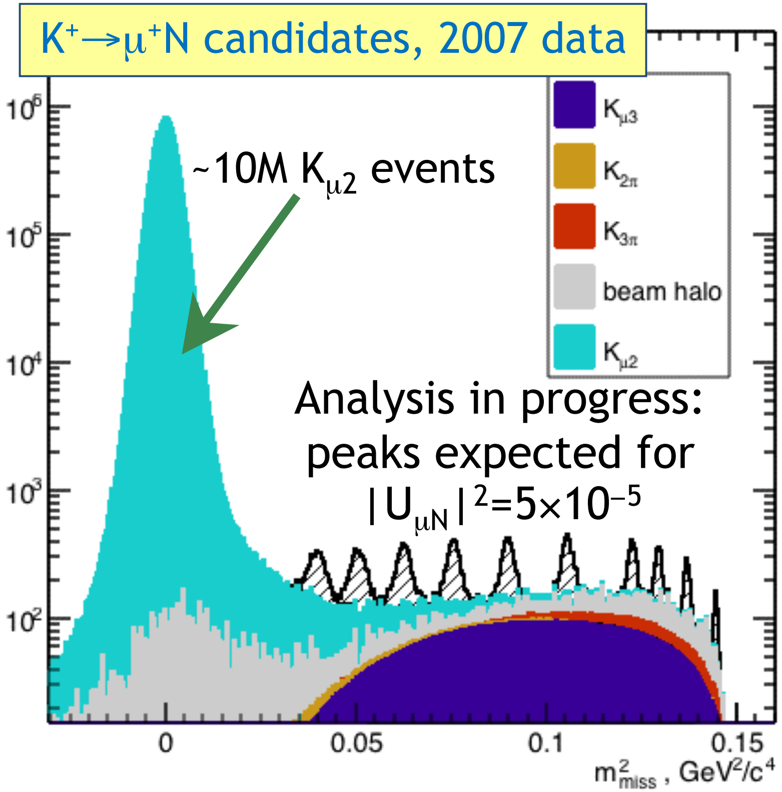
Heavy neutral leptons below M_K

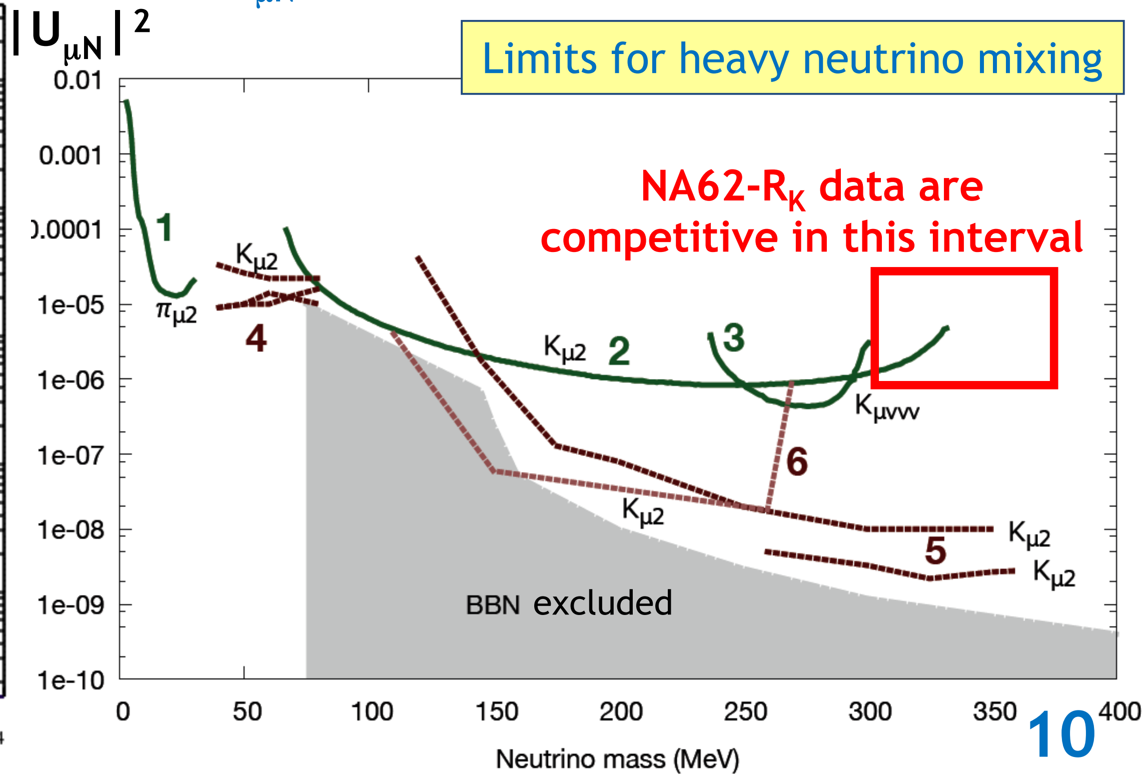
Neutrino minimal SM (νMSM):
3 heavy sterile RH Majorana νs ($N_{1,2,3}$).
$m_1 \sim 10$ keV/c^2: dark matter candidate.
$m_2 \sim m_3 \sim 1$ GeV/c^2:
observable in $K^\pm \to l^\pm N$, $D^\pm \to l^\pm N$ decays.

Asaka & Shaposhnikov, PLB620 (2005) 17

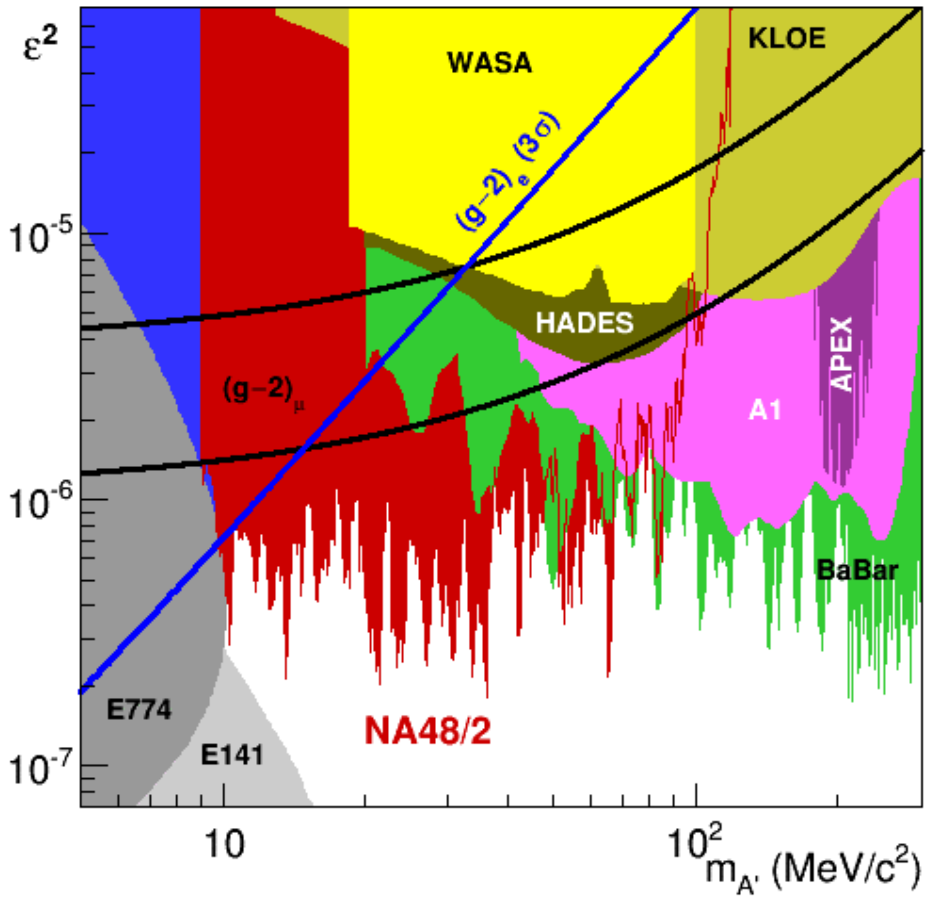
NA62-R_K subsample: ~10M $K^+ \to \mu^+ \nu_\mu$.
"Peak search" for HNL: $K^+ \to \mu^+ N$.

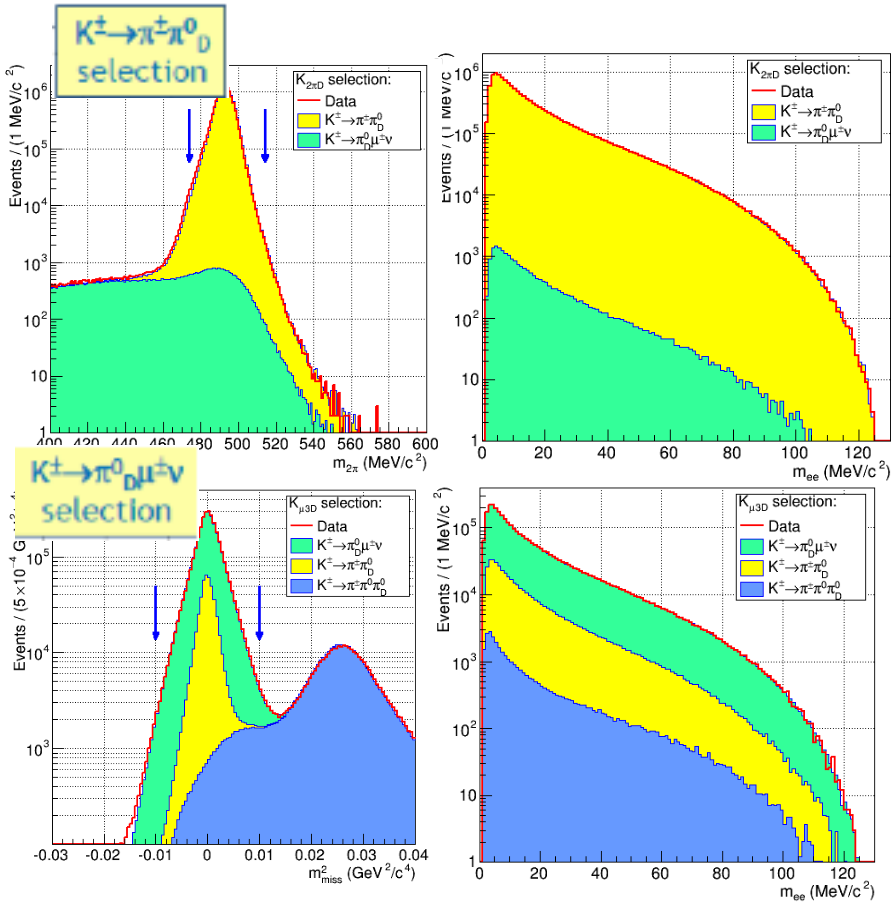
- Sensitivity is limited by background fluctuation (mainly beam halo).
- Competitive at $0.30 < M_N < 0.38$ GeV/c^2.
- **NA62:** larger sample and smaller bkg., $|U_{\mu N}| \sim 10^{-8}$ sensitivity in wider mass range.





Search for Dark Photon in the "old" data





Improvements on existing limits for 9-70 MeV/c^2

Sensitivity limited by irreducible π^0_D background

Published in Phys. Lett. B746 (2015) 178

Numerical UL data for each mass hypothesis available on HepData:

http://hepdata.cedar.ac.uk/view/ins1357601

1.7 10^7 π^0 with negligible mean free path

If DP couples to quarks and decays mainly to SM fermions, it's ruled out as explanation for anomalous $(g-2)_\mu$

Long-term future

❖ **Run 2015–2018**: dedicated to $K^+ \to \pi^+ \nu\nu$ and other rare/forbidden K^+ and π^0 decays

<u>SPS LS2: 2018–2019</u>

❖ **Run 2020–2023** (non-exclusive) possibilities:

a) Upgrades to improve precision on $K^+ \to \pi^+ \nu\nu$ (~**1000** SM events).

b) Switch to neutral beam to pursue $K_L \to \pi^0 \ell^+ \ell^-$ and prototype studies for $K_L \to \pi^0 \nu\nu$. Need ~**10** times higher SPS proton intensity (~10^{13} **ppp**), well within SPS capability. **A dedicated working group set up.**

c) Optimize for **heavy neutral lepton** searches (trigger, shielding upstream of the decay volume, ...).

<u>SPS LS3: 2024</u>

❖ **Run 2025–2028** possibility:

Next generation $K_L \to \pi^0 \nu\nu$ experiment: significant detector R&D required.

Summary

Improving the experimental precision on **BR($K \to \pi\nu\bar{\nu}$)** remains among the priority issues in flavour physics.

The first **NA62 physics run** (at lower intensity) with the complete detector has started in **2015**.

The **KTAG** sub-detector (**UK responsibility**) delivered on time. Main performance parameters are as expected.

UK groups play a key role in shaping a **the NA62 programme** ($K \to \pi\nu\nu$, CLFV, lepton universality, heavy neutral leptons) and publishing results based on existing **K^+** data sets (2003, 2004, 2007).

Spares

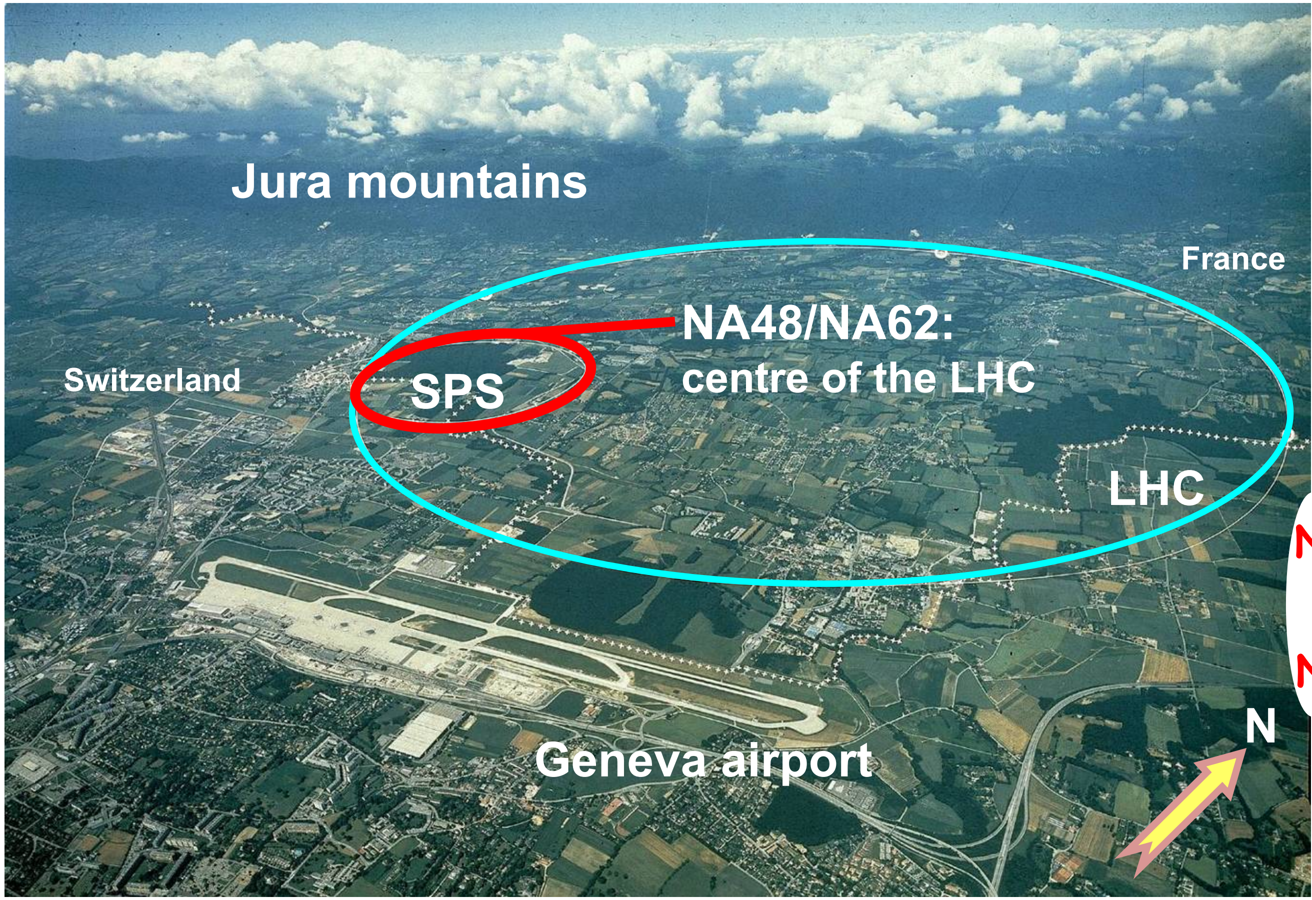
Where and Who

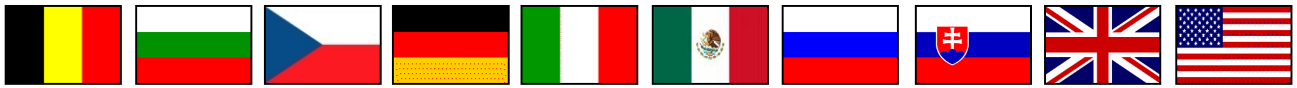
CERN
LHCb, NA48/NA62

LNF
KLOE,KLOE-2

KEK/JPARC
KOTO, TREK

CERN NA48/NA62 experiments





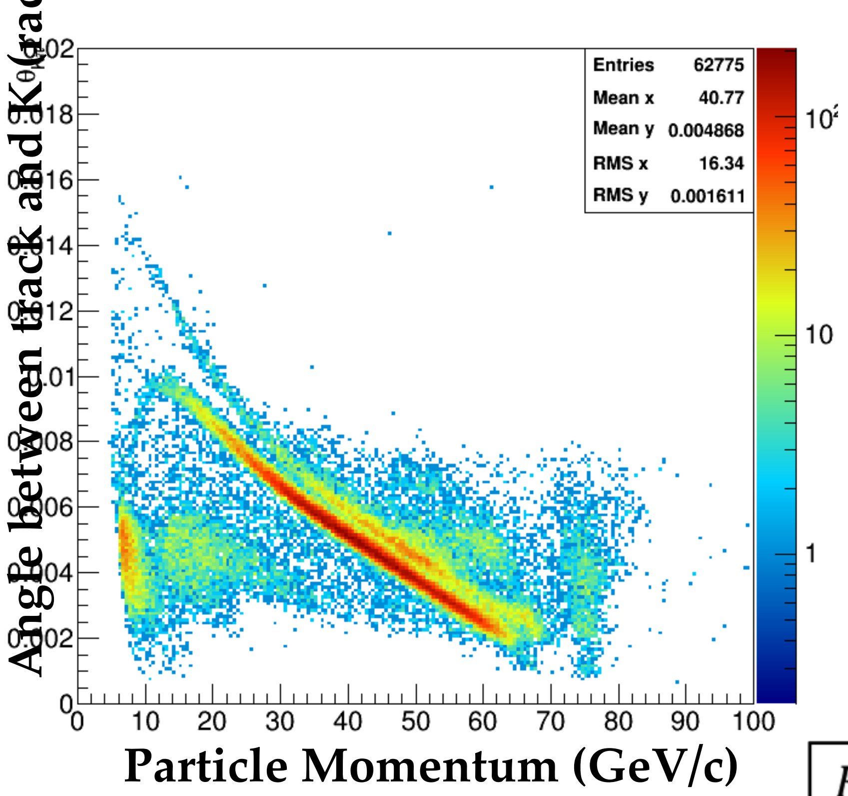
Kaon decay in flight experiments.
NA62: currently ~**200** participants, **29** institutions.
NA62UK: Birmingham, Bristol, Glasgow, Liverpool.

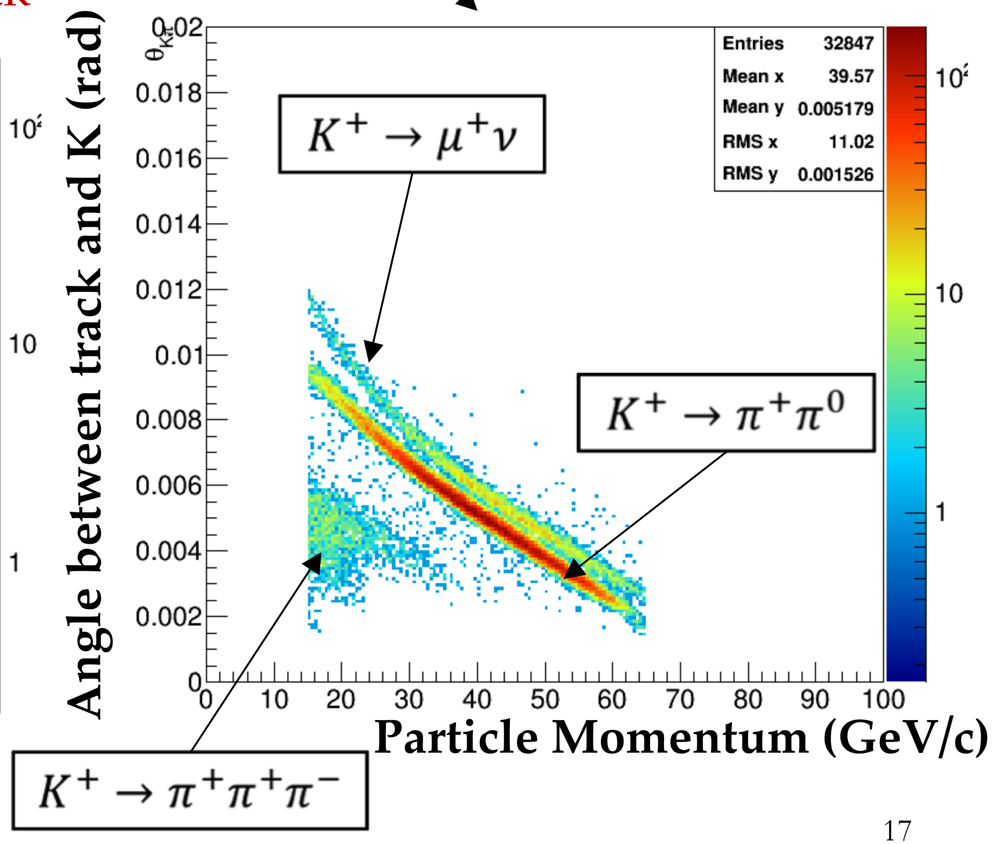
Earlier: NA31

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 phase	2007	$K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
	2008	$K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
NA62	2012-4	commissioning	
	2015-8	physics run	

- Apply KTAG for K ID
- Use track origin to suppress the background from kaon interactions
- Decay vertex from the intersection between the track and the nominal K direction to be in fiducial decay region and momentun cut

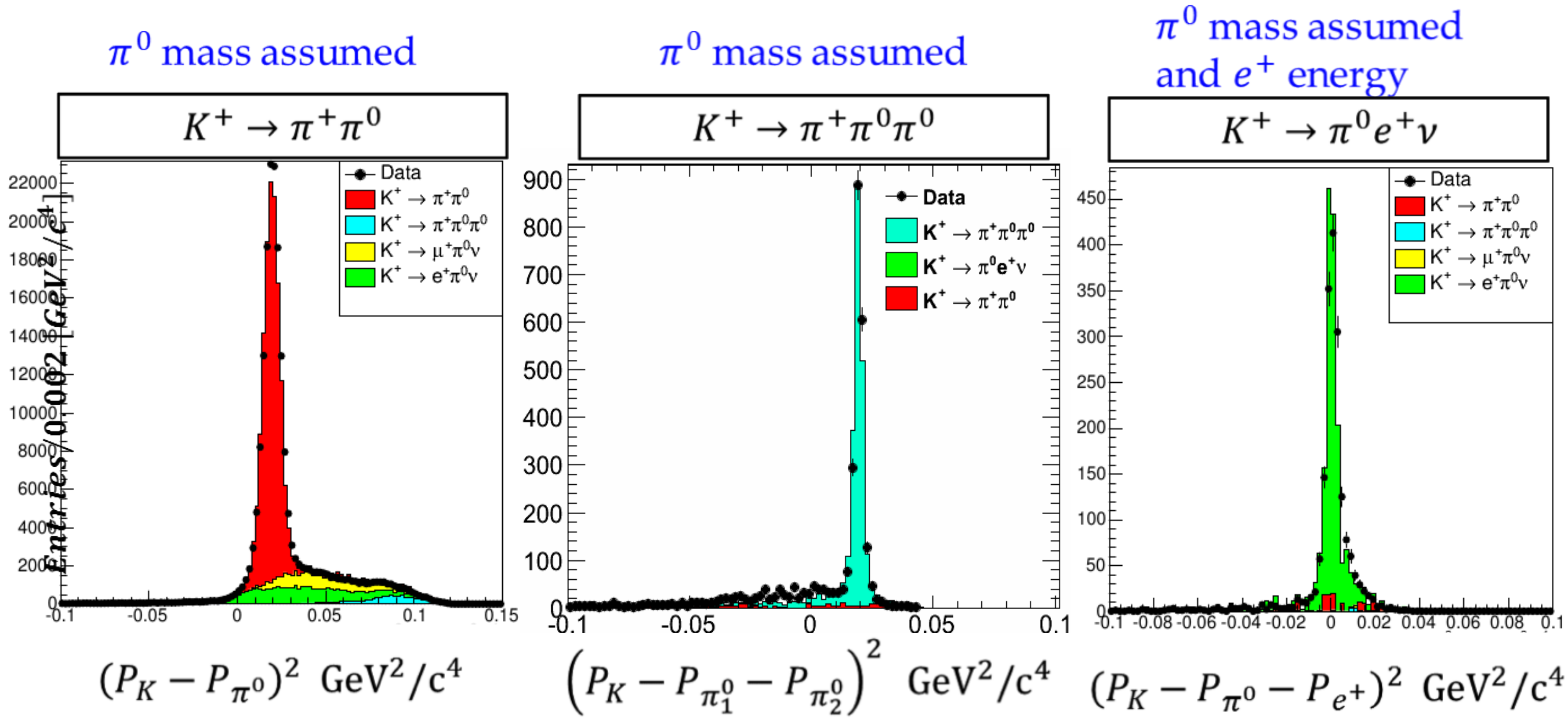
K ID from KTAG in time with the track



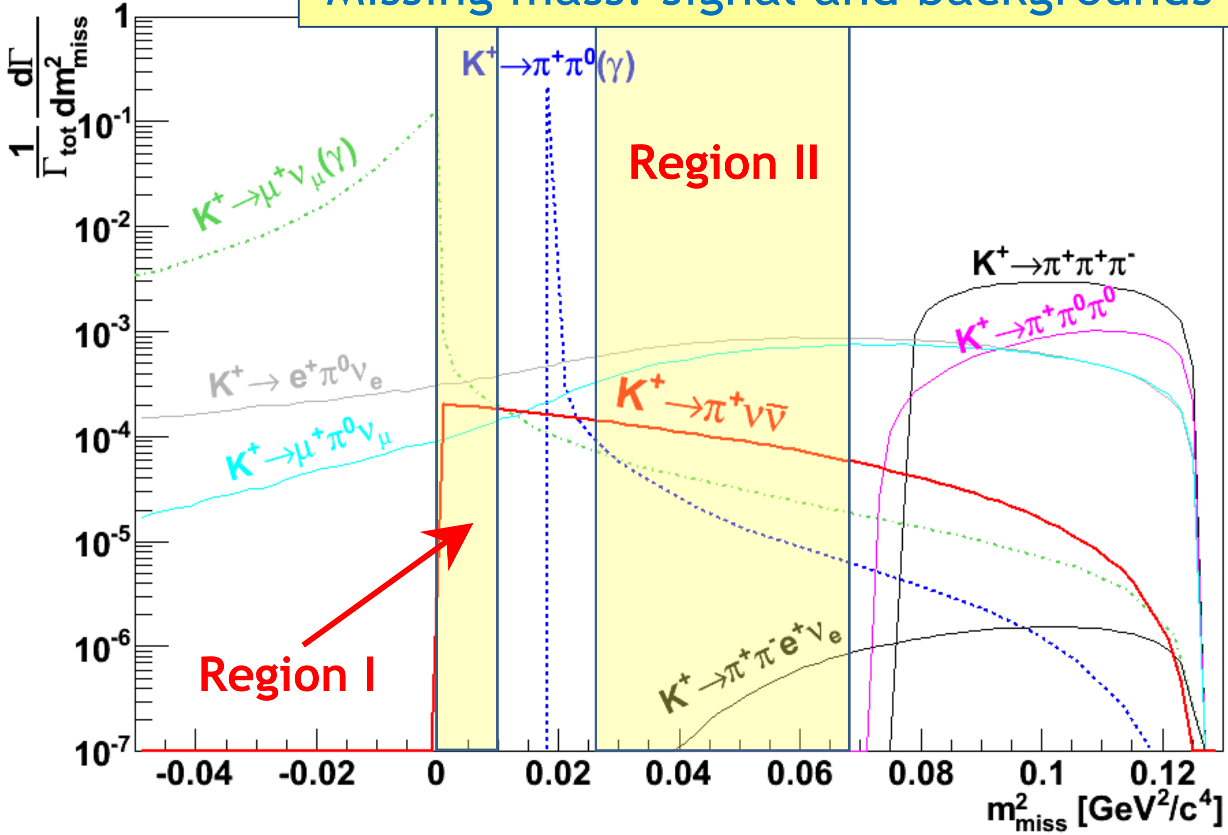


Examples of Control samples

- Kaon decay modes reconstructed with the liquid Krypton calorimeter only (from minimum bias data).
- Useful to measure the kinematic suppression factor, particle ID efficiency …



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



Signal & backgrounds (events/year)	
Signal	45
$K^+ \to \pi^+\pi^0$	5
$K^+ \to \mu^+\nu$	1
$K^+ \to \pi^+\pi^+\pi^-$	<1
Other 3-track decays	<1
$K^+ \to \pi^+\pi^0\gamma$ (IB)	1.5
$K^+ \to \mu^+\nu\gamma$ (IB)	0.5
Total background	<10

92% of total **BR(K^+)**:

- Outside the signal kinematic region.
- Signal region is split into **Region I** and **Region II** by the $K^+ \to \pi^+\pi^0$ peak.

8% of total **BR(K^+)** including multi-body:

- Span across the signal region (not rejected by kinematic criteria).
- Rejection relies on **vetoes**, **PID**.

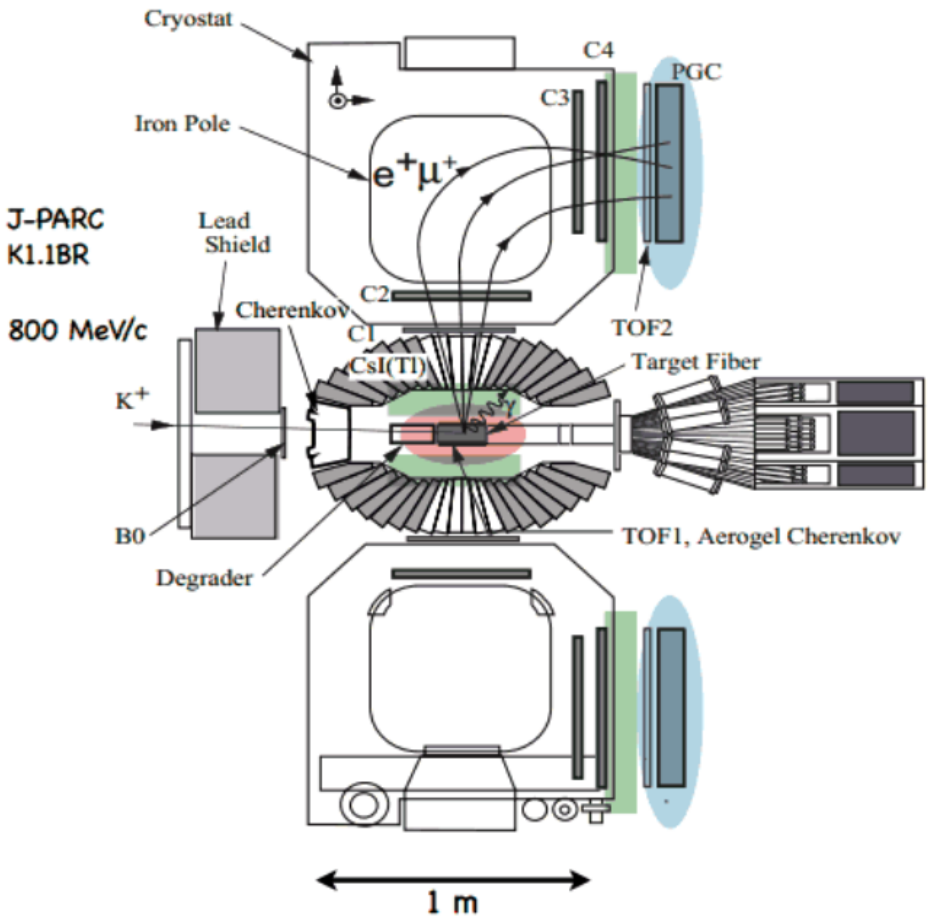
NA62: from K^+ to K_L

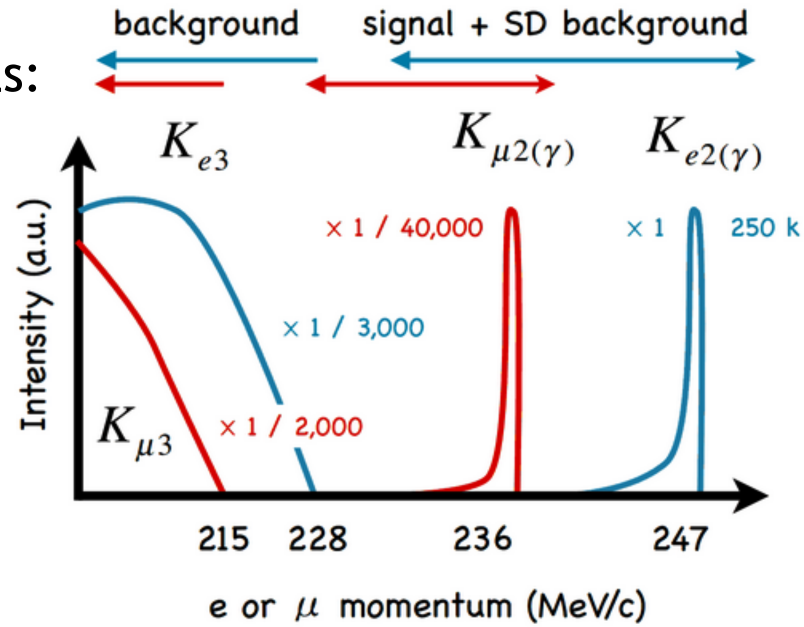
- Possibility of a neutral beam foreseen in the NA62 Technical Proposal: minor changes to production angle and upstream beam optics
- Running for $K_L \to \pi^0 \nu\nu$ or $K_L \to \pi^0 \ell^+ \ell^-$ will require a **substantial increase** in primary intensity, but well within what the SPS can provide.

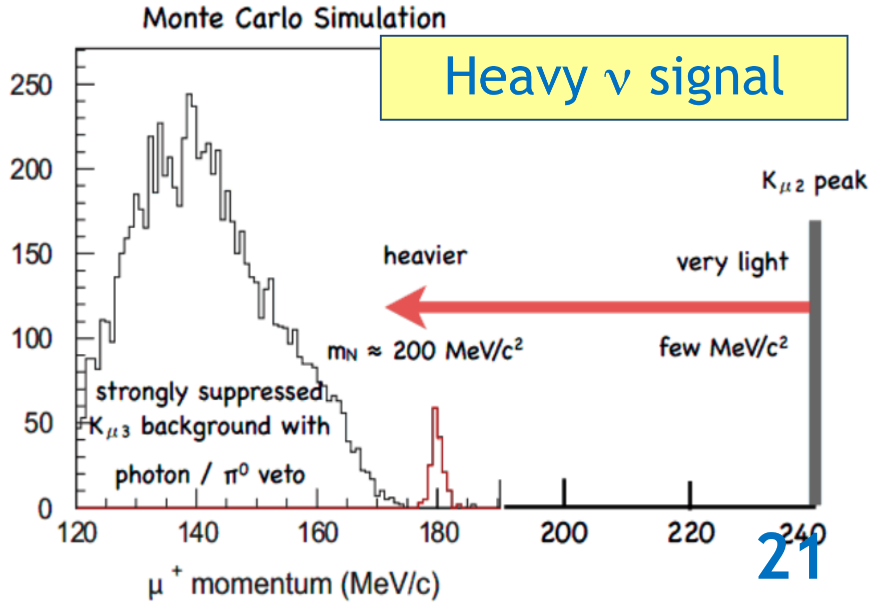
	NA62 K^+ beam	Future NA62 K_L beam
Primary intensity (ppp)	3×10^{12}	2.4×10^{13}
Production angle (mrad)	0	2.4
Angular acceptance (μsr)	12.7	0.125
Momentum	(75±1) GeV/c	97 GeV/c (mean)
Rates in fiducial volume, MHz	$525(\pi)+70(p)+45(K^+)$	$2000(\gamma)+800(n)+90(K_L)$
K decays in fiducial volume	4.5 MHz (4.5×10^{12}/year)	0.9 MHz (0.9×10^{12}/year)

TREK (E36) at J-PARC

Running starts in **FY 2014/15**. Short-term goals:
1) $R_K=\Gamma(K_{e2})/\Gamma(K_{\mu2})$ at 0.25% precision;
2) Heavy sterile neutrino: $BR(K^+\to\mu^+N)\sim10^{-8}$.
3) Dark photon ($\varepsilon^2\sim10^{-6}$): $K^+\to\mu^+\nu U$, $U\to e^+e^-$.



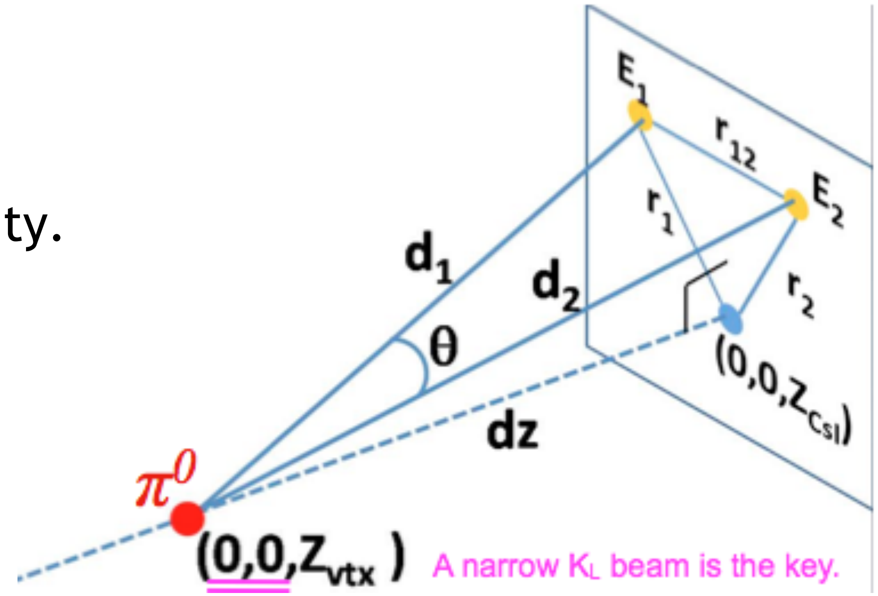




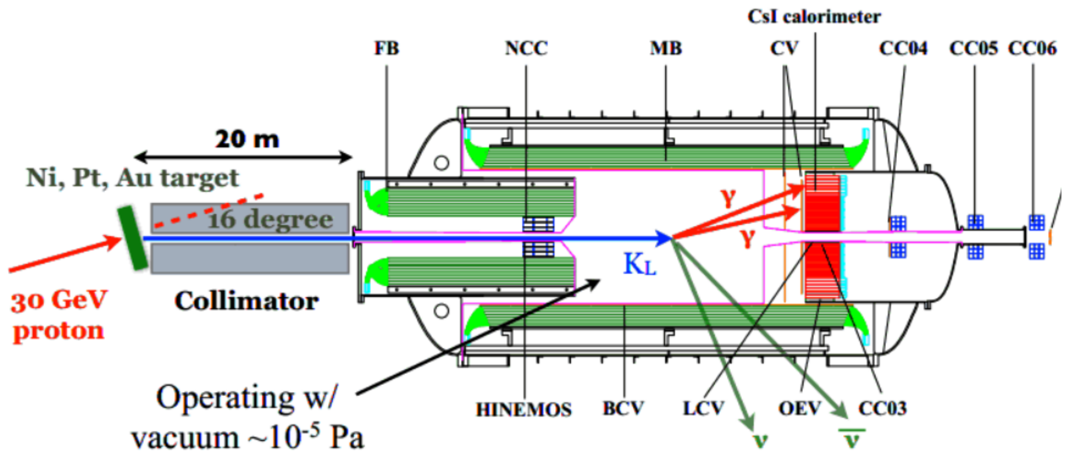
$K_L \to \pi^0 \nu\nu$

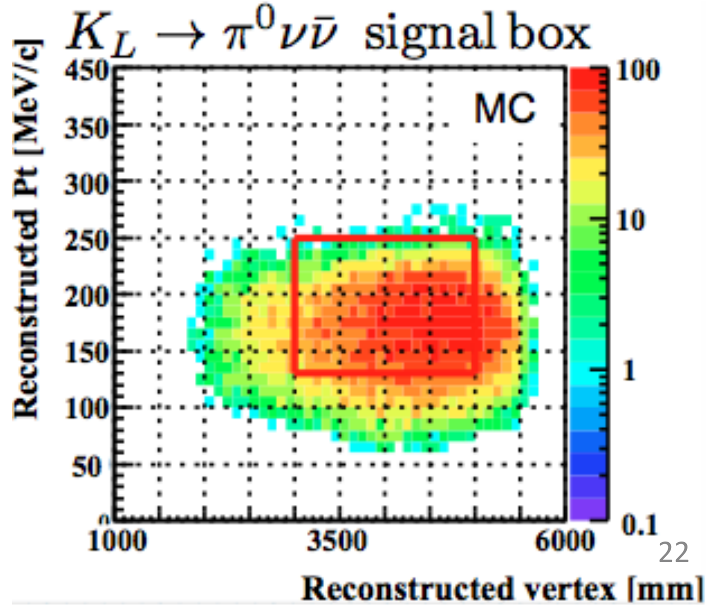
KOTO @ J-PARC (K_L):

- ❖ Builds on KEK E391a technique.
- ❖ E391a: **BR<6.8×10^{-8}** @ 90%CL.
- ❖ Expect **~10^3** times higher sensitivity.
- ❖ Goal: **~3** SM $K_L \to \pi^0 \nu\nu$ events.
- ❖ Data taking: **2013–2017**.
- ❖ Possible step 2: **~100** SM events.

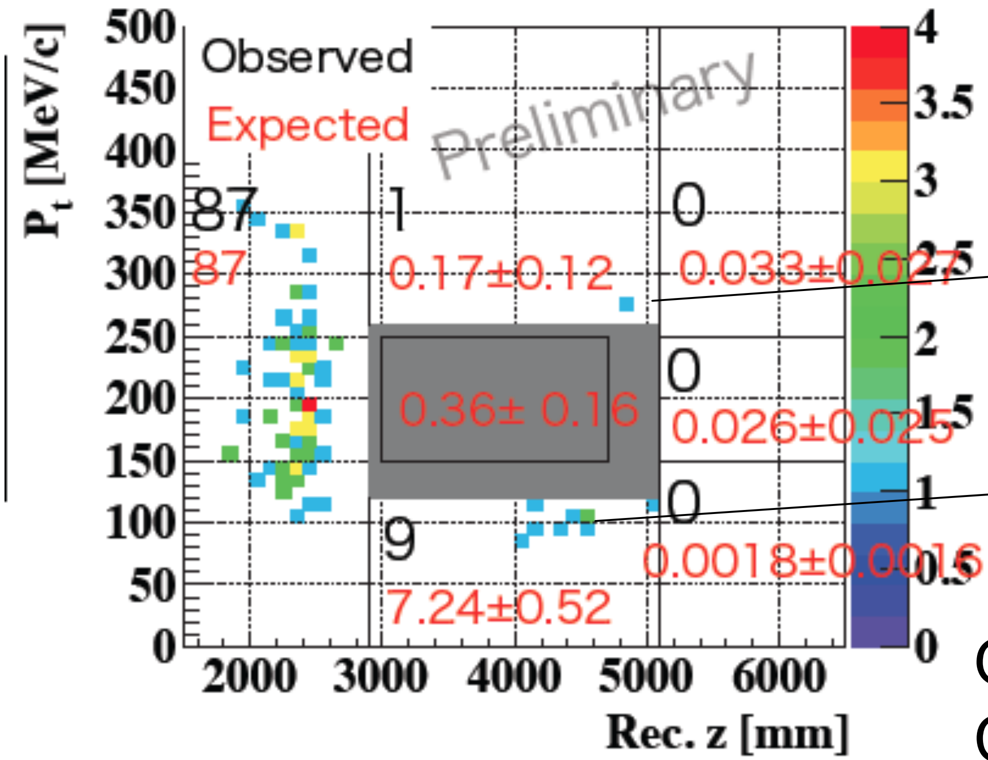


"Two photons + nothing"





KOTO Physics Run in 2013



100 hours, May 2013

Sensitivity = 1.29 10^{-8}

Single neutron makes 2 clusters in calo

$\pi 0 \pi + \pi -$ with charged pions disappearing Due to interactions in beam pipe

Observed 1 event in box, Consistent with SM expectations

Inside signal box:

BG source	#BG
Hadron interaction events	0.18±0.15
Kaon decay events	0.11±0.04
Upstream events	0.06±0.06
Sum	0.36± 0.16

KOTO Physics Run in 2015

Upgrade to reduce backgrounds:
- thinner vacuum window
- removable Al target inside the beam for cross-checks
- upgrade downstream detectors (beam pipe charged veto, beam hole charged veto, beam hole photon veto)

Restarted physics run in April 15
About twice 2013 data already collected,
Analysis is ongoing

Another run in Fall 15

Target sensitivity is 2015 is $O(10^{-9})$

Dark photon: experimental status

M.Pospelov, PRD80 (2009) 095002

Secluded U(1) sector with weak admixture to photons: a natural SM extension.

A new light vector boson: the **dark photon**.

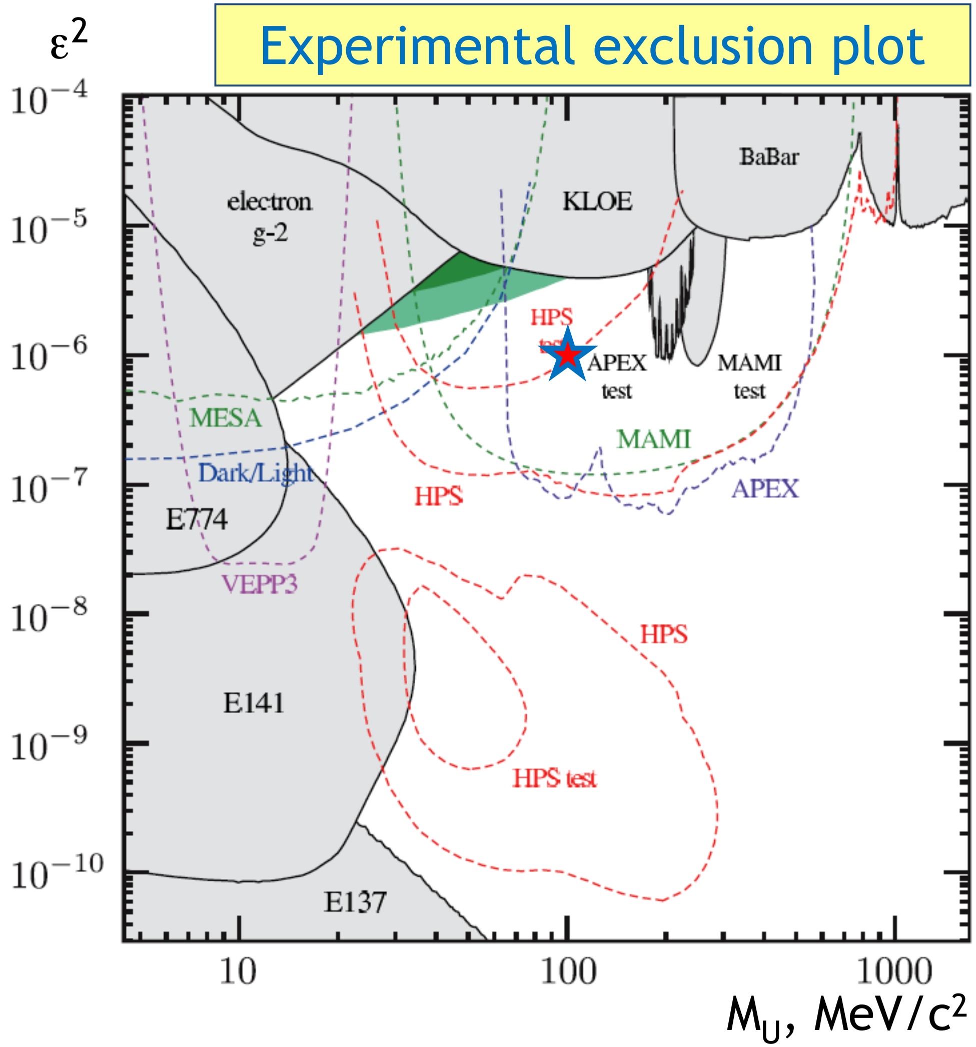
Possible parameters:
mixing parameter: $\varepsilon^2 \sim (\alpha/\pi)^2 \sim 10^{-6}$,
DP mass: $M_U \sim \varepsilon M_Z \sim 100$ MeV/c^2.

Possible explanations for:

Positron excess in cosmic rays (PAMELA, FERMI, AMS-02) by dark matter annihilation

Muon g-2 anomaly

Experimental exclusion plot



Plot from M.Endo et al., PRD86 (2012) 095029

Data Sample

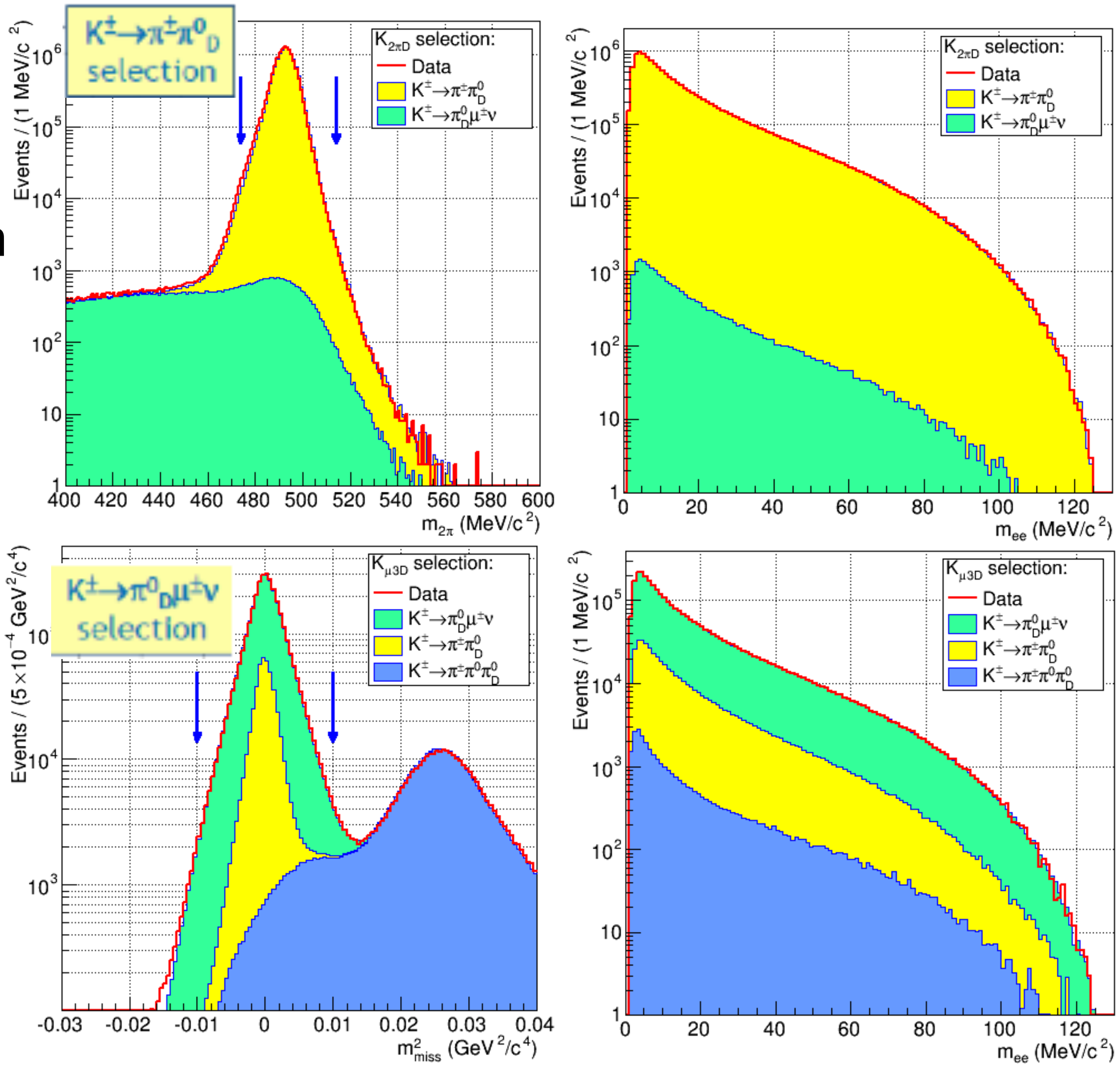
$(1.57\pm0.05)10^{11}$ kaon decays in fiducial volume

$1.7\ 10^{7}\ \pi^{0}$ with negligible mean free path

Search for prompt decay chain
$\pi^{0}\rightarrow\gamma A'\rightarrow\gamma e+e-$
and narrow peak in e+e- mass spectrum
excellent mass resolution
$\sigma_{m} \sim 0.011\ m_{ee}$

Acceptance depending on $m_{A'}$

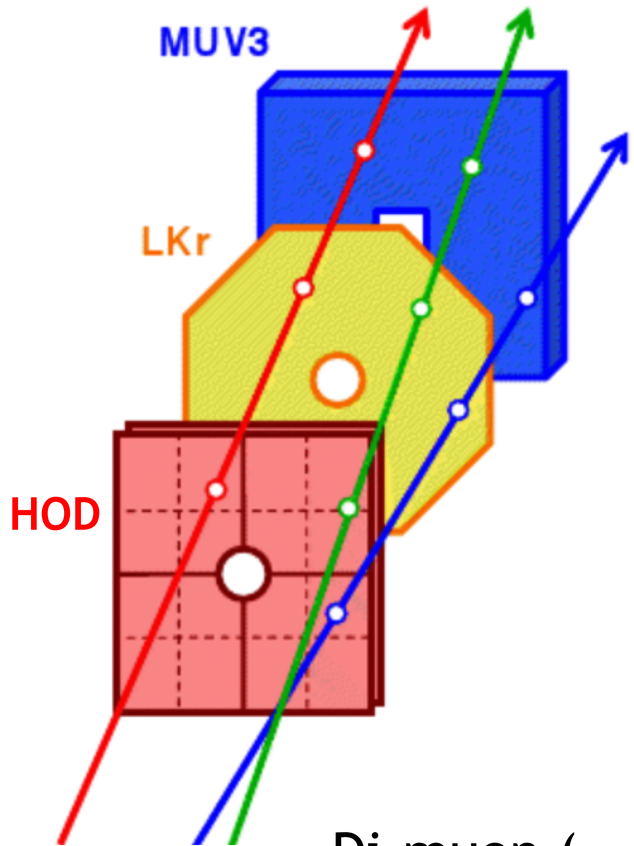
Sensitivity determined by irreducible π^{0}_{D} background



NA62 di-lepton L0 trigger

NA62 three-track decay rate upstream HOD: **F_{3track} = 640 kHz**

→ **Too high** to collect all three-track decays (the NA48/2 approach)



Birmingham-led effort: di-lepton L0 trigger

- Q_N: at least **N** hodoscope quadrants;
- LKR(x): total LKr energy deposit of at least **x** GeV;
- MUV_N: hits in at least **N** MUV3 pads.

L0 trigger conditions for di-lepton collection:

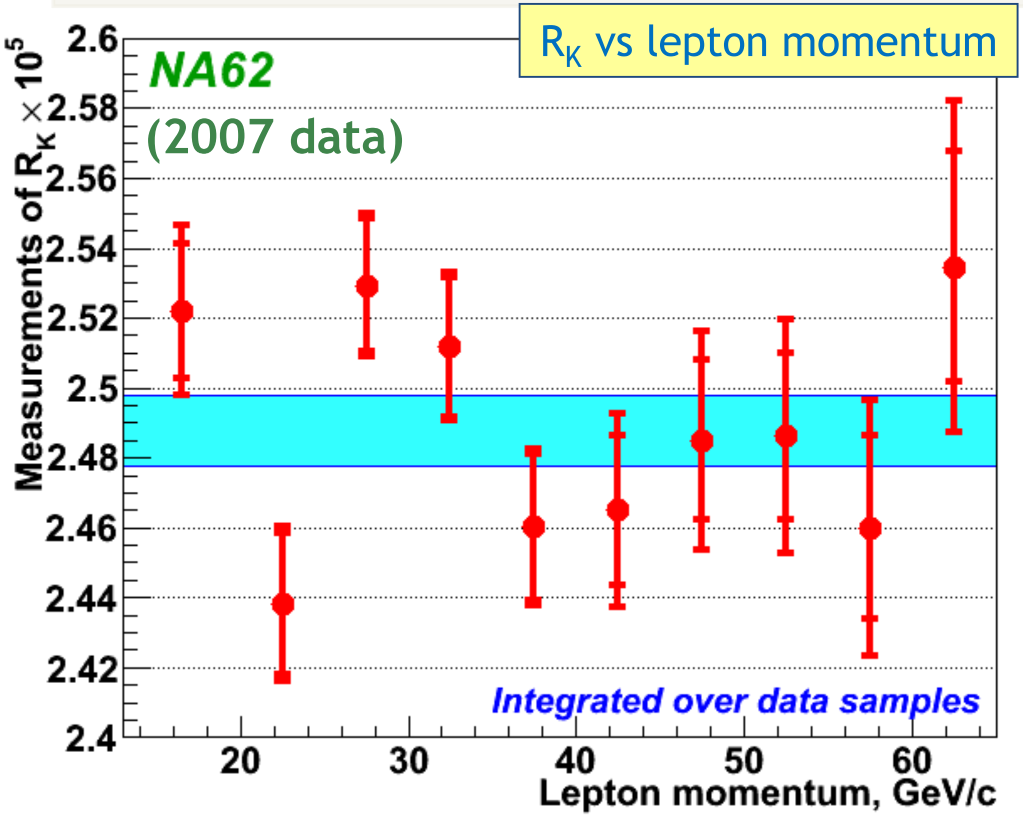
ee pair:	$Q_2 \times LKR(10)$
μe pair:	$Q_2 \times LKR(10) \times MUV_1$
μμ pair:	$Q_2 \times MUV_2$

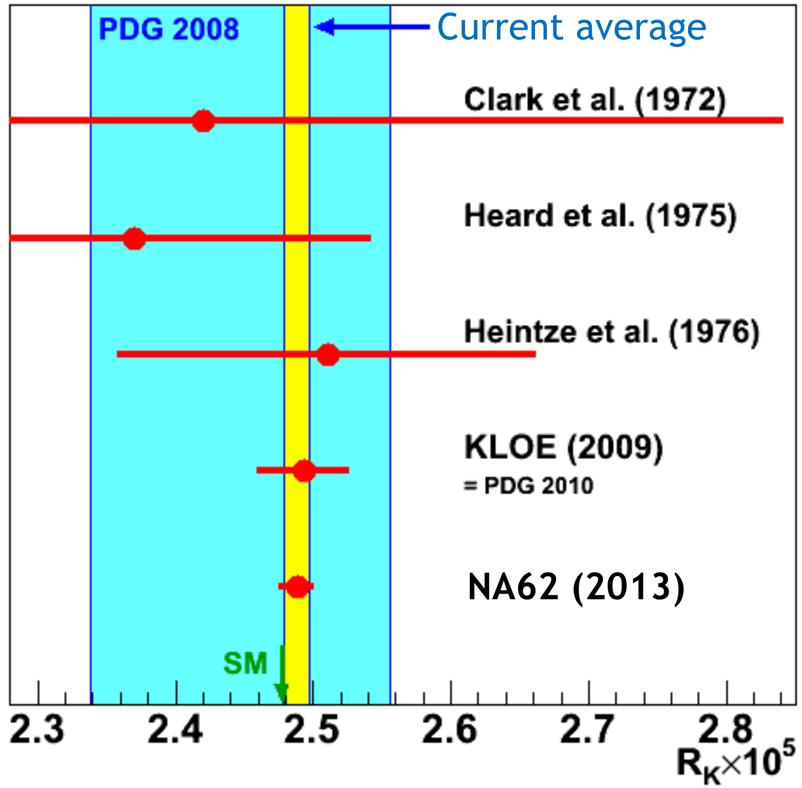
Di-muon (μμ) rate dominated by accidentals;
ee and μe rates dominated by $K^+ \to \pi^+\pi^+\pi^-$ and $K^+ \to \pi^+\pi^0$.
Total rate **F ~ 100 kHz**: charge blind di-lepton collection is feasible.

NA62-R_K final result & prospects

$$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$$
$$= (2.488 \pm 0.010) \times 10^{-5}$$

PLB719 (2013) 326





World average	$R_K \times 10^5$	Precision
PDG 2008	2.447±0.109	4.5%
2013	2.488±0.009	0.4%

Experimental status

Technique: K^+ decay at rest

Data taking: E787 (1995–98), E949 (2002)

Separated K^+ beam (710 MeV/c, 1.6MHz)

PID: range (entire $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain)

Hermetic photon veto system

1.8 x 10^{12} stopped K^+, ~0.1% signal acceptance

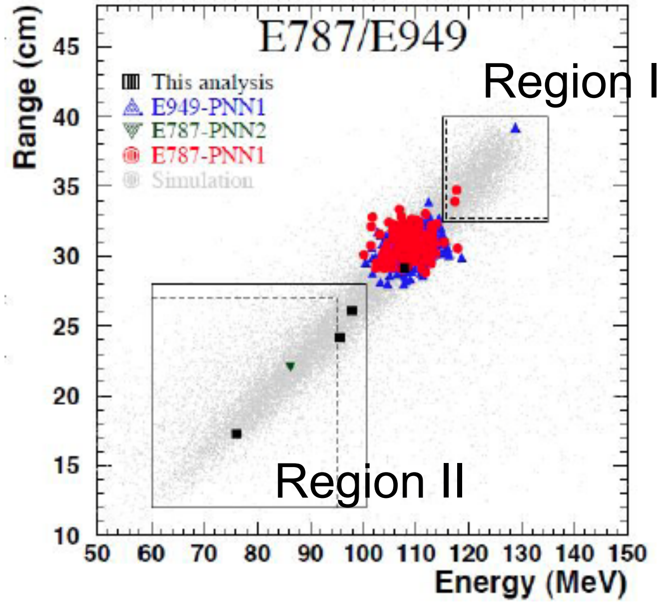
$$BR(K^+ \rightarrow \pi^+ \nu\nu) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$$

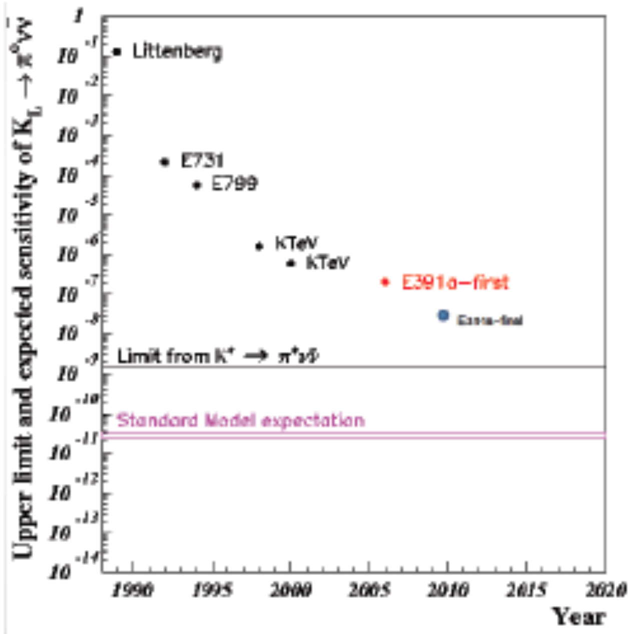
7 observed candidates, 2.6 expected background
Probability that 7 observed events are all background is 10^{-3}

E747/E949 collaborations, Phys. Rev. D 77, 052003 (2008)
Phys. Rev. D 79, 092004 (2009)]

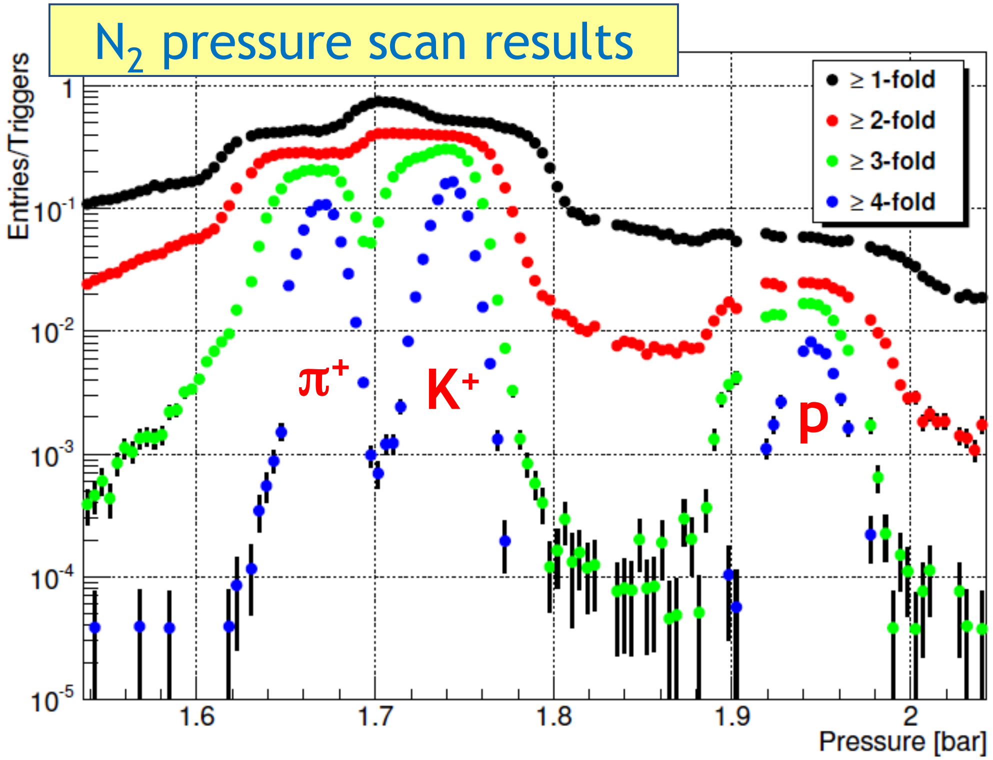
$$BR(K_L \rightarrow \pi^0 \nu\nu) < 2600 \times 10^{-11}$$

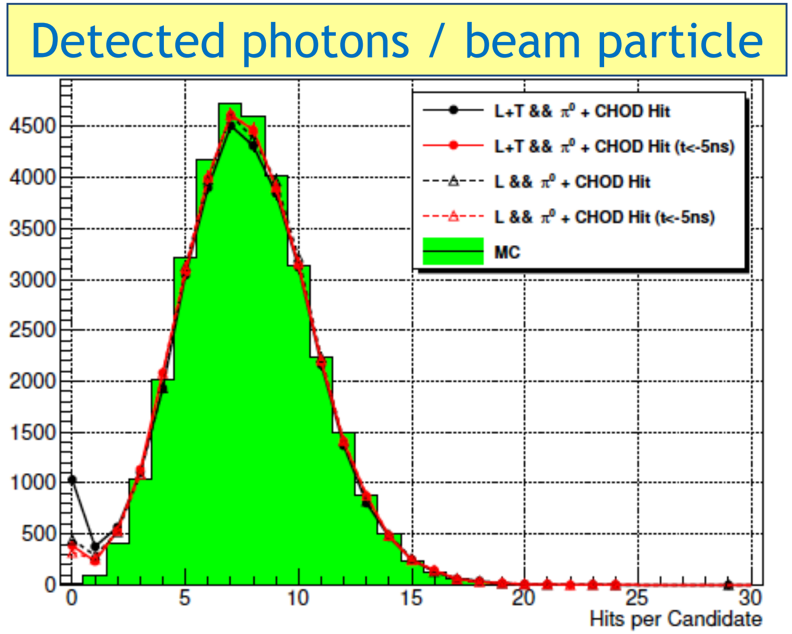
[E391a Collaboration , Phys. Rev. 100, 201802 (2008)]

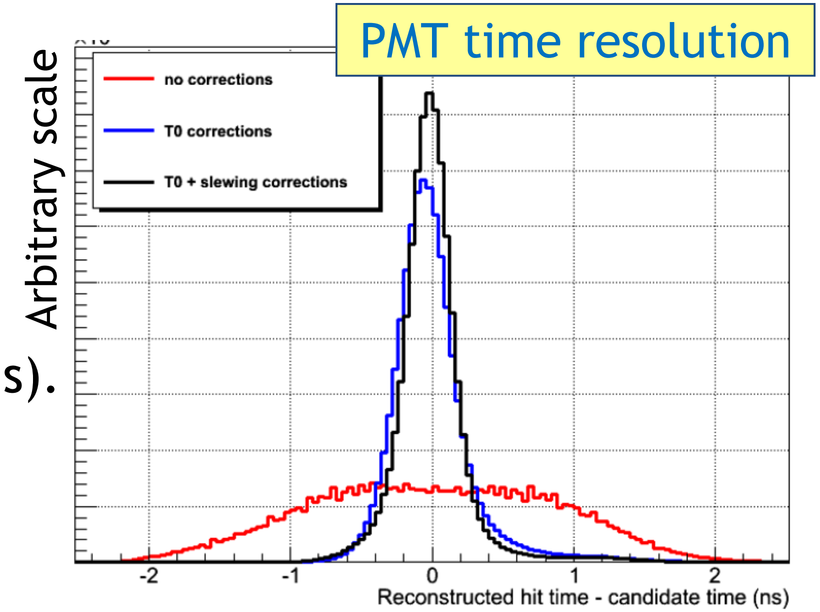




KTAG with 4 octants in 2012







- Pion, kaon and proton peaks are resolved.
- Mean number of detected photons per beam particle: **~8**, similar to expectation.
- Measured PMT time resolution: **280 ps** (rms).
- Kaon tag resolution: **100 ps**, will be improved with the 8-sector setup.