# Precision tests of the Standard Model with Kaon decays at CERN

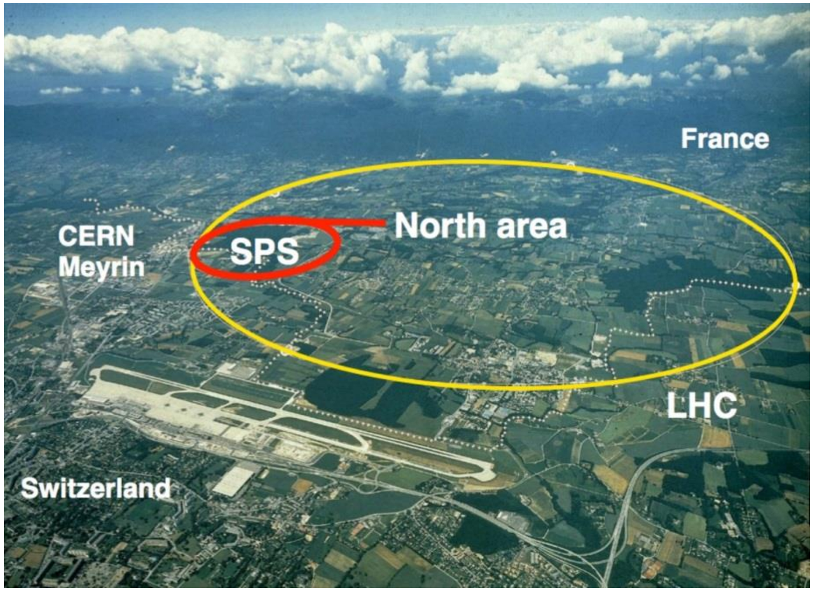
Chris Parkinson, on behalf of the NA62 collaboration

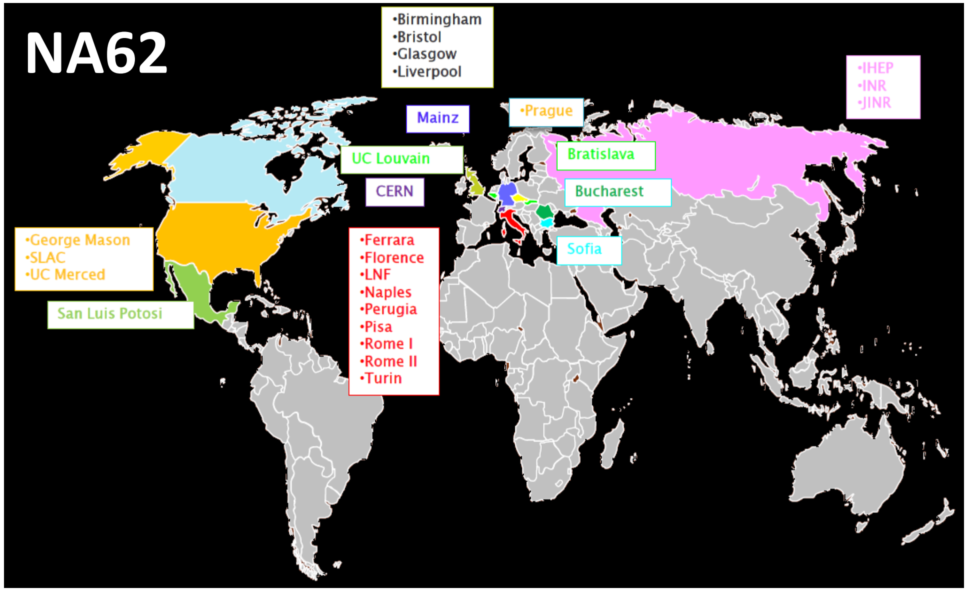
**HQL2014**

# Kaon physics at CERN



- What – three Kaon 'decay-in-flight' experiments: NA48/2, $NA62_{RK}$, NA62
- Where – the North Area (NA) at CERNs Prevessin site
- Who – collaborations of 100-200 scientists
- Why – to search for new physics (effects) in Kaon decays!
  - The NA62 primary physics goal is $K^+ \to \pi^+ \nu\nu$. See talk by Michal Koval

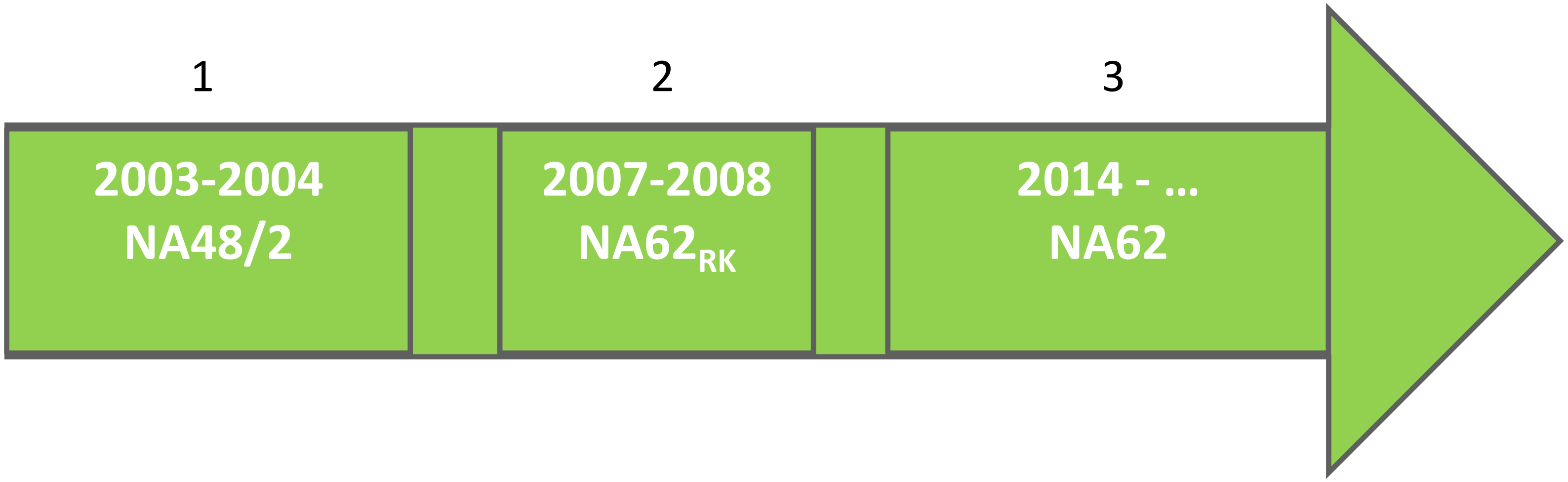


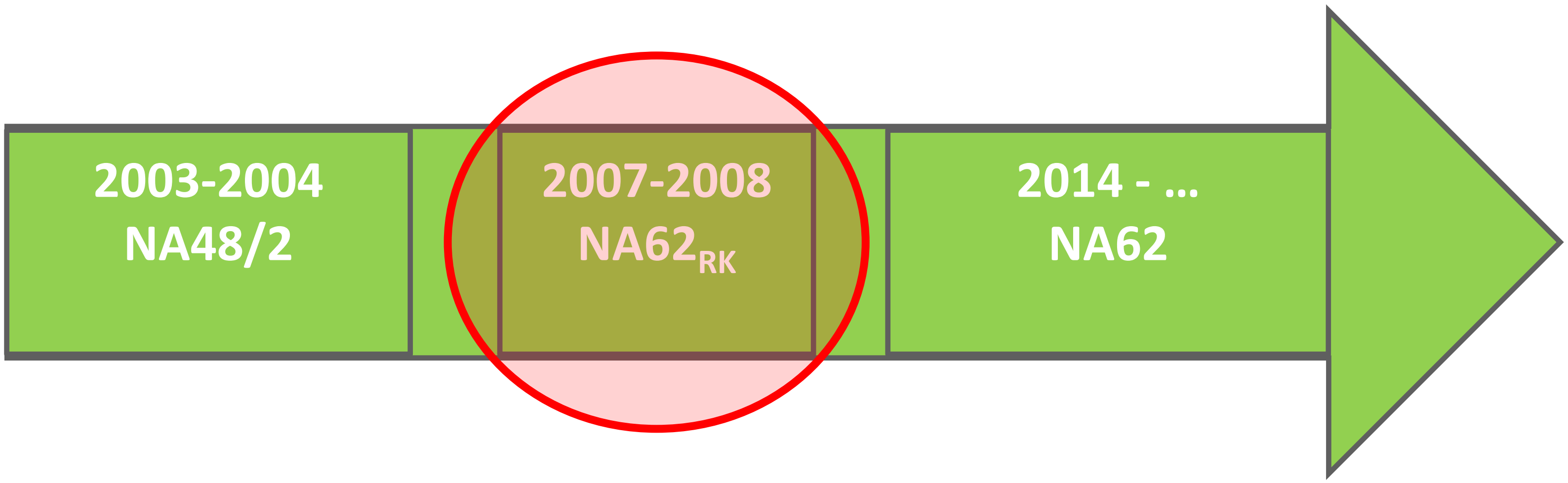
# Kaon physics at CERN



1. NA48/2 – data taking in 2003-2004, using the NA48/2 detector
2. $NA62_{RK}$ – data taking in 2007-2008, using the NA48/2 detector with optimisations for a measurement of $R_K$
3. NA62 – begins data taking in 2014 with new detector



# Precision measurement of $R_K$ at $NA62_{RK}$



# The ratio $R_K$

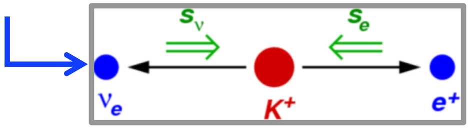
- Precise test of lepton universality in $K^+ \to \ell^+ \nu$

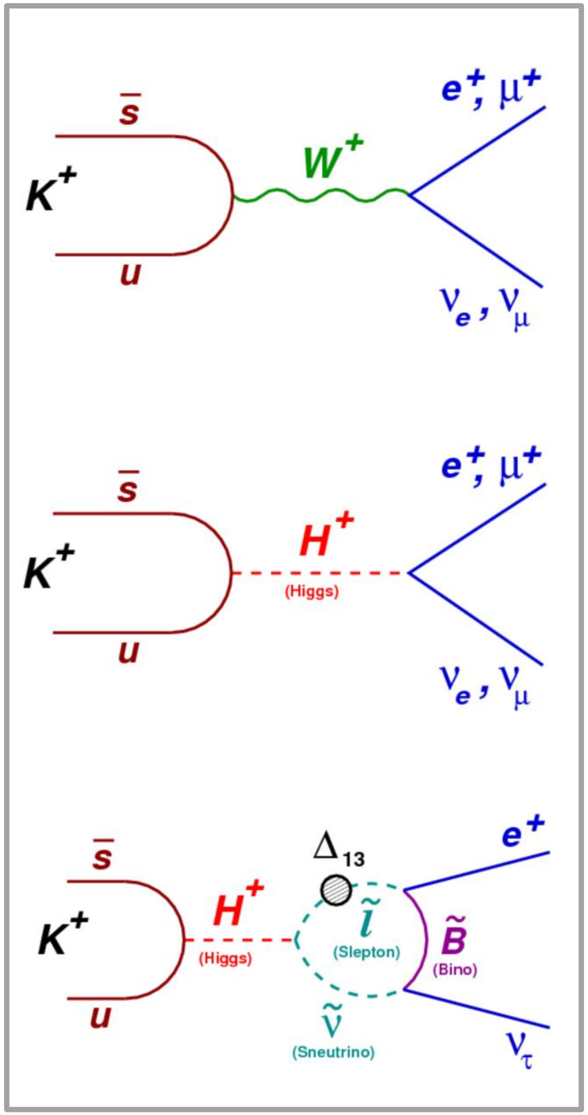
Helicity suppression

Radiative corrections

PRL 99 (2007) 231801

$$R_K^{SM} \equiv \frac{\Gamma(K \to e\nu(\gamma_{IB}))}{\Gamma(K \to \mu\nu(\gamma_{IB}))} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_K^{EM}) = 2.477(1) \times 10^{-5}$$



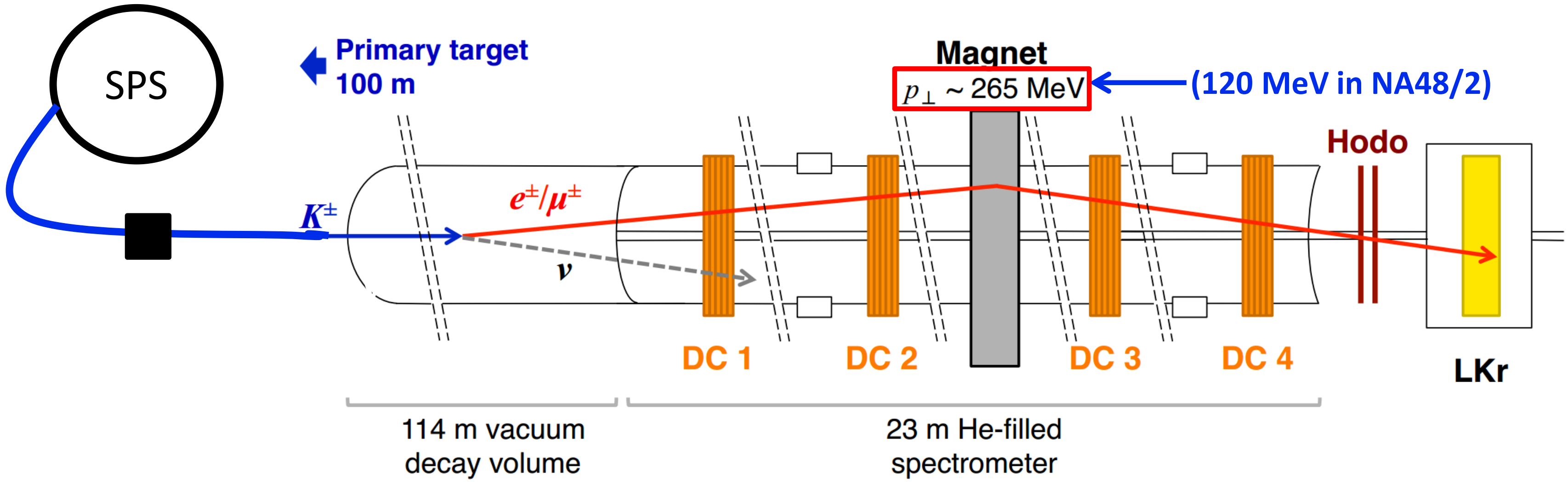

- Value of $R_K$ can be precisely calculated in the SM

- Large contribution from Lepton Flavour Violating (LFV) loop diagrams
  - Sensitivity to slepton mixing

$$R_K^{LFV} \approx R_K^{SM}\left[1 + \frac{m_K^4}{m_H^4}\frac{m_\tau^2}{m_e^2}|\Delta_R^{31}|^2 \tan^6\beta\right] \sim 1\%$$

from **PRD 74 (2006) 011701**

# The NA48/2 and NA62$_{RK}$ experiments




- Kaon yields:

  **NA62$_{RK}$** : ~$10^{10}$ decays in fiducial volume

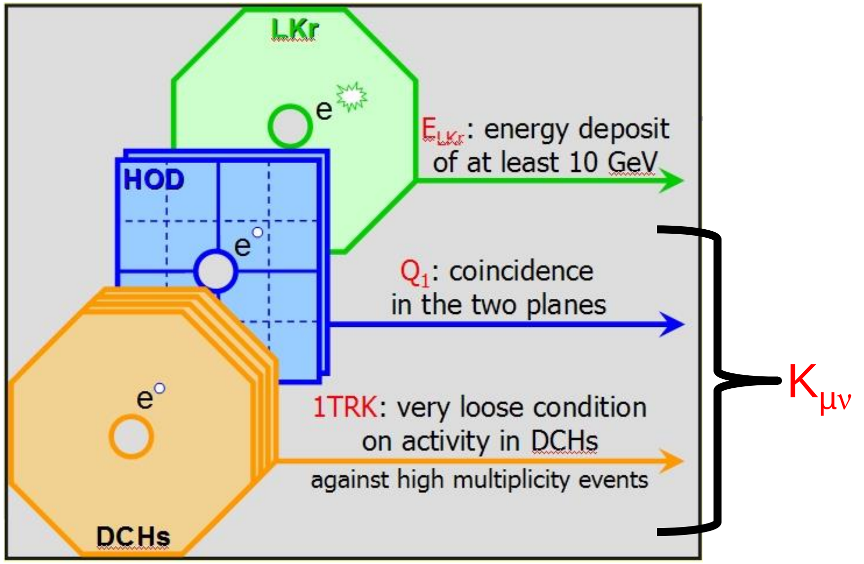
  **NA48/2** : ~$10^{11}$ decays in fiducial volume

- Select $K^+ \to \ell^+\nu$ with a MB trigger

  $K_{\mu\nu}$: 1 track event, downscaled by 1/150

  $K_{e\nu}$ : 1 track event with LKr energy deposit

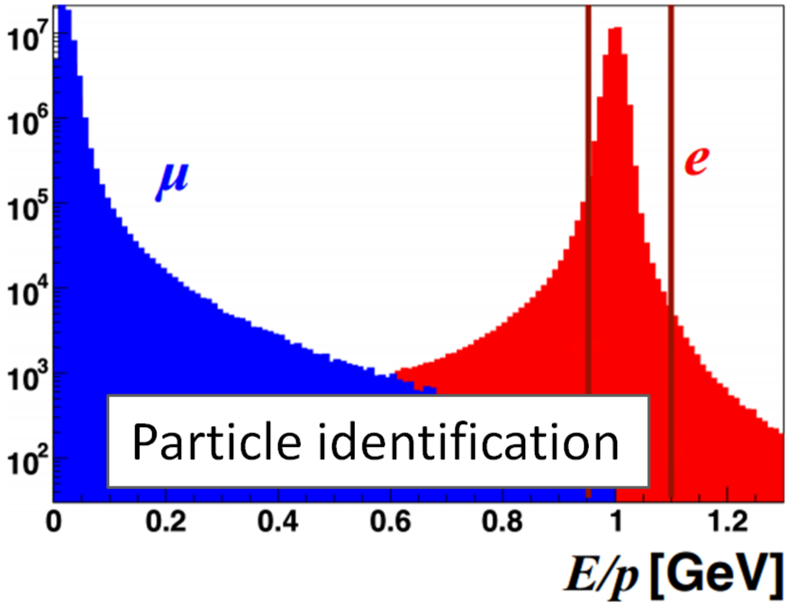
  Event rate of 1 MHz down to 10 kHz



# $R_K$ at $NA62_{RK}$

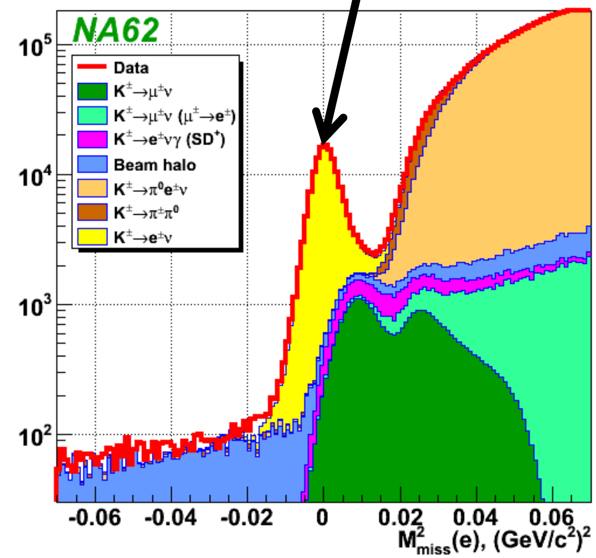


- Must select $K_{e\nu}$ events with low background




+ other selection criteria

146k $K_{e\nu}$ candidates




Background: B/(S+B)=**(10.95±0.27)%**

- **World's most precise** measurement of $R_K$ by $NA62_{RK}$

$$R_K = 2.488(7)_{st}(7)_{sy} \times 10^{-5}$$
$$= 2.488(10) \times 10^{-5} \qquad \Delta_r = 0.011 \pm 0.011$$

0.4% precision

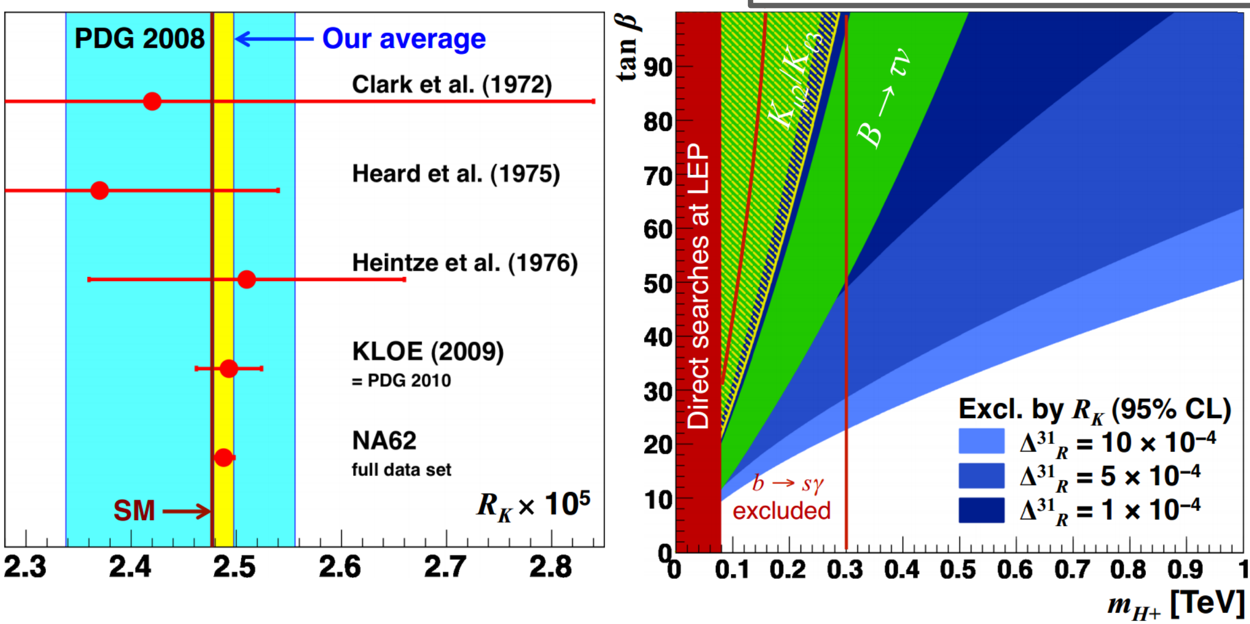
**PLB 719 (2013) 326**

# $R_K$ at $NA62_{RK}$

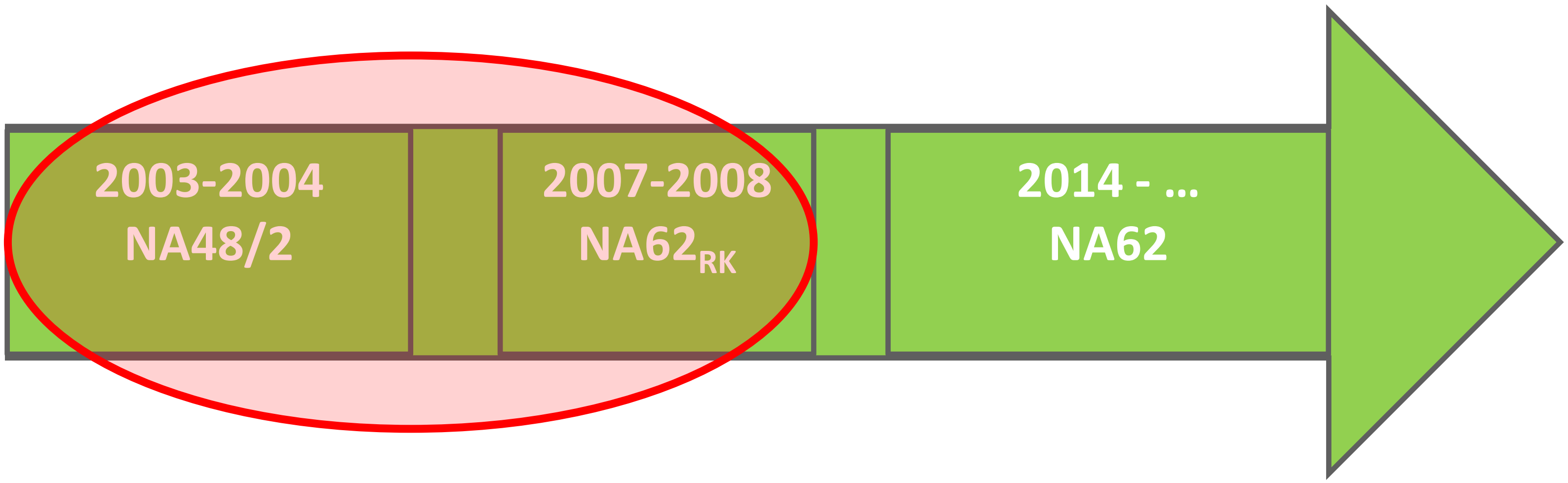
Eur. Phys. J. C64 (2009) 627

1. Considerable improvement over PDG2008 and KLOE (2009)
2. Stringent, model-independent constraints are imposed

e.g. MSSM ($m_{H+}$, tanβ) plane (July 2011)



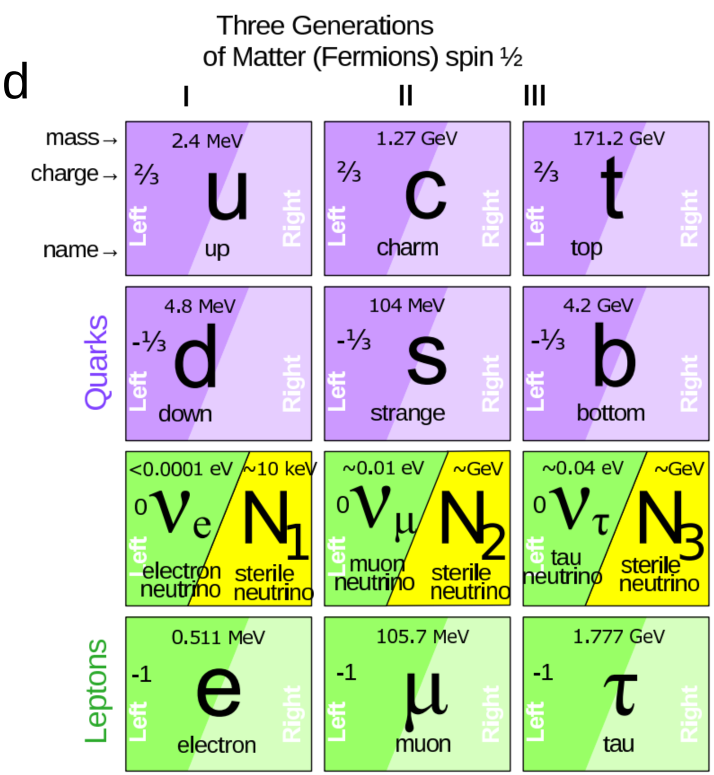
Searches for
1. Heavy Neutral Leptons
2. Dark Photon
with Kaon decays



# Heavy Neutral Leptons



- The **SM** contains three massless, left-handed neutral leptons (neutrinos)
- Since observation of neutrino oscillations, we know that neutrinos are massive. Require RH neutrinos
- Many models exist that incorporate RH neutrinos
- In the **νMSM***, three RH neutrinos are added
  - $N_1$ is light $\mathcal{O}$(few KeV)
  - $N_{2,3}$ are $\mathcal{O}$(100MeV to few GeV)
- This model can account for:
  1. Matter-antimatter asymmetry
  2. **Dark Matter** ($N_1$)
  3. Neutrino mixing




* [PLB 620 17-26], [PLB 631 151-156]

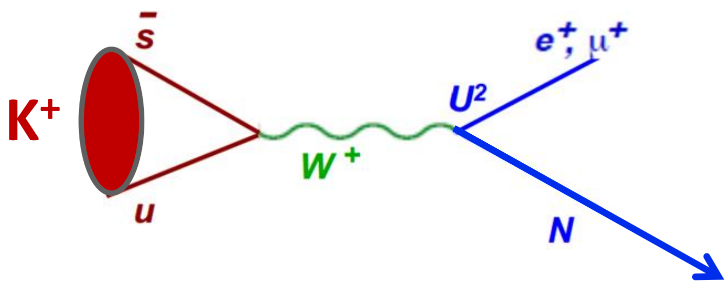
# Heavy Neutral Leptons I

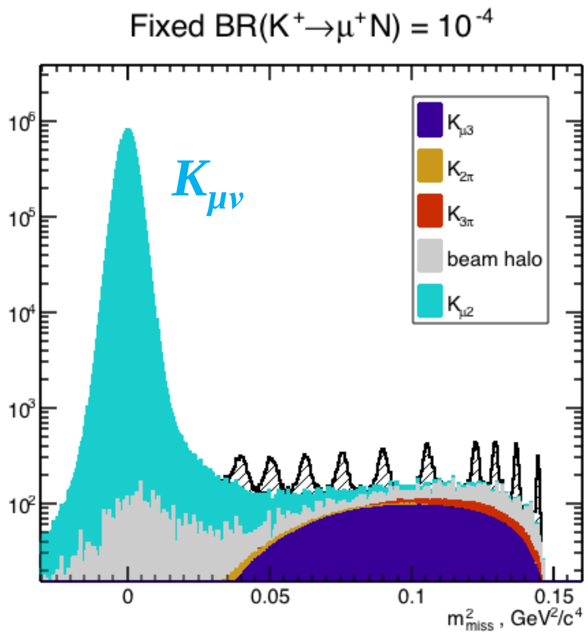


- For a Neutrino with mass $m_\pi \lesssim m_\nu \lesssim m_K$
- Two distinct searches, depending on HNL lifetime $\tau_N$

1. Long lifetime – HNL escapes detector

- **Peak** in $K^+ \to \ell^+ \nu$ missing mass




- Ongoing analysis of the $NA62_{RK}$ data

# Heavy Neutral Leptons II



- For a Neutrino with mass $m_\pi \lesssim m_\nu \lesssim m_K$
- Two distinct searches, depending on Neutrino lifetime $\tau_N$

2. Short lifetime – HNL decays within detector

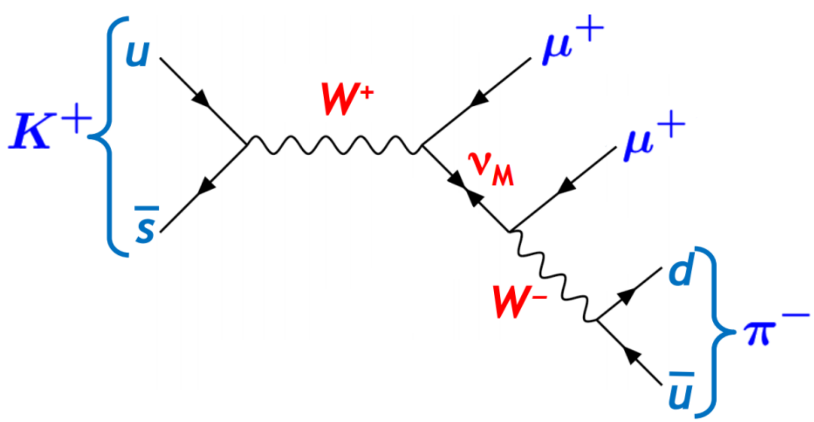
- **Fully reconstruct decay**. No secondary vertex if $\tau_N < 10$ ps

- **Several** final states available , e.g. $K^+ \to \mu^+\mu^+\pi^-$ **Lepton Number Violation!**

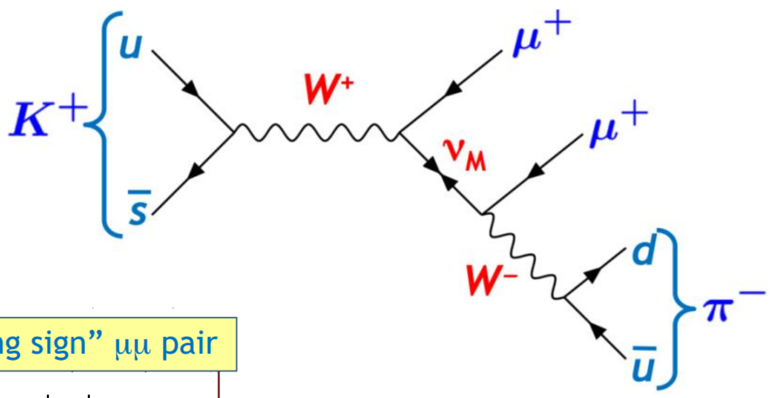
$K^+ \to e^+e^+\pi^-$

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

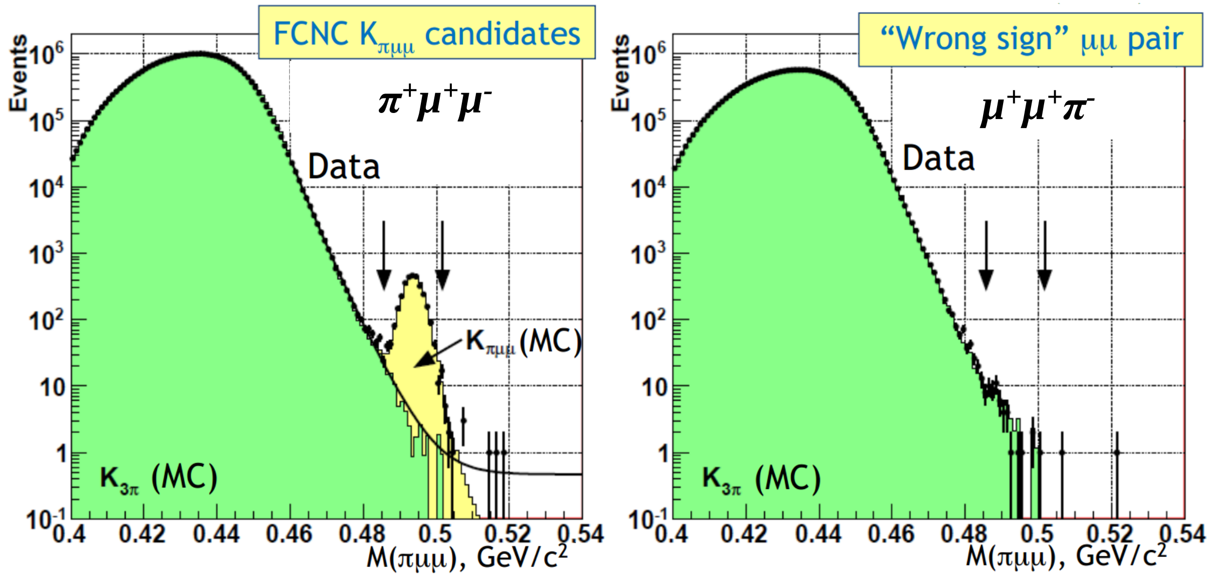
$K^+ \to \mu^+\mu^+e^-\nu$



# Heavy Neutral Leptons II




NA48/2 Analysis of $K^+ \to \mu^+\mu^+\pi^-$



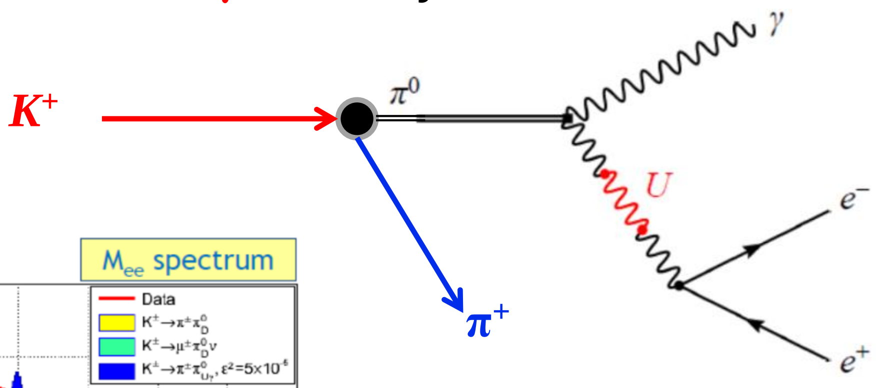

**NA48/2**
**$N_{data}$ = 52**
**$N_{bkg}$ = 52.6 ± $19.8_{sy}$**

- **World's best limit** from NA48/2: [PLB 697(2011)107]

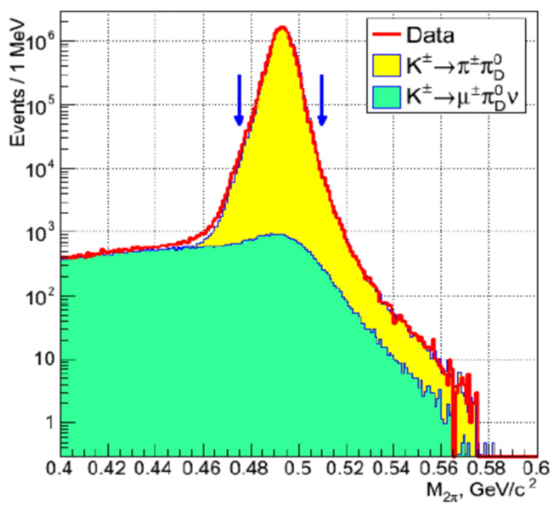
$$\mathcal{B}(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 1.1 \times 10^{-9} \quad \text{@90\% CL}$$

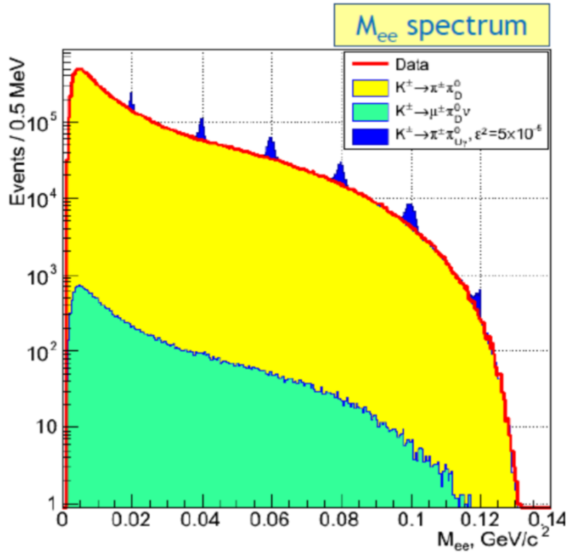
# Dark Photons

- With $\mathcal{B}(K^+\to\pi^+\pi^0)$ ~ 20%, Kaon decays produce a huge number of $\pi^0$, providing access to range of exotic $\pi^0$ decays
- **E.g.** a **dark photon*** that is only visible due to mixing with the SM photon
- Expect contributions of **dark photon** to $\pi^0\to\gamma ee$ decays




**$K^+\to\pi^+\pi^0$ peak**

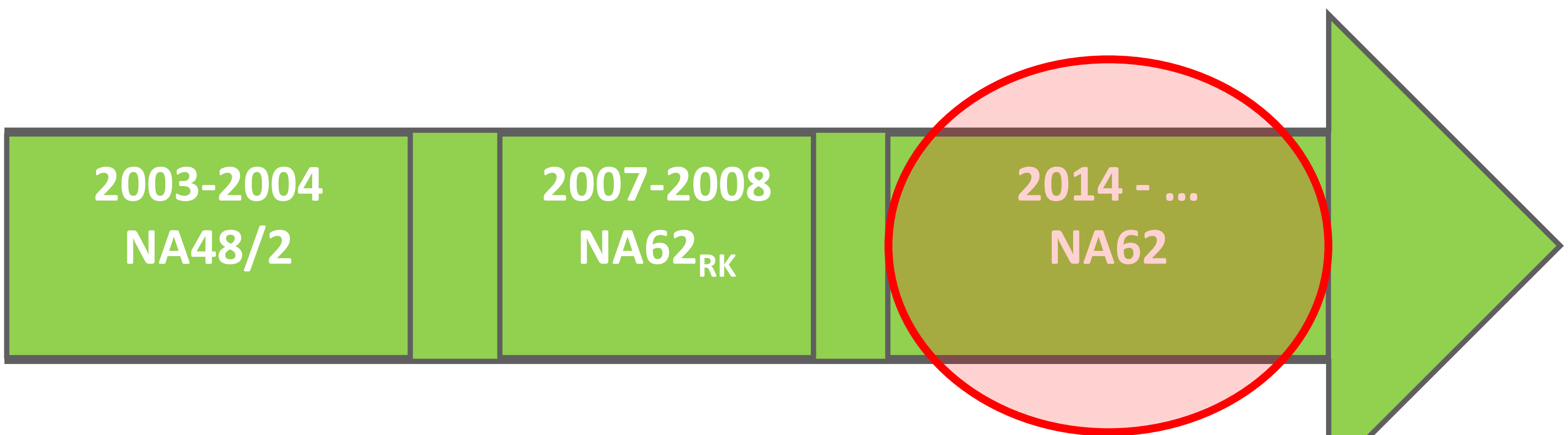



*see for example:
Nuclear Physics B 683 (2004)
Phys. Letters B 671 391
Phys. Rev. D 79 023519

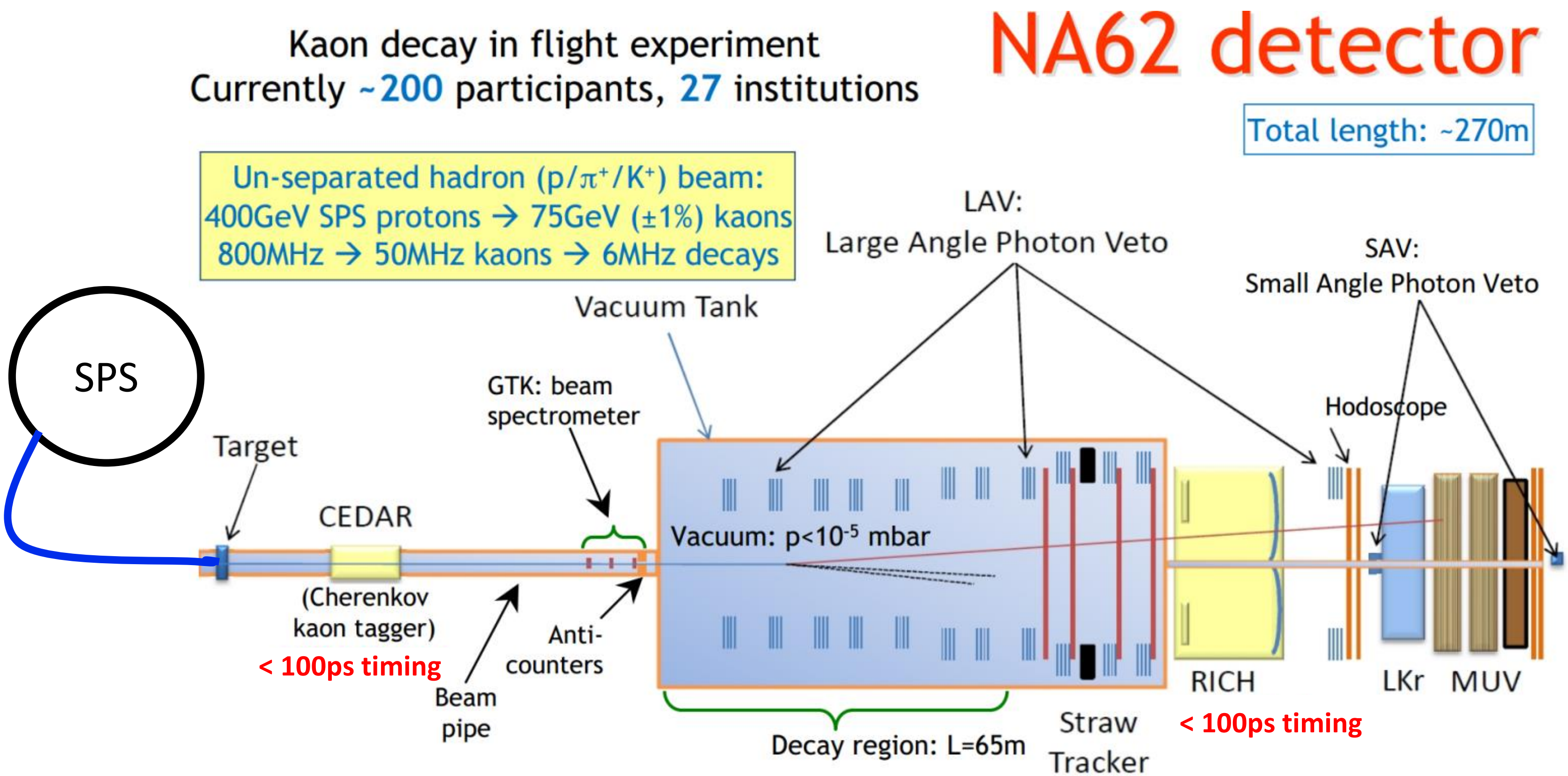
- Ongoing analysis of the NA48/2 data

# The NA62 Experiment



# The NA62 Experiment






Kaon flux expected ~ 60x higher than NA48/2

Expect ~$10^{13}$ $K^+$ decays in fiducial volume in 2 years

# The NA62 Trigger



- The particle flux of ~ 10 MHz demands a highly selective trigger

- Split the trigger into three stages:

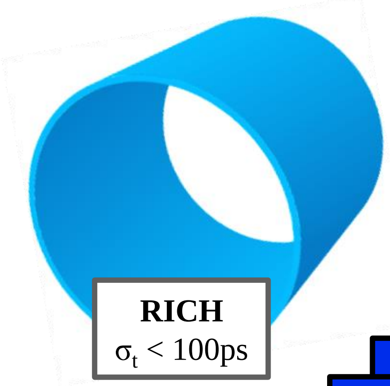
- **L0 Trigger**: Hardware (FPGA). Input rate: 10MHz, Output rate: 1MHz
  - Around 200kHz required for $K^+ \rightarrow \pi^+ \nu\nu$ trigger
  - Leaves 800kHz for (other studies + control channels)

    **~ few 100 kHz** for exotic decay program
- **L1 Trigger**: Software (Single detector). Output rate: ~100kHz
- **L2 Trigger**: Software (Full information). Output rate: ~ few kHz

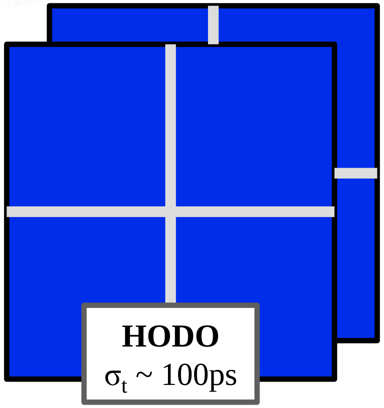
- **Next slides: Outline a prospective L0 trigger strategy**

# The NA62 L0 Trigger

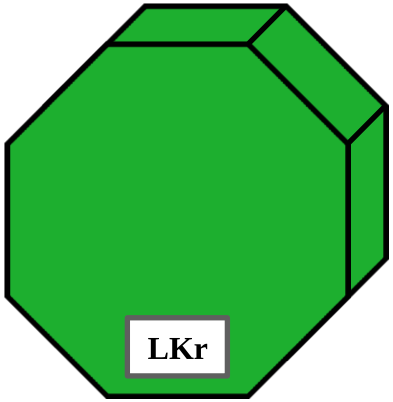
- The **RICH** : $R_N$ primitive
  - Number of hit **RICH** PMTs
    - $R_4 \rightarrow$ single track
    - $R_{10} \rightarrow$ multiple tracks




- The **HODO: $Q_1$, $Q_X$** primitives
  - $Q_1$: One **HODO** quadrant with coincident hits
    $\rightarrow$ single track
  - $Q_X$: Coincident hits in opposite **HODO** quadrants
    $\rightarrow$ multiple track from Kaon decay

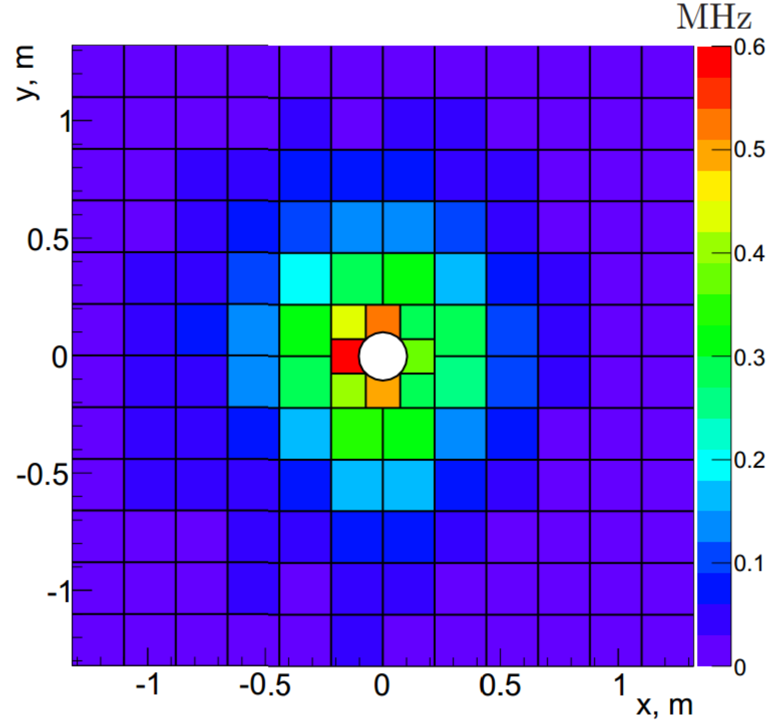


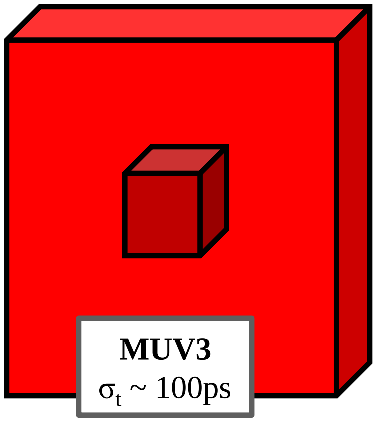

- The **LKr : $E_{10}$** primitive
  - $E_{10}$: 10 GeV deposited in **LKr**



# The NA62 L0 Trigger

- The muon rate is ~ 14 MHz
- Contributions from
  - Beam halo: 4 MHz
  - $\pi^+ \to \mu^+ \nu$ decays in the beam : 3 MHz in single 'inner' pad
- The **MUV3 : $MO_N$** primitives
  - **$MO_1$** : Hit in one outer **MUV3** pad
  - **$MO_2$** : Coincident hits in two outer **MUV3** pads
- **$MO_2$** trigger rate dominated by accidental coincidences, despite $\sigma_t$ ~ 100ps
- **NB: $!M_1$** : Muon veto condition for $K^+ \to \pi^+ \nu \nu$



# The NA62 L0 Trigger

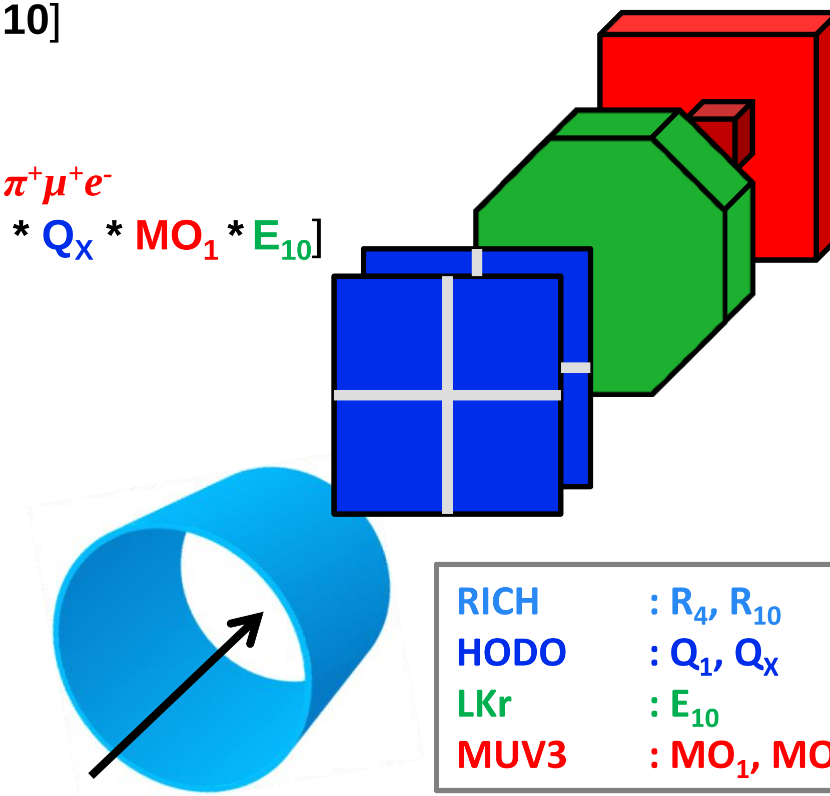
- General minimum bias triggers, e.g. monitoring the number of *K*+ decays
  - **Single track** (ST) : F[**$R_4$** * **$Q_1$** **/ 1000**]
  - **Multiple track** (MT) : F[**$R_{10}$** * **$Q_X$** **/ 100**]

- For decay with substantial rates, lacking distinctive signatures, e.g. $K^+ \to e^+\nu$
  - **Track + EM energy** (TE) : F[**$R_4$** * **$Q_1$** * **$E_{10}$** **/ 50**]

- Searches for **LNV**, **rare decays** and the **dark photon,** e.g. $K^+ \to \mu^+\mu^+\pi^-$, $K^+ \to e^+e^+\pi^-$
  - **Dielectron** (2E) : F[**$R_{10}$** * **$Q_X$** * **$E_{10}$** **/ 10**]
  - **Dimuon** (2M) : F[**$R_{10}$** * **$Q_X$** * **$MO_2$**]

- Search for **LFV** decays, and **HNLs**, e.g. $K^+ \to \pi^+\mu^+e^-$
  - **Muon+tracks+EM energy** (MTE) : F[**$R_{10}$** * **$Q_X$** * **$MO_1$** * **$E_{10}$**]

The total rate from the above L0 triggers ~ few 100 kHz



| | |
|---|---|
| **RICH** | **: $R_4$, $R_{10}$** |
| **HODO** | **: $Q_1$, $Q_X$** |
| **LKr** | **: $E_{10}$** |
| **MUV3** | **: $MO_1$, $MO_2$** |

# Physics prospects for NA62



Assume ~ 1% acceptance (pessimistic), no trigger downscaling

Single Event Sensitivity = 1 / ($N_{K+}$ * acceptance)

| Decay | Physics | Trigger | NA62 Prospects |
|---|---|---|---|
| $R_K$ | LU | TE | x2 better |
| $\pi^+\mu^+e^-$ | LFV | MTE | $\sim10^{-11}$ |
| $\pi^+\mu^-e^+$ | LFV | MTE | $\sim10^{-11}$ |
| $\pi^-\mu^+e^+$ | LNV | MTE | $\sim10^{-11}$ |
| $\pi^-e^+e^+$ | LNV | 2E | $\sim10^{-11}$ |
| $\pi^-\mu^+\mu^+$ | LNV | 2M | $\sim10^{-11}$ |
| $\mu^-\nu e^+e^+$ | LNV/LFV | 2E | $\sim10^{-11}$ |
| $e^-\nu\mu^+\mu^+$ | LNV | 2M | $\sim10^{-11}$ |
| $\pi^+e^+e^-, \pi^+\mu^+\mu^-$ | Rare, $\gamma_D$ | 2E/2M | $10^4$ events |
| $\pi^+\gamma e^+e^-, \pi^+\gamma\mu^+\mu^-$ | Rare | 2E/2M | $10^2$ (10) events |
| $\pi^+\pi^0e^+e^-, \pi^+\pi^0\mu^+\mu^-$ | Rare | 2E/2M | $10^3$(few) events |
| $e^+\nu\mu^+\mu^-, \mu^+\nu\mu^+\mu^-$ | Rare | 2M | $10^3$ events |
| $\pi^+X^0$ | New particle | ST | $\sim10^{-11}$ |
| $\pi^+\chi\chi$ | New particle | ST | $\sim10^{-11}$ |
| $\pi^+\pi^+e^-\nu$ | $\Delta S \neq \Delta Q$ | MTE | $\sim10^{-11}$ |
| $\pi^+\pi^+\mu^-\nu$ | $\Delta S \neq \Delta Q$ | MT | $\sim10^{-11}$ |
| $\pi^+\gamma$ | Ang. Mom. | TE | $\sim10^{-11}$ |
| $\mu^+N, N\rightarrow\nu\gamma$ | HNL | TE | $\sim10^{-11}$ |
| $N\rightarrow\mu^+\rho^-, \rho^-\rightarrow\pi^+\pi^0$ | HNL | MTE | |
| $\pi^+\gamma\gamma$ | $\chi$PT | TE | $10^5$ events |
| $\pi^0\pi^0e^+\nu$ | $\chi$PT | TE | $10^6$ events |
| $\pi^0\pi^0\mu^+\nu$ | $\chi$PT | TE | $10^5$ events |

# Physics prospects for NA62



## $R_K$

| Source | B/(S+B) |
|---|---|
| $K_{\mu 2}$ | (5.64±0.20)% |
| $K_{\mu 2}$ ($\mu \rightarrow e$) | (0.26±0.03)% |
| $K_{e2\gamma}$ (SD) | (2.60±0.11)% |
| $K_{e3(D)}$ | (0.18±0.09)% |
| $K_{2\pi(D)}$ | (0.12±0.06)% |
| Opposite sign K | (0.04±0.02)% |
| Beam halo | (2.11±0.09)% |
| Total | (10.95±0.27)% |

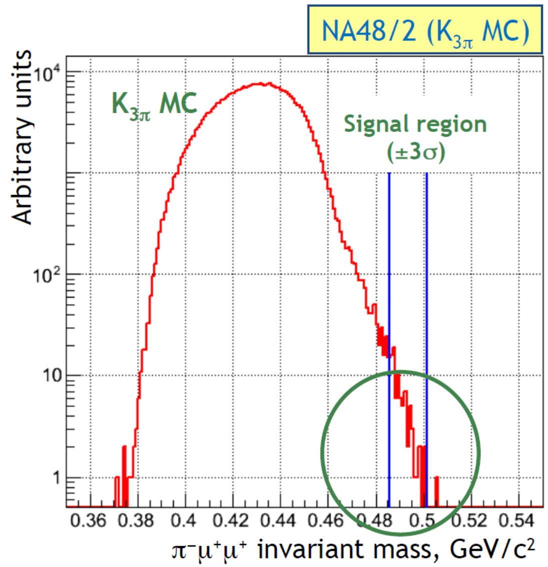
RICH PID

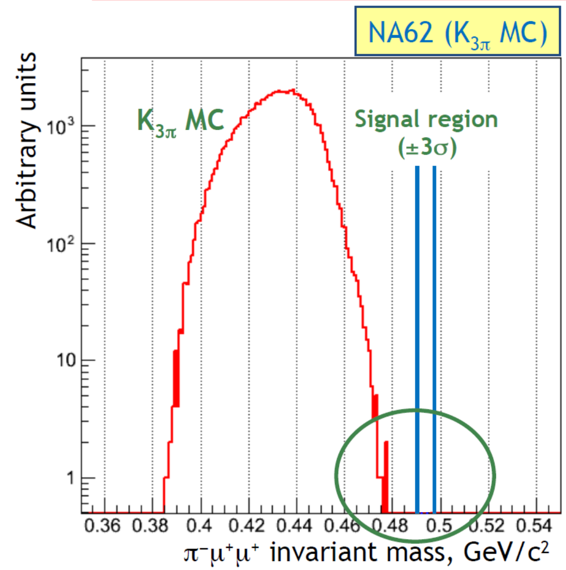
Hermetic photon vetoes

Precise timing

| Source | B/(S+B) |
|---|---|
| $K_{\mu 2}$ | ~~(5.64±0.20)%~~ |
| $K_{\mu 2}$ ($\mu \rightarrow e$) | (0.26±0.03)% ⇩ 0.1% |
| $K_{e2\gamma}$ (SD) | ~~(2.60±0.11)%~~ |
| $K_{e3(D)}$ | ~~(0.18±0.09)%~~ |
| $K_{2\pi(D)}$ | ~~(0.12±0.06)%~~ |
| Opposite sign K | ~~(0.04±0.02)%~~ |
| Beam halo | ~~(2.11±0.09)%~~ |
| Total | ~~(10.95±0.27)%~~ ~ 0.1% |

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




NA62: no $K_{3\pi}$ background expected due to higher spectrometer $p_T$ (270 vs 120 MeV/c) and improved $\pi\mu\mu$ mass resolution (1.1 vs 2.6 MeV/c²)

# Physics prospects for NA62



Expect ~$2 \times 10^{12}$ $\pi^0$ decays in FV in 2 years ($K^+ \rightarrow \pi^+\pi^0$ ~ 20%)
Assume ~ 1% acceptance (conservative), no trigger downscaling
Single Event Sensitivity = 1 / ($N_{\pi 0}$ * acceptance)

| Decay | Physics | Trigger | NA62 Prospects |
|---|---|---|---|
| $\pi^0 \rightarrow 3\gamma$ | C violation | TE | $\sim 10^{-10}$ |
| $\pi^0 \rightarrow 4\gamma$ | New scalars | TE | $\sim 10^{-10}$ |
| $\pi^0 \rightarrow$ inv. | LFV, HNL | $\pi^+\nu\nu$ | $\sim 10^{-9}$ |
| $\pi^0 \rightarrow e\mu$ | LFV | MTE | $\sim 10^{-10}$ |
| $\pi^0 \rightarrow 4e$ | New vectors | 2E | $10^5$ events |
| $\pi^0 \rightarrow ee\gamma$ | Dark photon | 2E | $10^7$ events |

# Summary



1. Several interesting extensions of the SM are being probed with precision measurements of Kaon decays at CERN, using the NA48/2 and $NA62_{RK}$ data.

2. The NA62 experiment will start taking data in 2014.

3. The flexible L0 trigger scheme that will allow study of a large number of new physics signatures

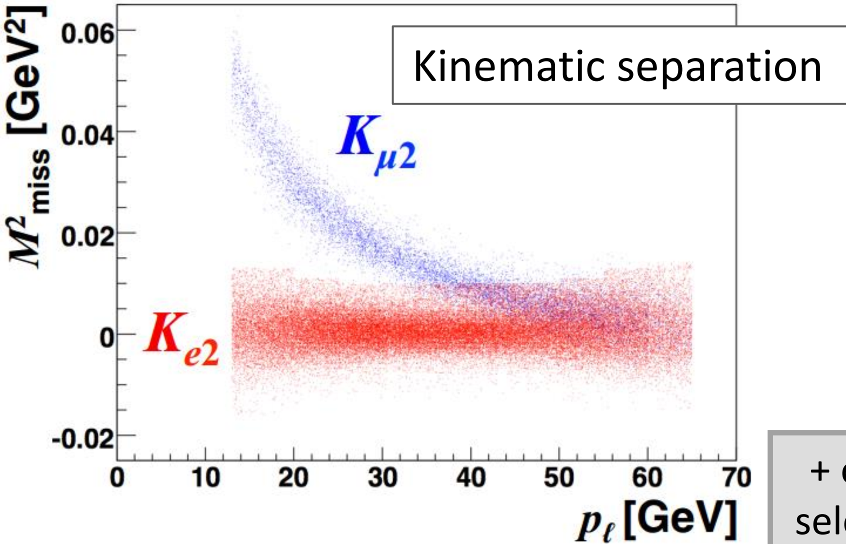
4. Many existing measurements can be improved by orders of magnitude

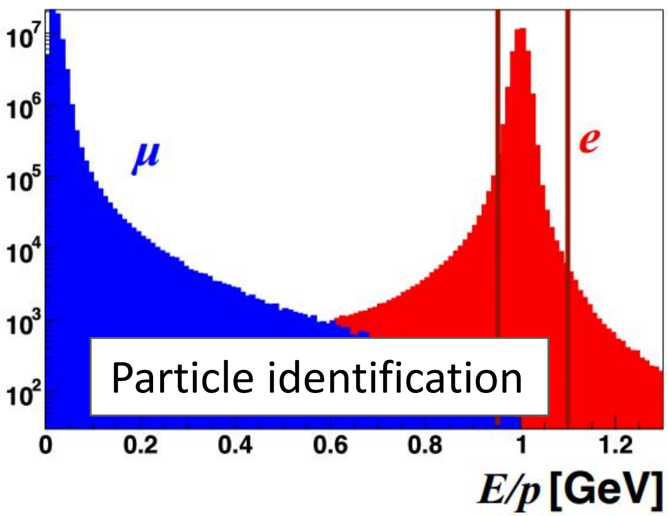
Stay tuned for physics results!

Thank you

# $R_K$ at $NA62_{RK}$

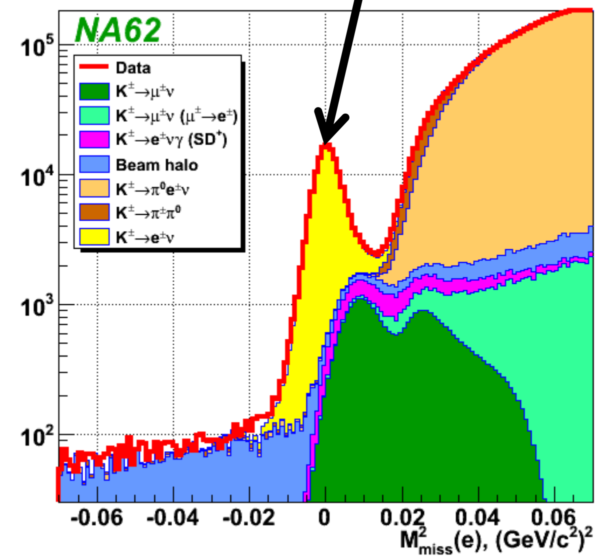
- The crucial aspect of the analysis is to isolate $K_{e\nu}$ decays




+ other selection criteria

**146k $K_{e\nu}$ candidates**




**146k $K_{e\nu}$ candidates (yellow)**

Background: B/(S+B)=**(10.95±0.27)%**

50% $K_{\mu\nu}$ (**dark green**)

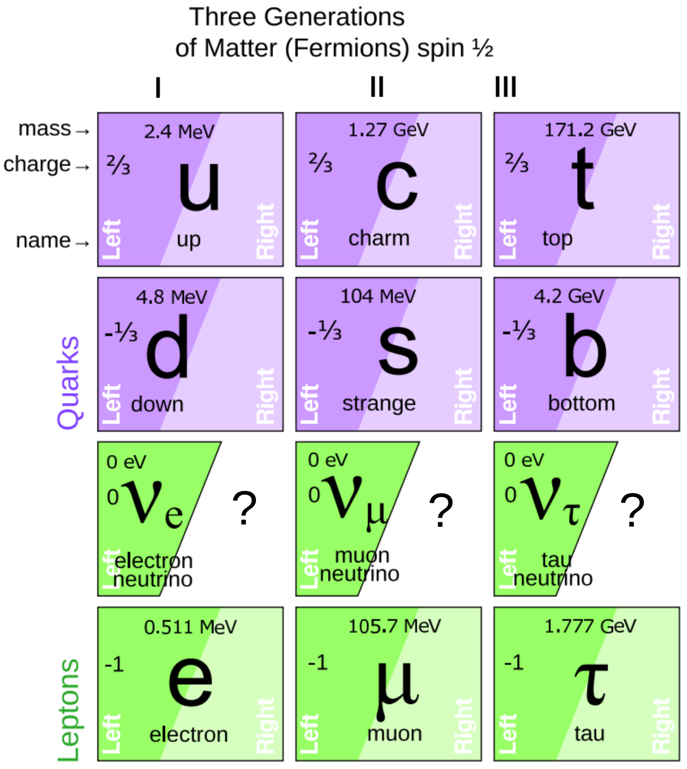
25% $K_{e\nu\gamma}$ (SD$^+$) (**pink**)

20% beam halo (**blue**)

# Heavy Neutral Leptons



- The **SM** contains three massless, left-handed neutral leptons (neutrinos)
- Conspicuous lack of RH neutrino ?
- Since observation of neutrino oscillations, we know that neutrinos are massive …
- Mass term for neutrino requires RH neutrinos

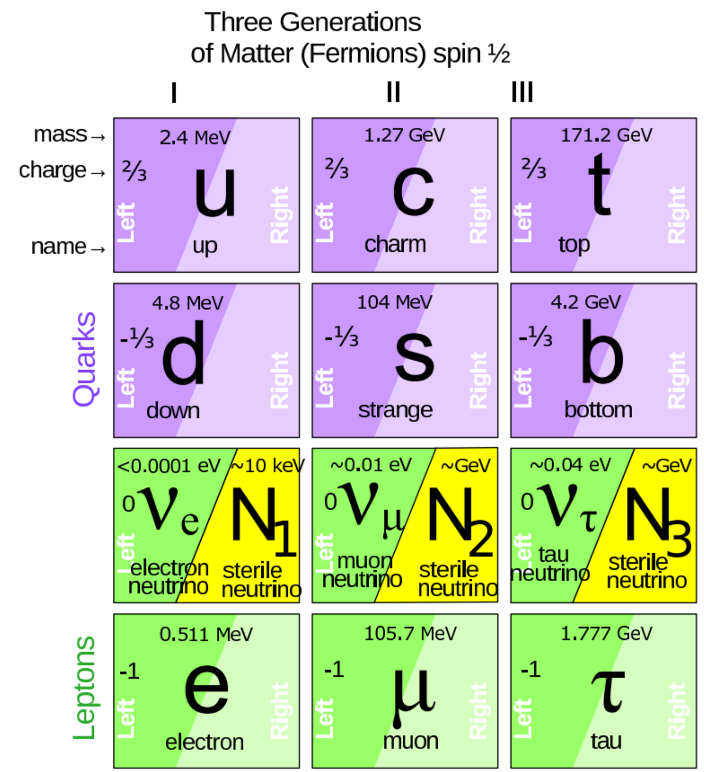


# Heavy Neutral Leptons

- The **SM** contains three massless, left-handed neutral leptons (neutrinos)

- Many models exist that incorporate RH neutrinos

- In the **νMSM***, three RH neutrinos are added
  - $N_1$ is light $\mathcal{O}$(few KeV)
  - $N_{2,3}$ are $\mathcal{O}$(100MeV to few GeV)



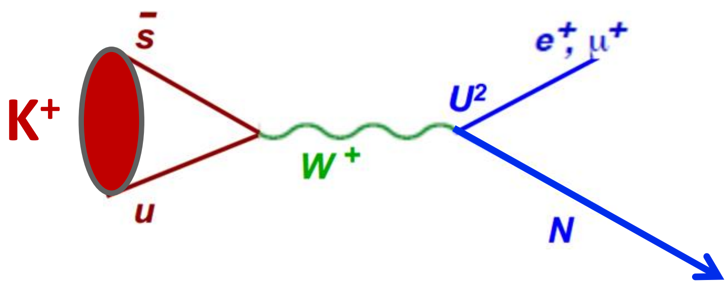

- This model can account for:
  1. Matter-antimatter asymmetry
  2. **Dark Matter** ($N_1$)
  3. Neutrino mixing

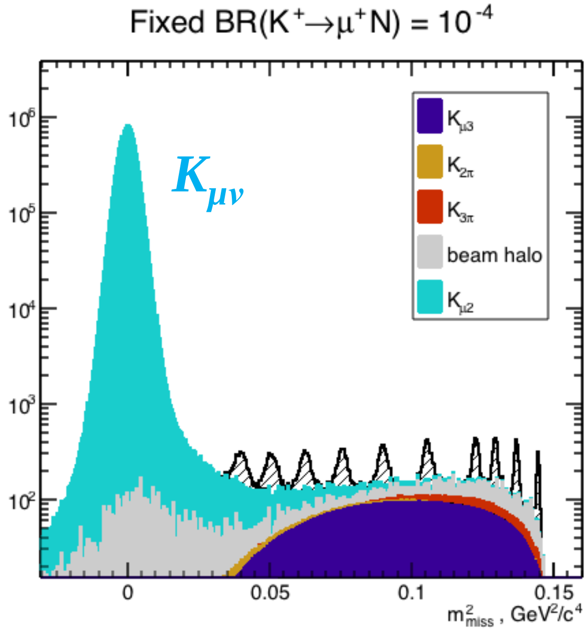
* [PLB 620 17-26], [PLB 631 151-156]

# Heavy Neutral Leptons I

- For a Neutrino with mass $m_\pi \lesssim m_\nu \lesssim m_K$
- Two distinct searches, depending on HNL lifetime $\tau_N$
  1. Long lifetime – HNL escapes detector

     **Peak** in $K^+ \to \ell^+ \nu$ missing mass




- Such a search is proceeding with the NA62$_{RK}$ data

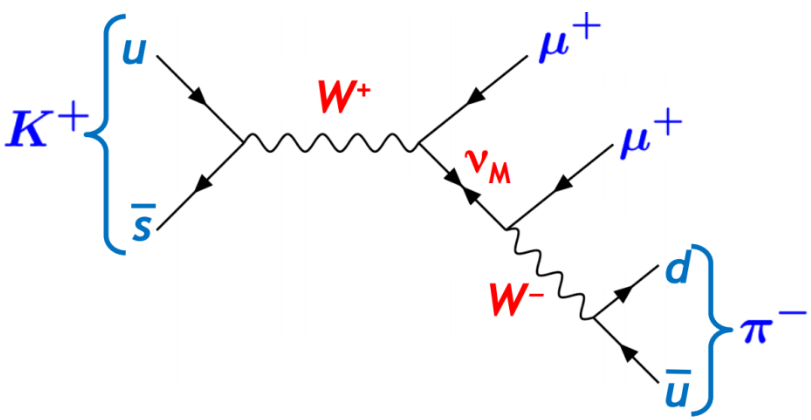
# Heavy Neutral Leptons II

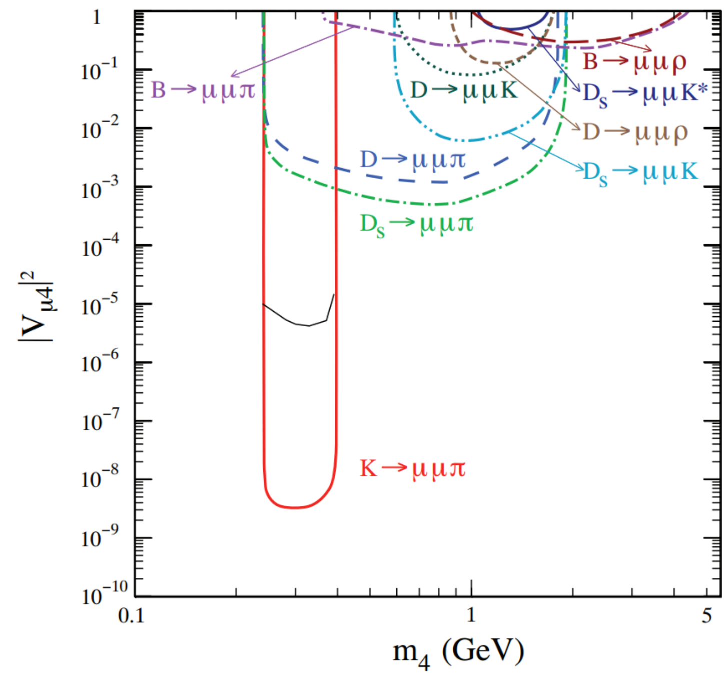
- For a Neutrino with mass $m_\pi \lesssim m_\nu \lesssim m_K$
- Two distinct searches, depending on Neutrino lifetime
  2. Short lifetime – HNL decays within detector

     **Fully reconstruct decay.** No secondary vertex if $\tau_N < 10$ ps

- **Several** final states available, for example: $K^+ \rightarrow \mu^+ \mu^+ \pi^-$

**Lepton Number Violation!**



# Heavy Neutral Leptons II



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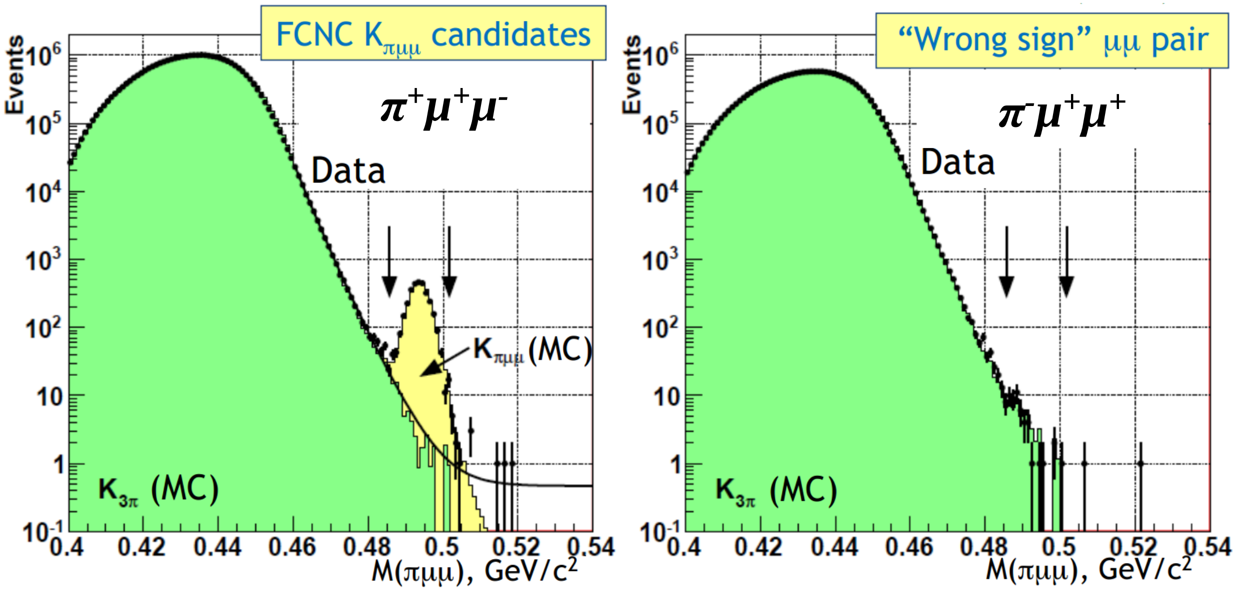
**Fully reconstruct decay**. No secondary vertex if $\tau_N$ < 10 ps

NA48/2 Analysis of $K^+ \to \mu^+\mu^+\pi^-$ [PLB 697(2011)107]




**NA48/2**
**$N_{data}$ = 52**
**$N_{bkg}$ = 52.6 ± 19.8$_{sy}$**

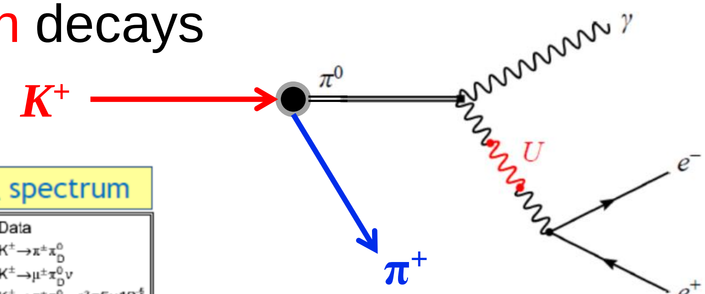
- **WBM** from NA48/2: $\mathcal{B}(K^\pm \to \pi^\mp\mu^\pm\mu^\pm) < 1.1 \times 10^{-9}$ @90% CL
- **Expect 10x better** measurement from re-analysis of the NA48/2 data

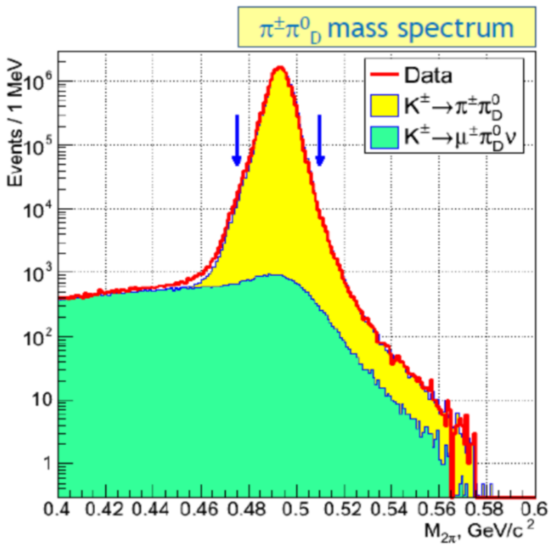
# Dark Photons

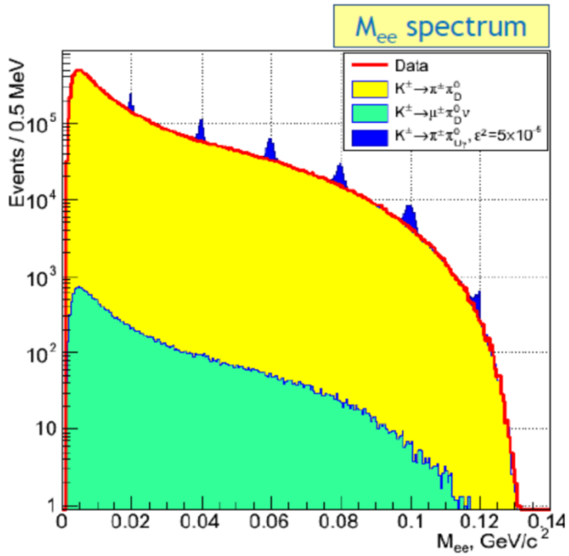


- Question: Why should **dark matter** be so simple (one or two particles) when the SM is so rich ?
- Consider a ‘**dark sector**’ of particles, that can communicate with the SM particles only via a messenger particle: the **dark photon, U**
- **U boson** mixes with the SM photon

  Expect contributions of **U boson** to $\boldsymbol{\pi^0 \rightarrow \gamma ee}$ decays
- Huge number of $\boldsymbol{\pi^0}$ are produced in Kaon decays




- Such a search is being performed using the NA62 data collected in 2007

# The NA62 Trigger



- **L0 Trigger**: Hardware (FPGA). Input rate: 10MHz, Output rate: 1MHz
  - Around 200kHz required for $K^+ \to \pi^+ \nu\nu$ trigger
  - About 800kHz remains for (other studies + control channels)

    **~ few 100 kHz** for exotic decay program
- **L1 Trigger**: Software (Single detector). Output rate: ~100kHz
- **L2 Trigger**: Software (Full information). Output rate: ~ few kHz

**L0 Trigger requirements**

1. Trigger on variety of exotic signatures, in multiple decay modes
   - **LFV, LNV** signatures, enhancements from **dark photon, HNL**, and more …
2. Charge-blind: Accept rare and LNV decays with same trigger
3. Not based on vertex topology: Accept HNL decays with $\boldsymbol{\tau_N > 10\mathrm{ps}}$
4. Use ‘fast’ detectors for timing: **RICH, CHOD, MUV3** have $\boldsymbol{\sigma_t \sim 100\mathrm{ps}}$
5. Simple and robust criteria