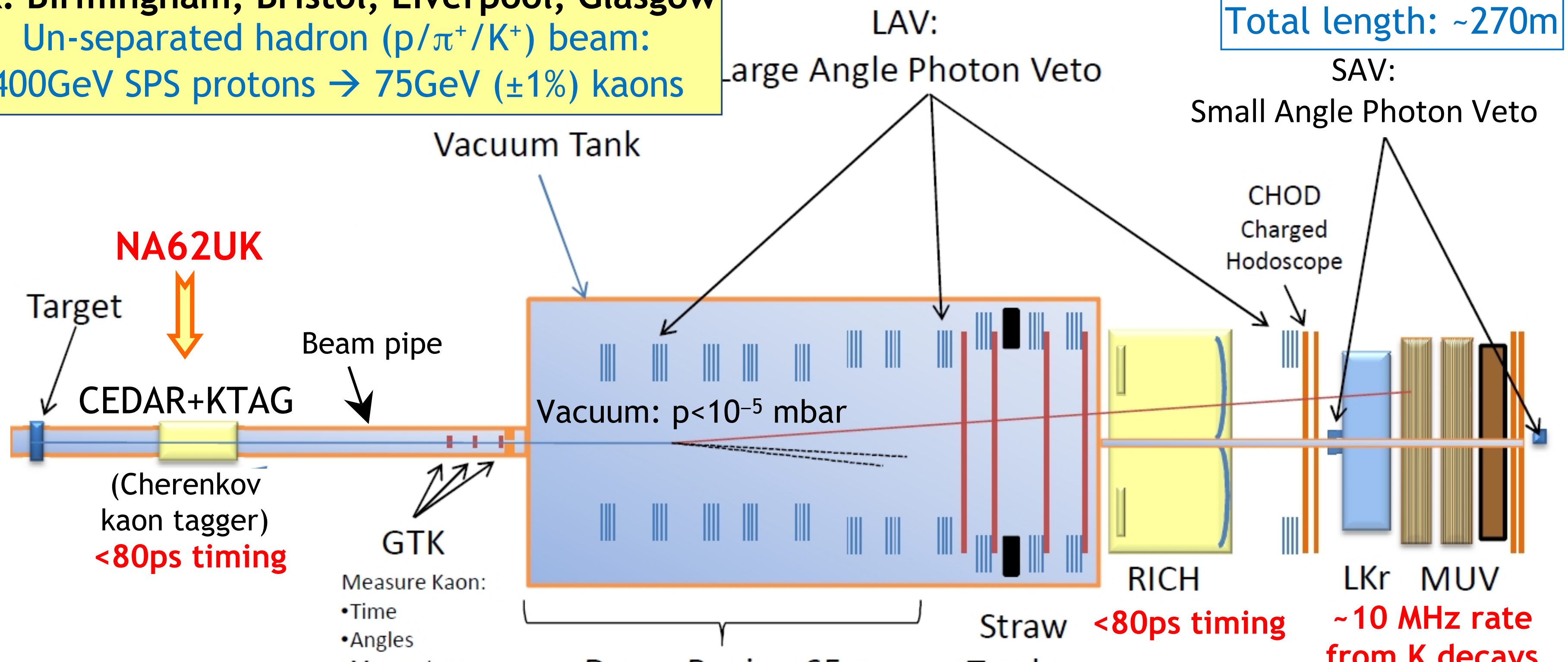
# NA62 experiment: $K^+\rightarrow\pi^+\nu\nu$

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

Total length: ~270m




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

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

# Extended NA62 Physics Program

| Decay | Physics | Present limit (90% C.L.) / Result | NA62 Potential |
| --- | --- | --- | --- |
| $\pi^+\mu^+e^-$ | LFV | $1.3 \times 10^{-11}$ | $10^{-12}$ |
| $\pi^+\mu^-e^+$ | LFV | $5.2 \times 10^{-10}$ | |
| $\pi^-\mu^+e^+$ | LNV | $5.0 \times 10^{-10}$ | |
| $\pi^-e^+e^+$ | LNV | $6.4 \times 10^{-10}$ | |
| $\pi^-\mu^+\mu^+$ | LNV | $1.1 \times 10^{-9}$ | |
| $\mu^-\nu e^+e^+$ | LNV/LFV | $2.0 \times 10^{-8}$ | |
| $e^-\nu\mu^+\mu^+$ | LNV | No data | |
| $\pi^+X^0$ | New Particle | $5.9 \times 10^{-11}$ $m_{X^0} = 0$ | $10^{-12}$ |
| $\pi^+\chi\chi$ | New Particle | – | $10^{-12}$ |
| $\pi^+\pi^+e^-\nu$ | $\Delta S \neq \Delta Q$ | $1.2 \times 10^{-8}$ | $10^{-11}$ |
| $\pi^+\pi^+\mu^-\nu$ | $\Delta S \neq \Delta Q$ | $3.0 \times 10^{-6}$ | $10^{-11}$ |
| $\pi^+\gamma$ | Angular Mom. | $2.3 \times 10^{-9}$ | $10^{-12}$ |
| $\mu^+\nu_h, \nu_h \to \nu\gamma$ | Heavy neutrino | Limits up to $m_{\nu_h} = 350\ MeV$ | |
| $R_K$ | LU | $(2.488 \pm 0.010) \times 10^{-5}$ | >×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 | - | $O(10^6)$ |

# NA62: UK responsibilities (B=Birmingham)

**Hardware and trigger:**

- **full responsibility** for the **KTAG subdetector (B has a big role!!)**;
- development and operation of the **L0 muon trigger (B)**;
- development and operation of the **L1 trigger (B)**;

**Physics programme:**

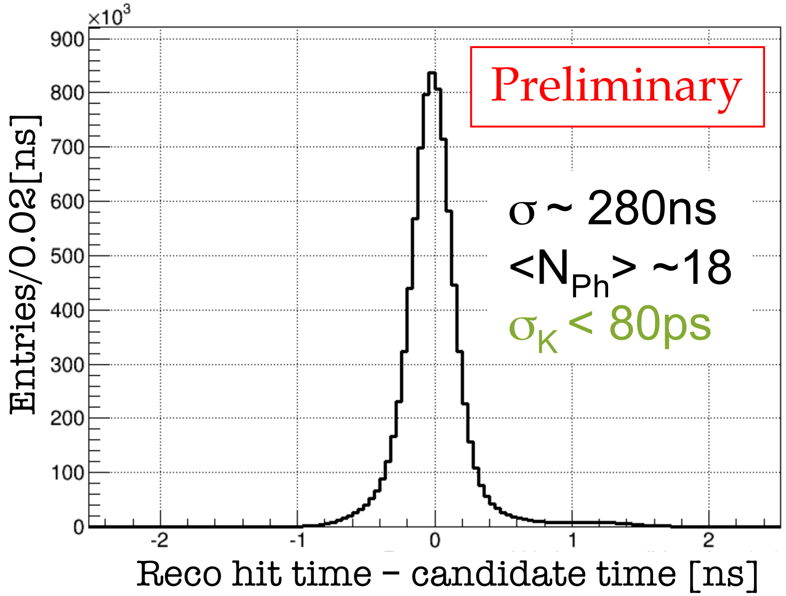
- **$K^+ \to \pi^+ \nu \nu$ analysis**
- lepton flavour and number conservation tests in **$K^+ \to \pi \ell\ell$** decays **(B)**;
- lepton universality tests in **$K^+ \to \ell^+ \nu$** decays **(B)**;
- **peak searches**: heavy neutral leptons, the dark photon **(B)**;

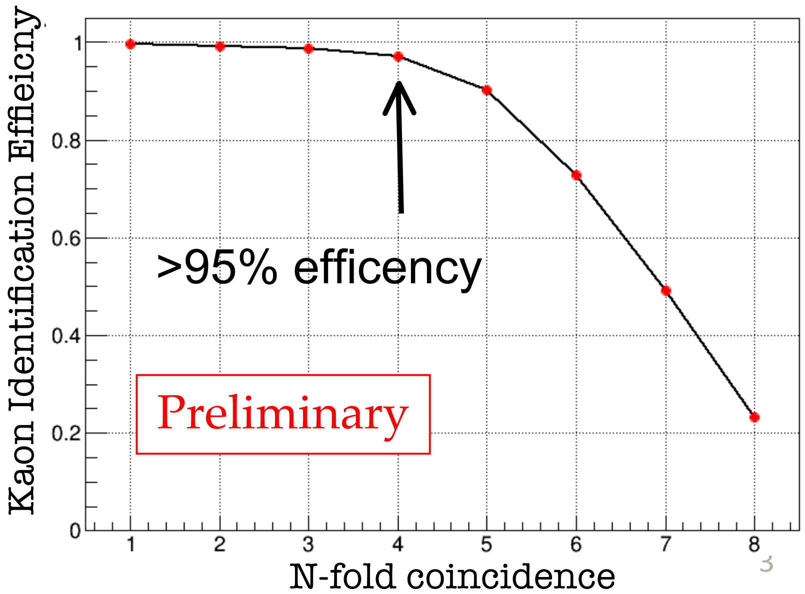
**Coordination:**

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

# Kaon Identification KTAG

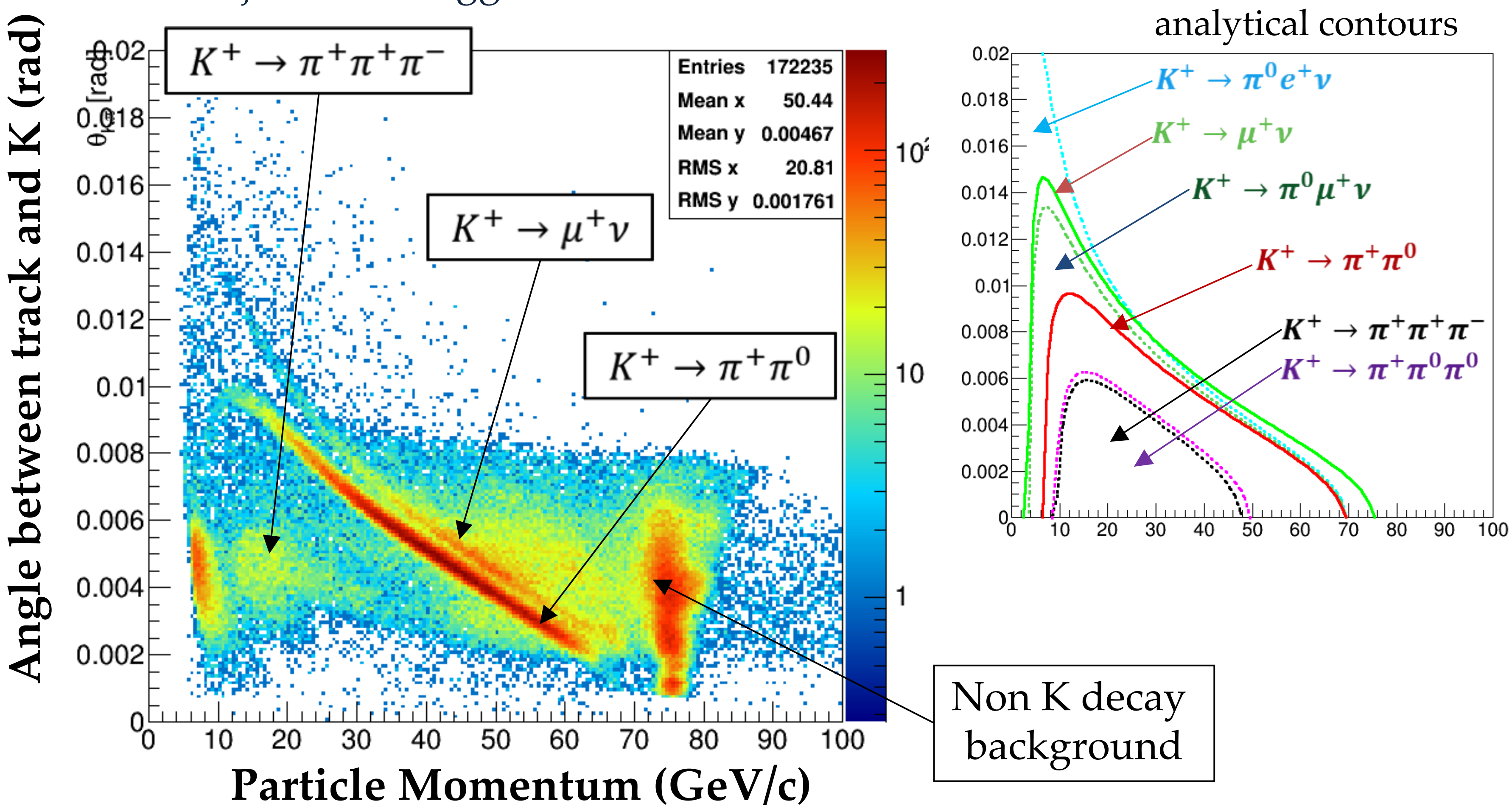
Detector completed
And fully functioning

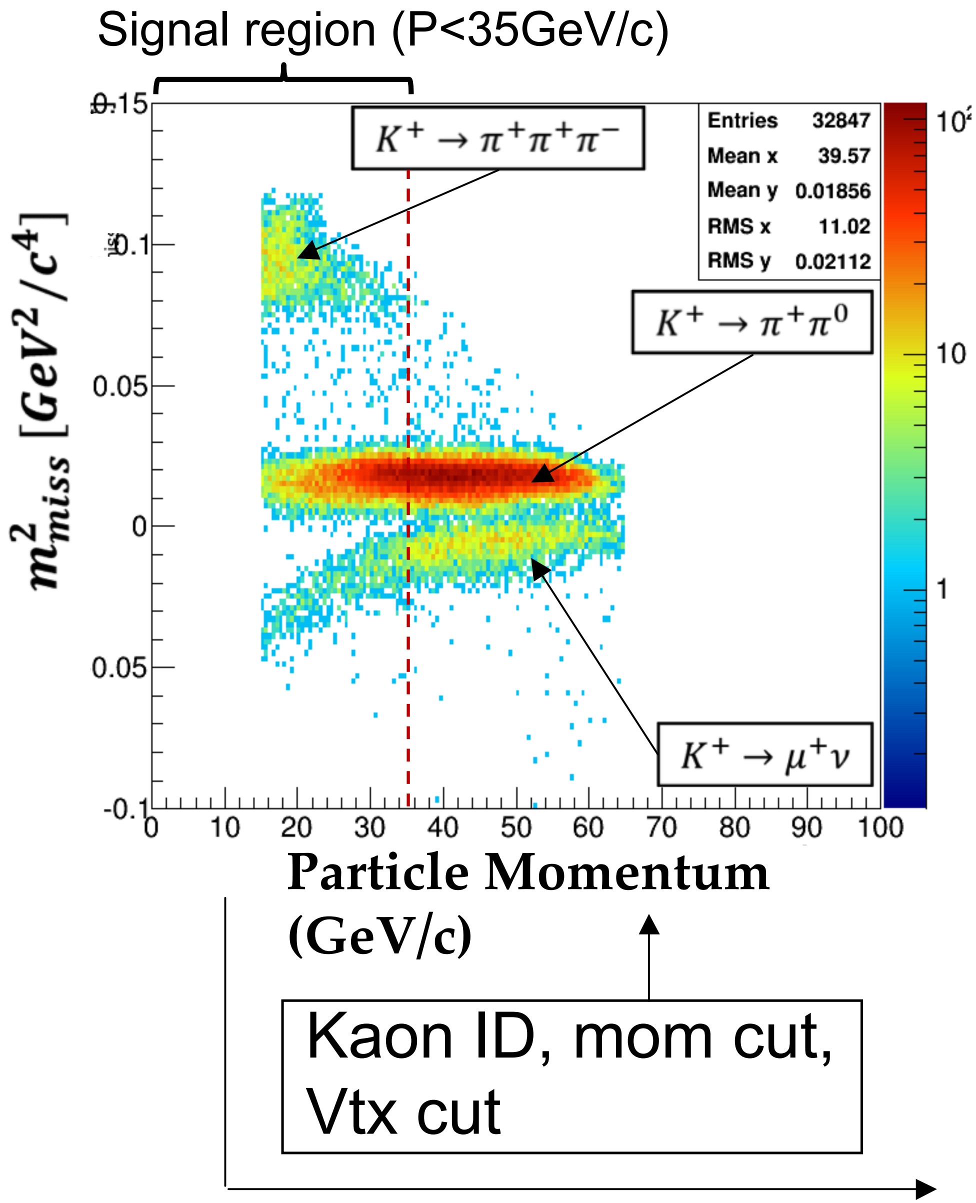


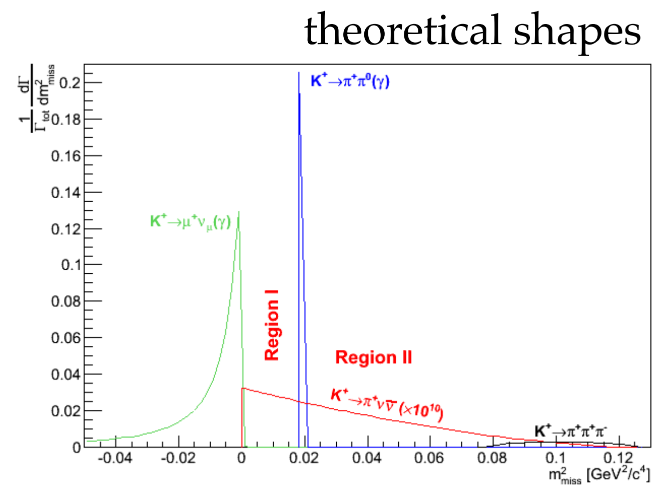



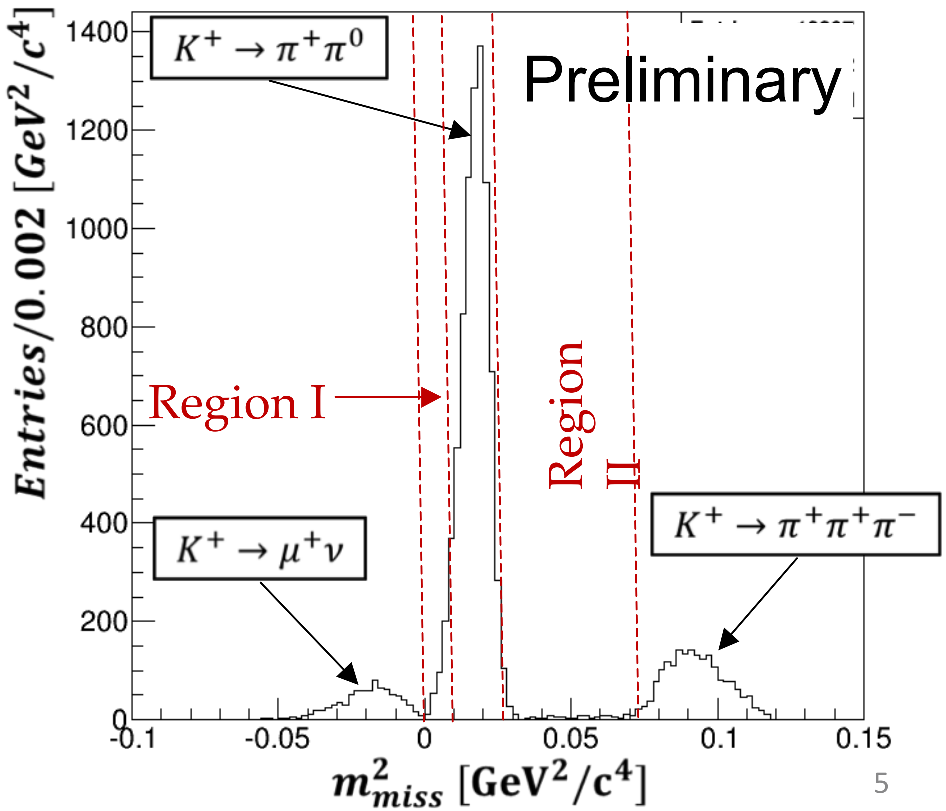
# First Look at 2014 Data Quality

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




Signal region (P<35GeV/c)
$K^+ \to \pi^+\pi^+\pi^-$
$K^+ \to \pi^+\pi^0$
$K^+ \to \mu^+\nu$
Entries 32847
Mean x 39.57
Mean y 0.01856
RMS x 11.02
RMS y 0.02112
$m^2_{miss}$ [GeV$^2$/c$^4$]
Particle Momentum (GeV/c)
Kaon ID, mom cut, Vtx cut


theoretical shapes
$K^+ \to \pi^+\pi^0(\gamma)$
$K^+ \to \mu^+\nu_\mu(\gamma)$
Region I
Region II
$K^+ \to \pi^+\nu\bar{\nu}$ (×10¹⁰)
$K^+ \to \pi^+\pi^+\pi^-$
$m^2_{miss}$ [GeV$^2$/c$^4$]


Preliminary
$K^+ \to \pi^+\pi^0$
$K^+ \to \mu^+\nu$
$K^+ \to \pi^+\pi^+\pi^-$
Region I
Region II
Entries/0.002 [GeV$^2$/c$^4$]
$m^2_{miss}$ [GeV$^2$/c$^4$]

# Long-term future

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

SPS LS2: 2018–2019

- **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, ...).

SPS LS3: 2024

- **Run 2025–2028** possibility:

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

# NA62 Birmingham

People:
MB Brunetti
(V Fascianelli leaving)
E Goudzovski
C Lazzeroni
N Lurkin
(F. Newson leaving)
C Parkinson
A Romano
A Sergi
A Sturgess

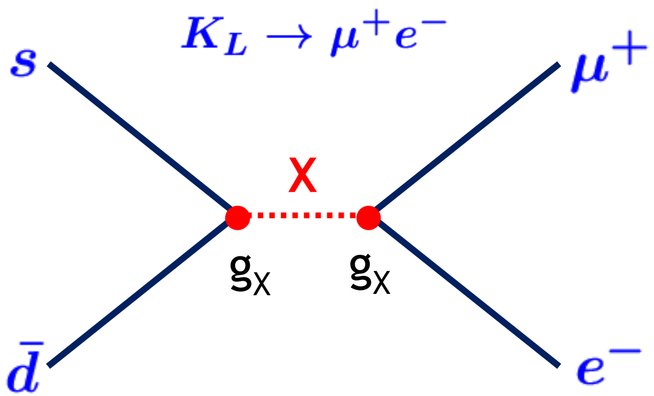
# Spares

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

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

| Mode | UL at 90% CL | Experiment | Reference |
|---|---|---|---|
| $K^+ \to \pi^+ \mu^+ e^-$ | $1.3 \times 10^{-11}$ | 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 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

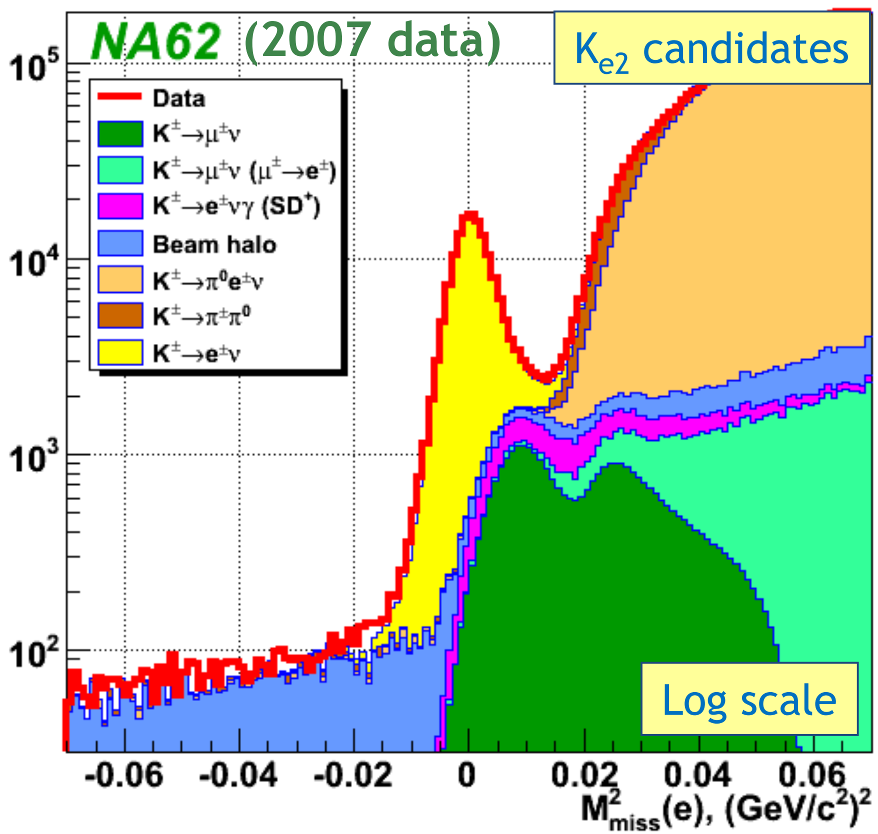
# NA62-$R_K$: lepton universality

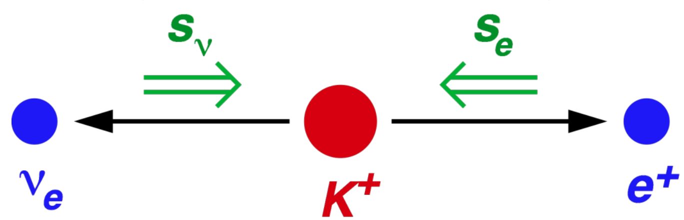
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{\text{rad.corr.}})$$

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).

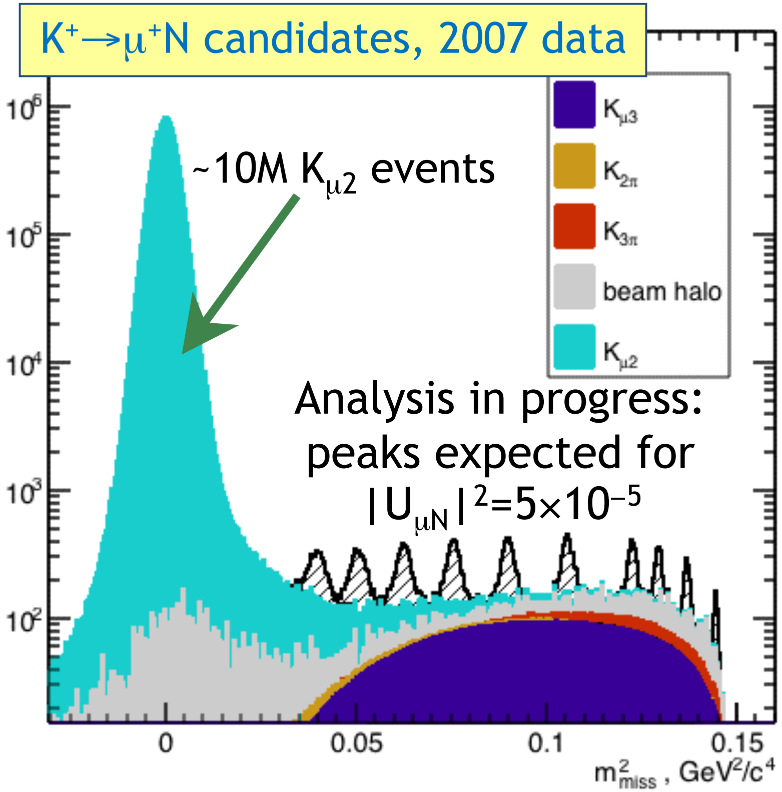
# Heavy neutral leptons below $M_K$

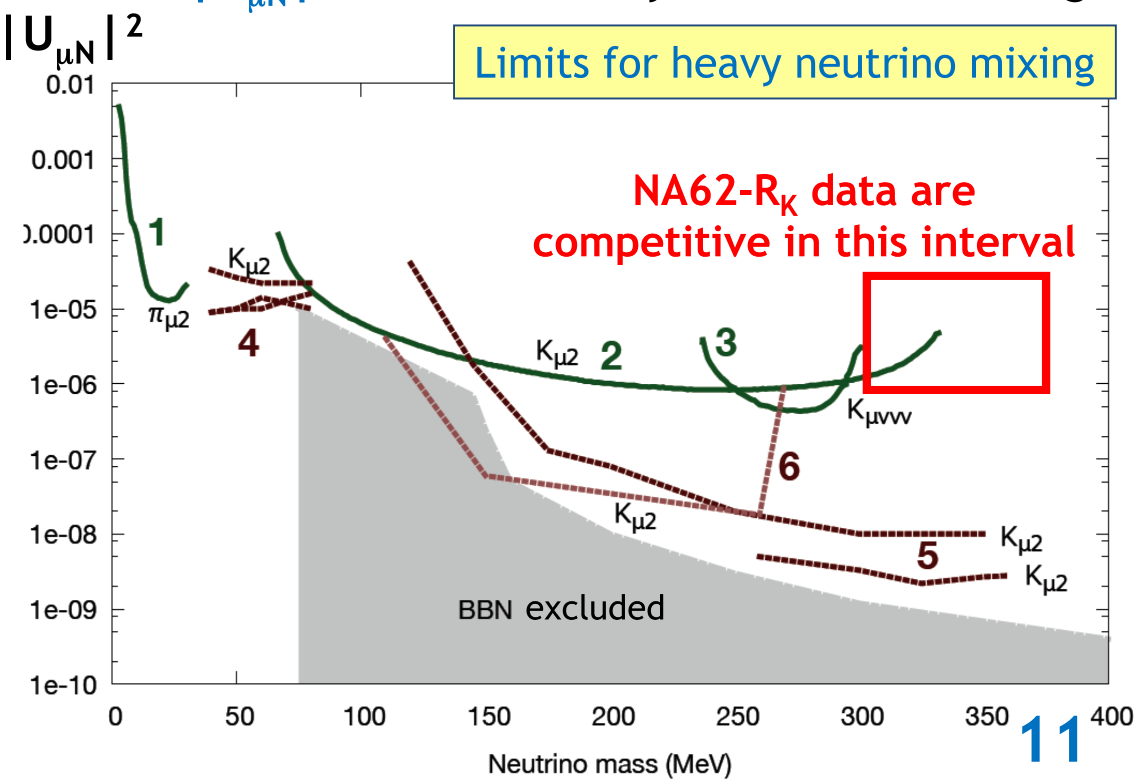
Neutrino minimal SM ($\nu$MSM):
3 heavy sterile RH Majorana $\nu$s ($N_{1,2,3}$).
$m_1 \sim 10$ keV/$c^2$: dark matter candidate.
$m_2 \sim m_3 \sim 1$ GeV/$c^2$:
observable in $K^\pm \to l^\pm N$, $D^\pm \to l^\pm N$ decays.

*Asaka & Shaposhnikov, PLB620 (2005) 17*

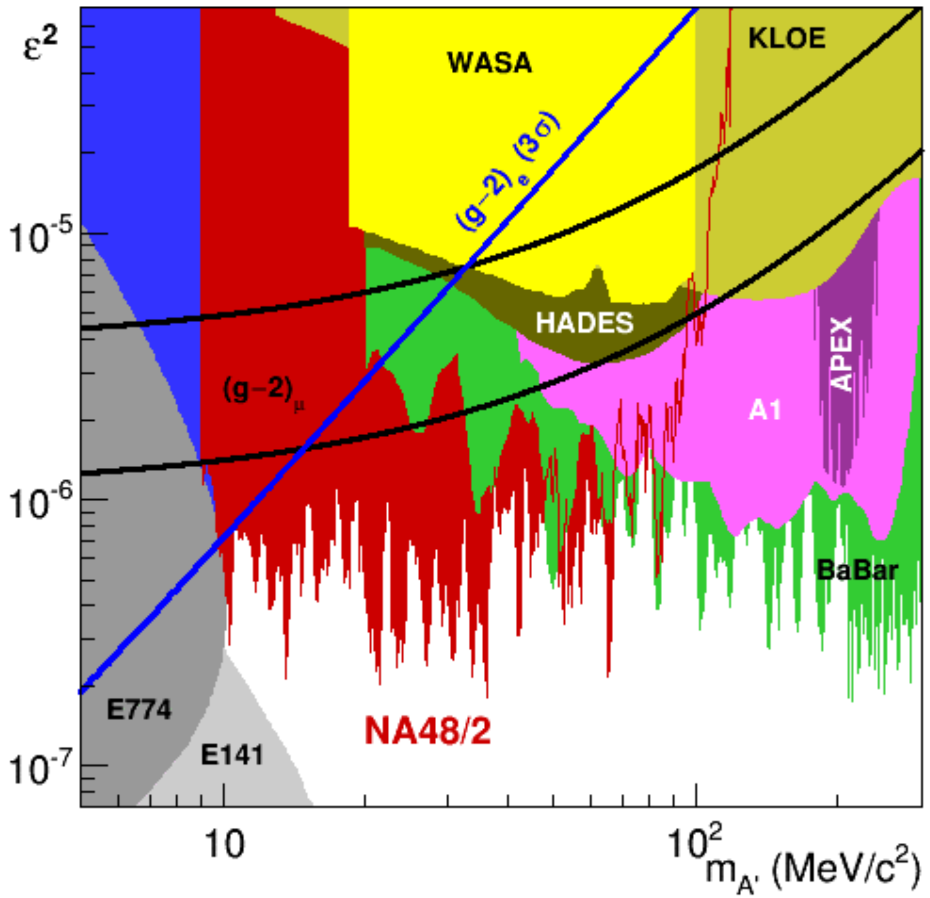
NA62-$R_K$ subsample: ~10M $K^+ \to \mu^+ \nu_\mu$.
**"Peak search"** for HNL: $K^+ \to \mu^+ N$.

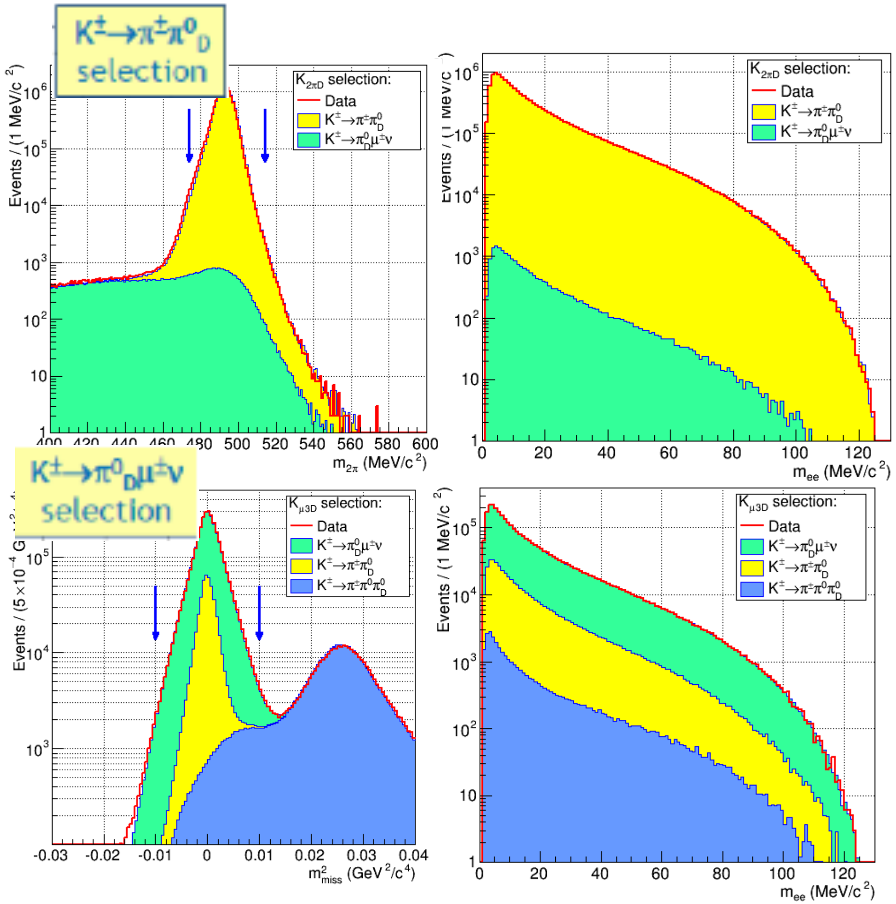
- Sensitivity is limited by background fluctuation (mainly beam halo).
- Competitive at $0.30 < M_N < 0.38$ GeV/$c^2$.
- **NA62:** larger sample and smaller bkg., $|U_{\mu N}| \sim 10^{-8}$ sensitivity in wider mass range.



# Search for Dark Photon in the “old” data




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

Sensitivity limited by irreducible $\pi^0_D$ background

Published in Phys. Lett. B746 (2015) 178

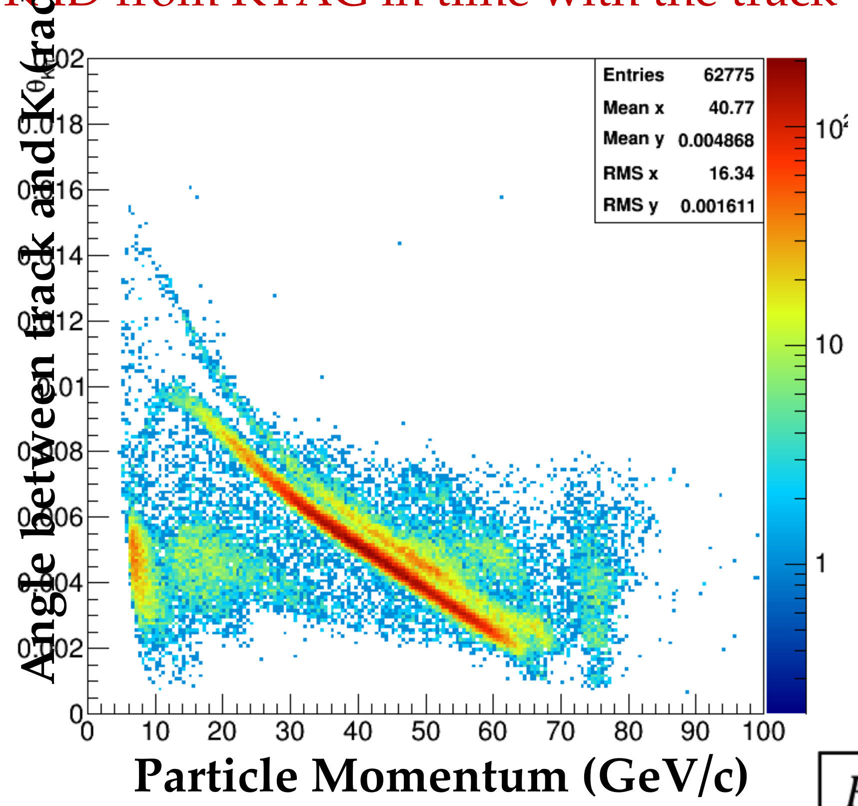
Numerical UL data for each mass hypothesis available on HepData: http://hepdata.cedar.ac.uk/view/ins1357601

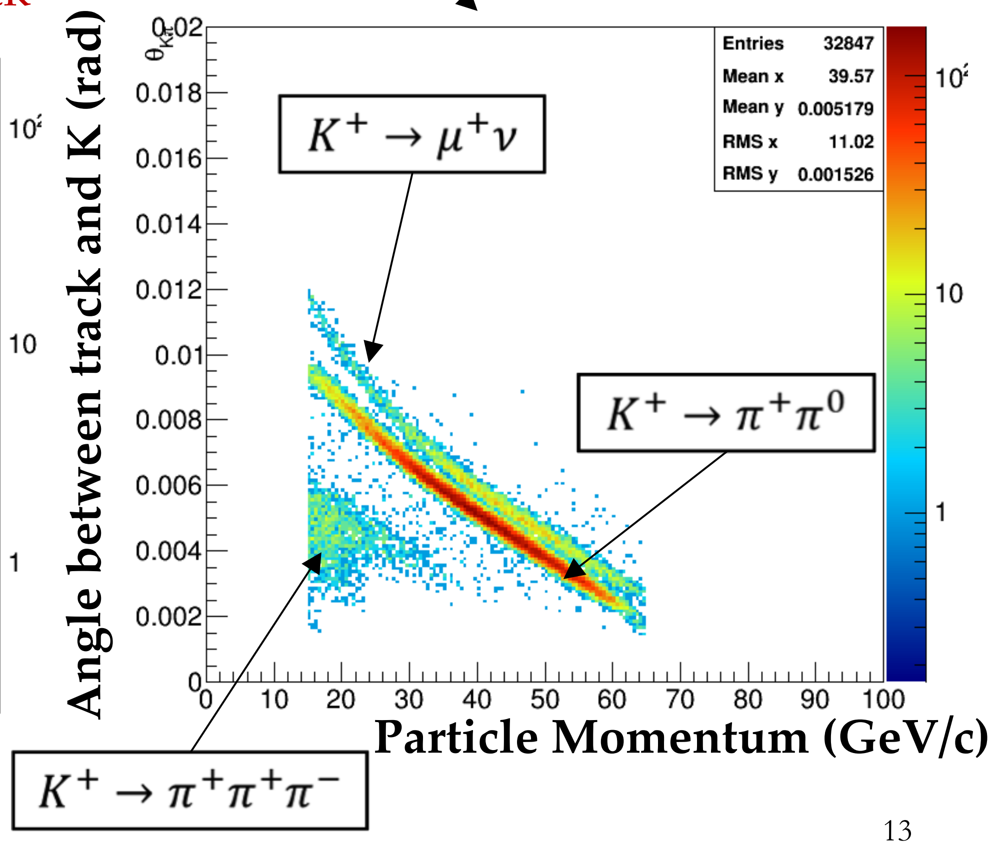
1.7 $10^7$ $\pi^0$ with negligible mean free path

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

- 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

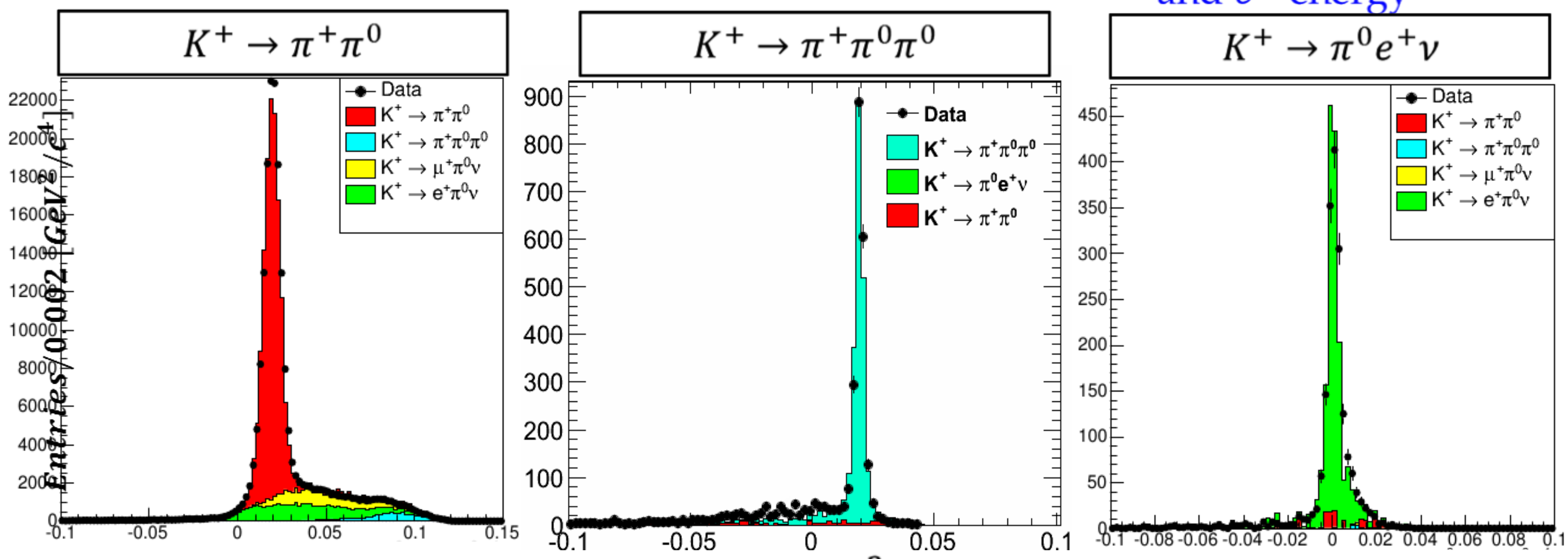


# Examples of Control samples

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

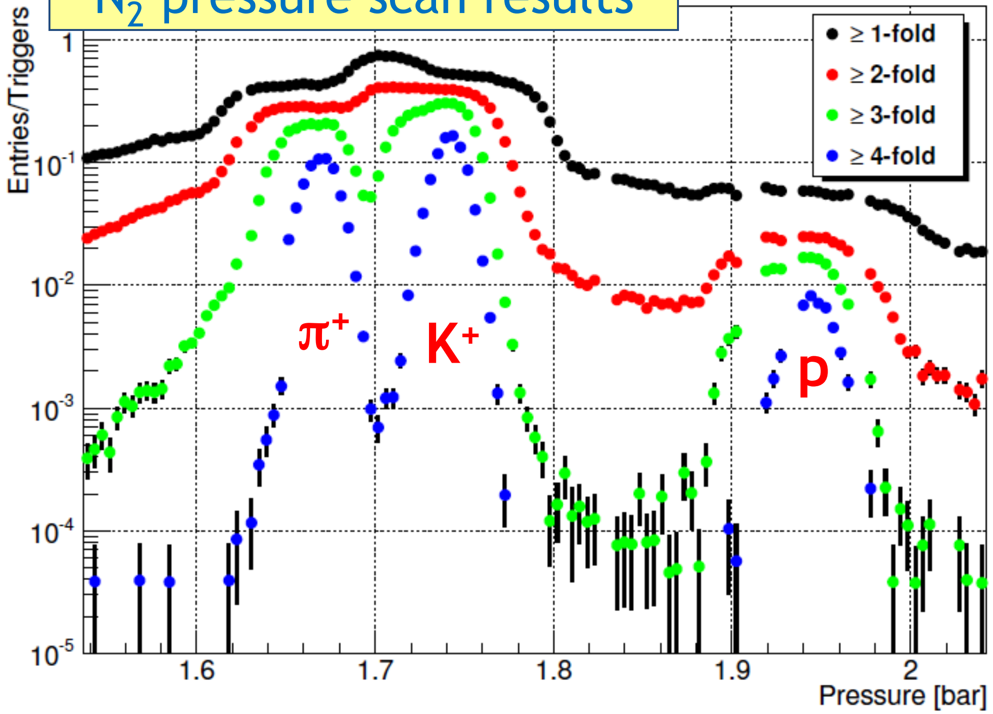
$\pi^0$ mass assumed | $\pi^0$ mass assumed | $\pi^0$ mass assumed and $e^+$ energy



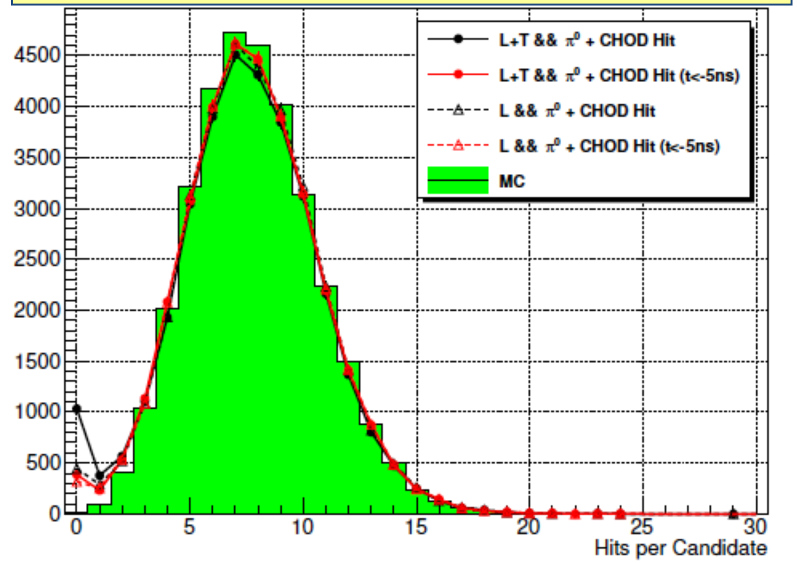

$(P_K - P_{\pi^0})^2$ GeV$^2$/c$^4$ | $\left(P_K - P_{\pi_1^0} - P_{\pi_2^0}\right)^2$ GeV$^2$/c$^4$ | $(P_K - P_{\pi^0} - P_{e^+})^2$ GeV$^2$/c$^4$

# KTAG with 4 octants in 2012

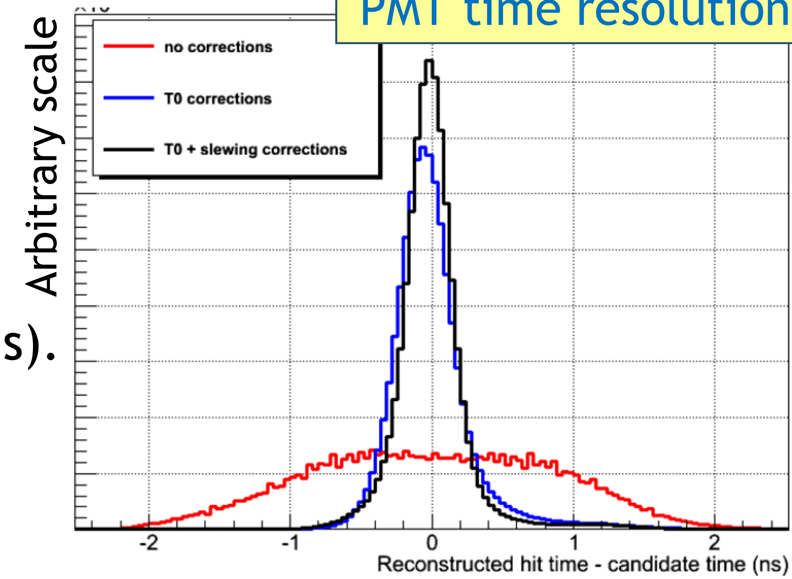
N$_2$ pressure scan results




Detected photons / beam particle




PMT time resolution




- 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.