Recent Results From NA62

Stoyan Trilov, University of Bristol
on behalf of the NA62 collaboration

28/09/2017

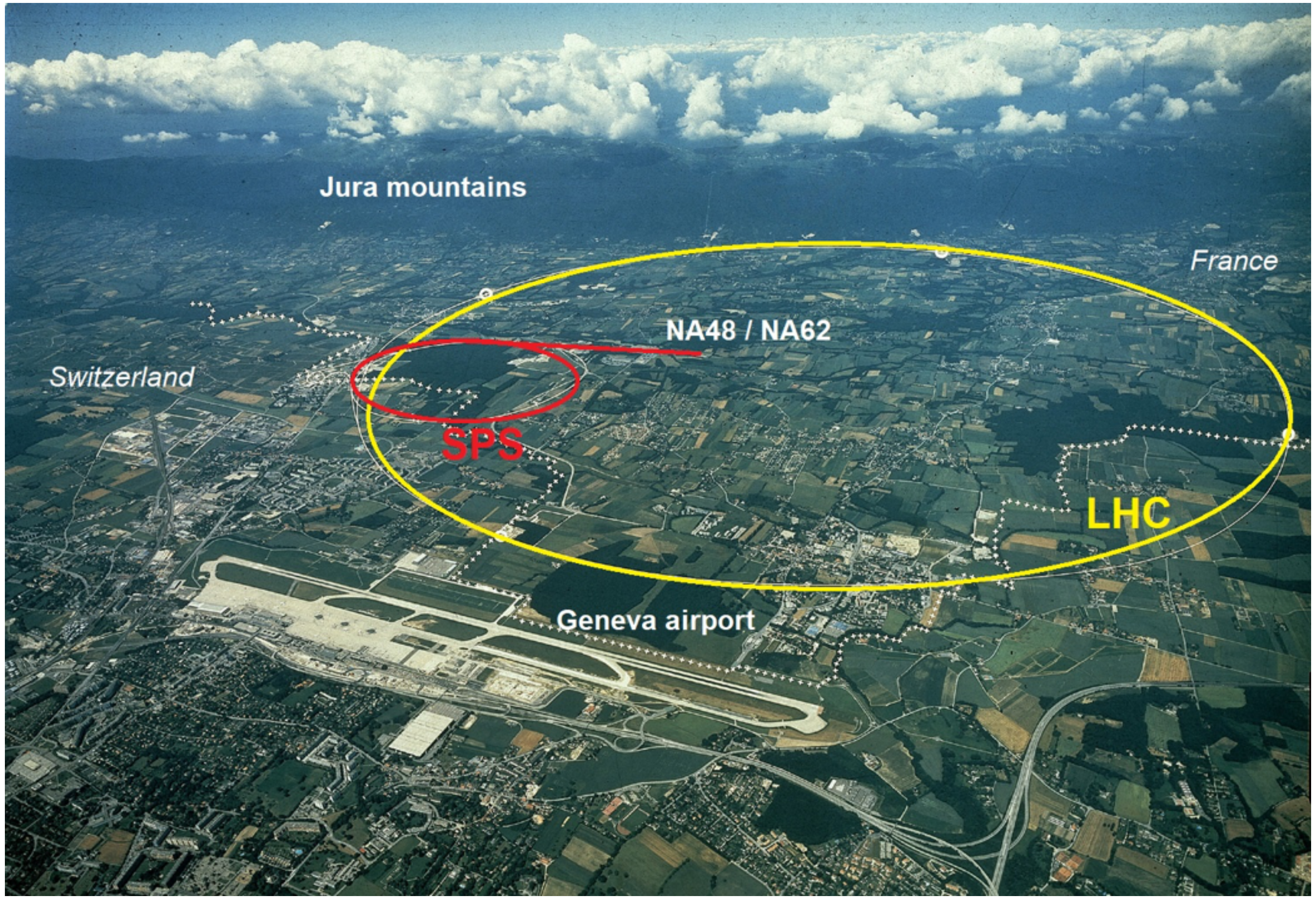
Salamanca
HADRON 2017
XVII International Conference on Hadron Spectroscopy and Structure

Outline

- Kaons at CERN
- Heavy Neutrinos Search
  - 2007 Data
  - 2015 Data
- $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$
  - Analysis strategy
  - Selection
  - Results
- Conclusions and Prospects

Kaons at CERN

- NA48 (1997-2001): ε/ε'
- NA48/1 (2002): K_s rare decays
- NA48/2 (2003-2004): $K^{\pm}$ decays
- **NA62 (2007)** (2007-2008)
    - NA48/2 detector
    - $R_K = K_{e2}/K_{\mu 2}$
    - Heavy neutrinos
- **NA62** (2014-2018):
    - 2014: Pilot run
    - 2015: Commissioning
    - 2016-2018: $K^+ \rightarrow \pi^+ \nu\bar{\nu}$



NA62 collaboration: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain-la-Neuve, Mainz, Merced, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP), Rome I, Rome II, San Luis Potosi, Sofia, TRIUMF,Turin, Vancouver (UBC)

νMSM

Neutrino oscillation experiments show that neutrinos have mass, however in the Standard Model (SM), neutrinos are massless. An extension to the SM is needed to accommodate massive neutrinos, for example:

The Neutrino Minimal Standard Model (νMSM):

- Addition of 3 right-handed neutrinos, one of them with mass of O(GeV)
- If $m_N < m_{K^\pm} - m_{l^\pm}$, then heavy neutrinos are observable via production in

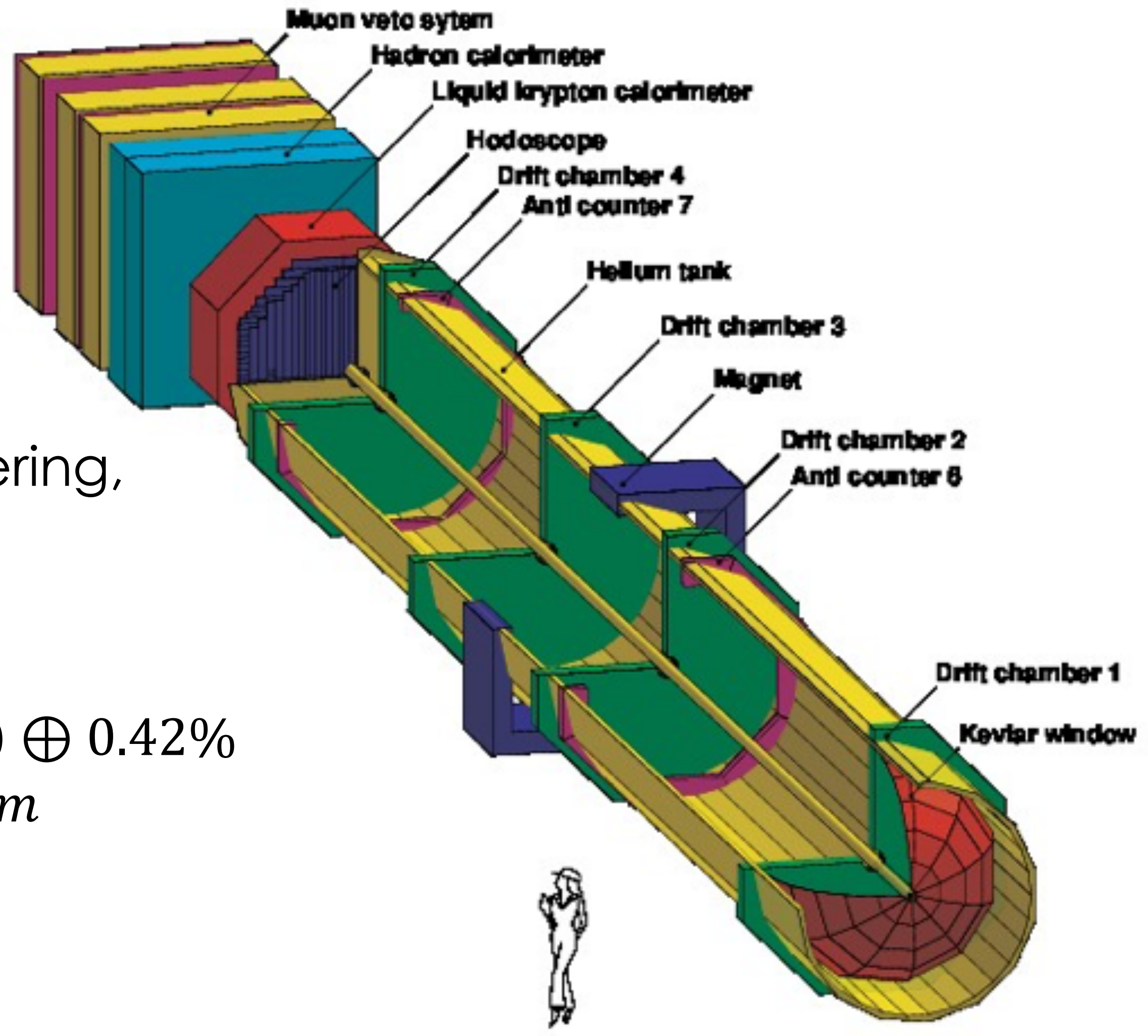
$$\Gamma(K^\pm \rightarrow l^\pm N) = \Gamma(K^\pm \rightarrow l^\pm \nu_l) \cdot \rho_{m_N} \cdot |U_{l4}|^2$$

ρ_{m_N}: kinematic phase-space factor, U_{l4}: mixing matrix

NA62 - 2007 Detector

Beam
- 74 ±1.4 GeV/c kaon momentum

Sub-detectors
- Magnetic spectrometer
- Scintillator hodoscope, used for triggering, σ_t~ 200ps
- LKr, EM calorimeter
  - 13 248 2×2 cm^2 cells
  - $\sigma_E/E = 3.2\%/\sqrt{E}(GeV) \oplus 9\%/E(GeV) \oplus 0.42\%$
  - $\sigma_x = \sigma_y = 4.2\,mm/\sqrt{E}(GeV) \oplus 0.6\,mm$
- Muon veto system



2007 Heavy Neutrino Search - I

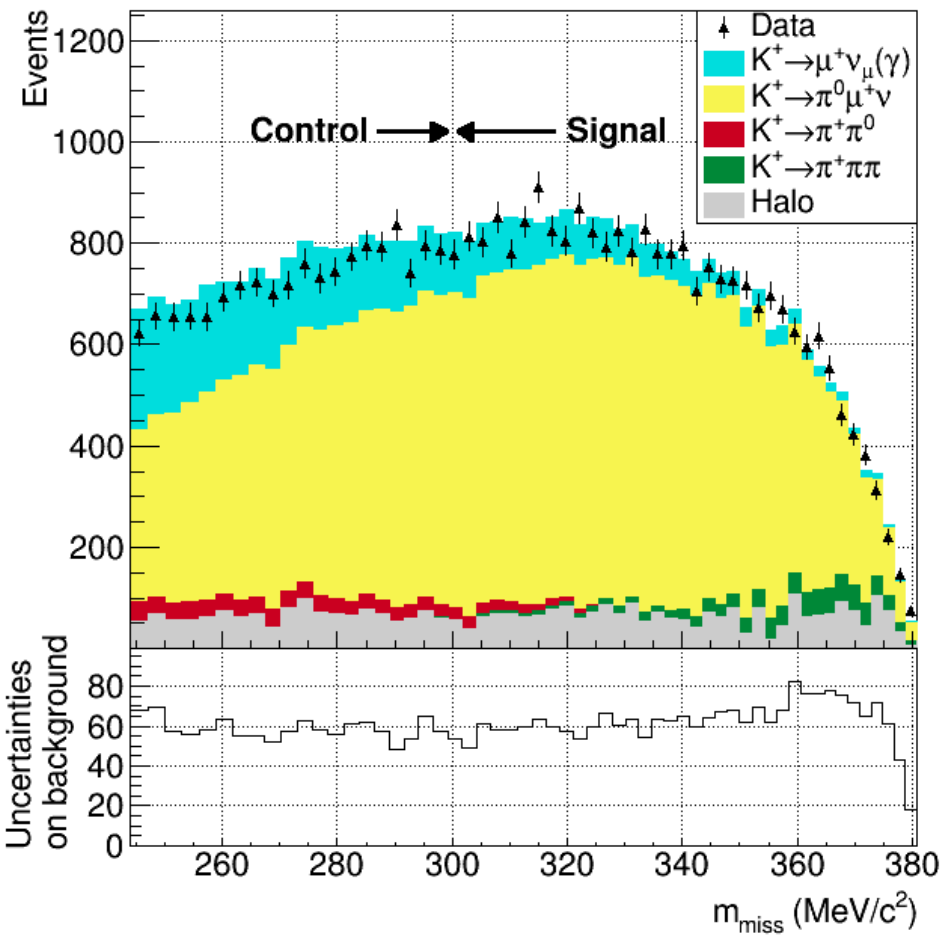
Analysis strategy

- Search for $K^+ \rightarrow \mu^+ N$
- Look for peak in $m_{miss} = \sqrt{P_{K^+} - P_{\mu^+}}$
- Monte Carlo used to evaluate signal acceptance, and kaon decay background contributions
- Halo contribution evaluated from data

Selection

- One positively charged track, with associated LKr cluster
- Other than the track cluster, no cluster with E > 2 GeV
- Cuts on decay Z_{vertex}, CDA, P_{track}, θ, and ϕ to suppress muon halo background

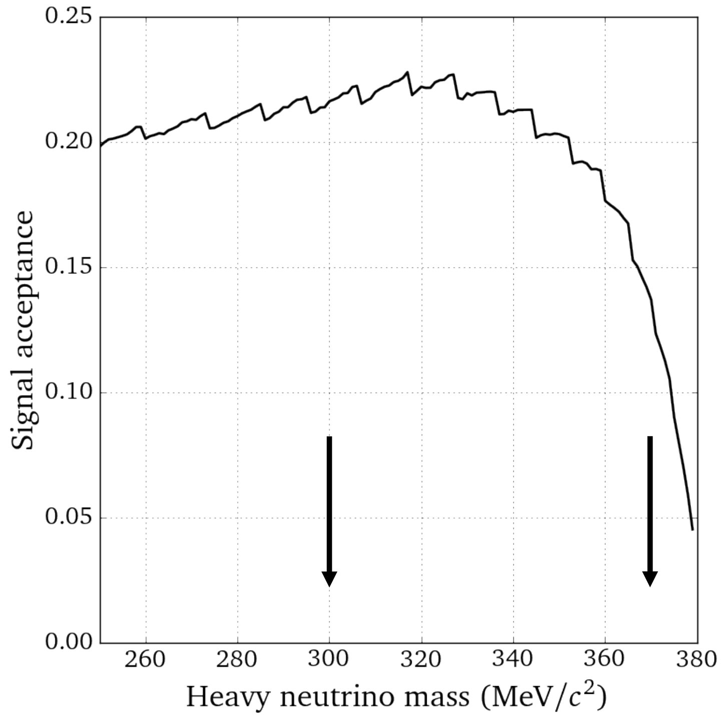
Missing mass spectrum



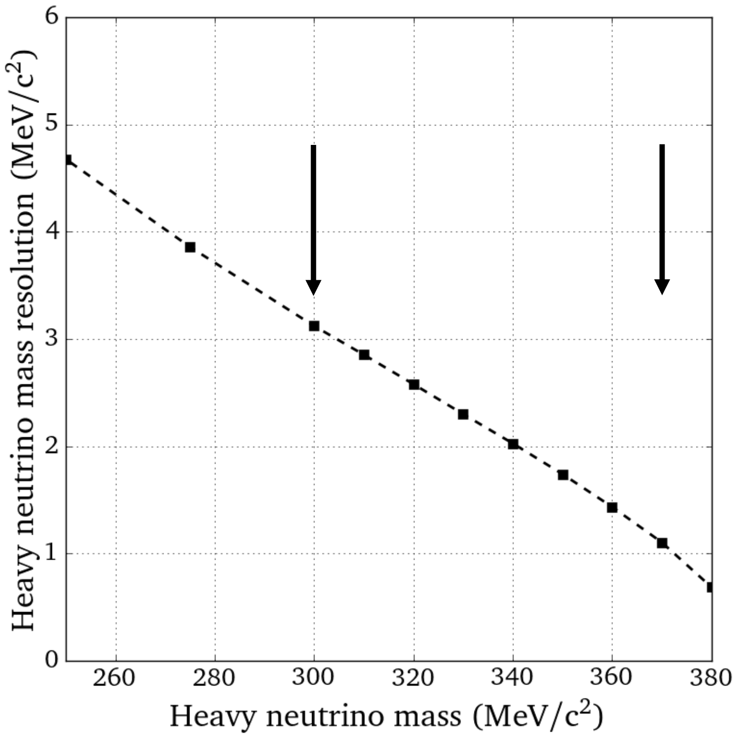
2007 Heavy Neutrino Search - II

- Around $6{\times}10^7$ kaon decays in the fiducial volume collected (N_K)
- Neutrino mass range: 300-370 MeV
- No acceptance for masses above 370 MeV
- Strong limits already present for m_N < 300 MeV

Signal acceptance



Mass resolution



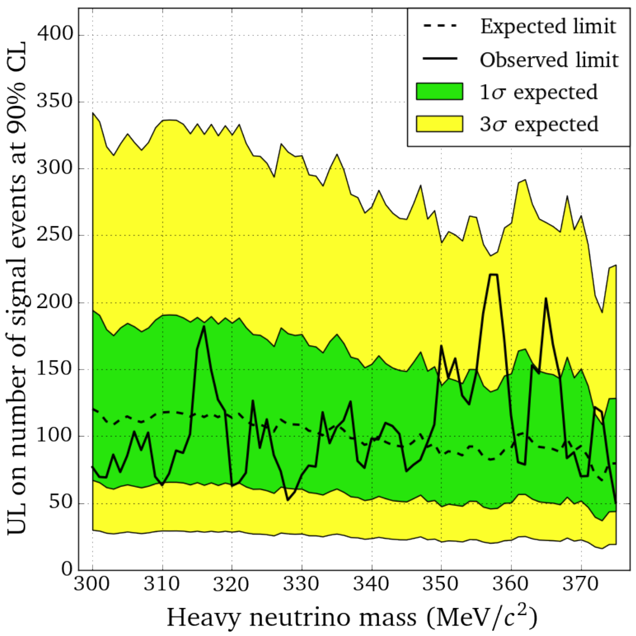
2007 Heavy Neutrino Search - III

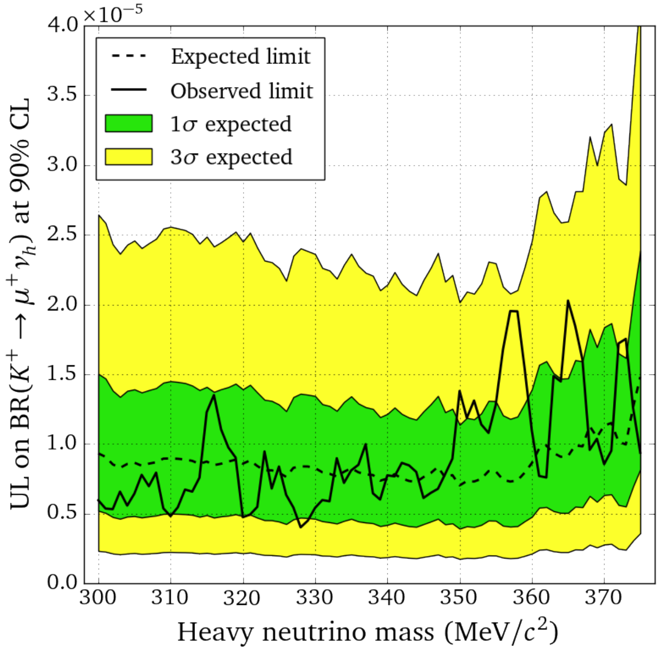
- Search performed in steps of 1 MeV/c²
- Window of $\pm\sigma_m$ (mass resolution)
- **No signal observed within 3σ significance**
- Upper limits on number of signal events (n_{UL}) were estimated using the Rolke-Lopez method

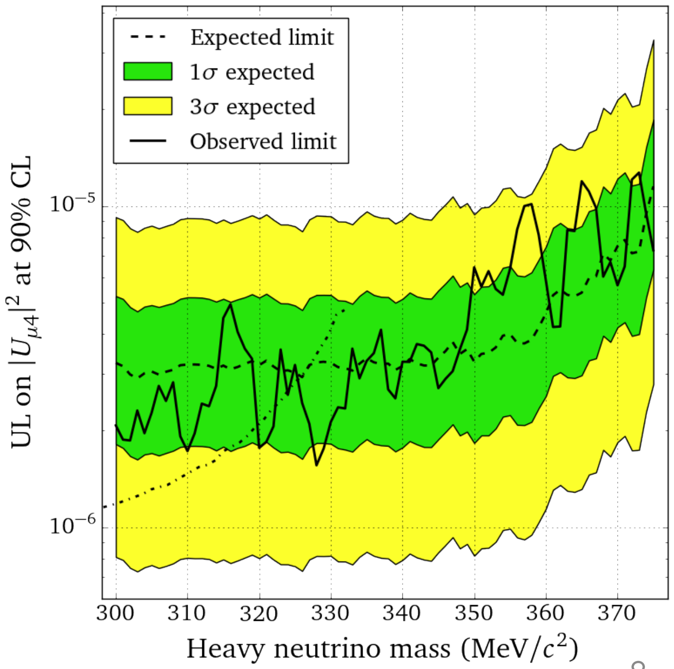
n_{UL}

$$B_{UL}(K^+ \to \mu^+ N) = \frac{n_{UL}}{N_K \times A(m_N)}$$

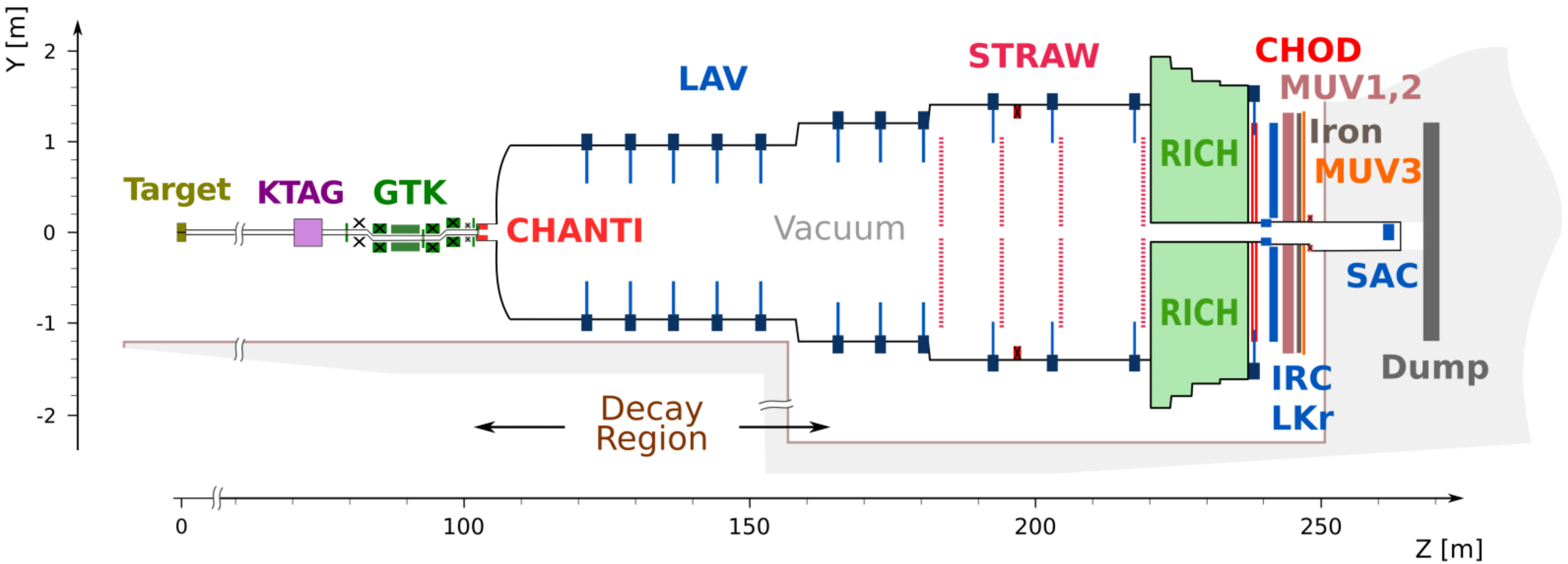
$$|U_{\mu 4}|^2_{UL} = \frac{B(K^+ \to \mu^+ N)}{B(K^+ \to \mu^+ \nu_\mu)} \times \frac{1}{\rho_{m_N}}$$







NA62 - 2015 Detector



Primary beam
- 400 GeV/c protons from SPS

Secondary beam
- 6% kaons, 75 GeV/c momentum
- Rest: 70% pions, 24% protons

Fiducial volume
- 60m region
- 10^{-6} mbar vacuum
- ~5 MHz K^+ decay rate

Sub detectors
- Upstream: KTAG, GTK, CHANTI
- Downstream tracking: STRAW, CHOD, NewCHOD
- PID: RICH, MUV1/2/3
- Photon veto: LAV, LKr, IRC, SAC

2015 Heavy Neutrino Search - I

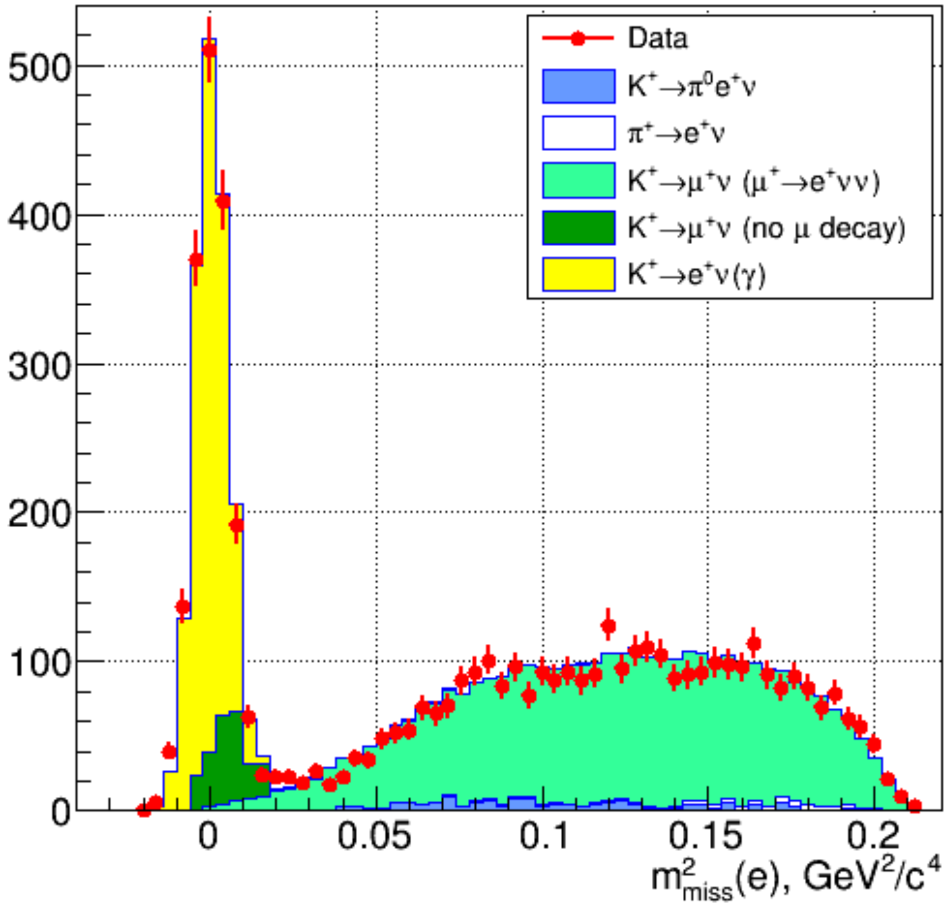
Analysis strategy

- Search for $K^+ \to e^+ N$
- Look for peak in $m_{miss} = \sqrt{P_{K^+} - P_{e^+}}$
- Monte Carlo used to evaluate signal acceptance
- Background contributions estimated from MC and data

Selection

- Kaon identification
- One positively charged track, with associated LKr cluster
- Other than the track cluster, no cluster with E > 0.8 GeV
- Cuts on vertex, CDA; electron PID

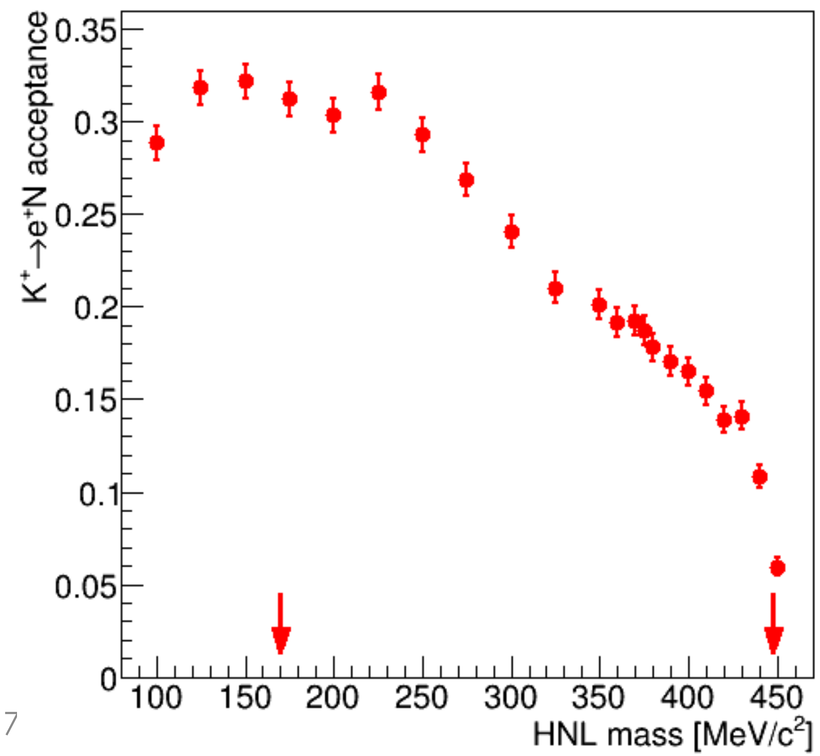
Missing mass spectrum



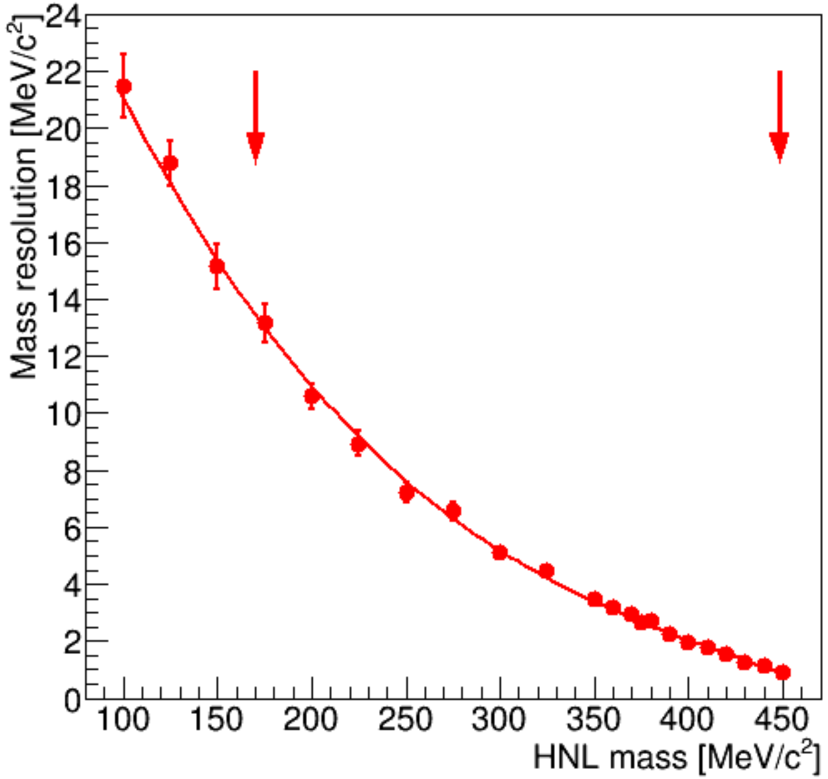
2015 Heavy Neutrino Search - II

- $(3.011 \pm 0.11) \times 10^{11}$ kaon decays recorded (N_K)
- Neutrino mass range: 170-448 MeV/c
- Acceptance drops off sharply above 448 MeV/c

Signal acceptance



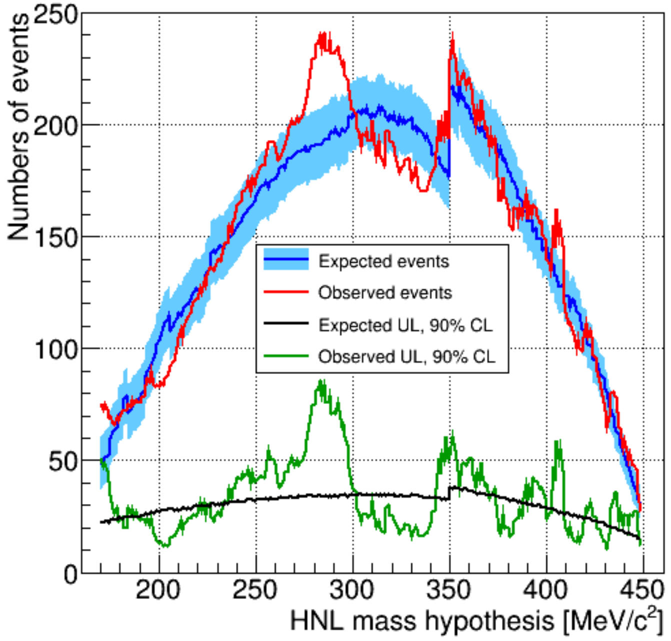
Mass resolution



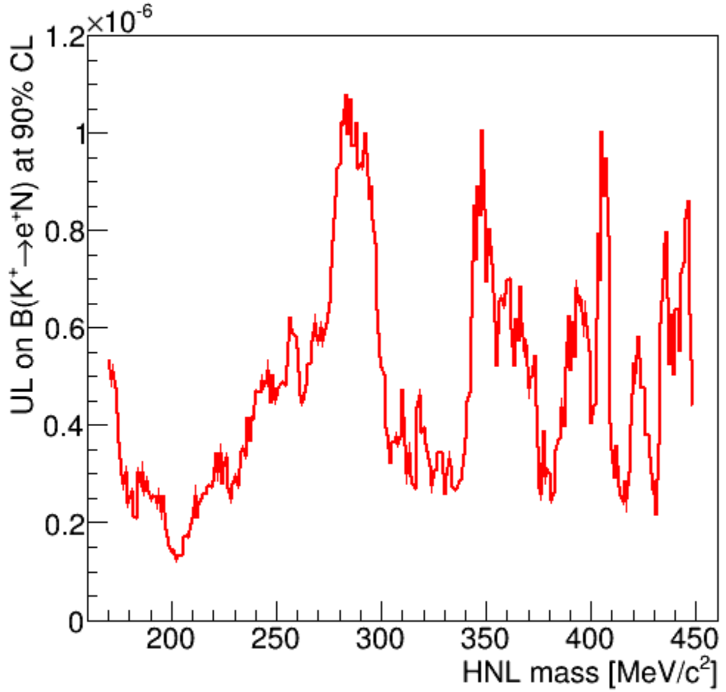
2015 Heavy Neutrino Search - III

- Mass search in steps of 1 MeV/c^2
- Search window of $\pm 1.5\sigma_m$ (mass resolution)
- **No signal observed within 3σ significance**
- Rolke-Lopez method was used to obtain upper limits on the number of signal events (n_{UL})

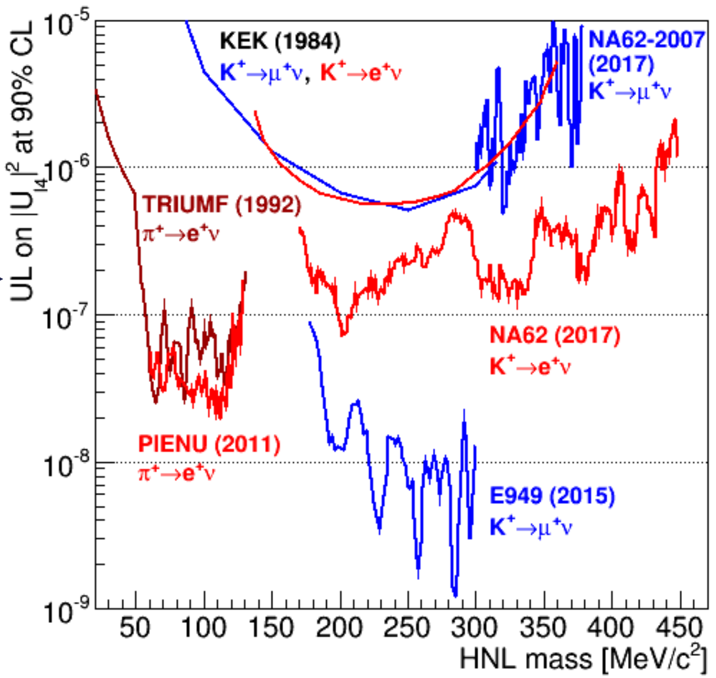
n_{UL}



$B_{UL}(K^+ \to e^+ N)$



$|U_{\mu 4}|^2_{UL}$



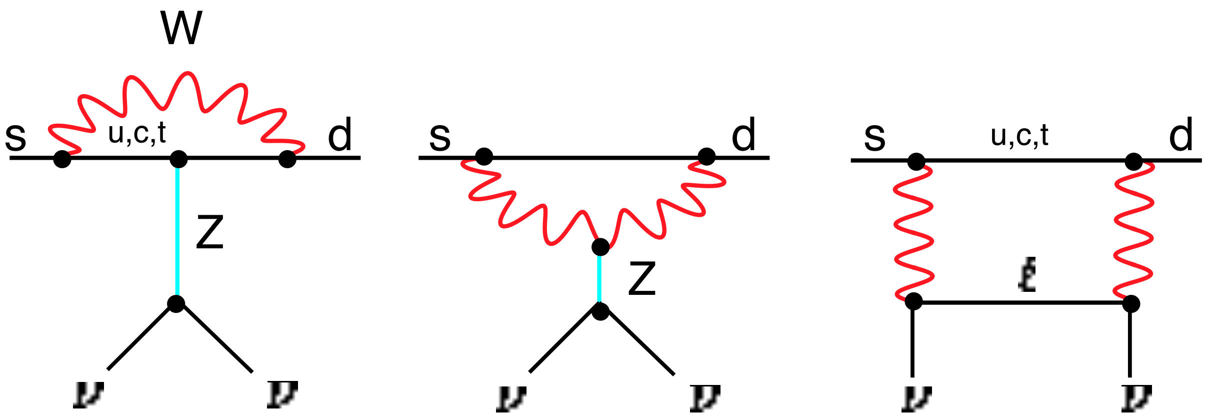
$K^{+} \rightarrow \pi^{+}\upsilon\bar{\upsilon}$

- FCNC process, proceeds via loop or box diagrams
- s→d coupling, highest CKM suppression
- Short-distance contributions dominate
- Theoretical prediction [A.J. Buras, et al. (2015), arXiv:1503.02693]:

  $$BR(K^{+} \rightarrow \pi^{+}\upsilon\bar{\upsilon}) = (9.11 \pm 0.72)\times 10^{-11}$$

- Best measurement to date [A. V. Artamonov, et al. (2009), arXiv:0903.0030]:

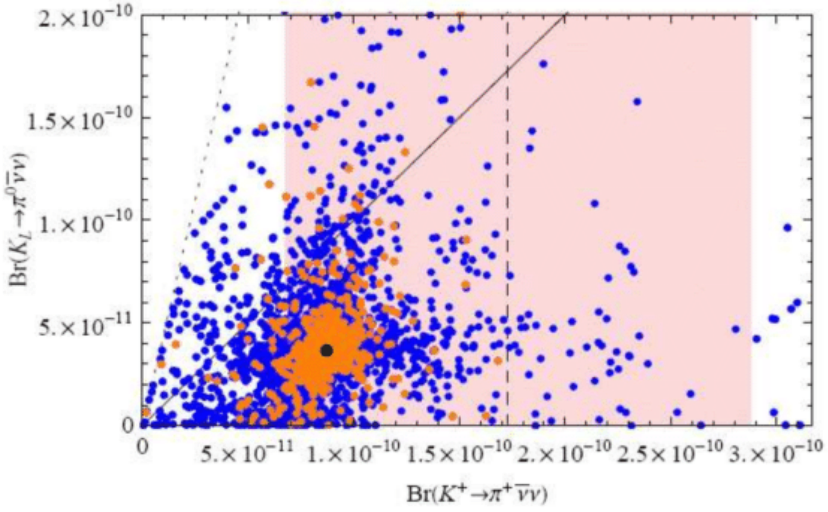
  $$BR(K^{+} \rightarrow \pi^{+}\upsilon\bar{\upsilon}) = \left(17.3^{+11.5}_{-10.5}\right)\times 10^{-11}$$



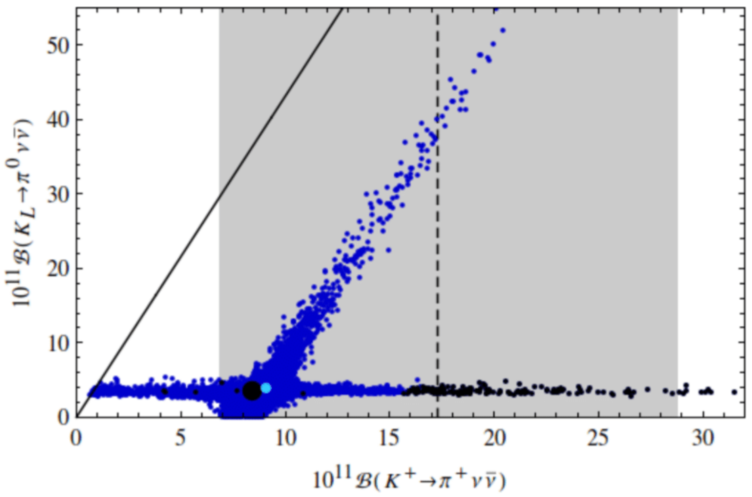
$K^+ \to \pi^+ \nu\bar{\nu}$ NP Sensitivity

- $K^+ \to \pi^+ \nu\bar{\nu}$ measurement complementary to LHC searches
- Can inform several beyond SM models
- Constraints from existing measurements (correlations model dependent)
  - Kaon mixing, CKM elements, K, B rare meson decays, NP limits from direct searches

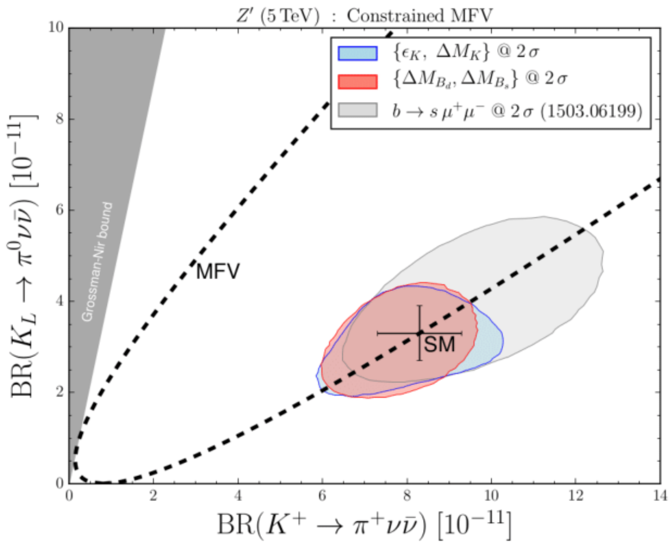
Custodial Randall Sundrum
[M. Blanke, A.J. Buras, S. Recksiegel, JHEP 0903 (2009) 108]



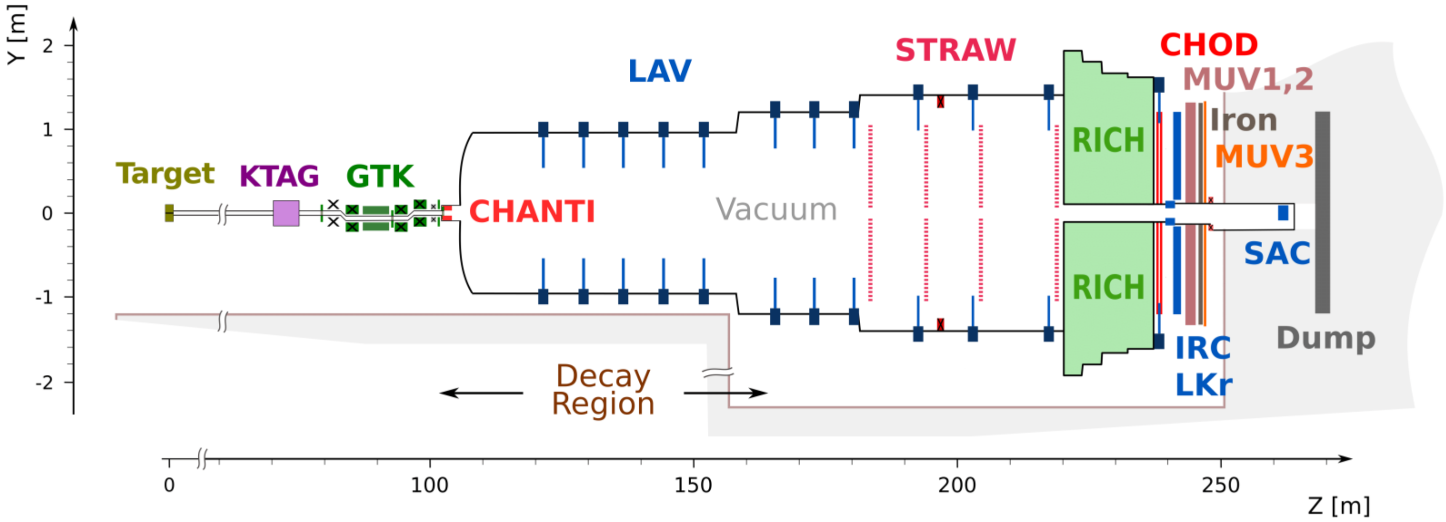
Littlest Higgs
[M. Blanke, A. J.Buras, S. Recksiegel, (2015) arXiv:1507.06316]



Simplified Z, Z'
[A. J. Buras, D. Buttazzo, R. Knegiens, (2015) arXiv:1507.08672]

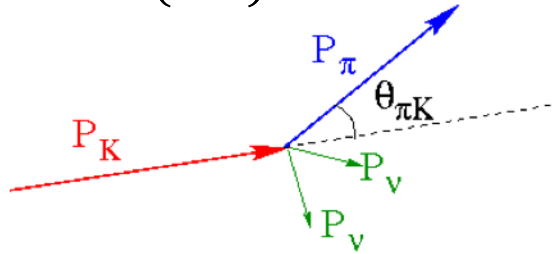


Analysis Strategy



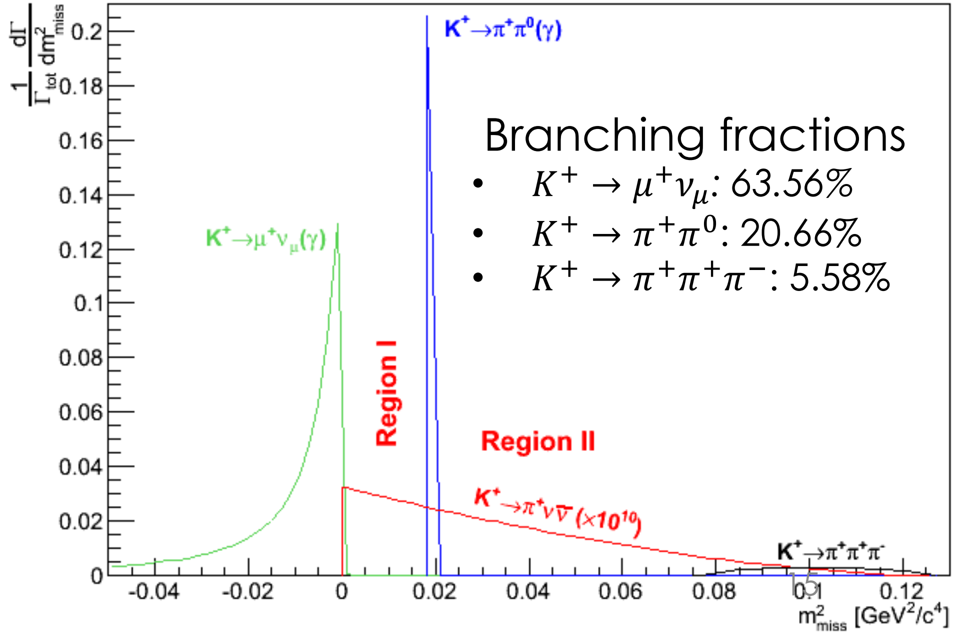
Guiding principles of NA62

- Precise timing: ~100ps resolution
- Kinematic rejection: ~ $O(10^4)$
- Photon rejection → π^0 suppression: ~ $O(10^7)$
- π/μ separation: ~ $O(10^7)$



Selection

- Select an upstream (K^+), and a downstream track (π^+)
- K^+ /π^+ matching in space and time: a K^+ decay event
- Fiducial decay region definition
- π^+ PID using RICH, calorimeters
- Photon rejection
- Multi-track rejection

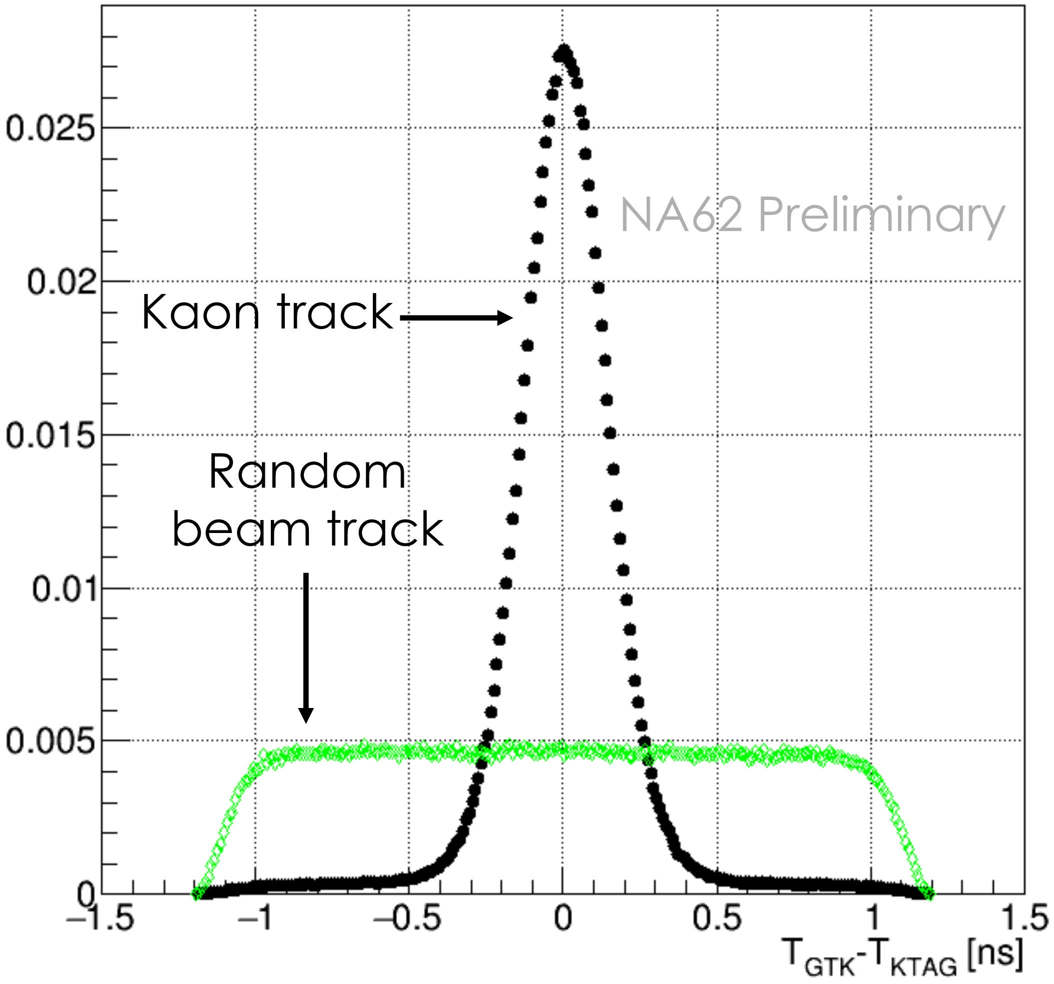


Branching fractions

- $K^+ \to \mu^+\nu_\mu$: 63.56%
- $K^+ \to \pi^+\pi^0$: 20.66%
- $K^+ \to \pi^+\pi^+\pi^-$: 5.58%

K^+- π^+matching

Sample of $K^+ \to \pi^+\pi^+\pi^-$



K^+ timing

- $\sigma(T_{KTAG}) \approx 80ps,\ \sigma(T_{GTK}) \approx 100ps$

π^+ timing

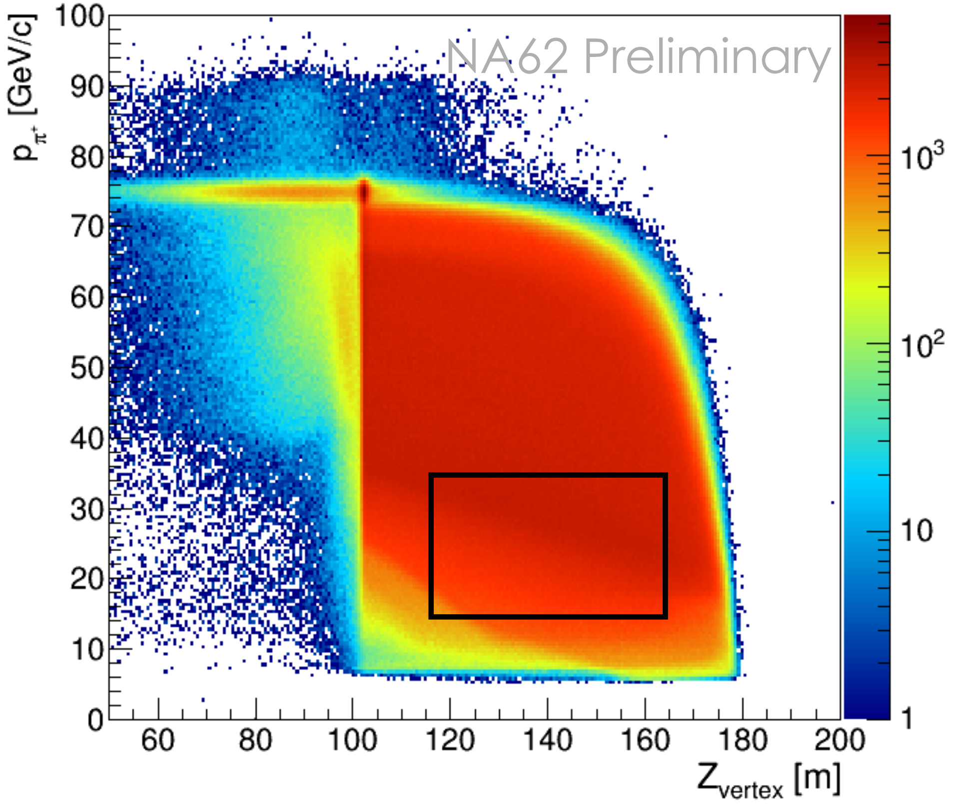
- $\sigma(T_{CHOD}) \approx 250ps,\ \sigma(T_{RICH}) \approx 150ps$

K^+- π^+matching

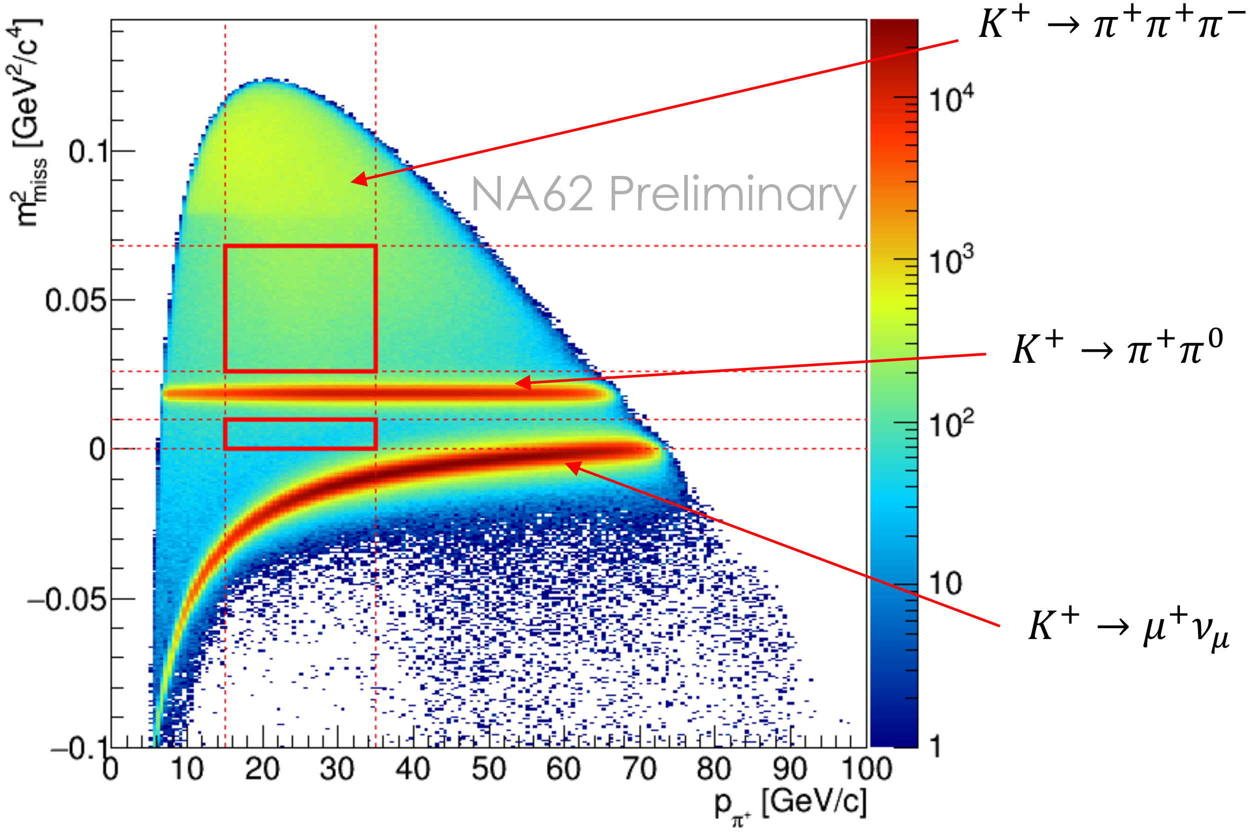
- $\sigma(CDA) \approx 1.5\ mm$
- 75% efficiency
- 1.7% mis-tagging probability

Fiducial decay and signal regions

Signal regions defined by Z_{vertex} , P_{π^+} , and m^2_{miss}

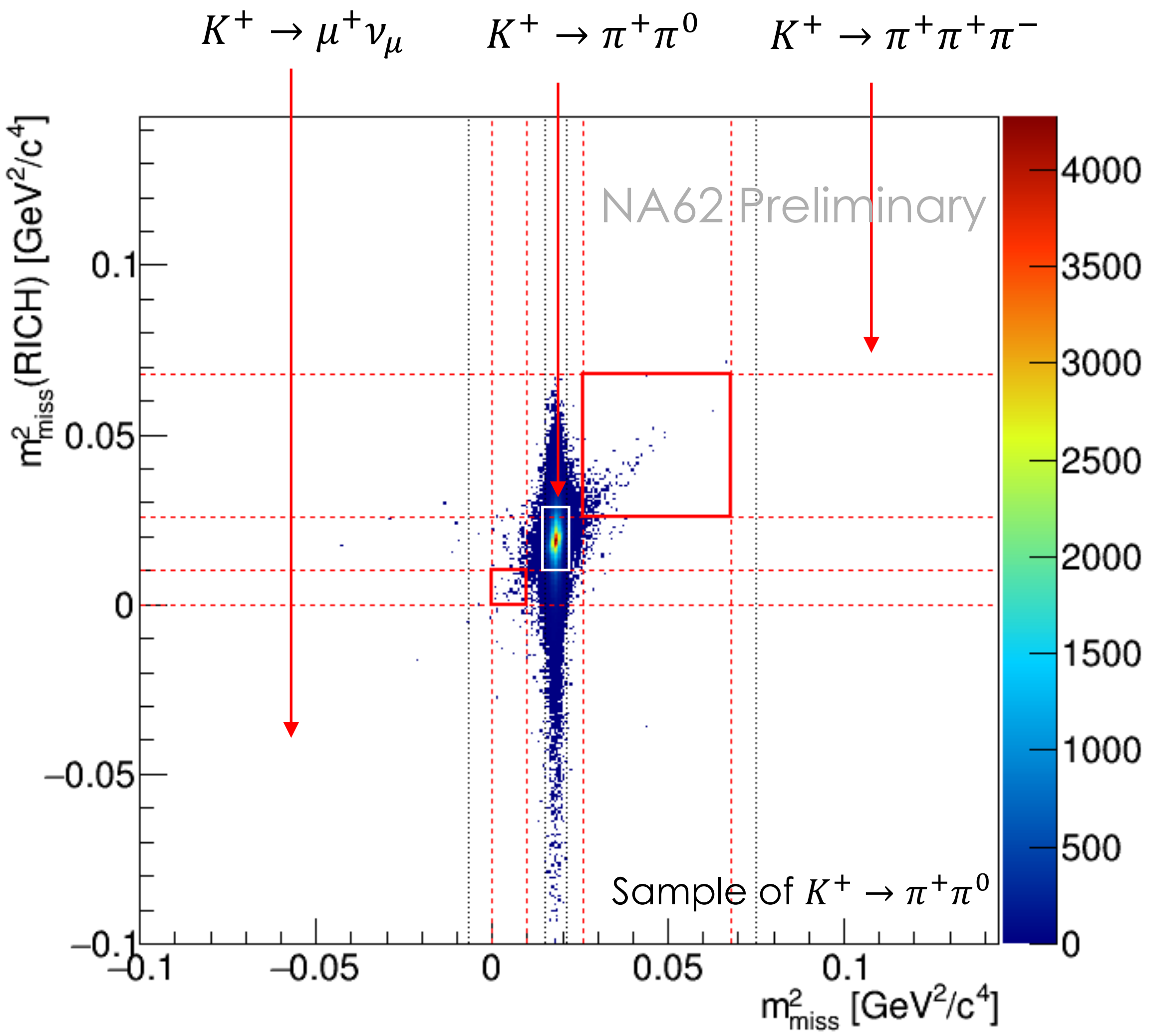


$115\ m < Z_{vertex} < 165\ m$



$15\ GeV/c < P_{\pi^+} < 35\ GeV/c$

Kinematics



Define m^2_{miss} in 3 ways

- $m^2_{miss}\ (STRAW) = (P_{K^+}^{GTK} - P_{\pi^+}^{STRAW})^2$
- $m^2_{miss}\ (RICH) = (P_{K^+}^{GTK} - P_{\pi^+}^{RICH})^2$
- $m^2_{miss}\ (Beam) = (P_{K^+}^{Beam} - P_{\pi^+}^{STRAW})^2$
- Useful to control non Gaussian tails

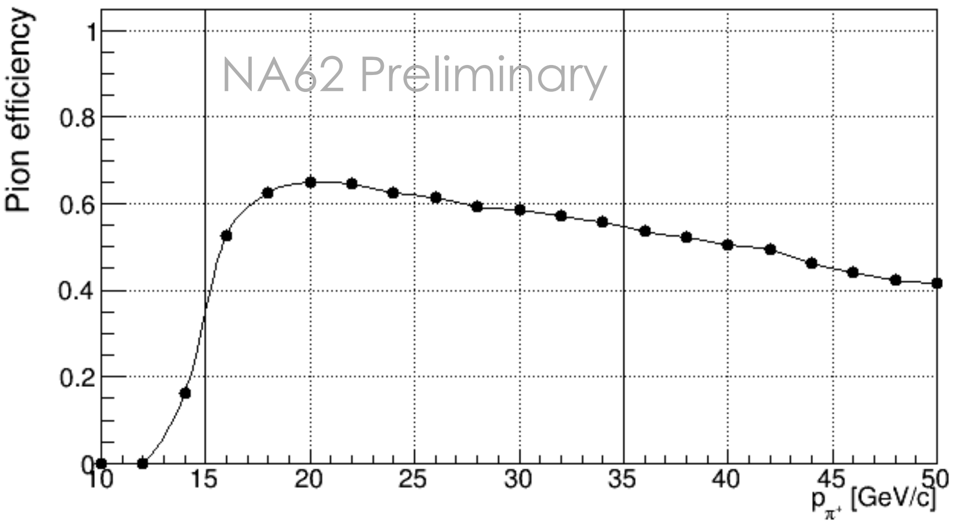
Kinematic suppression

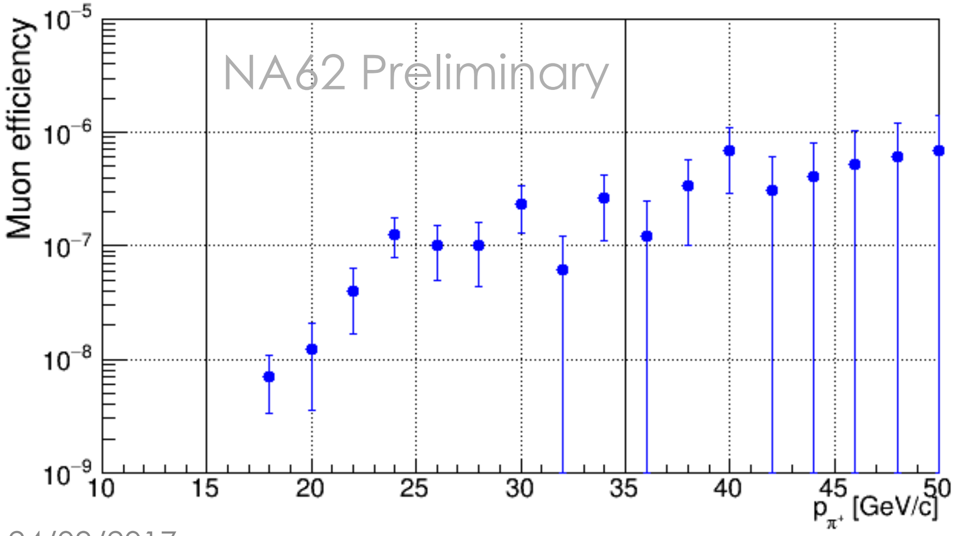
- Measured using data
- $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu_\mu$ samples

Fraction of events in signal regions

- $K^+ \to \pi^+\pi^0$: 6×10^{-4}
- $K^+ \to \mu^+\nu_\mu$: 3×10^{-4}

π^+ Identification





PID with calorimeters

- Multi-variate analysis: E, E sharing, cluster shape
- LKr, MUV1/2
- $\varepsilon(\mu) \approx 10^{-5}$
- $\varepsilon(\pi) \approx 80\%$

PID with RICH

- $\varepsilon_{\pi^+}^{RING} \approx 90\%$, function of P_{π^+}
- $\varepsilon_{\pi^+}^{ID} \approx 80\%$
- $\varepsilon_{\mu^+} \approx 10^{-2}$

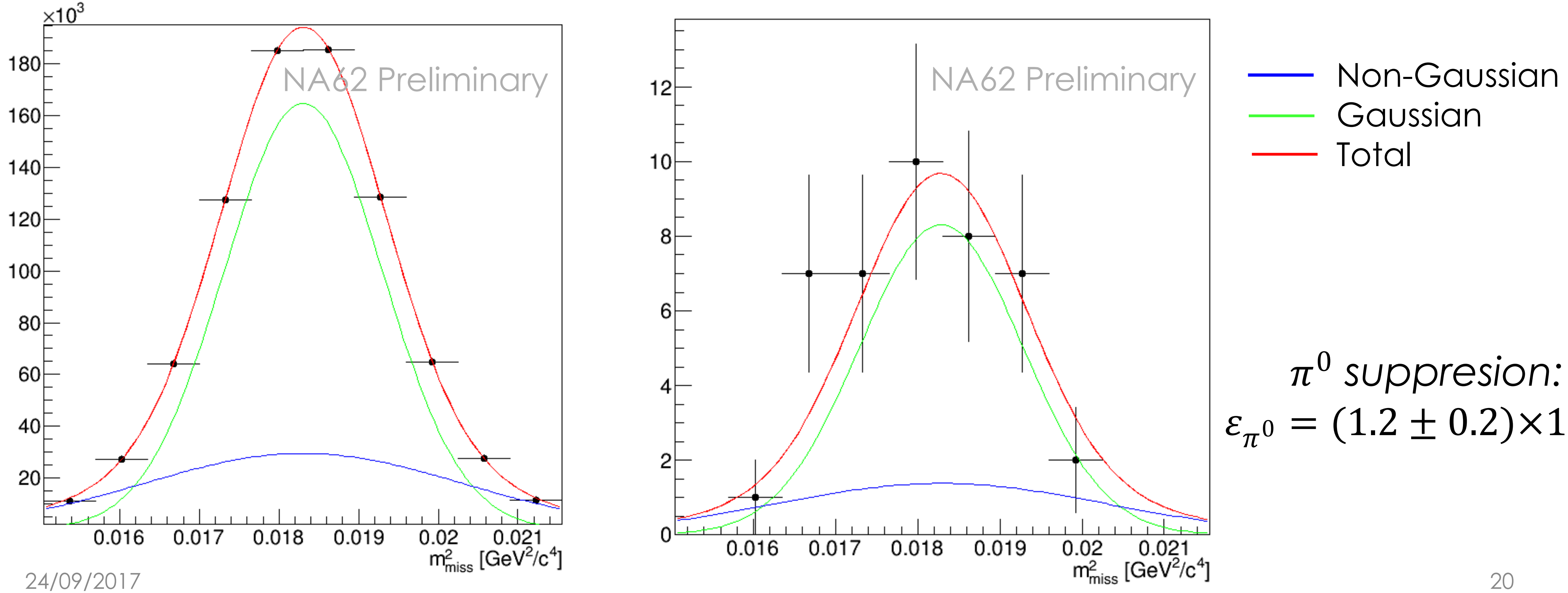
- Combine both techniques for a total of 10^7 π/μ separation

Photon rejection

- Photon veto detectors: LAV, LKr, IRC, SAC
- Rejection measurement performed in $K^+ \to \pi^+\pi^0$ region

Before γ rejection, minimum bias trigger

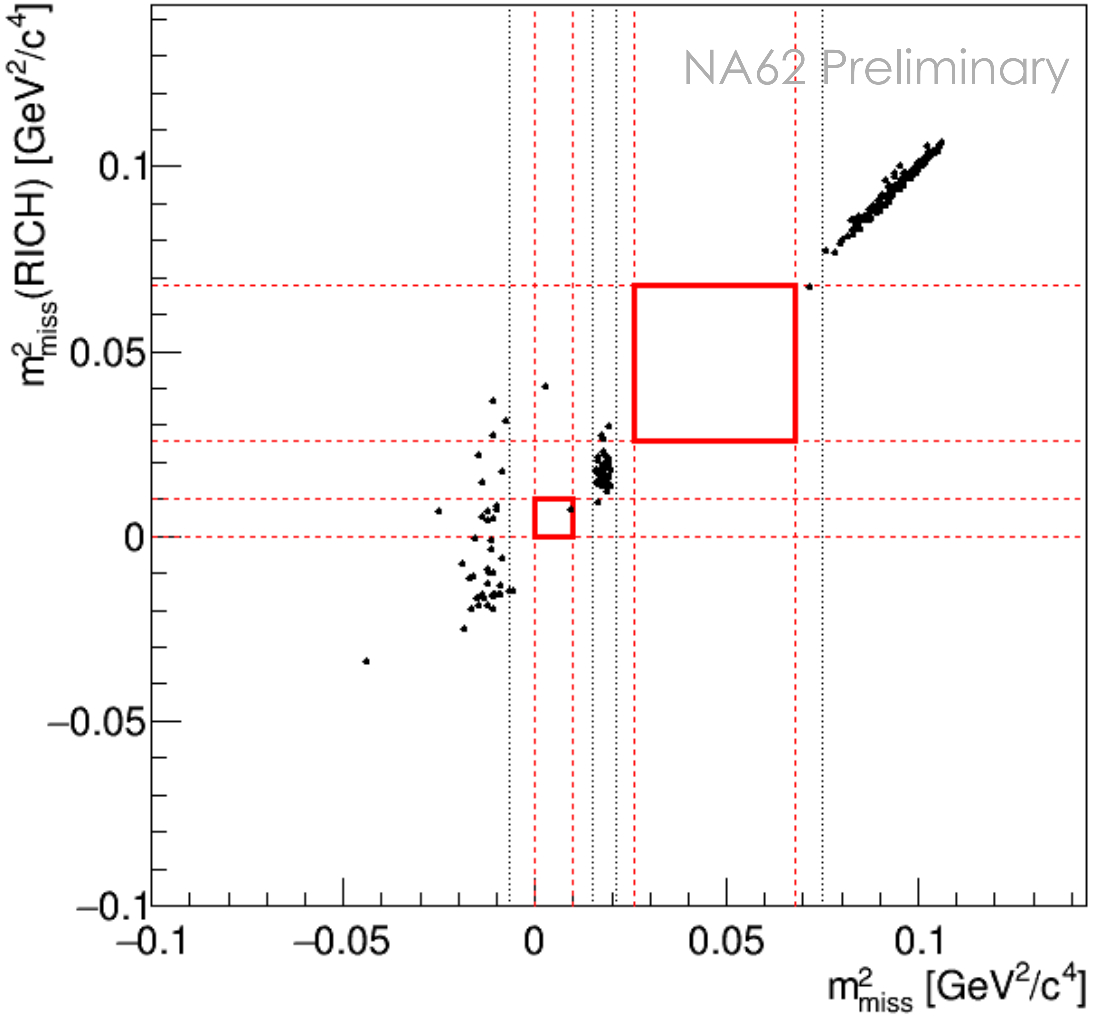
After γ rejection, PNN trigger



π^0 *suppresion:*

$$\varepsilon_{\pi^0} = (1.2 \pm 0.2)\times 10^{-7}$$

Preliminary Results



- 5% of 2016 data
- 2.3×10^{10} kaon decays
- Full $\pi^+\nu\bar{\nu}$ selection applied
- Expected number of events:
  - Signal: 0.064
  - Background: 0.052
- **No signal observed**
- Event inside the box has m^2_{miss} (no GTK) outside of the signal region
- Analysis still being optimized

Wider NA62 Programme

"Standard" kaon physics
- ChPT studies: $K^+ \to \pi^+\gamma\gamma, K^+ \to \pi^+\pi^0 e^+ e^-, K_{l4}$
- BR and form factors: $K^+ \to \pi^0\mu^+\upsilon_\mu,\ K^+ \to \pi^0 e^+\upsilon_e$

Lepton flavour/number violating decays
- $K^+ \to \pi^+\mu^\pm e^\mp, K^+ \to \pi^-\mu^+ e^+,\ K^+ \to \pi^- l^+ l^+$

Heavy neutral leptons
- $K^+ \to \mu^+\nu_h$
- ν_h from upstream K, D decays, $\nu_h \to \pi l$

Long lived dark sector particles
- Dark photon γ' produced in π/ρ decays in target with $\gamma' \to l^+ l^+$
- Axion-like particle A^0 produced in target/dump, with $A^0 \to \gamma\gamma$

π^0 decays
- $\pi^0 \to invisible, \pi^0 \to 3\gamma, 4\gamma;\ \pi^0 \to \gamma'\gamma$

Conclusion and Prospects

Heavy Neutrinos

- No signal observed in 2007 or 2015 data
- Improved upper limits set on branching ratios and mixing matrix U_{l4}

$\boldsymbol{K^+ \rightarrow \pi^+ \upsilon \bar{\upsilon}}$

- NA62 fully operational
- 5% of 2016 data presented, 2.3×10^{10} kaon decays
- No signal observed against expectation of 0.064
- Data taking until LS2
- Analysis in progress