NA62 experiment

Michal Zamkovsky

Charles University in Prague

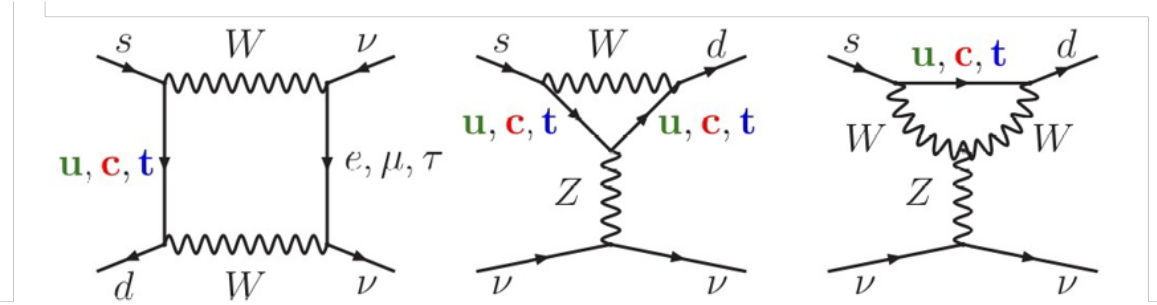
April 19, 2017

Outline

- Theoretical motivation for $\mathrm{K}^+ \to \pi^+ \nu\bar{\nu}$
- NA62 setup
- Event selection and analysis strategy
- Analysis status/prospects
- Heavy neutral lepton search with 2007 and 2015 data
- Future prospects of NA62 experiment
- Summary

Theoretical motivation

- FCNC loop process: s→d coupling and highest CKM suppression



- Very clean theoretically: Short distance contribution and no hadronic uncertainties - Hadronic matrix element extracted from well-known decay $\mathrm{K}^+ \to e^+\nu\pi^0$
- SM predictions: [Buras et al. arXiv:1503.02693], [Brod, Gorbahn, Stamou, Phys. Rev.D 83, 034030 (2011)]

$$BR(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30)\cdot 10^{-11}\left(\frac{|V_{cb}|}{0.0407}\right)^{2.8}\left(\frac{\gamma}{73.2\,[\mathrm{U+FFFD}]}\right)^{0.74} = (8.4 \pm 1.0)\cdot 10^{-11}$$

$$BR(\mathrm{K}_\mathrm{L}^0 \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05)\cdot 10^{-11}\left(\frac{|V_{ub}|}{0.00388}\right)^{2}\left(\frac{|V_{cb}|}{0.0407}\right)^{2}\left(\frac{\sin\gamma}{\sin 73.2}\right)^{2} = (3.4 \pm 0.6)\cdot 10^{-11}$$

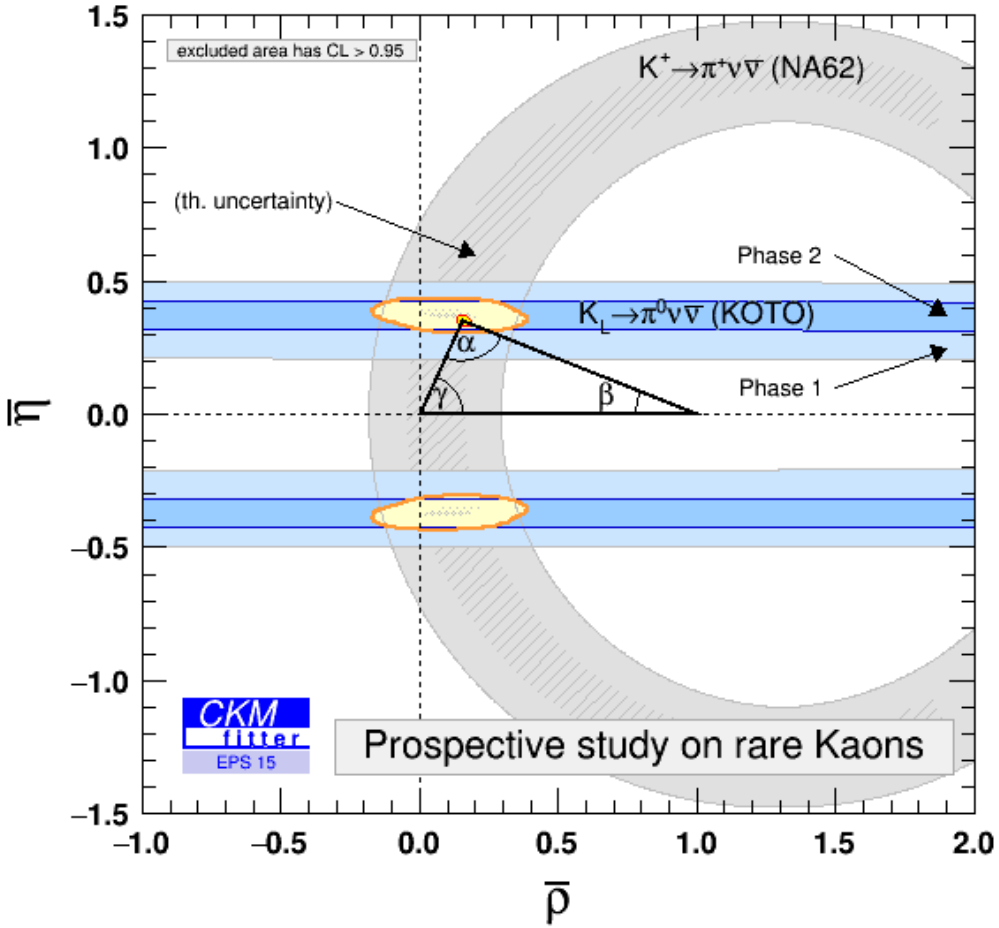
- Experiments:

$BR(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ Phys.Rev.D77, 052003(2008), Phys.Rev.D79, 092004(2009)

$BR(\mathrm{K}_\mathrm{L}^0 \to \pi^0\nu\bar{\nu}) < 2.6 \times 10^{-8}$ Phys.Rev.D81, 072004(2010)

Testing the Standard Model

- BR($K^+ \to \pi^+ \nu\bar{\nu}$) with 10% uncertainties allows to determine $|V_{td}|$ at 9% [Buras 0405132]
- With BR($K^+ \to \pi^+ \nu\bar{\nu}$), BR($K_L^0 \to \pi^0 \nu\bar{\nu}$) the CKM unitarity triangle can be built independently from B observables:



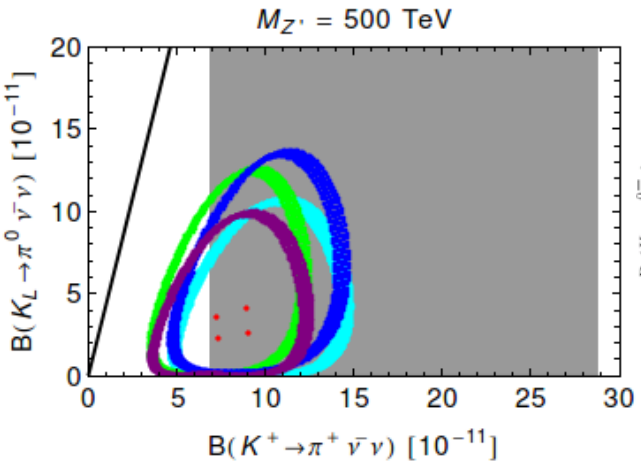
Going Beyond the Standard Model

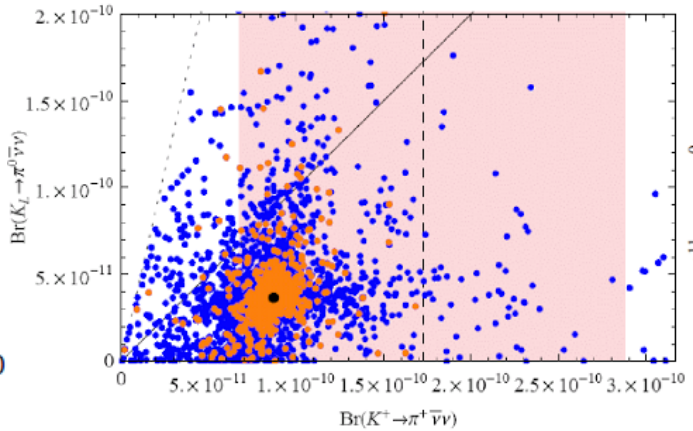
- Simplified Z, Z' models [Buras, Buttazzo,Knegjens, arXiv:1507.08672 (2015)]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, arXiv:1507.06316 (2015)]
- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM non-MFV [Blazek, Matak Int.J.Mod.Phys.A29 (2014) 1450162;

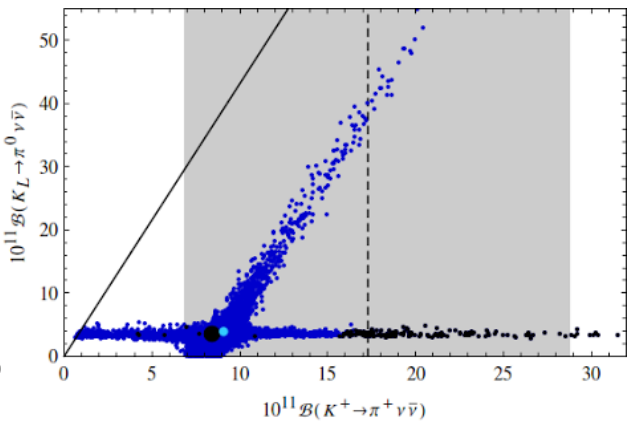
  Tanimoto, Yamamoto PTEP (2015) 053B07; Isidori et al. JHEP 0608 (2006) 064]

- Constraints from existing measurements (correlations model dependent):
  Kaon mixing and CPV, CKM fit, K,B rare meson decays,
  NP limits from direct searches

Z' model *Randall – Sundrum* *LittlestHiggs*





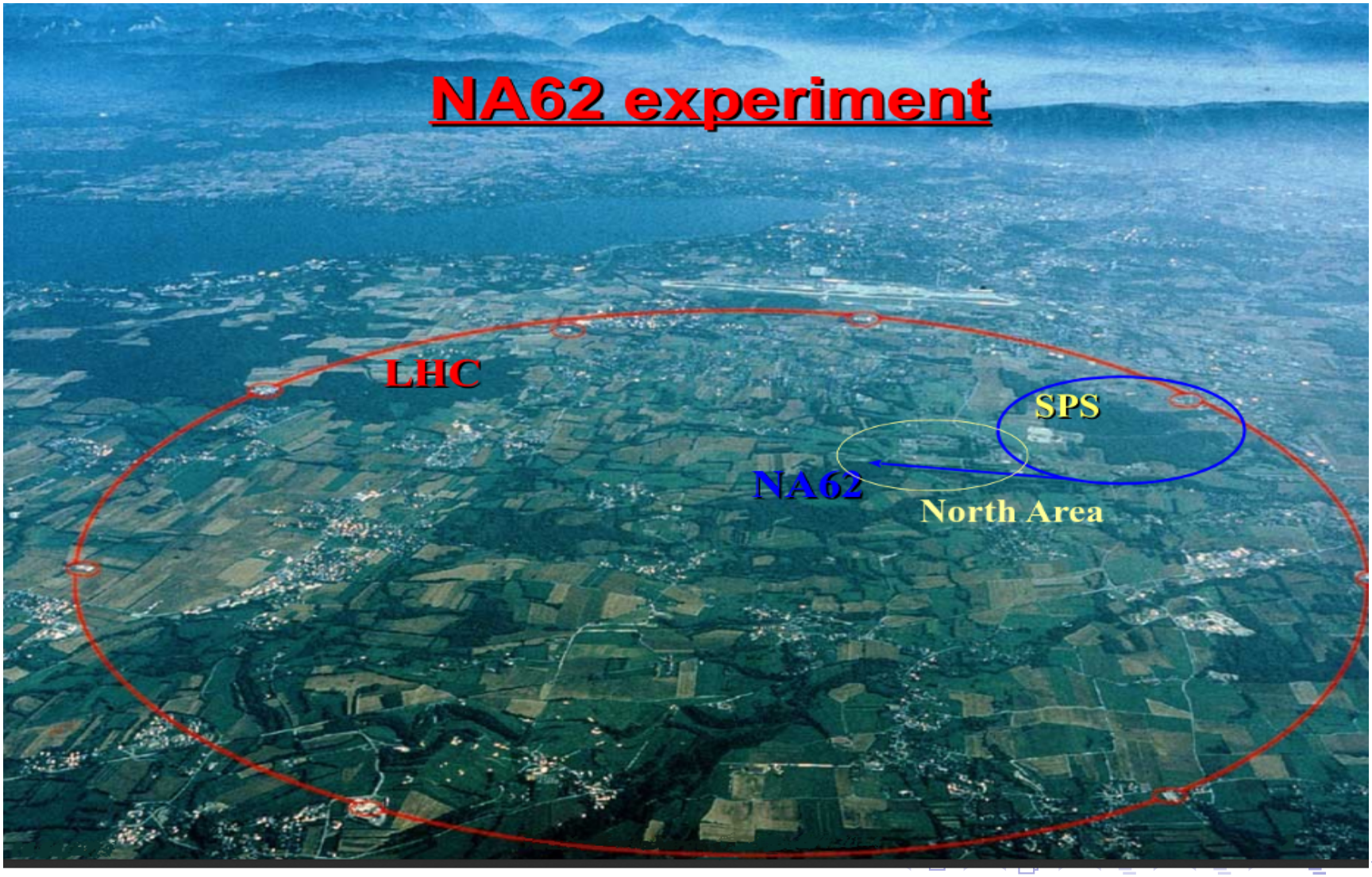


Physics program of NA62 experiment

- Main goal:
  - Collect O(100) signal events in 2 years $\Rightarrow 10^{13}$ Kaon decays
  - Measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) with 10% precision
  - Signal acceptance $\sim$ 10%
  - Systematics: <10% precision background measurement
  - $> 10^{12}$ background rejection ($<$ 20% background)
- Further goals:
  - Measure $|V_{td}|$ with $\sim$10% accuracy
  - Probe several NP scenarios in $K^+ \to \pi^+ \nu\bar{\nu}$
  - Probe NP in similar processes (e.g. $K^+ \to \pi^+ X$)
- Beyond the baseline:
  - LFV/LNV decays with 3 tracks in the final state
  - Heavy neutrino searches
  - π^0 decays
  - Dark photon searches

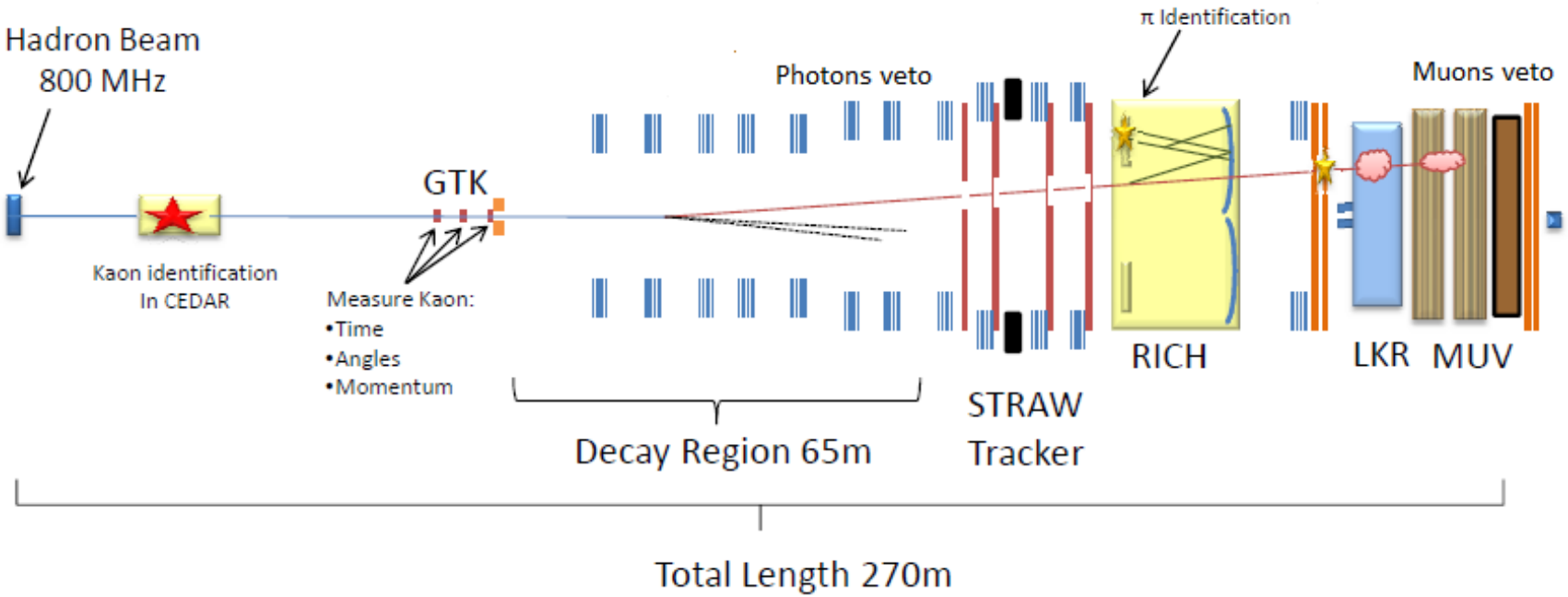
Experiment NA62 at CERN

- SPS experiment NA62 - North Area experiment, Prèvessin
- Extracting 74 GeV/c K^+ from 400 GeV/c proton beam



Detector layout

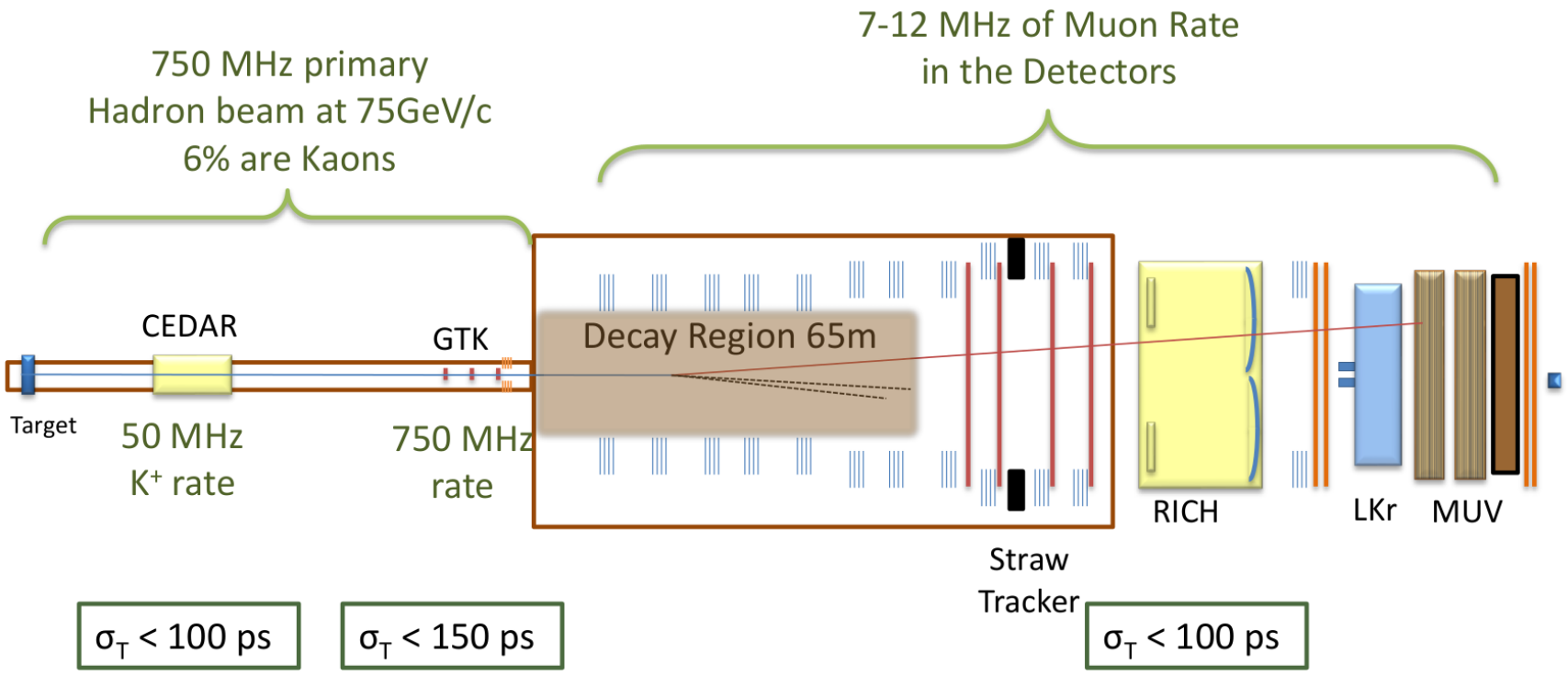
- $\sim$ 11MHz of K^+ decays



- High Intensity and fast Timing
- Low Mass Tracking
- Hermetic Vetoing for Photons and Muons
- Particle ID

Detector layout

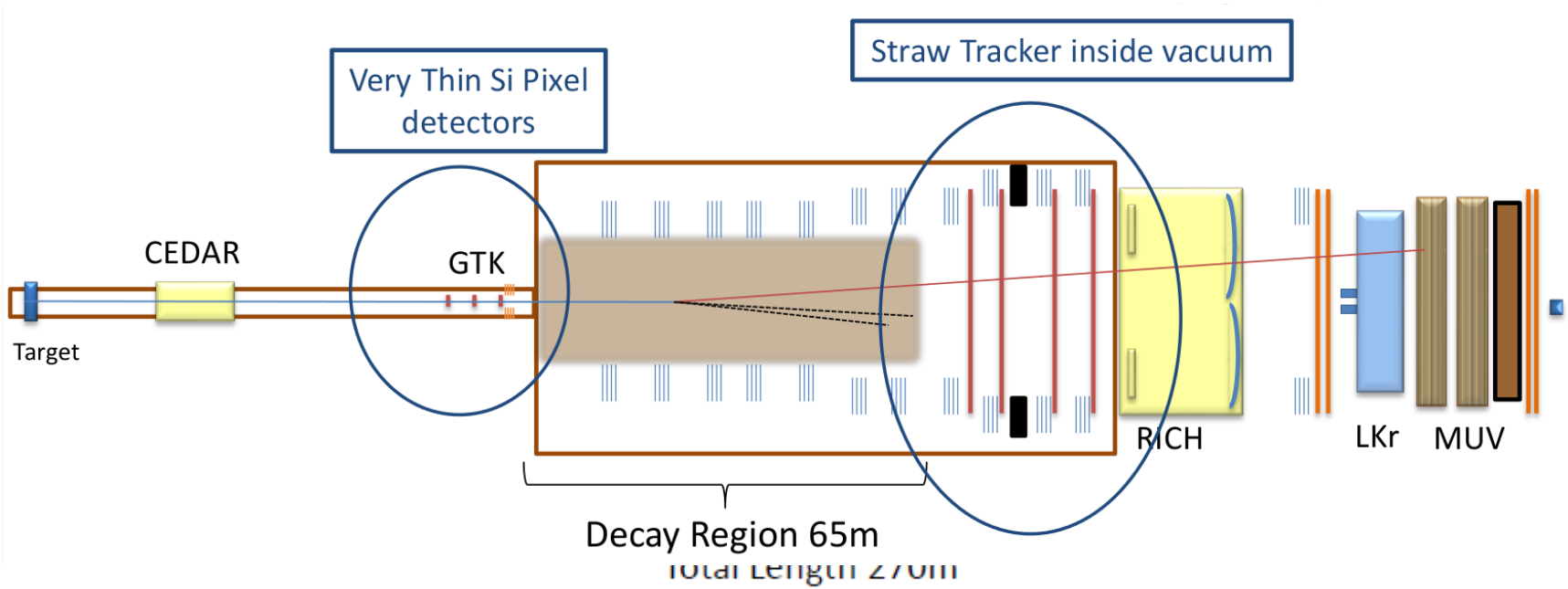
- $\sim$ 11MHz of K^+ decays



- High Intensity and fast Timing
- Low Mass Tracking
- Hermetic Vetoing for Photons and Muons
- Particle ID

Detector layout

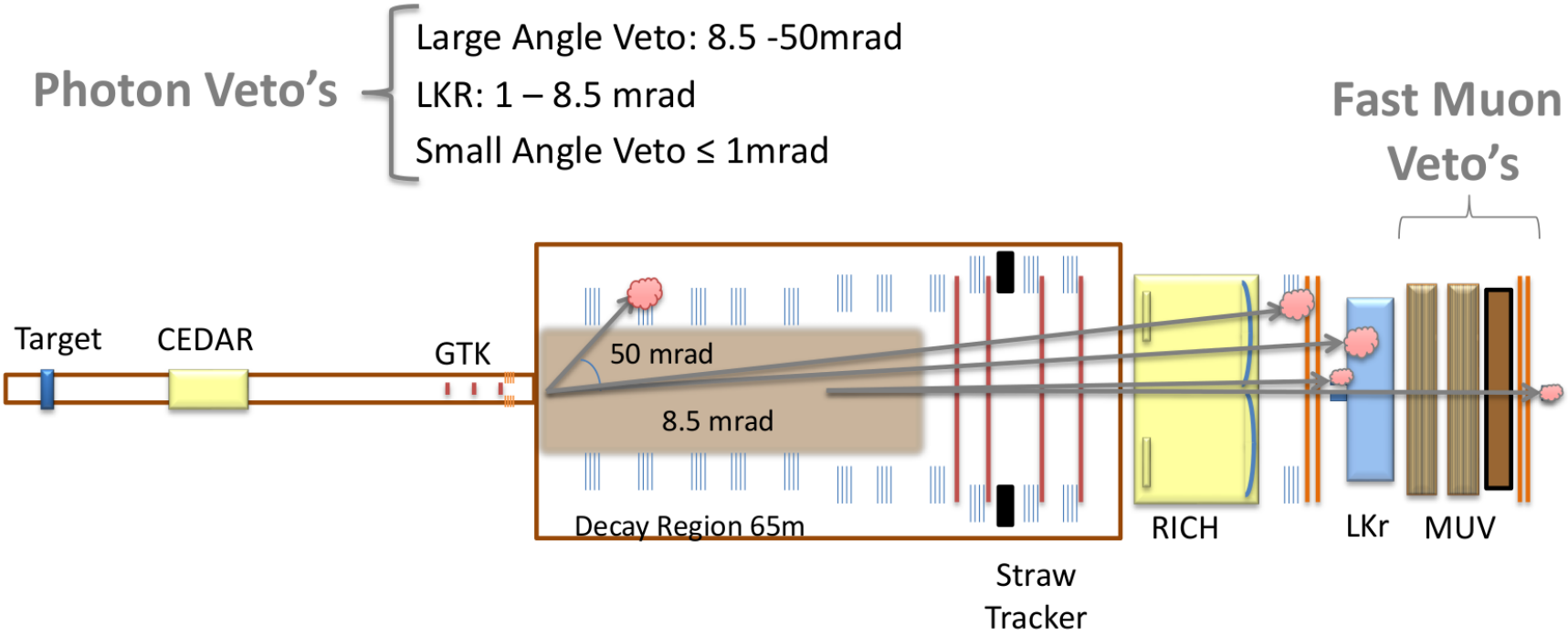
- $\sim$ 11MHz of K^+ decays



- High Intensity and fast Timing
- Low Mass Tracking
- Hermetic Vetoing for Photons and Muons
- Particle ID

Detector layout

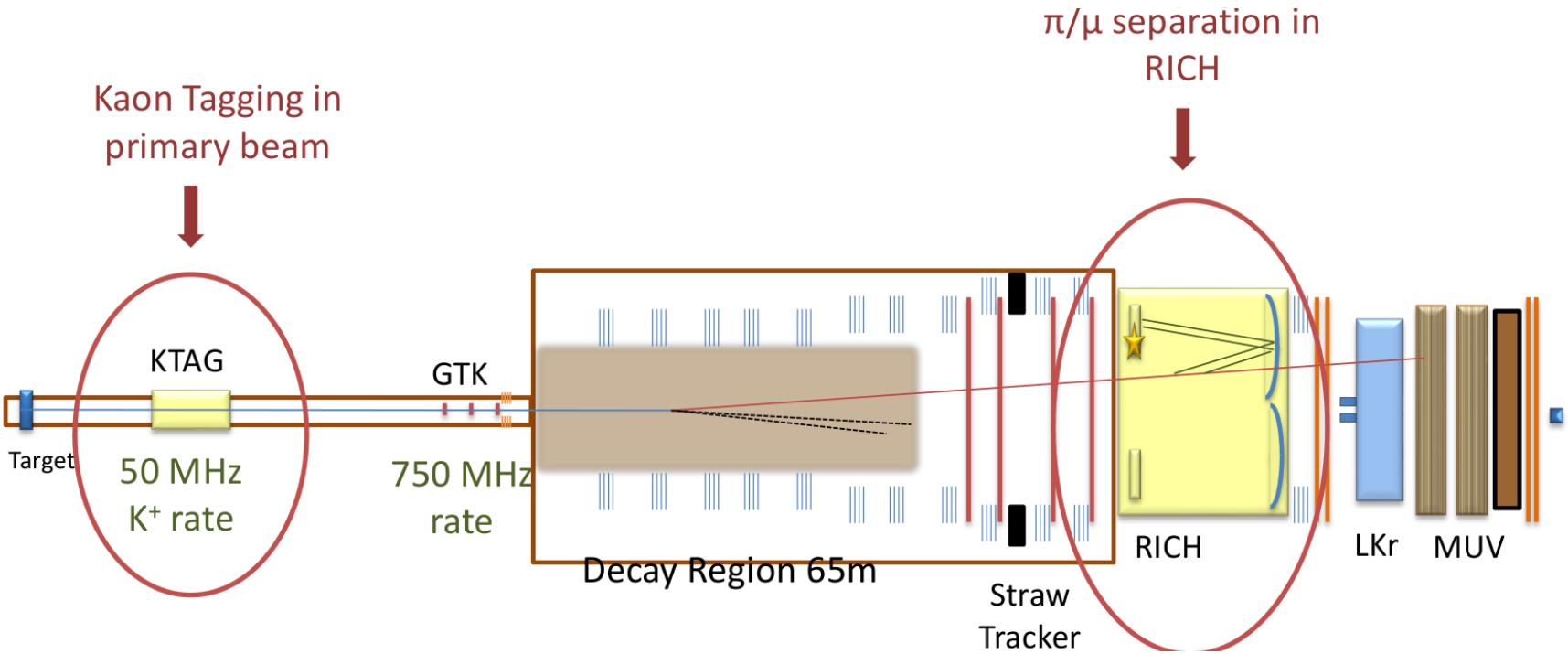
- $\sim$ 11MHz of K^+ decays



- High Intensity and fast Timing
- Low Mass Tracking
- Hermetic Vetoing for Photons and Muons
- Particle ID

Detector layout

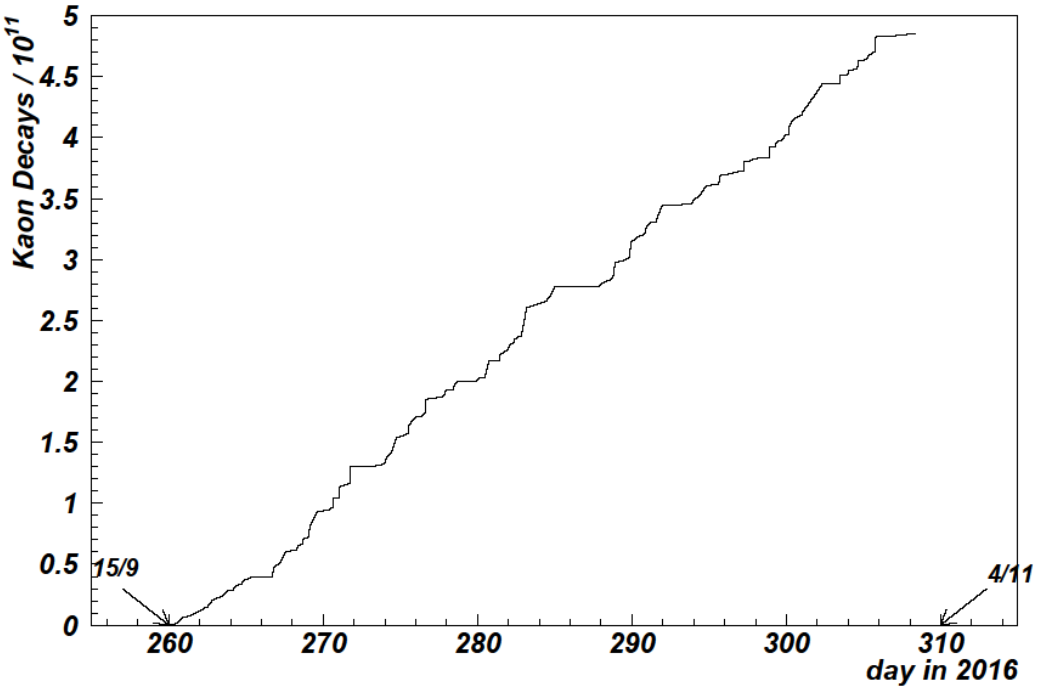
- $\sim$ 11MHz of K^+ decays



- High Intensity and fast Timing
- Low Mass Tracking
- Hermetic Vetoing for Photons and Muons
- Particle ID

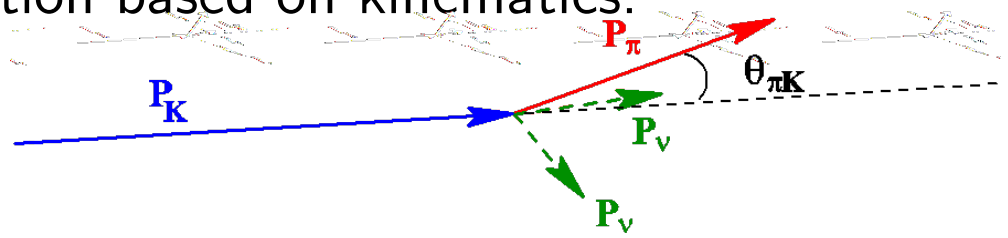
Experimental status

- NA62 took data in 2014, 2015 (only low intensity) and 2016
- Beam commissioned up to nominal intensity
- All subsystems installed and commissioned
- L0, L1 triggers commissioned
- $\sim 5 \times 10^{11}$ kaon decays recorded in 2016 $= 10^3$ TByte of data



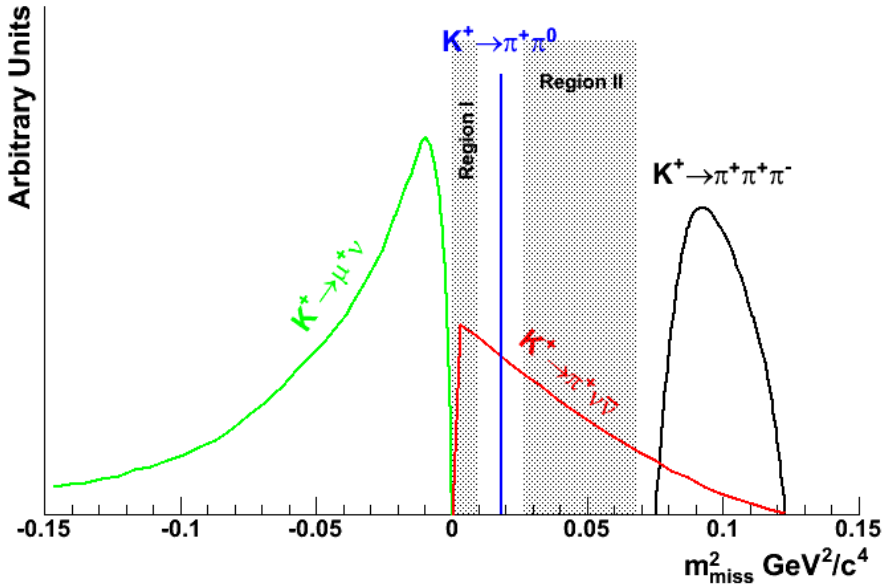
Scheme for $K^+ \to \pi^+ \nu\bar{\nu}$

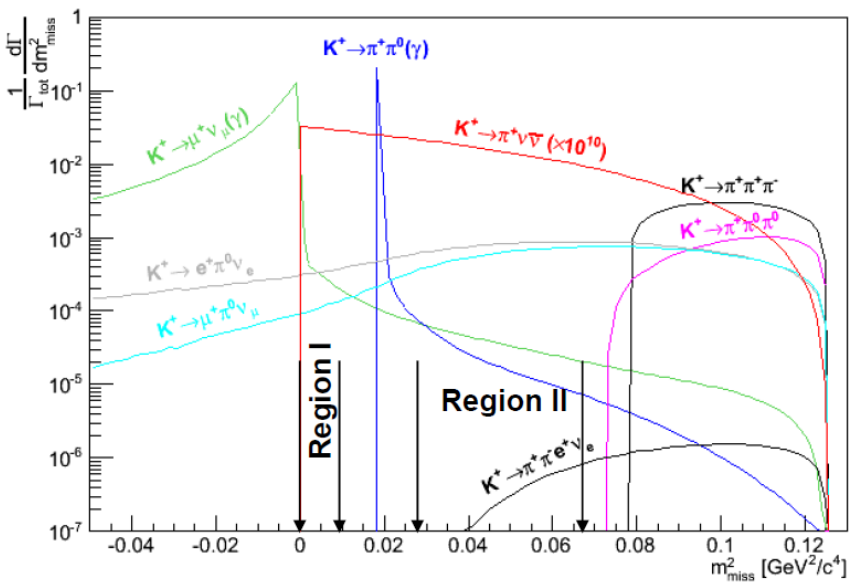
- Reconstruction based on kinematics:



$$m^2_{miss} = (P_K - P_\pi)^2 \approx m_k^2 \left(1 - \frac{|P_\pi|}{|P_K|}\right) + m_\pi^2 \left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\vartheta^2_{\pi K}$$

- 92% of Kaon decays are kinematically constrained





Analysis strategy and background sources

- Key analysis requirements:
  - 2 signal regions in m^2_{miss}
  - $15 < P_{\pi^+} < 35$ GeV/c
  - 65 m long decay region
- Expected 45 SM signal events/year with ≤ 10 background
- Main background sources:

Decay mode	event/year
$K^+ \to \pi^+\nu\bar{\nu}$ SM	45
Total Background	10
$K^+ \to \pi^+\pi^0$	5
$K^+ \to \mu^+\nu$	1
$K^+ \to \pi^+\pi^+\pi^-$	< 1
$K^+ \to \pi^+\pi^- e^+\nu$ + other 3 track decays	< 1
$K^+ \to \pi^+\pi^0\gamma^{IB}$	1.5
$K^+ \to \mu^+\nu\gamma^{IB}$	0.5
$K^+ \to \pi^0 e^+(\mu^+)\nu$ + others	negligible

- Other possible background:
  - Accidental tracks in time with kaon tracks
  - Beam-gas and upstream interactions

Signal topology & kaon ID: K/π *matching*

One-track selection

- Single downstream track topology
- Beam track matching the downstream track
- Beam track matching a K signal in Kaon ID
- Downstream track matching energy in calorimeters

π^+ timing

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

K^+ timing

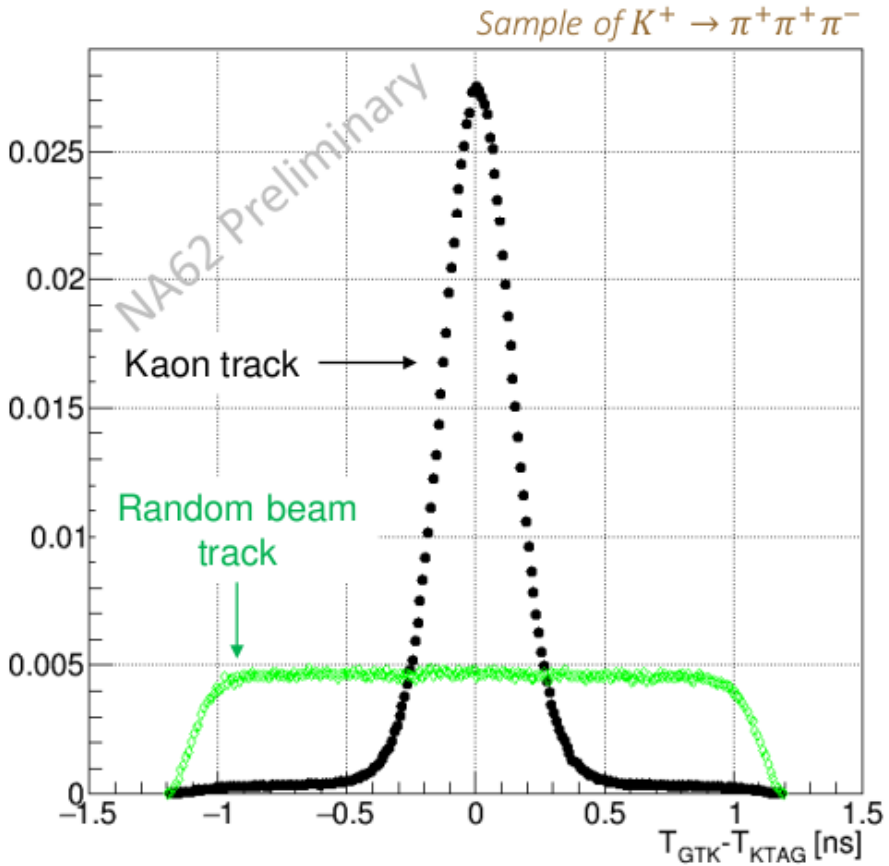
- $\sigma(T_{KTAG}) \sim$80 ps, $\sigma(T_{GTK}) \sim$ 100 ps

Spatial matching

- $\sigma(CDA) \sim$1.5 mm

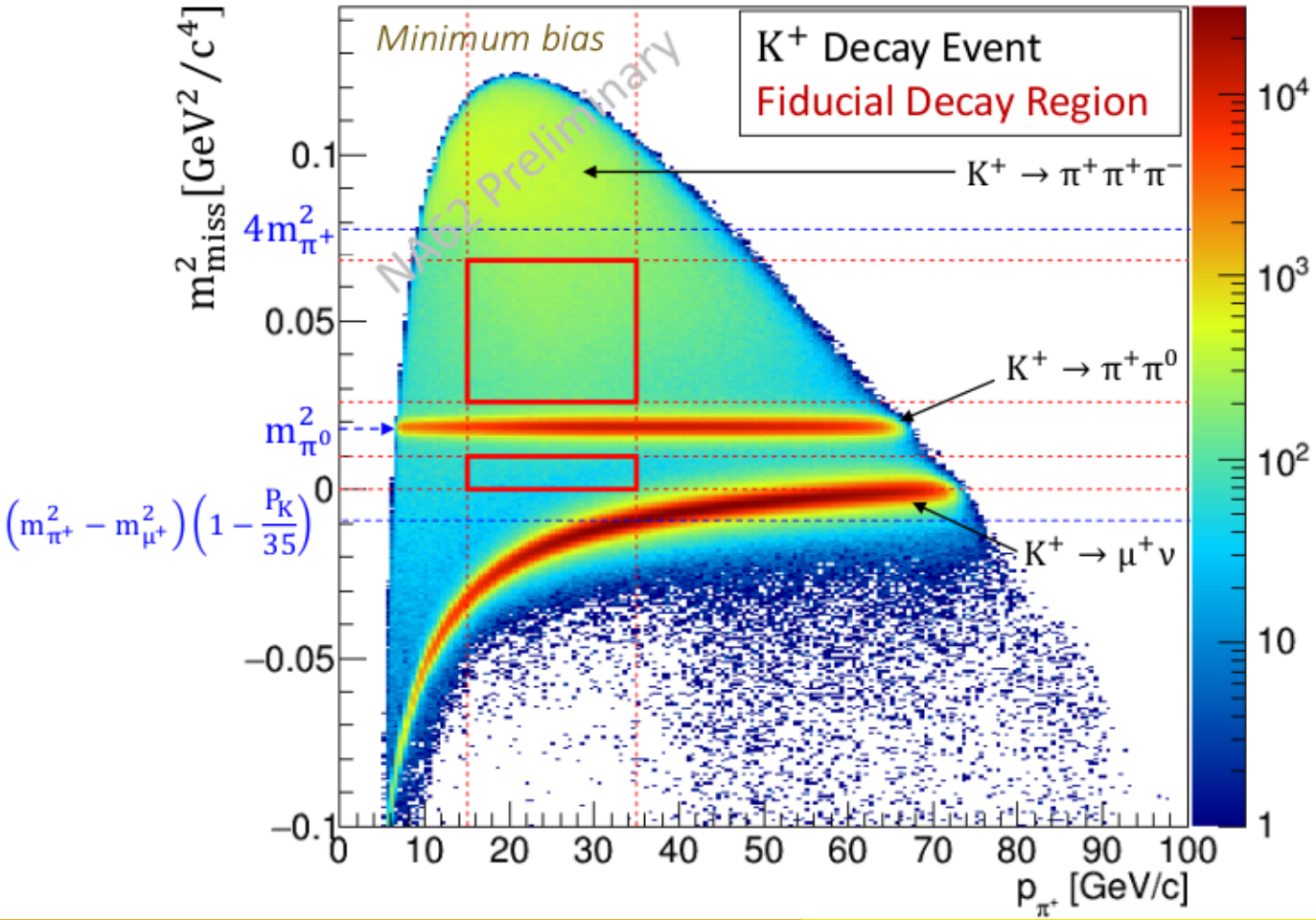
Mis-tagging probability

- ∼1.7% [40% nominal intensity, 75% eff]

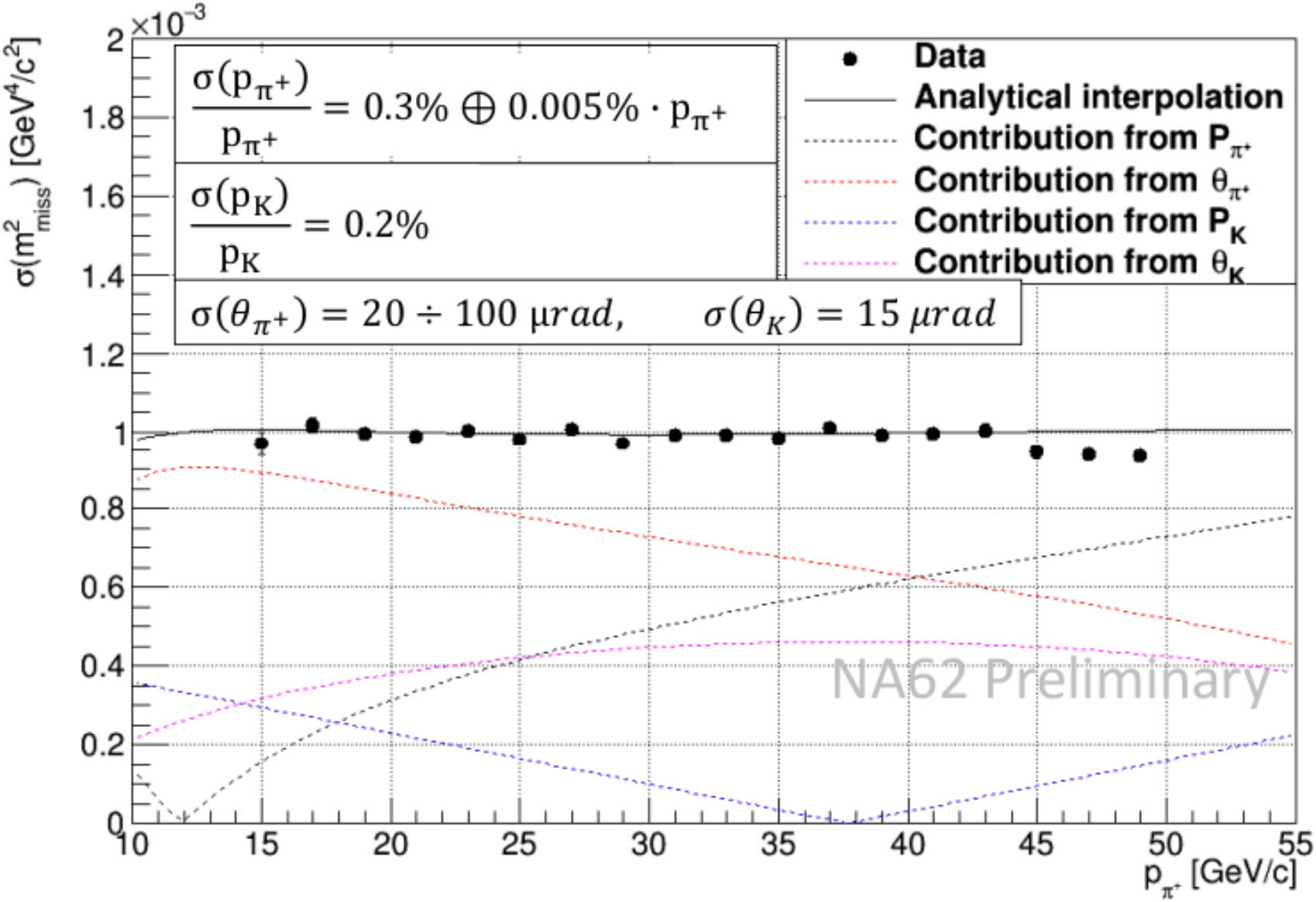


Signal Regions Definition

- Technique: Si-pixel tracker; Straw tube tracker in vacuum
- Goal: O($10^4 \div 10^5$) suppression factor of the main kaon decay modes
- $P_{\pi^+} < 35$ GeV/c: best $K^+ \to \mu^+\nu$ suppression
- Kinematics studied on $K^+ \to \pi^+\pi^0$ selected using LKr calorimeter

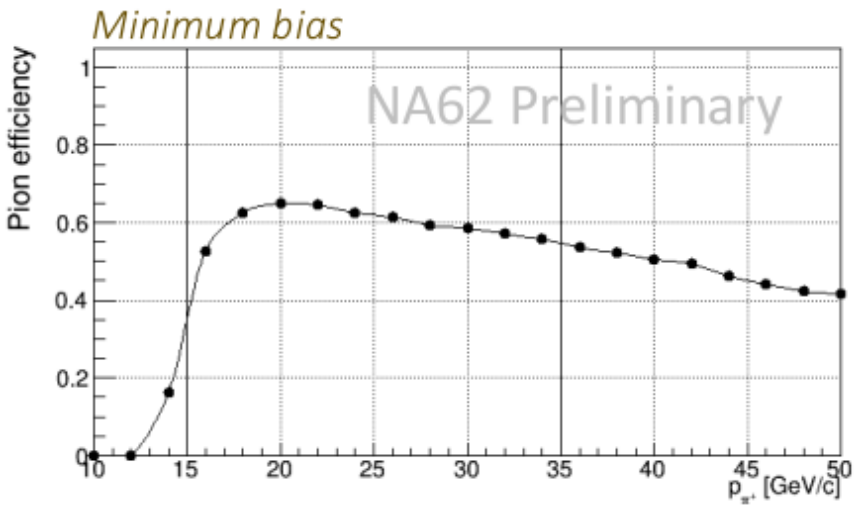


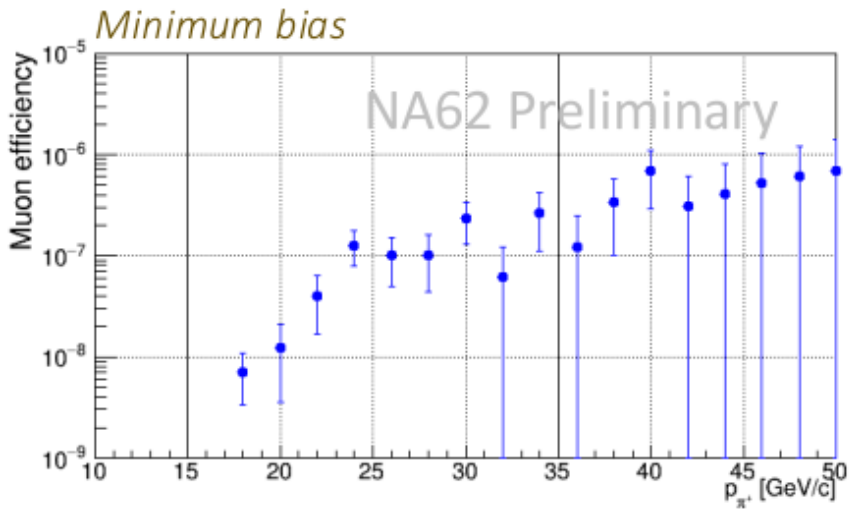
m^2_{miss} Resolution



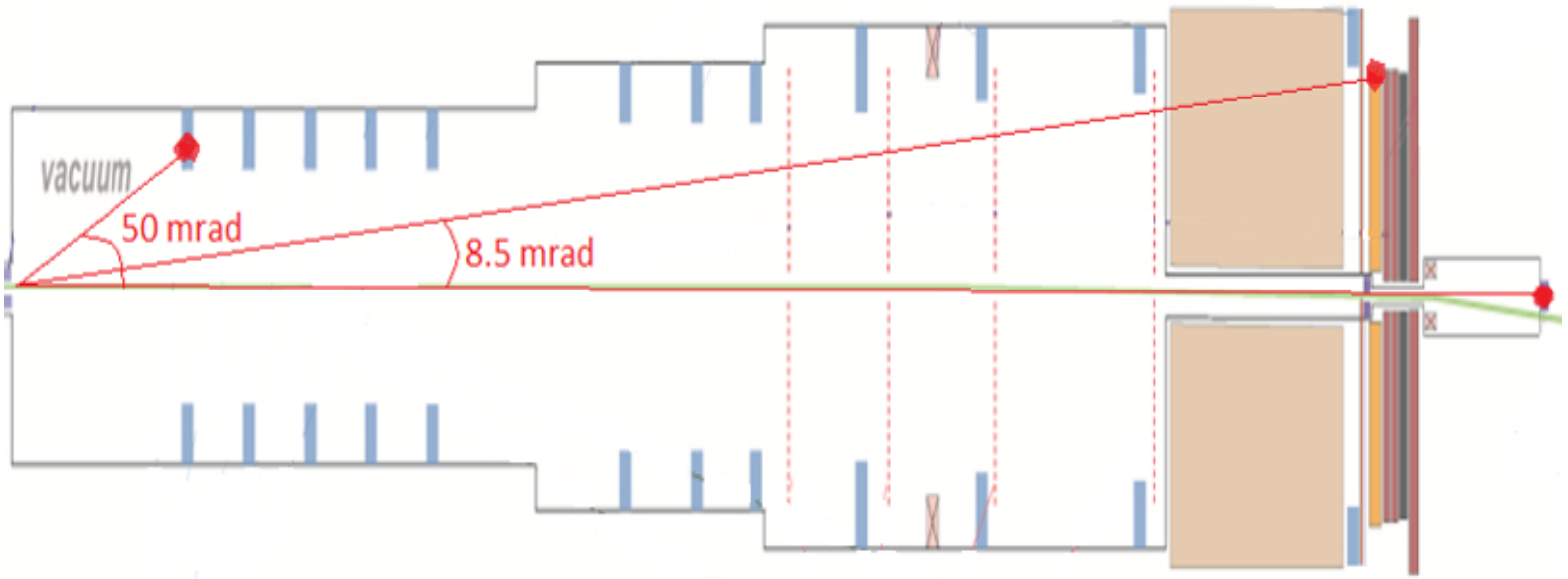
Particle ID

- Technique: RICH and calorimeters
- Goal: O(10^7) μ/π separation to suppress mainly $K^+ \to \mu^+\nu$
  $15 < P_{\pi^+} < 35$ GeV/c: best μ/π separation in RICH
- Pure samples of pions and muons selected using kinematics
- RICH: $\eta(\mu) \div \varepsilon(\pi) \sim 10^{-2} \div 80\%$
- Calorimeters: $\eta(\mu) \div \varepsilon(\pi) \sim 10^{-5} \div 80\%$





Photon rejection



- Technique: EM calorimeters exploiting correlations between γs' from π^0
- Goal: O(10^8) rejection π^0 from $\mathrm{K}^+ \to \pi^+\pi^0$
- $P_{\pi^+} < 35$ GeV/$c \Rightarrow E_{\pi^0} > 40$GeV
- Measured on data using $\mathrm{K}^+ \to \pi^+\pi^0$ selected kinematically
- $\varepsilon_{\pi^0} = (1.2 \pm 0.2) \times 10^{-7}$

Preliminary result

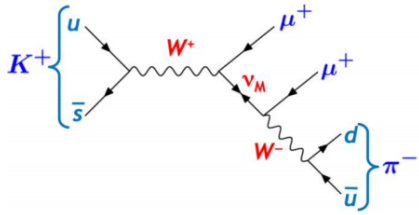
- N(K decays): $\sim 2.3 \times 10^{10}$
- N(expected $K^+ \to \pi^+ \nu\bar{\nu}$): ≈ 0.064
- N(normalization): 3.3×10^8
- Acceptance normalization ~ 0.07
- Acceptance signal ~ 0.033
- Measured background:

Process	Expected events	Branching ratio
$K^+ \to \pi^+\pi^0$	0.024	0.2066
$K^+ \to \mu^+\nu$	0.011	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.017	0.0558
Early decays	$<$0.005	

NP searches in $K^+ \to \pi\mu\mu$ *decays*

- Search for Majorana neutrinos in LNV $K^+ \to \pi^-\mu^+\mu^+$ decays

  [Asaka-Shaposhnikov model (νMSM) [PLB 620 (2005) 17]]



  - DM + Baryon Asymmetry + low mass of SM ν can be explained by adding three sterile Majorana neutrinos to the SM
  - Current limits set by NA48/2 *[submitted to Physics Letters B; arXiv:1612.04723]*

$$\mathrm{BR}(K^\pm \to \pi^\mp\mu^\pm\mu^\pm) < 8.6 \times 10^{-11} \;\; @ \;\; 90\%\ \mathrm{CL}$$

- Search for resonances (N, X, etc.) in the opposite-sign muons sample

  [Shaposhnikov-Tkachev model [PLB 639 (2006) 414]]

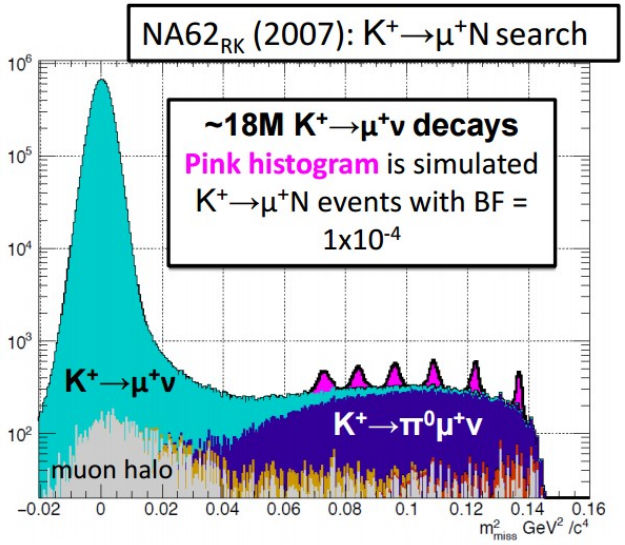
  - νMSM + real scalar field (inflaton X) with scale invariant couplings
  - Explains universe homogeneity and isotropy on large scales/structures on smaller scales
  - Current limits:
    - HN peak search in $K^+ \to \mu^+(\pi^+\mu^-)$
    - Inflatons peak search in $K^+ \to \pi^+(\mu^-\mu^+)$

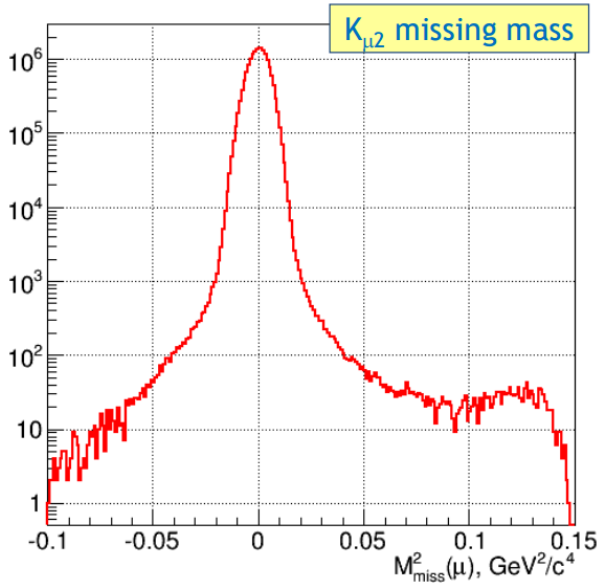
Limits set at $\sim 10^{-9}$ (90% CL) by NA48/2

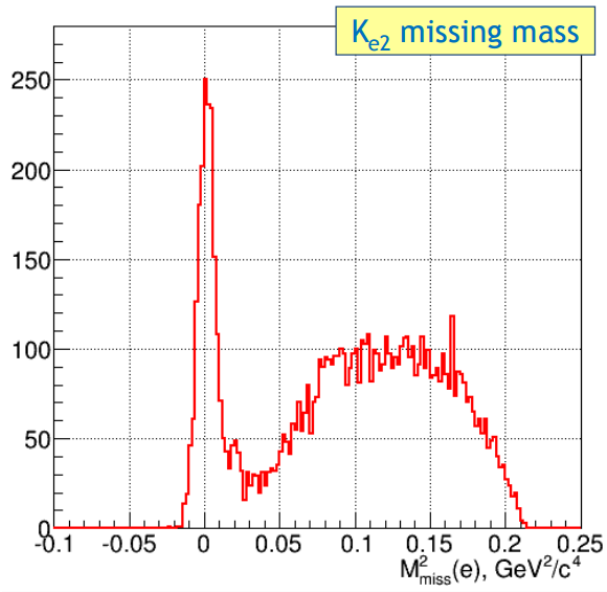
- Can also search for HNL in $K^+ \to l^+N$ with undecayed N
  - $K^+ \to l^+N$ events would appear as peaks in the $K^+ \to l^+\nu$ m^2_{miss}
  - Searches are model independent

Heavy neutral leptons in $K^+ \to l^+N$

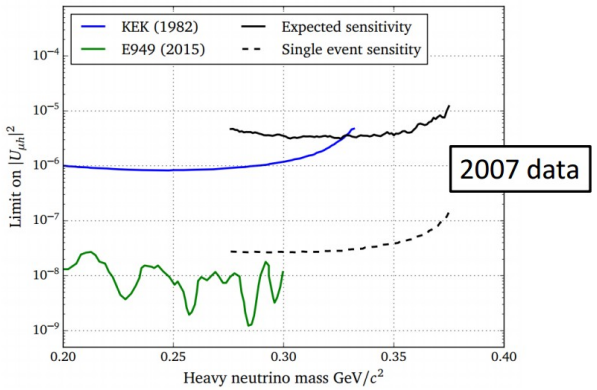
- The mass resolution at NA62 is better by a factor ∼2 compared to NA48/2
- NA62 can potentially improve by two orders of magnitude the NA48/2 results





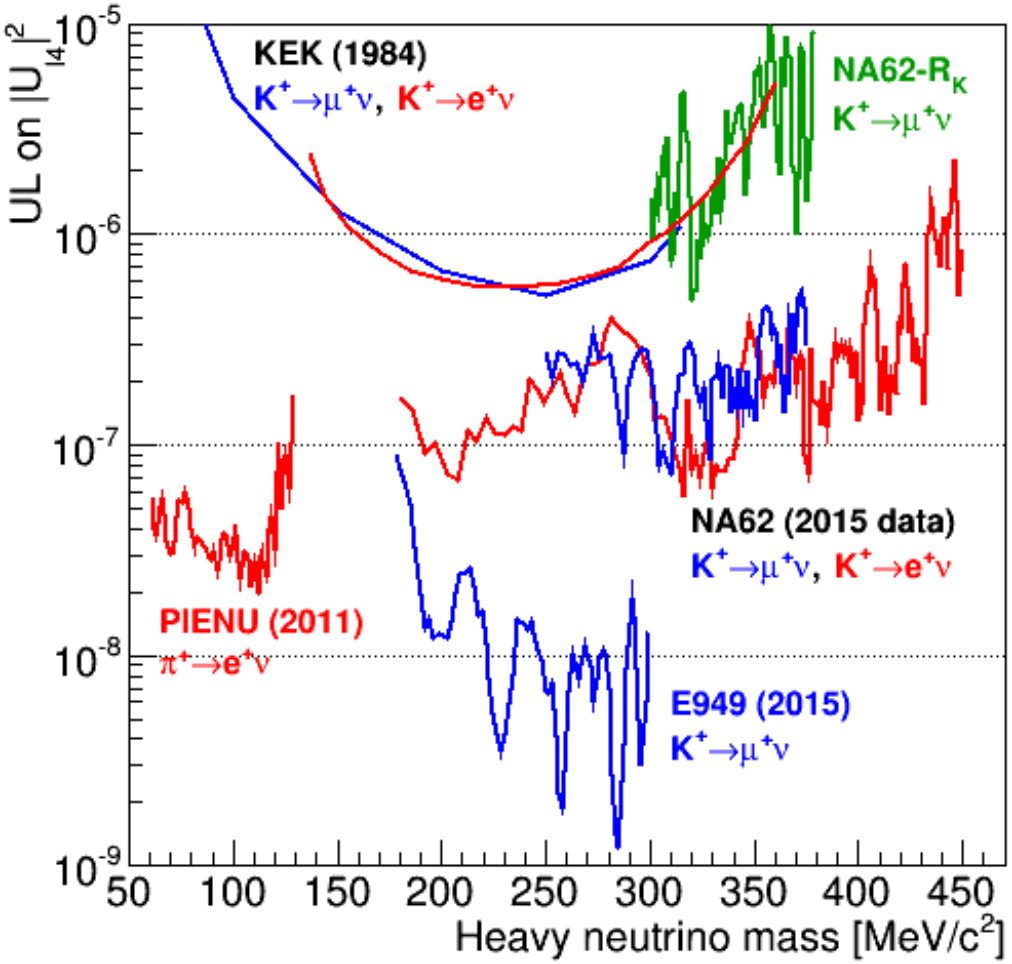


- Current experimental status:
  most stringent constraints from kaon measurements
- Expected SES with 2015 NA62 data at the level of 10^{-8} (similar for $K \to eN$ and $K \to \mu N$)
- Analysis underway with NA62 data from 2015.



Heavy neutral leptons in $K^+ \to l^+ N$

- Background estimated by fits with $3^{rd}/4^{th}$ order polynomials
- Possible to reach $\sim 10^{-7}$ limits for both $|U_{e4}|^2$ and $|U_{\mu 4}|^2$, improving on the world data $\rightarrow$ prospects only



NA62 further physics programme

- Run 2 (2015-2018): focused on the "golden mode" $K^+ \to \pi^+ \nu\bar{\nu}$.
  - Trigger bandwidth for other physics is limited.
  - Several measurements at nominal SES$\sim 10^{-12}$: $K^+ \to \pi^+ A'$, $\pi^0 \to \nu\nu$.
  - A few measurements do not require extreme SES: $K^+ \to l^+ \nu_H$, ...
  - In general, limited sensitivities for most rare/forbidden decays (SES$\sim 10^{-10}$ to $\sim 10^{-11}$, similar to NA48/2 and BNL-E865).
  - A proof of principle for a broad rare/forbidden decay programme.
- Run 3 (2021-2024): programme is under discussion.

  [Presented at the "Physics Beyond Colliders" workshop, CERN, Sep 2016]
  - Existing apparatus, different trigger logic: no capital investment.
  - Rare/forbidden K^+ and π^0 decays at SES$\sim 10^{-12}$:
    - K^+ physics: $K^+ \to \pi^+ l^+ l^-$, $K^+ \to \pi^+ \gamma l^+ l^-$, $K^+ \to l^+ \nu\gamma$, $K^+ \to \pi^+ \gamma\gamma$, ...
    - π^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: $K^+ \to \pi^- l^+ l^+$, $K^+ \to \pi^+ \mu e$, $\pi^0 \to \mu e$.
  - Dump mode: hidden sector searches (long-lived HNL, DP, ALP).
  - Possibly further $K^+ \to \pi^+ \nu\bar{\nu}$ data collection.
  - Possibly K_L rare decays (SES$\sim 10^{-11}$), including $K_L \to \pi^0 l^+ l^-$[CPV].

Conclusions

- Reported status of $K^+ \to \pi^+ \nu\bar{\nu}$ analysis
  - So far reconstructed $\sim 2.3 \times 10^{10}$ (5% of 2016 statistics)
  - No events found in the signal region
  - Single event sensitivity below 10^{-9}
  - Need of improvement in kinematic tails suppression and muon rejection
- Reported progress in the HNL searches
  - Draft in preparation for 2007 data (improved KEK limit above 320 MeV/c in the muon mode)
  - Possible improvement of current best results from NA48/2 experiment by two orders of magnitude with new data
  - Analysis underway with NA62 data from 2015.

Further NA62 physics programme

Decay	Physics	Present limit (90% C.L.) / Result	NA62
$\pi^+\mu^+e^-$	LFV	1.3×10^{-11}	0.7×10^{-12}
$\pi^+\mu^-e^+$	LFV	5.2×10^{-10}	0.7×10^{-12}
$\pi^-\mu^+e^+$	LNV	5.0×10^{-10}	0.7×10^{-12}
$\pi^-e^+e^+$	LNV	6.4×10^{-10}	2×10^{-12}
$\pi^-\mu^+\mu^+$	LNV	1.1×10^{-9}	0.4×10^{-12}
$\mu^-\nu e^+e^+$	LNV/LFV	2.0×10^{-8}	4×10^{-12}
$e^-\nu\mu^+\mu^+$	LNV	No data	10^{-12}
π^+X^0	New Particle	$5.9 \times 10^{-11}\ m_{X^0} = 0$	10^{-12}
$\pi^+\chi\chi$	New Particle	–	10^{-12}
$\pi^+\pi^+e^-\nu$	$\Delta S \neq \Delta Q$	1.2×10^{-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	$(2.488 \pm 0.010) \times 10^{-5}$	>×2 better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$O(10^6)$
$\pi^0\pi^0\mu^+\nu$	χPT	-	$O(10^5)$