NA62 experiment at CERN: status and recent results

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on behalf of the NA62 collaboration

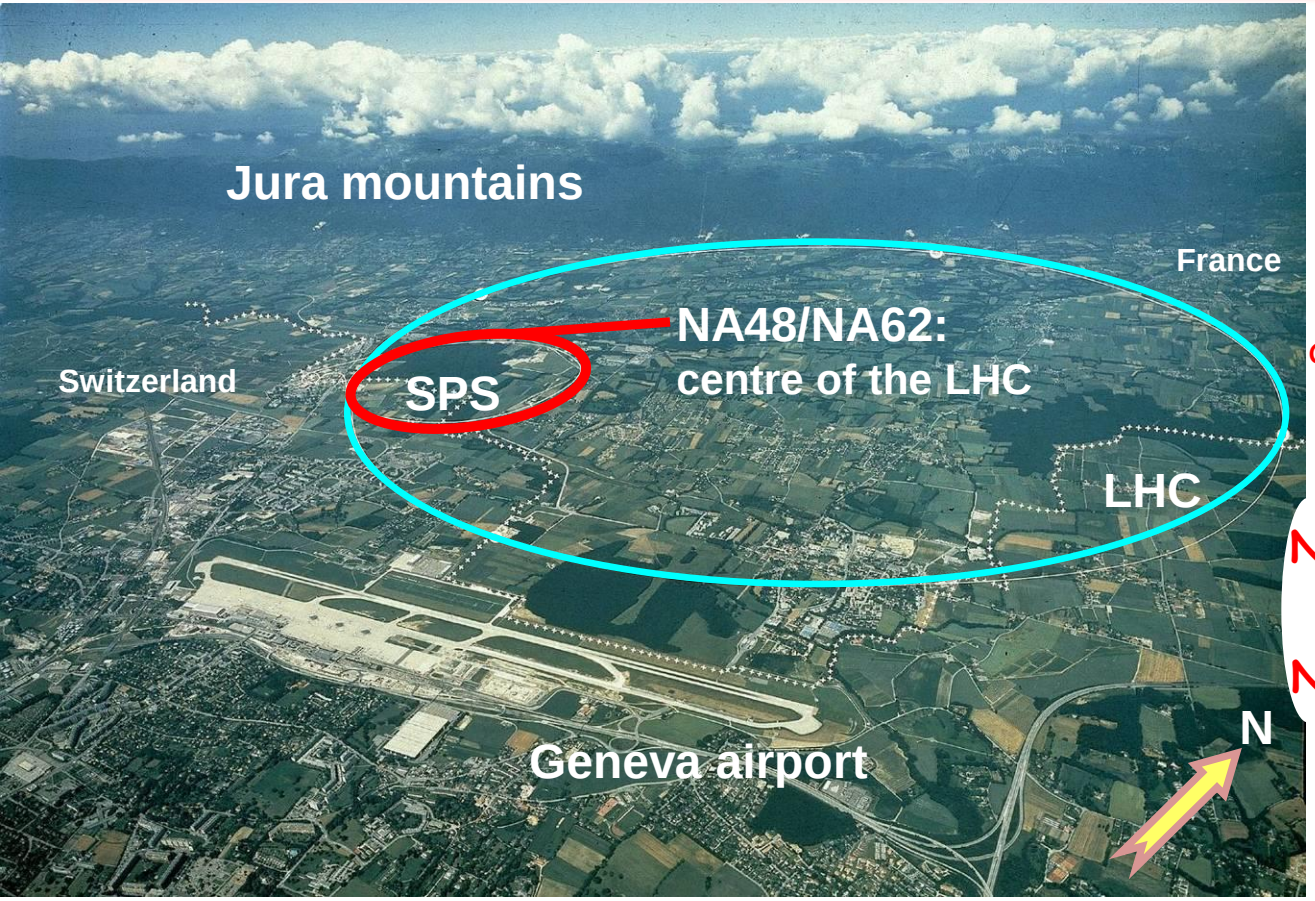
Outline:

1) Introduction: $K^{\pm}$ decay experiments at CERN
2) NA62 status and performance
3) First NA62 results: search for heavy neutral leptons
4) Summary

Weak Interactions and Neutrinos 2017

UC Irvine • 21 June 2017

Kaon programme at CERN



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 run	2007: $K^\pm_{e2}/K^\pm_{\mu2}$	tests
	2008: $K^\pm_{e2}/K^\pm_{\mu2}$	tests
NA62	2015: commissioning	
	2016–: physics run	

Kaon decay in flight experiments.
NA62: currently ~200 participants, ~30 institutions

$K^{\pm}$ decay experiments at CERN

Experiment	NA48/2 ($K^{\pm}$)	NA62 (2007) ($K^{\pm}$)	NA62 (K^{+})
Data taking period	2003–2004	2007–2008	2016–2018
Beam momentum, GeV/c	60	74	75
RMS momentum bite, GeV/c	2.2	1.4	0.8
Spectrometer thickness, X_0	2.8%	2.8%	1.8%
Spectrometer P_T kick, MeV/c	120	265	270
$M(K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-})$ resolution, MeV/c^2	1.7	1.2	0.8
K decays in fiducial volume	2×10^{11}	2×10^{10}	1.2×10^{13}
Main trigger	multi-track; $K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$	Min.bias + $e^{\pm}$	$K_{\pi\nu\nu}$ + …

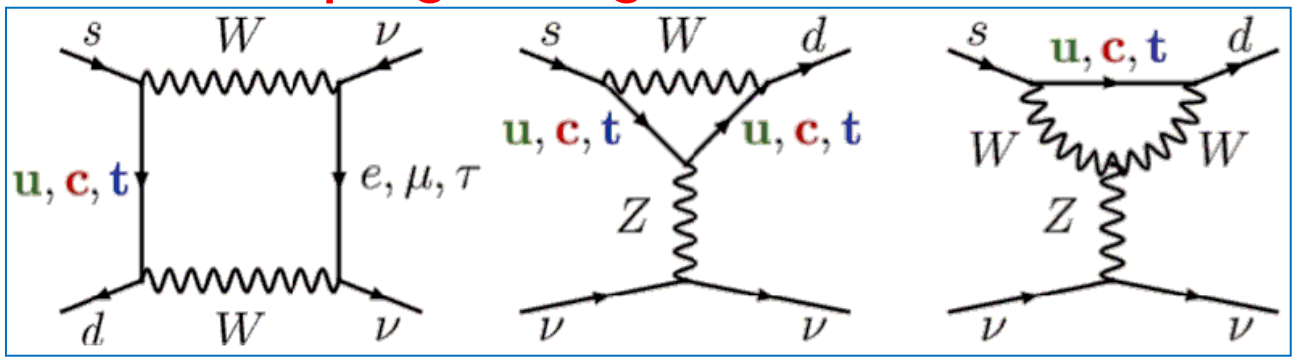
NA48 detector — NA62 detector

The NA62 experiment

- Main goal: collect 100 SM $K^{+}\to\pi^{+}\nu\nu$ decays, $BR_{SM}=(8.4\pm1.0)\times10^{-11}$.
  Buras et al., JHEP 1511 (2015) 033
- Current $K^{+}\to\pi^{+}\nu\nu$ experimental status: $BR = (1.73\,^{+1.15}_{-1.05})\times10^{-10}$ from 7 candidates with expected background of 2.6 observed by BNL-E949.
  PRL101 (2008) 191802

Rare kaon decays: $K \to \pi \nu \bar{\nu}$

SM: box and penguin diagrams



Ultra-rare decays with the highest CKM suppression:

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

- Hadronic matrix element is related to a measured quantity ($K^+ \to \pi^0 e^+ \nu$).
- SM precision surpasses any other FCNC process involving quarks.
- Measurement of $|V_{td}|$ complementary to those from B–$\bar{B}$ mixing or $B^0 \to \rho\gamma$.

SM branching ratios

Buras et al., JHEP 1511 (2015) 033

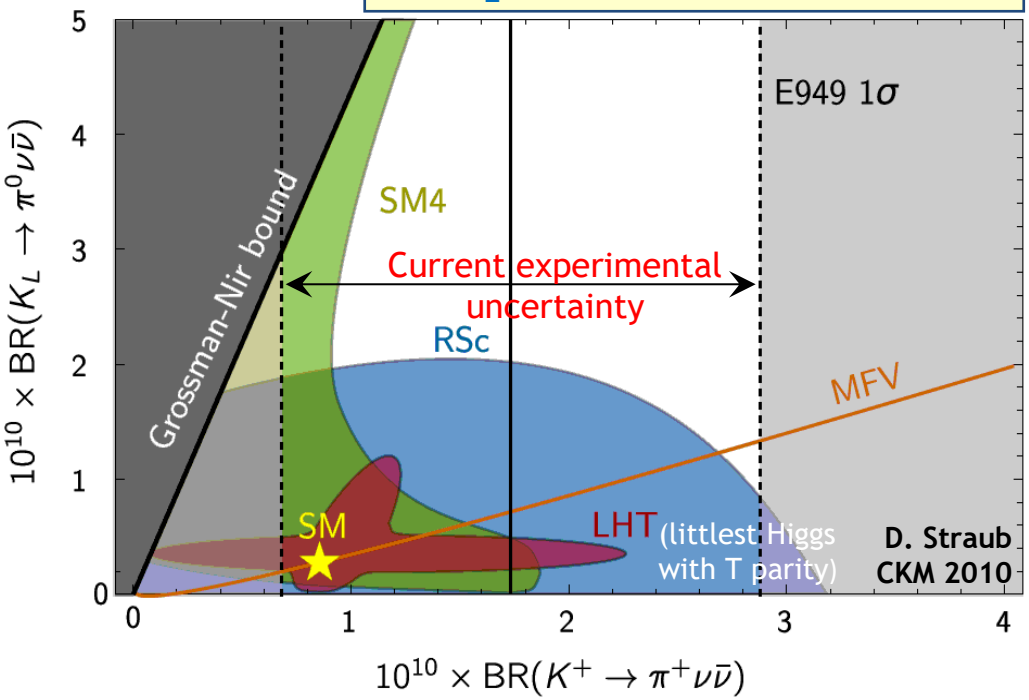
Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	8.4±1.0
$K_L \to \pi^0 \nu\bar{\nu}$	3.4±0.6

The uncertainties are largely parametric (CKM)

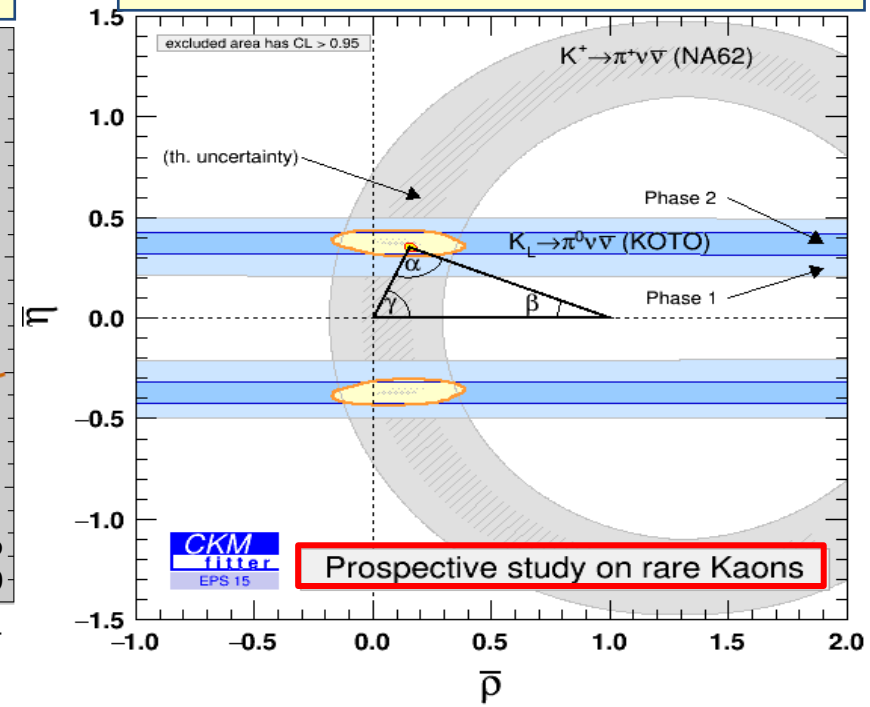
Theoretically clean, almost unexplored, sensitive to new physics.

$K \to \pi \nu \bar{\nu}$: experiment vs theory

$BR(K_L \to \pi^0 \nu \bar{\nu})$ vs $BR(K^+ \to \pi^+ \nu \bar{\nu})$



CKM unitarity triangle with kaons



NA62 aim: collect O(100) SM $K^+ \to \pi^+ \nu\bar{\nu}$ decays with <20% background in 3 years of data taking using a novel decay-in-flight technique.

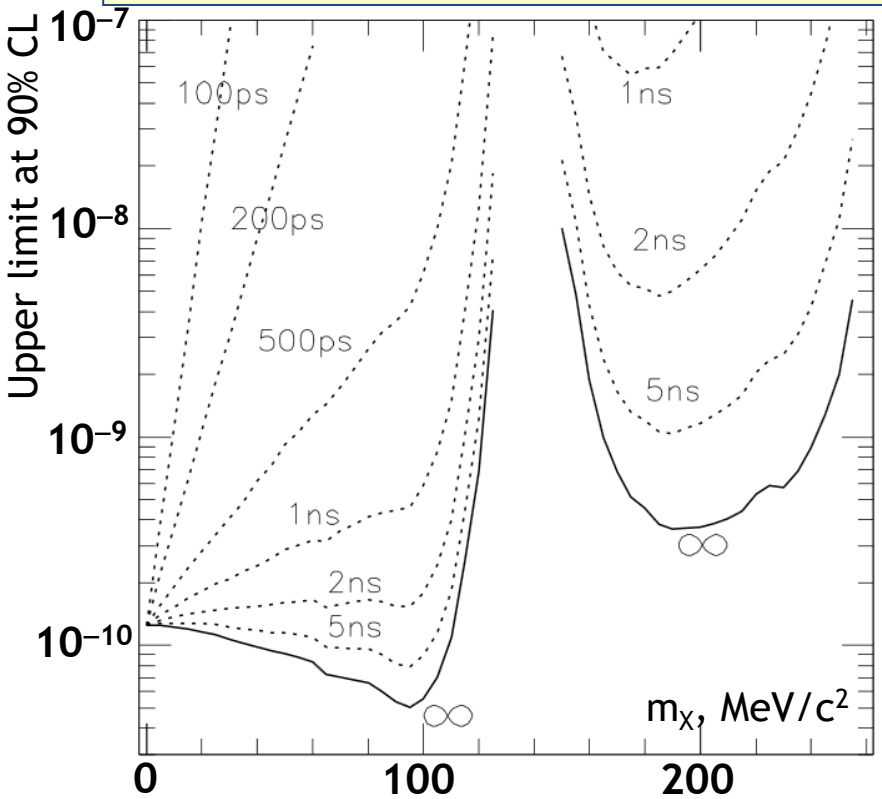
Signature: high momentum K^+ (**75GeV/c**) → low momentum π^+ (**15–35 GeV/c**).

Advantages: max detected K^+ decays/proton ($p_K/p_0 \approx 0.2$);
efficient photon veto (**>40 GeV** missing energy)

Un-separated beam (**6%** kaons) → high rates, additional background sources.

$K^+ \to \pi^+ A'$, $A' \to$ invisible

BNL-E949: limits on $BR(K^+ \to \pi^+ X)$ vs τ_X



The E949 $K^+ \to \pi^+ \nu\nu$ analysis:

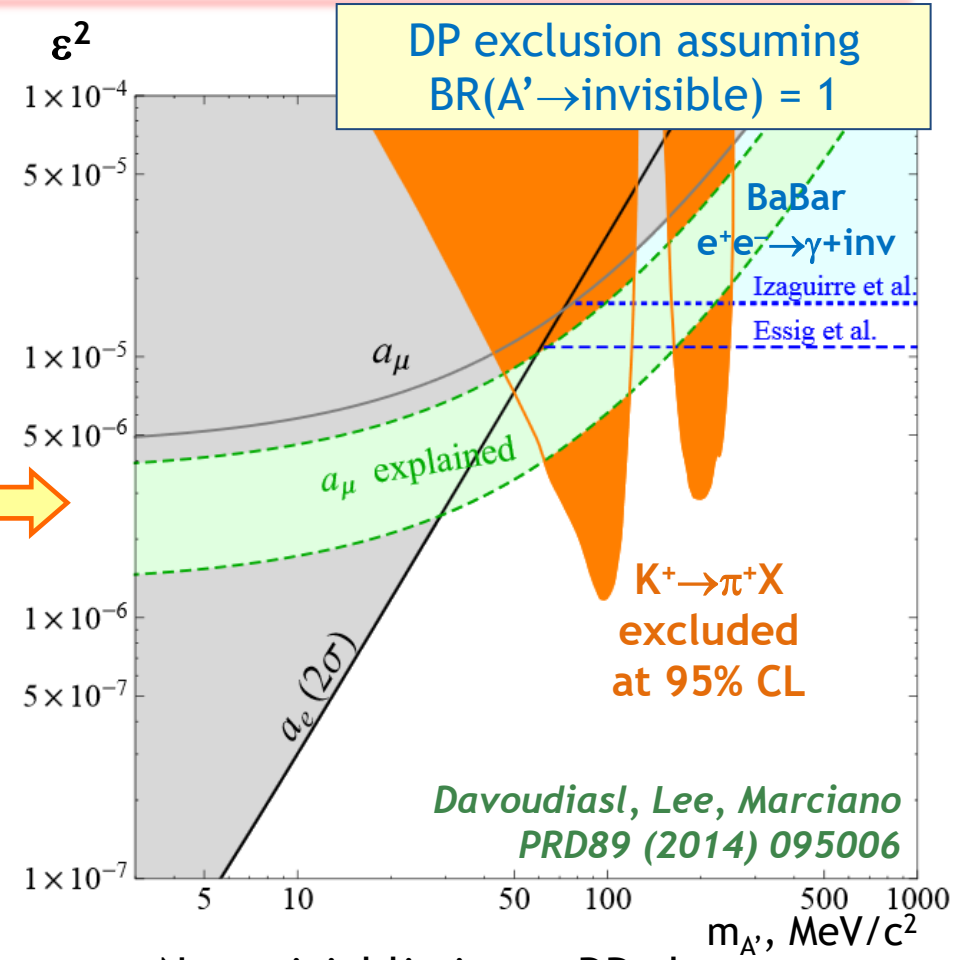
$K^+ \to \pi^+ X$ search (where X is invisible)

PRD79 (2009) 092004

$BR(\pi^0 \to \text{invisible}) < 2.7 \times 10^{-7}$ at 90% CL

PRD72 (2005) 091102

DP exclusion assuming $BR(A' \to \text{invisible}) = 1$



Non-trivial limits on DP phase space including the $(g-2)_\mu$ favoured band, assuming invisible DP decays.

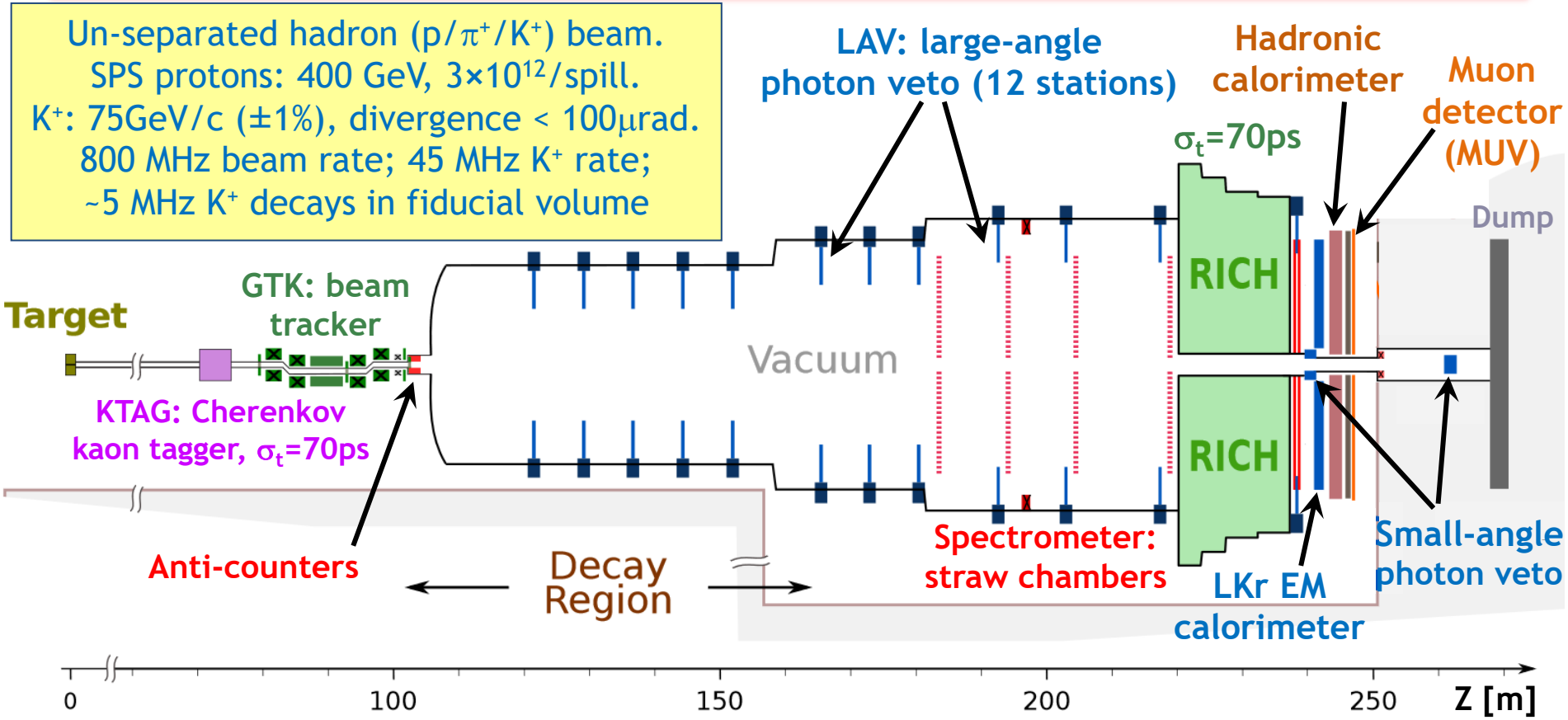
NA62: expect an order of magnitude improvement

NA62 status & performance

NA62 collaboration,
JINST 12 (2017) P05025

The NA62 detector

Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, 3×10^{12}/spill.
K^+: 75GeV/c (±1%), divergence < 100μrad.
800 MHz beam rate; 45 MHz K^+ rate;
~5 MHz K^+ decays in fiducial volume



- Expected single event sensitivity for K^+ decays: BR~10^{-12}.
- Measured kinematic rejection factors (limited by beam pileup & MCS tails): 6×10^{-4} for $K^+\to\pi^+\pi^0$, 3×10^{-4} for $K\to\mu^+\nu$.
- Hermetic photon veto: measured $\pi^0\to\gamma\gamma$ decay suppression = 1.2×10^{-7}.
- Particle ID (RICH+LKr+HAC+MUV): ~10^{-7} muon suppression.

NA62 physics programme

- **NA62 Run 2016–2018**: focused on the "golden mode" $K^+ \to \pi^+ \nu\nu$.
  - ✓ Trigger bandwidth for other physics is limited.
  - ✓ Several measurements at nominal **SES~10^{-12}**: $K^+ \to \pi^+ A'$, $\pi^0 \to \nu\nu$.
  - ✓ A few measurements do not require extreme SES: $K^+ \to \ell^+ N$, …
  - ✓ Sensitivities to most rare/forbidden decays are limited but still often world-leading (~10^{-10} to ~10^{-11}).
  - ✓ Proof of principle for a broad rare & forbidden decay programme.

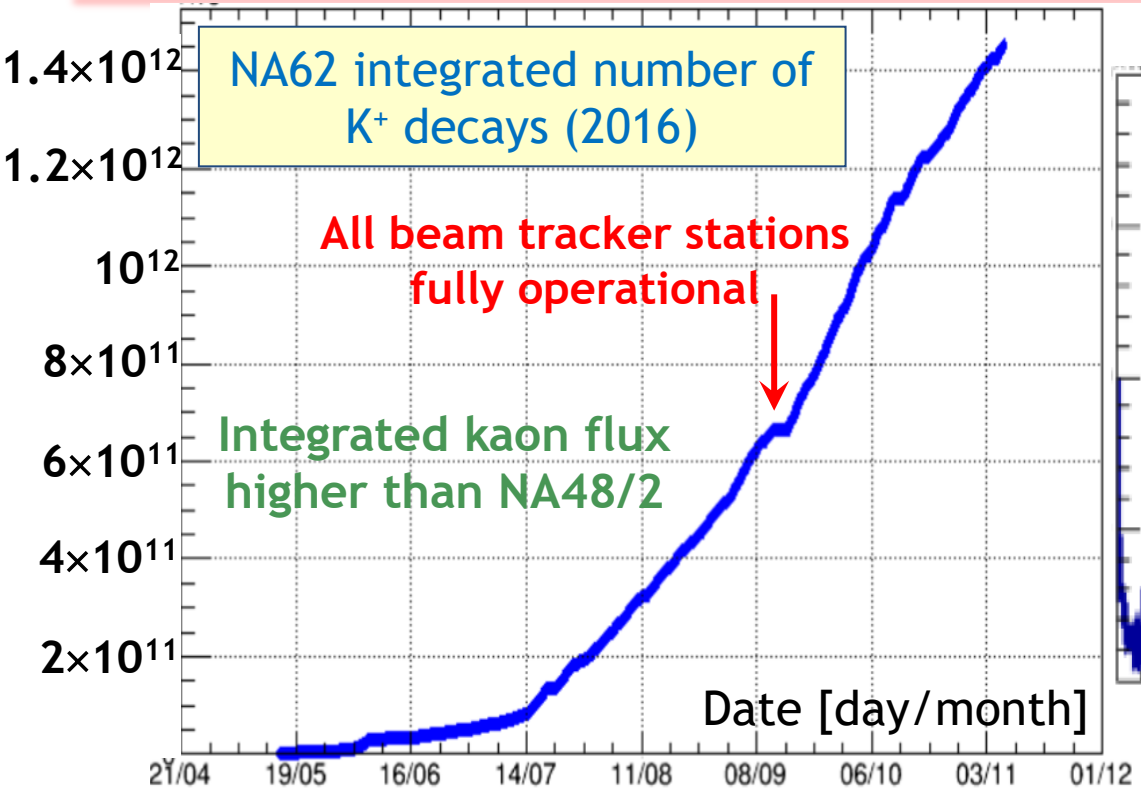
- **NA62 Run 2021–2024**: programme is under discussion.
  [Presented at Physics Beyond Colliders workshops, CERN, Sep 2016 & Mar 2017]
  - ✓ Existing apparatus with a different trigger logic.
  - ✓ Rare/forbidden K^+ and π^0 decays at **SES~10^{-12}**:
    - K^+ physics: $K^+ \to \pi^+ \ell^+ \ell^-$, $K^+ \to \pi^+ \gamma \ell^+ \ell^-$, $K^+ \to \ell^+ \nu\gamma$, $K^+ \to \pi^+ \gamma\gamma$, …
    - 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: $K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \pi^+ \mu e$, $\pi^0 \to \mu e$, …
  - ✓ Beam dump with **~10^{18} POT**: hidden sector (long-lived HNL, DP, ALP).
  - ✓ Further $K^+ \to \pi^+ \nu\nu$ data collection.

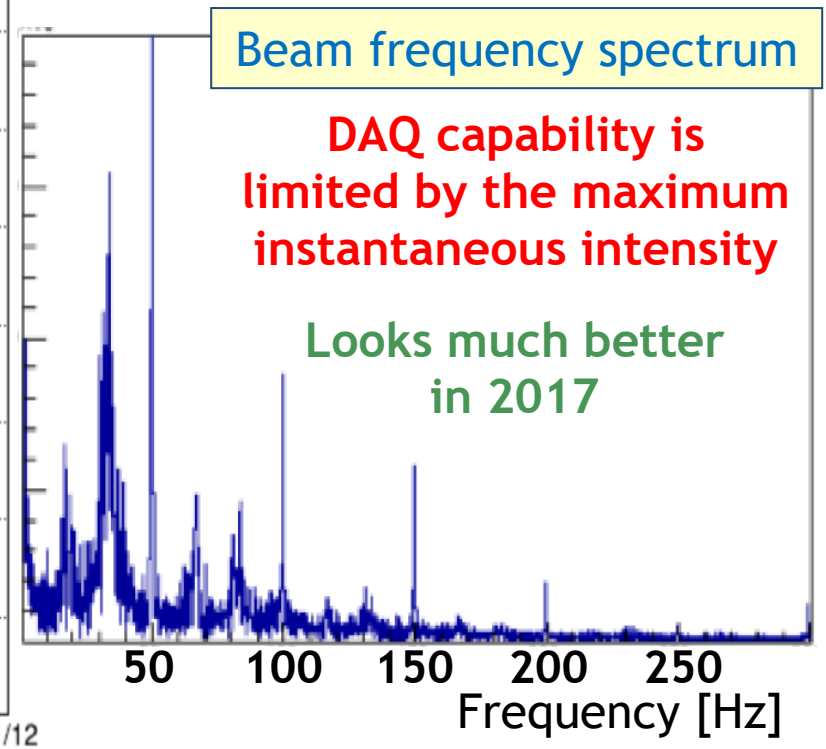
Data collection

- Commissioning run **2015**: minimum bias (**~1%** intensity) and **$K_{\pi\nu\nu}$ test** data.
  - ✓ Most systems commissioned and meet the design requirements
- First high intensity run: **3 May – 14 November 2016**
  - ✓ Data collection at **40%** of the nominal intensity (limited by beam quality)
- Long (~6 months) runs in **2017** (started in May) and **2018**

Reached sensitivity of ~1 SM **$K_{\pi\nu\nu}$** event with the **2016** data

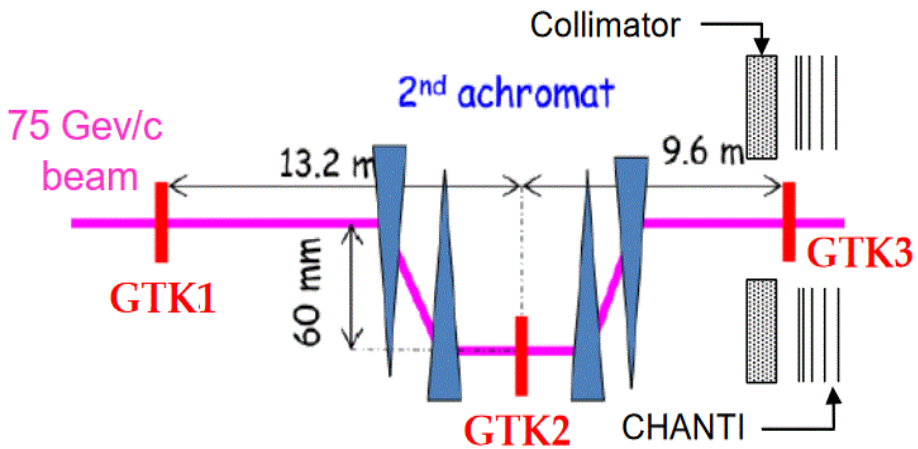
High intensity run in 2016

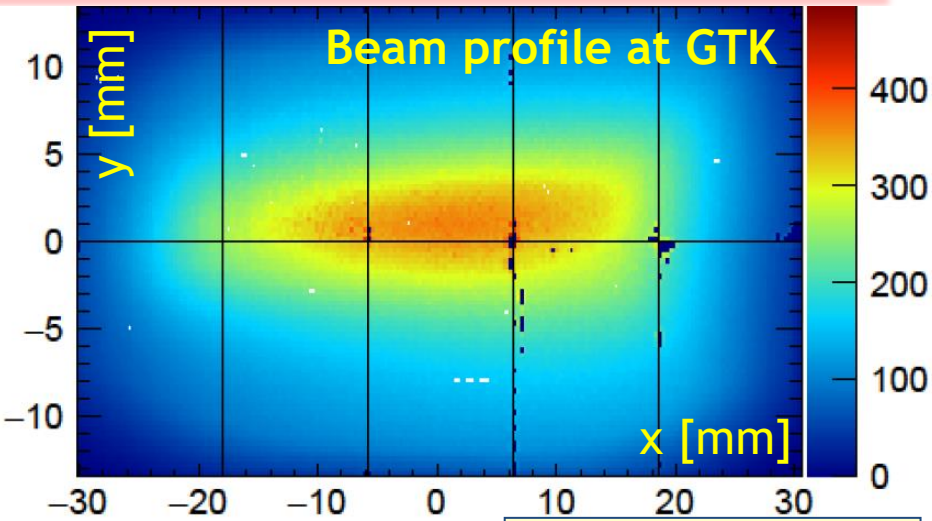




- Stable data collection at ~40% of the nominal intensity; limited by beam structure, including the 50 Hz harmonics.
- Simultaneous data taking for $K_{\pi\nu\nu}$ and rare/exotic decays.
- Extrapolation to end of 2018 (12 months of live time): 7×10^{12} K^+ decays.
- With improved extraction and incremental improvements in efficiency, the target of 10^{13} K^+ decays by end of 2018 is reachable.

Beam tracker: the Gigatracker



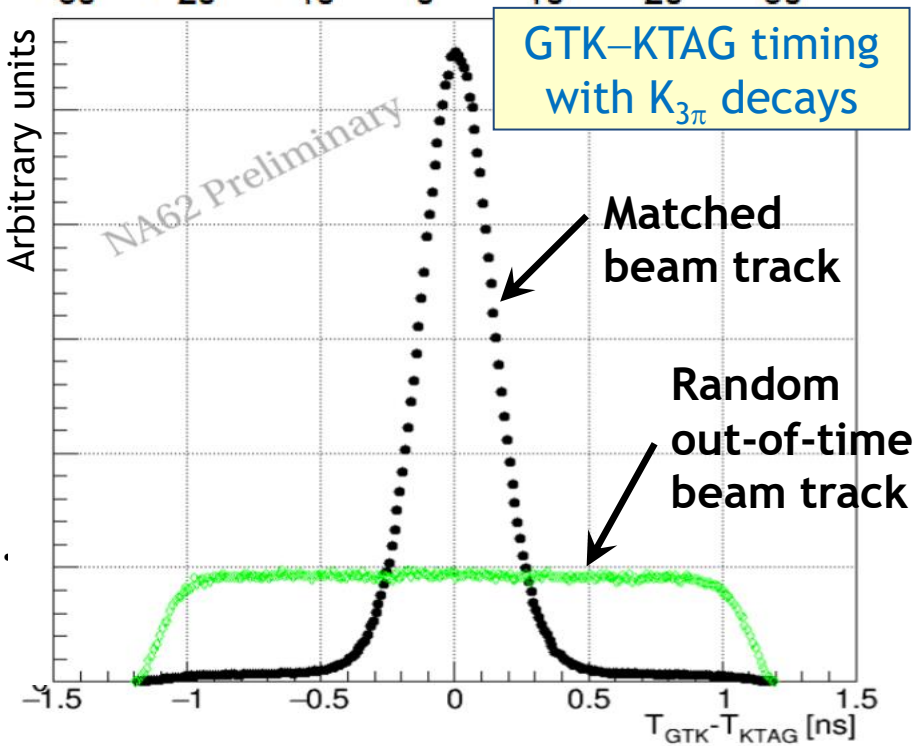


Tracker design:

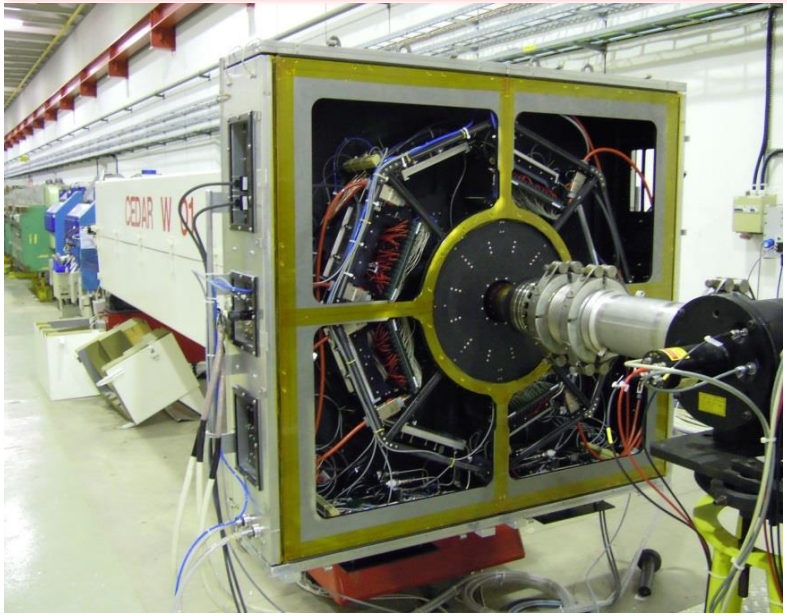
- Three Si pixel stations in the beam.
- Operation at beam rate up to **800 MHz**.
- In total, **54k** pixels (**300×300 μm²**).
- Thickness: **<0.5% X_0** per station.

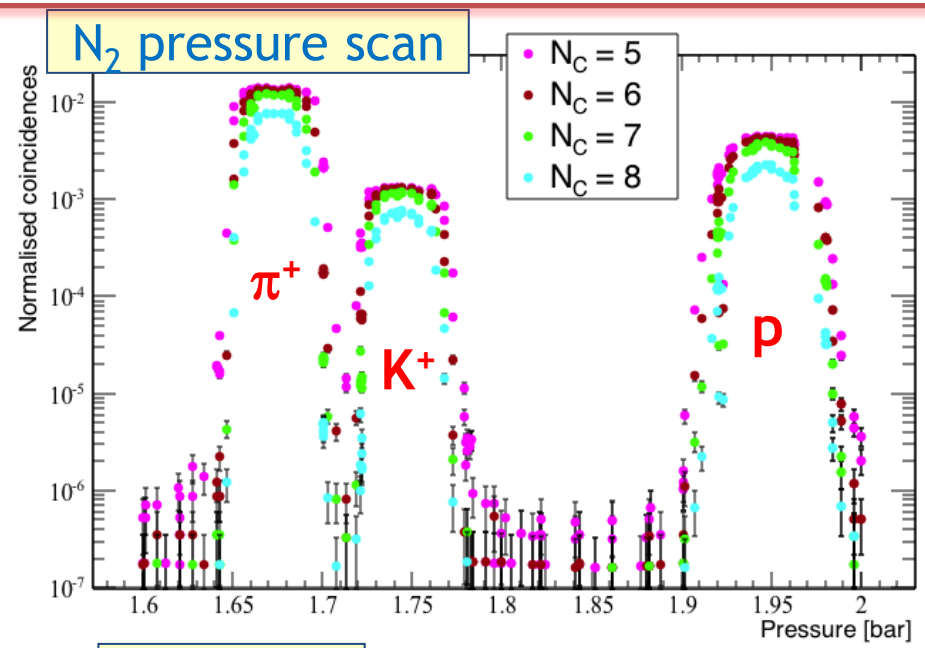
Performance at 40% beam intensity:

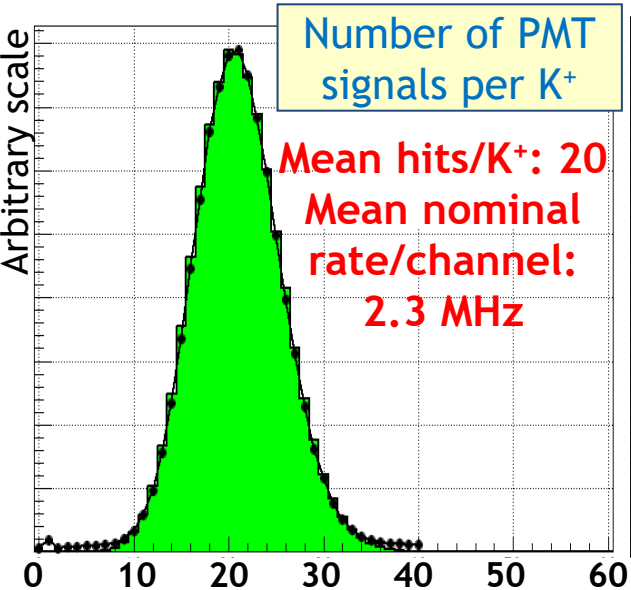
- Track reconstruction efficiency: **75%**.
- Time resolution **$\sigma(t_{BeamTrack}) \approx 100$ ps**.
- Beam track mis-tagging probability: **1.7%**.
- Spatial matching: beam/downstream track intersection, **$\sigma_{CDA} \approx 1.5$ mm**.

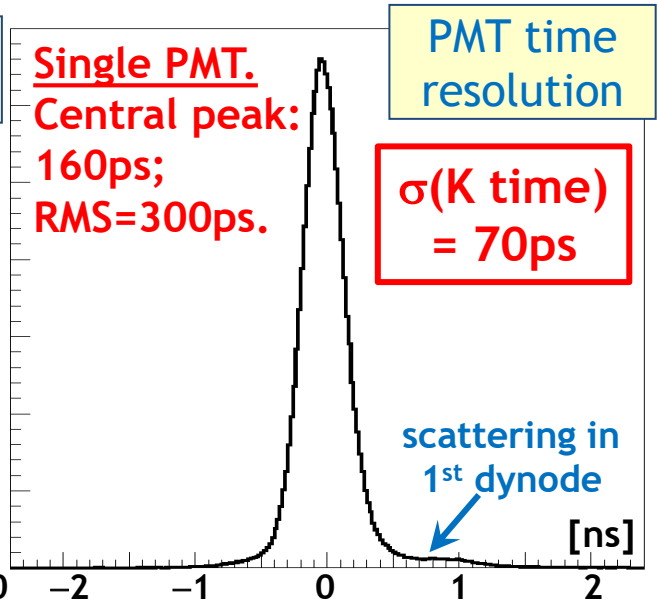


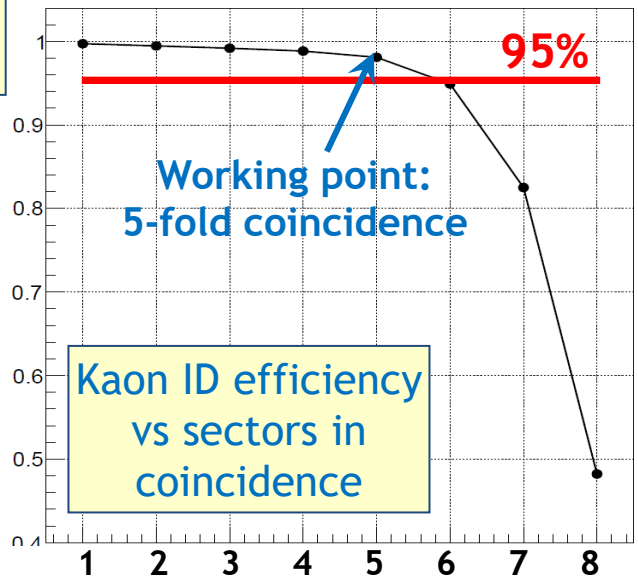
Kaon identification: KTAG



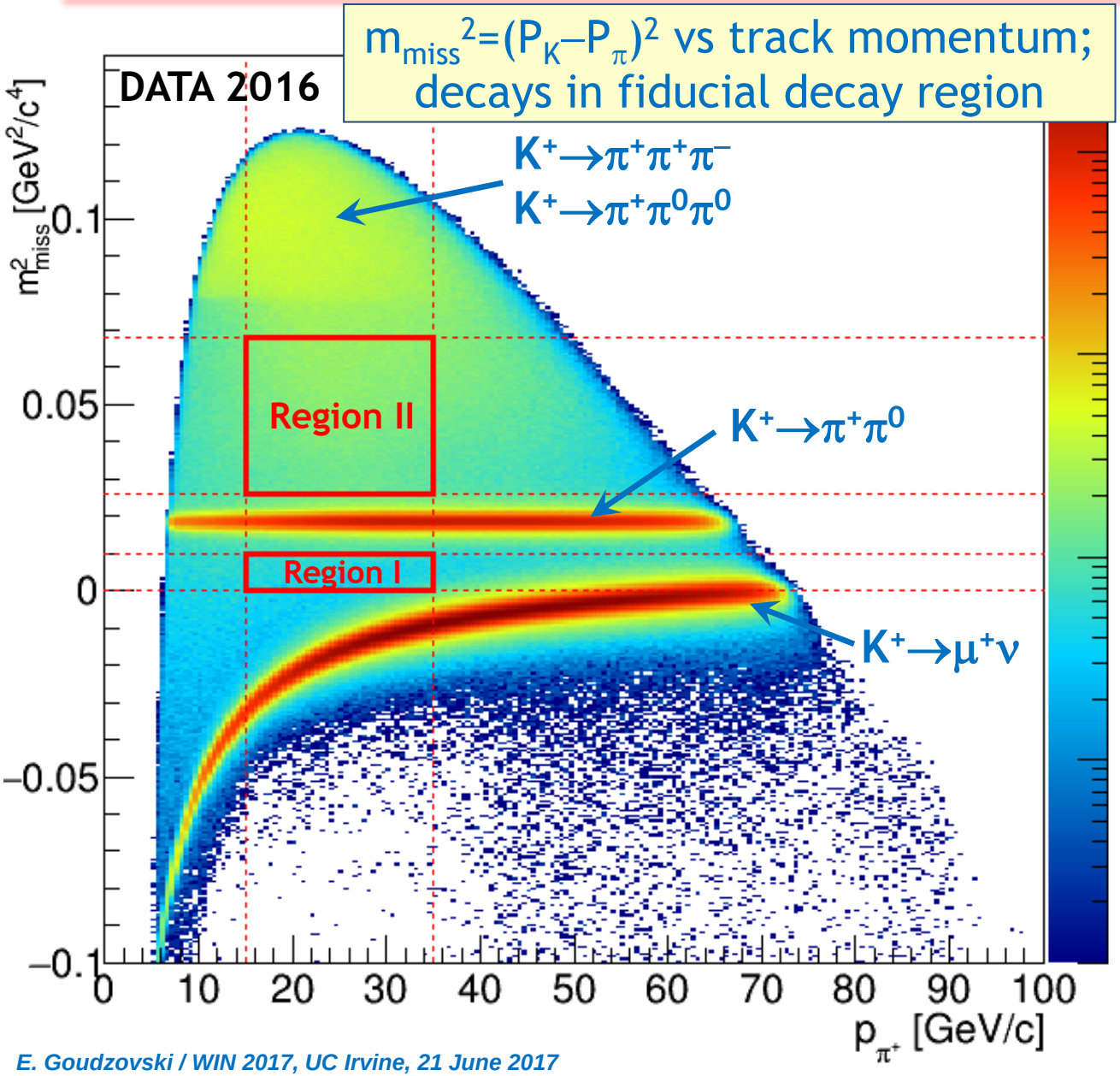








$K_{\pi\nu\nu}$ signal region definition



Main K^+ decay modes (>90% of BR) rejected kinematically.

Design kinematical resolution on m_{miss}^2 has been achieved ($\sigma=1.0\times10^{-3}$ GeV^4/c^2).

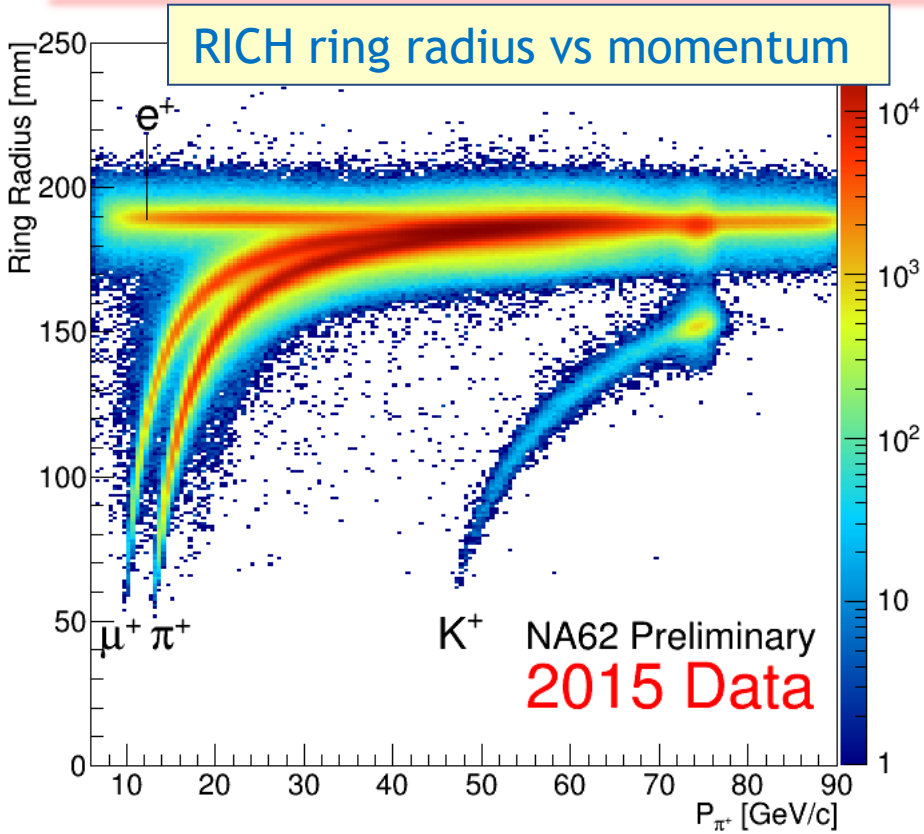
Measured kinematical background suppression:

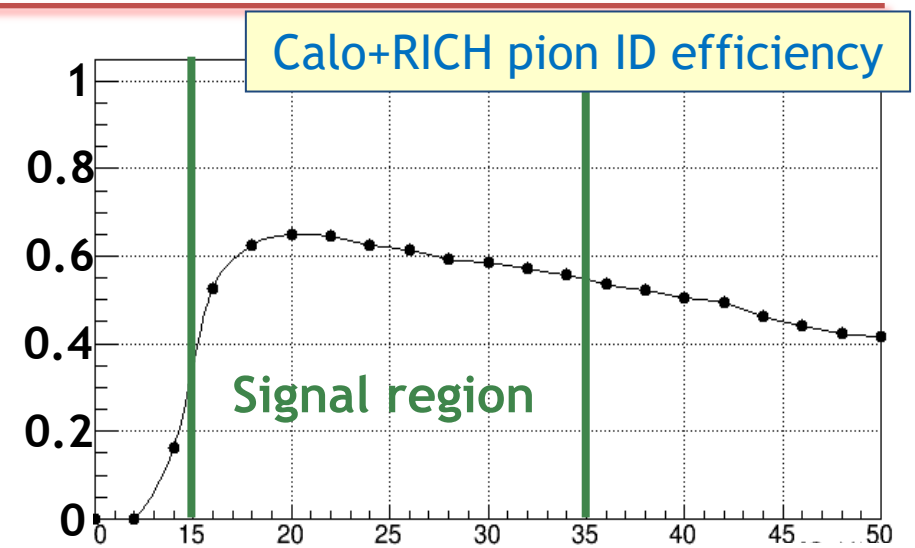
- ✓ $K^+\to\pi^+\pi^0$: 6×10^{-4};
- ✓ $K^+\to\mu^+\nu$: 3×10^{-4}.

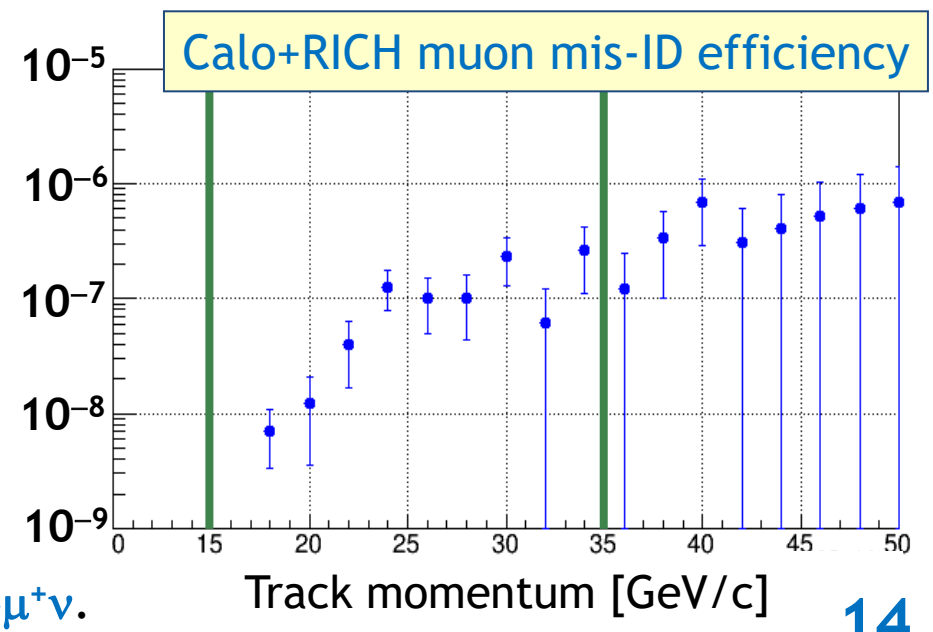
Further background suppression:

- ✓ PID (calorimeters & Cherenkov detectors): μ suppression $<10^{-7}$.
- ✓ Hermetic photon veto: suppression of $\pi^0\to\gamma\gamma$ decays $<10^{-7}$.

Identification with RICH & HAC







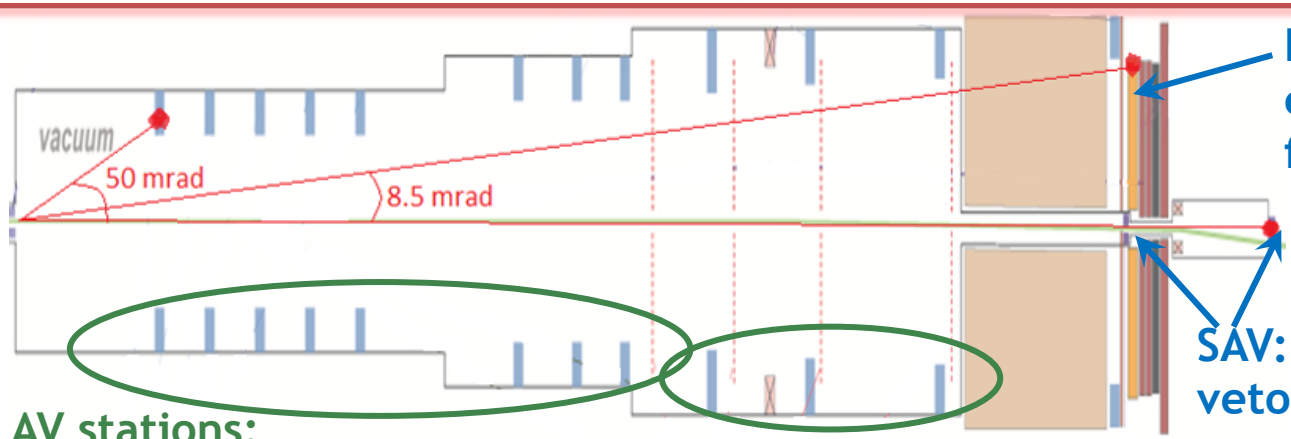
<u>Two independent PID measurements:</u>

1) with calorimeters & muon detector:
MVA technique used; $\varepsilon_\mu \div \varepsilon_\pi = 10^{-5} \div 80\%$,

2) with RICH: $\varepsilon_\mu \div \varepsilon_\pi = 10^{-2} \div 80\%$
in the signal momentum region.

Performance measured with $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$.

Photon rejection



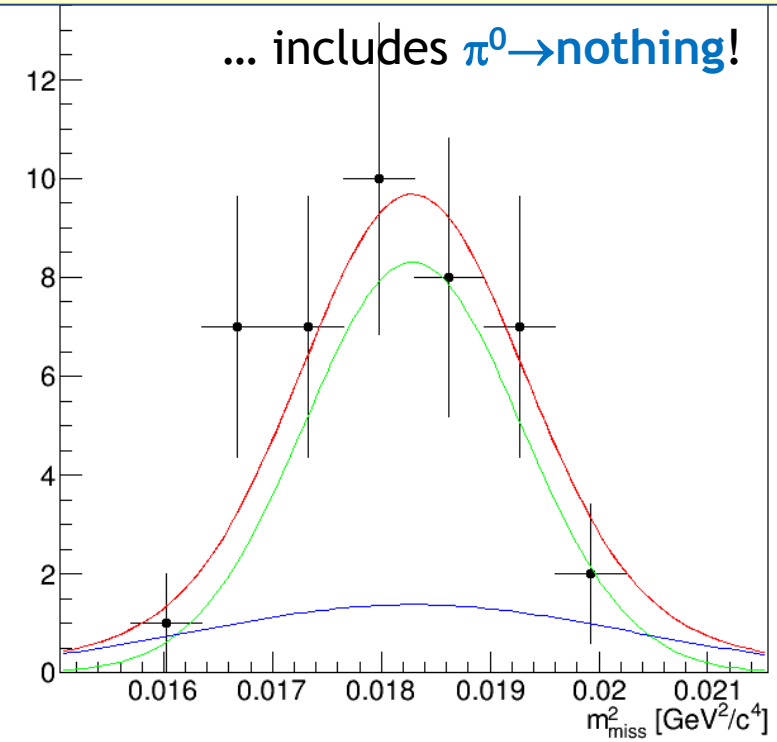
LKr EM calorimeter: forward veto

SAV: small-angle veto (sampling calo)

12 Pb glass LAV stations: hermetic up to 50 mrad

- Technique: EM calorimetry exploiting correlations between photons from $\pi^0 \to \gamma\gamma$ decays.
- Signal region: $p(\pi^+) < 35$ GeV/c, therefore $p(\pi^0) > 40$ GeV/c.
- Goal: $O(10^{-7})$ to $O(10^{-8})$ rejection of π^0 from $K^+ \to \pi^+\pi^0$ decays.
- Measured π^0 rejection factor with the $K_{\pi\nu\nu}$ selection: $\varepsilon = (1.2 \pm 0.2) \times 10^{-7}$. Accidental loss measured with $K_{\mu 2}$: 16% at 40% intensity, can be improved.

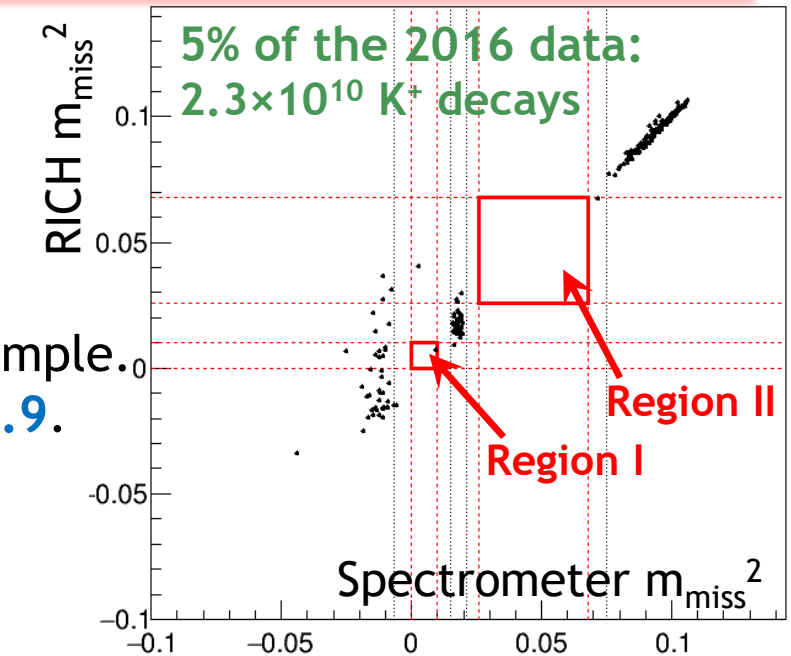
$m_{miss}^2 = (P_K - P_\pi)^2$: full $K_{\pi\nu\nu}$ selection



Data 2016: $K_{\pi\nu\nu}$ sample

$K^+ \to \pi^+ \nu\nu$ decay: ~50% of 2016 data is useful.

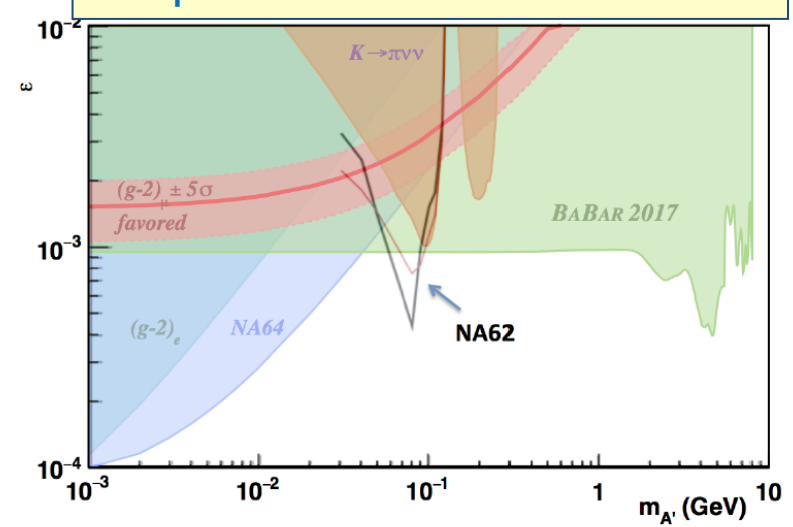
- Most of trigger bandwidth dedicated to $K_{\pi\nu\nu}$.
- Analysis of **5% of this sample** is presented.
- **No events found** in $K_{\pi\nu\nu}$ signal region.
- Expect **1.3** SM $K_{\pi\nu\nu}$ decays from total 2016 sample.
- Preliminary statement on background: **B/S<0.9**.
- Analysis in progress to increase signal acceptance and improve BKG suppression.



Related studies:

- Dark photon search in $K^+ \to \pi^+ \pi^0$, $\pi^0 \to \gamma A'$:
  - ✓ look for invisible A' decays;
  - ✓ peak search in $(P_K - P_\pi - P_\gamma)^2$ spectrum;
  - ✓ data-driven background estimate;
  - ✓ Expect improvement over the world data with **5%** of the 2016 sample.
- Improvement on **BR($\pi^0 \to$invisible)** over the current limit of **2.7×10^{-7}** is also possible.

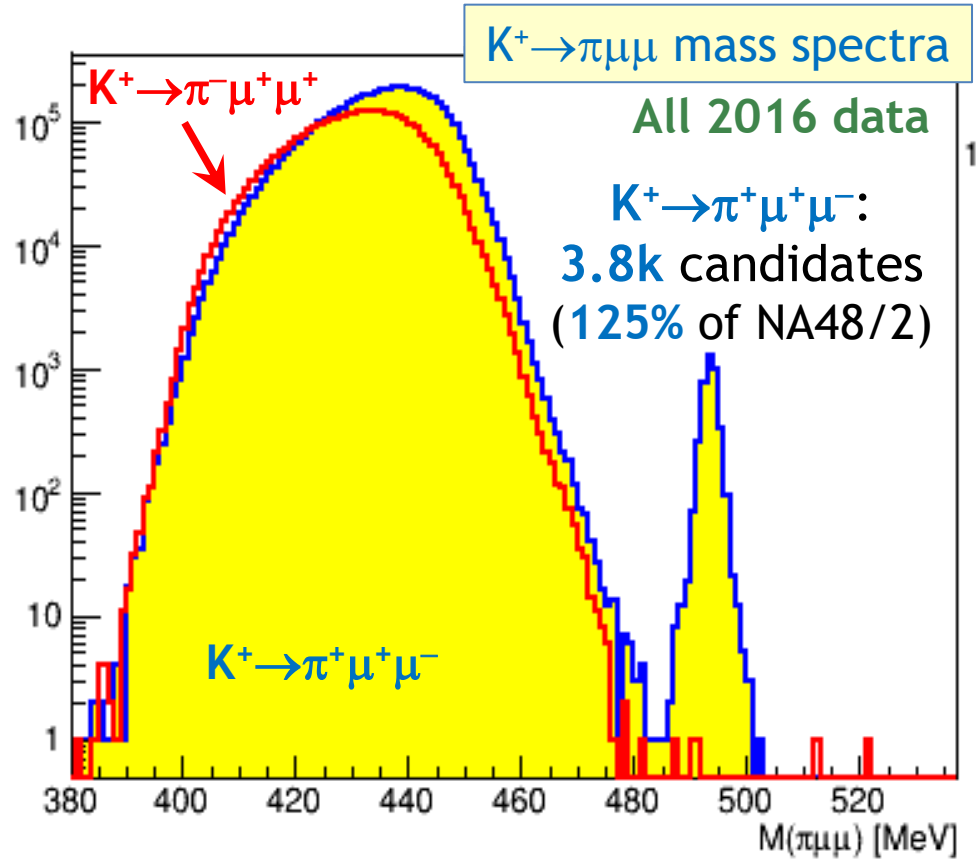
Expected DP exclusion limits

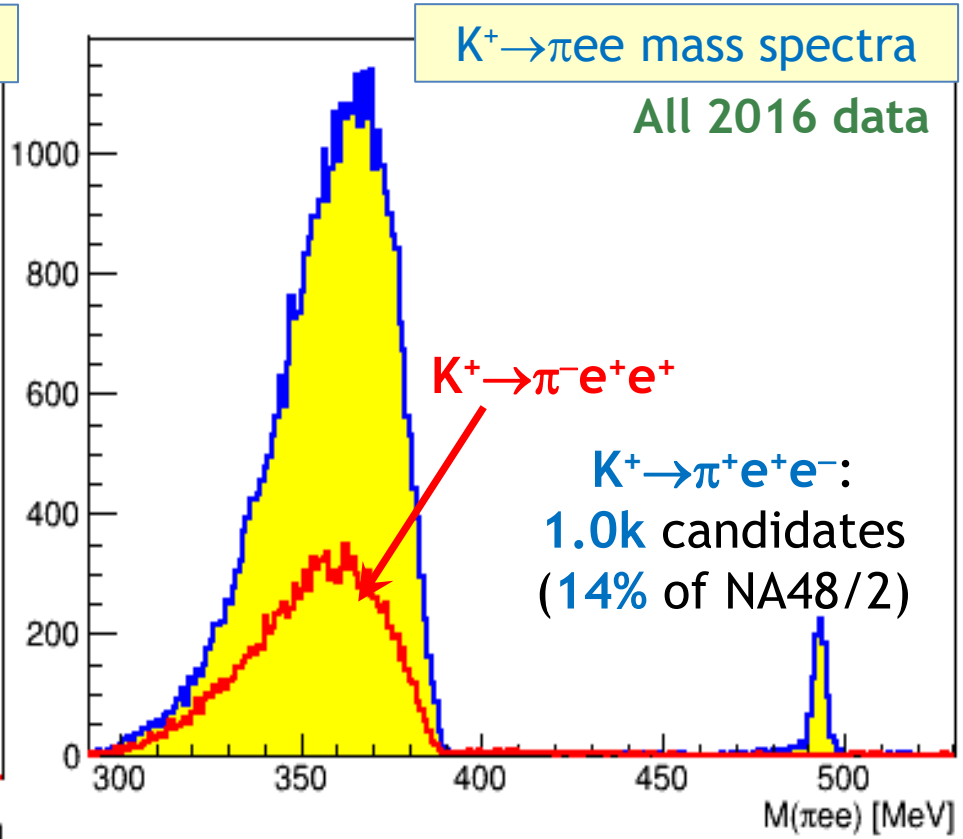


Data 2016: 3-track sample

Lepton flavour and number conservation tests:

- Dedicated trigger streams for **3-track decays with leptons**.
- Improved resolution, veto and PID: lower backgrounds wrt NA48/2.
- Expect to improve world limits on LFV/LNV K^+ and π^0 decays.





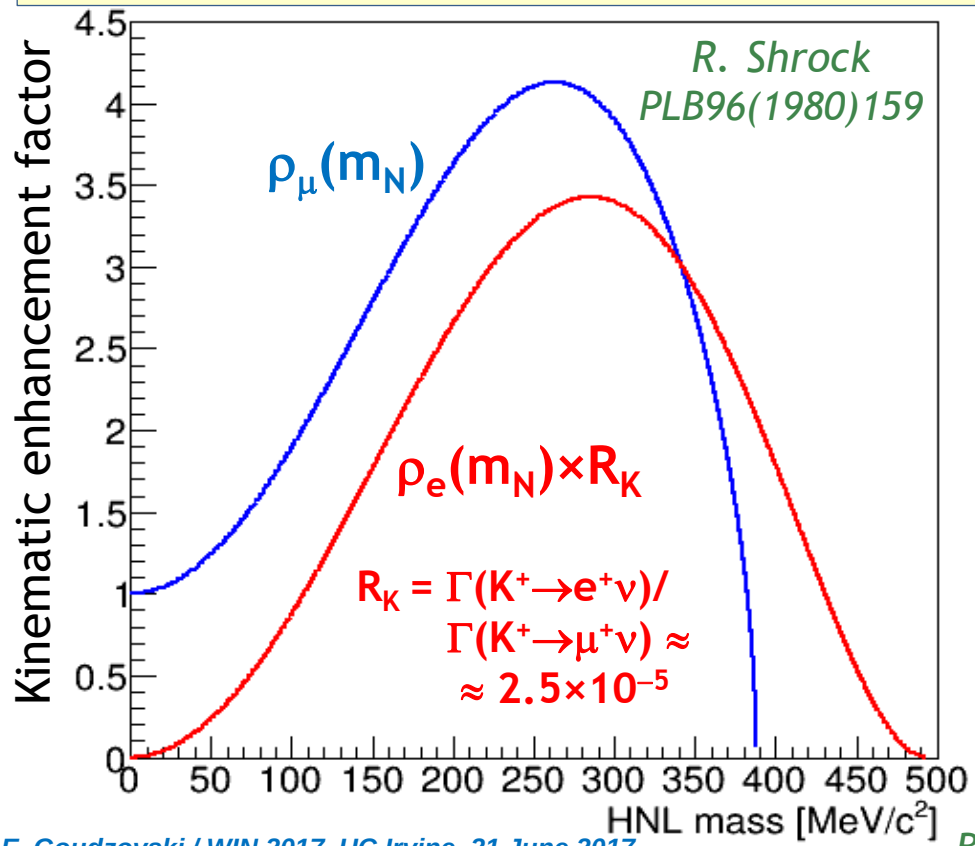
Search for heavy neutral lepton production with 2015 data

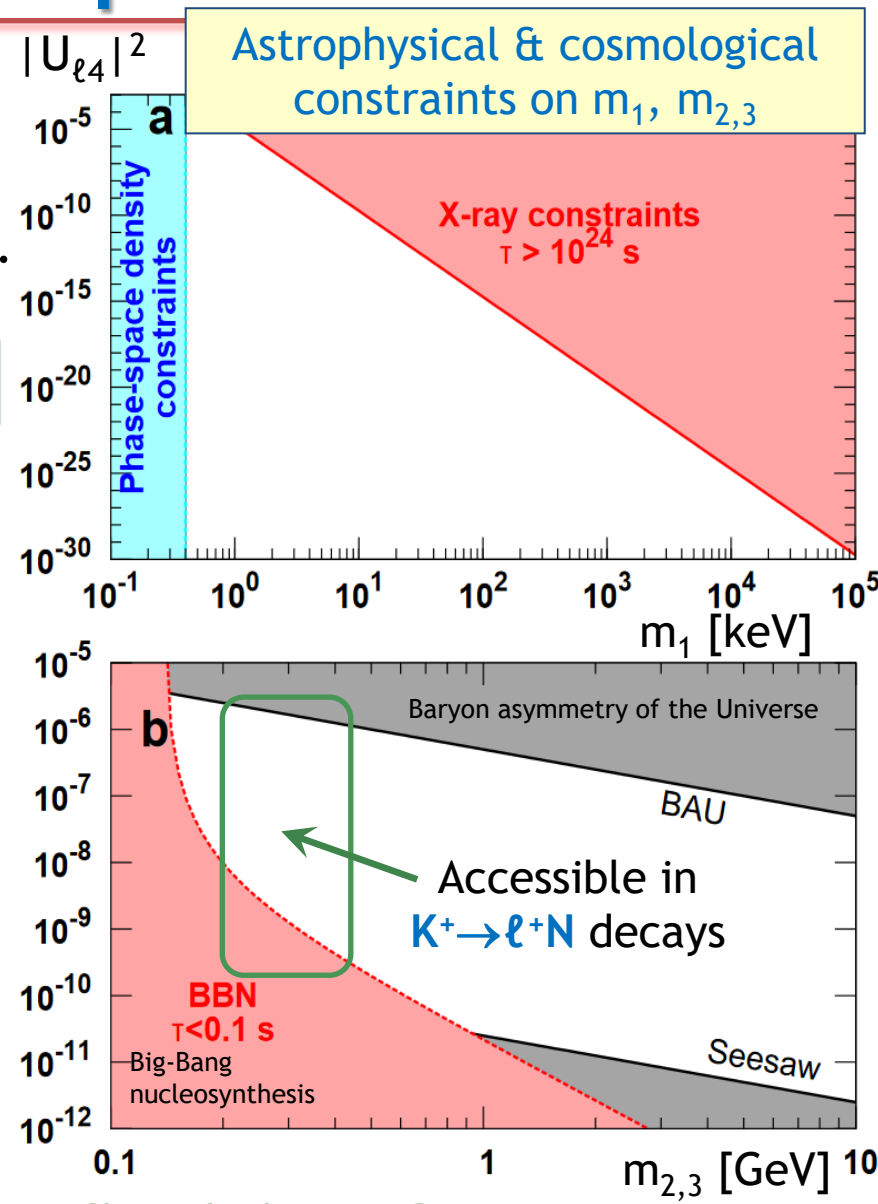
New result

Heavy neutral leptons in νMSM

Neutrino minimal SM (νMSM) =
SM + 3 right-handed neutral heavy leptons.
[Asaka et al., PLB 631 (2005) 151]
Masses: m_1~10 keV [DM candidate]; $m_{2,3}$~1 GeV.
HNLs observable via production and decay.

$$\Gamma(K^+\to\ell^+N) = \Gamma(K^+\to\ell^+\nu)\,\rho_\ell(m_N)\,|U_{\ell 4}|^2$$

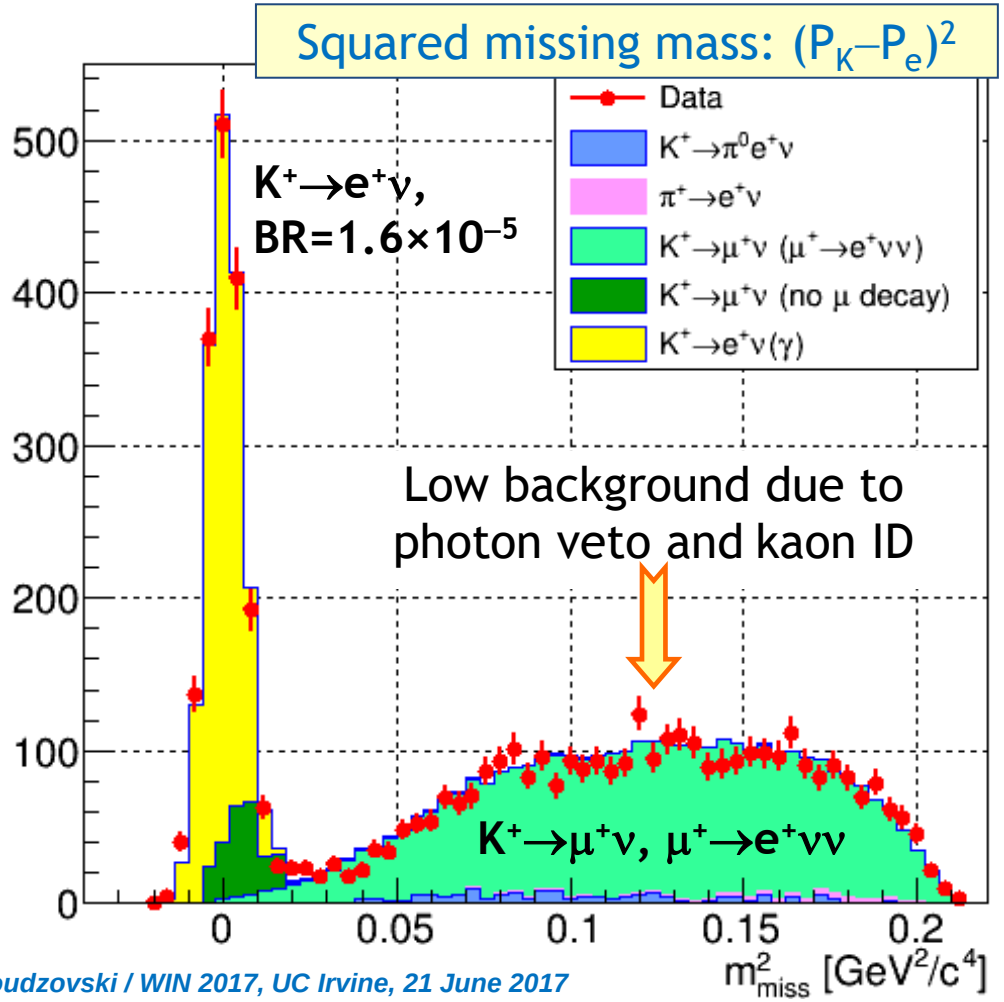


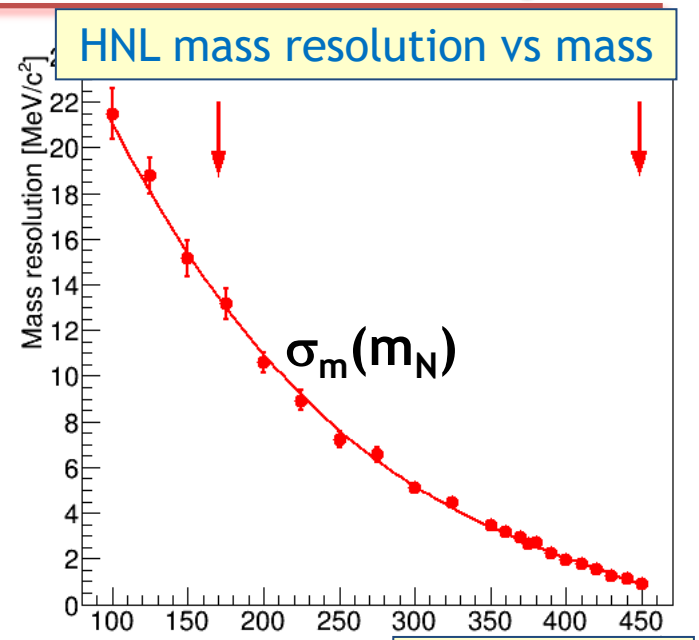


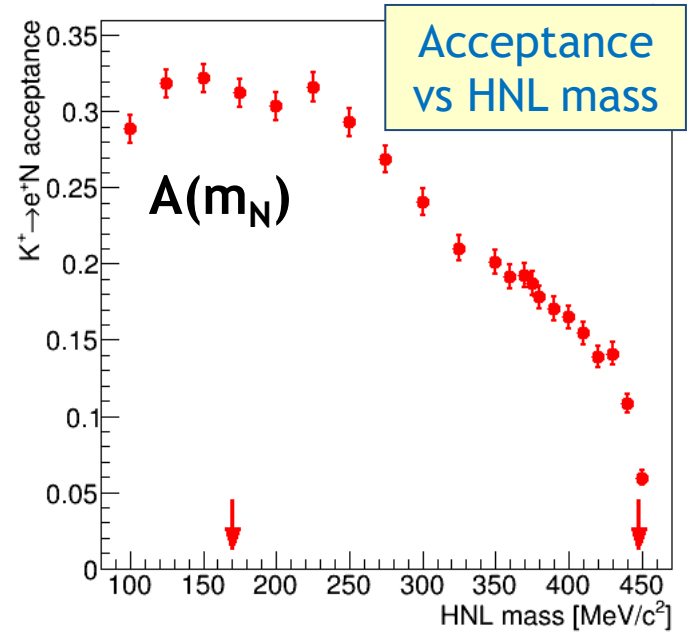
Shaposhnikov, JHEP 0808 (2008) 008
Boyarsky et al., Ann.Rev.Nucl.Part.Sci.59 (2009) 191

$K^+ \to e^+ N$: data sample

- Minimum bias (1% intensity); 11k SPS spills in 2015.
- K^+ decays in fiducial volume: $N_K = (3.01 \pm 0.11) \times 10^8$.
- Beam tracker not available: kaon momentum is estimated as the beam average.

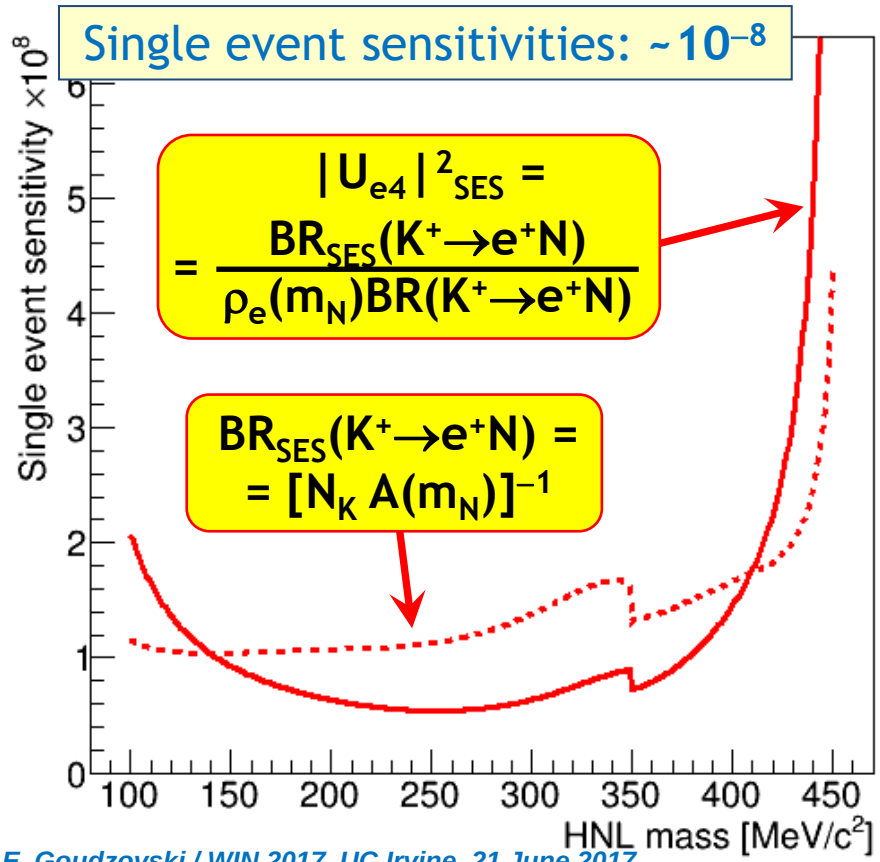


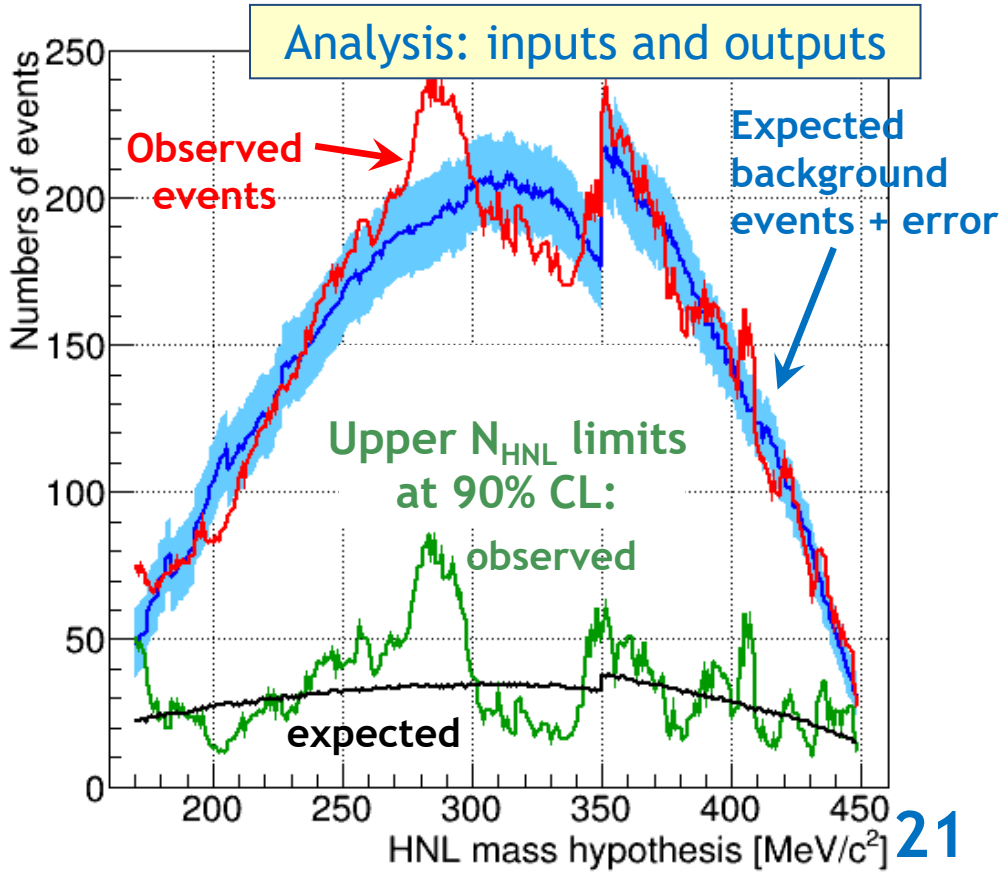




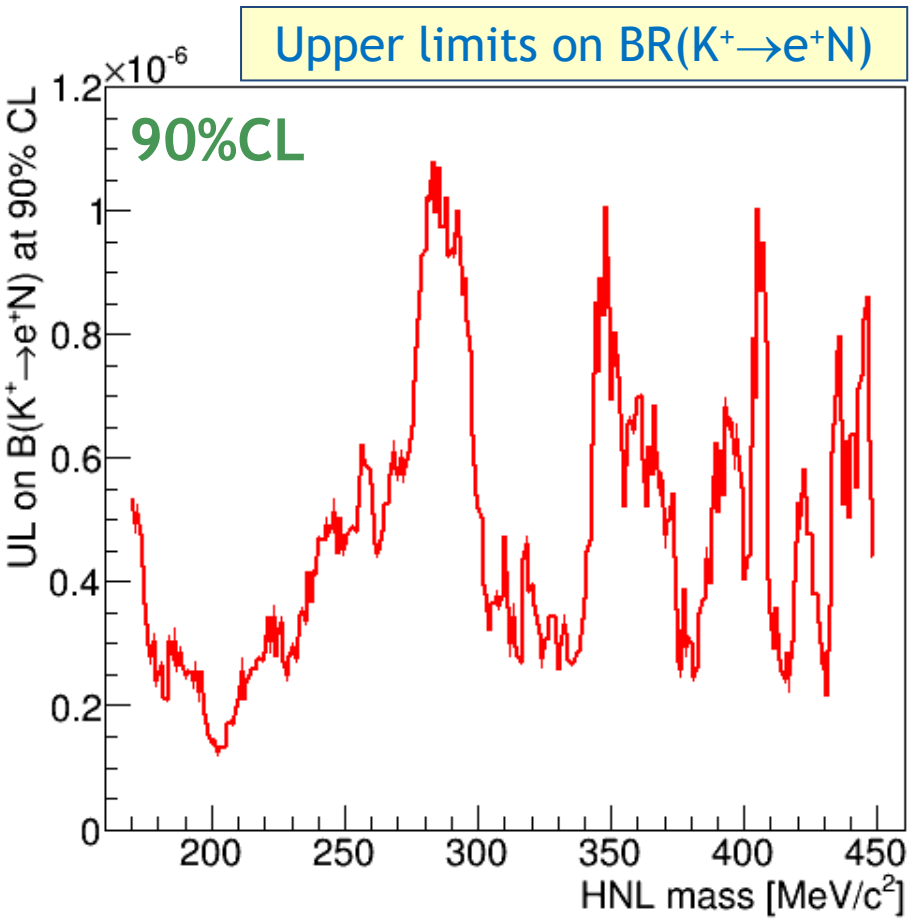
Search for HNL production signal

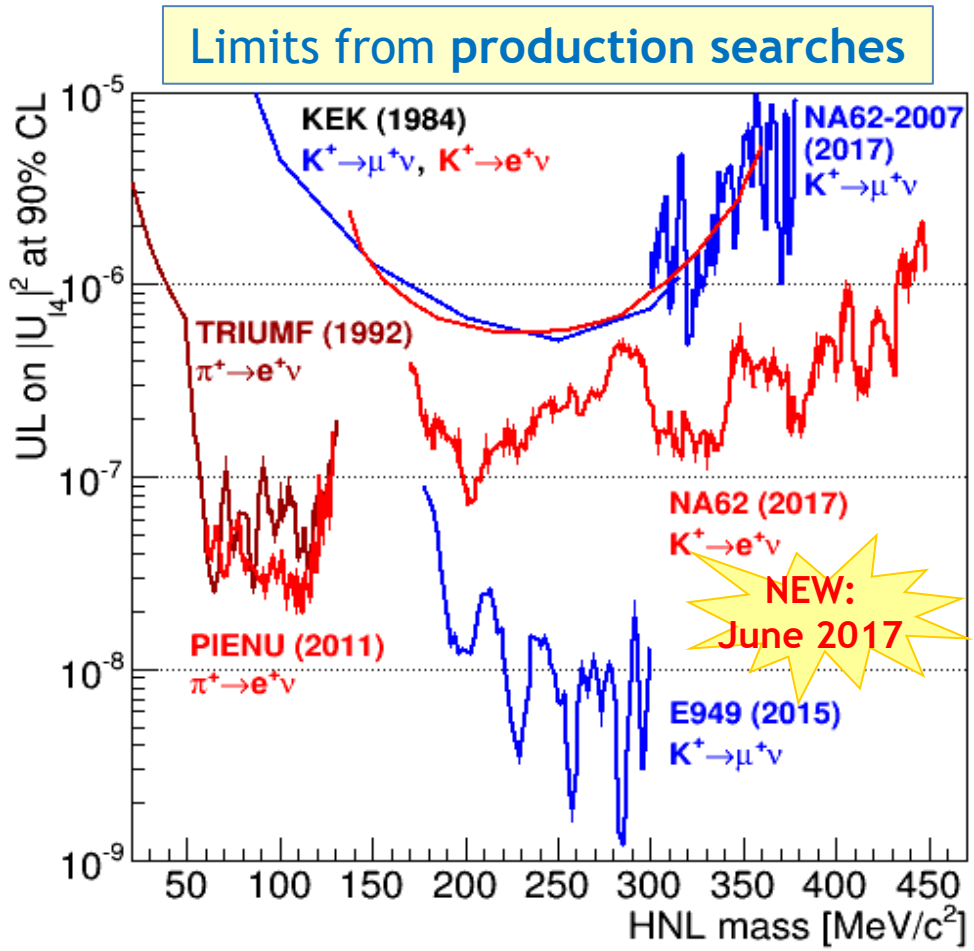
- HNL mass scan: $170\ \mathrm{MeV/c^2} < m_N < 448\ \mathrm{MeV/c^2}$, mass step = $1\ \mathrm{MeV/c^2}$.
- Signal search window for each mass hypothesis: $\pm 1.5\sigma_m$.
- Background estimate: polynomial fits to mass spectra outside signal window.
- Background statistical errors estimated with dedicated MC simulation.
- For each m_N, frequentist confidence intervals for N_{HNL} obtained from numbers of observed and expected events and their uncertainties.





HNL production search: results





- Local signal significance never exceeds 3σ: **no HNL signal** is observed.
- Reached 10^{-6}–10^{-7} limits for $|U_{e4}|^2$ in the 170–448 MeV/c² mass range.
- Major improvement foreseen with high intensity NA62 2016 data.

Summary

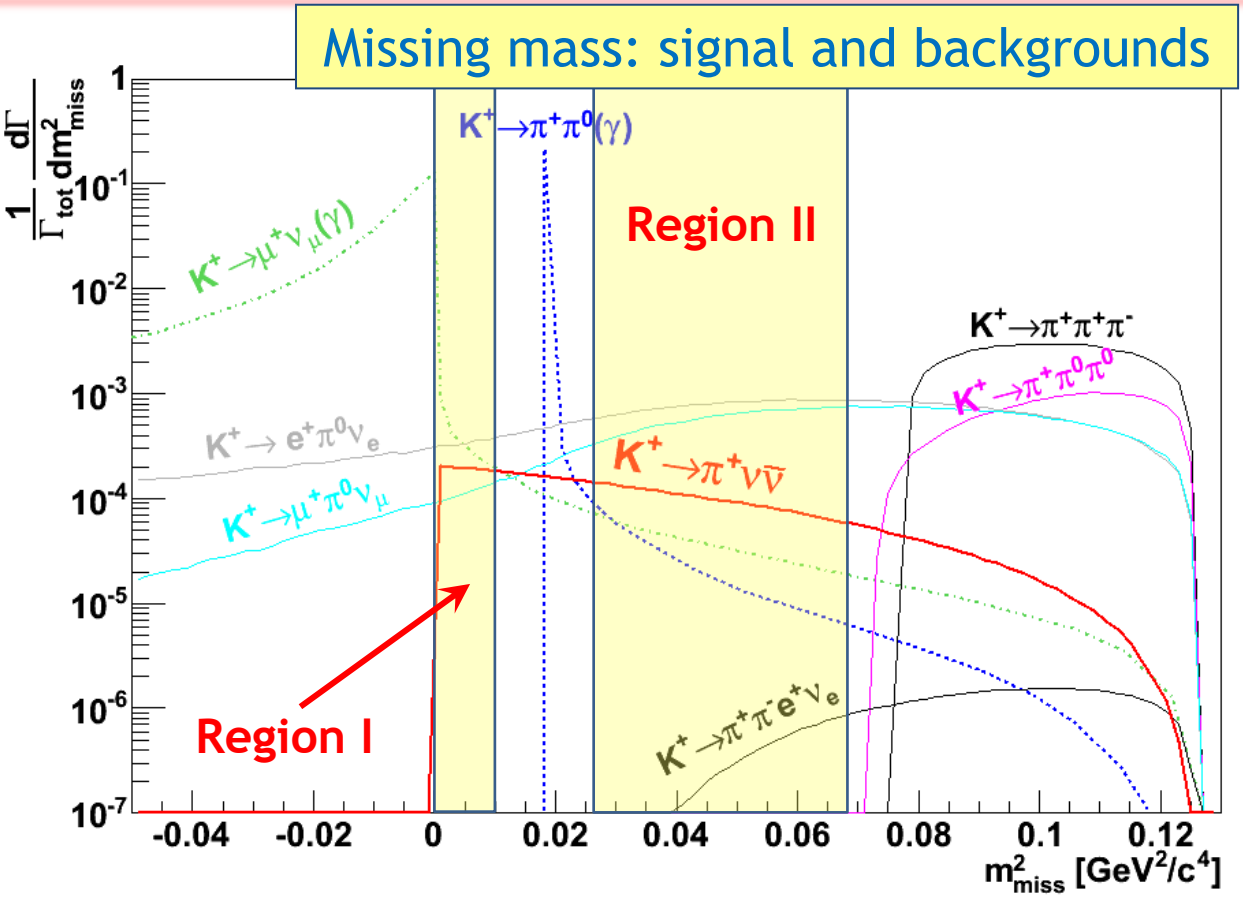
- **NA62 run 2016–2018:**
  - ✓ Detector is fully operational since September 2016
  - ✓ Detector performance is close to design parameters
  - ✓ The run is focused on the $K_{\pi\nu\nu}$ measurement (SES~10^{-12})
  - ✓ Large dataset at 40% of nominal intensity collected in 2016
  - ✓ Currently taking data at 50% of nominal intensity

- **First physics result from the 2015 run:**
  - ✓ Search for HNL production in $K^+ \to e^+ N$ decays with minimum bias data: 10^{-6}–10^{-7} limits on $|U_{e4}|^2$ in mass range 170–448 MeV/c^2

- **Future prospects:**
  - ✓ $K_{\pi\nu\nu}$ analysis of 2016 data is on-going: expect O(1) SM events
  - ✓ Further results with 2015 and 2016 data samples are expected in near future

Backup

$K_{\pi\nu\nu}$ kinematics



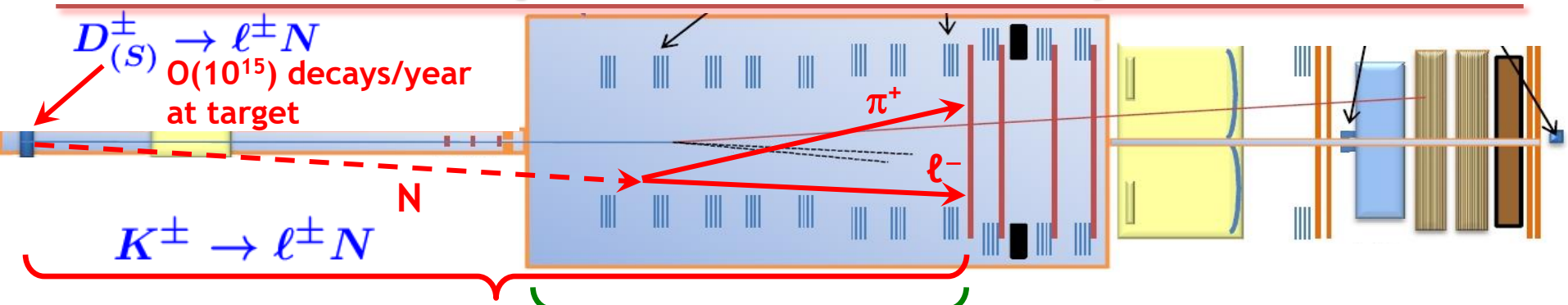
92% of total **BR(K^+)**:

- ❖ 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:

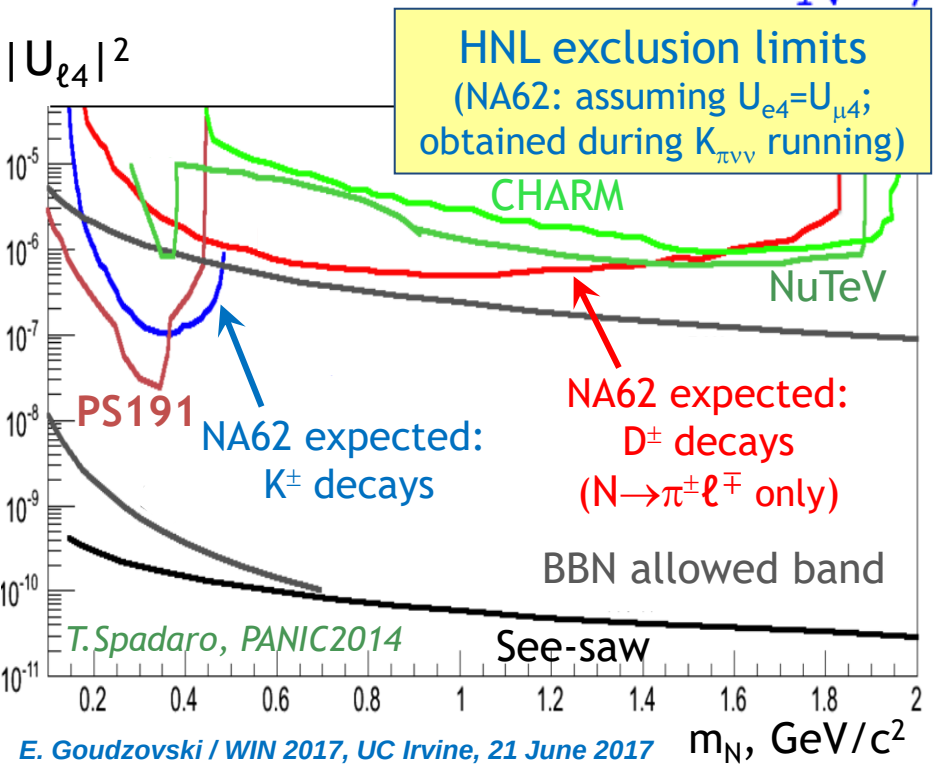
- ❖ Span across the signal region (not rejected by kinematic criteria).
- ❖ Rejection relies on hermetic photon system, PID, sub-ns timing.

HNL: possible decay searches



Search for decays: $N \to \pi^{\pm}\ell^{\mp}$ (0.14 GeV/c² < m_N < 1.9 GeV/c²)

$N \to \rho^{\pm}\ell^{\mp}$ (0.8 GeV/c² < m_N < 1.9 GeV/c²)



The expected sensitivity is evaluated assuming **zero background**.

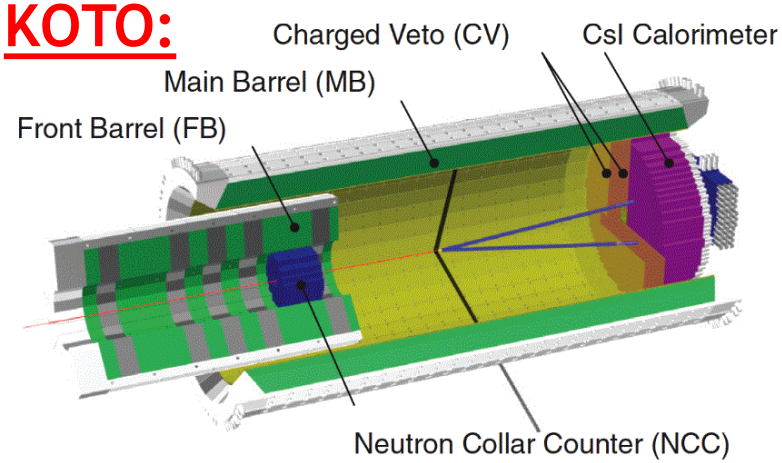
Backgrounds to be considered: scattering of halo muons ($\mu^{\pm}N\to K^0X$), charge exchange in KTAG/GTK ($K^+n\to K^0p$), accidentals (K^+ decays, halo muons).

Proof-of-principle: **2016 data**. Searches for dark photon and axion production at target: prospects are being evaluated.

Kaons at CERN beyond 2024

- Need to measure both $BR(K^+\to\pi^+\nu\nu)$ vs $BR(K_L\to\pi^0\nu\nu)$: affected differently by NP.
- In the next few years, we expect:
  - ✓ NA62 @ CERN to measure $BR(K^+\to\pi^+\nu\nu)$ to 10%;
  - ✓ KOTO @ J-PARC to observe a few $K_L\to\pi^0\nu\nu$ events.
- A new, possibly multi-purpose, K_L experiment at CERN focussed on $K_L\to\pi^0\nu\nu$, with $SES\sim0.5\times10^{-12}$ is under consideration for Run 4 (2026–2029).

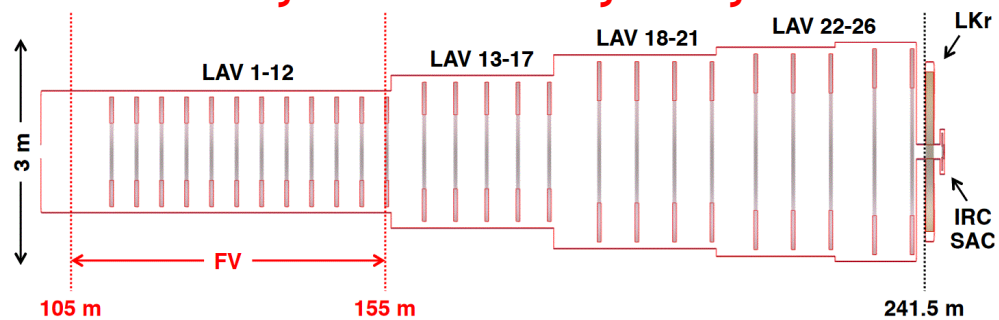
KOTO:



- 30 GeV protons (300 kW); $\langle p_{KL}\rangle$=2 GeV/c;
- Proposal: $SES=8\times10^{-12}$ (~4 SM evts) with S/B=1.4 in three years.
- Short (100h) run in 2013: $SES=1.3\times10^{-8}$;
- Observed 1 event, expected 0.36; *[CKM2014]*
- Collected ×20 more data in 2015;
- Intention (no proposal): upgrade to 100 SM evts.

KLEVER @ CERN:

feasibility and sensitivity study



- 400 GeV protons; $\langle p_{KL}\rangle\sim100$ GeV/c: complementary approach to KOTO.
- 60 SM events in 5 years with S/B≈1.
- Protons required: 5×10^{19} (NA62×10): target area & transfer line upgrade.
- Re-use NA62 infrastructure and parts of detector (LKr calorimeter; muon system).