PIC2018: XXXVIII International Symposium on Physics in Collision, Bogota, Colombia

Kaon Physics Status and Prospects

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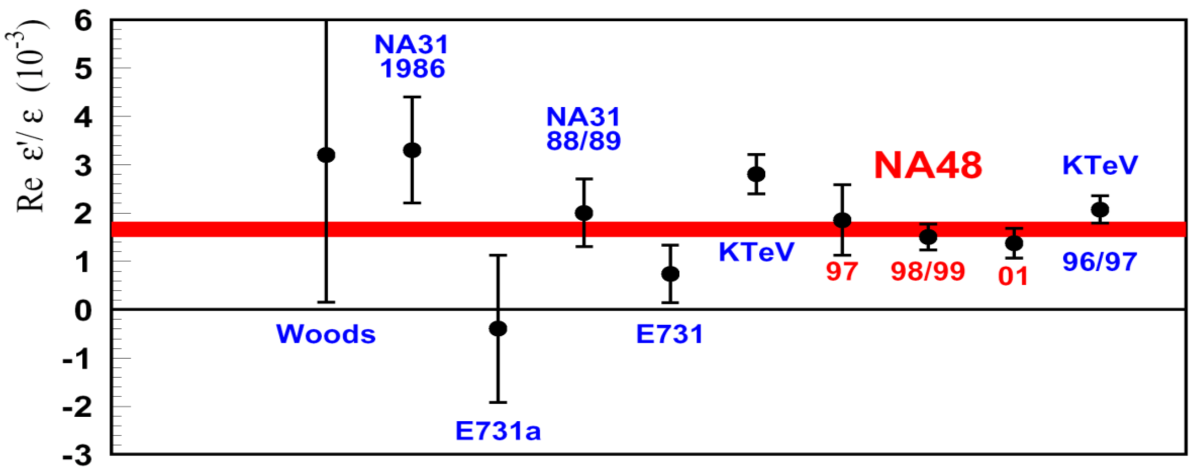
Outline

- CP-Violation
- Leptonic and Semileptonic decays
- Rare Decays, SM and Beyond
- Lepton Universality and Flavour Violation
- Exotics

ε'/ε

- Re(ε'/ε) is one of the important actors of 1990s particle physics
- A non-zero value of Re(ε'/ε) signals the direct CP violation in the decay of the neutral kaon
- It was demonstrated that Re(ε'/ε) is different from zero beyond doubt



ε'/ε

$$\left(\frac{\varepsilon'}{\varepsilon}\right)_{Exp} = (16.6 \pm 2.3)\cdot 10^{-4}$$

World average from NA48 and KTeV

- Precise theoretical prediction difficult because of strong interplay of QCD and EW penguin contributions
- SM prediction is still debated:

$$\left(\frac{\varepsilon'}{\varepsilon}\right)_{Th} = (1.9 \pm 4.5)\cdot 10^{-4}$$

Buras, Gorbahn, Jager, Jamin
arXiV 1507.06345

$$\left(\frac{\varepsilon'}{\varepsilon}\right)_{Th} = (15 \pm 7)\cdot 10^{-4}$$

Gisbert, Pich
arXiV 1712.06147

- Waiting for lattice QCD to clarify the SM prediction

$K_S \to \pi^0\pi^0\pi^0$

- The prediction in the SM is:

$$\mathrm{BR}\left(\mathrm{K_S} \to \pi^0\pi^0\pi^0\right) = |\varepsilon|^2 \times \frac{\tau_S}{\tau_L} \mathrm{BR}\left(\mathrm{K_L} \to \pi^0\pi^0\pi^0\right) \approx 3\times10^{-9}$$

- Currently the best limit is provided by the KLOE Collaboration:

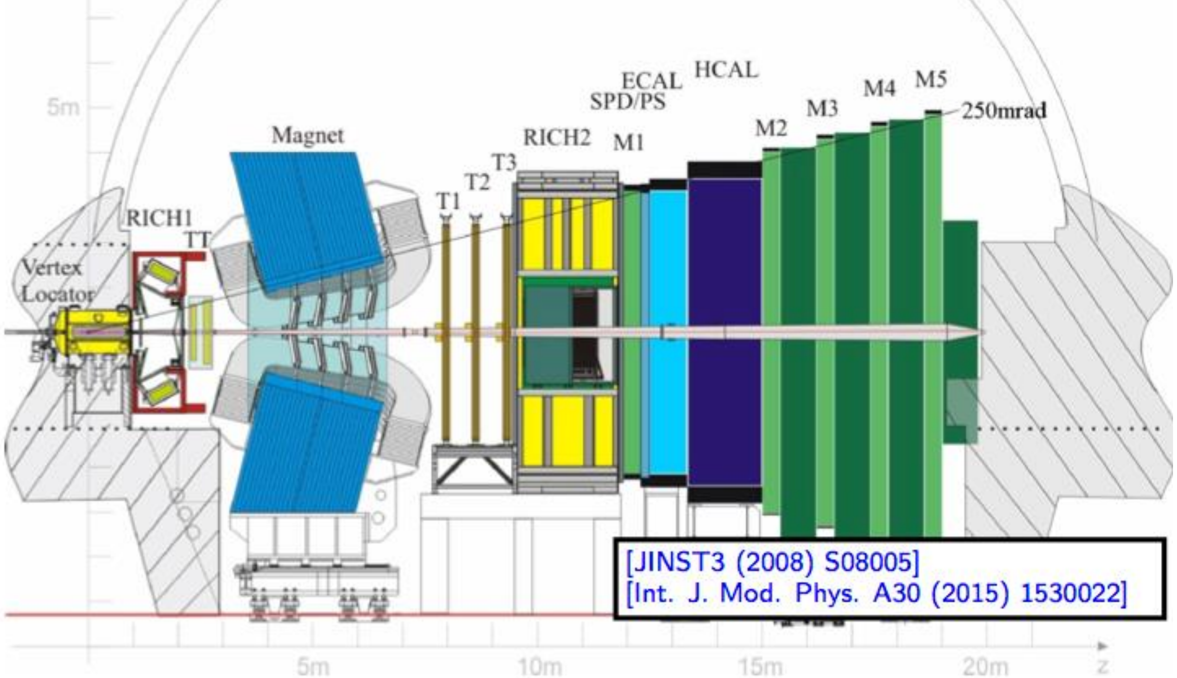
$$\mathrm{BR}\left(\mathrm{K_S} \to \pi^0\pi^0\pi^0\right) \leq 2.6\times10^{-8} \text{ at } 90\% \text{ C.L.}$$

D. Babushi et al., Phys. Lett. B 723, 54 (2013)

A deviation from the predicted value would be a sign of CP violation beyond the complex phase present in the CKM matrix

Since we are discussing K_S

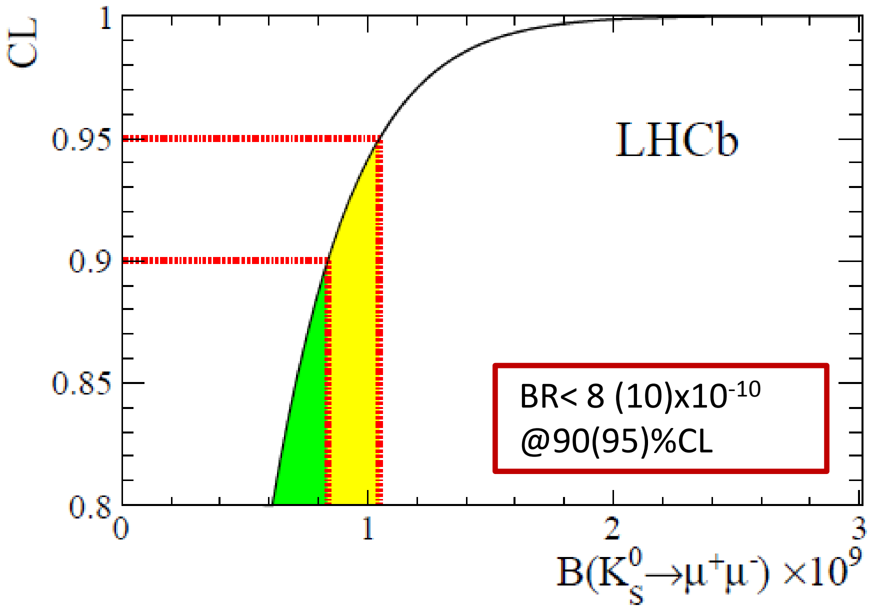
LHCb as K^0_s/Σ factory

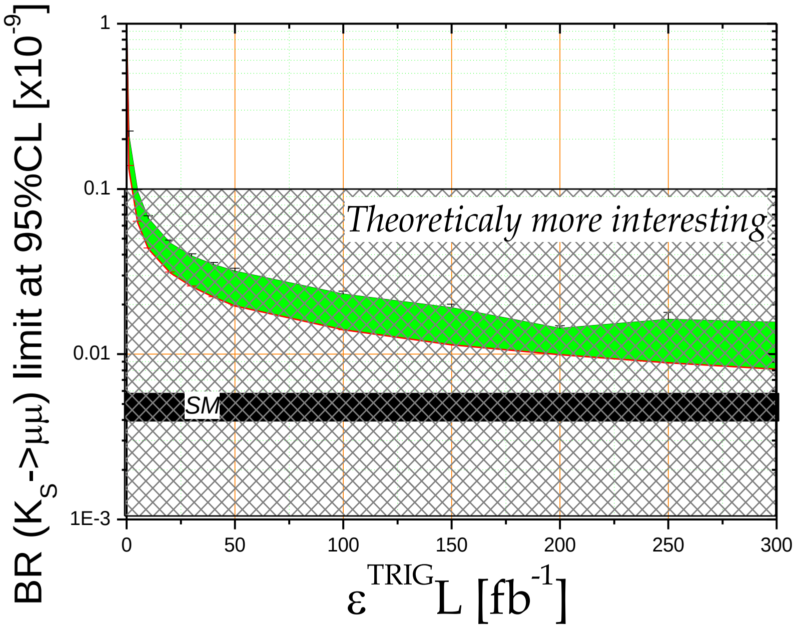


- 10^{13} K^0_S /fb^{-1} inside LHCb acceptance
- K^0_S decays in LHCb characterized by decay vertices separated from the interaction point
- Candidates required to decay in the VELO region (~40%)
- Trigger limitations will be overcome thanks to the LHCb upgrade

LHCb: $K^0_s \to \mu^+\mu^-$

- SM prediction: $BR(K_S \to \mu\mu) = (5.1\pm1.5)\times10^{-12}$
- Analysis performed on full Run-I data arXiv:1706.00758

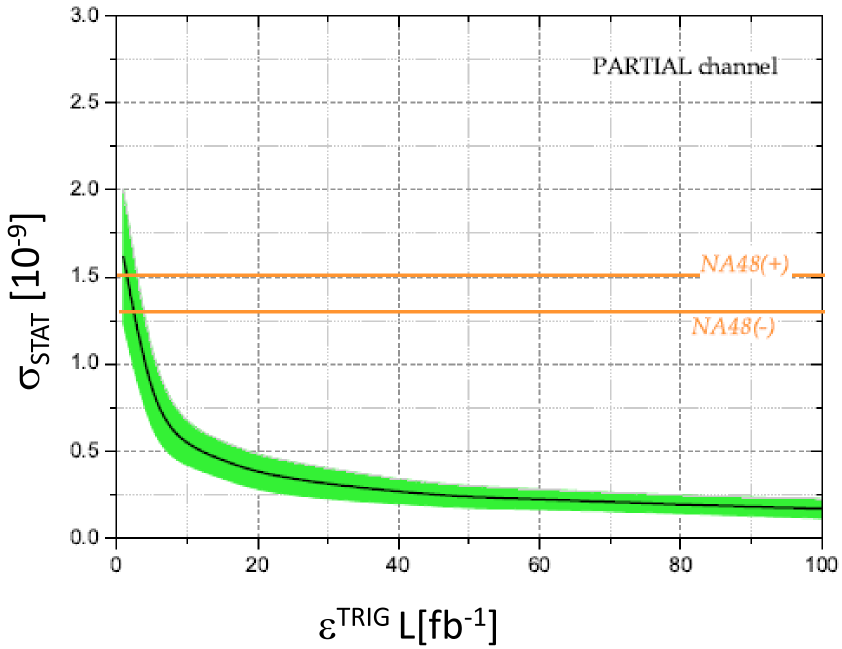




More interesting region can be achieved by LHCb upgrade with trigger improvements

LHCb: $K^0_S \to \pi^0 \mu^+ \mu^-$ feasibility study

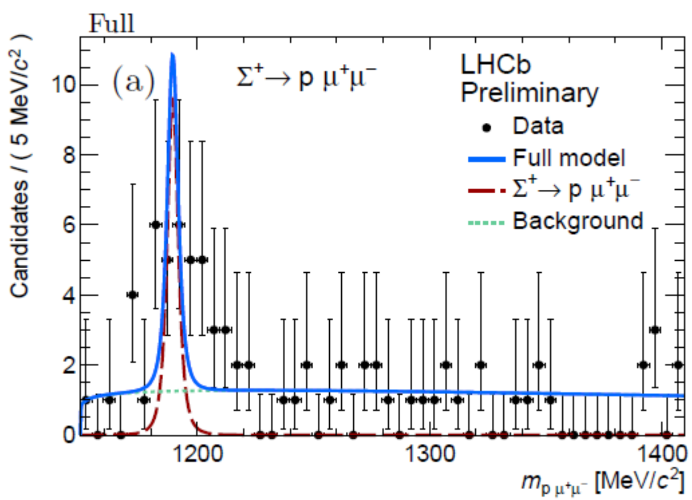
- Most precise measurement was performed by the NA48 experiment
  $BR\left(K^0_S \to \pi^0 \mu^+ \mu^-\right) = 2.9^{+1.5}_{-1.2} \times 10^{-9}$ Phys. Lett. B599 (2004) 197
- Improvements on $BR(K^0_S \to \pi^0 \mu^+ \mu^-)$ measurement would lead to better prediction for $BR(K^0_L \to \pi^0 \mu^+ \mu^-)$

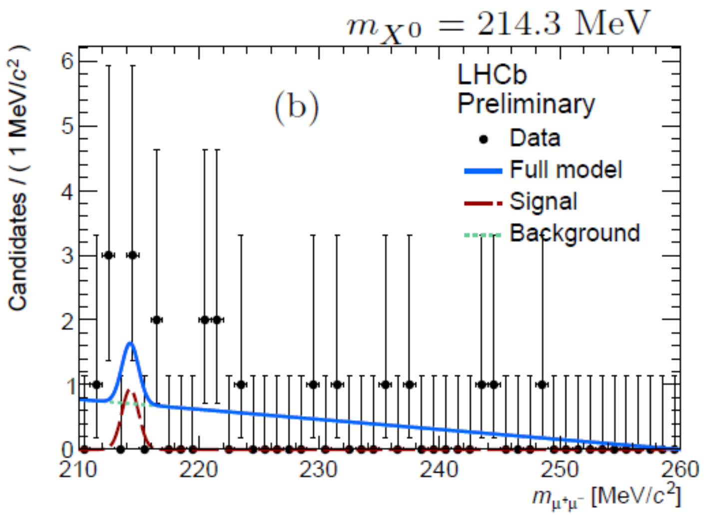


Excellent prospects for the LHCb upgrade

LHCb: evidence of $\Sigma^+\to p\mu^+\mu^-$

- The HyperCP collaboration found evidence for $\Sigma^+\to p\mu^+\mu^-$ decays
- 3 events clustered at $m_{\mu+\mu-}$ =214 MeV/c^2
- This suggested the existence of a new neutral particle
- LHCb analysis performed on full Run-I data LHCb-CONF-2016-013





- No bumpy feature in $m_{\mu+\mu-}$
- From the subset of events with available normalization

$$\mathrm{BR}\left(\Sigma^+ \to p\mu^+\mu^-\right) < 6.3\times10^{-8} \text{ at } 95\% \text{ C.L.}$$

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Leptonic K decays and V_{us}

V_{us} can be obtained from leptonic decays

$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = \left(\frac{\Gamma(K\to l\nu(\gamma))}{\Gamma(\pi\to l\nu(\gamma))}\frac{m_{\pi^\pm}}{m_{K^\pm}}\right)^{1/2}\frac{1-m_\mu^2/m_{\pi^\pm}^2}{1-m_\mu^2/m_{K^\pm}^2}\left(1-\frac{1}{2}\delta_{EM}-\frac{1}{2}\delta_{SU(2)}\right)$$

Using typical inputs:

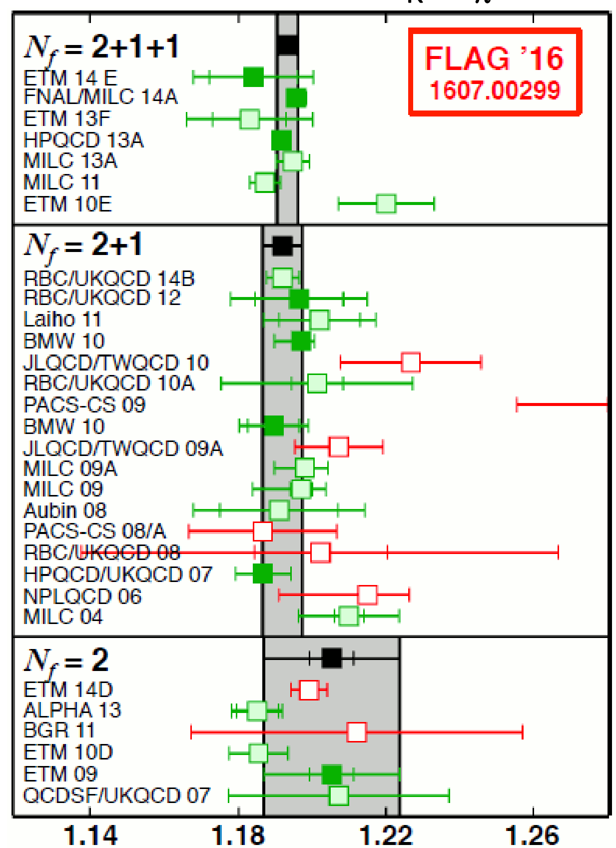
Blucher and Marciano, PDG2017

$$\frac{\Gamma(K\to\mu\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))}=1.3367(29)$$

$$\frac{f_{K^+}}{f_{\pi^+}}=1.1933(29)\quad N_f=2+1+1$$

$V_{us} = 0.2253(7)$

Evaluation of f_K/f_π



Semileptonic K decays and V_{us}

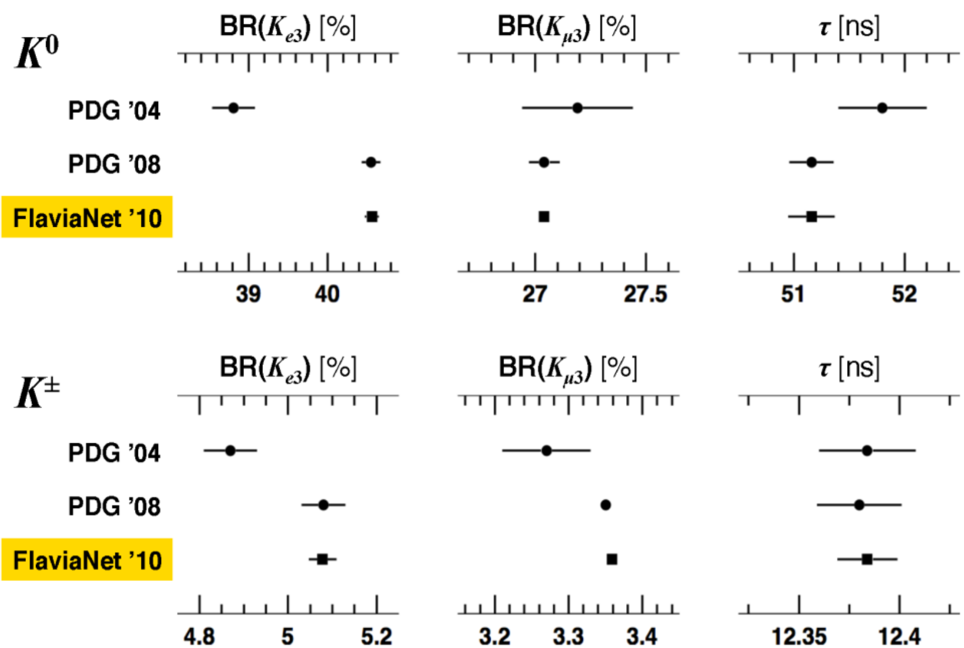
V_{us} can also be determined from semileptonic kaon decays

$$|V_{us}|\, f_+(0) = \sqrt{\frac{BR(K \to \pi l \nu)}{\tau} \cdot \frac{192\pi^3}{G_F^2 M_K^5 S_{EW} \left(1+\delta_K^l + \delta_{SU2}\right) C^2 I_K^l}}$$

phase space integral

short distance EW correction

long distance radiative correction



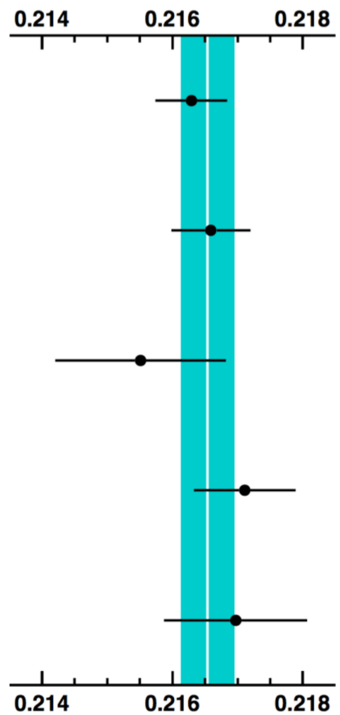
Experimental input changing ~5% in some cases...

Input from many experiments:

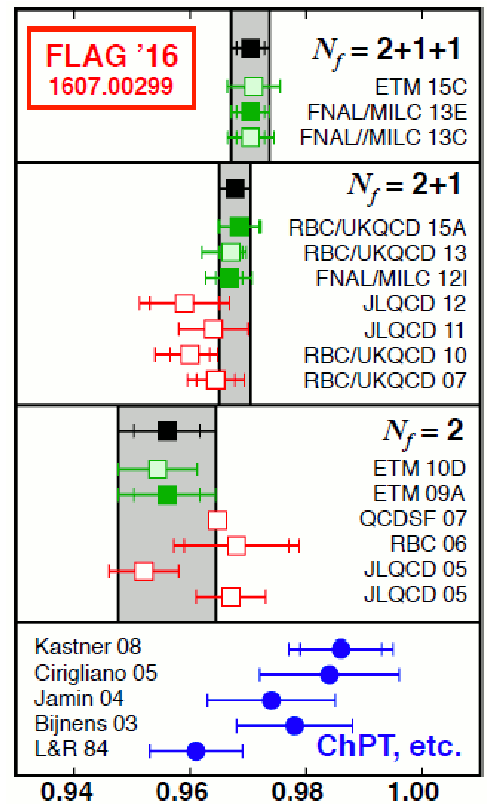
BNL865, KTeV, ISTRA+, KLOE, NA48, NA48/2

Semileptonic K decays and V_{us}

$|V_{us}| f_+(0)$ from world data



Evaluation of $f_+(0)$



$|V_{us}| f_+(0) = 0.21654(41)$ $\chi^2/\text{ndf} = 1.54/4$ (82%)

M. Moulson, CKM 2016

For $f_+(0) = 0.9704(32)$, $N_f = 2+1+1$: $V_{us} = 0.2231(4)_{ex}\ (7)_{latt}$

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$K \to \pi\nu\nu$ decays and CKM matrix

The very small hadronic error makes these decays special

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

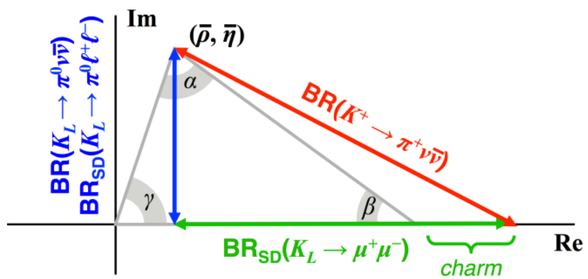
Buras et al., JHEP 1511

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

Precision of prediction limited by CKM parameters

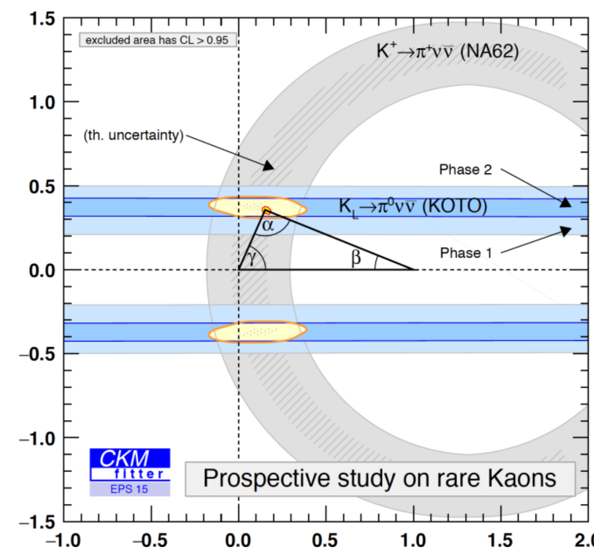
Knowledge of γ, V_{cb} and V_{ub} will be improved by LHCb and Belle II

Overconstrain UT triangle to reveal possible NP



SM prediction $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$

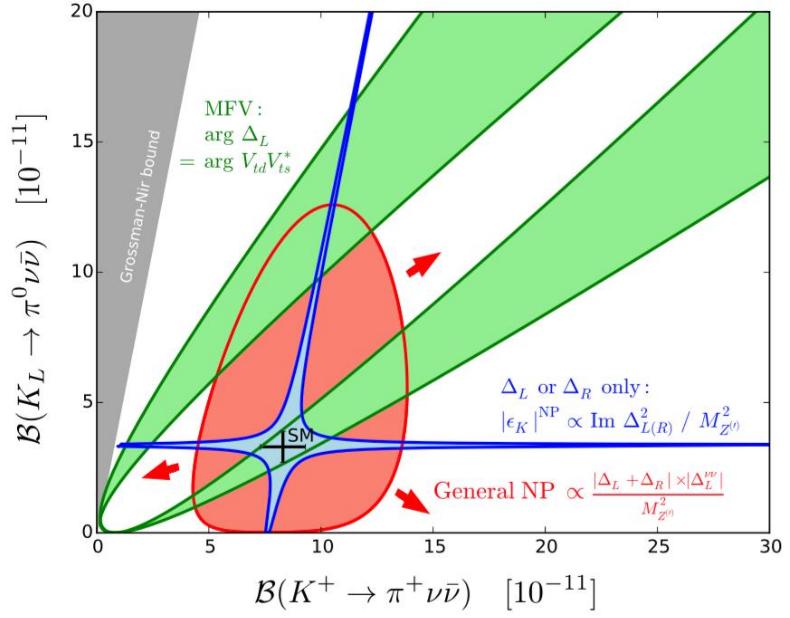
Experimental status $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$



K→πνν decays and New Physics

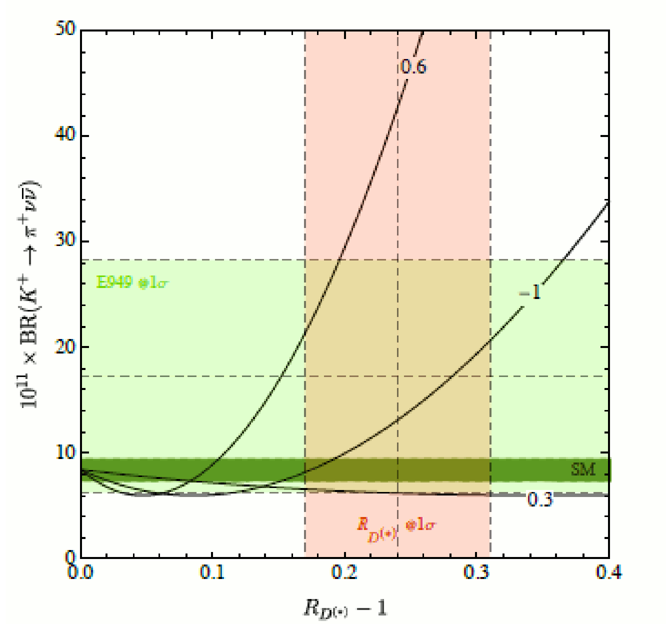
Extensions to the SM to which K→πνν are sensitive include

Simplified Z and Z' models



Buras, Buttazzo, Knegjens, JHEP 1511

LFU violation models



Bordone, Buttazzo, Isidori, Monnard arXiv:1705.10729

K→πνν are the only kaon decays with ν_τ in the final state

The NA62 Experiment for $K^+ \rightarrow \pi^+ \nu\nu$

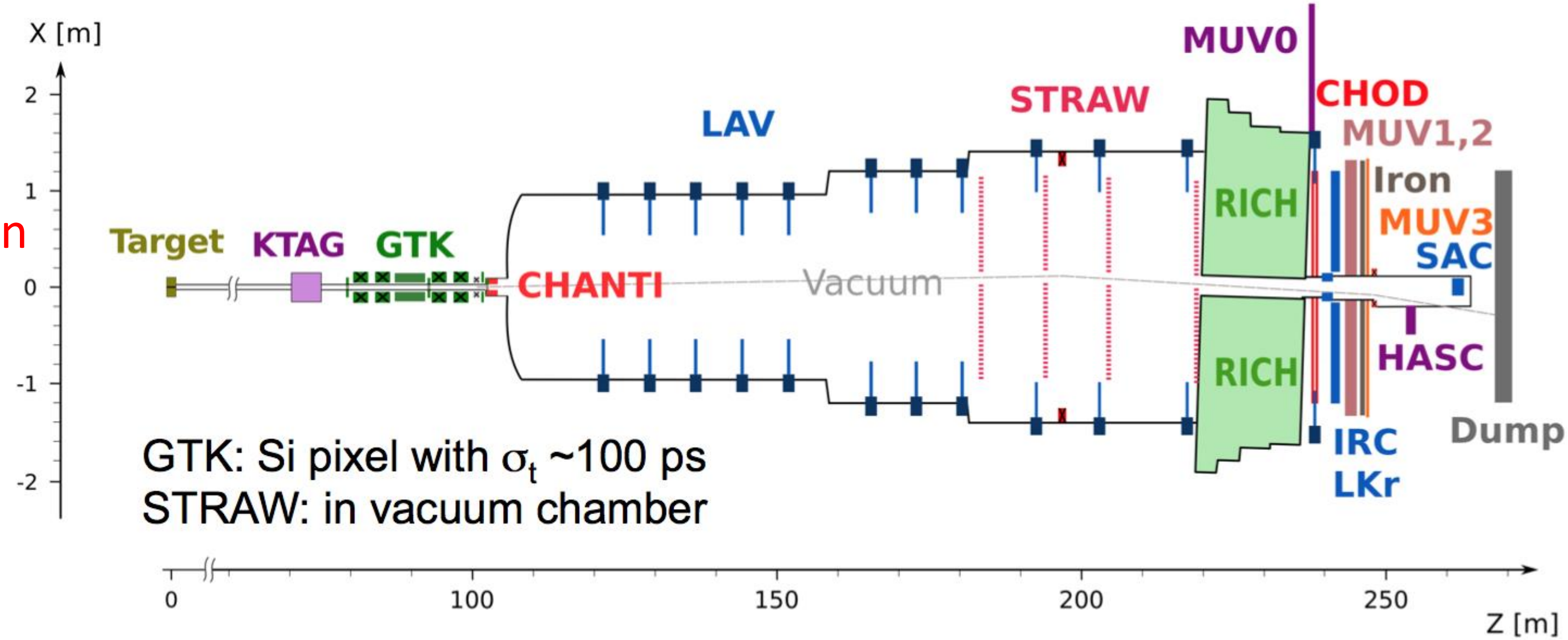
"In-flight" technique

JINST 12 (2017)no.05, P05025

SPS proton

400 GeV

10^{12}p/s



Secondary Beam

75GeV/c, $\Delta p/p \sim 1\%$

K(6%), π(70%), p(23%)

Decay region

60 m length

K^+ decay rate ~ 5 MHz

Vacuum O(10^{-6}) mbar

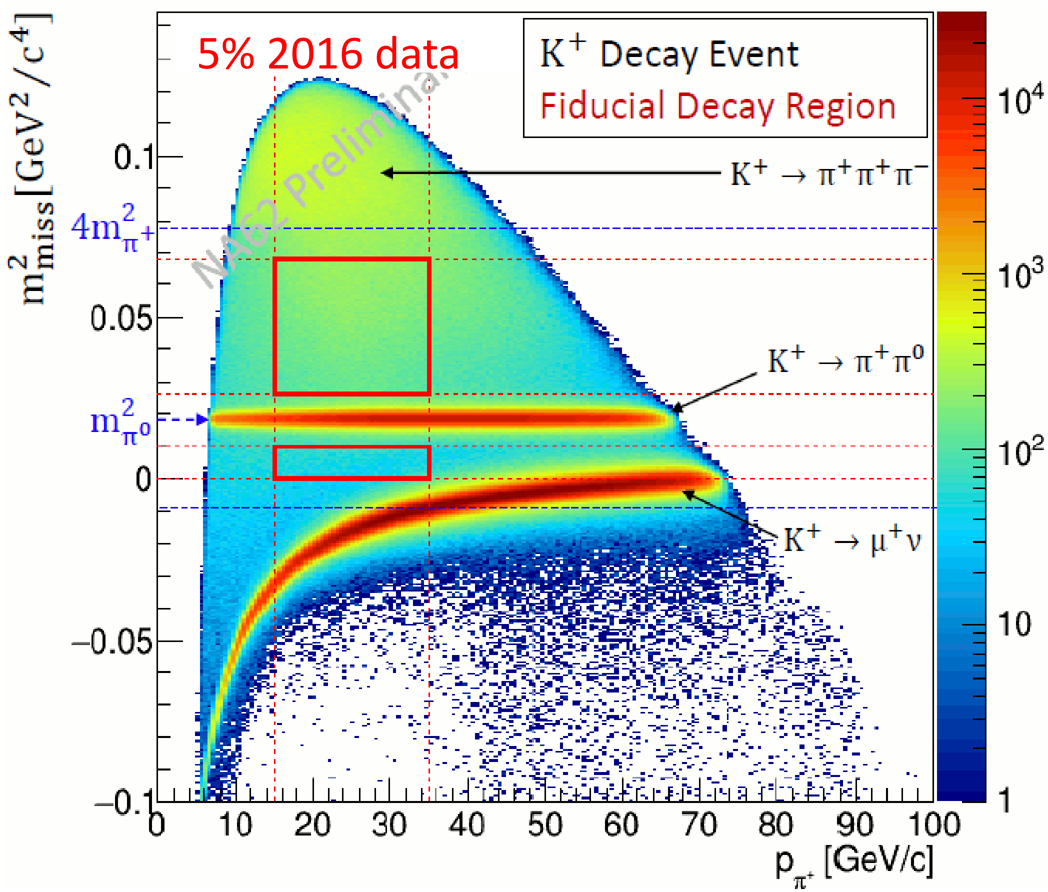
NA62: Data taking

- 2014 Pilot run
- 2015 Commissioning run
- Full detector installation completed in September 2016
- First dataset to look for $K^+ \rightarrow \pi^+ \nu\nu$ decay in 2016
- Continuous data-taking until the end of 2018

Plan to run after the CERN LS2 to complete the $K^+ \rightarrow \pi^+ \nu\nu$ measurement

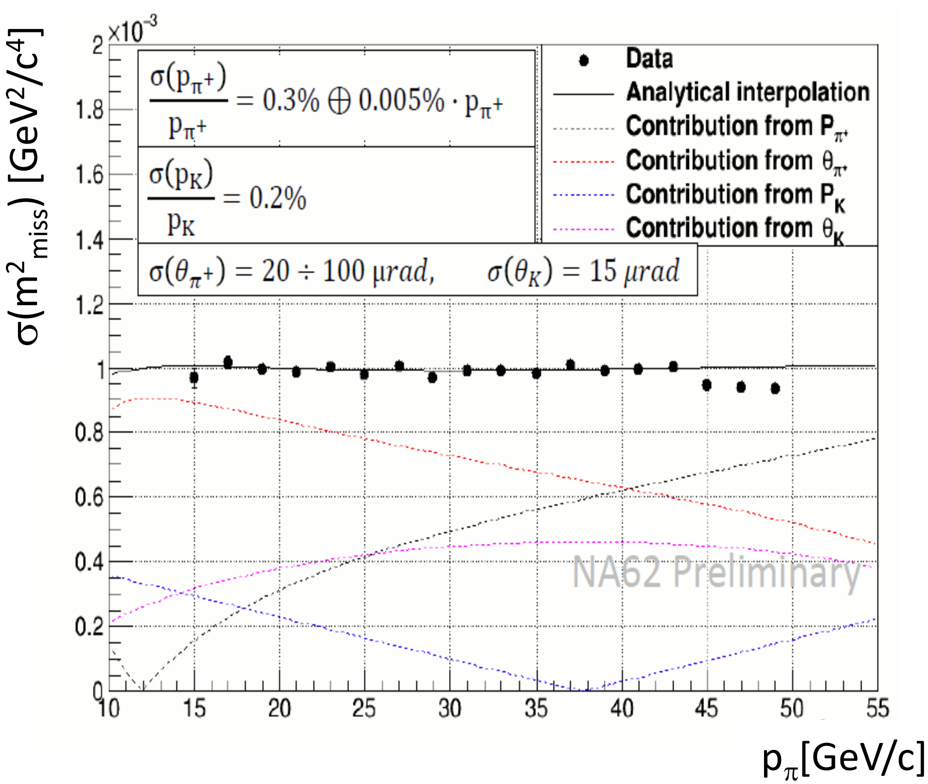
NA62: Kinematics

$m^2_{miss} = (p_K - p_\pi)^2$

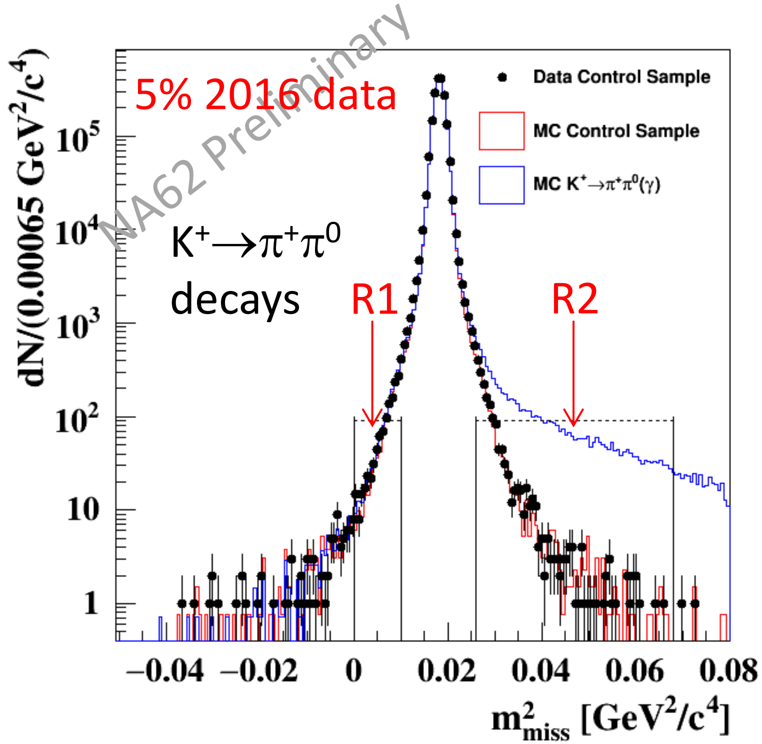


NA62: Signal region definition

Missing mass resolution for single track events



Protects against mis-recontruction



Three different ways to reconstruct m^2_{miss}:
m^2_{miss} (STRAW, GTK), m^2_{miss} (RICH, GTK), m^2_{miss} (STRAW, Beam)

NA62: Signal Selection

Selection criteria

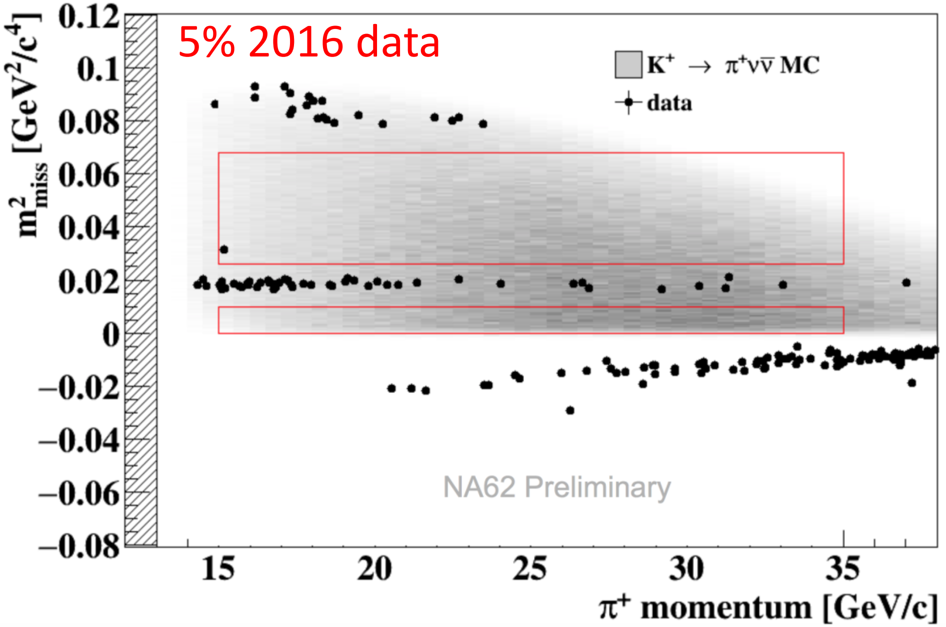
- single track decay topology
- π^+ identification
- photon rejection
- multi-track rejection

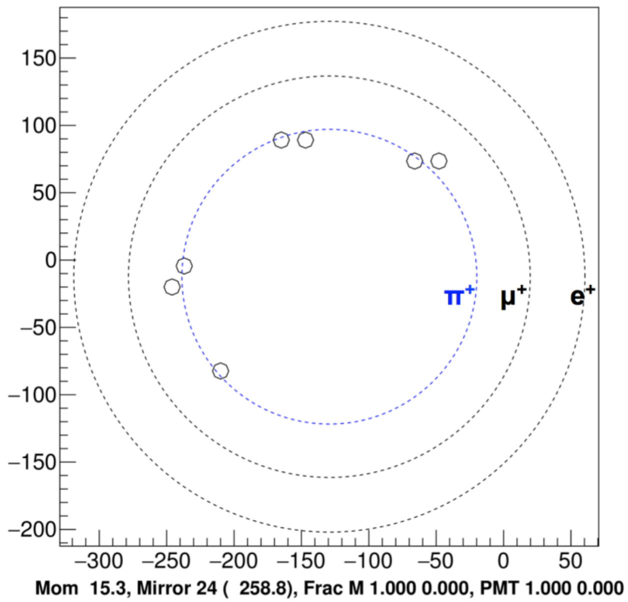
Performance

- $\sigma_t \sim O(100\ \text{ps})$
- $\sigma(m^2_{miss}) = 1\cdot 10^{-3}\ \text{GeV}^4/c^2$
- μ^+ mis-id = $1\cdot 10^{-8}$ (64% $\varepsilon_{\pi+}$)
- π^0 rejection $=3\cdot 10^{-8}$

NA62: Result

One candidate event in Region II with background expectation of 0.15±0.09





Event in box has m^2_{miss} (STRAW, Beam) outside the signal region

Display of RICH hits for the candidate event

$$BR\left(K^+ \rightarrow \pi^+ \nu\bar{\nu}\right) < 14 \times 10^{-10} \quad 95\%\ C.L.$$

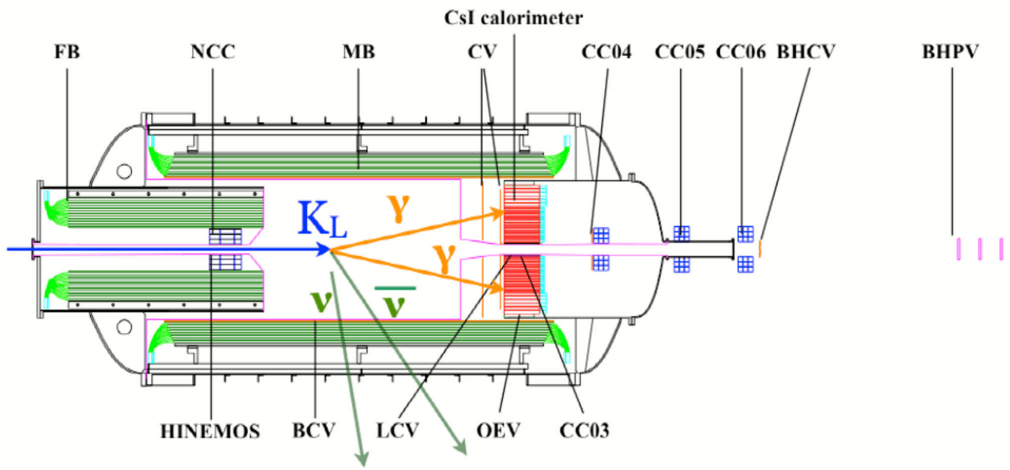
$$BR\left(K^+ \rightarrow \pi^+ \nu\bar{\nu}\right) = 28^{+44}_{-23} \times 10^{-11} \quad 68\% C.L.$$

NA62: $K^+ \to \pi^+ \nu\nu$ Outlook

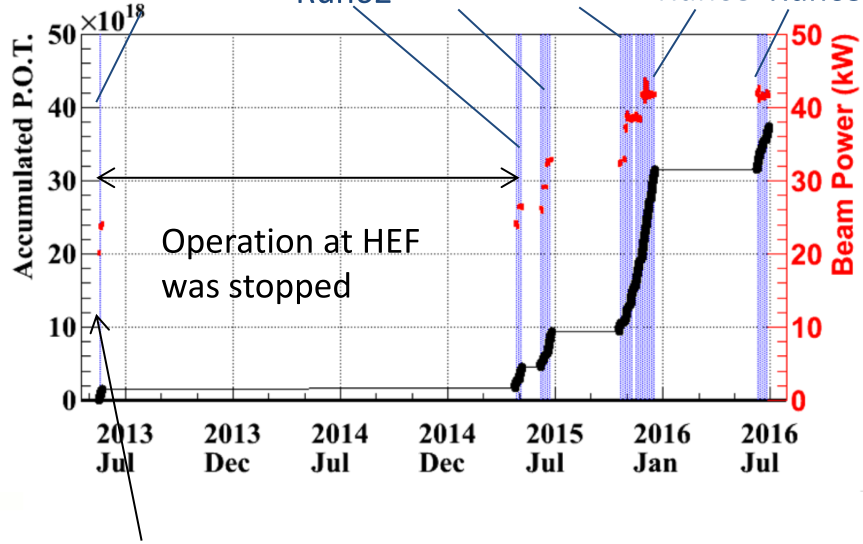
- The 2017 run has been very successful: $\sim 3 \cdot 10^{12}$ K^+ decays have been collected
- Data taking is underway and will continue until the CERN LS2
- By the end of 2018 NA62 should have accumulated about 20 SM signal events
- To reach ultimate sensitivity NA62 plans to continue data taking after LS2

The KOTO Experiment for $K_L \to \pi^0 \nu\nu$

Aims at the first observation of $K_L \to \pi^0 \nu\nu$ at the J-PARK HEF



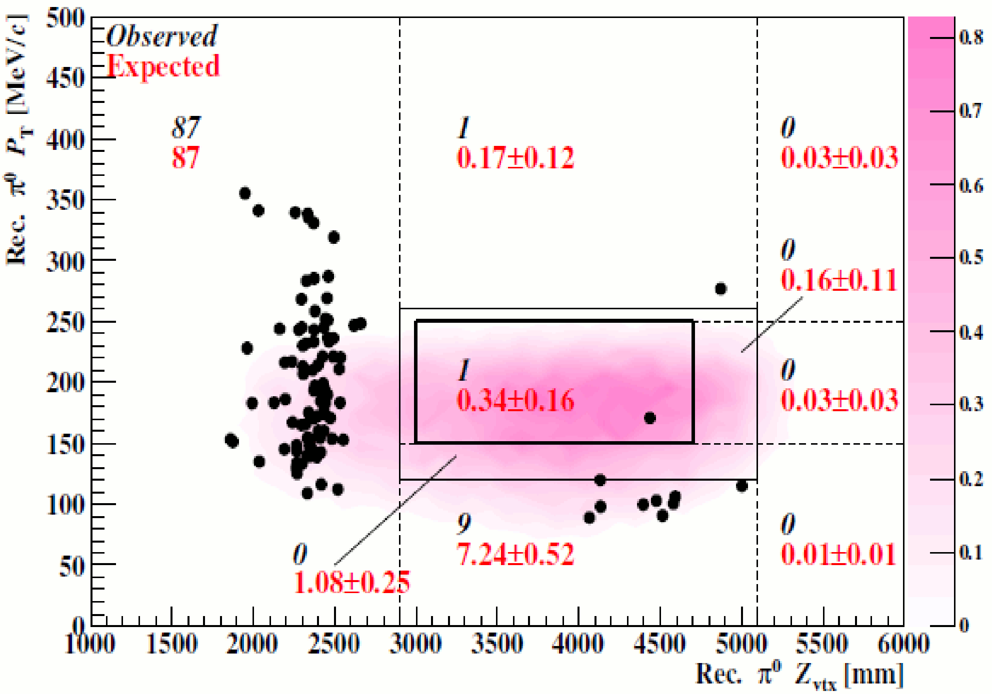
CsI calorimeter and hermetic veto system



First physics run (20kW) in May 2013
(100h before stop)

KOTO: Result of the first physics run

~ 2.3×10^{11} K_L



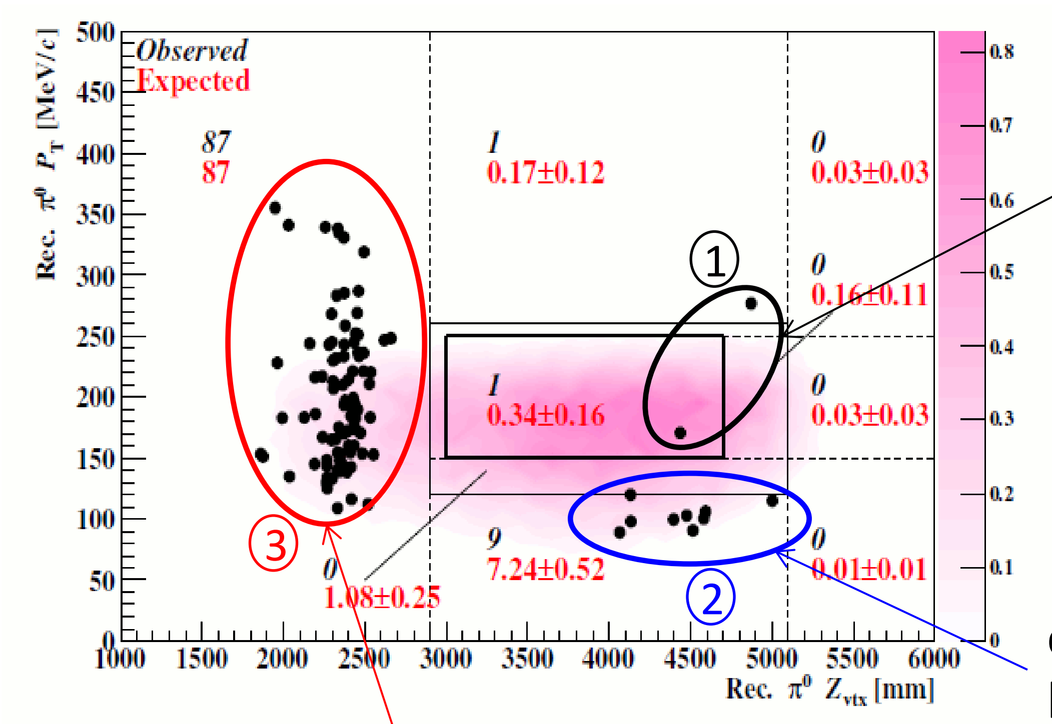
Prog. Theor. Exp. Phys. (2017) 021C01

background source	number of events
$K_L \to 2\pi^0$	0.047 ± 0.033
$K_L \to \pi^+\pi^-\pi^0$	0.002 ± 0.002
$K_L \to 2\gamma$	0.030 ± 0.018
pileup of accidental hits	0.014 ± 0.014
other K_L background	0.010 ± 0.005
halo neutrons hitting NCC	0.056 ± 0.056
alo neutrons hitting the calorimeter	0.18 ± 0.15
total	0.34 ± 0.16

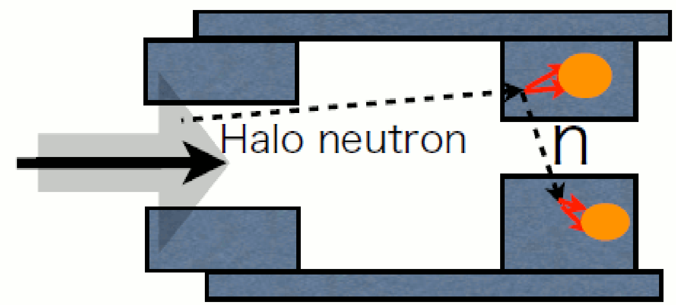
One event was observed consistent with bkg expectation

- BR($K_L \to \pi^0 \nu\nu$) $< 5.1\times10^{-8}$ (90%C.L.)
- BR($K_L \to \pi^0 X^0$) ($M_X = M_\pi$) $< 3.7\times10^{-8}$ (90%C.L.)

KOTO: Lesson from the 2013 run

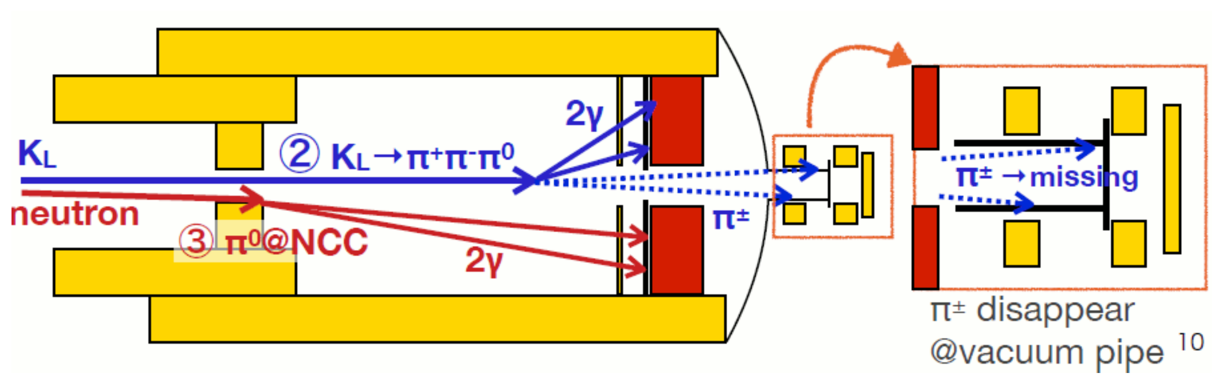


Main bkg due to halo neutrons hitting directly the calorimeter



charged pions from $K_L \rightarrow \pi^0\pi^+\pi^-$ decays hitting the downstream beam pipe

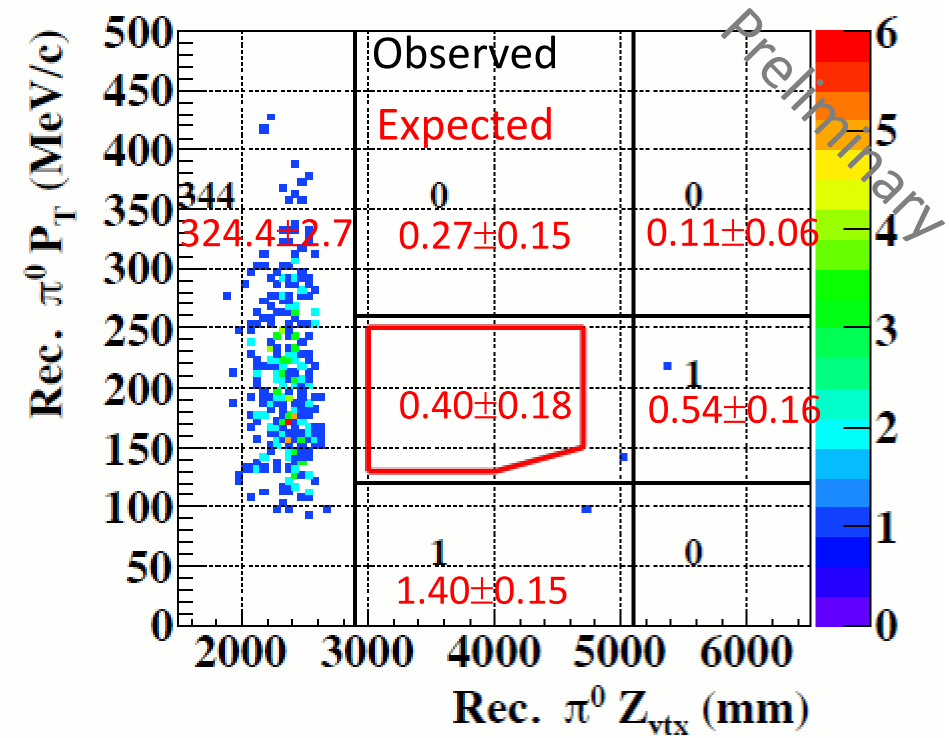
halo neutrons interacting with NCC material



KOTO: Preliminary results on 2015 data

Upgrade of the detector during the two years of beam break

No signal candidate observed



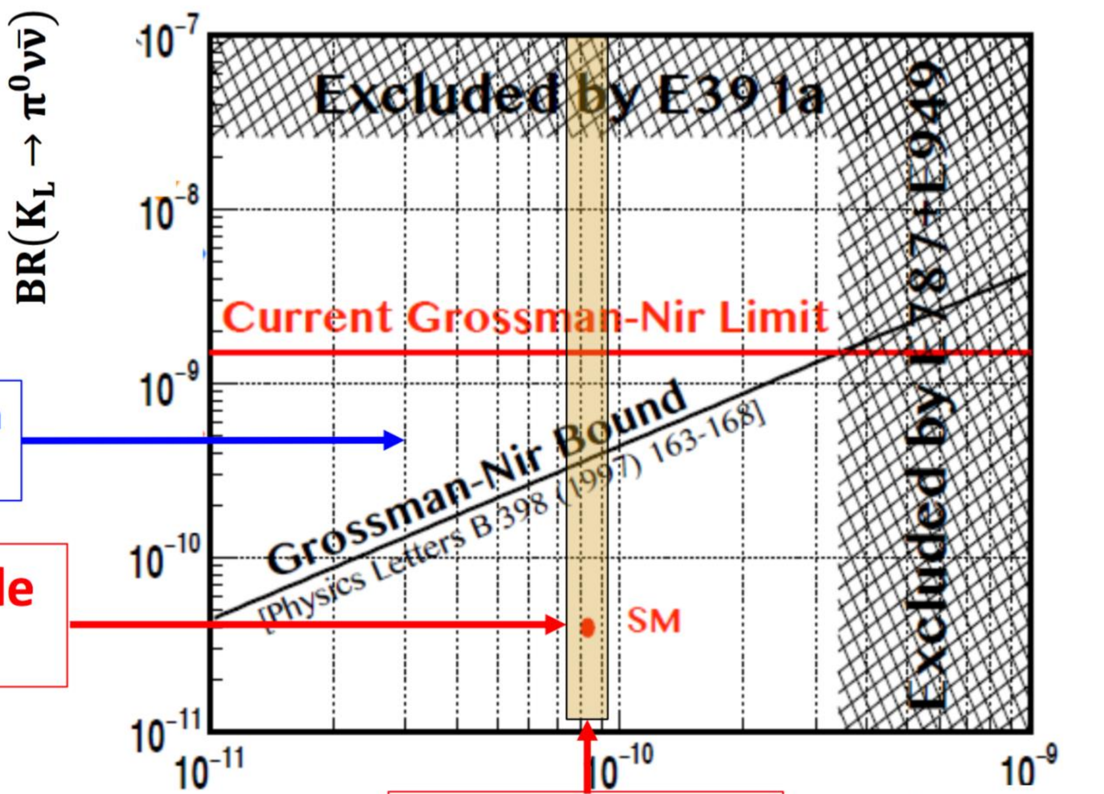
$BR(K_L \to \pi^0 \nu\nu) < 3.0 \times 10^{-9}$ (90%C.L.)

Koji SHIOMI, ICHEP 2018@Seul

Current upper limit improved by one order of magnitude

2016-2018 data analysis in ongoing

K→πνν prospects



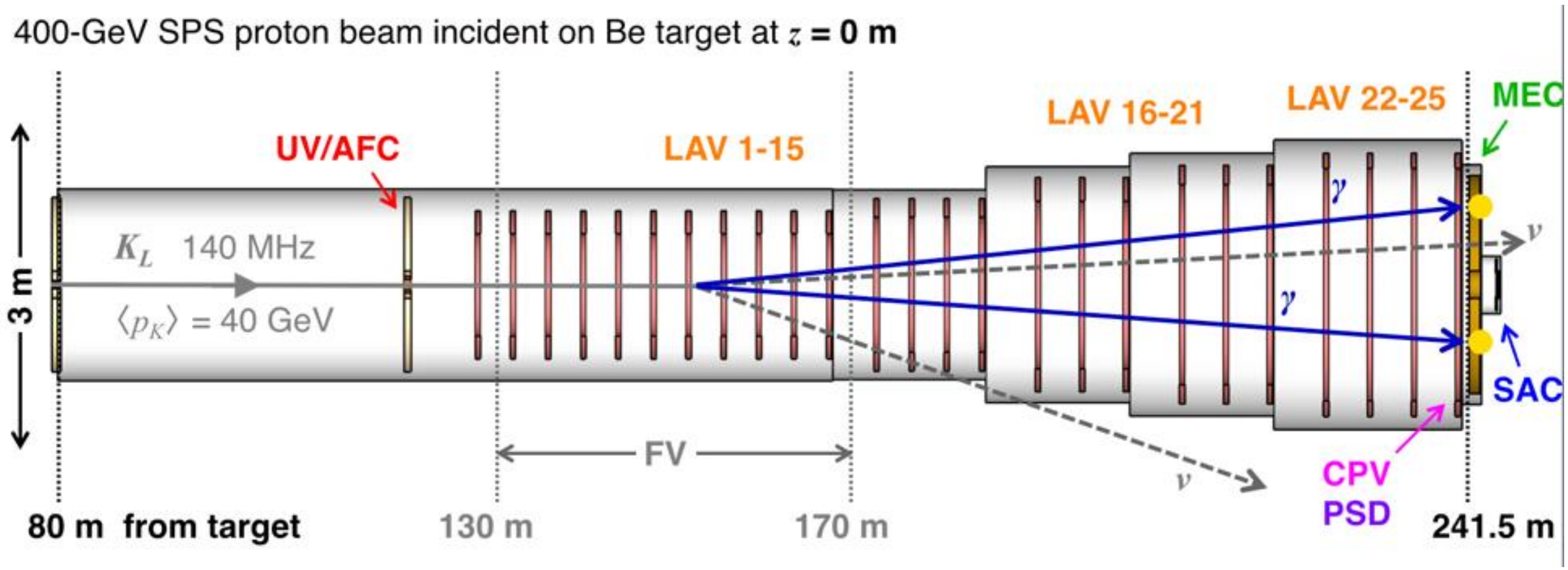
KOTO '15/'16 run
~ 2018

SM (SES)

KOTO upgrade
SM > 2021

NA62
$\mathcal{O}(10\%) \geq 2018$

The K_LEVER experiment for $K_L \to \pi^0 \nu\nu$



Target sensitivity:

5 years starting Run4

~60 SM $K_L \to \pi^0 \nu\nu$

S/B ~ 1

$\delta BR/BR(K_L \to \pi^0 \nu\nu) \sim 20\%$

Main detector/veto system:

- **UV/AFC** Upstream veto/Active final collimator
- **LAV1-25** Large-angle vetoes (25 stations)
- **MEC** Main electromagnetic calorimeter
- **SAC** Small-angle vetoes
- **CPV** Charged particle veto
- **PSD** Pre-shower detector

K_LEVER: Status and timeline

Project timeline – target dates:

2017-2018 **Project consolidation and proposal**

- Participation in Physics Beyond Colliders
- Beam test of crystal pair enhancement
- Input to European Strategy for Particle Physics
- Expression of Interest to CERN SPSC

2019-2021 **Detector R&D**

2021-2025 **Detector construction**

- Possible K12 beam test if compatible with NA62

2024-2026 **Installation during LS3**

2026- **Data taking beginning Run 4**

Expression of Interest to SPSC

- **Actively seeking new collaborators**
- **Institutes interested so far:** Birmingham, Bristol, Charles U., Comenius U., Dubna, Ferrara, Florence, Frascati, George Mason U., Glasgow, La Sapienza, Luovain, Mainz, Moscow INR, Naples, Perugia, Pisa, Protvino, Sofia, Tor Vergata, Turin

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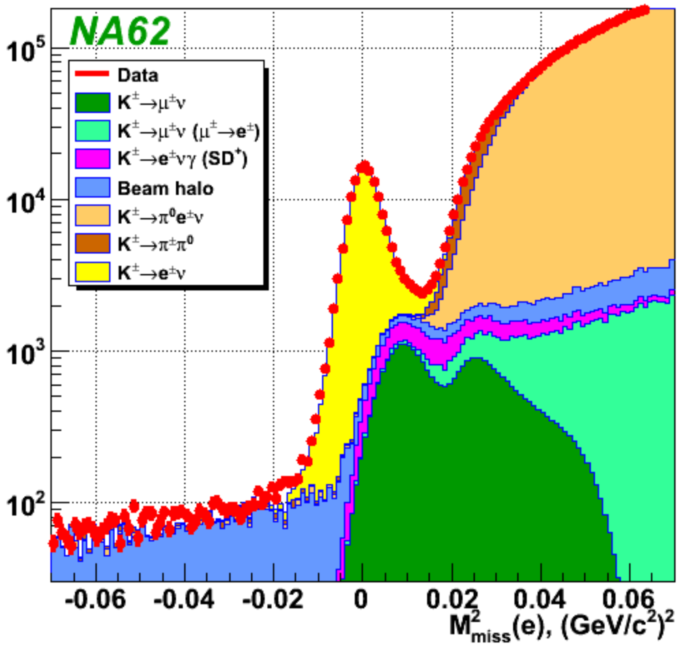
The "other" R_K

Hints of lepton non-universality have emerged from from the analysis of B decays

In kaon physics the best test at the moment comes from: $R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$

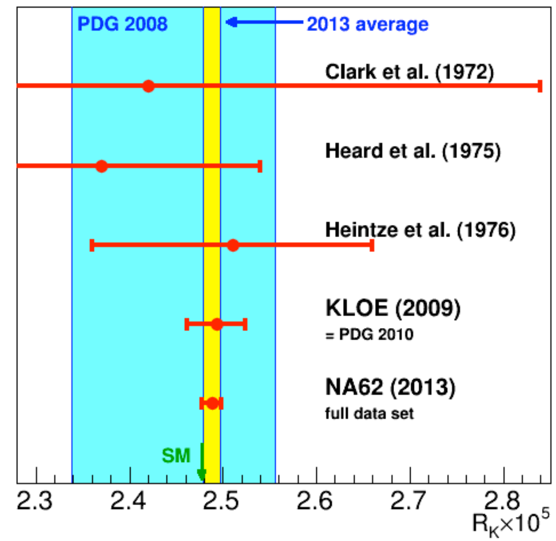
Most precise determination obtained by NA62 Phys. Lett. B778, 137 (2018)

$R_K = (2.488 \pm 0.010) \times 10^{-5}$



Old NA62 detector

0.4% precision



NA62 prospects: expected uncertainty 0.2% (better hermetic vetoing, resolution and PID)

TREK stopped K proposal: expected uncertainty 0.25%

NA62 Sensitivity for LFNV decays

10^{13} $K^+ \rightarrow$ single event sensitivity (SES) $\sim 10^{-12}$

10^{11} tagged $\pi^0 \rightarrow$ SES $\sim 10^{-10}$

Mode	UL at 90% CL	Experiment	NA62 acceptance*
$K^+ \rightarrow \pi^+\mu^+e^-$	1.3×10^{-11}	BNL 777/865	~10%
$K^+ \rightarrow \pi^+\mu^-e^+$	5.2×10^{-10}	BNL 865	
$K^+ \rightarrow \pi^-\mu^+e^+$	5.0×10^{-10}	BNL 865	~10%
$K^+ \rightarrow \pi^-e^+e^+$	6.4×10^{-10}	BNL 865	~5%
$K^+ \rightarrow \pi^-\mu^+\mu^+$	1.1×10^{-9}	NA48/2	~20%
$K^+ \rightarrow \mu^-\nu e^+e^+$	2.0×10^{-8}	Geneva Saclay	~2%
$K^+ \rightarrow e^-\nu\mu^+\mu^+$	no data		~10%
$\pi^0 \rightarrow \mu^+e^-$	3.6×10^{-10}	KTeV	~2%
$\pi^0 \rightarrow \mu^-e^+$			

* From fast Monte Carlo simulation with flat phase-space distribution. Includes trigger efficiency.

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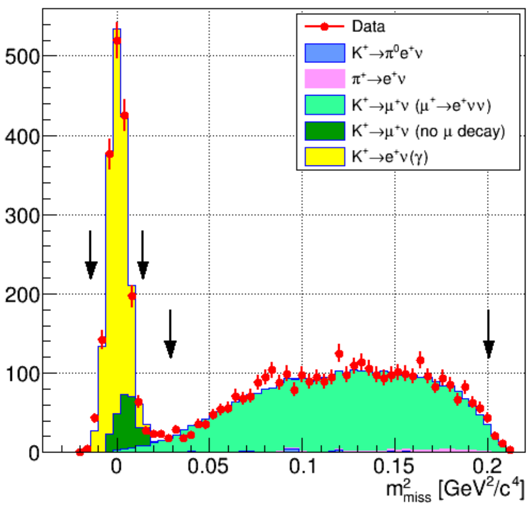
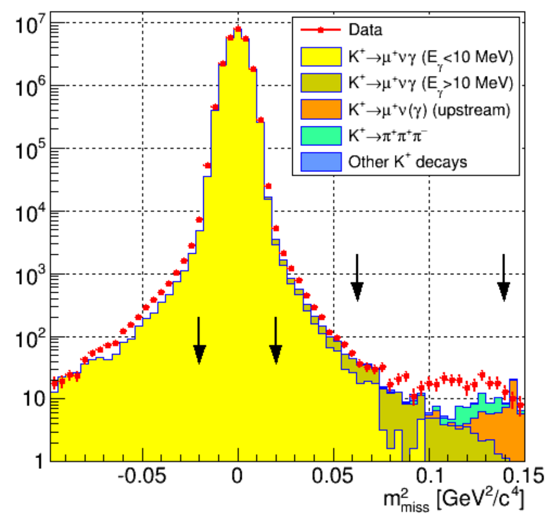
HNLs from kaon decays at NA62

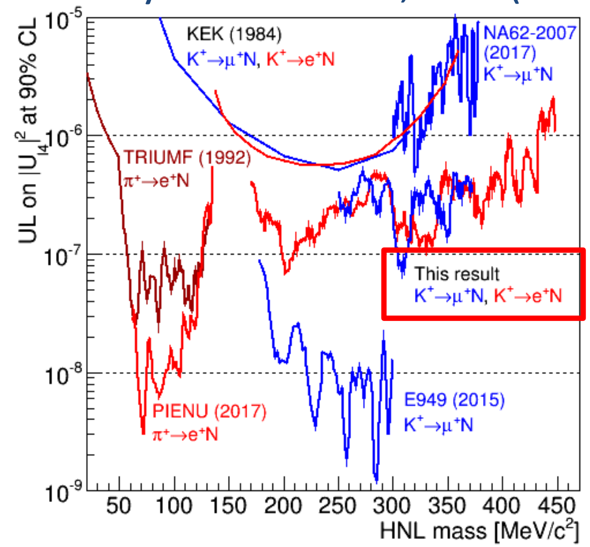
HNLs with mass $m_N < (m_K - m_e)$ can be produced in K^+ decays: $K^+ \to l^+N$ ($l=e,\mu$)

- NA62 analysis based 2015 data equivalent $\sim 3\times10^8$ K^+ decays in FV
- Search for bump in the missing mass distribution $m_{miss}=(p_K - p_l)^{1/2}$
- No hypothesis on decay mechanism, only production

Phys. Lett. B778, 137 (2018)



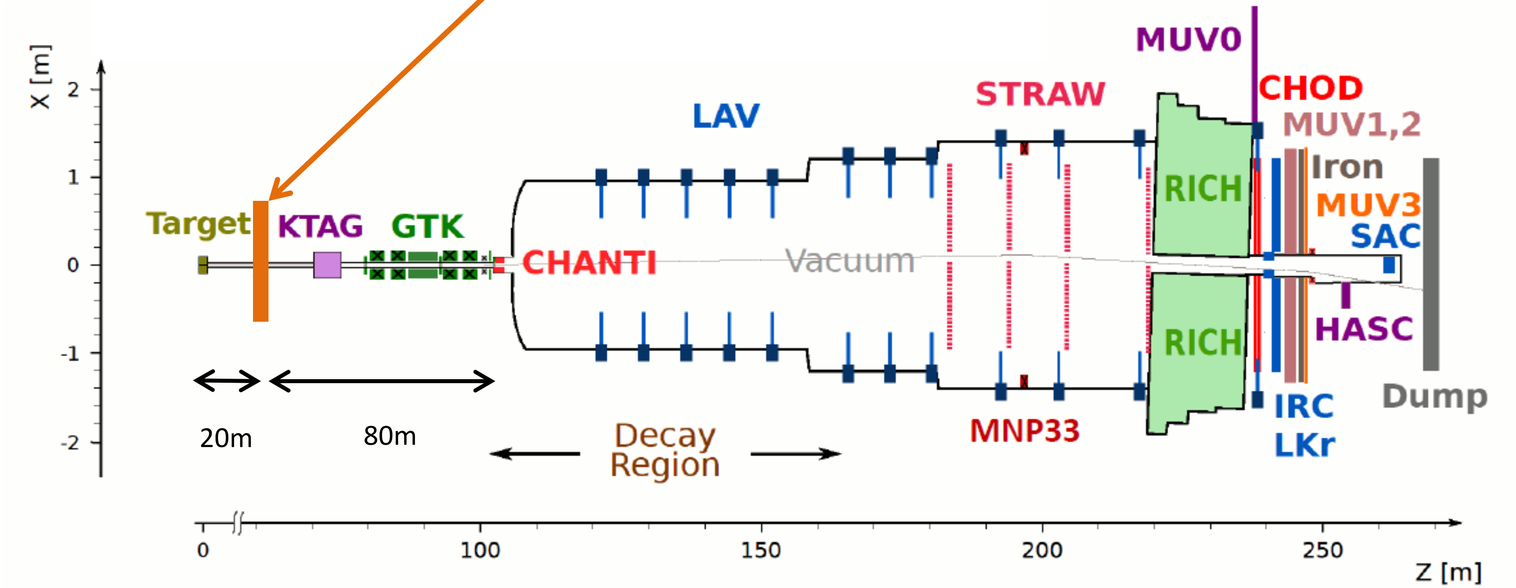




Improved sensitivity w.r.t. on the previous limits from HNL production searches over the whole mass range considered for $|U_{e4}|^2$, and above 300 MeV/c^2 for $|U_{\mu4}|^2$.

NA62 in dump mode

Beam defining collimators (TAX1 and TAX2)
~ 11 λ_I Cu-based can be used as a dump



Easy switch between K^+ beam and proton dump mode with TAXes

10^{18} PoT/nominal year: 10^{12}PoT/s on spill, 100 days/year, 60% run efficiency

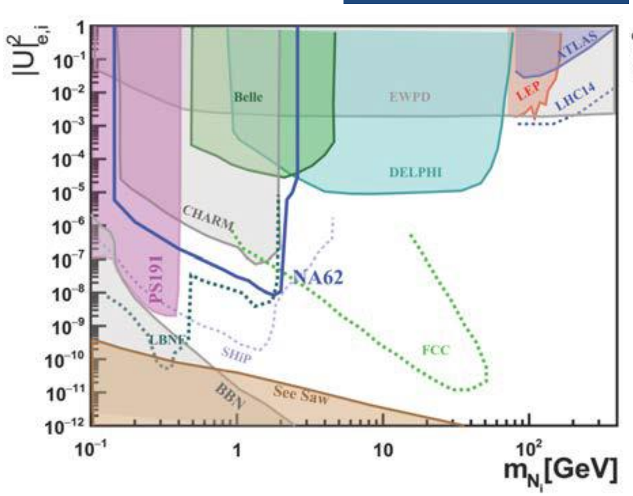
10^{15} $D_{(S)}$, 10^{14} K, 10^{18} $\pi^0/\eta/\eta'/\Phi/\rho/\omega$ with ratios 6.4/0.68/0.07/0.03/0.94/0.95 (B mesons too)

NA62-Dump sensitivity for HNLs

NA62 sensitivity with 10^{18} PoT in dump mode

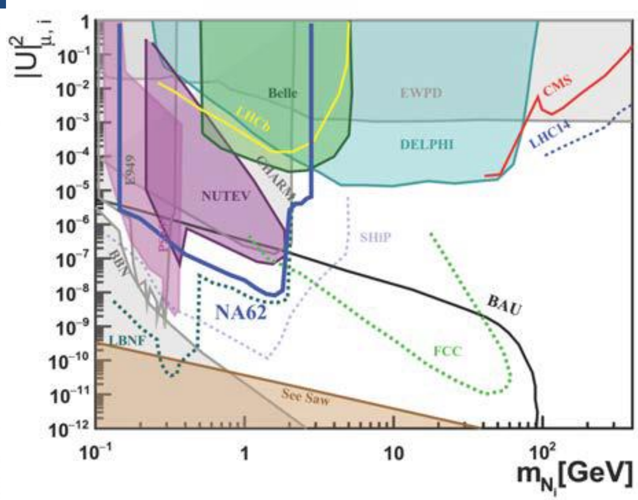
- Assume to detect all two-track final states, including open channels
- Assume zero background
- Separately address 3 extreme coupling scenarios

Scenario 1 — U^2_e enhanced



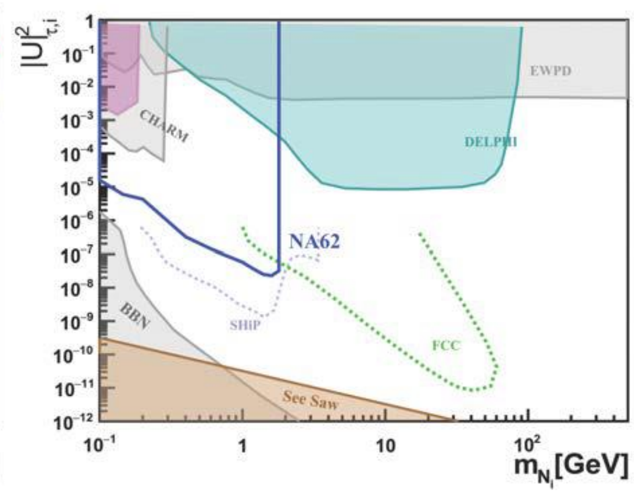
$U^2_e : U^2_\mu : U^2_\tau = 52 : 1 : 1$

Scenario 2 — U^2_μ enhanced



$U^2_e : U^2_\mu : U^2_\tau = 1 : 16 : 3.8$

Scenario 3 — U^2_τ enhanced



$U^2_e : U^2_\mu : U^2_\tau = 0.061 : 1 : 4.3$

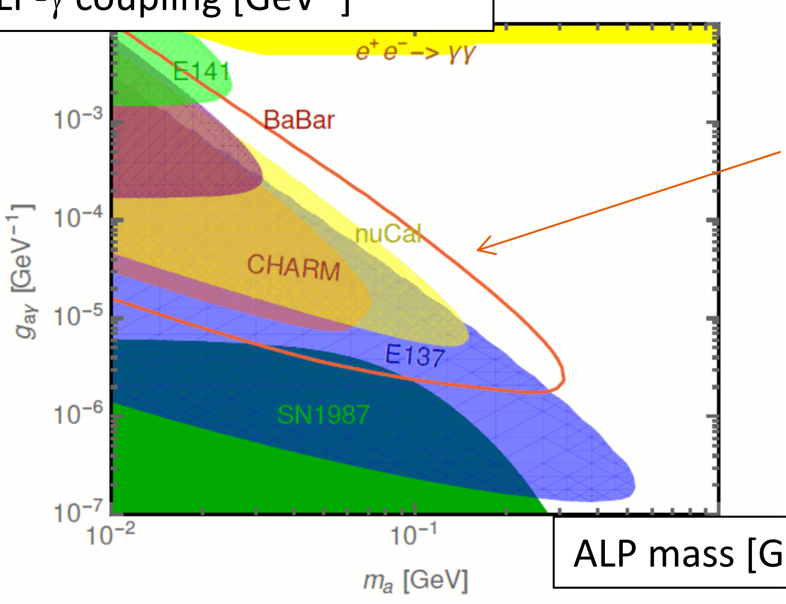
Window of opportunity to search for HNL above the K mass in the near future

NA62-Dump sensitivity for ALPs$\rightarrow\gamma\gamma$

NA62 sensitivity with 10^{18} PoT in dump mode

- Only prospect of a strictly predominant coupling to photons is shown
- Predominant ALPs production mechanism via Primakov production
- Search for ALPs$\rightarrow\gamma\gamma$ in NA62 FV, account for geometrical acceptance
- Assume zero background, evaluate 90%-CL exclusion plot

ALP-γ coupling [GeV^{-1}]



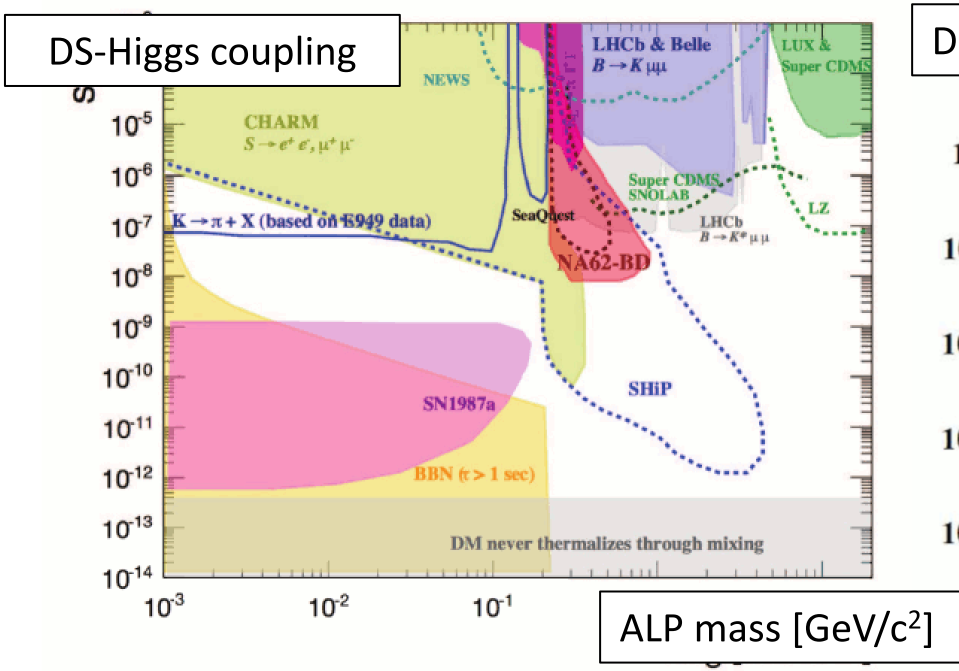
ALP mass [GeV]

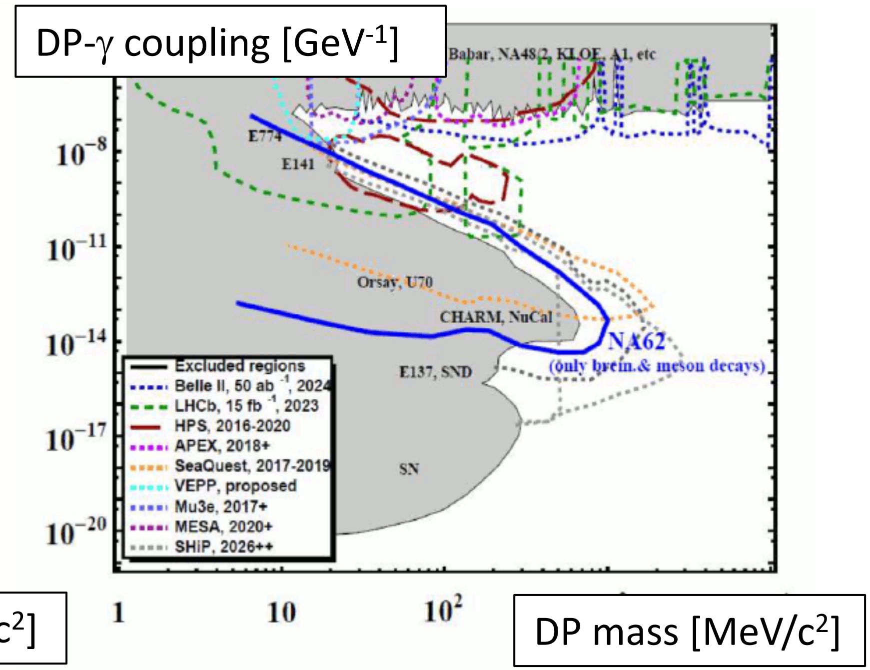
NA62 projections with 10^8 PoT

JHEP 1602, 018 (2016)
JHEP 1712, 094 (2017)
arXiv:1708.05776

NA62-Dump sensitivity for Dark scalar/γ

NA62 sensitivity with 10^{18} PoT





- Dominant production mode is from B mesons produced in the dump
- Assume all two tracks final states

- DP production (meson decays , bremmsstrahlung) in Be target
- Search for DP-decay to ee, μμ in the NA62 FV
- Projection is conservative

Conclusions

- After more than 70 years, kaons are still providing important tools to build the SM of particle physics and to see beyond it (CPV, LU, LVF, Exotics,…)
- The interplay between theory and experiment is very strong and mutually motivating (CKM, ε'/ε, Rare decays, LQCD)
- There are compelling questions and ambition to address them

Thanks for your attention