XXXVII International Symposium on Physics In Collision

Overview of Recent Results from Kaon Experiments

Angela Romano(*), University of Birmingham

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(*)NA62 Collaboration @ CERN SPS

Kaon role in SM and beyond - I

- Associated production of kaons: idea of hadronic flavour
- Strangeness as a quantum number
- Meson-antimeson oscillation
- θ-τ puzzle and parity violation
- Quark model and SU(3)
- Flavour mixing, Cabibbo angle
- CP violation ε
- Suppression of $K^0 \rightarrow \mu^+\mu^-$ and GIM mechanism
- Direct CP violation $\varepsilon' / \varepsilon$

Virtual contributions from particles in loop processes:
deviations have often preceded direct observation of new particles

Flavour Changing Neutral Currents (FCNC) forbidden at tree-level in SM
Hence necessarily sensitive to New Physics

Kaon role in SM and beyond - II

Mixing processes ($\Delta F=2$) and rare decays ($\Delta F=1$) :

- Complement each other in search for NP
- Test Minimal Flavour Violation
- Search for forbidden processes

LHC direct searches probe few TeV, or $O(10^{-19})$ m scale

Kaon $\Delta F=2$ and $\Delta F=1$ processes can access $O(10^{-21})$ m scale, the Zeptouniverse [JHEP 1411 (2014) 121]

$\Delta F=2$ alone is not enough: for example, to decide if new flavour changing dynamic is left-handed or righ-handed nature, need $\Delta F=1$

Depending on RH / LH couplings play, can reach scale up to 2000 TeV

Kaon revival: Why now?

(i) theoretical control of ϵ_K increases steadily (hadronic matrix elements and NNLO QCD under good control, $\epsilon_K \propto |V_{cb}|^4$ issue improving),

(ii) ϵ'_K now tractable with lattice QCD,

(iii) upcoming measurements of theoretically clean branching ratios $B(K^+ \to \pi^+ \nu\bar{\nu})$ (by NA62) and $B(K_L \to \pi^0 \nu\bar{\nu})$ (by KØTØ),

(iv) no new particles found at LHC:
$\Rightarrow$ weaker rationale for Minimal Flavour Violation (MFV)

If the flavour structure of new physics is unrelated to the SM Yukawa sector, one expects the largest effects in Kaon (and $\mu \to e$) FCNC processes.

Kaon "anomalies" - I

$$\frac{\epsilon'_K}{\epsilon_K} = (16.6 \pm 2.3) \times 10^{-4}$$ Experiments: NA48, KTeV

$$\frac{\epsilon'_K}{\epsilon_K} = \left(1.1 \pm 4.7_{\text{lattice}} \pm 1.9_{\text{NNLO}} \pm 0.6_{\text{isosp. br.}} \pm 0.2_{m_t}\right) \times 10^{-4} \qquad \text{(SM)}$$

Kitahara,UN,Tremper, JHEP 1612 (2016) 078

The prediction uses the lattice-QCD results from RBC-UKQCD, Phys. Rev. Lett. **115** 212001 (2015).

Buras, Jäger, Gorbahn (JHEP 1511 (2015) 202) find a 2.9σ deviation:

$$\frac{\epsilon'_K}{\epsilon_K} = (1.9 \pm 4.5) \times 10^{-4} \qquad \text{(SM)}$$

See Nierste's talk for details

Buras @ KAON2016

Stars of KAON Flavour Physics

$\varepsilon_K, \Delta M_K$ | ε'/ε | $K^+ \to \pi^+ \nu\bar{\nu}$ | $K_L \to \pi^0 \nu\bar{\nu}$

$K_L \to \mu^+\mu^-$ | $K_L \to \pi^0 e^+ e^-$ | $K_L \to \pi^0 \mu^+ \mu^-$

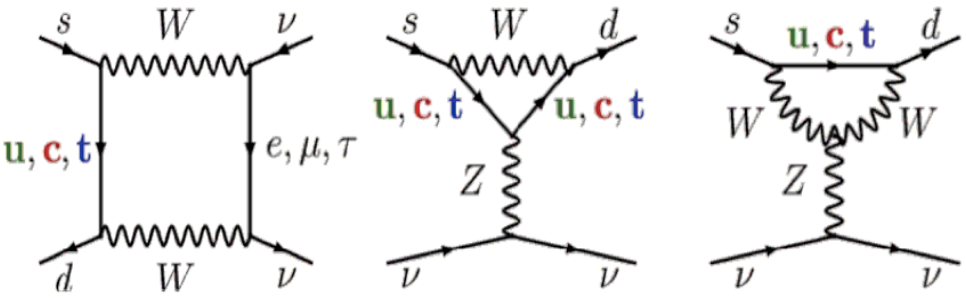
They all can give some information about very short distance scales but to identify new physics, correlations with $B_{s,d}$ and D observables, EDMs, Lepton physics crucial

In particular if we want to reach Zeptouniverse without any direct hints from the LHC

FCNC and Rare Decays

Motivations for $K \to \pi\nu\bar{\nu}$

Box & Penguin (one-loop) diagrams



- ✓High sensitivity to New Physics
- ✓FCNC process forbidden at tree level
- ✓ Highly CKM suppressed (BR ~ $|V_{ts}^* V_{td}|^2$)
- ✓Extraction of V_{td} with minimal (few %) non-parametric uncertainty

Theoretically very clean:

- (dominant) short-distance t quark part: NLO QCD and 2-loop EW corrections
- (small) c quark part: NNLO QCD and NLO EW corrections
- correction for long-distance contributions
- hadronic matrix element extracted from precisely measured $BR(K^+ \to \pi^0 e^+ \nu)$

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$	$BR(K_L \to \pi^0 \nu\bar{\nu}) = (3.00 \pm 0.31) \times 10^{-11}$
[Buras et al., JHEP 1511 (2015) 033]	[Buras et al., JHEP 1511 (2015) 033]

error: CKM parametric, dominated by V_{cb}

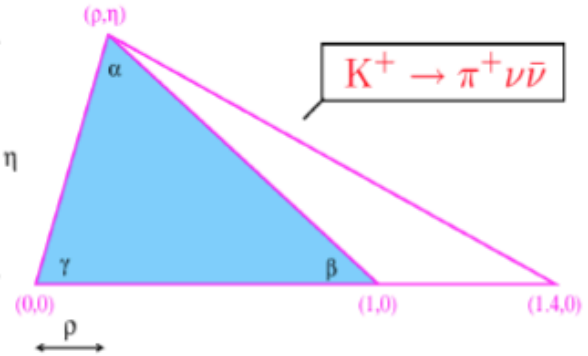
Indirect searches of NP with high precision studies of rare K decays

CKM Triangle

Kaons alone
can fully constrain
the CKM triangle

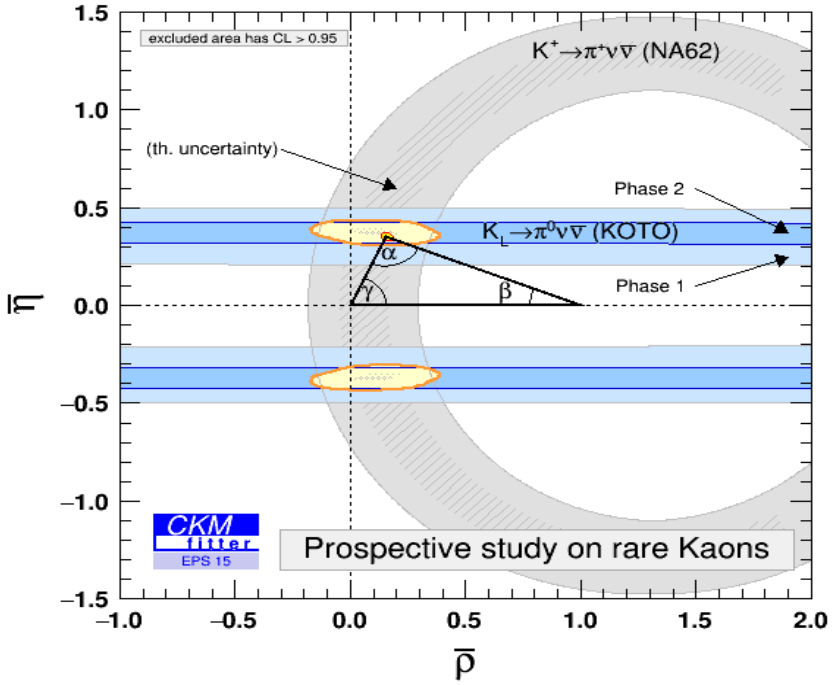
$K_L \to \pi^0 \nu\bar{\nu}$

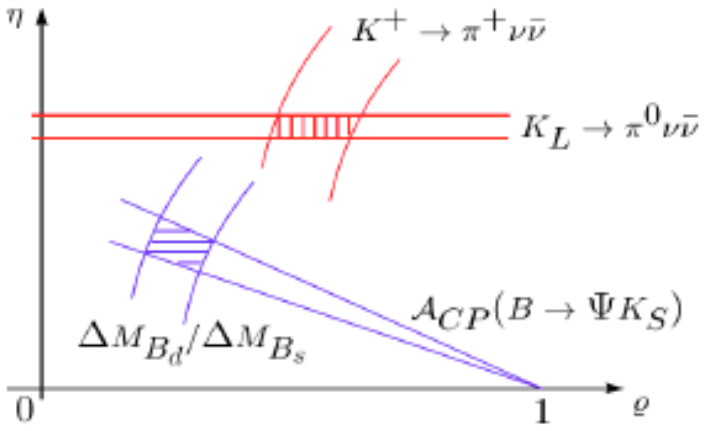
$K_L \to \pi^0 e^+ e^-$ { $K_S \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \gamma\gamma$, $K_L \to ee\gamma\gamma$ } — η



$K_L \to \mu^+ \mu^-$ { $K_L \to \gamma\gamma$, $K_L \to e^+e^-\gamma$, $K_L \to e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$ }

CKM unitarity triangle with kaons

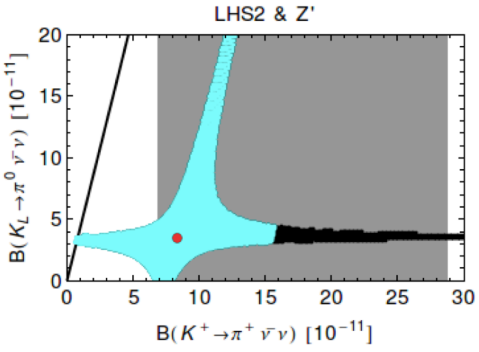


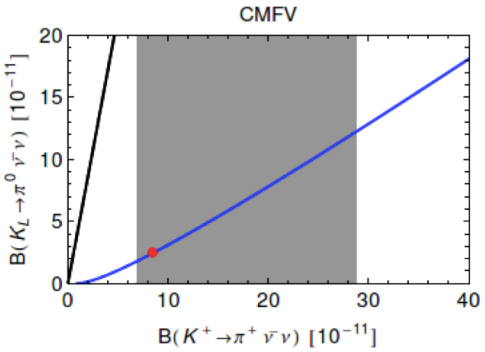


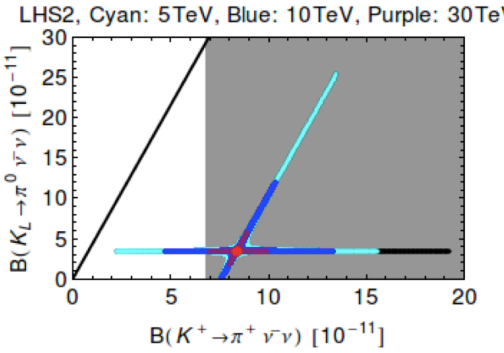
Comparison with B physics can provide hints on NP dynamics

K→ πνν̄: NP Sensitivity

Measurement of charged ($K^+ \to \pi^+ \nu\bar{\nu}$) and neutral ($K_L \to \pi^0 \nu\bar{\nu}$) modes can **discriminate among different NP scenarios**

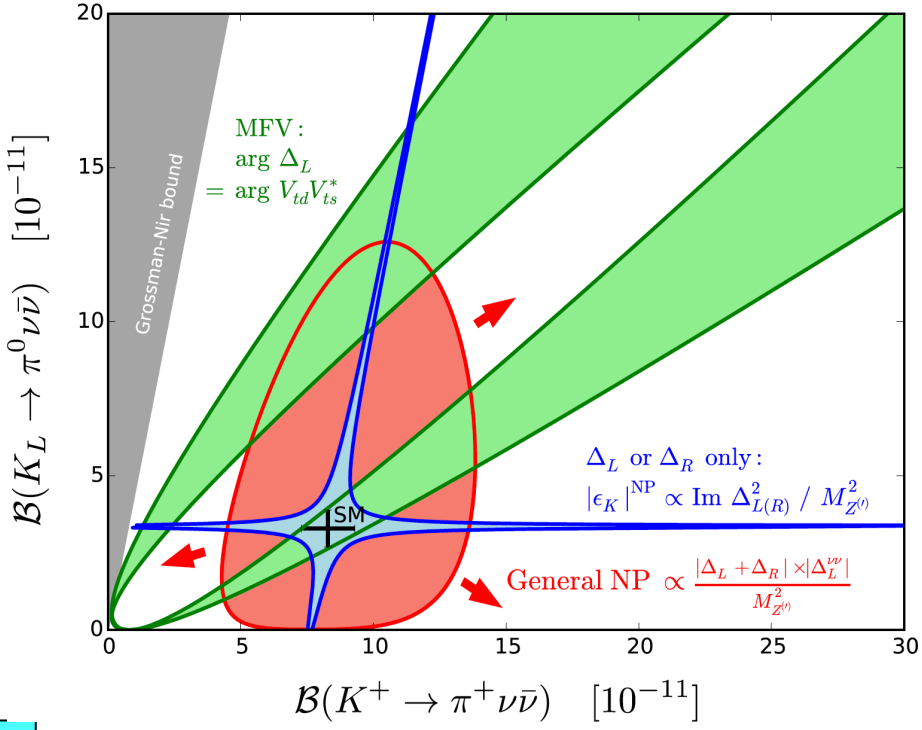






Sensitivity to $M_{Z'}$ beyond the LHC

Buras et al., JHEP 1302 (2013) 116



K→ πνν̄ probes of unique sensitivity for NP models among B and K decays

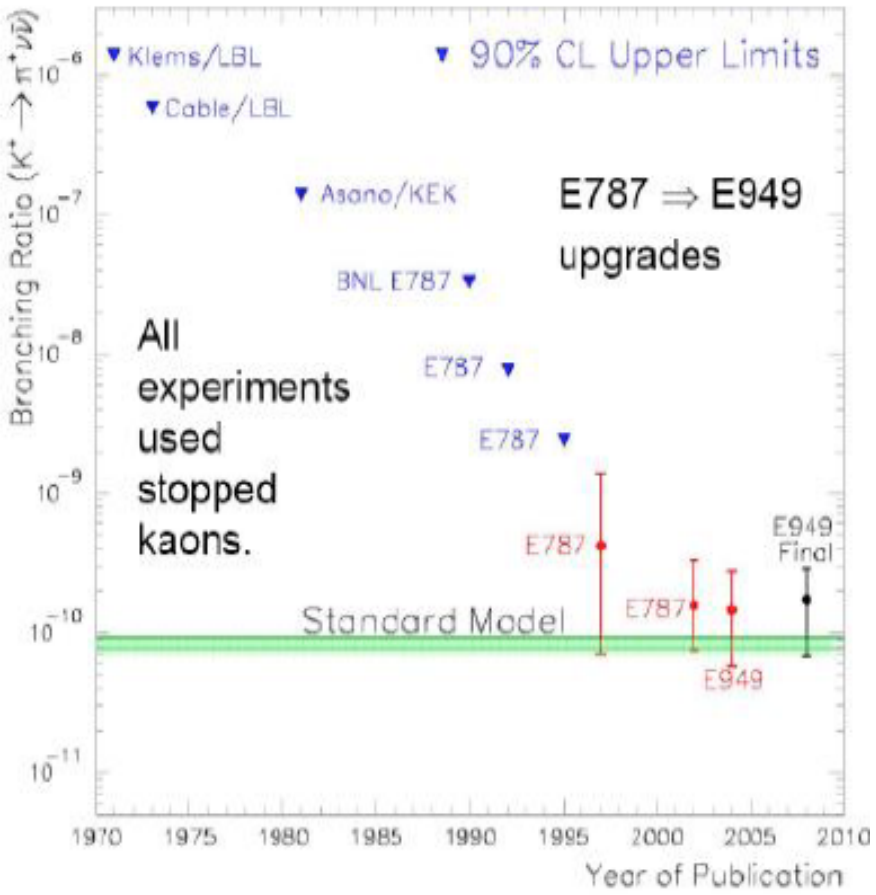
(NP searches complementary/alternative to LHC)

Correlations significantly change for different classes of NP models

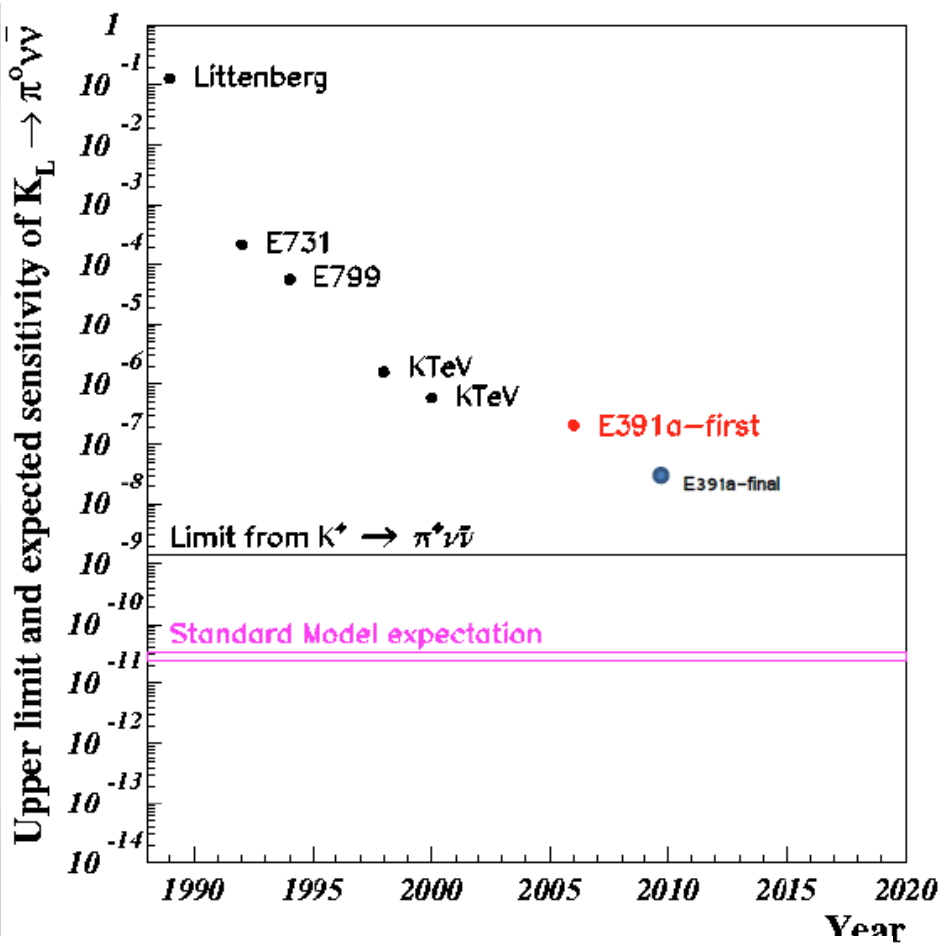
[JHEP 1511 (2015) 166, EPJ C76 (2016) 12]

K→ πνν̄ Experimental Status

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



$K^0 \rightarrow \pi^0 \nu\bar{\nu}$



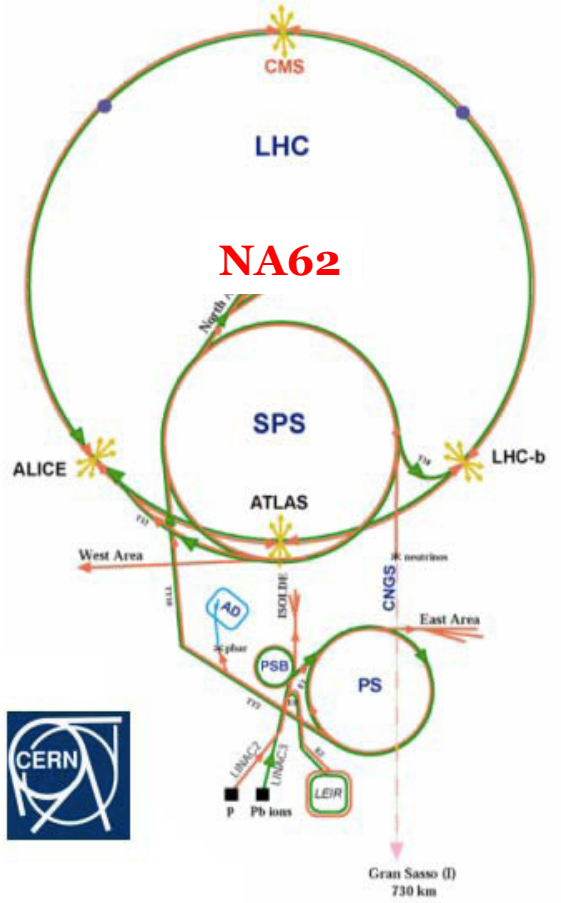
$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$ Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)

$BR(K_L \rightarrow \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-8}\ (90\%\ C.L.)$ Phys. Rev. D 81, 072004 (2010)

The NA62 experiment

High precision fixed-target Kaon experiment at CERN SPS

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



NA62 Timeline

Dec 2008 - NA62 Approval

2009 - 2014: Detector R&D, Installation

2015 Commissioning

2016 - 2018: Physics Runs

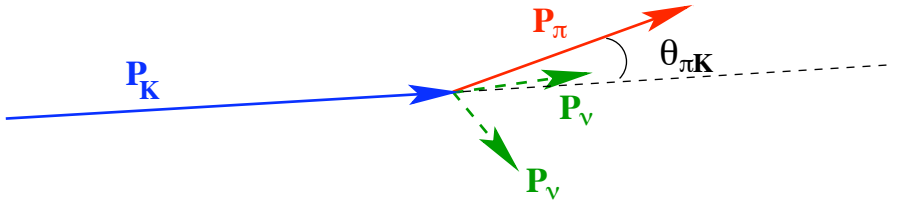
Primary goal: Measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) with 10% accuracy and S/B ~10

Technique: Kaon decay-in-flight experiment

$K^+ \to \pi^+ \nu\bar{\nu}$ Signal & Backgrounds

Signal $K^+ \to \pi^+ \nu\bar{\nu}$:

$m^2_{miss} = (P_K - P_\pi)^2$



Backgrounds: Kaon decays & Interactions

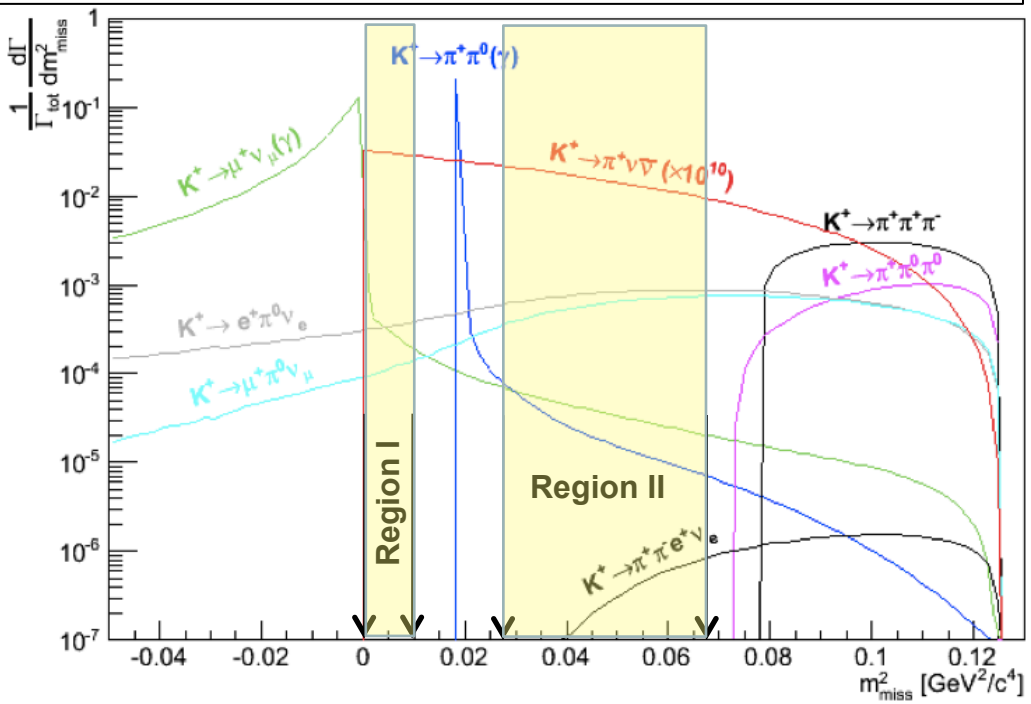
Decay backgrounds

Mode	BR
$\mu^+\nu(\gamma)$	63.5%
$\pi^+\pi^0(\gamma)$	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0 e^+\nu$	5.1%
$\pi^0\mu^+\nu$	3.3%
$\pi^+\pi^- e^+\nu$	4.1×10^{-5}
$\pi^0\pi^0 e^+\nu$	2.2×10^{-5}
$\pi^+\pi^-\mu^+\nu$	1.4×10^{-5}
$e^+\nu(\gamma)$	1.5×10^{-5}

Other backgrounds

Beam-gas interactions

Upstream interactions

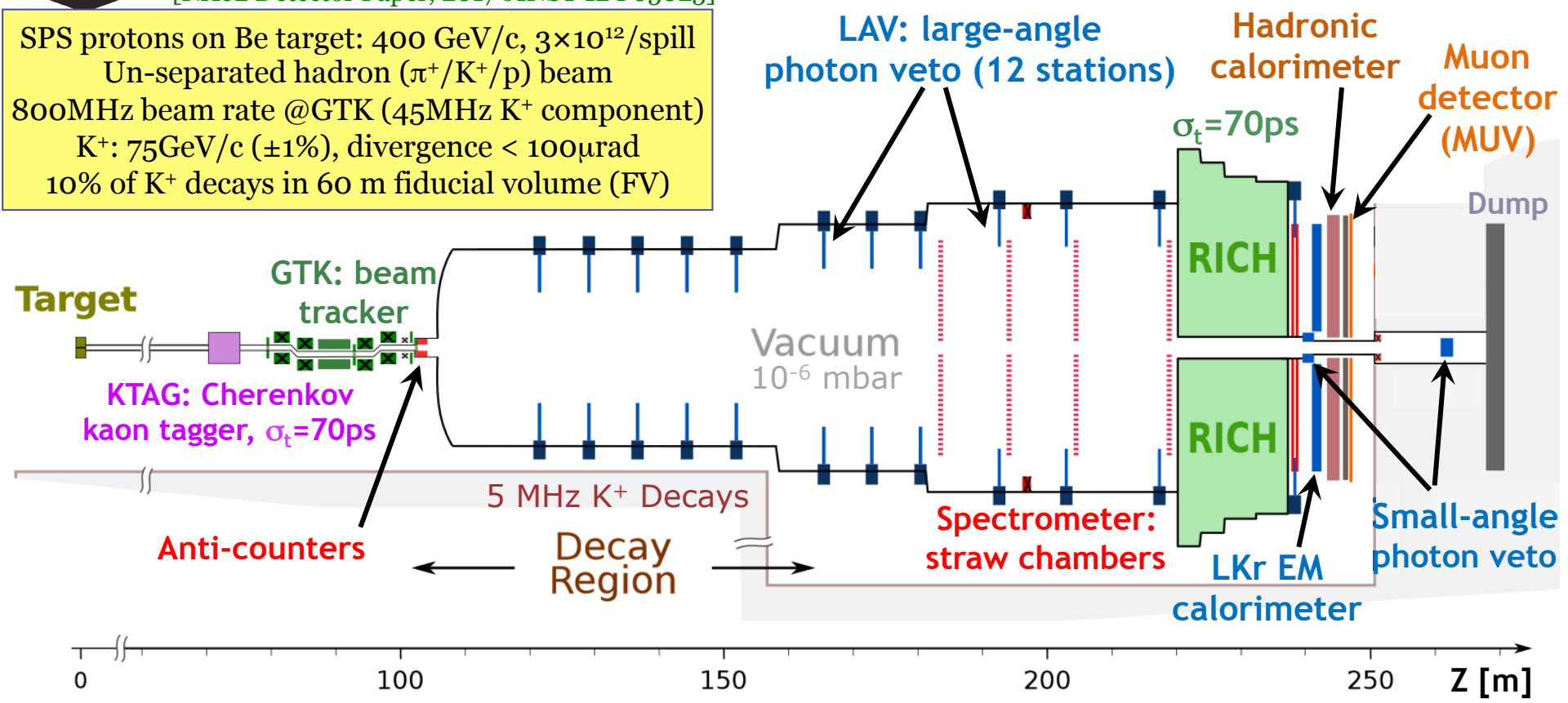


Background rejection relies on **Kinematics** (m^2_{miss}) used in conjunction with **PID**, **Veto systems** and **sub-ns timing**

The NA62 Detector

[NA62 Detector Paper, 2017 JINST 12 P05025]

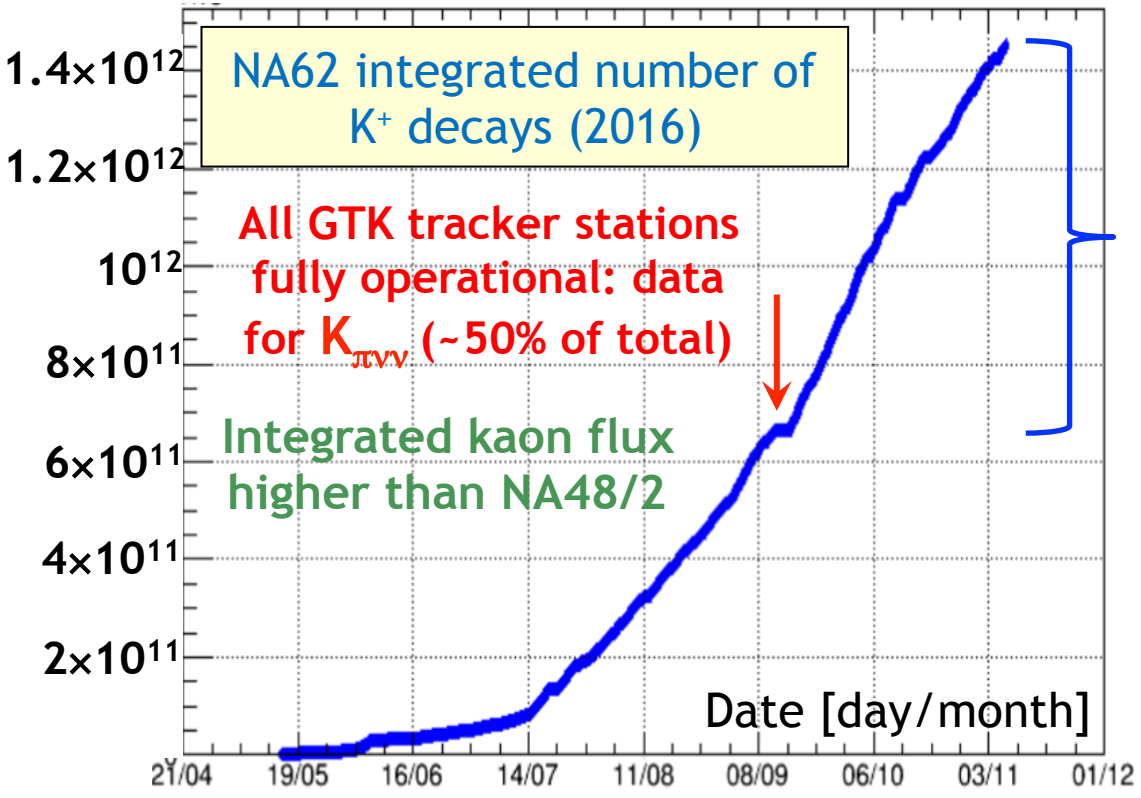
SPS protons on Be target: 400 GeV/c, 3×10^{12}/spill
Un-separated hadron ($\pi^+/K^+/p$) beam
800MHz beam rate @GTK (45MHz K^+ component)
K^+: 75GeV/c (±1%), divergence < 100μrad
10% of K^+ decays in 60 m fiducial volume (FV)



- 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 2016 Run

- Stable data dating at ~40% of nominal intensity; limited by beam structure
- Simultaneous data taking for $K_{\pi\nu\nu}$ and **rare/exotic decays** (later in this talk)
- Extrapolation to end of 2018 (12 months of live time): 7×10^{12} K^+ decays.
- Target of 10^{13} K^+ **decays** can be reached with improved beam extraction and data taking efficiency

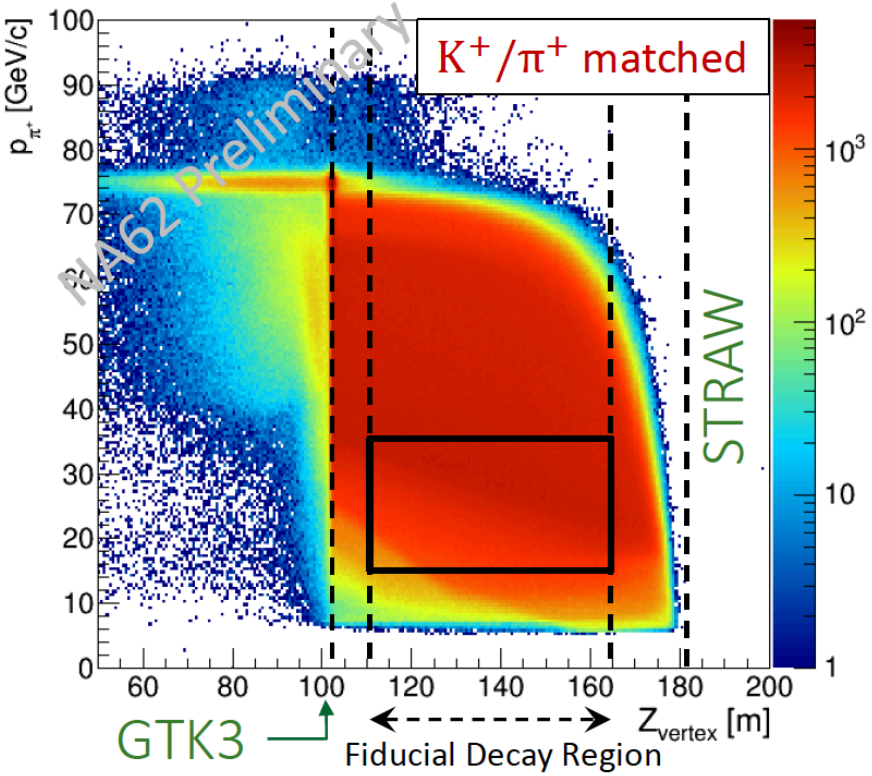


4×10^{11} K^+ decays collected useful for $K_{\pi\nu}$

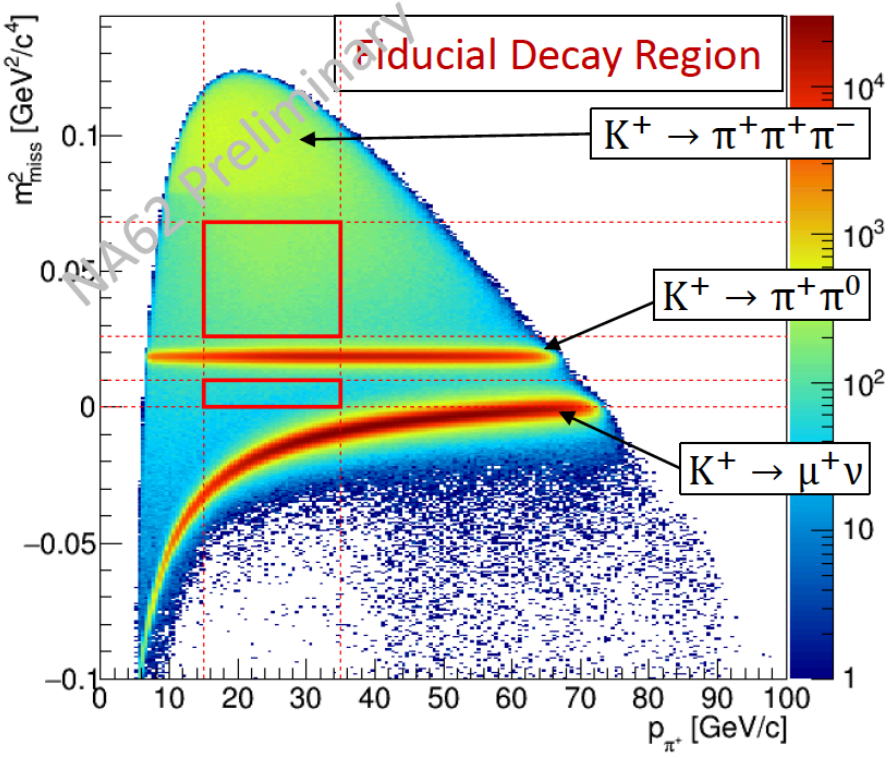
PRELIMINARY

$K_{\pi\nu}$ analysis of 2.3×10^{10} K^+ decays from 2016 [5% of 2016 data]

$K^+ \to \pi^+ \nu\bar{\nu}$ Signal Regions



$m^2_{miss} = (P_K - P_\pi)^2$



- K^+ decays between GTK3 and Straw
- K^+ decays before GTK3
- Beam particle interactions in GTK3

- Signal region defined by:

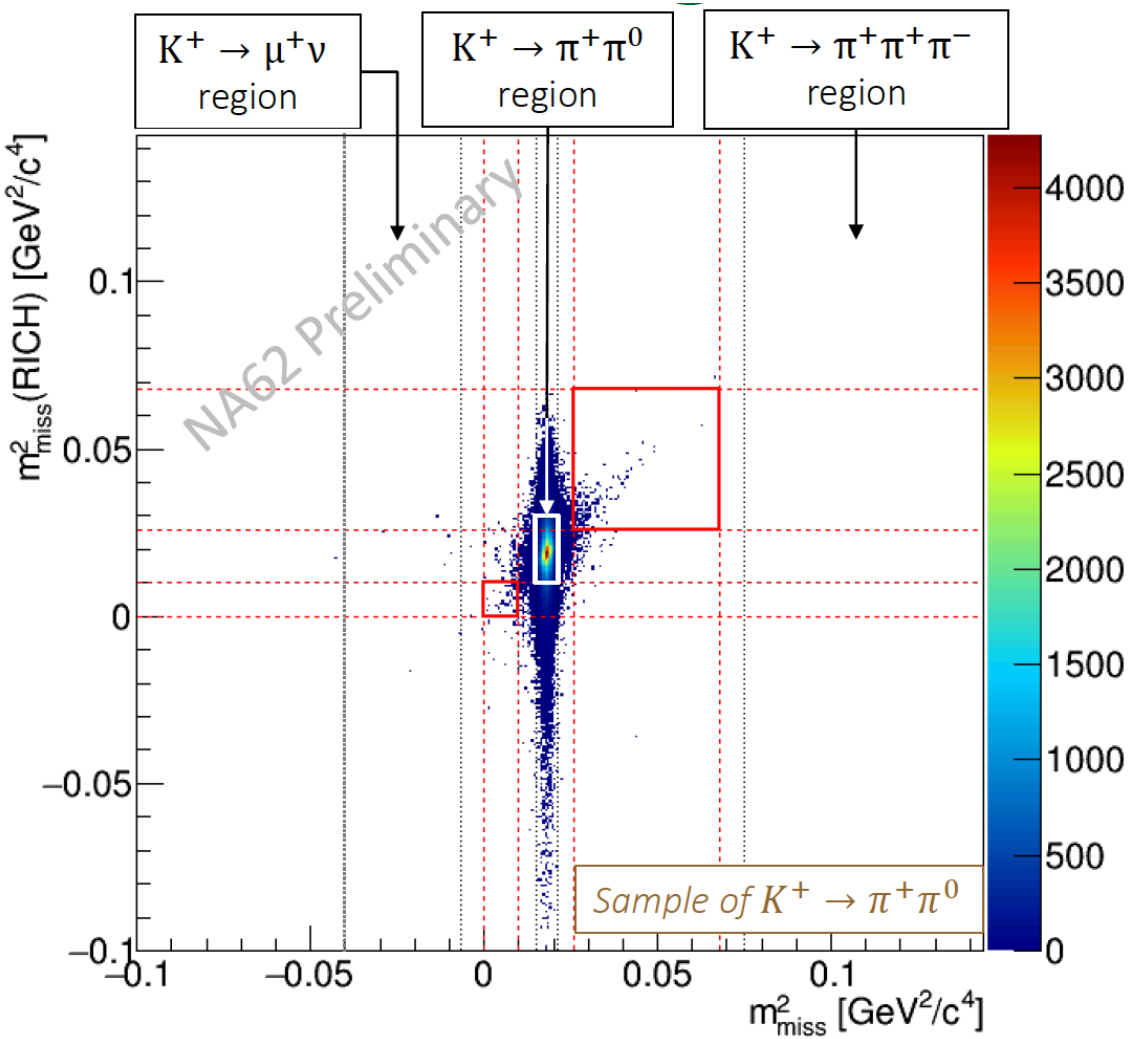
$$Z_{vertex} - p_{\pi^+} - m^2_{miss}$$

$K^+ \to \pi^+ \nu\bar{\nu}$ Kinematics & Background

m^2_{miss} , p_{π^+}

m^2_{miss}(RICH) p_{π^+} RICH (m_{π^+})

m^2_{miss}(No GTK) p_{K^+} nominal



Kinematical suppression

- Measured on data

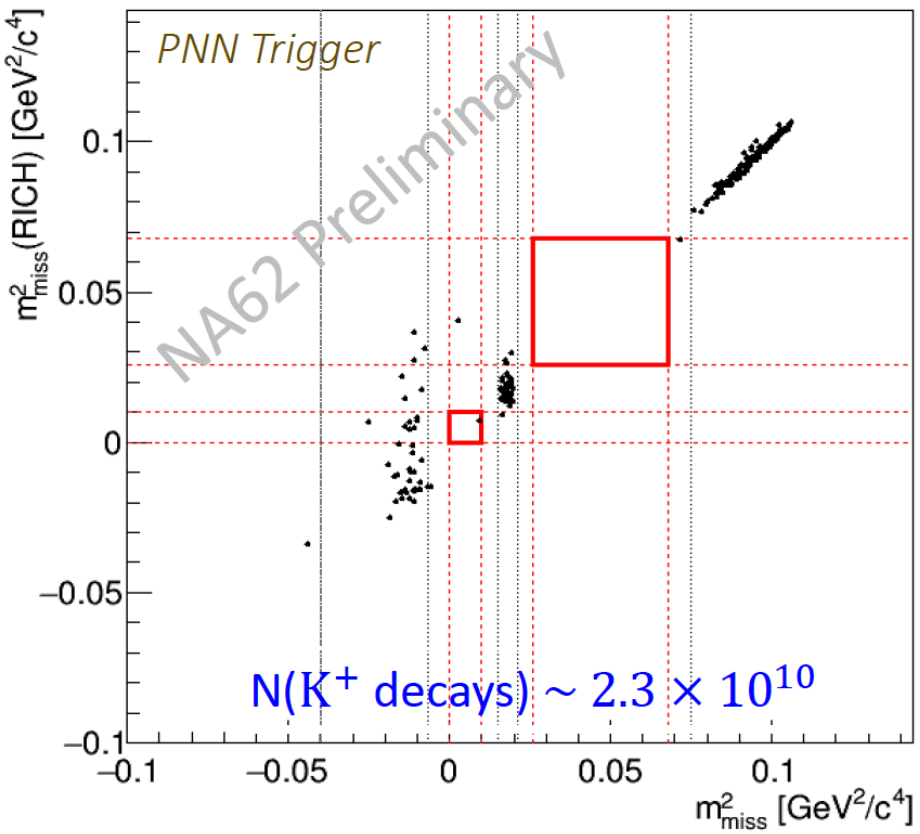
$K^+ \to \pi^+\pi^0$ $\sim 6 \times 10^{-4}$

$K^+ \to \mu^+\nu$ $\sim 3 \times 10^{-4}$

G.Ruggiero @ EPS2017

NA62 $K^+ \to \pi^+ \nu\bar{\nu}$ Preliminary Result

5% 2016 statistics



Expected $\pi\nu\nu \approx 0.064$

- Normalization: $K^+ \to \pi^+\pi^0$

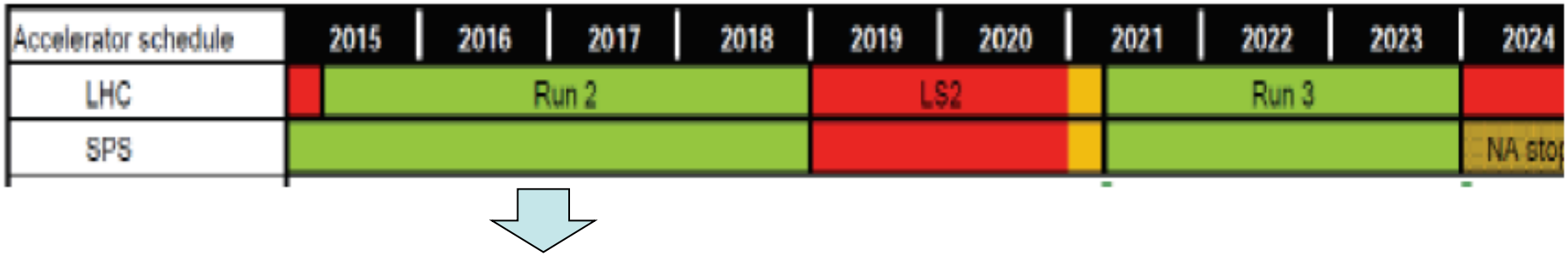
Expected backgrounds:

$K^+ \to \pi^+\pi^0$	0.024
$K^+ \to \mu^+\nu$	0.011
$K^+ \to \pi^+\pi^+\pi^-$	0.017
Beam - induced	< 0.005

- Estimated with data – driven methods
- Other backgrounds negligible

- No events in signal region
- Event in box has m^2_{miss}(No GTK) outside the signal region
- Analysis optimization in progress

NA62 Near Prospects



- Reach SM sensitivity with completion of 2016 data analysis

Data taking in 2017 currently at 55-60% nominal beam intensity:

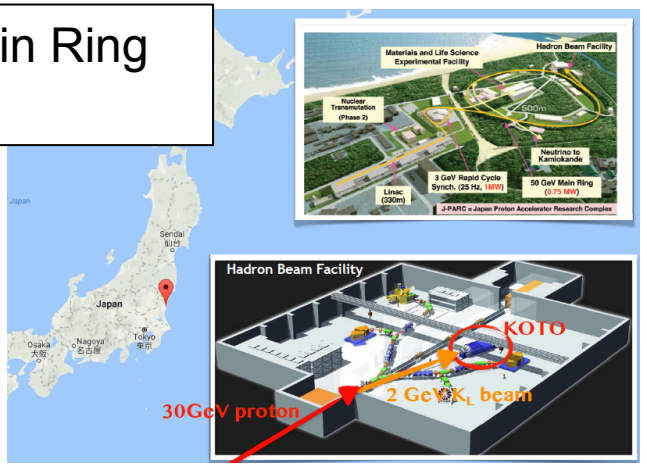
- focused on $\mathbf{K_{\pi\nu\nu}}$ measurement
- extrapolating from 2016, expect ~ 15 $\mathbf{K_{\pi\nu}}$ SM events
- trigger bandwidth for other physics is limited
- proof of principle for **broader rare/forbidden decay programme** (SES ~ 10^{-10}-10^{-11})

Data taking in 2018 → four months scheduled

Plans for **extending data taking beyond LS2** to complete the proposed programme and to implement new ideas (later in this talk)

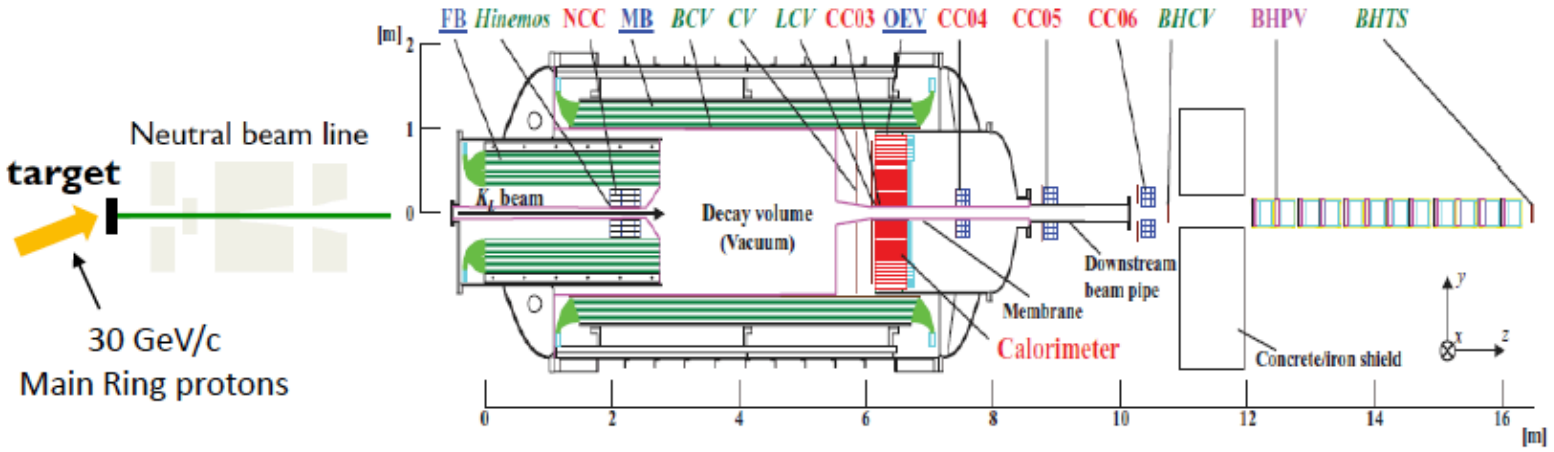
The KOTO Experiment

Study of $K_L \rightarrow \pi^0\nu\bar{\nu}$ @ JPARC 30GeV Main Ring
Goal is to observe few SM events



Primary 30 GeV/c protons on gold target
✓ Intensity (2013) 3 x 10^{13} ppp on target (2s spill)
Secondary neutral beam (K_L, neutron, photons)
✓ P = 1.4 GeV/c peak
✓ Transverse size: 80 x 80 mm^2
✓ Fiducial decay region ~3 m

Arizona, Chicago, Chonbuk, Hanyang, Jeju, JINR, KEK, Kyoto, Michigan, NDA, NTU, Okayama, Osaka, Pusan, Saga & Yamagata

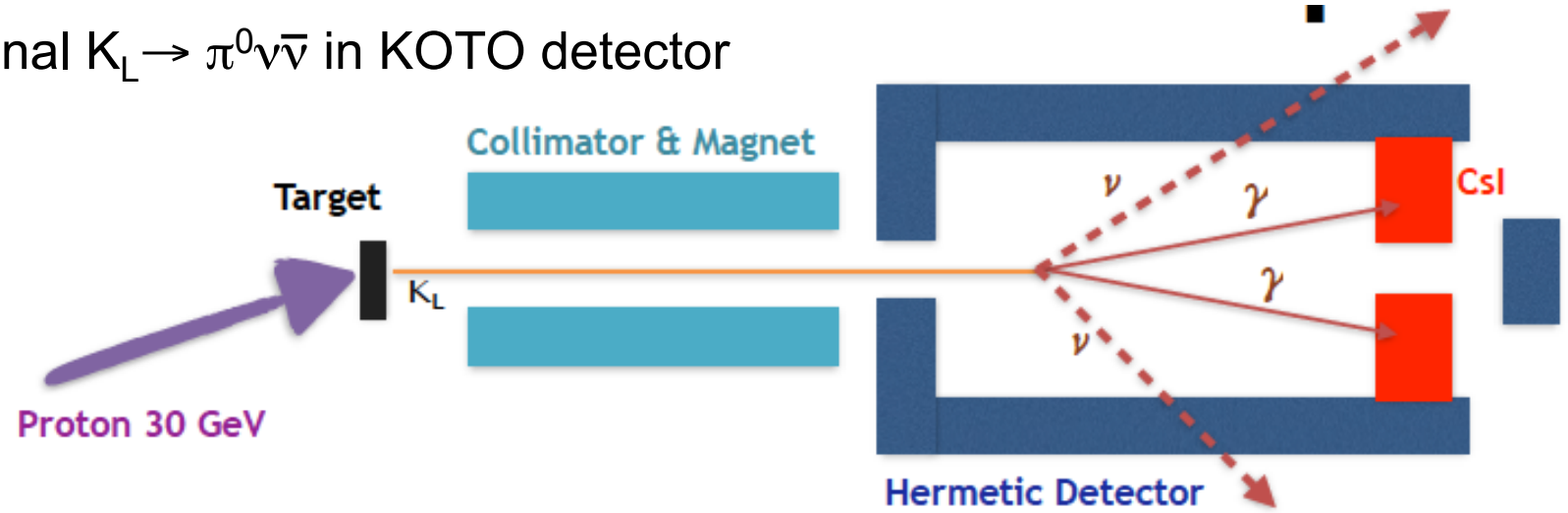


Lead-scintillator sandwich
Plastic scintillator counter
CsI Calorimeter from KTeV

} **Hermetic Veto Systems** ⟶ To suppress $K_L \rightarrow \pi^0\pi^0$

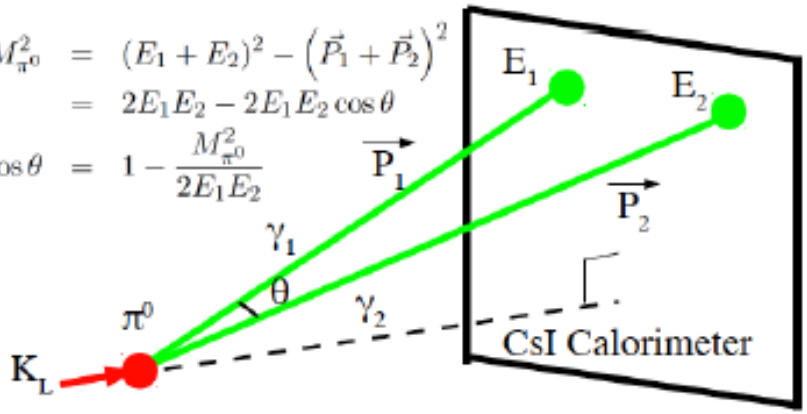
KOTO $K_L \to \pi^0 \nu\bar{\nu}$ Signal

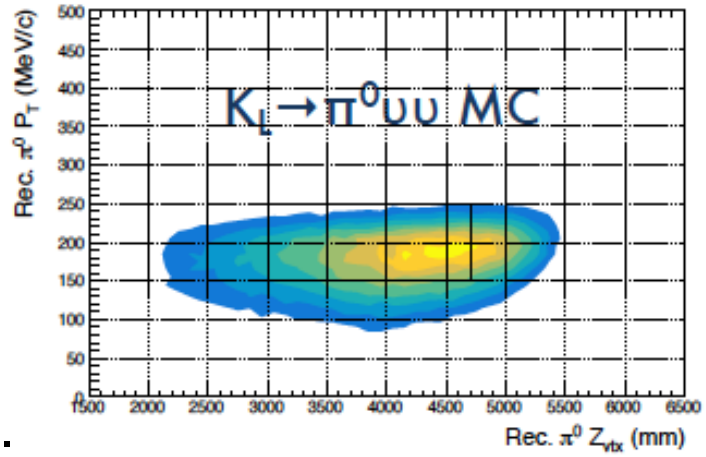
Signal $K_L \to \pi^0 \nu\bar{\nu}$ in KOTO detector



$$M_{\pi^0}^2 = (E_1+E_2)^2 - \left(\vec{P}_1+\vec{P}_2\right)^2 = 2E_1E_2 - 2E_1E_2\cos\theta$$

$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$





Assuming 2γ from π^0, calculate Z vertex (Z_{vtx}).

Signal region defined by π^0 Z_{vtx} and transverse momentum (P_T)

KOTO 2013 Result

Data from ~100 hours in 2013 run

✓ $N(K_L) \sim 2.4 \times 10^{11}$ (**SES 1.3×10^{-8}**)

Set upper limit on $BR(K_L \to \pi^0\nu\nu)$

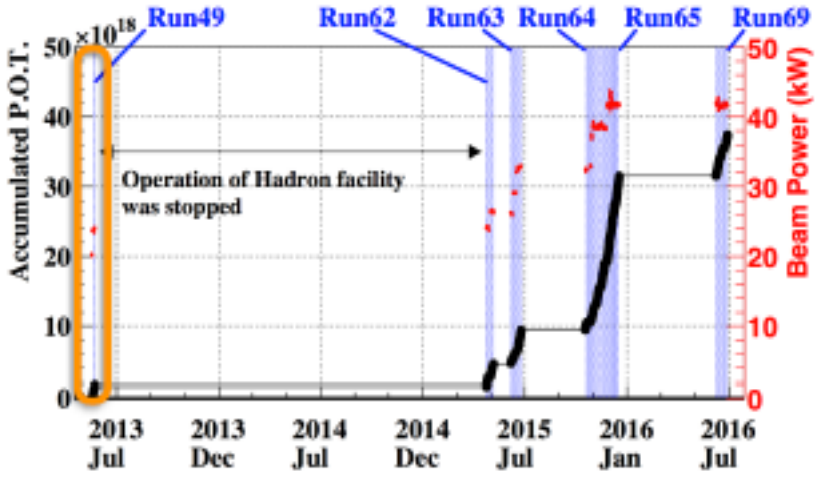
✓ $< 5.1 \times 10^{-8}$ (90% C.L.)

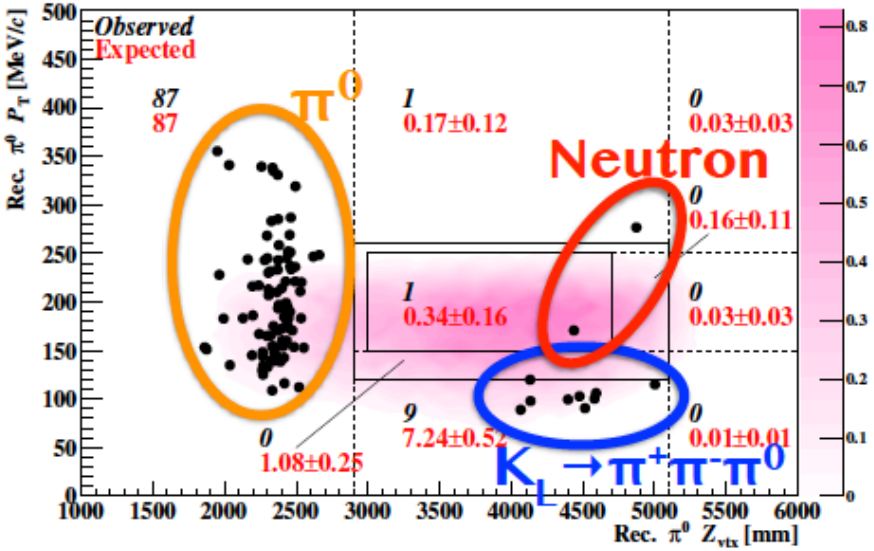
[PTEP 2017, 021C01]

Set upper limit on $BR(K_L \to \pi^0 X^0)$

✓ $< 3.7 \times 10^{-8}$ (90% C.L.)

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
Halo neutrons hitting the calorimeter	0.18 ± 0.15
Total	0.34 ± 0.16

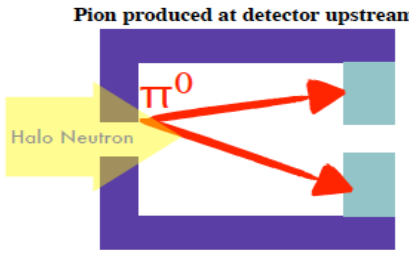




Background in signal region dominated by neutrons

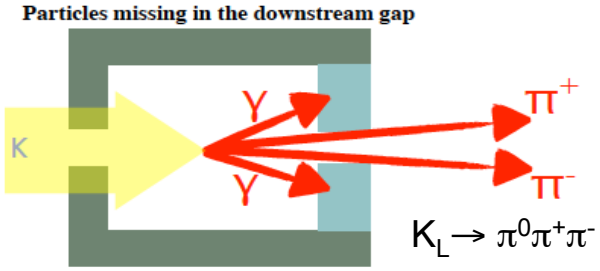
Improvement After 2013

- ✓ Thinner vacuum window (125μm -> 12.5μm) to reduce neutron interaction
- ✓ Beam Profile Monitor for better beam alignment



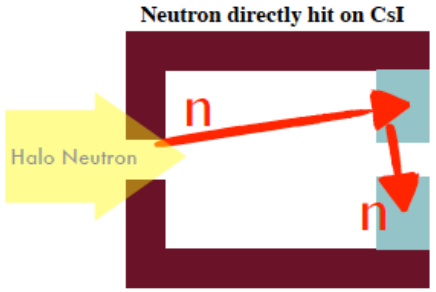
Halo Neutrons hitting the NCC

- ✓ Beam Pipe Charged Veto (BPCV) added
- ✓ 1/10 reduction of $K_L \rightarrow \pi^0\pi^+\pi^-$ background



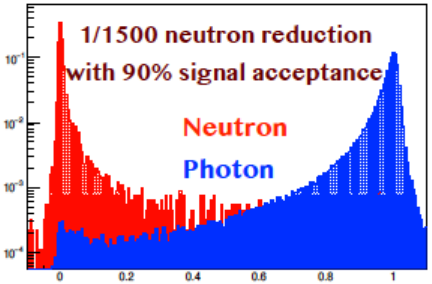
$K_L \rightarrow \pi^0\pi^+\pi^-$

- ✓ Special run with Al target to collect neutron enriched events
- ✓ Better photon – neutron ID in CsI calorimeter



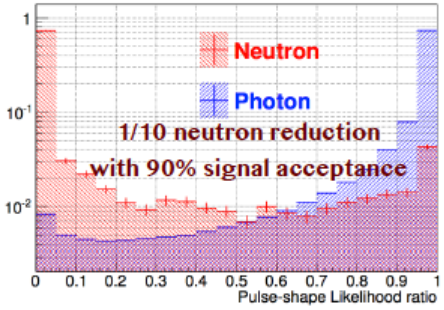
Halo Neutrons hitting the Calo

- **Cluster Shape Discrimination**



+

- **Pulse Shape Discrimination**

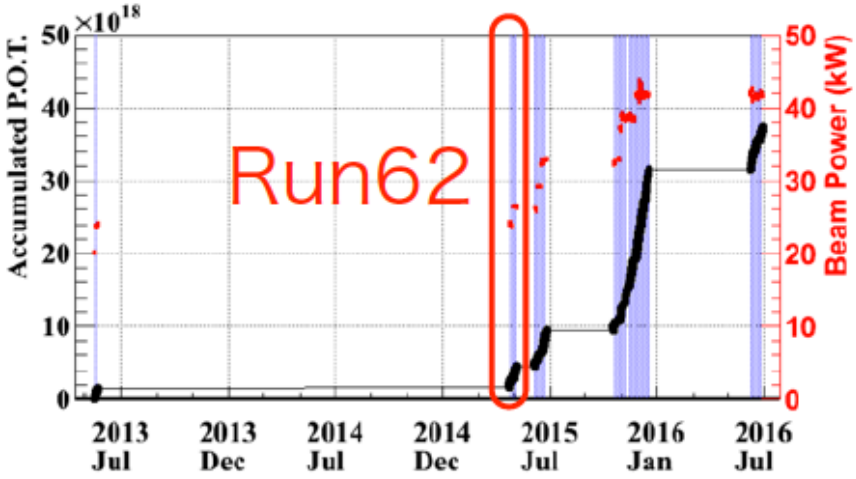


x 5 reduction of neutron background vs 2013 data analysis

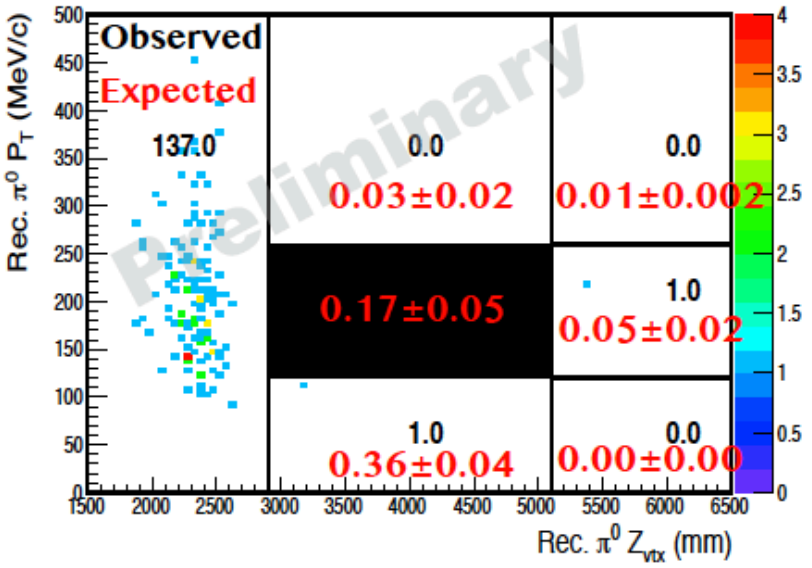
KOTO 2015 Analysis

Based on small subset (run62) of 2015-2016 statistics analysed

- ✓ N(K_L) x1.6 of 2013 run
- ✓ Wider signal region because of better BG rejection
- ✓ Signal acceptance improved by 40%
- ✓ **SES ~ 5.9 x 10^{-9}**



BG in Box	#BG
$K_L \to \pi^0\pi^0$	0.04±0.03
$K_L \to \pi^+\pi^-\pi^0$	0.04±0.01
Upstream Events	0.04±0.04
Neutron Events	0.05±0.02
Other BG	Under Estimation



KOTO Prospects

BG in Box	Run62 #BG	Projected #BG
$K_L \to \pi^0\pi^0$	0.04±0.03	7.86
$K_L \to \pi^+\pi^-\pi^0$	0.04±0.01	7.86
Upstream	0.04±0.04	7.86
Neutron	0.05±0.02	9.83

Preliminary

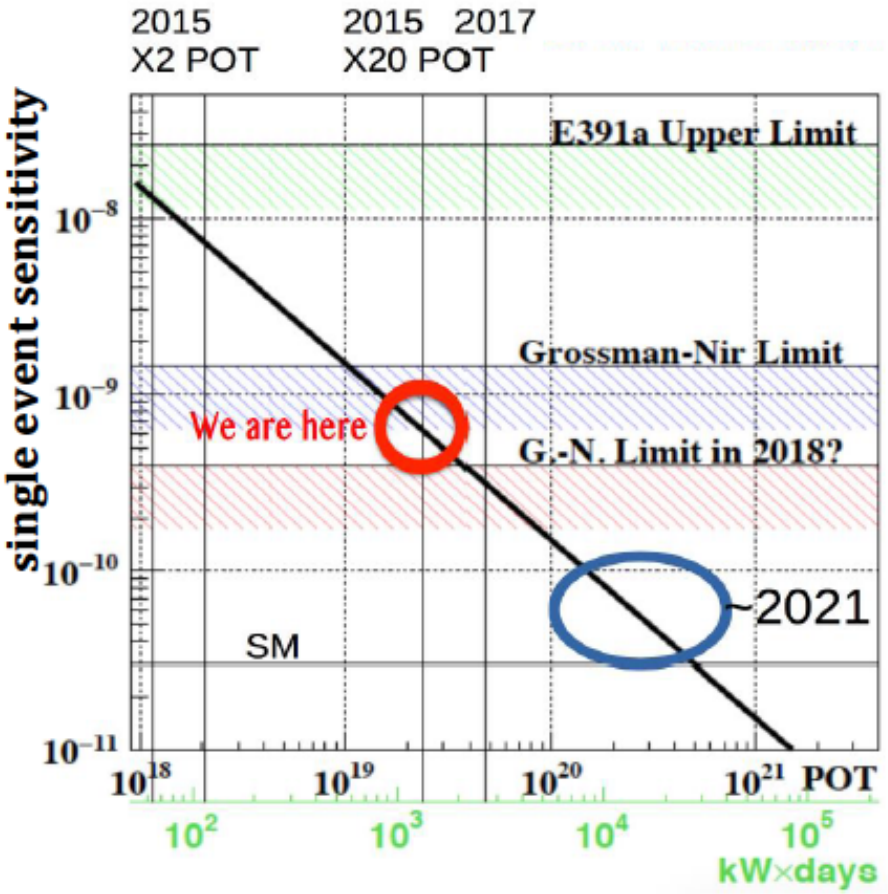
Projected background to SM sensitivity

Upgrades foreseen:

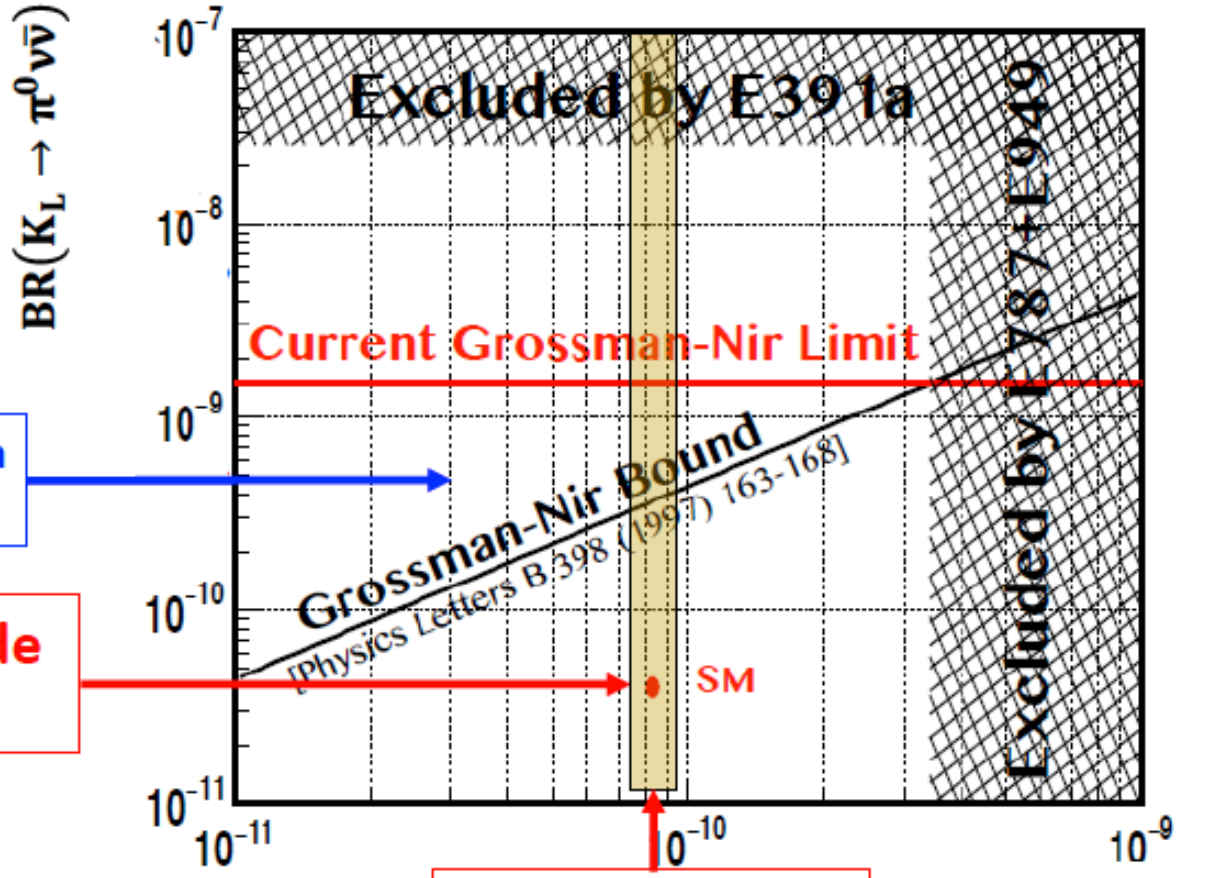
- ✓ New Barrel detector (April 2016)
- ✓ Beam pipe modification (ongoing)
- ✓ CsI both-end readout (2018)
- ✓ JPARC 42kW -> 100kW (2019)

KOTO 2015 - 2016 analysis: < 10^{-9} SES

Upgrades are needed to reach the SM



K →πνν Prospects



KOTO '15/'16 run
~ 2018

KOTO upgrade
SM > 2021

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

$K_{S(L)} \to \mu^+\mu^-$ @ LHCb

FCNC transitions forbidden at tree level

K_L mode rather well measured and in agreement with SM (BR= 7.18(17) x 10^{-9})
[D.Ambrose et al. PRL84 (2000)]

K_S mode further suppressed wrt K_L expected at 5 x 10^{-12} level.
SD amplitude linked to CPV part of $s \to d l^+ l^-$
[G. Isidori, R.Unterdorfer JHEP 0401 (2004) 009]

High sensitivity to New Physics (light scalars with CP-violating Yukawa couplings)

Possible increase up to 10^{-10} level in NP scenarios

An upper limit on BR($\mathbf{K}_{\mu\mu}$) close to 10^{-11} could be translated into model-independent bounds on the CP-violating phase of the s -> $d l^+ l^-$ amplitude

This would be very useful to discriminate between scenarios beyond the SM if other modes, such as $\mathbf{K}_{\pi\nu\nu}$, indicate a non-SM enhancement

$K_{S(L)} \rightarrow \mu^+\mu^-$ @ LHCb

Current experimental limit:

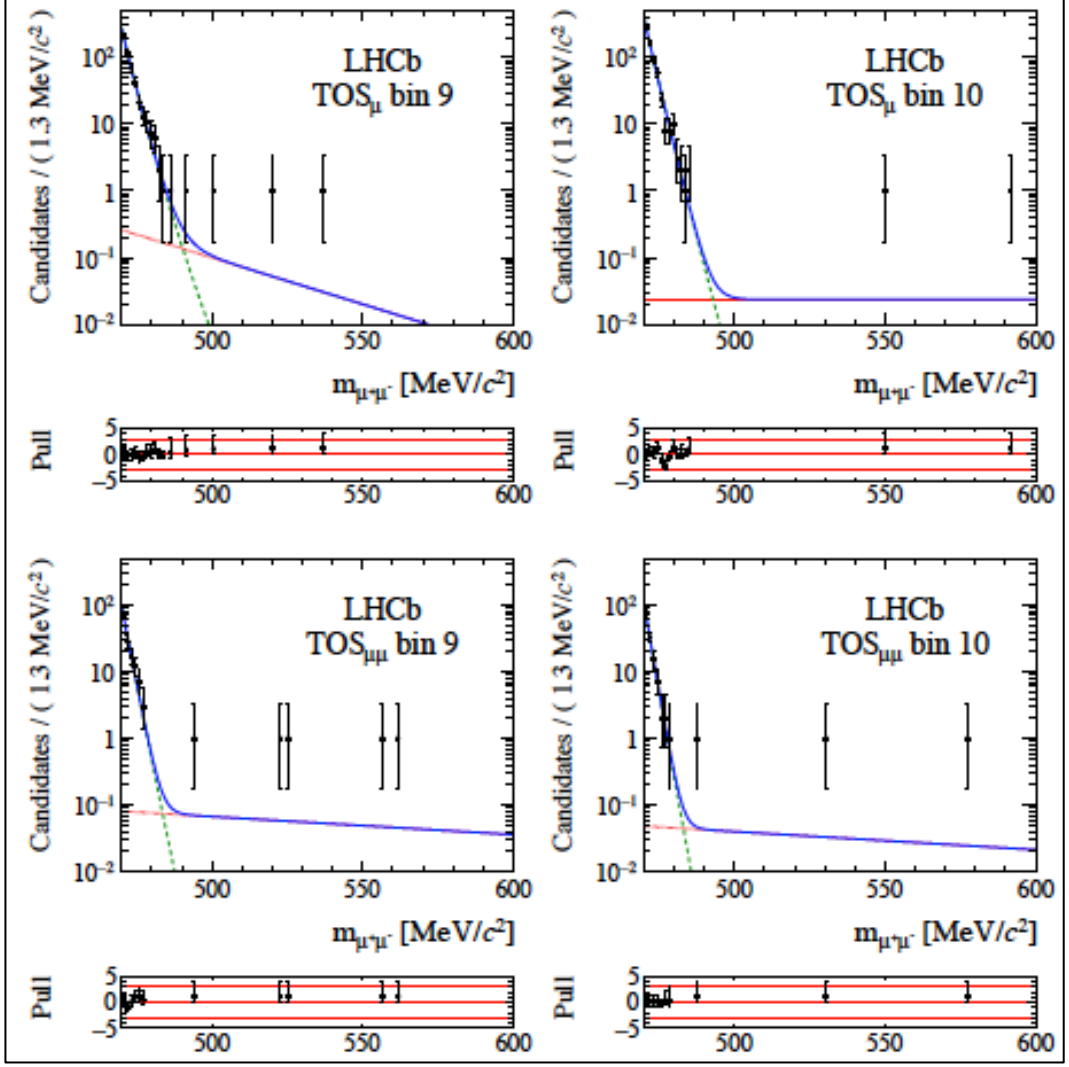
BR($K^0_S \rightarrow \mu^+\mu^-$) < 9×10^{-9} @90% CL

from LHCb proton-proton collision data (~1.0 fb^{-1} integrated luminosity) at $\sqrt{s}$ = 7TeV collected in 2011.
[JHEP 01 (2013) 090]

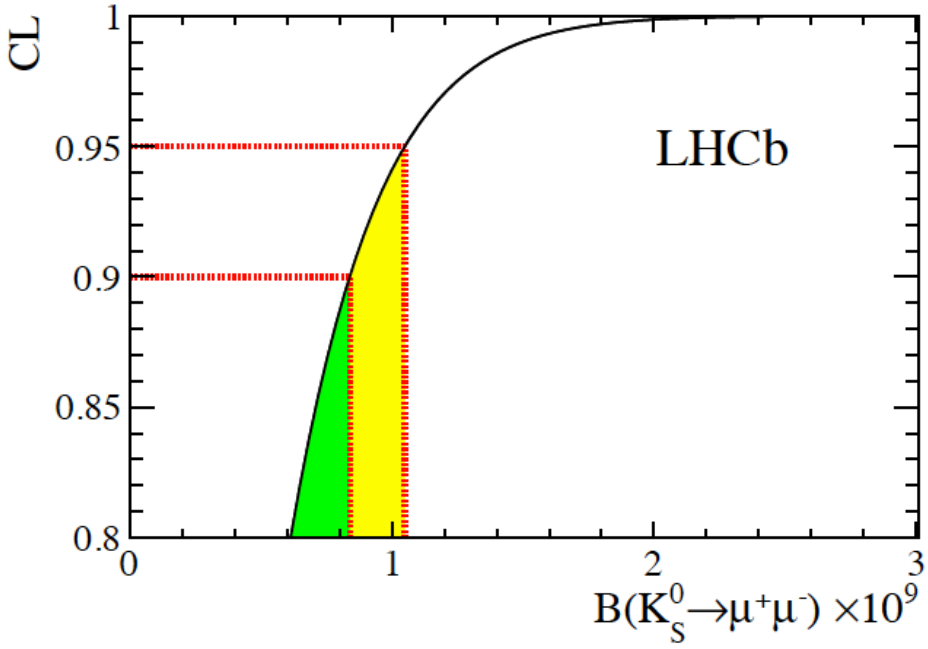
Recent update on $K^0_S \rightarrow \mu^+\mu^-$ search

Analysis performed on data sample corresponding to 2.0 fb^{-1} of integrated luminosity at $\sqrt{s}$ = 8TeV collected in 2012.

[arXiv:1706.00758v2]



$K_{S(L)} \rightarrow \mu^+\mu^-$ @ LHCb



[arXiv:1706.00758v2]

NEW

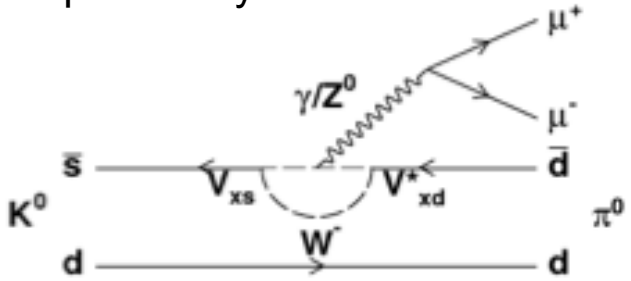
Combined results based on LHCb pp collisions data, corresponding to ~3 fb^{-1} integrated luminosity, collected at centre-of-mass energies of $\sqrt{s}$ = 7TeV and 8TeV.

$$\mathcal{B}(K_S^0 \rightarrow \mu^+\mu^-) < 0.8\ (1.0) \times 10^{-9} \text{ at } 90\%\ (95\%)\ \text{CL}$$

This result supersedes the previous upper limit [JHEP 01 (2013) 090] and represents a factor ~10 improvement

$K_S \to \pi^0\mu^+\mu^-$ @ LHCb

s→dll decays are potentially sensitive to NP



$BR(K_L \to \pi^0\mu^+\mu^-)_{EXP} < 3.8 \times 10^{-10}$ @90% CL [KTEV, PRL84 5279]

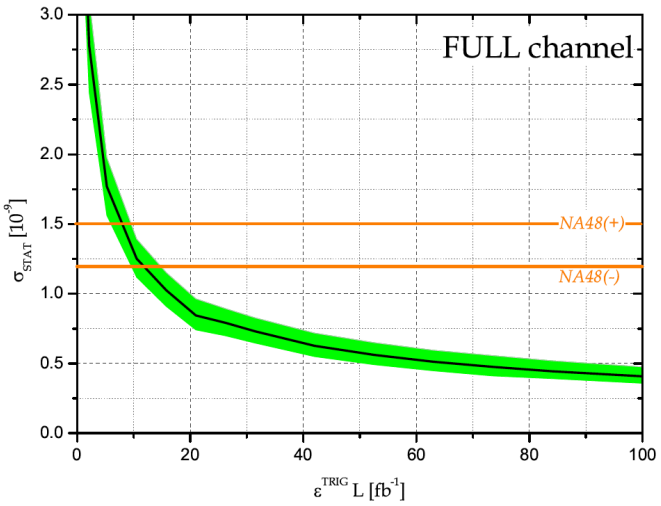
Could be enhanced up to one order of magnitude in NP (JHEP09 017)

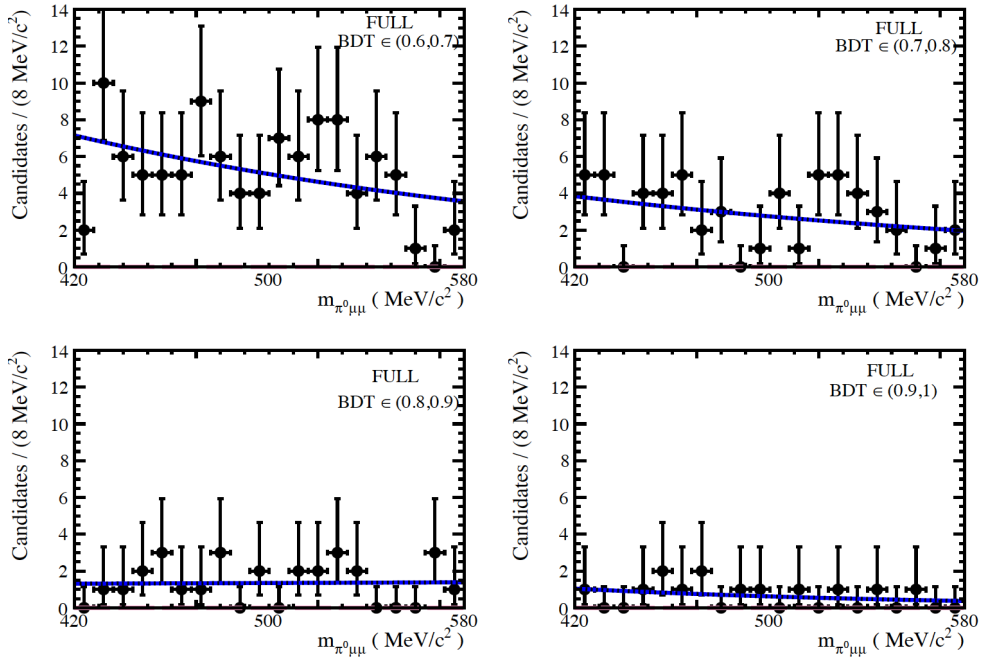
SM prediction for K_L is strongly limited by K_S measurement by NA48/1:

$BR(K_S \to \pi^0\mu^+\mu^-)_{EXP} = (2.9\ ^{+1.5}_{-1.2} \pm 0.2) \times 10^{-10}$ [PLB599 197]

Use BDT to suppress combinatorial bkg (physics bkg is negligible)

Use RUN I data to get realistic estimate of background for sensitivity studies





Expected precision strongly limited by hardware trigger

Improvement expected with fully software trigger

Heavy Neutrino, Dark Photon, LFV/LNV Searches

Broader Kaon Physics Programme @ NA62 - I

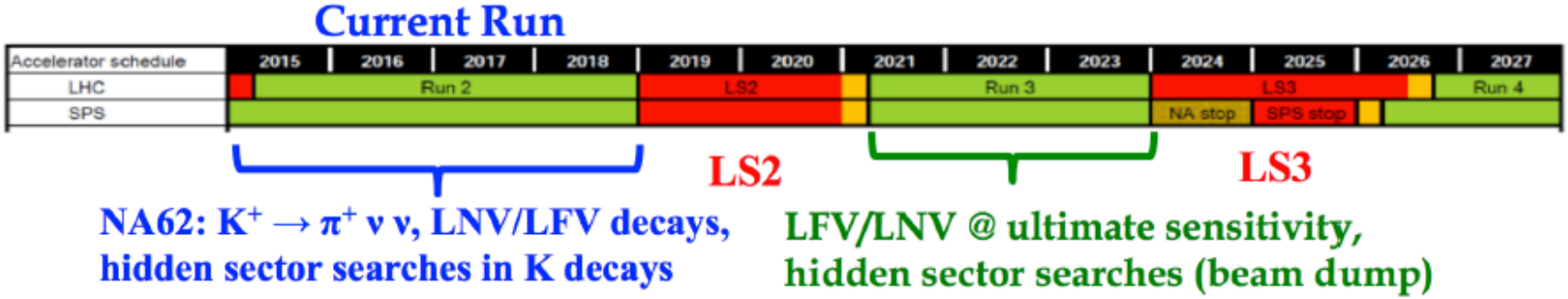
- **Standard Kaon Physics**
  - Measurements of the BR of all the main K^+ decay modes
  - χPT: $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+e^-$, $K^+ \to \pi^0(^+)\pi^0(^-)l^+\nu$
  - Precision measurement of $R_K = \Gamma(K^+ \to e^+\nu_e)/(K^+ \to \mu^+\nu_\mu)$
- **Rare/forbidden K^+ and π^0 decays at SES ~10^{-12}:**
  - K^+ physics: $K^+ \to \pi^+\ell^+\ell^-$, $K^+ \to \pi^+\gamma\ell^+\ell^-$, $K^+ \to \ell^+\nu\gamma$,
  - LFV-LNV searches: $K^+ \to \pi^+\mu^\pm e^\mp$, $K^+ \to \pi^-\mu^+e^+$, $K^+ \to \pi^- l^+ l^+$, ...
  - π^0 physics: $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-$, $\pi^0 \to e^+e^-e^+e^-$, $\pi^0 \to \gamma\gamma\gamma(\gamma)$, ...
- **Exotics searches**
  - Heavy Neutral Lepton (HNL) $K^+ \to l^+\nu_h$, $\nu_h \to \pi^\pm l^\mp$
  - Dark Photon (A') $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma$A', A' $\to$ invisible

New Results

Broader Kaon Physics Programme @ NA62 - II

A rich field to be explored with minimal/no upgrades to the present setup

0. **If needed, run for refining $\pi\nu\nu$ measurement**
1. **Present K^+ beam setup + dedicated runs: unprecedented LFV/LNV sensitivities from K^+/π^0**
2. **Year-long run in "beam-dump" mode, new program of NP searches for MeV-GeV mass hidden-sector candidates: Dark photons, Heavy neutral leptons, Axions/ALP's, etc.**



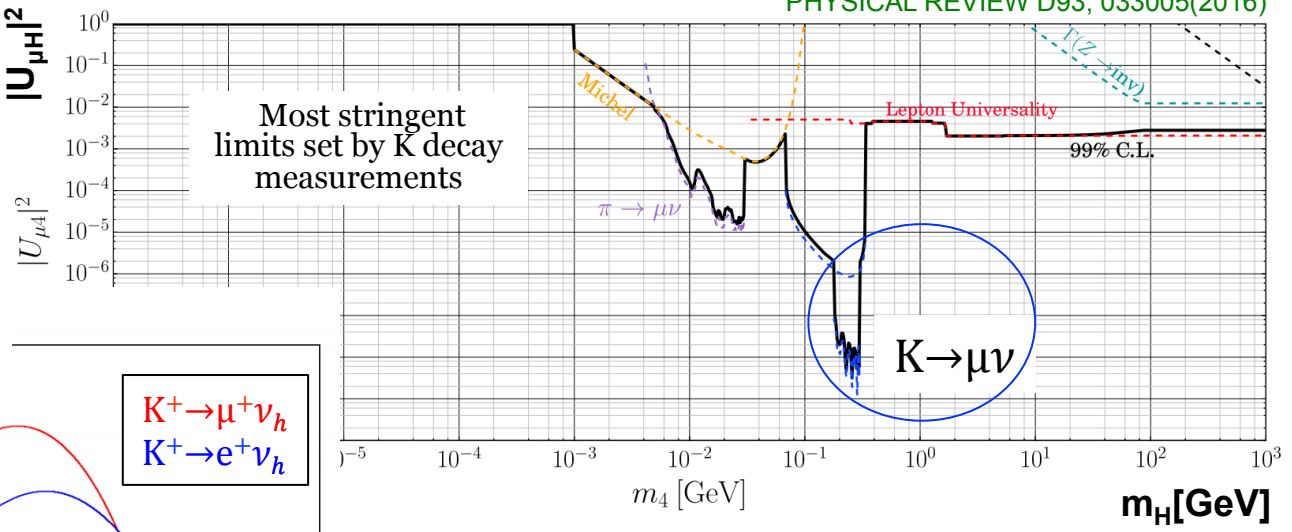
NA62 @ **Physics Beyond Colliders** 2016

Heavy Neutrino Searches

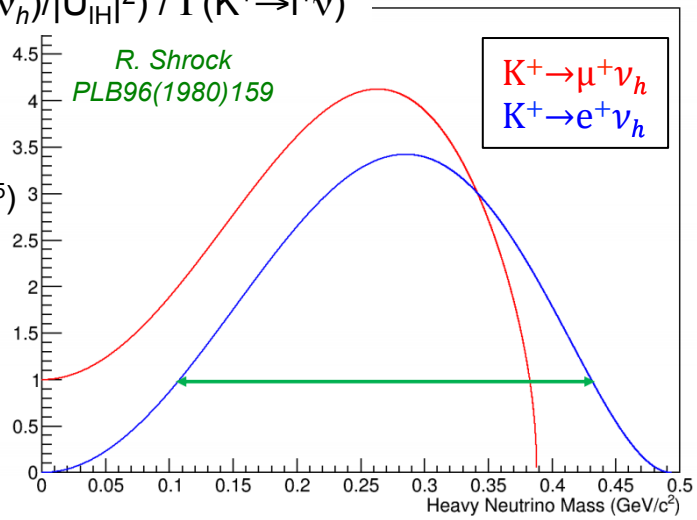
- **νMSM** = **SM** + 3 right-handed HNLs [Asaka et al., PLB 631 (2005) 151]
- Masses: **m_1~10 keV**; **$m_{2,3}$~1 GeV**
- HNLs observable via **production** and **decay**
- Production searches are model-independent
- NA62 searches for HNL produced in $K^+ \to \mu^+ \nu_h$ and $K^+ \to e^+ \nu_h$

Global limits on $|U_{\mu H}|^2$ as a function of HNL mass

PHYSICAL REVIEW D93, 033005(2016)



HNL production, kinematic factor
$(\Gamma(K^+ \to l^+ \nu_h)/|U_{lH}|^2) / \Gamma(K^+ \to l^+ \nu)$



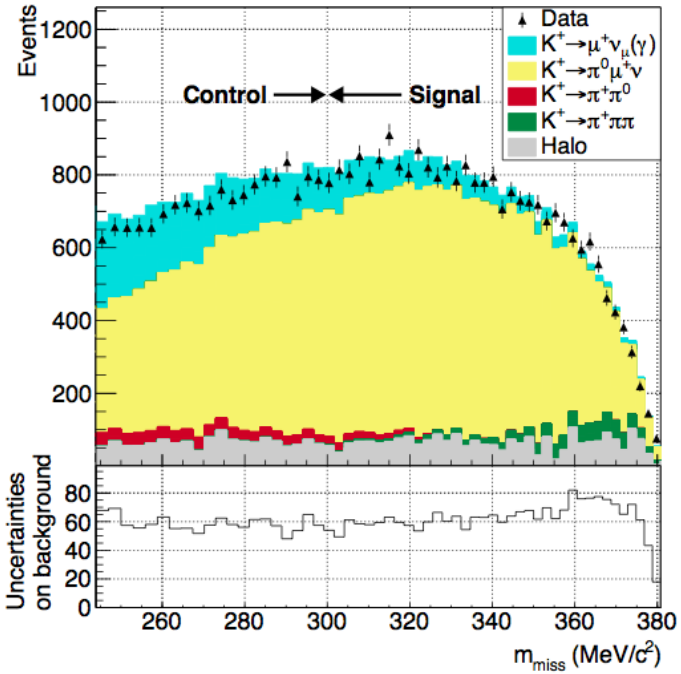
$K^+ \to e^+ \nu_h$ helicity suppressed (~10^{-5}) for m(ν_h)→0
PLB698 (2011) 105

Lifting of the suppression by the HNL (for m(ν_h) ~0.1GeV) means there could be a similar number of $K^+ \to e^+ \nu_h$ events as $K^+ \to \mu^+ \nu_h$

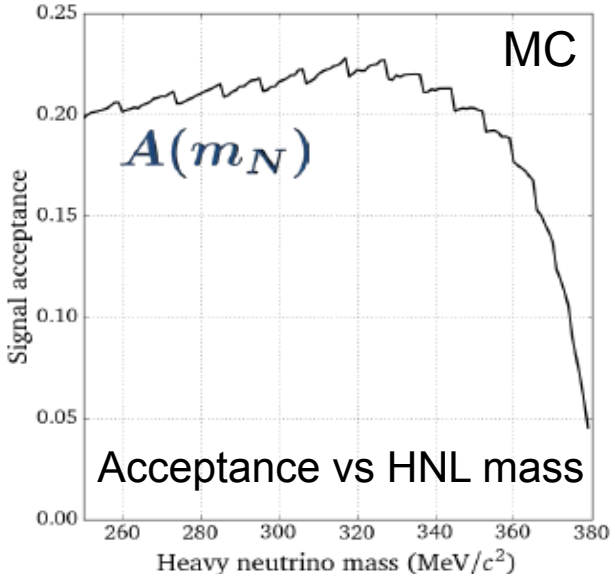
Heavy Neutrino @ NA62

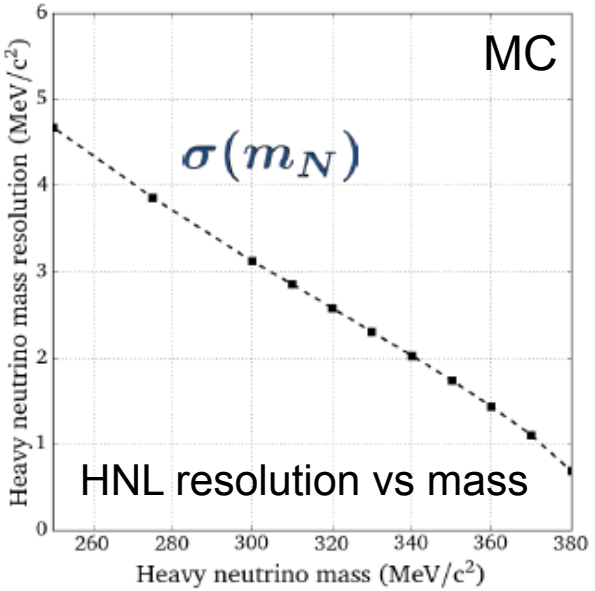
- Search for HNL produced in $K^+ \to \mu^+ \nu_h$ decays
- **NA62 2007 data** ($R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$)

  [Phys. Lett. B719 (2013) 326]
- Kaon decays in FV: $N_K \sim 6 \times 10^7$
- Search for peaks in $m_{miss}(K \to \mu\nu) = \sqrt{(P_K - P_\mu)^2}$



Signal region: m_{miss} (300 - 375) MeV/c^2





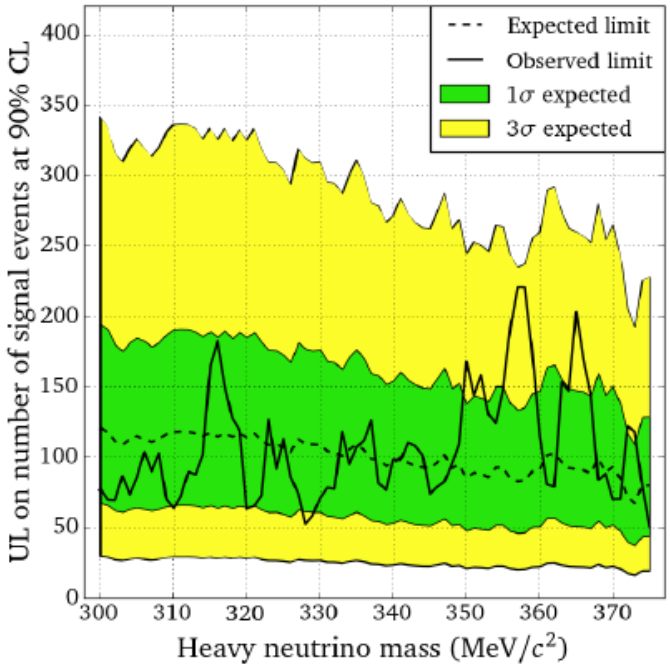
Heavy Neutrino @ NA62

- Rolke-Lopez method used to find upper limits on number of signal events
- Heavy neutrino mass step: 1 MeV/c²
- Search window size defined by HNL mass resolution

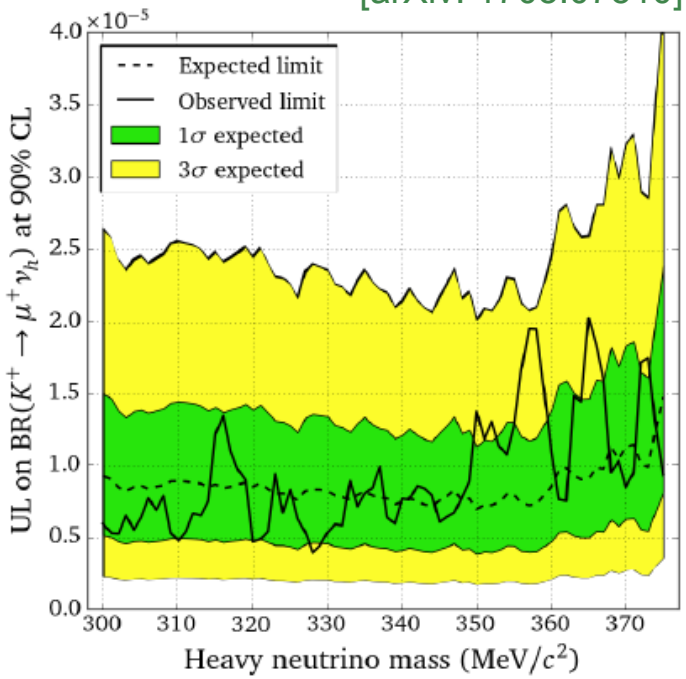
No HNL signal observed
~3σ significance

NA62 (2007): $K^+ \to \mu^+ \nu_h$ search

[arXiv: 1705.07510]



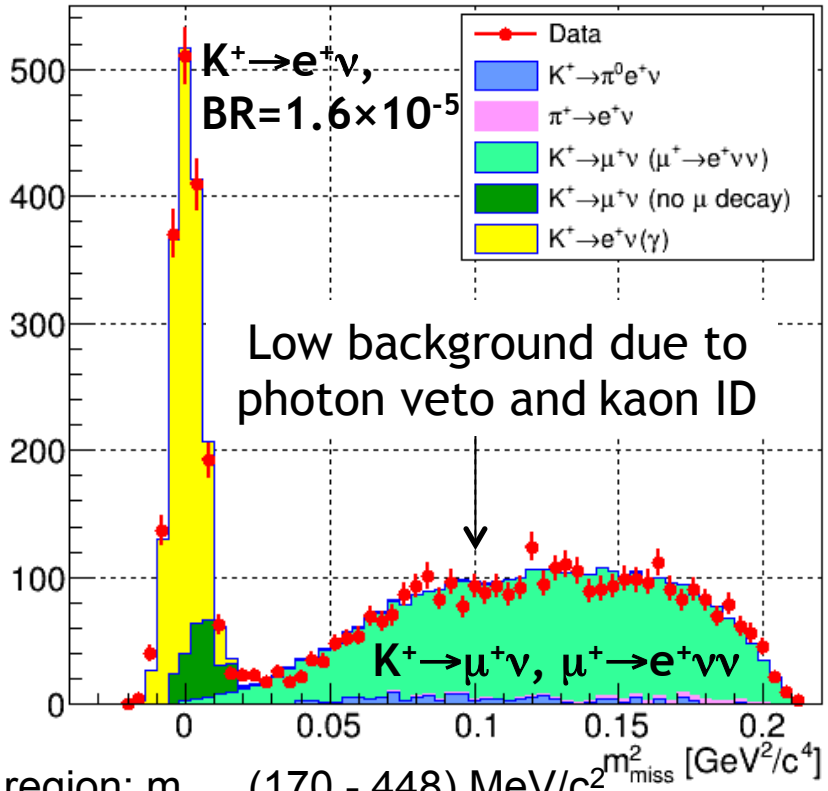
x 1/A(m_H)*N_K



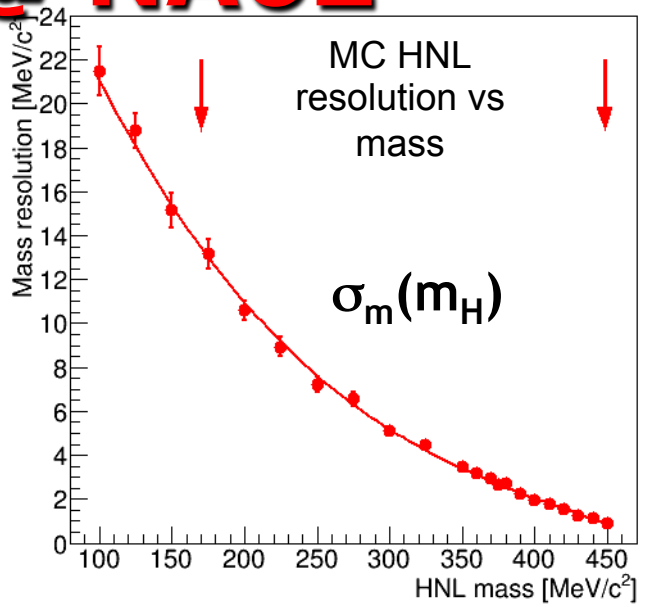
Limits on BR($K^+ \to \mu^+ \nu_\mu$) ~ 10^{-5}, limits on $|U_{\mu 4}|^2$ ~ 10^{-5} for M_H > 300MeV/c²

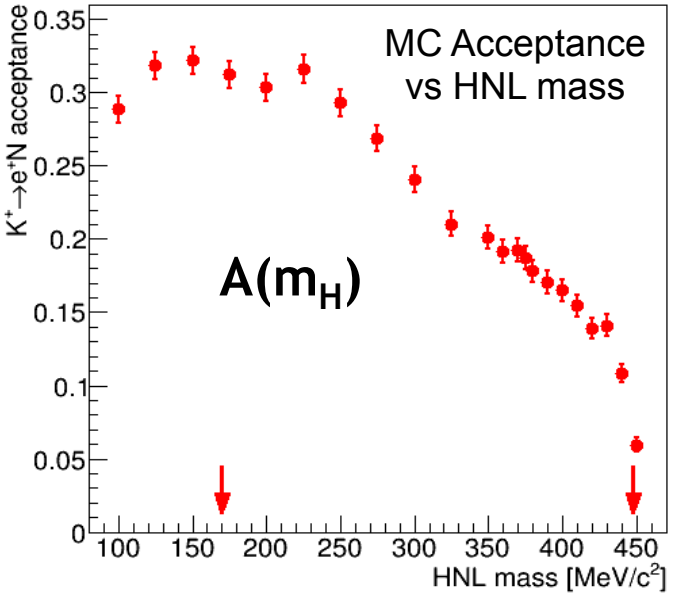
Heavy Neutrino @ NA62

- Search for HNL produced in $K^+ \to e^+ \nu_h$ decays
- **NA62 2015 data** (minimum bias @ 1% intensity)
- Kaon decays in FV: $N_K = (3.01 \pm 0.11) \times 10^8$
- Search for peaks in $m^2_{miss}(K \to e\nu) = (P_K - P_e)^2$



Signal region: m_{miss} (170 - 448) MeV/c^2



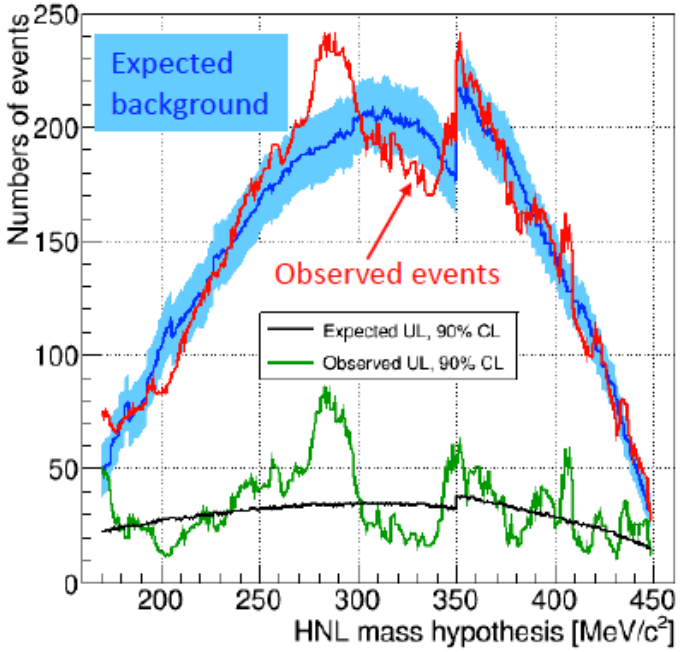


Heavy Neutrino @ NA62

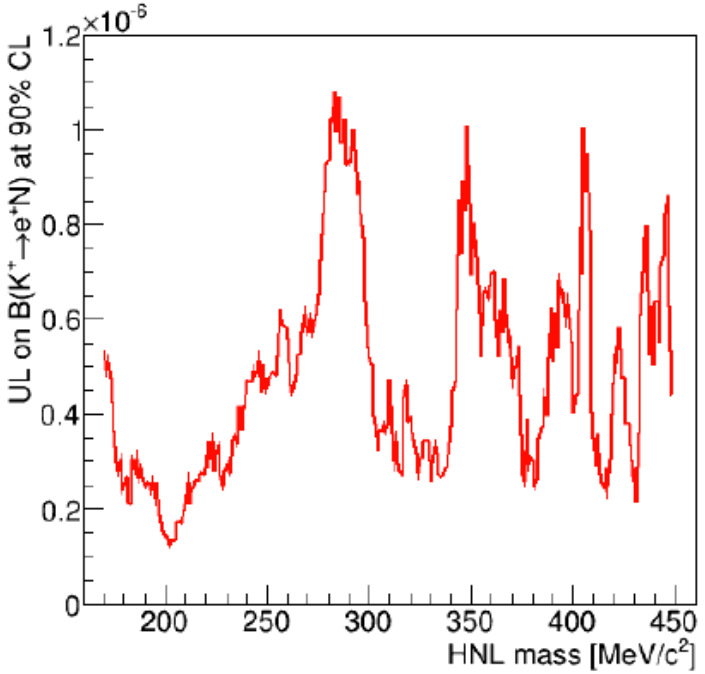
- Rolke-Lopez method used to find upper limits on number of signal events
- Heavy neutrino mass step: 1 MeV/c^2
- Search window size for each mass hypothesis: $\pm 1.5\sigma_m$
- Background estimate: polynomial fits to mass spectra outside signal window

No HNL signal observed
~3σ significance

NA62 (2015): $K^+ \to e^+ \nu_h$ search



x $1/A(m_H)*N_K$

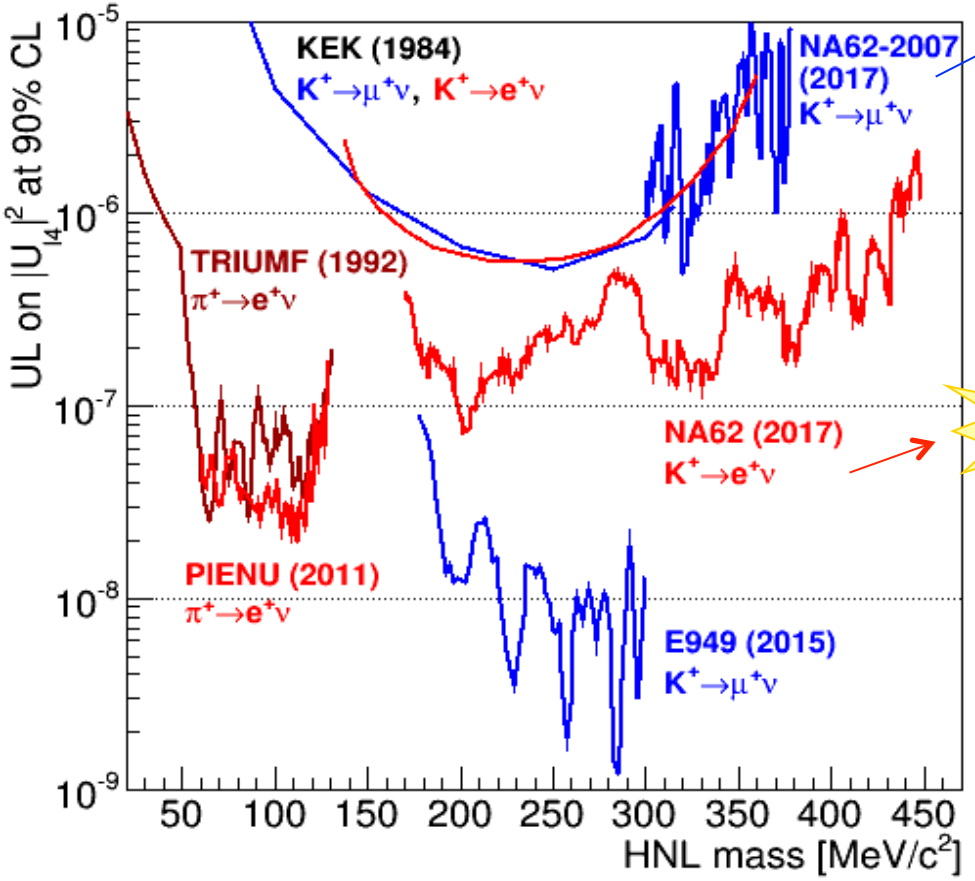


Limits on $BR(K^+ \to e^+ \nu_e) \sim 10^{-7}$, limits on $|U_{e4}|^2 \sim 10^{-7}$ for $M_H > 170$MeV/c^2

HNL Global Limits

$$|U_{l4}|^2 = \frac{\mathcal{B}(K^+ \to l^+ N)}{\mathcal{B}(K^+ \to l^+ \nu_l)\ \rho_l(m_N)}$$

Limits from heavy neutrino **production** searches



NEW

NA62 2007 Data Analysis:

- Extends the mass range for upper limits on $|U_{\mu 4}|^2$ [arXiv: 1705.07510]
- Most stringent limit in HNL **(300,375) MeV/c²** mass range

NEW

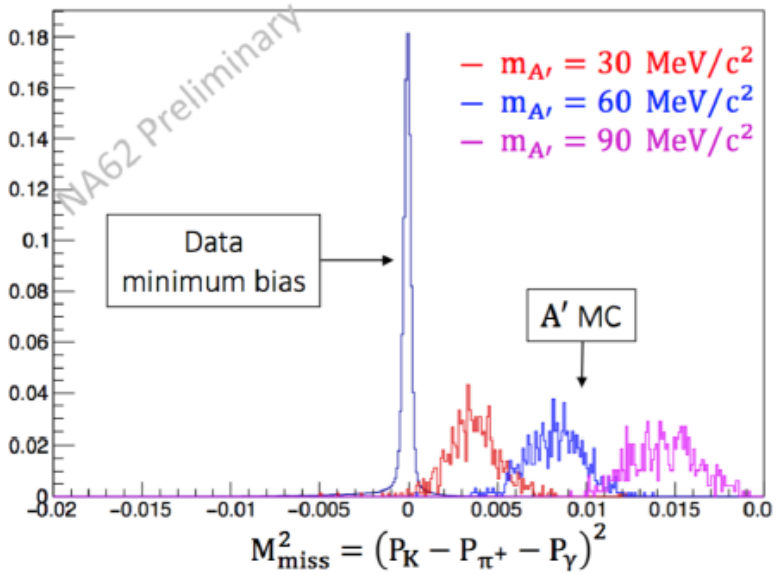
NA62 2015 Data Analysis:

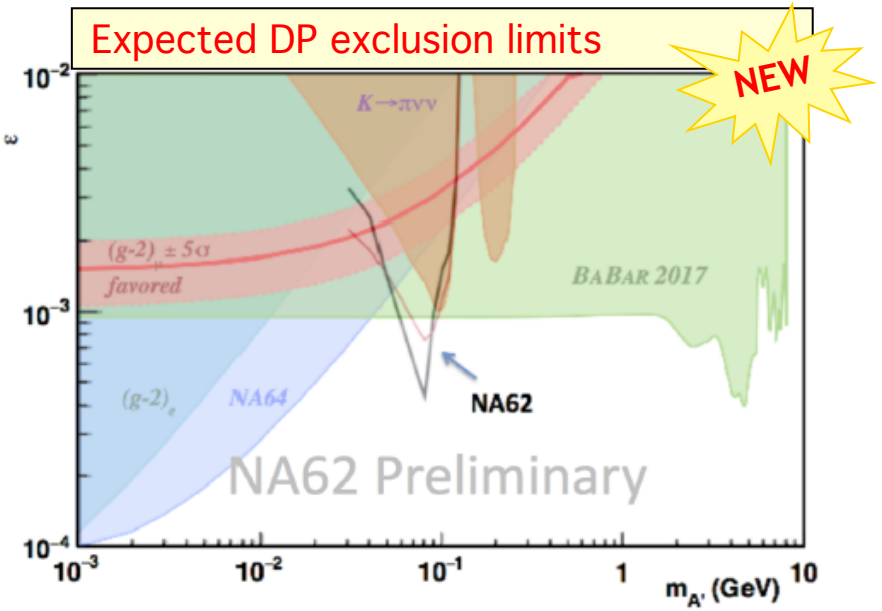
- Reaches **10^{-6}-10^{-7}** limits for $|U_{e4}|^2$ in HNL **(170,448) MeV/c²** mass range

Major improvement foreseen with high intensity NA62 2016 data !

Dark Photon Searches @ NA62

- Search for A' produced via: $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma A'$, $A' \to$ invisible
- Sensitivity to DP for $m(A') < m(\pi^0)$
- NA62 2016 data (40% nominal beam intensity)
- Kaon decays in fiducial volume: $N_K \sim 4 \times 10^{11}$
- Search for peaks in $M^2_{miss}(K^+ \to \pi^+\pi^0) = (P_K - P_\pi - P_\gamma)^2$





Preliminary results of the analysis of 1.5 x 10^{10} K^+ decays from 2016 [**~4% of 2016 data**]

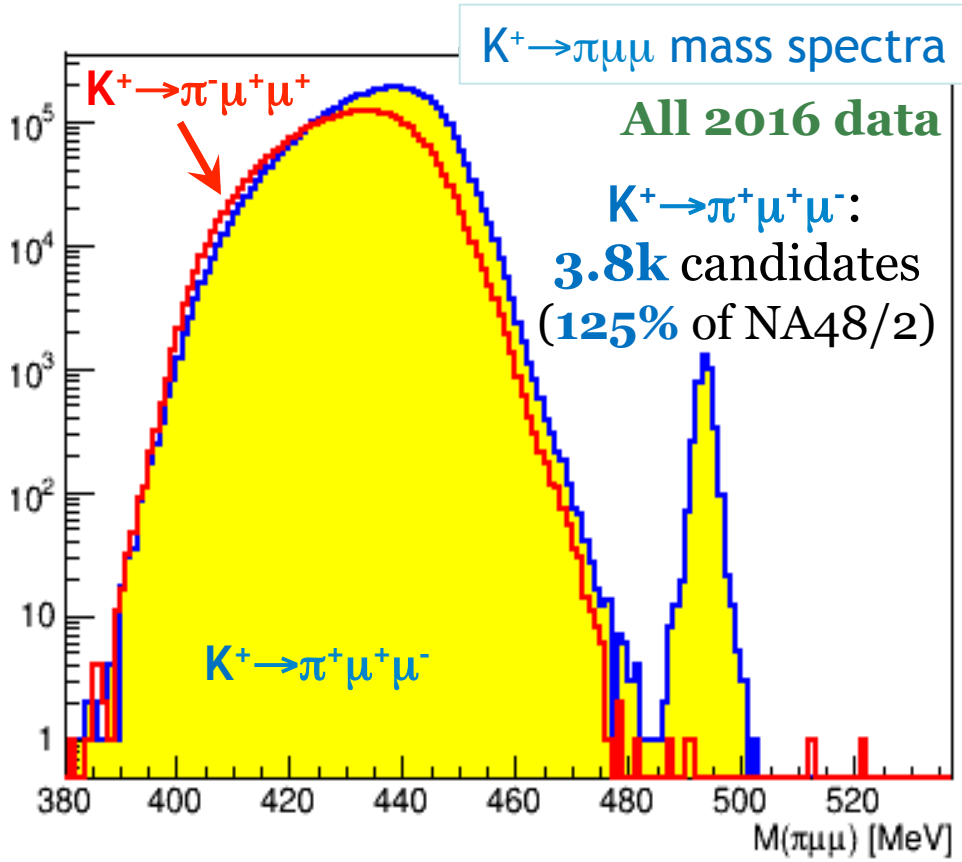
Expect improvement over the world data

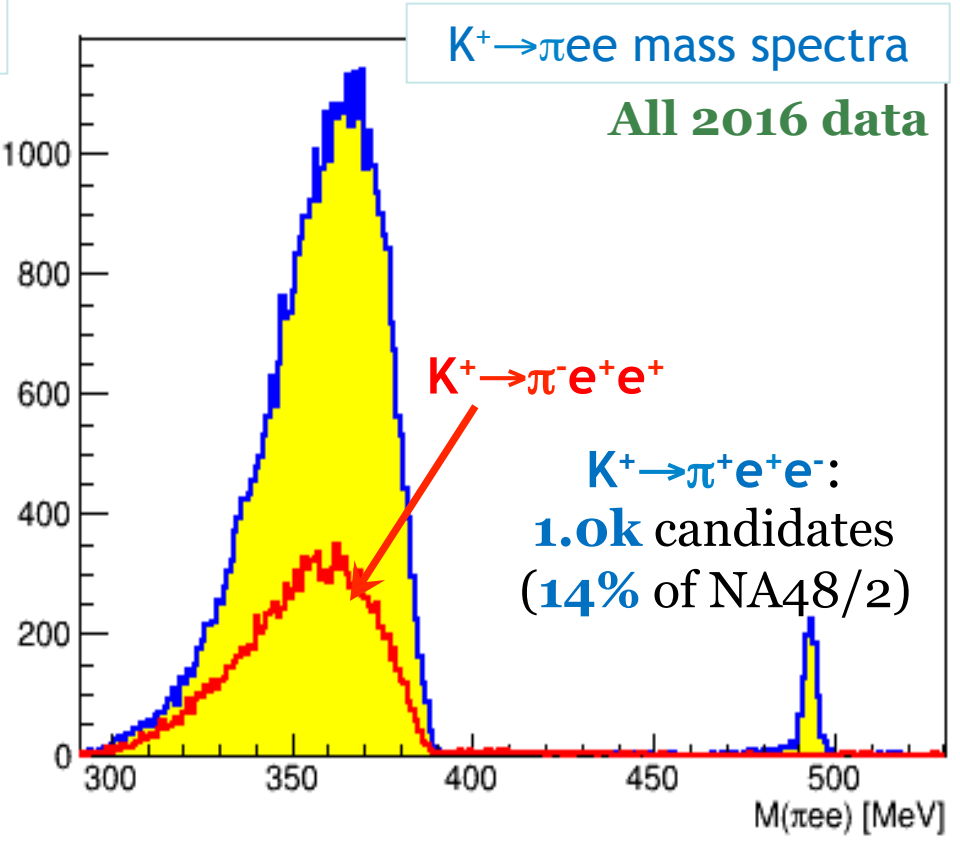
Improvement on BR($\pi^0 \to$invisible) over the current limit of 2.7×10^{-7} is also possible

LFV/LNV Searches @ NA62

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.



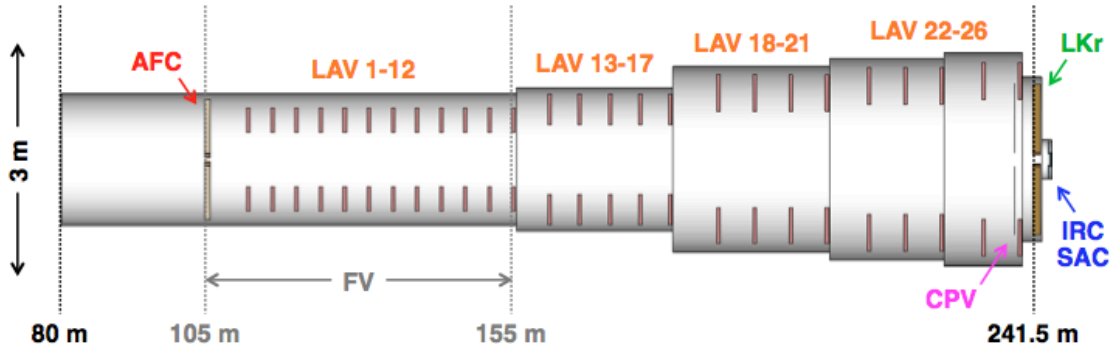


Future Experiments and Conclusions

Prospects beyond 2024

A **new K_L** experiment at CERN focussed on **$K_L \to \pi^0 \nu\nu$** with **SES~0.5×10^{-12}** is under study in the context of the **Physics Beyond Colliders** initiative for **2026-2029**

KLEVER @ CERN:



Main detector/veto systems:

AFC	Active final collimator/upstream veto
LAV1-26	Large-angle vetoes (26 stations)
LKr	NA48 LKr calorimeter
IRC/SAC	Small-angle vetoes (SAC in neutral beam)
CPV	Charged-particle veto

- High energy experiment (**<p>=70 GeV** for KL decays in FV), complementary 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)

Conclusions

Kaon physics has played a large role in establishing the basis of the SM, and now has a fundamental role in the search for NP

Kaon physics is a **broad and interesting subject**, carried out worldwide by experienced people and **several contributing experiments**: Kloe2, KOTO, LHCb, NA62 among others

The content of this review is far from being exhaustive and I have concentrated on recent results exploring possible NP scenarios

More **precise theoretical computations** and effort on **dedicated experimental apparata** are pushing down the level of SES achievable

Precise measurements from KOTO and NA62 will **target 10^{-11}-10^{-12} SES in the next few years**

Interesting times ahead !

XXXVII International Symposium on Physics In Collision

Spares

Angela Romano(*), University of Birmingham

Prague, 4 – 8 September, 2017

Experimental Status of R_K

- **Highly Precise SM value**

  $R_K = (2.477 \pm 0.001 \pm 0.007) \times 10^{-5}$

  [V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801 (2007)]

- **KLOE @ DAΦNE (in-flight decay) (2009)**

  $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$

  [F. Ambrosino et al., Eur. Phys. J. C64, 627 (2009)]

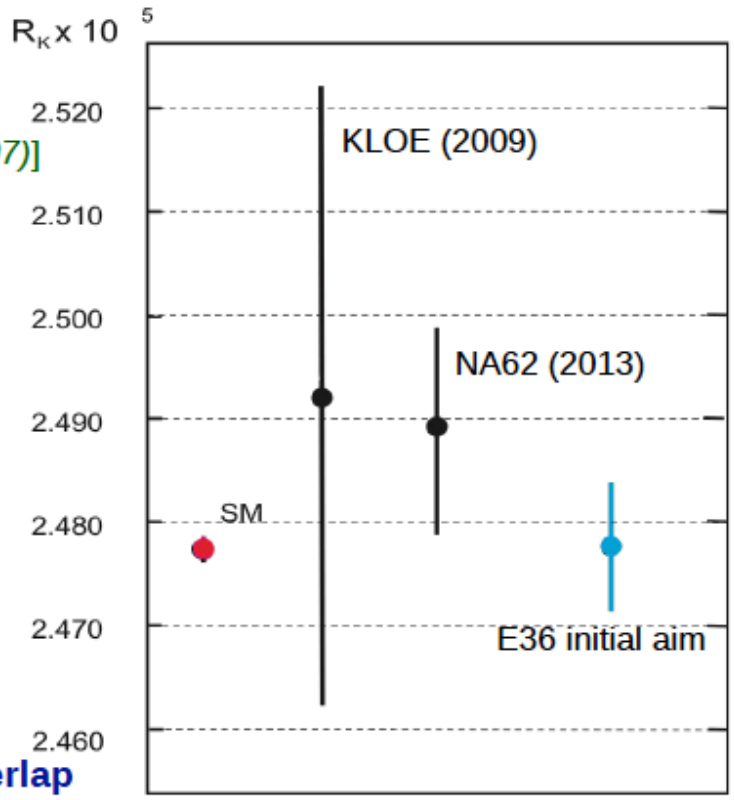
- **NA62 @ CERN-SPS (in-flight decay) (2013)**

  $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$

  [C. Lazzeroni et al., PLB 719, 326 (2013)]

- **World Average (2013)**

  $R_K = (2.488 \pm 0.01) \times 10^{-5}$ $\quad \Delta R_K/R_K \approx 0.4\%$



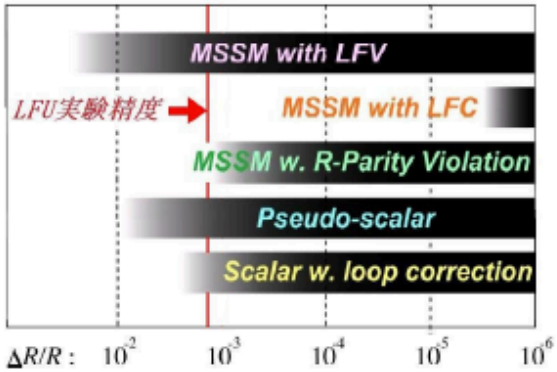
- **Different systematics**
  - In-flight-decay experiments : kinematics overlap
  - E36 stopped K+ decay experiment : detector acceptance and target interactions

- **E36 proposed $\Delta R_K/R_K$**

$\Delta R_K/R_K$: ≈ ± 0.20% (stat.) ± 0.15% (syst.) [0.25% total]

Lepton Universality Violation in K_{l2}

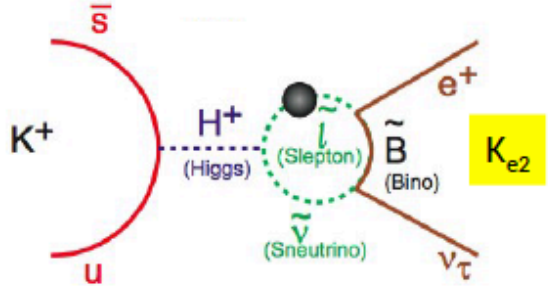
- **Possible New Physics**
  - -- MSSM with LFV
  - -- MSSM with R-Parity violation
  - -- Pseudo-scalar interaction
  - -- Scalar with loop correction



- **SUSY with LFV for K_{e2}**

$$R_K^{LFV} = R_K^{SM}\left(1 + \frac{m_K^4}{M_{H^+}^4}\cdot\frac{m_\tau^2}{m_e^2}\Delta_{13}^2\tan^6\beta\right)$$

  - -- Charged Higgs H^+ mediated LFV SUSY
  - -- Large enhancement for m_τ^2 / m_e^2
  - -- A sizable effect up to $\Delta R_K/R_K$~1.3% possible

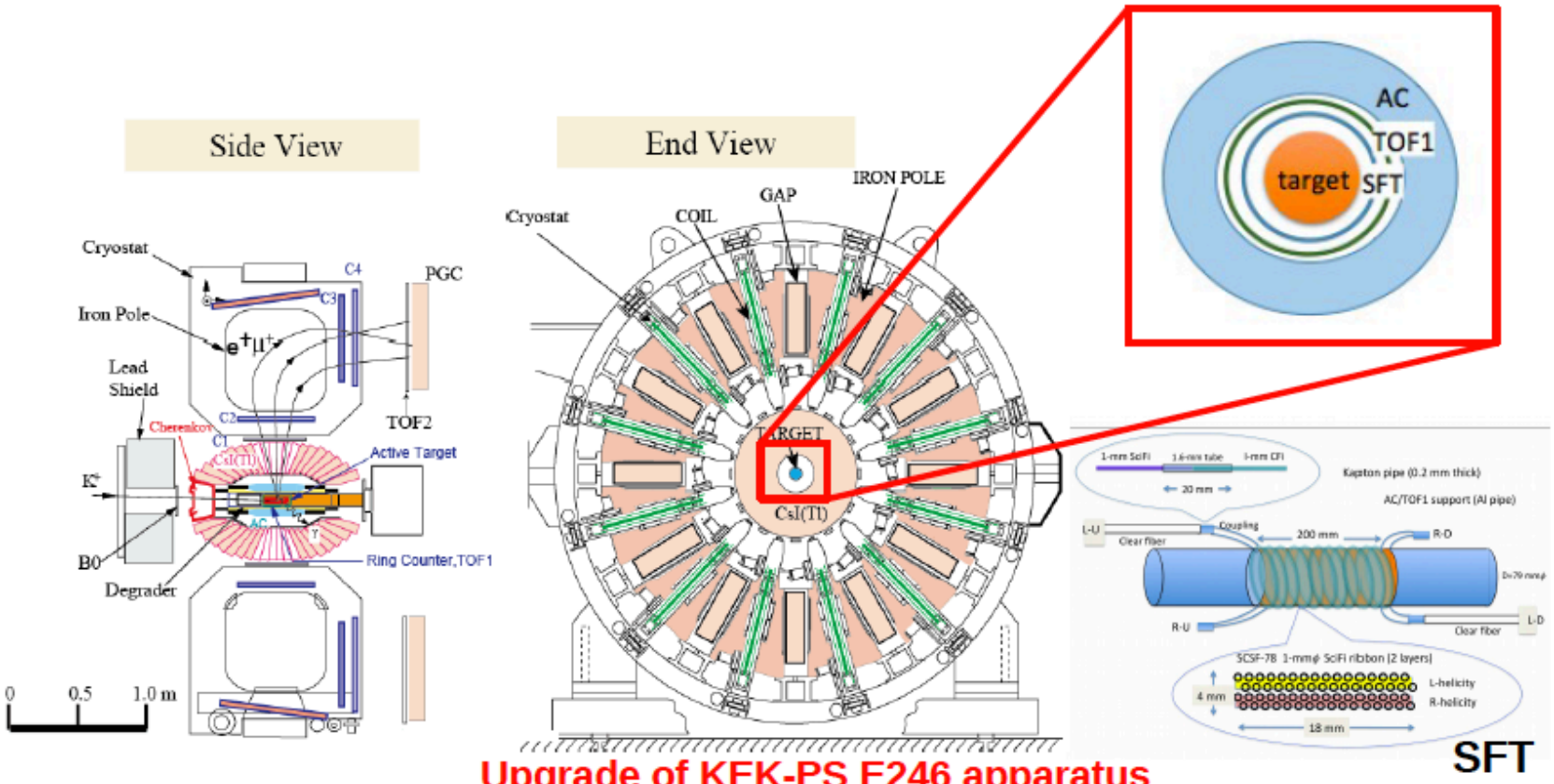


[Masiero, P. Paradisi, & R. Petronzio, Phys Rev D74(2006) 011701, JHEP 11(2008) 042]
[J. Girrbach and U. Nierste, JHEP 05 (2010) 026; arXiv:1202.4906]

- **Neutrino Mixing**
  - -- R_K sensitive to neutrino mixing parameters within SM with 4th generation of quarks and leptons or sterile neutrinos

[H. Lacker and A.Menzel, JHEP 1007 (2010) 006; A. Abada et al., arXiv: 1211.3052]

The TREK-E36 Apparatus



Upgrade of KEK-PS E246 apparatus

Stopped K Method

- K1.1BR beamline
- Fitch Cherenkov
- K^+ stopping target

Tracking

- MWPC (C2, C3, C4)
- Spiral Fiber Tracker (SFT)

PID

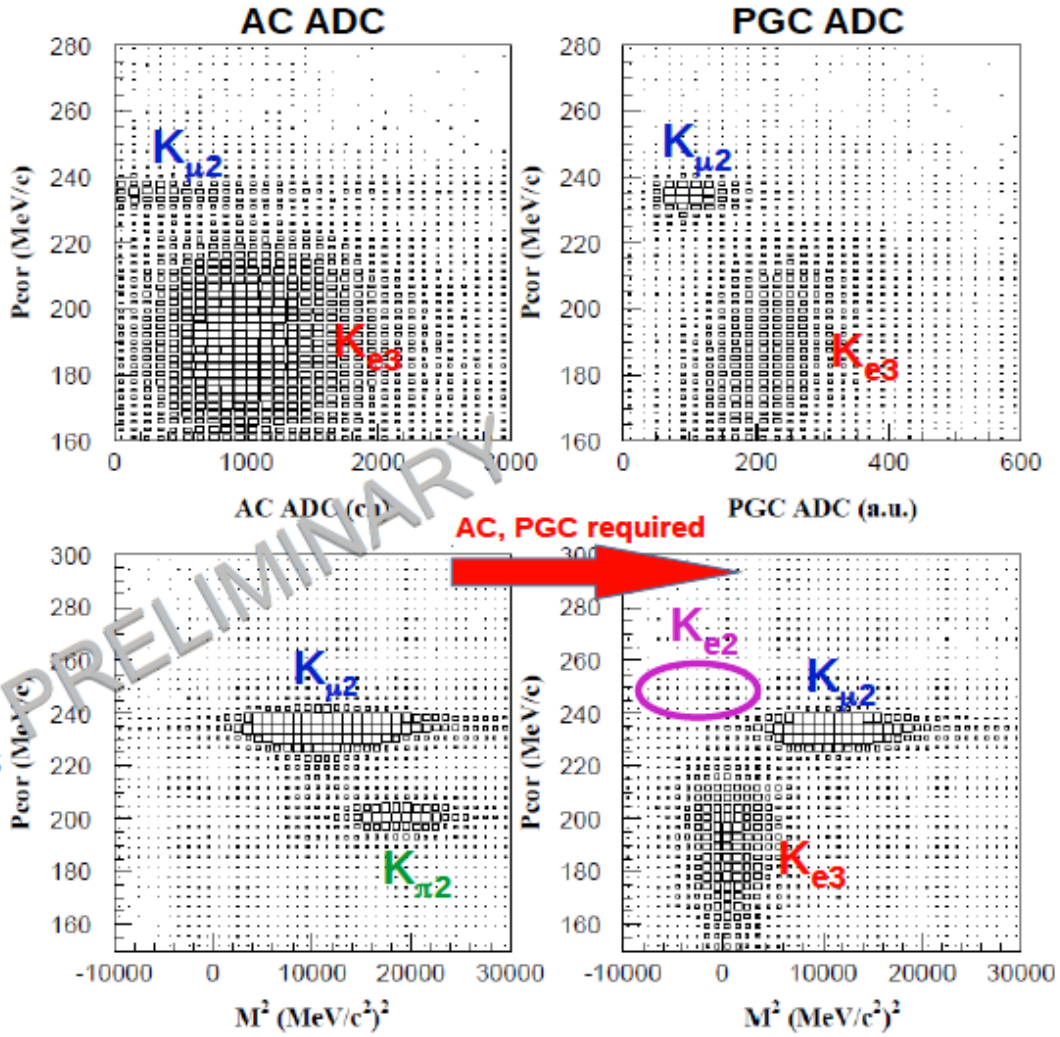
- TOF1,2; TTC
- Aerogel Cherenkov (AC)
- Pb glass counter (PGC)

Gamma Ray

- CsI(Tl)
- Gap Veto (GV)

PID @ TREK-E36

- Positrons are selected by AC, PGC and TOF
- PID performance by combining the three detectors is now being optimized
- Suppression of muon mis-identification below O(10^{-8}) level achievable with refined analysis
- TOF time walk correction has not yet been applied
- Refined analysis of PID performance in progress



Kaon "anomalies" - II

- The new lattice results for the matrix element $\langle(\pi\pi)_{I=0}|Q_6|K^0\rangle$ from RBC-UKQCD points to a tension between the experimental value of ϵ'_K and the Standard-Model prediction.
- If new physics enters through loops, a sizable effect in ϵ'_K requires a new source of flavour violation which is much larger then the CKM factor $\mathrm{Im}\,\dfrac{V_{td}V_{ts}^*}{V_{ud}V_{us}^*} \sim 6\cdot 10^{-4}$. But then the effect on ϵ_K will typically be too big.
- In the MSSM one can simultaneously enhance ϵ'_K and suppress the new-physics contributions to ϵ_K. This requires flavour mixing among left-handed squarks, masses of right-handed up-type squarks different from those of the down-type squarks, and a gluino mass above 1.5 times the mass of the left-handed squarks.

Kaon "anomalies" - III

Universal Unitarity Triangle 2016 (CMFV)

AJB, Gambino, Gorbahn, Jäger, Silvestrini 0007085

New Results from Fermilab Lattice + MILC 1602.03560

Hadronic matrix elements

$F_{B_s}\sqrt{\hat{B}_{B_s}} = (274.6 \pm 8.8\ \text{MeV})$

$F_{B_d}\sqrt{\hat{B}_{B_d}} = (227.7 \pm 9.8\ \text{MeV})$

Their ratio

$\xi = 1.206 \pm 0.019$

Similar but less precise results from ETM (1308.1851)

Blanke + AJB (1602.04020)

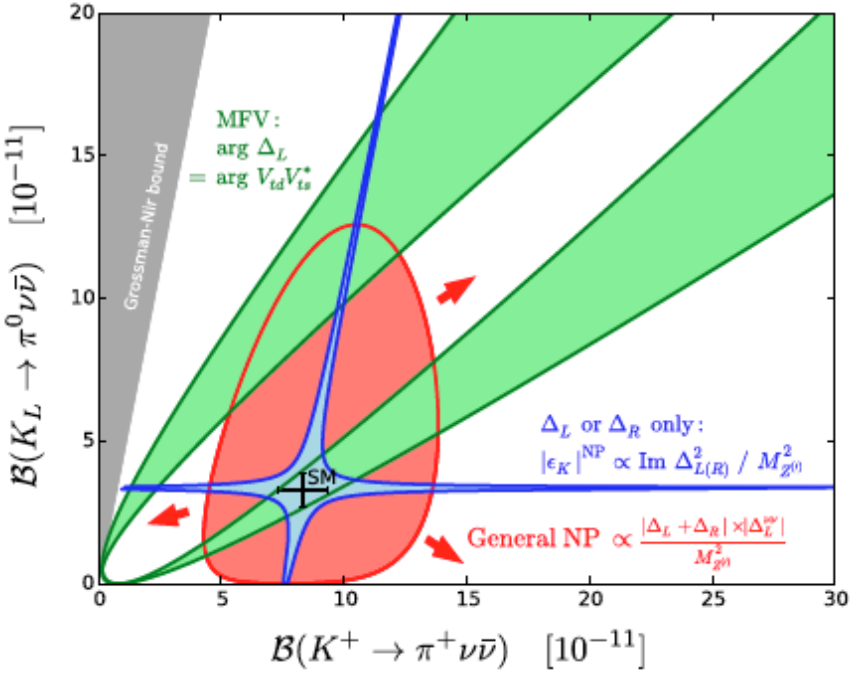
Requiring CMFV to reproduce data for $\Delta M_{s,d}$ favors low value of V_{cb} in agreement with exclusive determination and upper bound on ε_K significantly below data.

Requiring CMFV to reproduce data for ε_K favors high value of V_{cb} in agreement with inclusive determination and lower bound on $\Delta M_{s,d}$ significantly above data.

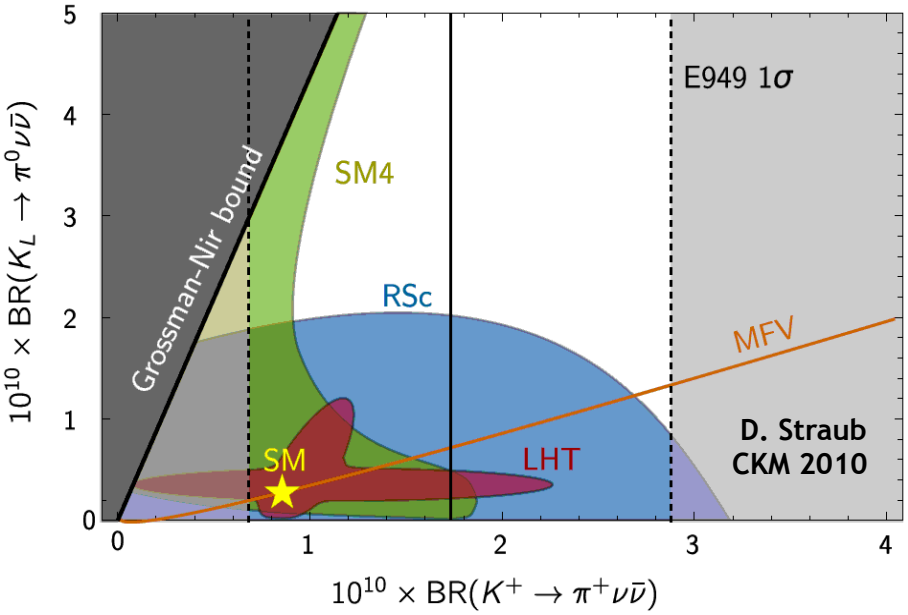
⇒ Tension between ΔM_s and ε_K

Testing the SM - I

JHEP 1511 (2015) Buras, Buttazzo, Girrbach,Knegjens
EPJ C76 (2016) Blanke, Buras, Recksigel
JHEP 0903 (2009) Blanke, Buras, Duling, Gemmler, Gori
JHEP 0608 (2006) Isidori, Mescia, Paradisi, Smith, Trine



Loose direct exp constraints:



- General Observables

Br($K^+ \to \pi^+\nu\nu$), Br ($K_L \to \pi^0\nu\nu$)

$K \to \pi\nu\nu$ vs ε'/ε, ΔM_K

$K \to \pi\nu\nu$ vs B decays ($B \to \mu\mu$, R_K, R_{D^*}, etc)

Correlations are model-dependent

- CMFV or general

- Specific models:

Modified Z' /Z

TeV SUSY

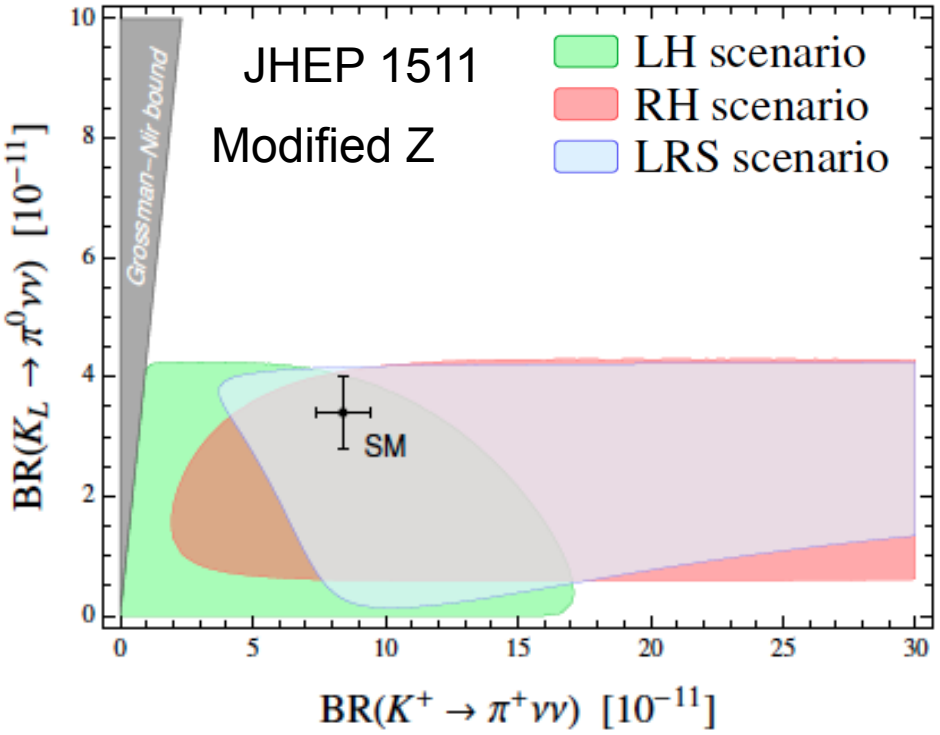
LFV in 3rd generation

Etc….

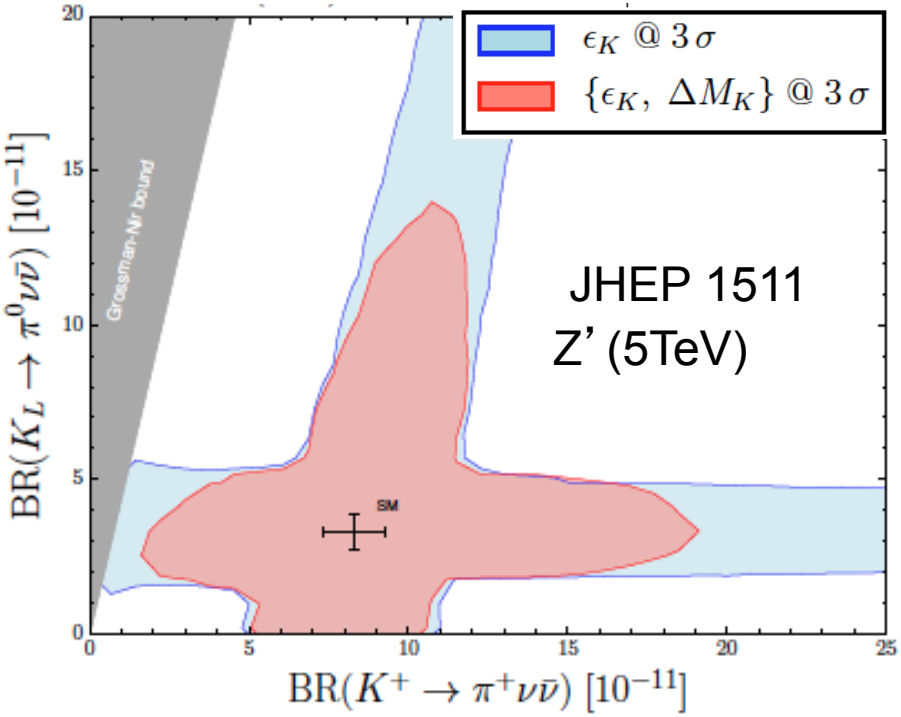
Testing the SM - II

Modified Z, Z' model used as paradigm:

ε'/ε, $Br(K_L \to \mu\mu)_{SD}$, ε_K , ΔM_K constraints



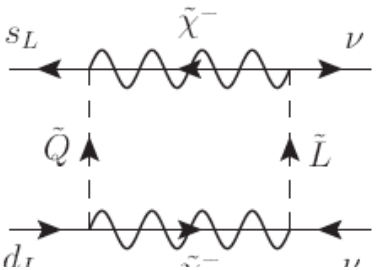
ε_K , ΔM_K constraints



LH and RH couplings allowed:
constraints from other kaon observables

Testing the SM - III

In our MSSM scenario:
Contributions from wino-like chargino box:



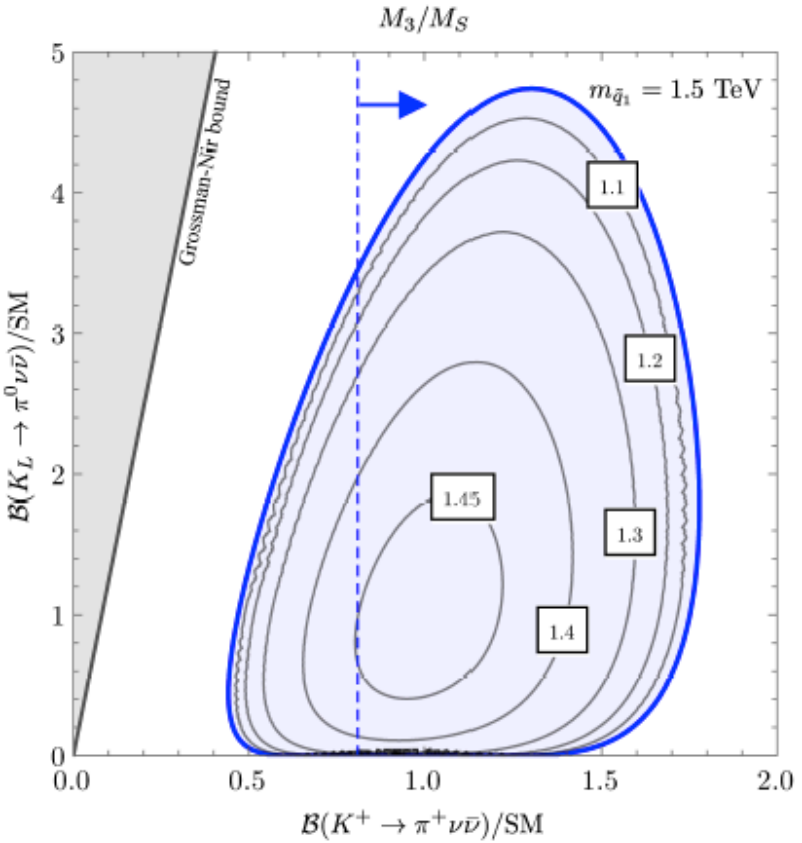
1703.05786
D' Ambrosio, Crivellin, Kitahara, Nierste

Our MSSM scenario makes falsifiable predictions for $B(K^+ \to \pi^+ \nu\bar{\nu})$ and $B(K_L \to \pi^0 \nu\bar{\nu})$:

Allowed region for the two branching ratios:

$m_{\tilde{q}_1} = 1.5\,\text{TeV}$ is the mass of the lightest ($\tilde{s}_L$–$\tilde{d}_L$–mixed) squark,
M_3 is the gluino mass, GUT relations for $M_{1,2}$,
M_S is the mass of all other sparticles.

The number in the squares show the value for M_3/M_S needed to cancel the MSSM contribution to ϵ_K.



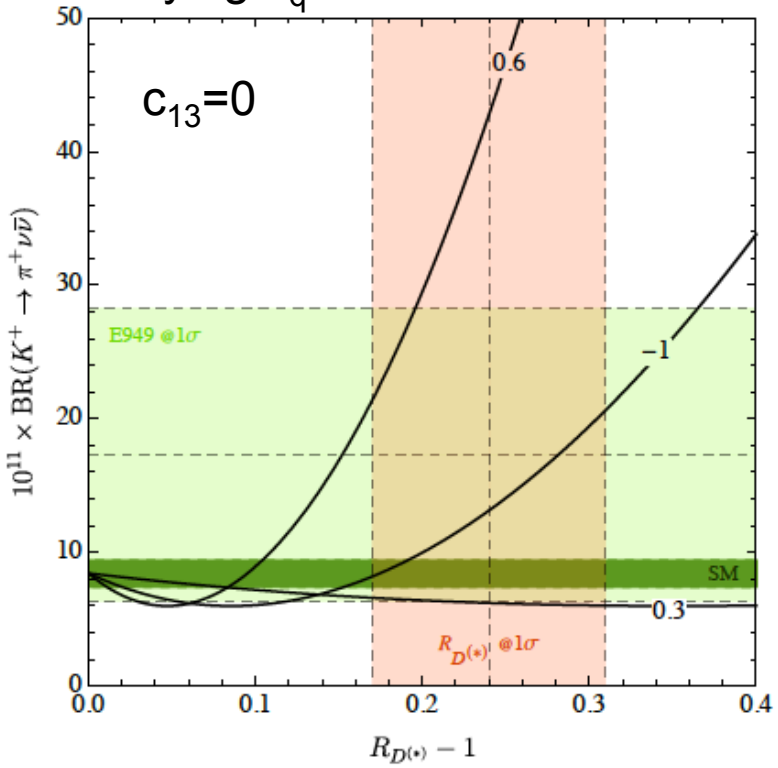
Testing the SM - IV

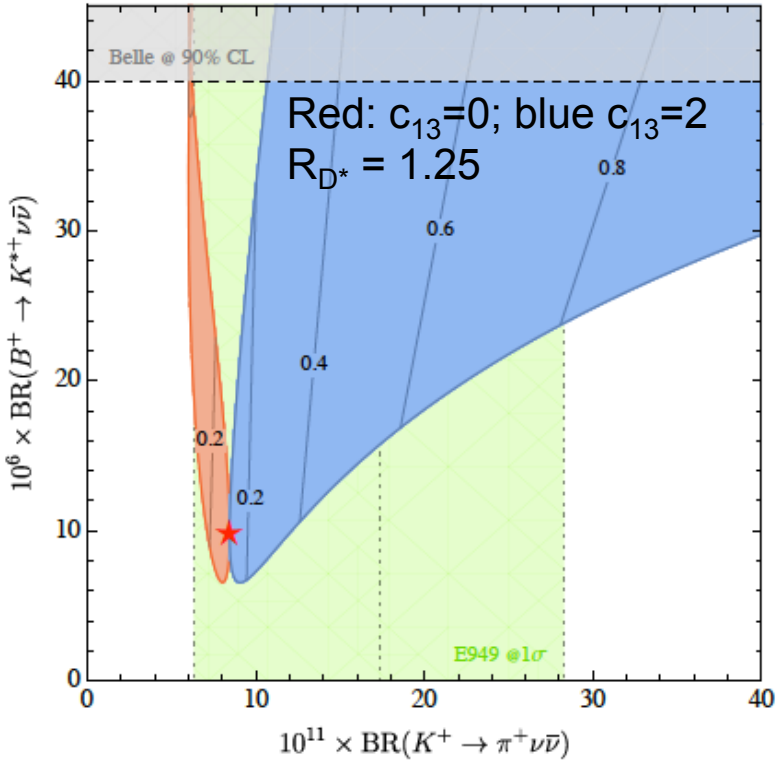
LFU violation in third generation, EFT approach:

$$\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}) = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})_{\rm SM} \left|1 + R_0 \left(1 - \theta_q e^{-i\phi_q}\right)\right|^2 \qquad R_0 = \frac{1}{\Lambda^2}\frac{1}{\sqrt{2}G_F}$$

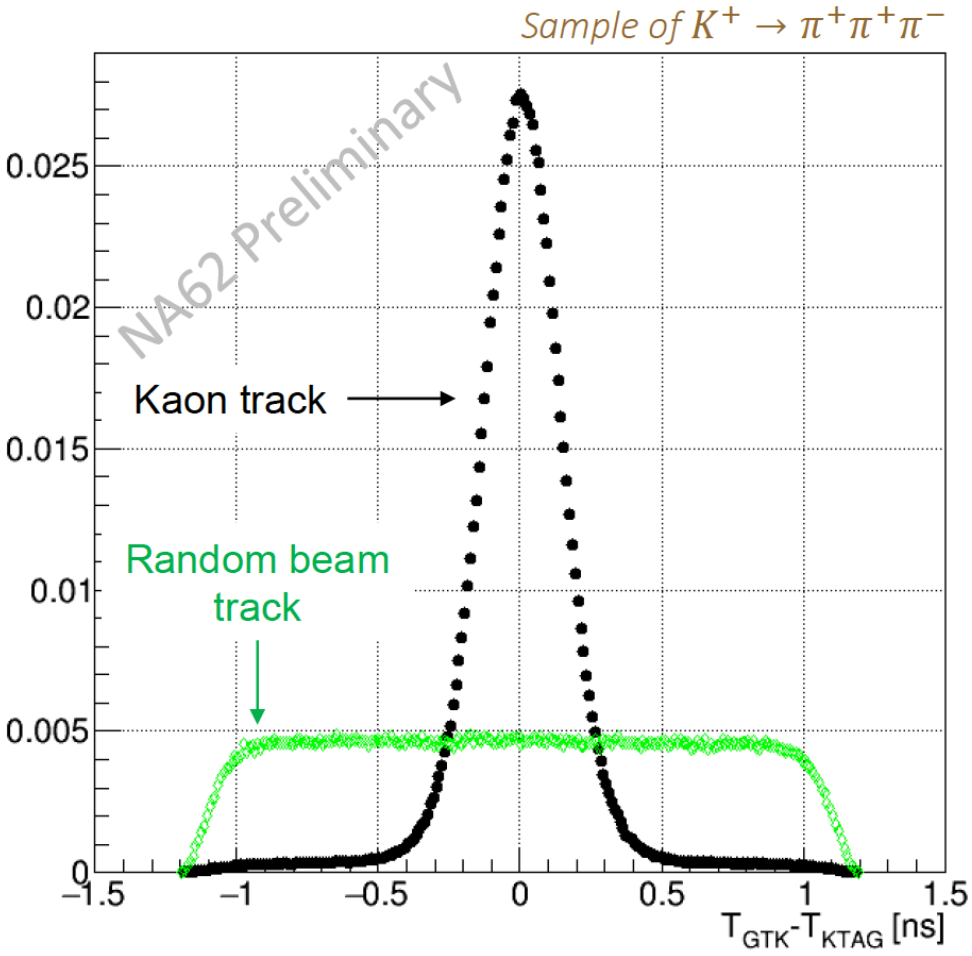
$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = 2\mathcal{B}(K_L \to \pi^0\nu_e\bar{\nu}_e)_{\rm SM} + \mathcal{B}(K_L \to \pi^0\nu_\tau\bar{\nu}_\tau)_{\rm SM} \left|1 - \frac{R_0\,\theta_q^2(1-c_{13})}{(\alpha/\pi)(X_t/s_w^2)}\right|^2$$

Varying θ_q : [Bordone, Buttazzo, Isidori, Monnard, arXiv:1705.10729v1]





NA62: K/π Matching



Timing π^+:

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

Timing K^+:

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

Spatial matching:

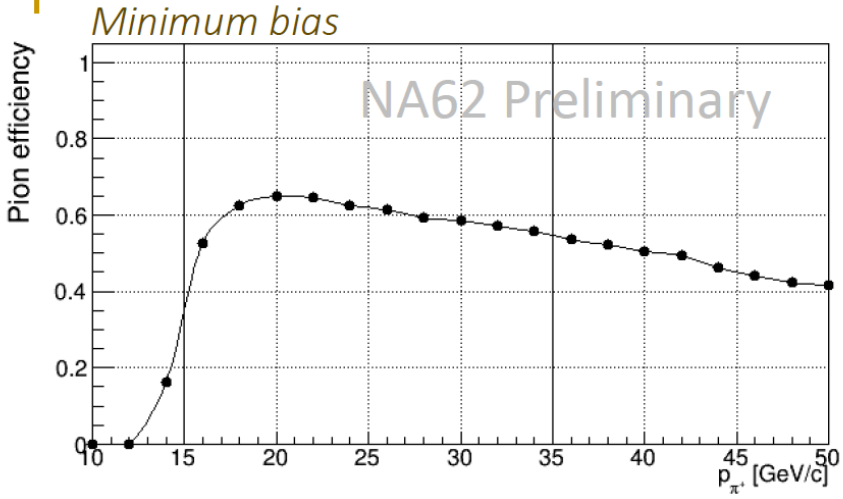
intersection of GTK and Straw track

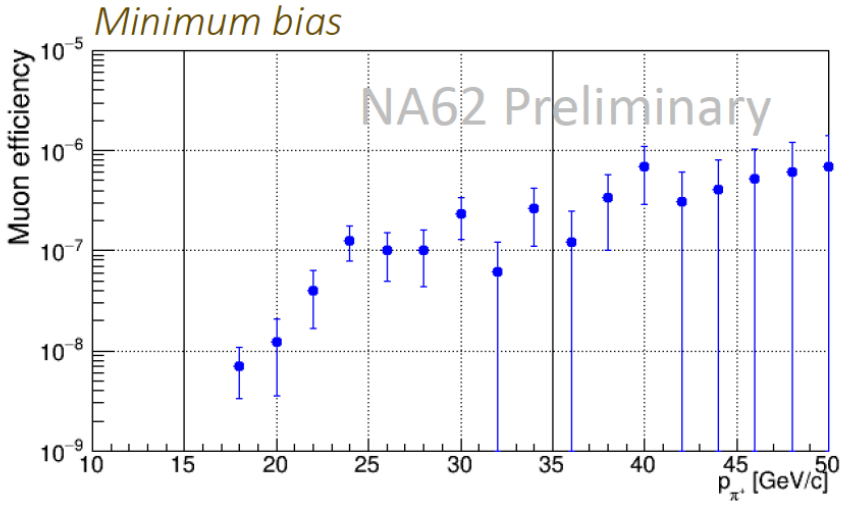
$\sigma(CDA) \sim 1.5$ mm

Mis-tagging probability: ~1.7%

[75% efficiency]

NA62 PID: $\pi^+ - \mu^+$ Separation





Particle ID with calorimeters

$\varepsilon(\mu) \div \varepsilon(\pi) \sim 10^{-5} \div 80\%$

- MVA discriminant

Particle ID with RICH

$\varepsilon_{\mathrm{ring}}(\pi) \sim 90\%$ [depends on p_{π^+}]

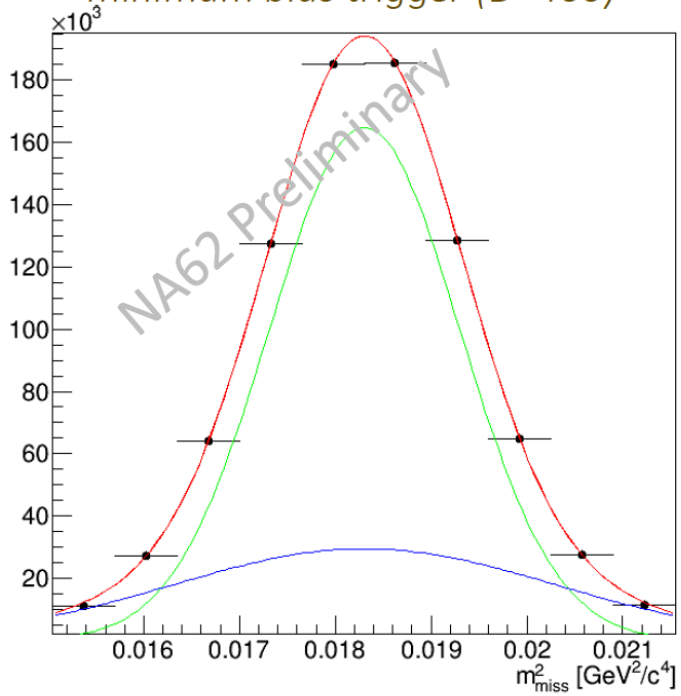
$\varepsilon(\mu) \div \varepsilon_{\mathrm{ID}}(\pi) \sim 10^{-2} \div 80\%$

PID performance measurement:

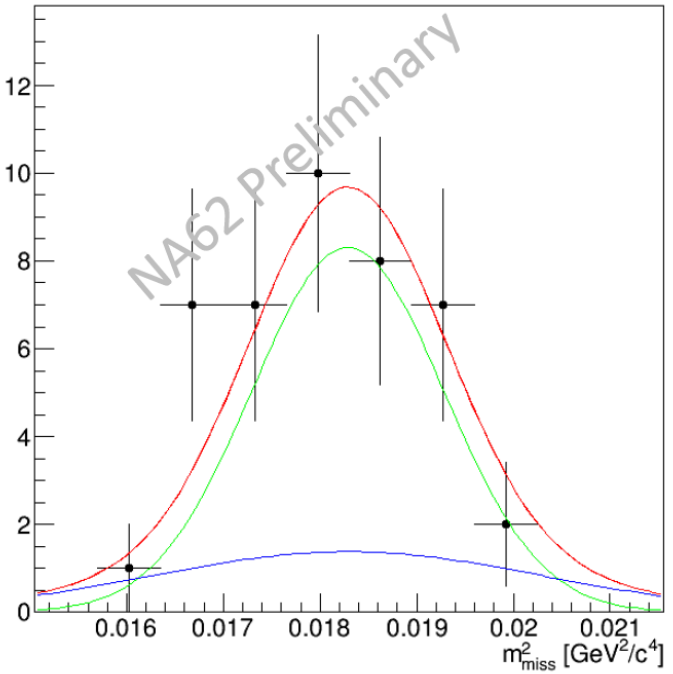
- RICH and calorimeter combined

NA62: Photon Rejection

Before γ-reject., minimum bias trigger (D=400)



After γ-reject., PNN Trigger



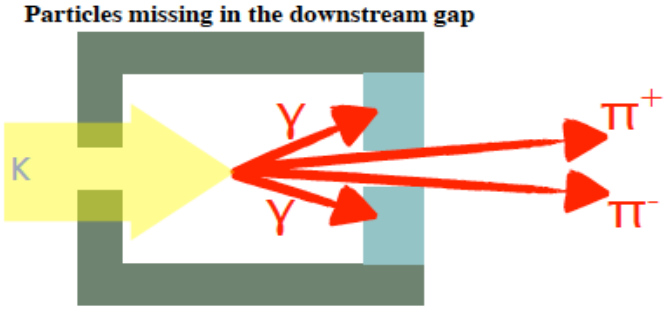
Photon Veto conditions: LKr, LAV, IRC, SAC

$\pi^+\pi^0$ suppression (estimated in $K^+ \to \pi^+\pi^0$ region) $\longrightarrow$ $\epsilon_{\pi^0} = (1.2 \pm 0.2) \times 10^{-7}$

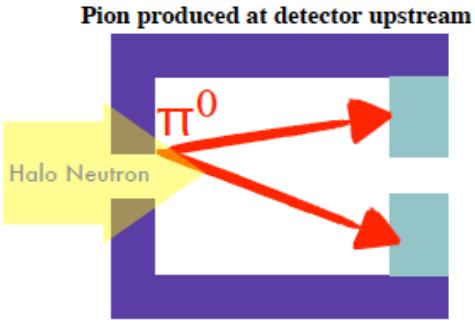
15–16% $\pi\nu\nu$ accidental losses (measured on data)

KOTO $K_L \to \pi^0 \nu\bar{\nu}$ Background

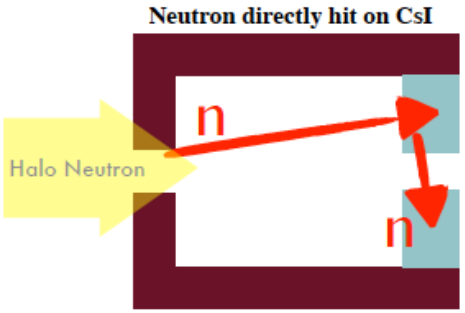
Main Backgrounds to $K_L \to \pi^0 \nu\nu$ in KOTO detector



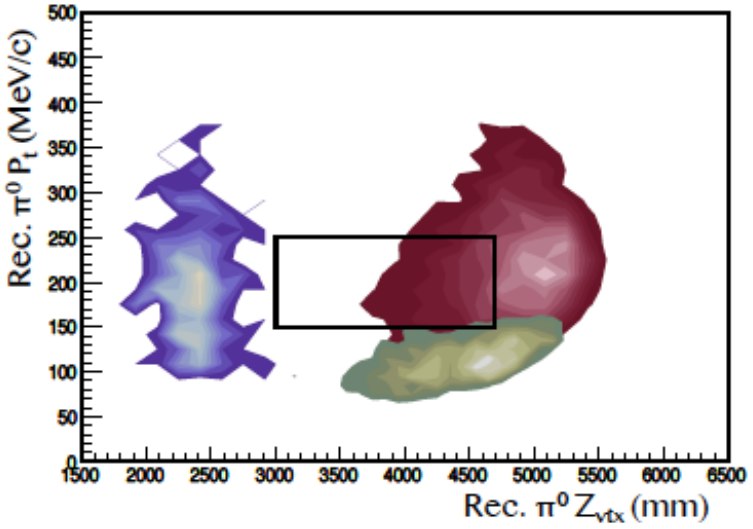
$K_L \to \pi^0\pi^+\pi^-$



Halo Neutrons hitting the NCC



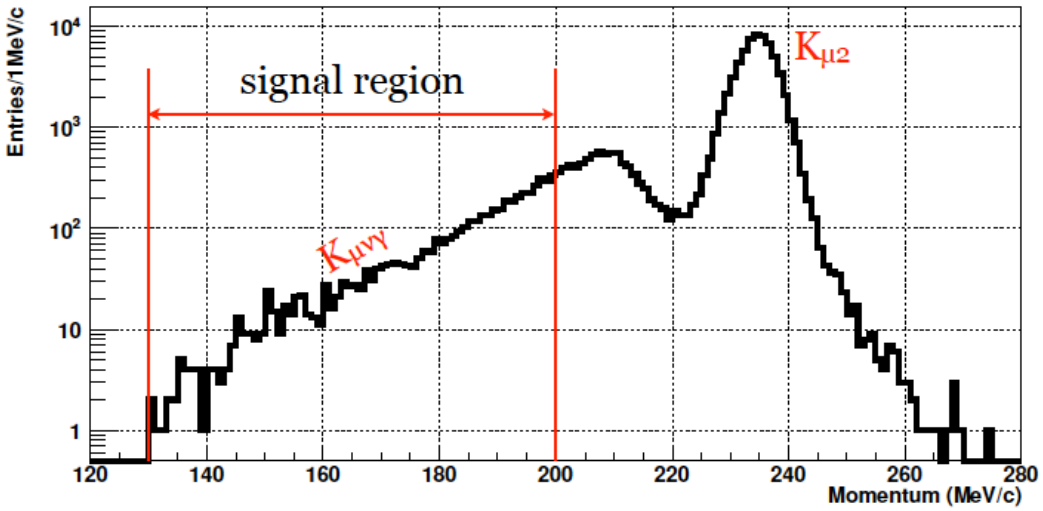
Halo Neutrons hitting the Calo



Rec π^0 (P_T,Z_{vtx}) for backgrounds and analysis signal region

Heavy Neutrino @E949-BNL

Search for ν_h in $K \to \mu\nu_h$ decay



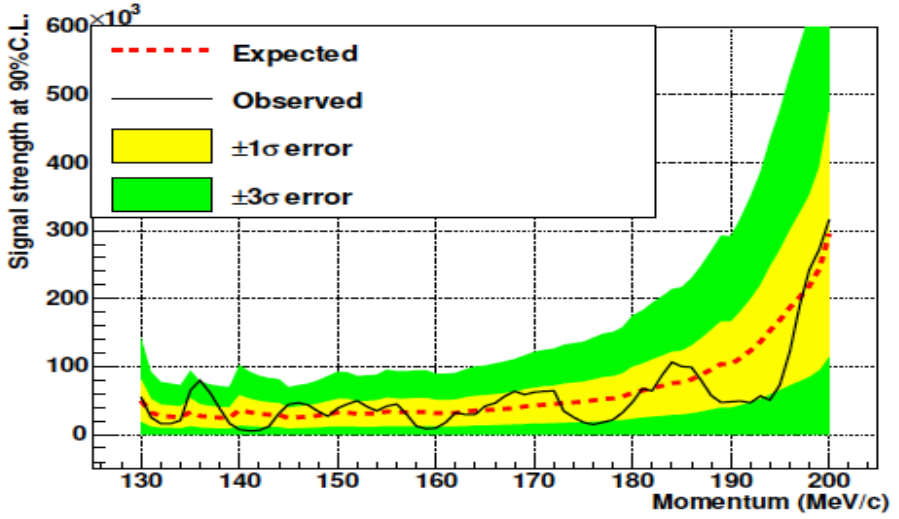
E949 @ KAON2016

[Phys. Rev. D 91, 052001 (2015)]

Sensitivity mass region: 175-300 MeV/c²

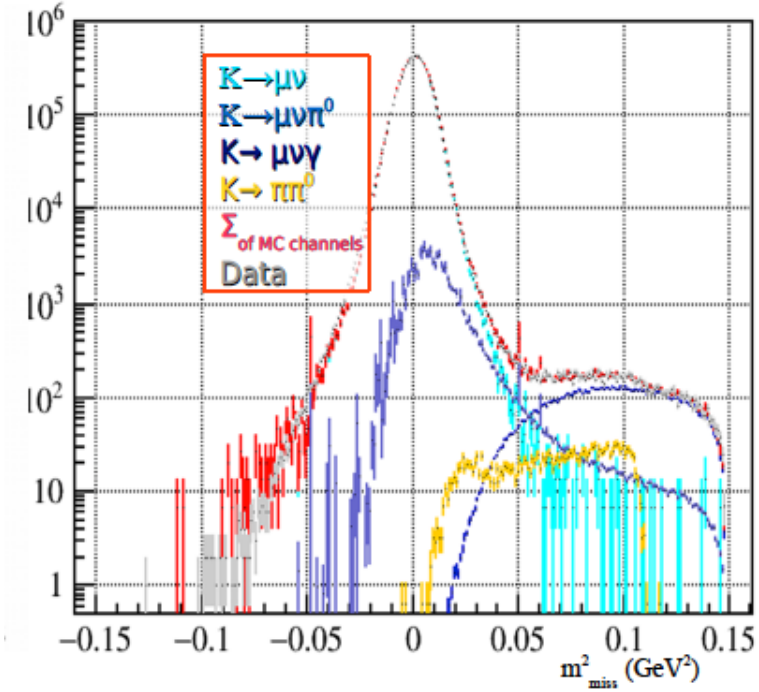
Constraints from CERN PS191 improved by order of magnitude

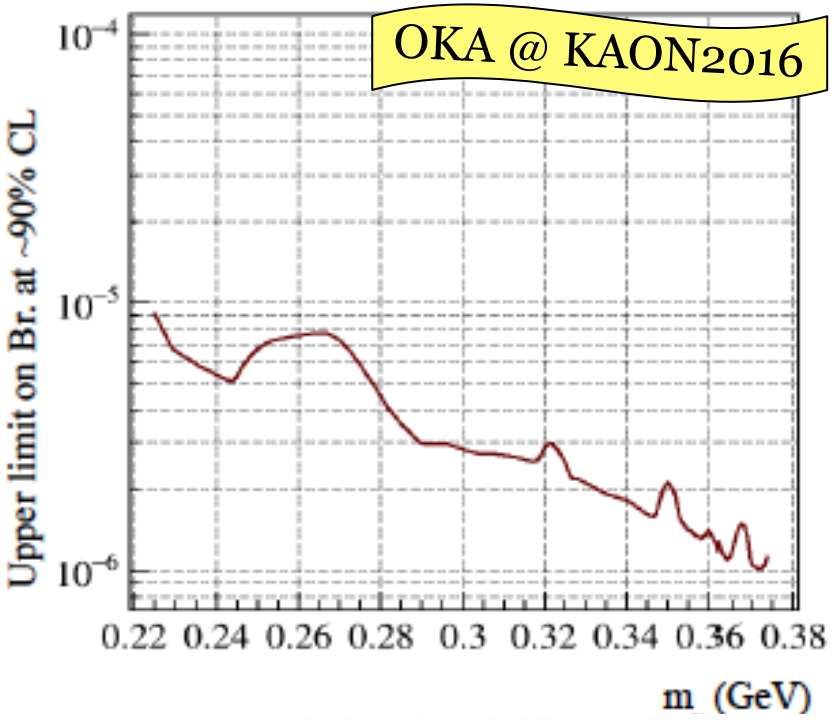
In contrast to CERN PS191 or BBN lower limit E949 result is model independent.



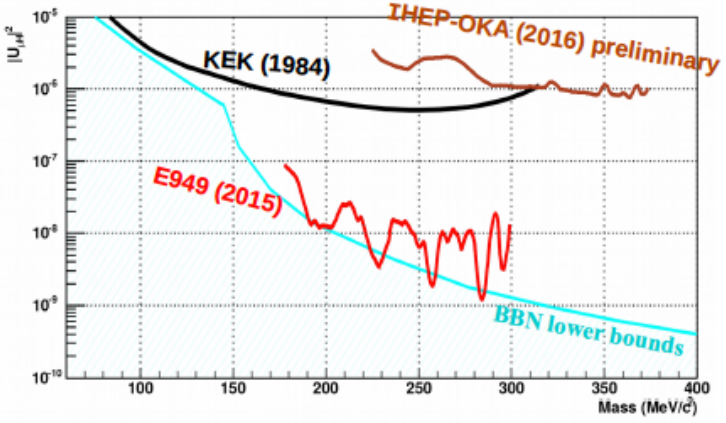
Heavy Neutrino @OKA-IHEP

Search for ν_h in $K \to \mu \nu_h$ decay





Statistics	Nov2010	Nov2011	Nov2012	Apr2013	Total
Beam Energy	12.5 ;17.7	17.7	12.5 ; 17.7	17.7	
Live Kaons, 10^9	6.2	5.1	17.4	12.2	40.9
K2pi, 10^6	15.2	15.5	61	42	134
Ke3, 10^6	2.5	2.0	8.1	~5	~17



Prospects for LFV/LNV with Kaons @ NA62

Search for forbidden states with lepton pair (ee, μμ, μe):

$K^+ \to \pi^+\mu^+e^-$ $\quad$ $K^+ \to \mu^-\nu e^+e^+$

$K^+ \to \pi^+\mu^-e^+$ $\quad$ $K^+ \to e^-\nu\mu^+\mu^+$

$K^+ \to \pi^-\mu^+e^+$

$K^+ \to \pi^-e^+e^+$ $\quad$ $K^+ \to \pi^+\pi^0,\ \pi^0 \to \mu^+e^-$

$K^+ \to \pi^-\mu^+\mu^+$ $\quad$ $K^+ \to \pi^+\pi^0,\ \pi^0 \to \mu^-e^+$

New Physics scenarios involving LFV:

- ✓ Neutrino is a **Maiorana fermion** (identical to antineutrino)
- ✓ Heavy (possible sterile) neutrino states
- ✓ **Supersymmetry** with R-parity violation or RH neutrinos

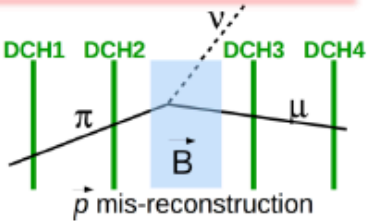
Astrophysical consequences:

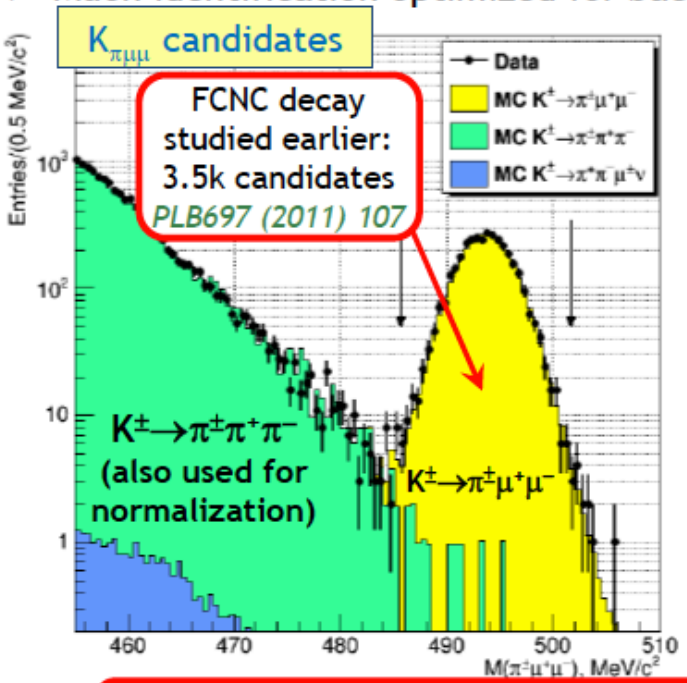
- ✓ **Dark matter**, nucleosynthesis, Supernova evolution, …

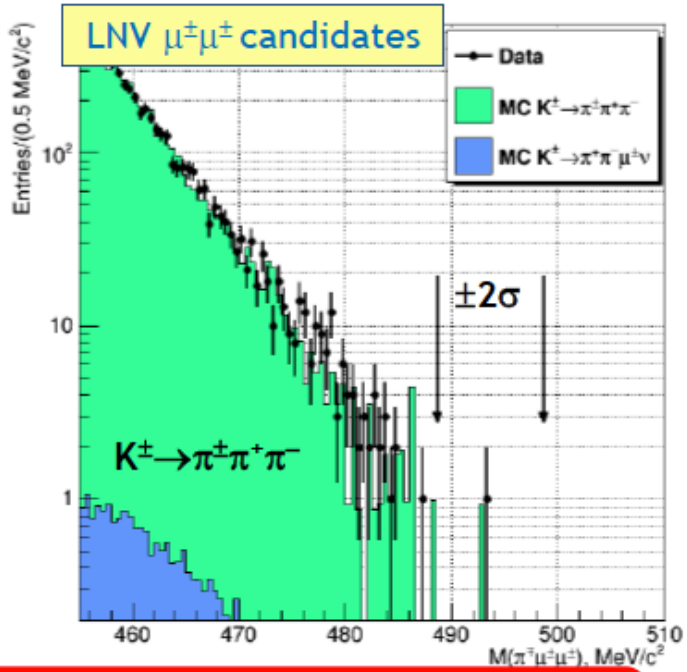
NA62 Recent Results - I

$K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$: lepton number violation

- NA48/2 data sample. $K^{\pm}\to\pi\mu\mu$ selection: 3-track vertex; no missing momentum; muon ID (LKr, muon detector).
- Blind analysis: selection optimized with dedicated MC samples.
- Main background: $K^{\pm}\to3\pi^{\pm}$ with $\pi^{\pm}\to\mu^{\pm}\nu$ decays in flight.
- Muon identification optimized for background reduction.







$N(\mu^{\pm}\mu^{\pm}) = 1$
$N_{bkg} = 1.16\pm0.87$
⇒ $BR(K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}) < 8.6\times10^{-11}$ [90% CL]

20

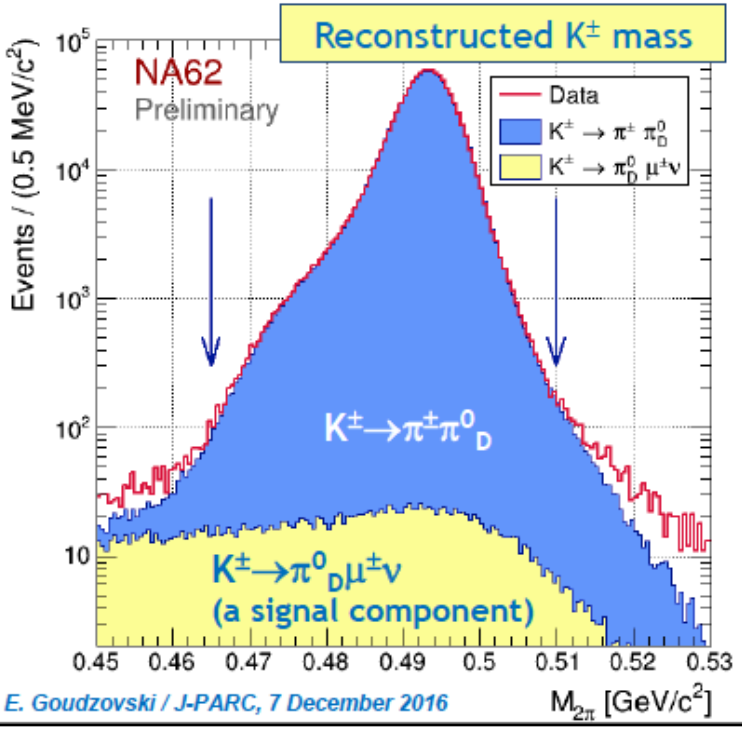
E. Goudzovski / J-PARC, 7 December 2016

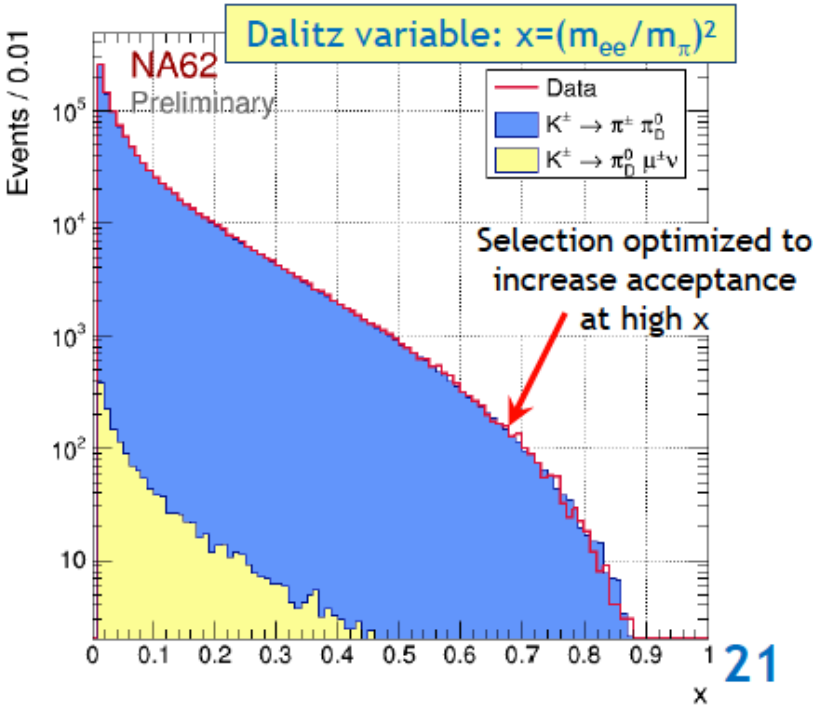
[Factor 13 improvement; final result; paper in preparation]

NA62 Recent Results - II

NA62-R_K: $\pi^0_D \to \gamma e^+ e^-$ sample

- NA62-R_K data: ~2×10^{10} $K^\pm$ decays in the fiducial decay region.
- Reconstructed π^0_D decay candidates, $x=(m_{ee}/m_\pi)^2>0.01$: $N(K_{2\pi D})=1.05\times10^6$.
- Despite ~10 times smaller sample wrt NA48/2, good for spectrum study:
  - ✓ minimum bias trigger: low systematics due to trigger efficiency;
  - ✓ low beam intensity: low systematics due to accidentals.
- Source of π^0 considered: $K^\pm \to \pi^\pm \pi^0$ decay (BR=20.7%).





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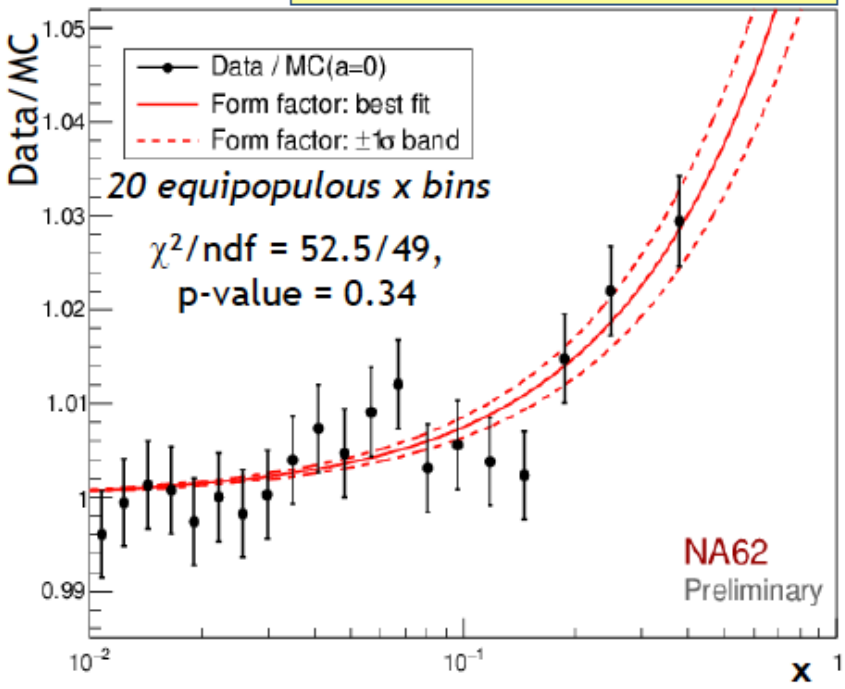
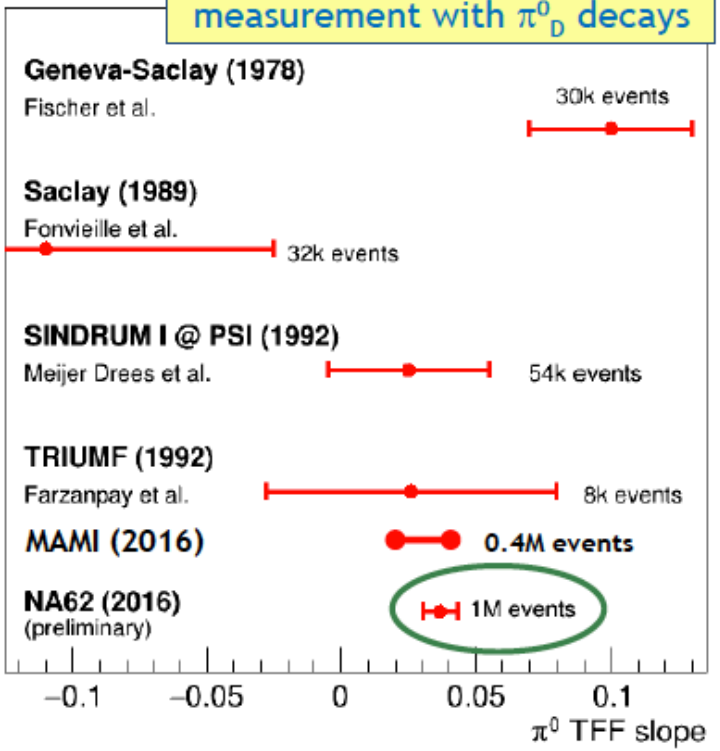
NA62 Recent Results - III

TFF slope measurement: result

Fit illustration: Data/MC(a=0)



World data: π^0 TFF slope measurement with π^0_D decays



NA62-R_K preliminary result (2016):

$a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst}) \times 10^{-2}$

[final result & paper in preparation]

Most precise measurement (5.8σ) of *TFF slope* in the time-like momentum transfer region.

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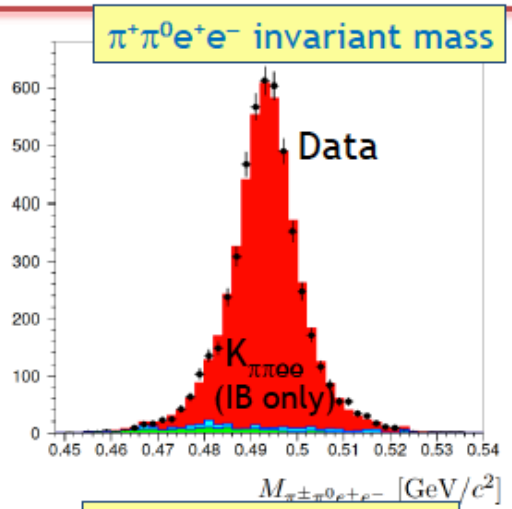
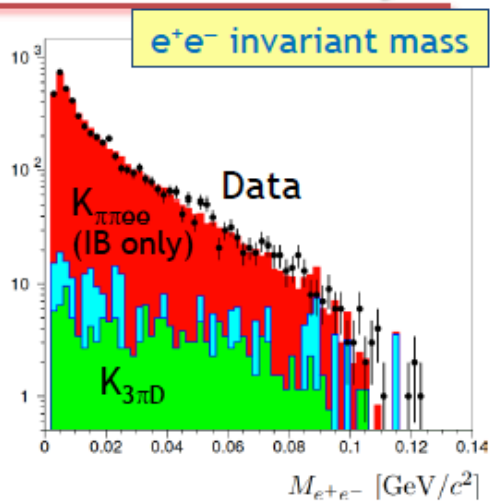
NA62 Recent Results - IV

New NA48/2 results on rare decays

First observation of the $K^{\pm}\to\pi^{\pm}\pi^{0}e^{+}e^{-}$ decay:

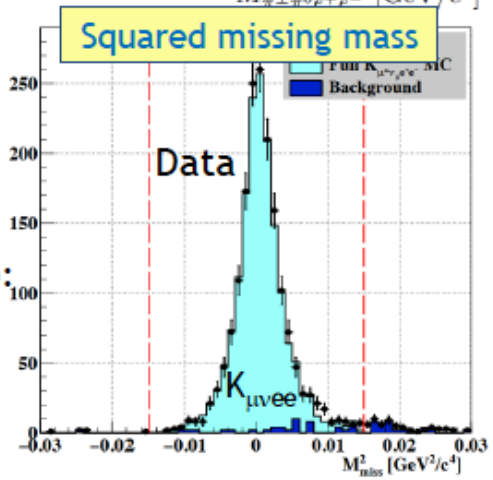
- Observe 5.1k candidates with 5% background.
- Decay rate measurement: $BR=(4.22\pm0.15)\times10^{-6}$.
- In agreement with ChPT expectations.

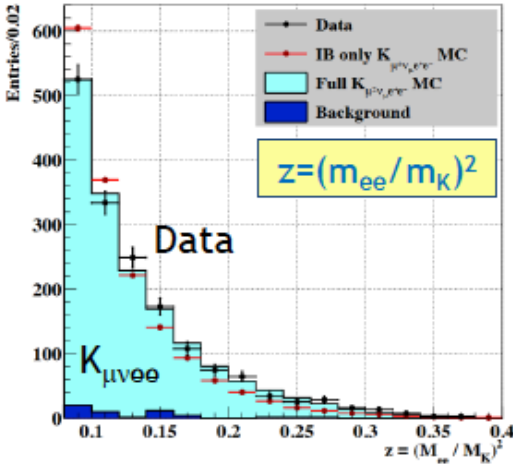




New measurement of the $K^{\pm}\to\mu^{\pm}\nu e^{+}e^{-}$ decay:

- Observe 1.7k candidates with 3% background.
- Model-independent rate measurement (m_{ee}>140 MeV/c^2): $BR=(7.84\pm0.23)\times10^{-8}$.
- In agreement with ChPT expectations; evidence for direct emission term.





Preliminary results reported in KAON 2016 and ICHEP 2016 proceedings

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$K_{\pi 0 \nu\nu}$ @ CERN SPS

Idea to make the measurement at the SPS:

1) High energy experiment ($<p_{K>}$=70 GeV for K_L decays in FV), complementary to KOTO
2) Photons from K_L decays boosted forward - makes photon vetoing easier, but more more demanding geometry
3) Perhaps possible to reuse NA62 infrastructure

- 400 GeV protons on 400 mm Be target
- Production at 2.4 mrad to optimize K_L versus neutron
- For ~100 events and reasonable acceptance:

Require 2 x 10^{13} protons per pulse/ 16.8 s = 6 x NA62

Currently not available, would require upgrades

Aim to take ~60 SM events in 5 years from 2026 with S/B~1
Project discussed at CERN as part of Physics Beyond Collider