Marie Skłodowska-Curie Actions

UNIVERSITY OF BIRMINGHAM

Hidden sector searches at the NA62 experiment

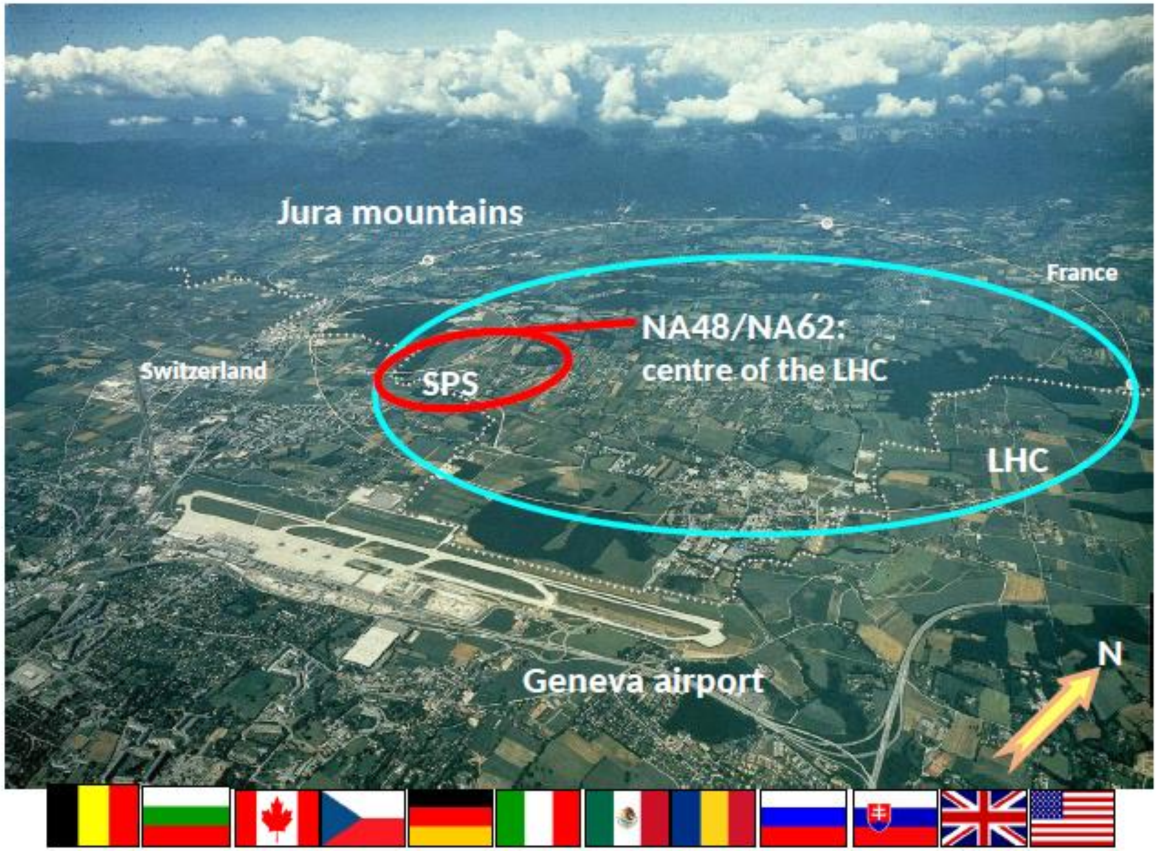
Viacheslav Duk, NA62 collaboration

Seminar at the University of Birmingham, November 14, 2018

Outline

- NA62 experiment
- First results on $K^+ \to \pi^+ \nu \bar{\nu}$
- Hidden sector searches at NA62
  - Neutrino portal
  - Vector portal
  - Scalar portal
- Conclusions

NA62 experiment at CERN SPS



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

NA62 timeline

- ✓ **2015:** commissioning (1% of the nominal beam intensity I_0)
- ✓ **2016:** commissioning + physics (40% I_0)
- ✓ **2017:** physics (60% I_0)
- ✓ **2018:** physics (60% I_0)

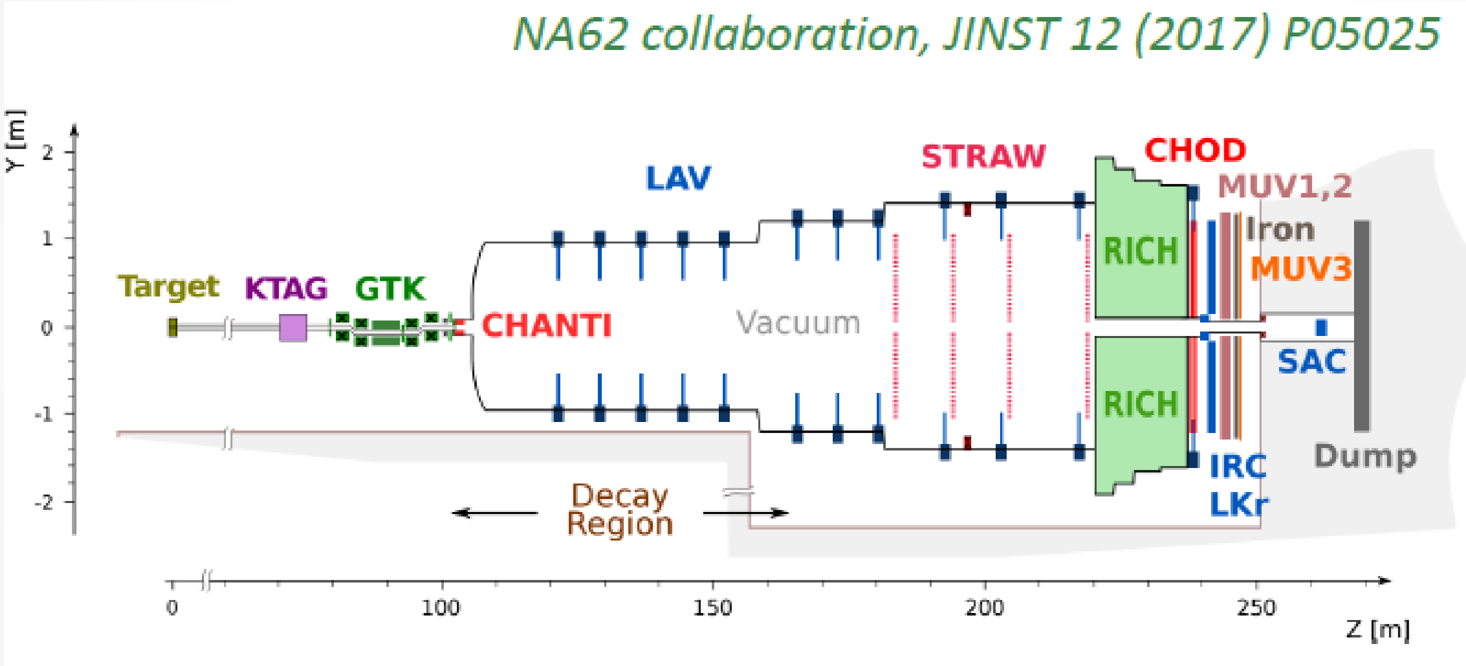
NA62 future

- **2021-2022:** approved

NA62 experiment

Main goal: 10% precision measurement of BR ($K^+ \rightarrow \pi^+ \nu \bar{\nu}$)

Technique:
K^+ decays in flight



Primary beam:

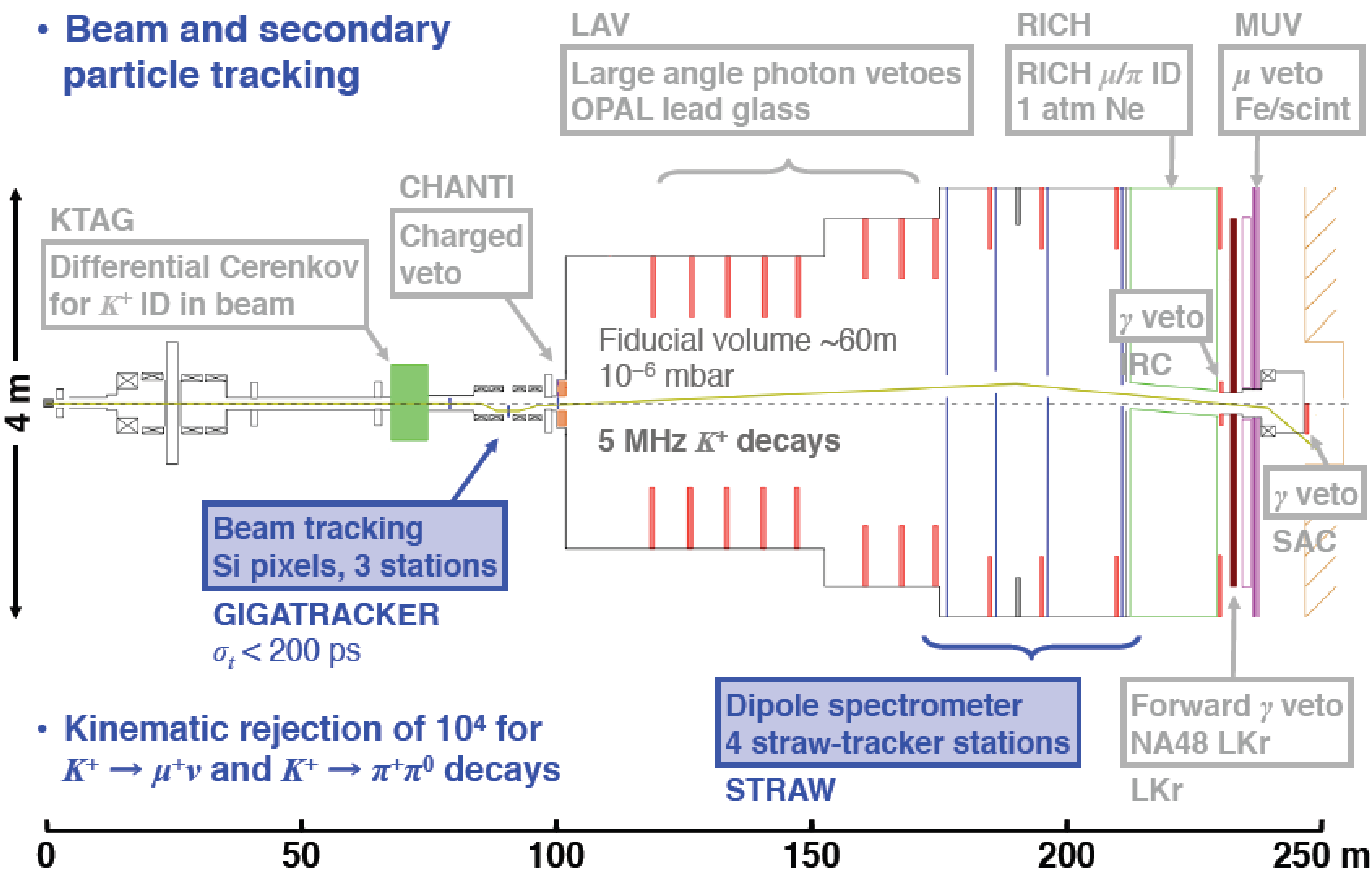
- p = 400 GeV SPS protons
- 10^{12} protons/effective second

Secondary beam:

- p = 75 GeV positive, unseparated
- Total rate: 750 MHz
- K^+ rate: 45 MHz

NA62 detectors: trackers

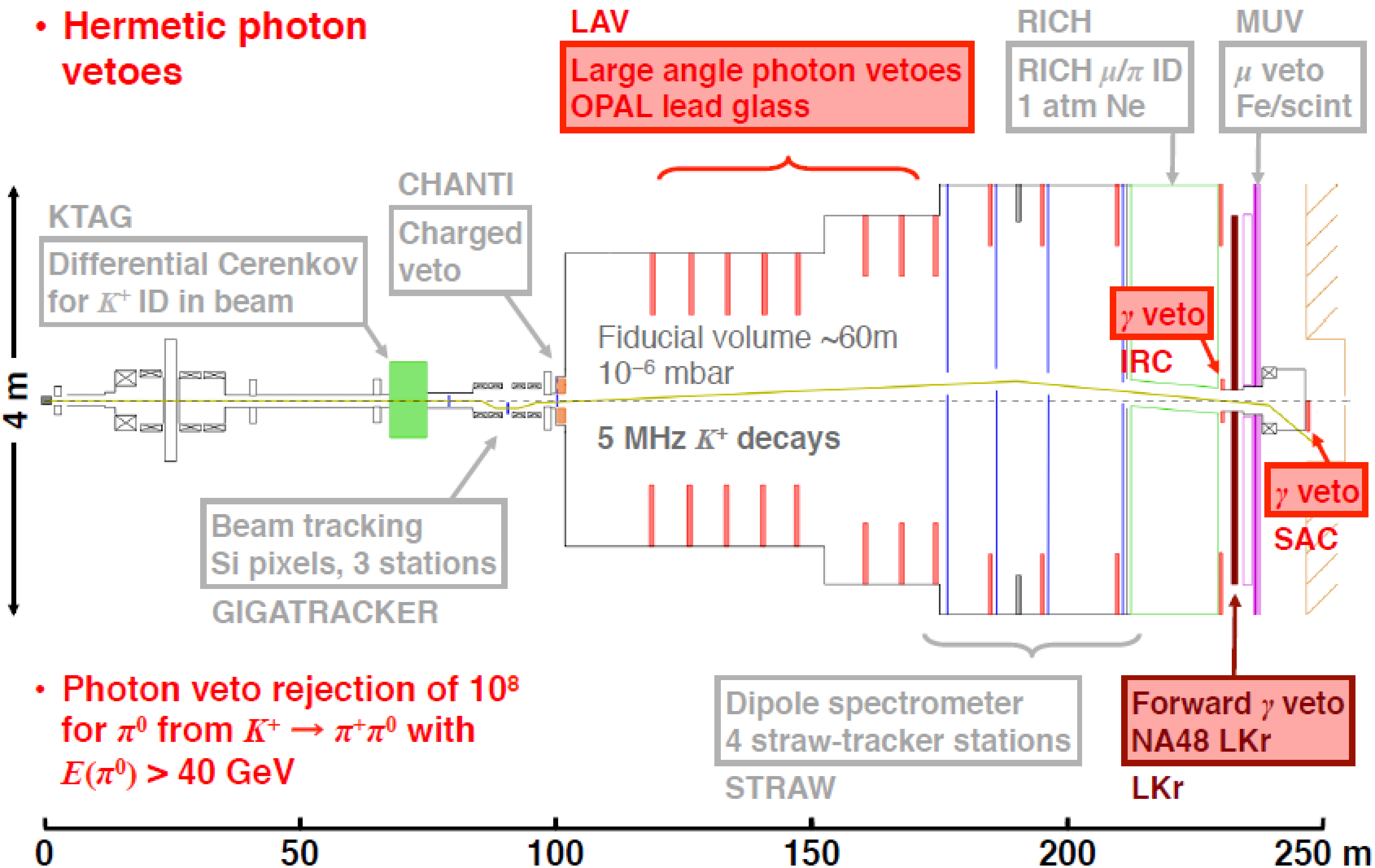
- **Beam and secondary particle tracking**



- **Kinematic rejection of 10^4 for $K^+ \rightarrow \mu^+\nu$ and $K^+ \rightarrow \pi^+\pi^0$ decays**

NA62 detectors: vetoes

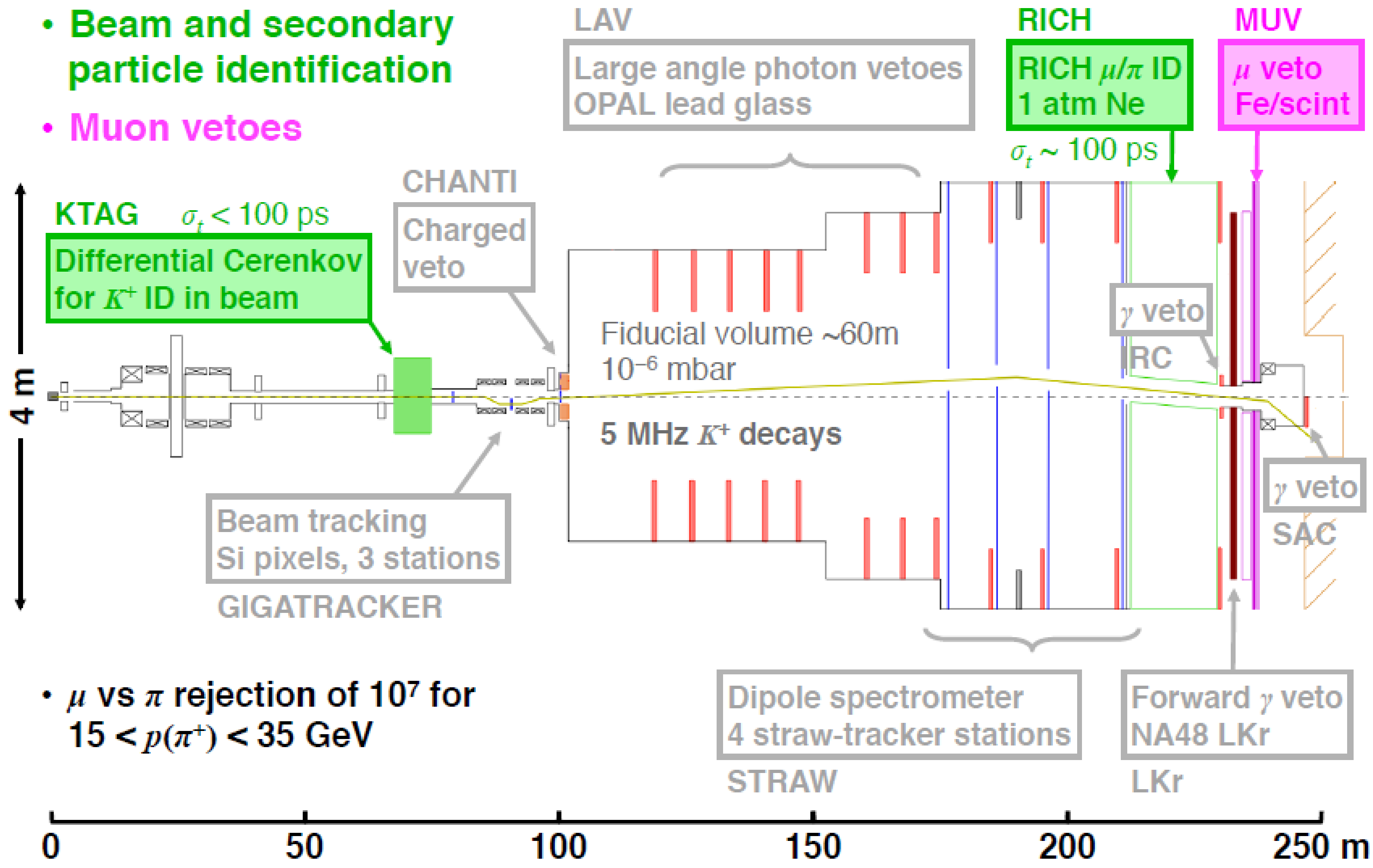
- **Hermetic photon vetoes**



- **Photon veto rejection of 10^8 for π^0 from $K^+ \rightarrow \pi^+\pi^0$ with $E(\pi^0) > 40$ GeV**

NA62 detectors: PID

- **Beam and secondary particle identification**
- **Muon vetoes**



- μ vs π rejection of 10^7 for $15 < p(\pi^+) < 35$ GeV

FCNC processes

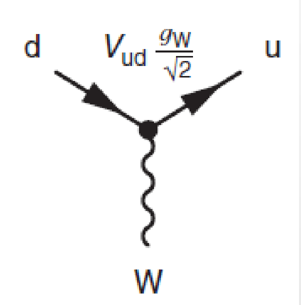
Weak interactions:

- Quarks are organized in doublets $\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L$
- Weak current: quarks are rotated by a unitary matrix V (CKM matrix)

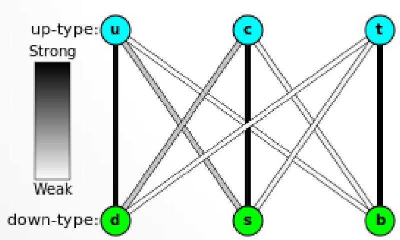
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

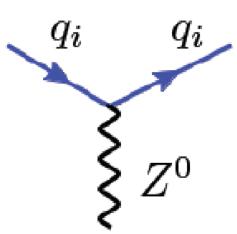
$$j^{\mu}_{du} = -i\frac{g_W}{\sqrt{2}} V_{ud}\, \overline{u}\gamma^{\mu}\tfrac{1}{2}(1-\gamma^5)d$$

- Quark flavor changes in charge currents



- Flavor does not change in neutral currents at tree level





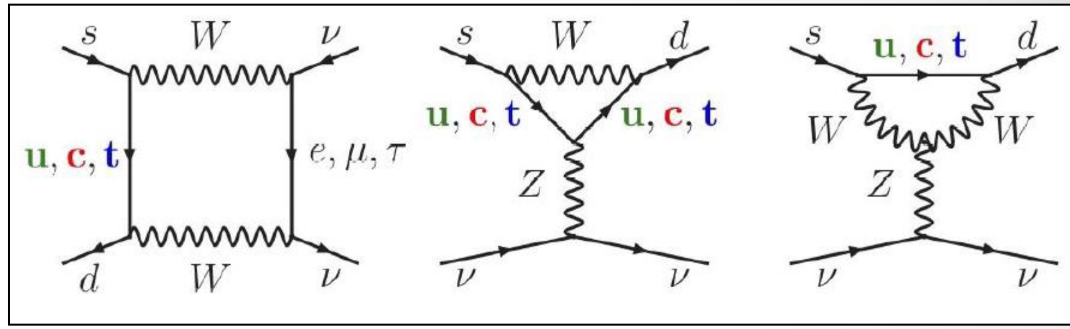
- FCNC (**flavor changing neutral current**) processes are allowed at loop level

$K \to \pi\nu\bar{\nu}$ in SM

2 modes: charged, neutral

- FCNC loop process
- Theoretically clean
- CKM suppression: BR ~ $|V^*_{ts}\ V_{td}|^2$

SM one-loop diagrams: box and penguins



Hadronic matrix element extracted from well-known decay $K^+ \to e^+\nu\pi^0$

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5}X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda}P_c(X)\right)^2\right](1+\Delta_{EM})$$

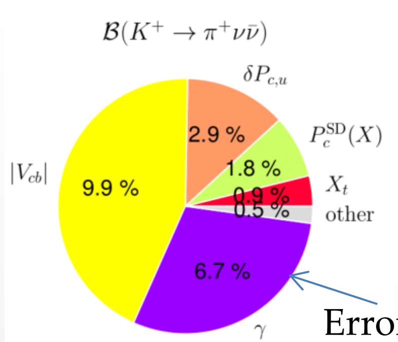
$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2$$

charm contribution

EM radiative correction

Top contribution (dominant)

$$\lambda = V_{us}$$
$$\lambda_c = V^*_{cs}V_{cd}$$
$$\lambda_t = V^*_{ts}V_{td}$$
$$x_q \equiv m_q^2/m_W^2$$



Error budget for BR(SM)

SM branching ratios

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

$\mathrm{BR}(K^0 \to \pi^0\nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$

[Buras et al. JHEP 1511 (2015) 33]

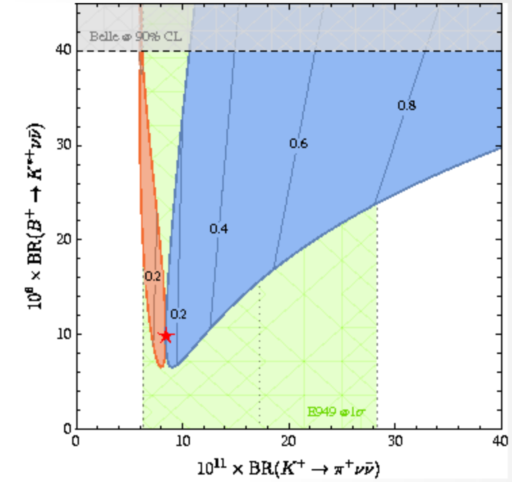
K→πνν̄ in New Physics

Searches for NP in K→πνν̄:

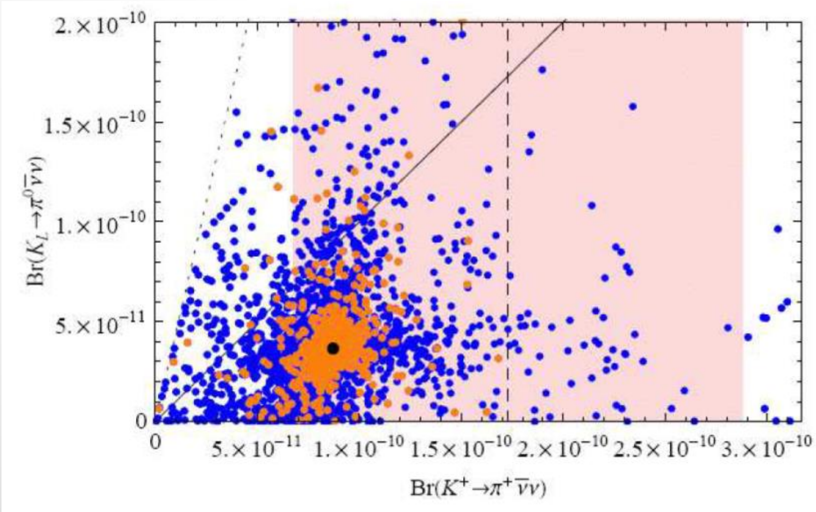
- High masses and sizable couplings to SM
- Constraints from existing measurements
- Best constraints: from charged and neutral mode

- Custodial Randall-Sundrum [Blanke et al., JHEP 0903 (2009) 108]
- Simplified Z′ [Buras, Buttazzo, Knegjens, JHEP 11(2015) 166]
- LFU violation [Isidori et al., Eur. Phys. J. C (2017) 77: 618]

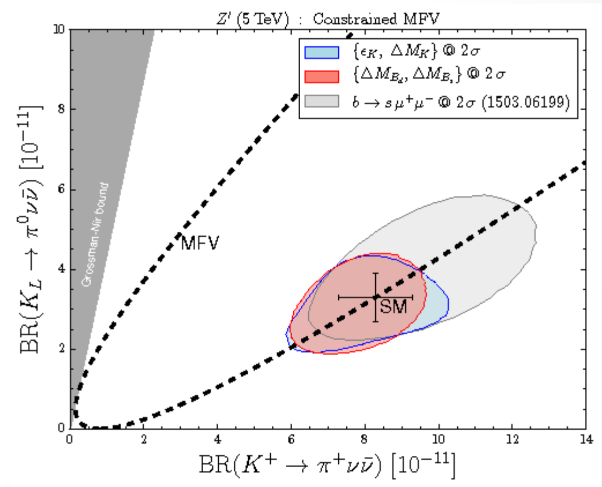
LFU violation



Randall-Sundrum



Z′ (5 TeV) in constrained MFV



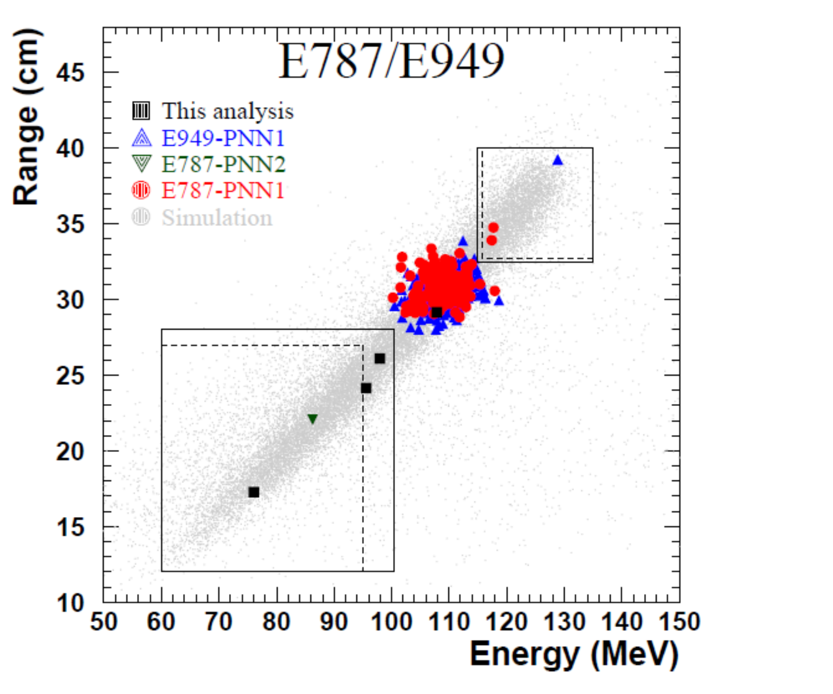
NP effect on BR: factor of 2-3 enhancement

$K \to \pi\nu\bar{\nu}$ in experimental physics

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

E949 experiment @ BNL

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$



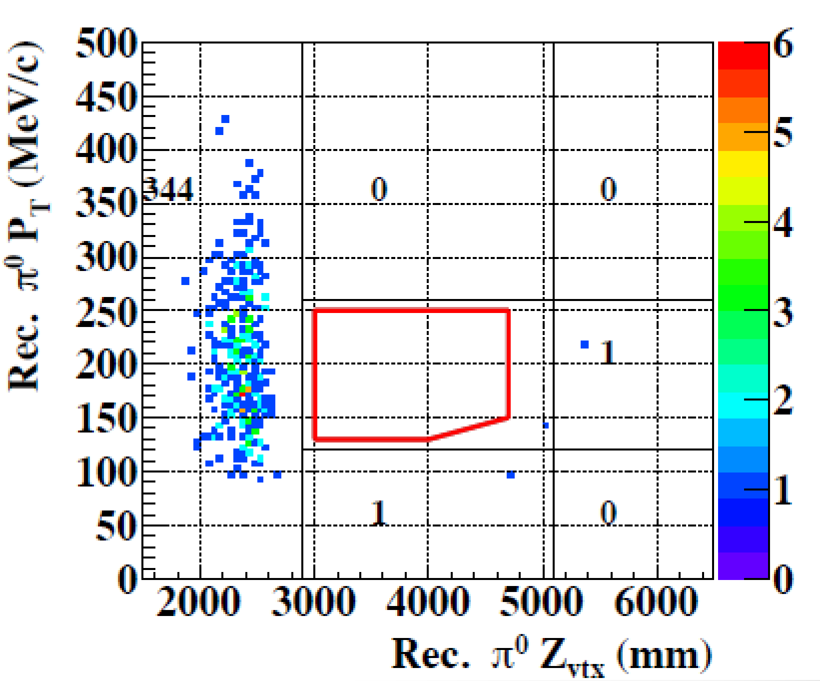
Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)

Technique: stopped kaons

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

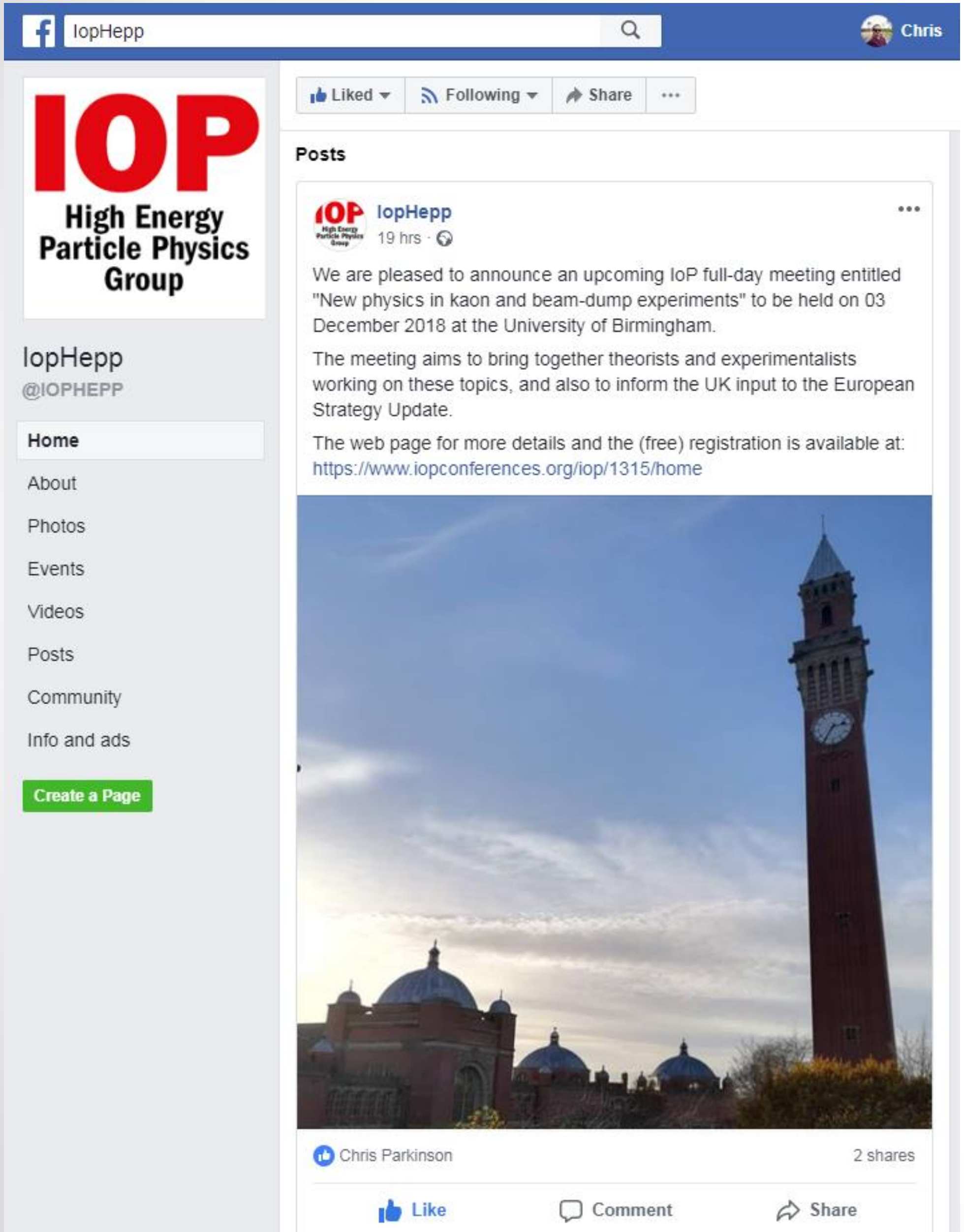
KOTO experiment @ JPARC

$BR(K_L \to \pi^0 \nu\bar{\nu}) < 3.0 \times 10^{-9}$ @ 90% CL



Talk @ ICHEP-2018, analysis of the 2015 data

Find out more on December 3rd!

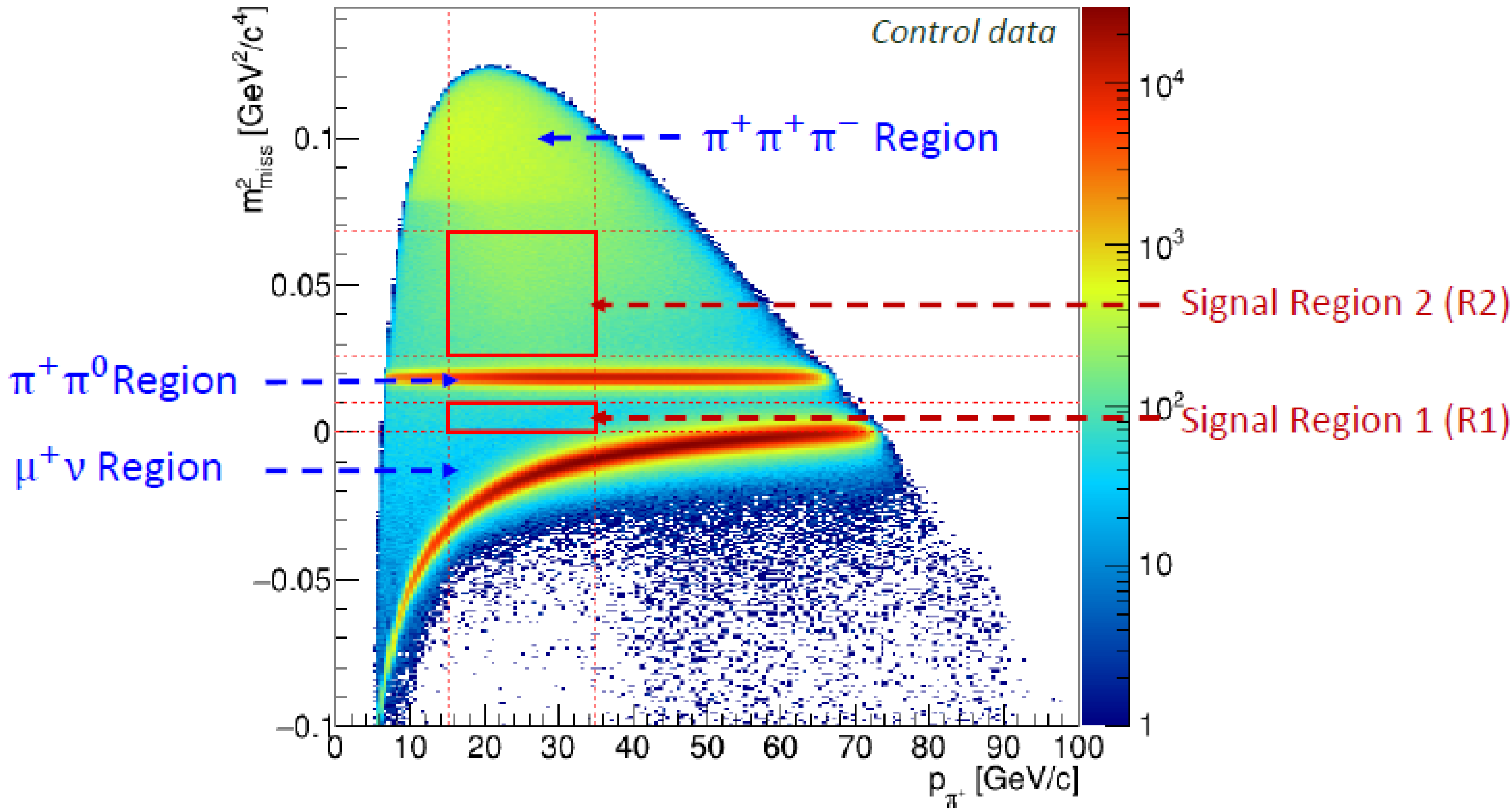


IoP one-day meeting at UoB:

New physics in kaon and beam-dump experiments

NA62: analysis of 2016 data

$m^2_{miss} \equiv m^2_{miss}(\text{Straw}, \text{GTK}) = (P_{\pi^+} - P_{K^+})^2$, m_{π^+} hypothesis



SES and backgrounds

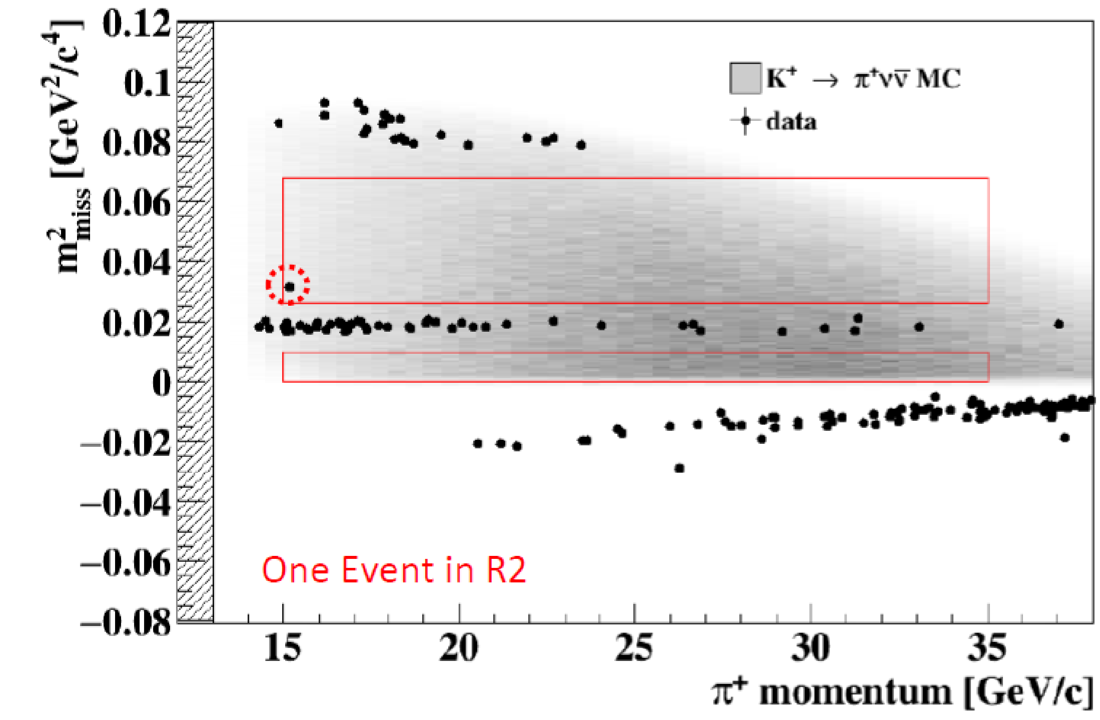
Process	Expected events in R1+R2
$K^+ \to \pi^+ \nu \bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{\mathrm{stat}} \pm 0.01_{\mathrm{syst}}$
$K^+ \to \pi^+ \pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+ \nu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+ \pi^- e^+ \nu$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+ \pi^+ \pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream Background	$0.050^{+0.090}_{-0.030}\vert_{stat}$

Signal acceptance : 4 %

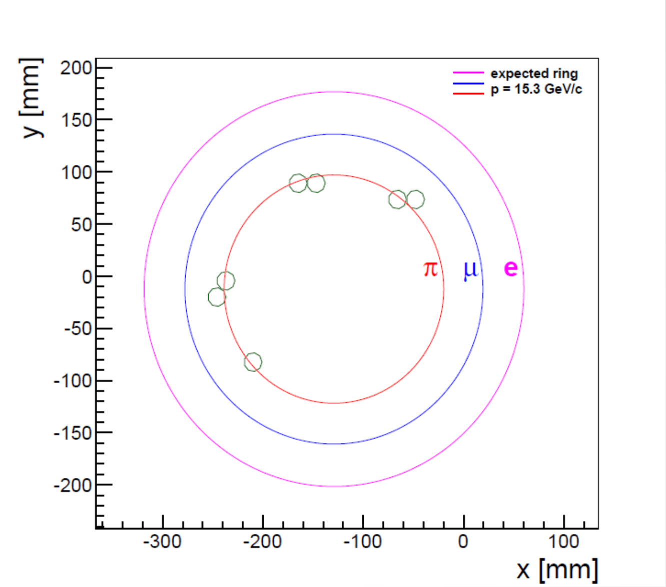
Number of kaon decays in the fiducial volume : $N_K = 1.21(2) \times 10^{11}$

$$SES = (3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$$

Results and prospects



Event in the RICH



2016 data

Upper limit setting (Rolke-Lopez method):
- Poissonian signal
- Gaussian background

$$BR(K^+ \to \pi^+\nu\bar{\nu}) < 11 \times 10^{-10}\ @\ 90\%\ CL$$

$$BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10}\ @\ 95\%\ CL$$

Prospects for 2017-2018 data sample:
- ~20 SM events
- Improved background rejection

New Physics and hidden sector

New Physics searches at NA62

High masses & sizable couplings to SM (short-lived)

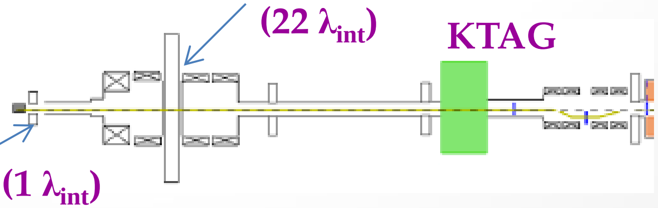
Indirect effects in loops (e.g. $K^+ \rightarrow \pi^+ \nu\nu$)

Low masses & feeble couplings to SM (long-lived) → **hidden sectors**

New particle searches

this talk ←

mode	production	decay	trigger
Kaon decays	fiducial volume (FV)	FV or fly away	Standard (K-decays)
Parasitic	target	FV	Dilepton
Beam-dump	collimator	FV	Dilepton, diphoton



Hidden sector searches at NA62

Neutrino portal:
mixing with ν

Vector portal:
Mixing with γ

Scalar portal:
Mixing with H

Hidden sector searches at NA62

Neutrino portal:
Search for heavy neutral lepton N in $K^+ \to \mu^+ N$

Vector portal:
Search for dark photon A′ in $K^+ \to \pi^+ \pi^0$, $\pi^0 \to \gamma A'$

Scalar portal:
Search for inflaton/sgoldstino S in $K^+ \to \pi^+ S$, $S \to \mu^+ \mu^-$

Heavy neutral leptons (HNL): motivation

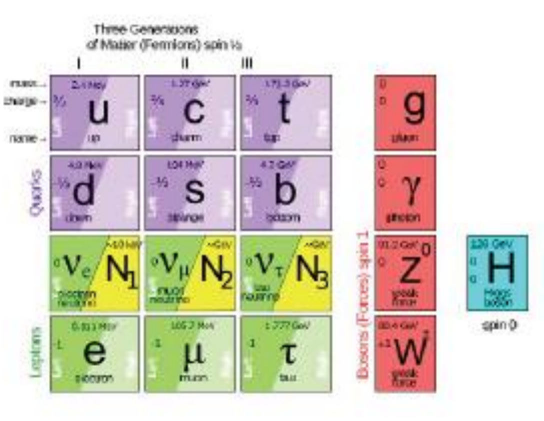
Three major tensions in SM:

- Neutrino oscillations
- Dark Matter
- Baryon asymmetry of the Universe

SM extension resolving all 3 problems: νMSM

- 3 heavy neutral leptons (heavy neutrinos) N_1, N_2, N_3
- m_1~10 keV (DM candidate)
- m_2, m_3 ~ 1 GeV (BAU, neutrino oscillations)

[*Asaka et al., PLB 620 (2005) 17*]



Heavy neutrino searches in kaon decays:

- Kinetic mixing between SM neutrinos and N
- **Production search** in $K^+ \to l^+ N$ (Kl2) ; l=e, μ
- $m(N) < m_K - m_l$
- Signature: peak in $m^2_{miss} = (P_K - P_l)^2$

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

Mixing matrix element

SM decays

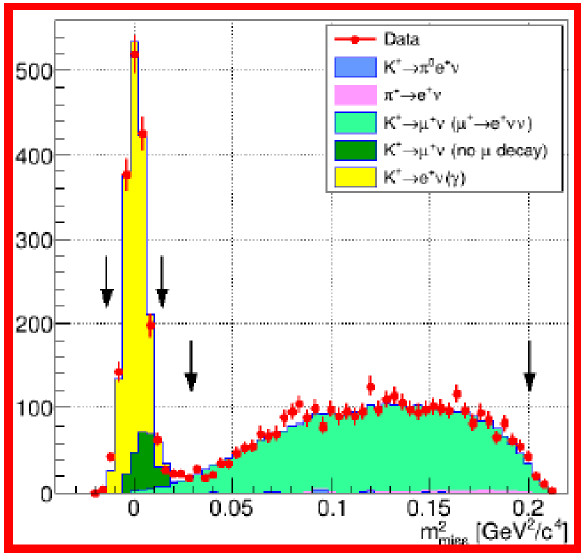
- BR(Kμ2) ~0.64
- BR(Ke2) ~1.6*10^{-5}

HNL search at NA62

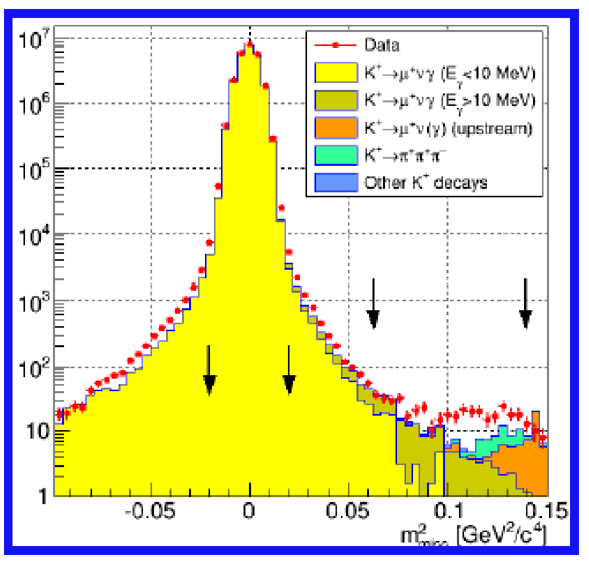
Data sample:

- 2015, N_K~$3*10^8$
- Low intensity
- Beam tracker (GTK) not used

$K^+ \to e^+ N$ (1767 candidates)
Normalization: $K^+ \to e^+ \nu_e$
Mass scan region: 170-448 MeV/c^2



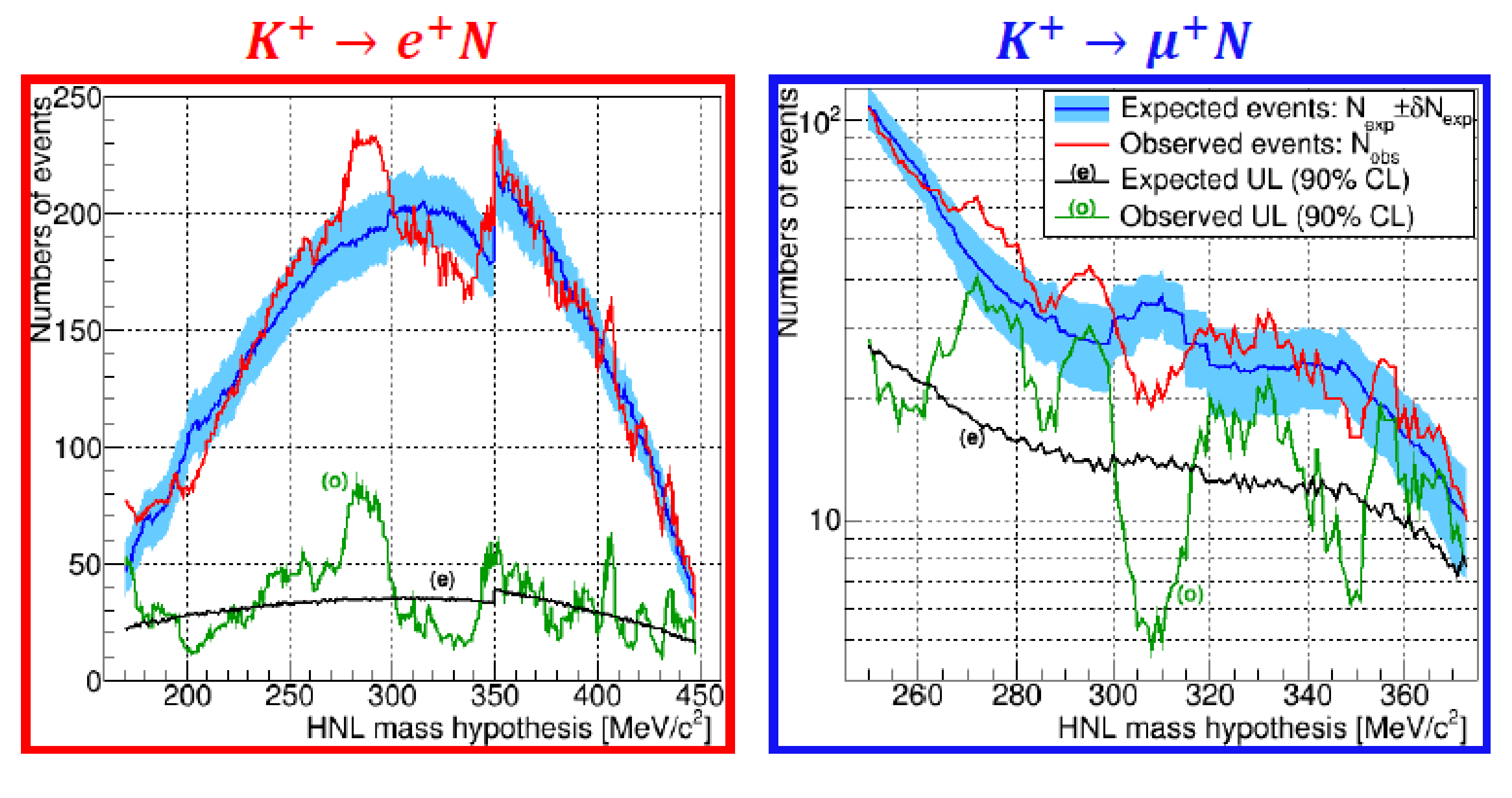
$K^+ \to \mu^+ N$ (24M candidates)
Normalization: $K^+ \to \mu^+ \nu_\mu$
Mass scan region: 250-373 MeV/c^2



Heavy neutrino search in 2015 data

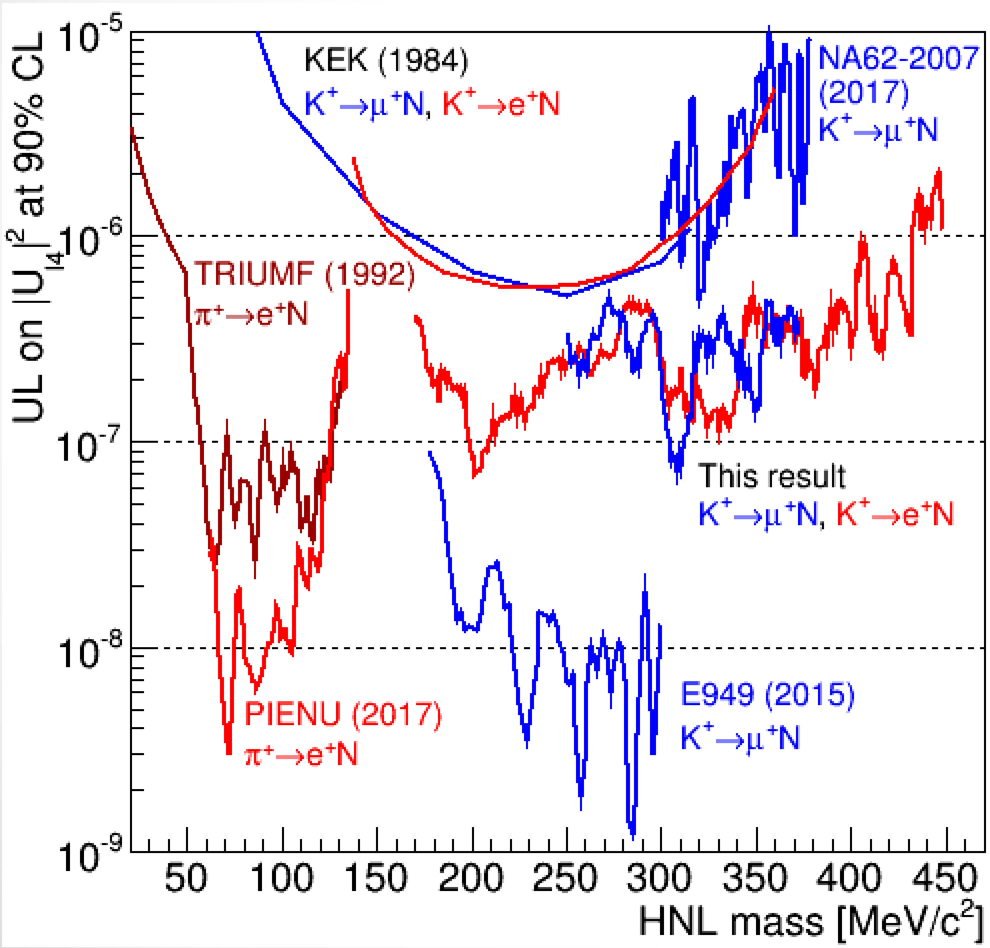
Rolke-Lopez method used to find upper limits on number of signal events

- Heavy neutrino mass step: $1\,\mathrm{MeV}/c^2$
- Search window size for each mass hypothesis: $\pm 1.5\,\sigma(m_N)$



Upper limits on $|U_{14}|^2$

n^l_{UL} → $B(K^+ \to \ell^+ N) = \frac{n^{\ell}_{UL}}{N^{\ell}_{K} \cdot A^{\ell}_{N}(m_N)}$ → $|U_{\ell 4}|^2 = \frac{B(K^+ \to \ell^+ N)}{B(K^+ \to \ell^+ \nu)} \times \frac{1}{\rho(m_N)}$



First NA62 physics result !

[*PLB 778 (2018) 137*]

Prospects for 2016-2018 data:

- Better resolution (GTK)
- Much higher statistics

Expected limits: $\sim 10^{-9}$ on $|U_{e4}|^2$, $\sim 10^{-8}$ on $|U_{\mu 4}|^2$

Hidden sector searches at NA62

Neutrino portal:
Search for heavy neutral lepton N in $K^+ \to \mu^+ N$

Vector portal:
Search for dark photon A′ in $K^+ \to \pi^+ \pi^0$, $\pi^0 \to \gamma A'$

Scalar portal:
Search for inflaton/sgoldstino S in $K^+ \to \pi^+ S$, $S \to \mu^+ \mu^-$

Dark photons

Models with dark photons (DP):

- Can explain (g-2) anomaly
- DP is a mediator between DM and SM particles
- DP can be light (MeV – GeV)
- DP feebly interacts with γ (kinetic mixing)

Dark photon searches at NA62:

Visible mode

- Decay searches in $\pi^0 \to \gamma A'$, $A' \to e^+ e^-$ — NA48/2: Phys Lett B 746 (2015), p. 178-185

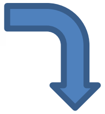
Invisible mode

- Production searches in $K^+ \to \pi^+ \pi^0$, $\pi^0 \to \gamma A'$ → This talk
- Production searches in $K^+ \to \pi^+ A'$

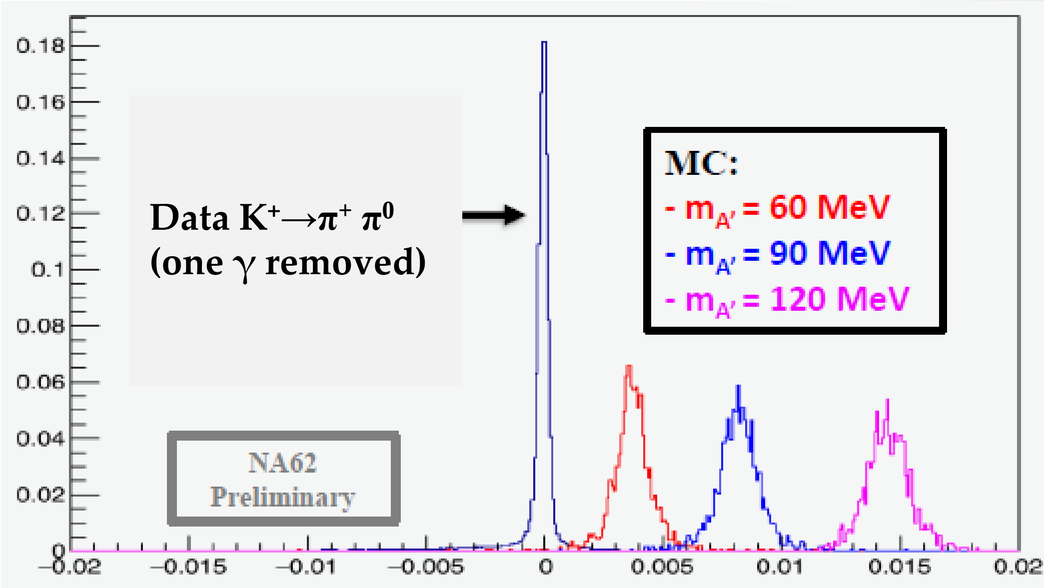
Dark photon search at NA62

Decay channel: $K^+ \to \pi^+ \pi^0$, $\pi^0 \to \gamma A'$
Normalization: $K^+ \to \pi^+ \pi^0$
Data: 4% of 2016, $N_K \sim 1.5 \cdot 10^{10}$
Main variable:

$$BR(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \times BR(\pi^0 \to \gamma\gamma)$$



$$M_{miss}^2 = (P_K - P_\pi - P_\gamma)^2$$



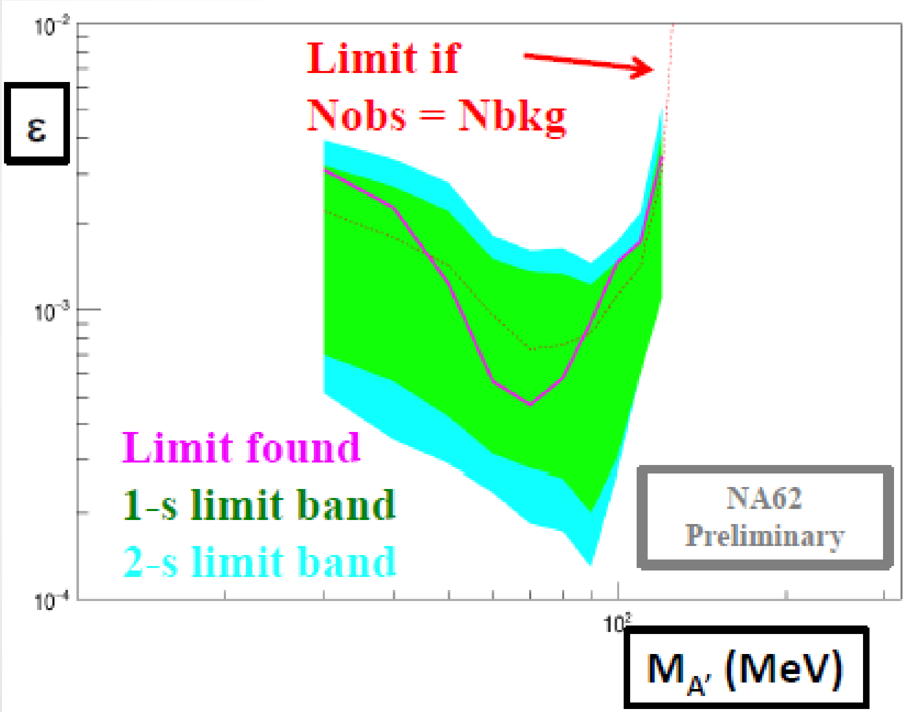
M^2_{miss} [GeV²/c⁴]

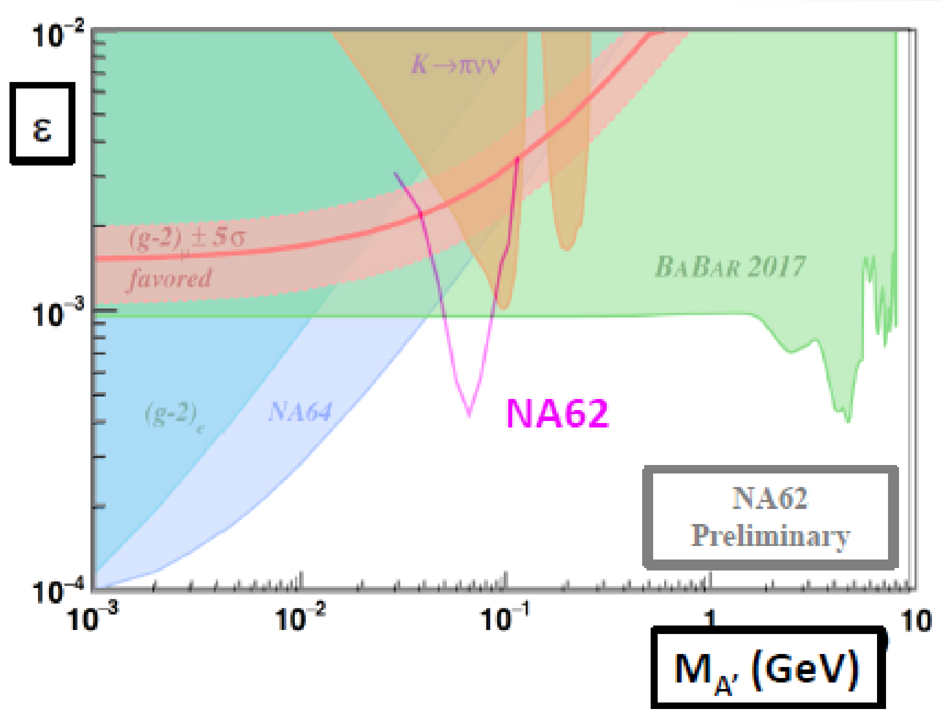
Analysis principle:
Look for peaks in M^2_{miss}
Scan over m(A′)

Dark photon search at NA62

$n_{UL} \Rightarrow BR(n_{UL}) \Rightarrow \varepsilon^2$

$$BR\left(\pi^0 \to A'\gamma\right) = 2\epsilon^2 \left(1 - \frac{m_A^2}{m_{\pi^0}^2}\right)^3 \times BR\left(\pi^0 \to \gamma\gamma\right)$$





No signal observed
Limits for m=30 to 105 MeV

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Vector portal:
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Scalar portal:
Search for inflaton/sgoldstino S in $K^+ \to \pi^+ S$, $S \to \mu^+ \mu^-$

Search for a new scalar in $K^+ \to \pi^+ S$ ($S \to \mu^+ \mu^-$)

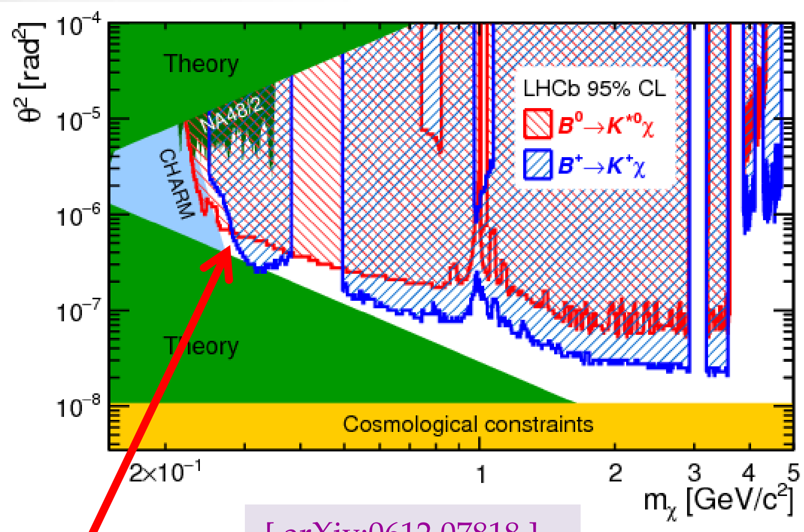
Light inflaton model:

- Inflaton **X** is a new scalar
- 3 parameters in the model, 2 free
- Inflaton production: B and K decays are governed by the same parameters
- Inflaton decays to SM particles

Low energy SUSY models :

- Sgoldstinos **P** (pseudoscalar) and **S** (scalar) are superpartners of goldstino
- No strict limits on the mass and lifetime
- Sgoldstino production: K and ∑ decays are driven by the same coupling constants
- P and S can be light and decay to SM particles

Experimental limits (inflaton search):



[arXiv:0612.07818]

Region accessible in $K^+ \to \pi^+ S$, $S \to \mu^+\mu^-$:
$\theta^2 \sim 4*10^{-7}$ (m~270-300 MeV)

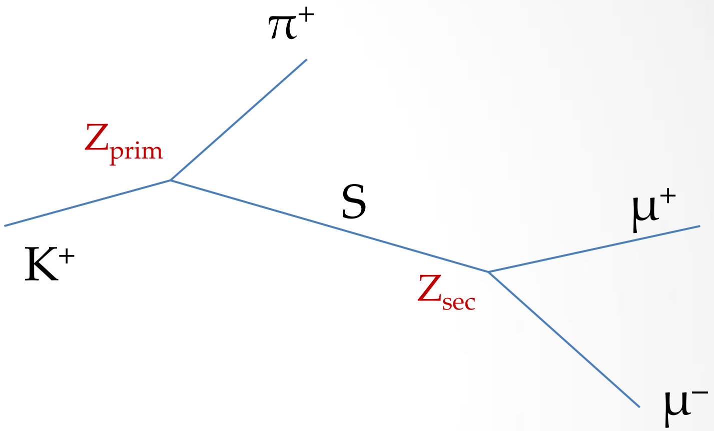
Experimental limits (sgoldstino search):

- Hyperon decays: $\Sigma^+ \to pP^0, P^0 \to \mu^+\mu^-$
  HyperCP, LHCb [arXiv:hep-ex/0501014] [arXiv:1712.08606]
- K_L decays: $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$
  kTeV [arXiv:1105.4800]
- $K^\pm$ decays: $K^+ \to \pi^+ S, S \to \mu^+\mu^-$
  NA48/2 [arXiv:1612.04723]

Search for a new scalar at NA62 in $K^+ \to \pi^+ S$ ($S \to \mu^+ \mu^-$)

NA62 prospects:

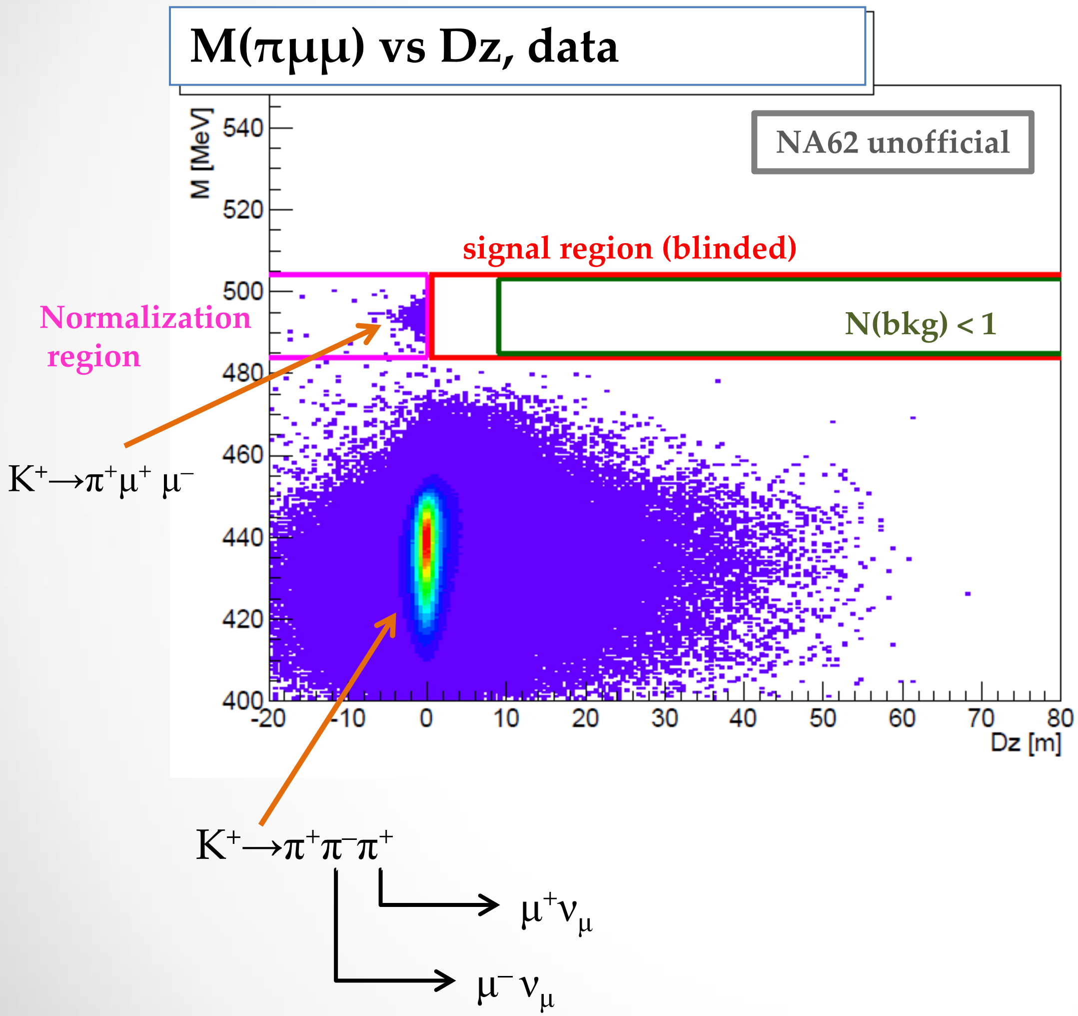
- $O(10^{12})$ K decays in 2016-2017
- Almost background free for long-lived particles
- Acceptance O(1)% for long-lived particles

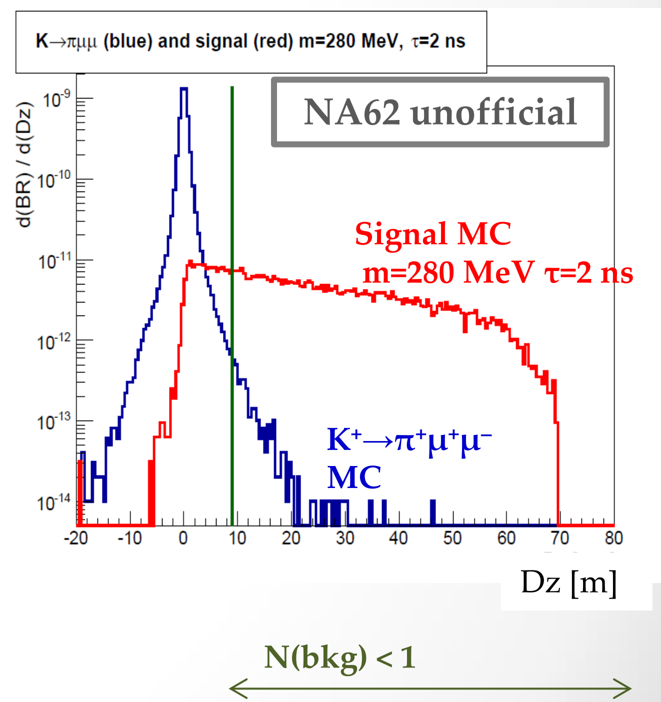


Analysis principles:

- Displaced vertex approach: K-π (primary), μ-μ (secondary)
- Main kinematical variables: $Dz = Z_{sec} - Z_{prim}$ and $M_K = M(\pi\mu\mu)$
- Main backgrounds: $K^+ \to \pi^+ \mu^+ \mu^-$ and $K \to \pi^+ \pi^+ \pi^-$ followed by two $\pi \to \mu \nu_\mu$
- Signal region: $484 < Mk < 504$ MeV, $Dz > 0$
- Normalization: $K^+ \to \pi^+ \mu^+ \mu^-$ in $484 < M_K < 504$ MeV, $Dz < 0$

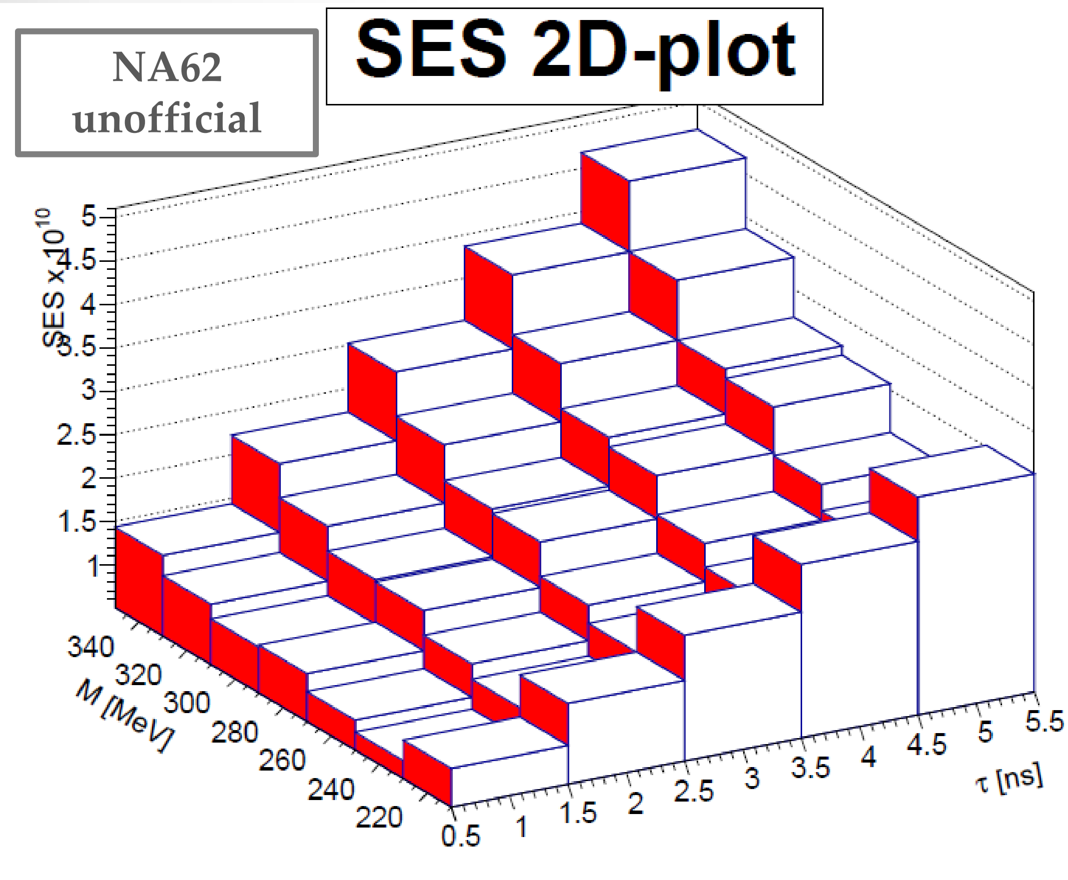
Search for a new scalar at NA62 in $K^+ \to \pi^+ S$ ($S \to \mu^+ \mu^-$)





Search for a new scalar at NA62 in $K^+ \to \pi^+ S$ ($S \to \mu^+ \mu^-$)

SES = 1 / (N_K*Acc)



2016+2017(part) data sample

- $N_K \sim 5.6 \times 10^{11}$
- SES: from 0.7×10^{-10} to 5×10^{-10}
- Best limits: m~240 MeV

Large τ: acc ~ τ^{-1}
Large m: π at rest ($K^+ \to \pi^+ S$), low acceptance
Small m: parallel muons, bad secondary vertex

Conclusions

- ✓ NA62 first physics result published [*PLB 778 (2018) 137*]
- ✓ First results on $K^+ \rightarrow \pi^+ \nu \nu$, paper in preparation
- ✓ Good prospects for hidden sector searches with 2016-2018 data

Neutrino portal :
- ❑ Limits on $|U_{e4}|^2$ from $K^+ \rightarrow e^+ N$ @ 10^{-6} to 10^{-7} (170-448 MeV/c^2)
- ❑ Limits on $|U_{\mu 4}|^2$ from $K^+ \rightarrow \mu^+ N$ @ 10^{-6} to 10^{-7} (250-373 MeV/c^2)
- ❑ 2015 data: published
- ❑ 2016 data: analysis in progress

Vector portal :
- ❑ limits on ε from $K^+ \rightarrow \pi^+ \pi^0$, $\pi^0 \rightarrow \gamma A'$ @ 10^{-3} to 10^{-4}
- ❑ 2016 data: analysis in progress

Scalar portal :
- ❑ SES~10^{-10} for long-lived scalars in $K^+ \rightarrow \pi^+ S$, $S \rightarrow \mu^+ \mu^-$
- ❑ 2016-2017 data: analysis in progress

Spare

Dark photon: parasitic mode

Search for A' produced in target or dump with decay to e^+e^- or $\mu^+\mu^-$ in FV

- Meson decays: From primary beam secondaries, e.g., $pN \to X\pi^0$, $\pi^0 \to \gamma A'$
- Bremsstrahlung from primary beam: $pN \to XA'$

Sensitivity estimate assumes:

- **10^{18} pot on Be target**
- Production in meson decays and bremsstrahlung
- Reconstruction of both e^+e^- and $\mu^+\mu^-$ channels
- 90% CL exclusion in zero-background assumption

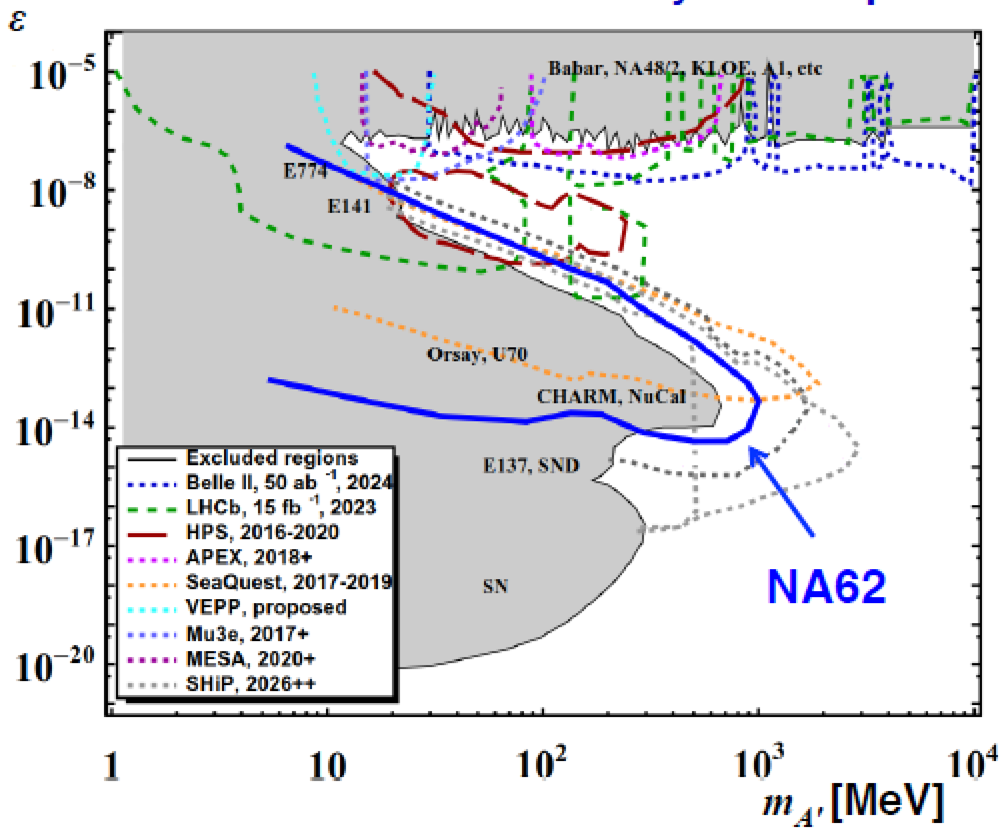
Sensitivity estimate does not include contributions from:

- A' from QCD processes
- A' produced in TAX

Data from 2016-2017 runs

- 3×10^{17} pot with $\mu\mu$ trigger
- 5×10^{16} pot with ee trigger

NA62 estimated sensitivity for 10^{18} pot



Dark scalar: parasitic mode

Dark sector coupled to Higgs by new singlet scalar field S

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H$$

Expansion of the field H around VEV v gives mixing of physical h and S with parameter θ

$$\mathcal{L}_{\text{DS}} = S\bar{\chi}\chi + \ldots \qquad \theta = \frac{\mu v}{m_h^2 - m_S^2}$$

Sensitivity estimate assumes:

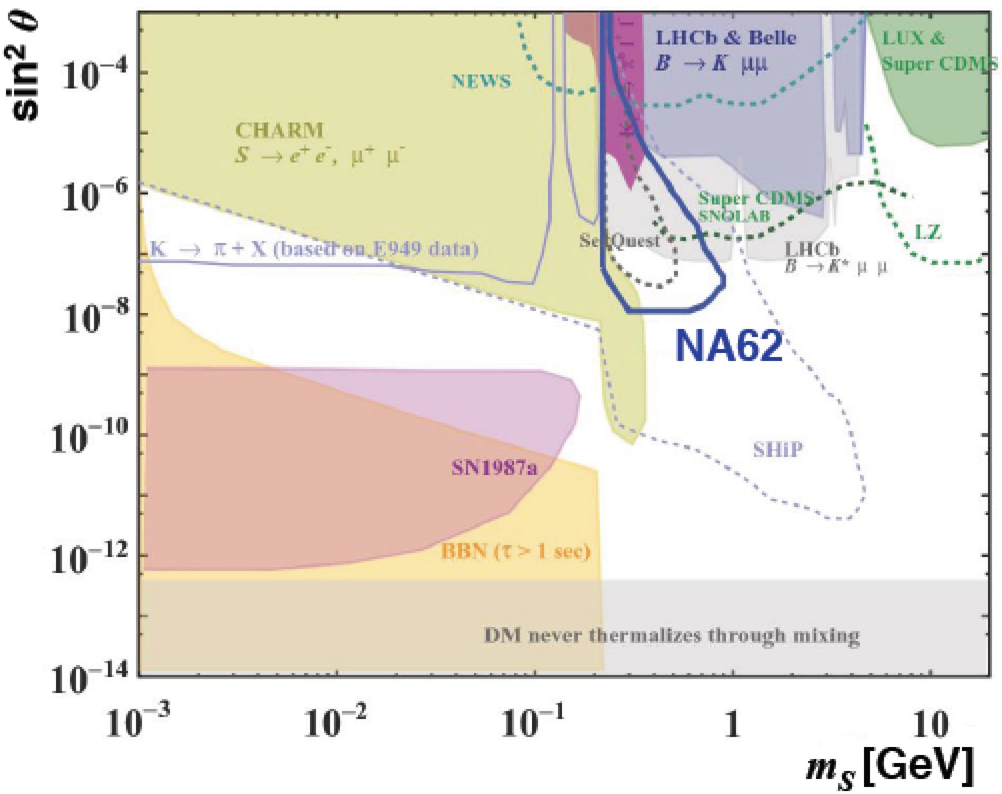
- 10^{18} pot on Be target
- Reconstruction of 2-track final states (ee, $\mu\mu$, $\pi\pi$, KK) with vertex pointing back to TAX:

  S produced most efficiently by decays of B-mesons from interactions in TAX
- 90% CL exclusion in zero-background assumption

Data from 2016-2017 runs

- 3×10^{17} pot with $\mu\mu$ trigger
- 5×10^{16} pot with ee trigger

NA62 estimated sensitivity for 10^{18} pot



Axions: beam-dump mode

Light pseudoscalar ALP may act as a mediator between SM and dark matter

$$\mathcal{L}_{\rm axion} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} + \frac{a}{4f_\gamma}F_{\mu\nu}\tilde{F}_{\mu\nu} + \frac{a}{4f_G}{\rm Tr}G_{\mu\nu}\tilde{G}_{\mu\nu} + \frac{\partial_\mu a}{f_l}\sum_\alpha \bar{l}_\alpha\gamma_\mu\gamma_5 l_\alpha + \frac{\partial_\mu a}{f_q}\sum_\beta \bar{q}_\beta\gamma_\mu\gamma_5 q_\beta$$

NA62 can explore ALP masses in the MeV-GeV range

Focus on pseudoscalar ALPs whose dominant interaction is with photons:

- Dedicated running in beam dump mode (TAX closed)
- Primakoff ($\gamma\gamma$ fusion) production from interaction in TAX with $a \to \gamma\gamma$ decay
- ALP produced at low $p_\perp$ → good acceptance even if detector far from production point

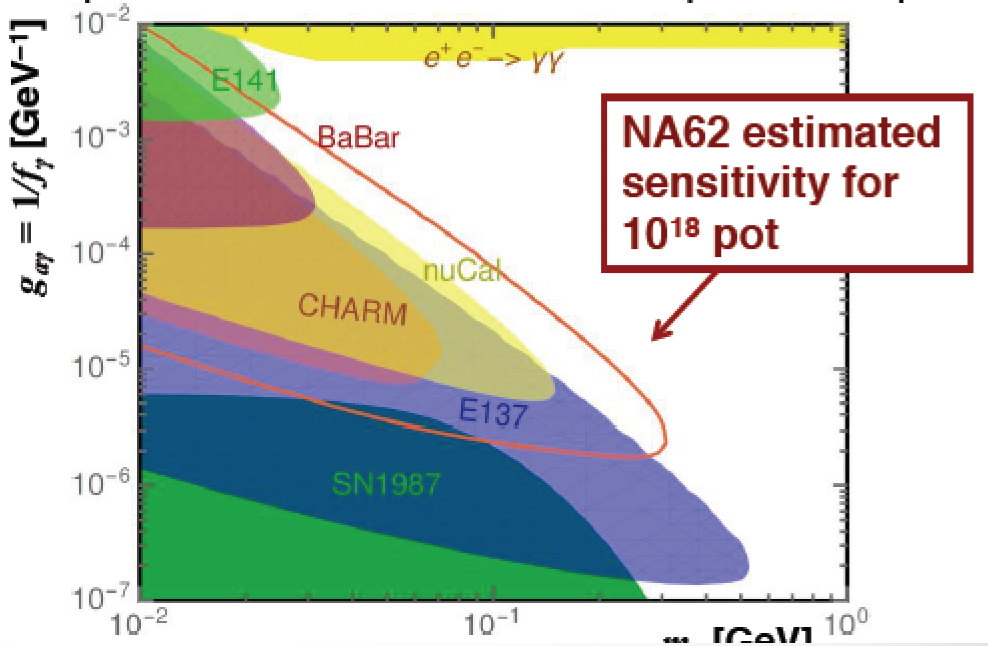
Sensitivity estimate assumes:

- **10^{18} pot on closed TAX**
- 90% CL exclusion in zero-background assumption

Significant results obtainable with only 1 day of data taking (1.3×10^{16} pot)

- Analysis of 2017 data in progress:

  5×10^{15} pot in dump mode



HNL: dump mode

$\mathcal{L}_{DS}$ **may include mass terms for one or more HNLs N (Dirac or Majorana)**

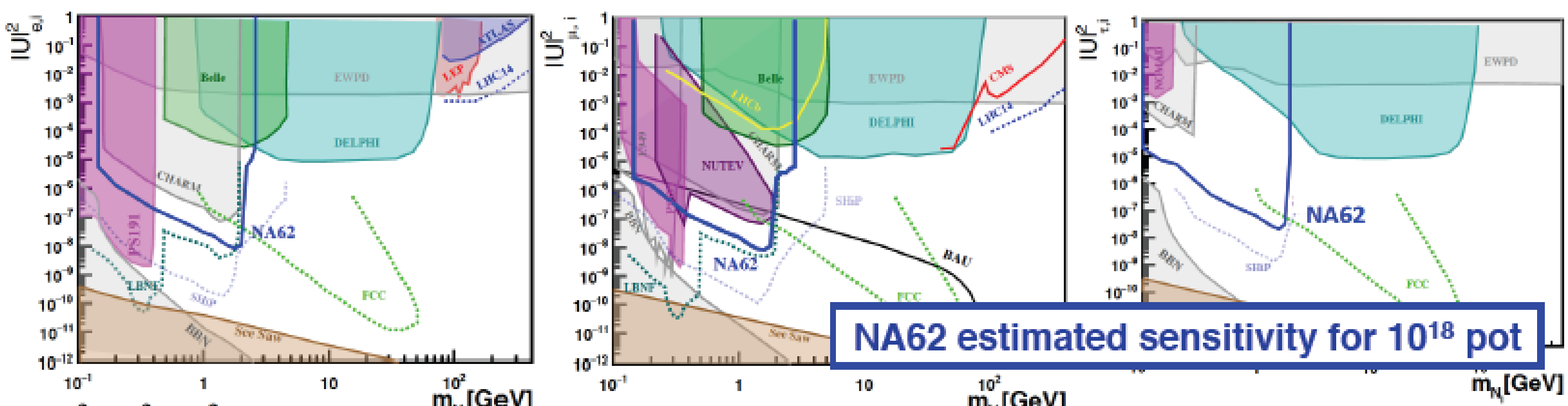
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} + \sum F_{\alpha I}(\bar{L}_\alpha H) N_I$$

Ns mix with $\nu_{1,2,3}$ to give $\nu_{e,\mu,\tau}$ + RH "sterile" neutrinos

$$\nu_\alpha \rightarrow \sum_I U_{\alpha I} N_I$$

Search for N produced in TAX with decays to two-track final states:

- Assume 10^{18} pot on closed TAX
- Reconstruct two-track final states, including open channels
- 90% CL exclusion in zero-background assumption
- Derive sensitivity for coupling scenarios in Shaposhnikov & Gorbunov 0705.1729v2



$U^2_e : U^2_\mu : U^2_\tau = 52:1:1$
Normal hierarchy of active ν masses

$U^2_e : U^2_\mu : U^2_\tau = 1:16:3.8$
Normal hierarchy of active ν masses

$U^2_e : U^2_\mu : U^2_\tau = 0.061:1:4.3$
Normal hierarchy of active ν masses

Data from 2016-2017 runs: 10^{17} pot with $\pi\mu$ trigger; few 10^{16} pot with πe trigger