Поиск экзотических частиц на протонных ускорителях

Ю.Г. Куденко

ИЯИ РАН

Марковские чтения,
Москва , 16 мая 2018 г.

Поздравления лауреатам !

Physics beyond the SM

-*Neutrino masses and mixings*

-*Baryon Asymmetry of Universe*

- *Dark matter and dark energy*

Extensions of SM

Hidden sector

Heavy Neutral Leptons (massive neutrinos)

Dark Photons

Axion-Like Particles

Heavy Neutral Leptons

Neutrino oscillations, BAU, DM can be explained in νMSM model with 3 heavy right handed Majorana neutrinos (heavy neutral leptons) N_1, N_2, N_3.

Mixing between active and heavy sterile ν's:
→ production of heavy ν's in weak decays of mesons.
The same mixing: → decay of heavy ν's to SM particles

νMSM Model, T.Asaka, M.Shaposhnikov PL B620 (2005) 17

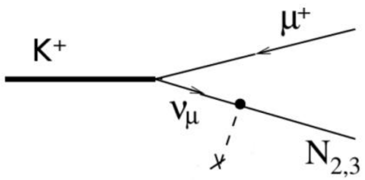
3 heavy sterile neutrinos N (Neutral leptons) coupled with active neutrinos
– N_1: m_1 ~ O(10 keV) → dark matter candidate
– $N_{2,3}$: $m_{2,3}$ ~ O(1 GeV) → extra-CPV: baryon asymmetry, $m\nu \neq 0$ (seesaw)

How to search for HNL's?

- <u>Meson decays</u>

  - search for extra peaks **R.Shrock, PRD, 24, 1232 (1981)**

$$\Gamma(K^+ \to \mu^+ N) = \rho\Gamma(K^+ \to \mu^+\nu_\mu)\left|U_{\mu N}\right|^2$$

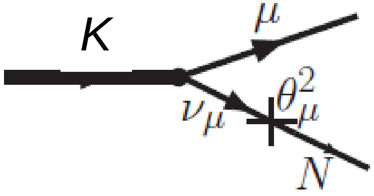


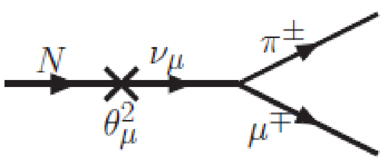
- <u>Decays of HNL's</u>

  - "nothing" ➢ leptons and hadrons

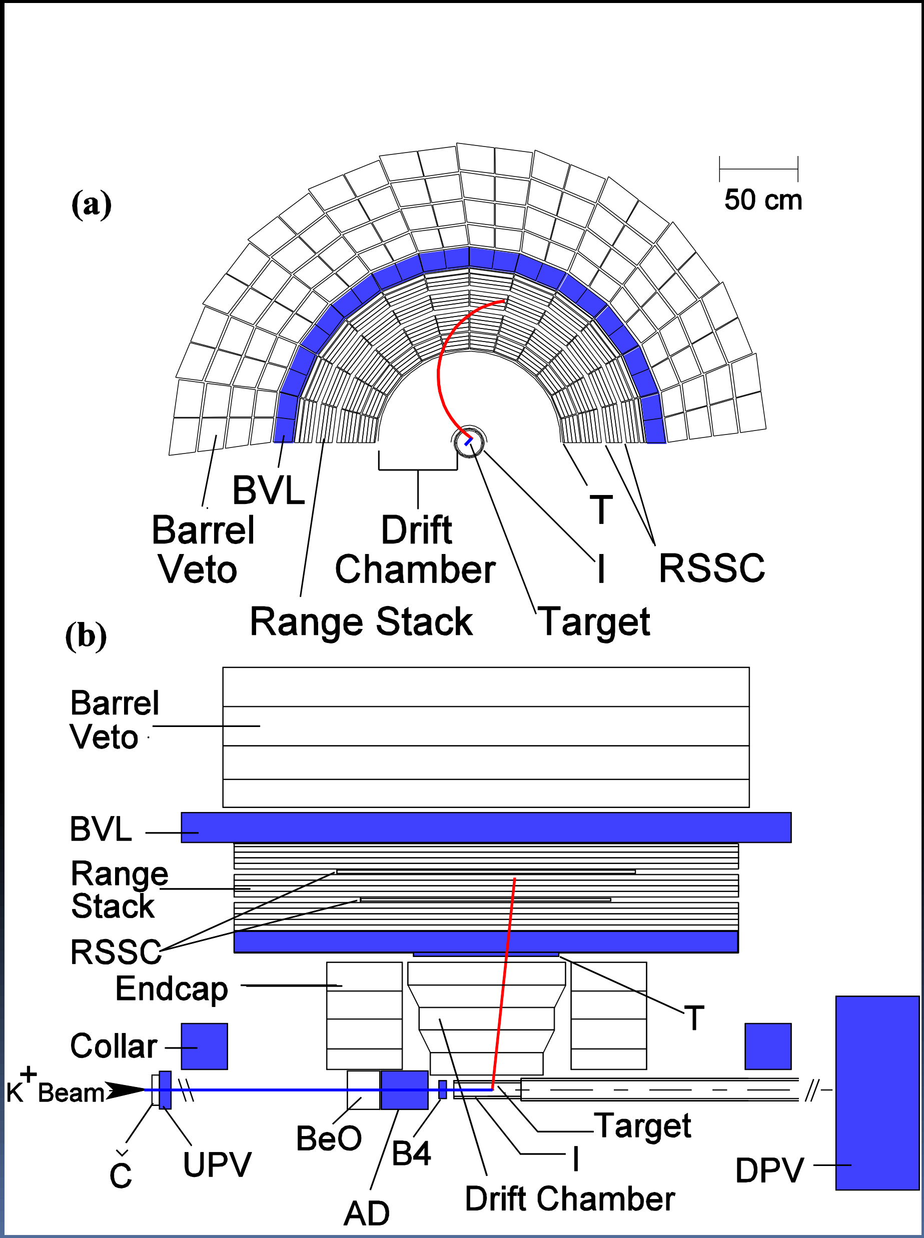
p + A → mesons + …

$N_{2,3}$ +





Experiment E949 at BNL



Main goal: measurement of rare decay K+ $\rightarrow \pi\nu\nu$

7 events detected

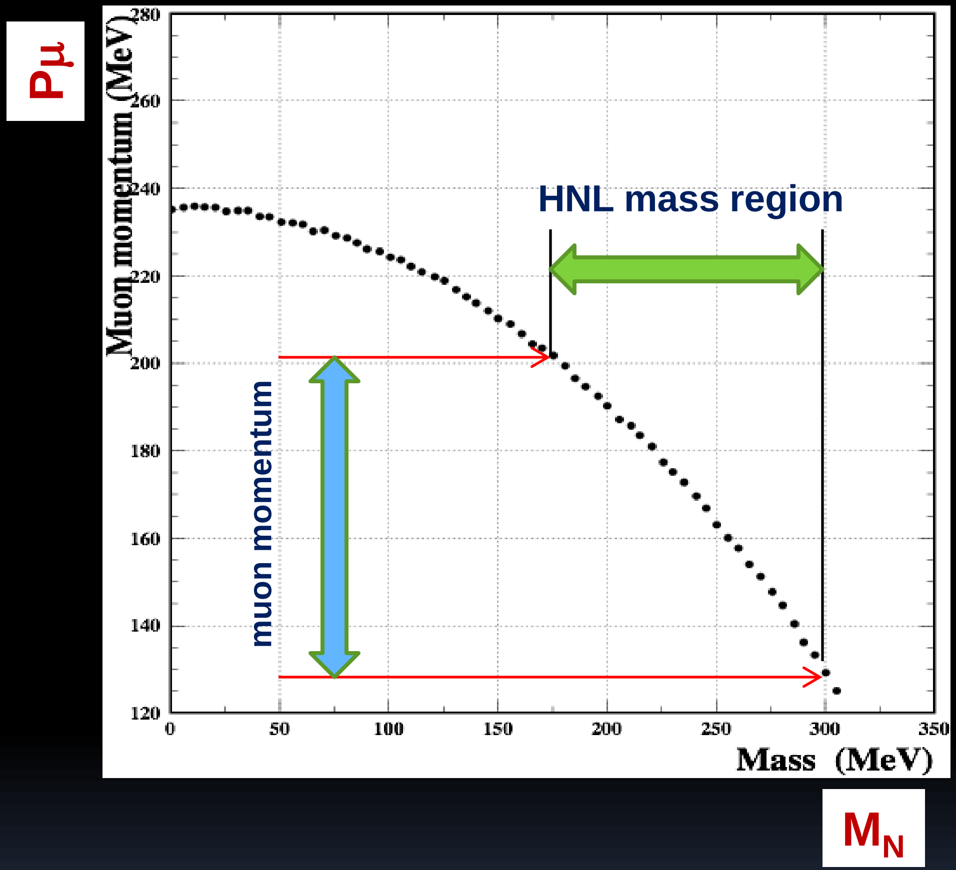
$$Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

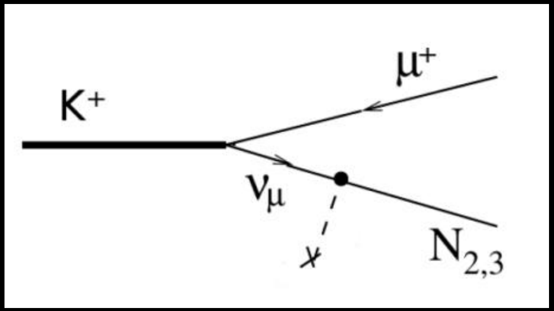
p_K = 710 MeV/c
- Stopped K+ decays in active target
- Momentum and energy of charged particles from kaon decays measured by drift chamber and range stack
- Photon detectors suppress events with photons

Trigger: decay of stopped kaon -> muon track -> stop and decay + no any activity in detector

1.7x10^{12} decays of stopped kaons were analyzed

Mass interval



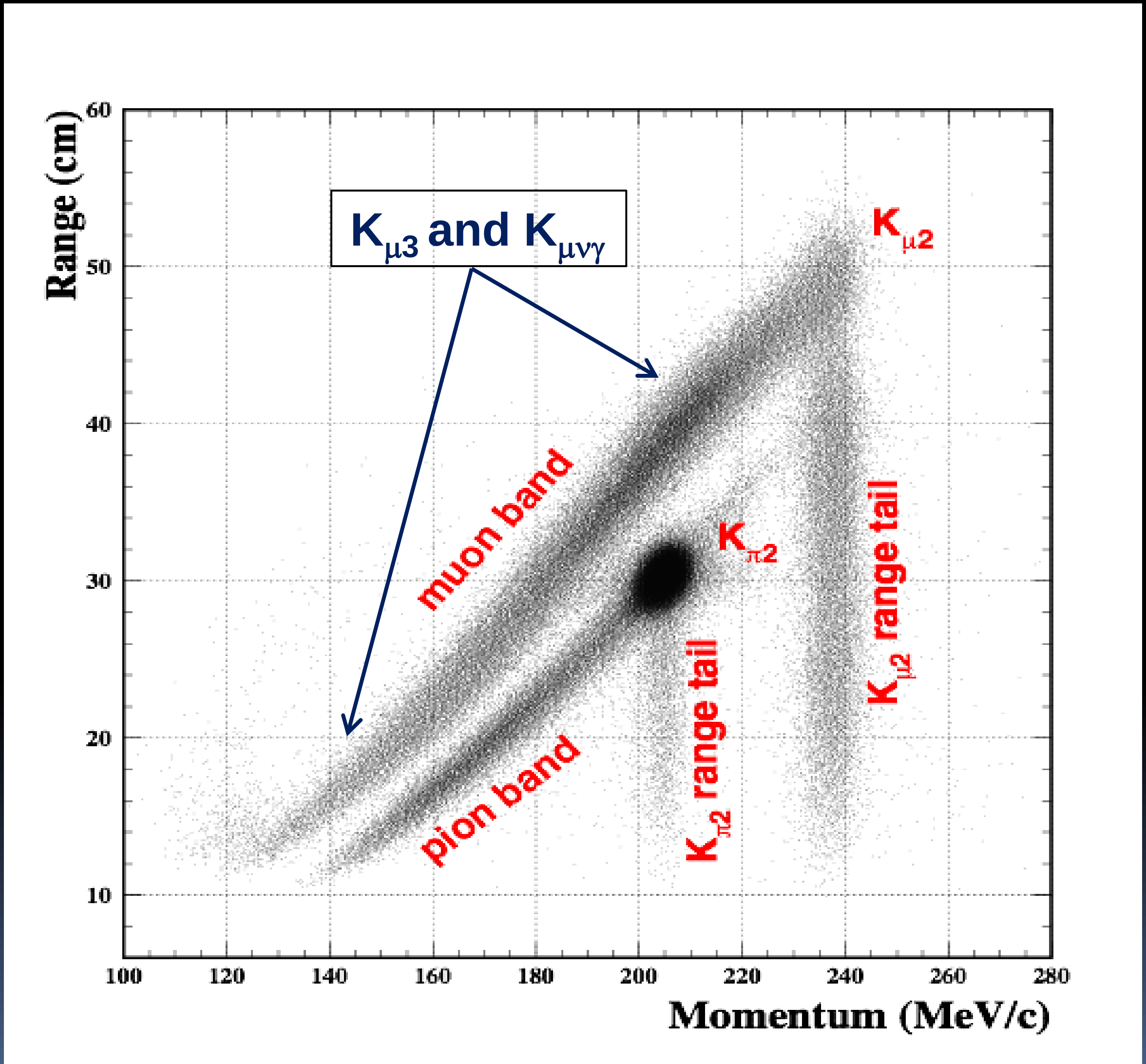


Search for peaks in the muon spectra from kaon decays

$$P_{\mu} = \frac{1}{2} M_K \sqrt{1 + \left(\frac{m_{\mu}^2}{M_K^2}\right)^2 + \left(\frac{m_N^2}{M_K^2}\right)^2 - 2\left(\frac{m_{\mu}^2}{M_K^2} + \frac{m_N^2}{M_K^2} + \frac{m_{\mu}^2}{M_K^2}\frac{m_N^2}{M_K^2}\right)}$$

Events

after $\pi \to \mu \to e$ trigger

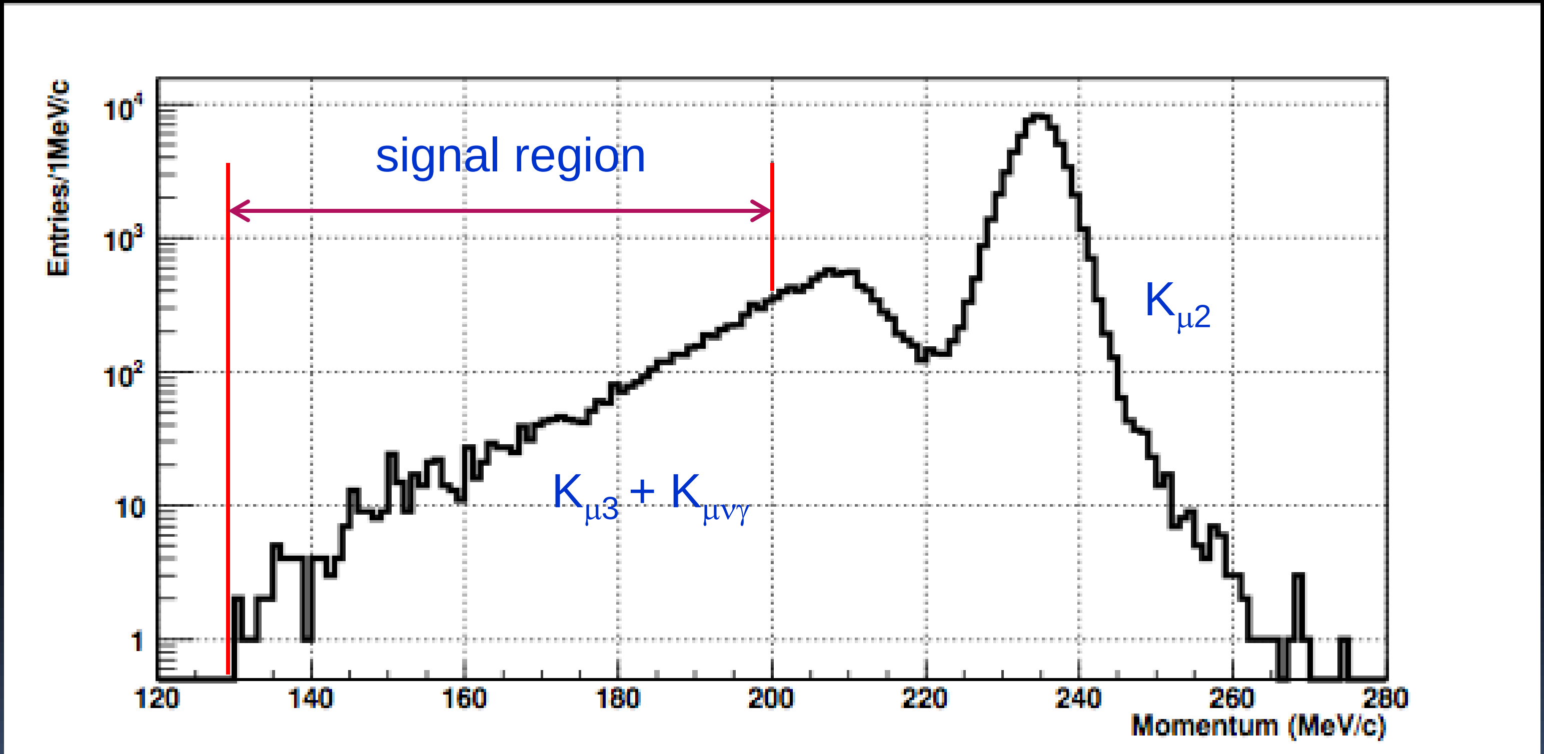


Muon spectrum

	Br	Trigger + Cuts	Total rejection
$K_{\mu 3}$	3.3×10^{-2}	$\sim10^{7}$	$\sim10^{9}$
$K_{\mu\nu\gamma}$	6.2×10^{-3}	$\sim10^{4}$	$\sim10^{7}$

Suppression of kaon decays

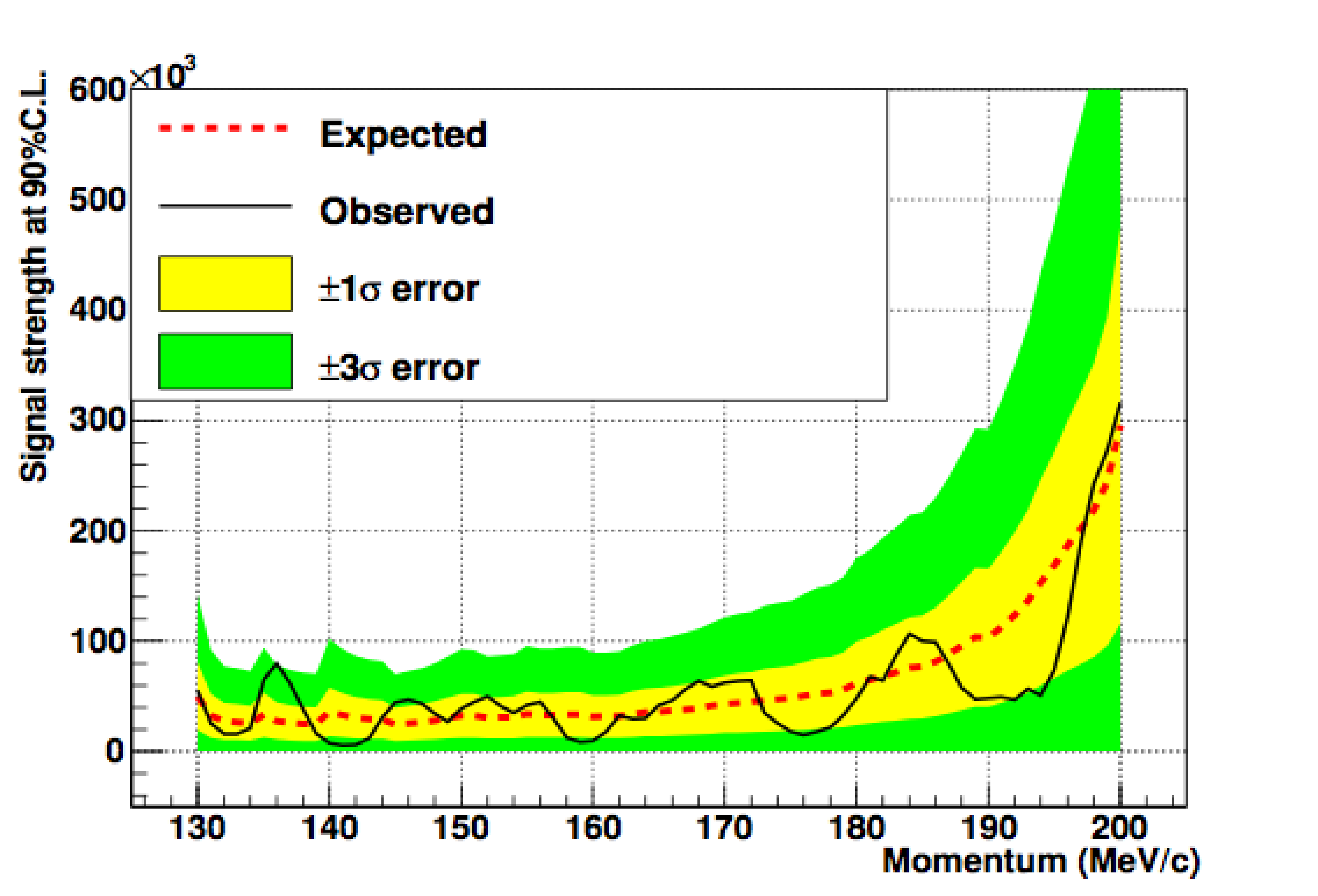
Muon spectrum after all cuts



E949 sensitive to heavy neutrinos in the mass region 175-300 MeV

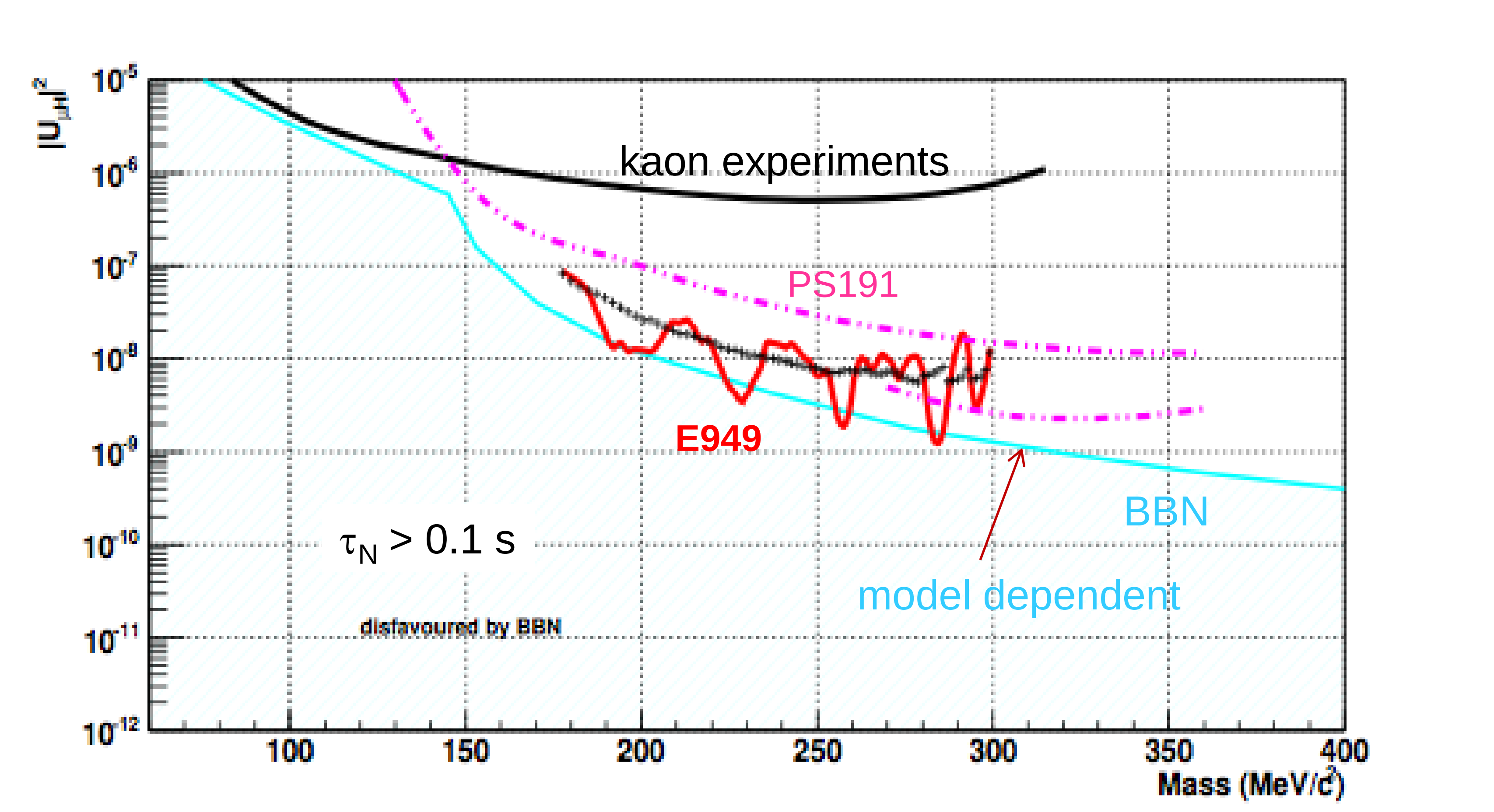
Search for peaks

$$L(\mu,\theta) = \left\{\prod_{i=1}^{N_{bin}} \frac{(\mu\cdot\epsilon s_i+\beta b_i)^{n_i}}{n_i!} e^{-(\mu\cdot\epsilon s_i+\beta b_i)}\right\}$$
$$\times Gauss(\epsilon;\epsilon_{peak},\sigma_{\epsilon_{peak}}),$$



E949 result

Phys.Rev. D91 (2015) 5, 052001



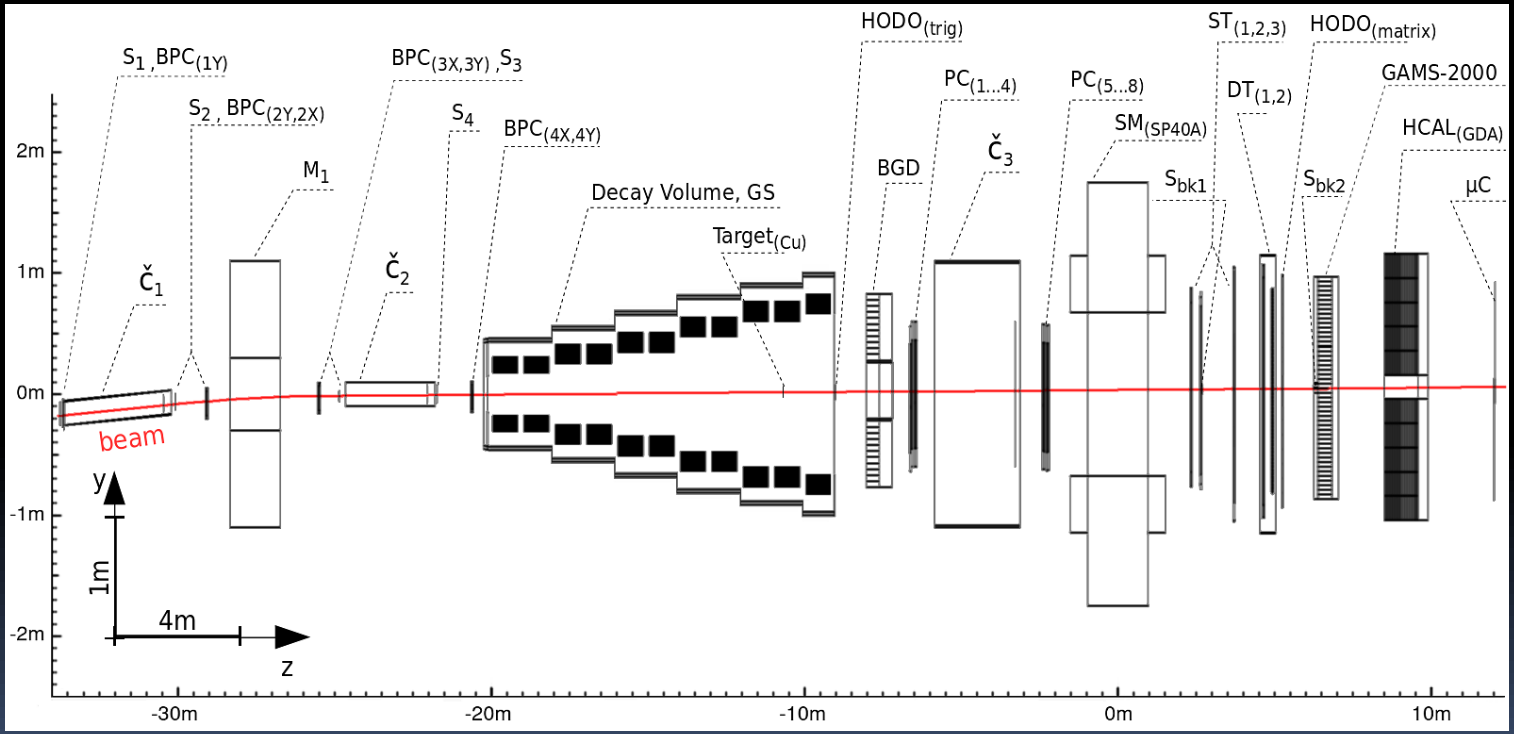
$$M_{N_{2,3}} = 175 - 300\,\mathrm{MeV} \quad |U_{\mu H}|^2 < 10^{-7} - 10^{-9} \quad (90\%\ \mathrm{C.L.})$$

Experiment OKA

Collaboration IHEP-INR-JINR

$p_K = 17.7$ GeV/c
$I_K = 2.5 \times 10^5$ kaon/spill

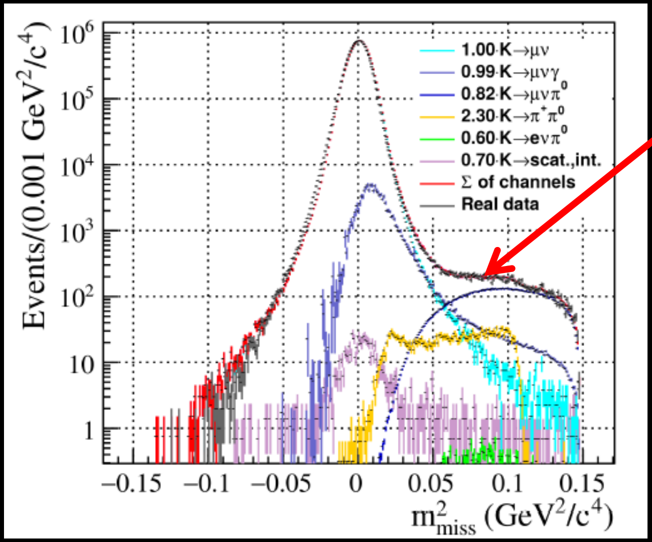
Kaon decays in-flight
Data accumulated in 2012



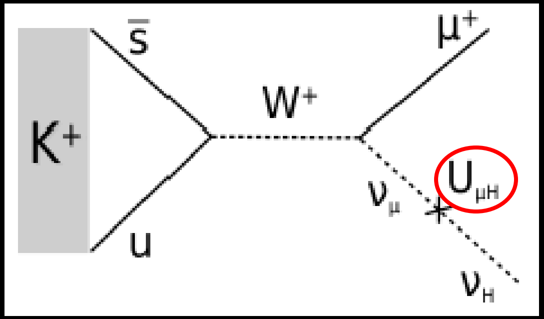
OKA result

PL B778 (2018) 137

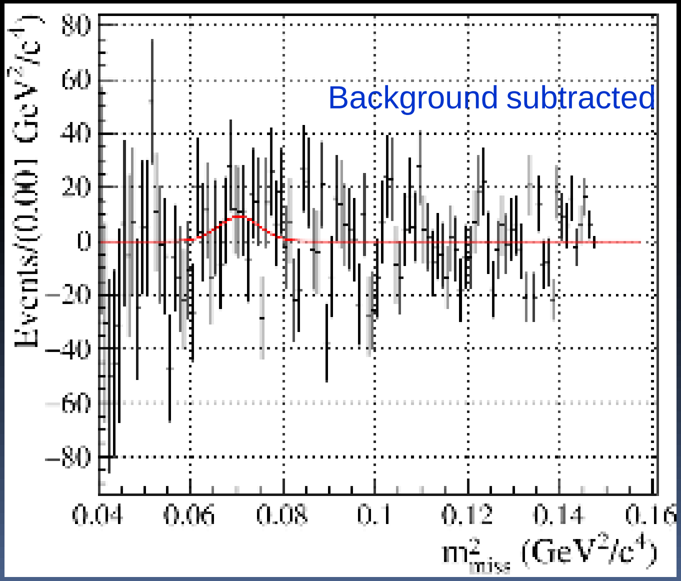
Missing mass spectrum after all cuts

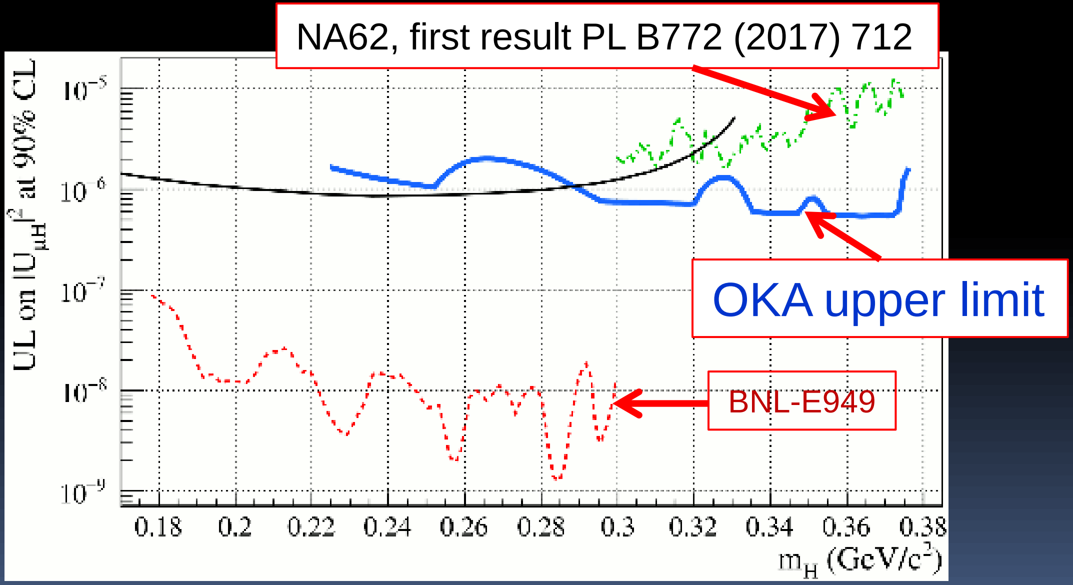


Method: search of a peak in spectrum of missing mass



Experiment sensitive to mixing of heavy and muon neutrino in mass region 0.22 – 0.37 GeV





$|U_{\mu H}|^2 < 10^{-6}$ (90% CL) for M_{HNL} = 220-370 MeV

NA62 at CERN

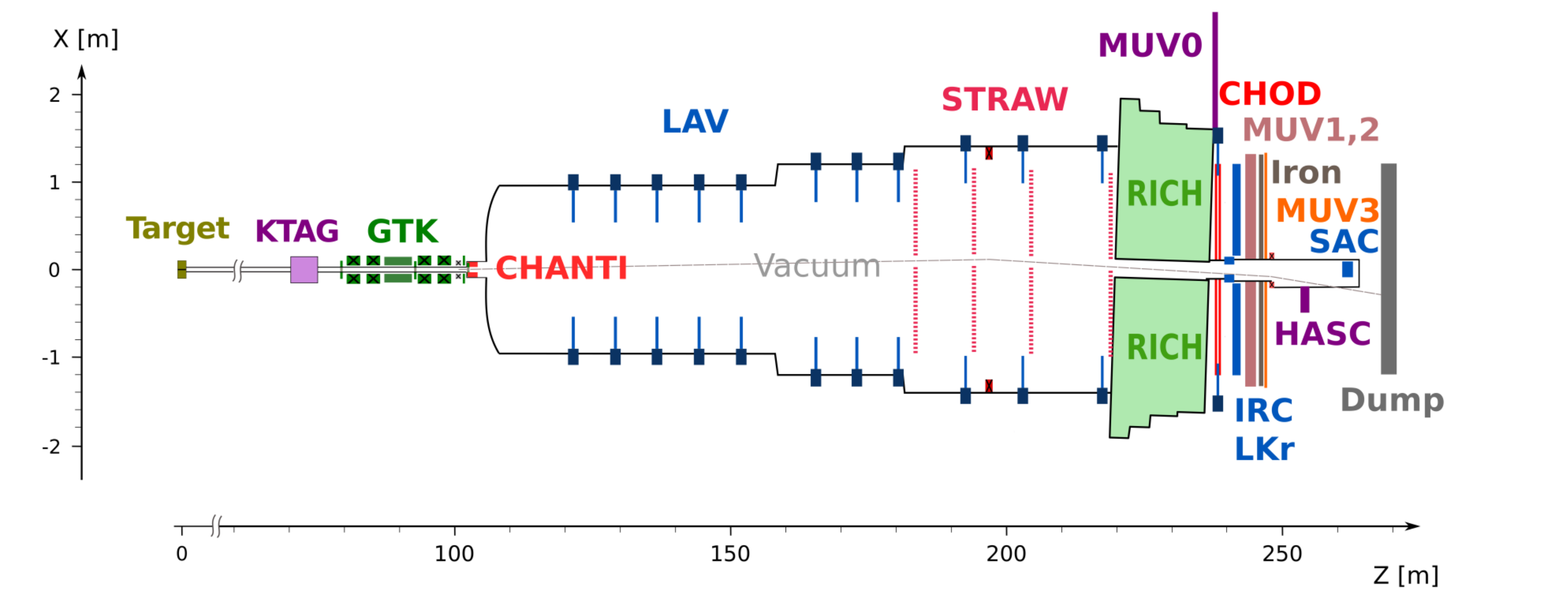
Main goal:
Measurement of the rare decay $K^+ \to \pi^+\nu\nu$
- Collect about **80** events at the SM prediction
- Extract $|V_{td}|$ with a precision of 10%

NA62 is to accumulate 1.2×10^{13} kaon decays in the fiducial volume

~200 participants from ~30 institutes:
Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC.

Experiment NA62

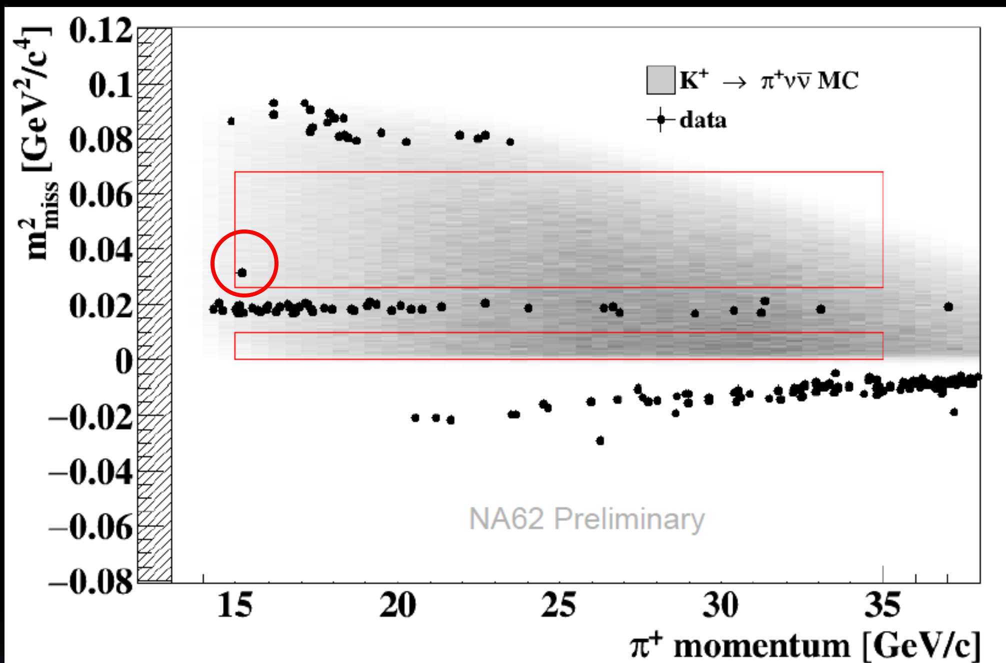
- SPS Beam:
  - 400 GeV/c protons
  - 2.10^{12} protons/spill
  - 3.5s spill
- Secondary positive Beam:
  - 75 GeV/c momentum, 1 % bite
  - 100 mrad divergence (RMS)
  - 60x30 mm^2 transverse size
  - $K^+(6\%)/p^+(70\%)/p(24\%)$
  - 33×10^{11} ppp on T10 (750 MHz at GTK3)
- Decay Region:
  - 60 m long fiducial region
  - ~ 5 MHz K^+ decay rate
  - Vacuum ~ $O(10^{-6})$ mbar

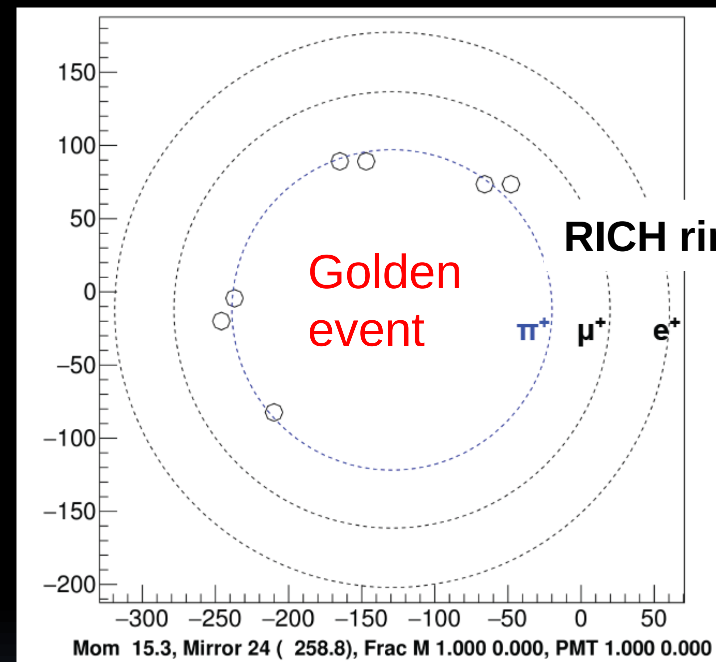


First NA62 result

Data 2016: Number of kaon decays in fiducial volume = 1.21 x 10^{11}

First NA62 result: one $K^+ \to \pi^+ \nu\nu$ event observed





SM

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

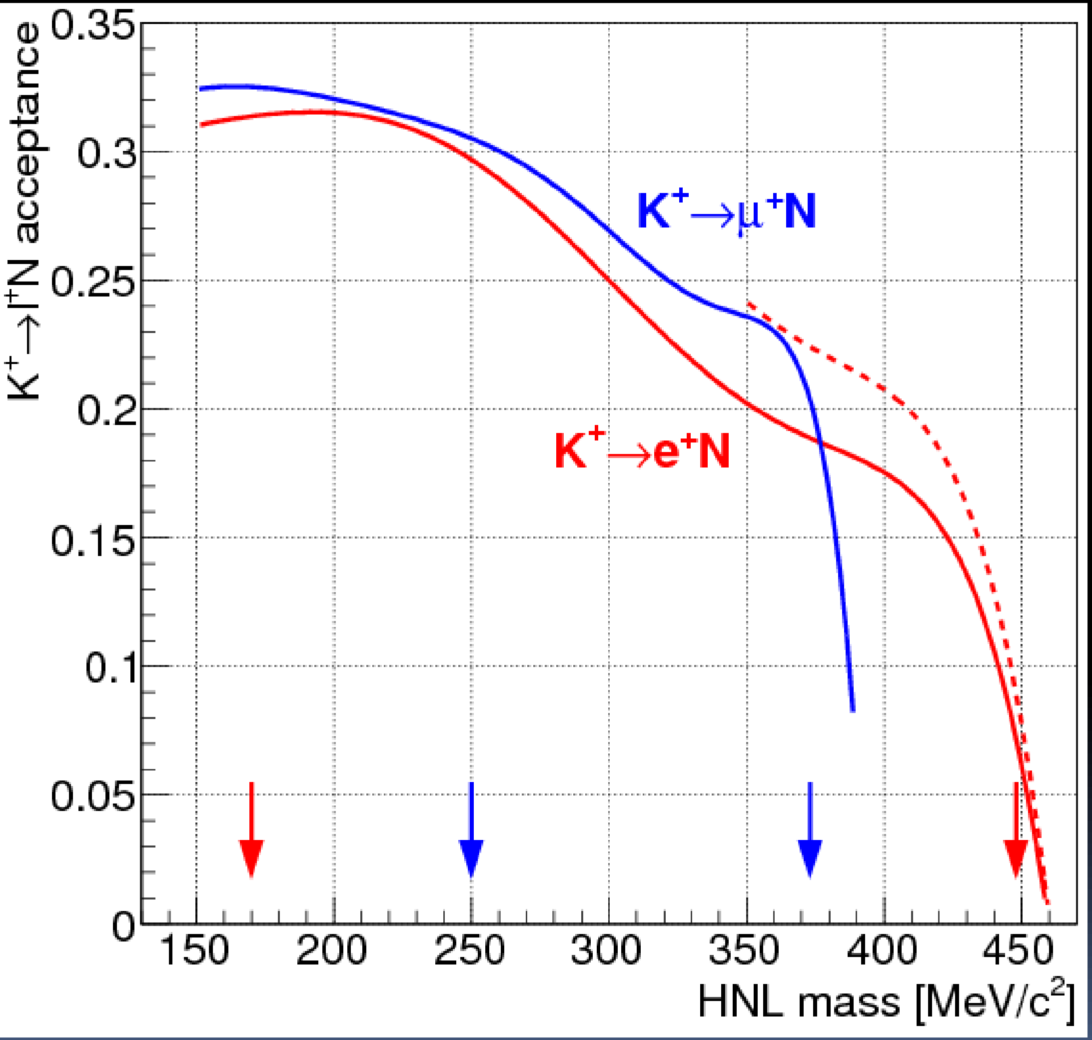
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10} \;@\; 95\%\;CL$$

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

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

BNL-E949:
7 events

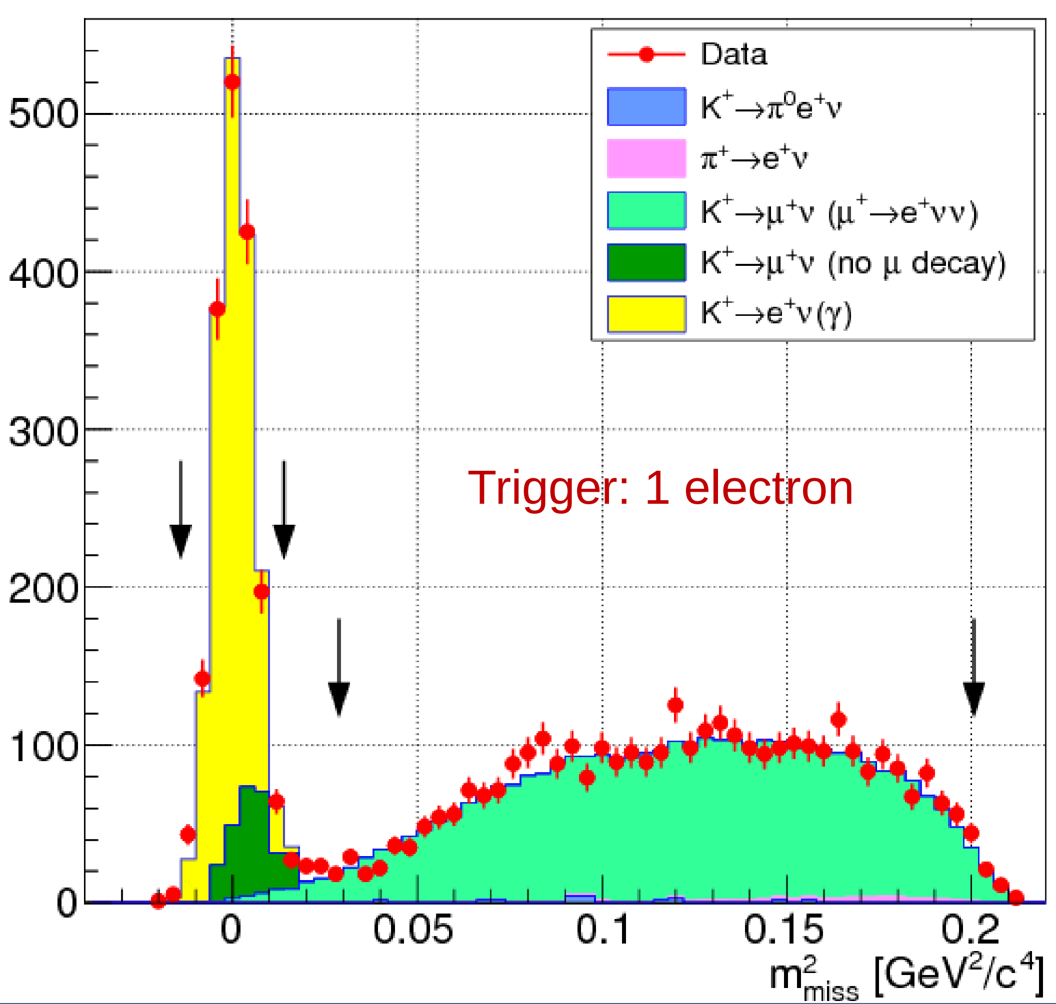
Acceptance to HNL



Trigger:
- one electron
- one muon

Missing mass

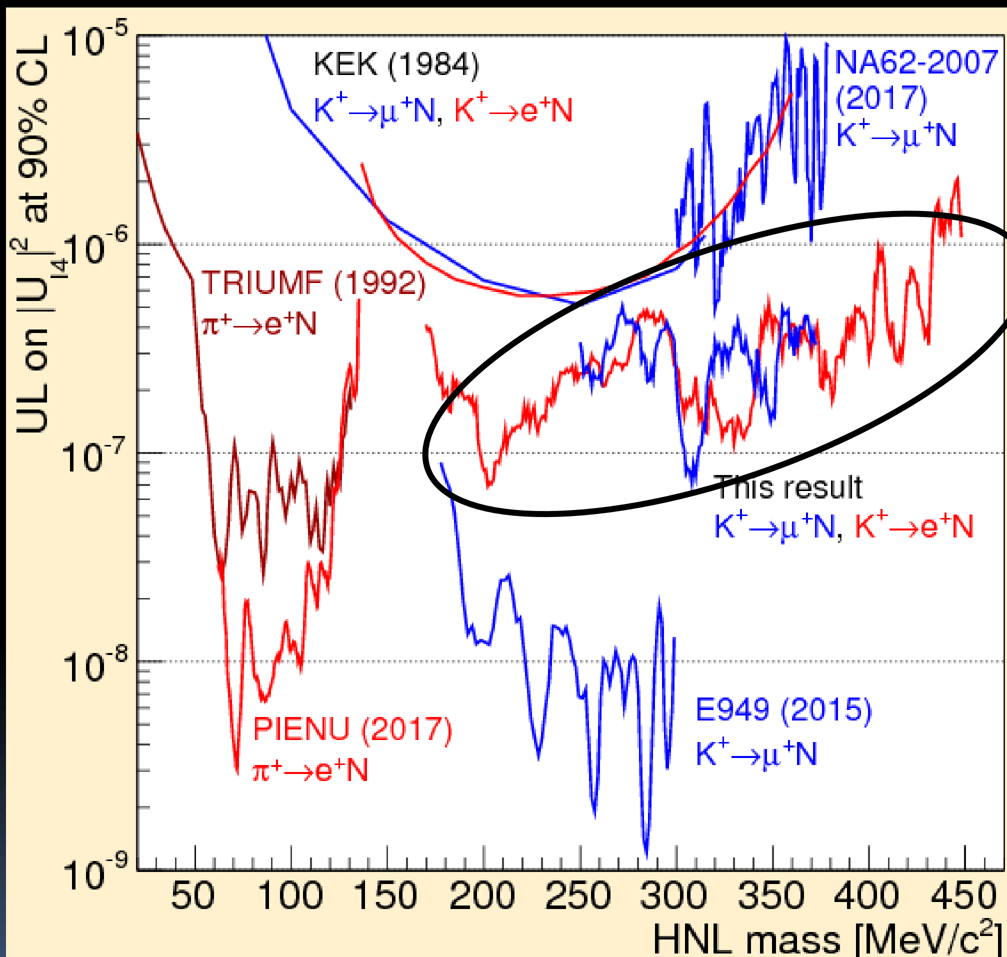
2015 data: ~3×10⁸ $K^+ \to e^+\nu$, ~1×10⁸ $K^+ \to \mu^+\nu$



NA62 result: search for HNL

No signal observed
Upper limits on $|U_{eN}|^2$ and $|U_{\mu N}|^2$

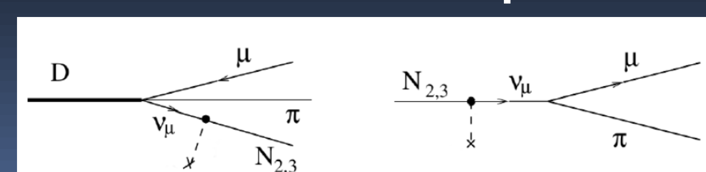
PL B778 (2018) 137



Analysis
2016-2018 data
in progress

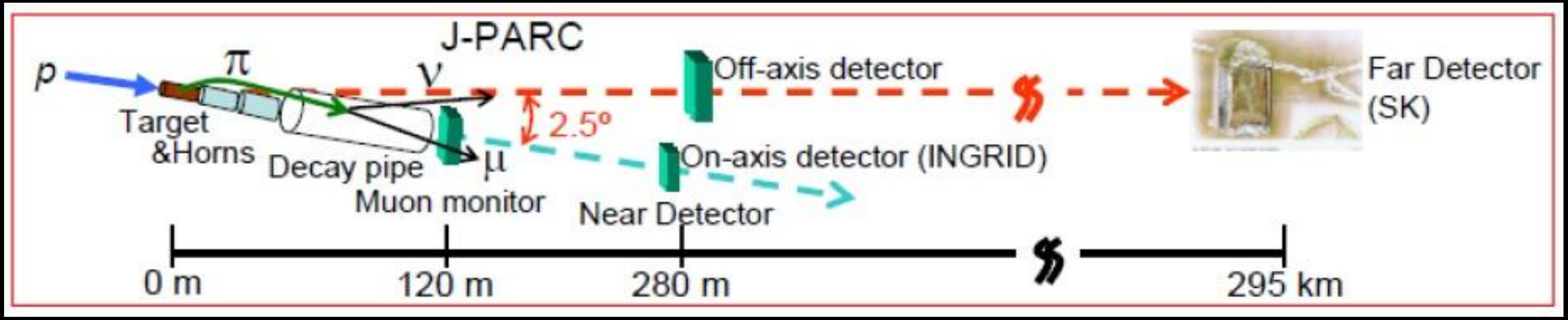
Expected limits (if no events)
$|U_{eN}|^2 \sim 10^{-9}$
$|U_{\mu N}|^2 \sim 10^{-8}$

NA62 – beam dump mode

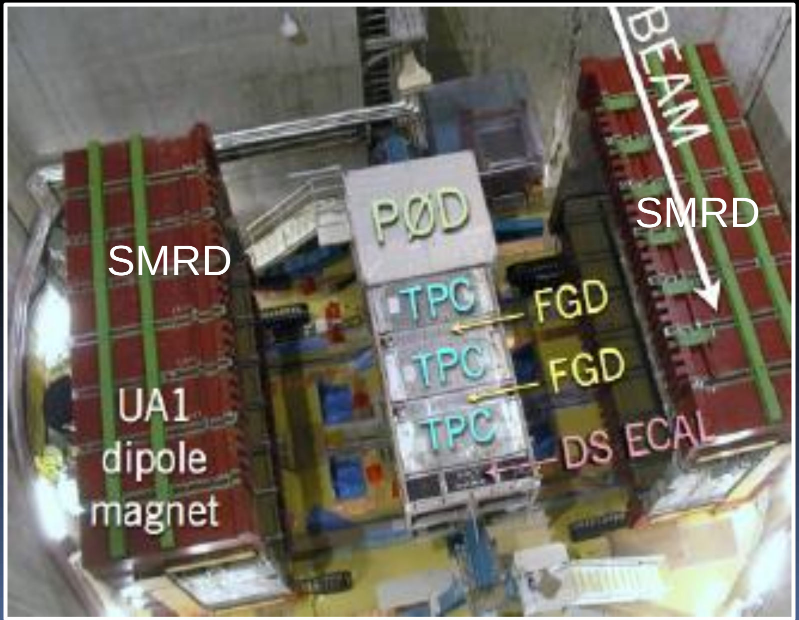


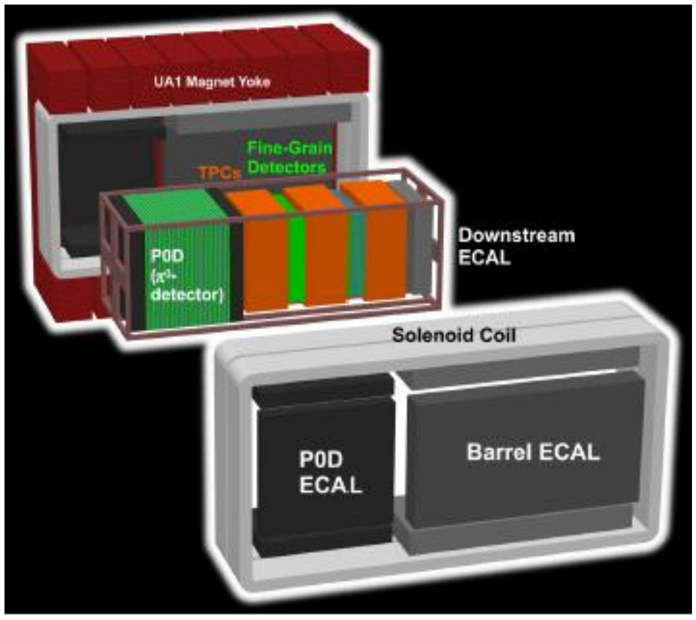
Experiment T2K

Study of neutrino oscillations, search for CP violation, ν cross sections….



Off-axis near neutrino detector ND280

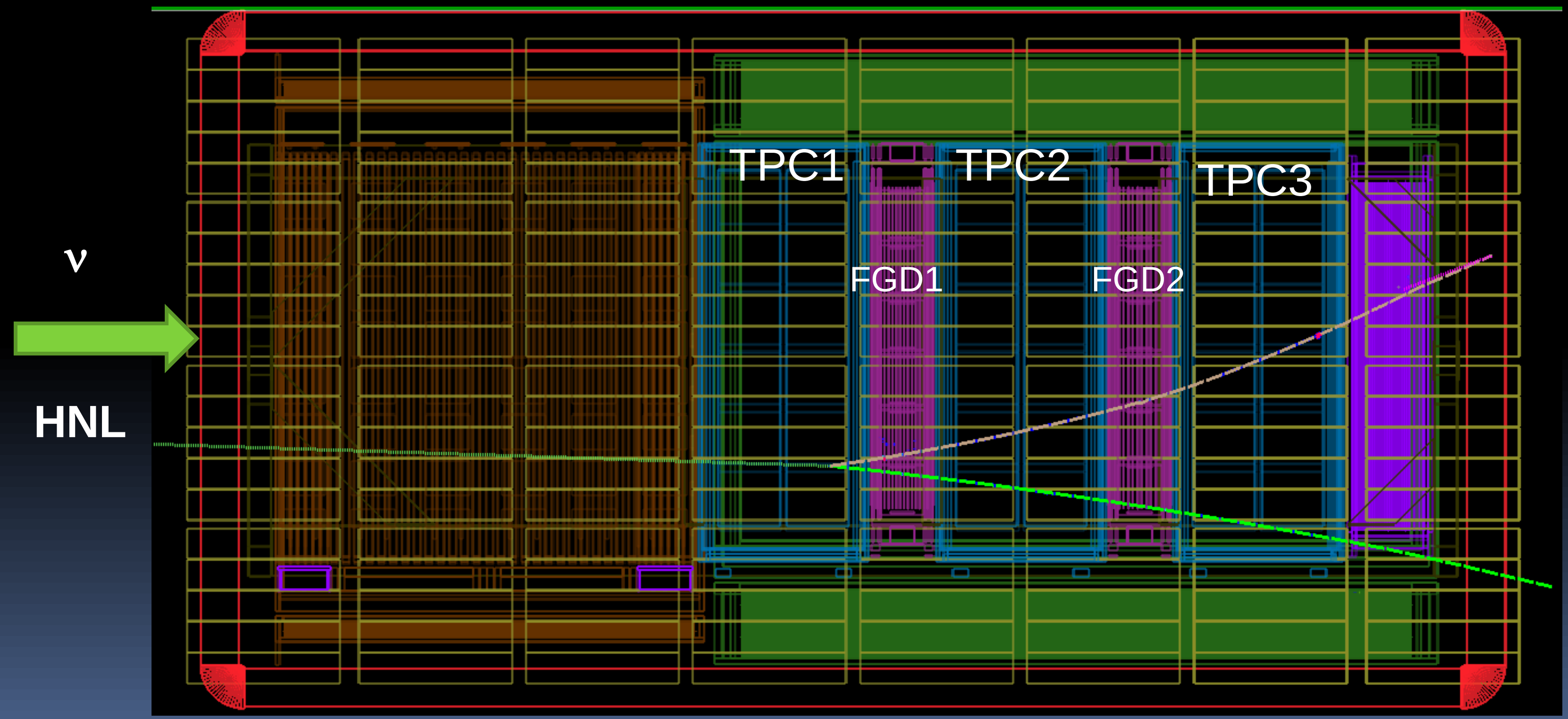




Principle of HNL detection

- vertex of NHL decay in TPC volume (Ar+CO_2)
- 2 tracks of opposite charge
- suppression of neutrino interactions
- p_T = 0

Three TPC's → total decay length = 3m



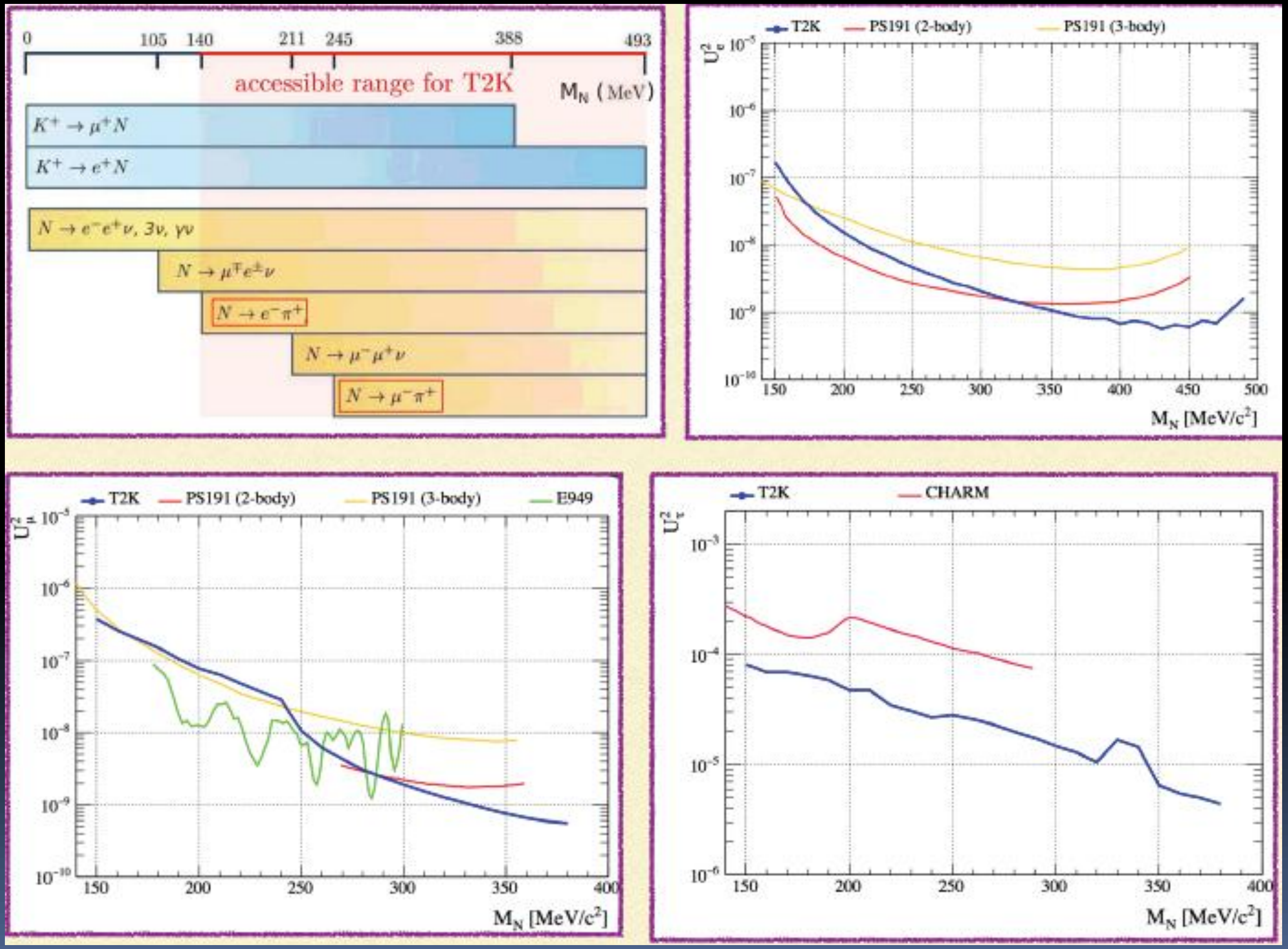
T2K result

Neutrino mode 6 x 10^{20} POT
Anti-neutrino mode 6.5 x 10^{20} POT

Preliminary

Limits (90% CL)
to mixing elements
$|U_\mu|^2$, $|U_e|^2$, $|U_\tau|^2$

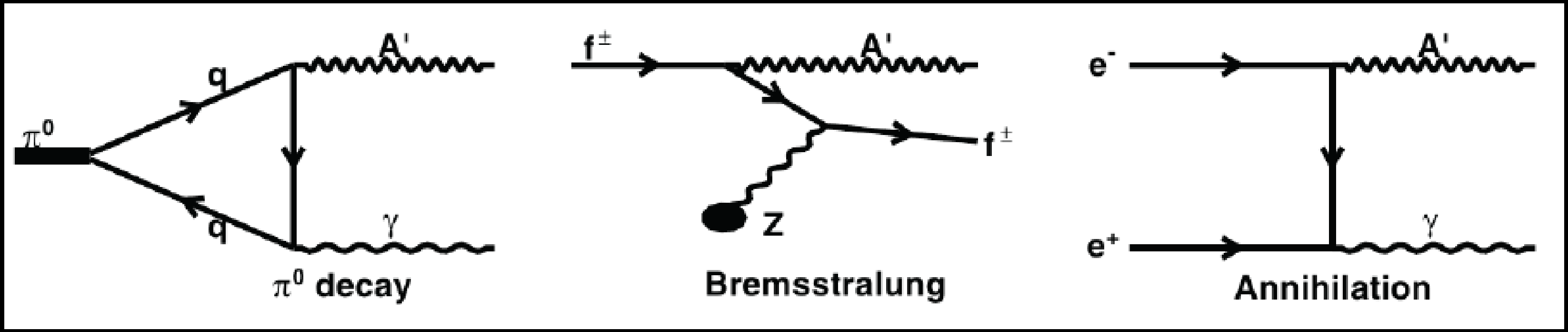
Expected background
~1 event



Dark photons

New force between dark sector and visible particles – dark photon (A')

$m_{A'} \leq 1$ GeV

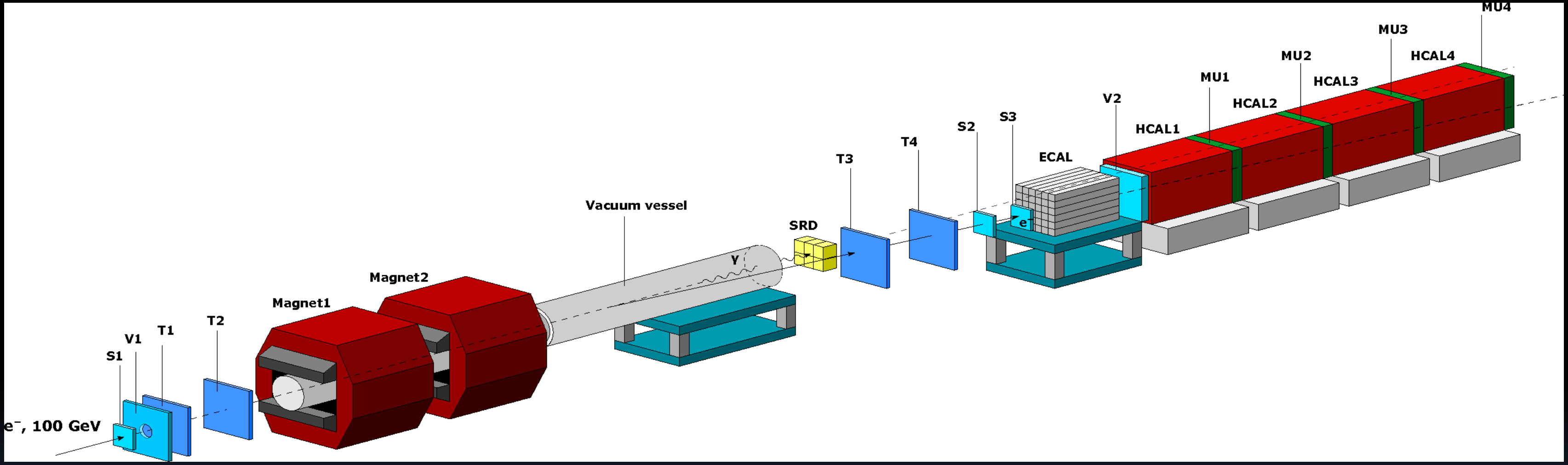


A' $\rightarrow$ invisible ($\chi\chi$)
A' $\rightarrow$ $\gamma\gamma$
A' $\rightarrow$ $\mu^+\mu^-$, e^+e^-

NA64 at CERN

$e Z \rightarrow e Z A'$ $A' \rightarrow$ invisible $E_{measured} = E_0 - E_{A'}$

$E_0 = 100$ GeV $I = (3\text{-}4) \times 10^6$ e/spill

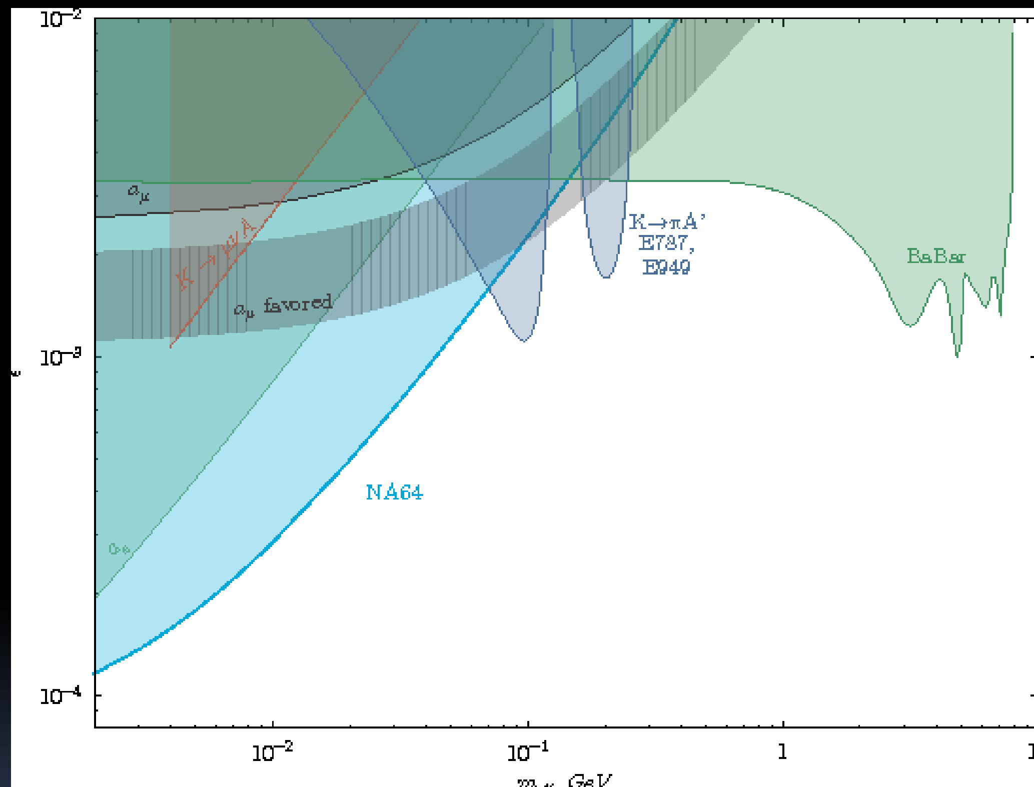


NA64 result

No events observed

PRL 118 (2017) 011802

90% CL limit on A'- γ strength



Expected number
of background events
in the signal box
for 2.75 x 10^9 eot
0.15
0.4 $\pm$ 0.3

Invisible A' with masses ≤100 MeV is excluded as an explanation of the g – 2 muon anomaly

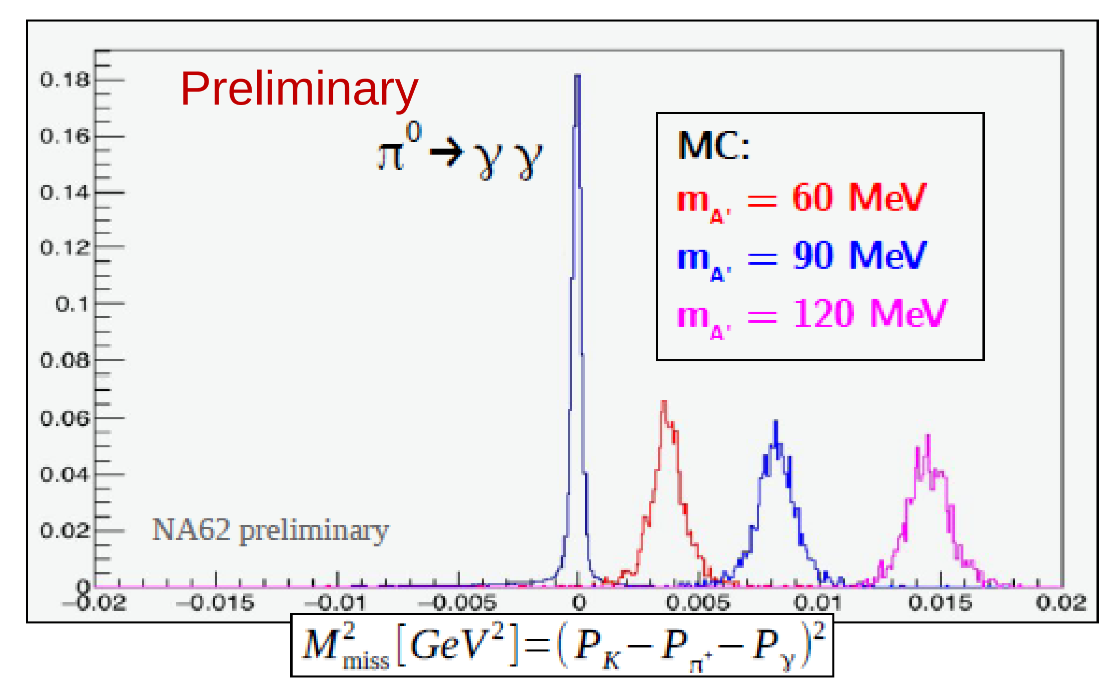
NA62 at CERN

Invisible decay

$K^+ \to \pi^+ \pi^0$, $\pi^0 \to A' \gamma$, $A' \to$ *invisible*

$BR(\pi^0 \to A' \gamma) = 2\epsilon^2[1-(m_{A'}/m_{\pi 0})^2]^3 \times BR(\pi^0 \to \gamma\gamma)$

$K+ \to \pi+ A'$ *(byproduct of* $K+ \to \pi+ \nu\nu$*)*



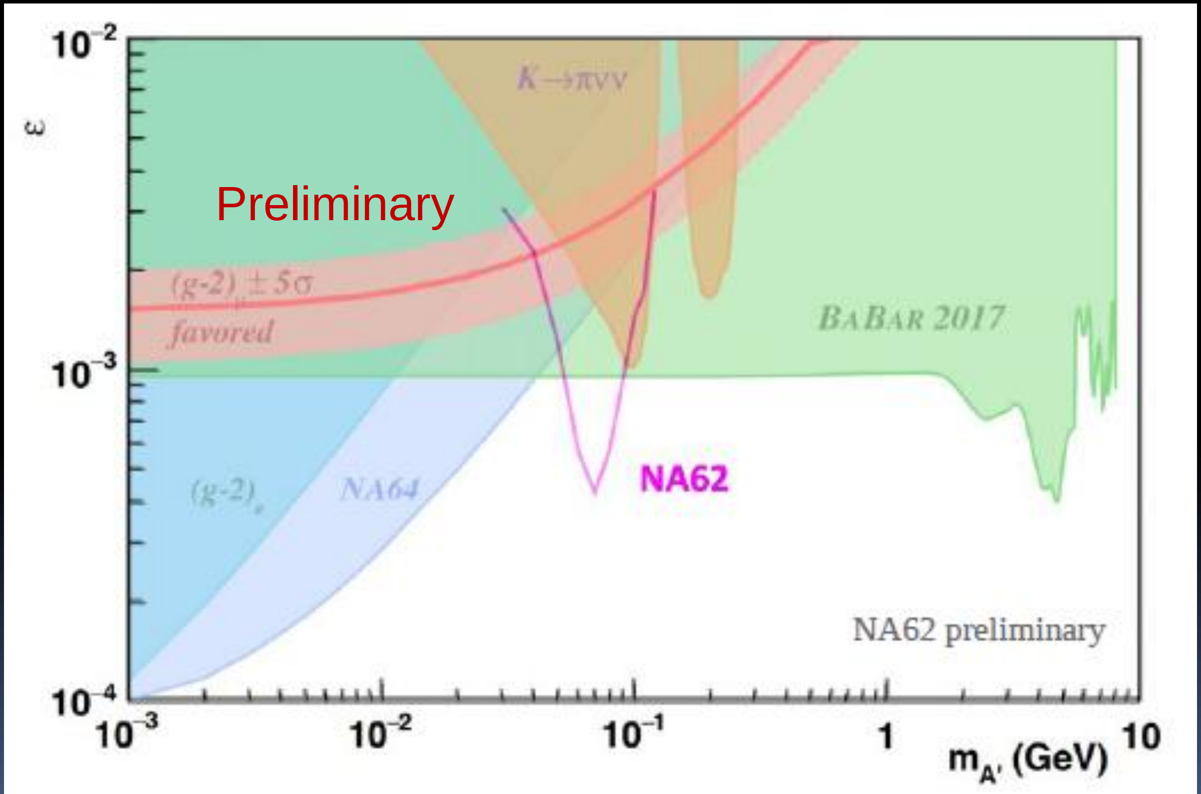
Main background $\pi^0 \to \gamma\gamma$ with one photon missed

NA62 result

Analysis of 4% of 2016 data $\rightarrow$ 1.5 x 10^{10} K+ decays

No events observed, 90% CL upper limit

P.Mermod, NuFact17



NA62

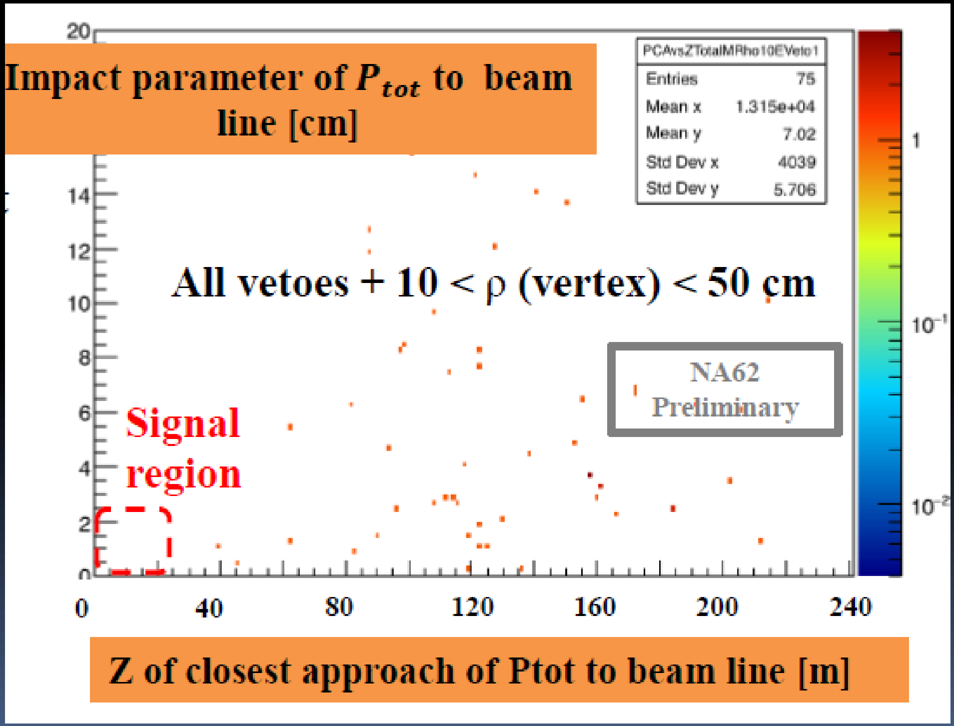
Visible decay

$pN \to X\pi^0 \quad \pi^0 \to A'\gamma \quad A' \to l^+l^-$
$pN \to X A' \quad A' \to l^+l^-$

M.Mirra, Moriond 2018

3×10^{17} PoT acquired in 2016/17 with di-muon parasitic trigger, 5×10^{16} PoT with ee trigger

$\sim 10^{15}$ PoT, search for $A' \to \mu\mu$



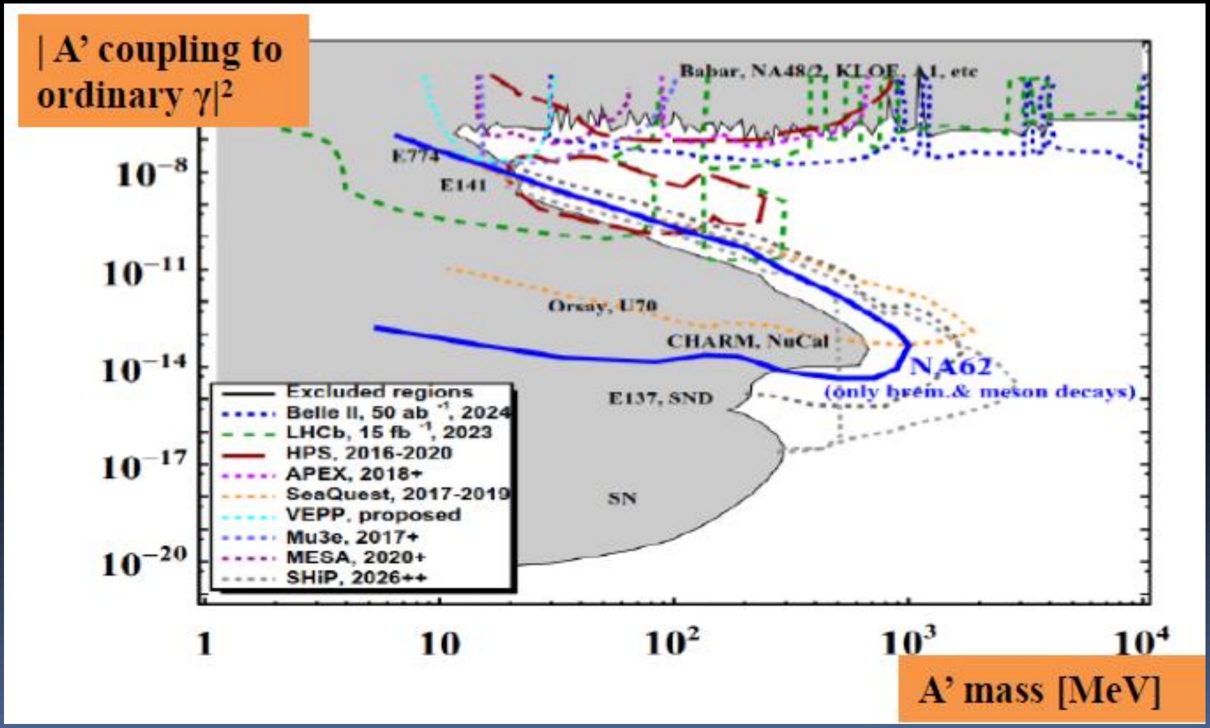
No events found
in the signal region

NA62

Visible decay

$pN \rightarrow X\pi^0 \quad \pi^0 \rightarrow A'\gamma \quad A' \rightarrow l^+l^-$
$pN \rightarrow X A' \quad A' \rightarrow l^+l^-$

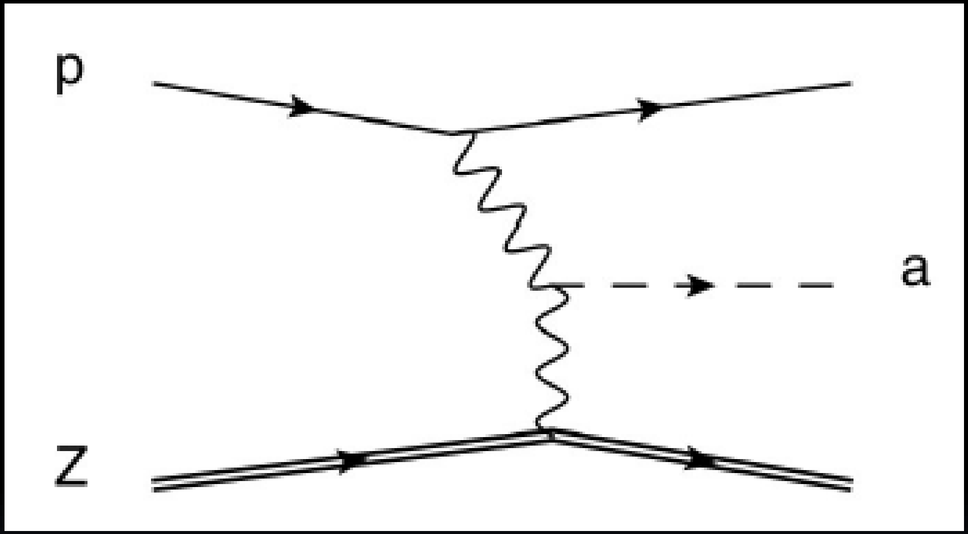
Assuming 10^{18} POT, 400 GeV protons, beam-dump mode



Axion-like particles

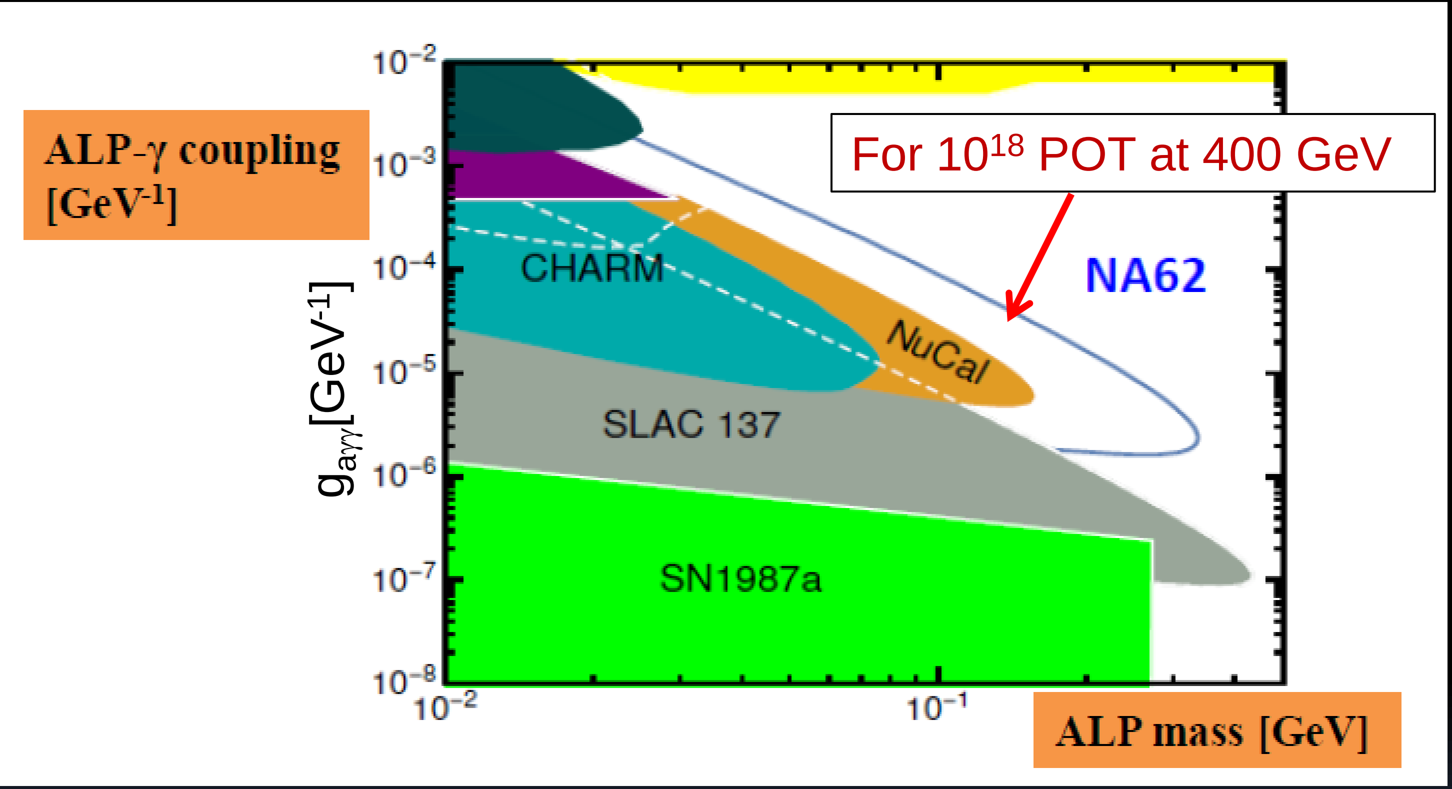
ALP's (a) can be a mediator between DM particles and SM particles

Production of ALP's in proton-nucleus interaction through the coherent scattering between proton and nuclei (Primakoff effect)
Cross section ~Z^2



Decay $a \rightarrow \gamma\gamma$

NA62: sensitivity to ALP's



Analysis of 2017 data in progress

Perspectives

Experiments sensitive to hidden particles

Current experiments:

T2K $\rightarrow$ T2K-II $\rightarrow$ T2HK
NA62, NA62 beam dump
NA64

Future projects:

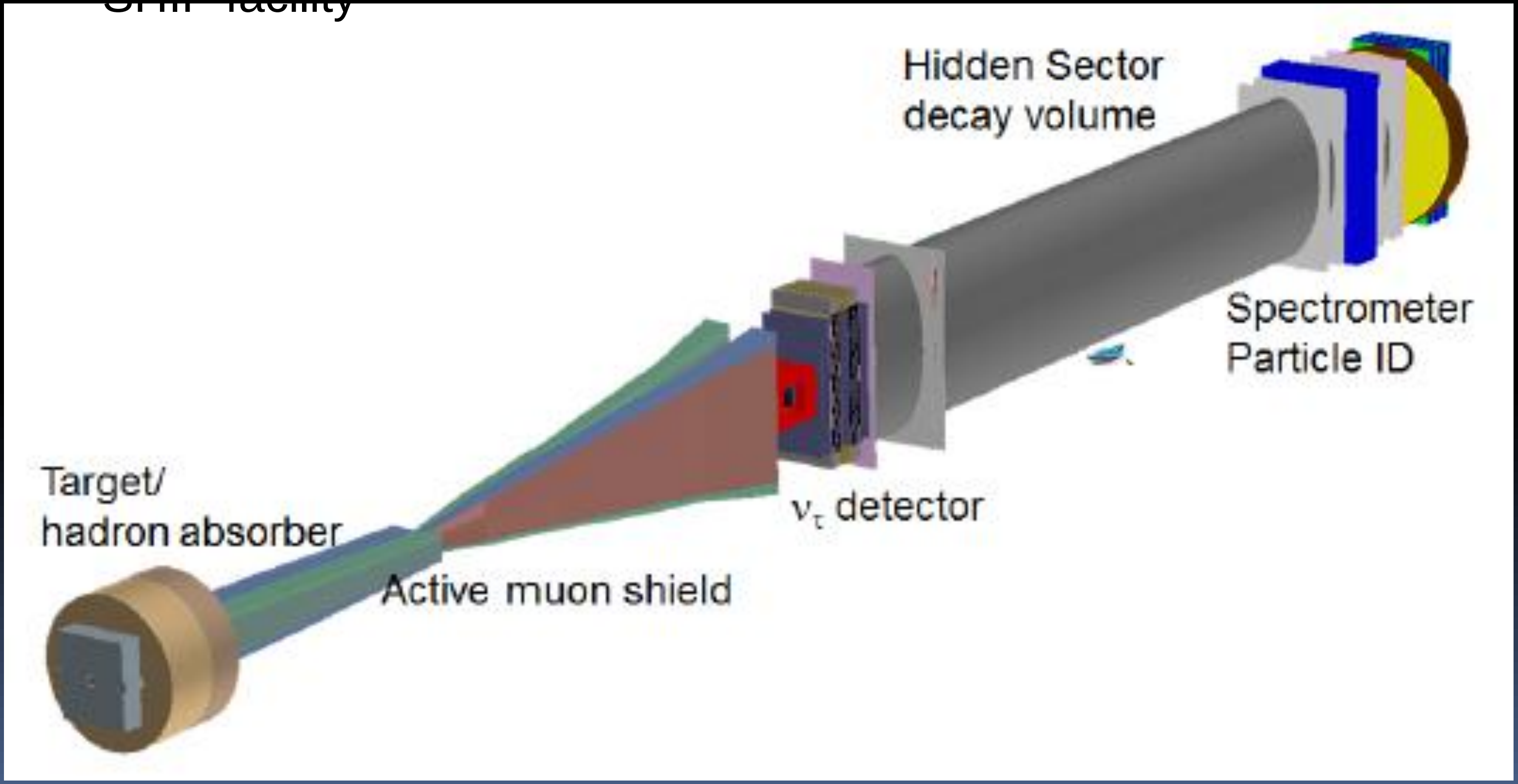
DUNE - LBL neutrino experiment
SHIP at CERN

Experiment SHIP at CERN

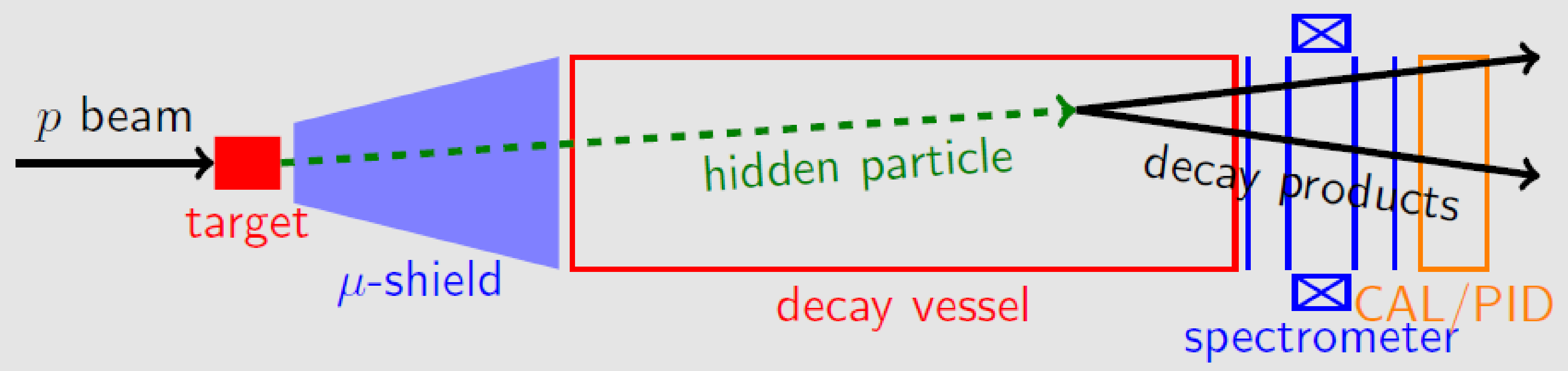
arXiv:1505.04956

400 GeV protons,
2×10^{20} POT over 5 years of running
$> 10^{18}$ D mesons

"Zero background" experiment
- *Heavy target*
- *Muon shield*
- *Surrounding Veto detectors*
- *Timing and PID detectors, …*

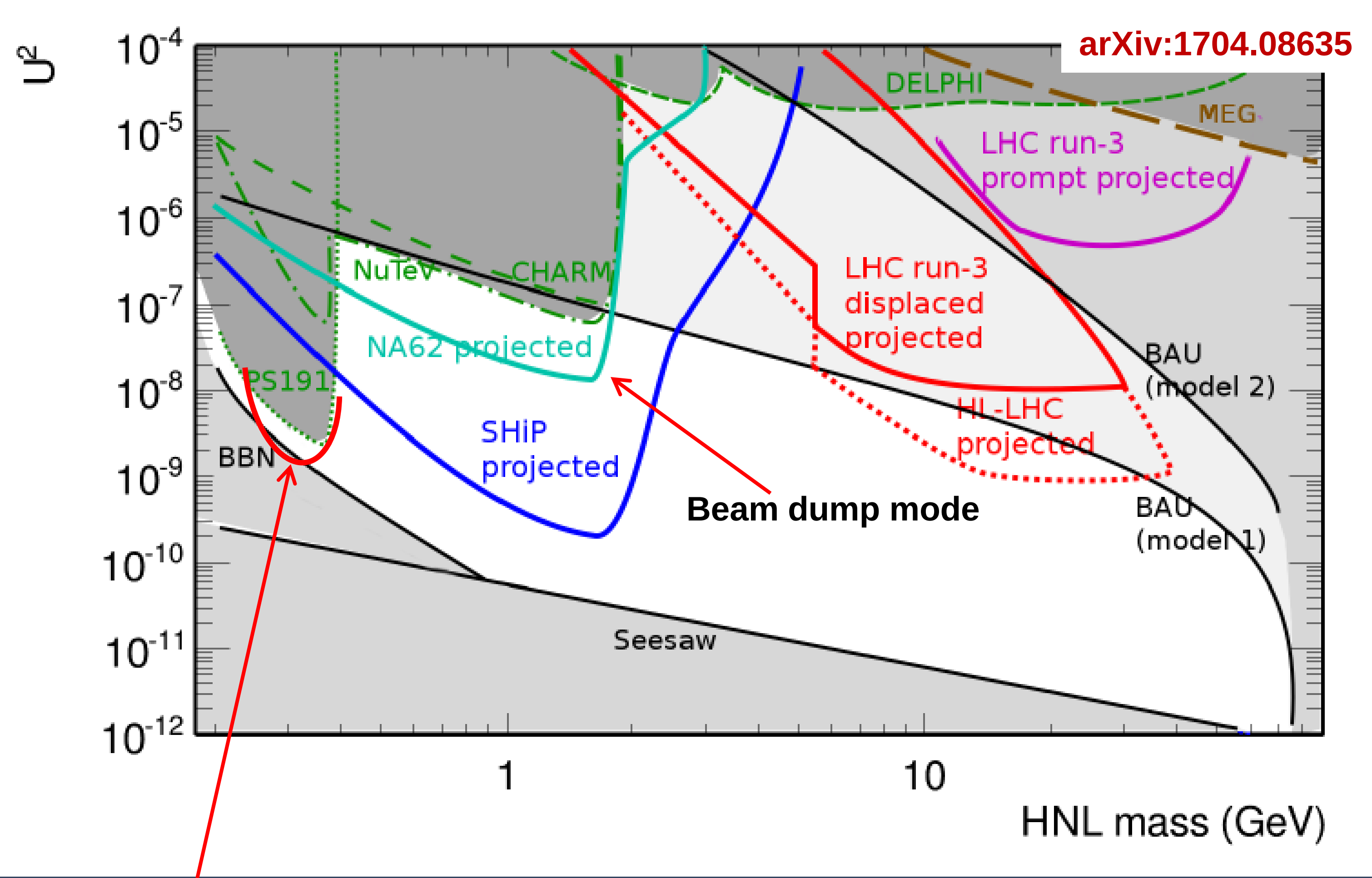


SHIP Principle



SHIP expected sensitivity

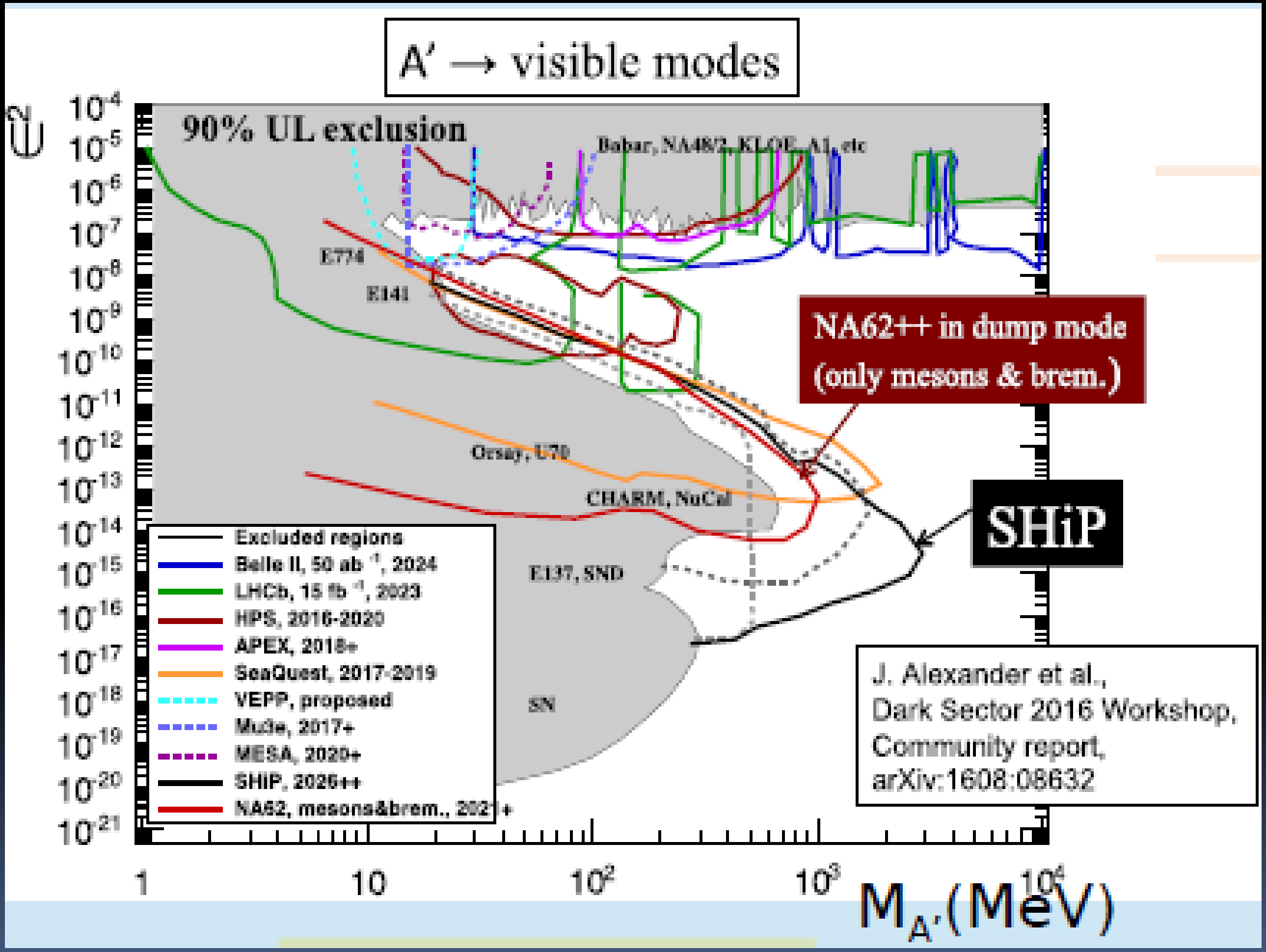
HNL



Form masses ≤ 500 MeV almost excluded by E949,T2K, NA62

SHIP expected sensitivity

Dark photons



Conclusion

Fixed target experiments at proton accelerators have good chances to test New Physics (hidden sector) beyond SM:

- **sensitive to HNL (heavy sterile neutrinos) in the mass range up to ~ few GeV**

- **probe "dark photons"**

- **search for ALP's**