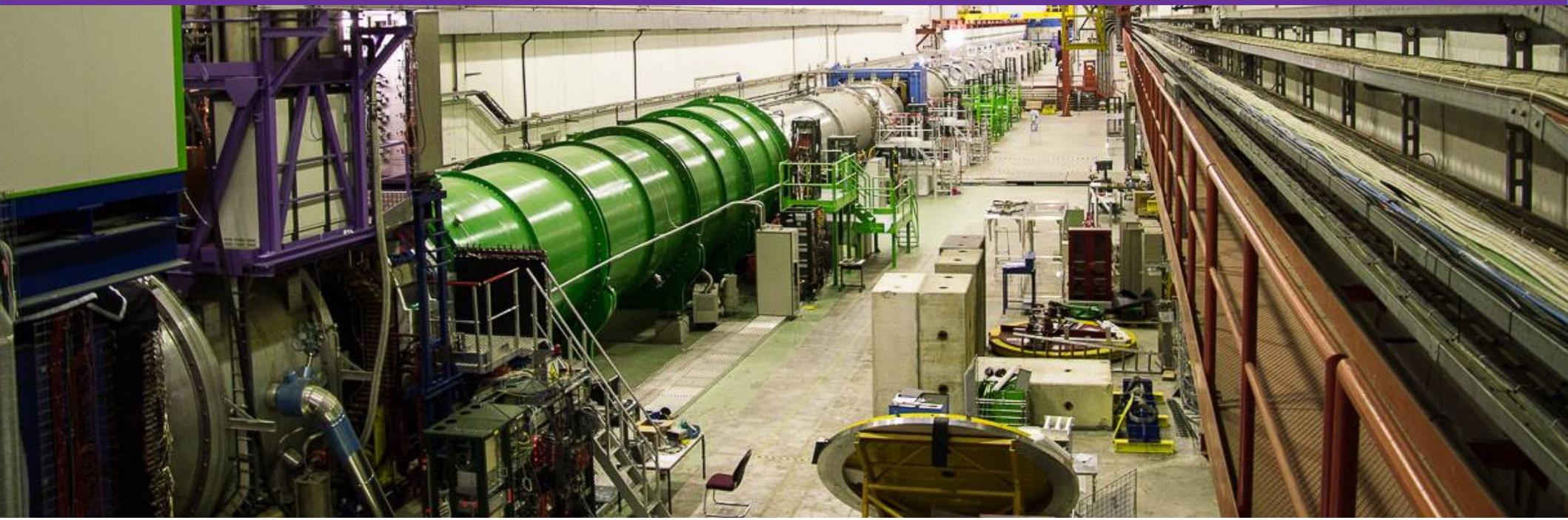
The $K^+ \to \pi^+ \nu\bar{\nu}$ decay and New Physics searches at NA62



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University of Perugia and INFN

on behalf of the NA62 Collaboration

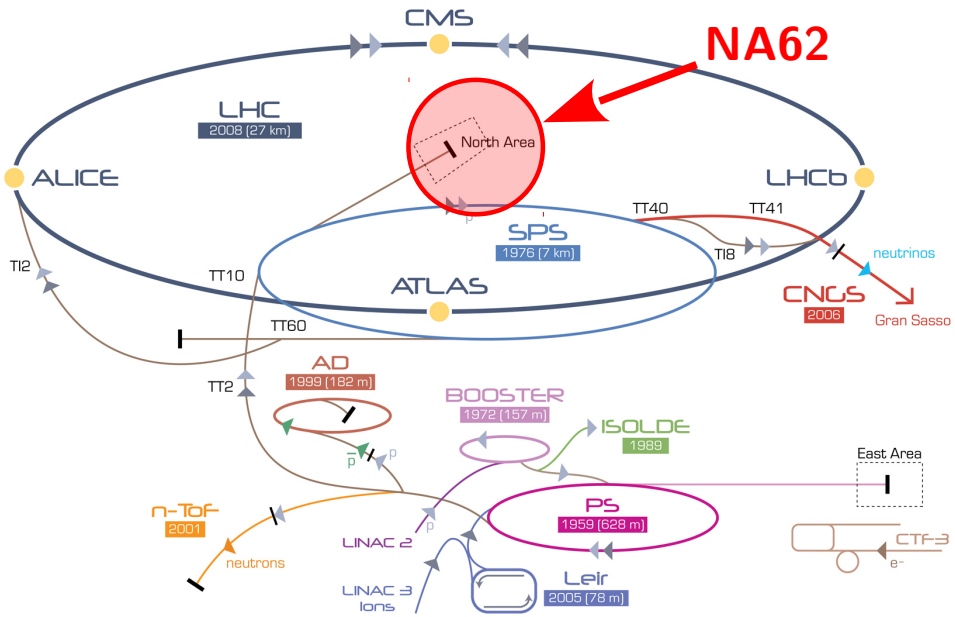
Excited QCD – February 2020

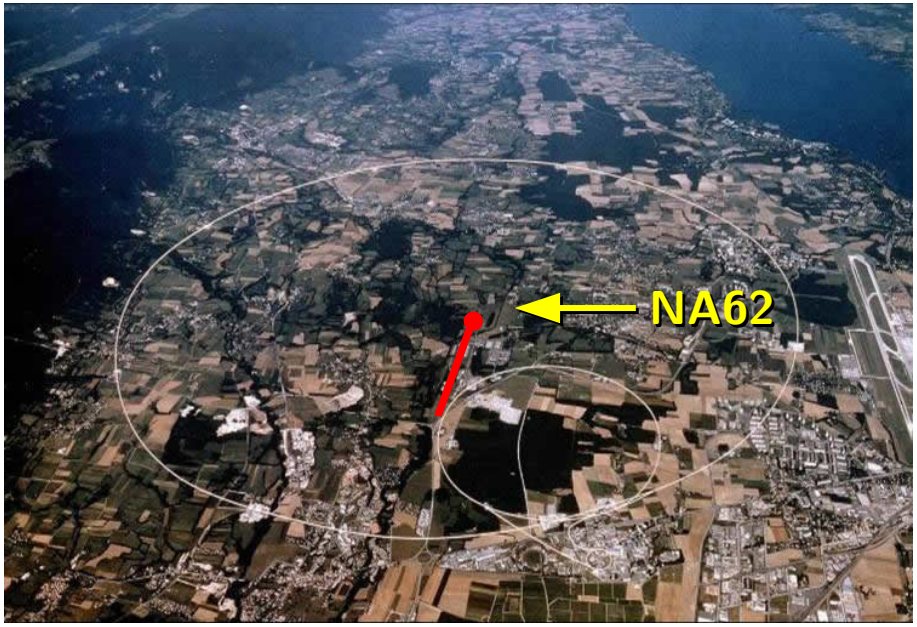
The NA62 experiment

The NA62 experiment

- Fixed target experiment, located in the North Area of the CERN SPS.
- Main goal: **BR(K+→π+ν$\bar{\nu}$)** with decay in flight technique.
- $\mathrm{BR}_{\mathrm{th}}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$
  [Buras et al., JHEP11(2015)033]

  $\mathrm{BR}_{\mathrm{exp}}(K^+ \to \pi^+ \nu \bar{\nu}) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$
  [E949, Phys. Rev D 79, 092004 (2009)]
- ~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.





The NA62 experiment

Main goal

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

Exotic searches

Heavy neutral leptons, dark photons, dark scalars, axion-like particles, ...

Forbidden decays

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

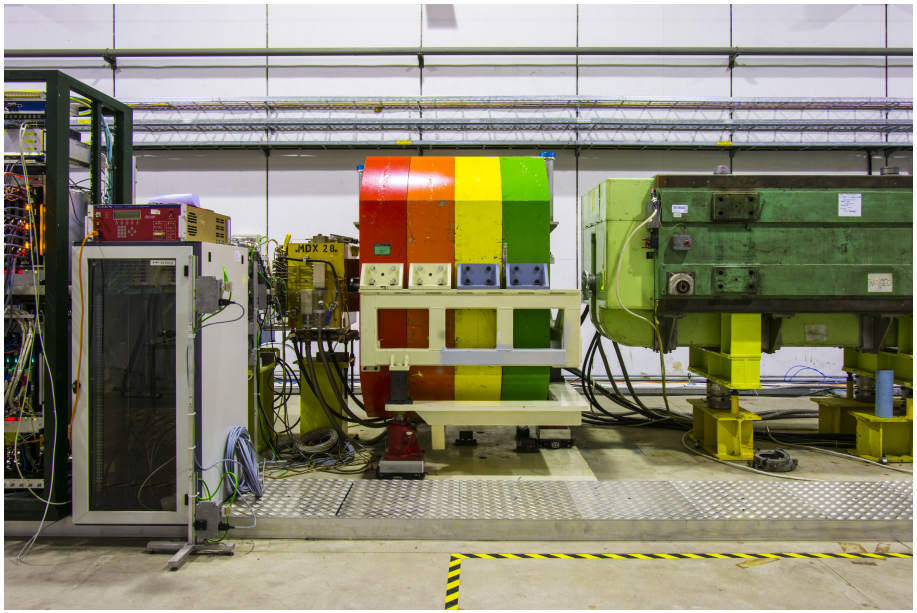
Rare decays

$K^+ \to \pi^+ \mu^+ \mu^-$, $K^+ \to \pi^+ \gamma \gamma$, ...

The NA62 experiment

Status and timeline:

- 2016
  - Commissioning + 1st physics run.
  - First $K^+ \to \pi^+\nu\bar{\nu}$ result published.
- 2017
  - Physics run, better collection efficiency for physics data.
  - 3 x 10^{12} K^+ decays recorded (> 10x more than 2016).
  - Preliminary results on $K^+ \to \pi^+\nu\bar{\nu}$ This talk
- 2018
  - Physics run, better shielding of upstream background.
  - 5 x 10^{12} K^+ decays recorded (> 20x more than in 2016).
- 2019 – 2020: CERN Long Shutdown 2.



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

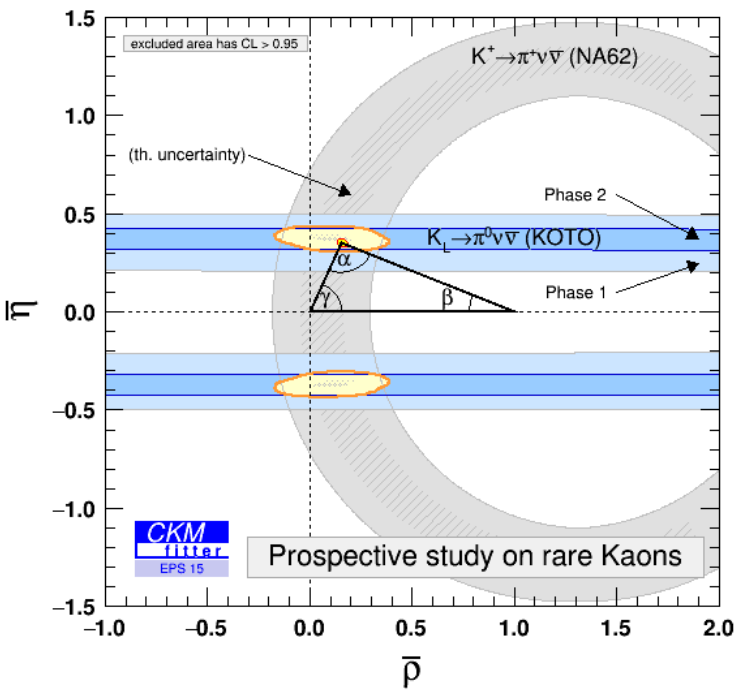
$K^+ \to \pi^+ \nu\bar{\nu}$: theoretical framework

- $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ provide an important test for the SM.
- FCNC processes dominated by Z-penguins and box amplitudes, main uncertainties from CKM matrix elements.
- Theoretically clean.

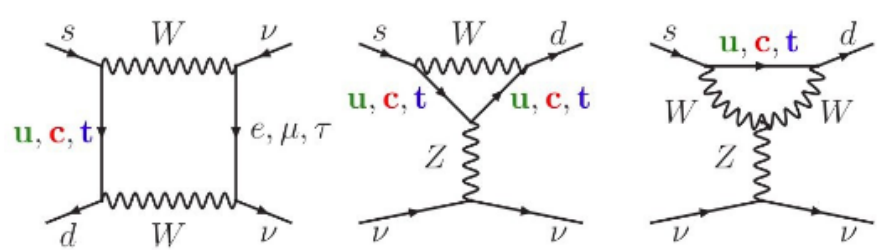
[Buras et al., JHEP 1551 (2015) 033]

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

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

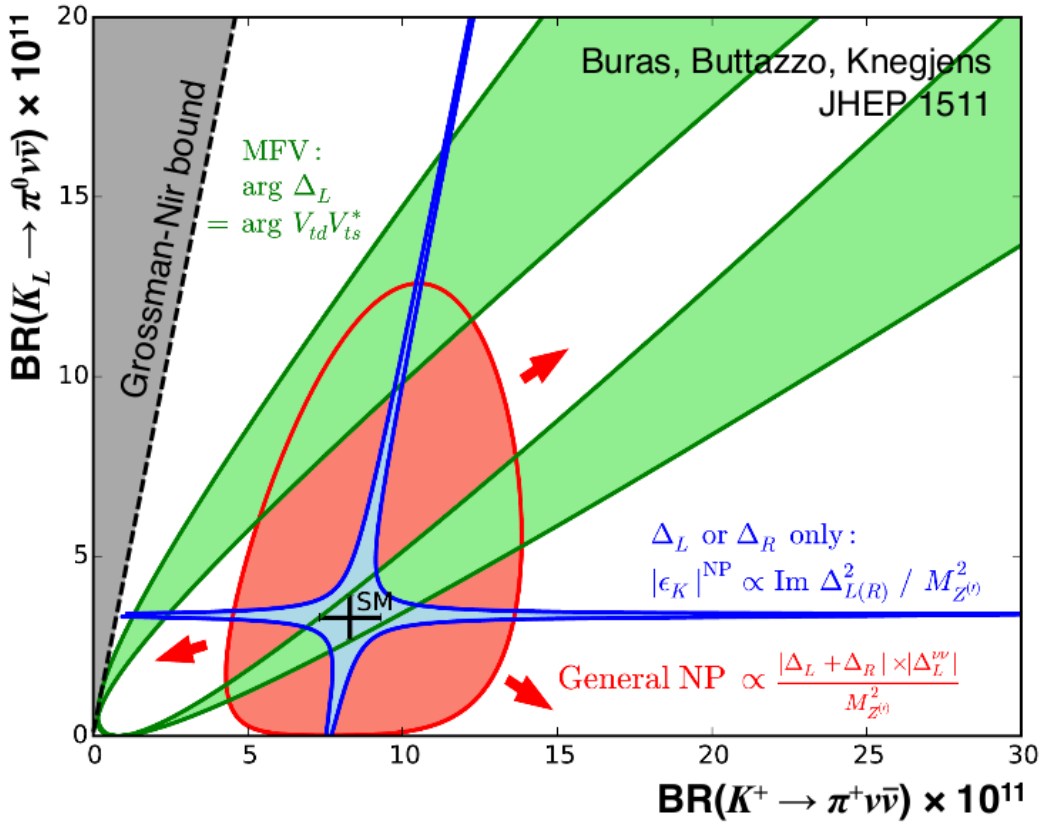


- Measuring both $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ provides the CKM unitarity triangle independently from measurements in B mesons sector.



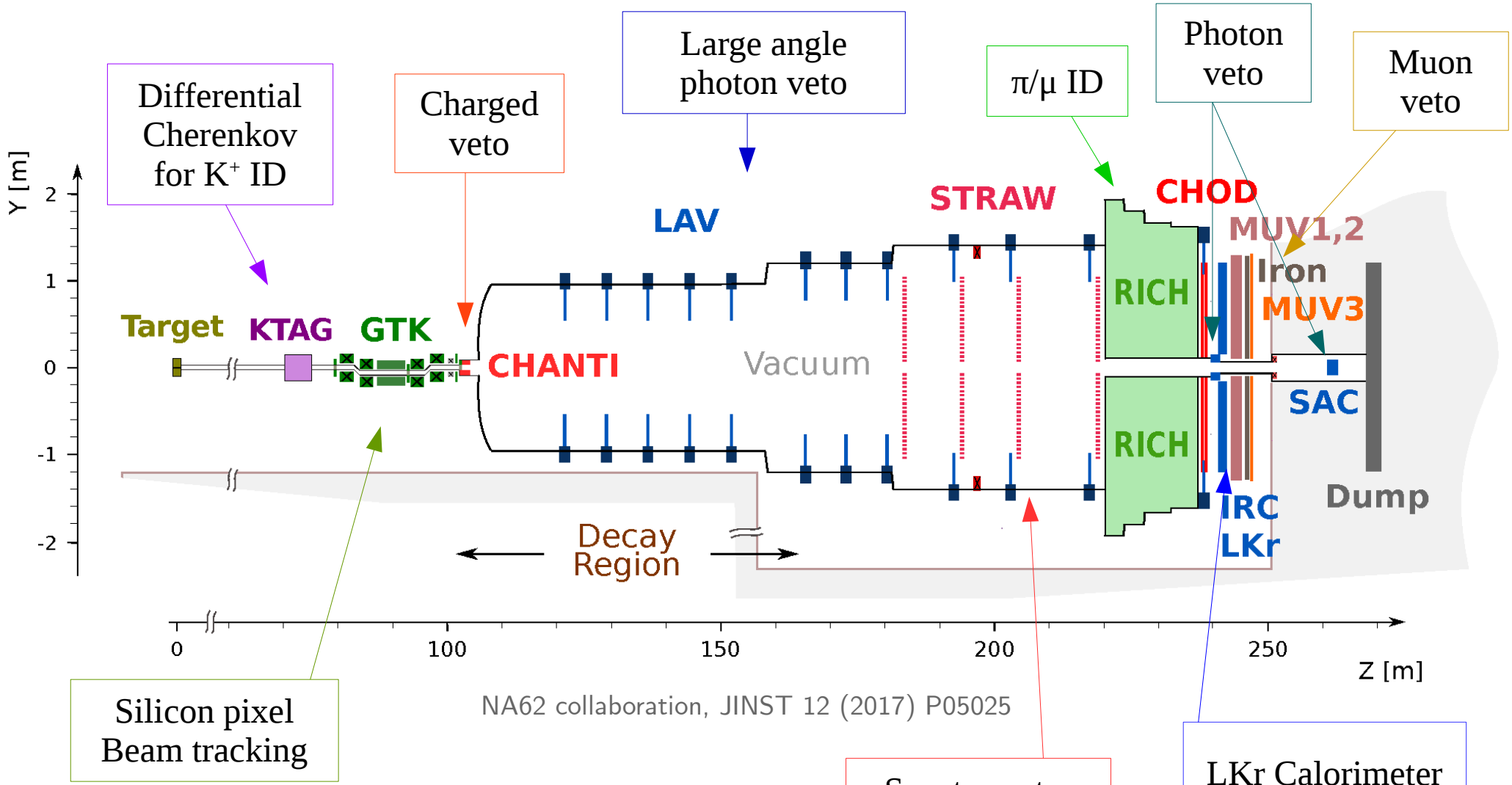
$K^+ \to \pi^+ \nu\bar{\nu}$: theoretical framework

- Correlations between $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ in most of the NP models.



- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM Analysis [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27], [Isidori et al. JHEP 0608 (2006) 064]
- Simplified Z, Z' models [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- LFU violation models [Isidori et al., Eur. Phys. J. C (2017) 77: 618]

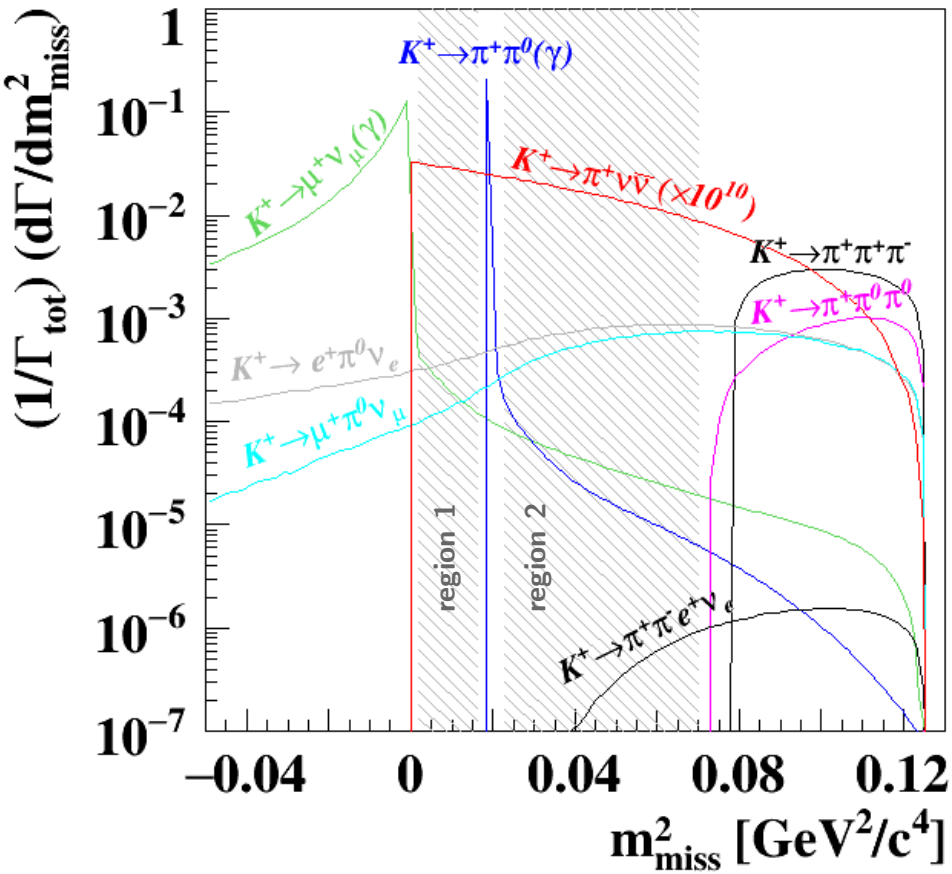
NA62 detector



- Primary beam: 400 GeV/c protons from SPS.
- Secondary beam: 75 GeV/c positively charged particles, 70% π^+, 23% p, 6% K^+.

$K^+ \to \pi^+ \nu\bar{\nu}$: decay in flight technique at NA62

Main background sources



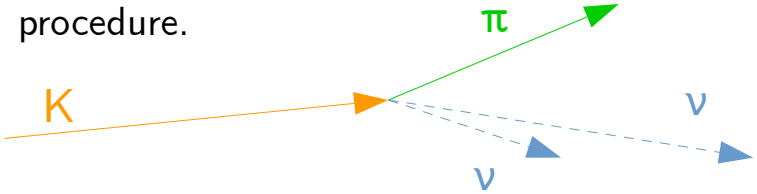
Decay mode	BR	Main rejection tools
$K^+ \to \mu^+\nu(\gamma)$	63%	μ−ID + kinematics
$K^+ \to \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	multi + kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+\nu_e$	5%	e−ID + γ-veto
$K^+ \to \pi^0\mu^+\nu_\mu$	3%	μ−ID + γ-veto

- The squared missing mass is the main variable used to kinematically separate signal from background:

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

$$15\ \text{GeV/c} < P_{\pi^+} < 35\ \text{GeV/c}$$

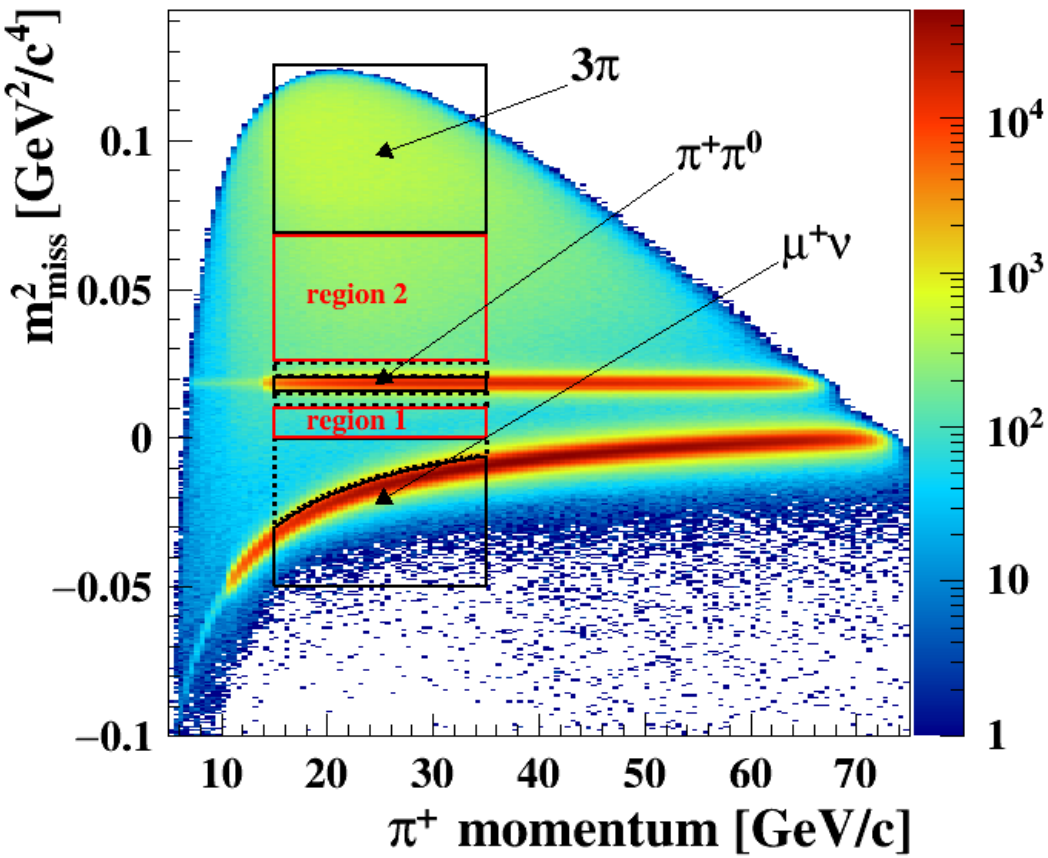
- Two signal region on each side of the $K^+ \to \pi^+\pi^0$ peak.
- Cut based analysis (mostly), blind analysis procedure.



- Requirements:
  - O(100 ps) timing between sub-detectors
  - O(10^4) background suppression with kinematics
  - O(10^7) background muon suppression ($K^+ \to \mu^+\nu_\mu$)
  - O(10^7) photon suppression ($K^+ \to \pi^+\pi^0$)

$K^+ \to \pi^+ \nu\bar{\nu}$: signal and control regions

- Two signal regions kept blinded
- In order to evaluate the background from K decays, the tails of the distribution are extrapolated into the signal regions.
- The control regions are kept blinded too, to validate the procedure.



- Selection:
  - single track in final state
  - π^+ identification
  - photon rejection
  - Multiplicity rejection
  - $110\ \text{m} < z_{vertex} < 165\ \text{m}$
  - $15\ \text{GeV/c} < p_{\pi+} < 35\ \text{GeV/c}$, in order to have at least $E_{miss} = 40$ GeV and have an optimal π/μ separation in the RICH.
- Performances:
  - $\varepsilon(\mu^+) \sim 10^{-8}$ (64% π^+ efficiency)
  - $\varepsilon(\pi^0) \sim 1.4 \cdot 10^{-8}$
  - $\sigma(m^2_{miss}) \sim 10^{-3}\ \text{GeV}^2/c^4$
  - $\sigma_t \sim O(100\ \text{ps})$

$K^+ \to \pi^+ \nu\bar{\nu}$: Single Event Sensitivity (2017)

$$N_{\pi\nu\nu}^{\text{expected}}(\text{SM}) = \frac{BR_{\pi\nu\nu}(\text{SM})}{SES}$$

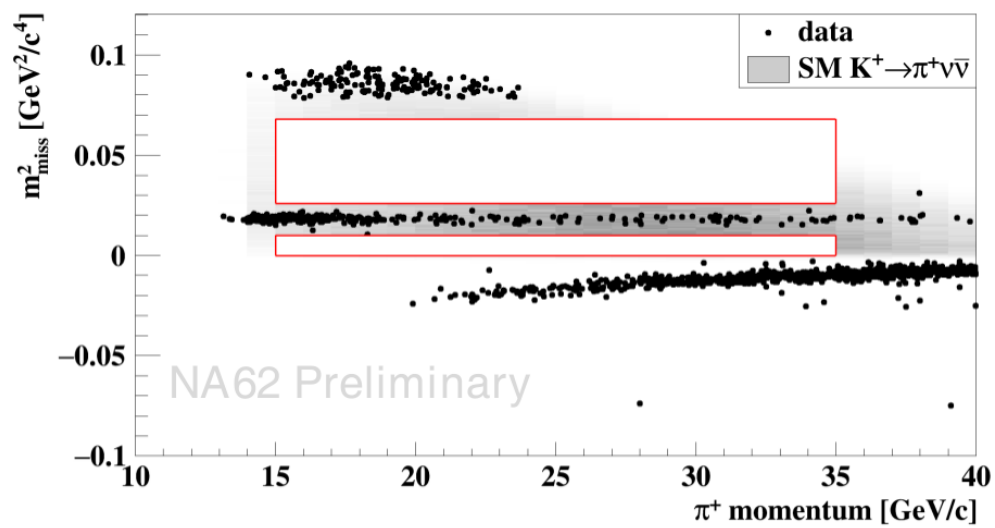
$$SES = \frac{1}{N_K \cdot \sum_j \left(A_{\pi\nu\nu}^j \cdot \epsilon_{\text{trig}}^j \cdot \epsilon_{\text{RV}}^j \right)}$$

- $A_{\pi\nu\nu}$: signal acceptance
- ϵ_{trig}: trigger efficiency
- ϵ_{RV}: random veto efficiency
- j: bin of momentum and beam intensity

$$N_K = \frac{N_{\pi\pi} \cdot R}{A_{\pi\pi} \cdot BR_{\pi\pi}} = (1.3 \pm 0.1) \times 10^{12}$$

- $N_{\pi\pi}$: number of $K^+ \to \pi^+\pi^0$ observed
- $A_{\pi\pi}$: normalization decay acceptance
- $BR_{\pi\pi}$: normalization decay branching ratio
- R: reduction factor applied to CTRL trigger

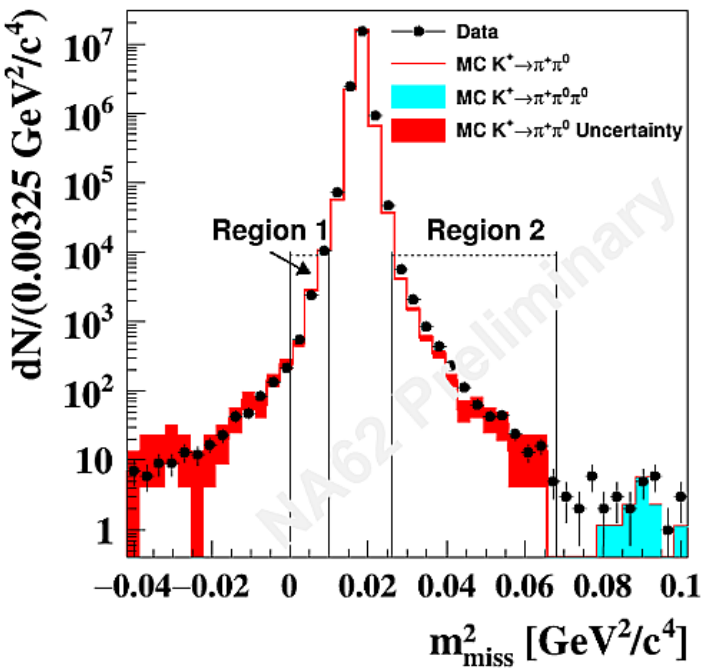
Source	$\delta SES \times 10^{-10}$
L0 trigger	± 0.015
Acceptance	± 0.012
Random veto	± 0.008
L1 trigger	± 0.003
Normalization background	negligible



$$SES = (0.389 \pm 0.021) \cdot 10^{-10}$$

$$N_{\pi\nu\nu}^{\text{expected}}(\text{SM}) = 2.16 \pm 0.12_{\text{stat}} \pm 0.26_{\text{extr}}$$

Expected background from $K^+ \to \pi^+\pi^0$



Control data used to study tails of m^2_{miss} distributions

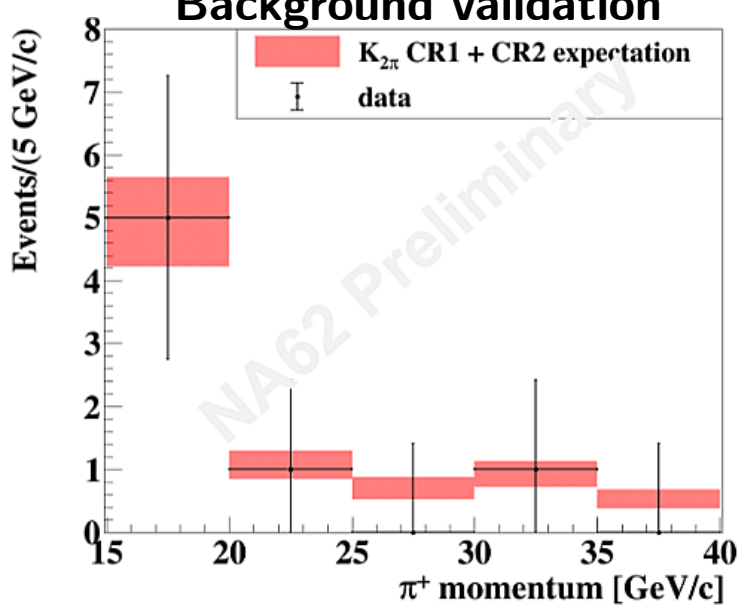
$$N^{exp}_{\pi\pi}(\text{region}) = N(\pi^+\pi^0)\cdot f_{kin}(\text{region})$$

– $N^{exp}_{\pi\pi}(\text{region})$: expected $K^+ \to \pi^+\pi^0$ events in the signal region after the $\pi\nu\nu$ selection

– $N(\pi^+\pi^0)$: events in the $K^+ \to \pi^+\pi^0$ region after the $\pi\nu\nu$ selection

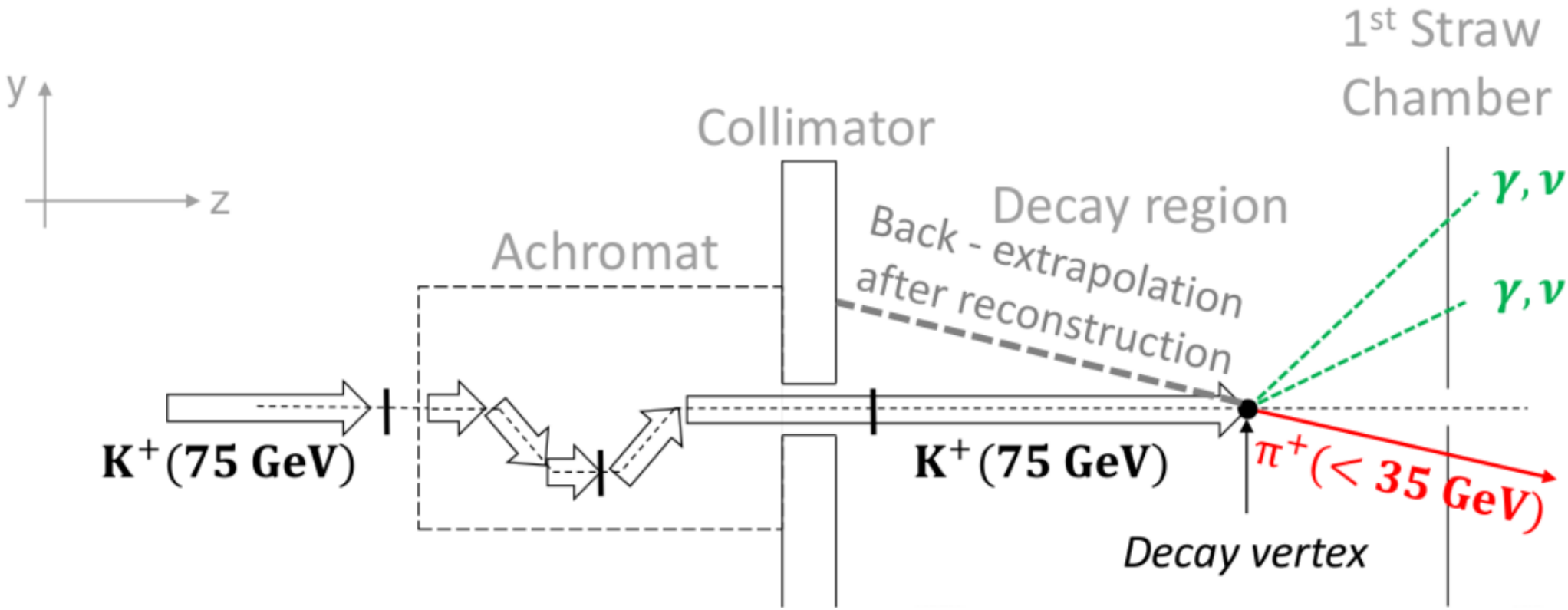
– $f_{kin}(\text{region})$: fraction of $K^+ \to \pi^+\pi^0$ in signal region measured on control data

Background validation



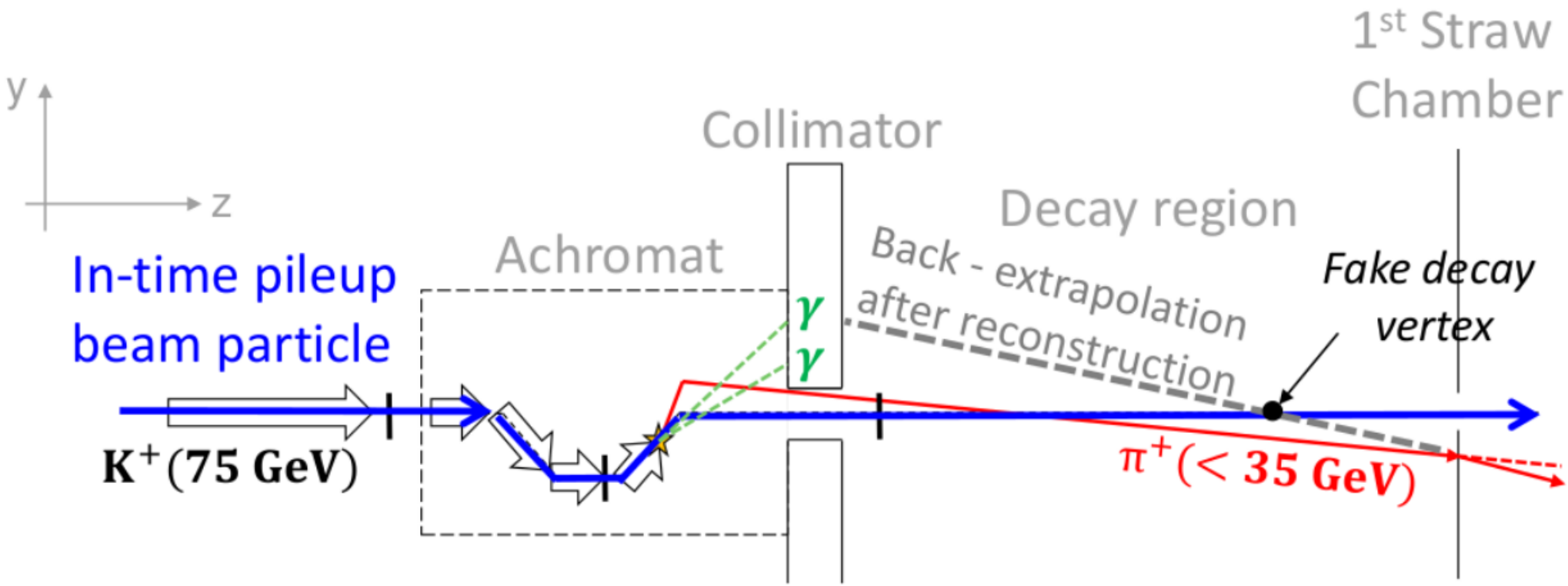
Upstream background

Upstream events: particles originated before the fiducial decay volume (early decays and interactions).



Normal K^+ decay: back-extrapolation of the charged track in final state is far from the beam direction. Tracks back-extrapolated near the beam direction are rejected.

Upstream background



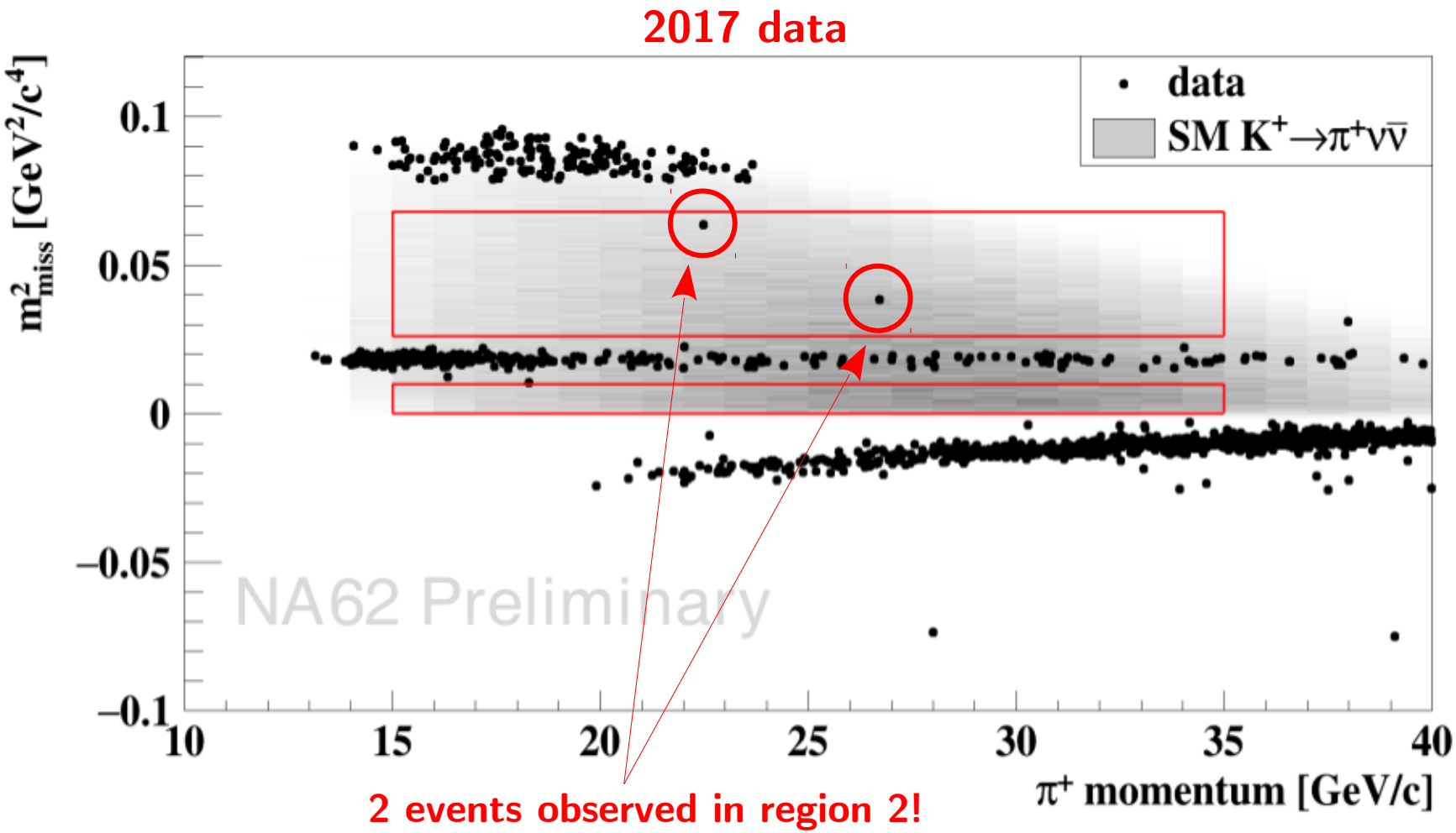
Background if in-time **pile-up beam particle** (in KTAG and GTK). The upstream generated track enters the fiducial decay region and undergoes **multiple scattering** in the 1st chamber of the STRAW.

$K^+ \to \pi^+ \nu\bar{\nu}$: expected background (2017)

2017 data preliminary

Process	Expected events
$K^+ \to \pi^+ \nu\bar{\nu}$ (SM)	$2.16 \pm 0.12_{stat} \pm 0.26_{ext}$
$K^+ \to \pi^+ \pi^0(\gamma)$ IB	$0.29 \pm 0.03_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+ \nu_\mu(\gamma)$ IB	$0.15 \pm 0.02_{stat} \pm 0.04_{syst}$
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	$0.12 \pm 0.05_{stat} \pm 0.03_{syst}$
$K^+ \to \pi^+ \pi^- \pi^+$	$0.02 \pm 0.02_{syst}$
$K^+ \to \pi^+ \gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+ \pi^0 \nu_l$	negligible
Upstream background	$0.9 \pm 0.2_{stat} \pm 0.2_{syst}$
Total background	$1.5 \pm 0.2_{stat} \pm 0.2_{syst}$

$K^+ \to \pi^+ \nu\bar{\nu}$: 2017 preliminary results



Signal events expected in signal region (SM)

$2.16 \pm 0.12_{stat} \pm 0.26_{ext}$

Background events expected in signal region

1.50 ± 0.30

$K^+ \to \pi^+ \nu\bar{\nu}$: 2016+2017 preliminary results

2016 + 2017 uncorrelated

Events observed	3
Single Event Sensitivity	$(0.346 \pm 0.017) \times 10^{-10}$
Expected background	1.65 ± 0.31

Upper limits: $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) < 1.85 \cdot 10^{-10}$ @90%CL

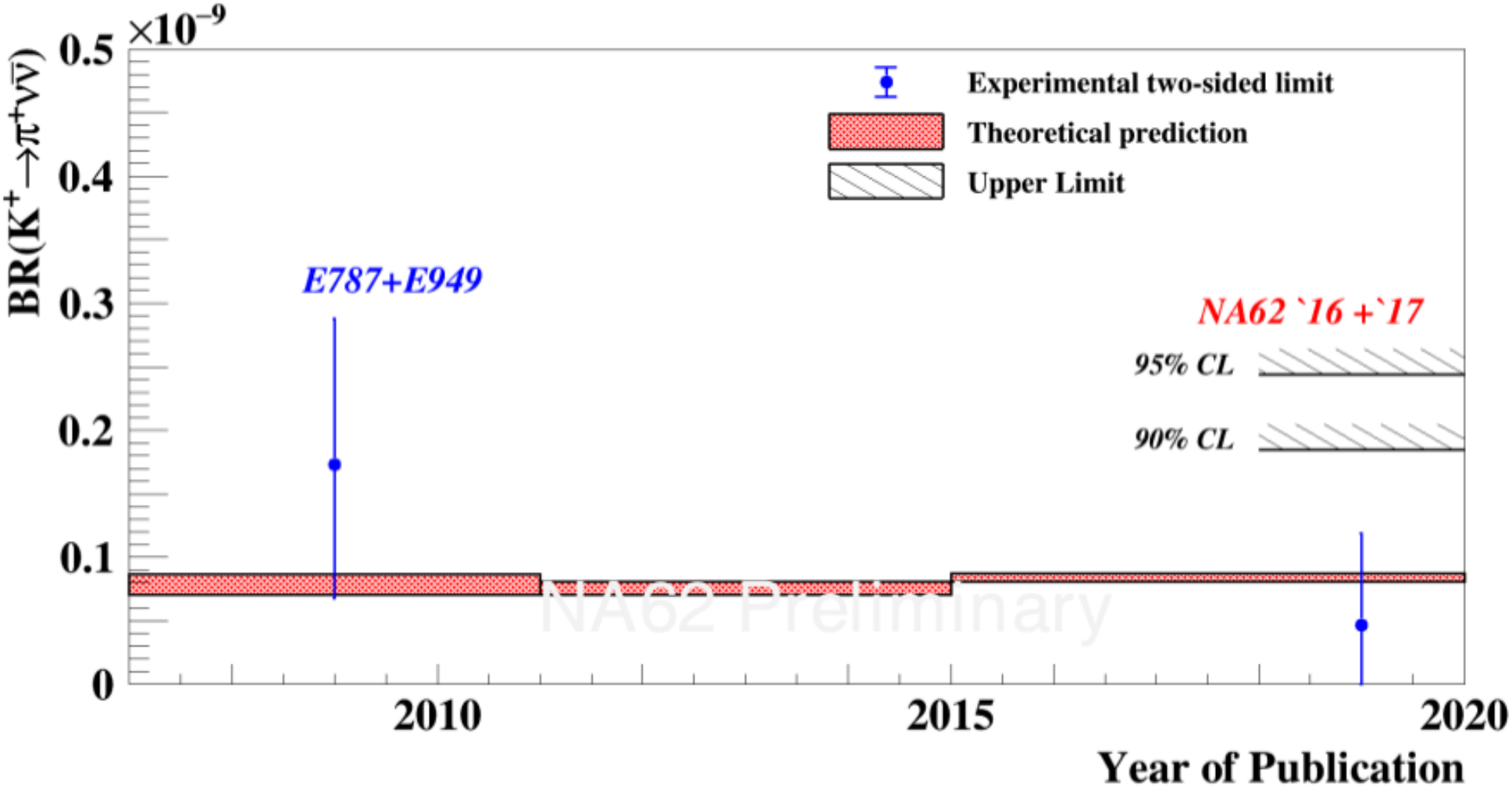
$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) < 2.44 \cdot 10^{-10}$ @95%CL

Two-sided 68% sideband: $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = 0.47^{+0.72}_{-0.47} \times 10^{-10}$

New Grossman-Nir limit: $\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) < 8.14 \times 10^{-10}$ @90%CL

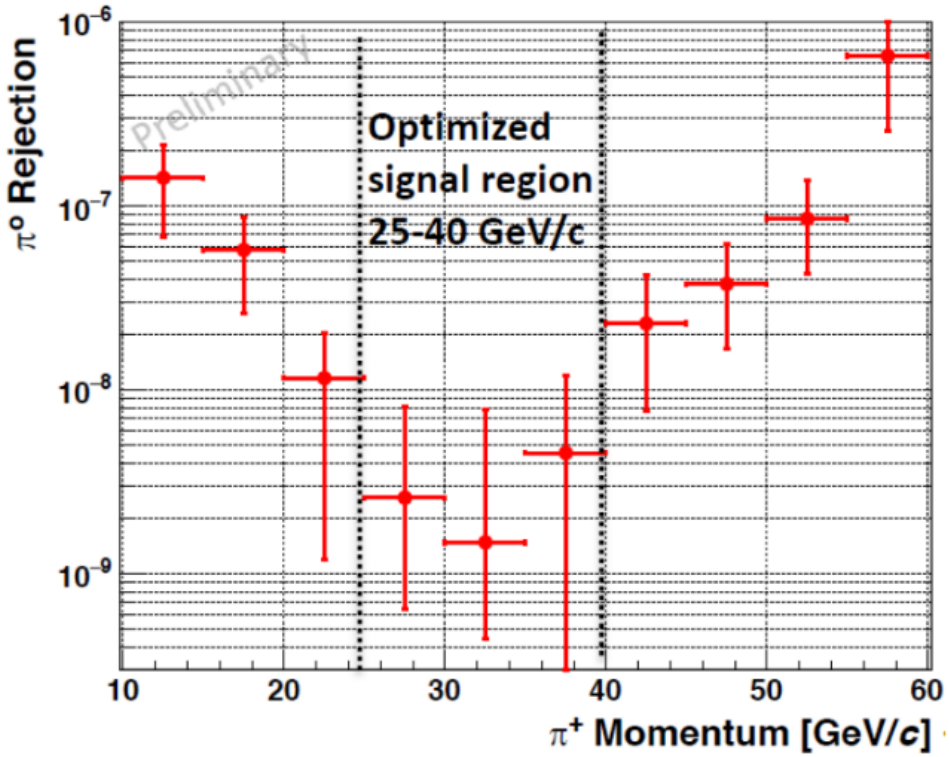
SM prediction on the Branching Ratio: $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.10) \cdot 10^{-10}$

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



Exotic searches
and
Forbidden decays

$\pi^0 \rightarrow$ invisible



- A-priori evaluation of π^0 suppression in $K^+ \rightarrow \pi^+\pi^0$ kinematic region
- Same selection of $K^+ \rightarrow \pi^+\nu\bar{\nu}$
- Normalization channel: $\pi^0 \rightarrow \gamma\gamma$
- Number of expected background events: 10^{+22}_{-8}
- Number of observed events: 12

- Preliminary result: $\mathrm{BR}(\pi^0 \rightarrow \mathrm{invisible}) < 4.4 \times 10^{-9}$ @90% C.L.
- Factor 60 improvement with respect to the state of the art.

LNV and LFV: NA62 search

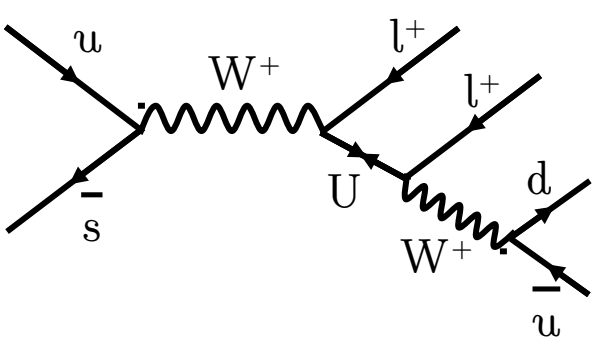
- In the SM, if neutrinos are massless, lepton flavour numbers and total lepton number are conserved
- Violation of these conservation laws in models BSM via Majorana neutrinos (U) [JHEP 0905 (2009) 030], [Phys.Lett. B491 (2000) 285-290]
- E.g. $K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^- \mu^+ \mu^+$
- NA62 results with a subset of 2017 data improve world upper limits on the BR of $K^+ \to \pi^- e^+ e^+$ and $K^+ \to \pi^- \mu^+ \mu^+$ by a factor 2-3:

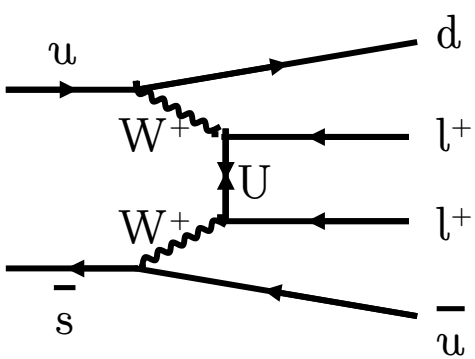
$$\mathrm{BR}\left(K^+ \to \pi^- e^+ e^+\right) < 2.2 \times 10^{-10} \quad 90\%\ \mathrm{C.L.}$$

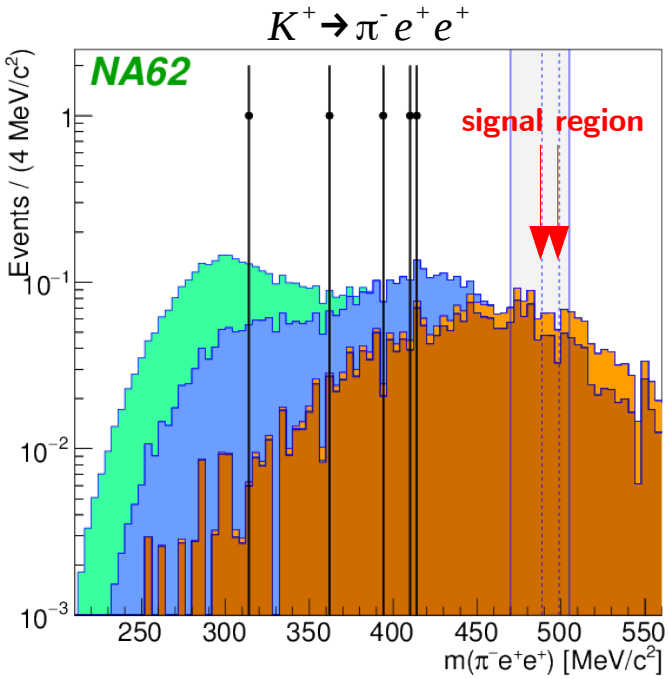
$$\mathrm{BR}\left(K^+ \to \pi^- \mu^+ \mu^+\right) < 4.2 \times 10^{-11} \quad 90\%\ \mathrm{C.L.}$$

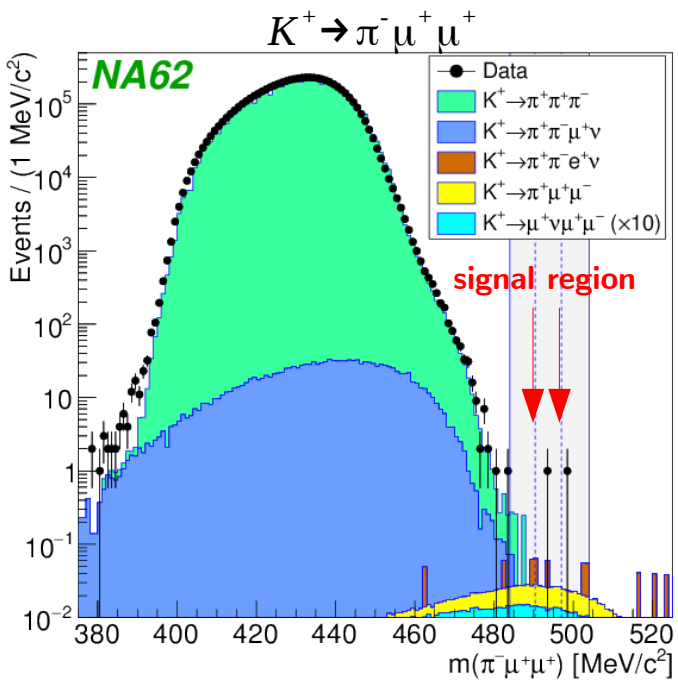
[Phys.Lett. B797 (2019) 134794]

- Full data sample (2016-2018): 3x more statistics





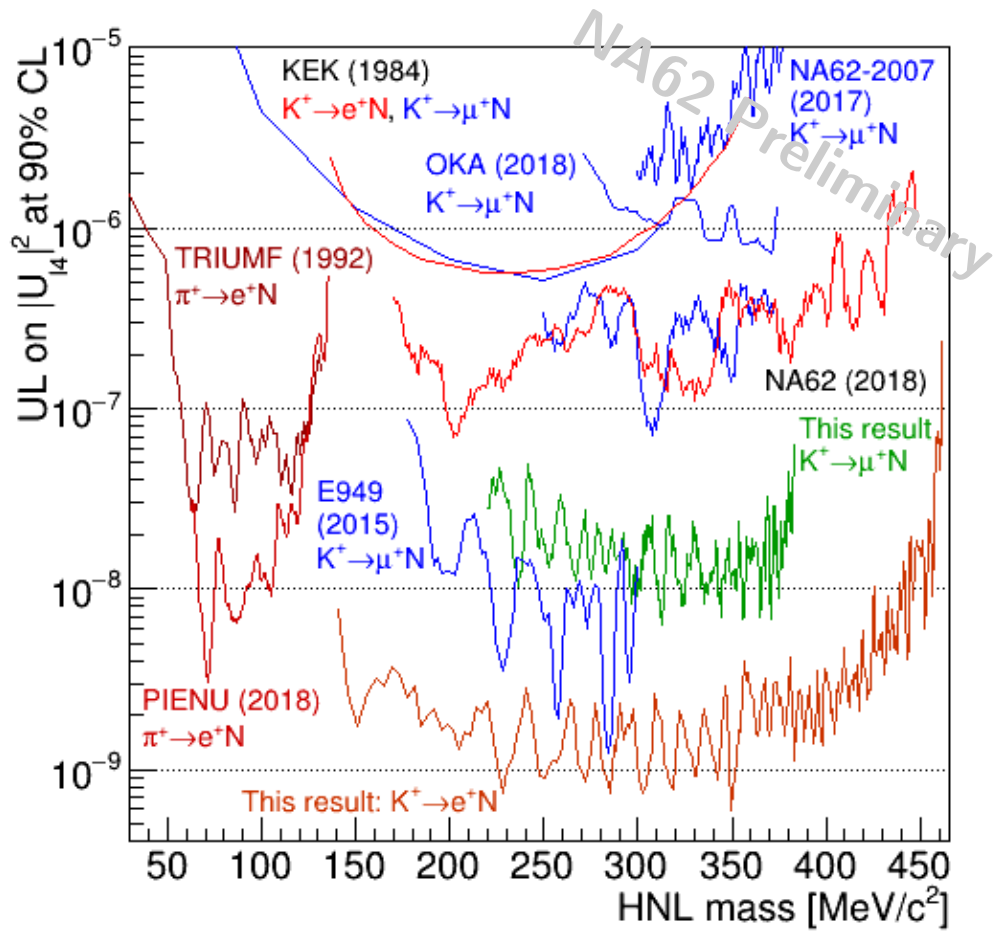




HNL: analysis of 2016+2017 sample

- The **νMSM** predicts three heavy sterile neutrinos, with $N_1 \sim O(10\ keV/c^2)$ and $N_{2,3} \sim O(1\ GeV/c^2)$.
- Production of $N_{2,3}$ in meson decays, such as $K^+ \to e^+N$ and $K^+ \to \mu^+N$.
- Mass scan in the range 141-462 (220-383) MeV/c² in the e^+ (μ^+) case.
- Preliminary 2016+2017 result: new upper limit on mixing parameter $|U_{l4}|^2$

  [Goudzovski KAON 2019]
- More than 2 orders of magnitude improvements with respect to previous results.
- Improvement by almost a factor 2 with the full data set.

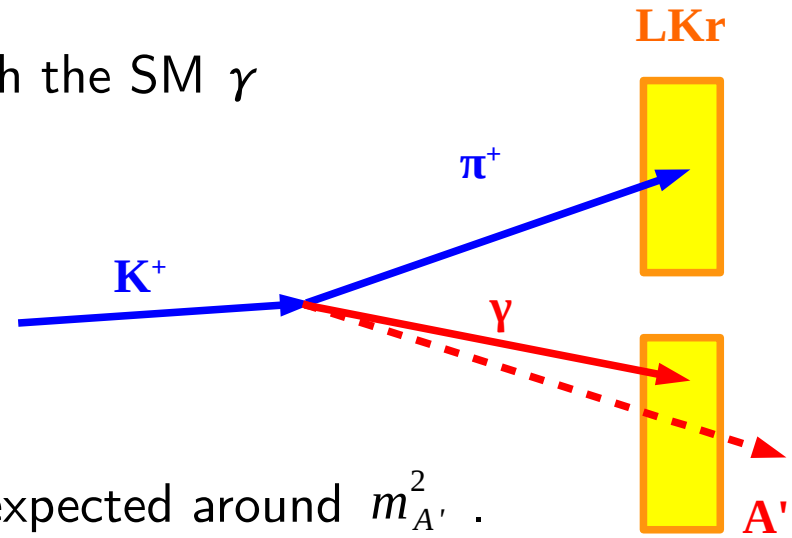


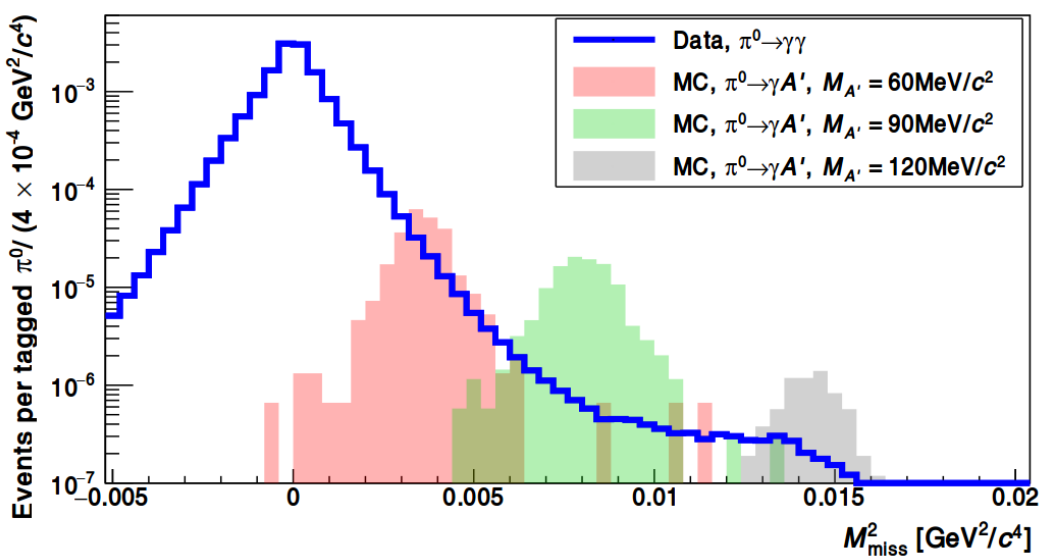
Dark Photons

- SM extension – new vector field A' mixing with the SM γ

  [B. Holdom, Phys. Lett. B 166 (1986) 196]

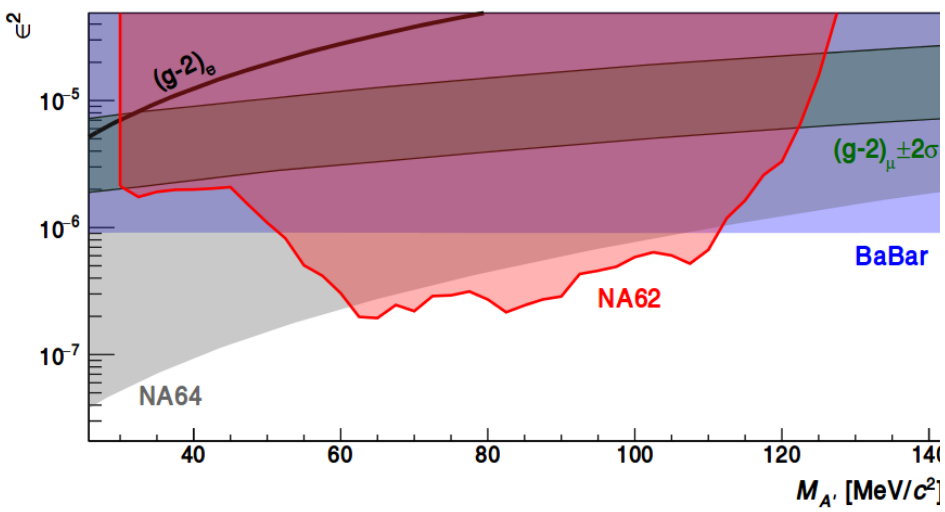
- $K^+ \to \pi^+ \pi^0, \ \pi^0 \to A'\gamma, \ A' \to \text{invisible}$
- $\mathrm{BR}(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \times \mathrm{BR}(\pi^0 \to \gamma\gamma)$
- Missing mass squared is computed, a peak is expected around $m_{A'}^2$.
- Main background comes from $\pi^0 \to \gamma\gamma$ with a lost photon.

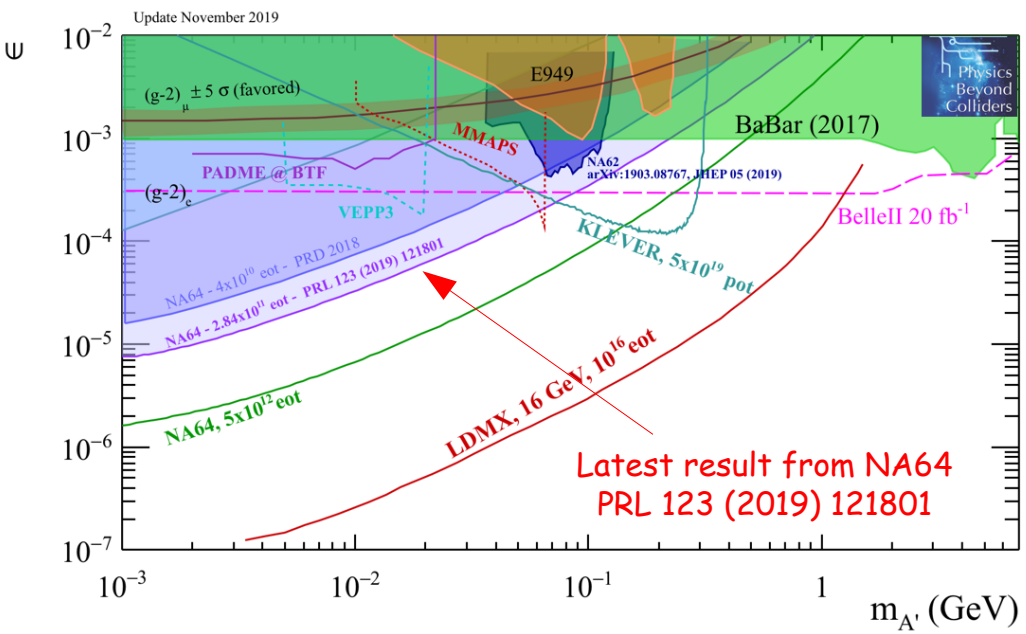




Dark Photons

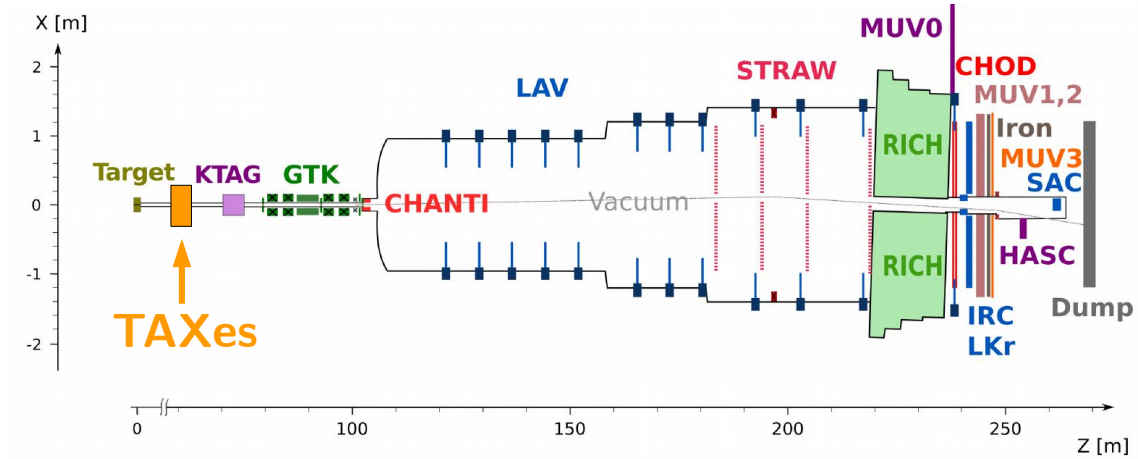
- Evaluation of background from data, inverting the veto condition on the charged hodoscopes; background normalized to data in the region already covered by other experiments.
- Analysed a subsample of 2016 data, ~1% of 2016-2018 data.
- No signal observed, new upper limits at 90% CL in the (ε^2,$m_{A'}$) plane.





- $BR(\pi^0 \rightarrow \gamma \nu \bar{\nu}) < 1.9 \times 10^{-7}$ @ 90% C.L. [JHE05 (2019) 182]
  - Improvement on the state of the art by more than 3 orders of magnitude

Beam dump

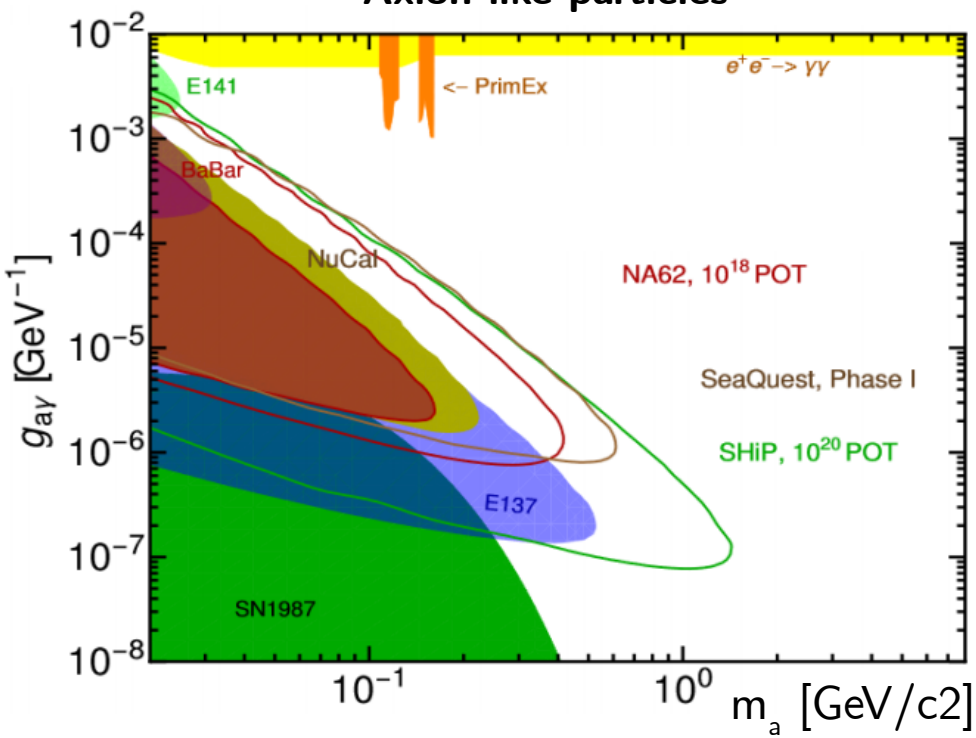


- Beam dumped in the TAXes (2 copper collimators, 25 m after the target, 2x10.7 λ_I).
- Dumping the beam before the detector allows for the production of exotic particles or B and D mesons decaying promptly into exotic mediators and SM particles.
- In this way, the exotic searches extend up to masses of ~1.7 GeV.
- 3×10^{16} protons on target already taken in 2017-2018
- 3-4 months of run in dump mode foreseen after the LS → O(10^{18}) protons on target (POT).
- In the next slides, expected limits in 5 years are shown.

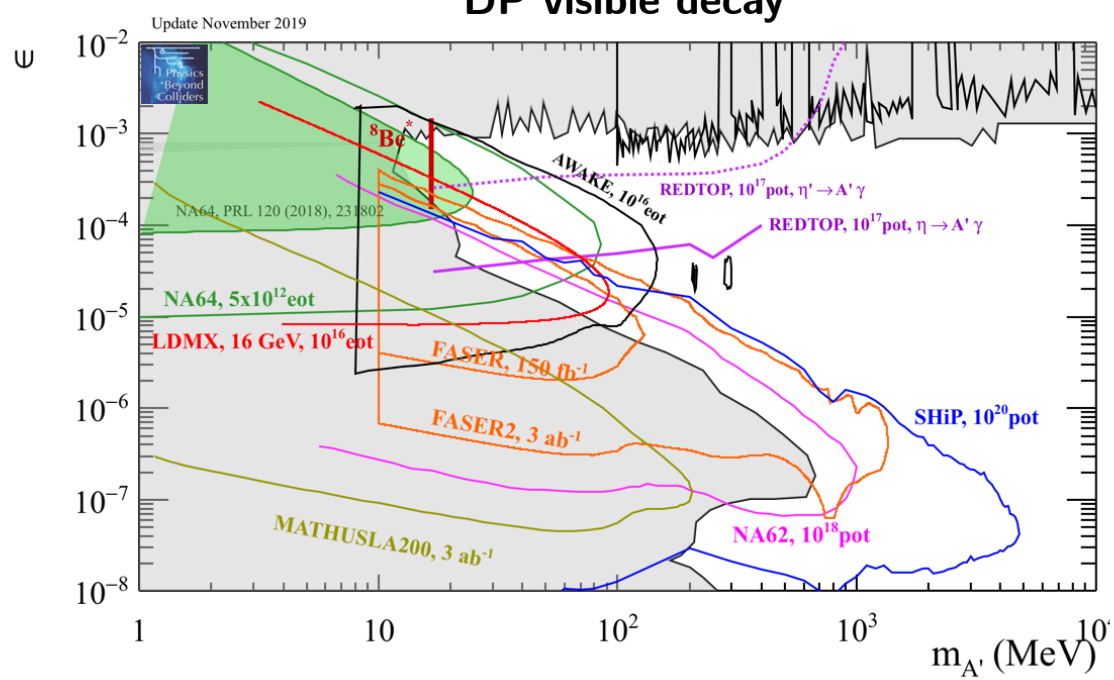
Beam dump

- NA62 can explore **ALP**s masses in the **MeV** to **GeV** range. [JHEP 1602 (2016) 018]
  - π^0 are a major background to $K^+ \to \pi^+\nu\bar{\nu}$, therefore an hermetic photon veto is essential to the measurement: search **ALP → γγ** .
- **Dark photon** visible decay at NA62: DP produced in the dump, **A' → l^+l^-**

Axion-like particles

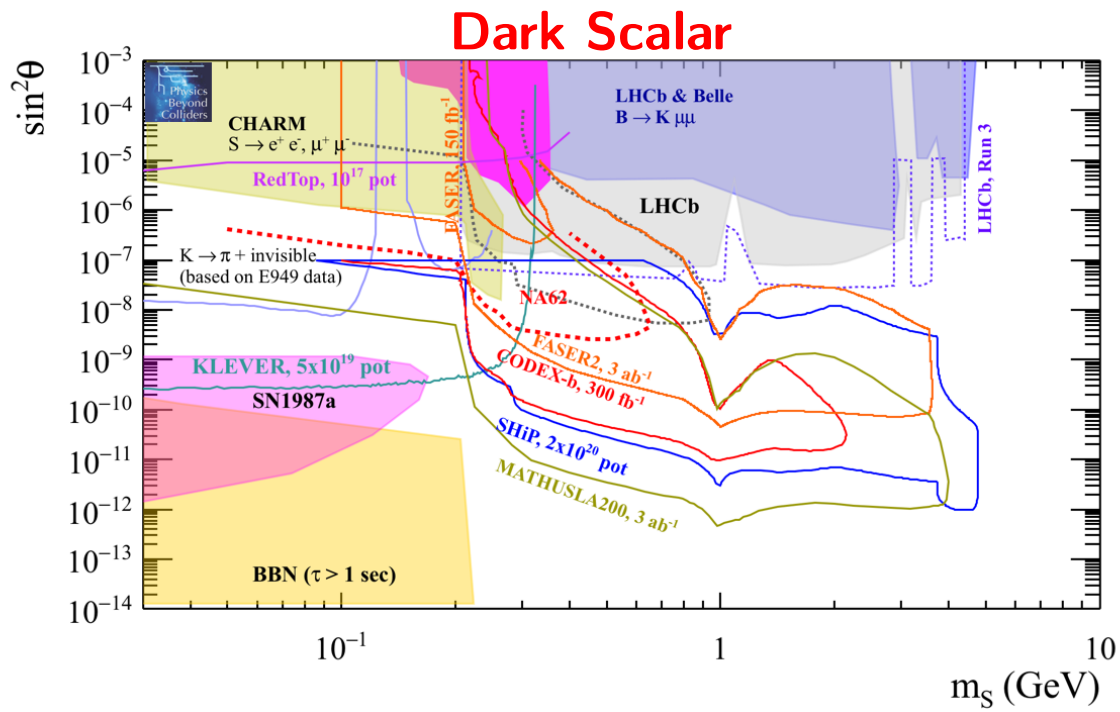


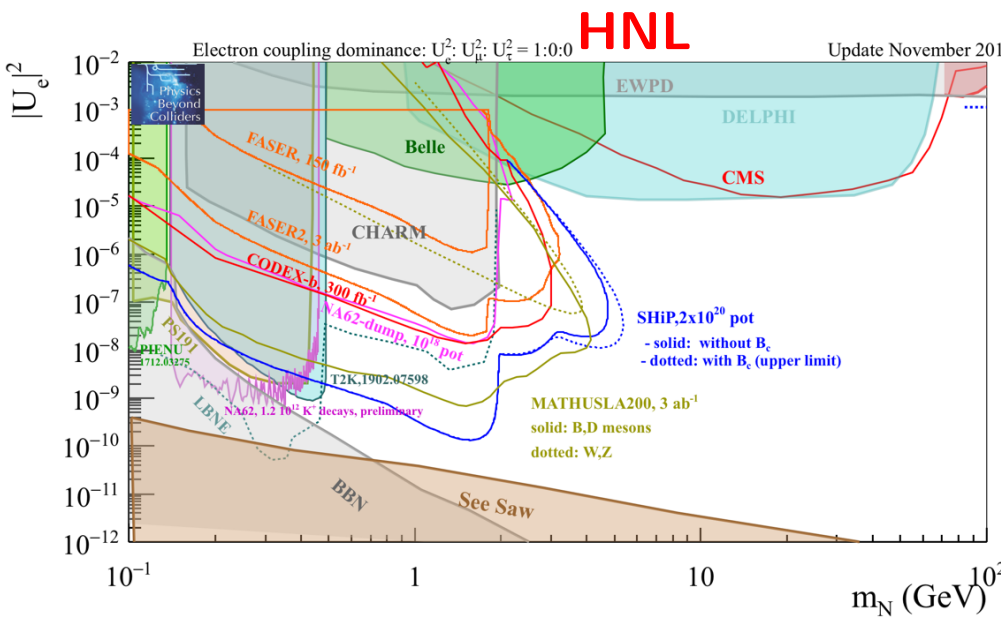
DP visible decay

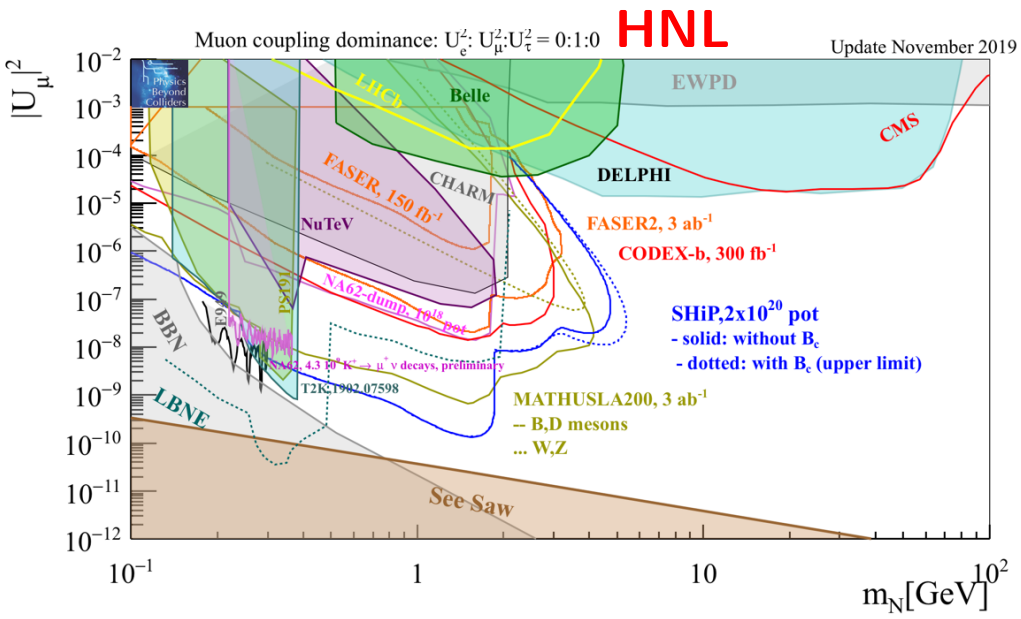


Beam dump

- **Dark scalar**: $S \to \mu^+\mu^-$
- **HNL**: $D/D_s \to \ell^+ N$, $N \to \pi e$, $N \to \pi\mu$
- Exclusion plots at 90% CL, zero background hypothesis.







Conclusions

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

- 2 signal candidates observed in 2017.
- SES = $(0.389 \pm 0.021) \times 10^{-10}$
- Expected background events: 1.5 ± 0.3
- Preliminary results (2016+2017): $\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) < 1.85 \times 10^{-10}$ @90 % CL

  $\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) < 2.44 \times 10^{-10}$ @95 % CL
- Constraints on largest enhancements allowed by NP models.

Exotic searches

- BR($\pi^0 \to$invisible) upper limit
- HNL upper limits ($K^+ \to e^+ N$, $K^+ \to \mu^+ N$)
- LNV/LFV upper limits ($K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^- \mu^+ \mu^+$)
- Limits on DP mass and BR($\pi^0 \to \gamma \nu\bar{\nu}$)
- BR($\pi^0 \to \gamma \nu\bar{\nu}$) upper limit

Future prospects

- **$K^+ \to \pi^+ \nu\bar{\nu}$**
  - Analysis of 2018 data on-going.
  - Factor 2 wrt 2017 data set.
  - On-going studies to optimize the signal selection, reduce the random veto and increase the signal efficiency.
  - Shape analysis and statistical treatment.
- **Data taking after the LS2 (≥2021)**
  - Plans to strongly suppress the upstream background (modification to the beam line, add fourth GTK station).
  - Higher beam intensity.
- **Exotic searches**
  - Improvements expected with the analysis of the full data sample.
  - Special beam-dump runs already taken to study the background for future beam dump data taking.
  - Dedicated beam-dump runs expected after the LS2 ($O(10^{18})$ protons on target).

DZIĘKUJĘ!

(Thank you!)

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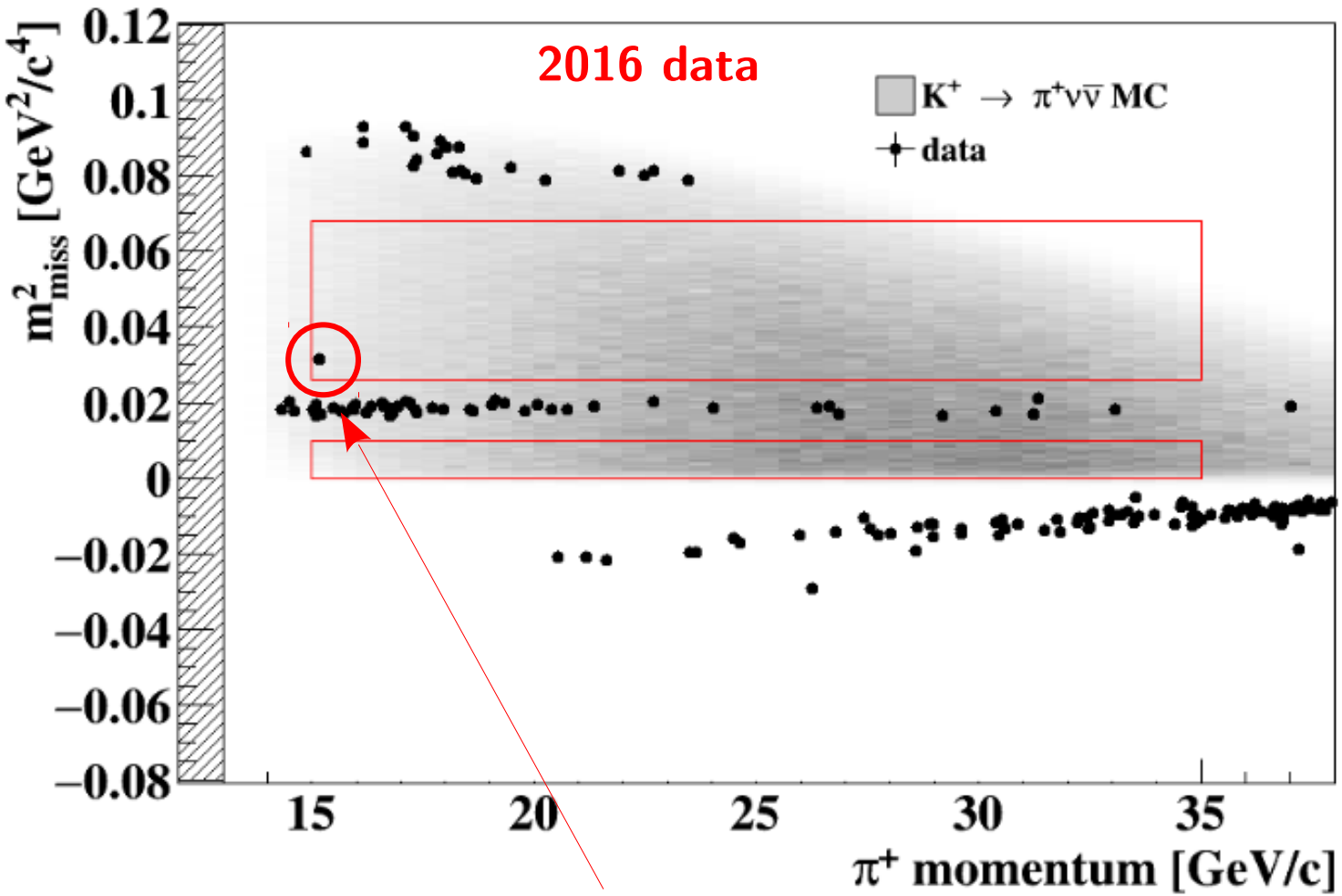
BACKUP

$K^+ \to \pi^+ \nu\bar{\nu}$: results (2016)



1 event observed in region 2

$$\mathrm{BR}_{\mathrm{NA62}}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) < 14 \cdot 10^{-10} \quad @95\,\%\,\mathrm{CL}$$

[Phys Lett B 791 (2019) 156-166]

$K^+ \to \pi^+ \nu\bar{\nu}$: 2017 preliminary results

Events observed	2
Single Event Sensitivity	$(0.389 \pm 0.021) \times 10^{-10}$
Expected background	1.50 ± 0.30

Upper limits:

$$\mathrm{BR}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) < 1.76 \cdot 10^{-10} \quad @90\%\,\mathrm{CL}$$

$$\mathrm{BR}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) < 2.11 \cdot 10^{-10} \quad @95\%\,\mathrm{CL}$$

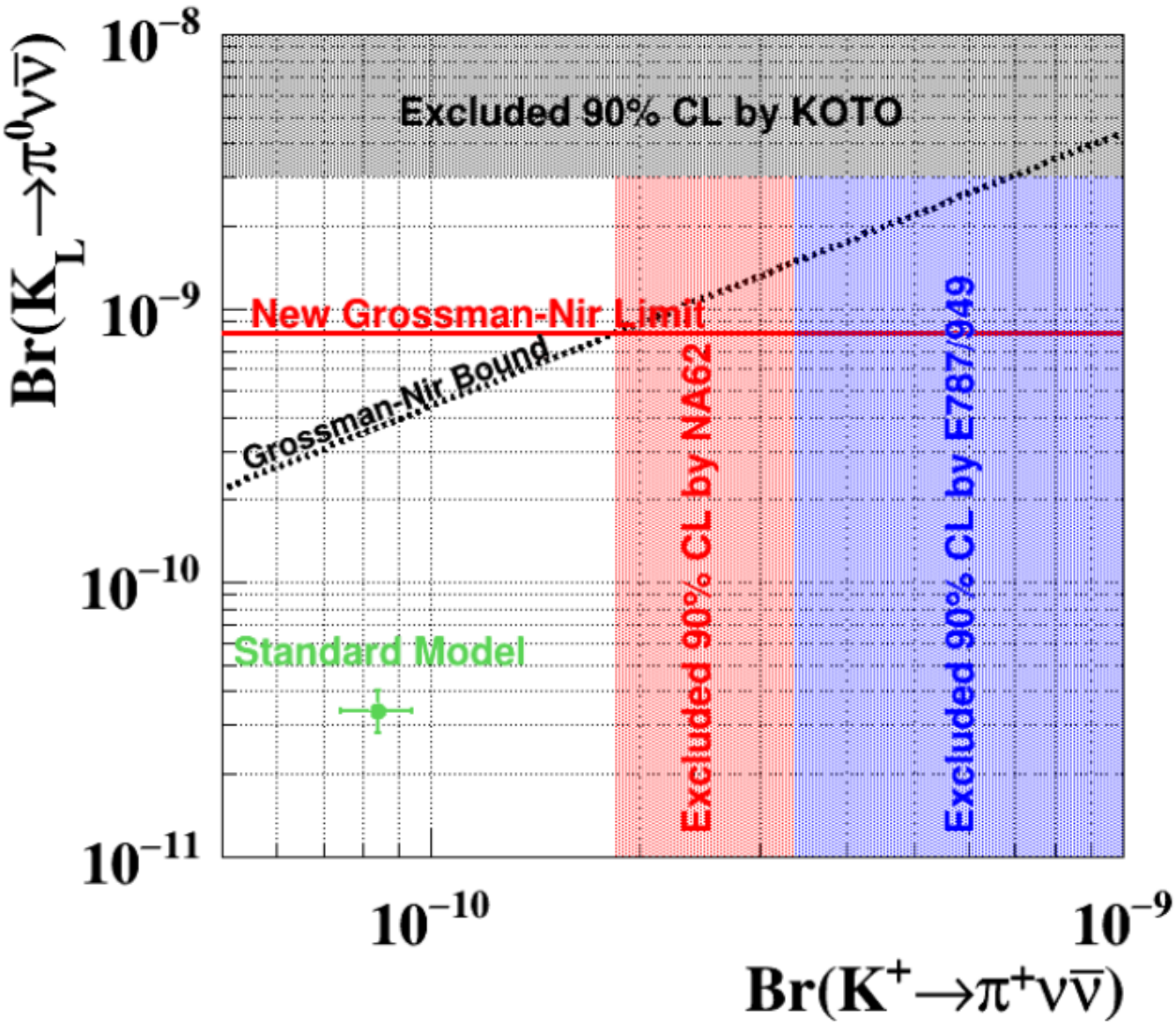
Two-sided 68% sideband:

$$\mathrm{BR}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = 0.20^{+0.69}_{-0.20} \times 10^{-10}$$

SM prediction on the Branching Ratio:

$$\mathrm{BR}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = \left(0.84 \pm 0.10\right) \cdot 10^{-10}$$

$K^+ \to \pi^+ \nu\bar{\nu}$: New Grossman-Nir limit

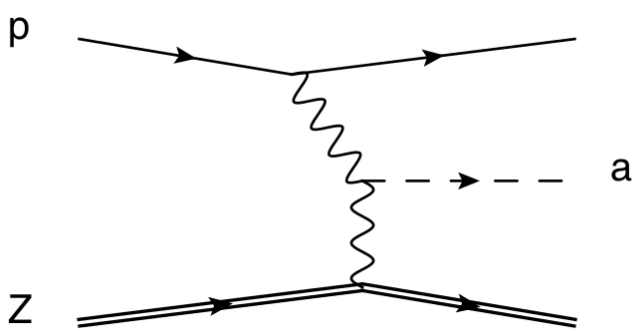


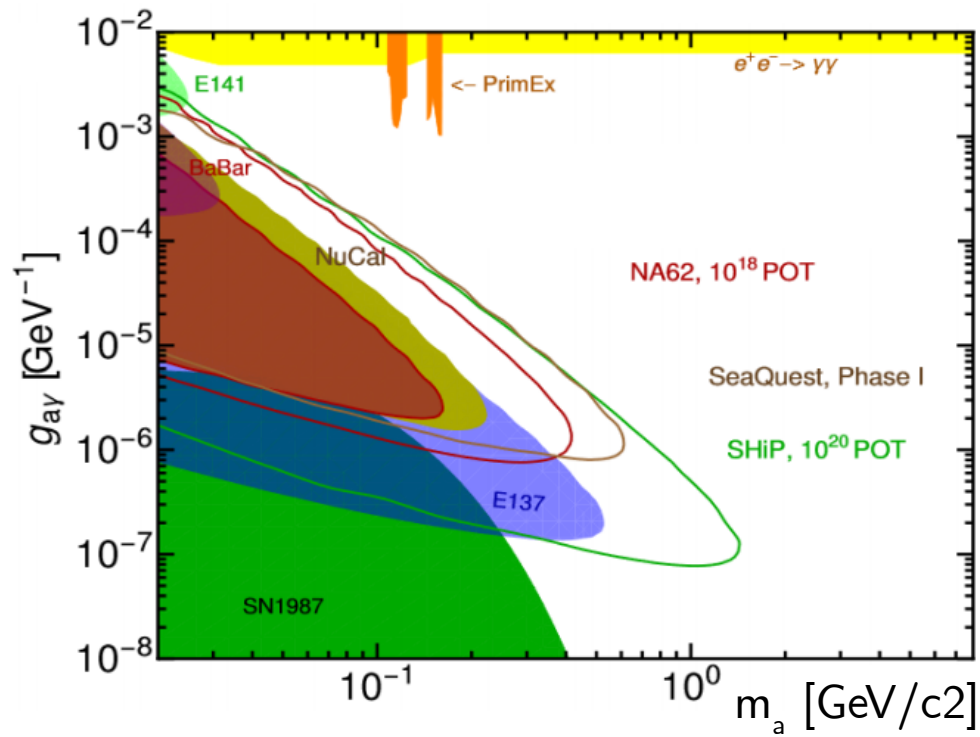
[Y. Grossman and Y. Nir, Phys Lett B398.1 (1997) 163-168]

[G. Ruggiero, KAON 2019]

Beam dump: Axion-Like Particles

- ALPs are candidates for cold dark matter.
- **NA62** can explore ALPs masses in the **MeV** to **GeV** range. [JHEP 1602 (2016) 018]
  - π^0 are a major background to $K^+ \to \pi^+\nu\bar{\nu}$, therefore an hermetic photon veto is essential to the measurement: search **ALP → $\gamma\gamma$** .





- Beam dump: **Primakoff** production of ALPs via beam protons interactions with the TAXes:
  - In dump mode, only μ e ν reach the fiducial decay volume.
  - ALPs are produced with a low transverse momentum: a small detector far away from the production point has a good acceptance for the process.

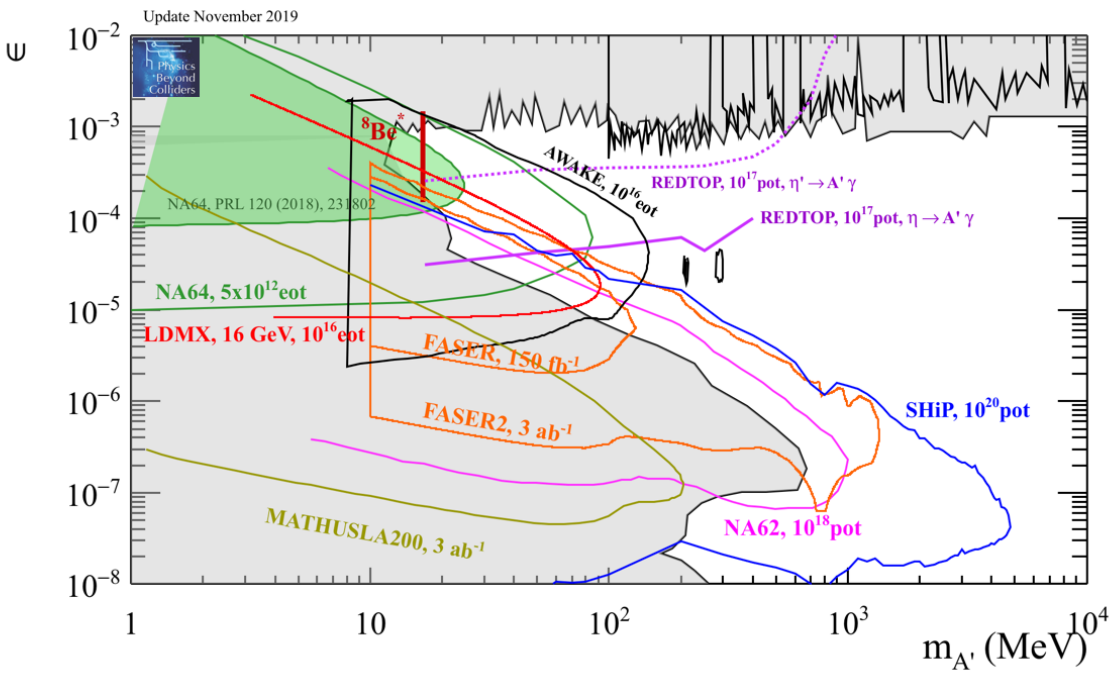
Beam dump: Dark Photon

Dark photon visible decay in NA62.

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

  $pN \rightarrow XA', \ A' \rightarrow l^+l^-$

- Assuming 10^{18} POT with 400 GeV.
- A' produced from interaction with target (bremsstrahlung and meson decays).
- Exclusion plot at 90% CL, in the zero background hypothesis.



- Better sensitivity expected taking into account A' QCD production and production in the dump (at the moment, only production in the target is considered).
- 3×10^{17} POT taken during 2016/2017 di-μ trigger, 5×10^{16} with ee trigger.