Searches for hidden-sector particles & LFC tests at NA62

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Outline:

1) Introduction: $K^{\pm}$ decay experiments at CERN
2) Searches for heavy neutral lepton production in K^{+} decays
3) Searches for dark photon in π^{0} and K^{+} decays
4) Searches for LNV and resonances in $K^{\pm}\rightarrow\pi\mu\mu$ decays
5) NA62 operation in beam dump mode

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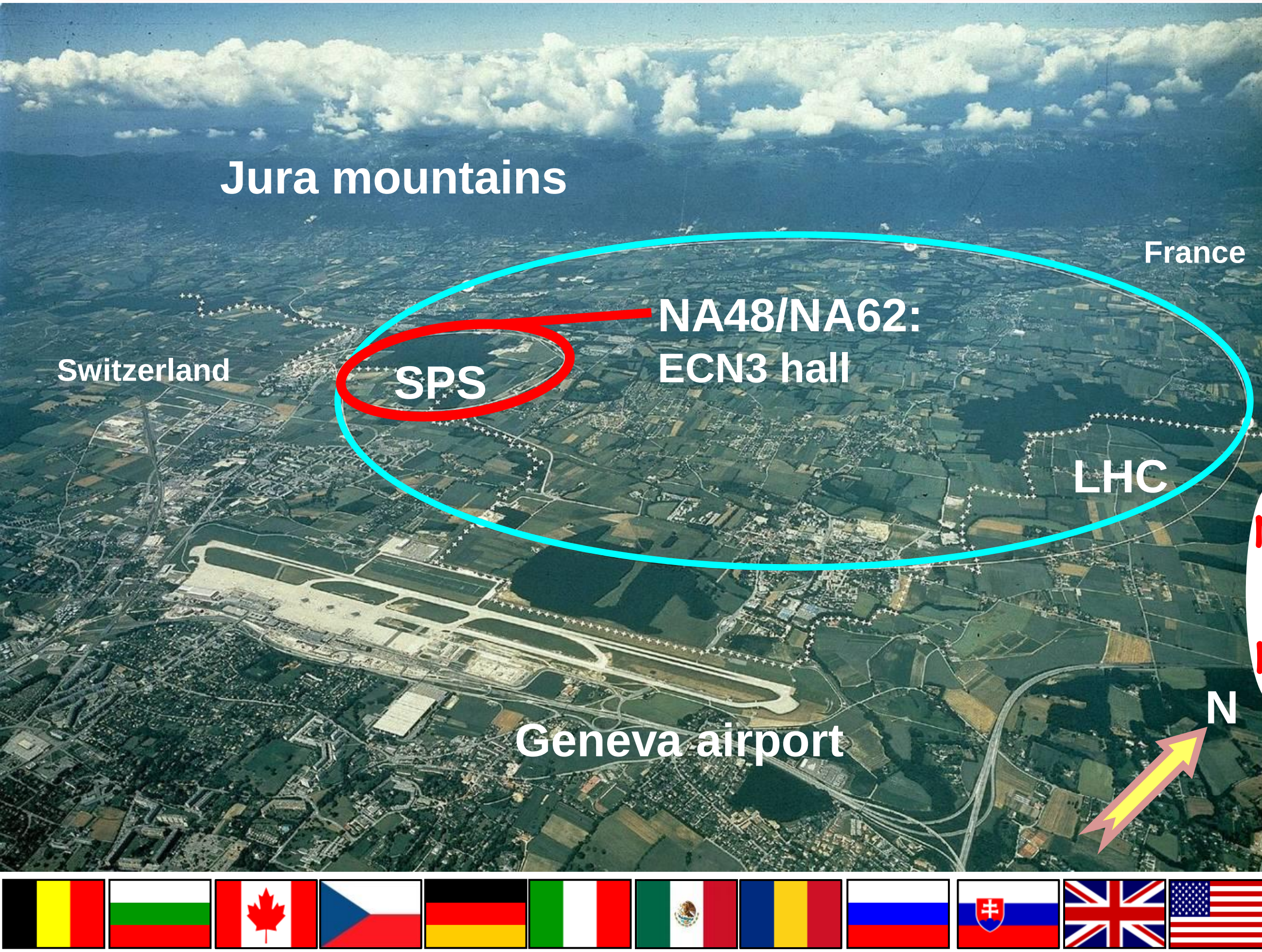
EXCELLENCE IN SCIENCE

Kaon programme at CERN



Earlier: NA31

NA48 discovery of direct CPV
- 1997: ε'/ε: K_L+K_S
- 1998: K_L+K_S
- 1999: K_L+K_S | K_S HI
- 2000: K_L only | K_S HI
- 2001: K_L+K_S | K_S HI

NA48/1
- 2002: K_S/hyperons

NA48/2
- 2003: K^+/K^-
- 2004: K^+/K^-

NA62 R_K run
- 2007: $K^\pm_{e2}/K^\pm_{\mu2}$ | tests
- 2008: $K^\pm_{e2}/K^\pm_{\mu2}$ | tests

NA62
- 2015: commissioning
- 2016–: K^+ physics run

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

$K^\pm$ decay experiments at CERN

Experiment	NA48/2 ($K^\pm$)	NA62 R_K run ($K^\pm$)	NA62 (K^+)
Data taking period	2003–2004	2007–2008	2016–2018
Beam momentum, GeV/c	60	74	75
RMS momentum bite, GeV/c	2.2	1.4	0.8
Spectrometer thickness, X_0	2.8%	2.8%	1.8%
Spectrometer P_T kick, MeV/c	120	265	270
$M(K^\pm \to \pi^\pm\pi^+\pi^-)$ resolution, MeV/c^2	1.7	1.2	0.8
K decays in fiducial volume	2×10^{11}	2×10^{10}	1.2×10^{13}
Main trigger	multi-track; $K^\pm \to \pi^\pm\pi^0\pi^0$	Min.bias + $e^\pm$	$K_{\pi\nu\nu}$ + rare + forbidden decays

NA48 detector (NA48/2, NA62 R_K run) NA62 detector (NA62)

The NA62 experiment

- ❖ Main goal: collect 100 SM $K^+ \to \pi^+\nu\nu$ decays, $BR_{SM}=(8.4\pm1.0)\times10^{-11}$.
  Buras et al., JHEP 1511 (2015) 033
- ❖ Current $K^+ \to \pi^+\nu\nu$ experimental status: $BR = (1.73^{+1.15}_{-1.05})\times10^{-10}$ from 7 candidates with expected background of 2.6 observed by BNL-E949.
  PRL101 (2008) 191802

NA48/2 and NA62-R_K experiments

2003–2007: charged kaon beams,
NA48 detector *[NIM A574 (2007) 433]*

Narrow momentum band $K^{\pm}$ beams:
P_K= 60 (74) GeV/c, $\delta P_K/P_K$ ~ 1% (rms).

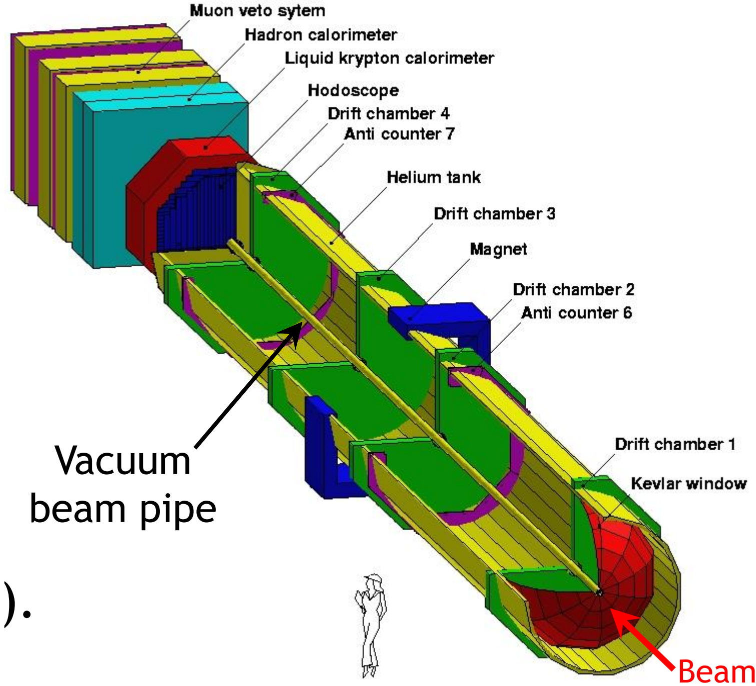
❖ Maximum $K^{\pm}$ decay rate ~100 kHz;
❖ **NA48/2:** six months in 2003–04;
❖ **NA62-R_K:** four months in 2007.

Principal subdetectors:

❖ Magnetic spectrometer (4 DCHs)
4 views/DCH: redundancy ⇒ efficiency;
$\delta p/p = 0.48\% \oplus 0.009\% p$ [GeV/c] (in 2007)

❖ Scintillator hodoscope (HOD)
Fast trigger, time measurement (150ps).

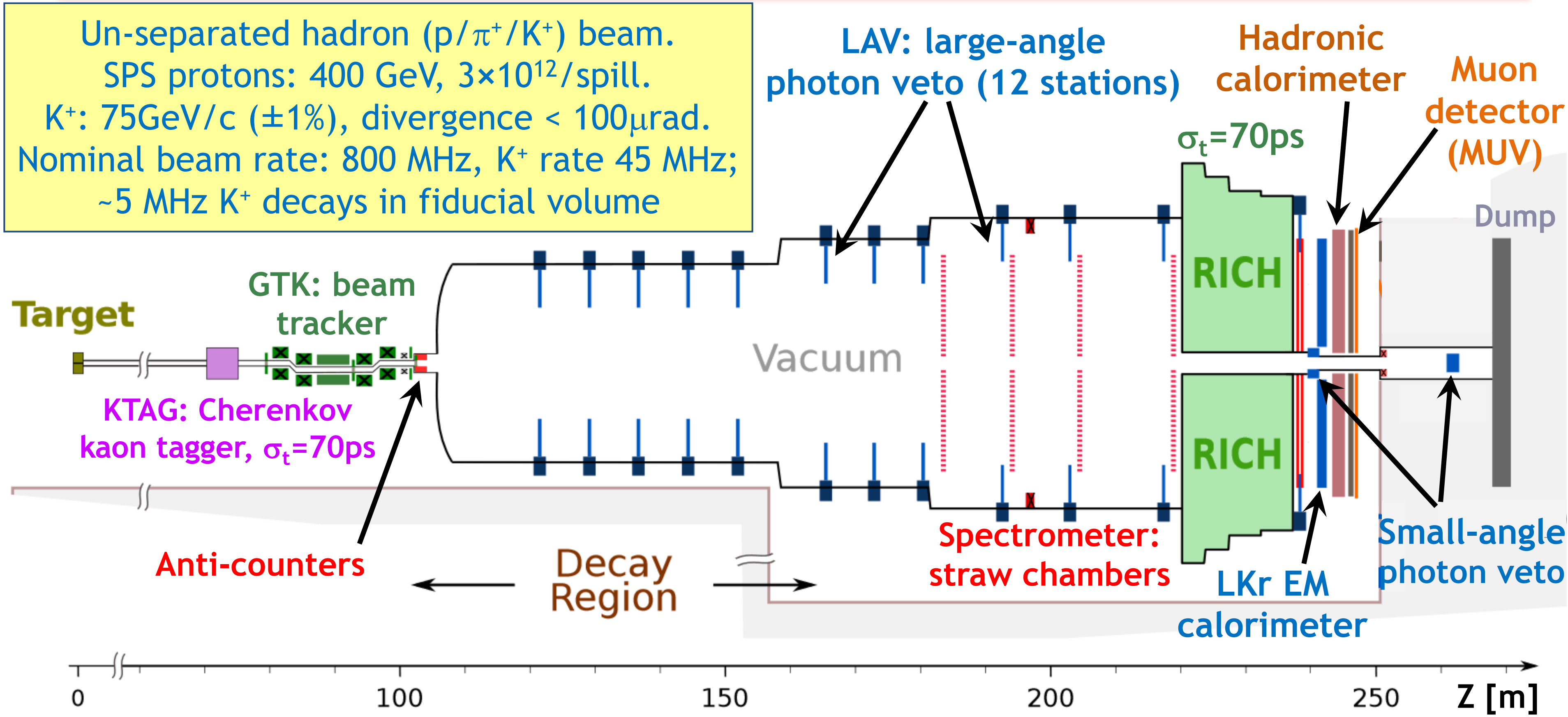
❖ Liquid Krypton EM calorimeter (LKr)
High granularity, quasi-homogeneous;
$\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$ [GeV];
$\sigma_x=\sigma_y=4.2\text{mm}/E^{1/2} \oplus 0.6\text{mm}$ (1.5mm@10GeV).



*NA62 collaboration,
JINST 12 (2017) P05025*

The NA62 detector

Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, 3×10^{12}/spill.
K^+: 75GeV/c (±1%), divergence < 100μrad.
Nominal beam rate: 800 MHz, K^+ rate 45 MHz;
~5 MHz K^+ decays in fiducial volume



- 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 physics programme

- ❖ **NA62 Run 2016–2018**: focused on the "golden mode" $K^+ \to \pi^+ \nu\nu$.
  - ✓ Trigger bandwidth for other physics is limited.
  - ✓ Several measurements at SES~10^{-12}: $K^+ \to \pi^+ A'$ ($A' \to$ invisible), $\pi^0 \to \nu\nu$.
  - ✓ Improve on precision where extreme SES is not required: $K^+ \to \ell^+ N$, …
  - ✓ Sensitivities to most rare/forbidden decays are limited but still often world-leading (~10^{-10} to ~10^{-11}).
  - ✓ Proof of principle for a broad rare & forbidden decay programme.

- ❖ **NA62 Run 2021–2024**: programme is under discussion.
  [Presented at Physics Beyond Colliders workshops, CERN, Sep 2016 & Mar 2017]
  - ✓ Existing apparatus with different and improved trigger logic.
  - ✓ Further $K^+ \to \pi^+ \nu\nu$ data collection.
  - ✓ Rare/forbidden K^+ and π^0 decays at SES~10^{-12}:
    K^+ physics: $K^+ \to \pi^+ \ell^+ \ell^-$, $K^+ \to \pi^+ \gamma \ell^+ \ell^-$, $K^+ \to \ell^+ \nu \gamma$, $K^+ \to \pi^+ \gamma\gamma$, …
    π^0 physics: $\pi^0 \to e^+e^-$, $\pi^0 \to e^+e^-e^+e^-$, $\pi^0 \to 3\gamma$, $\pi^0 \to 4\gamma$, …
    Searches for LFV/LNV: $K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \pi^+ \mu e$, $\pi^0 \to \mu e$, …
  - ✓ Beam dump with ~10^{18} POT (=3 months of dedicated data collection): hidden sector (decays of long-lived HNL, DP, ALP).

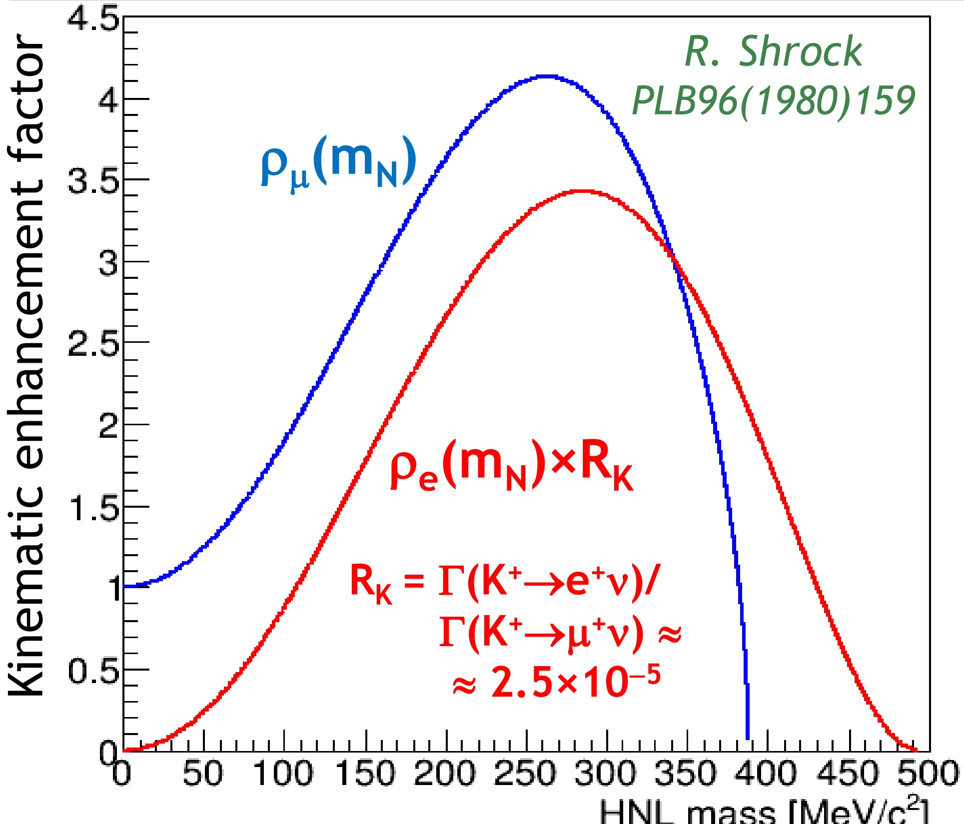
Search for heavy neutral lepton production with 2015 data

To be published in 2017;
see also Phys. Lett. B772 (2017) 712

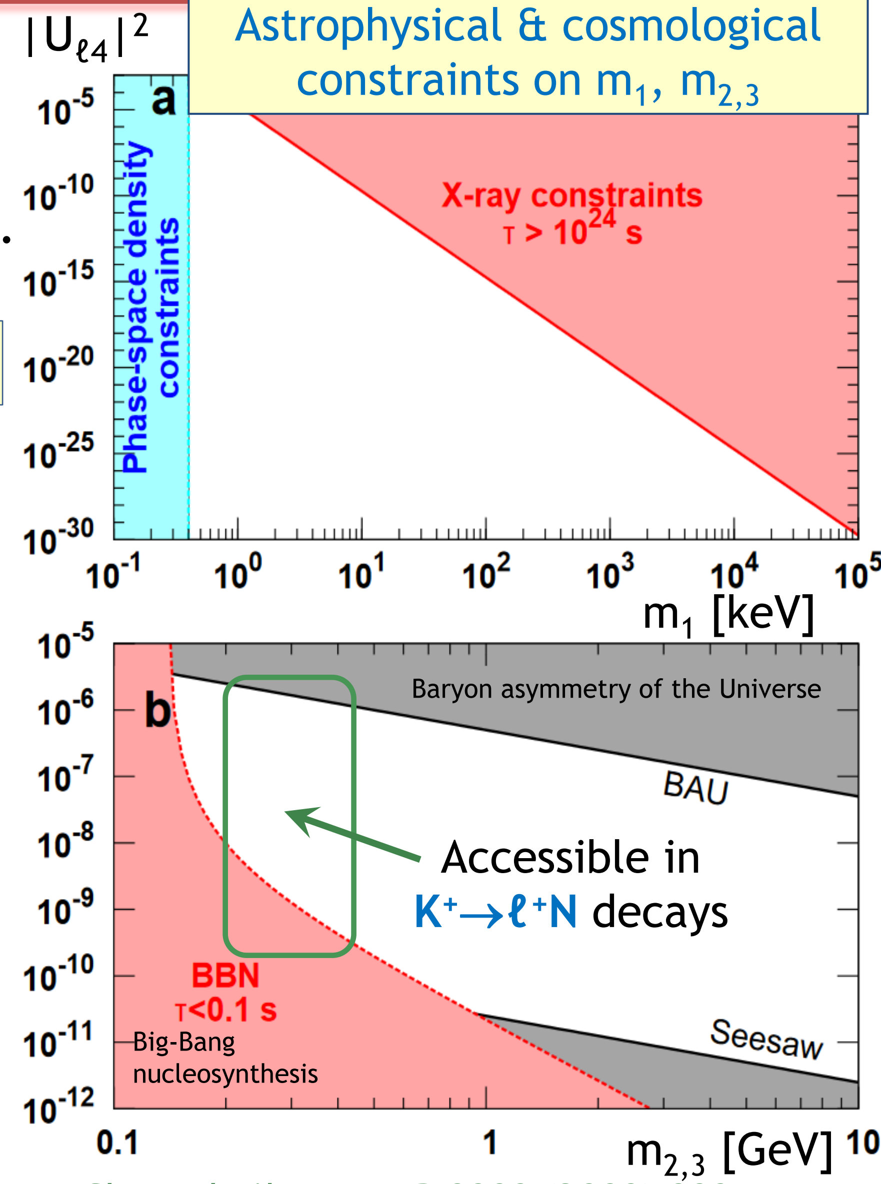
Heavy neutral leptons in νMSM

Neutrino minimal SM (νMSM) =
SM + 3 right-handed neutral heavy leptons.
[Asaka et al., PLB 631 (2005) 151]
Masses: **m_1~10 keV** [DM candidate]; **$m_{2,3}$~1 GeV**.
HNLs observable via **production** and **decay**.

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



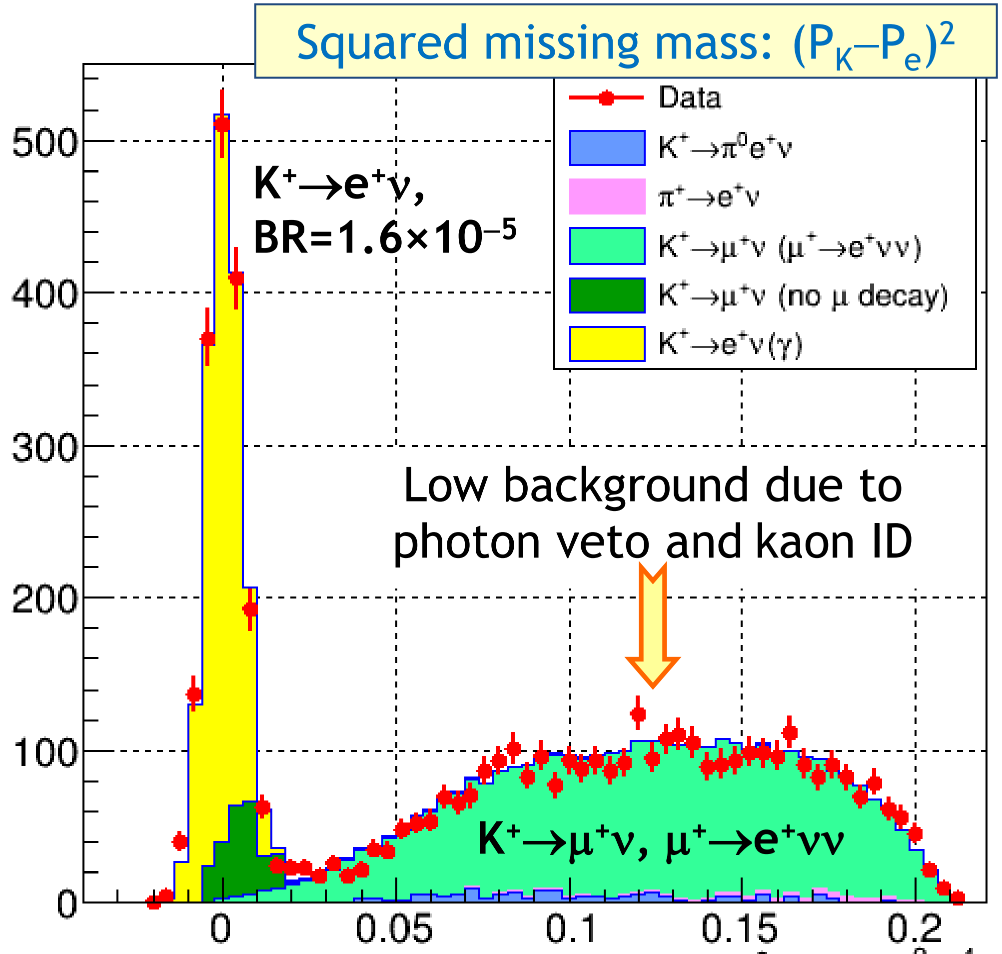
Astrophysical & cosmological constraints on m_1, $m_{2,3}$

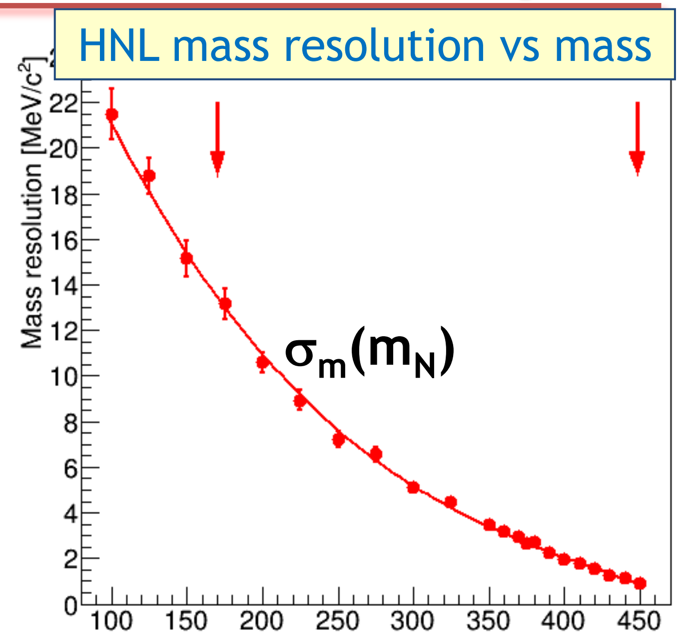


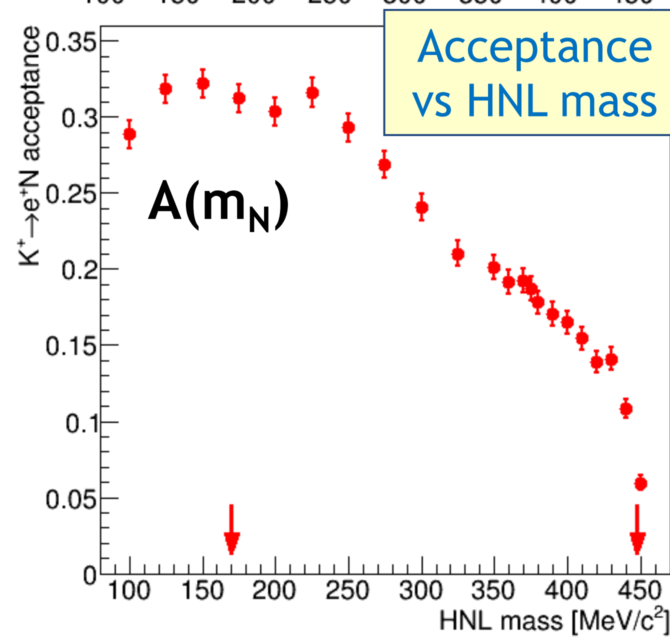
Shaposhnikov, JHEP 0808 (2008) 008
Boyarsky et al., Ann.Rev.Nucl.Part.Sci.59 (2009) 191

$K^+ \to e^+ N$: data sample

- Minimum bias (1% intensity); 11k SPS spills in 2015.
- K^+ decays in fiducial volume: $N_K = (3.01 \pm 0.11) \times 10^8$.
- Beam tracker not available: kaon momentum is estimated as the beam average.

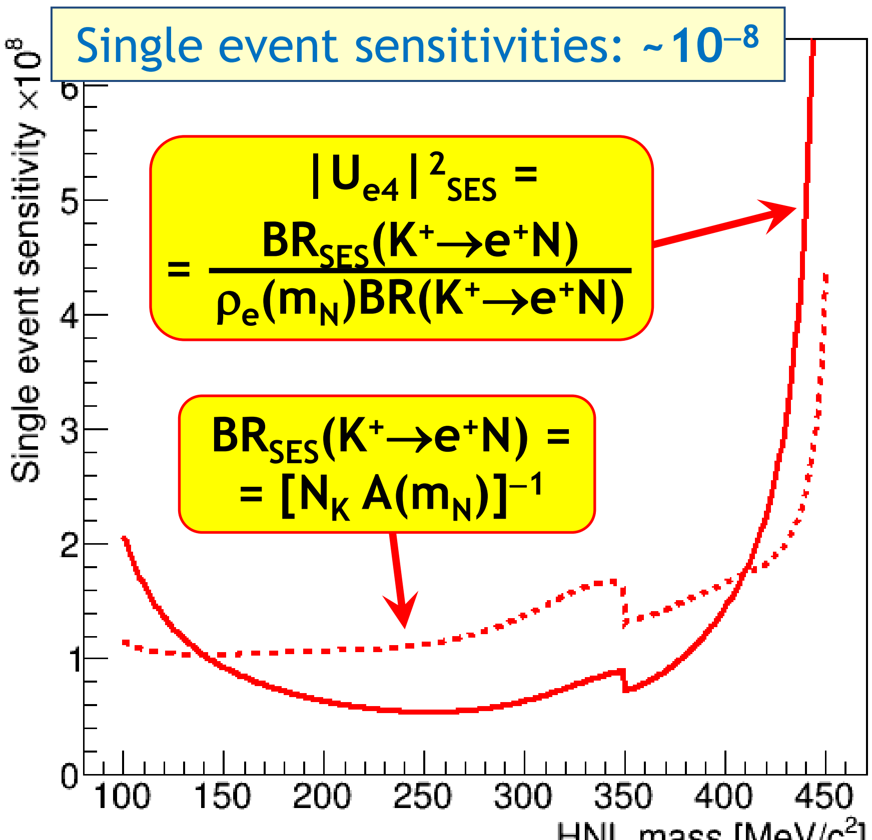


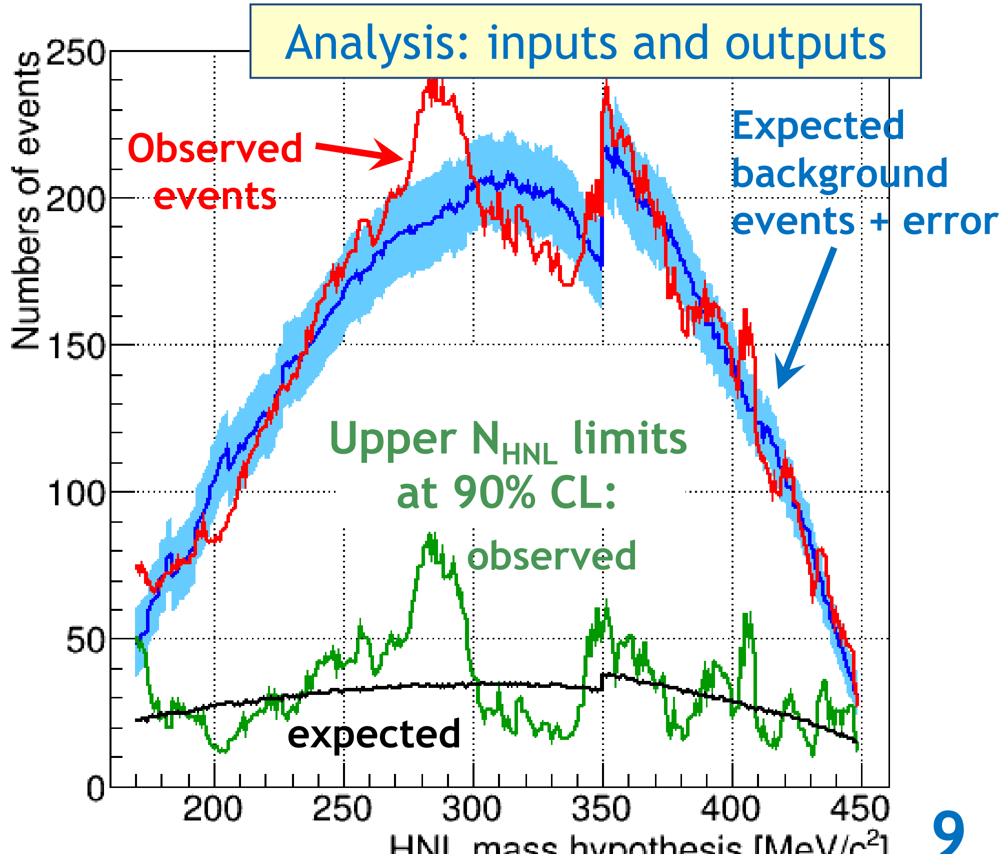




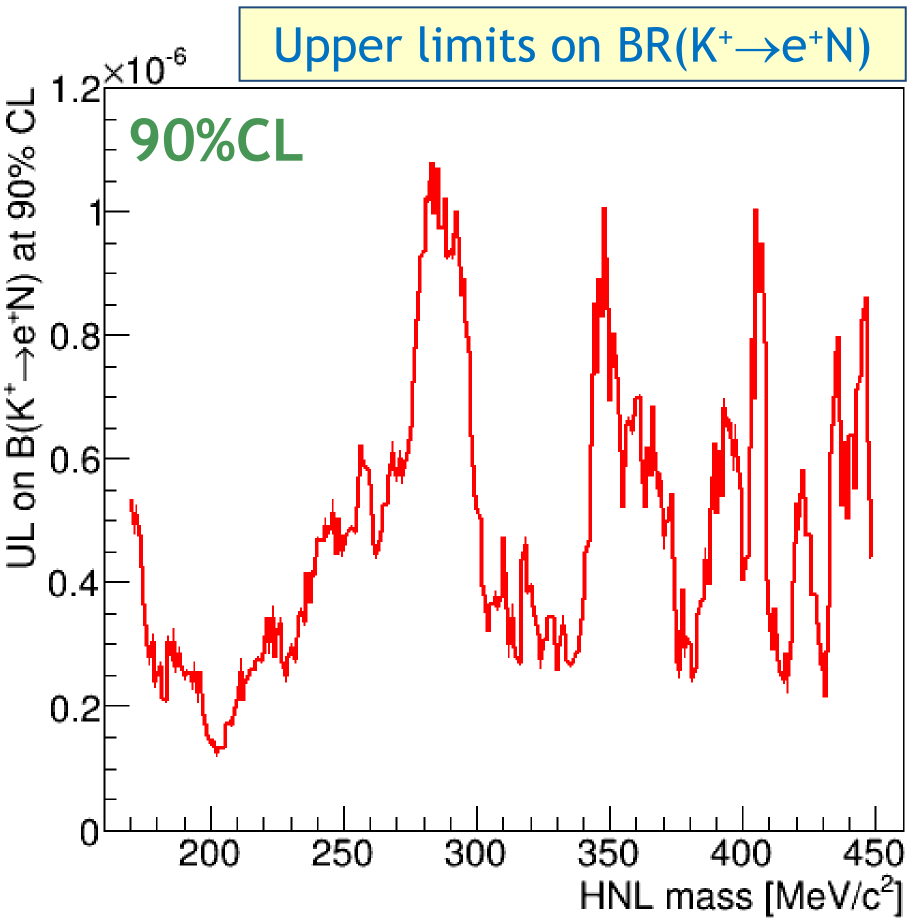
Search for HNL production signal

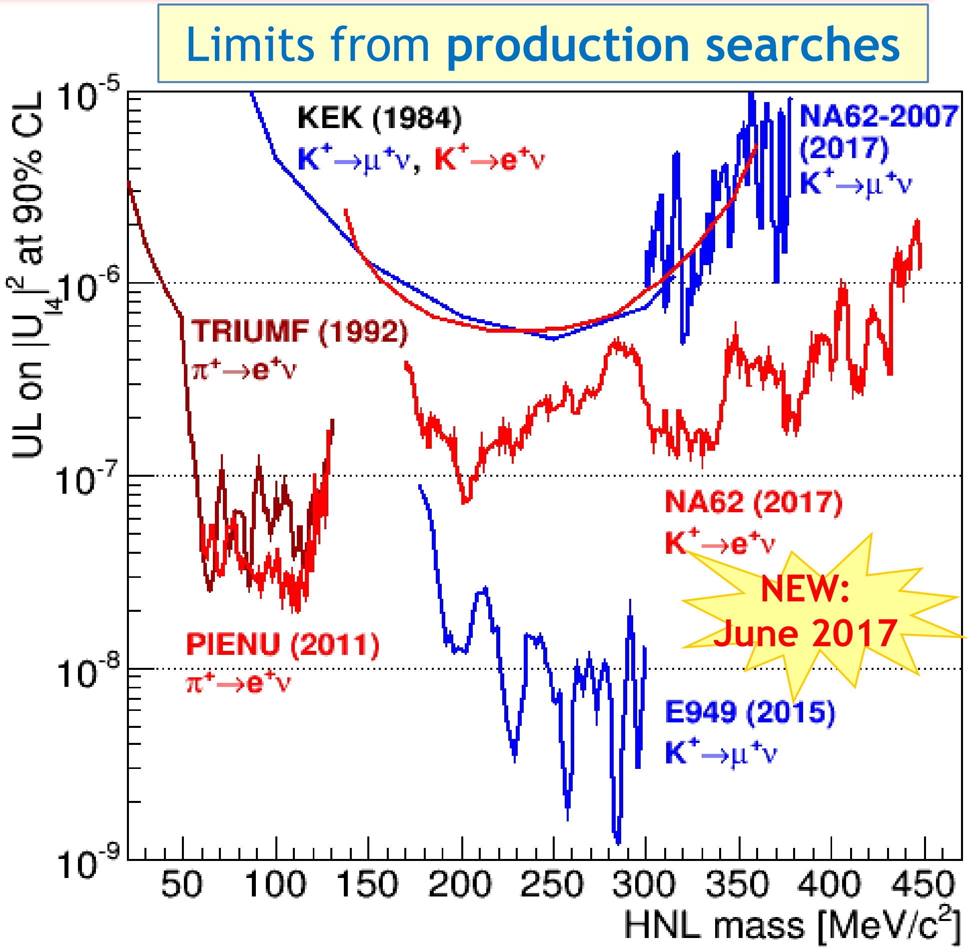
- HNL mass scan: $170\ \text{MeV}/c^2 \le m_N \le 448\ \text{MeV}/c^2$, mass step = $1\ \text{MeV}/c^2$.
- Signal search window for each mass hypothesis: $\pm 1.5\sigma_m$.
- Background estimate: polynomial fits to mass spectra outside signal window.
- Background statistical errors estimated with dedicated MC simulation.
- For each m_N, frequentist confidence intervals for N_{HNL} obtained from numbers of observed and expected events and their uncertainties.





HNL production search: results





- Local signal significance never exceeds 3σ: **no HNL signal** is observed.
- Reached **10^{-6}–10^{-7}** limits for $|U_{e4}|^2$ in the **170–448 MeV/c^2** mass range.
- Major improvement foreseen with high intensity NA62 2016 data.
- New result from **$K^+ \to \mu^+ N$** search with 2015 data is coming later this year.

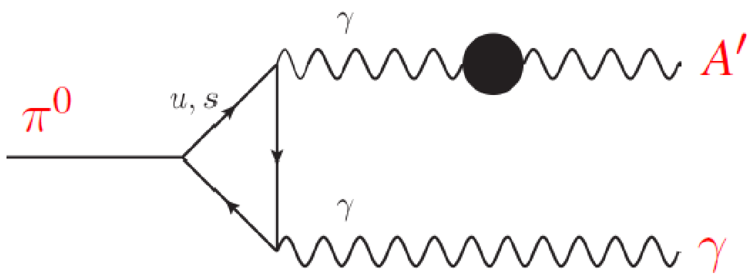
Search for dark photon in the $\pi^0 \to \gamma A'$ decay

Phys. Lett. B746 (2015) 178;
Phys. Lett. B768 (2017) 38

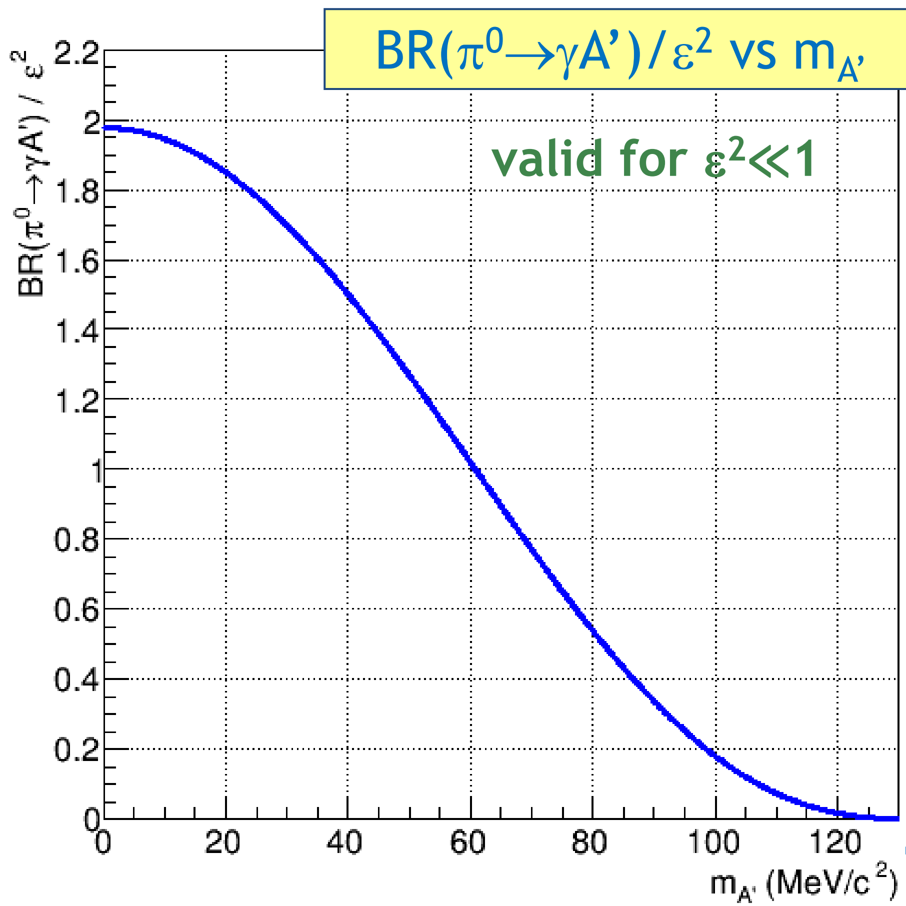
DP production in $\pi^0 \to \gamma A'$ decay

Batell, Pospelov and Ritz, PRD80 (2009) 095024

$$\mathcal{B}(\pi^0 \to \gamma A') = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathcal{B}(\pi^0 \to \gamma\gamma)$$

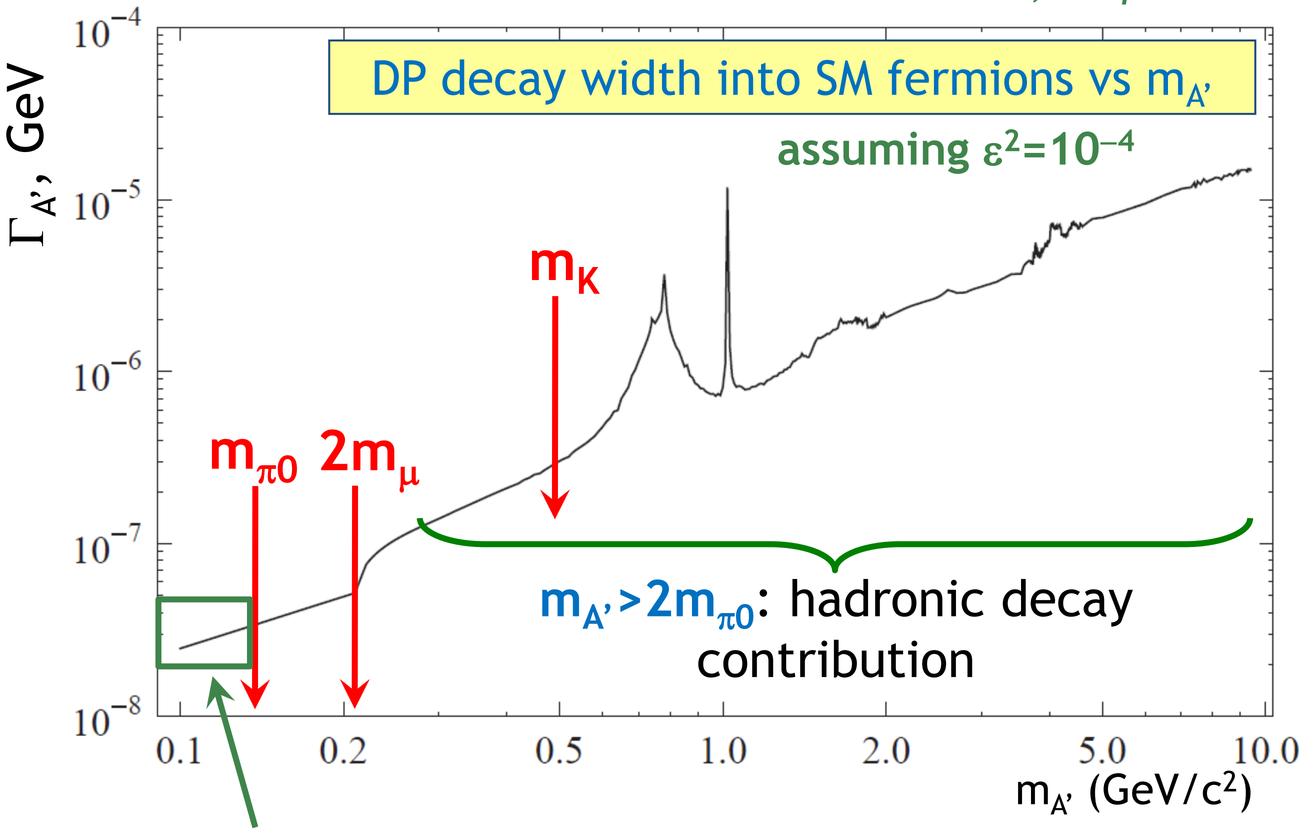


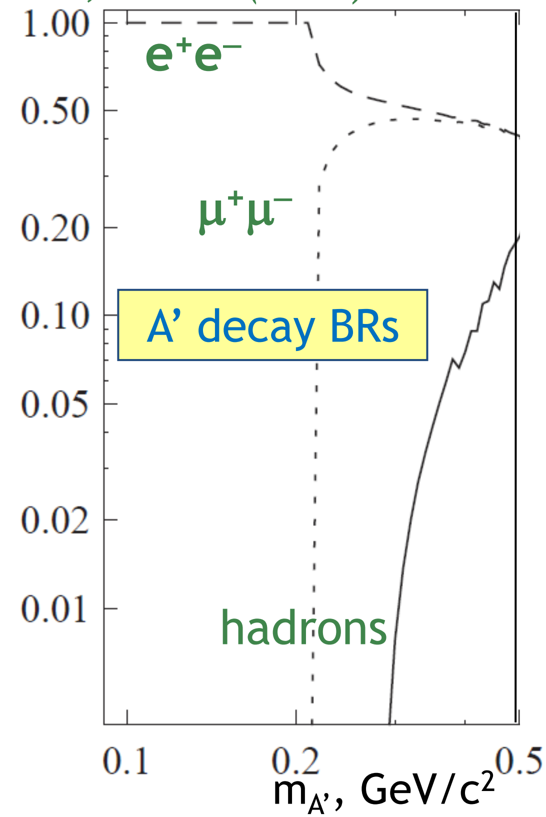
- Probing the Dark Sector.
- Two unknown parameters: mass ($m_{A'}$) and mixing (ε^2).
- Sensitivity to DP for $m_{A'} < m_{\pi 0}$.
- Loss of sensitivity to ε^2 as $m_{A'}$ approaches $m_{\pi 0}$, due to kinematical suppression of the $\pi^0 \to \gamma A'$ decay.



DP decays into SM fermions

Batell, Pospelov and Ritz, PRD79 (2009) 115008





Accessible in π^0 decays: assuming decays only into SM fermions,

$$\Gamma_{A'} \approx \Gamma(A' \to e^+e^-) = \frac{1}{3}\alpha\varepsilon^2 m_{A'}\sqrt{1-\frac{4m_e^2}{m_{A'}^2}}\left(1+\frac{2m_e^2}{m_{A'}^2}\right) \approx \alpha\varepsilon^2 m_{A'}/3$$

For $\varepsilon^2>10^{-7}$ and $m_{A'}>10$ MeV/c^2, **prompt A' decay** (z vertex resolution ~1 m).
Therefore $\pi^0_D \to e^+e^-\gamma$ is an irreducible background.

NA48/2: $\pi^0 \to \gamma e^+ e^-$ sample

Two exclusive selections

$K^\pm \to \pi^\pm \pi^0_D$ selection:

- $|m_{\pi\gamma ee} - m_K| < 20$ MeV/c^2;
- $|m_{\gamma ee} - m_{\pi 0}| < 8$ MeV/c^2;
- no missing momentum.

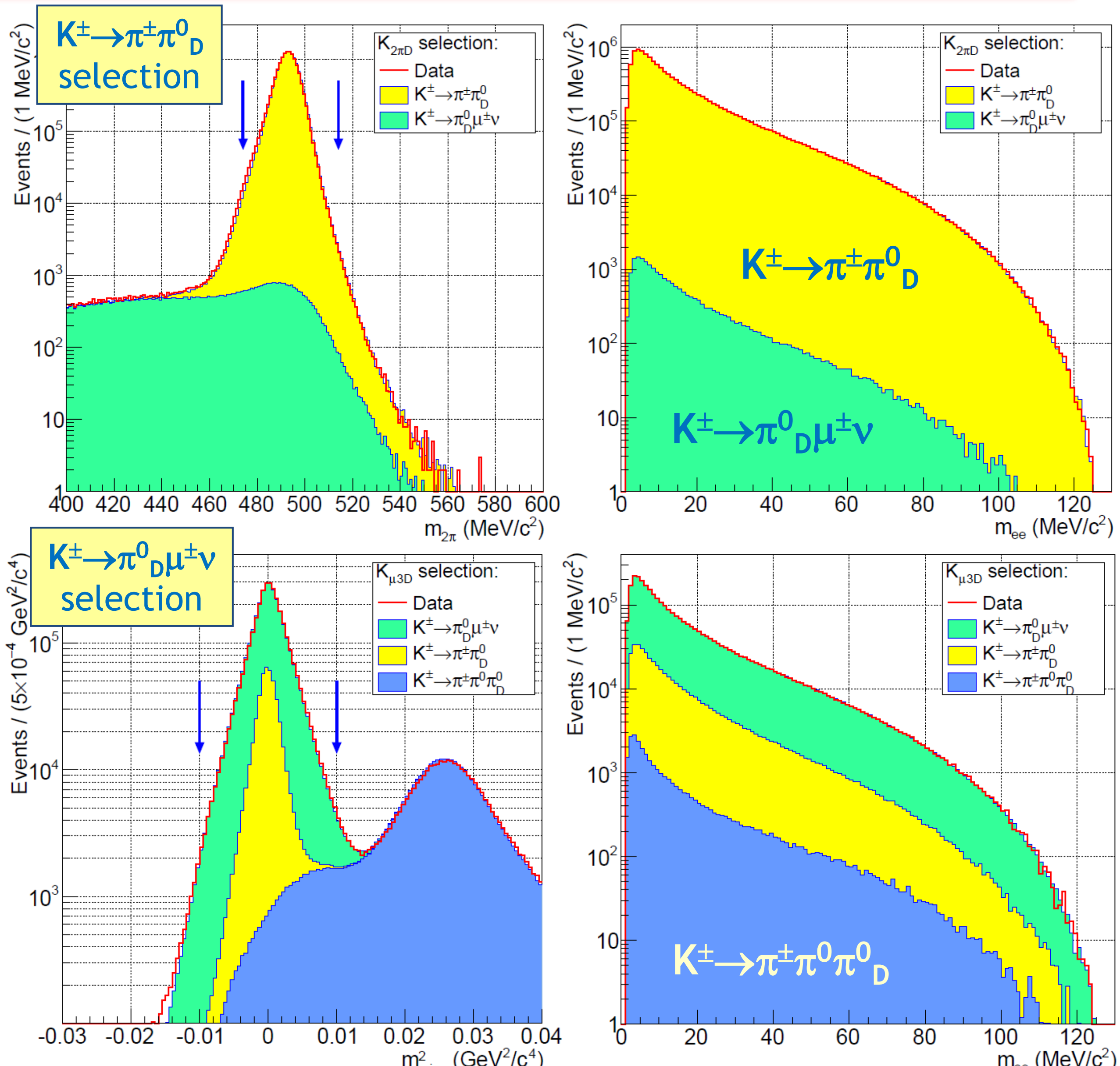
$K^\pm \to \pi^0_D \mu^\pm \nu$ selection:

- $m_{miss}^2 = (P_K - P_\mu - P_{\pi 0})^2$ compatible with zero;
- $|m_{\gamma ee} - m_{\pi 0}| < 8$ MeV/c^2;
- missing total and transverse momentum.

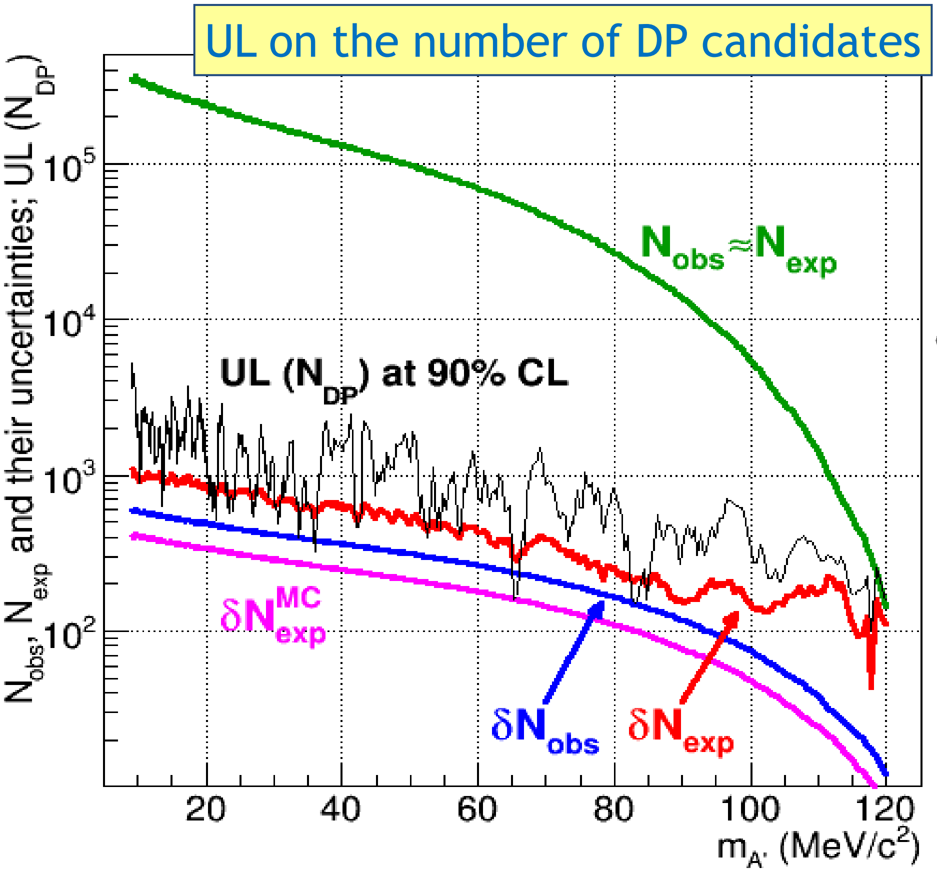
Reconstructed π^0_D decay candidates:

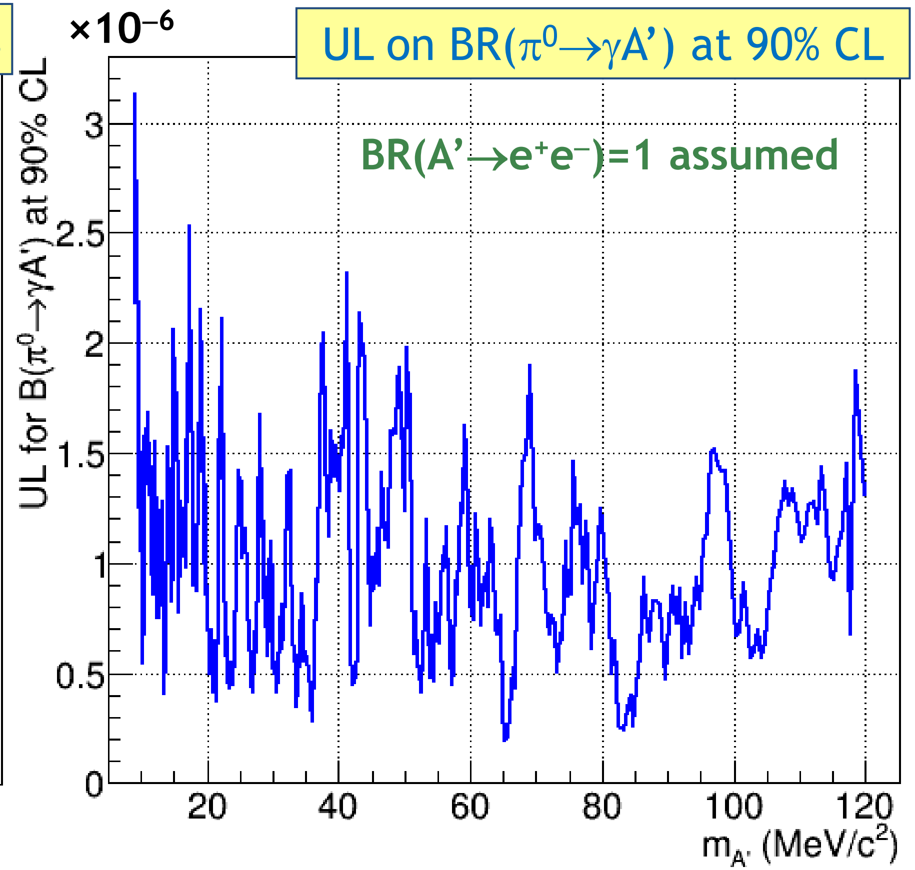
- $N(K_{2\pi D}) = 1.38 \times 10^7$,
- $N(K_{\mu 3D}) = 0.31 \times 10^7$,
- total $= 1.69 \times 10^7$.

$K^\pm$ decays in fiducial region:
$N_K = (1.57 \pm 0.05) \times 10^{11}$.



NA48/2: search for DP signal





DP mass scan:

- range: $9\ \mathrm{MeV}/c^2 \le m_{A'} < 120\ \mathrm{MeV}/c^2$;
- mass step $0.5\sigma_m$, signal window $\pm 1.5\sigma_m$;
- DP mass hypotheses tested: 404;
- global fit for the background shape.

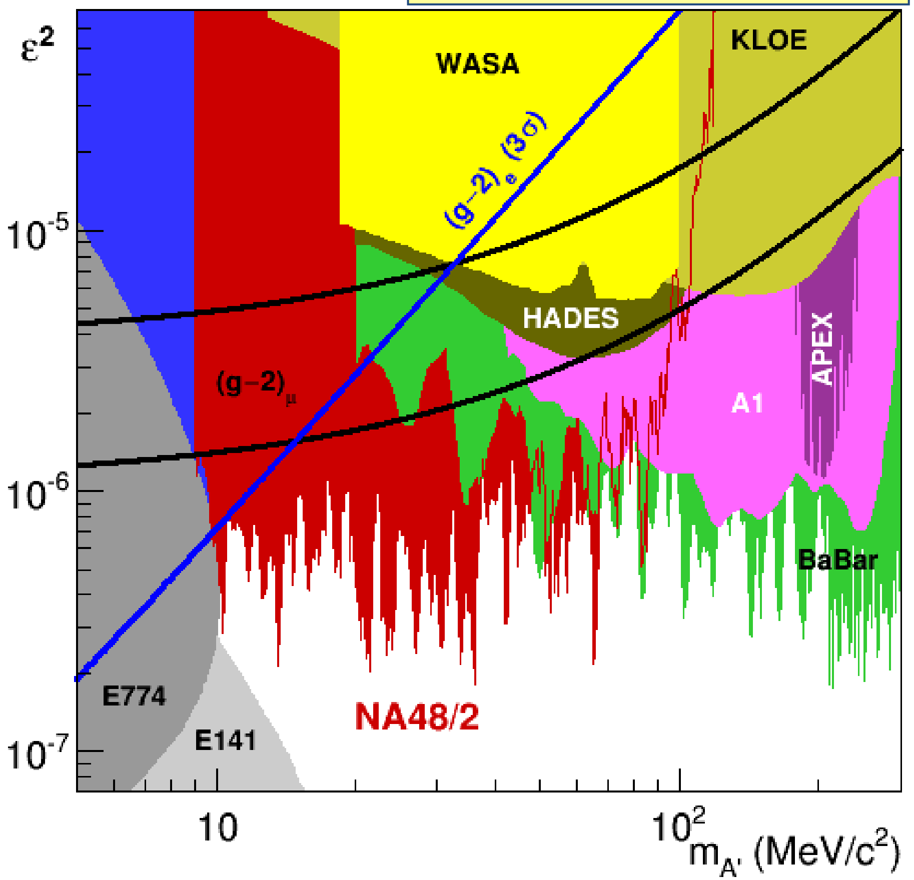
✓ Local signal significance never exceeds 3σ: **no DP signal** observed.

✓ The obtained limits are background limited: 2–3 orders of magnitude above single event sensitivity.

NA48/2: dark photon exclusion

Phys. Lett. B746 (2015) 178

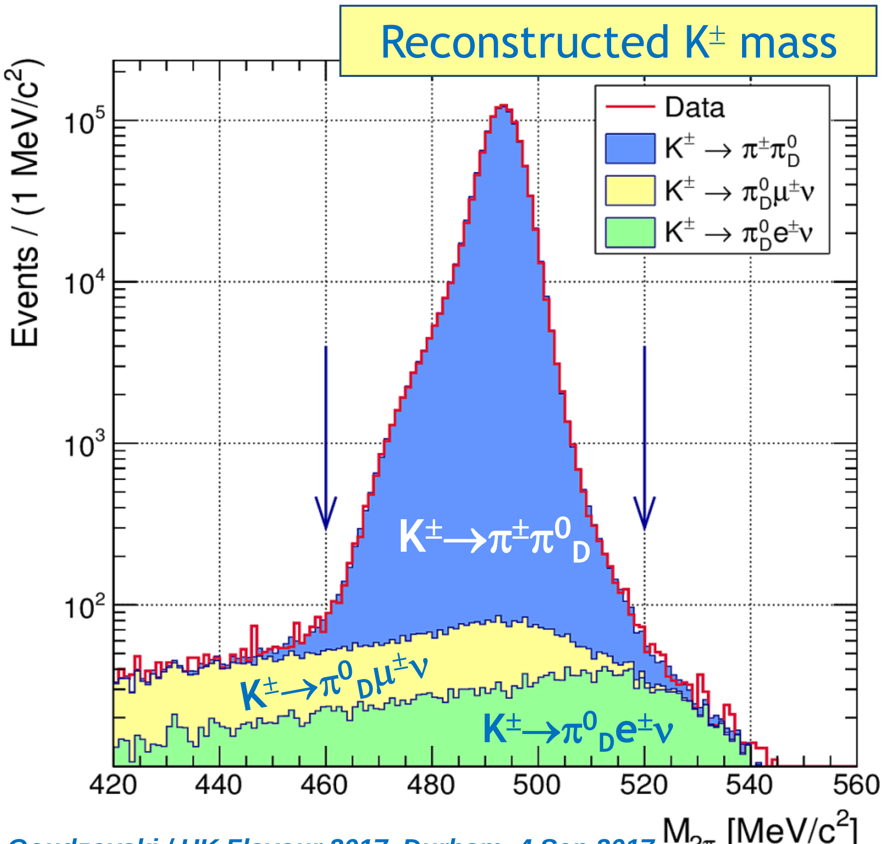
DP exclusion summary

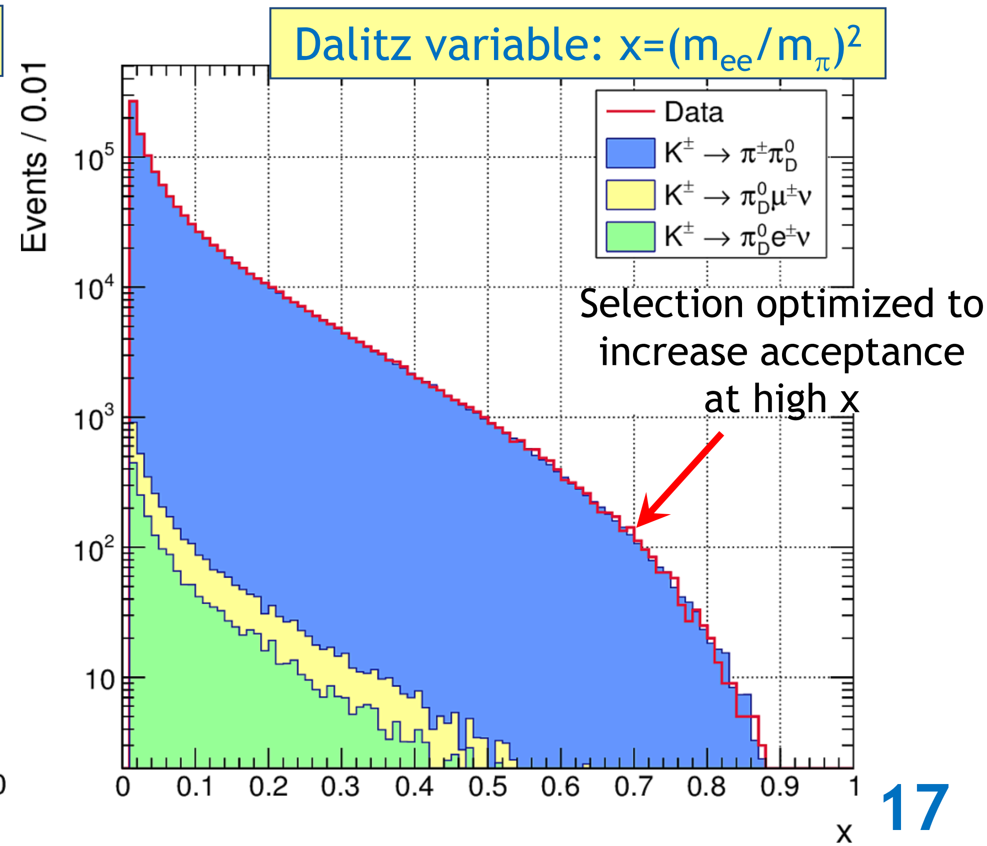


- Improvement on the existing limits in the $m_{A'}$ range **9–70 MeV/c²**.
- Most stringent limits are at low $m_{A'}$ (kinematic suppression is weak).
- Sensitivity limited by irreducible π^0_D background: upper limit on ε^2 scales as $\sim(1/N_K)^{1/2}$, modest improvement with larger data samples.
- If DP couples to quarks and decays **mainly to SM fermions**, it is ruled out as the explanation for the anomalous $(g\text{–}2)_\mu$.
- Sensitivity to smaller ε^2 with displaced vertex analysis: to be investigated.

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

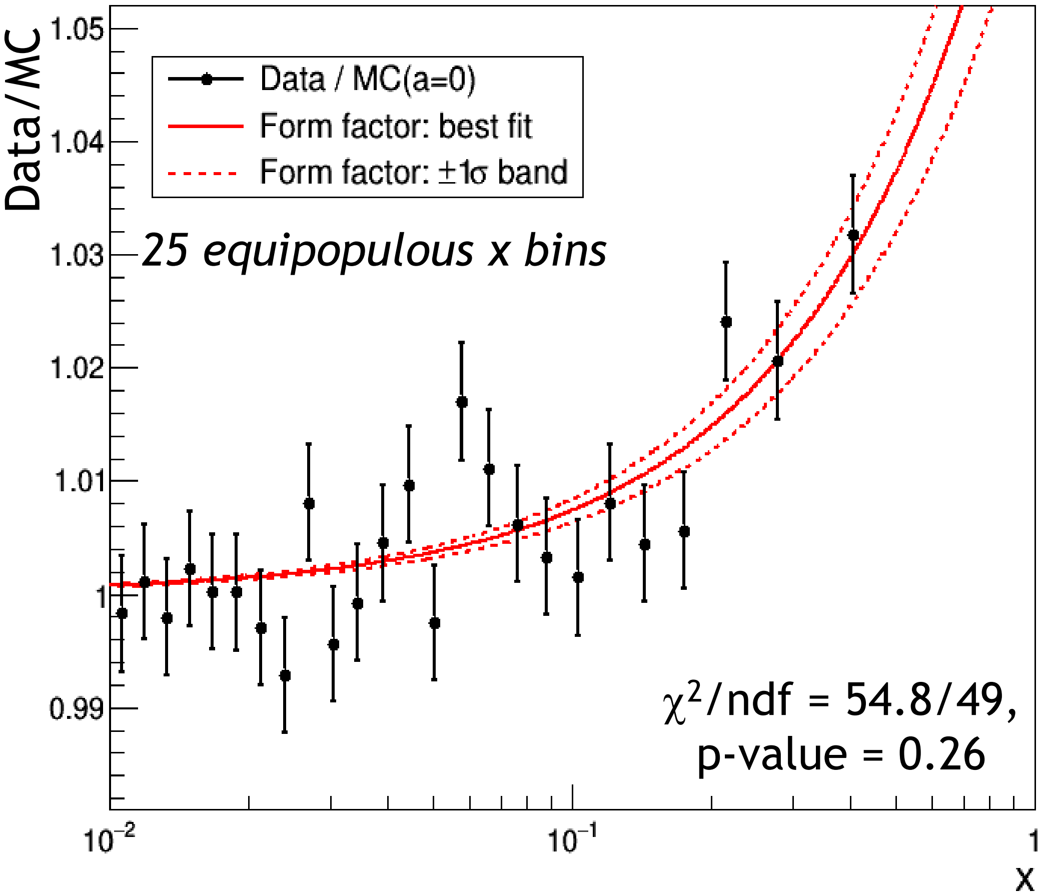
- NA62-R_K data: **~2×10^{10} $K^\pm$** decays in the fiducial decay region.
- Reconstructed π^0_D decay candidates, **$x=(m_{ee}/m_\pi)^2>0.01$**: **$N(K_{2\pi D})=1.05\times10^6$**.
- Despite **~10** times smaller sample wrt NA48/2, good for **spectrum study**:
  - ✓ minimum bias trigger: low systematics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



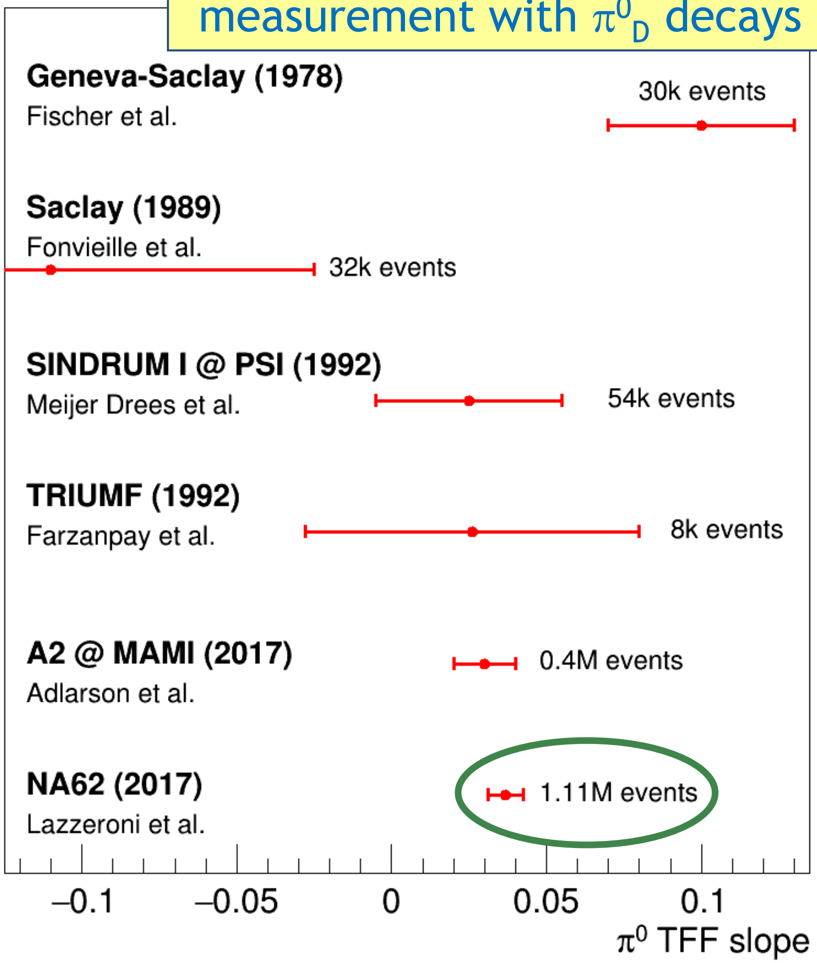


TFF slope measurement: result

Fit illustration: Data/MC(a=0)



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



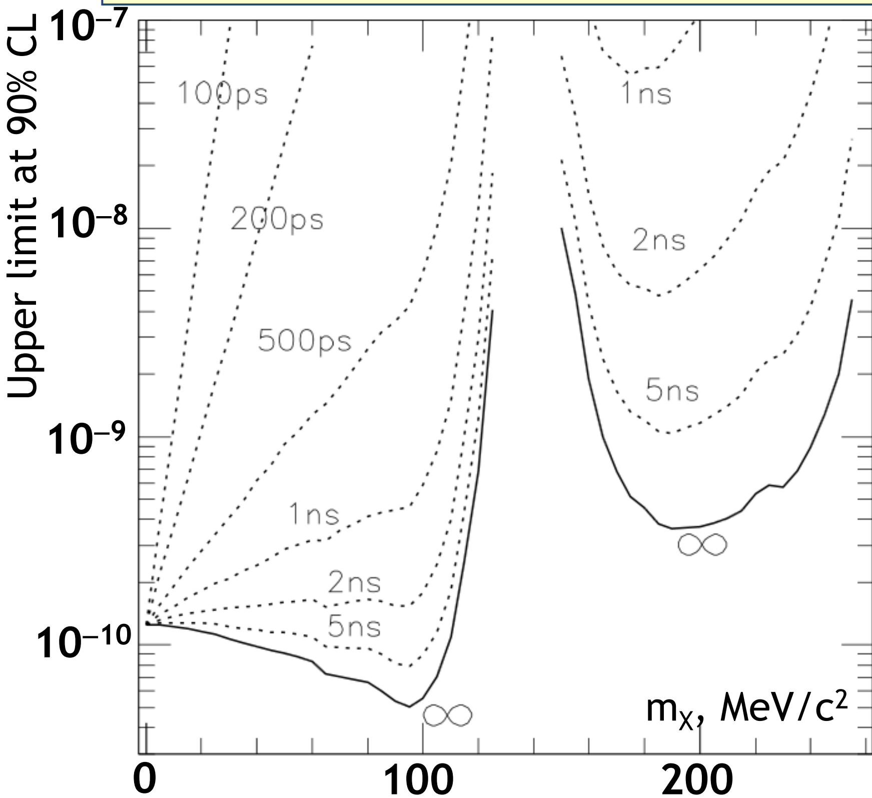
$a = (3.68 \pm 0.51_{stat} \pm 0.25_{syst}) \times 10^{-2}$

[Phys. Lett. B768 (2017) 38]

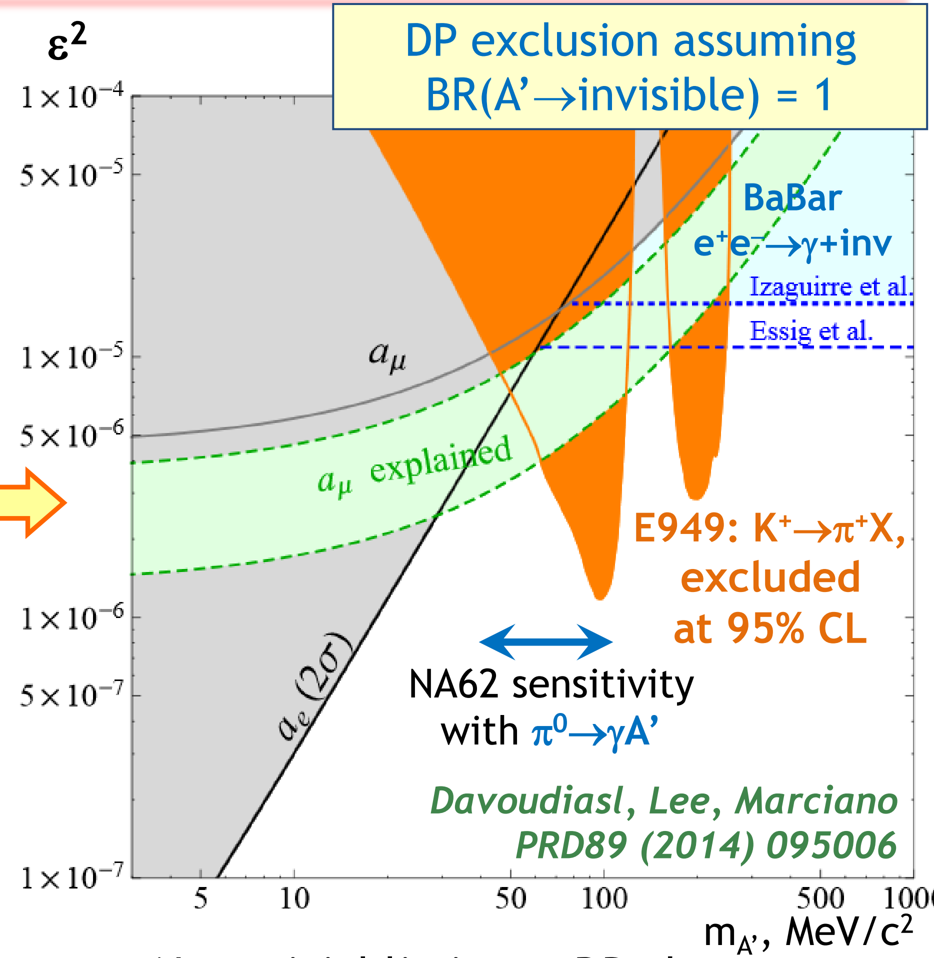
First observation (6.5σ) of *non-zero TFF slope* in the time-like momentum transfer region.

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

BNL-E949: limits on $BR(K^+ \to \pi^+ X)$ vs τ_X



DP exclusion assuming $BR(A' \to \text{invisible}) = 1$



The E949 $K^+ \to \pi^+ \nu\nu$ analysis:
$K^+ \to \pi^+ X$ search (where X is invisible)
PRD79 (2009) 092004

$BR(\pi^0 \to \text{invisible}) < 2.7\times10^{-7}$ at 90% CL
PRD72 (2005) 091102

Non-trivial limits on DP phase space including the $(g-2)_\mu$ favoured band, assuming invisible DP decays.

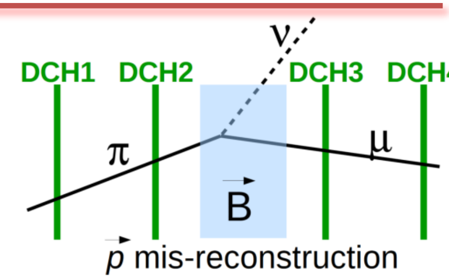
NA62 improves $K^+ \to \gamma A'$ with the whole dataset; non-trivial $\pi^0 \to \gamma A'$ limits with ~1% of the data

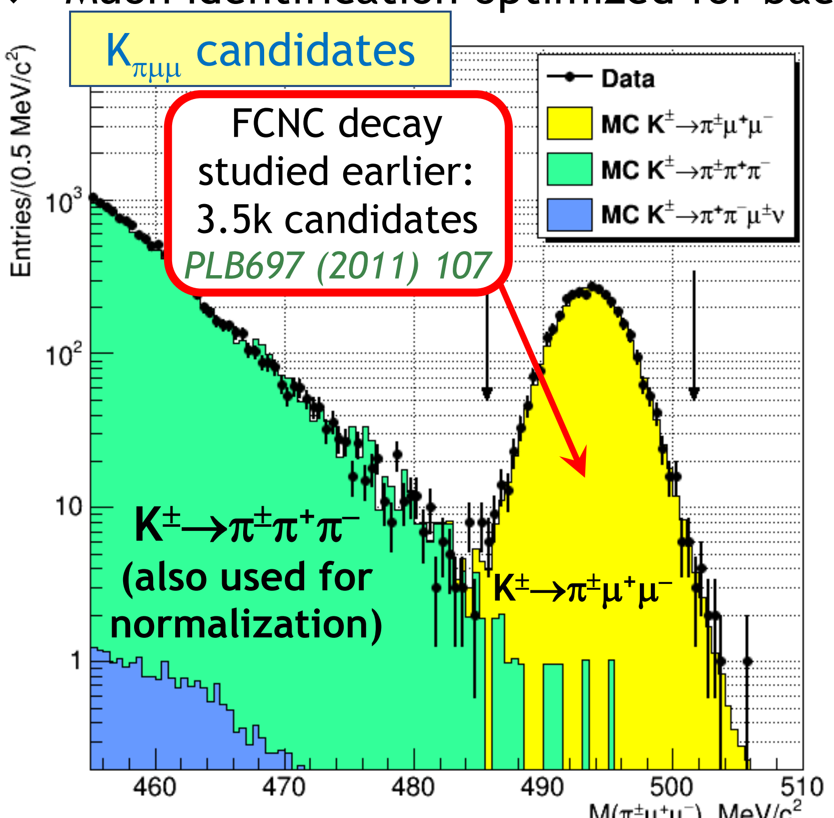
$K^{\pm}\to\pi\mu\mu$ decays: search for lepton number violation and 2-body resonances

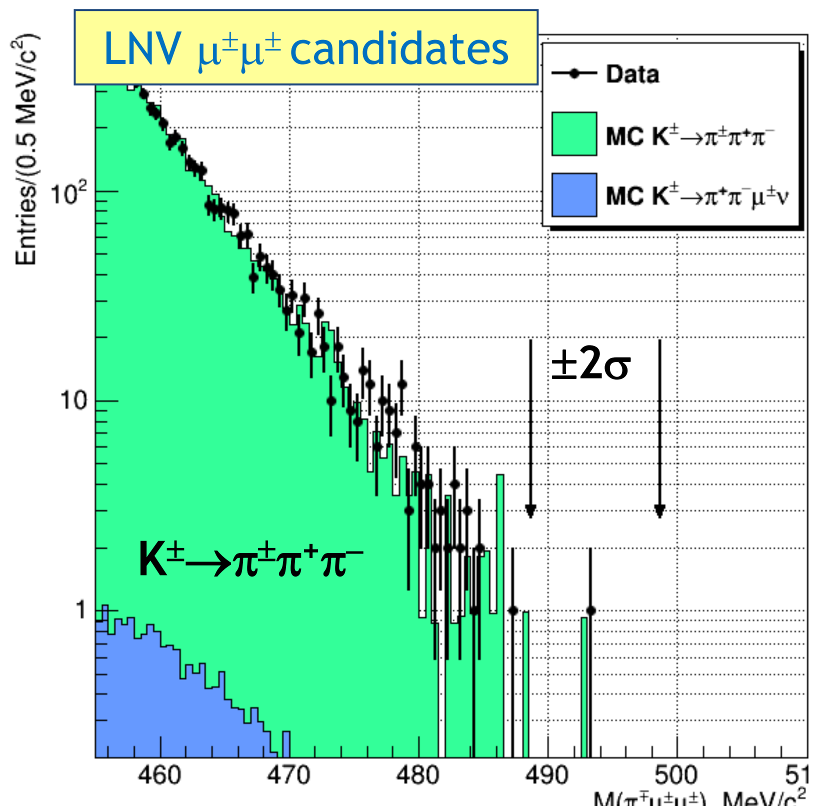
Phys. Lett. B769 (2017) 67

$K^\pm \to \pi^\mp \mu^\pm \mu^\pm$: 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: $K^\pm \to 3\pi^\pm$ with $\pi^\pm \to \mu^\pm\nu$ decays in flight.
- Muon identification optimized for background reduction.







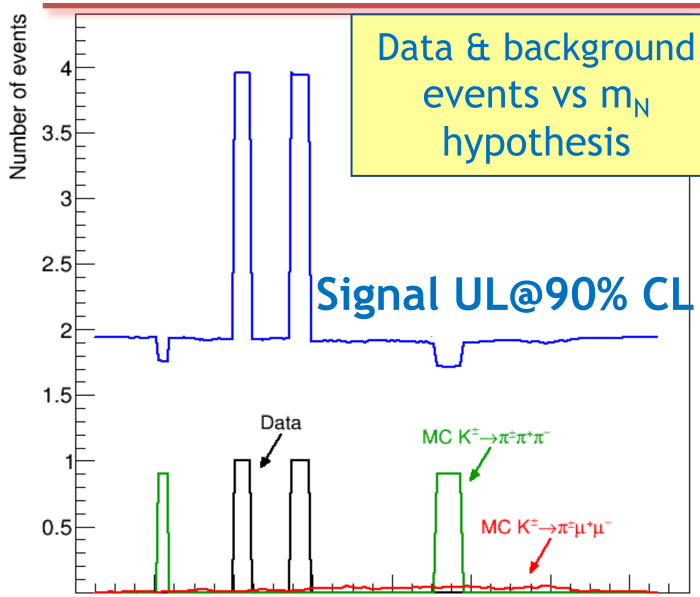
$N(\mu^\pm\mu^\pm) = 1$

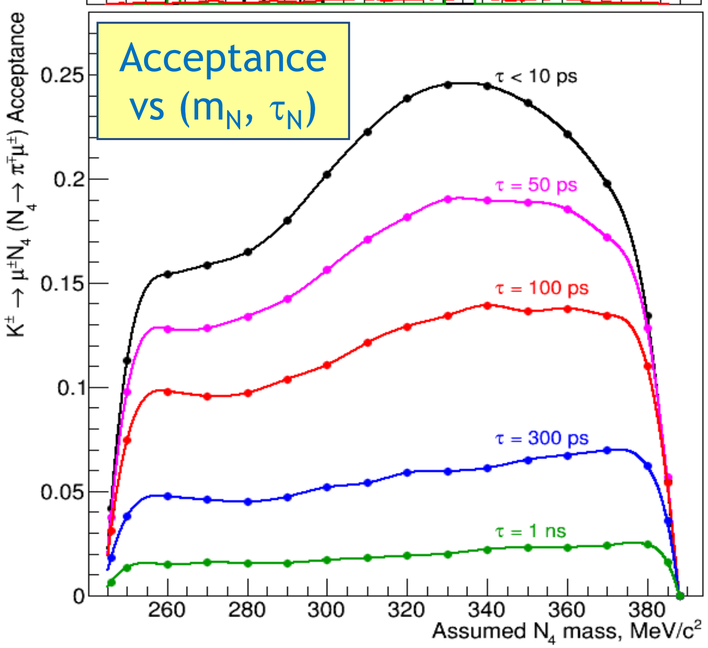
$N_{bkg} = 1.16 \pm 0.87$

⇒ $BR(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 8.6\times10^{-11}$ [90% CL]

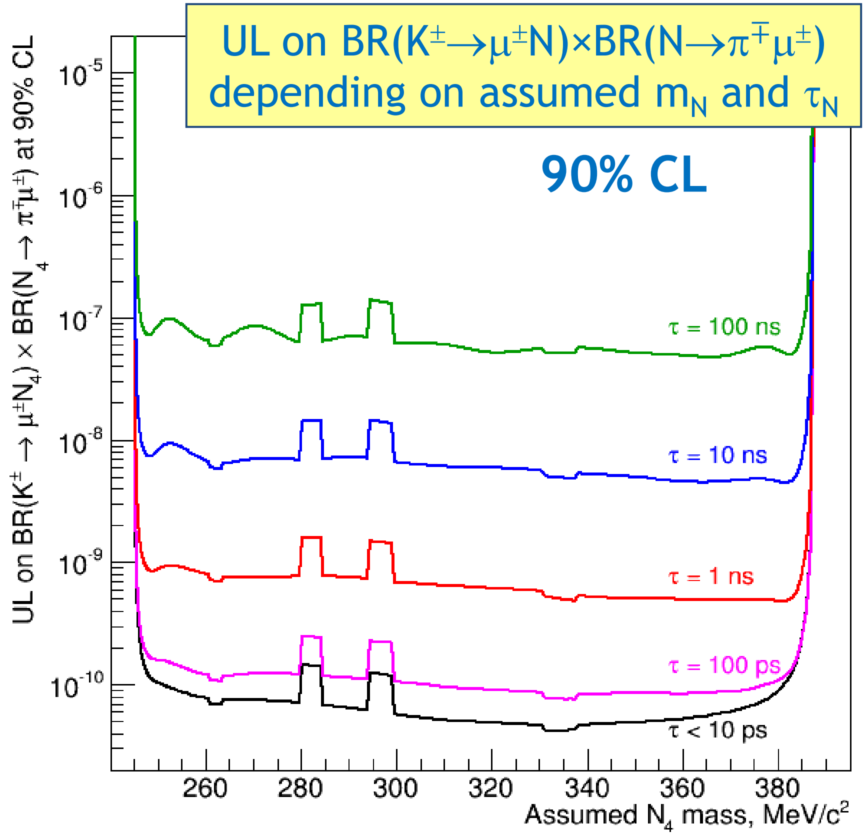
[Factor 13 improvement]

Search for $K^{\pm}\to\mu^{\pm}N$, $N\to\pi^{\mp}\mu^{\pm}$

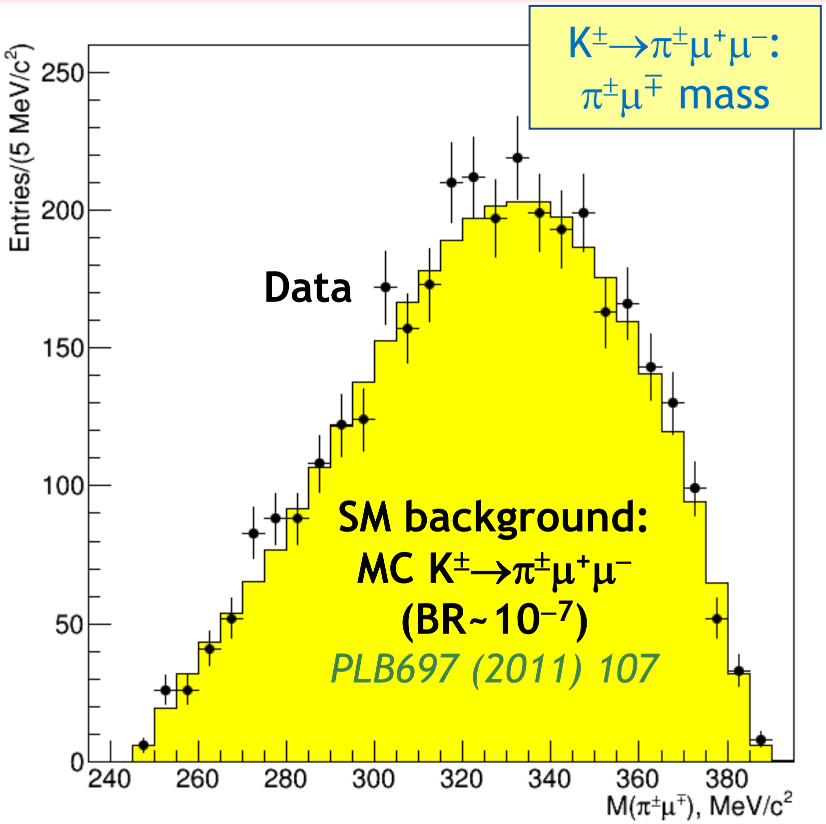


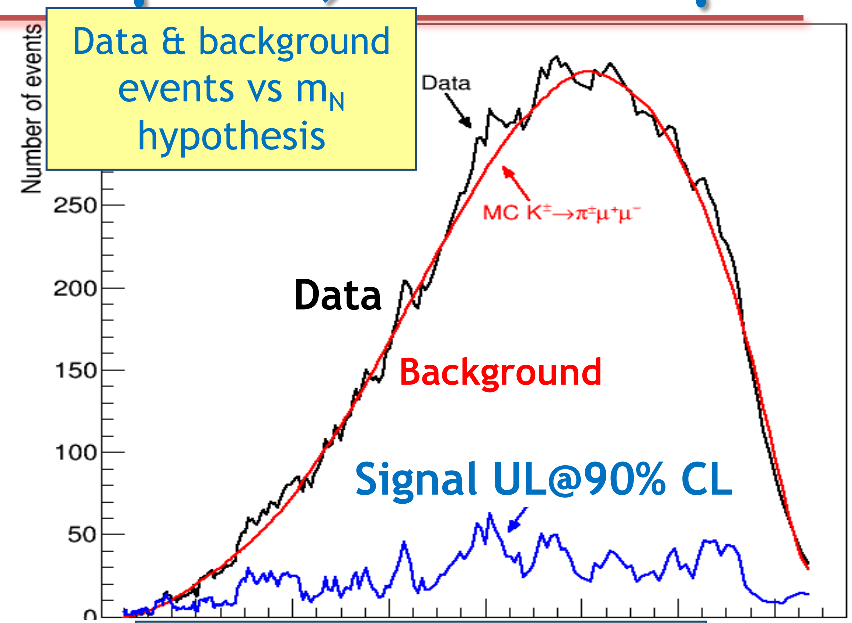


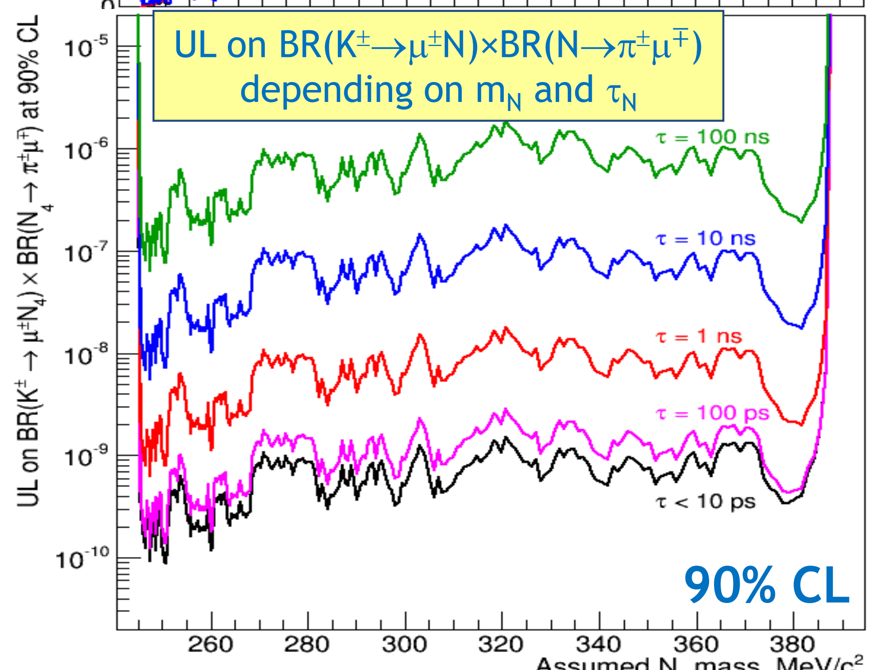
- Interpretation of the LNV result in terms of **Majorana neutrino** (**N**) production and decay. *[Atre et al., JHEP 0905 (2009) 030]*
- A scan in the parameter space: m_N and τ_N.
- Due to the 3-track vertex selection constraint, acceptance falls as **~1/τ_N** for **τ_N>1 ns**.
- Limits of **~10^{-10}** set for **τ_N<100 ps**.



Search for $K^{\pm}\to\mu^{\pm}N$, $N\to\pi^{\pm}\mu^{\mp}$

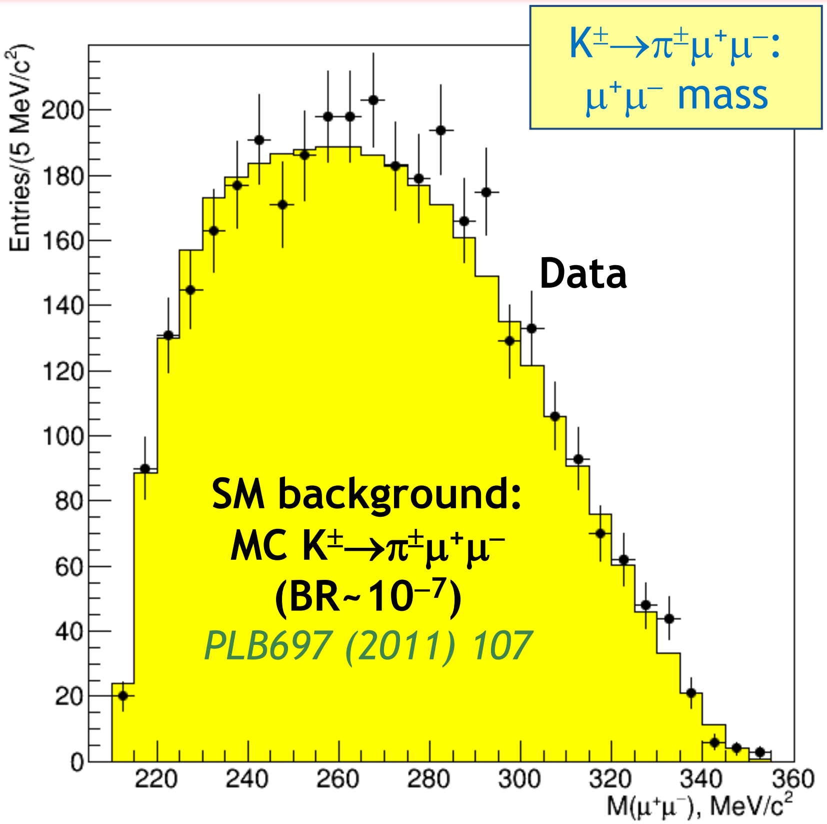


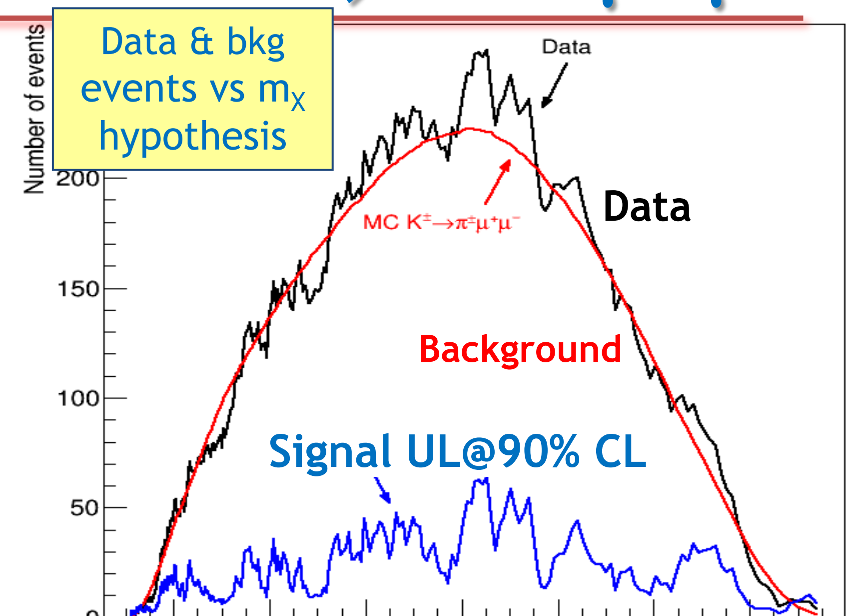


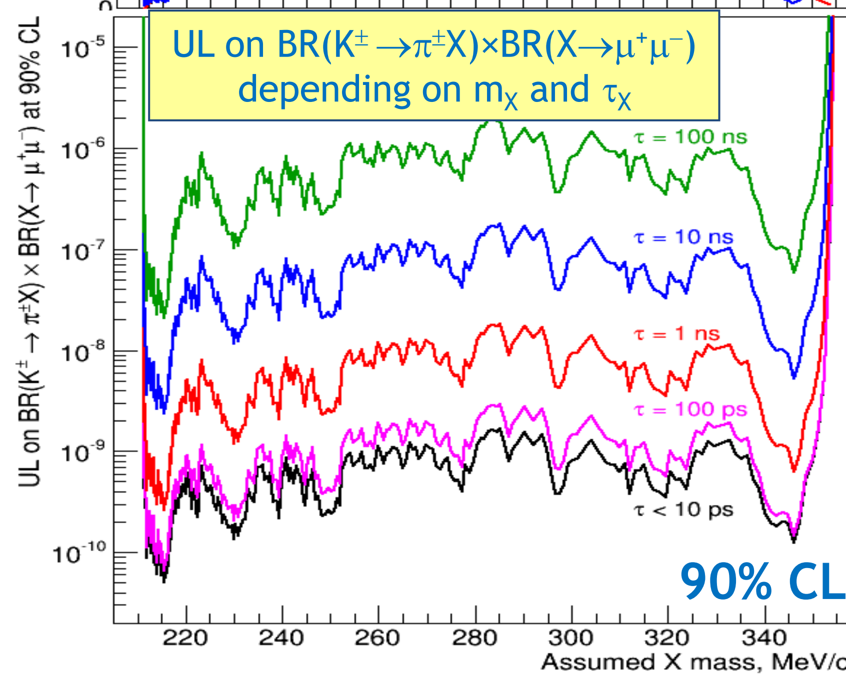


- Search for **LN conserving heavy neutrino** production and decay.
- Sensitivity limited by background from the FCNC $K^{\pm}\to\pi^{\pm}\mu^{+}\mu^{-}$ decay.
- Limits of **~10^{-9}** set for **τ_N<100 ps**.

Search for $K^{\pm}\rightarrow\pi^{\pm}X$, $X\rightarrow\mu^{+}\mu^{-}$







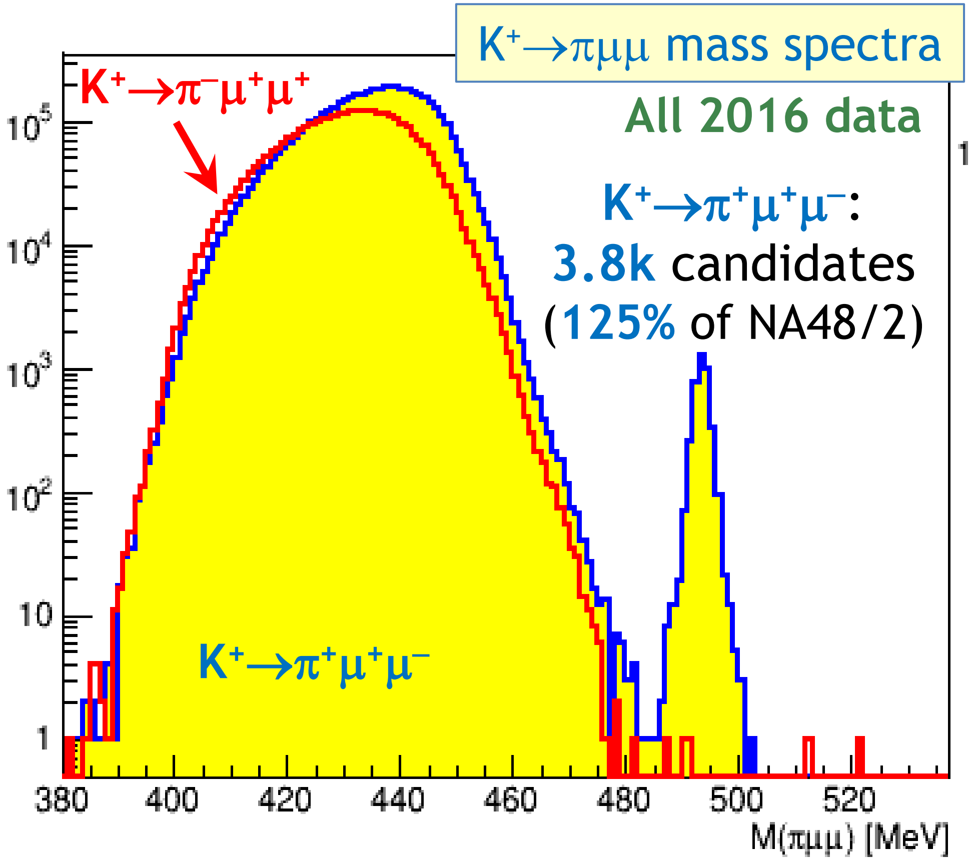
- Also background limited; **UL~10^{-9}**.
- This leads to non-trivial limitations on the inflation (χ) phase space: $\chi\rightarrow\mu^{+}\mu^{-}$ decay dominates at **m_χ~300 MeV/c^2**.

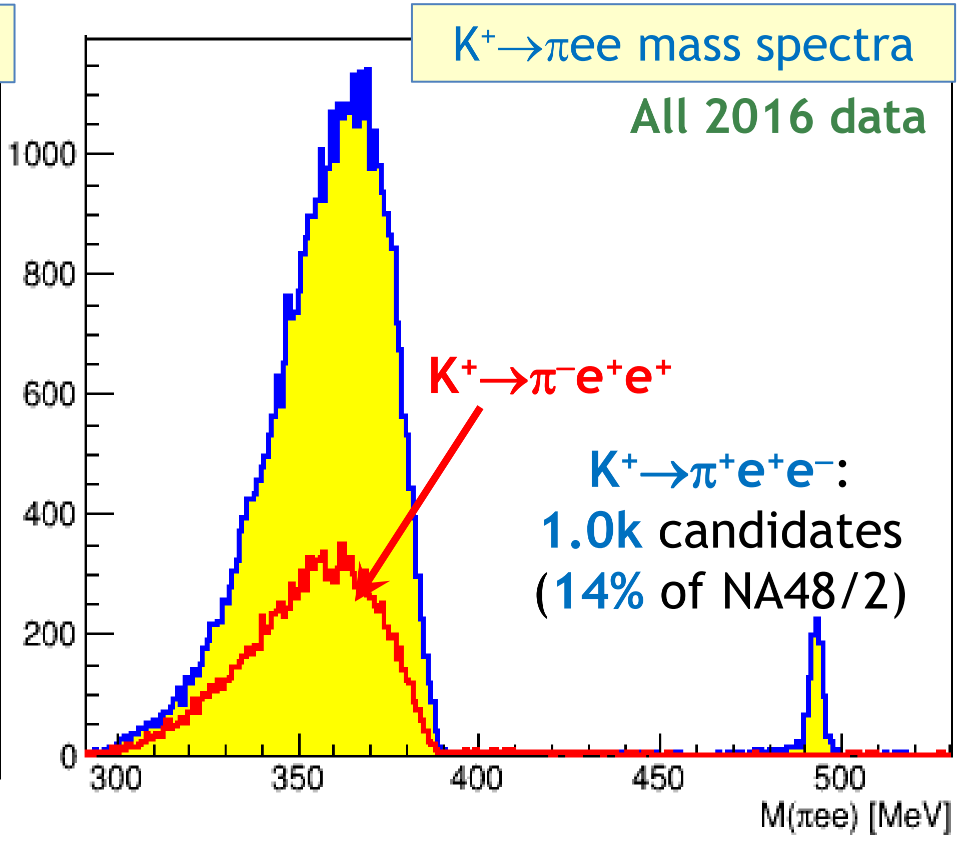
[Shaposhnikov, Tkachev, PLB 639 (2006) 414; Bezrukov, Gorbunov, PLB736 (2014) 494]

Data 2016: 3-track sample

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.

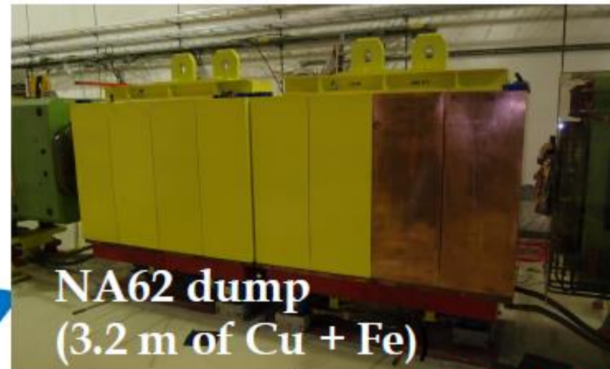




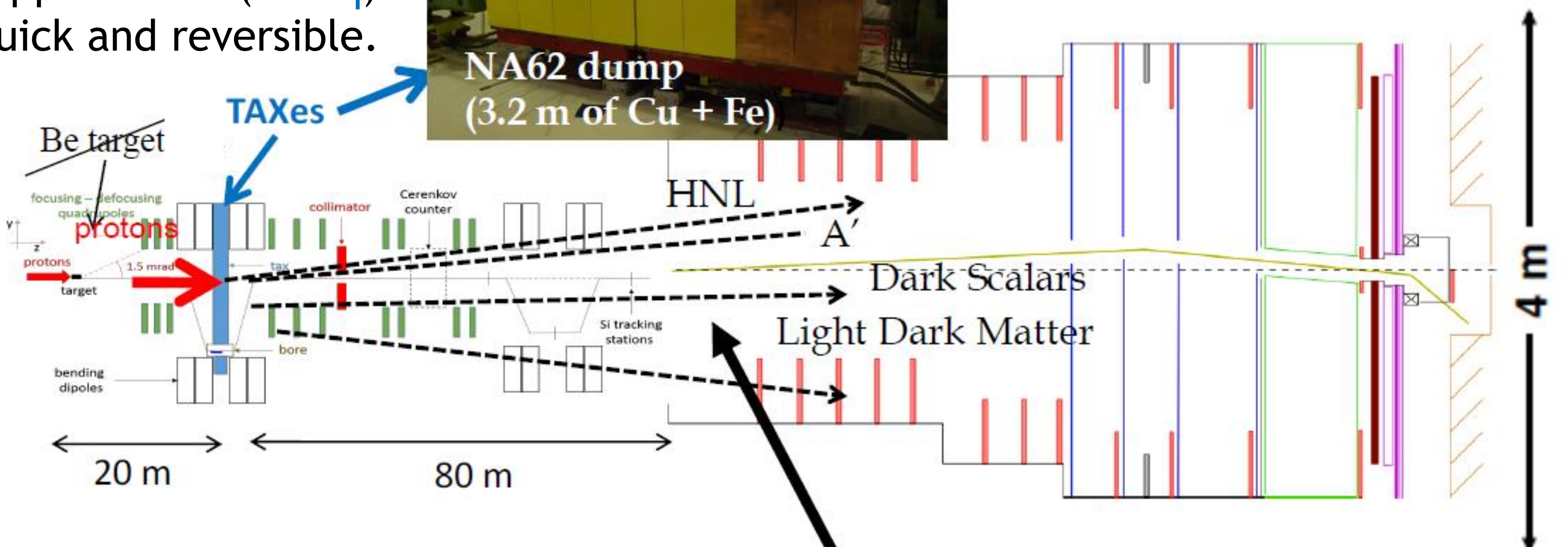
NA62 operation in beam dump mode

NA62 beam dump operation

Dump mode:
Be target is removed;
beam is dumped into
copper TAXes (~20λ_I).
Quick and reversible.



Possibility: 10^{18} pot in dump mode by 2023 (3 months of dedicated data taking)

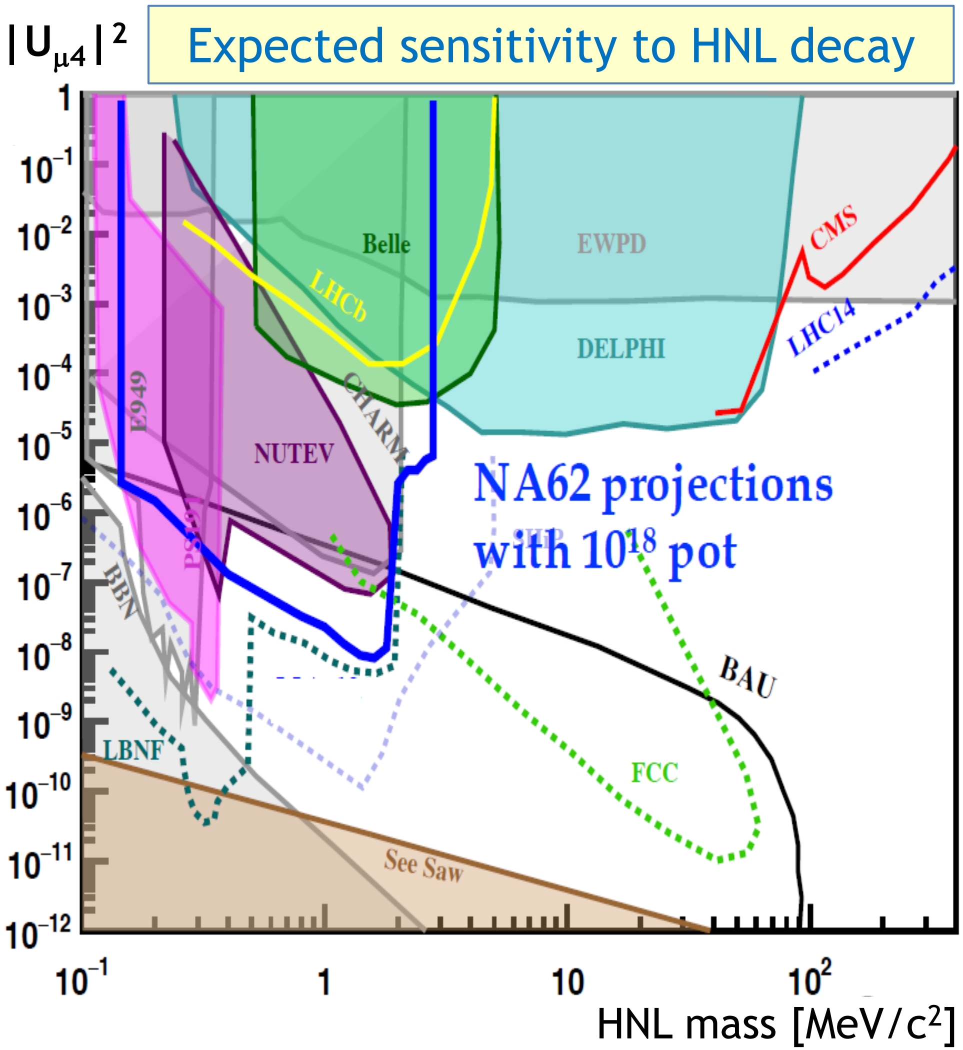


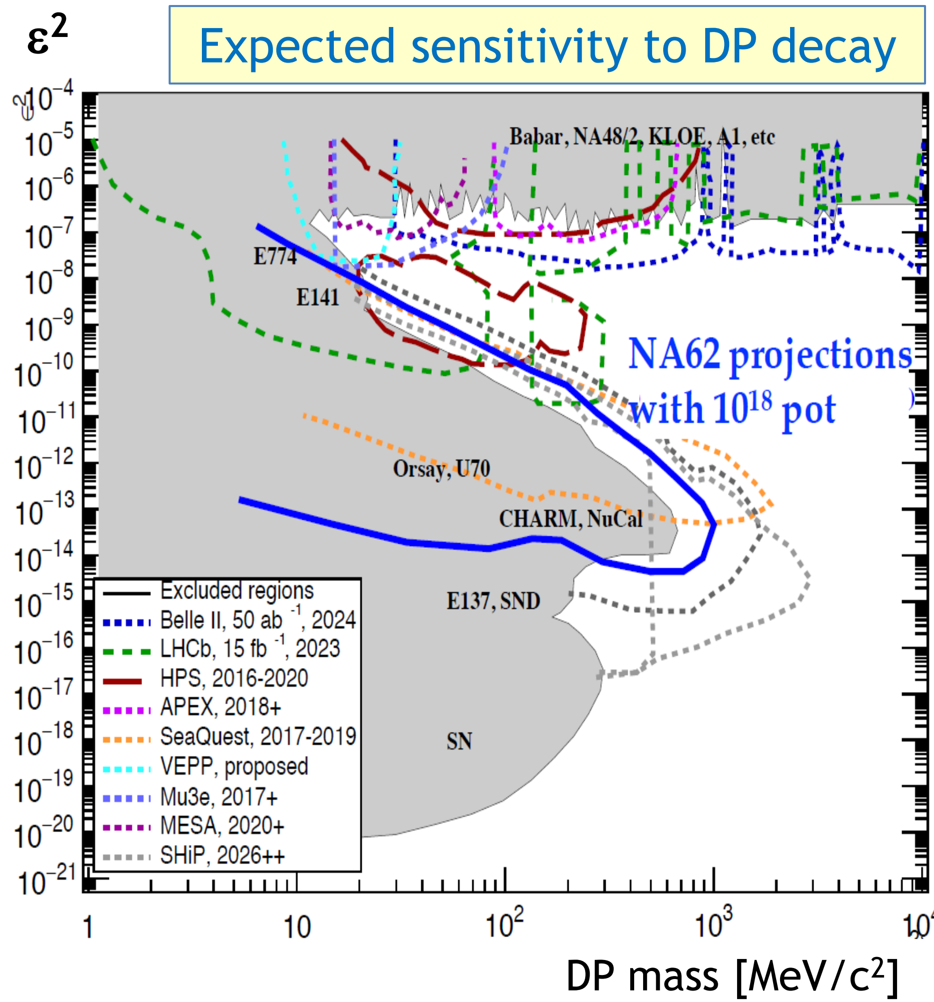
Heavy Neutral Leptons, Dark Photons, Dark scalars, and ALPS can be originated by charm, beauty and photons produced in the interaction of protons with the dump.

2016 data:

- 2×10^{15} pot with **TAX** dump;
- ~10^{16} pot with **Be target** dump concurrently with K^+ beam.

Expected sensitivities: examples





For more details, see talk by G.Lanfranchi at EPS HEP 2017

Summary

- **NA62 run 2016–2018:**
  - ✓ Detector is fully operational since September 2016.
  - ✓ Detector performance is close to design parameters.
  - ✓ The run is focused on the $K_{\pi\nu\nu}$ measurement (**SES~10^{-12}**).
  - ✓ Large dataset at **40%** of nominal intensity collected in 2016.
  - ✓ Currently taking data at **60%** of nominal intensity.
  - ✓ Programme for NA62 run in 2021–2023 is under discussion.

- **The first (UK-led) NA62 physics result is out:**
  - ✓ Search for HNL production in $K^+ \to e^+ N$ with minimum bias data; 10^{-6}–10^{-7} limits on $|U_{e4}|^2$ in mass range **170–448 MeV/c^2**.

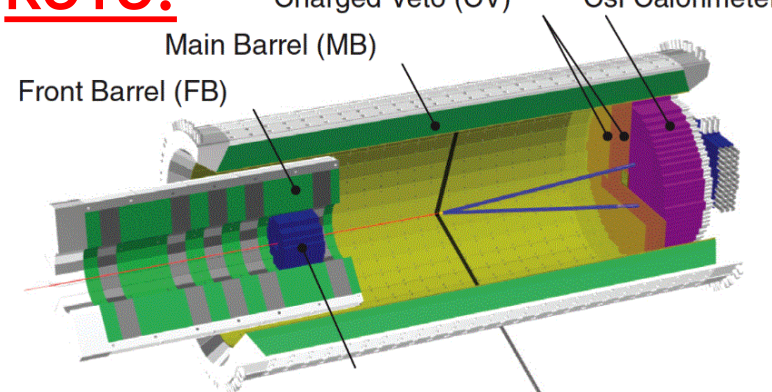
- **Further results expected soon:**
  - ✓ $K_{\pi\nu\nu}$ search with the 2016 data; expect **≈1** SM event.
  - ✓ Searches for dark photon production in $\pi^0 \to \gamma A'$ decays ($A' \to$ **invisible**), $K^+ \to \mu^+ N$, $K^+ \to e^+$ **+ invisible**; …

Backup

Kaons at CERN beyond 2024

- Need to measure both BR($K^+ \to \pi^+ \nu\nu$) vs BR($K_L \to \pi^0 \nu\nu$): affected differently by NP.
- In the next few years, we expect:
  - ✓ NA62 @ CERN to measure BR($K^+ \to \pi^+ \nu\nu$) to 10%;
  - ✓ KOTO @ J-PARC to observe a few $K_L \to \pi^0 \nu\nu$ events.
- A new, possibly multi-purpose, K_L experiment at CERN focussed on $K_L \to \pi^0 \nu\nu$, with SES~0.5×10^{-12} is under consideration for Run 4 (2026–2029).

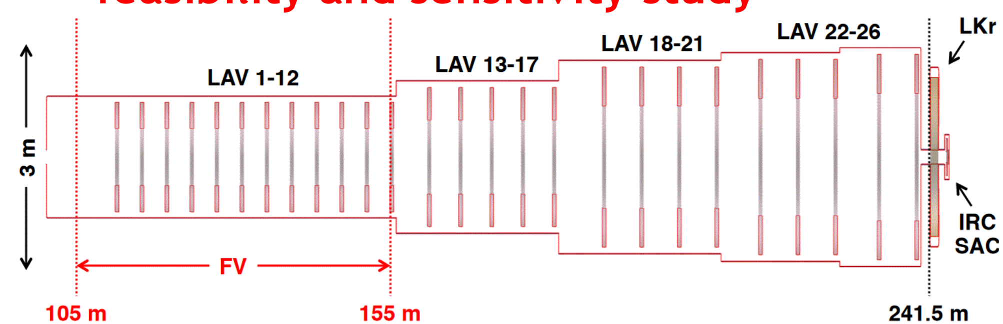
KOTO:



- 30 GeV protons (300 kW); $\langle p_{KL} \rangle$=2 GeV/c;
- Proposal: SES=8×10^{-12} (~4 SM evts) with S/B=1.4 in three years.
- Short (100h) run in 2013: SES=1.3×10^{-8};
- Observed 1 event, expected 0.36; *[CKM2014]*
- Collected ×20 more data in 2015;
- Intention (no proposal): upgrade to 100 SM evts.

KLEVER @ CERN:

feasibility and sensitivity study



- 400 GeV protons; $\langle p_{KL} \rangle$~100 GeV/c: complementary approach 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).