Kaon experiments at CERN: recent results & prospects

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on behalf of the NA48/2 and NA62 collaborations

Outline:

1) $K^{\pm}$ decay experiments at CERN: NA48/2 and NA62
2) Searches for new physics in $K^{\pm}\to\pi\mu\mu$ decays
3) Prospects for heavy neutral lepton searches
4) Neutral pion decays: $\pi^0\to\gamma e^+e^-$, $\pi^0\to\gamma A'$, $\pi^0\to e^+e^-$
5) Summary

MESON 2016

Krakow, Poland • 6 June 2016

Kaon physics facilities

BNL
E865, E777, E787, E949

CERN
NA48, **NA62**, **LHCb**

IHEP Protvino
ISTRA+, OKA, KLOD

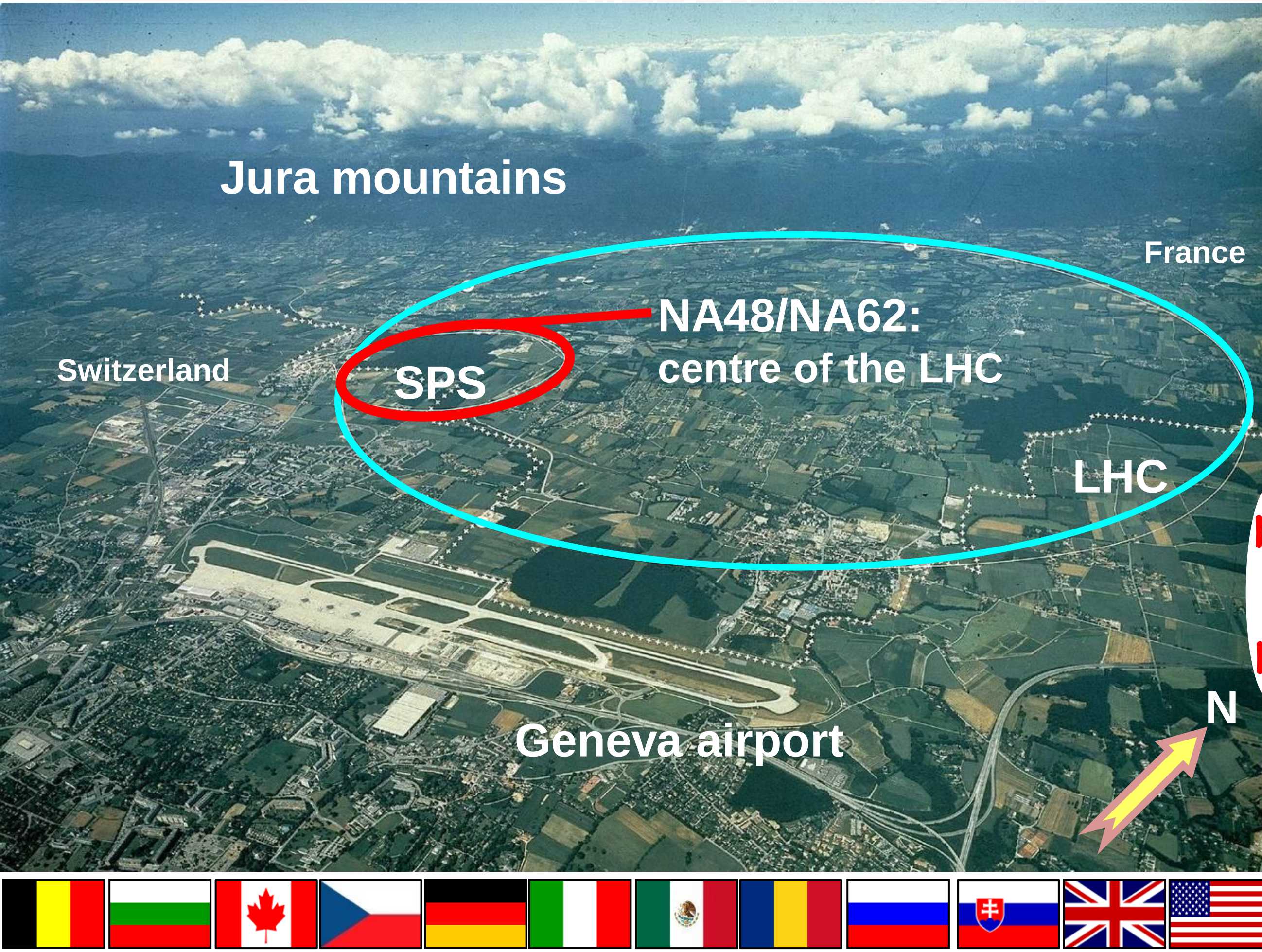
FNAL
KTeV

LNF
KLOE, **KLOE-2**

KEK/J-PARC
E391a, **KOTO**, **TREK**

A variety of experimental techniques:
K decay-in-flight (e.g. CERN), stopped **K**$^+$, ϕ factory

Kaon experiments 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 phase
- 2007: $K^\pm_{e2}/K^\pm_{\mu 2}$ | tests
- 2008: $K^\pm_{e2}/K^\pm_{\mu 2}$ | tests

NA62
- 2014: pilot run
- 2015–: data taking

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

Recent experiments at CERN

Experiment	NA48/2 ($K^{\pm}$)	NA62 (R_K phase) ($K^{\pm}$)	NA62 (K^{+})
Data taking period	2003–2004	2007–2008	2015–
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 + $e^{\pm}$	$K_{\pi\nu\nu}$ + …

The NA48 detector (NA48/2 and NA62 R_K phase) — New detector (NA62)

The NA62 experiment

- Main goal: collect 100 SM $K^{+}\to\pi^{+}\nu\nu$ decays, $BR_{SM}=(9.11\pm0.72)\times10^{-11}$.
  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

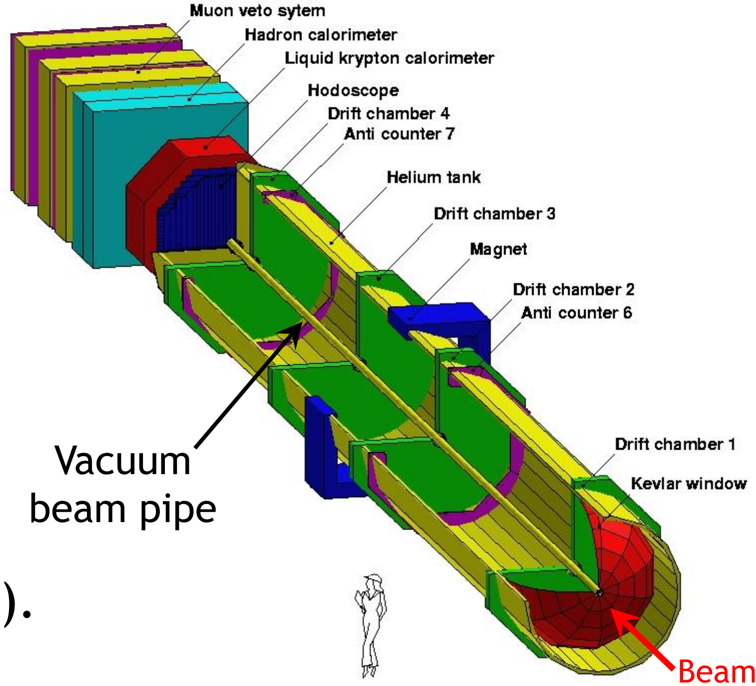
2003–2007: charged kaon beams,
the NA48 detector

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:

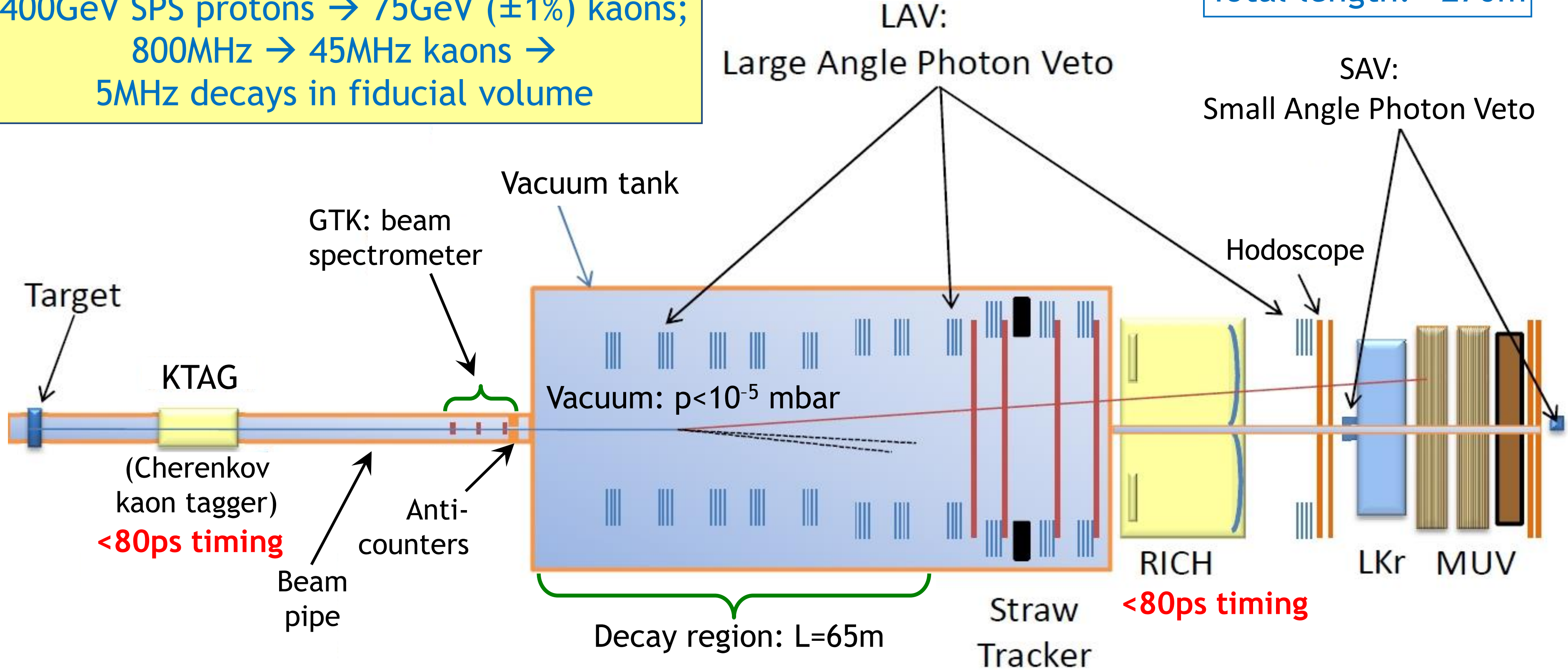
- Magnetic spectrometer (4 DCHs)
  4 views/DCH: redundancy ⇒ efficiency;
  $\delta p/p = 0.48\% \oplus 0.009\%p$ [GeV/c] (in 2007)
- Scintillator hodoscope (HOD)
  Fast trigger, time measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$ [GeV];
  $\sigma_x=\sigma_y=4.2\text{mm}/E^{1/2} \oplus 0.6\text{mm}$ (1.5mm@10GeV).



The NA62 experiment

Un-separated hadron ($p/\pi^+/K^+$) beam:
400GeV SPS protons → 75GeV (±1%) kaons;
800MHz → 45MHz kaons →
5MHz decays in fiducial volume

Total length: ~270m



- Expected single event sensitivities: ~10^{-12} for $K^\pm$ decays, ~10^{-11} for π^0 decays.
- Kinematic rejection factors (limited by beam pileup and tails of MCS): 5×10^3 for $K^+\to\pi^+\pi^0$, 1.5×10^4 for $K\to\mu^+\nu$.
- Hermetic photon veto: ~10^8 suppression of $\pi^0\to\gamma\gamma$.
- Particle ID (RICH+LKr+MUV): ~10^7 muon suppression.

More details in a talk by Slava Duk this afternoon

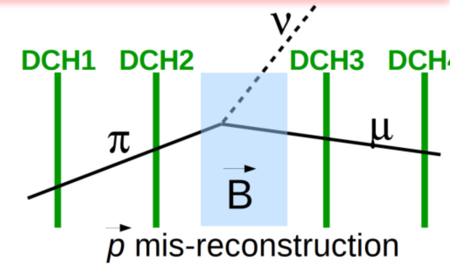
The NA62 detector

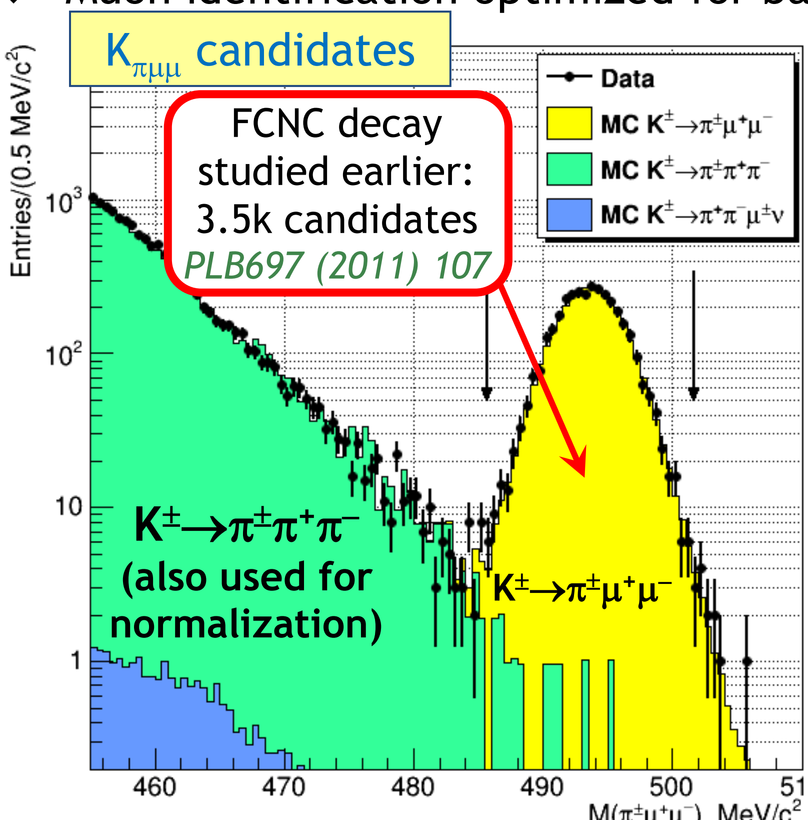
NA62 physics data taking started in June 2015

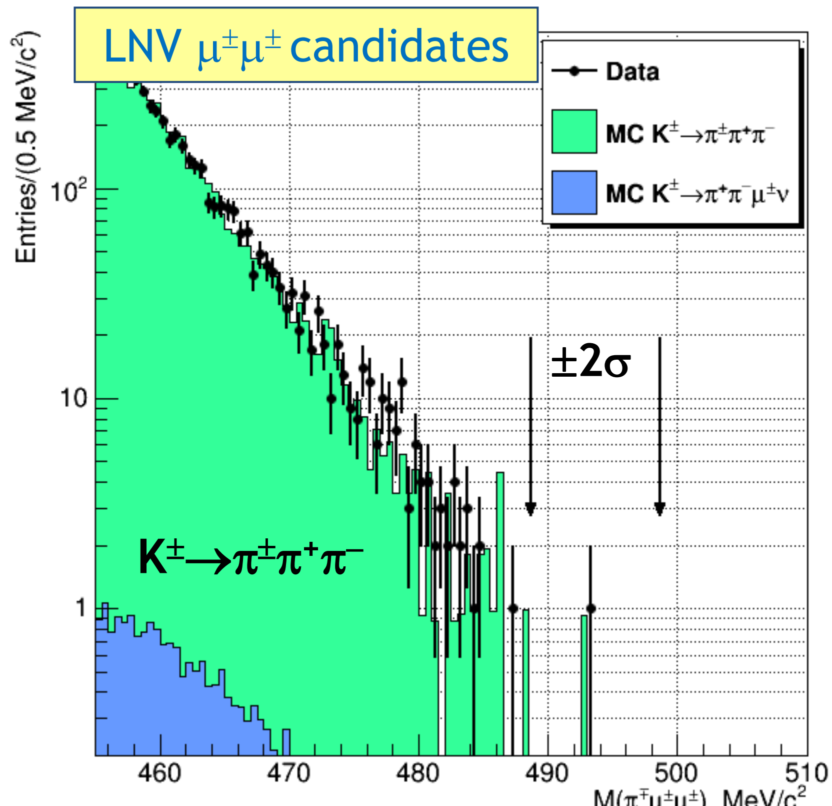
$K^{\pm}\rightarrow\pi\mu\mu$ decays: search for lepton number violation and 2-body resonances

$K^\pm \to \pi^\mp \mu^\pm \mu^\pm$: 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.







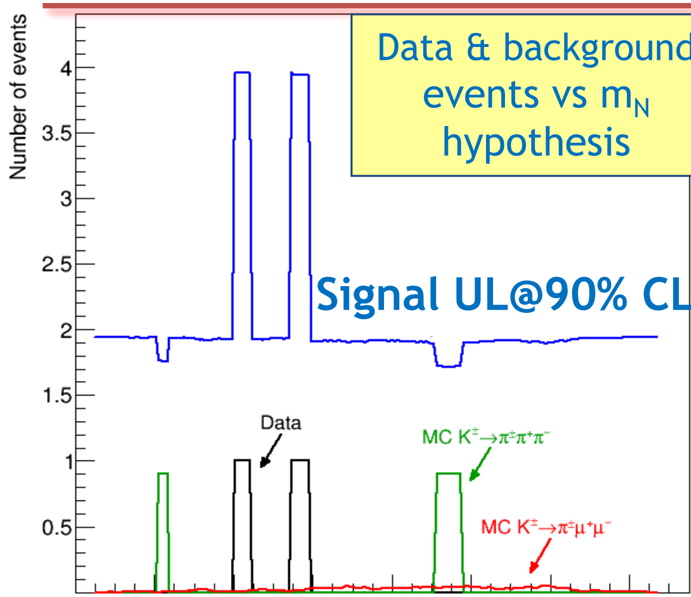
$N(\mu^\pm\mu^\pm) = 1$

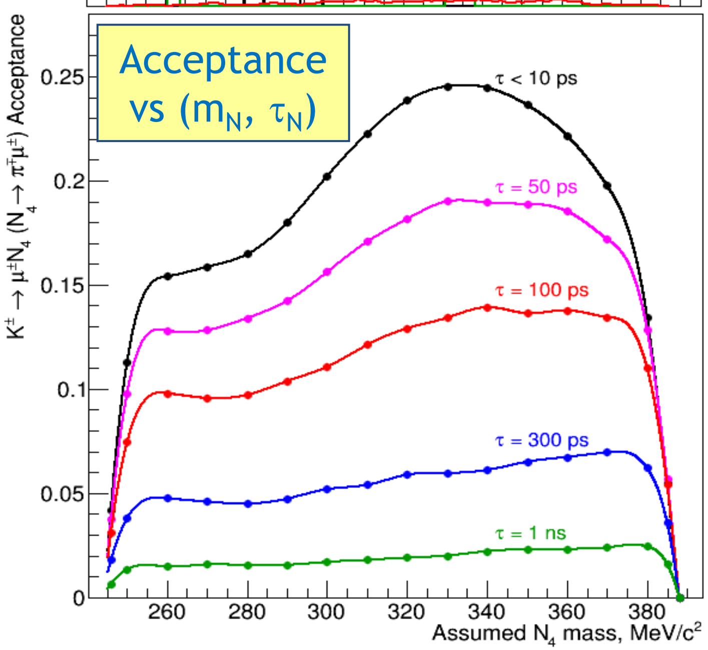
$N_{bkg} = 1.16 \pm 0.87$

⇒ $BR(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 8.6 \times 10^{-11}$ [90% CL]

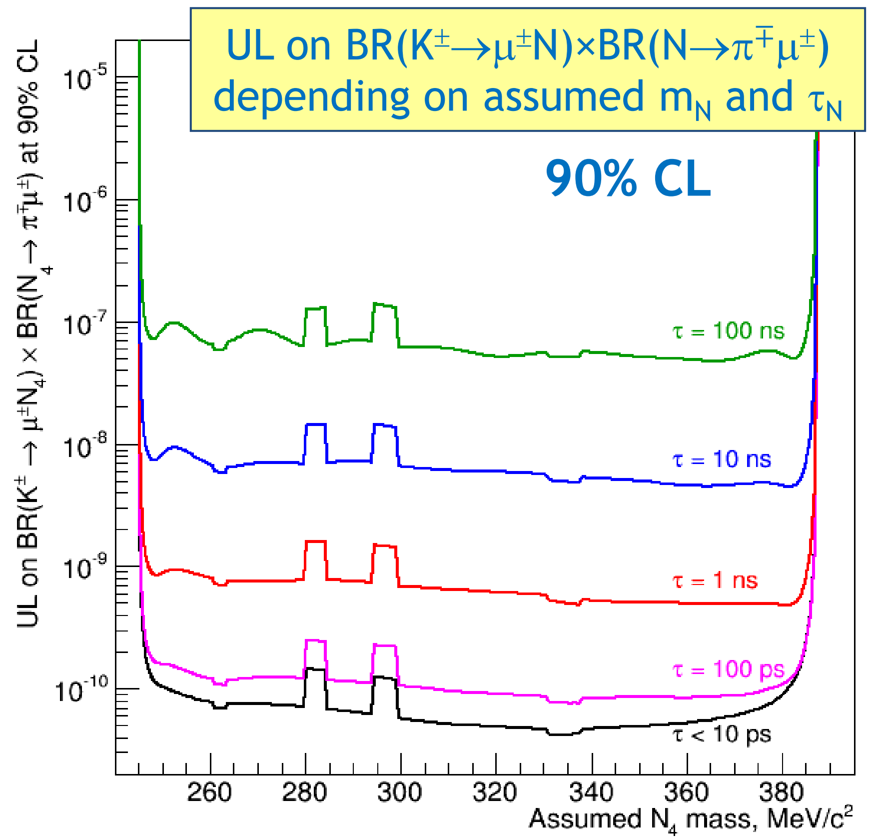
[Factor 13 improvement; final result; paper in preparation]

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

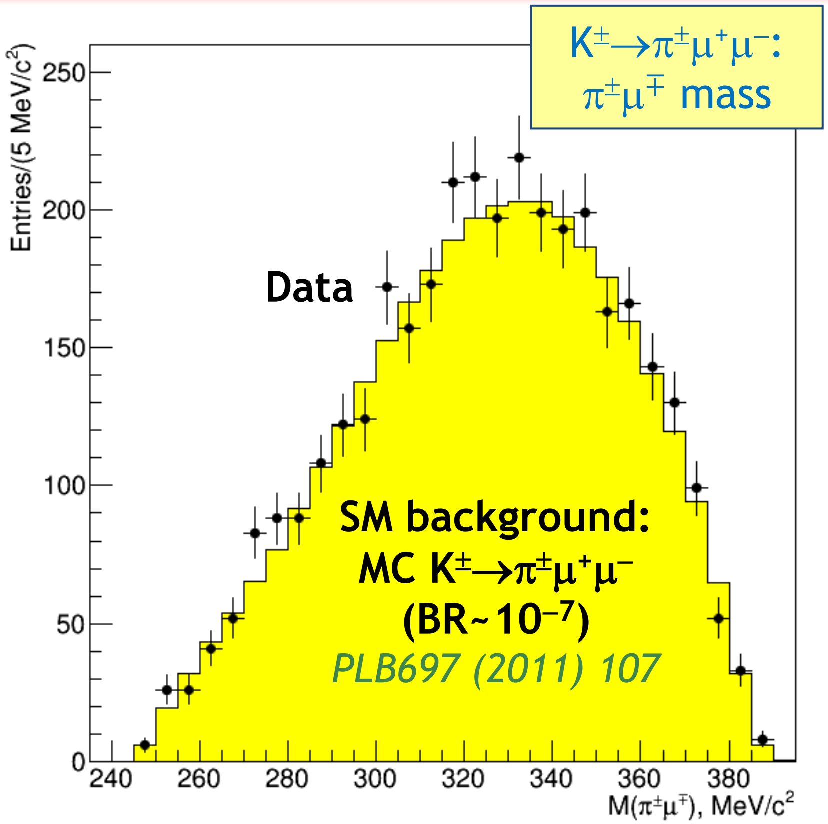


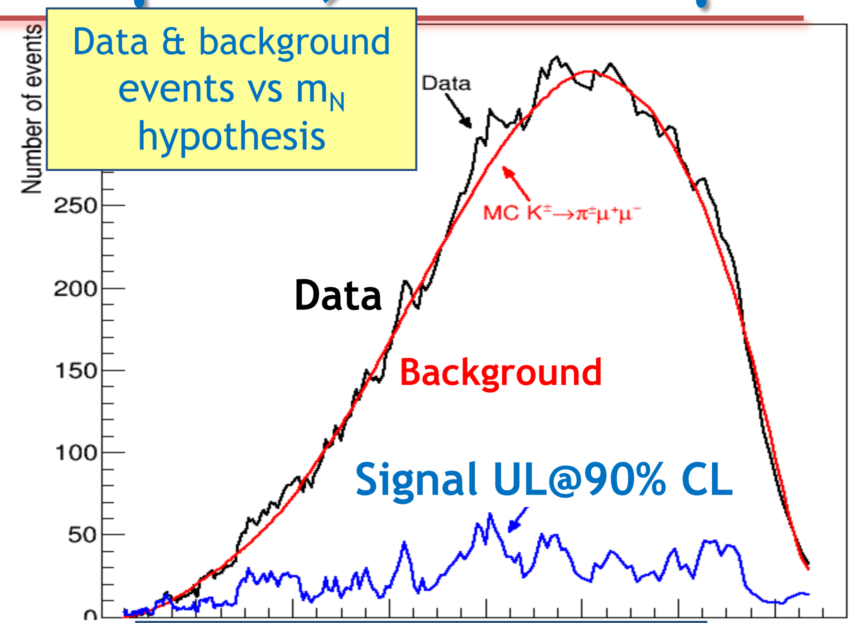


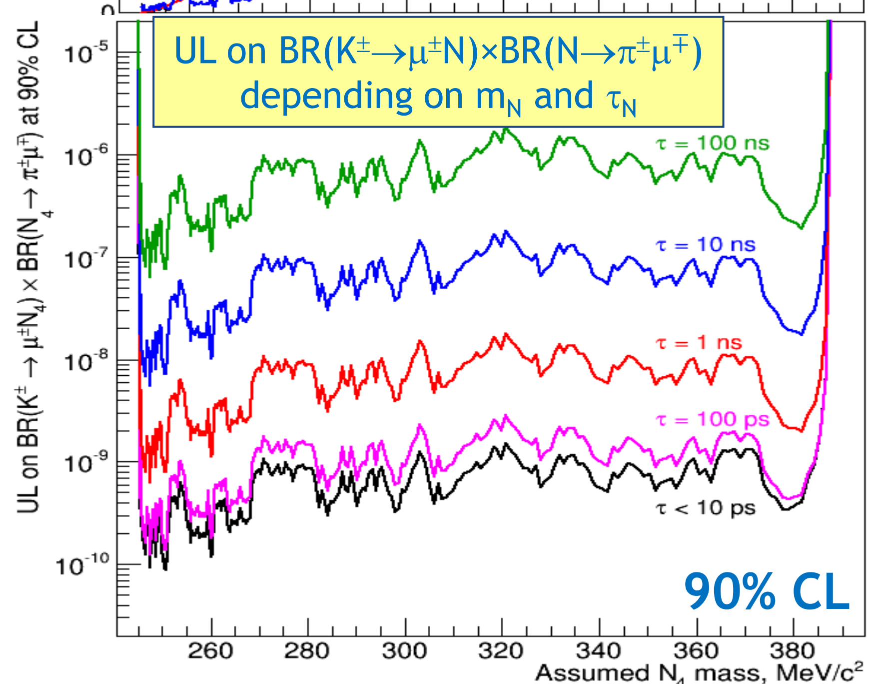
- Interpretation of the LNV result in terms of **Majorana neutrino** (**N**) production and decay. *[Atre et al, JHEP 0905 (2009) 030]*
- A scan in the parameter space: m_N and τ_N.
- Due to the 3-track vertex selection constraint, acceptance falls as **~1/τ_N** for **τ_N>1 ns**.
- Limits of **~10^{-10}**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



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

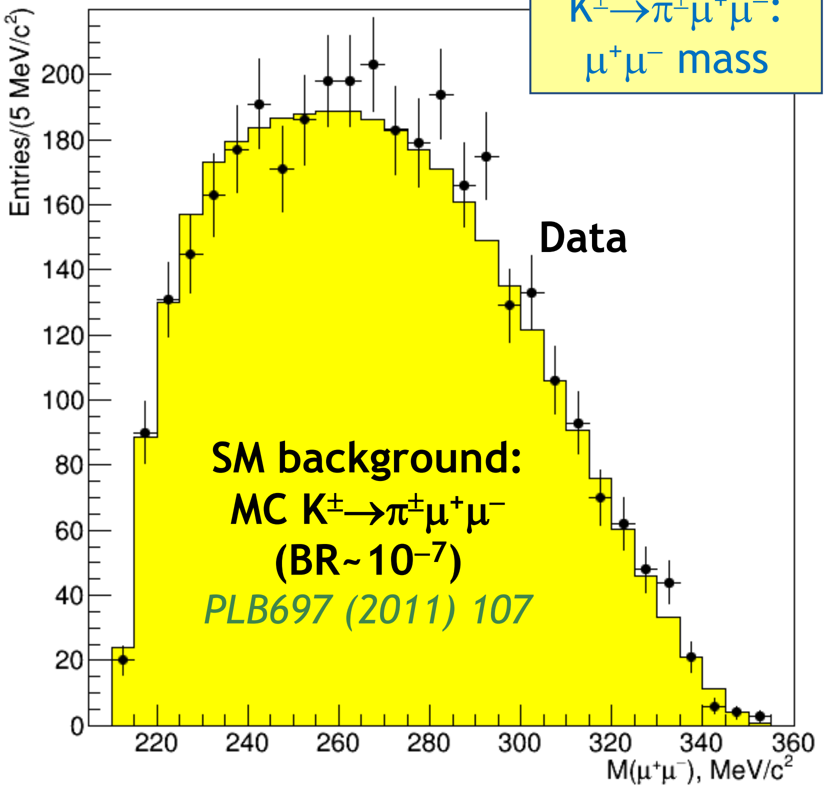


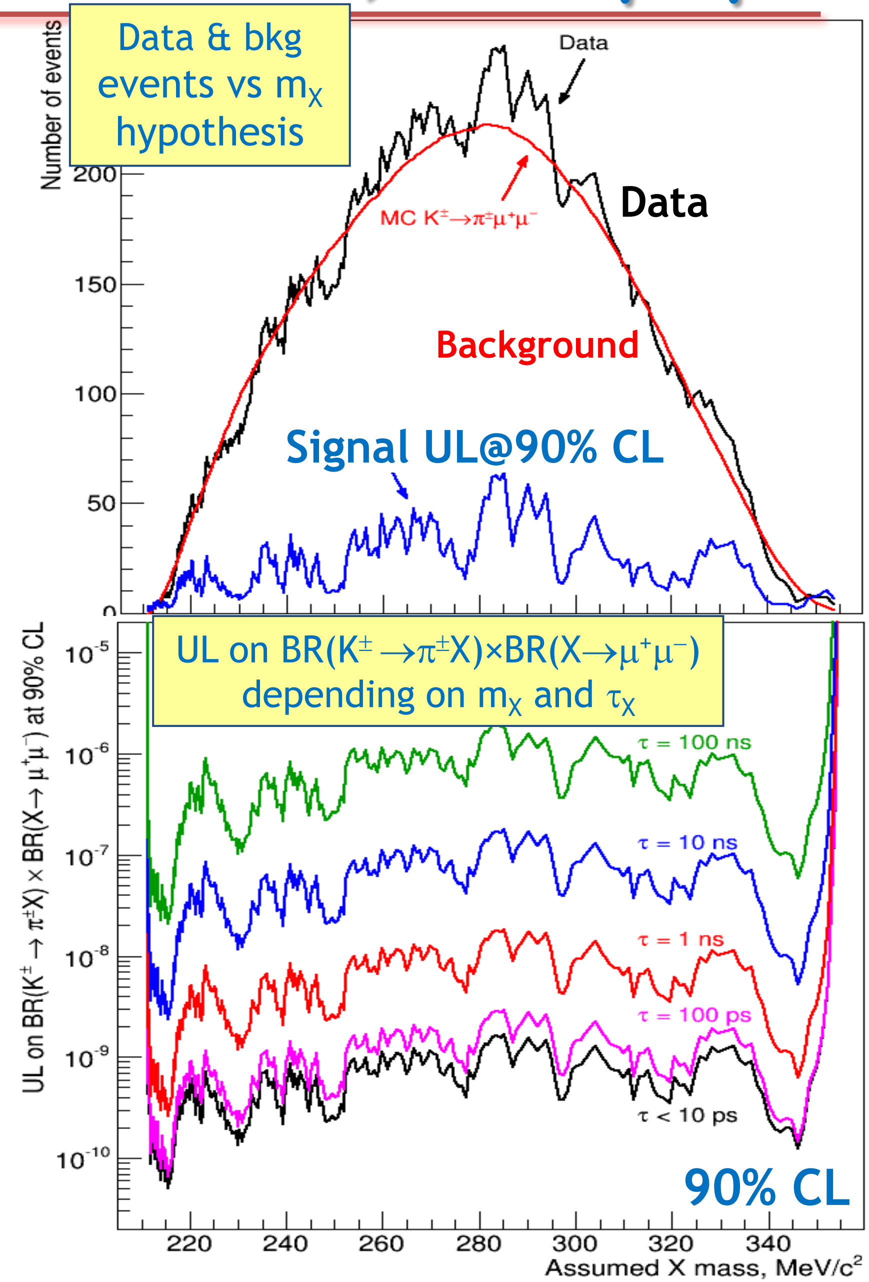




- Search for **LN conserving heavy neutrino** production and decay.
- Sensitivity limited by background from the FCNC $K^\pm \to \pi^\pm \mu^+ \mu^-$ decay.
- Limits of **~10^{-9}** set for **τ_N<100 ps**.

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





❖ Also background limited; **UL~10^{-9}**.

❖ This leads to non-trivial limitations on the inflation (χ) phase space: $\chi\to\mu^{+}\mu^{-}$ decay dominates at **m_{χ}~300 MeV/c²**.

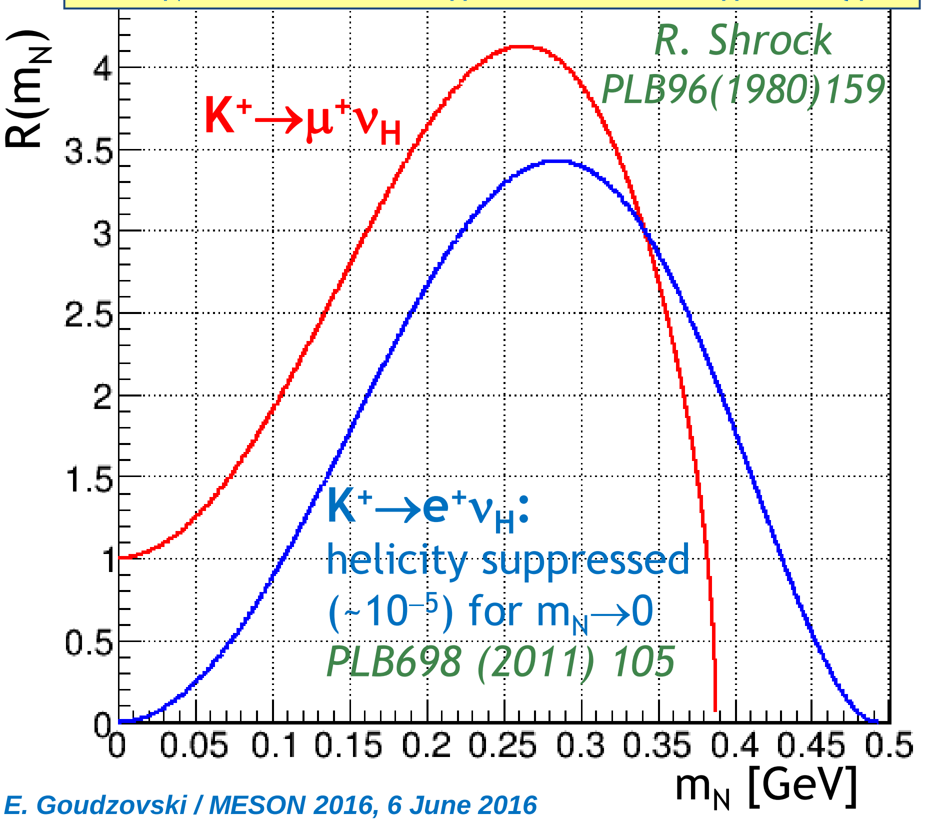
[Shaposhnikov, Tkachev, PLB 639 (2006) 414; Bezrukov, Gorbunov, PLB736 (2014) 494]

Heavy neutral leptons

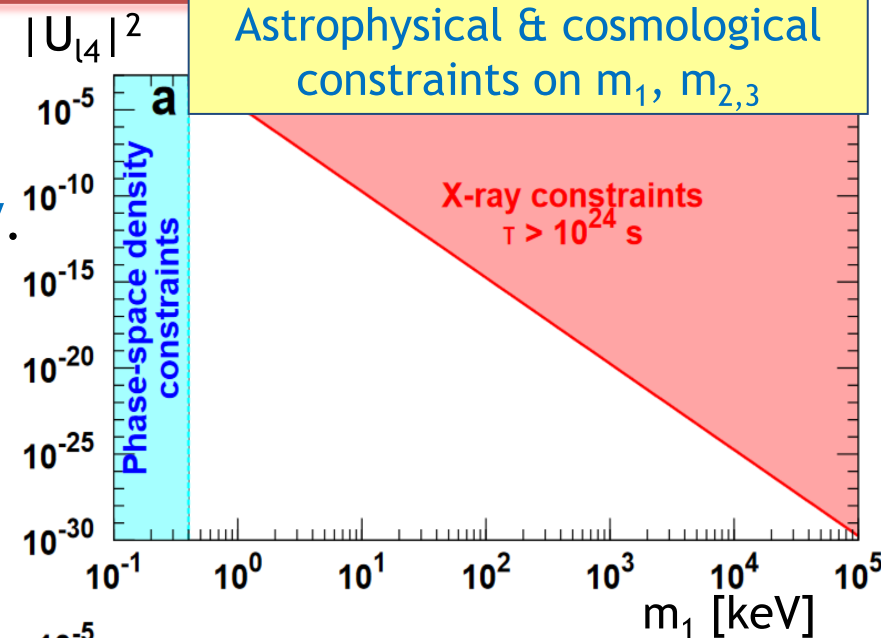
Constraints on the νMSM

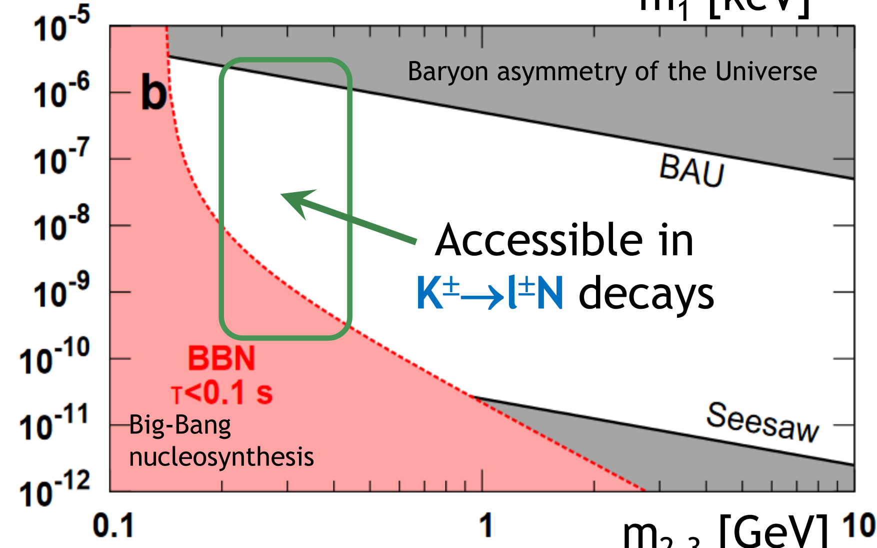
Neutrino minimal SM (**νMSM**) =
SM + 3 right-handed neutral heavy leptons.
[Asaka et al., PLB 631 (2005) 151]
Masses: $m_1 \sim 10$ **keV** [DM candidate]; $m_{2,3} \sim 1$ **GeV**.
HNLs observable via **production** and **decay**.

HNL production, kinematic factor:
$R(m_N) = \Gamma(K^+ \to l^+\nu_H)/\Gamma(K^+ \to \mu^+\nu_H)/|U_{l4}|^2$



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

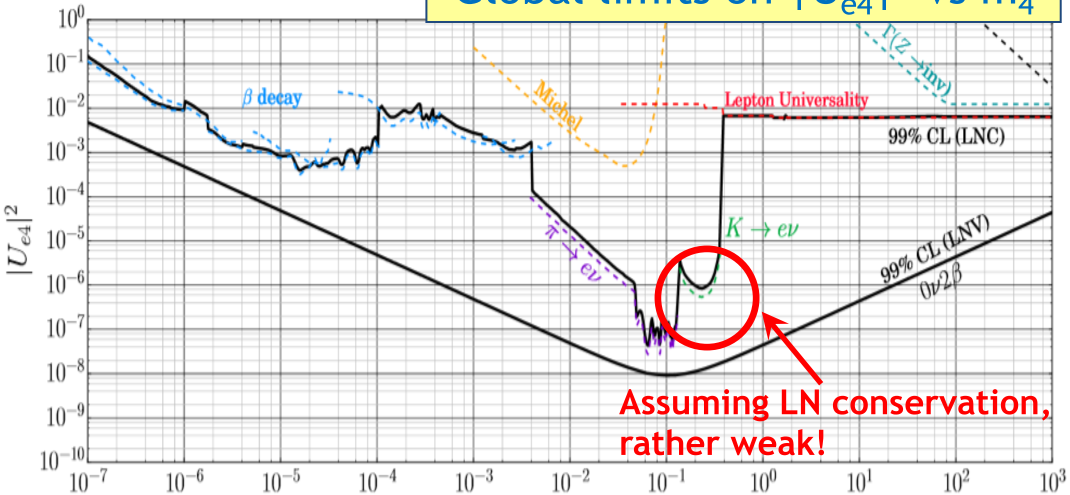




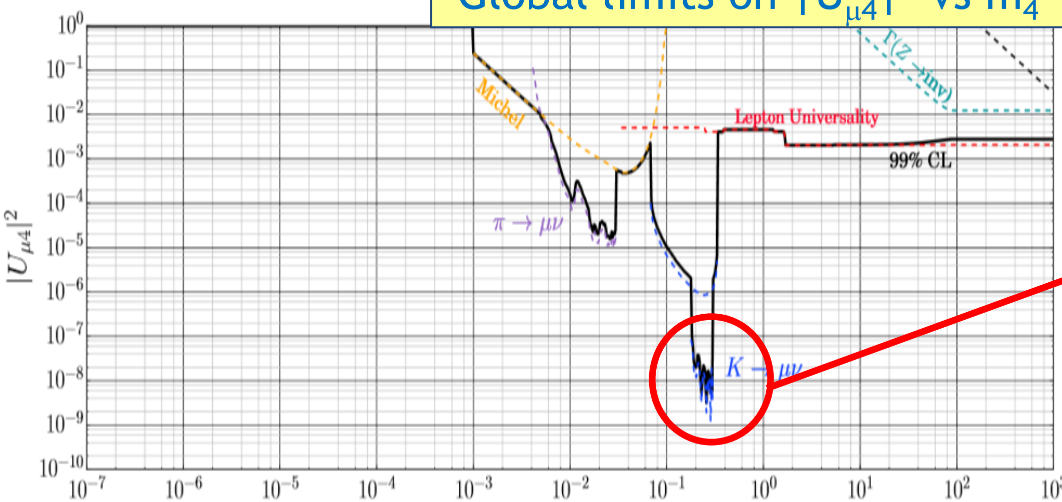
Shaposhnikov, JHEP 0808 (2008) 008
Boyarsky et al., Ann.Rev.Nucl.Part.Sci.59 (2009) 191

HNL: global limits

Global limits on $|U_{e4}|^2$ vs m_4



Global limits on $|U_{\mu 4}|^2$ vs m_4

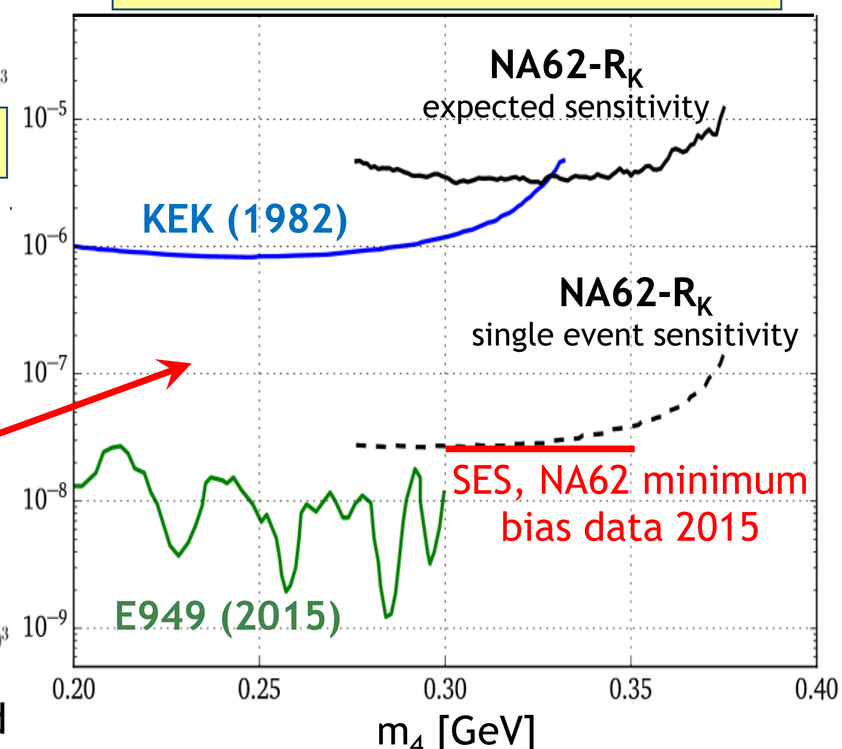


Model-dependent HNL decay searches not considered

[De Gouvêa and Kobach, PRD93 (2016) 033005]

In contrast to decay searches (e.g. $N \to \pi l$ at beam dump expt's), **production search** results are model-independent.

Limits on $|U_{\mu 4}|^2$ from $K^{\pm} \to \mu^{\pm} \nu$ (production searches)



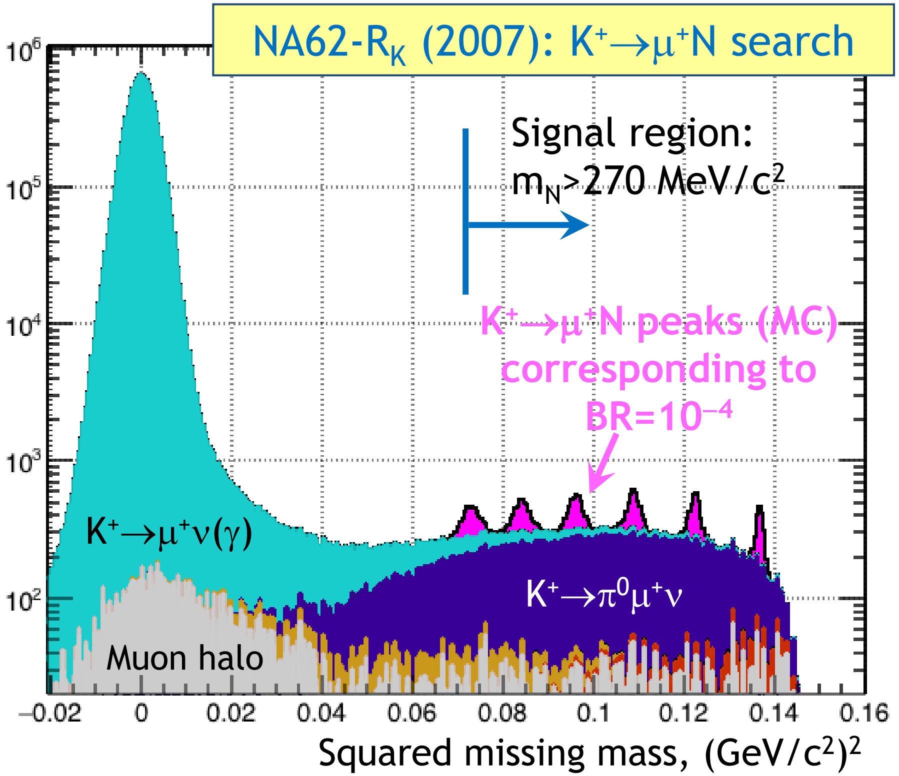
HNL: status of production searches

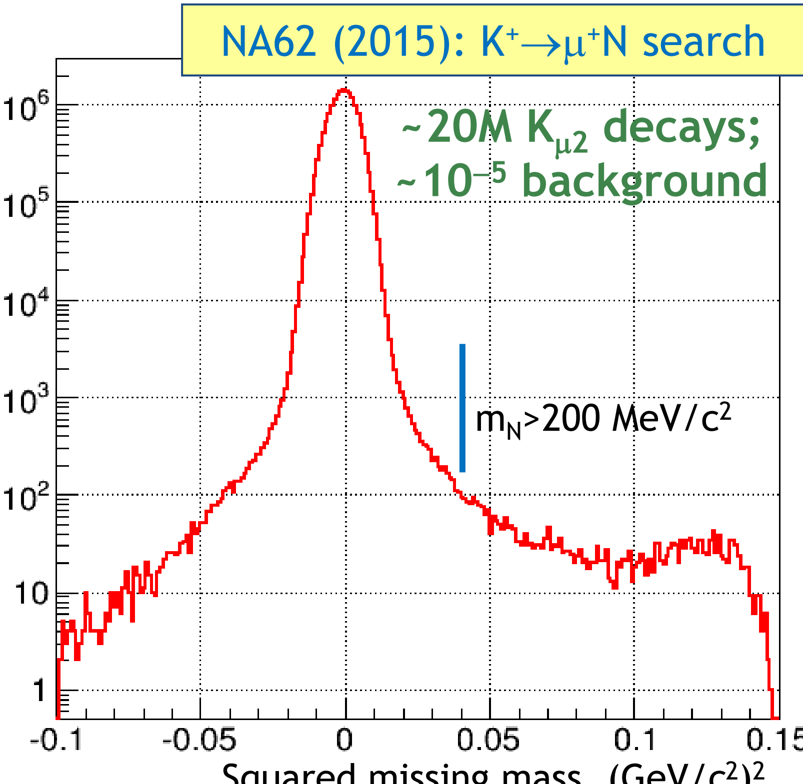
Peak search for $K^+ \to \mu^+ N$ at **NA62-R_K (2007 data)**:

- Three months of data with downscaled trigger: ~10^8 K^+ decays in fiducial volume.
- Background-limited; sensitive above m_N=300 MeV/c^2 unlike BNL E949 (decay at rest).

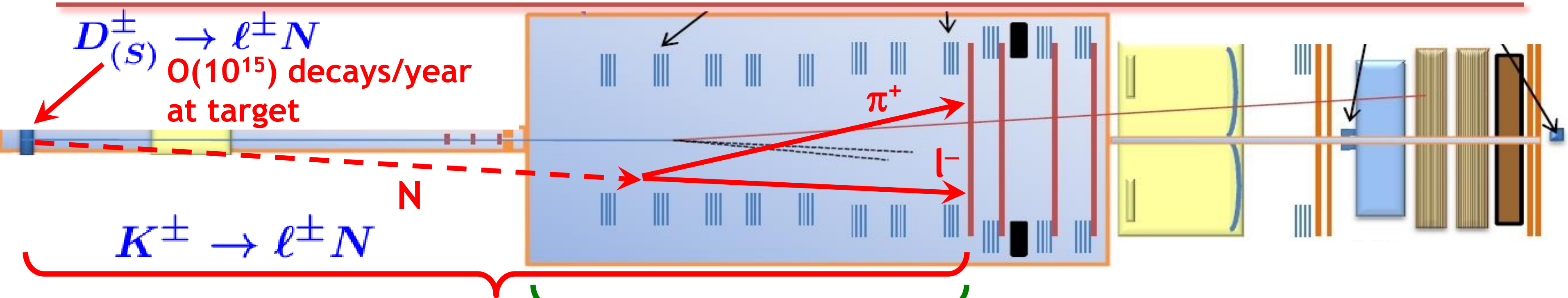
Peak search for $K^+ \to \mu^+ N$ at **NA62 (2015 data)**:

- Integrated 2007 K^+ flux reached with 1 week of minimum bias data in 2015;
- Low background (hermetic veto, K^+ tagger); search region extends into lower m_N;
- Background conditions allow a search for $K^+ \to e^+ N$.



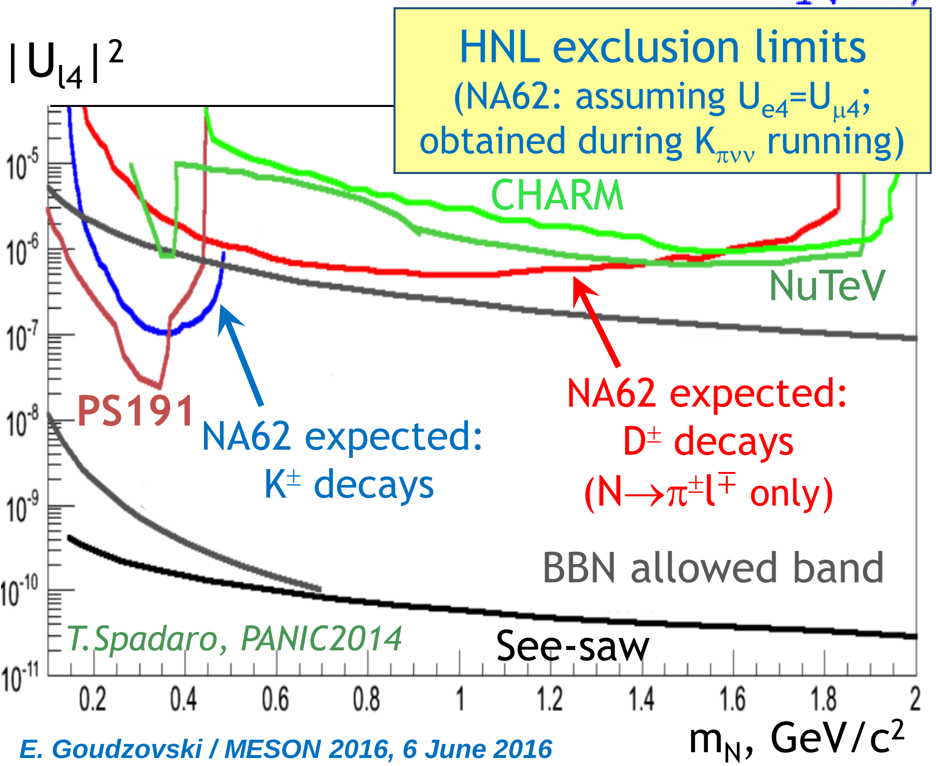


HNL: possible decay searches



Search for decays: $N \to \pi^{\pm}\ell^{\mp}$ (0.14 GeV/c² < m_N < 1.9 GeV/c²)

$N \to \rho^{\pm}\ell^{\mp}$ (0.8 GeV/c² < m_N < 1.9 GeV/c²)



The expected sensitivity is evaluated assuming **zero background**.

Backgrounds to be considered: scattering of halo muons ($\mu^{\pm}N \to K^0X$), charge exchange in KTAG/GTK ($K^+n \to K^0p$), accidentals (K^+ decays, halo muons).

Proof-of-principle: **2016 data**. Searches for dark photon and axion production at target: prospects are being evaluated.

π^0 physics:
π^0 transition form factor;
dark photon search ($\pi^0 \rightarrow \gamma A'$);
status of $\pi^0 \rightarrow e^+e^-$

TFF measurement with π^0_D decay

Differential decay width:

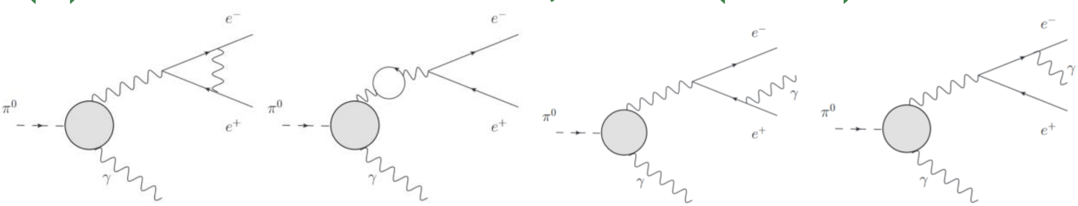
$$\frac{1}{\Gamma(\pi^0_{2\gamma})}\frac{d^2\Gamma(\pi^0_D)}{dx\,dy} = \frac{\alpha}{4\pi}\frac{(1-x)^3}{x}\left(1+y^2+\frac{r^2}{x}\right)|\mathcal{F}(x)|^2$$

$x = (q_1+q_2)^2/m_\pi^2 = (m_{ee}/m_\pi)^2$, $y = 2p(q_1-q_2)/[m_\pi^2(1-x)]$

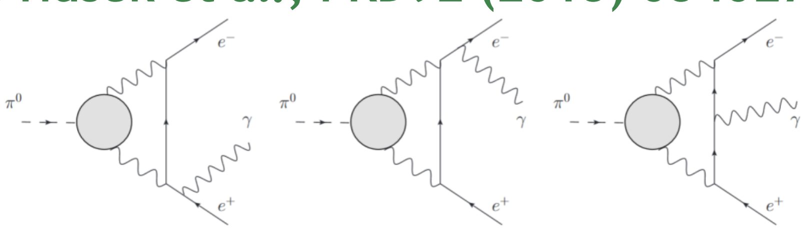
Key issue: radiative corrections (larger effect than TFF)

$$\delta(x,y) = \frac{d^2\Gamma^{NLO}}{dx\,dy} \Big/ \frac{d^2\Gamma^{LO}}{dx\,dy}$$

(1) Mikaelian and Smith, PRD5 (1972) 1763



(2) Husek et al., PRD92 (2015) 054027

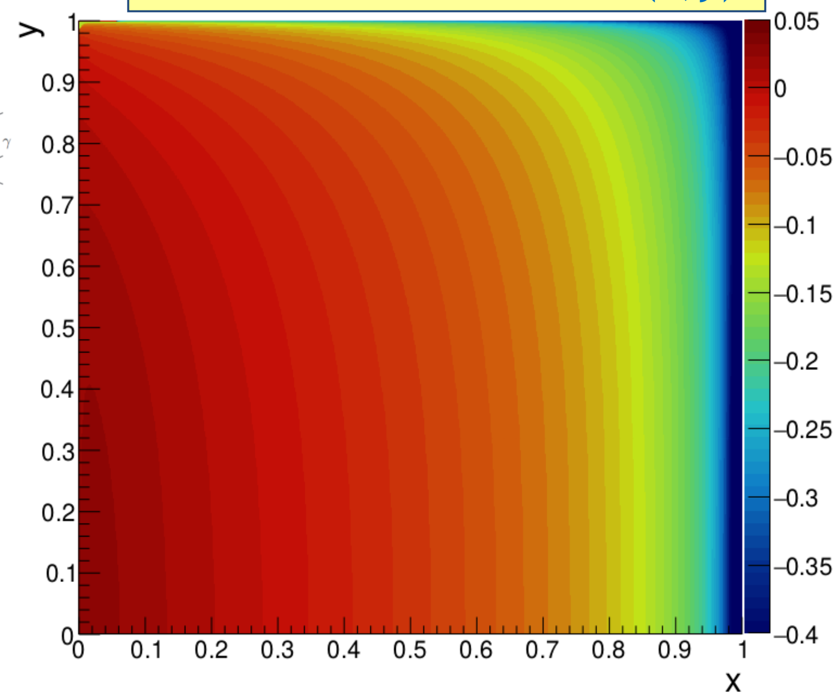


- ✓ Additional diagrams (1γ irreducible).
- ✓ Radiative photon emission simulated.

Measurement of the TFF: $F(x)=1+ax$

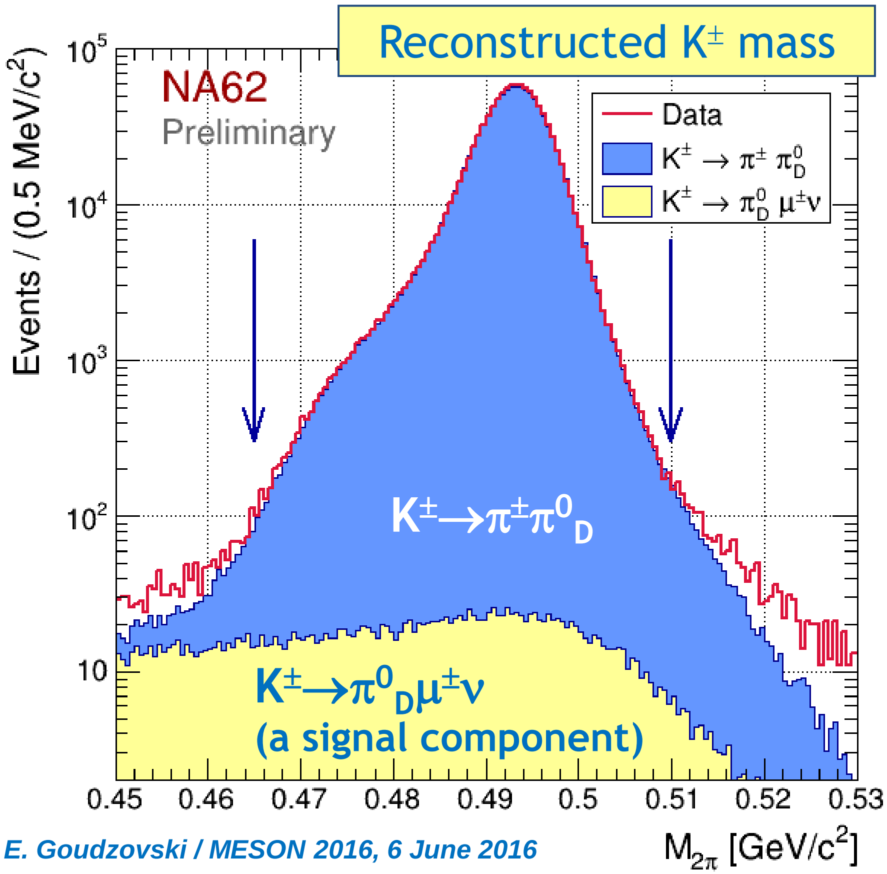
- ❖ VMD expectation: TFF slope $a\approx0.03$ [Hoferichter et al., EPJC74 (2014) 3180]
- ❖ Enters hadronic contribution to $(g-2)_\mu$ [e.g. Nyffeler, arXiv:1602.03398]
- ❖ Influences the $\pi^0\to e^+e^-$ decay rate [Husek et al., EPJC74 (2014) 3010]

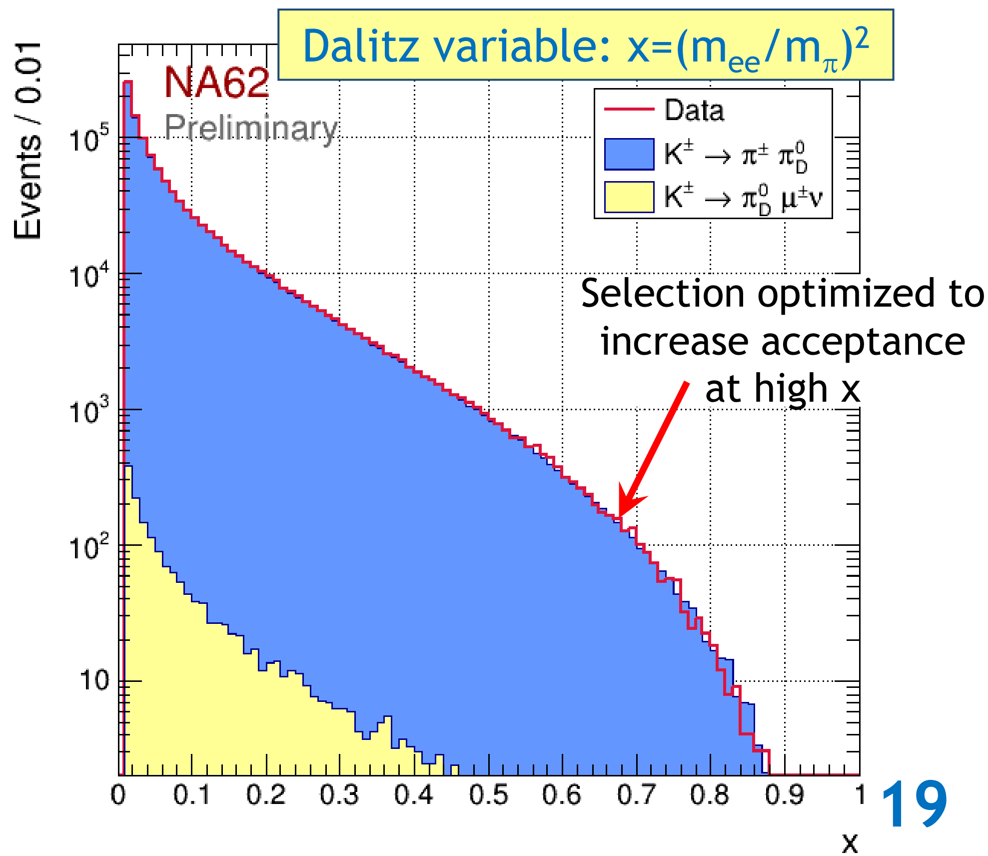
Radiative corrections: δ(x,y)



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

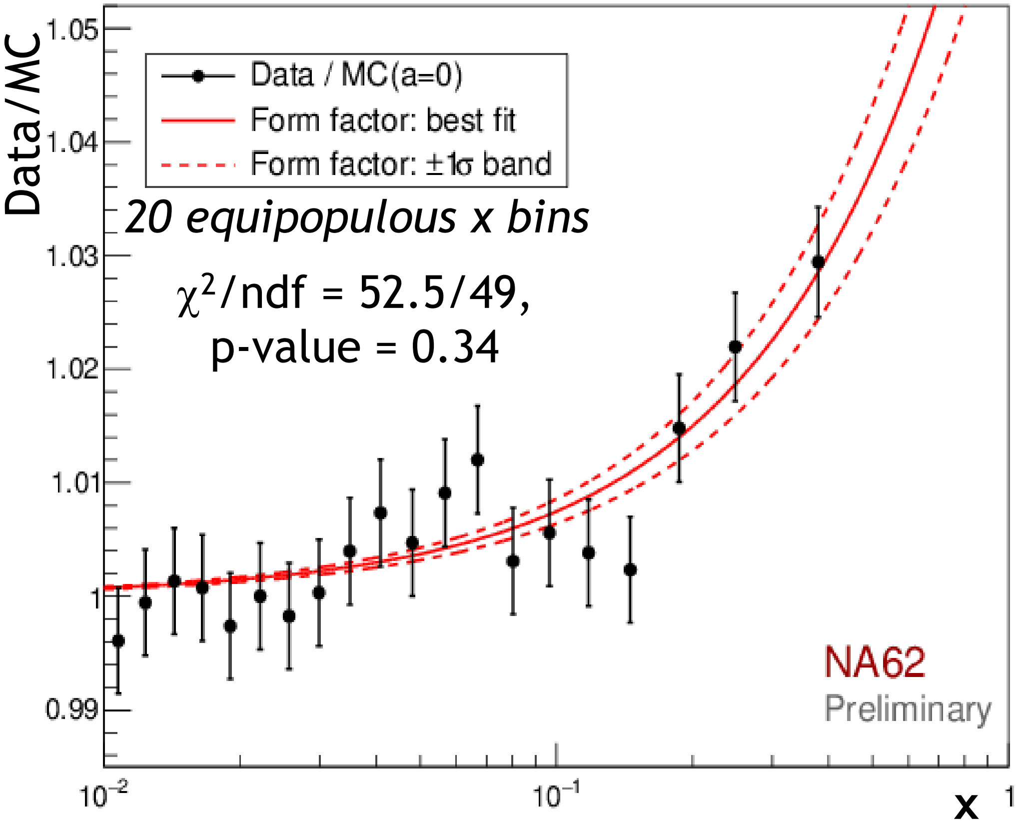
- NA62-R_K data: **~2×10^{10} $K^\pm$** decays in the fiducial decay region.
- Reconstructed π^0_D decay candidates, **$x=(m_{ee}/m_\pi)^2>0.01$: $N(K_{2\pi D})=1.05\times10^6$**.
- Despite **~10** times smaller sample wrt NA48/2, good for **spectrum study**:
  - ✓ minimum bias trigger: low systematics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



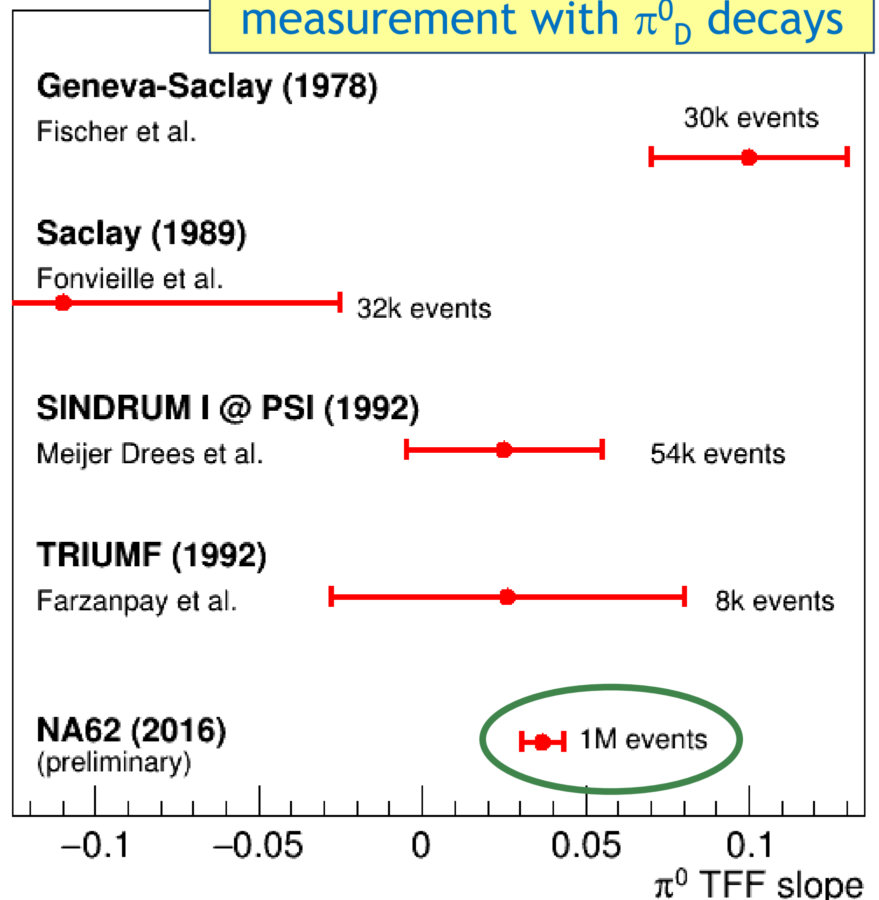


TFF slope measurement: result

Fit illustration: Data/MC(a=0)



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



NA62-R_K preliminary result (2016):

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

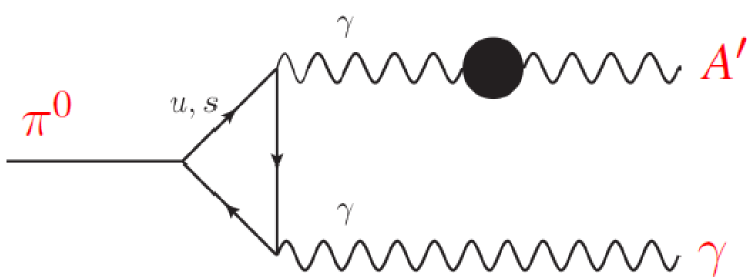
[final result & paper in preparation]

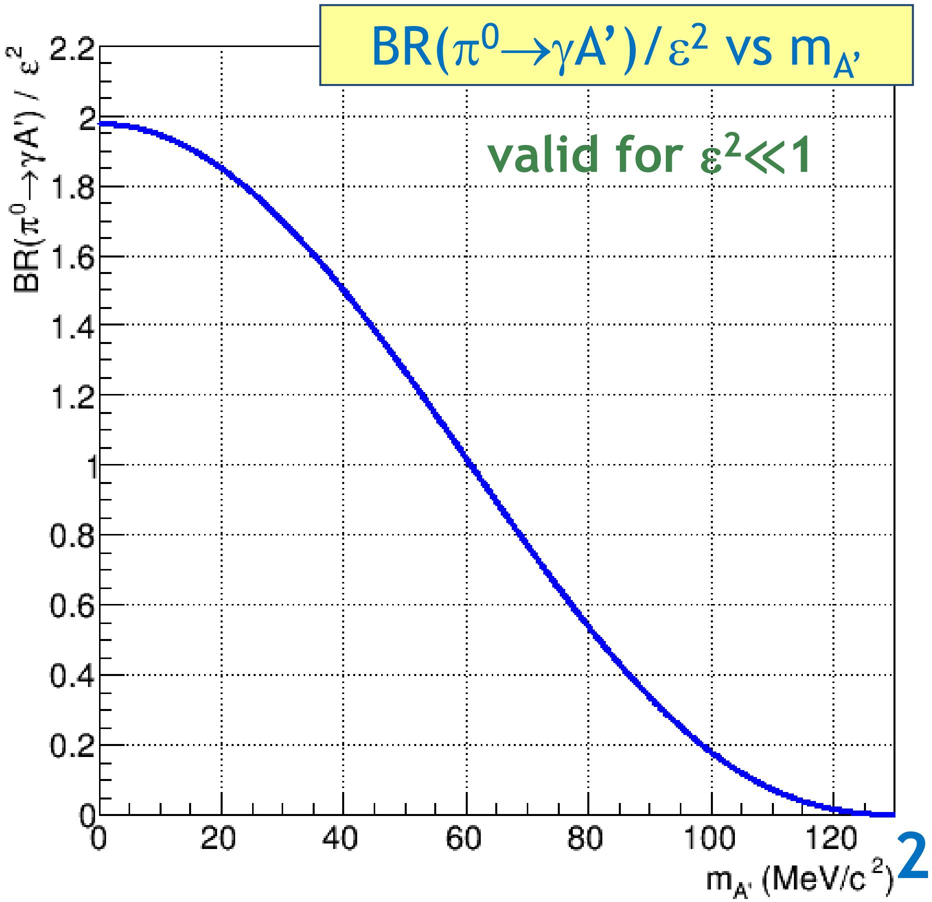
First observation (**5.8σ**) of *non-zero TFF slope* in the time-like momentum transfer region.

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

Batell, Pospelov and Ritz, PRD80 (2009) 095024

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

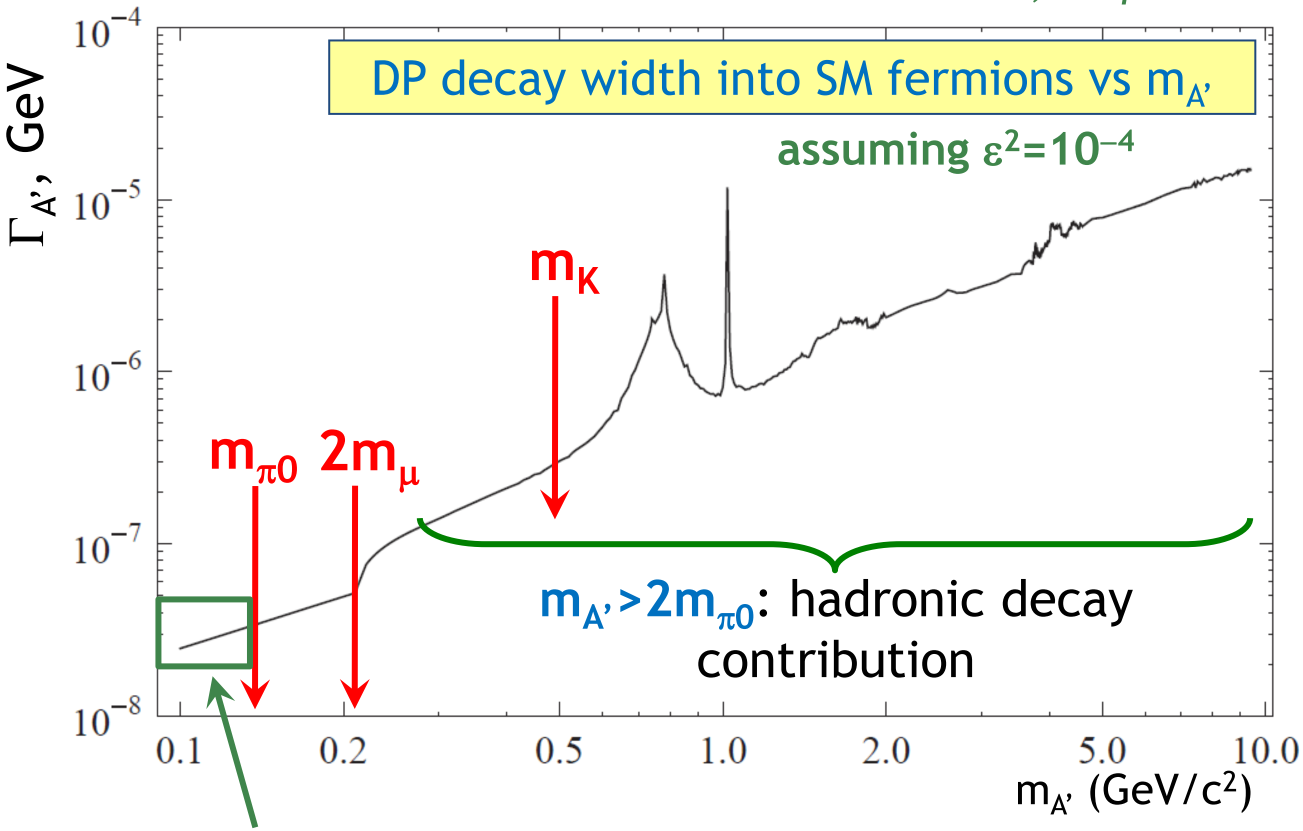


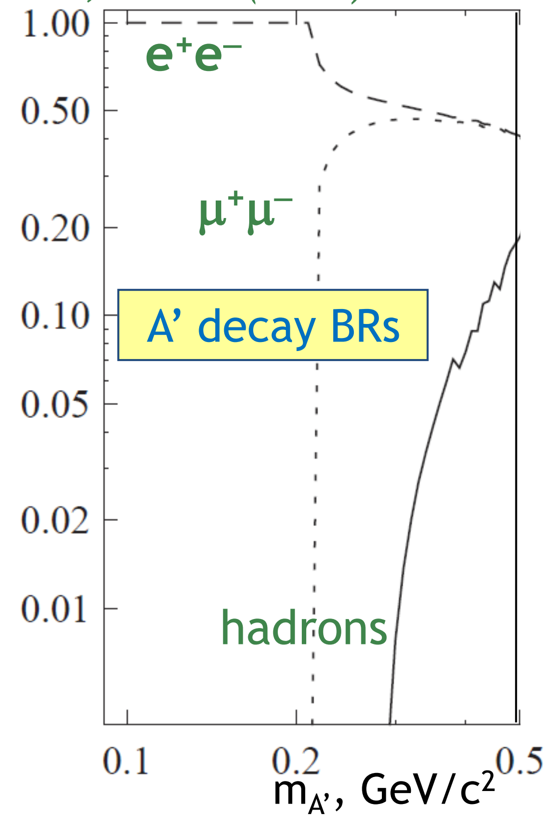


- Probing the Dark Sector.
- Two unknown parameters: mass ($m_{A'}$) and mixing (ε^2).
- Sensitivity to DP for $m_{A'} < m_{\pi 0}$.
- Loss of sensitivity to ε^2 as $m_{A'}$ approaches $m_{\pi 0}$, due to kinematical suppression of the $\pi^0 \to \gamma A'$ decay.

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

<u>Two exclusive selections</u>

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

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

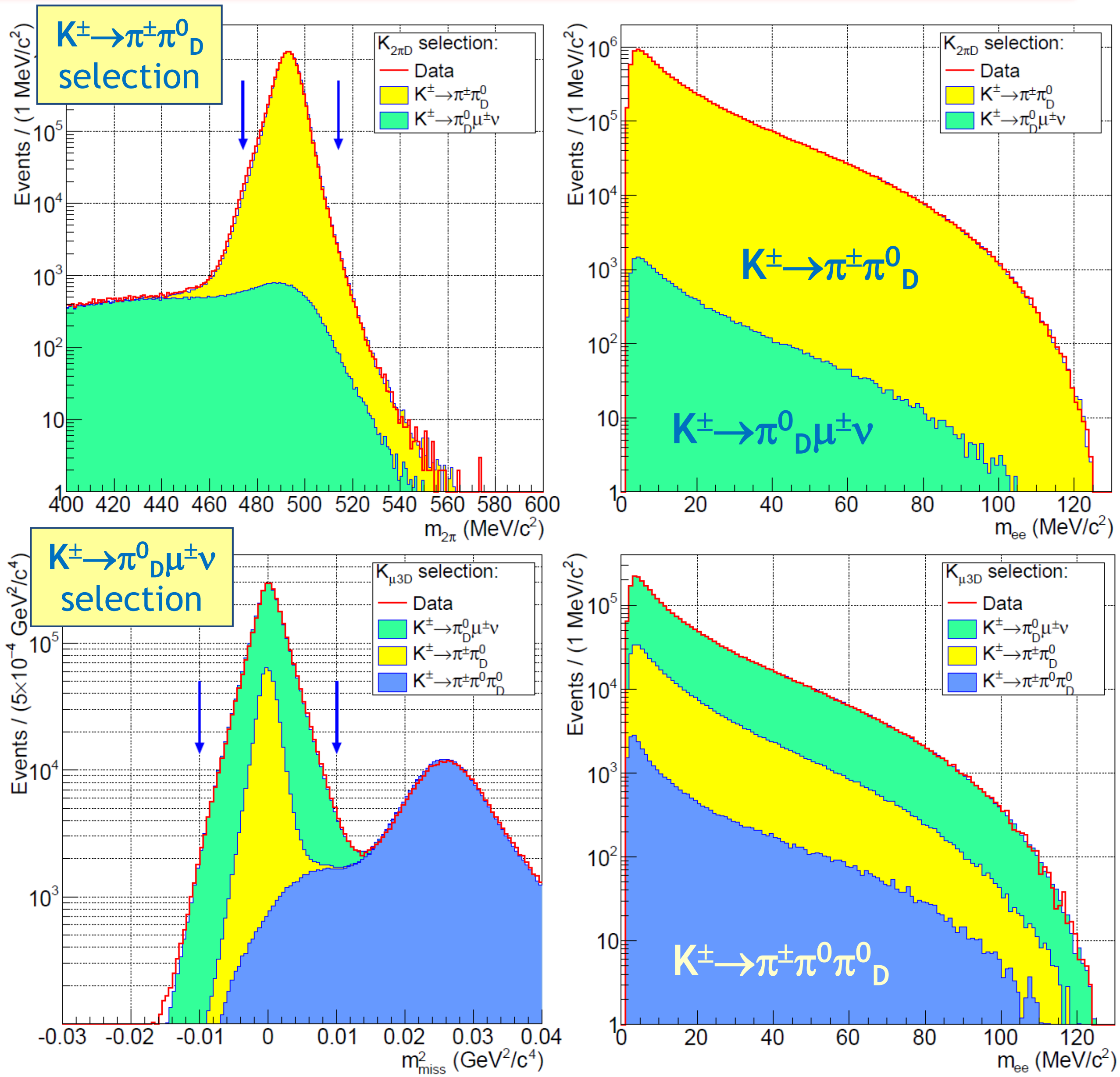
$K^\pm \to \pi^0_D \mu^\pm \nu$ selection:

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

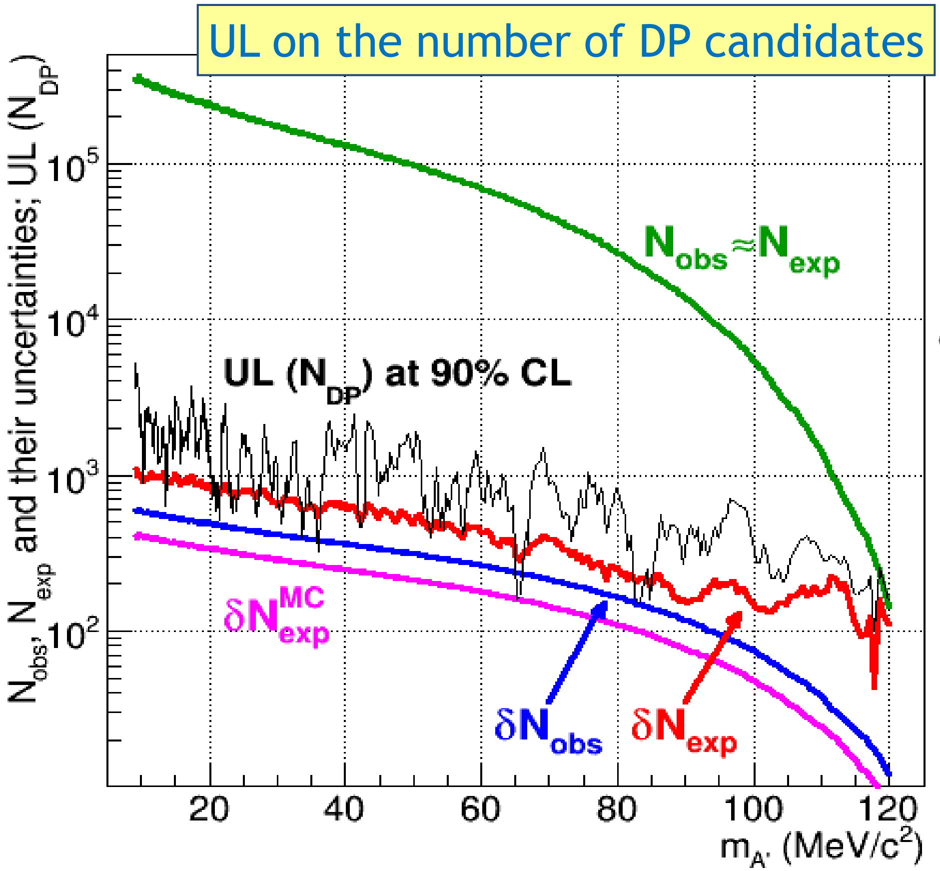
Reconstructed π^0_D decay candidates:

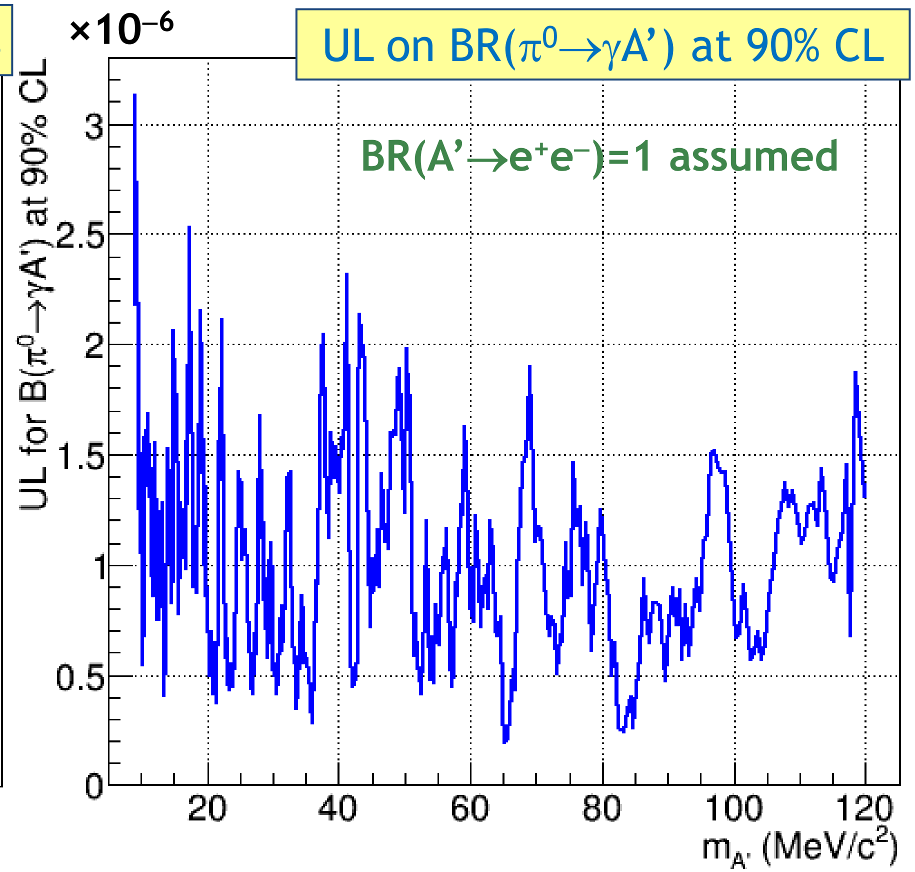
- $N(K_{2\pi D}) = 1.38 \times 10^7$,
- $N(K_{\mu 3D}) = 0.31 \times 10^7$,
- total $= 1.69 \times 10^7$.

$K^\pm$ 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 MeV/$c^2 \leq m_{A'} <$ 120 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.

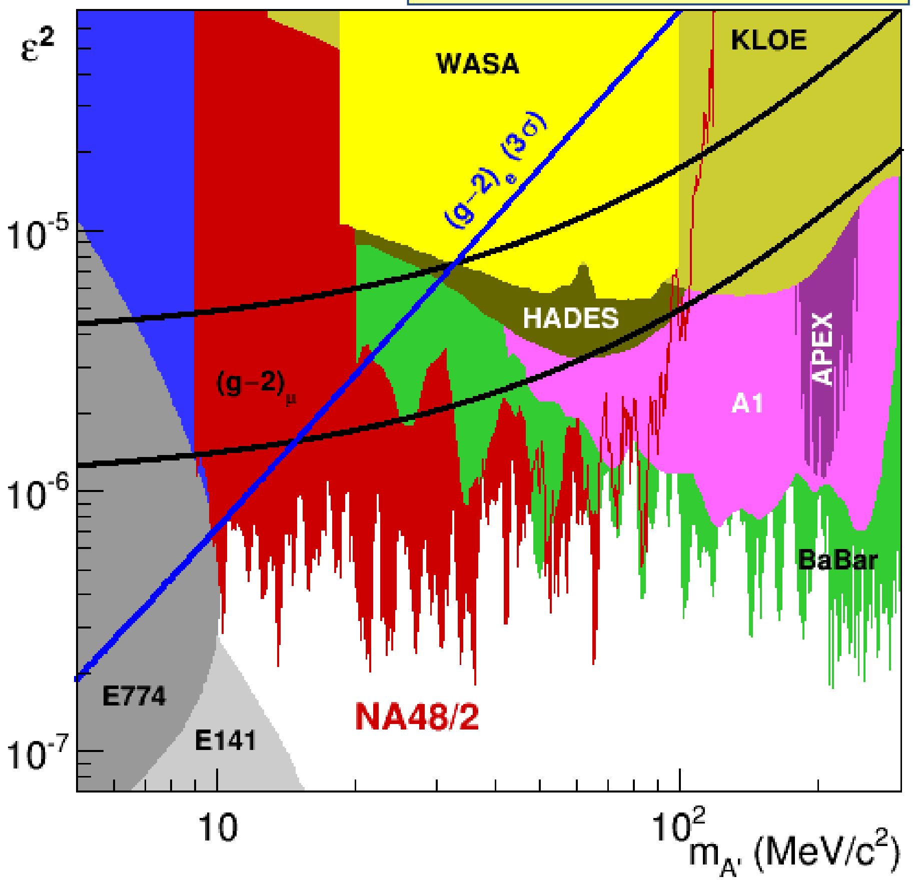
✓ Local signal significance never exceeds 3σ: **no DP signal** observed.

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

NA48/2: dark photon exclusion

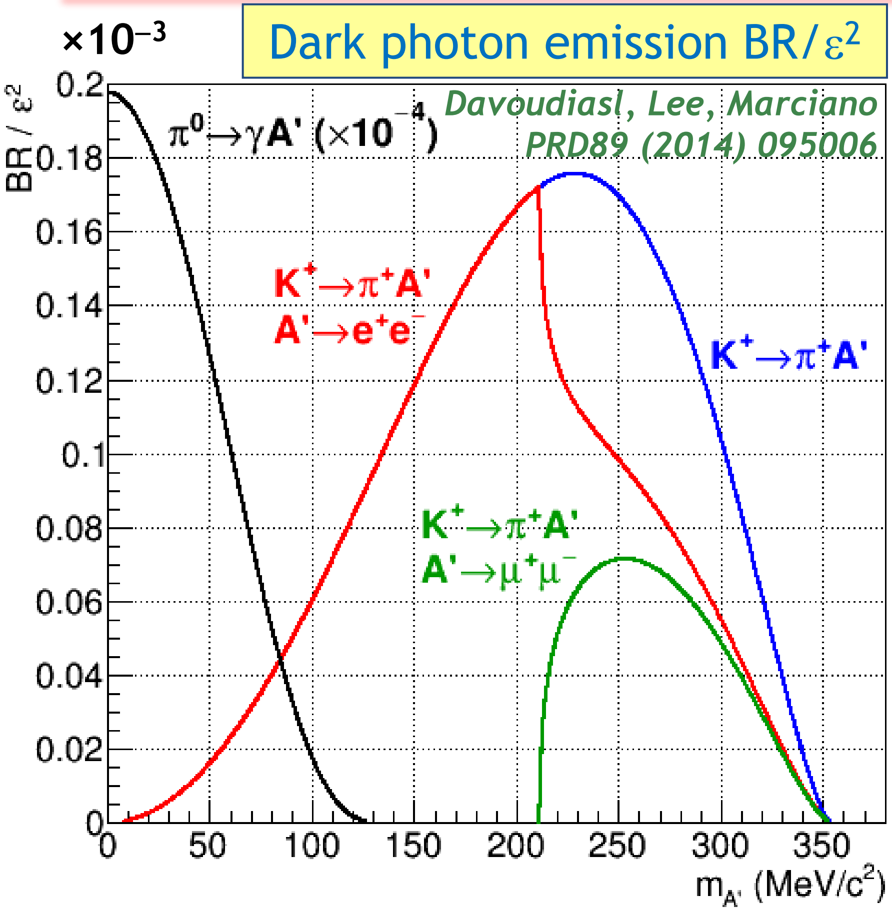
Final result: PLB746 (2015) 178

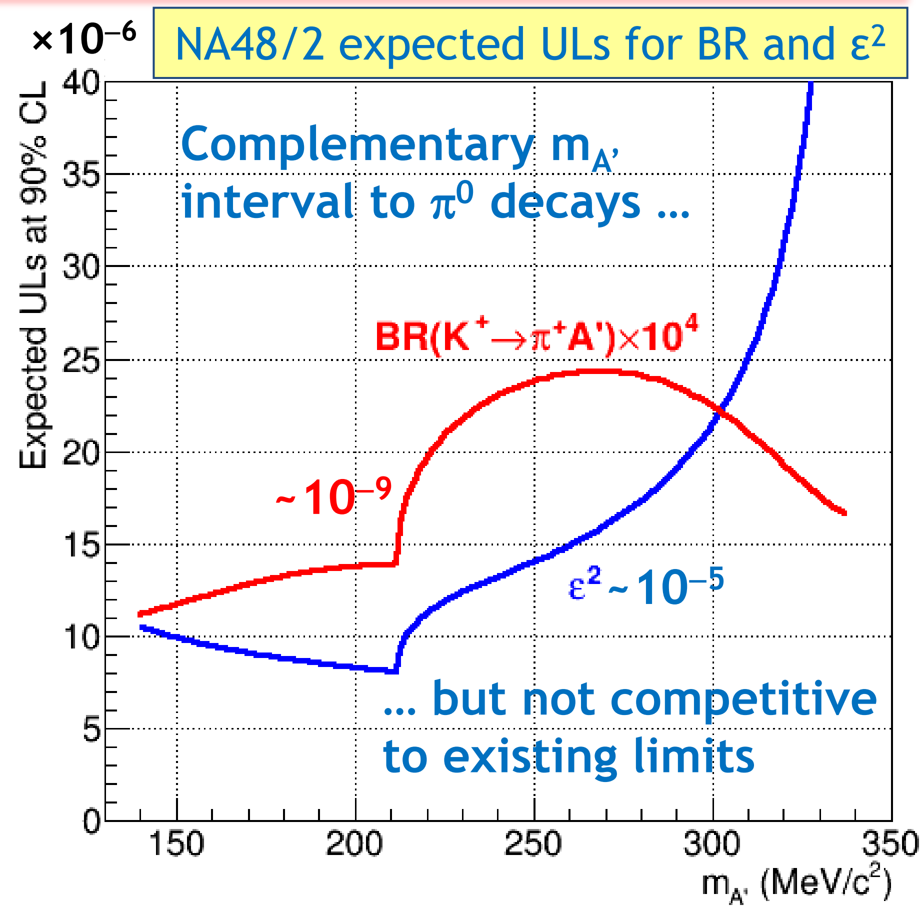
DP exclusion summary



- Improvement on the existing limits in the $m_{A'}$ range **9–70 MeV/c^2**.
- 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 **~$(1/N_K)^{1/2}$**, 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 **$(g-2)_\mu$**.
- Sensitivity to smaller ε^2 with displaced vertex analysis: to be investigated.

Prospects for $K^\pm \to \pi^\pm A'$, $A' \to l^+l^-$



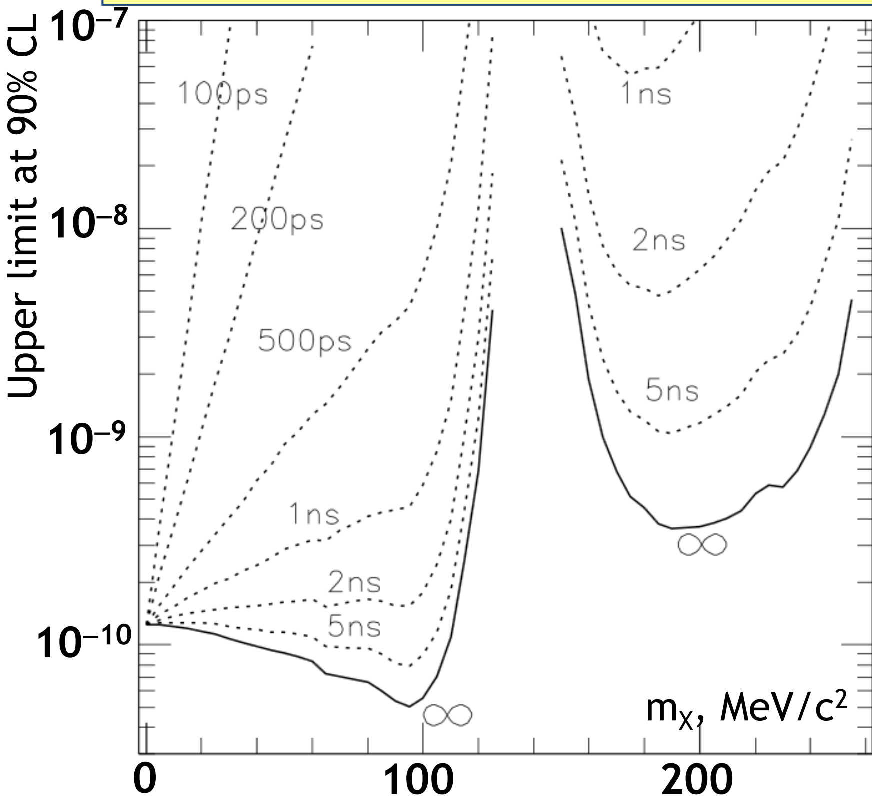


Comparison of ($K^\pm \to \pi^\pm A'$, $A' \to e^+e^-$, $m_{A'} > m_{\pi 0}$) vs ($\pi^0 \to \gamma A'$, $A' \to e^+e^-$, $m_{A'} < m_{\pi 0}$):

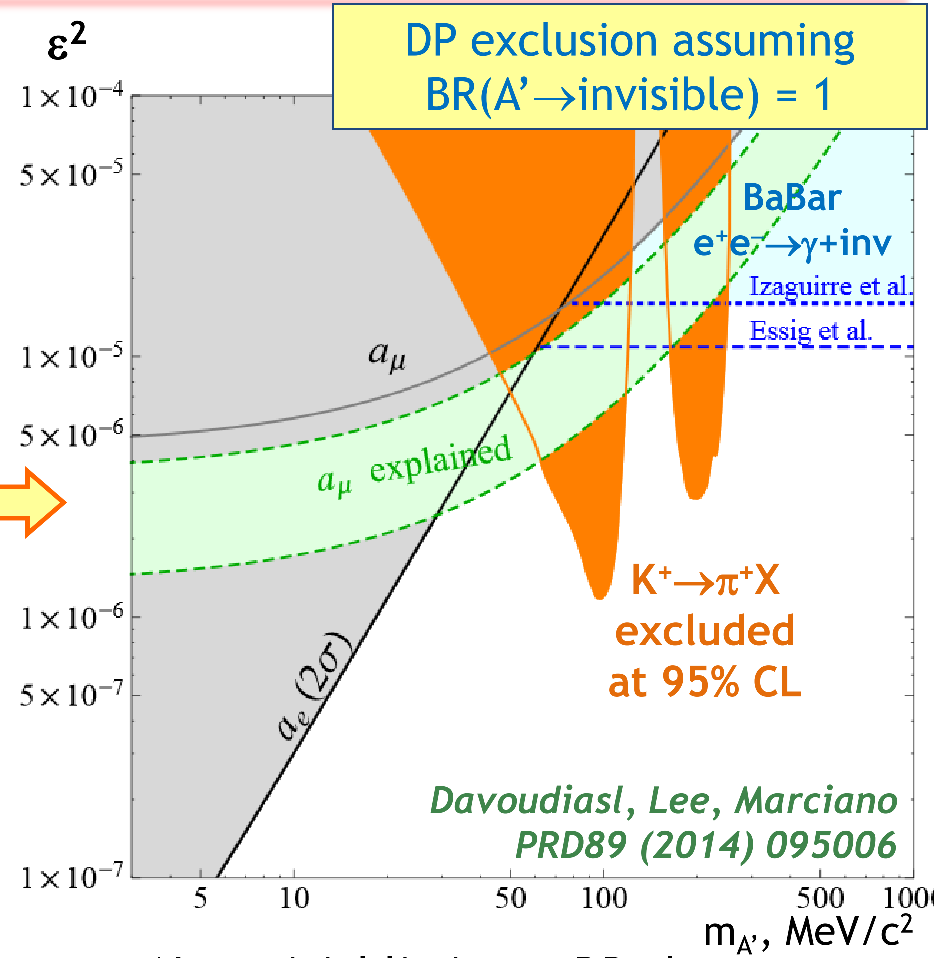
- ❖ Lower irreducible background: $BR(K^\pm \to \pi^\pm e^+e^-) \sim 10^{-7}$ vs $BR(\pi^0_D) \sim 10^{-2}$.
- ❖ Higher acceptance (×4), favourable K/π^0 flux ratio (×4).
- ❖ Therefore the expected BR limits: $BR(K^\pm \to \pi^\pm A') \sim 10^{-9}$ vs $BR(\pi^0 \to \gamma A') \sim 10^{-6}$.
- ❖ However $BR(K^\pm \to \pi^\pm A')/BR(\pi^0 \to \gamma A') \sim 10^{-4}$, expected ε^2 limits are $\varepsilon^2 \sim 10^{-5}$.

$K^{\pm} \to \pi^{\pm} A'$, $A' \to$ 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

$BR(\pi^{0} \to \text{invisible}) < 2.7 \times 10^{-7}$ at 90% CL

PRD72 (2005) 091102

Non-trivial limits on DP phase space

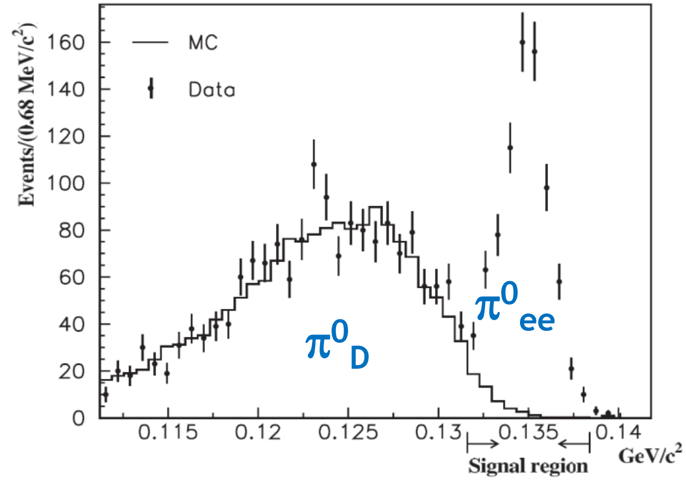
Including the $(g-2)_{\mu}$ favoured band,

assuming invisible DP decays.

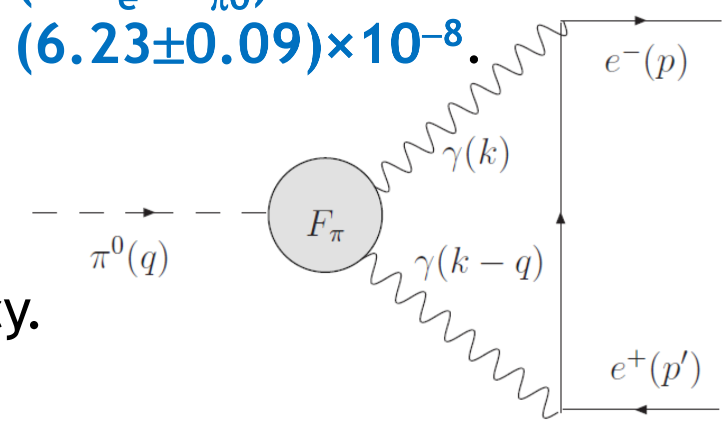
NA62: expect an order of magnitude improvement

$\pi^0 \to e^+e^-$: state of the art

- World data is dominated by the **KTeV** measurement from $K_L \to 3\pi^0$:
  794 candidates with 7% background.
  Measurement:
  $BR(\pi^0_{ee}, x>0.95) = (6.44\pm0.25\pm0.22)\times10^{-8}$.
  Extrapolation:
  $BR(\pi^0_{ee}) = (7.48\pm0.29\pm0.25)\times10^{-8}$.
  [PRD 75 (2007) 012004]

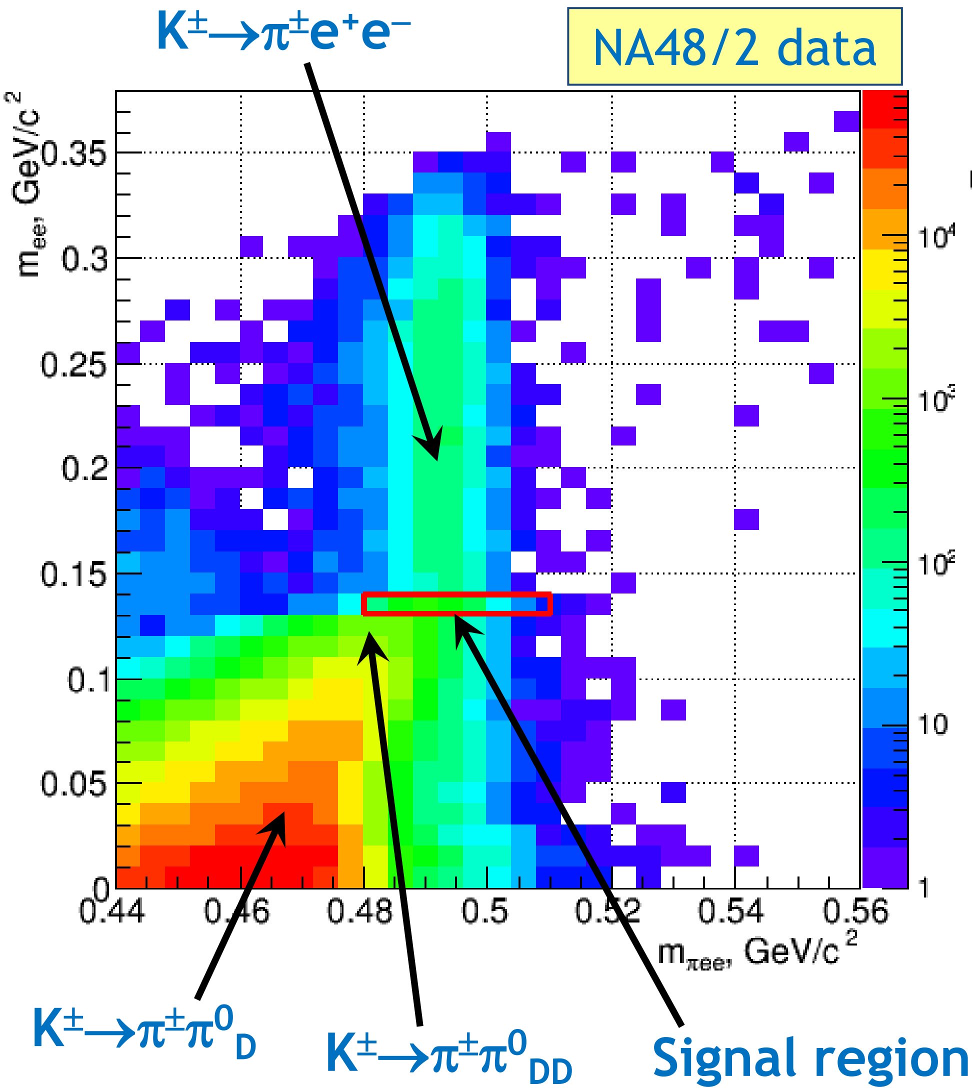


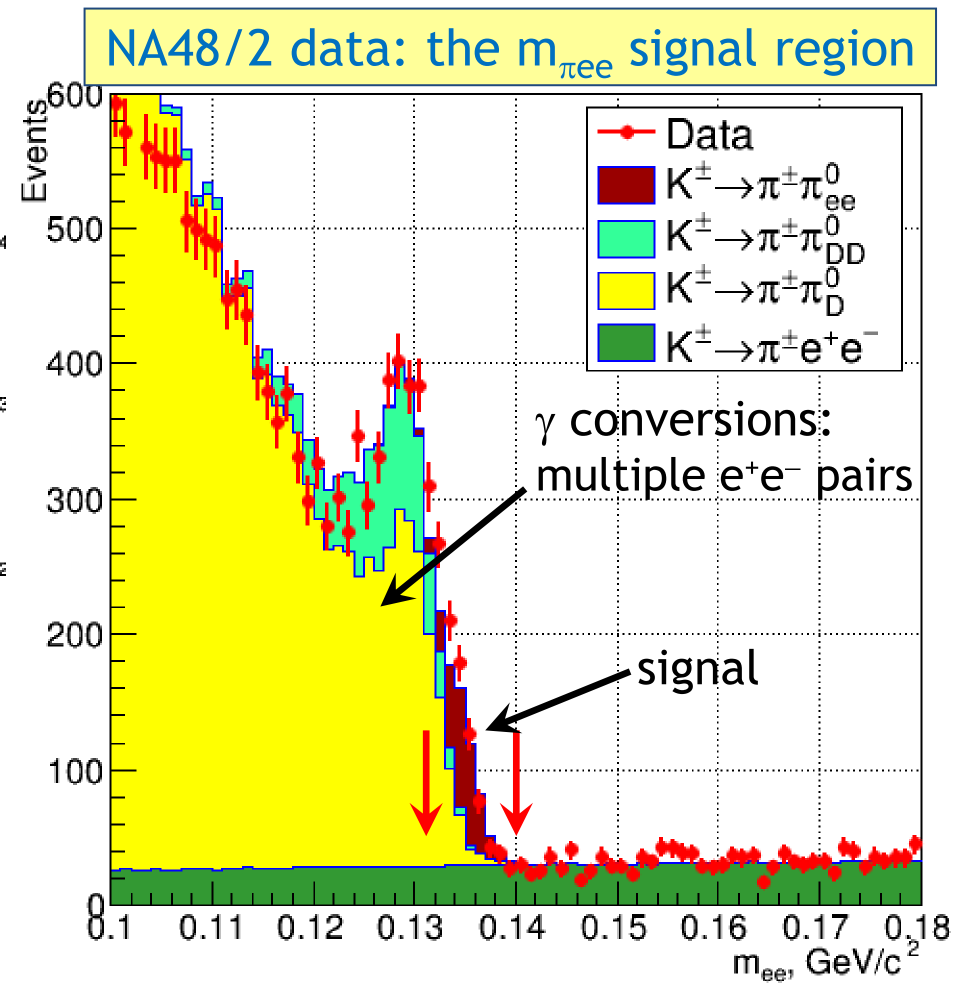
- SM prediction: *loop-induced* and *helicity-suppressed* decay.
  Naïve estimate: $BR(\pi^0_{ee}) \sim (\alpha m_e/m_{\pi 0})^2 \sim 10^{-9}$.
  Detailed calculations: $BR(\pi^0_{ee}) = (6.23\pm0.09)\times10^{-8}$.
  *[Dorokhov et al., PRD75 (2007) 114007,
  Husek et al., EPJ C74 (2014) 3010]*



- Experiment vs theory: **~3σ** discrepancy.

NA48/2 data: $K^\pm \to \pi^\pm \pi^0$, $\pi^0 \to e^+e^-$





NA48/2: about **300** events collected,
but **signal/background < 1**.
Can be better at NA62.

Summary

- New NA48/2 results on $K\to\pi\mu\mu$ decays (with ~2×10^{11} $K^\pm$ decays):
  - ✓ Strongest limit on LFV decay, $BR(K^\pm\to\pi^\mp\mu^\pm\mu^\pm)<8.6\times10^{-11}$ [90% CL].
  - ✓ Searches for two-body resonances: the limits on $BR_K\times BR_{Res}$ are ~10^{-10} (~10^{-9}) for LFV (LFC) processes for $\tau_N<100$ ps.
  - ✓ Leads to limitations on HNL/inflaton parameters.

- $K^\pm\to l^\pm\nu$ decays: optimal for HNL production search in the ~200 to ~400 MeV/c^2 mass range. NA62 analyses probing the νMSM phase space are in progress.

- New NA62-R_K preliminary result on π^0 TFF: *[paper in preparation]*
  - ✓ TFF slope: $a = (3.70\pm0.53_{stat}\pm0.36_{syst})\times10^{-2}$.
  - ✓ First observation of non-zero TFF slope in time-like region.
  - ✓ Triggered progress in radiative corrections. *Husek et al., PRD92(2015)054027*

- New NA48/2 result: dark photon search in π^0 decays *PLB746 (2015) 178*
  - ✓ Improved limits (down to $\varepsilon^2=2\times10^{-7}$) in the 9–70 MeV/$c^2$ mass range.
  - ✓ The whole region favoured by $(g-2)_\mu$ is excluded now, assuming DP decays into SM ferminons only.