Kaon experiments at CERN: recent results & prospects

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<u>Outline:</u>

1) $K^{\pm}$ decay experiments at CERN: NA48/2, NA62-R_K, NA62
2) NA62 status and data quality
3) Recent results from Birmingham-led analyses
4) Conclusions

European Research Council
Established by the European Commission

Particle physics seminar
University of Birmingham • 2 November 2016

EXCELLENCE IN SCIENCE

Energy & precision frontiers

Discovery of a **Higgs boson**: success of the **Standard Model** (SM)
No roadmap and "guaranteed discoveries" any longer: a data-driven era

Limitations of the SM:
SM matter ≈ **5%** of total mass-energy

⇒ **"New physics"** extensions: undiscovered particles

Searches for New physics: two complementary approaches

Energy frontier (LHC)

Direct production of new particles in high-energy collisions.

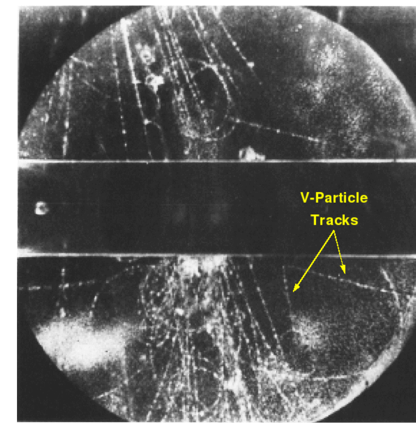
Precision (intensity) frontier

Low-energy observables:
tests of precise SM predictions
for rare or forbidden processes.

The precision frontier: kaon physics

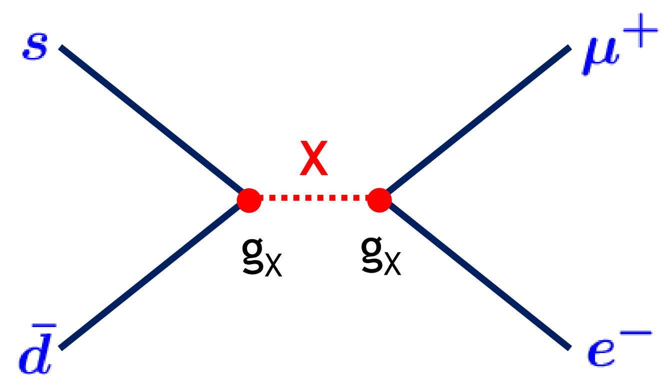
The kaon:

- One of the lightest unstable particles (discovered in 1947); the "**minimal flavour laboratory**".
- High production rates: high statistical precision. An example of rare K decay measurement: **BR($K_L \to e^+e^-$) = $(9\pm5)\times10^{-12}$**. *(BNL E871)*



- Essential in establishing the **foundations of particle physics** (quark mixing, CPV).
- Current focus: searches for **new physics** with rare and forbidden decays.

Example: $K_L \to \mu^+ e^-$



Tree-level process: $\frac{\Gamma_X}{\Gamma_{SM}} \sim \left(\frac{g_X}{g_W} \cdot \frac{M_W}{M_X}\right)^4$

For $g_X \approx g_W$ and $\mathcal{B} \sim 10^{-12}$,

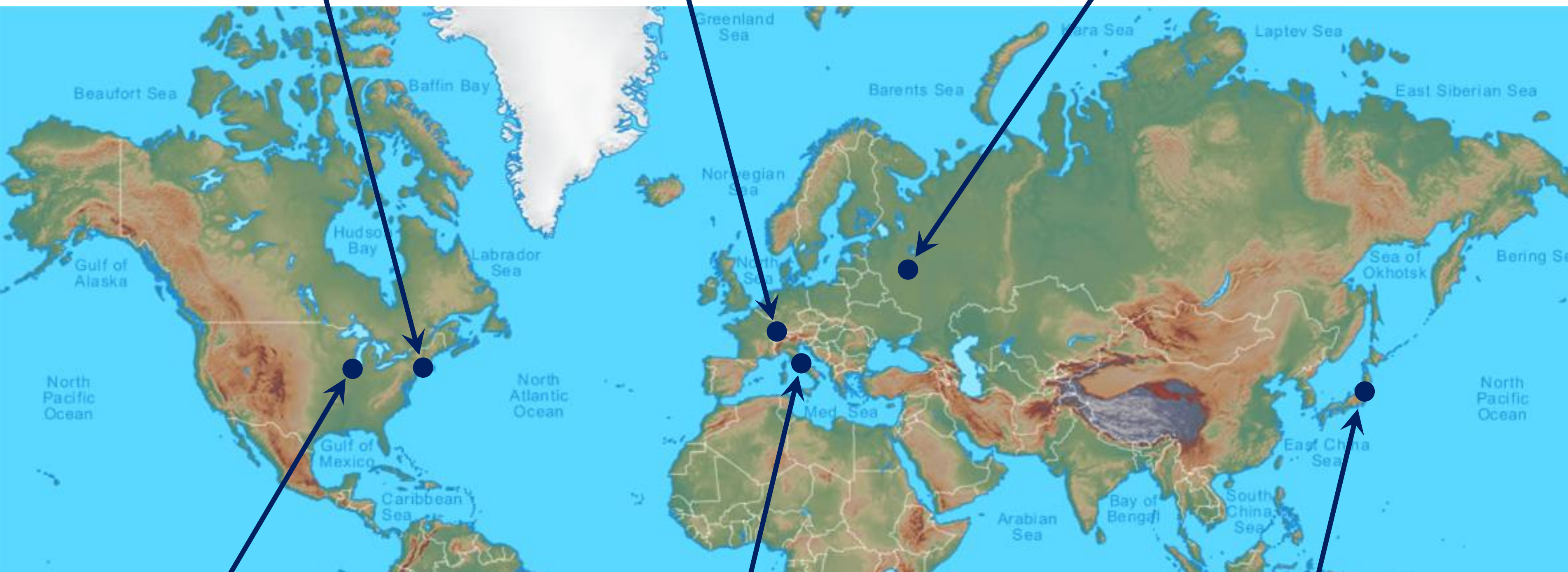
$M_X \sim 100\ \mathrm{TeV}$

Kaon physics facilities

BNL
E865, E777, E787, E949

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

IHEP Protvino
ISTRA+, OKA, KLOD



FNAL
KTeV

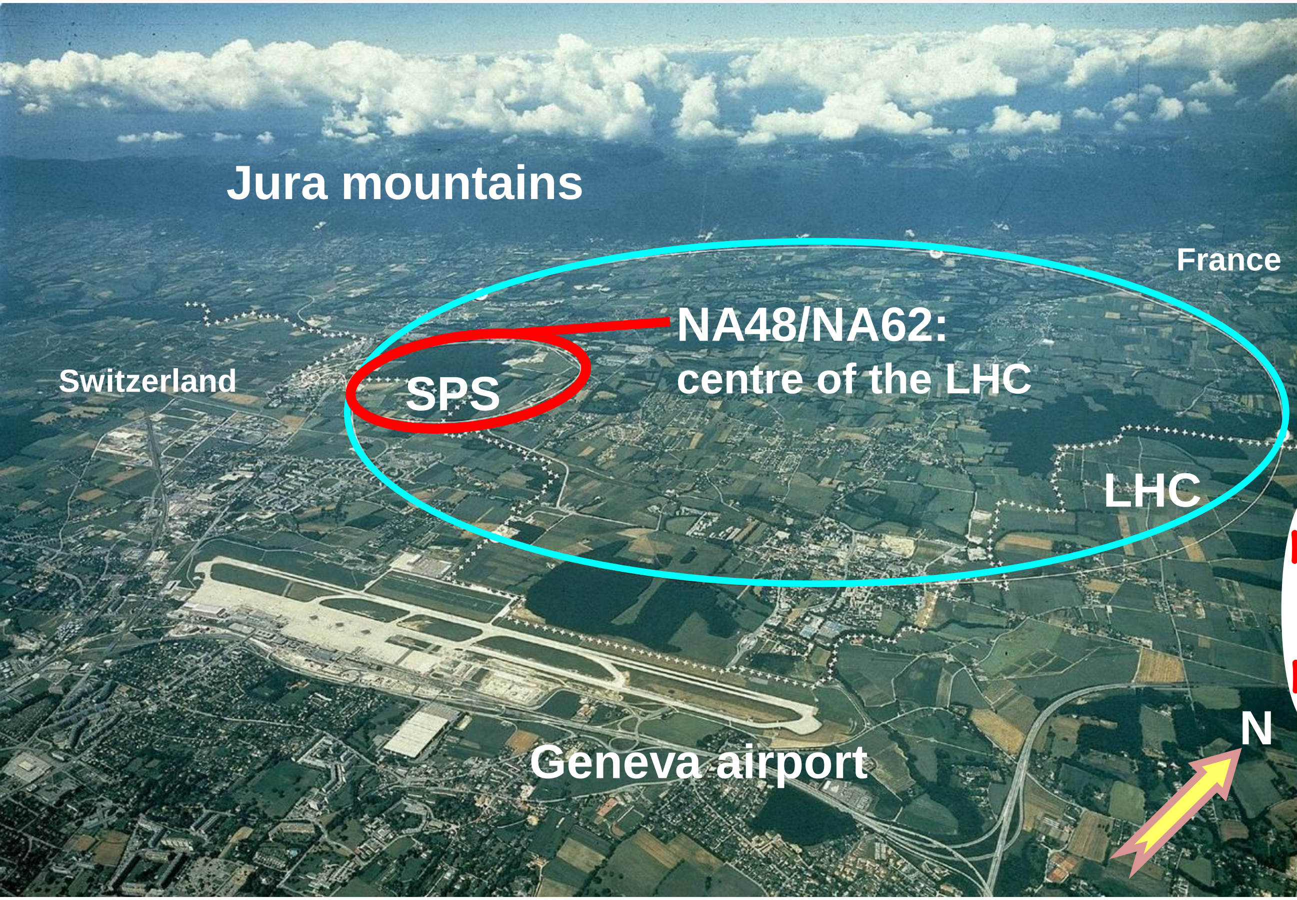
LNF
KLOE, **KLOE-2**

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

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

Kaon experiments at CERN

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 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

$K^{\pm}$ decay experiments at CERN

Experiment	NA48/2 ($K^{\pm}$)	NA62 (R_K phase) ($K^{\pm}$)	NA62 (K^{+})
Data taking period	2003–2004	2007–2008	2015–2018
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 + $e^{\pm}$	$K_{\pi\nu\nu}$ + …

The NA48 detector (NA48/2, 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

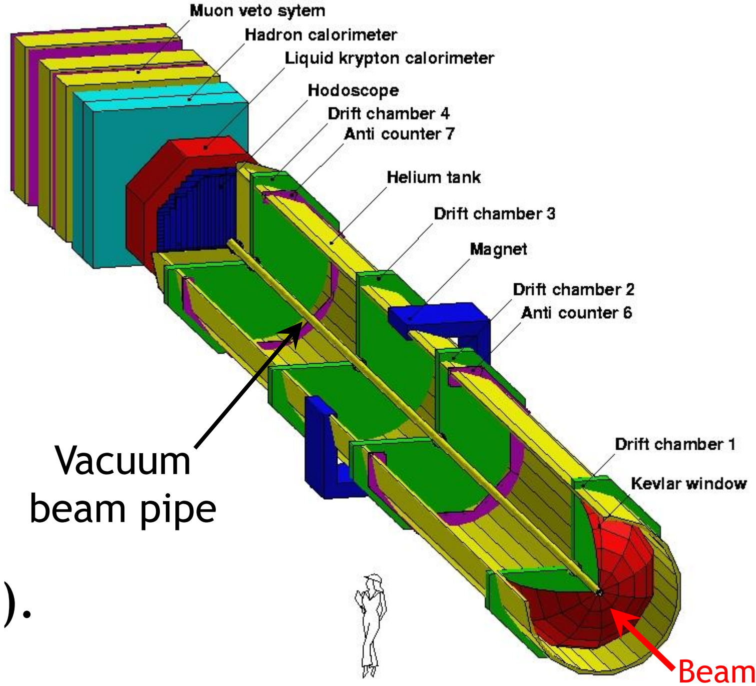
2003–2007: charged kaon beams, the NA48 detector

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:

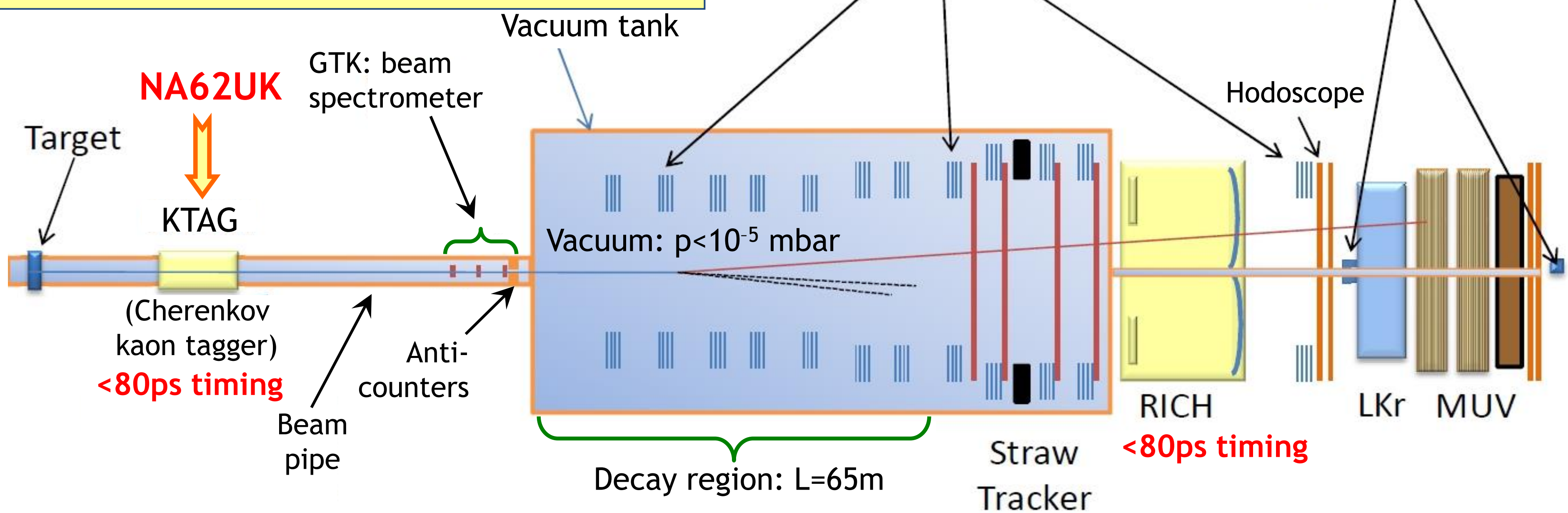
- Magnetic spectrometer (4 DCHs)
  4 views/DCH: redundancy $\Rightarrow$ efficiency;
  $\delta p/p = 0.48\% \oplus 0.009\% p$ [GeV/c] (in 2007)
- Scintillator hodoscope (HOD)
  Fast trigger, time measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$ [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 (10^{12}/spill);
K^+: 75GeV/c (±1%), divergence < 100μrad.
800MHz beam rate → 45MHz K^+ rate →
5MHz K^+ decays in fiducial volume

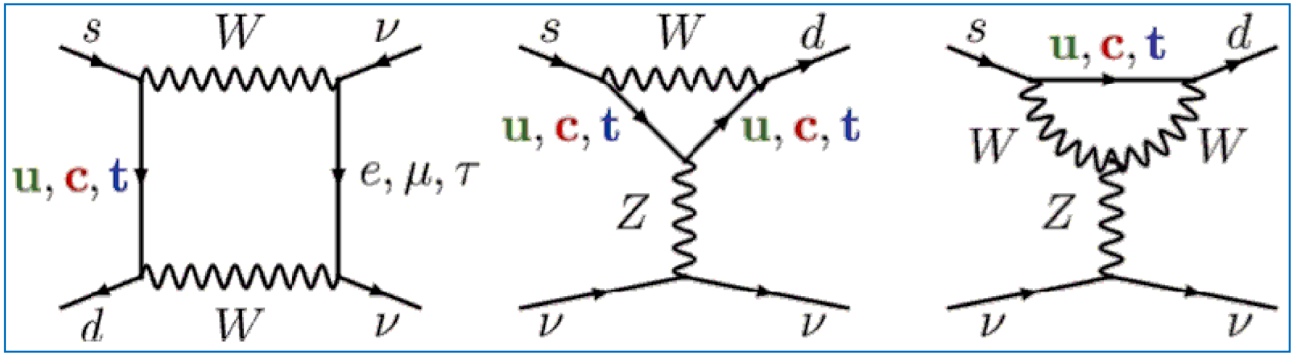
Total length: ~270m



- Expected single event sensitivities: $\sim10^{-12}$ for $K^\pm$ decays, $\sim10^{-11}$ 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: $\sim10^8$ suppression of $\pi^0\to\gamma\gamma$.
- Particle ID (RICH+LKr+MUV): $\sim10^7$ muon suppression.

Rare kaon decays: $K \to \pi \nu \bar{\nu}$

SM: box and penguin diagrams



Ultra-rare decays with the highest CKM suppression:

$A \sim (m_t/m_W)^2 |V^*_{ts}V_{td}| \sim \lambda^5$

- Hadronic matrix element is related to a measured quantity ($K^+ \to \pi^0 e^+ \nu$).
- SM precision surpasses any other FCNC process involving quarks.
- Measurement of $|V_{td}|$ complementary to those from B–$\bar{B}$ mixing or $B^0 \to \rho\gamma$.

SM branching ratios

Buras et al., JHEP 1511 (2015) 033

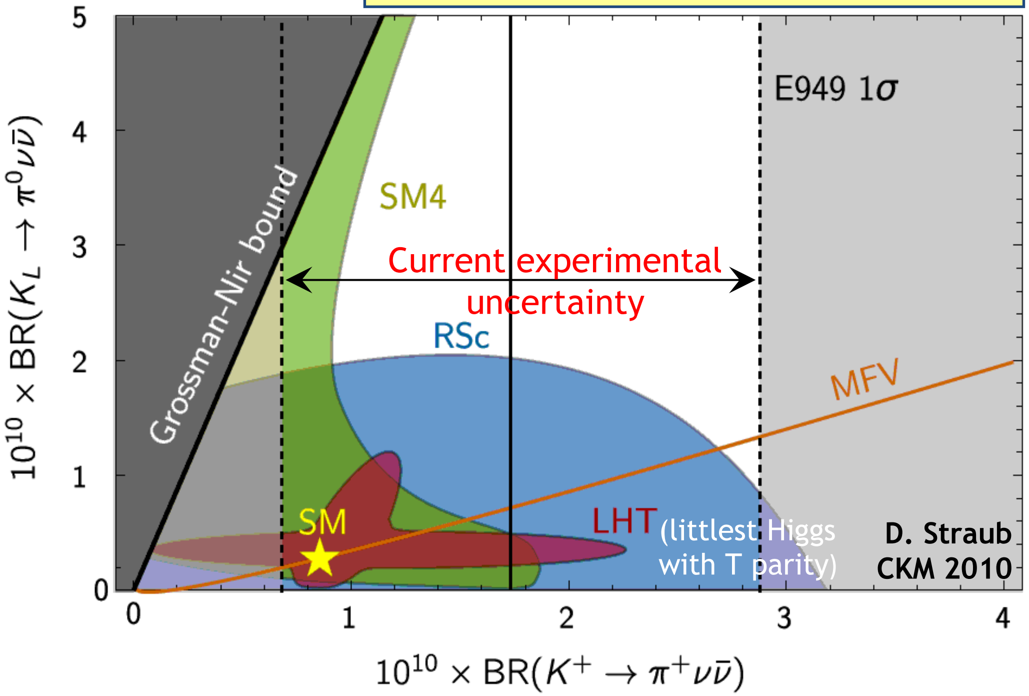
Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	9.11 ± 0.72
$K_L \to \pi^0 \nu\bar{\nu}$	3.00 ± 0.31

The uncertainties are largely parametric (CKM)

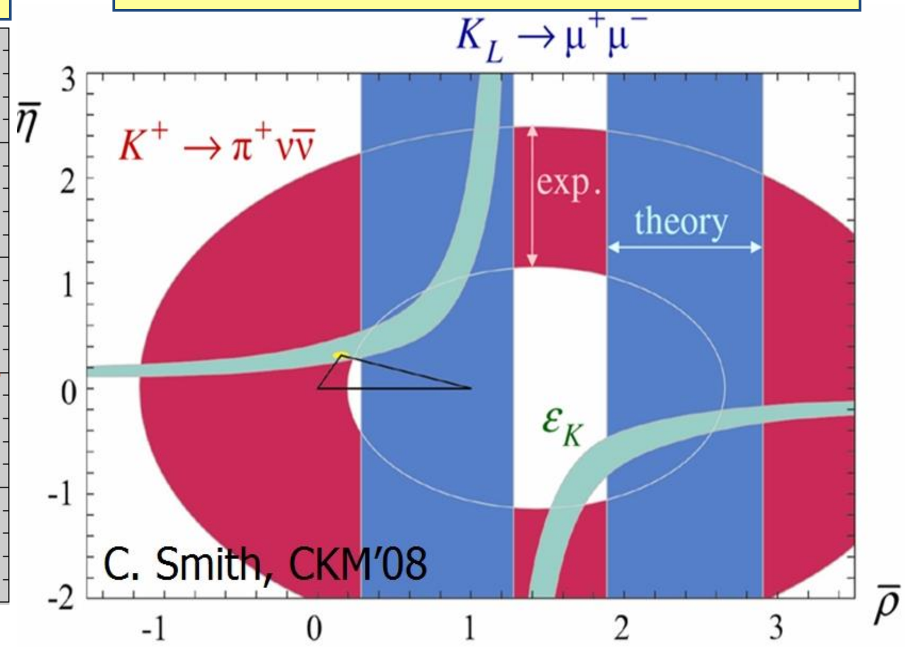
Theoretically clean, almost unexplored, sensitive to new physics.

$K \to \pi\nu\bar{\nu}$: experiment vs theory

BR($K_L \to \pi^0\nu\bar{\nu}$) vs BR($K^+ \to \pi^+\nu\bar{\nu}$)



CKM unitarity triangle with kaons



NA62 aim: collect O(100) SM $K^+ \to \pi^+\nu\bar{\nu}$ decays with <20% background in 3 years of data taking using a novel decay-in-flight technique.

Signature: high momentum K^+ (75GeV/c) → low momentum π^+ (15–35 GeV/c).

Advantages: max detected K^+ decays/proton ($p_K/p_0 \approx 0.2$);
efficient photon veto (>40 GeV missing energy)

Un-separated beam (6% kaons) → high rates, additional background sources.

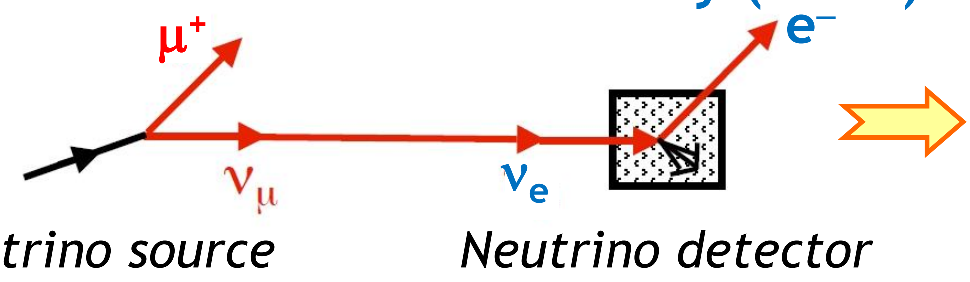
NA62 physics programme

- **NA62 Run 2 (2015–2018)**: focused on the "golden mode" $K^+ \to \pi^+ \nu\nu$.
  - ✓ Trigger bandwidth for other physics is limited.
  - ✓ Several measurements at nominal SES~10^{-12}: $K^+ \to \pi^+ A'$, $\pi^0 \to \nu\nu$.
  - ✓ A few measurements do not require extreme SES: $K^+ \to \ell^+ \nu_H$, …
  - ✓ In general, limited sensitivities to rare/forbidden decays (SES~10^{-10} to ~10^{-11}, similar to NA48/2 and BNL-E865).
  - ✓ A proof of principle for a broad rare/forbidden decay programme.

- **NA62 Run 3 (2021–2024)**: programme is under discussion.
  [Presented at "Physics Beyond Colliders" workshop, CERN, Sep 2016]
  - ✓ Existing apparatus, different trigger logic: **no capital investment**.
  - ✓ 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: $K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \pi^+ \mu e$, $\pi^0 \to \mu e$, …
  - ✓ Possibly K_L rare decays (SES~10^{-11}), including $K_L \to \pi^0 \ell^+ \ell^-$ [CPV].
  - ✓ Dump mode: hidden sector searches (long-lived HNL, DP, ALP).

The lepton programme

Neutrino oscillations discovery (1998)



First non-SM phenomenon:

1) Lepton Flavour Violation;
2) non-zero neutrino mass.

New physics scenarios involving **LFV**:

- ✓ Neutrino is a **Majorana fermion** (identical to antineutrino)
- ✓ Heavy (possibly sterile) neutrino states

Astrophysical consequences:

- ✓ Dark matter, nucleosynthesis, Supernova evolution, ...

❖ Birmingham-led programme (supported by ERC starting grant): search for forbidden states with lepton pair (**ee**, **μμ**, **μe**)

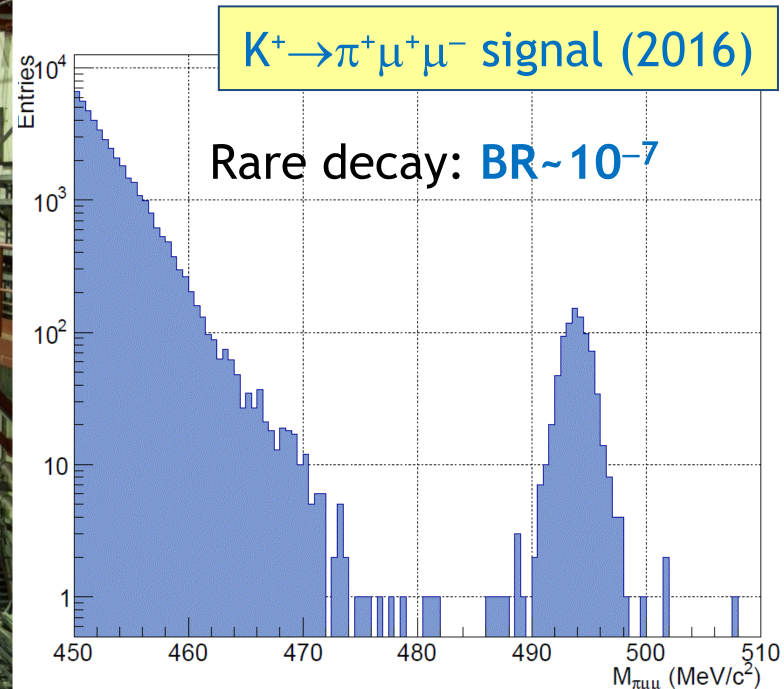
$$K^+ \to \pi^+ \mu^+ e^-$$
$$K^+ \to \pi^+ \mu^- e^+$$
$$K^+ \to \pi^- \mu^+ e^+$$
$$K^+ \to \pi^- e^+ e^+$$
$$K^+ \to \pi^- \mu^+ \mu^+$$

$$K^+ \to \mu^- \nu e^+ e^+$$
$$K^+ \to e^- \nu \mu^+ \mu^+$$

$$K^+ \to \pi^+ \pi^0, \quad \pi^0 \to \mu^+ e^-$$
$$K^+ \to \pi^+ \pi^0, \quad \pi^0 \to \mu^- e^+$$

NA62 status & data quality

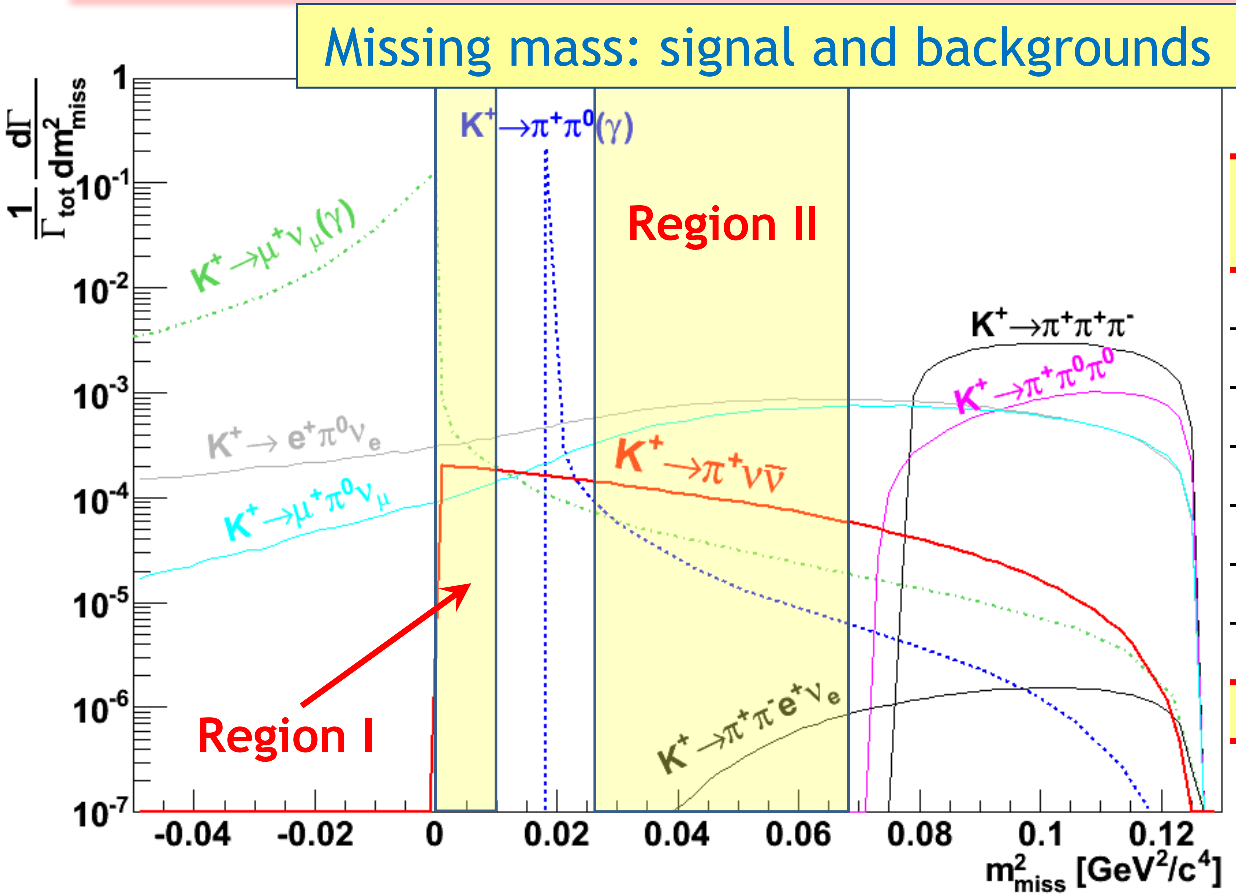
Data collection



- Minimum bias (~1% intensity) and $K_{\pi\nu\nu}$ test data collected in 2015
  - ✓ Most systems commissioned and meet the design requirements
- Beam time in 2016: 3 May – 14 November.
  - ✓ running at ~35% of the nominal intensity now (limited by SPS capability)
- Long (~6 months) runs scheduled in 2017 and 2018.

Expect to reach a few SM $K_{\pi\nu\nu}$ events sensitivity with 2016 data

$K^+ \to \pi^+\nu\nu$ kinematics



Signal & backgrounds (events/year)	
Signal	45
$K^+ \to \pi^+\pi^0$	5
$K^+ \to \mu^+\nu$	1
$K^+ \to \pi^+\pi^+\pi^-$	<1
Other 3-track decays	<1
$K^+ \to \pi^+\pi^0\gamma$ (IB)	1.5
$K^+ \to \mu^+\nu\gamma$ (IB)	0.5
Total background	<10

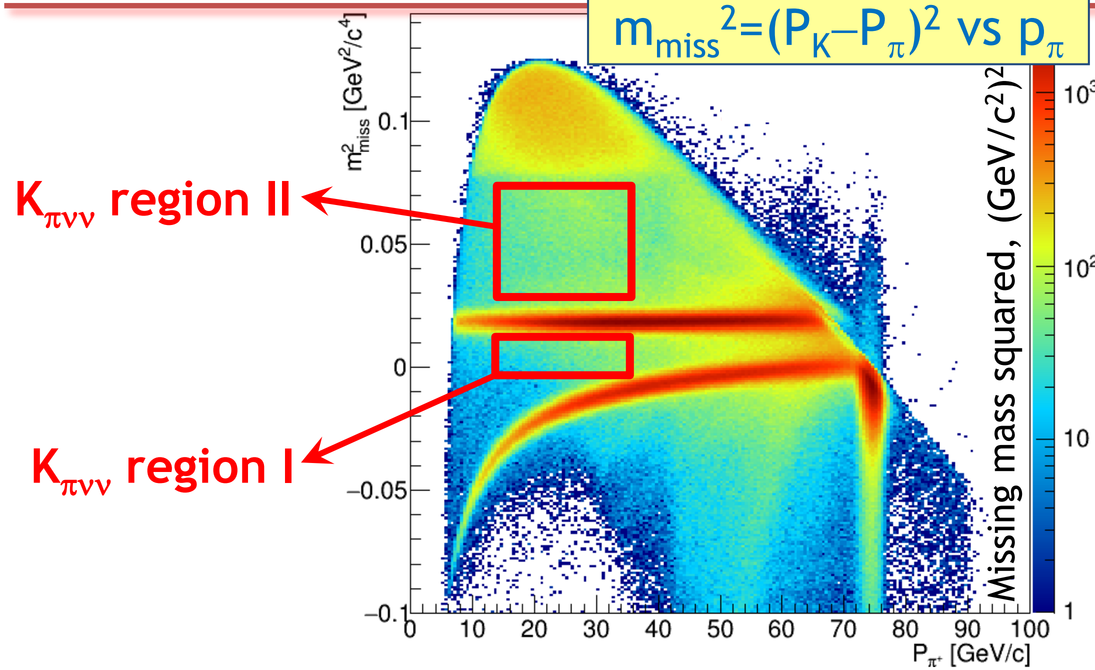
92% of total **BR(K^+)**:

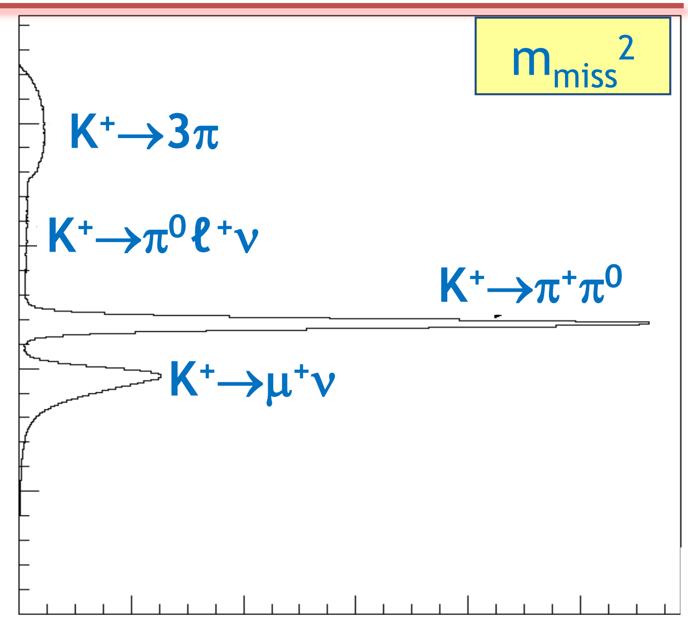
- Outside the signal kinematic region.
- Signal region is split into **Region I** and **Region II** by the $K^+ \to \pi^+\pi^0$ peak.

8% of total **BR(K^+)** including multi-body:

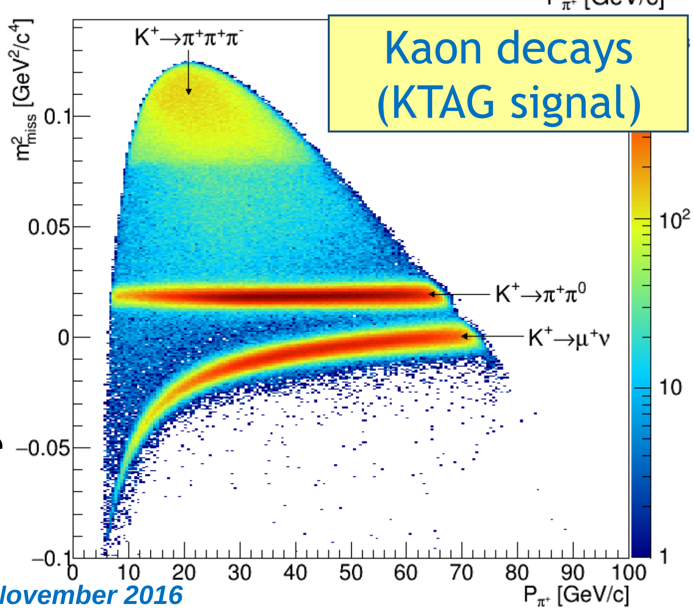
- Span across the signal region (not rejected by kinematic criteria).
- Rejection relies on hermetic photon system, PID, sub-ns timing.

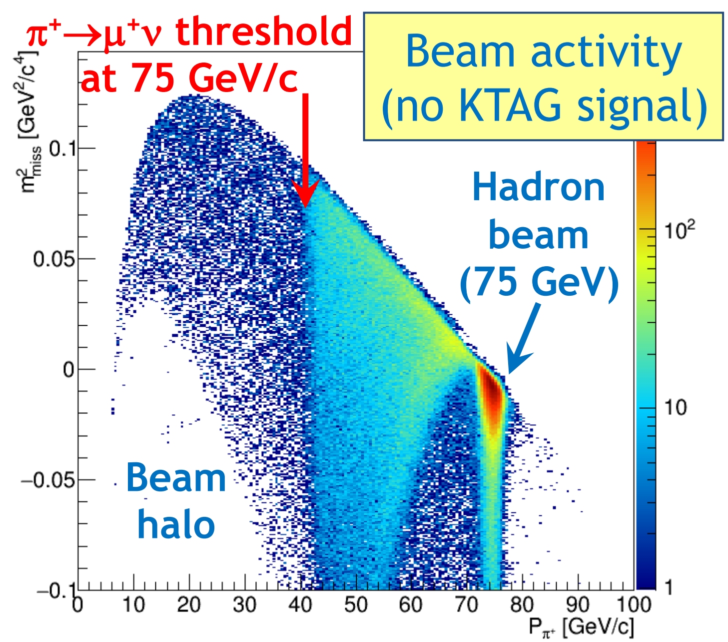
Kinematics: 2015 data



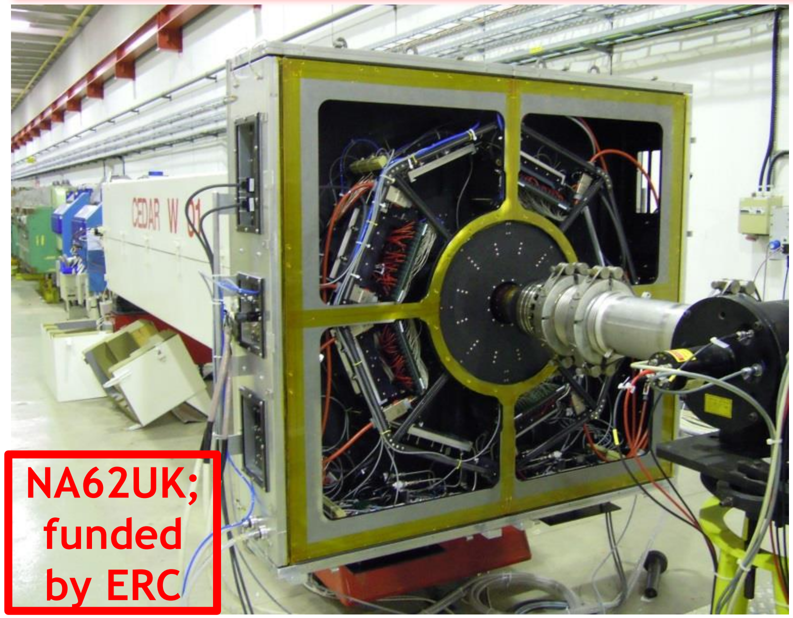


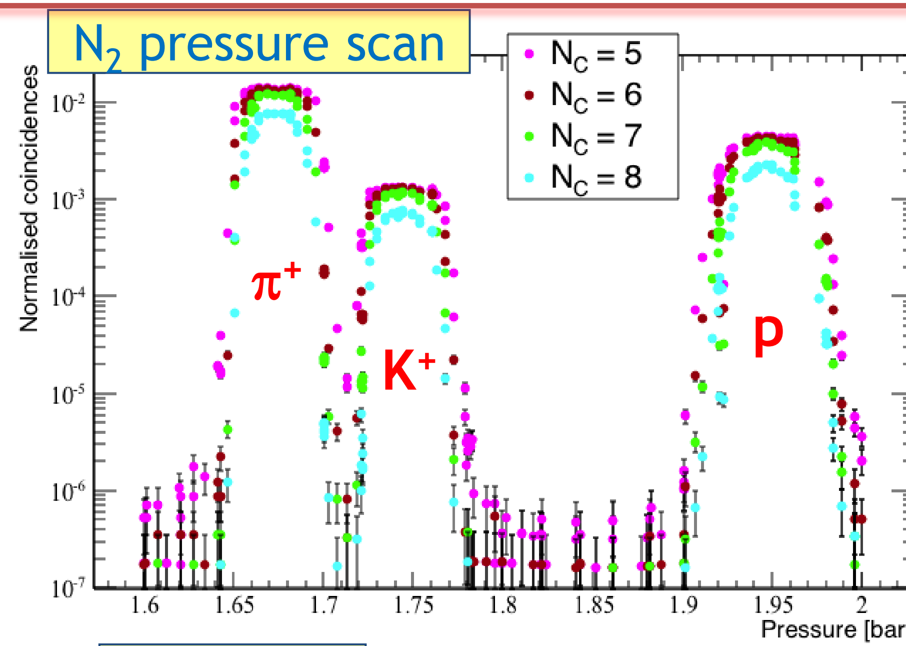
- ❖ Gigatracker information not used in this study.
- ❖ Photon veto criteria not applied on purpose.
- ❖ Kinematic & time resolutions are close to the design.

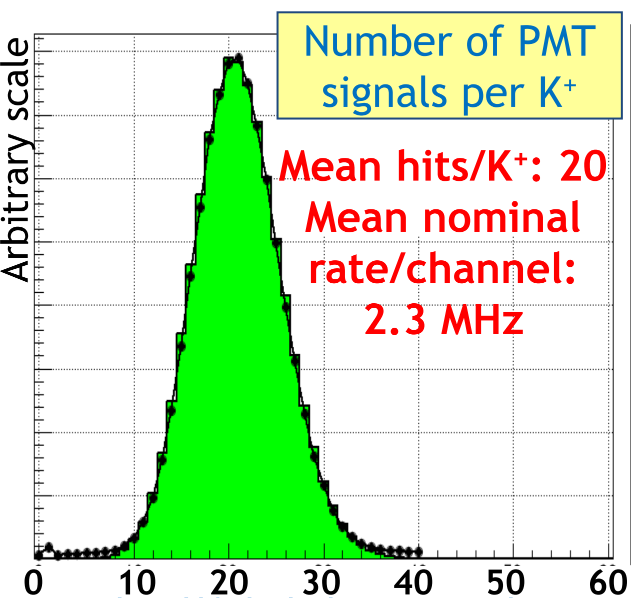


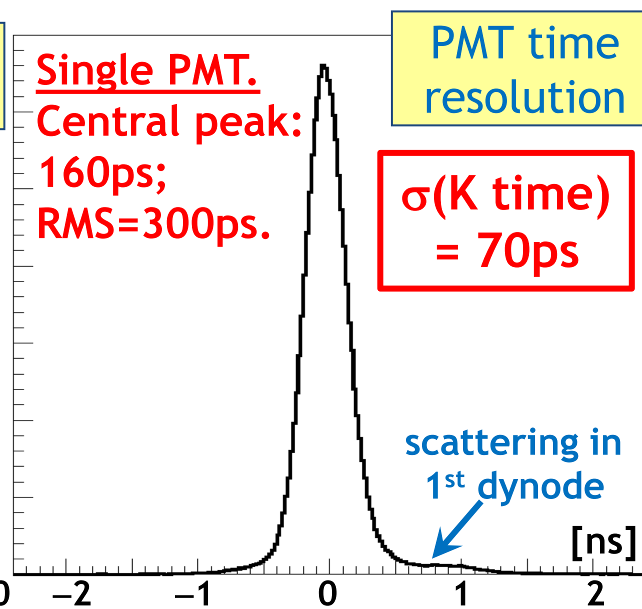


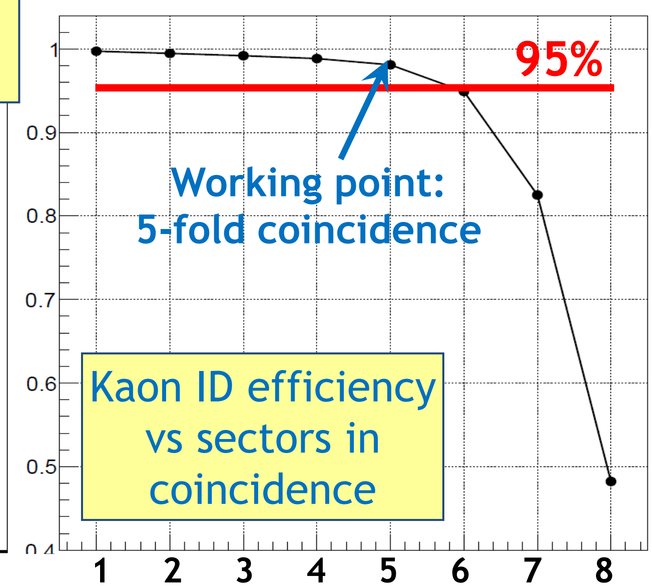
Kaon identification: KTAG



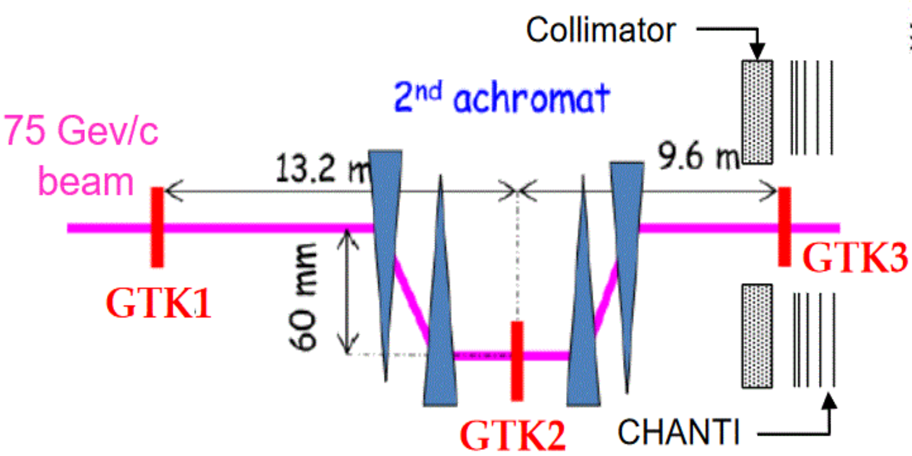


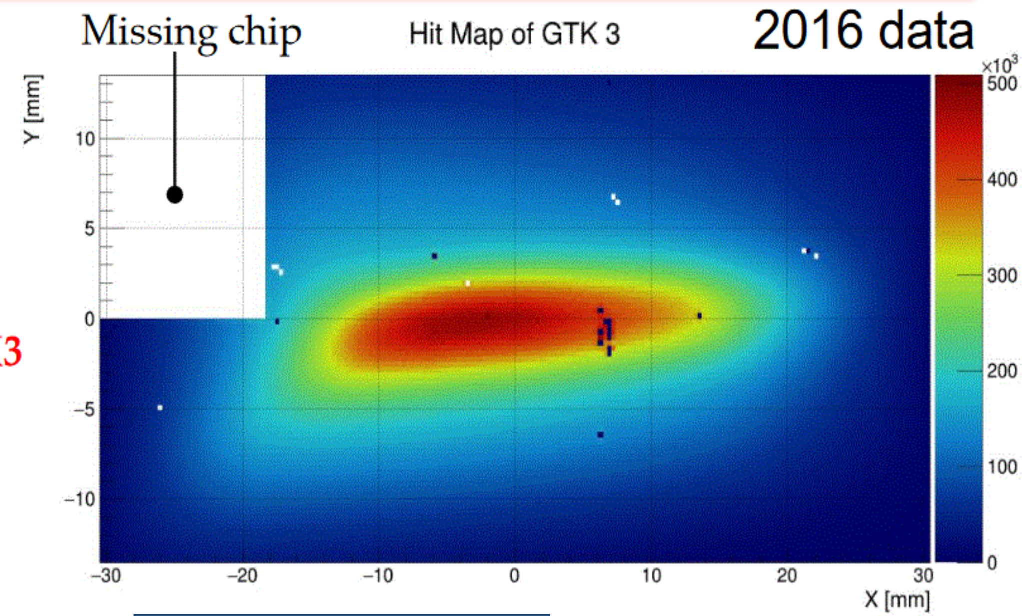






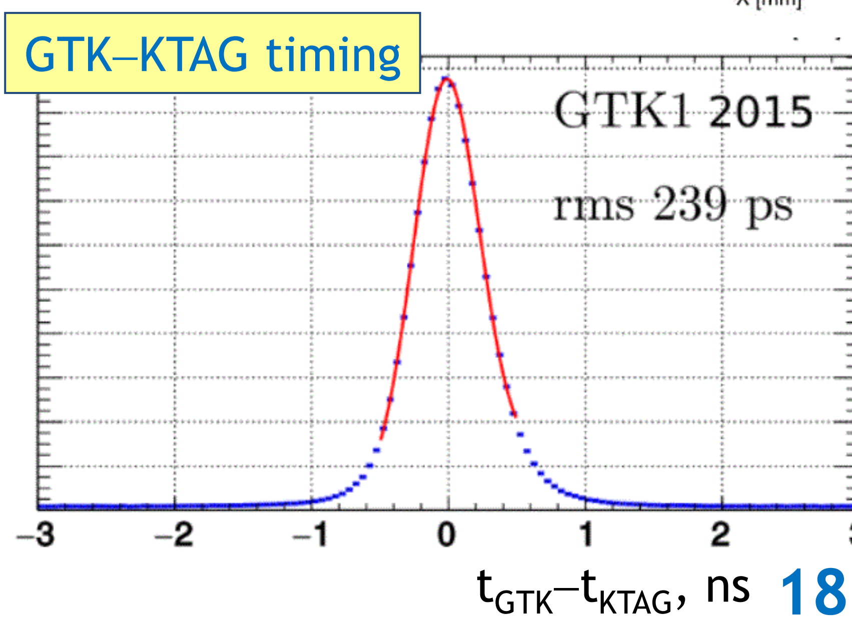
Beam tracker: the Gigatracker



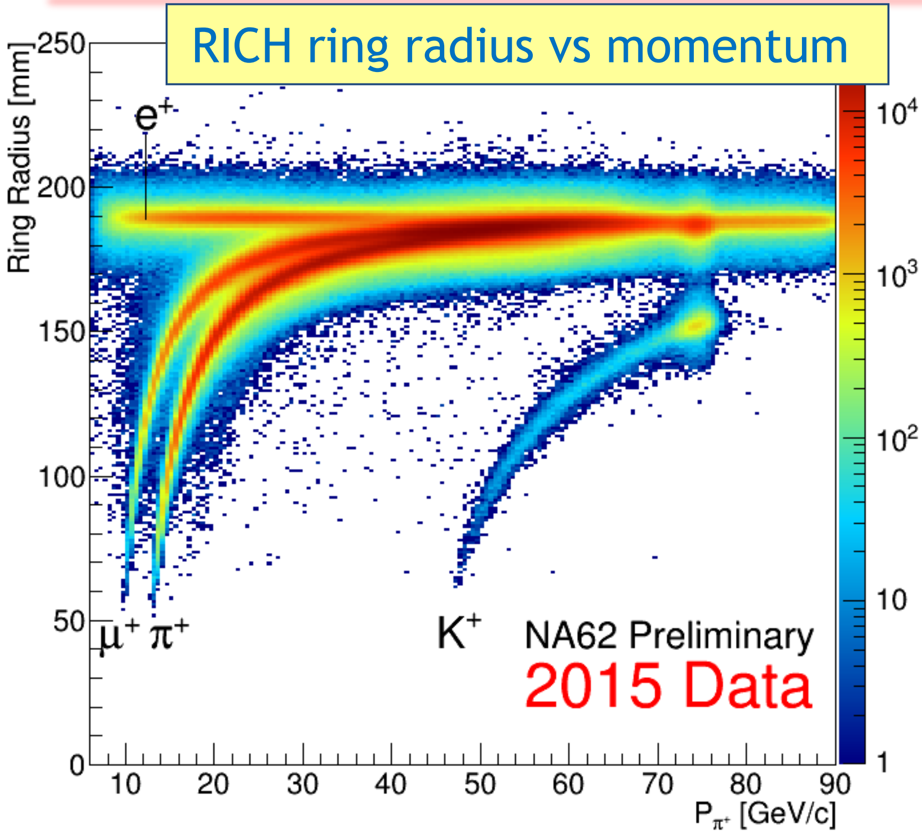


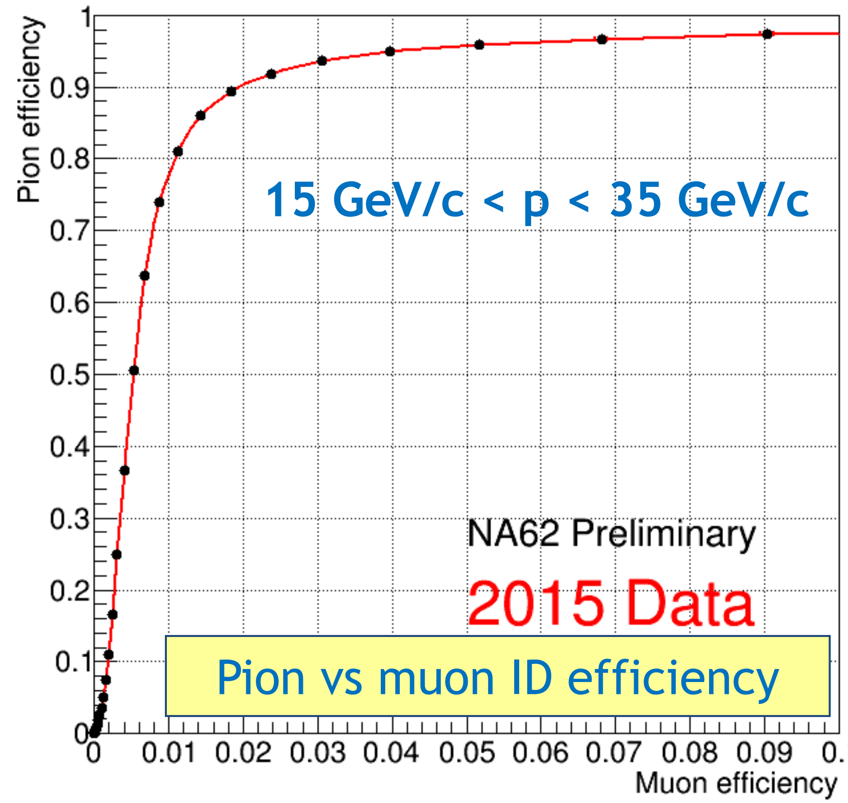
- Three Si pixel stations on the beam.
- Operation at beam rates up to **800 MHz**.
- In total, **54k** pixels (**300×300 μm²**).
- Thickness: **<0.5% X_0** per station.
- Cooling using microchannel technique.
- On-sensor TDC readout chip.
- Commissioned in 2015–2016.
- Measured performances match the design.

  $\sigma(t_{BeamTrack}) \approx 200$ ps.



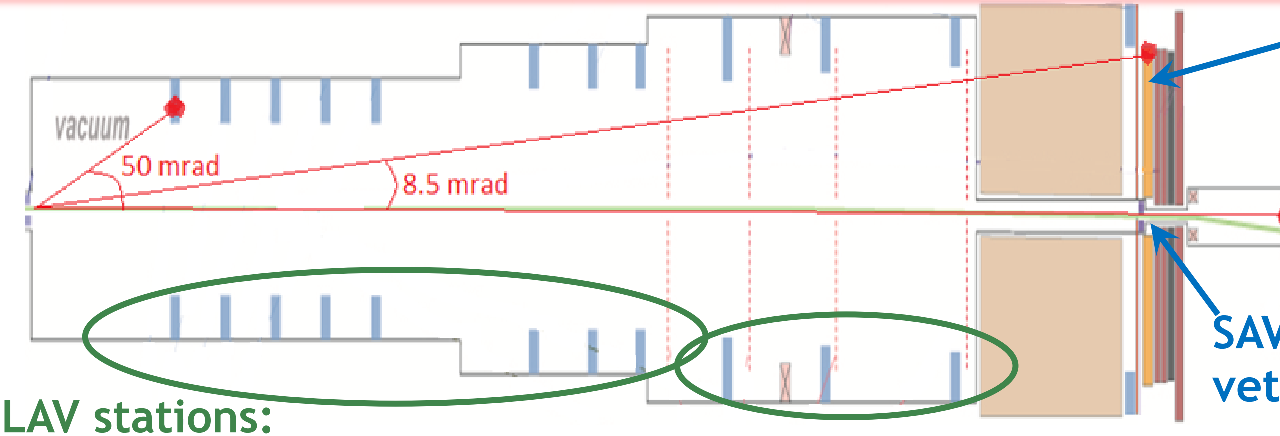
Downstream particle identification



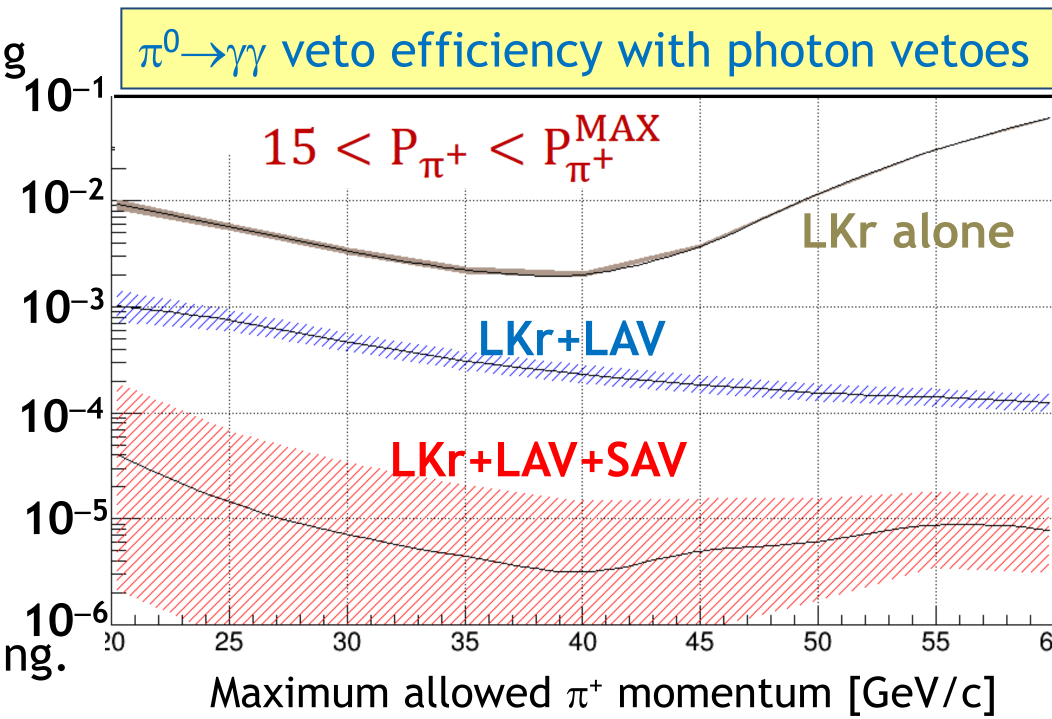


- PID technique: RICH, EM & hadronic calorimeters.
- Goal: O(10^7) muon mis-ID suppression to reduce $K^+\to\mu^+\nu$ background to $K^+\to\pi^+\nu\nu$.
- RICH provides optimal μ/π separation at 15 GeV/c<p<35 GeV/c: measured μ suppression $\approx 10^2$ at π ID efficiency of ~90%.
- Calorimeters: EM (LKr), hadronic (MUV1+MUV2); additional ($10^4 \div 10^6$) μ suppression at (90%÷40%) π^+ ID efficiency.

Photon rejection



- Technique: EM calorimetry exploiting correlations between photons from $\pi^0\to\gamma\gamma$ decays.
- Goal: $O(10^8)$ rejection of π^0 from $K^+\to\pi^+\pi^0$ decays.
- Signal region: $p(\pi^+)<35$ GeV/c, therefore $p(\pi^0)>40$ GeV/c.
- Rejection factor measured with 2015 data from $K^+\to\pi^+\pi^0$ decays: $O(10^6)$ rejection achieved; analysis of large 2016 sample on-going.



Birmingham-led analyses

The Birmingham NA62 group has produced
>50% of the physics output of the "old" CERN **$K^{\pm}$** experiments

Recent results with 2003–2007 data:

❖ Search for lepton number violation and resonances in $K^{\pm}\to\pi\mu\mu$ decays
[presented at 2016 conferences; to be published in early 2017]

❖ π^0 transition form factor measurement
[presented at 2016 conferences; to be published in early 2017]

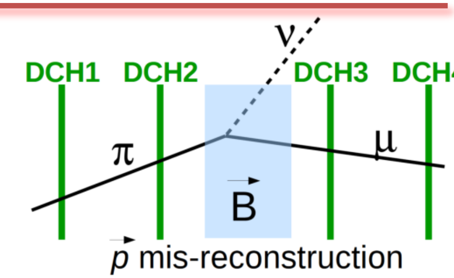
❖ Search for dark photon production: $\pi^0\to\gamma A'$
[published in 2015]

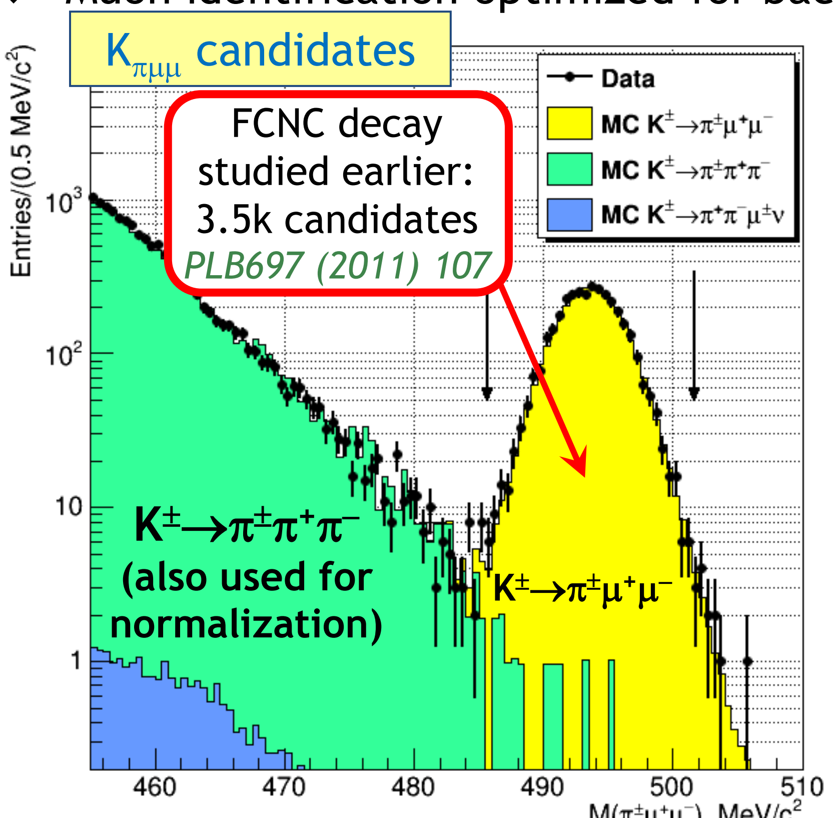
Near-future prospects:

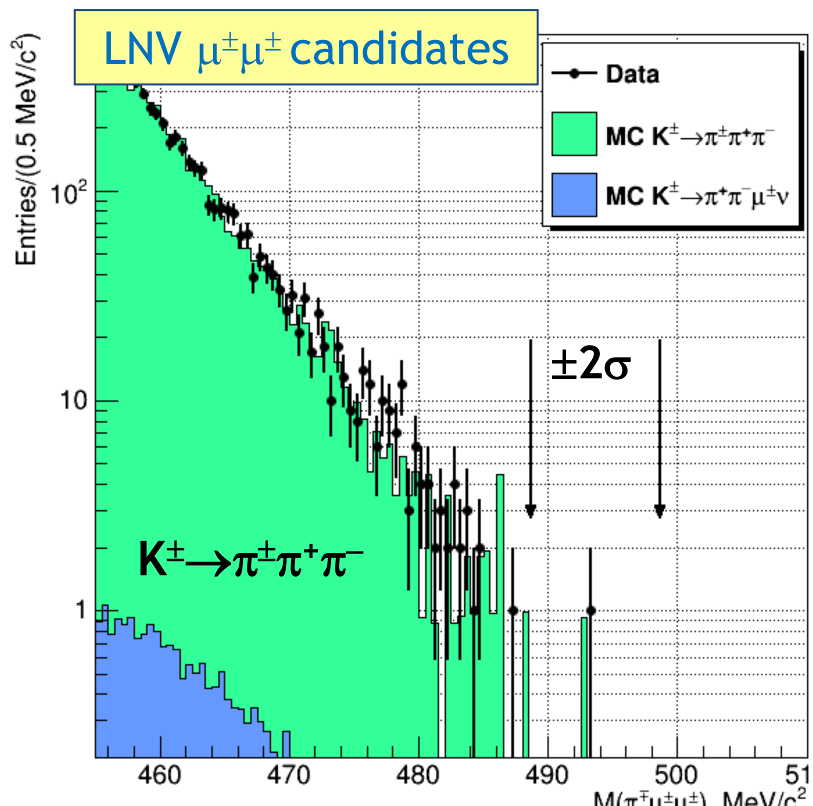
❖ Searches for heavy neutral leptons: $K^+\to\ell^+\nu_H$
[expect to presented at the 2017 winter conferences]

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







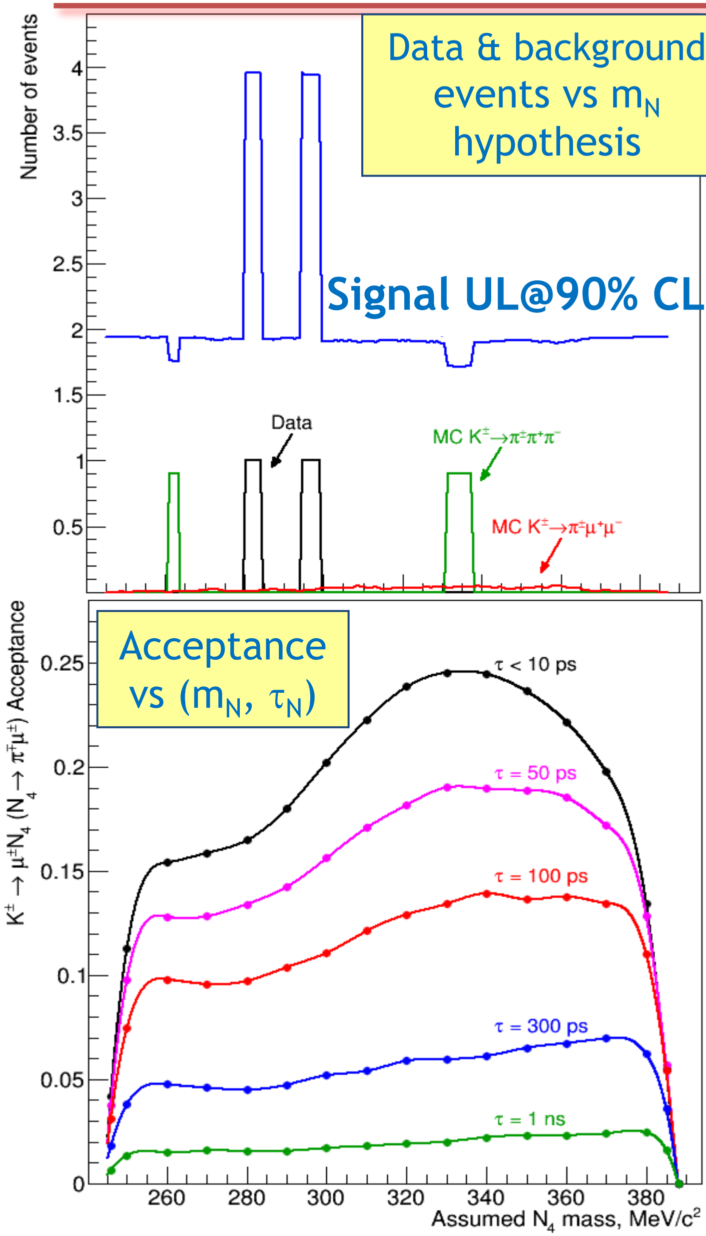
$N(\mu^\pm\mu^\pm) = 1$

$N_{bkg} = 1.16 \pm 0.87$

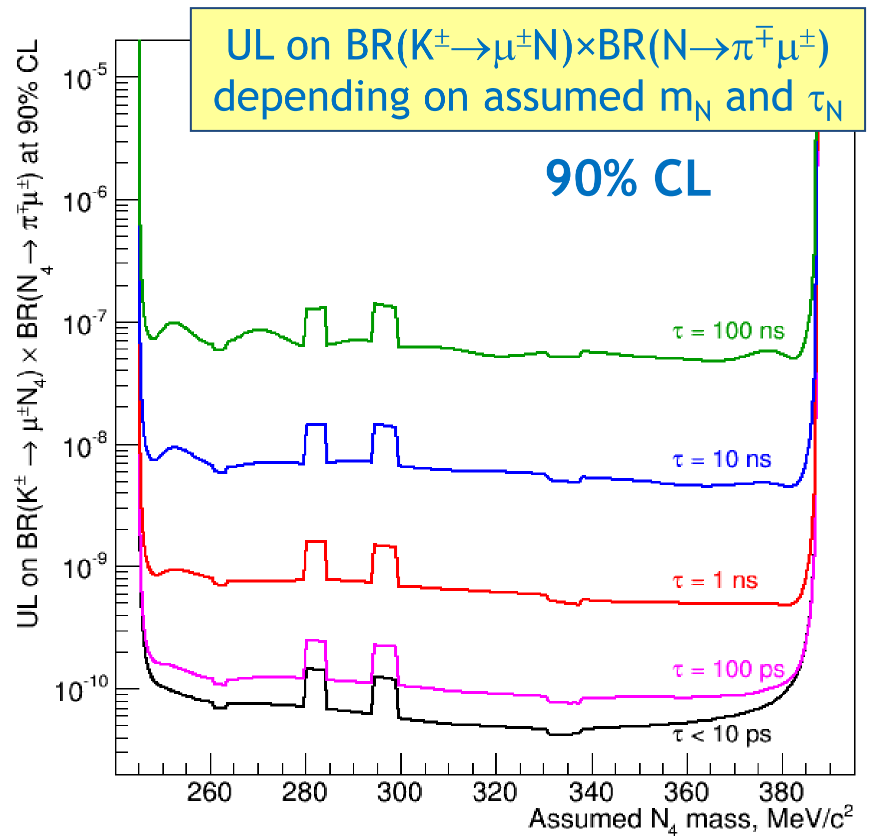
⇒ $BR(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 8.6 \times 10^{-11}$ [90% CL]

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

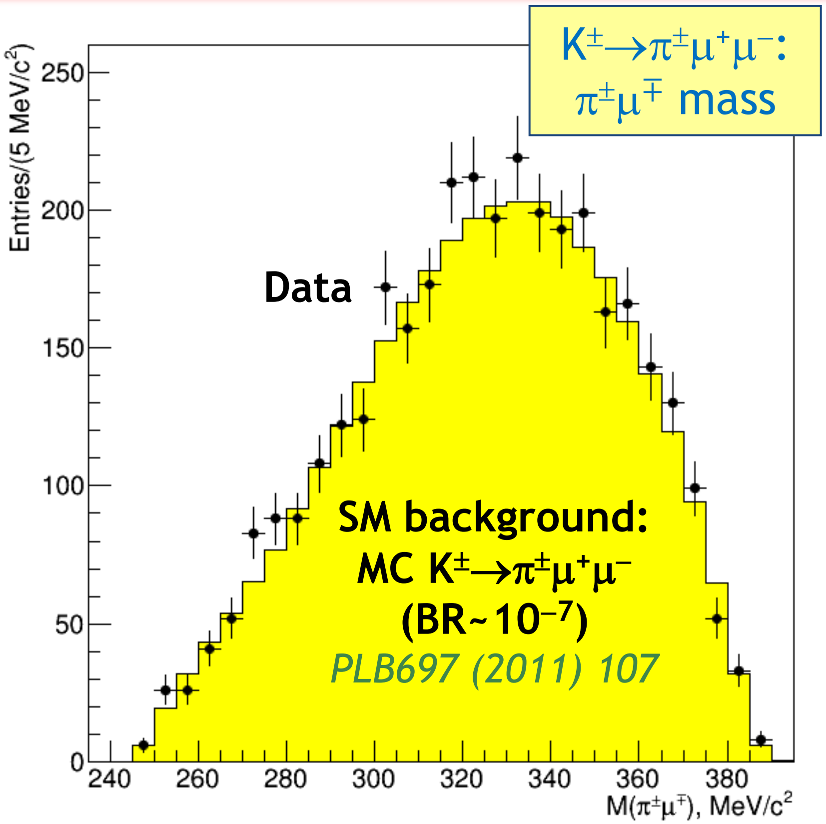
Search for $K^{\pm}\rightarrow\mu^{\pm}N$, $N\rightarrow\pi^{\mp}\mu^{\pm}$

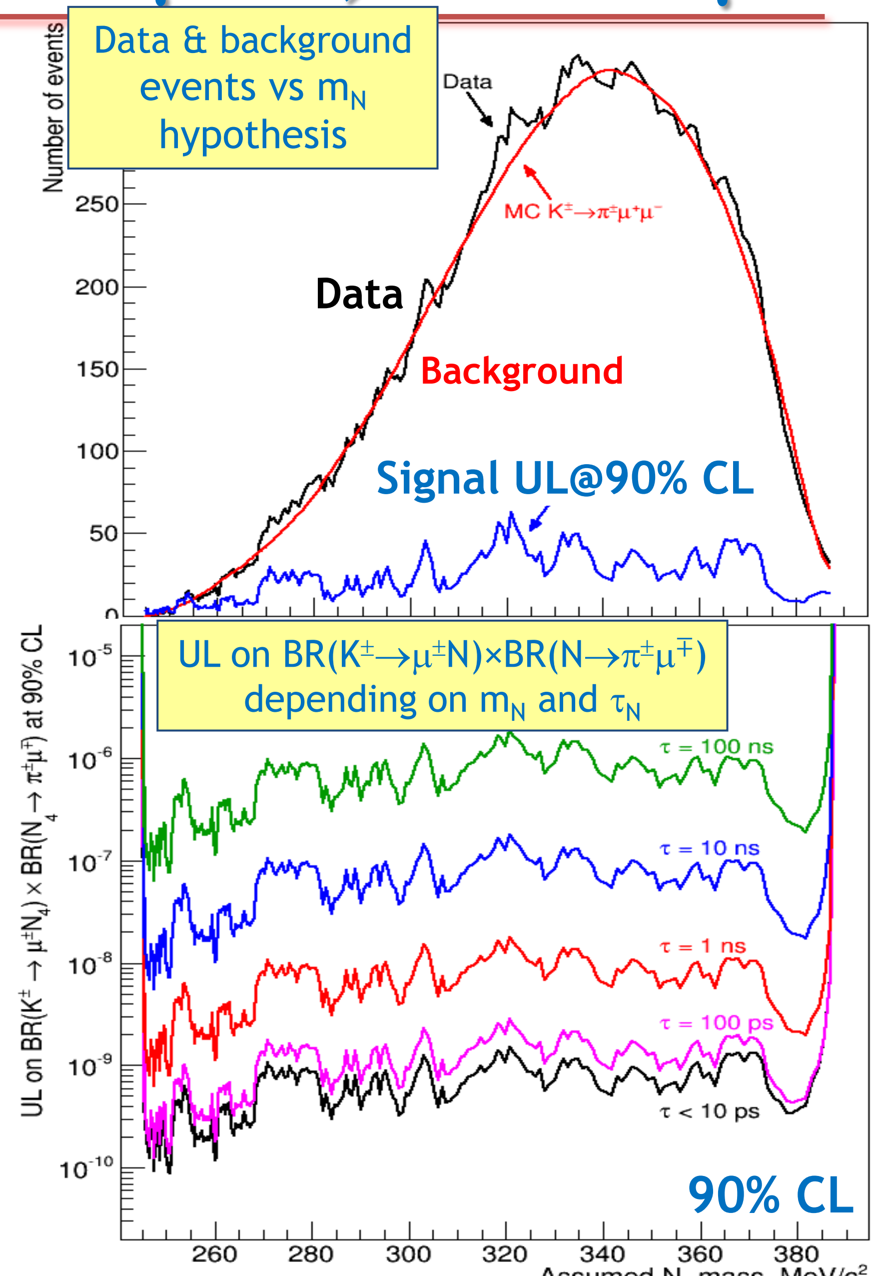


- Interpretation of the LNV result in terms of **Majorana neutrino** (**N**) production and decay. *[Atre et al, JHEP 0905 (2009) 030]*
- A scan in the parameter space: m_N and τ_N.
- Due to the 3-track vertex selection constraint, acceptance falls as **~1/τ_N** for **τ_N>1 ns**.
- Limits of **~10^{-10}**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



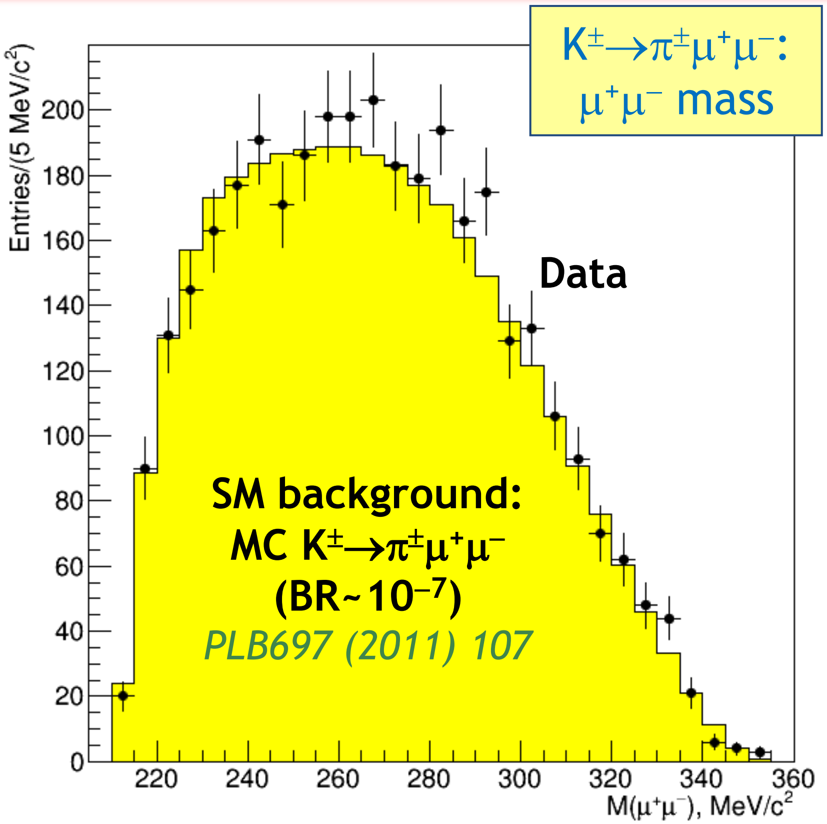
Search for $K^\pm \to \mu^\pm N$, $N \to \pi^\pm \mu^\mp$

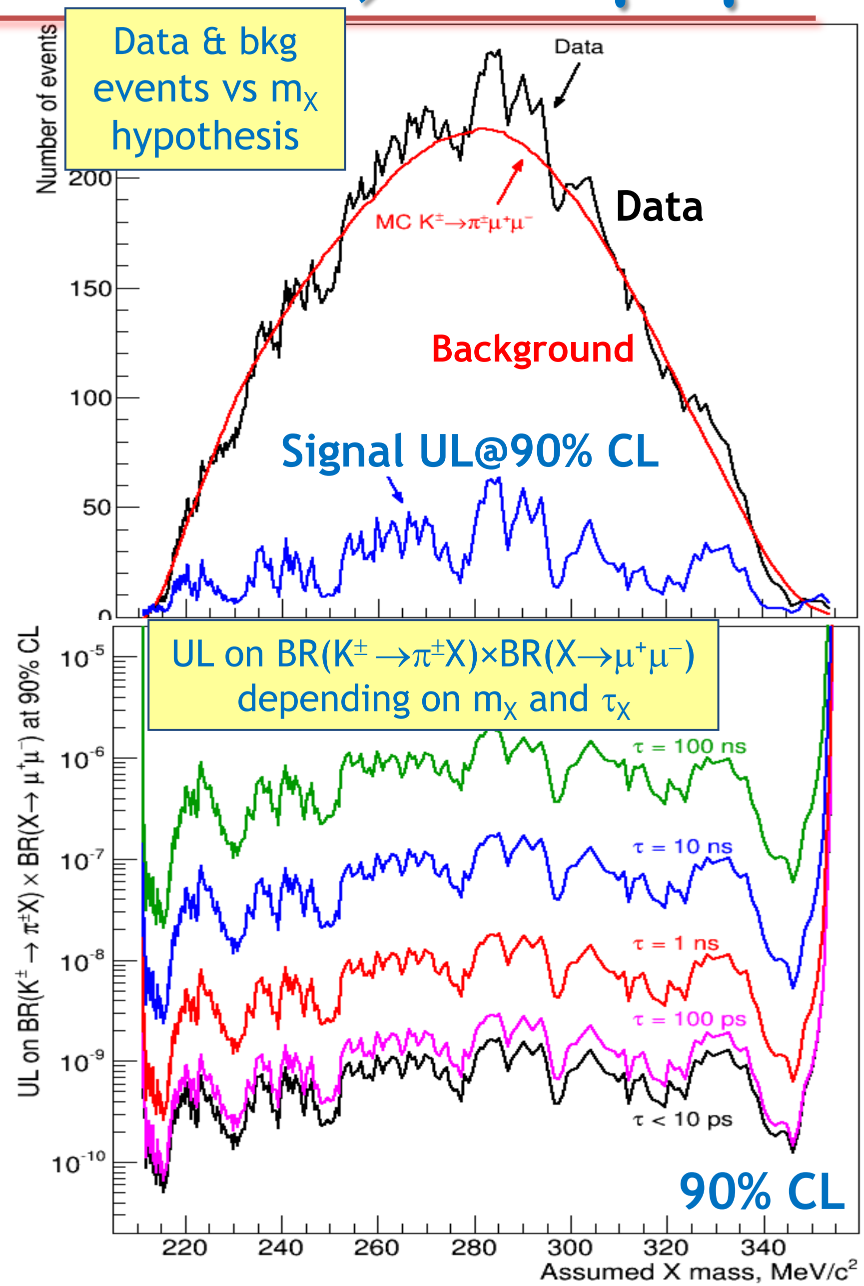




- Search for **LN conserving heavy neutrino** production and decay.
- Sensitivity limited by background from the FCNC $K^\pm \to \pi^\pm \mu^+ \mu^-$ decay.
- Limits of **~10^{-9}** set for **τ_N<100 ps**.

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





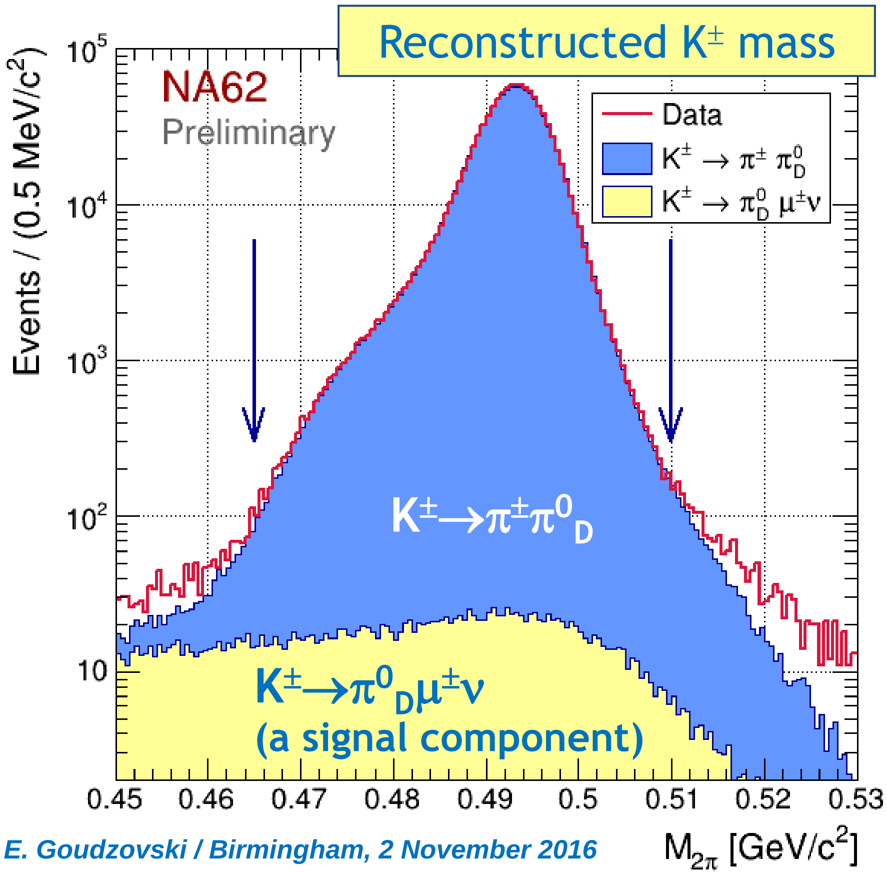
- Also background limited; **UL~10^{-9}**.
- This leads to non-trivial limitations on the inflation (χ) phase space: $\chi\to\mu^{+}\mu^{-}$ decay dominates at **m_{χ}~300 MeV/c²**.

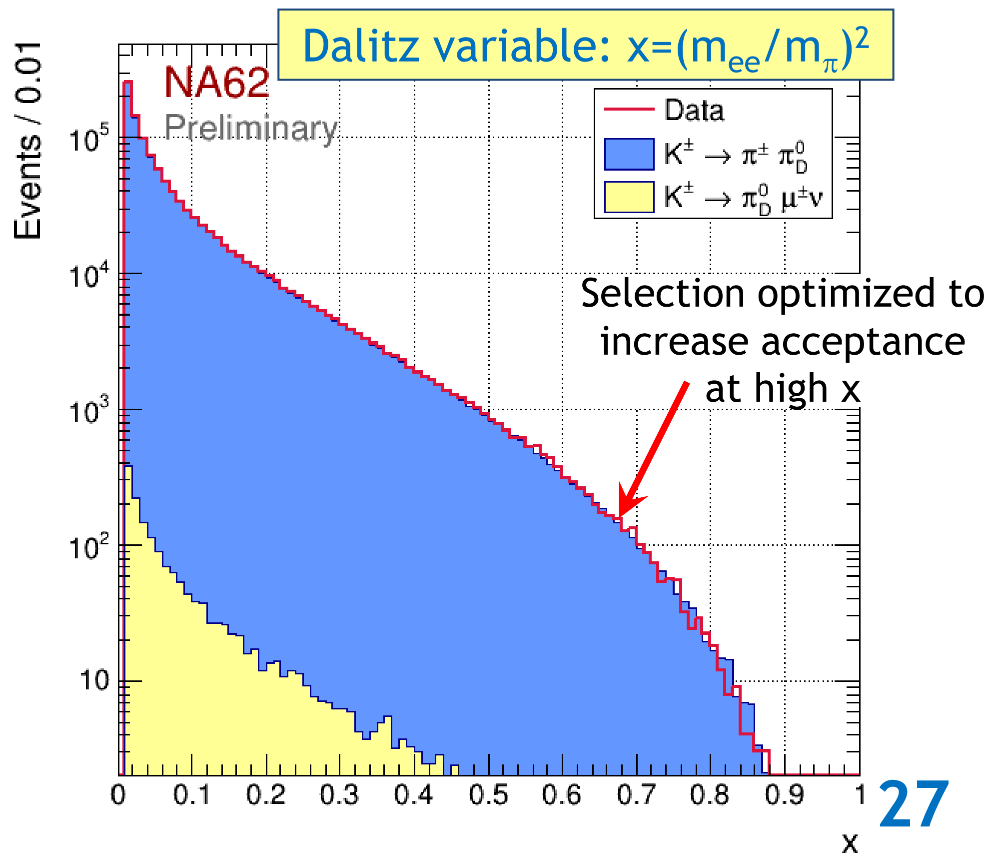
[Shaposhnikov, Tkachev, PLB 639 (2006) 414; Bezrukov, Gorbunov, PLB736 (2014) 494]

π^0 physics: π^0 transition form factor; search for dark photon ($\pi^0 \to \gamma A'$)

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

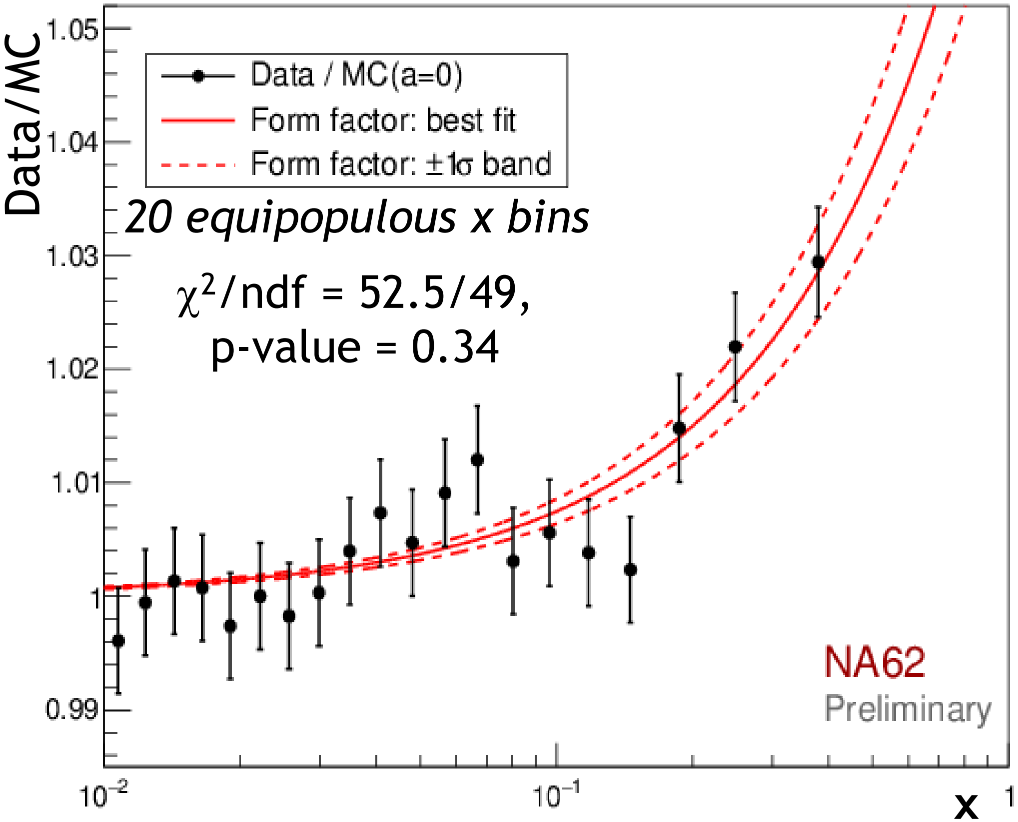
- NA62-R_K data: **~2×10^{10} $K^\pm$** decays in the fiducial decay region.
- Reconstructed π^0_D decay candidates, **$x=(m_{ee}/m_\pi)^2>0.01$: $N(K_{2\pi D})=1.05\times10^6$**.
- Despite **~10** times smaller sample wrt NA48/2, good for **spectrum study**:
  - ✓ minimum bias trigger: low systematics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



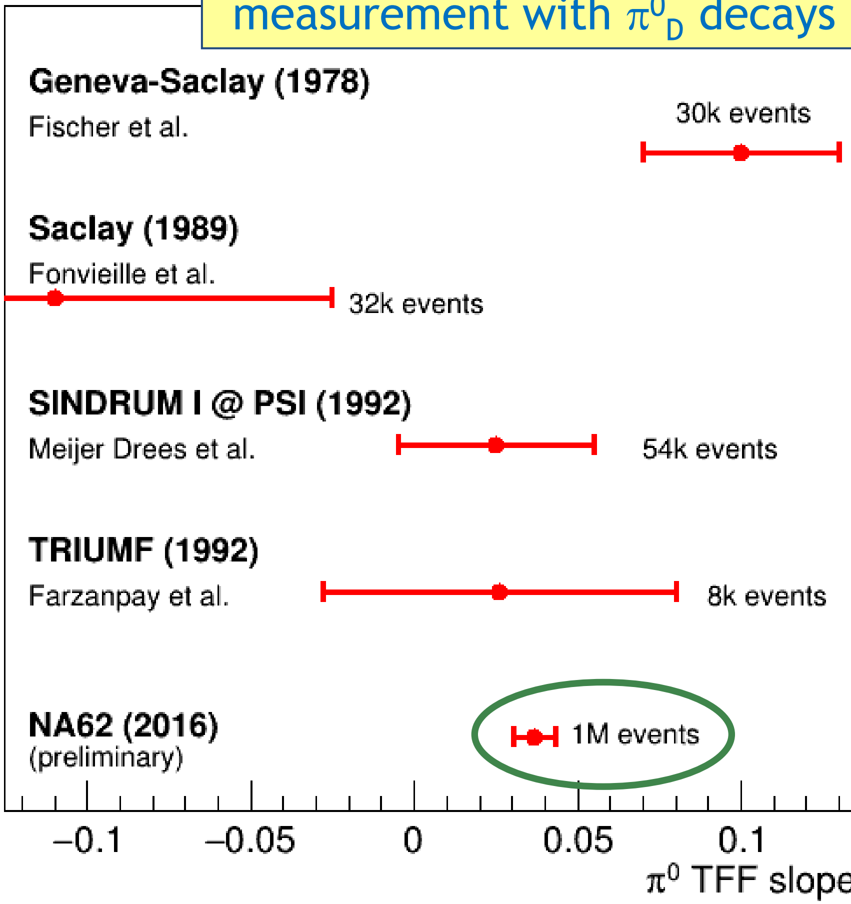


TFF slope measurement: result

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.

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

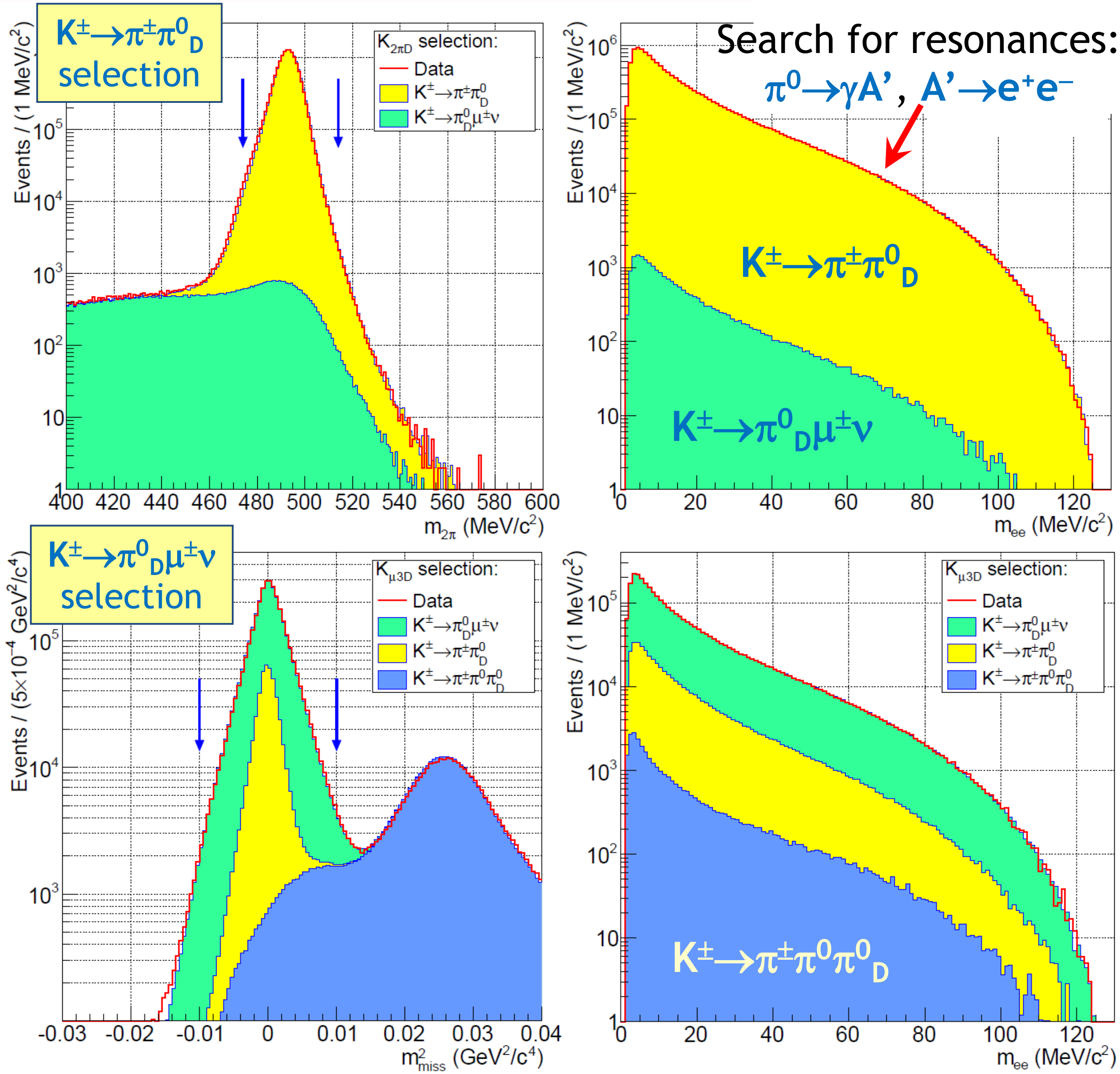
- $m_{miss}^2 = (P_K - P_\mu - P_{\pi 0})^2$ compatible with zero;
- $|m_{\gamma ee} - m_{\pi 0}| < 8$ MeV/c^2;
- missing total and transverse momentum.

Reconstructed π^0_D decay candidates:

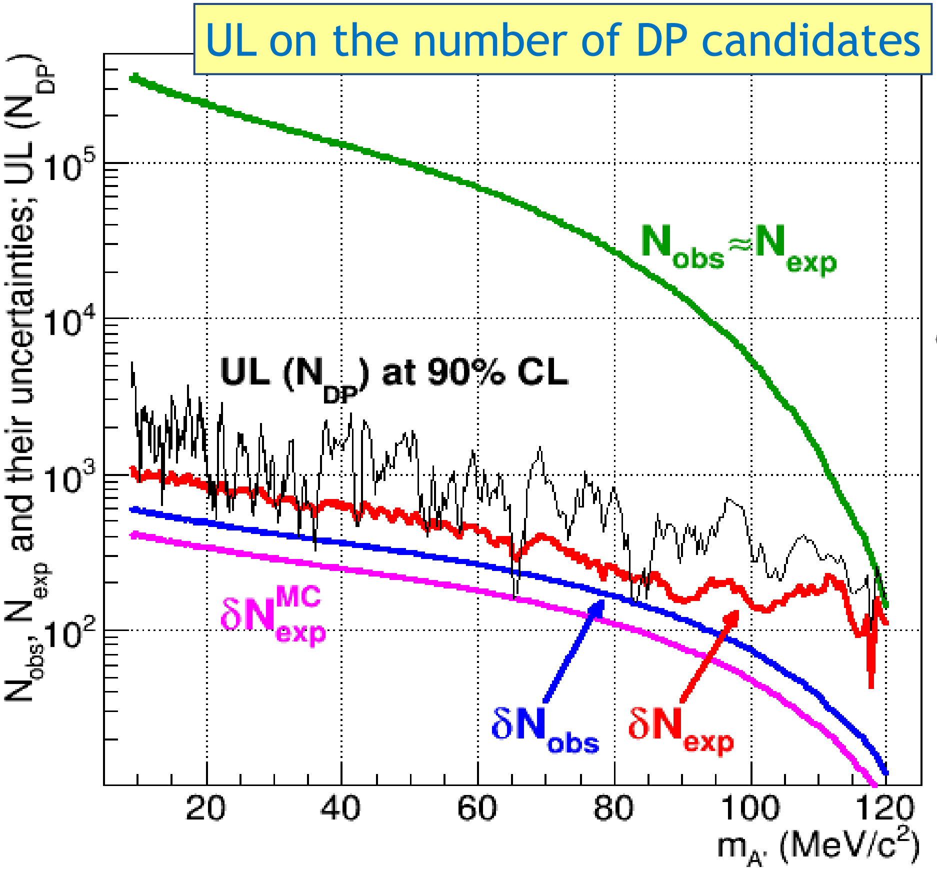
- $N(K_{2\pi D}) = 1.38 \times 10^7$,
- $N(K_{\mu 3D}) = 0.31 \times 10^7$,
- total $= 1.69 \times 10^7$.

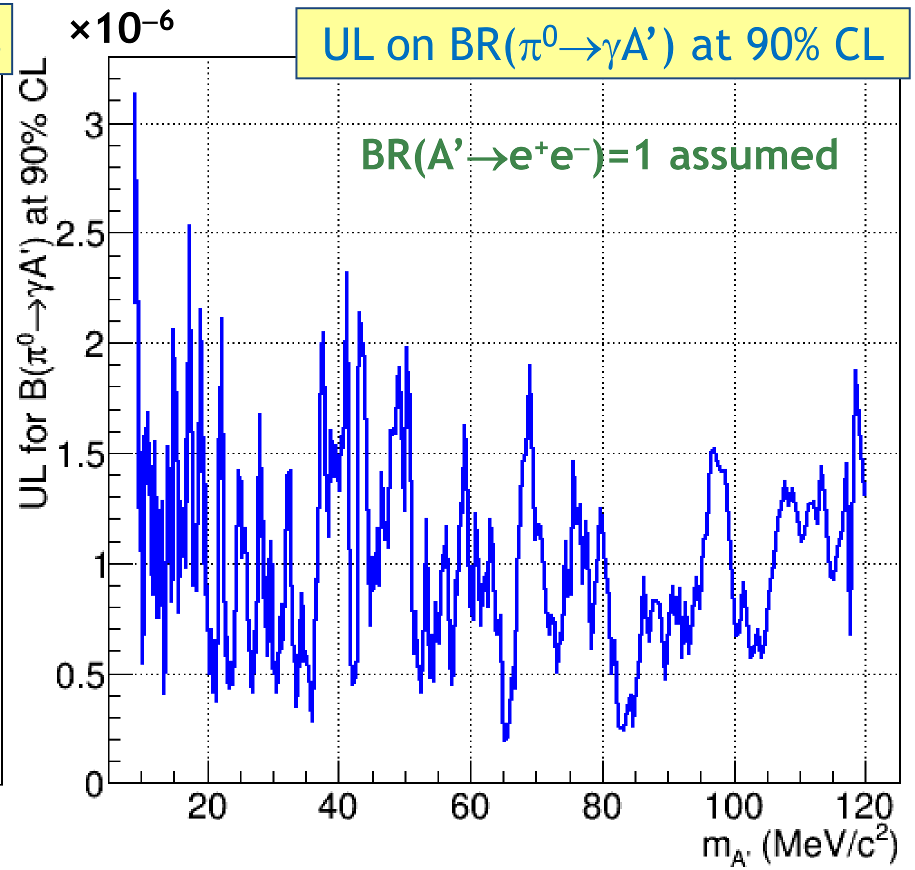
$K^\pm$ decays in fiducial region:

$N_K = (1.57 \pm 0.05) \times 10^{11}$.



NA48/2: search for DP signal





DP mass scan:

- range: 9 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.

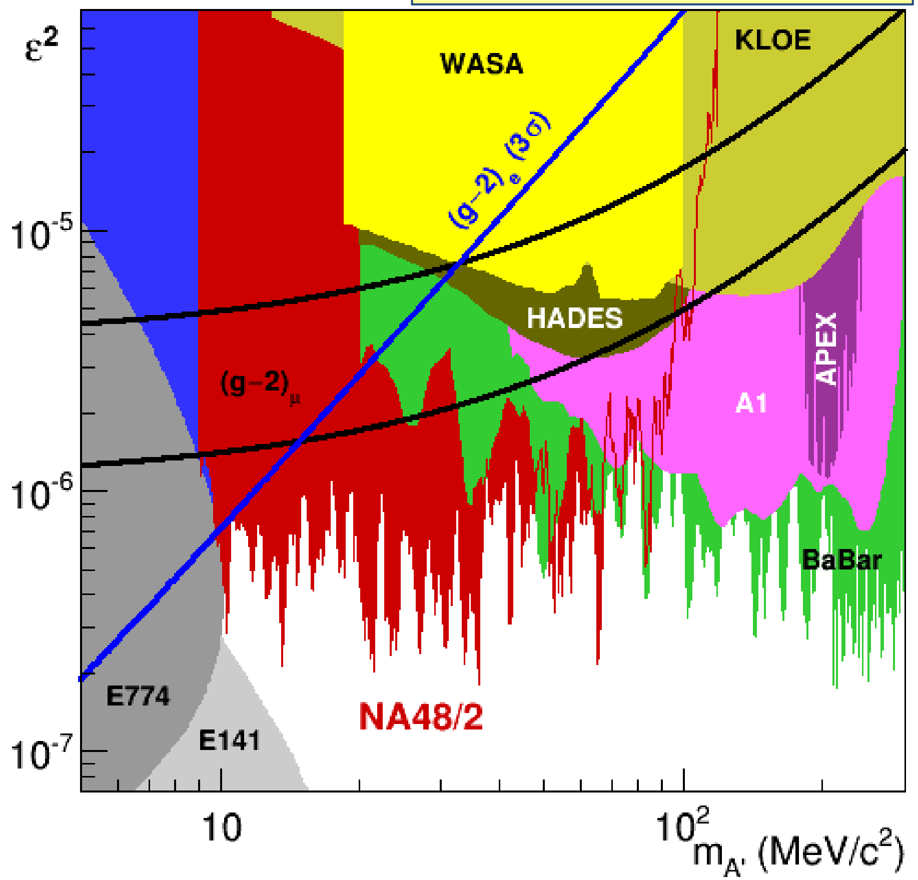
✓ Local signal significance never exceeds 3σ: **no DP signal** observed.

✓ 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



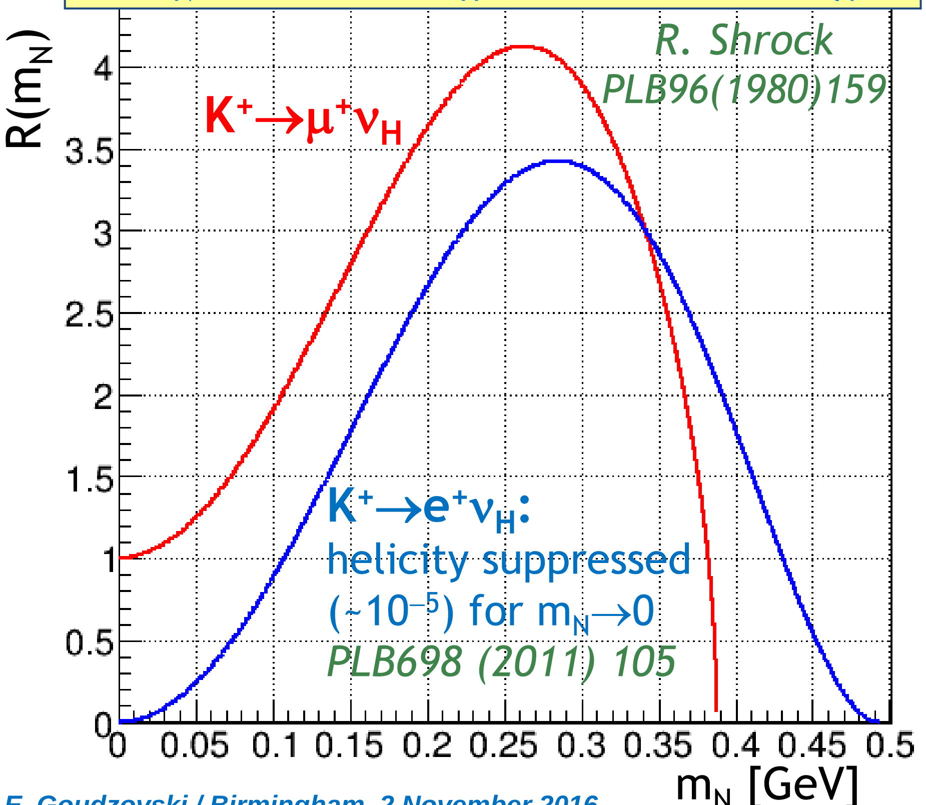
- Improvement on the existing limits in the $m_{A'}$ range **9–70 MeV/c²**.
- Most stringent limits are at low $m_{A'}$ (kinematic suppression is weak).
- Sensitivity limited by irreducible π^0_D background: upper limit on ε^2 scales as $\sim(1/N_K)^{1/2}$, modest improvement with larger data samples.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

Heavy neutral leptons

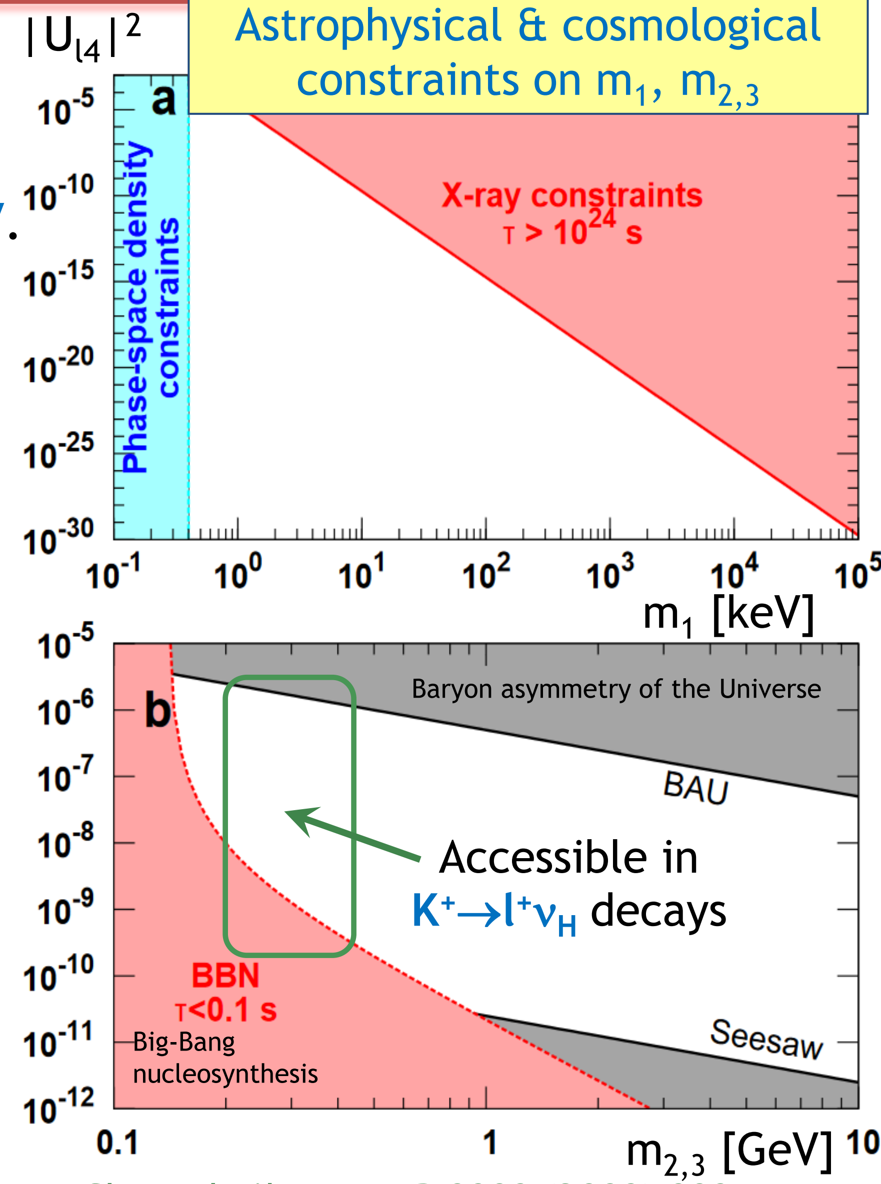
Constraints on the νMSM

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

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



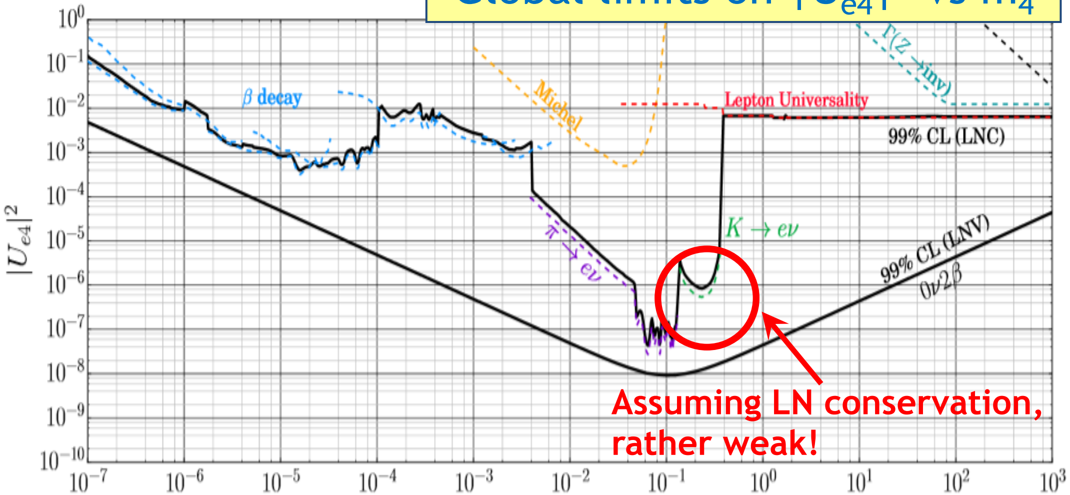
Astrophysical & cosmological constraints on m_1, $m_{2,3}$



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

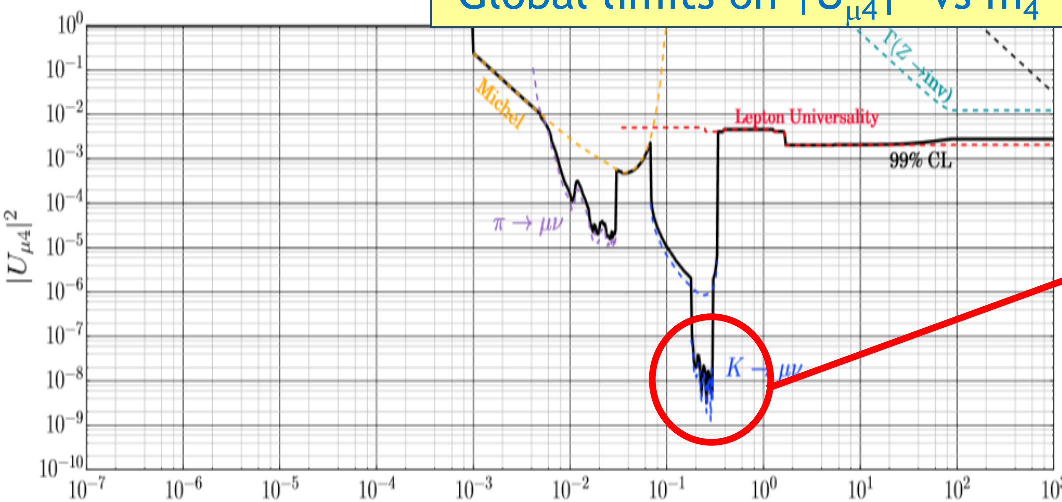
HNL: global limits

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



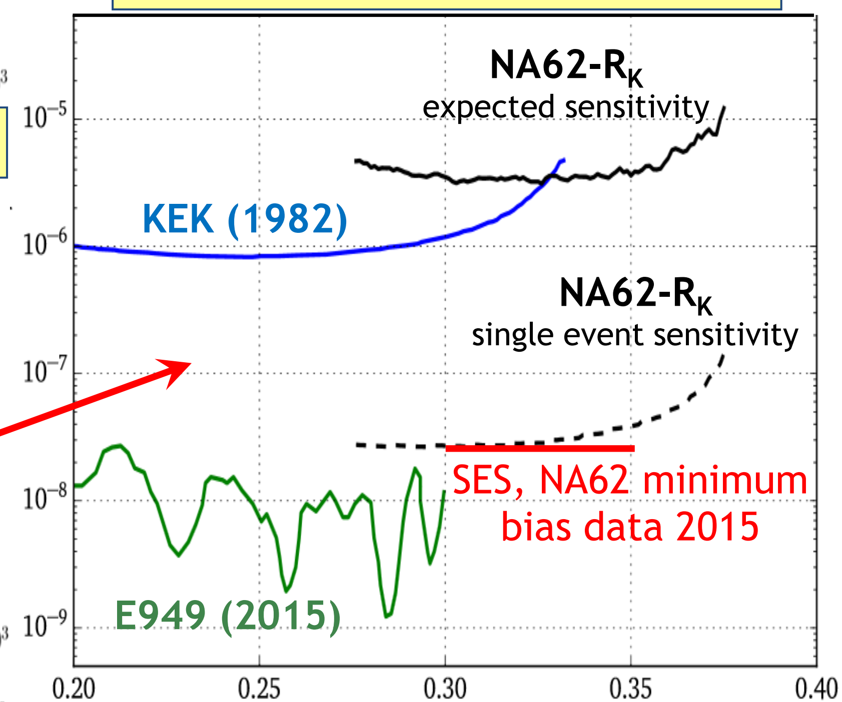
In contrast to decay searches (e.g. $N \to \pi l$ at beam dump expt's), **production search** results are model-independent.

Global limits on $|U_{\mu4}|^2$ vs m_4



m_4 [GeV]

Limits on $|U_{\mu4}|^2$ from $K^\pm \to \mu^\pm \nu$ (production searches)



m_4 [GeV]

Model-dependent HNL decay searches not considered

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

HNL: status of production searches

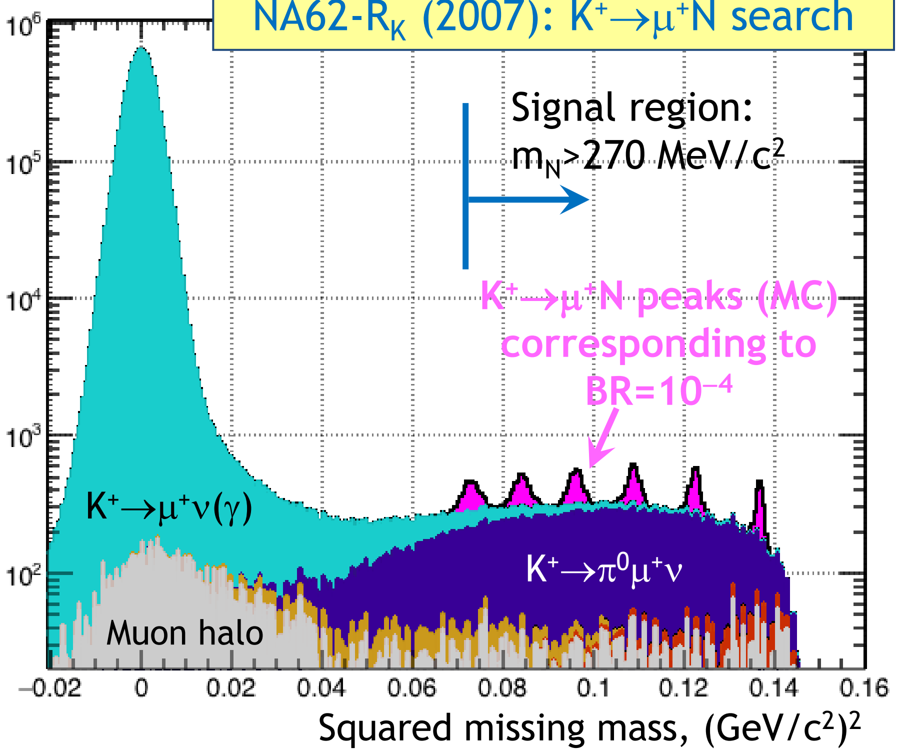
Peak search for $K^+ \to \mu^+ N$ at **NA62-R_K (2007 data)**:

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

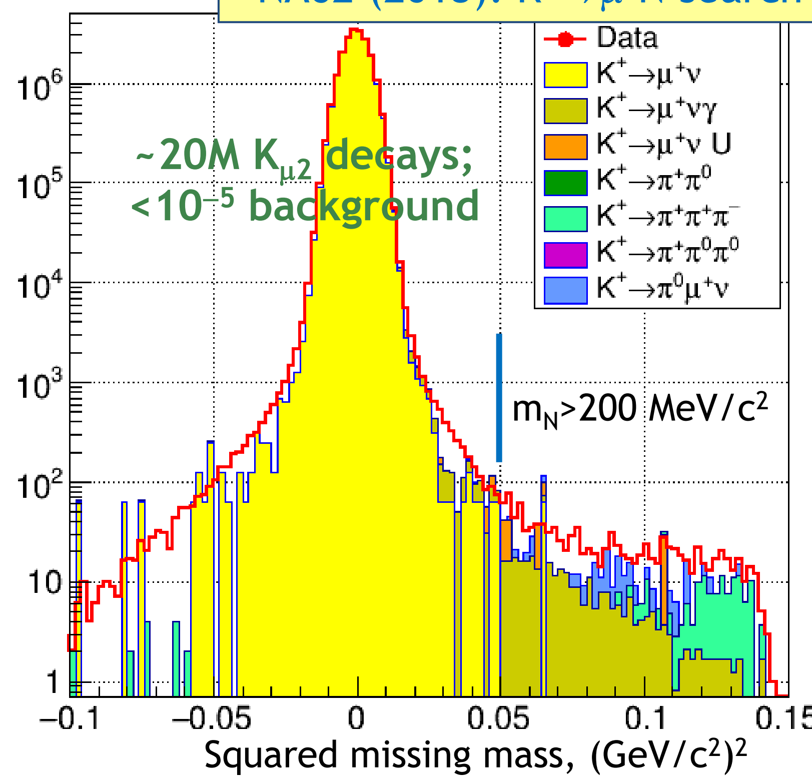
Peak search for $K^+ \to \mu^+ N$ at **NA62 (2015 data)**:

- 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;
- Excellent conditions to a search for $K^+ \to e^+ N$.

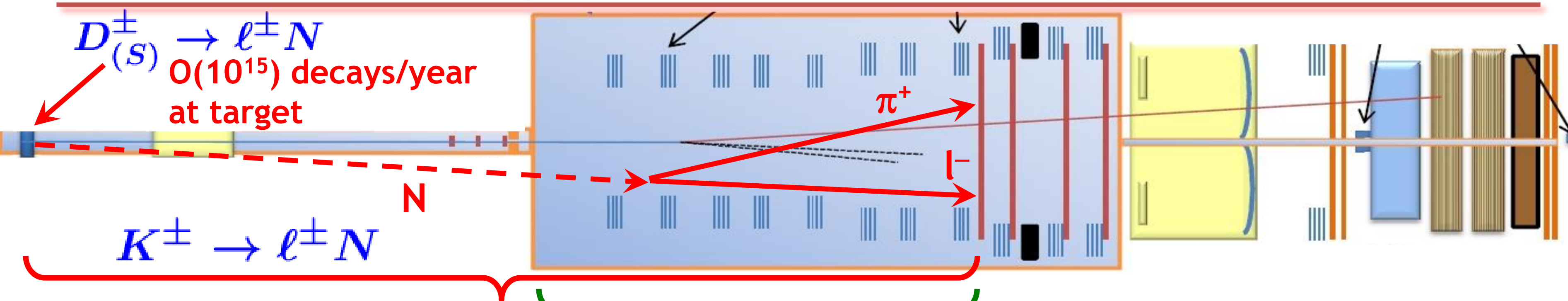
NA62-R_K (2007): $K^+ \to \mu^+ N$ search



NA62 (2015): $K^+ \to \mu^+ N$ search

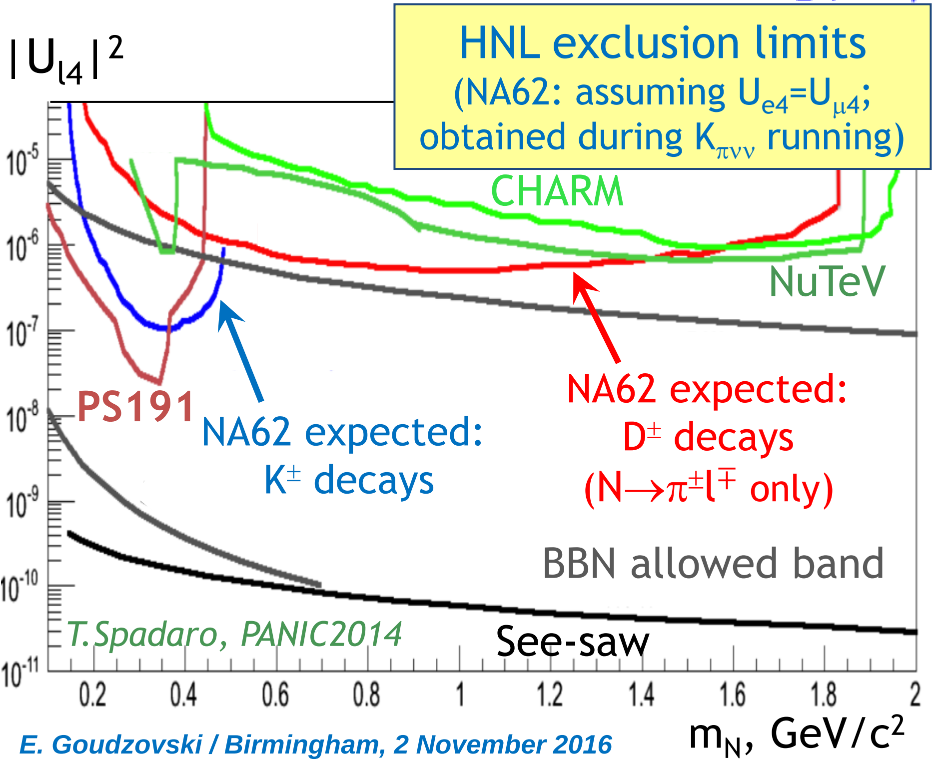


HNL: possible decay searches



Search for decays: $N \to \pi^{\pm}\ell^{\mp}$ ($0.14\ \mathrm{GeV}/c^2 < m_N < 1.9\ \mathrm{GeV}/c^2$)

$N \to \rho^{\pm}\ell^{\mp}$ ($0.8\ \mathrm{GeV}/c^2 < m_N < 1.9\ \mathrm{GeV}/c^2$)



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.

Summary

- **NA62 run 2015–2018:**
  - ✓ The run is focused on the $K_{\pi\nu\nu}$ measurement (**SES~10^{-12}**)
  - ✓ All subdetectors installed and commissioned by 2015
  - ✓ Detector performances are close to the design ones
  - ✓ Collecting data at **35%** intensity now
  - ✓ Expect a few SM $K_{\pi\nu\nu}$ events sensitivity with the **2016** data

- **NA62 run 2021–2024:**
  - ✓ An extensive $K^+/K_L/\pi^0$ rare decay and **beam dump** programme with existing detector is being developed

- **Physics outputs:**
  - ✓ First NA62 results with 2015 data relying on hermetic veto rather than high statistics are expected in 2017
  - ✓ The recent measurement with "old" data (2003–2007) are a training ground and a proof of concept

Backup

TFF measurement with π^0_D decay

Differential decay width:

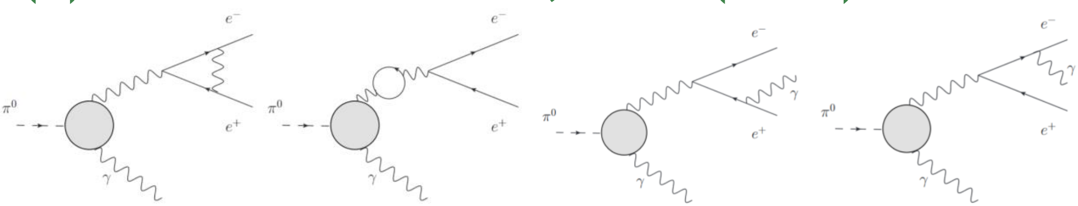
$$\frac{1}{\Gamma(\pi^0_{2\gamma})}\frac{d^2\Gamma(\pi^0_D)}{dx\,dy} = \frac{\alpha}{4\pi}\frac{(1-x)^3}{x}\left(1+y^2+\frac{r^2}{x}\right)|\mathcal{F}(x)|^2$$

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

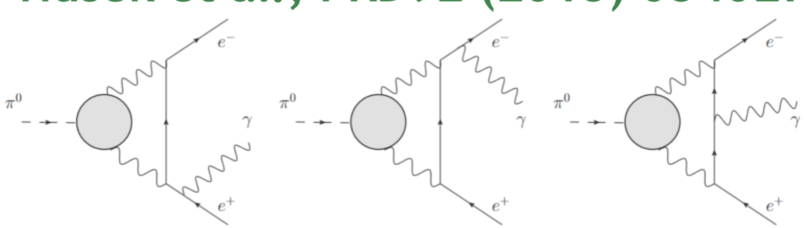
Key issue: radiative corrections (larger effect than TFF)

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

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



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

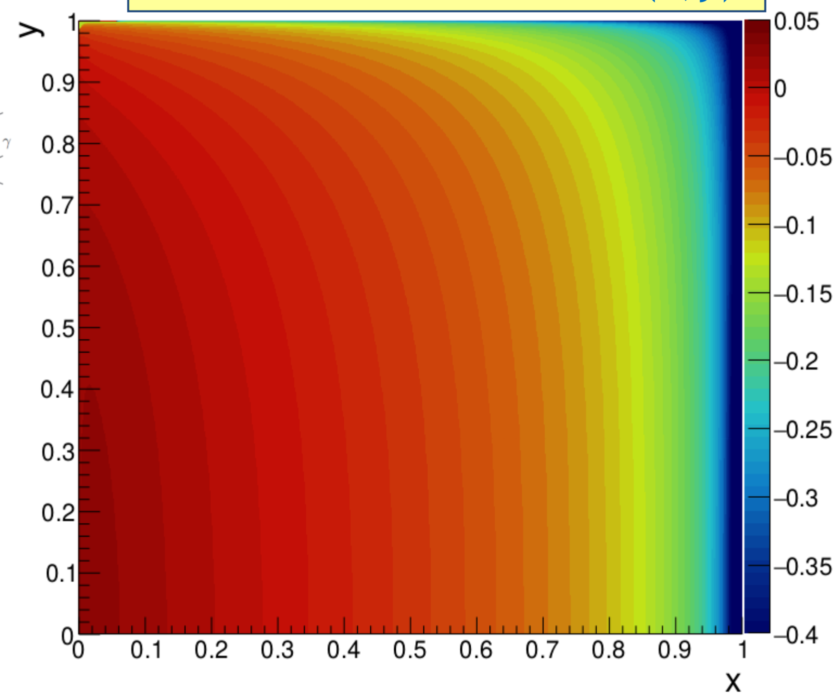


- ✓ Additional diagrams (1γ irreducible).
- ✓ Radiative photon emission simulated.

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

- ❖ VMD expectation: TFF slope $a \approx 0.03$ [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]

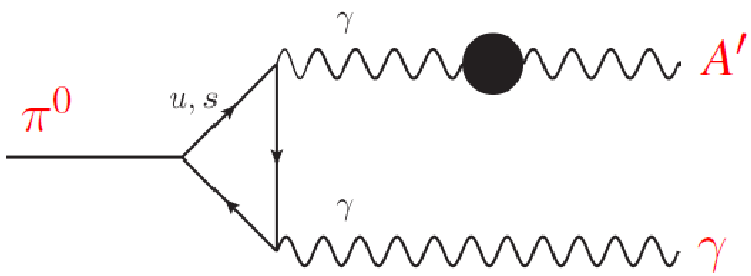
Radiative corrections: $\delta(x,y)$



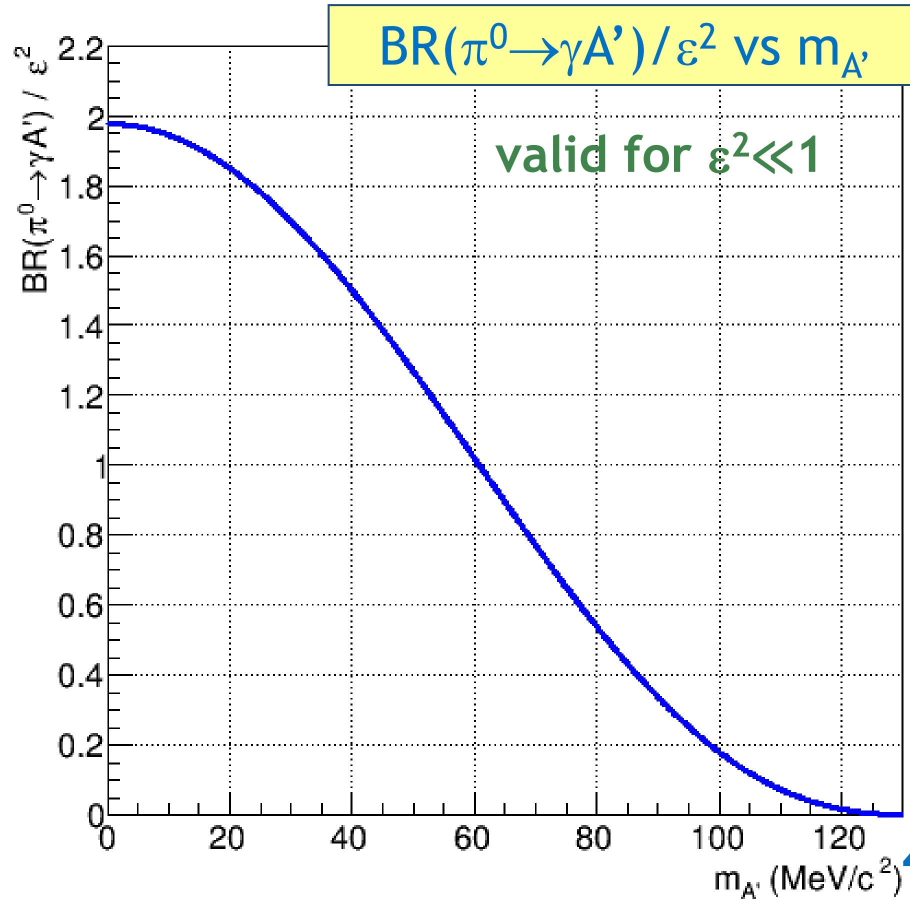
DP production in $\pi^0 \to \gamma A'$ decay

Batell, Pospelov and Ritz, PRD80 (2009) 095024

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

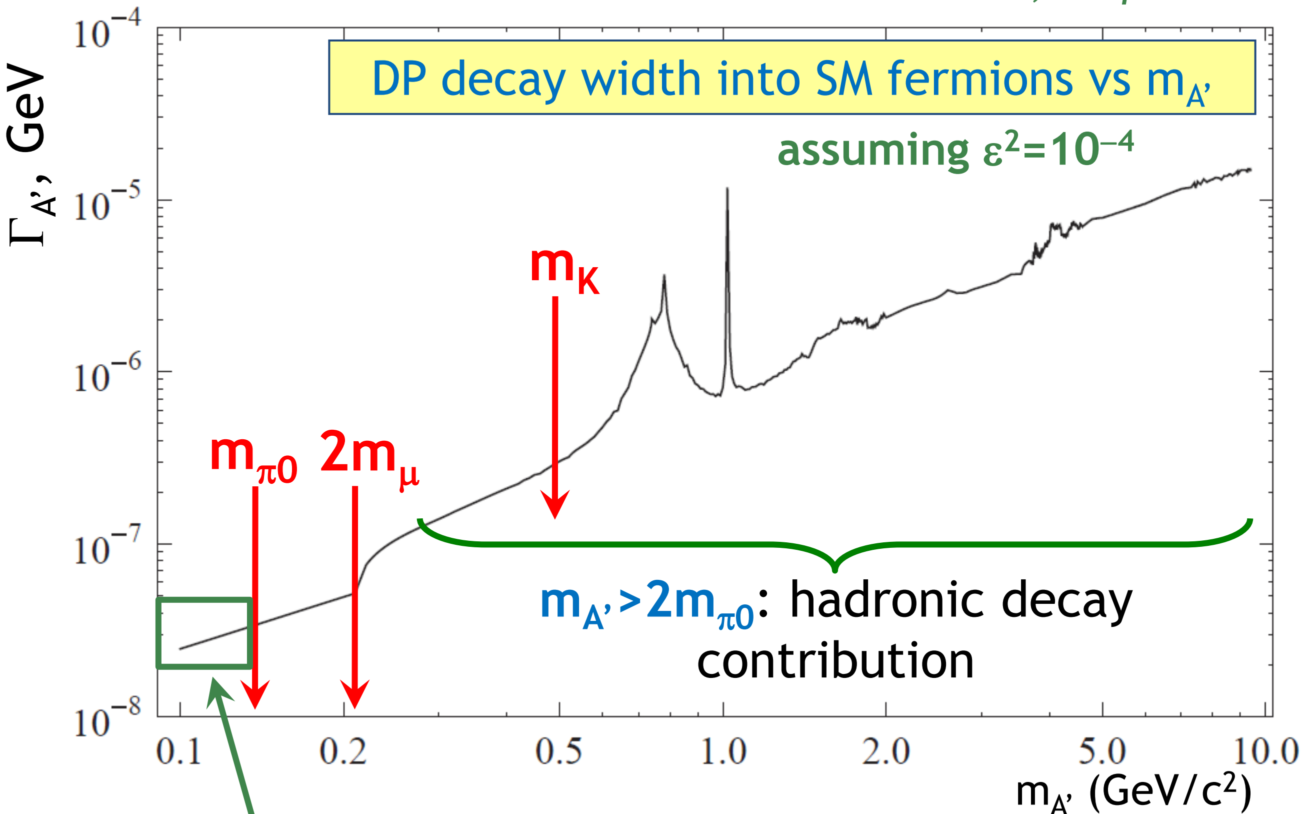


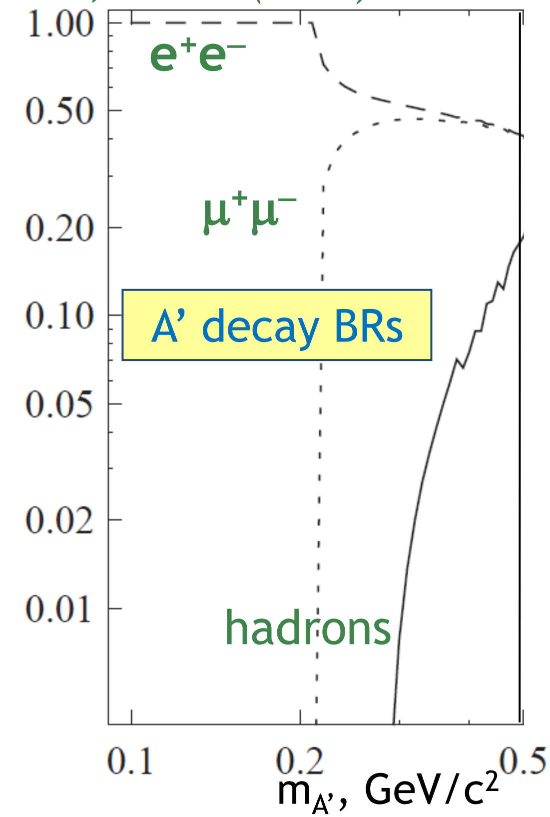
- Probing the Dark Sector.
- Two unknown parameters: mass ($m_{A'}$) and mixing (ε^2).
- Sensitivity to DP for $m_{A'} < m_{\pi 0}$.
- Loss of sensitivity to ε^2 as $m_{A'}$ approaches $m_{\pi 0}$, due to kinematical suppression of the $\pi^0 \to \gamma A'$ decay.



DP decays into SM fermions

Batell, Pospelov and Ritz, PRD79 (2009) 115008



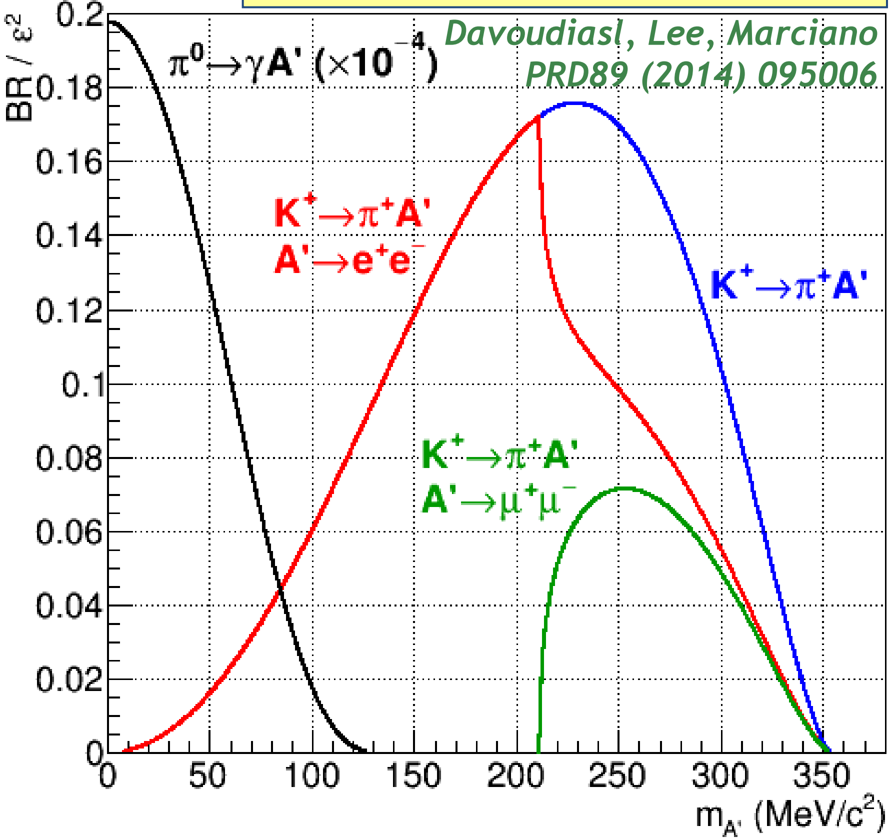


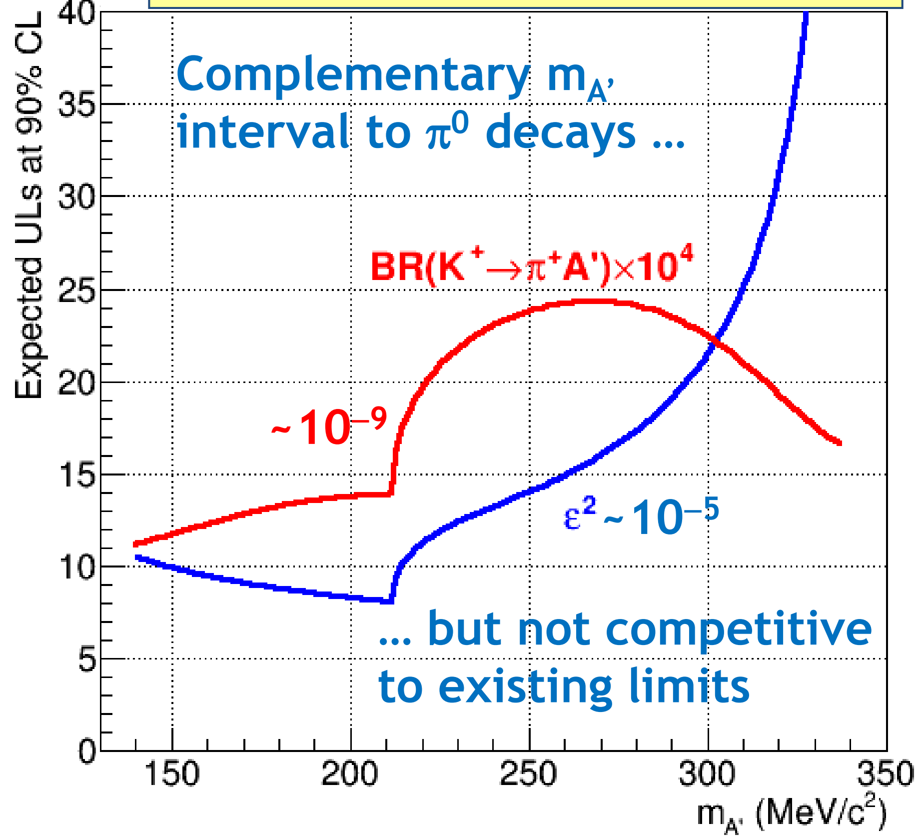
Accessible in π^0 decays: assuming decays only into SM fermions,

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

⇨ 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.

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



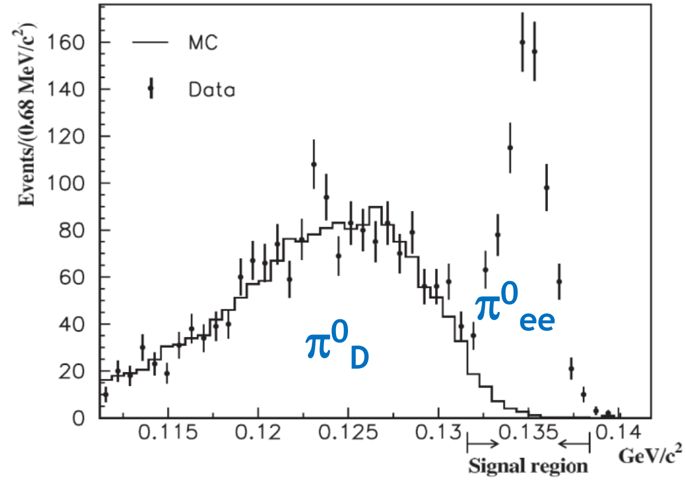


Comparison of ($K^\pm \to \pi^\pm A'$, $A' \to e^+e^-$, $m_{A'} > m_{\pi 0}$) vs ($\pi^0 \to \gamma A'$, $A' \to e^+e^-$, $m_{A'} < m_{\pi 0}$):

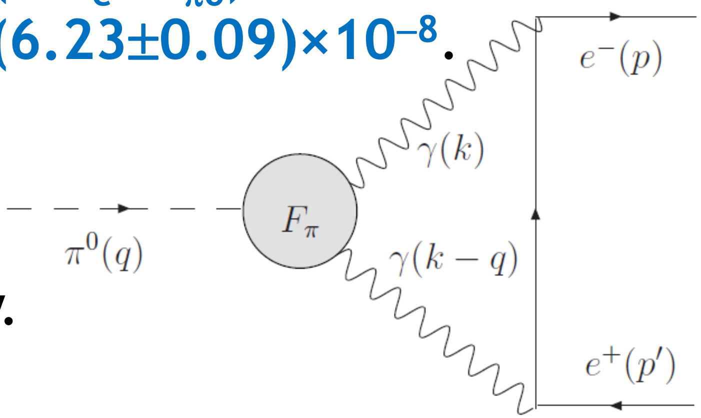
- ❖ Lower irreducible background: $BR(K^\pm \to \pi^\pm e^+e^-) \sim 10^{-7}$ vs $BR(\pi^0_D) \sim 10^{-2}$.
- ❖ Higher acceptance (×4), favourable K/π^0 flux ratio (×4).
- ❖ Therefore the expected BR limits: $BR(K^\pm \to \pi^\pm A') \sim 10^{-9}$ vs $BR(\pi^0 \to \gamma A') \sim 10^{-6}$.
- ❖ However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

$\pi^0 \to e^+e^-$: 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:
  $BR(\pi^0_{ee}, x>0.95) = (6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$.
  Extrapolation:
  $BR(\pi^0_{ee}) = (7.48 \pm 0.29 \pm 0.25) \times 10^{-8}$.
  [PRD 75 (2007) 012004]

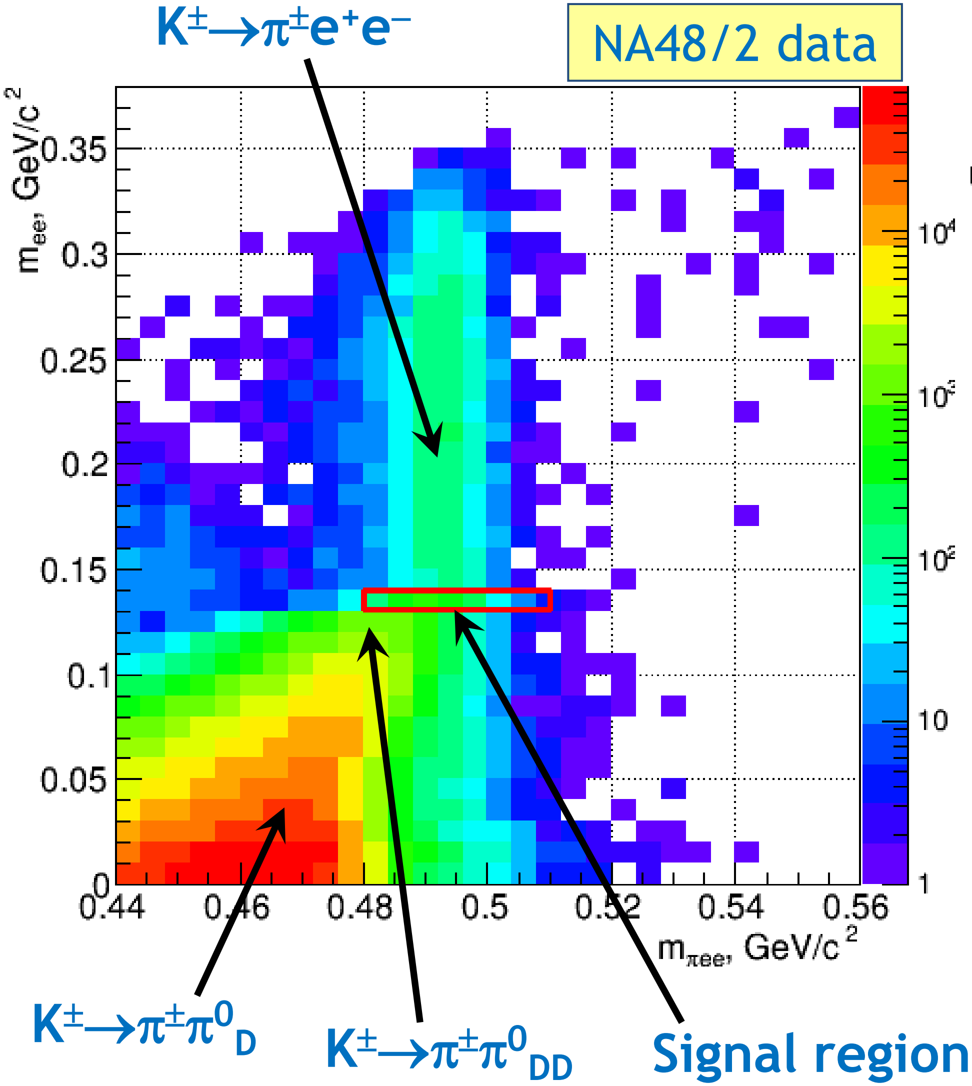


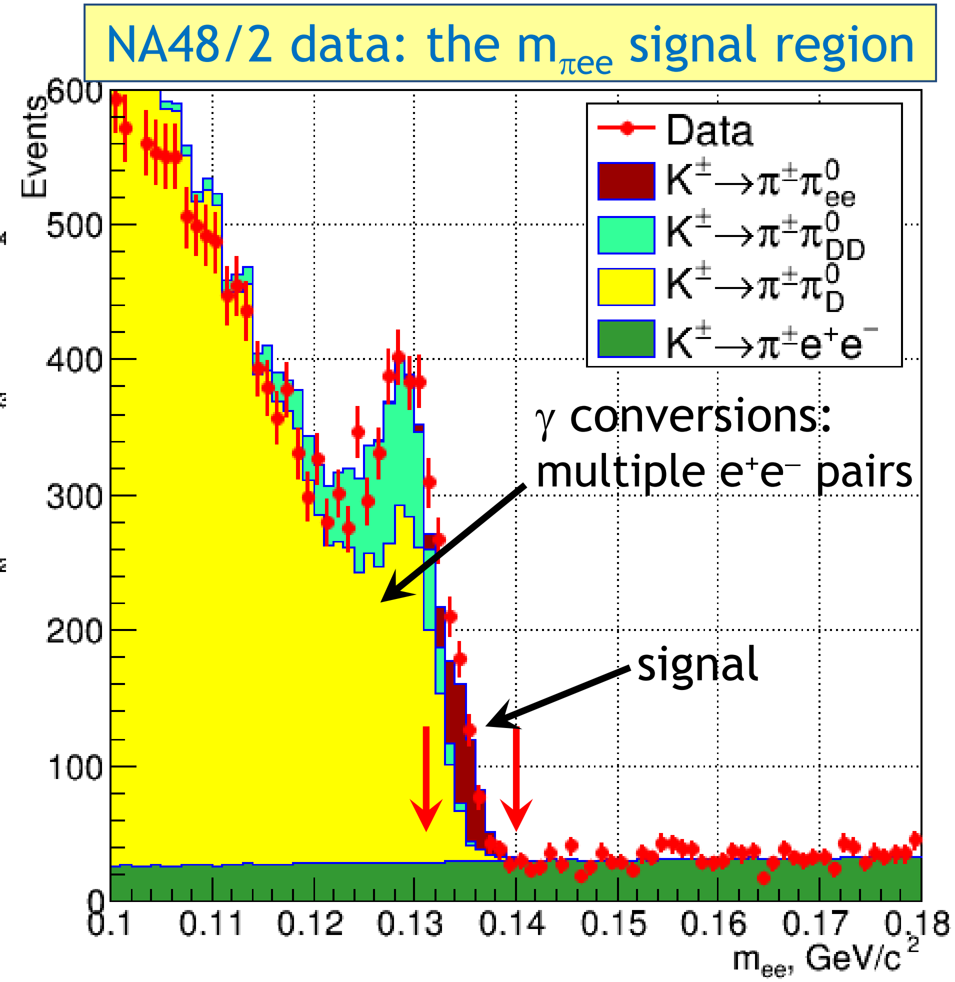
- SM prediction: *loop-induced* and *helicity-suppressed* decay.
  Naïve estimate: $BR(\pi^0_{ee}) \sim (\alpha m_e/m_{\pi 0})^2 \sim 10^{-9}$.
  Detailed calculations: $BR(\pi^0_{ee}) = (6.23 \pm 0.09) \times 10^{-8}$.
  [Dorokhov et al., PRD75 (2007) 114007,
  Husek et al., EPJ C74 (2014) 3010]



- Experiment vs theory: ~3σ discrepancy.

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

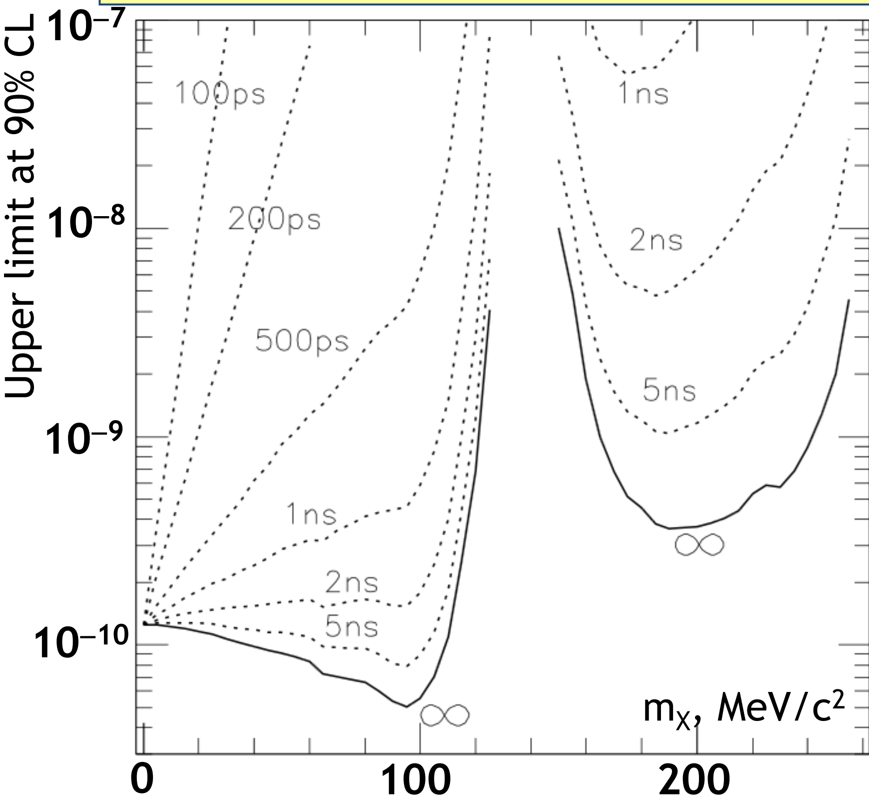




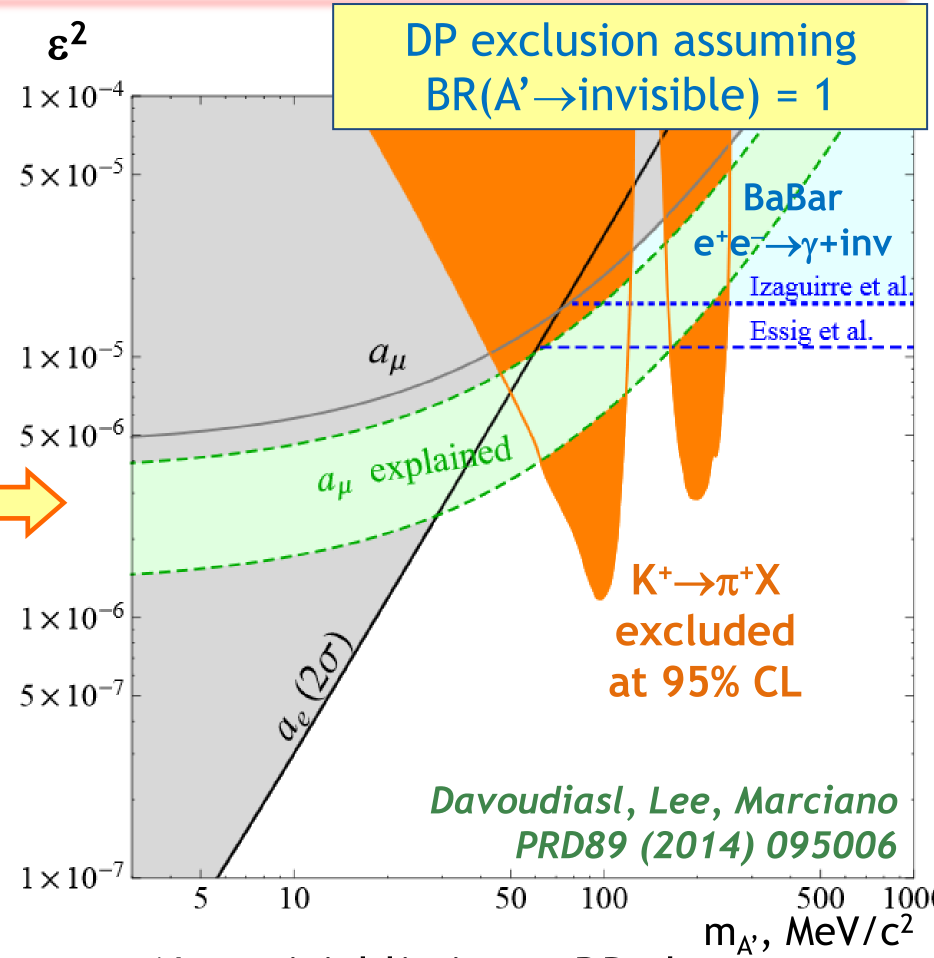
NA48/2: about **300** events collected, but **signal/background < 1**. Can be better at NA62.

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

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

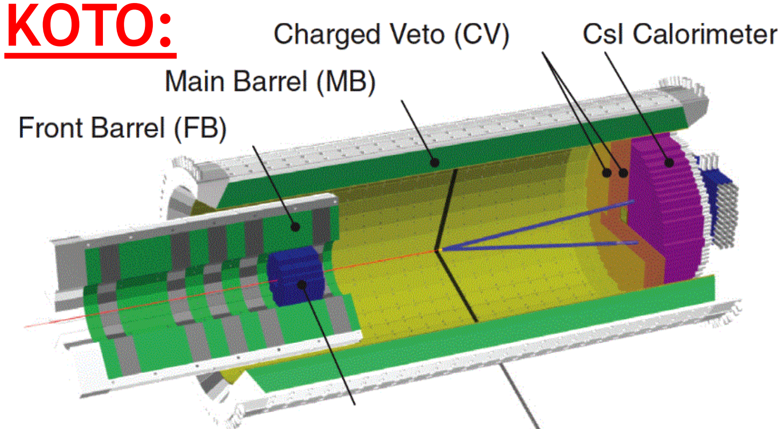
Non-trivial limits on DP phase space
Including the $(g-2)_\mu$ favoured band,
assuming invisible DP decays.

NA62: expect an order of magnitude improvement

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 $SES\sim0.5\times10^{-12}$ is under consideration for Run 4 (2026–2029).

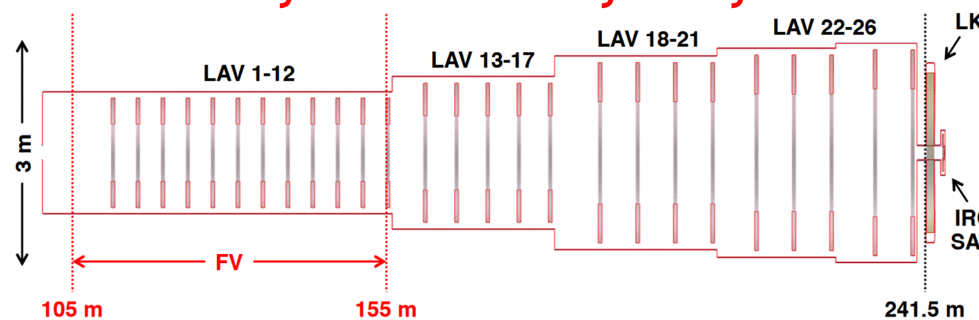
KOTO:



- 30 GeV protons (300 kW); $\langle p_{KL}\rangle=2$ GeV/c;
- Proposal: $SES=8\times10^{-12}$ (~4 SM evts) with S/B=1.4 in three years.
- Short (100h) run in 2013: $SES=1.3\times10^{-8}$;
- 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; $\langle p_{KL}\rangle\sim100$ 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).