На конкурс научных работ ОИЯИ
(экспериментальная работа)

Представляется цикл работ

Изучение редких и поиск запрещённых распадов заряженных каонов

По данным NA48/2 и NA62 (SPS CERN)

Коллектив соавторов:

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- **K_{l3} form factors (NA48/2)**

- **Study of the $K^+ \to \pi^+\pi^0 e^+ e^-$ decay (NA48/2)**

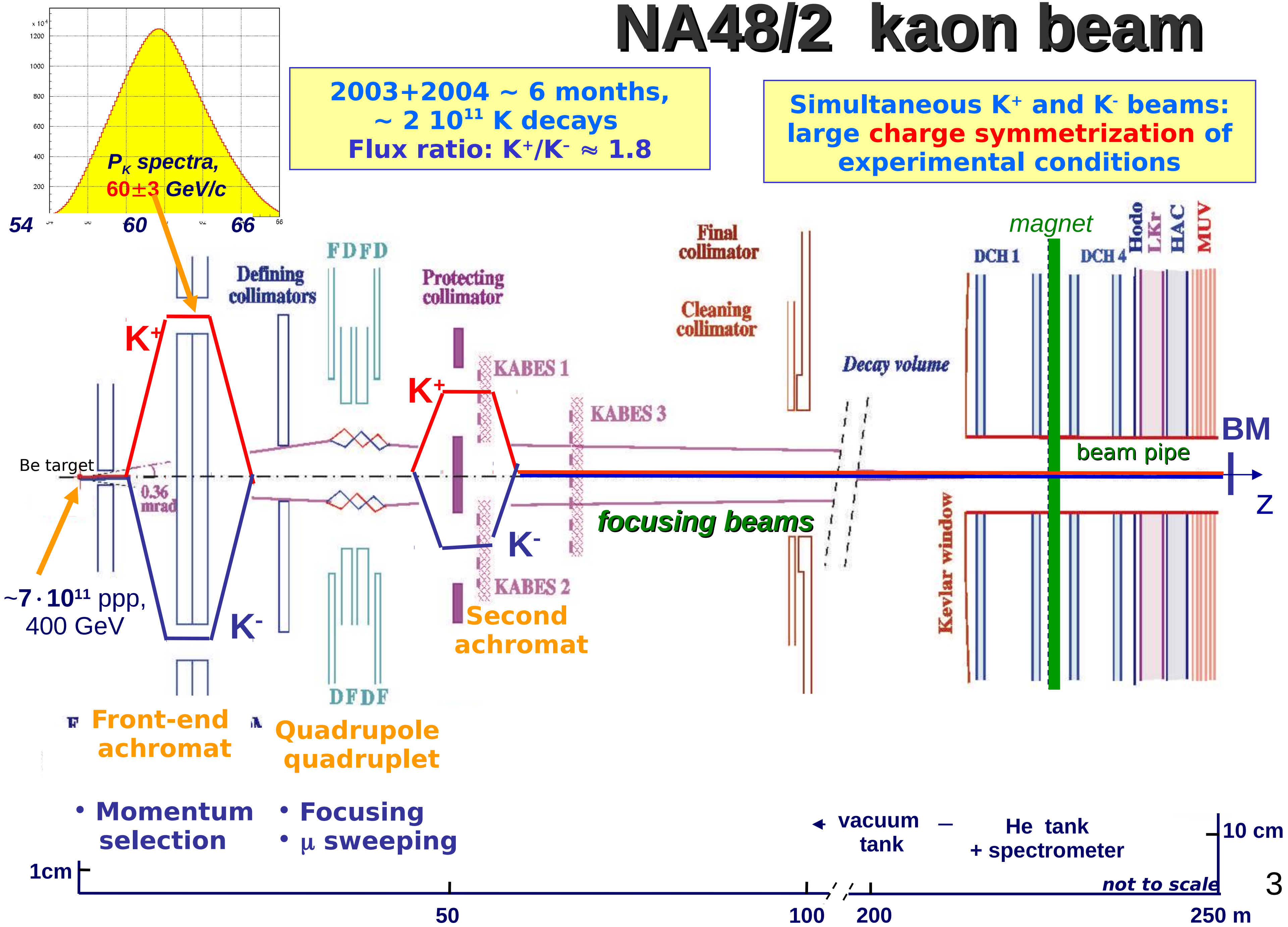
- **Search for lepton number violation in K+ decays (NA62)**

- **Search for heavy neutral lepton production in K+ decays (NA62)**

NA48/2 kaon beam

2003+2004 ~ 6 months,
~ 2 10^{11} K decays
Flux ratio: K^+/K^- ≈ 1.8

Simultaneous K^+ and K^- beams:
large charge symmetrization of
experimental conditions



$K^{\pm} \rightarrow \pi^0 l^{\pm} \nu$ (K_{l3}) form factors

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JHEP 1810 (2018) 150.

experimental input for $|V_{us}|$ extraction (in addition to $\Gamma(K_{l3}^{\gamma})$)

Without radiative effects : $\rho_0 = d^2N/(dE_l\, dE_\pi) \sim A\,|f_+(t)|^2 + B\, f_+(t)\, f_-(t) + C\,|f_-(t)|^2$,
where $t = (P_K - P_\pi)^2 = M_K^2 + M_\pi^2 - 2\, M_K E_\pi$
and $f_-(t) = (f_+(t) - f_0(t))(m_K^2 - m_\pi^2)/t$. (just another formulation, f_0 is «scalar» and f_+ is «vector» FF), E_l is charged lepton energy, E_π is π^0 energy (both in the kaon rest frame).

$A = M_K(2\, E_l E_\nu - M_K(E_\pi^{max} - E_\pi)) + M_l^2\, ((E_\pi^{max} - E_\pi)/4 - E_\nu)$
$B = M_l^2(E_\nu - (E_\pi^{max} - E_\pi)/2)$ negligible for Ke3
$C = M_l^2(E_\pi^{max} - E_\pi)/4$ negligible for Ke3
$E_\pi^{max} = (M_K^2 + M_\pi^2 - M_l^2)/(2\, M_K)$

FF Parameterisation	f_+(t,parameters)	f_0(t,parameters)
Taylor expansion	$1+\lambda'_+\, t/m^2_{\pi+} + ½\, \lambda''_+ (t/m^2_{\pi+})^2$	$1 + \lambda'_0\, t/m^2_{\pi+}$
Pole	$M_V^2 / (M_V^2 - t)$	$M_S^2 / (M_S^2 - t)$
Dispersive* H(t), G(t) functions fixed from theory and other data. Depend on extra external parameters.	$\exp((\Lambda_+ + H(t))\, t/m^2_{\pi+})$	$\exp((\ln[C] - G(t))\, t/(m_K^2 - m^2_{\pi0}))$

* [V. Bernard, M. Oertel, E. Passemar, J. Stern. Phys.Rev. D80 (2009) 034034]

Data: 3 days from the NA48/2 data taken in 2004 (low intensity)

Trigger: 1 charged track (2 hodoscope hits) and E_{LKr} > 10 GeV

Registered :

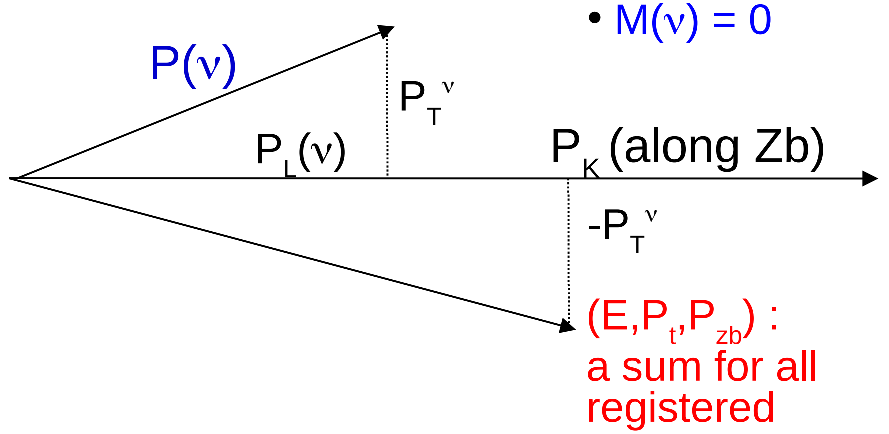
- **1 track** (> 0 candidates): **P_e >= 5 GeV, P_μ >= 10 GeV , R_{MUV} > 30 cm, $|X_{MUV},Y_{MUV}|$<115 cm.**
- **2 LKr clusters** (> 1 candidates): **E > 3 GeV, distance to closest track > 15 cm.**

Kaon momentum reconstruction

Neutrino is missing, beam geometry and average momentum P_b are measured from $K_{3\pi}^{\pm}$

Two solutions of the quadratic equation for P_K

Assumptions:
- $P_T(\nu) = - P_t$
- $M(\nu) = 0$

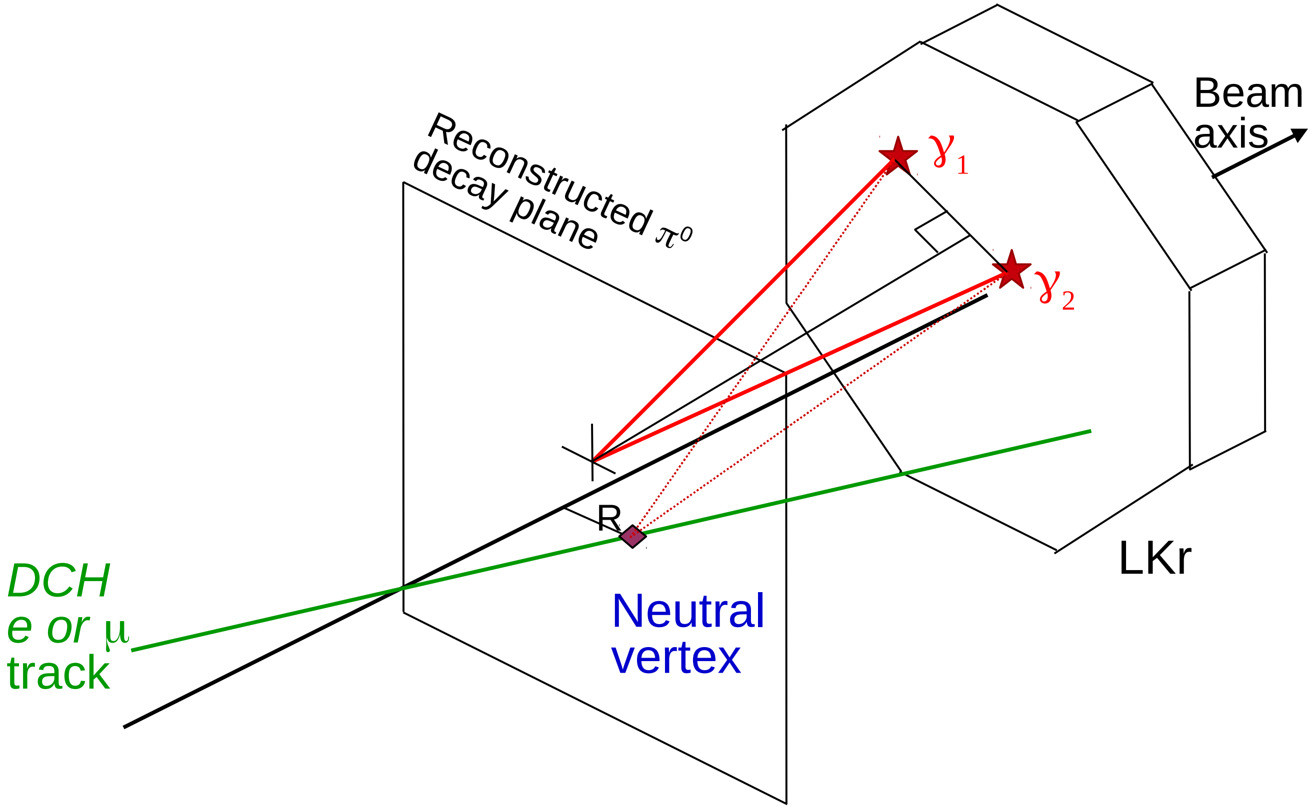


- Best P_K solution = closest $P_{1,2}$ to the average beam momentum P_b (measured from $3\pi^{\pm}$ decays for each run).
- Select: -7.5 GeV/c < (P_K — P_b) < 7.5 GeV/c
- For each event, separately for K_{e3} and $K_{\mu3}$ selections, the combination with a minimum $\Delta P = |P_K - P_b|$ is the best candidate.

Selection:

π^0 :

- A pair of clusters in-time (within 5 ns) without any in-time extra clusters (to suppress BG)
- Distance between the clusters in a pair > 20 cm
- $E(\pi^0)$ > 15 GeV (for the trigger efficiency)
- Z of decay: from 2γ assuming π^0 mass («neutral Z»); Z > 200 cm downstream the last collimator
- DCH1 inner flunge cut for the both γ



Track selection and identification

- A good track in-time with the π^0 within 10 ns.
- No extra good track within 8 ns (against showers).

- If **2.0 > E_{LKr}/P_{DCH} > 0.9**, it is an electron of K_{e3} .

- If **E_{LKr}/P_{DCH} < 0.9** (for true muons it cuts nothing) and there is a MUV muon associated, it is a $K_{\mu3}$ muon.

Loose **E_{LKr}/P_{DCH}** cuts <=> negligible related systematics.

Neutral vertex:

$Z_{decay} = Z(\pi^0)$; X_{decay}, Y_{decay} = impact point of reconstructed charged track on Z_{decay} plane

Specific $K_{\mu3}$ selection cuts

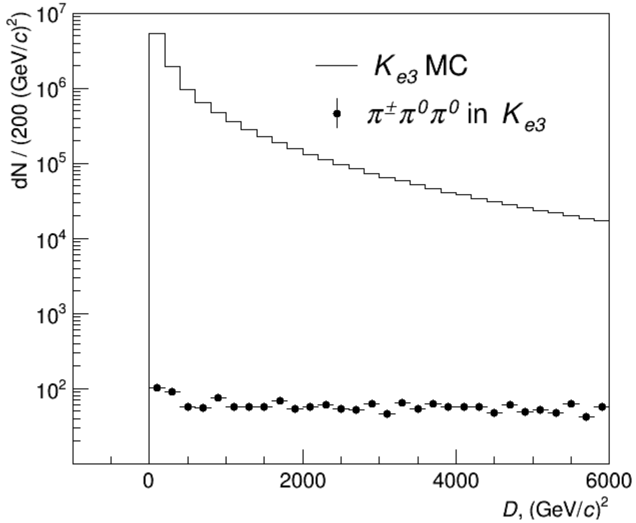
Against $\pi^{\pm}\pi^{0}\pi^{0}$:

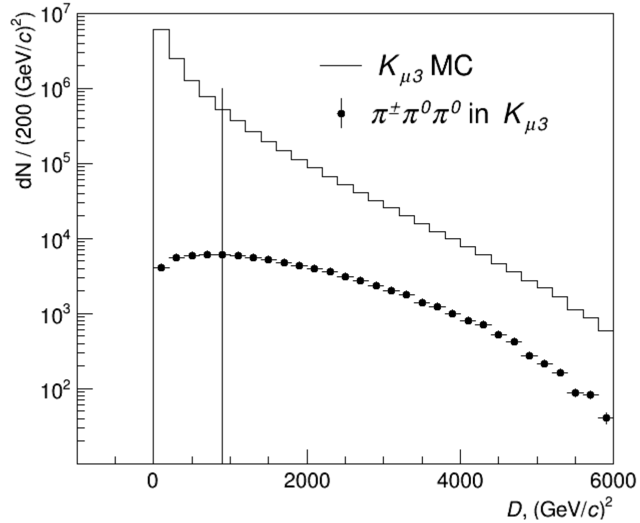
- **$|P_2 - P_1| < 60$ GeV**

  <=>

  $D < 900$ GeV^2

[D is large when one pion is missing]





Against $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$

& $\pi^{\pm}$ misidentification as μ

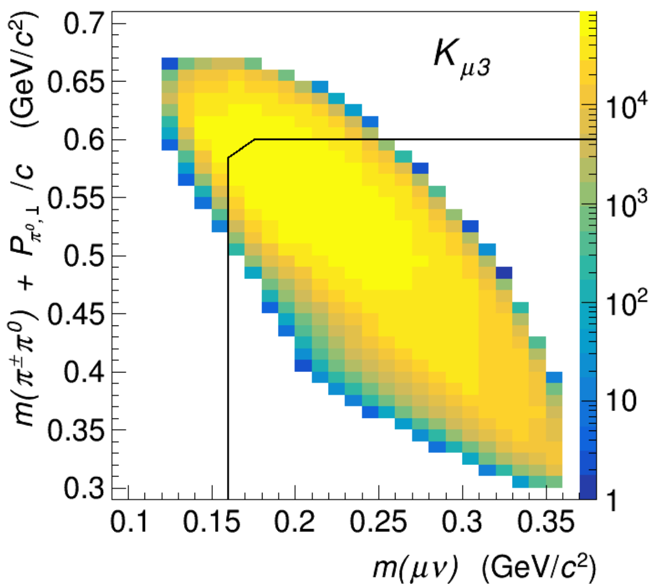
$m(\pi^{+}\pi^{0}) < 0.475$ GeV/c^2

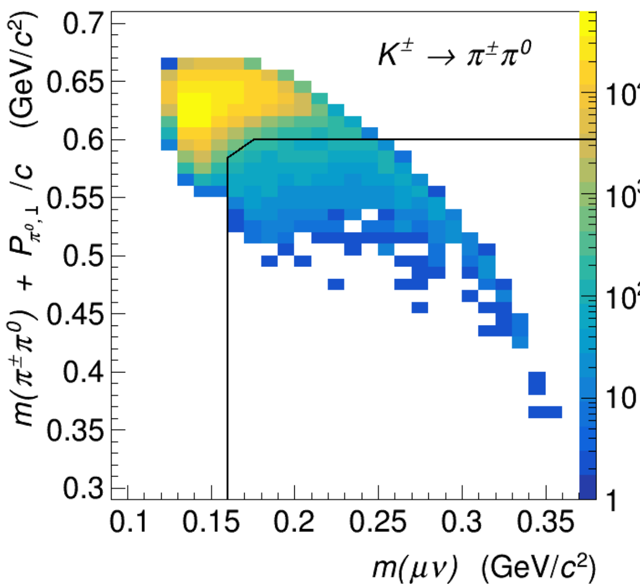
& $\pi^{\pm} \rightarrow \mu^{\pm}\nu$

$m(\pi^{+}\pi^{0}) < 0.6 - P_t(\pi^{0})/c$

$m(\mu^{\pm}\nu) > 0.16$ GeV/c^2

(to exclude π^{+} mass region)

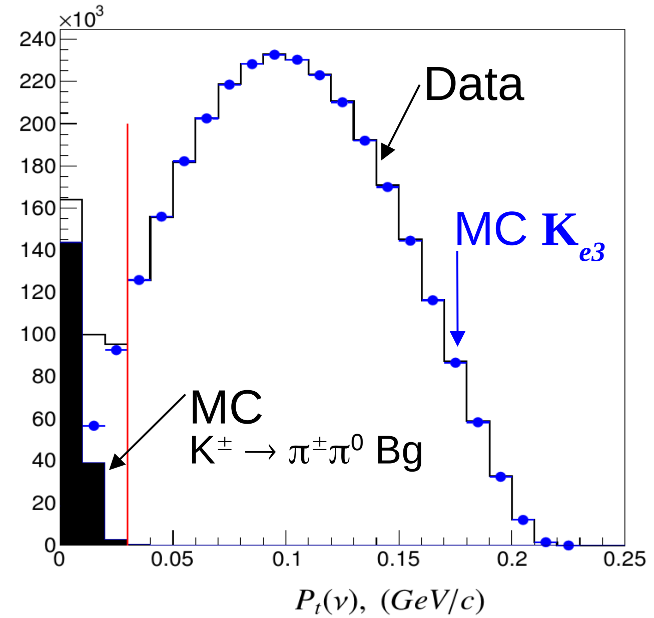




Specific K_{e3} selection cut

ν transversal momentum with respect to beam axis P_t >= 0.03 GeV

against $K^{\pm} \to \pi^{\pm}\pi^{0}$ with $\pi^{\pm}$ misidentified as *e* (when E/P > 0.9);



Common cuts:

- **Beam (transverse elliptic) variable B< 11.** →

B $$= \sqrt{\left(\frac{X_n - X_n^0(Z_n)}{\sigma_{Xn}(Z_n)}\right)^2 + \left(\frac{Y_n - Y_n^0(Z_n)}{\sigma_{Yn}(Z_n)}\right)^2},$$

X_n, Y_n, Z_n are the reconstructed neutral vertex coordinates, X^0_n, Y^0_n , σ_{Xn}, σ_{Yn} are the reconstructed beam central positions and widths **(1-0.6 cm)**.

- $\mathbf{P_L(\nu)^2 = (E^{\nu})^2/c^2 - (P_t^{\nu})^2 > 0.0014\ GeV^2/c^2}$

negative and zero regions are difficult to simulate exactly: sensitive to beam shape.

- **Z > -1600 cm**

(Final collimator is at Z = -1800 cm)

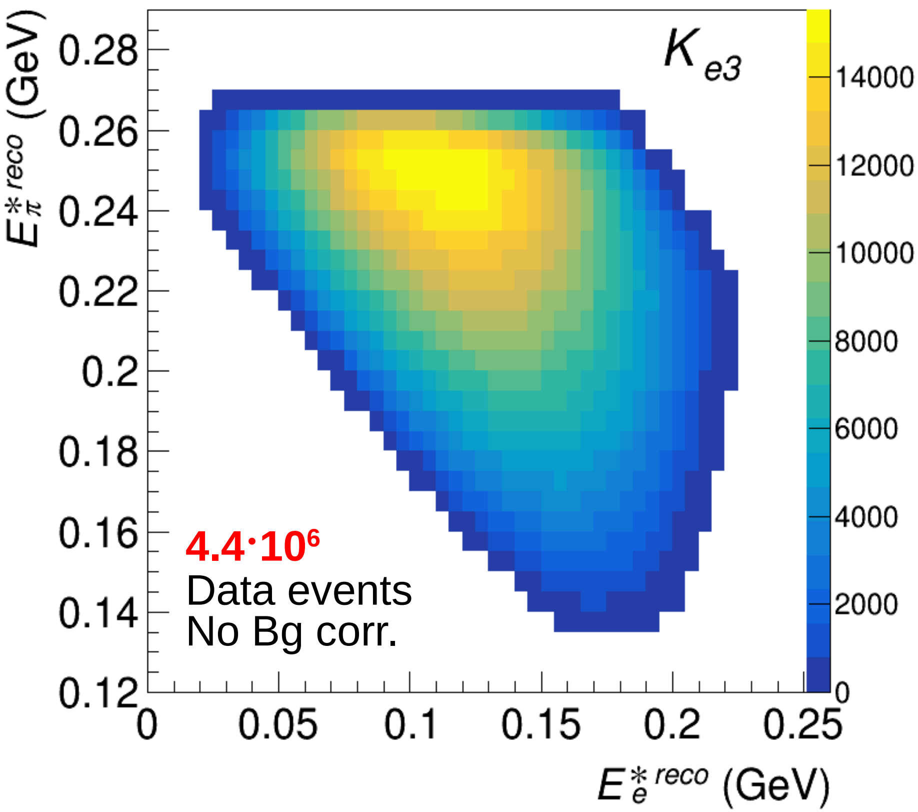
Background

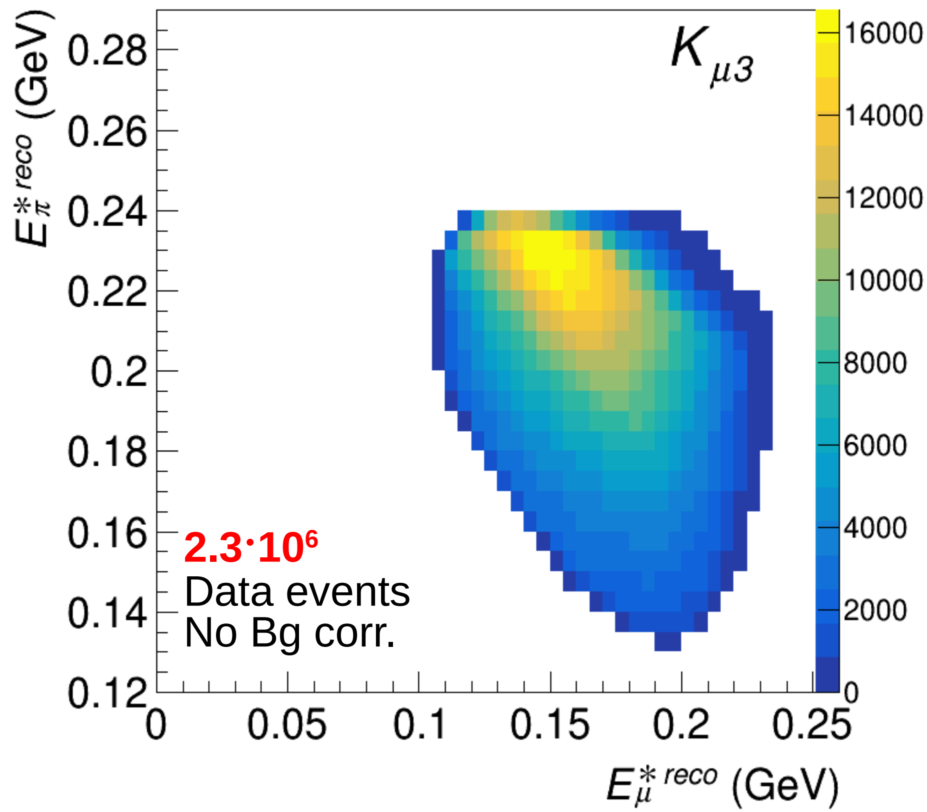
Decay	r_e, 10^{-3}	r_μ, 10^{-3}
$K^\pm \to \pi^\pm(\pi^0 \to 2\gamma)$	0.272	0.392
$K^\pm \to \pi^\pm 2(\pi^0 \to 2\gamma)$	0.287	2.192
$K^\pm \to \pi^\pm(\pi^0 \to e^+e^-\gamma)$	0.049	0.000
$K^\pm \to \pi^\pm\gamma(\pi^0 \to 2\gamma)$	0.004	0.044
$K^\pm \to \pi^0\mu^\pm\nu(\mu \to e\nu)$	0.004	0.000

$\mathbf{r_e}$ — background to signal ratio in K_{e3} data
$\mathbf{r_\mu}$ — background to signal ratio in $K_{\mu3}$ data

BG contamination from 2π and 3π: very small, $O(10^{-4} - 10^{-3})$
BG contamination from other channels: negligible

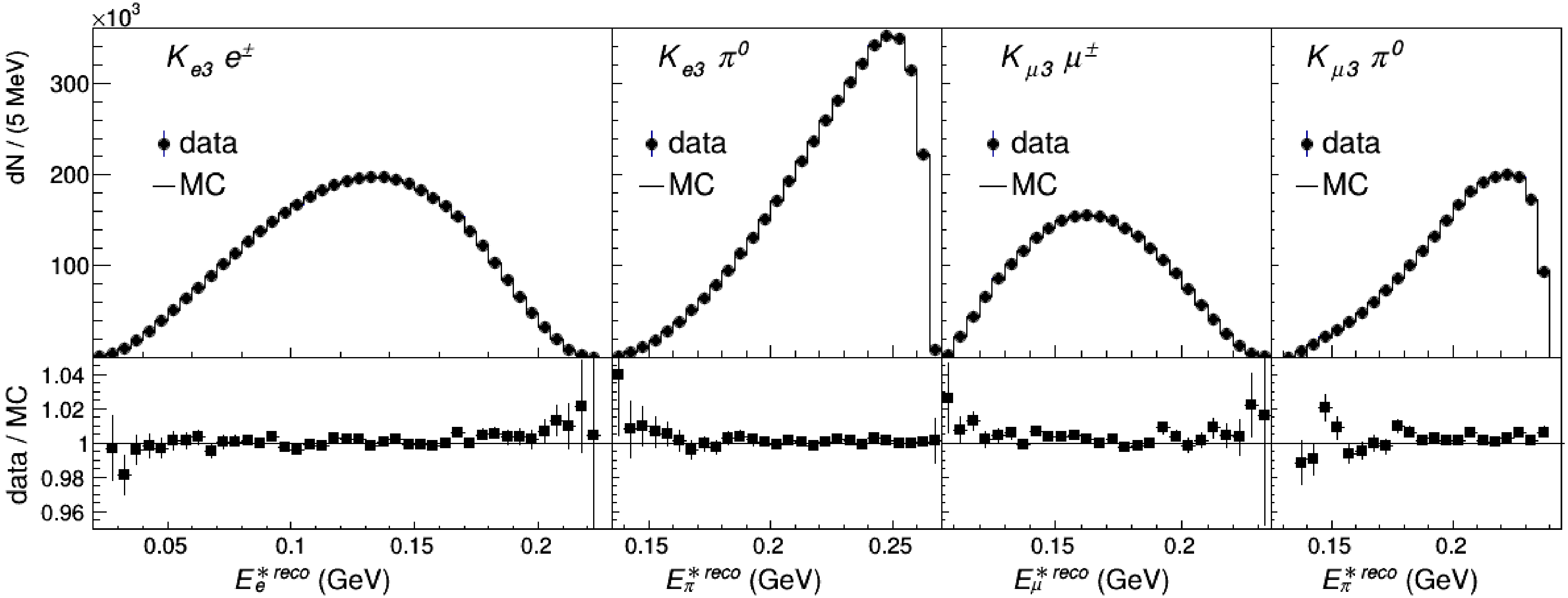
Experimental Dalitz plots (5x5 MeV cells)





In order to extract form factors, the background-corrected Dalitz plots were fitted by reweighting of each MC event using variable form factor parameters.

Dalitz plot projections



Reconstructed lepton energy and pion energy distributions for data after background subtraction and simulated samples according to the fit results using the Taylor expansion model (other parameterisations look very similar).

The fit results and systematic uncertainties obtained (see **JHEP 1810 (2018) 150)** :

- **For K_{e3}**
- **For $K_{\mu 3}$**
- **For the combined K_{l3} result:**

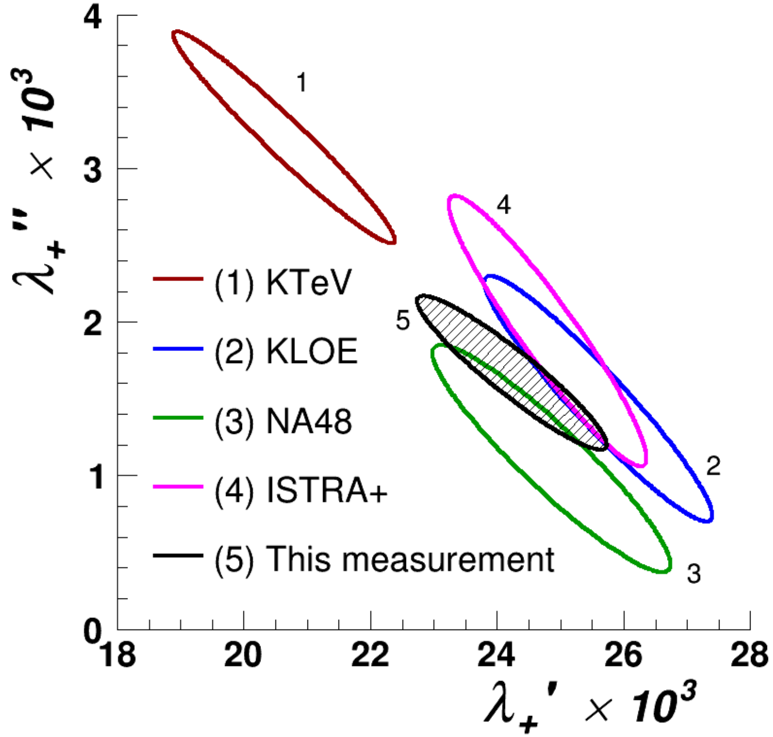
Joint fits minimizing $\chi^2(K_{e3}) + \chi^2(K_{\mu 3})$ with a common set of fit parameters.

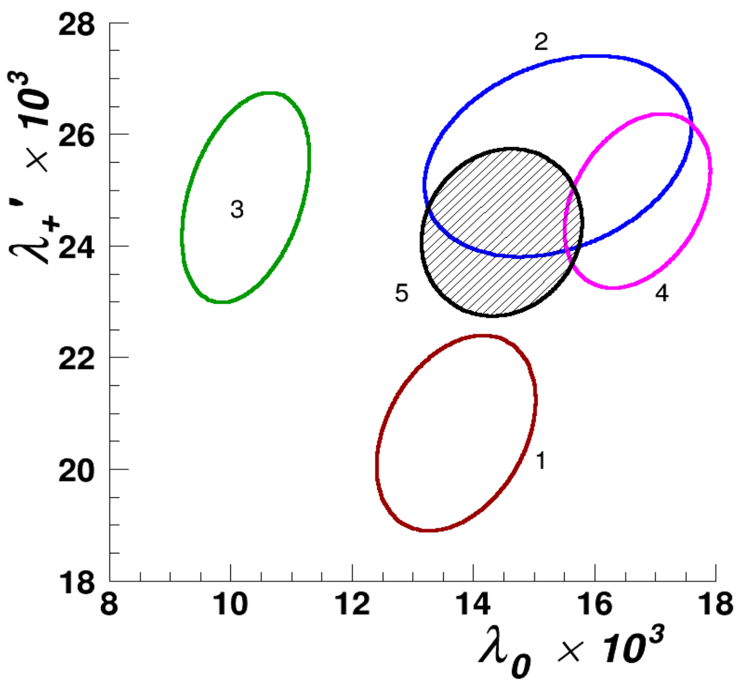
Results of the joint K_{l3} (K_{e3} + $K_{\mu3}$) analysis

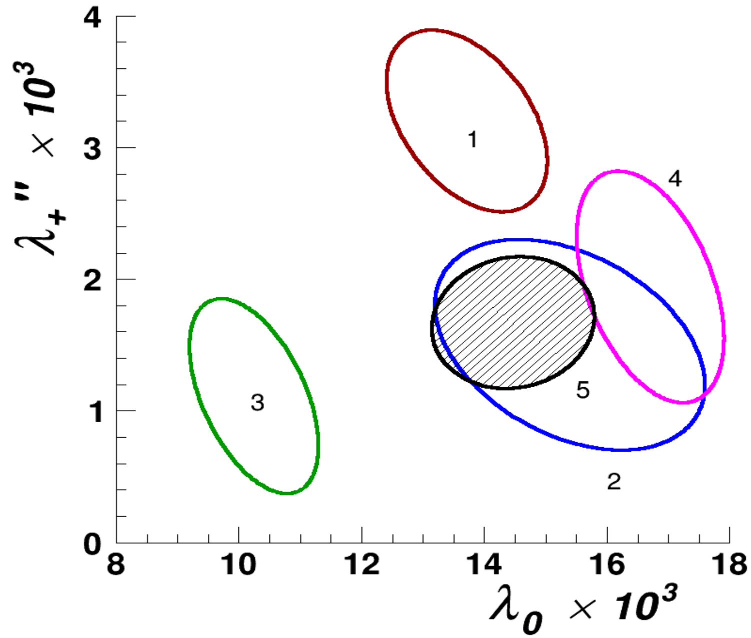
	λ'_+	λ''_+	λ_0	m_V	m_S	Λ_+	$\ln C$
Central values	24.24	1.67	14.47	884.4	1208.3	24.99	183.65
Statistical error	0.75	0.29	0.63	3.1	21.2	0.20	5.92
Diverging beam component	0.97	0.35	0.55	1.1	32.2	0.08	9.43
Kaon momentum spectrum	0.00	0.00	0.02	0.1	0.7	0.00	0.19
Kaon mean momentum	0.04	0.01	0.04	0.2	1.7	0.01	0.47
LKr energy scale	0.66	0.12	0.61	4.9	17.4	0.32	5.16
LKr non-linearity	0.20	0.01	0.55	3.1	19.6	0.20	5.77
Residual background	0.08	0.03	0.04	0.1	0.7	0.01	0.16
Electron identification	0.01	0.01	0.01	0.2	0.2	0.01	0.05
Event pileup	0.23	0.08	0.08	0.4	0.2	0.03	0.07
Acceptance	0.23	0.07	0.03	0.7	4.3	0.05	1.11
Neutrino momentum resolution	0.16	0.04	0.04	0.9	3.3	0.06	0.88
Trigger efficiency	0.29	0.13	0.20	1.1	9.9	0.07	2.82
Dalitz plot binning	0.05	0.04	0.06	0.9	1.1	0.06	0.29
Dalitz plot resolution	0.02	0.01	0.03	0.0	1.3	0.00	0.39
Radiative corrections	0.17	0.01	0.57	2.5	20.1	0.16	5.92
External inputs						0.44	2.94
Systematic error	1.30	0.41	1.17	6.7	47.5	0.62	14.25
Total error	1.50	0.50	1.32	7.4	52.1	0.65	15.43
Correlation coefficient	-0.934 (λ'_+/λ''_+) 0.118 (λ'_+/λ_0) 0.091 (λ''_+/λ_0)			0.374		0.354	
χ^2/NDF	979.6/1070			979.3/1071		979.7/1071	

Joint K_{l3} results comparison for quadratic parameterization

1σ ellipses (39.4% CL) rather than 68% for better visibility







$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ decay

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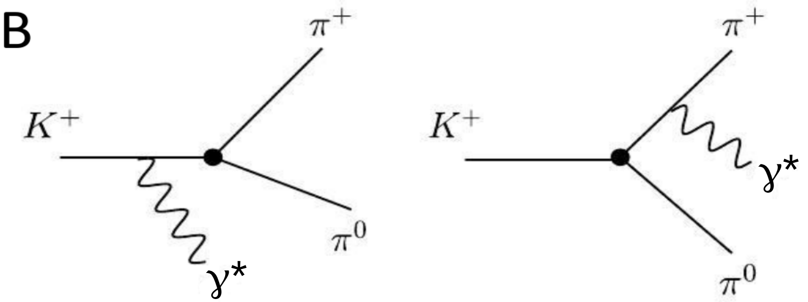
Motivation:

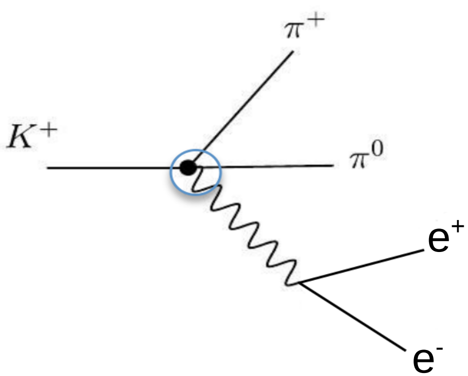
- Never observed so far: confirmation of BR magnitude ChPT predictions:
  - H.Pichl, EPJ C20 (2001) 371;
  - L.Cappiello, O.Cata, G.D'Ambrosio, D. Gao, EPJ C72 (2012) 1872;
  - L.Cappiello, O.Cata, G.D'Ambrosio, EPJ C78 (2018) 265.

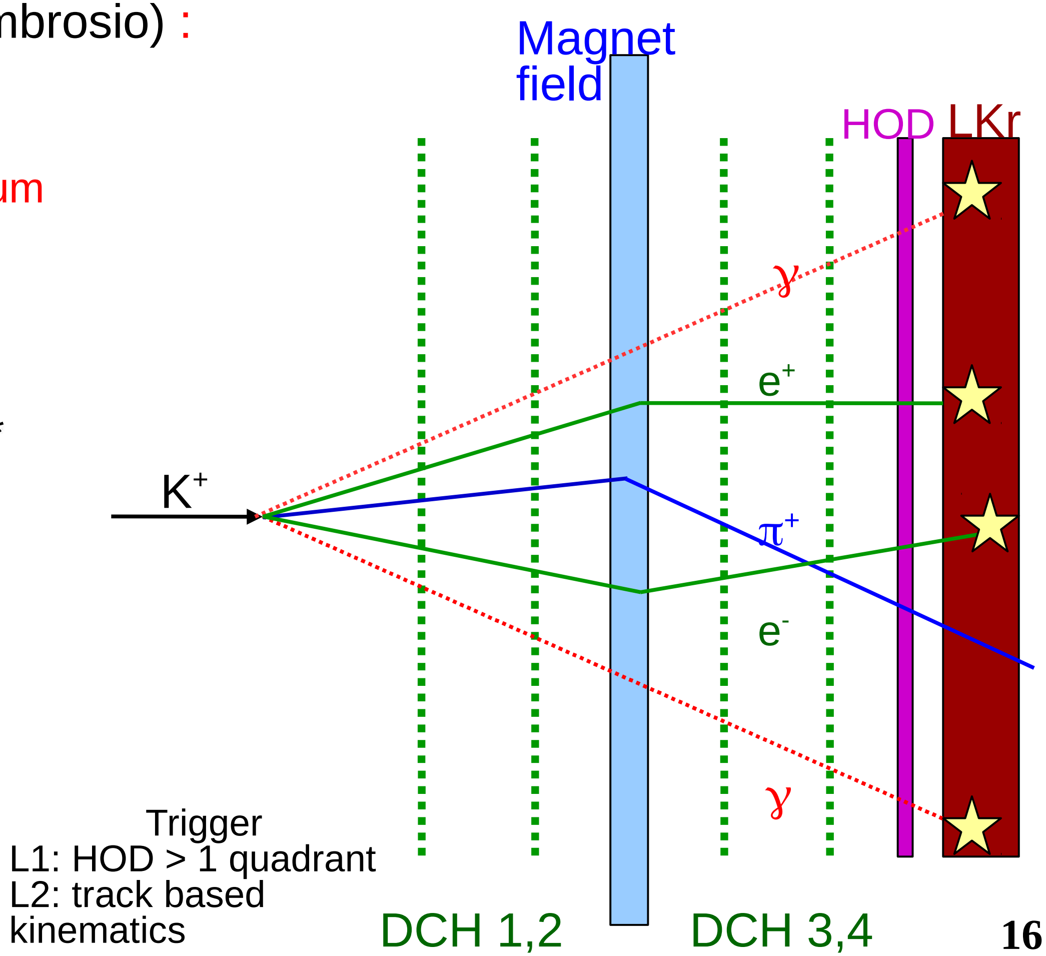
- If a detailed analysis possible (G.D'Ambrosio) :
  - Sign of interference term (IB,E),
  - Magnetic term from (IB,M) interference
  - Charge asymmetry — direct CPV
  - ChPT predicted bump in $M(e^{+}e^{-})$ spectrum

IB



DE(M,E)





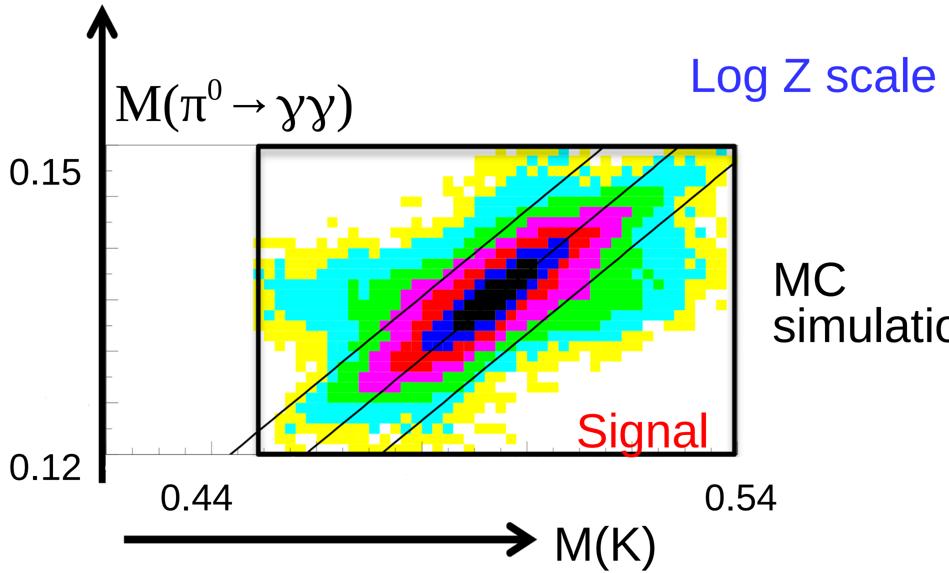
Events selection

Signal: $\pi^{\pm}(\pi^0 \to \gamma\gamma)e^+e^-$ Normalization: $\pi^{\pm}(\pi^0_D \to \gamma e^+e^-)$

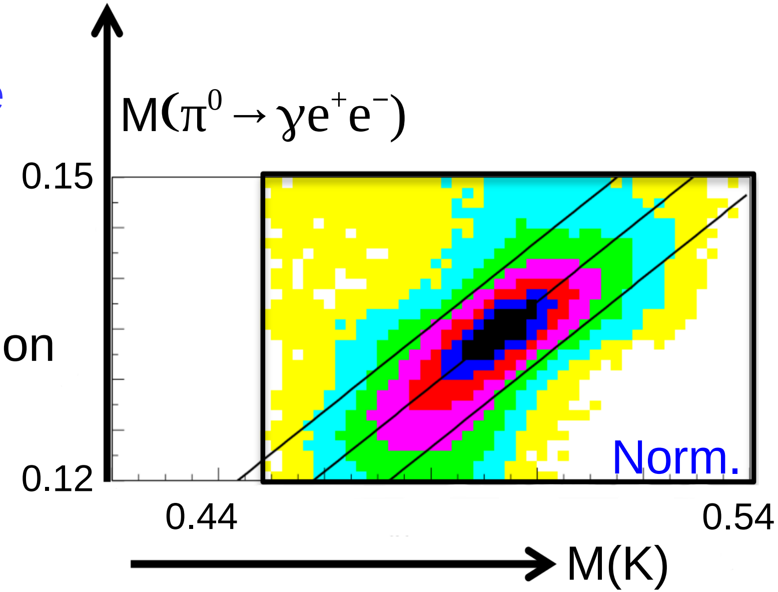
3 tracks in both cases, but one photon less in the normalization channel.

Cut for trigger efficiency: no 3 track in one HOD quadrant.

- No PID from LKr => no LKr acceptance cuts for tracks;
- Assign electron mass to the track with a charge opposite to kaon charge;
- For both other tracks using both M(e) and $M(\pi^{\pm})$ reconstruct $M(\pi^0)$ and $M(K^{\pm})$;
- $|M(\pi^0) — M_{PDG}| < 15$ MeV/c^2;
- $|M(K^{\pm}) — M_{PDG}| < 45$ MeV/c^2;
- $|M(\pi^0) — 0.42\, M(K^{\pm}) + 72.3$ MeV/c^2 $| < 6$ MeV/c^2



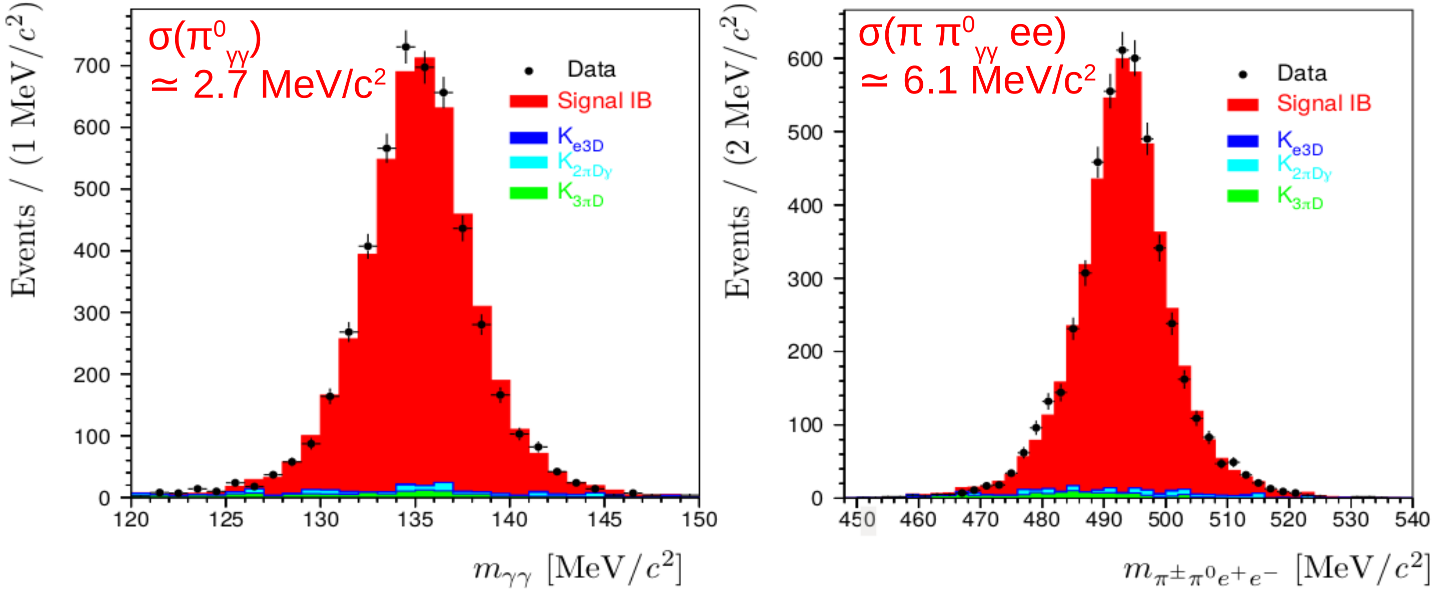
MC simulation



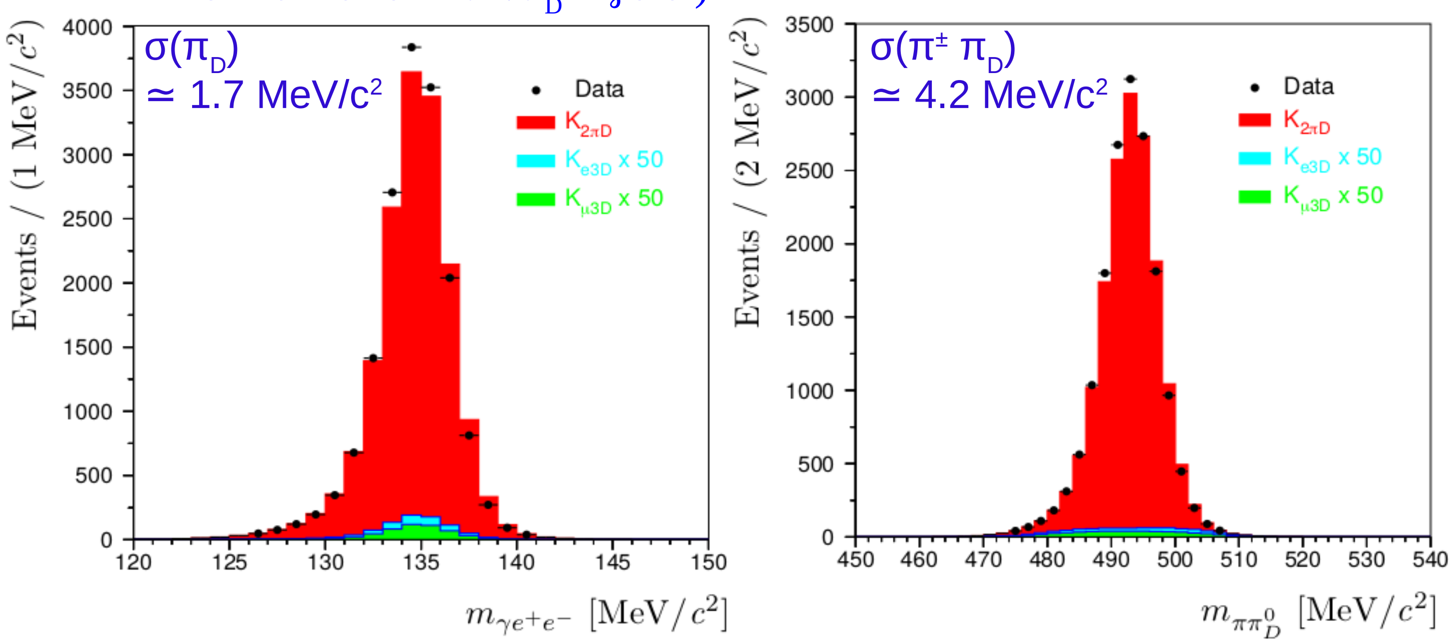
Selection results

The mass resolutions (Gaussian rms) are measured from data and agree with MC

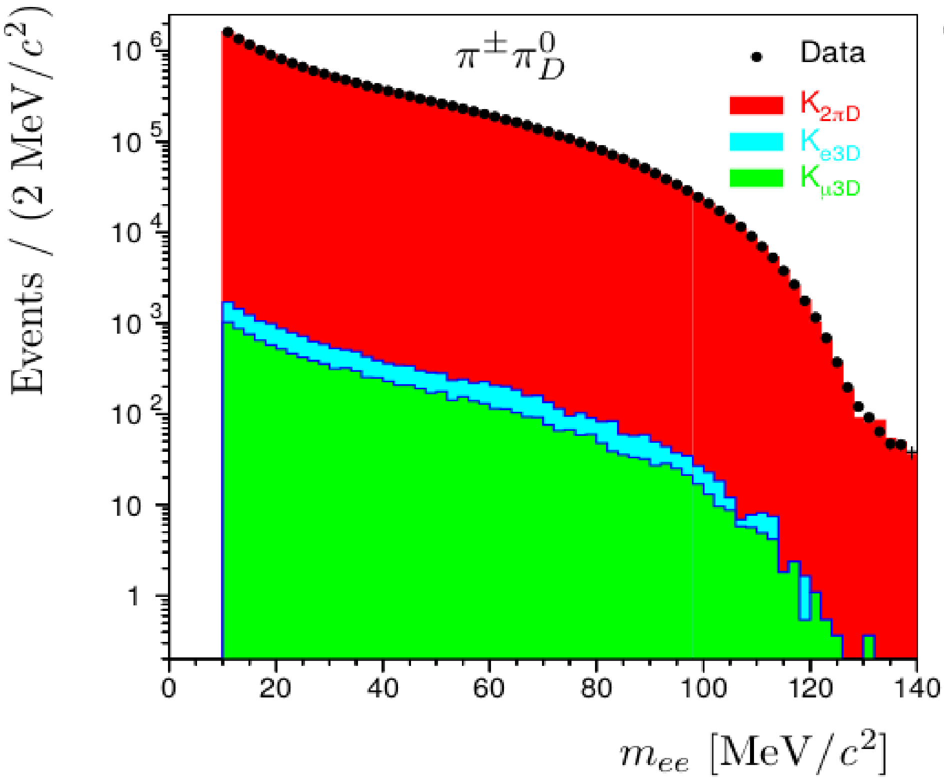
Signal: $\pi^{\pm}(\pi^0 \to \gamma\gamma)e^+e^-$

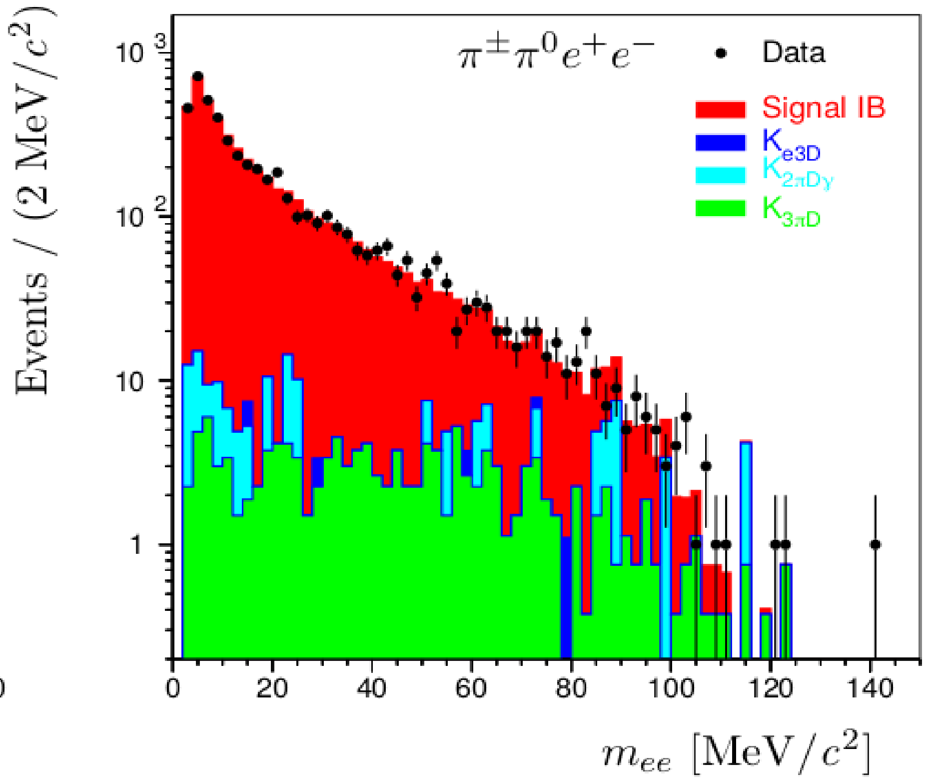


Normalization: $\pi^{\pm}(\pi^0_D \to \gamma e^+e^-)$



Selection results





Candidates N_N	16.3 x 10^6
Background N_{BN}	17288 ± 159
Acceptance A_N	3.981%
L1 eff. ε_{L1S}	(99.767±0.003)%
L2 eff. ε_{L2S}	(98.495±0.006)%

Candidates N_S	4919
Background N_{BS}	241 ± 21
Acceptance A_S	0.662%
L1 eff. ε_{L1S}	(99.729±0.009)%
L2 eff. ε_{L2S}	(98.604±0.021)%

Background

All background contributions are estimated from simulation

Decay	N	R,%
Normalization		
$K_{\mu 3D}$	10437 ± 119	
K_{e3D}	6851 ± 106	
Total		0.106
Signal		
$K_{3\pi D}$	132 ± 8	
$K_{2\pi D\gamma}$	102 ± 19	
K_{e3D}	7 ± 3	
Total		4.9 ± 0.4

R — background to signal ratio

Branching ratio measurement

$$BR = BR(\pi^{\pm}\pi^{0}) \times \Gamma(\pi^{0}_{D})/\Gamma(\pi^{0}_{\gamma\gamma})$$
$$\times (N_S - N_{BS})/(N_N - N_{BN})$$
$$\times (A_N \times \varepsilon_N)/(A_S \times \varepsilon_S)$$

$\Gamma(\pi^0_D)/\Gamma(\pi^0_{\gamma\gamma}) = (1.188 \pm 0.035)\%$

FINAL RESULT:

$BR = (4.237 \pm 0.063_{stat} \pm 0.033_{syst} \pm 0.126_{ext})\ 10^{-6}$

Error is dominated by external error of $\Gamma(\pi^0_D)/\Gamma(\pi^0_{\gamma\gamma})$

In perfect agreement with ChPT
[EPJ C72 (2012) 1872, EPJ C78 (2018) 265]:

For IB only

$BR(IB) = 4.183\ 10^{-6}$;

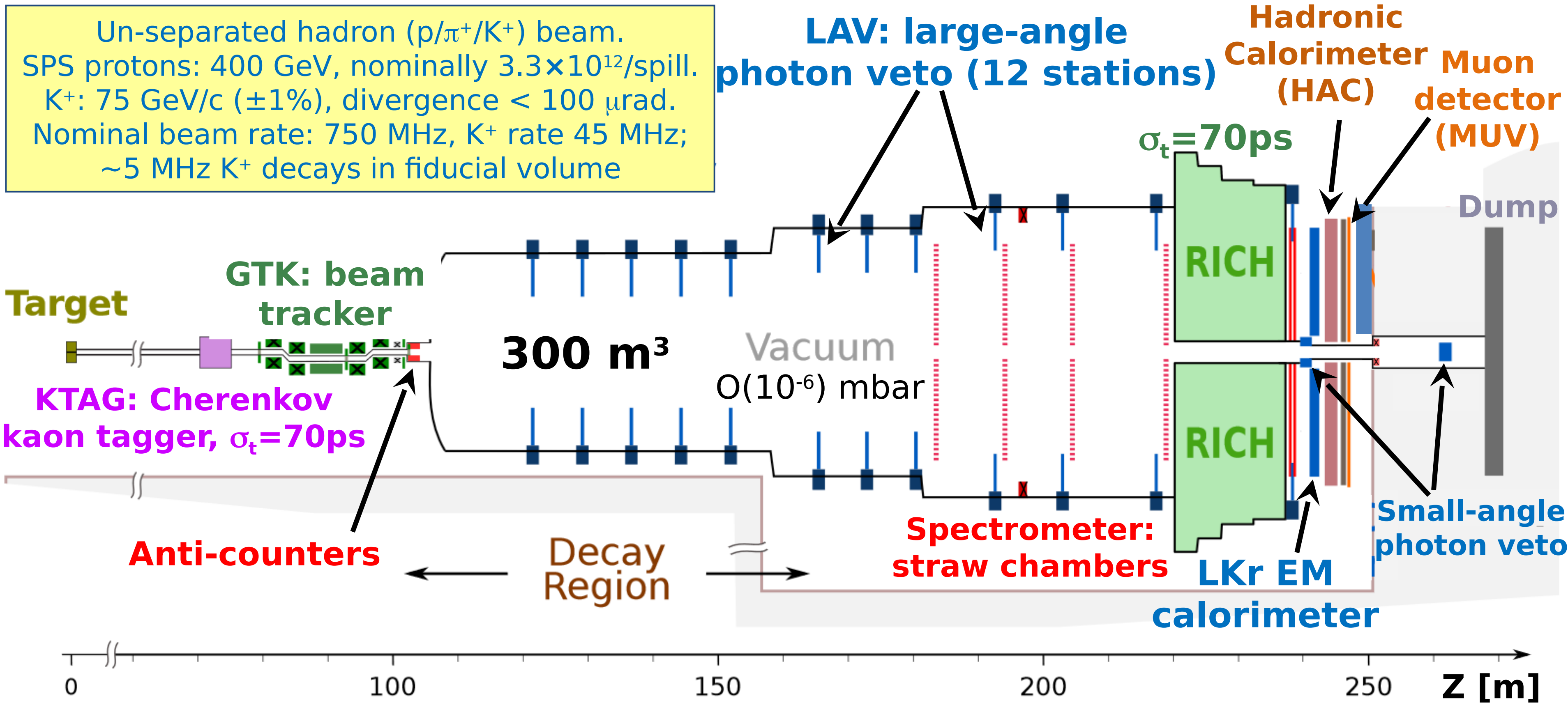
When including all DE and INT terms

$BR(IB) = 4.229\ 10^{-6}$.

	Source	$\delta BR/BR \times 100$
Statistical	N_S	1.426
	N_{BS}	0.416
	N_N	0.025
	N_{BN}	Negl.
Systematic	A_S	0.171
	A_N	0.051
	$\varepsilon_{L1N}\ \varepsilon_{L2N}$	0.007
	$\varepsilon_{L1S}\ \varepsilon_{L2S}$	0.023
	A(geom control)	0.083
	A(time var. control)	0.064
	Trig. efficiency	0.400
	Model dependence	0.285
	Radiative effects	0.490
	Background control	0.280
External	$BR(2\pi)$	0.387
	$\Gamma(\pi^0_D)/\Gamma(\pi^0_{\gamma\gamma})$	2.946

NA62 Beamline & detector

Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, nominally 3.3×10^{12}/spill.
K^+: 75 GeV/c (±1%), divergence < 100 μrad.
Nominal beam rate: 750 MHz, K^+ rate 45 MHz;
~5 MHz K^+ decays in fiducial volume

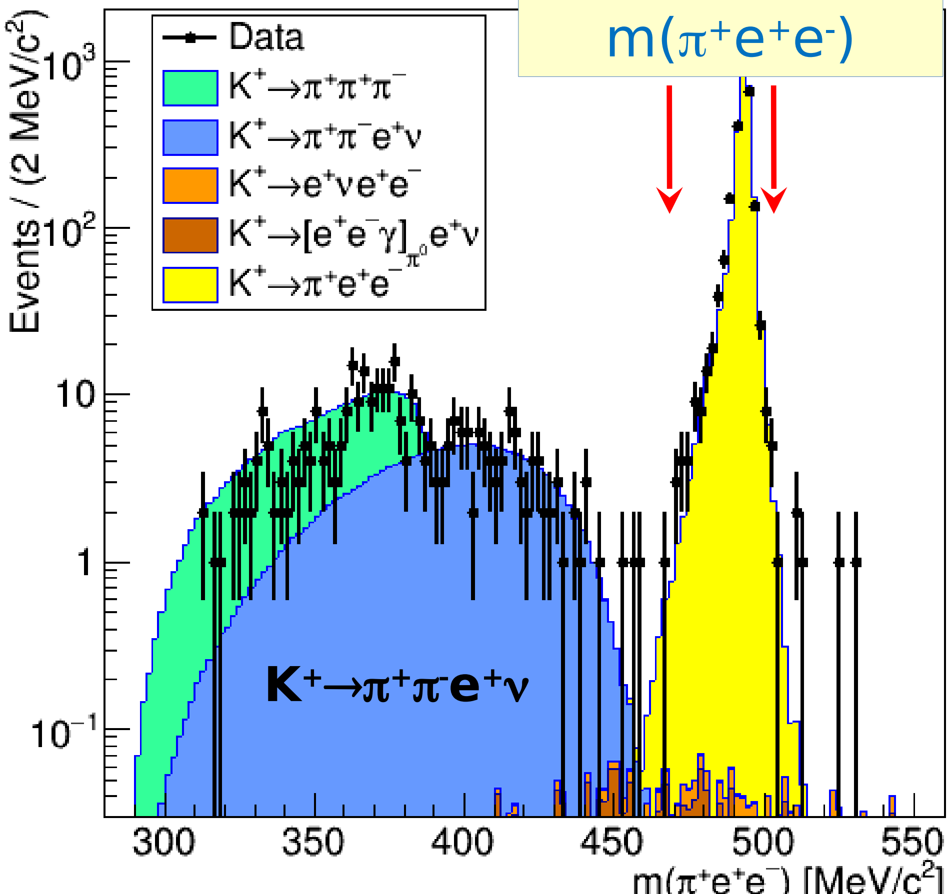


NA62 collaboration, JINST 12 (2017) P05025

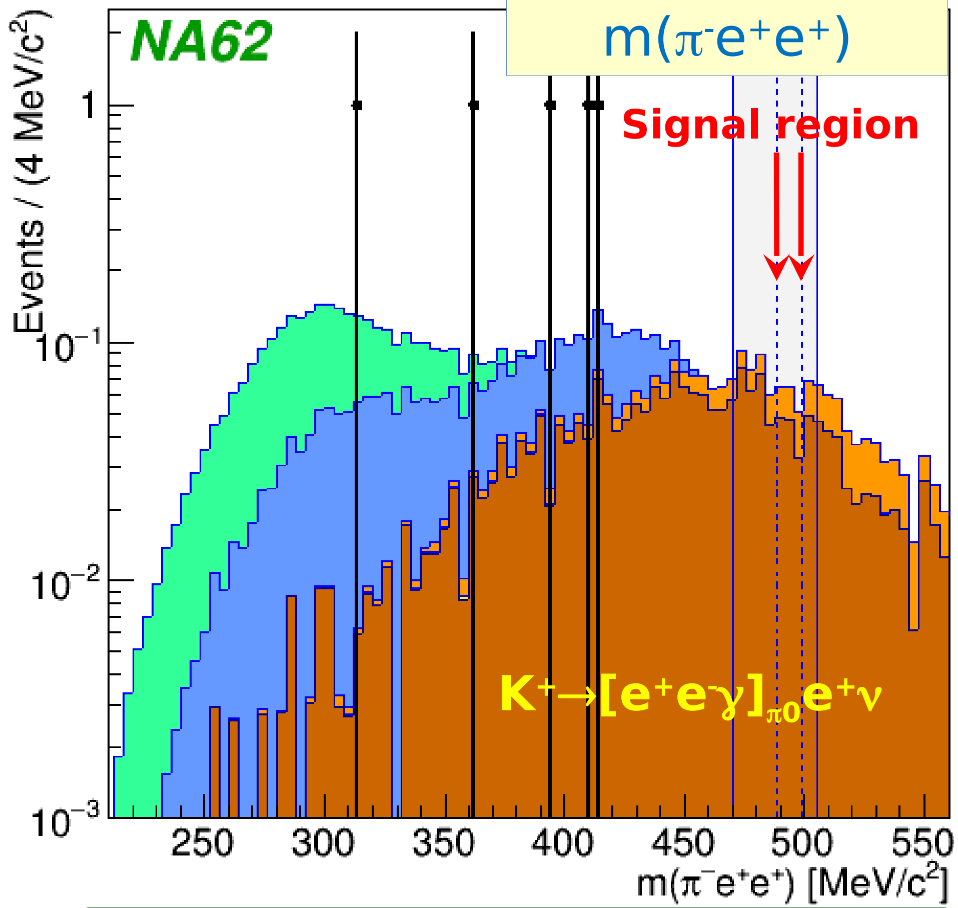
Searches for lepton flavour and lepton number violation

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

SM selection: $m(\pi^+ e^+ e^-)$



LNV selection: $m(\pi^- e^+ e^+)$



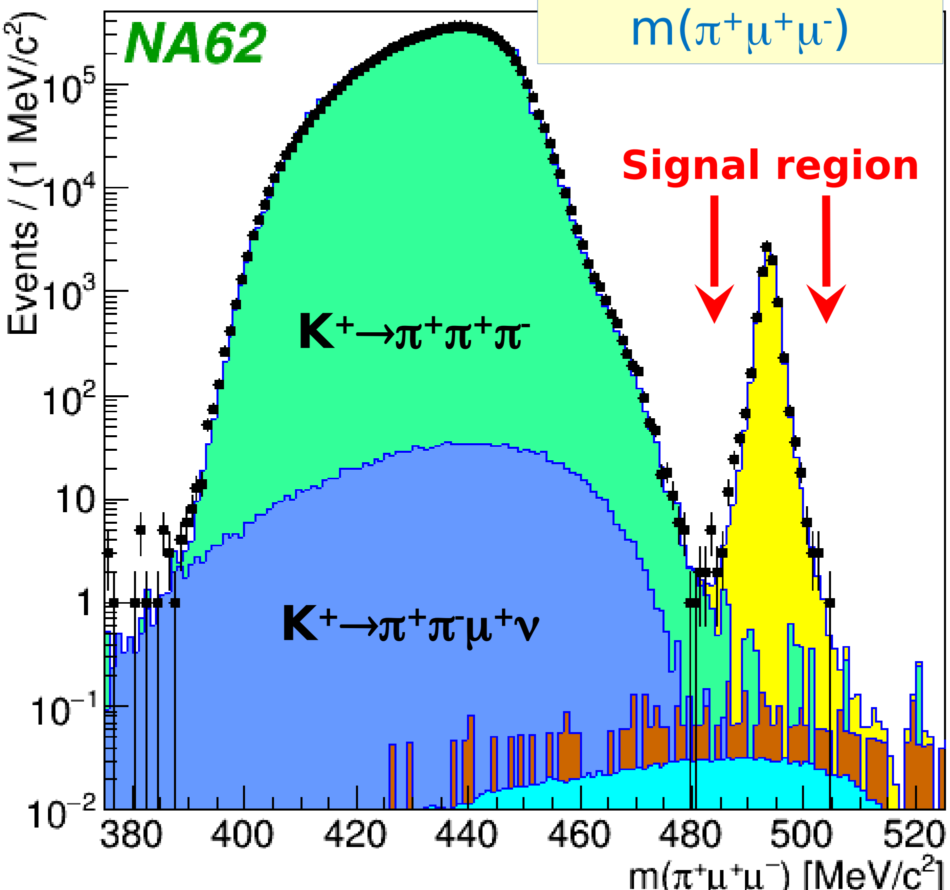
Candidates observed: **2484**
$BR(K^+ \to \pi^+ e^+ e^-) = (3.00 \pm 0.09) \times 10^{-7}$
K^+ decays in FV: **$(2.14 \pm 0.07) \times 10^{11}$**

$SES = (0.94 \pm 0.03) \times 10^{-10}$
Expected background: **0.16 ± 0.03** evt
Candidates observed: **0**

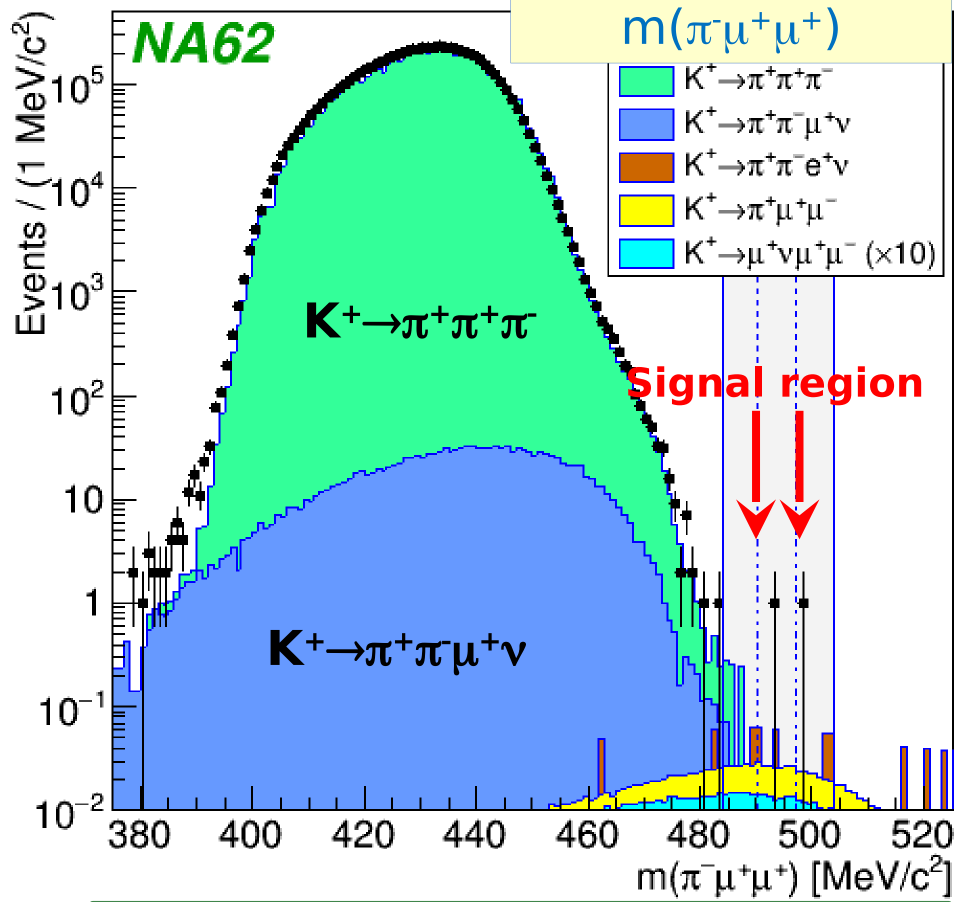
Result: **$BR(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}$** at 90% CL

Search for $K^+ \to \pi^- \mu^+ \mu^+$ decay

SM selection: $m(\pi^+\mu^+\mu^-)$



LNV selection: $m(\pi^-\mu^+\mu^+)$



Candidates observed: **8357**
Background: **0.07%**
BR($K^+ \to \pi^+\mu^+\mu^-$) = $(0.962 \pm 0.025) \times 10^{-7}$
K^+ decays in FV: **$(7.94 \pm 0.23) \times 10^{11}$**

SES = $(1.28 \pm 0.04) \times 10^{-11}$
Expected background: **0.91 ± 0.41** evt
Candidates observed: **1**

$K^+ \to \pi^- \mu^+ \mu^+$ decay: results

Backgrounds to $K^+ \to \pi^- \mu^+ \mu^+$ decay

Process	Expected background
$K_{3\pi}$ (no $\pi^\pm$ decays)	0.007 ± 0.003
$K_{3\pi}$ (one $\pi^\pm$ decay)	0.25 ± 0.25
$K_{3\pi}$ downstream (at least two $\pi^\pm$ decays)	0.20 ± 0.20
$K_{3\pi}$ upstream (at least two $\pi^\pm$ decays)	0.24 ± 0.24
$K^+ \to \pi^+ \mu^+ \mu^-$	0.08 ± 0.02
$K^+ \to \pi^+ \pi^- \mu^+ \nu$	0.05 ± 0.05
$K^+ \to \pi^+ \pi^- e^+ \nu$	0.07 ± 0.05
$K^+ \to \mu^+ \nu \mu^+ \mu^-$	0.01 ± 0.01
Total	0.91 ± 0.41

Data-driven estimates (inversion of PID criteria)

Biased fast simulations with forced pion decays: dominated by pion decays in the spectrometer

Full MC simulations tuned using measured misID probabilities and measured pileup rates

One candidate observed

Final result with the 2017 data set:

$BR(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ at 90% CL

Searches for heavy neutral lepton production in K^+ decays

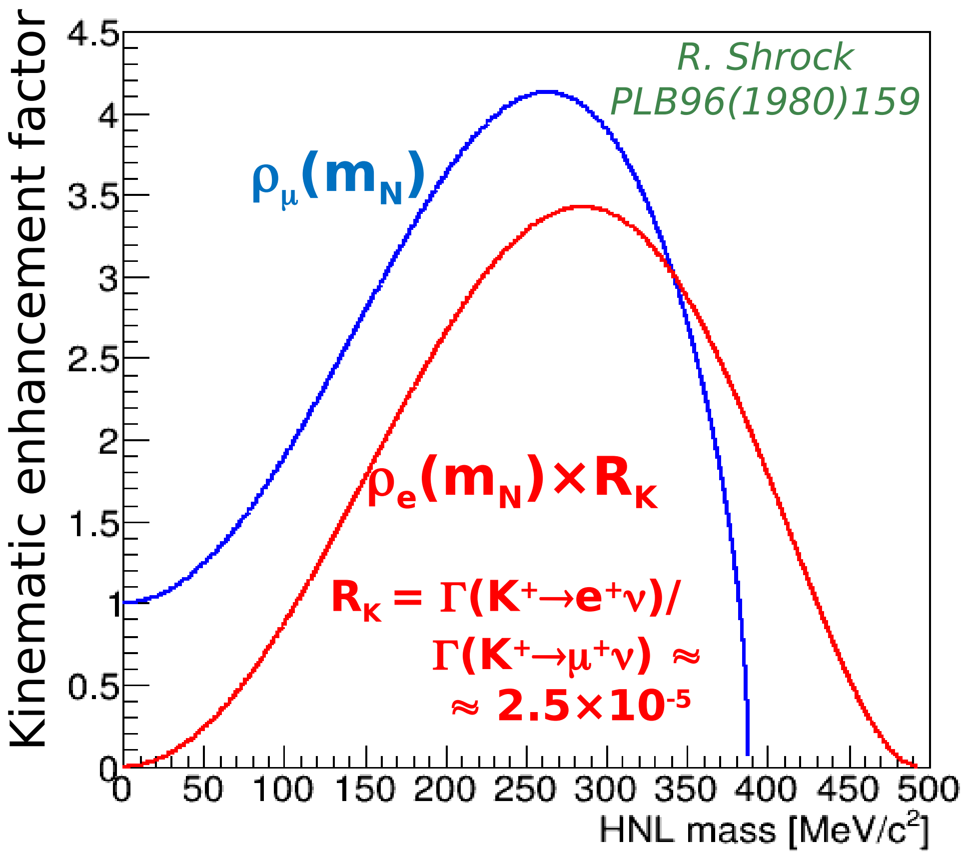
Results based on the pilot 2015 data

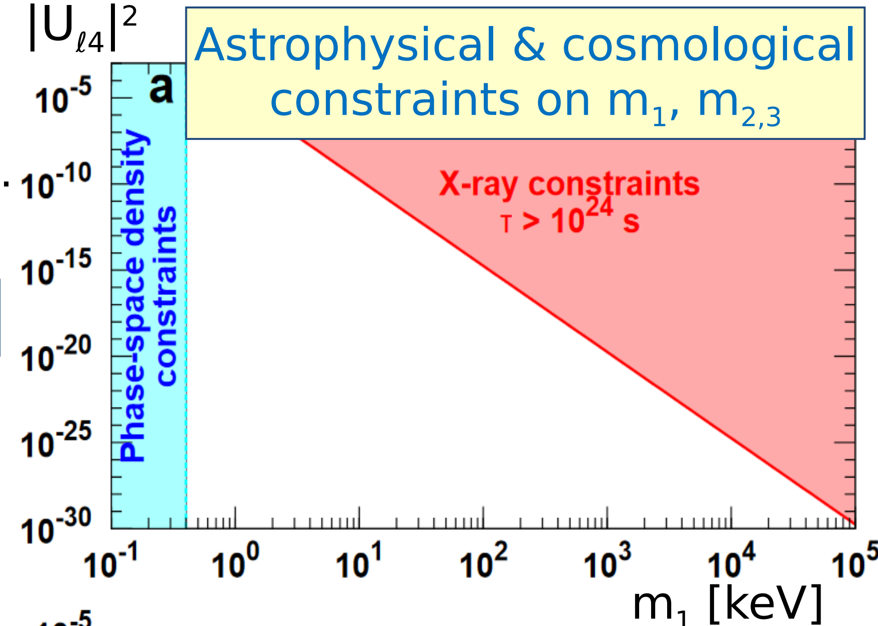
Heavy neutral leptons in νMSM

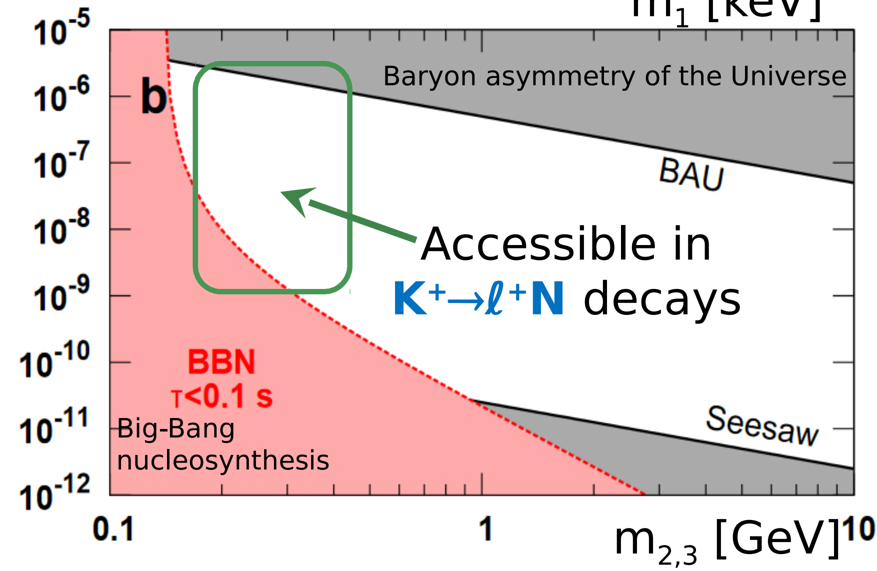
Neutrino minimal SM (**νMSM**) =
SM + 3 right-handed neutral heavy leptons.
[Asaka et al., PLB631 (2005) 151]
Masses: **m_1~10 keV** [DM candidate]; **$m_{2,3}$~1 GeV**.

HNLs observable via **production** and **decay**.

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





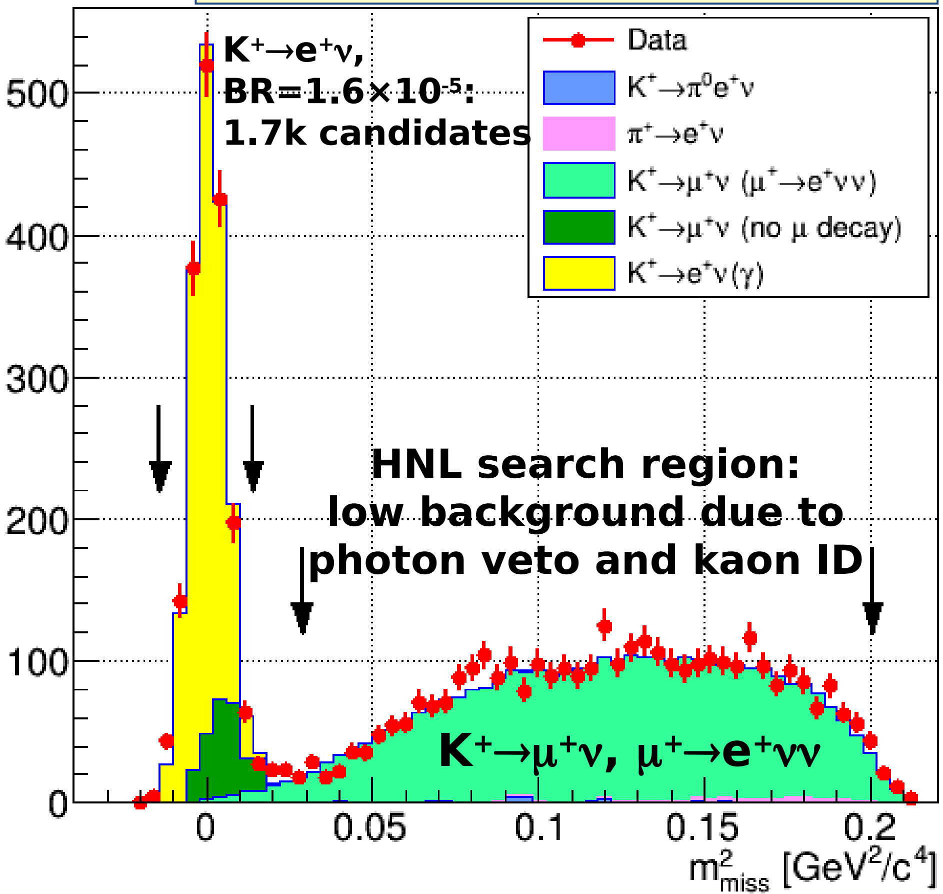


Shaposhnikov, JHEP 0808 (2008) 008
Boyarsky et al., Ann.Rev.Nucl.Part.Sci.59 (2009) 191

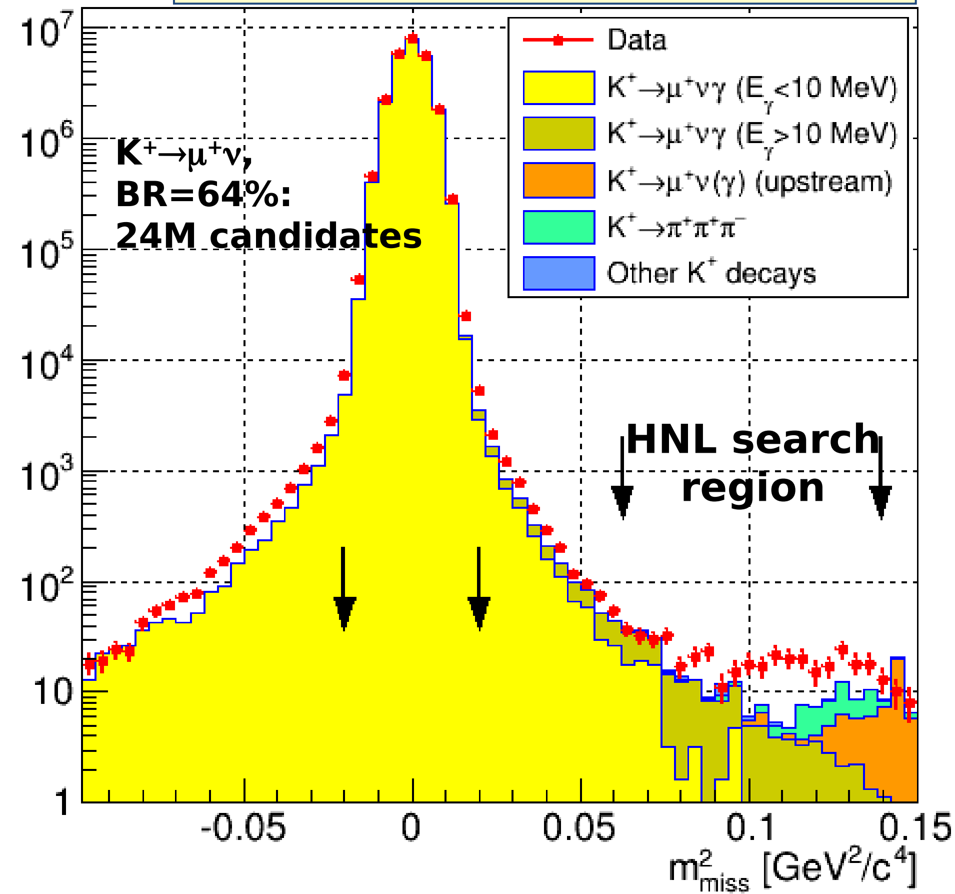
$K^+ \to \ell^+ N$ data samples

- Minimum bias data (**1%** intensity); **12k** SPS spills (=**5** days) in **2015**.
- Numbers of **K^+** decays in fiducial volume:
  $N_K=(3.01\pm0.11)\times10^8$ in positron case; **$N_K=(1.06\pm0.12)\times10^8$** in muon case.
- Beam tracker not available: beam average kaon momentum is used.
- HNL production signal: **a spike above continuous missing mass spectrum**.

Squared missing mass: $(P_K-P_e)^2$

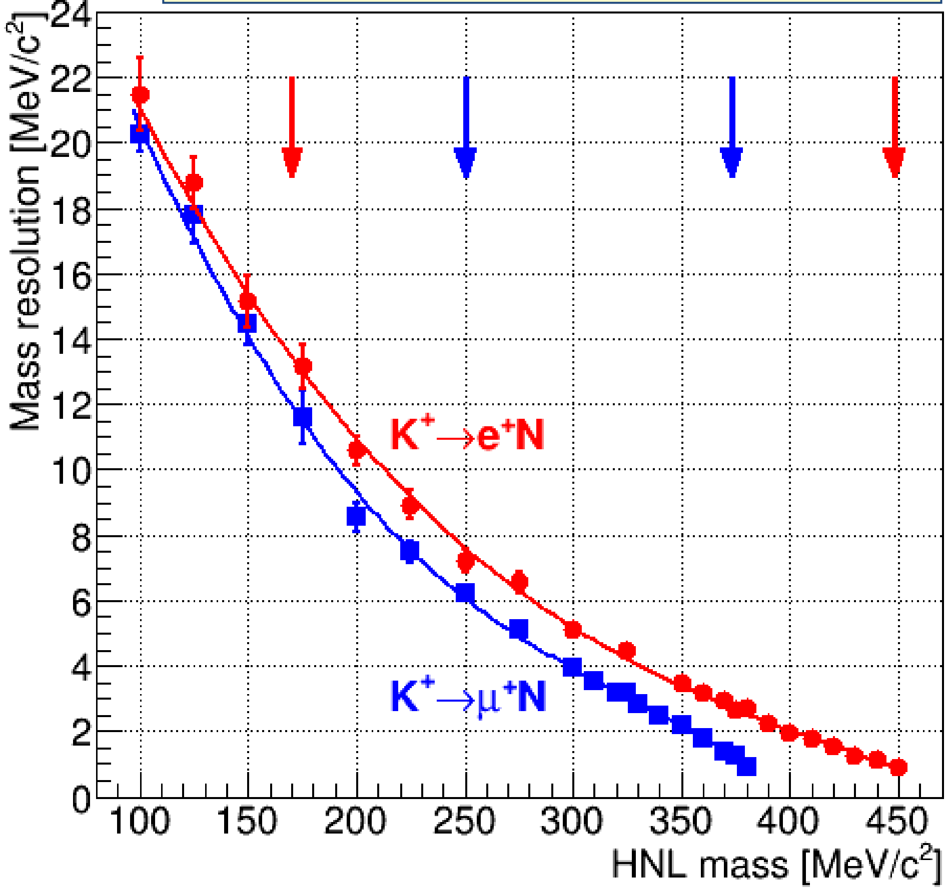


Squared missing mass: $(P_K-P_\mu)^2$

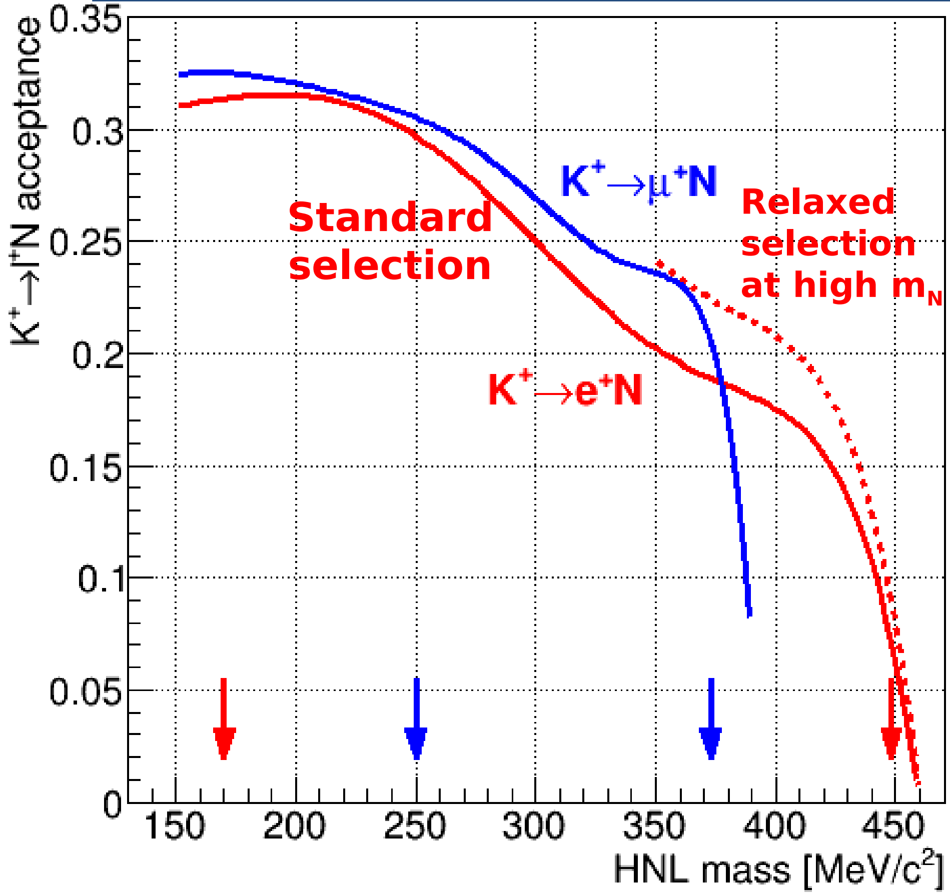


$K^+ \to \ell^+ N$: resolution & acceptance

HNL mass resolution σ_m vs mass



Signal selection acceptance vs mass

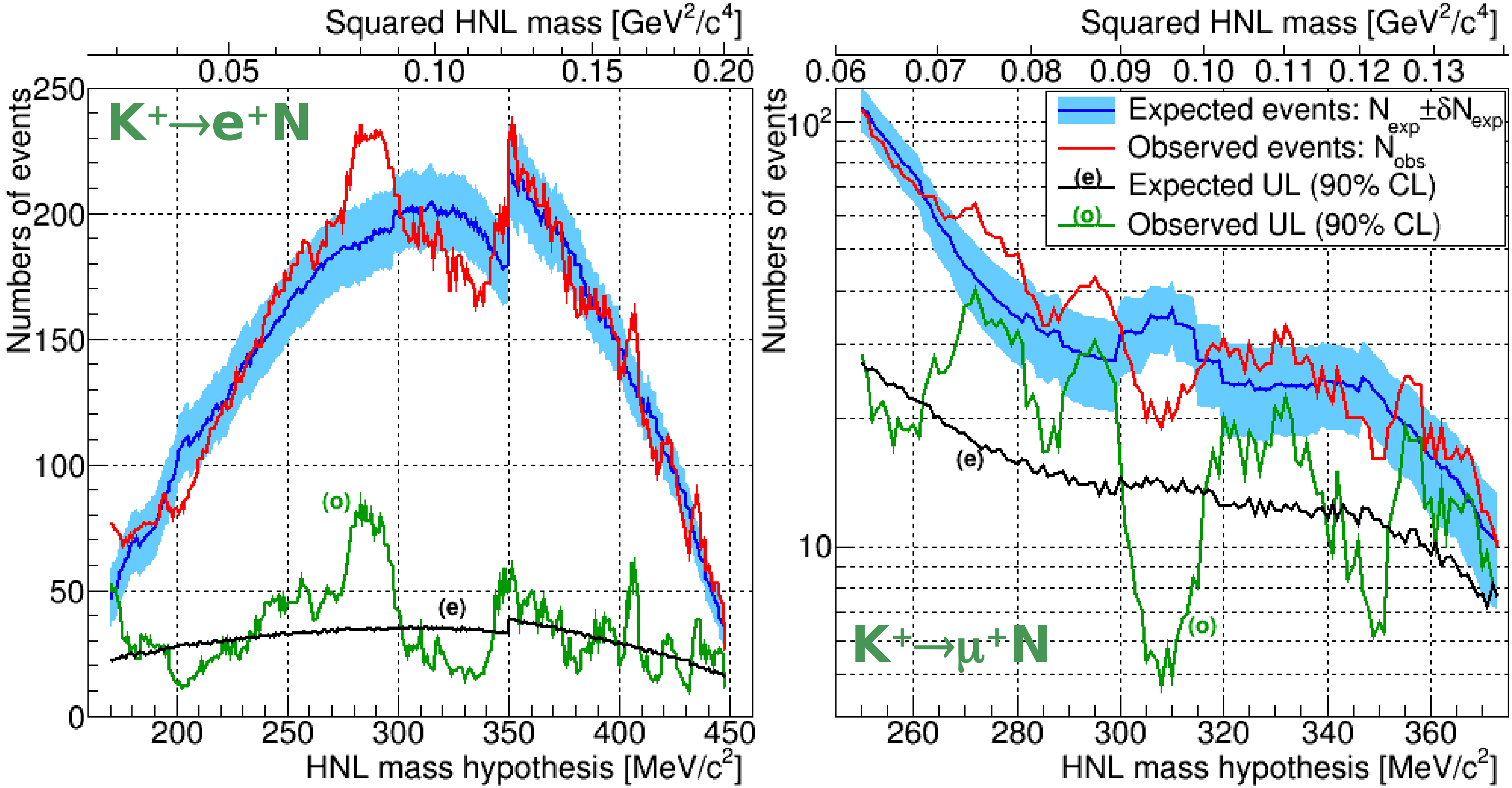


- Selection for each HNL mass hypothesis (**m_{HNL}**) includes the “mass window” condition: **$|m-m_{HNL}|<1.5\sigma_m$**: background is proportional to mass resolution.

- Also, resolution is crucial to resolve possible HNL mass splitting.

[Baryogenesis: 2 quasi-degenerate mass states; Canetti et al., PRD87 (2013) 093006]

Statistical analysis

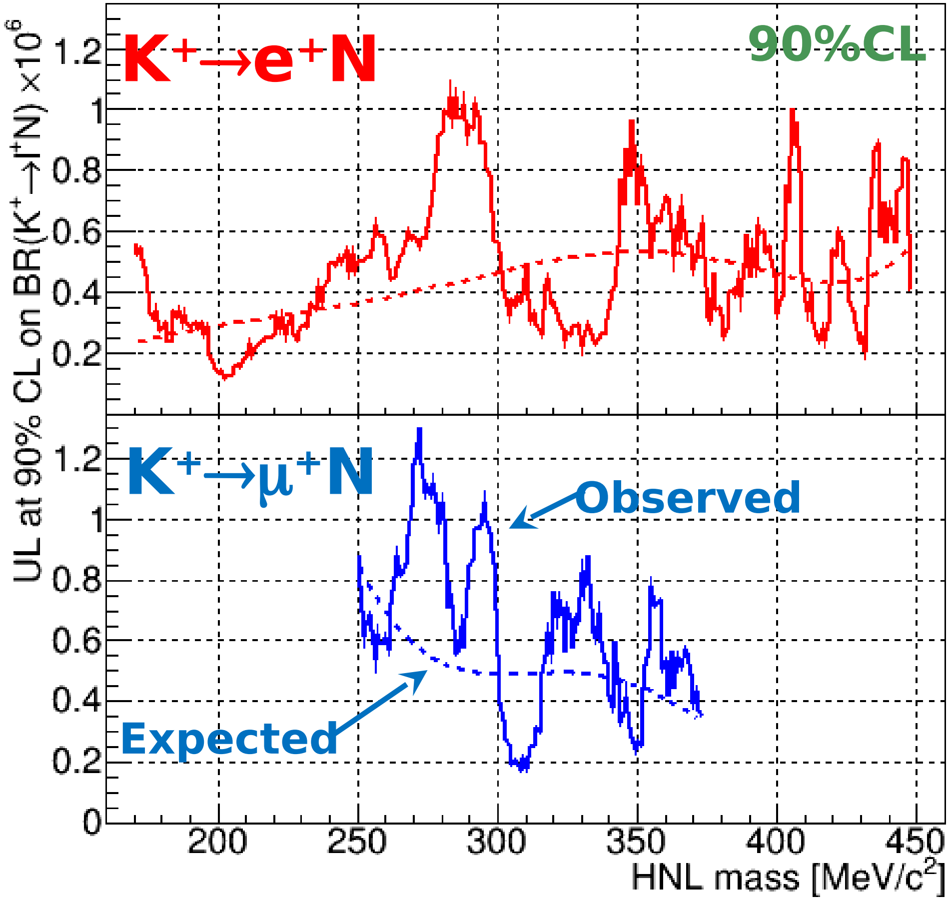


- Expected background (and stat.error) estimated from fits to the sidebands.
- Numbers of observed and expected events converted into limits for the signal.
- Background simulations used to certify the absence of peaking structures.
- Full MC background estimate would allow **searches for $K^+ \to \ell^+ \nu\nu\nu$**.

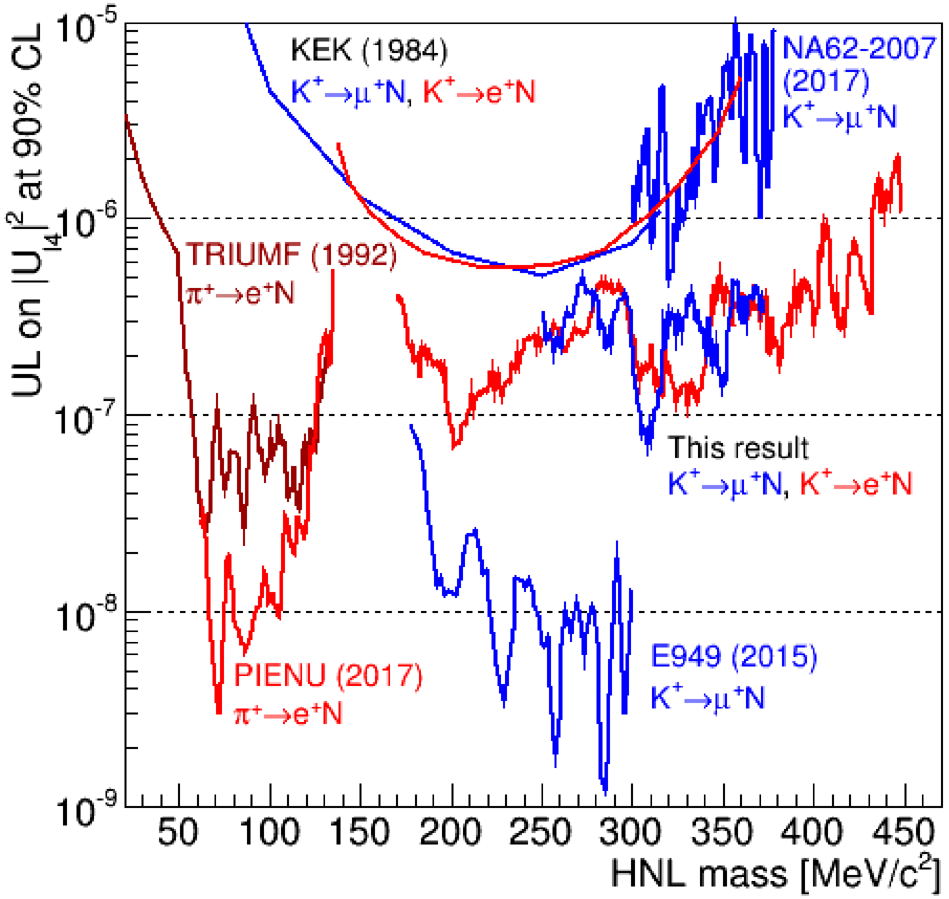
HNL production search: results

Phys. Lett. B778 (2018) 137

Upper limits on BR($K^+ \to \ell^+ N$)



$|U_{\ell 4}|^2$ limits from production searches



- Local signal significance never exceeds **2.2σ**: **no HNL signal** is observed.
- Reached **10^{-6}-10^{-7}** limits for **$|U_{\ell 4}|^2$** in the **170-448 MeV/c²** mass range.

Summary

- $\mathbf{K}_{l3}$ form factors measurement is performed by NA48/2 on the basis of 2004 run selected **$4.4\cdot10^6$ (K_{e3})** and **$2.3\cdot10^6$ ($K_{\mu3}$)** events. Result is competitive with the other ones in $\mathbf{K}_{\mu3}$ mode, and a smallest error in $\mathbf{K}_{e3}$ has been reached, that gives us also the most precise combined $\mathbf{K}_{l3}$ result. [JHEP 1810 (2018) 150].

- The 4919 $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}e^{+}e^{-}$ rare decay candidates, with a **5%** background contamination, are first observed. Branching ratio is measured to be **$(4.24 \pm 0.15)\times10^{-6}$**, that is in good agreement with ChPT-based theoretical predictions. The relative contributions of **(M)/IB** and **(IB-E)/IB** are also in agreement with the theory. Several CP-violating asymmetries and a long-distance P-violating asymmetry have been evaluated and found to be consistent with zero. [PLB788 (2019) 552].

- Analysis of the 2017 NA62 data: **$BR(K^+\rightarrow\pi^-e^+e^+)<2.2\times10^{-10}$**, **$BR(K^+\rightarrow\pi^-\mu^+\mu^+)<4.2\times10^{-11}$** at **90%** CL. *[PLB797 (2019) 134794].*

- Analysis of the 2015 NA62 minimum bias data: sub-**10^{-6}** limits on **$|U_{\ell4}|^2$** from HNL production searches. *[PLB778 (2018) 137].*

Финальные результаты в журнальных статьях (JINR corresponding authors)

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3. Eduardo Cortina Gil *et al.* (NA62 Collaboration). Search for heavy neutral lepton production in K^{+} decays, Phys.Lett. B778 (2018) 137-145.
4. Eduardo Cortina Gil *et al.* (NA62 Collaboration). Searches for lepton number violating K^{+} decays, Phys.Lett. B797 (2019) 134794.

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6. M.H.Misheva. First observation and study of $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ decay at the NA48/2 experiment. Proc. of 50th Rencontres de Moriond on QCD and High Energy Interactions. 21-28 Mar 2015. La Thuile, Italy. ARISF 2015. p.237-240.
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11. D. Madigozhin. Recent NA48/2 results on rare kaon decays. ISMD 2018, Singapore, 3-7 Sep 2018. EPJ Web Conf. 206 (2019) 05001.