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Latest results on rare kaon decays from the NA48/2 experiment at CERN

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on behalf of the NA48/2 collaboration

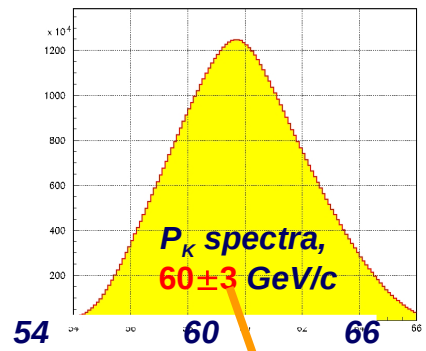
Outline

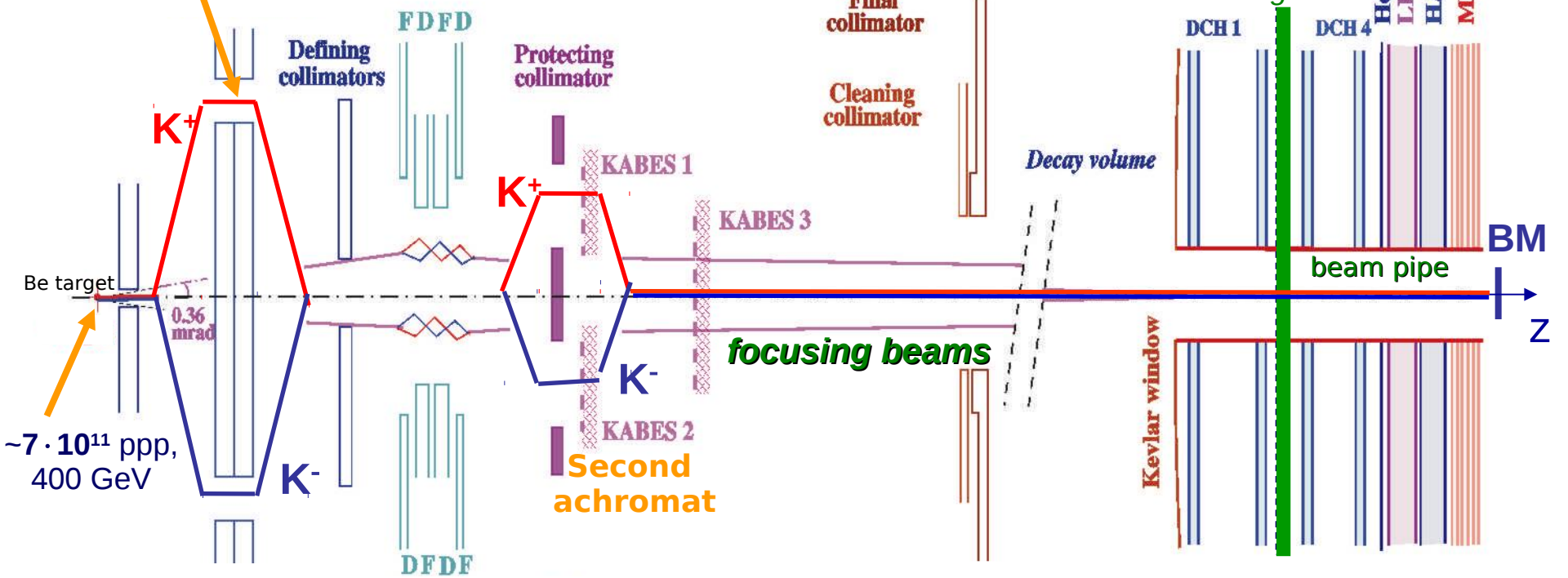
- NA48/2 experiment
- Study of the $K^+ \to \pi^+\pi^0 e^+ e^-$ decay
- K_{l3} form factors precision measurement
- Conclusion

NA48/2 kaon beam

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

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





Front-end achromat

Quadrupole quadruplet

- Momentum selection
- Focusing
- μ sweeping

NA48/2 detector

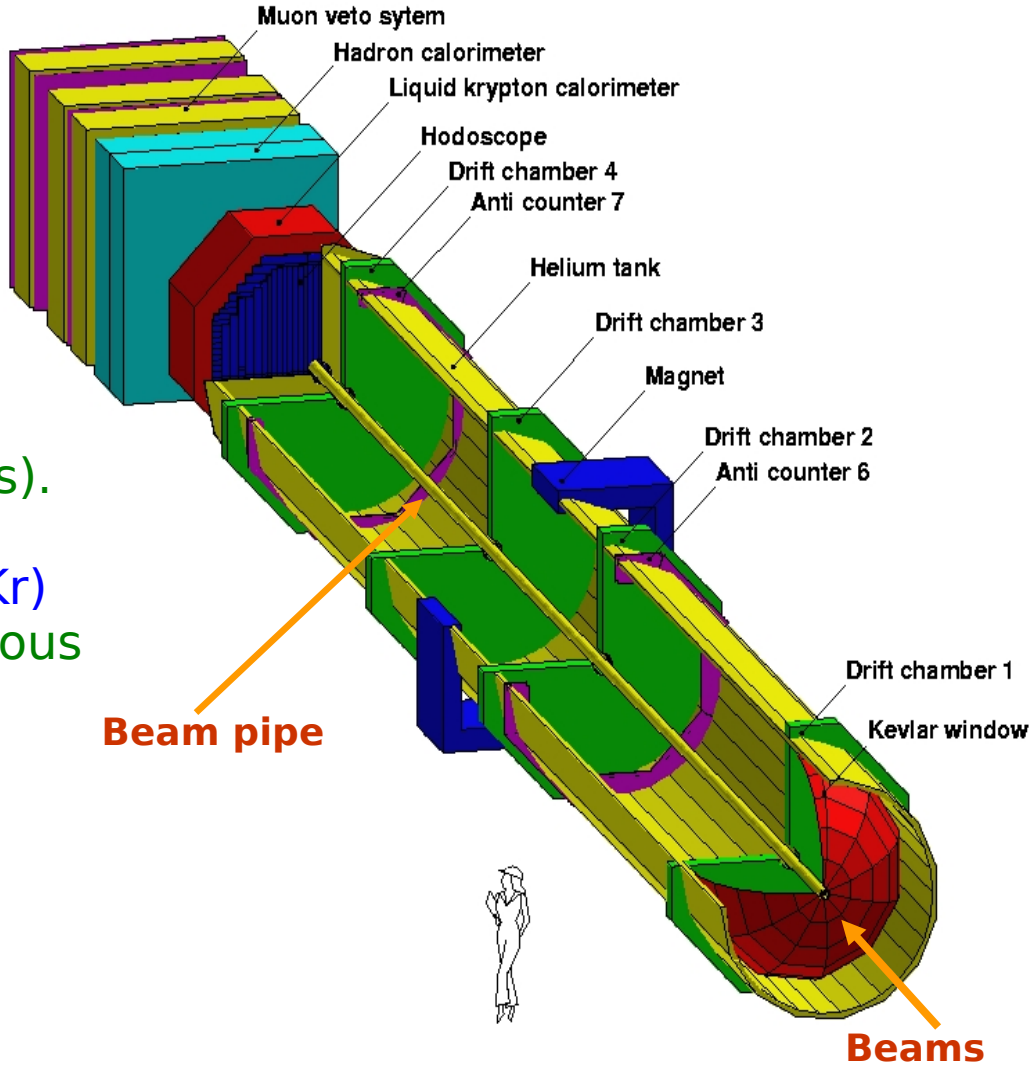
Main detector components:

- Magnetic spectrometer (4 DCHs):
  4 views/DCH inside a He tank
  $\Delta p/p = 1.02\% \oplus 0.044\% * p$
  [p in GeV/c].

- Hodoscope
  fast trigger;
  precise time measurement (150ps).

- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogenious
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$
  $\sigma_x = \sigma_y = 0.42/E^{1/2} \oplus 0.06$cm
  [E in GeV]. (0.15cm@10GeV).

- Hadron calorimeter, muon veto counters, photon vetoes.



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

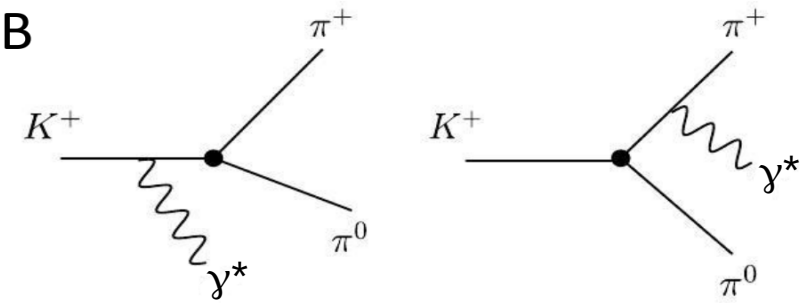
Phys.Lett. B788 (2019) 552

Motivation:

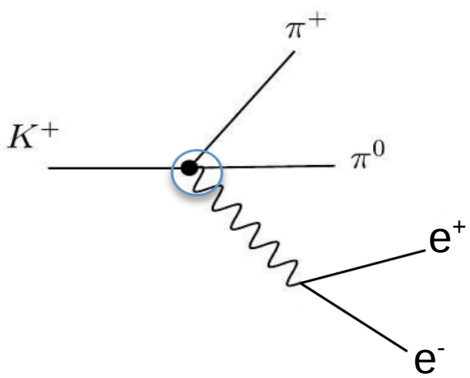
- Never observed so far: confirmation of BR magnitude ChPT predictions:
  - H.Pichl, EPJ C20 (2001) 371;
  - L.Cappiello, O.Cata, G.D'Ambrosio, D. Gao, EPJ C72 (2012) 1872;
  - L.Cappiello, O.Cata, G.D'Ambrosio, EPJ C78 (2018) 265.

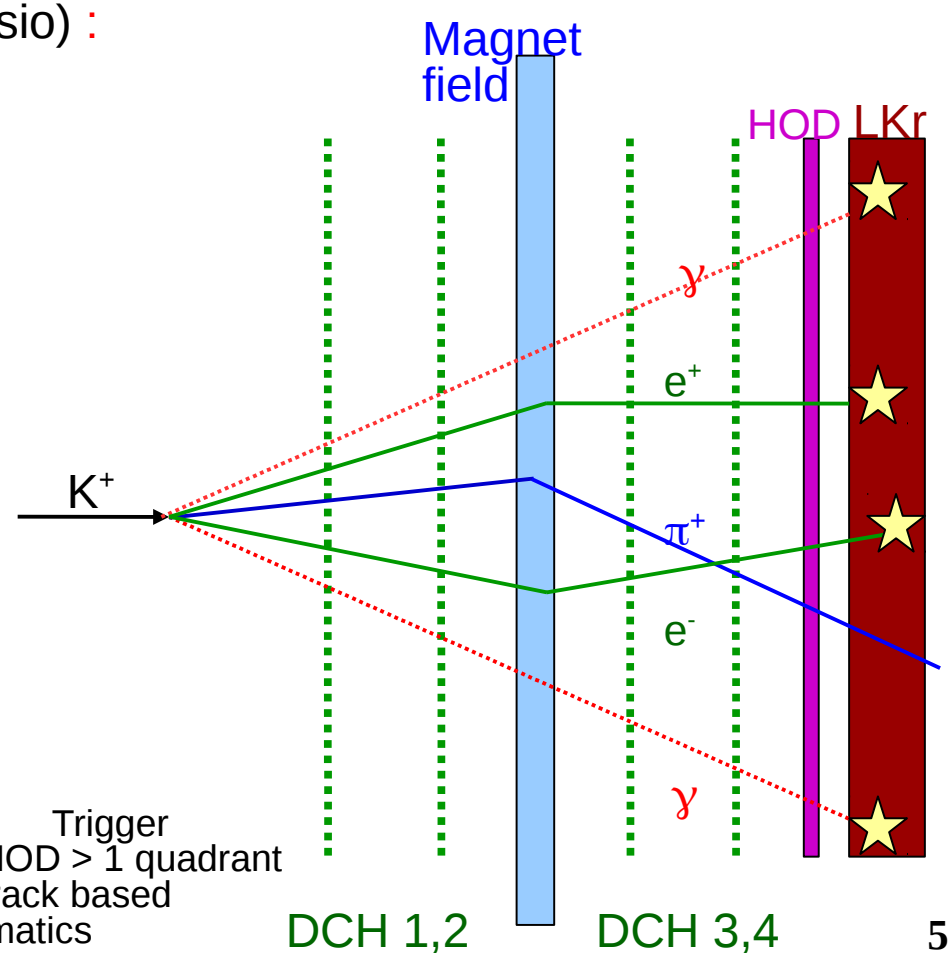
- If a detailed analysis possible (G.D'Ambrosio) :
  - Sign of interference term (IB,E),
  - Magnetic term from (IB,M) interference
  - Charge asymmetry — direct CPV
  - ChPT predicted bump in $M(e^{+}e^{-})$ spectrum

IB



DE(M,E)





Trigger
L1: HOD > 1 quadrant
L2: track based kinematics

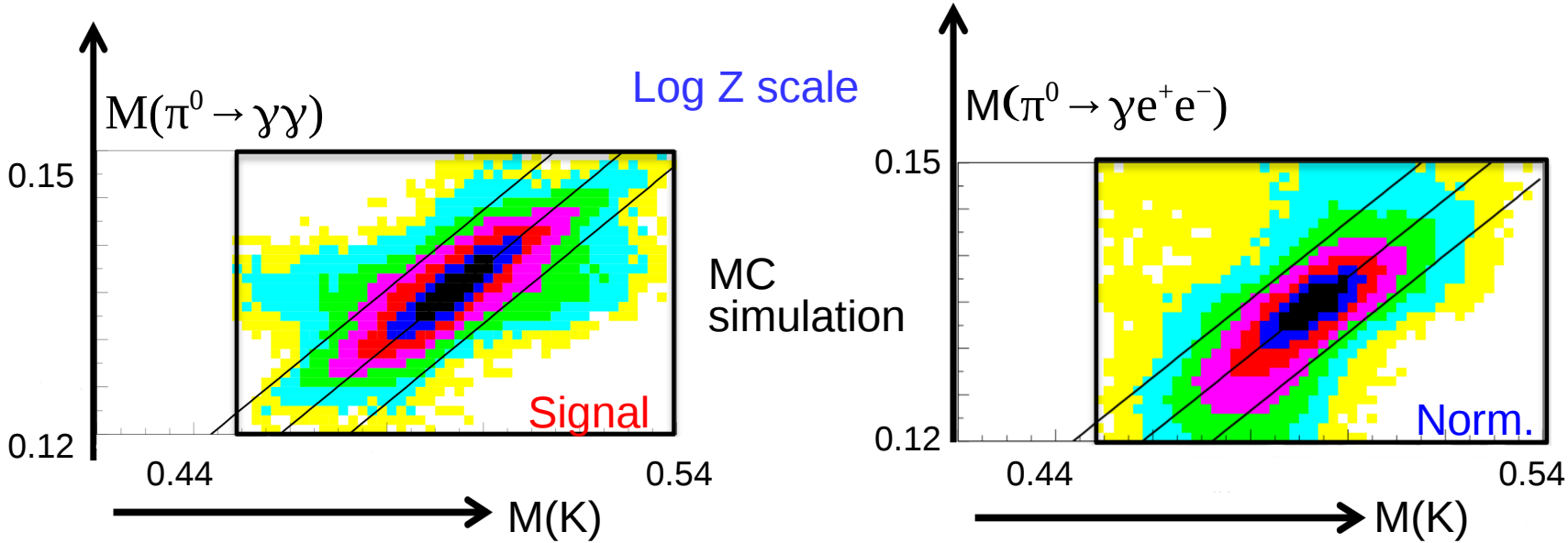
Events selection

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.

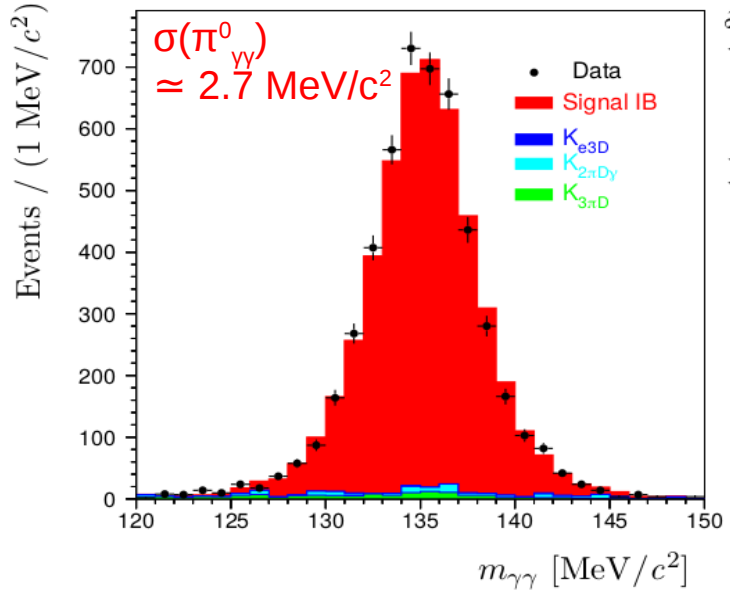
- No PID from LKr => no LKr acceptance cuts for tracks;
- Assign electron mass to the track with a charge opposite to kaon charge;
- For both other tracks using both M(e) and M($\pi^{\pm}$) reconstruct M(π^0) and M($K^{\pm}$);
- $|M(\pi^0) — M_{PDG}| < 15$ MeV/c^2;
- $|M(K^{\pm}) — M_{PDG}| < 45$ MeV/c^2;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

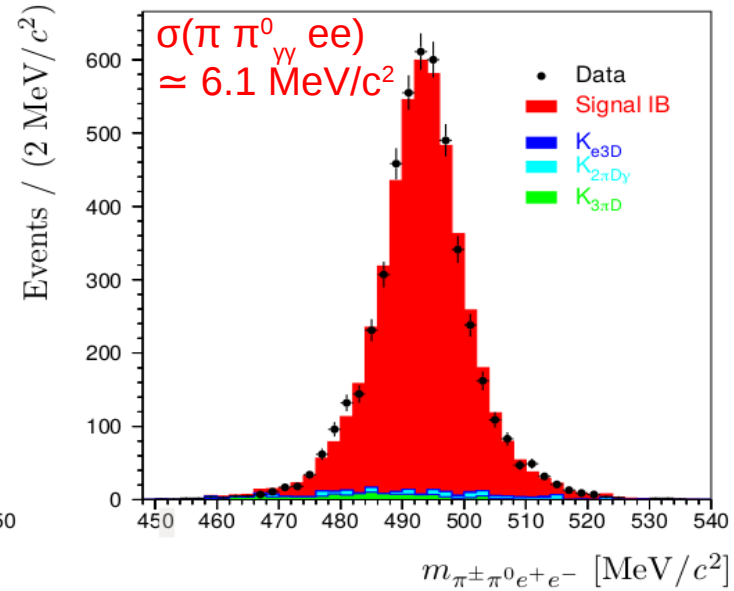


Selection results

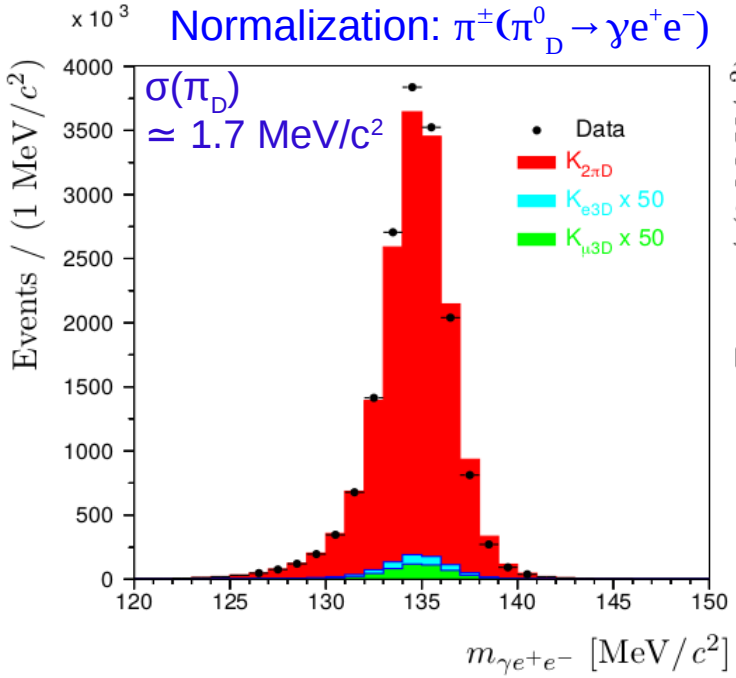
The mass resolutions (Gaussian rms) are measured from data and agree with MC

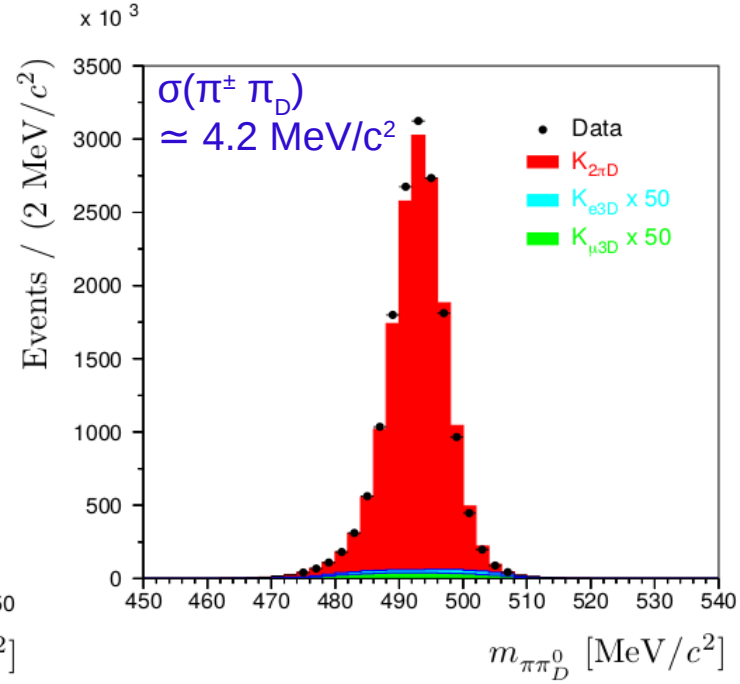
Signal: $\pi^{\pm}(\pi^0 \to \gamma\gamma)e^+e^-$



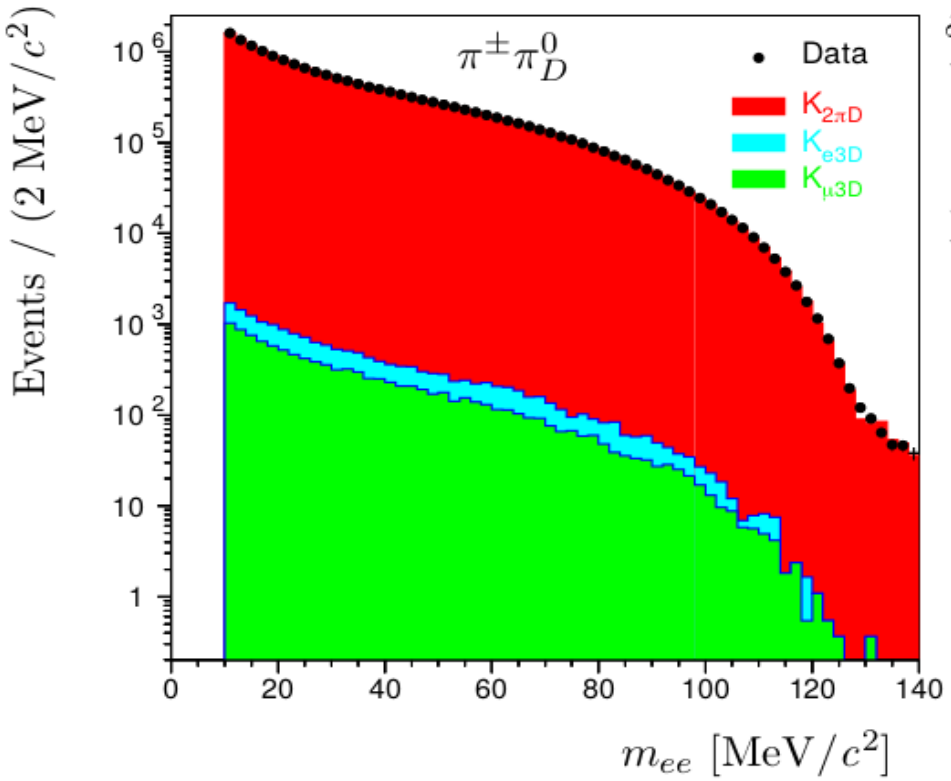


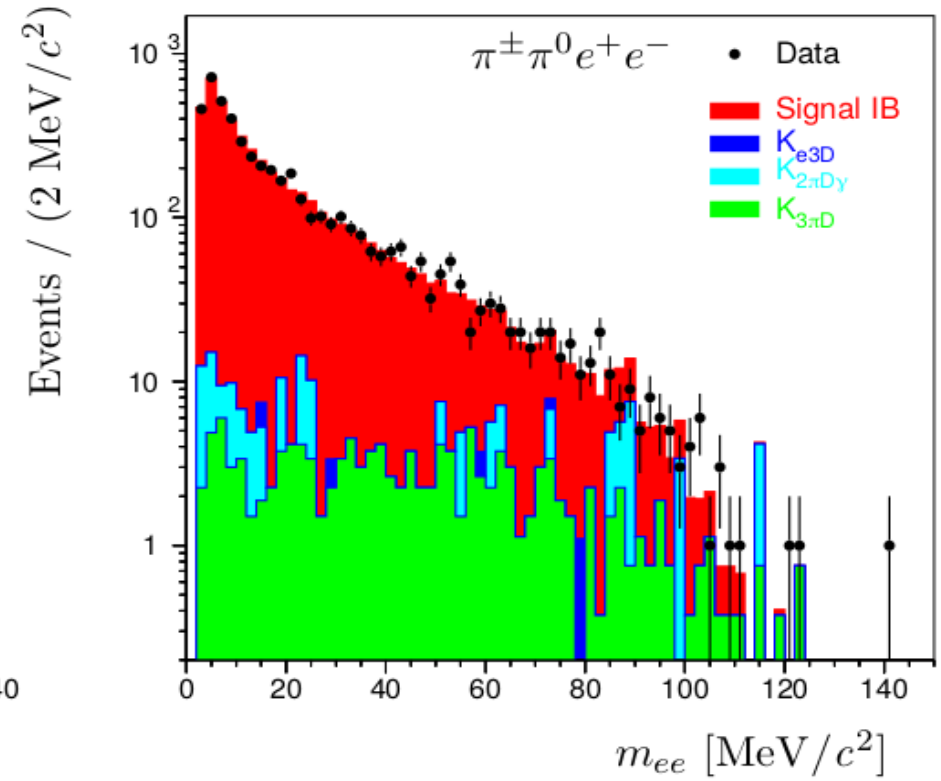
Normalization: $\pi^{\pm}(\pi^0_D \to \gamma e^+e^-)$





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

Kinematic space study

- Predictions for IB and full BR differ only by 1%. The BR measurement is not precise enough to extract information on the contributions. But some information can be extracted from the kinematic space distribution.
- In [Eur. Phys. J. C 72 (2012) 1872, Eur. Phys. J. C 78 (2018) 265] pointed out that the contributions of IB, M, and IB-E terms have different distributions in the Dalitz plot (T^*_π , E^*_γ) for different ranges of q^2 values. T^*_π - charged pion kinetic energy. E^*_γ - virtual photon energy in the kaon rest frame. q^2 - e^+e^- mass squared.
- The population of 3d-boxes in the kinematic space (q^2, T^*_π, E^*_γ) is used to determine the relative fraction of each component. The 3d-space is split into N1 slices along q^2, N2 slices along T^*_π and then into N3 E^*_γ slices, all boxes with equal populations.
- To obtain the fractions (M)/IB and (IB-E)/IB reproducing the data, a χ^2 estimator is minimized:

$$\chi^2 = \sum_{i=1}^{\mathrm{N1}\times\mathrm{N2}\times\mathrm{N3}} (N_i - M_i)^2/(\delta N_i^2 + \delta M_i^2)$$

where N_i (δN_i) - data population (error), M_i (δM_i) - expected population (error) in box i.
The expected number of events in box I is

$$M_i = N \times (N_i^{\mathrm{IB}} + a \cdot N_i^{\mathrm{M}} + b \cdot N_i^{\mathrm{IB\text{-}E}}) + N_i^{Bkg}$$

where N is normalization factor. The relative contributions (M)/IB and (IB-E)/IB are defined as

$$(\mathrm{M})/\mathrm{IB} = (a \pm \delta a)/\rho_{\mathrm{M}}, \qquad (\mathrm{IB\text{-}E})/\mathrm{IB} = (b \pm \delta b)/\rho_{\mathrm{IB\text{-}E}}$$

	Data	Theory
M/IB	$0.0114 \pm 0.0043_{stat}$	$1/71 = 0.0141 \pm 0.0014_{ext}$
(IB-E)/IB	$-0.0014 \pm 0.0036_{stat}$	$-1/253 = -0.0039 \pm 0.0028_{ext}$
χ^2/ndf	98.2/87	
probability	19%	
Correlation C(a, b)	0.06	

Asymmetries

The simplest CP-violating asymmetry is the charge asymmetry between K^+ and K^- partial rates integrated over the whole phase space:

$$A_{CP} = \frac{\Gamma(K^+ \to \pi^+\pi^0 e^+e^-) - \Gamma(K^- \to \pi^-\pi^0 e^+e^-)}{\Gamma(K^+ \to \pi^+\pi^0 e^+e^-) + \Gamma(K^- \to \pi^-\pi^0 e^+e^-)}$$

$BR(K^+) = (4.151 \pm 0.078_{stat})\times10^{-6}$, $BR(K^-) = (4.394 \pm 0.108_{stat})\times10^{-6}$

$A_{CP} = -0.0284 \pm 0.0155_{stat}$, the systematic and external errors cancel in the ratio. This value is translated to a single-sided limit: **$|A_{CP}| < 4.82\times10^{-2}$** at 90% CL.

The **$A^{\varphi^*}_{CP}$** and **$A^{\tilde{\varphi}}_{CP}$** angular asymmetries are defined in [Eur. Phys. J. C 72 (2012) 1872]:

$A^{\varphi^*}_{CP} = 0.0119 \pm 0.0150_{stat}$ and **$A^{\tilde{\varphi}}_{CP} = 0.0058 \pm 0.0150_{stat}$**

Both asymmetries are consistent with zero. The single-sided upper limits:

$|A^{\varphi^*}_{CP}| < 3.11\times10^{-2}$, $|A^{\tilde{\varphi}}_{CP}| < 2.50\times10^{-2}$ at 90% CL

The long-distance P-violating asymmetry $A^{(L)}_P$ defined in [Eur. Phys. J. C 72 (2012) 1872]

$A^{(L)}_P(K^+) = 0.0059 \pm 0.0180_{stat}$ and **$A^{(L)}_P(K^-) = -0.0166 \pm 0.0237_{stat}$**

The combined value is

$A^{(L)}_P(K^\pm) = -0.0023 \pm 0.0144_{stat}$

The single-sided upper limit:

$A^{(L)}_P < 2.07 \times 10^{-2}$ at 90% CL.

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

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	$f_+(t,\text{parameters})$	$f_0(t,\text{parameters})$
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

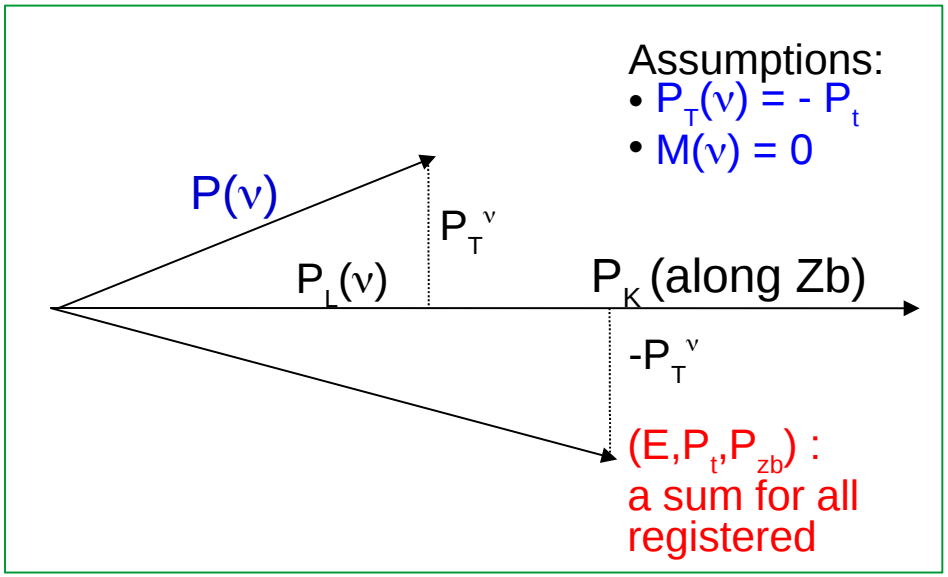
Registered :

- **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

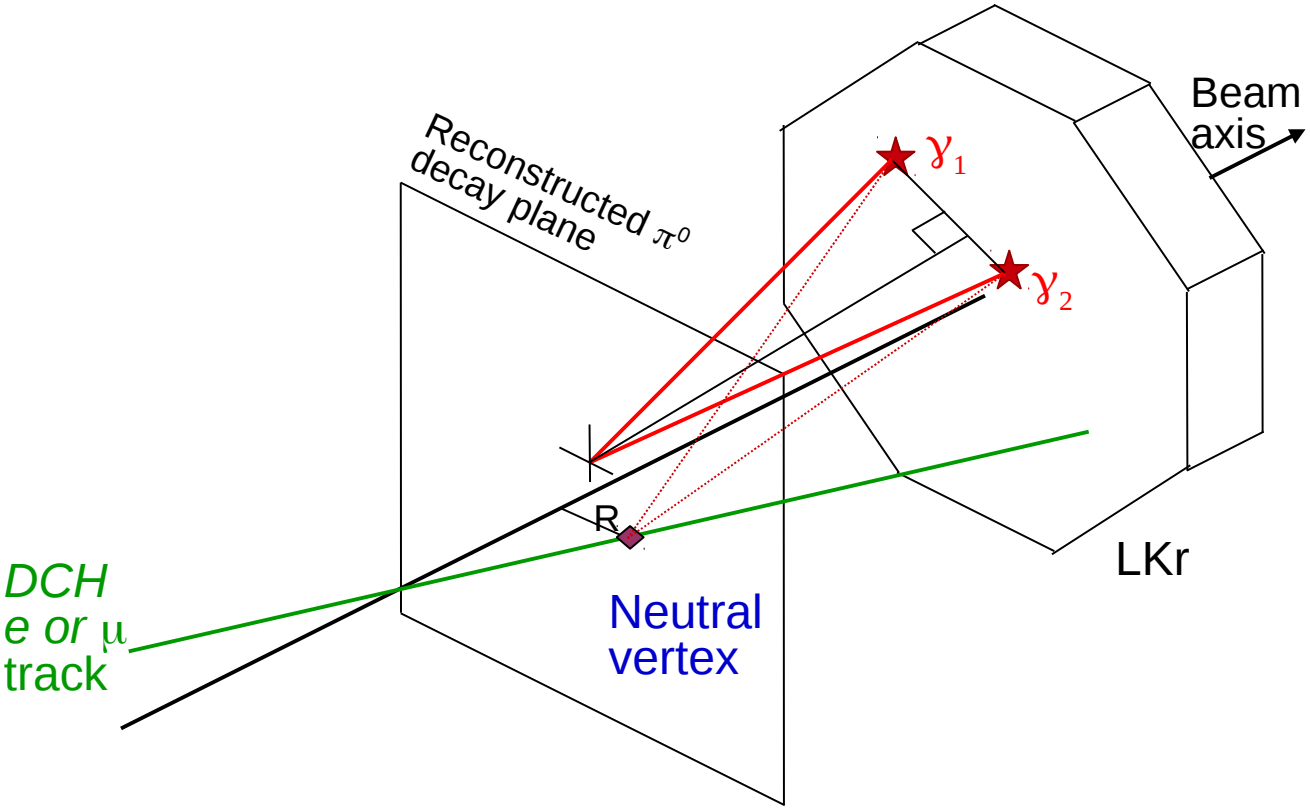


- Best P_K solution = closest $P_{1,2}$ to the average beam momentum P_b (measured from $3\pi^{\pm}$ decays for each run).
- Select: -7.5 GeV/c < (P_K — P_b) < 7.5 GeV/c
- For each event, separately for K_{e3} and $K_{\mu3}$ selections, the combination with a minimum $\Delta P = |P_K — P_b|$ is the best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

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

Neutral vertex:

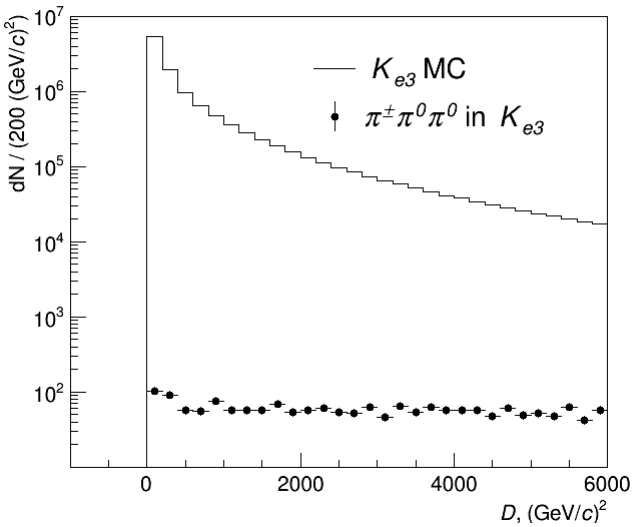
$Z_{decay} = Z(\pi^0)$; X_{decay}, Y_{decay} = impact point of reconstructed charged track on Z_{decay} plane

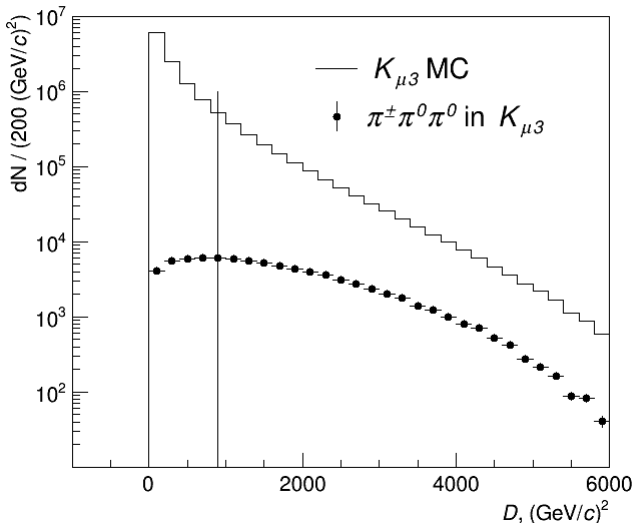
Specific $K_{\mu 3}$ selection cuts

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

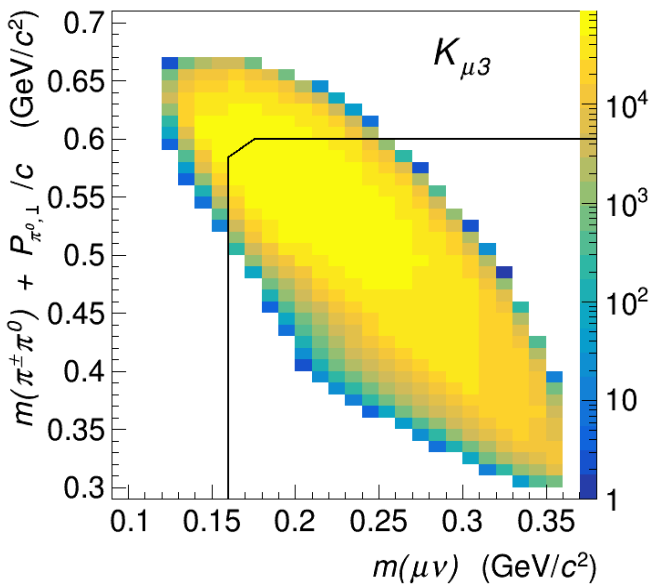
$m(\pi^{+}\pi^{0}) < 0.475$ GeV/c^2

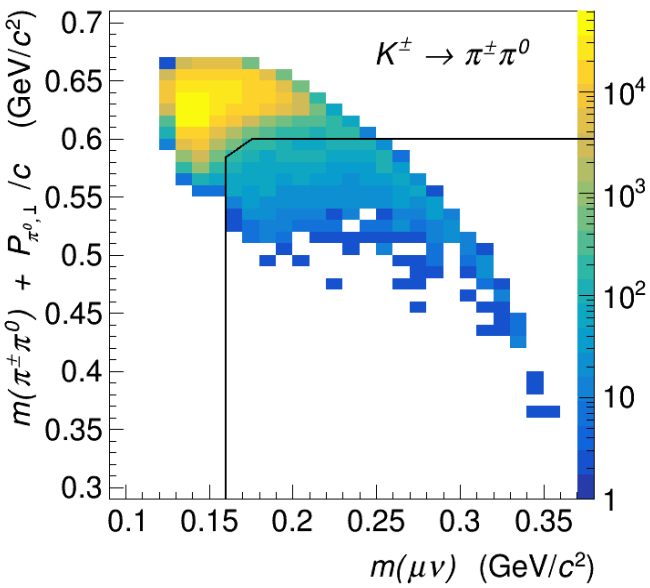
& $\pi^{\pm} \rightarrow \mu^{\pm}\nu$

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

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

(to exclude π^{+} mass region)

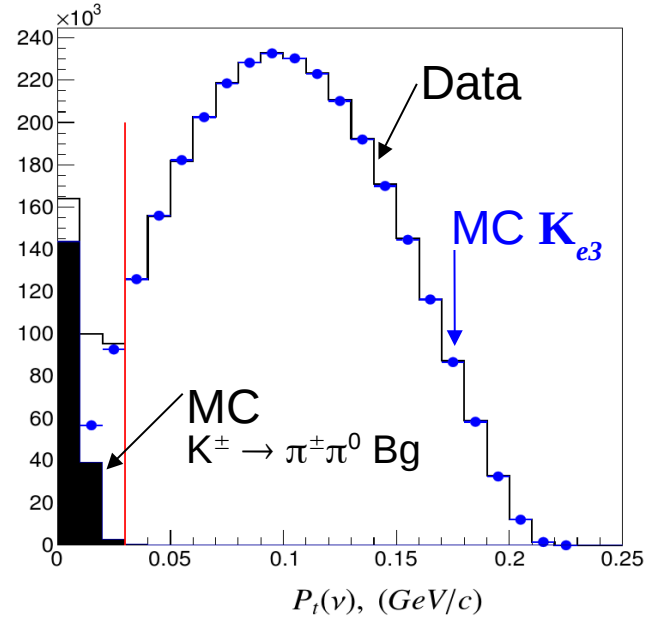




Specific K_{e3} selection cut

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

against $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ 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)**.

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

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

- **Z > -1600 cm**

(Final collimator is at Z = -1800 cm)

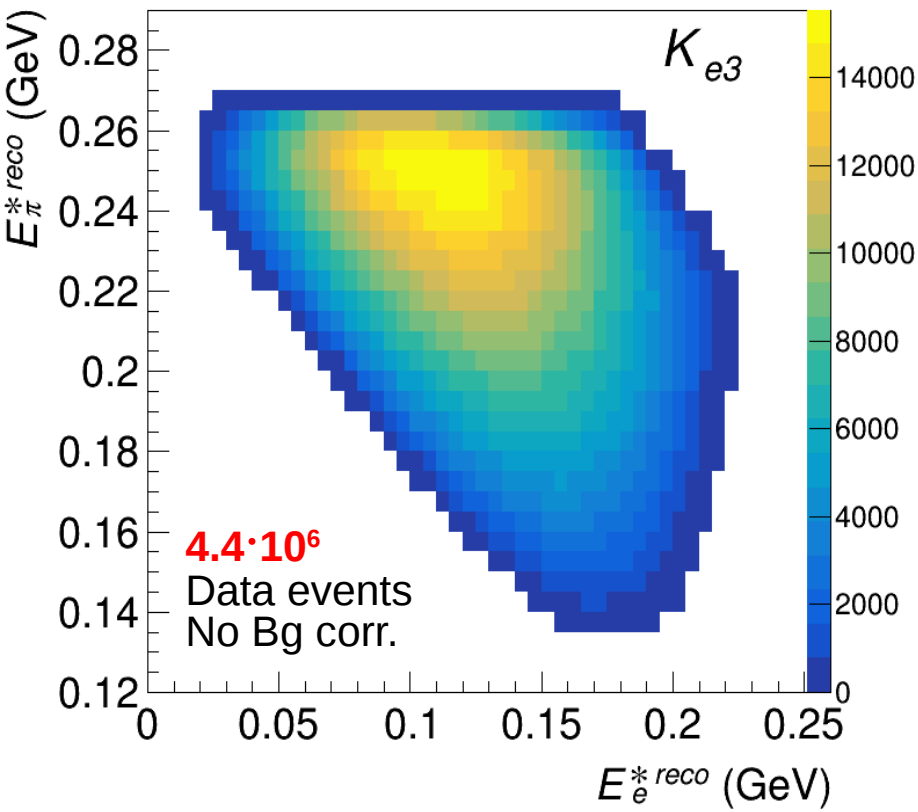
Background

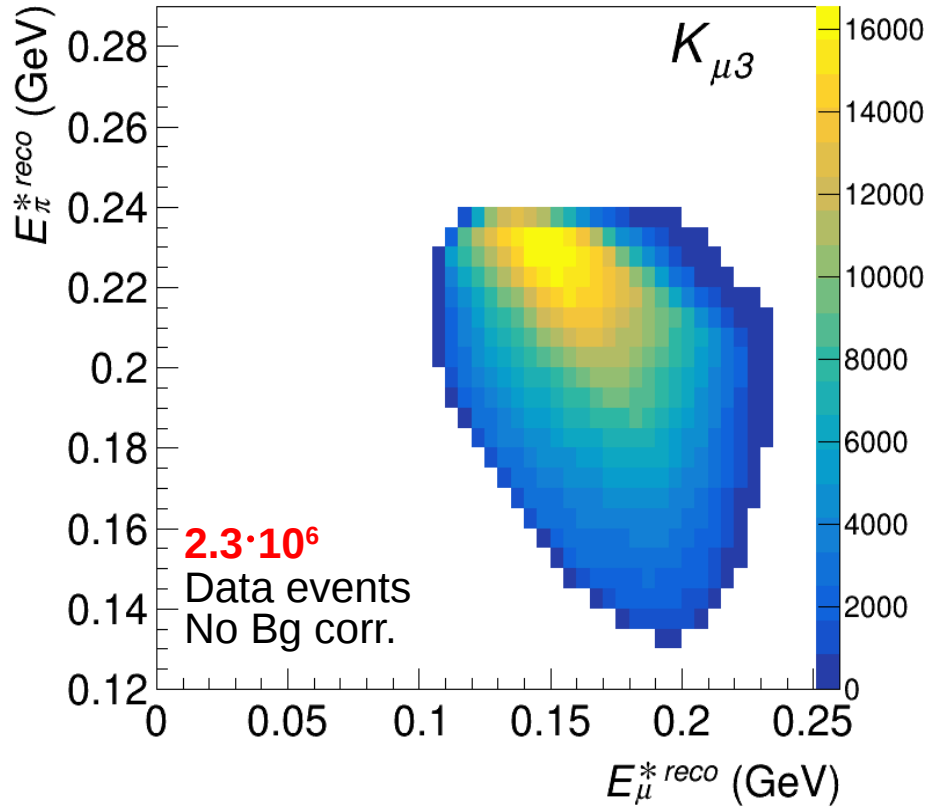
Decay	r_e, 10^{-3}	r_μ, 10^{-3}
$K^\pm \to \pi^\pm(\pi^0 \to 2\gamma)$	0.272	0.392
$K^\pm \to \pi^\pm 2(\pi^0 \to 2\gamma)$	0.287	2.192
$K^\pm \to \pi^\pm(\pi^0 \to e^+e^-\gamma)$	0.049	0.000
$K^\pm \to \pi^\pm\gamma(\pi^0 \to 2\gamma)$	0.004	0.044
$K^\pm \to \pi^0\mu^\pm\nu(\mu \to e\nu)$	0.004	0.000

$\mathbf{r_e}$ — background to signal ratio in K_{e3} data
$\mathbf{r_\mu}$ — background to signal ratio in $K_{\mu 3}$ data

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

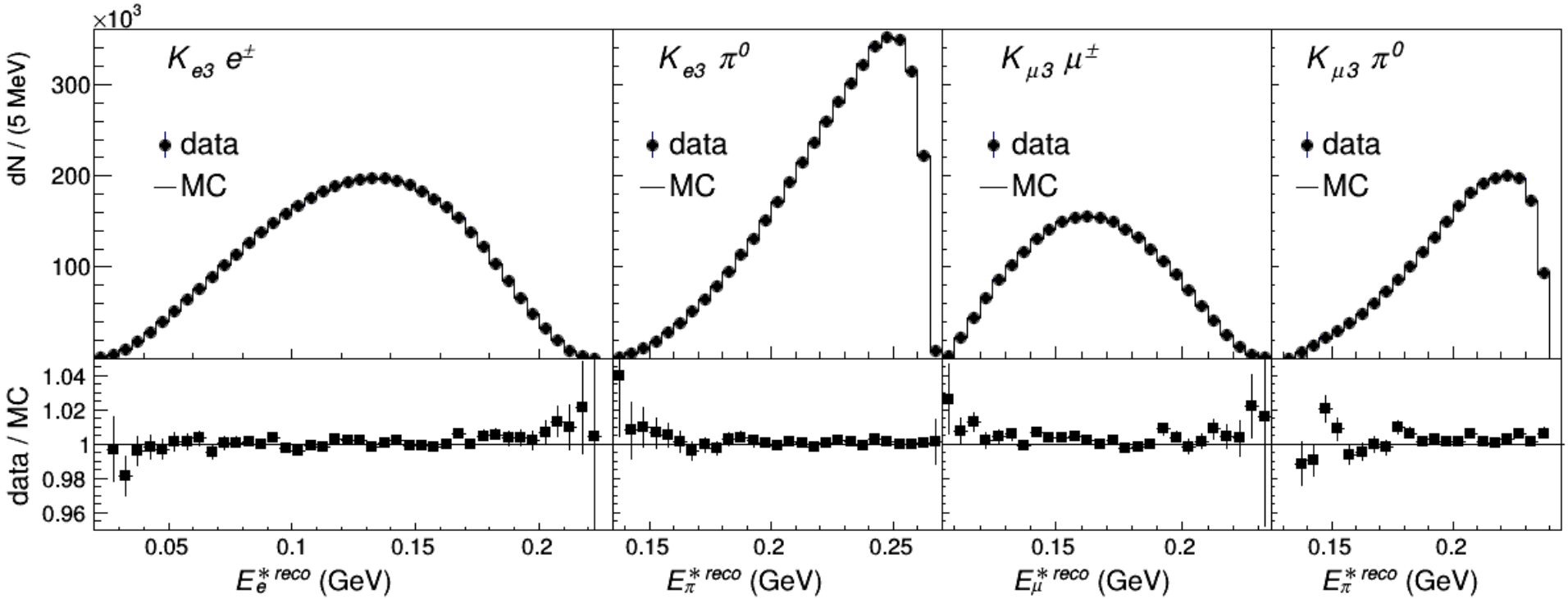
Experimental Dalitz plots (5x5 MeV cells)





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:**

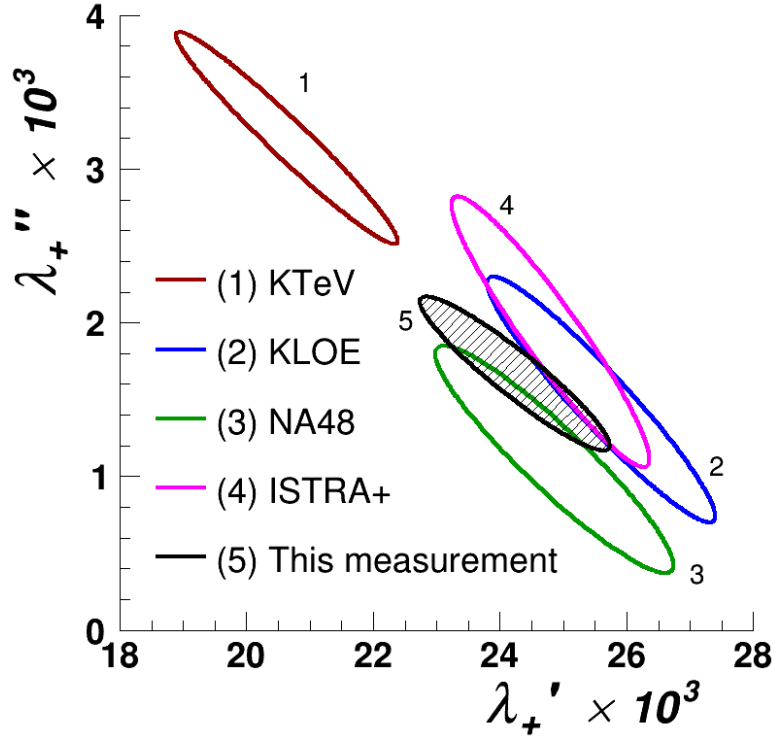
Joint fits minimizing $\chi^2(K_{e3}) + \chi^2(K_{\mu 3})$ with a common set of fit parameters.

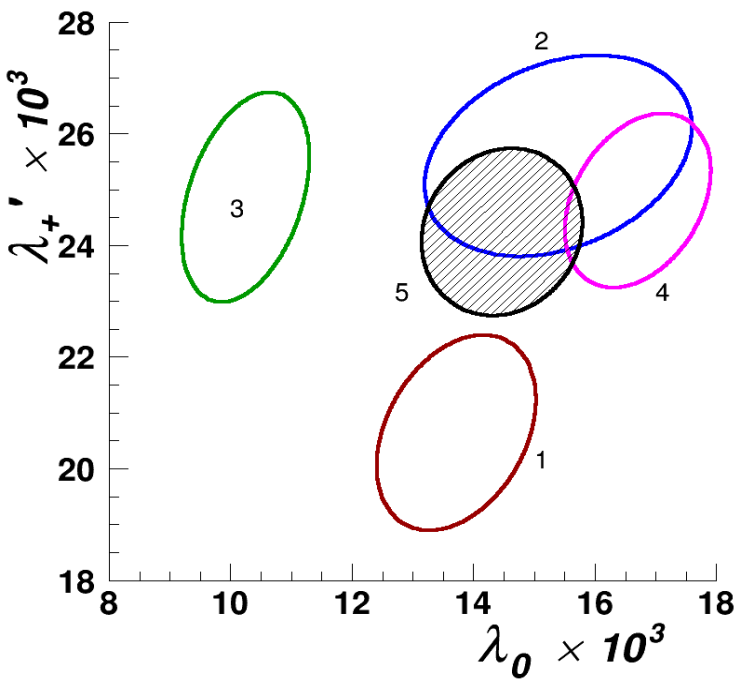
Results of the joint K_{l3} (K_{e3} + $K_{\mu 3}$) analysis

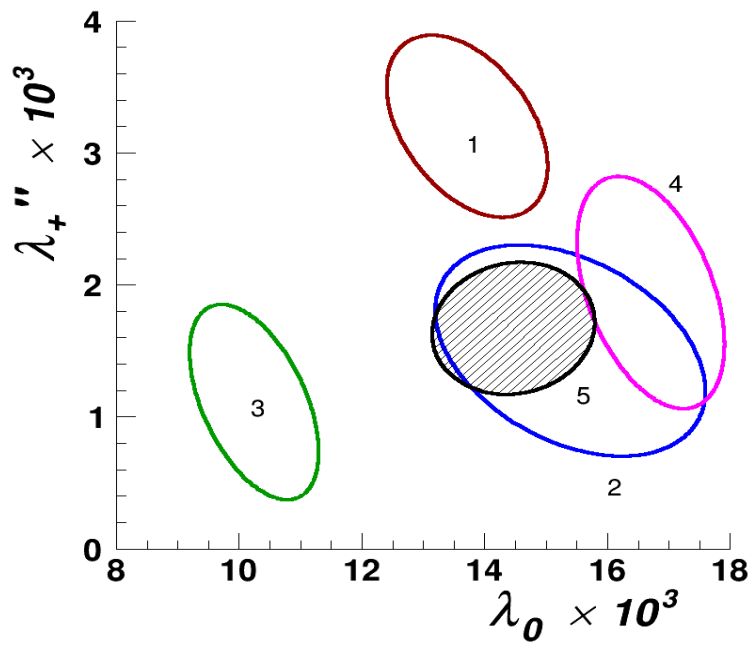
	λ'_+	λ''_+	λ_0	m_V	m_S	Λ_+	$\ln C$
Central values	24.24	1.67	14.47	884.4	1208.3	24.99	183.65
Statistical error	0.75	0.29	0.63	3.1	21.2	0.20	5.92
Diverging beam component	0.97	0.35	0.55	1.1	32.2	0.08	9.43
Kaon momentum spectrum	0.00	0.00	0.02	0.1	0.7	0.00	0.19
Kaon mean momentum	0.04	0.01	0.04	0.2	1.7	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







Conclusion

- The 4919 $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ 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.

  Published in Phys.Lett. B788 (2019) 552.

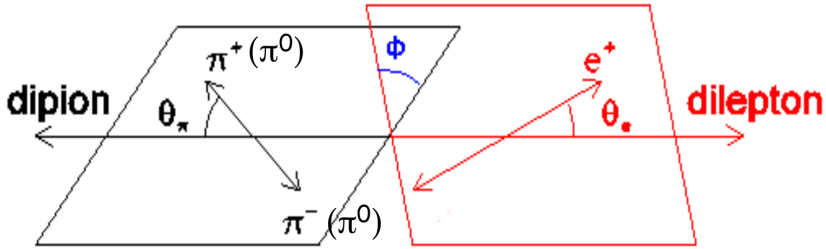
- **K_{l3}** form factors measurement is performed by NA48/2 on the basis of 2004 run selected **$4.4\cdot10^{6}$ (K_{e3})** and **$2.3\cdot10^{6}$ ($K_{\mu3}$)** events. Result is competitive with the other ones in **$K_{\mu3}$** mode, and a smallest error in **K_{e3}** has been reached, that gives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

  Published in JHEP 1810 (2018) 150.

SPARES

Angular asymmetries definition

The asymmetries are defined in [Eur. Phys. J. C 72 (2012) 1872] using the so-called Cabibbo-Maksymowicz [N. Cabibbo and A. Maksymowicz, Phys. Rev. 137 (1965) B438] variables:



$$A_{CP}^{\phi^*} = \frac{\int_0^{2\pi} \frac{d\Gamma_{(K^+-K^-)}}{d\phi} d\phi^*}{\int_0^{2\pi} \frac{d\Gamma_{(K^++K^-)}}{d\phi} d\phi}, \text{ where } \int_0^{2\pi} d\phi^* \equiv \left[\int_0^{\pi/2} - \int_{\pi/2}^{\pi} + \int_{\pi}^{3\pi/2} - \int_{3\pi/2}^{2\pi}\right] d\phi,$$

$$A_{CP}^{\tilde{\phi}} = \frac{\int_0^{2\pi} \frac{d\Gamma_{(K^+-K^-)}}{d\phi} d\tilde{\phi}}{\int_0^{2\pi} \frac{d\Gamma_{(K^++K^-)}}{d\phi} d\phi}, \text{ where } \int_0^{2\pi} d\tilde{\phi} \equiv \left[\int_0^{\pi/2} + \int_{\pi/2}^{\pi} - \int_{\pi}^{3\pi/2} - \int_{3\pi/2}^{2\pi}\right] d\phi.$$

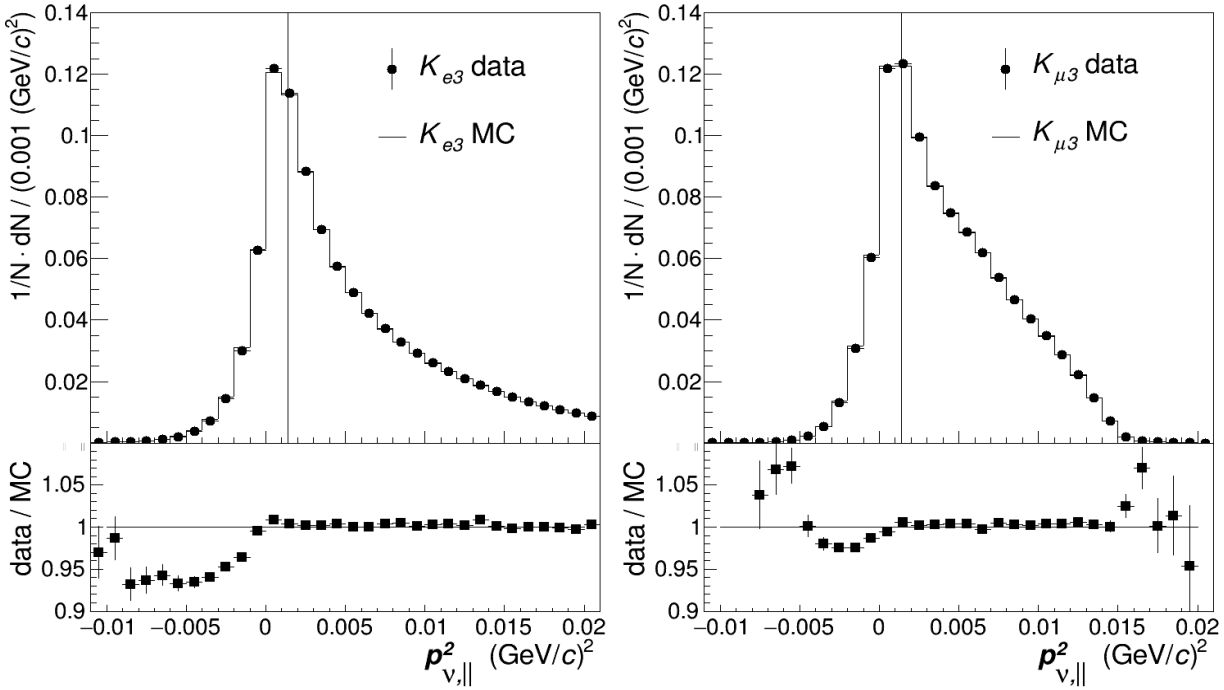
Defining sectors of the **φ** space between 0 and 2π as **Φ1 (0, π/2), Φ2 (π/2, π), Φ3 (π, 3π/2), Φ4 (3π/2, 2π)**, and combining them as statistically independent sector sums (**Φ13 = Φ1 + Φ3, Φ24 = Φ2 + Φ4**), one can define the long-distance asymmetry as:

$$A_P^{(L)} = \frac{\int_0^{2\pi} \frac{d\Gamma}{d\phi} d\phi^*}{\int_0^{2\pi} \frac{d\Gamma}{d\phi} d\phi} = \frac{\Gamma(\Phi 13) - \Gamma(\Phi 24)}{\Gamma}$$

K_{l3} common cuts

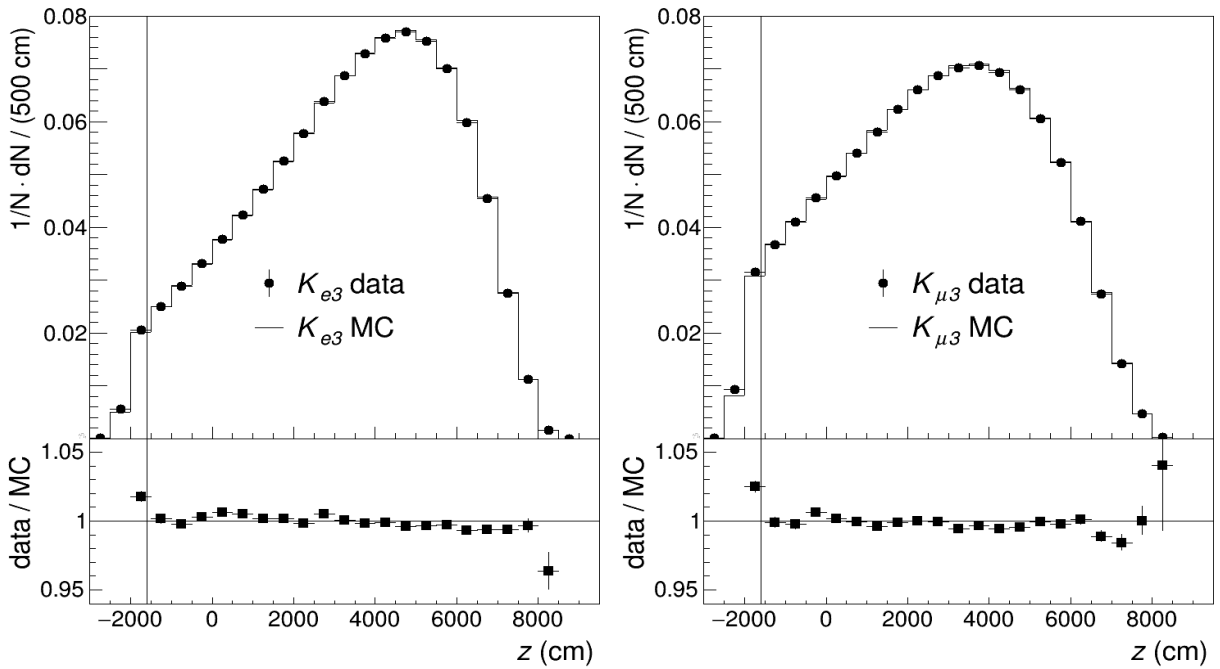
$P_L(\nu)^2 = (E^\nu)^2/c^2 - (P_t^\nu)^2$
$> 0.0014\ GeV^2/c^2$

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



Z > -1600 cm

Final collimator is at
Z = -1800



Kaon momentum reconstruction

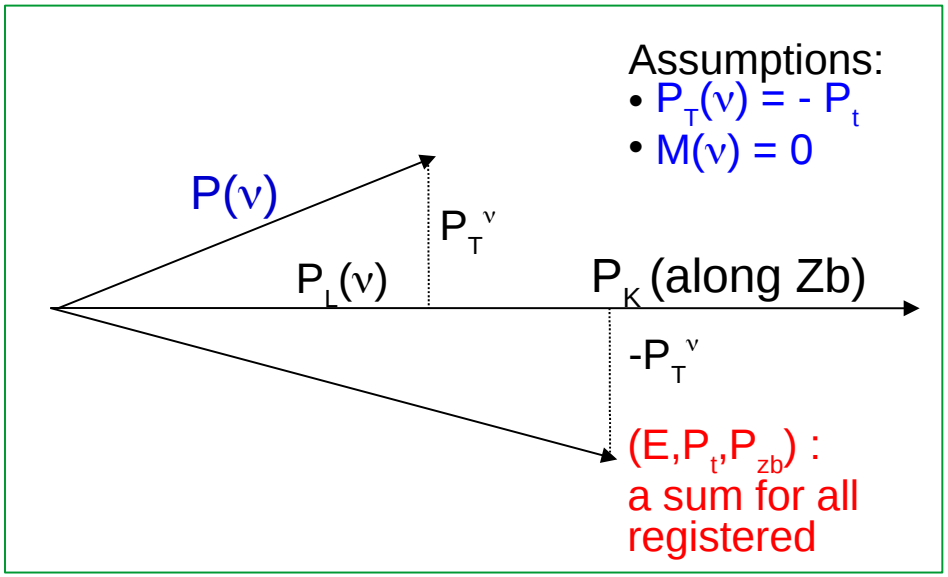
Two solutions of the quadratic equation for P_K:

$P_{1,2} = (\phi P_{Zb} \pm SQRT(\mathbf{d})) / (E^2 - P_{zb}^2)$, where

$\phi = 0.5 (M_K^2 + E^2 — P_t^2 — P_{Zb}^2)$,

$\mathbf{D} = (\phi^2 P_{Zb}^2 — (E^2 — P_{Zb}^2)(M_K^2 E^2 — \phi^2))$

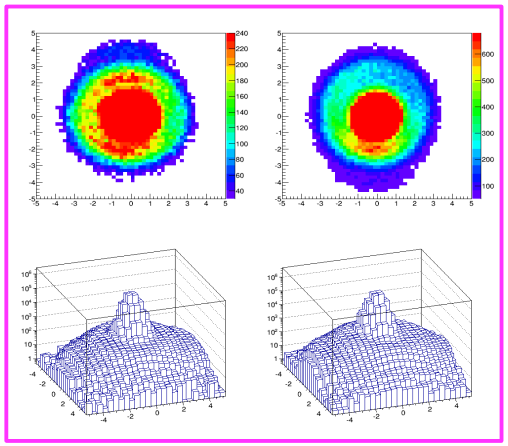
When D<0, we assume D=0.



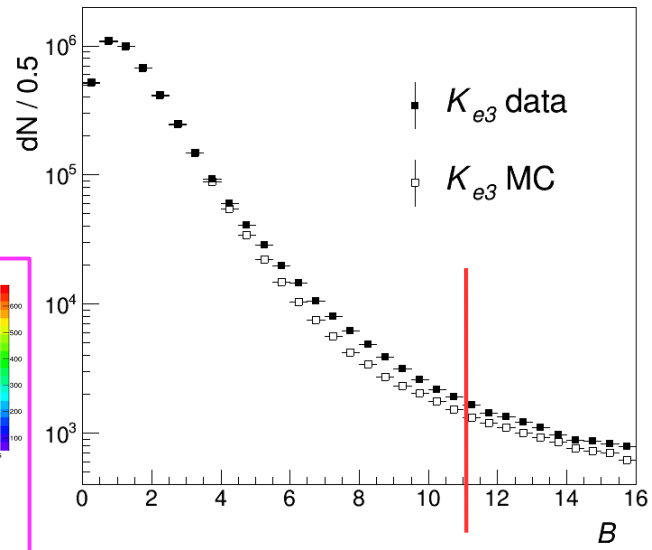
- Best P_K solution = closest $P_{1,2}$ to the average beam momentum P_b (measured from $3\pi^\pm$ decays for each run).
- Select: -7.5 GeV/c $< (P_K — P_b) < 7.5$ GeV/c
- For each event, separately for K_{e3} and $K_{\mu 3}$ selections, the combination with a minimum $\Delta P = |P_K — P_b|$ is the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

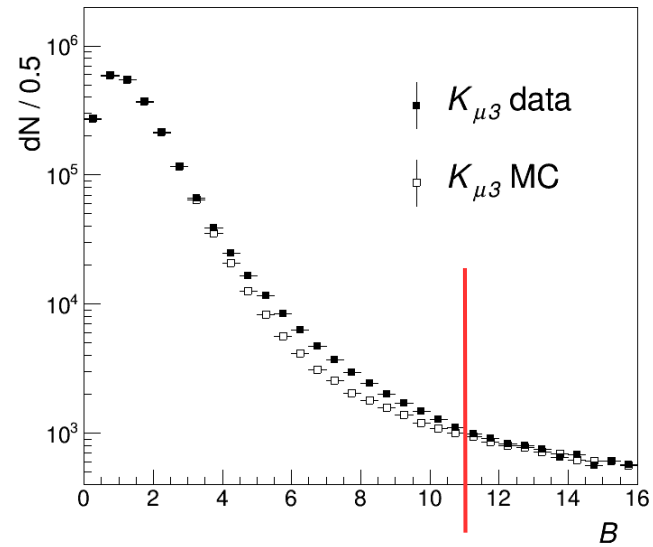
Beams shape

Data $3\pi^{\pm}$ decay: Kaon impact points X,Y at the focus plane (4500 cm)



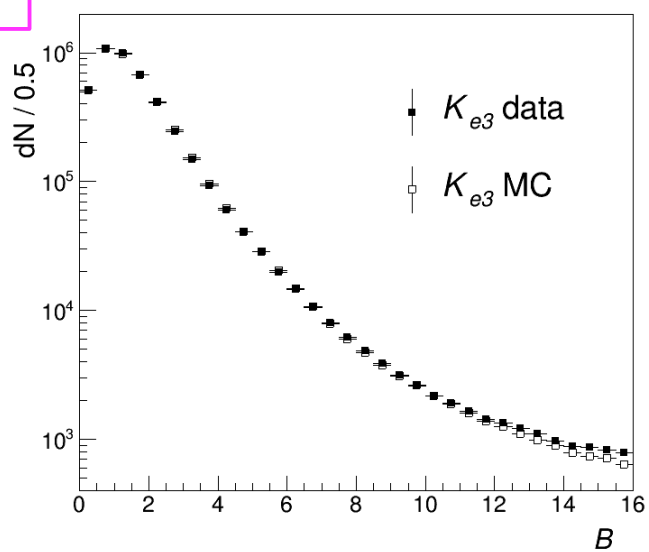
Standard simulation

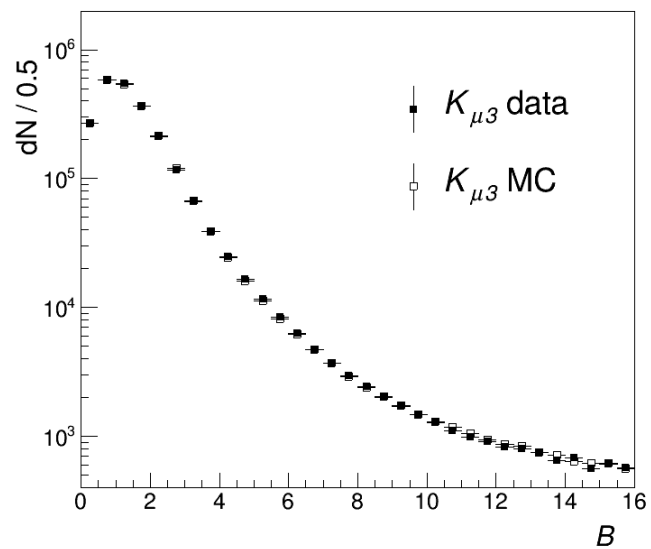




Diverging beam component added (for systematics only)

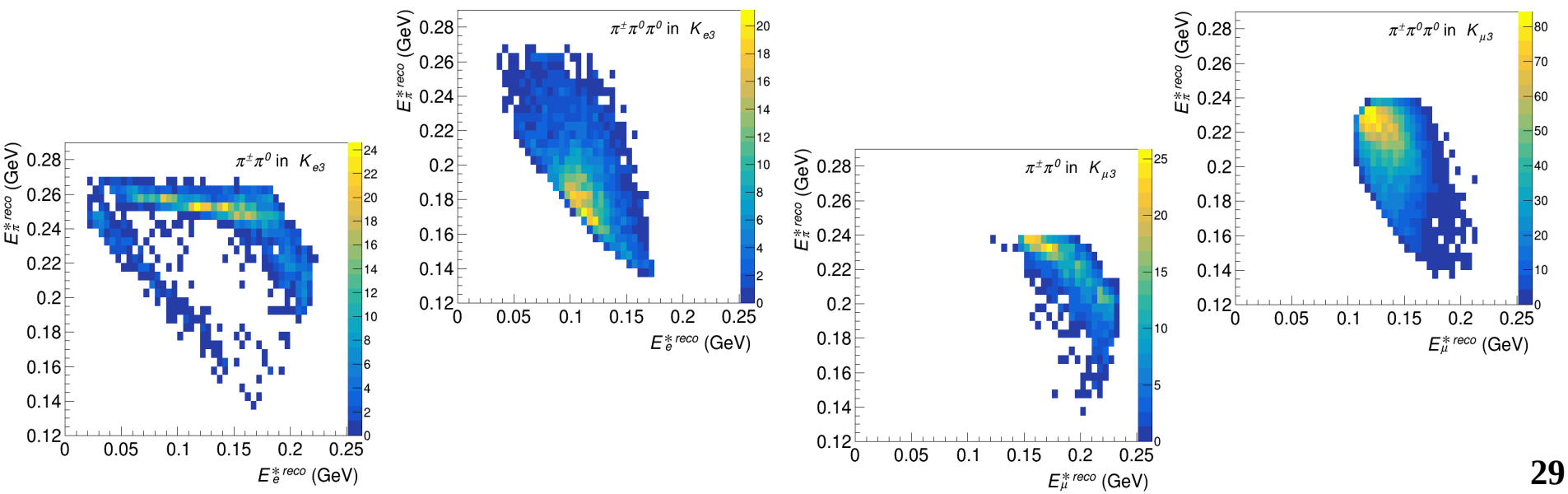
Focused scattering is simulated in MC:
3% of beam kaons are additionally directed into a series of rings at the focus plane with a different radius > 2.2 cm.





Background processes, branching ratios $\mathcal{B}$ generated MC statistics in the fiducial volume 112 m long, N_{gen}, and the estimated contributions f_{Ke3} and $f_{K\mu3}$ in the selected K_{e3} and $K_{\mu3}$ samples. The upper limit for one of the values is shown at 95% CL.

Process	$\mathcal{B}$ [%]	N_{gen} [10^6]	f_{Ke3} [10^{-3}]	$f_{K\mu3}$ [10^{-3}]
$K^\pm \to \pi^\pm\pi^0\pi^0$ ($\pi^0 \to \gamma\gamma, \pi^0 \to \gamma\gamma$)	1.72(2)	62.5	0.286(6)	2.192(32)
$K^\pm \to \pi^\pm\pi^0$ ($\pi^0 \to \gamma\gamma$)	20.43(8)	393.2	0.271(6)	0.392(10)
$K^\pm \to \pi^\pm\pi^0_D$ ($\pi^0_D \to e^+e^-\gamma$)	0.243(7)	1.5	0.049(5)	0.0008(8)
$K^\pm \to \pi^0\mu^\pm\nu$ ($\pi^0 \to \gamma\gamma$)[$via\ \mu \to e\bar{\nu}\nu$]	0.033(3)	174.3	0.044(5)	—
$K^\pm \to e^\pm\nu\pi^0\pi^0$ ($\pi^0 \to \gamma\gamma, \pi^0 \to \gamma\gamma$)	0.0022(4)	5.0	0.019(3)	$< 4 \times 10^{-6}$
$K^\pm \to \pi^\pm\pi^0\gamma$ ($T^*_{\pi+} = 55 - 90MeV, \pi^0 \to \gamma\gamma$)	0.027(2)	35.3	0.0044(3)	0.071(4)
$K^\pm \to \pi^\pm\pi^0\pi^0$ ($\pi^0 \to \gamma\gamma, \pi^0 \to e^+e^-\gamma$)	0.0204(7)	9.9	0.0028(2)	0.0130(5)
$K^\pm \to \mu^\pm\nu\pi^0\pi^0$ ($\pi^0 \to \gamma\gamma, \pi^0 \to \gamma\gamma$)	0.0004(2)	5.0	$0.19(11) \times 10^{-5}$	0.004(2)



K_{l3} events-weighting fit procedure

We use MC radiative decay generator of C.Gatti [Eur.Phys.J. C45 (2006) 417–420] provided by KLOE collaboration. It includes $f_0=f_+=1+\lambda'_+ t/m^2_\pi$.
Generator for K_{e3} is corrected by weighting to conform to the «universal» part of radiative effects ($K_{\mu 3}$ is OK) [Cirigliano et al. Eur.Phys. J. C 23 (2002) 121] .
So we measure «effective» FF-s that absorb interplay between QED and low-energy QCD.

• For each fit iteration, the model Dalitz plot is filled in with an MC simulated reconstructed center-of-mass pion and lepton energies. Each event is weighted by

$$w = \rho_0(E_\pi^{true}, E_l^{true}, FF_{fit}) \,/\, \rho_0(E_\pi^{true}, E_l^{true}, FF_{MC\ enerator}),$$

where ρ_0 is the non-radiative Dalitz density formula **(for K_{e3} an additional factor is applied to conform the universal correction)**.

• MINUIT package is searching for the FF_{fit} parameters minimizing the standard χ^2 value:

$$\chi^2 = \Sigma_{i,j} \frac{(D_{i,j} - MC_{i,j})^2}{(\delta D_{i,j})^2 + (\delta MC_{i,j})^2},$$

where *i,j* means the Dalits plot cell indices, $D_{i,j}$ is the background-corrected experimental data content of the cell, $MC_{i,j}$ is the weighted MC bin content, and $\delta D_{i,j}$, $\delta MC_{i,j}$ are the corresponding statistical errors. **Background correction contribution also has some dependence on FF due to the signal acceptance sensitivity.**

At least 20 data events per cell are required in the fit area, so χ^2 works well.