Latest results from NA48/2

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On behalf of the NA48/2 collaboration

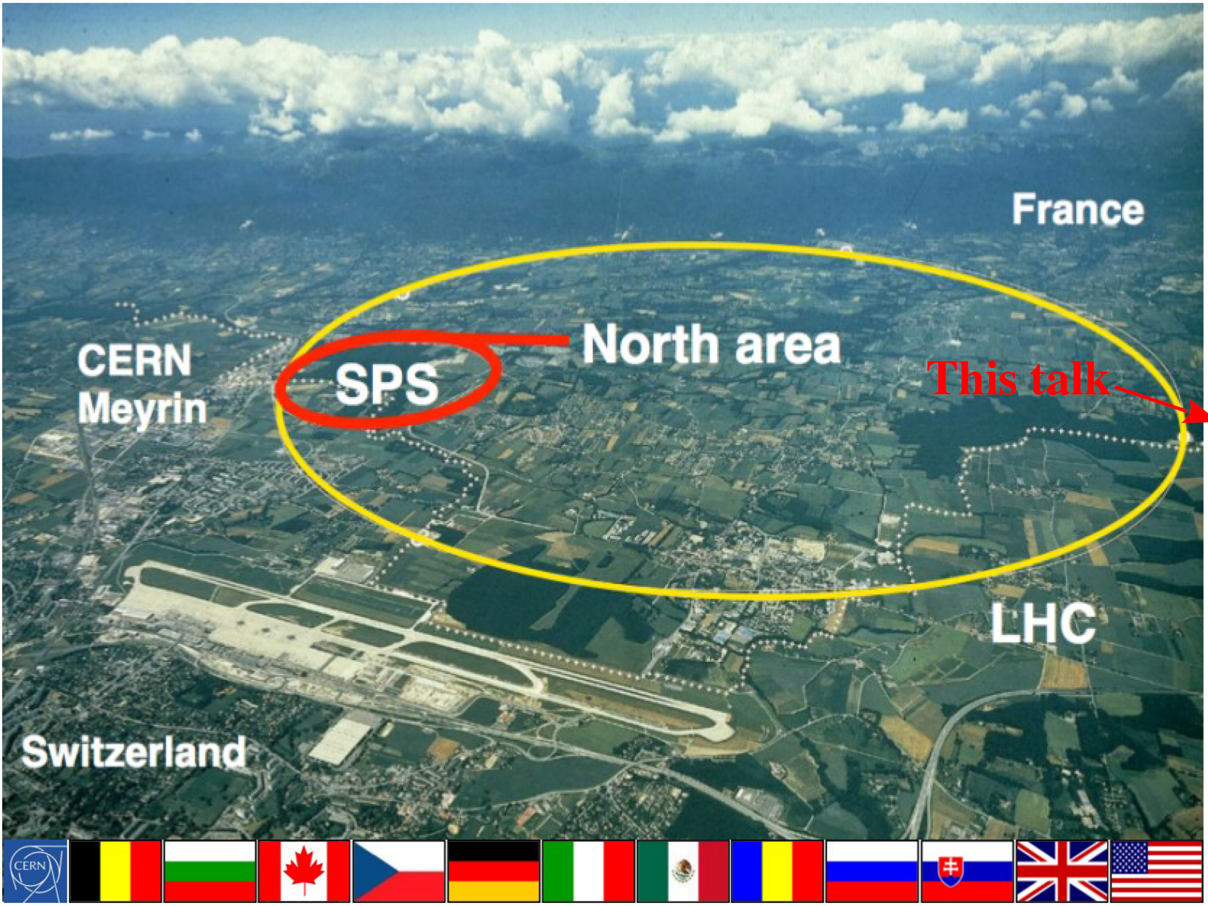
RKF 2019 -2nd forum on rare kaon deacy

Outline

- The NA48/2 experiment: beam and detectors
- The semileptonic decays $K^{\pm} \to \pi^0 \ell^{\pm} \nu_l$
  - > Signal selection and reconstruction
  - > Form factors measurement
- First observation of the $K^{\pm} \to \pi^{\pm}\pi^0 e^+ e^-$ decay
  - > BR measurement
  - > Comparison with χPT predictions
  - > K^+/K^- asymmetry measurement

The NA48 and NA62 collaborations

NA62 is the last from a long tradition of fixed-target Kaon experiments in the CERN North Area



History of NA48/NA62 experiments		
1997 ↓ 2001	NA48 (K_S/K_L)	Re ε′/ε **Discovery of direct CPV**
2002	NA48/1 (K_S/hyperons)	Rare K_S and hyperon decays
2003 ↓ 2004	**NA48/2 (K^+/K^-)**	Direct CPV, **Rare K^+/K^- decays**
2007 ↓ 2008	NA62-R_K (K^+/K^-)	$R_K = K^{\pm}_{e2}/K^{\pm}_{\mu2}$
2015 ↓ -	NA62 (K^+)	$K^+ \to \pi^+ \nu\bar{\nu}$, Rare K^+ and π^0 decays

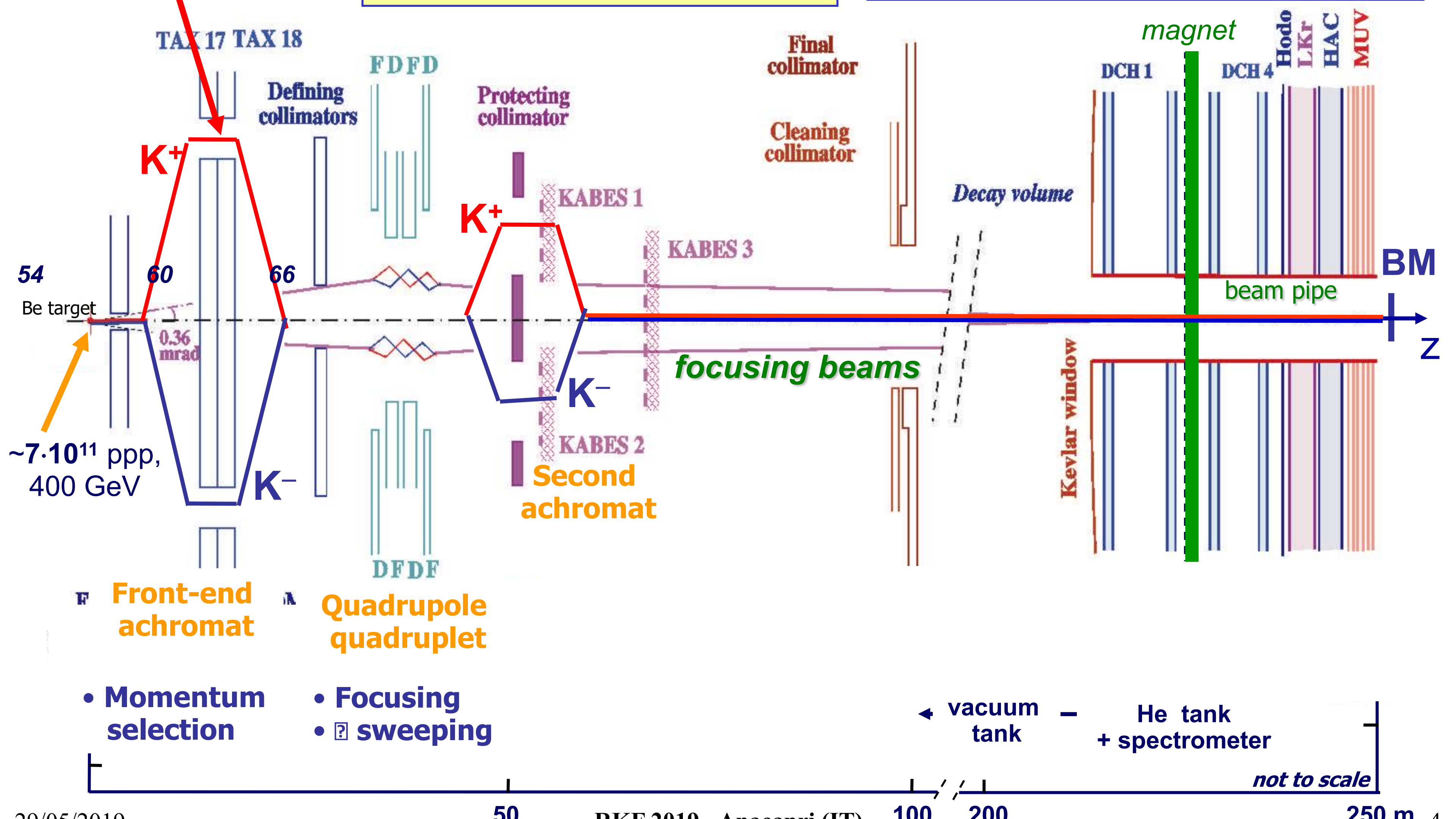
NA62: currently ~ 200 participants, 29 institutions from 12 countries

The NA48/2 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

P_K spectra: 60±3 GeV/c



The NA48/2 detector

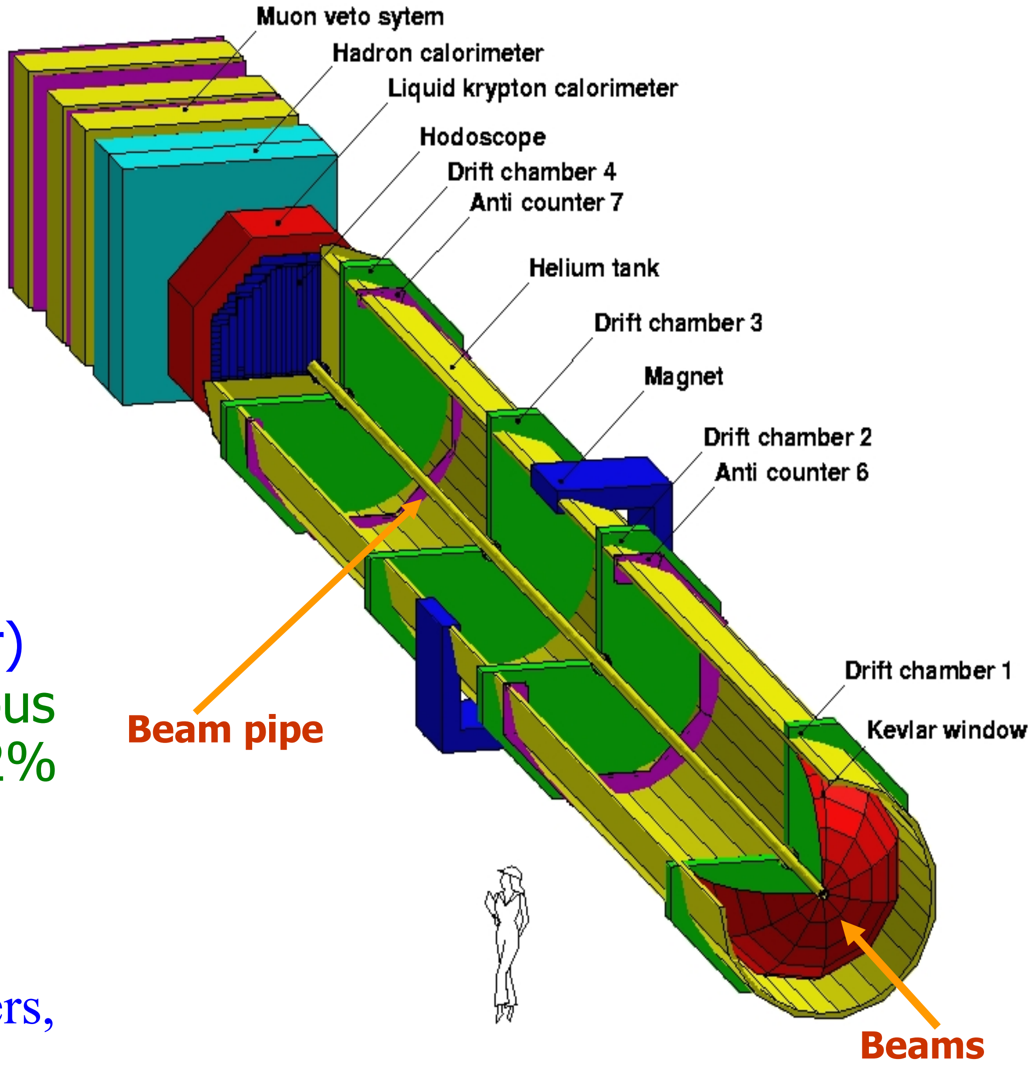
Main detector components:

- 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 (150 ps).

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

- Hadron calorimeter, muon veto counters, photon vetoes.



$K^{\pm} \to \pi^0 e^{\pm} \nu_e$ and $K^{\pm} \to \pi^0 \mu^{\pm} \nu_\mu$ decays @ NA48/2

[JHEP 1810 (2018) 150]

Reconstruction of $K^{\pm} \rightarrow \pi^0 \ell^{\pm} \nu_{\ell}$ decays

- Data sample: 16 special runs of NA48/2 data taken in 2004 (3 days)
- Minimum bias trigger: 1 charged track and $E_{LKr} > 10$ GeV
- Beam geometry and average momentum P_{beam} are measured from $K_{3\pi}$

In the $K_{\ell 3}$ analysis the reconstruction of Kaon momentum has 2 solutions

➡ choose solution with smallest $\Delta P = |P_K - P_{beam}|$, $\Delta P < 7.5$ GeV/c

Improved decay vertex:

CDA (previous 2012 analysis):

> systematic shift of the vertex closer to the beam

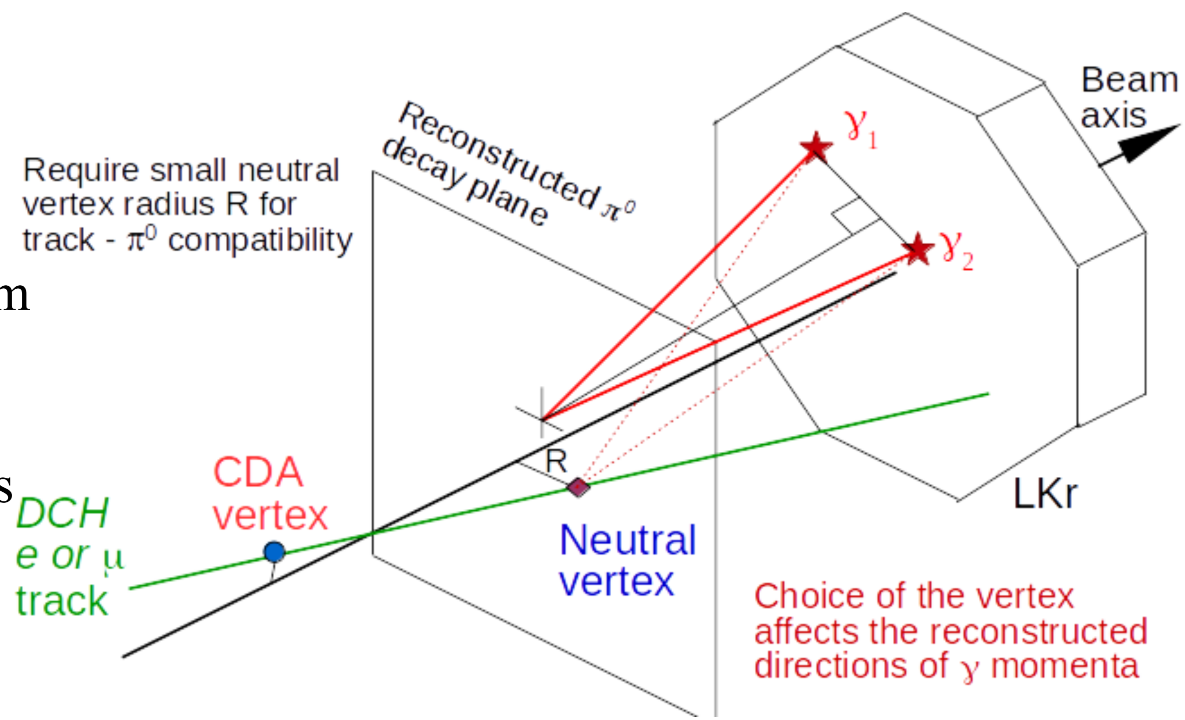
> High sensitivity to exact beam shape simulation

Neutral vertex (this analysis):

> Z_n obtained imposing π^0 mass

> X_n , Y_n = impact point of charged track at $Z=Z_n$ plane

> No transverse bias



Main selection cuts

General cuts:

- 2 γ in time (within 5 ns) detected in the LKr, separated by > 20 cm
- Photon distance > 15 cm from closest track in LKr, no extra-clusters
- $E(\pi^0) > 15$ GeV
- Compatibility of neutral vertex (X_n, Y_n, Z_n) with beam axis
- Good track in-time with the π^0 (10 ns), no extra good tracks (8 ns)

K_{e3} selection:

- 1 track with p > 5 GeV/c
- Track with E/p > 0.9
- p^{ν}_T (w.r.t. beam axis) > 0.03 GeV/c

$K_{\mu3}$ selection:

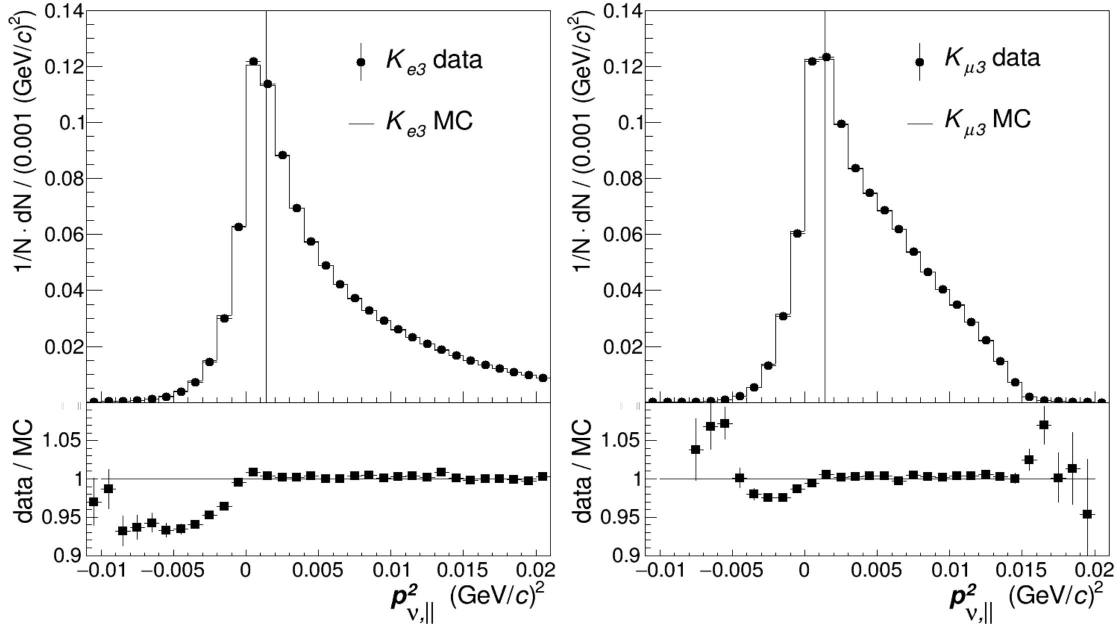
- 1 track with p > 10 GeV/c
- Track with E/p < 0.9 and MUV signal
- Selective cuts against $K^{\pm} \to \pi^{\pm}\pi^0$ and $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ decays (followed by a $\pi^{\pm} \to \mu^{\pm}\nu_{\mu}$ decay/with a missing π^0)

Residual background from 2π and 3π decay very small: $O(10^{-4}$-$10^{-3})$

General cuts

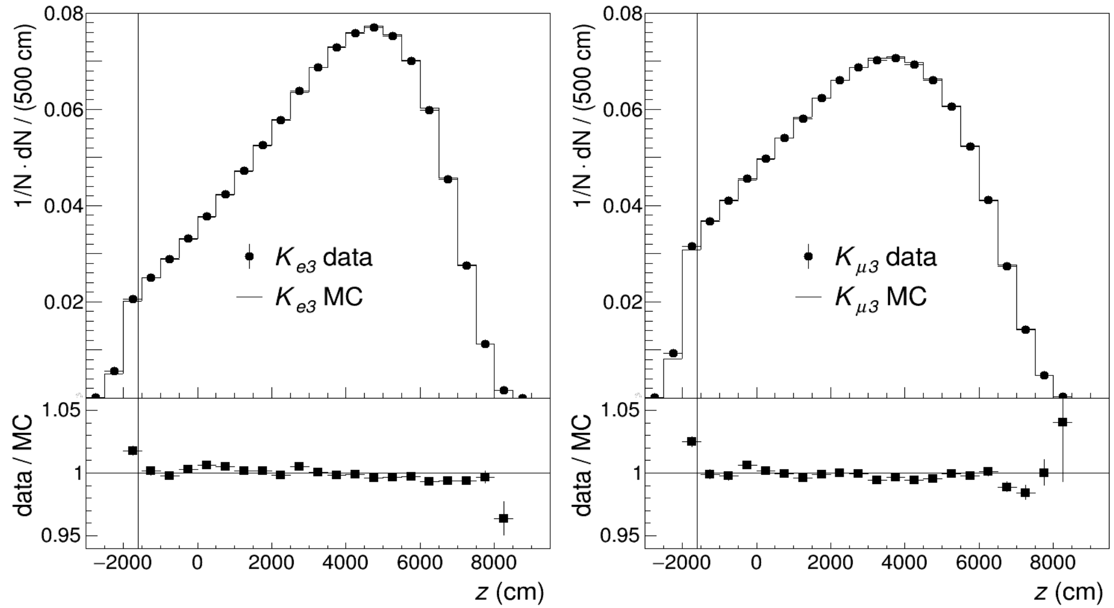
$P_L(\nu)^2 = (E^\nu)^2/c^2 - (P_t^\nu)^2 > 0.0014\ GeV^2/c^2$

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



Z > -1600 cm

To reduce background from interactions in the final collimator placed at Z = -1800 cm



Beam profile

Main source of systematic error.

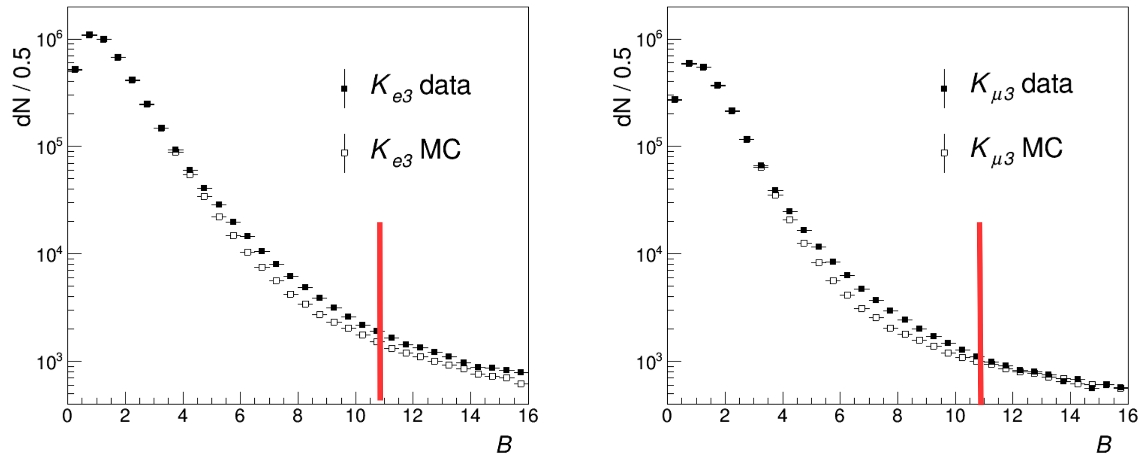
Beam (transverse elliptic) variable:

$$B = \sqrt{\left(\frac{x - x_0(z)}{\sigma_x(z)}\right)^2 + \left(\frac{y - y_0(z)}{\sigma_y(z)}\right)^2}$$

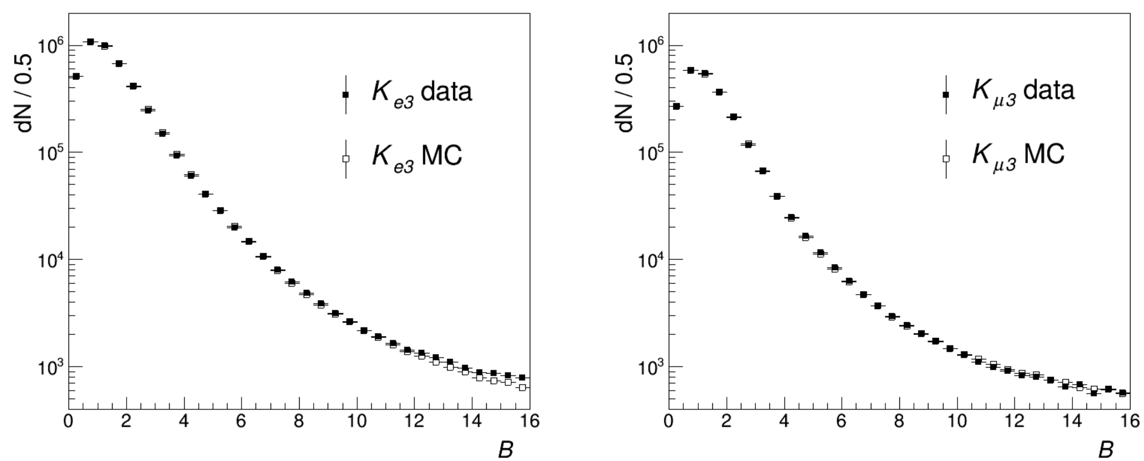
x,y,z are the reconstructed neutral vertex coordinates, $x_0(z)$, $y_0(z)$, $\sigma_x(z)$, $\sigma_y(z)$ are the reconstructed beam central positions and widths obtained by run-dependent reconstruction of $K_{3\pi}$ decays .

Requiring **B<11**

Standard simulation



Diverging beam component added (for systematics only)

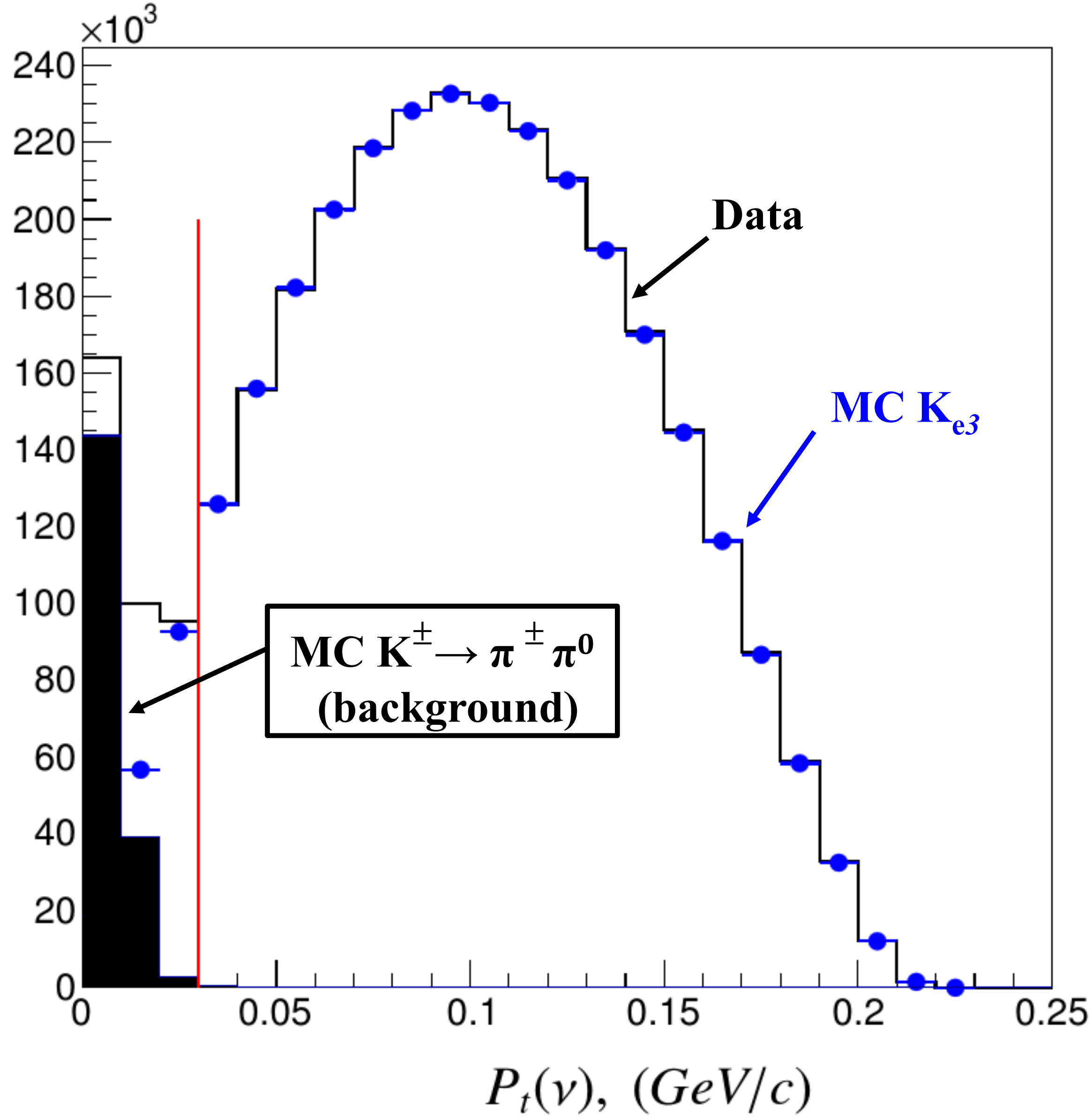


Specific K_{e3} selection cut

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

(with the $\pi^{\pm}$ is misidentified as a $e^{\pm}$)

p^{ν}_{T} (w.r.t. beam axis) > 0.03 GeV/c



Specific $K_{\mu 3}$ selection cuts

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

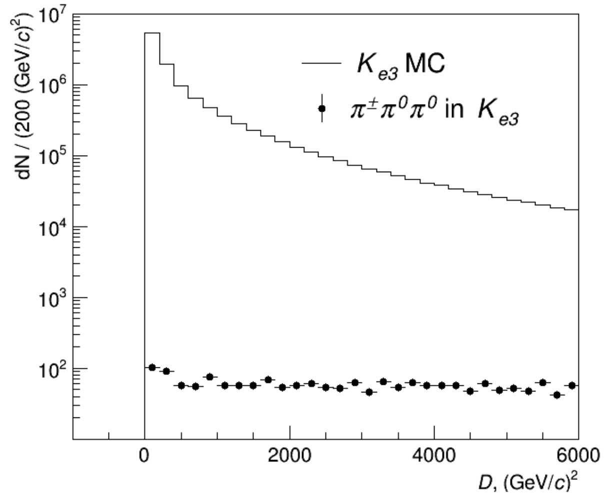
two solutions for P_K requiring energy and momentum conservation and imposing K and μ masses:

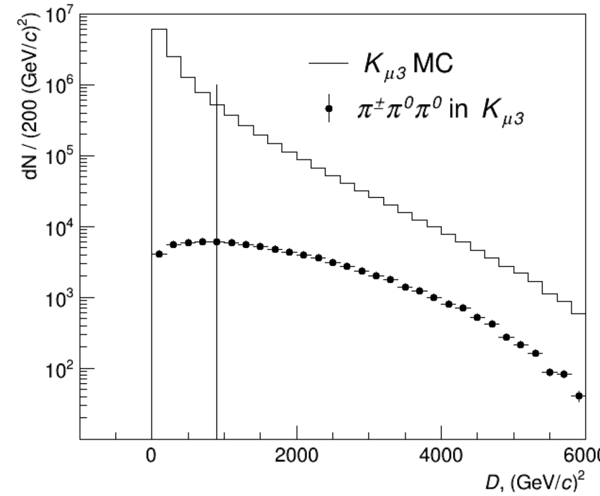
$$p_K = \frac{\psi\, p_{\parallel}}{E^2 - p_{\parallel}^2} \pm \sqrt{D}$$

with $\psi = \frac{1}{2}\left(m_K^2 + E^2 - p_{\perp}^2 - p_{\parallel}^2\right)$

$D < 900\ \mathrm{GeV}/c^2$

(D is large when a π^0 is missing)





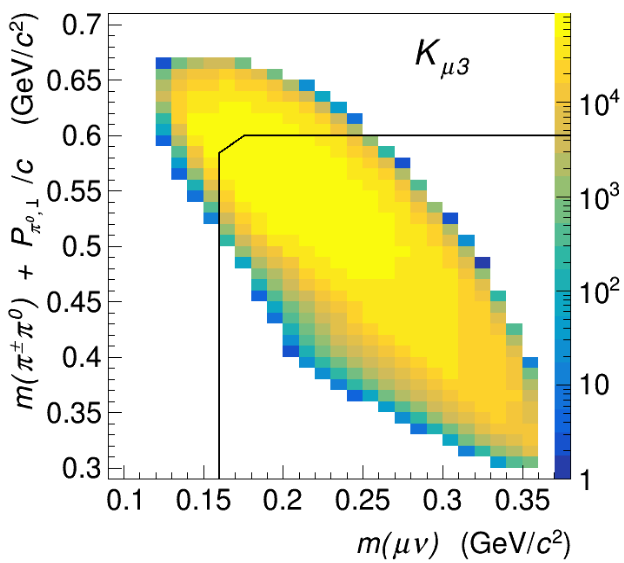
Against $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$:

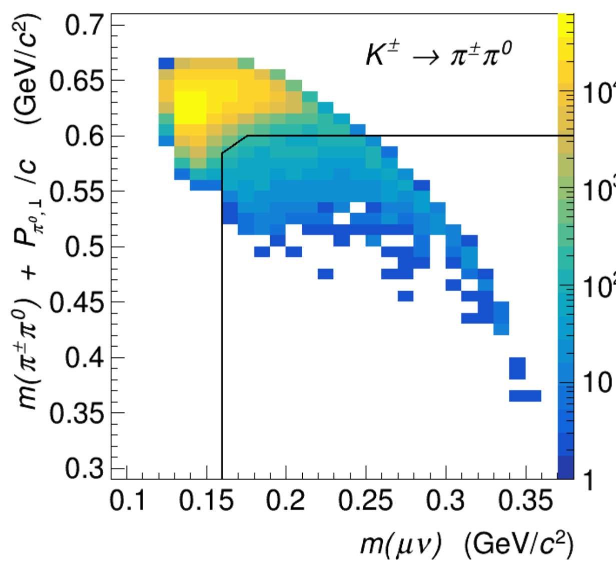
If the $\pi^{\pm}$ is misidentified as a $\mu^{\pm}$:

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

If $\pi^{\pm} \rightarrow \mu^{\pm}\nu$:

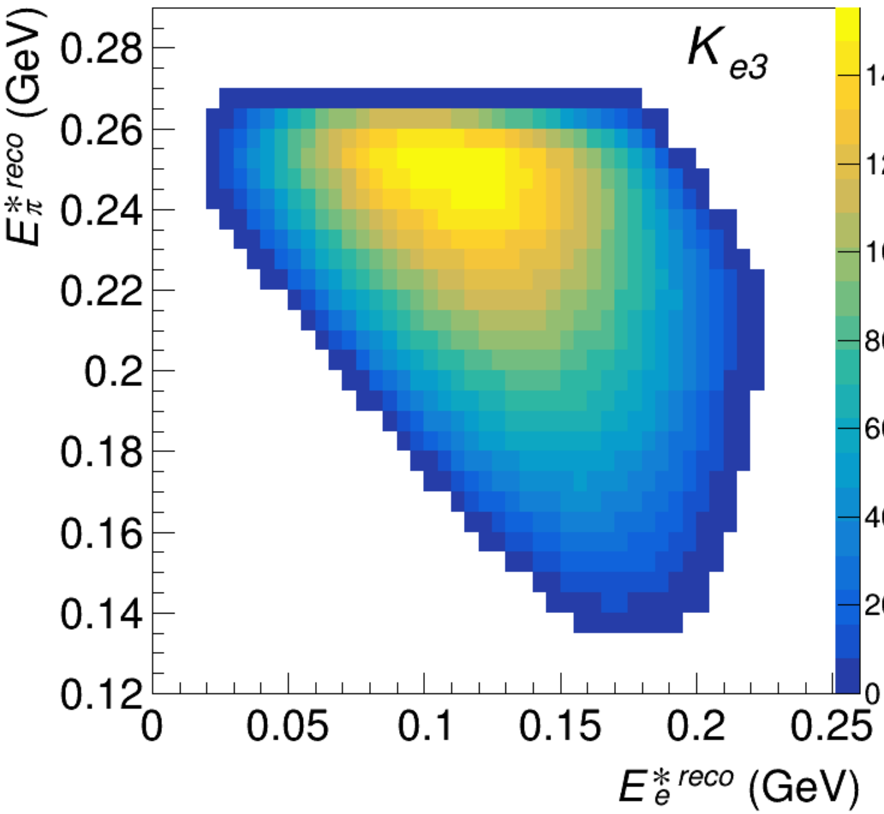
$m(\mu^{\pm}\nu) + P_t(\pi^0)/c < 0.6\ \mathrm{GeV}/c^2$



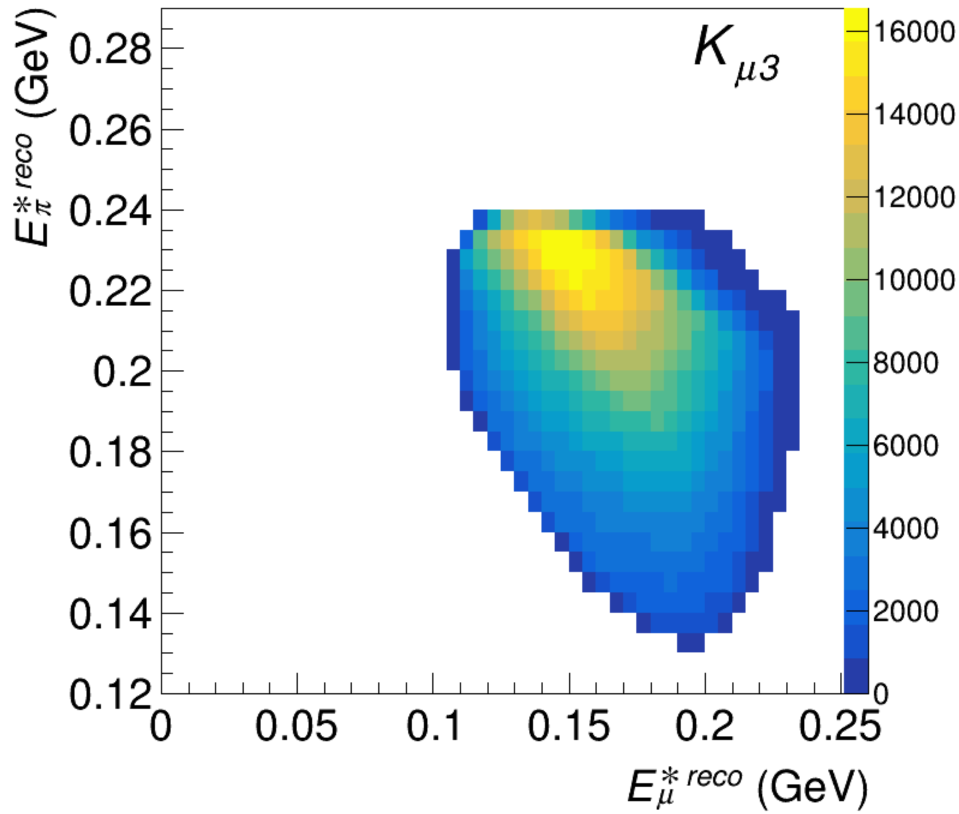


Final samples

Experimental Dalitz plots (5x5 MeV cells), background not subtracted



4.4·10^6 reconstructed K_{e3} candidates

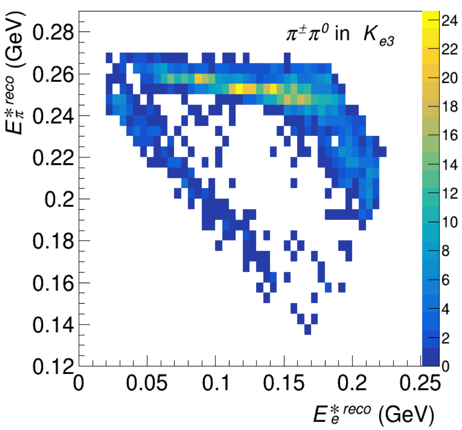


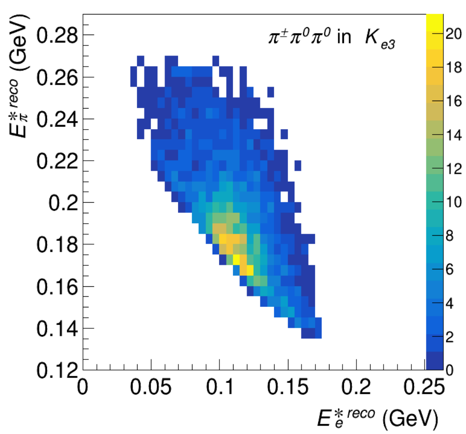
2.3·10^6 reconstructed $K_{\mu 3}$ candidates

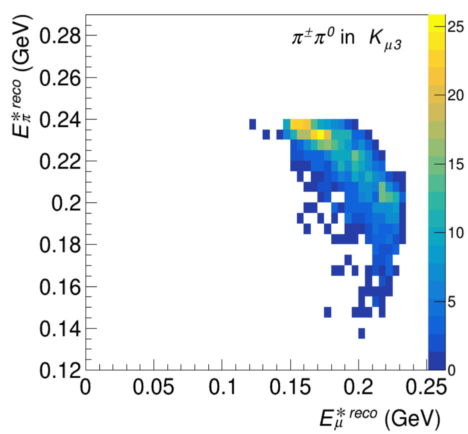
Backgrounds

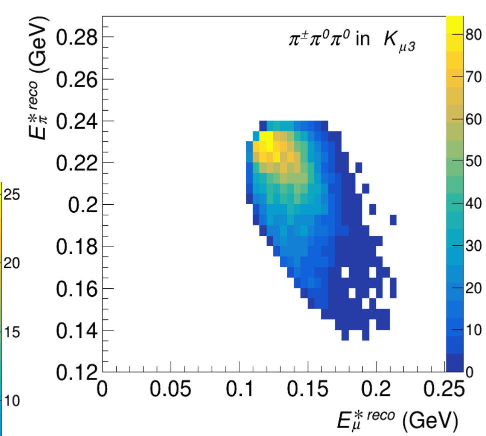
Process	$\mathcal{B}$ [%]	N_{gen} [10^6]	f_{Ke3} [10^{-3}]	$f_{K\mu3}$ [10^{-3}]
$K^\pm \to \pi^\pm\pi^0\pi^0$ ($\pi^0 \to \gamma\gamma, \pi^0 \to \gamma\gamma$)	1.72(2)	62.5	0.286(6)	2.192(32)
$K^\pm \to \pi^\pm\pi^0$ ($\pi^0 \to \gamma\gamma$)	20.43(8)	393.2	0.271(6)	0.392(10)
$K^\pm \to \pi^\pm\pi^0_D$ ($\pi^0_D \to e^+e^-\gamma$)	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_{e3}









$K_{\mu3}$

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Form factors

$$\frac{d^2\Gamma}{dE_l\, dE_\pi} \propto A\, f_+^2(t) + B\, f_+(t) f_-(t) + C\, f_-^2(t)$$ (neglecting radiative effects), where:

$t = M_{l\nu}^2 \quad = (P_K - P_\pi)^2 = m_K^2 + m_\pi^2 - 2m_K E_\pi$

E_π, E_l, E_ν = energies in the $K^\pm$ rest frame

$f_-(t) \quad = (f_+(t) - f_0(t))\,(m_K^2 - m_\pi^2)\,/\,t$

$f_0(t), f_+(t)$= "scalar" and "vector" FF

$A = M_K[2E_l E_\nu - m_K(E_\pi^{max} - E_\pi)] + M_l^2\,[\frac{1}{4}(E_\pi^{max} - E_\pi) - E_\nu]$

$B = M_l^2[E_\nu - \frac{1}{2}(E_\pi^{max} - E_\pi)]$ negligible for K_{e3}

$C = \frac{1}{4}M_l^2(E_\pi^{max} - E_\pi)4$ negligible for K_{e3}

FF parametrization	$f_+(t, \text{parameters})$	$f_0(t, \text{parameters})$
Quadratic (linear for $f_0(t)$)	$1 + \lambda'_+ t/m_\pi^2 + \lambda''_+ (t/m_\pi)^2$	$1 + \lambda'_0 t/m_\pi^2$
Pole	${M_V}^2/({M_V}^2 - t)$	${M_S}^2/({M_S}^2 - t)$
Dispersive *	$\exp\left((\Lambda_+ + H(t))t/m_\pi^2\right)$	$\exp\left((\ln[C] - G(t))t/(m_K^2 - m_\pi^2)\right)$

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

We use MC radiative decay generator of C. Gatti [Eur.Phys.J. C45(2006) 417-420] provided by the KLOE collaboration. It includes $f_0 = f_+ = 1 + \lambda' t/m_\pi^2$

Events-weighting fit procedure

Experimental Dalitz plot is corrected for the simulated background

Cells are included in the fit only if at least 20 events are present in data.

Only one MC sample is generated and then is re-weighted according to FF effects.

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

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

where:

- i,j are the indices of the Dalits plot cells,
- $D_{i,j}$ is the background-corrected number of events in the cells (data)
- $MC_{i,j}$ is the weighted MC bin content (FF dependent)
- $\delta D_{i,j}$ and $\delta MC_{i,j}$ are the corresponding statistical errors

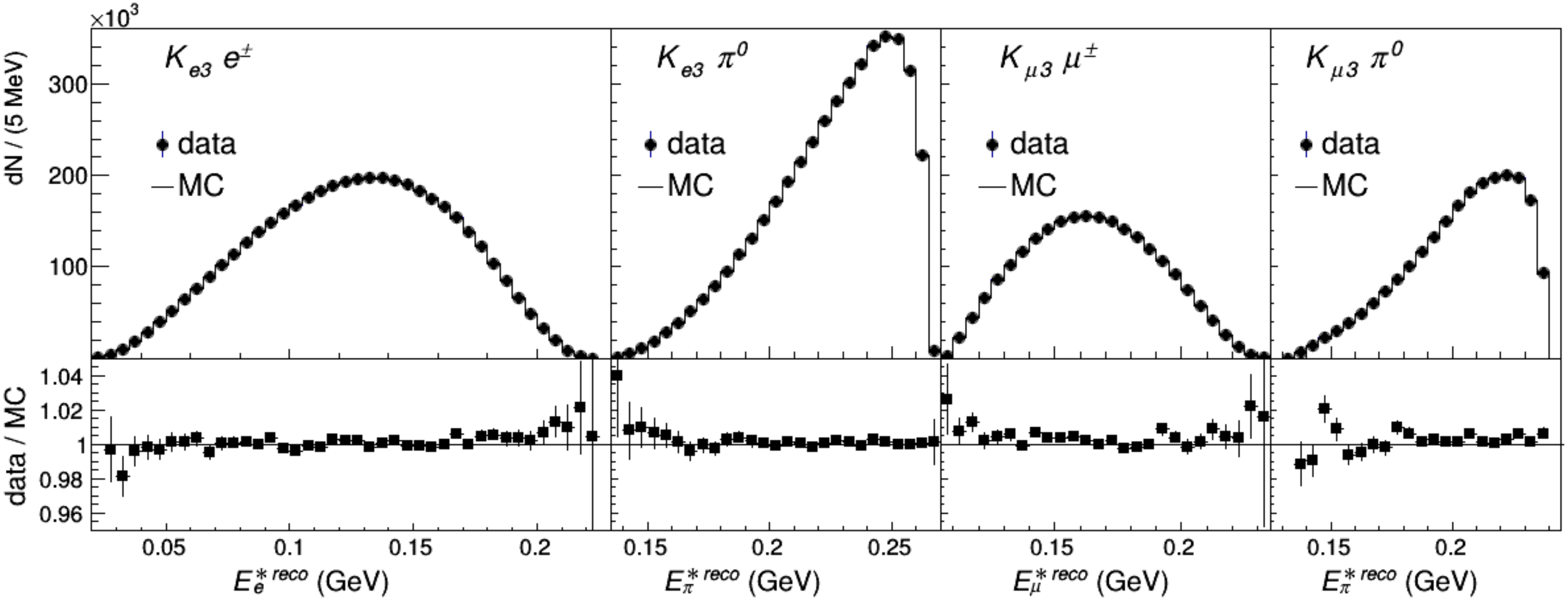
Analysis has been performed:

- for K_{e3} and $K_{\mu 3}$ separately
- for the combined $K_{\ell 3}$ sample (joint fit)

Results for the joint $K_{\ell 3}$ 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	

Dalitz plot projections

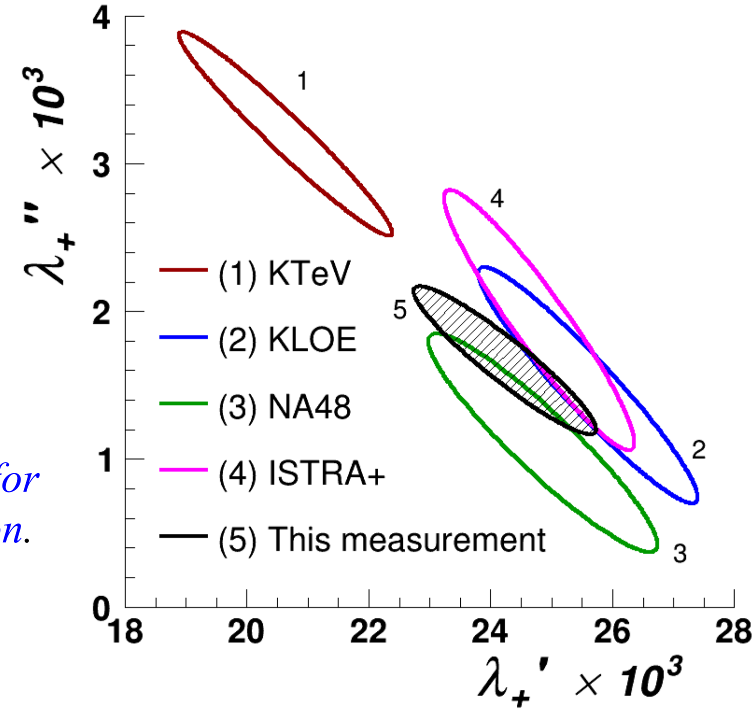


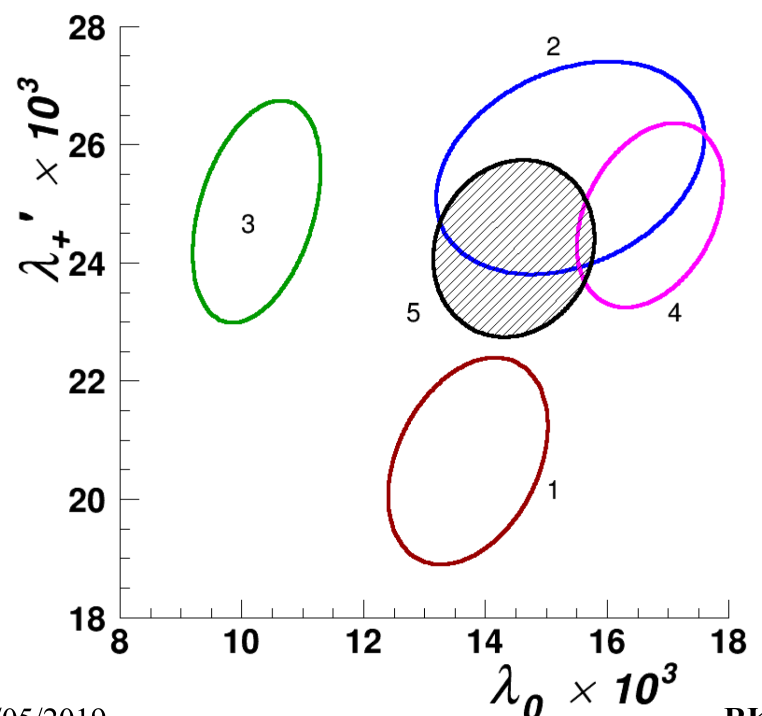
Reconstructed lepton energy and pion energy distributions for data after background subtraction. Simulated samples are superimposed according to the results of the fit using the Taylor expansion model (other parameterisations look very similar).

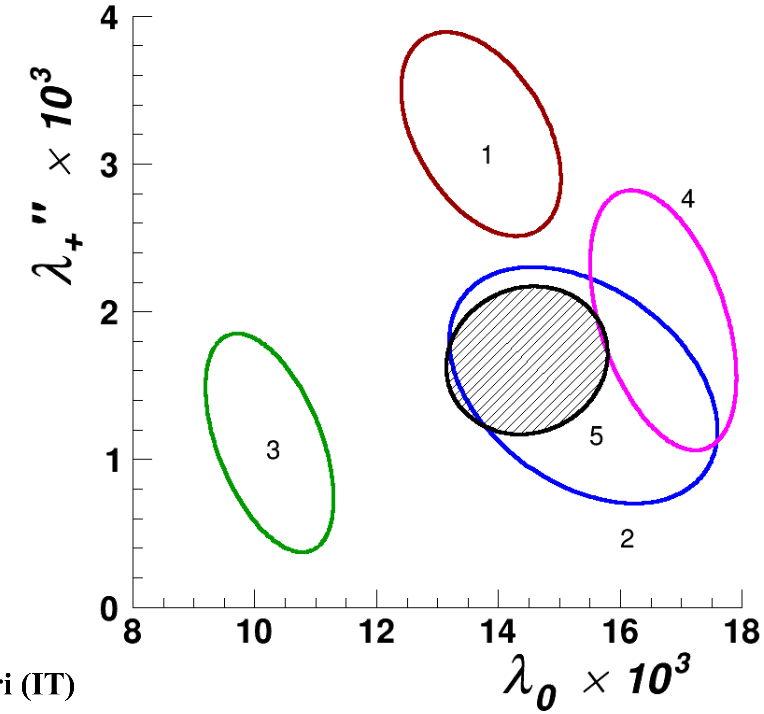
Comparisons

Joint K_{13} results comparison for quadratic parameterization: 1σ ellipses (39.4% CL)

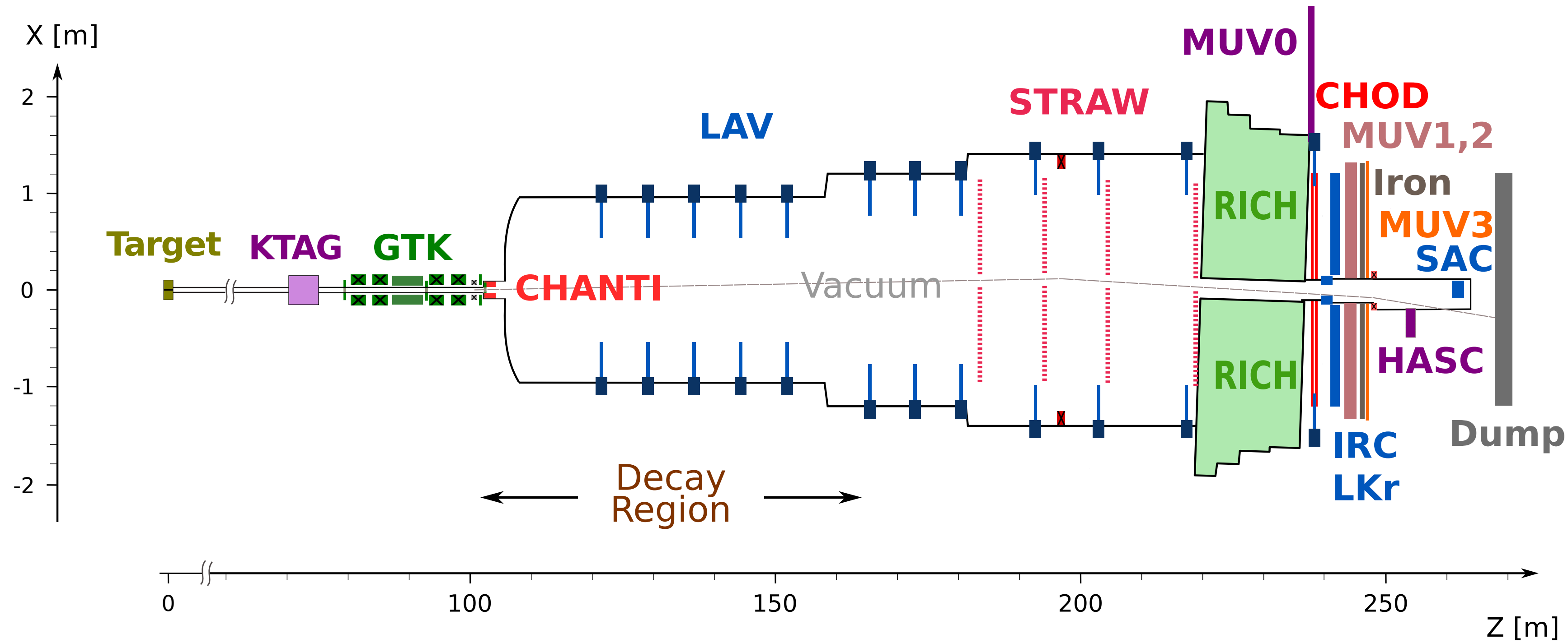
Our preliminary results (2012) were shifted due to charged vertex definition leading to the beam shape sensitivity, while for the present result we use less sensitive neutral vertex definition.







NA62 Prospects



Main goal, collect $O(100)$ SM events of $K^+ \to \pi^+ \nu \bar{\nu}$

$$O(100)^{SM}_{K^+ \to \pi^+ \nu \bar{\nu}} = BR^{SM} \cdot Acc \cdot \text{Kaon Flux}$$

$$= \sim 10^{-10} \cdot 10\% \cdot 10^{13}$$

Kaon decays in the fiducial volume

See R. Lollini talk tomorrow!

NA62 Projections

- Kaon flux: 10^{13} decays

- Improved resolution on kinematic observables wrt NA48/2:
  - Kaon tracker available (GTK)
  - Lepton tracker operating in vacuum (STRAW)

  Neutral vertex not needed! (no E_{scale} error)

- Only minimum bias triggers (strongly downscaled) available:
  - Trigger with at least one track and no muons $D(K_{e3})=200$
  - Trigger with at least one track $D(K_{\mu3})=400$

$$N(K_{e3}) \simeq K_{flux} \cdot A(K_{e3}) \cdot BR(K_{e3})/D(K_{e3}) = 10^{13} \cdot 0.05 \cdot 0.0507/200 = 1.26 \cdot 10^{8}$$

$$N(K_{\mu3}) \simeq K_{flux} \cdot A(K_{\mu3}) \cdot BR(K_{\mu3})/D(K_{\mu3}) = 10^{13} \cdot 0.05 \cdot 0.0335/400 = 4.2 \cdot 10^{7}$$

First observation of the $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ decay

[Phys.Lett. B788 (2019) 552-561]

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

Similar to $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$, but with a virtual photon

- never observed so far
- the magnitude of the BR is a test of χPT predictions

[H. Pichl, EPJ C20 (2001) 371]
[L. Cappiello, O. Catà, G. D'Ambrosio, D. Gao, EPJ C72 (2012) 1872]
[L. Cappiello, O. Catà, G. D'Ambrosio EPJ C78 (2018) 265]

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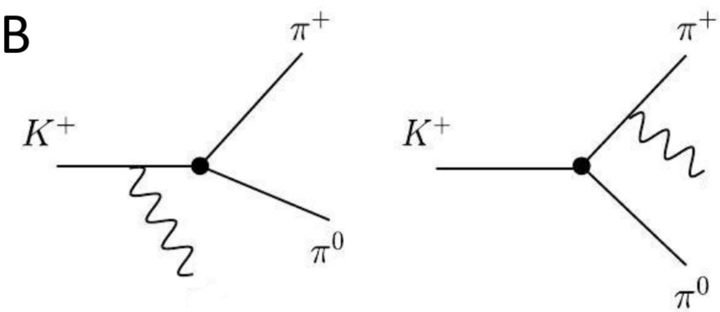
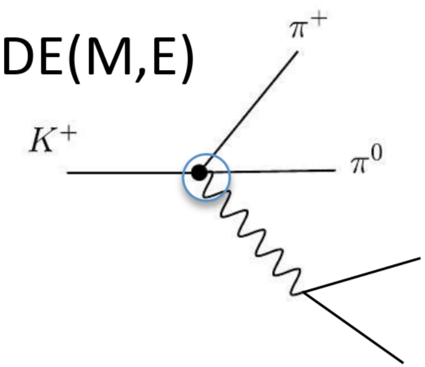
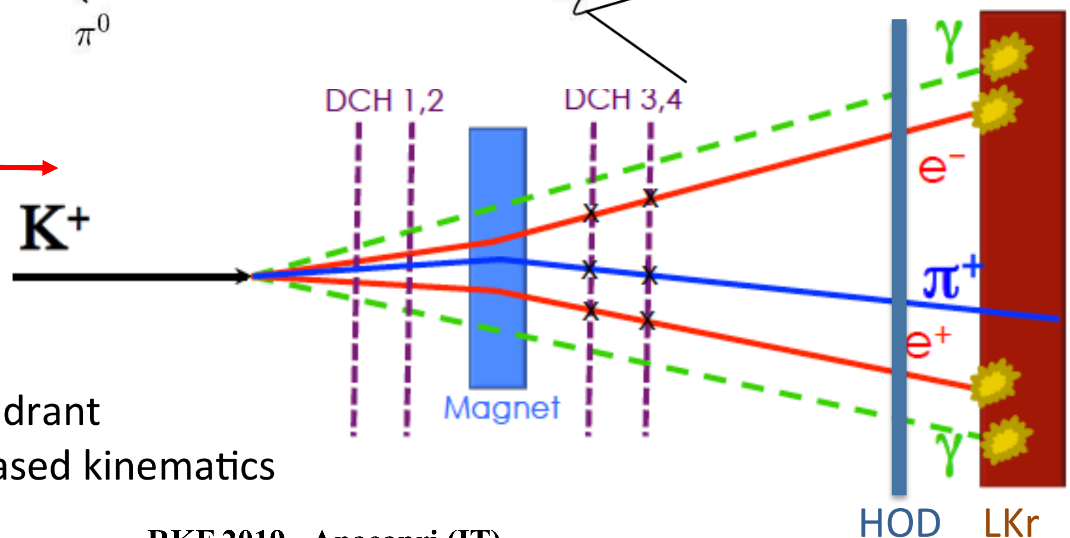


DE(M,E)



+ interference

Event topology in the NA48/2 detector →



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

Selection of signal and normalization

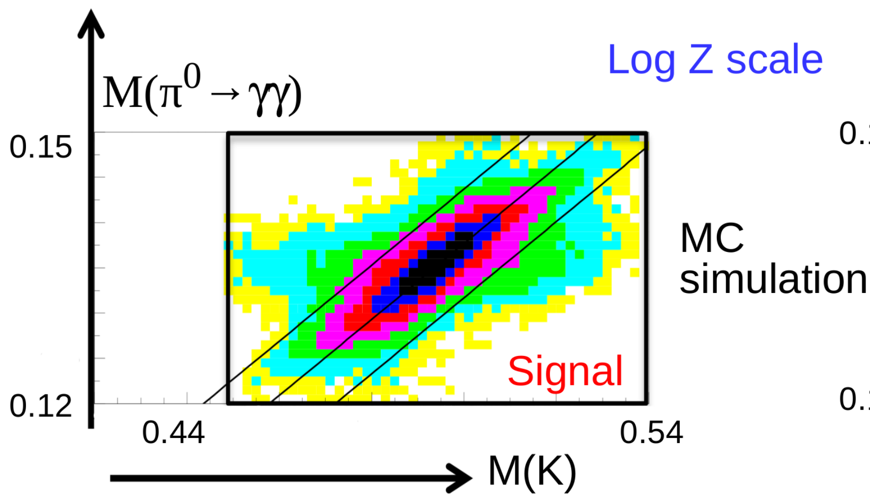
Signal: $\pi^\pm\pi^0 e^+e^- \to \pi^\pm \underline{\gamma\gamma}\, e^+e^-$ Normalization: $\pi^\pm\pi^0_D \to \pi^\pm \underline{\gamma\, e^+e^-}$

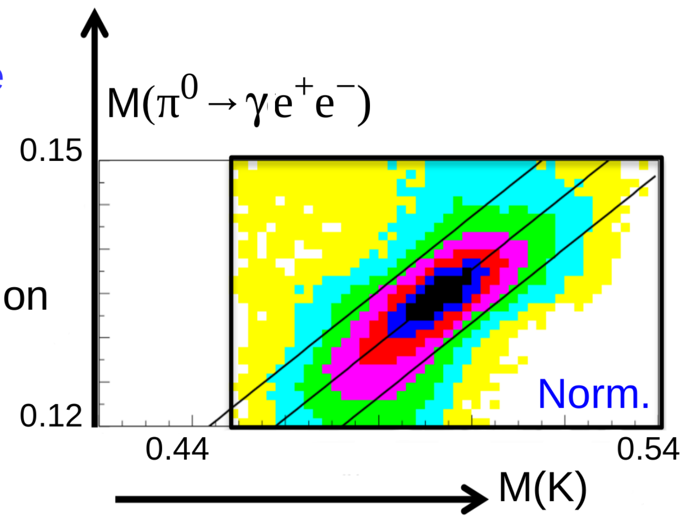
- 3 charged tracks (2 "same-sign" + 1 "opposite-sign") forming a vertex

+ 2 photon clusters in LKr + 1 photon cluster in LKr

- No PID from LKr but only kinematics ⇒ no LKr acceptance cuts on tracks
- Assign electron mass to the "opposite-sign" track
- For both (m_e , m_π) assignments to same-sign charged tracks compute reconstructed masses $M(\pi^0)$ and $M(K^\pm)$ and apply the cuts

$$|M(\pi^0) - M^{PDG}_{\pi^0}| < 15\ \mathrm{MeV}/c^2 \ , \quad |M(K^\pm) - M^{PDG}_{K^\pm}| < 45\ \mathrm{MeV}/c^2 \ ,$$
$$|M(\pi^0) - 0.42\, M(K^\pm) + 72.3\ \mathrm{MeV}/c^2| < 6\ \mathrm{MeV}/c^2$$



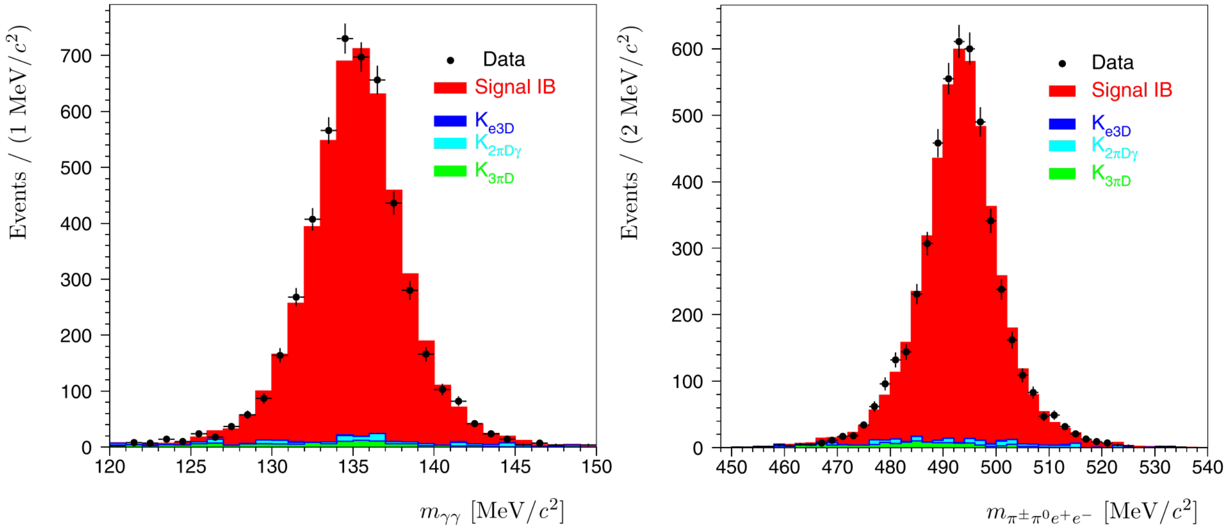


Evaluation of backgrounds

Main backgrounds to signal $\rightarrow$ specific cuts to suppress them

- $K_{3\pi D}(K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}_{D})$ with 1 γ lost $\rightarrow$ $M^2(\pi^+\pi^0) > 0.12\ \mathrm{GeV}^2/c^4$
- $K_{2\pi D}(K^{\pm} \rightarrow \pi^{\pm}\pi^{0}_{D})$ + 1 extra γ $\rightarrow$ $|M(e^+e^-\gamma) - M_{\mathrm{PDG}}(\pi^0)| > 7\ \mathrm{MeV}/c^2$

Residual background: 4.9%, estimated from simulation using the number of kaon decays from normalisation.

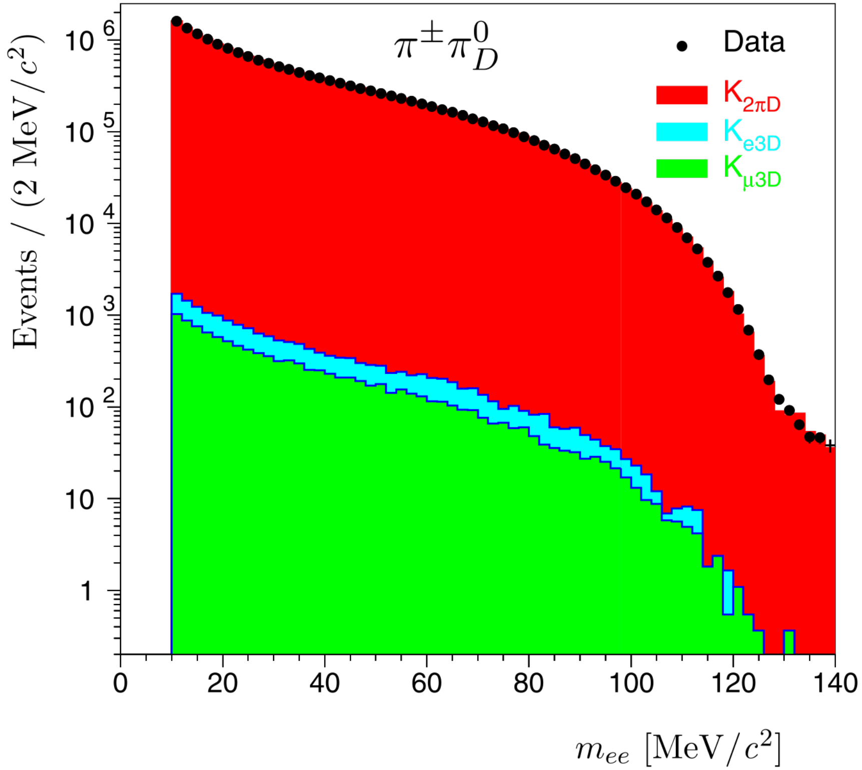


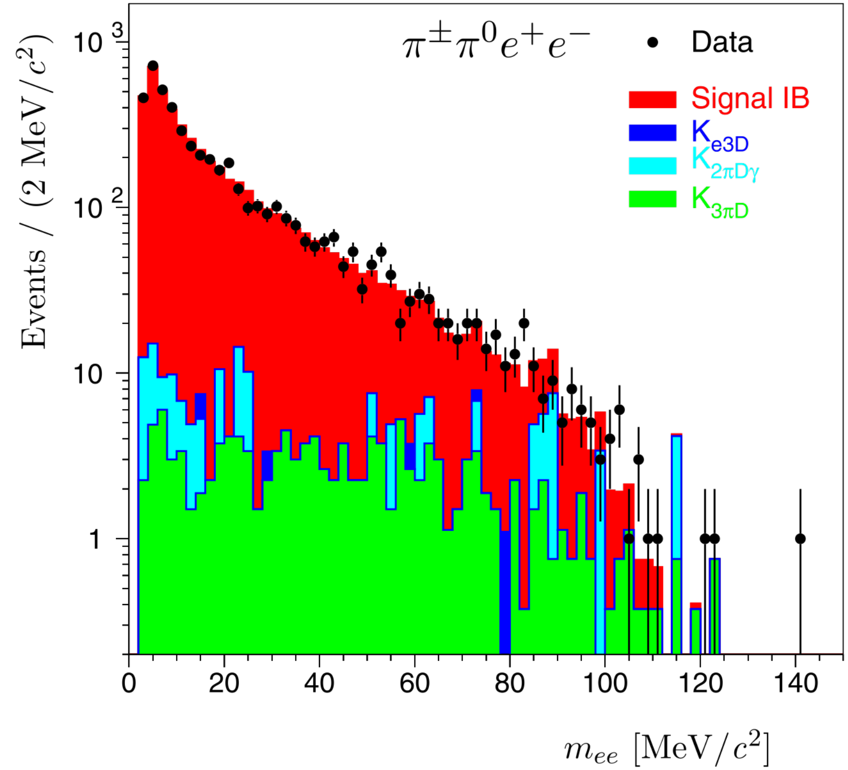
Main backgrounds to normalization

- $K_{\mu 3D}(K^{\pm} \rightarrow \mu^{\pm}\nu\pi^{0}_{D})$ with $\mu^{\pm}$ mis-ID
- $K_{e3D}(K^{\pm} \rightarrow e^{\pm}\nu\pi^{0}_{D})$ with $e^{\pm}$ mis-ID

Background: 0.11%, estimated from simulation.

M_{ee} spectra



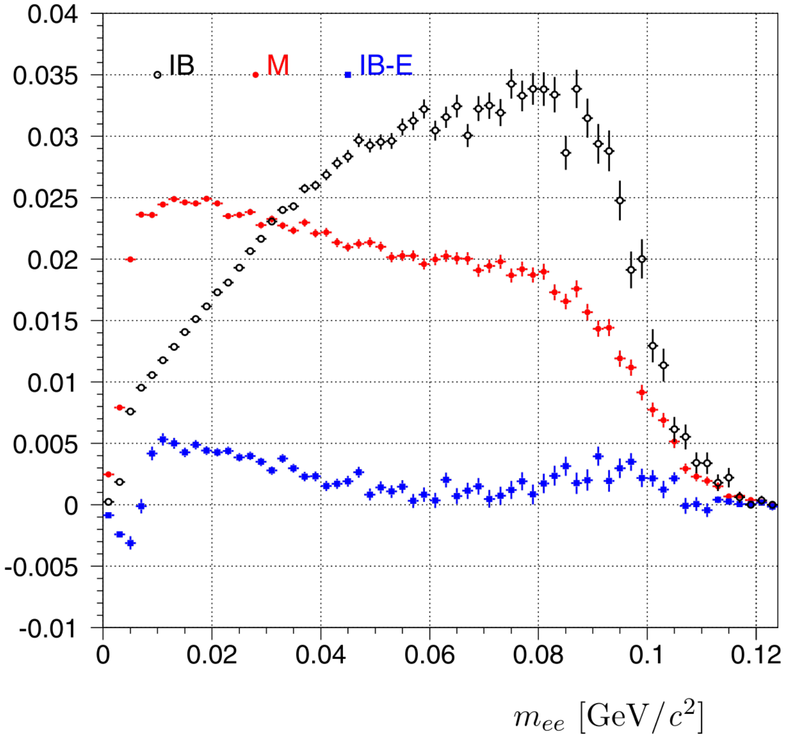


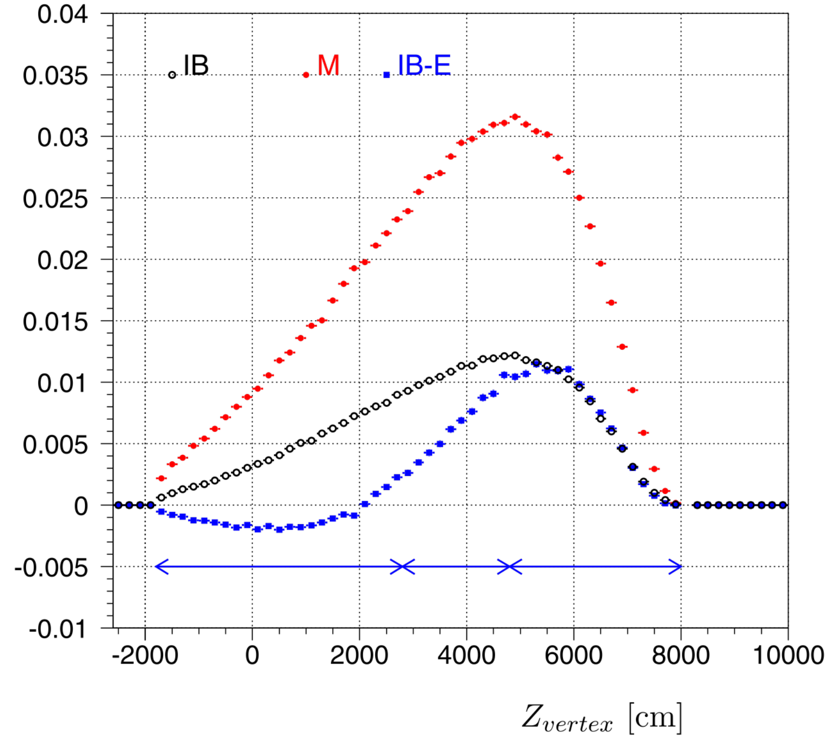
Candidates N_n	16.3×10^6
Background N_{bn}	17288
Accept (rad) A_n	3.981(2)%
L1 eff. ε_{L1S}	99.767(3)%
L2 eff. ε_{L2S}	98.495(6)%

Candidates N_s	4919
Background N_{bs}	289
Accept (rad) A_s	0.662(1)%
L1 eff. ε_{L1S}	99.729(9)%
L2 eff. ε_{L2S}	98.604(21)%

Acceptance

Weighted average of IB, DE, INT acceptances using expected relative contributions





- Only the magnet part (M) of direct emission contributes, electric part (E) expected 15 times lower
- The interference terms IB-M and M-E do not contribute to the total decay rate in the limit of full angular integration, only from IB-E considered
- Radiative corrections taken into account by using PHOTOS in MC simulations
- Prague group π^0_{Dalitz} generator [PRD 92 (2015) 054027] in MC for normalization mode

Results: Branching Ratio measurement

$$BR(K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-})/BR(K^{\pm} \to \pi^{\pm}\pi^{0}) = \frac{N_s - N_{bs}}{N_n - N_{bn}} \cdot \frac{A_n \times \varepsilon_n}{A_s \times \varepsilon_s} \cdot \frac{\Gamma(\pi^0_D)}{\Gamma(\pi^0_{\gamma\gamma})}$$

$$BR(K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}) = (4.237 \pm 0.063_{stat} \pm 0.033_{syst} \pm 0.126_{ext}) \times 10^{-6}$$

Error source	$\delta BR/BR \times 10^2$
N_s	1.426
N_{bs}	0.416
N_n	0.025
N_{bn}	negl.
Total statistical	*1.486*
A_s (MC statistics)	0.171
A_n (MC statistics)	0.051
$\varepsilon(\mathrm{L1}_s \times \mathrm{L2}_s)$ (MC statistics)	0.023
$\varepsilon(\mathrm{L1}_n \times \mathrm{L2}_n)$ (MC statistics)	0.007
Acceptance geometry control	0.083
Acceptance time variation control	0.064
Background control	0.280
Trigger efficiency (systematics)	0.400
Model dependence	0.285
Radiative effects	0.490
Total systematic	*0.777*
$BR(K_{2\pi})$	0.387
$\Gamma(\pi^0_D)/\Gamma(\pi^0_{\gamma\gamma})$	2.946
Total external	*2.971*

- Error is dominated by external error on $BR(\pi^0_{Dalitz})$
- The BR measurement is in good agreement with χPT predictions:
  - > IB only BR = 4.183×10^{-6}
  - > With all IB, DE and INT terms: BR = 4.229×10^{-6}

CP-violating asymmetry also measured:

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

$A_{CP} < 4.82 \times 10^{-2}$ at 90% CL.

Summary

$K_{\ell 3}$ decays :

- Form factors have been measured by NA48/2 from 4.4 million K_{e3} and 2.3 million $K_{\mu 3}$ events collected in 2004
- Improved vertex definition, analysis almost insensitive to beam shape
- The NA48/2 combined analysis of K_{e3} and $K_{\mu 3}$ decays provides the most precise measurement of $K_{\ell 3}$ form factors

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

- 4919 decay candidates with <6% background
- decay observed for the first time, BR has been measured:
  - > uncertainty is dominated by external error
  - > good agreement with χPT-based theoretical predictions
- CP-violating asymmetry A_{CP} also measured