Kaon semileptonic decays

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On behalf of the NA48/2 collaboration

CKM 2018

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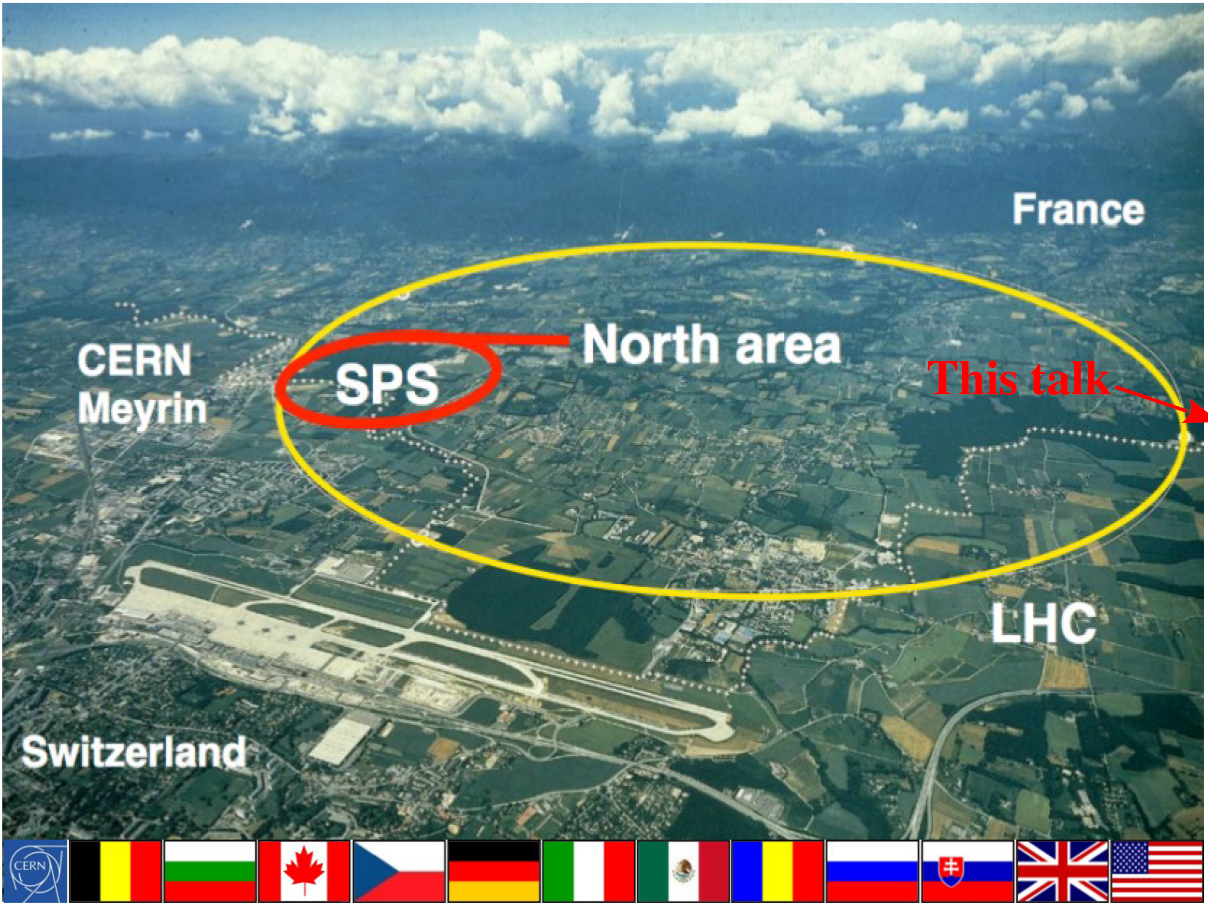
Outline

- **Recent results on Kaon semileptonic decays:**
  - Final results on the measurement of the Form Factors in the decays $K^{\pm} \to \pi^0 \ell^{\pm} \nu_l$ at NA48/2
    - > The beam and detector
    - > Signal selection and reconstruction
    - > Form factors measurement
  - New OKA result on $K^{\pm} \to \pi^0 e^{\pm} \nu_e$
    - > Beam and Detector
    - > Form factors measurement
- **Future prospects from OKA, NA62 and KLOE-2**

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^+)	$K^+ \rightarrow \pi^+\nu\bar{\nu}$, Rare K^+ and π^0 decays

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

$K^{\pm} \rightarrow \pi^0 \boldsymbol{e}^{\pm} \nu_{\mathbf{e}}$ and $K^{\pm} \rightarrow \pi^0 \mu^{\pm} \nu_{\mu}$ decays @ NA48/2

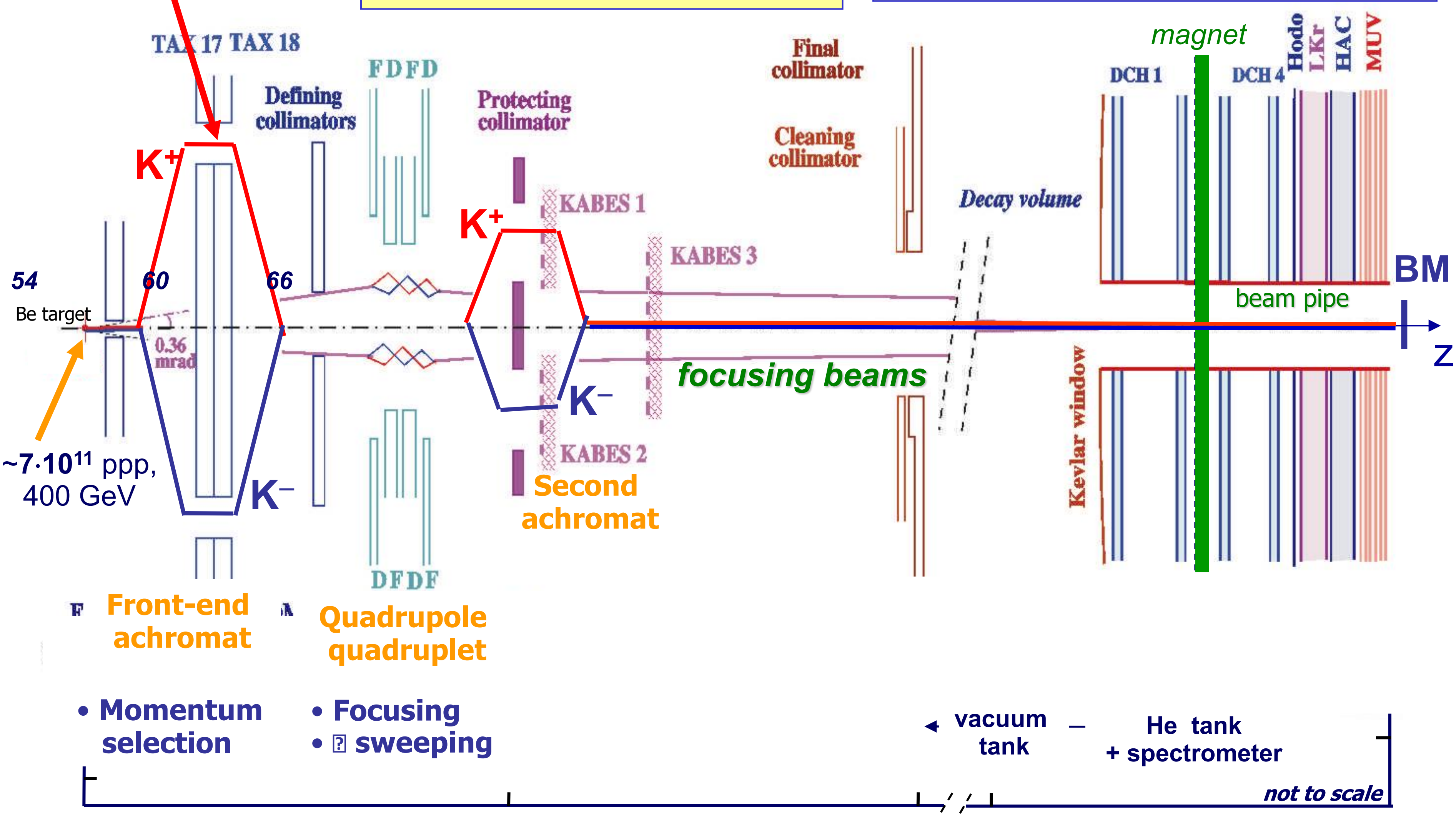
[arXiv:1808.09041; CERN-EP-2018-231]

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



- **Momentum selection**
- **Focusing**
- **□ sweeping**

The NA48/2 detector

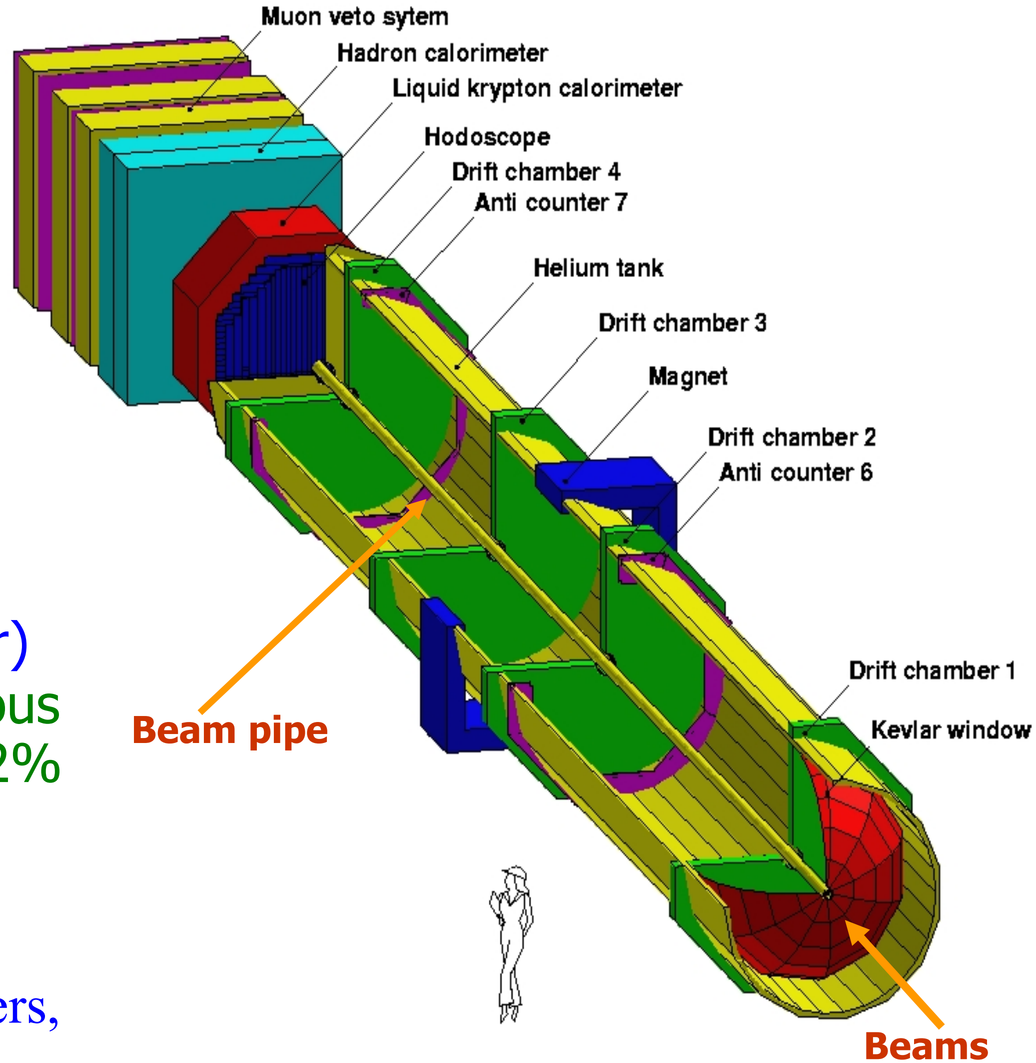
Main detector components:

- 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.



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

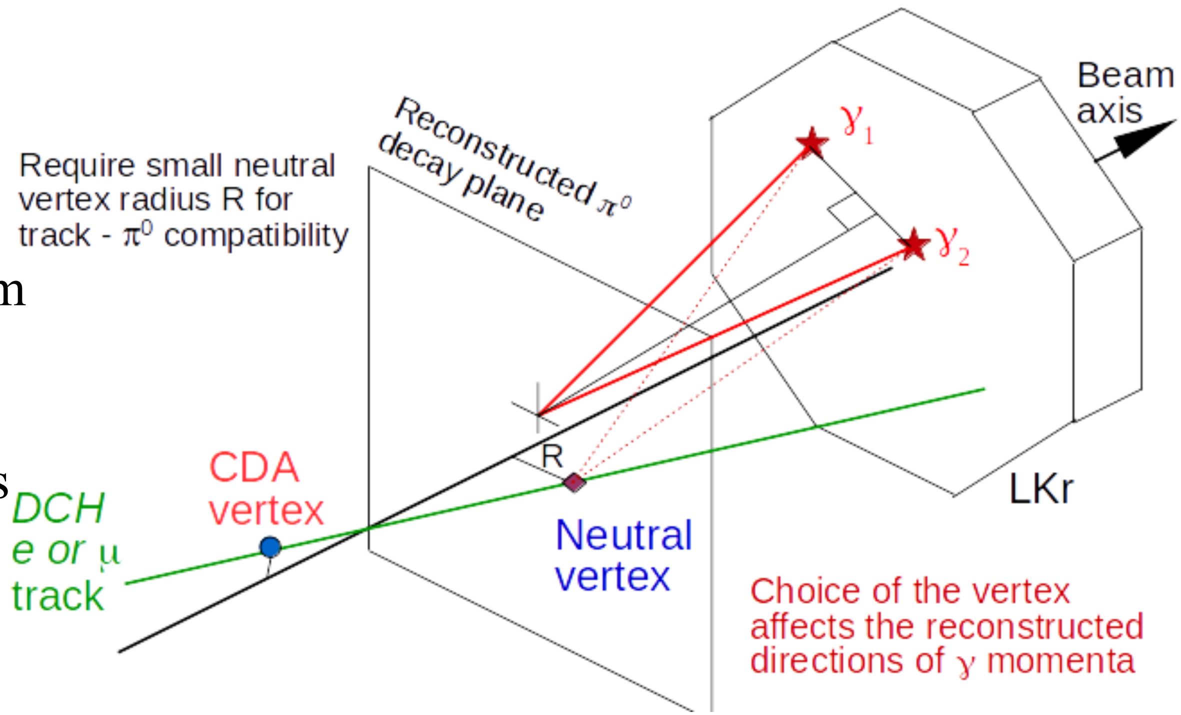
> High sensitivity to exact beam shape simulation

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

$K_{\mu 3}$ selection:

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

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

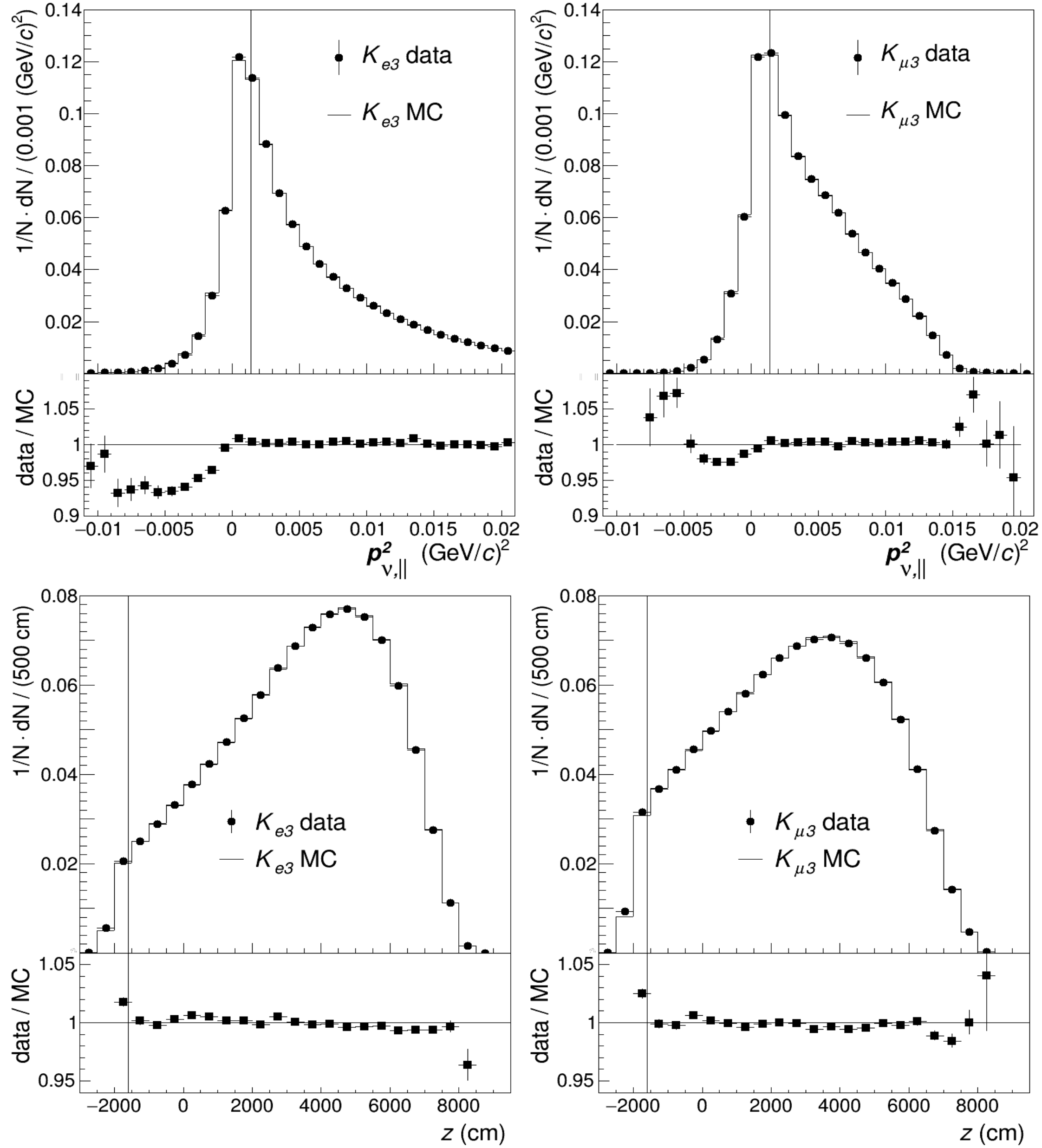
General cuts

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

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.

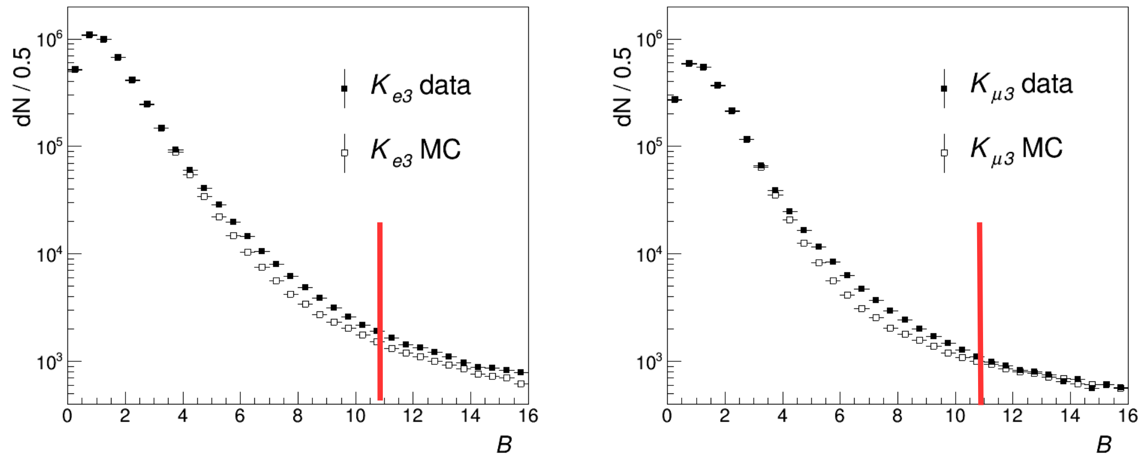
Beam (transverse elliptic) variable:

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

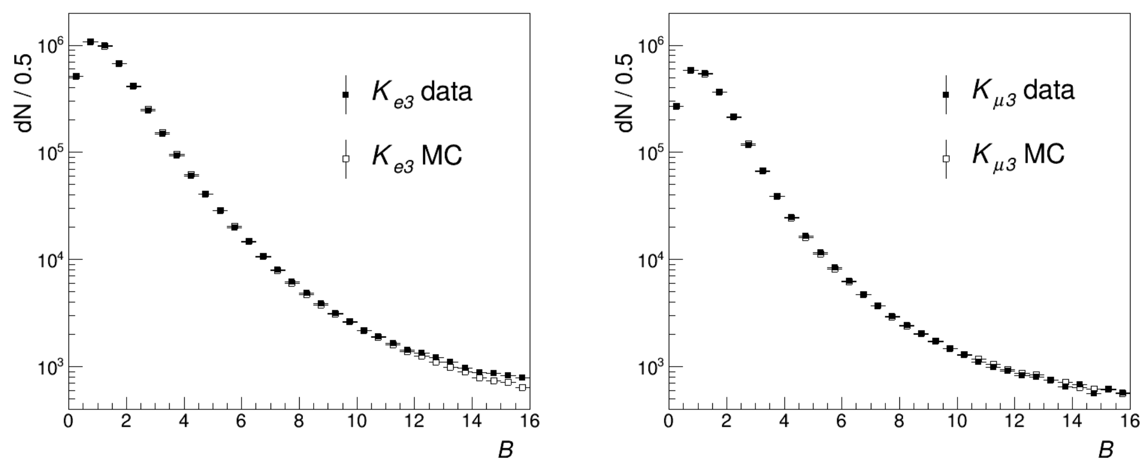
x,y,z are the reconstructed neutral vertex coordinates, $x_0(z)$, $y_0(z)$, $\sigma_x(z)$, $\sigma_y(z)$ are the reconstructed beam central positions and widths obtained by run-dependent reconstruction of $K_{3\pi}$ decays .

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

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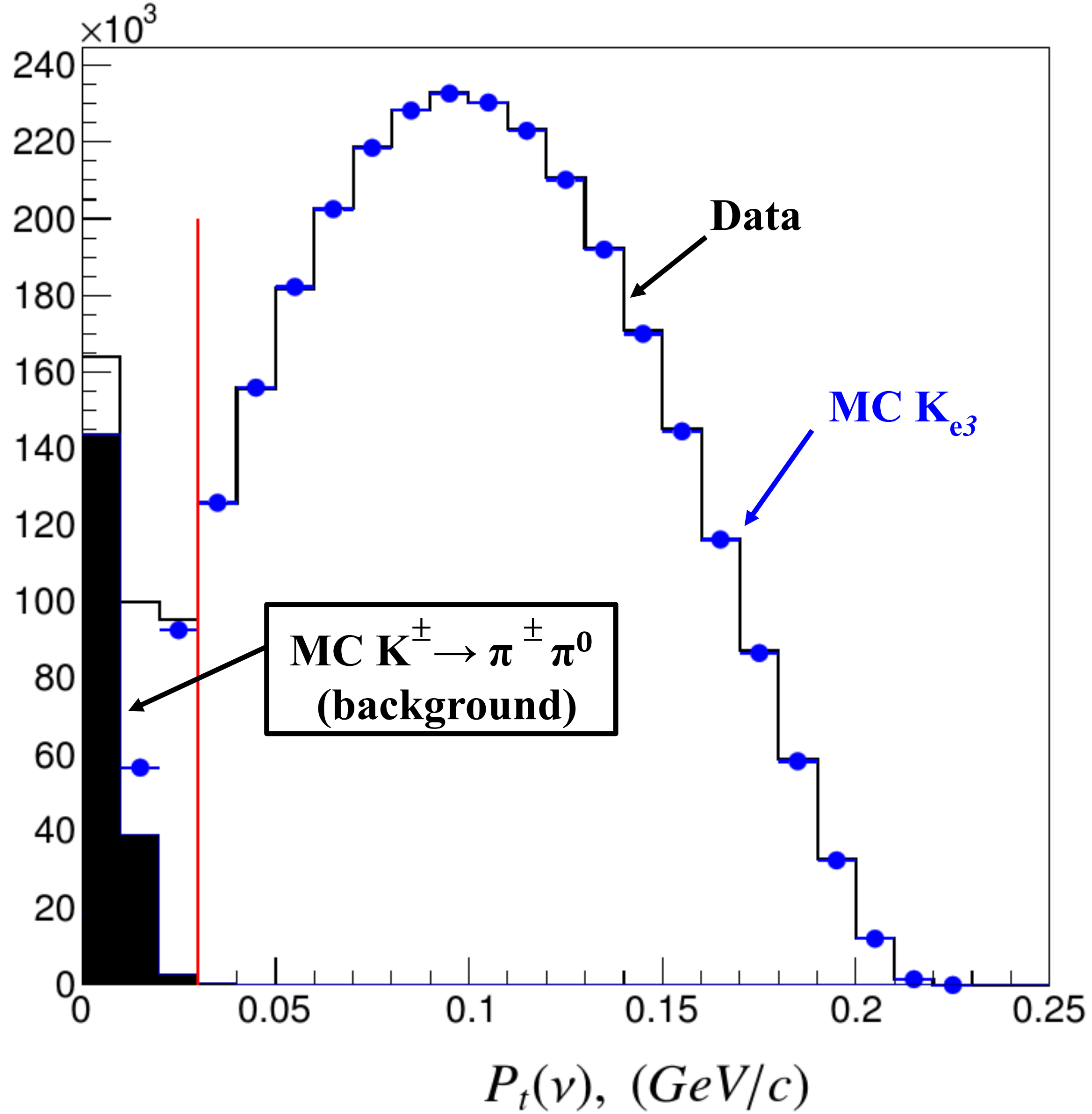


Specific $K_{\mu 3}$ selection cuts

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

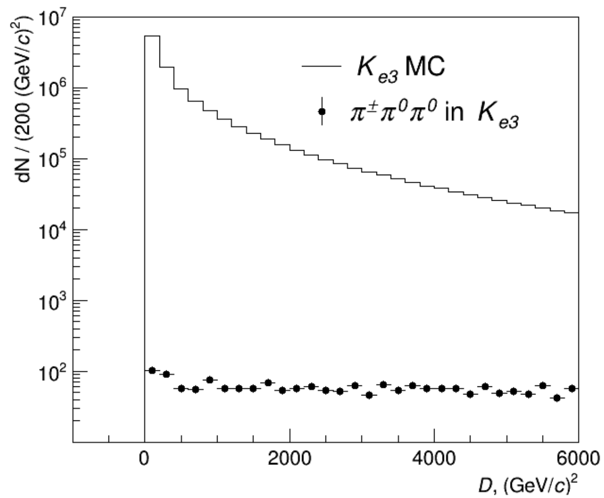
two solutions for P_K requiring energy and momentum conservation and imposing K and μ masses:

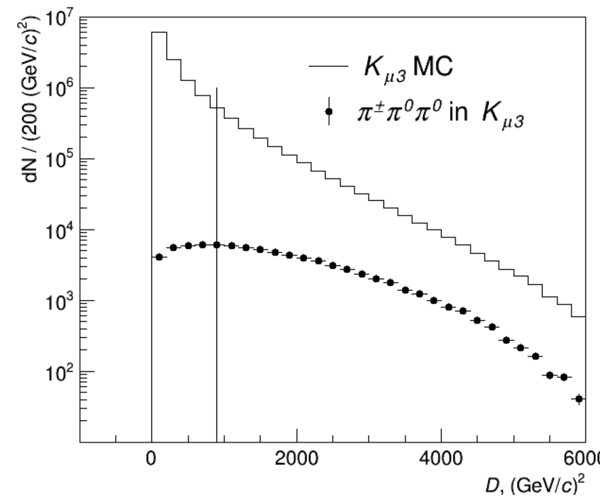
$$p_K = \frac{\psi \, p_{\parallel}}{E^2 - p_{\parallel}^2} \pm \sqrt{D}$$

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

D<900 GeV/c^2

(D is large when a π^0 is missing)





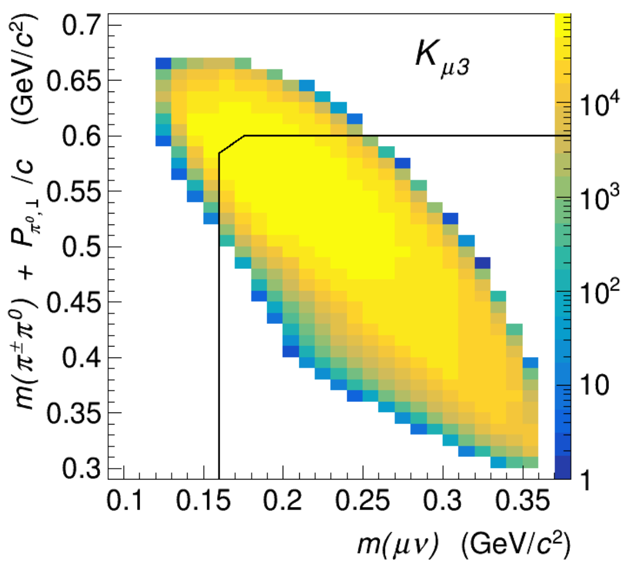
Against $K^{\pm} \rightarrow \pi^{\pm} \pi^{0}$:

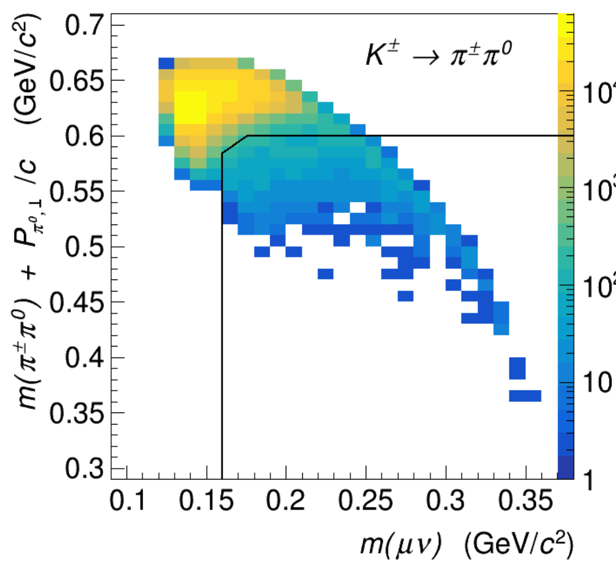
If the $\pi^{\pm}$ is misidentified as a $\mu^{\pm}$:

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

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

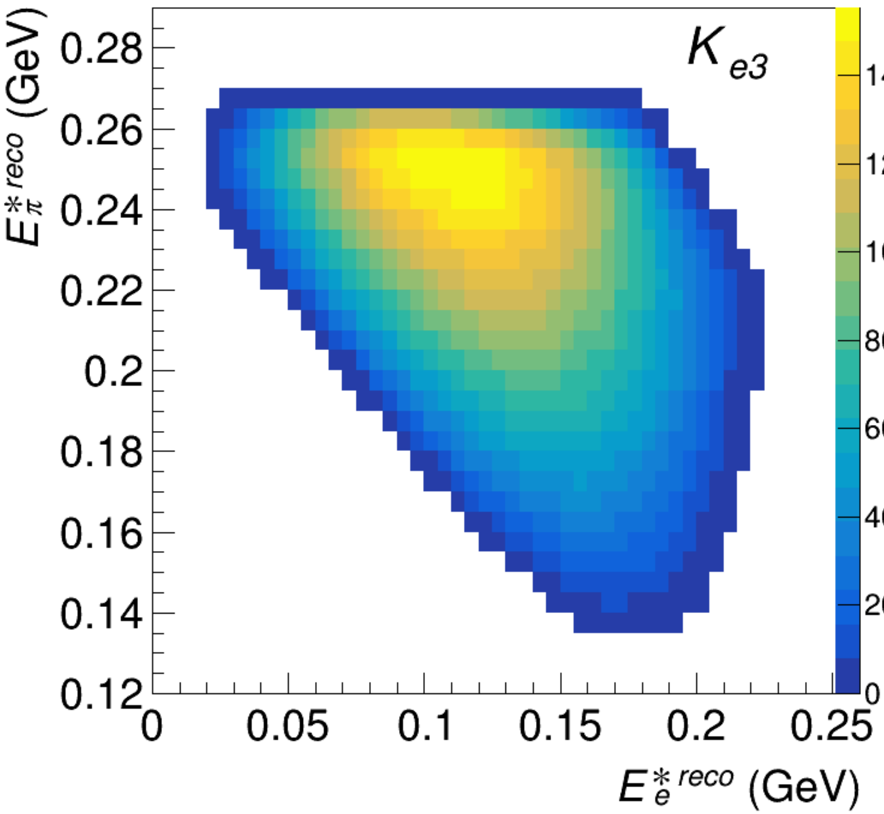
$m(\mu^{\pm}\nu) + P_t(\pi^0)/c < 0.6$ GeV/c^2



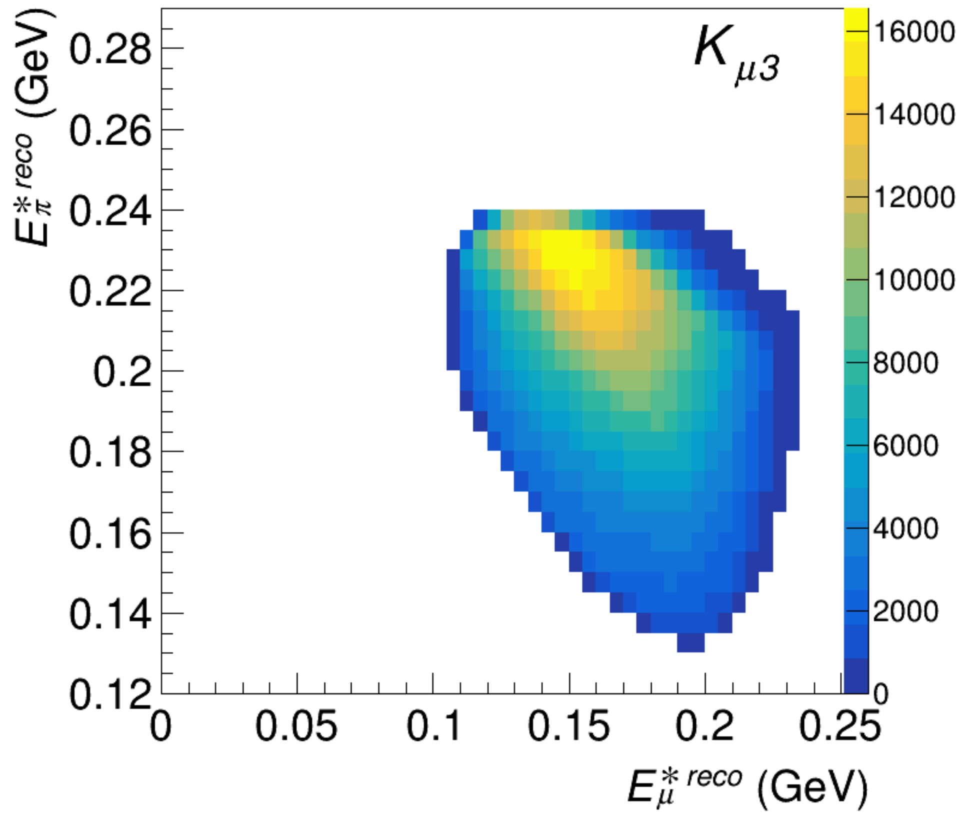


Final samples

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



4.4·10^6 reconstructed K$_{e3}$ candidates

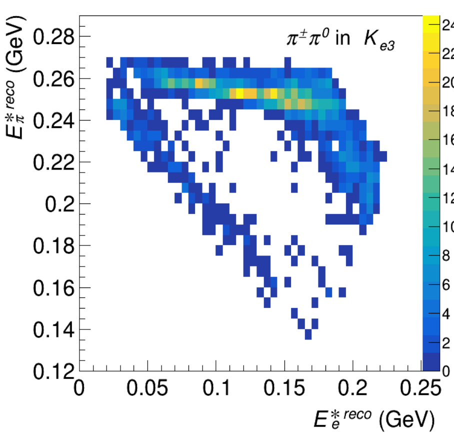


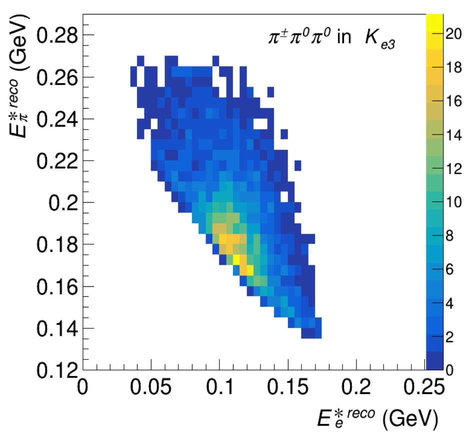
2.3·10^6 reconstructed K$_{\mu3}$ candidates

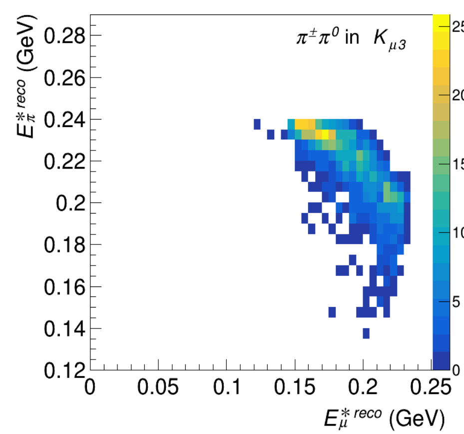
Backgrounds

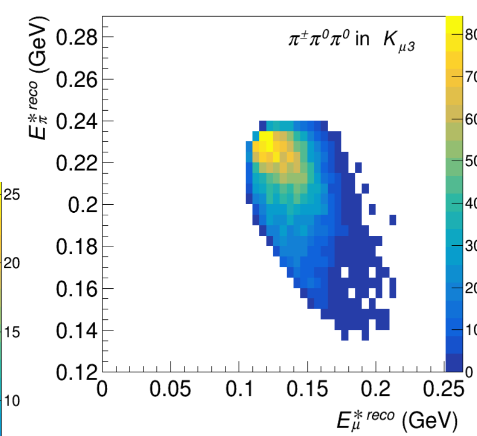
Process	$\mathcal{B}$ [%]	N_{gen} [10^6]	f_{Ke3} [10^{-3}]	$f_{K\mu3}$ [10^{-3}]
$K^\pm \to \pi^\pm\pi^0\pi^0$ ($\pi^0 \to \gamma\gamma, \pi^0 \to \gamma\gamma$)	1.72(2)	62.5	0.286(6)	2.192(32)
$K^\pm \to \pi^\pm\pi^0$ ($\pi^0 \to \gamma\gamma$)	20.43(8)	393.2	0.271(6)	0.392(10)
$K^\pm \to \pi^\pm\pi^0_D$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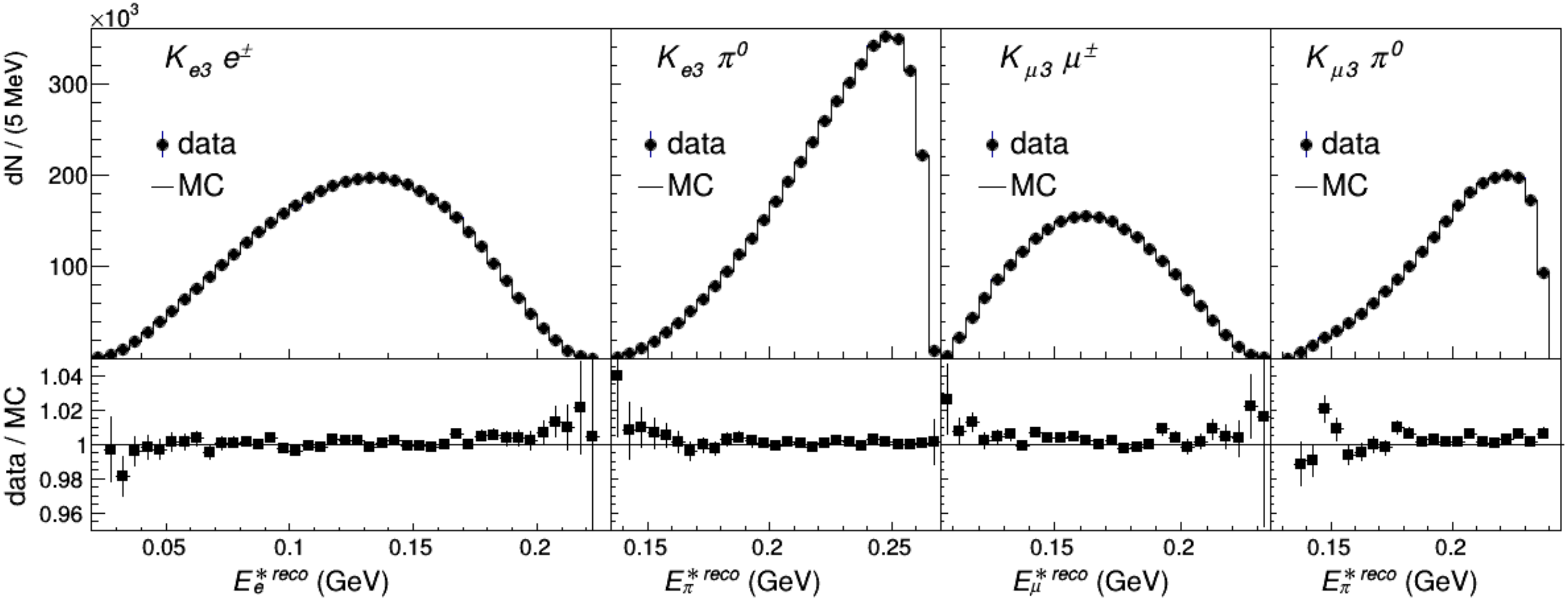
Dalitz plot projections



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).

Form factors

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

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

$E_\pi, E_l, E_\nu =$ 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)

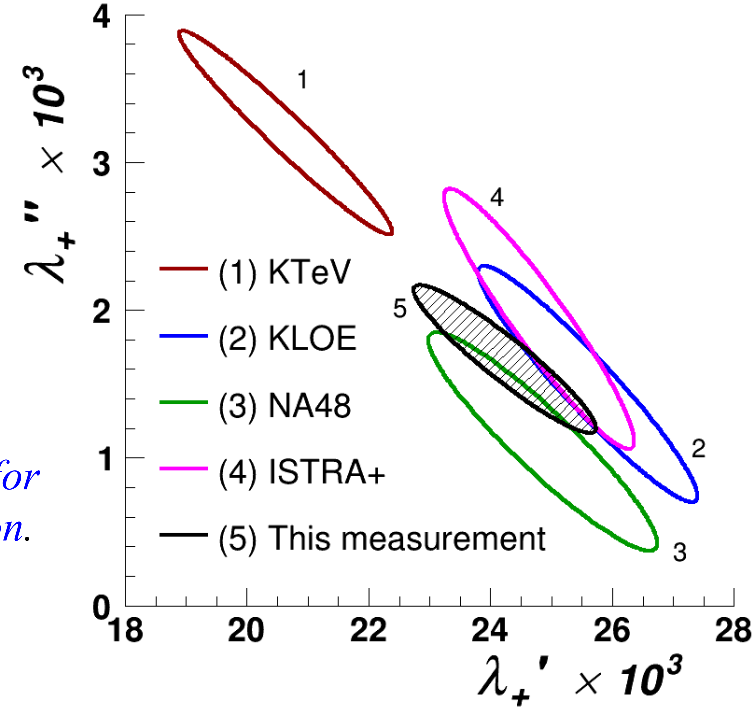
Results for the joint $K_{\ell 3}$ analysis

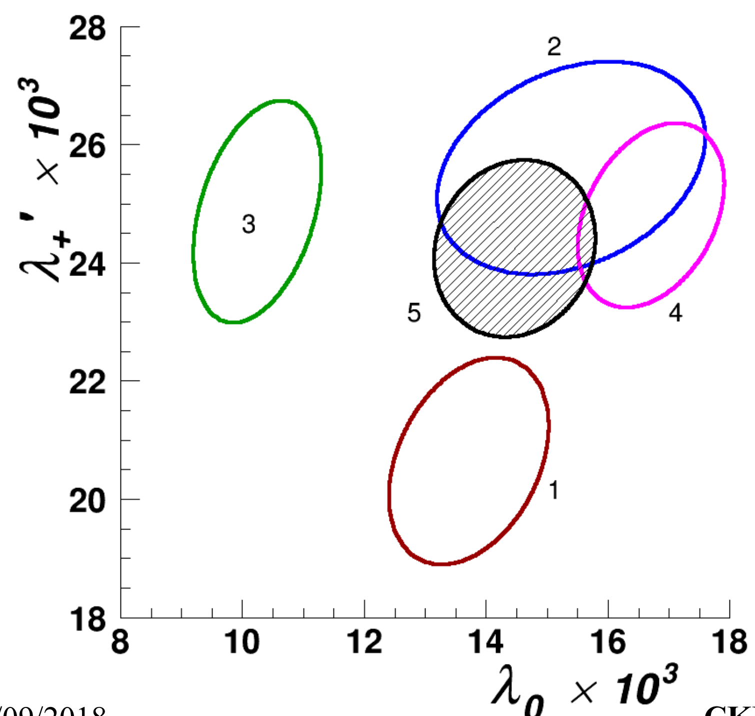
	λ'_+	λ''_+	λ_0	m_V	m_S	Λ_+	$\ln C$
Central values	24.24	1.67	14.47	884.4	1208.3	24.99	183.65
Statistical error	0.75	0.29	0.63	3.1	21.2	0.20	5.92
Diverging beam component	0.97	0.35	0.55	1.1	32.2	0.08	9.43
Kaon momentum spectrum	0.00	0.00	0.02	0.1	0.7	0.00	0.19
Kaon mean momentum	0.04	0.01	0.04	0.2	1.7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

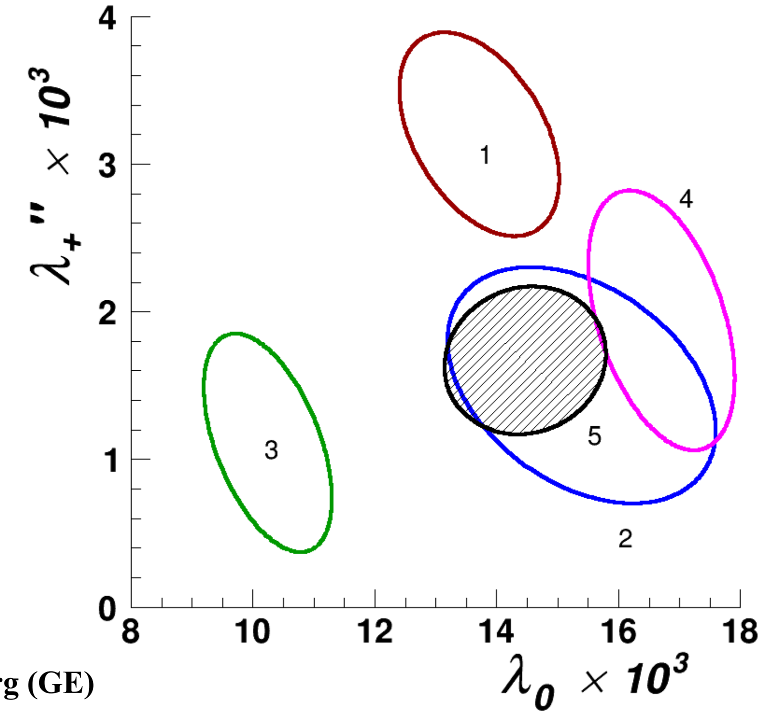
Comparisons

Joint K_{l3} 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.







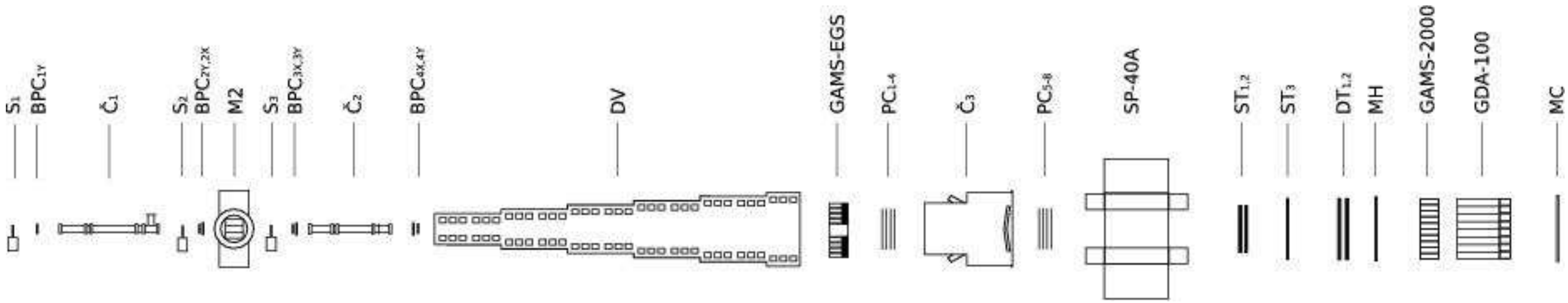
$K^{\pm} \rightarrow \pi^0 e^{\pm} \nu_e$ decays @ OKA

[JETP Lett. 107 (2018) no.3, 139-142]

DOI: 10.1134/S0021364018030037

OKA beam and detector

OKA @ IHEP, Protvino



Beam:

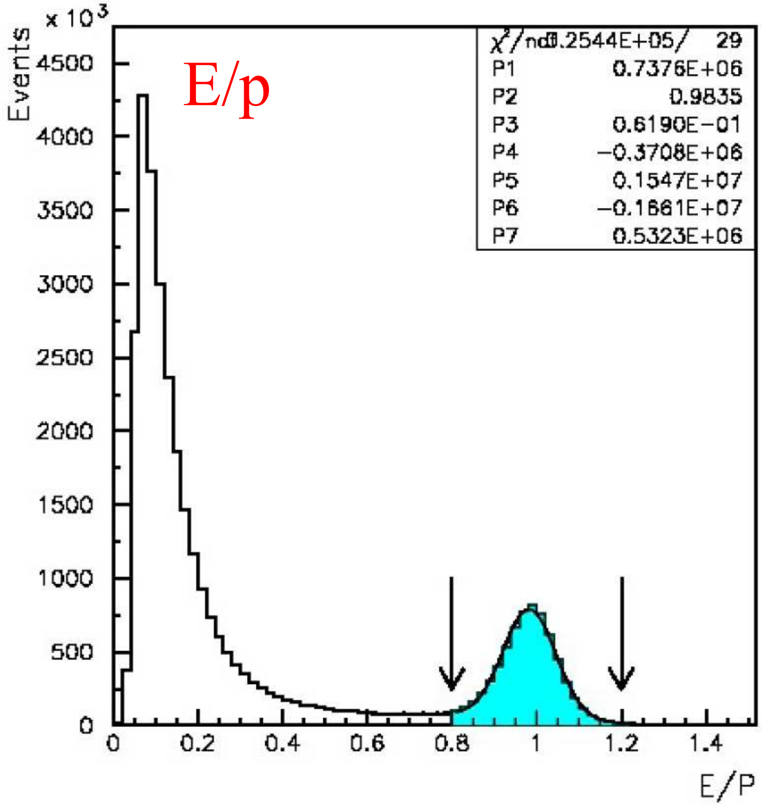
- Primary 70 GeV/c proton beam (U-70 Proton Synchrotron)
- Secondary beam at 17.7 GeV/c:
  - RF-separation with Panofsky scheme
  - 20% charged kaon component
  - 10^6 kaons in each 3 s spill

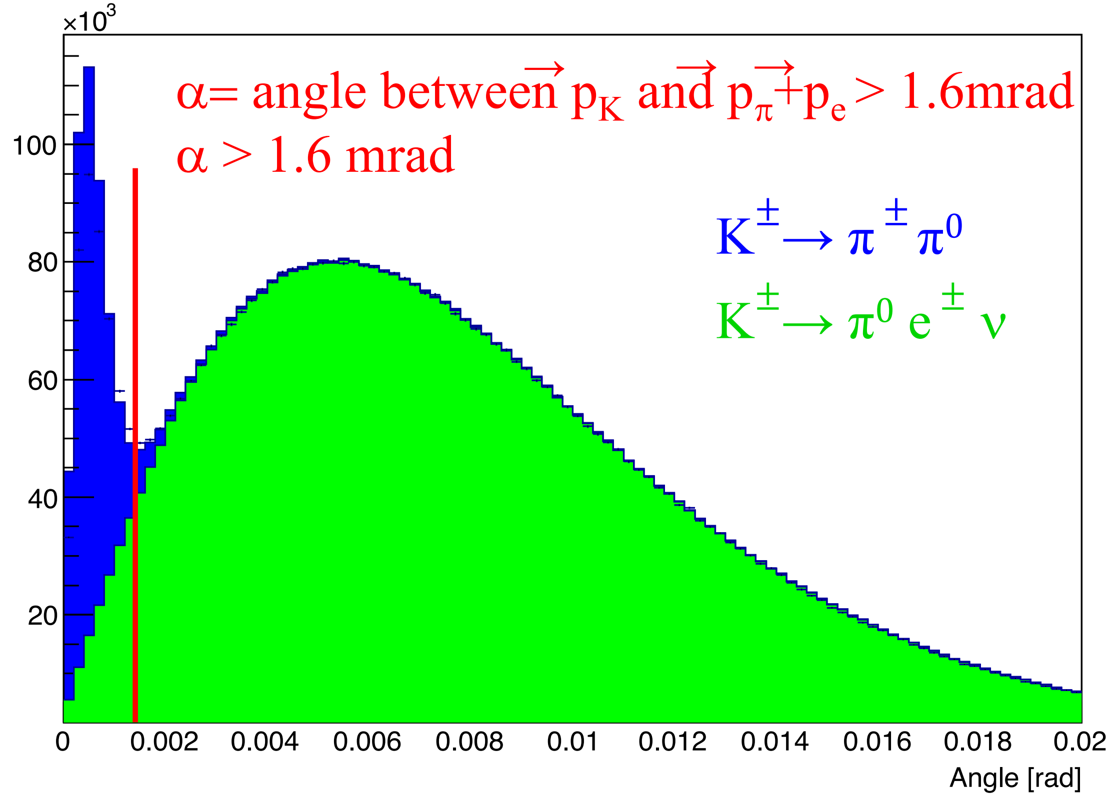
Detector:

- Beam spectrometer (proportional chambers) and two threshold Cherenkov counters
- Decay volume (filled with Helium) 11 m long surrounded by lead-scintillator vetos
- Main spectrometer with a magnet (1T·m) and trackers (Proportional chambers, Straws and Drift Tubes)
- Photon detector: Lead glass blocks
- Hadron calorimeter and muon detector

Sample

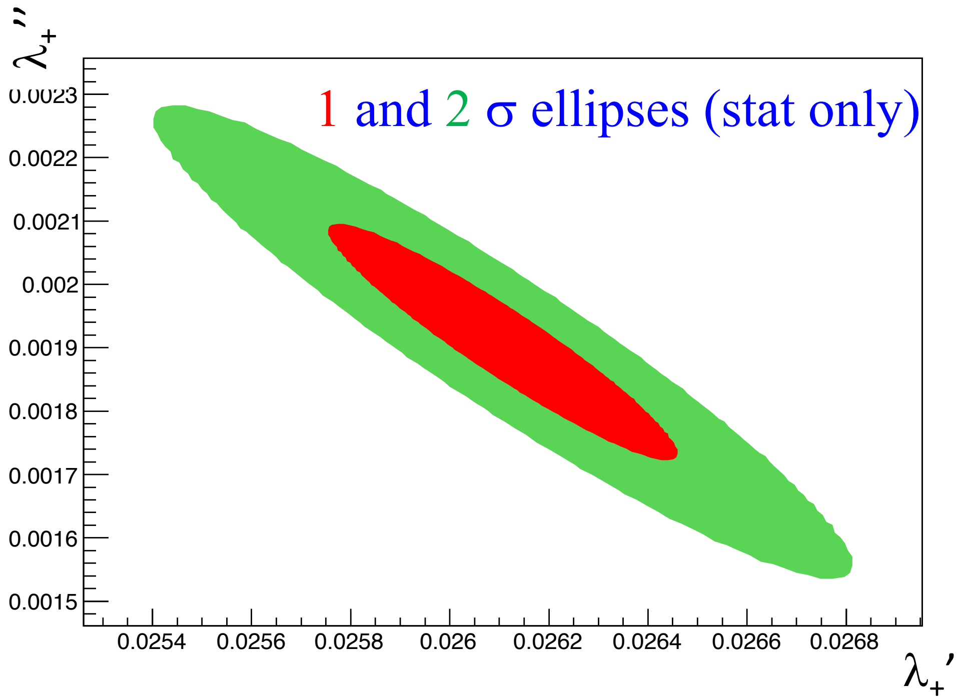
Sample from 2012-2013 data taking collected by a minimum bias trigger

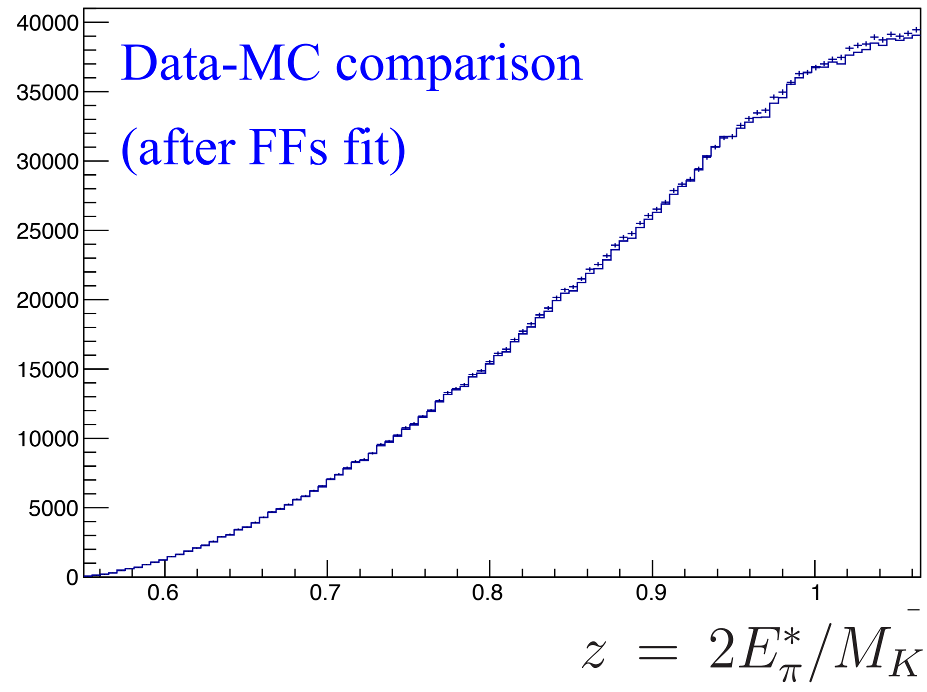




- Final sample with $5.25 \cdot 10^6$ K_{e3} candidates
- Main background from $K^\pm \to \pi^\pm \pi^0$ (<1% at the end of the selection)

Results





λ'_+ (10^{-2})	m [GeV]	Λ_+ (10^{-2})	λ''_+ (10^{-3})
$2.611^{+0.035}_{-0.035}$	$0.891^{+0.003}_{-0.003}$	$2.458^{+0.018}_{-0.018}$	$1.91^{+0.19}_{-0.18}$

Main source of systematics:

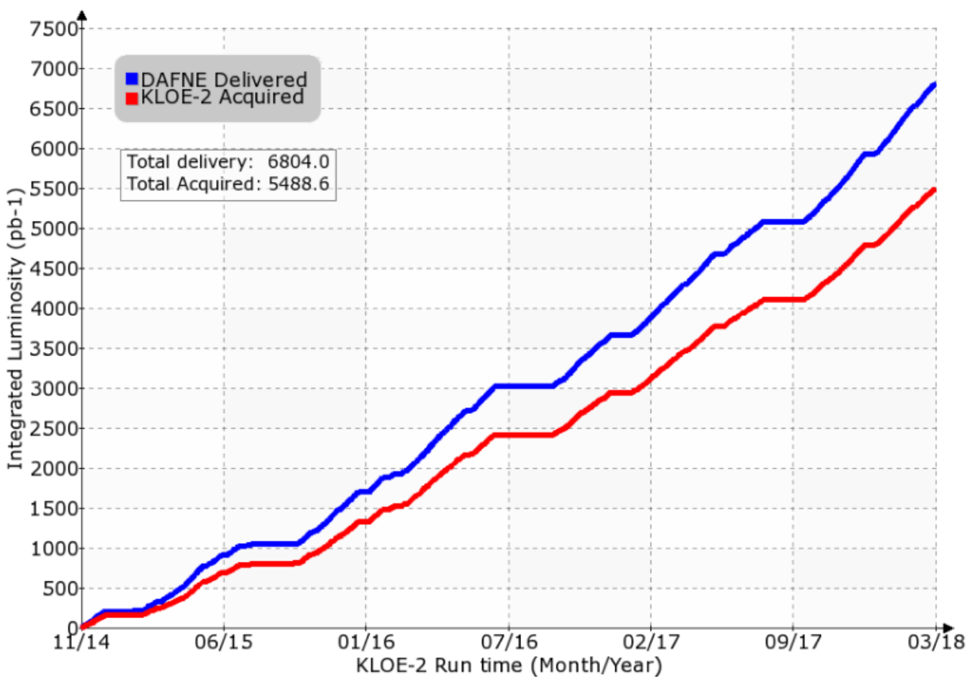
- z vertex cut
- α angle cut

$$\lambda'_+ = (2.611 \pm 0.035 \pm 0.028) \cdot 10^{-2} \qquad \lambda''_+ = (1.91^{+0.19}_{-0.18} \pm 0.14) \cdot 10^{-3}$$

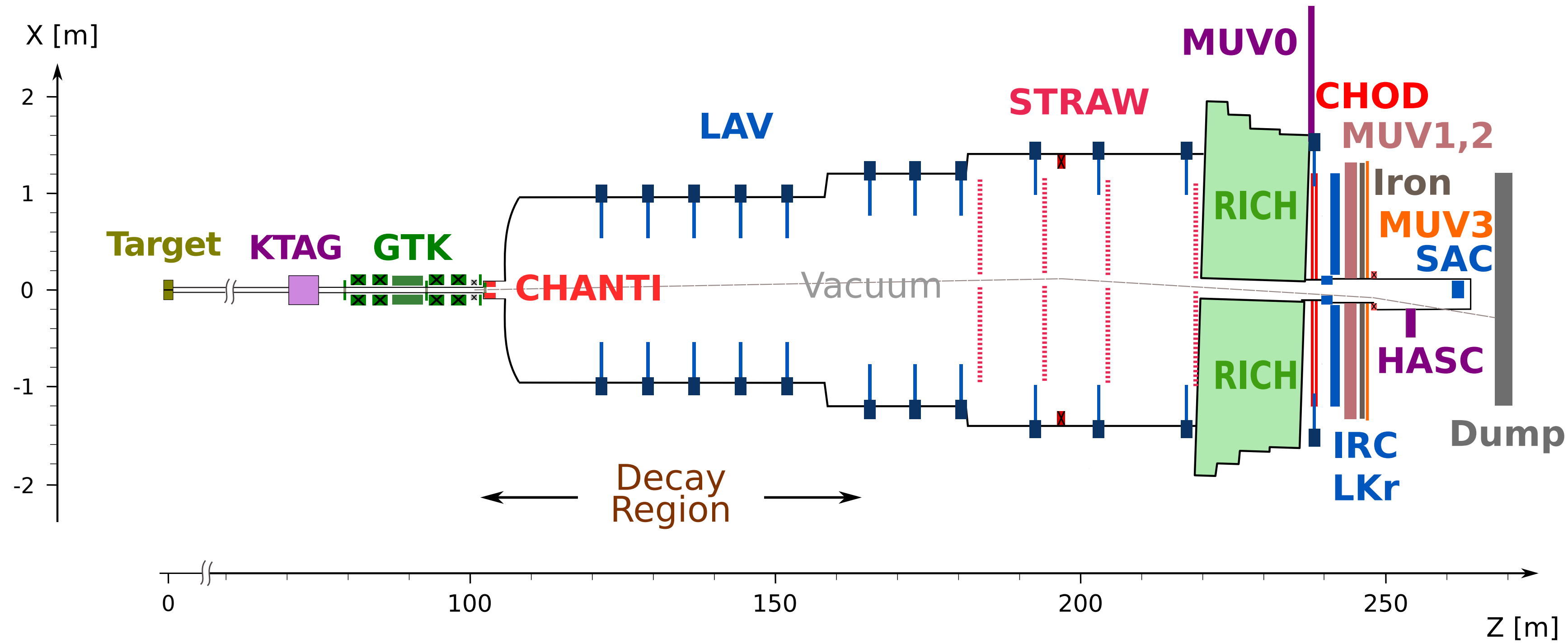
THE FUTURE

OKA and KLOE-2 prospects

- OKA experiment:
  - Currently working on $k_{\mu3}$ sample, results expected for end of 2018/beginning 2019
  - Still $\sim10^7$ K_{e3} candidates to analyze (twice the statistics shown today)
- KLOE-2 experiment:
  - In march 2018 data taken ended fulfilling their latest goal (**5 fb^{-1}**)



NA62 Prospects



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

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

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

Kaon decays in the fiducial volume

See M. Koval talk tomorrow! *[WG3, 09:00]*

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

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

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

Conclusions

- K_{l3} form factors measurement has been performed by NA48/2 on the basis of a 2004 special run selecting $4.4 \cdot 10^6$ K_{e3} and $2.3 \cdot 10^6$ $K_{\mu 3}$ candidates. The results are obtained with improved precision as compared to earlier measurements.

- New and competitive measurement of K_{e3} form factors from OKA, with a sample of $5.25 \cdot 10^6$ K_{e3}, one third of the overall sample collected up to 2018. Result on $K_{\mu 3}$ expected in few months.

- Future measurement from OKA and NA62 can further improve the precision on the measurement of the FFs of kaon semileptonic decays.