Rencontres de Moriond 2017, La Thuile

QCD and High Energy Interactions

New and recent results from NA48

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on behalf of the NA48/2 collaboration

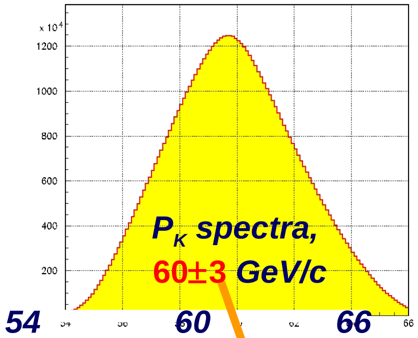
Outline

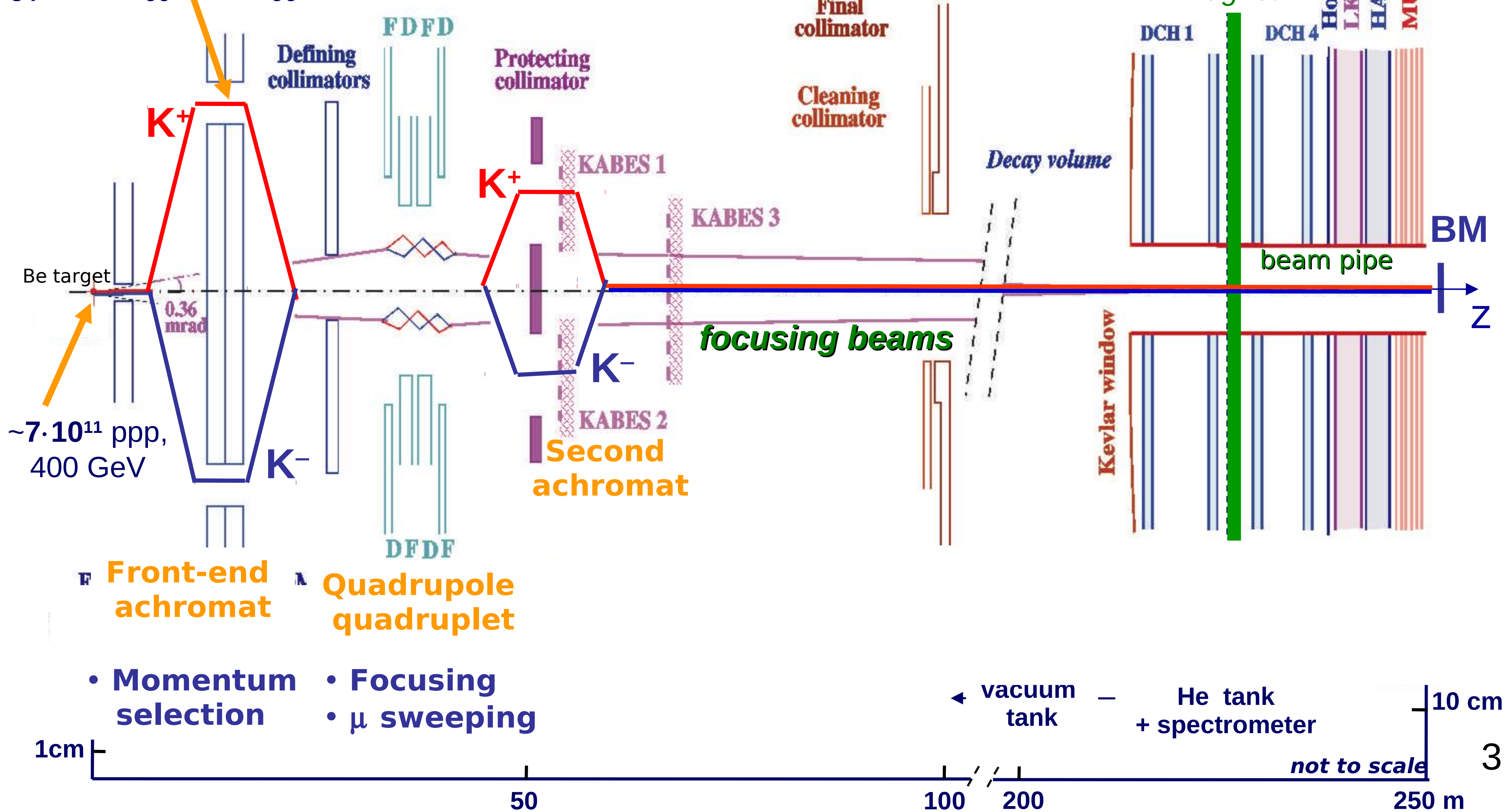
- NA48/2 experiment
- K_{l3} form factors precision measurement
- Model independent measurement of $K^{\pm} \rightarrow \mu^{\pm} \nu e^{+} e^{-}$
- Study of the $K^{+} \rightarrow \pi^{+} \pi^{0} e^{+} e^{-}$ decay
- Conclusion

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





NA48/2 detector

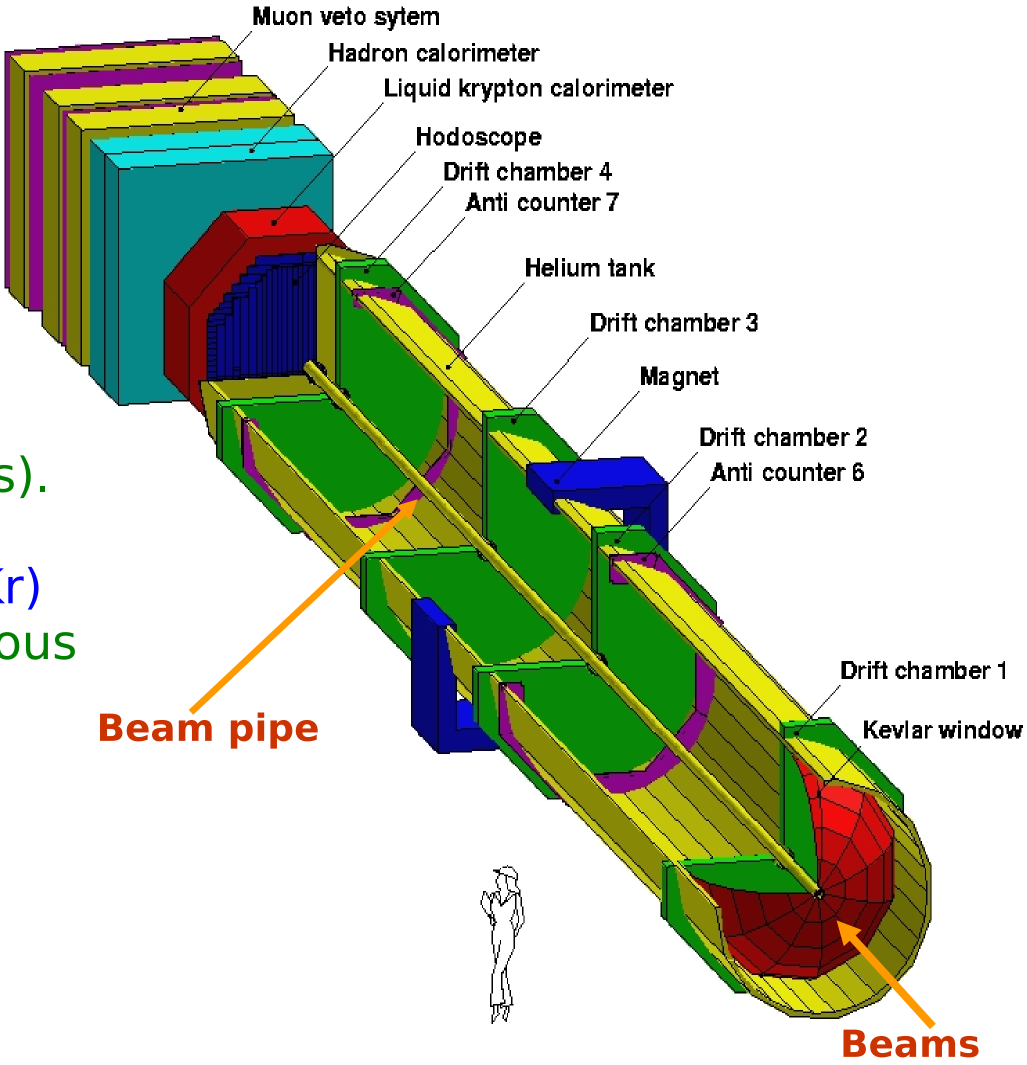
Main detector components:

- 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.



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

exper. input for $|V_{us}|$ extraction (apart from $\Gamma(K_{l3}\gamma)$)

Without radiative effects : $\rho_0 = d^2N/(dE_l\, dE_\pi) \sim A\, f_+^2(t) + B\, f_+(t)\, f_-(t) + C\, f_-^2(t)$, where

$t = (P_K - P_\pi)^2 = M_K^2 + M_\pi^2 - 2\, M_K\, E_\pi$

$f_-(t) = (f_+(t) - f_0(t))(m_K^2 - m_\pi^2)/t$. (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 (PDG name)	f_+(t,parameters)	f_0(t,parameters)
Quadratic (linear for $\bar{f}_0(t)$)	$1+\lambda'_+\, t/m^2_\pi + ½\, \lambda''_+(t/m^2_\pi)^2$	$1 + \lambda'_0\, t/m^2_\pi$
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 experiments. Depend on 2 (H) and 3 (G) extra external parameters known with a given* uncertainty.	$\exp((\Lambda_+ + H(t))\, t/m^2_\pi)$	$\exp((\ln[C] - G(t))\, t/(m_K^2 - m^2_\pi))$

* [V. 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 KLOE collaboration. It includes $f_0 = f_+ = 1 + \lambda'_+\, t/m^2_\pi$.

Data: 16 special runs from the NA48/2 data taken in 2004 (3 days)

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, to closest track > 15 cm.**

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

Kaon momentum reconstruction

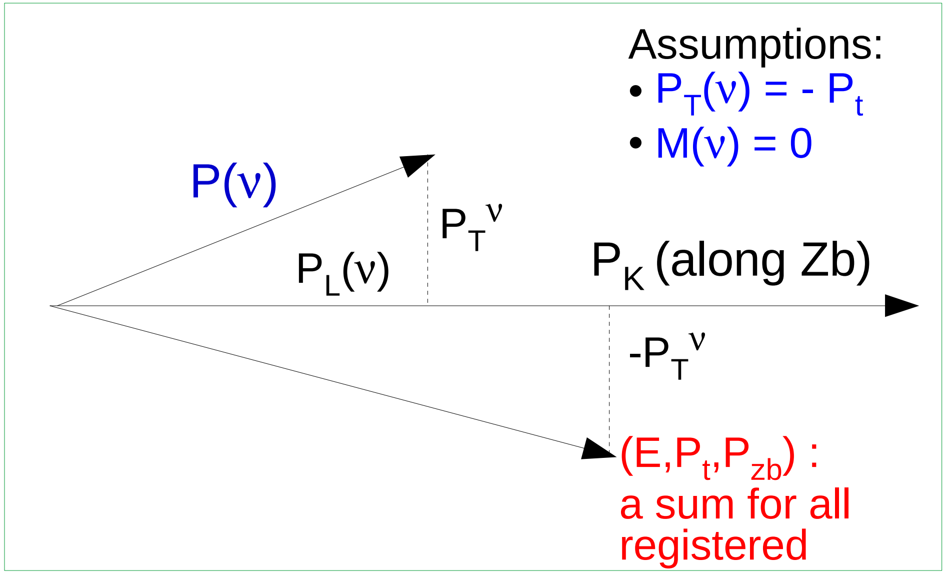
Two solutions of the quadratic equation for P_K:

$P_{1,2} = (\phi P_{Zb} \pm \mathrm{SQRT}(\mathbf{d})) / (E^2 - P_{zb}^2)$, 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 is used to choose the.
- A cut: -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

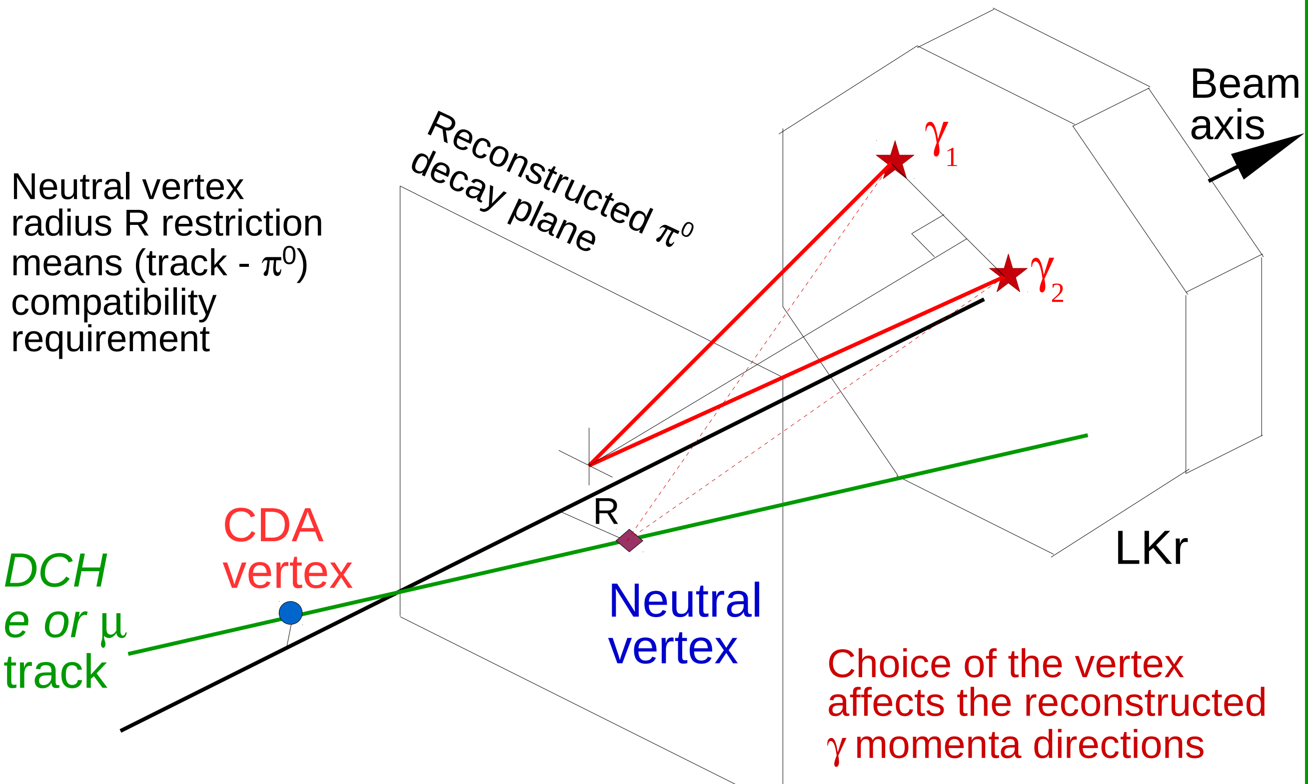
Track selection and identification

- 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.



Reminder: Preliminary result reported in 2012 was based on the «charged» vertex definition (from CDA between the track and the beam), that leads to high sensitivity to the exact beam shape simulation (due to the systematic shift of the vertex closer to beam).

Neutral vertex is chosen finally
(no transverse bias): $Z_{decay} = Z(\pi^0)$;
X_{decay}, Y_{decay} = impact point of reconstructed charged track on Z_{decay} plane

Final cuts

For K_{e3}

- 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);

- $P_L(\nu)^2 = (E^{\nu})^2/c^2 - (P_t^{\nu})^2 > 0.0014\ GeV^2/c^2$
  [negative tail and zero region are difficult to simulate exactly – sensitive to beam shape]
  [**For K_{e3} only** in the region of small and negative $P_L(\nu)^2$ fit results depend on $P_L(\nu)^2$ cut]

For $K_{\mu 3}$

- against the background from $K^{\pm} \to \pi^{\pm}\pi^0$ with $\pi^{\pm} \to \mu^{\pm}\bar{\nu}$
  $m(\pi^+\pi^0) < 0.47\ GeV/c^2$
  $m(\pi^+\pi^0) < (0.6 - P_t(\pi^0))\ GeV/c^2$
  $m(\mu^{\pm}\bar{\nu}) > 0.18\ GeV/c^2$ (to exclude π^+ mass region)

- a cut against $\pi^{\pm}\pi^0\pi^0$: $(P_2-P_1)<60$ GeV
  [a difference between two P solution is large when one pion is missing]

For both K_{l3}

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

Beam transverse elliptic variable **$B_{ell} < 11$**.
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 with respect to the run-dependent beam axis Zb.

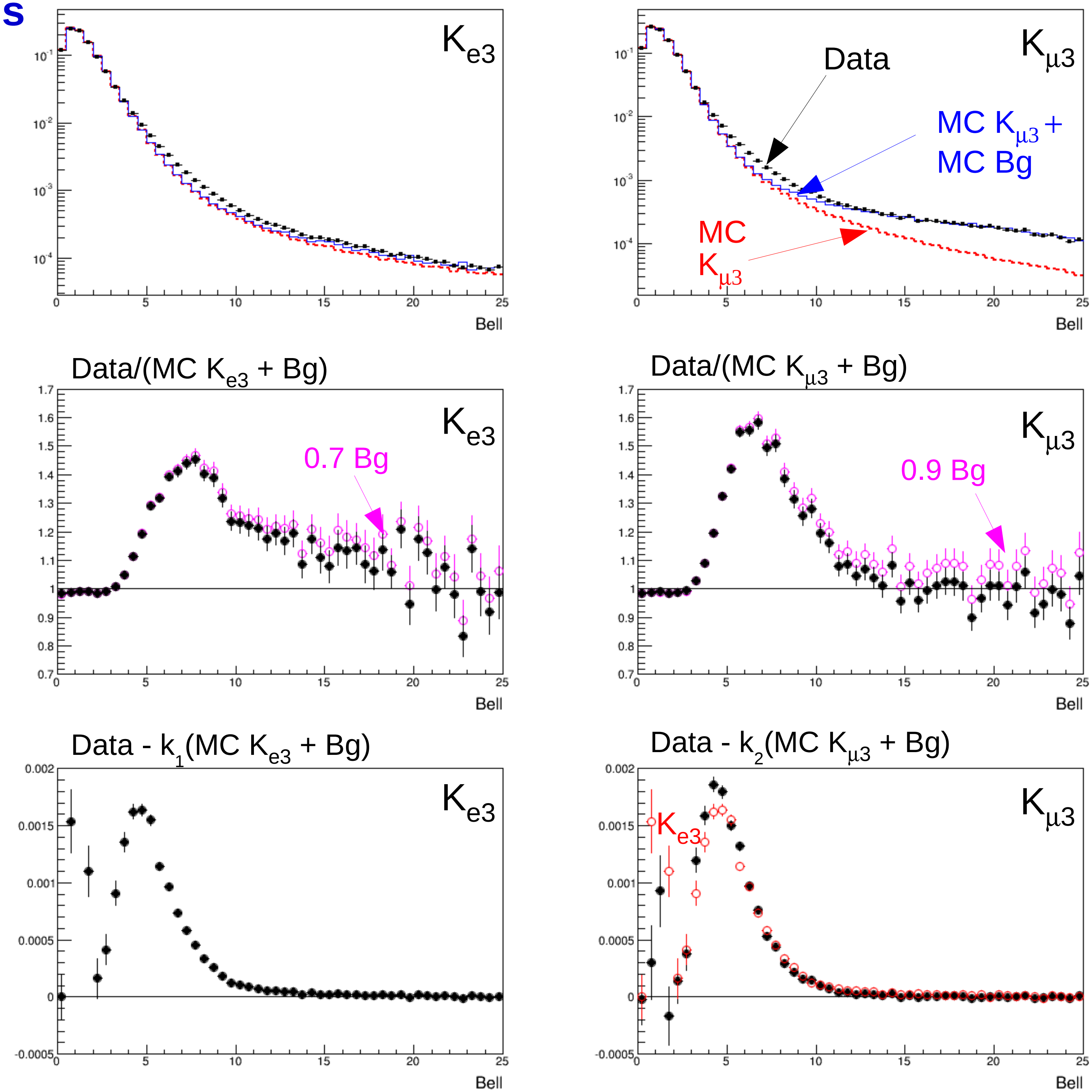
B_{ell} distributions in a wide area

~ 3σ range is relatively well simulated as well as the very far tail.

But the discrepance near ~5-10 is not described by the known background.

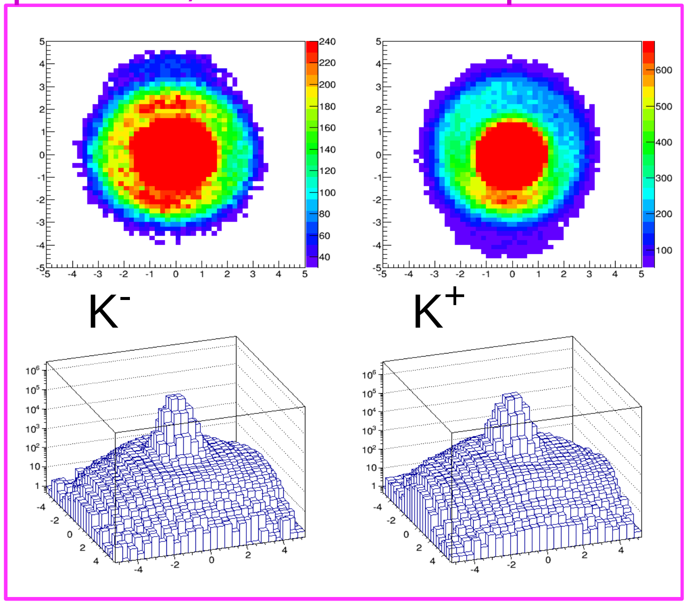
Sensitivity to the background variation at the very far tail (>20) is used to measure the Bg-related systematic uncertainty.

It looks like a small wide component of the beam, that becomes negligible for B_{ell} > 11. For wider cuts final results are stable.

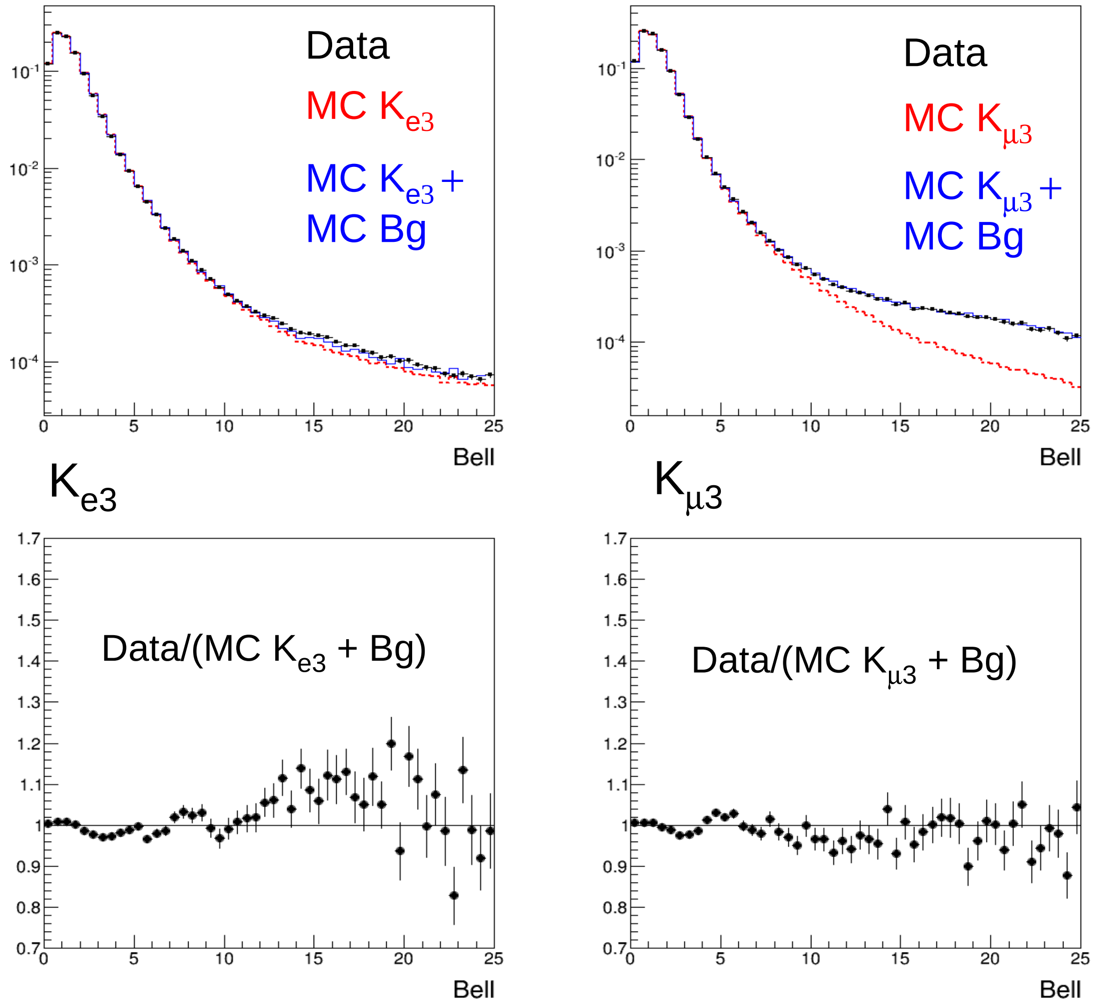


B_{ell} distributions with the modified MC beam (systematics)

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



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



This MC simplified modification is not used for the FF central values extraction (only for systematics estimate). So we need a wide radius cut to avoid the acceptance distortion, and also we need a vertex reconstruction, that is not too sensitive to the transverse general shift of the decay — it is a Neutral vertex rather than CDA.

Really important only $K_{2\pi}$ and $K_{3\pi}$ sources of Bg, others are negligible.

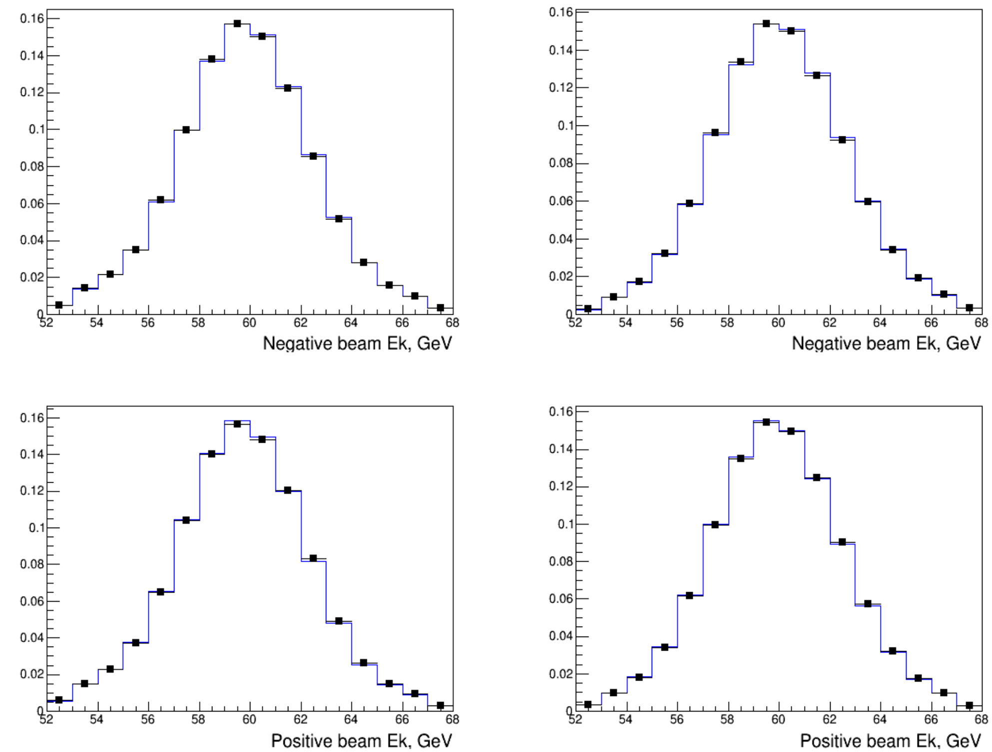
Process	Notation	Br	N_g	F_e	F_μ
$K^\pm \to \pi^\pm(\pi^0 \to 2\gamma)$	2π	20.66	393.2	0.270	0.264
$K^\pm \to \pi^\pm 2(\pi^0 \to 2\gamma)$	3π	1.761	62.5	0.286	1.833
$K^\pm \to \pi^\pm(\pi^0 \to e^+e^-\gamma)$	$2\pi D$	1.174	1.5	0.049	0.000
$K^\pm \to \pi^\pm\gamma(\pi^0 \to 2\gamma)$	$2\pi\gamma$	0.0275	35.3	0.004	0.044
$K^\pm \to \pi^0\mu^\pm\nu(\mu \to e\nu)$	$K^e_{\mu 3}$	0.03353	174.3	0.004	0.000

Table *Simulated background processes, their probabilities Br (in %), generated MC statistics N_g (in 10^6 events) and the estimated fractions F_e and F_μ (both in units of per mill) in K_{e3} and $K_{\mu 3}$ samples for the present selection.*

Reconstructed kaons energy normalized distributions (as a signal manifestation)

Histograms: MC.

Points: Data (corrected for background).



Events-weighting fit procedure

• Experimental Dalitz plot is corrected for the simulated background.

• 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.

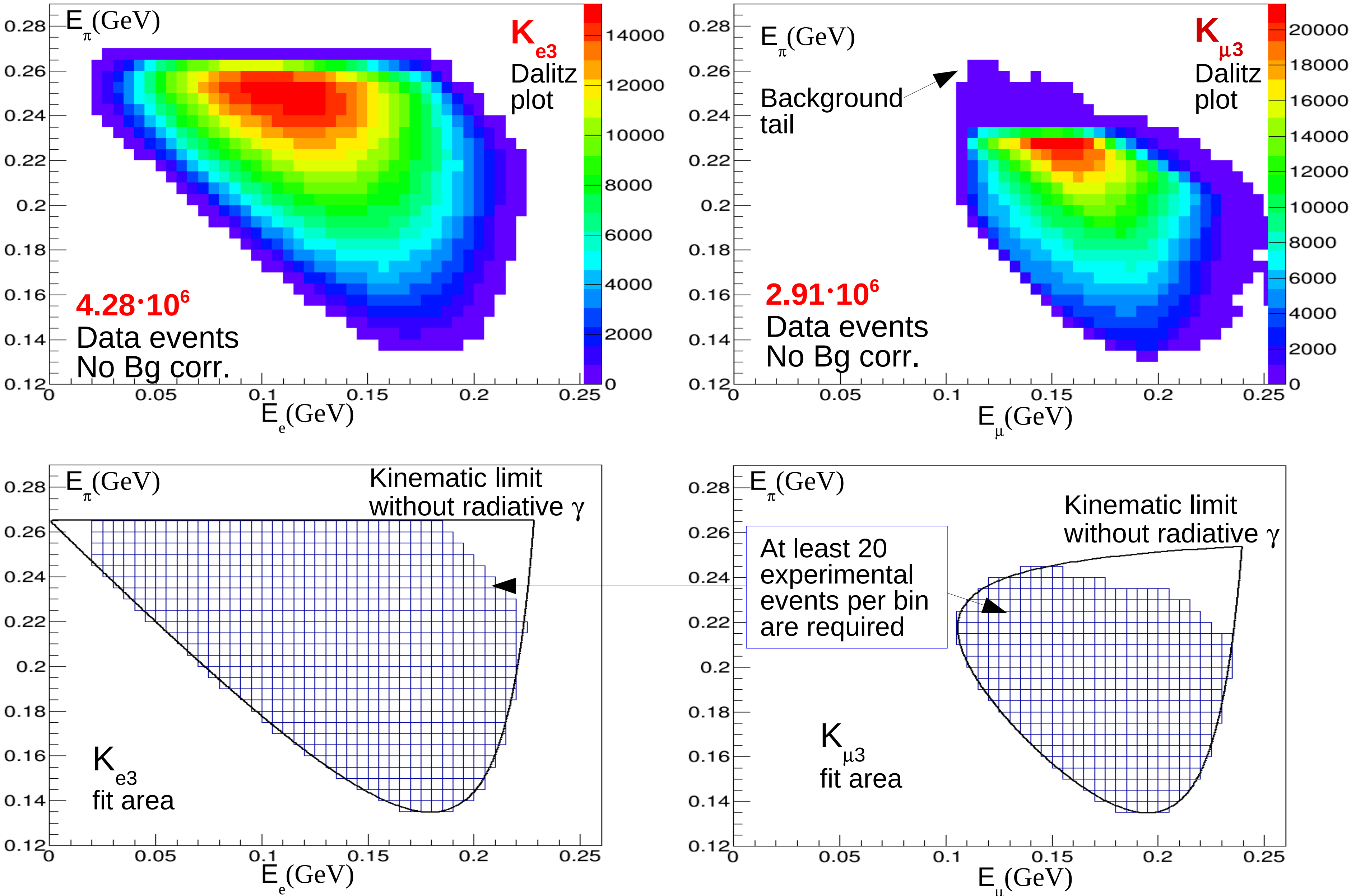
• MINUIT package is searching for the FF_{fit} parameters minimizing the standard χ^2 value:

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

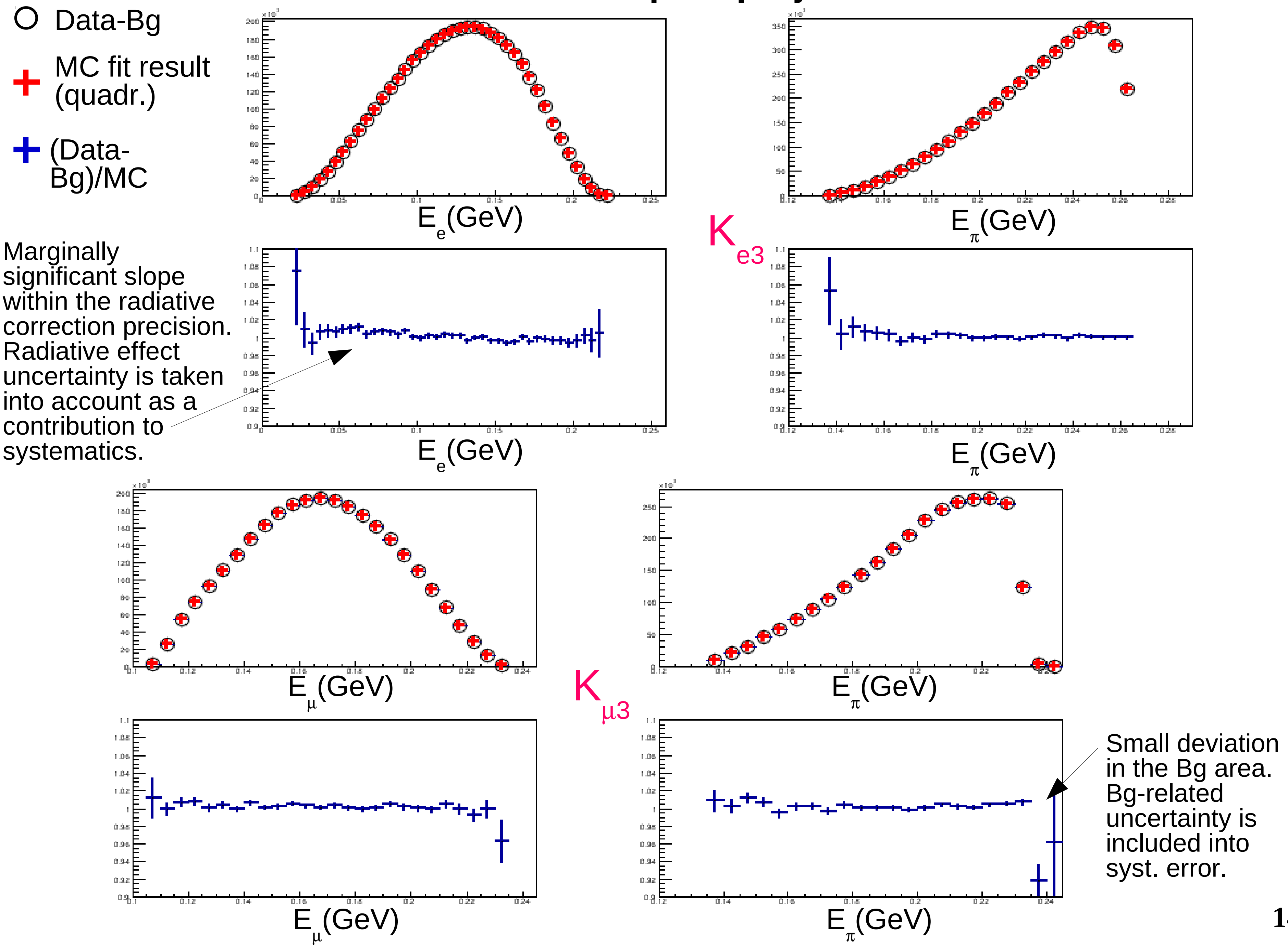
where *i,j* means the Dalits plot cell indices, $D_{i,j}$ is the background-corrected experimental data content of the cell, $MC_{i,j}$ is the weighted MC bin content, and $\delta D_{i,j}$, $\delta MC_{i,j}$ are the corresponding statistical errors.

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

Experimental Dalitz plots and fit areas (5x5 MeV cells)



Dalitz plot projections



Results for the joint K_{l3} analysis

Analysis has been performed:

- For K_{e3}
- For $K_{\mu3}$
- For the combined K_{l3} result:

A joint fits are done minimizing

$$\chi^2(K_{e3}) + \chi^2(K_{\mu3})$$

with a common set of fit parameters.

Quadratic parameterization (in units of 10^{-3})

$\chi^2/ndf = 1004.6/1073$

Correlation coefficients

	$\lambda''_+(K_{l3})$	$\lambda_0(K_{l3})$
$\lambda'_+(K_{l3})$	-0.954	-0.076
$\lambda''_+(K_{l3})$		0.035

	$\lambda'_+(K_{l3})$	$\lambda''_+(K_{l3})$	$\lambda_0(K_{l3})$
Central values	23.35	1.73	14.90
Stat. error	0.75	0.29	0.55
Beam scattering	0.90	0.35	0.45
LKr nonlinearity	0.19	0.03	0.35
LKr scale	0.66	0.15	0.08
Background	0.07	0.03	0.04
Trigger	0.20	0.10	0.45
Accidentals	0.23	0.08	0.08
Acceptance	0.24	0.07	0.01
Pk average	0.04	0.01	0.24
Pk spectra	0.01	0.00	0.04
Neutrino P cut	0.18	0.04	0.03
Binning	0.08	0.02	0.16
Resolution	0.00	0.02	0.14
Radiative	0.22	0.01	0.06
Syst. error	1.23	0.41	0.80
Total error	1.44	0.50	0.97

Pole parameterization (in MeV)

χ^2/ndf = 1001.1/1074

	$m_V(K_{l3})$	$m_S(K_{l3})$
Central values	894.3	1185.5
Stat. error	3.2	16.6
Beam scattering	0.1	27.2
LKr nonlinearity	1.7	14.3
LKr scale	3.9	3.6
Background	0.1	0.6
Trigger	0.7	12.9
Accidentals	0.5	0.0
Acceptance	0.7	3.3
Pk average	0.3	8.8
Pk spectra	0.1	1.5
Neutrino P cut	1.0	0.7
Binning	0.4	5.1
Resolution	0.8	4.3
Radiative	2.7	2.7
Syst. error	5.4	35.5
Total error	6.3	39.2

Correlation = - 0.278

Dispersion parameterization (in units of 10^{-3})

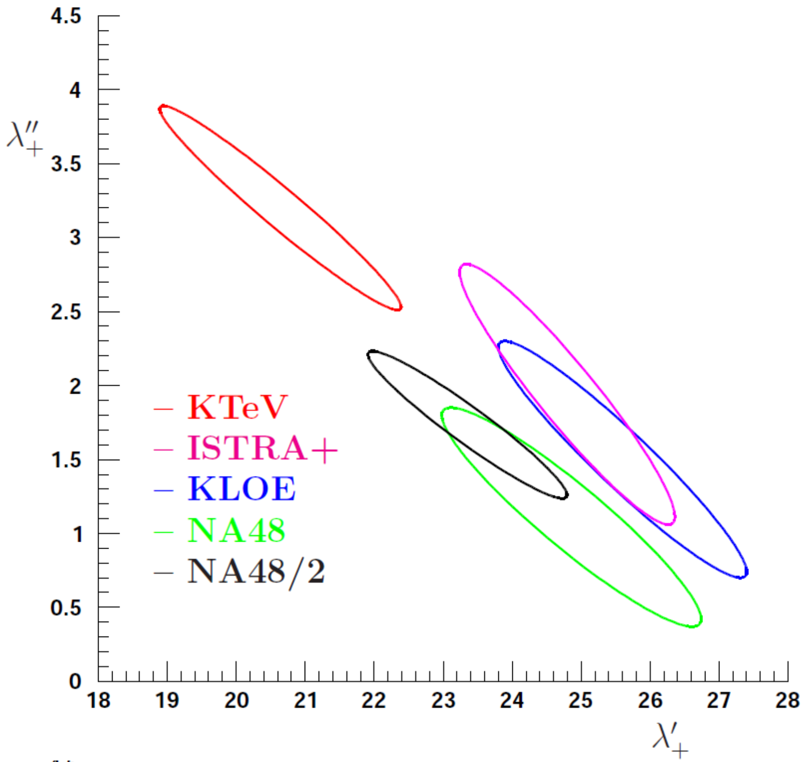
χ^2/ndf = 998.3/1074 (the best)

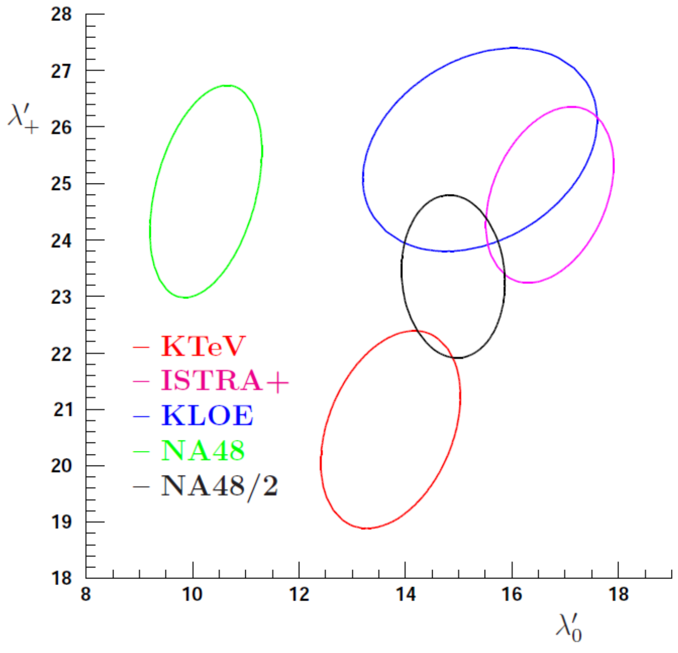
	$\Lambda_+(K_{l3})$	$ln[C](K_{l3})$
Central values	22.67	189.12
Stat. error	0.18	4.91
Beam scattering	0.01	8.39
LKr nonlinearity	0.10	4.04
LKr scale	0.23	0.88
Background	0.00	0.14
Trigger	0.04	3.73
Accidentals	0.03	0.01
Acceptance	0.04	0.92
Pk average	0.02	2.63
Pk spectra	0.00	0.44
Neutrino P cut	0.06	0.16
Binning	0.03	1.46
Resolution	0.05	1.28
Radiative	0.16	0.75
Parameterization	0.44	3.04
Syst. error	0.55	11.09
Total error	0.58	12.13

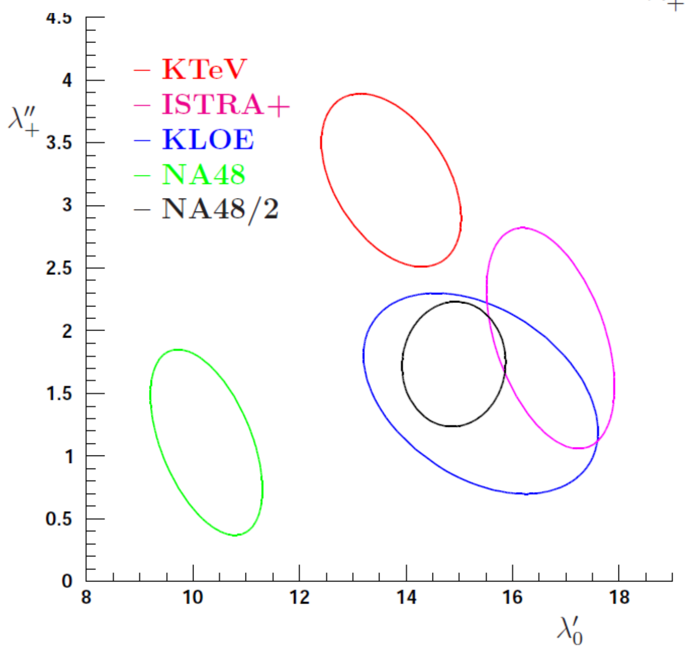
Correlation = - 0.035

Joint K_{l3} results comparison for quadratic parameterization

1σ ellipses rather than 68% for better visibility

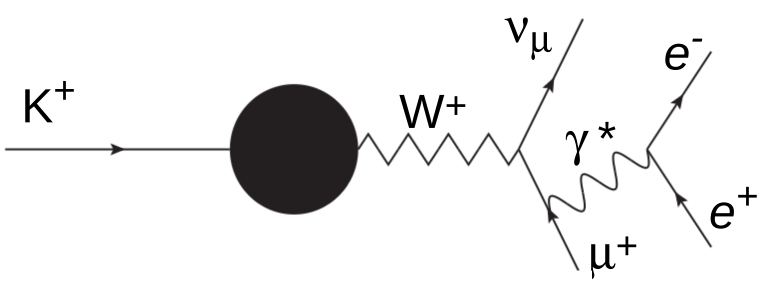




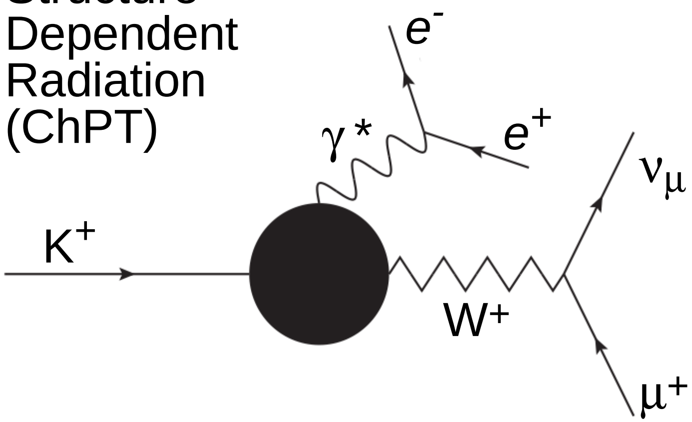


Model independent measurement of the leptonic kaon decay $K^{\pm} \rightarrow \mu^{\pm} \nu e^{+} e^{-}$

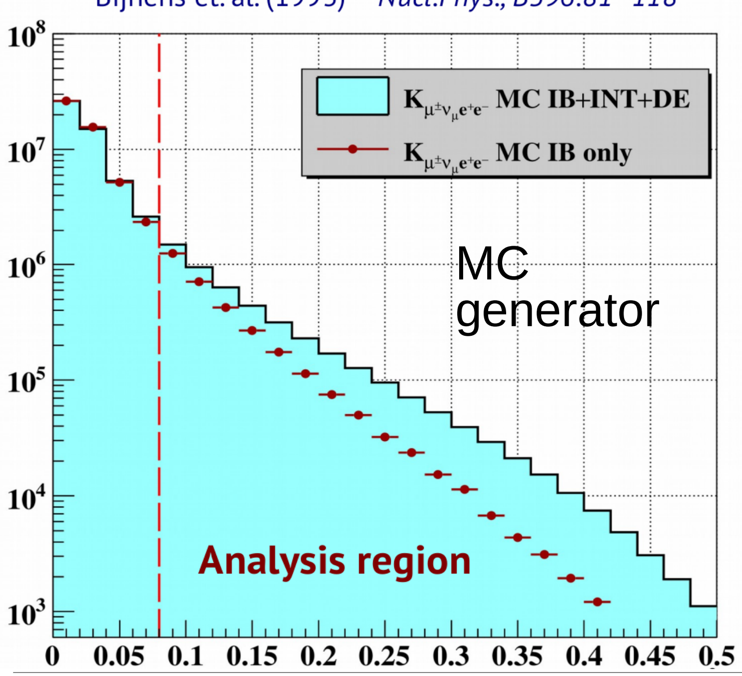
Final State Radiation (QED)



Structure Dependent Radiation (ChPT)



Bijnens et. al. (1993) - *Nucl.Phys., B396:81–118*



$Z = [M(e^{+}e^{-})/M(K^{\pm})]^{2}$

3 charged tracks **μee** in the final state

Analysis region is:

- sensitive to ChPT contributions;
- clean of background decays $\pi^{0} \rightarrow e^{+}e^{-}\gamma\ (\pi^{0}_{D})$

Background and normalization

$K_{3\pi 0}$ background:

$K^{\pm} \to (\pi^{\pm} \to \mu^{\pm}\nu)(\pi^0 \to e^+e^-\gamma^*)(\pi^0 \to e^-e^+\gamma^*)$

K_{e4} background: $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$

$K_{3\pi}$ background: $K^{\pm} \to \pi^+\pi^-(\pi^{\pm} \to \mu^{\pm}\nu)$

Red: registered;
Blue: missing;
Green: misidentified as electron
Pink: misidentified as muon

For these 3 sources a Wrong Sign selection (e^+e^+ or e^-e^-)+MC helps to estimate the background size. ~ 2 possibilities to enter signal vs 1 possibility to pass the Wrong Sign selection.

$K_{\pi ee}$ background: $K^{\pm} \to (\pi^{\pm} \to \mu^{\pm}\nu)e^+e^-$

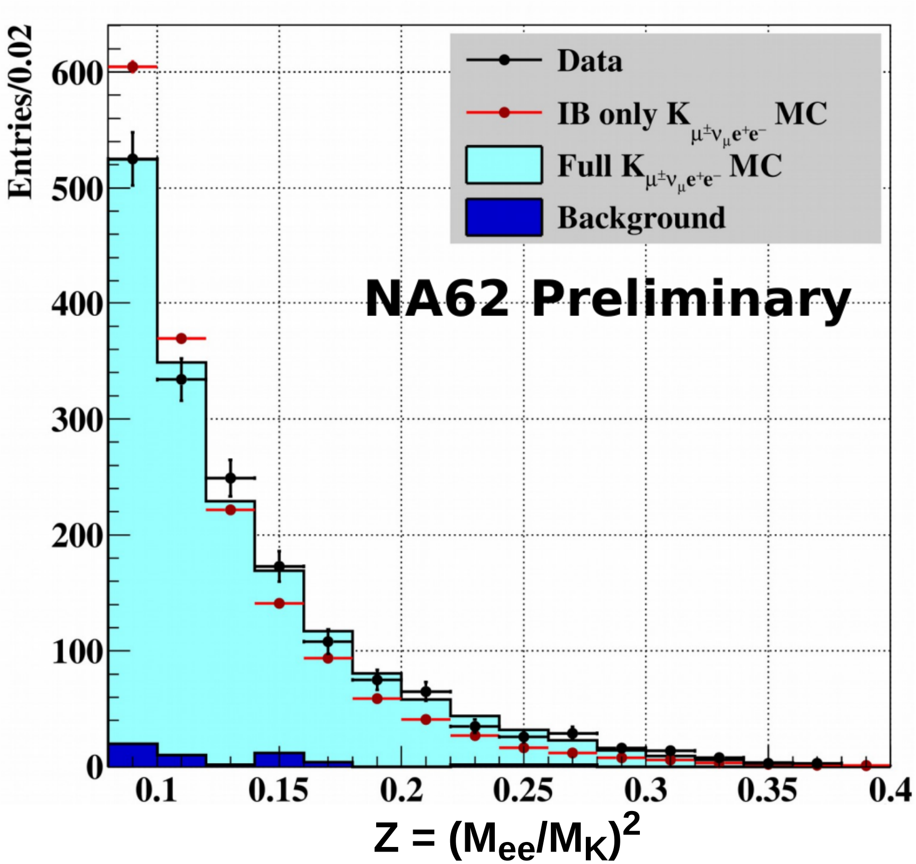
A cut on the pion expected mass $M(\mu^{\pm}\nu)$ > 170 MeV/c^2 kills this background reducing signal by 11%

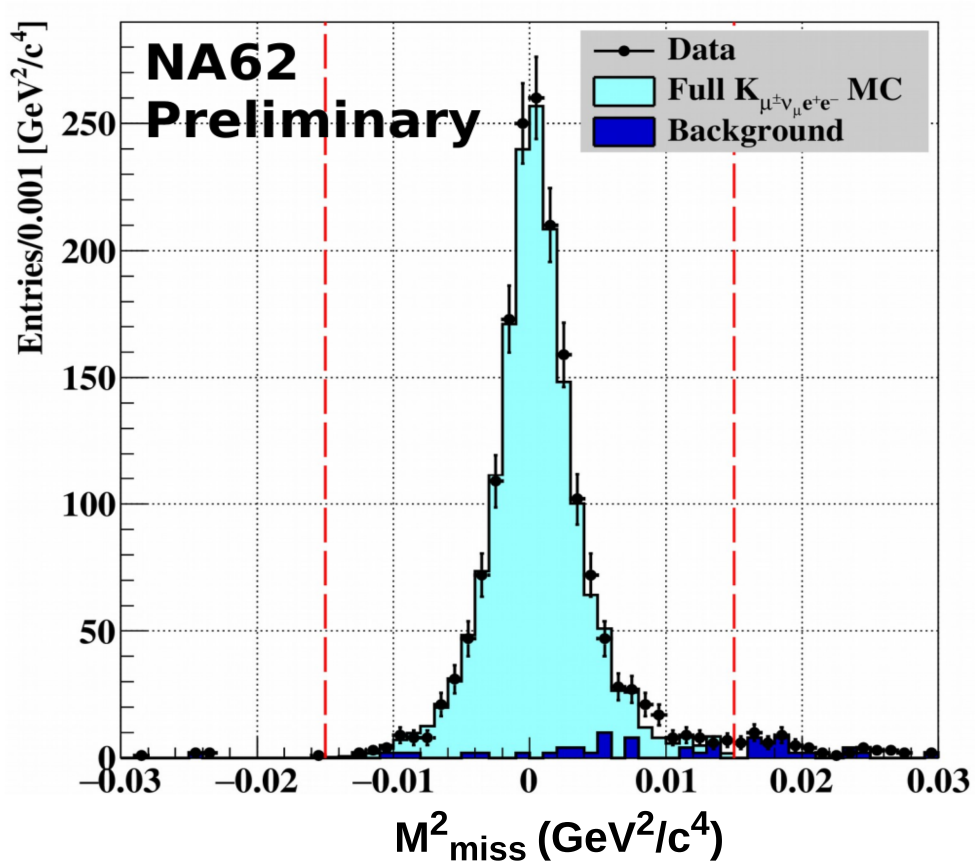
Normalization channel $K_{3\pi}$: $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$

Good reconstruction, negligible background, huge statistics ~ 10^9

Selection results

1663 data events observed
Background 3%
Shape matches MC with ChPT FF





The BR is computed for each Z bin independently.
Results are summed to get the branching ratio for $M_{ee} > 140$ MeV/c^2

Branching ratio measurement

Errors budget

	Source	δBR/BR x 100
Stat	Signal stat	2.54
	Normalization stat	0.02
Systematic	Rad. Corr.	0.70
	Background stat	0.62
	Background syst	0.30
	Trig. efficiency	0.54
	Muon ID	0.13
	Electron ID	0.04
	Acceptance stat	0.12
	External BR($K_{3\pi}$)	0.72

$BR(K^{\pm} \to \mu^{\pm} \nu e^{+} e^{-} \mid M_{ee} > 140\ MeV/c^2) =$

$(7.84 \pm 0.21_{stat} \pm 0.08_{syst} \pm 0.06_{ext})\ 10^{-8} =$

$(7.84 \pm 0.23)\ 10^{-8}$

Previous measurements:

Diamant-Berger et.al. 1976:
$Br(M_{ee} > 140\ MeV/c^2) = (12.3 \pm 3.2)\ 10^{-8}$

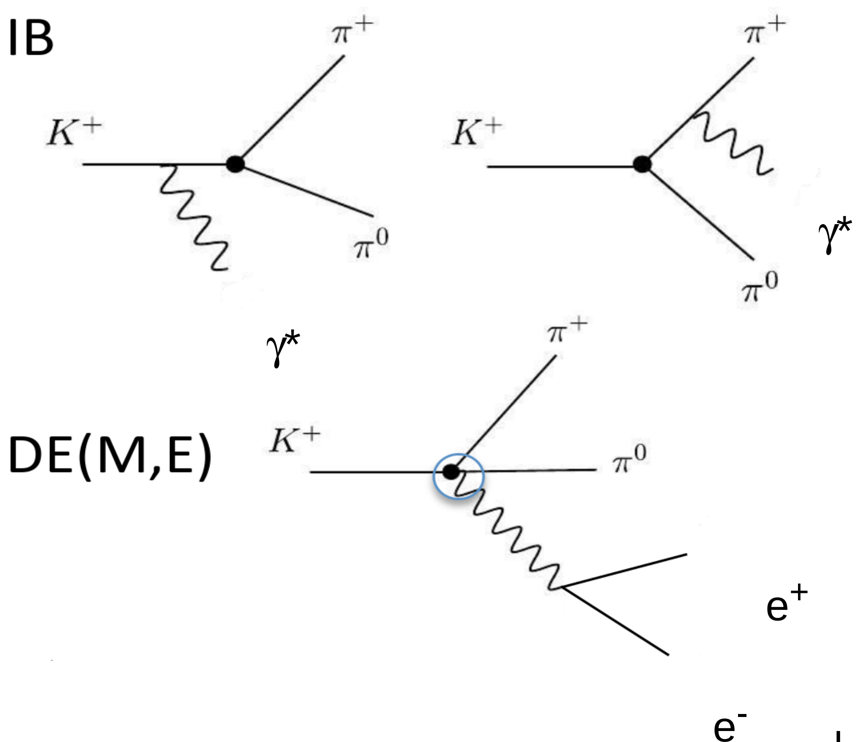
Poblaguev et.al. 2002:
$Br(M_{ee} > 140\ MeV/c^2) = (7.06 \pm 0.31)\ 10^{-8}$

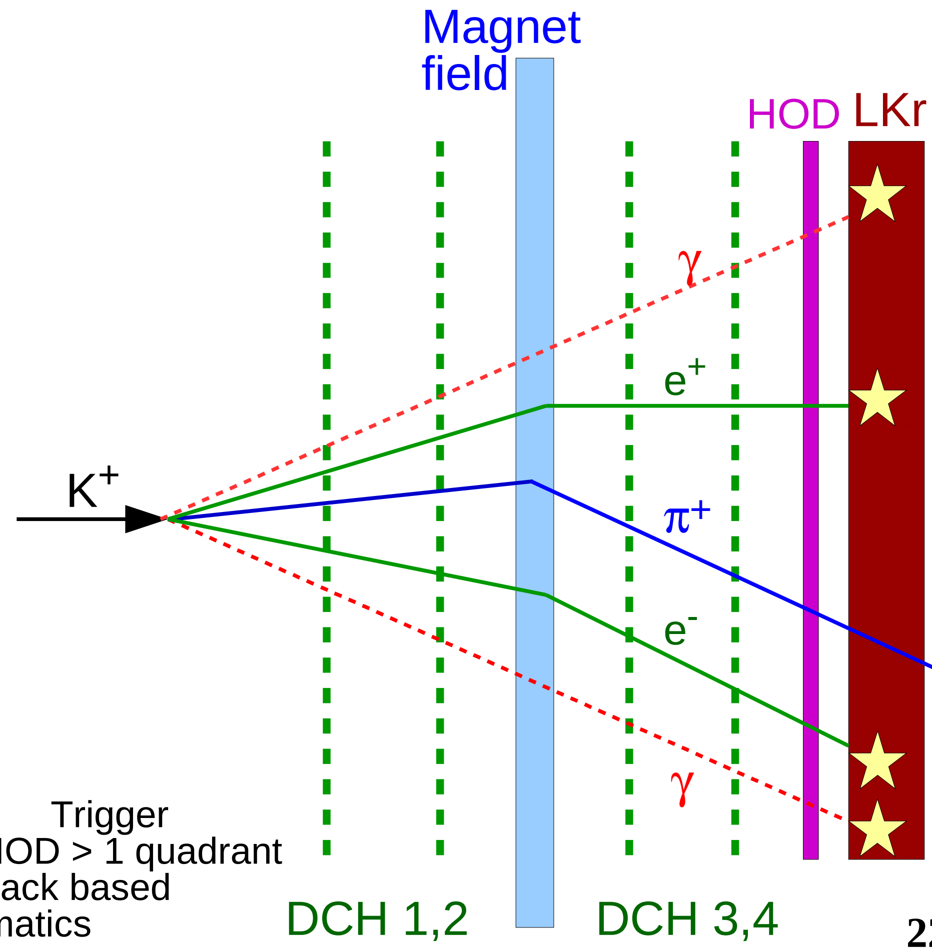
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ decay

Motivation:

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

- 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





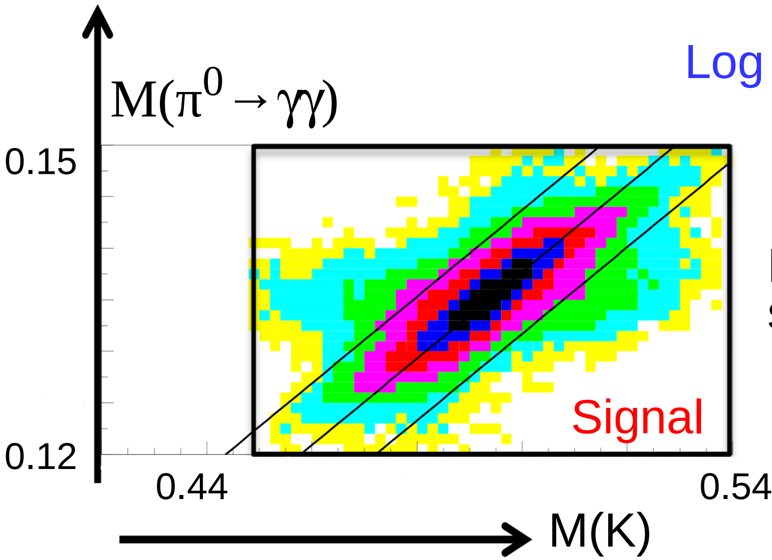
Trigger
L1: HOD > 1 quadrant
L2: track based kinematics

Events selection

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

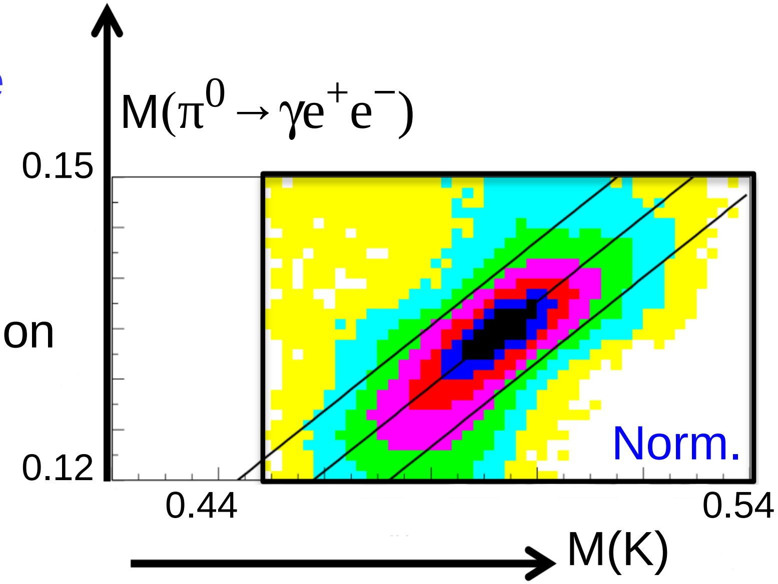
3 tracks in both cases, but one photon less in the normalization channel.
Cut for trigger efficiency: no 3 track in one HOD quadrant.

- 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 $M(\pi^0)$ and $M(K^{\pm})$;
- $|M(\pi^0) - M_{PDG}| < 15$ MeV/c^2;
- $|M(K^{\pm}) - M_{PDG}| < 45$ MeV/c^2;
- $|M(\pi^0) - 0.42\, M(K^{\pm}) + 73.2$ MeV/$c^2| < 6$ MeV/c^2

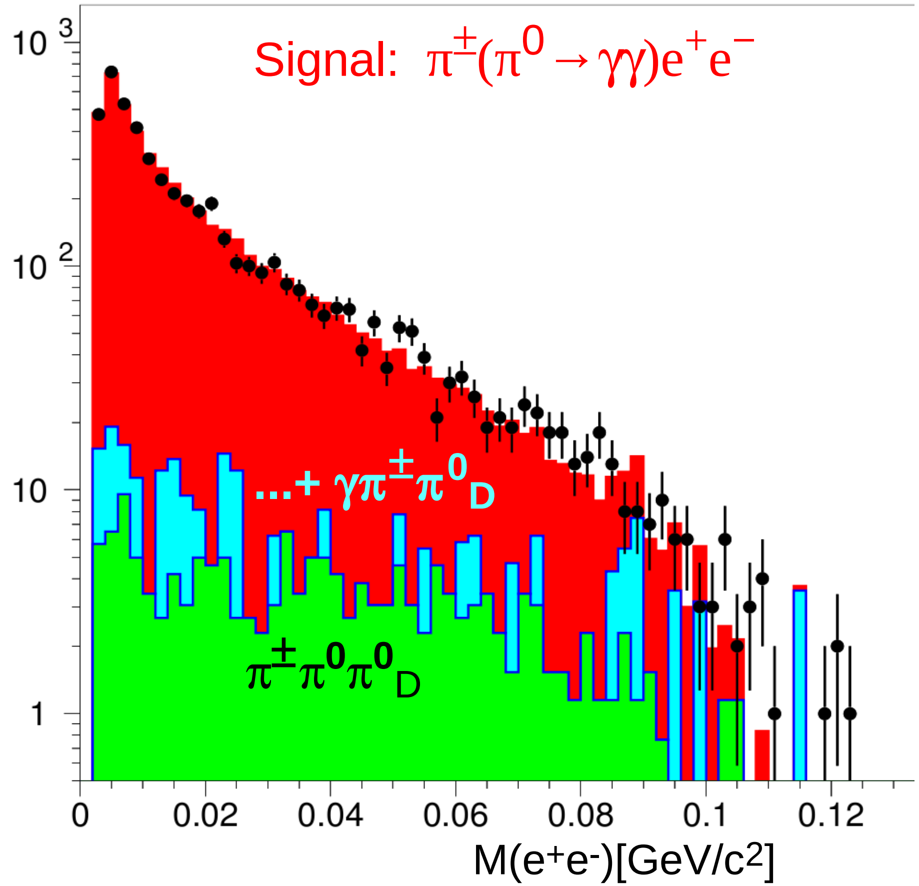


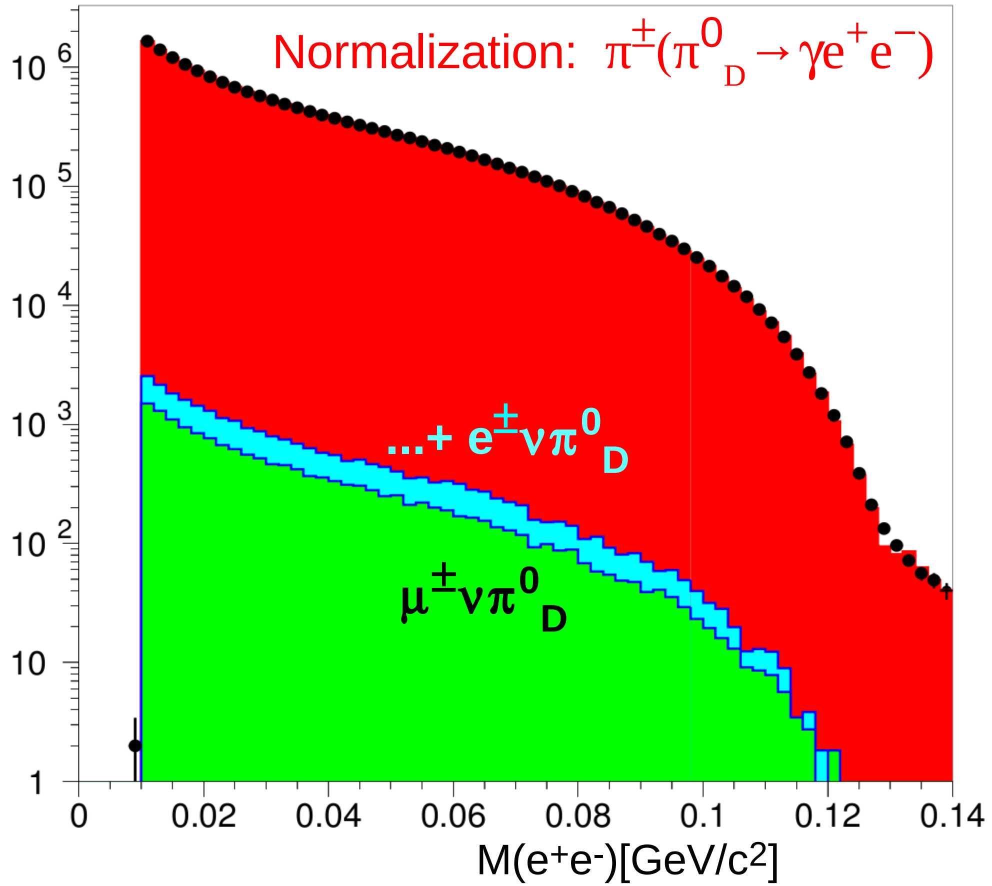
Log Z scale

MC simulation



Selection results





Candidates N_S	5076
Background N_{BS}	289
Accept (rad) A_S	0.666(1)%
L1 eff. ε_{L1S}	99.73(1)%
L2 eff. ε_{L2S}	99.46(2)%

Candidates N_N	16774613
Background N_{BN}	25517
Accept (rad) A_N	4.083(2)%
L1 eff. ε_{L1S}	99.767(3)%
L2 eff. ε_{L2S}	98.584(7)%

Branching ratio measurement

$BR = BR(\pi^{\pm}\pi^{0}) \times BR(\pi^{0}_{D}) \times (N_S - N_{BS})/(N_N - N_{BN}) \times (A_N/A_S) \times (\varepsilon_{L1N}\,\varepsilon_{L2N})/(\varepsilon_{L1S}\,\varepsilon_{L2S})$

	Source	$\delta BR/BR \times 100$
Statistical	N_S	1.4
	N_{BS}	0.51
	N_N	0.02
	N_{BN}	0.00
Systematic	A_S	0.18
	A_N	0.05
	$\varepsilon_{L1N}\,\varepsilon_{L2N}$	0.01
	$\varepsilon_{L1S}\,\varepsilon_{L2S}$	0.04
	A(rad corr)	0.56
	A(frac. DE)	0.25
	Trig. efficiency	0.8
External	$BR(2\pi)$	0.39
	$BR(\pi^{0}_{D})$	2.98

Preliminary result:

$BR = (4.22 \pm 0.06_{stat} \pm 0.04_{syst} \pm 0.13_{ext})\ 10^{-6}$

Error is dominated by external error of $BR(\pi^{0}_{D})$

In perfect agreement with ChPT [EPJ C72 (2012)]:

without radiative and isospin breaking corrections

$BR(IB) = 4.19\ 10^{-6}$;

With isospin breaking

$BR(IB) = 4.10\ 10^{-6}$.

Conclusion

- K_{l3} form factors measurement is performed by NA48/2 on the basis of 2004 run $4.28 \cdot 10^6$ (K_{e3}) and $2.91 \cdot 10^6$ ($K_{\mu3}$) selected events. Result is competetive with the other ones in $K_{\mu3}$ mode, and a smallest error in K_{e3} has been reached, that leads to the most precise combined K_{l3} result and allows to reduce the form factor uncertainty of $|V_{US}|$.

  Our preliminary K_{l3} results shown in 2012 were somewhat shifted due to apriory biased charged vertex definition leading to beam shape simulation sensitivity, while for the present result we use almost unbiased neutral vertex definition.

- About 1500 events of the very rare decay $K^{\pm} \to \mu^{\pm} \nu e^{+} e^{-}$ are reconstructed, with almost negligible background in the region with $M(e^{+}e^{-}) > 140$ MeV, which is of great interest in Chiral Perturbation Theory. $M(e^{+}e^{-})$ spectrum is obtained as well as a model-independent measurement of the decay rate for this region.

- More than 5000 $K^{+} \to \pi^{+}\pi^{0}e^{+}e^{-}$ rare decay candidates, with a 5% background contamination, are first observed. Preliminary branching ratio is measured to be $(4.22 \pm 0.15) \times 10^{-6}$, that is in good agreement with ChPT-based theoretical predictions.