Measurement of $K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} e^{+}e^{-}$ with NA48/2 at CERN

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$K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} e^{+}e^{-}$ / Motivation

- One of the interesting modes of radiative semileptonic decays, $K^{\pm} \rightarrow l^{\pm} \nu_{l} l'^{+} l'^{-}$
  - $l, l' = e, \mu$ and $l = l'$ or $l \neq l'$
  - NA48/2 large data sample

- Test of **Ch**iral **P**erturbation **T**heory at $O(p^4)$

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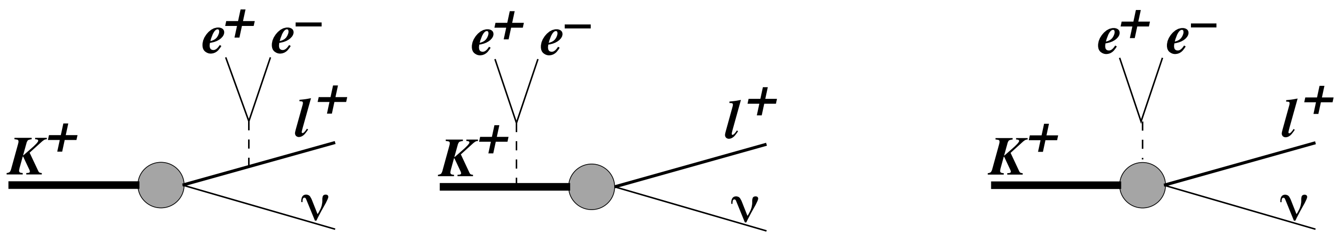
- Test of **Ch**iral **P**erturbation **T**heory at $O(p^4)$
  - Effective chiral Lagrangian: $\mathcal{L}_2 + \mathcal{L}_4 + \mathcal{L}_{anomaly}$
  - Unambiguous predictions
    - Known low energy constants of chiral expansion

- Theory guide of the NA48/2 study of $K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} e^{+}e^{-}$
  - Bijnens et al. (1993), Nucl.Phys., B396:81-118
    - Implemented in NA48/2 Monte-Carlo simulation program

Theory Predictions for $K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} e^{+}e^{-}$

- Inner Bremsstrahlung (**IB**), Structure Dependent (**SD**) and their interference (**INT**) terms in the decay amplitude



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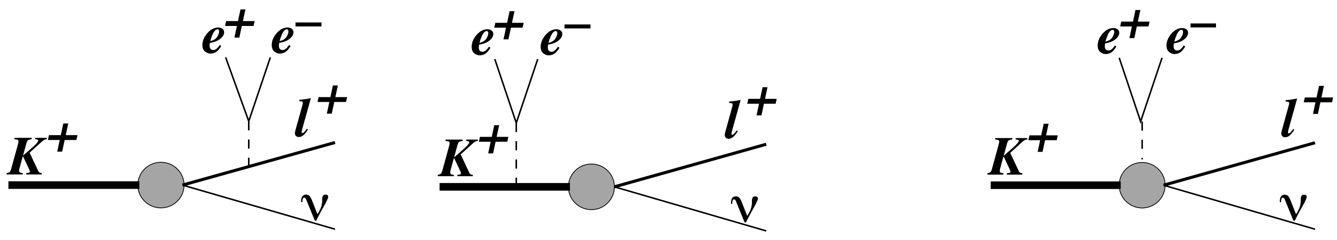

	IB	IB+SD+INT
Full phase space	2.49×10^{-5}	2.49×10^{-5}
$z \geq (140\mathrm{MeV}/M_K)^2$	**4.98×10^{-8}**	**8.51×10^{-8}**

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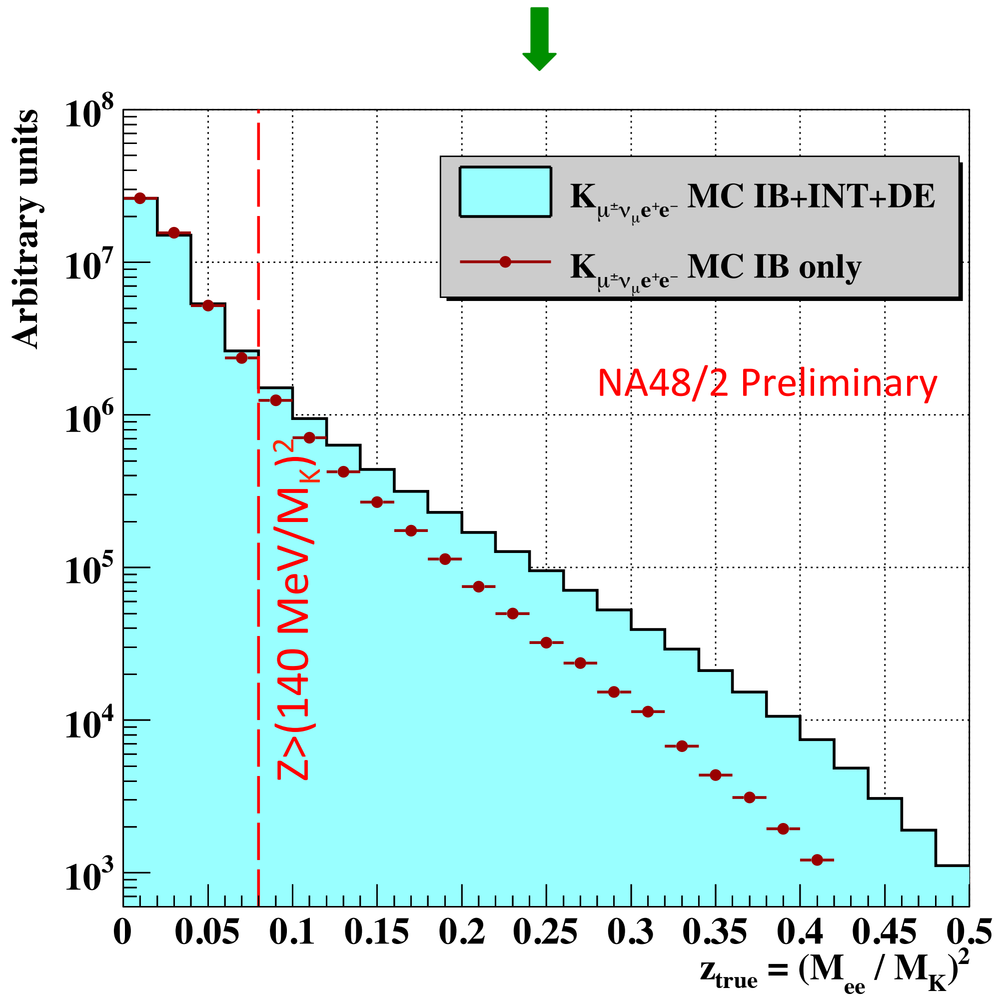
$z = (M_{e+e-} / M_K)^2$

- SD + INT (ChPT Form Factors) contribution is ~40% at large z
  - Zero at tree level, arises from next-to-leading order loops

MC Simulation of $K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} e^{+} e^{-}$

- Decay spectrum as a function of $z=(M_{e+e-}/M_K)^2$
  - MC generator level – no selection criteria applied



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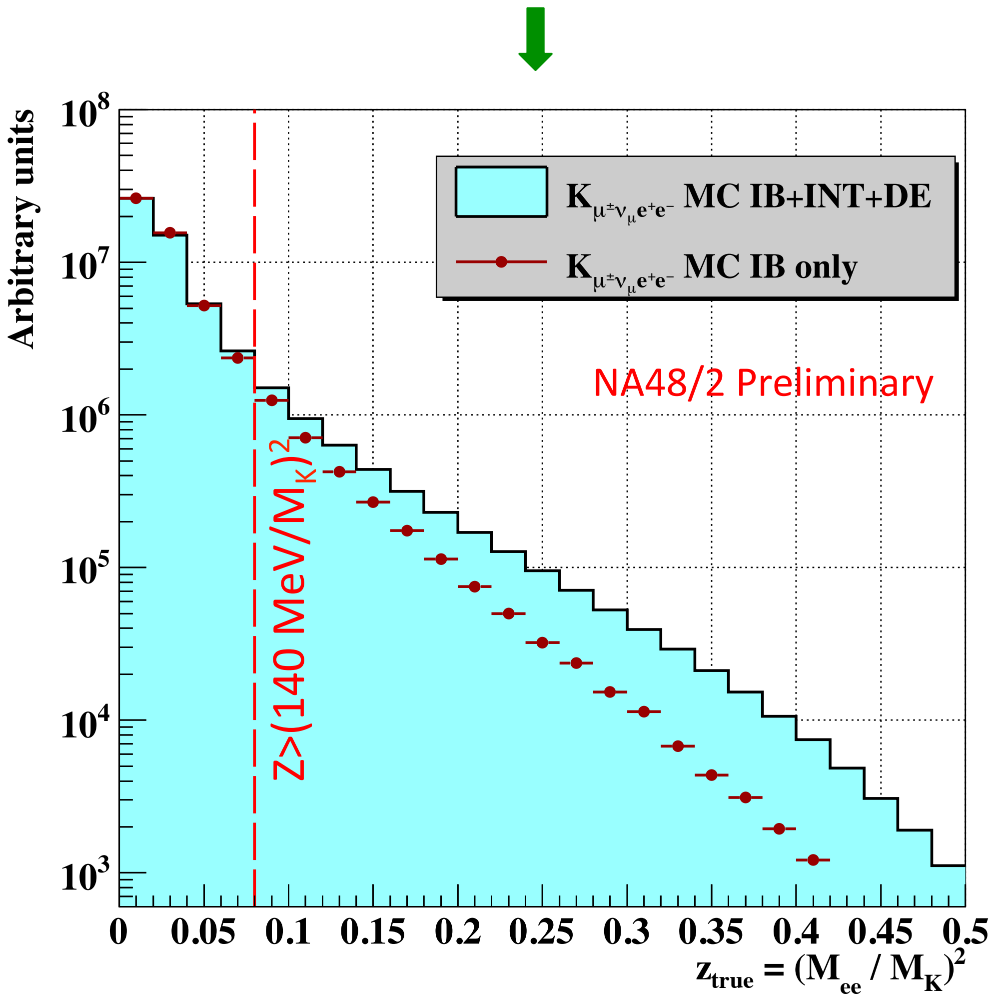


- z - most sensitive variable to ChPT FF contribution

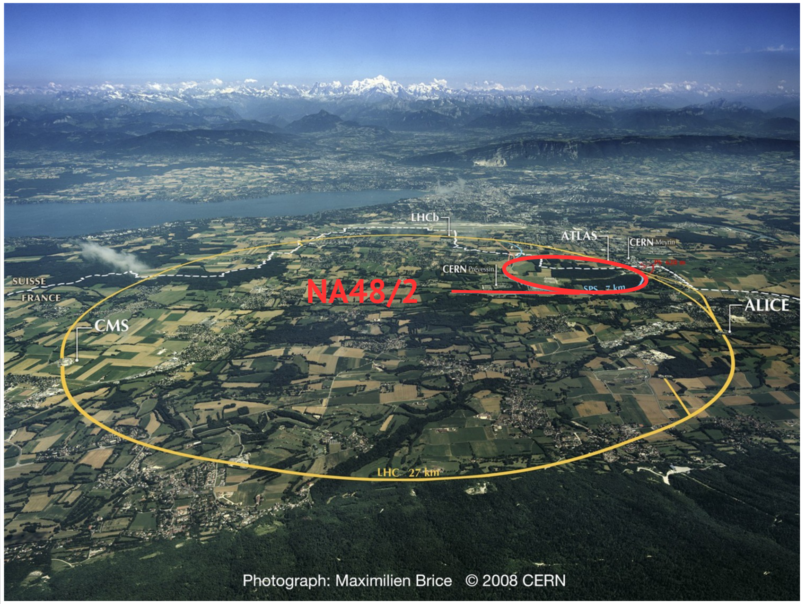
- Region clean of Dalitz decays $\pi^0 \rightarrow e^+e^-\gamma$
  - $M_{e+e-} \geq 140$ MeV/c^2
  - $M_{\pi^\circ} = 135$ MeV/c^2

Decays suppressed by phase space	Total branching fraction
$K^{\pm} \rightarrow \pi^{\pm}\pi^0 (\pi^0 \rightarrow e^+e^-\gamma)$	3.6x10^{-3}
$K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}\pi^0(\pi^0 \rightarrow e^+e^-\gamma)$	5.8x10^{-4}

NA48/2 Experiment

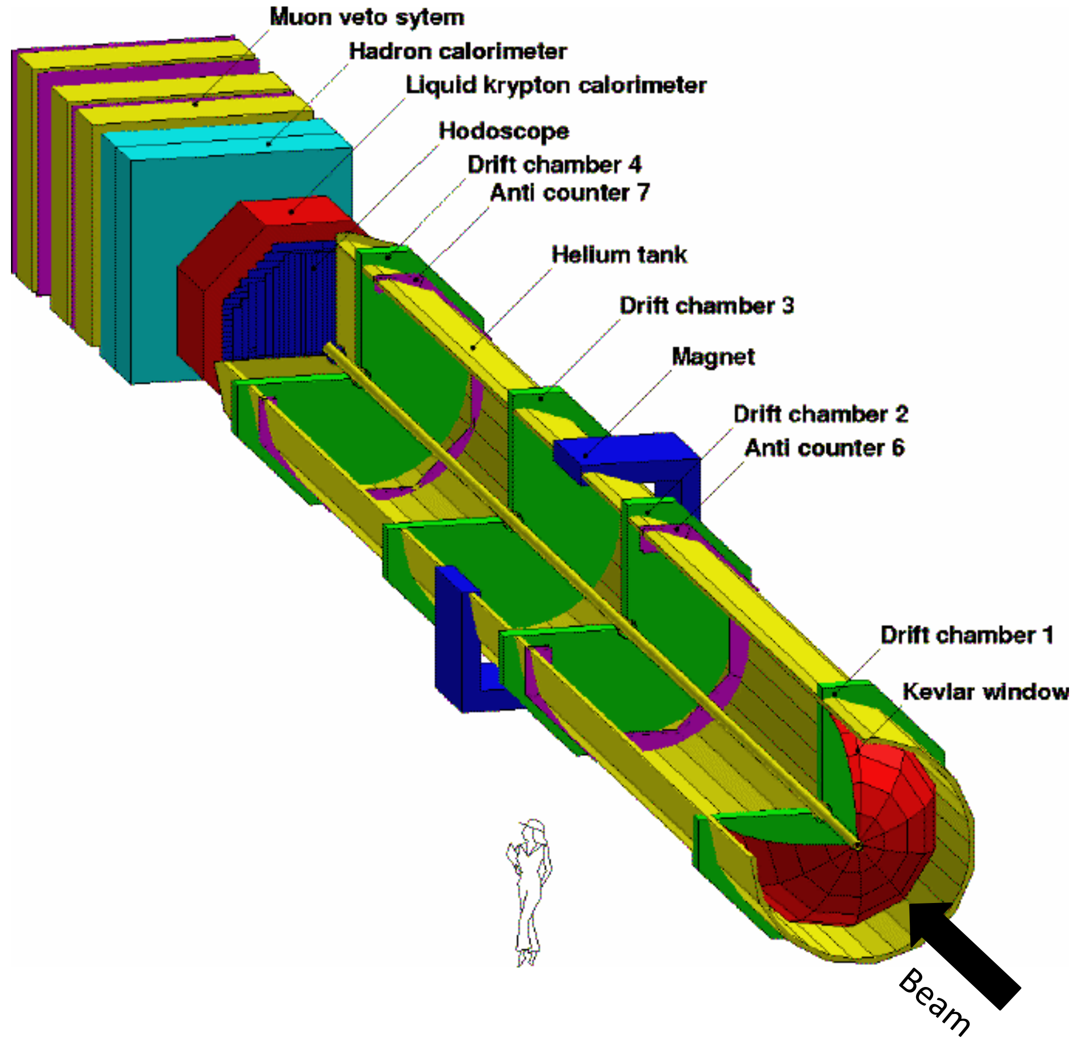
- Fixed-target experiment at CERN North Area
  - 400 GeV/c proton beam from SPS

History of NA48/NA62 experiments		
97–01	NA48(K_S / K_L)	Re ε'/ε Direct CPV
02	NA48/1 (K_S / hyperons)	Rare K_S and hyperon decays
03 – 04	**NA48/2 (K^+ / K^-)**	**Direct CPV search in $K^\pm$**
07–08	NA62-R_K (K^+ / K^-)	$R_K = K^\pm_{e2} / K^\pm_{\mu 2}$
15–	NA62 (K^+)	$K^+ \rightarrow \pi^+ \nu \bar{\nu}$



NA48 Detector and Beam

- Simultaneous $K^{\pm}$ beam
  - p_K=60 GeV/c
  - $\Delta p_K/p_K$=4% (rms)
  - Total $K^{\pm}$ decays: ~10^{11}
  - Main triggers:
    - Three-tracks
    - $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$



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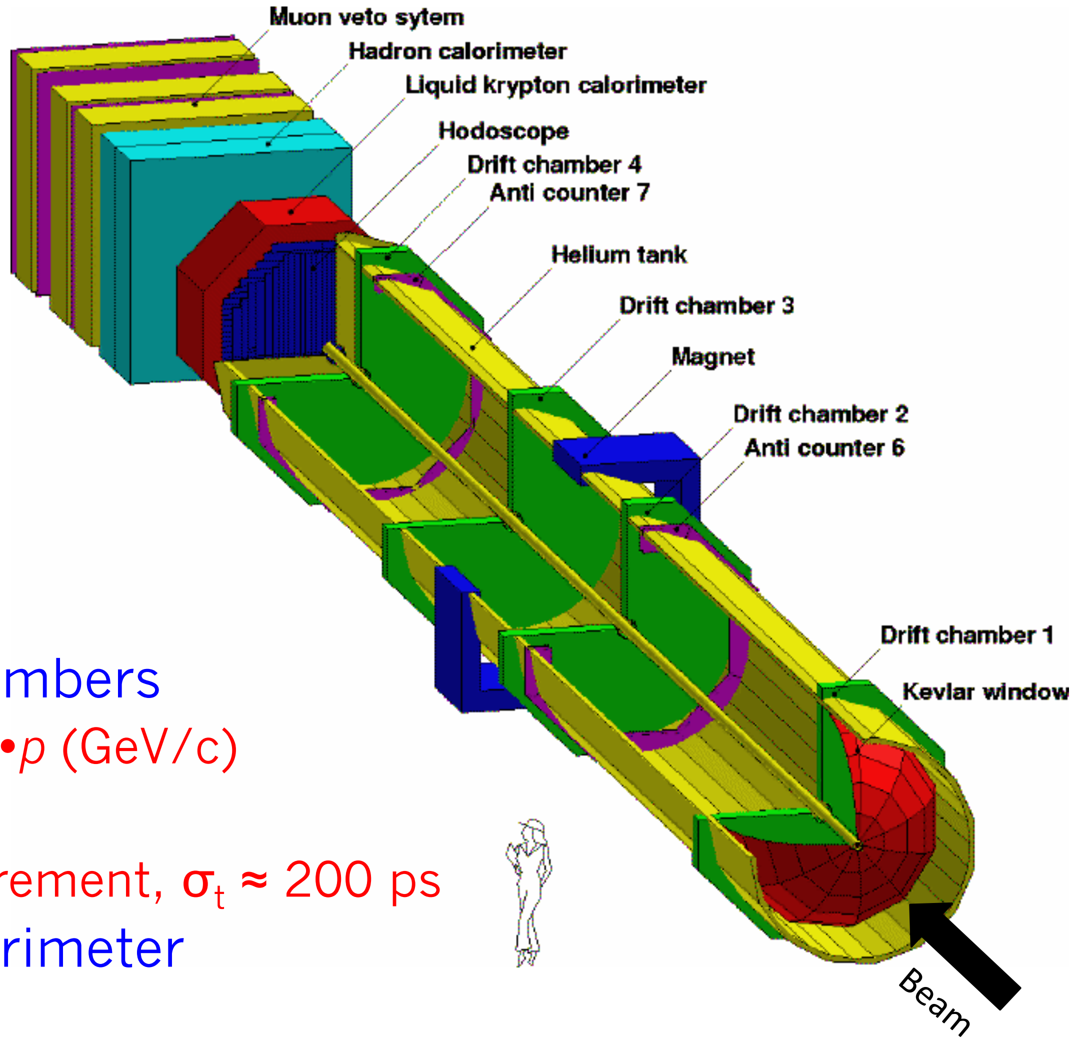
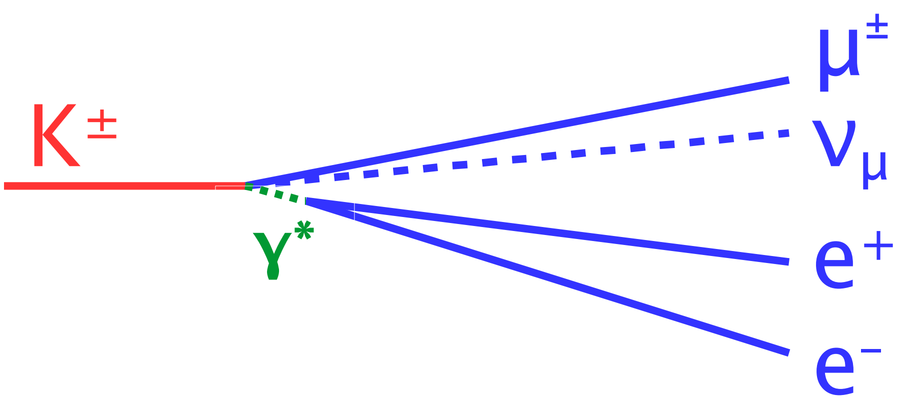


- Major sub-detectors
  - Spectrometer, 4 drift chambers
    - σ_p/p = 1.02% + 0.044%•p (GeV/c)
  - Scintillator hodoscope
    - Fast trigger, time measurement, $\sigma_t \approx$ 200 ps
  - LKr electromagnetic calorimeter
    - σ_E/E = 1.4% @ 10 GeV
    - $\sigma_x = \sigma_y$ = 1.5mm @ 10 GeV

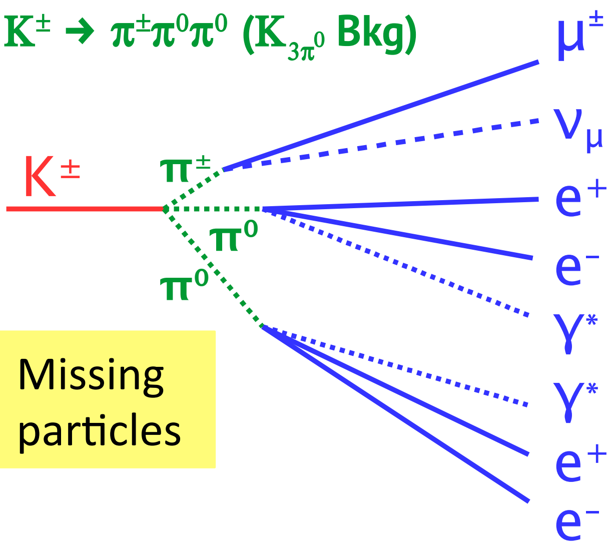
Signal Event Topology



- Experimental signature
  - 3 charged tracks
  - Missing P_T
  - No missing mass
  - Vertex charge |Q|=1
- Signal pre-selection cuts

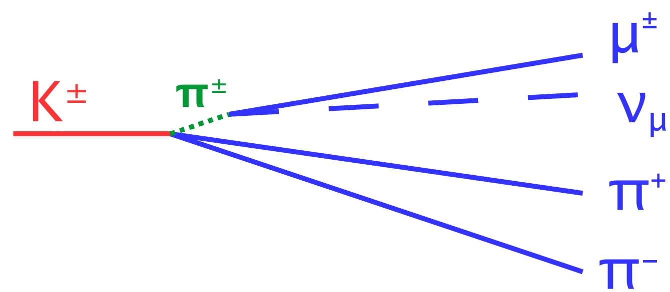
Background Estimation

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ ($K_{3\pi^0}$ Bkg)



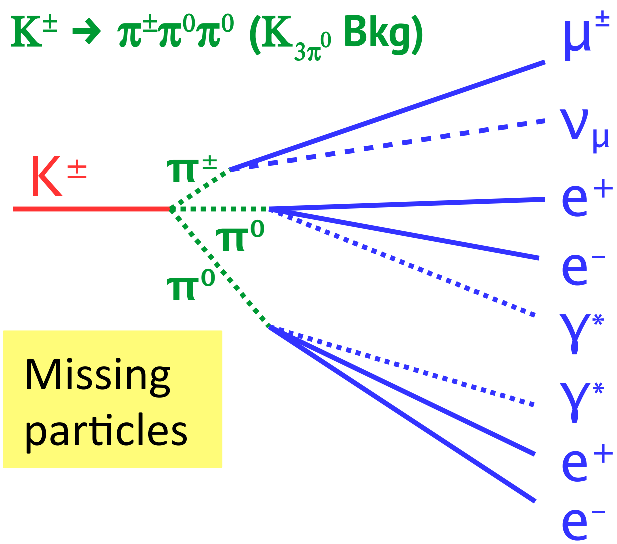
Missing particles

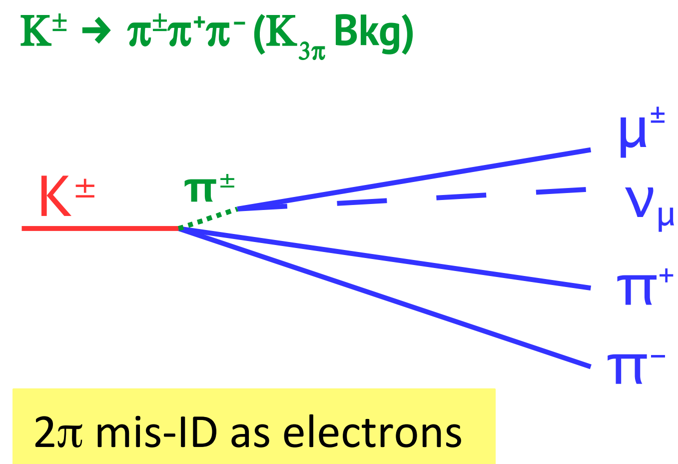
$K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ ($K_{3\pi}$ Bkg)

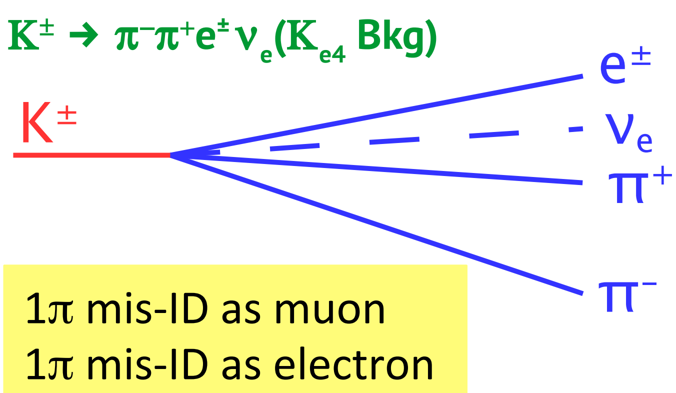


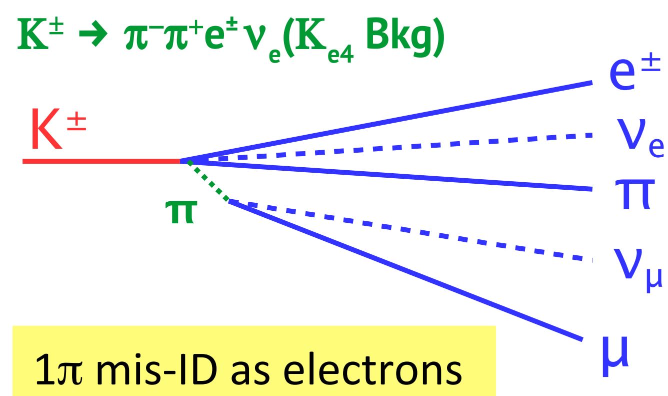
2π mis-ID as electrons

Background Estimation





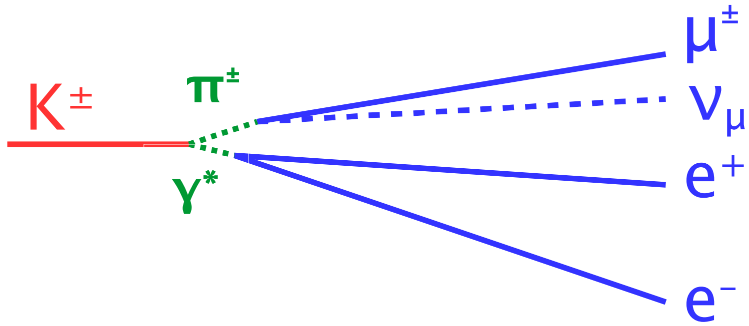




- ❑ Data driven estimate of $K_{3\pi^\circ}$, $K_{3\pi}$ and K_{e4} background
  - ◆ Sideband selection with the same sign electrons, $\mu^+e^-e^-$ or $\mu^-e^+e^+$

Further Background Rejection

$K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}$ ($K_{\pi ee}$ Bkg)



Exact signal signature

- Missing mass
  - $M_{\mu\nu} = \sqrt{(P_K - P_{ee})^2}$
- $M_{\mu\nu}(K^{\pm} \rightarrow \pi^{\pm} e^{+}e^{-})$ peaks at $M_{\pi\pm} = 140\ \text{MeV}/c^2$
- MC study of $M_{\mu\nu}$ resolution at $M_{\pi\pm}$:
  - $\sigma(M_{\mu\nu}) = 10\ \text{MeV}/c^2$

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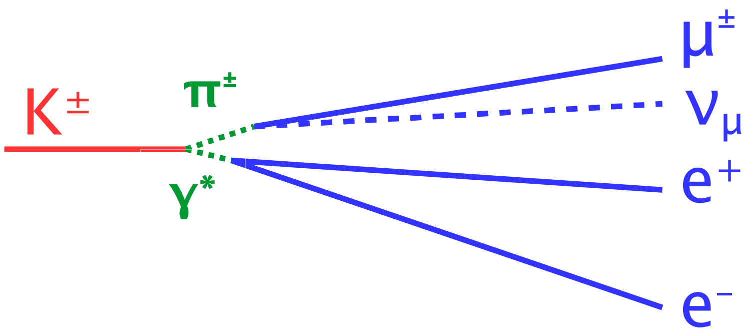

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- MC study of $M_{\mu\nu}$ resolution at $M_{\pi\pm}$:
  - $\sigma(M_{\mu\nu})$ = 10 MeV/c^2

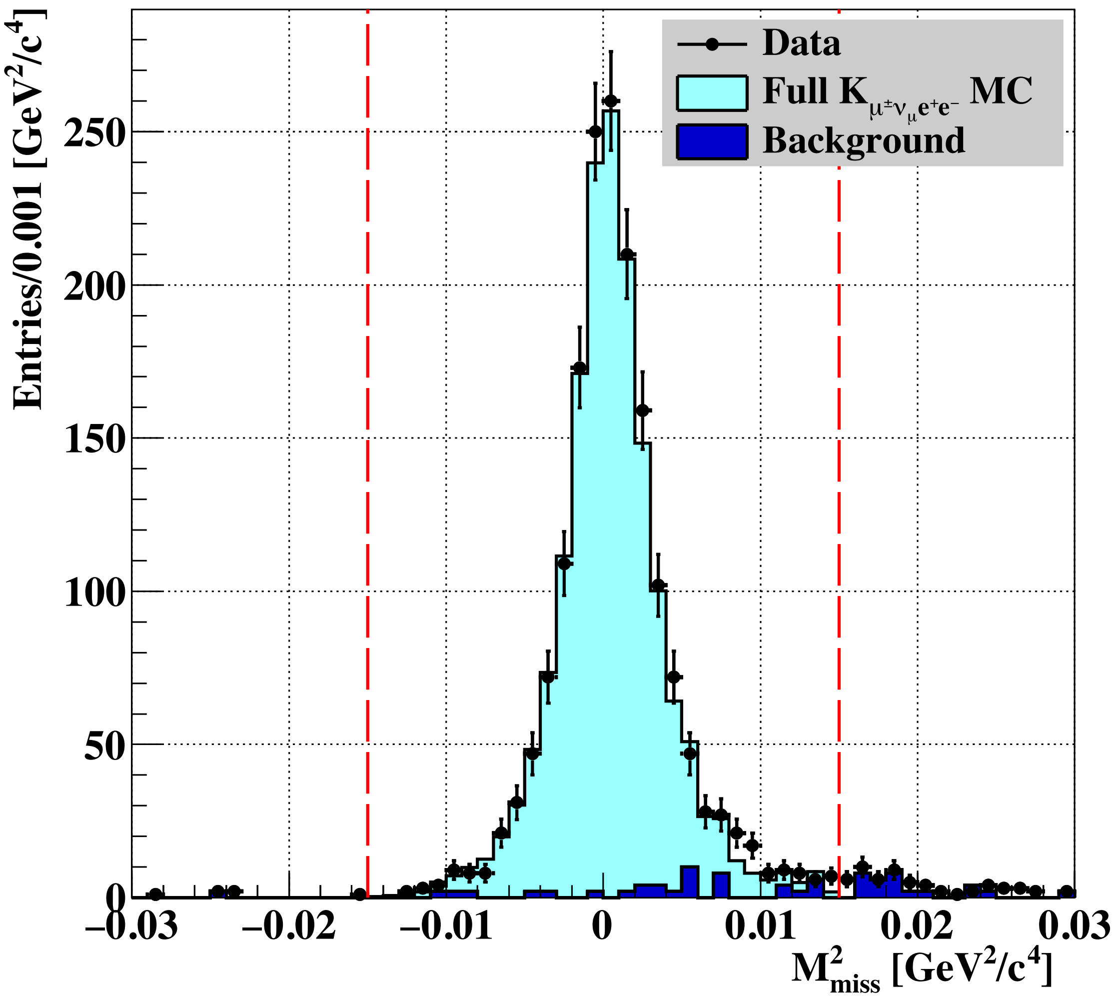
- Selection cut $M_{\mu\nu}$>170 MeV/c^2 ($<M_{\pi\pm}> + 3\sigma(M_{\mu\nu})$)

⬇

- Effect:
  - Signal acceptance reduced by 11%
  - Complete rejection of $K^{\pm} \rightarrow \pi^{\pm} e^{+}e^{-}$ background (was ~10%)

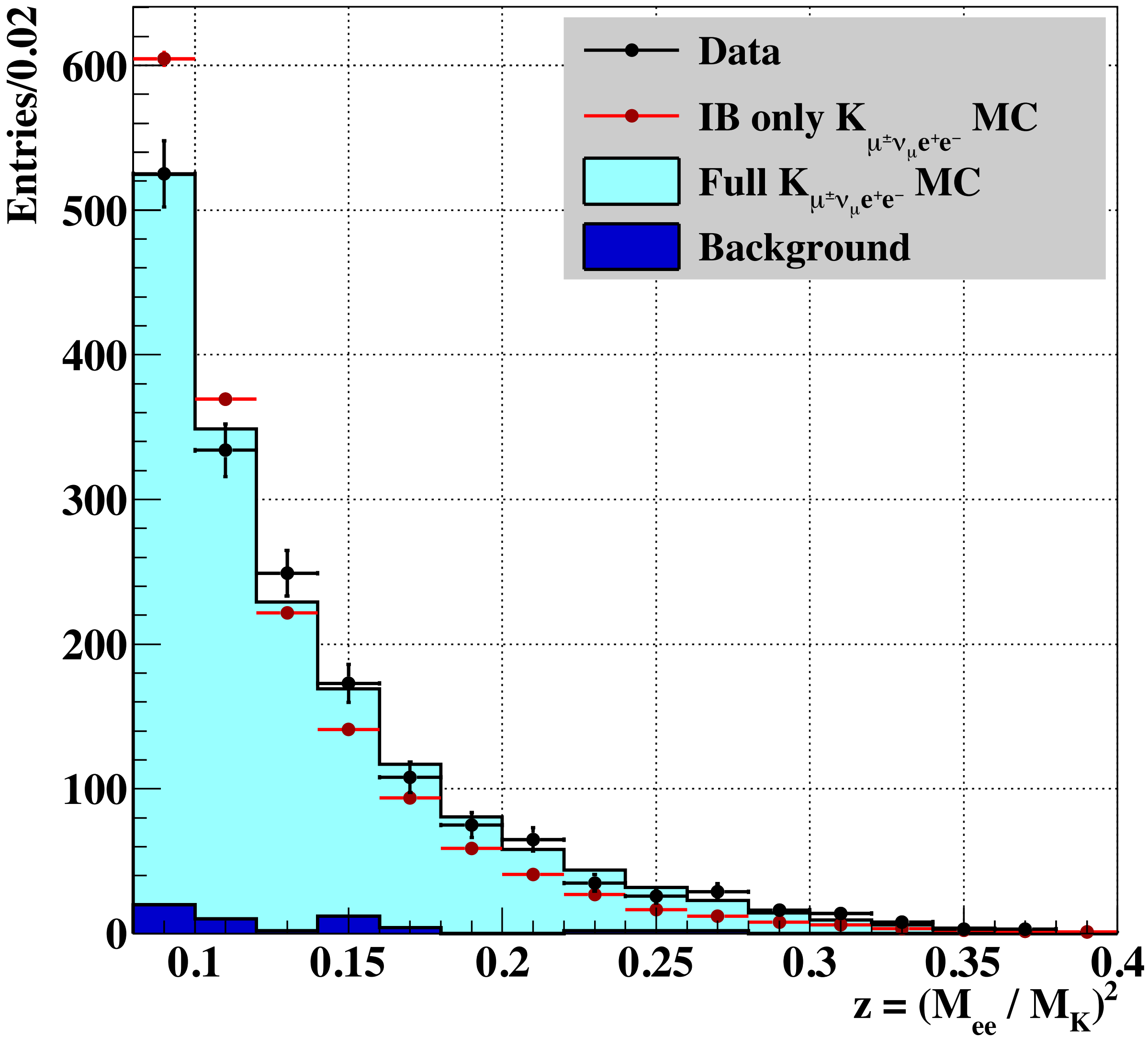
Final Selection of Signal Events

- Cut on Missing Squared Mass
  - $M^2_{miss} = (P_K - P_{\mu ee})^2$
- **1663** data events selected
- Estimation of background contamination: 3%
  - Data driven



- Signal acceptance: 12-14% depending on z

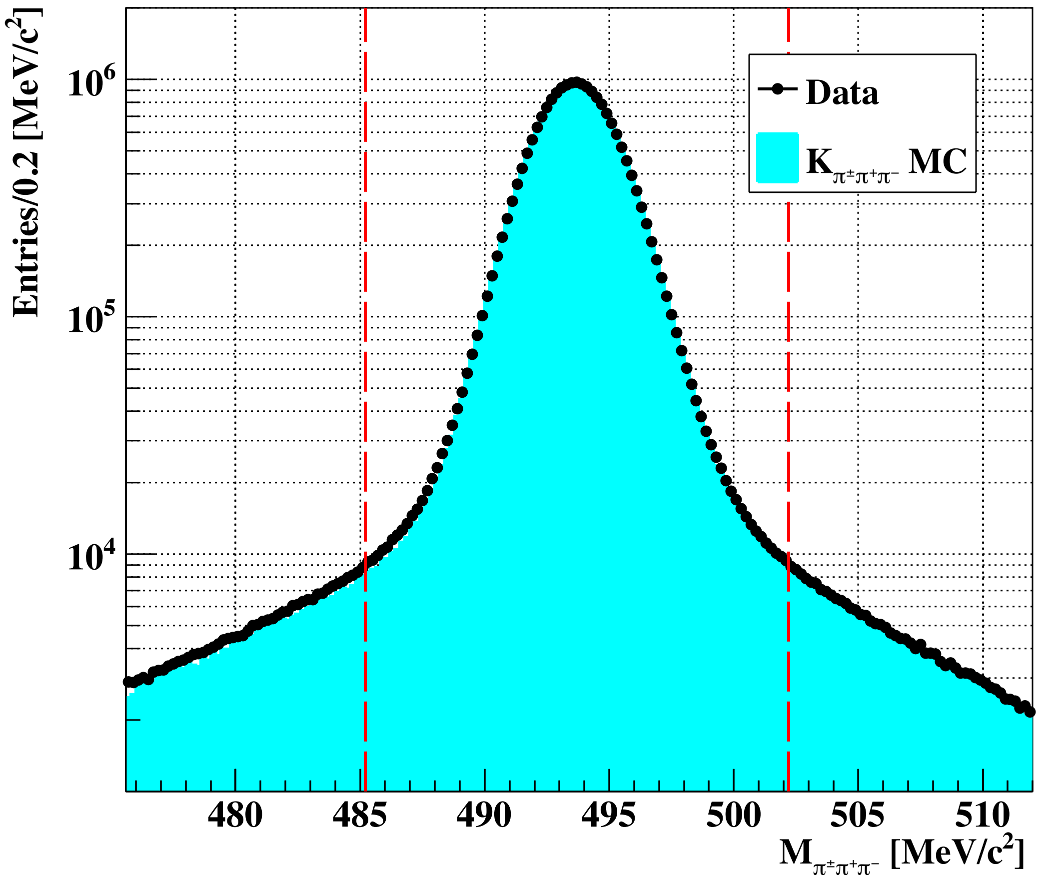
Comparison with ChPT MC Results in Z



- Pure **IB** not matching to the observed z-distribution shape
- **IB+SD+INT** fitting data very well
- Measurement of the branching fraction for each bin of the z-distribution

$K^{\pm}$ Flux Measurement for Normalization

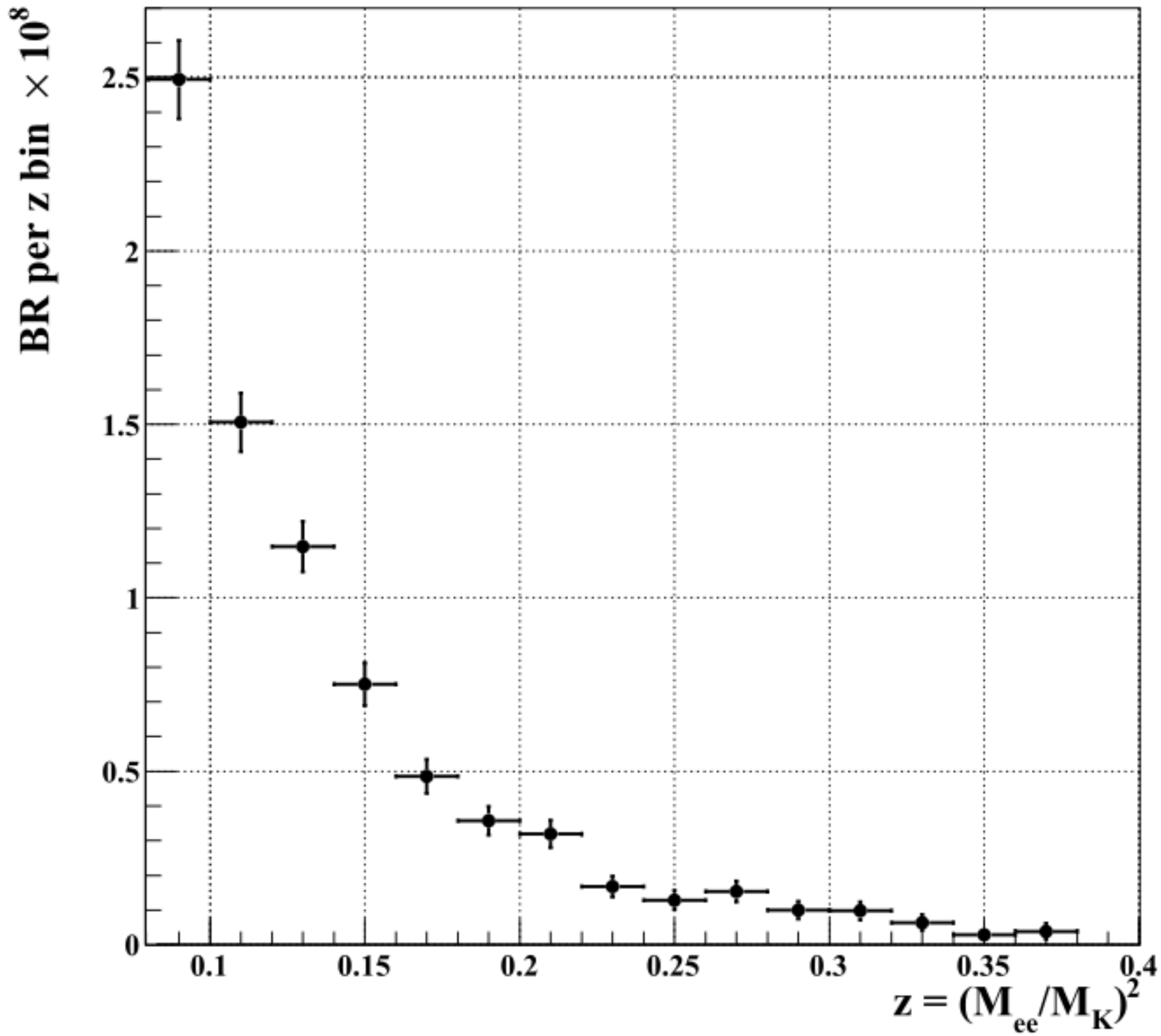
- Normalization channel: $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$
  - Similarities with signal channel, three-tracks
  - Background free selection
  - Large statistics, ~10^9 decays



- $K_{3\pi}$ acceptance = (24.04 ± 0.01)%

- Number of $K^{\pm}$ decayed in the fiducial volume
  - $N_{K\pm} = (1.56 \pm 0.01) \times 10^{11}$

Results / BR($K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} e^{+}e^{-}$) vs. Z



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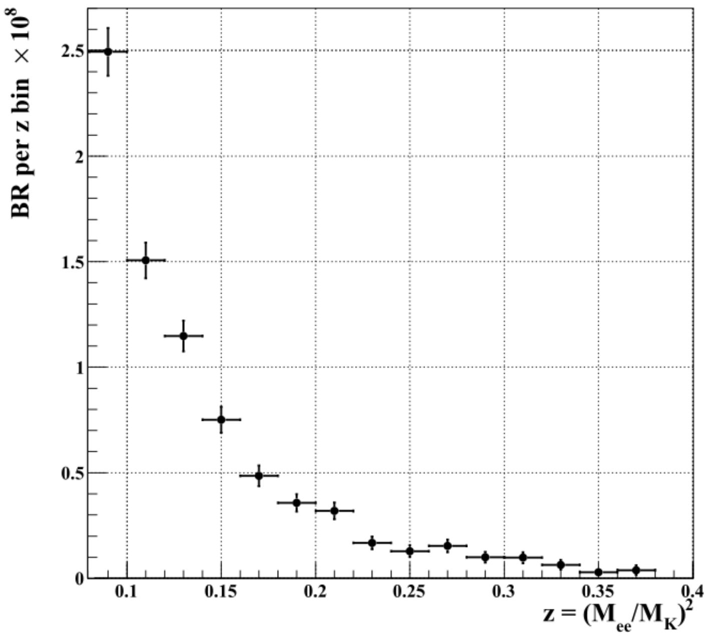
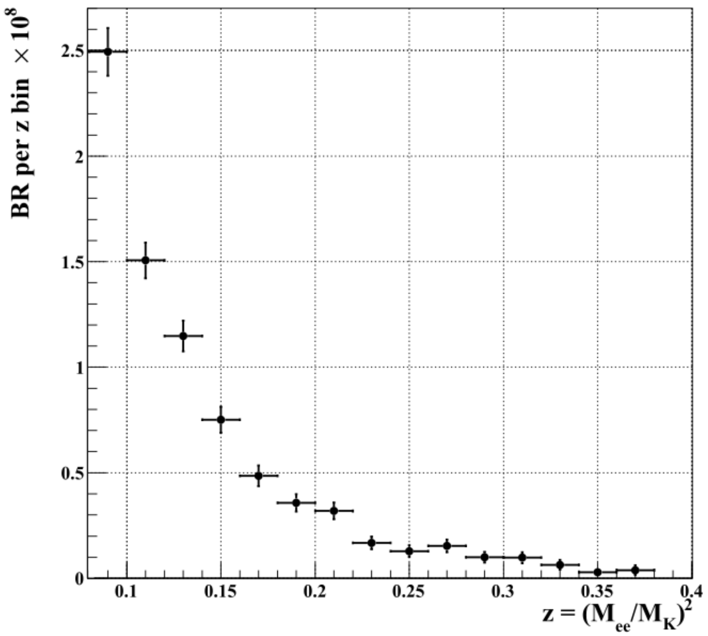


- Final result: sum of individual contributions in each bin
  - Properly accounted bin-by-bin variation of the acceptance
- Measurement dominated by the statistical uncertainty

$$BR(K^{\pm} \to \mu^{\pm}\nu_{\mu}e^{+}e^{-}|M_{ee} \geq 140MeV/c^2) =$$
$$(7.84 \pm 0.21(stat.) \pm 0.08(syst.) \pm 0.06(ext.)) \times 10^{-8}$$

Results



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- Previous measurements

BR $(z \geq (140MeV/M_K)^2) = (12.3 \pm 3.2)x10^{-8}$ (Diamant-Berger et.al. `76)

BR $(z \geq (145MeV/M_K)^2) = (7.06 \pm 0.31)x10^{-8}$ (Poblaguev et.al. `02)

Error Budget

$$BR(K^{\pm} \to \mu^{\pm}\nu_{\mu}e^{+}e^{-}|M_{ee} \geq 140MeV/c^2) =$$
$$(7.84 \pm 0.21(stat.) \pm 0.08(syst.) \pm 0.06(ext.)) \times 10^{-8}$$

- Main sources of the systematic uncertainty
  - BR($K_{3\pi}$)
  - Radiative corrections
  - Limited statistics of data driven background
  - Trigger efficiency

Uncertainty type	δBR/BR[x10^2]
Data statistics	2.54
Normalization channel statistics	0.02
Total statistical	**2.54**
Rad. corr.	0.70
Background statistics	0.62
Trigger efficiency	0.54
Background systematic	0.30
Muon ID efficiency	0.13
Acc signal statistics	0.12
Electron ID uncertainty	0.04
Acc normalization statistics	0.03
Total systematic	**1.15**
External uncertainty (Br $K_{3\pi}$)	**0.72**
Total uncertainty	**2.88**

Summary

- Model independent measurement of the radiative semileptonic decay $K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} e^{+}e^{-}$ using NA48/2 data:
  - $BR_{exp}(K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} e^{+}e^{-} \mid z \geq (140\ MeV/M_K)^2) =$ **$(7.84 \pm 0.23) \times 10^{-8}$**
- Factor of 3 improved systematic uncertainty wrt to the previous measurements
- Factor of 1.5 improved total uncertainty
  - Dominated by the statistical uncertainty
- Measurement in good agreement with predictions of Chiral Perturbation Theory at the next-to-leading order
  - $BR_{theory}(K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} e^{+}e^{-} \mid z \geq (140\ MeV/M_K)^2) =$ **8.51×10^{-8}**