Precision Measurements of Charged Kaon Decays with the NA48/2-NA62 Experiments

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for the **NA48/2-NA62** Collaborations:

Birmingham, Bratislava, Bristol, Cambridge, CERN, Chicago, Dubna, Edinburgh, Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain-La-Neuve, Mainz, Menlo Park, Merced, Moscow, Naples, Northwestern, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, Saclay, Sofia, San Luis Potosi, Siegen, Torino, Vienna

CERN

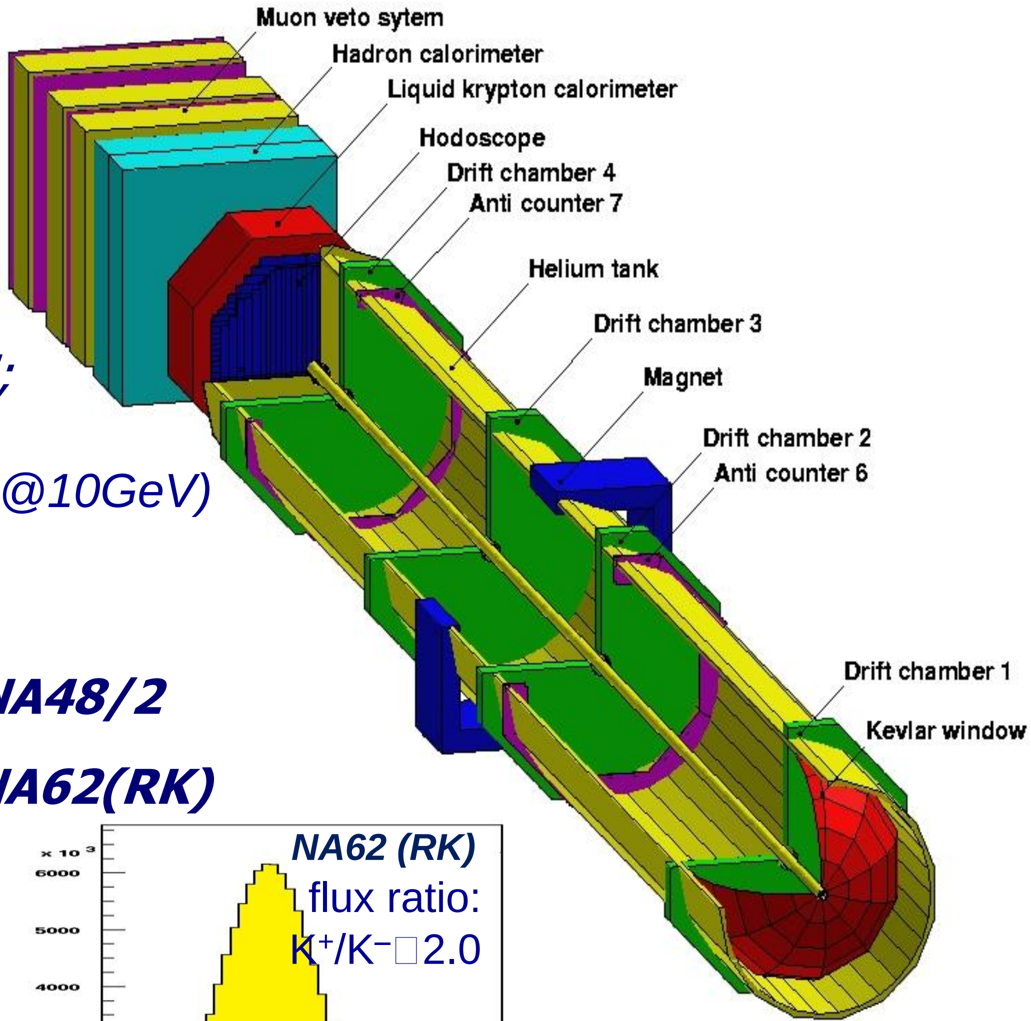
Content

- **The NA48 detector**
- $\mathbf{R_K} = K_{e2}/K_{\mu 2}$ - ***NA62*** *(RK)*
- $\mathbf{K}^{\pm} \longrightarrow \pi^{\pm}\gamma\,\gamma$ - *min bias data of* ***NA48/2*** *(2004),* ***NA62*** *(RK, 2007)*
- $\mathbf{K}^{\pm} \longrightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ - ***first observation****,* ***NA48/2*** *(2003-2004)*
- $\mathbf{K}^{\pm} \longrightarrow e^{\pm}\nu\gamma$ - *min bias data of* ***NA62*** *(RK, 2007)*
- $\mathbf{K}^{\pm} \longrightarrow \pi^{\pm}\nu\nu$ – ***NA62***
- **Summary**

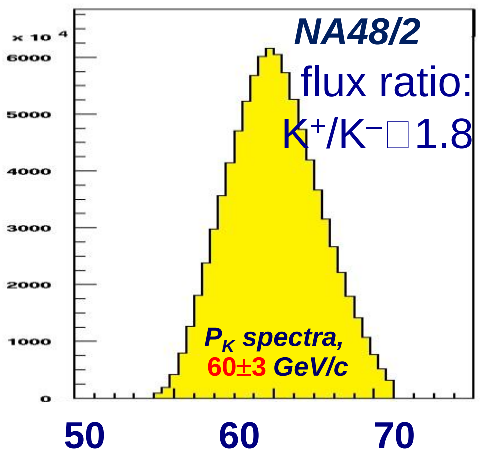
The NA48/2 - NA62(RK) detector

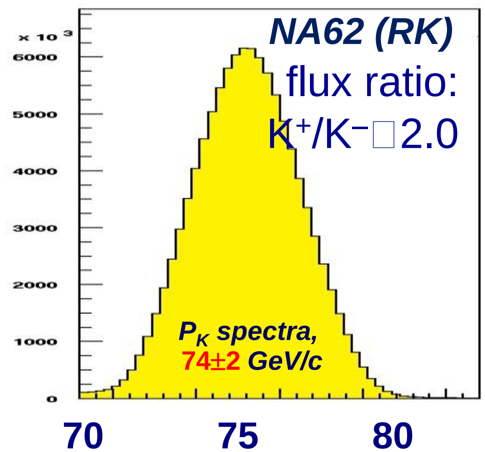
Main detector components:

- **Hodoscope**
  fast trigger (150ps).
- **Liquid Krypton EM cal. (LKr):**
  high granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} + 9\%/E + 0.42\%$ *[GeV];*
  $\sigma_x = \sigma_y = 4.2/E^{1/2} + 0.6$ *mm*
  (E in Gev, 1.5mm@10GeV)
- **Magnetic spectrometer:**
  4 DCHs (4 views each)
  $\Delta p/p = 1.0\% + 0.044\% * p$ *[GeV/c]* - ***NA48/2***
  $\Delta p/p = 0.48\% + 0.009\% * p$ *[GeV/c]* - ***NA62(RK)***



- **Hadron cal.**
- **Muon veto**
- **Photon vetoes**

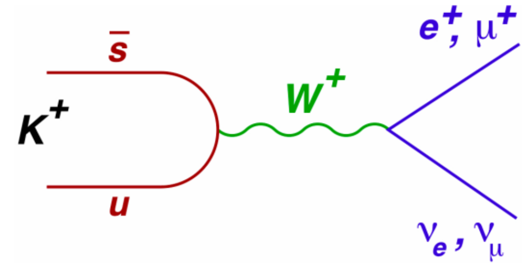




$K^{\pm}$ beams

2-3M K/spill ($\pi/K \sim 10$), π decay products stay in pipe;

$$R_K = K_{e2}/K_{\mu 2}$$



SM: $R_K^{SM} = \Gamma(K^\pm \to e^\pm \nu) / \Gamma(K^\pm \to \mu^\pm \nu)$

$$= (m_e^2/m_\mu^2) \times (m_K^2 - m_e^2)^2/(m_K^2 - m_\mu^2)^2 \times (1+\delta R_K^{rad})$$

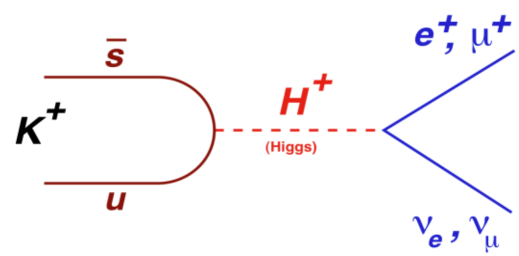
$$= (2.477 \pm 0.001) \times 10^{-5}$$

[Cirigliano, Rosell, PRL 99 (2007) 231801]

- **hadronic uncertainties cancel in the ratio**
- **excellent test of SM** (μ-e universality)

beyond SM:

*2HDM → presence of extra charged Higgs introduces **LFV** at one-loop level*

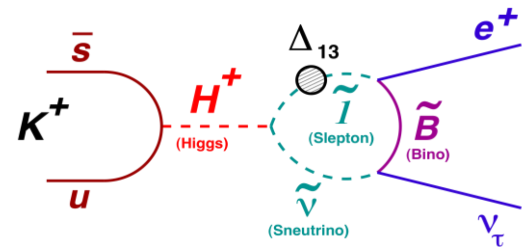


$$R_K^{LFV} = R_K^{SM} [1 + (m_K/m_{H^\pm})^4) \times (m_\tau / m_e)^2 |\Delta_{13}|^2) \times \tan^6\beta]$$

[Masiero, Paradisi, Petronzio, PRD 74 (2006) 011701 ; JHEP 0811 (2008) 042]

MSSM: *1% effect*

[Girrbach, Nierste, arXiv: 1202.4906]



$$R_K = K_{e2}/K_{\mu 2}$$

NA62*(RK): the measurement is based on ~* **150 000** *reconstructed* $K^{\pm} \rightarrow e^{\pm} \nu$ (K_{e2}) *decays*

(helicity suppressed)

the measured parameters:

$$R_K = (1/D) \times [N(K_{e2}) - N_{bgr}(K_{e2})] / [N(K_{\mu 2}) - N_{bgr}(K_{\mu 2})]$$

$$\times [A(K_{\mu 2}) \times id(e) \times tr(K_{e2})] / [A(K_{e2}) \times id(\mu) \times tr(K_{\mu 2})] \times (1//\varepsilon_{LKr})$$

- **D=150** – *downscaling factor for* $(K_{\mu 2})$ *trigger*
- **N** – *number of selected events*
- $\mathbf{N_{bgr}}$ – *number of background events*
- **A** – *acceptances (MC)*
- **id** – *particle (e,* μ*) identification efficiencies*
- **tr** – *trigger efficiencies*
- ε_{LKr} = *(0,9980±0,0003) - LKr global readout efficiency*

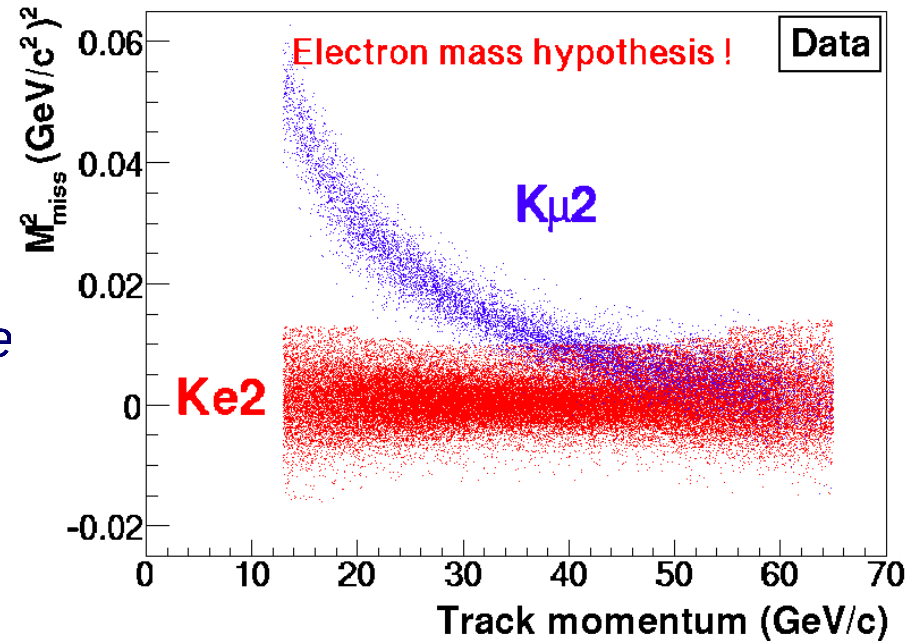
K_{e2} and $K_{\mu 2}$ selection

Kinematic separation:

missing mass: $M^2_{miss} = (p_K - p_l)^2$

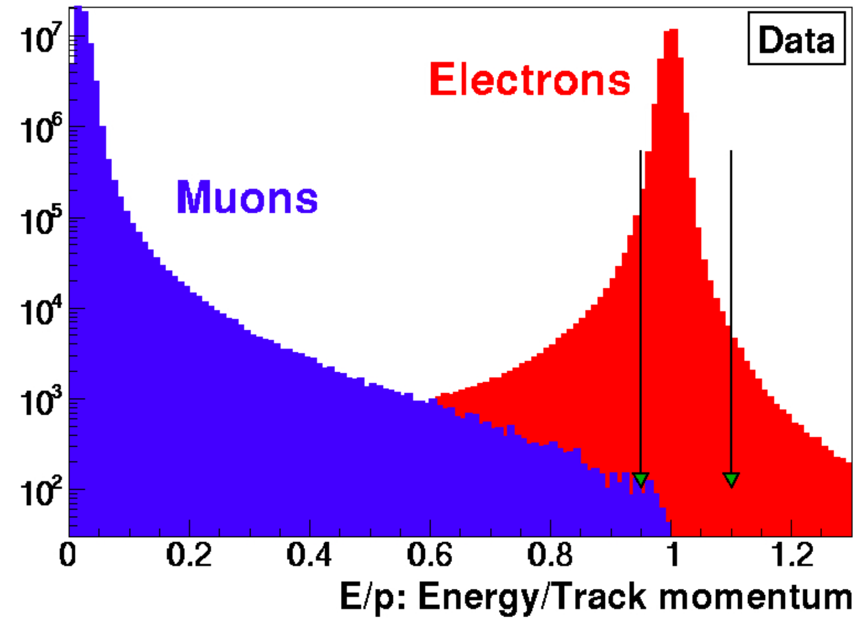
P_K: average monitored from $K3\pi$ decays as a function of time

good separation at $p_{track} < 30$ GeV/c



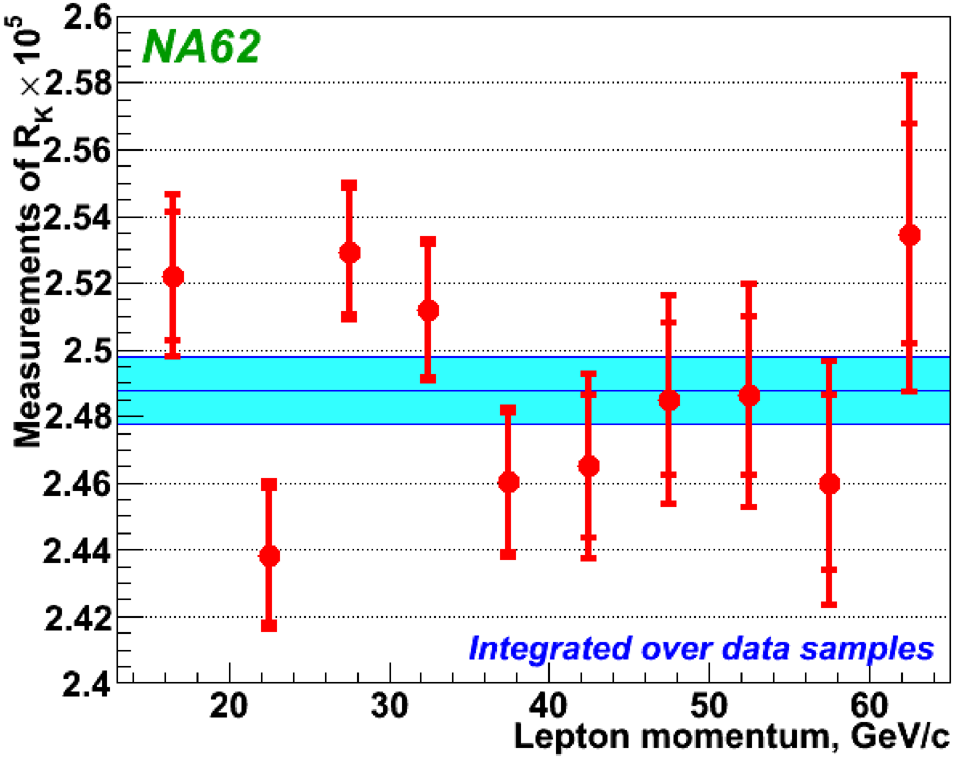
Lepton identication:

- E/p = LKr energy deposition / p_{track}
  - $0.95 < E/p < 1.1$ for electrons
  - $E/p < 0.85$ for muons
- μ suppression in the e sample ~ 10^6



$$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^5$$
$$= (2.488 \pm 0.010) \times 10^5$$

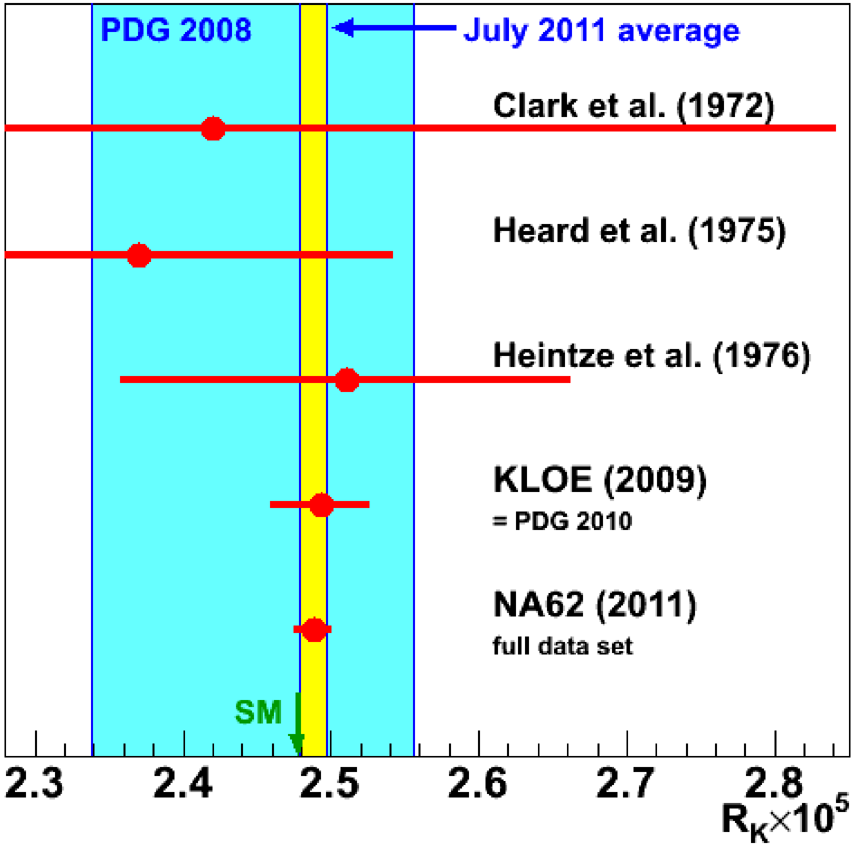
averaged over 10 momentum bins

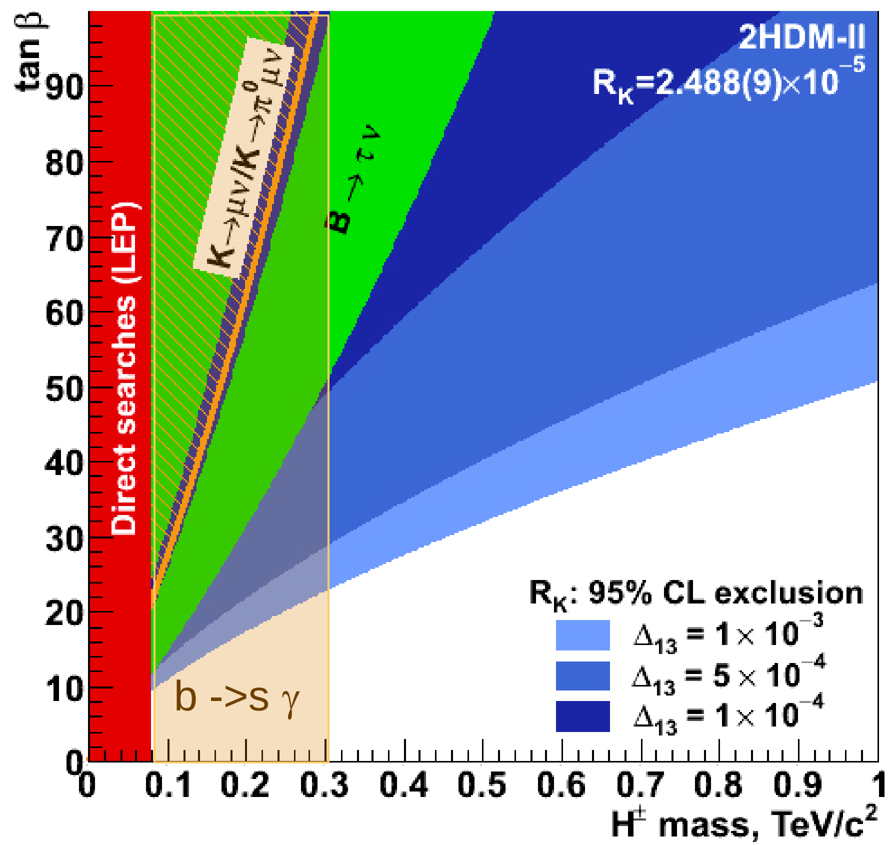


systematic uncertainties

source	$\delta R_K \times 10^5$
$K_{\mu 2}$ background	0.004
$K^{\pm} \rightarrow e^{\pm} \nu \gamma$ (SD+)	0.002
K_{e3}, $K_{2\pi}$	0.003
beam halo background	0.002
Matter composition	0.003
Acceptance correction	0.002
DCH alignment	0.001
Electron identification	0.001
1TRK trigger efficiency	0.001
LKR readout efficiency	0.001
total	**0.007**

R_K world average & limits for 2HDM





	$R_K \times 10^5$	*precision*
PDG 2008	2.447 ± 0.109	4.5 %
PDG 2010	2.493 ± 0.031	1.3 %
now	2.488 ± 0.009	0.4 %
SM	2.477 ± 0.001	0.04 %

$K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$

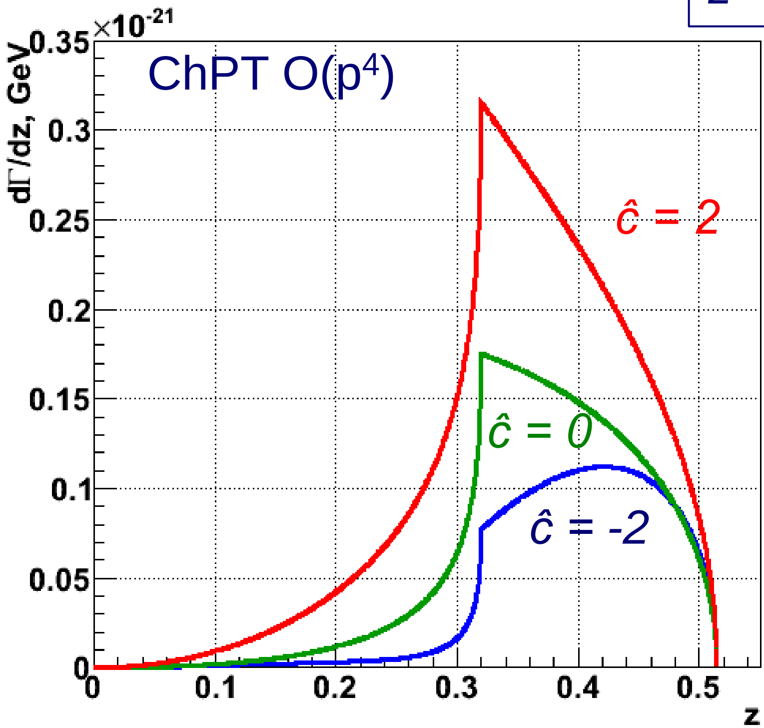
minimum bias data samples:

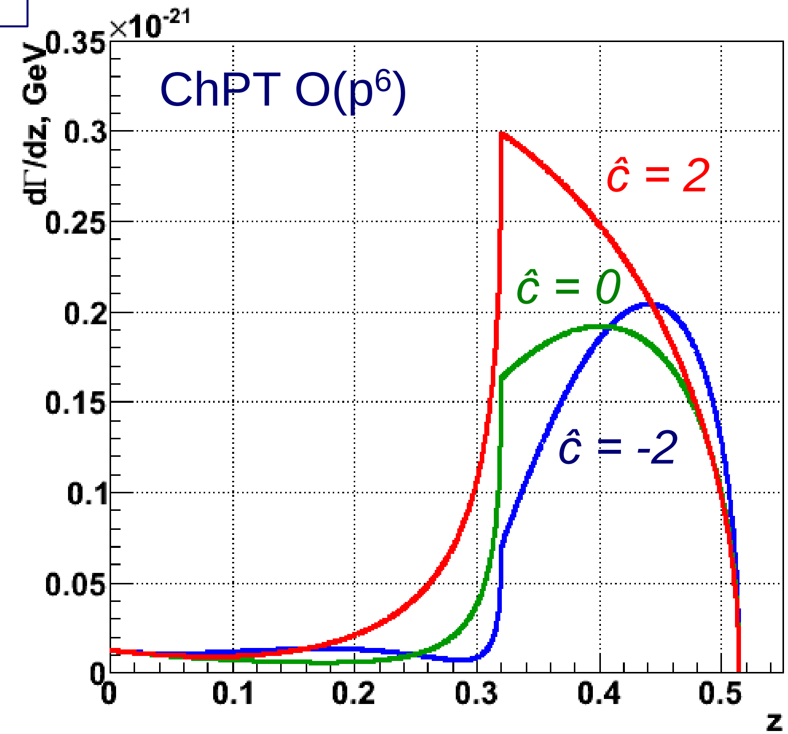
NA48/2 *(2004) &* **NA62** *(RK, 2007)*

$K^\pm \to \pi^\pm \gamma \gamma$: ChPT description

rate & spectrum depend on a single unknown O(1) parameter $\hat{c}$

$z = (m_{\gamma\gamma}/m_K)^2$





$O(p^4)$ *Loop diagrams:*

cusp at $2m_\pi$ threshold: $z = 0.32$

[Ecker, Pich, de Rafael, NPB303 (1988) 665)]

$O(p^6)$ *'Unitarity corrections'*

increase BR at low $\hat{c}$

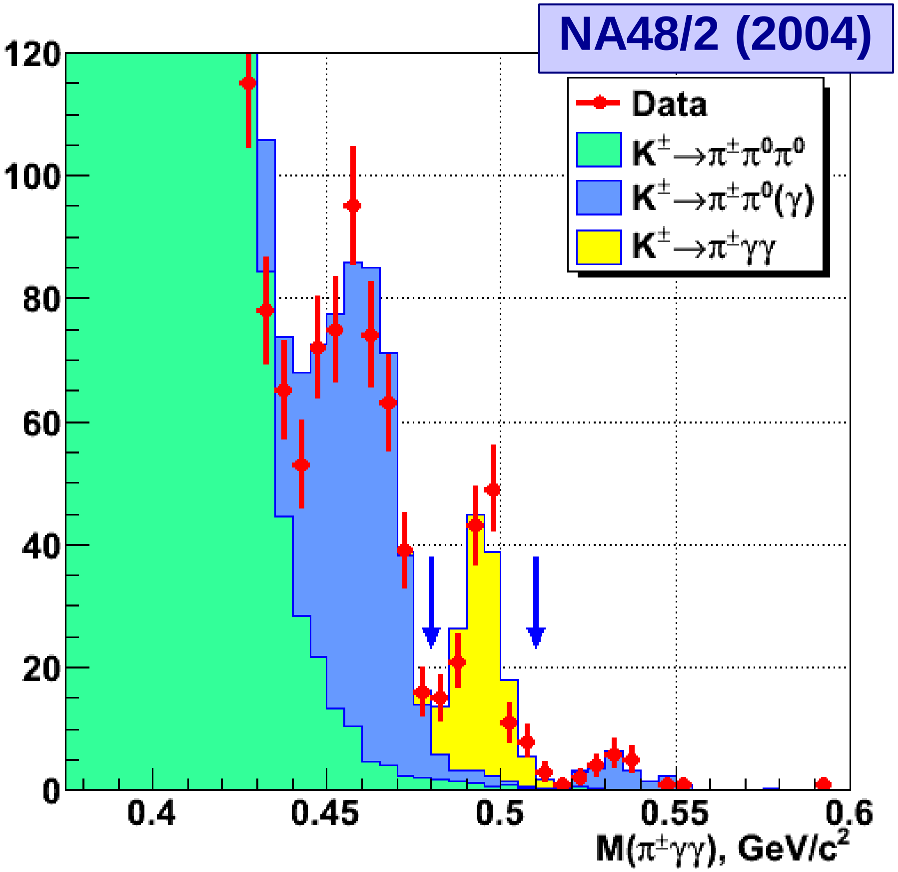
& result in a non-zero rate at $m_{\gamma\gamma} \to 0$

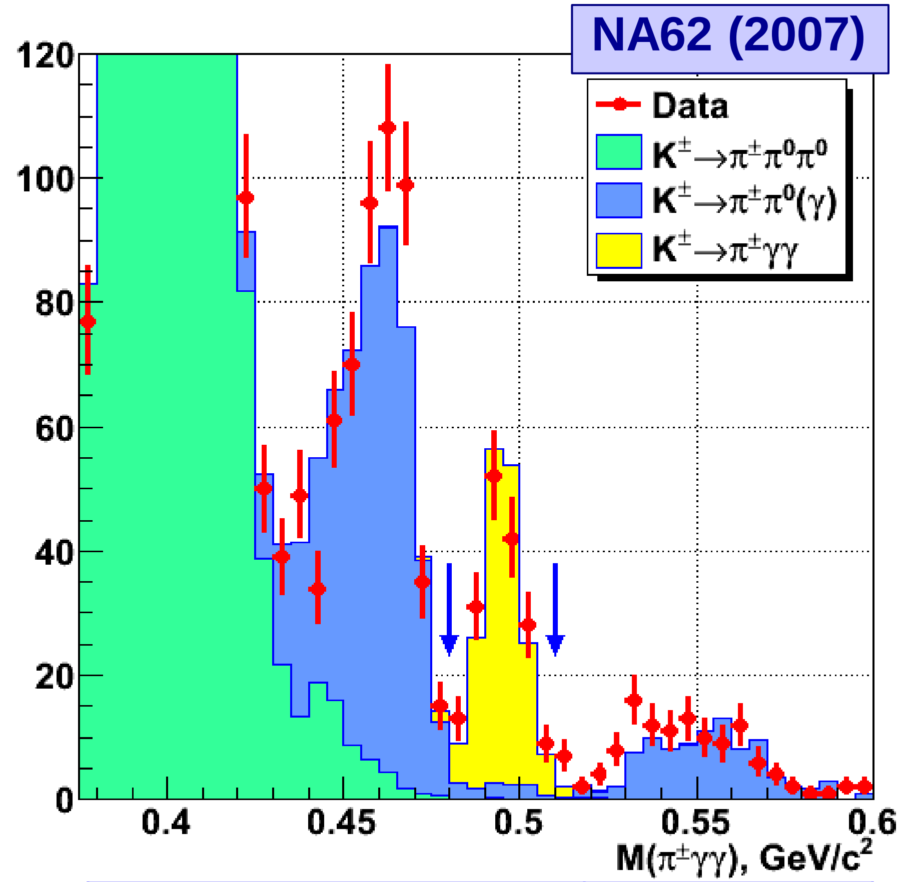
[D'Ambrosio, Portoles, PLB386(1996)403)]

BNL E787: *31 candidates with 5 bkg. events; BR = $(1.10 \pm 0.32) \times 10^{-6}$*

[PRL79 (1997) 4079)]

$K^{\pm} \to \pi^{\pm} \gamma \gamma$: the signal versus the background

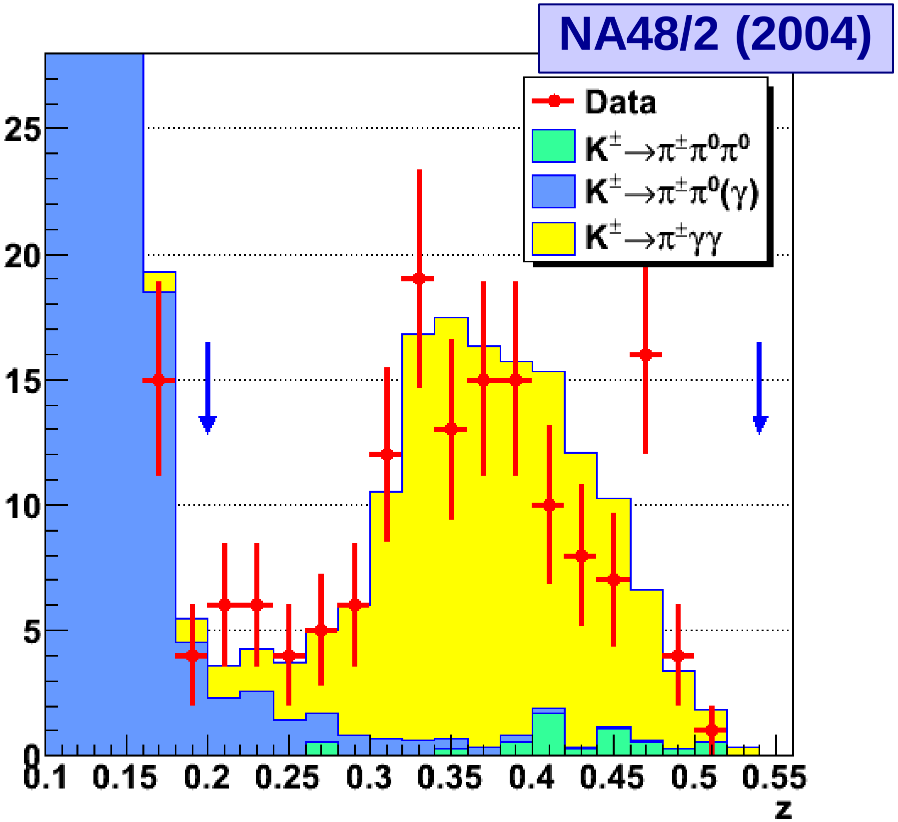


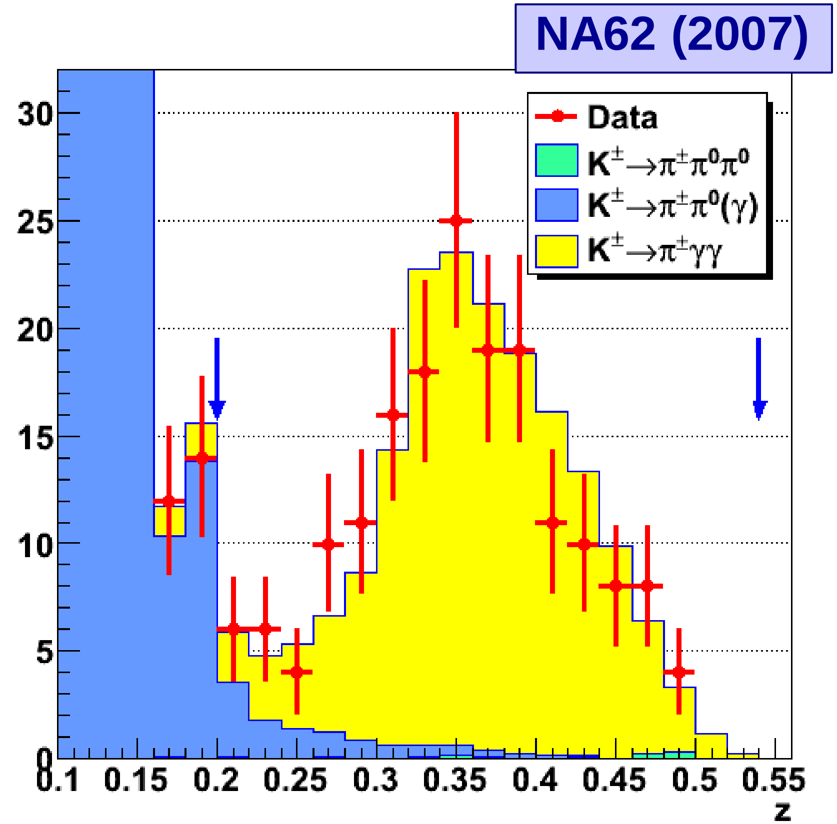


$K^{\pm} \to \pi^{\pm}\gamma\gamma$ candidates	147
$K^{\pm} \to \pi^{\pm}\pi^{0}(\gamma)$ backgr	11.0 ± 0.8
$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ backgr	5.9 ± 0.7
$K^{\pm} \to \pi^{\pm}\gamma\gamma$ signal	**130 ± 12**

$K^{\pm} \to \pi^{\pm}\gamma\gamma$ candidates	175
$K^{\pm} \to \pi^{\pm}\pi^{0}(\gamma)$ backgr	11.1 ± 1.8
$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ backgr	1.3 ± 0.3
$K^{\pm} \to \pi^{\pm}\gamma\gamma$ signal	**163 ± 13**

$K^\pm \to \pi^\pm \gamma \gamma$: z-spectra ChPT fits





- *visible region is above the* $K^\pm \to \pi^\pm \gamma \gamma$ *peak with* $m_{\gamma\gamma} = m_{\pi 0}$ *:*
  z > 0.2 or $m_{\gamma\gamma}$ *> 220 MeV/c2.*
- *cusp-like behavior at* $2m_\pi$ *is clearly observed*

$K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$ – fit results *(preliminary)*

$\hat{C}$ =	O (p4)	O (p6)
NA48/2 (2004)	$1.36 \pm 0.33_{stat} \pm 0.07_{syst} = 1.36 \pm 0.34$	$1.67 \pm 0.39_{stat} \pm 0.09_{syst} = 1.67 \pm 0.40$
NA62 (2007)	$1.71 \pm 0.29_{stat} \pm 0.06_{syst} = 1.71 \pm 0.30$	$2.21 \pm 0.31_{stat} \pm 0.08_{syst} = 2.21 \pm 0.32$
combined	$1.56 \pm 0.22_{stat} \pm 0.07_{syst} = 1.56 \pm 0.23$	$2.00 \pm 0.24_{stat} \pm 0.09_{syst} = 2.00 \pm 0.26$

ChPT **O(p6) combined BR fit:** **BR = (1.01 ± 0.06)×10^{-6}**

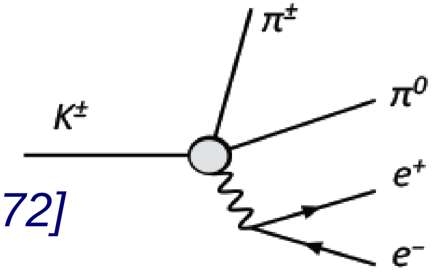
- ***the combined 2004+2007 results contain correlated uncertainties***
- ***PDG (= BNL E787): BR = (1.10 ± 0.32)×10^{-6}***

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

NA48/2 *(2003-2004)*

Preliminary; analysis is in progress

first observation: $K^{\pm} \to \pi^{\pm}\pi^{0} e^{+}e^{-}$

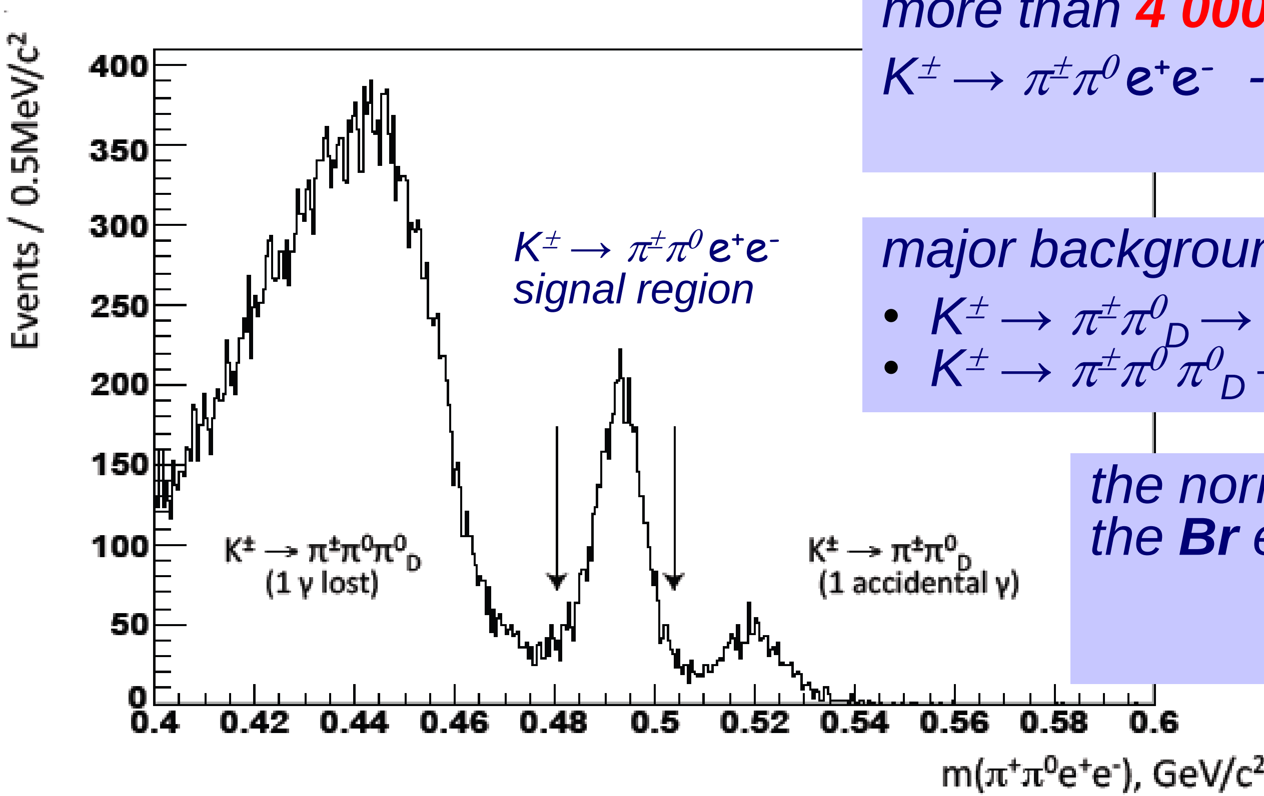


with internal γ conversion

[Cappiello, Cata, D'Ambrosio,Gao, EPJ C72 (2012) 1872]

*the decay is sensitive to **CPV** & **New Physics***

analysis - in progress



*more than **4 000***
$K^{\pm} \to \pi^{\pm}\pi^{0} e^{+}e^{-}$ - events are observed in the signal region

major background sources:

- $K^{\pm} \to \pi^{\pm}\pi^{0}_{D} \to \pi^{\pm} e^{+}e^{-}\gamma$ $(+\gamma$ acc)
- $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}_{D} \to \pi^{\pm}\pi^{0} e^{+}e^{-}\gamma$ (γ lost)

*the normalization channel for the **Br** evaluation:*
$K^{\pm} \to \pi^{\pm}\pi^{0}_{D} \to \pi^{\pm} e^{+}e^{-}\gamma$

$K^{\pm} \rightarrow e^{\pm} \nu \gamma$

minimum bias data sample: **NA62 (***RK, 2007)*

Preliminary; analysis is in progress

Decay formalism

the decay matrix element is described by two terms:

- **IB** (**I**nner **B**remsstrahlung term) - *could be reliably evaluated (Low theorem)*
- **SD** (**S**tructure **D**ependent term) – *should be parameterized with vector $F_V(p^2)$ and axial-vector $F_A(p^2)$ **F**orm **F**actors*

dependent on momentum transferred to the leptonic pair: $p^2 = (\boldsymbol{p}_K - \boldsymbol{p}_\gamma)^2$

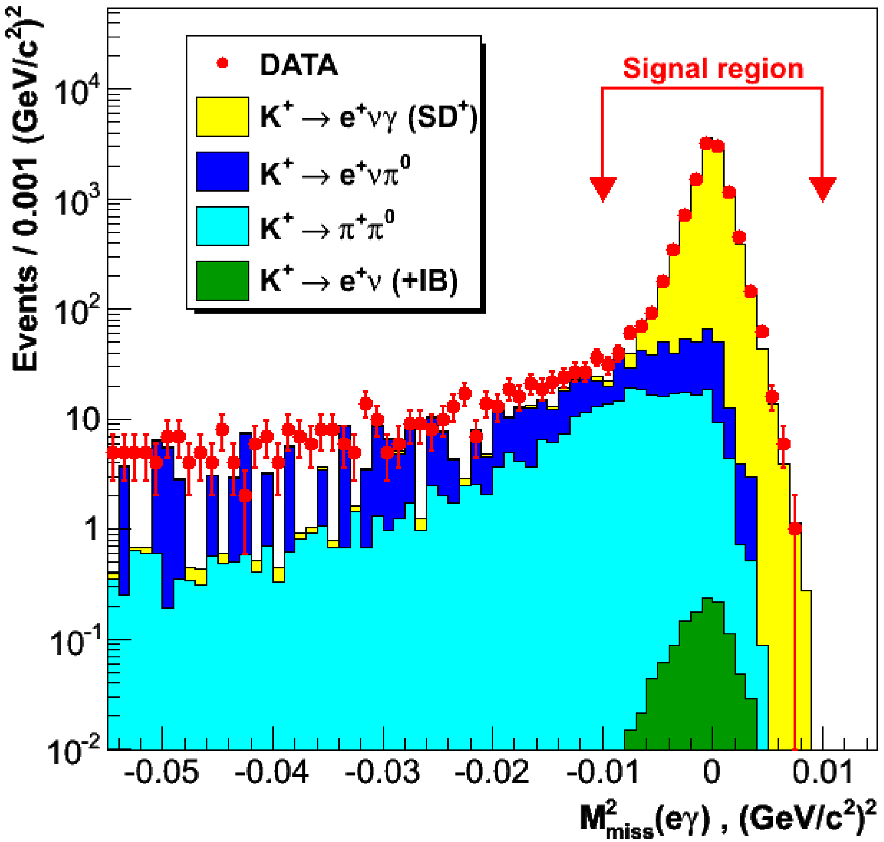
two variables define the kinematics: $x = (2p_K \times p_\gamma) / m^2_K$ $y = (2p_K \times p_e) / m^2_K$

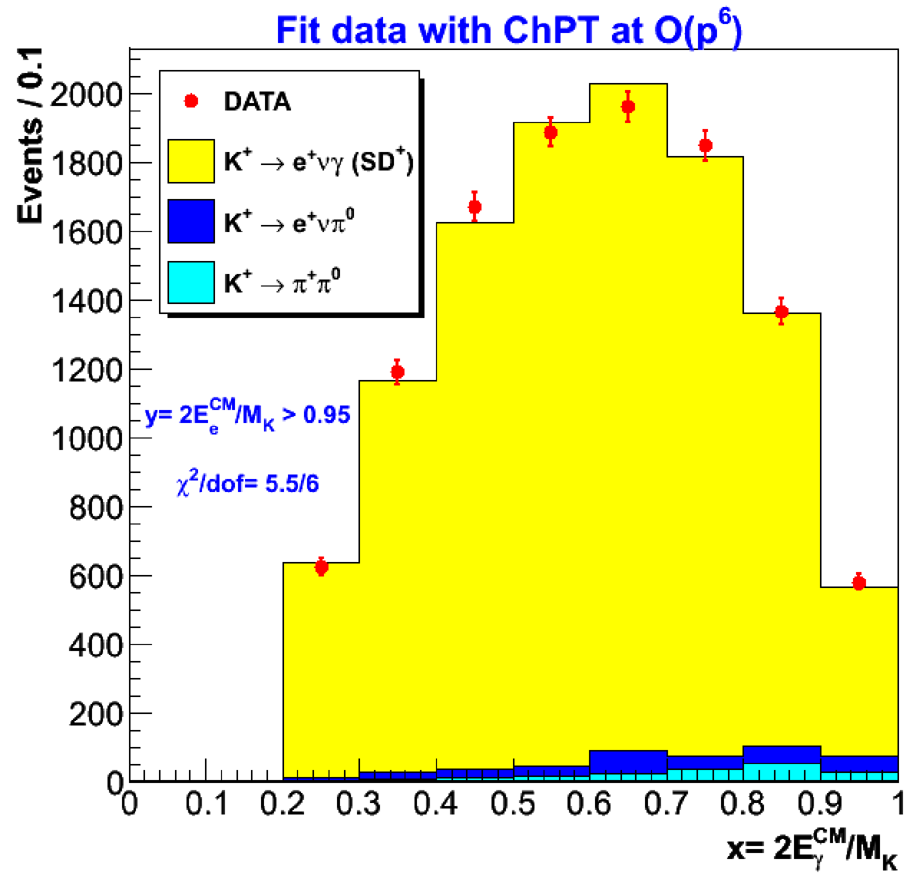
$$d2\Gamma/dxdy\,(SD) = (1/64\pi^2) \times (m^5_K\, G^2_F\, |V_{us}|^2) \times [(F_V + F_A)^2 f^+_{SD}(x;y) + (F_V - F_A)^2 f^-_{SD}(x;y)]$$

SD+ sensitive to $(F_V + F_A)$ SD- sensitive to $(F_V - F_A)$

$K^+ \to e^+ \nu \gamma$ (SD$^+$)

NA62(RK) *partial (40%) data set: 2007*





- ~**10 000** *signal candidates (normalization mode* $K^+ \to \pi^0 e^+ \nu$*)*
- *acceptance for the signal ~ 7% at the background level of ~ 5%*
- *systematic uncertainties dominated by background subtraction*
- K^+ *sample analysed first, than* K^- *sample will be added*

NA62:
the ultra-rare decay $K^{\pm} \rightarrow \pi^{\pm}\nu\bar{\nu}$

in preparation

The major goal:	*detection of ~100 decays with a 10% background*

Experimental status:

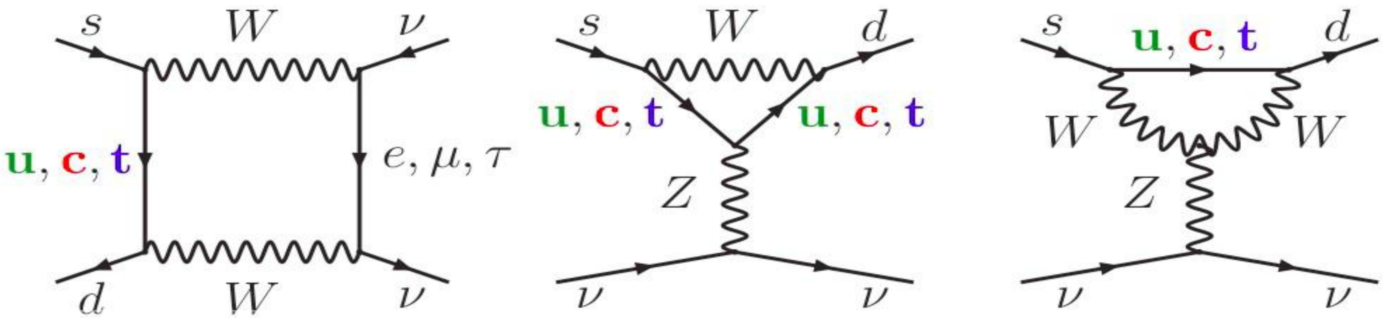
Few decays observed (E787/E949 at BNL) =>

$BR_{SM}(K^{\pm} \rightarrow \pi^{\pm}\nu\nu) = (17.3\ {}_{-10.5}\ {}_{+11.5}) \times 10^{-11}$

SM prediction: $BR(K^{\pm} \rightarrow \pi^{\pm}\nu\nu) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$

SM prediction for the decay $K^{\pm} \to \pi^{\pm}\nu\nabla$

FCNC processes described with penguin and box diagrams



With the highest CKM suppression:

b □ s — $|V^*_{tb}\, V_{ts}| \sim \lambda^2$

b □ d — $|V_{tb}{}^* V_{td}| \sim \lambda^3$

s □ d — $|V_{ts}{}^* V_{td}| \sim \lambda^5$

Kl3 can be used to compute the hadronic matrix element

SM predictions with a 10% precision
error dominated by CKM parameterization

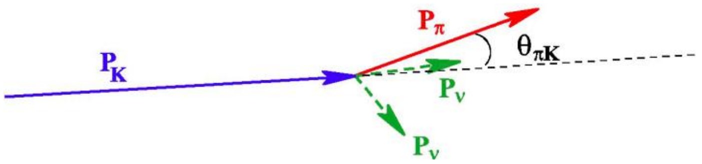
$$BR_{SM}(K^{\pm} \to \pi^{\pm}\nu\nu) = (7.81 \pm 0.75 \pm 0.29)\times 10^{-11}$$

the measurement of BR(K+ → π+ ν ν) with 10% precision
will give a direct (7% precision) determination of the CKM element V_{td}

the signal event selection & background suppression are based on:

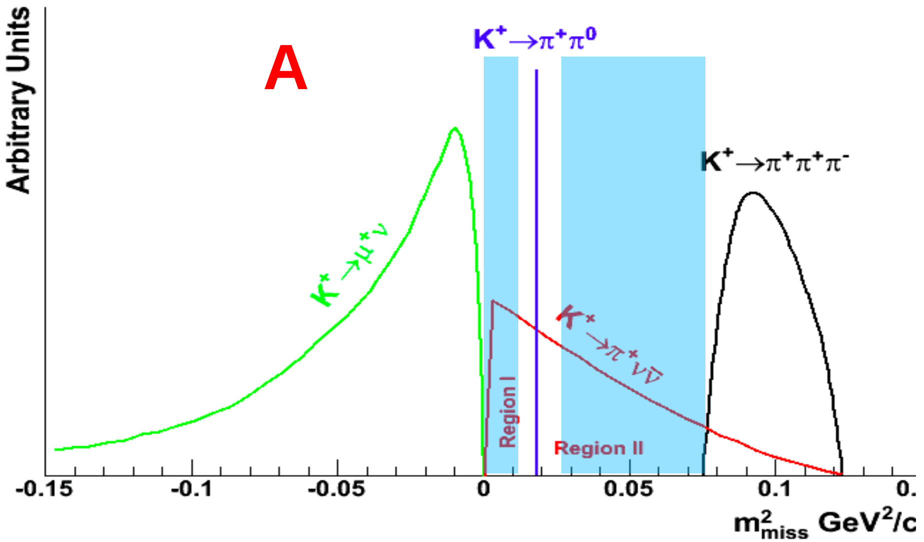
- *kinematical cuts* - *to suppress 92% of background* (**A**) (*suppressed by kin. cuts)*
- *high efficiency of particle ID & veto's for γ's and μ*
  - *to suppress 8% of background* (**B**) *(not suppressed by kin. cuts))*

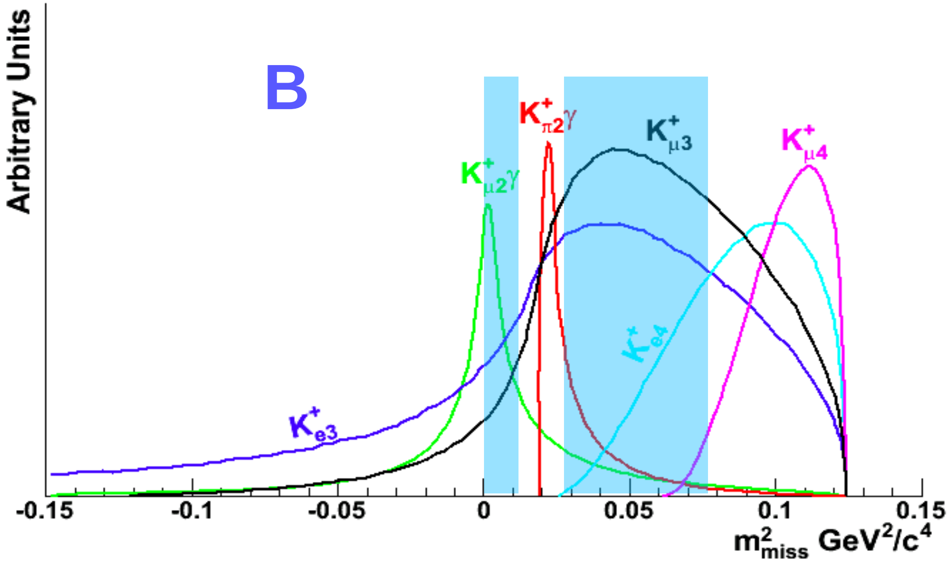
$$m^2_{miss} = (P_\pi - P_K)^2 \approx m^2_K \times (1 - |p_\pi|/|p_K|) + m^2_\pi \times (1 - |p_K|/|p_\pi|) - |p_K| \times |p_\pi| \times \theta^2_{\pi K}$$



- *kinematical rejection: O(10^5)*
- *precise timing O(100 ps)*
- *associate decayed and incoming K*
- *two spectrometers:* ***GTK*** *for* ***K*** *and* ***Straw*** *for* ***pions***

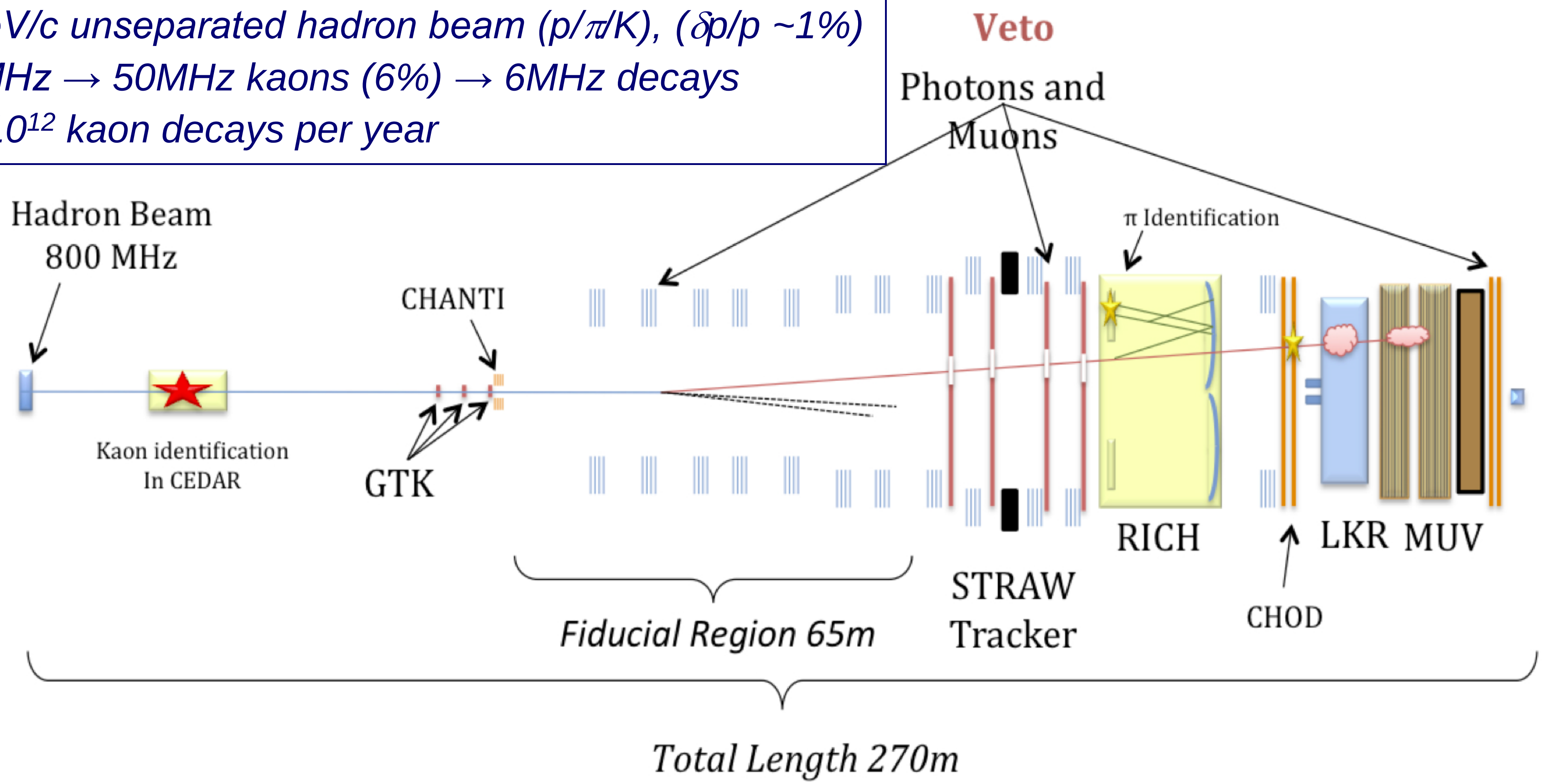
- 2 regions of m^2_{miss} for signal selection





The NA62 detector for $K^{\pm} \rightarrow \pi^{\pm}\nu\bar{\nu}$

- *SPS primary protons @ 400GeV/c*
- *75GeV/c unseparated hadron beam (p/π/K), (δp/p ~1%)*
- *750MHz → 50MHz kaons (6%) → 6MHz decays*
- *4.8×10^{12} kaon decays per year*



NA62 timeline:

- *first technical run in autumn 2012 including many parts of the experiment*
- *2013: complete detector installation*
- *2014-?: data taking with full detector*

(driven by CERN accelerator schedule)

Summary

- a high precision measurement of charged kaon decay rates ratio RK = Br(Ke2)/Br(Kμ2) is fulfilled
  confirming the μ-e universality
  and giving a new constrain to the 2HDM

- a study of a large sample of decay $K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$, collected in NA48/2 and NA62(RK) experiments with min bias trigger,
  led to a high precision test of the ChPT

- the largest samples of rare and very rare charged kaon decays
  $K^{\pm} \rightarrow e^{\pm} \nu \gamma$ and $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ respectively,
  are collected in the experiment with min bias trigger
  /analyses are in progress/

- preparation of the NA62 experiment dedicated to study of
  very rare charged kaon decays - is well progressing;
  the main goal is to measure the BR($K^{\pm} \rightarrow \pi^{\pm}\nu\bar{\nu}$) with 10% precision,
  obtaining a strong test of the SM
  or indicating to a new physics


Thank you!