K Rare Decays with NA62

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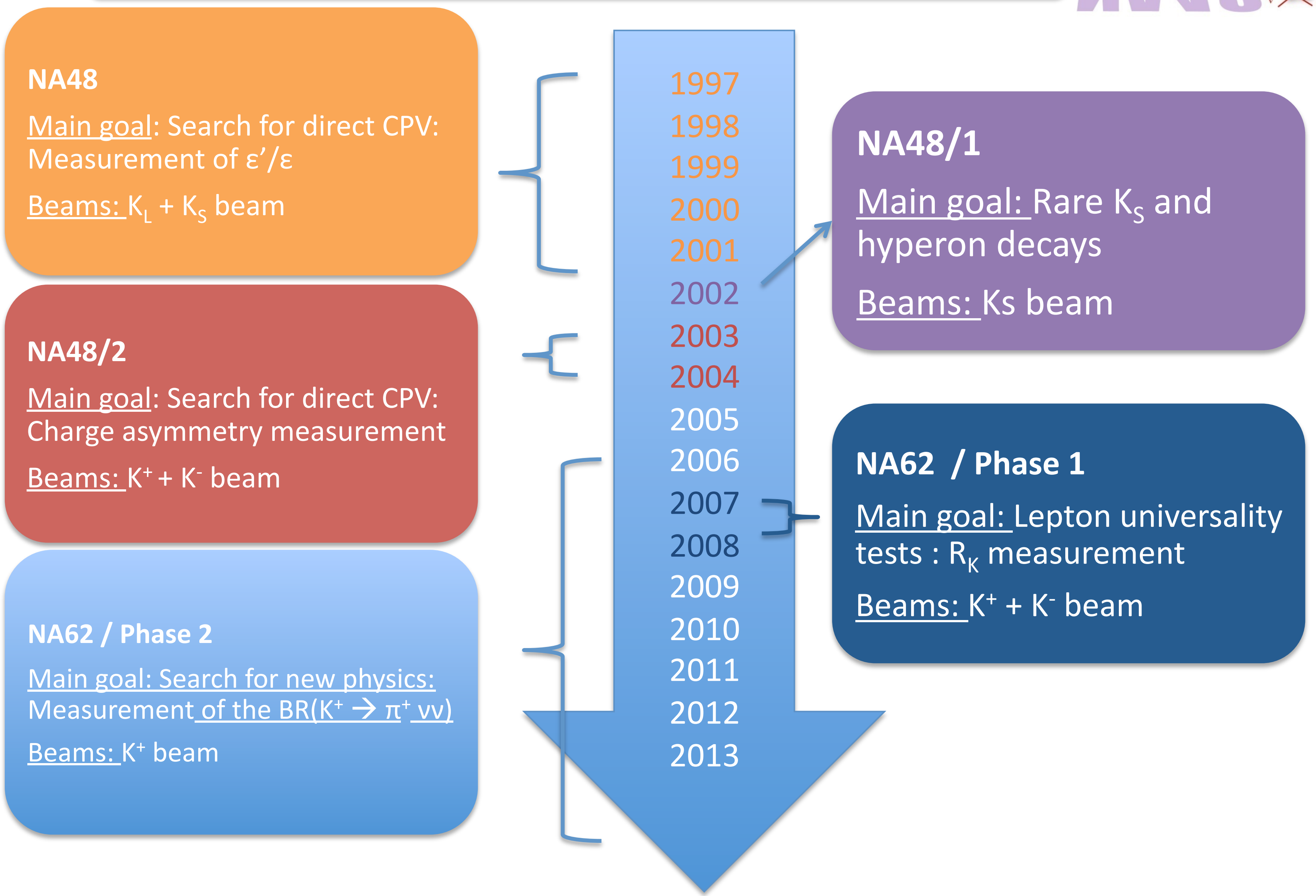
On behalf of NA62 collaboration: Bern ITP, Birmingham, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, IHEP Protvino, INR Moscow, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin

Les Rencontres de Physique de la Vallee d'Aoste

La Thuile, Aosta Valley, Italy

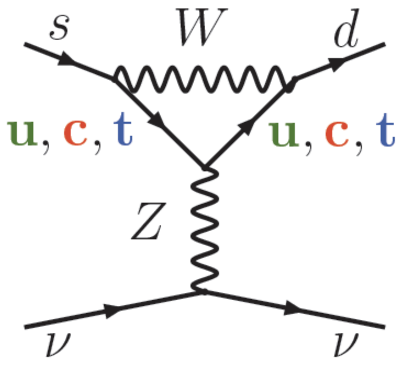
February 28 - March 6, 2010

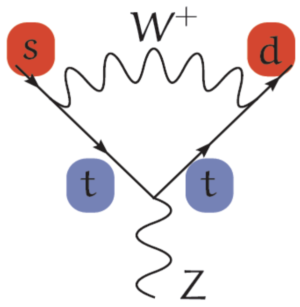
NA48 & NA62 history line

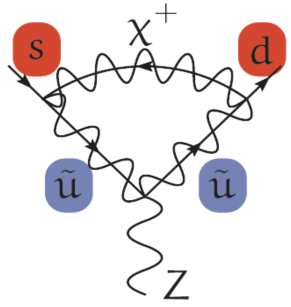


NA62 Phase II:
Measurement of the ultra-rare BR($K^+ \rightarrow \pi^+ \nu\nu$)

NA62: Physics motivation







- Ultra-rare FCNC processes, proceed via penguin and loop diagrams only.
- BR calculable with excellent precision
- Uncertainties mainly come from charm contributions.

NA62 Goal:

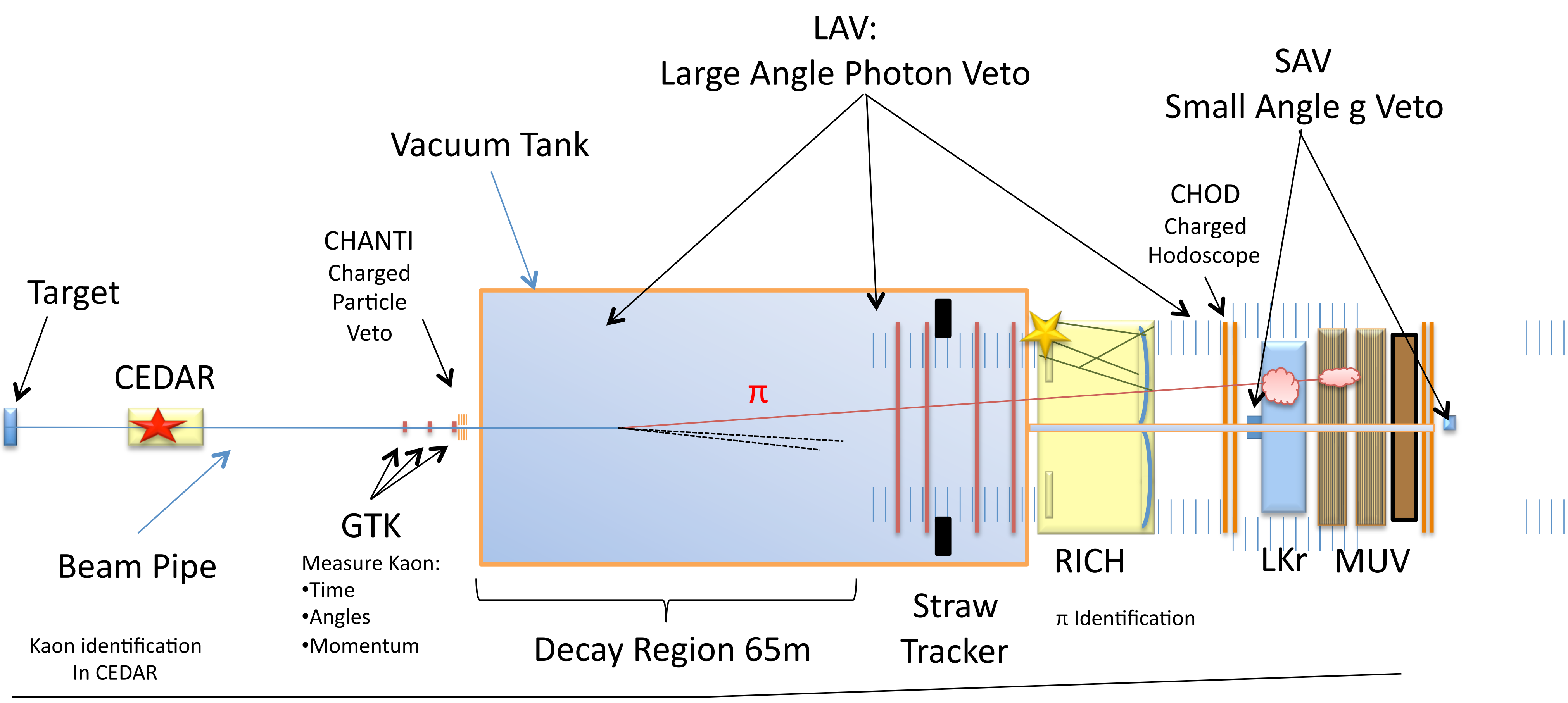
10% precision measurement of BR($K^+ \rightarrow \pi^+ \nu\nu$)

~ 100 events in 2 years

- Background:
  - all K+ decay modes
  - accidental charged particles: beam particle interactions

selected models	BR($K^+ \rightarrow \pi^+ \nu\nu$) $\times 10^{10}$
Theory:	
SM, J.Brod, M.Gorban,PRD78 arxiv : 0805:4119	0.85±0.07
MFV (hep-ph/0310208)	1.91
EEWP (NPB697 (2004) 133, hep-ph/0402112)	0.75±0.21
EDSQ (PRD70 (2004) 093003, hep-ph/0407021)	Up to 1.5
MSSM(NPB713 (2005) 103, hep-ph/0408142)	Up to 4.0
Experiment:	
AGS –E787/E949: PRL101, arXiv:0808.2459 (7 events)	$1.73^{+1.15}_{-1.05}$

NA62: Detectors

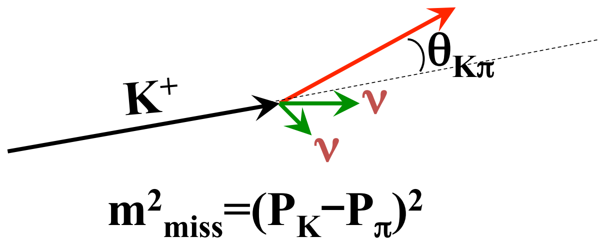


Total Length 270m

Courtesy: Ferdinand Hahn

Veto – photons and muons

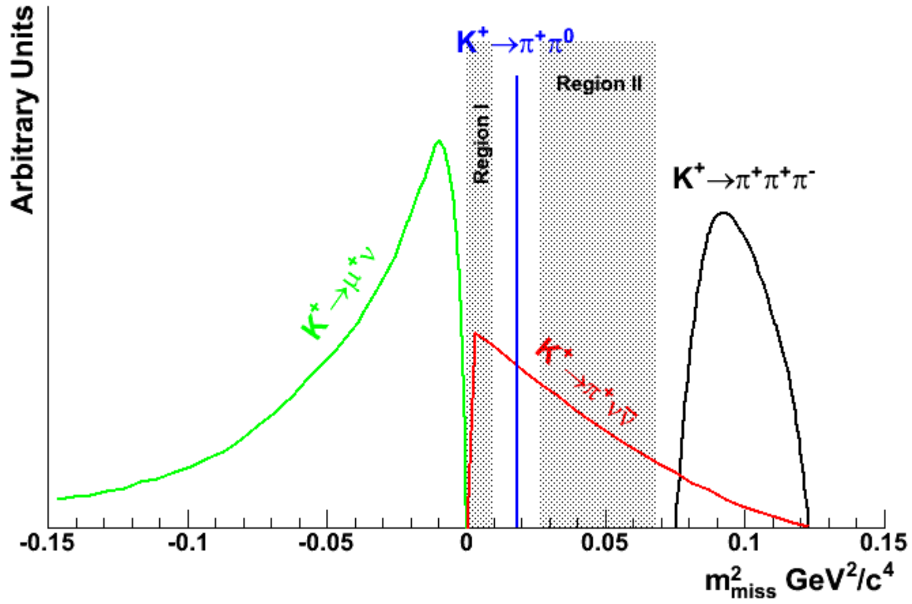
NA62: Experimental techniques : $K^+ \rightarrow \pi^+\nu\nu$ kinematics



P_K : beam spectrometer Gigatracker

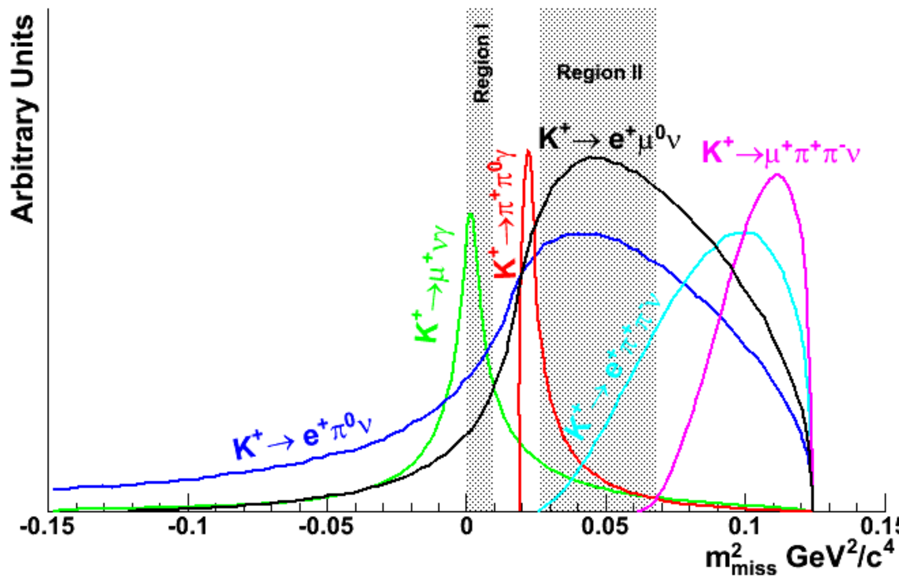
P_π : straw chambers spectrometer

92% K^+ decays



Constrained by kinematics

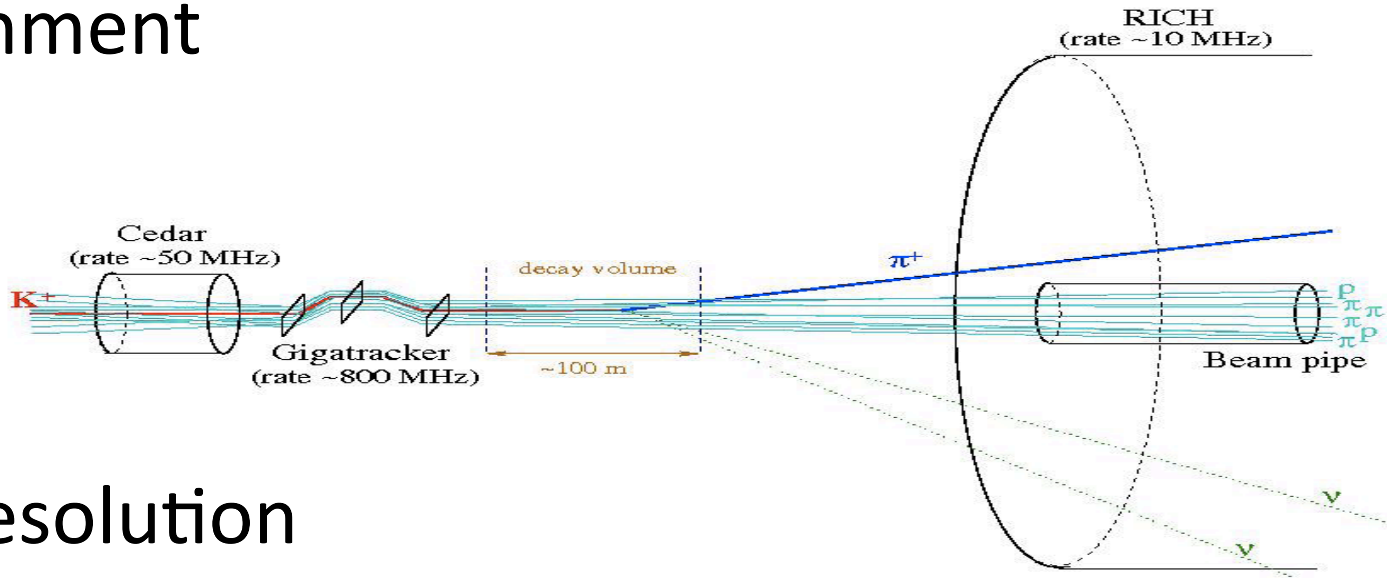
8% K^+ decays



Not constrained by kinematics

Background due to 1) resolution and 2) non constrained modes.

- Precise timing needed to match K and π
  - Possible mismatching weakens the kinematics rejection power
- Challenge – identify the kaons and associate them to the decay at ~800 MHz beam rate environment



- Time resolution
  - σ_t = 100 ps both for K and π

- Photon vetoes
  - Further suppression of $K \rightarrow \pi\pi_0$ decays
- Geometrical coverage
  - 0 - 50 mrad (LKr, IRC, SAC, LAV)
- Essential
  - $p_\pi < 35$ GeV , 40 GeV π_0 is almost impossible to miss in the calorimeters

➔In total, 2 - 3.5 $\times 10^{-8}$ π_0 rejection inefficiency

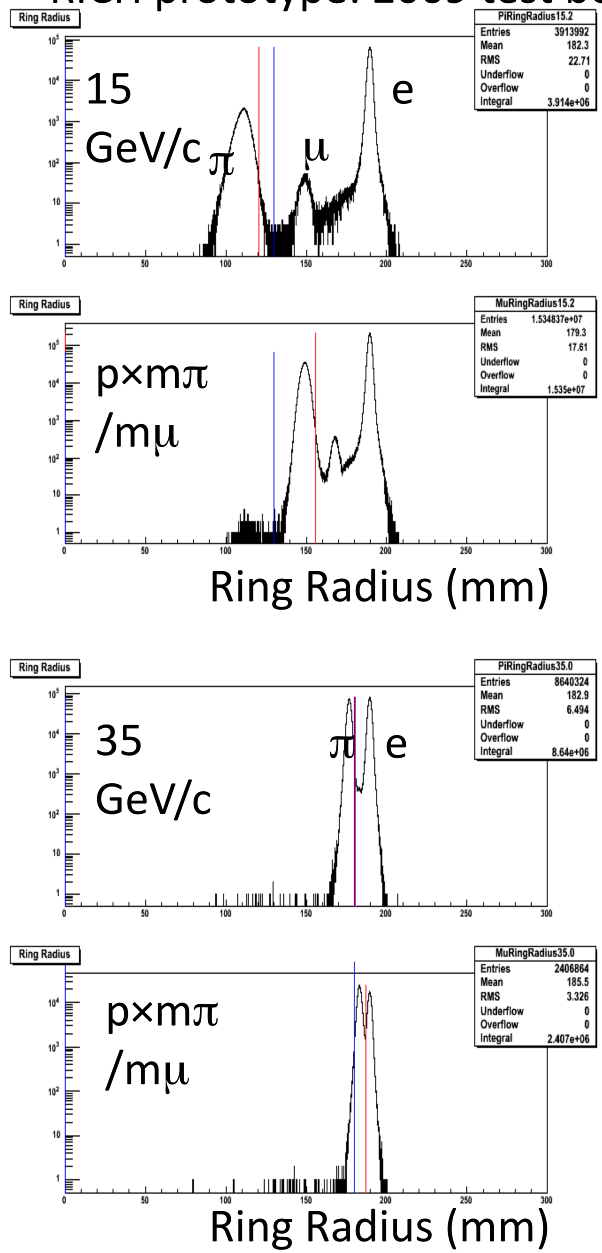
Muon veto:

- Designed to reject $K+ \rightarrow \mu+\nu$ together with the kinematic rejection and particle ID.
- $O(10^{-5})$muon rejection inefficiency

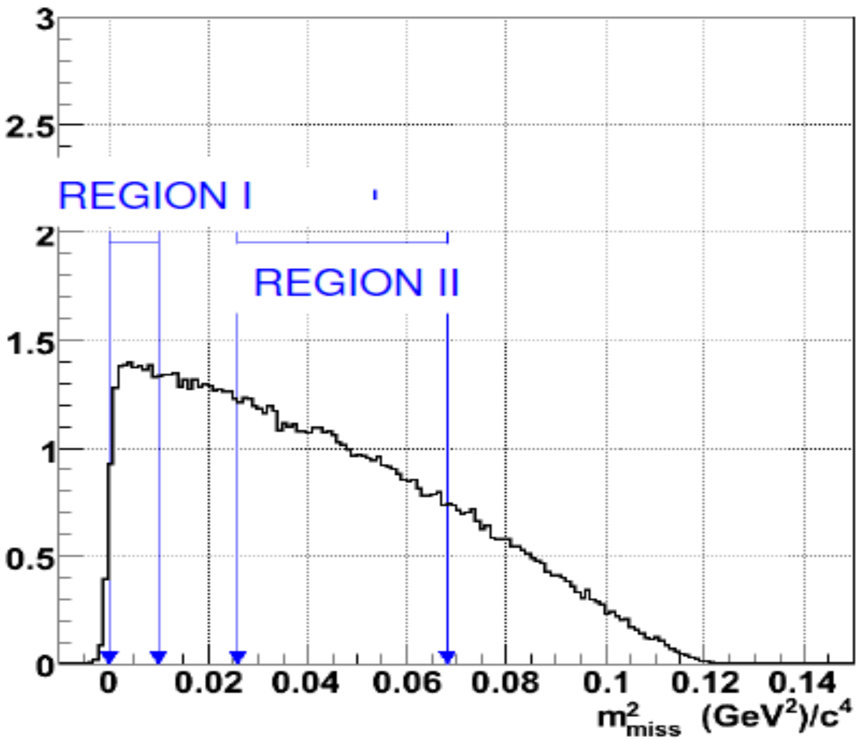
NA62: Experimental techniques - Particle identification

- Identify K+ decays
  - RICH for πμ separation
  - LKr and RICH for e+ identification
- Identify accidentals
  - CEDAR for K+ identification
- Performances and constraints (RICH)
  - πμ separation up to 35 GeV/c ~10^{-2}
  - Minimum pion momentum 15 GeV/c (Cerenkov threshold).
- Redundancy
  - Kinematic rejection,
  - muon rejection,
  - Positron, gamma rejection.

RICH prototype: 2009 test beam



NA62 sensitivity + broader program



Decay Mode	Events
Signal: $K^+ \to \pi^+ \nu\nu$ *[flux = 4.8×10^{12} decay/year]*	55 *evt/year*
$K^+ \to \pi^+ \pi^0$ *[$\eta_{\pi 0}$ = 2×10^{-8} (3.5×10^{-8})]*	4.3% (7.5%)
$K^+ \to \mu^+ \nu$	2.2%
$K^+ \to e^+ \pi^+ \pi^- \nu$	≲3%
Other 3 – track decays	≲1.5%
$K^+ \to \pi^+ \pi^0 \gamma$	~2%
$K^+ \to \mu^+ \nu \gamma$	~0.7%
$K^+ \to e^+(\mu^+)\ \pi^0 \nu$, others	negligible
Expected background	≲13.5% (≲17%)

15 < p_π < 35 GeV/c

Fiducial decay region: 60 m

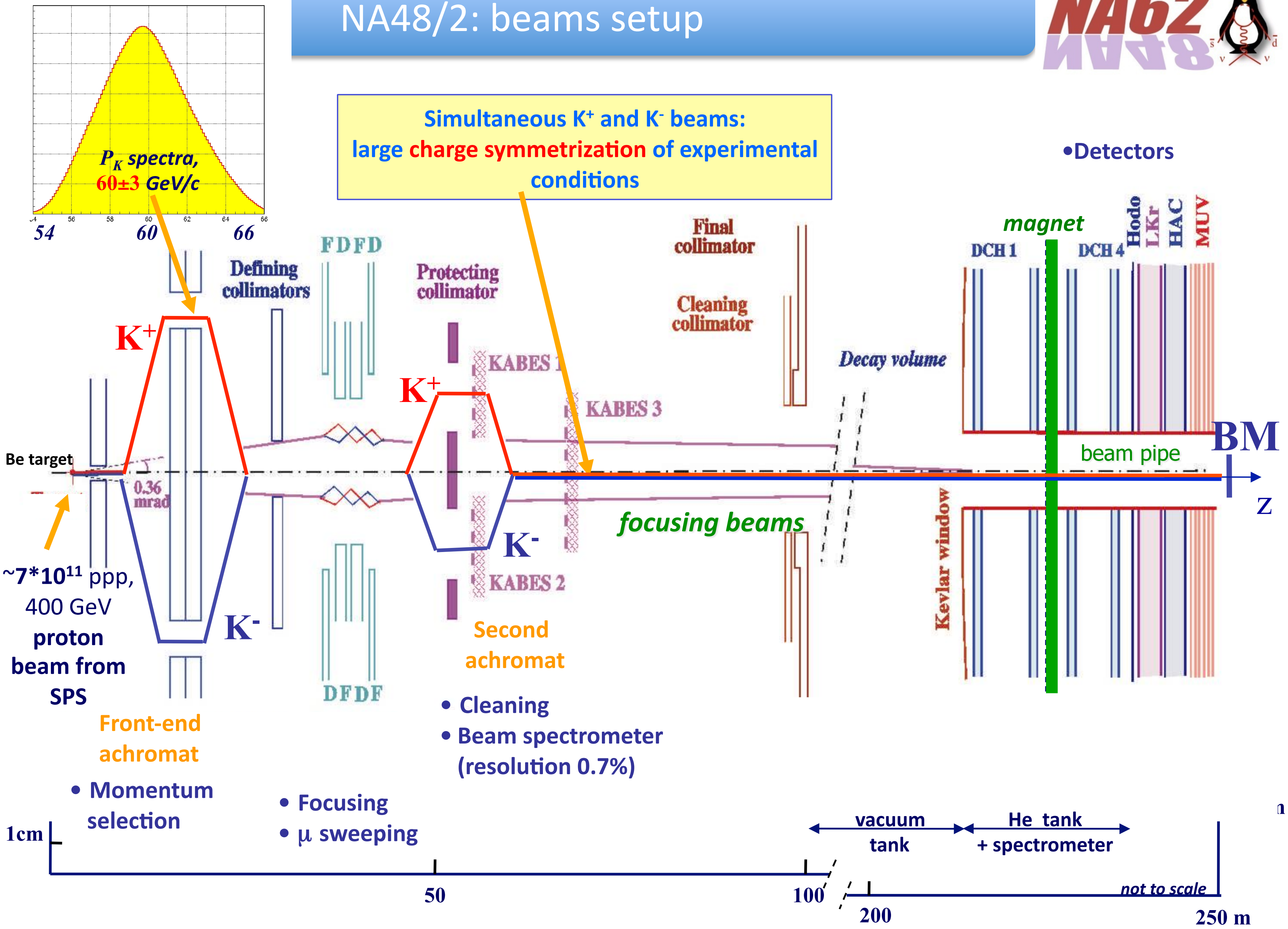
Acceptance: 3.5% (Region I), 10.9% (Region II): 14.4% (I+II)

NA62 optimized for BR(K→πνν) measurement but broader physics programme has already been discussed at the NA62 Physics Handbook Workshop, Dec 2009 http://indico.cern.ch/ conferenceDisplay.py?confId=65927

NA48/2:

The rare decays **$K^{\pm} \rightarrow \pi^{\pm} l^{+} l^{-}$**

NA48/2: beams setup



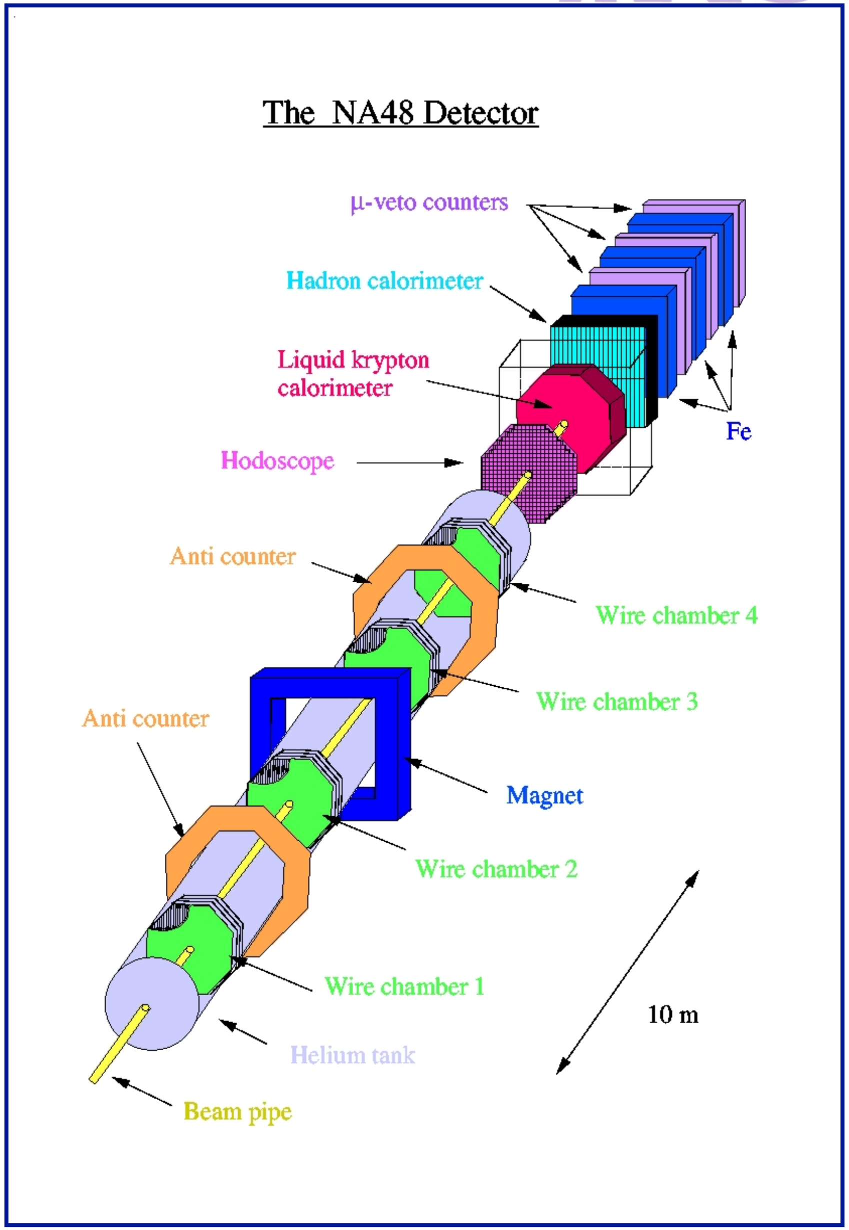
NA48/2: detector

- ***Magnetic spectrometer (4 DCHs):***
  - 4 views : redundancy ⇒ high efficiency;
  - Δp/p = 1.0%⊕0.044%*p [GeV/c]

- ***Hodoscope***
  - fast trigger;
  - precise time measurement (σ_t = 150 ps) .

- ***Liquid Krypton EM calorimeter (LKr)***
  - Quasi-homogeneous ionization chamber
  - 27 electromagnetic radiation lengths long active volume
  - Segmented transversally 13248 cells, 2x2 cm2
  - Energy resolution (E in GeV):

$$\frac{\sigma(E)}{E} = \frac{0.032}{\sqrt{E}} \oplus \frac{0.09}{E} \oplus 0.0042$$

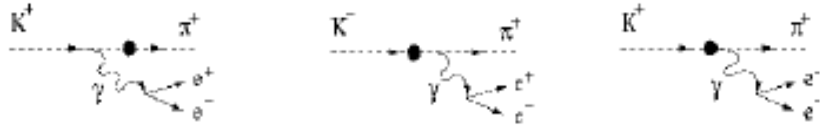


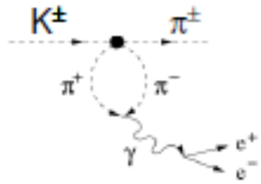
NA48/2: : $K^{\pm} \rightarrow \pi^{\pm} l^{+} l^{-}$ – motivation and theory

$$d\Gamma_{\pi ee}/dz \sim \rho(z)\cdot|W(z)|^2$$

$z=(M_{ee}/M_K)^2$, $\rho(z)$ phase space factor

- suppressed FCNC processes
- one-photon exchange
- useful test for ChPT





(1) polynomial: $W(z) = G_F M_K^2 \cdot f_0 \cdot (1+\delta z)$

(2) ChPT $O(p^6)$: $W(z) = G_F M_K^2 \cdot (a_+, b_+, z) + W^{\pi\pi}(z)$

(3) ChPT, large-Nc QCD: $W(z) = W(w, \beta, z)$

(4) Mesonic ChPT: $W(z) = W(M_a, M_\rho, z)$

(2) D'Ambrosio et al. JHEP 8 (1998) 4
(3) S. Friot et al. PLB 595 (2004) 301
(4) Dubnickova et al. hep-ph/0611175

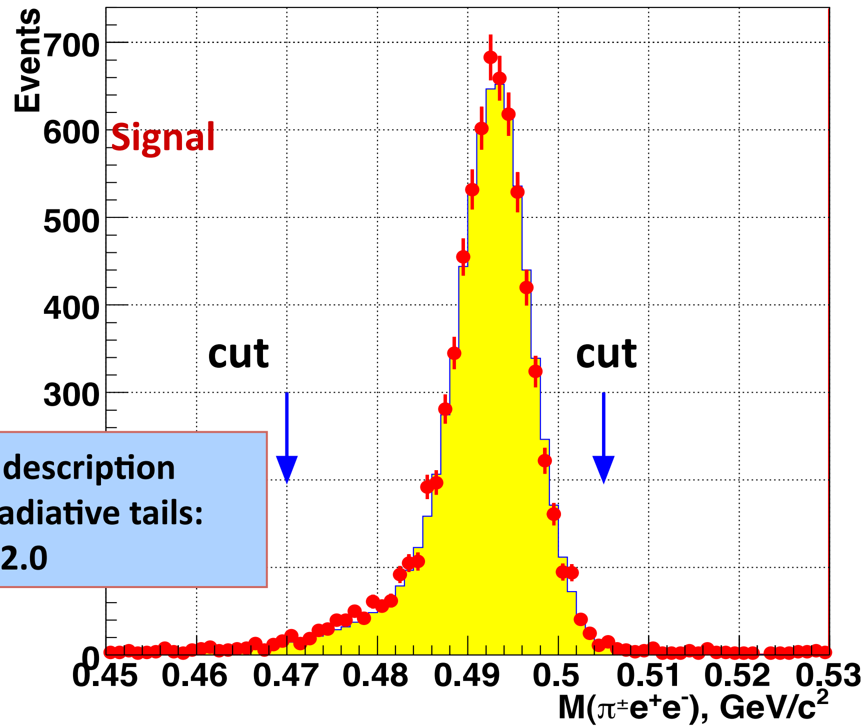
(f_0,δ) or (a_+,b_+) or (w, β) or (M_a,M_ρ) determine a model-dependent BR

- Parameters of models and BR in full kinematical range
- Model-independent BR ($z > 0.08$) in visible kinematical range

NA48/2: $K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}$ - signal and normalization samples

Selections of both channels based on very similar conditions: systematics (trigger, PID) in the BR ratio cancel particially

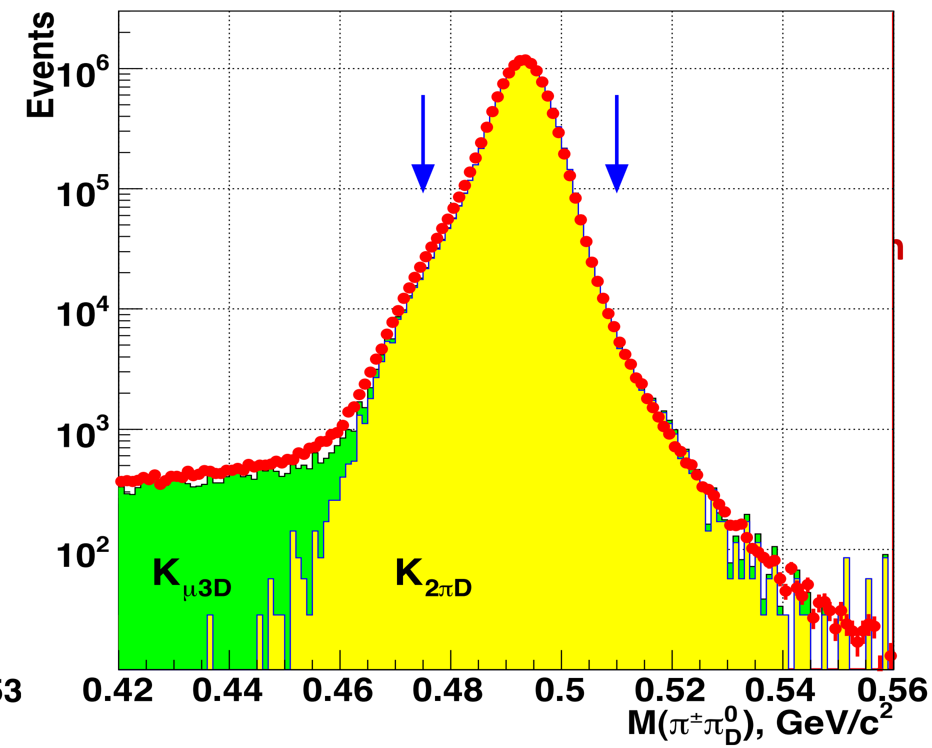
- **Mee > 140 MeV – cut for bg suppression**



Perfect description of the radiative tails: Photos 2.0

7253 candidates
BG: 71 events estimated with data BG/SIG. ~ 1.0%

- **Aditional γ in the normalisation channel**



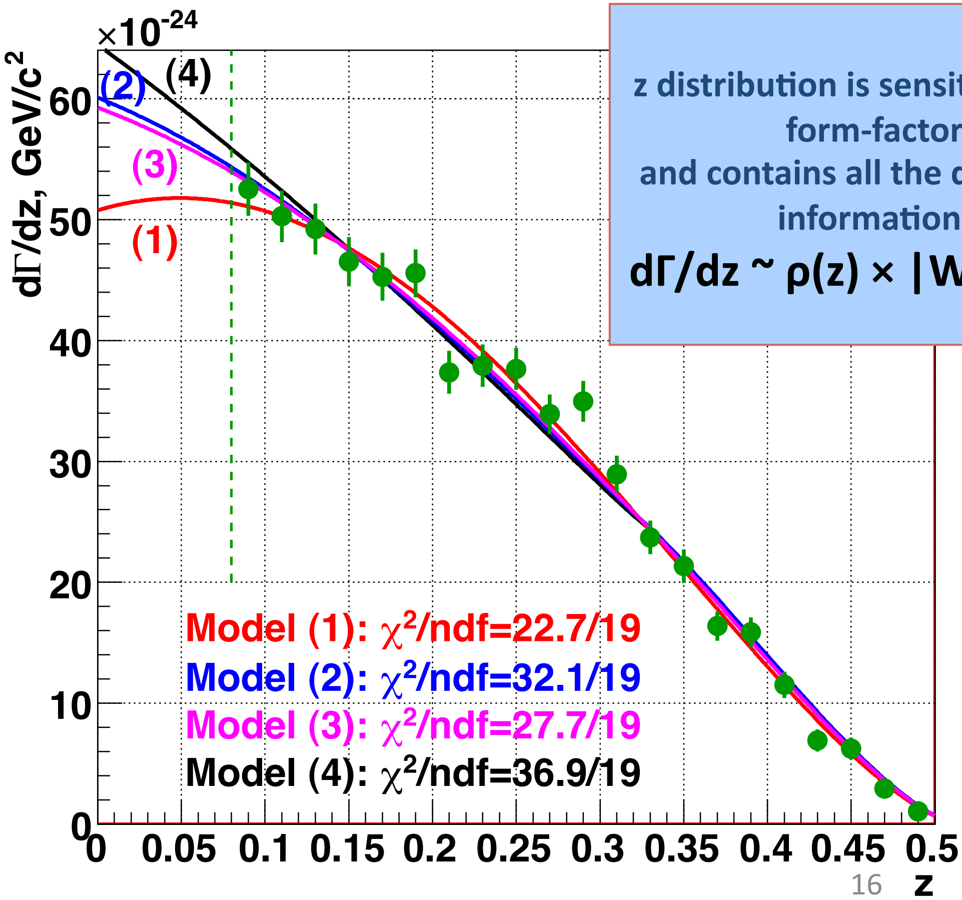
12.12 M candidates
BG/Signal ~ 0.15%
BG subtracted with MC

Kaon decay flux (2003+2004): $\Phi_K = 1.70\times10^{11}$ with Flavianet'08 $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ BR

NA48/2: $K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$ - form factor measurement

GOALS

- Model-independent BR integrating **dΓ/dz in the observable z region**
- Model dependent BRs using fit parameters.
- All models agree reasonably well with data



z distribution is sensitive to the form-factor and contains all the dynamical information:

$$d\Gamma/dz \sim \rho(z) \times |W(z)|^2$$

Fit results

$\delta = 2.32 \pm 0.18_{stat+syst}$

$|f_0| = 0.531 \pm 0.016_{stat+syst}$

$a_+ = -0.578 \pm 0.016_{stat+syst}$

$b_+ = -0.779 \pm 0.066_{stat+syst}$

$w = 0.057 \pm 0.007_{stat+syst}$

$\beta = 3.45 \pm 0.30_{stat+syst}$

$M_a = 0.974 \pm 0.035_{stat+syst}$ GeV

$M_\rho = 0.716 \pm 0.014_{stat+syst}$ GeV

Model independent measurement

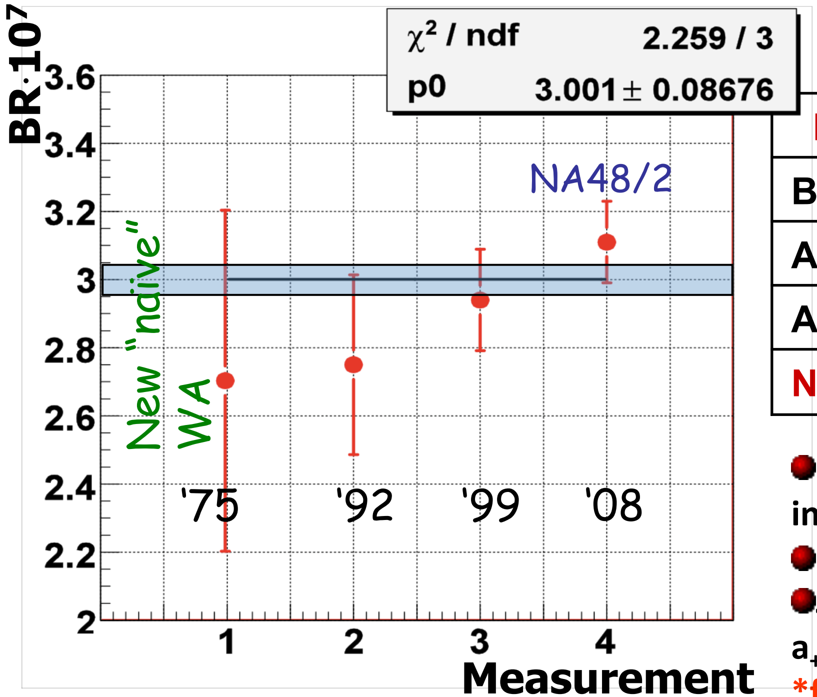
$BR_{mi}\times10^{7}$ $(M_{ee}>140MeV/c^{2})$ = $2.28 \pm 0.03_{stat} \pm 0.04_{syst} \pm 0.06_{ext}$ = 2.28 ± 0.08

Combined result of the 4 models

$BR = (3.11\pm0.04_{stat}\pm0.05_{syst}\pm0.08_{ext}\pm 0.07_{model})\times10^{-7} = (3.11\pm0.12)\times10^{-7}$

CP violating asymmetry (first measurement! correlated K^{+}/K^{-} uncertainties excluded):

$\Delta(K^{\pm}_{\pi ee}) = (BR^{+}-BR^{-}) / (BR^{+}+BR^{-}) = (-2.2\pm1.5_{stat}\pm0.6_{syst})\%$



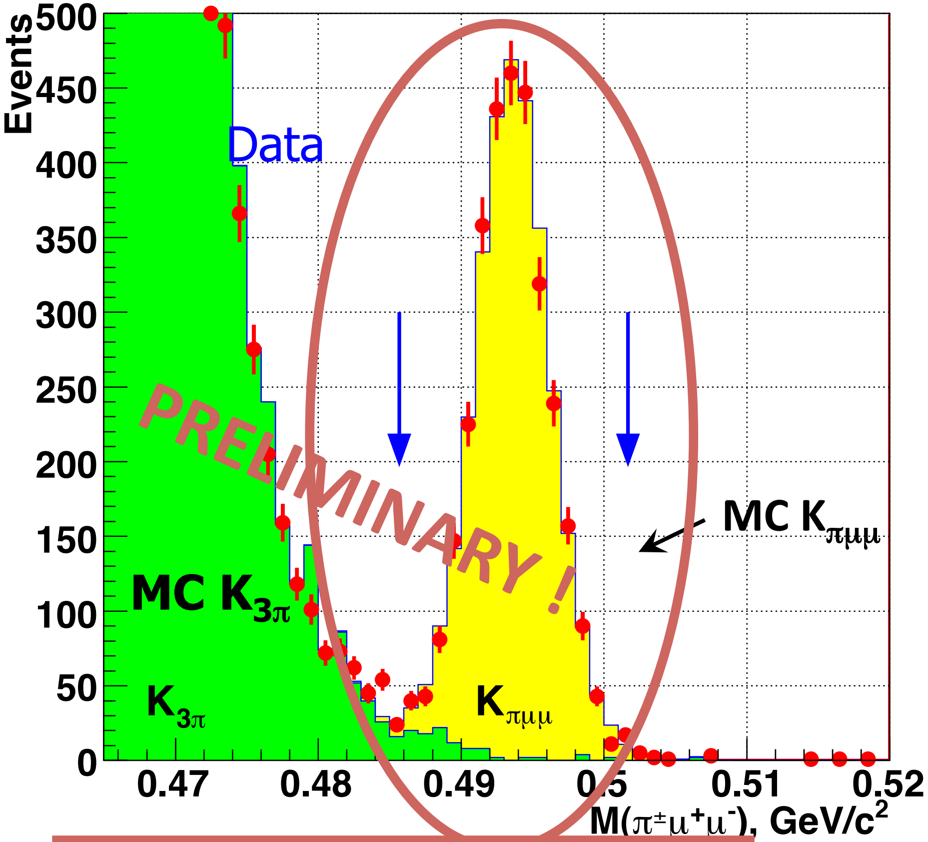
Measurement	events	$BR\times10^{7}$
Bloch et al., PL 56 (1975) B201	(41)	2.70±0.50
Alliegro et al.[E777], PRL 68 (1992) 278	(500)	2.75±0.26
Appel et al. [E865], PRL 83 (1999) 4482	(10000)	2.94±0.15
NA48/2 final (2009)	(7253)	3.11±0.12

- Form factor measurements for Model 1, 2 and 3*
in agreement with previous measurements
- Model 4 – never tested before
- J.Prades, e-Print: arXiv:0707.1789 [hep-ph], predicts (up to its sign)
$a_{+} = -(0.6\ ^{+0.6}_{-0.23})$, in agreement with our result

*fit done by the authors of Model 3 using BNL E865 data

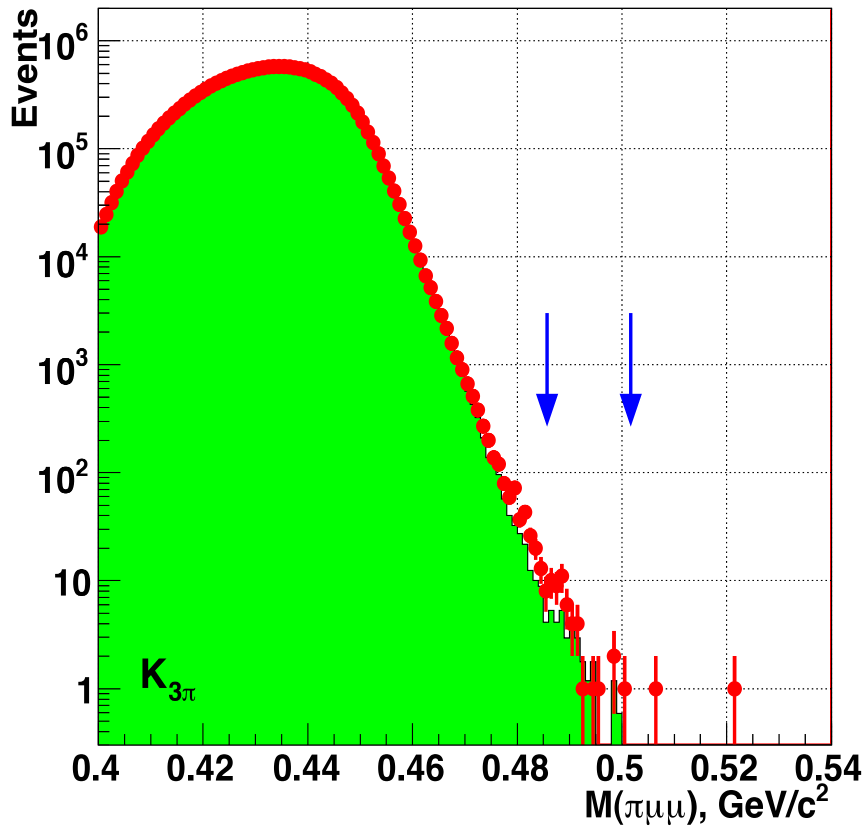
NA48/2: $K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$ - signal region and background

Data: Normal $\mu^{+}\mu^{-}$ candidates



3120 reconstructed events in the signal region:
4 times larger sample than the existing world statistics!

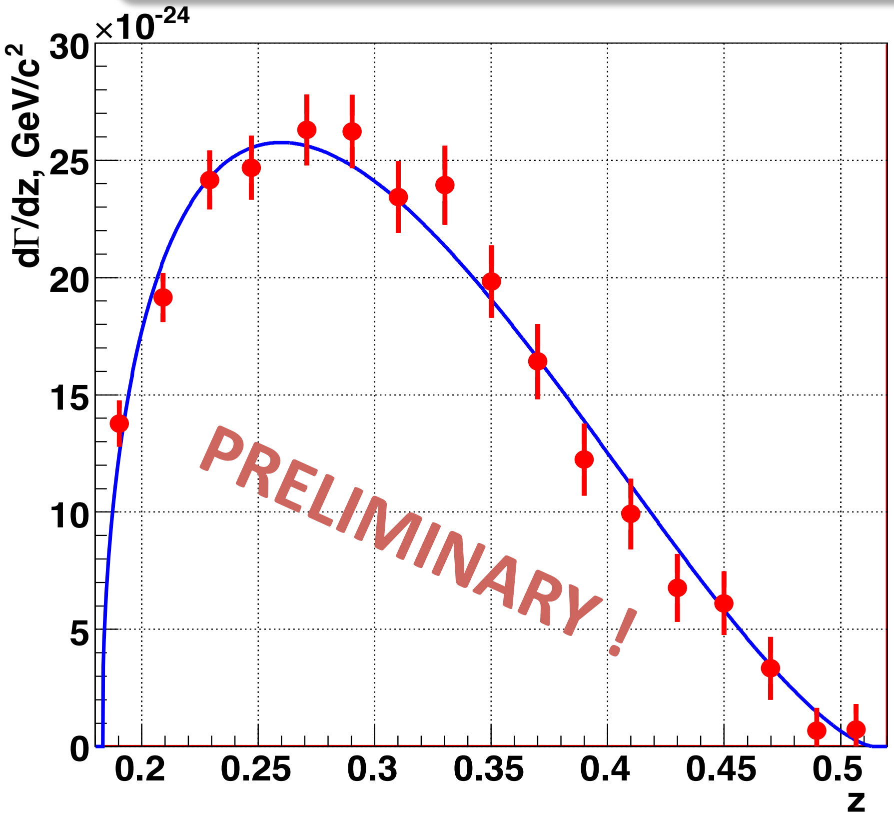
Same sign events



Good background control

$B/(S+B) = (3.3 \pm 0.5_{stat})\%$

NA48/2: : $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ - fit results



CPV charge asymmetry:
$\Delta(K^{\pm} \to \pi\mu\mu) = (1.1\pm2.3) \times 10^{-2}$

Forward-backward asymmetry:

$$A_{FB} = \frac{N(\cos\theta_{K\mu} > 0) - N(\cos\theta_{K\mu} < 0)}{N(\cos\theta_{K\mu} > 0) + N(\cos\theta_{K\mu} < 0)}$$

where $\Theta_{K\mu}$ is the angle between the kaon (or pion) and the opposite sign muon in dimuon rest frame.
$A_{FB} = (-2.4\pm1.8) \times 10^{-2}$

Linear
$f_0 = 0.470\pm0.039$
$\delta = 3.11\pm0.56$
$\chi^2/ndf = 12.0/15$

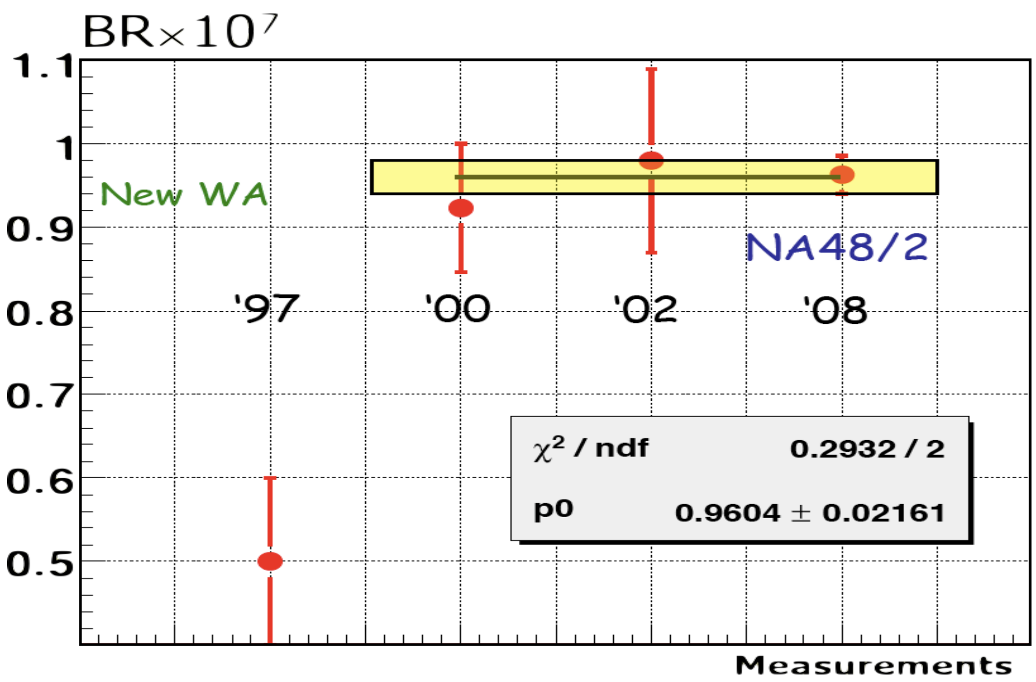
ChPT
$a_+ = -0.575\pm0.038$
$b_+ = -0.813\pm0.142$
$\chi^2/ndf = 14.8/15$

ChPT + large-N_c QCD
$w = 0.064\pm0.014$
$\beta = 3.77\pm0.61$
$\chi^2/ndf = 13.7/15$

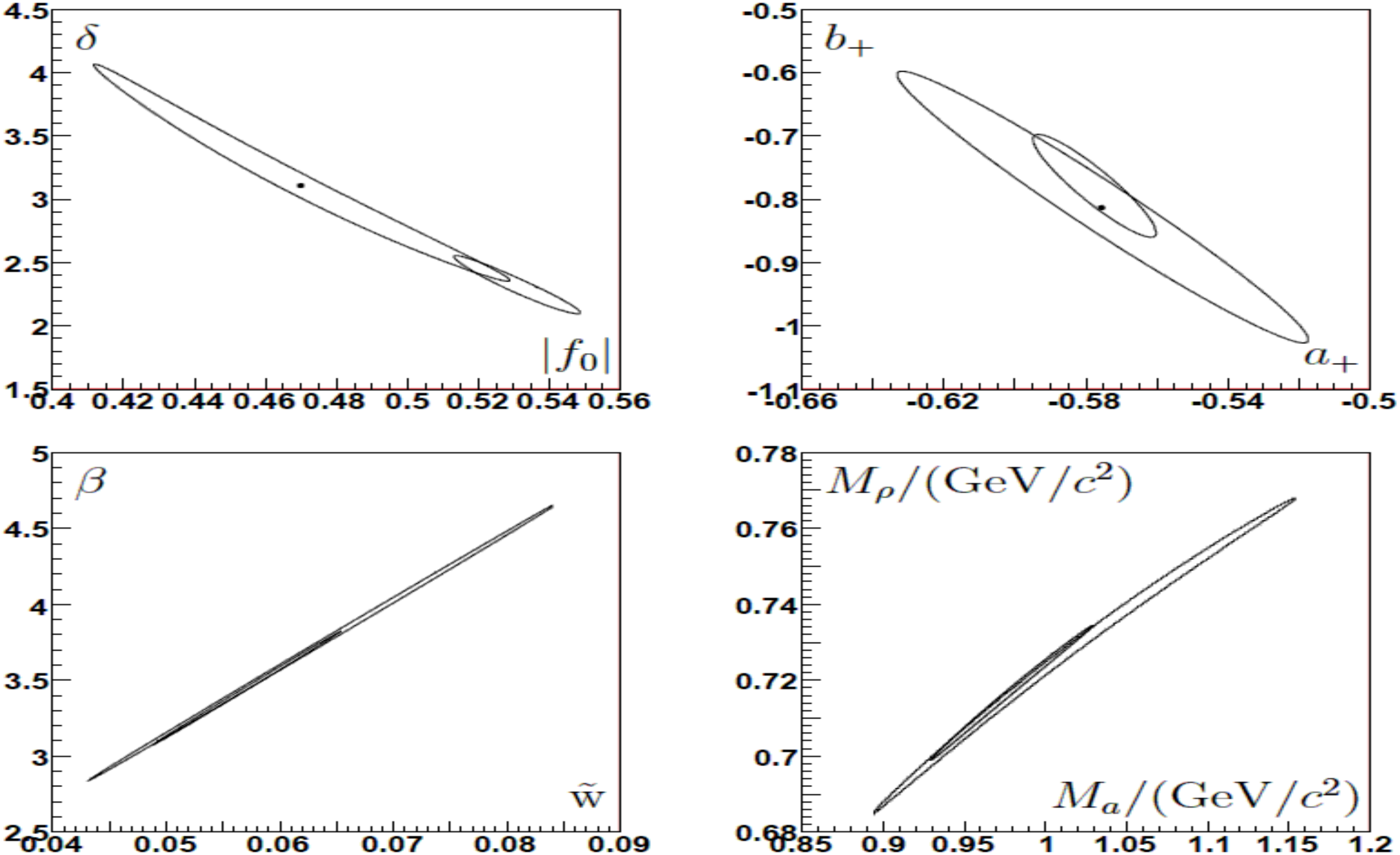
“Meson” ChPT
$M_a = 1.014\pm0.090$
$M_\rho = 0.725\pm0.028$
$\chi^2/ndf = 15.4/15$

NA48/2: : $K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$ - comparison with previous measurements

Measurement	events	background	BR✖10 8
Adler et al. [E787], PRL 79 (1997) 2204	207	11%	5.0 ± 1.0
Ma et al. [E865], PRL 84 (2000) 2580	430	6.5%	9.22 ± 0.77
Park et al. [HyperCP], PRL 88 (2002) 111801	110	~3%	9.8 ± 1.1
NA48/2 (present analysis)	3120	3.3%	9.62 ± 0.23



NA48/2: Agreement between $K^{\pm} \to \pi^{\pm}e^{+}e^{-}$ and: $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$



68% contours from K→πee and K→πμμ

NA62 Phase I:
R_K measurement

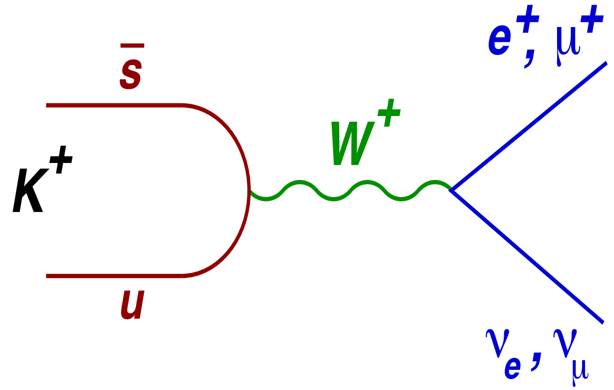
R_K: Theoretical motivation

R_K in the Standard model:

$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{\mathrm{rad.corr.}})$$

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

V. Cirigliano, I.Rosell JHEP 0710:005(2007)

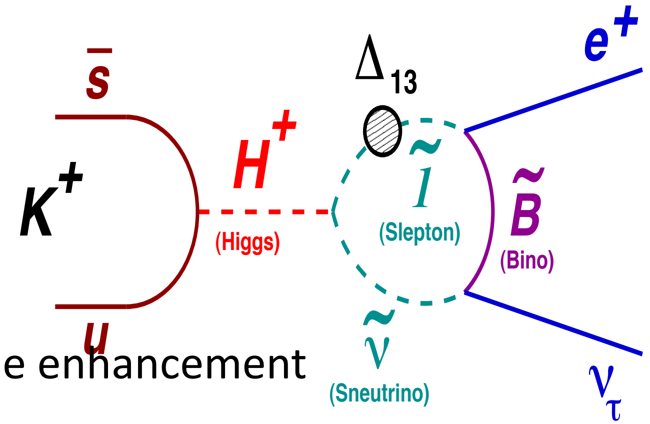


❖Hadronic uncertainties cancel in the ratio
❖Helicity suppression ($f \sim 10^{-5}$)
❖Radiative correction (few %) due to $K^+ \to e^+ \nu\gamma$ (IB) process, by definition included into RK

Due to helicity suppression R_K sensitive to New Physics
In MSSM – H^+ mediated lepton flavor violating contribution with emission of ν_τ.

$$R_K^{LFV} \approx R_K^{SM}\left[1 + \left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)|\Delta_{13}|^2 \tan^6\beta\right]$$

A. Masiero, P. Paradisi and R. Petronzio,
PRD74 (2006) 011701 and JHEP 0811 (2008) 042



Example: with $|\Delta_{13}|=5\times10^{-4}$, $\tan\beta=40$, $M_H=500$ GeV/c^2, the enhancement is **experimentally accessible** (1.3%)

R_K: Experimental status

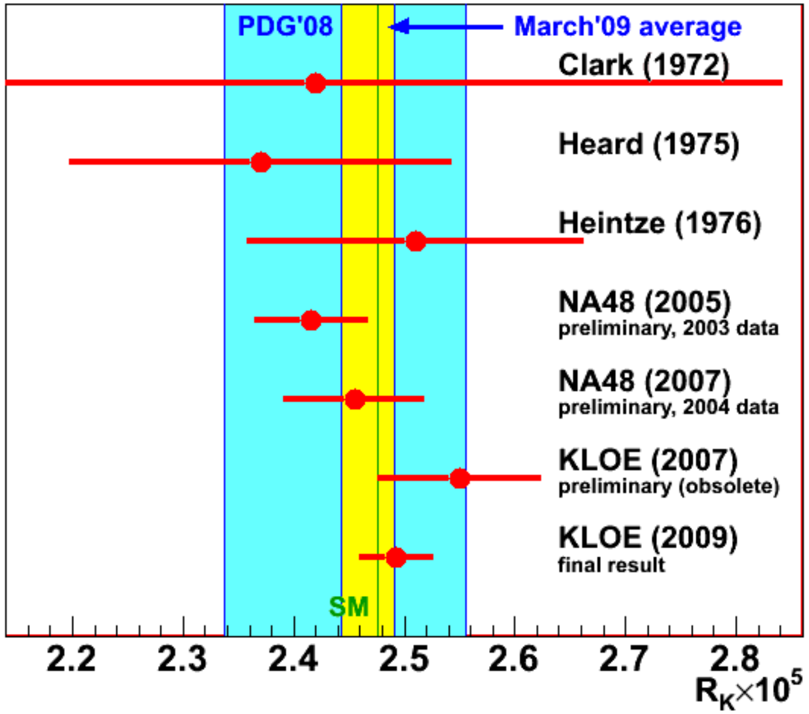
- PDG'08 average (1970s measurements):

  $R_K=(2.45\pm0.11)\times10^{-5}$ ($\delta R_K/R_K=4.5\%$)

- Recent improvement: KLOE (Frascati)
  - Data collected in 2001–2005
  - 13.8K K_{e2} candidates, 16% background

  $R_K=(2.493\pm0.031)\times10^{-5}$ ($\delta R_K/R_K=1.3\%$)

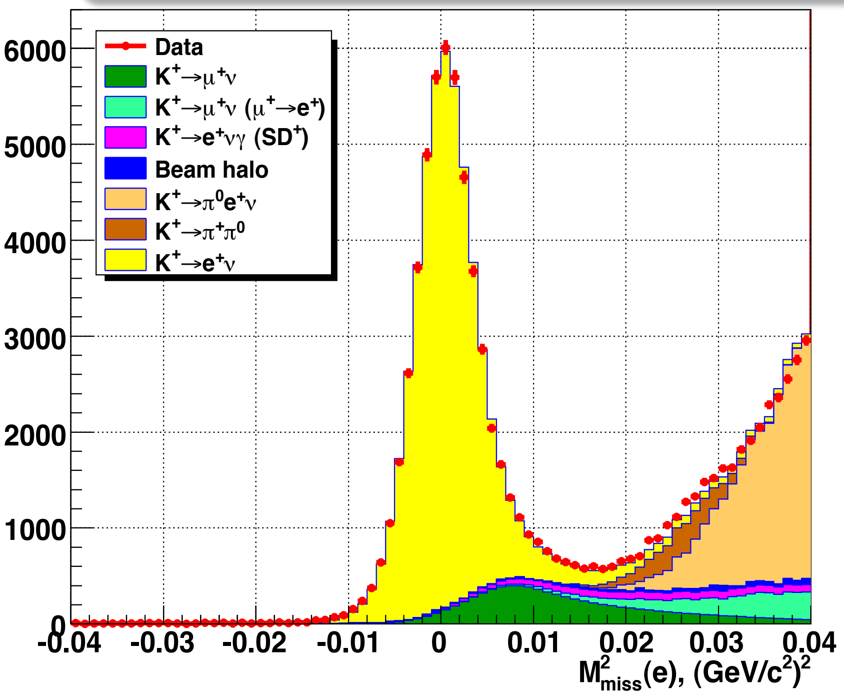
  [arXiv:0907:3594]

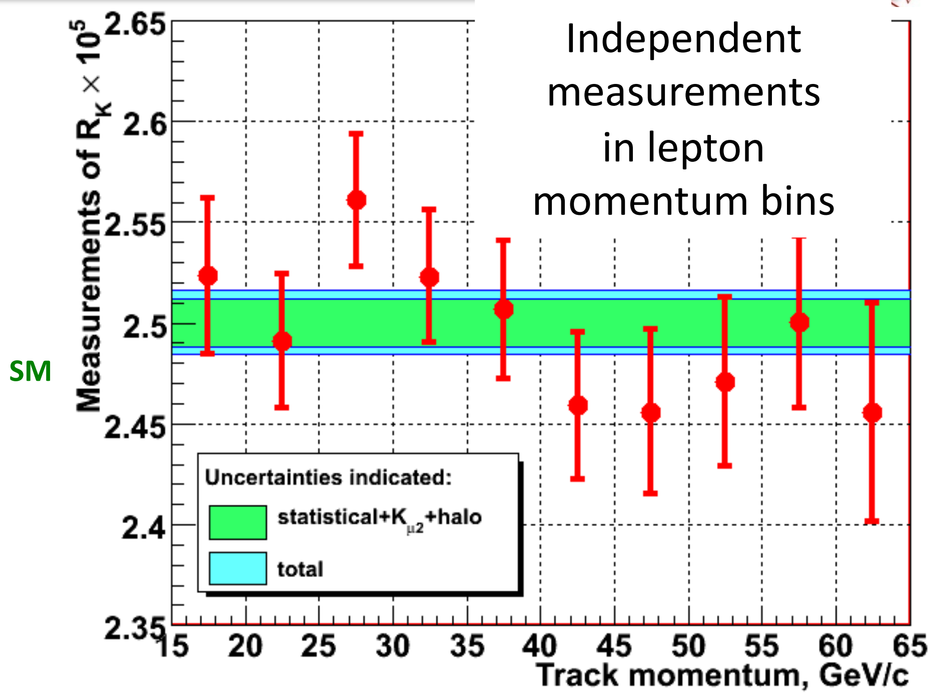


NA62 (phase I) goal:
dedicated data taking strategy,
~150K K_{e2} candidates, **<10%** background,
$\delta R_K/R_K$<0.5% as needed for stringent SM test.

- Beam setup and detector of NA48/2 experiment slightly optimized for Ke2 measurement
- K+ and K− beams with narrow momentum band (74 ± 2 GeV/c)
- Nominal momentum kick of spectrometer magnet doubled

R_K: Ke2 events and backgrounds





40% of data analyzed,

Record sample K_{e2} candidates :51089,

Estimated total Ke2 sample: ~120 k K_{e2}+ and ~15k K_{e2}- candidates

8% background

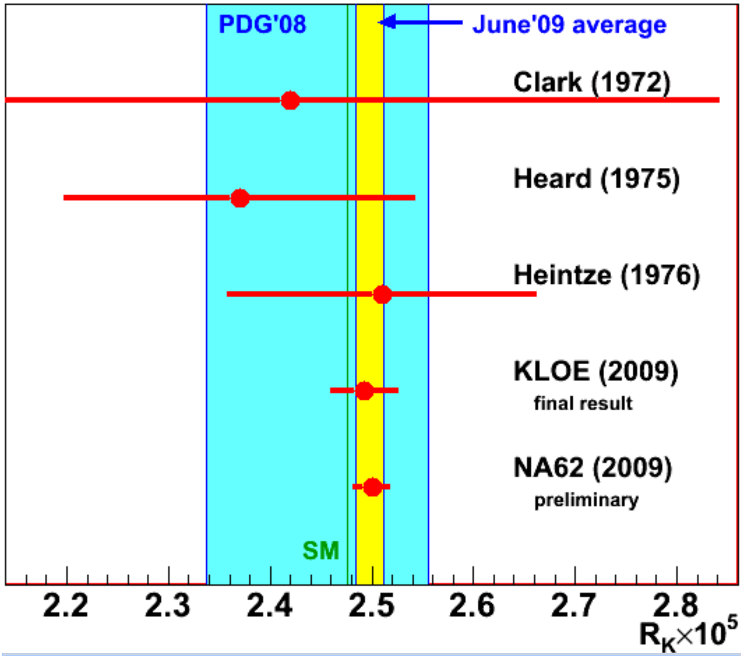
Source	B/(S+B)
$K_{\mu2}$	(6.28±0.17)%
$K_{\mu2}$ ($\mu \to e$)	(0.23±0.01)%
$K_{e2\gamma}$ (SD$^+$)	(1.02±0.15)%
Beam halo	(0.45±0.04)%
K_{e3}	0.03%
$K_{2\pi}$	0.03%

15.56M K+ → μ+v candidates with very low background B/(S+B) = 0.25 %

R_K: Preliminary result

Uncertainties

Source	$\delta R_K \times 10^5$
Statistical	0.012
$K_{\mu 2}$	0.004
Beam halo	0.001
$K_{e2\gamma}$ (SD^+)	0.004
Electron ID	0.001
IB simulation	0.007
Acceptance	0.002
Trigger timing	0.007
Total	**0.016**



World average	$\delta R_K \times 10^5$	Precision
March 2009	2.467±0.024	0.97%
Today	2.498±0.014	0.56%

$$R_K = (2.500 \pm 0.012_{stat} \pm 0.011_{syst}) \times 10^{-5}$$
$$= (2.500 \pm 0.016) \times 10^{-5}$$

0.64% precision

The whole 2007 sample of NA62 experiment will allow statistical uncertainty **~0.3%** and total uncertainty of **0.4–0.5%**.

Conclusions

- **Precise measurement of $K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$**
  - Precision comparable with world's best;
  - BR and form factor measurements in agreement with ChPT and other measurements;
  - First limit on CPV asymmetry.
  - Paper published in PLB

New result !

- **Precise measurement of $K^{\pm} \rightarrow \pi^{\pm} \mu^{+} \mu^{-}$ - preliminary results**
  - Four times larger sample than the existing world statistics has been collected
  - Unprecedented precision achieved. Results in agreement with previous measurements and with NA48/2 results.
  - Limit on CPV asymmetry and forward back asymmetry.

- **Precise measurement of R_K – preliminary results**
  - The NA62 2007 run has increased the world Ke2 sample by more than an order of magnitude.
  - Data taking had been optimized for K_{e2} Preliminary result based on (~ 40 %) of the NA62 K_{e2} sample: $R_K = (2.500 \pm 0.016) \times 10^{-5}$ with a record accuracy of 0.64 %, compatible with the SM
  - With full data sample, overall uncertainty of 0.4 %, as declared in the proposal, is within reach.

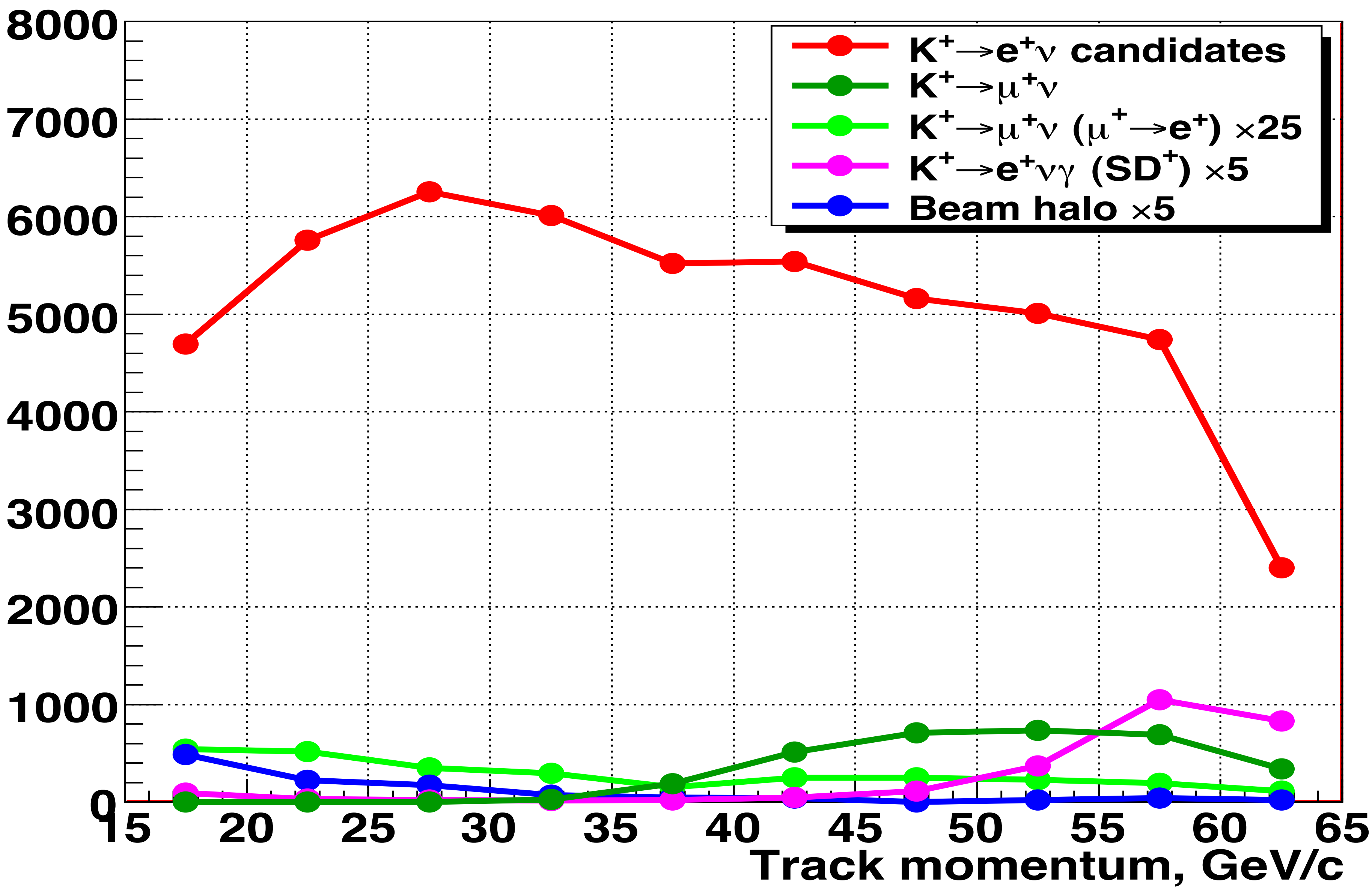
- **Precise measurement of BR($K \rightarrow \pi \nu \nu$)**
  - With 2 years of data taking NA62 will provide a 10% precision measurement of BR($K \rightarrow \pi \nu \nu$)
  - Key points: excellent resolutions, hermetic coverage, reliable particle ID.
  - The high performance of the detectors allows further rich physics program.

BACK UP SLIDES

NA48/2 K→πμμ systematics

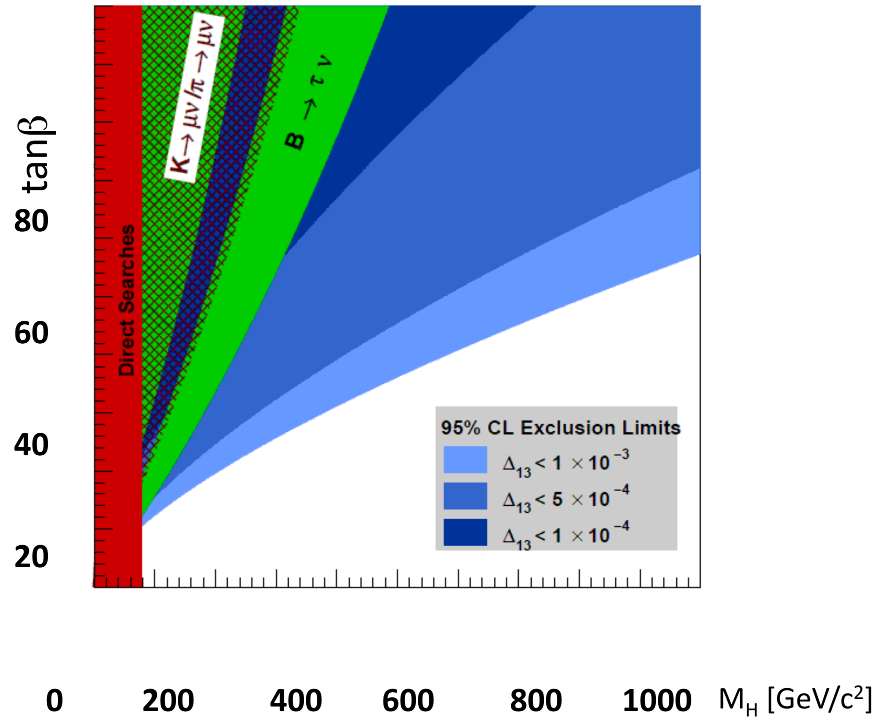
Model	Parameter	Statistical	Background	Muon ID	Pion ID	External
(1)	$\|f_0\|$	0.036	0.014	0	0	0.002
	δ	0.52	0.20	0.01	0	0
(2)	a_+	0.034	0.017	0	0.002	0.002
	b_+	0.123	0.070	0.005	0.006	0.005
(3)	$\tilde{w}$	0.012	0.007	0	0.001	0
	β	0.54	0.29	0.02	0.02	0.02
(4)	M_a/GeV	0.070	0.044	0.002	0.001	0.001
	M_b/GeV	0.023	0.014	0.001	0.001	0.001
	$\mathrm{BR} \times 10^8$	0.20	0.04	0.04	0.08	0.07

RK backgrounds



RK exclusion limits

Exclusion limits at 95% CL derived from the new R_K world average



R_K measurements are currently in agreement with the SM expectation at ~1.5σ. Any significant enhancement with respect to the SM value would be an evidence of new physics.