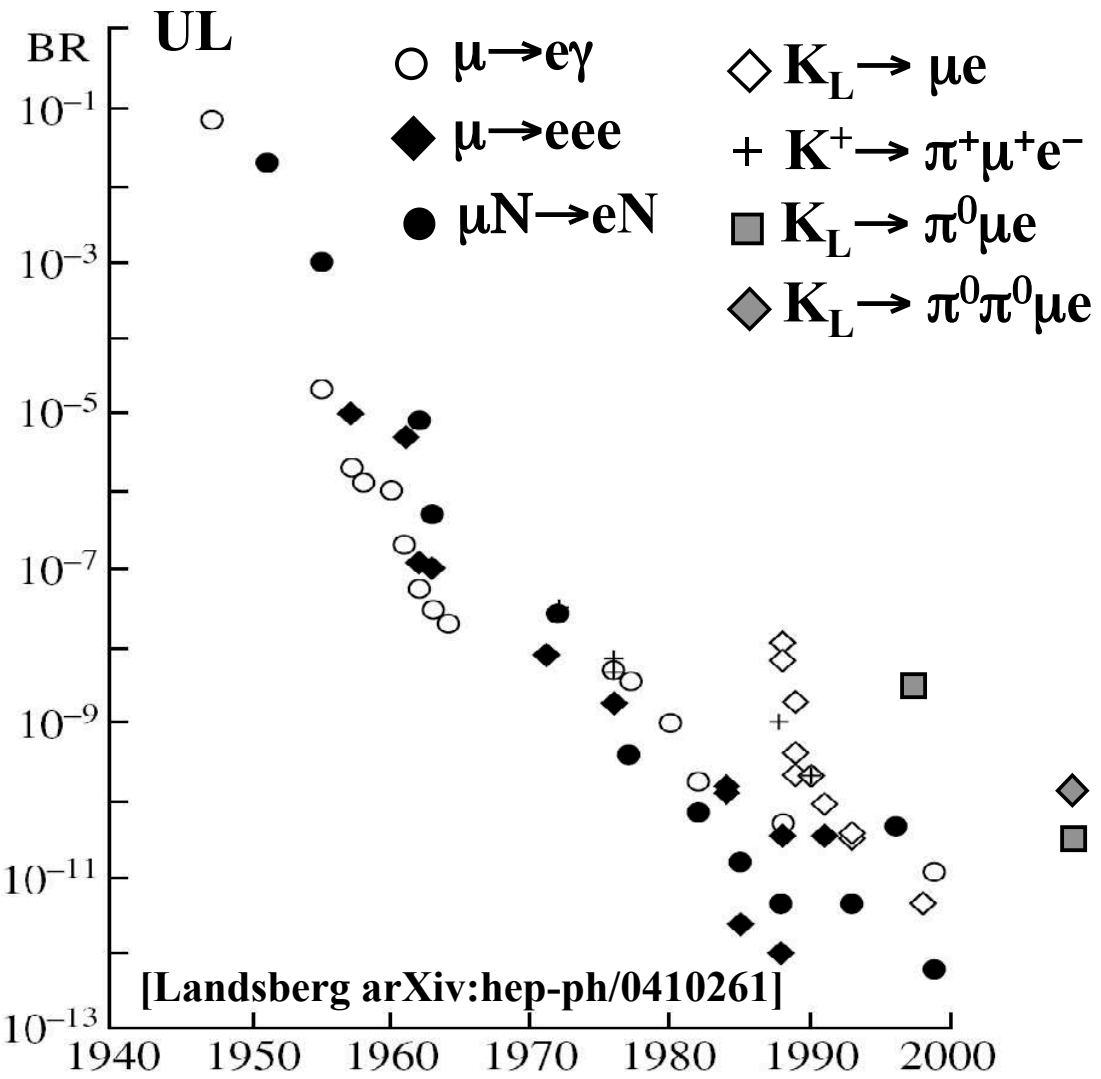
T. Spadaro, LNF INFN

Heavy quarks and leptons
Melbourne, 8th June, 2008

Direct searches for LFV – history

Huge efforts along the years to isolate signals from LFV transitions, which are forbidden/ultra rare in the SM

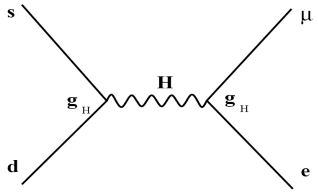
Sensitivity roughly increased by 2 order of magnitudes per decade



Direct searches for LFV with kaons

Searches motivation: tests for tree-level LFV amplitudes possible in Technicolor, SUSY, …

E.g., horizontal bosons in extended TC: $M_H \approx 85\ \mathrm{TeV}\left[\frac{10^{-11}}{B(K^+ \to \pi^+\mu^+ e)}\right]^{1/2}$



Activity still alive, results continue to come (new KTeV limits, → Akashi-Ronquest at this conference):

$K_L \to \mu e$ (10^{-11})

- 22 PRL 63 (1989) 2181, BNL E791
- 3.9 PRL 70 (1993) 1049, BNL E791
- 3.3 PRL 70 (1993) 1049, BNL E791
- 9.4 PR D51 (1995) 2061 KEK E137
- 0.5 PRL 81 (1998) 5734 BNL E871

$K_L \to \pi^0\mu e$ (10^{-11})

- 620 PL B432 (1998) 230, FNAL E799
- 7.6 PRL 100 (2008) 131803, FNAL KTeV

$K_L \to \pi^0\pi^0\mu e$ (10^{-11})

- 17 PRL 100 (2008) 131803, FNAL KTeV

$K^+ \to \pi^+\mu^+e^-$ (10^{-11})

- 2.1 PRL 64 (1990) 165, BNL E777
- 0.39 PRL 85 (2000) 2450, BNL E865
- 0.21 PR D72 (2005) 012005, BNL E865
- 0.13* PR D72 (2005) 012005, BNL E865

*E865 combined

$K_L \to \mu^\pm\mu^\pm e^\mp e^\mp$ (10^{-11})

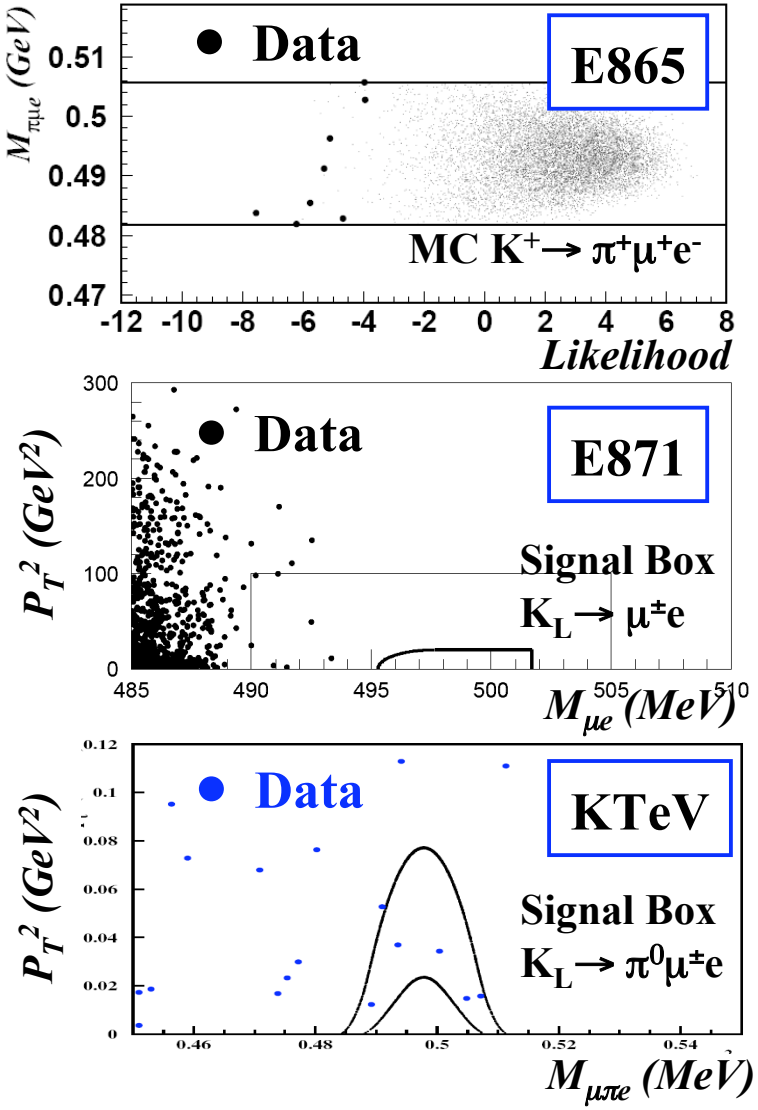
- 610 PRL 76 (1996) 4312, FNAL E799
- 12 PRL 87 (2001) 111802, FNAL KTeV
- 4.1 PRL 90 (2003) 141801, FNAL KTeV

Direct search for LFV

World kaon data dominated by results from fixed target experiments

Results generally dominated by statistics collected

Would simply need higher fluxes to improve by relevant factors



Direct search for LFV – the results

SM extensions with < ~100 TeV mediator masses ruled out by exp, with some model variation (Technicolor, SUSY)

Outcome might have been regarded as disappointing, but allowed focus to be put on new possibilities:

- **Presence of NP-LFV effects in loop amplitudes**
- **Seek LFV-induced deviations in processes suppressed in the SM**
- **Precision physics of rare and not-so-rare processes**

Kaon decay studies are very well suited to match required precisions:

- **Experiments with clean environment, low level of background**
- **Ratios of leptonic and semi-leptonic widths in the SM are predicted @ <0.1% level, accounting for radiative corrections**

Interest in LU tests with kaons

In SM, electron and muon differs only by mass and coupling to Higgs

Can measure ratio of coupling constants, seeking deviations from prediction in processes well determined in SM, like:

$$R_{e\mu} = \Gamma(K_{e3})/\Gamma(K_{\mu 3}) \rightarrow G_F^{\,e}/G_F^{\,\mu},$$

Test of lepton universality for weak vector currents

$$R_{K\pi} = \Gamma(K \rightarrow \mu\nu)/\Gamma(\pi \rightarrow \mu\nu),$$

Test for H^+ exchange (scalar) or presence of right-handed currents

$$R_K = \Gamma(K \rightarrow e\nu)/\Gamma(K \rightarrow \mu\nu)$$

Test for LFV due to effective pseudoscalar weak currents

Vus and LU from Kl3 decays

Motivated by precision unitarity test of CKM 1st row, an intense experimental effort allowed the error on $f_+(0)V_{us}$ to be pushed @ ~0.2%

World data for K_L, $K^+ \to \pi l \nu$ BR's quite satisfactory, determined by experiments with very different techniques:

KLOE @ DAΦNE e^+e^- collider (tagged $K_{L,S}$, $K^{+,-}$ from ϕ decays)

absolute branching ratios for K_L, K^+, and K_S

NA48 @ CERN (intense K^0,K^+ beams from SPS proton beam)

ratio of BR's for K_L and $K^{+,-}$

KTeV @ Fermilab (intense K_L beam from Tevatron proton beam)

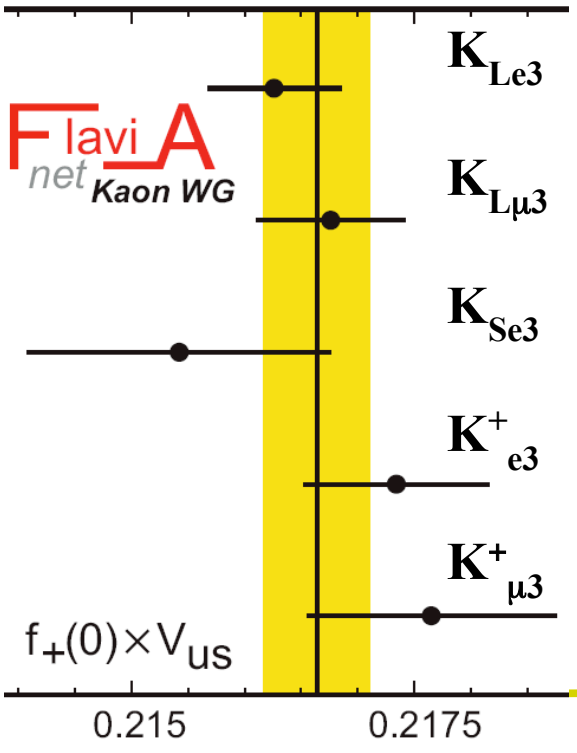
ratio of K_L BR's

ISTRA+ @ IHEP, Protvino

ratio of K^-_{l3} BR's

Experimental status of Kl3 BR's

From: $\Gamma(K_{\ell 3(\gamma)}) = \frac{G_F^2 m_K^5}{192\pi^3} C_K S_{\rm ew} |V_{us}|^2 f_+(0)^2 I_K^\ell(\lambda_{+,0}) \left(1 + \delta_{SU(2)}^K + \delta_{\rm em}^{K\ell}\right)^2$



	$f_+(0) \times \lvert V_{us}\rvert$	Error,%	Contributions to % error			
			BR	τ	Δ	I^l_K
K_{Le3}	0.2163(6)	0.28	0.09	0.19	0.15	0.09
$K_{L\mu 3}$	0.2168(7)	0.31	0.10	0.18	0.15	0.15
K_{Se3}	0.2154(13)	0.67	0.65	0.03	0.15	0.09
K^+_{e3}	0.2173(8)	0.39	0.26	0.09	0.26	0.09
$K^+_{\mu 3}$	0.2176(11)	0.51	0.40	0.09	0.26	0.15
	0.2166(5)	0.22	$P(\chi^2/ndf) = 58\%$			

Vus and LU from Kl3 decays: results

For each K charge state of K_{l3} decays, can evaluate:

$$\frac{(R_{\mu e})_{\rm obs}}{(R_{\mu e})_{\rm SM}} = \frac{\Gamma_{\mu 3}}{\Gamma_{e3}} \cdot \frac{I_{e3}\,(1+\delta_{e3})}{I_{\mu 3}\,(1+\delta_{\mu 3})} = \frac{[|V_{us}|\,f_+(0)]^2_{\mu 3,\,\rm obs}}{[|V_{us}|\,f_+(0)]^2_{e3,\,\rm obs}} = \frac{g_\mu^2}{g_e^2}$$

Result: e/μ universality satisfied:

K_L	$g_\mu^2/g_e^2 = 1.0049(61)$	cfr with	$g_\mu^2/g_e^2 = 1.054(15)$ [PDG04]
K^+	$g_\mu^2/g_e^2 = 1.0029(86)$	cfr with	$g_\mu^2/g_e^2 = 1.019(13)$ [PDG04]
Avg	$g_\mu^2/g_e^2 = 1.0043(52)$		

Compare with test sharing the same theoretical scenario, $\tau \to l\nu\nu$ decays:

$\tau \to l\nu\nu$ $\quad g_\mu^2/g_e^2 = 0.9998(40)$ [PDG07]

Precision from K's comparable with that from τ's

NP effects in Kl2 vs πl2 decays

In two Higgs doublet models (MSSM, too), exchange of H^+ provides an additional scalar current, which might contribute sizeably wrt to SM:

$$\frac{\Gamma(K \to \ell\nu)}{\Gamma_{SM}(K \to \ell\nu)} \cong \left| 1 - \frac{m_{K+}^2}{M_{H+}^2}\left(1 - \frac{m_d}{m_s}\right)\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right|$$

[Hou PRD48 (1992) 2342, Isidori-Paradisi]

NP effect is suppressed for π_{l2} wrt K_{l2}, so NP might appear in K*l2* / π*l2*, predicted in the SM to be:

$$\frac{\Gamma(K^{\pm}_{\ell 2(\gamma)})}{\Gamma(\pi^{\pm}_{\ell 2(\gamma)})} = \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{f_K^2 m_K}{f_\pi^2 m_\pi}\left(\frac{1-m_\ell^2/m_K^2}{1-m_\ell^2/m_\pi^2}\right)^2 \times (1+\delta_{\rm em})$$

NP test from comparing V_{us}/V_{ud} from M→*l*ν with $V_{us}(K_{l3})/V_{ud}(0^+ \to 0^+)$:

$$\left|\frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\ell 2})}\right| \stackrel{?}{=} \left| 1 - \frac{m_{K+}^2}{M_{H+}^2}\left(1 - \frac{m_d}{m_s}\right)\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right|$$

NP effects in Kl2 vs πl2 decays

Experimental inputs are known at few per-mil level:

$m_{K,\pi,\mu}$, $\Gamma(\pi_{\mu 2})$	[PDG]
$\tau^+ = 12.384(19)$	[average of PDG and recent KLOE measurement]
$BR(K^+ \to \mu^+\nu(\gamma)) = 63.66(17)\%$	[KLOE]
$\lvert f_+(0)V_{us}\rvert = 0.2166(5)$	[world average K*l3*]
$V_{ud} = 0.97372(26)$	[world average $0^+ \to 0^+$]

Theoretical inputs dominate the uncertainty, through the form factors:

$f_K / f_\pi = 1.189(7)$	[MILC-HPQCD arXiv:0706.1726]
$f_+(0) = 0.964(5)$	[UKQCD-RBC hep-lat/0702026]
$\delta_{em} = -0.0070(35)$	[Marciano PRL 93 (2004) 231803, Cirigliano Rosell JHEP 0710, 005 (2007)]

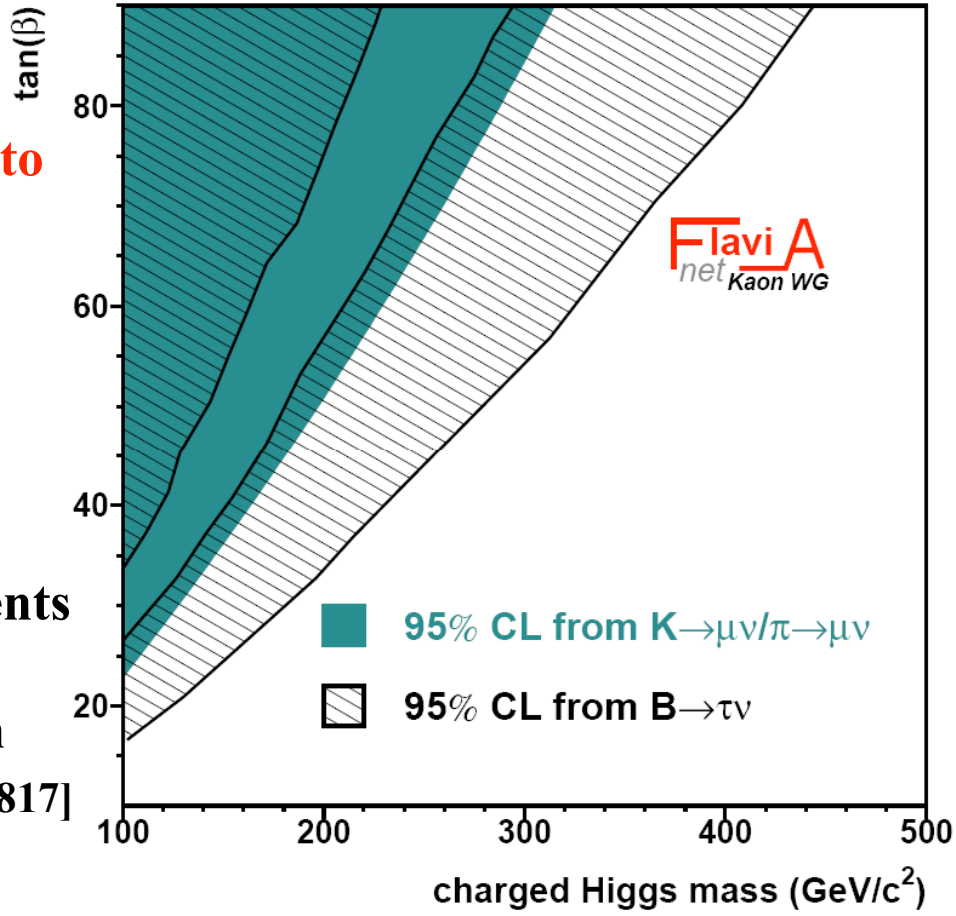
NP effects in Kl2 vs πl2 decays

Result is: $\left|\frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\ell 2})}\right|$ **= 1.0018(57)**

NP sensitivity from K→ μν comparable to that from BR(B → τν) = 1.42(44)×10^{-4}
[Babar-Belle average]

Error dominated by theoretical uncertainties in form factors

NP induced by weak right-handed currents can be also tested (there, complement lattice information with Callan-Treiman scalar ff constraint) [FlaviaNet arXiv:0801.1817]



New-physics potential of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$

SM prediction w 0.04% precision, benefits of cancellation of hadronic uncertainties (no f_K): $R_K = 2.477(1) \times 10^{-5}$ [Cirigliano Rosell arXiv:0707:4464]

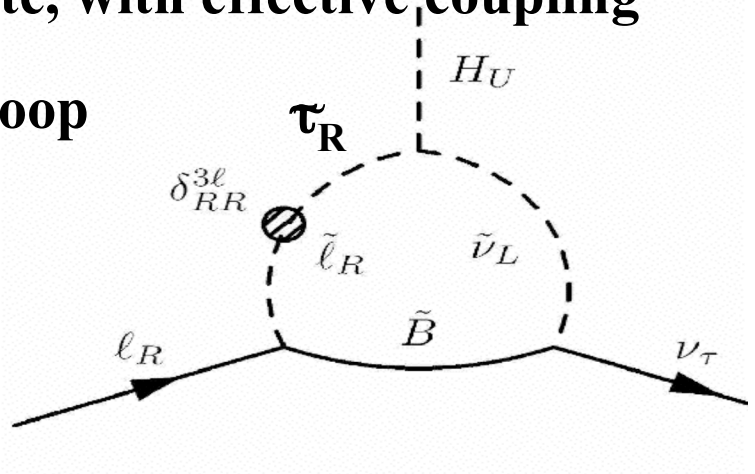
Helicity suppression can boost NP [Masiero-Paradisi-Petronzio PRD74 (2006) 011701]

In R-parity MSSM, LFV can give 1% deviations from SM:

$$R_K^{LFV} \simeq R_K^{SM}\left[1+\left(\frac{m_K^4}{M_H^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_R^{31}|^2\ \tan^6\beta\right]$$

NP dominated by contribution of $e\nu_\tau$ final state, with effective coupling

$$lH^{\pm}\nu_\tau \ \rightarrow\ \frac{g_2}{\sqrt{2}}\frac{m_\tau}{M_W}\,\Delta_{13}$$ **, from loop**



Present exp. accuracy on R_K @ 6%

New measurement of R_K can be very interesting, if error is pushed @1% or better

Entering the precision realm for R_K

Main actors (experiments) in the challenge to push down precision on R_K:

KLOE

- **preliminary result with 2001—5 data: $R_K = 2.55\ (5)_{stat}\ (5)_{syst}\ 10^{-5}$, from ~ 8000 Ke2 candidates (3% accuracy), perspectives to reach 1% error after analysis completion**

NA48/2

- **preliminary result with 2003 data: $R_K = 2.416\ (43)_{stat}\ (24)_{syst}\ 10^{-5}$, from ~ 4000 Ke2 candidates, statistical error dominating (2% accuracy)**

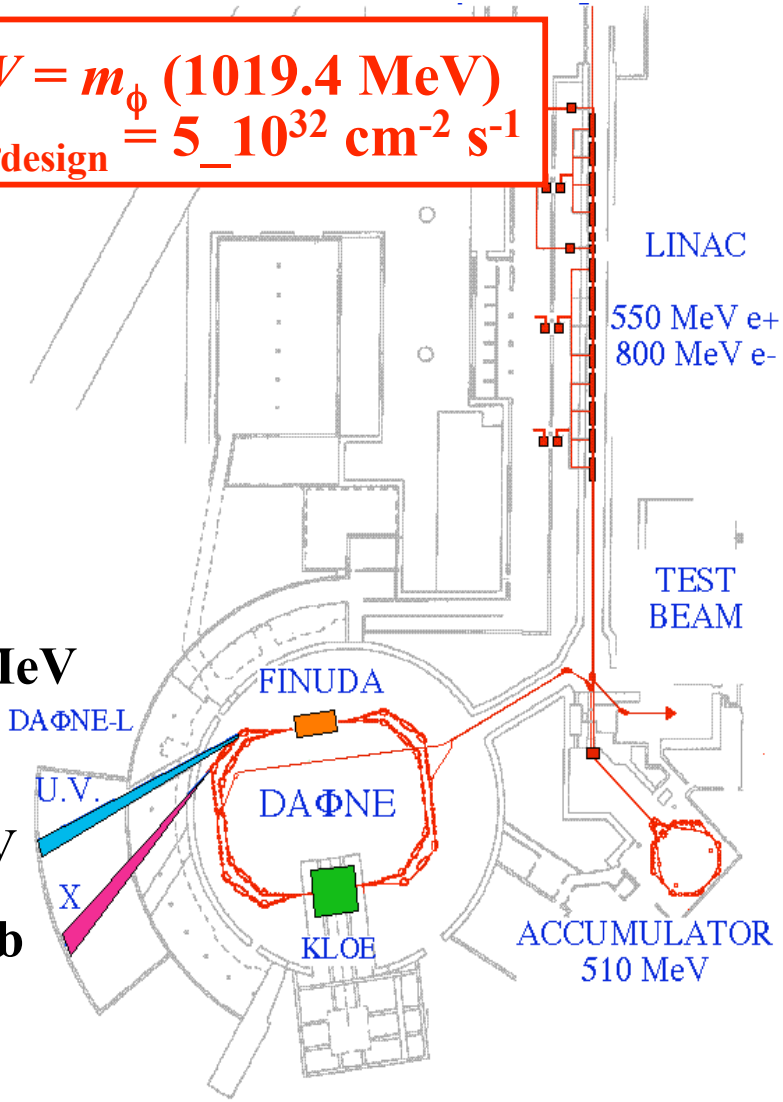
- **preliminary result with 2004 data: $R_K = 2.455\ (45)_{stat}\ (41)_{syst}\ 10^{-5}$, from ~ 4000 Ke2 candidates from special minimum bias run (3% accuracy)**

NA62 (ex NA48)

- **collected ~ 100,000 Ke2 events in dedicated 2007 run, aims at breaking the 1% precision wall, possibly reaching < ~0.5%**

The DAΦNE e^+e^- *collider*

$W = m_\phi$ (1019.4 MeV)
$\mathcal{L}_{design} = 5_10^{32}\ cm^{-2}\ s^{-1}$



Collisions at cm energy around m_ϕ: **$\sqrt{s} \sim 1019.4$ MeV**

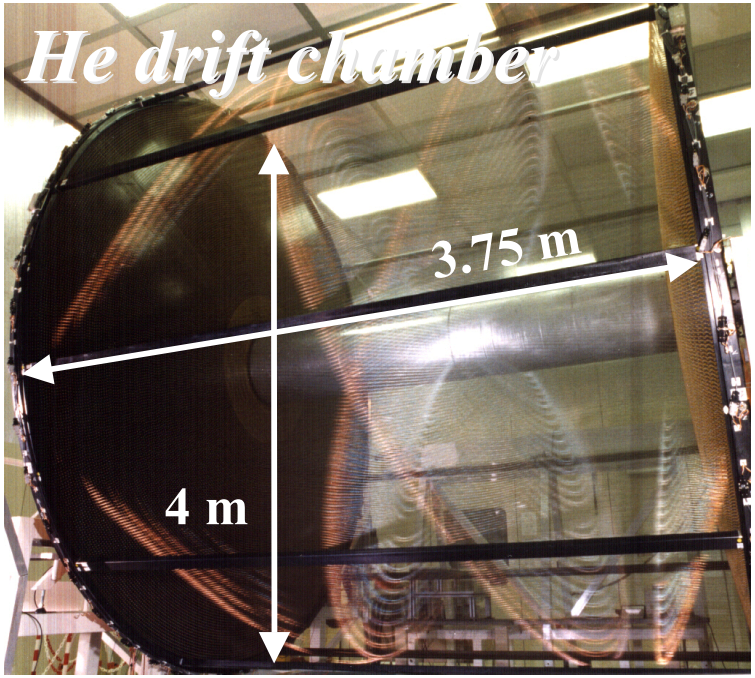
Angle between the beams @ IP: **$\alpha \sim 12.5$ mrad**

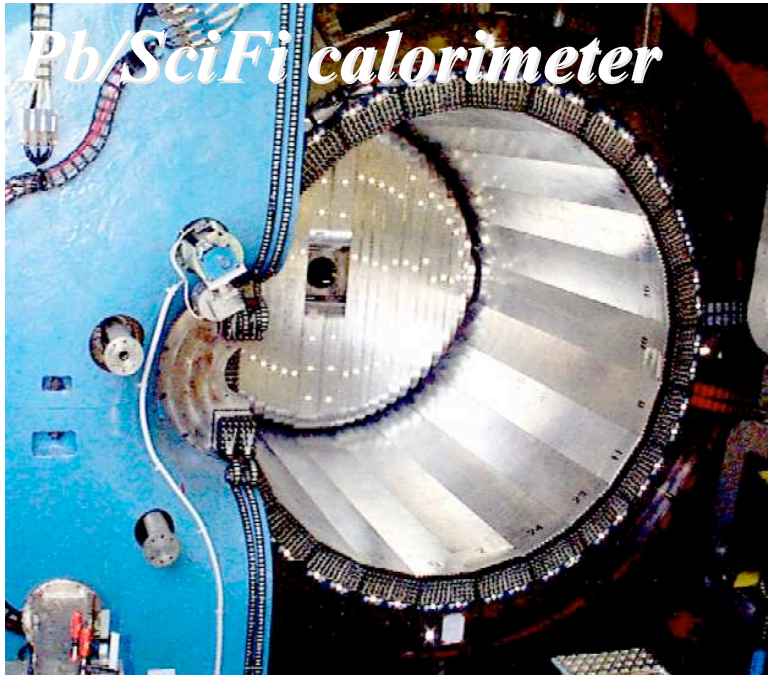
Residual laboratory momentum of ϕ: **$p_\phi \sim 13$ MeV**

Cross section for ϕ production @ peak: **$\sigma_\phi \sim 3.1$ μb**

The KLOE detector

Large cylindrical drift chamber + lead/scintillating-fiber calorimeter + superconducting coil providing a 0.52 T field





σ_p/p **0.4 %** (tracks with $\theta > 45°$)
σ_x^{hit} **150 μm (*xy*), 2 mm (*z*)**
σ_x^{vertex} **~1 mm**

σ_E/E **5.7% /√*E*(GeV)**
σ_t **54 ps /√*E*(GeV) ⊕ 50 ps**
(relative time between clusters)
$\sigma_L(\gamma\gamma)$ **~2 cm** (π^0 from $K_L \to \pi^+\pi^-\pi^0$)

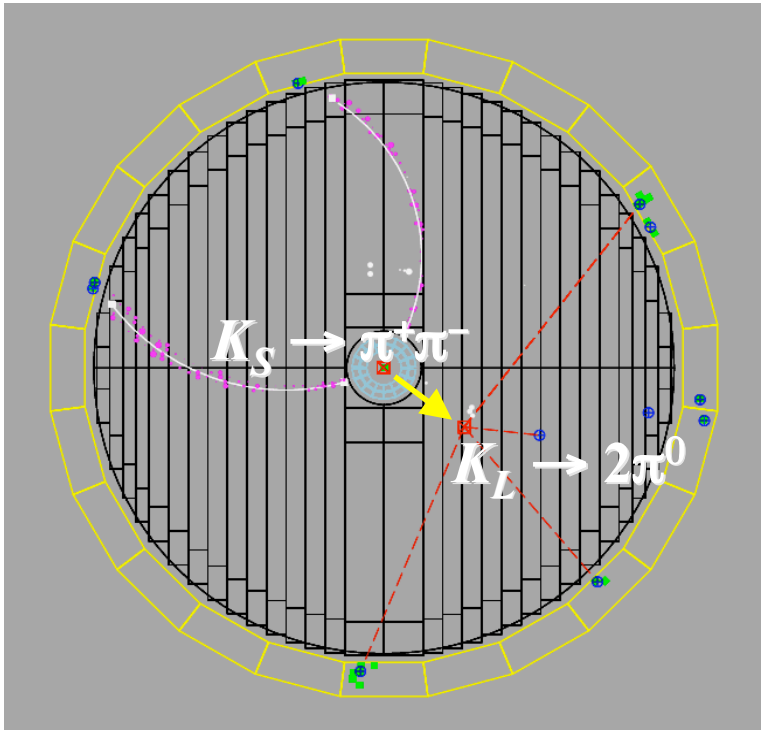
Kaon physics at KLOE

KK pairs emitted ~back to back, p ~ 110 MeV

Identification of $K_{S,L}$ ($K^{+,-}$) decay tags presence of $K_{L,S}$ ($K^{-,+}$)

Almost pure $K_{L,S}$ and $K^{-,+}$ beams of known momentum + PID (kinematics & TOF):

- **Access to absolute BR's**
- **Precise measurements of K_{Le3} from factors and K_L, K^+ lifetimes (acceptance ~0.5 τ_L, τ_+)**



Above points crucial for V_{us} determination

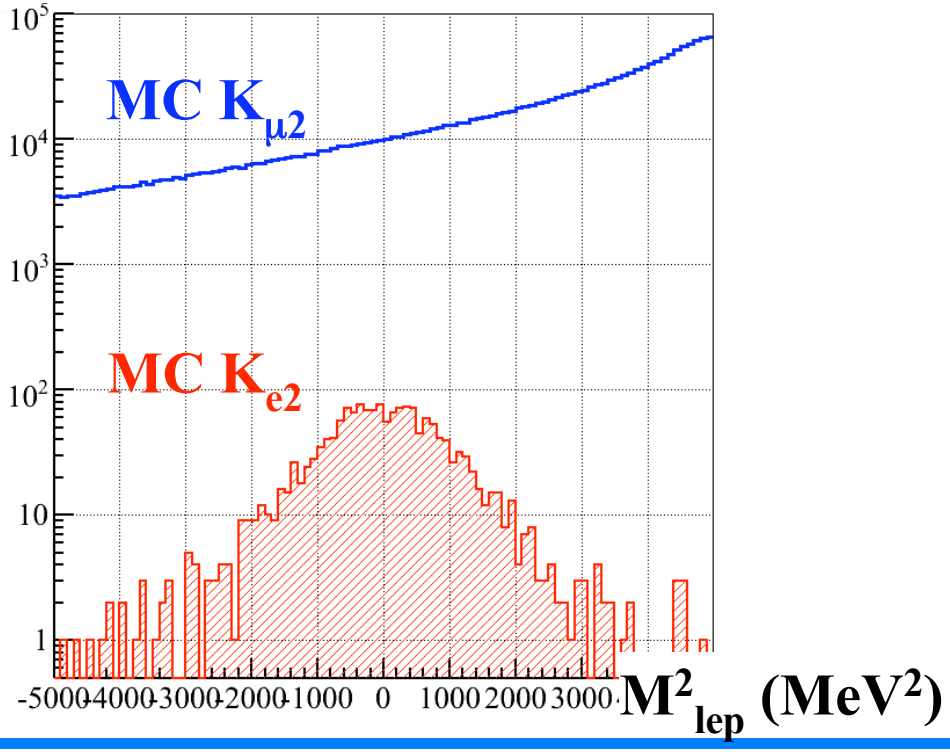
Analysis of Ke2/Kμ2 at KLOE

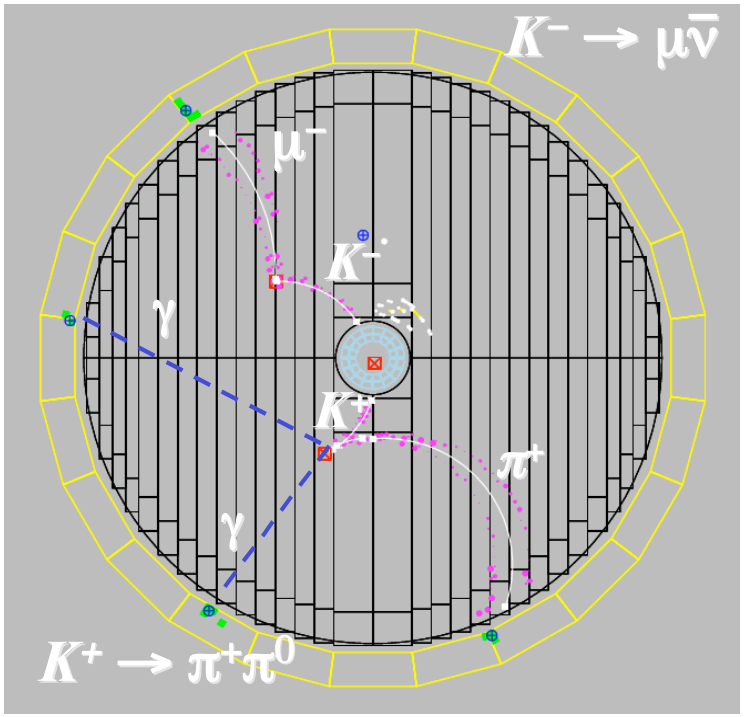
KLOE integrated ~2.5 fb^{-1} of data & BR(K_{e2})~10^{-5}: expect < ~4×10^4 events

Perform direct search for K_{e2} and $K_{\mu 2}$, no tag: gain ×4 of statistics

Select 1-prong kinks in DC, K track from IP & secondary P > 220 MeV

Exploit tracking of K and secondary: assuming m_ν=0 get M^2_{lep}





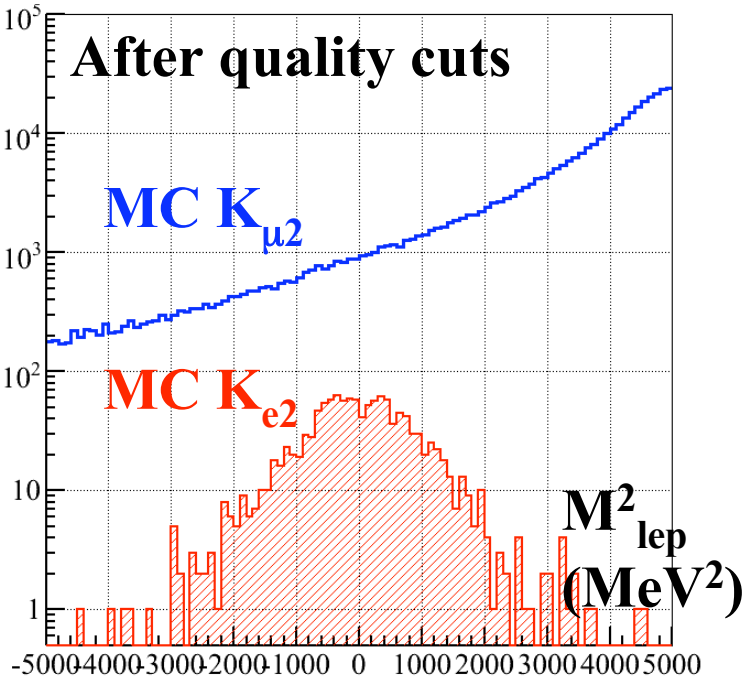
Analysis of R_K = Ke2/Km2

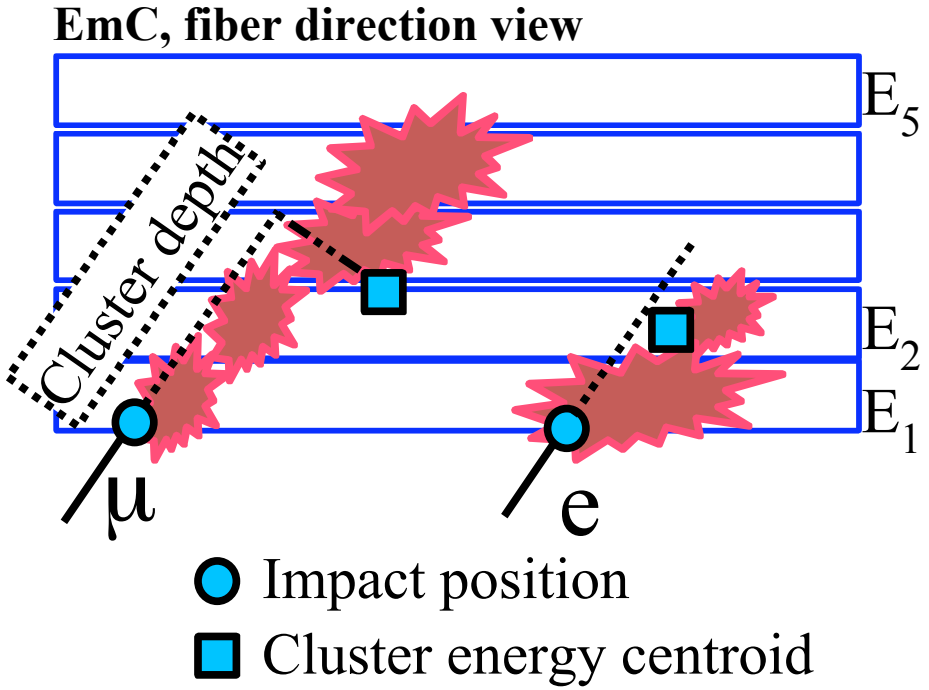
Apply quality cuts, enough to count $K_{\mu 2}$, not for K_{e2} (still Bkg ~ 10×Sig)

1-prong efficiency ratio correction only 2%, use data CS of $K_{\mu 2}$ to check

Further rejection for K_{e2}: extrapolate track to EmC, select closest cluster

PID exploits EmC granularity: energy deposits E_k into 5 layers in depth

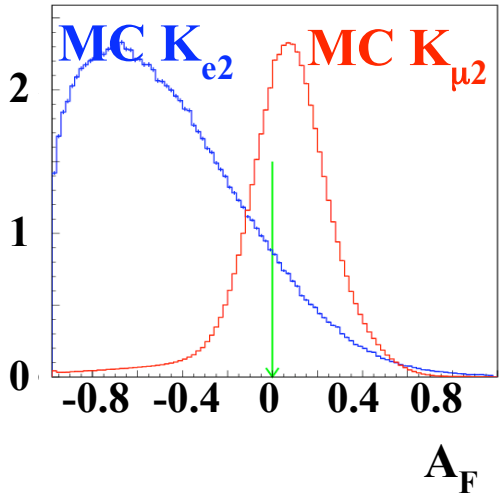


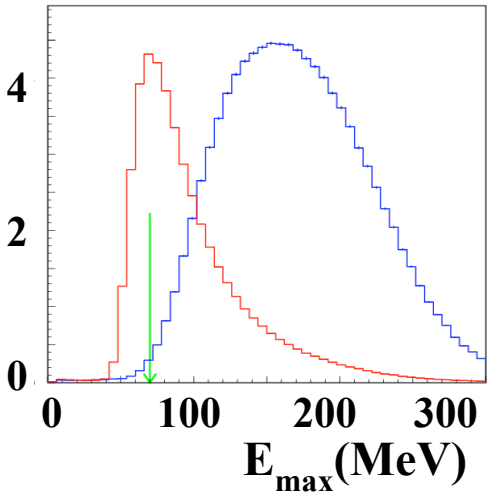


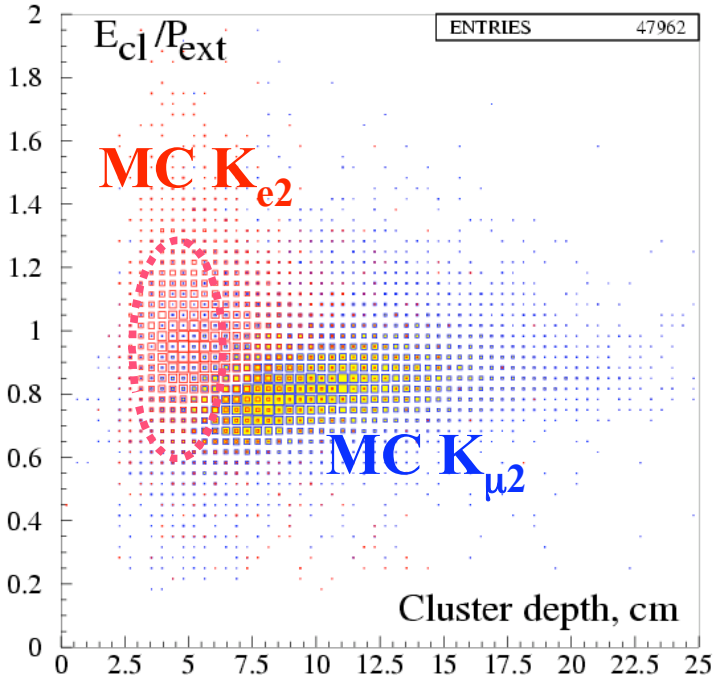
Analysis of R_K – PID using EmC

e's: initiate shower @ EmC entrance, $E_{cl}/P \sim 1$
μ's: MIP-like in layers 1-2, Bragg peak @ end

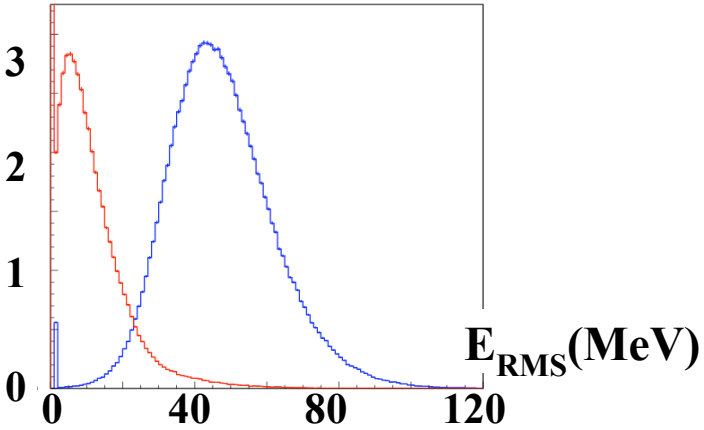
Cut on $A_F = \dfrac{(E_2 - E_1)}{(E_2 + E_1)}$ **,** $E_{max} = \max\{E_k\}$







Cut on $A_L = \dfrac{(E_n - E_{n-1})}{(E_n + E_{n-1})}$ **,** $E_{RMS} = \mathrm{RMS}\{E_k\}$ **left for signal counting**

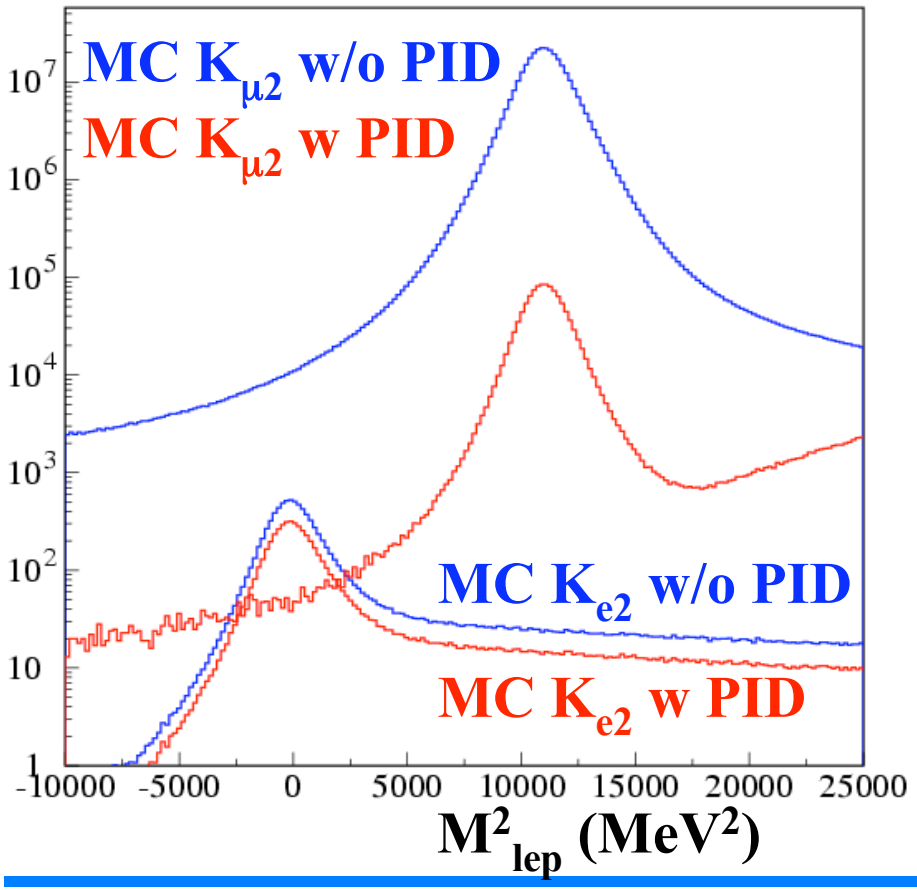


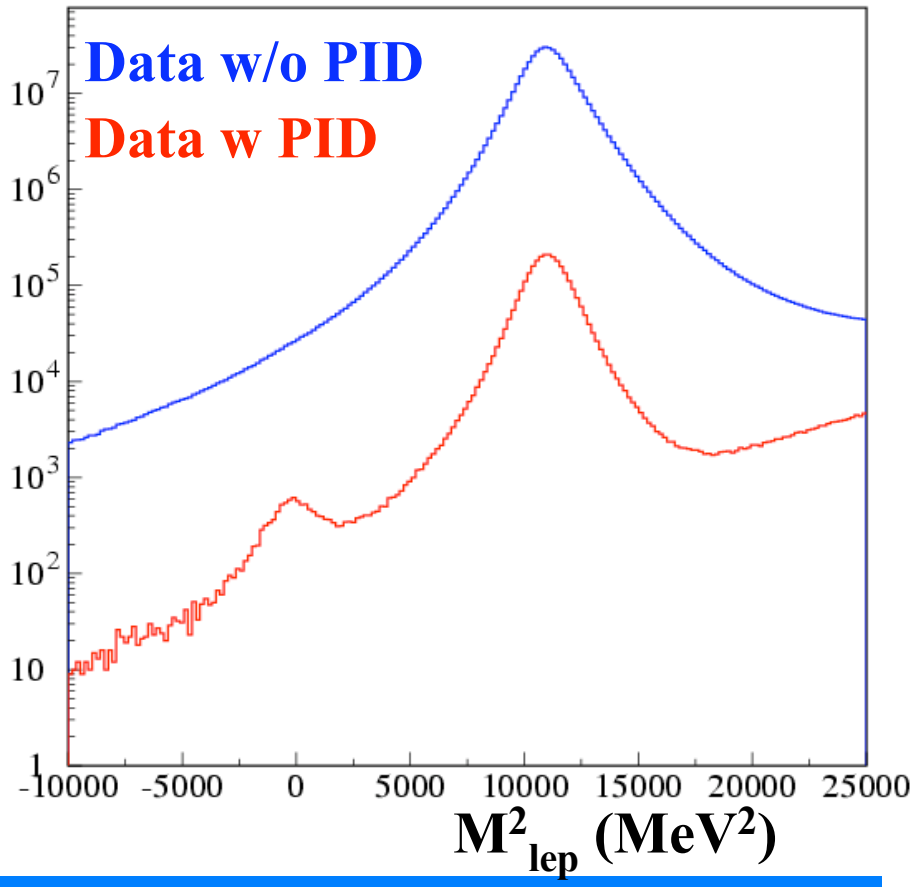
Analysis of Ke2/Km2 – PID via EmC

Impact of PID: retain 60% of signal, reject all but 0.2% of background

Check with K_{Le3} data/MC control sample

After PID (rejection factor is ~500) count Ke2 events

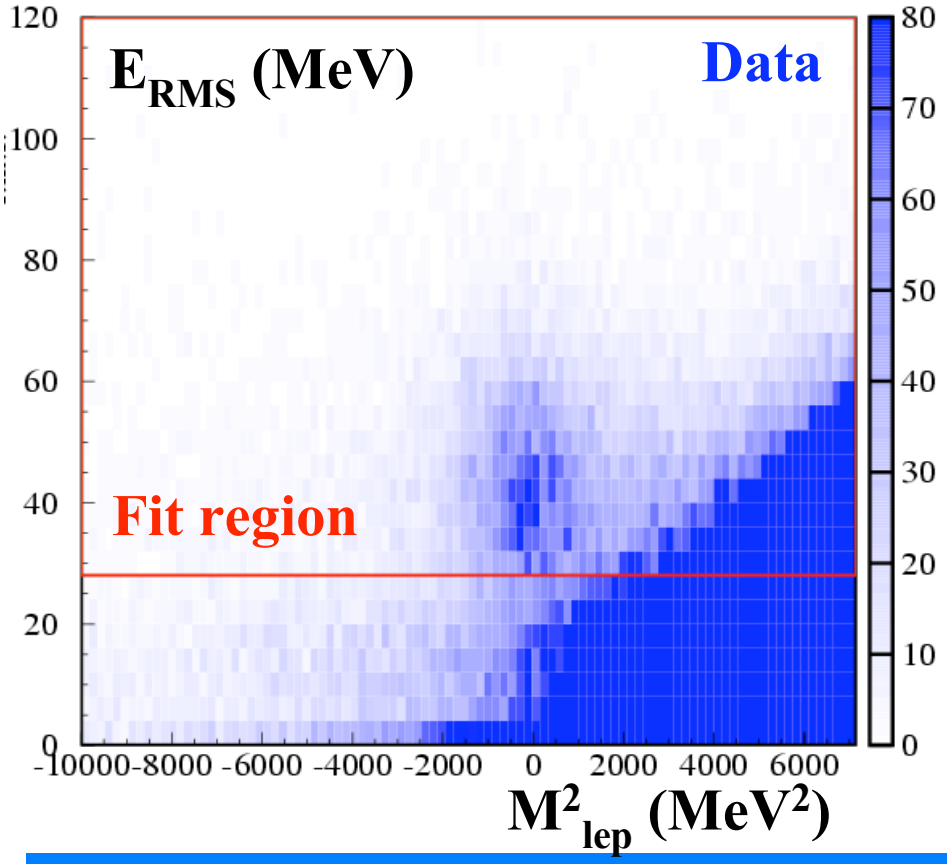


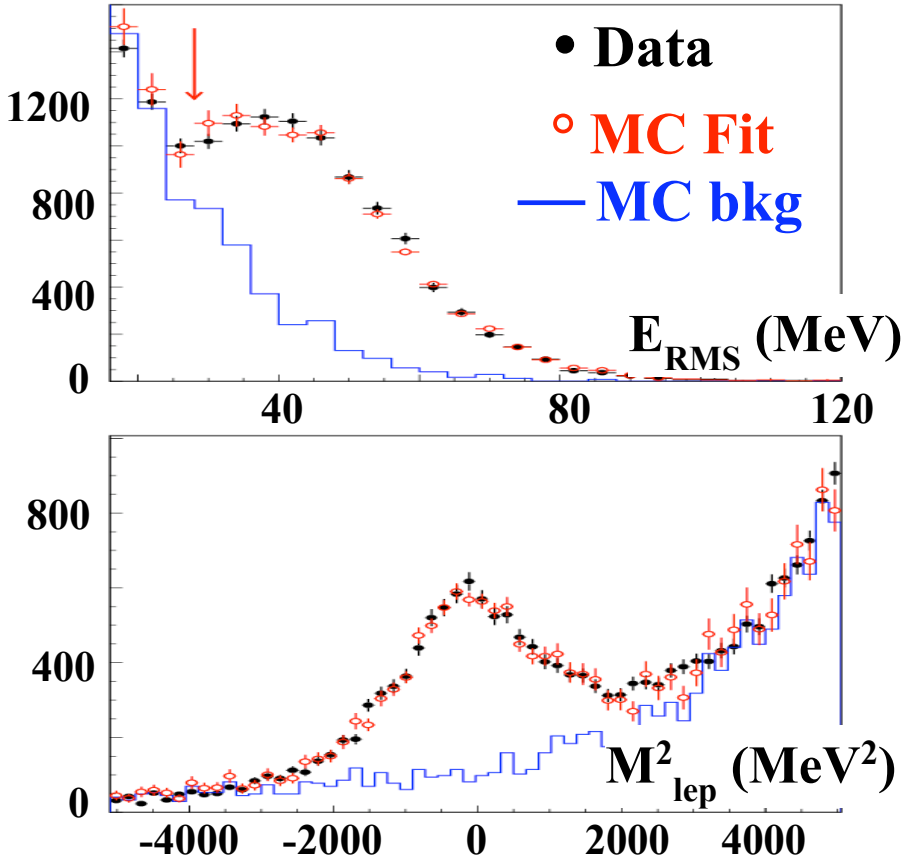


Analysis of R_K – Count Ke2 events

K_{e2} event counts: likelihood fit of M_{lep} vs E_{RMS}

- **Input: MC shapes for $K_{e2(\gamma)}$ and background**
- **Fit parameters: # of K_{e2} and background, result: 8090±160 observed evts**

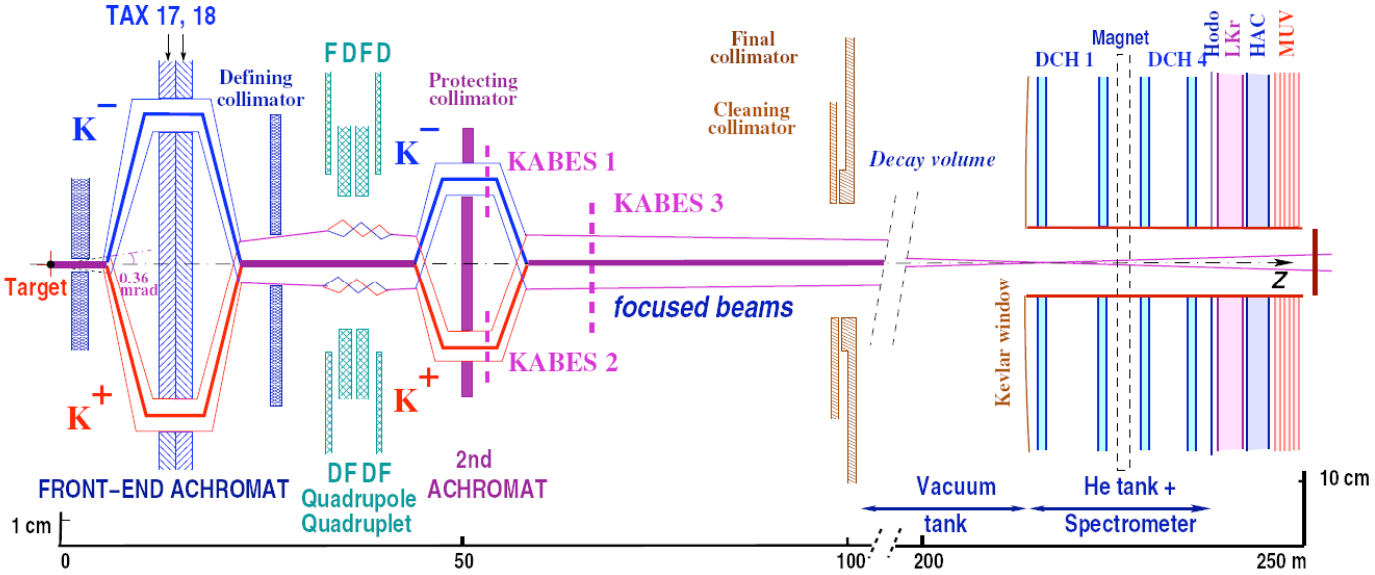


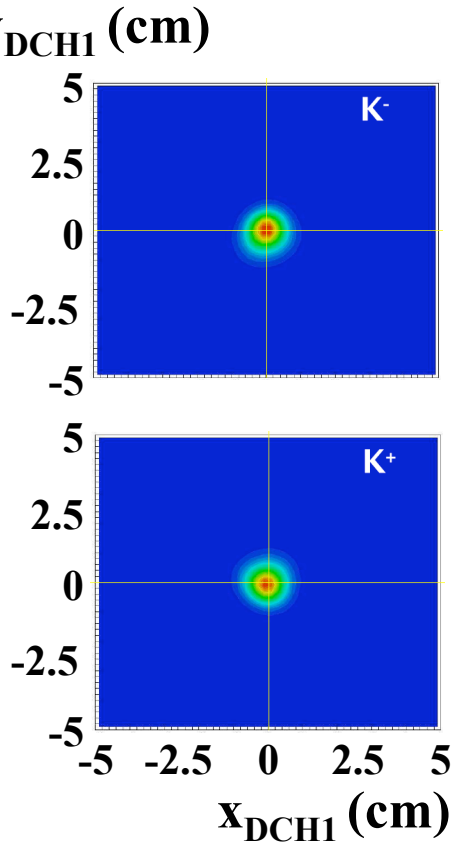


The NA48/2 experiment

Unseparated, simultaneous $K^{\pm}$ highly collimated beams, designed to precisely measure $K^{\pm} \to \pi^{+,0}\pi^{-,0}\pi^{\pm}$ dalitz-plot density:

- $p_K \sim 60$ GeV, $\sigma_p \sim 3$ GeV (3.8% p-bite)
- spot of ~ 5 mm width @ DCH1 entrance





Track decay products with 4 DCH's:

- $P_\perp$ kick of 121 MeV after DCH2
- $\sigma_p/p \sim 1.02\% \oplus 0.044\%\ p$ [GeV]

Analysis of Ke2/Kμ2 at NA48/2

Scintillator hodoscope:

- **establish event time (σ~150 ps), initiate trigger**

LKr calorimeter: efficient vetoing, e.m. energy resolution

- **$\sigma_E/E = 3.2\%/\sqrt{E[GeV]} \oplus 9\%/E[GeV] \oplus 0.42\%$**
- **$\sigma_{x,y} = 4.2mm/\sqrt{E[GeV]} \oplus 0.6$ mm, granularity of ~13,000 2×2 cm^2 cells**

Hadron calorimeter, Muon veto system

Analysis starting samples:

- **1-track minimum bias trigger, acquired during 12-hour run in 2003**
- **1-track triggers, acquired during 56-hour special run in 2004**

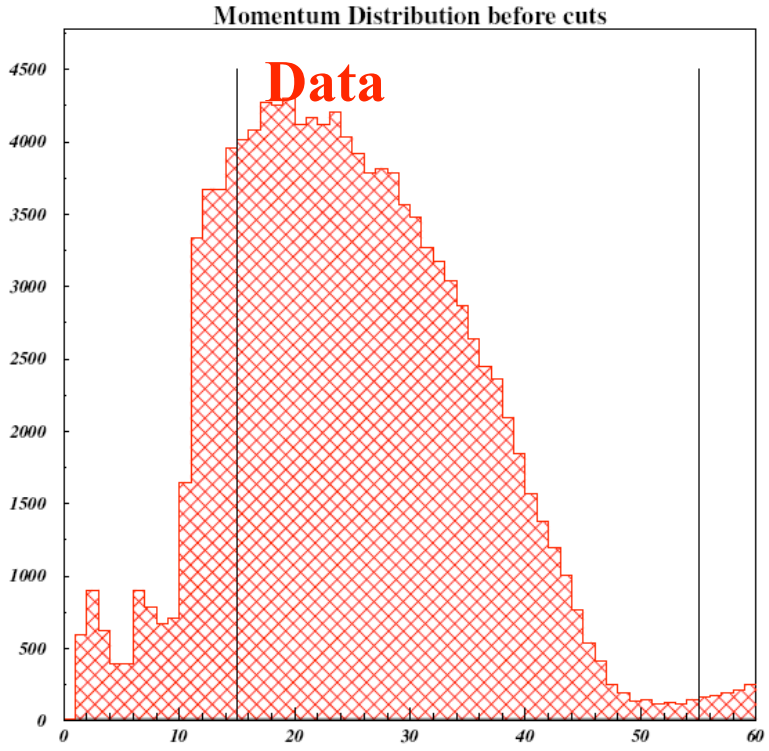
  Ke2 trigger: 1 track (hodoscope) + ELKR > 10 GeV

  Kμ2 trigger: 1 track (hodoscope), possibly downscaled

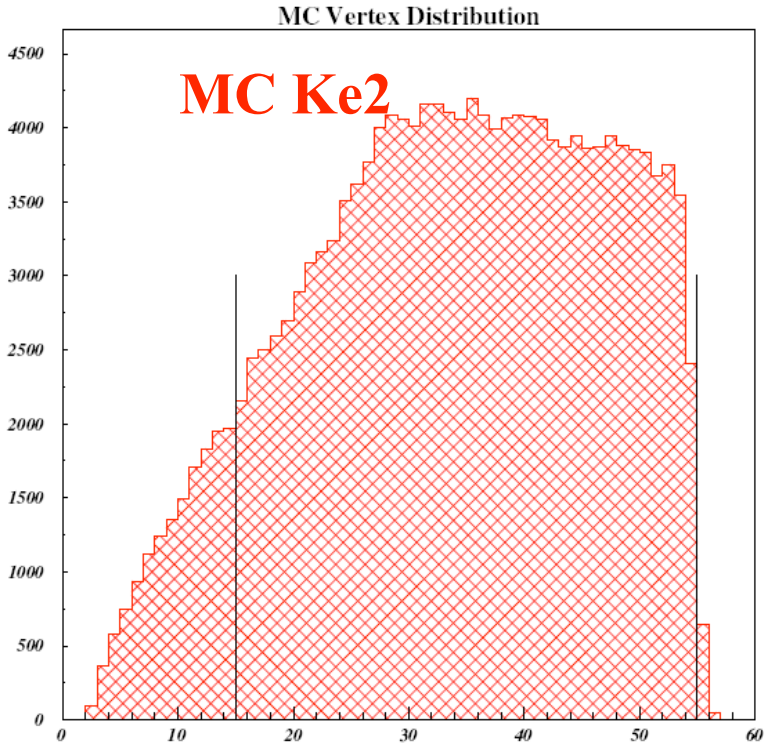
Analysis of Ke2/Km2 at NA48/2

Main analysis steps for Ke2, Kμ2 selection:

One track with 15 < p < 50 GeV, passing acceptance + quality cuts



p (GeV)



p (GeV)

Analysis of Ke2/Kμ2 at NA48/2

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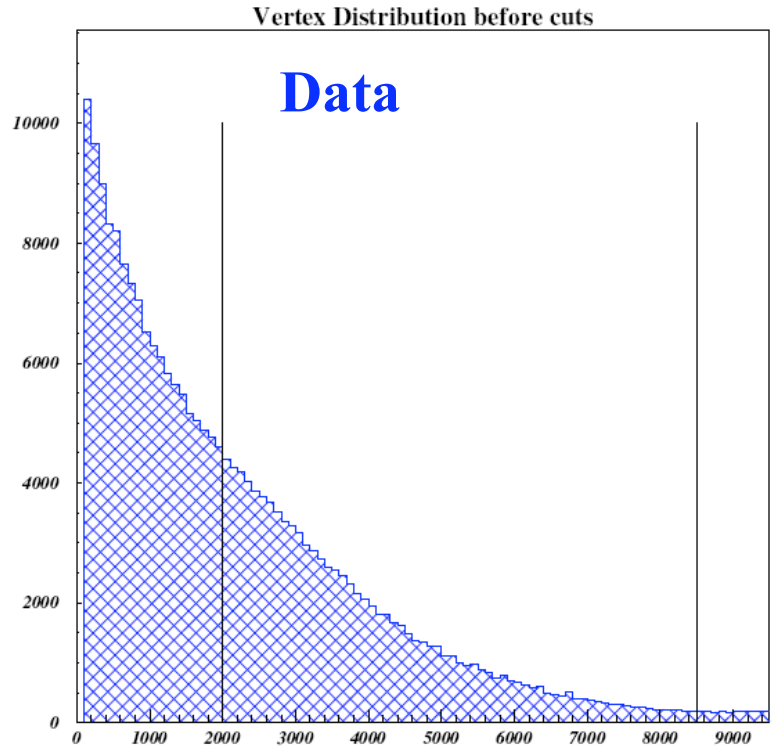
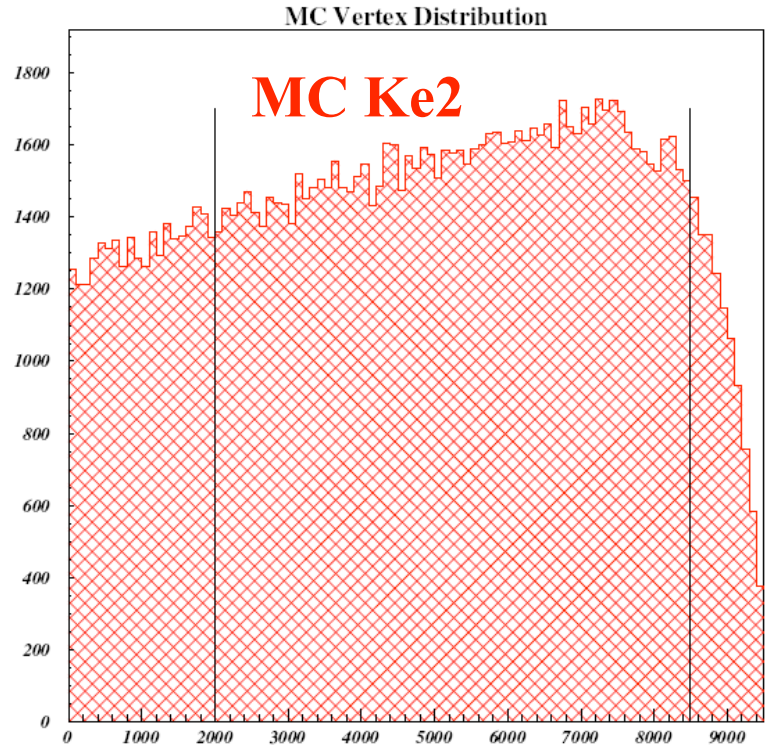


Z_{vtx} (cm)



Z_{vtx} (cm)

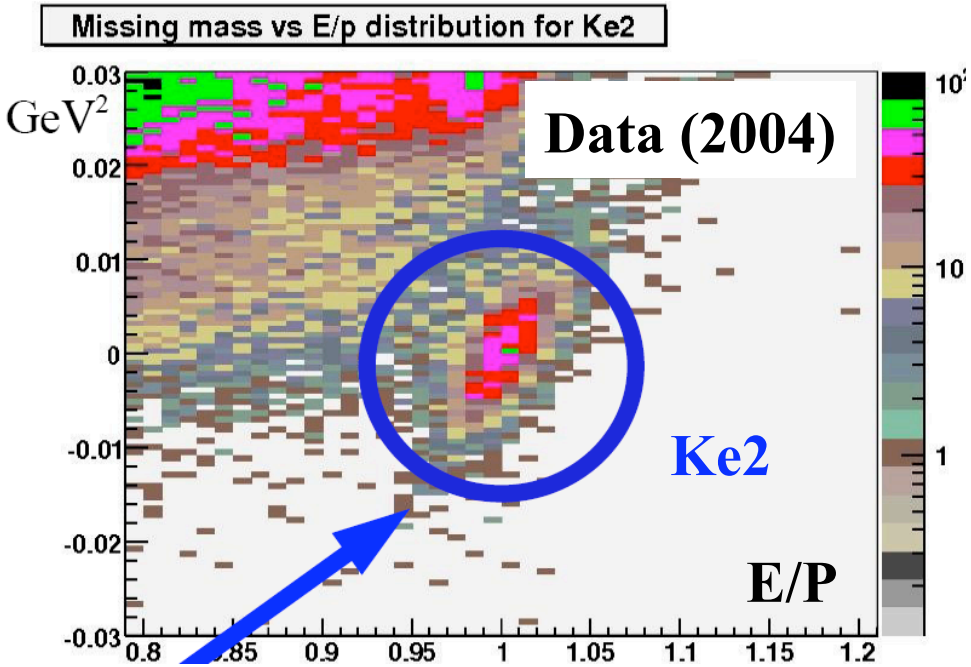
Analysis of Ke2/Kμ2 at NA48/2

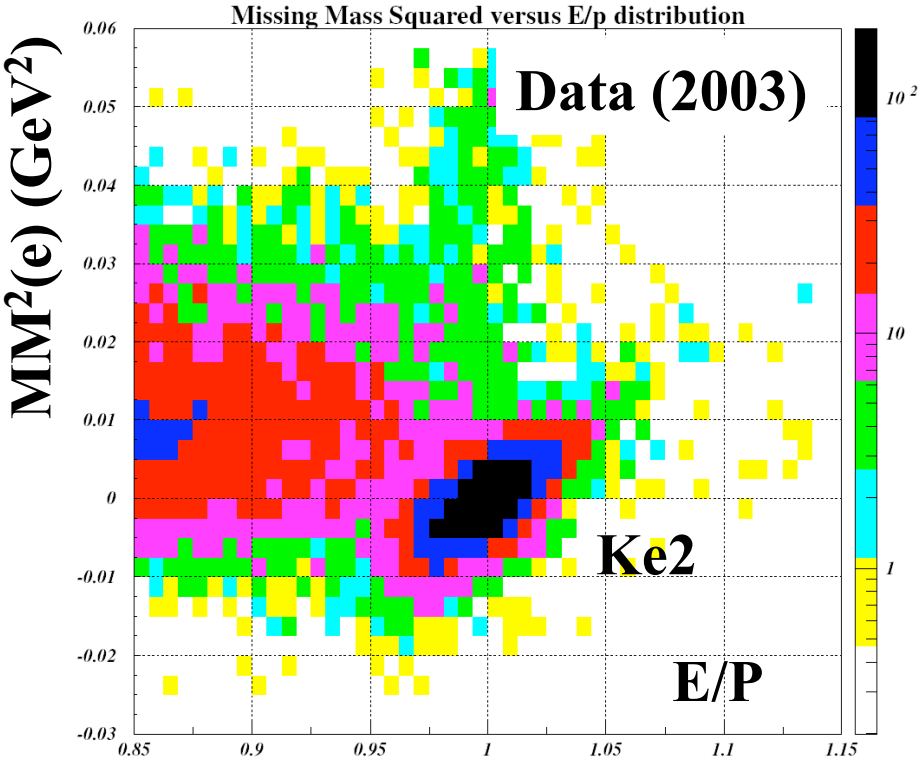
Main analysis steps for Ke2, Kμ2 selection:

Associate electron track to LKr cluster, compute E/P

Veto events with extra energy in LKr above 1.5 GeV

Calculate missing mass squared, assuming electron hypothesis

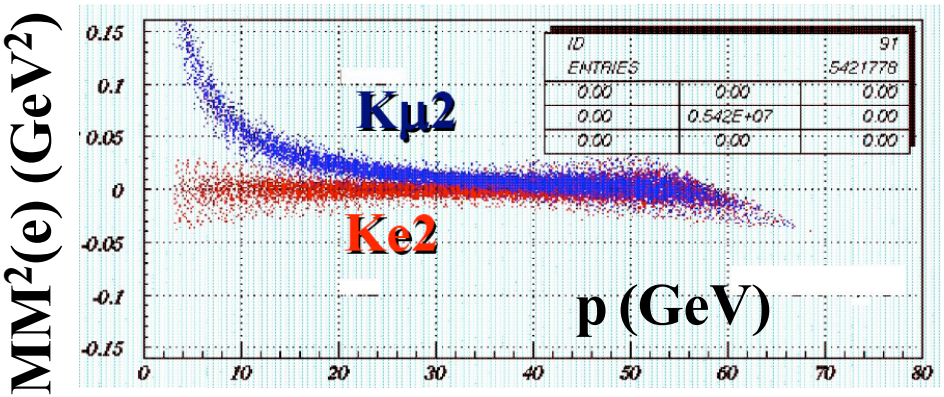


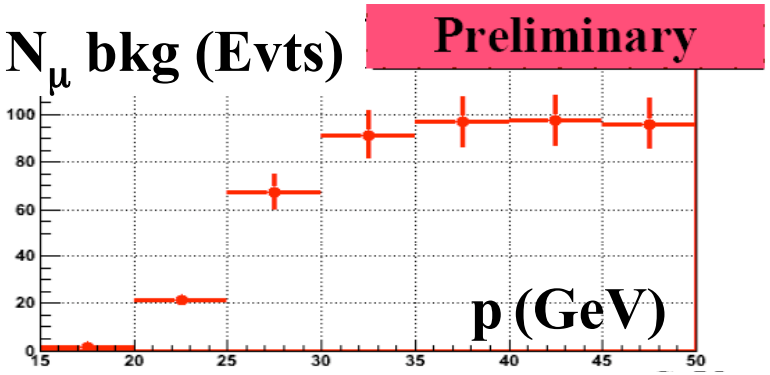


Analysis of Ke2/Km2 at NA48/2

Main bkg to Ke2 selection due to Kμ2 with μ faking e cluster, O(5×10^{-6}):

- **At high momentum, p > ~30 GeV, can't reject Kμ2 using kinematics**
- **Evaluate probability of "catastrophic release" from selected μ sample**
- **Statistics of μ sample induces a systematic error for bkg subtraction**





For the analysis of 2004 data:

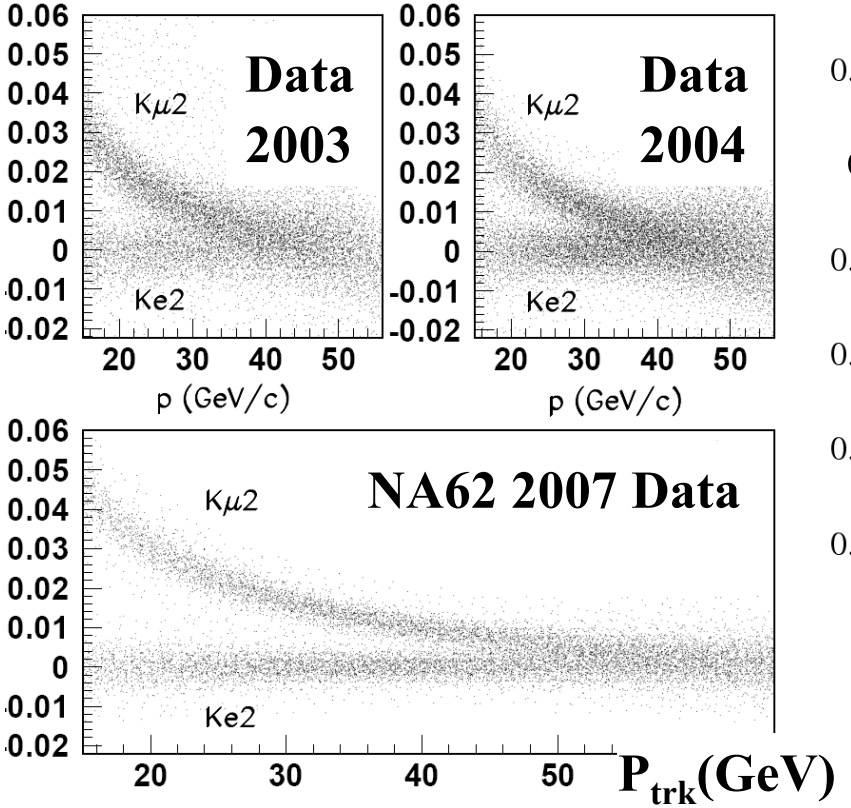
- **1.85% statistical error due to Ke2 counts**
- **1.59% systematic error due to subtraction of Kμ2 bkg for Ke2**

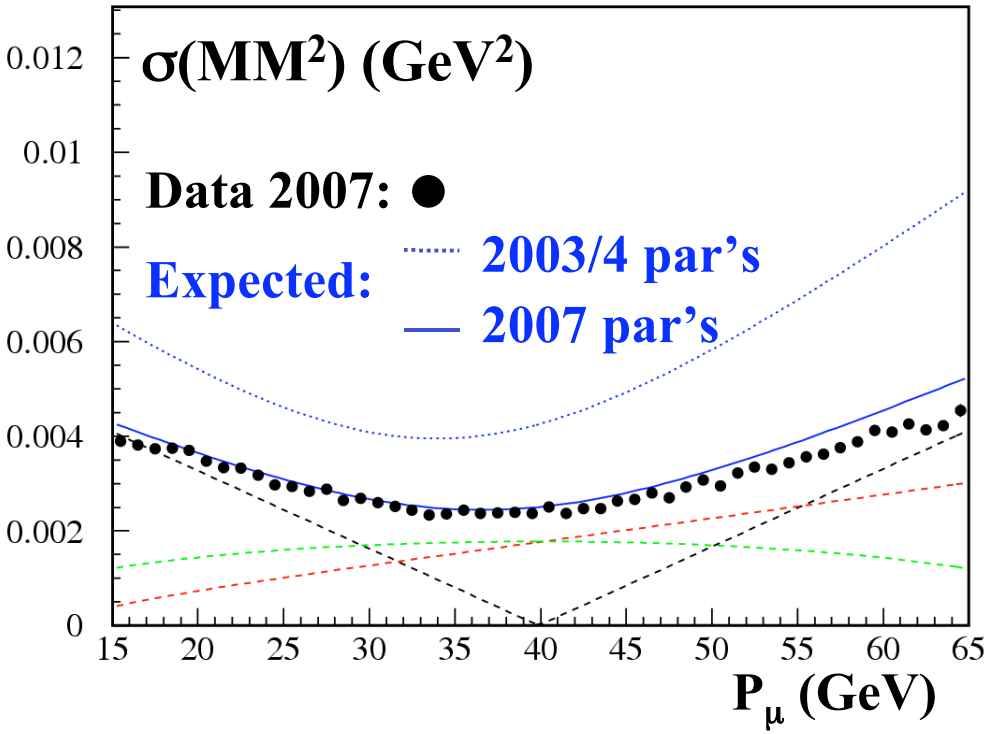
Analysis of Ke2/Km2 at NA62

Design of NA62 run optimized for Ke2/Km2, major parameters tuned:

P_K: ~60 GeV → ~75 GeV
Momentum bite: 3.8% → 2.5%
$P_\perp$ kick: 120 MeV → 263 MeV

MM^2 resolution improved
Better separation for Ke2 and Kμ2





Resolution contributions: P_K, P_μ, $\theta_{K\mu}$

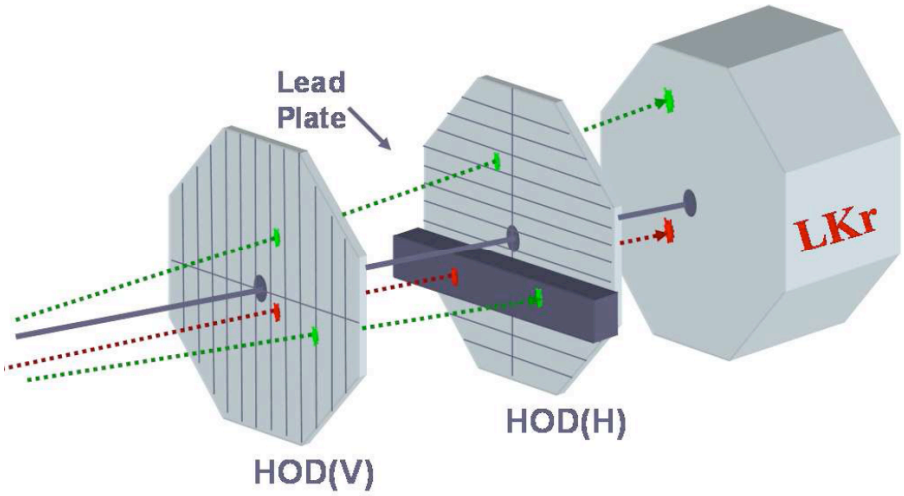
Analysis of Ke2/Km2 at NA62

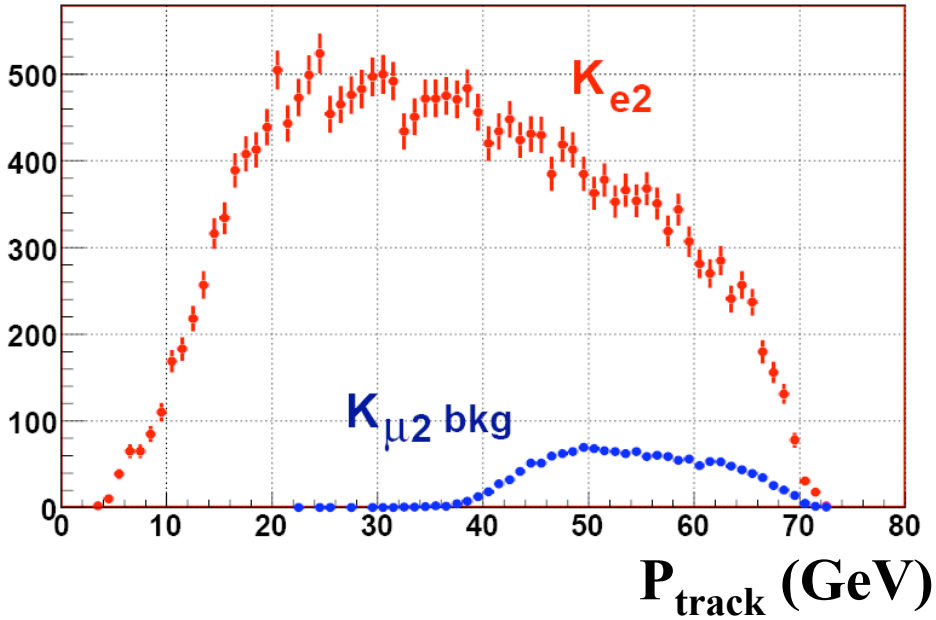
Will check probability for μ to fake e, directly measuring it:

Subsample of data taken with Pb wall between HOD's

Use HOD pulse heights to select μ's with MIP energy loss in Pb

Expect ~ 7% total bkg to Ke2, dominated by Kμ2

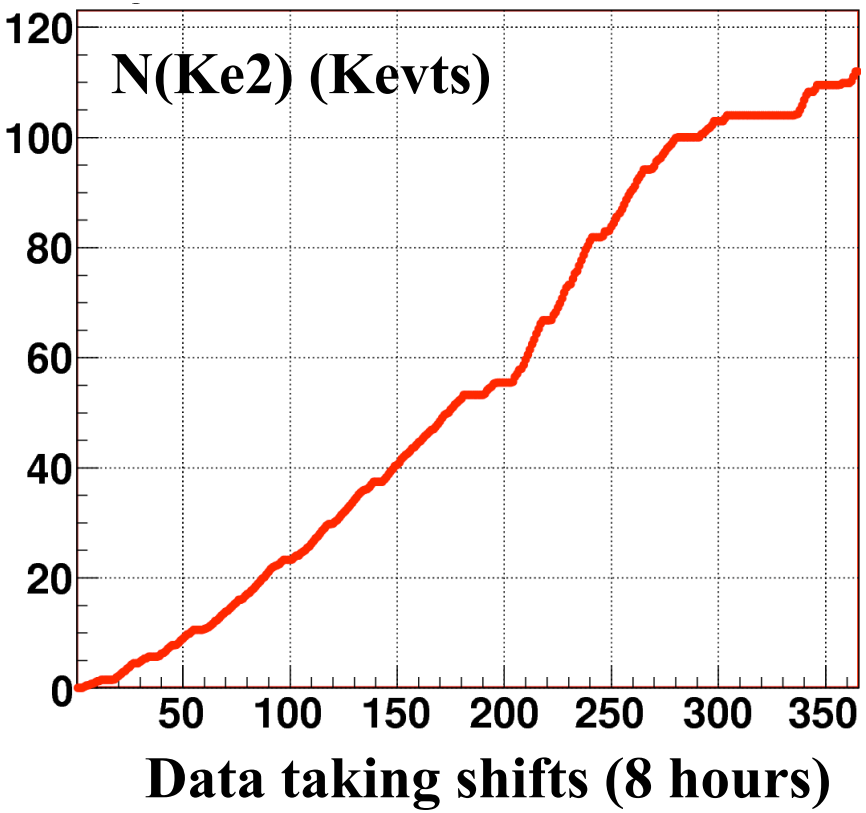


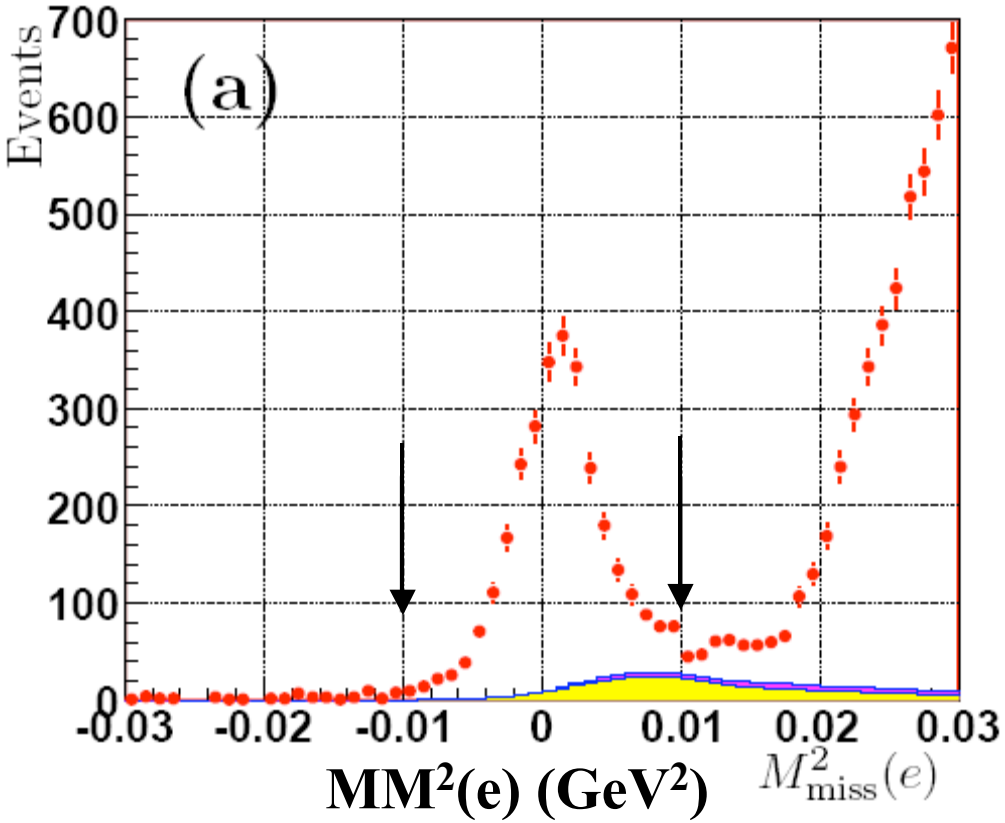


Analysis of Ke2/Km2 at NA62

Data taking lasted 4 months with Ke2 and Kμ2 triggers

NA62 acquired the world largest data set of Ke2, > 100 Kevts





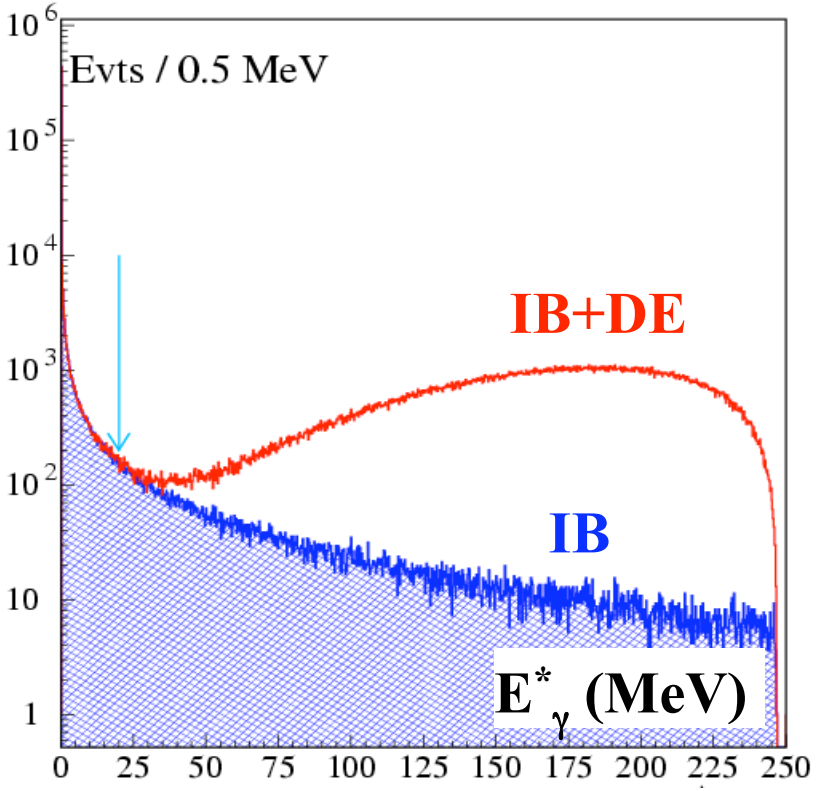
Analyses of R_K – Radiative corrections

To match theory, has to count IB only

Preliminary results (KLOE, NA48):

- **measure inclusively of radiation**
- **counts IB by considering as "signal" E^*_γ values below threshold**
- **Correct for IB tail, ε^{IB}**
- **Repeat fit varying DE by its 15% uncertainty, get systematic error (conservatively few per mils)**

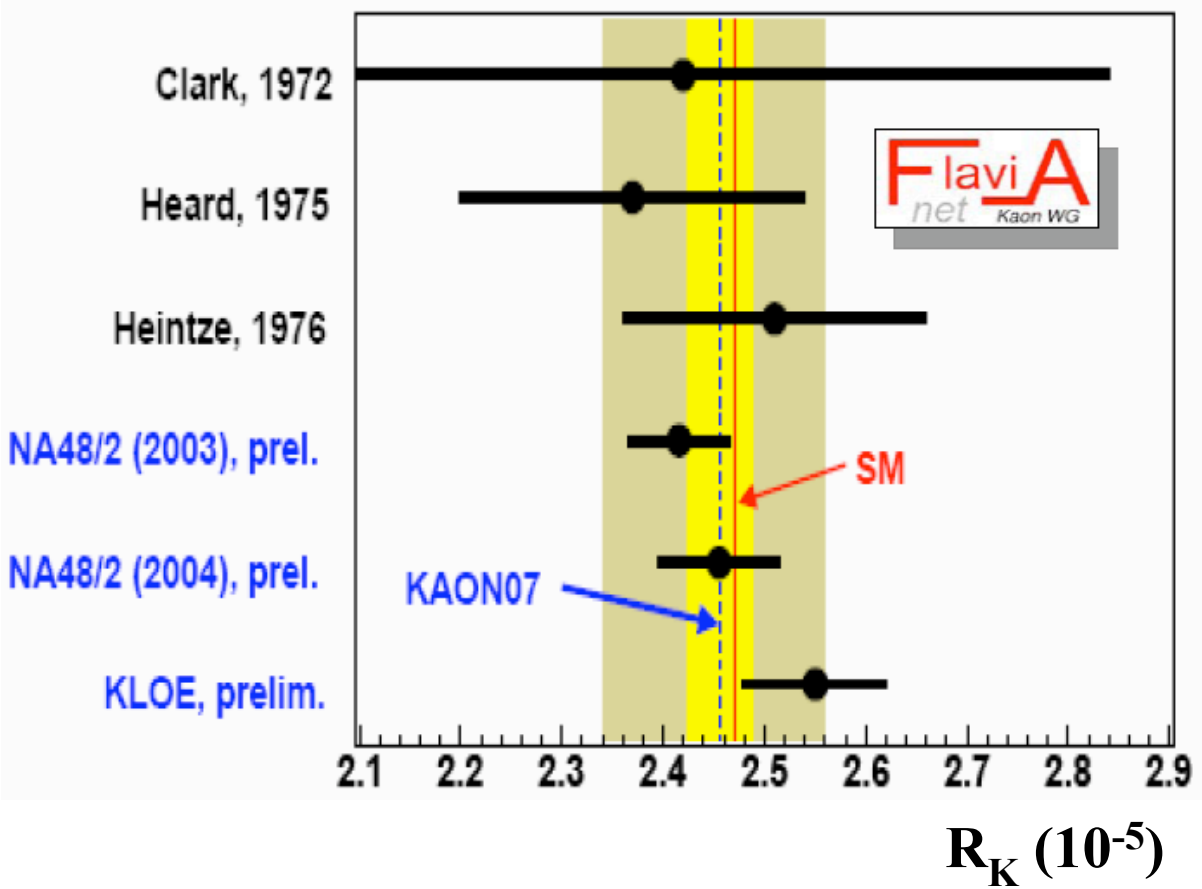
If needed, each experiment can possibly measure the DE contribution



R_K – *Present and future experimental status*

Recent (preliminary) results improved greatly with respect to 2006 PDG

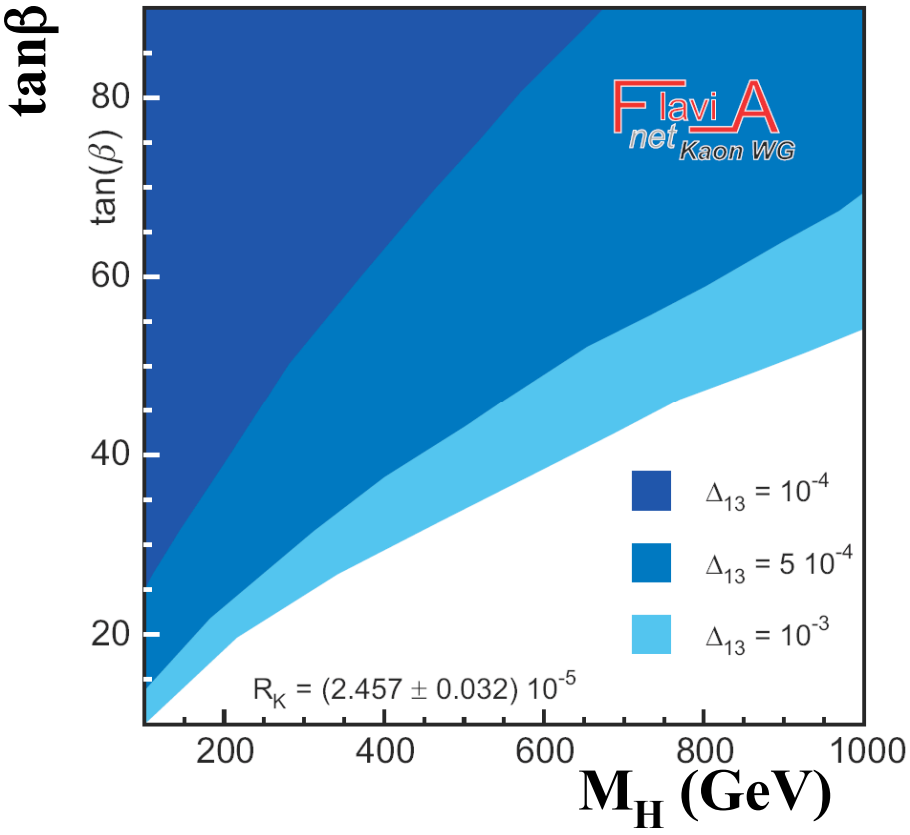
World average, $R_K = 2.457(32)\times10^{-5}$, agrees with SM



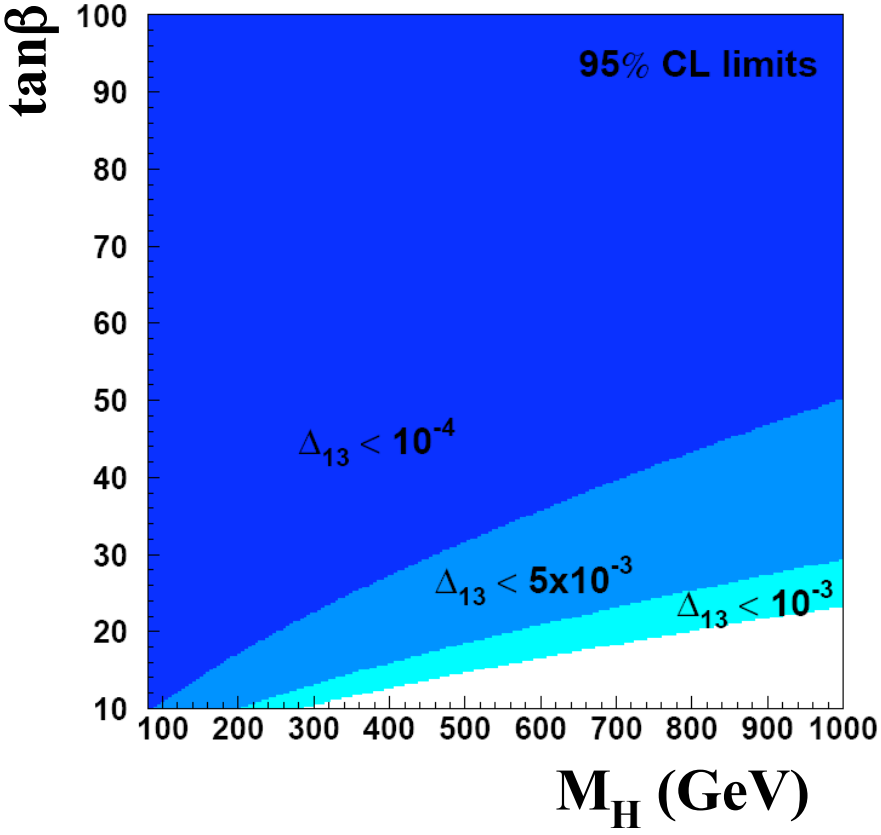
R_K – Present and future sensitivity to NP

Sensitivity shown as 95%-CL excluded regions in the tanβ - M_H plane, for fixed values of the 1-3 slepton-mass matrix element, Δ_{13} = 10^{-3},0.5×10^{-3},10^{-4}

Present world avg: R_K= 2.457(32)×10^{-5}



Perspective: same R_K, δR_K=0.3%



Conclusions – kaon physics alive and kicking

Direct LFV searches go on toward the sensitivity frontier

No NP seen, but allowed exclusion of light mediators @ tree level

Recent K decay mmts greatly improve knowledge of gauge coupling:

- **Effective coupling known @ 0.2%**
- **Lepton universality test from K_{l3} decays satisfied at < 0.5%**

New and interesting tests of NP effects from two-body decay studies:

- **Sensitivity to NP effects from $K_{\mu 2}/\pi_{\mu 2}$:**
  - **NP test, complementary with respect to test from $B \rightarrow \tau\nu$**

- **Golden LFV observable is R_K:**
  - **Preliminary mmt @ 2% from NA48/2, 3% from KLOE**
  - **KLOE expects to push error @ ~1%, after analysis completion**
  - **NA62 dedicated 2007 run aims at reaching <0.5% error**

HQ
&L08
Heavy Quarks
& Leptons
Spare slides

R_K – KLOE perspectives toward 1% error

Present status	To complete analysis
1.1% Signal counts/1.7fb^{-1}	+30% of data under processing
	+40% w recover of prompt K decays
0.7% Bkg subtraction	×2 rejection from kinematics
1.4% MC Bkg statistics	×2 MC stat under processing
1.9% stat error	
1.5% incomplete PID CS coverage	× 4--8 CS stat available, loosen PID cut
0.9% one-prong CS stat	< 0.3% using all data
0.9% TRG minimum-bias stat	Better control of trigger variables
2.0% syst error	

Will push error @ 1%

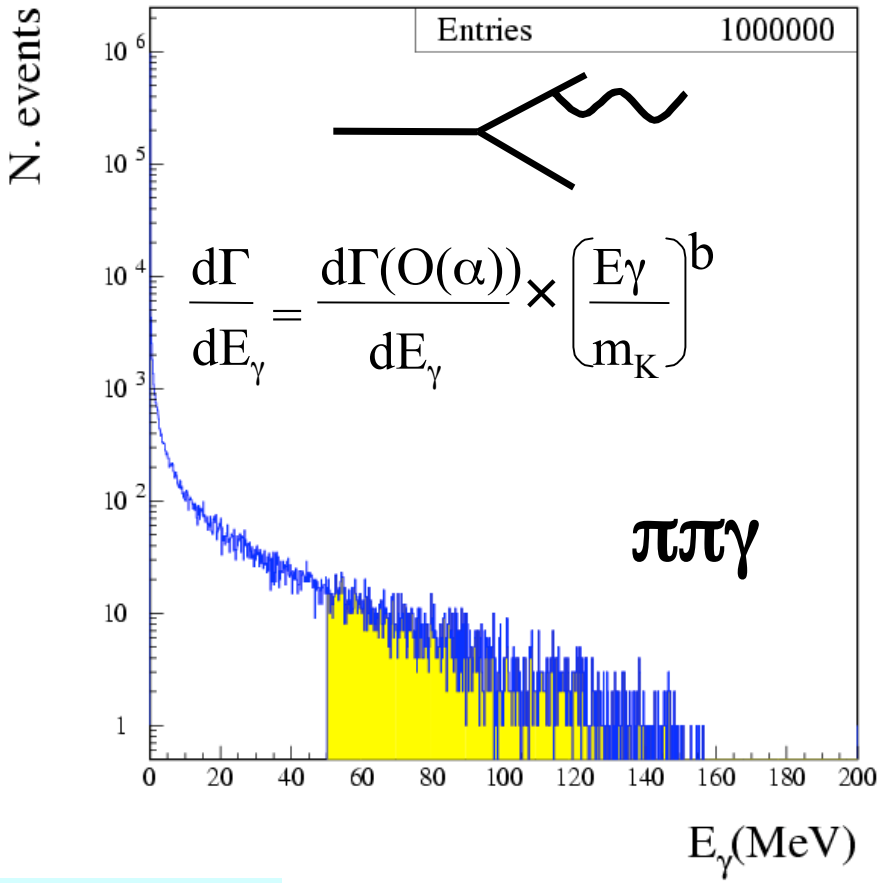
KLOE generators for radiative K decays

Generators for neutral kaon decays include radiation, no cutoff energy

- Full O(α) amplitudes (real and virtual contributions) summed to all orders in α by exponentiation (soft-photon approximation)
- Carefully checked against all available data and calculations

$$\frac{BR(K_L \to \pi e \nu \gamma, E_\gamma > 30\,MeV\ \theta_{e\gamma} > 20°)}{BR(K_L \to \pi e \nu)} =$$

kTeV	$(0.908 \pm 0.015) \times 10^{-2}$
Bijnens et al	0.93×10^{-2}
MC	0.93×10^{-2}



$$\frac{BR(K_S \to \pi\pi\gamma, E_\gamma > 50\,MeV)}{BR(K_S \to \pi\pi)} =$$

E731	$(2.56 \pm 0.09) \times 10^{-3}$
MC	2.6×10^{-3}

[C. Gatti, EPJC 45 (2006)]