Precision test of the SM with Kl2 and Kl3 decays at the KLOE experiment

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XLIV Renconstres de Moriond
La Thuile, Italy, 11th March, 2009

NP from (semi)leptonic K decays?

KLOE measurements of $K \to \pi l\nu$, $l\nu$ decays can shed light on NP BSM

Precise determination of V_{us} from BR's for $K \to \pi l\nu$, ff slopes, etc.:

- **allows most precise test of unitarity of the CKM matrix**
- **translates into a severe constraint for many NP models**

Test of SM from $\Gamma(K_{\mu2})/\Gamma(\pi_{\mu2})$:

- **probes NP RH contributions to charged weak currents**
- **probes H^+ exchange in every SM extension with 2 Higgs doublets**

LF violation test from $\Gamma(K_{e2})/\Gamma(K_{\mu2})$:

- **sensitive to NP effects, which might be at % level wrt SM prediction**

CPT test from BR's and charge asymmetry in $K_{L,S} \to \pi l\nu$ decays:

- **dramatically improve precision of CPT test via unitarity relation**

Interest in V_{us} measurement with kaons

In SM, universality of weak coupling dictates:

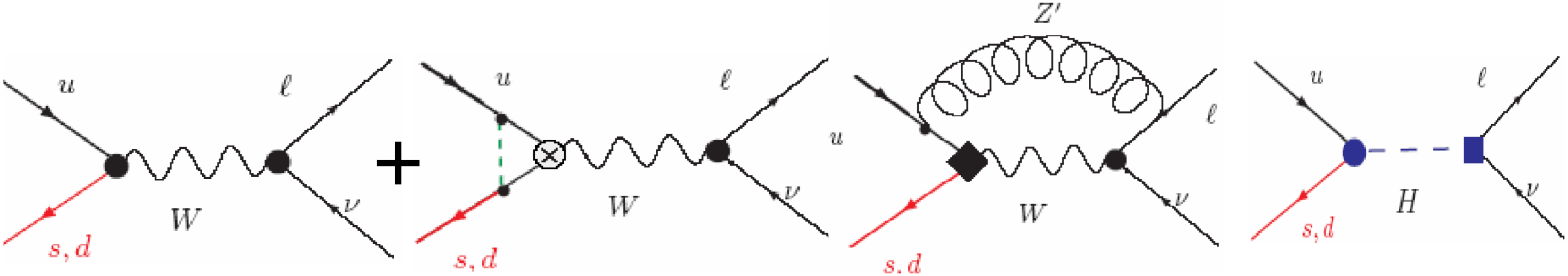
$$G_F^2\,(|V_{ud}|^2 + |V_{us}|^2) = G^2(\text{from } \mu \text{ lifetime}) = (g_w/M_w)^2\ [V_{ub} \text{ negligible}]$$

One can test for possible breaking of one of the two conditions:

CKM unitarity: is $(|V_{ud}|^2 + |V_{us}|^2) = 1$?

coupling universality: is $G_F^2\,(|V_{ud}|^2 + |V_{us}|^2) = G^2(\text{from } \mu \text{ lifetime})$?

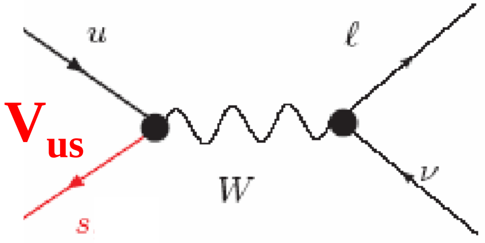
New physics extensions of the SM can indeed break coupling universality:



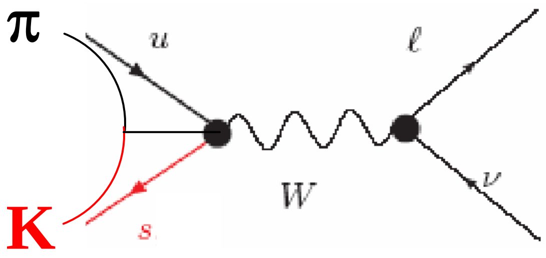
SM + NP $\propto G_F^2\,|V_{uq}|^2\,(1 + a\,M_{NP}^2/M_W^2)^2$, naively $a_{tree} \sim 1$, $a_{loop} \sim g^2_W/16\pi^2$

Kaon decay observables

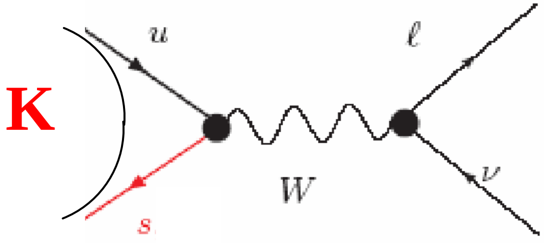
Kl2 and Kl3 decay observables linked to the wanted short distance physics with independent theoretical uncertainty



For Kl3 decays, Ademollo-Gatto theorem dictates ~~SU~~(3) terms appear at 2nd order in $f^{+}_{K\pi}(0)$



$K_{\mu2}/\pi_{\mu2}$: f_K/f_π uncertainty reduced from latest lattice results

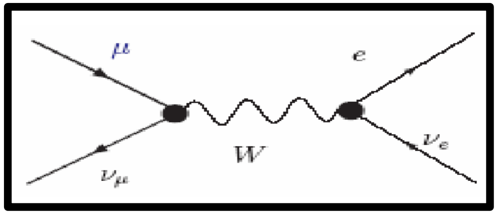


Interest in V_{us} measurement with kaons

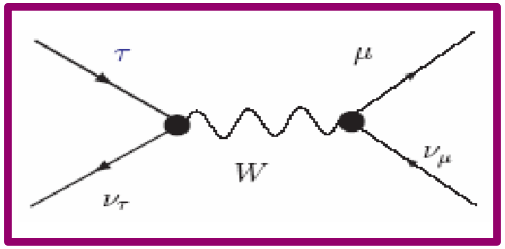
A measurement of $G_{CKM} = G_F\,(|V_{ud}|^2 + |V_{us}|^2)$ with error @ 0.5%

- **is sensitive to tree masses $M_{NP} \sim 10$ TeV and to loop masses $M_{NP} \sim 1$ TeV**
- **is competitive with ew precision tests:**

$G_F = 1.166371(6) \times 10^{-5}\ \mathrm{GeV}^{-2} \leftarrow$



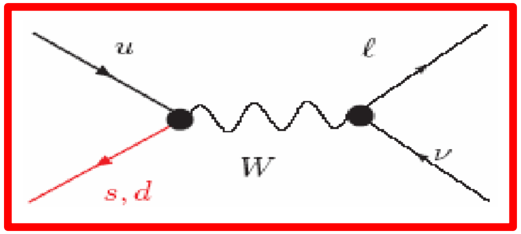
$G_\tau = 1.1678(26) \times 10^{-5}\ \mathrm{GeV}^{-2} \leftarrow$



$G_{ew} = 1.1655(12) \times 10^{-5}\ \mathrm{GeV}^{-2} \leftarrow$

$\alpha_{em} + M_W + s_W$
[ew precision tests]

$G_{CKM} = 1.16xx(04) \times 10^{-5}\ \mathrm{GeV}^{-2} \leftarrow$



V_{us} from semileptonic kaon decays

Master formula: $\Gamma(K_{l3(\gamma)}) = |V_{us}|^2 \, |f_+^{K^0\pi^-}(0)|^2 \, \frac{G_F^2 \, m_K^5}{128\pi^3} S_{\mathrm{EW}} \, C_K^2 \, I_{K\ell} \, (1+\delta_K^\ell)$

Theoretical inputs:

- **$f_+(0)$**, form factor at zero momentum transfer: purely theoretical calculation
  Recent result from UKQCD/RBC, 07 prel.: **$f_+(0) = 0.964(5)$**
- **$\delta^\ell_K = 2(\Delta_K^{SU(2)} + \Delta^{\ell\,em}_K)$**, I-breaking and e.m. effects:
  Recent χPt results: **$\Delta_{K+}^{SU(2)} = +2.36(22)\%$, $\Delta^{\ell\,em}_K =$**

K0	K+	
+0.57(15)%	+0.08(15)%	ℓ = e
+0.80(15)%	–0.12(15)%	ℓ = μ

- S_{EW}, short distance corrections (1.0232), $C_K = 1$ ($2^{-½}$) for K^0 (K^+) decays

Experimental inputs:

- **$I^\ell_K = I(\{\lambda_+\},\{\lambda_0\},0)$**, phase space integral, λ_+, λ_0 → t-dependence of vector, scalar ffs
- **$\Gamma_{K\ell 3(\gamma)}$**, semileptonic decay width evaluated from γ-inclusive BR and lifetime
- **m_K**, appropriate kaon mass

KLOE measurements for all relevant inputs: BR's, τ's, ff's

V_{us}/V_{ud} from $K_{\mu2}$ decays

Can also get $|V_{us}/V_{ud}|$ from K,π → μν widths [Marciano PRL93 231803,2004]**:**

$$\frac{\Gamma(K\to\mu\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))}=\frac{m_K\left(1-\frac{m_\mu^2}{m_K^2}\right)^2}{m_\pi\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^2}\boxed{\frac{|V_{us}|^2}{|V_{ud}|^2}}\frac{f_K^2}{f_\pi^2}\frac{1+\frac{\alpha}{\pi}C_K}{1+\frac{\alpha}{\pi}C_\pi}$$

Theoretical inputs:

radiative correction C_K, C_π

form factor ratio $\mathbf{f_K/f_\pi}$

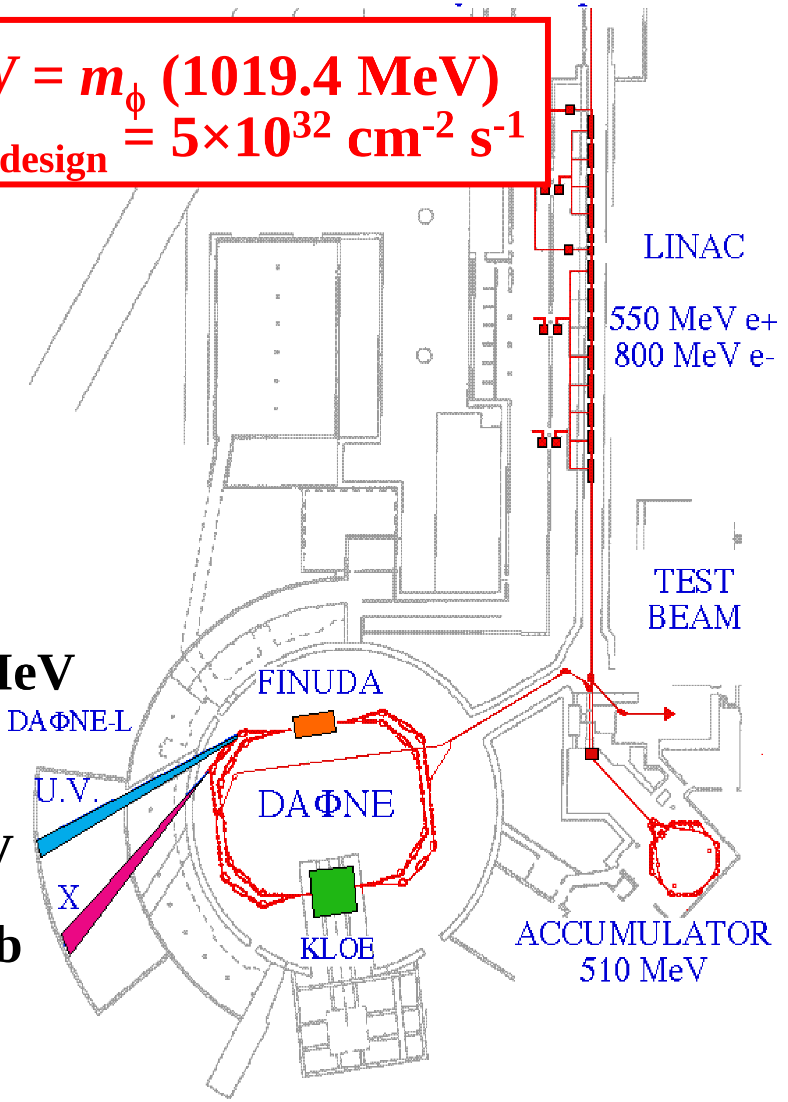
Experimental inputs:

$m_{K,\pi,\mu}$, $\Gamma(K_{\mu2})/\Gamma(\pi_{\mu2})$

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$_\phi$: √**s ~ 1019.4 MeV**

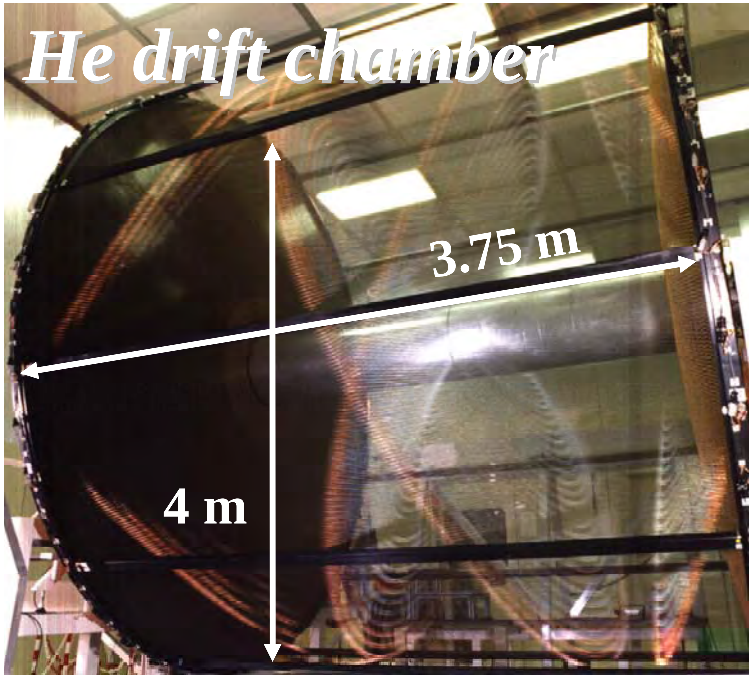
Angle between the beams @ IP: **α ~ 12.5 mrad**

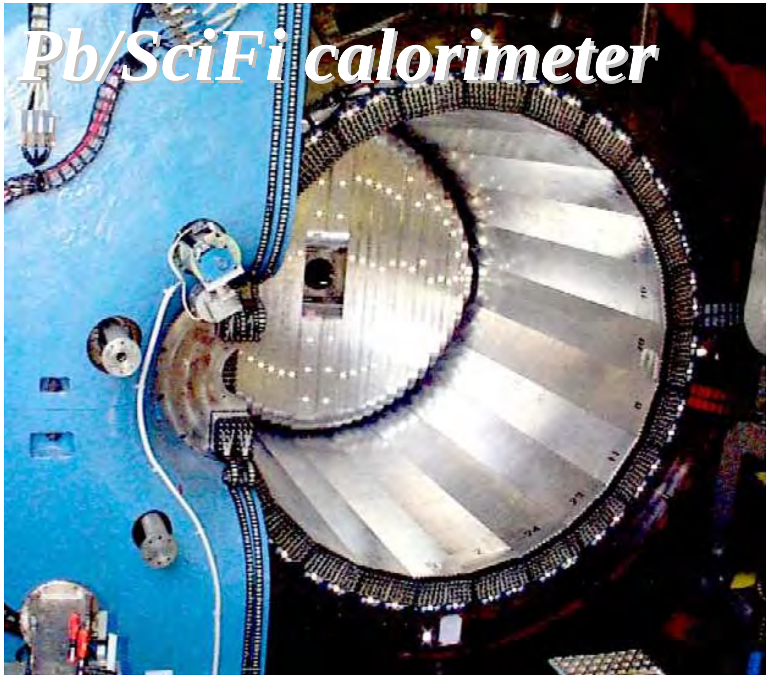
Residual laboratory momentum of ϕ: **p$_\phi$ ~ 13 MeV**

Cross section for ϕ production @ peak: **σ$_\phi$ ~ 3.1 μb**

The KLOE detector

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





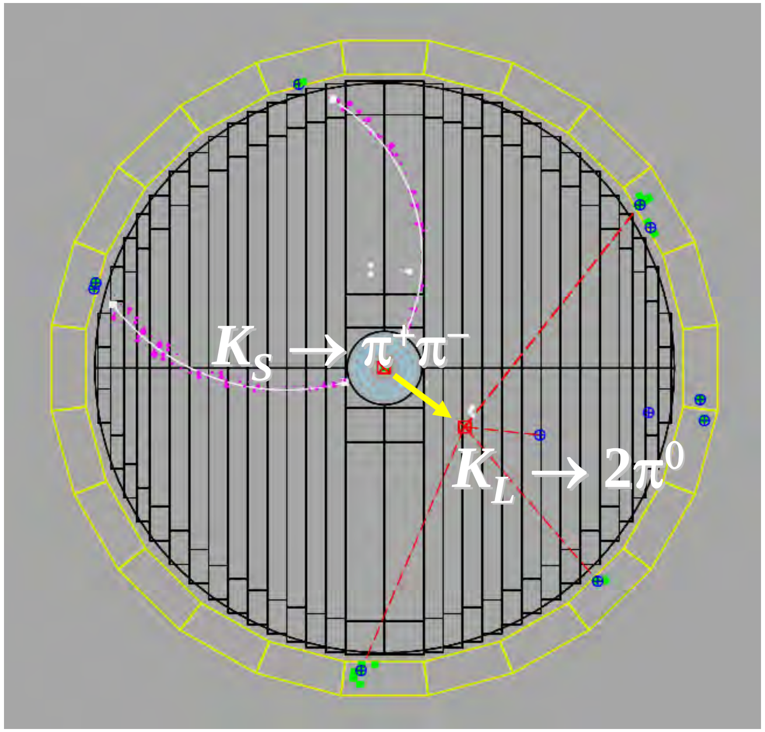
σ_p/p	**0.4 %** (tracks with $\theta > 45°$)
σ_x^{hit}	**150 μm (*xy*), 2 mm (*z*)**
$\sigma_x^{\mathrm{vertex}}$	**~1 mm**

σ_E/E	**5.7% /$\sqrt{E(\mathrm{GeV})}$**
σ_t	**54 ps /$\sqrt{E(\mathrm{GeV})} \oplus$ 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 (interaction) tags presence of $K_{L,S}(K^{-,+})$



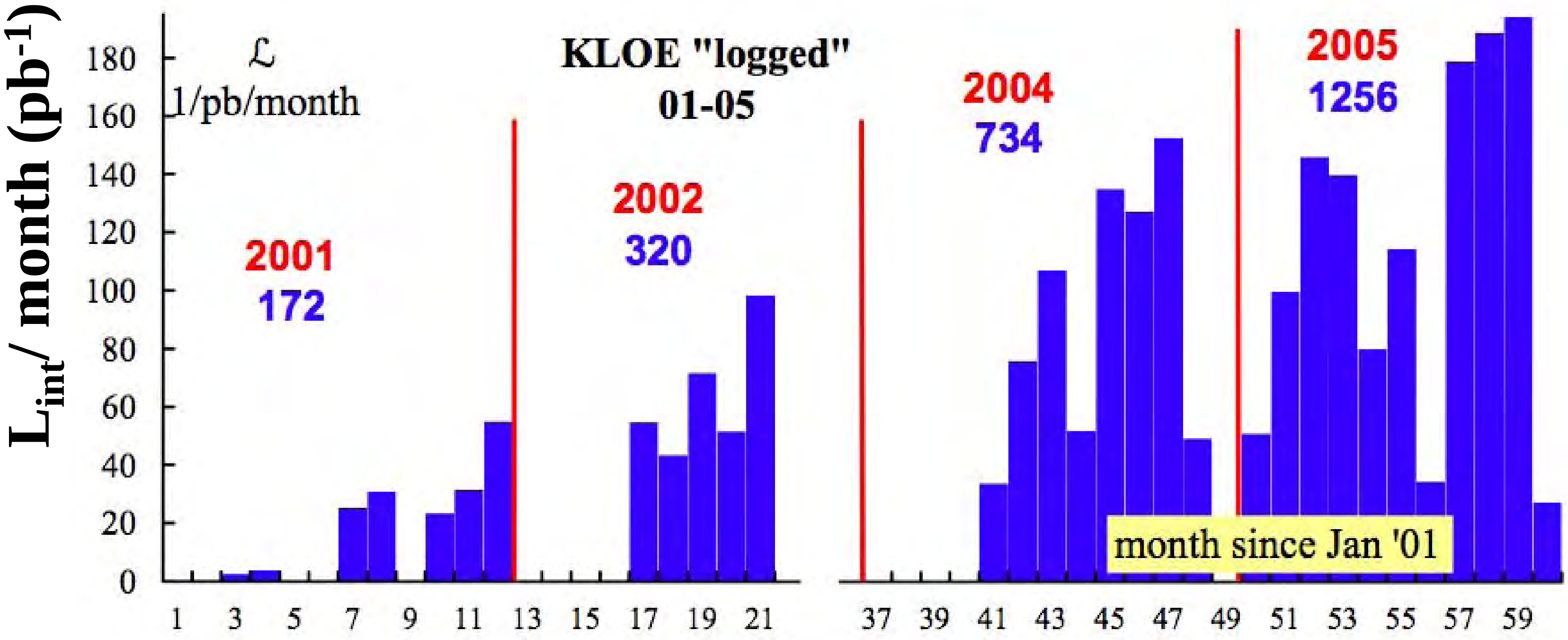
Almost pure $K_{L,S}$ and $K^{+,-}$ beams of known momentum + PID (kinematics & TOF):

- **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

Overview of KLOE data

Data taking for KLOE experiment, years 2001-2005, now run completed



2001–5: ~2.5 fb^{-1} integrated @ √s=M(ϕ), yielding ~2.5 × 10^{9} K_SK_L pairs

Maximum peak luminosity, 2.5 10^{32} cm^{-2} s^{-1}

Recent KLOE results in kaon physics

Focus on V_{us} determination, LFV violation, and CPT and χPt tests

KLOE results from kaon decays in last year:

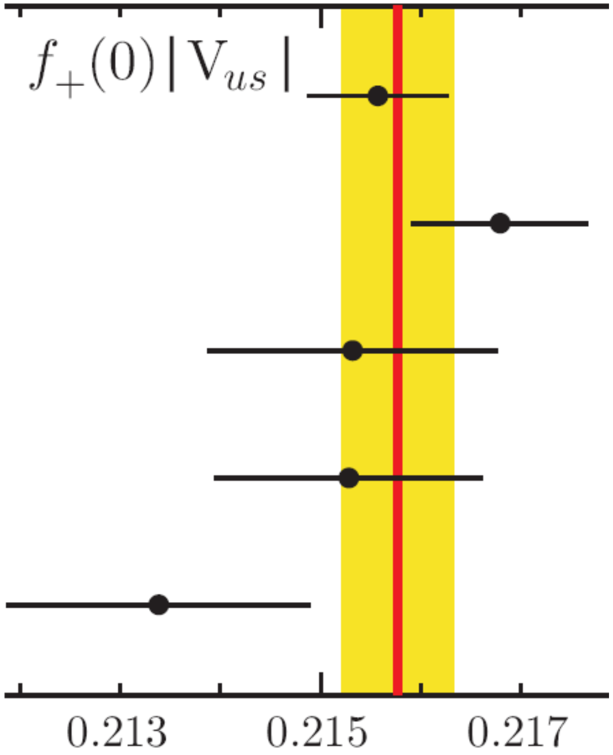
Neutral Kaon mass	JHEP 0712:073
Scalar form factor slope from $K_{L\mu3}$	JHEP 0712:105
Absolute BR for $K^+\to\pi^+\pi^0$ decay	PLB 666 (2008)
Absolute BR's for $K^{+,-}\to\pi l\nu$	JHEP 0802:098
$K^{+,-}$ lifetime	JHEP 0801:073
Combined V_{us} determination	JHEP 0804:059
CP, CPT parameters of K^0 system via BSR	JHEP 0612:011, review PDG'08
$d\Gamma(K_L\to\pi e\nu\gamma)/dE_\gamma$	EPJC 55 (2008)
$BR(K_S\to\gamma\gamma)$	JHEP 0805:051

Preliminary mmts have also been announced:

Updated form factor slopes from $K_{L\mu3}$	PoS KAON:016, 2008
$UL[BR(K_S\to e^+e^-)]$	ArXiv:0707.2687 (now final)
$\Gamma(K^+\to e\nu)/\Gamma(K^+\to\mu\nu)$	ArXiv:0707.4623

Vus from Kl3 decays: results

Only use KLOE inputs, except τ_S from PDG:



	$f_+(0) \times \lvert V_{us}\rvert$	Error,%
K_{Le3}	0.2155(7)	0.3
$K_{L\mu3}$	0.2167(9)	0.4
K_{Se3}	0.2153(14)	0.7
K^+_{e3}	0.2152(13)	0.6
$K^+_{\mu3}$	0.2132(15)	0.7
Avg	**0.2157(6)**	**0.28**

Compare with world average including KLOE: 0.2166(5)

Use $f_+(0) = 0.9644(49)$ from UKQCD/RBC: $|V_{us}| = 0.2237(13)$

Use $|V_{ud}| = 0.97418(26)$ from $0^+ \to 0^+$ β decays: $1-|V_{ud}|^2-|V_{us}|^2 = 9(8)\times10^{-4}$

V_{us}/V_{ud} from $K_{\mu 2}$ vs V_{us} from Kl3

From the following inputs:

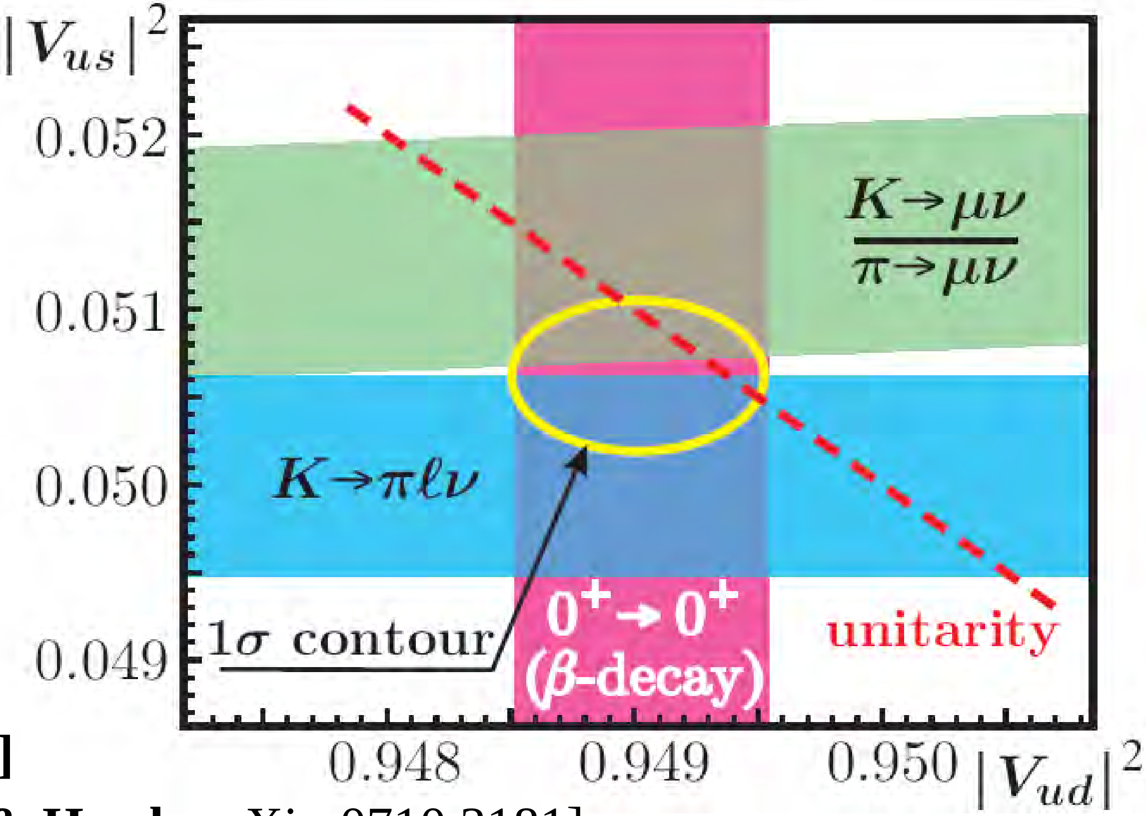
BR($K^+ \to \mu^+\nu$), $\tau(K^+)$ [KLOE]

f_K/f_π =1.189(7) [HP/UKQCD 07]

C_K, C_π [Marciano PRL93, 2004]

$M_{K,\pi,\mu}$, $\Gamma(\pi^+ \to \mu^+\nu)$ [PDG]

Result: $|V_{us}/V_{ud}| = 0.2323(15)$



Now can fit:

1) $|V_{us}/V_{ud}| = 0.2323(15)$

2) $|V_{us}| = 0.2237(13)$ **[KLOE K_{l3}]**

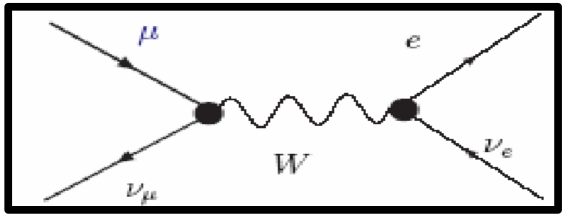
3) $|V_{ud}| = 0.97418(26)$ **[Towner & Hardy** arXiv:0710.3181]

Obtain: $|V_{ud}| = 0.97417(26)$, $|V_{us}| = 0.2249(10)$, $P(\chi^2=2.34/1) = 13\%$

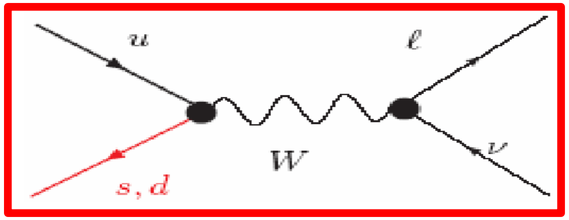
CKM unitarity satisfied: $1-|V_{ud}|^2-|V_{us}|^2 = 4(7)\times 10^{-4}$

Weak coupling universality test

Agreement between weak couplings from K decays and from μ lifetime:



G_F = 1.166371(6)×10^{-5} GeV^{-2} ←



G_{CKM}= 1.16604(40)×10^{-5} GeV^{-2}←

Agreement at this level of accuracy implies observation of short distance radiative corrections at ~40 σ level [Marciano]:

$2\,\alpha/\pi \log M_Z/M + \ldots \sim 2.5\%$

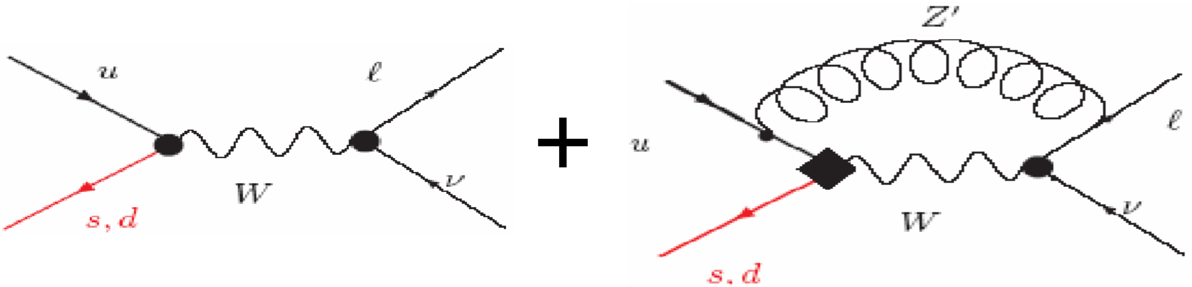
Agreement of $f_+(0)\times V_{us}$ for K^+ and K^0, brilliant success of the calculation of isospin breaking and e.m. corrections at few per mils

Weak coupling universality test: BSM

Agreement between weak couplings from K and from μ constraints NP

In SO(10) Z_χ boson [Marciano]:

$$G_F = G_{CKM}\,[\,1 - 0.007 \times 8/3 \times \ln(M_{Z'}/M_W)/(M_{Z'}^2/M_W^2 - 1)\,]$$



Implies: $M_{Z'} > 750$ GeV @ 95% CL

Weak coupling universality test: BSM

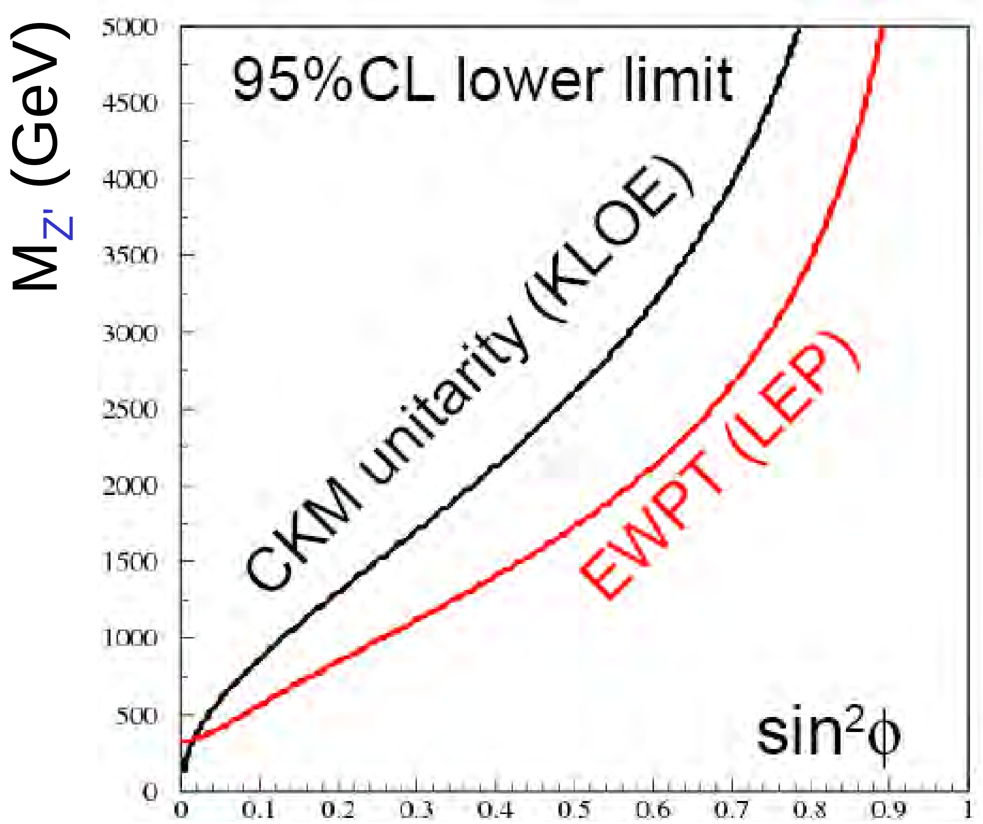
In non-universal gauge interaction model, a tree level contribution from a Z' boson breaking unitarity might be present [K. Y. Lee PRD 76, 117702 2007]

Assume different couplings of 1st-2nd lepton generation (g_l) and 3rd (g_h):

$$g_l = e/\sin\theta_w \cos\phi$$
$$g_h = e/\sin\theta_w \sin\phi$$
$$g' = e/\cos\theta_w$$

θ_w is the weak mixing angle

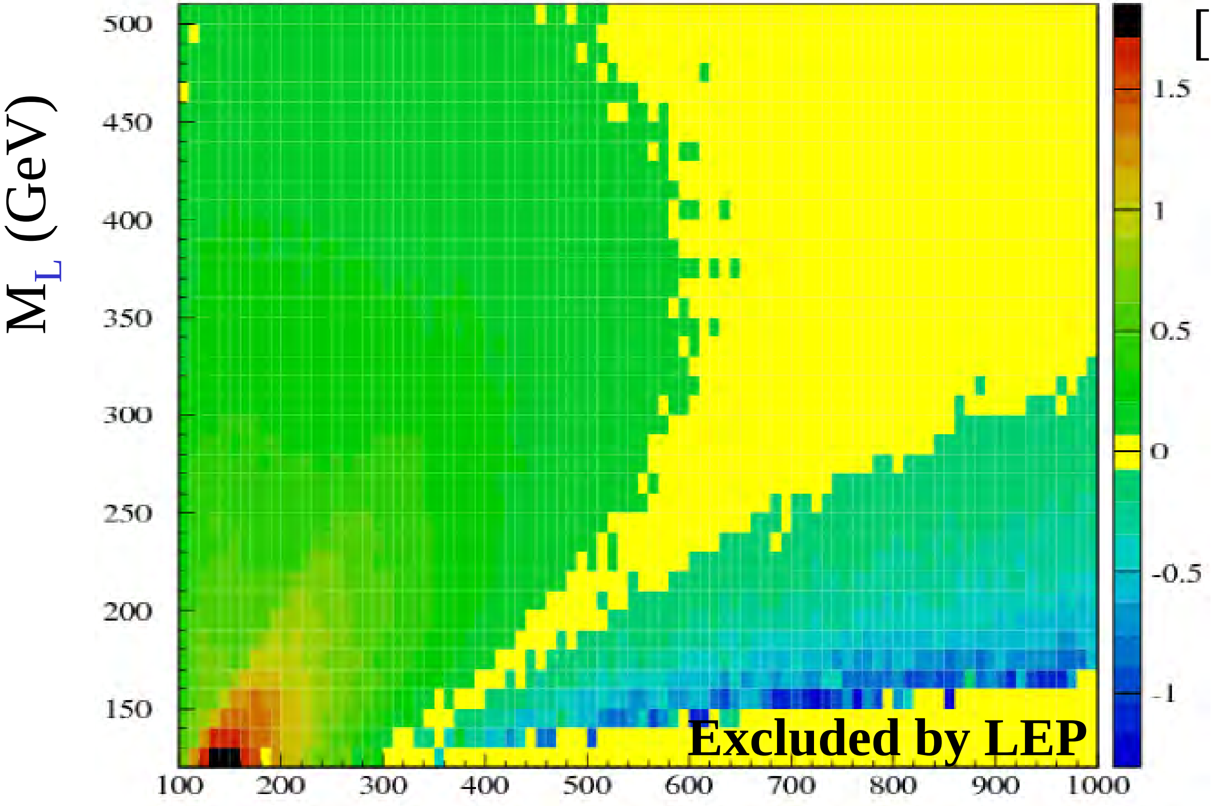
ϕ is the mixing angle between $SU(2)_l$ and $SU(2)_h$



Gauge structure appears in extended technicolor

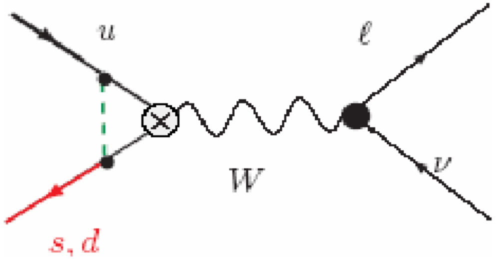
Weak coupling universality test: MSSM

Scanning over MSSM parameter space, unitarity is sensitive to the squark-slepton mass difference [R. Barbieri 85, K. Hagiwara et al. 95, A Kurylov 00]



[Code by Mescia and Paradisi]

$[1-(V_{ud}^2+V_{us}^2)^{½}] \times 10^4$

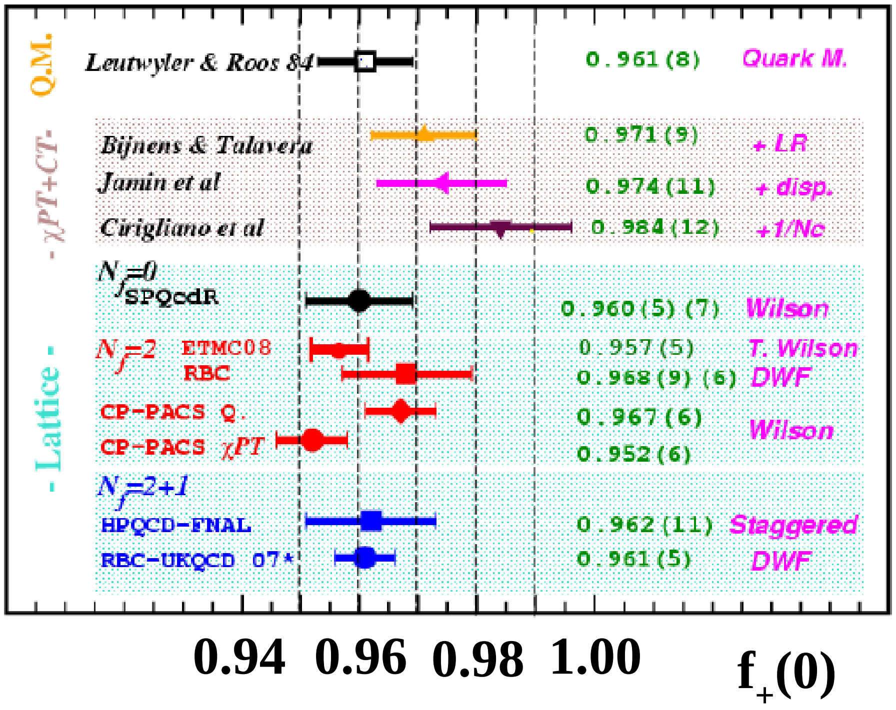


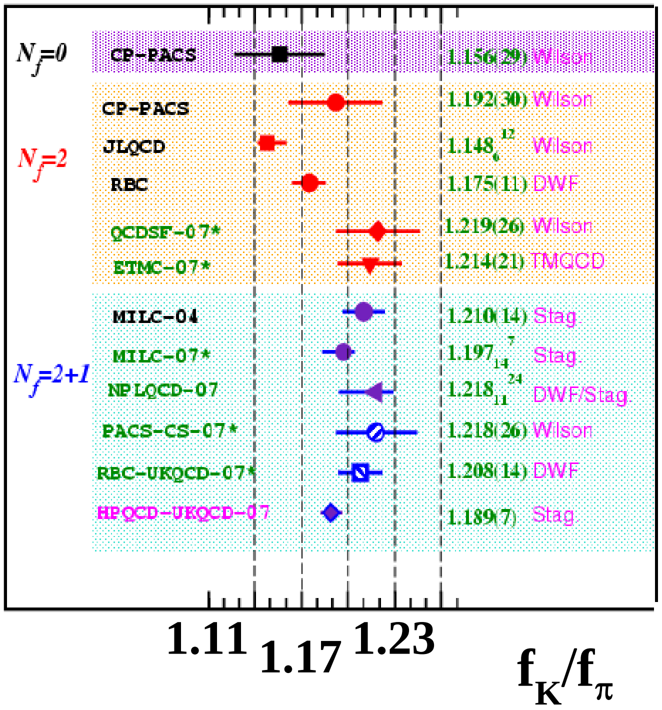
Present error 0.35%

Need to improve it by ×2 to really enter this game

Weak coupling universality test: MSSM

Chance of improving? Lattice seems very solid:



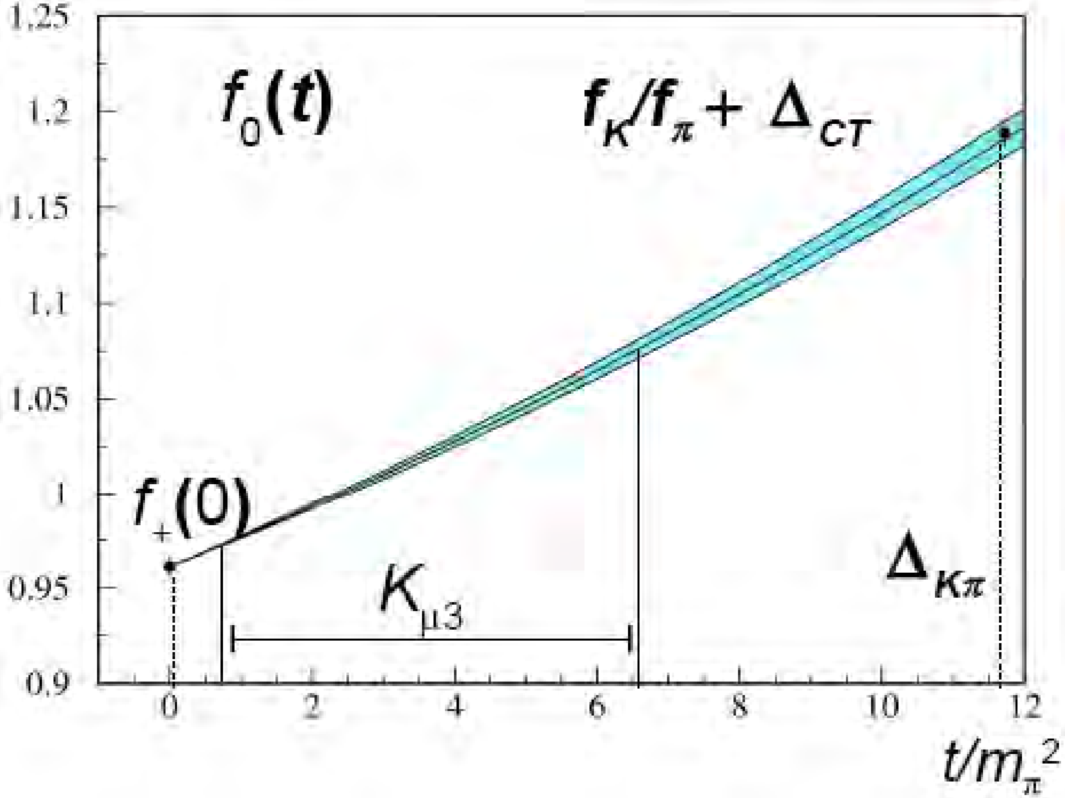


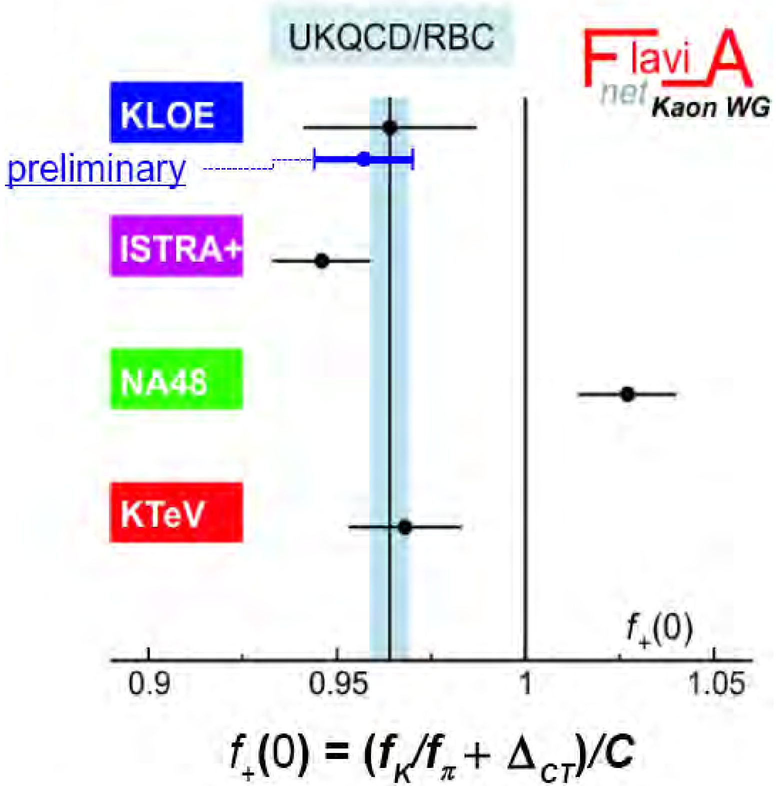
Other tools are available to validate lattice results

Weak coupling universality test: MSSM

Dispersive parametrization of $f_0(t)$ from Kμ3 + Kπ scattering data relate value in the Callan-Treiman point to f_K/f_π [Stern et al., Pich et al.]

The correction Δ_{CT} is evaluated in p-QCD





Perspectives: info from τ decay + theory improvements possible

$K_{\mu2}$ again – Sensitivity to NP

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

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

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

NP effect is suppressed for π_{l2} wrt K_{l2}, so NP might appear in $Kl2$ / $\pi l2$, predicted in the SM to be:

$$\frac{\Gamma(K^\pm_{\ell2(\gamma)})}{\Gamma(\pi^\pm_{\ell2(\gamma)})} = \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{f_K^2 m_K}{f_\pi^2 m_\pi}\left(\frac{1-m_\ell^2/m_K^2}{1-m_\ell^2/m_\pi^2}\right)^2 \times (1+\delta_{\rm em})$$

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

$$\left|\frac{V_{us}(K_{\ell2})}{V_{us}(K_{\ell3})}\times\frac{V_{ud}(0^+\to 0^+)}{V_{ud}(\pi_{\ell2})}\right| \overset{?}{=} \left|1-\frac{m_{K^+}^2}{M_{H^+}^2}\left(1-\frac{m_d}{m_s}\right)\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right|$$

$K_{\mu 2}$ – Sensitivity to NP

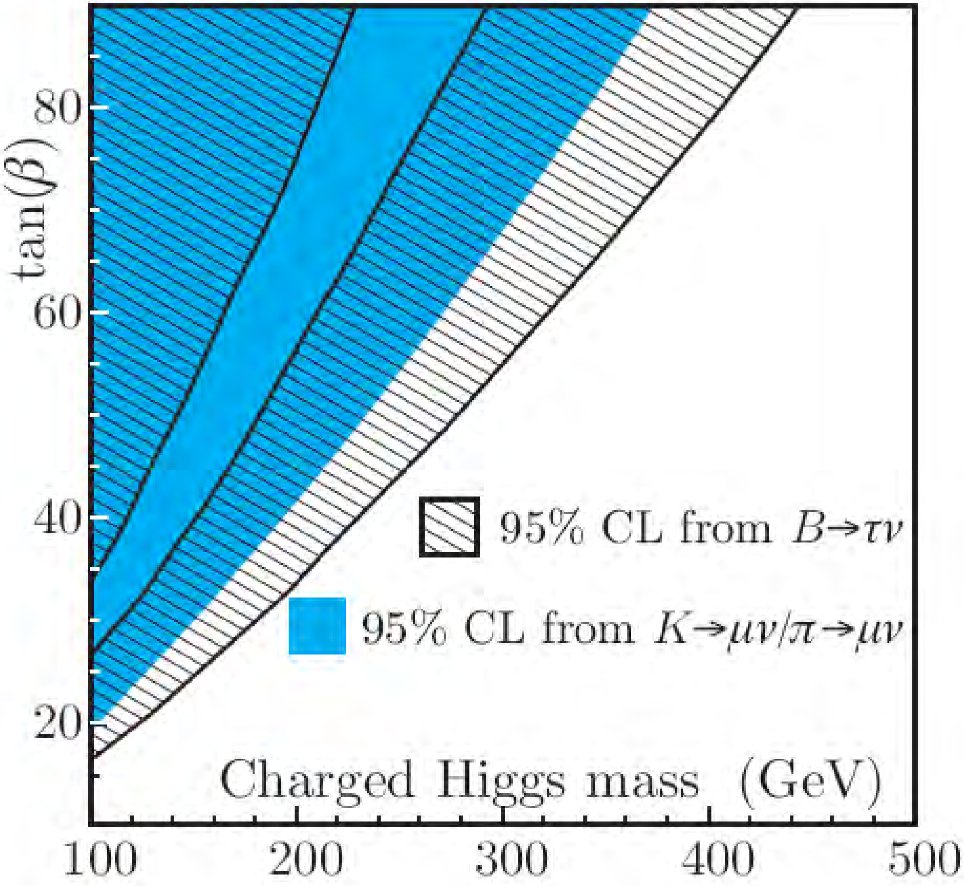
Result is: $$\left|\frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\ell 2})}\right| = 1.008(8)$$

NP sensitivity from K→ μν ~ as that from BR(B → τν) = $1.73(35)\times 10^{-4}$

For Belle update see A. Bozek and E. Baracchini talks. For a combined fit in 2-Higgs doublet models, see M. Goebel talk in this conference

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]



NP potential of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$

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 JHEP 710:005, 2007]

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

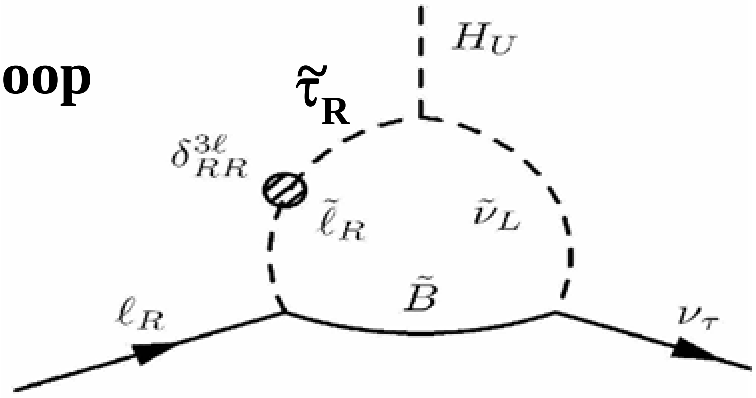
In R-parity MSSM, LFV can give 1% deviations from SM:

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

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

$$l\mathrm{H}^{\pm}\nu_\tau \ \rightarrow\ \frac{\mathrm{g}_2}{\sqrt{2}}\frac{\mathrm{m}_\tau}{\mathrm{M_W}}\,\boldsymbol{\Delta}_{13}$$

, 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)**

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), see talk by A. Winhart in this conference

- **collected ~ 150,000 Ke2 events in dedicated 2007 run, aims at breaking the 1% precision wall, possibly reaching < ~0.5%**

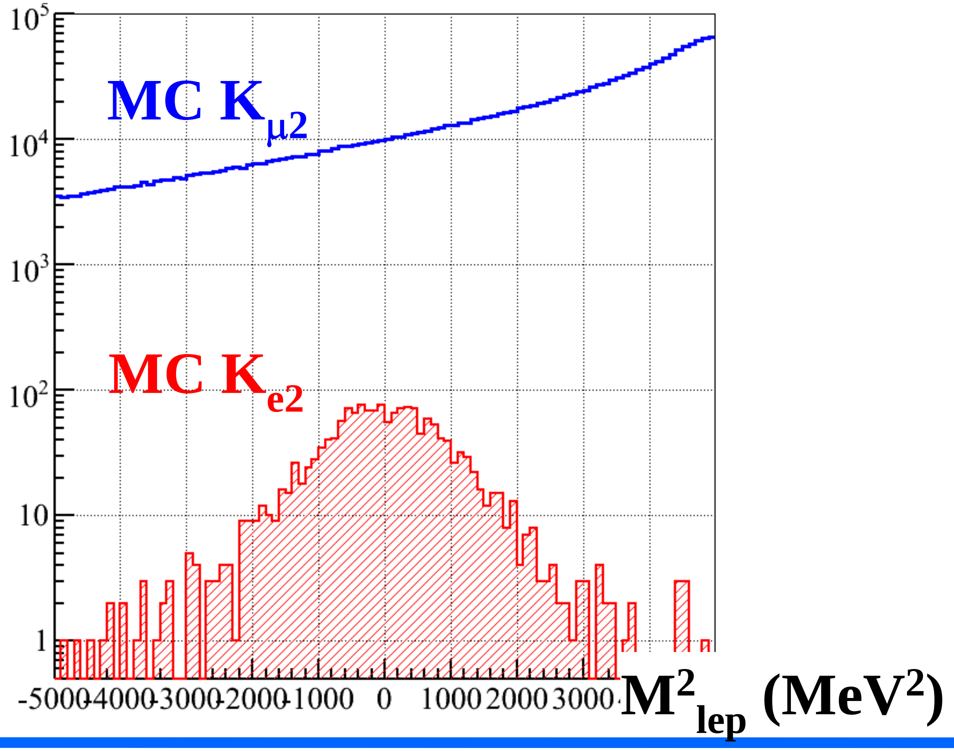
Analysis of $K_{e2}/K_{\mu2}$ – basic principles

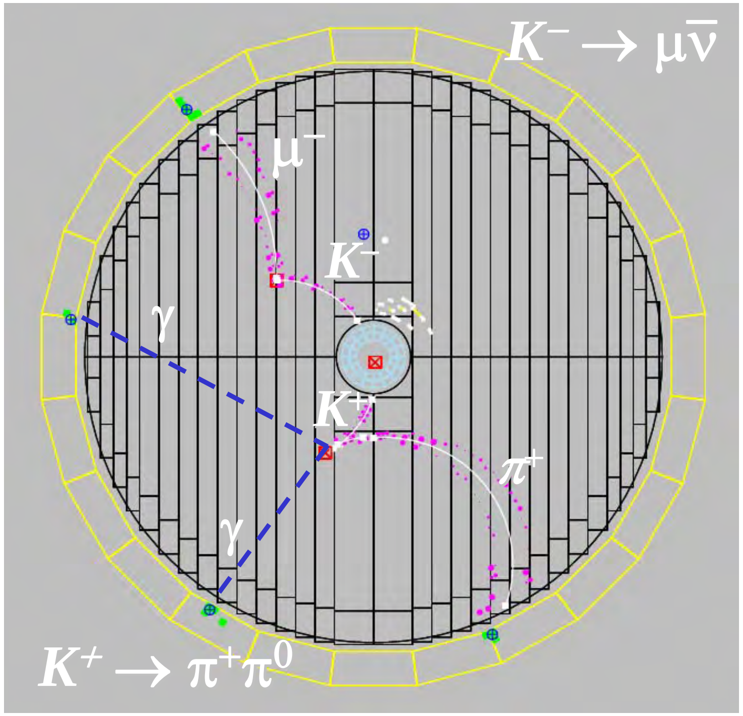
KLOE integrated ~2.5 fb^{-1} of data & BR(K_{e2})~10^{-5}: expect < ~4×10^{4} events

Perform direct search for K_{e2} and $K_{\mu2}$, no tag: gain ×4 of statistics

Select 1-prong kinks in DC, K track from IP & secondary P > 180 MeV

Exploit tracking of K and secondary: assuming $m_\nu=0$ get M^2_{lep}



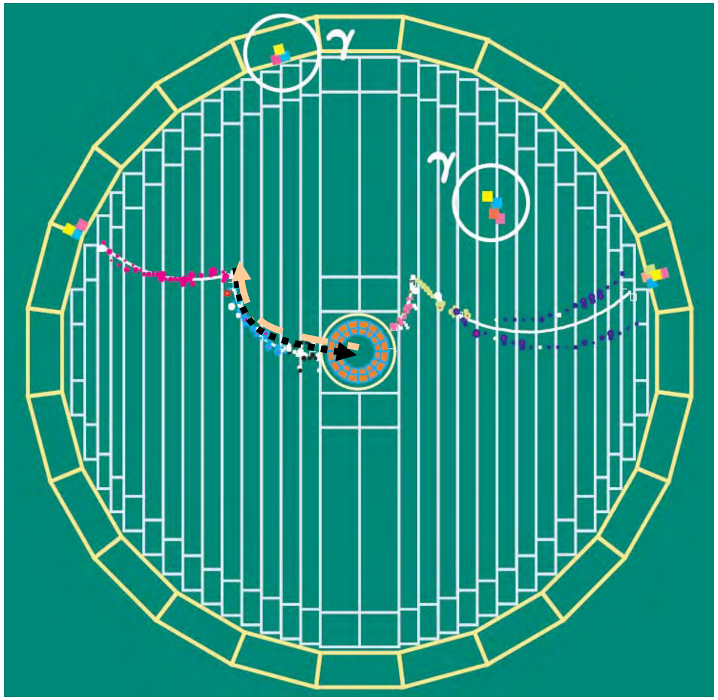


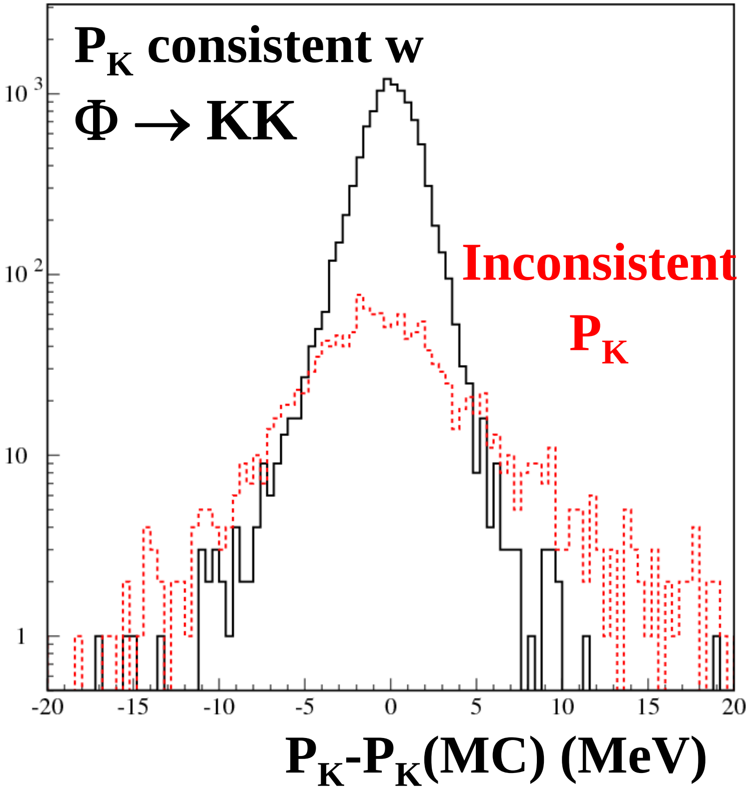
R_K analysis, kinematic selection

Rule of the game: reject Kμ2 by 10^4, with Ke2 efficiency of O(50%)…

Background composition: Kμ2 events with bad P_K, bad P_l reconstruction

Apply quality cuts for K and exploit $\Phi \to KK$ two-body kinematics



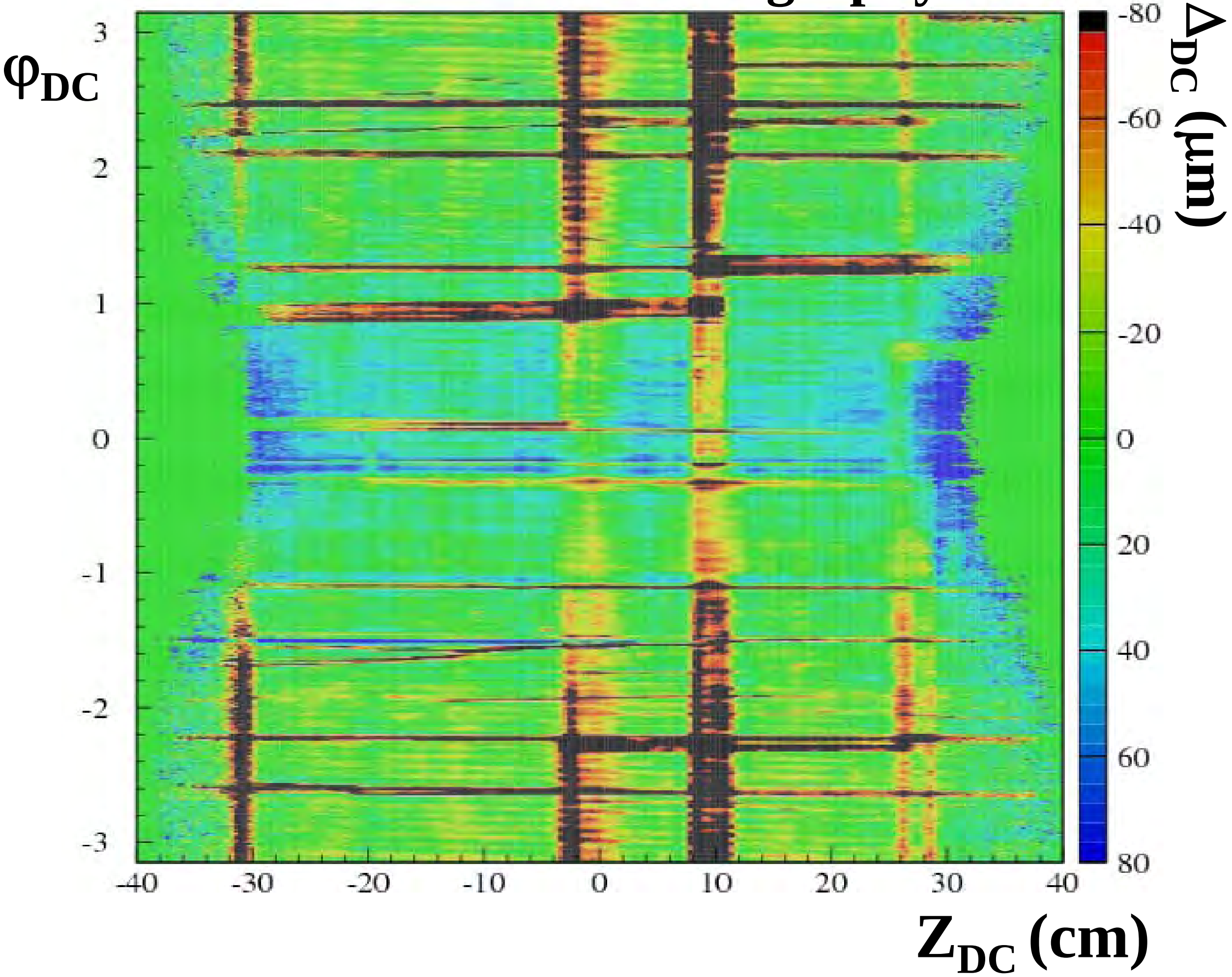


R_K analysis, kinematic selection

In doing extrapolation for K, material budget is a key issue: $\beta_K \sim 0.2$

For the Carbon-fiber DC inner wall, sensititivity on thickness difference Δ_{DC} wrt nominal value of 0.9 mm is order of 10 μm

DC inner wall "Kaography"

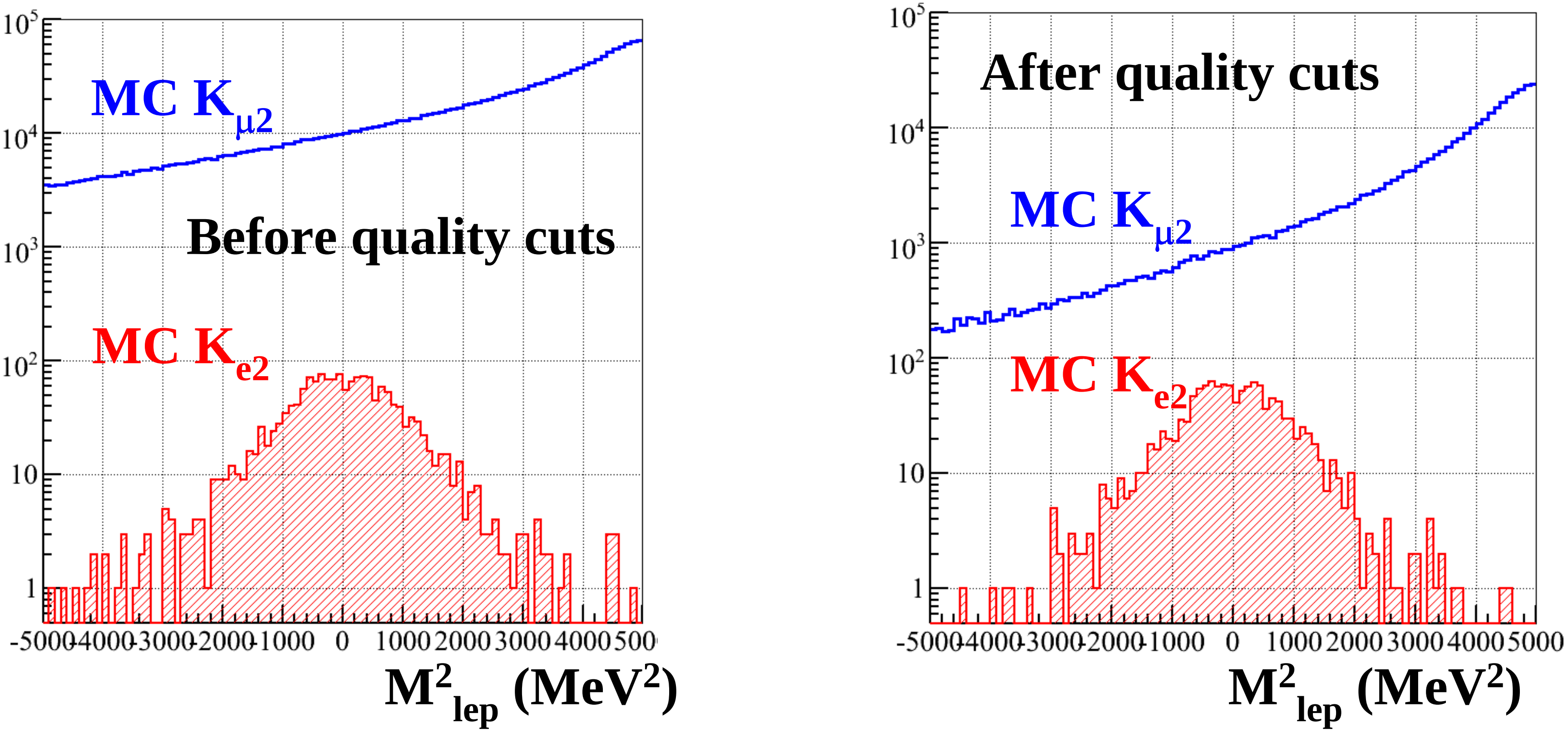


Get rid of bad-P_l's using fit quality + asymmetry of DC hits in L & R views

R_K analysis, quality criteria

$M_{lep}^2 = f(P_K, P_l, \cos\theta) \rightarrow$ a-priori error δM_{lep}^2 is scaled by opening angle

Achieve cancellation in Ke2/Kμ2 efficiencies, applying cosθ trailing cuts



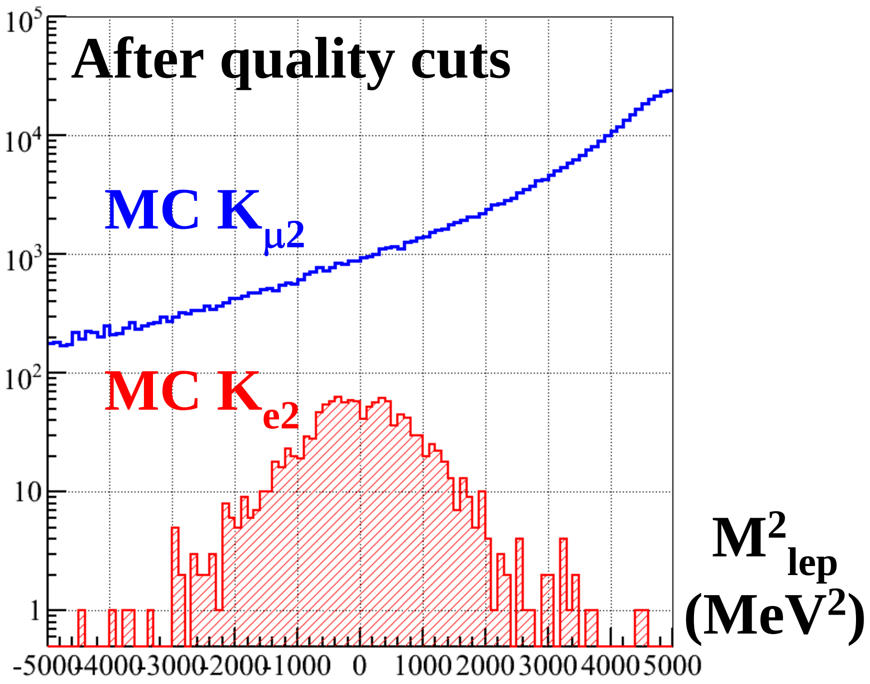
Efficiency ~ 33% at this level

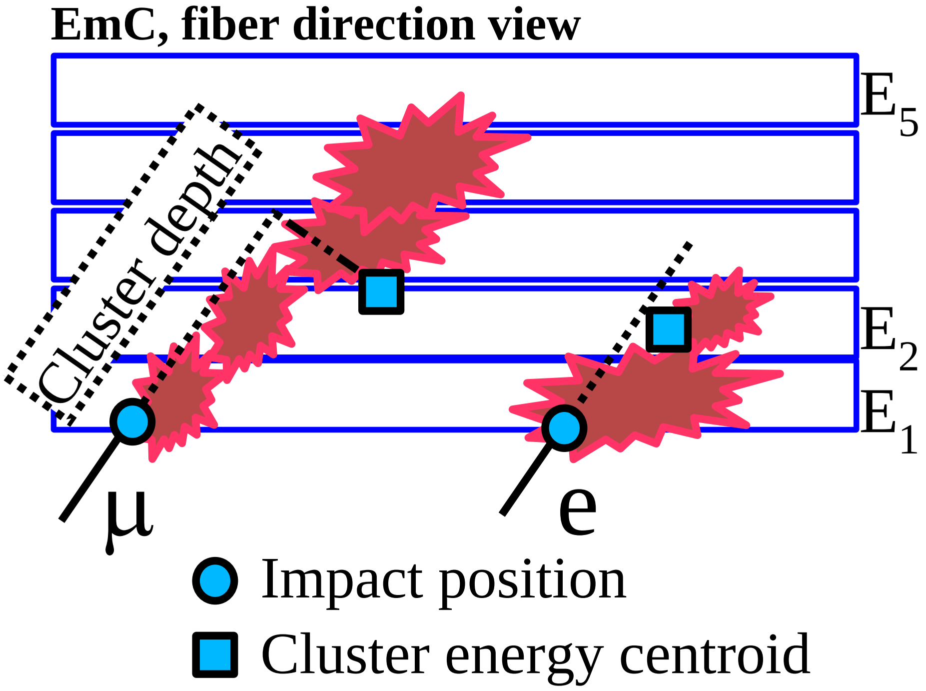
Analysis of R_K, electron identification

Apply quality cuts, enough to count $K_{\mu2}$, not for K_{e2} (still Bkg ~ 10×Sig)

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




EmC, fiber direction view

● Impact position

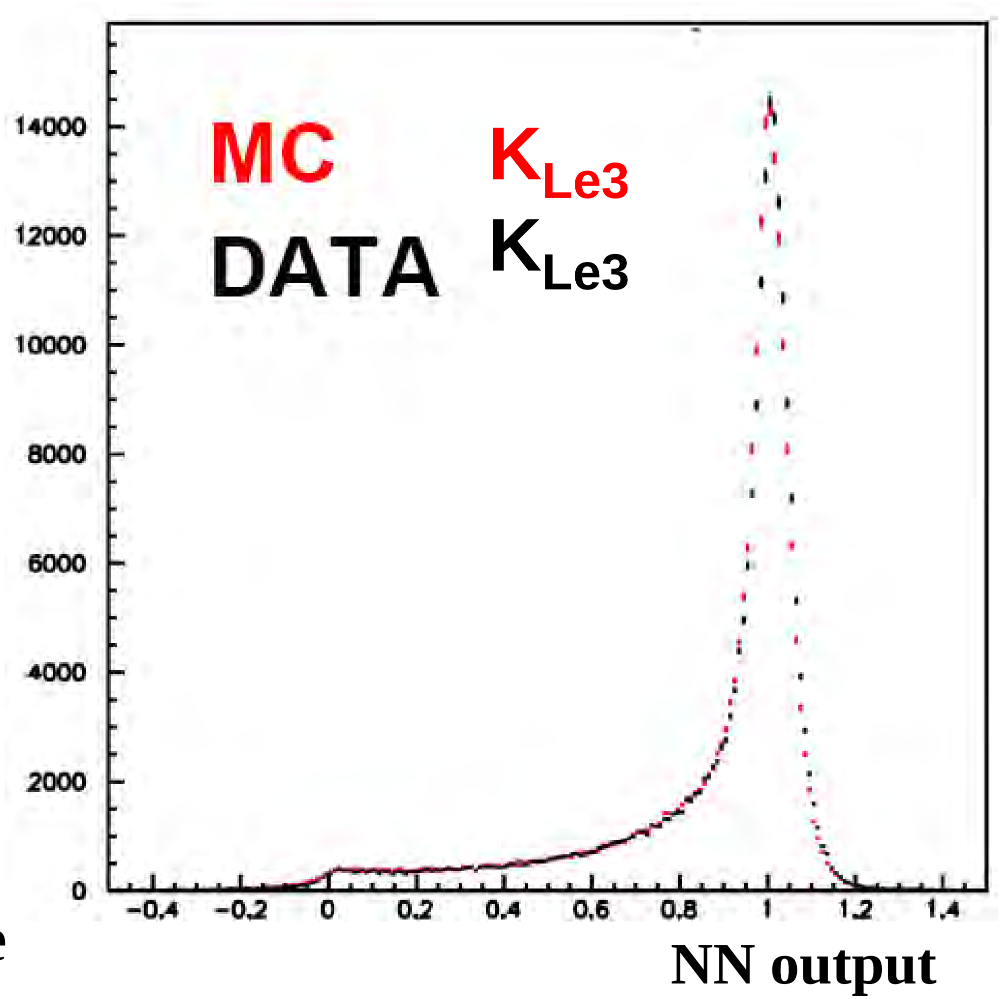
■ Cluster energy centroid

Analysis of R_K, electron identification

Improve bkg rejection, PID refined

Combine 12 variables using NN

- E/P
- Cluster depth
- Asymmetry of energy lost in first two innermost (outermost) planes
- **T2p, Aet (curvature of the fit)**
- **Energy deposit in first 15 cm**
- **Skewness of cell-depth distribution**
- RMS of plane energies (E_{RMS})
- Plane releases: E1, Nmax, Emax
- **TOF**

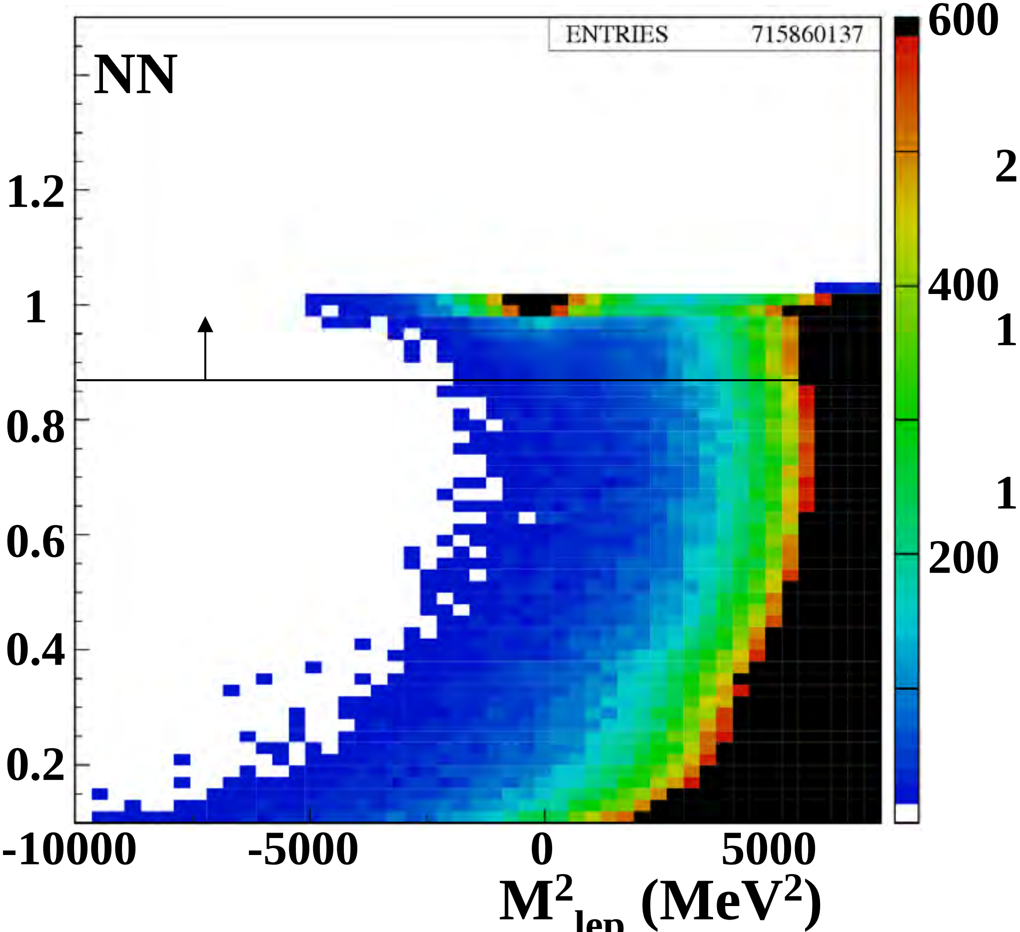


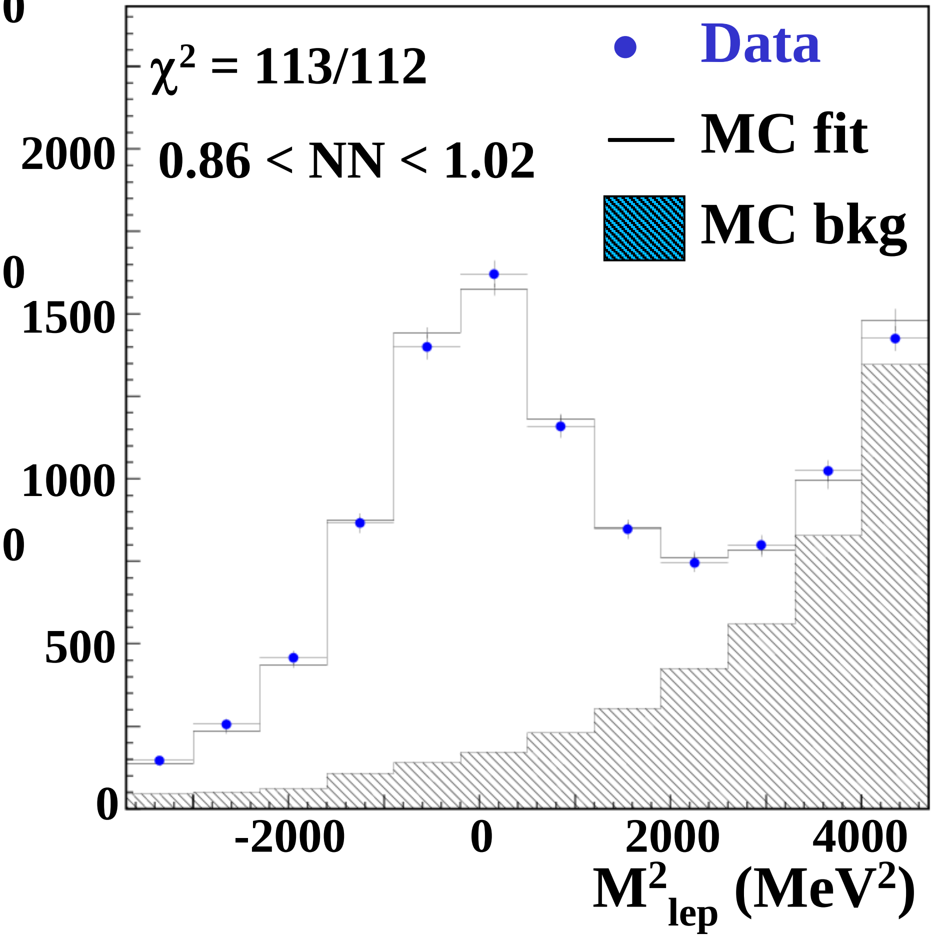
Parametrize with P_{lep}, impact angle

Use K_{Le3} to correct MC response at cell level and use MC to train NN

R_K *analysis, fitting for Ke2 counting*

Two-dimensional binned likelihood fit in the NN- M^2_{lep} plane

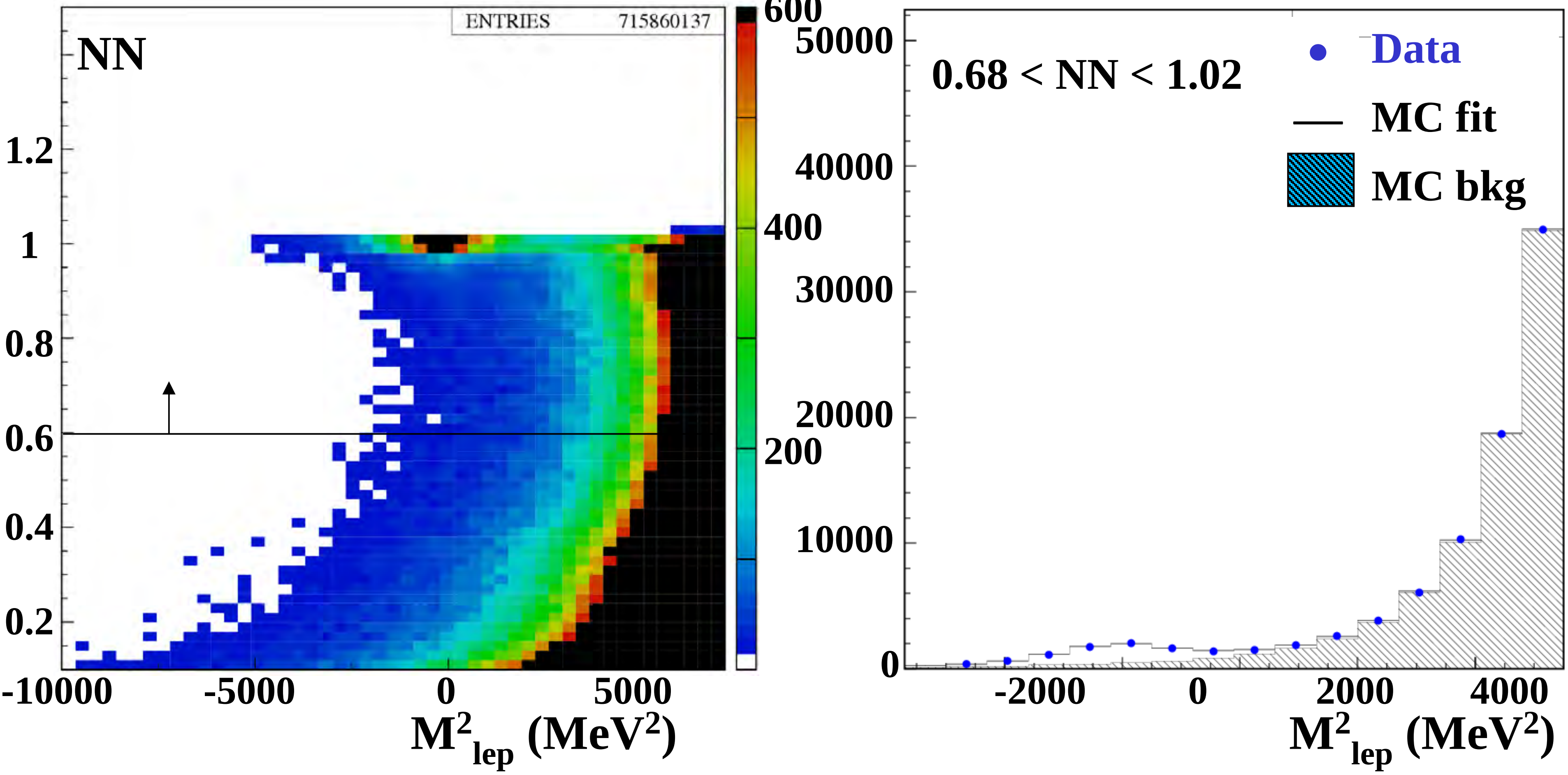




Count in entire statistics: NKe2(e^+) = 7060(98), NKe2(e^-) = 6750(97)

R_K analysis, fitting for Ke2 counting

Two-dimensional binned likelihood fit in the NN- M^2_{lep} plane



Vary significantly contamination + lever arm to assess fit systematics

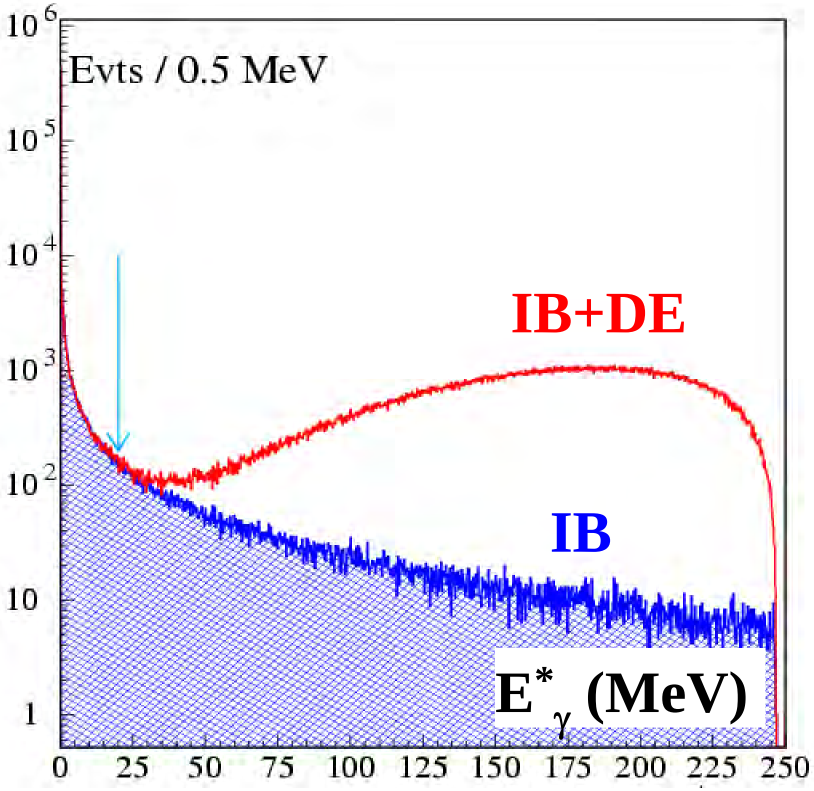
Analysis of R_K – Radiative corrections

To match theory, has to count IB only

Expect DE ~ IB , but we poorly know

δDE/DE ~ 15%

- **Fit using IB+DE, count IB by considering as "signal" events those with E^*_γ<20 MeV**
- **Correct for IB tail, ε^{IB} = 95.28(5)**
- **Repeat fit varying DE by its 15% uncertainty, get 0.45% error…**



…too bad. Perform a dedicated analysis to measure DE:

- **Explicitly detect radiated photon**
- **Compare DE/IB ratio with expectation from theory**

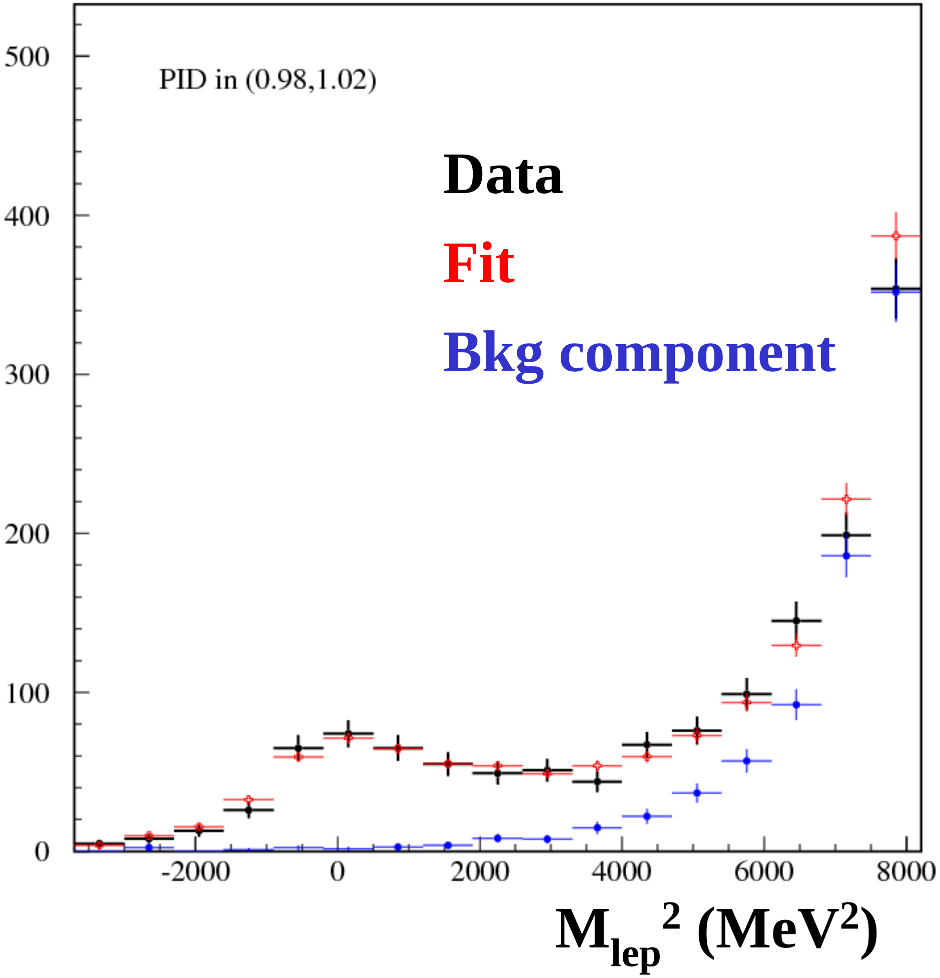
Analysis of R_K – Radiative corrections

Pass from IB/DE ~ 9 to IB/DE ~ 0.6 by explicitly detecting radiated γ

Count 752(36) + 692(36) events

Obtain: IB/(IB+DE) = 0.5153(96)

- **Agrees with expectation, $IB_{SM}/(IB_{SM}+DE_{mmt}) = 0.509(38)$**
- **Allow systematics from DE to IB measurement to be pushed down at 0.1%**

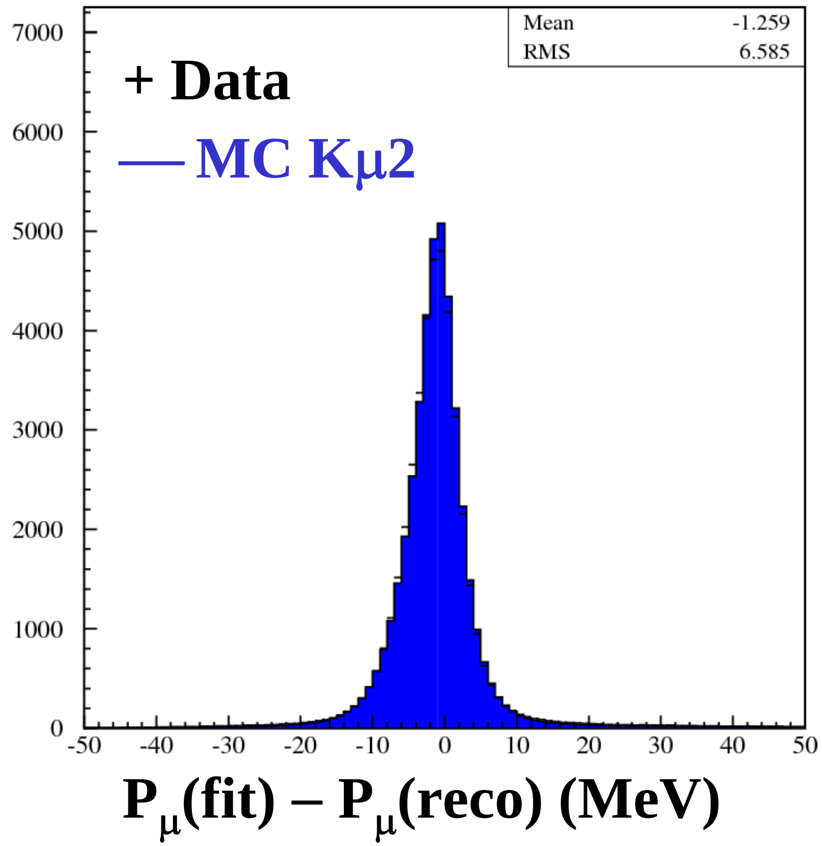


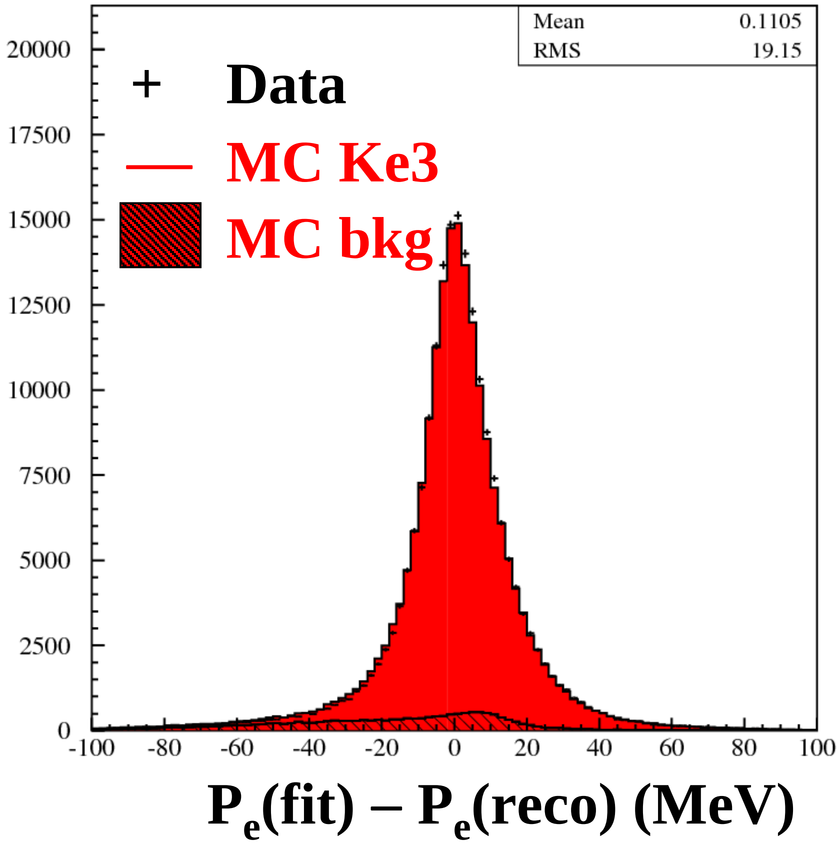
R_K at KLOE, efficiency evaluation

Reconstruction efficiency from MC, corrections from control samples

Select $K^{+,-}_{\mu 2}$ and $K^{+,-}_{e3}$ in events tagged by identification of a $K^{-,+}_{\mu 2}$ decay

Fit P_μ(P_e) using μ(e) cluster r,t (& E), kinematics: no K, μ(e) trks required





R_K systematic error budget

Source	Systematic error [%]		Main method
	Stat	Syst	
Reconstruction	0.4	0.4	Control samples
Trigger efficiency	0.4		Downscaled events
Bkg subtraction		0.3	Fit range variation
Ke2(DE) component	0.1		Measurement on data
Clustering for e, μ	0.3		KL control samples
Total	**0.6**	**0.5**	

Further systematic check: use same algorithms to measure R_3 = Ke3/Kμ3

$R_3 = 1.507 \pm 0.005$ for K^+

$R_3 = 1.510 \pm 0.006$ for K^-

world avg $R_3 = 1.506 \pm 0.003$ (FlaviaNet)

R_K result

$R_K = (2.493 \pm 0.025 \pm 0.019)\ 10^{-5}$

Stat error is 1.1% (0.85% from 14K Ke2 events ⊕ bkg subtraction)

Syst error is dominated by statistics again (0.015)

Measurement do not depend on K charge (good systematic check)

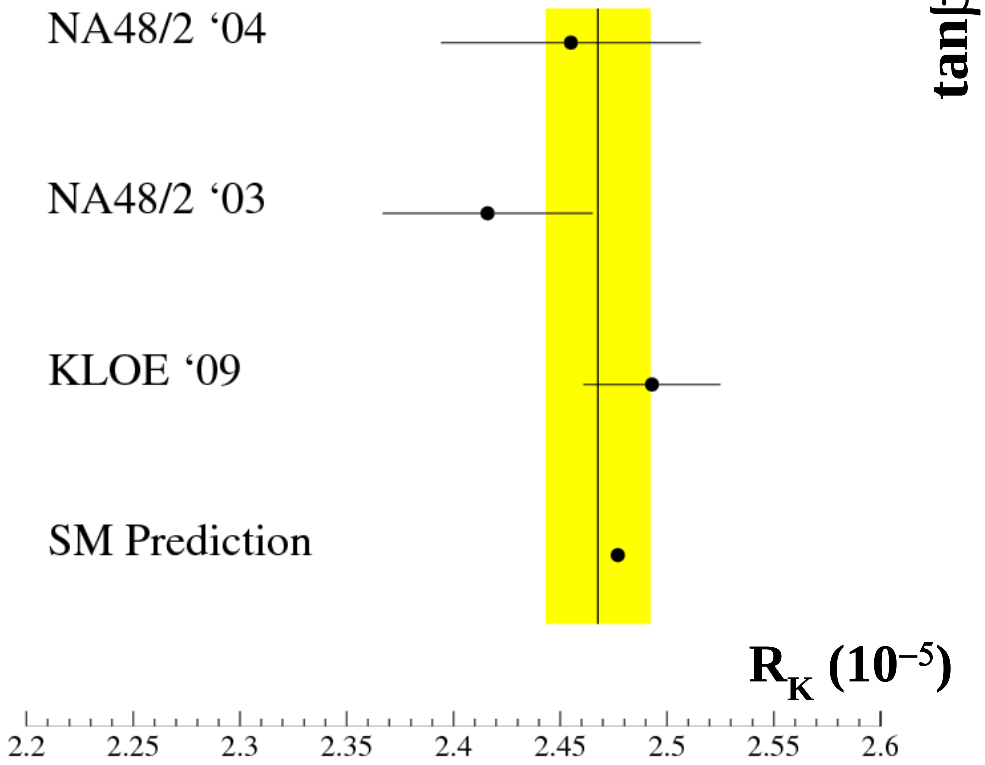
K^+: 2.496(37) vs K^-: 2.490(38), (uncorrelated errors only)

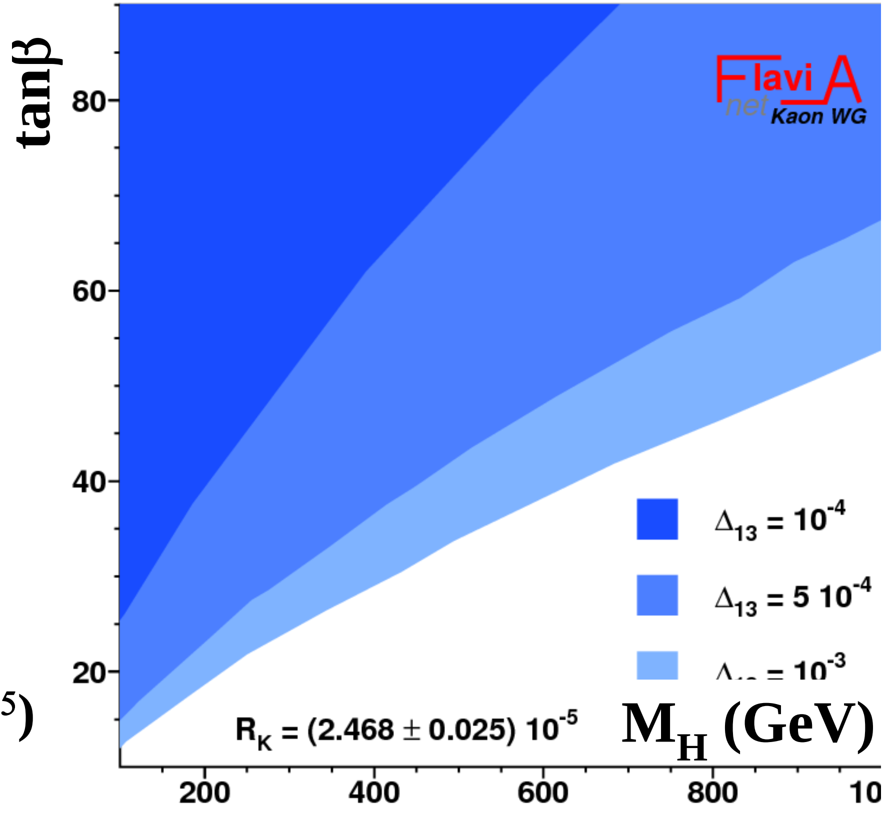
Measurement agrees with SM prediction, $R_K = 2.477(1)$

R_K – 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, $\Delta_{13} = 10^{-3}, 0.5\times10^{-3}, 10^{-4}$

WA w new KLOE result: $R_K = 2.468(25)\times10^{-5}$





Conclusions – kaon physics

Recent KLOE mmts greatly improve knowledge of gauge coupling:

- **Comprehensive set of observables for K decays: BR's, τ's, FF's**
- **Improved unitarity test of 1st row of CKM matrix: $1–V_{ud}^2–V_{us}^2 = 4(7)\ 10^{-4}$**
- **Sensitivity to NP contribution from test of universality of gauge coupling**
- **Lepton universality test from K_{l3} decays satisfied at < 0.5%**

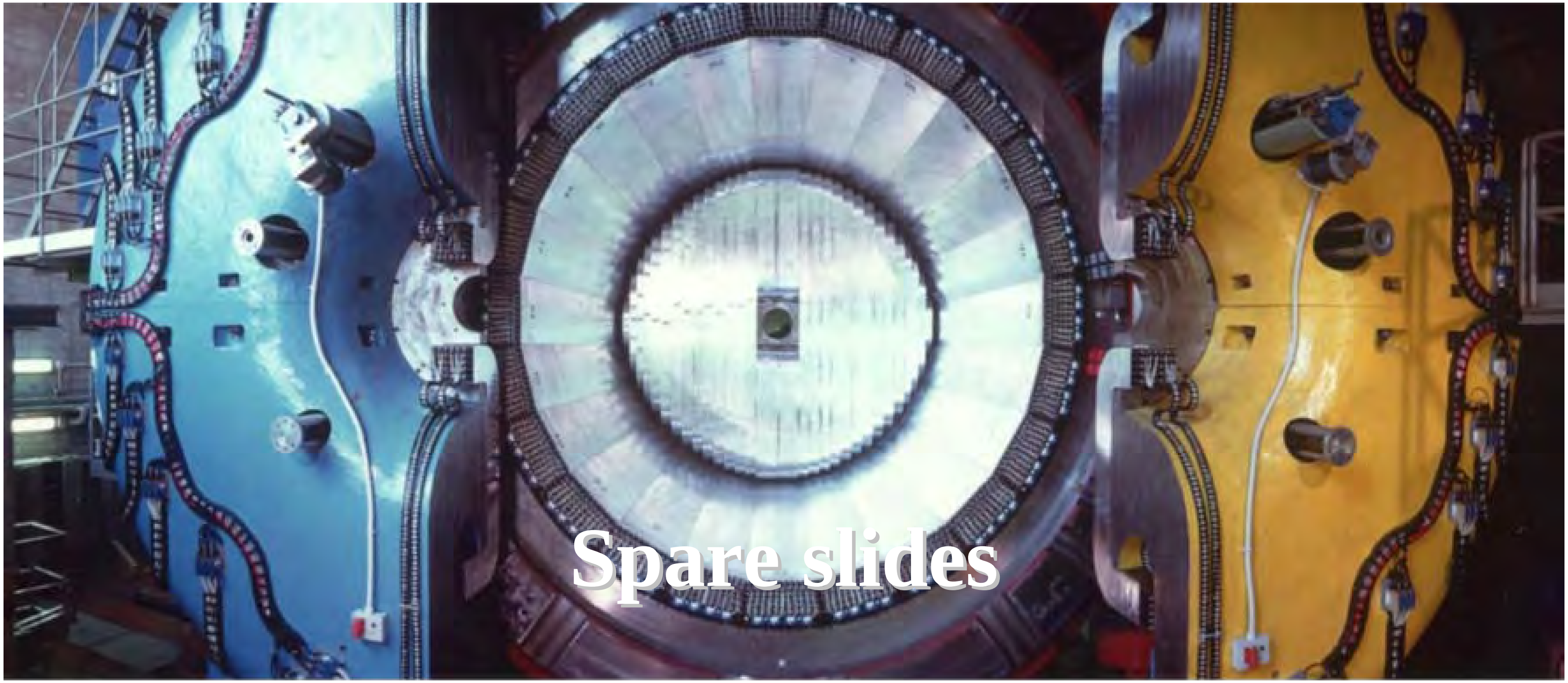
New and interesting tests of NP effects from two-body decay studies

- **Sensitivity to NP effects from $K_{\mu2}/\pi_{\mu2}$: comparable to $B \to \tau\nu$**

Golden observable: R_K, final result $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$

Future developments:

- **Focus on FF slopes from $K^{\pm}_{l3}$ decays + BR($K_S \to \pi\mu\nu$), still missing**



Spare slides

Status of Vud in 2008

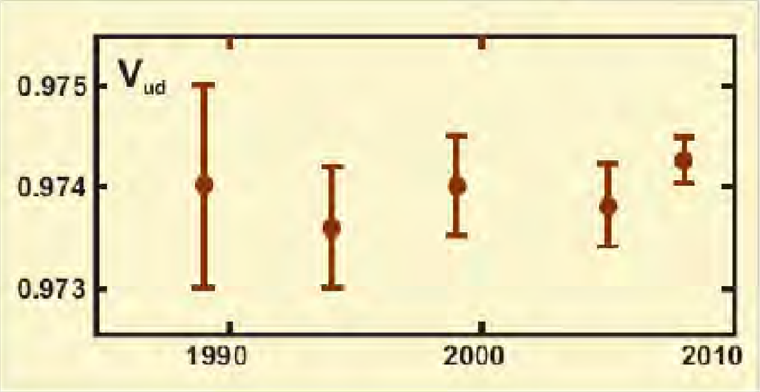
1) G_V constant $\boxed{\mathcal{F}t = \frac{K}{2G_V^2\,(1 + \Delta_R)}}$ ✓ verified to ± 0.013%

2) Scalar current zero ✓ limit, $C_S/C_V = 0.0011\ (14)$

3) Precise value determined for V_{ud} $\boxed{V_{ud} = G_V/G_\mu}$

$\boxed{V_{ud} = 0.97425 \pm 0.00023}$

Compare:
neutron $V_{ud} = 0.9746 \pm 0.0019$
pion $V_{ud} = 0.9749 \pm 0.0026$

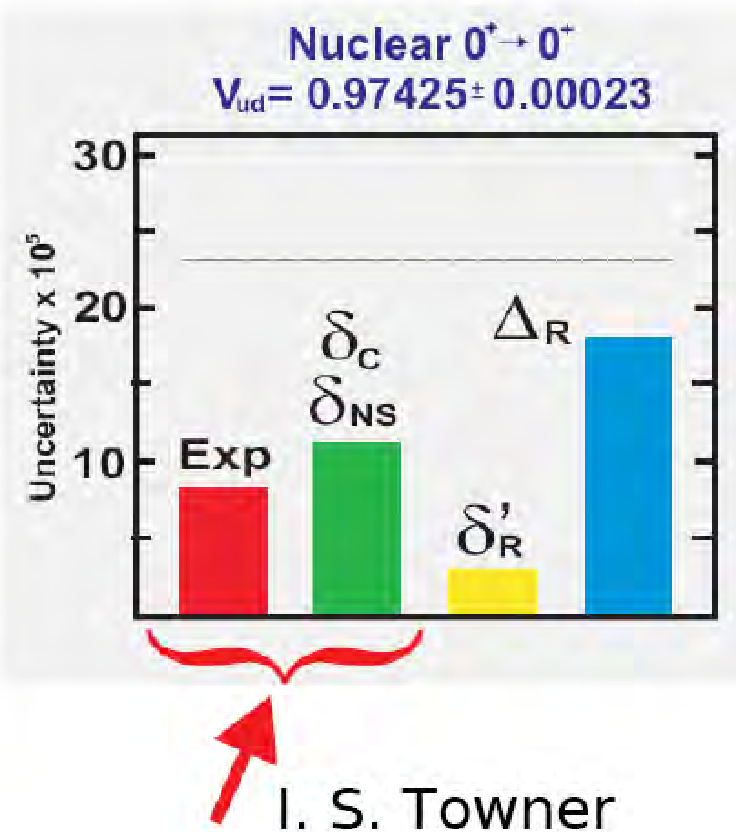


I. S. Towner
@ CKM08

Possible improvements in Vud

- Goal remains to tighten the window for new physics by reducing the uncertainty on V_{ud}.
- Uncertainty on calculated radiative correction Δ_R is the dominant contribution to the error budget.
- Nuclear-structure-dependent corrections, δ_C and δ_{NS}, can be tested by experiment; this has already led to improvements, but more are still possible.

Data on "well known" transitions can be made more precise, and new cases can be measured.



Nuclear $0^+ \rightarrow 0^+$
$V_{ud} = 0.97425 \pm 0.00023$

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Beyond the quadratic ff parametrization

[Stern et al]

Dispersion relation for ln $f_0(t)$ subtracted at $t = 0$ and $t = m_K^2 - m_\pi^2$, giving:

$$\tilde{f}_0(t) = \exp\left[\frac{t}{m_K^2 - m_\pi^2}(\ln C - G(t))\right]$$

$G(t)$ evaluated using $K\pi$ scattering data

1 fit parameter:
log C

log $C = 0.204 \pm 0.023$

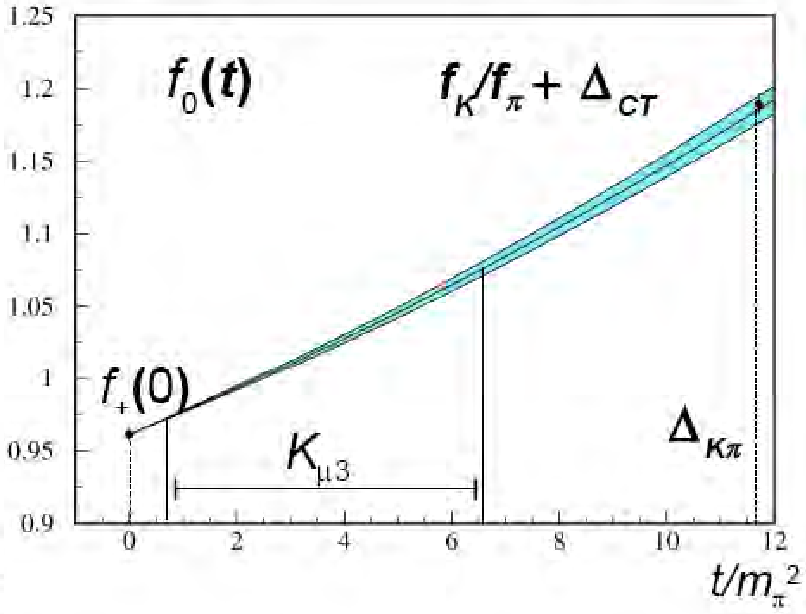
JHEP0712:105

Very precise relation between $f_0(0)^*$ and f_K/f_π :

$$f_0(\Delta_{K\pi}) = f_K/f_\pi + \Delta_{CT}$$

$$f_+(0)\,\tilde{f}_0(\Delta_{K\pi}) = f_K/f_\pi + \Delta_{CT}$$

$\Delta_{K\pi} = m_K^2 - m_\pi^2$; $\Delta_{CT} = 3.5 \times 10^{-3}$ ~~SU(2)~~



Interest in LU tests with kaons

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

New physics extensions of the SM with LFV not ruled out, so:

- **Can search for processes forbidden/ultra-rare in SM, e.g. K→ μe**
- **Can measure ratio of coupling constants, seeking deviations from 1 in processes well known in SM, like:**

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

Testing H^+ effects or right-handed currents in:

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

Testing LFV violation NP amplitudes contributing to:

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

Vus and LU from Kl3 decays: results

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

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

e/μ universality satisfied, using only KLOE results get accuracy < 0.01:

K_L	**$g_\mu^2/g_e^2 = 1.011(9)$**	**cfr with**	**$g_\mu^2/g_e^2 = 1.0232(68)$ [PDG04]**
K^+	**$g_\mu^2/g_e^2 = 0.99(1)$**	**cfr with**	**$g_\mu^2/g_e^2 = 1.0020(80)$ [PDG04]**
Avg	**$g_\mu^2/g_e^2 = 1.000(8)$**		

Compare with

$\tau \to l\nu\nu$	**$g_\mu^2/g_e^2 = 1.000(4)$ [Davier, Höcker, Zhang '06]**
$\pi \to l\nu$	**$g_\mu^2/g_e^2 = 1.004(3)$ [Erler, Ramsey-Musolf '06]**

$K_{\mu 2}$ – Sensitivity to NP

Experimental inputs are known at few per-mil level:

$m_{K,\pi,\mu}$, $\Gamma(\pi_{\mu 2})$	[PDG]
$\tau^{+} = 12.347(30)$	[KLOE]
$BR(K^{+} \to \mu^{+}\nu(\gamma)) = 63.66(17)\%$	[KLOE]
$\lvert f_{+}(0)V_{us}\rvert = 0.2157(6)$	[KLOE]
$V_{ud} = 0.97418(26)$	[world average $0^{+} \to 0^{+}$]

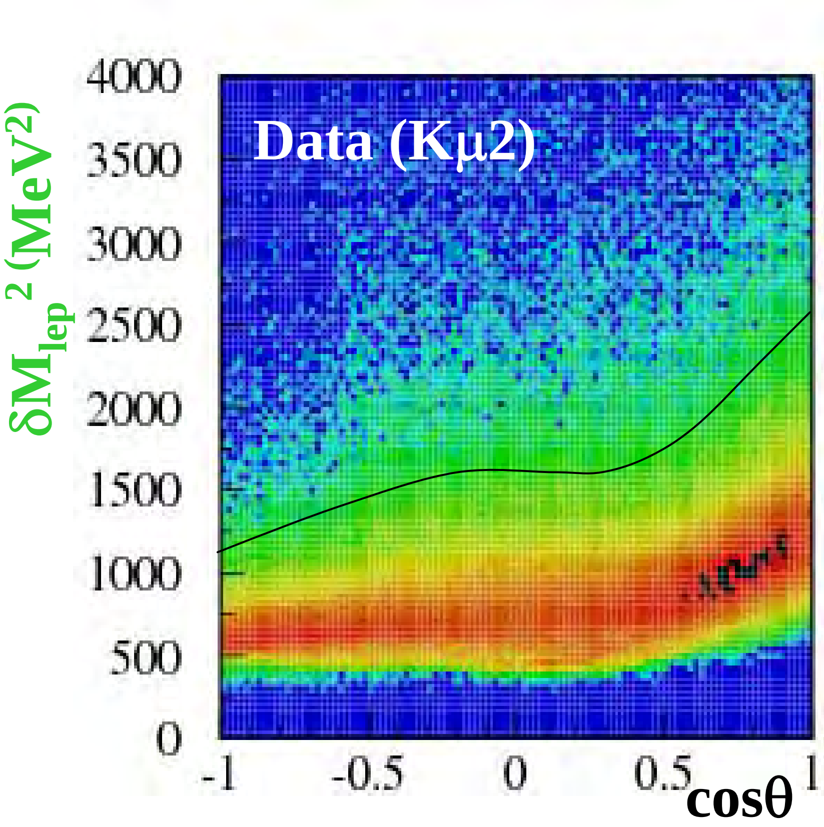
Theoretical inputs dominate the uncertainty, through the form factors:

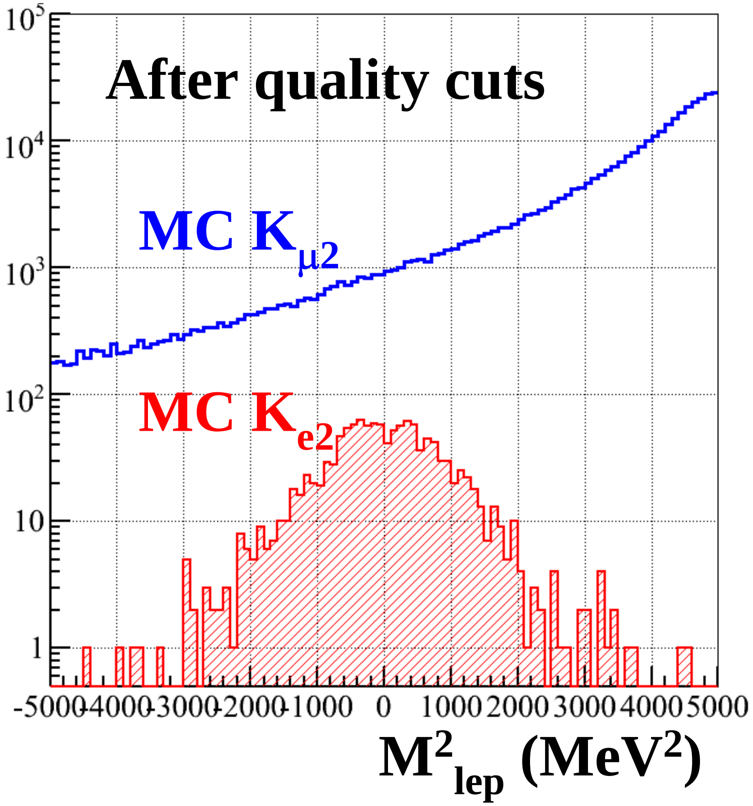
$f_{K}/f_{\pi} = 1.189(7)$	[MILC-HPQCD arXiv:0706.1726]
$f_{+}(0) = 0.964(5)$	[UKQCD-RBC hep-lat/0702026]
$\delta_{em} = -0.0070(35)$	[Marciano PRL 93 (2004) 231803, Cirigliano Rosell JHEP 0710, 005 (2007)]

R_K *analysis, quality criteria*

$M_{lep}^2 = f(P_K, P_l, \cos\theta) \rightarrow$ a-priori error δM_{lep}^2 is scaled by opening angle

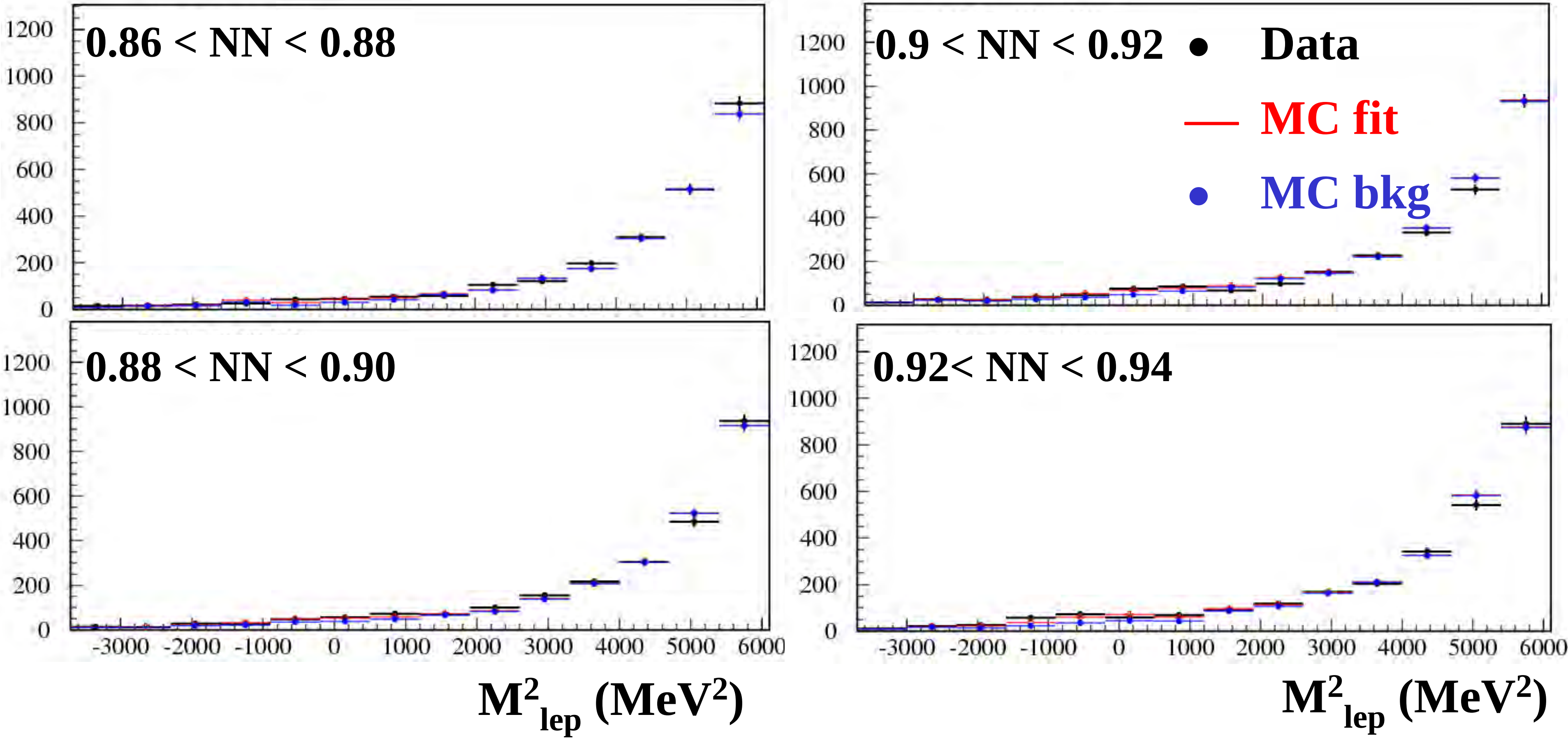
Achieve cancellation in Ke2/Kμ2 efficiencies, applying cosθ trailing cuts





R_K analysis, fitting for Ke2 counting

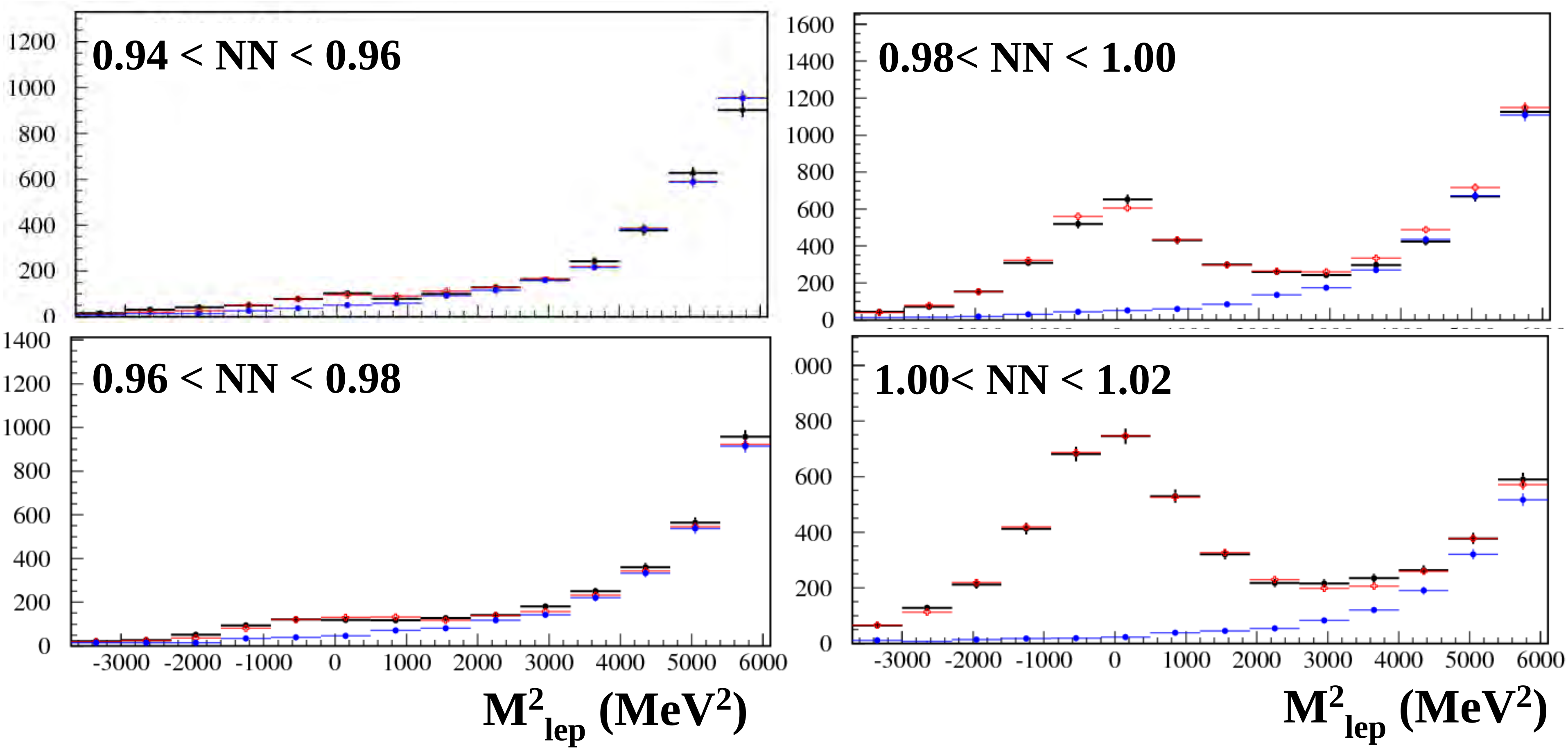
Two-dimensional binned likelihood fit in the NN- M^2_{lep} plane



Count in entire statistics: NKe2(e^+) = 7060(98), NKe2(e^-) = 6750(97)

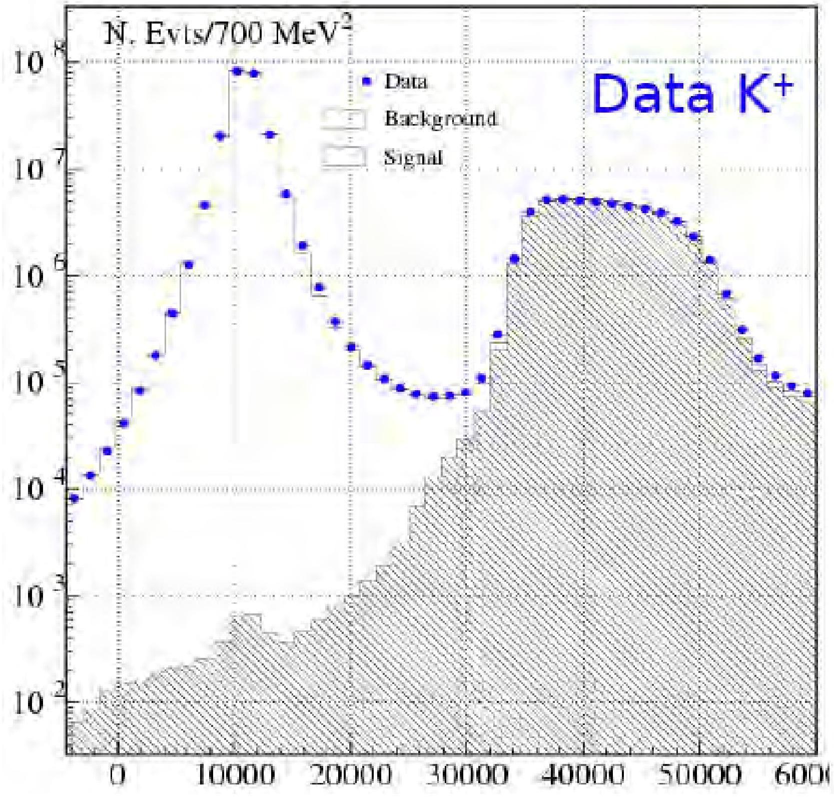
R_K analysis, fitting for Ke2 counting

Two-dimensional binned likelihood fit in the NN- M^2_{lep} plane

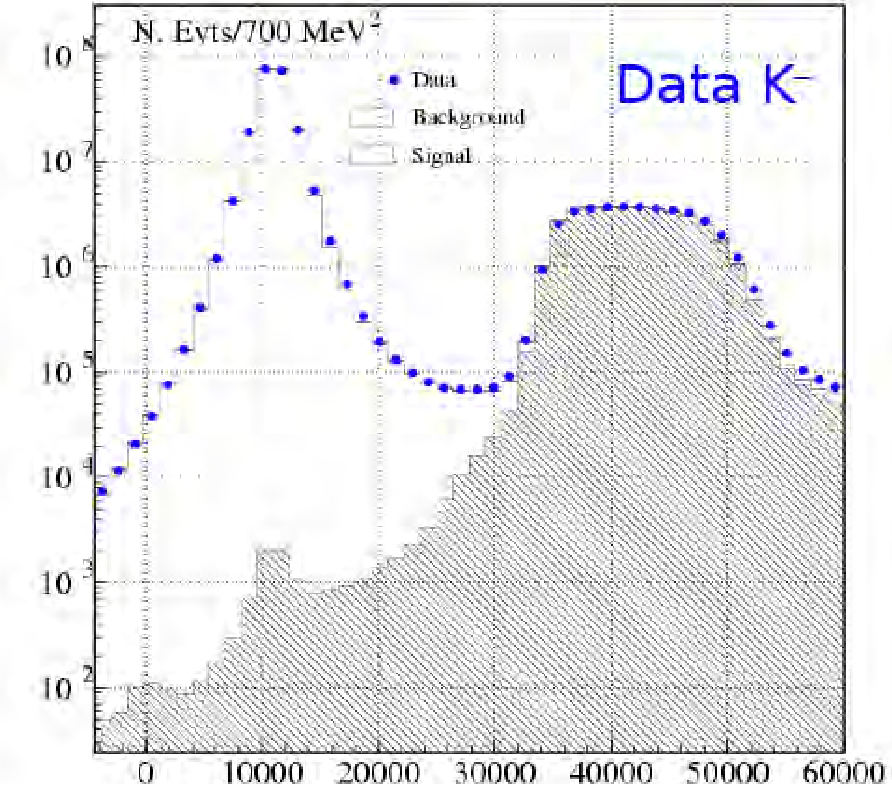


Count in entire statistics: **NKe2(e^+) = 7060(98), NKe2(e^-) = 6750(97)**

R_K analysis, counting Km2 events



M^2_{lep} (MeV^2)

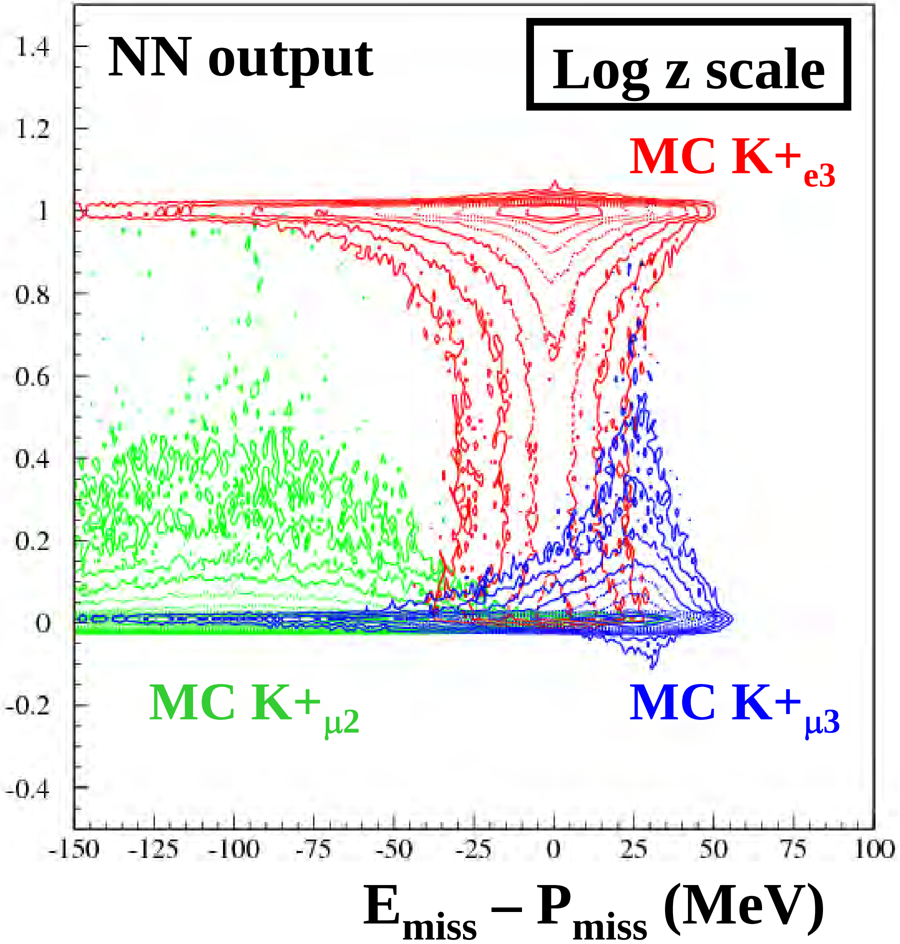


M^2_{lep} (MeV^2)

R_K at KLOE, control samples

Check NN output using $K^{\pm}_{e3}$, $K^{\pm}_{\mu 3}$ (can check TOF, not possible with K_L)

- **Require π^0 detection**
- **Cut against $\pi\pi^0$ bkg**
- **Use π^0 γ's to evaluate E_{miss}, P_{miss}**

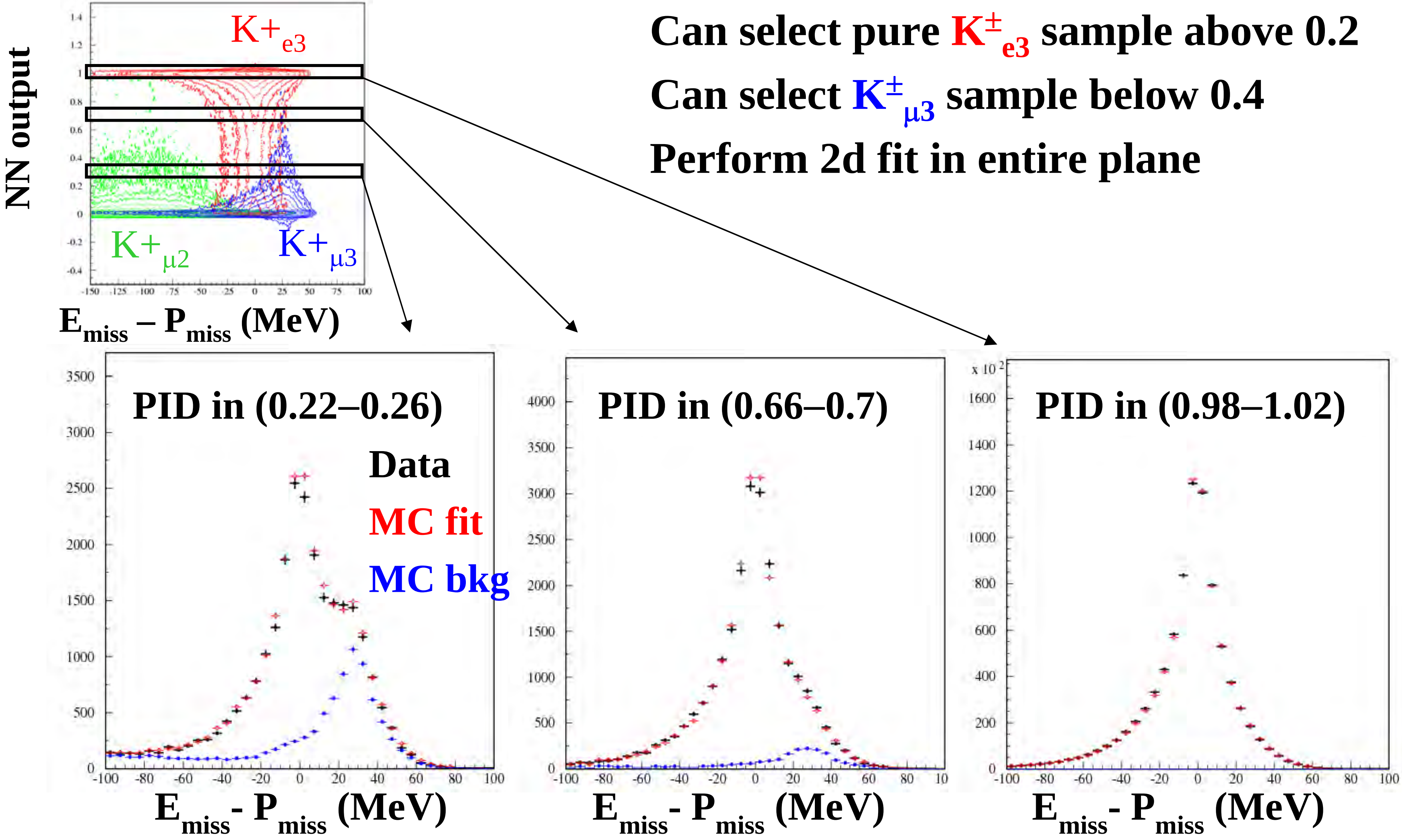


R_K at KLOE, control samples

Can select pure $K^{\pm}_{e3}$ sample above 0.2

Can select $K^{\pm}_{\mu3}$ sample below 0.4

Perform 2d fit in entire plane

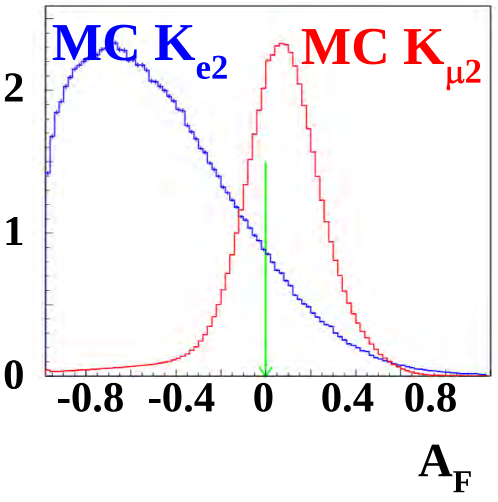


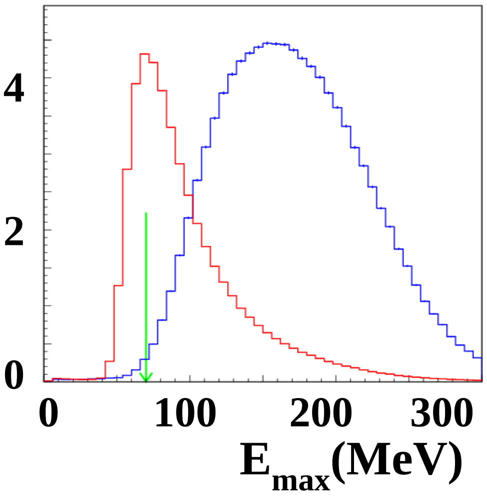
Analysis of R_K – PID using EmC

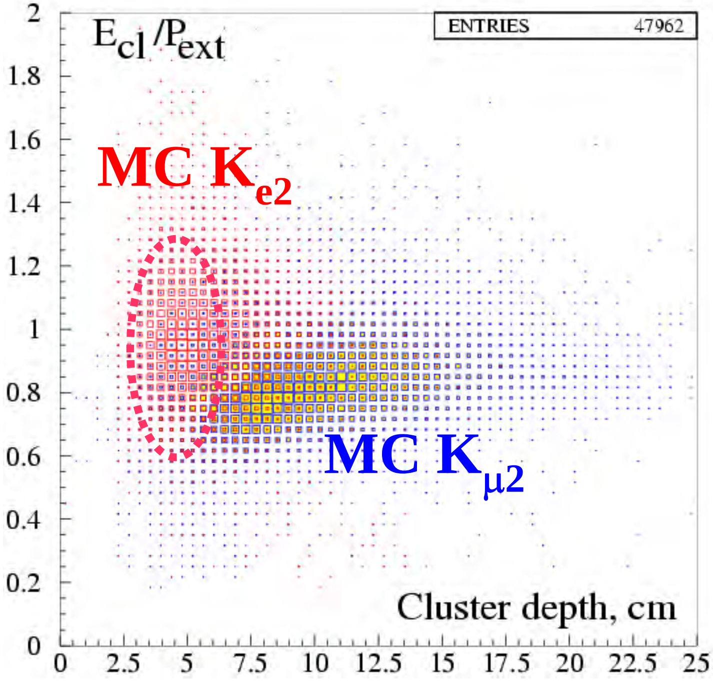
e’s: initiate shower @ EmC entrance, $E_{cl}/P \sim 1$

μ’s: MIP-like in layers 1-2, Bragg peak @ end

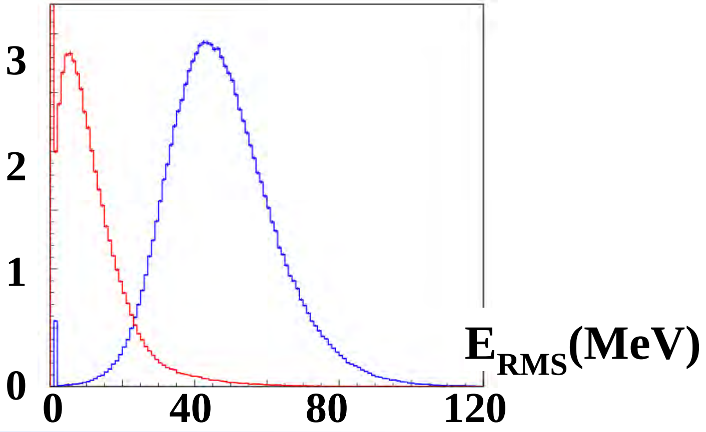
Cut on $A_F = \dfrac{(E_2 - E_1)}{(E_2 + E_1)}$ **,** $E_{max} = \max\{E_k\}$







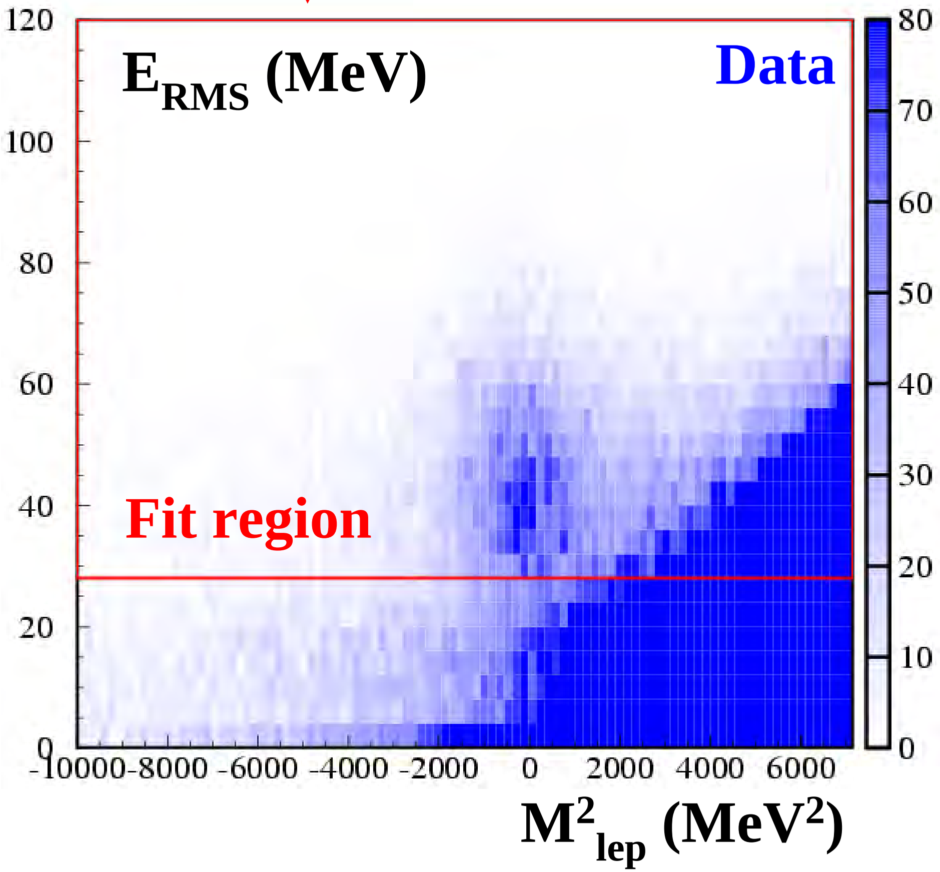
Cut on $A_L = \dfrac{(E_n - E_{n-1})}{(E_n + E_{n-1})}$ **,** $E_{RMS} = \text{RMS}\{E_k\}$ **left for signal counting**

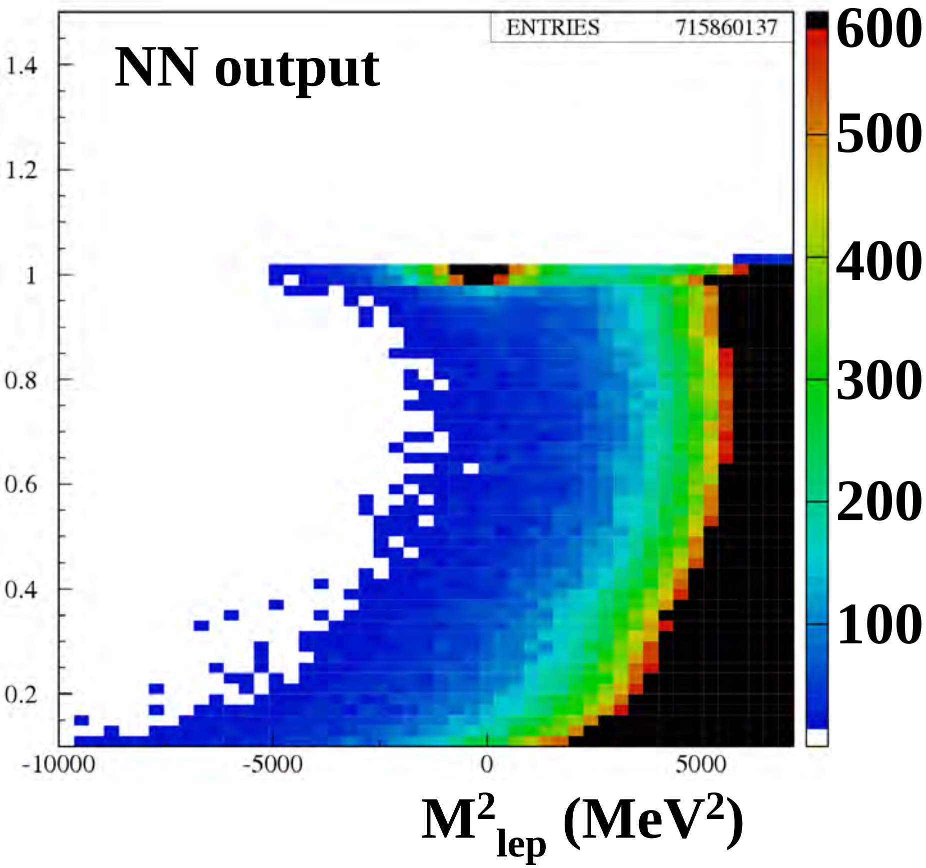


R_K *at KLOE, compare wrt preliminary*

Rejection from PID now > 1000 → loosen kinematic criteria

Compare OLD selection with NEW selection



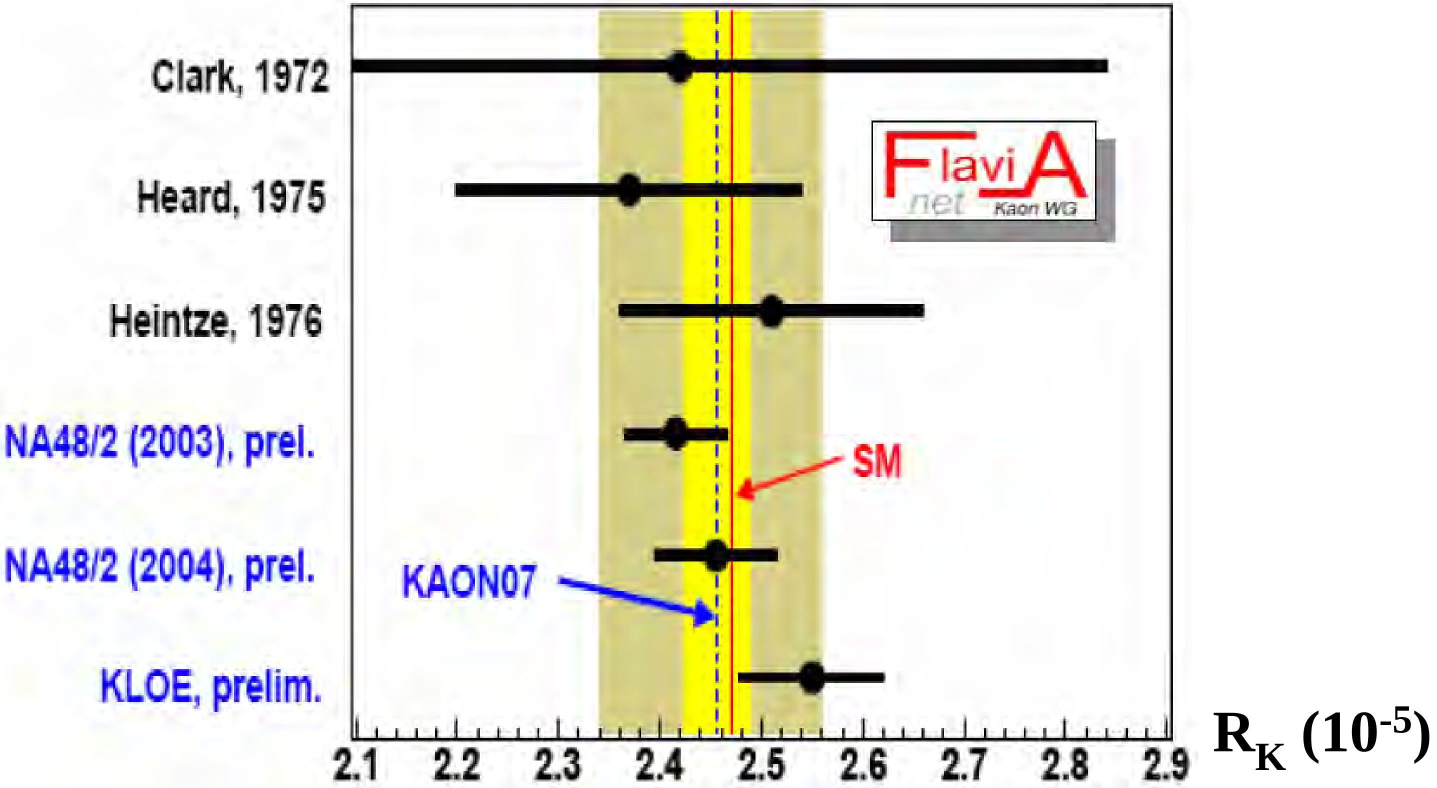


R_K – experimental status as of yesterday

$$R_K = \frac{N_{Ke2}}{N_{K\mu2}} \left[\frac{\varepsilon^{\mathrm{TRG}}_{K\mu2}}{\varepsilon^{\mathrm{TRG}}_{Ke2}}\right] \left[C^{\mathrm{TRK}} \frac{\varepsilon^{\mathrm{TRK}}_{K\mu2}}{\varepsilon^{\mathrm{TRK}}_{Ke2}}\right] \left[\frac{1}{C^{\mathrm{PID}} \varepsilon^{\mathrm{PID}}_{Ke2}}\right] \frac{1}{\varepsilon^{\mathrm{IB}}} = (2.55 \pm 0.05 \pm 0.05)\times10^{-5}$$

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

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



Measurement of K_{Le3} form factor slopes

Both linear and quadratic fits show good χ^2 probabilities, 89% and 92%

Linear fit	$\lambda_+ \times 10^3$	χ^2/ndf
$K_L \to \pi^- e^+ \nu$	28.7 ± 0.7	$156/181$
$K_L \to \pi^+ e^- \overline{\nu}$	28.5 ± 0.6	$174/181$
Combined	28.6 ± 0.5	$330/363$

Quadratic fit	$\lambda'_+ \times 10^3$	$\lambda''_+ \times 10^3$	χ^2/ndf
$K_L \to \pi^- e^+ \nu$	24.6 ± 2.1	1.9 ± 1.0	$152/180$
$K_L \to \pi^+ e^- \overline{\nu}$	26.4 ± 2.1	1.0 ± 1.0	$173/180$
Combined	25.5 ± 1.5	1.4 ± 0.7	$325/362$

$$\lambda_+ = (28.6 \pm 0.5_{\mathrm{stat.}} \pm 0.4_{\mathrm{syst.}}) \times 10^{-3}$$

$$\lambda'_+ = (25.5 \pm 1.5_{\mathrm{stat.}} \pm 1.0_{\mathrm{syst.}}) \times 10^{-3}$$

$$\lambda''_+ = (1.4 \pm 0.7_{\mathrm{stat.}} \pm 0.4_{\mathrm{syst.}}) \times 10^{-3}$$

$\rho(\lambda', \lambda'') \sim -0.95$

Pole fit result (92% χ^2 probability) indicates dominance of K*(892)-exchange in the Kπ transition:

$$M_V = (870 \pm 6_{\mathrm{stat.}} \pm 7_{\mathrm{syst.}})\ \mathrm{MeV}$$

Systematic errors dominated by uncertainties in TOF efficiency correction

Measurement of K_{Le3} form factor slopes

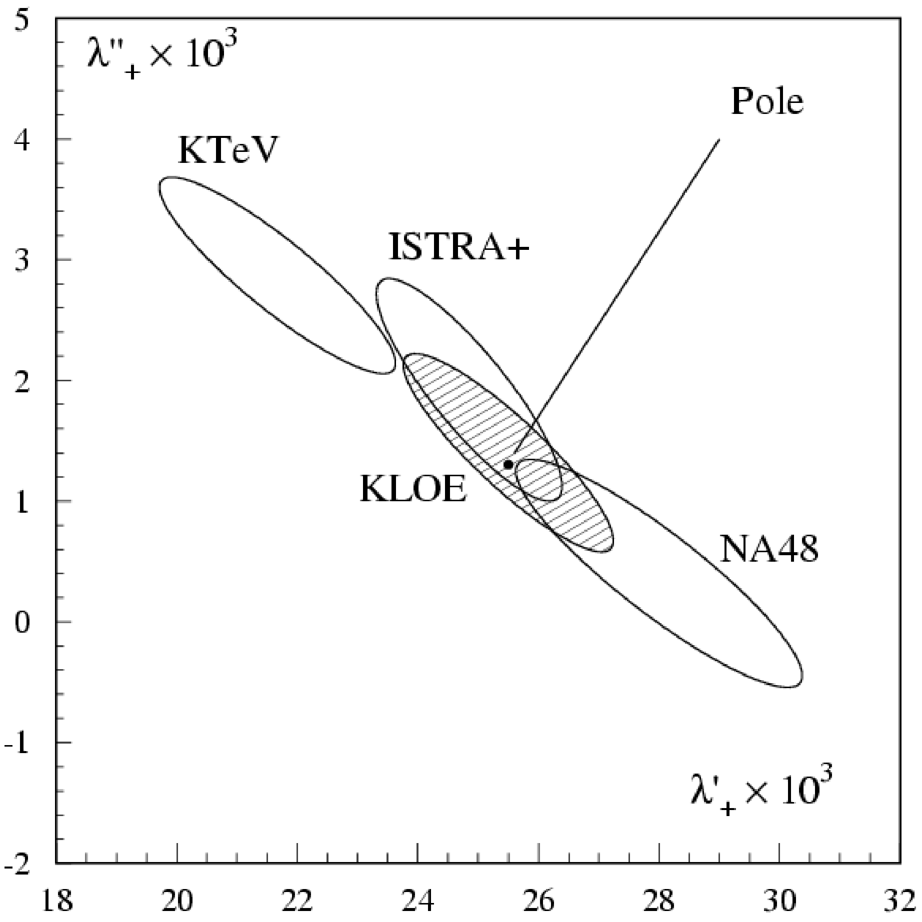
- **KLOE measurements of K_{Le3} and $K_{l\mu3}$ BR and ff slopes determine:**

$f_+(0) \times |V_{us}| = 0.21561(69)$

$f_+(0) \times |V_{us}| = 0.21633(78)$

Inputs only from KLOE, errors of 0.32% and 0.40%

- **In comparing with results from other experiments, have to take correlations into account, especially for ff's**



Other impacts from K_{se3} (1)

Comparing $\Gamma(K_S \to \pi e \nu)$ to $\Gamma(K_L \to \pi e \nu)$, test $\Delta S = \Delta Q$:

×2 improvement in precision on $\mathrm{Re}\, x_+ = (-0.5 \pm 3.6) \times 10^{-3}$

Sensitivity to CPT violating effects through charge asymmetry:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})} \quad \begin{cases} A_S - A_L = 4\,[\mathrm{Re}\,(\delta) + \mathrm{Re}\,(x_-)] \\ A_S + A_L = 4\,[\mathrm{Re}\,(\varepsilon) - \mathrm{Re}\,(y)] \end{cases}$$

Evaluate A_S from: $$A_S = \frac{N(\pi^- e^+ \nu)/\epsilon^+_{\mathrm{tot}} - N(\pi^+ e^- \bar{\nu})/\epsilon^-_{\mathrm{tot}}}{N(\pi^- e^+ \nu)/\epsilon^+_{\mathrm{tot}} + N(\pi^+ e^- \bar{\nu})/\epsilon^-_{\mathrm{tot}}}$$

A_S measured for the first time: $A_S = (1.5 \pm 9.6_{\mathrm{stat}} \pm 2.9_{\mathrm{syst}}) \times 10^{-3}$

Error dominated by statistics, ×3 improvement after analysis of 2.5 fb^{-1}

Impact of new data on K0 decays: BSR

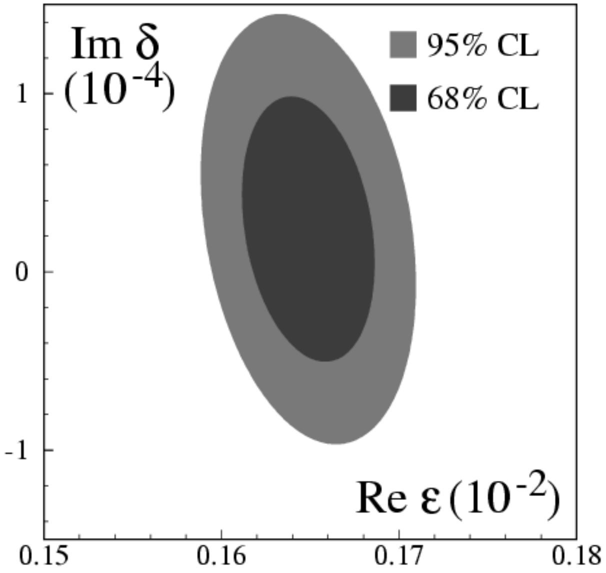
With KLOE data improved ~~CPT~~ test via Bell-Steinberger (unitarity) relation:

$$\left(\frac{\Gamma_S+\Gamma_L}{\Gamma_S-\Gamma_L}+i\tan\phi_{SW}\right)\left(\frac{\Re\epsilon-i\Im\delta}{1+\epsilon^2}\right)=\frac{1}{\Gamma_S-\Gamma_L}\Sigma_f A_L(f)\,A_S^{*}(f)$$

After CPLEAR measurements (2001)

$$\mathrm{Re}(\epsilon) = (164.9 \pm 2.5) \times 10^{-5}$$

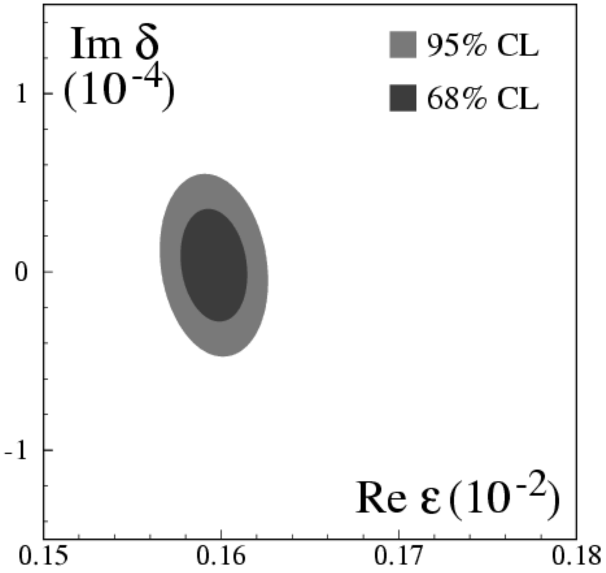
$$\mathrm{Im}(\delta) = (\ 2.4 \pm 5.0) \times 10^{-5}$$



After KLOE measurements (2006)

$$\mathrm{Re}(\epsilon) = (159.6 \pm 1.3) \times 10^{-5}$$

$$\mathrm{Im}(\delta) = (\ 0.4 \pm 2.1) \times 10^{-5}$$



Impact of new data on K0 decays: UT

From BSR, shift central value of $\Re\varepsilon$ by 3.6 σ with respect to PDG04

$|\varepsilon|$ is related to the η and ρ parameters of the CKM matrix:

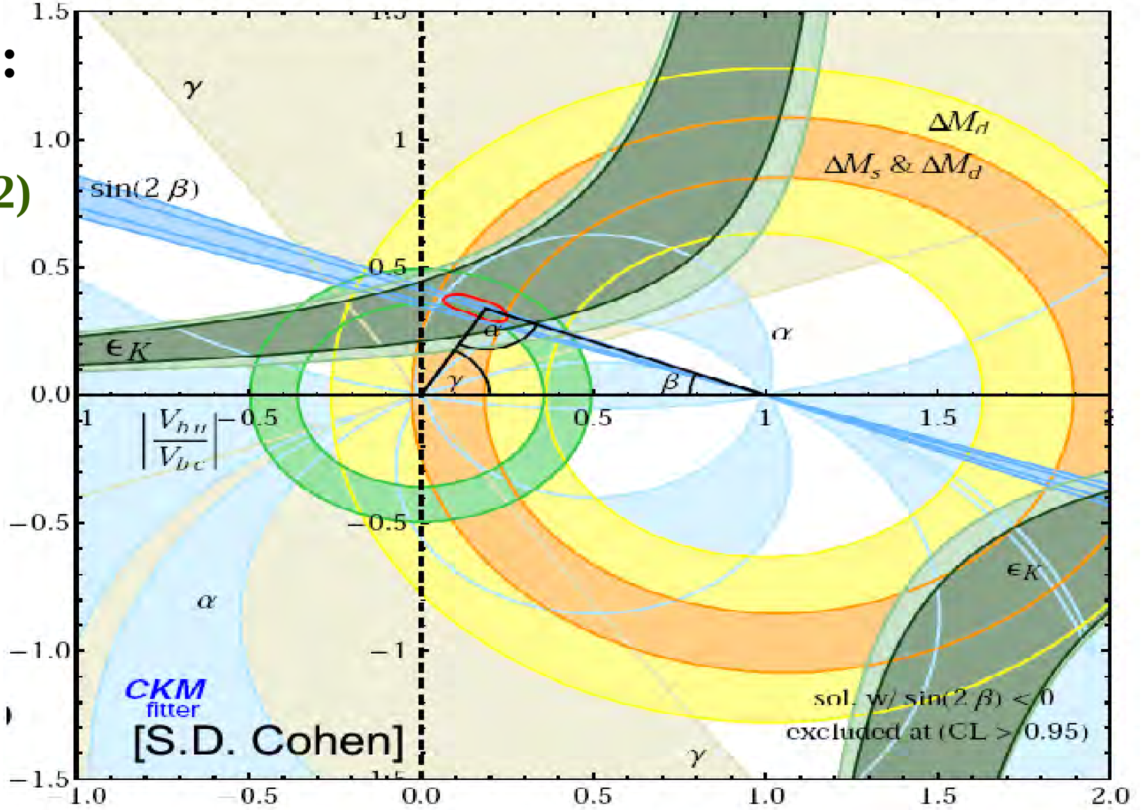
$$|\varepsilon| = C_1 B_K V_{cb}^2 \eta [C_2 + C_3 V_{cb}^2 (1-\rho)]$$

Compare input values for B_K:

Standard, **$B_K = 0.79(2)(9)$**

RBC/UKQCD, **$B_K = 0.770(15)(22)$**

Impact on UT fit now limited by δV_{cb}



Measurements of $K^{+,-}$ BR's

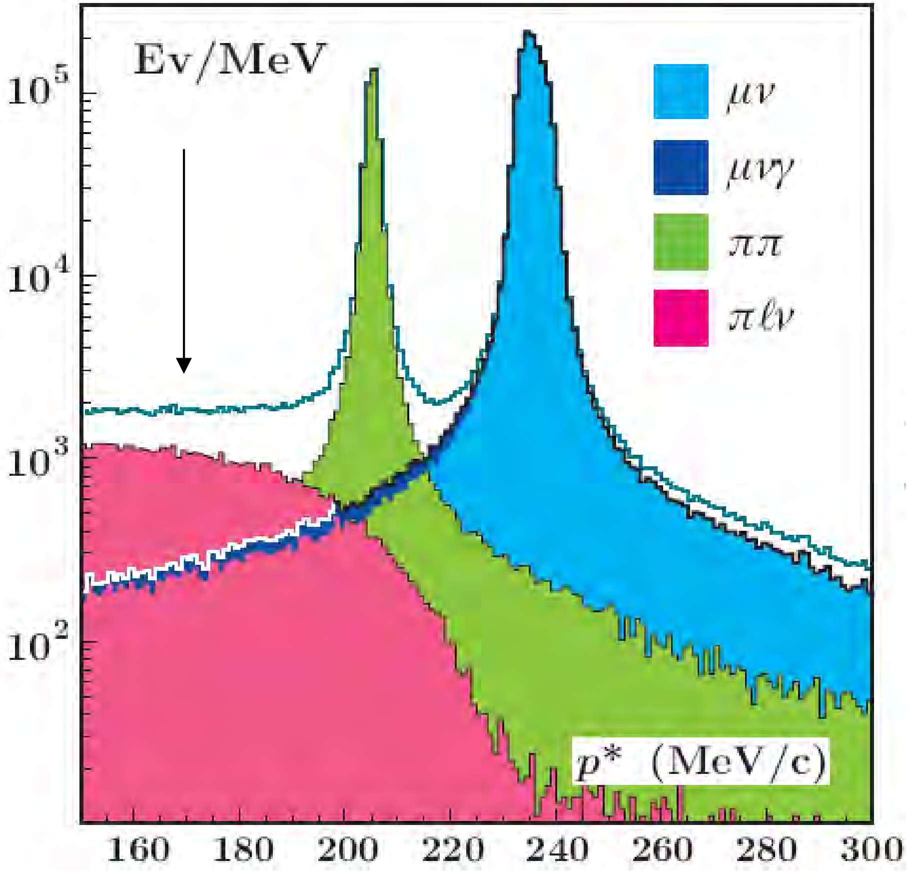
Tagging starts from one-prong decay reconstruction in drift chamber

Cut on p^*_π to identify two-body decays, $K \to \pi\pi^0$ and $K \to \mu\nu$

4 independent taggings: $K^\pm\pi2$ & $K^\pm\mu2$:

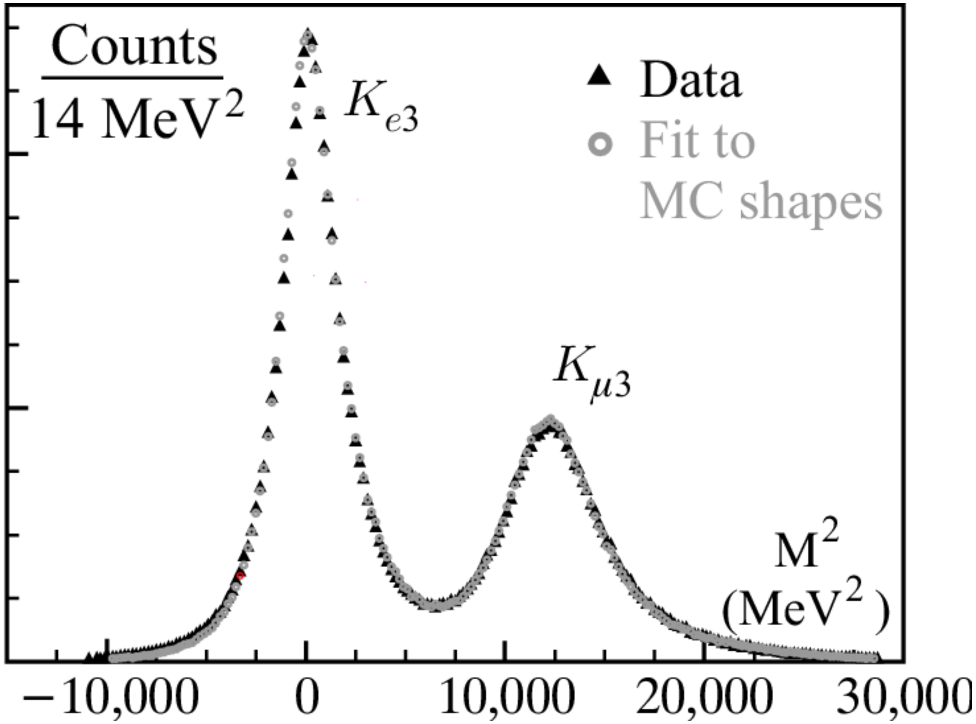
- **Can measure absolute BR's for each tag sample separately: keep tag-bias effects under control**

- **Compare results by charge: keep systematics from K^- nuclear interactions in traversed material under control**



Measurements of $K^{+,-}$ semileptonic BR's

- **Detect photons from π^0**
- **Kinematical cuts to reject non-Kl3 decays: not-Kl3 background ~1.5%**
- **Signal counts: log-*L* fit of distribution of lepton mass squared (M^2) from TOF**



Result:

$BR(K^{\pm}_{e3}) = 4.965(19)_{stat}(33)_{corr\text{-}stat}(37)_{syst}\,\%$

$BR(K^{\pm}_{\mu 3}) = 3.233(16)_{stat}(24)_{corr\text{-}stat}(26)_{syst}\,\%$

$\rho(K_{e3},K_{\mu 3}) = 0.63$

Above mmt @ τ^{+}=12.384 ns, for V_{us} use dependency dBR/BR = -0.45dτ/τ

Systematics dominated by uncertainty on tracking efficiency correction

Measurements of $K^{+,-}$ lifetime

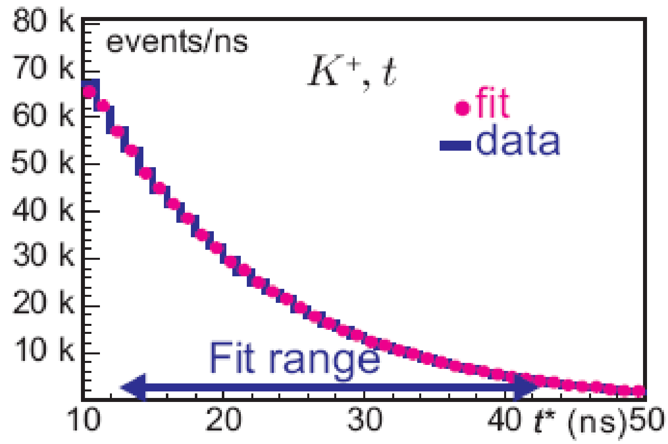
Experimental status unclear:

PDG average $\delta\tau/\tau \sim 0.2\% \rightarrow \delta V_{us}/V_{us} \sim 0.1\%$

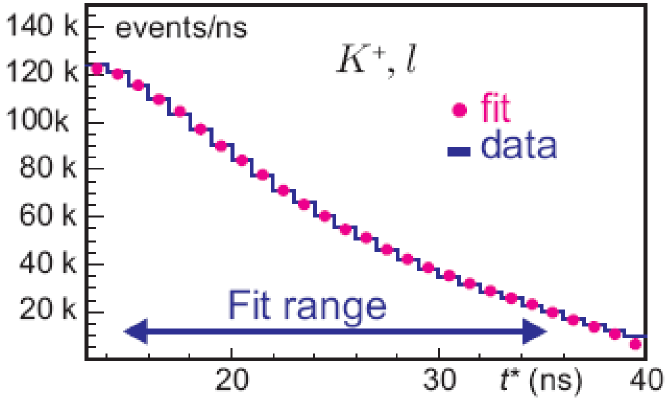
Mmts spread $\delta\tau/\tau \sim 0.8\% \rightarrow \delta V_{us}/V_{us} \sim 0.4\%$

Two methods to measure $\tau_{\pm}$ at KLOE:

1) From $\mathbf{K^+ \rightarrow X\pi^0}$, proper time t* from γ TOF's



2) From $\mathbf{K^+ \rightarrow}$ 1**track** decay-length, $t^* = \sum_i L_i/(\beta_i\gamma_i c)$



Allow systematic checks, only features in common to both methods are:

Tag is done with $K_{\mu 2}$ decay identification

Kaon decay vertex is in the DC

4 results are compatible, thus can average:

$$\tau_{\pm} = 12.347(30) \text{ ns}$$

$$\tau(K^+)/\tau(K^-) = 1.004(4)$$

Unique to KLOE: $K_{S\mu3}$ decays

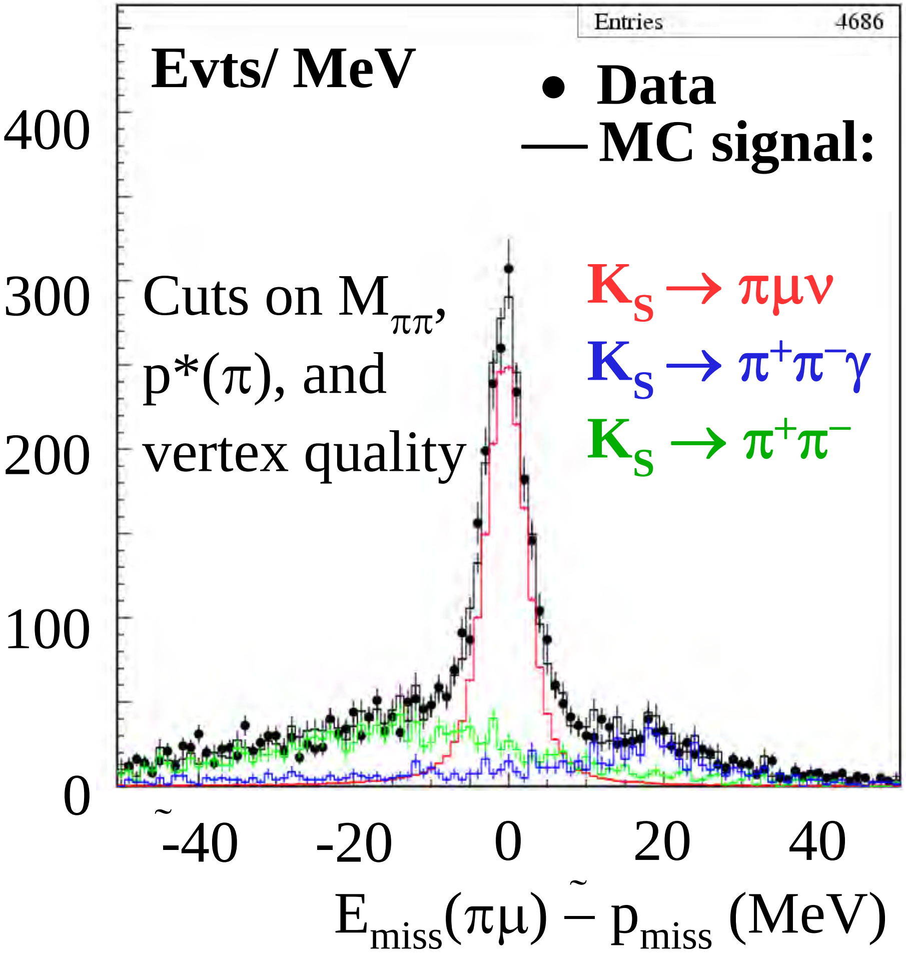
Decay mode has never been observed

Compare width with $K_L \to \pi\mu\nu$: test of validity of $\Delta S = \Delta Q$ rule

Compare with $K_S \to \pi e\nu$: test universality of lepton couplings

Measure charge asymmetry: test of CPT, CP violation

Total error dominated by statistics, expect 3% @ the end of analysis



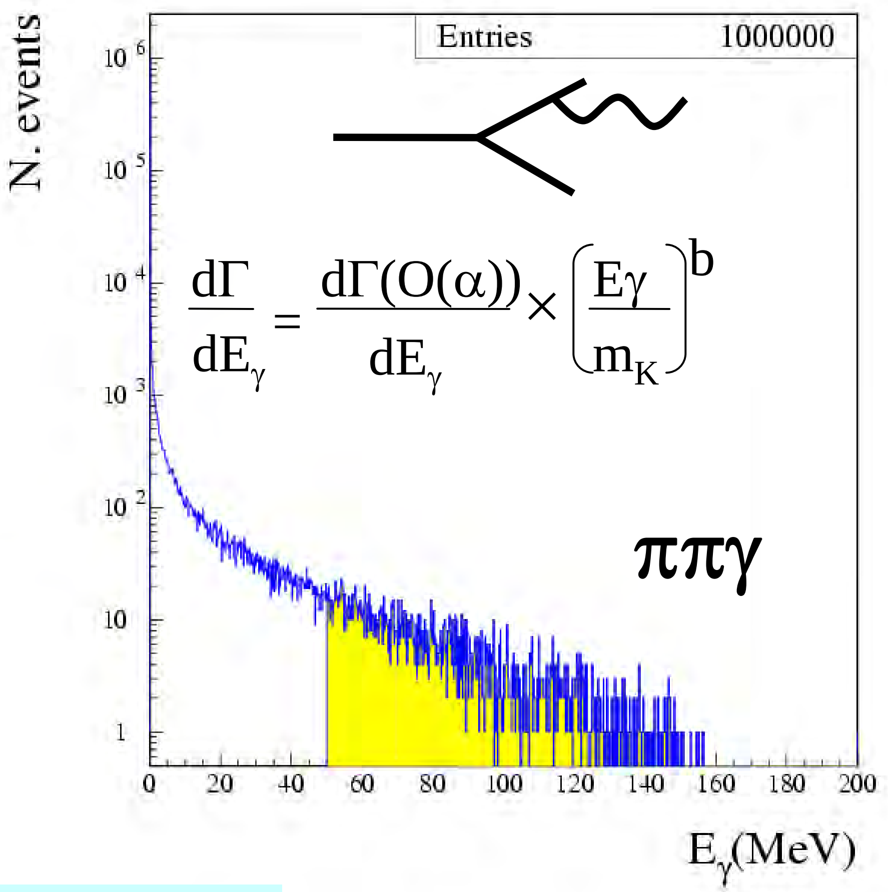
Generators for radiative K decays

Generators for 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, e.g:

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

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



$$\frac{d\Gamma}{dE_\gamma} = \frac{d\Gamma(O(\alpha))}{dE_\gamma} \times \left(\frac{E\gamma}{m_K}\right)^b$$

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

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

[C. Gatti, EPJC 45 (2006)]