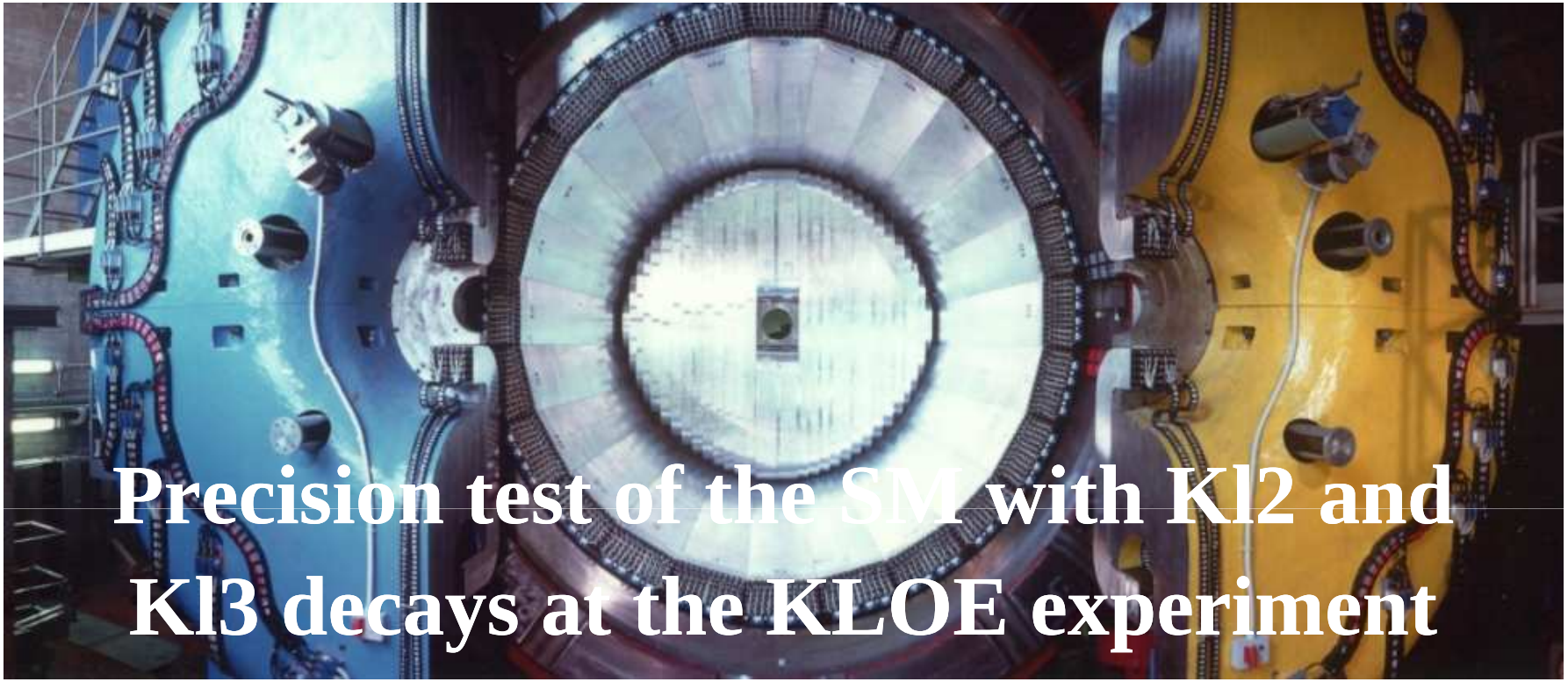


Precision test of the SM with Kl2 and Kl3 decays at the KLOE experiment

T. Spadaro, LNF INFN
for the KLOE collaboration

University of South Carolina
Columbia, SC, 29th June, 2008

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 every NP model

Test of SM from $\Gamma(K_{\mu 2})/\Gamma(\pi_{\mu 2})$:

probes NP RH contributions to charged weak currents

probes H^+ exchange in every SM extension with 2 Higgs doublets

LF violation test from $\Gamma(K_{e2})/\Gamma(K_{\mu 2})$:

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:

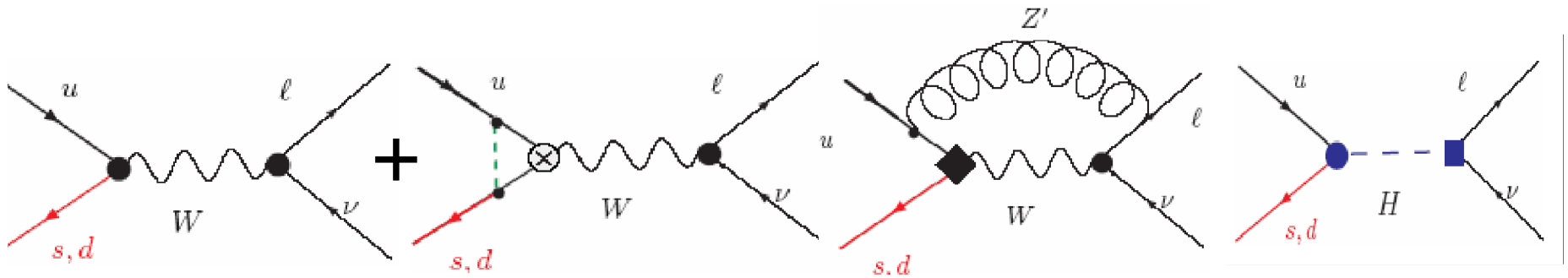
$$G_F^2\,(|V_{ud}|^2 + |V_{us}|^2) = G^2(\text{from } \mu \text{ lifetime}) = (g_w/M_w)^2\ [V_{ub} \text{ negligible}]$$

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

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

Gauge 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 gauge universality:



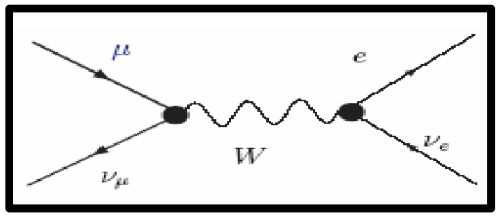
SM + NP $\propto G_F^2\,|V_{uq}|^2\,(1 + a\,M_{NP}^2/M_W^2)^2$, naively $a_{tree} \sim 1$, $a_{loop} \sim g^2_W/16\pi^2$

Interest in V_{us} measurement with kaons

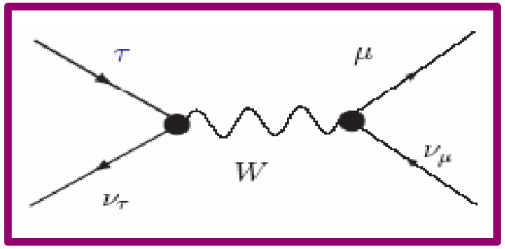
A measurement of $G_{CKM} = G_F (|V_{ud}|^2 + |V_{us}|^2)$ with error @ 0.5%

- **is sensitive to tree masses $M_{NP} \sim 13$ TeV and to loop masses $M_{NP} \sim 1$ TeV**
- **is competitive with ew precision tests:**

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



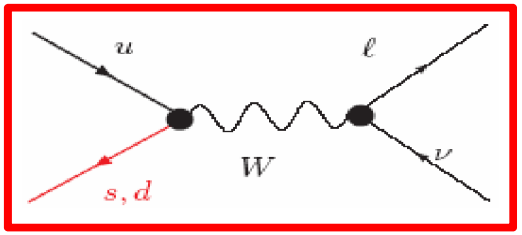
$G_\tau = 1.1678(26) \times 10^{-5}\ GeV^{-2} \leftarrow$



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

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

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



V_{us} *from semileptonic kaon decays*

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

Theoretical inputs:

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

	K0	K+
$\ell = e$	+0.57(15)%	+0.08(15)%
$\ell = \mu$	+0.80(15)%	–0.12(15)%

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

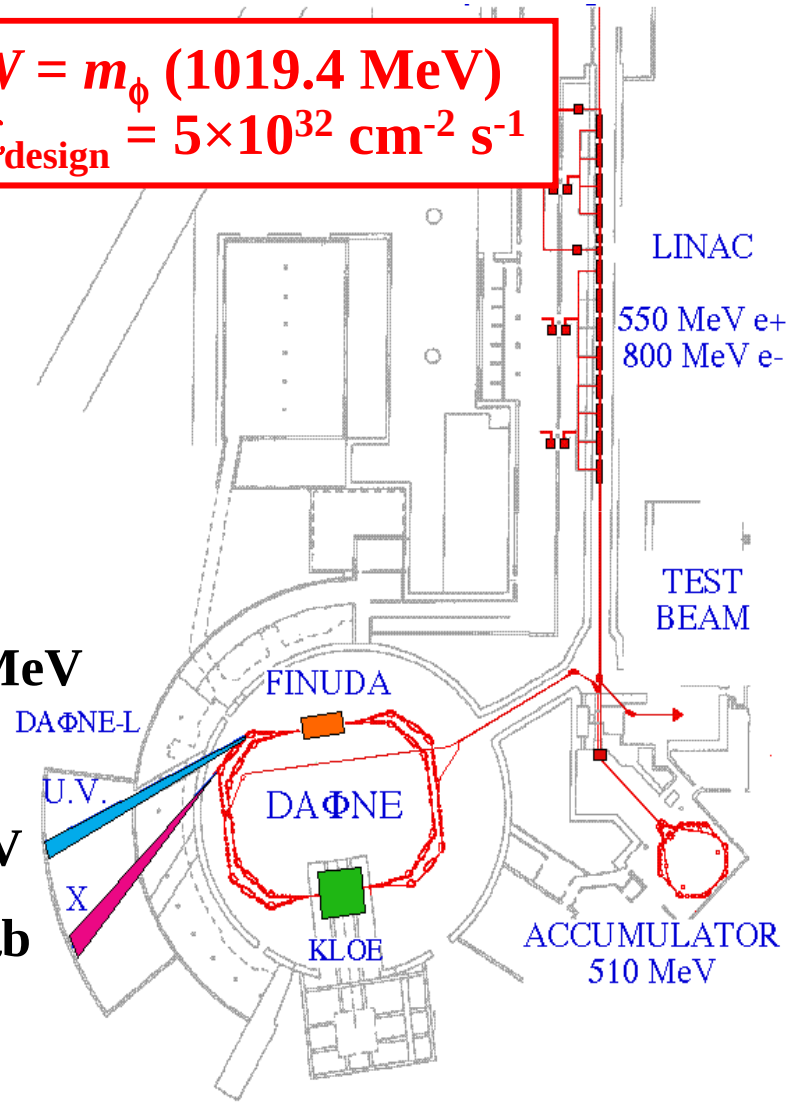
Experimental inputs:

- **$I^\ell_K = I(\{\lambda_+\},\{\lambda_0\},0)$**, phase space integral, λ_+, λ_0 → t-dependence of vector, scalar ffs
- **$\Gamma_{K\ell3(\gamma)}$**, 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

The DAΦNE e^+e^- *collider*

$W = m_\phi$ **(1019.4 MeV)**
$\mathcal{L}_{design} = 5\times10^{32}$ **cm^{-2} s^{-1}**



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

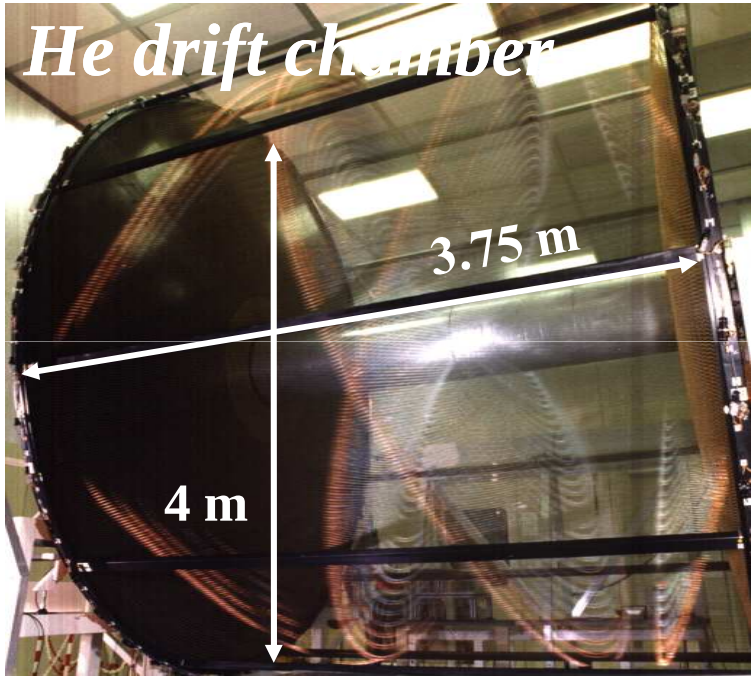
Angle between the beams @ IP: α ~ **12.5 mrad**

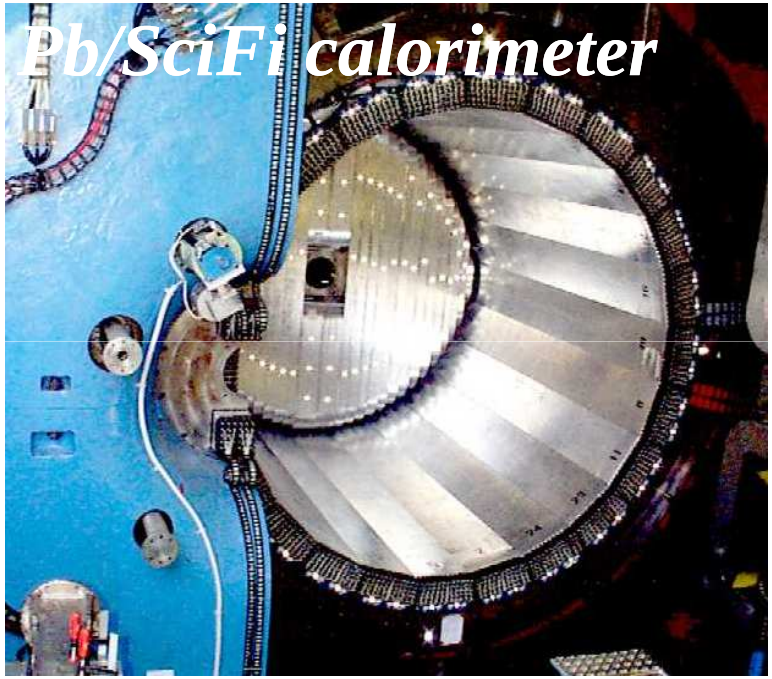
Residual laboratory momentum of ϕ: p_ϕ ~ **13 MeV**

Cross section for ϕ production @ peak: σ_ϕ ~ **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 $K_L \to \pi^+\pi^-\pi^0$)

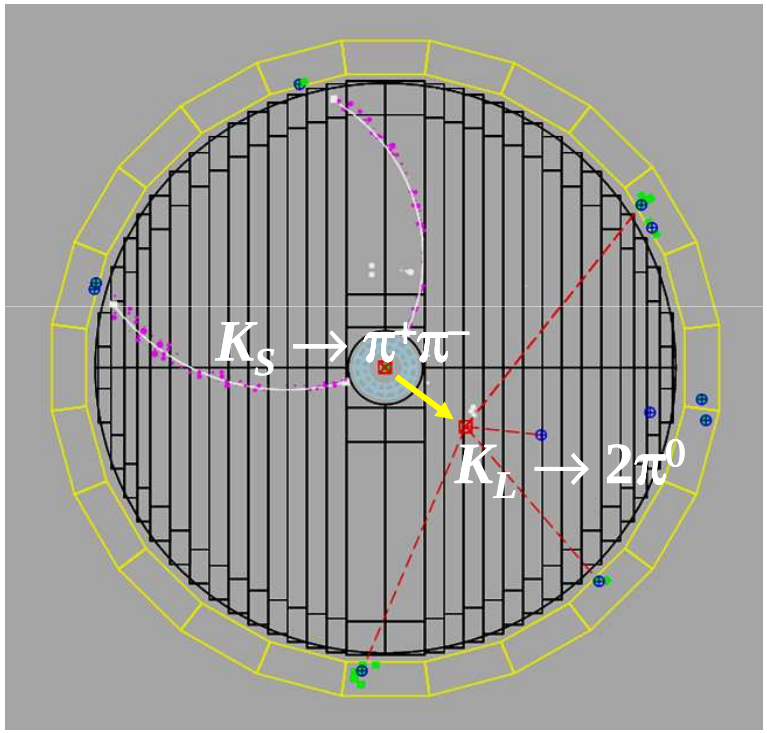
Kaon physics at KLOE

$K_S K_L$ 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):

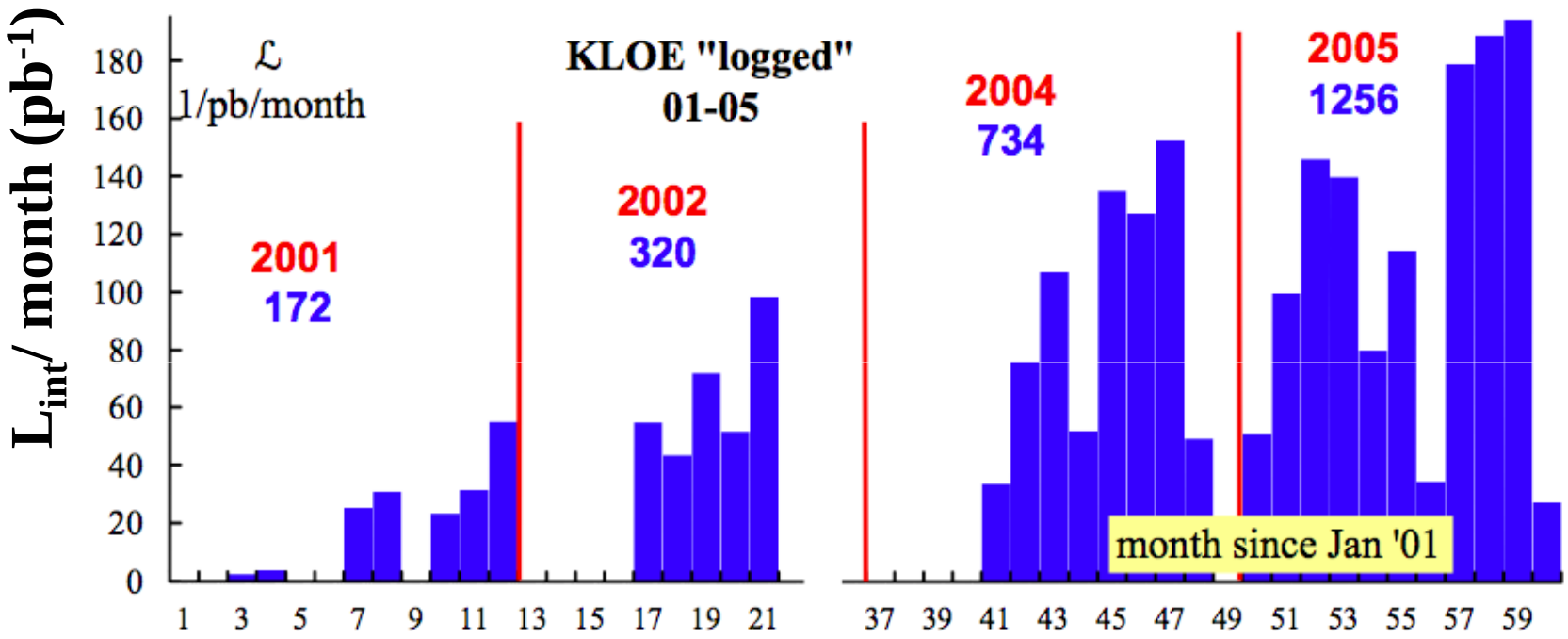
- **Access to absolute BR's**
- **Precise measurements of K_{Le3} from factors and K_L, K^+ lifetimes (acceptance ~0.5 τ_L, τ_+)**



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 @ $\sqrt{s}=M(\phi)$, yielding ~2.5×10^9 $K_S K_L$ 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	**ArXiv:0804.4577, subm. to PLB**
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**
$d\Gamma(K_L \to \pi e \nu \gamma)/dE_\gamma$	**ArXiv 0710.3993, accepted EPJC**
$BR(K_S \to \gamma\gamma)$	**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**

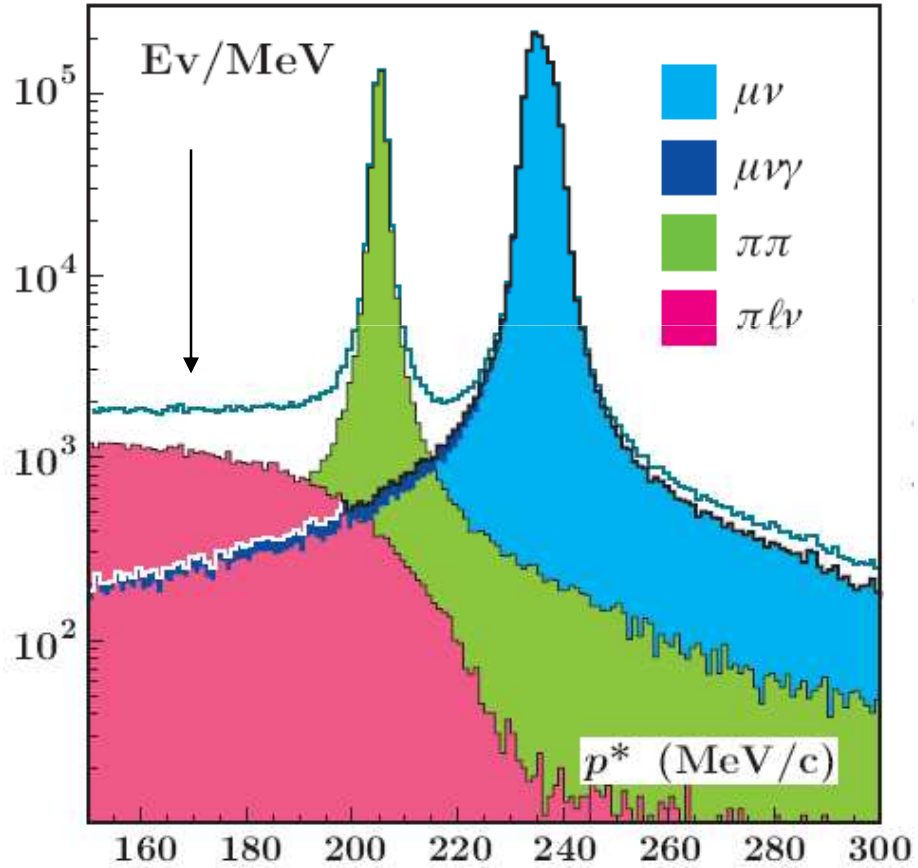
Measurements of $K^{+,-}$ BR's

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 $K \to \mu\nu$

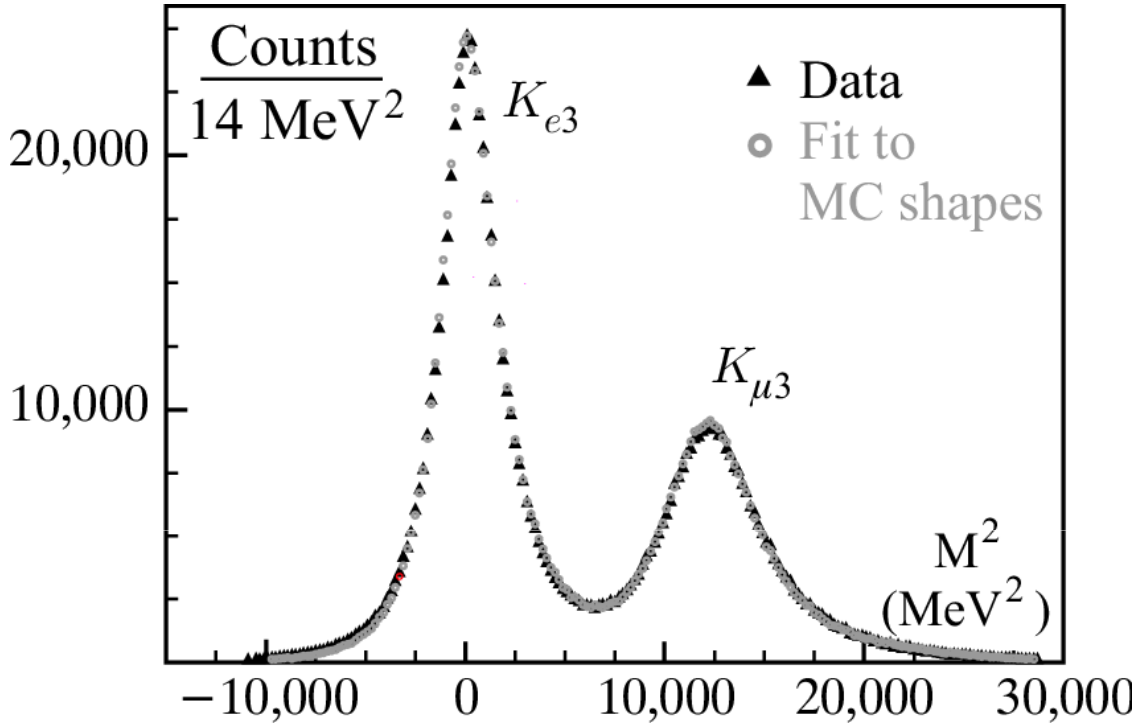
4 independent taggings: $K^\pm\pi 2$ & $K^\pm\mu 2$:

- **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**



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

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

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

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

Systematics dominated by uncertainty on tracking efficiency correction

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

Experimental status unclear:

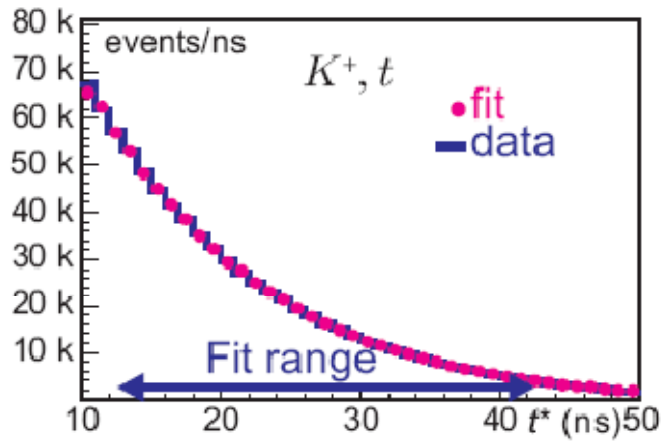
PDG average $\delta\tau/\tau \sim 0.2\% \rightarrow \delta V_{us}/V_{us} \sim 0.1\%$

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

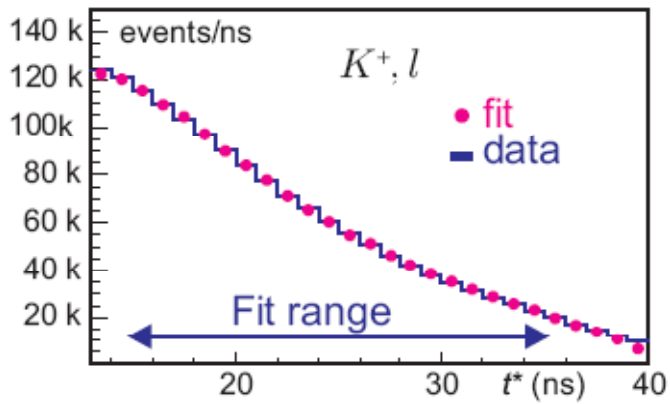
2) From $\mathbf{K^+ \rightarrow 1track}$ decay-length, $t^* = \sum_i L_i/(\beta_i\gamma_i c)$



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



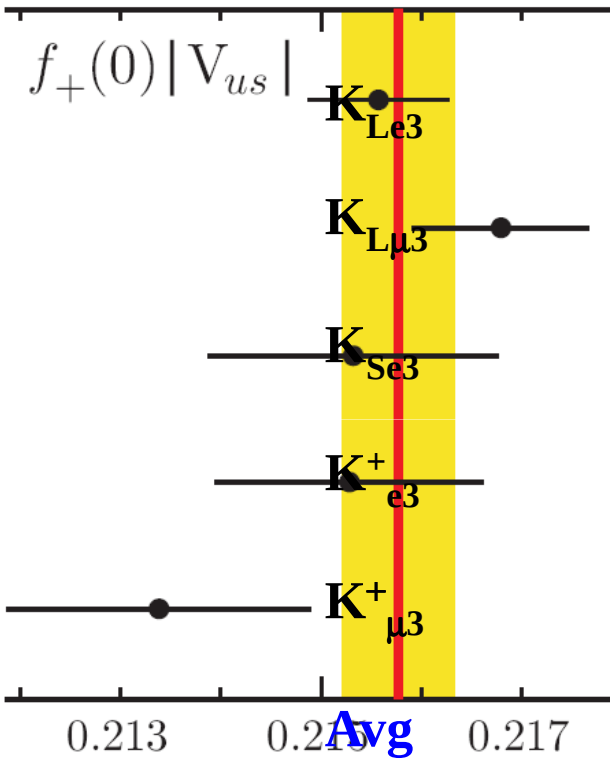
4 results are compatible, thus can average:

$\tau_\pm$= 12.347(30) ns

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

Vus from Kl3 decays: results

Only use KLOE inputs, except τ_S from PDG:



$f_+(0) \times \lvert V_{us} \rvert$	Error, %
0.2155(7)	0.3
0.2167(9)	0.4
0.2153(14)	0.7
0.2152(13)	0.6
0.2132(15)	0.7
0.2157(6)	0.28

Compare with world average including KLOE (see Passemar's talk): 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 $K_{\mu 2}$ decays

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

Theoretical inputs:

radiative correction C_K, C_π

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

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

Experimental inputs:

$m_{K,\pi,\mu}$, $\Gamma(K_{\mu 2})/\Gamma(\pi_{\mu 2})$

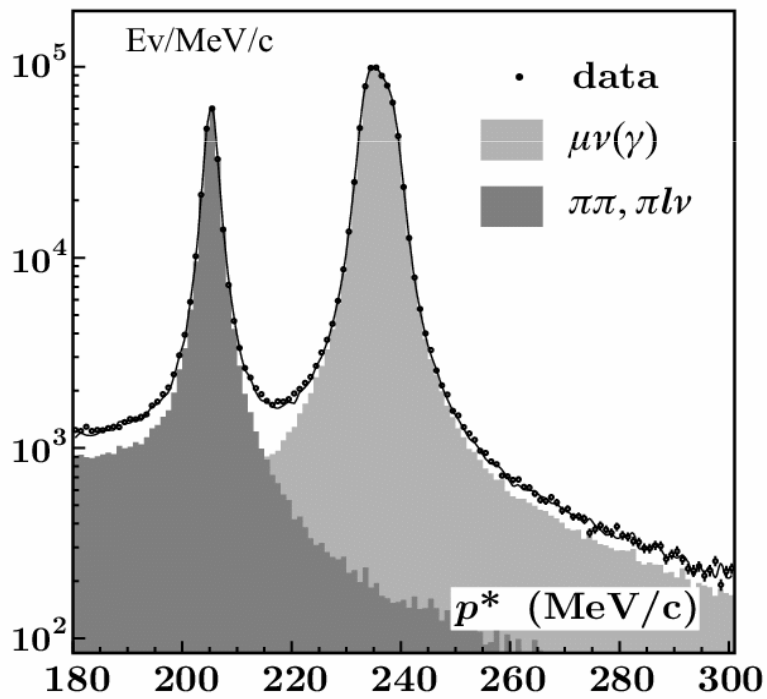
KLOE measurement of BR($K^+ \to \mu^+\nu$):

Tag events from $K^- \to \mu^-\nu$

Select K^+ decays to a charged track in FV

Event count, fit **p*** distribution of secondary

Result: BR($K^+ \to \mu^+\nu(\gamma)$) = 63.66(9)(15)%

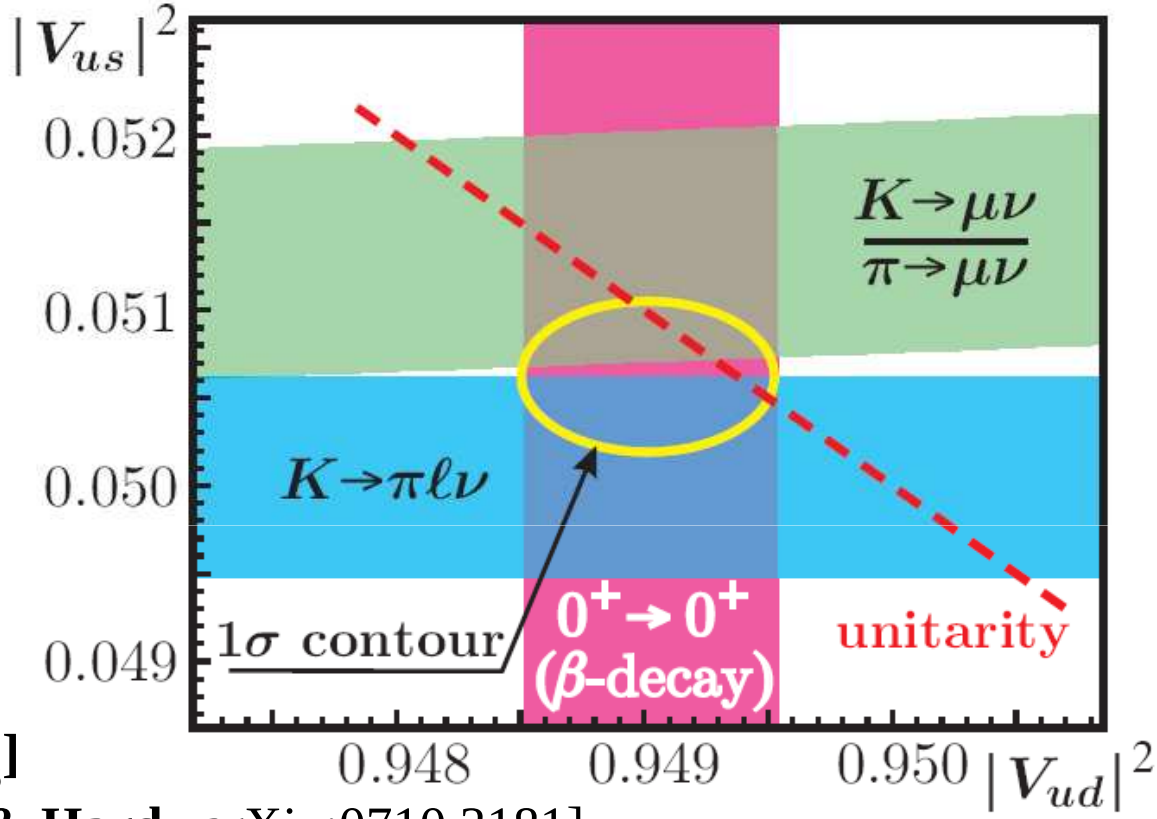


V_{us}/V_{ud} from $K_{\mu 2}$ vs V_{us} from Kl3

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: $|V_{us}/V_{ud}|$ = 0.2326(15)



Now can fit:

1) **$|V_{us}/V_{ud}|$ = 0.2326(15)**

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

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

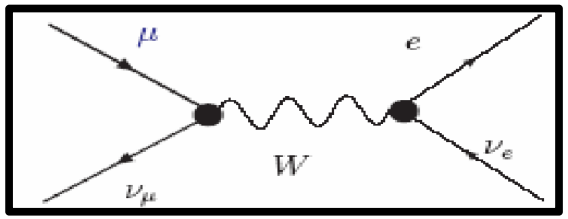
Obtain: $|V_{ud}|$ = 0.97417(26), $|V_{us}|$ = 0.2249(10), P(χ^2=2.34/1) = 13%

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

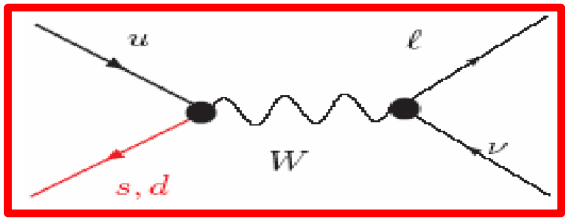
Weak coupling universality test

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

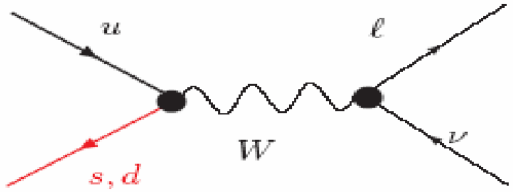
$G_F = 1.166371(6)\times10^{-5}\ GeV^{-2}$ ←



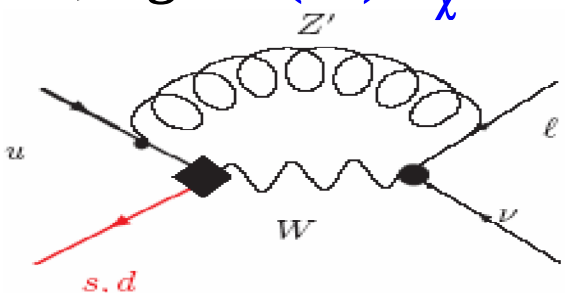
$G_{CKM} = 1.16604(40)\times10^{-5}\ GeV^{-2}$ ←



Leads to constraints on NP models, e.g. 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: $M_{Z'} > 1.4$ TeV @ 95% CL

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. $K \rightarrow \mu e$**
- **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]

$K_{\mu 2}$ 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:

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

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

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

$K_{\mu 2}$ – *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)]**

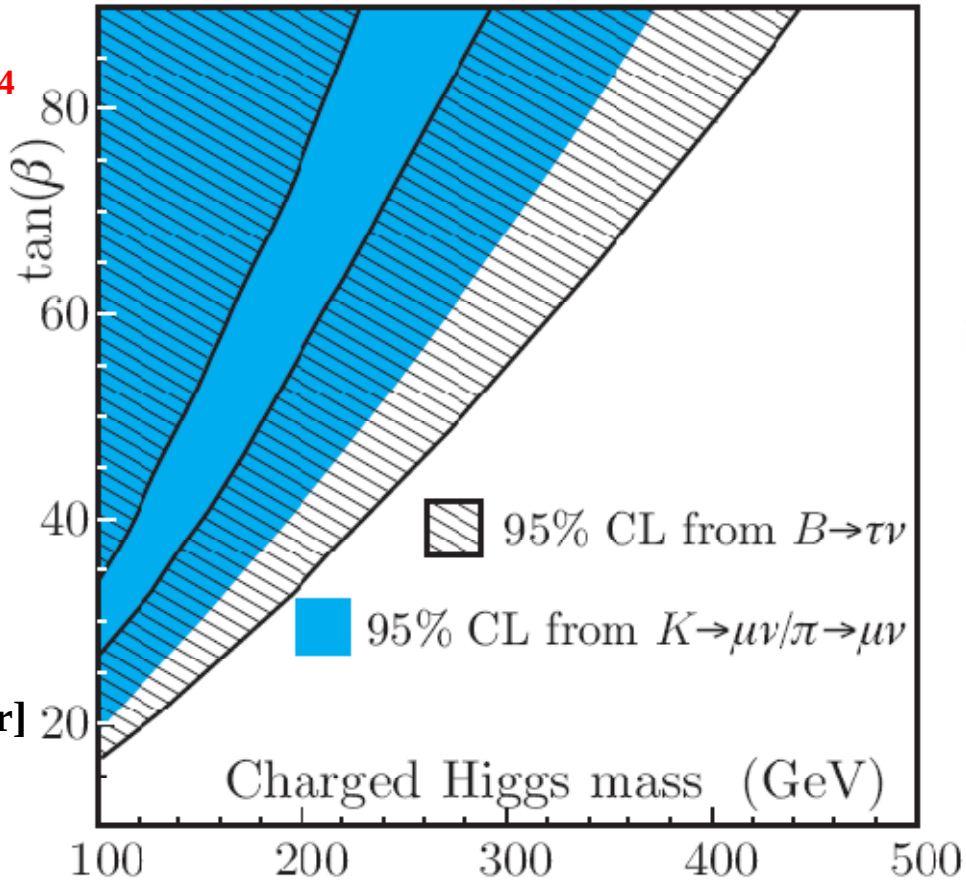
$K_{\mu 2}$ – Sensitivity to NP

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 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 + talk by E. Passemar]



NP 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]

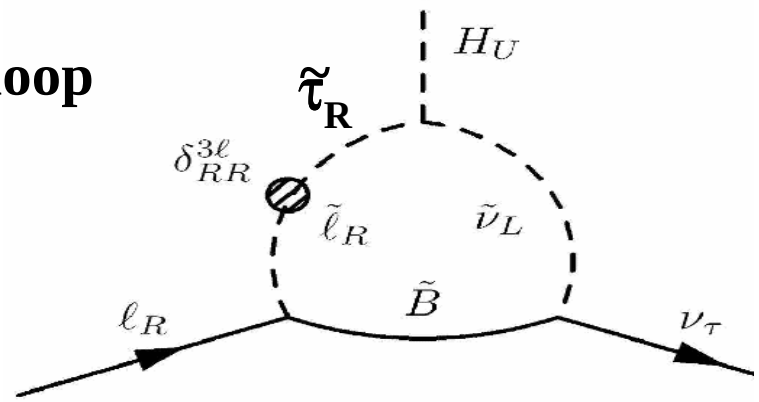
Helicity suppression can boost NP [Masiero-Paradisi-Petronzio PRD74 (2006) 011701]

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

$$l H^\pm \nu_\tau \rightarrow \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_{13}$$ **, 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), see talk by G. Saracino

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

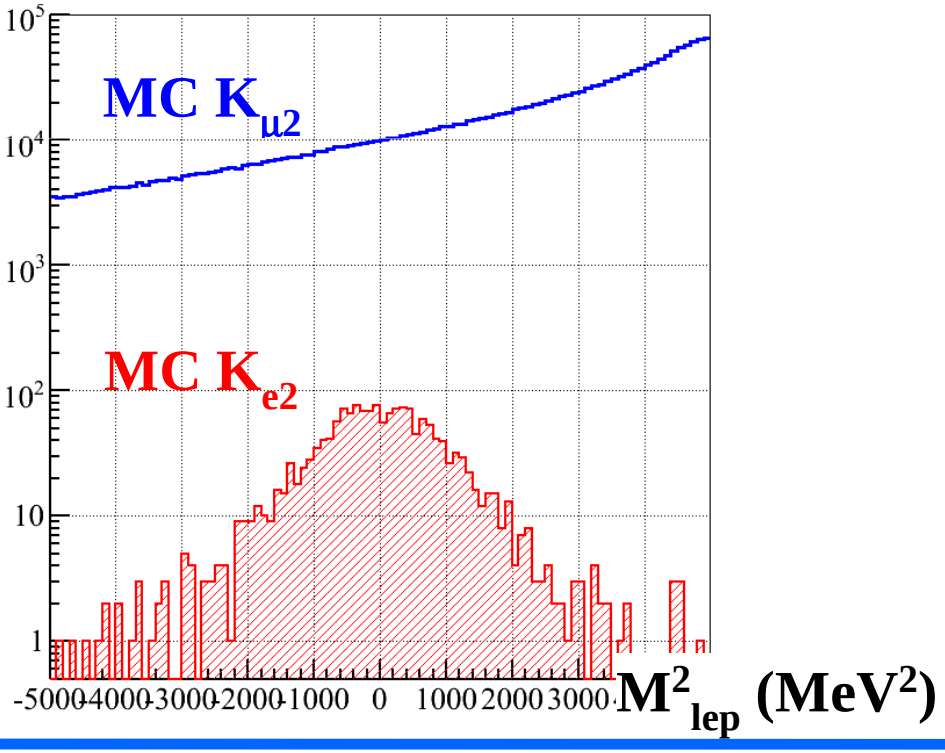
Analysis of $K_{e2}/K_{\mu 2}$

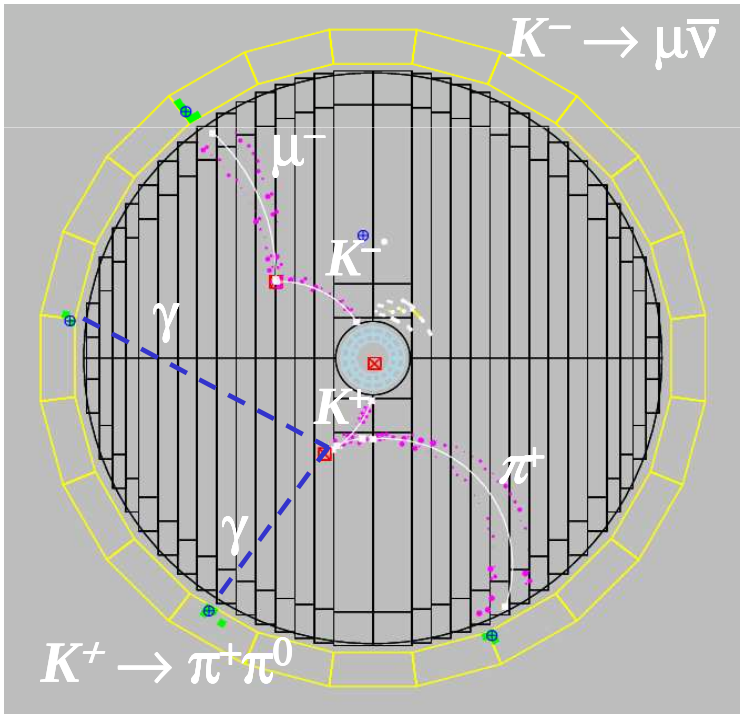
KLOE integrated ~2.5 fb^{-1} of data & $BR(K_{e2})$~10^{-5}: expect < ~4×10^4 events

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 > 180 MeV

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





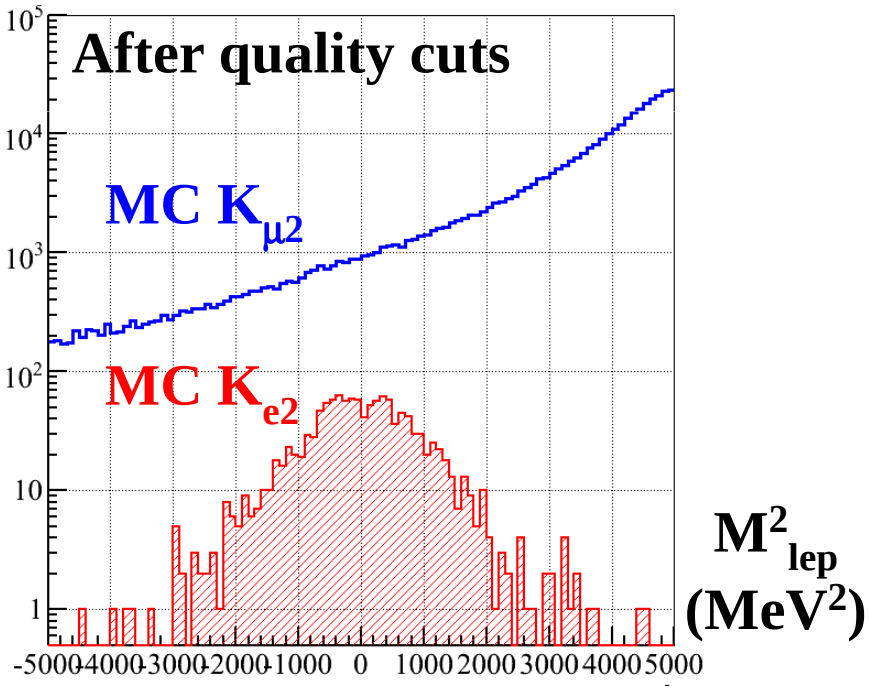
Analysis of R_K = Ke2/Km2

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

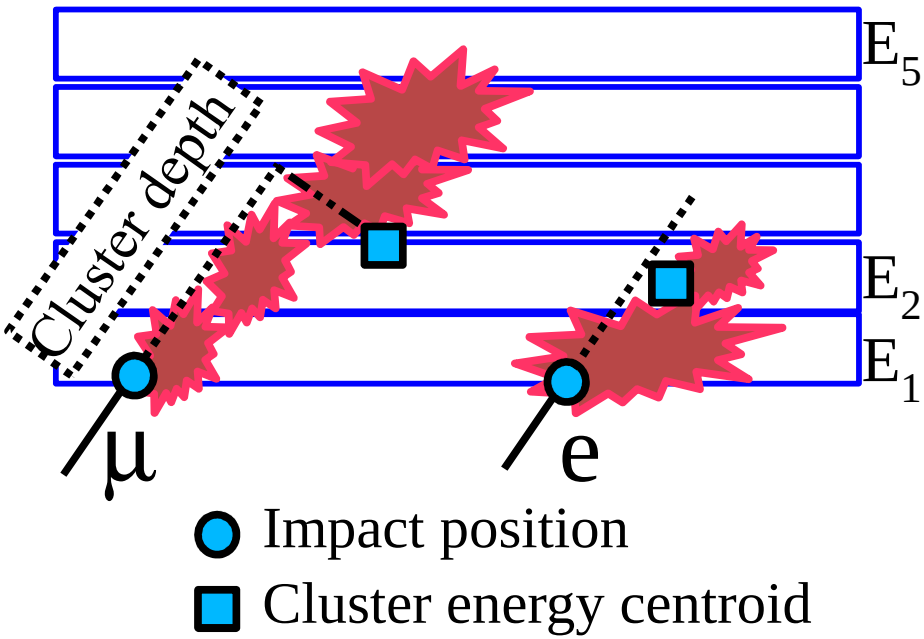
1-prong efficiency ratio correction only 2%, use data CS of $K_{\mu 2}$ to check

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



EmC, fiber direction view

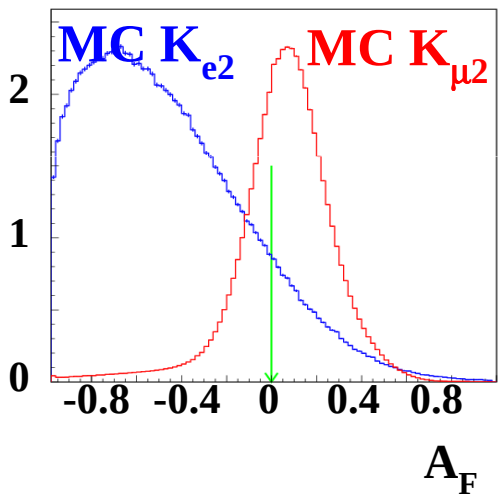


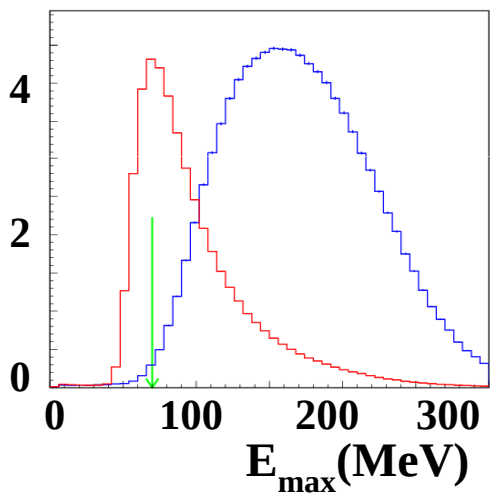
Analysis of R_K – PID using EmC

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

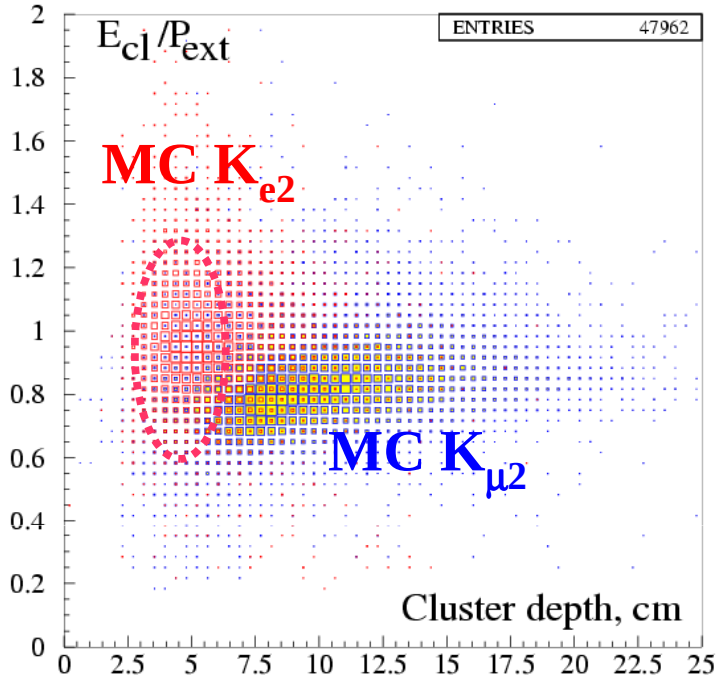
μ's: MIP-like in layers 1-2, Bragg peak @ end

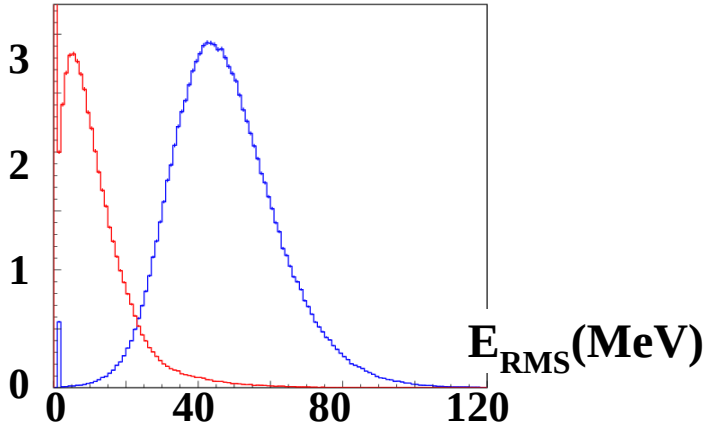
$$\text{Cut on } A_F = \frac{(E_2 - E_1)}{(E_2 + E_1)}, \quad E_{max} = \max\{E_k\}$$





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



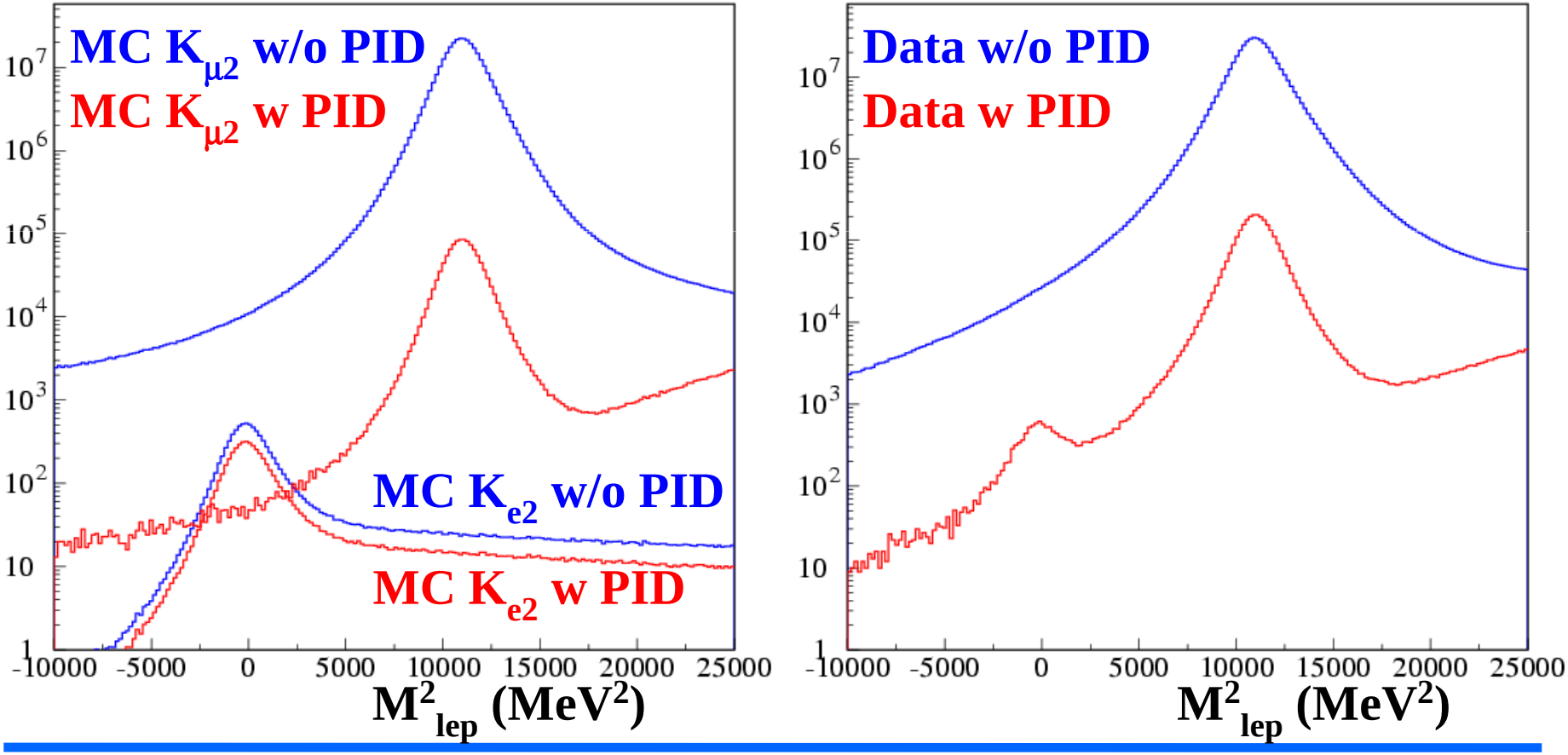


Analysis of Ke2/Km2 – PID via EmC

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

Check with K_{Le3} data/MC control sample

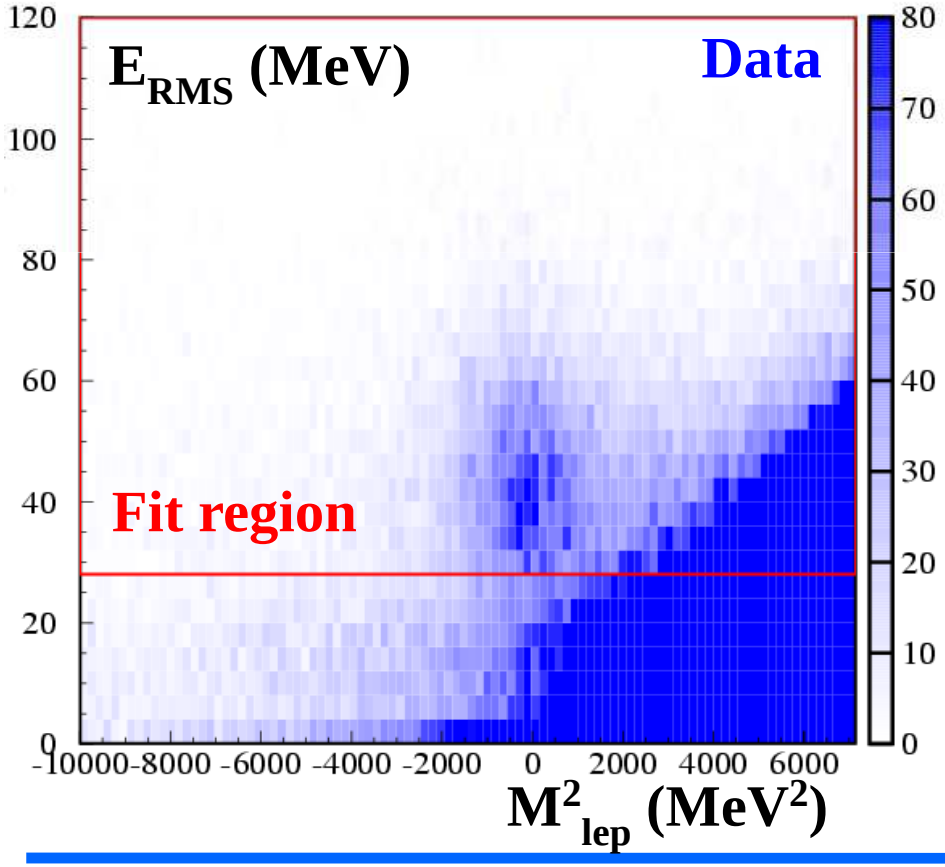
After PID (rejection factor is ~500) count Ke2 events

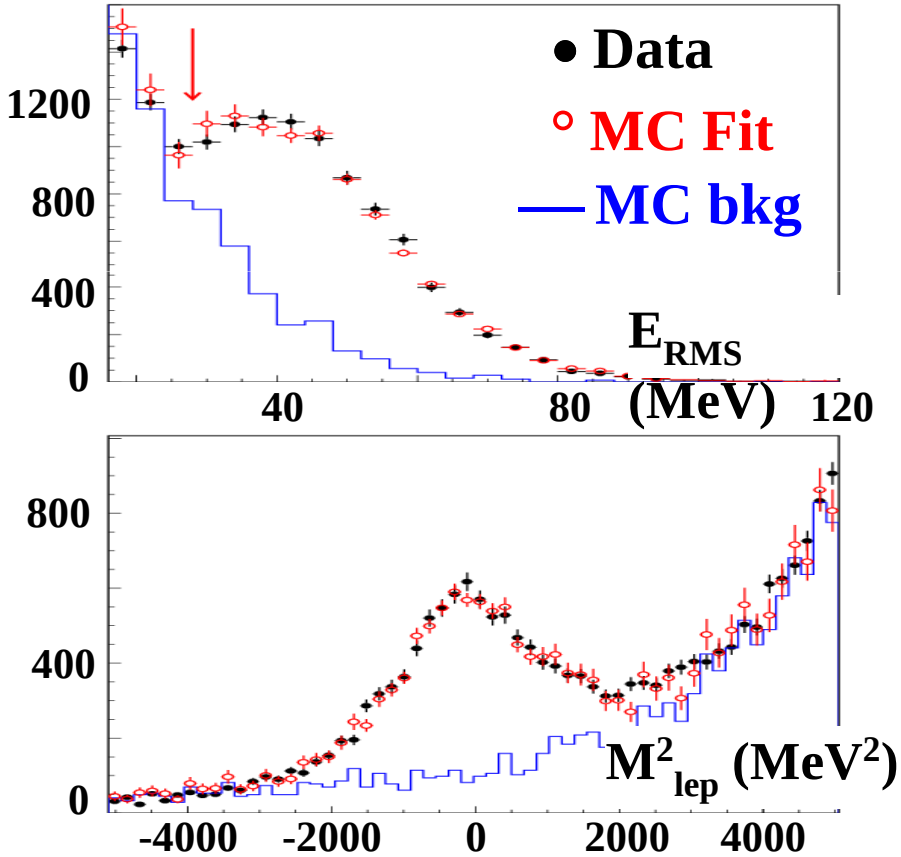


Analysis of R_K – Count Ke2 events

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**



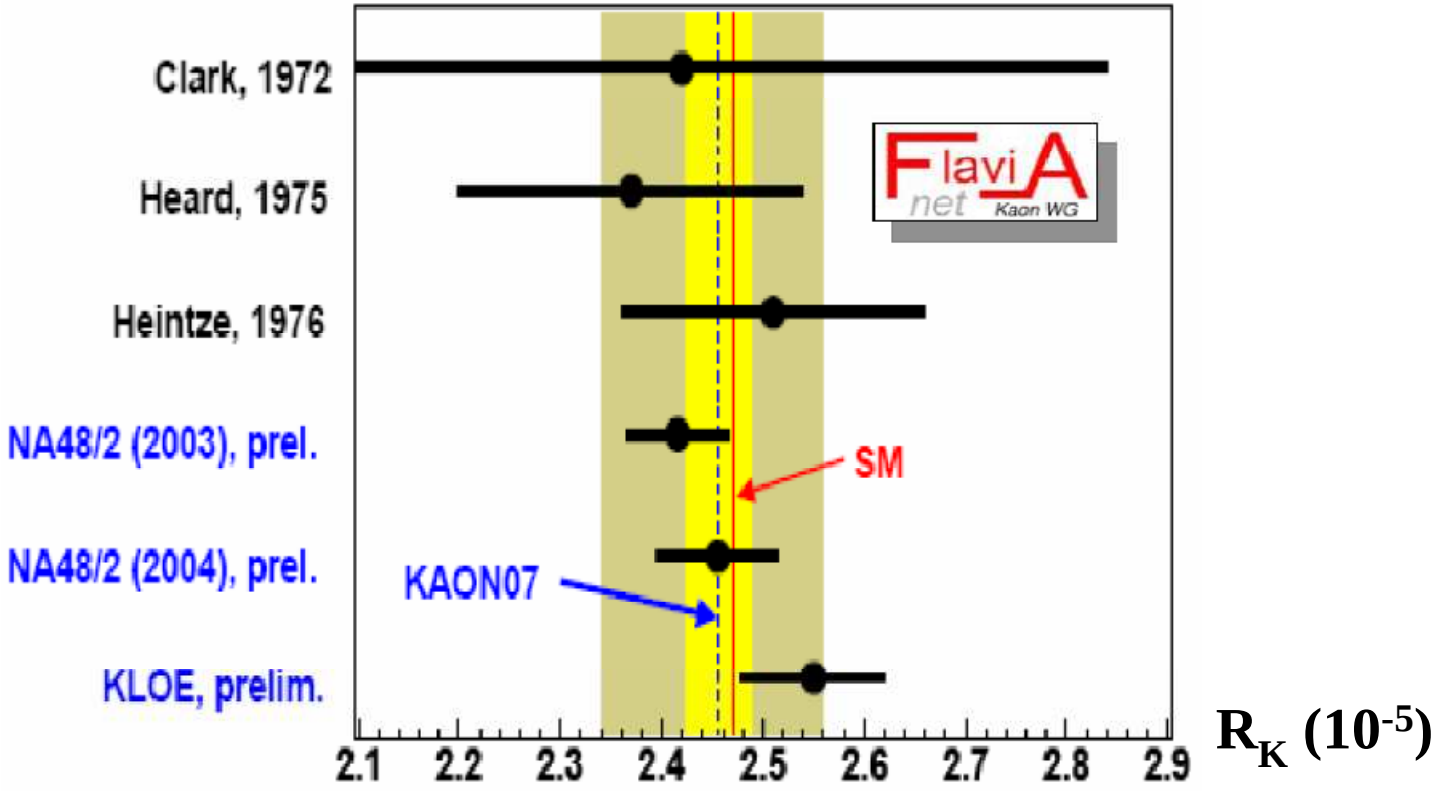


R_K – present experimental status

$$R_K = \frac{N_{Ke2}}{N_{K\mu 2}} \left[\frac{\varepsilon^{\rm TRG}_{K\mu 2}}{\varepsilon^{\rm TRG}_{Ke2}} \right] \left[C^{\rm TRK} \frac{\varepsilon^{\rm TRK}_{K\mu 2}}{\varepsilon^{\rm TRK}_{Ke2}} \right] \left[\frac{1}{C^{\rm PID} \varepsilon^{\rm PID}_{Ke2}} \right] \frac{1}{\varepsilon^{\rm IB}} = (2.55 \pm 0.05 \pm 0.05)\times 10^{-5}$$

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

World average, $R_K = 2.457(32)\times 10^{-5}$, agrees with SM

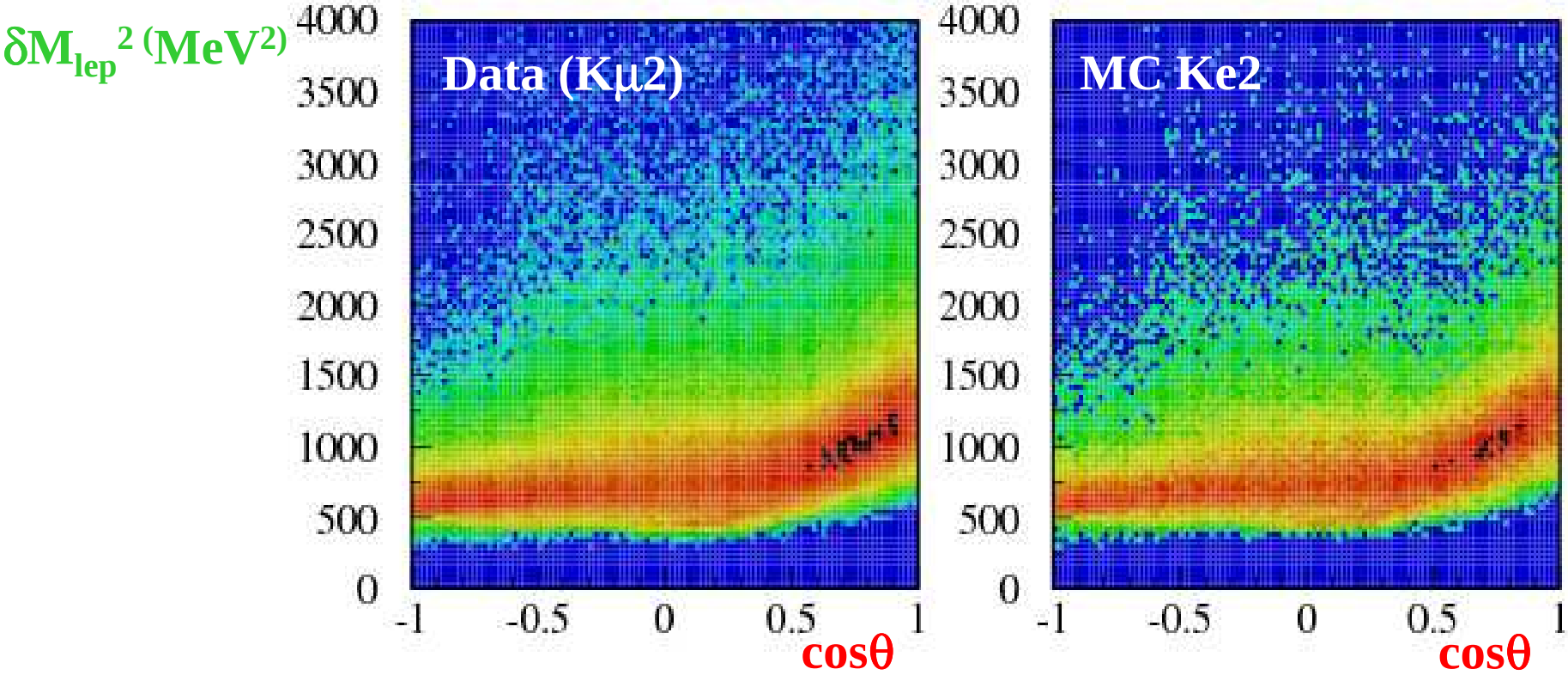


R_K at KLOE, toward the final result

Better parametrization of kinematic criteria, better understanding of bkg

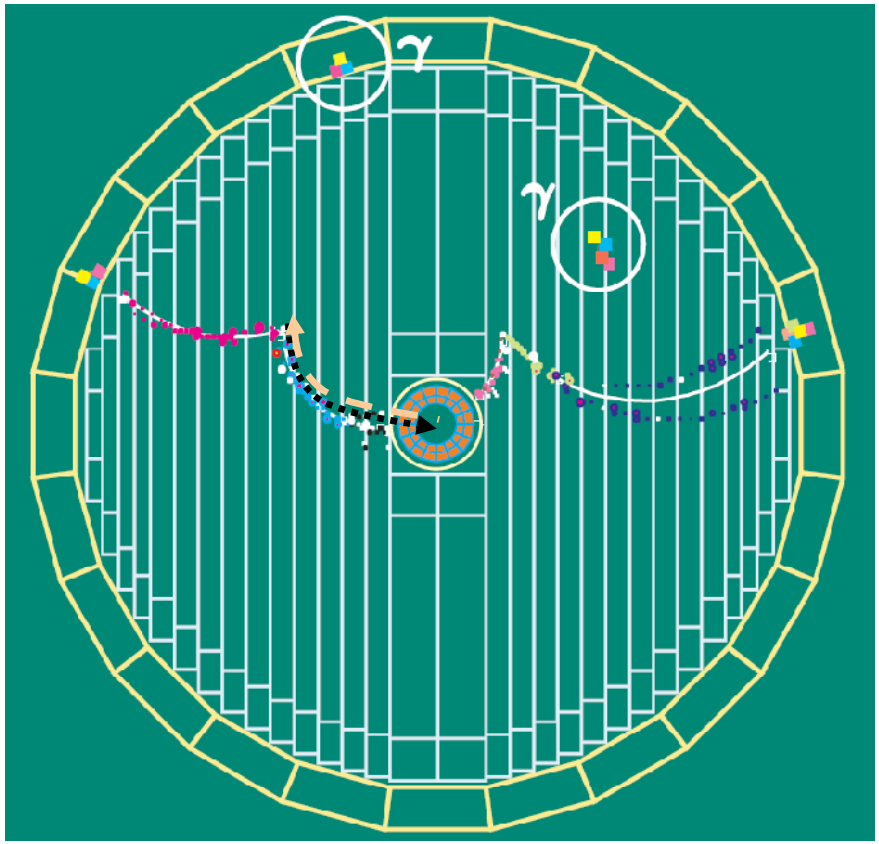
$M_{lep}^2 = f(P_K, P_l, \cos\theta) \rightarrow$ a-priori error δM_{lep}^2 is scaled by opening angle

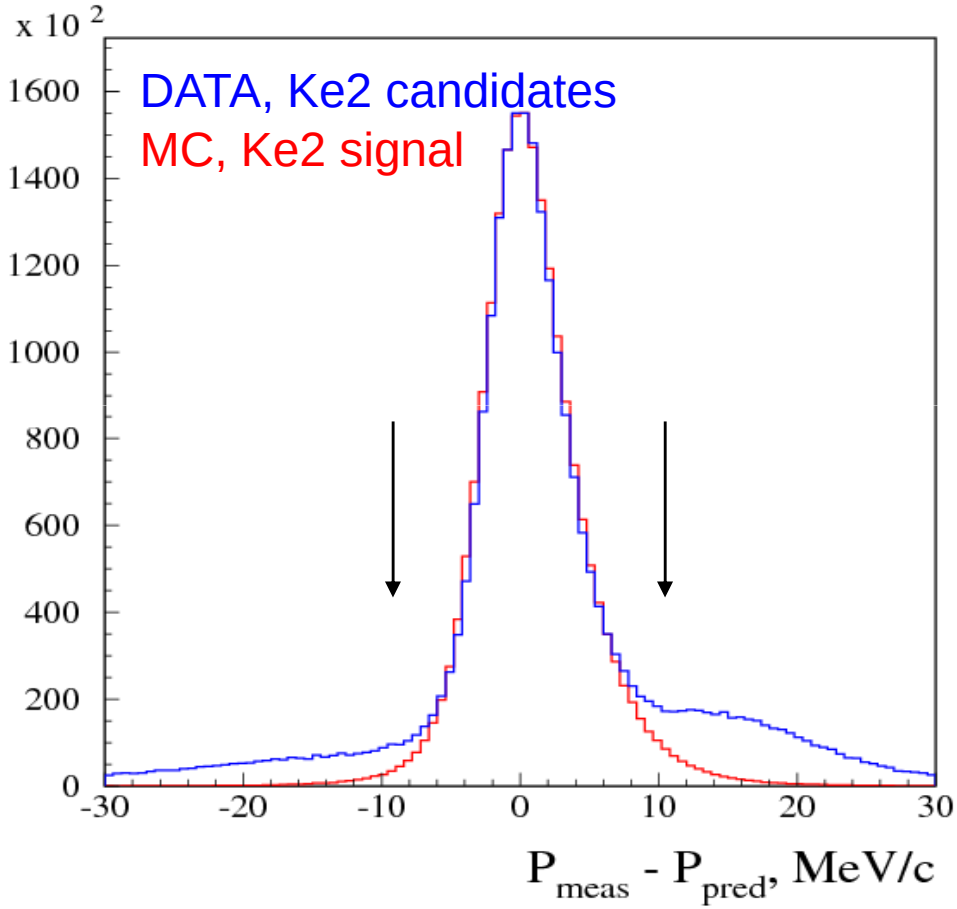
Achieve cancellation in Ke2/Kμ2 efficiencies, applying cosθ trailing cuts



R_K at KLOE, toward the final result

Get rid of bad-PK component using redundant measurement



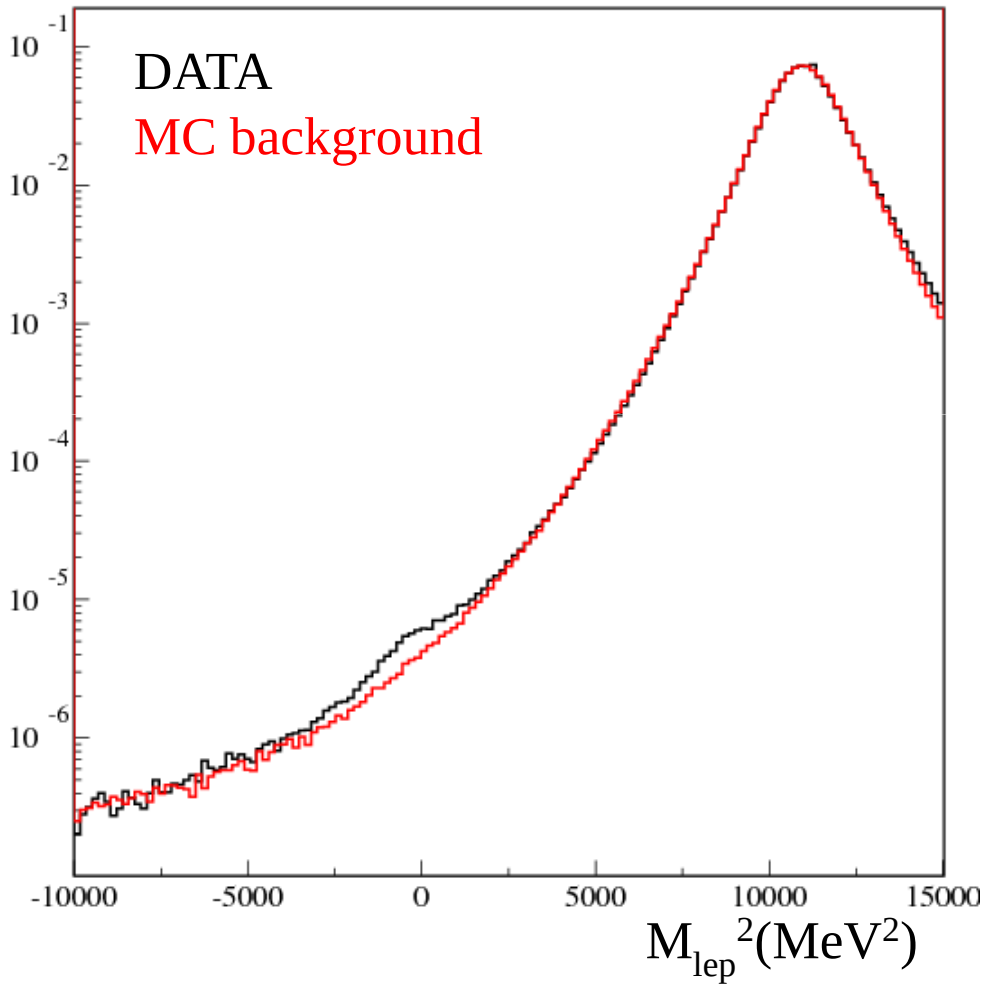


Get rid of bad-P_l's using asymmetry of DC hits in left and right views

R_K at KLOE, toward the final result

Enough bkg rejection from kinematics to see Ke2 w/o any EmC-based PID

MC agrees with data, including very far resolution tails



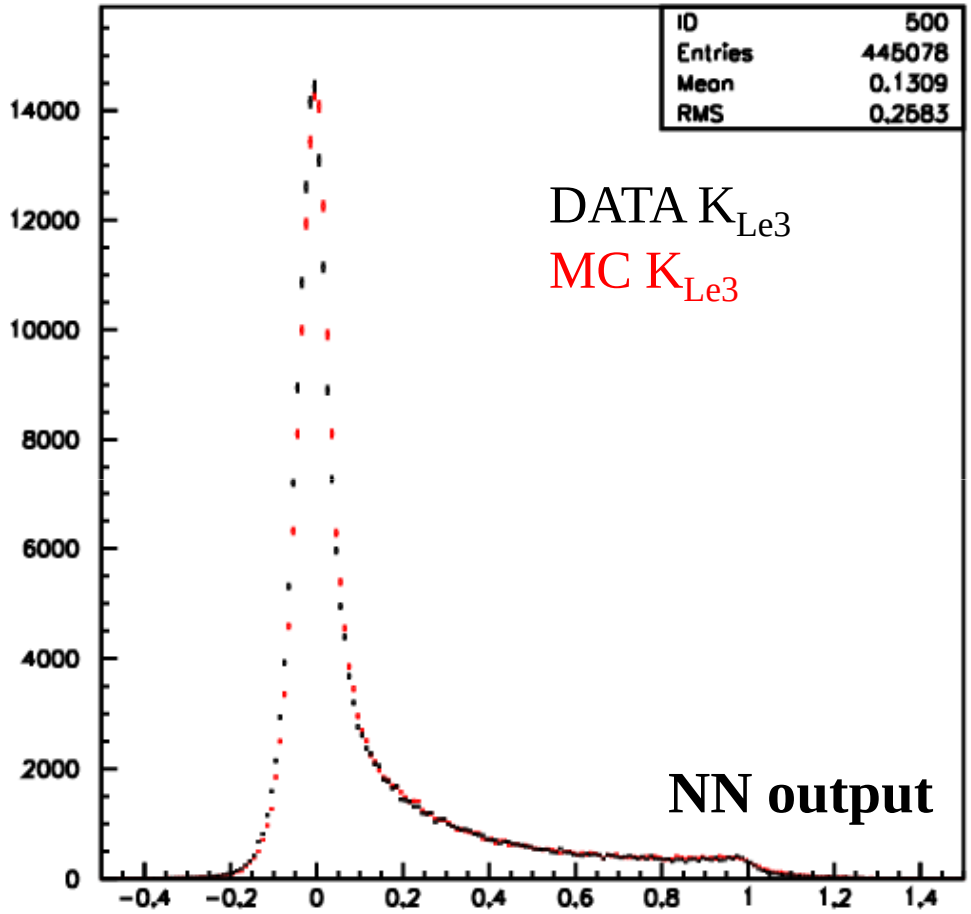
R_K at KLOE, toward the final result

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



Check Data-MC agreement for NN output: K_{Le3}

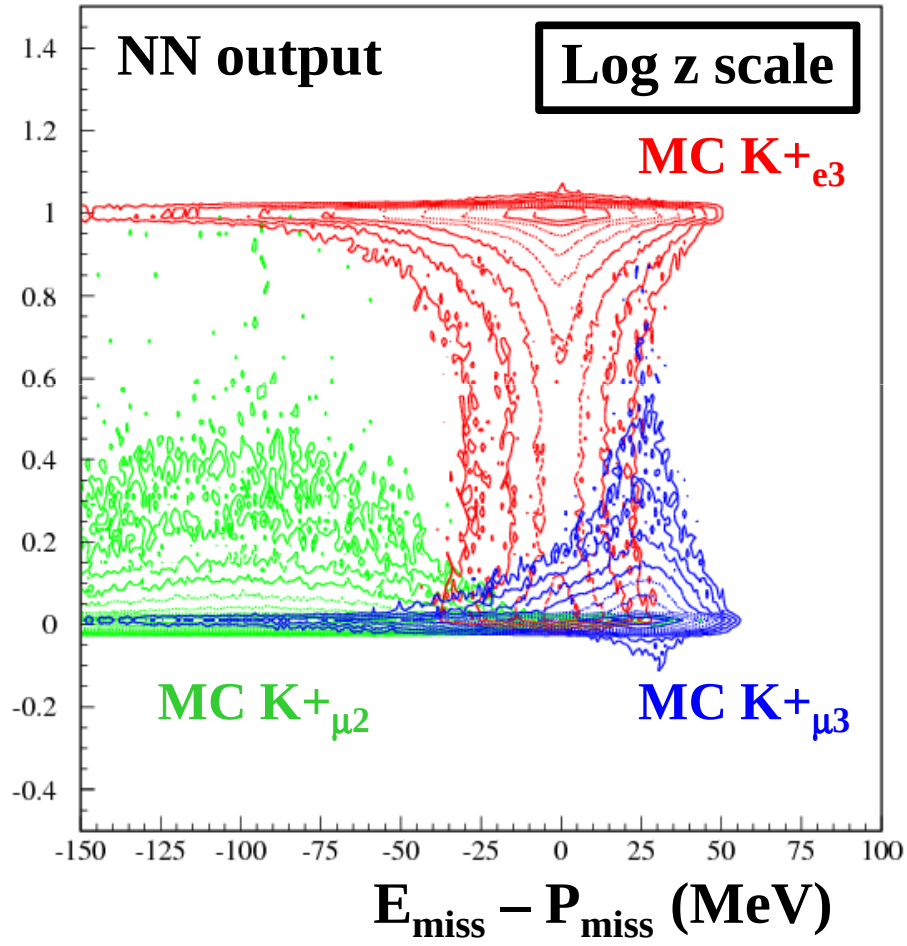
R_K at KLOE, control samples

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

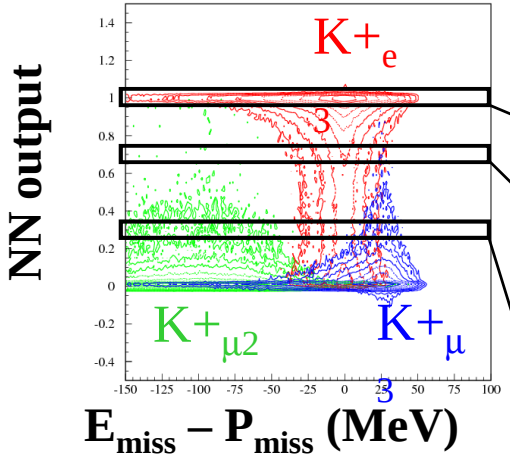
Require π^0 detection

Cut against $\pi\pi^0$ bkg

Use π^0 γ's to evaluate E_{miss}, P_{miss}



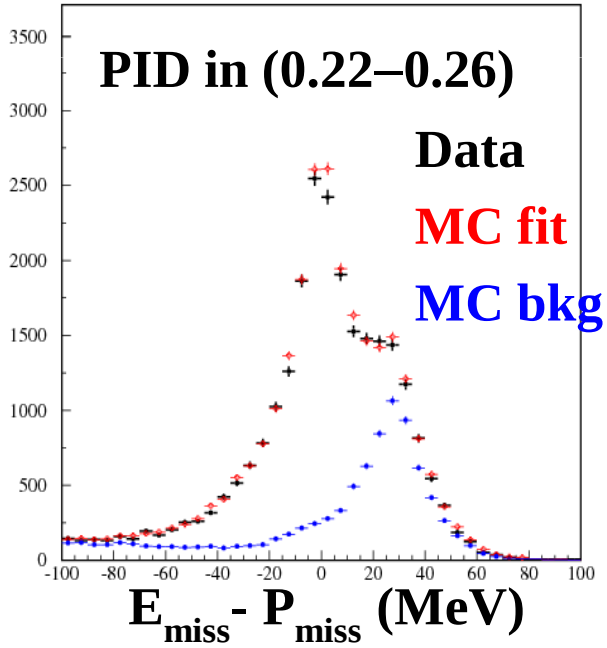
R_K at KLOE, control samples

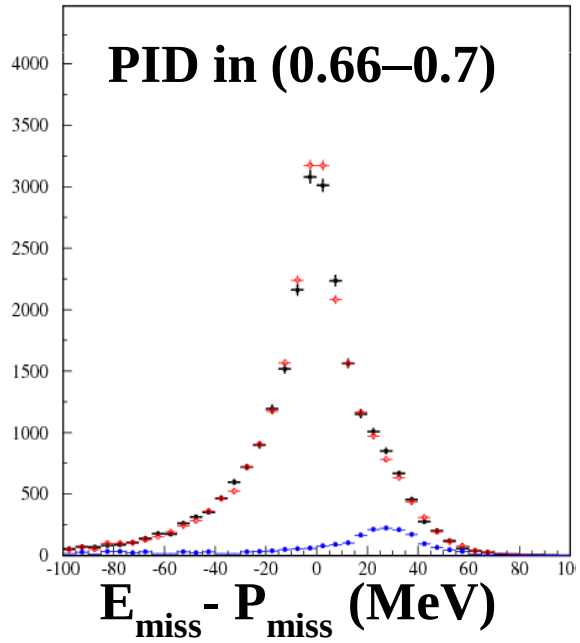


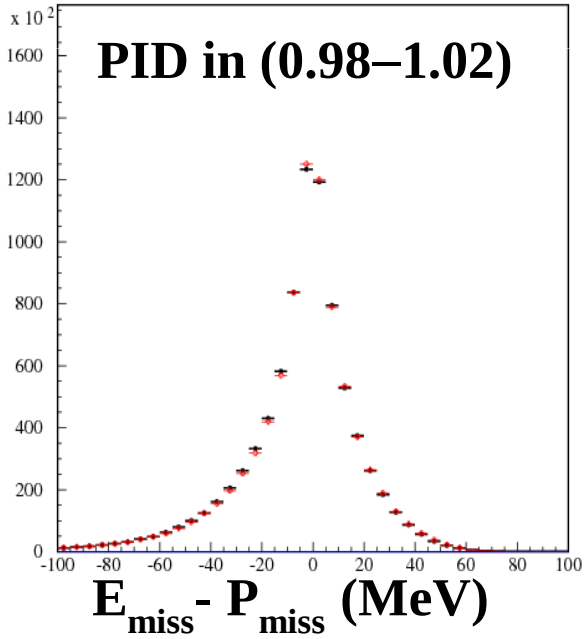
Can select pure $K^{\pm}_{e3}$ sample above 0.2

Can select $K^{\pm}_{\mu 3}$ sample below 0.4

Perform 2d fit in entire plane



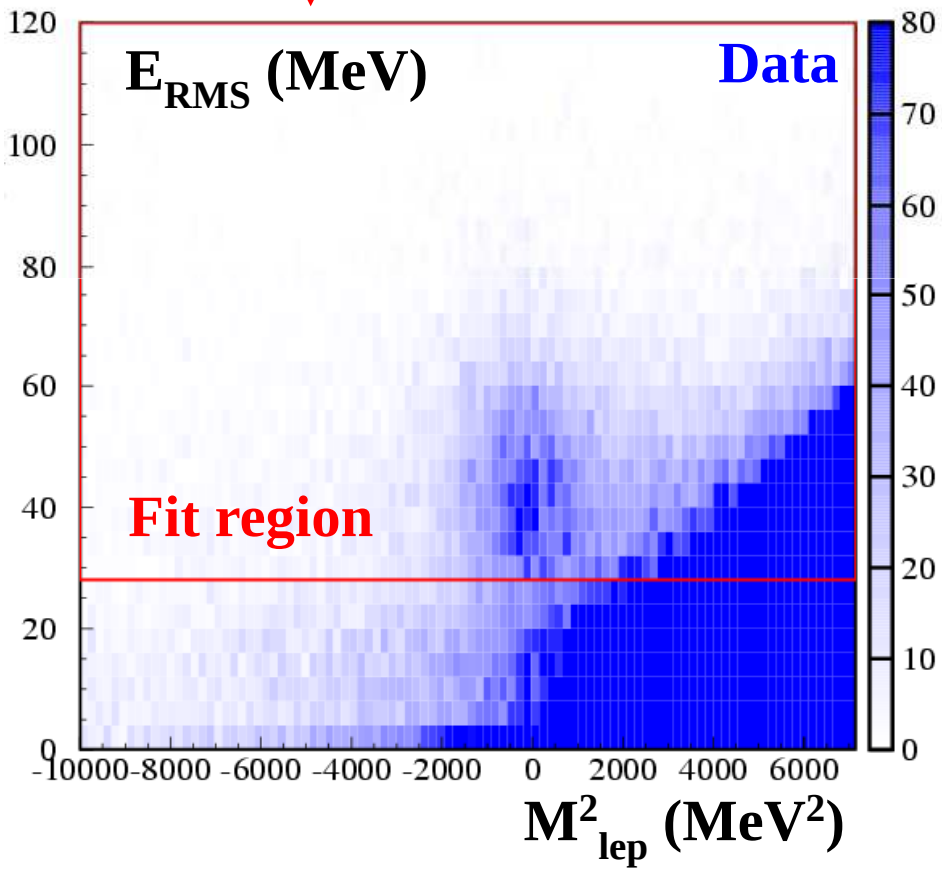


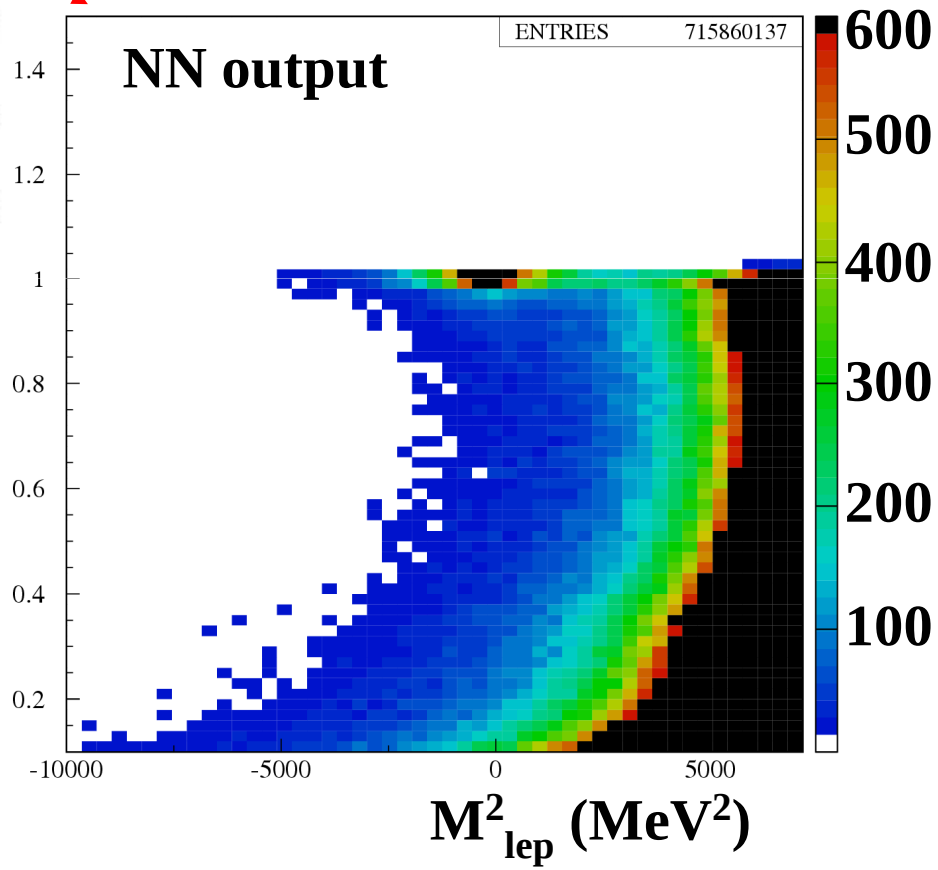


R_K at KLOE, toward the final result

Rejection from PID now > 1000 → loosen kinematic criteria

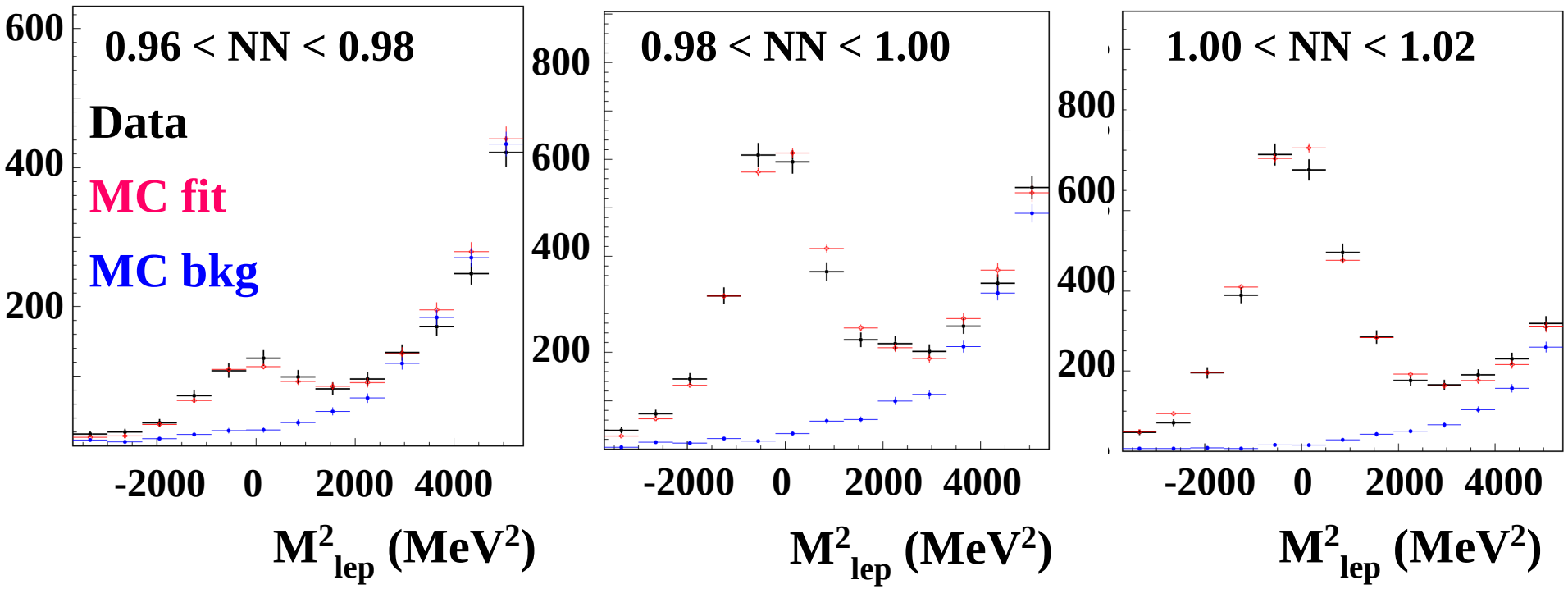
Compare OLD selection with NEW selection





R_K at KLOE, fitting for Ke2 counting

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



Count in entire statistics: NKe2(e^+) = 6901(98), NKe2(e^-) = 6514(97)

Yield +30% wrt old analysis, reach 1.1% statistical error

R_K at KLOE, error budget

Compare errors from preliminary result to present analysis

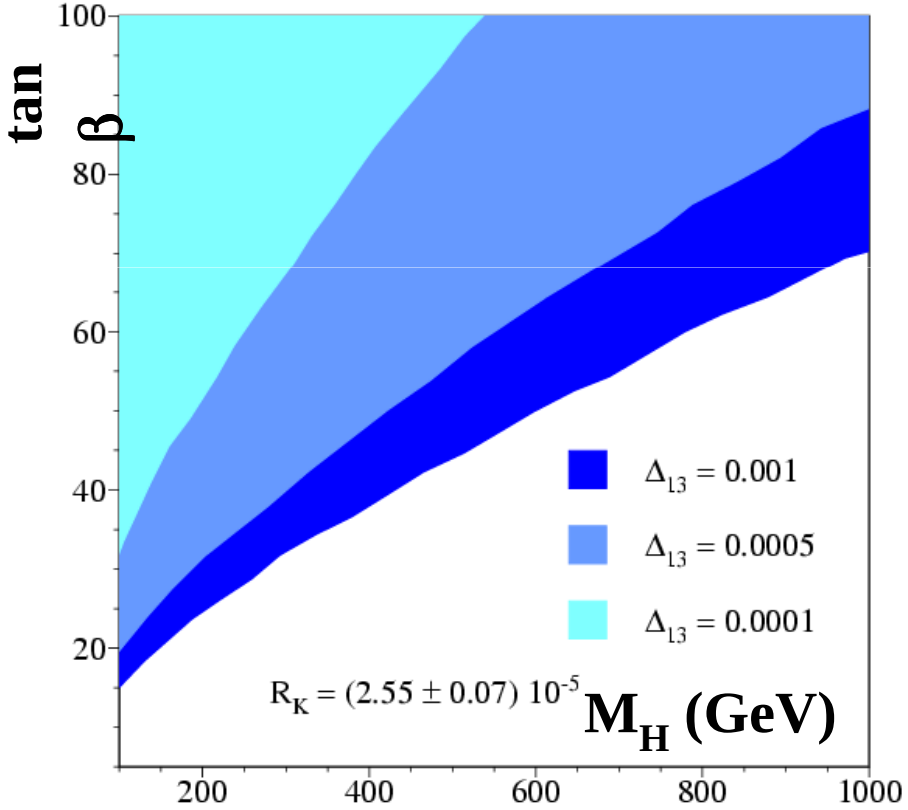
Error	Source	Preliminary	Present
Statistical	Count + bkg subtraction	1.9	1.1
Systematic	Radiative correction (DE)	0.5	0.15
Systematic	Tracking efficiency	0.9	0.1
Systematic	PID efficiency	1.5	0.15
Statistical	Trigger efficiency	0.9	0.4
Total		2.9	1.3

Can reach < ~1.3% level after analysis completion

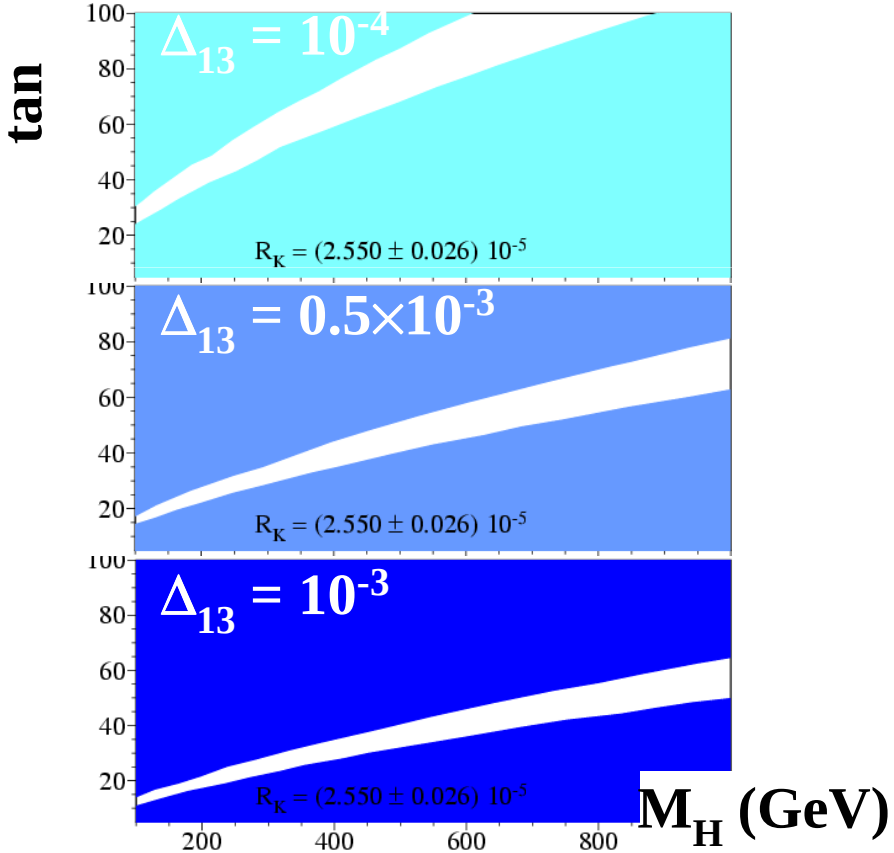
R_K – Sensitivity to NP

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

Present KLOE result: R_K= $2.55(7)\times10^{-5}$



Perspective: R_K= $2.55(3)10^{-5}$



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

Sensitivity to NP contribution from gauge invariance test

Lepton universality test from K_{l3} decays satisfied at < 0.5%

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

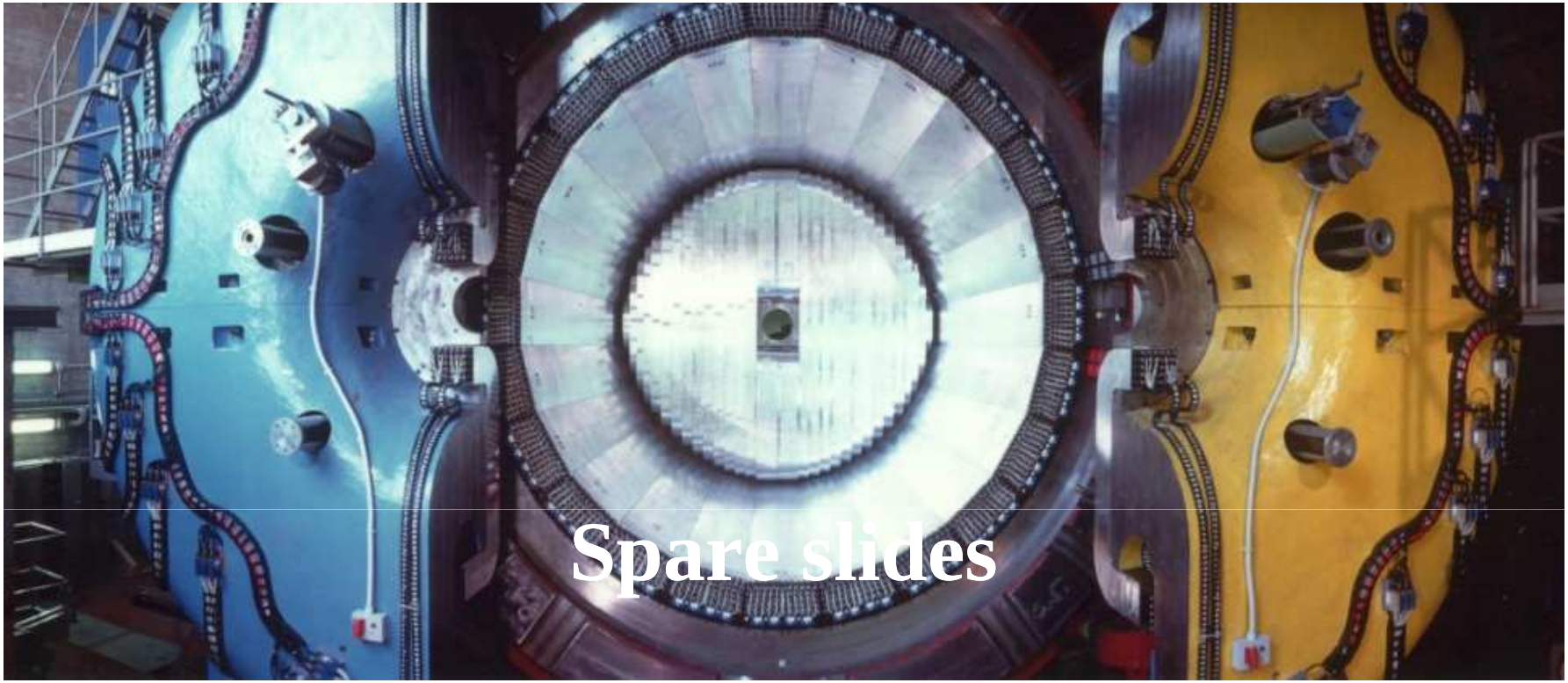
Sensitivity to NP effects from $K_{\mu 2}/\pi_{\mu 2}$: comparable to $B \to \tau\nu$

Golden observable: R_K, preliminary @ 3%

Future developments:

Completion of R_K analysis with total error < 1.5%

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



Spare slides

Analysis of R_K – Radiative corrections

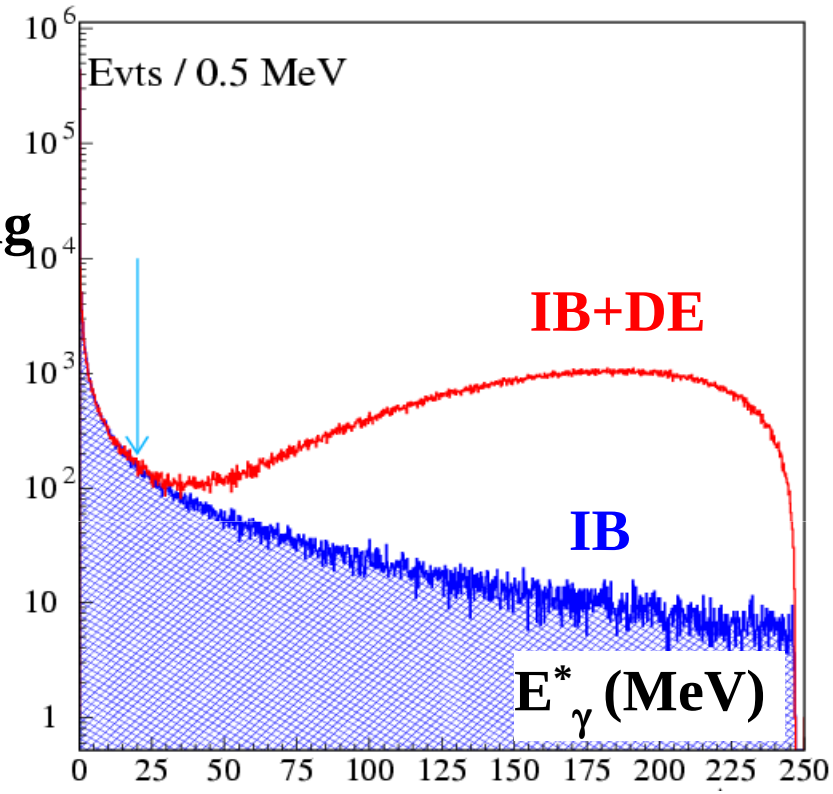
To match theory, has to count IB only:

Old analysis:

- **Fit using IB+DE, count IB by considering as "signal" 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**

New analysis:

- **Explicitly detect radiated photon**
- **Compare DE/IB ratio with expectation from theory**
- **Can pin down error on DE term @ 3%**



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

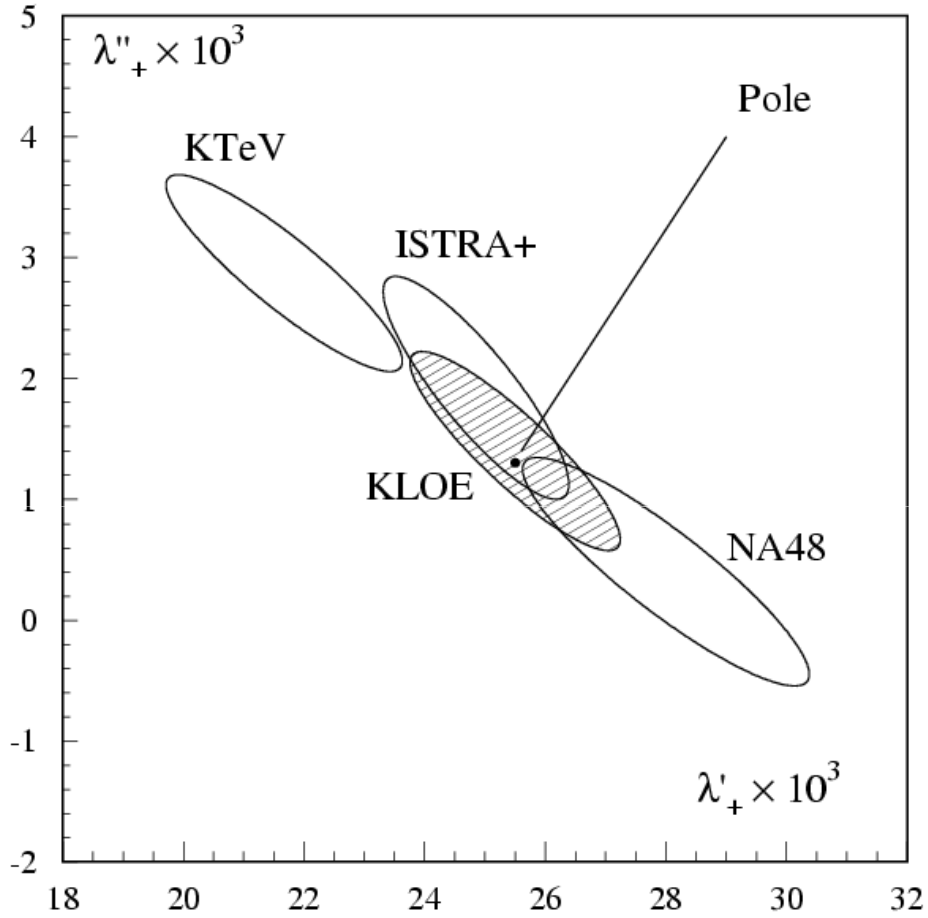
- **KLOE measurements of K_{Le3} and $K_{l\mu 3}$ BR and ff slopes determine:**

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

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

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)

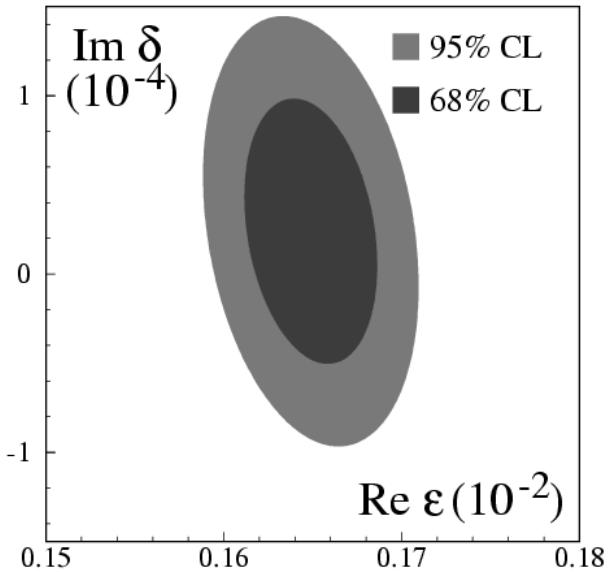
$$\mathrm{Re}(\epsilon) = (164.9 \pm 2.5) \times 10^{-5}$$

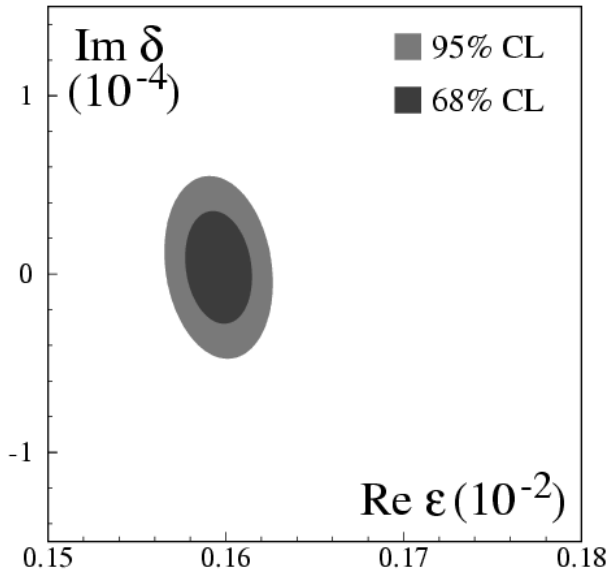
$$\mathrm{Im}(\delta) = (\ 2.4 \pm 5.0) \times 10^{-5}$$

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:

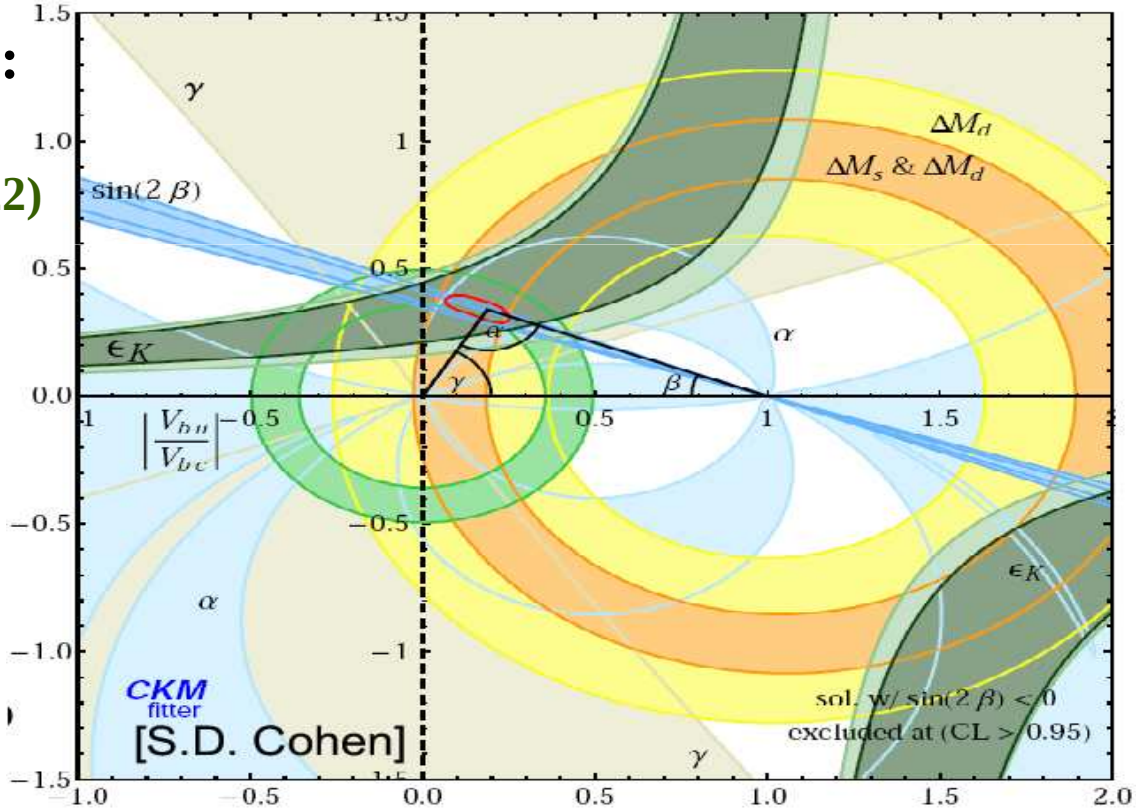
$|\varepsilon| = C_1 B_K V_{cb}^2 \eta [C_2 + C_3 V_{cb}^2 (1-\rho)]$

Compare input values for B_K:

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

New[RBC/UKQCD], $B_K = 0.770(15)(22)$

Impact on UT fit now limited by δV_{cb}



Unique to KLOE: $K_{S\mu 3}$ decays

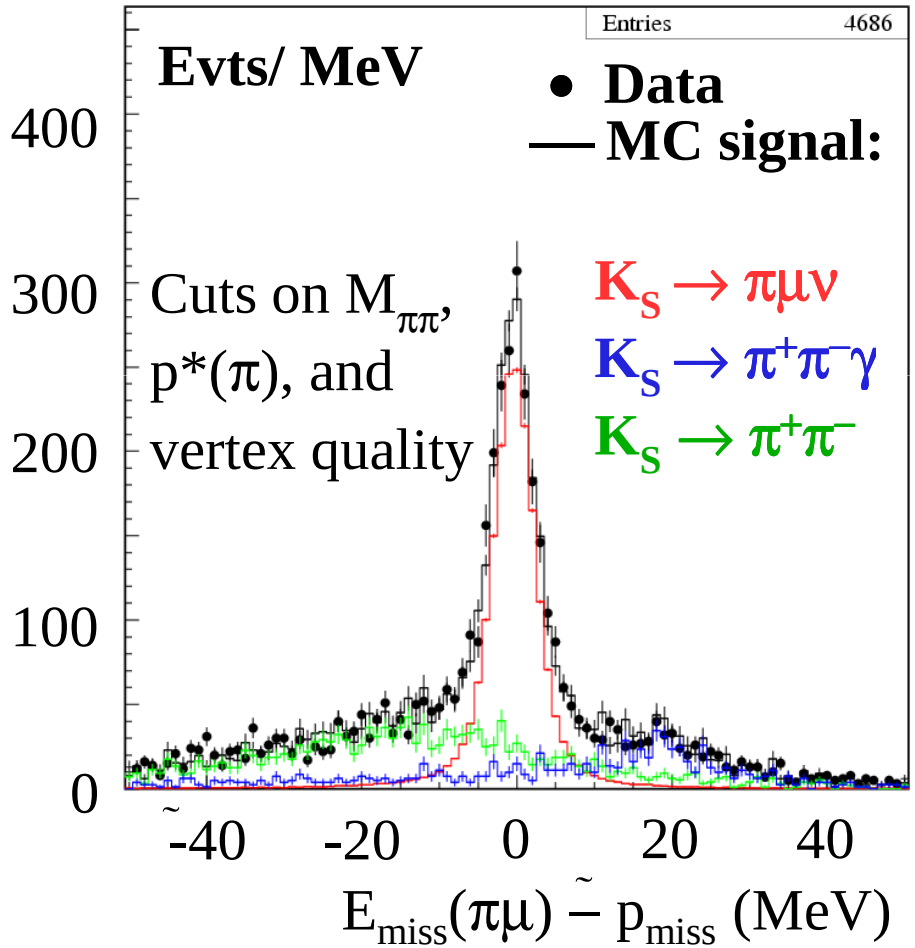
Decay mode has never been observed

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



R_K – *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%: final mmt will be compared with forecoming mmt with 0.3% accuracy from P326/NA62 [R. Fantechi, EPS HEP 2007]

Generators for radiative K decays

Generators for neutral kaon decays include radiation, no cutoff energy

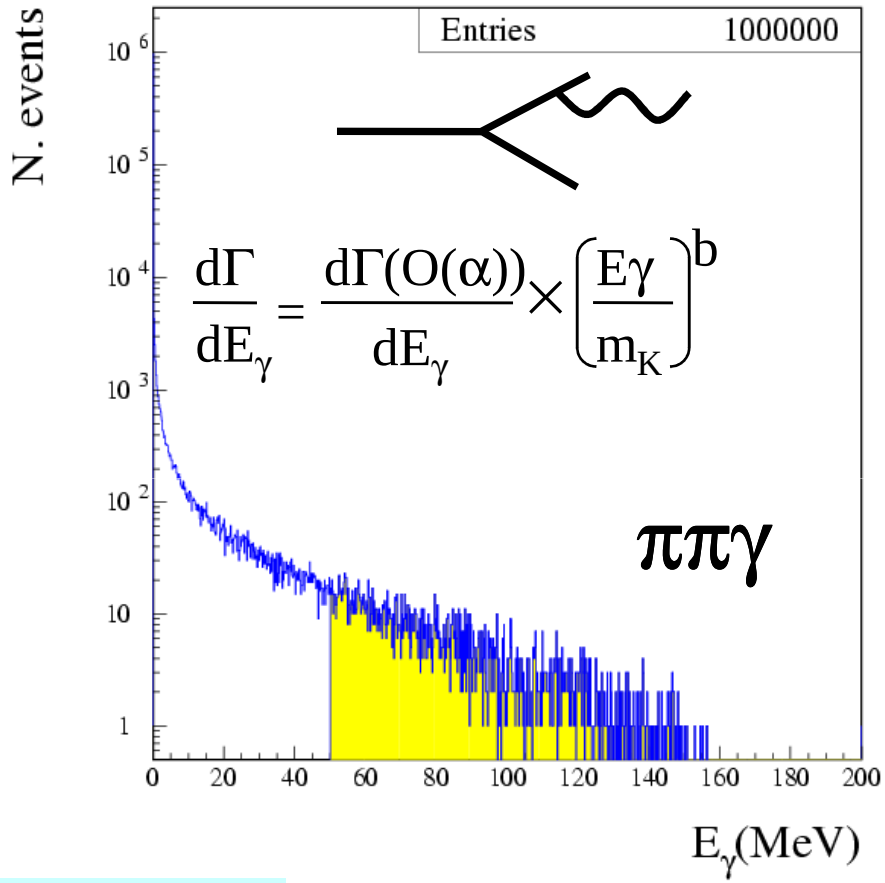
- Full O(α) amplitudes (real and virtual contributions) summed to all orders in α by exponentiation (soft-photon approximation)
- Carefully checked against all available data and calculations, e.g:

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

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

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

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



[C. Gatti, EPJC 45 (2006)]