CKM 2008

5th Workshop on the Unitary Triangle

Università degli Studi di Roma, "La Sapienza"

Experimental Results for ε_K and Re$(\varepsilon'/\varepsilon_K)$

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CP violation with Kaons

- CP violation established in the K sector through,
  - Charge asymmetry in semileptonic decays: A_L , A_T
  - $K_L \to \pi\pi$: η_{+-}, η_{00}
  - $K_L \to \pi^+\pi^-\gamma$: $\eta_{+-\gamma}$
  - $K_L \to \pi\pi ee$:

$$A_{\cos\phi \cdot \sin\phi} = \frac{N_{\cos\phi \cdot \sin\phi > 0} - N_{\cos\phi \cdot \sin\phi < 0}}{N_{\cos\phi \cdot \sin\phi > 0} + N_{\cos\phi \cdot \sin\phi < 0}}$$

- CP violating processes are dominated by mass mixing, described by ε_K

- Direct CP violation observed by the measurement of a tiny difference between η_{+-} and η_{00}
- Described by the ε' parameter

$$\frac{|\eta_{00}|}{|\eta_{+-}|} = 0.9950 \pm 0.0008 \cong 1 - 3\,\mathrm{Re}\,(\varepsilon'/\varepsilon)$$

CP-violating observables

$$A_L = \frac{\Gamma(K_L \to \pi^- e^+ \nu) - \Gamma(K_L \to \pi^+ e^- \nu)}{\Gamma(K_L \to \pi^- e^+ \nu) + \Gamma(K_L \to \pi^+ e^- \nu)} \cong 2\,\mathrm{Re}(\varepsilon)$$

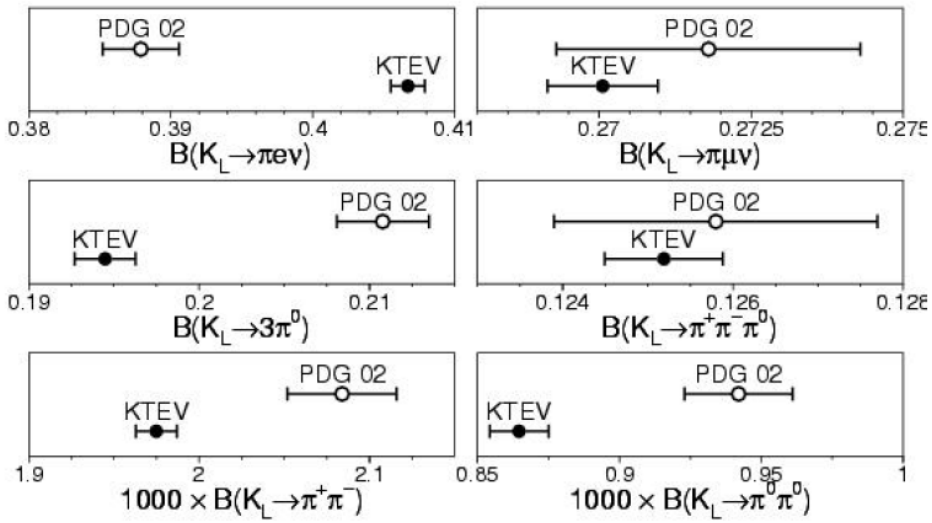
$$A_T = \frac{\Gamma(\bar{K}^0_{(t=0)} \to \pi^- e^+ \nu) - \Gamma(K^0_{(t=0)} \to \pi^+ e^- \nu)}{\Gamma(\bar{K}^0_{(t=0)} \to \pi^- e^+ \nu) + \Gamma(K^0_{(t=0)} \to \pi^+ e^- \nu)} \cong 4\,\mathrm{Re}(\varepsilon)$$

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \cong \varepsilon + \varepsilon' \qquad \eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \cong \varepsilon - 2\,\varepsilon'$$

- Recent measurements include $BR(K_L \to \pi^+\pi^-)$, $\mathrm{Re}(\varepsilon'/\varepsilon_K)$, $A_{\cos\phi \cdot \sin\phi}$
- The improvements on K_L, K_S branching fractions, the first measurement of A_S, the charge asymmetry in K_S semileptonic decays, contributed to the knowledge of $\mathrm{Re}(\varepsilon_K)$ (and in testing CPT symmetry) through the constraint imposed by unitarity (Bell-Steinberg relation, BSR)

CP-violation: recent results

- $K_L \to \pi^+\pi^-$
  - KLOE: PLB 638 (2006) 140
  - NA48: PLB 645 (2007) 26



KTeV: PRD70 (2004) 092006

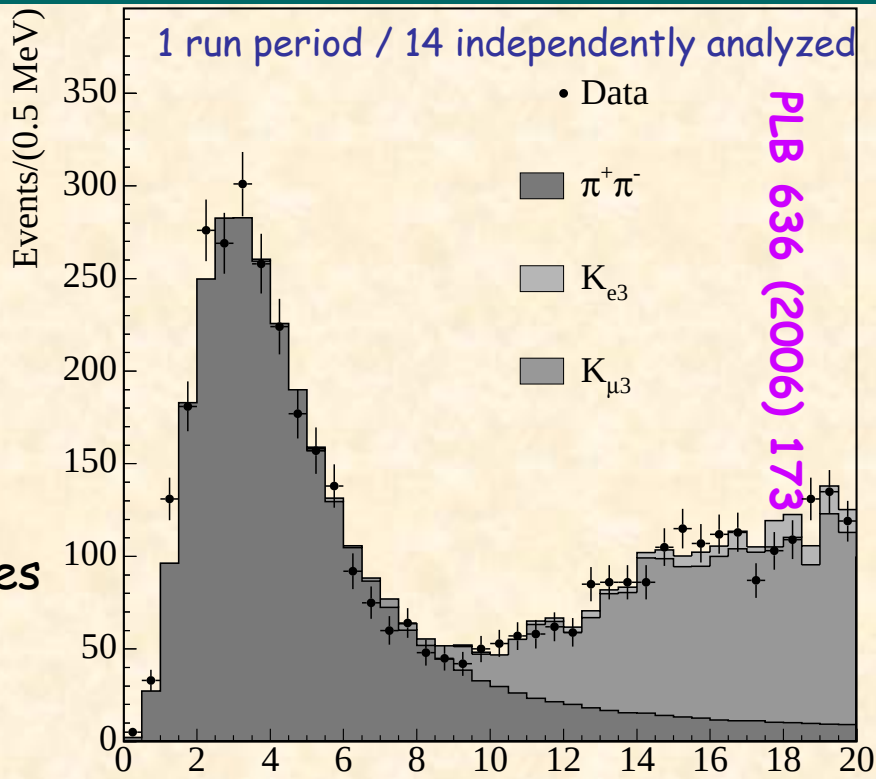
- Re(ε'/ε)
  - KTeV: Moriond Electroweak, La Thuile, March 08, HQL08, Melbourne, June

- Re(ε)
  - KLOE: JHEP 0612 (2006) 011
  - PDG: PLB 667 (2008) 1 ["CPT invariance tests in Neutral Kaon Decay"]
  - Flavianet: Capri Workshop, June 2008

- CP-violating angular asymmetry $A_{\cos\phi \cdot \sin\phi}$ in $K_L \to e^+e^- \pi^+\pi^-$ decays
  - KTeV: PRL 96 (2006) 101801

KLOE: BR ($K_L \to \pi^+\pi^-$)

- Measurement of the ratio $BR(K_L \to \pi^+\pi^-)/BR(K_L \to \pi\mu\nu)$
- $K_L \to \pi^+\pi^-$ tagged by $K_S \to \pi^+\pi^-$
- Closest approach to the tagging direction considered for neg/pos tracks separately
- Radiative events (IB and DE contrib.) included in the simulation
- Efficiencies from MC distributions
- MC distrib. corrected for data/MC discrepancy as measured by control samples of $K_L \to \pi^+\pi^-\pi^0$ and $K_L \to \pi e\nu$
- Systematics from data/MC control procedure include MC and control-sample statistics



Branching ratio inclusive of radiative decays (IB and DE)

$$BR(K_L \to \pi^+\pi^-(\gamma)) = (1.963 \pm 0.012_{stat} \pm 0.017_{syst}) \times 10^{-3}$$

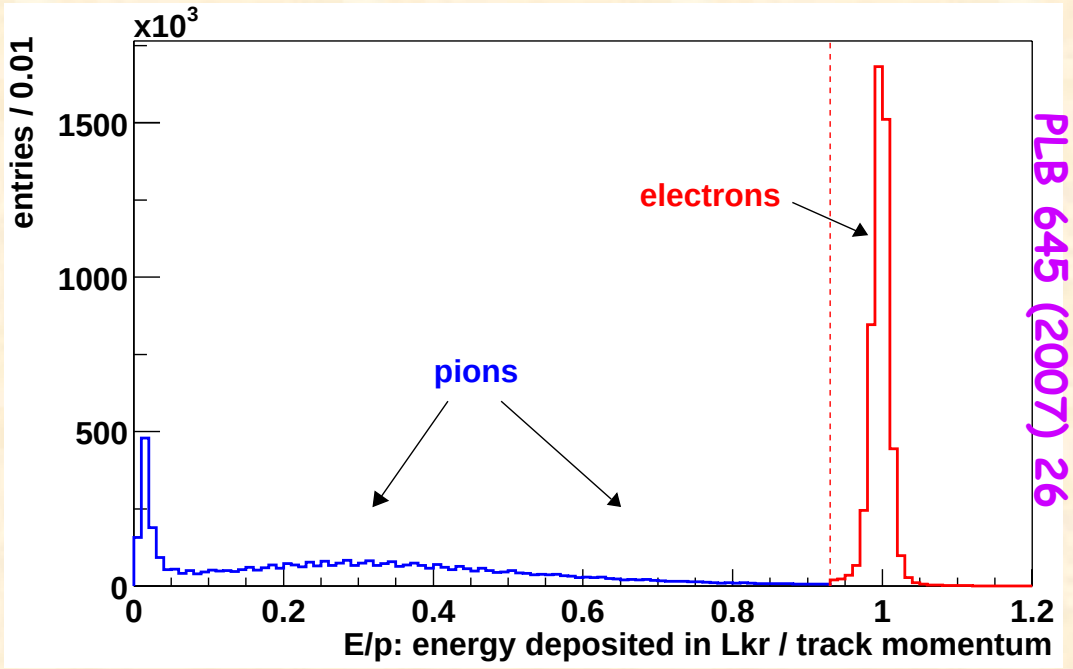
fractional error: 1.1% = $0.6\%_{stat} \oplus 0.9\%_{syst}$

Amplitude ratio

$$|\eta_{+-}| = (2.219 \pm 0.013) \times 10^{-3}$$

NA48 results on $K_L \to \pi^+\pi^-$

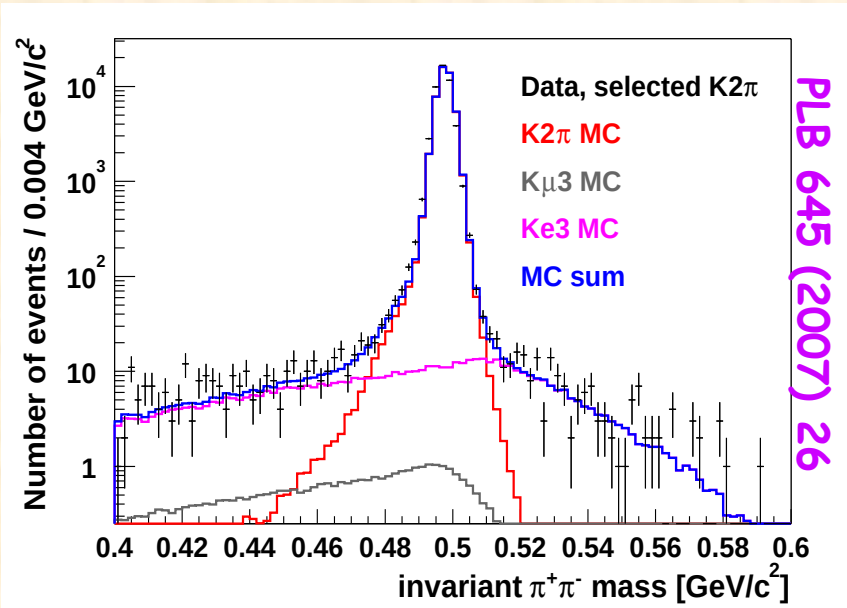
- Measurement of the ratio BR ($K_L \to \pi^+\pi^-$) / BR ($K_L \to \pi e \nu$)
- Data sample for the measurement of BR(K_{e3})
- Two tracks of opposite charge at small DoCA
- Background from $K_L \to \pi e \nu$ and $K_L \to \pi \mu \nu$ suppressed by p_T cut E/p cut (for $e^\pm$), muon-counter response (for $\mu^\pm$)
- Trigger efficiency from downscaled samples



- MC simulation of the relevant distributions for efficiency evaluation of the analysis cuts corrected using control samples

NA48: BR ($K_L \to \pi^+\pi^-$)

- Background subtraction from sidebands of the $M_{\pi\pi}$ distribution (0.5% correction)
- A final correction to the ratio of +0.04% has been applied and the total systematic error associated to the ratio is 0.33%



$$\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi e \nu)} = (4.835 \pm 0.022_{stat} \pm 0.016_{syst})\ 10^{-3}$$

Branching ratio inclusive of IB

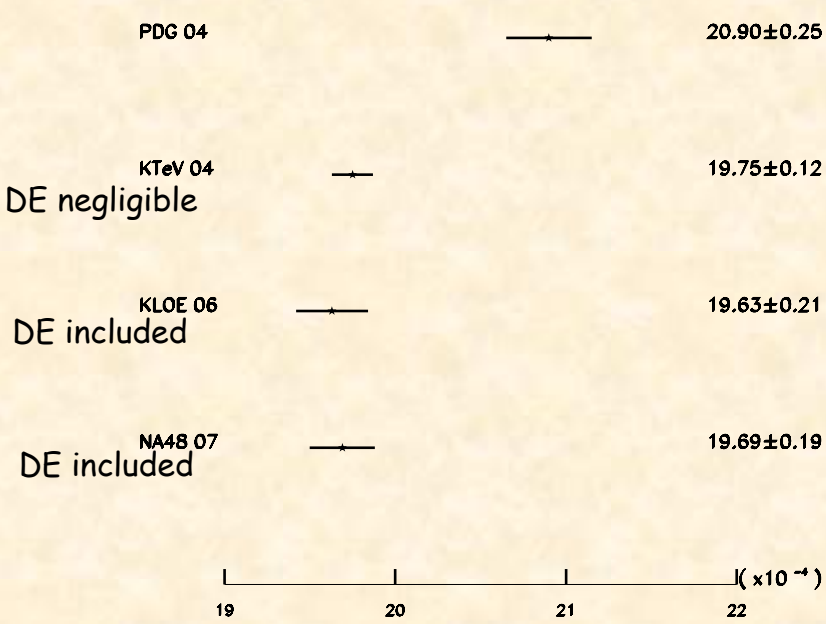
$$BR\ (K_L \to \pi^+\pi^-(\gamma)) = (1.941 \pm 0.019)\ 10^{-3}$$

Amplitude ratio

$$|\eta_{+-}| = (2.223 \pm 0.012)\ 10^{-3}$$

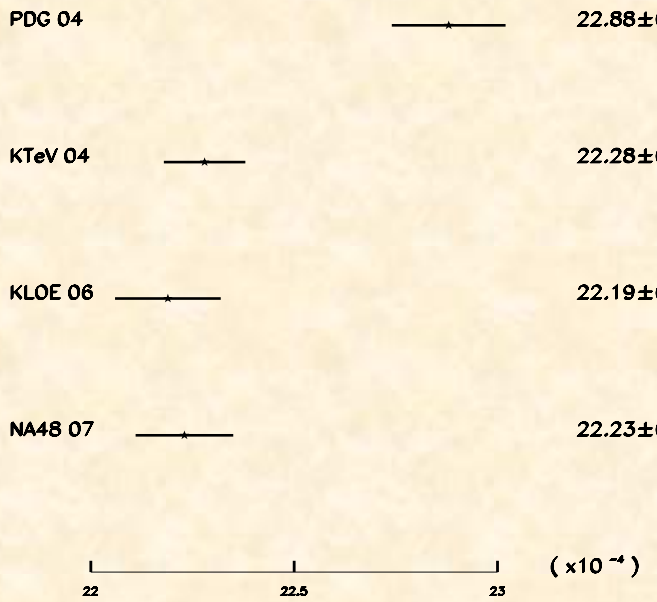
$K_L \to \pi^+\pi^-$

$BR(K_L \to \pi^+\pi^-(\gamma))$



- New data are consistent and confirms the KTeV value, 6% lower than the older measurements

$|\eta_{+-}|$

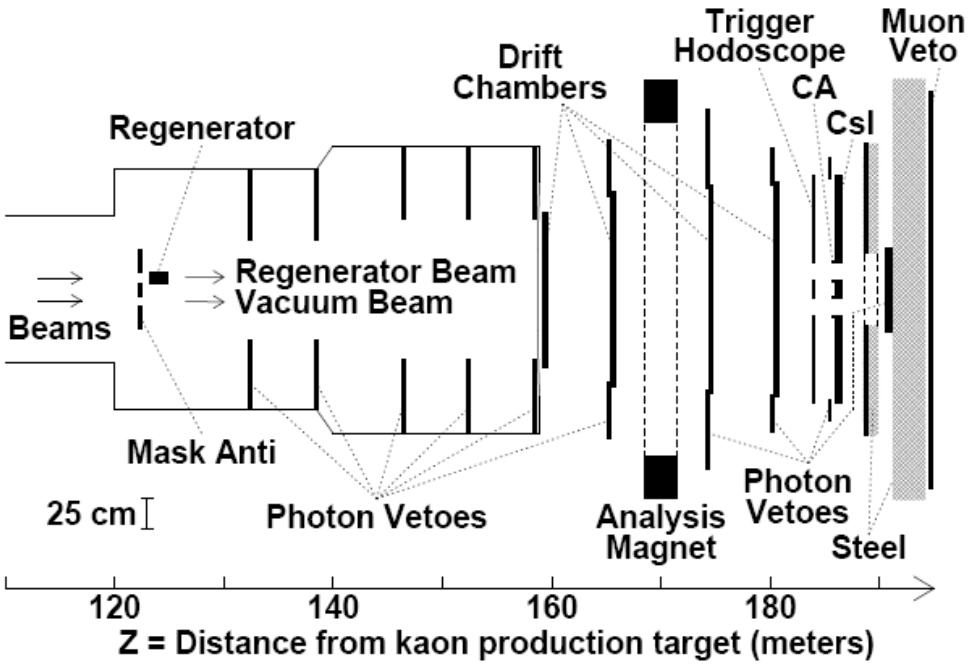


KLOE, NA48: $|\eta_{+-}|$ from BR($K_L \to \pi^+\pi^-(\gamma_{IB})$), τ_S(NA48), τ_L(KLOE), BR($K_S \to \pi^+\pi^-$)(KLOE)

KTeV: BR($K_L \to \pi^+\pi^-(\gamma_{IB})$), BR($K_L \to \pi^0\pi^0$), Re$(\varepsilon'/\varepsilon)$, BR($K_L \to \pi l \nu$) and CPT assumption

KTeV final results on Re(ε'/ε)

Proceedings: Moriond Electroweak, March 08

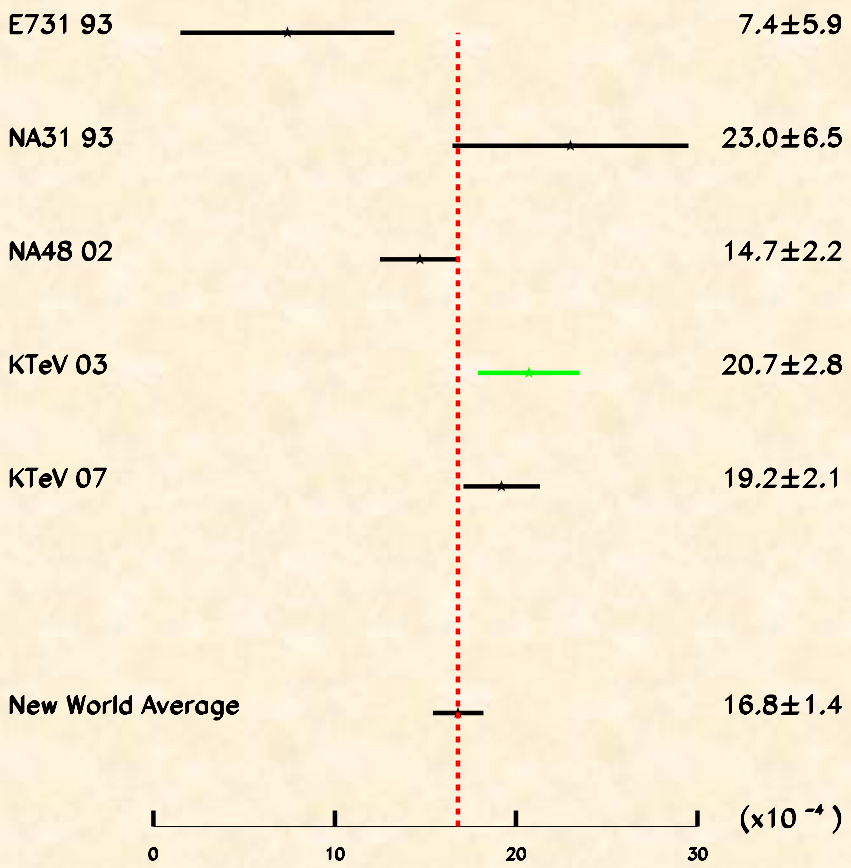


- New results include data from 1999 run, better data-taking conditions and
- Analysis improvements from more detailed detector simulation (both, charged particle, and shower simulation)
- Total systematic error from 2.4 10^{-4} to 1.8 10^{-4} thanks mainly to the better knowledge of cluster reconstruction and of the detector acceptance reducing data/MC corrections
- Statistical error reduced from 1.5 10^{-4} to 1.1 10^{-4}

Re(ε'/ε)

Re(ε'/ε) = (1.92 ± 0.11 ± 0.18) 10^{-3}

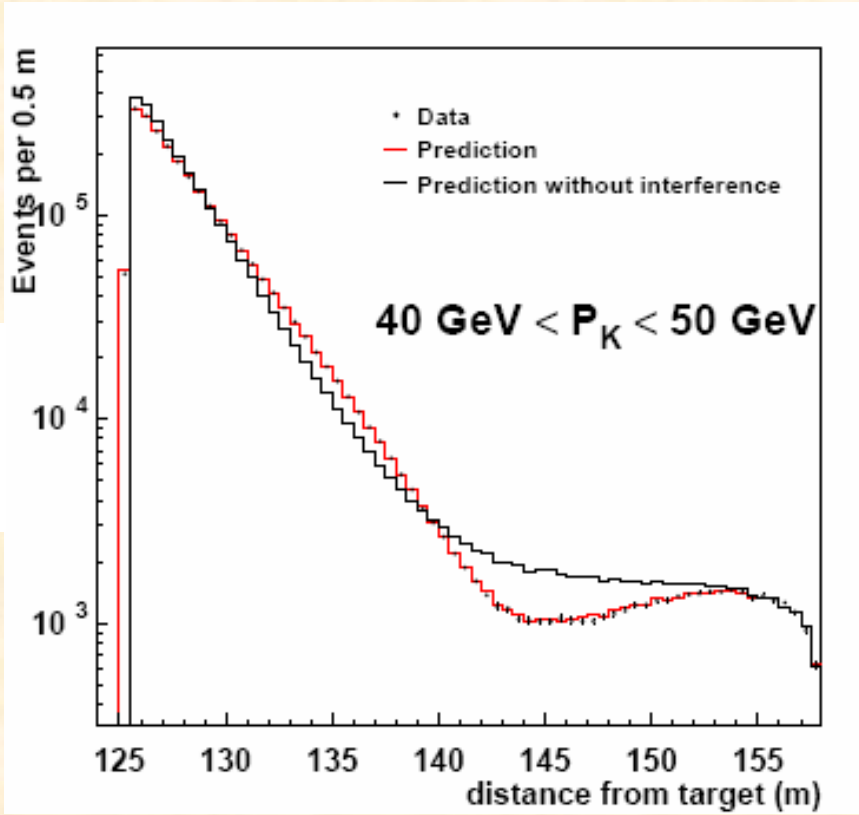
Re(ε'/ε)



KTeV results on phases, Δm and τ_s

- With the interference in the beam regenerator KTeV has also measured the phases, Δm and τ_s

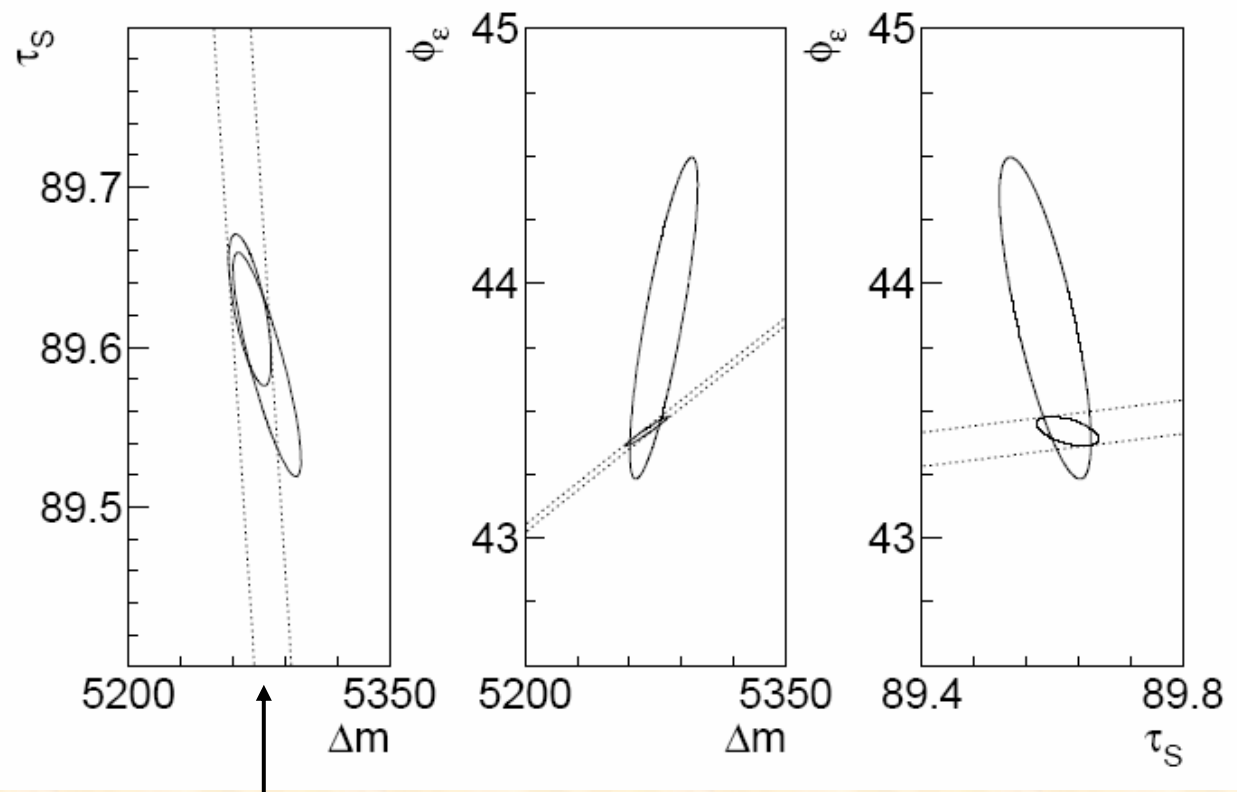
$$N(p,z) \sim |\rho|^2 e^{-\Gamma_S t} + |\eta|^2 e^{-\Gamma_L t} + |\rho||\eta| cos(\Delta m t + \phi_\rho - \phi_\eta) e^{-\overline{\Gamma} t}$$



Moriond Electroweak, March 08

- Fit for Δm, τ_s ϕ_ε, Re$(\varepsilon'/\varepsilon)$, Im$(\varepsilon'/\varepsilon)$
  - $\phi_{+-} \sim \phi_\varepsilon$ + Im$(\varepsilon'/\varepsilon)$
  - $\phi_{00} \sim \phi_\varepsilon$ - 2 Im$(\varepsilon'/\varepsilon)$
  - $\Delta\phi = \phi_{00} - \phi_{+-} \sim$ - 3 Im$(\varepsilon'/\varepsilon)$

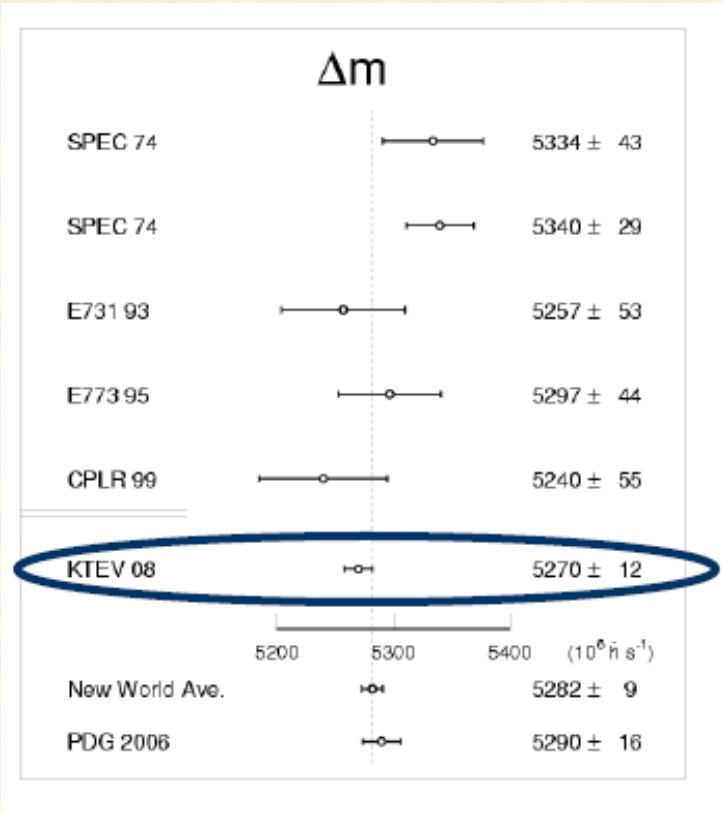
KTeV results on τ_s, ϕ_ε and ΔM

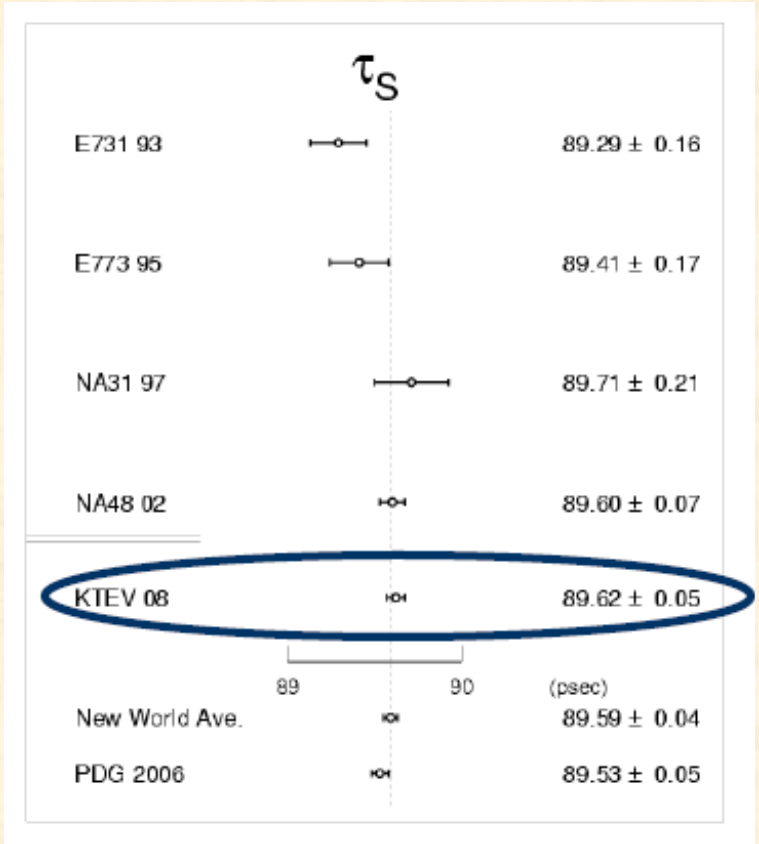


Proceedings: Moriond Electroweak, March 08

- Results CPT-constrained have:
  - $\phi_\varepsilon = \phi_{SW} = \tan^{-1}(2\ \Delta M/\Delta\Gamma)$

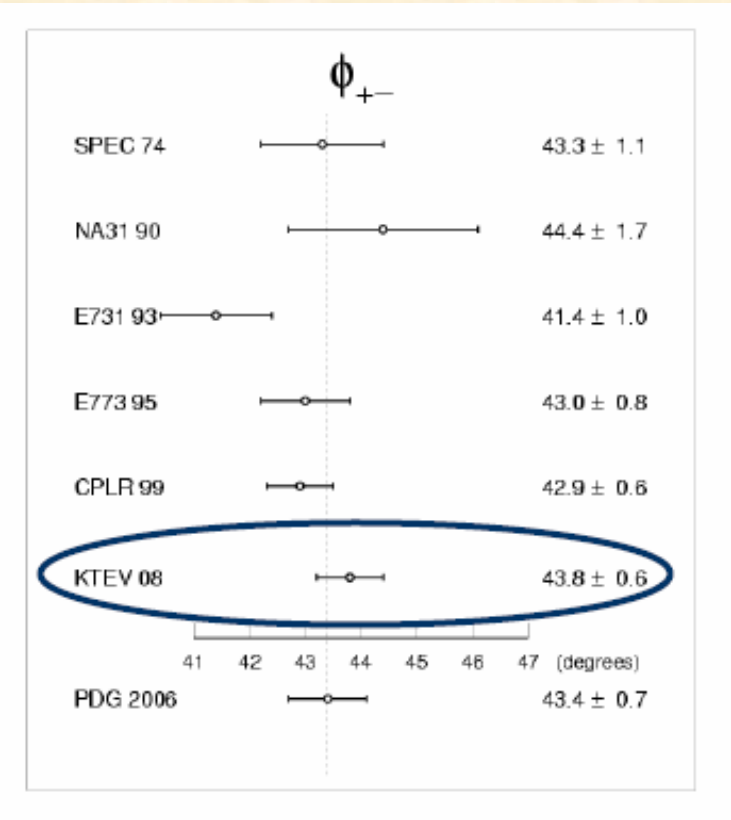
Improvement on τ_s, ΔM

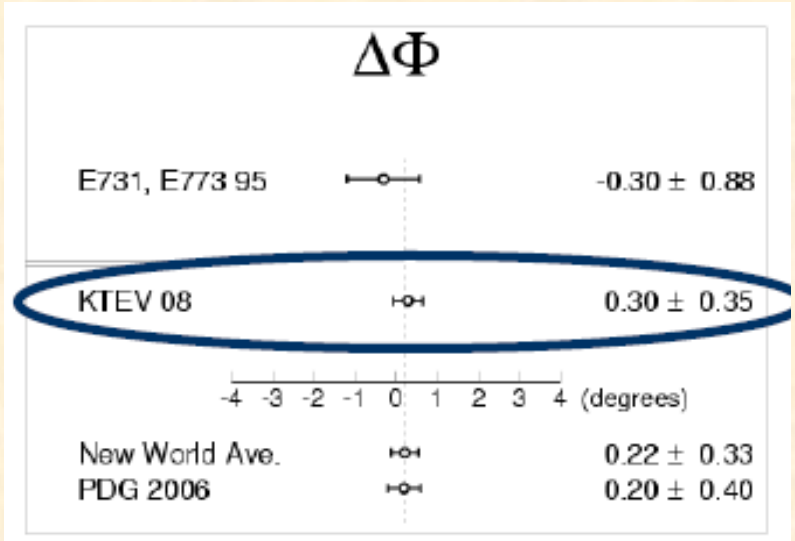




HQL08, Melbourne, June 08

Improvement on ϕ_{+-}



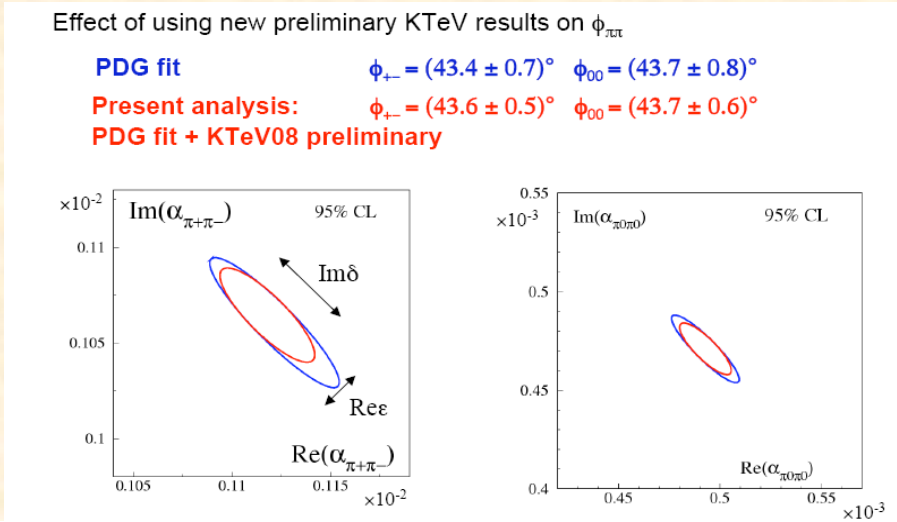


HQL08, Melbourne, June 08

Re(ε) from Bell-Steinberger

$$\left(\frac{\Gamma_S+\Gamma_L}{\Gamma_S-\Gamma_L}+i\tan\phi_{SW}\right)\left(\frac{\mathrm{Re}(\epsilon)}{1+|\epsilon|^2}-i\mathrm{Im}(\delta)\right)=\frac{1}{\Gamma_S-\Gamma_L}\sum_f \mathcal{A}_L(f)\mathcal{A}_S^*(f)$$

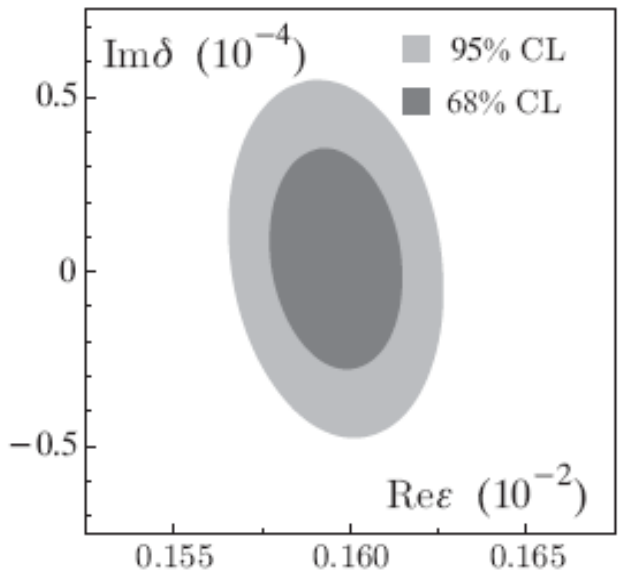
- Unitarity allows to express the CP-violating parameter Re(ε), and Im(δ) in terms of combination of decay amplitudes
- 2π, 3π and semileptonic modes contribute to the sum
- Contribution from $\pi\pi$ channel:



M. Palutan - Flavianet, Capri Workshop, June08

Results from BSR

JHEP 0612 (2006) 011



$Re(\varepsilon) = (159.6 \pm 1.3) 10^{-5}$

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

BR's from KLOE

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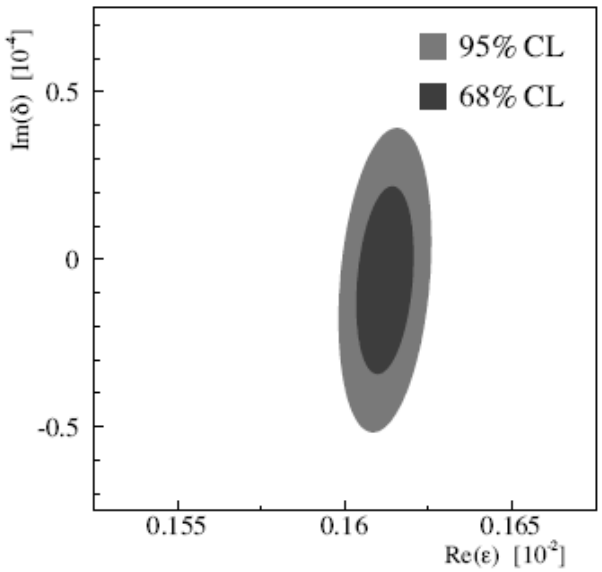

$(161.2 \pm 0.6) 10^{-5}$

$(-0.6 \pm 1.9) 10^{-5}$

BR's from KLOE, KTeV, NA48

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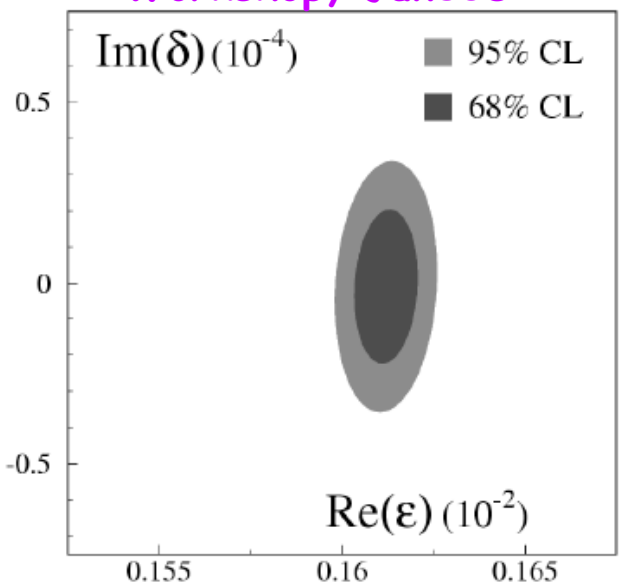


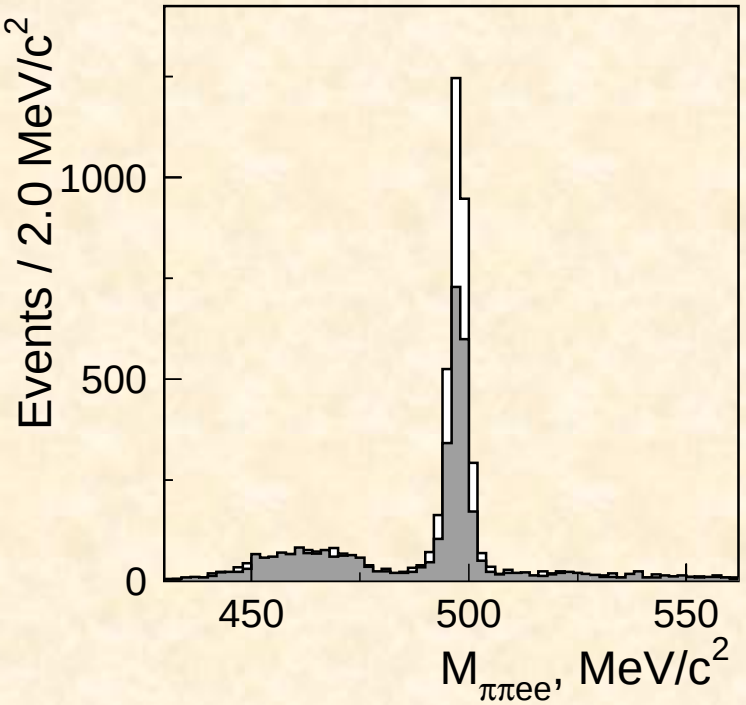
$(161.2 \pm 0.6) 10^{-5}$

$(-0.1 \pm 1.4) 10^{-5}$

KTeV08 phases included

Angular asymmetry in $K_L \to e^+e^- \pi^+\pi^-$

- Results from the entire data set
- 5241 candidates including 204±14 background events
- 2 neg and 2 pos tracks required, pointing to a good quality, common vertex
- Calorimeter PID (e vs π) based on E/p
- Cut on p_T for background rejection
- Major background from $K_L \to \pi^+\pi^-\pi^0_D$



- Background under the invariant-mass peak determined by sidebands in the $M_{\pi\pi ee}$ distribution
- Acceptance using a fit to theoretical predictions
- Control sample of $K_L \to \pi^+\pi^-\pi^0_D$ decays used to rule out detector effects in creating false asymmetries

KTeV results on $A_{\cos\phi \cdot \sin\phi}$

- Large CP-violating angular asymmetry expected due to the interference between M1 direct emission process and the IB radiation
- It was observed by KTeV and NA48
- The new analysis confirms previous results on the CP-violating angular asymmetry $A_{\cos\phi \cdot \sin\phi}$, where ϕ is the angle between ee and $\pi\pi$ planes in the K_L rest frame

$$A_{\cos\phi \cdot \sin\phi} = \frac{N_{\cos\phi \cdot \sin\phi > 0} - N_{\cos\phi \cdot \sin\phi < 0}}{N_{\cos\phi \cdot \sin\phi > 0} + N_{\cos\phi \cdot \sin\phi < 0}}$$

$$A_{\cos\phi \cdot \sin\phi} = (13.6 \pm 1.4_{stat} \pm 1.5_{syst}) 10^{-2}$$

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- OLD:
- NA48-03: $A_{\cos\phi \cdot \sin\phi} = (14.2 \pm 3.0_{stat} \pm 1.9_{syst}) 10^{-2}$
- KTeV-00 : $A_{\cos\phi \cdot \sin\phi} = (13.6 \pm 2.5_{stat} \pm 1.2_{syst}) 10^{-2}$

Conclusions

- In recent years the knowledge of CP-violation parameters in the Kaon sector has been improved by precision experiments
- Data are consistent with CPT symmetry and unitarity
- Present generation of experiments, KTeV, NA48 and KLOE have obtained precision results in disagreement with older data
- Present results are limited to the mixing and the direct-decay phenomena
- To investigate CP-violation in the interference between mixing and direct-decay transition with Kaons, a challenging experimental program on the very rare $K \to \pi\nu\nu$ channel (and 2 generations of experiments) has to be pursued