KTeV Determination of the CKM Parameter $|V_{us}|$

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KTeV Institutions

- University of Arizona
- University of California, Los Angeles
- University of California, San Diego
- University of Chicago
- University of Colorado, Boulder
- Elmhurst College
- Fermi National Accelerator Laboratory
- Osaka University
- Rice University
- University of Virginia
- University of Wisconsin

Motivation

- According to PDG, first row of CKM matrix is 2 sigma away from unitarity.

- BNL-E865 recently reported that charged K_{e3}^{+} branching fraction is 6% higher than PDG; their new Vus is consistent with unitarity, but not consistent with Vus from K_L decay.

- Need to improve K_L semileptonic measurements.

Method to Extract Vus

KTeV measures B(Ke3) and B(Kmu3)

WANT THIS!

KTeV measures form factors to determine phase space integrals

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW}(1+\delta_K^\ell)\,|V_{us}|^2\,|f_+^2(0)|\,I_K^\ell$$

radiative corrections (theory)

Form Factor at t=0 (theory)

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1 + \delta_K^\ell) \, |V_{us}|^2 \, |f_+^2(0)| I_K^\ell$$

- $\Gamma_{K\ell 3}$ = B(Kℓ3) / τ_L (τ_L from PDG)

- To measure the semileptonic branching fractions, B(Ke3) and B(Kμ3), KTeV measures the six largest BFs which account for 99.93% of the K_L decay rate.

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1 + \delta_K^\ell) \, |V_{us}|^2 \, |f_+^2(0)| I_K^\ell$$

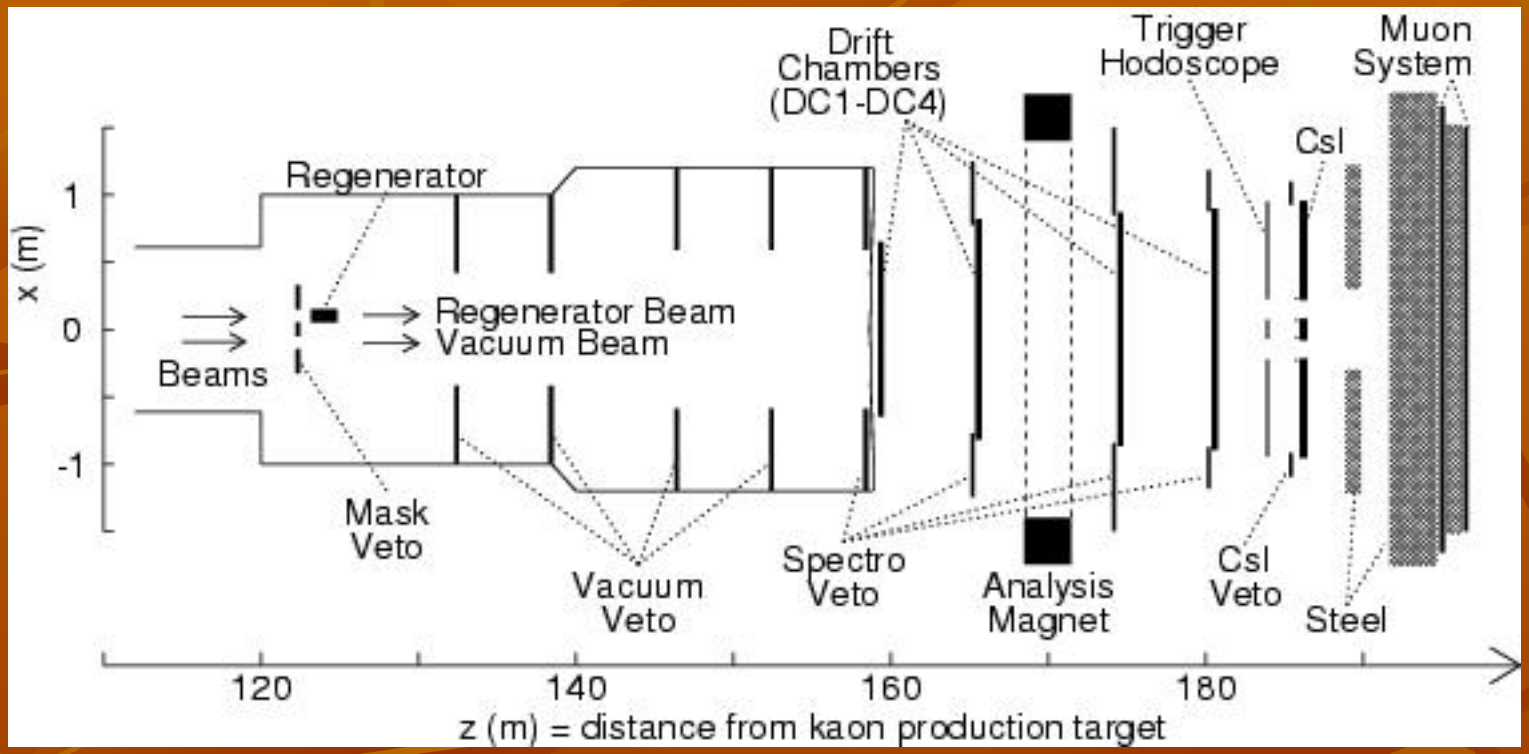
To determine the six main branching fractions, KTeV measures the following ratios of partial decay rates:

$$\Gamma_{K\mu 3}/\Gamma_{Ke3} \equiv \Gamma(K_L \to \pi^\pm \mu^\mp \nu)/\Gamma(K_L \to \pi^\pm e^\mp \nu)$$
$$\Gamma_{+-0}/\Gamma_{Ke3} \equiv \Gamma(K_L \to \pi^+ \pi^- \pi^0)/\Gamma(K_L \to \pi^\pm e^\mp \nu)$$
$$\Gamma_{000}/\Gamma_{Ke3} \equiv \Gamma(K_L \to \pi^0 \pi^0 \pi^0)/\Gamma(K_L \to \pi^\pm e^\mp \nu)$$
$$\Gamma_{+-}/\Gamma_{Ke3} \equiv \Gamma(K_L \to \pi^+ \pi^-)/\Gamma(K_L \to \pi^\pm e^\mp \nu)$$
$$\Gamma_{00}/\Gamma_{000} \equiv \Gamma(K_L \to \pi^0 \pi^0)/\Gamma(K_L \to \pi^0 \pi^0 \pi^0)$$

Ke3+Kμ3: 70% 3π: 30% 2π: 0.3%

Sample sizes: 10^5 to 10^6

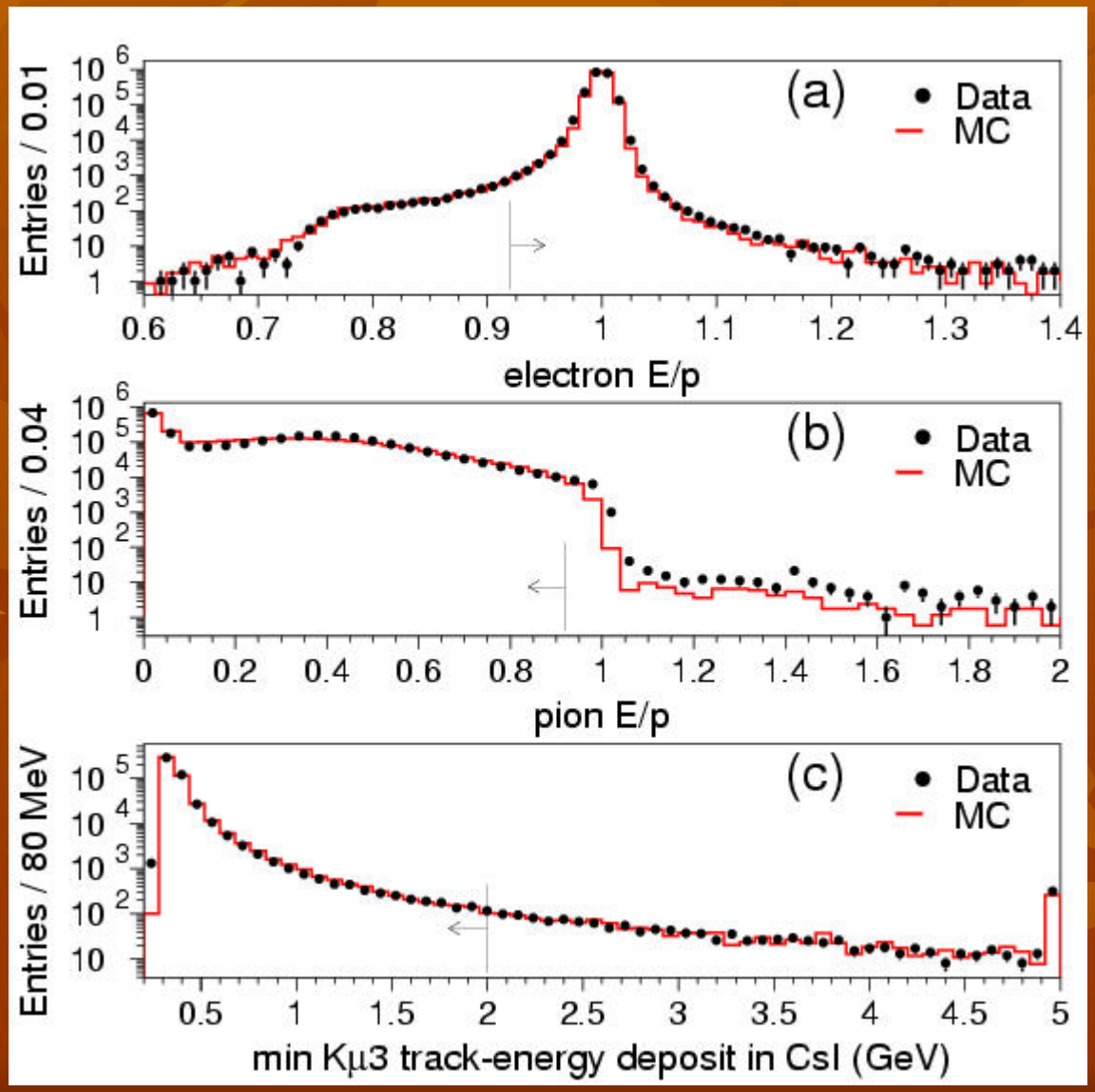
KTeV Detector at Fermilab



- Ignore regenerator (K_S) beam
- Track momentum resolution < 1% (above 8 GeV/c) and momentum scale known to 0.01% using $K \mapsto \pi^+\pi^-$
- CsI energy resolution < 1% (E_γ > 3 GeV) and energy scale known to 0.1% using Ke3 electrons.

Particle Identification

Energy response tails measured in data, and modeled in Monte Carlo simulation.



BRs Include Radiated Photons !

- $K_{e3(\gamma)}+K_{\mu 3(\gamma)}$ M C generator (KLOR) written by U. Chicago student T.Andre (advisor: J.Rosner). Includes virtual and real photons.

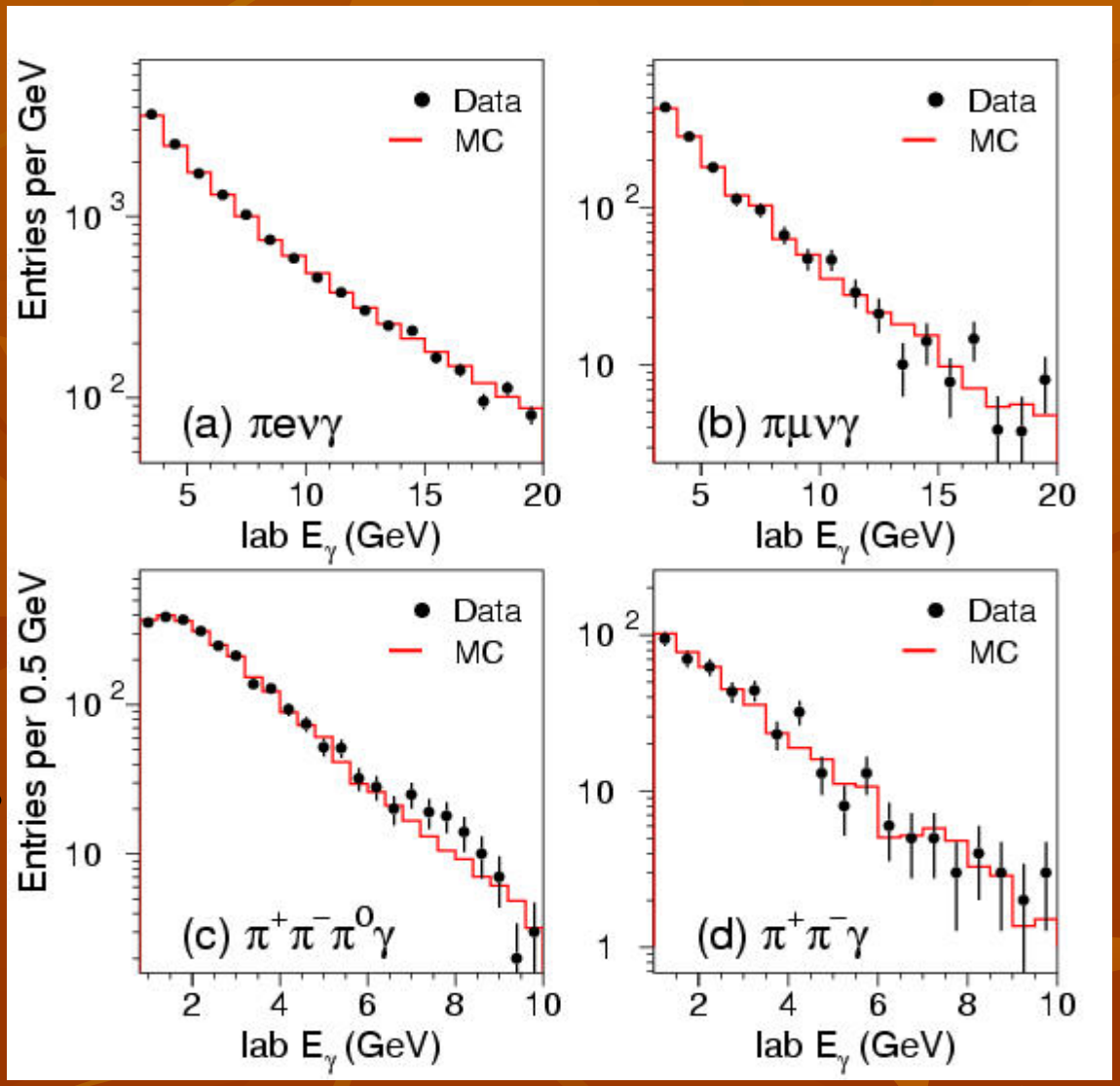
  KLOR: Kaon Leading Order Radiation

- $K_{+-0(\gamma)}$ MC generator uses PHOTOS.
- $K_{+-(\gamma)}$ MC generator includes IB.

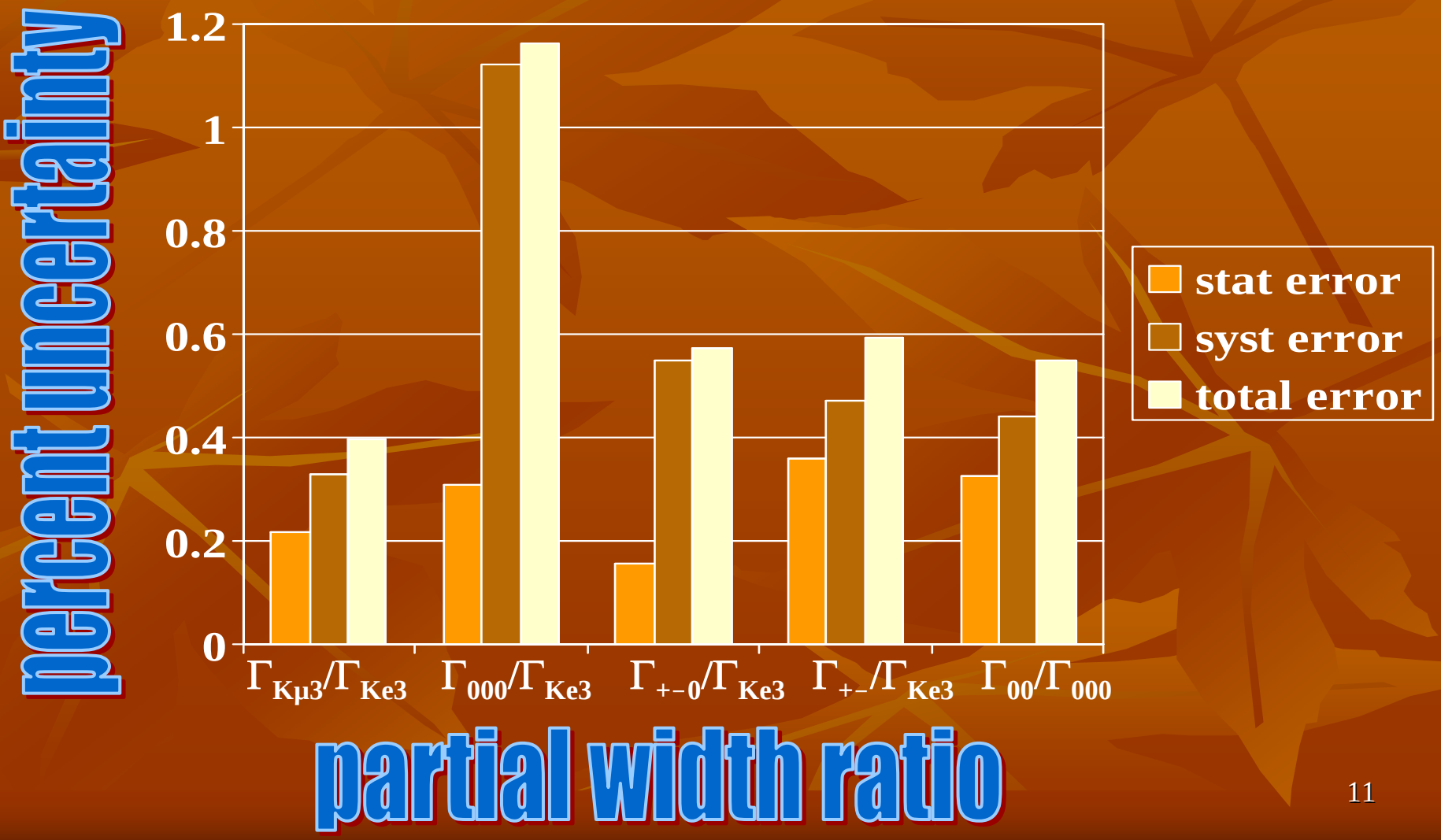
- Radiation changes K_{e3} acceptance by 3%;
- Effect on other modes is < 0.5%

Radiative MC Check

data-MC comparison of lab E_γ (right) and rad-BRs agree well for all 4 charged modes.



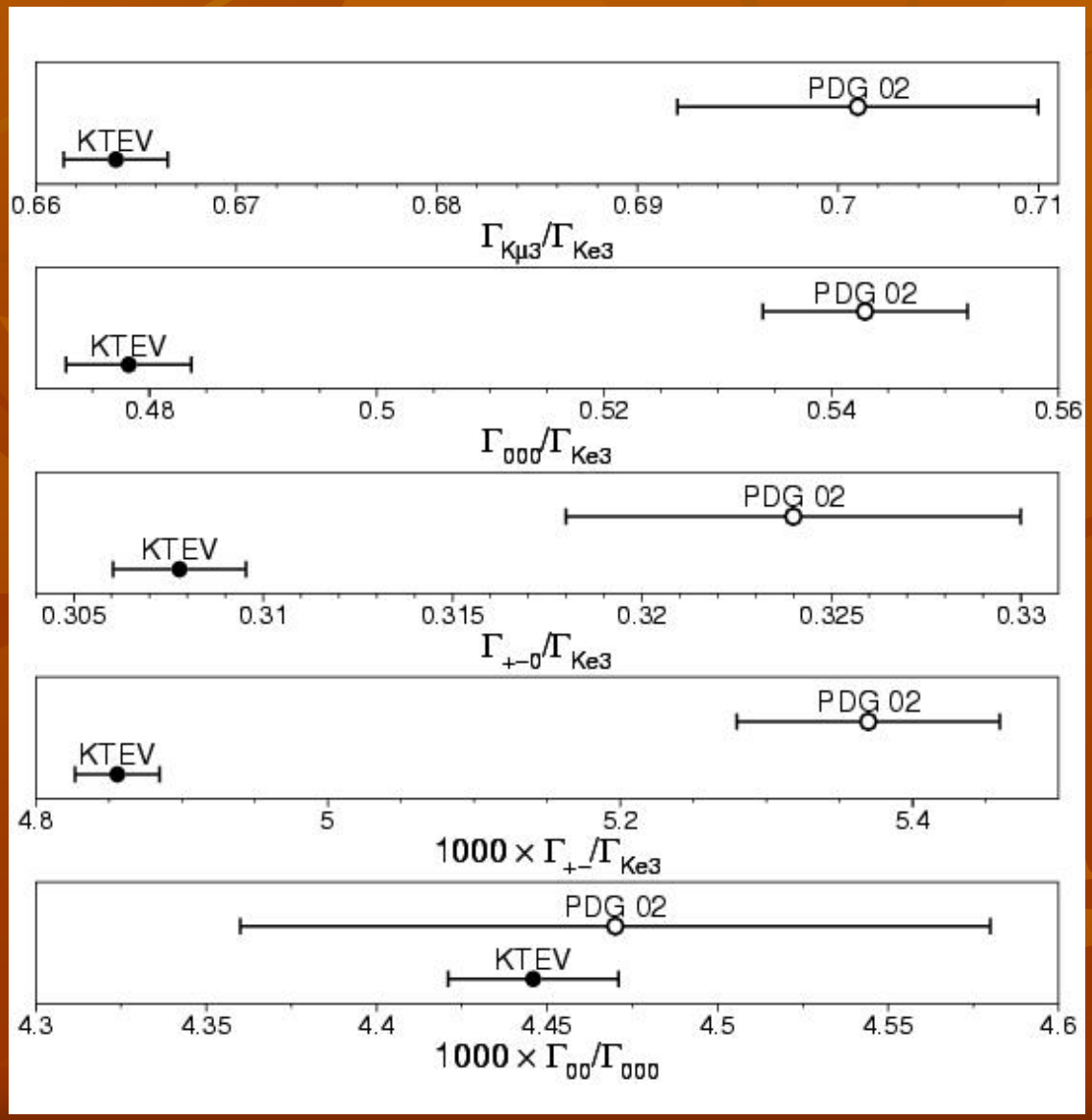
Uncertainties on Partial Width Ratios



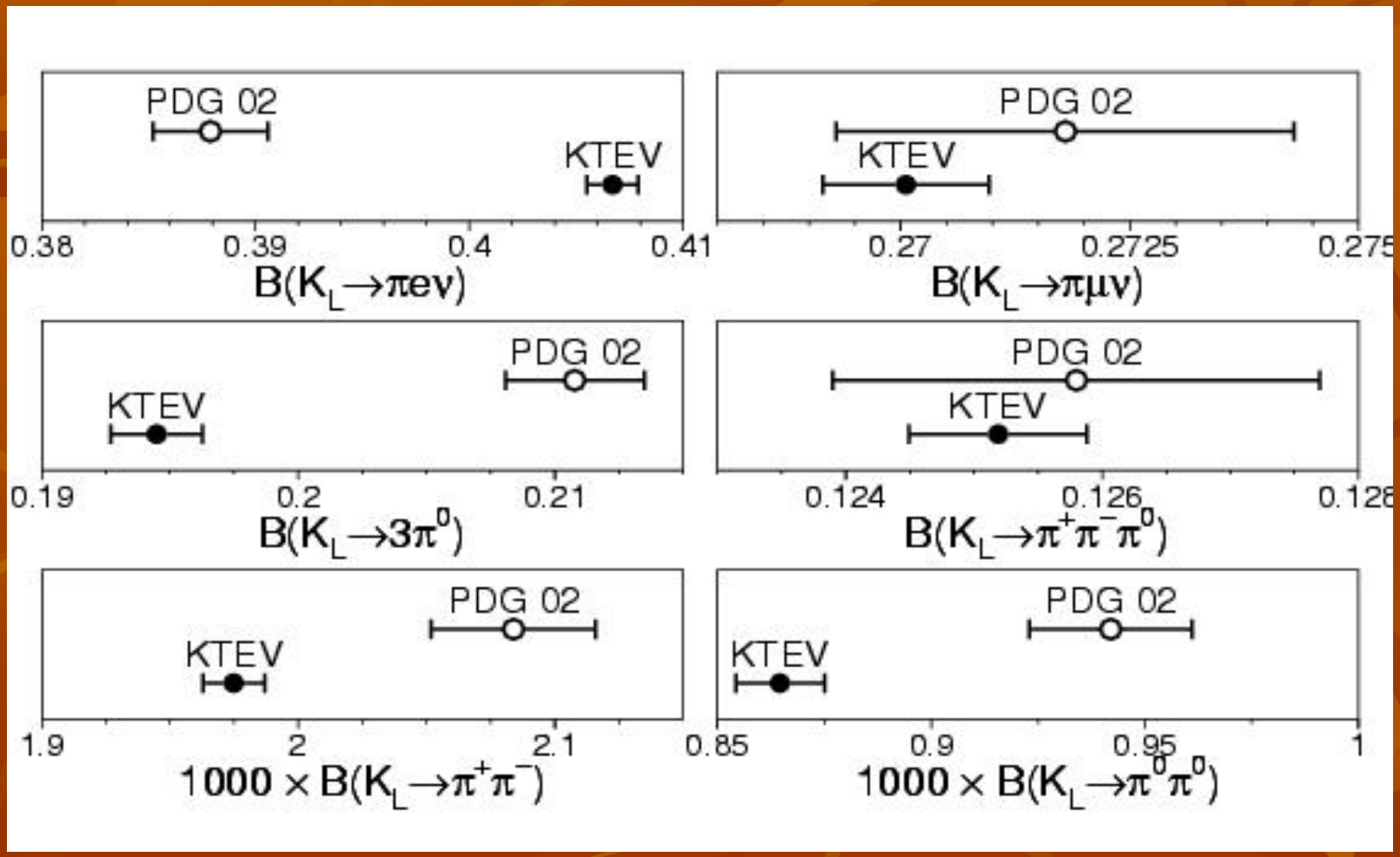
Partial Width Ratio Results

KTeV ratios with K_{e3} in denominator disagree with PDG.

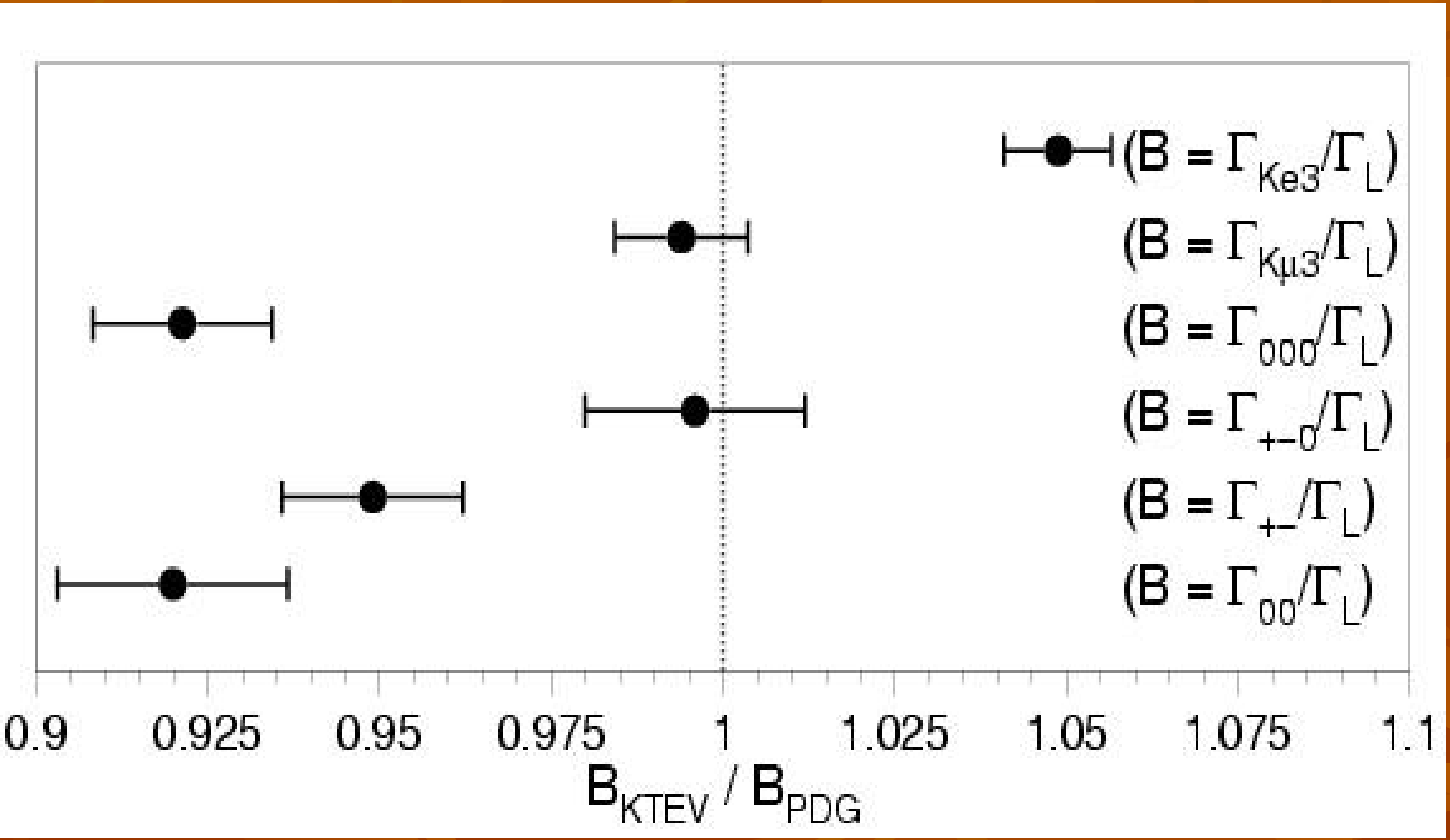
Only Γ_{00}/Γ_{000} agrees with PDG.



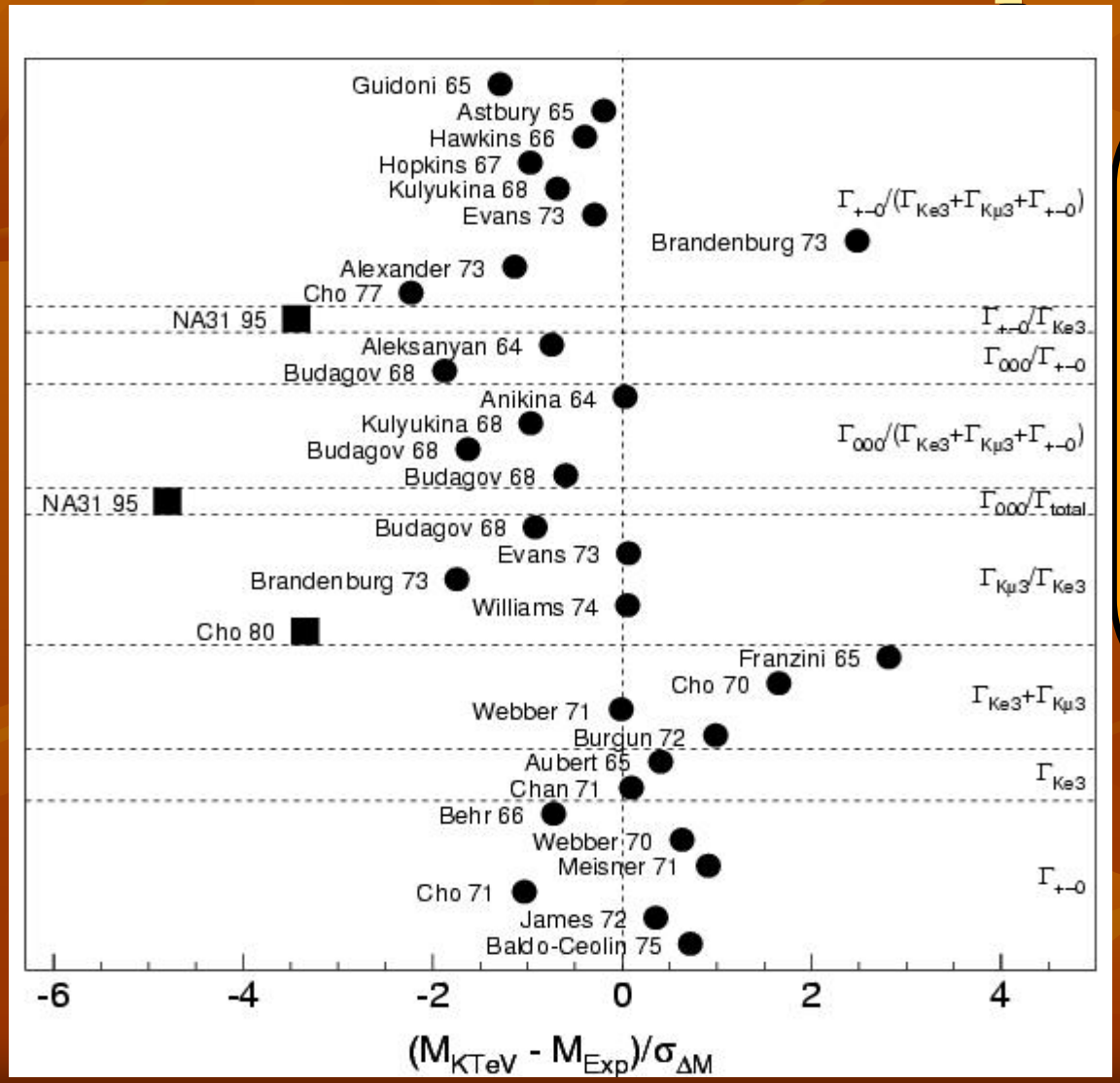
KTeV Branching Fractions assuming $\Sigma B = 0.9993$



KTeV/PDG Ratios



KTeV Comparison with Individual Experiments



M_{KTeV} = KTeV measurement

M_{exp} = measurement from previous experiment

Aside: CP Violation Parameter $|\eta_{+-}|$ Determined from KTeV Branching Fractions

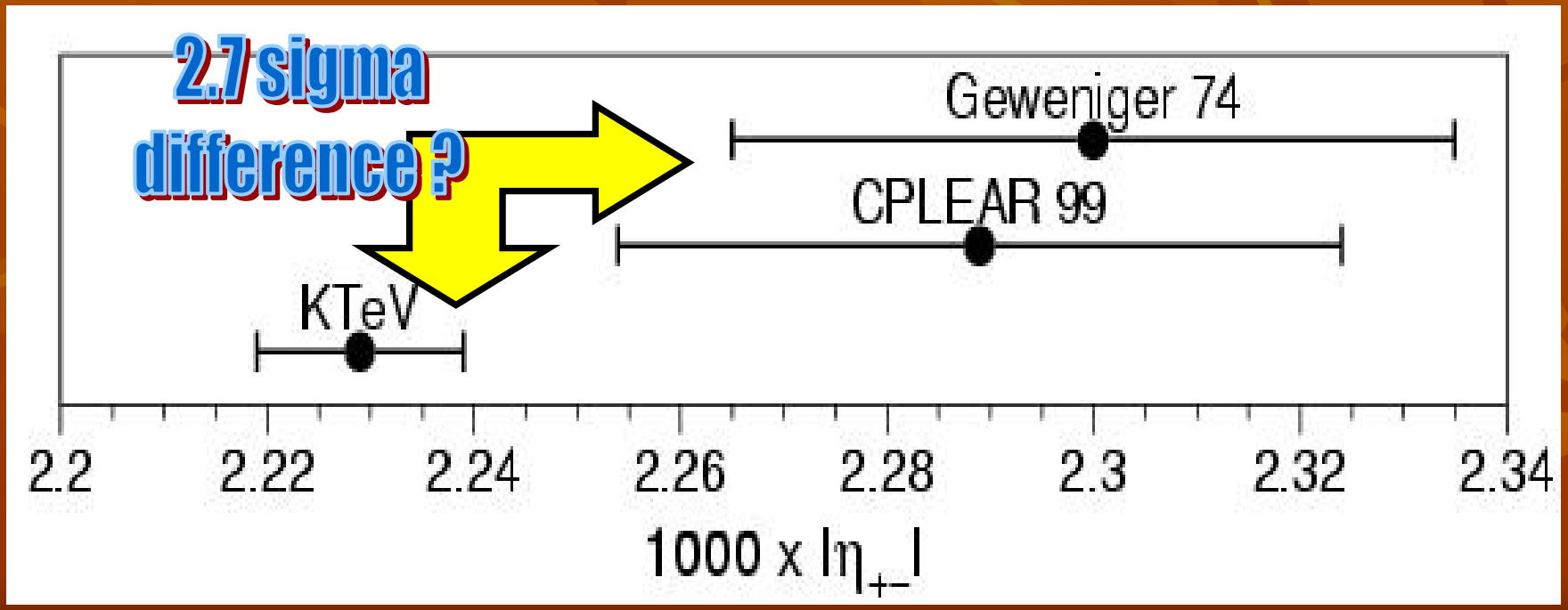
KTeV 2π BRs

$$|\eta_{+-}|^2 = \frac{\Gamma_L}{\Gamma_S}\left\{\frac{B^L_{\pi^+\pi^-} + B^L_{\pi^0\pi^0}[1 + 6Re(\epsilon'/\epsilon)]}{1 - B^S_{\pi\ell\nu}}\right\}$$

K_L and K_S lifetimes

K_S semileptonic BR: 0.12%

Compare KTeV $|\eta_{+-}|$ with previous results using K_L-K_S interference [independent of KTeV-PDG discrepancy in $B(K_L \to \pi\pi)$]



Semileptonic Form Factors (to determine I_K integrals)

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1 + \delta_K^\ell) \, |V_{us}|^2 \, |f_+^2(0)| I_K^\ell$$

Parametrization:

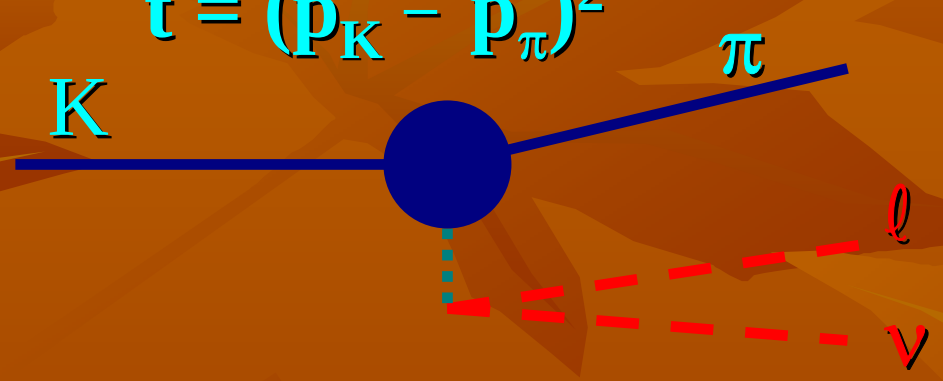
$$f_+(t) = f_+(0) \left[1 + \lambda'_+ \frac{t}{M_\pi^2} + \frac{1}{2} \lambda''_+ \frac{t^2}{M_\pi^4} \right]$$

$$f_0(t) = f_+(0) \left[1 + \lambda_0 \frac{t}{M_\pi^2} \right]$$

where $t = (P_K - P_\pi)^2$

Semileptonic Form Factors: Method

$t = (p_K - p_\pi)^2$



* Kinematic ambiguity => two possible t-values

*To avoid ambiguity, compute "$t_\perp$" using only transverse quantities:

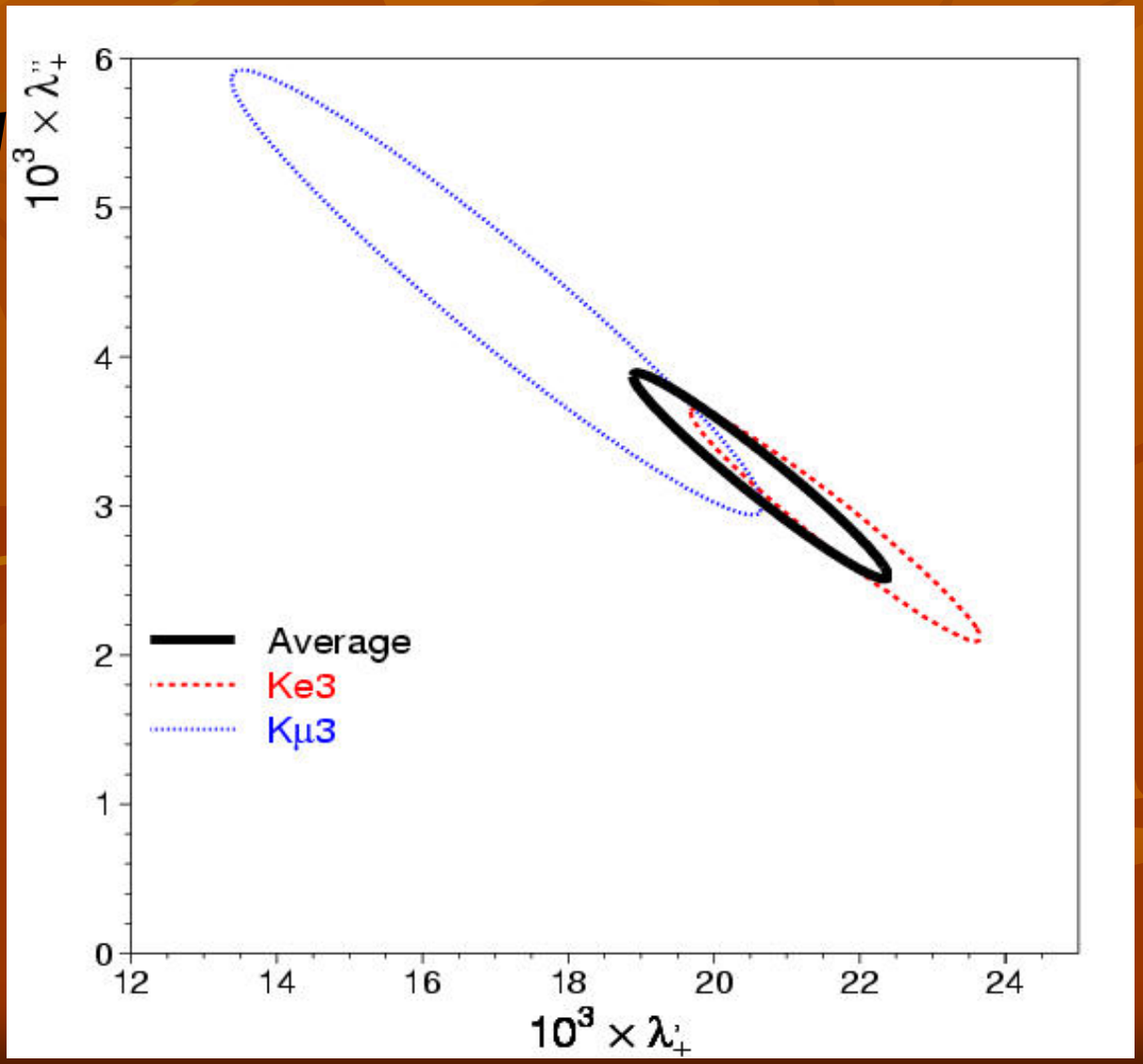
$\vec{p}_K \mapsto \vec{p}_{K,\perp} = 0$ (defines transverse)

$\vec{p}_\pi \mapsto \vec{p}_{\pi,\perp}$ (invariant under K boost)

Semileptonic Form Factors: λ_+' and λ_+''

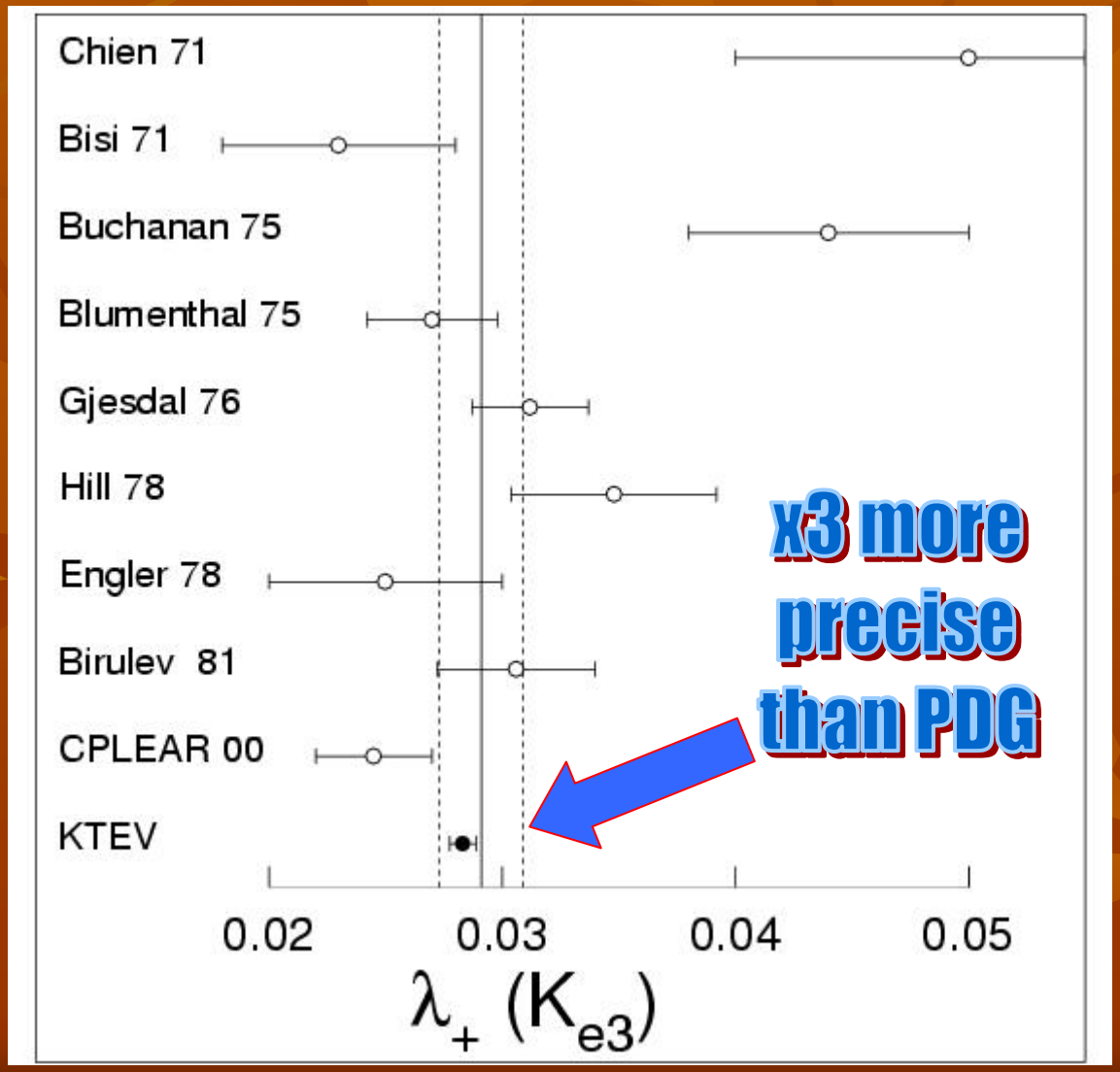
NEW!

λ_+'' has 4σ significance !



λ_+ Comparisons for linear $f_+(t)$

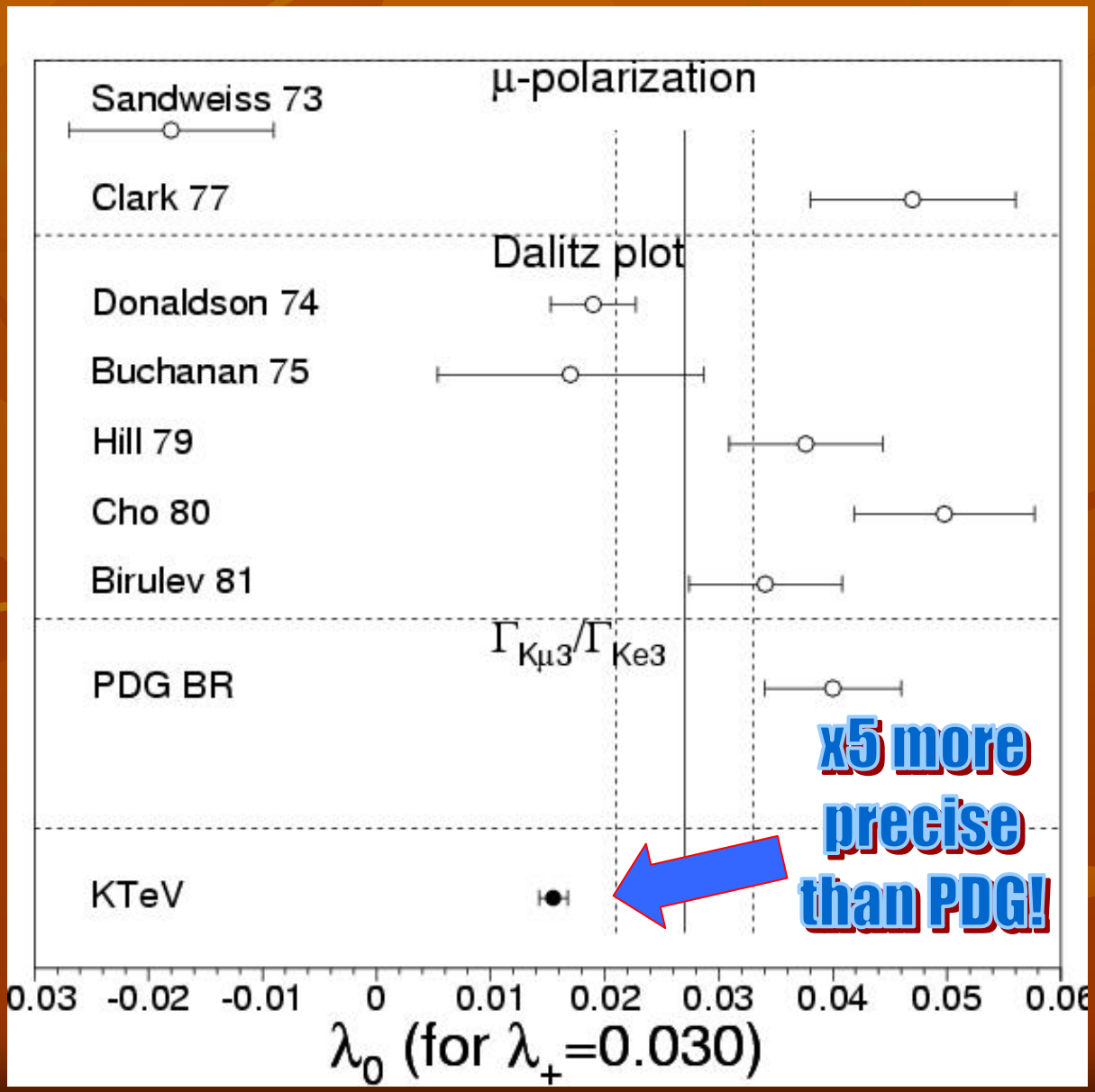
Ignore 2nd order term in KTeV to compare with previous measurements



λ_0 Comparisons with $\lambda_+ = 0.030$

KTeV λ_0 agrees with only 2 of 8 previous measurements.

(see our paper for nominal λ_0 result)



I_K Uncertainty from Semileptonic Form Factors

- we include 0.7% uncertainty from model dependence (doubles error!).

$$\frac{I_K(\text{quadratic: } \chi^2/\text{dof}=62/64)}{I_K(\text{pole model: } \chi^2/\text{dof}=66/65)} - 1 = 0.7\%$$

- Although KTeV form factors are much more precise than PDG, KTeV I_K uncertainty is comparable to PDG uncertainty based on linear FF model.
- small effect on $I_{K\mu 3}/I_{Ke3}$ ratio.

Lepton Universality Test with Semileptonic Branching Fractions and Form Factors

Long-distance rad cor ratio from KLOR is 1.0058(10)

KTeV measures 0.6622 +- 0.0018

$$[\Gamma_{K\mu 3}/\Gamma_{Ke3}]_{\rm pred} = \frac{1+\delta_K^\mu}{1+\delta_K^e} \cdot \frac{I_K^\mu}{I_K^e}$$

Note that $[\Gamma_{K\mu 3}/\Gamma_{Ke3}]_{KTeV}$ is 5% lower than PDG

Lepton Universality Test with Semileptonic Branching Fractions and Form Factors

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$$[\Gamma_{K\mu 3}/\Gamma_{Ke3}]_{\rm pred} = \frac{1+\delta_K^\mu}{1+\delta_K^e} \cdot \frac{I_K^\mu}{I_K^e}$$

$$\frac{[\Gamma_{K\mu 3}/\Gamma_{Ke3}]_{\rm KTeV}}{[\Gamma_{K\mu 3}/\Gamma_{Ke3}]_{\rm pred}} = 0.9969 \pm 0.0048$$

(same test with PDG BR+FF = 1.0270 ± 0.0182)

Summary of Vus Changes from KTeV

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1 + \delta_K^\ell) \, |V_{us}|^2 \, |f_+^2(0)| I_K^\ell$$

*Γ_{Ke3} : goes up by 5%

*$\Gamma_{K\mu 3}$:no significant change

*I^e goes down 1.7%

*I^μ goes down 4.2%

(each includes -1% shift from λ'')

Theory Corrections

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1 + \delta_K^\ell) \, |V_{us}|^2 \, |f_+^2(0)| I_K^\ell$$

short-distance rad cor: 1.022

long-distance rad cor from Andre,

δ^e = 1.013

δ^μ = 1.019

Leutwyler-Roos 84:

$f_+(0)$=0.961(8)

+ recent works …

KTeV |Vus| Result

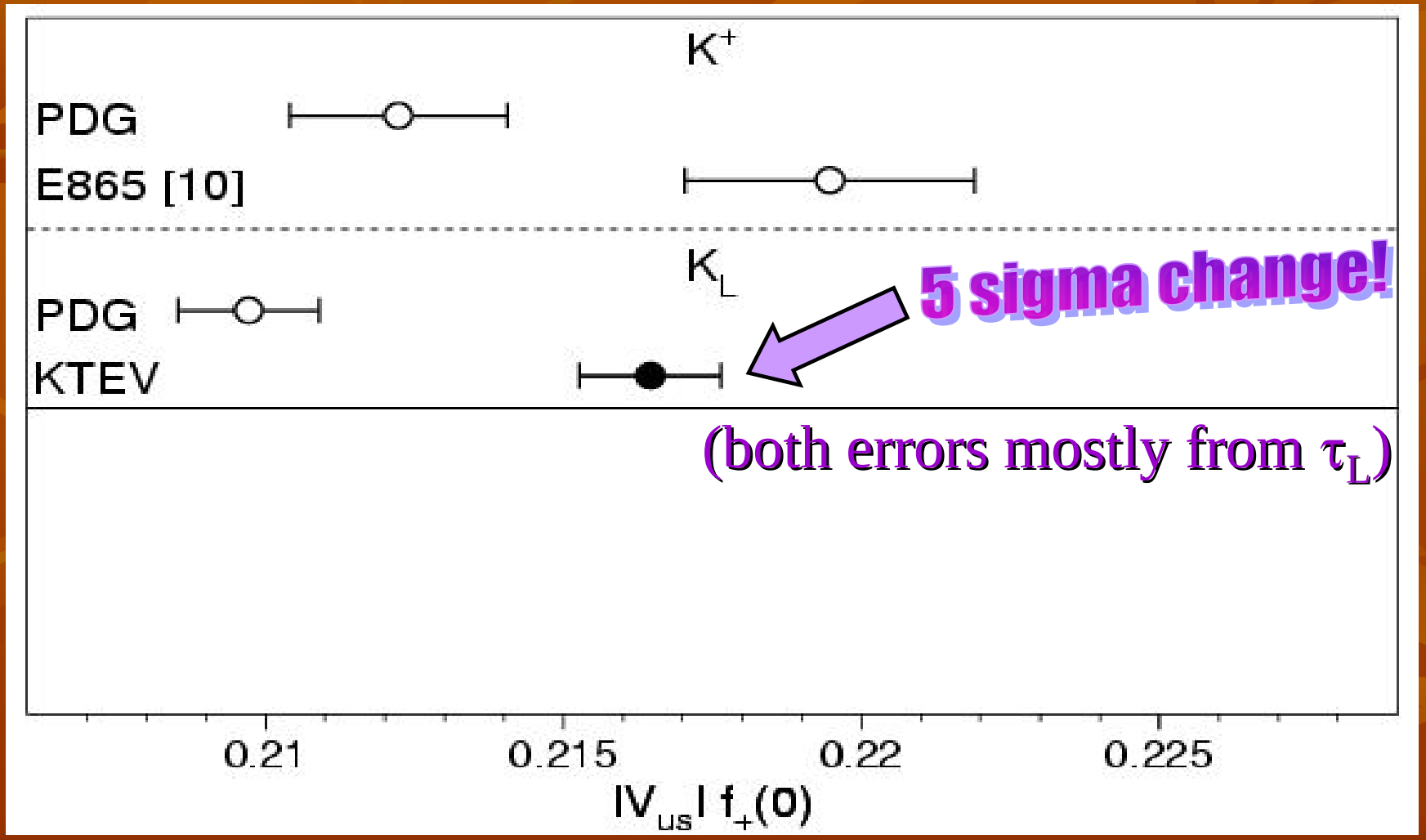
$$|V_{us}| f_+(0) = 0.2165 \pm 0.0012$$

$$|V_{us}| = 0.2252 \pm 0.0008_{KTeV} \pm 0.0021_{ext}$$

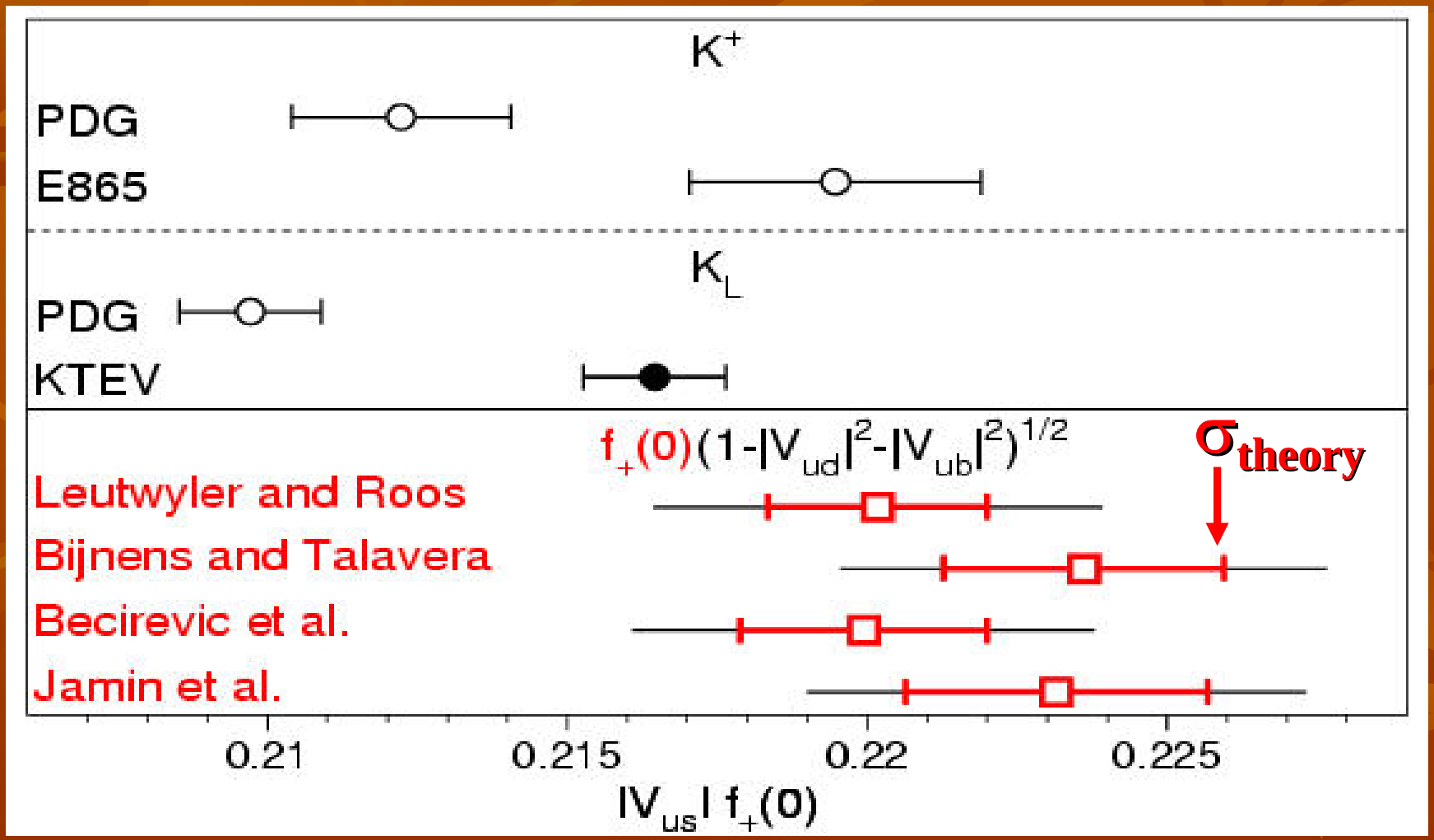
$\rightarrow \{f_+(0), \tau_L\}$

$$1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = 0.0018 \pm 0.0019$$

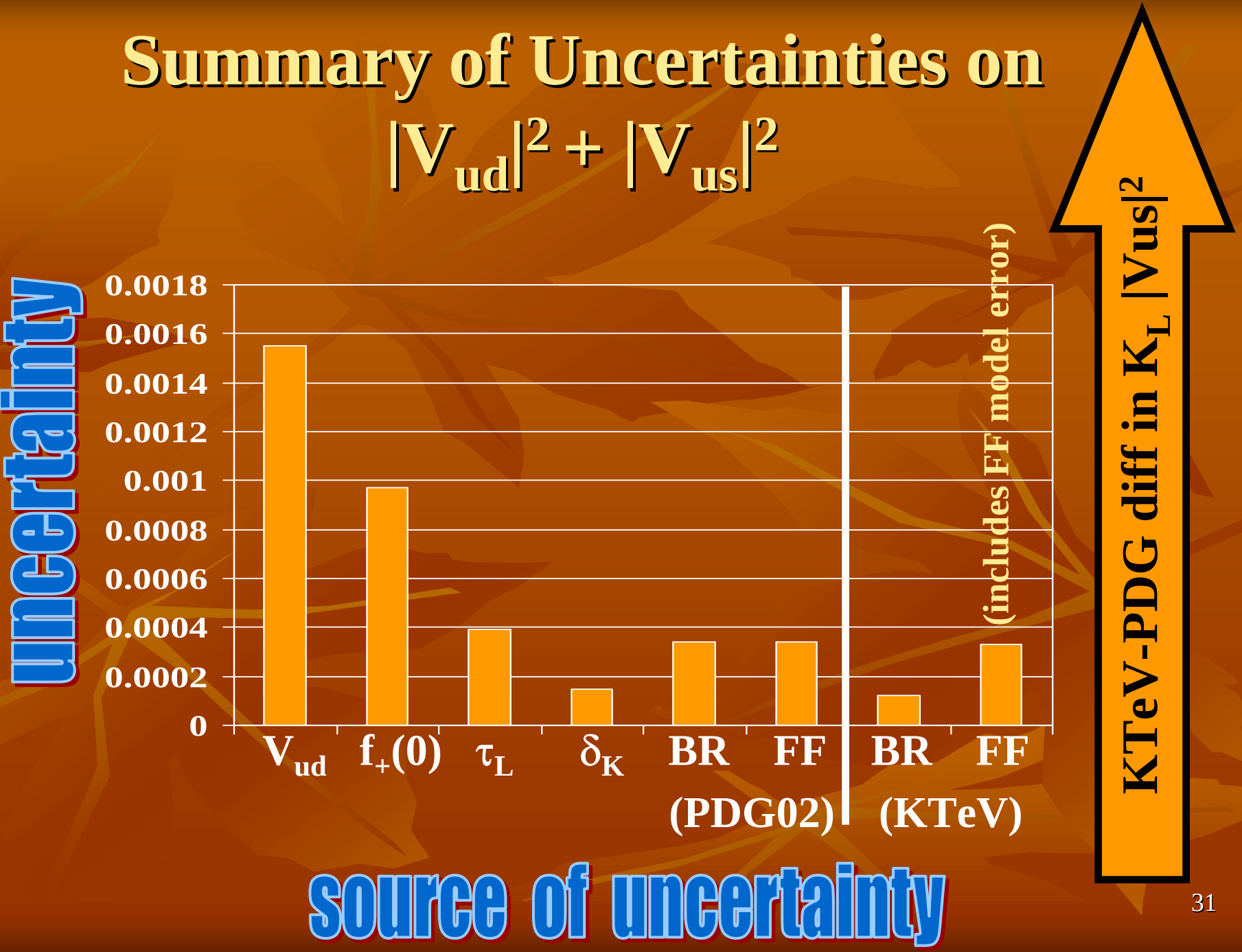
$|Vus|*f_+(0)$ Comparisons with Data



$|Vus|*f_+(0)$ Comparisons with Theory and $|V_{ud}|$



Summary of Uncertainties on $|V_{ud}|^2 + |V_{us}|^2$



Conclusions

- KTeV measurements result in +3% shift in |Vus| compared to PDG (from K_L decays); KTeV-PDG difference in K_L-|Vus| is 5σ !
- Our |Vus| value is consistent with unitarity.
- |Vus| from K^+ : PDG and recent BNL-E865 result are both consistent with KTeV |Vus| from K_L .
- Four of the six largest K_L branching fractions differ from PDG by 5-8% (also affects rare decays).
- Our $|\eta_{+-}|$ value is 2.6% lower than PDG.
- Improved form factors (FF) for Ke3 and Kμ3
- First detection of 2nd order term (λ'') in Kℓ3 FF.

KTeV Publications on Vus (see LANL archive)

Subject	Journal	Submit date
$\|V_{us}\|$	Phys. Rev. Lett	June 1, 2004
K_L BRs	Phys. Rev. D	June 1, 2004
Kℓ3 form factors	Phys. Rev. D	June 1, 2004

Supporting Publication

Kℓ3 Radiation (KLOR)	HEP archive	June 1, 2004