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

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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)

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

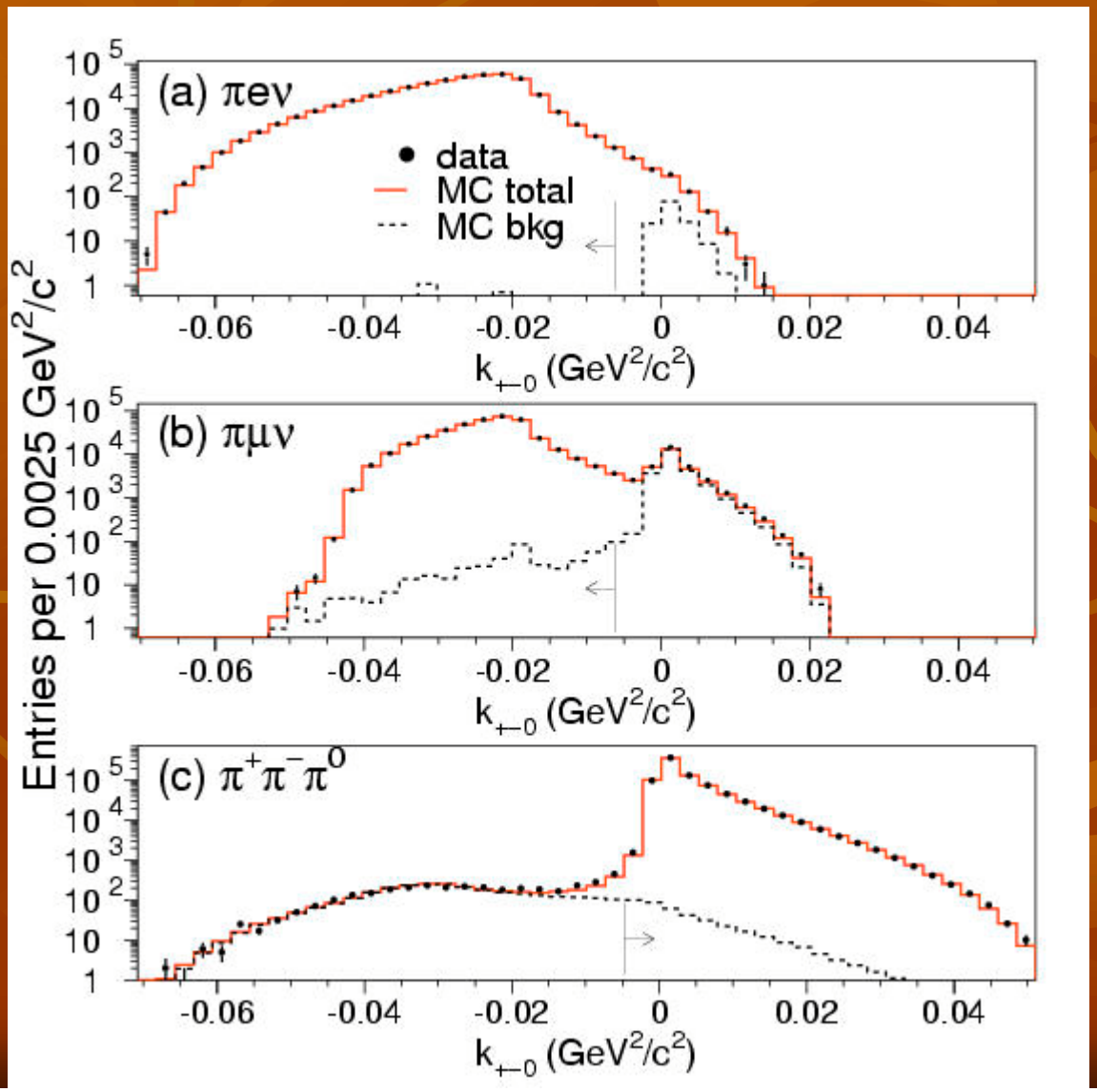
To determine the six main branching fractions, KTeV measures the following ratios of partial decay rates:

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

Ke3+Kμ3: 70% 3π: 30% 2π: 0.3%

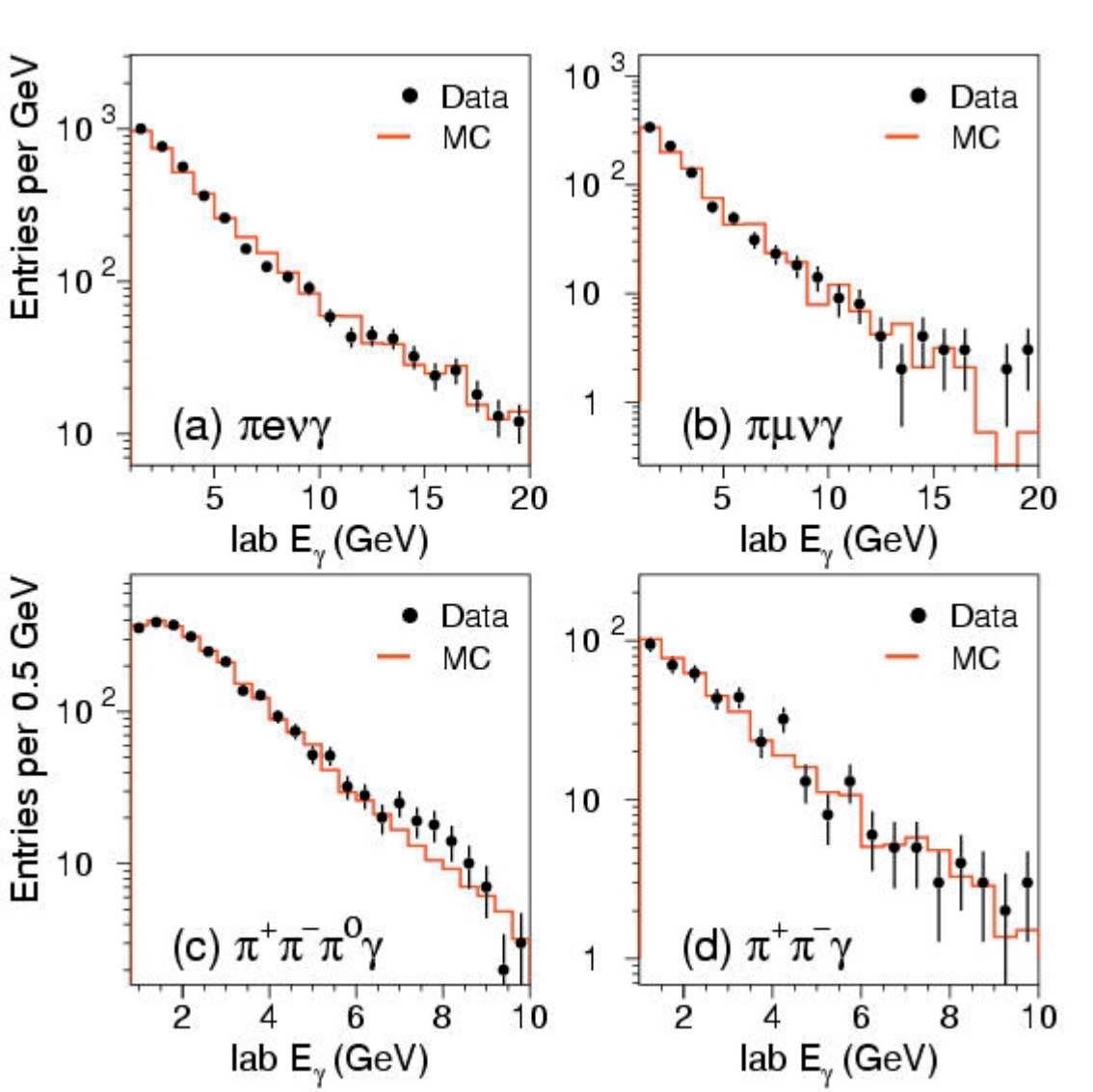
Sample sizes: 10^5 to 10^6

$k_{+\ell 0}$ for Partially Reconstructed Decays



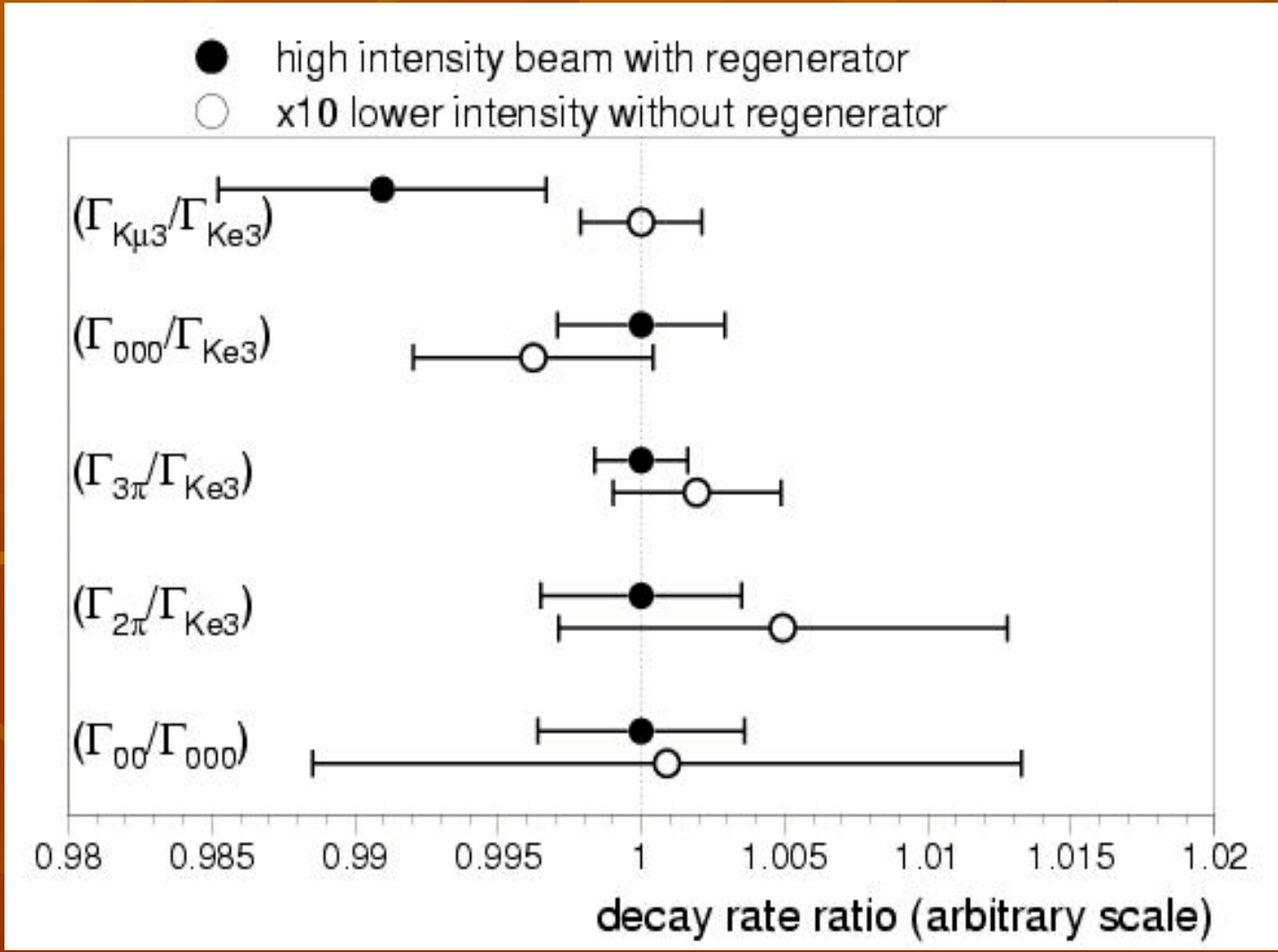
BRs Include Radiated Photons!

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



Beam Intensity Crosschecks

High vs. Low Intensity χ^2/ dof = 3.4/5



Analysis Crosschecks

- K_L ✪ $\pi^+\pi^-\pi^0$ yield without/with π^0 ✪$\gamma\gamma$ detection in CsI agree to (0.03 ✂ 0.28)%

- $K_{\mu 3}$ yield without/with μ system agree to 0.06%

Main Systematic Uncertainties

- $3\pi^0$/Ke3 ratio :

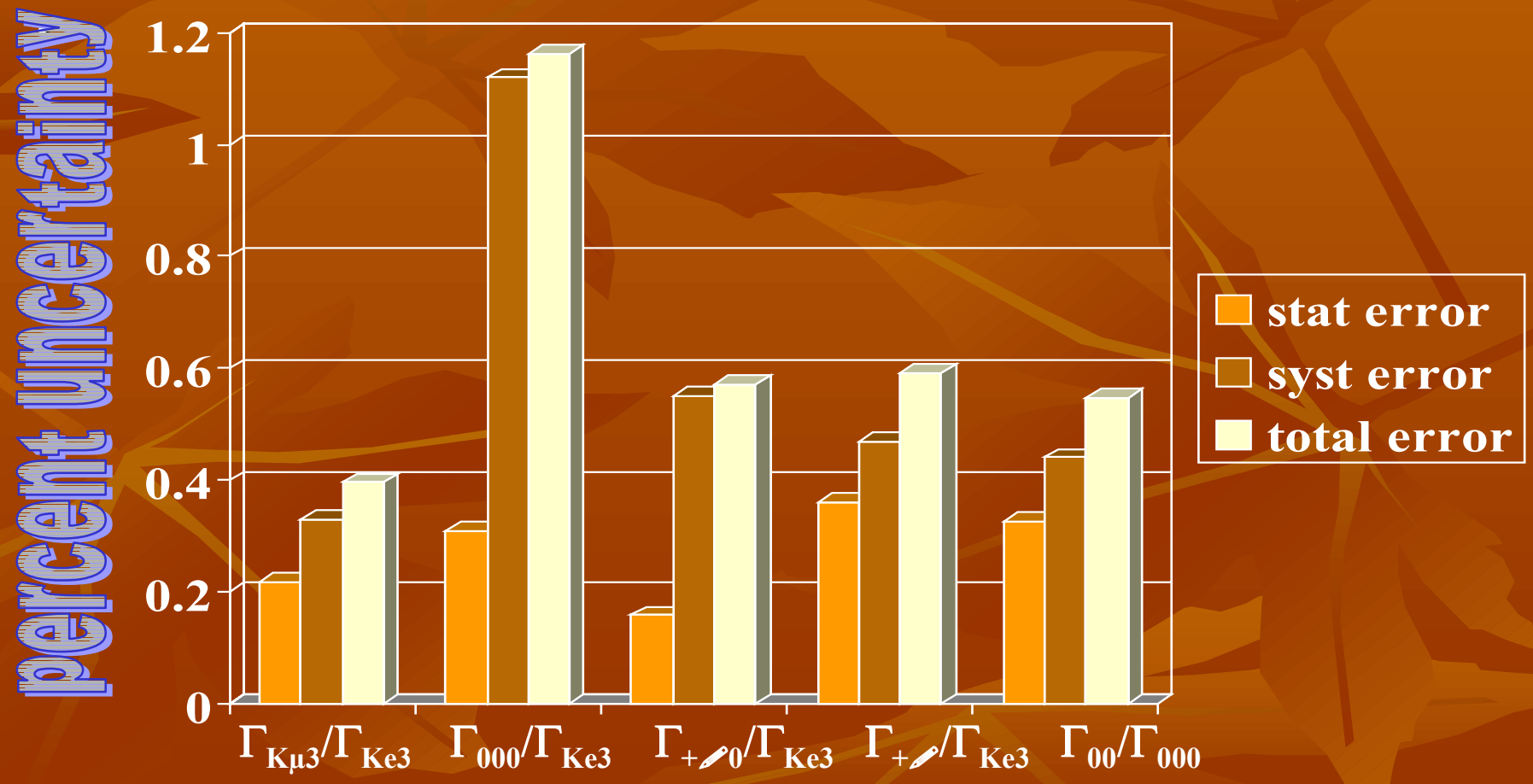
  => 0.6% two-track efficiency uncertainty

  => 0.4% uncertainty in $3\pi^0$ recon

  => 0.6% uncertainty from detector material
- 0.35% uncertainty in loss from π-interactions

  (affects ratios with different # of charged π)

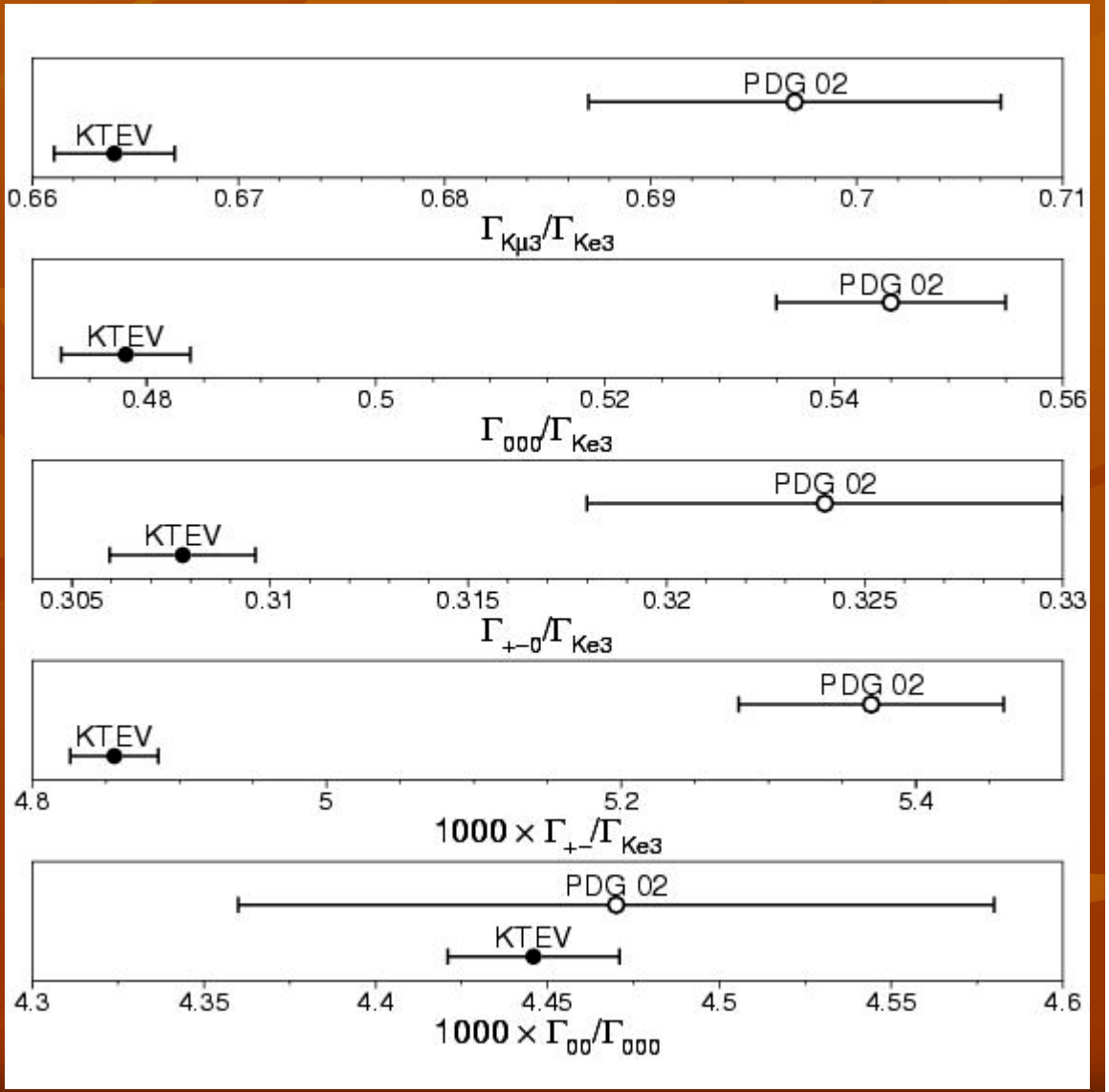
Uncertainties on Partial Width Ratios



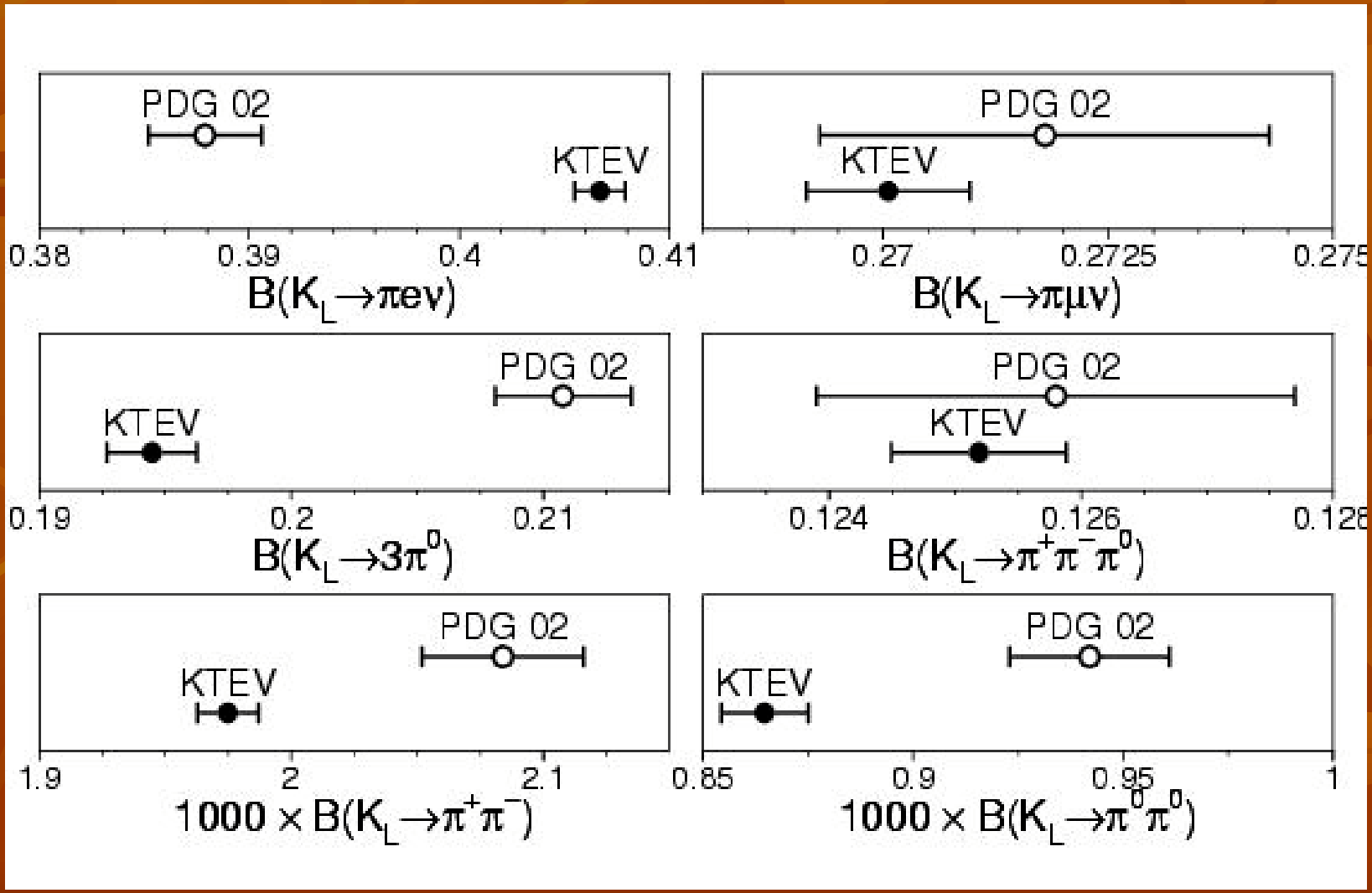
Partial Width Ratio Results

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

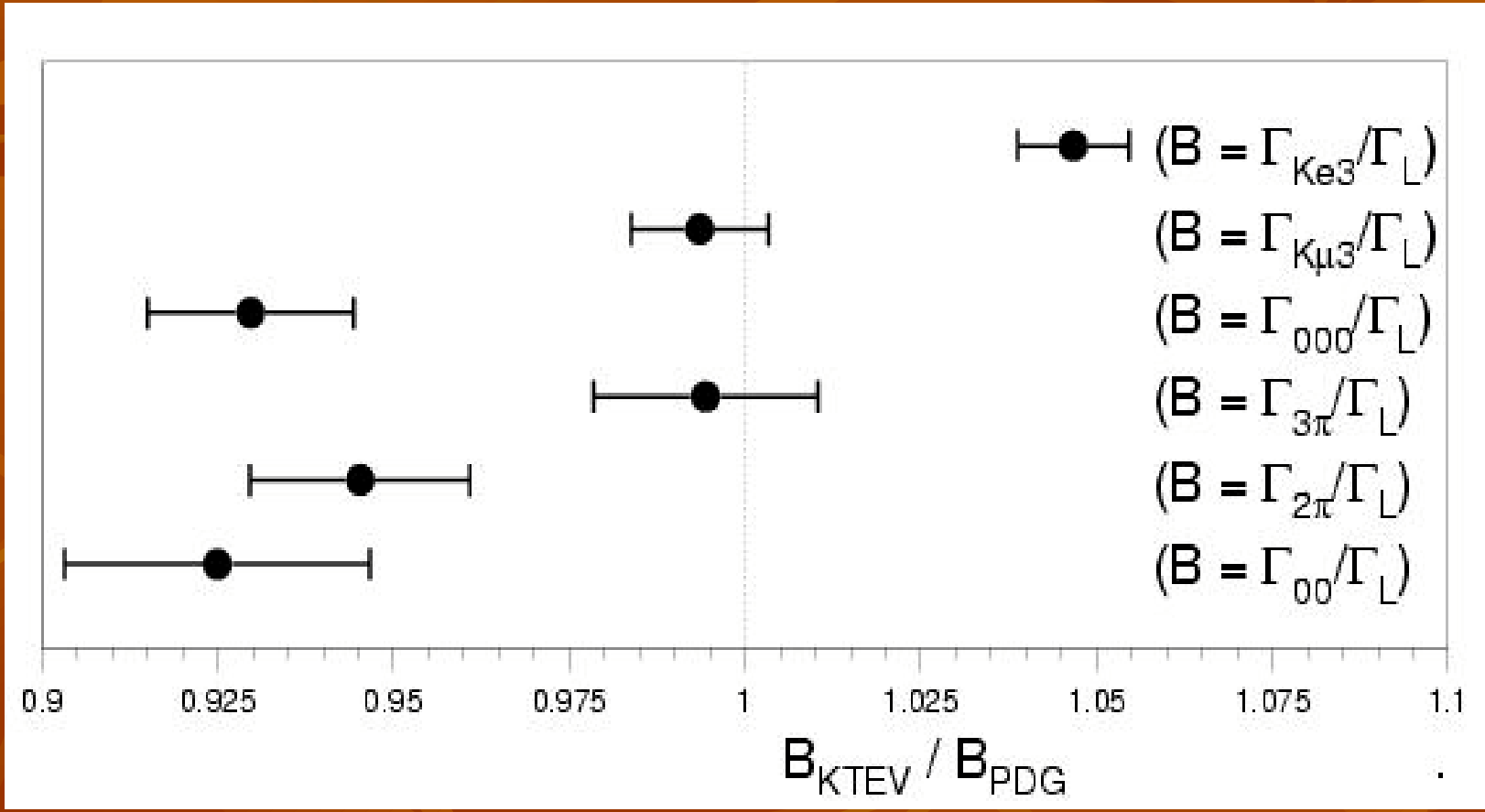
Only $\Gamma(2\pi^0)/\Gamma(3\pi^0)$ agrees with PDG.



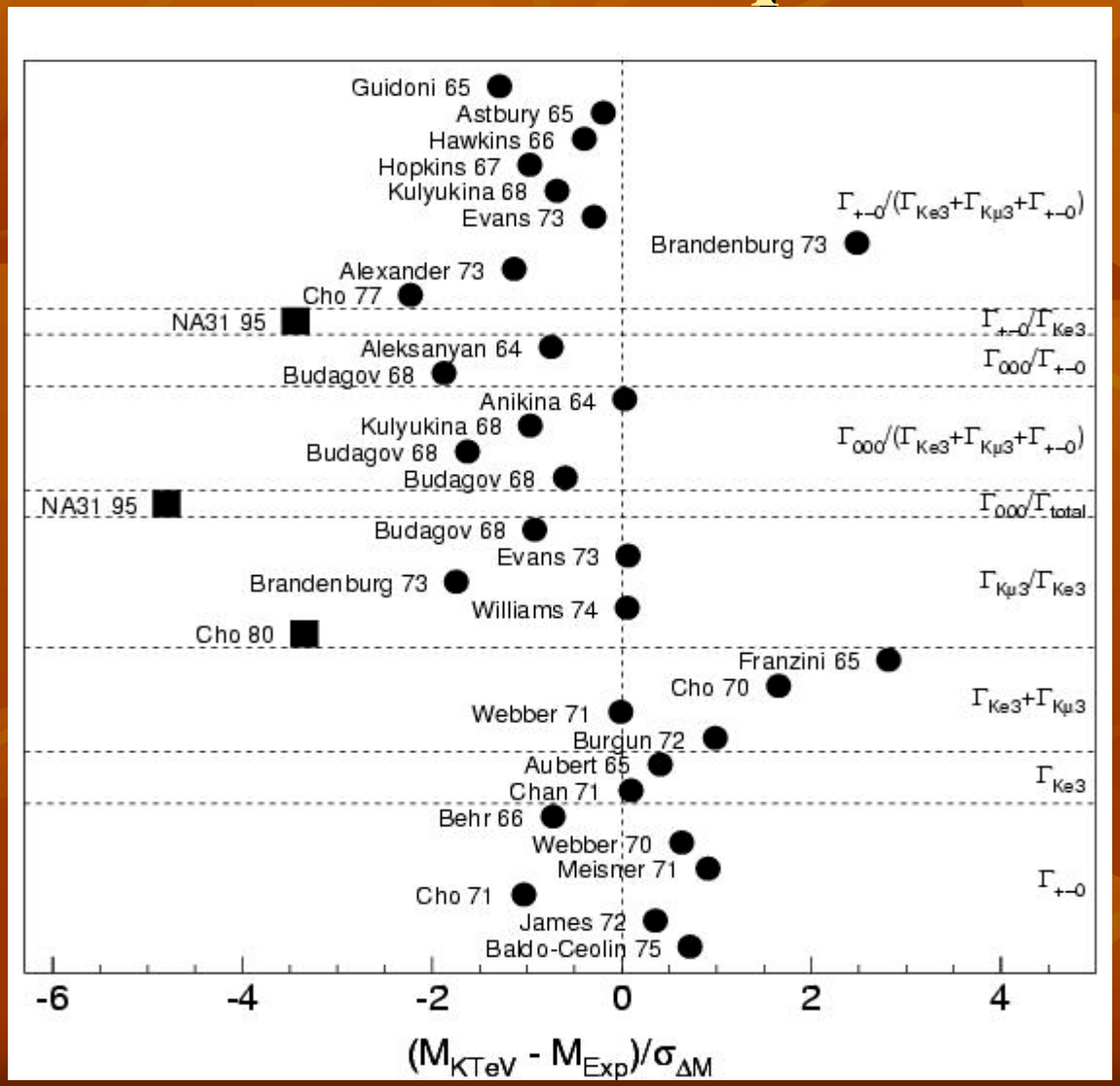
KTeV Branching Fractions assuming $\Sigma B = 0.9993$



KTeV/PDG Ratios



Comparison with Individual Experiments



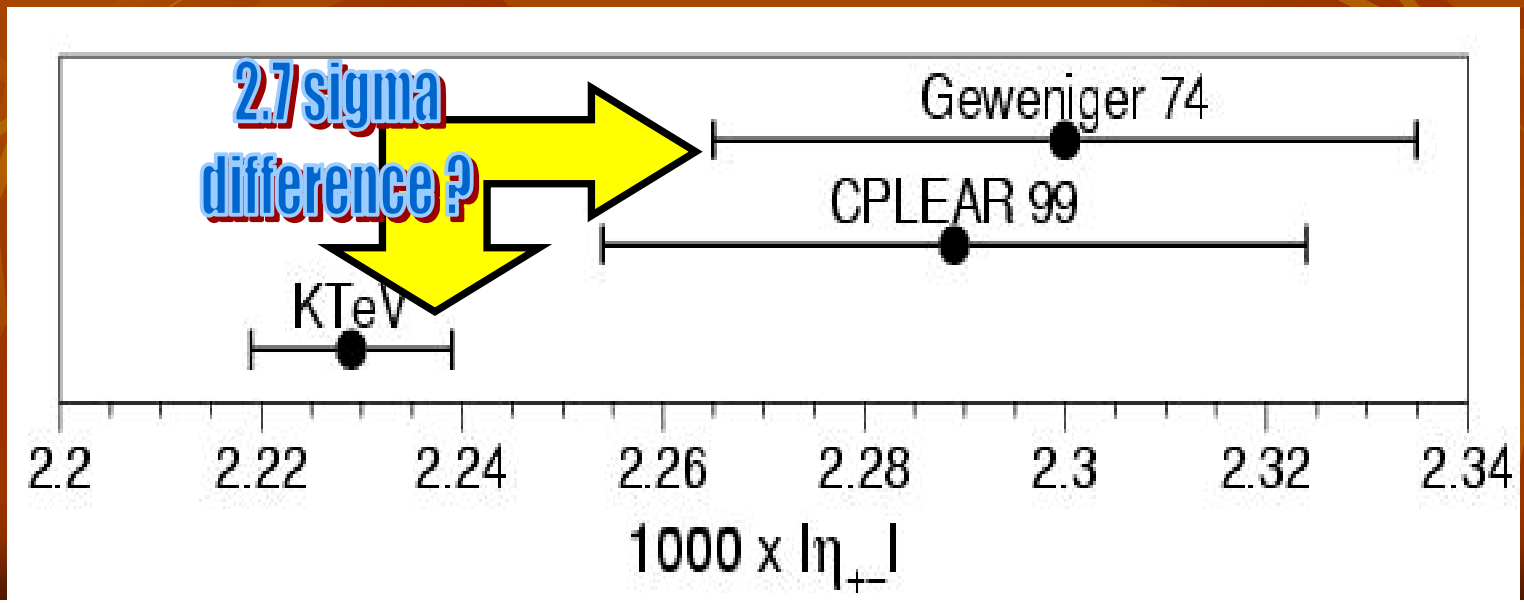
M_{KTeV} = KTeV measurement

M_{exp} = measurement from previous experiment

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

KTeV 2π BRs

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



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:

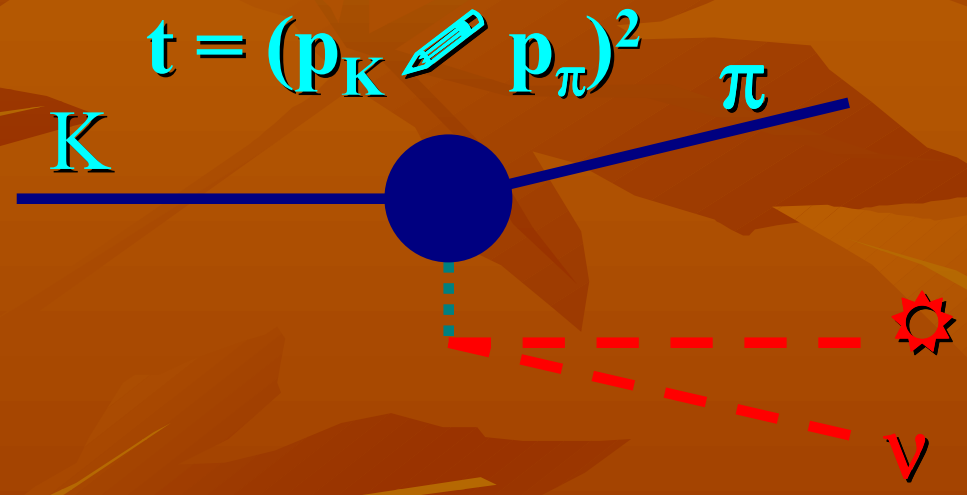
$$f_+(t) = f_+(0) \left[1 + \lambda'_+ \frac{t}{M_\pi^2} + \frac{1}{2} \lambda''_+ \frac{t^2}{M_\pi^4} \right]$$

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

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.

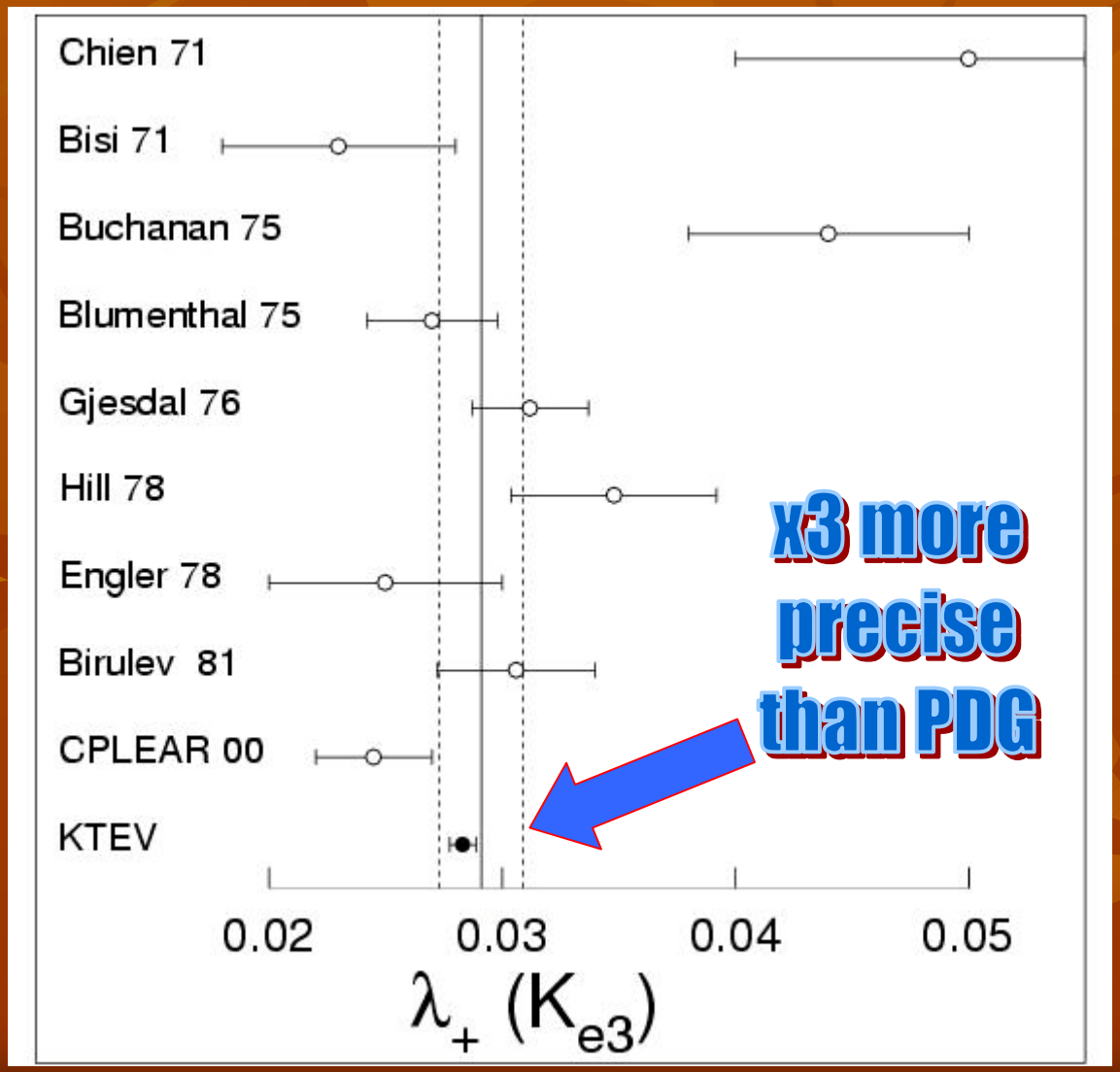
Semileptonic Form Factors

Form Factor Parameter	Value ($\times 10^{-3}$)
λ_+'	20.64 ± 1.75
λ_+''	3.20 ± 0.69
λ_0	13.72 ± 1.31

NEW !

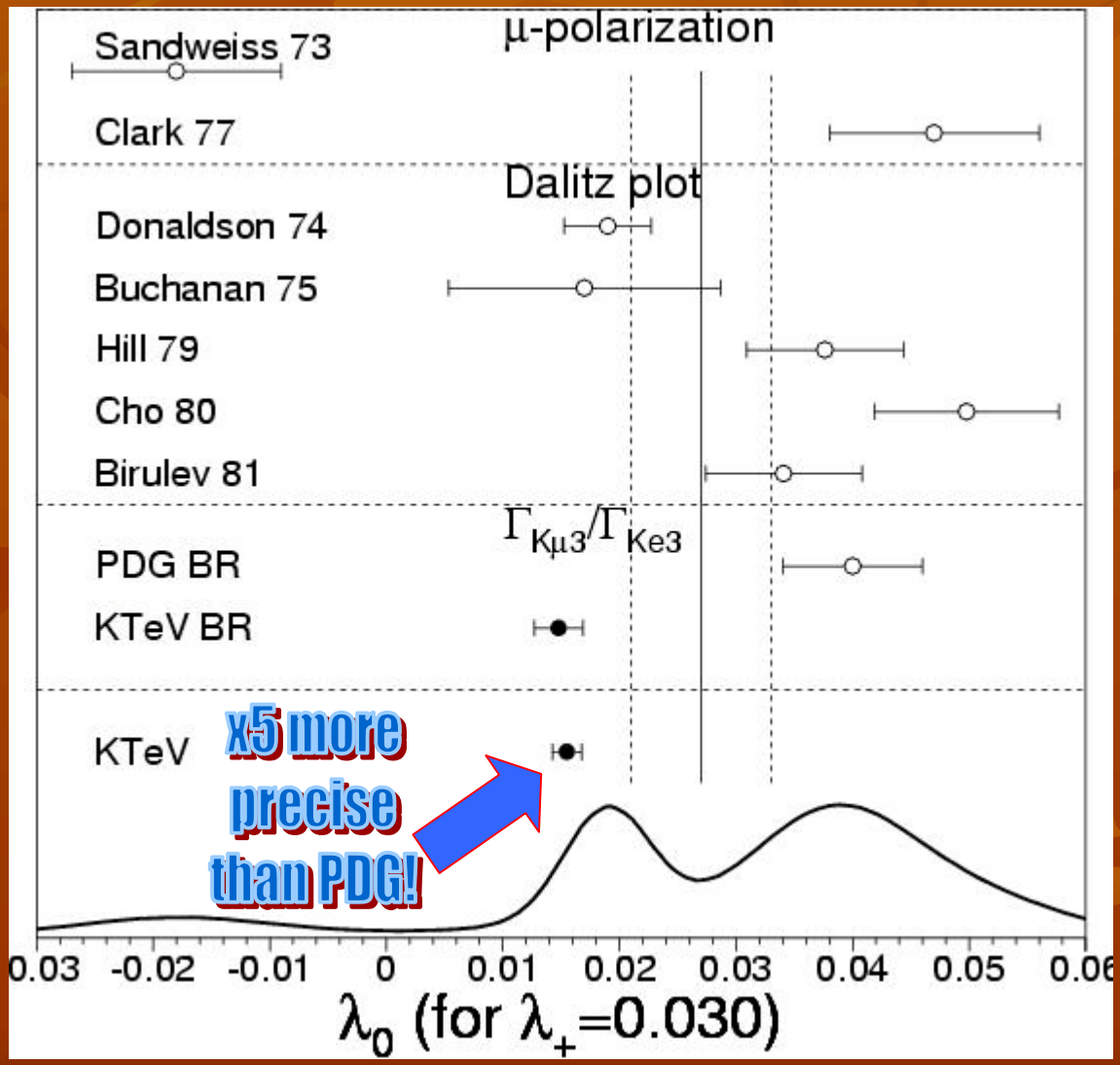
Semileptonic Form Factors

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



Semileptonic Form Factors

KTeV λ_0 agrees with only 2 of 8 previous measurements.



Lepton Universality Check with Semileptonic Branching Fractions and Form Factors

Long-distance rad corrections:

Andre calculates ratio

to be 1.0058(10)

KTeV measures

0.6622 +- 0.0017

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

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

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,

$\delta^e = 1.013$

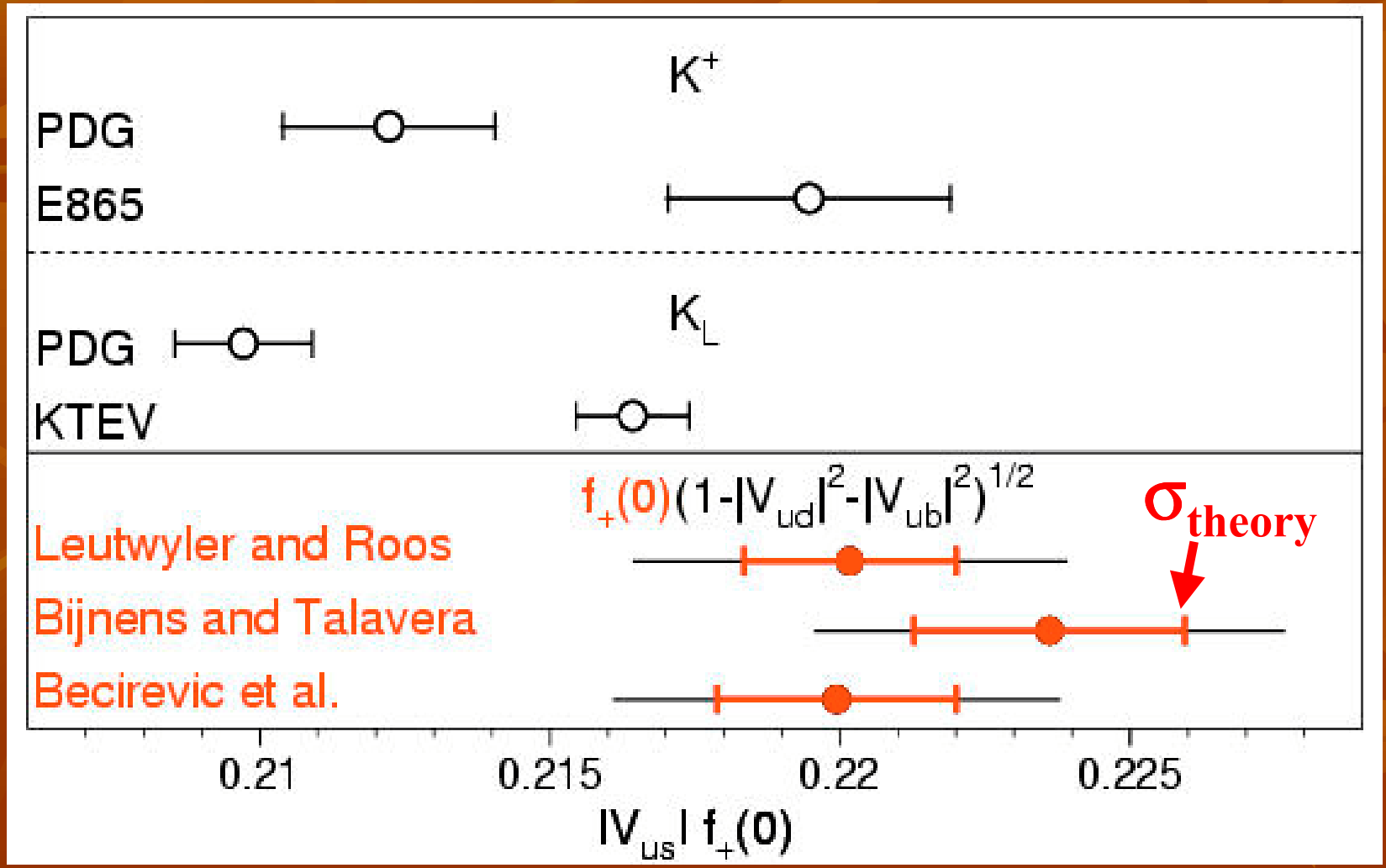
$\delta^\mu = 1.019$

Leutwyler-Roos 84:

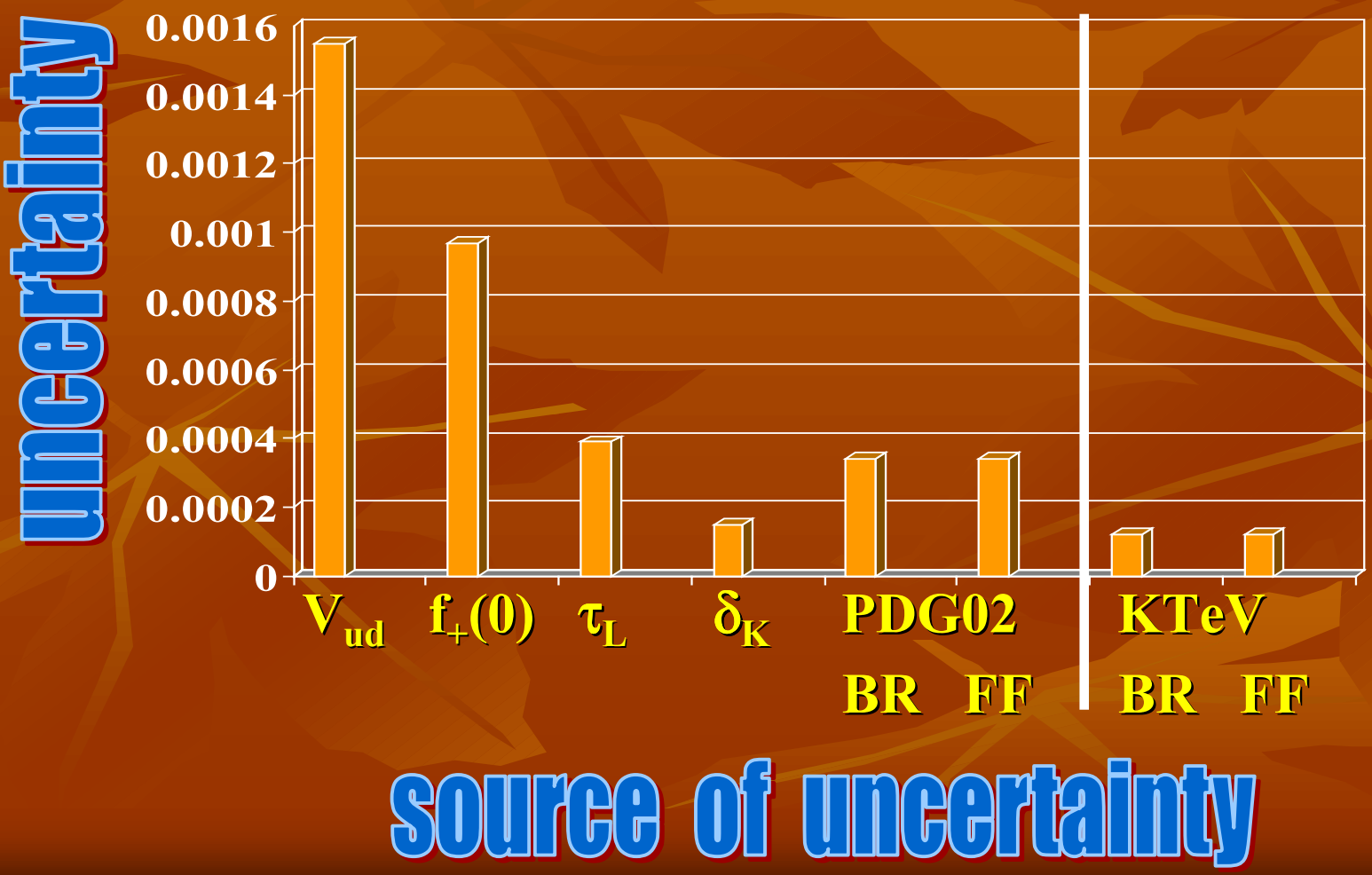
$f_+(0)=0.961(8)$

+ recent works …

$|V_{us}|*f_+(0)$ Results and Comparisons



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



KTeV-PDG diff in K_L $|V_{us}|^2$

Conclusions

- KTeV measurements result in +3% shift in |Vus| compared to PDG (from K_L decays);
- Our |Vus| value is consistent with unitarity and also consistent with BNL-E865.
- Four of the six largest K_L branching fractions differ from PDG by 5-7%.
- Our $|\eta_{+-}|$ value is 2.6% lower than PDG.
- First detection of 2nd order term (λ'') in t-dependence of semileptonic form factor.
- To improve $|Vud|^2 + |Vus|^2$ unitarity test:

  => more precise |Vud|

  => better theoretical treatment of $f_+(0)$.

  => more precise τ_L

KTeV Publications on Vus

Subject	Journal	Submit date
$\|V_{us}\|$ overview	Phys. Rev. Lett	June ? 2004
K_L BRs	Phys. Rev. D	June ? 2004
K✡3 form factors	Phys. Rev. D	June ? 2004

Supporting Publication

K✡3 Radiative Corrections	HEP archive	June ? 2004