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

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Precision of CKM Unitarity Tests

			Uncertainty on $\Sigma_j \, \lvert V_{ij} \rvert^2$
Vud	Vus	Vub	<0.2%
Vcd	Vcs	Vcb	2.7%
Vtd	Vts	Vtb	30%

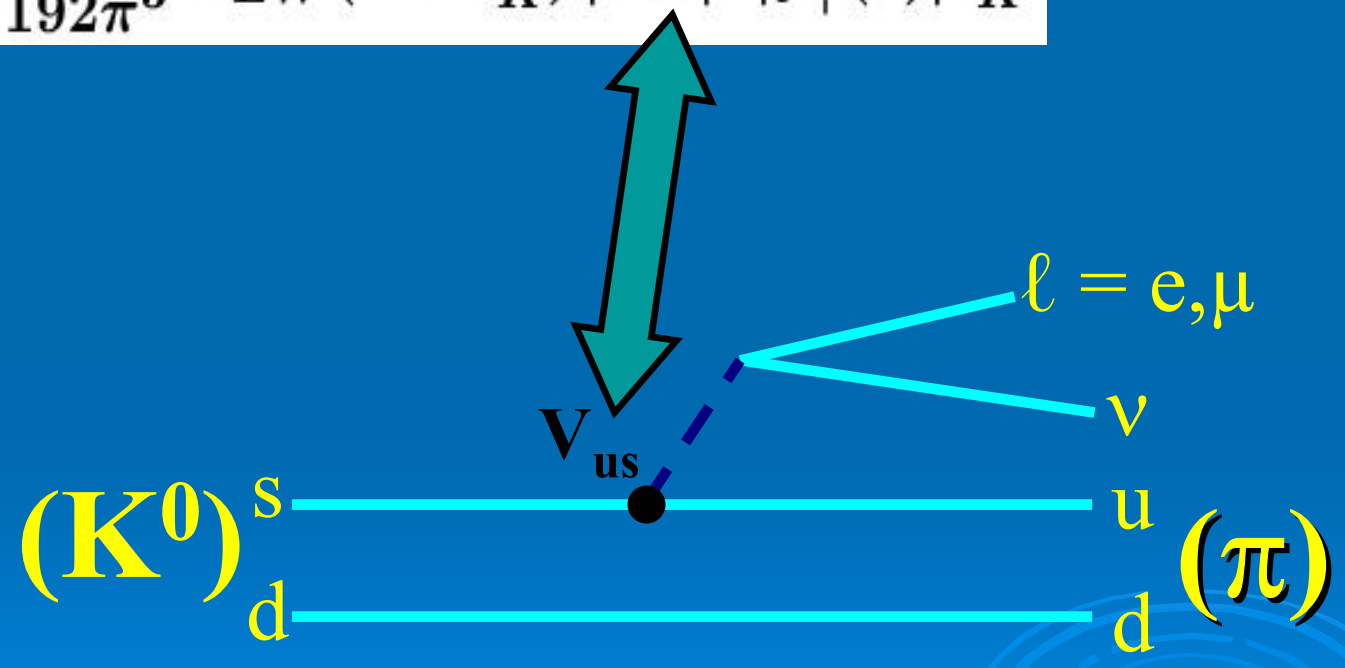
(other expts make unitarity tests involving CPV phase)

Brief History of |Vus|

- **PDG early 1980s – early 2000s, first row of CKM matrix is 2 sigma away from unitarity (in K_L , K^+ , and hyperons).**
- **In 2003, BNL-E865 measures K_{e3}^+ branching fraction resulting in $|V_{us}|$ consistent with unitarity.**
- **June 1, 2004: three KTeV papers report new measurements based on K_L decays (main subject of this talk).**
- **LP04: new K_L results from NA48 and KLOE.**

Method to Extract $|V_{us}|$ from K_L (K^+) Semileptonic Decays

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



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)

only external measurement

- 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.

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

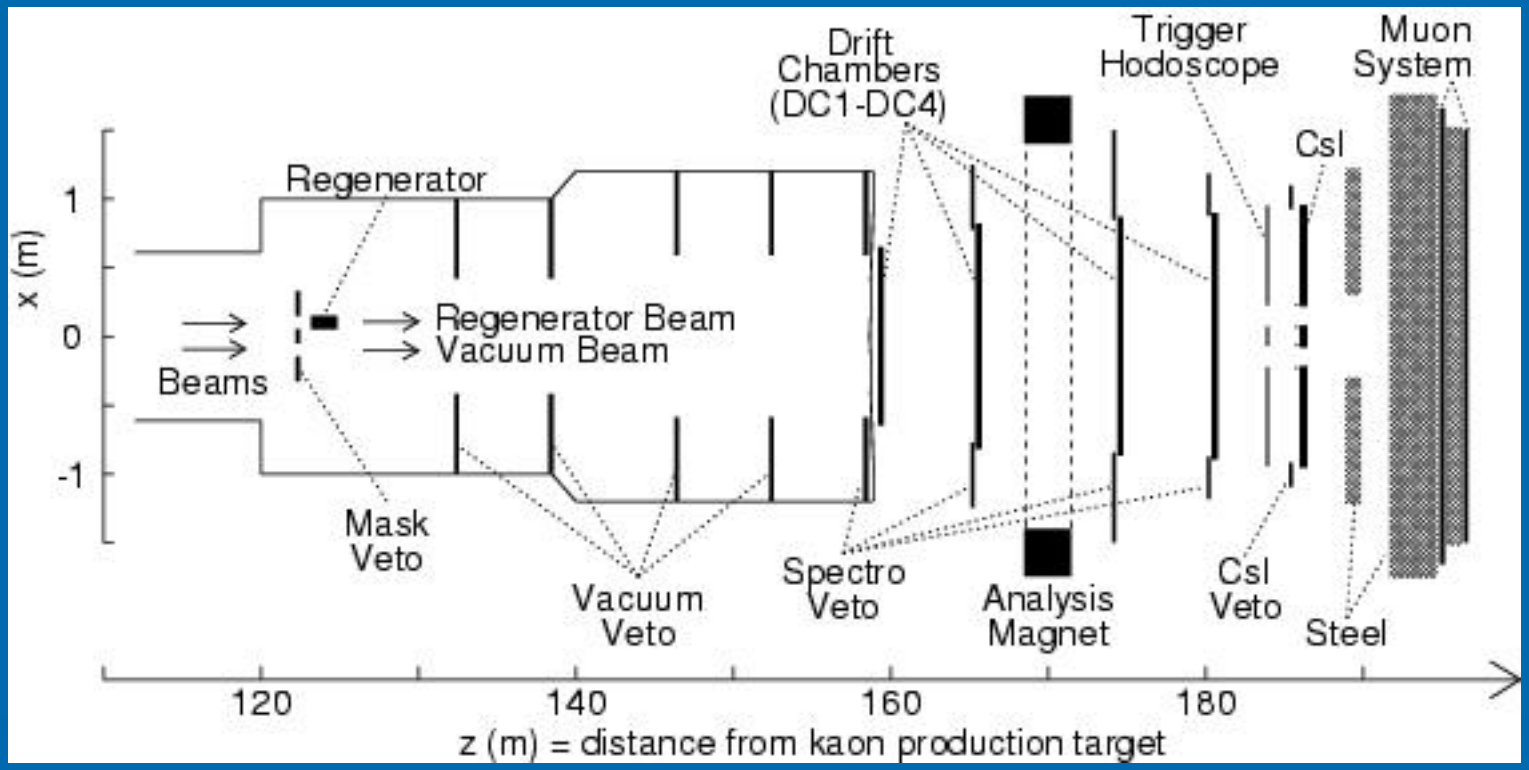
To determine the six main branching fractions, KTeV measures the following ratios of partial decay rates:

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

Ke3+Kμ3: 70% 3π: 30% 2π: 0.3%

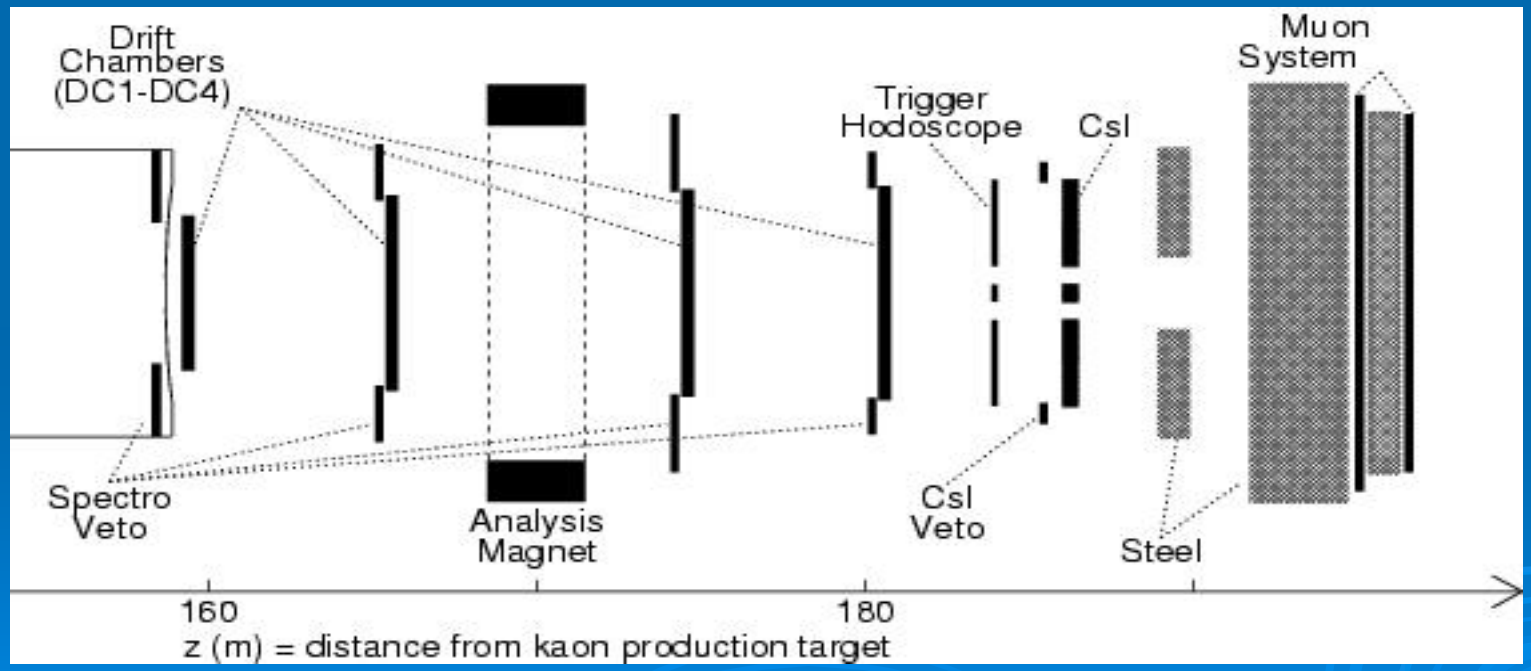
Sample sizes: 10^5 to 10^6

KTeV Detector



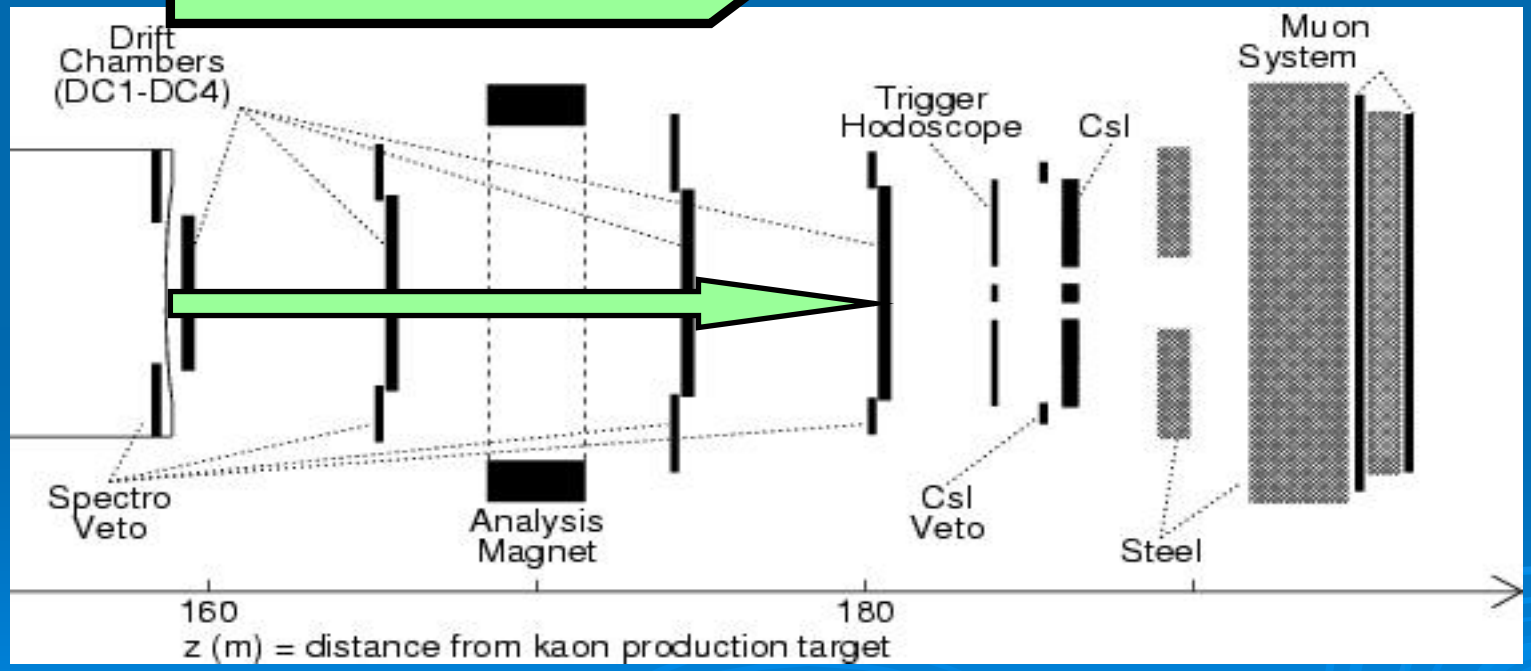
- **Ignore regenerator beam**
- **CsI energy resolution < 1% (E_γ > 3 GeV) and energy scale known to 0.1% using Ke3 electrons.**
- **Track momentum resolution < 1% (above 8 GeV/c) and momentum scale known to 0.01% using $K \rightarrow \pi^+\pi^-$**

KTeV Detector has little material upstream of CsI



KTeV Detector has little material upstream of CsI

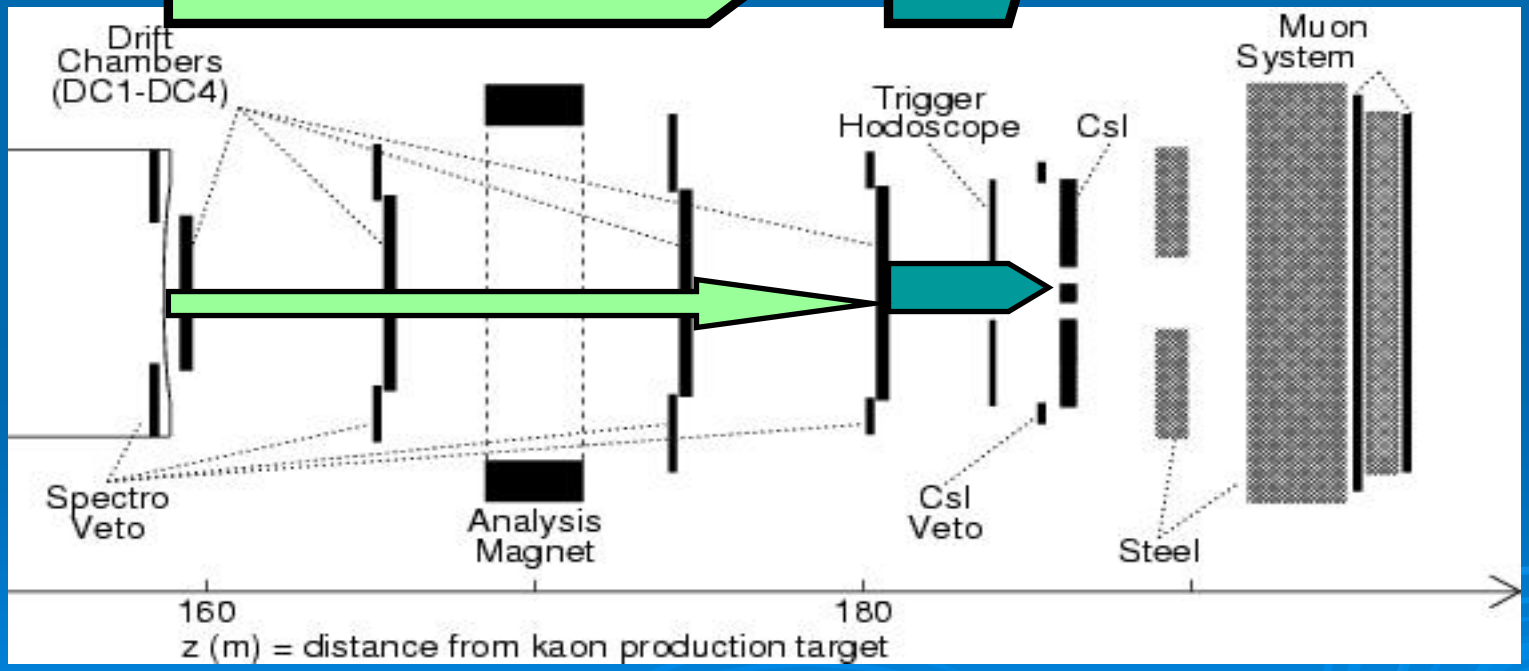
Spectrometer:
1.2% rad-len,
0.7% π-had len



KTeV Detector has little material upstream of CsI

Spectrometer:
1.2% rad-len,
0.7% π-had len

3.1% rad-len,
1.4% π-had len

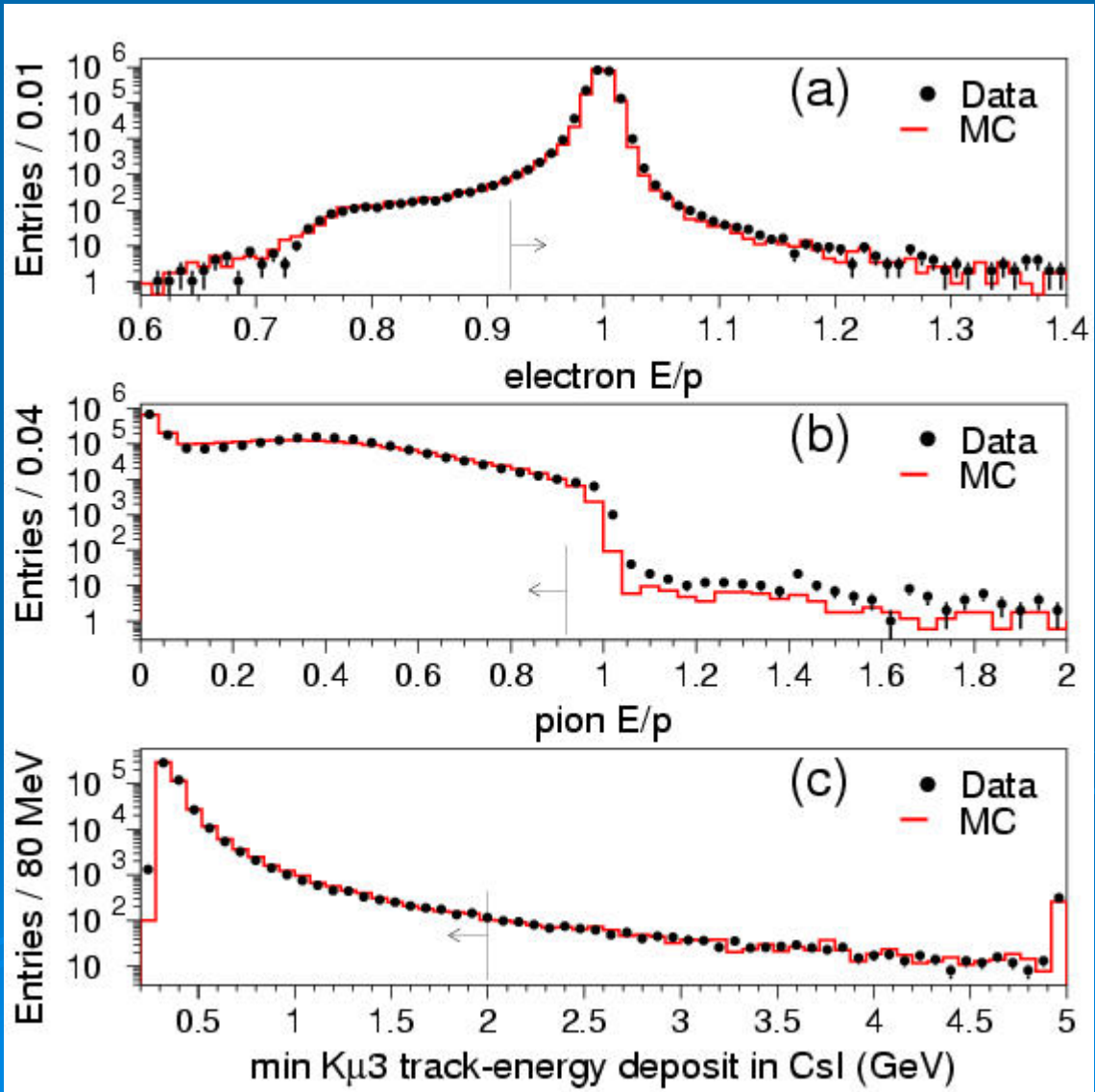


Material checked with Ke3 + external brem,

and with $K_L \rightarrow 3\pi^0 + \gamma \rightarrow e^+e^-$

Particle Identification

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



Branching Fraction Analysis: General Features

- Each pair of decays collected in same trigger.
- Each partial width ratio measured at both

  => nominal intensity used to measure ε'/ε

  (with min-bias, pre-scaled triggers)

  => x10 lower intensity without regenerator

  (x20 less detector activity).
- KTeV result based on measurement with smaller uncertainty between two intensities.

Branching Fraction Analysis: Mode-by-Mode

- K_{e3}: identify e, π with E/p in CsI
- $K_{\mu 3}$: identify π, μ with E/p and Eclus<2GeV;
  to reduce error, do NOT use μ system.
- K_{+-0}: identify π^+ and π^- with E/p;
  to reduce error, ignore π^0 .
- K_{000}: identify $3\pi^0$ in CsI.
- $K_{\pi\pi}$: almost identical to ε' analysis.

Partially Reconstructed Decays

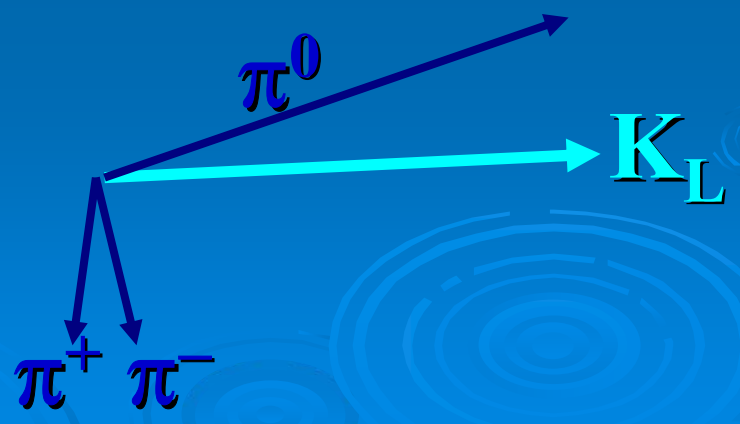
- K_{e3}, $K_{\mu 3}$, K_{+-0} each have missing particle (ν or π^0), resulting in multiple kaon energy solutions.
- all E_K solutions must be within 40-120 GeV.
- For $K_{\mu 3}$, we do not distinguish π and μ; this results in four E_K solutions!

Partially Reconstructed Decays

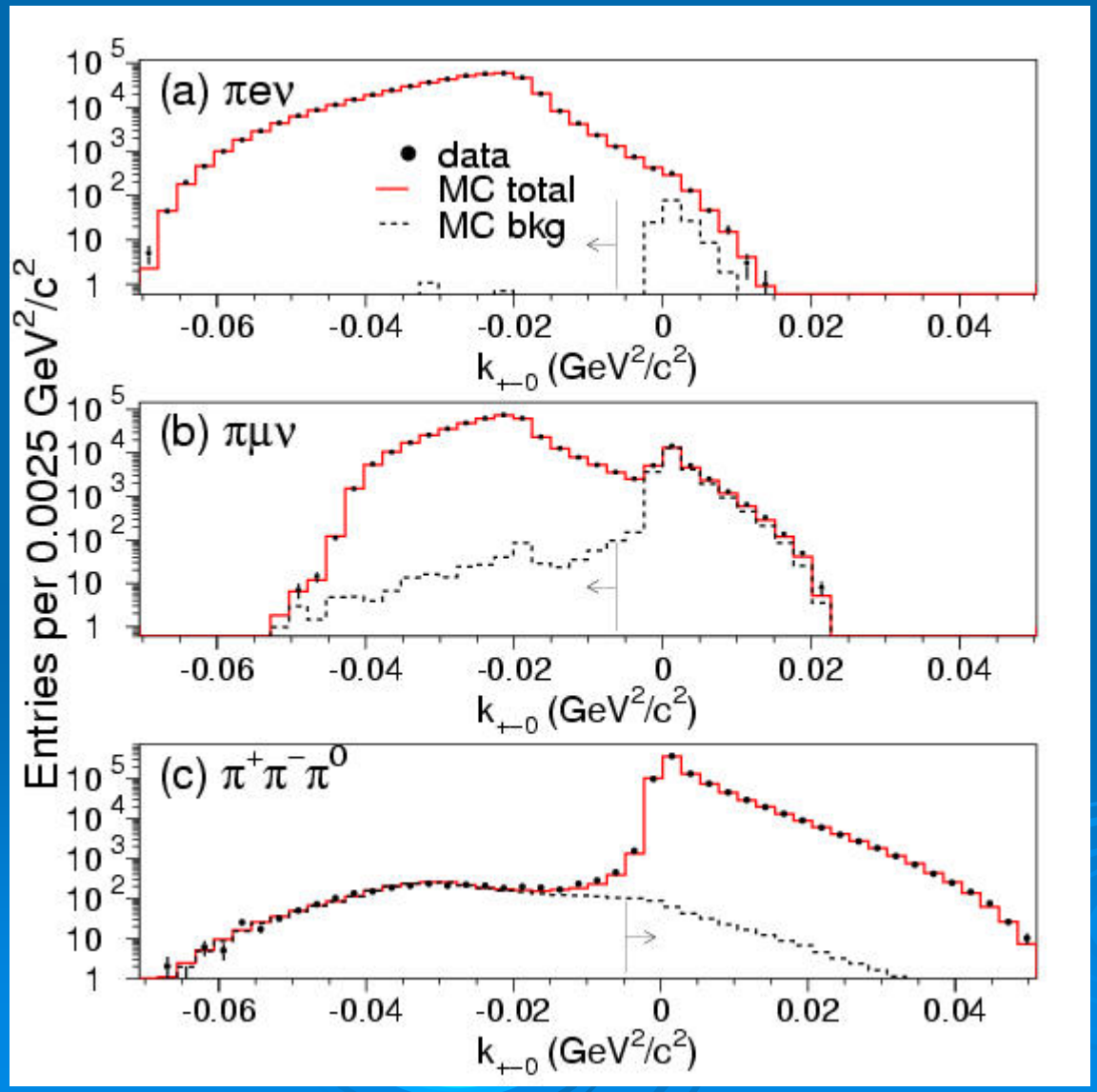
Ke3 and Kμ3 are separated by particle id

- **To separate Kℓ3 from $K_L \to \pi^+\pi^-\pi^0$ use k_{+-0} = longitudinal π^0 momentum-squared in frame where $\pi^+\pi^-$ is orthogonal to K_L**

- **$k_{+-0} > 0$ for $K_L \to \pi^+\pi^-\pi^0$**
- **$k_{+-0} < 0$ for $K_L \to \pi\ell\nu$**



k_{+-0} for Partially Reconstructed Decays

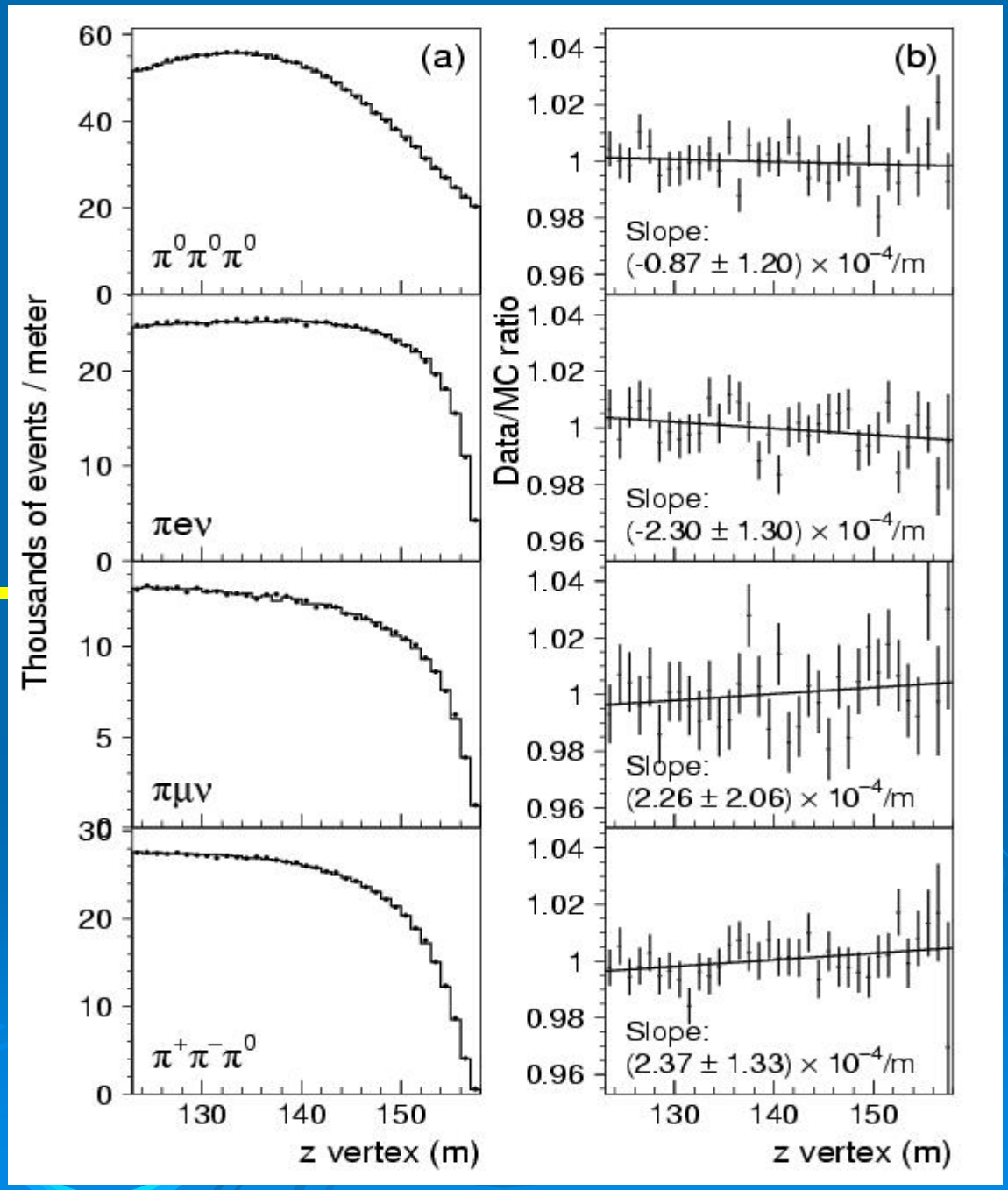


Background from other K_L Decays

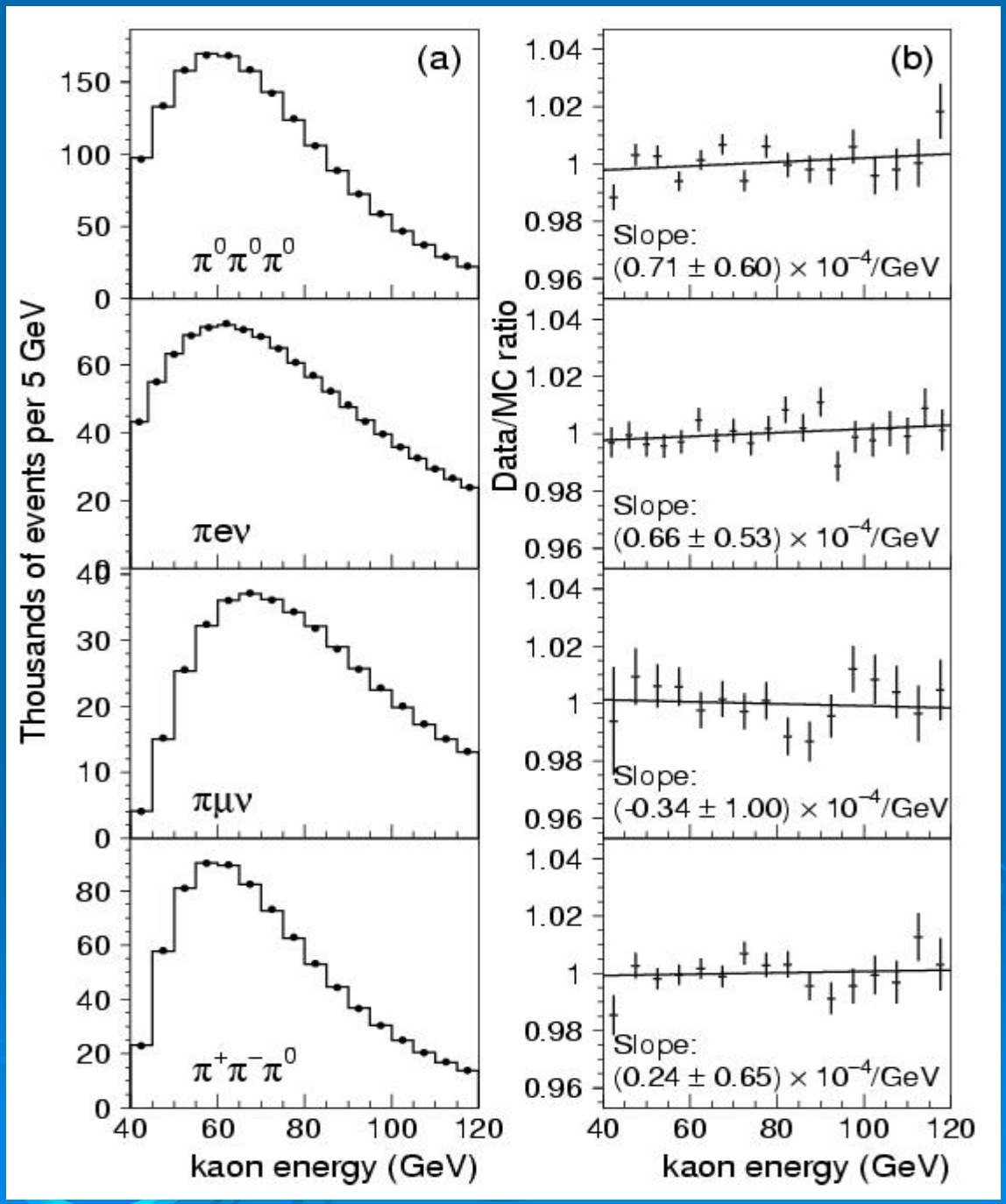
Decay Mode	Background (percent)
$K_L \rightarrow \pi e \nu$	< 0.003
$K_L \rightarrow \pi \mu \nu$	0.01
$K_L \rightarrow \pi^+ \pi^- \pi^0$	0.05
$K_L \rightarrow \pi^+ \pi^-$	0.16
$K_L \rightarrow 2\pi^0$	0.71
$K_L \rightarrow 3\pi^0$	none

Data-MC comparisons of decay vertex.

(Note MC determines acceptances)



Data-MC comparisons of kaon energy (or max E_K) after tuning with 10 million $K_L \rightarrow \pi^+ \pi^-$



BRs Include Radiated Photons !

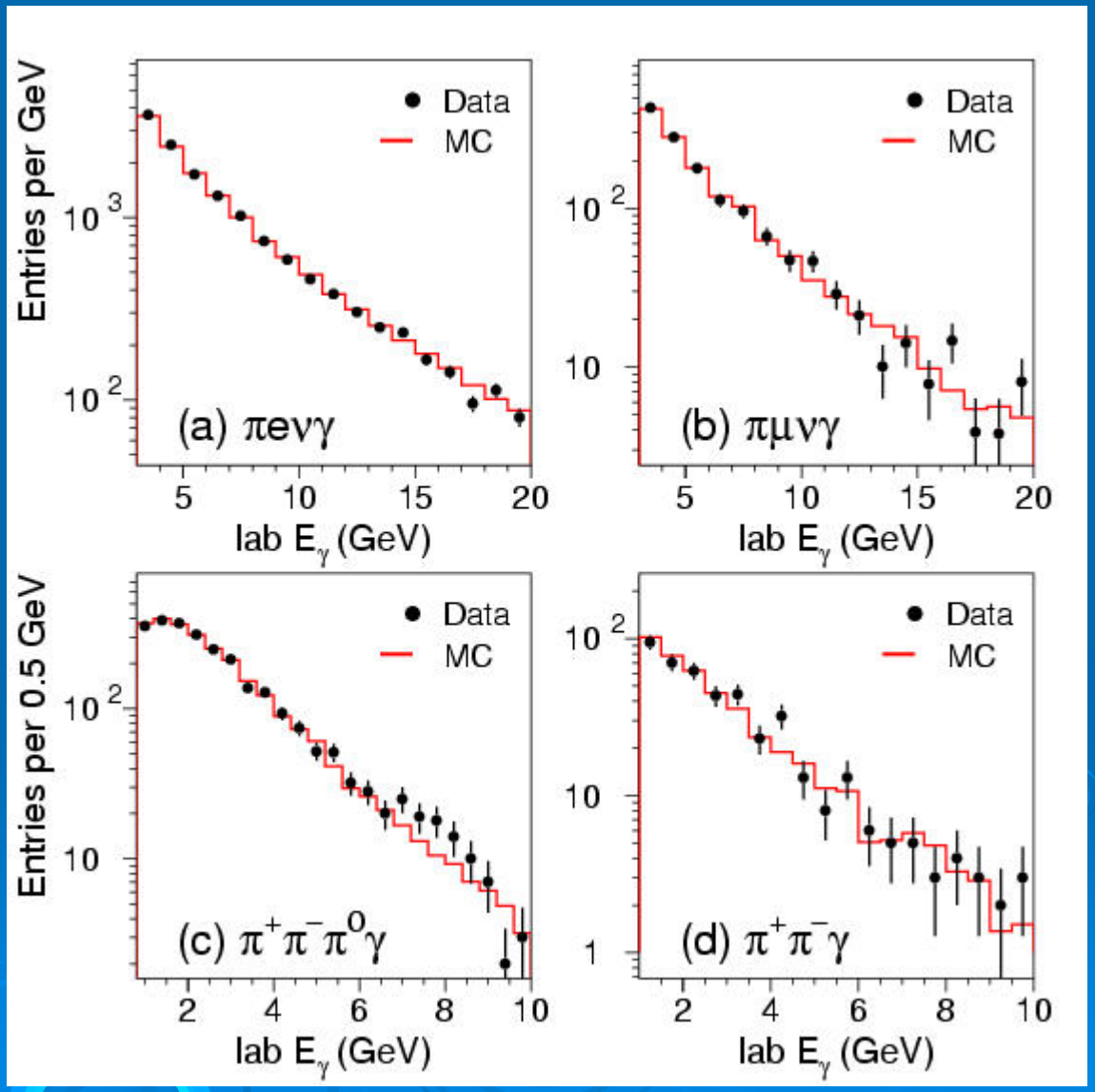
- $K_{e3(\gamma)}+K_{\mu 3(\gamma)}$ MC generator (KLOR) written by U. Chicago student T.Andre (advisor: J.Rosner). Includes virtual and real photons.

  KLOR: Kaon Leading Order Radiation
- $K_{+-0(\gamma)}$ MC generator uses PHOTOS.
- $K_{+-(\gamma)}$ MC generator includes IB, but ignores direct emission.

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

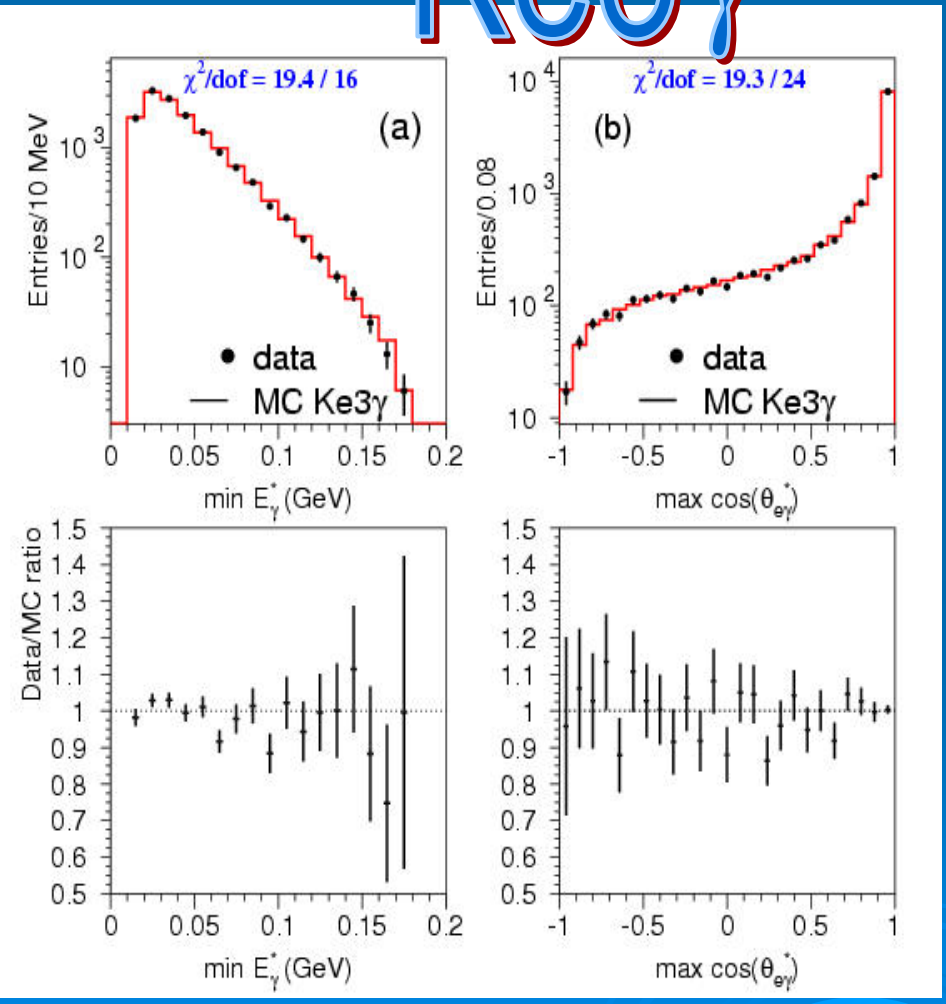
Radiative MC Check

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



Check New Kℓ3γ Generator

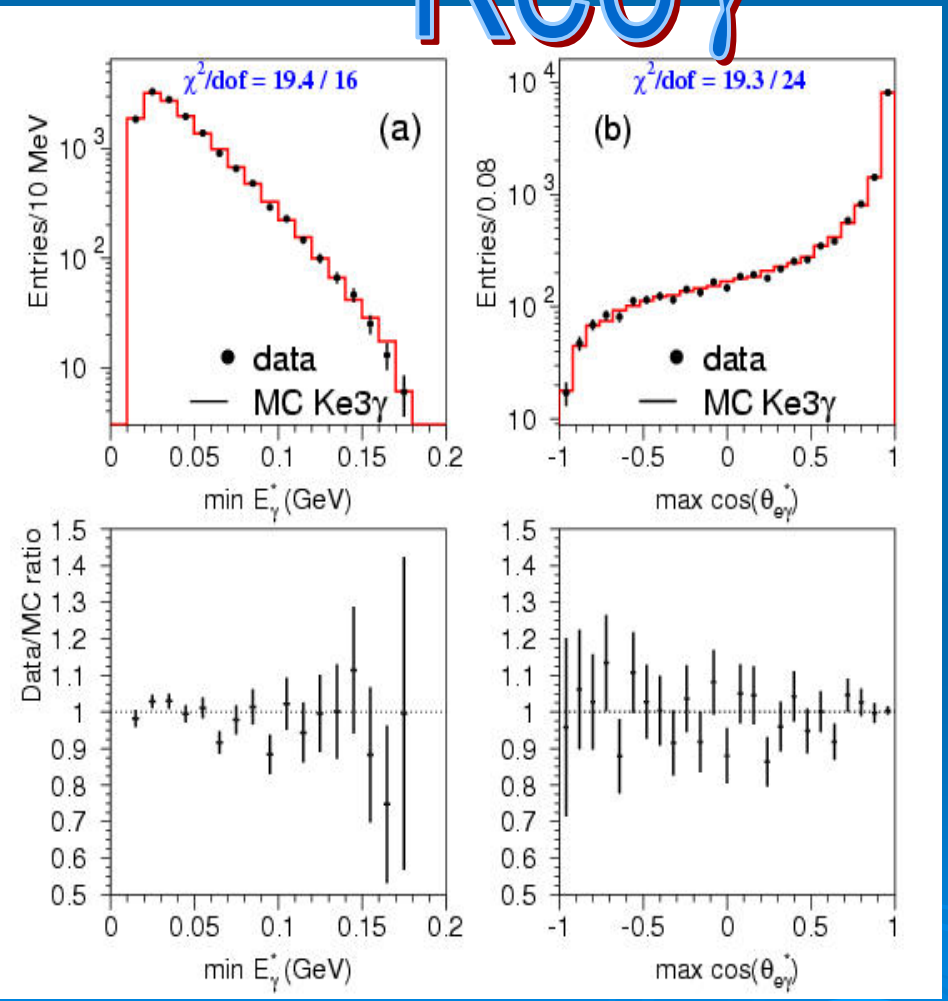
Ke3γ



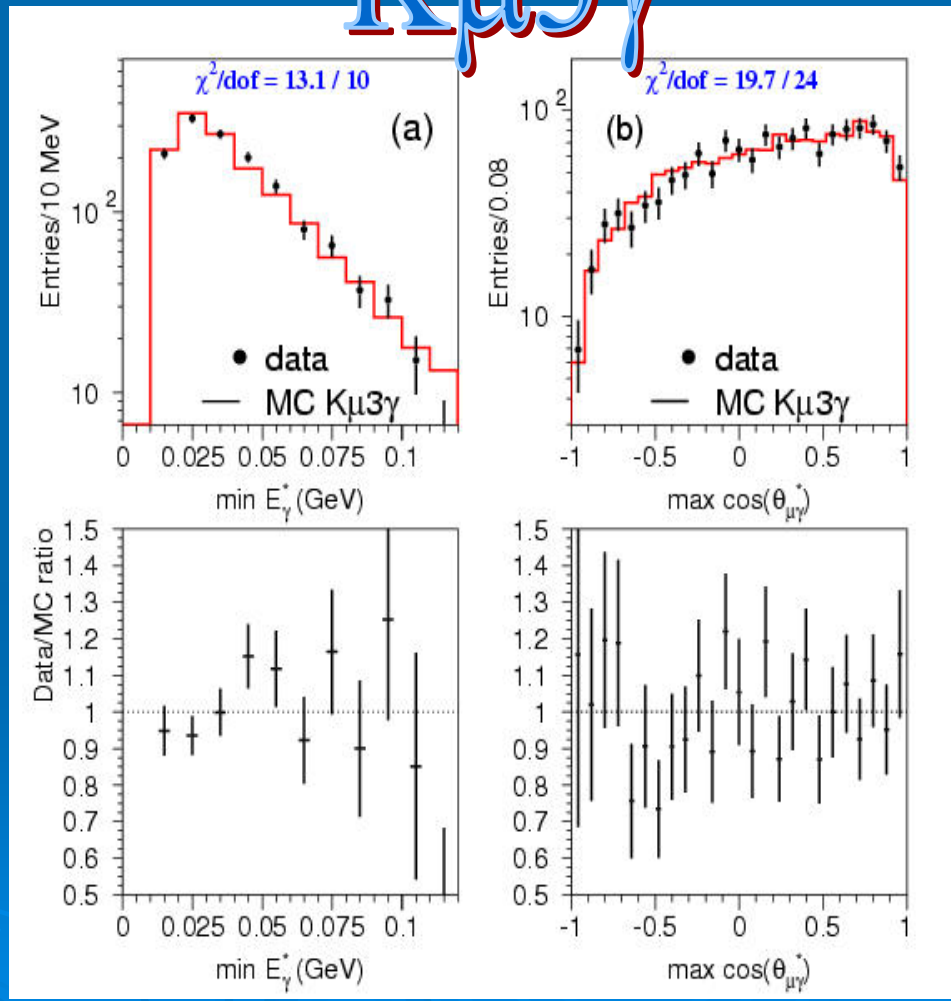
KTeV Kℓ3γ BRs and plots in: PRD 71, 012001 (2005)

Check New Kℓ3γ Generator

Ke3γ



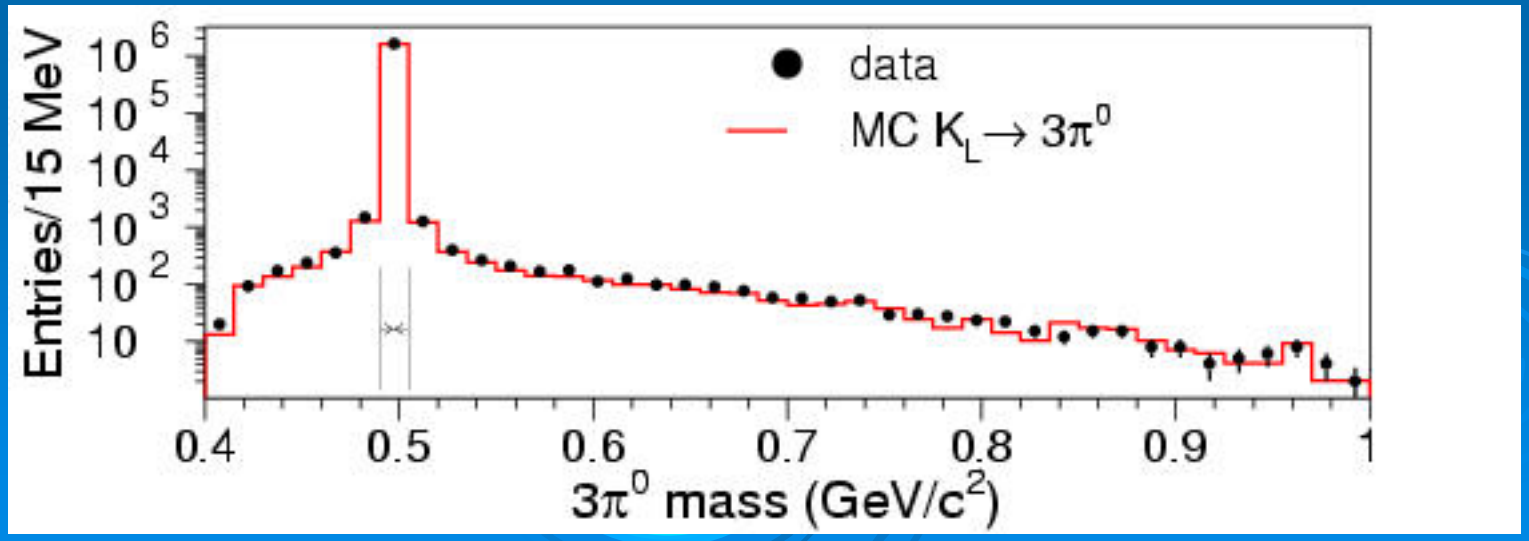
Kμ3γ



KTeV Kℓ3γ BRs and plots in: PRD 71, 012001 (2005)

Absolute Efficiency for $3\pi^0$ in $B(3\pi^0)/B(K_{e3})$ ratio

- **CsI inefficiency (10^{-6}) monitored by laser.**
- **Photon mis-pairings checked in $3\pi^0$ mass; for events outside signal-mass region, data-MC difference is only 0.14% (included as systematic uncertainty)**



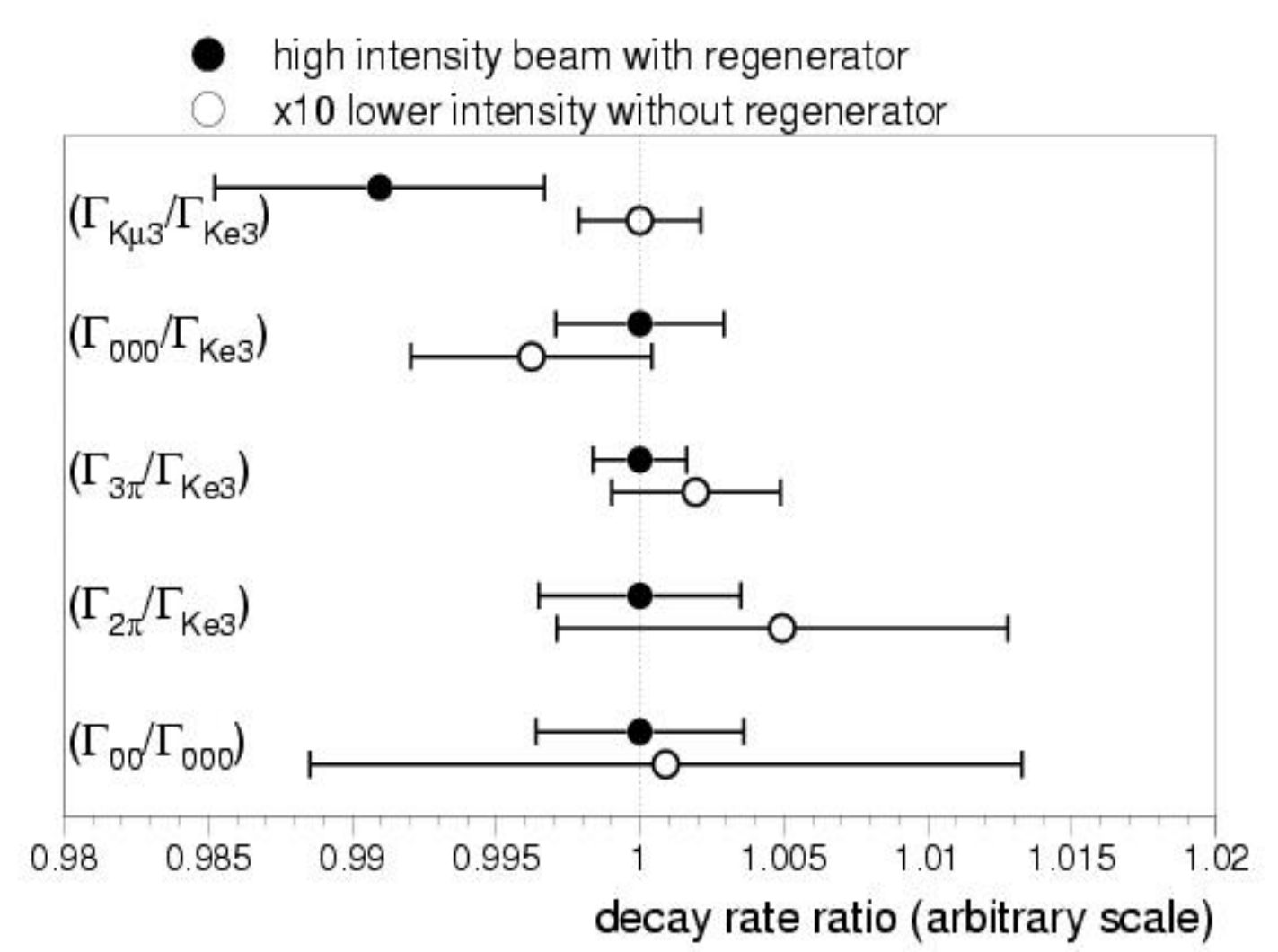
Absolute Efficiency for K_{e3} in $B(3\pi^0)/B(K_{e3})$ ratio

- **Electron E/p ineff is 0.2% (both data and MC)**
- **Pion E/p ineff measured with $K_L \rightarrow \pi^+\pi^-\pi^0$**
- **2-track ineff measured by tagging tracks and segments in $K_L \rightarrow \pi^+\pi^-\pi^0$ decays ; data-MC difference = 0.6% ; difference included as correction and systematic error**

Beam Intensity Crosschecks

High vs. Low Intensity

χ^2/ dof = 3.4/5



Analysis Crosschecks

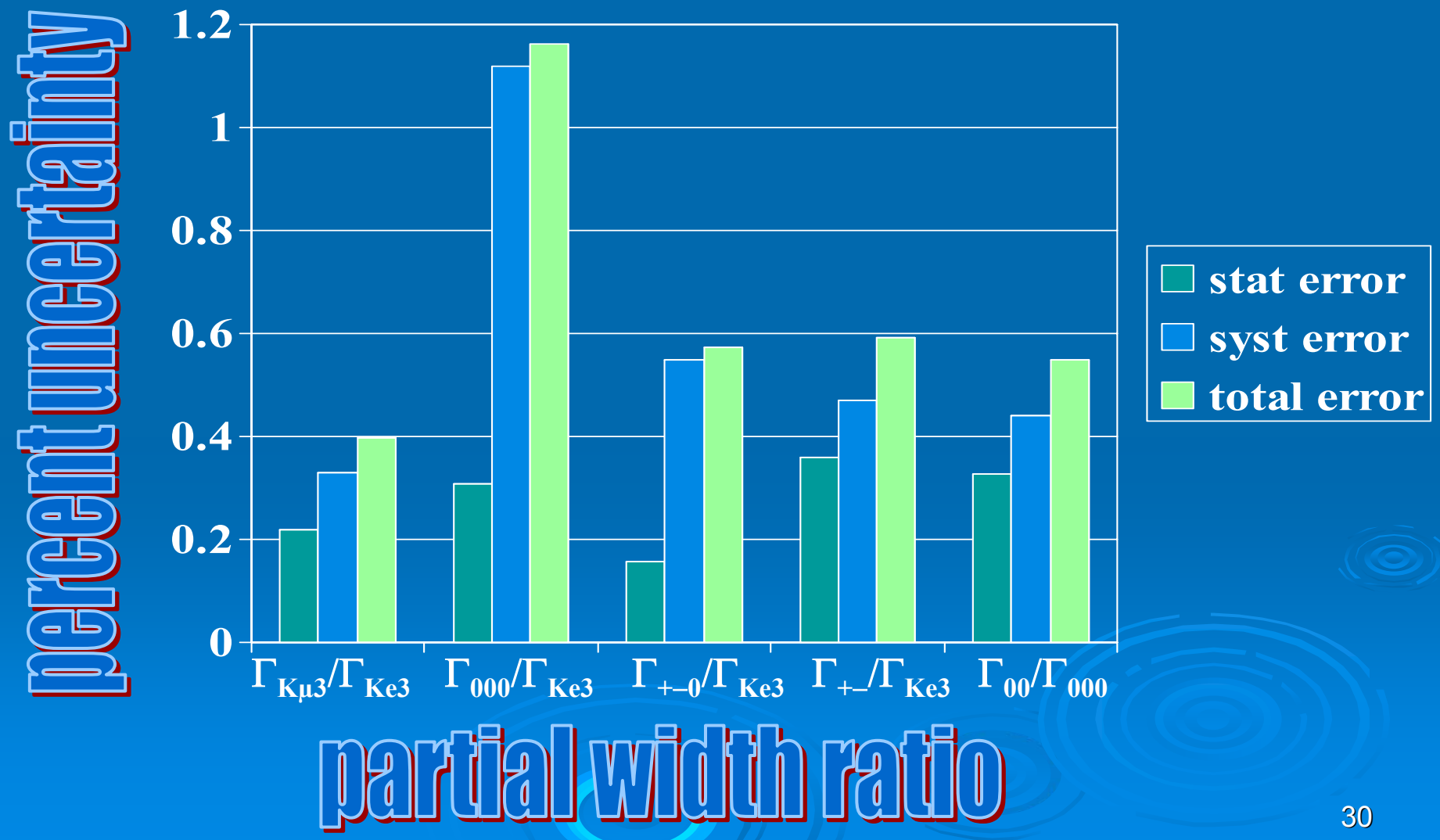
- **$K_L \rightarrow \pi^+\pi^-\pi^0$ yield without/with $\pi^0 \rightarrow \gamma\gamma$ detection in CsI agree to (0.03 ± 0.28)%**

- **$K_{\mu 3}$ yield without/with μ system agree to (0.08 ± 0.02) %**

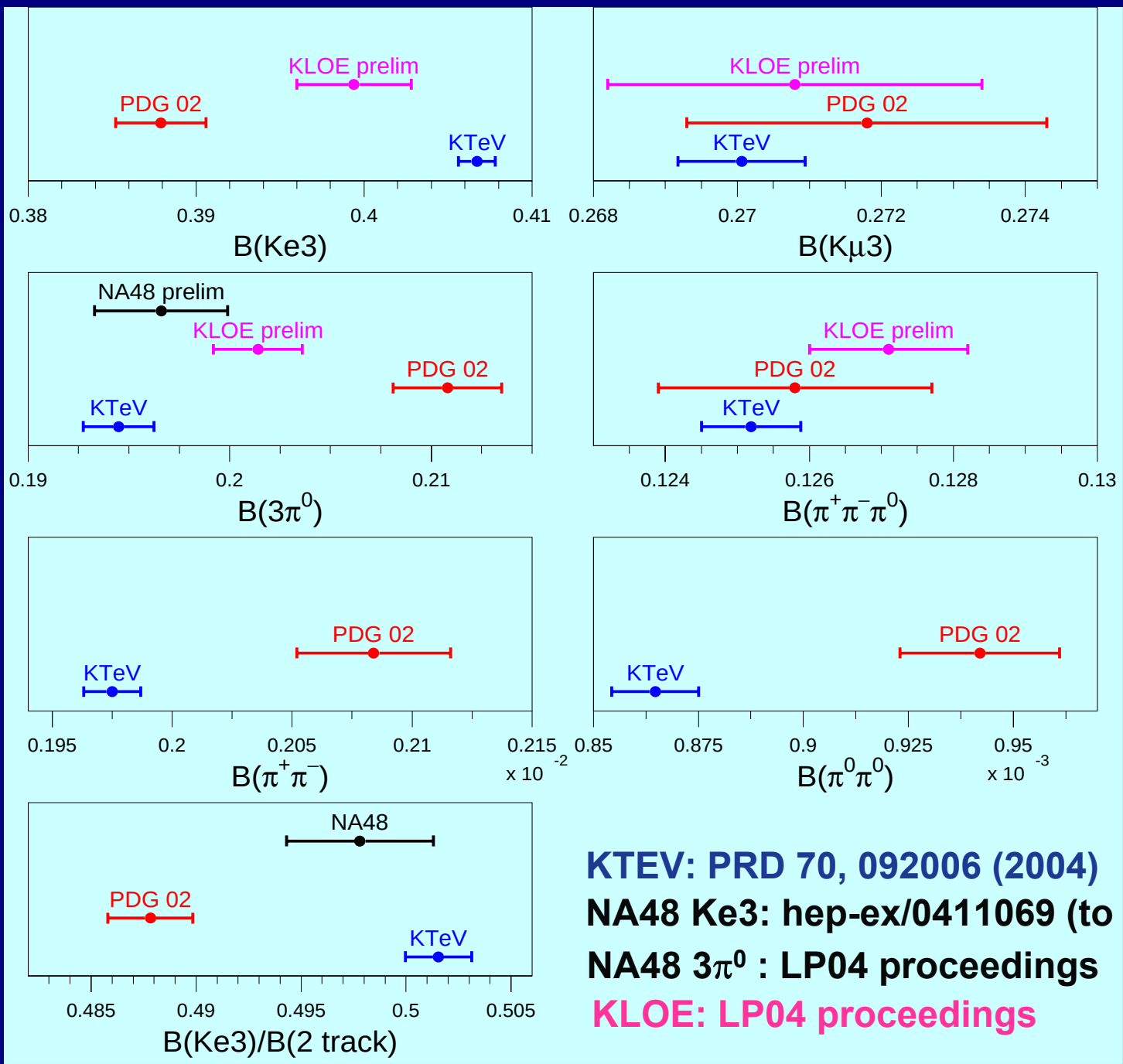
Main Systematic Uncertainties

- **$3\pi^0$/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



K_L BR Measure-ments



KTEV: PRD 70, 092006 (2004)

NA48 Ke3: hep-ex/0411069 (to appear in PLB)

NA48 $3\pi^0$: LP04 proceedings

KLOE: LP04 proceedings

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

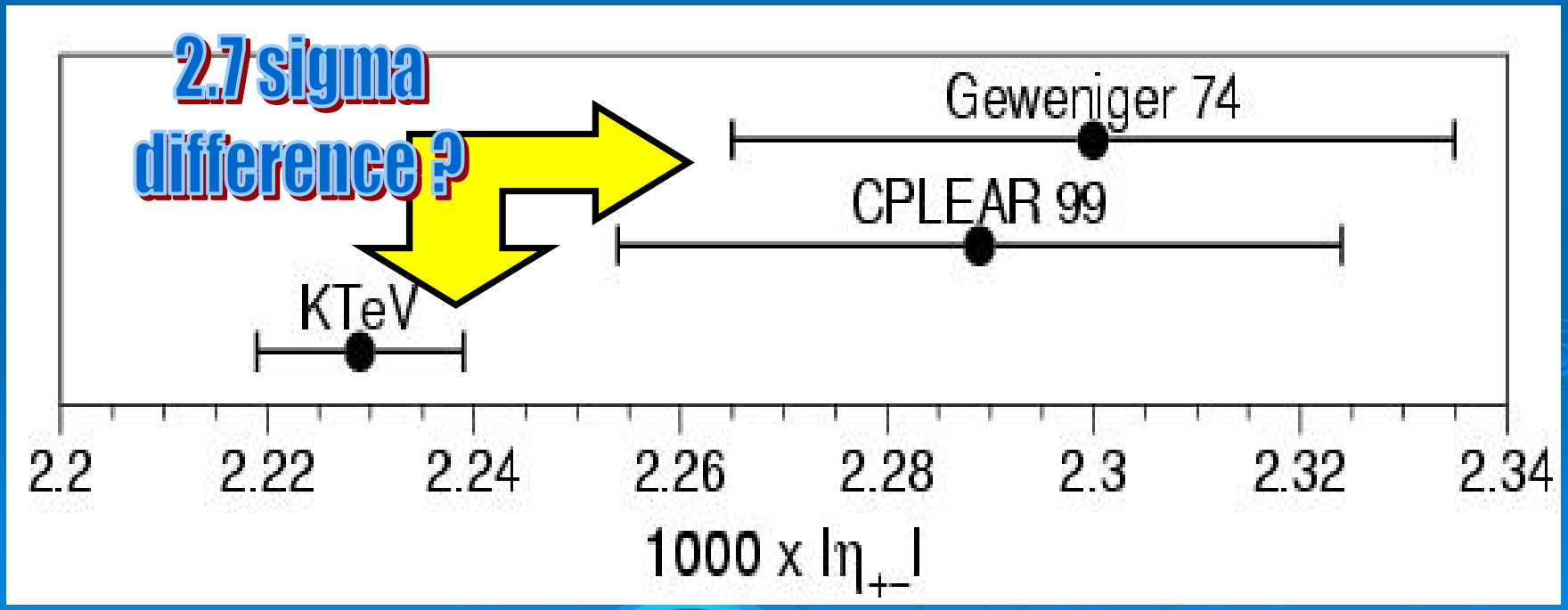
KTeV 2π BRs

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

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 $B(K_L \rightarrow \pi\pi)$]



Semileptonic Form Factors (to determine I_K integrals)

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

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} V_{us} \left[f_+(t)(P_K + P_\pi)_\mu\, \overline{u_\ell}\gamma^\mu(1+\gamma_5)u_\nu \right.$$
$$\left. + \quad f_-(t)(P_K - P_\pi)_\mu\, \overline{u_\ell}\gamma^\mu(1+\gamma_5)u_\nu \right],$$

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

$$f_0(t) = f_+(t) + f_-(t)[t/(m_K^2 - m_\pi^2)]$$

$$I_K^\ell = \mathcal{F}\left(\frac{f_+(t)}{f_+(0)}, \frac{f_0(t)}{f_+(0)}, \prod_i \frac{d^3\vec{p}_i}{2E_i} \right)$$

[1]

⇒ Assumes pure vector hadron-current.

⇒ Scalar and tensor terms < few percent (NA48)

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:

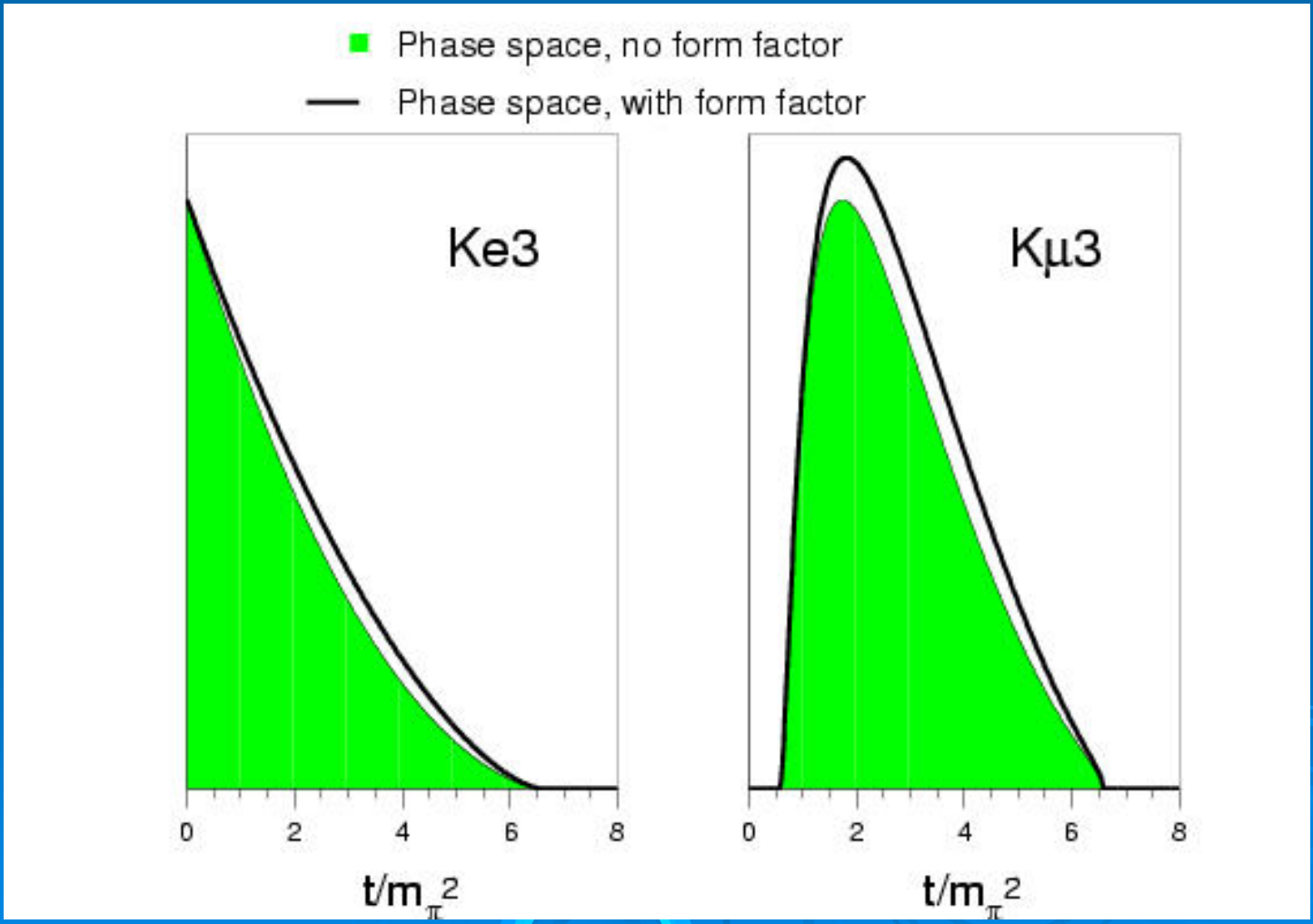
$$f_+(t) = f_+(0) \left[1 + \lambda'_+ \frac{t}{M_\pi^2} + \frac{1}{2} \lambda''_+ \frac{t^2}{M_\pi^4} \right]$$

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

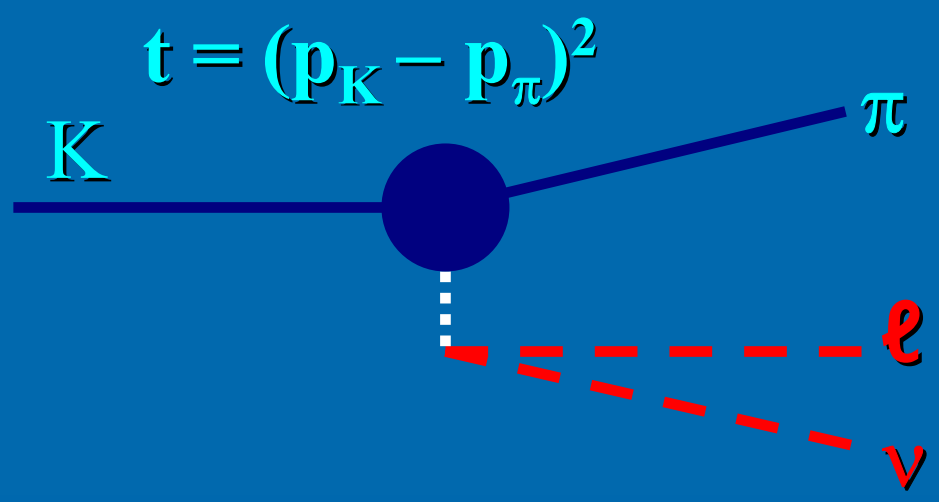
where $t = (P_K - P_\pi)^2$

Ke3	Kμ3
y	y
--	y

Form Factor Illustration



Semileptonic Form Factors: Method

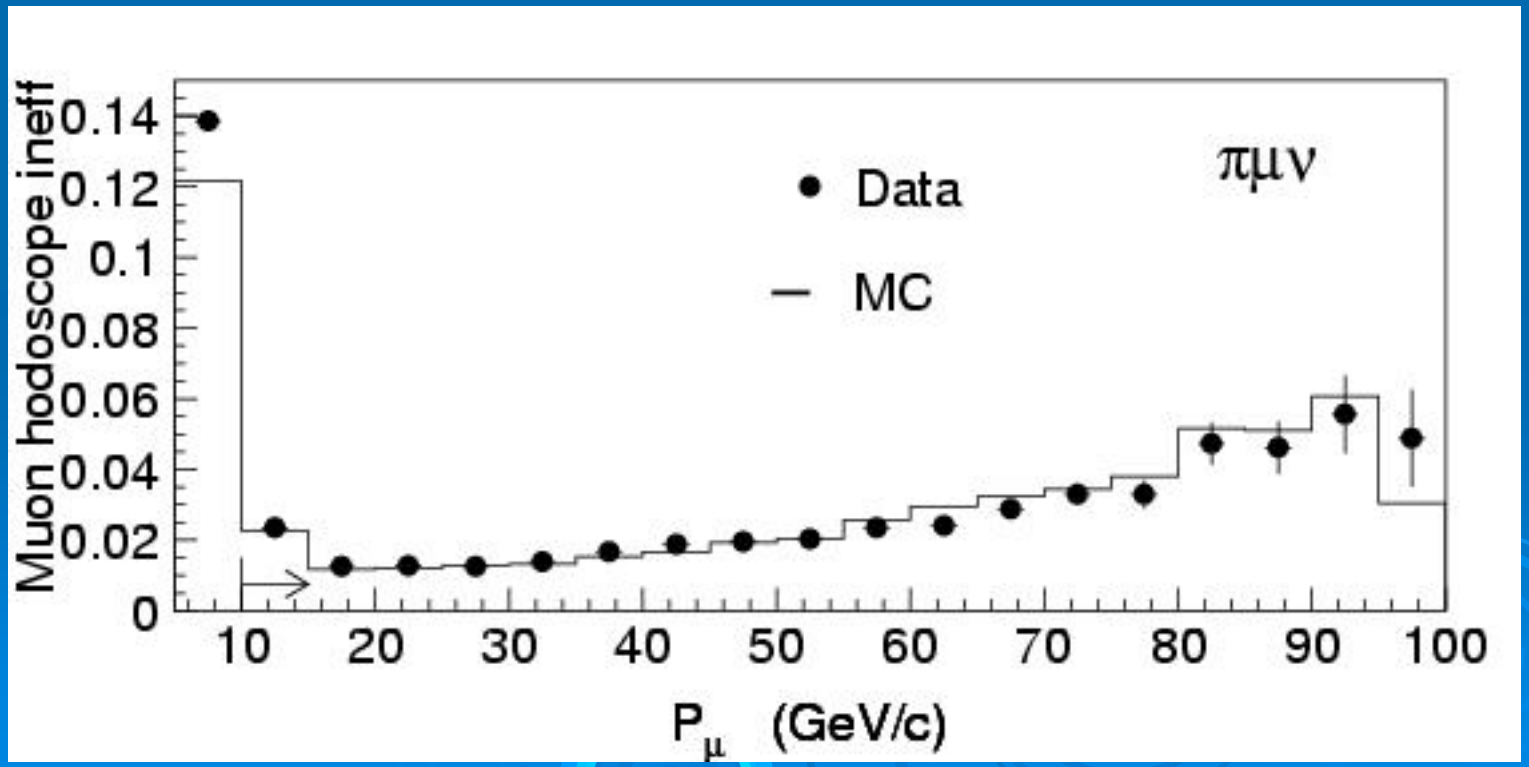


* Kinematic ambiguity => two possible t-values

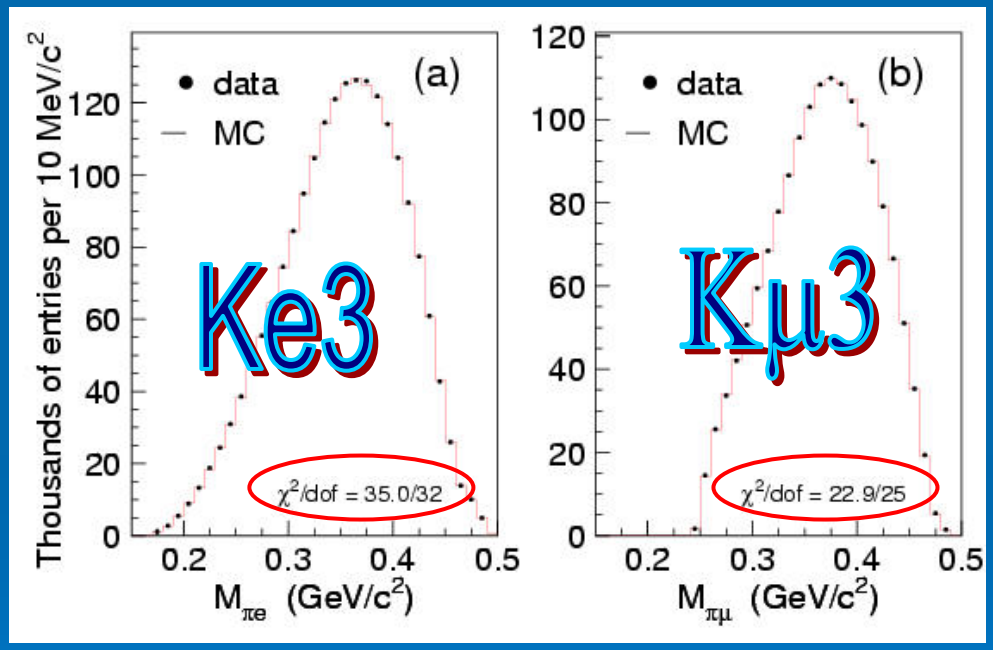
*To avoid ambiguity, compute "$t_\perp$" using only transverse quantities.

Analysis Selection

* Ke3: same as for branching fraction analysis.
* Kμ3: use muon system to identify muon



Data/MC Comparisons (MC uses KTeV FF + KLOR)



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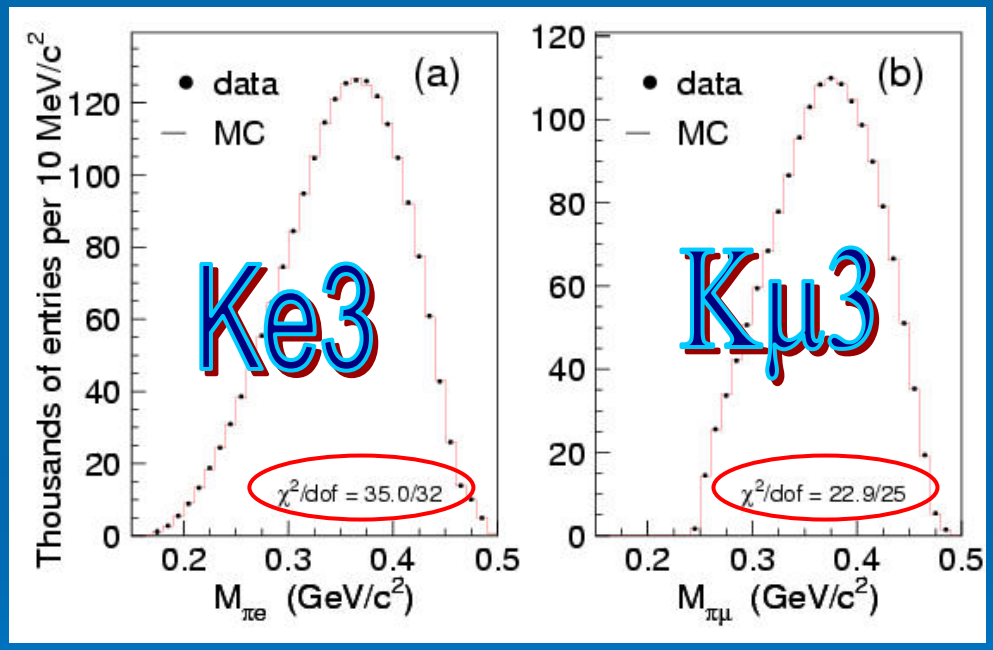
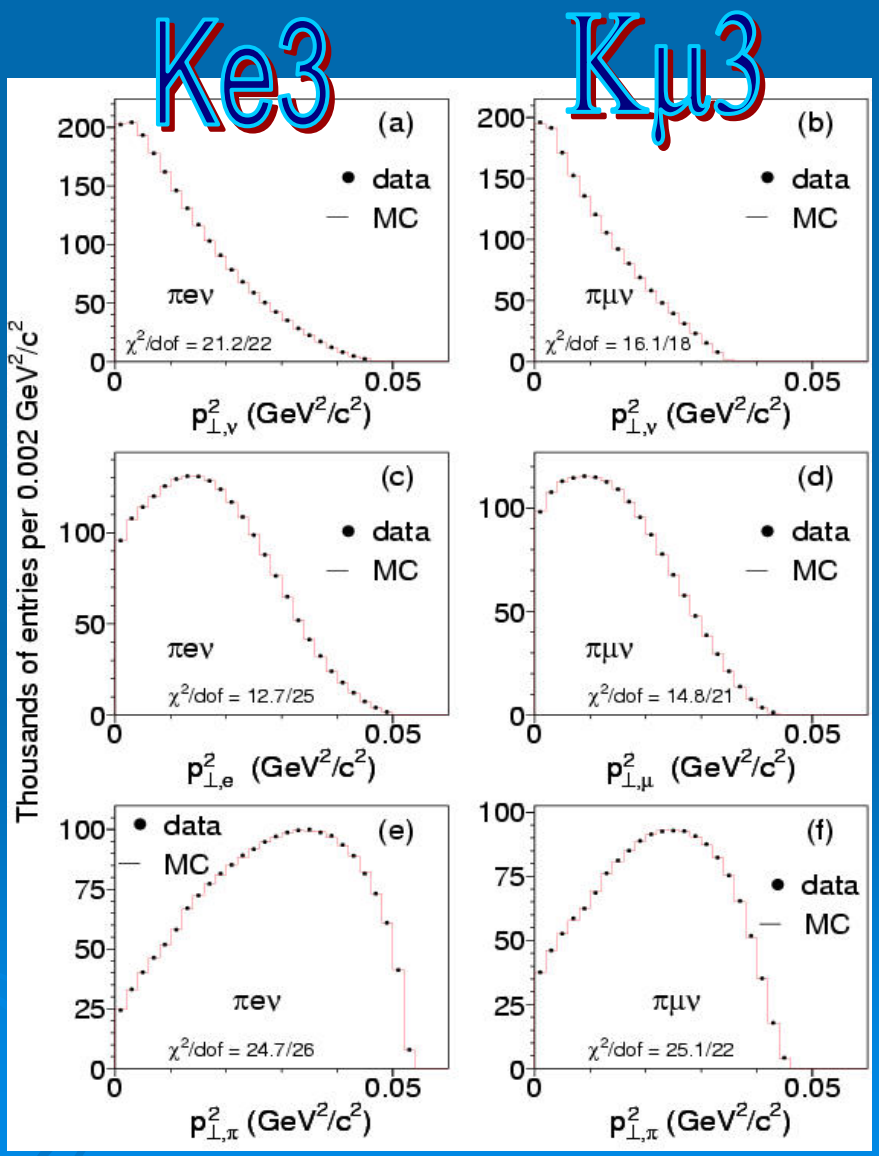
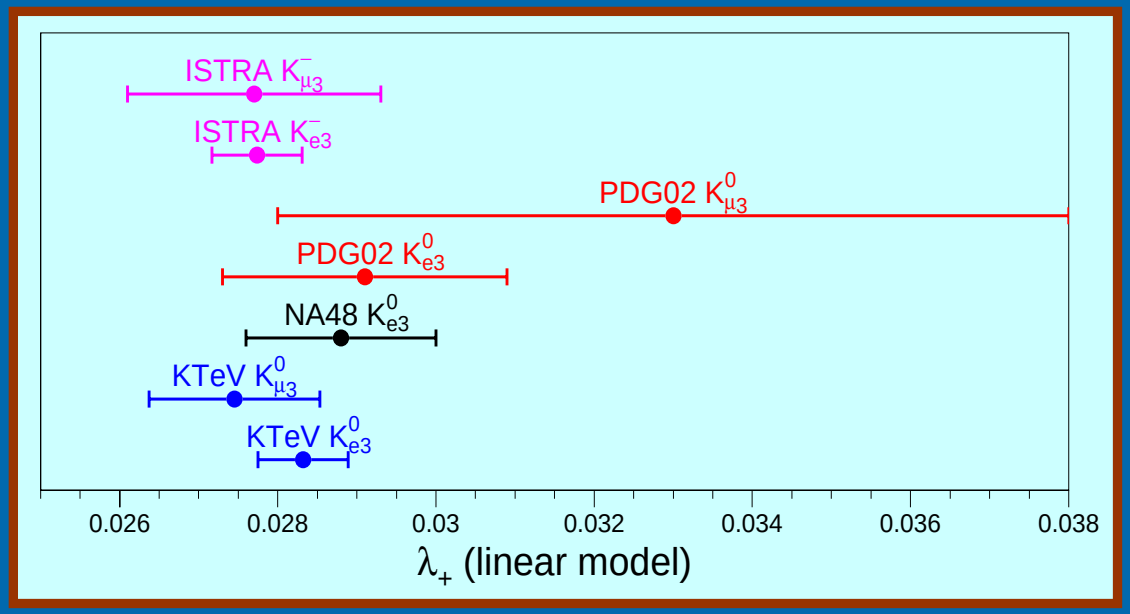




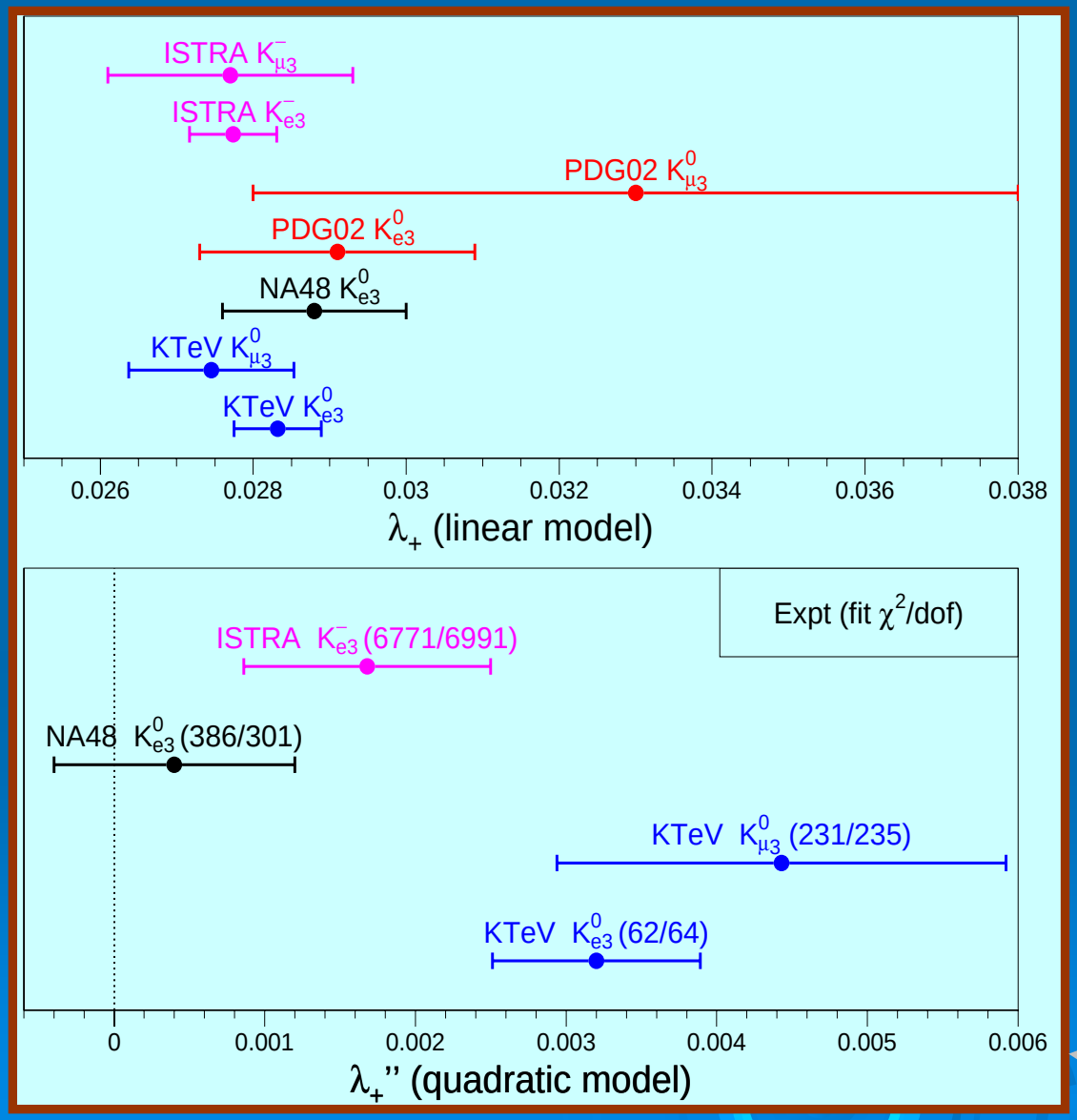
Note: replacing KLOR with re-weighted PHOTOS, cannot get good chi2 in all distributions.

Recent $f_+(t)$ Comparisons



$$f_+(t) = f_+(0)\,[\,1 + \lambda_+ t/m_\pi^2\,]$$

Recent $f_+(t)$ Comparisons

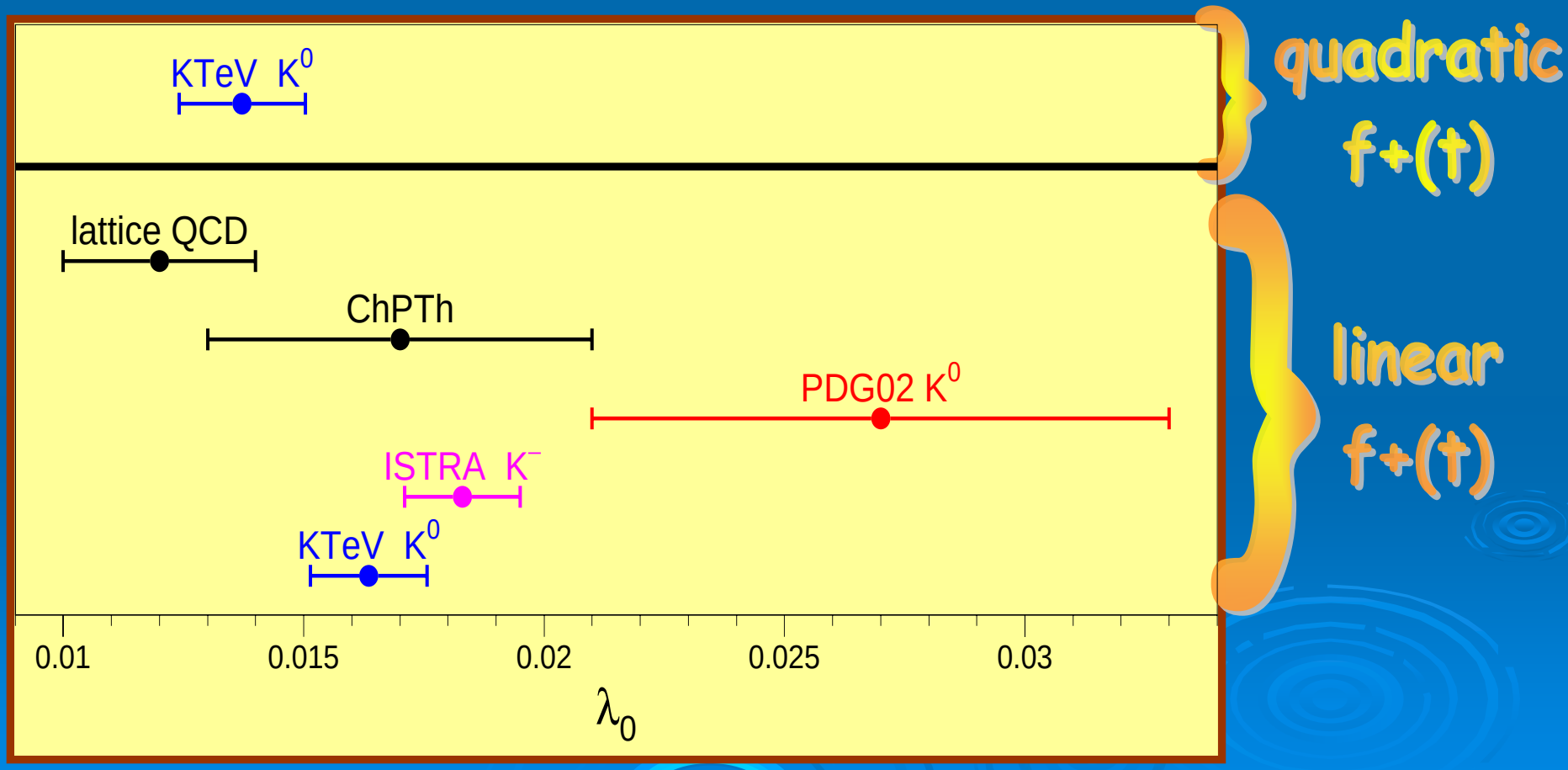


$$f_+(t) = f_+(0)\,[\,1 + \lambda_+ t/m_\pi^2\,]$$

$$f_+(t) = f_+(0)\,[\,1 + \lambda_+' t/m_\pi^2 + \tfrac{1}{2}\lambda_+'' t^2/m_\pi^4\,]$$

Recent $f_0(t)$ Comparisons ($K\mu3$ FF)

Fit with:



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.
- $I_{K\mu3} / I_{Ke3}$ ratio is not affected.

Lepton Universality Test with Semileptonic Branching Fractions and Form Factors

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

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

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

Lepton Universality Test with Semileptonic Branching Fractions and Form Factors

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

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

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

(same test with PDG02 BR and FF: 1.027 ± 0.018)

Summary of Vus Changes from KTeV (relative to PDG-02)

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

*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 KLOR,

$\delta^e = 1.013$

$\delta^\mu = 1.019$

Use Leutwyler-Roos 84:

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

Recent works: 0.96-0.98

(no consensus yet ?)

Results

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

Because of theory uncertainty in $f_+(0)$, we report product of $|Vus| * f_+(0)$.

Then report $|V_{us}|$ for particular choice of $f_+(0)$.

Who's $|V_{us}|$ Result ?

Claim	Source of B(Kℓ3)	Source of FormFactor	Source of lifetime
BNL-$|V_{us}|$ K^+_{e3}	BNL+PDG	PDG	PDG
KTeV-$|V_{us}|$ K^L_{e3}	KTeV	KTeV	PDG
KTeV-$|V_{us}|$ $K^L_{\mu 3}$	KTeV	KTeV	PDG
NA48-$|V_{us}|$ K^L_{e3}	Na48+KTeV+PDG	NA48	PDG
KLOE $|V_{us}|$ $K^{L,S}$, K^+ (e, μ)	KLOE (prelim)	KTeV (KLOE later?)	KLOE (prelim)

NOTE1: in principle, KLOE can measure all inputs to $|V_{us}|$

NOTE2: all experiments use $f_+(0)$ and radiative corrections from theorists.

KTeV $|V_{us}|$ Result

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

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

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

KTeV $|V_{us}|$ Result

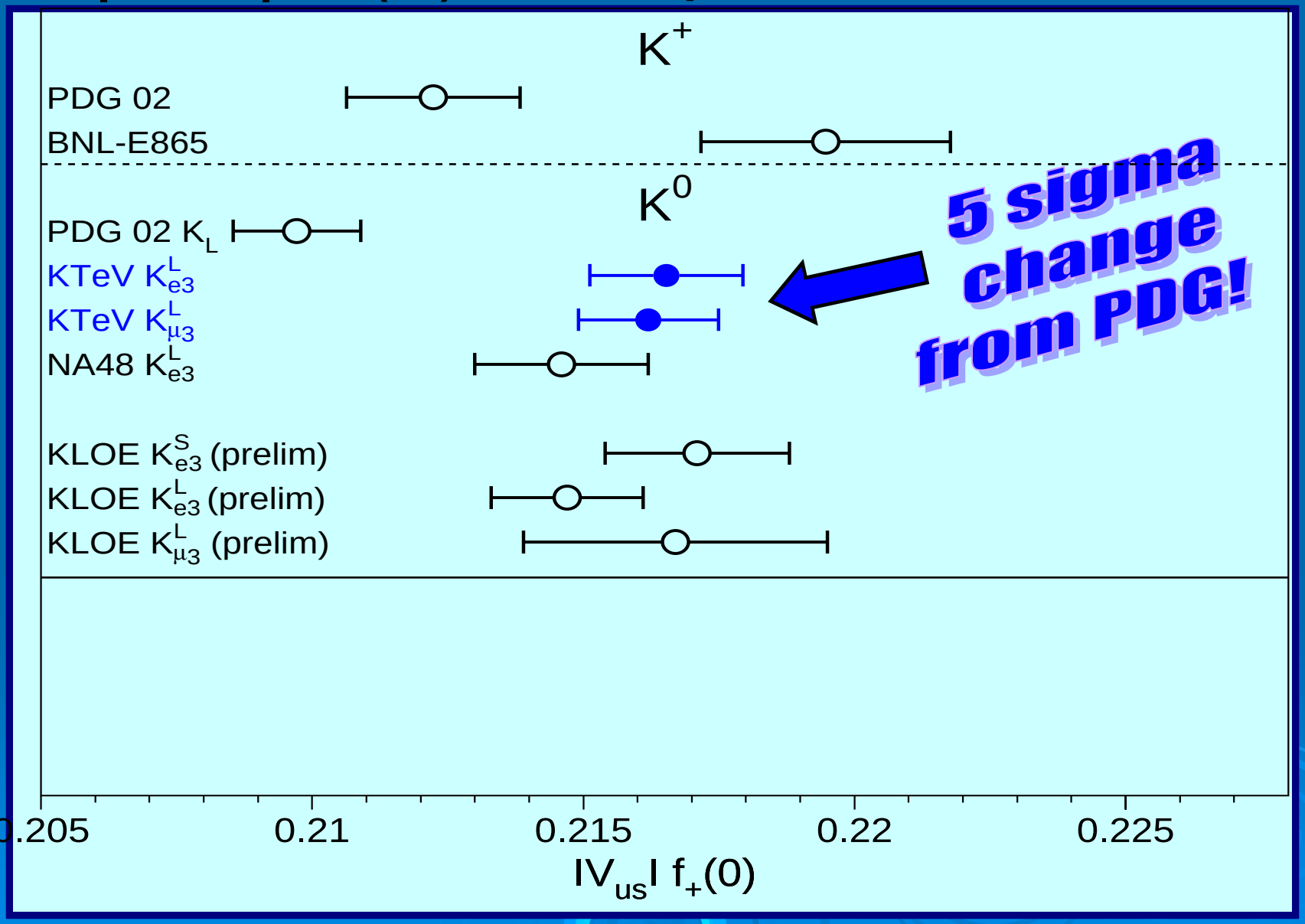
$$|V_{us}| f_+(0) = 0.2165 \pm 0.0012$$

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

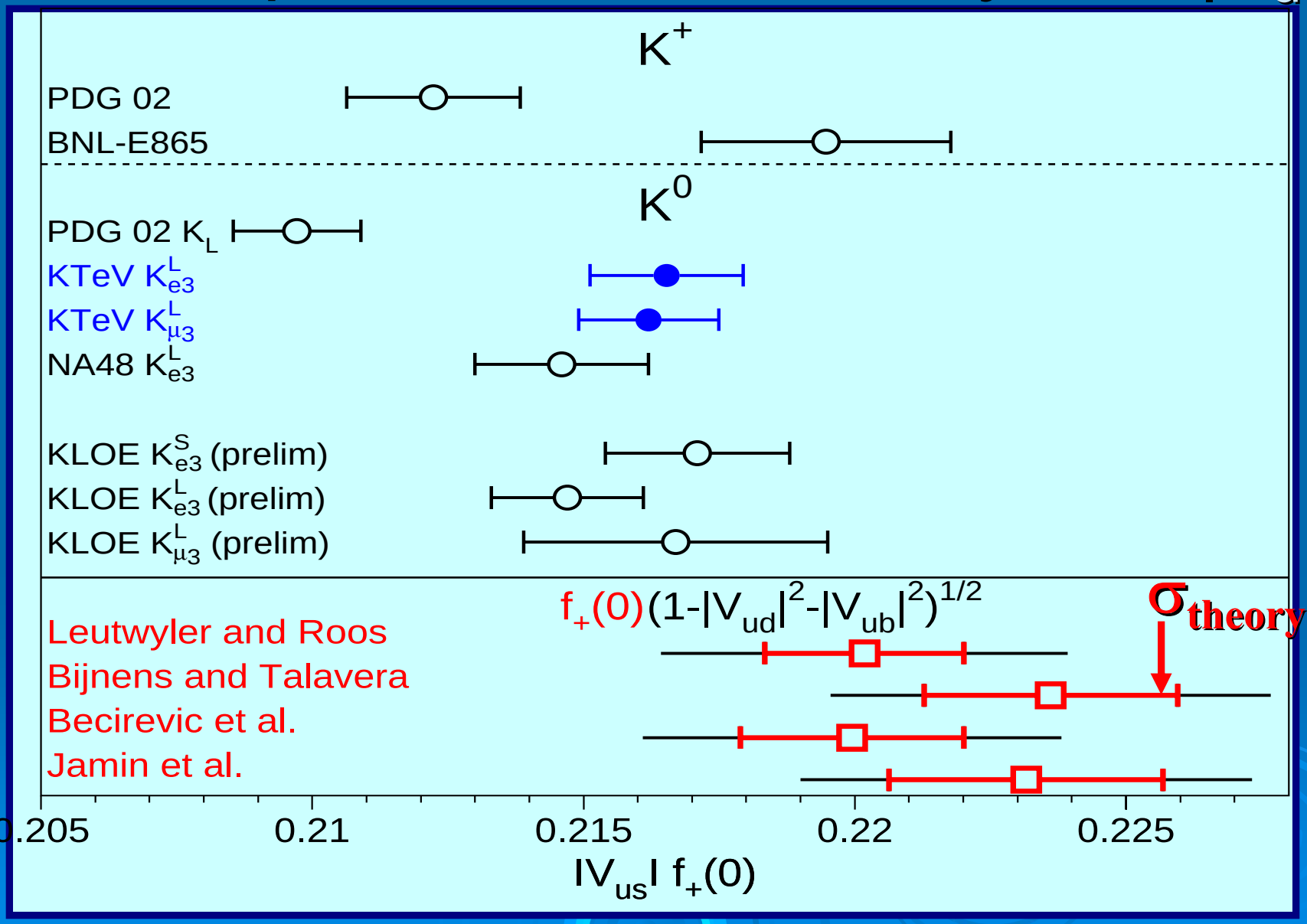
$\rightarrow \{f_+(0), \tau_L\}$

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

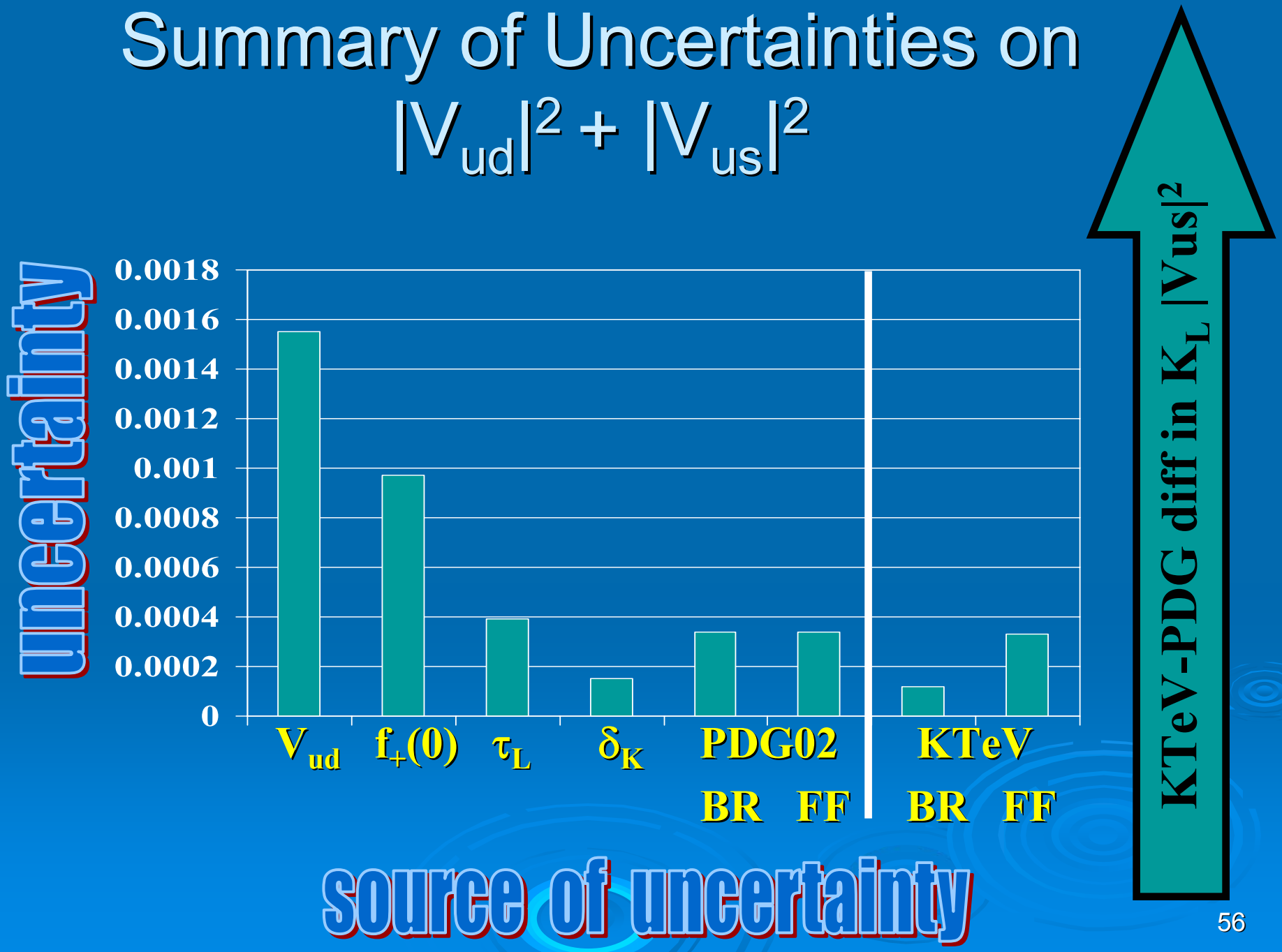
$|V_{us}|*f_+(0)$ Comparisons with Data



Comparisons with Theory and $|V_{ud}|$

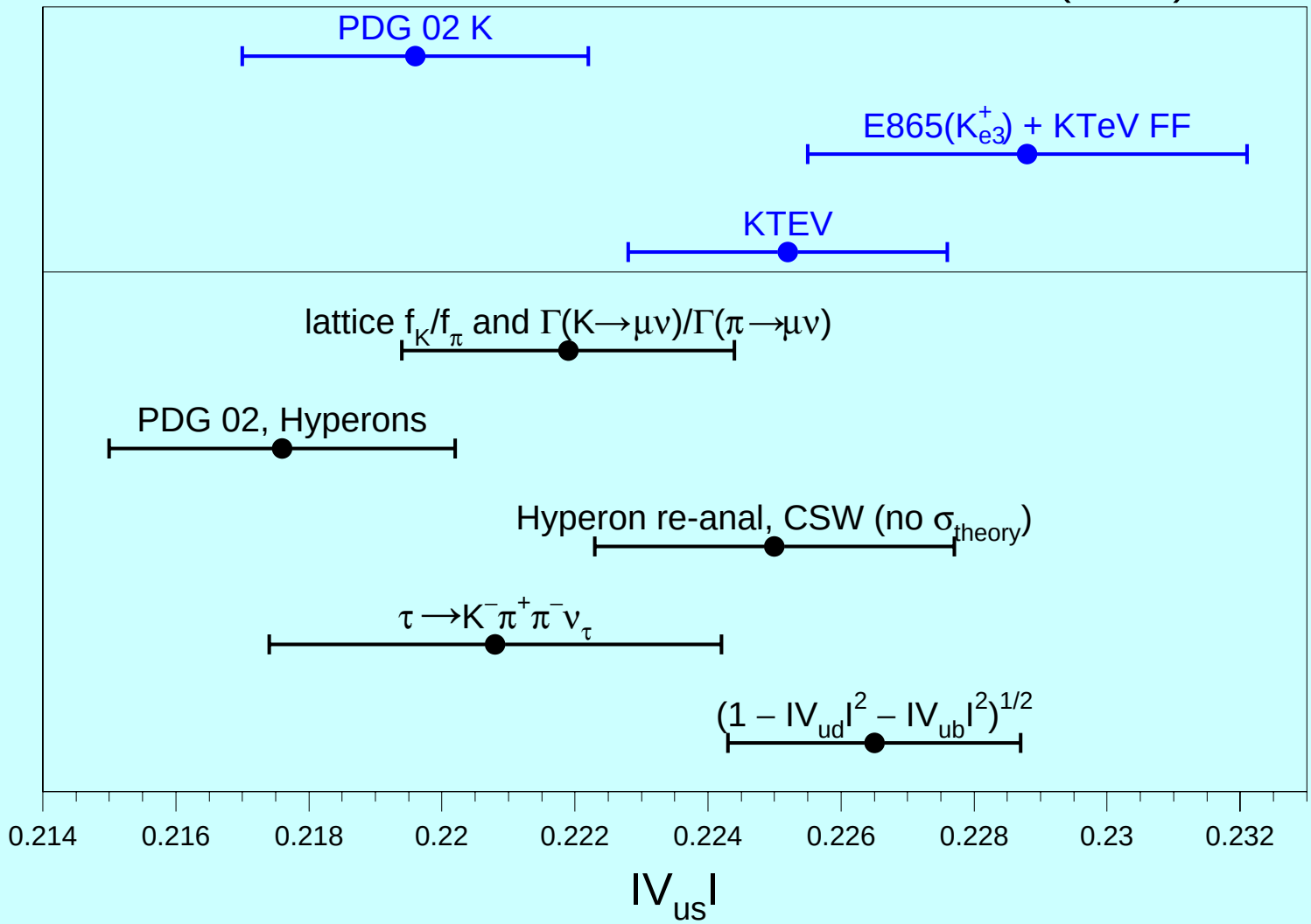


Summary of Uncertainties on $|V_{ud}|^2 + |V_{us}|^2$



Other Methods to Determine $|V_{us}|$

Czarnecki, Marciano, Sirlin, PRD 70 093006 (2004)



KTeV Measurement Summary

- **Four of the six largest K_L branching fractions differ from PDG02 by 5-8%**
  (rare decays normalizations ??).

- **Improved form factors for Ke3 and Kμ3**
  (x3 and x5 better precision than PDG02);
  allows similar $|V_{us}|$ errors from both Kℓ3 modes.

- **Our $|\eta_{+-}|$ value is 2.6% lower than PDG02.**

KTeV $|V_{us}|$ Summary

- **KTeV measurements result in +3% shift in $|V_{us}|$ compared to PDG02 (from K_L decays); KTeV-PDG02 difference in K_L-$|V_{us}|$ is 5σ !**

- **Our $|V_{us}|$ value is consistent with unitarity: $1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = 0.0018 \pm 0.0019$.**

KTeV Publications on $|V_{us}|$

$|V_{us}|$ determination	PRL 93, 181802 (2004)
K_L branching fractions	PRD 70, 092006 (2004)
Kℓ3 form factors	PRD 70, 092007 (2004)
B(Kℓ3γ)/B(Kℓ3) and γ decay distributions	PRD 71, 012001 (2005)

Supporting Publication

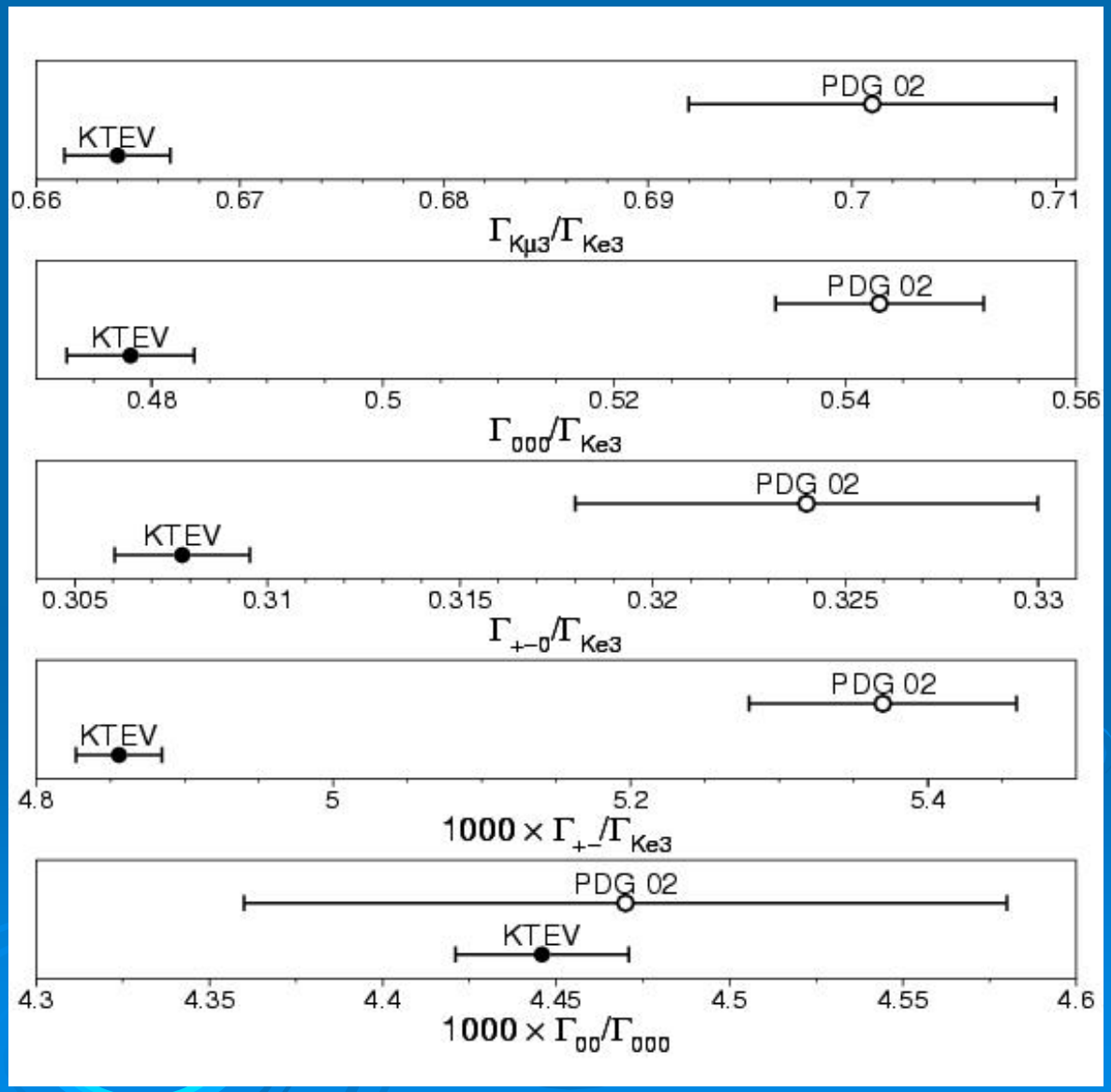
Kℓ3γ Theory (KLOR)	hep-ph/0406006

Extra Slides

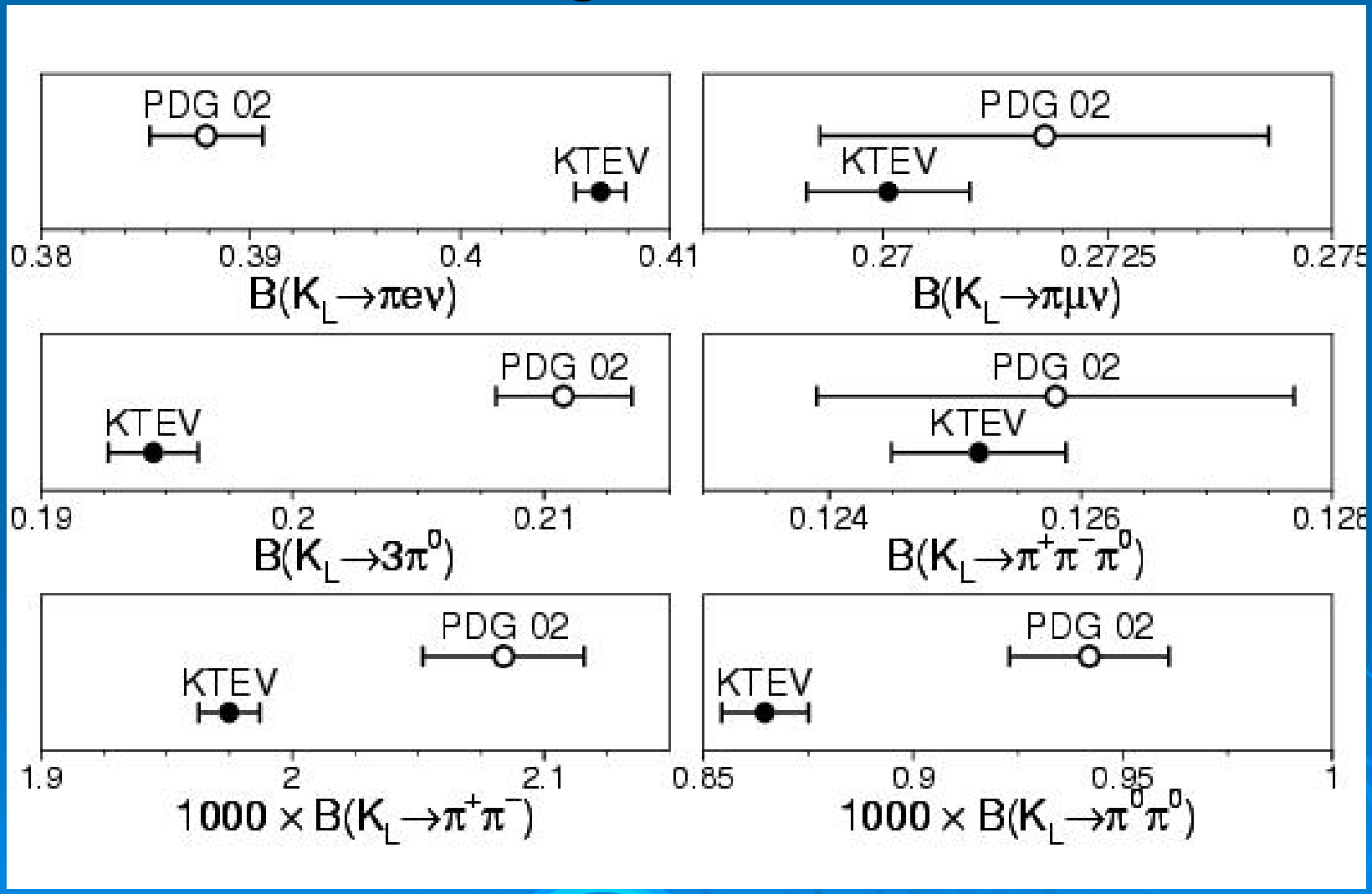
Partial Width Ratio Results

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

Only Γ_{00}/Γ_{000} agrees with PDG.

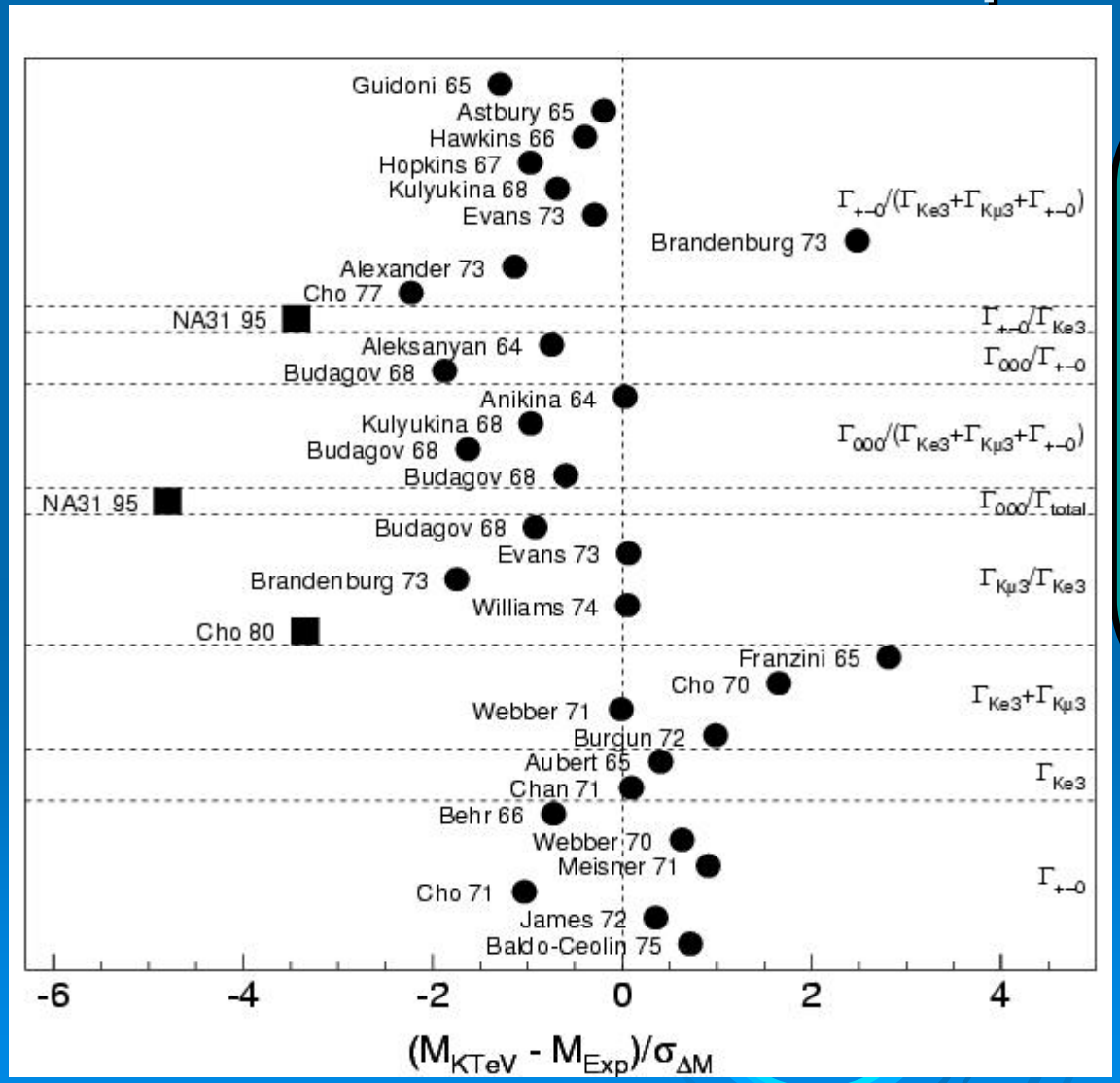


KTeV Branching Fractions assuming $\Sigma B = 0.9993$



PRD 70, 092006 (2004)

KTeV Comparison with Individual Experiments

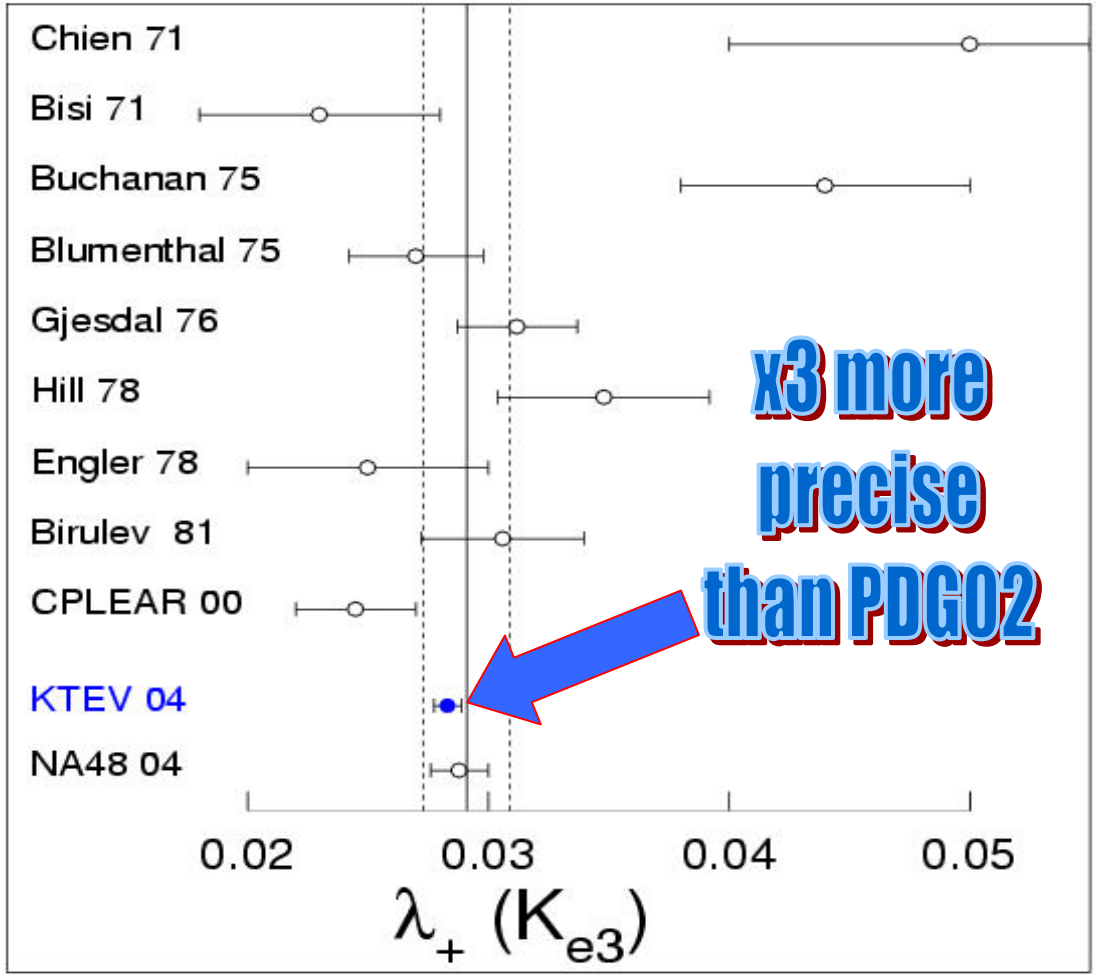


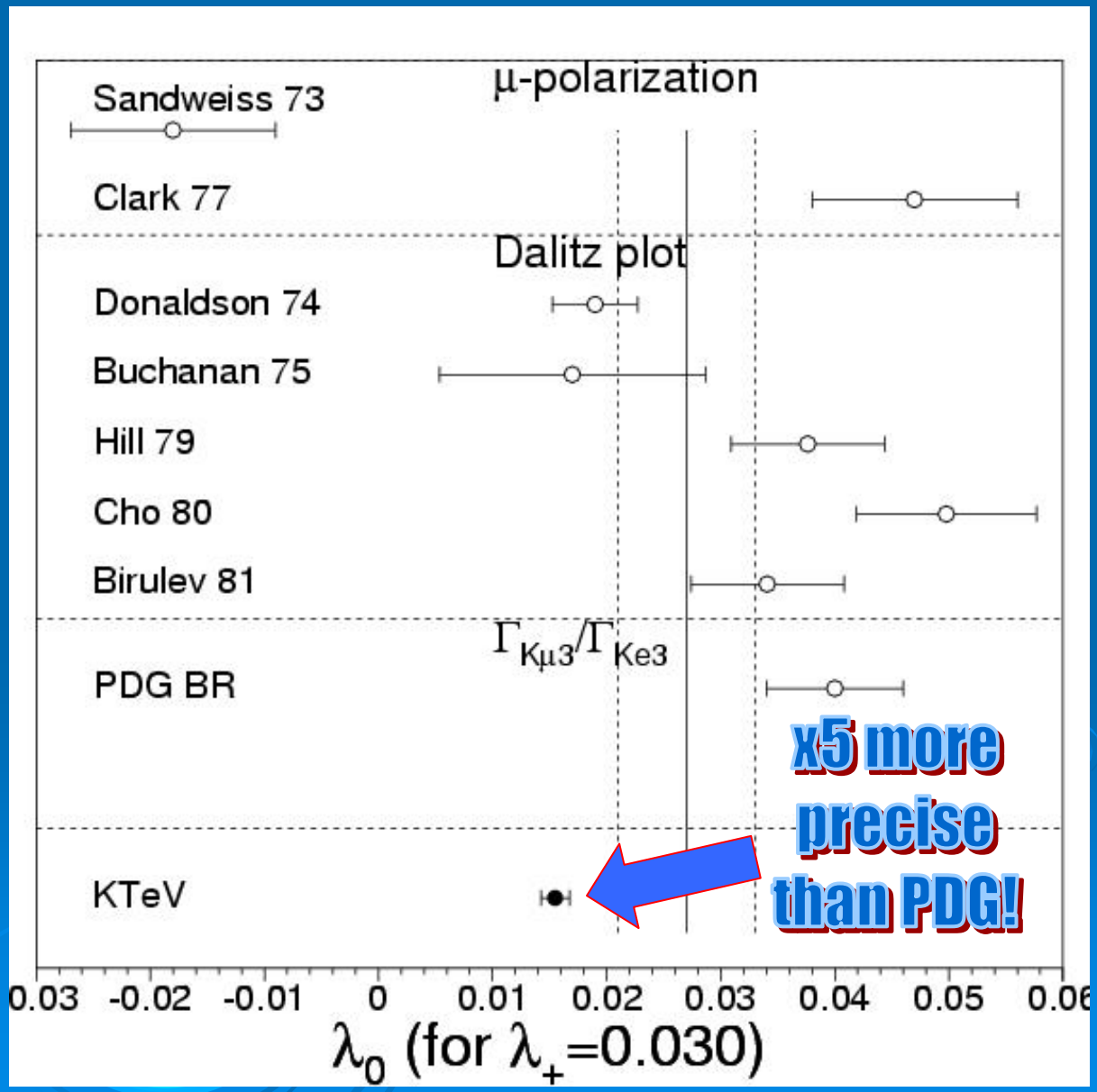
M_{KTeV} = KTeV measurement

M_{exp} = measurement from previous experiment

Semileptonic Form Factors: λ_+

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



Semileptonic Form Factors: λ_0

KTeV λ_0 agrees with only 2 of 8 previous measurements.