KTeV Results on |Vus| and Rare K_L Decays

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|Vus|
Unitarity of CKM matrix

- PDG 2004 : 2.2σ deviation

  $$1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) = (3.30 \pm 1.50) \times 10^{-3}$$

- Error on |Vus| contributes 1.14x10^{-3}
- |Vus| by BNL E865 ($K^+ \to \pi^0 e\nu$) is consistent with unitarity
- |Vus| by $K_L \to \pi e\nu$, $\pi\mu\nu$ BR should be remeasured

How to measure |Vus|

KTeV measures $B(K_L \to \pi e \nu)$ and $B(K_L \to \pi \mu \nu)$

KTeV measures form factors needed to calculate phase space integrals

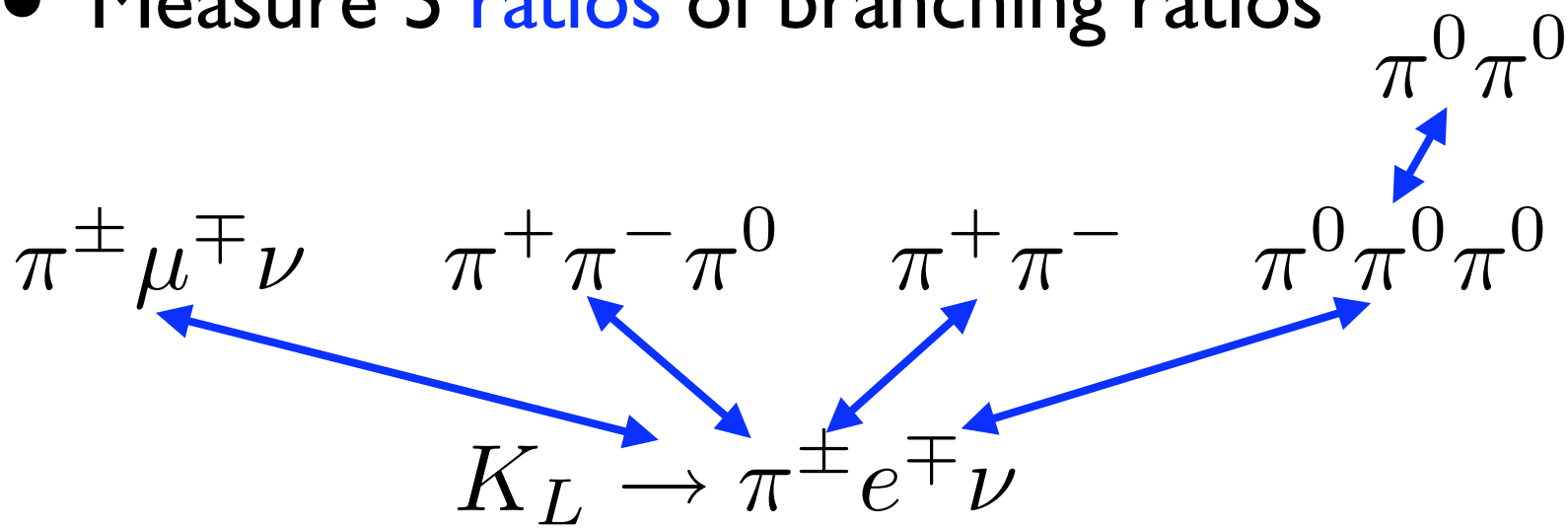
$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} \underbrace{S_{EW}(1+\delta_K^\ell)} \left|V_{us}\right|^2 f_+^2(0) I_K^\ell$$

Rad. Corrections (theory)

Form factor at t=0 (theory)

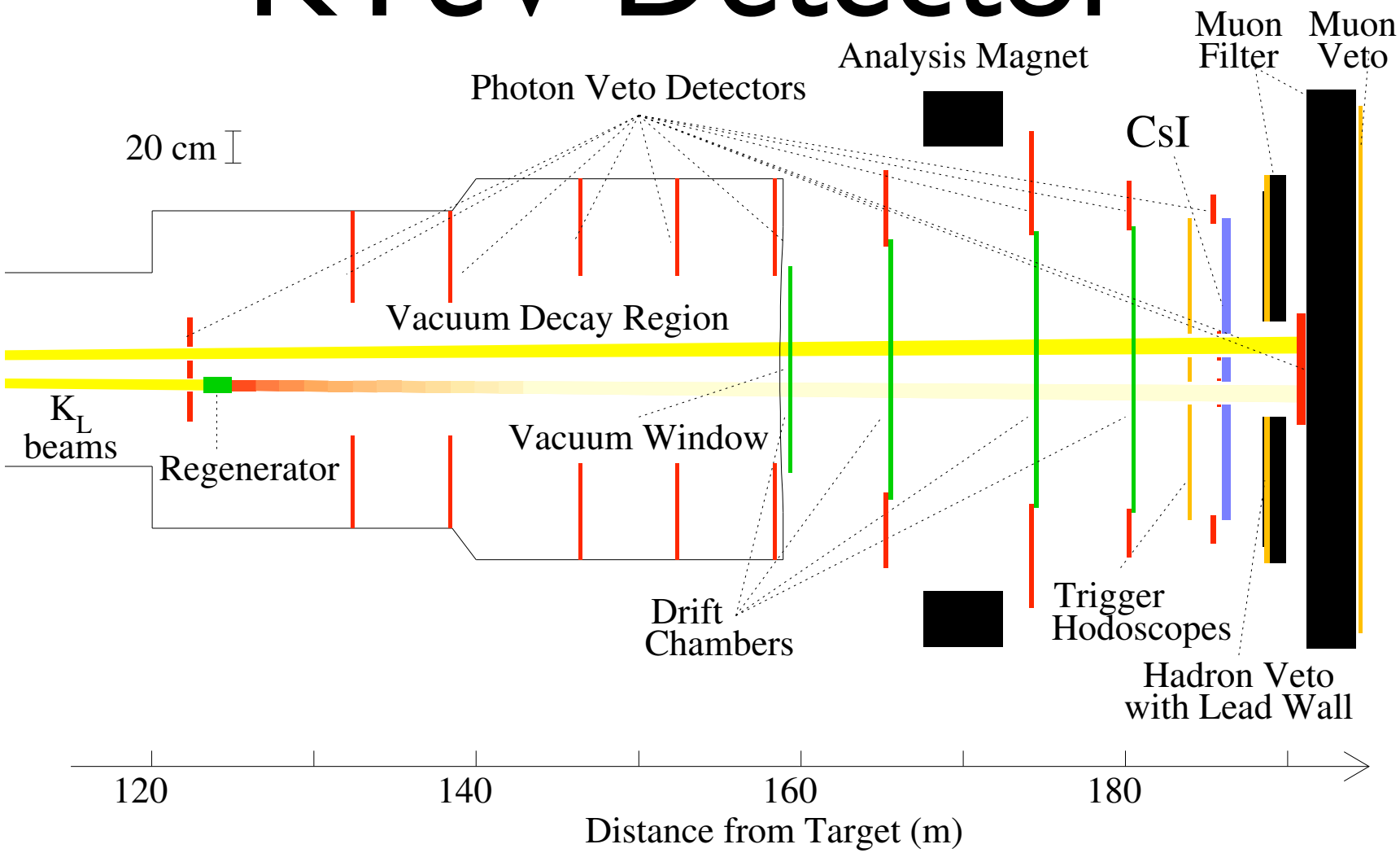
How to measure BRs

- Measure 5 ratios of branching ratios



- Sum of 6 BRs = 99.93%
- Each ratio is measured in statistically independent samples collected with the same trigger

KTeV Detector

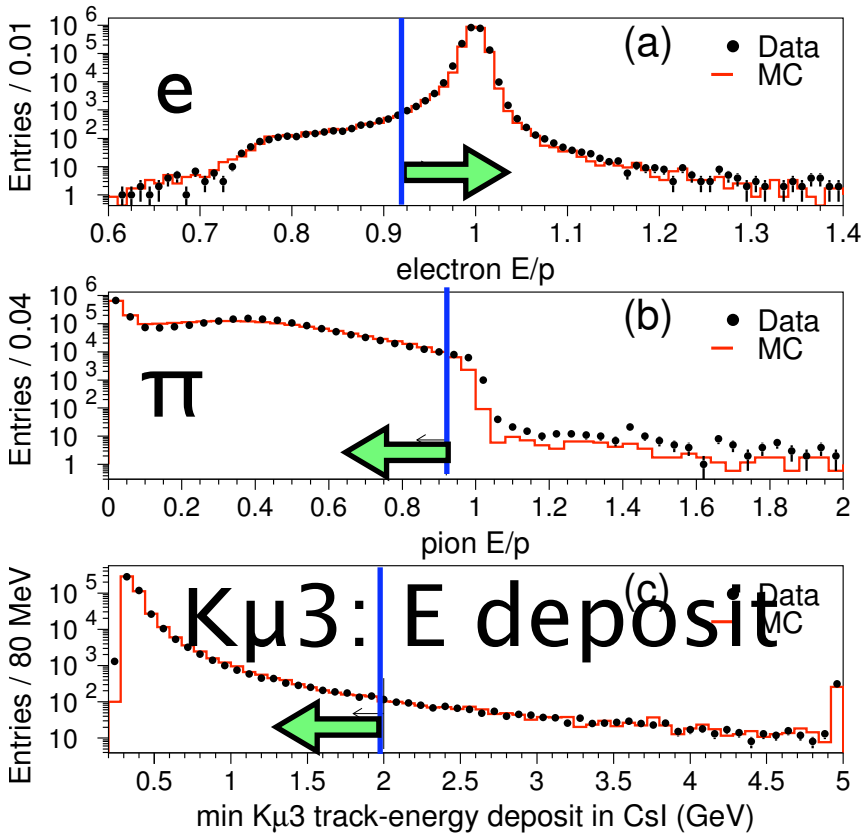


- $\Delta p/p < 1\%$ ($p > 8$GeV), p scale known to 0.01%
- $\Delta E/E < 1\%$ ($E\gamma > 3$GeV), E scale known to 0.1%

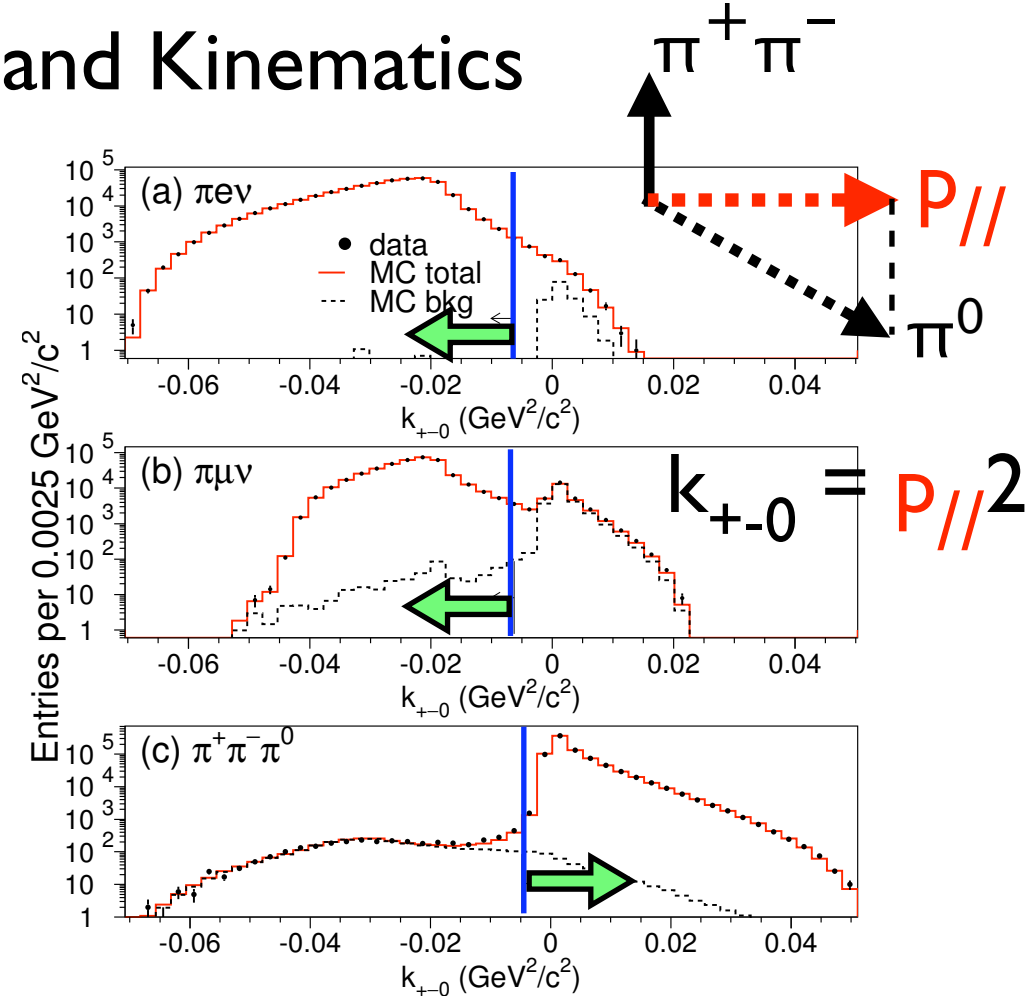
Charged modes

To minimize biases:

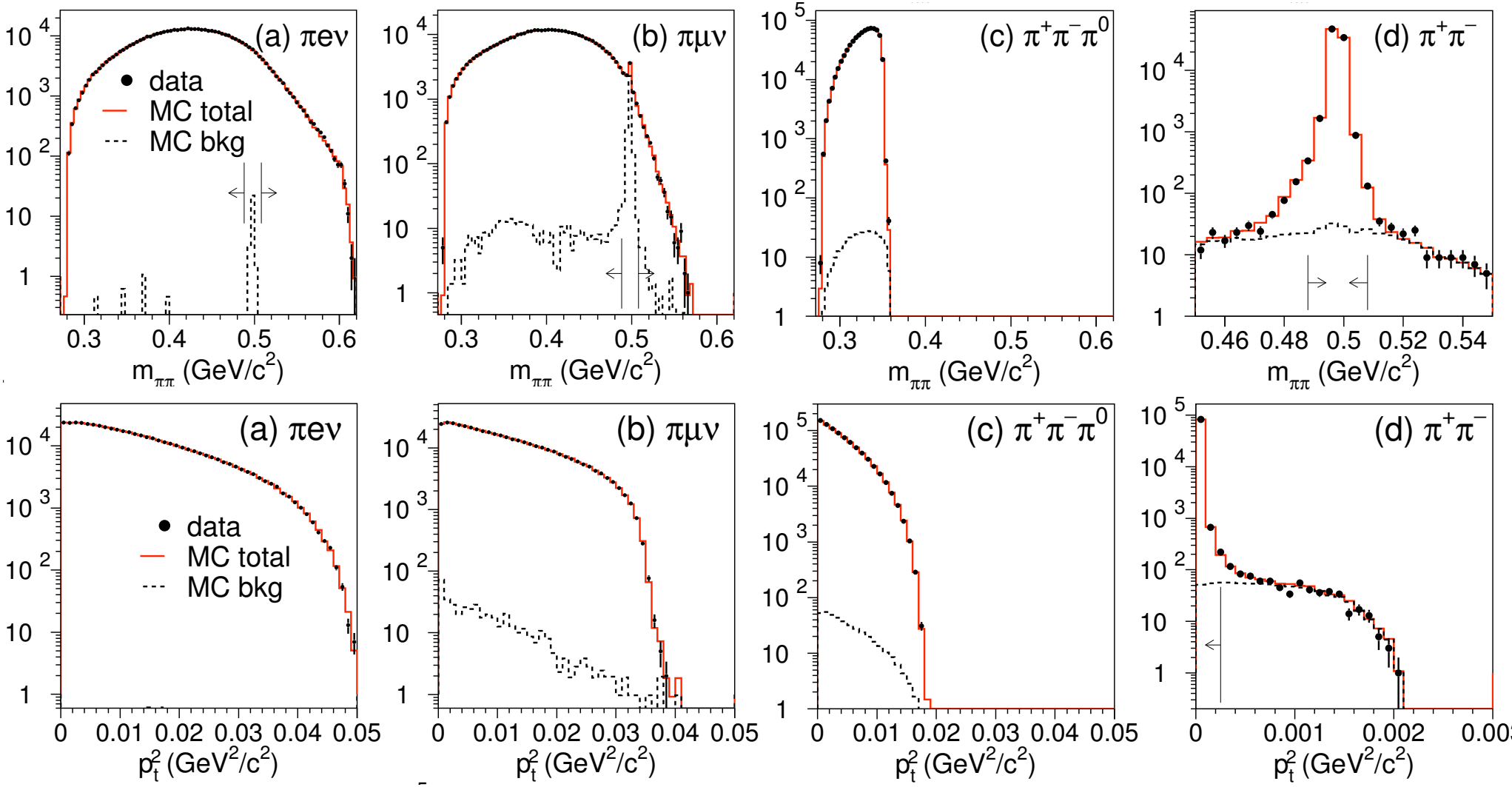
- Require only 2 tracks (even for $\pi^+\pi^-\pi^0$)
- Particle ID with E/p and Kinematics



Kμ3: E deposit



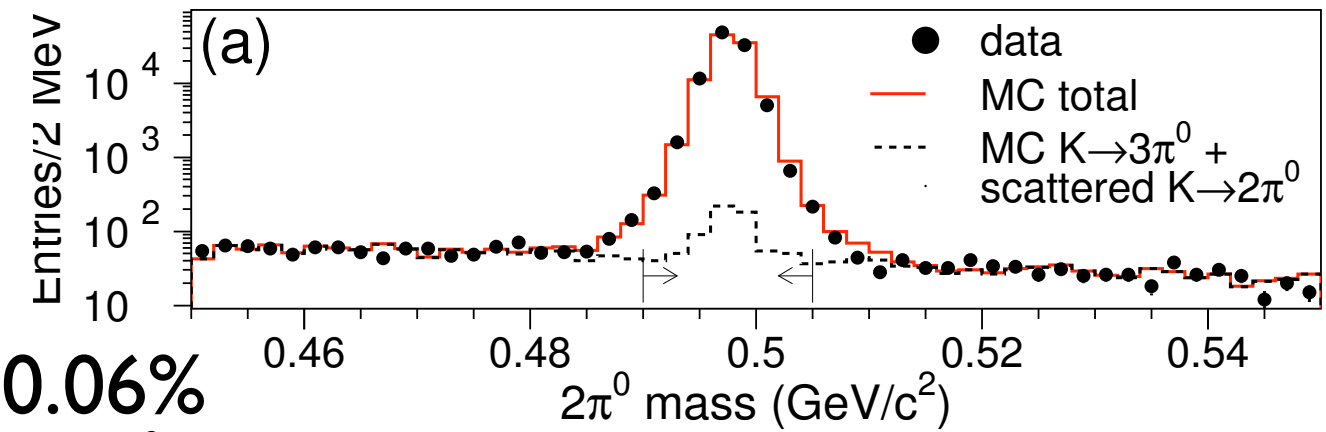
Charged modes

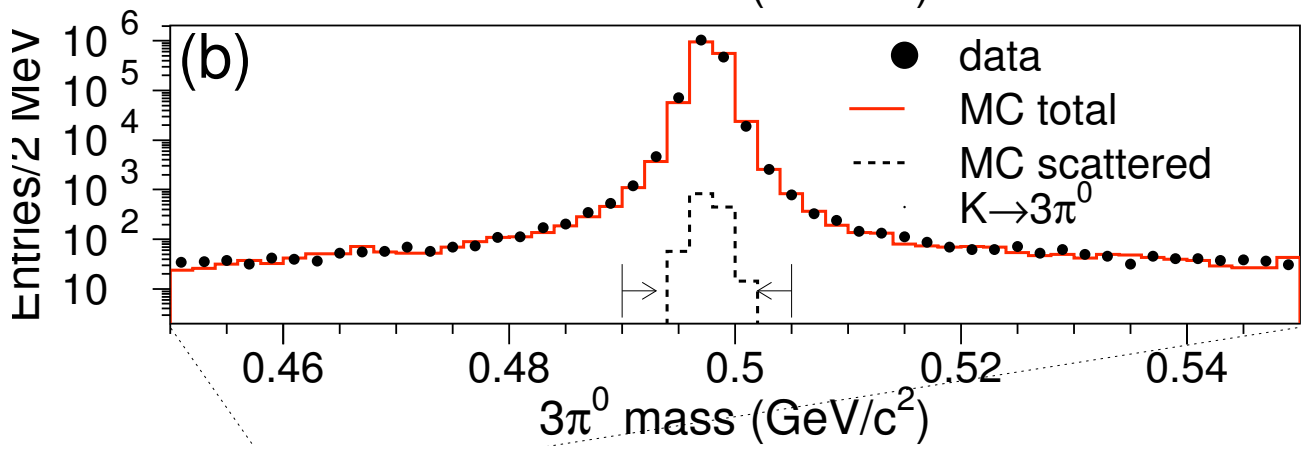


Bkg <0.003% 0.0011% 0.0005% 0.0016%

Neutral modes

- $2\pi^0$
  - 4clusters
  - Bkg: 0.71±0.06%
- $3\pi^0$
  - 6clusters
  - Bkg: none

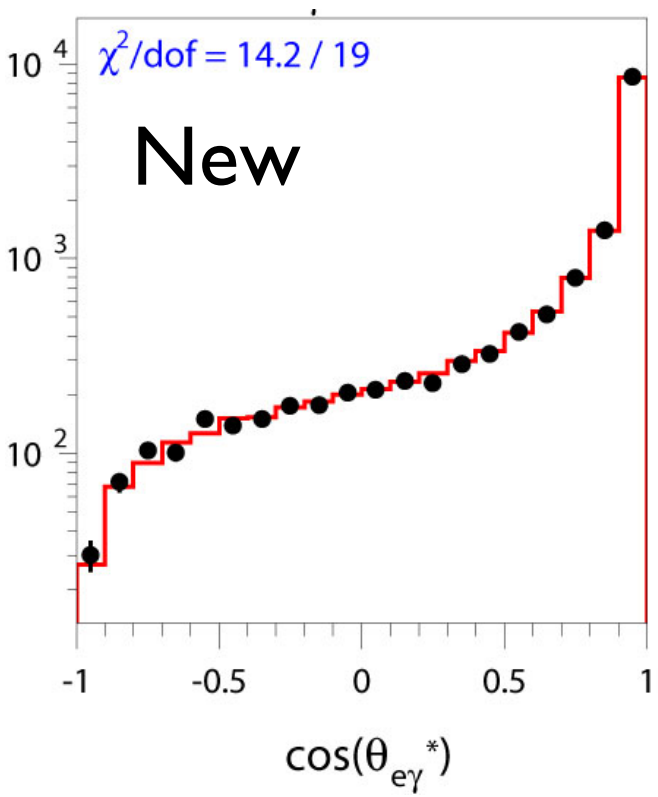


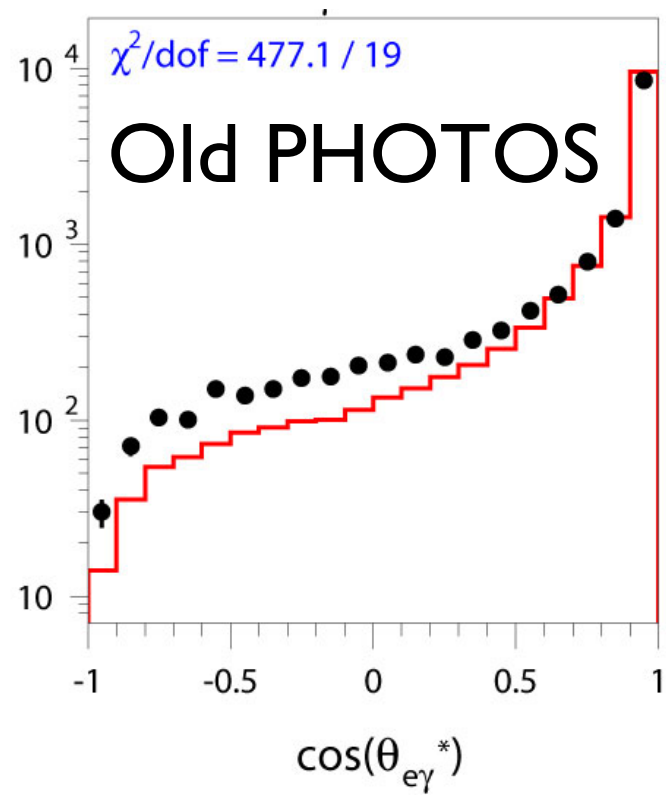


$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW}(1+\delta_K^\ell) |V_{us}|^2 f_+^2(0) I_K^\ell$$

Radiative Corrections

- New inner brems MC for Ke3γ and Kμ3γ (T.Andre, hep-ph/0406006)
- Acceptance for Ke3 changes by 2-3% w/o innerbrem. uncertainty = 0.14~0.20%.





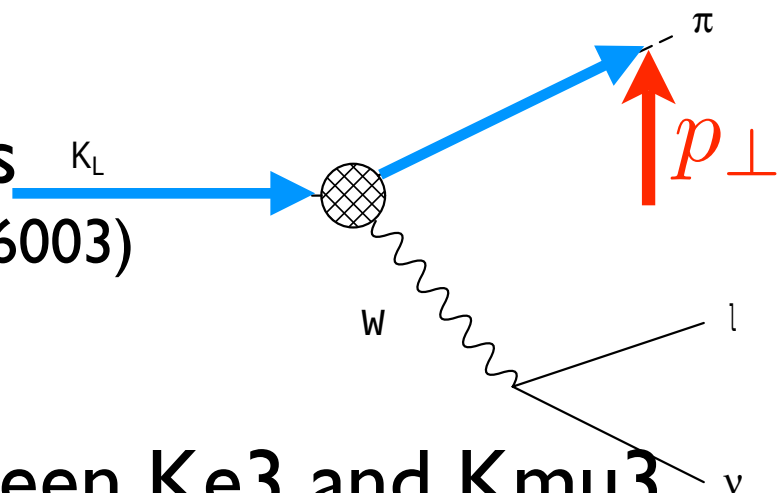
$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW}(1+\delta_K^\ell) |V_{us}|^2 f_+^2(0) I_K^\ell$$

Form Factor

- Use transverse version of 4-mom transfer

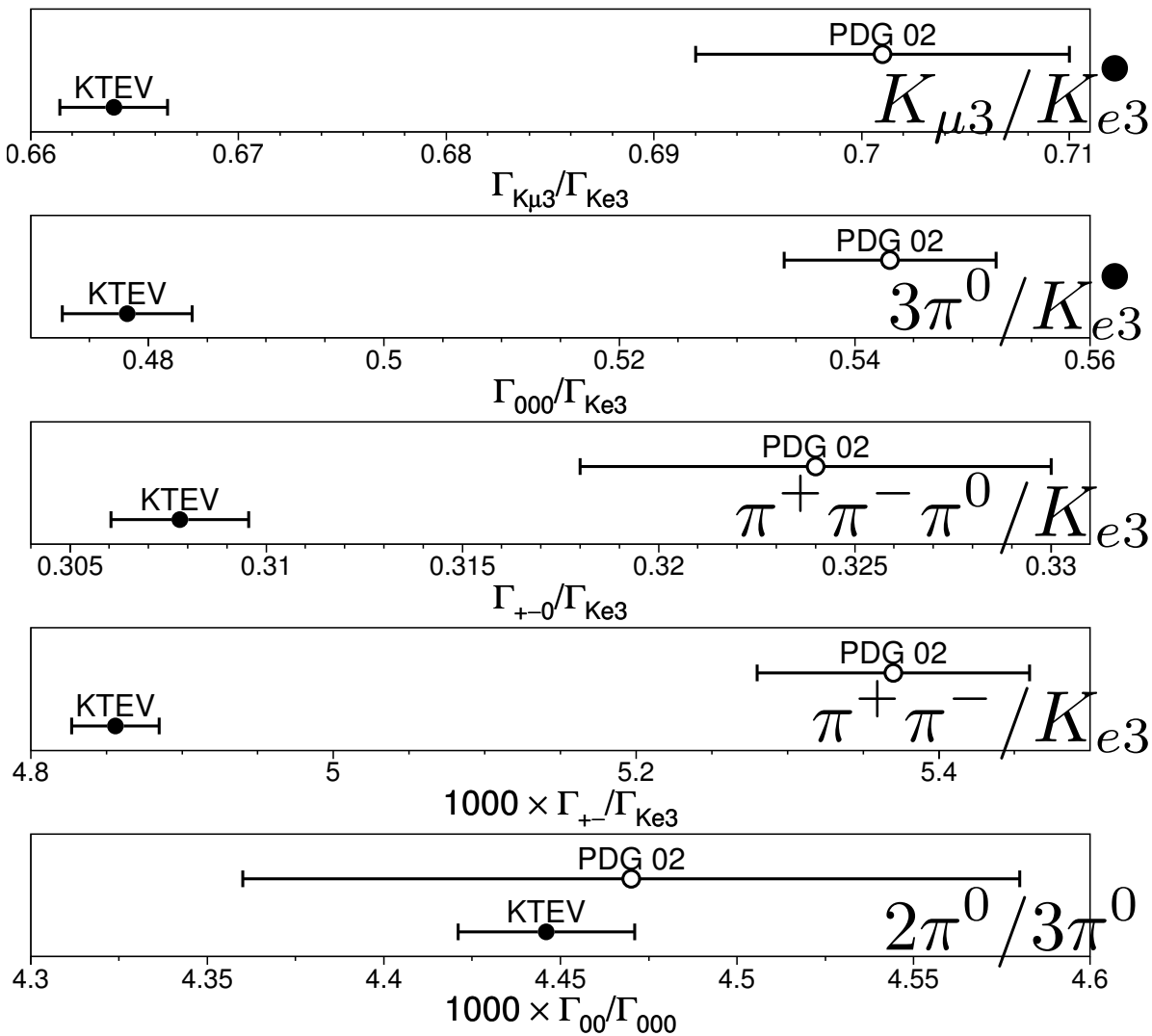
  $$t = (P_K - P_\pi)^2$$

  to measure form factors
  (submitted to PRD, hep-ex/0406003)



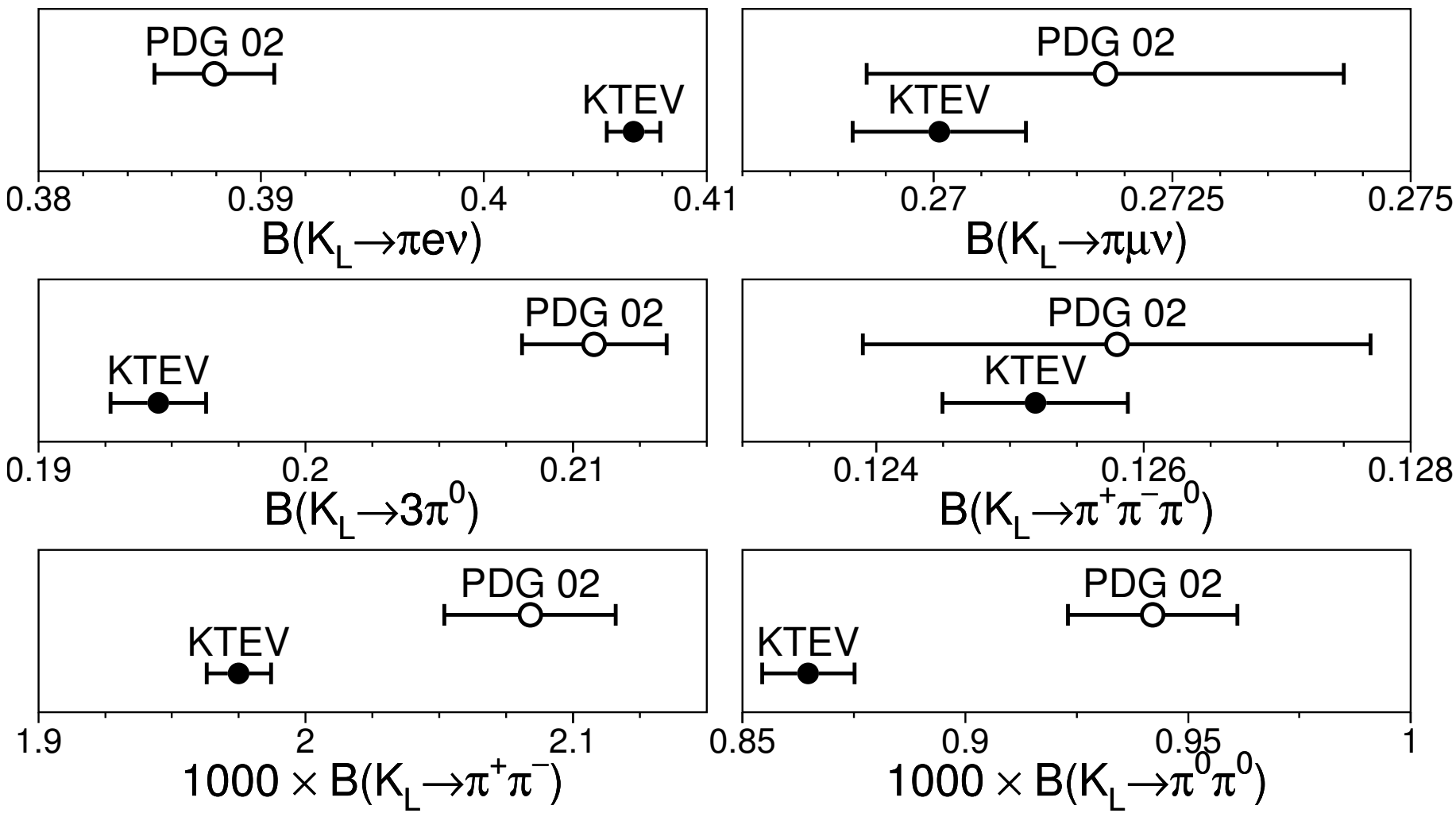
- Consistent results between Ke3 and Kmu3
- x3 ~ x5 more precise than PDG values
- Our form factor decreases Kmu3 phase space integral by 4.2% compared to PDG ff

BR Ratio Results



- 0.35% error per pion for track loss
- $\Gamma_{000}/\Gamma_{Ke3}$ systematic error
  - 0.6% : two track efficiency
  - 0.4% : 3pi0 reconstruction
  - 0.6% : detector materials

BR Results


PDG 02
KTEV
0.38
0.39
0.4
0.41
B(K_L→πeν)
PDG 02
KTEV
0.27
0.2725
0.275
B(K_L→πμν)
PDG 02
KTEV
0.19
0.2
0.21
B(K_L→3π^0)
PDG 02
KTEV
0.124
0.126
0.128
B(K_L→π^+π^−π^0)
PDG 02
KTEV
1.9
2
2.1
1000 × B(K_L→π^+π^−)
PDG 02
KTEV
0.85
0.9
0.95
1
1000 × B(K_L→π^0π^0)

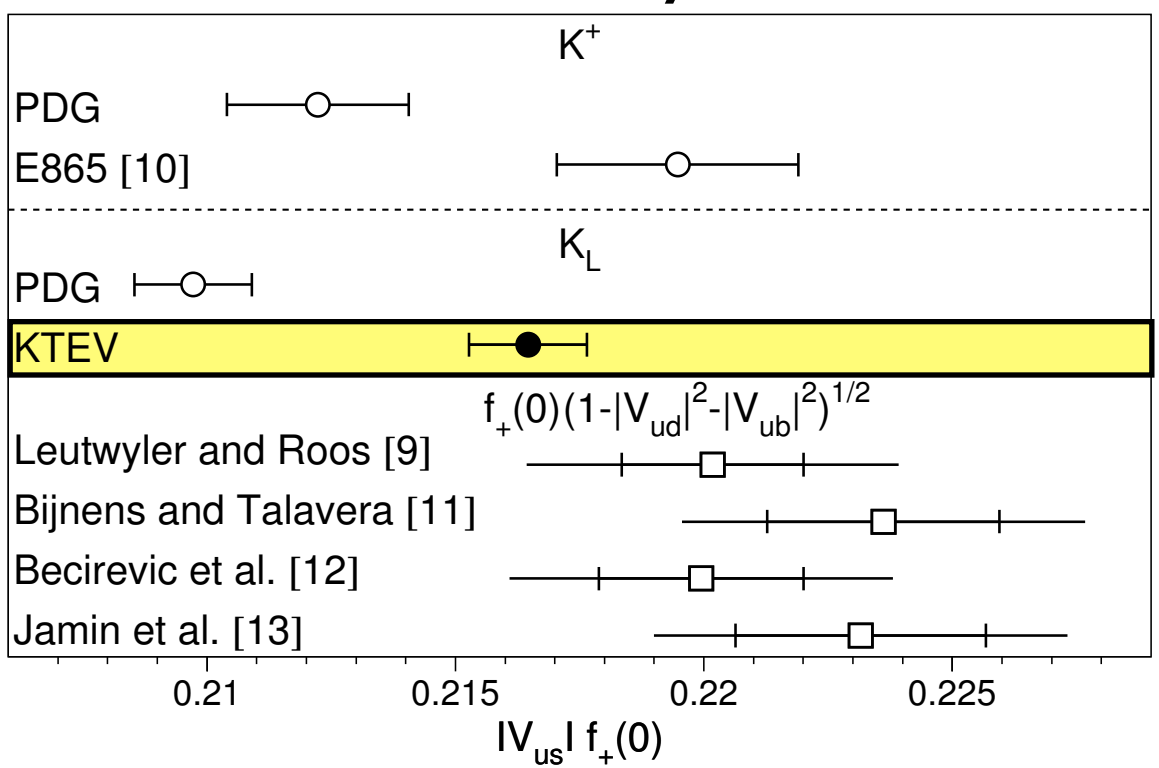
$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW}(1+\delta_K^\ell)|V_{us}|^2 f_+^2(0) I_K^\ell$$

|Vus| Result

- |Vus| = 0.2252±0.0008(KTeV)±0.0021(ext)
  - =0.2253±0.0023(Ke3), 0.2250±0.0023(Kμ3)

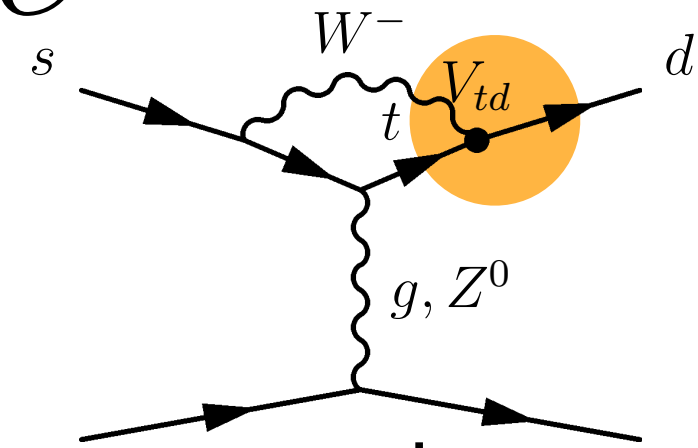
f+(0), KL lifetime, rad.corr.

- $1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) = 0.0018 \pm 0.0019$
- Consistent with unitarity

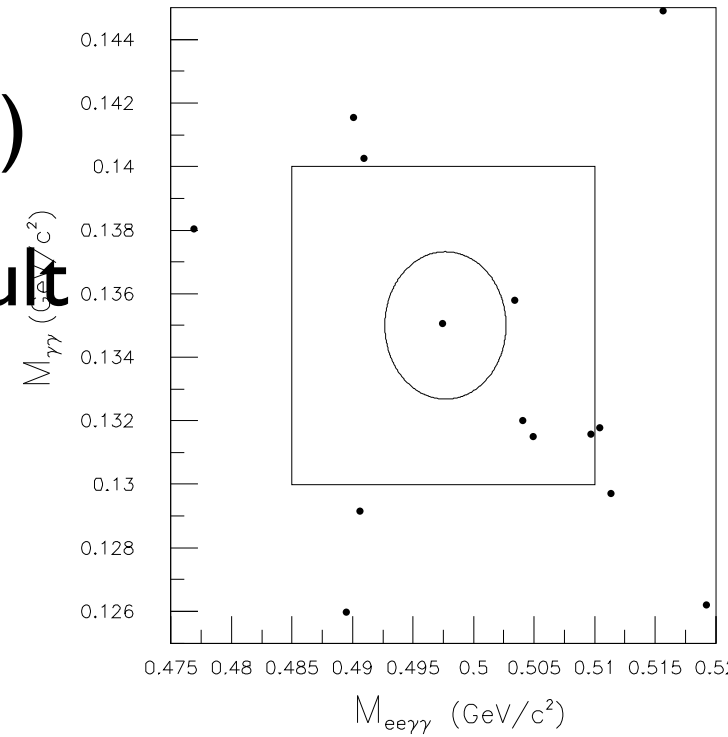


Rare Decays

$K_L \to \pi^0 e^+ e^-$



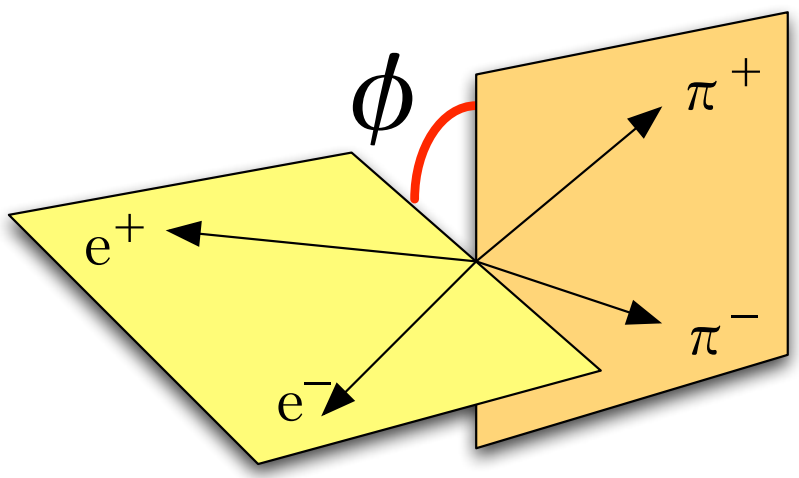
- 1999 run
  - 1 event in signal region, while 0.99±0.35 bkg events are expected.
  - BR < 3.50 x 10^{-10} (90% CL)
- Combined with 1997 run result
  - BR < 2.8 x 10^{-10} (90% CL)
- PRL 93, 021805 (2004).

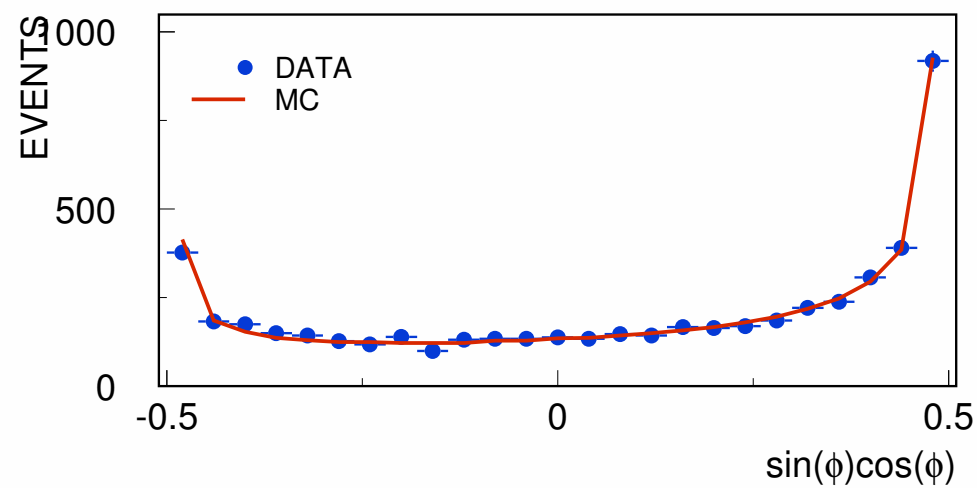


CP Violation in

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

- 5241 events (185±14 background events) in 1997 + 1999 run data
- Asymmetry = 13.7±1.4(stat)±1.5(syst)% (preliminary)
  - CP violation in K0-K0bar mixing
  - Consistent with previous KTeV and NA48 results





Conclusions

- Measured 6 major KL branching ratios and Kl3 form factors in the same detector
- Four BR differ from PDG by 5~8%
- |Vus| is 3% higher than PDG, and unitarity holds
  - Submitted to PRL and PRD: hep-ex/0406001~3/
- New limit on $K_L \to \pi^0 ee$ (PRL93,0218055(2004))
- New asymmetry and form factor meas. on $K_L \to \pi\pi ee$

Backup slides

Lepton universality

Compare $\Gamma_{K\ell 3} = \dfrac{G_F^2 M_K^5}{192\pi^3} S_{EW}(1+\delta_K^\ell)\left|V_{us}\right|^2 f_+^2(0) I_K^\ell$ for K_{e3} and $K_{\mu 3}$

$$\left[\frac{\Gamma_{K\mu 3}}{\Gamma_{Ke3}}\right]_{PRED} = \left(\frac{1+\delta_K^\mu}{1+\delta_K^e}\right)\left(\frac{I_K^\mu}{I_K^e}\right)$$

1.0058(10) from Andre

0.6622(18) from KTeV

$$\left[\frac{\Gamma_{K\mu 3}}{\Gamma_{Ke3}}\right]_{MEAS} \Big/ \left[\frac{\Gamma_{K\mu 3}}{\Gamma_{Ke3}}\right]_{PRED} = 0.9969 \pm 0.0048 = \left(\frac{G_F^\mu}{G_F^e}\right)^2$$

Same test with PDG widths and FF gives 1.0270±0.0182

What changed |Vus|?

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

Compared to PDG:

Γ_{Ke3} increases by 5%
$\Gamma_{K\mu 3}$ doesn't change

I^e decreases by 1.7%
I^μ decreases by 4.2%
(both include -1% shift from λ_+'')

Partial decay width ratios

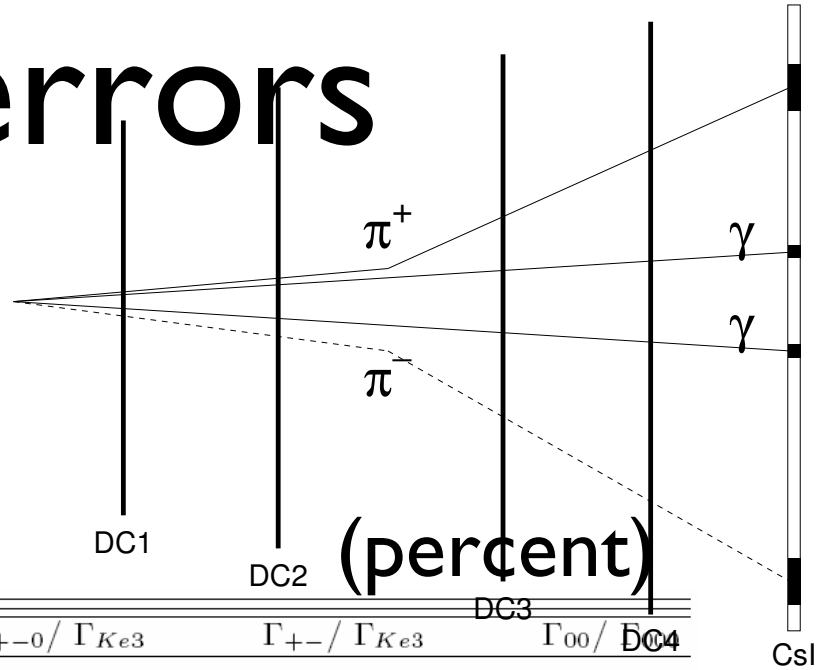
Decay Modes	Partial Width Ratio
$\Gamma_{K\mu 3} / \Gamma_{Ke3}$	$0.6640 \pm 0.0014 \pm 0.0022$
$\Gamma_{000} / \Gamma_{Ke3}$	$0.4782 \pm 0.0014 \pm 0.0053$
$\Gamma_{+-0} / \Gamma_{Ke3}$	$0.3078 \pm 0.0005 \pm 0.0017$
$\Gamma_{+-} / \Gamma_{Ke3}$	$(4.856 \pm 0.017 \pm 0.023) \times 10^{-3}$
$\Gamma_{00} / \Gamma_{000}$	$(4.446 \pm 0.016 \pm 0.019) \times 10^{-3}$

BR results

Decay Mode	Branching Fraction	Γ_i (10^7 s^{-1})
$K_L \to \pi e \nu$	0.4067±0.0011	0.7897±0.0065
$K_L \to \pi \mu \nu$	0.2701±0.0009	0.5244±0.0044
$K_L \to \pi^+ \pi^- \pi^0$	0.1252±0.0007	0.2431±0.0023
$K_L \to \pi^0 \pi^0 \pi^0$	0.1945±0.0018	0.3777±0.0045
$K_L \to \pi^+ \pi^-$	$(1.975 \pm 0.012) \times 10^{-3}$	$(3.835 \pm 0.038) \times 10^{-3}$
$K_L \to \pi^0 \pi^0$	$(0.865 \pm 0.010) \times 10^{-3}$	$(1.679 \pm 0.024) \times 10^{-3}$

Systematic errors

- Largest : 3pi0/Ke3 due to track and pi0 reconstruction efficiencies, as they do not cancel : Studied with +-0, etc.

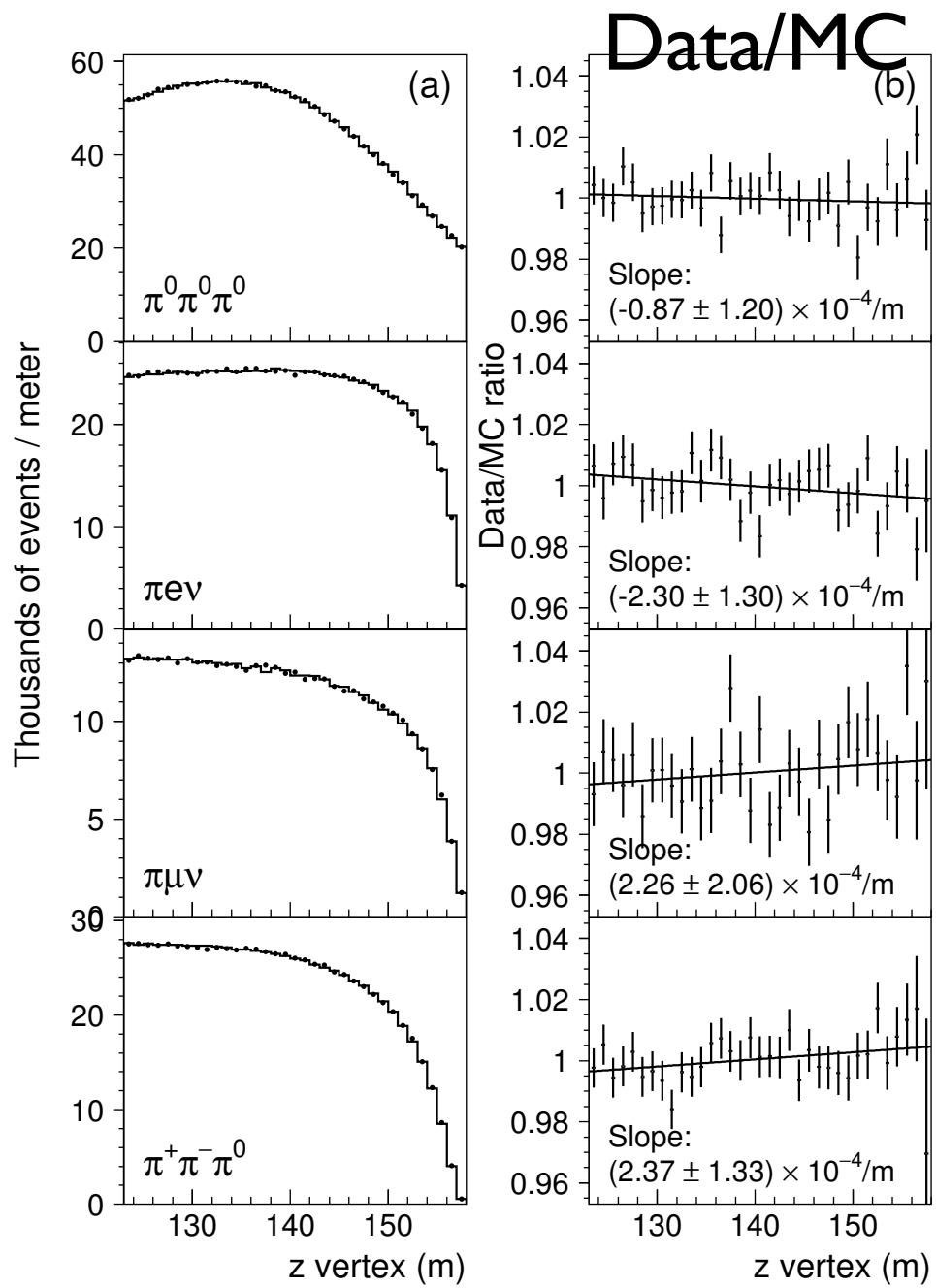


(percent)

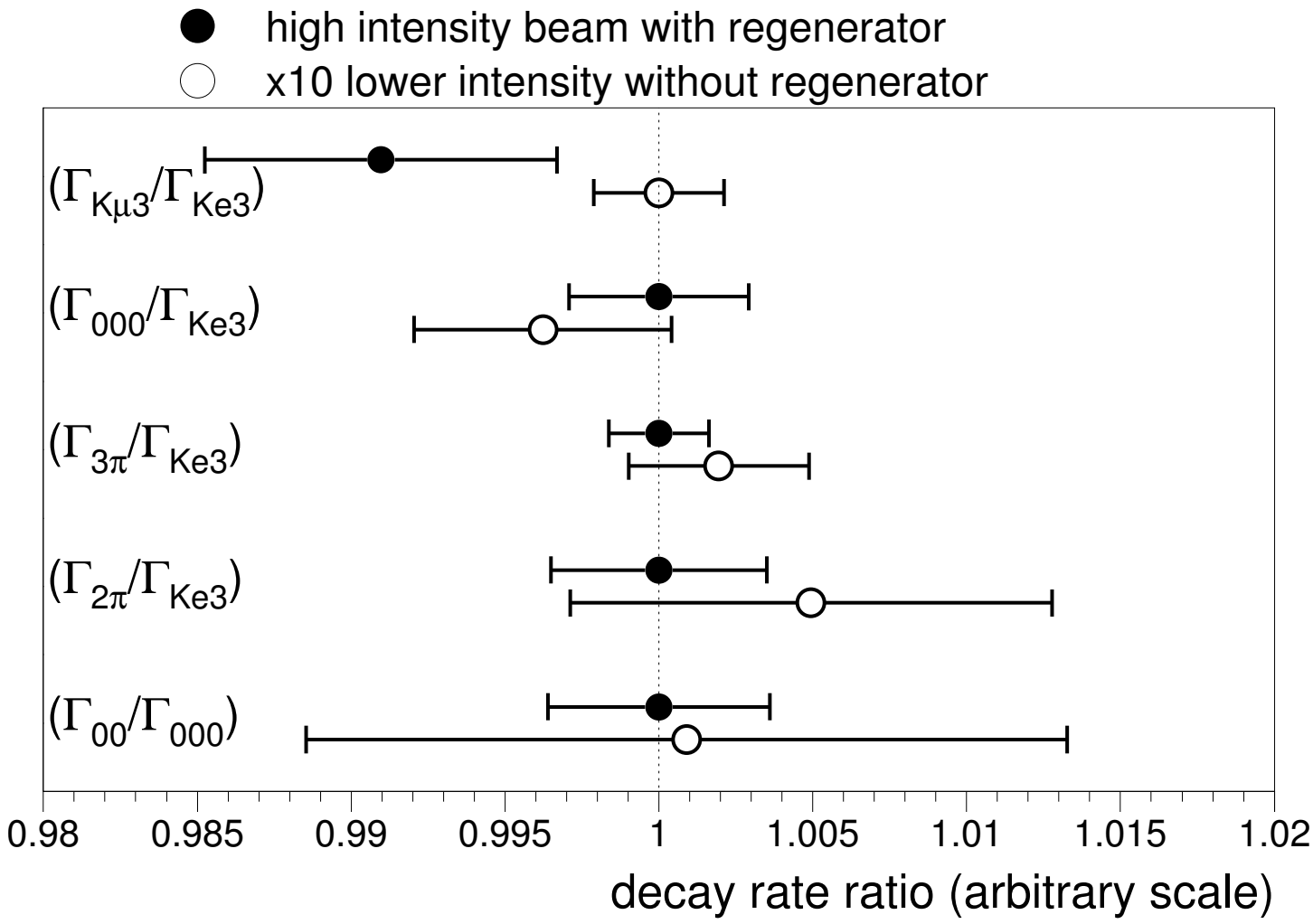
Source of uncertainty	$\Gamma_{K\mu3}/\ \Gamma_{Ke3}$	$\Gamma_{000}/\ \Gamma_{Ke3}$	$\Gamma_{+-0}/\ \Gamma_{Ke3}$	$\Gamma_{+-}/\ \Gamma_{Ke3}$	$\Gamma_{00}/\ \Gamma_{Ke3}$
Acceptance (MC Simulation)					
Event Generation:					
- Kaon energy spectrum	0.02	0.16	0.04	0.02	0.01
- Form factor	0.11	0.08	0.29	0.08	0.00
Radiative corrections:					
-	0.15	0.20	0.14	0.14	0.00
Particle Propagation:					
- Detector material	0.10	0.56	0.33	0.33	0.15
- Detector geometry	0.02	0.39	0.05	0.02	0.08
Detector Response:					
- Accidental activity	0.00	0.22	0.04	0.02	0.03
- Trigger	0.00	0.07	0.10	0.07	0.28
- $e^{\pm}, \mu^{\pm}, \pi^{\pm}$ reconstruction	0.21	0.70	0.24	0.26	0.00
- π^0 reconstruction	0.00	0.37	0.00	0.00	0.23
Background	0.10	0.00	0.02	0.04	0.04
$B(\pi^0 \to \gamma\gamma)$	0.00	0.10	0.10	0.00	0.03
Monte Carlo Statistics	0.10	0.12	0.05	0.13	0.16
Total	0.33	1.12	0.55	0.47	0.44

Acceptance check

- Error on BR ratio = z slope x difference in average z of 2 modes



Beam intensity



Comparisons with other experiments

