

REVIEW ON ϵ'/ϵ

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WHAT IS ϵ'/ϵ ?

□ CP VIOLATION IN KAON

□ INDIRECT CP VIOLATION
DUE TO K^0 - \bar{K}^0 MIXING
($\Delta S=2$)

CP ~ - CP- CP+

$$K_L \simeq K_2 + \epsilon K_1$$

ϵ' ↓

↘ $\pi\pi$ CP+

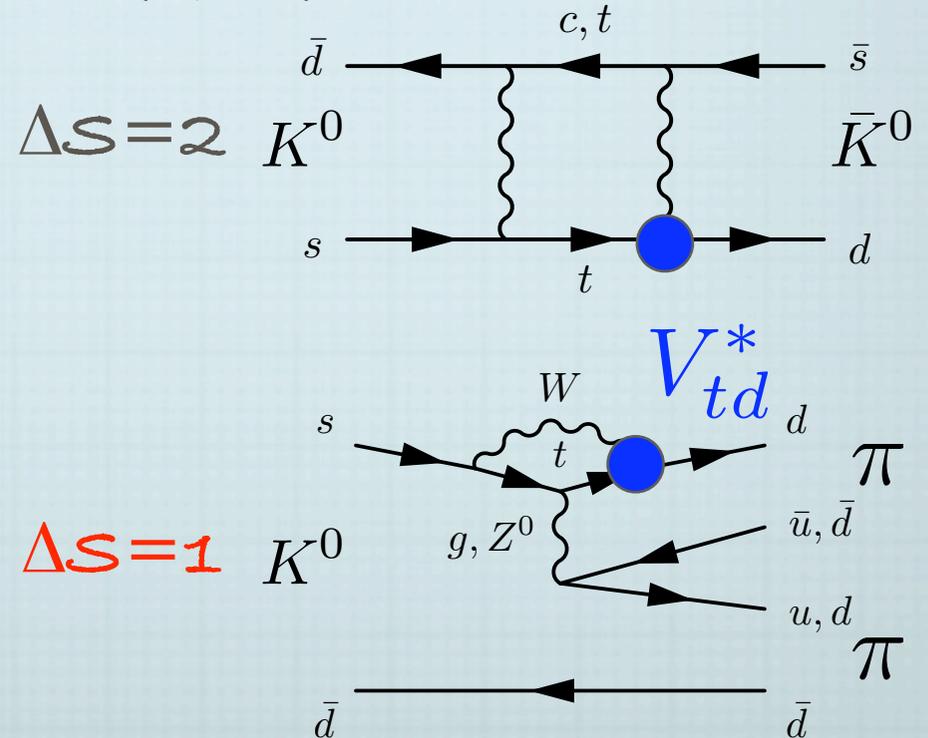
□ DIRECT CP VIOLATION IN
DECAY ($\Delta S=1$)

□ $\pi\pi$ CP+
□ allowed in SM, but not in
superweak ($\Delta S=2$)

SUPERWEAK $\Delta S=2$ interaction?



STANDARD MODEL?



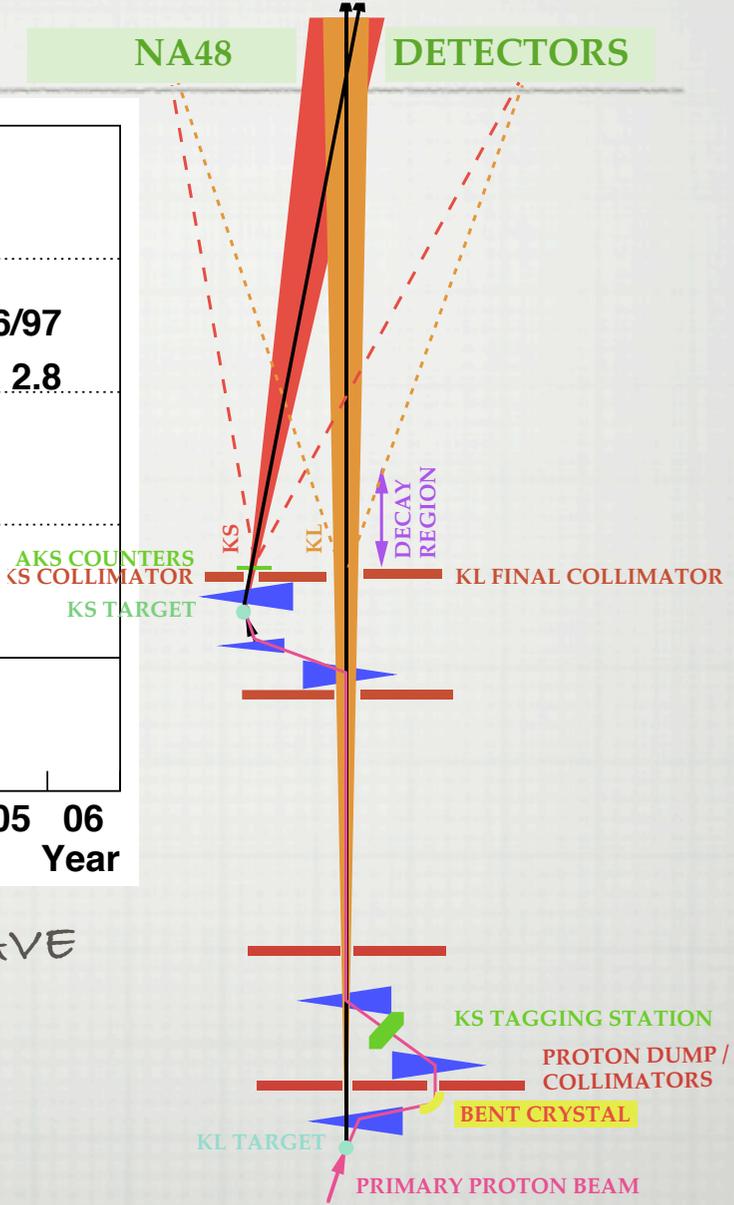
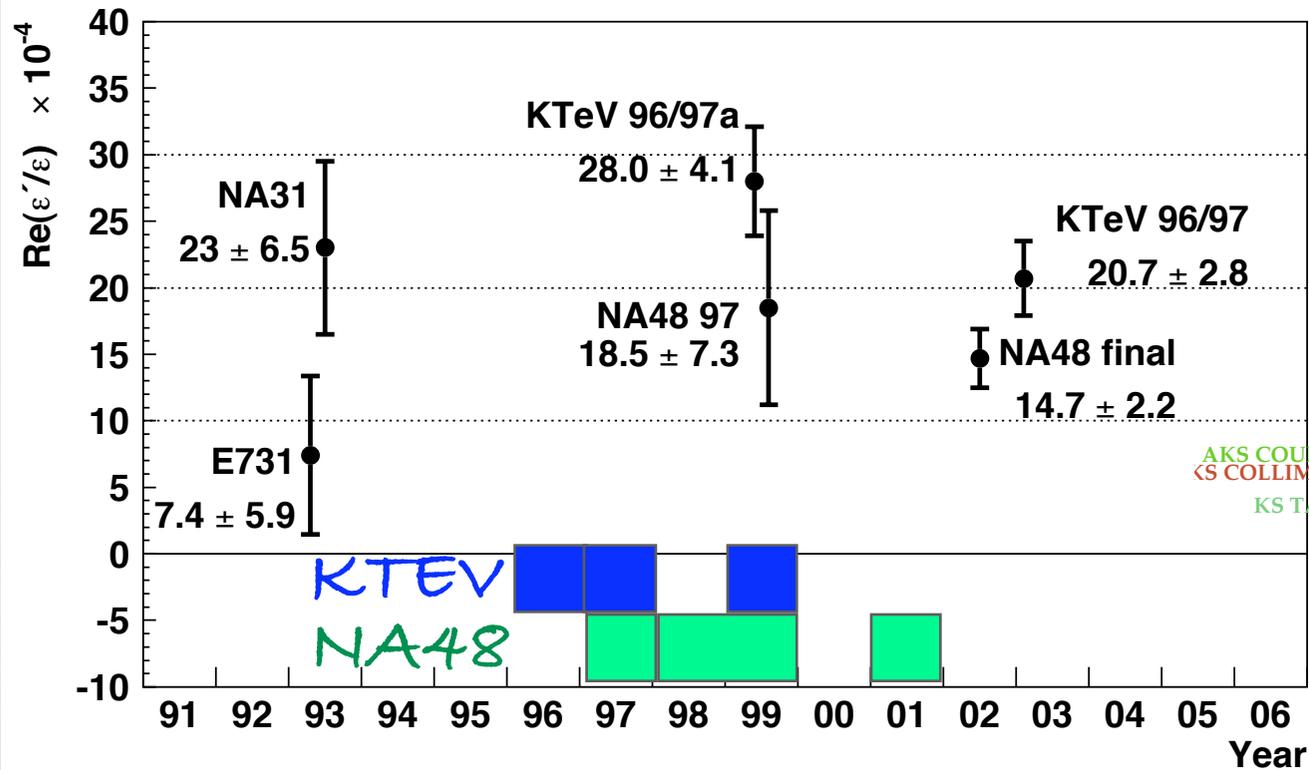
HOW TO MEASURE ϵ'/ϵ

$$R = \frac{BR(K_L \rightarrow \pi^+ \pi^-) / BR(K_S \rightarrow \pi^+ \pi^-)}{BR(K_L \rightarrow \pi^0 \pi^0) / BR(K_S \rightarrow \pi^0 \pi^0)}$$
$$= 1 + 6\text{Re}(\epsilon'/\epsilon)$$

□ REQUIRED ACCURACY ON $R \sim 1 \times 10^{-3}$

□ OBSERVE THE 4 DECAY MODES SIMULTANEOUSLY TO SUPPRESS SYSTEMATIC ERRORS

PAST RESULTS ON ϵ'/ϵ



CERN NA31, NA48, AND FNAL KTeV HAVE ESTABLISHED $\epsilon'/\epsilon \neq 0$

SUPERWEAK IS DEAD

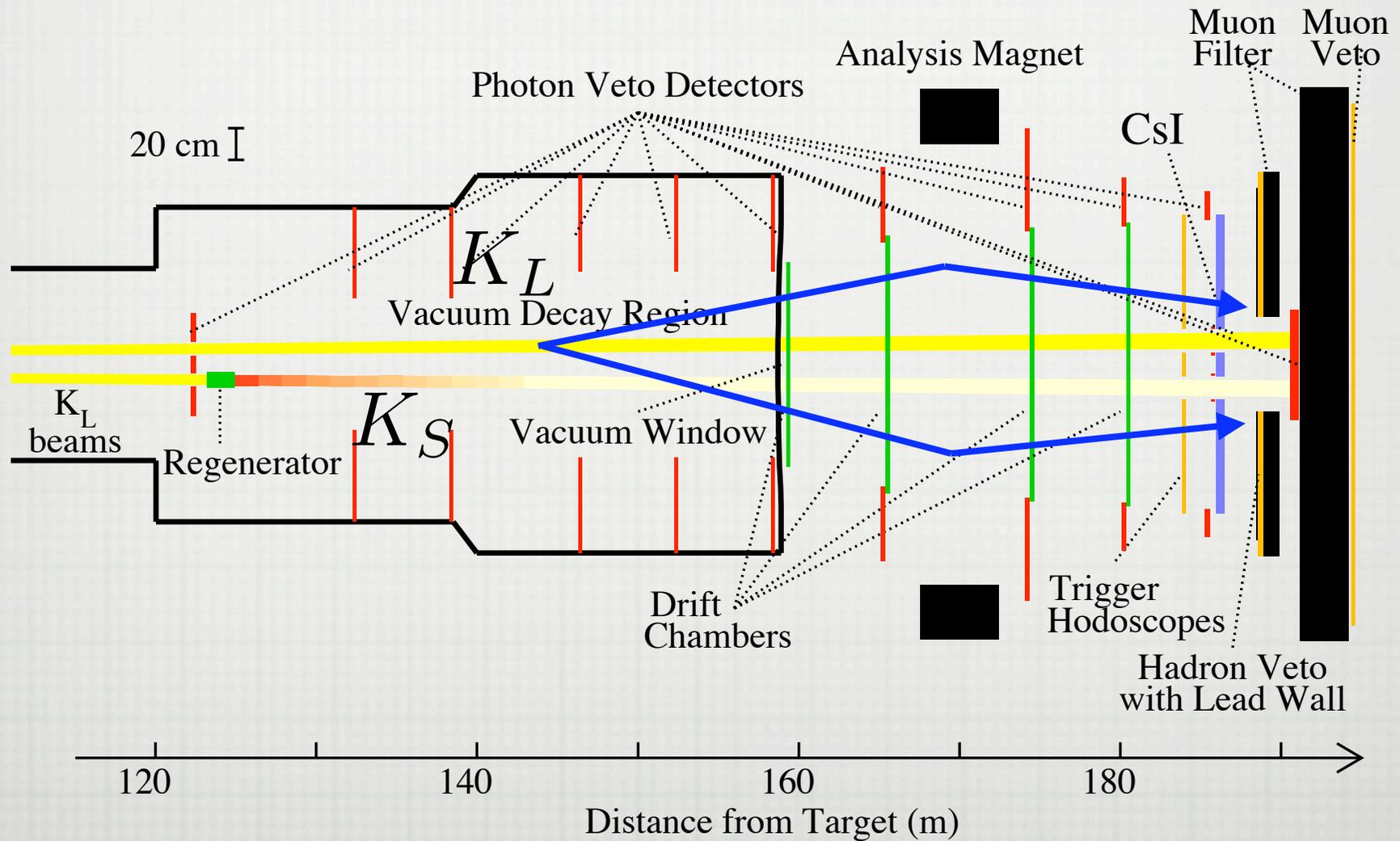
NEW AND FINAL RESULT FROM FERMILAB KTEV

KTEV 

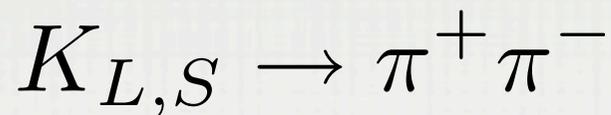
96,97+99 DATA

Arizona, Campinas, Chicago, Colorado, Elmhurst,
FNAL, Osaka, Rice, SaoPaulo, UCLA, Virginia, Wisconsin

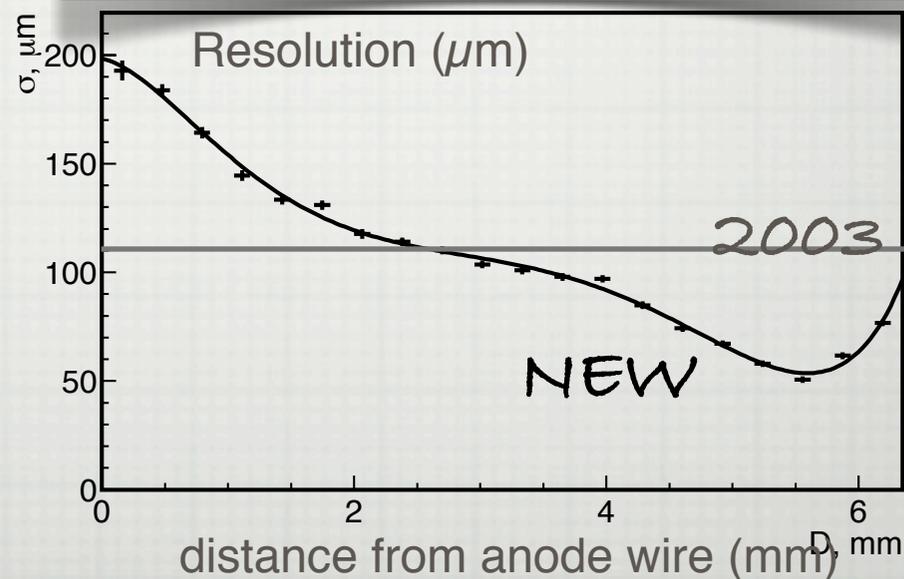
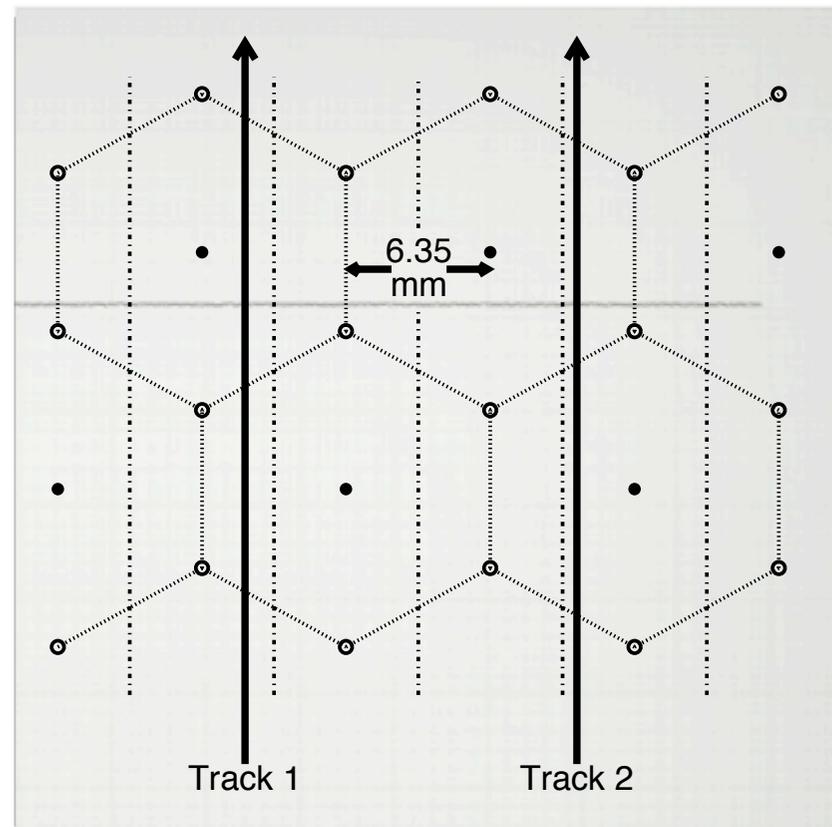
KTeV DETECTOR



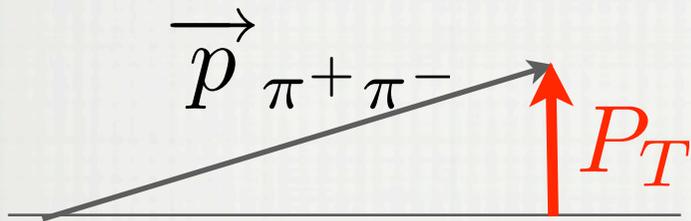
CHARGED MODE:



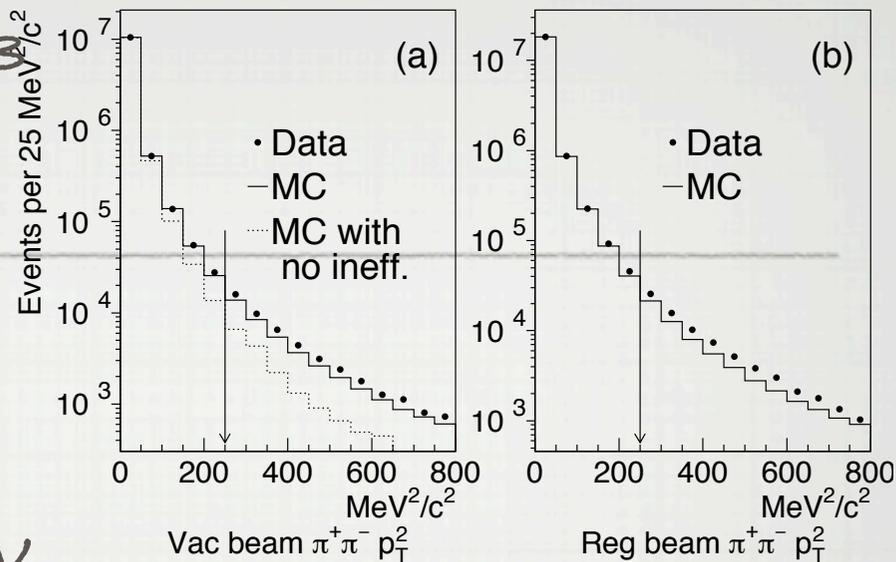
- IMPROVEMENTS
 - FULL DELTA-RAY SIMULATION
 - USE MEASURED RESOLUTION WITHIN THE CELL IN MC AND TRACK RECONSTRUCTION
 - TREAT HADRONIC INTERACTIONS
 - BREMSSTRAHLUNG AT DOWNSTREAM OF MAGNET
 - dE/dx IN MATERIAL (~ 4.5 MEV)



$$K_{L,S} \rightarrow \pi^+ \pi^-$$



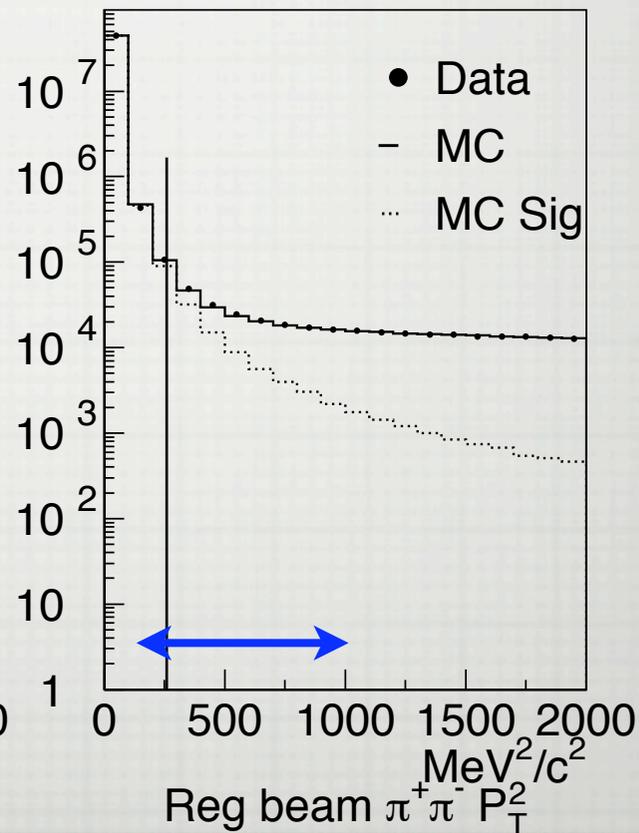
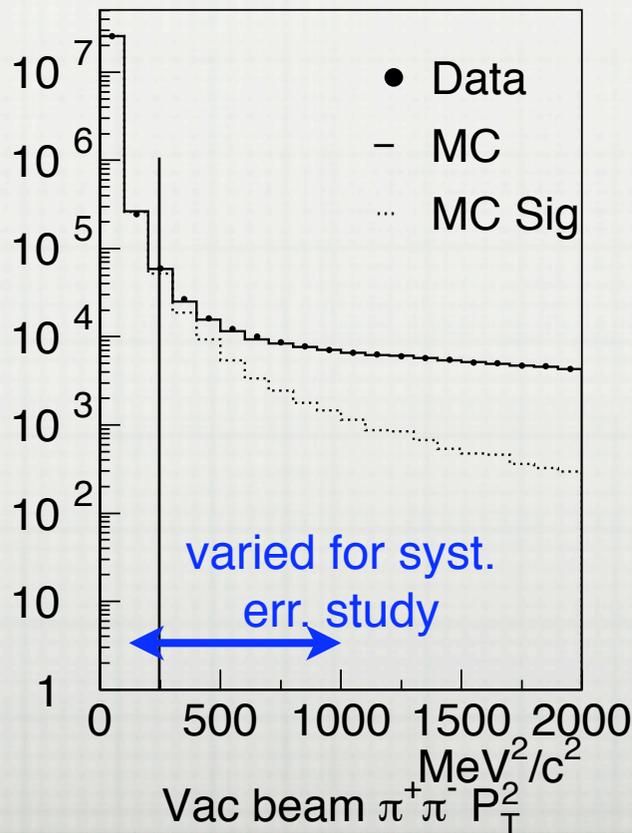
2003



NEW

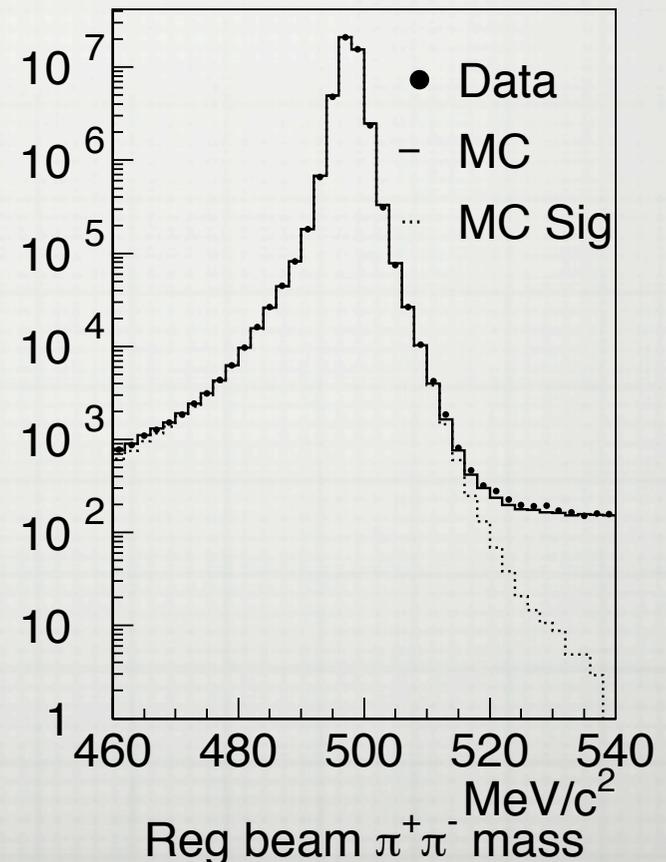
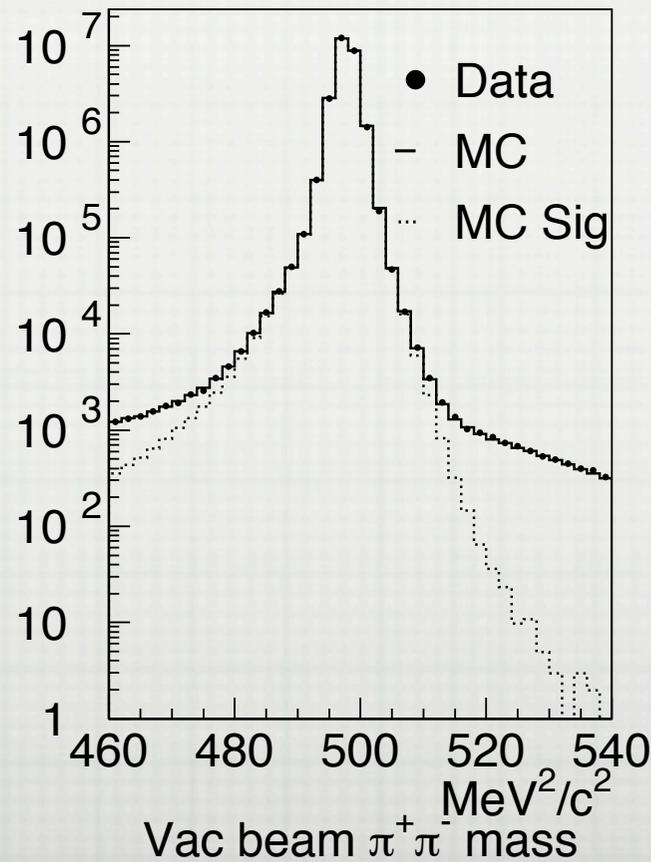
BETTER AGREEMENT DOWN TO TAILS

SYST. ERROR ON P_T^2 CUT: 0.25×10^{-4}
 $\rightarrow 0.10 \text{ E-}4$

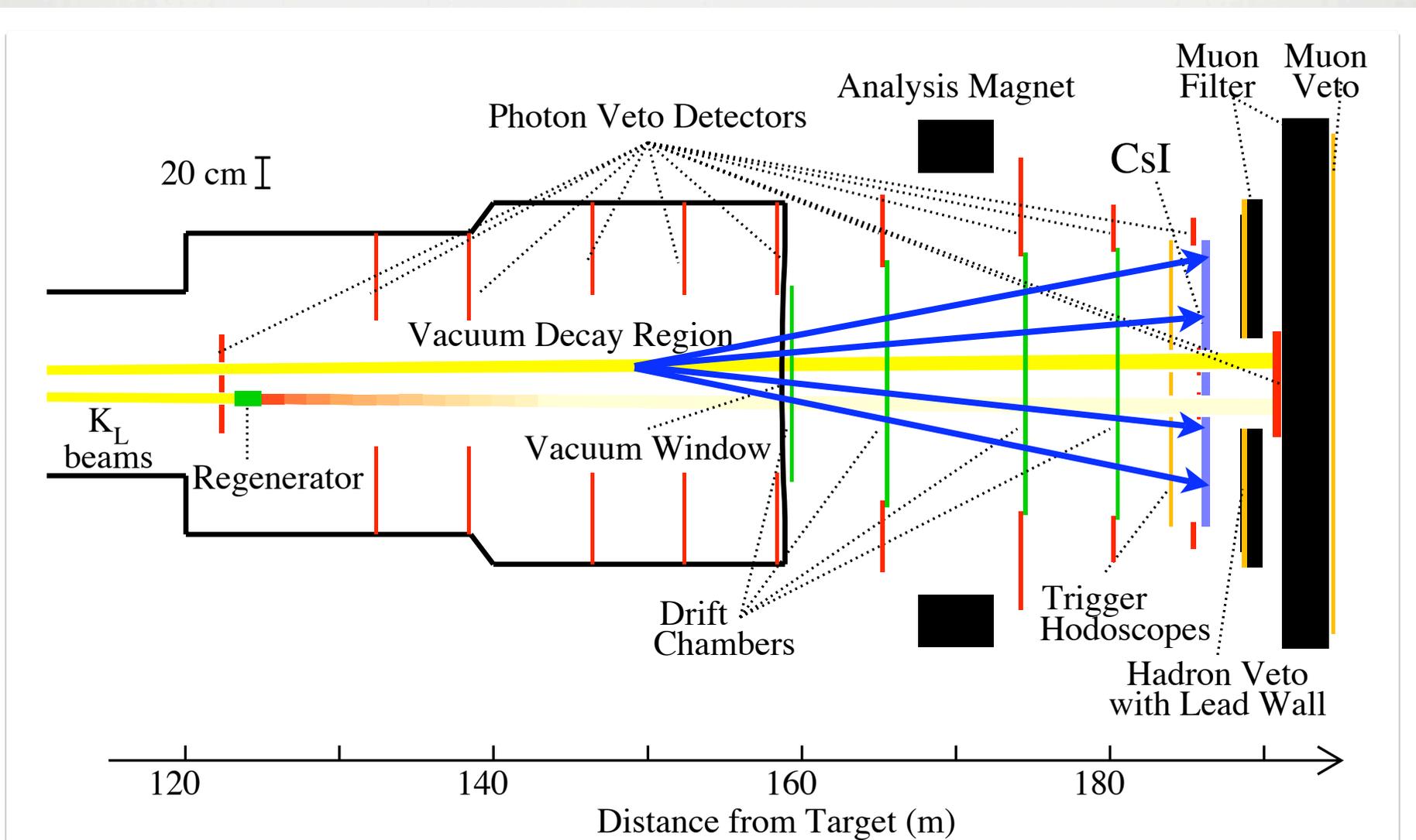


$K_{L,S} \rightarrow \pi^+ \pi^-$ MASS

- 14% NARROWER THAN 2003 PAPER, ~25% FOR HIGH ENERGY K
- GOOD DATA/MC MATCH IN DOWN TO TAILS

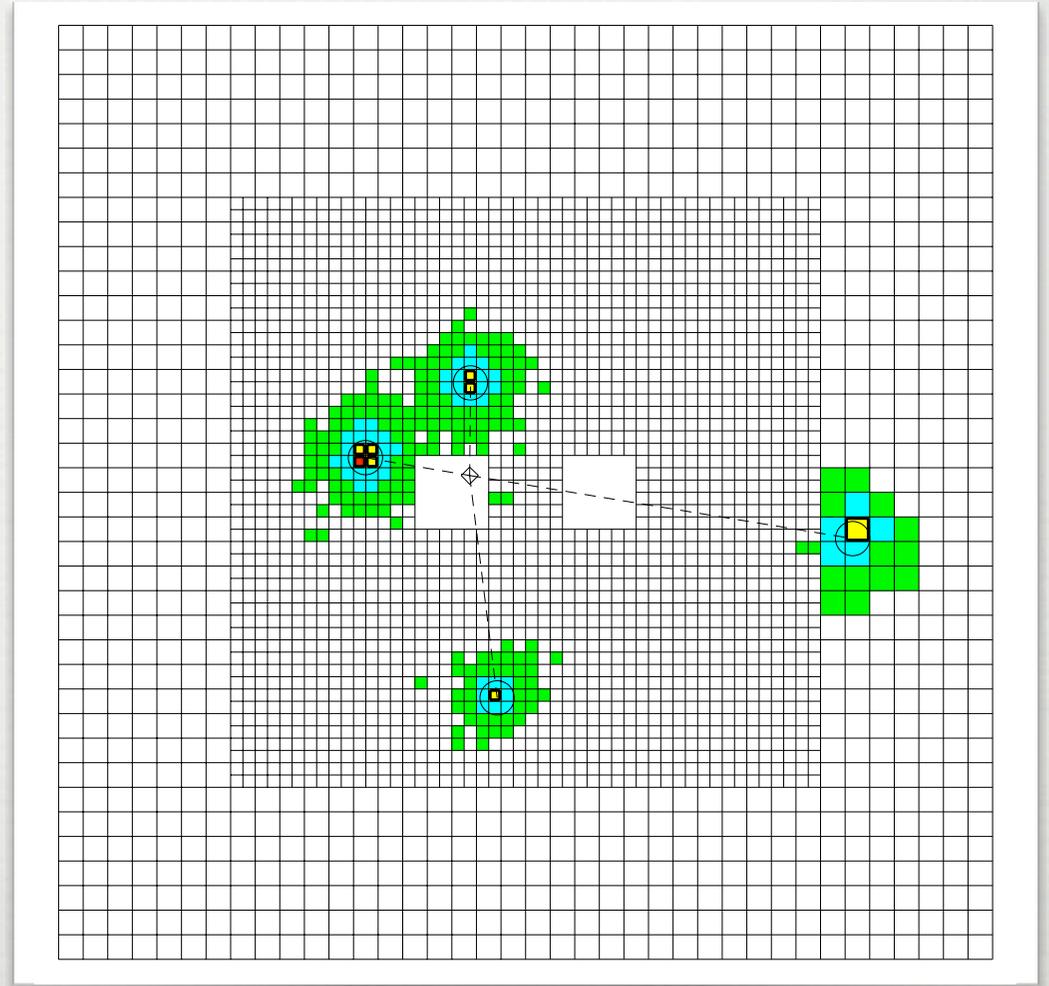


NEUTRAL MODE: $K_{L,S} \rightarrow \pi^0 \pi^0 \rightarrow \gamma\gamma\gamma\gamma$



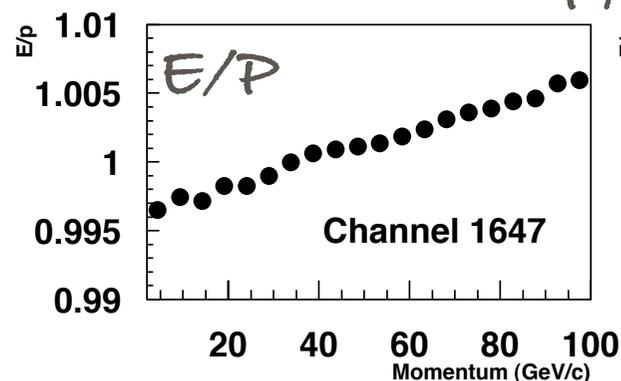
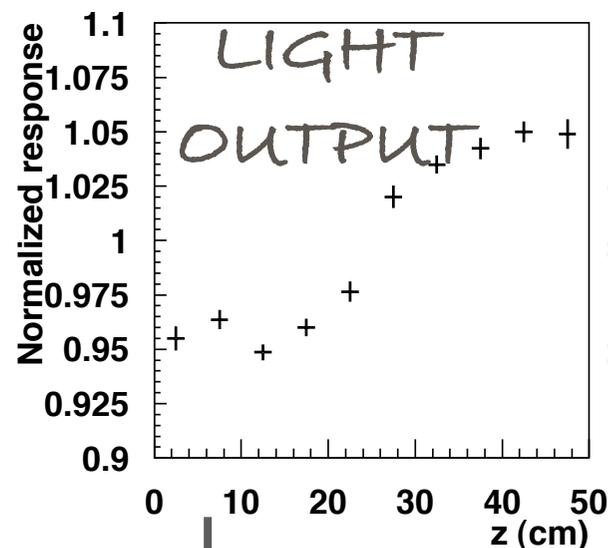
CsI ELECTROMAGNETIC CALORIMETER

- 2.5CM AND 5CM SQUARE BLOCKS
- 50CM ($27X_0$) LONG



IMPROVED EM SHOWER TREATMENTS

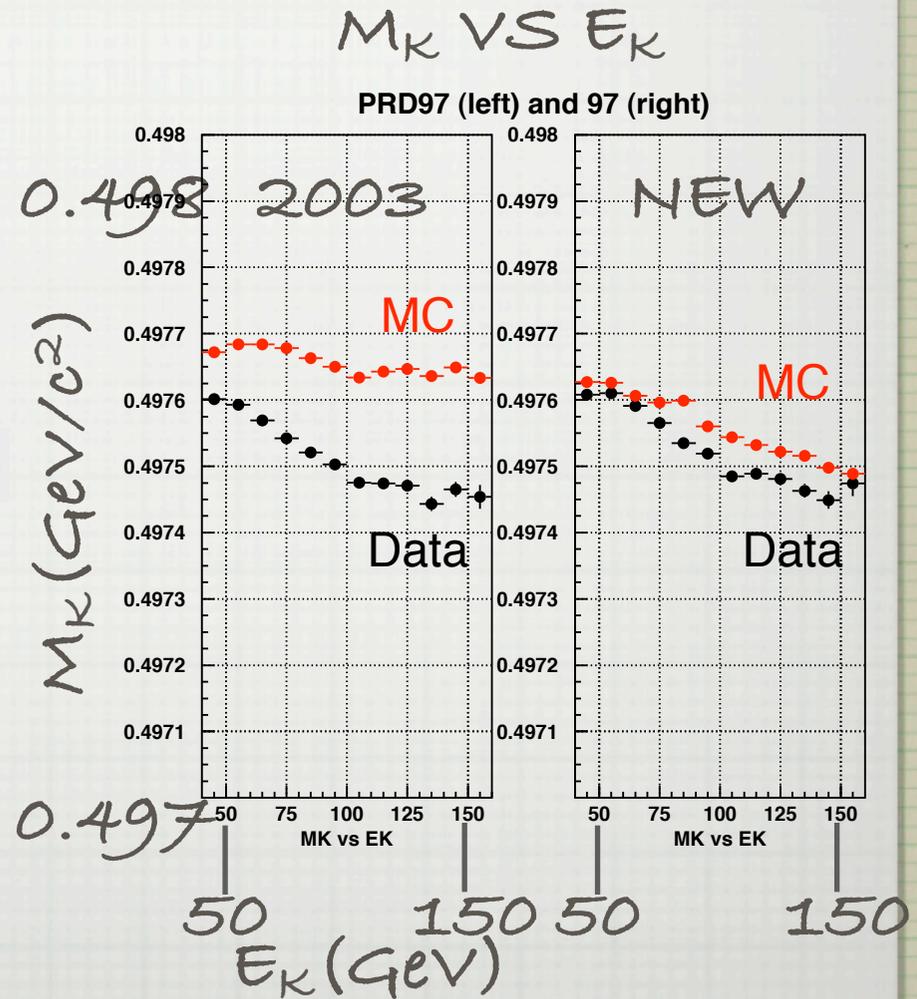
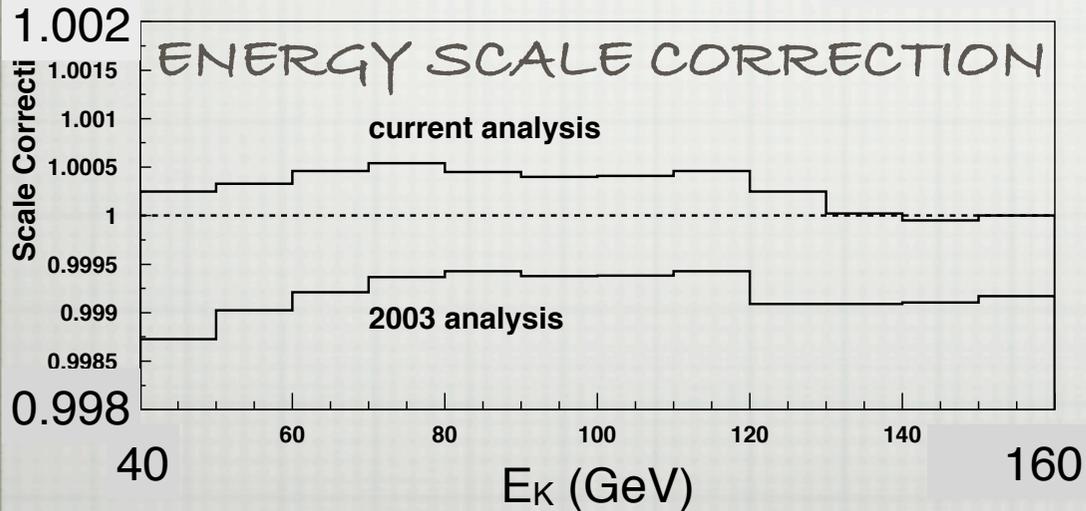
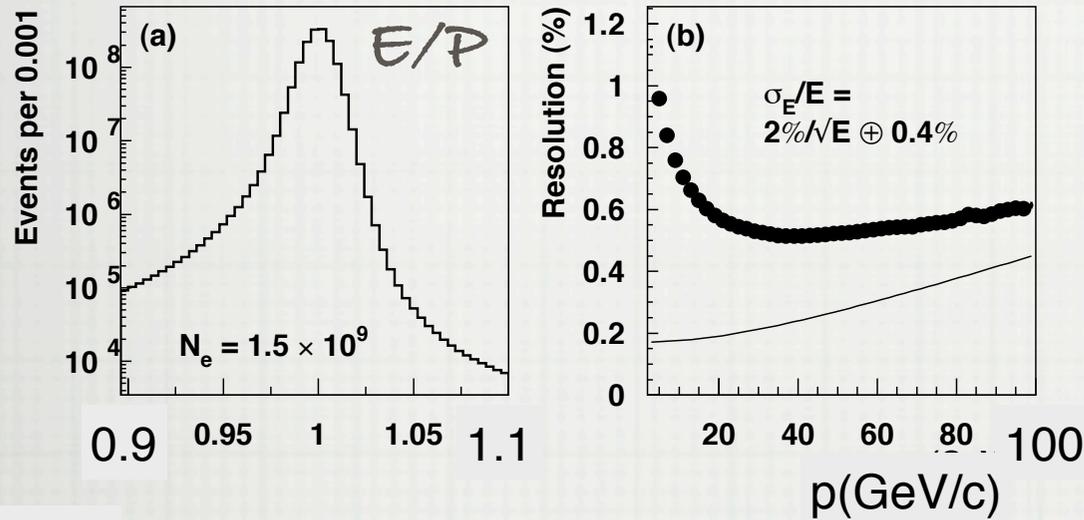
- FOR EACH CRYSTAL, CORRECT FOR
 - LIGHT UNIFORMITY
 - NON-LINEARITY
- MC GENERATES SHOWERS WITH FINITE INCIDENT ANGLES
- MC SIMULATES WRAPPINGS AND SHIMS BETWEEN CRYSTALS
- AND MORE...



P (GEV/C)

CsI PERFORMANCE

$$\sigma_E/E = 2\%/\sqrt{E} \oplus 0.4\%$$



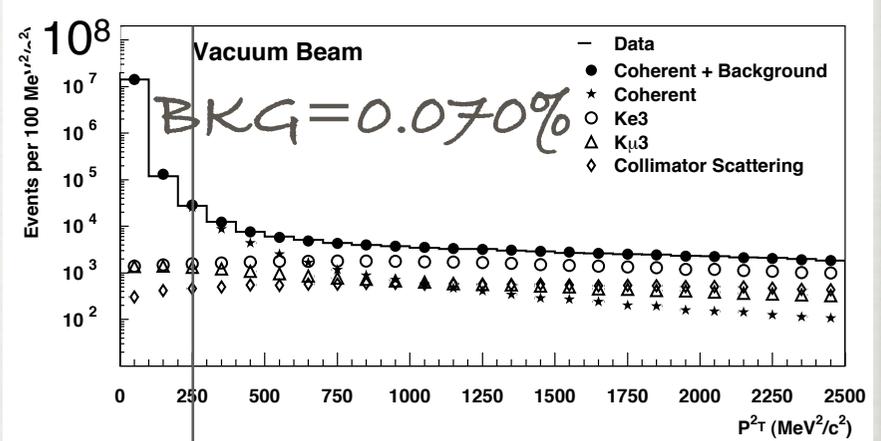
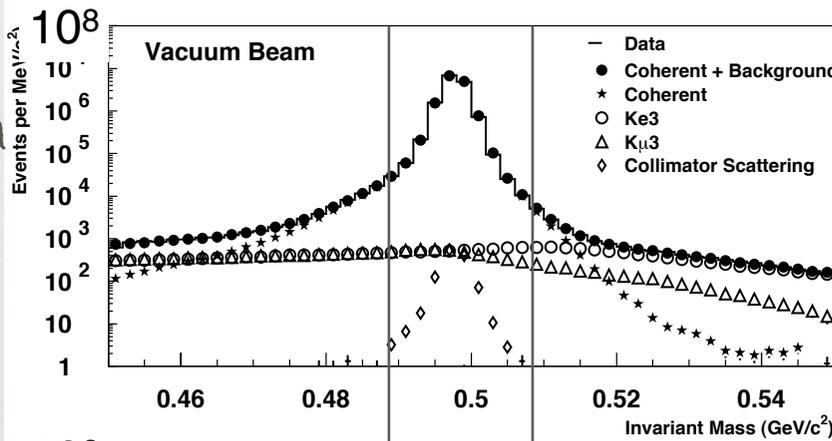
#EVENTS AND BACKGROUNDS IN CHARGED MODE

\square 25.1M $K_L \rightarrow \pi\pi$, 43.7M $K_S \rightarrow \pi\pi$ signal events \blacksquare DATA
 \bullet \circ \triangle \dots MC

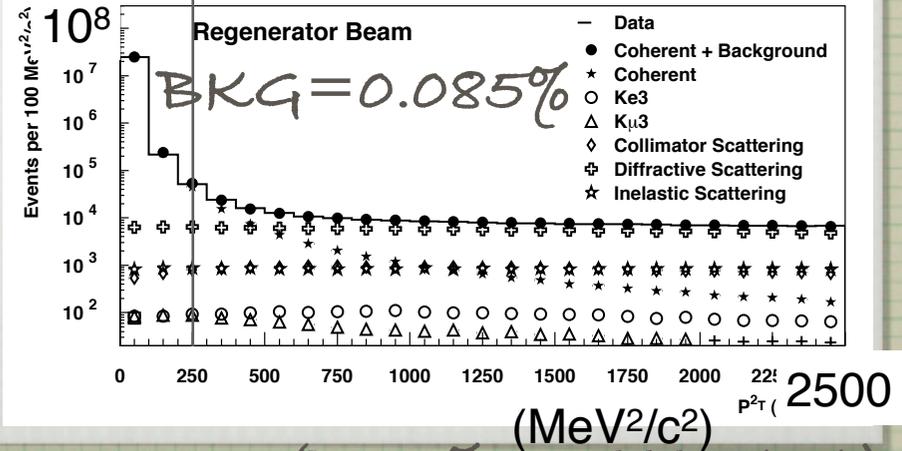
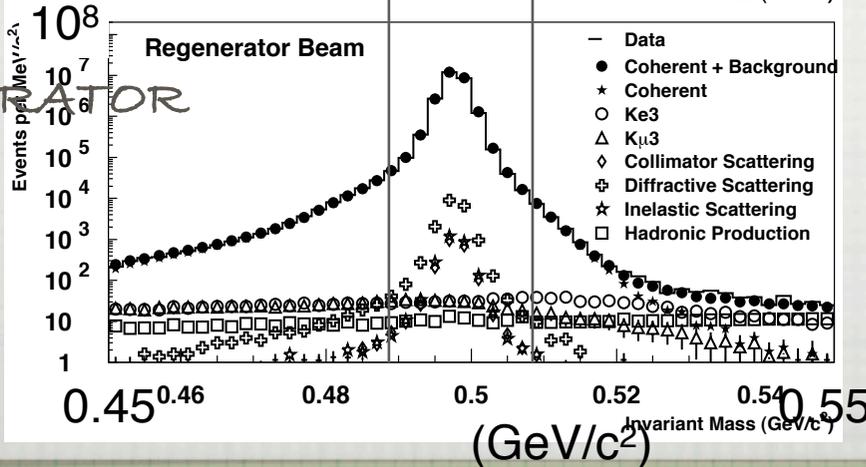
$M_{\pi\pi}$

P_T^2

VACUUM BEAM
~ K_L



REGENERATOR BEAM
~ K_S

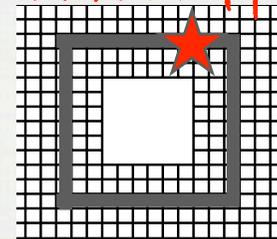


(BKG % IN 1999 DATA)

#EVENTS AND BACKGROUNDS IN NEUTRAL MODE

CENTER OF ENERGY

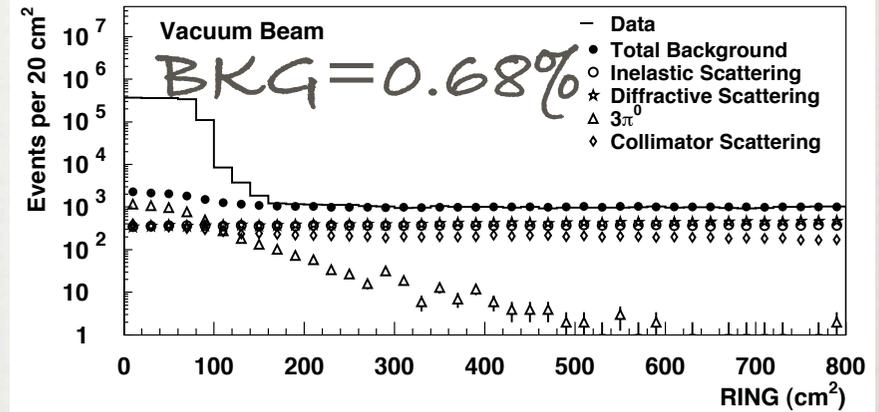
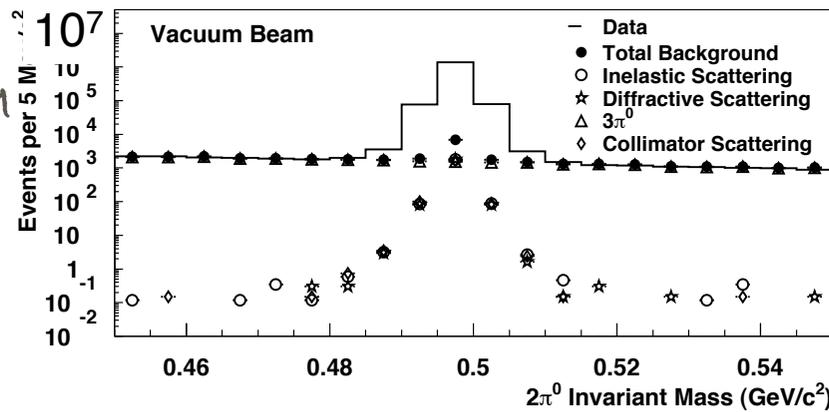
□ 6.0M K_L , 10.2M K_S signal events



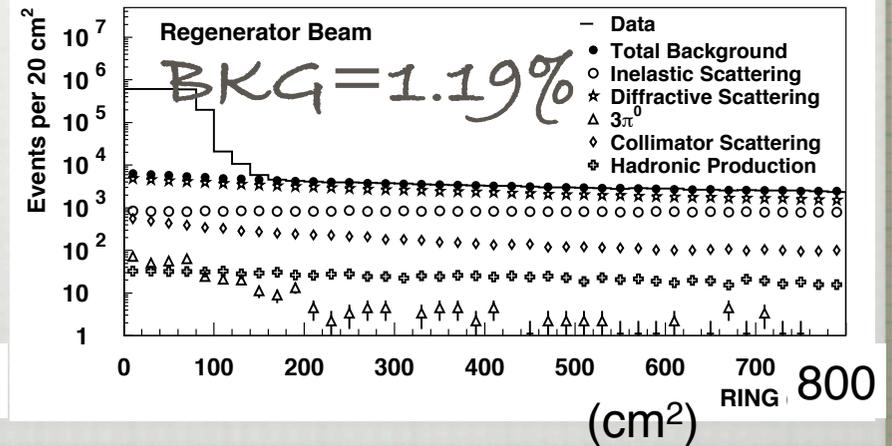
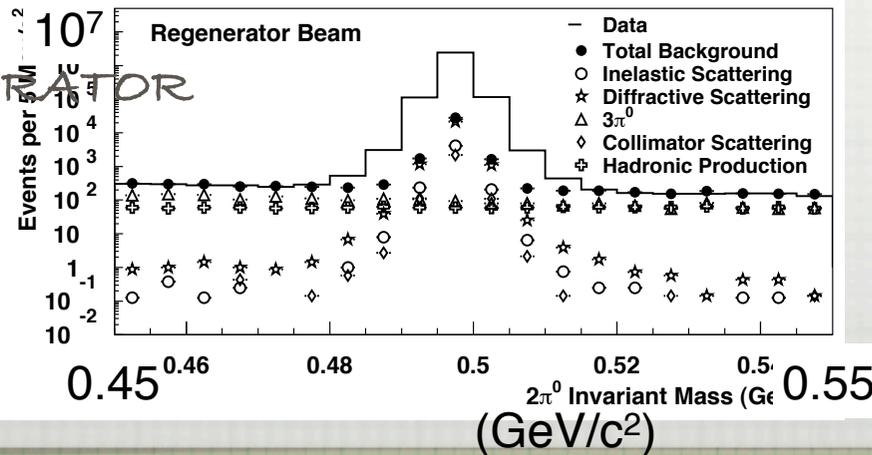
DATA
MC

$M_{\pi\pi}$

VACUUM BEAM
 $\sim K_L$



REGENERATOR BEAM
 $\sim K_S$



ACCEPTANCE CORRECTION

$N_{\text{DECAY}} = N_{\text{OBSERVED}} / \text{ACCEPTANCE}$

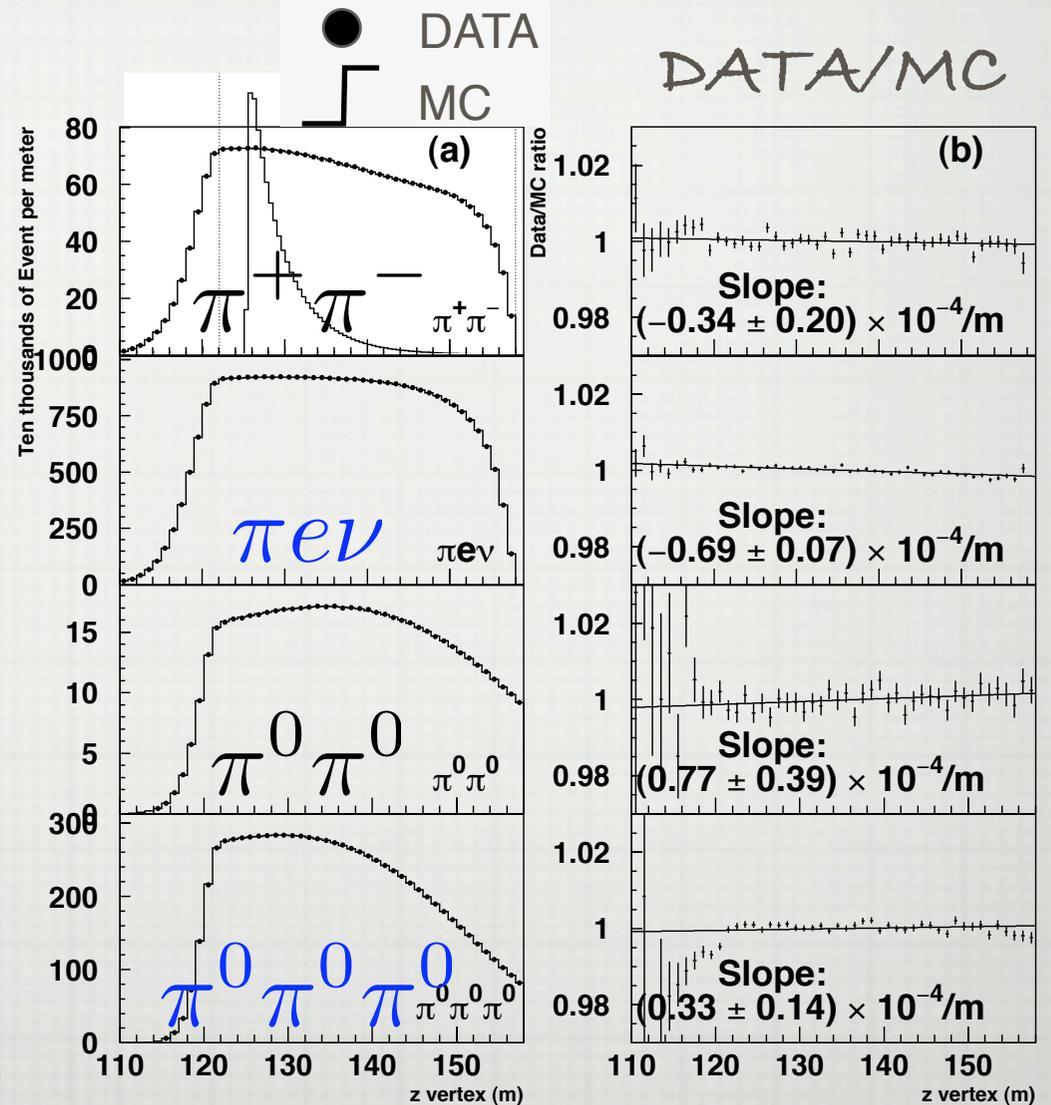
IN 10GEV/C PK BIN

CHECK ACCEPTANCE WITH HIGH STATISTICS MODES

SYST ERROR ON ϵ'/ϵ

CHARGED: $0.57 \text{ E-}4$

NEUTRAL: $0.48 \text{ E-}4$



EXTRACTING ϵ'/ϵ

□ BASIC IDEA: AMPLITUDE RATIO IS:

$$\frac{A \left(\begin{array}{c} \xrightarrow{K_L} A(K_L \rightarrow \pi\pi) \\ \text{---} K_L \end{array} \right)}{A \left(\begin{array}{c} \xrightarrow{\rho} \square \xrightarrow{K_S} A(K_S \rightarrow \pi\pi) \\ \text{---} K_S \end{array} \right)} \approx \frac{\eta}{\rho}$$

$$\frac{\#K_L \rightarrow \pi^+ \pi^- / \#K_S \rightarrow \pi^+ \pi^-}{\#K_L \rightarrow \pi^0 \pi^0 / \#K_S \rightarrow \pi^0 \pi^0} \approx \left| \frac{\eta_{\pm} / \rho}{\eta_{00} / \rho} \right|^2 = 1 + 6\text{Re}(\epsilon'/\epsilon)$$

□ ACTUALLY, MULTI-PARAMETER FIT USING EXACT FUNCTIONS

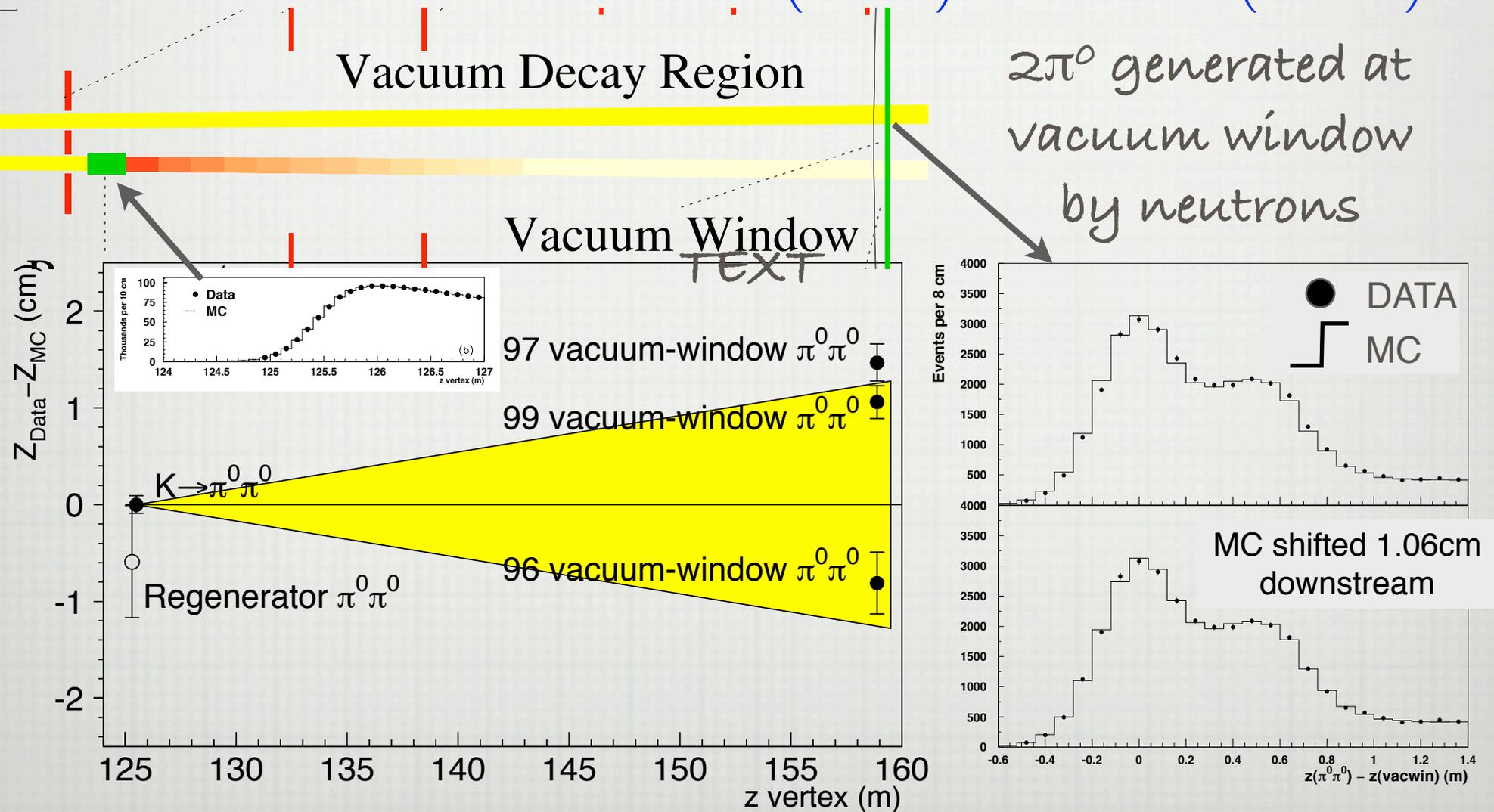
SYSTEMATIC ERRORS

2003 → NEW

Source	Error on $Re(\epsilon'/\epsilon)$ ($\times 10^{-4}$)	
	$K \rightarrow \pi^+ \pi^-$	$K \rightarrow \pi^0 \pi^0$
Trigger	0.58 → 0.23	0.20
CsI cluster reconstruction	—	1.47 → 0.75
Track reconstruction	0.32 → 0.22	—
Selection efficiency	0.47 → 0.23	0.34
Apertures	0.30	0.48
Acceptance	0.79 → 0.57	0.39 → 0.48
Backgrounds	0.20	1.07
MC statistics	0.41 → 0.20	0.40 → 0.25
Total	0.81	1.55
Fitting		0.31
Total		1.78

SYSTEMATIC ERRORS PHOTON ENERGY SCALE

1.25E-4(2003) → 0.65E-4(NEW)

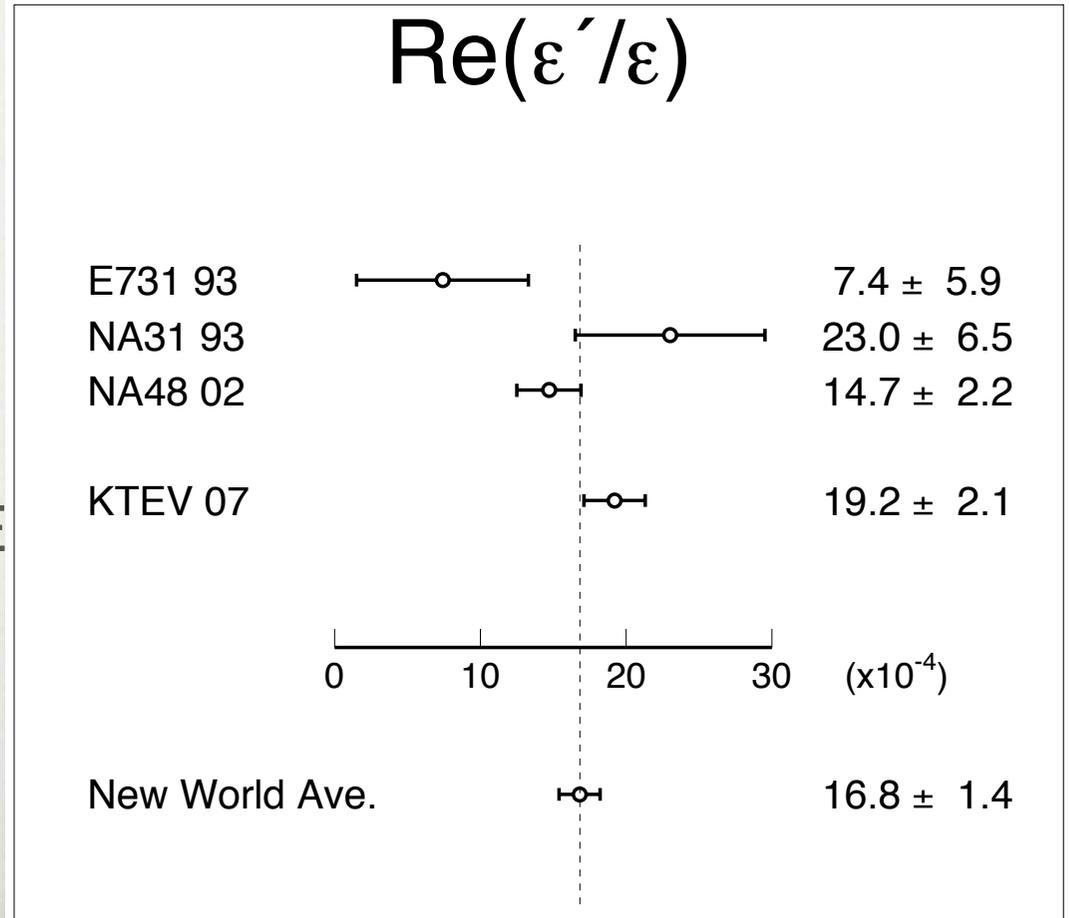


RESULT

□ $\text{Re}(\varepsilon'/\varepsilon)$ from full KTeV data
= $[19.2 \pm 1.1(\text{stat}) \pm 1.8(\text{syst})] \times 10^{-4}$
= $[19.2 \pm 2.1] \times 10^{-4}$

□ 2003:
 $[20.7 \pm 1.48 \pm 2.39] \times 10^{-4}$
= $[20.7 \pm 2.8] \times 10^{-4}$

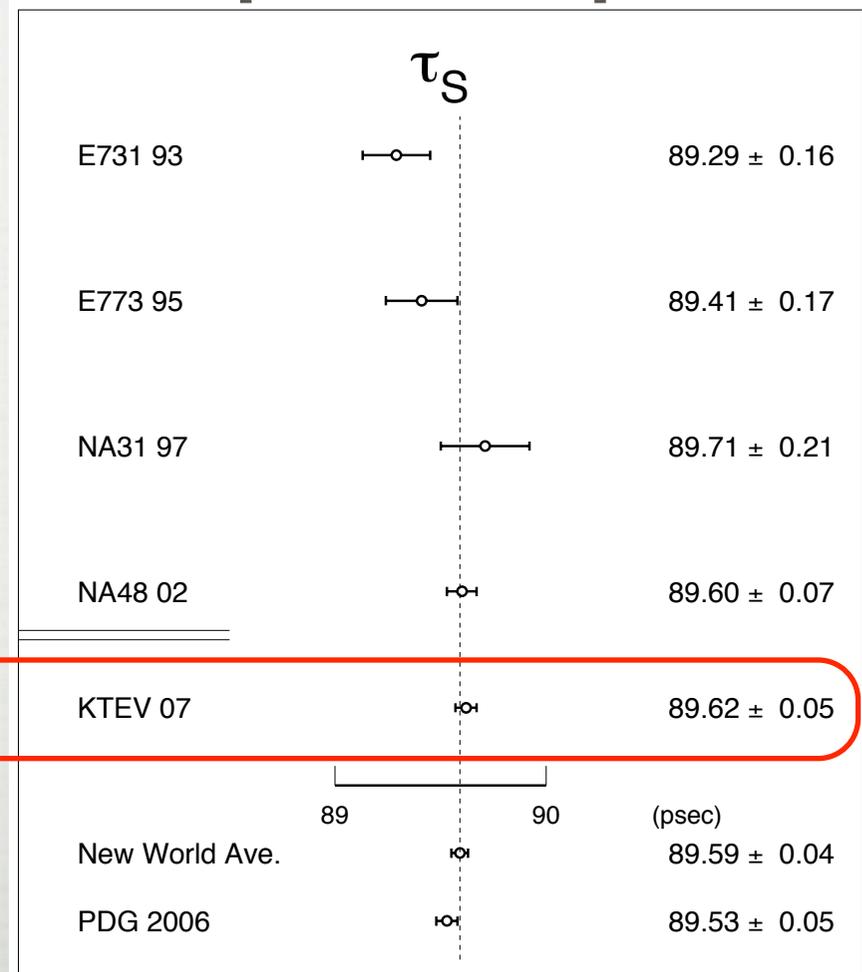
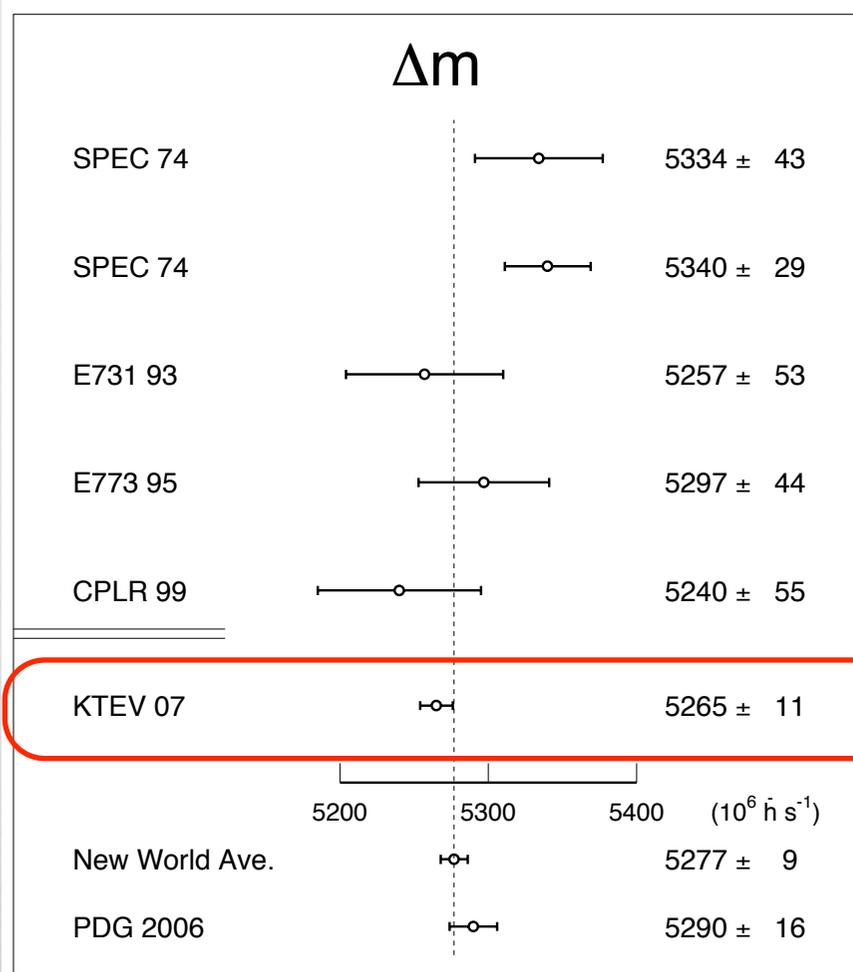
□ NEW WORLD AVERAGE
= $[16.8 \pm 1.4] \times 10^{-4}$



OTHER PARAMETERS

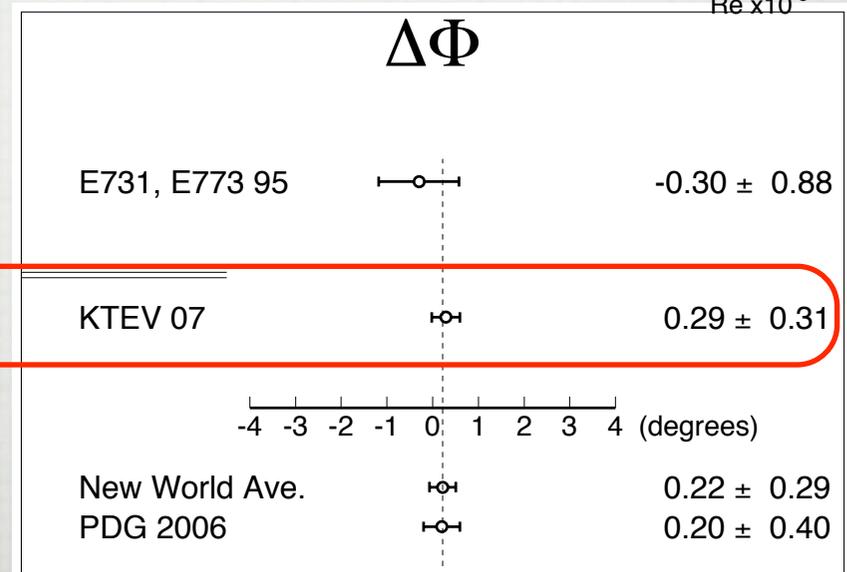
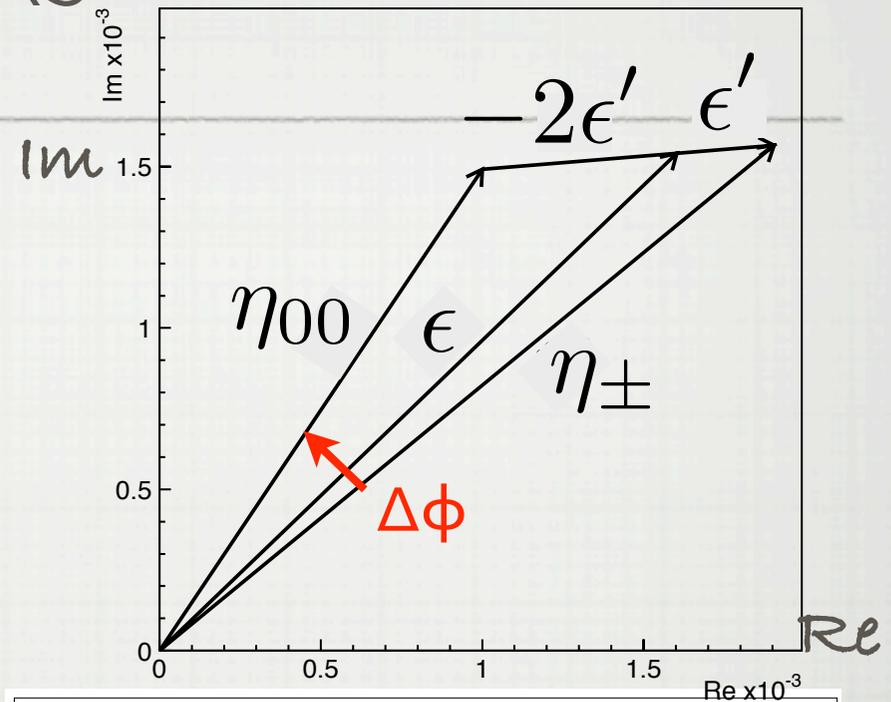
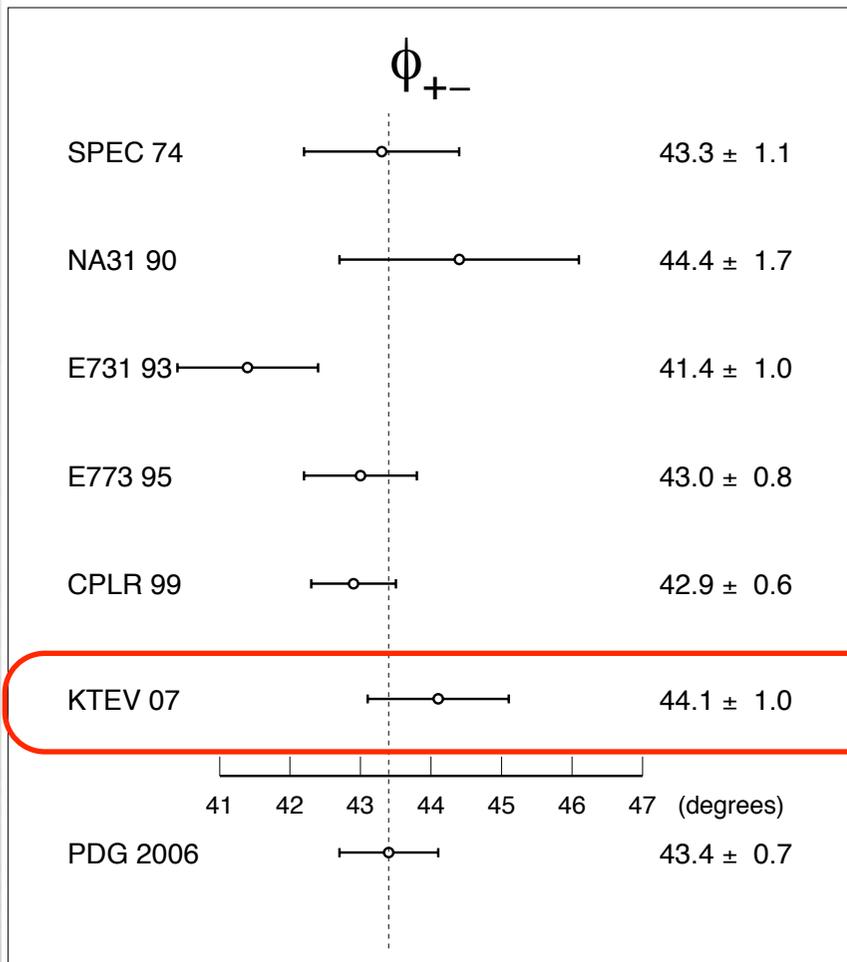
$$\Delta m = [5265 \pm 11] \times 10^{-6} \text{ hs}$$

$$\tau_S = [89.62 \pm 0.05] \times 10^{-12} \text{ hs}$$



OTHER PARAMETERS

ϕ_{\pm} = phase of $\eta_{\pm} = [44.1 \pm 1.0]^{\circ}$



CONCLUSION

□ FINAL RESULTS FROM KTEV FULL DATA SET
WITH MANY IMPROVEMENTS

$$\text{Re}(\epsilon'/\epsilon) = [19.2 \pm 1.1(\text{stat}) \pm 1.81(\text{syst})] \times 10^{-4}$$

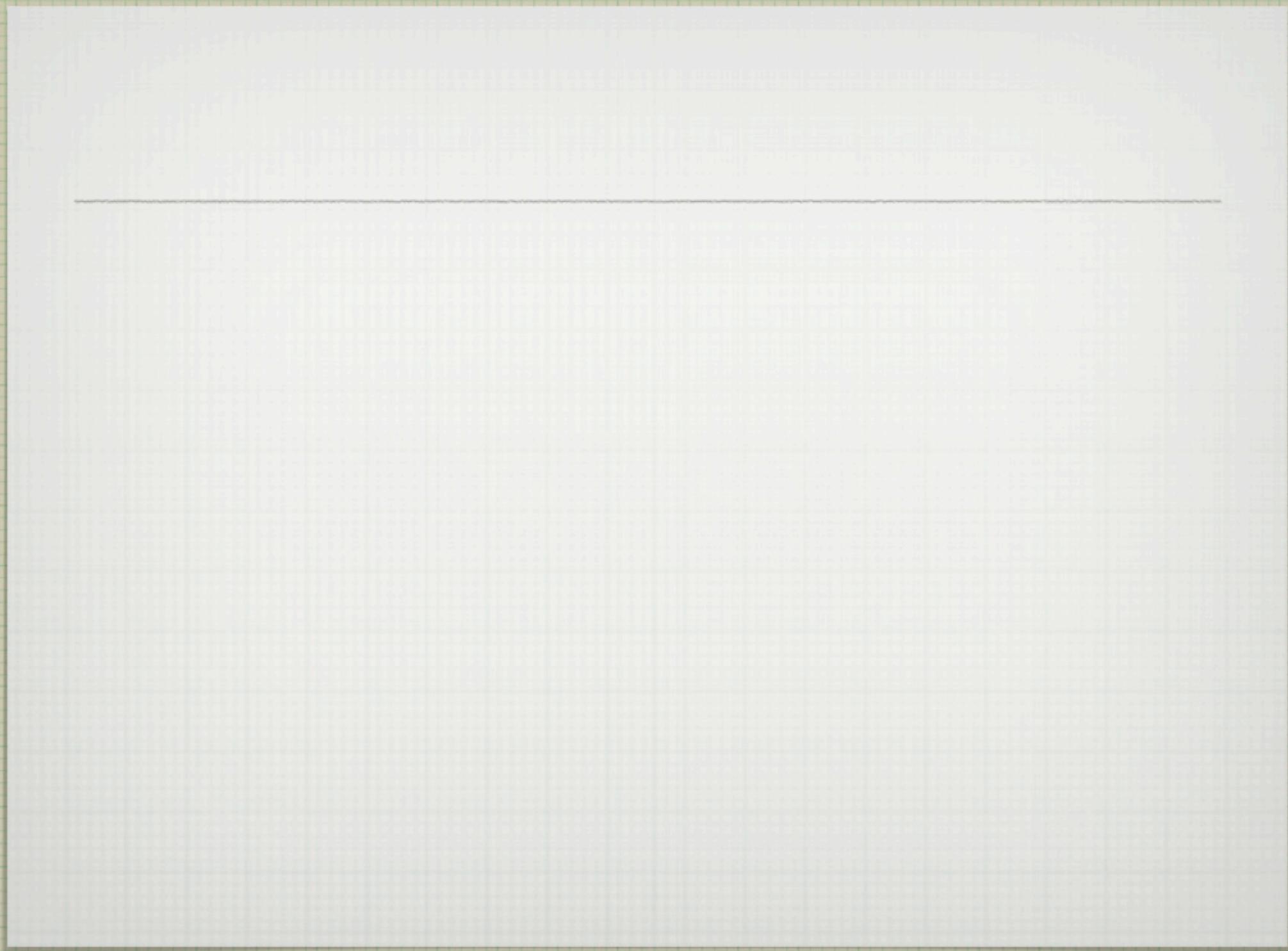
$$\Delta m = (5265 \pm 10) \times 10^6 \hbar s^{-1}$$

$$\tau_S = (89.62 \pm 0.05) \times 10^{-12} s$$

□ CONSISTENT WITH CPT SYMMETRY

$$\phi_\epsilon = (44.09 \pm 1.00)^\circ$$

$$\Delta\phi = (0.29 \pm 0.31)^\circ$$



BACKGROUNDS

□ CHARGED MODE

Source	Vacuum Beam		Regenerator Beam	
	1997	1999	1997	1999
Regenerator Scattering	—	—	0.073%	0.075%
Collimator Scattering	0.009%	0.008%	0.009%	0.008%
$K_L \rightarrow \pi^\pm e^\mp \nu$	0.032%	0.032%	0.001%	0.001%
$K_L \rightarrow \pi^\pm \mu^\mp \nu$	0.034%	0.030%	0.001%	0.001%
Total Background	0.074%	0.070%	0.083%	0.085%

□ NEUTRAL MODE

Source	Vacuum Beam			Regenerator Beam		
	1996	1997	1999	1996	1997	1999
Inelastic Scattering	0.153%	0.132%	0.128%	0.214%	0.186%	0.175%
Diffraction Scattering	0.135%	0.128%	0.130%	0.893%	0.906%	0.906%
Collimator Scattering	0.102%	0.122%	0.120%	0.081%	0.093%	0.091%
$K_L \rightarrow \pi^0 \pi^0 \pi^0$	0.444%	0.220%	0.301%	0.015%	0.006%	0.012%
Photon Mispairing	0.007%	0.007%	0.008%	0.007%	0.008%	0.007%
Hadronic Production	0.002%	0.001%	—	0.007%	0.007%	0.007%
Total Background	0.835%	0.603%	0.678%	1.209%	1.197%	1.190%

2003 Z VERTEX

