KTeV Results on Not-so-Rare Decays

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KTeV: Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Sao Paolo, UCLA, Virginia, Wisconsin

K_L Decays: Physics Menu

mode	**fraction**
$K_L \rightarrow \pi e \nu$	0.406
$K_L \rightarrow \pi \mu \nu$	0.270
$K_L \rightarrow \pi^0 \pi^0 \pi^0$	0.195
$K_L \rightarrow \pi^+ \pi^- \pi^0$	0.125
$K_L \rightarrow \pi^+ \pi^-$	0.002
$K_L \rightarrow \pi^0 \pi^0$	0.001
$K_L \rightarrow$ rare	< 0.001

Vus (2004)

$3\pi^0$ phase space

Final KTeV ε'

this talk

← **see Ronquest talk**

The Final Measurement of ε′/ε from KTeV

$$\mathrm{Re}(\varepsilon'/\varepsilon) \approx \frac{1}{6}\left[\frac{\Gamma(K_L \to \pi^+\pi^-)\,\Gamma(K_s \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)\,\Gamma(K_s \to \pi^0\pi^0)} - 1\right]$$

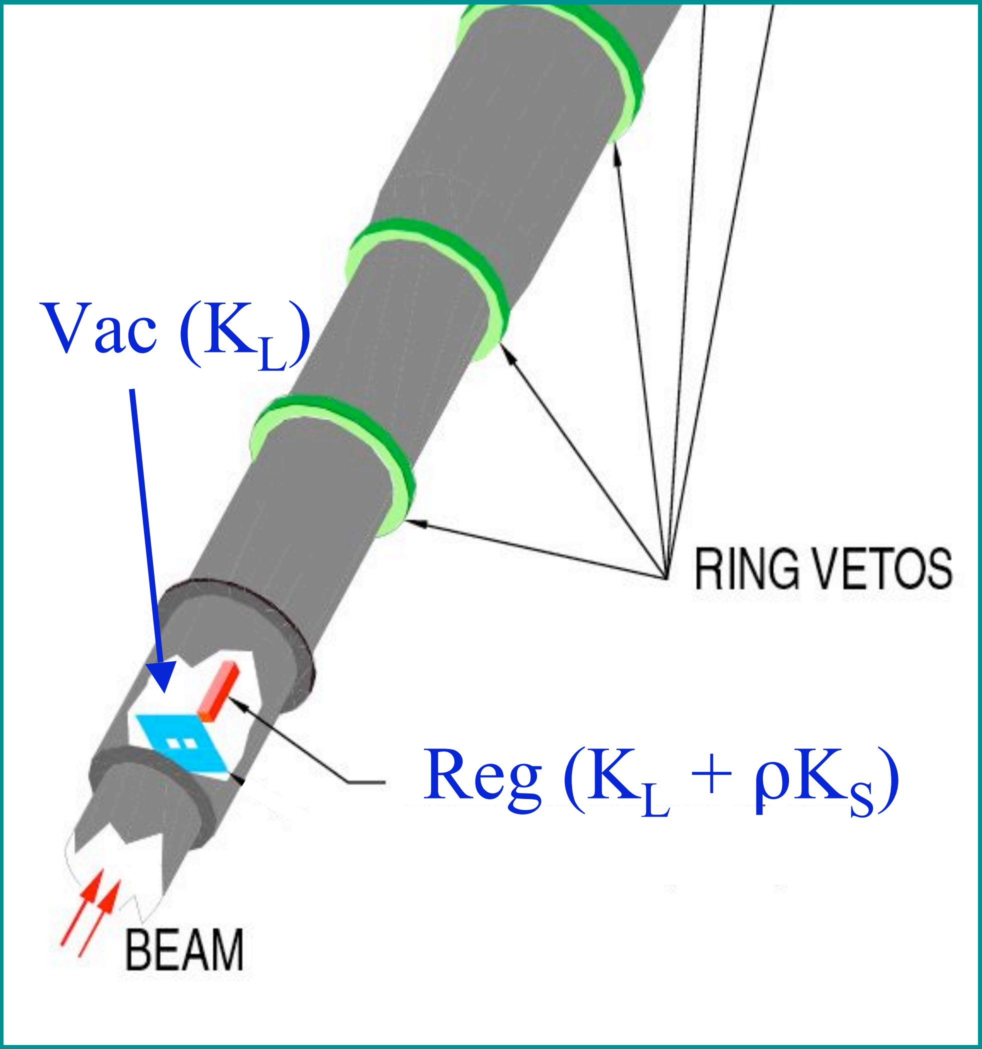
$\varepsilon'/\varepsilon \neq 0$ ⟹ direct CP violation

⟹ $\Gamma(K^0 \to \pi^+\pi^-) \neq \Gamma(\overline{K^0} \to \pi^+\pi^-)$

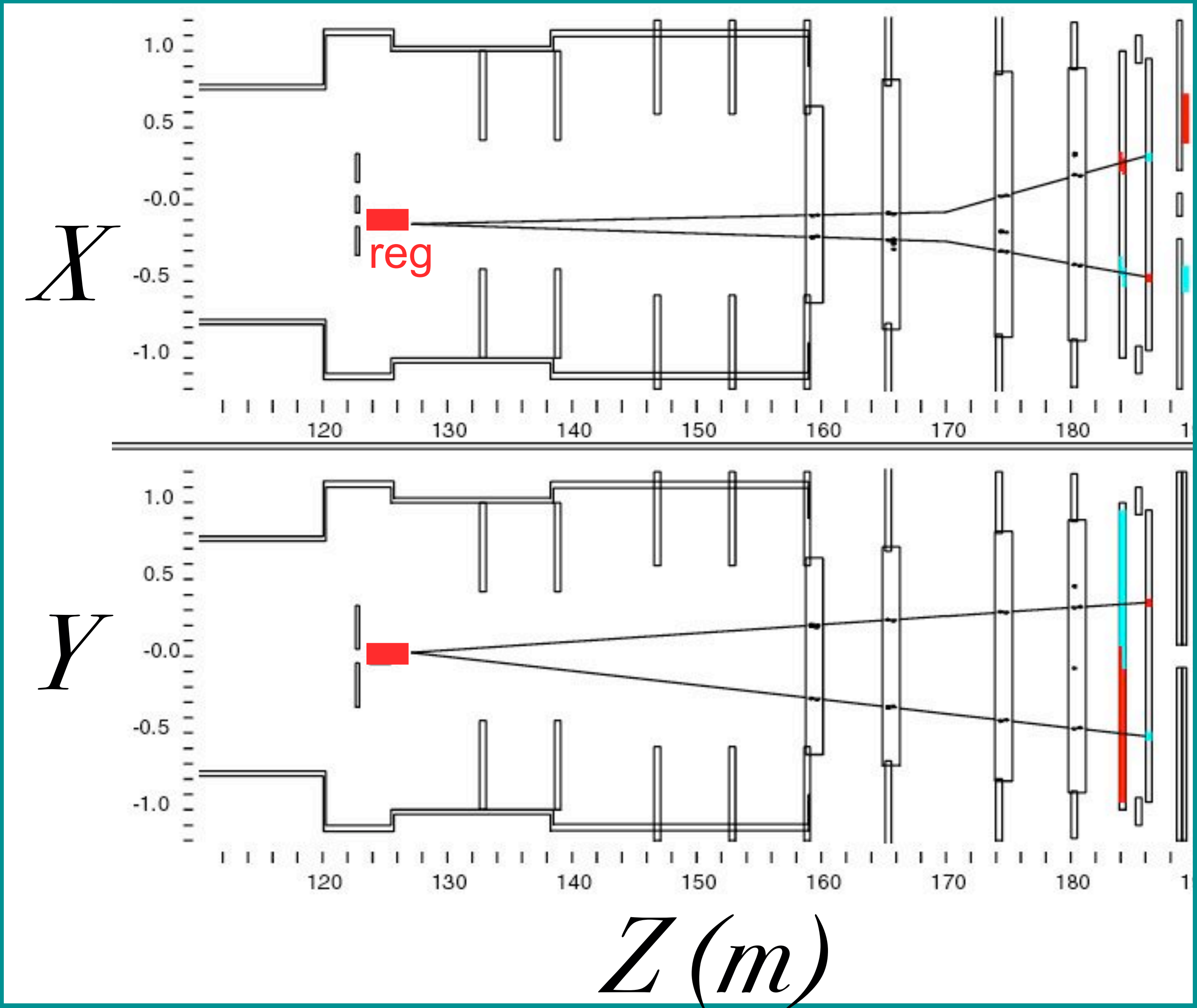
Samples

Vac $K \rightarrow \pi^0\pi^0$	6 million
Reg $K \rightarrow \pi^0\pi^0$	10 million
Vac $K \rightarrow \pi^+\pi^-$	25 million
Reg $K \rightarrow \pi^+\pi^-$	43 million

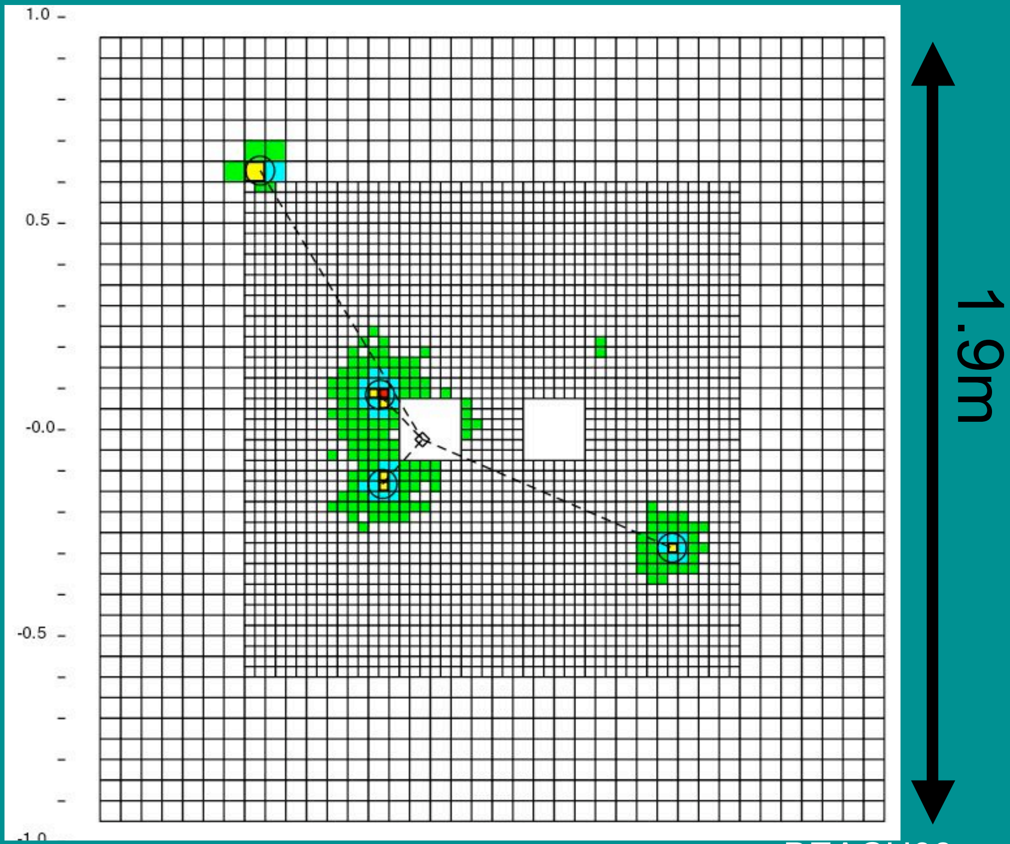
$$\sigma_{stat} = 1.1 \times 10^{-4}$$

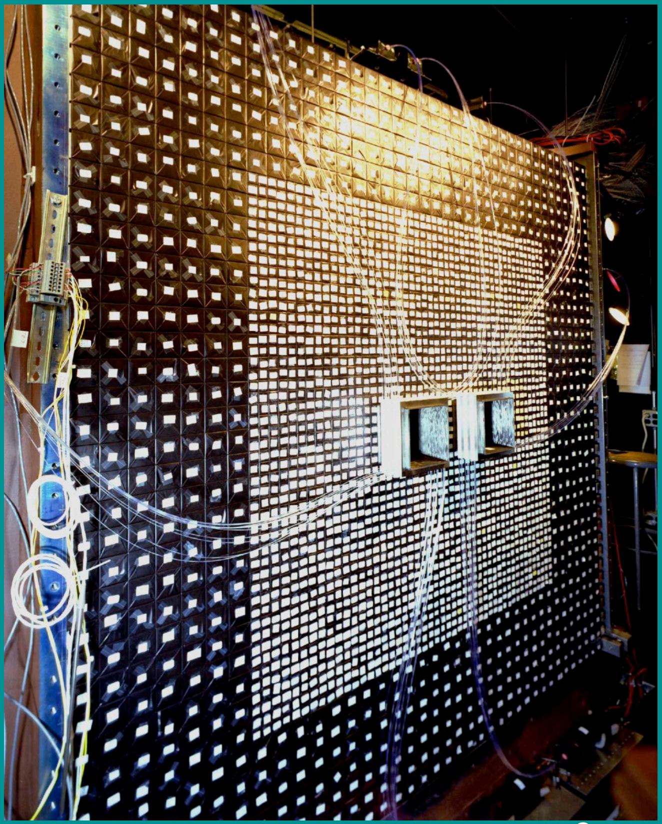


Reg $K \to \pi^+ \pi^-$ (four drift chambers)



$K_L \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$
(3100 channel CsI calorimeter)



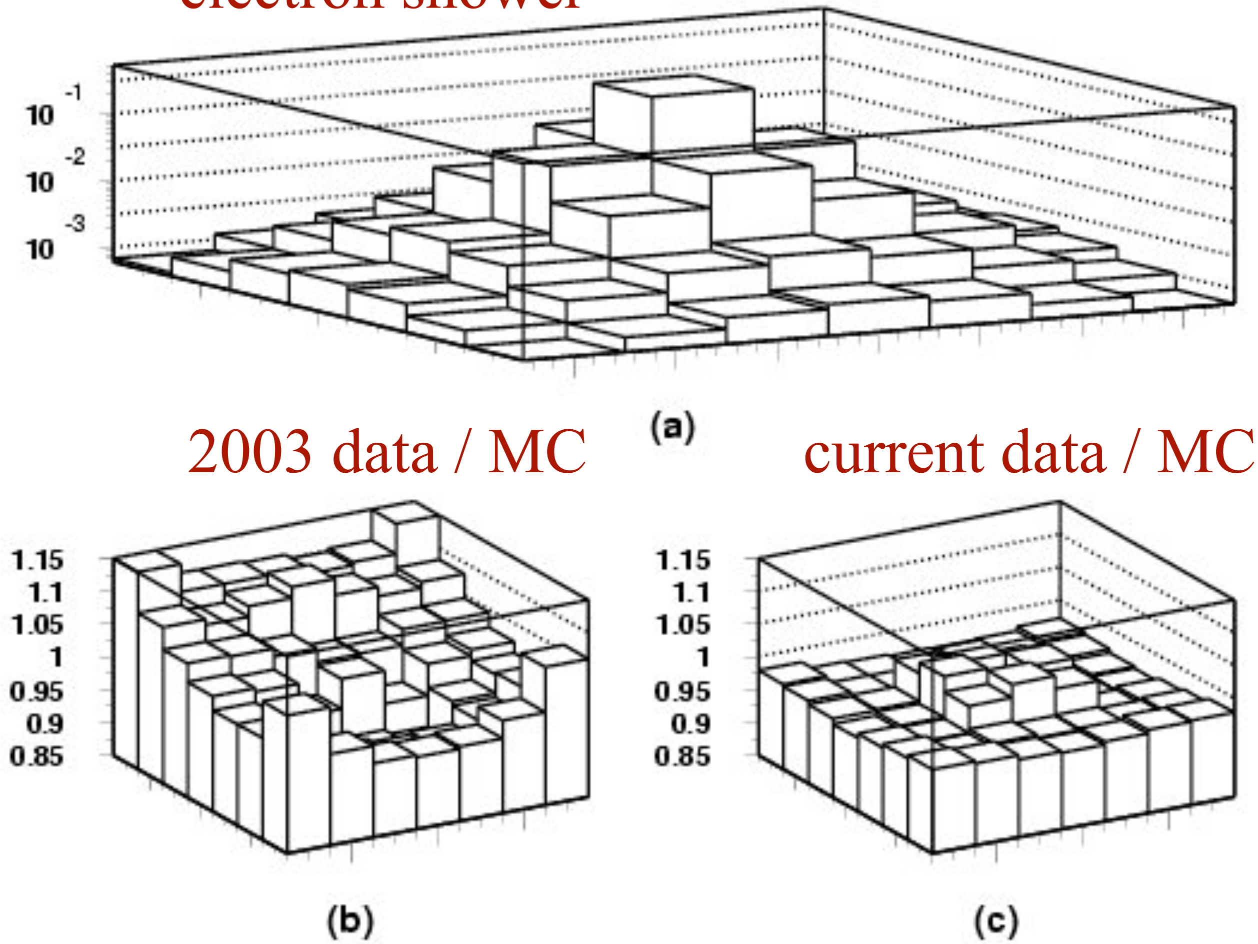


Kaon beam into page

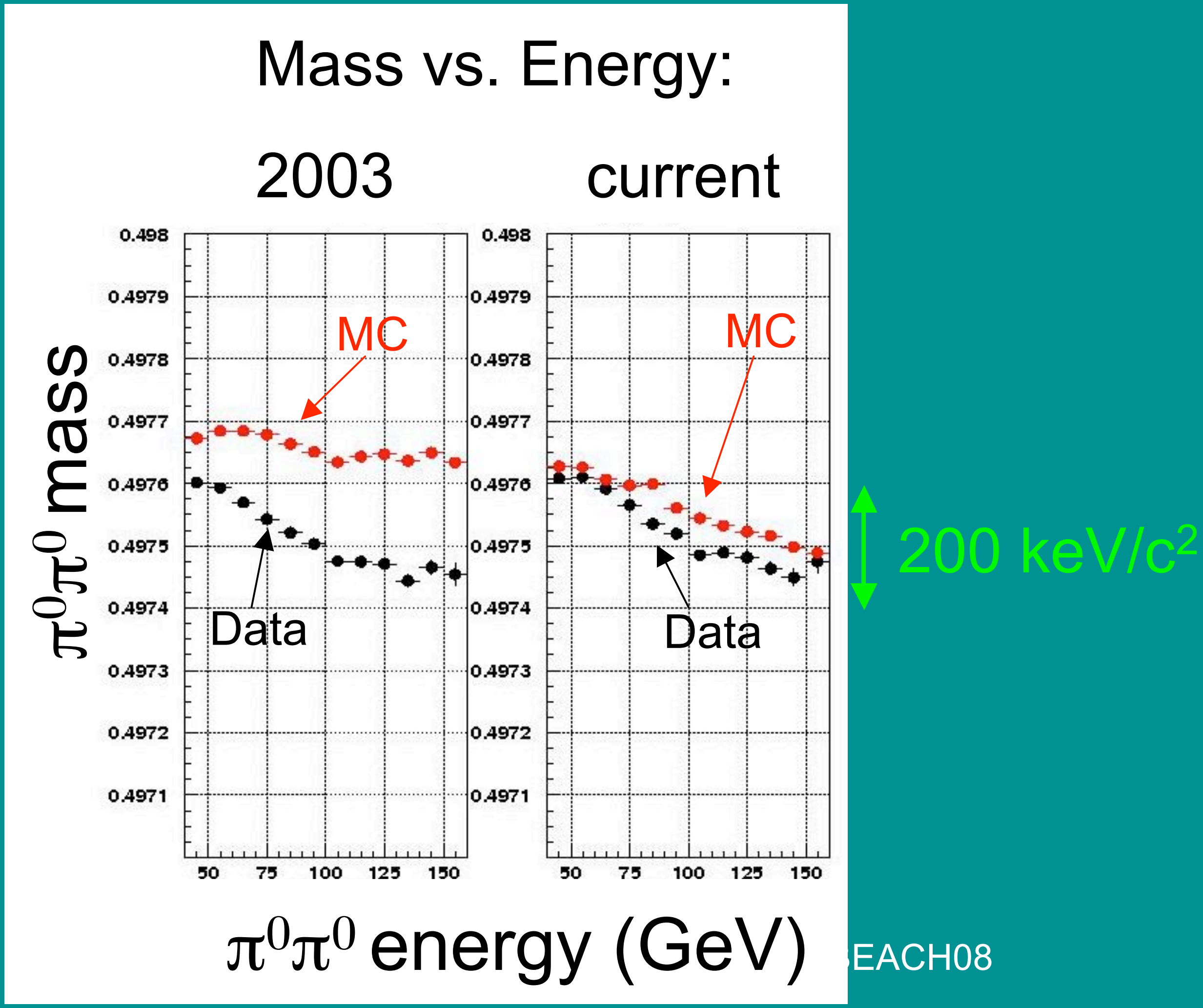
Monte Carlo Improvements:

Simulation of photon angles and mylar wrapping

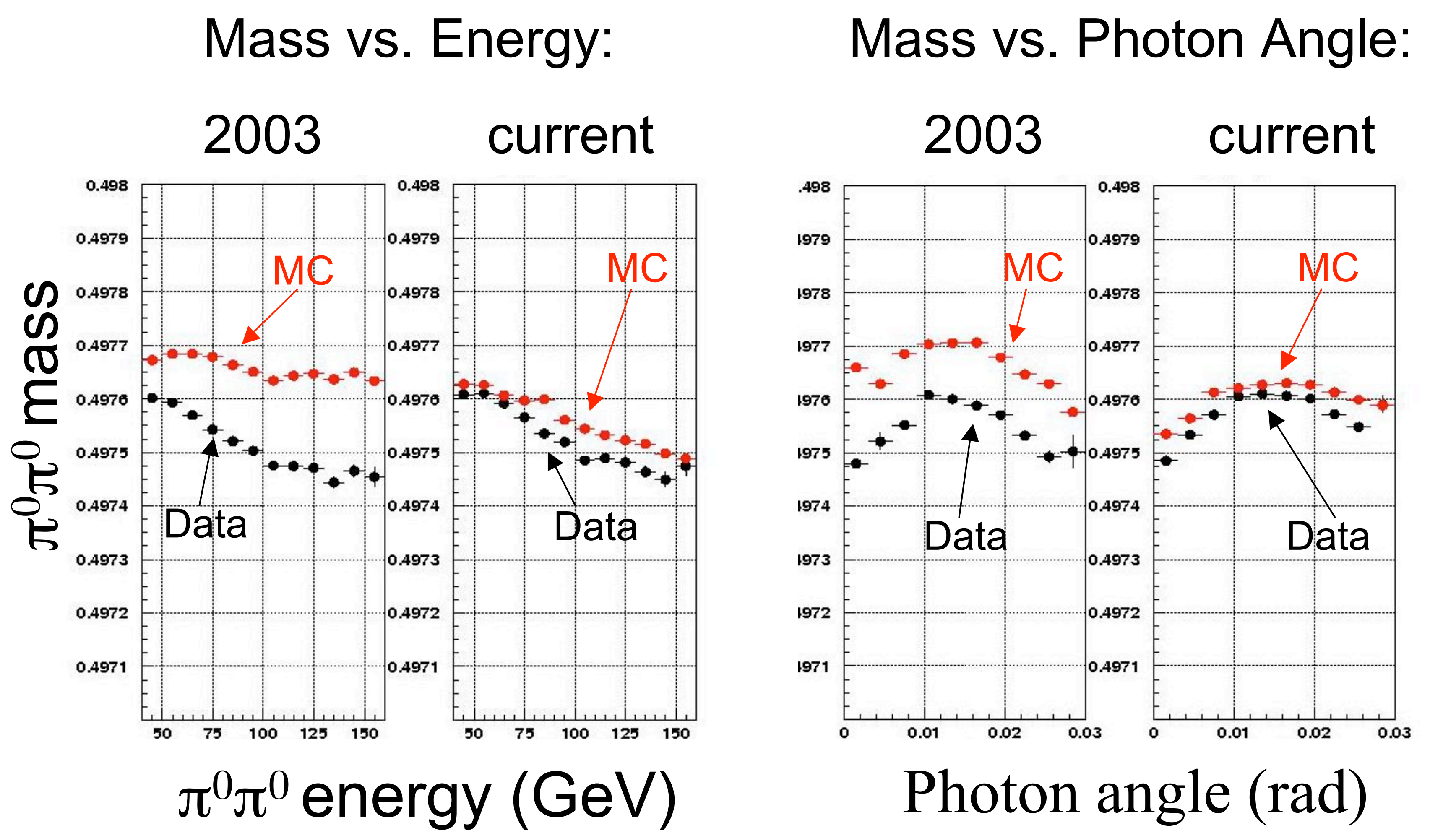
Fraction of energy in 49 crystals for electron shower



Improved Modeling of Energy Nonlinearities



Improved Modeling of Energy Nonlinearities



Systematic Uncertainties in Re(ε′ / ε)

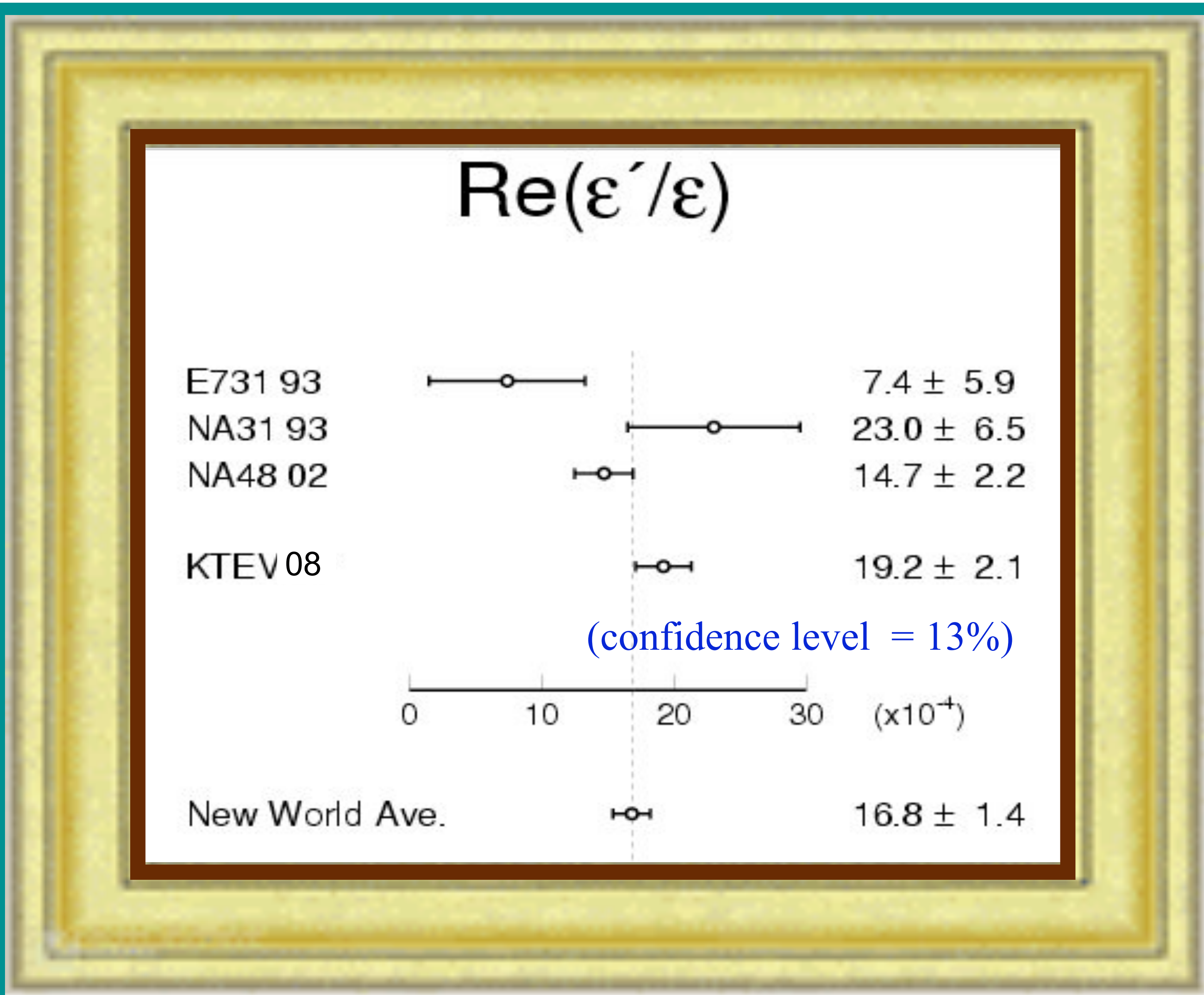
Source	Error on $Re(\epsilon'/\epsilon)$ $(\times 10^{-4})$ $K \to \pi^+\pi^-$	$K \to \pi^0\pi^0$
Trigger	0.23	0.20
CsI cluster reconstruction	—	0.75
Track reconstruction	0.22	—
Selection efficiency	0.23	0.34
Apertures	0.30	0.48
Acceptance	0.57	0.48
Backgrounds	0.20	1.07
MC statistics	0.20	0.25
Total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

reduced from 1.47

reduced from 2.39

KTeV Result: $\mathrm{Re}(\varepsilon'/\varepsilon) = [19.2 \pm 1.1(\mathrm{stat}) \pm 1.8(\mathrm{syst})] \times 10^{-4}$
$= (19.2 \pm 2.1) \times 10^{-4}$

(KTeV 2003: $\mathrm{Re}(\varepsilon'/\varepsilon) = [20.7 \pm 1.5(\mathrm{stat}) \pm 2.4\ (\mathrm{syst})] \times 10^{-4}$)


Re(ε´/ε)
E731 93
7.4 ± 5.9
NA31 93
23.0 ± 6.5
NA48 02
14.7 ± 2.2
KTEV 08
19.2 ± 2.1
(confidence level = 13%)
0
10
20
30
(x10⁻⁴)
New World Ave.
16.8 ± 1.4

Other "most precise" KTeV Results (using Reg beam)

- $\Delta m = (5269.9 \pm 12.3) \times 10^6\ \hbar s^{-1}$
- $\tau_S = (89.623 \pm 0.047) \times 10^{-12}$ s
- $\phi_\varepsilon = (43.86 \pm 0.63)^\circ$
- $\phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)^\circ$
- $\Delta\phi = (0.30 \pm 0.35)^\circ$

→ $\phi_{00} - \phi_{+-}$

Other "most precise" KTeV Results (using Reg beam)

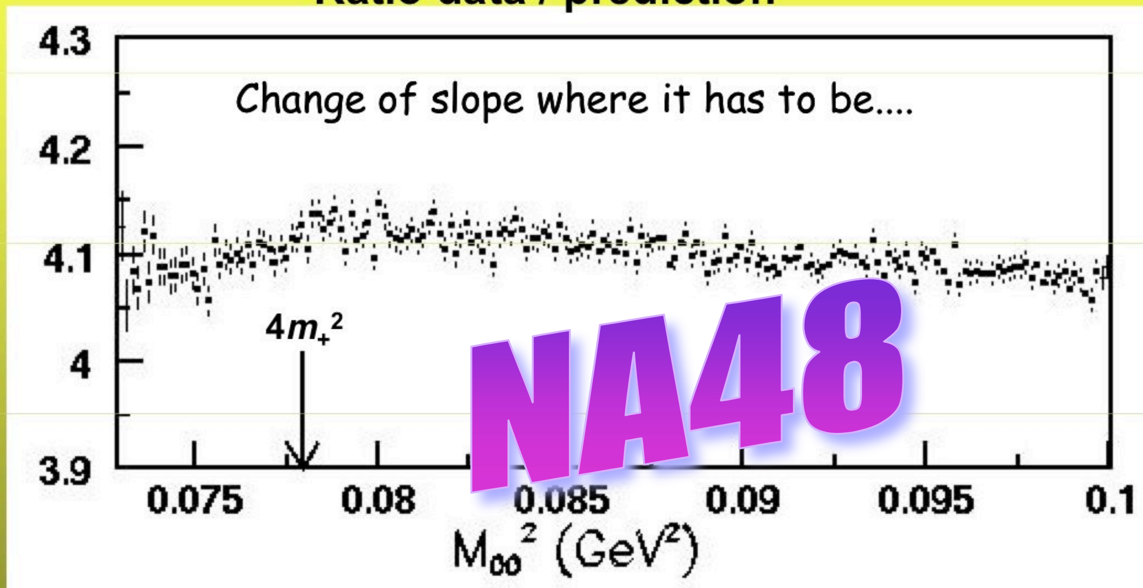
	Next-best error / KTeV error
$\Delta m = (5269.9 \pm 12.3) \times 10^{6}\ \hbar s^{-1}$	2.5
$\tau_S = (89.623 \pm 0.047) \times 10^{-12}$ s	1.4
$\phi_\varepsilon = (43.86 \pm 0.63)^\circ$	1.0 (2)
$\phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)^\circ$	-
$\Delta\phi = (0.30 \pm 0.35)^\circ$	2.5

$\Delta\phi$ → $\phi_{00} - \phi_{+-}$

(2) without KTeV Δm

CUSP effect in $K_L \rightarrow 3\pi^0$

Ratio data / prediction



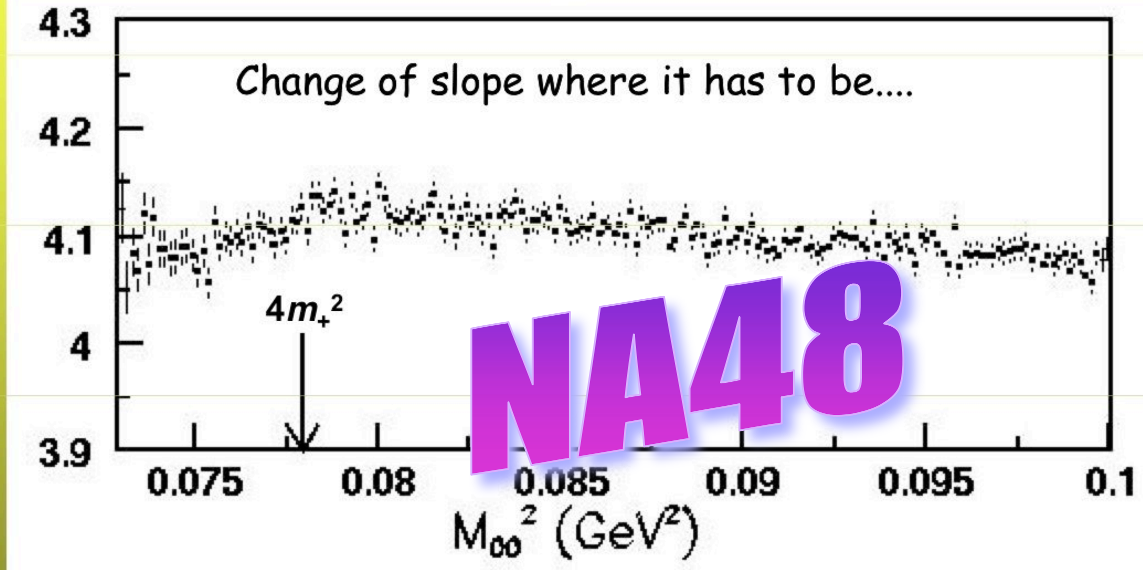
K long sample of ~ 100M events collected in 2000
The CUSP visibility is ~ 13 smaller

CALL TO KTEV : LET THE CUSP BE SEEN IN YOUR HUGE Klong statistics

NA48 slide from S. Giudici talk at HQL08-Melbourne

CUSP effect in $K_L \to 3\pi^0$

Ratio data / prediction



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CALL TO KTEV : LET THE CUSP BE SEEN IN YOUR HUGE Klong statistics

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KTeV response: "OK. But we have less than your 100M"

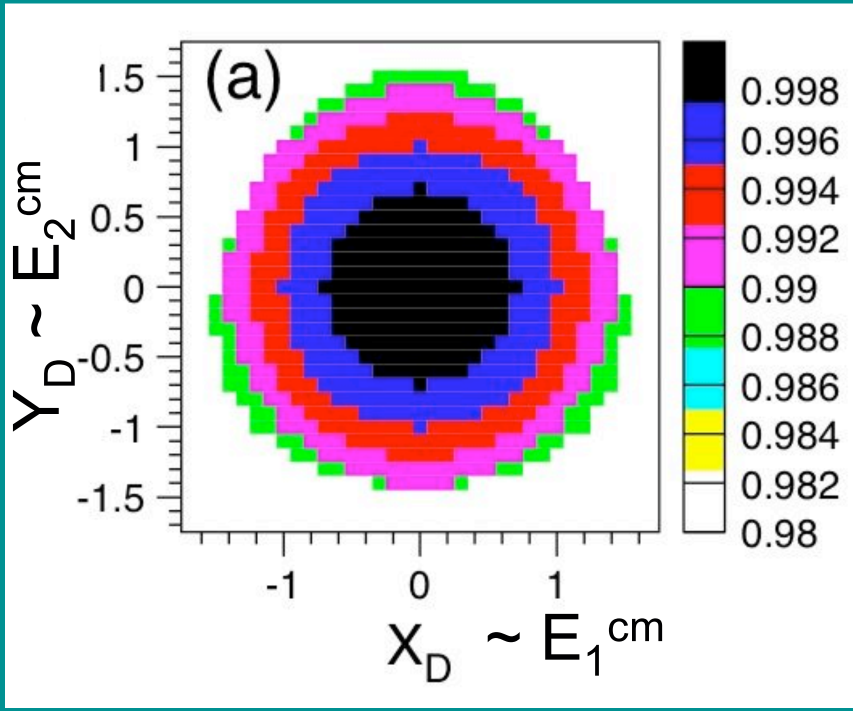
Study of the $K_L \rightarrow \pi^0 \pi^0 \pi^0$ Phase Space

- data collected to study detector acceptance for ε' analysis (trigger pre-scale = 5)

- many years later … Cabibbo-Isidori model motivates some nice physics.

- KTeV sample after cuts (96+97+99) : 68 million

$K_L \rightarrow \pi^0 \pi^0 \pi^0$ Phase Space: Theoretical Expectation

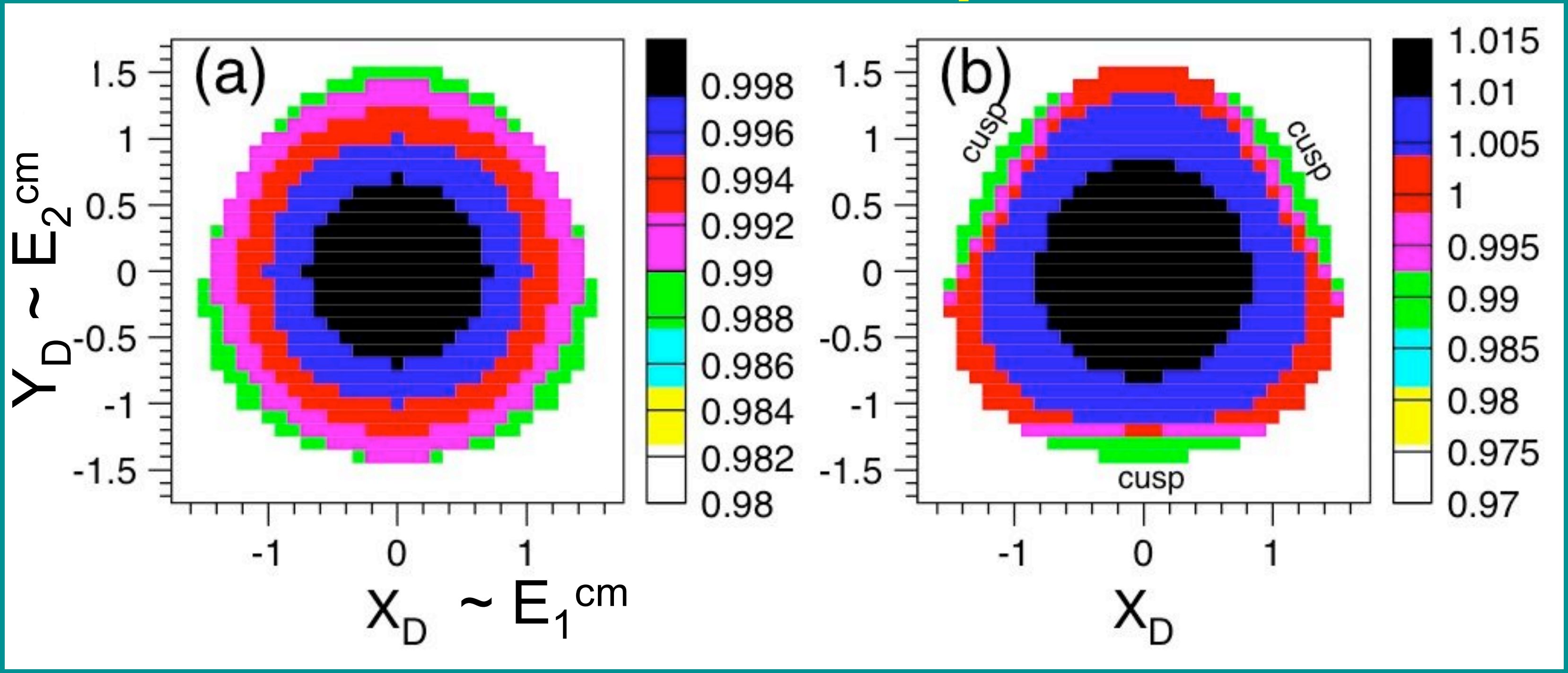


Pre-2004 Expectation:

Decay dynamics.
PDG: $h_{000} = -0.005$
(quad. slope parameter)

$$|\mathcal{M}|^2 \sim 1 + h_{000} \times R^2$$

$K_L \rightarrow \pi^0 \pi^0 \pi^0$ Phase Space: Theoretical Expectation



Decay dynamics.
PDG: $h_{000} = -0.005$
(quad. slope parameter)

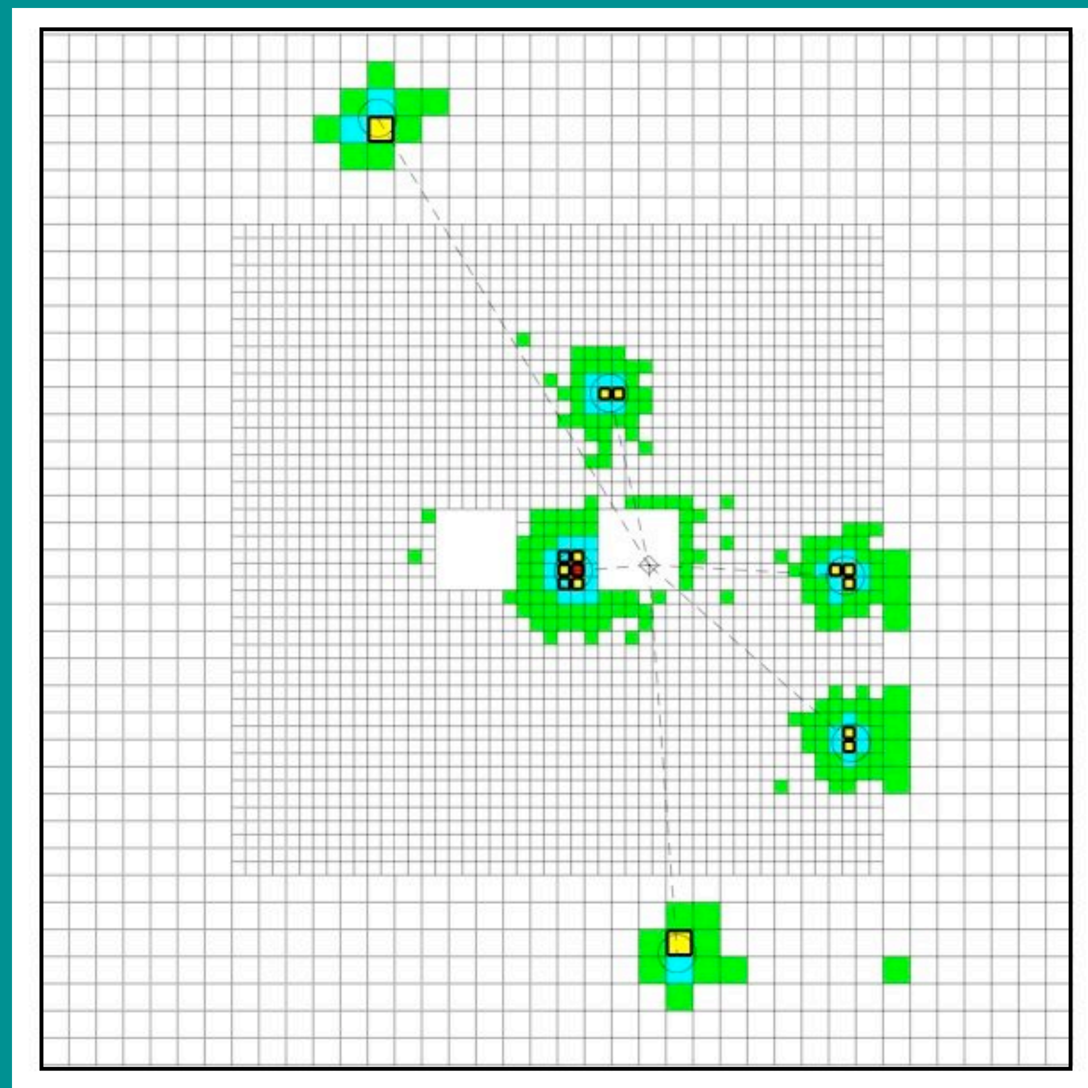
Interference from $K_L \rightarrow \pi^+\pi^-\pi^0$
& rescattering: $\pi^+\pi^- \rightarrow \pi^0 \pi^0$
(and $h_{000} = 0$)

$K_L \rightarrow \pi^0 \pi^0 \pi^0$ Phase Space: Theoretical Expectation

- Shape of phase space sensitive to difference in $\pi\pi$ scattering lengths $a_0 - a_2$, and h_{000}
- Offers experimental opportunity to check precise $a_0 - a_2$ prediction from CHPTH.
- $K^{\pm}$ much more sensitive than K^0 ; see Payaud (NA48) talk
- Previous results on h_{000} (E731 & NA48) ignored rescattering; KTeV presents first measurement of h_{000} that accounts for rescattering.

KTeV Neutral Detector for $K_L \rightarrow \pi^0 \pi^0 \pi^0 \rightarrow 6\gamma$

- Take advantage of years of calibration on 3100-channel CsI calorimeter [for Re(ε'/ε)]: energy resolution better than 1%



$K_L \rightarrow \pi^0 \pi^0 \pi^0$ Reconstruction

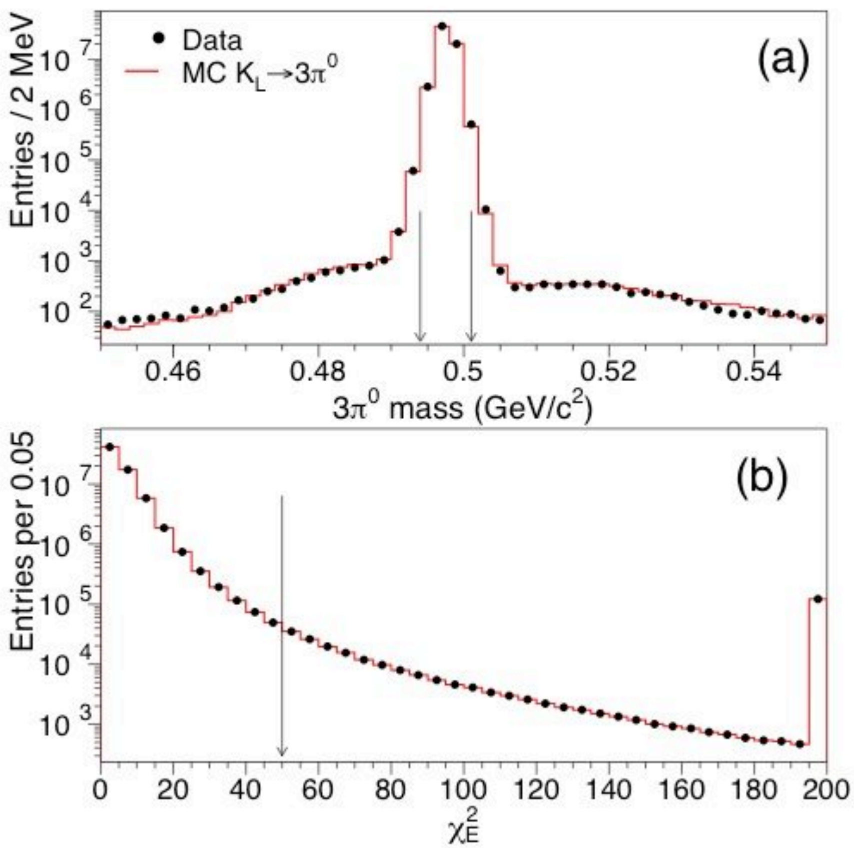


FIG. 4: (a) Invariant $\pi^0\pi^0\pi^0$ mass with all selection requirements except for the $\pi^0\pi^0\pi^0$-mass and χ^2_E. The $\pi^0\pi^0\pi^0$ mass resolution (from Gaussian fit) is 0.94 MeV$/c^2$. (b) shows χ^2_E distribution with all other selection requirements; last bin includes all events with $\chi^2_E > 200$. Dots are data and the histogram is MC. Vertical arrows show the selection requirements.

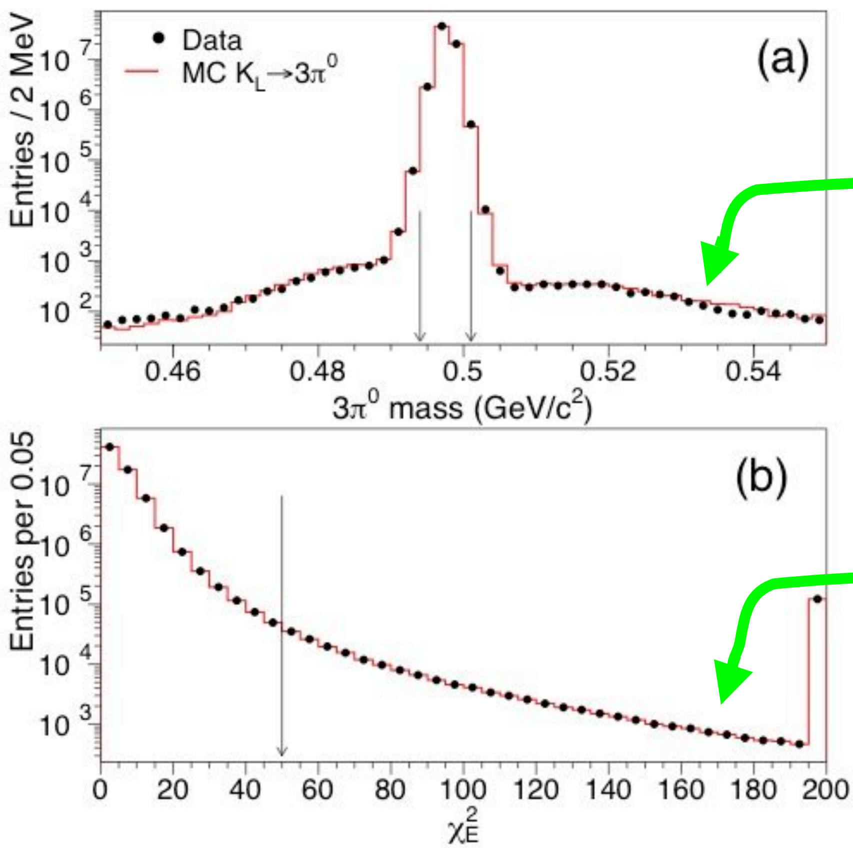
6 energies and
4 kin constraints:
$m_{\gamma\gamma} = m_{\pi 0}$ and
$m_{6\gamma} = M_K$

↓

Two-parameter fit for EVERY event improves Dalitz variable precision:
$\sigma(R_D{}^2) = 0.070 \rightarrow 0.014$

See fit χ^2 distribution at left

$K_L \rightarrow \pi^0 \pi^0 \pi^0$ Reconstruction



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mass-tail fraction:
0.21% (data)
0.20% (sim)

χ^2-tail fraction:
0.43% (data)
0.47% (sim)

$K_L \rightarrow \pi^0 \pi^0 \pi^0$ Raw Dalitz Density

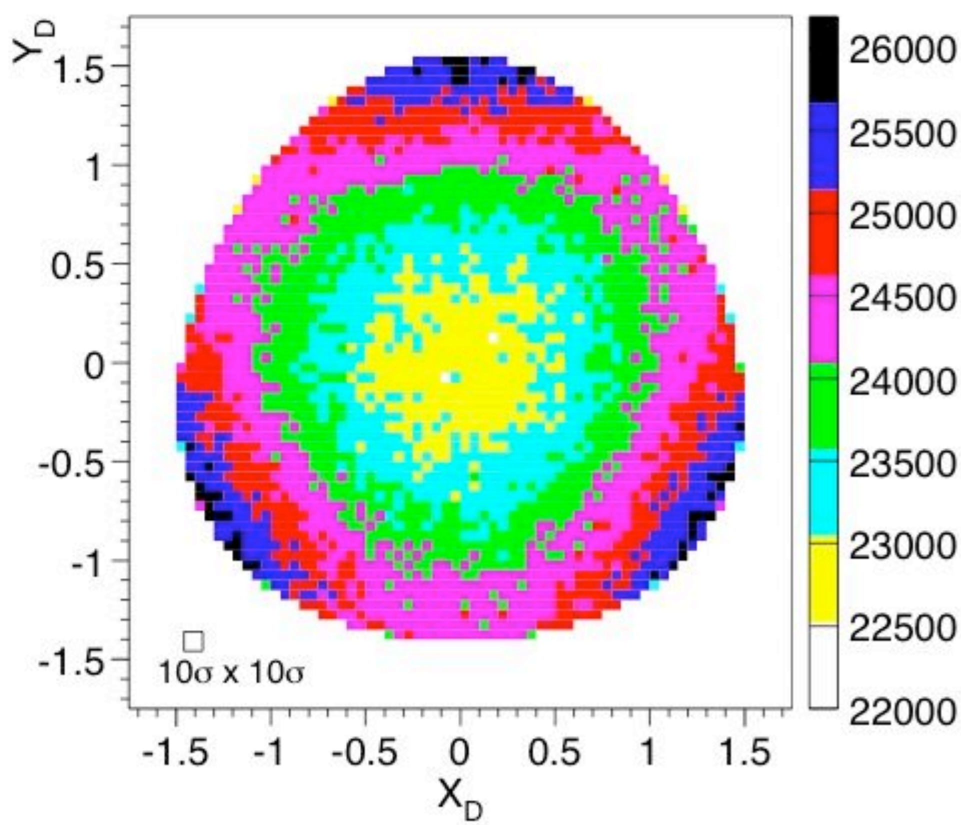


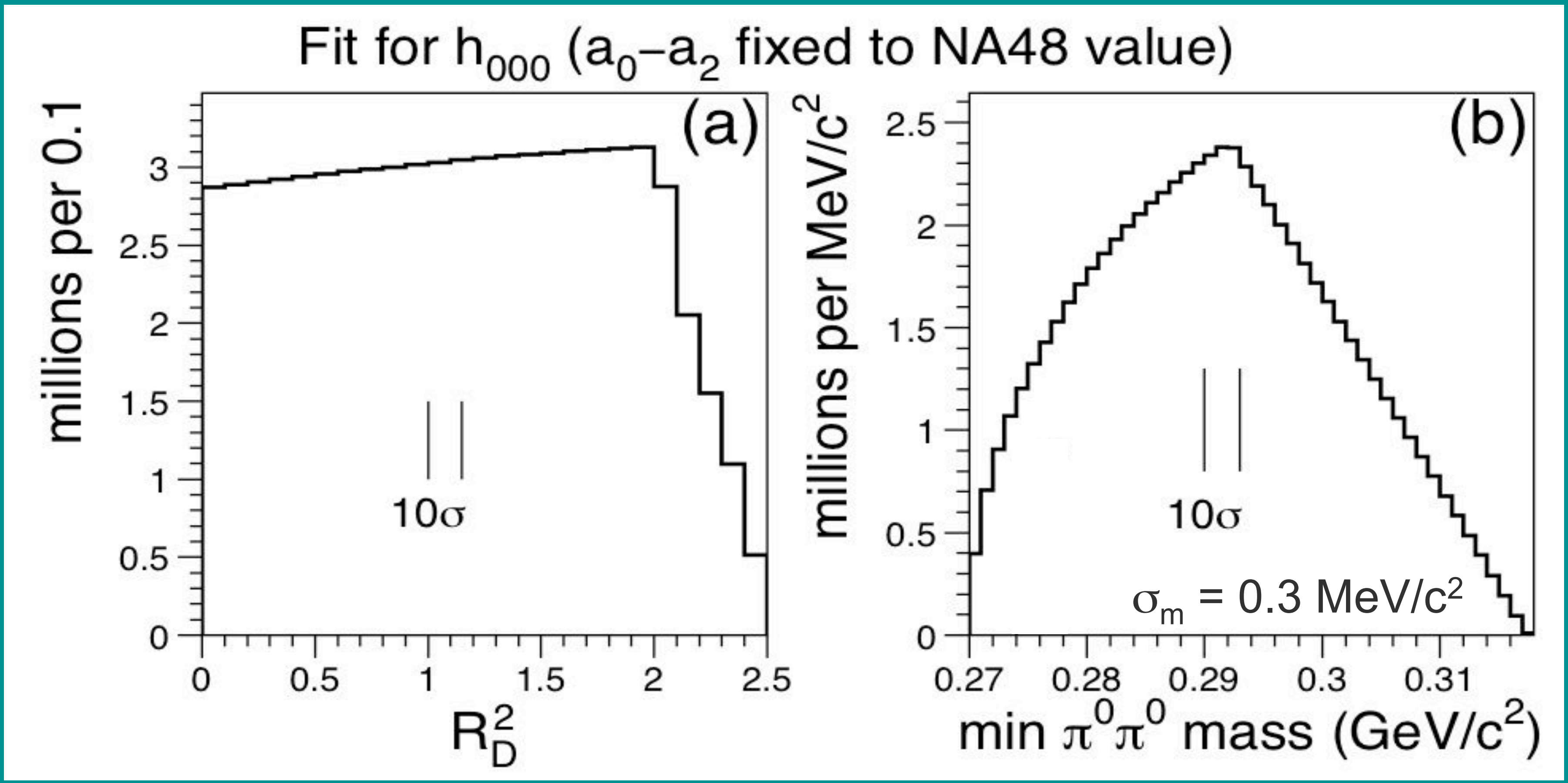
FIG. 5: Dalitz plot density, Y_D vs. X_D, for 68.3 million $K_L \rightarrow \pi^0\pi^0\pi^0$ decays in the KTeV data sample after all selection requirements. The color-scale at right shows the number of events in each 0.05×0.05 pixel. The reconstruction resolution on X_D and Y_D is $\sigma \sim 0.01$ as determined by the MC; the box in the lower-left corner shows $10\sigma \times 10\sigma$ for illustration.

Combine data taken in 96+97+99:

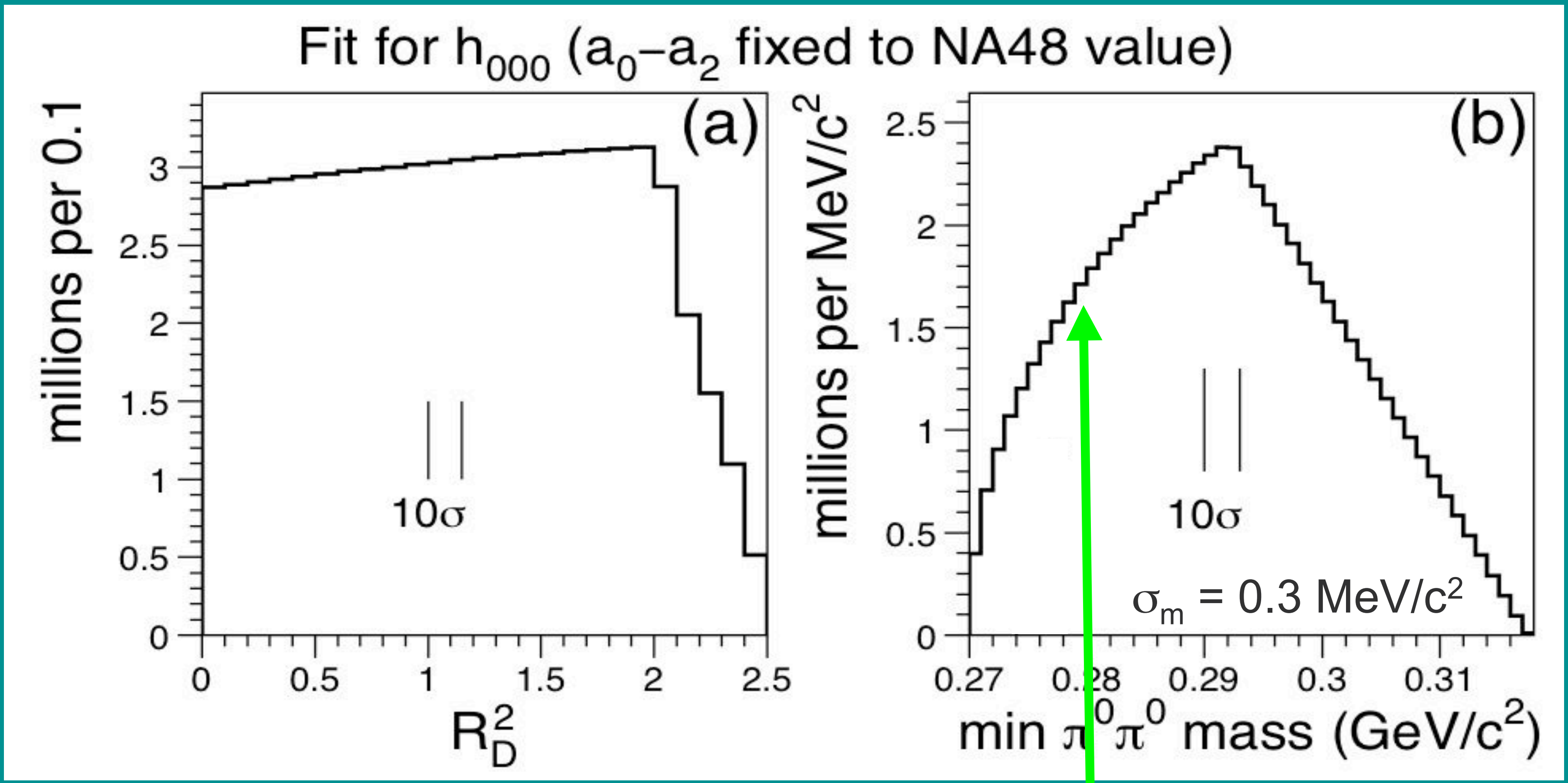
➜ 68 million decays !

10% variation is mostly due to acceptance: physics effects give ~1% variations

$K_L \rightarrow \pi^0 \pi^0 \pi^0$ Raw Dalitz Density

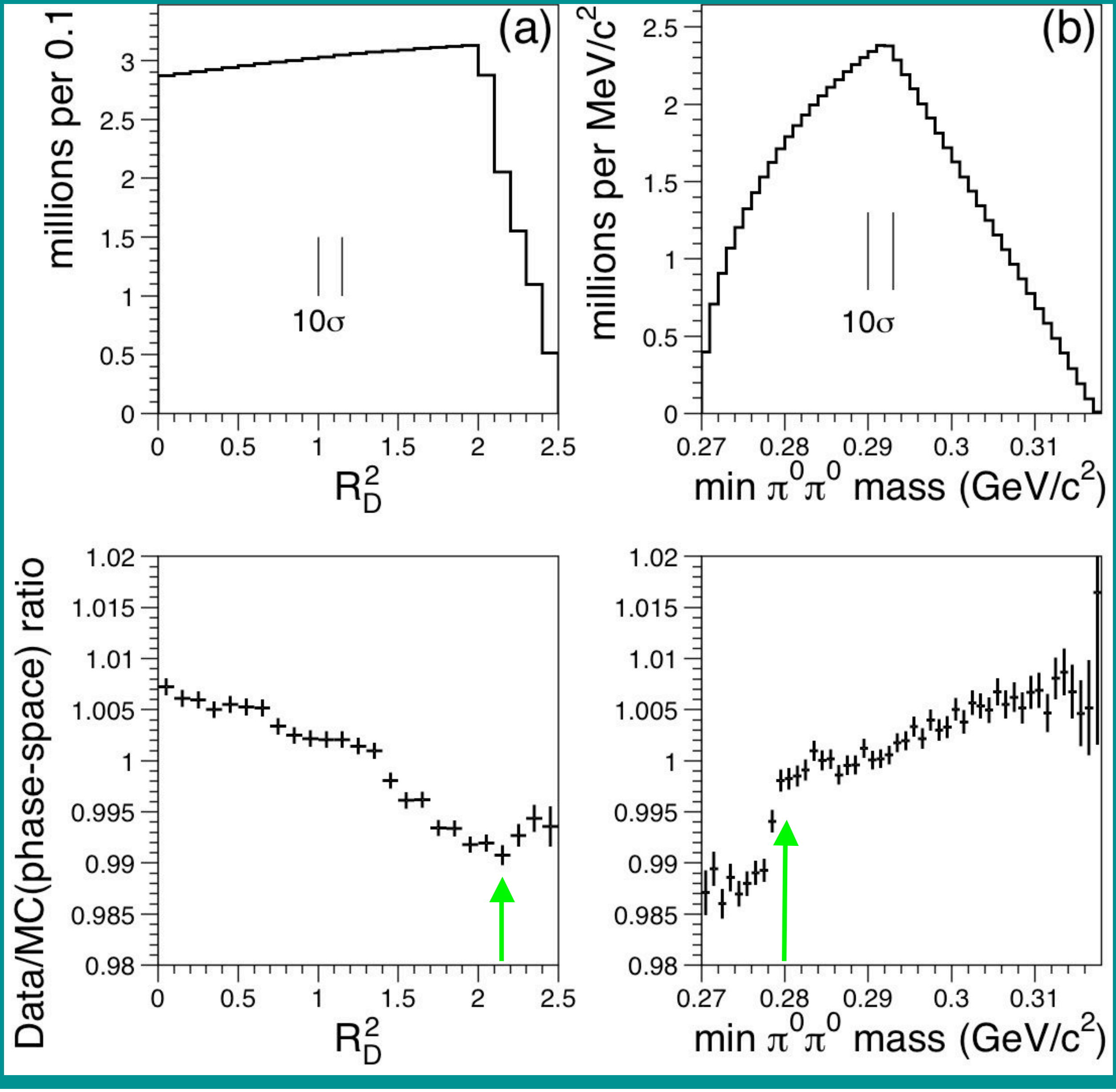


$K_L \rightarrow \pi^0 \pi^0 \pi^0$ Raw Dalitz Density



no obvious cusp effect as in $K^\pm$

Cusp in $K_L \rightarrow \pi^0 \pi^0 \pi^0$



$$\frac{\text{Raw dalitz density}}{\text{MC phase space}}$$

➘

visible cusp

$K_L \to \pi^0 \pi^0 \pi^0$ Model

- Cabibbo & Isidori JHEP 503, 21 (2005)
- "CI3PI"
- CI3PI used in NA48's 2006 result ($K^{\pm}$).
- Free parameters for $K_L \to \pi^0 \pi^0 \pi^0$:

  h_{000} and $a_0 - a_2$

fix to NA48 value, or float

$K_L \to \pi^0\,\pi^0\,\pi^0$ Model

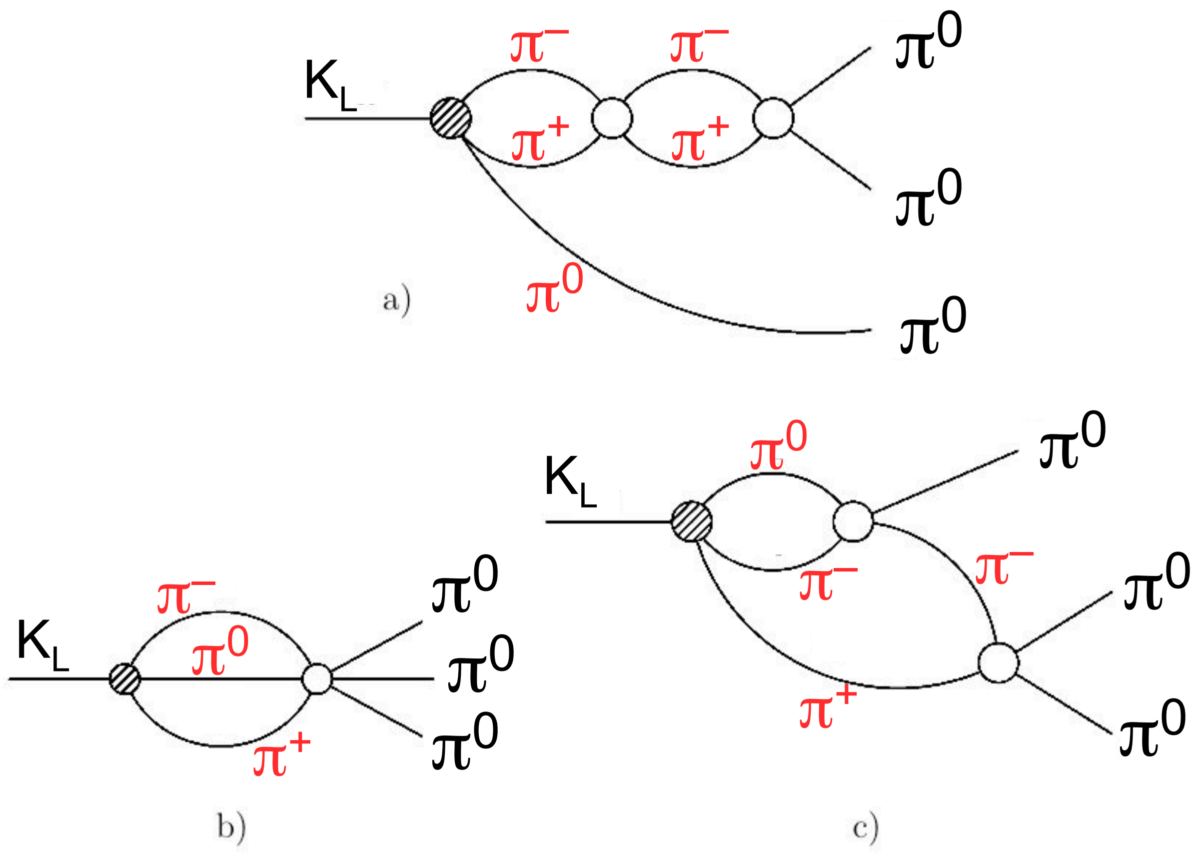


Figure 1: Examples of $K \to 3\pi$ rescattering topologies at the two-loop level: a) single-channel $\pi\pi$ scattering; b) irreducible $3\pi \to 3\pi$ contributions; c) $3\pi \to 3\pi$ amplitude due to multi-channel $\pi\pi$ scattering.

two loops from “CI3PI”

Fit Results: fix $a_0 - a_2$

0.268(17) from NA48 K±

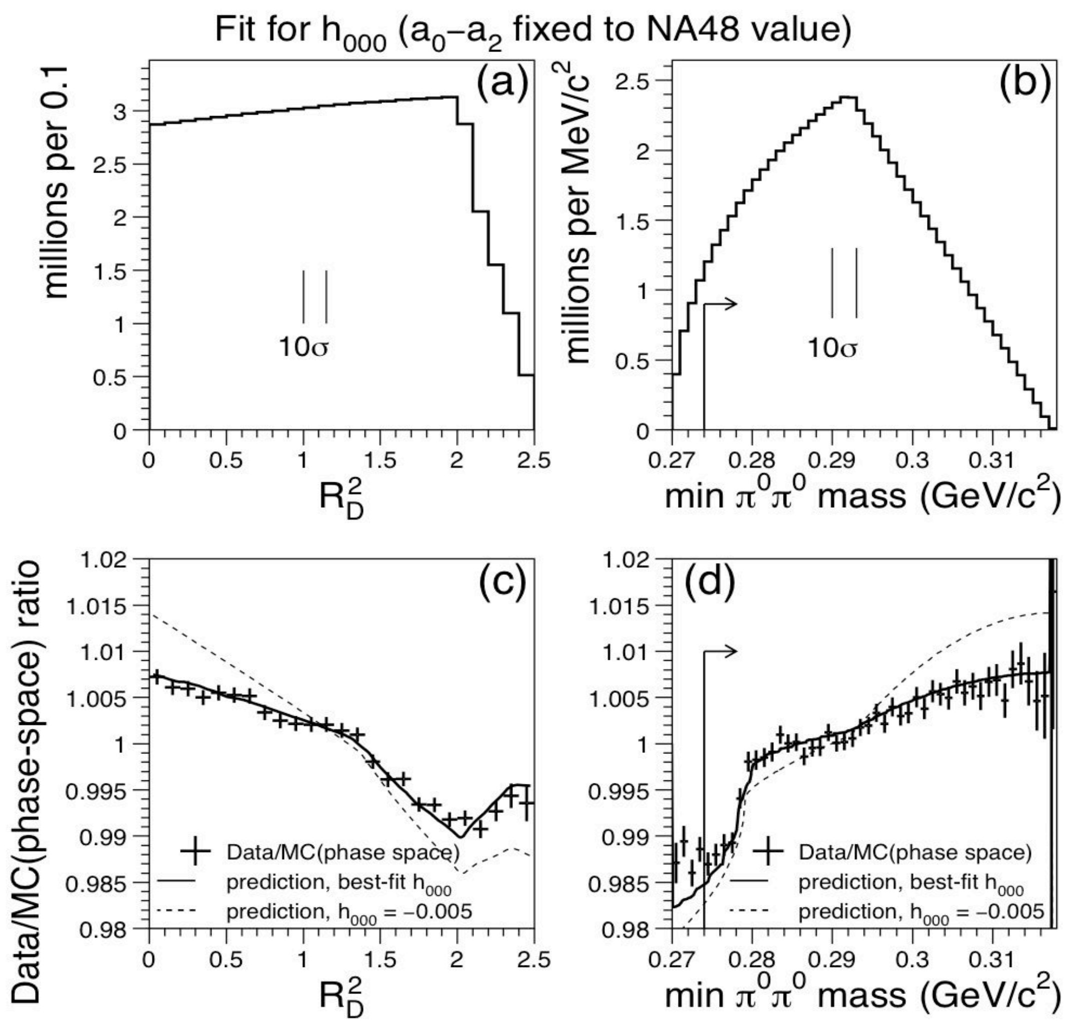
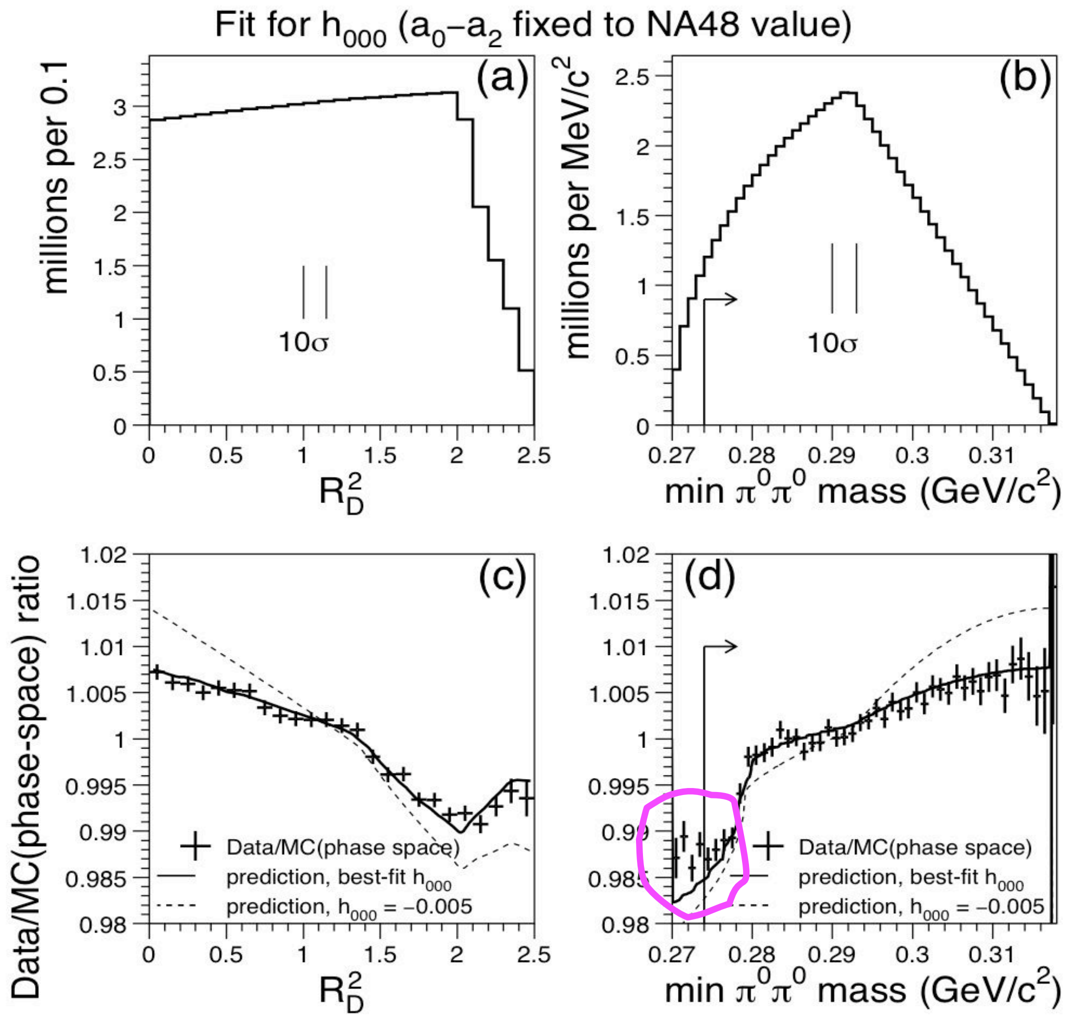


FIG. 6: For the 68.3 million $K_L \to \pi^0\pi^0\pi^0$ in the KTeV sample, projected Dalitz distributions are shown for (a) R_D^2 and (b) $m^{min}_{\pi^0\pi^0}$. The average reconstruction resolution determined by the simulation is $\sigma(R_D^2) \sim 0.014$ and $\sigma(\min m_{\pi^0\pi^0}) \sim 0.3$ MeV$/c^2$: these resolutions are indicated by a 10σ marker on each plot. The data/MC(phase-space) ratio is shown as a function of (c) R_D^2 and (d) $m^{min}_{\pi^0\pi^0}$ (points with error bars). The solid curve is the prediction from our best fit h_{000}. The dashed curve is the prediction using $h_{000}(\mathrm{PDG06}) = (-5.0 \pm 1.4) \times 10^{-3}$. The arrow in (d) shows the selection requirement $m^{min}_{\pi^0\pi^0} > 0.274$ GeV$/c^2$. Note that previous analyses [6, 7] ignored rescattering and excluded $R_D^2 > 1.9$; the corresponding data/MC ratio was assumed to be a straight line with slope of -0.005.

Fit Results: fix $a_0 - a_2$



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good overall data-model agreement, except for $m_{\pi\pi} < 0.274$:

discrepant region is EXCLUDED for nominal results, but included as part of systematic error.

Many experimental tests ➜ no change ! discrepancy remains a mystery.

Fit Results: fix $a_0 - a_2$

VII. RESULT FOR h_{000} WITH FIXED $a_0 - a_2$

Here we fix $m_{\pi^+}(a_0 - a_2) = 0.268$ as measured by NA48 [2]), and determine h_{000}. The result from minimizing the χ^2 in Eq. 12 is

$$h_{000} = (+0.59 \pm 0.20_{stat}) \times 10^{-3} \quad (14)$$

$$\chi^2/\text{dof} = 2805.3/2765 \quad \text{(all pixels)} \quad (15)$$

$$\chi^2/\text{dof} = 125.3/130 \quad \text{(edge pixels)}\ . \quad (16)$$

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185/130
without
kinematic fit

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185/130 without kinematic fit

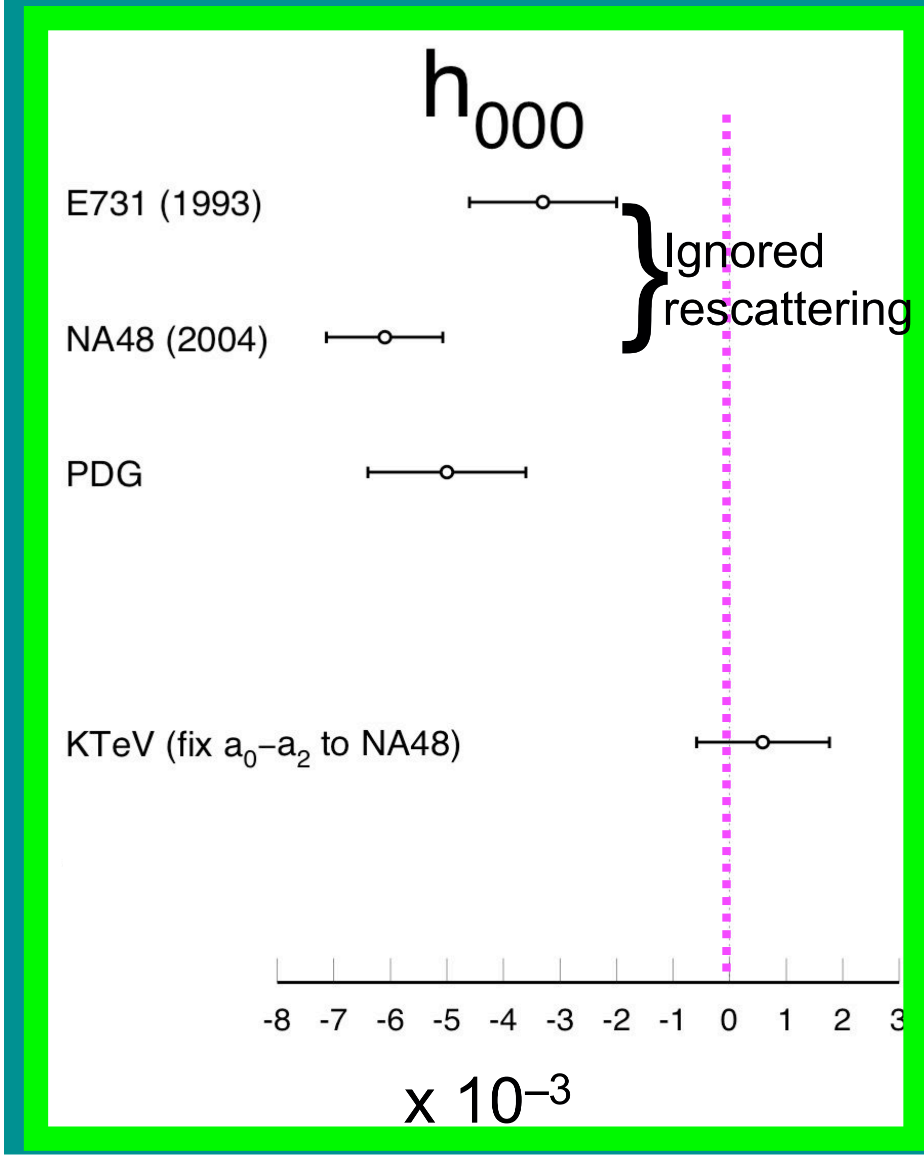
TABLE II: Systematic uncertainties on h_{000}. For each external parameter $\mathcal{X}$, the sign (+ or −) is indicated for the partial derivative, $\partial h_{000}/\partial \mathcal{X}$, so that our h_{000} result can be updated when an external parameter is updated.

source of uncertainty	uncertainty on h_{000} ($\times 10^{-3}$)
DETECTOR & RECON	
kaon scattering	0.05
accidentals	0.02
photon energy scale	0.06
energy resolution	0.04
low-side energy tail	0.02
position resolution	0.07
χ^2_E-cut	0.07
(sub-total)	(0.13)
FITTING	
MC statistics	0.14
Ignore PSF for N^{pred}_{xy}	0.02
remove $m^{min}_{\pi^0\pi^0}$ cut	0.44
(sub-total)	(0.46)
KTeV TOTAL	0.48
EXTERNAL	
$(a_0 - a_2)m_{\pi^+}$	(+) 1.03
$a_0 m_{\pi^+}$	(−) 0.12
r_0, r_2	(+) 0.21, (+) 0.04
A_L^+/A_L^0	(+) 0.01
g_{+-0}, h_{+-0}	(−) 0.05, (−) 0.05
(sub-total)	(1.06)

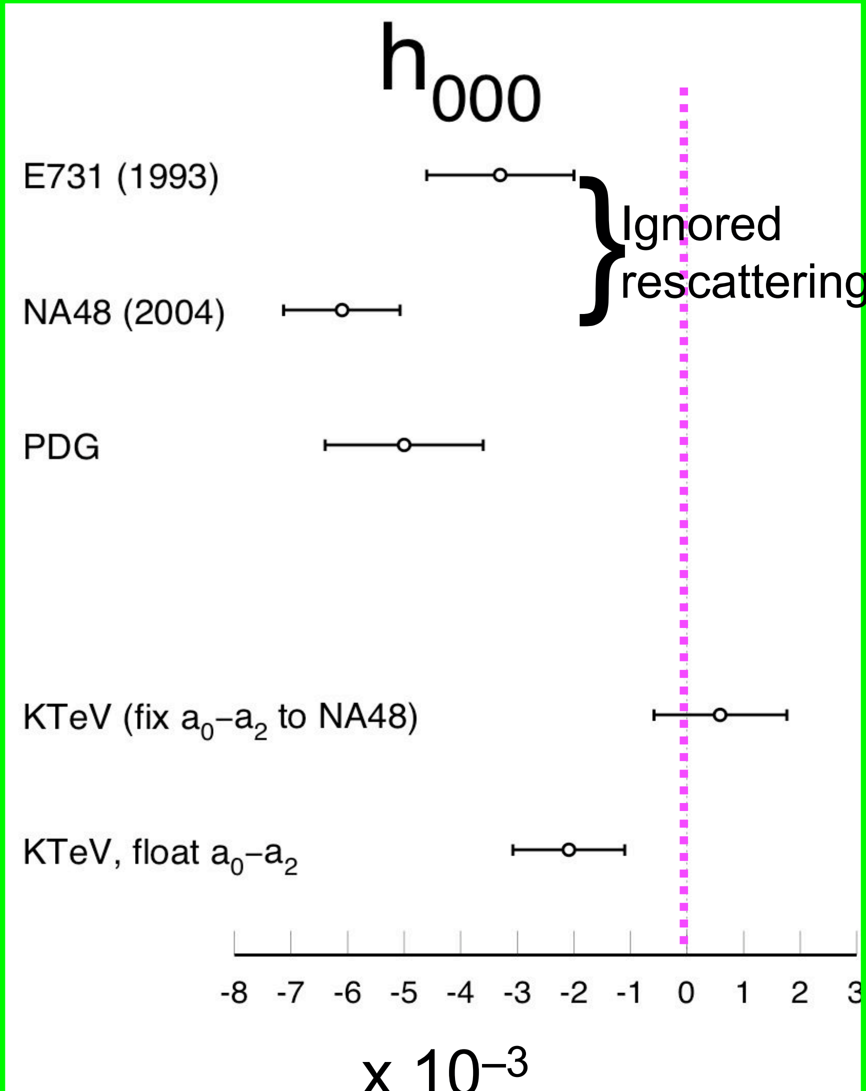
Floating both h_{000} and $a_0 - a_2$

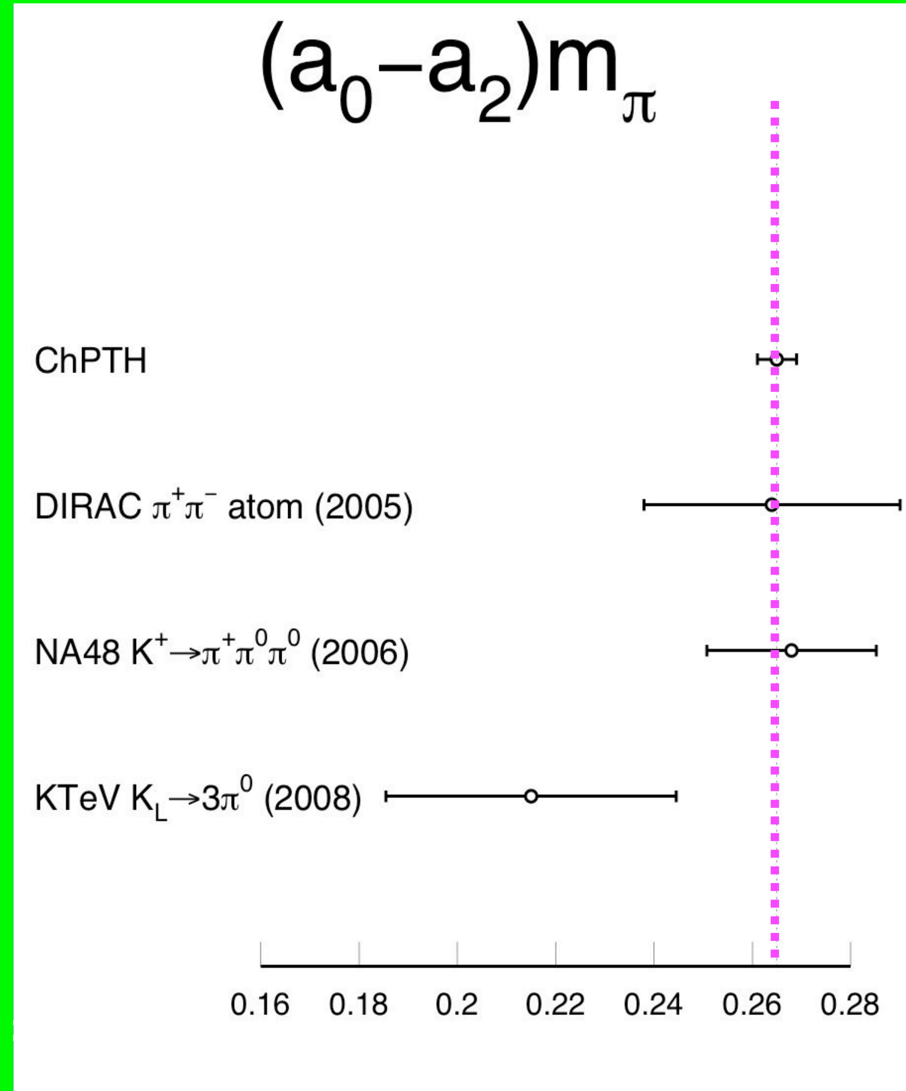
- KTeV $K_L \to \pi^0 \pi^0 \pi^0$ sample is more than twice as large as the [published] NA48 $K^\pm \to \pi^\pm \pi^0 \pi^0$ sample
- … yet KTeV error on $a_0 - a_2$ is almost twice as large.
- Isospin decomposition favors $K^\pm$ over K^0 .

Summary/History



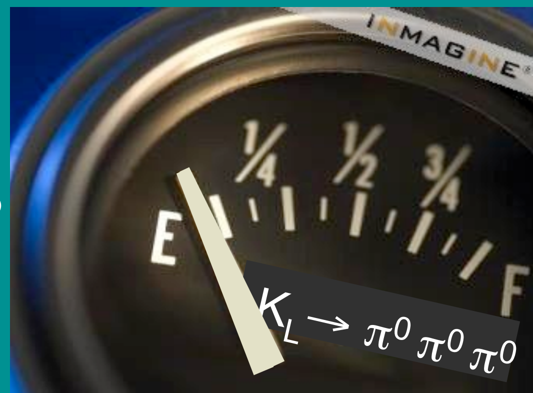
Summary/History



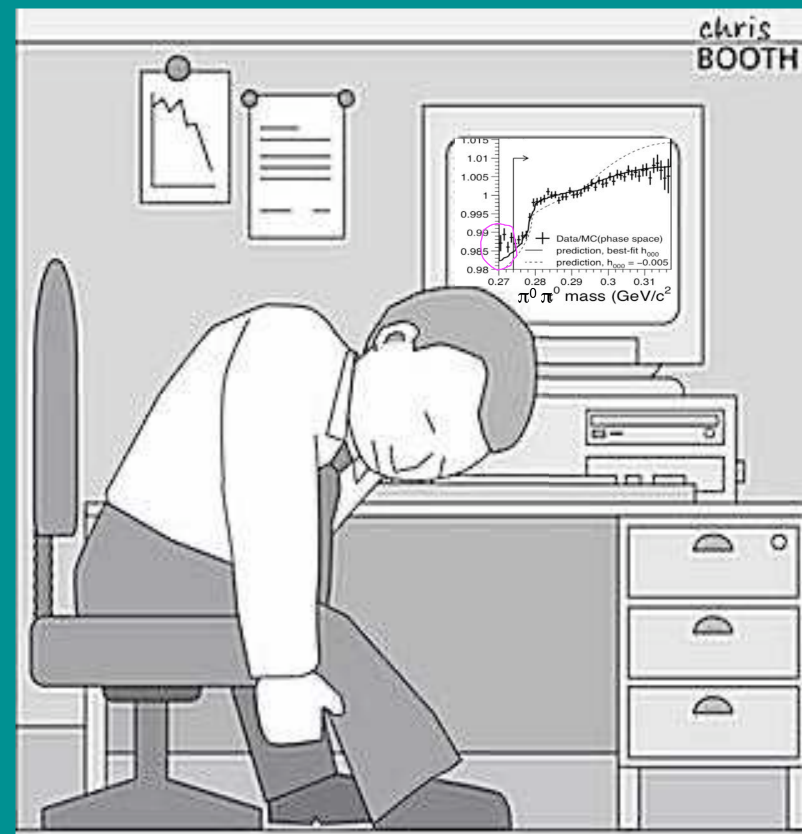


Conclusions

- Out of gas



- Out of ideas on slight data-model discrepancy



- Results submitted to PRD (arXiv:0806.3535)