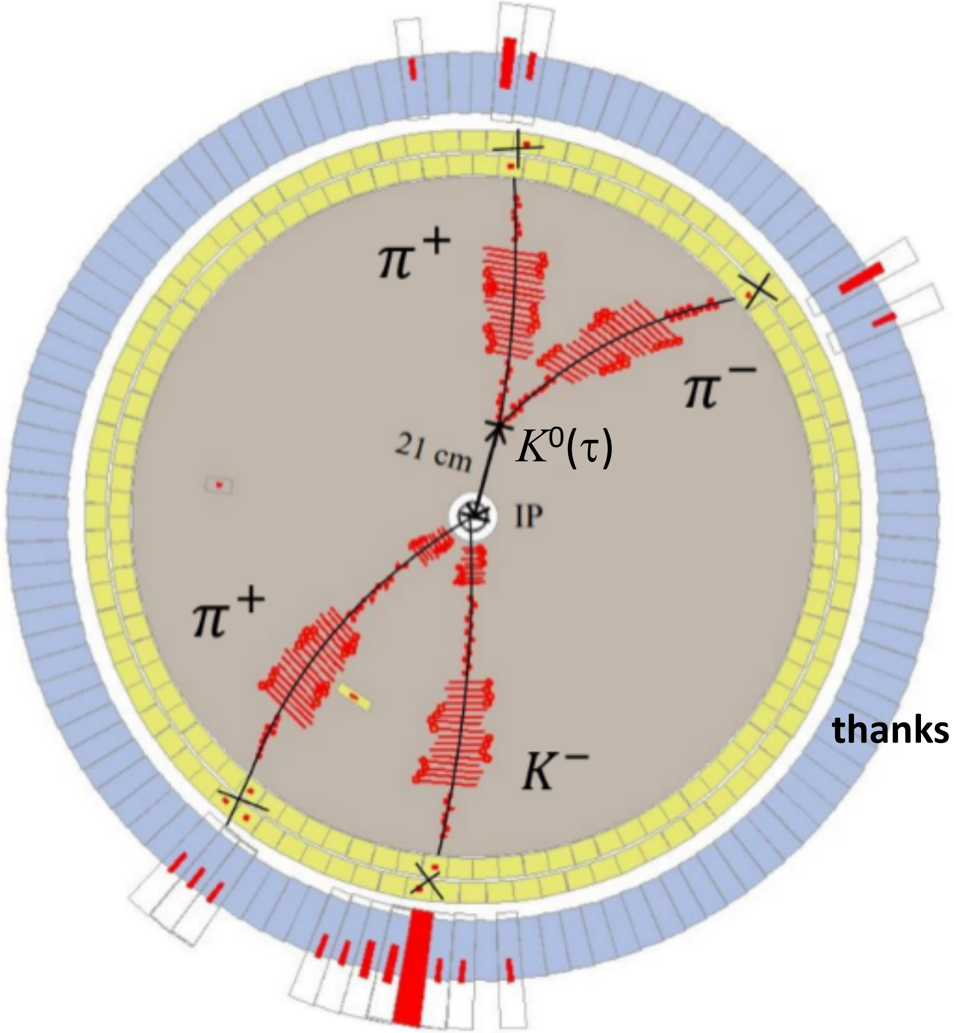
Testing CPT with $J/\psi \rightarrow K^{\mp}\pi^{\pm}K^0$ decays at STCF



thanks to Jian-Yu Zhang

Stephen Lars Olsen
Institute for Basic Science
Daejeon Korea

Why CPT?

any Lorentz-invariant *local* quantum field theory with a hermitian Hamiltonian *must* have CPT symmetry.

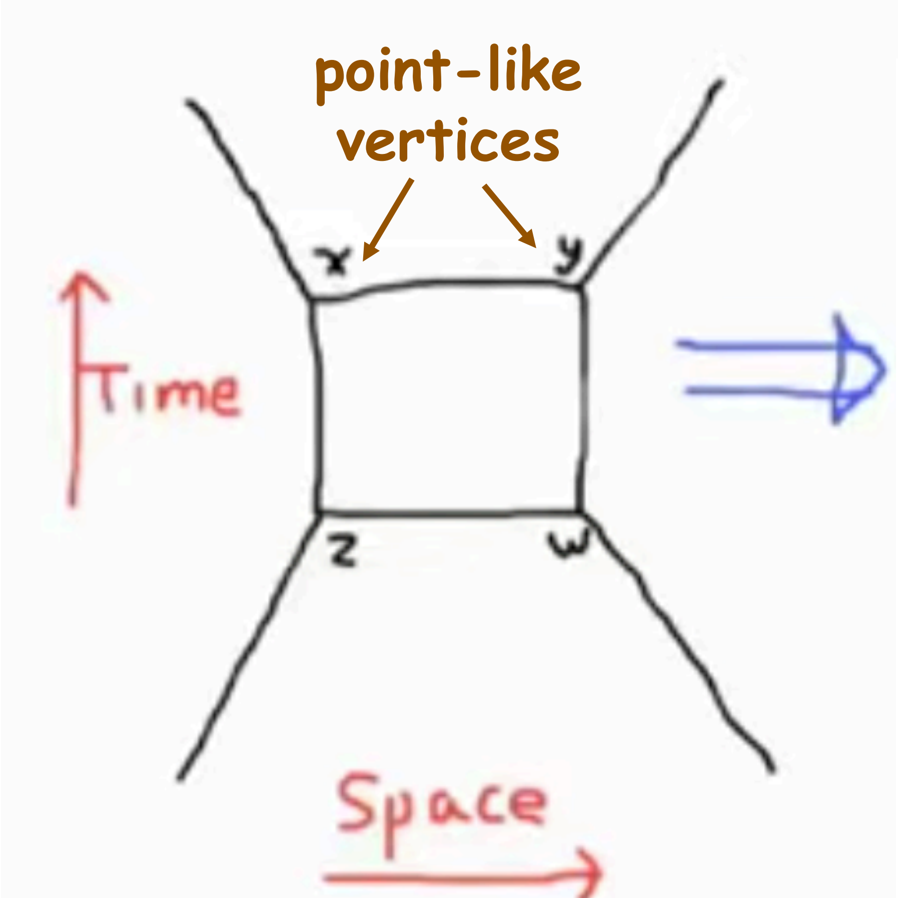
what theory is a Lorentz-invariant *local* quantum field theory with a hermitian Hamiltonian?

the Standard Model

CPT must be violated!

In QFT, 2nd and higher perturbation diagrams have loops:

picture (& argument) from an Ed Witten public talk:



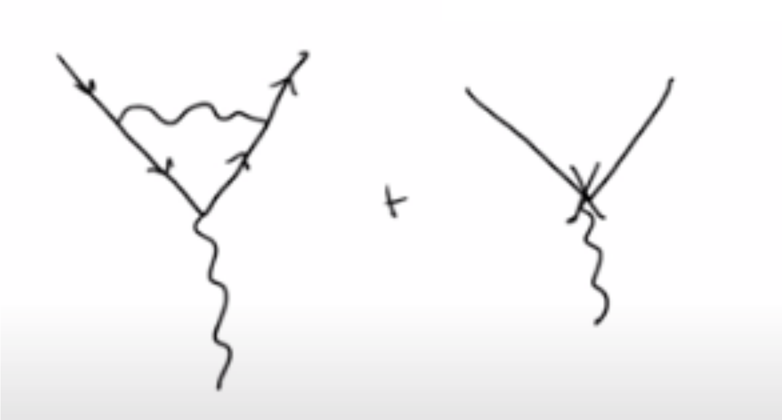
when any two of the point-like vertices coincide, there is an infinite value & these make the space-time integral diverge.

∞

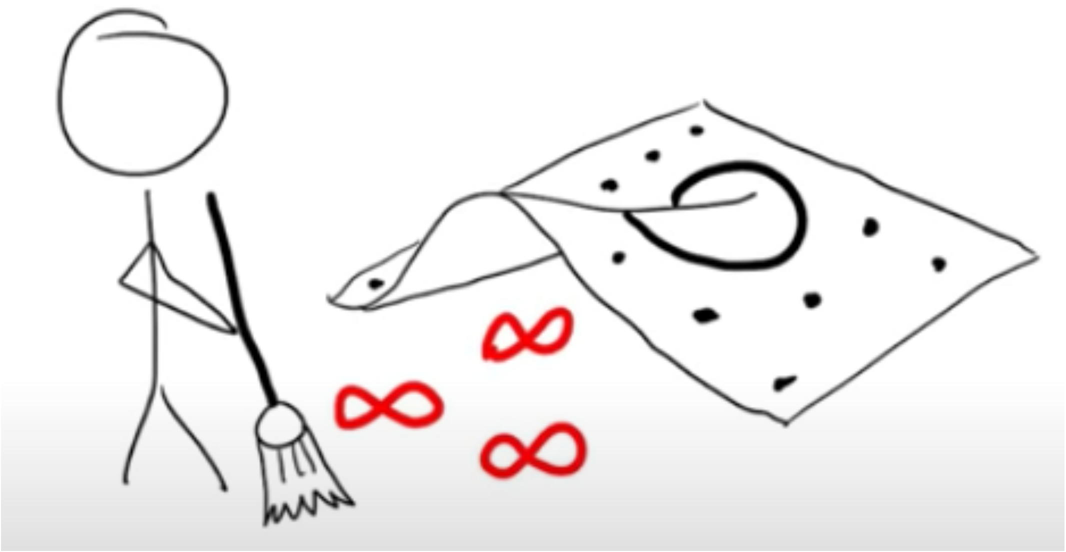
How does QFT deal with these infinities?

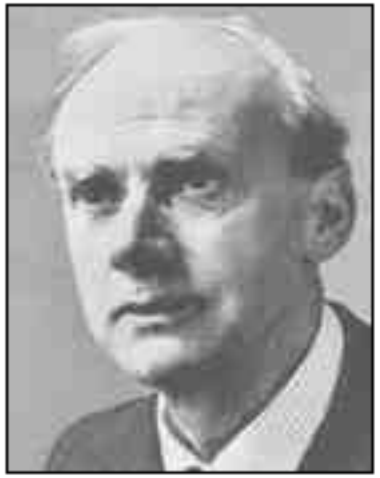
renormalization

term counter-term



∞+something −∞ = something





Dirac:

Renormalization is just a stop-gap procedure. There must be some fundamental change in our ideas, probably a change just as fundamental as the passage from Bohr's orbit theory to quantum mechanics. When you get a number turning out to be infinite which ought to be finite, you should admit that there is something wrong with your equations, and not hope that you can get a good theory just by doctoring up that number.

in a 1970 interview with Dirac conducted by David Peat and Paul Buckley for the CBC show, "Physics and Beyond").

Feynman:

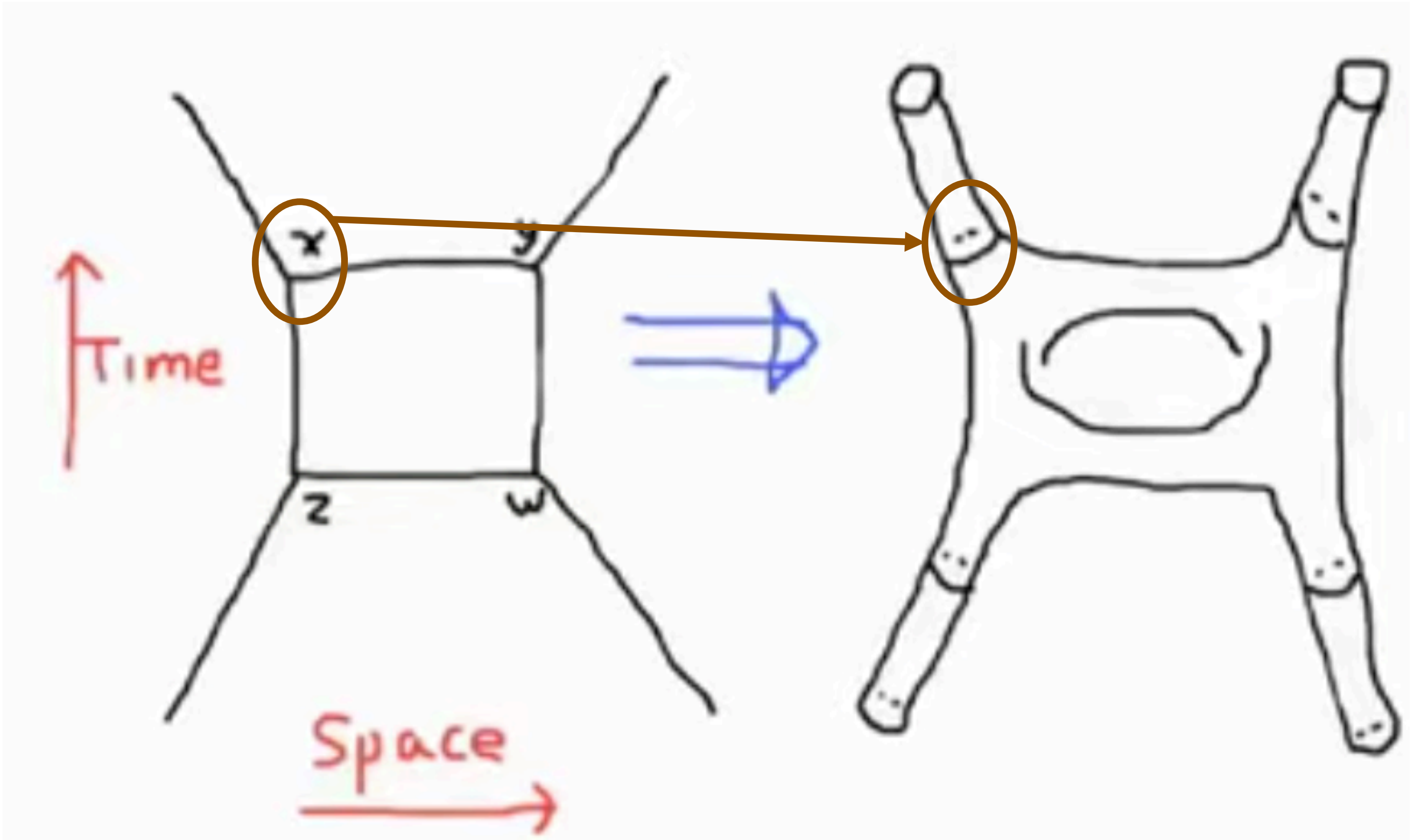
The shell game that we play ... is technically called 'renormalization'. But no matter how clever the word, it is still **what I would call a dippy process!** Having to resort to such hocus-pocus has prevented us from proving that the theory of quantum electrodynamics is mathematically self-consistent. It's surprising that the theory still hasn't been proved self-consistent one way or the other by now; I suspect that renormalization is not mathematically legitimate

Richard P. Feynman (2014). "QED: The Strange Theory of Light and Matter", p.128, Princeton Univ. Press

Gravity is not renormalizable

Witten's preferred solution: Strings (=non-locality)

CPT violation



CPT has to be violated somewhere

but where? **at least by the Planck scale?** ⇦ **…but maybe lower?**

we have to keep looking

note: CP has to be violated to explain the baryon symmetry of the Universe. Leptogenesis models say this happened at $T \sim 10^{14}$ GeV

⇨ but traces of CPV show up in K- & B-meson decay, etc.

main consequence of CPT violation

$$m_{particle} \neq m_{antiparticle}$$

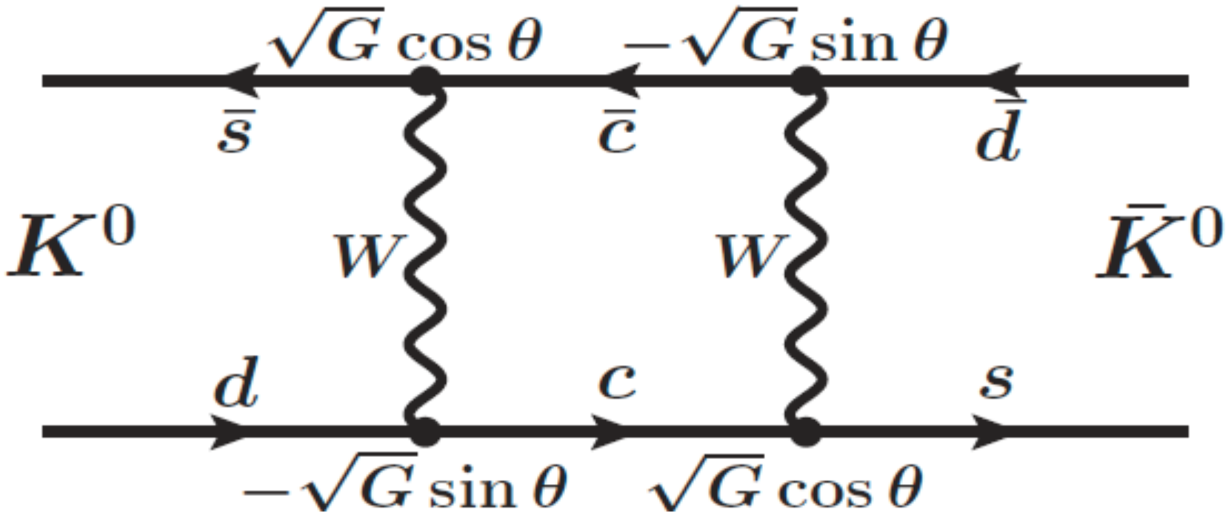
PDG limits

$$m_p - m_{\bar{p}} < 0.7\ eV$$
$$m_{K^0} - m_{\bar{K}^0} < 5x10^{-11}\ eV$$

why is the K^0-$\bar{K}^0$ limit 10 orders of magnitude better?

Why Kaons?

Nature's great gift:



This beautiful diagram allows 2nd-order Weak Interaction effects to how up in 1st-order W.I. processes in experimentally accessible quantities

K-mesons: the gift that keeps on giving

1954: flavor quantum numbers (conserved by Strong & EM, violated by W.I.

1955: particle-antiparticle oscillations (CP vs flavor eigenstates)

1956: Parity is not conserved (Lee Yang Nobel prize)

1963: flavor mixing (Cabibbo angle)

1964: CP is not conserved (Fitch-Cronin Nobel prize)

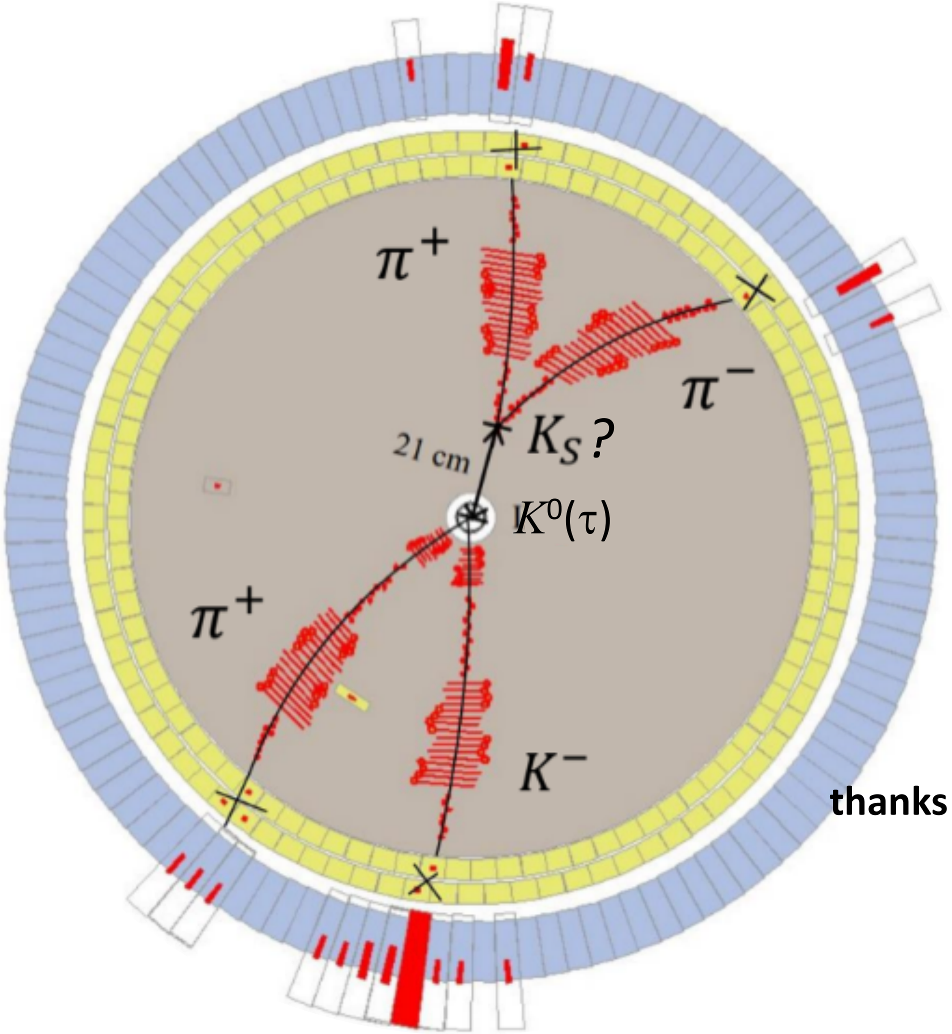
1970: GIM mechanism (predict the existence of the charmed quark)

1973: KM 6-quark model for CPV (Kobayashi-Maskawa Nobel prize)

⋮

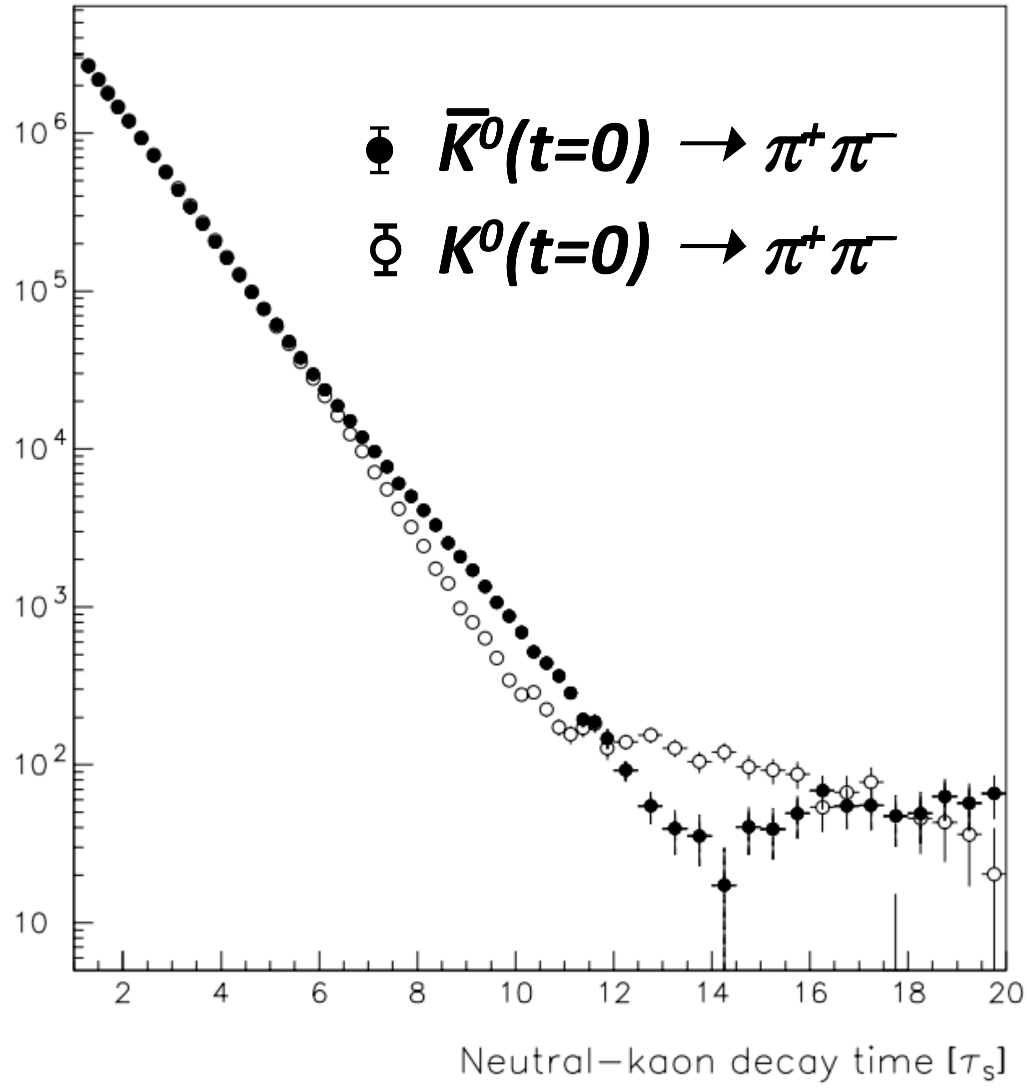
202? kaons will teach us that CPT is not conserved (???? Nobel prize)

$J/\psi \rightarrow K^{\mp}\pi^{\pm}\overset{(-)}{K}{}^{0}$ in BESIII



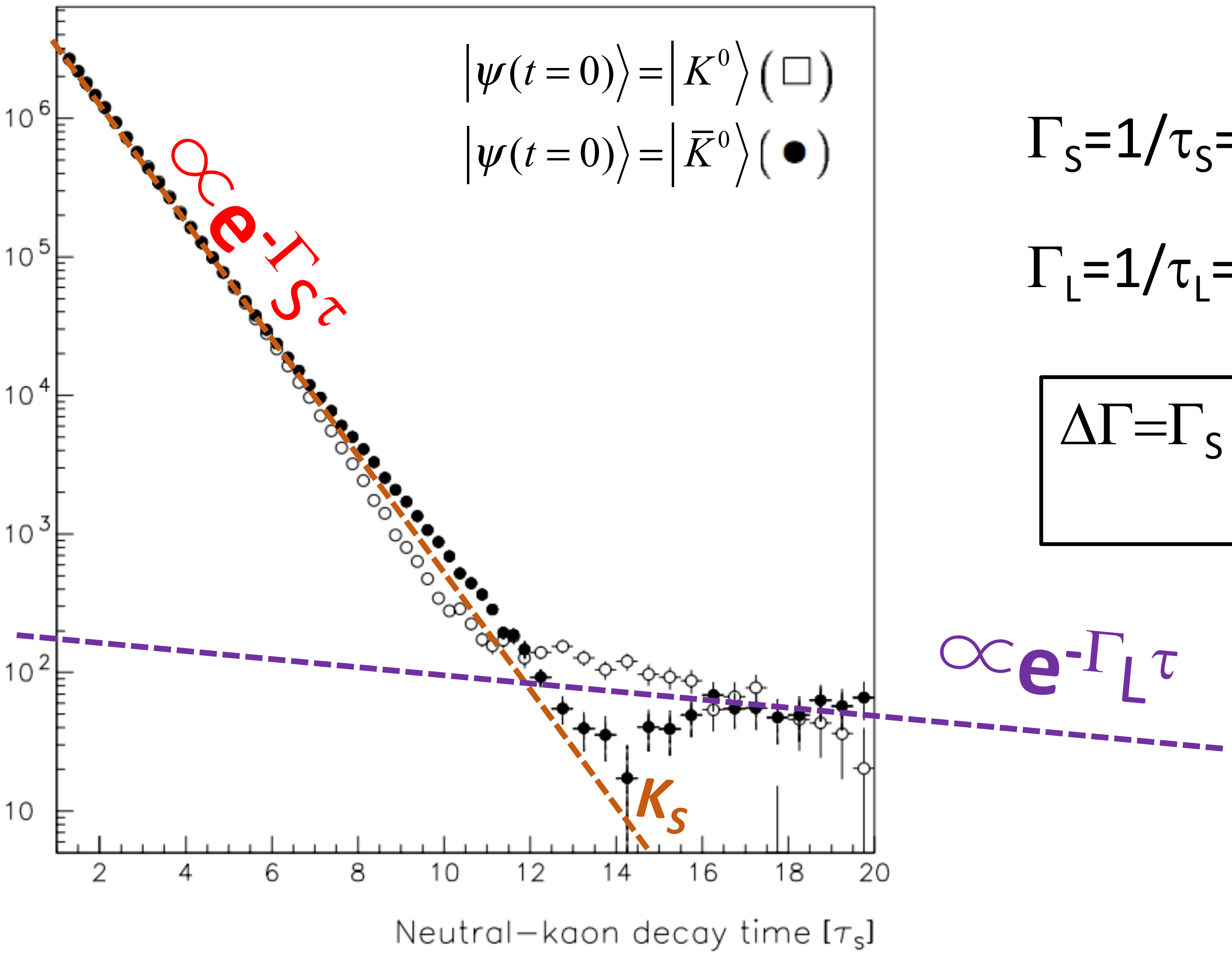
thanks to Jian-Yu Zhang

Lifetimes?



$\bar{K}^0(t=0) \rightarrow \pi^+\pi^-$
$K^0(t=0) \rightarrow \pi^+\pi^-$
10^6
10^5
10^4
10^3
10^2
10
2
4
6
8
10
12
14
16
18
20
Neutral−kaon decay time [τ_S]

Time-dependence of $K^0(\bar{K}^0) \rightarrow \pi^+\pi^-$



± 0.03%

$\Gamma_S=1/\tau_S=1/[(0.089564 \pm 0.000033) \times 10^{-9}\ s]$

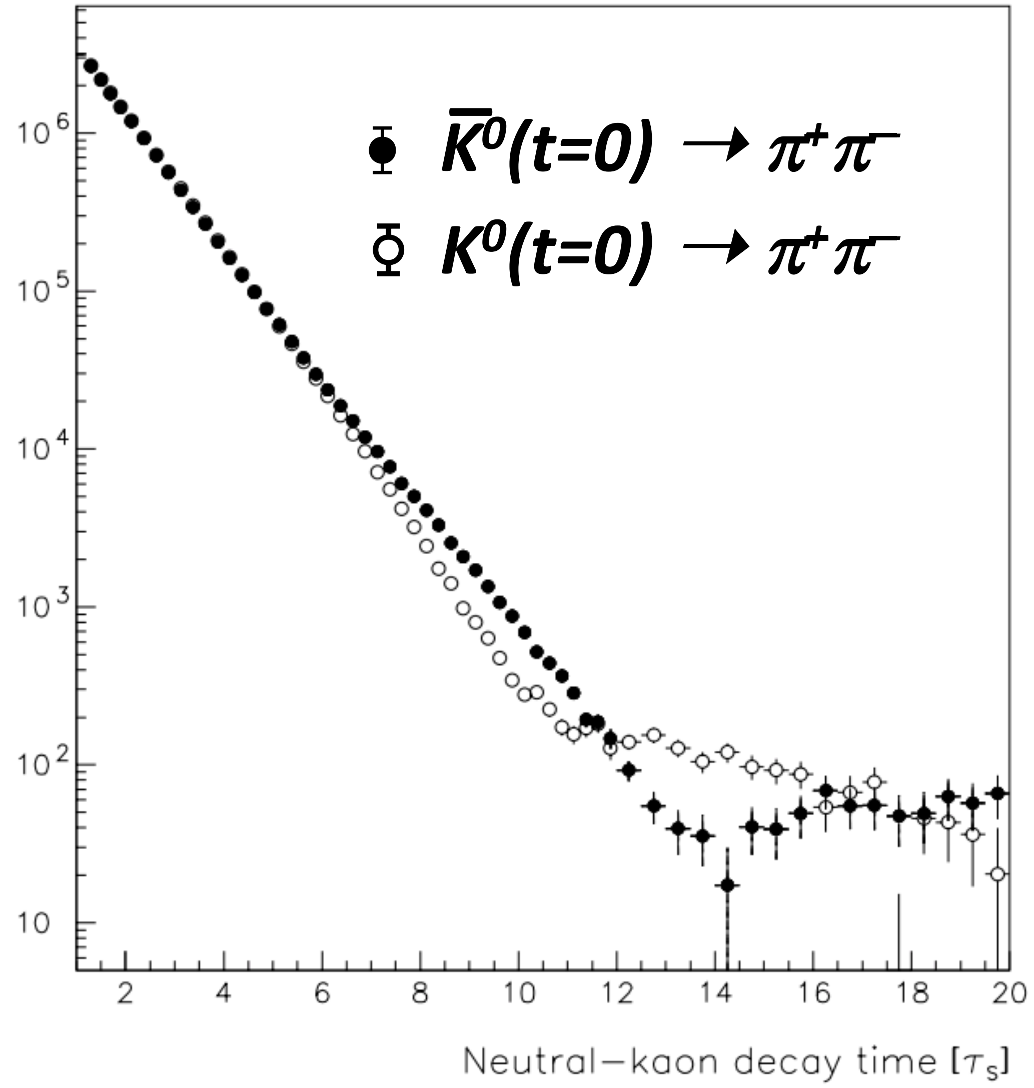
$\Gamma_L=1/\tau_L=1/[(51.16 \pm 0.010) \times 10^{-9}\ s]$

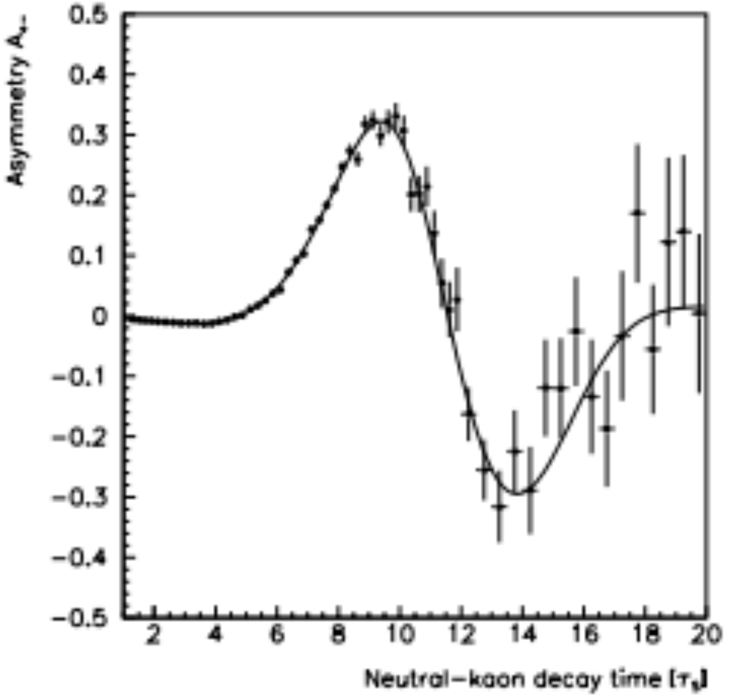
± 0.02%

$\Delta\Gamma=\Gamma_S - \Gamma_L=(1.1145 \pm 0.004) \times 10^{10}\ s^{-1}$
$=7.336 \pm 0.026 \times 10^{-12}$ MeV

± 0.04%

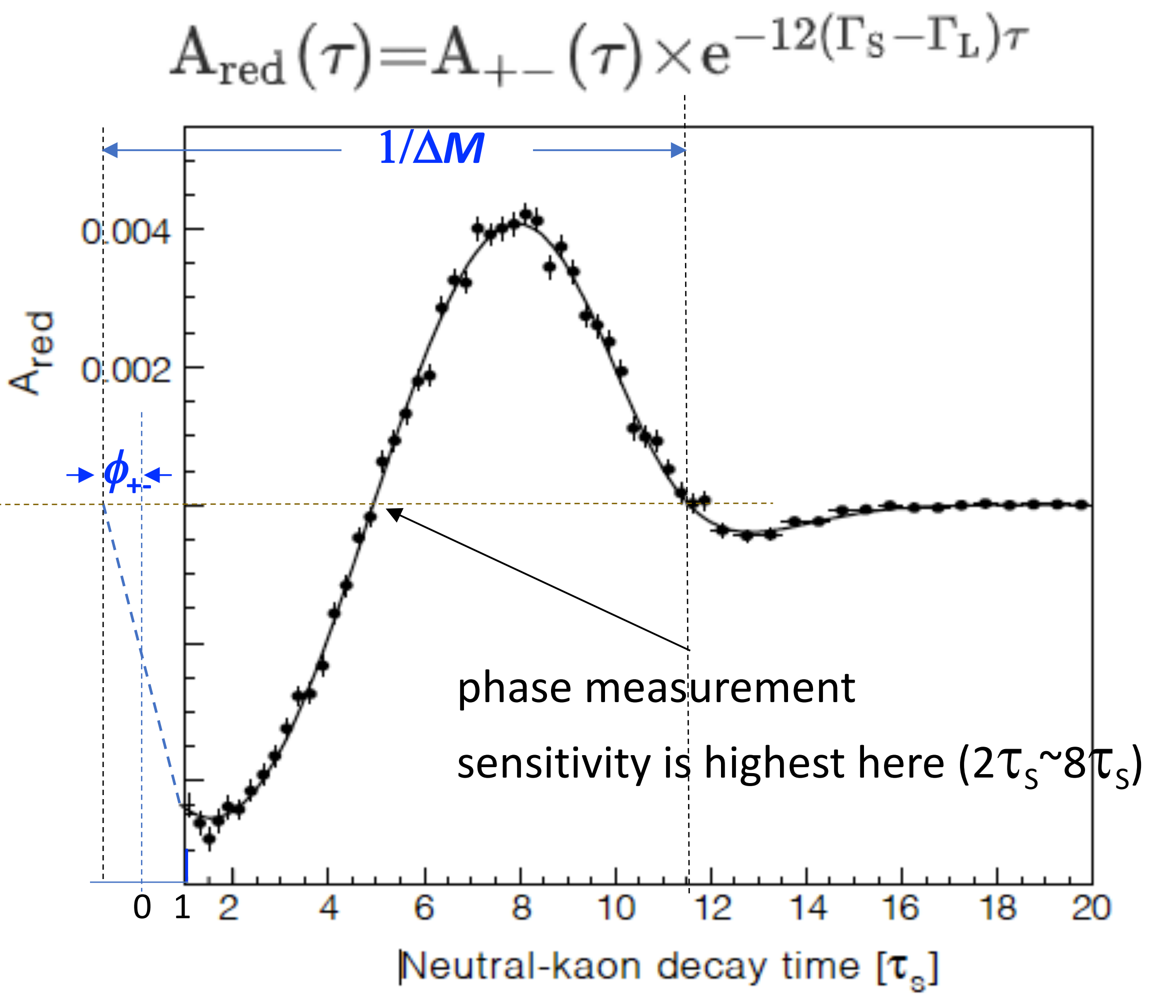
Asymmetry





CPLEAR Phys. Lett. B458, 545 (1999)

weight events according to "usefulness"



If CPT is valid:

$\phi_{+-} = \tan^{-1}(2\Delta M/\Delta\Gamma)$

$\Delta M = m_{K_L} - m_{K_S} = (3.484 \pm 0.006) \times 10^{-12}$ MeV

± 0.02%

$\Delta\Gamma = \Gamma_S - \Gamma_L = (7.336 \pm 0.026) \times 10^{-12}$ MeV

± 0.04%

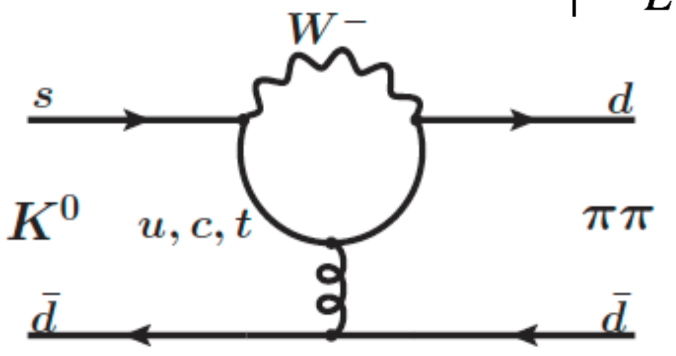
$\phi_{SW} = 43.53^\circ \pm 0.02^\circ$

the "super-weak" phase

two ways that a K_L can decay to $\pi^+\pi^-$

$\mathcal{CP}$ odd $\mathcal{CP}$ even

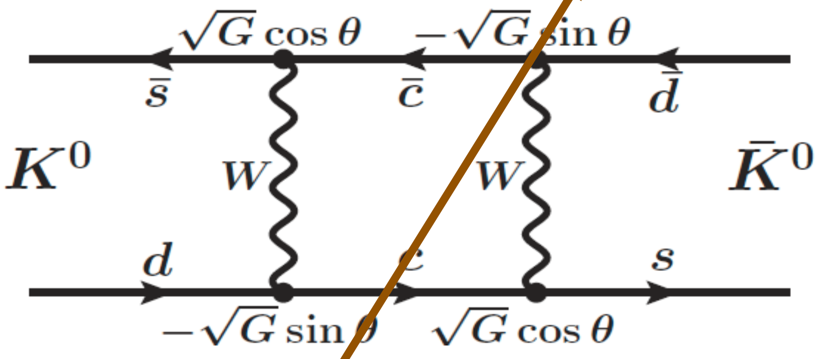
$$|K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left(|K_2\rangle + \varepsilon|K_1\rangle\right)$$



ε′ → $\pi^+\pi^-$ ε → $\pi^+\pi^-$

$\eta_{+-} = \varepsilon + \varepsilon'$

phase= ϕ_{SW} = 43.52°



$$\varepsilon' = \frac{i}{\sqrt{2}}\frac{\mathrm{Im}\,A_2}{A_0}e^{i(\delta_2-\delta_0)}$$

strong interaction
ππ phase shifts

$$\phi_{\varepsilon'} = \delta_2 - \delta_0 + \frac{\pi}{2} \approx 42.3^\circ \pm 1.5^\circ$$

equal!!

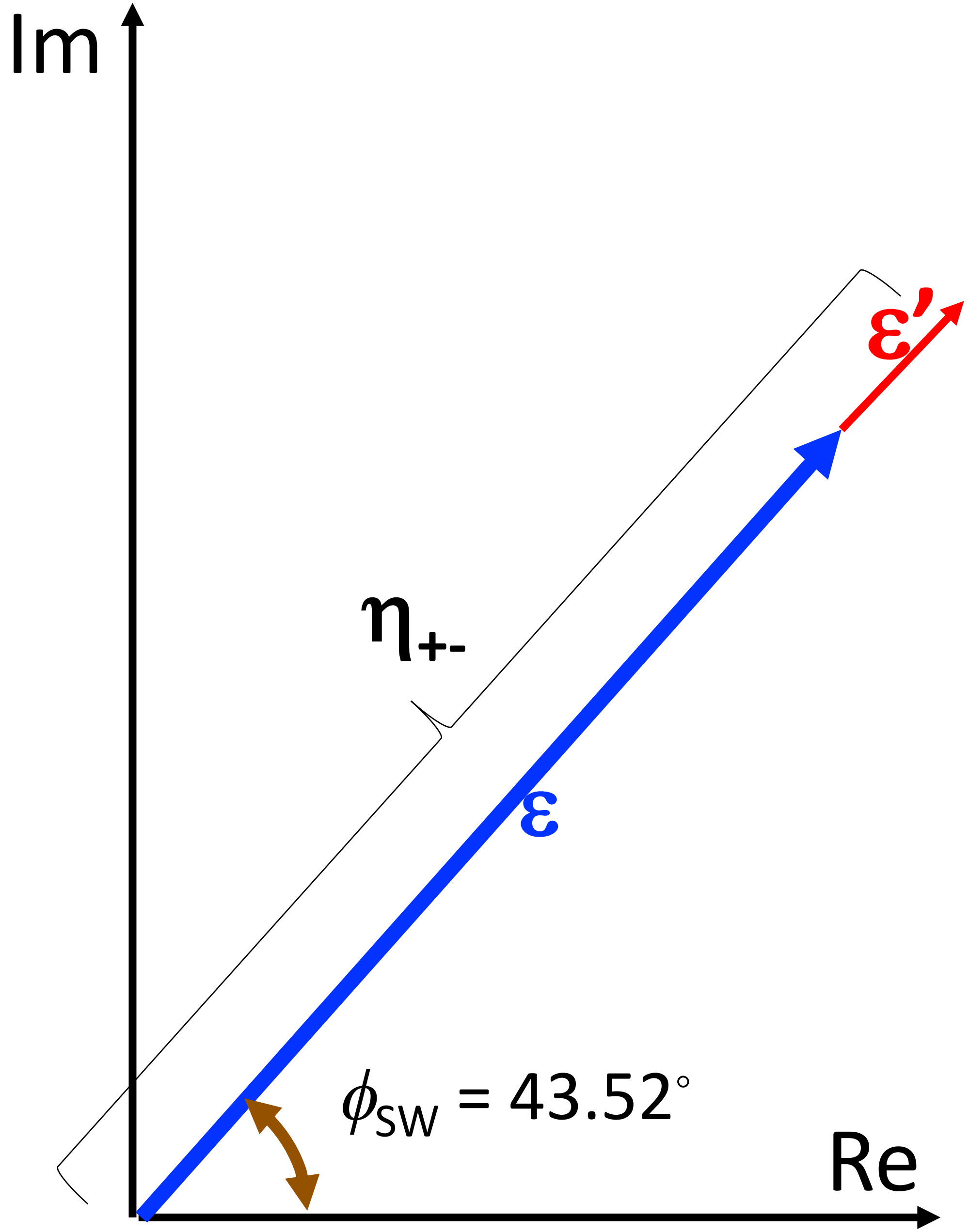
$$\delta_2 - \delta_0 = -47.7^\circ \pm 1.5^\circ$$

G. Colangelo, J. Gasser and H. Leutwyler, ππ scattering, *Nucl. Phys. B* **603**, pp. 125–179 (2001), doi:10.1016/S0550-3213(01)00147-X, arXiv:hep-ph/0103088.

Miracle

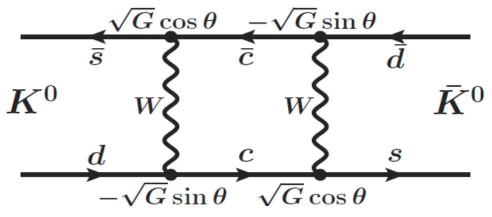
ε' and ε are parallel
(to within ~< 1.5°)

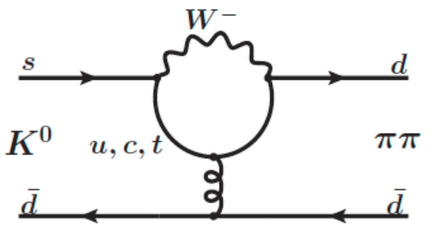
phase of η_{+-} insensitive to
to uncertainty in the length of ε'



Add a CPT violation

here I assume it is completely from the box diagram



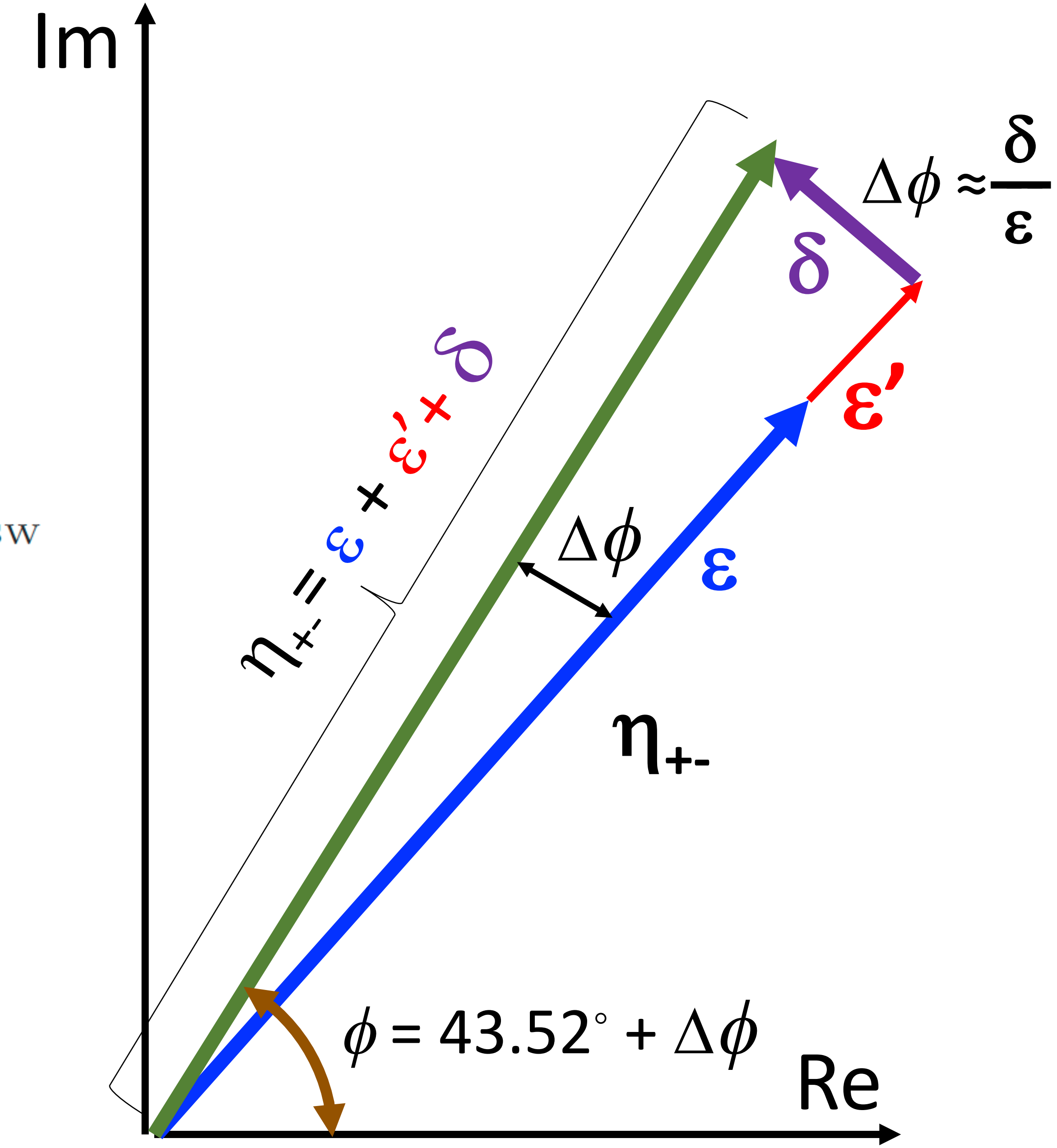


$$\delta \approx \frac{i(M_{\bar{K}^0} - M_{K^0}) + (\Gamma_{\bar{K}^0} - \Gamma_{K^0})/2}{2\sqrt{2}\Delta M} e^{i\phi_{\rm SW}}$$

$$M_{\bar{K}0} - M_{K0} \approx 2\sqrt{2}\ \Delta M\ \varepsilon\ \Delta\phi$$

$$\approx 3 \times (3.4 \times 10^{-12}\ \text{MeV}) \times (2 \times 10^{-3}) \times \Delta\phi$$

$$M_{\bar{K}0} - M_{K0} \approx 2\text{x}10^{-14}\text{MeV x } \Delta\phi$$

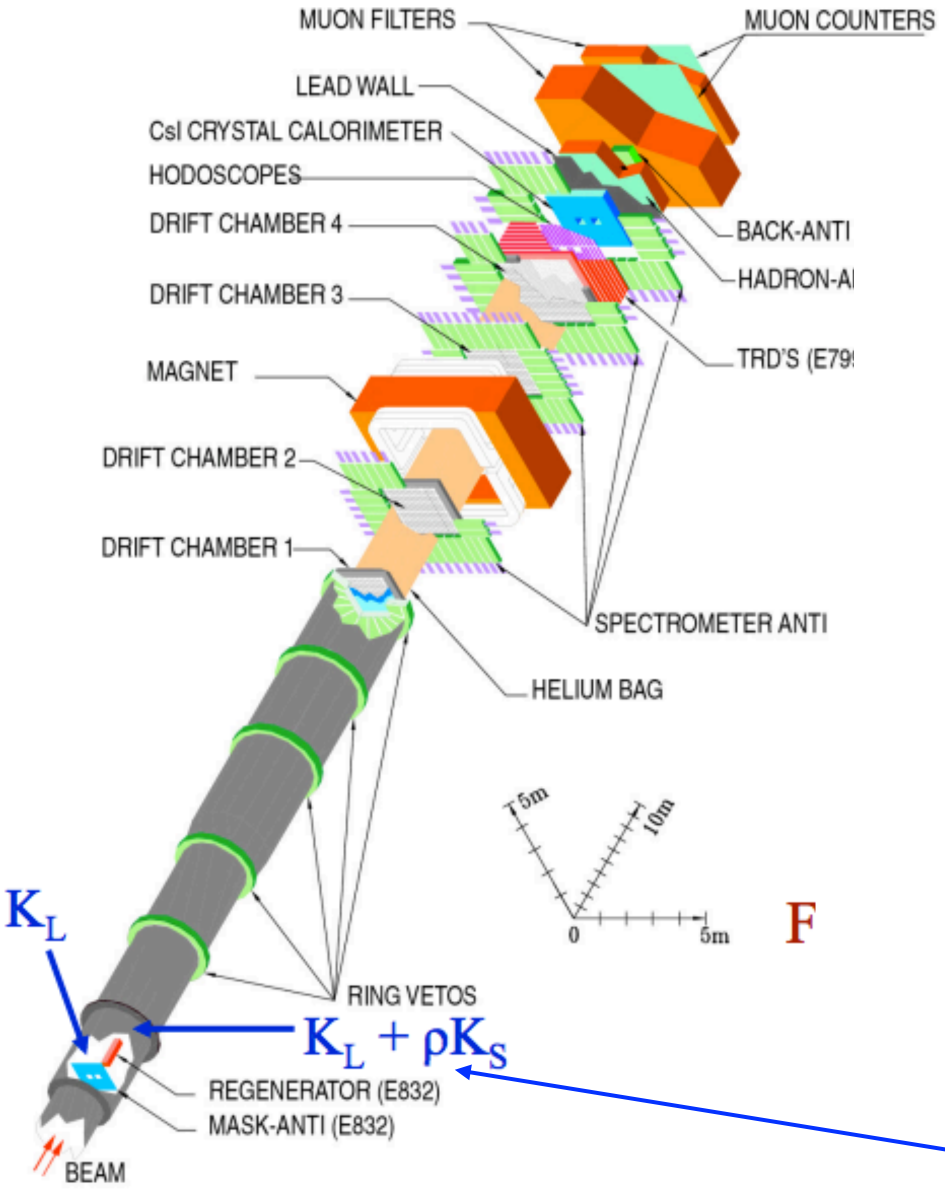


Best measurements to date

KTeV (Fermilab)

CPlear

The KTeV Detector
@ Fermilab



modulo a model-dependent regeneration phase

VOLUME 74, NUMBER 22 pg. 4376 PHYSICAL REVIEW LETTERS 29 MAY 1995

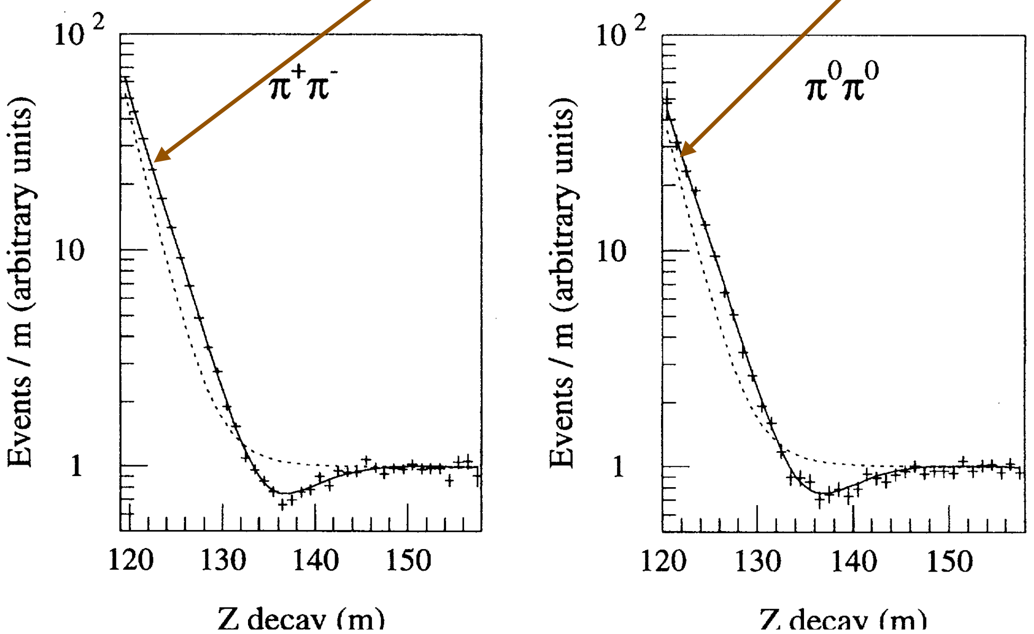
CPT Tests in the Neutral Kaon System

B. Schwingenheuer, R. A. Briere, A. R. Barker, E. Cheu, L. K. Gibbons, D. A. Harris, G. Makoff, K. S. McFarland, A. Roodman, Y. W. Wah, B. Winstein, and R. Winston
The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637

E. C. Swallow
Elmhurst College, Elmhurst, Illinois 60126

...

unequal K^0 & $\overline{K}^0$ mixture ($N_{K0} > N_{\overline{K}0}$)



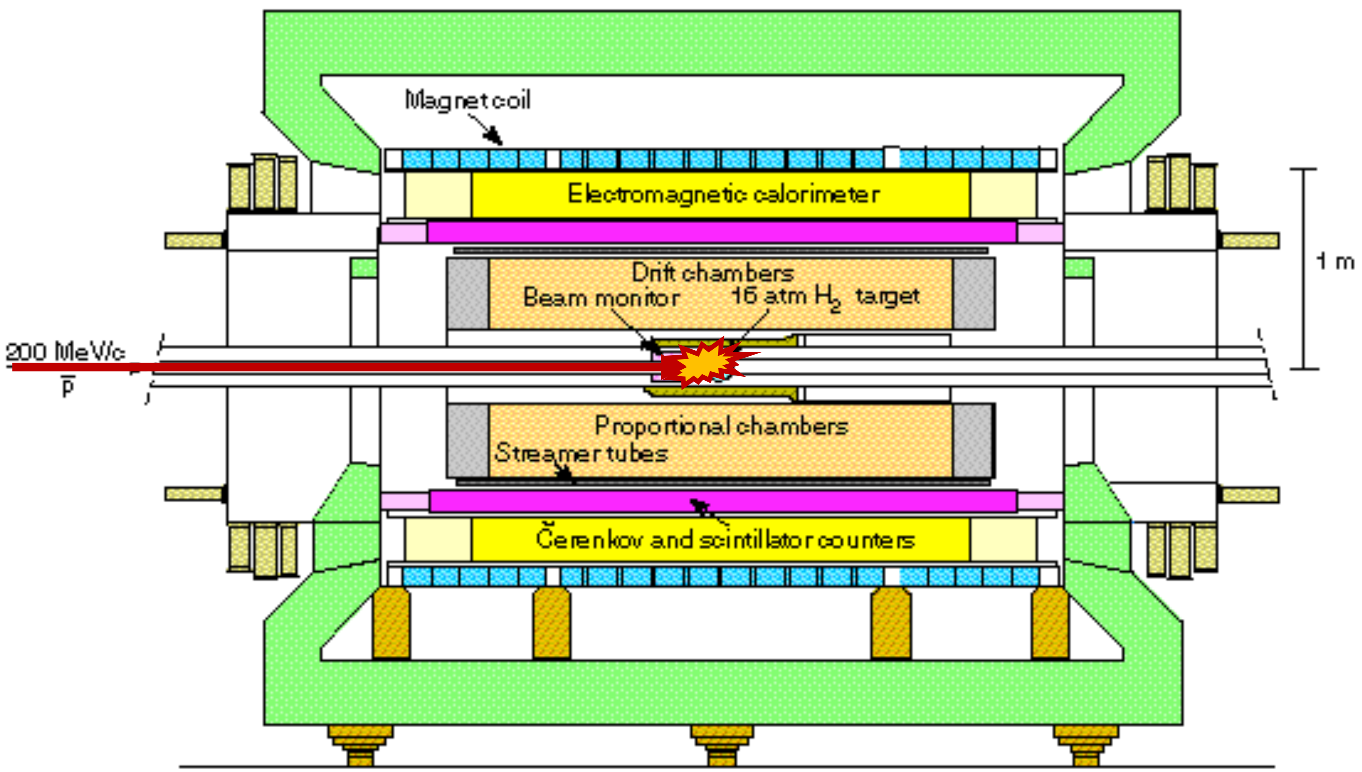
$$\Phi_{+-} = 43.53^\circ \pm 0.58^\circ(\text{stat}) \pm 0.49^\circ(\text{syst}) .$$

The CPLEAR anti-proton experiment at CERN

$\bar{p}$ beam stops in a H_2 target &

$\bar{p}p \rightarrow \bar{K}^0K^+\pi^-$ or $K^0K^-\pi^+$

CPLEAR Detector



N·H ELSEVIER

15 July 1999

PHYSICS LETTERS B

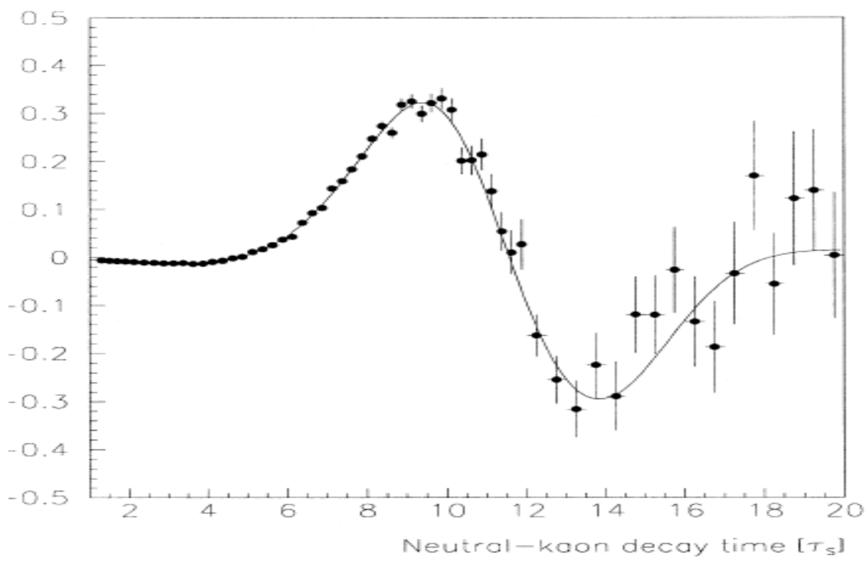
Physics Letters B 458 (1999) 545–552

A determination of the CP violation parameter η_{+-} from the decay of strangeness-tagged neutral kaons

CPLEAR Collaboration

A. Apostolakis [a], E. Aslanides [k], G. Backenstoss [b], P. Bargassa [m], O. Behnke [q], A. Benelli [i], V. Bertin [k], F. Blanc [g,m], P. Bloch [d], P. Carlson [o], M. Carroll [i],

…



$$\phi_{+-} = 43.19^\circ \pm 0.53^\circ_{stat} \pm 0.28^\circ_{syst} \pm 0.42^\circ_{\Delta m}$$

no regenerator: model-independent

Flavor-tagged production & Flavor-tagged decay

An example of a CPLEAR event

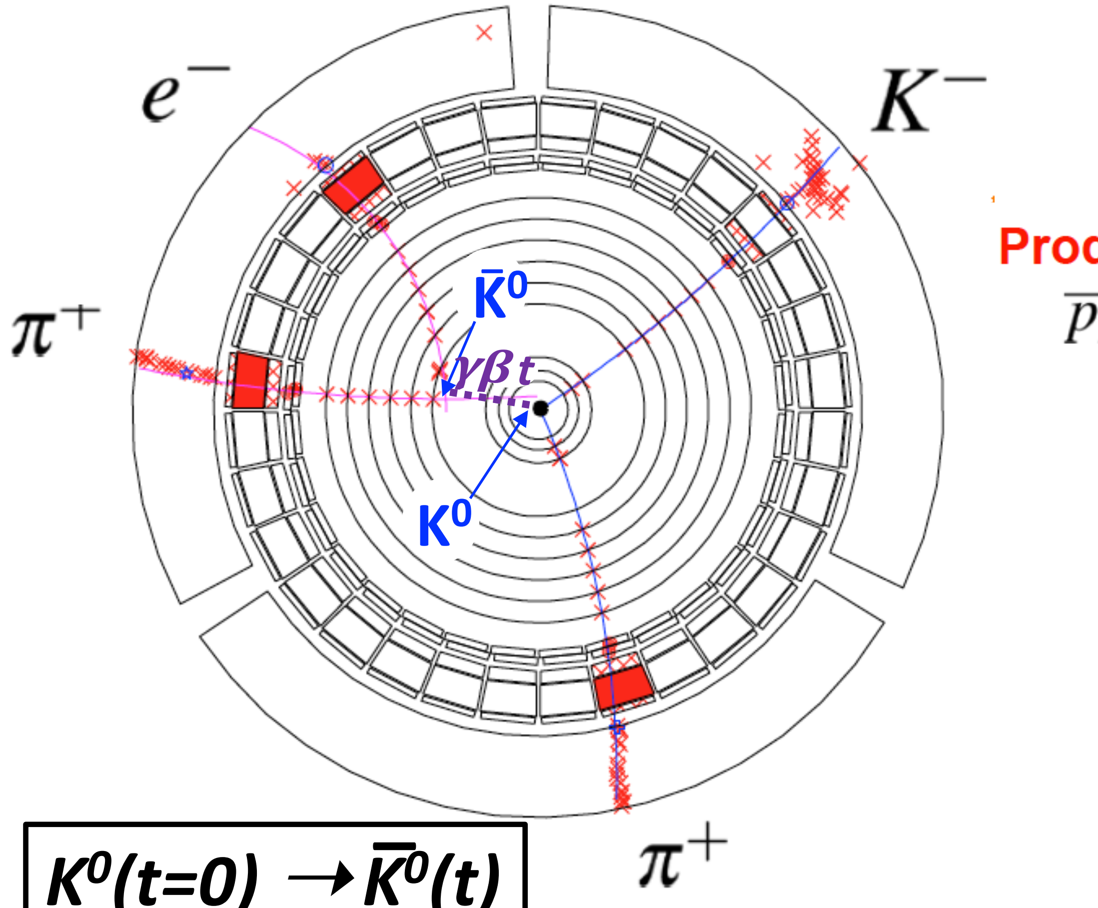
$\bar{p}p \to K^0 K^-\pi^+$

or

$\to \bar{K}^0 K^+\pi^-$

$\bar{K}^0 \to \pi^+ e^- \nu$

$K^0 \to \pi^- e^+ \nu$



Decay:

$\bar{K}^0 \to \pi^+ e^- \bar{\nu}_e$

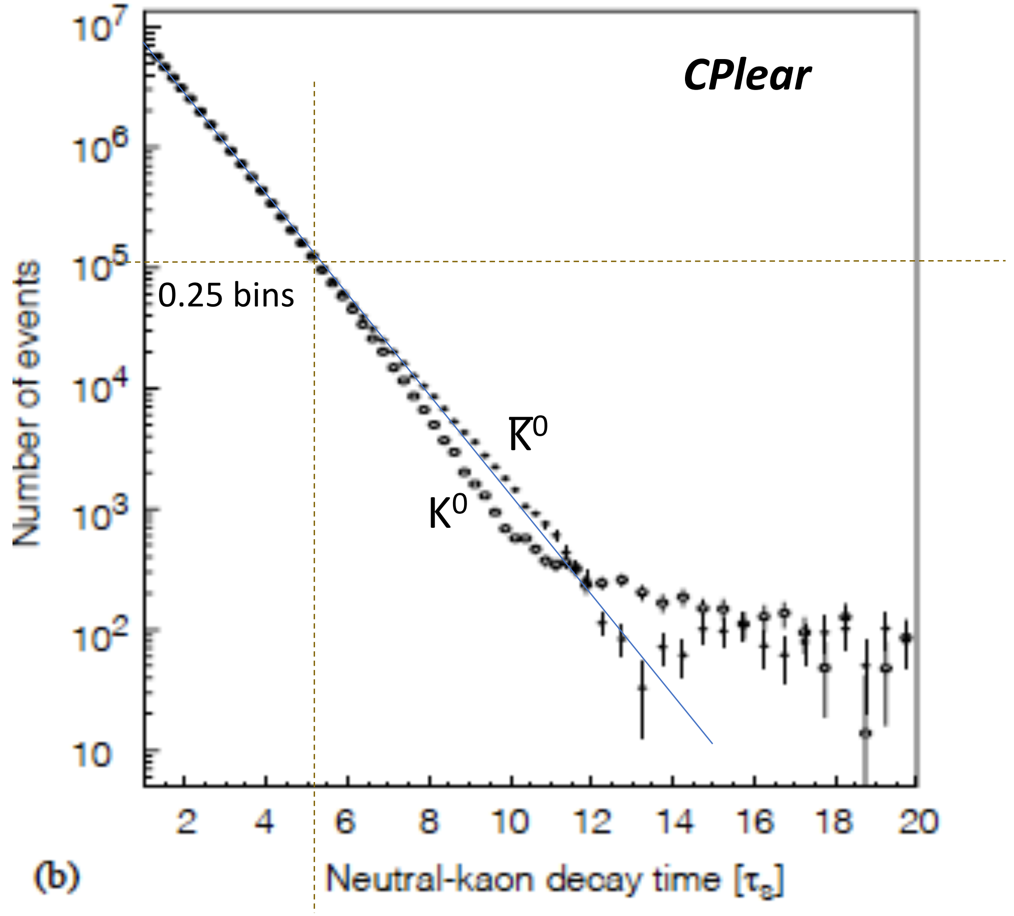
Production:

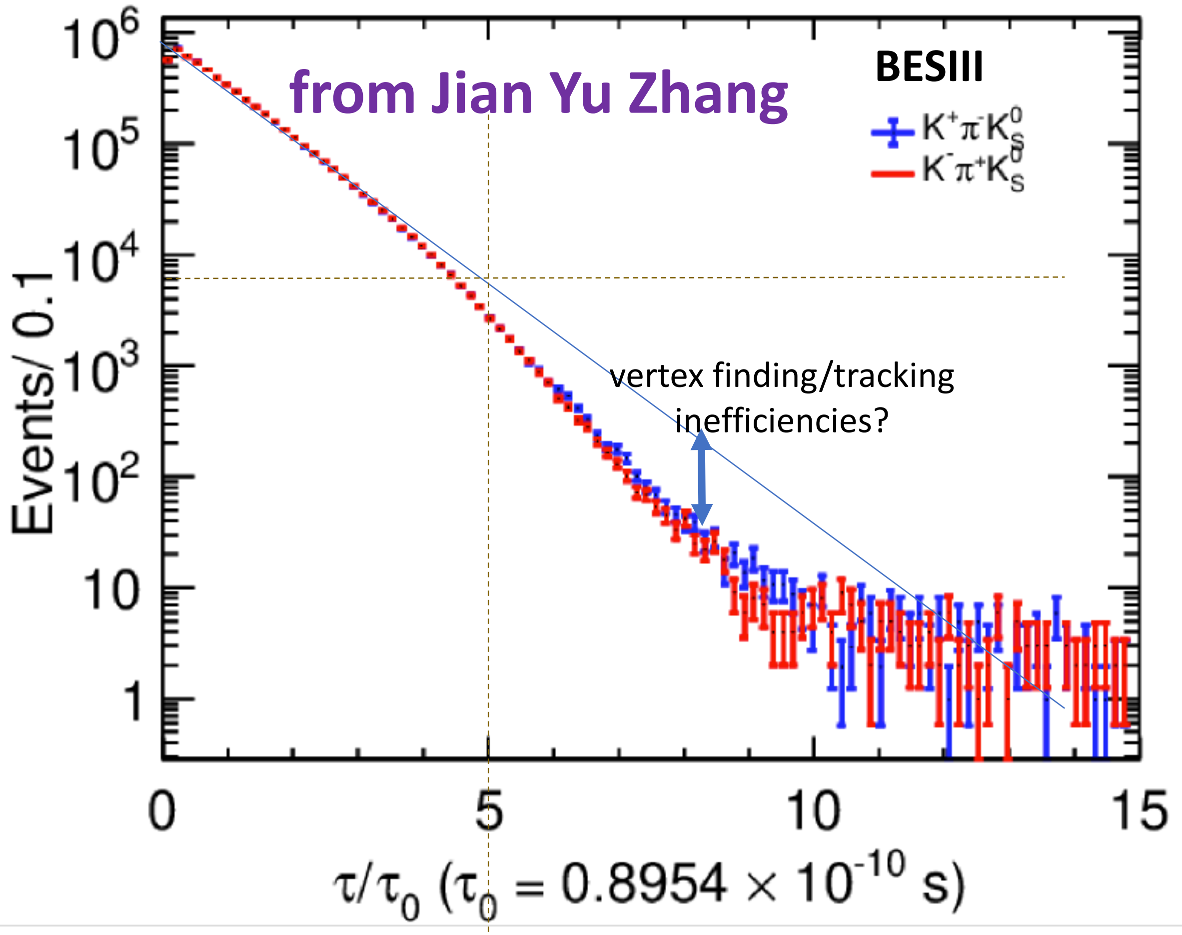
$\bar{p}p \to K^-\pi^+ K^0$

$K^0(t=0) \to \bar{K}^0(t)$

BESIII (first peek) vs CPlear (10 years of data)

Flavor-tagged K^0 and $\overline{K}^0$ decays to $\pi^+\pi^-$

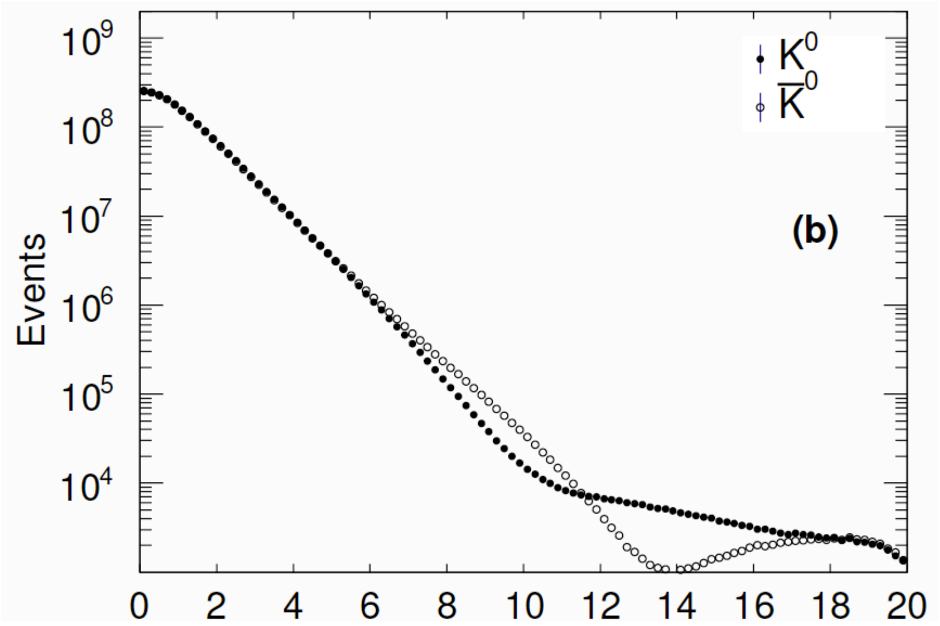


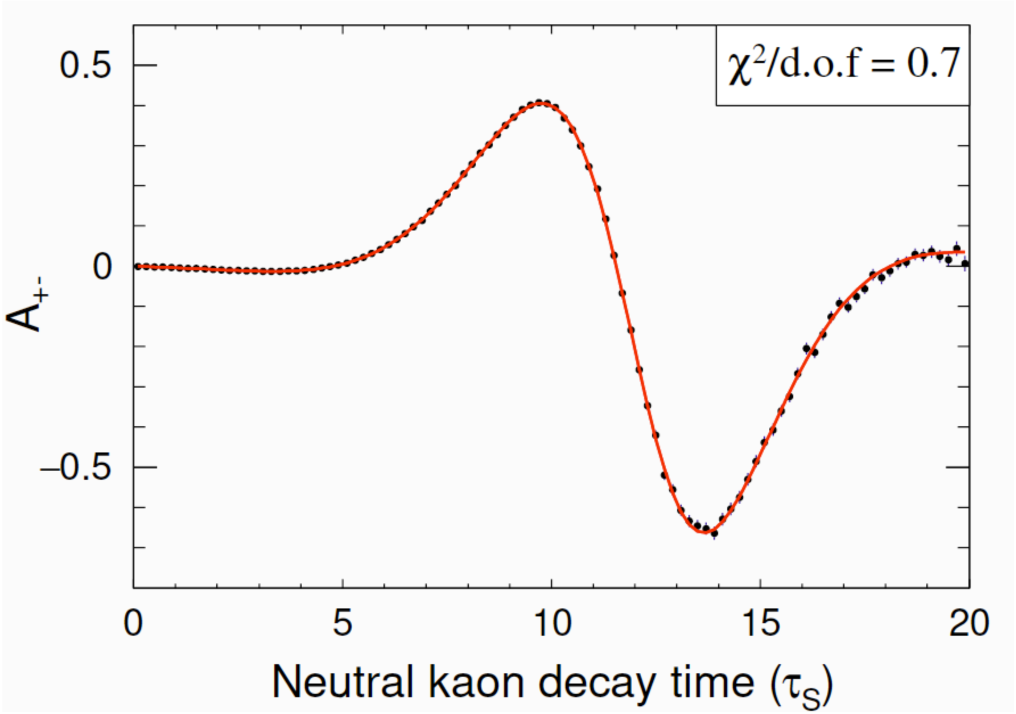


CPLEAR measurements had about 7x as much data as BESIII has

SCTF with 10^{12} J/ψ events

-- from Jian-Yu Zhang --





~30x as much data as CPLEAR had ⇒ 10x reduction in errors

Par.	$\lvert\eta_{+-}\rvert(10^{-3})$	ϕ_{+-}(degree)
PDG	2.232 ± 0.011	43.4 ± 0.5
STCF	$2.2320 \pm 0.0025 \pm 0.0027$	$43.510 \pm 0.051 \pm 0.059$

CPT test with neutral kaon decays to two pions

-- in 3 easy steps --

4 CP parameters
(complex numbers)

η_{+-} η_{00} ε ε'

2 auxiliary parameters
(real numbers)

ΔM_K $\Delta\Gamma_K = \Gamma_{K_S} - \Gamma_{K_L}$

1. measure these *and these*

2. compare **CPT:** $\phi_{+-} \stackrel{?}{=} \phi_{00} \stackrel{?}{=} \phi_{SW} = \arctan \dfrac{2\Delta M_K}{\Delta\Gamma_K}$

3. if they are not equal **call Yifeng**

Comments

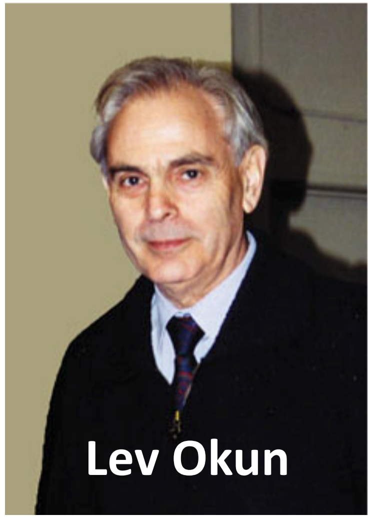
CPT ***will be violated*** at some level, the only question is where?

Flavor-tagged K^0 & K^0 mesons **are *by far the best probes*** of CPT

STCF is the ***only planned facility that can improve*** *on current limits*

This is a ***unique opportunity*** for STCF, that should not be compromised

Afterword



1929-2015

" A special search at Dubna was carried out [in 1962] by E. Okonov and his group. They did not find a single $K_L \to \pi^+\pi^-$ event among 600 decays into charged particles [256]. At that stage the search was terminated by the administration of the Lab. The group was unlucky."

Bf($K_L \to \pi^+\pi^-$) = 1/500 !!