Testing matter-antimatter and other discrete symmetries in Particle Physics

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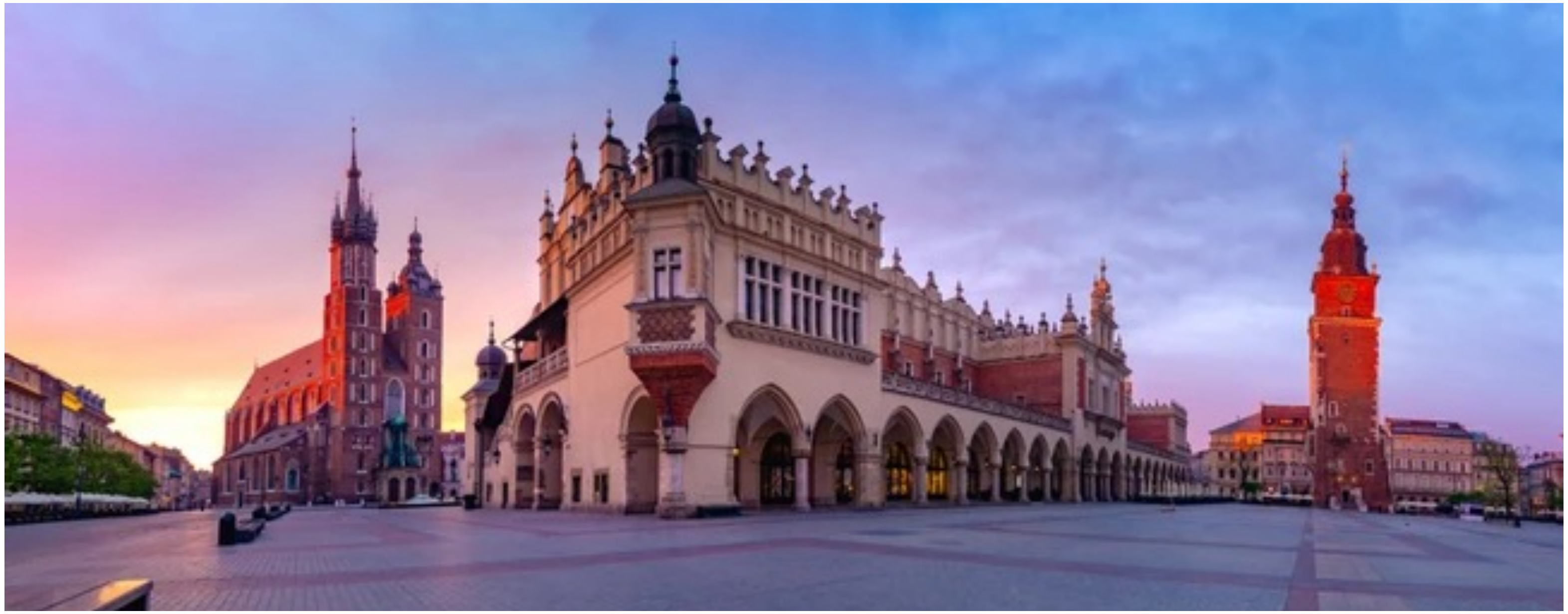


6th Jagiellonian Symposium on Advances in Particle Physics and Medicine,

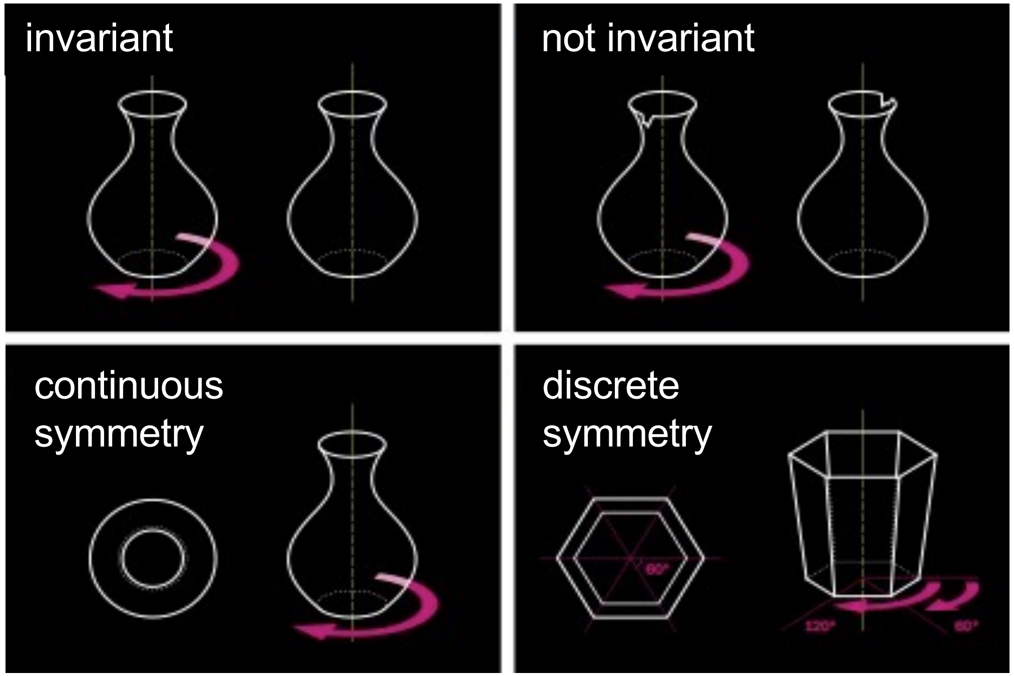
Krakow, Poland, 6–10 July 2026

Symmetries: a guiding principle of fundamental physics

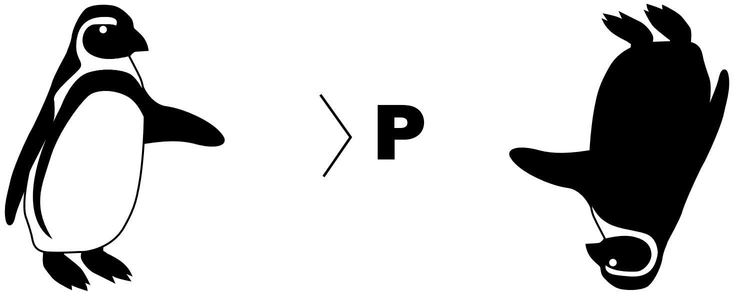
- Symmetries determine the mathematical structure of physical laws.
- Continuous symmetries can be changed by an arbitrary continuous amount, and lead to conservation laws (Noether's theorem):
  - time translations → energy conservation
  - spatial translations → momentum conservation
  - rotations → angular momentum conservation

- Discrete symmetries involve only a finite set of transformations —there is no "intermediate" transformation.

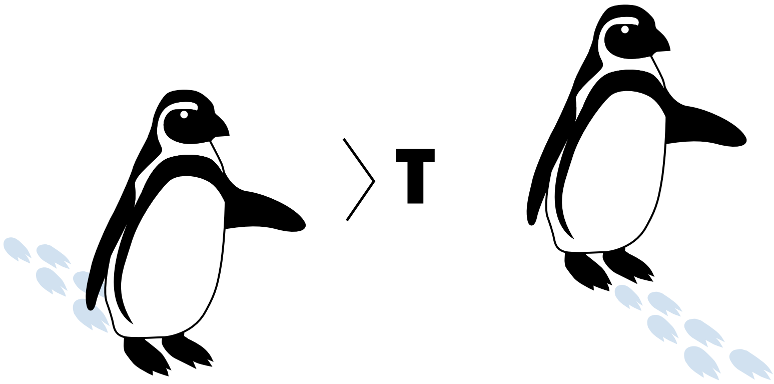
  They may constrain the form of physical interactions and determine whether certain processes are allowed or forbidden.



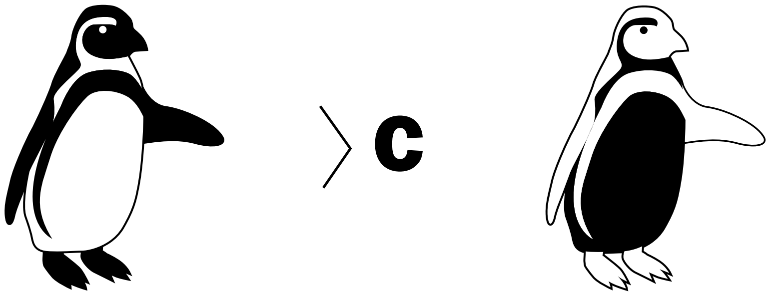
The fundamental discrete symmetries



Transformation under **parity (P)**
- spatial directions are all inverted:
  (x,y,z → -x,-y,-z)



Transformation under **time reversal (T)**
- direction of time (motion) is inverted:
  (t → -t)



Transformation under **charge conjugation (C)**
- all particles are transformed in anti-particles and viceversa:
  (q, S → -q, -S)

Why Test Discrete Symmetries?

Discrete symmetry tests are precision probes of fundamental physics

- They reveal the structure of the weak interaction.
- They test the foundations of quantum field theory (QFT).
- Tiny symmetry violations may signal physics beyond the Standard Model.
- They can answer fundamental questions about our Universe

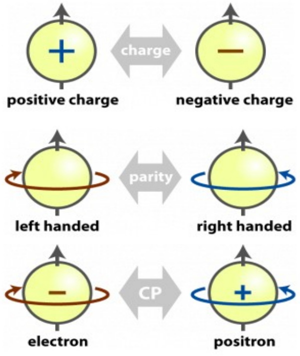
Historical milestones

- **1957: P** violation discovered (Wu experiment).
- **1964: CP** violation in mixing discovered in neutral kaons.
- **2012: T** violation discovered in neutral B mesons
- **Present:** increasingly precise searches for CP, T and CPT violation.

CP symmetry

Where did the antimatter go?

CP symmetry connects
matter and antimatter



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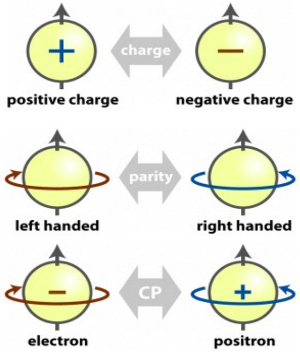

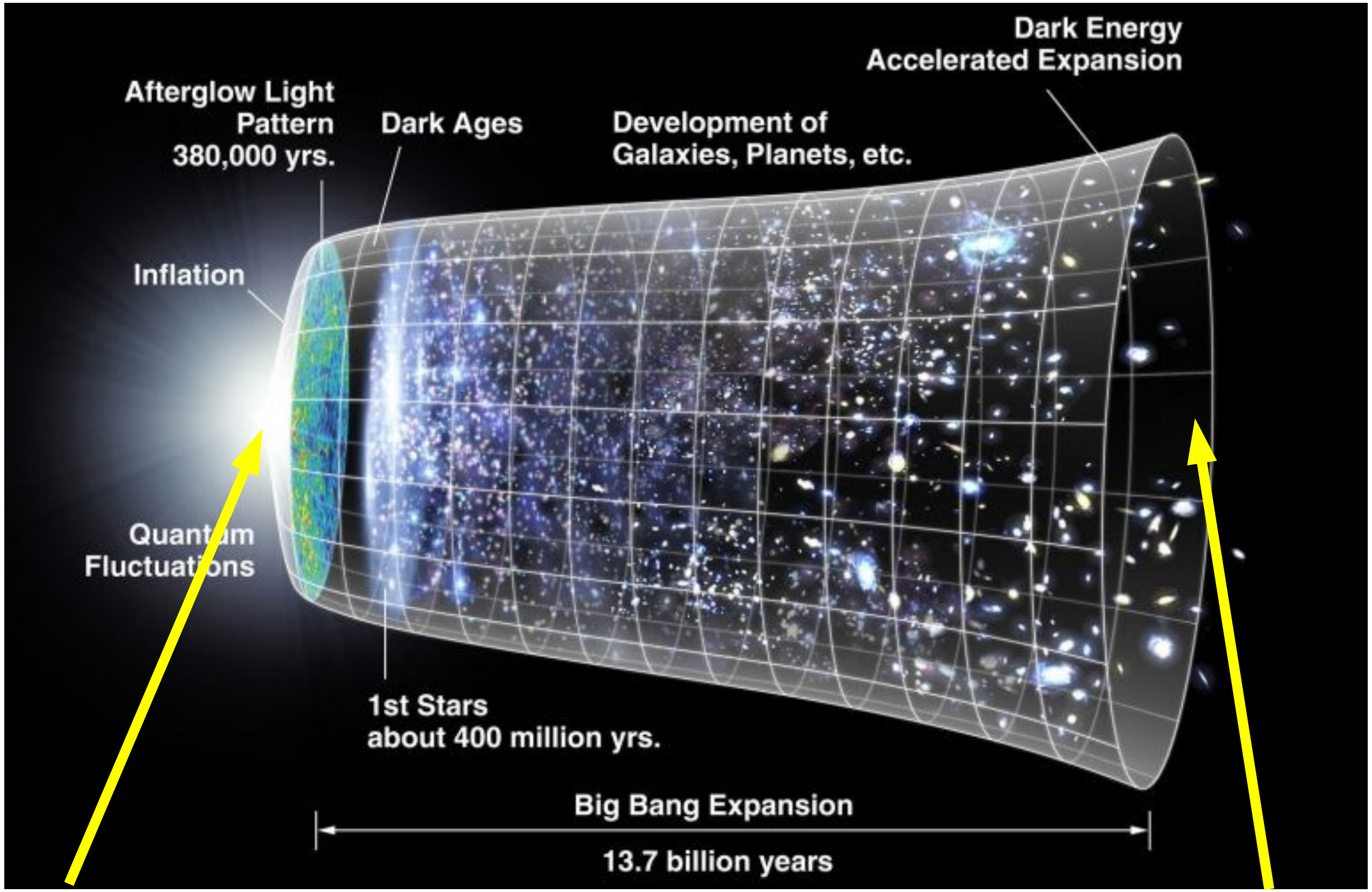

matter and antimatter in equal amounts after big bang

no large-scale structures made of antimatter

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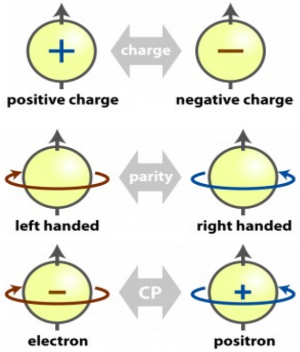
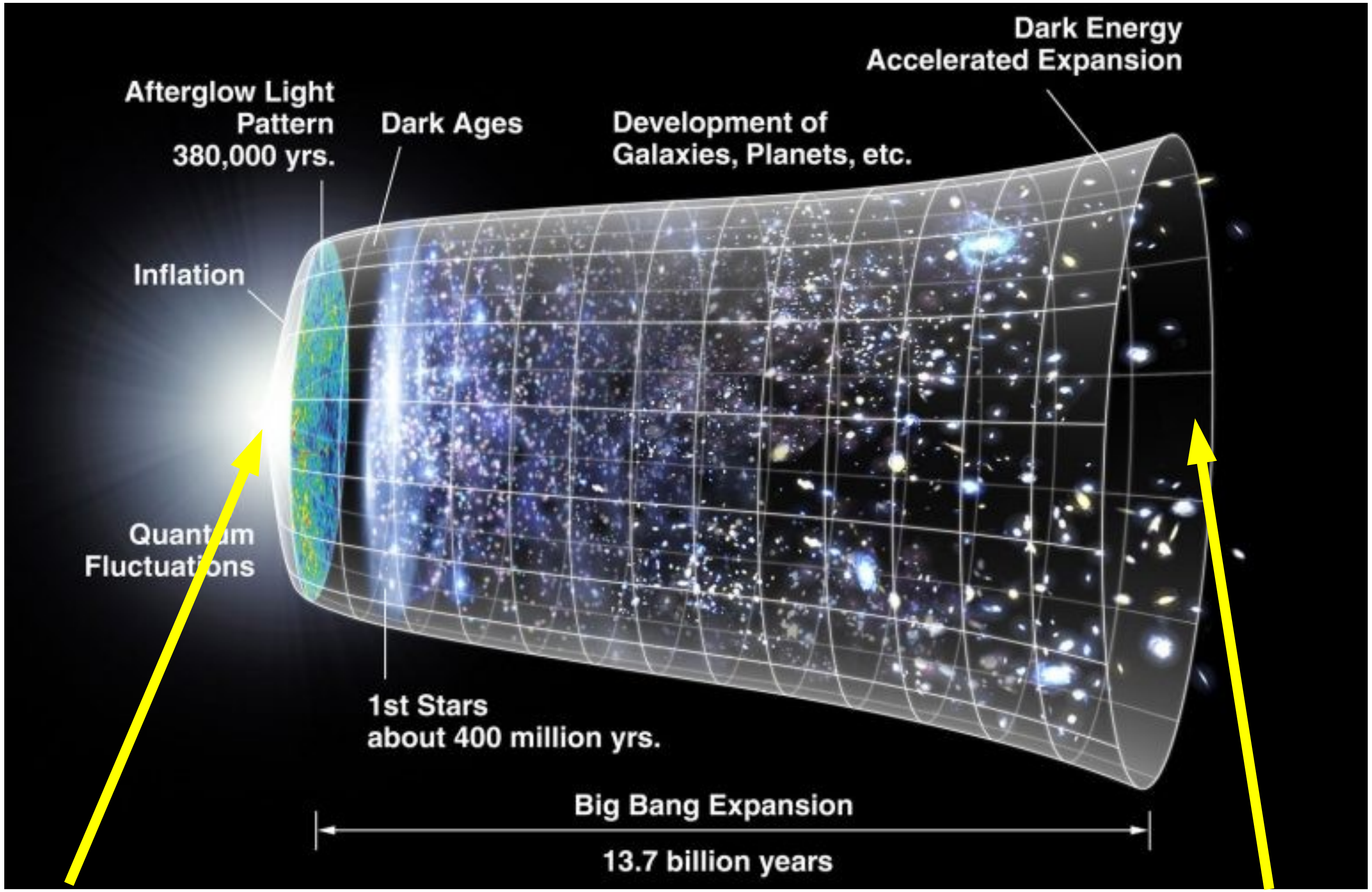


CP violation is a key ingredient to explain the absence of anti-matter in the Universe
(A. Sakharov, 1967)



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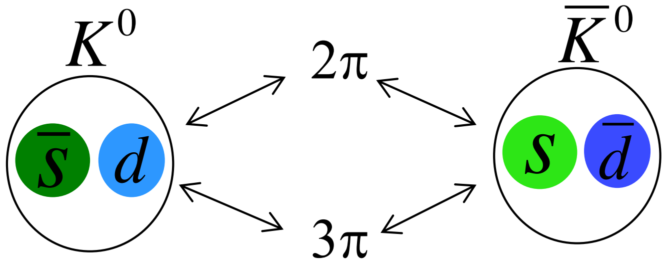
The neutral kaon two-level oscillating system in a nutshell

K^0 and $\overline{K^0}$ can decay to common final states due to weak interactions: strangeness oscillations



$$|\Psi\rangle = a|K^0\rangle + b|\overline{K}^0\rangle$$

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Diagonalizing the effective Hamiltonian:

eigenvalues

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$$|K_{S,L}(t)\rangle = e^{-i\lambda_{S,L}t}|K_{S,L}(0)\rangle$$

τ_S ~ 90 ps τ_L ~ 51 ns

eigenstates: physical states

Assuming CP invariance:

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\overline{K}^0\rangle\right]$$

CP = +1

$$|K_2\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\overline{K}^0\rangle\right]$$

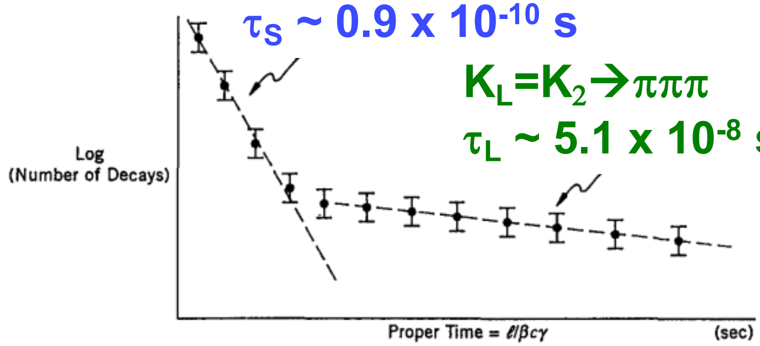
CP = -1

K_S=K_1→ππ

τ_S ~ 0.9 x 10^{-10} s

K_L=K_2→πππ

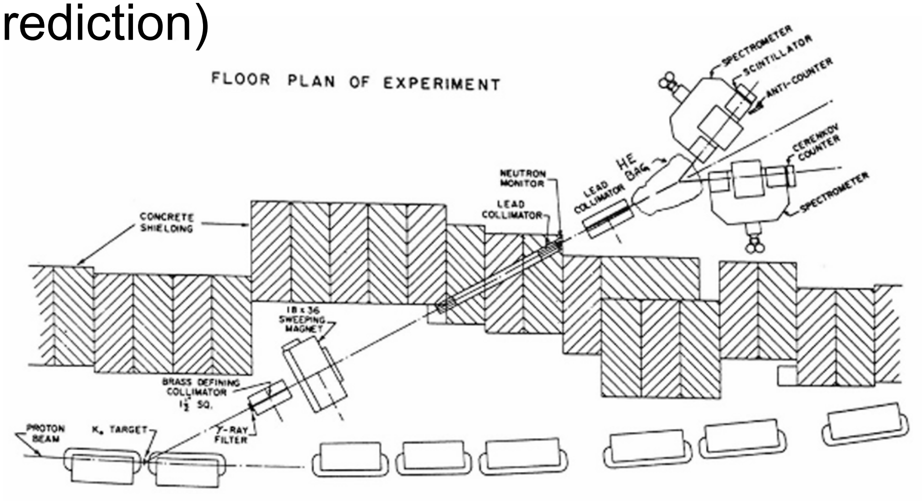
τ_L ~ 5.1 x 10^{-8} s

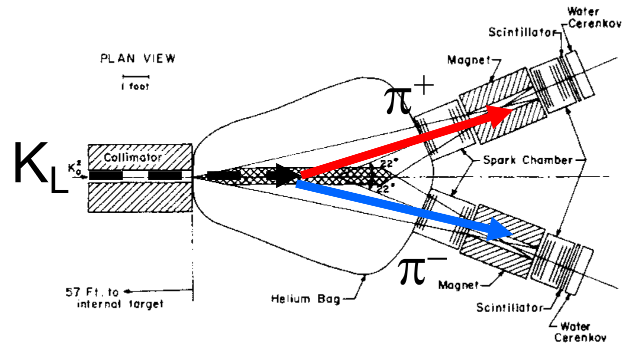


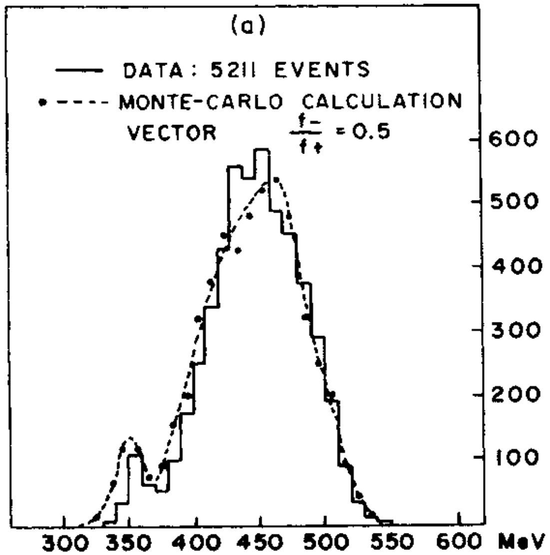
1956 K. Lande, L. Lederman

Discovery of CP violation

In 1964 Christenson, Cronin, Fitch, Turlay discover $K_L \to 2\pi$ decays (branching ratio ~ 0.2%) in a K_L beam (Brookhaven) => **CP symmetry violation** (pure experimental discovery, no theory prediction)







invariant mass

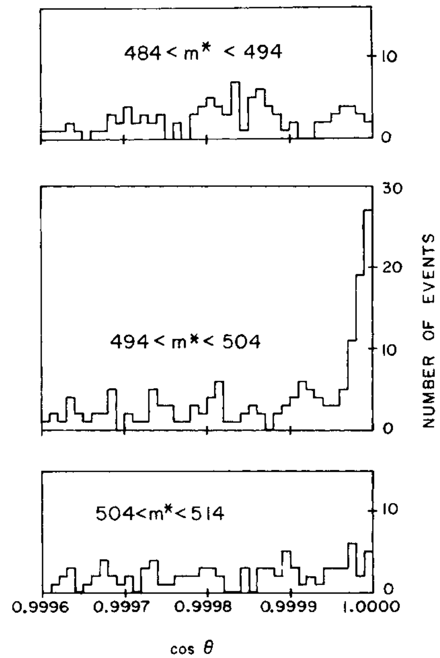


FIG. 3. Angular distribution in three mass ranges for events with $\cos\theta > 0.9995$.

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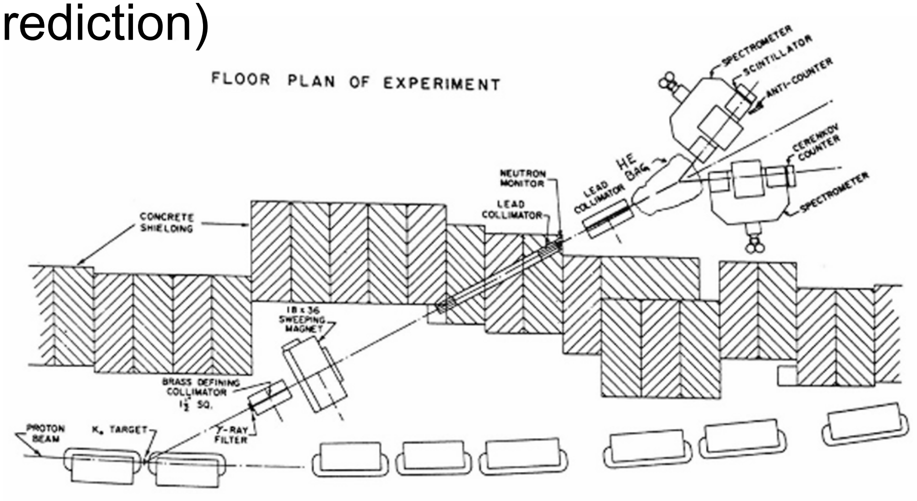

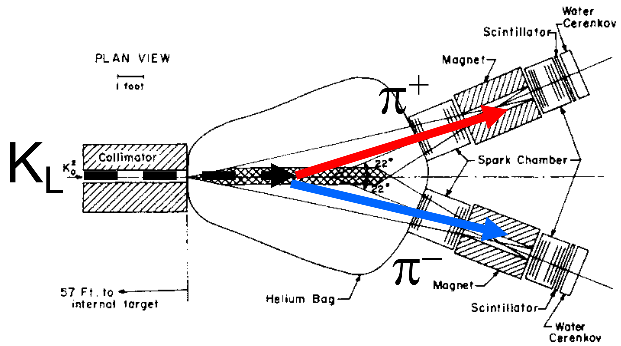

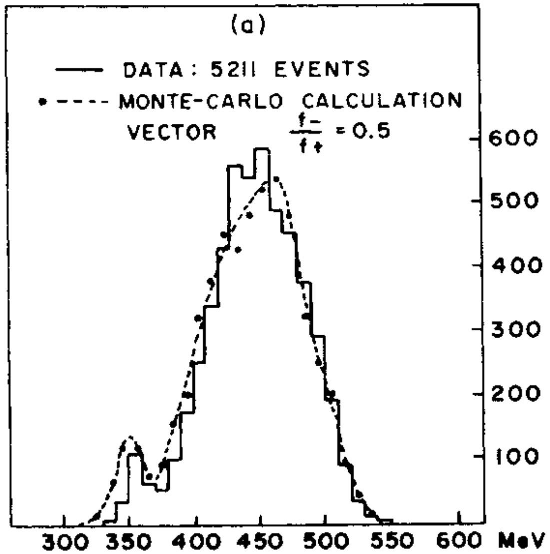

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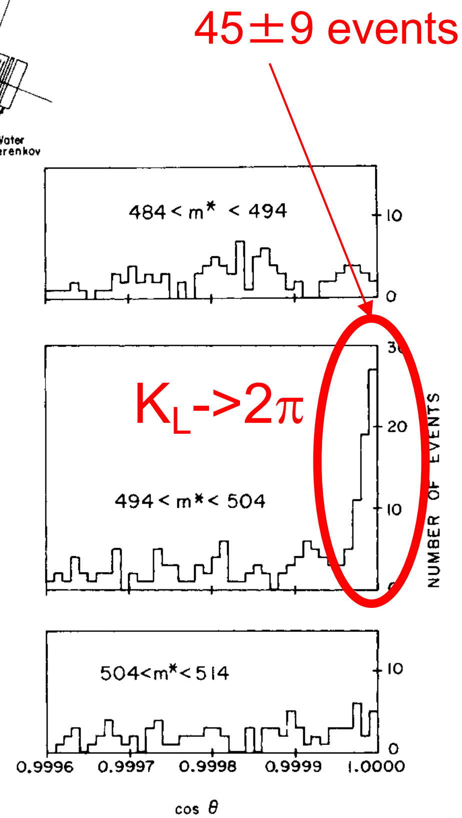

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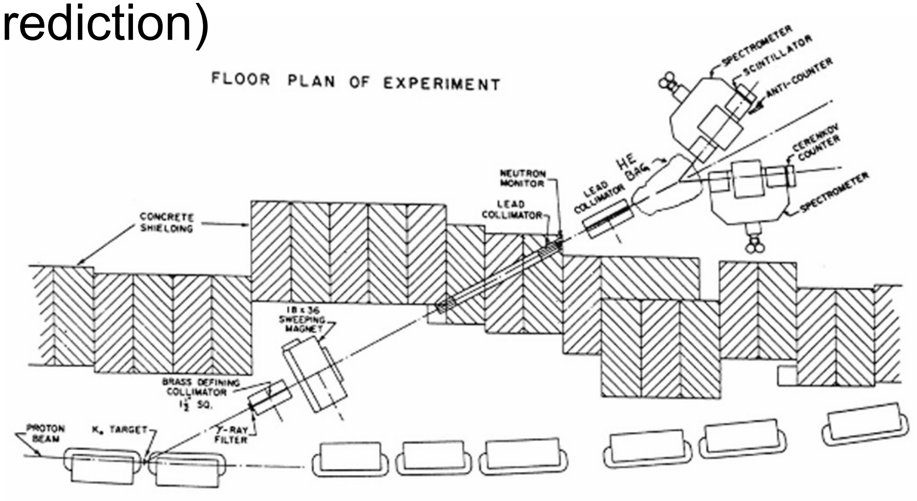

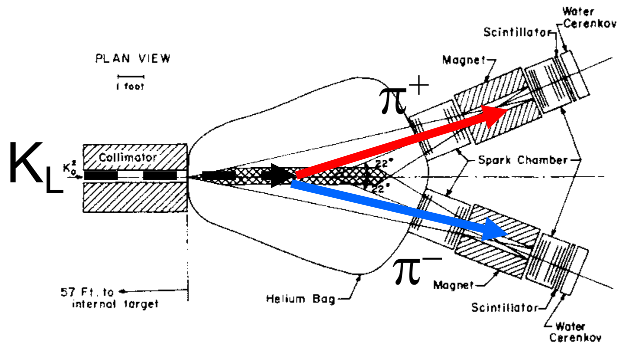

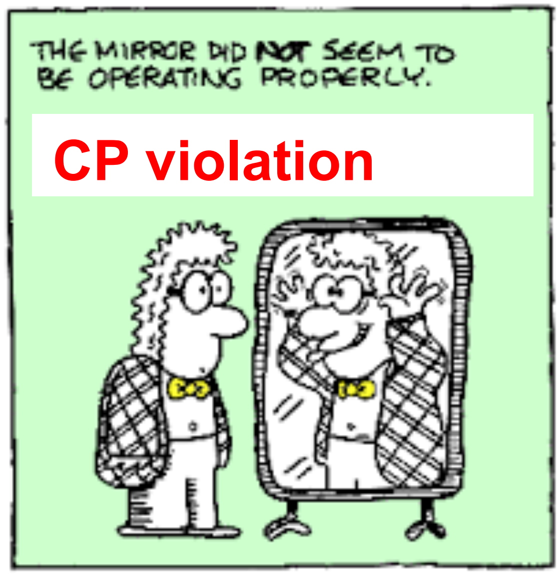

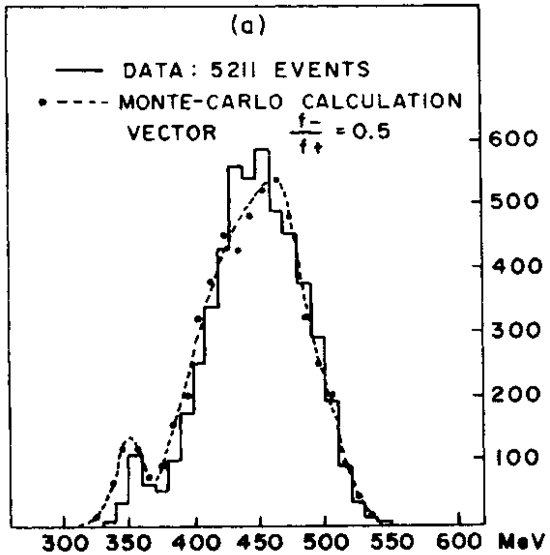

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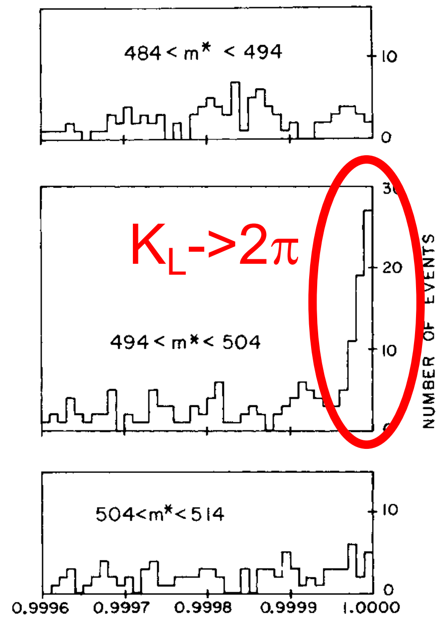

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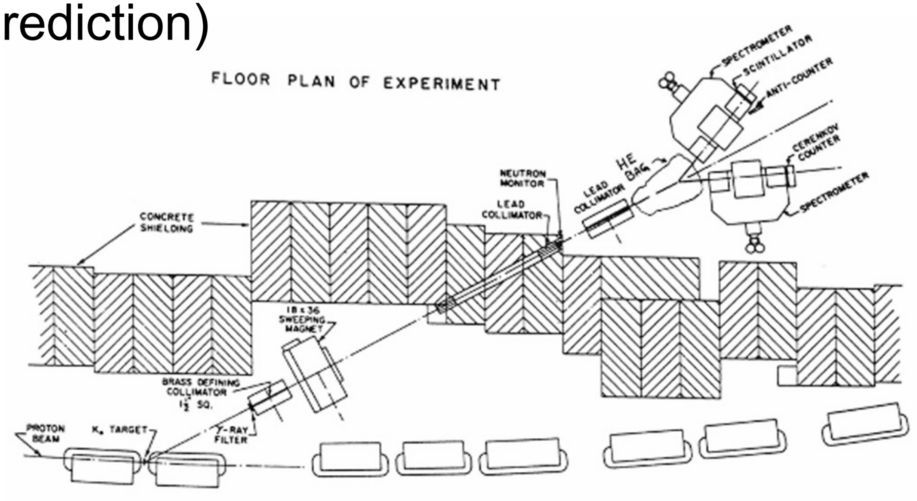

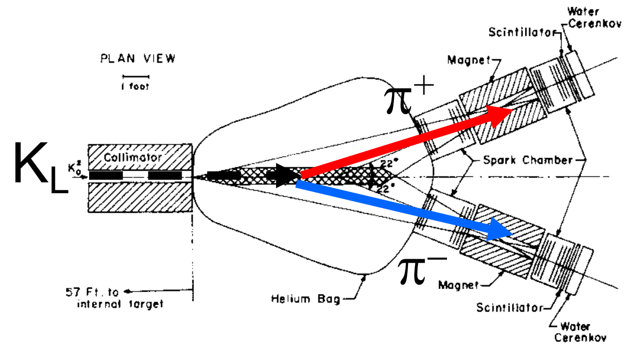

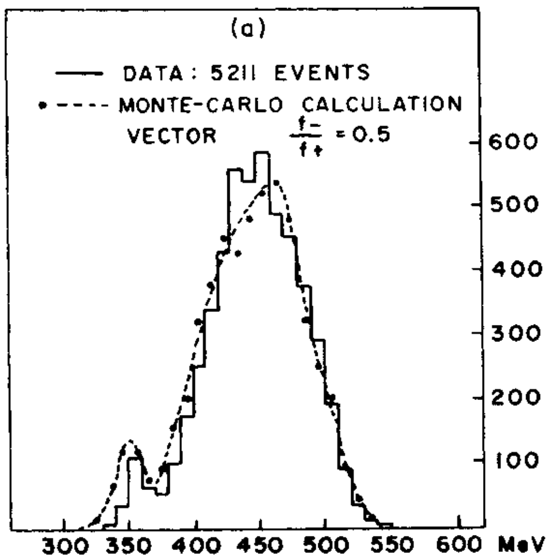

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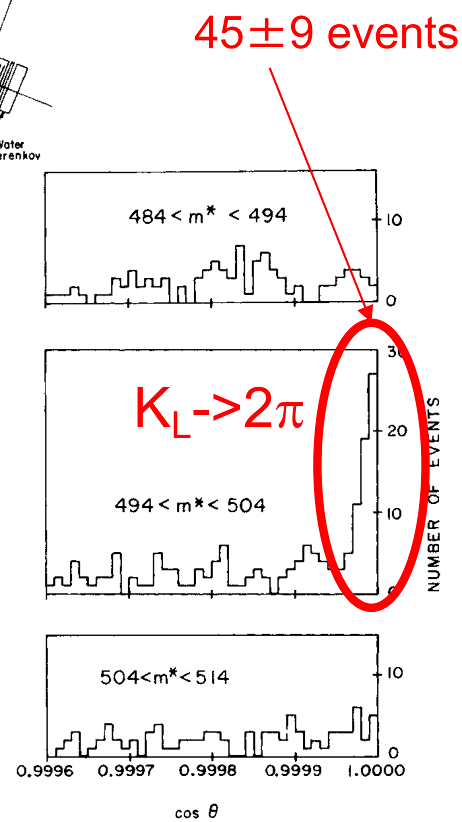

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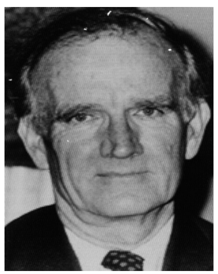

V. Fitch J. Cronin

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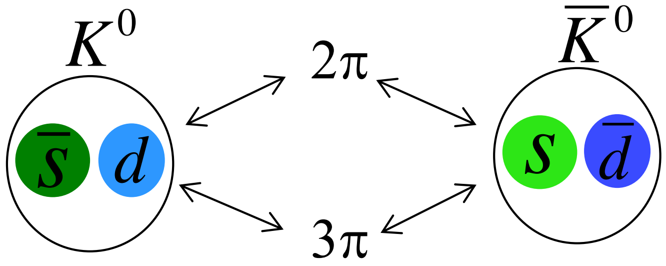

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τ_S ~ 90 ps τ_L ~ 51 ns

$K_L \to \pi\pi$ violates CP

eigenstates: physical states

$$|K_{S,L}\rangle = \frac{1}{\sqrt{2(1+|\varepsilon_{S,L}|)}}\left[(1+\varepsilon_{S,L})|K^0\rangle \pm (1-\varepsilon_{S,L})|\overline{K}^0\rangle\right]$$

$$= \frac{1}{\sqrt{(1+|\varepsilon_{S,L}|)}}\left[|K_{1,2}\rangle + \varepsilon_{S,L}|K_{2,1}\rangle\right]$$

$|K_{1,2}\rangle$ are CP=±1 states

$$\langle K_S|K_L\rangle \cong \varepsilon_S^* + \varepsilon_L \neq 0$$

small **CP impurity** ~2 x 10^{-3}

The neutral kaon two-level oscillating system in a nutshell

$$|K_{S,L}\rangle \propto \left[\left(1+\varepsilon_{S,L}\right)|K^0\rangle \pm \left(1-\varepsilon_{S,L}\right)|\bar{K}^0\rangle\right]$$

CP violation:

$$\varepsilon_{S,L} = \varepsilon \pm \delta$$

T violation:

$$\varepsilon = \frac{H_{12} - H_{21}}{2\left(\lambda_S - \lambda_L\right)} = \frac{-i\Im M_{12} - \Im\Gamma_{12}/2}{\Delta m + i\Delta\Gamma / 2}$$

CPT violation:

$$\delta = \frac{H_{11} - H_{22}}{2\left(\lambda_S - \lambda_L\right)} = \frac{1}{2}\frac{\left(m_{\bar{K}^0} - m_{K^0}\right) - (i/2)\left(\Gamma_{\bar{K}^0} - \Gamma_{K^0}\right)}{\Delta m + i\Delta\Gamma/2}$$

- $\delta \neq 0$ implies CPT violation
- $\varepsilon \neq 0$ implies T violation
- $\varepsilon \neq 0$ or $\delta \neq 0$ implies CP violation

(with a phase convention $\Im\Gamma_{12} = 0$)

$$\Delta m = m_L - m_S \quad , \quad \Delta\Gamma = \Gamma_S - \Gamma_L$$

$$\Delta m = 3.5 \times 10^{-15} \text{ GeV}$$

$$\Delta\Gamma \approx \Gamma_S \approx 2\Delta m = 7 \times 10^{-15} \text{ GeV}$$

CP violation found in other processes or systems

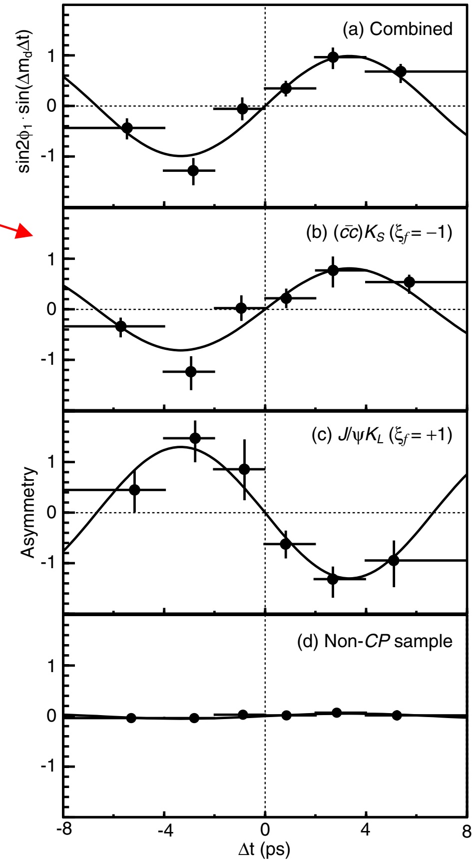
2001 - K^0 meson system: direct CP violation

NA48 (CERN) and KTeV (FNAL) experiments

$$\mathrm{Re}(\epsilon'/\epsilon) = \frac{1}{3}\,(1 - |\eta_{00}/\eta_{+-}|) = (1.66 \pm 0.23) \times 10^{-3}$$

2001 - B^0 meson system: CP violation in interference between mixing and decay amplitudes – Exploiting entanglement of $B^0\bar{B}^0$ pairs at collider

Babar (SLAC) and Belle (KEK) experiments



2019 - D^0 meson system

LHCb (CERN) experiment

$$\Delta a_{CP}^{\mathrm{dir}} \equiv a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) - a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-) = (-15.7 \pm 2.9) \times 10^{-4}\,.$$

$$a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-) = (23.2 \pm 6.1) \times 10^{-4}\,.$$

2025 - Λ^0_b baryon system

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$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$$

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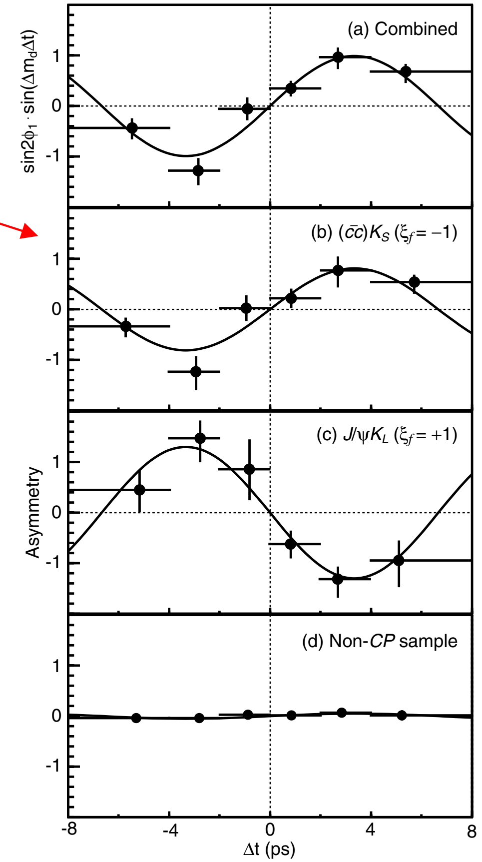

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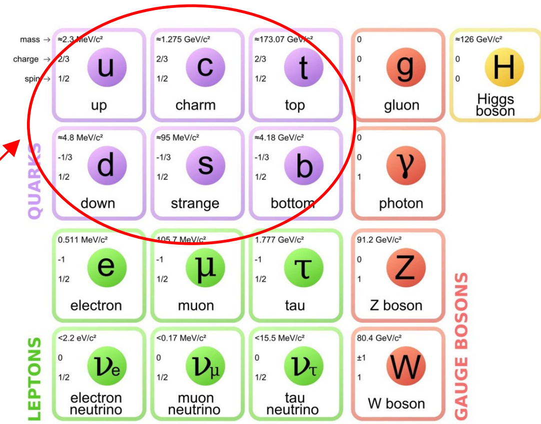
CP violation discovered so far only in mesons or baryons (made by quarks), not in leptons, like electrons or neutrinos

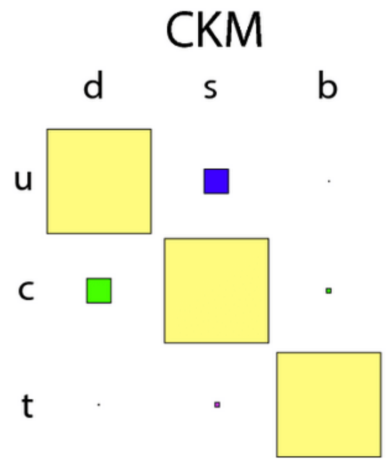


CP violation in the Standard Model

- In the Standard Model, the **only source of CP violation in the quark sector** is a single **irreducible complex phase** δ in the Cabibbo–Kobayashi–Maskawa matrix (CKM matrix).

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \mathbf{V} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\mathbf{V} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

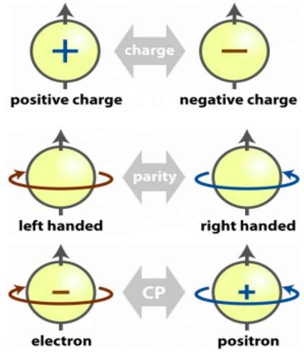


small mixing angles in CKM induce small CP violation

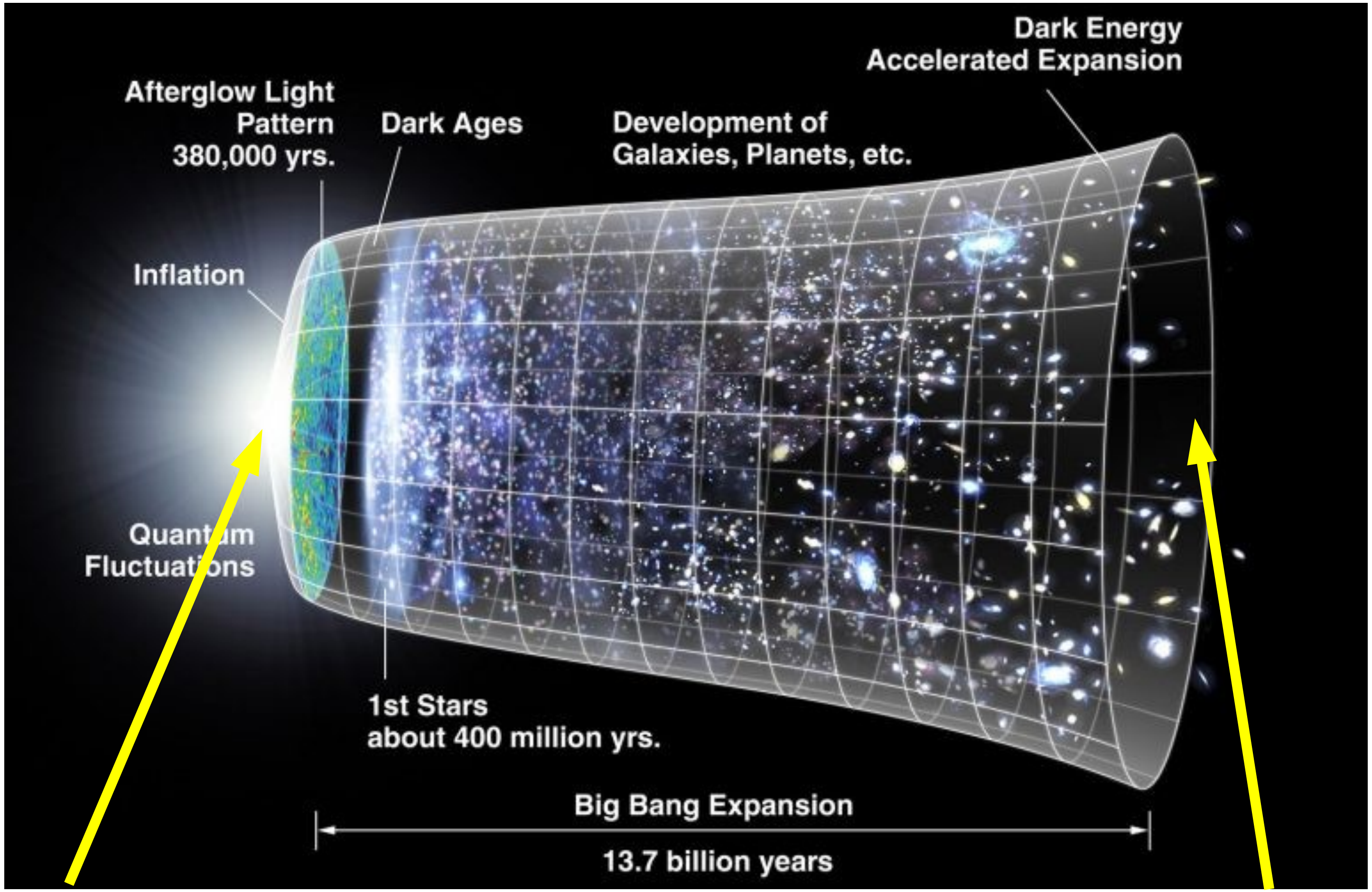
- This phase appears in the charged-current weak interaction.
- This phase exists only because there are at least three generations of quarks.
- Quantitatively the observed CP violation in the quark sector appears consistent with the prediction of the SM CKM mechanism.

Where did the antimatter go?

CP symmetry connects matter and antimatter



CP violation is a key ingredient to explain the absence of anti-matter in the Universe
(A. Sakharov, 1967)



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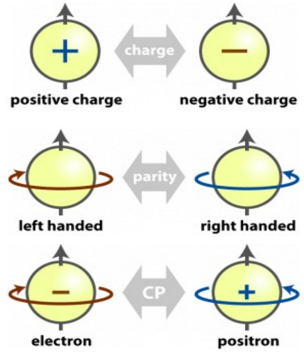

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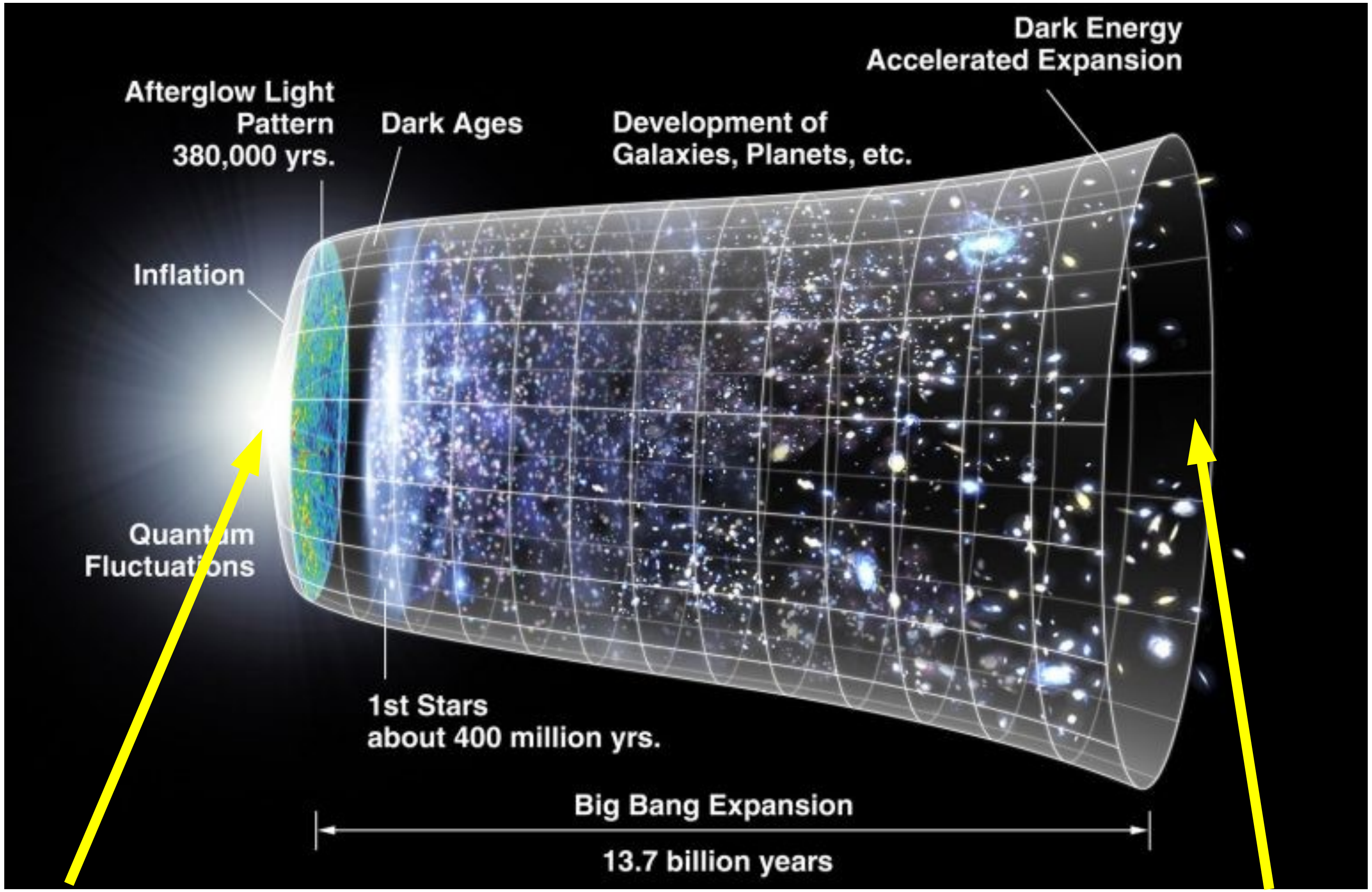
The observed CP violation in quarks is too small to explain the imbalance matter-antimatter in the Universe.



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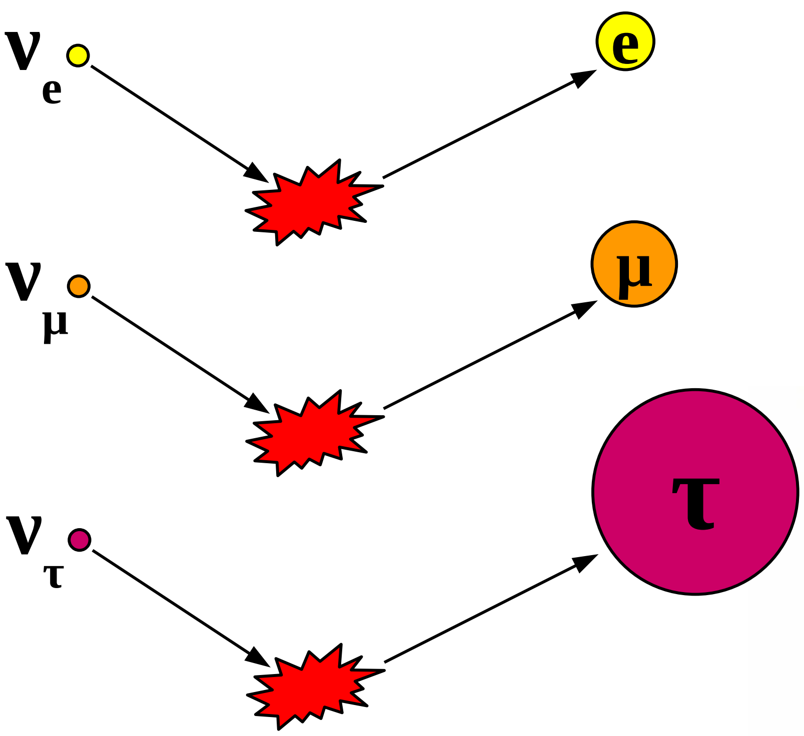
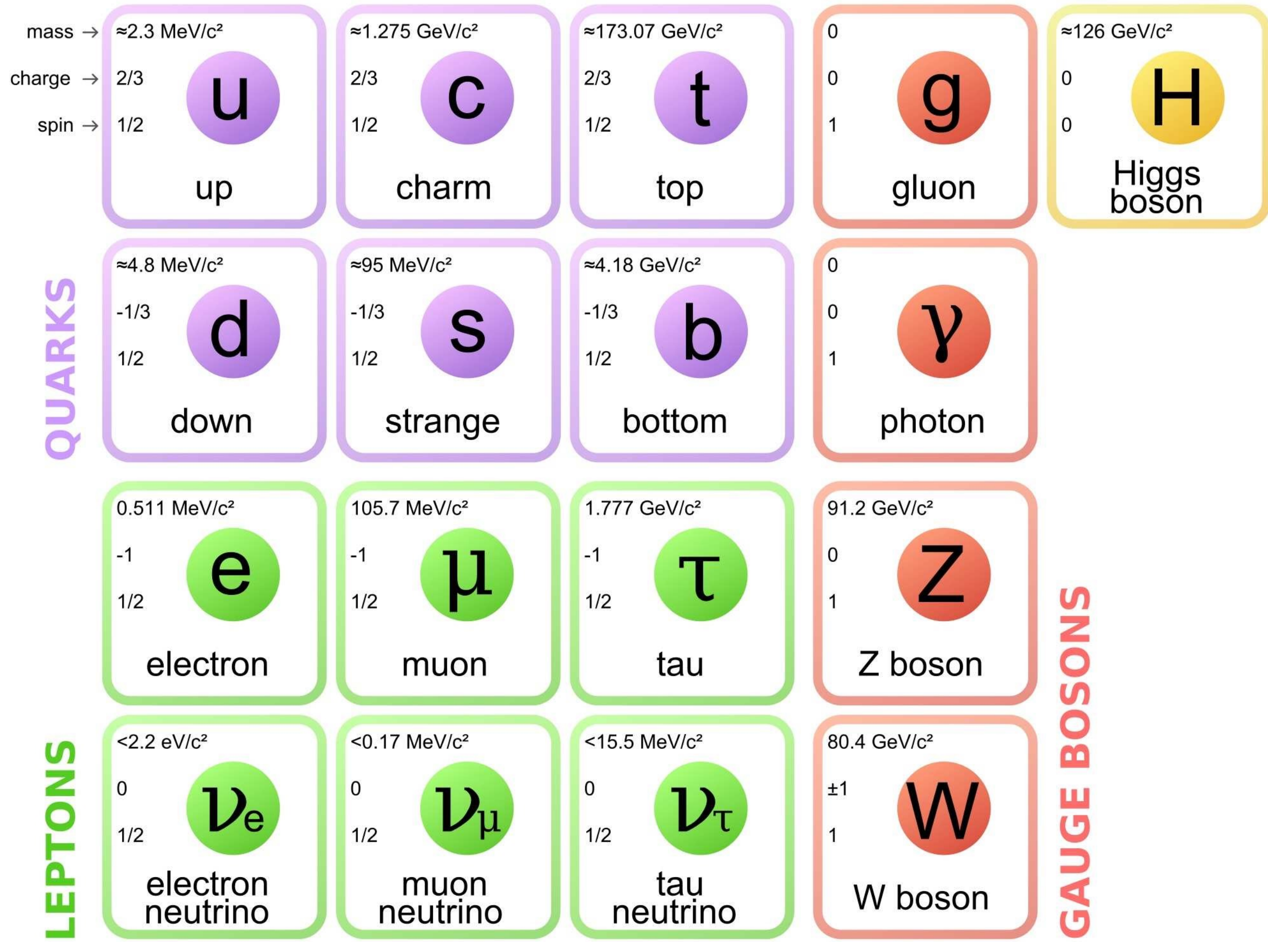
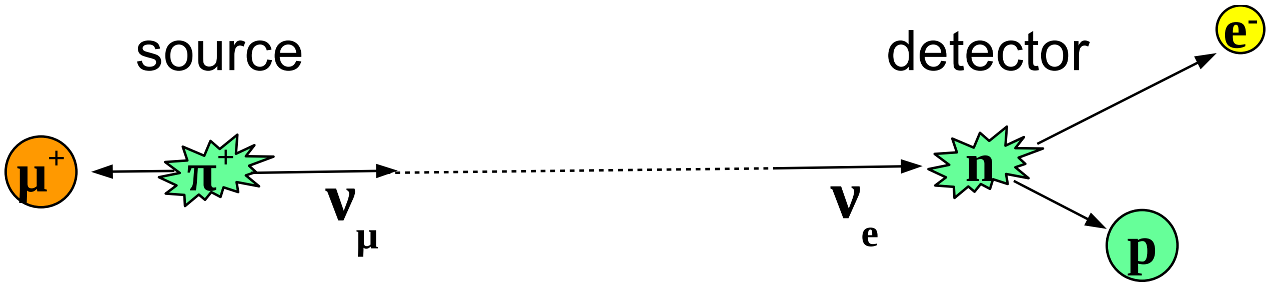
Neutrinos in the Standard Model





Neutrinos in SM are expected to have zero mass.

Neutrino oscillation



Pontecorvo

Sov.Phys.JETP 6:429,1957

Sov.Phys.JETP 26:984-988,1968

- We can create neutrinos of one flavor, say ν_μ
- And detect them later as some other flavor, say ν_e
- This is weird...why?

Maki, Nakagawa, Sakata

Prog.Theor.Phys. 28, 870 (1962)

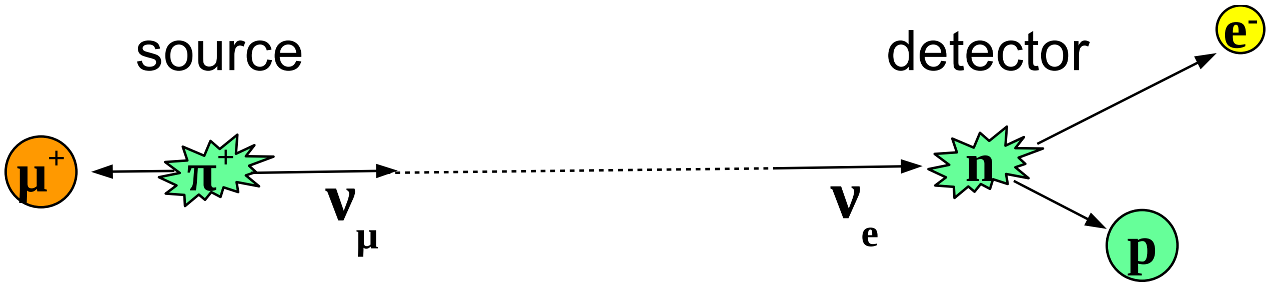
- if neutrinos have mass...
  - a neutrino that is produced as a ν_μ
    - (e.g. $\pi^+ \to \mu^+ \nu_\mu$)
  - might some time later be observed as a ν_e
    - (e.g. $\nu_e\, n \to e^-\, p$)

Neutrino oscillation

Pontecorvo

Sov.Phys.JETP 6:429,1957

Sov.Phys.JETP 26:984-988,1968



Maki, Nakagawa, Sakata

Prog.Theor.Phys. 28, 870 (1962)

- We can create neutrinos of one flavor, say ν_μ
- And detect them later as some other flavor, say ν_e
- This is weird...why?

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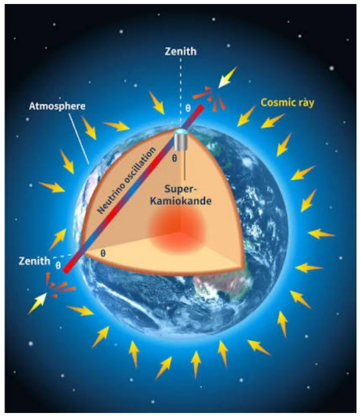
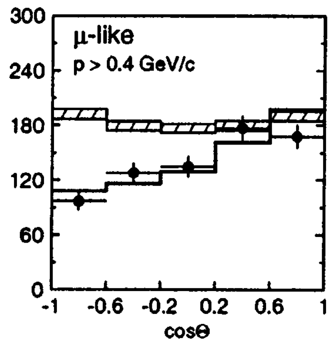
    - (e.g. $\pi^+ \to \mu^+ \nu_\mu$)
  - might some time later be observed as a ν_e
    - (e.g. $\nu_e\, n \to e^- p$)

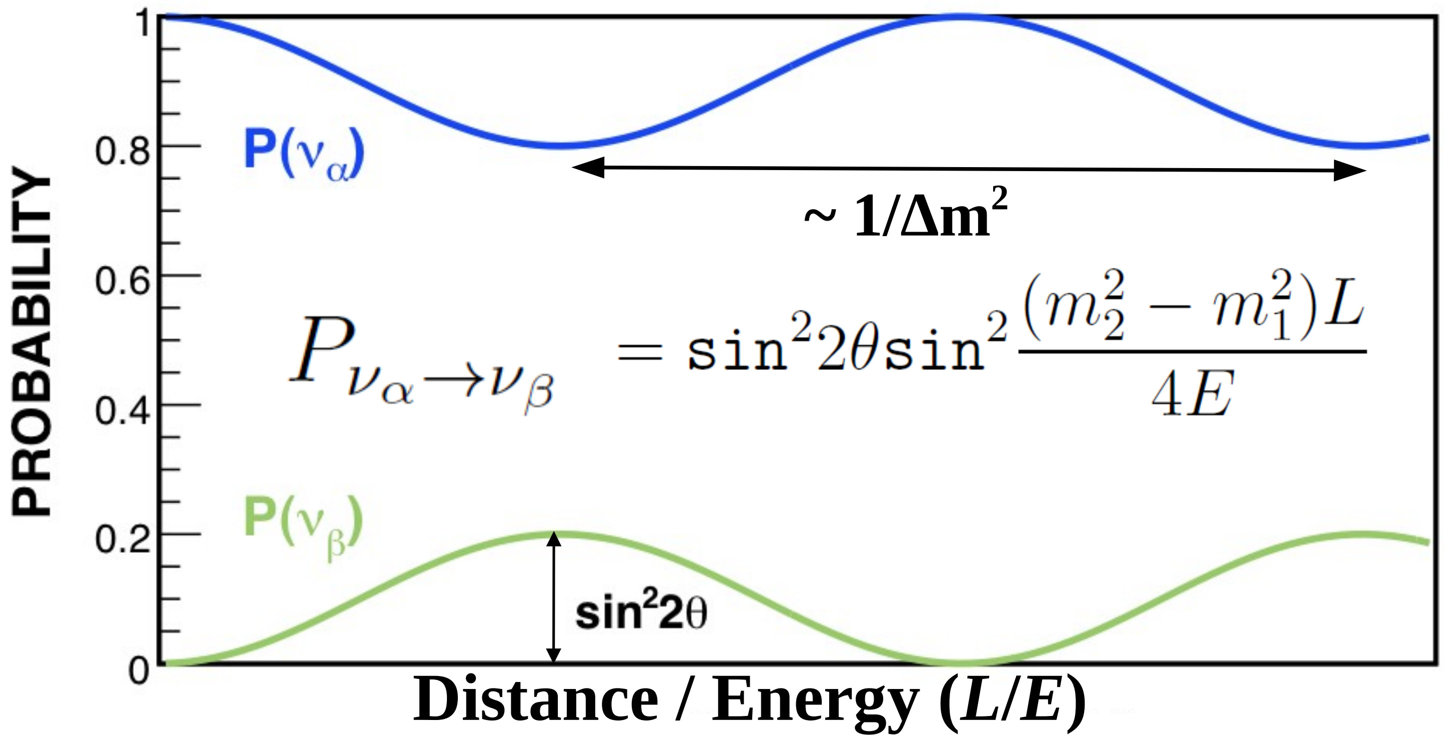
1998 – SuperKamiokande:
Oscillations discovered in atmospheric neutrinos





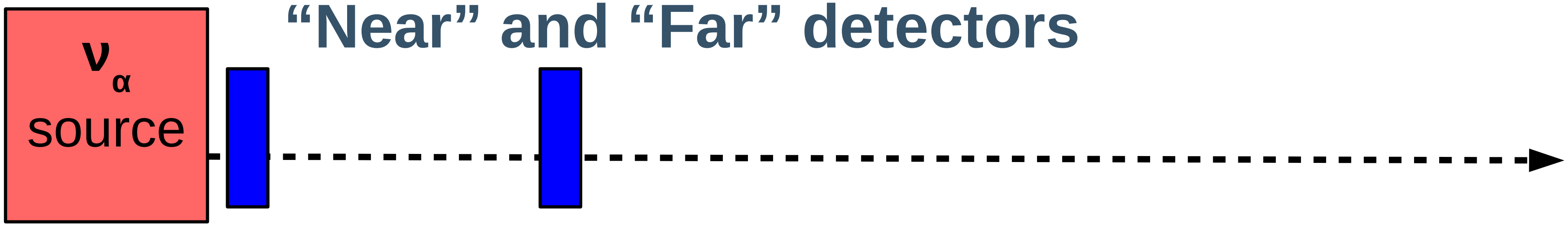
$\Rightarrow$ neutrinos have a tiny mass

Neutrino oscillations



$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 \frac{(m_2^2 - m_1^2)L}{4E}$$

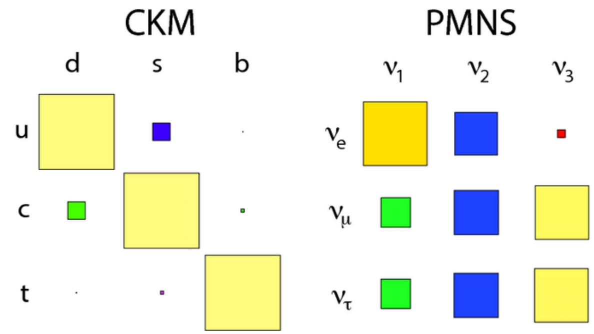
"Near" and "Far" detectors



Mixing with three neutrinos

Flavor eigenstates   Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

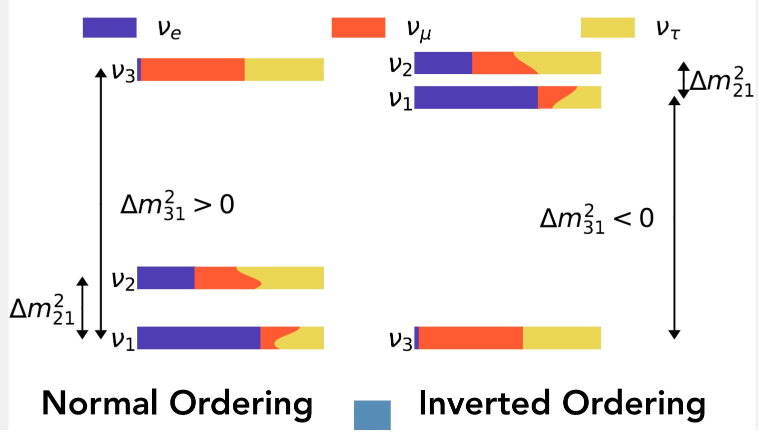
In PMNS mixing angles are large, observable CP violation can be large.

Next generations of neutrino experiments have to:

- improve the precision of PMNS parameters
- determine the neutrino mass ordering
- determine if CP is violated in neutrino oscillations

- test the consistency of the three flavor unitary mixing model -> overconstrain the model
- characterize the new Physics or put stringent limits on it

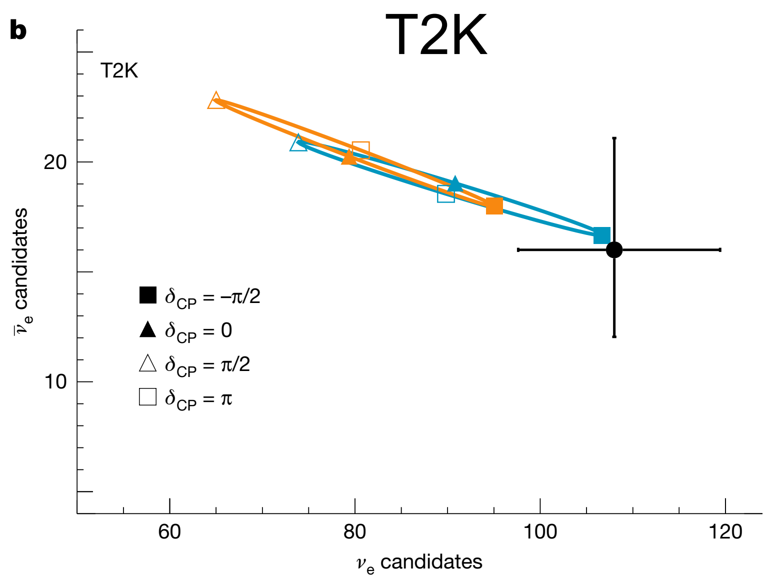
Neutrino mass spectrum

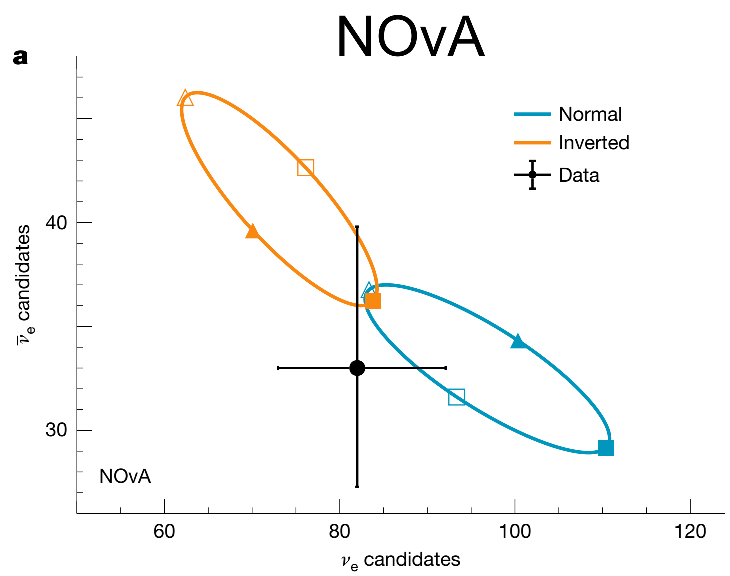


Search for CP violation: T2K and NOvA experiments

Measure the difference between the probabilities of a transition and its CP-conjugate

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

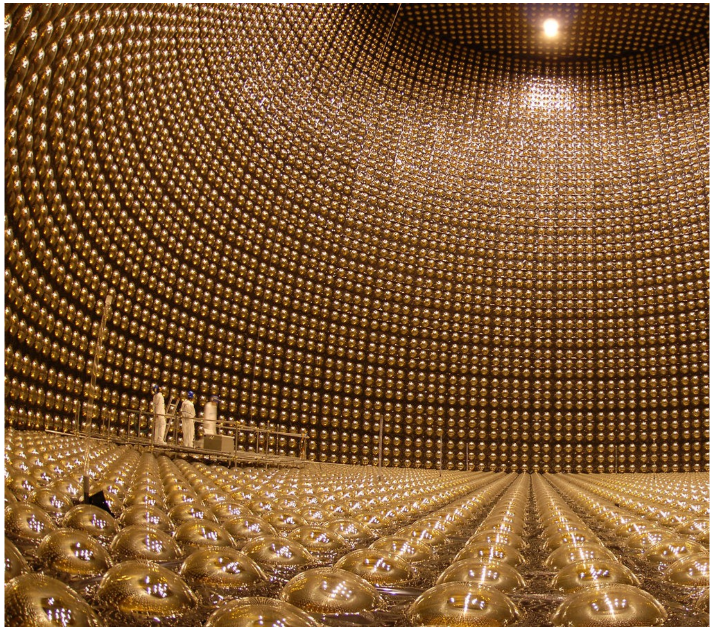


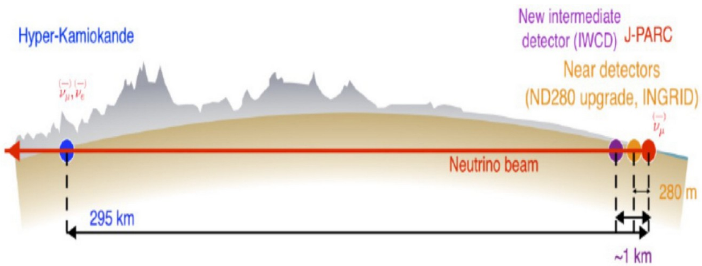


- Matter effect and CP violation both increase either ν_e or $\bar{\nu}_e$ appearance and suppress the other
- Product of $\sin^2\theta_{13}\sin^2 2\theta_{23}$ effects ν_e and $\bar{\nu}_e$ appearance in the same way
- Narrow-band experiments like T2K and NOvA functionally just count ν_e and $\bar{\nu}_e$ events

Hyper-Kamiokande experiment

Hyper-K will start operations in 2028 and search for CP violation

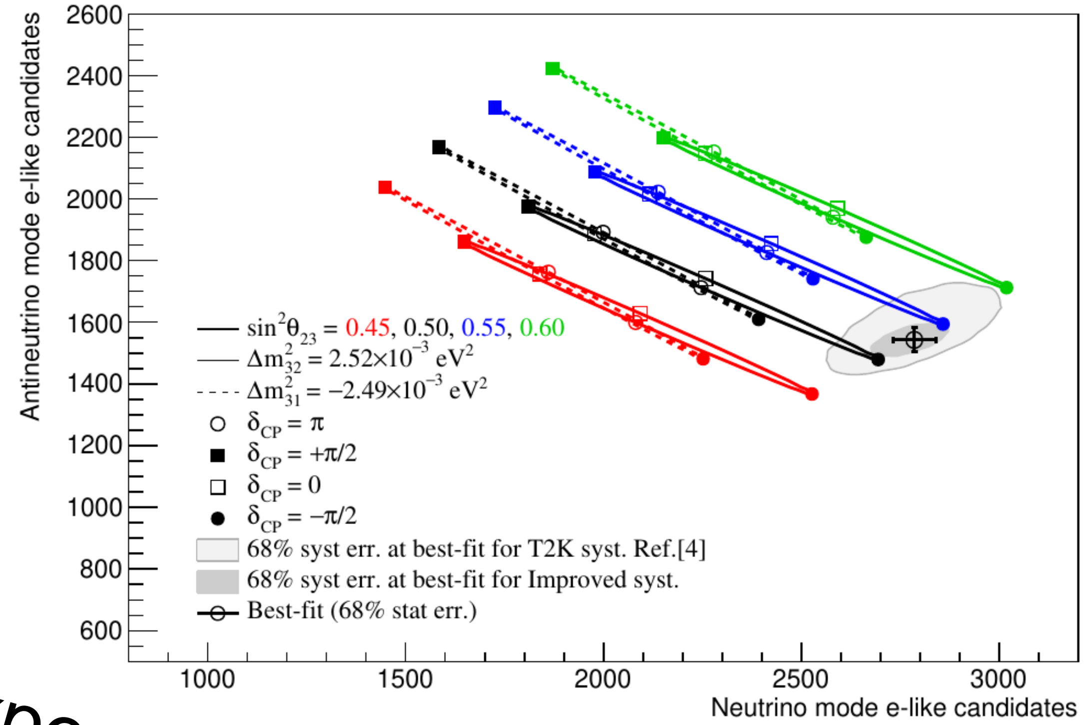




- Hyper-K will reuse the (upgraded) T2K beamline
- Same detector technology, but much larger (FV =188 kton ~ T2K x 8)
- Similar off-axis location → very, very, very high statistics measurements of ν_e appearance
- Hyper-K is an *excellent* experiment for CP violation in the three-flavor framework, provided the mass ordering is known

Hyper-Kamiokande search for CP violation

Hyper-K's bi-event plot is identical to T2K, with smaller error

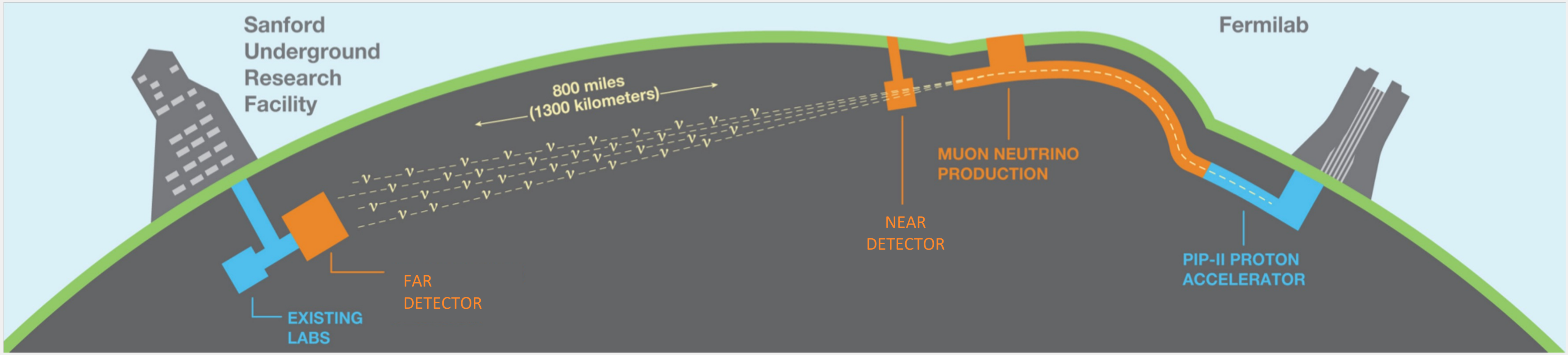


Expectations from MC simulation

- Really good at distinguishing CP conserving vs. CP violating values **provided MO is known**
- Degeneracy between MO and δ_{CP}, and between different values of δ_{CP} with same $\sin(\delta_{CP})$

DUNE - The Deep Underground Neutrino Experiment

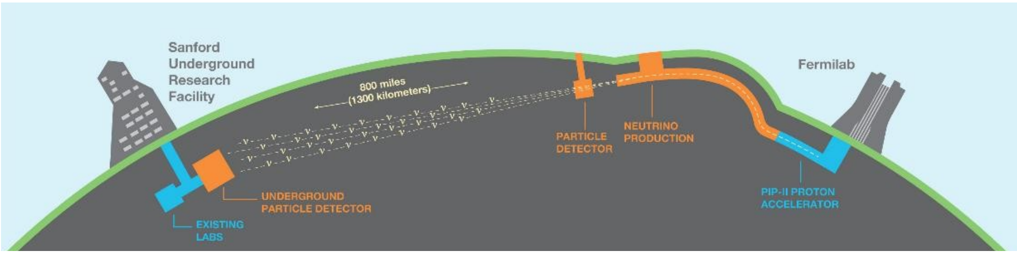
DUNE TDR Volumes: JINST 15 (2020) 08, T08008, T08009, T08010, arXiv:2002.03005, JINST 19 (2024) 08, T08004
ND CDR Instruments 5 (2021) 4, 31

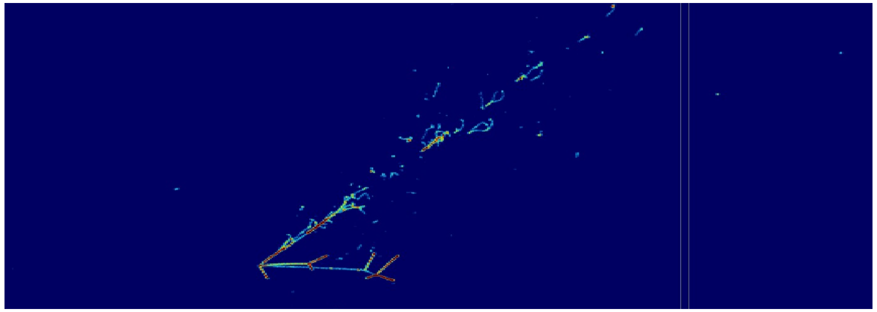


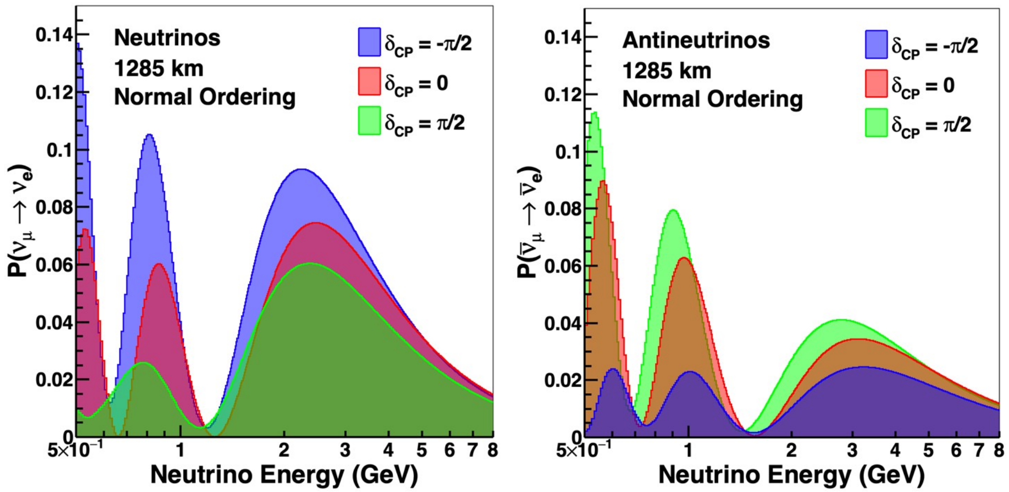
The **most powerful neutrino beam in the world** (>2 MW) will be sent from Fermilab (Chicago) to SURF (South Dakota) along 1300 km distance to be detected by four liquid argon **far detector** modules (70 kton LAr) at 1.5 km deep underground and a **near detector** complex at 560 m from the neutrino source

DUNE - The Deep Underground Neutrino Experiment

DUNE: completely measure 3-flavor picture + search for new physics





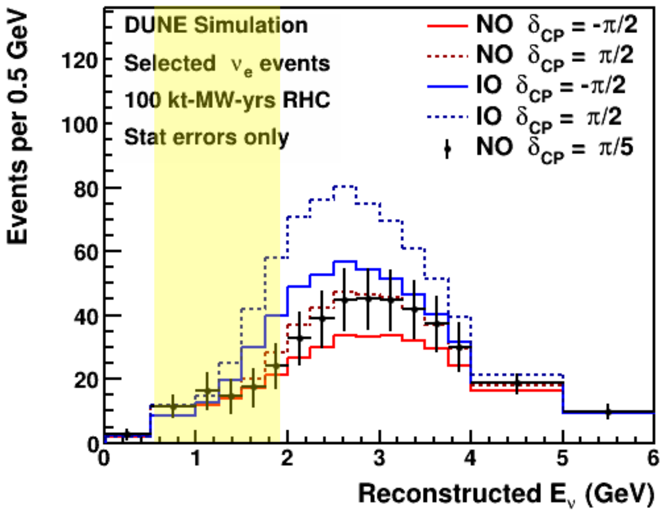


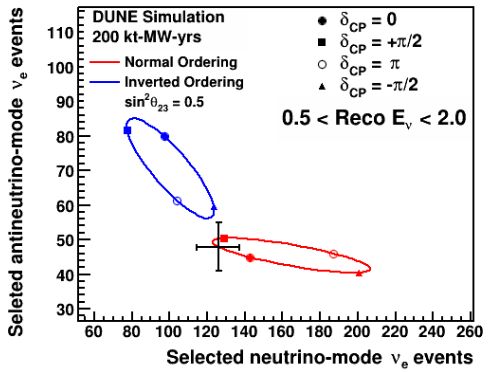
- DUNE has a very different design philosophy from Hyper-K: measure oscillations over >1 full period, long baseline → parameters are not degenerate, **measure everything in one experiment**
- DUNE is a multi-purpose experiment, more like a collider detector than previous neutrino experiments that were largely designed to measure a single parameter
- This has many advantages
  - More robust to parameter degeneracies
  - Better long-term precision
  - More robust to unexpected results
  - Much better sensitivity to new physics in neutrino oscillations

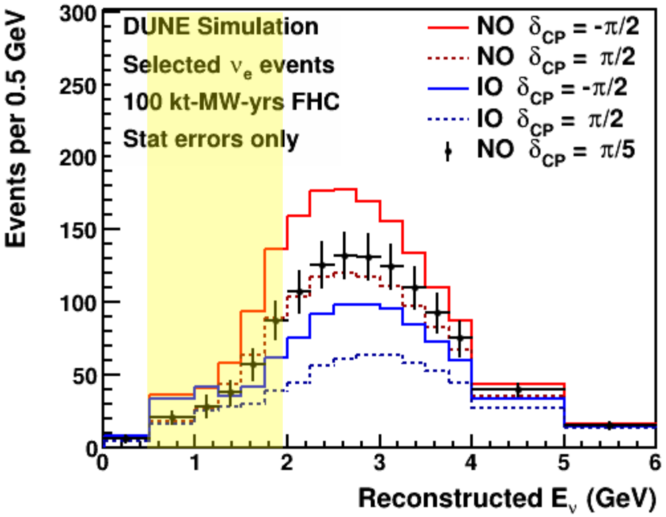
DUNE measures neutrino energy spectra

DUNE can make a different bi-event plot in each energy bin

Expectations from MC simulation





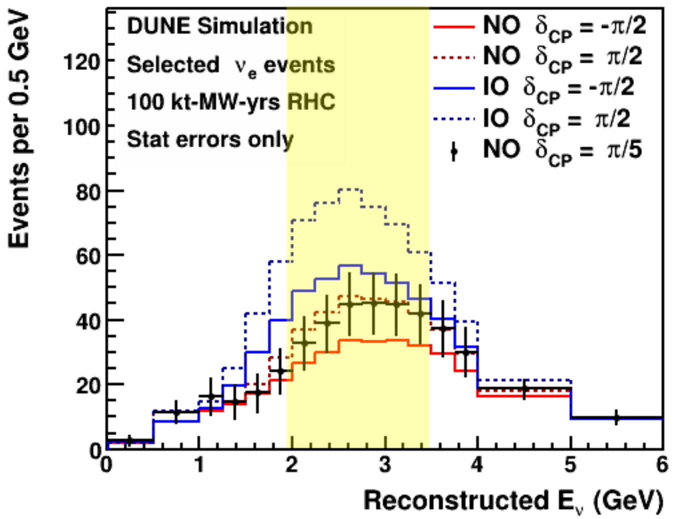


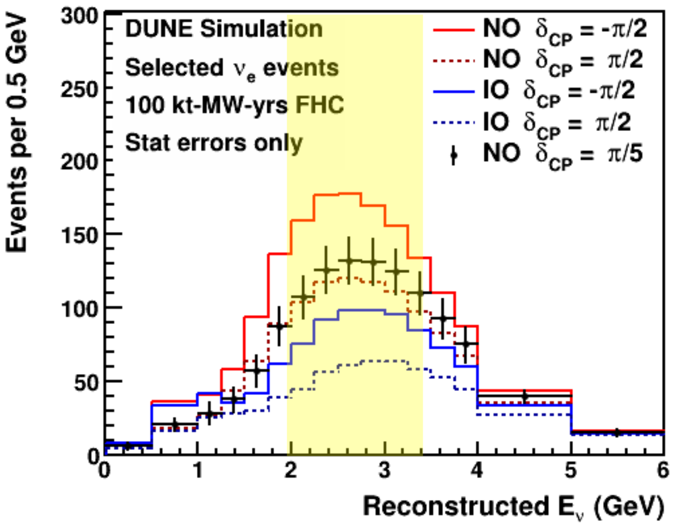
- As an illustration, divide the sample into three energy bins
- Asymmetry due to mass ordering is small at low energy

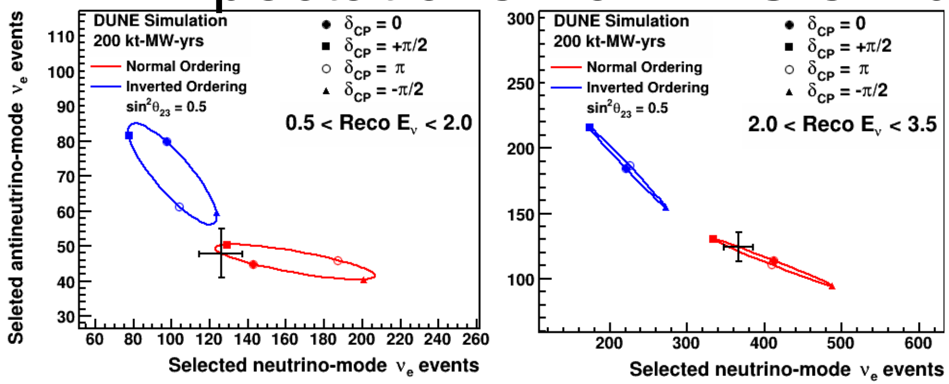
DUNE measures neutrino energy spectra

DUNE can make a different bi-event plot in each energy bin

Expectations from MC simulation





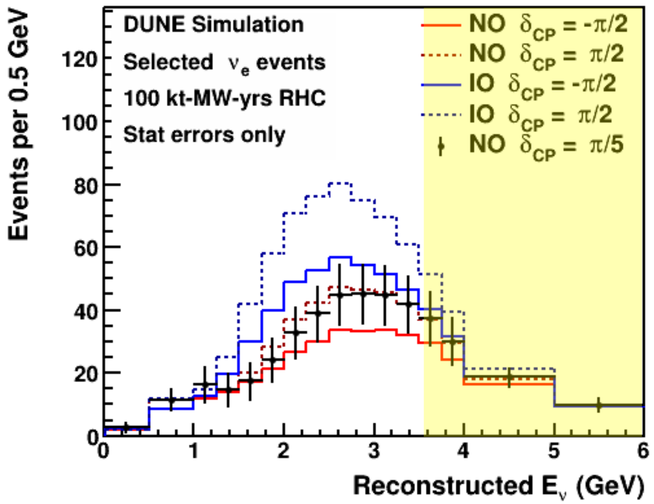


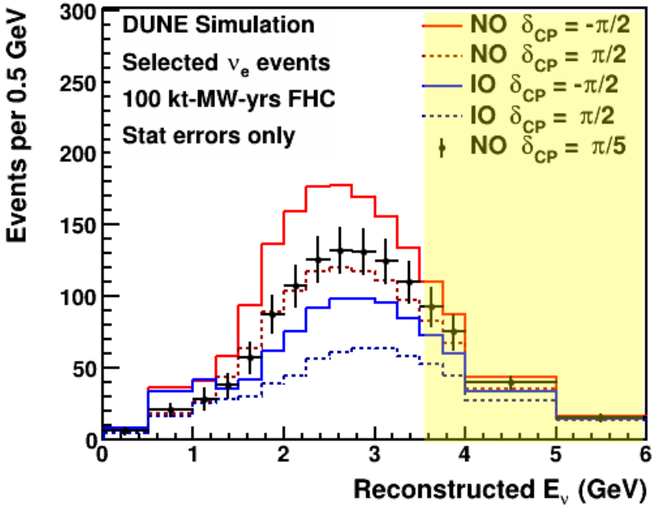
- In the oscillation maximum, we see the largest separation between the mass orderings
- But ellipses flatten – cannot resolve degeneracies with peak region alone

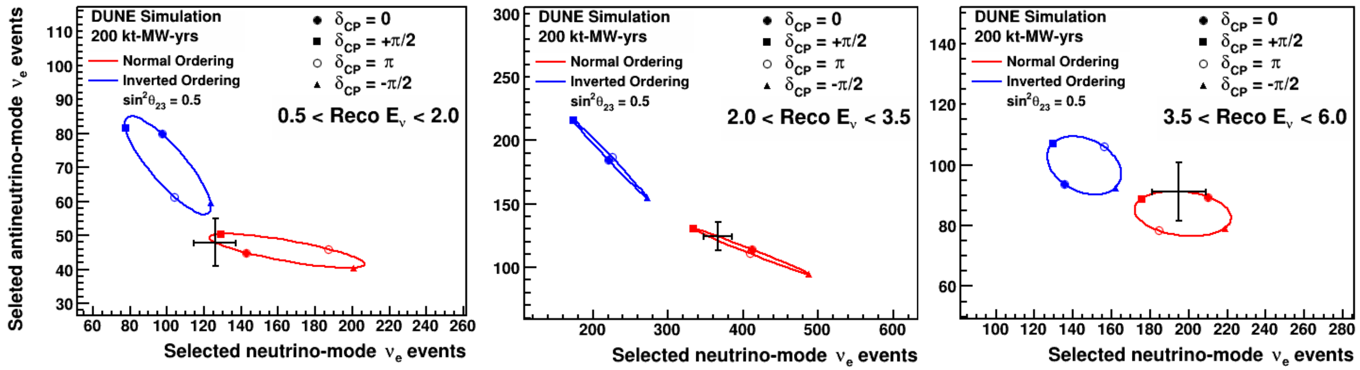
DUNE measures neutrino energy spectra

DUNE can make a different bi-event plot in each energy bin

Expectations from MC simulation



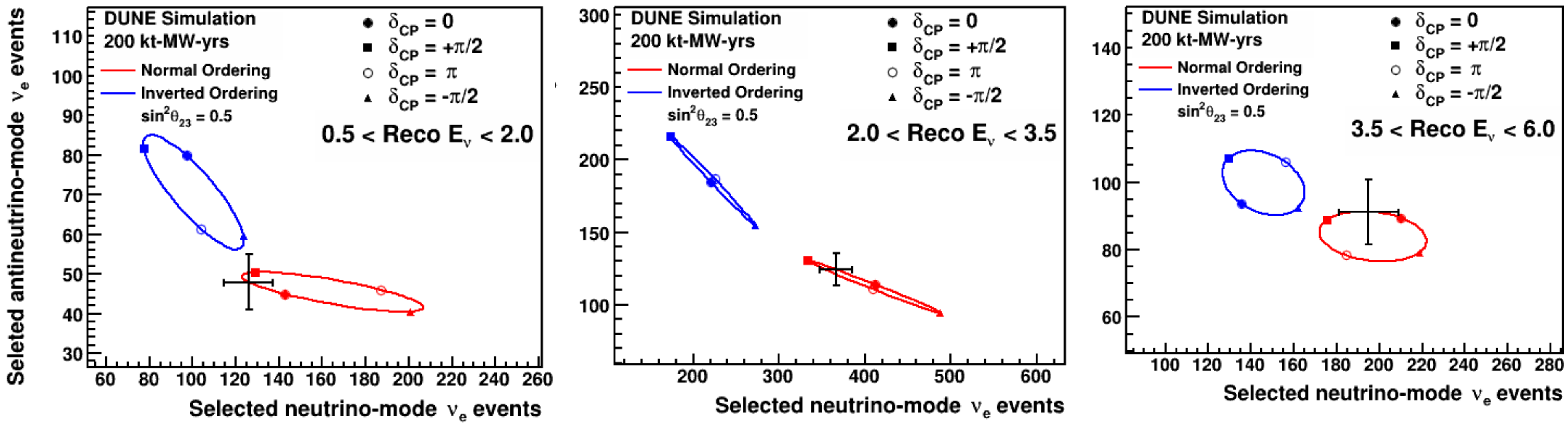




- At low L/E, shape of ellipse changes, and degeneracies disappear
- Demonstrates power of DUNE's wideband spectrum → broad L/E range is essential to resolving all parameters at once

DUNE is sensitive to new physics in neutrino oscillations

Expectations from MC simulation

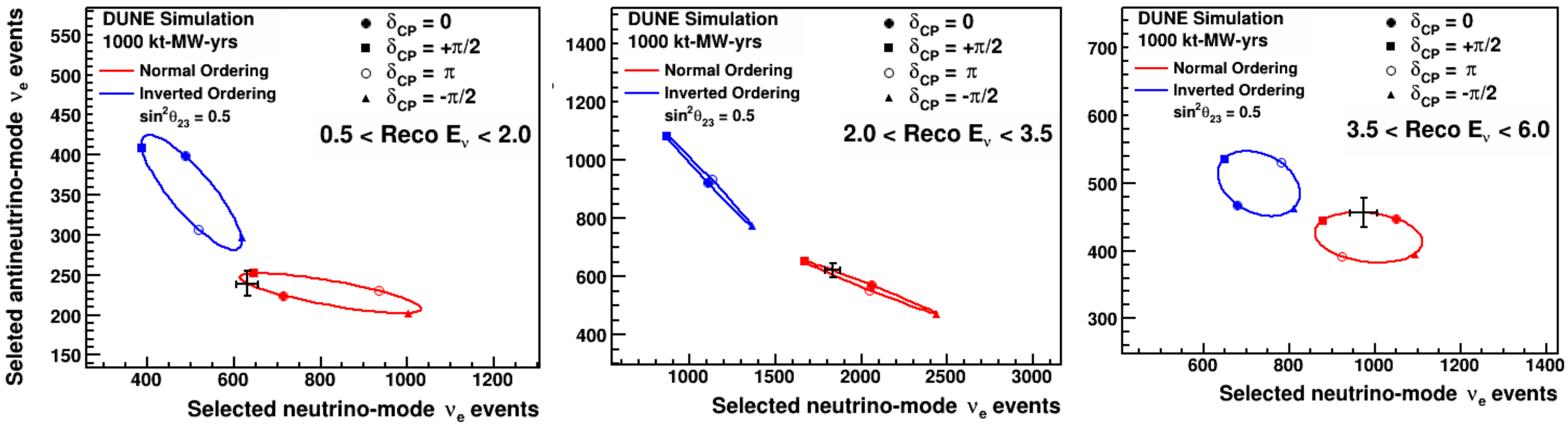


- DUNE can measure oscillation parameters at each bin of L/E
- If 3-flavor PMNS picture is correct, data should prefer the same point in every bin
- It is likely that new physics would distort the result *as a function of L/E* → DUNE has qualitatively unique sensitivity

DUNE is sensitive to new physics in neutrino oscillations

Expectations from MC simulation

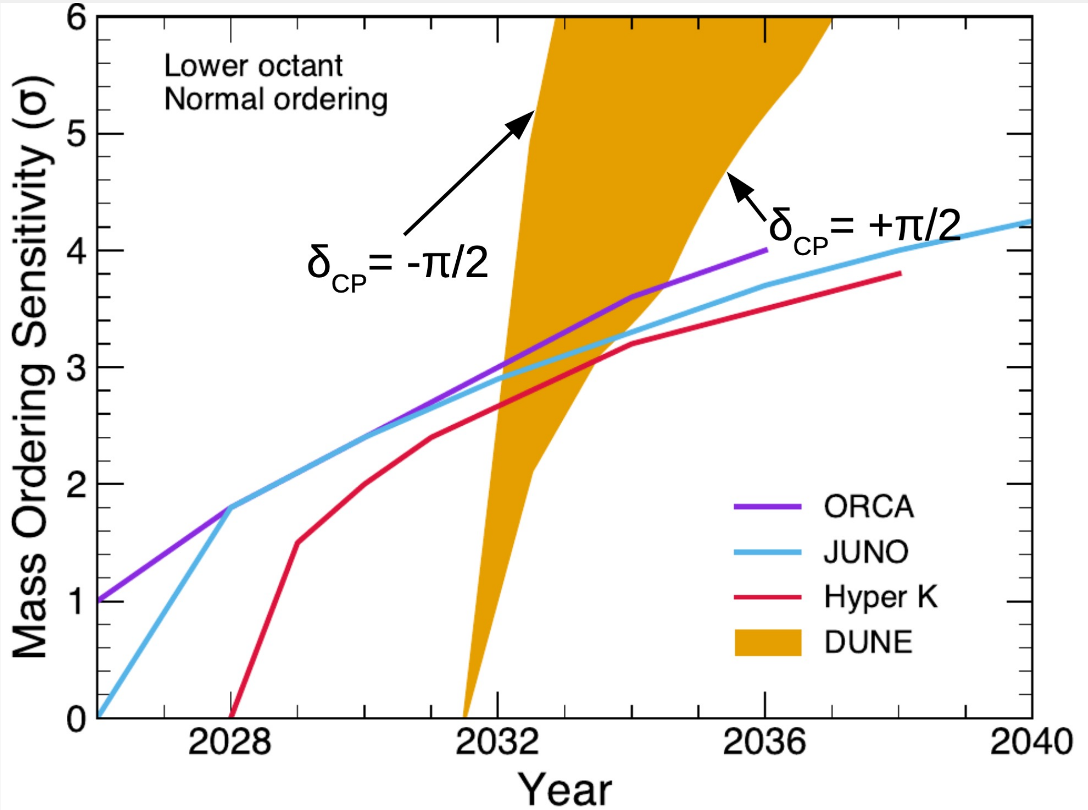
With a very long exposure DUNE is sensitive to small deviations



- Shown is 1000 kt-MW-yrs, which requires upgraded beam to achieve on a reasonable timescale
- DUNE can make extremely precise measurements of δ_{CP}, and becomes sensitive to even small deviations from three-flavor mixing

Mass ordering determination

- DUNE is the only experiment that measures the mass ordering by separately measuring $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations



- Existing Super-K atmospheric data (weakly) prefers normal ordering and lower octant
- In this scenario, atmospheric experiments do not reach 5σ for mass ordering discovery
- Despite starting later, **DUNE is the only experiment to reach >5σ**, even in the most pessimistic case

T and CPT symmetries

CPT theorem

The three discrete symmetries of QM, C (charge conjugation: q → -q), P (parity: x → -x), and T (time reversal: t → -t) are known to be violated in nature both singly and in pairs. Only CPT appears to be an exact symmetry of nature.

CPT theorem :

J. Schwinger (1951)

G. Lüders (1954)

R. Jost (1957)

W. Pauli (1952)

J. Bell (1955)

Exact CPT invariance holds for any quantum field theory (like the Standard Model) formulated on flat space-time which assumes:
(1) Lorentz invariance (2) Locality (3) Unitarity (i.e. conservation of probability).

Testing the validity of the CPT symmetry probes the most fundamental assumptions of our present understanding of particles and their interactions.

CPT symmetry tests

Extension of CPT theorem to a theory of quantum gravity far from obvious.
(e.g. CPT violation appears in several QG models)
No predictive theory incorporating CPT violation => only phenomenological models to be constrained by experiments.

Consequences of CPT symmetry: equality of masses, lifetimes, |q| and |μ| of a particle and its anti-particle.

Neutral meson systems offer unique possibilities to test CPT invariance;

e.g. taking as figure of merit the fractional difference between the masses of a particle and its anti-particle:

neutral K system $\left|m_{K^0} - m_{\overline{K}^0}\right| / m_K < 10^{-18}$

neutral B system $\left|m_{B^0} - m_{\overline{B}^0}\right| / m_B < 10^{-14}$

proton- anti-proton $\left|m_p - m_{\overline{p}}\right| / m_p < 10^{-8}$

Other interesting CPT tests: e.g. the study of anti-hydrogen atoms, etc..

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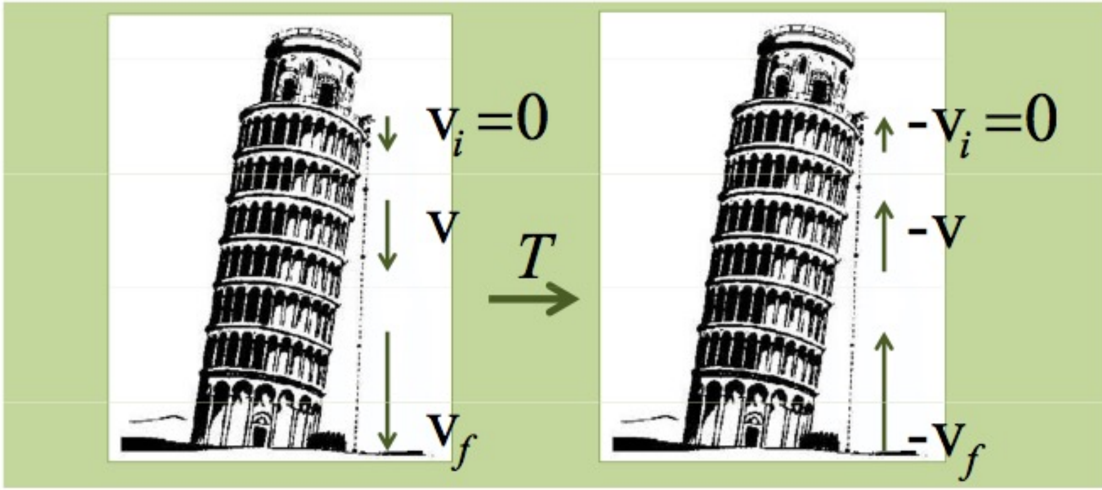
Other interesting CPT tests: e.g. the study of anti-hydrogen atoms, etc..

Time Reversal - T

•The transformation of a system corresponding to the inversion of the time coordinate, the formal substitution t → −t, is usually called '**time reversal**', but a more appropriate name would actually be **motion reversal**.



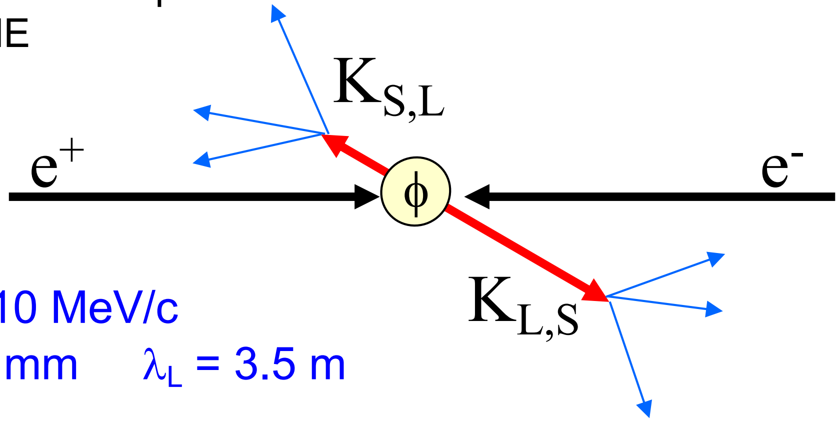
•Exchange of in <-> out states and reversal of all momenta and spins tests time reversal, i.e. the symmetry of the responsible dynamics for the observed process under time reversal t → −t (transformation implemented in QM by an antiunitary operator)

•Similarly for CPT tests: the exchange of in <-> out states etc.. is required.

Quantum entanglement as a tool for T and CPT tests

KLOE/KLOE-2 experiment
at DAΦNE

- The in<->out states inversion required in a DIRECT test of T or CPT can be performed exploiting the properties of the quantum entanglement.
- In maximally entangled systems the complete knowledge of the system as a whole is encoded in the state, no information on single subsystems is available.
- Once a measurement is performed on one subsystem, then the information is immediately transferred to its partner, which is prepared in the orthogonal state
- At the DAΦNE ϕ-factory in Frascati:
  $\sigma(e^+e^- \to \phi) \sim 3$ mb; $W = m_\phi = 1019.4$ MeV; BR($\phi \to K^0\bar{K}^0$) ~34%; ~10^6/pb^{-1}
  KK pairs produced in max. entangled quantum state with $J^{PC} = 1^{--}$:

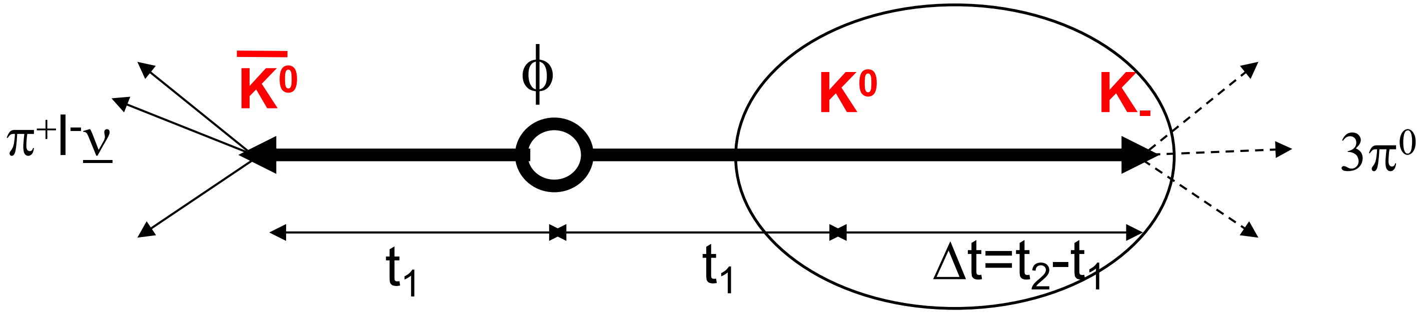


p_K = 110 MeV/c
λ_S = 6 mm λ_L = 3.5 m

$$|i\rangle = \frac{1}{\sqrt{2}}\left[\left|K^0(\vec{p})\right\rangle\left|\bar{K}^0(-\vec{p})\right\rangle - \left|\bar{K}^0(\vec{p})\right\rangle\left|K^0(-\vec{p})\right\rangle\right]$$
$$= \frac{N}{\sqrt{2}}\left[\left|K_S(\vec{p})\right\rangle\left|K_L(-\vec{p})\right\rangle - \left|K_L(\vec{p})\right\rangle\left|K_S(-\vec{p})\right\rangle\right]$$

$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)}\Big/\left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

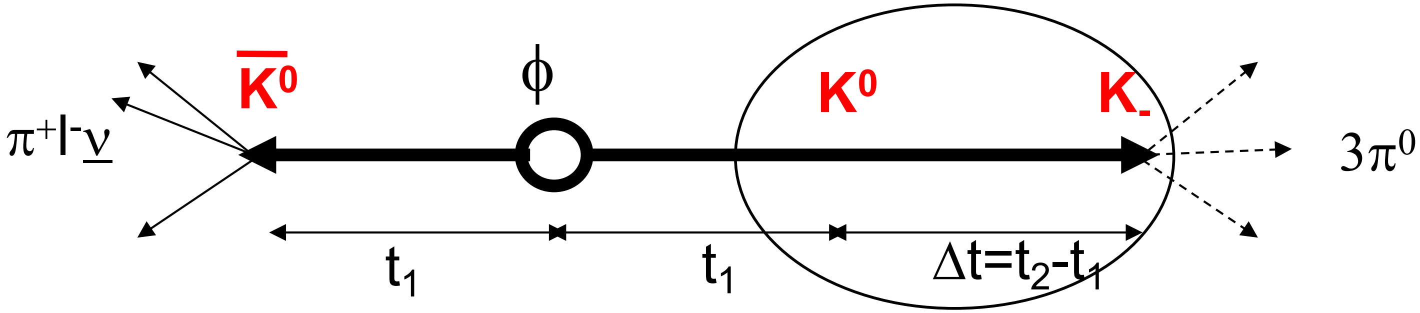
T, CPT, CP tests in transitions



$$K^0 \to K_-$$ reference process

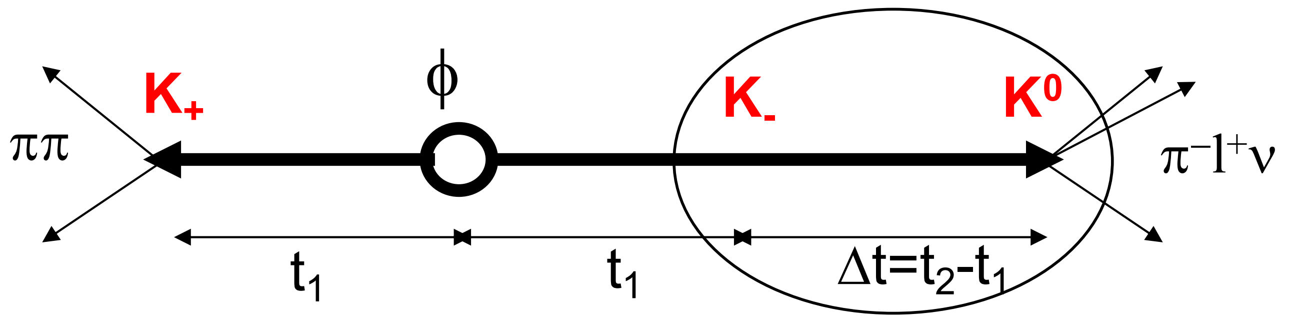
* (K_+ and K_- are CP eigenstates not to be confused with charged kaons K^+ and K^-)

T test in transitions



$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow K^0$ T-conjugated process



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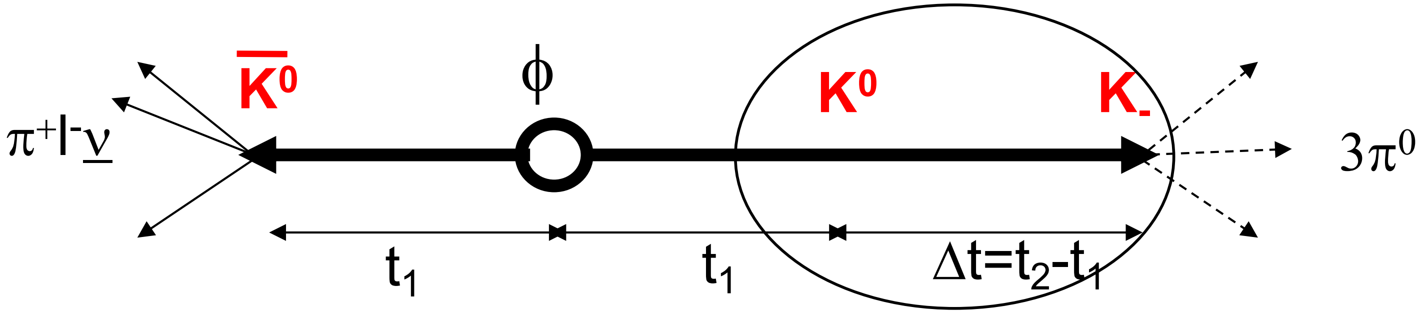
T test in transitions



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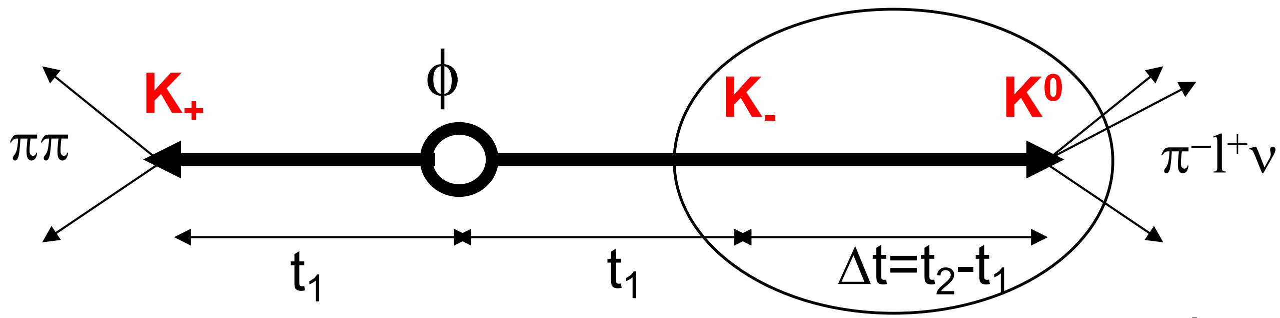
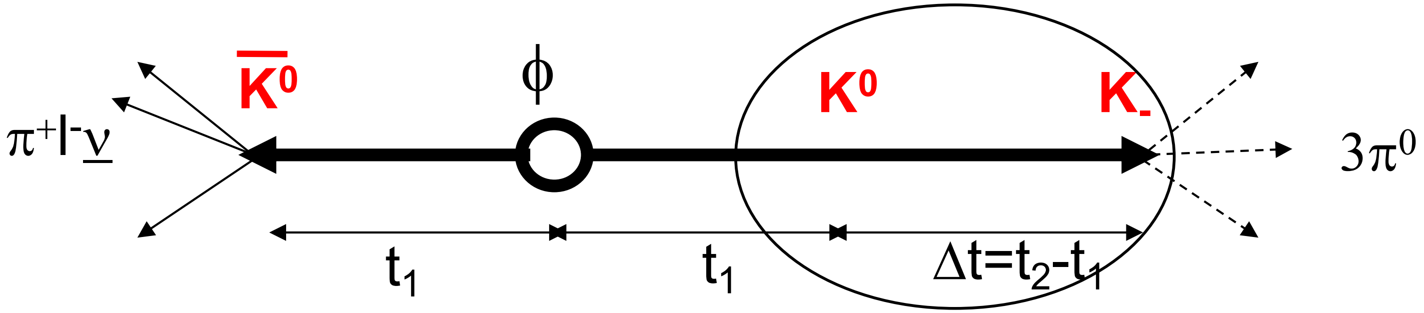


$$R_2(\Delta t) = P\left[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)\right] / P\left[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)\right]$$

Any deviation from R_2=1 constitutes a violation of T-symmetry
NPB 868 (2013) 102

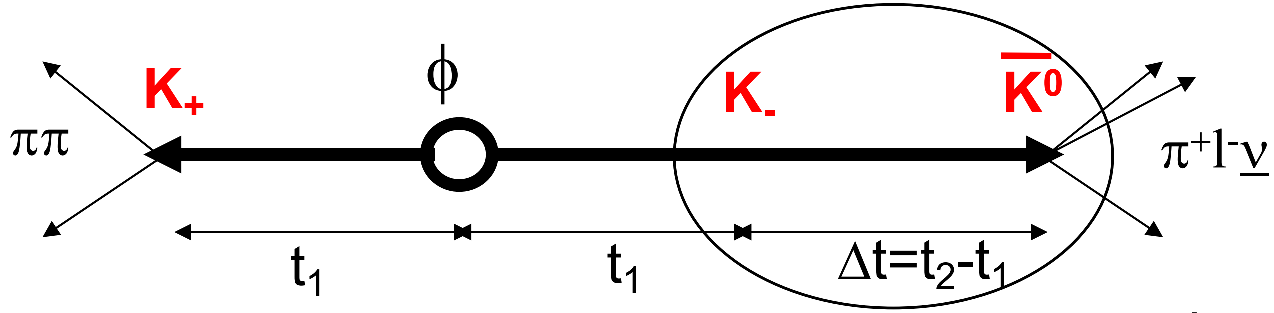
* (K_+ and K_- are CP eigenstates not to be confused with charged kaons K^+ and K^-)

CPT test in transitions



$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow \overline{K}^0$ CPT-conjugated process



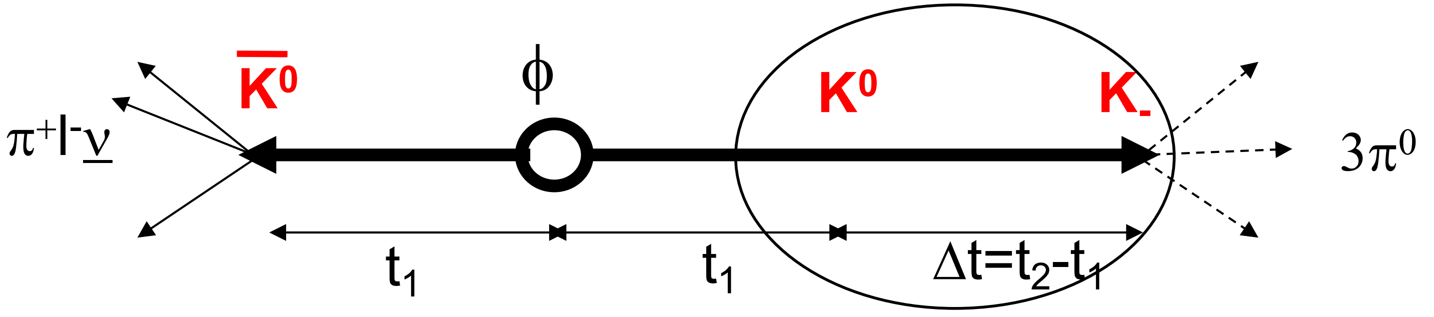
$$R_{2,\mathcal{CPT}}(\Delta t) = P\left[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)\right] / P\left[\mathrm{K}_-(0) \to \bar{\mathrm{K}}^0(\Delta t)\right]$$

Any deviation from $R_{2,CPT}$=1 constitutes a violation of CPT-symmetry

JHEP 10 (2015) 139

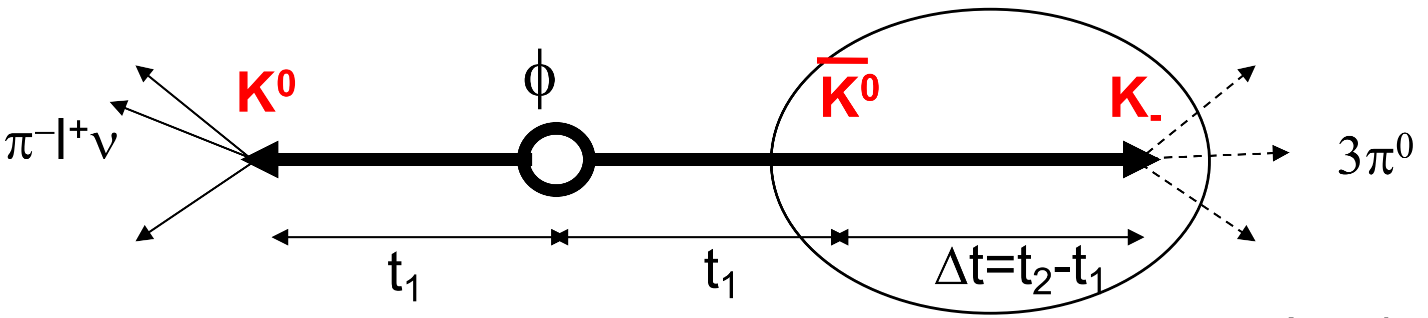
* (K_+ and K_- are CP eigenstates not to be confused with charged kaons K^+ and K^-)

CP test in transitions



$K^0 \rightarrow K_-$ reference process

$\overline{K}^0 \rightarrow K_-$ CP-conjugated process



$$R_{2,\mathrm{CP}}(\Delta t) = P\left[\mathrm{K}^0(0) \rightarrow \mathrm{K}_-(\Delta t)\right] / P\left[\overline{\mathrm{K}}^0(0) \rightarrow \mathrm{K}_-(\Delta t)\right]$$

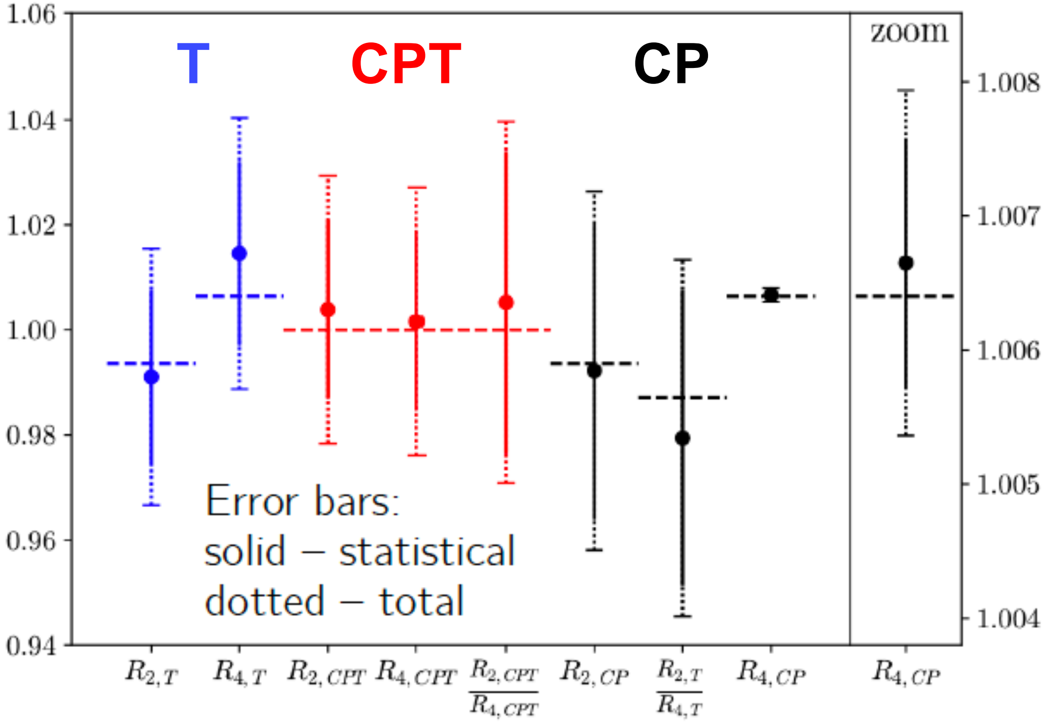
Any deviation from $R_{2,CP}$=1 constitutes a violation of CP-symmetry

* (K_+ and K_- are CP eigenstates not to be confused with charged kaons K^+ and K^-)

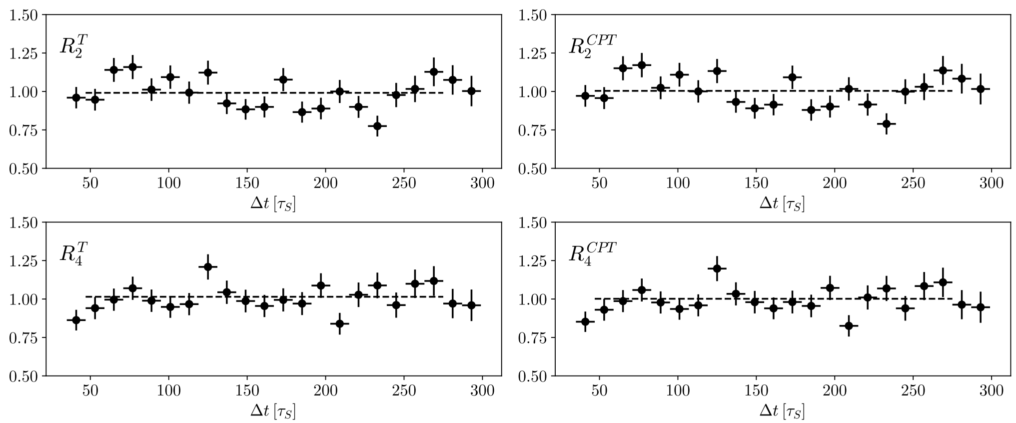
T, CP, CPT tests in neutral kaon transitions at KLOE

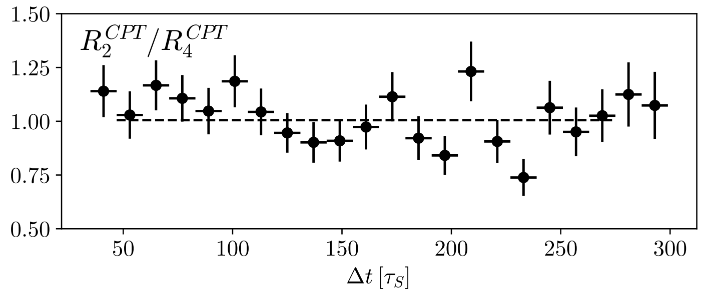
horizontal dashed lines denote expected values:
CPT invariance and TV extrapolated from observed CPV (PDG)

KLOE-2 result
PLB 845 (2023) 138164



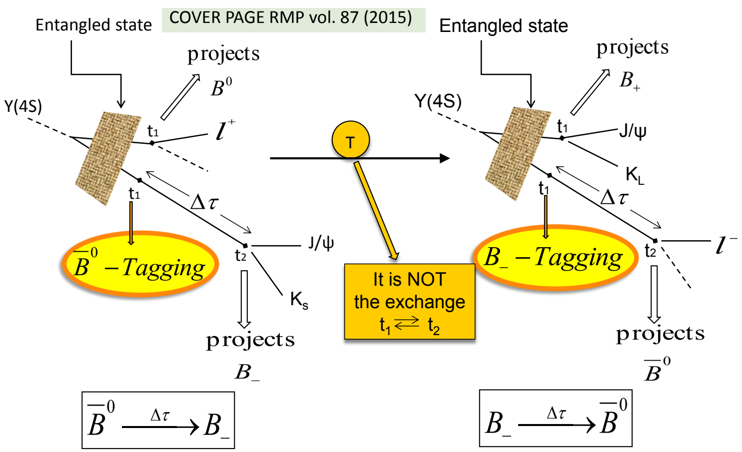
$$R_{2,\mathrm{T}} = 0.991 \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_D \ ,$$
$$R_{4,\mathrm{T}} = 1.015 \pm 0.018_{stat} \pm 0.015_{syst} \pm 0.012_D \ ,$$
$$R_{2,\mathrm{CPT}} = 1.004 \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_D \ ,$$
$$R_{4,\mathrm{CPT}} = 1.002 \pm 0.017_{stat} \pm 0.015_{syst} \pm 0.012_D \ ,$$
$$R_{2,\mathrm{CP}} = 0.992 \pm 0.028_{stat} \pm 0.019_{syst} \ ,$$
$$R_{4,\mathrm{CP}} = 1.00665 \pm 0.00093_{stat} \pm 0.00089_{syst} \ ,$$
$$DR_{\mathrm{T,CP}} = R_{2,\mathrm{T}}/R_{4,\mathrm{T}} = 0.979 \pm 0.028_{stat} \pm 0.019_{syst} \ ,$$
$$DR_{\mathrm{CPT}} = R_{2,\mathrm{CPT}}/R_{4,\mathrm{CPT}} = 1.005 \pm 0.029_{stat} \pm 0.019_{syst} \ .$$



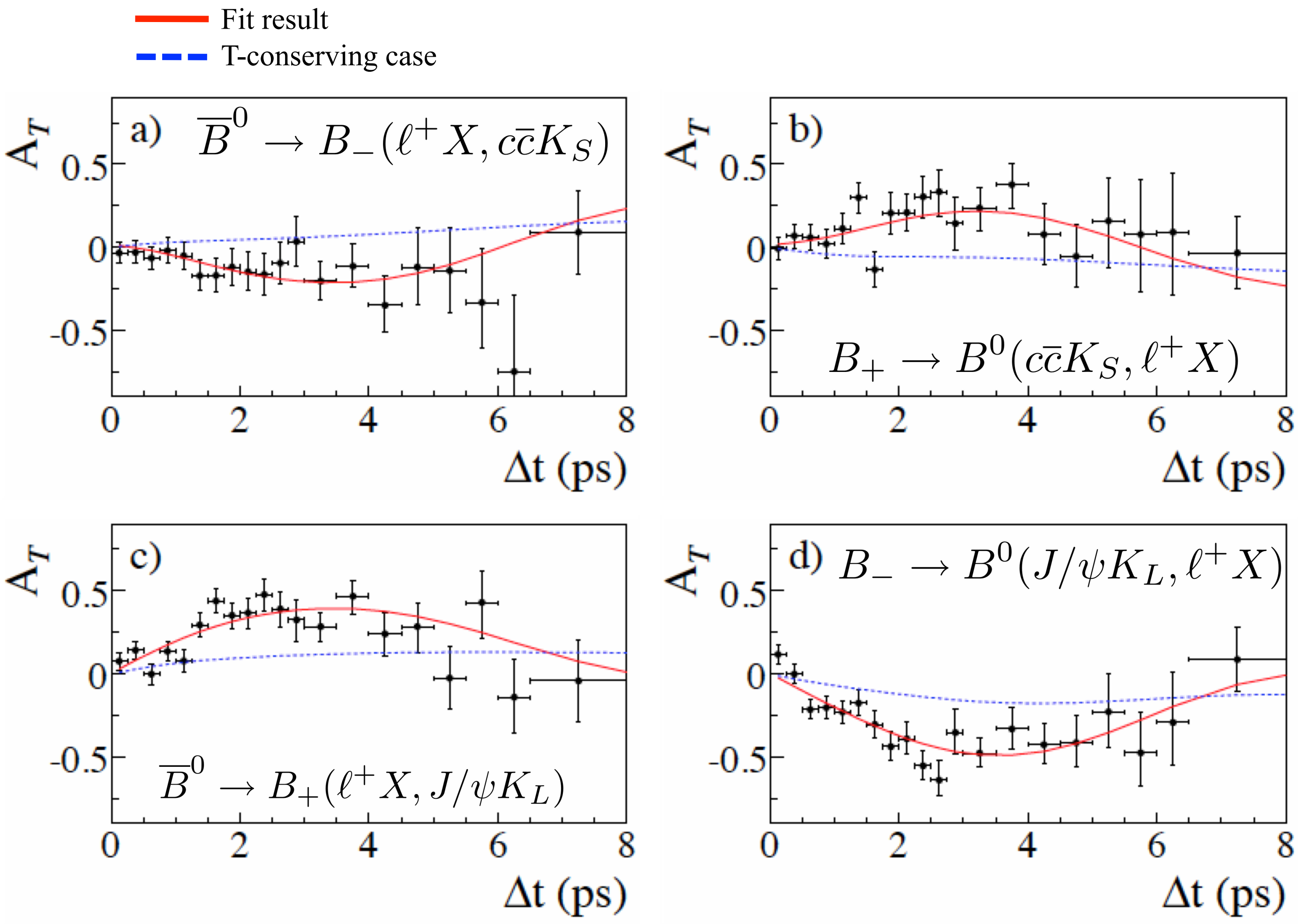


First T and CPT test in kaon transitions
First CP violation observed in $K \to K^0 / \bar{K}^0$

T violation observed in neutral B meson transitions

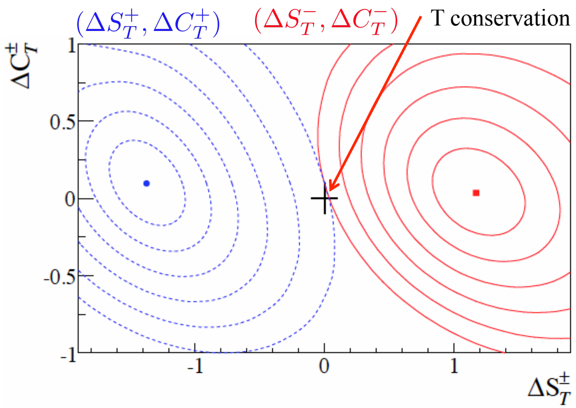


Exploiting entanglement of B meson pairs



2012 - Observation of T violation in B mesons Babar experiment (SLAC)

Fit result is 14σ from the T conserving case



Result independent from CP tests but consistent with CPT theorem

Conclusions

- Discrete symmetry tests have repeatedly changed our understanding of Nature.
- The discovery of CP violation in neutral kaons paved the way for further theoretical and experimental investigations, shaping our understanding of interactions in the Standard Model.
- CP violation discovered also in B, D meson and Λ_b baryon systems.

- T violation has been unambiguously observed in neutral B mesons.
- The entanglement of neutral K and B meson pairs produced at e^+e^- collider facilities has been demonstrated to be a key ingredient to perform clean and precise tests of T and CPT symmetries in these systems.

- Stringent limits an CPT violation have been set in the neutral K, B systems, as well as in several other systems.

- Several fundamental questions remain unanswered:
  - Why is the Universe made almost entirely of matter?
  - Is there additional CP violation beyond the Standard Model?
  - Is CPT symmetry exact?
  - Could tiny symmetry violations reveal new physics at energy scales beyond direct accelerator reach?

- The search for new sources of CP violation continues (e.g. in neutrinos), as well as new T and CPT tests, in several physical systems, including the positronium system that recently joined the “club” with stringent limits on discrete symmetry violations and featuring entangled photons.