LECTURE 2

(direct) CP violation

neutral meson mixing

measuring an oscillation frequency

CP violation

- what is it?

$$CP\text{-symmetry violation } (\cancel{CP}): \qquad P(A \to B) \neq P(\bar{A} \to \bar{B})$$

decay width: Γ [E]
cross-section: σ [L^2]

- why is it interesting?
  - big picture: matter versus anti-matter
  - small picture: precision tests of SM (electroweak symmetry breaking)

$$\boxed{A_f = \mathcal{A}(B^0 \to f) = \langle f | H_{\text{weak}} | B^0 \rangle}$$

$$= \sum_{\text{diagrams}} \text{"CKM matrix elements"} \times \langle f | \mathcal{O} | B^0 \rangle$$

$$\boxed{\bar{A}_{\bar{f}} = \mathcal{A}(\bar{B}^0 \to \bar{f}) = \langle \bar{f} | H_{\text{weak}} | \bar{B}^0 \rangle}$$

$$= \sum_{\text{diagrams}} \text{"CKM matrix elements*"} \times \langle \bar{f} | \mathcal{O} | \bar{B}^0 \rangle$$

$$A_f = \sum_{\text{diagrams}} \text{"CKM matrix elements"} \times \langle f | \mathcal{O} | B^0 \rangle$$

same size, opposite phase

same size, same phase

$$\bar{A}_{\bar{f}} = \sum_{\text{diagrams}} \text{"CKM matrix elements*"} \times \langle \bar{f} | \mathcal{O} | \bar{B}^0 \rangle$$

- from amplitudes to counting events

$$\boxed{\Gamma(i \to f) \; = \int \; |\mathcal{A}(i \to f)|^2 \; \mathrm{d(phase\ space)}}$$

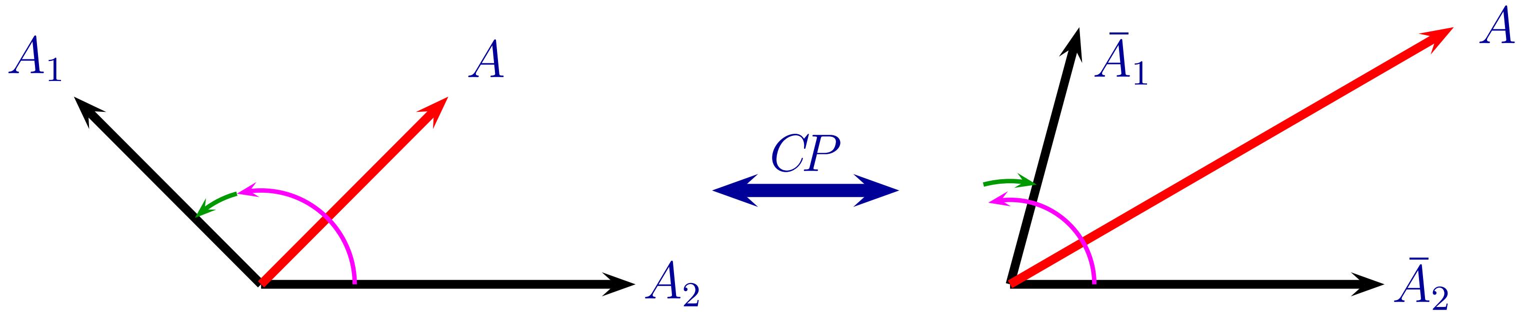
(silly representation
of Fermi's Golden Rule)

- decay width proportional to amplitude-squared

- consequence: no CP asymmetry if there is only a single 'diagram'

Interfering amplitudes

- CP violation is consequence of (at least two) interfering amplitudes:



- need both "CP-violating" and "CP-conserving" phases

$$\mathcal{A}_f \equiv \frac{N(\bar{B} \to \bar{f}) - N(B \to f)}{N(\bar{B} \to \bar{f}) + N(B \to f)} = \frac{2 \sin \Delta\phi_w \sin \Delta\phi_s}{|A_1/A_2| + |A_2/A_1| + 2 \cos \Delta\phi_w \cos \Delta\phi_s}$$

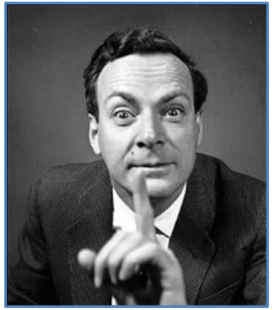
- sizable only if interfering amplitudes are of similar magnitude

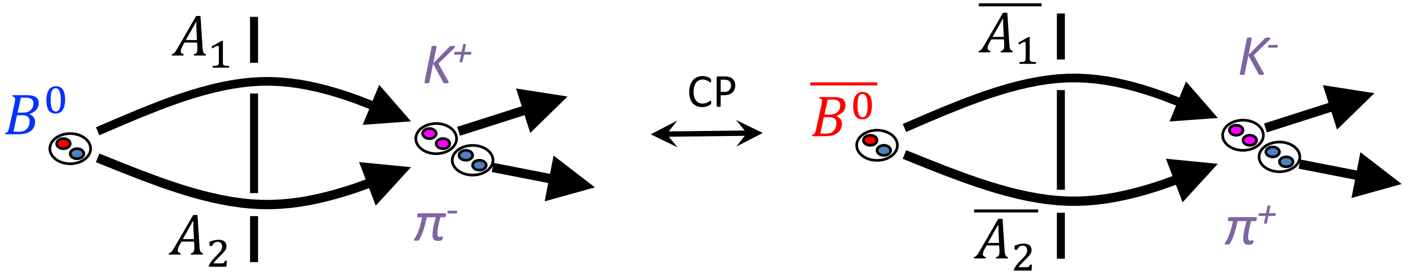
weak vs strong phases

- weak (CP-odd) phase: changes sign with CP transformation
  - only phases from Higgs-Yukawa couplings
  - called ‘weak’ because only affects (charged) weak interaction vertices

- strong (CP-even) phase: does not change sign with CP transformation
  - phases come from ‘time-evolution’
    - simplest example: $\Phi(t) = e^{-iEt}\Phi(0)$
    - same for particle and anti-particle
  - called `strong’ because in SM strong interaction generates non-trivial CP-even phases

- CP violation is a true quantum interference effect

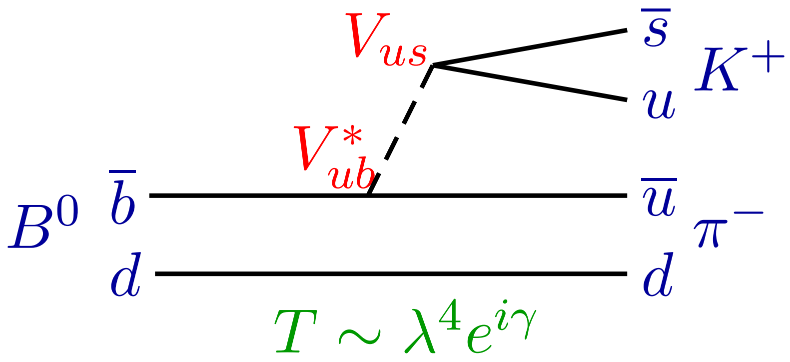


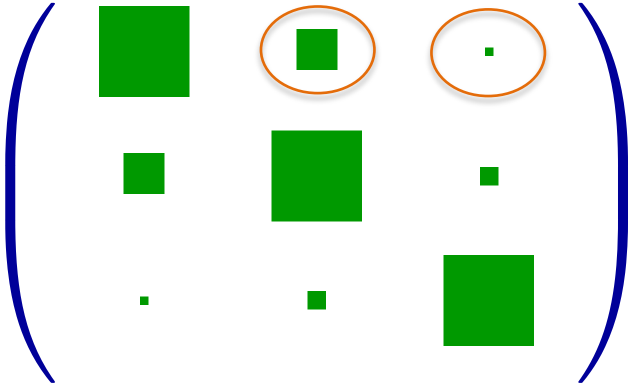


- as we shall see, there are different sources for the interference

Example: $B^0 \to K^+ \pi^-$

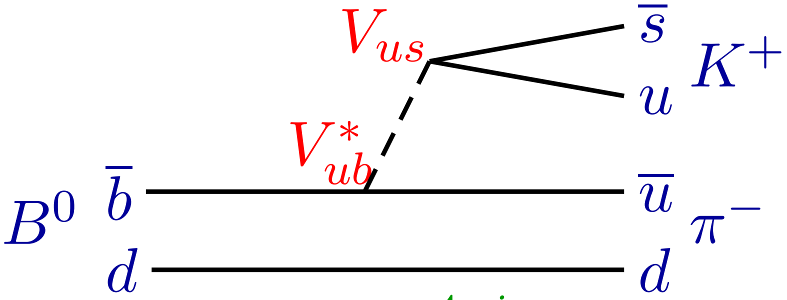
"CKM-suppressed tree-diagram"





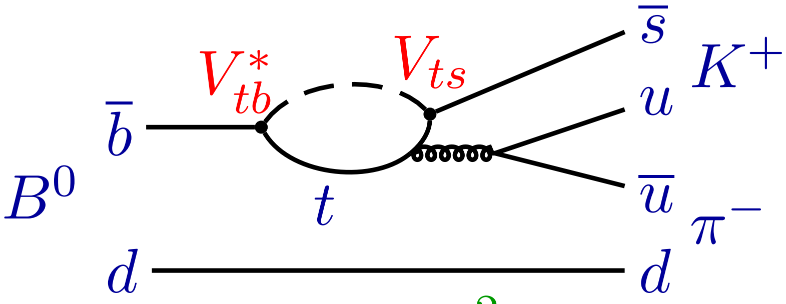
Example: $B^0 \to K^+ \pi^-$

"CKM-suppressed tree-diagram"



$T \sim \lambda^4 e^{i\gamma}$

"penguin-diagram"



$P \sim \lambda^2$

- penguin amplitude: 'loop-suppressed'
- tree amplitude: 'CKM suppressed'

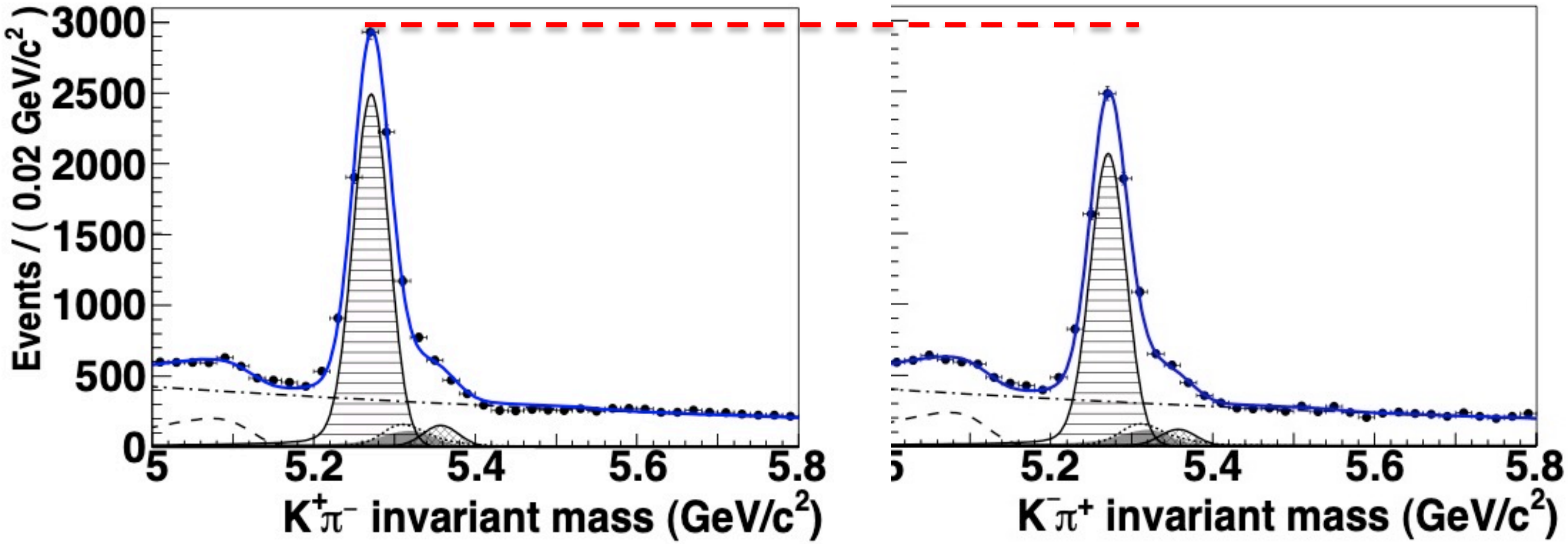
⇒ similar sized amplitudes with different weak phases!

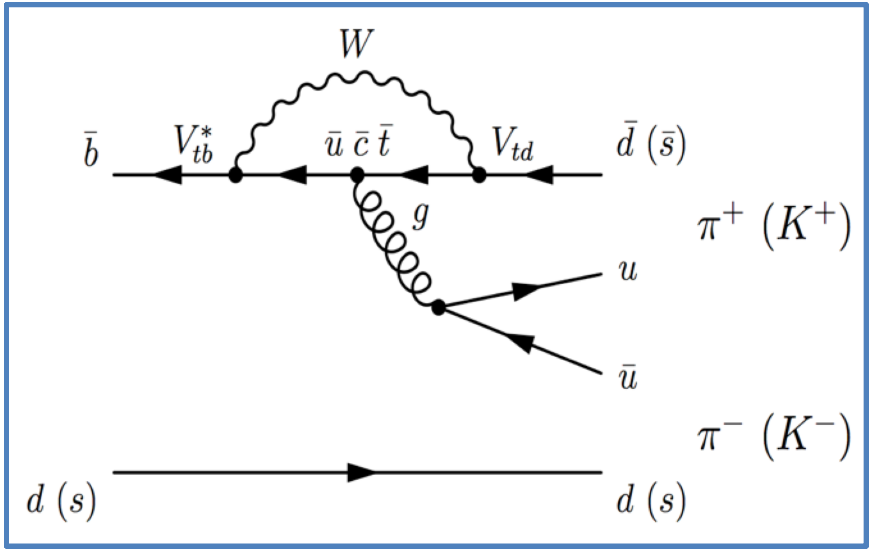
- SM computation difficult because of 'hadronic stuff': A ~ -0.1

Direct CP-violation in B->Kpi

$B^0 \rightarrow K^+\pi^-$ decays

anti-$B^0 \rightarrow K^-\pi^+$ decays




W
$\bar{b}$
V_{tb}^{*}
$\bar{u}\ \bar{c}\ \bar{t}$
V_{td}
$\bar{d}\ (\bar{s})$
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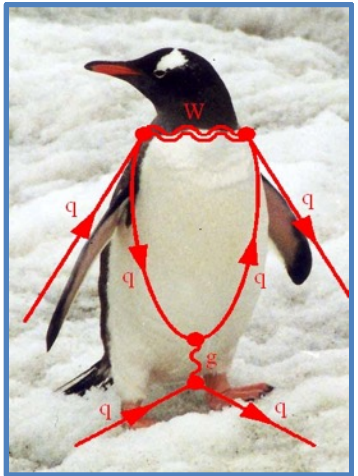
$\bar{u}$
$\pi^{-}\ (K^{-})$
$d\ (s)$
$d\ (s)$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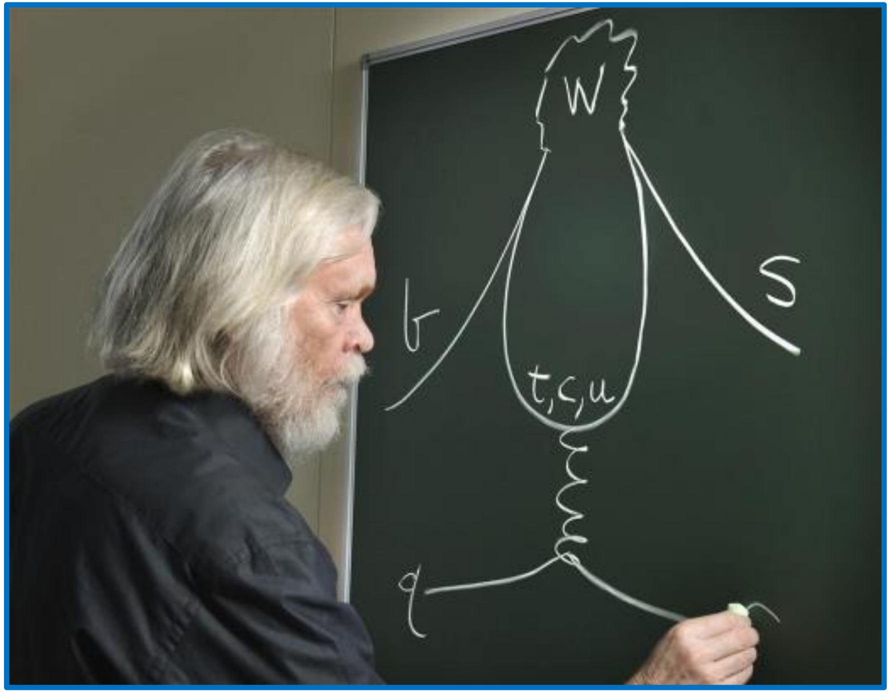
W
b
S
t,c,u
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Neutral meson mixing

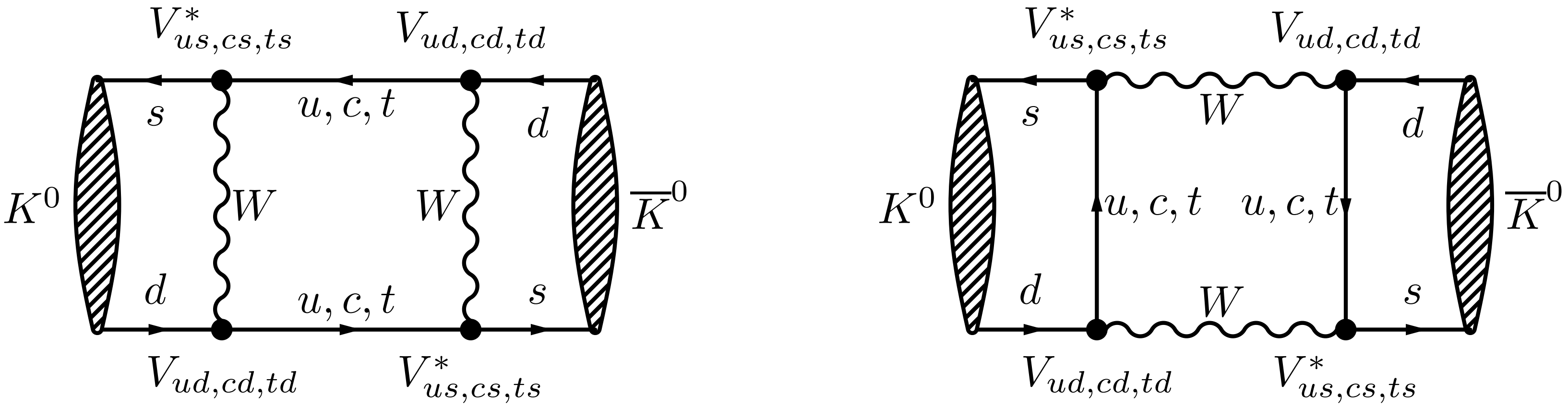
- SM has small set of ‘stable’ neutral mesons:

name	quark content	mass/MeV	lifetime/ps
K^0	$d\bar{s}$	498	180
D^0	$c\bar{u}$	1865	0.41
B^0	$d\bar{b}$	5280	1.5
B_s^0	$s\bar{b}$	5367	1.5

- meson and anti-meson state ‘degenerate’ if only strong+EM
  - weak interaction ‘mixes’ the meson and anti-meson states
  - removes degeneracy
  - leads to interesting mixing and CPV phenomenology

Mixing diagram

- leading order diagrams for neutral meson mixing:



- sensitive to CP-violating phases
- sensitive to virtual quark masses

Mixing formalism

- consider a two-component state

$$\boxed{|\psi(t)\rangle \;=\; a(t)\left|B^0\right\rangle + b(t)\left|\bar{B}^0\right\rangle}$$

$\boxed{\text{eigenstates of } H_{\text{strong}} + H_{\text{em}}}$

- time-evolution follows from Schrodinger equation

$$\boxed{i\hbar\frac{\mathrm{d}\psi}{\mathrm{d}t} \;=\; H\psi}$$

what is H?

Mixing formalism

- without weak interaction, solution is, in ”rest frame” (E=m)

$$H \rightarrow \begin{pmatrix} m & 0 \\ 0 & m \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = e^{-imt} \begin{pmatrix} a_0 \\ b_0 \end{pmatrix}$$

degenerate states with equal mass

Mixing formalism

- without weak interaction, solution is, in ”rest frame” (E=m)

$$H \to \begin{pmatrix} m & 0 \\ 0 & m \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = e^{-imt} \begin{pmatrix} a_0 \\ b_0 \end{pmatrix}$$

- with weak interaction
  - states mix
  - states ‘decay’ → described by ‘open system Hamiltonian’

$$\boxed{H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}}$$

open system → not Hermitian H

reflects transitions into Hilbert space of final states

$$H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = M - \frac{i}{2}\Gamma$$

$$\boxed{\begin{aligned} M &\equiv \tfrac{1}{2}\left(H + H^\dagger\right) \\ \Gamma &\equiv i\left(H - H^\dagger\right) \end{aligned}}$$

Hermitian matrices

$$P(t) = \left|e^{-i(M-i\Gamma/2)t}\right|^2 = e^{-\Gamma t}$$

"exponential decay

$$H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}$$

- CPT invariance: M_{11}=M_{22} and $\Gamma_{11} = \Gamma_{22}$

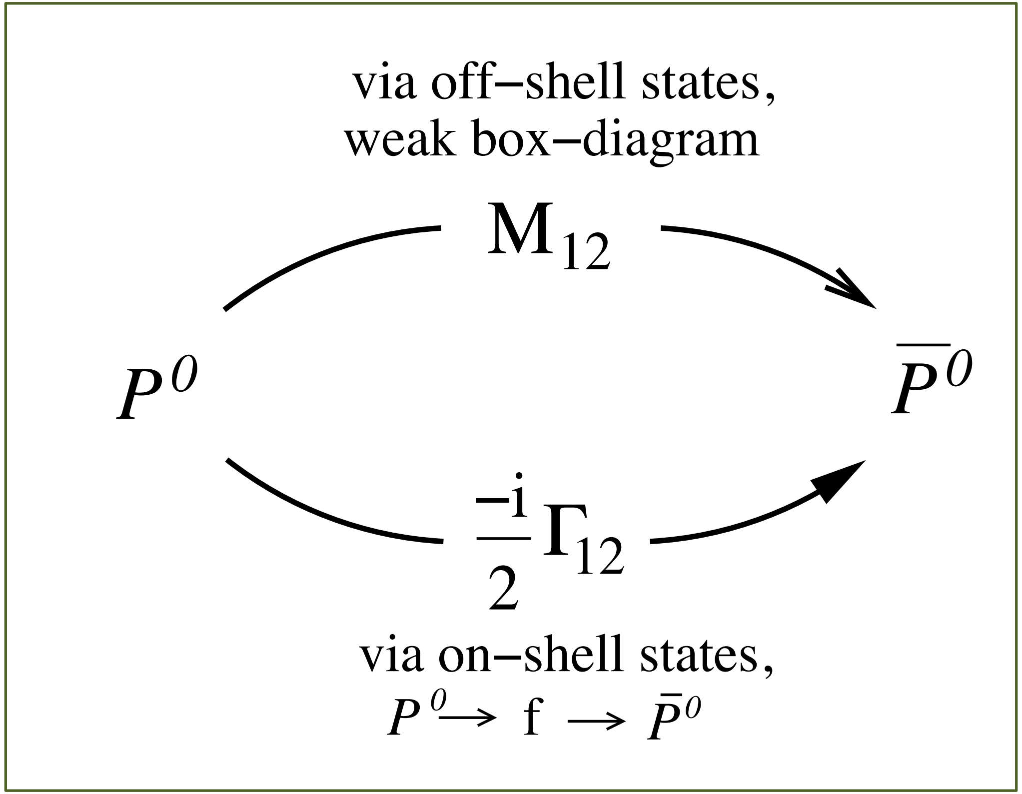
→ 6 real parameters:

$$\boxed{M_{11} \quad \Gamma_{11} \quad |M_{12}| \quad |\Gamma_{12}| \quad \phi_M \equiv \arg(M_{12}) \quad \phi_\Gamma \equiv \arg(\Gamma_{12})}$$

from full Hamiltonian

$$M_{11} \gg \Gamma_{11}, |M_{12}|, |\Gamma_{12}|$$

Interpretation of off-diagonal elements



interference!

diagonalize: mass eigen values

- compute eigenvalues of H (details: your homework)

$$\boxed{\mu_{\mathrm{H,L}} = M_{11} - \frac{i}{2}\Gamma_{11} \pm \sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}}$$

H: "heavy"
L: "light"

- mass and width of the mass eigenstates are

$$m_L \equiv \mathrm{Re}\,(\mu_L) \qquad \Gamma_L \equiv -2\,\mathrm{Im}\,(\mu_L)$$

$$m_H \equiv \mathrm{Re}\,(\mu_H) \qquad \Gamma_H \equiv -2\,\mathrm{Im}\,(\mu_H)$$

- mass and width usually expressed in terms of average and difference

$$
\begin{aligned}
m &\equiv (m_H + m_L)/2 &&= M_{11} \\
\Gamma &\equiv (\Gamma_H + \Gamma_L)/2 &&= \Gamma_{11} \\
\Delta m &\equiv m_H - m_L &&= 2\,\mathrm{Re}\left(\sqrt{\left(M_{12} - \tfrac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \tfrac{i}{2}\Gamma_{12}^*\right)}\right) \\
\Delta\Gamma &= \Gamma_H - \Gamma_L &&= -4\,\mathrm{Im}\left(\sqrt{\left(M_{12} - \tfrac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \tfrac{i}{2}\Gamma_{12}^*\right)}\right)
\end{aligned}
$$

- mass and width usually expressed in terms of average and difference

$$m = M_{11}$$

$$\Gamma = \Gamma_{11}$$

hard to compute, but we can 'measure' them

$$\Delta m = 2\,\mathrm{Re}\left(\sqrt{\left(M_{12} - \tfrac{i}{2}\Gamma_{12}\right)\left(M_{12}^{*} - \tfrac{i}{2}\Gamma_{12}^{*}\right)}\right)$$

$$\Delta\Gamma = -4\,\mathrm{Im}\left(\sqrt{\left(M_{12} - \tfrac{i}{2}\Gamma_{12}\right)\left(M_{12}^{*} - \tfrac{i}{2}\Gamma_{12}^{*}\right)}\right)$$

also hard to compute, but this is where the interesting physics is!

mass eigenstates

- define ‘light’ and ‘heavy’ mass states

$$\boxed{\begin{aligned} |B_L\rangle &= p\,|B^0\rangle + q\,|\overline{B}^0\rangle \\ |B_H\rangle &= p\,|B^0\rangle - q\,|\overline{B}^0\rangle \end{aligned}}$$

normalization:

$$|p|^2 + |q|^2 = 1$$

- these are eigenstates of H if

$$\boxed{\frac{p}{q} = \sqrt{\frac{M_{12} - \frac{i}{2}\Gamma_{12}}{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}}.}$$

- common phase of p and q can be absorbed in states
- the physical parameters are phase and magnitude of p/q

CP violation in mixing

- suppose $\arg(\Gamma_{12}) = \arg(M_{12}) \equiv \phi_M$

$$\frac{p}{q} = \sqrt{\frac{M_{12} - i\Gamma_{12}/2}{M_{12}^* - i\Gamma_{12}^*/2}} \longrightarrow e^{i\phi_M}$$

- we shall later see that $|q\,/\,p\,| \neq 1$ leads to "<u>CP violation in mixing</u>"

- in case of no CPV in mixing, we have

$$\boxed{\Delta m \stackrel{CP}{=} 2\,|M_{12}|} \qquad \boxed{\Delta\Gamma \stackrel{CP}{=} |\Gamma_{12}|}$$

CP eigenstates

- flavour eigenstates

$$|K^0\rangle = |d\bar{s}\rangle$$

$$|\bar{K}^0\rangle = |\bar{d}s\rangle$$

- CP eigenstates

$$|K_{\text{even}}\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right)$$

$$|K_{\text{odd}}\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right)$$

- if we can produce an 'even' (or 'odd) state, then without CP violation, it will remain even (or odd)

epsilon

- alternative parametrization, traditional for Kaon system

$$\frac{p}{q} = \frac{1+\epsilon}{1-\epsilon}$$

CPV in mixing: $\mathrm{Re}(\epsilon) \neq 0$

- mass eigenstates expressed in terms of the CP-even and CP-odd states

$$|K_{\text{light}}\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}} \left[|K_{\text{even}}\rangle + \epsilon \, |K_{\text{odd}}\rangle \right]$$

$$|K_{\text{heavy}}\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}} \left[|K_{\text{odd}}\rangle + \epsilon \, |K_{\text{even}}\rangle \right]$$

in practice,
epsilon turns out to be small

summary of definition of states

- flavour eigenstates: can be produced in hadronization process

$$\left|K^0\right\rangle = |d\bar{s}\rangle$$
$$\left|\bar{K}^0\right\rangle = \left|\bar{d}s\right\rangle$$

- CP eigenstates: states with definite CP

$$|K_{\text{even}}\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\bar{K}^0\right\rangle\right)$$
$$|K_{\text{odd}}\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle\right)$$

- mass eigenstates: eigenstates of ‘open’ Hamiltonian

$$\begin{aligned} |K_{\text{light}}\rangle &= p\left|K^0\right\rangle + q\left|\bar{K}^0\right\rangle &= \frac{1}{\sqrt{1+|\epsilon|^2}}\Big[|K_{\text{even}}\rangle + \epsilon\,|K_{\text{odd}}\rangle\Big] \\ |K_{\text{heavy}}\rangle &= p\left|\bar{K}^0\right\rangle - q\left|K^0\right\rangle &= \frac{1}{\sqrt{1+|\epsilon|^2}}\Big[|K_{\text{odd}}\rangle + \epsilon\,|K_{\text{even}}\rangle\Big] \end{aligned}$$

K-short and K-long

- without CPV in mixing, mass eigenstates correspond to "CP eigenstates"

$$\boxed{\begin{aligned} |K_{\text{light}}\rangle &= \sqrt{\tfrac{1}{2}}\,\left(|K^0\rangle + |\bar{K}^0\rangle\right) \equiv |K_{\text{even}}\rangle \\ |K_{\text{heavy}}\rangle &= \sqrt{\tfrac{1}{2}}\,\left(|K^0\rangle - |\bar{K}^0\rangle\right) \equiv |K_{\text{odd}}\rangle \end{aligned}}$$

CP-even

CP-odd

- as a result, the K^0 decays are predominantly

$$\boxed{\begin{aligned} K_{\text{light}} &\to \pi\pi \\ K_{\text{heavy}} &\to \pi\pi\pi \end{aligned}}$$

"K-short"

much less phase space:
much longer lifetime!

$$\Gamma_{\text{light}} \gg \Gamma_{\text{heavy}}$$

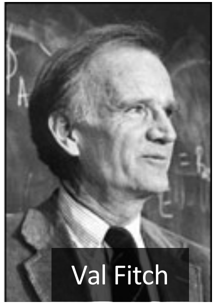
"K-long"

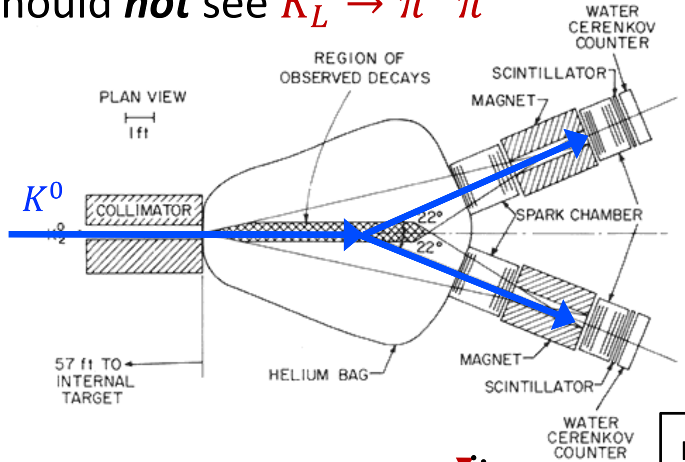
Discovery of CP-Violation

- Create a pure K_L beam ("wait" for K_S to decay)
- If CP is conserved, should ***not*** see $K_L \to \pi^+\pi^-$

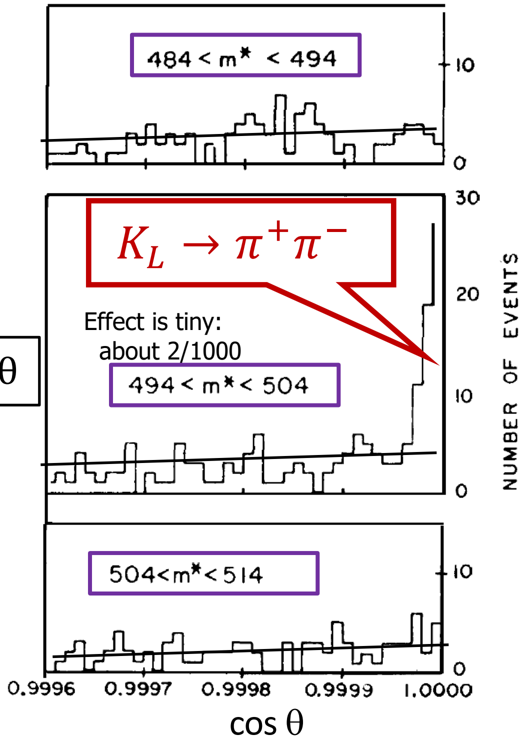
K_S: Short-lived is CP even:
$K_1^0 \to \pi^+\pi^-$ (fast)
K_L: Long-lived is CP odd:
$K_2^0 \to \pi^+\pi^-\pi^0$ (slow)


James Cronin


Val Fitch

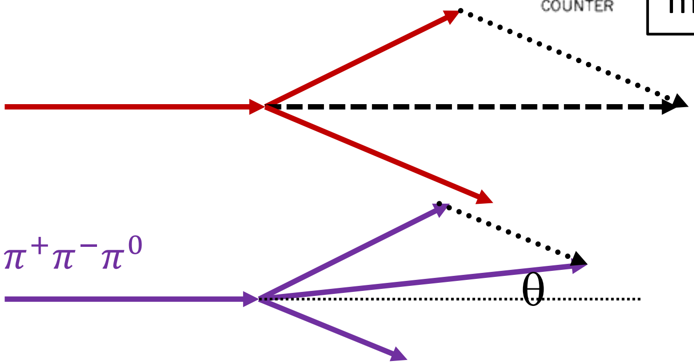


mass, θ



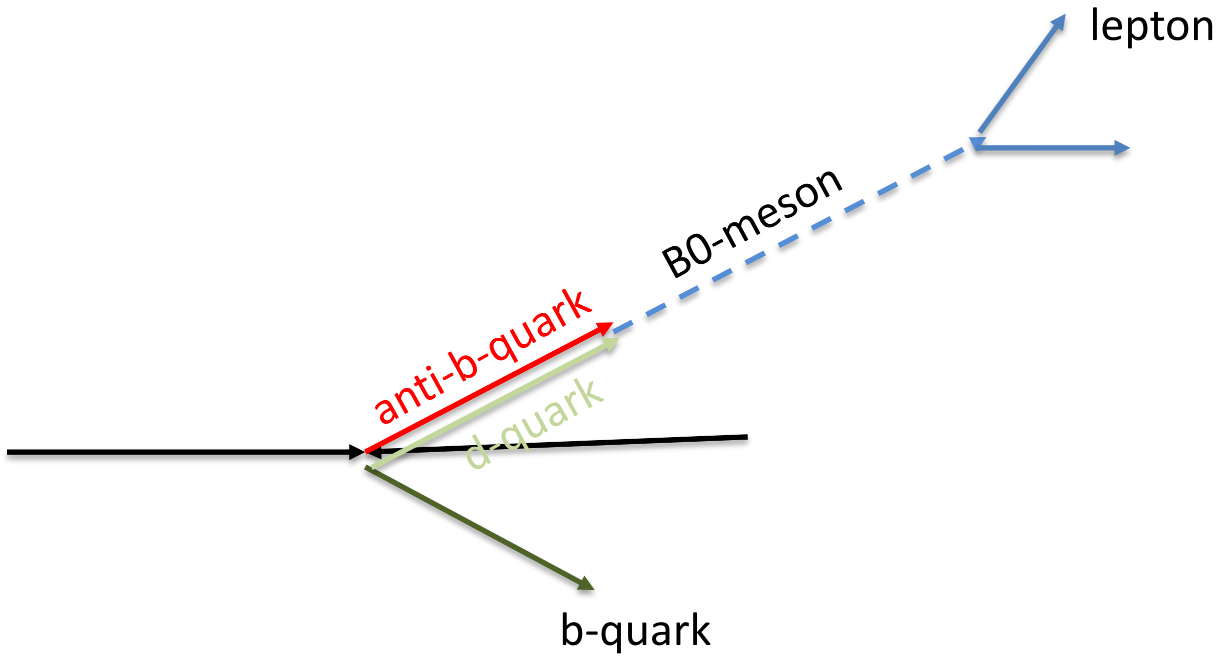
Signal: $K_L \to \pi^+\pi^-$

Background: $K_L \to \pi^+\pi^-\pi^0$



Time evolution

- production happens through flavour eigenstates (strong interaction)
- detection (usually) also happens through flavour eigenstates (EM interaction)
- in between: propagation of mass eigenstates



Time-evolution

- time-evolution of *mass eigenstates* follows from SE:

$$\boxed{|B_\mathrm{L}(t)\rangle \;=\; e^{-i\,\mu_\mathrm{L}\,t}\,|B_\mathrm{L}\rangle \qquad\qquad |B_\mathrm{H}(t)\rangle \;=\; e^{-i\,\mu_\mathrm{H}\,t}\,|B_\mathrm{H}\rangle}$$

eigenvalue of ‘open’ Hamiltonian

- remember: mu is complex, so this includes the decay:

$$\boxed{\mu_L \;\equiv\; m_L - \frac{i}{2}\Gamma_L}$$

oscillation

exponential decay

Time-evolution

- time-evolution of *mass eigenstates* follows from SE:

$$|B_{\mathrm{L}}(t)\rangle \;=\; e^{-i\,\mu_{\mathrm{L}}\,t}\,|B_{\mathrm{L}}\rangle \qquad\qquad |B_{\mathrm{H}}(t)\rangle \;=\; e^{-i\,\mu_{\mathrm{H}}\,t}\,|B_{\mathrm{H}}\rangle$$

eigenvalue of ‘open’ Hamiltonian

- now consider time-evolution of *flavour eigenstates*

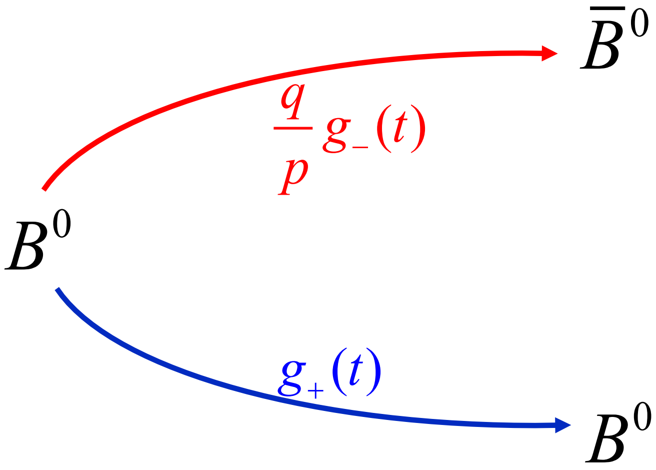
$$\begin{aligned} |B_{\mathrm{L}}\rangle &= p\,|B^0\rangle + q\,|\bar{B}^0\rangle \\ |B_{\mathrm{H}}\rangle &= p\,|B^0\rangle - q\,|\bar{B}^0\rangle \end{aligned} \quad \Rightarrow \quad \begin{aligned} |B^0\rangle &= \frac{1}{p}\left(|B_{\mathrm{L}}\rangle + |B_{\mathrm{H}}\rangle\right) \\ |\bar{B}^0\rangle &= \frac{1}{q}\left(|B_{\mathrm{L}}\rangle - |B_{\mathrm{H}}\rangle\right) \end{aligned}$$

Time-evolution

- after doing the math, find that for state *produced as* B^0

$$\left|B^0(t)\right\rangle \;=\; g_+(t)\,\left|B^0\right\rangle \;+\; \frac{q}{p}\,g_-(t)\,\left|\bar{B}^0\right\rangle$$

$$\left|\bar{B}^0(t)\right\rangle \;=\; g_+(t)\,\left|\bar{B}^0\right\rangle \;+\; \frac{p}{q}\,g_-(t)\,\left|B^0\right\rangle$$



with

$$g_\pm(t) \;=\; \frac{1}{2}\,\left(\,e^{-i\,\mu_{\mathrm{L}}\,t} \;\pm\; e^{-i\,\mu_{\mathrm{H}}\,t}\,\right)$$

Mixing ‘probability’

- mixing probability:

$$\Gamma(B^0 \to B^0) \propto \left|\langle B^0 | B^0(t)\rangle\right|^2 = |g_+(t)|^2$$

$$\Gamma(\bar{B}^0 \to \bar{B}^0) \propto \left|\langle B^0 | B^0(t)\rangle\right|^2 = |g_+(t)|^2$$

$$\Gamma(B^0 \to \bar{B}^0) \propto \left|\langle B^0 | B^0(t)\rangle\right|^2 = |g_-(t)|^2 \left|\frac{q}{p}\right|^2$$

$$\Gamma(\bar{B}^0 \to B^0) \propto \left|\langle B^0 | B^0(t)\rangle\right|^2 = |g_-(t)|^2 \left|\frac{p}{q}\right|^2$$

CP violation in mixing:

$$\Gamma(B^0 \to \bar{B}^0) \neq \Gamma(\bar{B}^0 \to B^0)$$

- what is $\left|g_\pm(t)\right|^2$?

Mixing probability

- after some algebra find

$$|g_\pm(t)|^2 = \frac{e^{-\Gamma t}}{2}\left[\cosh\frac{\Delta\Gamma t}{2} \pm \cos\Delta m t\right]$$

exponential decay

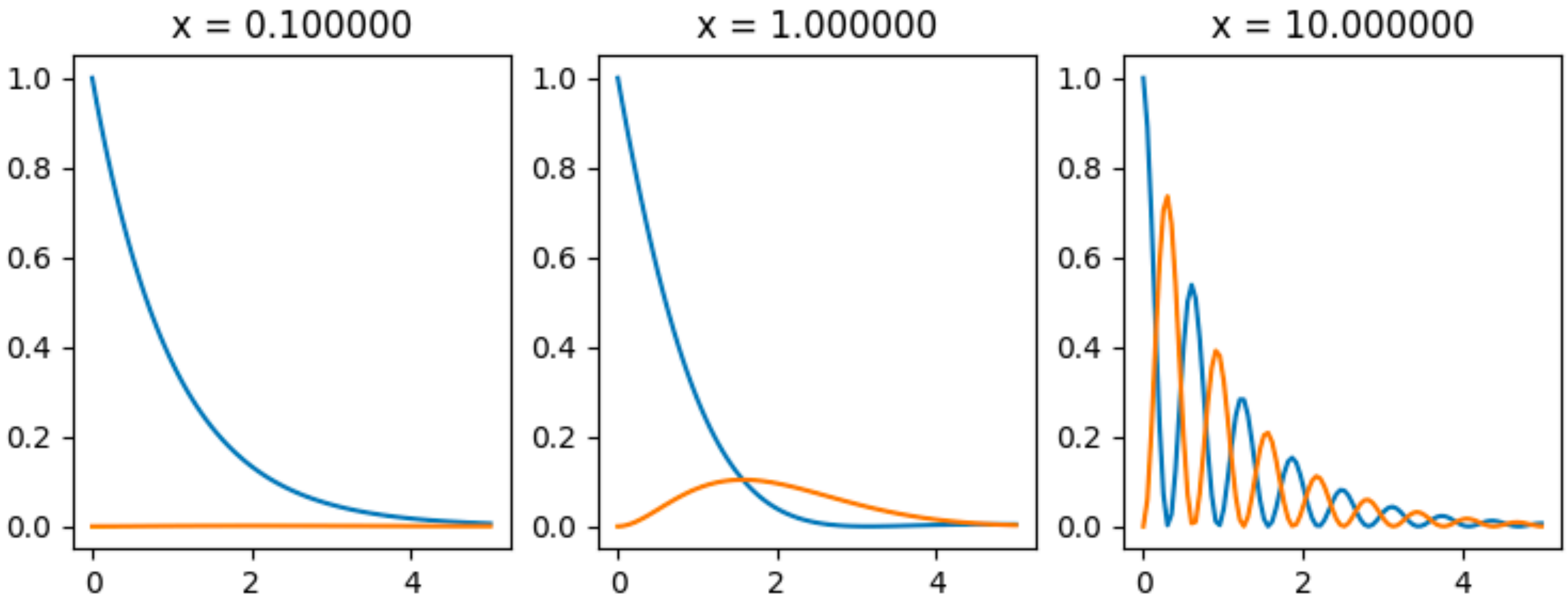
oscillation with period $2\pi/\Delta m$

- in the B_d^0 system, $\Delta\Gamma \ll \Gamma$, giving for the ‘mixing asymmetry’

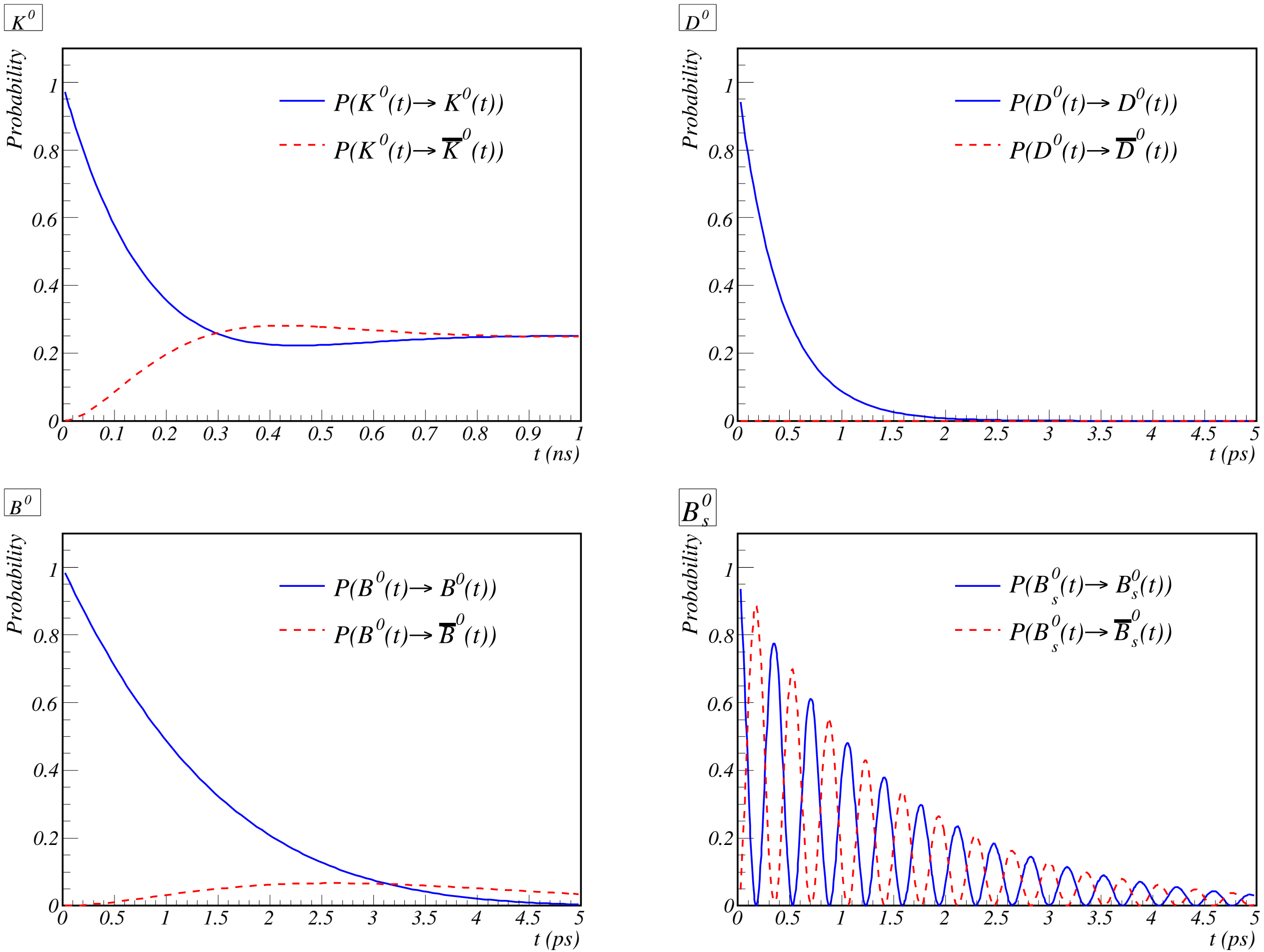
$$\boxed{A_{\text{mix}}(t) \equiv \frac{N(\text{flavour didn't change}) - N(\text{flavour changed})}{N(\text{flavour didn't change}) + N(\text{flavour changed})} = \frac{1}{2}\left(1 + \cos(\Delta m\, t)\right)}$$

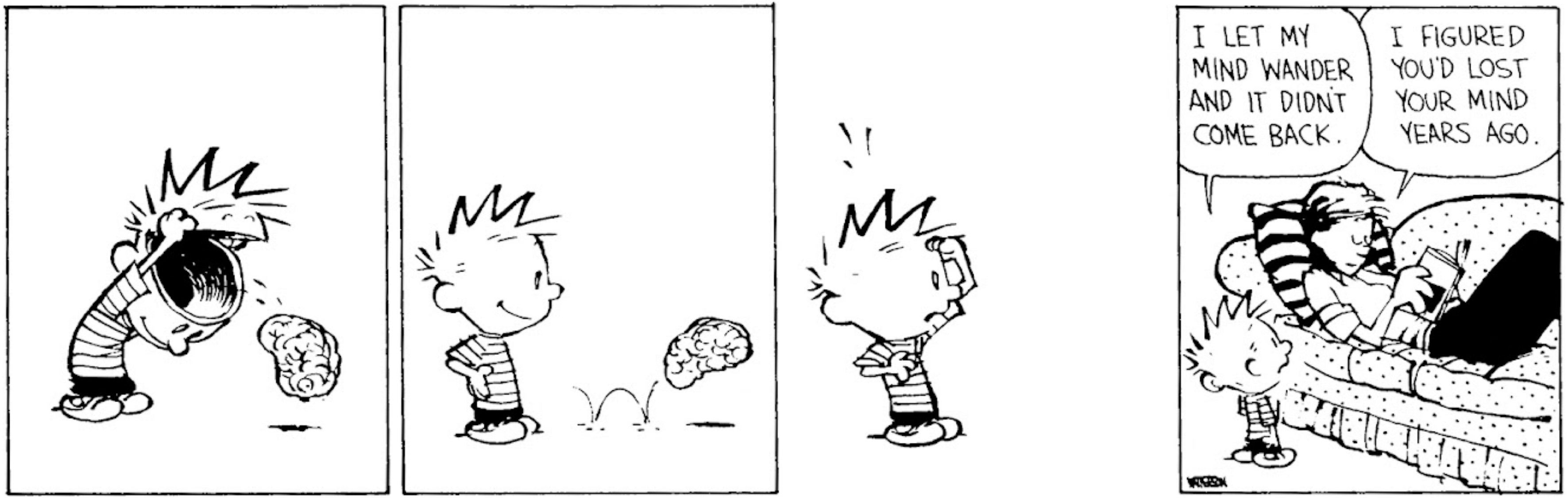
Time-evolution

to characterize time-behaviour define $x = \Delta m/\Gamma$



	$<\tau>$ [ps]	Δm [hbar/ps]
K^0	180	0.005
D^0	0.41	~0.01
B^0	1.5	0.507
B_s^0	1.5	17.8





I LET MY MIND WANDER AND IT DIDN'T COME BACK.
I FIGURED YOU'D LOST YOUR MIND YEARS AGO.

Measuring the oscillation frequency

B^0 produced in flavour eigenstate at t'=0

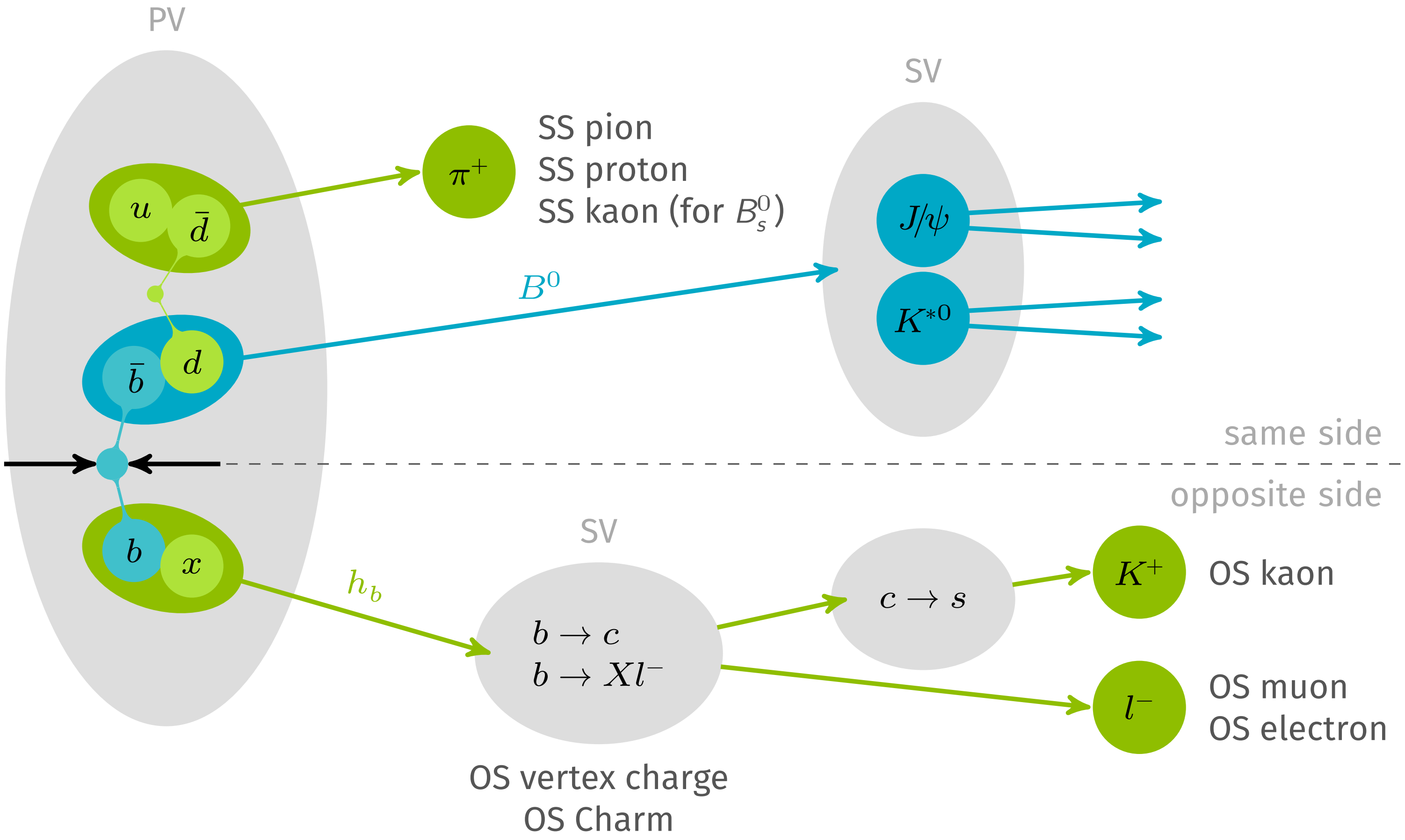
B^0 decays to flavour eigenstate at t'=t

B^0 oscillates

$$\boxed{A_{\mathrm{mix}}(t) \equiv \frac{N(\text{flavour didn't change}) - N(\text{flavour changed})}{N(\text{flavour didn't change}) + N(\text{flavour changed})} = \frac{1}{2}\left(1 + \cos(\Delta m\, t)\right)}$$

- we can identify flavour at decay by looking at final state
- but how do we know the flavour at production?

Flavour tagging



Flavour tagging

two different inputs:

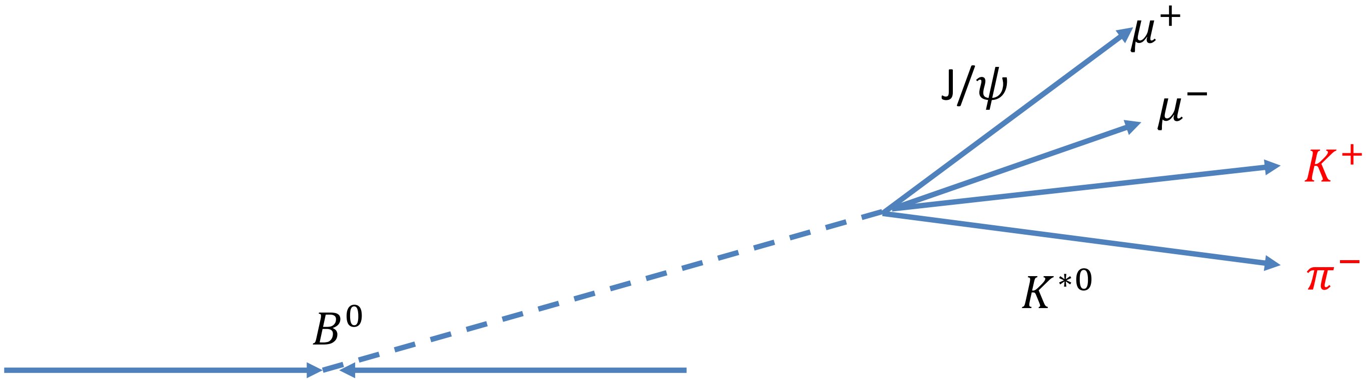
1. “opposite-side flavour tagging”
   - measure the flavour of the other b-quark in the event
   - at production, it has the opposite charge

2. “same-side flavour tagging”
   - measure correlation with other particles during hadronization phase
   - only available at LHC (not at B-factories)

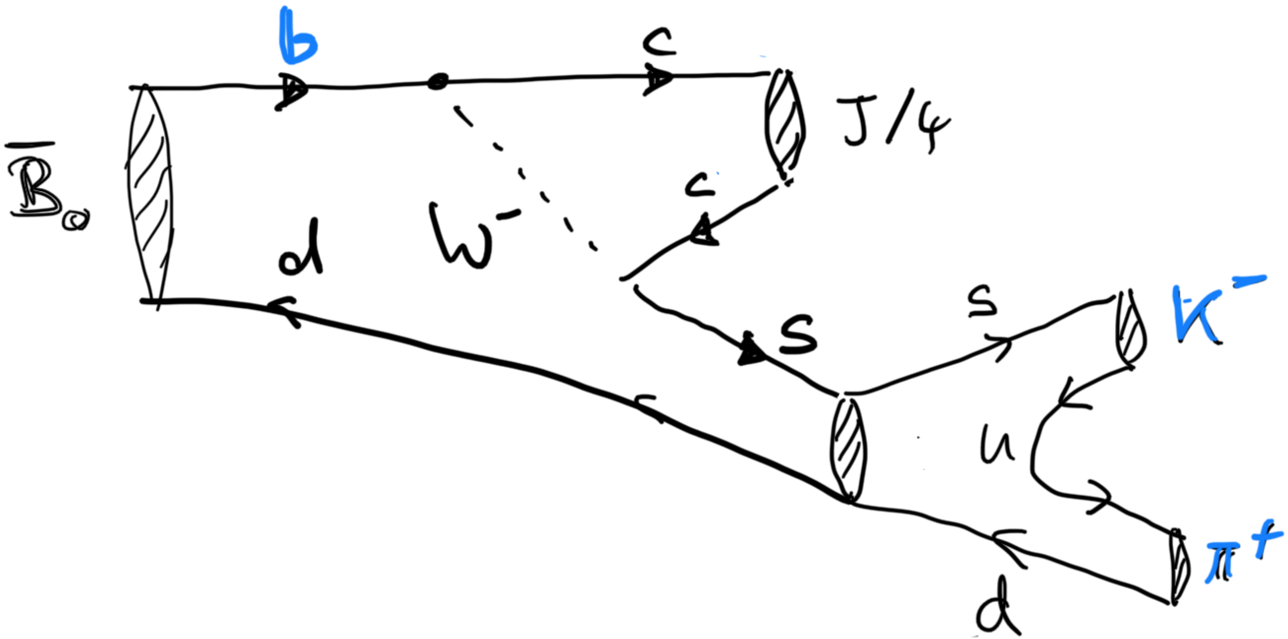
no perfect method: all information combined in MV classifier

For the exercise

- in the exercise we will measure Δm_d on a sample of $B^0 \to \psi K^{*0}$ events



The 'Feynman diagram'



- charge of the Kaon is related to the *flavour of the B at decay*
- in the ntuple, B flavour at decay is represented by the variable ***pid***

mistag rate

- flavour tag determines *B flavour at production*, but it makes errors:
  - oscillations of tag side B
  - picked wrong OS kaon/lepton
  - picked wrong SS pion

- output of flavour tagger in ntuple is
  - **q**: flavour of B
  - **eta**: estimate of mistag rate

$$\boxed{\begin{aligned}\text{Prob(right tag)} &= (1-\eta)\\ \text{Prob(tag wrong)} &= \eta\end{aligned}}$$

Dilution from mistag rate

- tagging errors lead to a 'dilution' of observed asymmetry

- perfect tagging:

$$\boxed{A_{\text{mix}}(t) \;\equiv\; \frac{N(\text{flavour didn't change}) - N(\text{flavour changed})}{N(\text{flavour didn't change}) + N(\text{flavour changed})} \;=\; \frac{1}{2}\,(\,1 + \cos(\Delta m\; t)\,)}$$

- tagging with mistag rate η:

$$\boxed{A^{\text{obs}}_{\text{mix}}(t) \;=\; (1-2\eta)\,\frac{1}{2}\,(\,1 + \cos(\Delta m\; t)\,)}$$

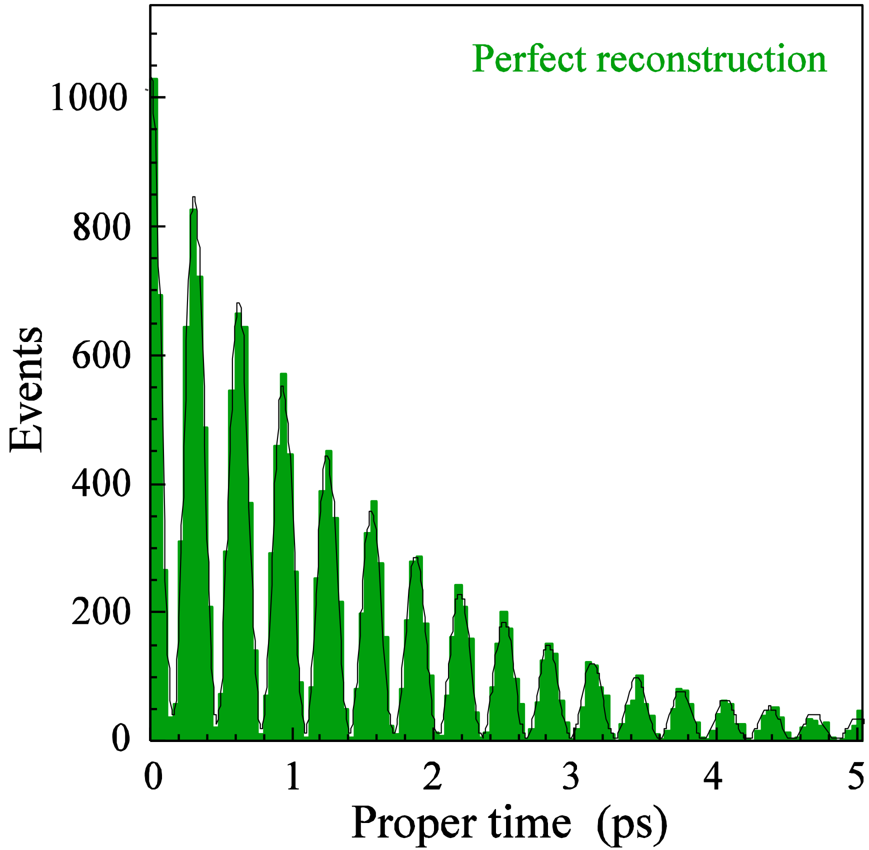
"dilution factor:" $\boxed{D^{\text{tag}} \;=\; (1-2\eta)}$

Asymmetry dilution due to resolution

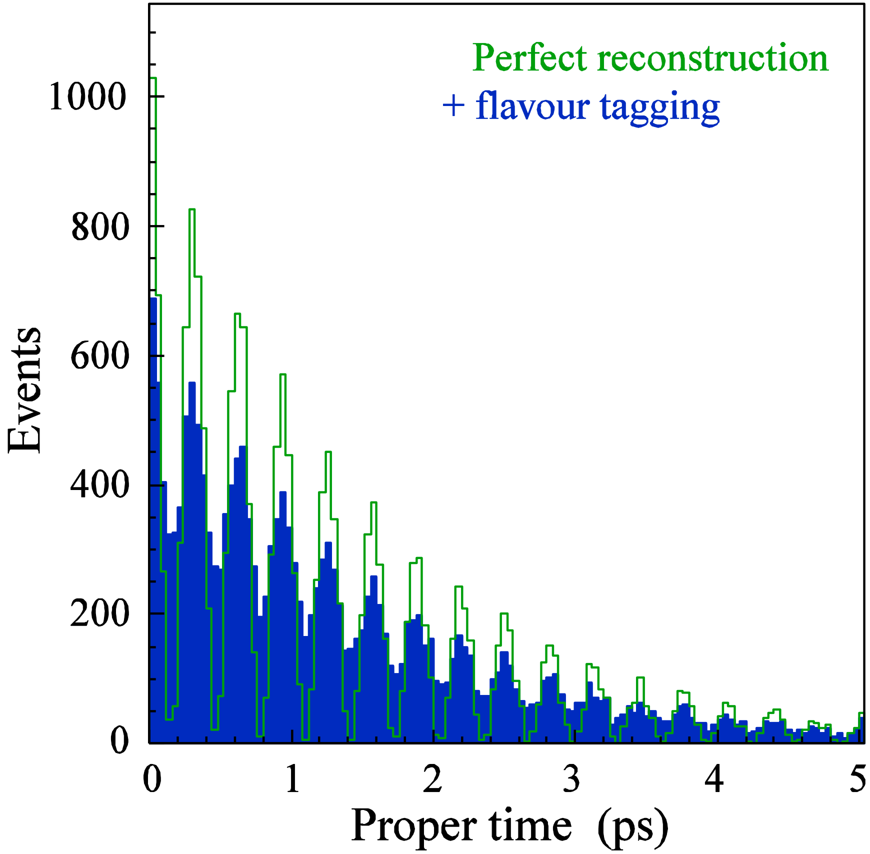
- finite decay time resolution also leads to a ‘dilution’
- effective dilution factor from gaussian resolution $\boldsymbol{\sigma_t}$:

$$\boxed{D^{\mathrm{reso}} \;=\; \exp\left[-\left(\Delta m\, \sigma_t\right)^2\right]}$$

- dilution from resolution is
  - tiny effect for measurement of B_d^0 oscillations
  - big effect for measurement of B_s^0 oscillations

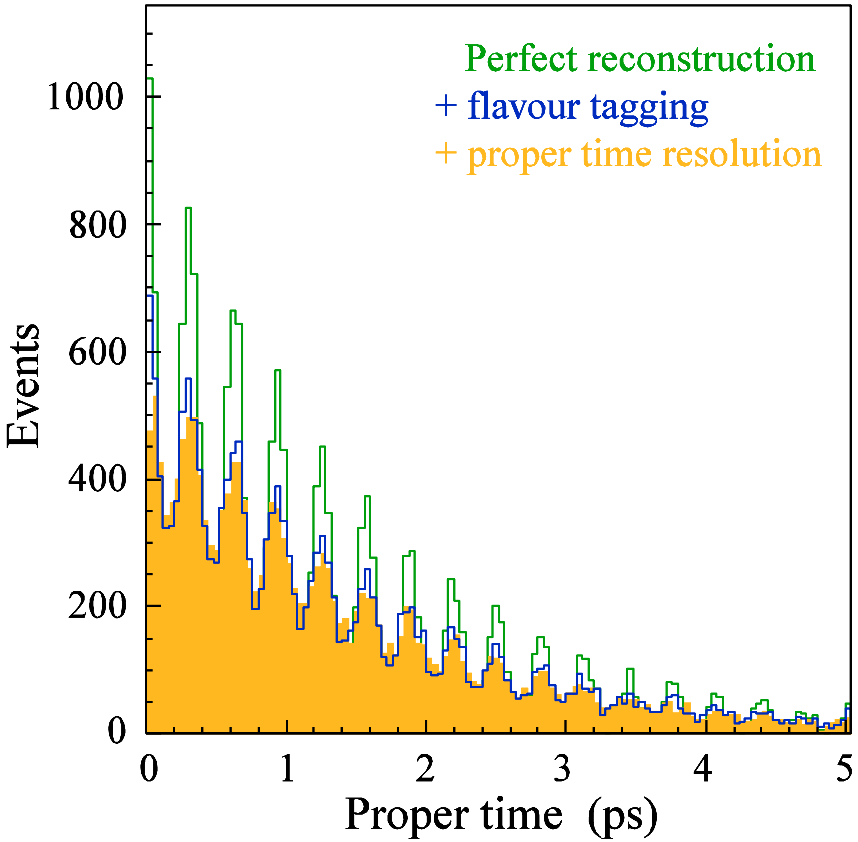


$$N(t) \;=\; \frac{N_0}{2}\, e^{-t/\tau}\; [1 + \cos(\Delta m\, t)\,]$$



$$N(t) = \frac{N_0}{2} e^{-t/\tau} \left[1 + \cos(\Delta m\, t) \right]$$

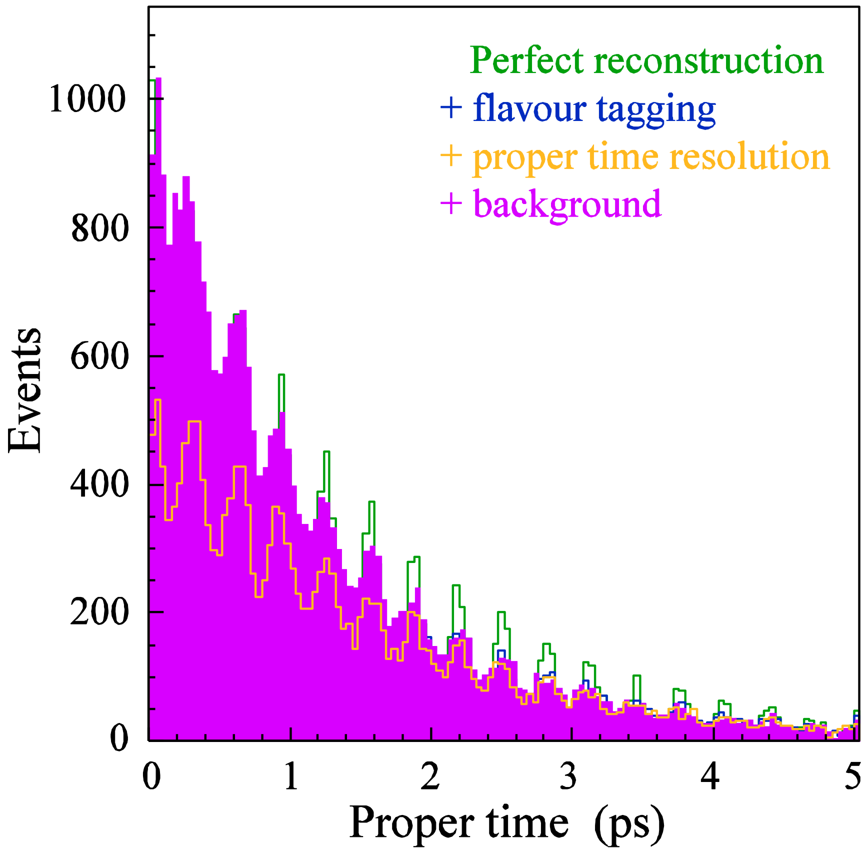
x D^{tag}



$$N(t) \;=\; \frac{N_0}{2}\, e^{-t/\tau}\; [1 + \cos(\Delta m\, t)\,]$$

x D^{tag}

x D^{reso}

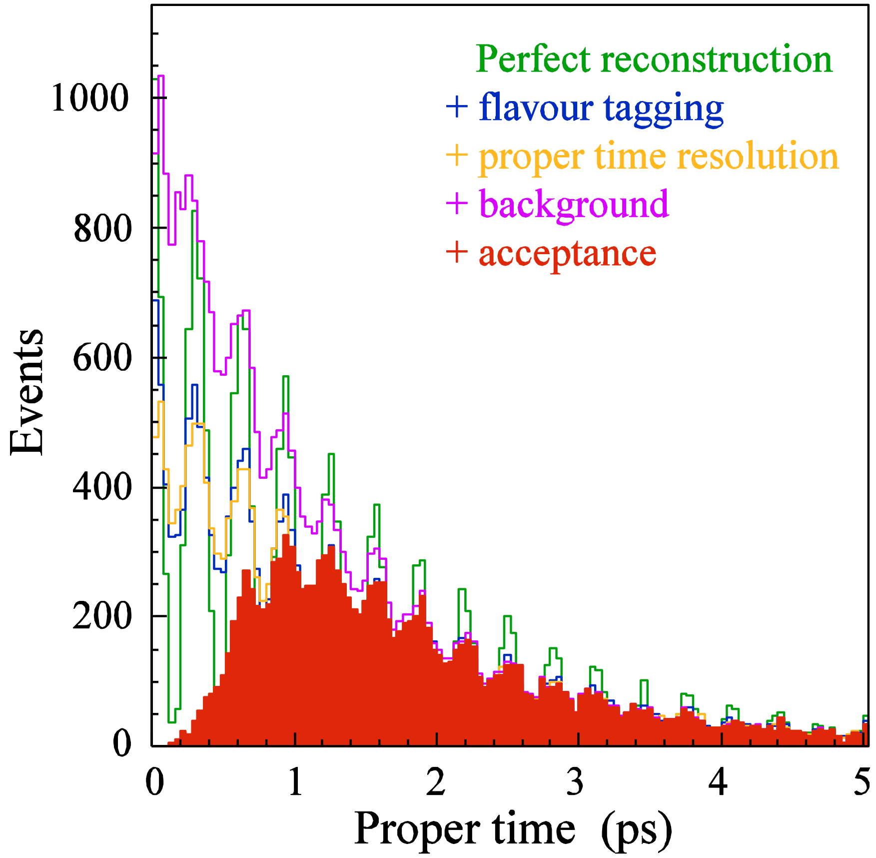


$$N(t) = \frac{N_0}{2}\, e^{-t/\tau}\, [1 + \cos(\Delta m\, t)\,]$$

x D^{tag}

x D^{reso}

+ non-oscillation backgrounds



$$N(t) = \frac{N_0}{2} e^{-t/\tau} [1 + \cos(\Delta m\, t)]$$

x D^{tag}

x D^{reso}

+ non-oscillation backgrounds

+ acceptance effects due to cuts removing prompt backgrounds

Exercises

- see README.md file at

  https://github.com/wouterhuls/FlavourPhysicsBND2023/

- **now: exercises 5-7**