

Status of section

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D-mixing and CP violation

Theory

Brief history

Mixing

CPV

NP

11 p.

layout of section as
presented at the KEK meeting
(50-60 pages)

General Exp. Remarks

D^* tagging

Decay-t resolution

5 p.

Decays to CP eigenstates

Method

Results $KK/\pi\pi$

Results $K_S\phi$ + others

6 p.

Hadronic WS decays

Formalism

Results $K\pi$

3 p.

t-dependent Dalitz

$K\pi\pi\pi^0$

$K_S h h$

Other multibody

10 p.

Semileptonic

General remarks

comparison of results

6 p.

tagged/un-tagged

t-integrated CPV measurements

Using data to measure

eff. asymmetry

15 p.

Results $KK/\pi\pi$

Multi-body ($KK\pi^0$, $\pi\pi\pi^0$, $KK\pi\pi$)

T-odd correlations

t-dependent CPV measurements

1 p.

Summary

2 p.

Theory

Mixing

CPV \longrightarrow in next
subsect.

NP \longrightarrow not yet

D^* tagging

2.5 p.
(3.5 p.)

Decay-t resolution

previous estimate (~15 p.) 2x longer

13

Mixing

Starts with the question why the mixing rate in the D^0 system is small.

Definitions of the specific D^0 mixing parameters, with references to ‘Mixing and time-dependent analyses’ for general aspects regarding the effective Hamiltonian and mass eigenstates $|F_{1,2}\rangle$.

$$\begin{aligned} R &= \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2} \\ x &= \frac{m_1 - m_2}{\Gamma_1 + \Gamma_2} \\ y &= \frac{1}{\Gamma_1 + \Gamma_2} \end{aligned} \quad (1)$$

Fig. 2. B^0 as an example of the intermediate state decaying to $2\pi^0$ and K^0, contributing to \overline{D}^0 mixing.

quark masses such that the D^0 mixing appears only due to the non-exact $SU(3)_C$ symmetry.

To the second order in the perturbation theory the elements of the effective Hamiltonian (see Sect. 1) are related to the above amplitudes as

$$\begin{aligned} (M - \frac{1}{2}(\Gamma_1 + \Gamma_2)) m_{D^0} &+ \\ &+ \frac{1}{2m_{D^0}} \\ &= \frac{1}{2m_{D^0}} \sum_i \langle \overline{D}^0 | H^{eff} | D^0 \rangle \langle D^0 | H^{eff} | D^0 \rangle. \end{aligned} \quad (6)$$

Considering for the moment only the box diagram, and taking into account the relations

$$\begin{aligned} (m_1 - m_2)^2 &= \frac{(\Gamma_1 - \Gamma_2)^2}{4} + 4 |M_{12}|^2 - \frac{(\Gamma_1 \mp \Gamma_2)^2}{4} \\ (m_1 - m_2)(\Gamma_1 - \Gamma_2) &= 4 \operatorname{Re}[M_{12}^* \Gamma_{12}] \end{aligned} \quad (7)$$

it is possible to estimate the expected magnitude of the mixing parameter x , viz. $x \sim O(10^{-3})$. The mixing with this rate should be unobservable with the present experiments.

However, there is another term in Eq. (6), describing the long distance contribution to the elements of the effective Hamiltonian. The contribution arises from the D^0 and \overline{D}^0 intermediate states, which are both CP and C eigenstates (see for example Fig. 2). Due to the perturbative QCD effects these contributions are much more difficult to evaluate. In general two theoretical approaches are exploited to estimate the magnitude of the mixing parameters taking into account the long distance contribution, the exclusive approach (see Sect. 1) and the inclusive approach (see Sect. 1). The exclusive approach (see Sect. 1) is based on the use of the operator product expansion (OPE) method (Bali and Unbehauen, 2001; Goeke, 1992). The first one is based on conceptually not complicated, if we consider only two-body perturbative intermediate states, K^0 , π^0 , η , η' , ω , ϕ , ρ^0 , ω , ϕ , their contributions are summarized in Tab. 2.

The first three columns of the table show the CKM diagram for various states entering the expressions $\langle \overline{D}^0 | H^{eff} | D^0 \rangle$ and $\langle \overline{D}^0 | H^{eff} | D^0 \rangle$, $\langle \overline{D}^0 | H^{eff} | D^0 \rangle$, $\langle \overline{D}^0 | H^{eff} | D^0 \rangle$, as well as the corresponding contributions to the effective Hamiltonian H^{eff} in the D^0 and \overline{D}^0 states.

where the kinematic function F arises after the loop over the momenta of particles exchanged between the top. The above formalism naturally reflects the GIM mechanism of masses of all (down) quarks flavors were equal, $m_s = m_d$, the function F can be factored out of the sum. The remaining sum and consequently the amplitude is small due to the unitarity of the CKM matrix. The D^0 mixing thus arises only as a consequence of the $SU(3)_C$ breaking, that is a result of small differences among the masses of the quarks.

Based on dimensional arguments (Nachtmann, 1980) the form of F is

$$F(m_1^2, m_2^2, m_3^2, m_4^2, m_5^2, m_6^2, m_7^2, m_8^2, m_9^2, m_{10}^2, m_{11}^2, m_{12}^2, m_{13}^2, m_{14}^2, m_{15}^2, m_{16}^2, m_{17}^2, m_{18}^2, m_{19}^2, m_{20}^2, m_{21}^2, m_{22}^2, m_{23}^2, m_{24}^2, m_{25}^2, m_{26}^2, m_{27}^2, m_{28}^2, m_{29}^2, m_{30}^2, m_{31}^2, m_{32}^2, m_{33}^2, m_{34}^2, m_{35}^2, m_{36}^2, m_{37}^2, m_{38}^2, m_{39}^2, m_{40}^2, m_{41}^2, m_{42}^2, m_{43}^2, m_{44}^2, m_{45}^2, m_{46}^2, m_{47}^2, m_{48}^2, m_{49}^2, m_{50}^2, m_{51}^2, m_{52}^2, m_{53}^2, m_{54}^2, m_{55}^2, m_{56}^2, m_{57}^2, m_{58}^2, m_{59}^2, m_{60}^2, m_{61}^2, m_{62}^2, m_{63}^2, m_{64}^2, m_{65}^2, m_{66}^2, m_{67}^2, m_{68}^2, m_{69}^2, m_{70}^2, m_{71}^2, m_{72}^2, m_{73}^2, m_{74}^2, m_{75}^2, m_{76}^2, m_{77}^2, m_{78}^2, m_{79}^2, m_{80}^2, m_{81}^2, m_{82}^2, m_{83}^2, m_{84}^2, m_{85}^2, m_{86}^2, m_{87}^2, m_{88}^2, m_{89}^2, m_{90}^2, m_{91}^2, m_{92}^2, m_{93}^2, m_{94}^2, m_{95}^2, m_{96}^2, m_{97}^2, m_{98}^2, m_{99}^2, m_{100}^2, m_{101}^2, m_{102}^2, m_{103}^2, m_{104}^2, m_{105}^2, m_{106}^2, m_{107}^2, m_{108}^2, m_{109}^2, m_{110}^2, m_{111}^2, m_{112}^2, m_{113}^2, m_{114}^2, m_{115}^2, m_{116}^2, m_{117}^2, m_{118}^2, m_{119}^2, m_{120}^2, m_{121}^2, m_{122}^2, m_{123}^2, m_{124}^2, m_{125}^2, m_{126}^2, m_{127}^2, m_{128}^2, m_{129}^2, m_{130}^2, m_{131}^2, m_{132}^2, m_{133}^2, m_{134}^2, m_{135}^2, m_{136}^2, m_{137}^2, m_{138}^2, m_{139}^2, m_{140}^2, m_{141}^2, m_{142}^2, m_{143}^2, m_{144}^2, m_{145}^2, m_{146}^2, m_{147}^2, m_{148}^2, m_{149}^2, m_{150}^2, m_{151}^2, m_{152}^2, m_{153}^2, m_{154}^2, m_{155}^2, m_{156}^2, m_{157}^2, m_{158}^2, m_{159}^2, m_{160}^2, m_{161}^2, m_{162}^2, m_{163}^2, m_{164}^2, m_{165}^2, m_{166}^2, m_{167}^2, m_{168}^2, m_{169}^2, m_{170}^2, m_{171}^2, m_{172}^2, m_{173}^2, m_{174}^2, m_{175}^2, m_{176}^2, m_{177}^2, m_{178}^2, m_{179}^2, m_{180}^2, m_{181}^2, m_{182}^2, m_{183}^2, m_{184}^2, m_{185}^2, m_{186}^2, m_{187}^2, m_{188}^2, m_{189}^2, m_{190}^2, m_{191}^2, m_{192}^2, m_{193}^2, m_{194}^2, m_{195}^2, m_{196}^2, m_{197}^2, m_{198}^2, m_{199}^2, m_{200}^2, m_{201}^2, m_{202}^2, m_{203}^2, m_{204}^2, m_{205}^2, m_{206}^2, m_{207}^2, m_{208}^2, m_{209}^2, m_{210}^2, m_{211}^2, m_{212}^2, m_{213}^2, m_{214}^2, m_{215}^2, m_{216}^2, m_{217}^2, m_{218}^2, m_{219}^2, m_{220}^2, m_{221}^2, m_{222}^2, m_{223}^2, m_{224}^2, m_{225}^2, m_{226}^2, m_{227}^2, m_{228}^2, m_{229}^2, m_{230}^2, m_{231}^2, m_{232}^2, m_{233}^2, m_{234}^2, m_{235}^2, m_{236}^2, m_{237}^2, m_{238}^2, m_{239}^2, m_{240}^2, m_{241}^2, m_{242}^2, m_{243}^2, m_{244}^2, m_{245}^2, m_{246}^2, m_{247}^2, m_{248}^2, m_{249}^2, m_{250}^2, m_{251}^2, m_{252}^2, m_{253}^2, m_{254}^2, m_{255}^2, m_{256}^2, m_{257}^2, m_{258}^2, m_{259}^2, m_{260}^2, m_{26$$

State	$ \langle \hat{H}^{(0)} \hat{H}^{(2)} \alpha \rangle ^2 \propto$	$ \langle \hat{H}^{(0)} \hat{H}^{(2)} \beta \rangle ^2 \hat{H}^{(2)} \hat{H}^{(0)} \propto$	measured E ₀	corr. to mixing
$E^+ \cdot E^+$	1	$\sim 3^2$	τ_1	$-\sqrt{1/2} \tau_2 \tau_3 \tau_4^{1/2}$
$E^+ \cdot E^-$	3^2	3^2	$\tau_2 \tau_3^{1/2}$	τ_3
$E^- \cdot E^+$	3^2	3^2	$\tau_3 \tau_4^{1/2}$	τ_4
$E^- \cdot E^-$	3^2	$\sim 3^2$	$\tau_4 \tau_1^{1/2}$	$-\sqrt{1/2} \tau_1 \tau_2 \tau_3^{1/2}$
		$E = 0$		$E = 1/2 (\tau_1 + \tau_2 + \tau_3 + \tau_4) \tau_4$

Fig. 3. Illustration of D^+ meson decay length determination with typical silicon detector.

Two experimental ingredients are necessary to exploit the decay length of charm D^0 , D^+ and D_s^+ for measuring the mixing parameters. The first one is to determine the decay length of the charm meson, that is, the distance it travels before it decays. This distance is determined in pp or $p\bar{p}$ collisions by the decay of a charm meson into a lepton and a D^* meson. The second ingredient is a powerful technique for the determination of the decay time of a single neutral D meson based on the measurement of its decay length between the production and decay point.

The initial flavor tagging is based on the decay chain $D^+ \rightarrow \ell^+ \nu_\ell + D^0$, and its charge conjugate $D^0 \rightarrow \ell^- \bar{\nu}_\ell + D^+$. The charge of the pion produced in the decay of a D^* determines the flavor of the charm meson. In addition, the usage of $\ell^+ \nu_\ell$ or $\ell^- \bar{\nu}_\ell$ from D^* allows the charge of D arising from D^* to be inferred the content of background in the signal.

Considering the influence of invariant masses of D^* and D mesons, $\Delta m = m(\ell^+ \nu_\ell) - m(\ell^- \bar{\nu}_\ell)$ is used to describe the amount of combinatorial background due to a good experimental resolution on the invariant mass. This solution depends on the resolution on $m(\ell^+ \nu_\ell)$ is a consequence of a correlation of experimental uncertainty in the determination of the moments of particles composing final state.

The determination of the D meson decay length is illustrated in Fig. 3 with typical silicon detector. The accuracy depends critically on the nonreconstructing detector.

The key to the experimental observation of the CP mixing lies in the time evolution of an initially produced neutral meson. At the B -factories, c pairs are produced in the electromagnetic annihilation of electrons and positrons. In the fragmentation of primary quark-antiquark pairs of charged hadrons together with lighter hadrons are produced. Any pair of D^0 and \bar{D}^0 is hence produced in a quantum supercoerated state¹. While the time evolution

² It is different than the production of D mesons at the charm threshold where the pairs of mesons are in a quantum correlated state, similarly as pairs of B mesons produced at the B -factories.

Theory

Brief history

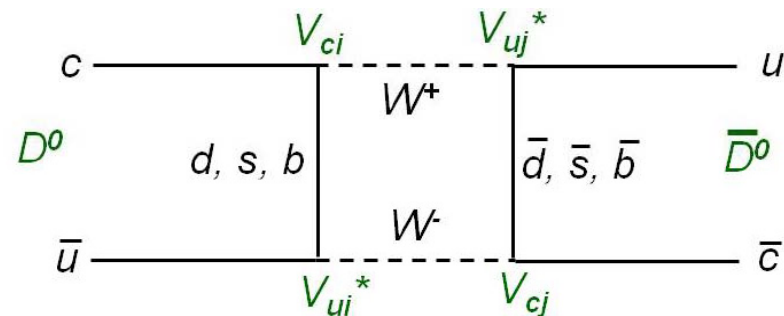
Table;
short explanation of the importance of the mixing phenomena;
GIM mechanism historical intro to be included;
shortly on specifics of D^0 system (FCNC of up-like quarks)

Mixing

definitions specific to D^0 ;
→ interplay with Sect. “Mixing and time dependent analyses”
e.g. Δm not defined +ve, but use H_{eff} from there;

Signs of x and y , based on masses ($m_{1,2}$) and widths ($\Gamma_{1,2}$) of the two mass eigenstates $P_{1,2}$, are defined in such a way that in the absence of the CP violation $P_{1(2)}$ is the CP -even (odd) state, adopting the phase convention $CP|D^0\rangle = |\bar{D}^0\rangle$ and $CP|\bar{D}^0\rangle = |D^0\rangle$.

Meson	Discovery place	Time span	Prediction
K^0	1950 Caltech		
mixing	1956 Columbia	6	c quark mass
B_d^0	1983 Cern		
mixing	1987 Desy	4	t quark mass
B_s^0	1992 LEP		
mixing	2006 Fermilab	14	?
D^0	1976 SLAC		
mixing	2007 KEK, SLAC	31	?



$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

$$x = \frac{m_1 - m_2}{\Gamma}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

Theory

Mixing

why mixing rate is small;

short distance;

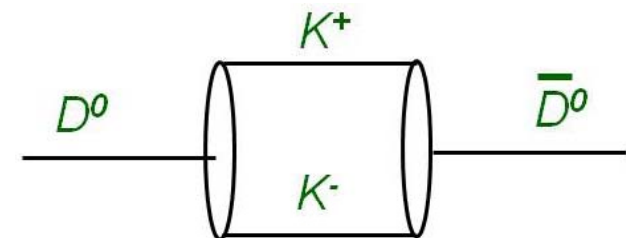
$$\langle \bar{D}^0 | H^{\Delta C=2} | D^0 \rangle = \sum_{i,j=d,s,b} V_{ui}^* V_{ci} V_{cj} V_{uj}^* m_i m_j$$

$$\langle \bar{D}^0 | H^{\Delta C=2} | D^0 \rangle = \frac{G_F^2}{4\pi^2} V_{cs}^* V_{cd}^* V_{ud} V_{us} \frac{(m_s^2 - m_d^2)^2}{m_c^2} \cdot \langle \bar{D}^0 | \bar{u} \gamma_\mu (1 - \gamma^5) c \bar{u} \gamma^\mu (1 - \gamma^5) c | D^0 \rangle$$

DCS, SU(3) breaking

$$\begin{aligned} (M - \frac{i}{2}\Gamma)_{ij} &= m_D \delta_{ij} + \\ &+ \frac{1}{2m_D} \langle \bar{D}^0 | H^{\Delta C=2} | D^0 \rangle + \\ &+ \frac{1}{2m_D} \sum_n \frac{\langle \bar{D}^0 | H^{\Delta C=1} | n \rangle \langle n | H^{\Delta C=1} | D^0 \rangle}{m_D - E_n + i\epsilon} \end{aligned}$$

long distance;



difficult to estimate

Theory

Mixing

why mixing rate is small;

long distance;
example of PP intermediate
states;

$$(M - \frac{i}{2}\Gamma)_{ij} = m_D \delta_{ij} + \frac{1}{2m_D} \langle \bar{D}^0 | H^{\Delta C=2} | D^0 \rangle + \frac{1}{2m_D} \sum_n \frac{\langle \bar{D}^0 | H^{\Delta C=1} | n \rangle \langle n | H^{\Delta C=1} | D^0 \rangle}{m_D - E_n + i\epsilon}.$$

State	$ \langle \bar{D}^0 H^{\Delta C=1} n \rangle ^2 \propto$	$\langle \bar{D}^0 H^{\Delta C=1} n \rangle \langle n H^{\Delta C=1} D^0 \rangle \propto$	measured Br	contrib. to mixing
$K^- \pi^+$	1	$-\lambda^2$	r_1	$-\sqrt{(r_1 r_4)} \lambda^2$
$K^- K^+$	λ^2	λ^2	$r_2 \lambda^2$	$r_2 \lambda^2$
$\pi^- \pi^+$	λ^2	λ^2	$r_3 \lambda^2$	$r_3 \lambda^2$
$K^+ \pi^-$	λ^4	$-\lambda^2$	$r_4 \lambda^4$	$-\sqrt{(r_1 r_4)} \lambda^2$
$\Sigma = 0$			$\Sigma = \lambda^2 (r_2 + r_3 - 2\sqrt{(r_1 r_4)})$	

→ interplay with Sect. “Charmed meson decays”?

$$|x|, |y| \leq \mathcal{O}(10^{-3} - 10^{-2})$$

In summary, the mixing rate in the D^0 system is small. It arises mainly due to the difficult to estimate long distance contributions. Nevertheless, the measurement of the mixing in this system can provide for non-trivial constraints on possible NP parameters, complementary to the constraints from down-like FCNC processes.

General Exp. Remarks

starts with decay time evolution as the exp. tool to access the mixing parameters; first order approximation (after full formulae);

CPV is small;

can/should be moved to “Theory” subsect.?

$$\frac{d\Gamma(D^0 \rightarrow f)}{dt} \propto |A_f + \frac{q}{p} \frac{ix + y}{2} \bar{A}_f \Gamma t|^2 e^{-\Gamma t} . \quad (11)$$

A_f and \bar{A}_f denote the instantaneous decay amplitudes $\langle f|D^0 \rangle$ and $\langle f|\bar{D}^0 \rangle$, respectively. Analogously for an initially produced \bar{D}^0 one finds

$$\frac{d\Gamma(\bar{D}^0 \rightarrow f)}{dt} \propto |\bar{A}_f + \frac{p}{q} \frac{ix + y}{2} A_f \Gamma t|^2 e^{-\Gamma t} . \quad (12)$$

The time dependent decay rates are thus sensitive to the mixing parameter x and y , and the dependence on those differs for various final states f .

$$2 \arg(V_{cs} V_{us}^*) = 2 \arg(-V_{cd} V_{ud}^* - V_{cb} V_{ub}^*) \approx \\ \approx -2A^2 \lambda^4 \eta = 1.2 \cdot 10^{-3} ,$$

General Exp. Remarks

CPV: parametrization
→ discuss with Brian

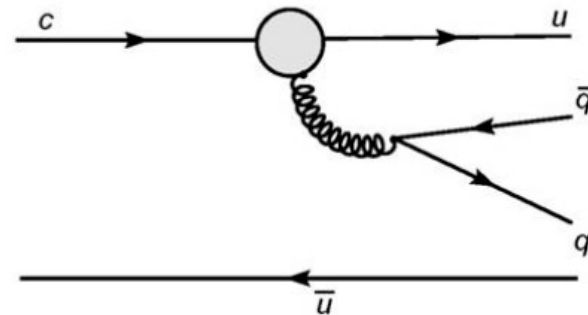
→ DCPV: two
amplitudes,
described before?

can/should be
moved to “Theory”
subsect.?

$$\left|\frac{q}{p}\right|^2 \equiv 1 + A_M \quad (15)$$

is often used. Three types of the CP violating effects can be distinguished, as in any other neutral mesons system. First, the CP violation in the mixing occurs if $A_M \neq 0$ (alternatively, $|q/p| \neq 1$). CP violation in decays is present if $|\bar{A}_{\bar{f}}/A_f| \neq 1$. This effect is sometimes parametrized in terms of

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right|^2 \equiv 1 + A_D^f . \quad (16)$$



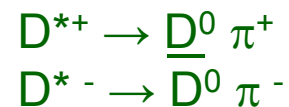
$$\lambda_f = -\sqrt{R_D^f} \frac{1 + A_M/2}{1 + A_D/2} e^{-i(\delta_f - \phi)}$$

General Exp. Remarks

D^* tagging

Δm definition, explanation
on background reduction;

need rule on inv./nominal
mass notation?



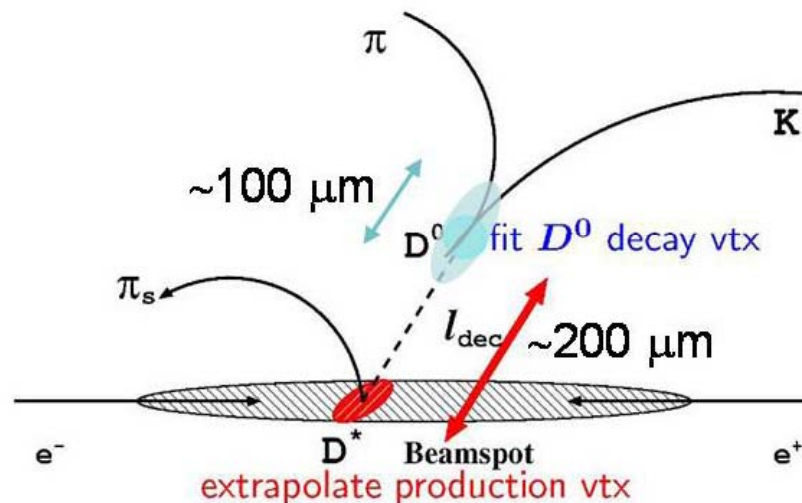
$$m(K\pi)$$

$$m_{D^0}$$

Decay-t resolution

illustration with typical
dimensions;

→ interplay with
Sect. “Vertexing”?
(IP profile)



General Exp. Remarks

Decay-t resolution

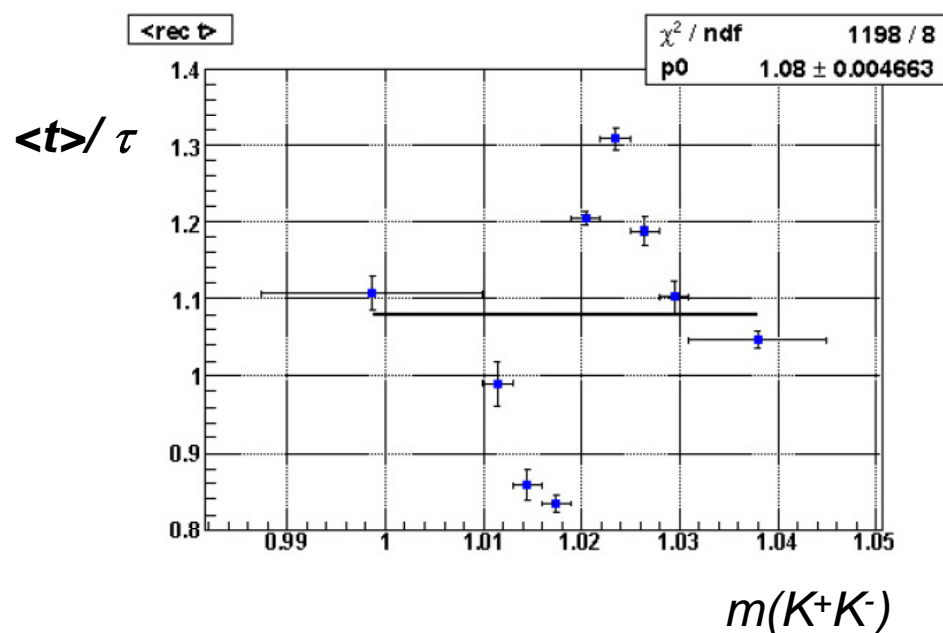
example of \mathcal{L} ;

→ interplay with
Sect. “Mixing
and time dependent
analyses”

give examples of values
(e.g. for $K\pi$)?

biases, non-zero t_0 ;
examples?

$$\mathcal{L}_i(x, y) = \int_0^\infty dt' \frac{d\Gamma}{dt'}(t'; x, y) \left[e^{(t_i - t')^2 / 2S_1\sigma_i^2} + e^{(t_i - t')^2 / 2S_2\sigma_i^2} \right]$$



Summary

Introductory subsections
(with exception of NP)
ready to be discussed
and edited

Plan:
list of references to be divided
among exp. subsect.;

after general part ok →
start work on individual
experimental subsect.
(divide among contributors)