Decoherence: Status and Plans at MPP

Primary goal:
Is Entanglement of B-Mesons in Y(4s) decays 100%
=> Effects on B^0 Oscillations and CP Violation

Secondary goals
Can Bell's Inequality be checked?
Searches for general decoherence

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Entanglement in Υ(4s) decays

$B^0/\overline{B}^0$ from a Υ(4s) decay are supposed to be in an entangled state

$$\Psi = \frac{1}{\sqrt{2}} \left[|B^0(p)\rangle|\overline{B}^0(-p)\rangle - |\overline{B}^0(p)\rangle|B^0(-p)\rangle \right]$$

If one B decays, the common wave function collapses and the $B^0/\overline{B}^0$ are in a defined state.

$\gamma\beta c\tau/r(B^0) \sim 5\text{x}10^{10}$ => well separated spatially

Measurements of Δm_d and CP violation are based on entanglement (B-tag).

1) Can we demonstrate the entanglement (e.g. checking Bell's inequality) ?

2) How certain are we that the entanglement is always 100% ?

$\Upsilon(4s) \rightarrow B^0 \overline{B}^0 \gamma$

Decoherence due to interaction with (BSM) background fields

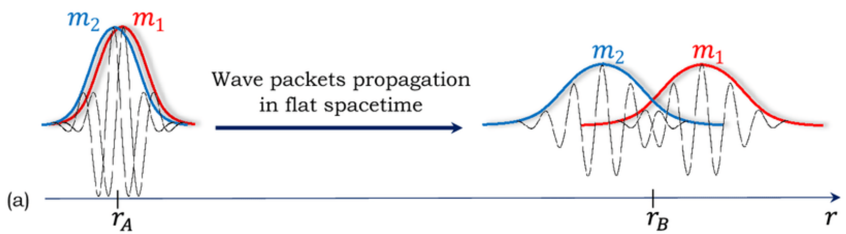
Such effects could lead to systematic errors of our CP violation measurements

Disclaimer

Loss of entanglement is a special case of decoherence

In general decoherence is understood as the loss of coherence of quantum states so that they cannot interfere anymore

E.g. the mass eigenstates of the B^0: B_l and B_h stop interfering:
No time dependent oscillations any more, description by a density matrix
Could happen due to a different propagation speed (but also due to interaction with environment)



B_l is faster than B_h
⇒ wave packets don‘t overlapp after some propagation distance
⇒ No interference possible

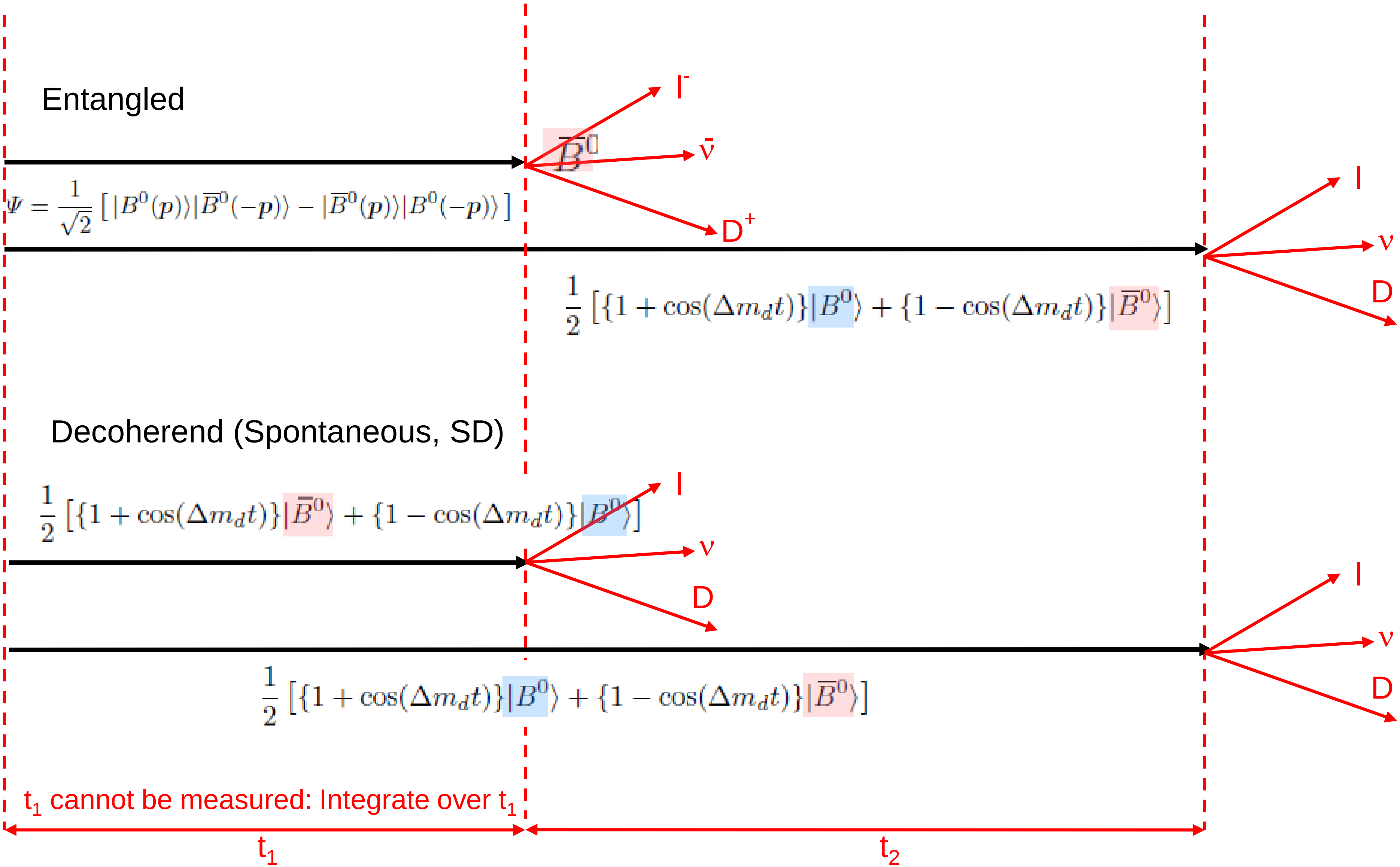
Described by Lindblad and Kraus-Operator models with a decoherence parameter λ

Most recent: **Alok et al, arXiv:2402.02470v2 [hep-ph], April 2024**

This (and similar effects) are a topic in neutrino physics

We do not consider this for the moment, but may follow this up in future

Time dependence if decoherent



Spontaneous Decoherence

$B^0/\bar{B}^0$ Oscillations: Probability to measure a same sign (SS) event:

a) Full coherence:

$$P(B^0B^0, \overline{B^0B^0}) = \frac{1}{2}\Gamma\exp(-\Gamma t_2)(1-\cos\Delta m t_2)$$

b) Full decoherence (Spontaneous decoherence, SD)

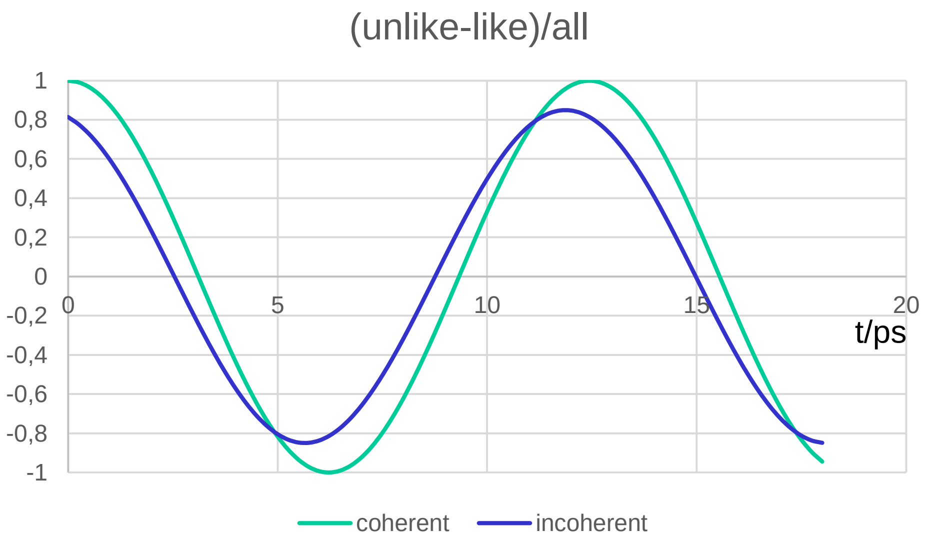
$$P(B^0B^0, \overline{B^0B^0}) = \frac{1}{2}\Gamma\exp(-\Gamma t_2)(1-\frac{1}{2}\frac{\Delta m+2\Gamma^2}{\Gamma^2+\Delta m^2}\cos\Delta m t_2 + \frac{1}{2}\frac{\Gamma\Delta m}{\Gamma^2+\Delta m^2}\sin\Delta m t_2)$$

Damping by $\frac{1}{2}\frac{\Delta m+2\Gamma^2}{\Gamma^2+\Delta m^2}$ ~ 0.81

Additional SIN-term: $\frac{1}{2}\frac{\Gamma\Delta m}{\Gamma^2+\Delta m^2}$ ~ 0.24

(using PDG averages: $\Delta m = 0.505 \pm 0.002\ ps^{-1}$, $\Gamma = 0.658 \pm 0.002\ ps^{-1}$)

Time Dependence (SD)



The damping is probably difficult to measure, as it could be interpreted as mistag.

The sine term (or phase shift) should be measurable.

Similar damping and phase shifts in measurements of time dependent CP violation

The damping could lead to a wrong measurement of sin(2β).
This might be compensated if the mistag is calibrated using oscillation measurements.

The phase shift leads to a cross talk between S and C.

Redo Belle Δm Analyis

arXiv:2302.12791, Feb 2023 Based on 190 fb^{-1} $B^0 \to D^{(*)-}\pi^+$ (and CC) events

$\Rightarrow$ Full luminosity, improved flavour tag

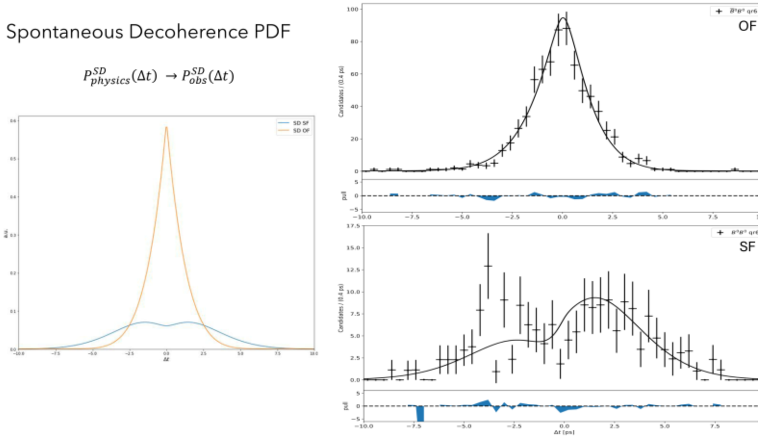
Belle Analysis
A.Go & Belle, Phys. Rev. Lett 99 (2007) 131802

Based on 140 fb^{-1}, restricted to $B^0 \to D^{*-}l^+\nu$, lepton tag

Should be statistically more powerful

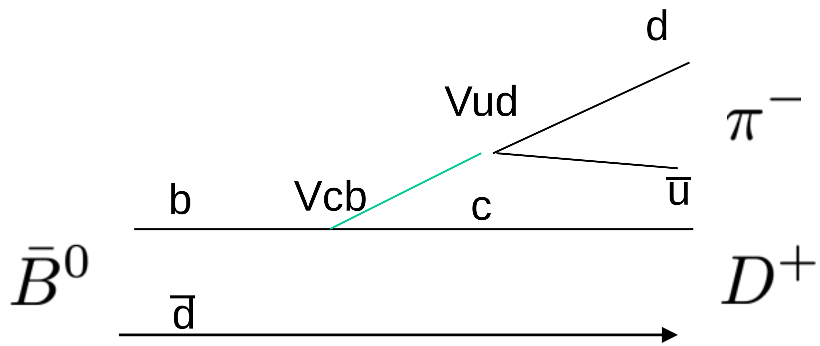
To do: Implement new resolution function (analytical convolution)

However: TSI (Tag side interference)

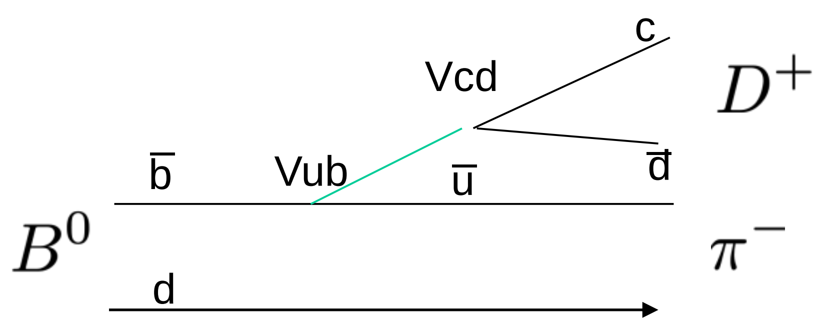


Tag Side Interference

$$\bar{B}^0 \to D^+\pi^-$$



$$B^0 \to D^+\pi^-$$



=> Mixing induced CP violation

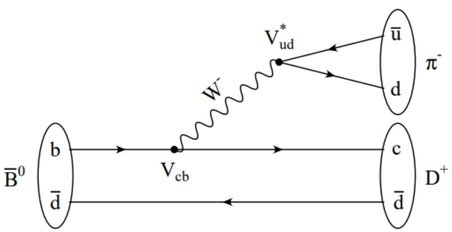
$$\frac{\#(B^0_{tag};B^0_{sig}) + \#(\overline{B}^0_{tag};\overline{B}^0_{sig})}{\#(B^0_{tag};B^0_{sig}) + \#(\overline{B}^0_{tag};\overline{B}^0_{sig}) + \#(B^0_{tag};\overline{B}^0_{sig}) + (\overline{B}^0_{tag};B^0_{sig})} = \frac{1}{2}\Big[1 - \cos(\Delta m \Delta t) + 2\sin(\Delta m \Delta t)\cos(2\beta+\gamma)(r\sin\delta - r'\sin\delta')\Big]$$

Sine term as for decoherence, but ~Δt, not ~|Δt| => disentagle, but systematics
Perhaps semileptonic decays better?
Same effect on tag side (hence the name)

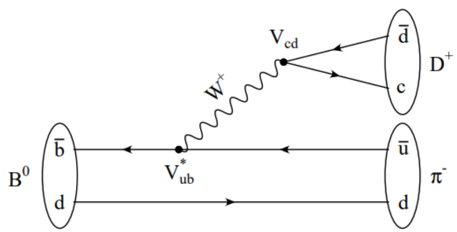
Tag Side Interference

Further: important sys. error of TDCPV

In hadronic decays, CKM favored and doubly CKM suppressed amplitudes in final states used for B flavor tagging gives deviations from the standard time evolution assumed in CP -violation measurements

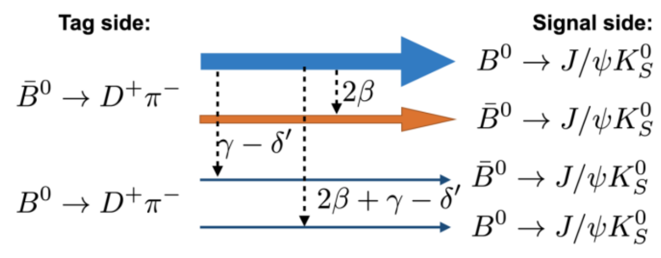


CKM-favored amplitude



doubly-CKM suppressed amplitude

Owen Long et. al.



$$R = \frac{1+|\lambda_{CP}|}{2} - 2r'\mathrm{Re}(\lambda_{CP})\cos(2\beta+\gamma-\delta')$$

$$S = \mathrm{Im}(\lambda_{CP}) + 2r'\mathrm{Re}(\lambda_{CP})\cos(2\beta+\gamma-\delta')$$

$$C = \frac{1-|\lambda_{CP}|}{2} + r'(1-|\lambda^2_{CP}|)\sin(2\beta+\gamma-\delta')$$

Takeo Higuchi, Thibaud Humair, Michele Veronesi Physics meeting, 29 April 2024

Source	ε_{tag} [%]	S	C	ε_{tag} [%]	S	C
Detector alignment	0.08	0.005	0.003	0.08	0.005	0.003
Interaction region	0.16	0.002	0.002	0.16	0.002	0.002
Beam energy	0.03	$<$ 0.001	0.001	0.03	$<$ 0.001	0.001
ΔE-fit background model	0.11	0.001	0.001	0.11	0.001	0.001
ΔE-fit signal model	0.08	0.003	0.006	0.08	0.003	0.006
sWeight background subtraction	0.24	0.001	0.001	0.24	0.001	0.001
Fixed resolution-function parameters	0.07	0.004	0.004	0.07	0.004	0.004
τ and Δm_d	0.06	0.001	$<$ 0.001	0.06	0.001	$<$ 0.001
$\sigma_{\Delta t}$ binning	0.04	$<$ 0.001	$<$ 0.001	0.04	$<$ 0.001	$<$ 0.001
Δt-fit bias	0.09	0.002	0.005	0.09	0.002	0.005
CP violation in B_{tag} decay		0.011	0.006		$<$ 0.001	0.027
$B^0 \to D^{(*)-}\pi^+$ sample size		0.004	0.007		0.004	0.007
Total systematic uncertainty	0.36	0.014	0.013	0.36	0.009	0.029
Statistical uncertainty	0.43	0.035	0.026	0.43	0.035	0.026

Measurement of TSI parameters in BELLE are done assuming ALL tag-side are $B^0 \to DX$

Ongoing: For sin(2β), additional $B^0 \to J/\psi\ K^0_L$ mode
⇒ reduce systematic uncertainty

(Okan Eren)

Team and Tasks

Max Hattenbach (master) : Δm analysis (took over from Benedikt Wach)
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Franz Jackl (bachelor): calculate time dependence for various DC models
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Simeon Hamurcu (bachelor): implement and test resolution functions for various DC models
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Okan Eren: (bachelor): study effect of TSI
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Hans-Günther Moser, Stefan Wallner (Postdoc): supervision
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Status: Belle II Δm analysis reproduced
resolution function (spontaneous DC) implemented
TSI effect (basically) understood