Quantum Decoherence Activities at the University of Hawai'i

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Belle II Summer School - University of Mississippi

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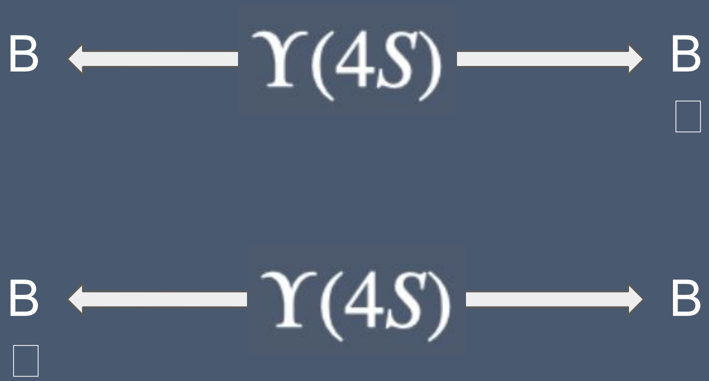
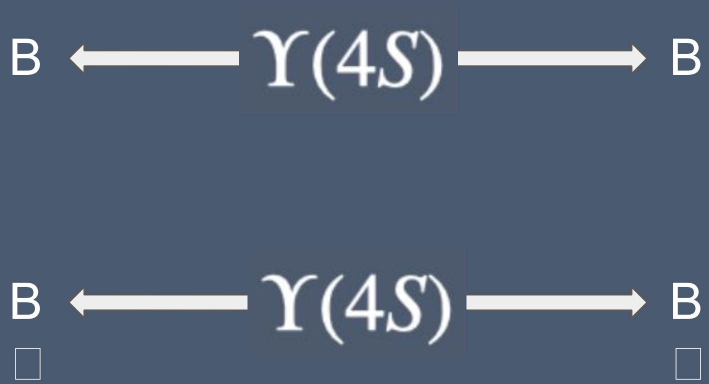
Define: Entanglement and Decoherence

Entanglement



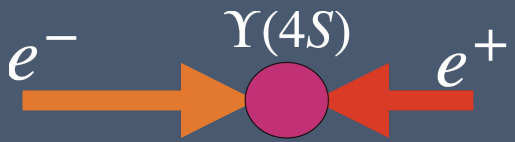
Decoherence



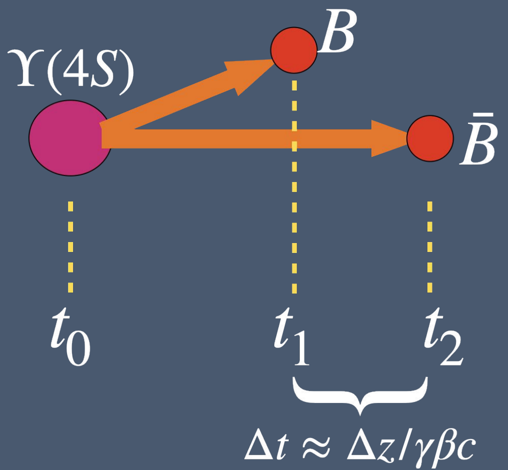
- When the BB□ decay at the same time (Δt=0), one is tagged to be the B, which makes the other instantaneously the B□
- Decoherence would allow same flavor → Interesting to test!

Using B-Factories for probing quantum effects

- About SuperKEKB:
  - Main purpose → produce B-meson pairs that are quantum entangled
  - $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
  - Asymmetric beam energies result in boost and displaced B vertices Δz≈200 μm
  - Δz gives the decay time difference
  - Absolute decay times t_1 & t_2 were not accessible in Belle, but how about Belle II?



Lab Frame:

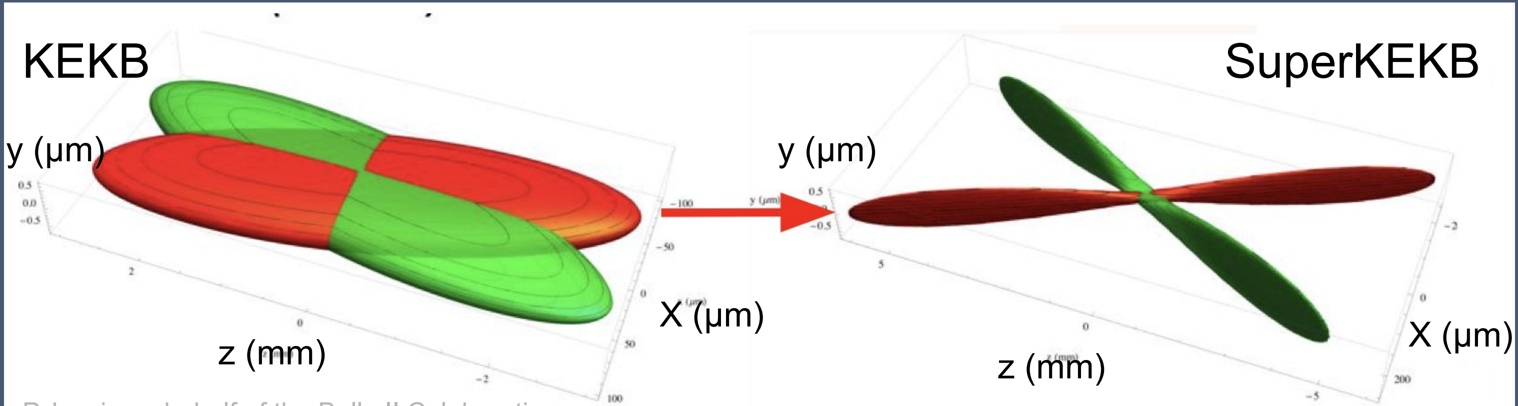


K. Akai et al, on behalf of the SuperKEKB Accelerator Team, https://arxiv.org/pdf/1809.01958

Improvements to KEKB

- Upgrade to SuperKEKB resulted in an increase of luminosity
- Achieved by beam focusing ("Nanobeam collision scheme") using the final-focus superconducting magnet system (QCS)

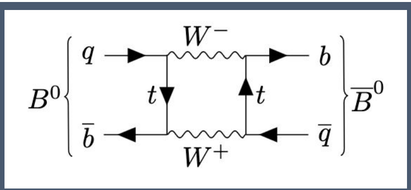
	KEKB	SuperKEKB
σ_x	150 μm	10 μm
σ_y	940 nm	50 nm
σ_z, eff	7 mm	0.25 mm

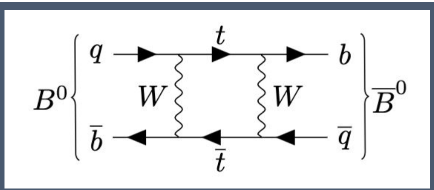


P. Lewis on behalf of the Belle II Colaboration, https://docs.belle2.org/record/666/files/BELLE2-TALK-CONF-2017-078.pdf

B$\bar{B}$ quantum entanglement

$$|\Psi(t)\rangle = \frac{e^{-t/\tau_{B^0}}}{\sqrt{2}} \left[|B^0(\vec{p})\overline{B}^0(-\vec{p})\rangle - |\overline{B}^0(\vec{p})B^0(-\vec{p})\rangle \right] \quad \text{(Eq. 1)}$$



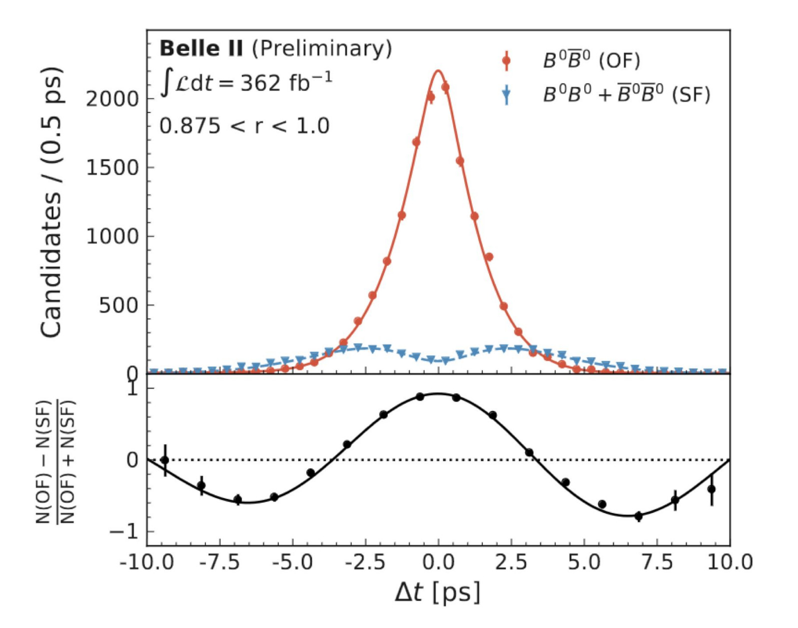


- In an $\Upsilon(4S) \to B\bar{B}$ decay the initial state has C=-1 charge conjugation
- In strong interaction, charge conjugation must be conserved → The B$\bar{B}$ pair has to be flavor entangled!
- If the first meson decays at t_1 (flavor known) …
  - … the other meson collapse into the flavor opposite state
  - … however, the second meson can still undergo mixing

BB□ quantum entanglement

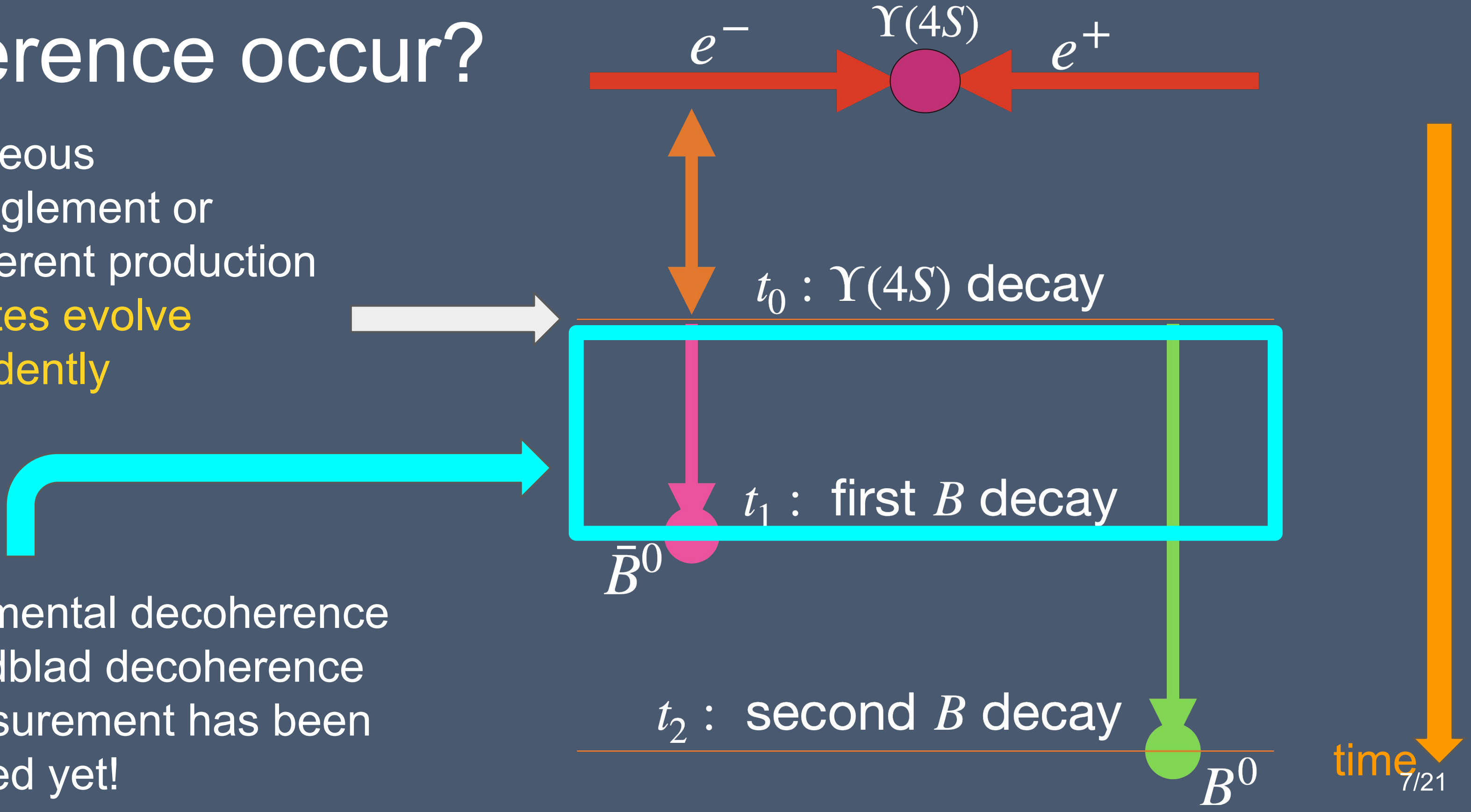
I. Adachi et al, https://arxiv.org/pdf/2402.17260

- Up to now, flavor entanglement assumed "perfect" in B-mixing analysis
- But, searches for deviations from nominal mixing are desirable
- Belle II very well suited for this:
  - More data
  - Better vertex resolution
  - Smaller interaction point region → access absolute decay times



When does spontaneous and environmental decoherence occur?

- Spontaneous disentanglement or non-coherent production
  → B states evolve independently



- Environmental decoherence
- E.g. Lindblad decoherence
- No measurement has been performed yet!

First approaches at Belle

- Attempts to measure EPR-type flavor entanglement at Belle by A. Go 2007
- Two models where tested
  - Pompili-Selleri hidden variable model
  - Spontaneous Disentanglement of all BB pairs
- Both models depend on the absolute decay times, not accessible at Belle!
- Determine the asymmetry by $B \to D^{*-}\ell\nu$ decays and integrating out the absolute time dependence

Pompili-Selleri model:

$$A_{PS}^{max}(t_1, t_2) = 1 - |\{1 - \cos(\Delta m_d \Delta t)\} \cos(\Delta m_d t_{min}) + \sin(\Delta m_d \Delta t) \sin(\Delta m_d t_{min})|, \text{ and} \quad (3)$$

$$A_{PS}^{min}(t_1, t_2) = 1 - \min(2 + \Psi, 2 - \Psi), \text{ where} \quad (4)$$

$$\Psi = \{1 + \cos(\Delta m_d \Delta t)\} \cos(\Delta m_d t_{min}) - \sin(\Delta m_d \Delta t) \sin(\Delta m_d t_{min}). \quad (5)$$

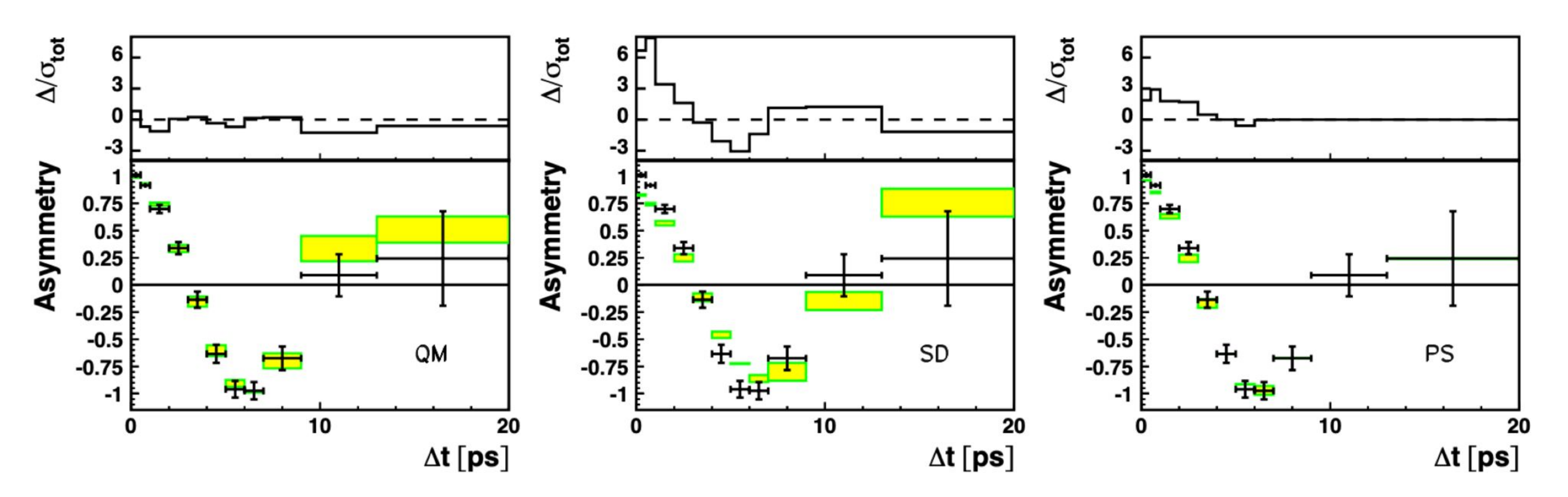
Spontaneous Disentanglement:

$$A_{SD}(t_1, t_2) = \cos(\Delta m_d t_1) \cos(\Delta m_d t_2) = \frac{1}{2}[\cos(\Delta m_d (t_1 + t_2)) + \cos(\Delta m_d \Delta t)], \quad (2)$$

A. Go et al, https://arxiv.org/pdf/quant-ph/0702267

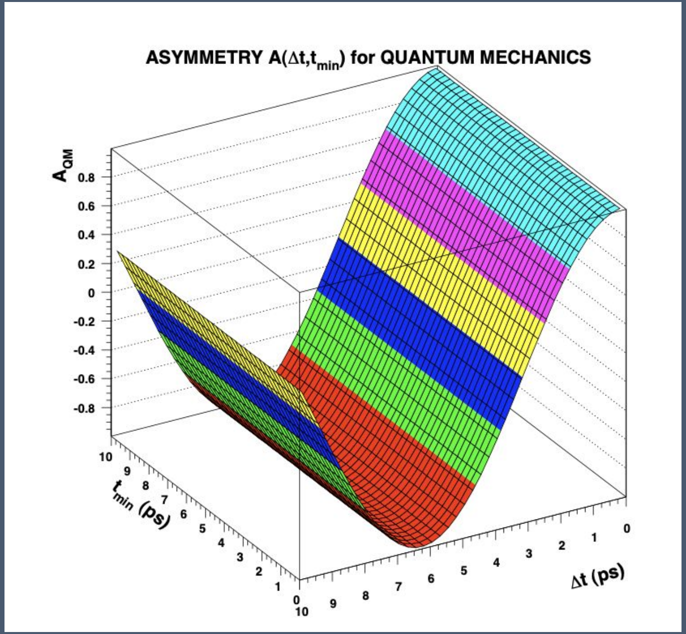
First approaches at Belle

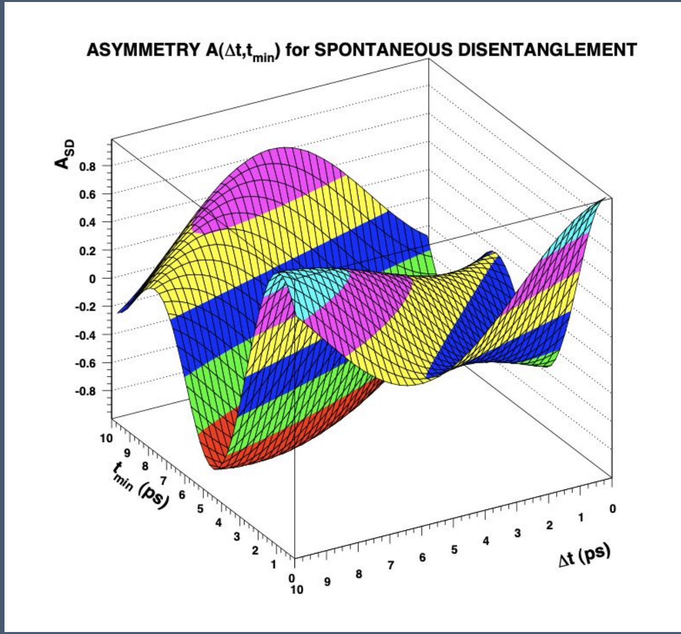
A. Go et al, https://arxiv.org/pdf/quant-ph/0702267



- Total spontaneous disentanglement disfavored by 13σ
- Pompili-Selleri model disfavored by 5.1σ
- Also tested fractional spontaneous disentanglement → (3 ± 6)%

The power of individual B-meson decay times





B. D. Yabsley, https://arxiv.org/pdf/0810.1822

- In QM only depend on Δt
- For disentanglement & decoherence, absolute time is an additional dimension
- Possible increase of sensitivity through t_1, t_2

Hershel

Lindblad Type Decoherence

With our form of Lindblad type decoherence (decoherence via environmental interaction), the time-evolution of the $B^0\overline{B}^0$ pair can be written as:

$$\frac{d\rho}{dt} = -iH\rho + i\rho H^\dagger - D[\rho]$$

R.A. Bertlmann and W. Grimus
https://arxiv.org/abs/hep-ph/0101160

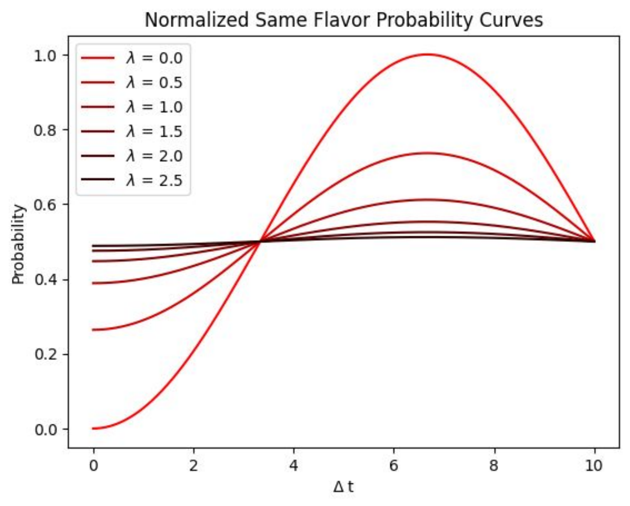
(decoherence term)

$$D[\rho] = \lambda\left(P_1\rho P_2 + P_2\rho P_1\right)$$

λ parameterizes the strength of decoherence

This leads to a decoherence-dependent flavour distribution:

$$P = \frac{\cosh(\frac{\Delta\Gamma\Delta t}{2}) - \mu e^{-\lambda t_{min}} \cos(\Delta m \Delta t)}{2\cosh(\frac{\Delta\Gamma\Delta t}{2})}$$

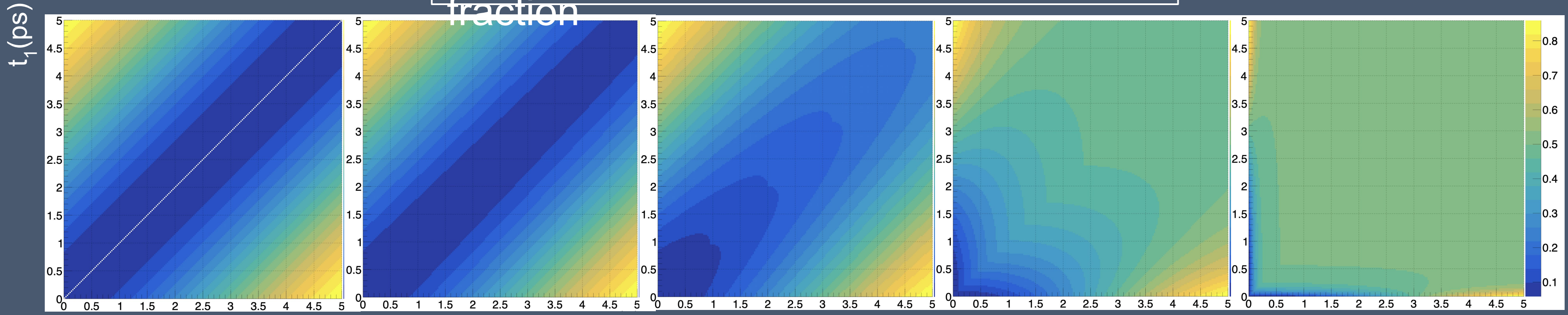


Alexei

Modeling Decoherence

We see that increasing decoherence “washes out” the flavour correlation between the two B mesons. This decoherence pattern is distinct from mis-tagging.

$N_{BB}/(N_{BB} + N_{B\bar{B}})$: Same-flavour fraction



t_2(ps)

λ = 0 (no decoherence)

λ = 0.01

λ = 0.1

λ = 1

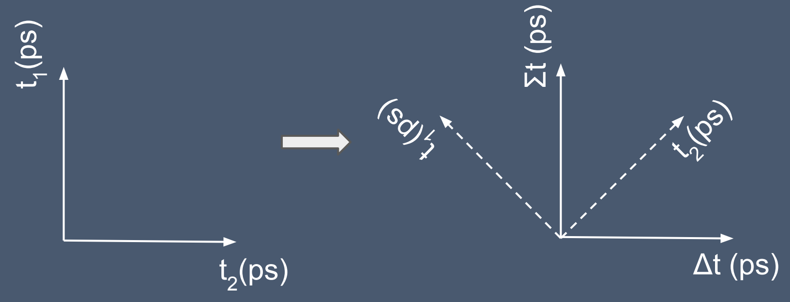
λ = 10

Increasing decoherence strength

Alexei

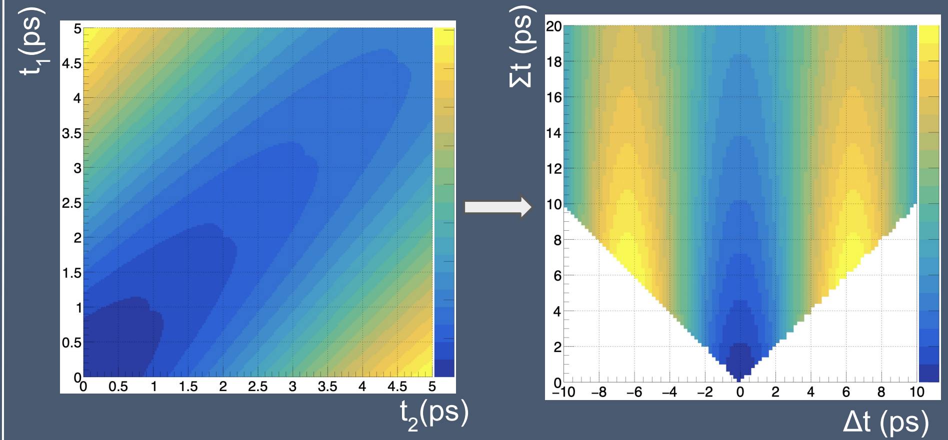
Modeling Decoherence

Changing basis to one that we can have access to at Belle II:

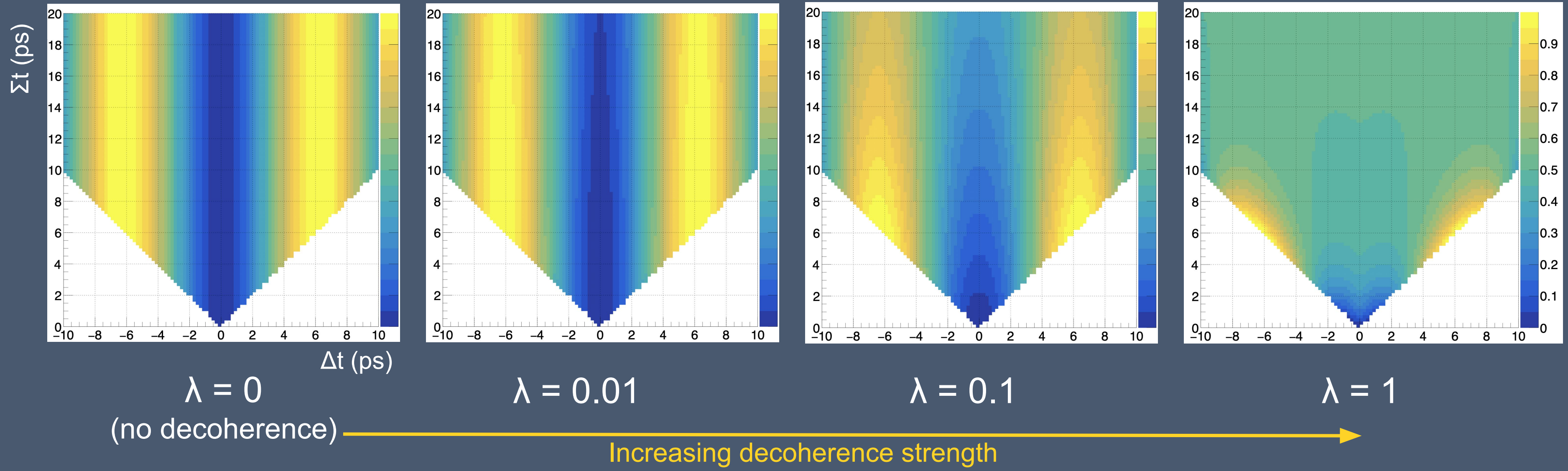


t_1 - decay time of B_1
t_2 - decay time of B_2

Δt - difference in decay times
Σt - sum of the two decay times



Modeling Decoherence

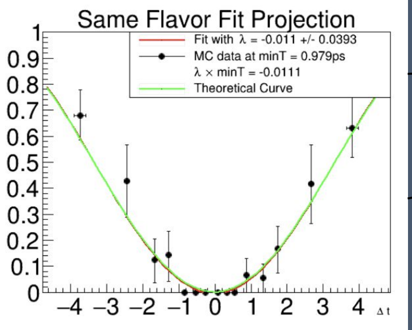


The flavour oscillation's dependence on absolute lifetime (Σt) grants us sensitivity.

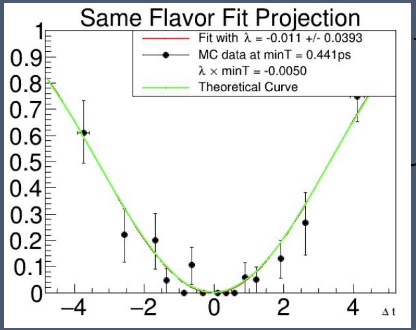
Σt is used here, but we can equivalently use one of the individual decay times.

Modeling Decoherence

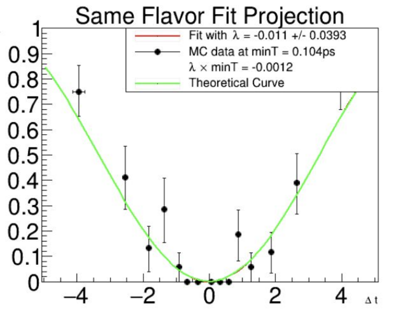
$\lambda_{gen} = 0$



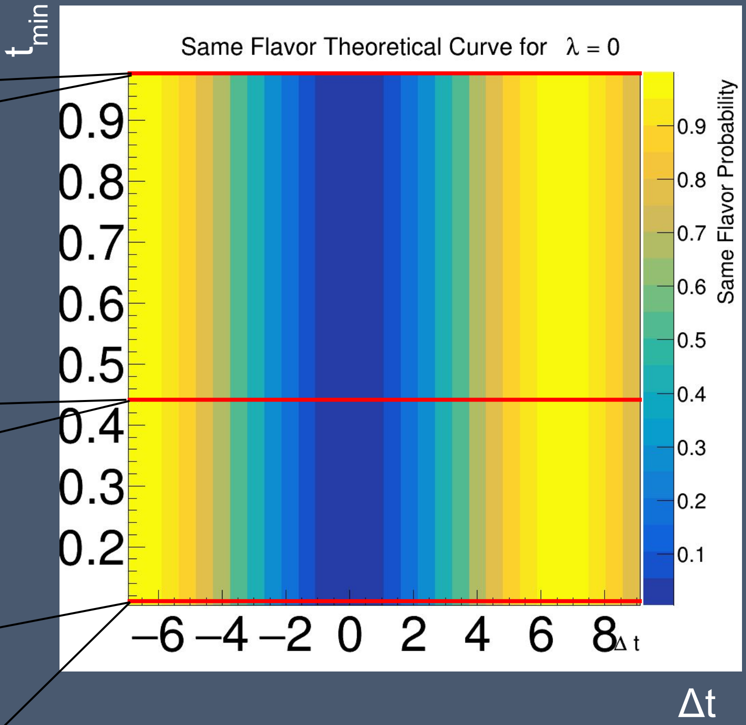
$t_{min} = 0.979$ps



$t_{min} = 0.441$ps



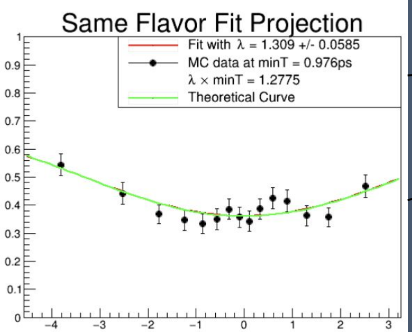
$t_{min} = 0.104$ps



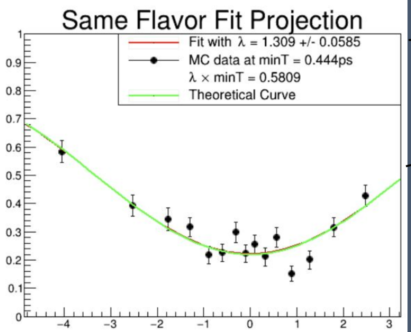
$\lambda_{fit} = -0.011 \pm 0.0393$

Modeling Decoherence

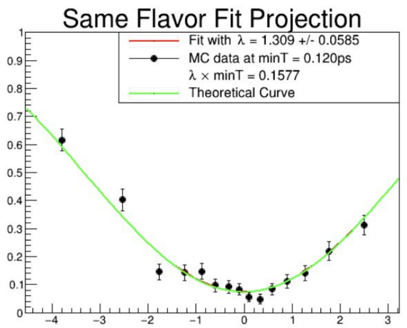
$\lambda_{gen} = 1.3$



$t_{min} = 0.976ps$

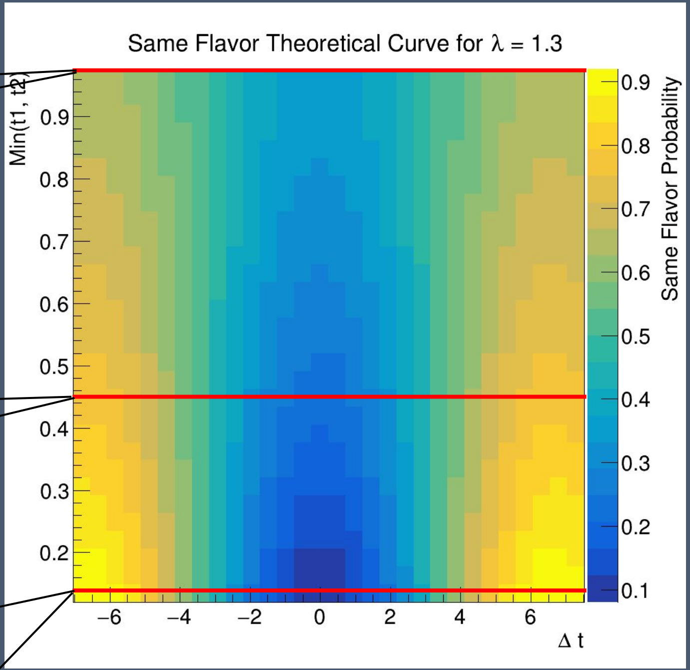


$t_{min} = 0.444ps$



$t_{min} = 0.120ps$

t_{min}



Δt

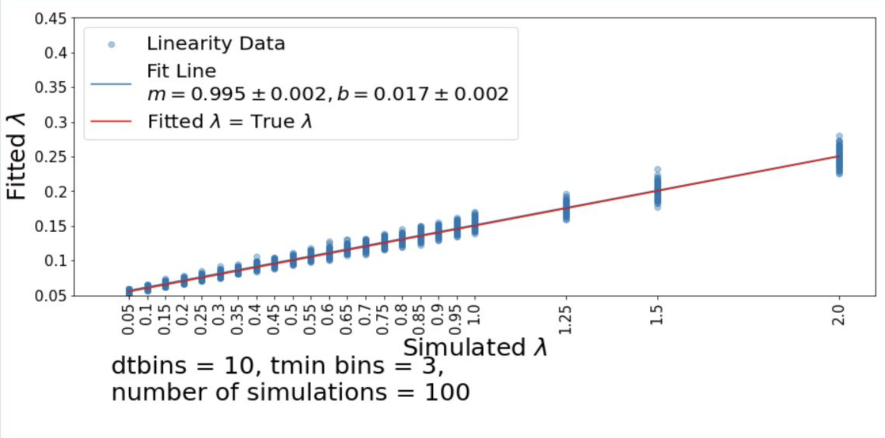
$\lambda_{fit} = 1.309 \pm 0.0585$

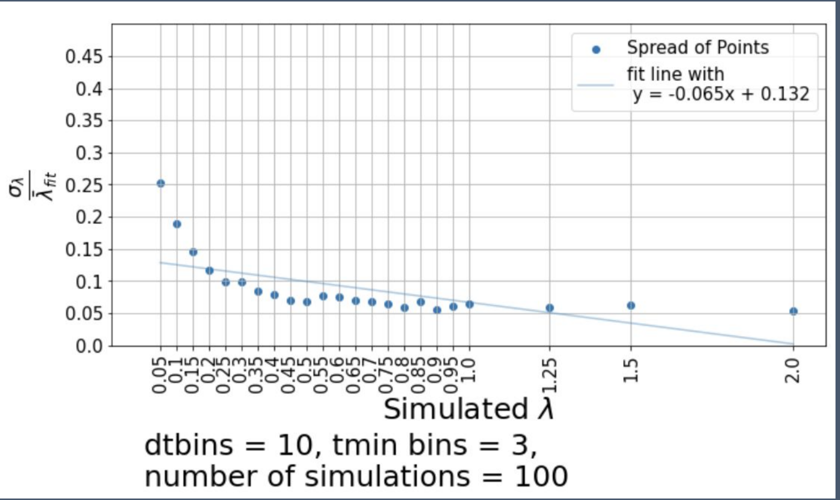
Modeling Decoherence

Performing a linearity test on the fitter for different λ values: Good agreement

Analyzing the sensitivity of the fitter at low λ values: Small fractional error for small λ

These made w/ 5,000 events. Anticipate ~80,000 experimental data!





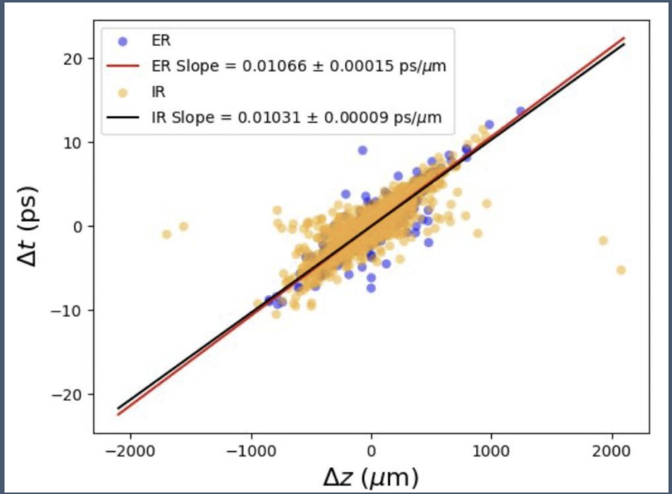
10 bins per Δt, 3 bins per t_{min}

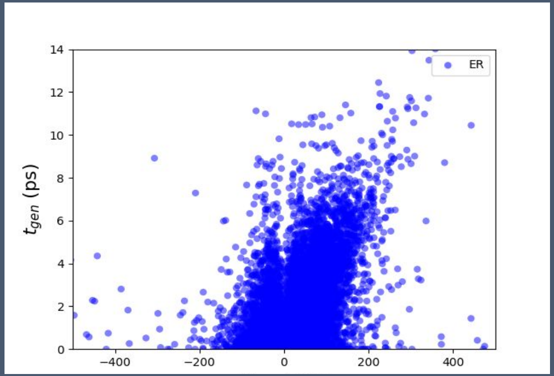
Aleczander

Reconstruction Efforts

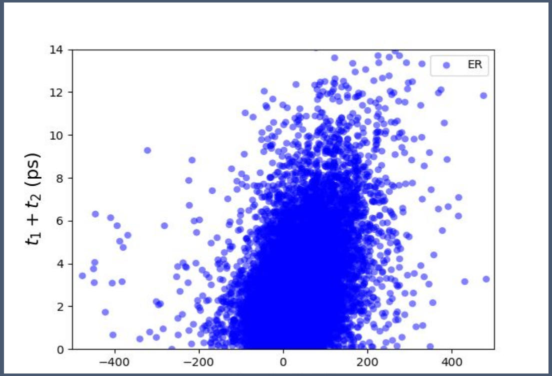
At Belle II, we obtain Δt from Δz. To get t_{min}, we see a correlation between the generated t-value and the reconstructed x-position of individual B mesons.

This gives us some sensitivity to individual decay times!





x_{max}



$x_{min}+x_{ma}$

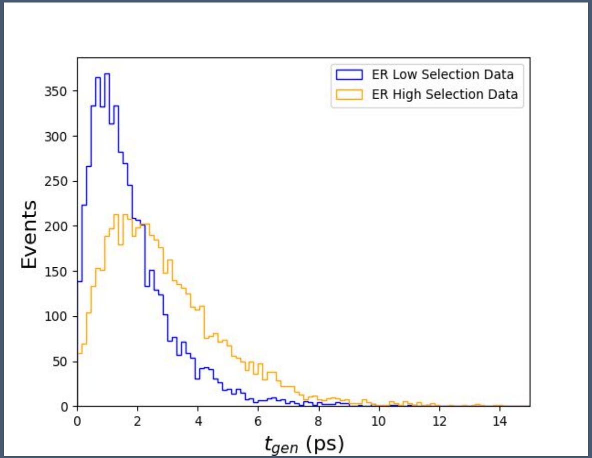
Aleczander

Reconstruction Efforts

Compare the decay time distributions for different bins in both x_{max} and $x_{min}+x_{max}$

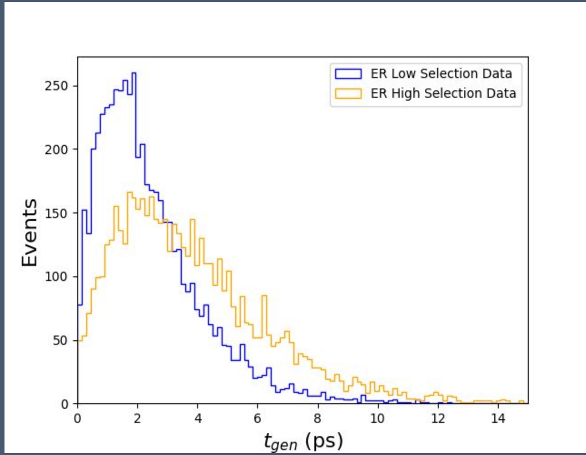
We see distinct shapes ✓

good separation



via x_{max}

good separation



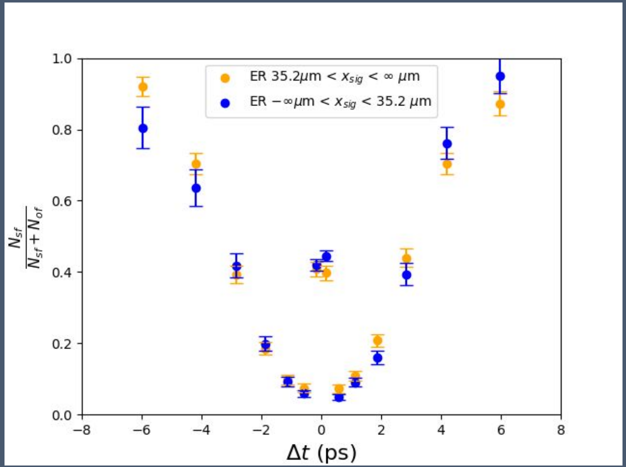
via $x_{min}+x_{max}$

Reconstruction Efforts

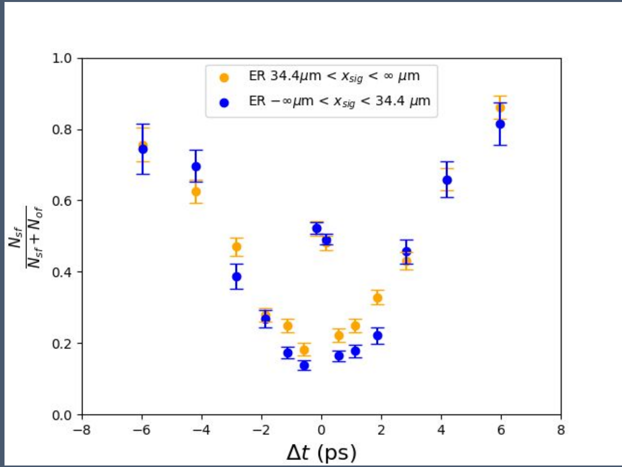
We use a modified version of EvtGen (thanks to Alexei) which implements decoherence.

We analyze two bins in x_{max} as a proxy for t_{max} (blue and orange).

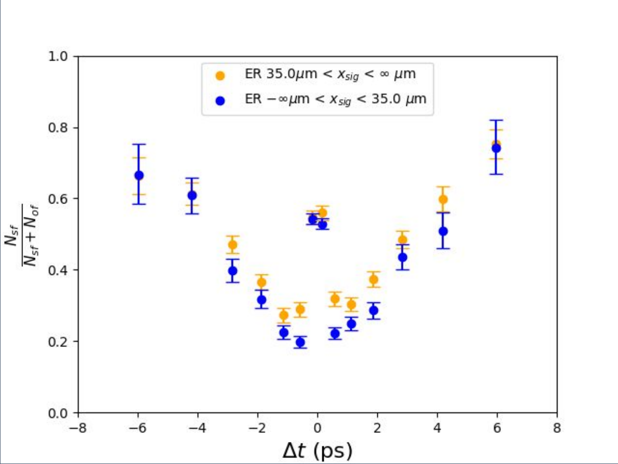
Observe separation of the two bins as λ increases → indicates experimental feasibility



λ = 0



λ = 0.5



λ = 1

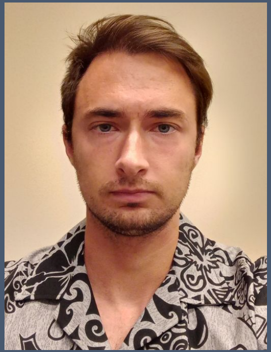
Summary & Further Plans

- Hershel and Aleczander developed a proof of concept…
  - … that on truth-level, binned fits in the absolute decay time are sensitive to Lindblad decoherence
  - … that an estimation of the absolute decay time is possible on reconstructed data
  - … we are sensitive to Lindblad decoherence in reconstructed data
- We will continue to work on this topic by two UHM students…
  - Tim: “Lindblad” environmental decoherence, hadronic decays
  - Lucas: Fractional spontaneous decoherence, hadronic decays

Thank you for your attention!

Prof. Sven Vahsen

Dr. Alexei Sibidanov



Timothy Mahood (Grad)

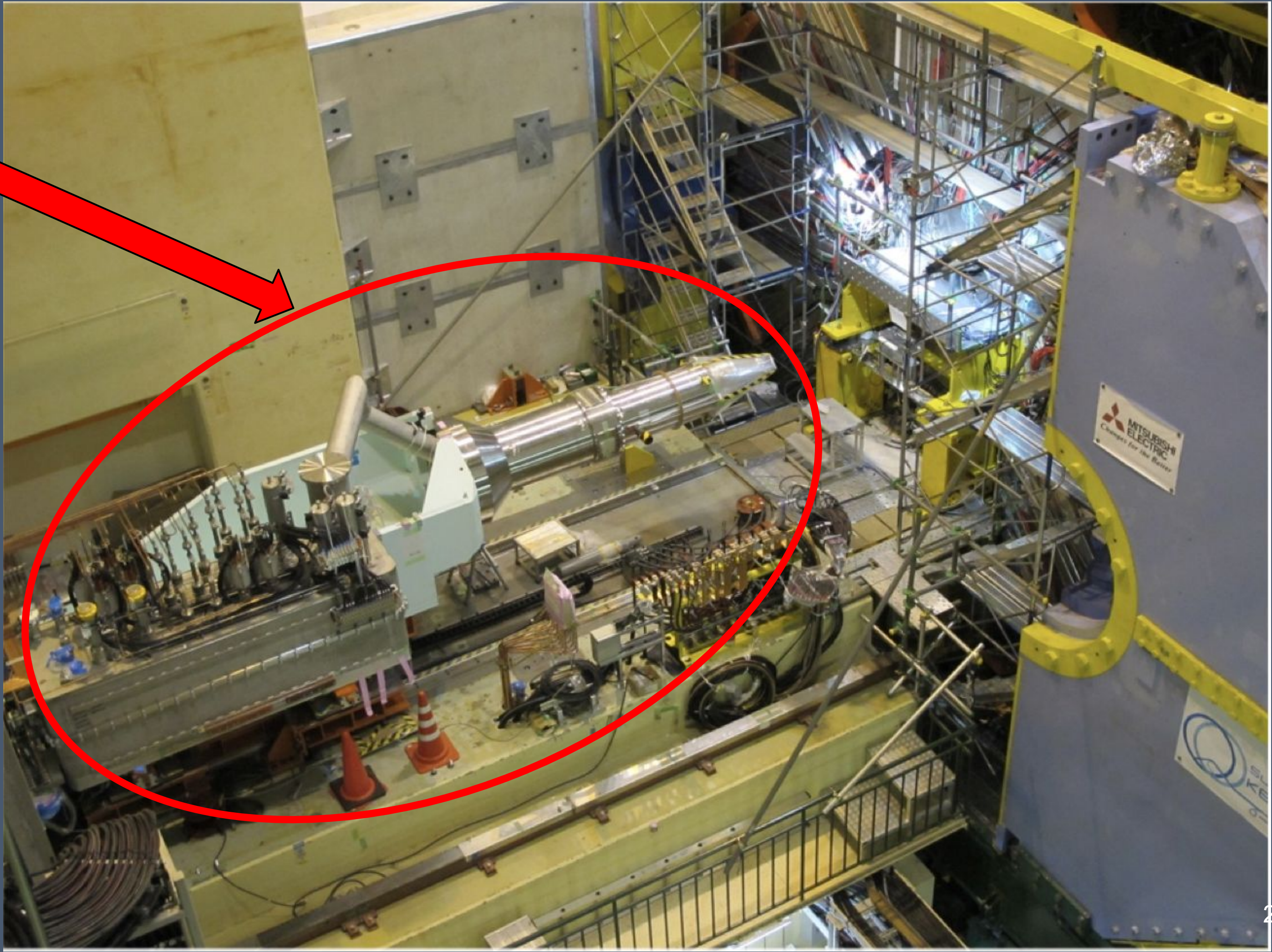
Lucas Stoetzer (Grad)

Hershel Weiner (Undergrad)

Aleczander Paul (Undergrad)

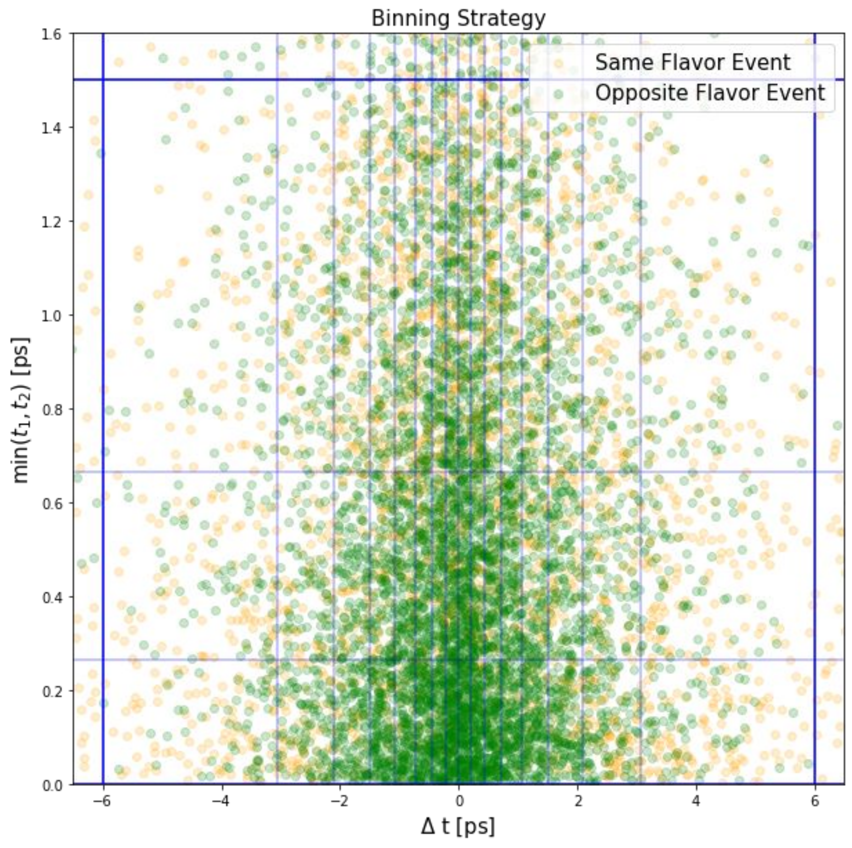
QCS

- 4 Quadrupole Magnets for each beam line
- 43 corrector/cancel coils
- 4 compensation solenoids

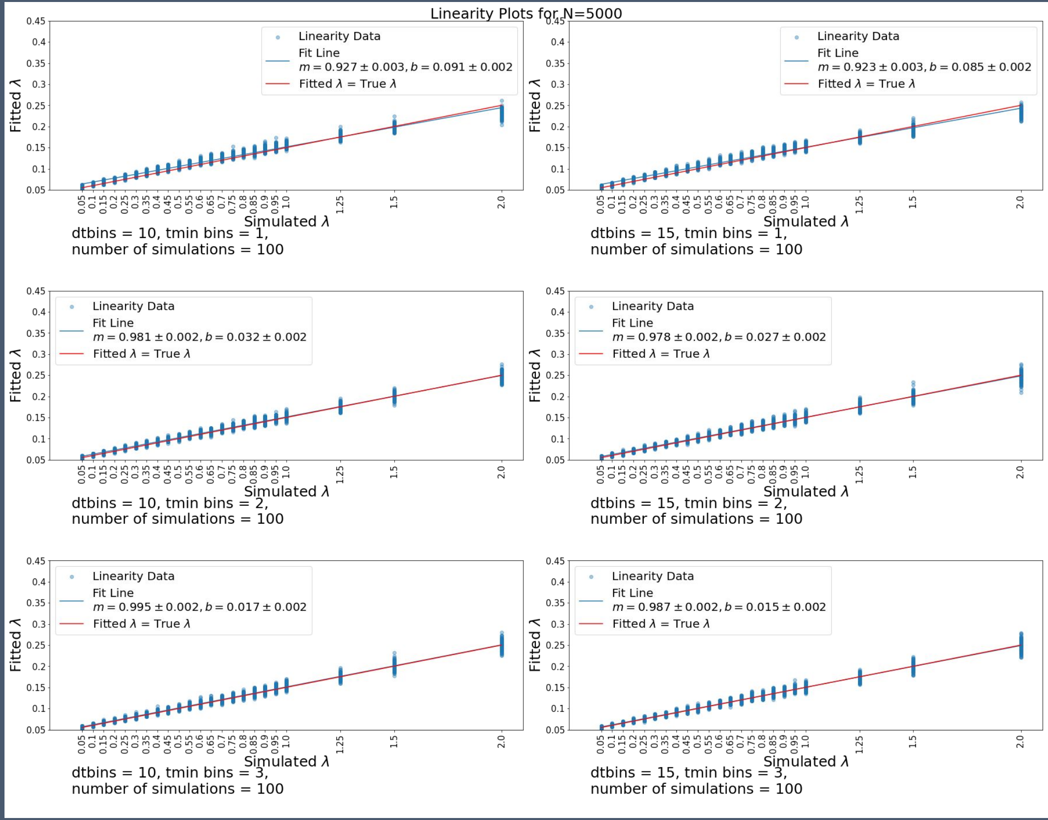


Y. Arimoto, https://conference-indico.kek.jp/event/18/sessions/111/attachments/132/139/171212-asian_school-YA.pdf

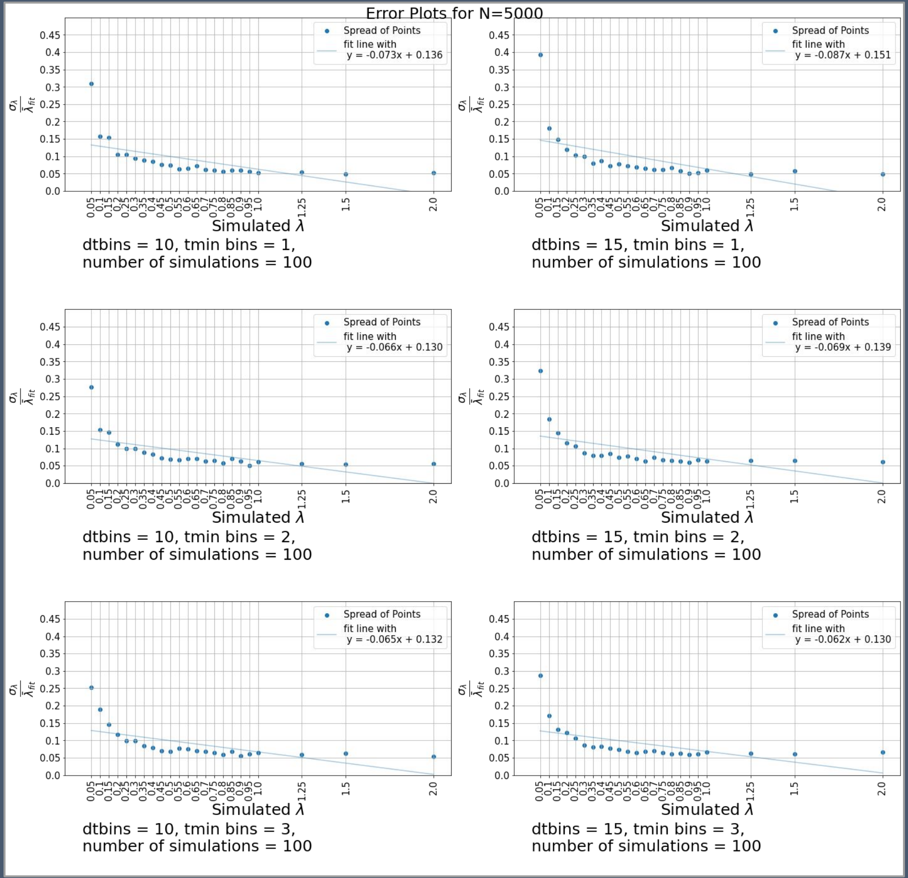
Backup - Binning



Backup - Fitter Linearity

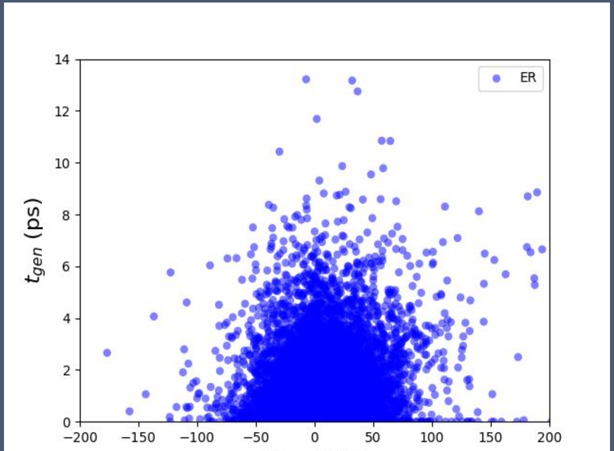


Backup - Fitter Sensitivity



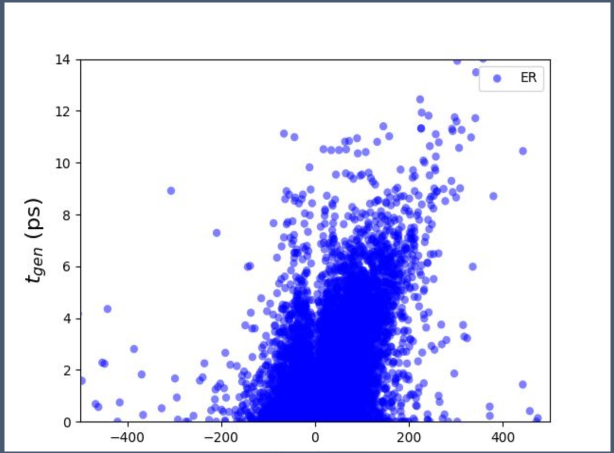
Backup - Correlation of various x-values

poor correlation



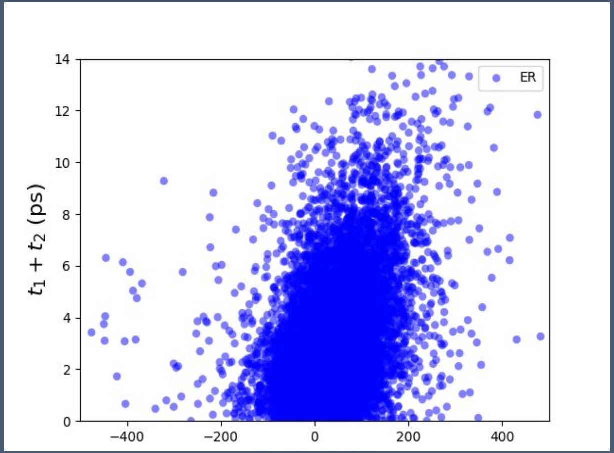
x_{min}

good correlation



x_{max}

good correlation

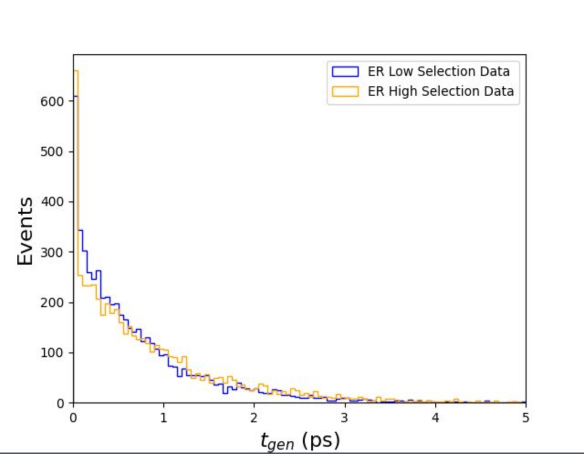


$x_{min}+x_{ma}$

x

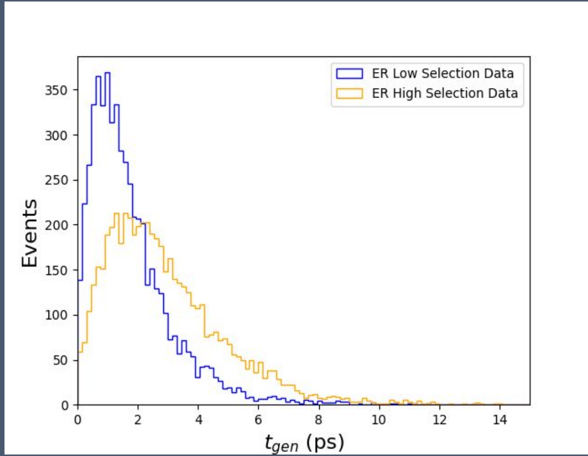
Backup - Distinguishing x-bins

poor separation



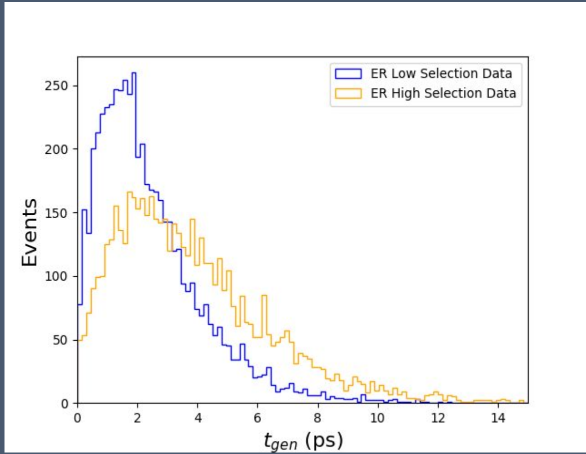
via x_{min}

good separation



via x_{max}

good separation



via $x_{min}+x_{max}$