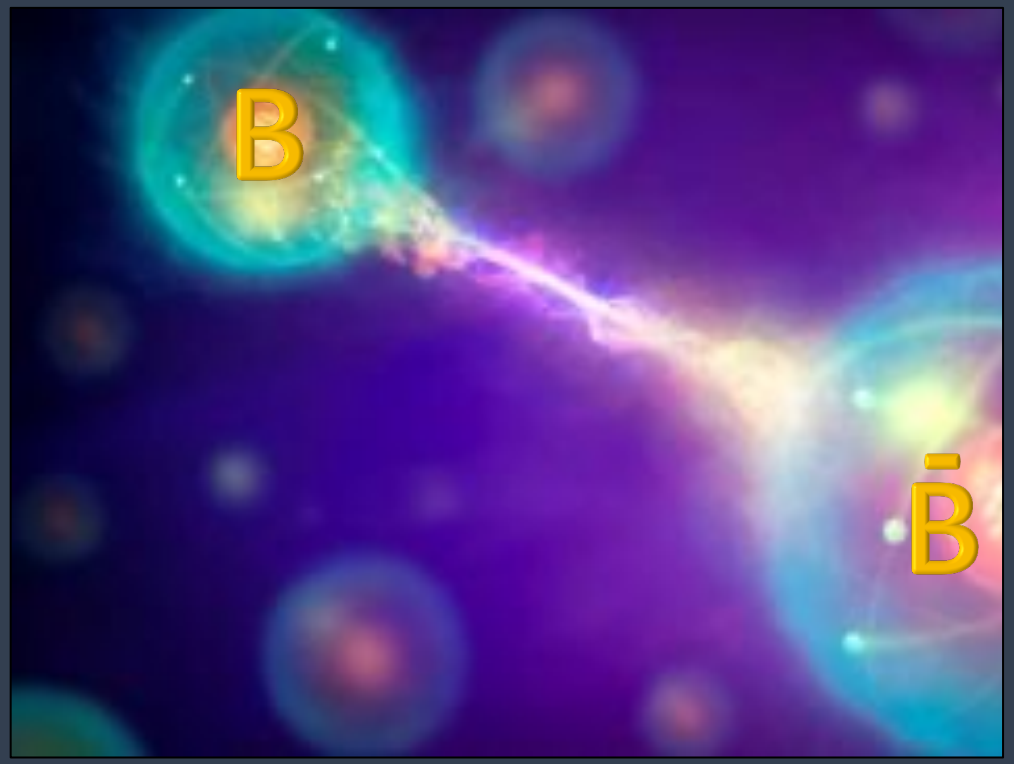
Update on Quantum Decoherence Activities @ U. Hawaii

MPI / Hawaii meeting

May 6th, 2024

Sven Vahsen, U. Hawaii



QM Decoherence Team at U. Hawaii

Sven Vahsen (professor)

Alexei Sibidanov (postdoc)

Timothy Mahood (grad student)

Lucas Stötzer (grad student)

Aleczander Paul (undergrad)

Hershel Weiner (undergrad)

- Sven, Aleczander, Hershel
  - Exploring basic QM decoherence analysis ideas/strategies
- Alexei
  - Implementing EvtGen models
  - Lindblad done
- Tim
  - Updating resolution function for TDCPV fits, hadronic decays
  - Belle II PhD thesis on “Lindblad” environmental decoherence, hadronic decays (?)
- Lucas
  - Generator validation
  - Belle II PhD thesis on fractional spontaneous decoherence, hadronic decays (?)
- Jeff Schueler (former PhD student):
  - Started analysis similar to A. Go’s Belle analysis / PRL paper

Recent activities I: Hershel and Aleczander

- Both wrote honor's theses on quantum decoherence
  - Worked two semesters, at the 10h/week level of effort
  - Completed May 30th, 2024 !
- Performed literature survey, verified calculation in foundatinal papers
  EPR paradox, Bell inequality, Lindblad decoherence
- Worked on early/exploratory MC-only studies with basf2
  - How to measure 'Lindblad decoherence' parameter λ
  - Binned fitting strategy (Hershel)
  - Flavor-tagging/vertexing strategy (Aleczander) with signal MC (two B's reconstructed exclusively vs one B generally) and t_{min} measurement
- Both applying for graduate school, may continue on this topic if they stay at U. Hawaii

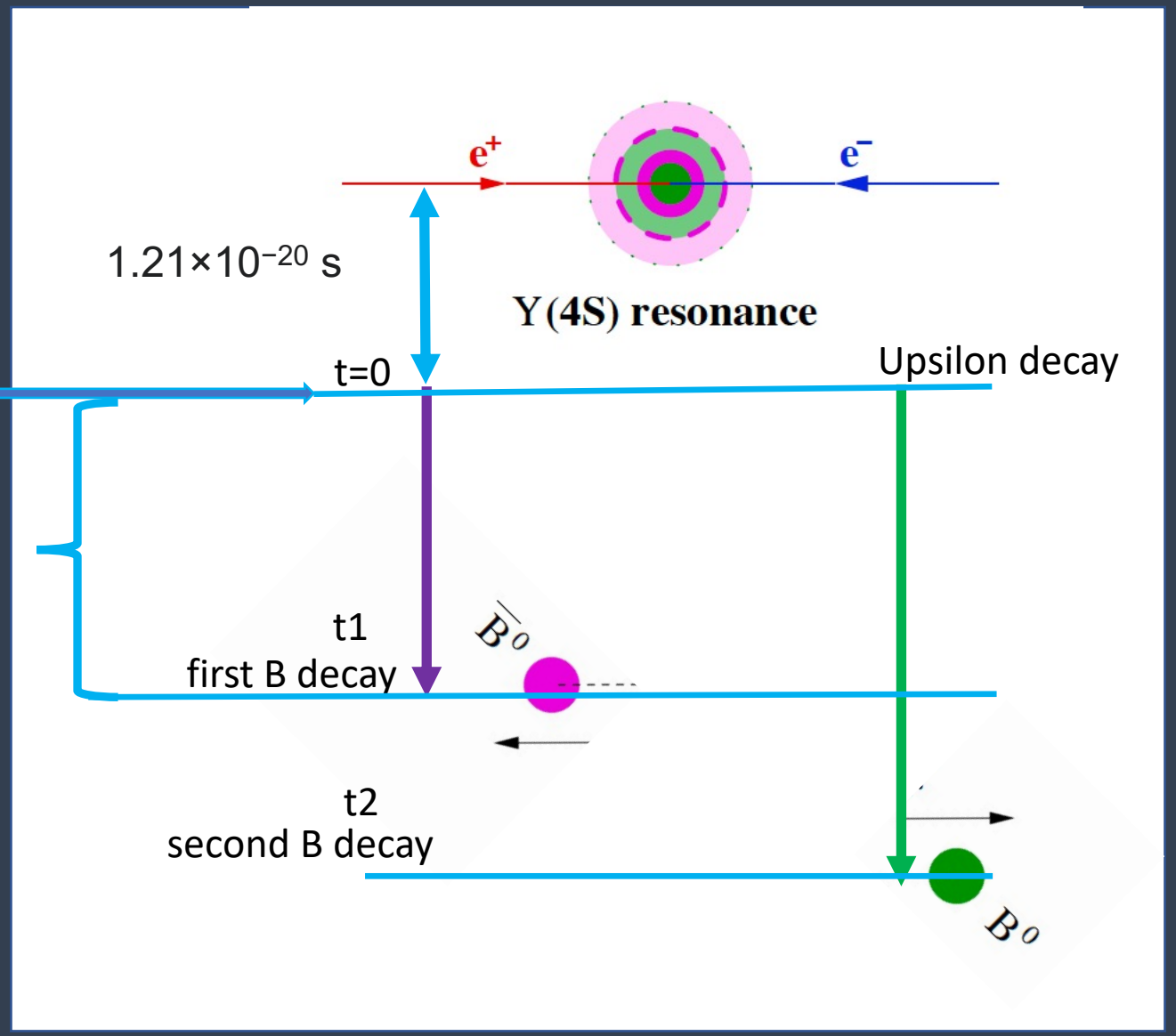
Recent activities II: Alexei

- Alexei Sibidanov (postdoc) has become an EvtGen Developer
- He has made a number of EvtGen modifications, which are slowly being submitted to the official EvtGen repository (interacting with Thomas Latham at University of Warwick
  - Improved efficiency in multi-particle phase space generation
  - K*ll BSM
  - D*lnu BSM
  - Quantum Decoherence
- Recently implemented new BB mixing model w/ Lindblad Decoherence
  - See model predictions on p.7-8
- It will likely take a long time until Alexei's full work reaches Belle II via official EvtGen
- Therefore, he has made a compiled version available on KEKCC
- We will also work also to get Decoherence models directly into Belle II EvtGen
- Some discrepancy between Alexei's predictions and Hershel's --- validation still needed

Spontaneous disentanglement
or non-coherent production

Lindblad type decoherence

time

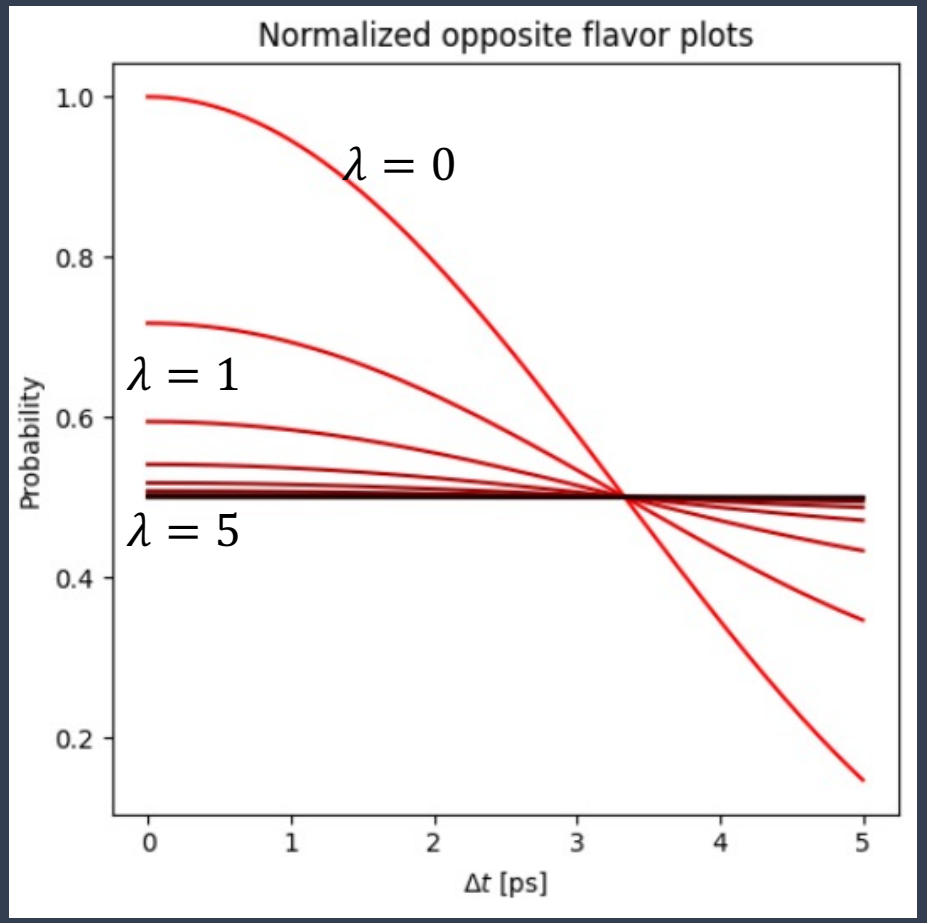


Lindblad Type Decoherence

- Decoherence begins after $\Upsilon(4S)$ decay and ends at first B meson decay
- Parameter $\lambda \in [0, \infty)$ characterizes how much decoherence is in the system
- Slow acting decoherence
- Hershel Weiner (Hawaii undergrad) confirmed theory predictions for Belle II:

$$N = \frac{1}{4} e^{-\Gamma(t_1+t_2)} \left[\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) - \mu e^{-\lambda t_1} \cos(\Delta m \Delta t) \right]$$

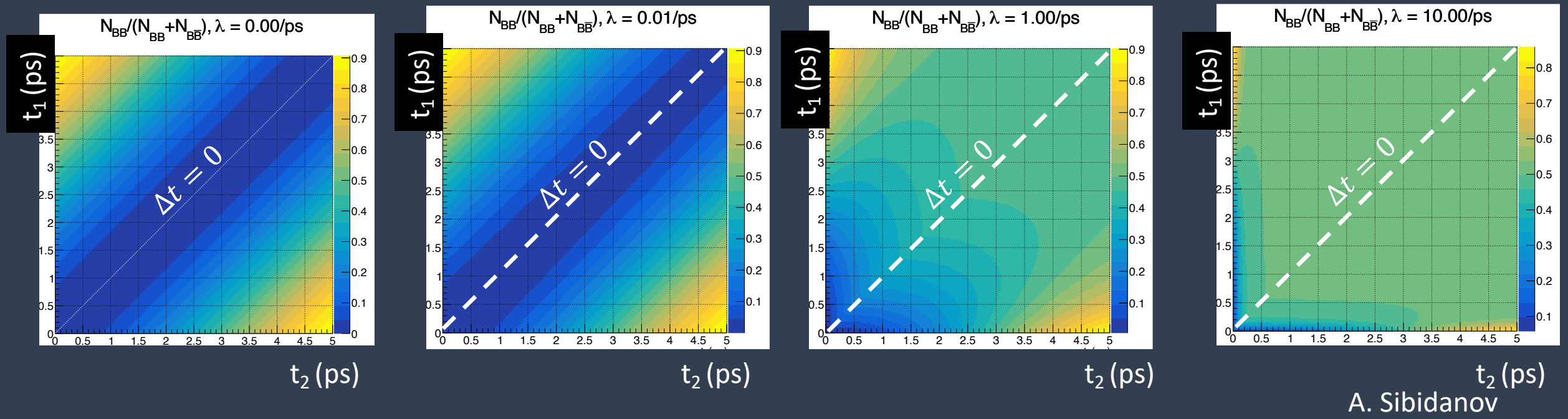
μ=+1: same flavor decays, -1: opposite flavor decays



- As decoherence strength parameter λ increases; same-sign B meson pairs at $\Delta t = 0$ become allowed
- model depends on individual t1 and t2, but that has been integrated out in figure → Δt dependence looks like miss-tagging

BB pair flavor vs t_1, t_2 for Lindblad decoherence

λ (decoherence strength)



A. Sibidanov

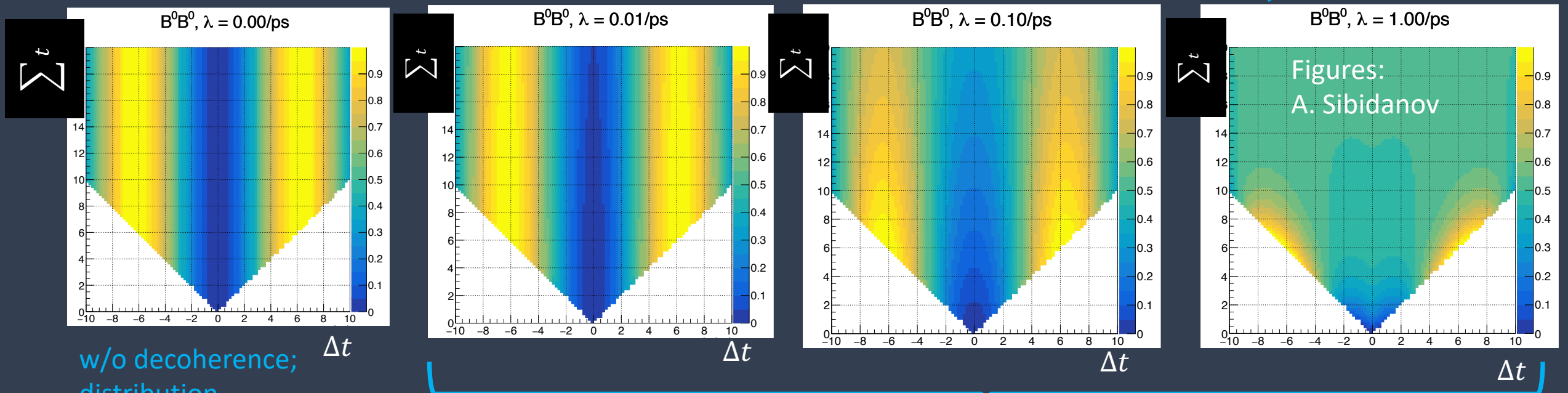
- As decoherence strength parameter λ increases
- Number of same-sign B meson pairs at $\Delta t = 0$ increases
- In this 2d plane, pattern distinct from miss-tagging (assigning wrong b-flavor in reconstruction)

B meson flavor vs $\sum t$, Δt for Lindblad decoherence

$$\sum t = t_1 + t_2$$

$$\Delta t = t_2 - t_1$$

λ (decoherence strength)

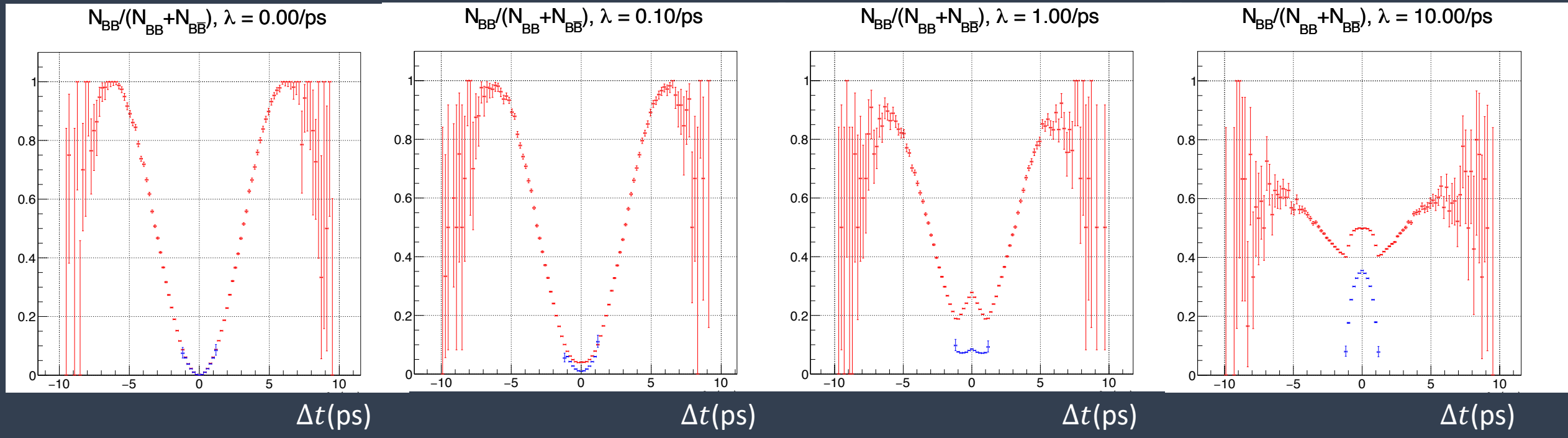


w/o decoherence; distribution independent of $\sum t$

w/ decoherence; Δt distribution depends on $\sum t$

Measuring $\sum t$ (or equivalently; just t_1) in addition to Δt likely enhances sensitivity to decoherence, and the difference between miss-tagging and decoherence

Example: weak sensitivity to $\sum t$ → two bins only



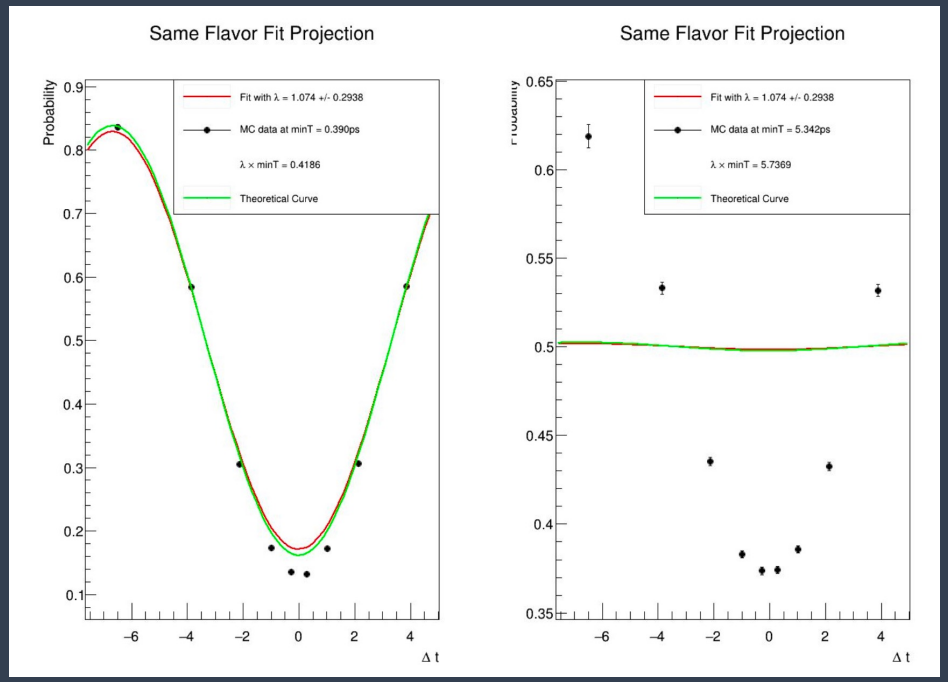
Red: event with high $\sum t$
Blue: event with low $\sum t$

A. Sibidanov

Fitting for Lindblad Decoherence Parameter λ using truth-level decay times and flavor

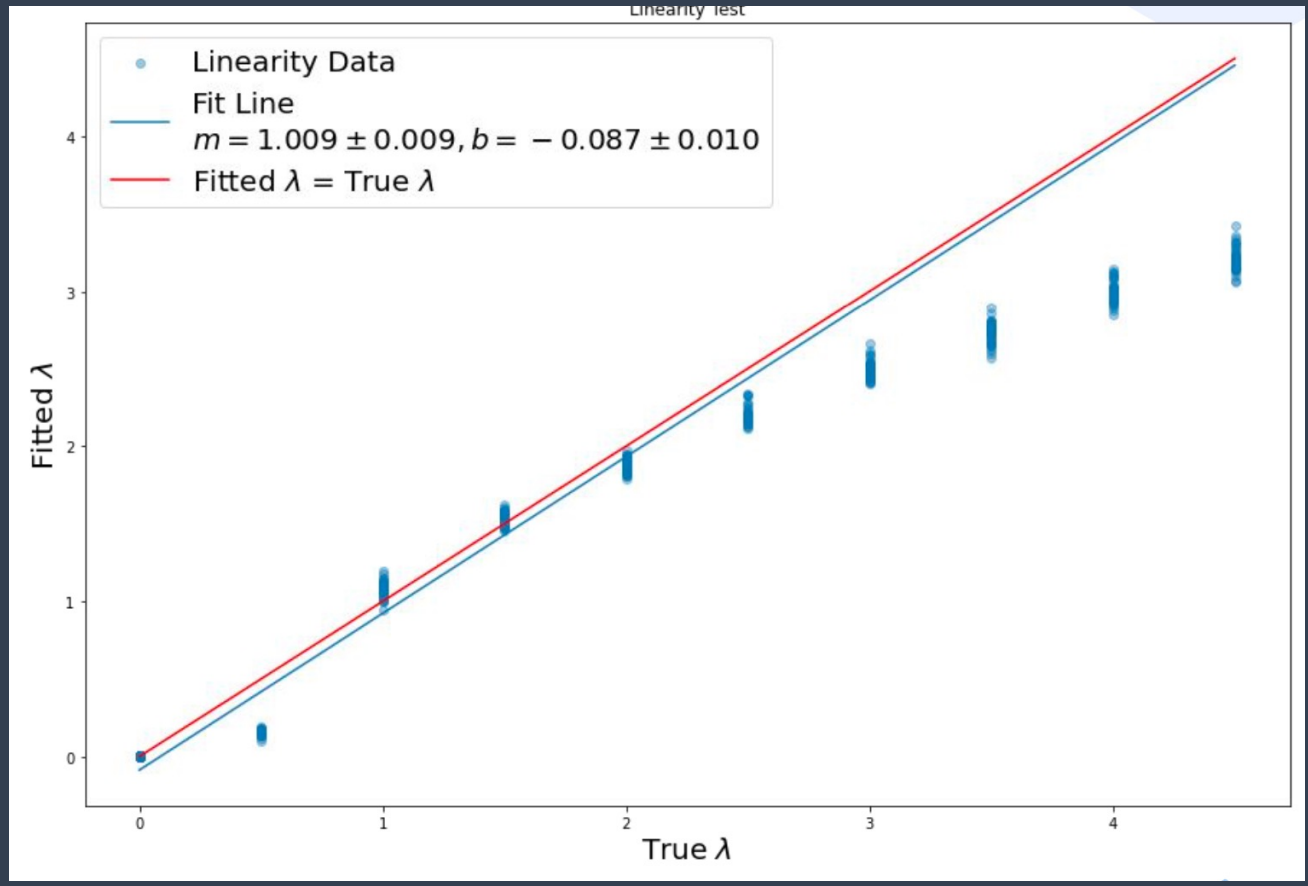
Hershel

Performing 2d binned fit: 10 Δt bins and 2 t_{min} bins



Starting to work. There's still a bug related to binning which biases the data at high t_{min}.

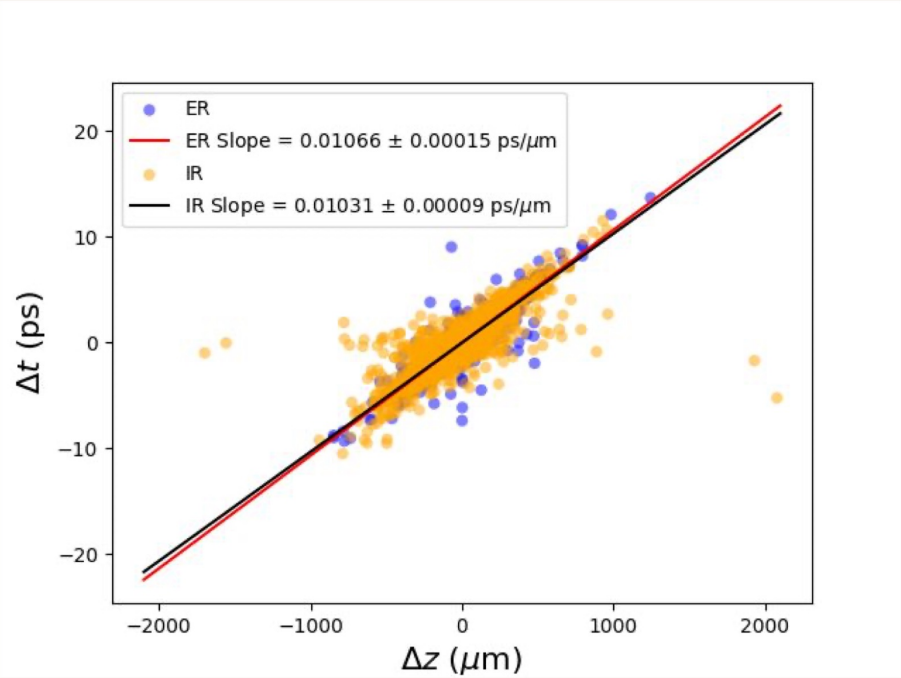
Linearity test w/ 100k events per fit



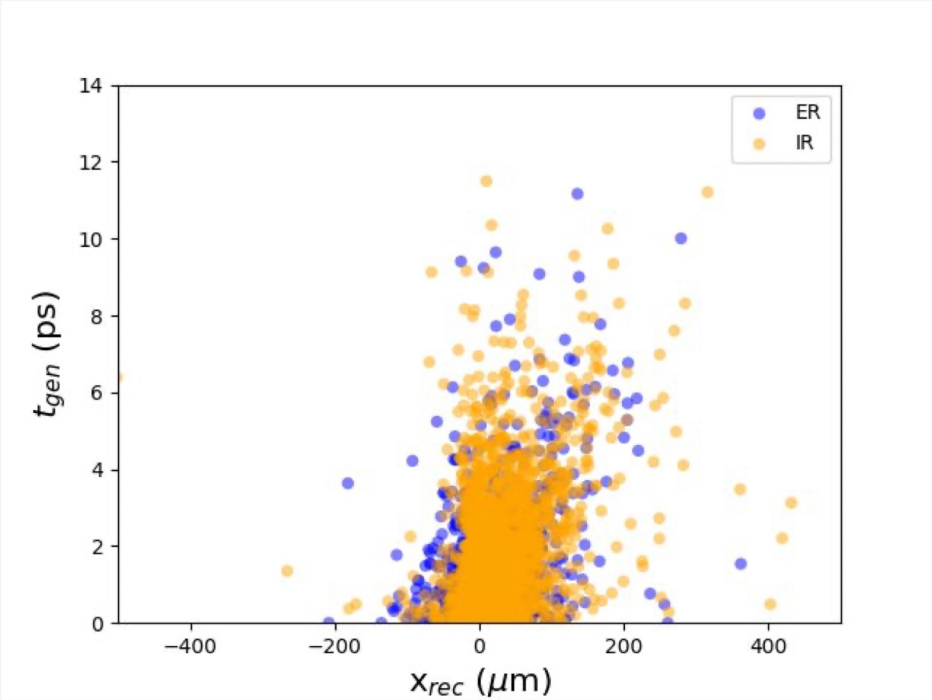
Sensitive to true λ. Biased at larger λ.

Aleczander

Obtaining reconstructed quantities: Δt, t_{min}



Use correlation to find difference in B meson lifetime (commonly done)



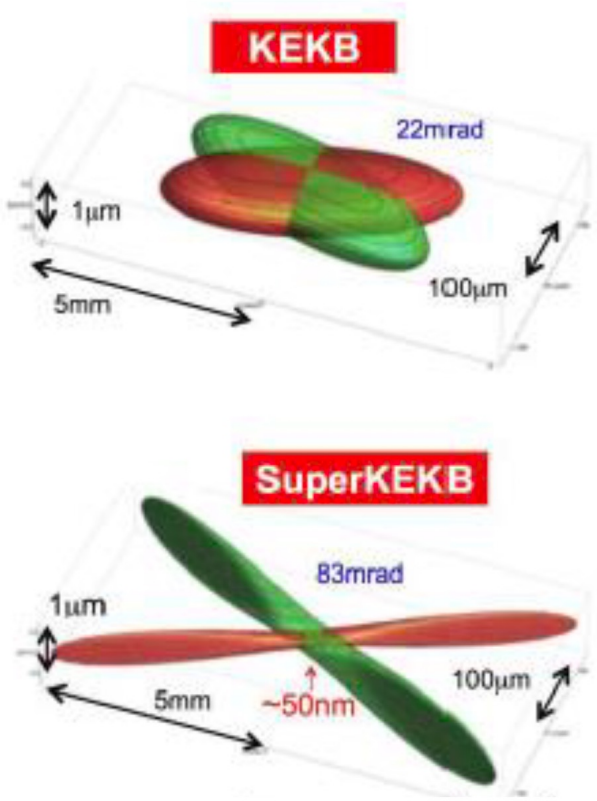
Discovered correlation between t and x, found proxy for absolute B meson lifetime!

Non-zero correlation due to crossing angle!

Critical issue: Size of IP

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

	KEKB (LER, achieved)	SuperKEKB (LER, design)	SuperKEKB (LER, achieved)
σ_x^*	147 μm	10.1 μm	17.9 μm
σ_x^*effective	-	249 μm	249 μm
σ_y^*	~1 μm	48 nm	223 nm
σ_z^*	~7 mm	6 mm	~6 mm
σ_z^* effective	-	0.24 mm	0.43 mm



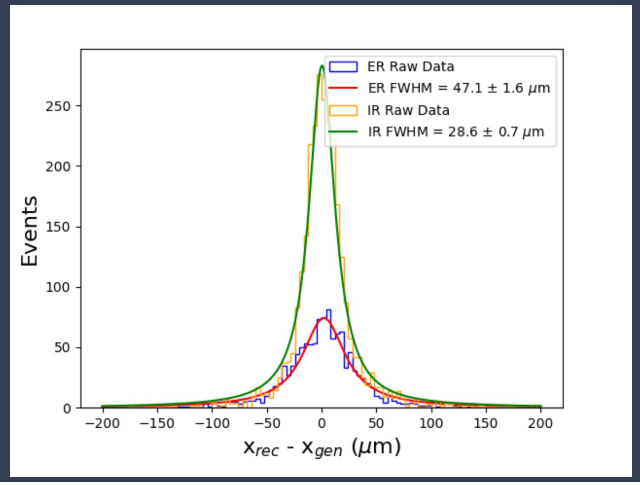


Figure 8: Decay vertex accuracy distributions with best fit Lorentzian for signal decays (left) and generic decays overlaid with signal decays (right) along each coordinate axis of the detector. "ER" refers to exclusive reconstruction B mesons, and "IR" refers to inclusive reconstruction B mesons.

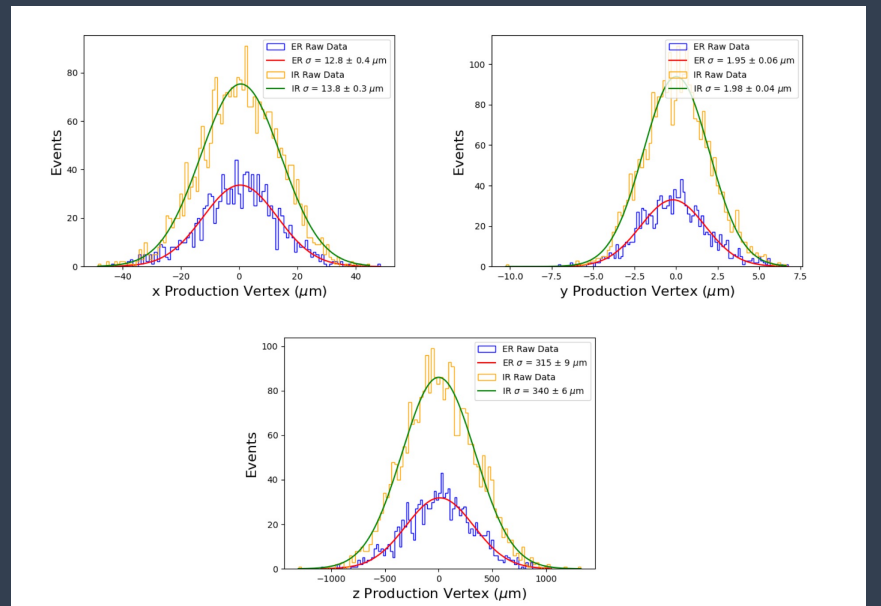
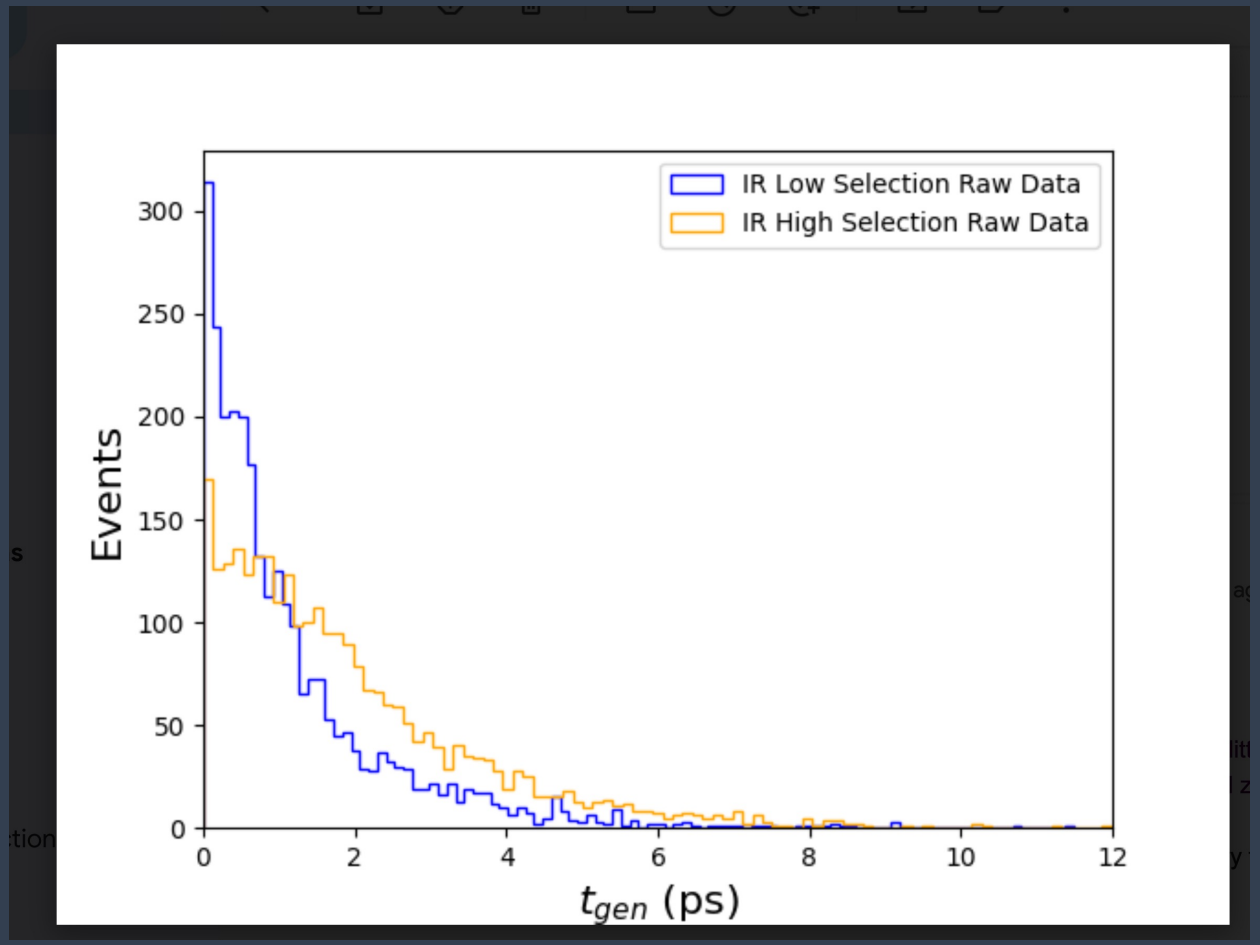


Figure 11: Distribution of the truth level production vertex of the B mesons. "ER" refers to exclusive reconstruction B mesons, and "IR" refers to inclusive reconstruction B mesons.

Looks like IP shape in simulation is based on SuperKEKB *design* --> should switch to run-dependendent MC. Not fully sure if yellow table (from machine group) is accurate for x. But it appears σ_x is small even before beams are fully focused? Lucky for us! Measurement looks feasible already now!

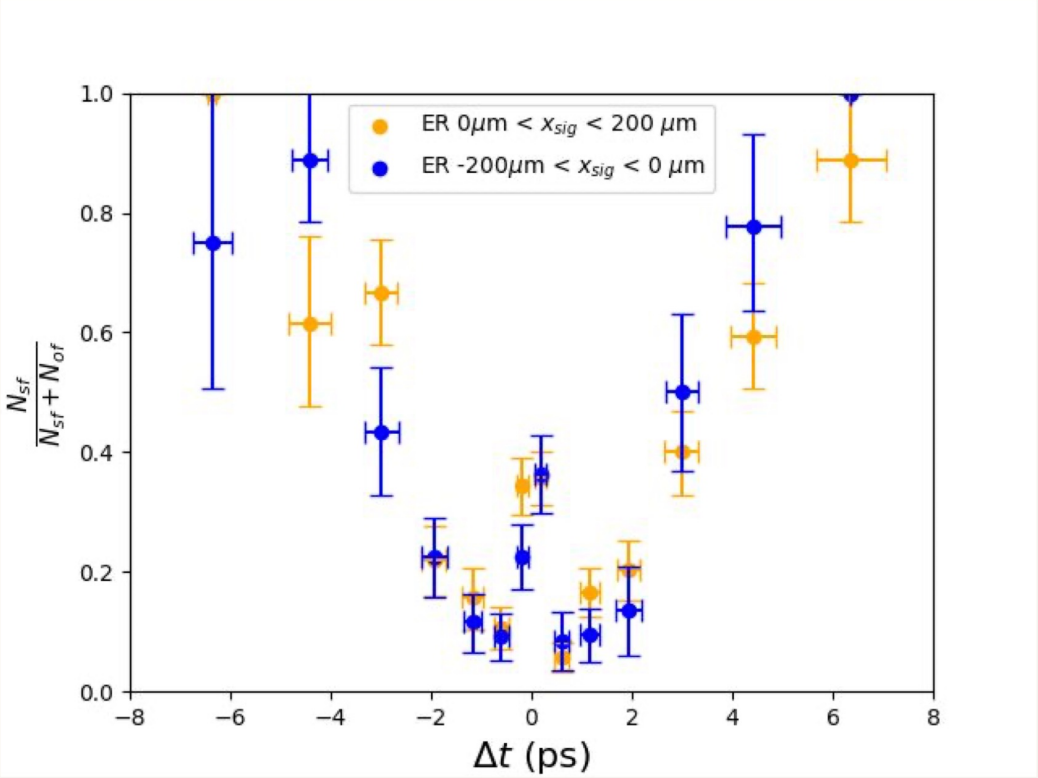
Selecting on reconstructed x_{vertex} of B meson

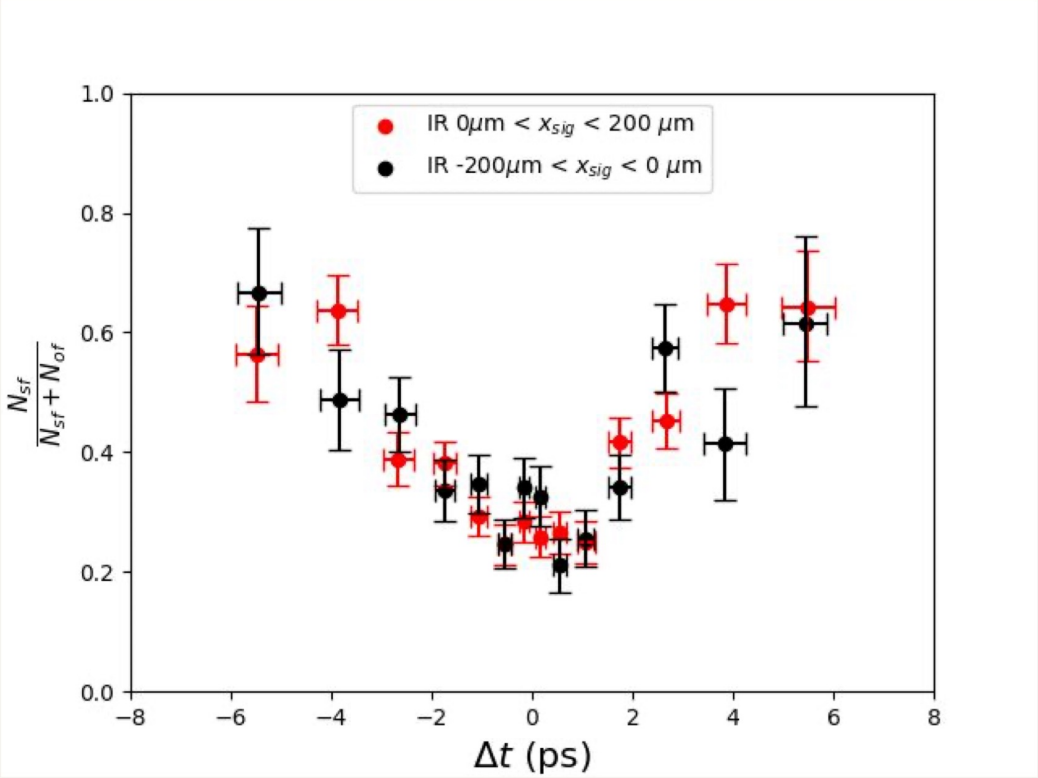


- We obtain two different *t* distributions.
- Technique appears feasible!

Reconstructed Δt distributions

Flavor vs Reconstructed Lifetime





This is for λ =0. Plan to repeat with new MC w/ λ != 0 next week! Exciting!

Summary

- Exploratory studies by Hershel and Aleczander nearly complete
  - Truth-level binned fits sensitive to Lindblad decoherence. (Proof-of-concept; not the optimal/final analysis technique)
  - We seem to have a first, straightforward experimental strategy to reconstruct t_{min}!
  - Measurements of Lindblad decoherence and other models appear realistic!
- Tentative PhD topics
  - Tim: “Lindblad” environmental decoherence, hadronic (?) decays
  - Lucas: fractional spontaneous decoherence, hadronic (?) decays
  - This plan may need more thinking and optimization
  - Hershel & Aleczander?
- We would prefer to collaborate closely instead of competing. Could MPI develop the convolution techniques needed for fitting the Lindblad decoherence PDF and other models?
- Need to discuss promise of semi-leptonic vs hadronic decays.

BACKUP

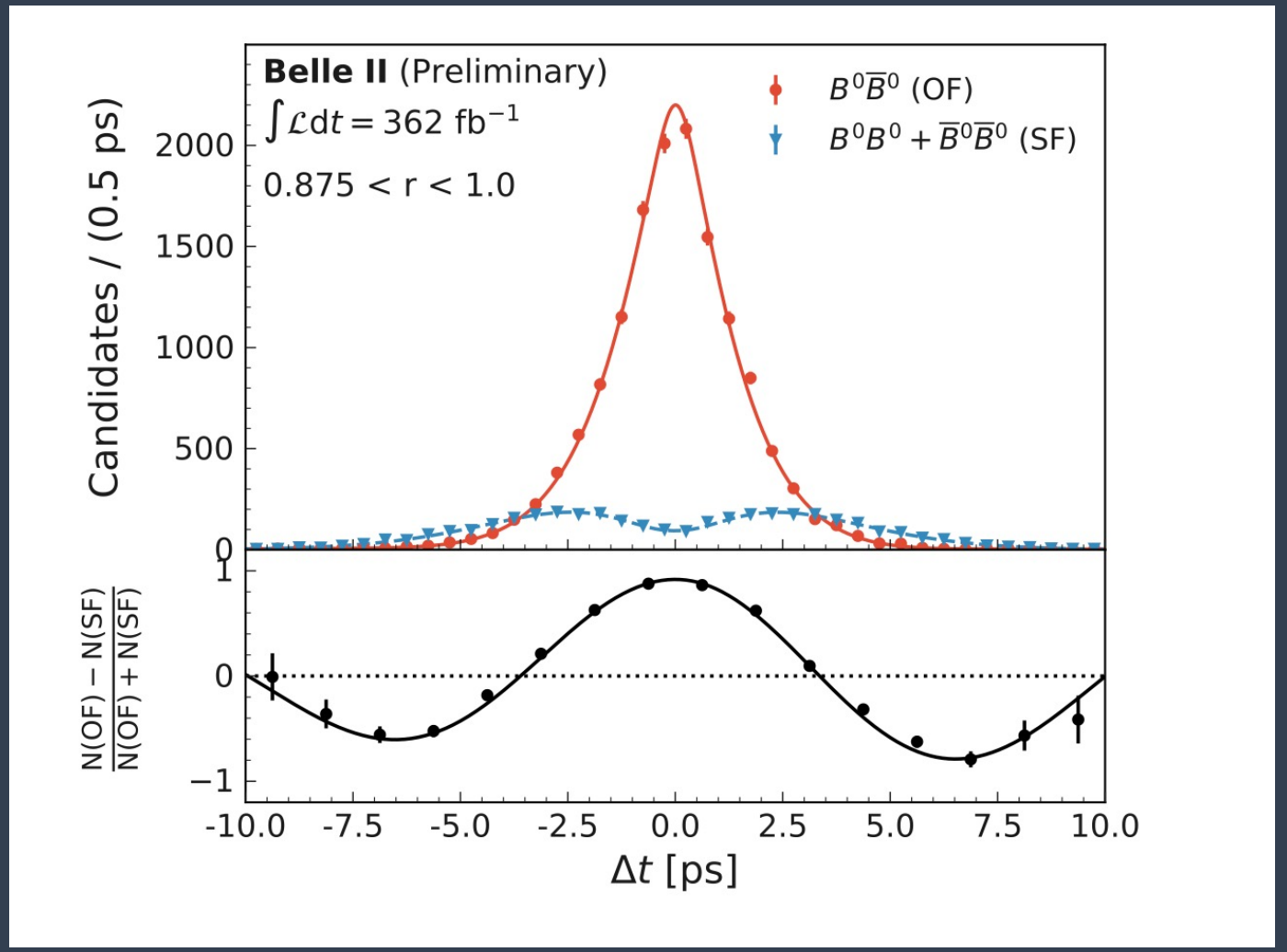
Recent Activities IV: Tim and Lucas

- Both Tim and Lucas now have passed university requirements to transition to PhD program
  - i.e. don't have to take more classes, can do research full-time
- Plan is for both to do a PhD thesis on quantum decoherence
- Exact but details to be decided
  - One option: Tim searches for Lindblad decoherence, Lucas spontanous decoherence
  - Another option: Tim Lindblad w/o t1 measurement, Lucas w/ t1
  - But also need to coordinate with MPI/IPMU
- Tim doing service work on resolution function to prepare
- Lucas was planning to measure K_L efficiency, as service work
  - But that may now be sufficiently covered by two other groups?
  - If so, might be beneficial to do service more closely related to TDCPV analyses – suggestions?

$\Upsilon(4S) \rightarrow B^0\overline{B^0}$: a Quantum Laboratory

https://arxiv.org/abs/2402.17260

- Non-local flavor entanglement is assumed "perfect" in analyses of B-mixing and TDCPV
- Sensitive searches for *deviations from nominal mixing and perfect entanglement are possible*
  - *using Δt distributions*
  - *desirable to also measure individual B meson decay times (t1,t2)*
- Belle II better suited than Belle
  - (eventually) higher statistics
  - improved vertex resolution
  - better tagging efficiency
  - smaller luminous region → access to t1,t2



What can we probe in this Quantum Laboratory?

Six broad categories

1. B meson properties ($\Delta m, \tau_B$), CPV in the weak interaction (e.g. sin $2\emptyset_1$)
2. BSM Symmetry violations (CPTV, Lorentz symmetry violation)
3. Search for evidence of hidden variable theories (alternatives to QM)
4. Collapse theories (augmentations of QM)
5. Quantum Decoherence

✅ Bread and butter of B factories

✅ Belle, Babar, (D0, LHCb,…)

✅ Belle (PRL 99, 131802 – 2007)

not attempted?
(except for spontaneous decoherence, included in 2007 Belle PRL)

The Belle PRL on EPR

A. Go et al. used deconvolved Δ*t distribution*, excluded

- "Pompili-Selleri" hidden variable model

$$\begin{aligned} A_{PS}^{max}(t_1,t_2) &= 1 - |\{1-\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{min}) \\ &\quad + \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{min})|, \text{ and} \quad (3) \\ A_{PS}^{min}(t_1,t_2) &= 1 - \min(2+\Psi, 2-\Psi), \text{ where} \quad (4) \\ \Psi &= \{1+\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{min}) \\ &\quad - \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{min}). \quad (5) \end{aligned}$$

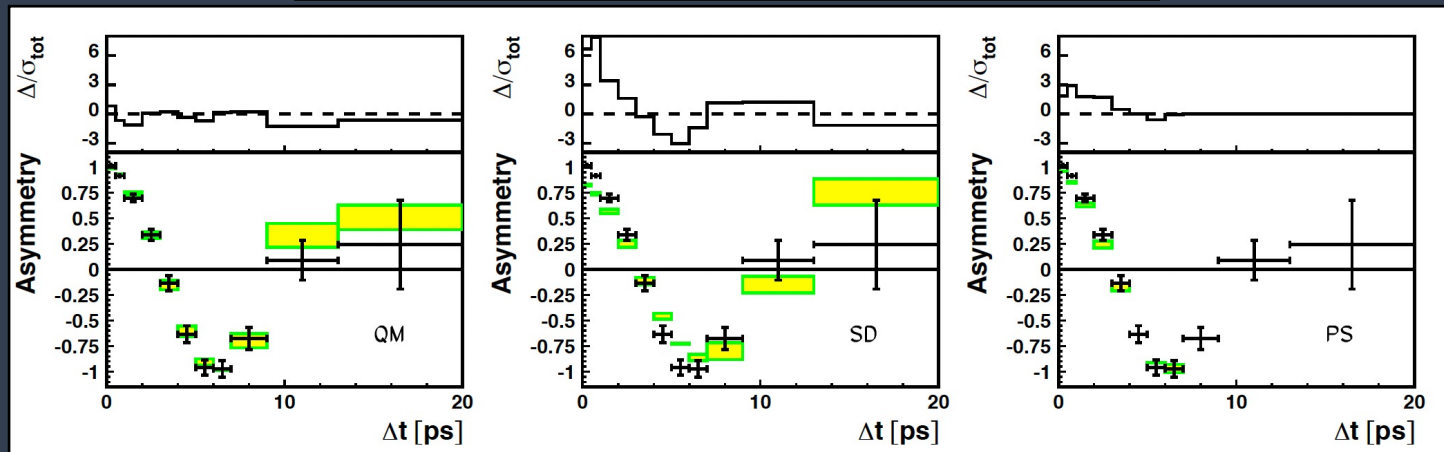
- "Spontaneous Disentanglement" of all BB pairs

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

- Fractional Spontaneous Disentanglement
  - 3% +/- 6%

Measurement of Einstein-Podolsky-Rosen-Type Flavor Entanglement in $\Upsilon(4S) \to B^0\overline{B}^0$ Decays

A. Go *et al.* (Belle Collaboration)
Phys. Rev. Lett. **99**, 131802 – Published 26 September 2007



QM fits well
$\chi^2/n_{dof} = 5/11$

SD disfavoured: 13σ
$\chi^2/n_{dof} = 174/11$

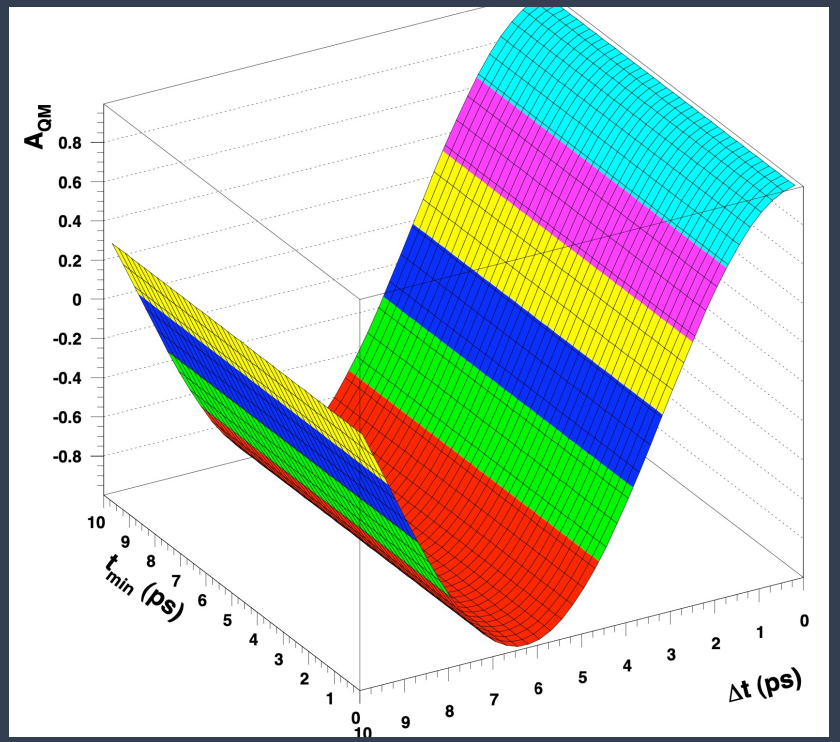
PS disfavoured: 5.1σ
$\chi^2/n_{dof} = 31/11$

Note: models depend on t1, t2, but these were not measurable in Belle, hence integrated out

Discrimination Power of individual B meson decay times t1, t2

Access to t_1 generally adds a new dimensions and should result higher sensitivity

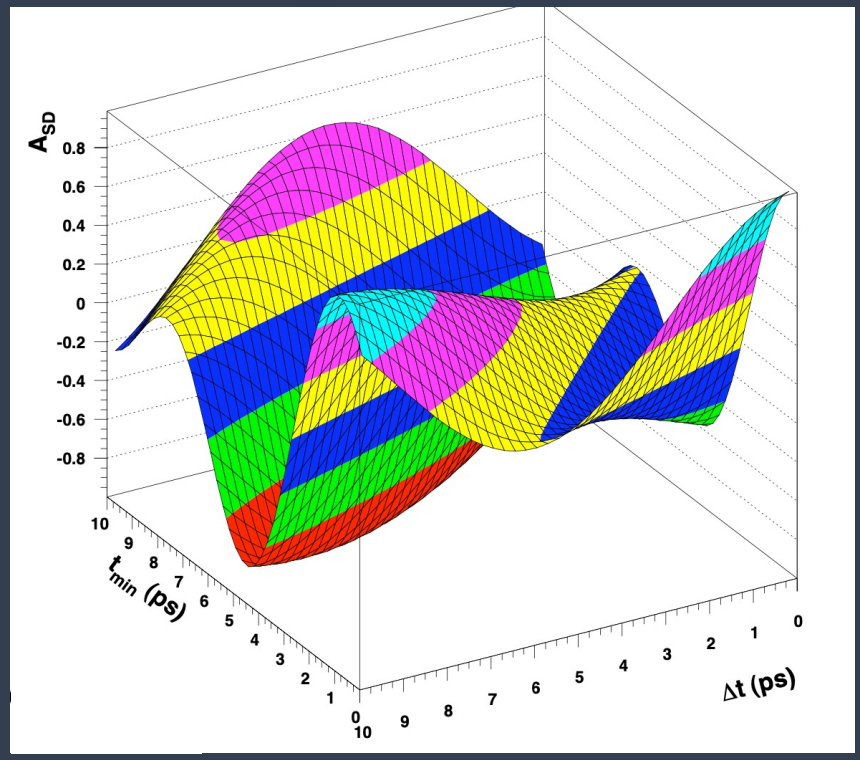
Asymmetry for QM



Entanglement: depends only on Δt

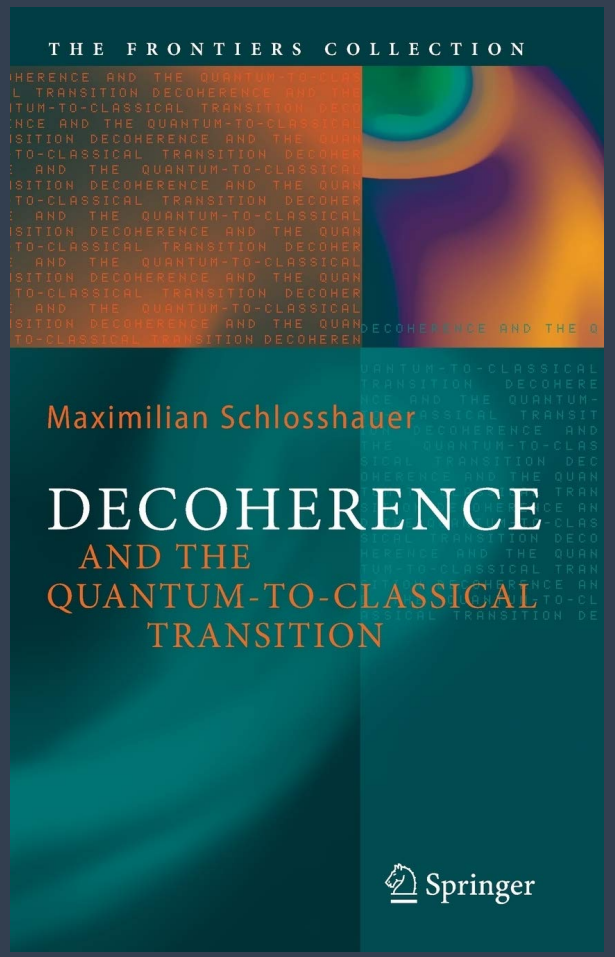
B. Yabsley

Asymmetry for Spontaneous Disentanglement



Disentanglement and decoherence: depends on t_1 and Δt

Quantum Decoherence



- Interaction of entangled states with environment can explain appearance of classical behavior at macroscopic scales
- Not an extension of QM, but rather a consequence of QM that was not previously appreciated
- Entangled states decohere over time
- Limits quantum computers
- SM decoherence
  - Our $B\overline{B}$ system evolves inside the SuperKEKB beam pipe
  - But even such an ”isolated” system still interacts with background fields: CMB, cosmological neutrinos, Higgs condensate…
- BSM decoherence
  - Energy density components that we do not fully understand, yet, may also contribute: dark matter & energy

Recent activities I: Sven

- Gave Belle II talk at March ‘24 PITT PACC Workshop: Exploring Quantum Mechanics in High Energy Physics
- Talk generated lots of discussion, positive feedback from a diverse audience (LHC experimentalists, quantum information theorists, ...)
- Take-away messages (my biased opinion)
  - Belle only published a single paper (PRL) that studies BB entanglement, in 2007, with partial dataset
  - Belle probably ‘backed off’ too far in this PRL, after theorists rejected A. Go’s initial claim (in a conference paper) of having observed Bell-inequality violation.
  - Several intriguing studies possible on Belle II data, participants strongly encouraged our plans
  - Theorists seemed motivated to predict decoherence times for difference processes

Recent activities II: Hershel and Aleczander

- Both writing honor's theses on quantum decoherence
  - over two semesters, at the 10h/week level of effort
- Performed literature survey, verified calculation in foumdatinal papers
  EPR paradox, Bell inequality, Lindblad decoherence
- Now working on early/exploratory MC-only studies
  - Fitting for 'Lindblad decoherence' parameter λ
  - Studying fitting strategy (Hershel) and flavor-tagging/vertexing strategy (Aleczander) with signal MC (one B decays generally)
  - Won't look at experimental data
  - Both applying for graduate school, some chance they may continue on these topics if they stay at U. Hawaii

Recent activities III: Alexei

- Alexei Sibidanov (postdoc) has become an EvtGen Developer
- He has made a number of EvtGen modifications, which are slowly being submitted to the official EvtGen repository (interacting with Thomas Latham at University of Warwick
  - Improved efficiency in multi-particle phase space generation
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  - Quantum Decoherence
- Recently implemented new BB mixing model w/ Lindblad Decoherence
  - See model predictions on p.14-16
- It will likely take a long time until Alexei's work reaches Belle II via official EvtGen
- Therefore, he will a make compiled version available on KEKCC

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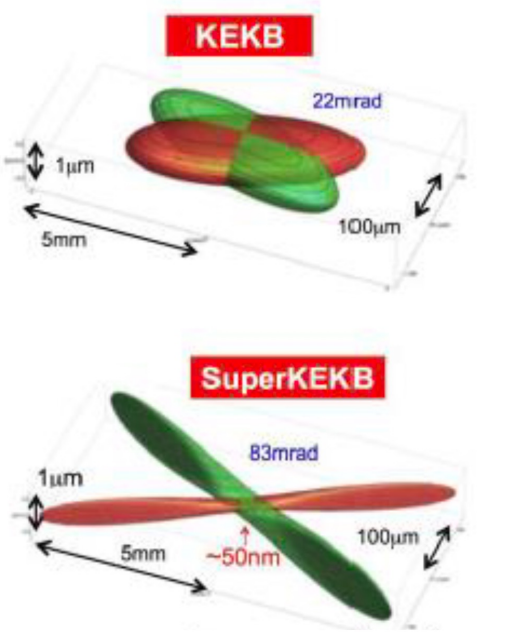
Plans @ Belle II (Hawaii/MPI/IPMU)

1. Repeat Belle analysis, but with higher statistics, more channels, better resolution

$$B^0 \to D^- \pi^+, D^{*-} \pi^+, D^{*-} \rho^+$$

2. Make use of better vertex resolution, better tagging, and smaller interaction region:



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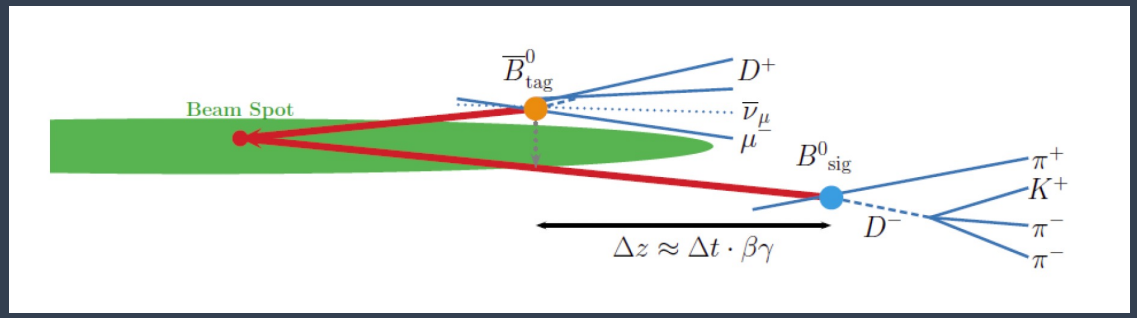

$\gamma\beta\tau c$ = 0.125 mm
Not ideal, but some sensitivity to t_1 should be achievable
- Transverse separation ~50 μm
- Vertex resolution σ_{res} ~20 μm

3. Probe more general decoherence models (such as Lindblad)
4. Work with theorists to estimate SM and BSM decoherence times
5. Understand possible systematics from unconstrained decoherence in other Belle II measurements (see talk by H.G. Moser)

Summary

- Δt (and t_1, t_2) distributions enable interesting studies of quantum entanglement
- Belle II + SuperKEKB likely more suitable than Belle + KEKB
- Vahsen group at Hawaii working on
  - MC-only exploratory studies of QM decoherence (undergrads)
  - TDCPV service work by PhDs as a technical foundation
    - Resolution function + potentially one more task
  - Sibidanov (postdoc) providing new EvtGen models
- Desire to collaborate with MPI + IPMU and would like to avoid redundant work – we need some discussion/planning/coordination

BACKUP