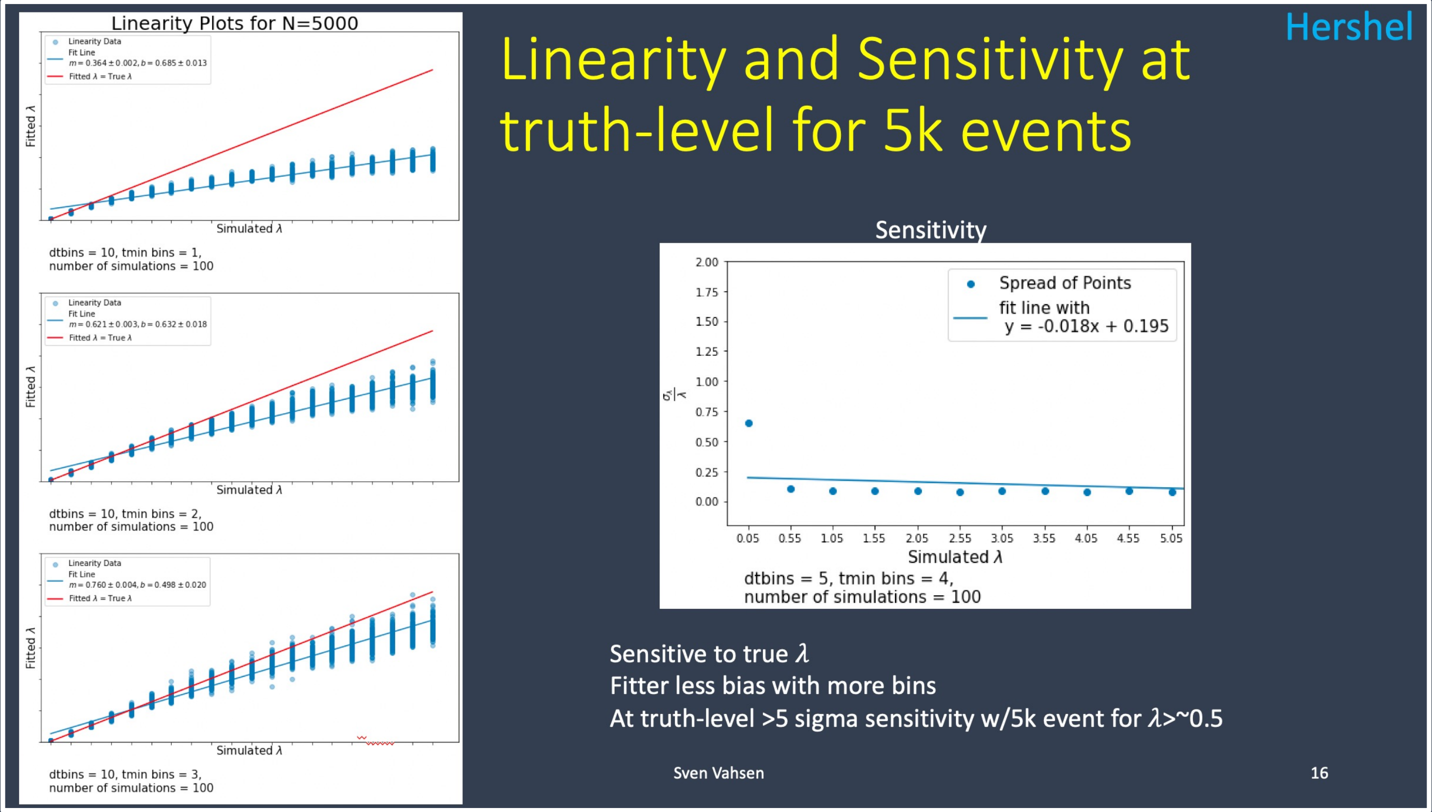
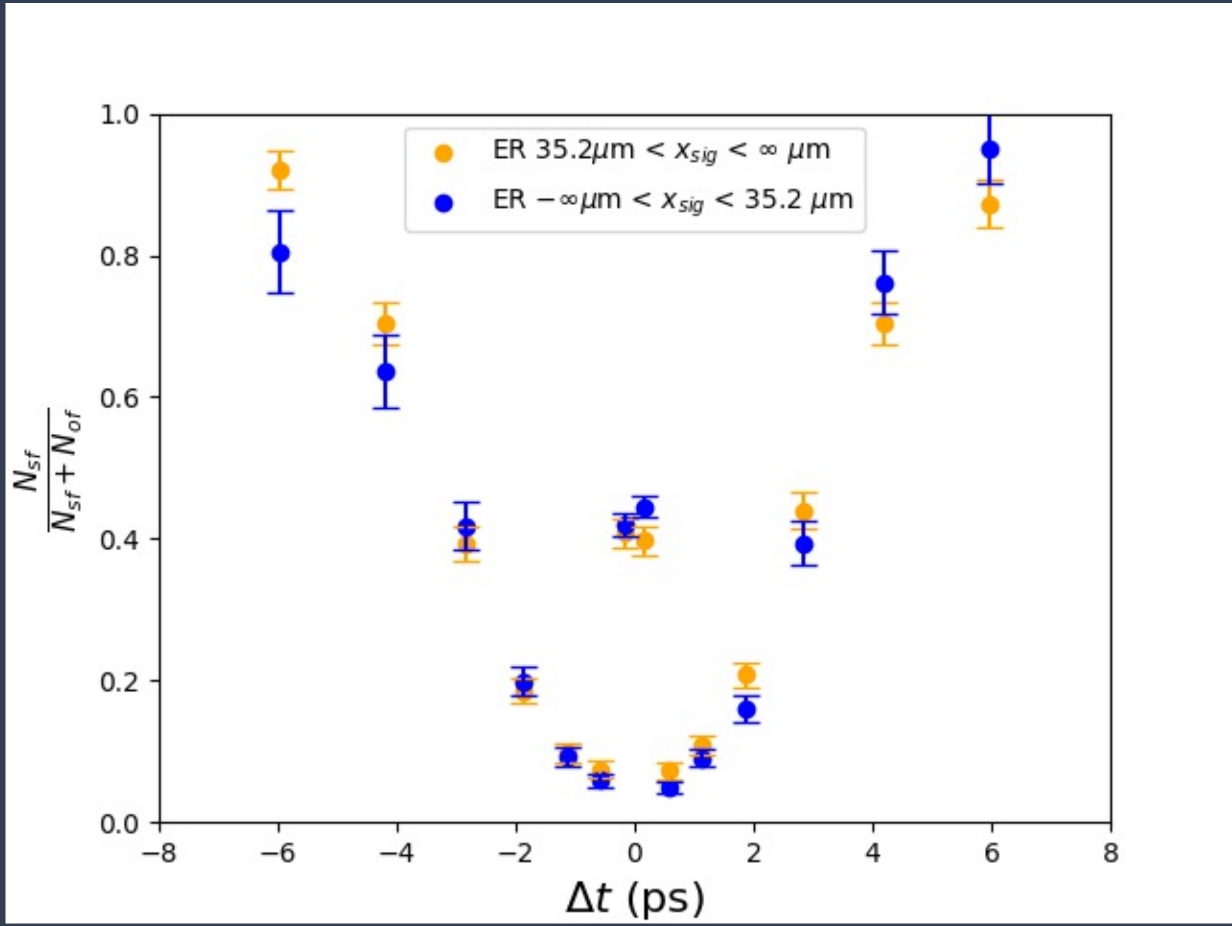
Work left to (almost) demonstrate feasibility of measuring Lindblad decoherence parameter λ at Belle II

Hershel:



1. Estimate sensitivity to λ
   - Plot sigma_λ/λ for λ <1.0. We expect λ<<1.0 in nature. You could start with lambda = 0.05, 0.10, 0.15, 0.2, etc.
2. When the fitted lambda is biased, so is sigma_λ. I think you can simple correct it as follows:
   - sigma_λ_corrected = sigma_λ*true_λ/mean_fitted_λ
3. chose a) bins (for delta_t and t_min) and b) errors bars after binning so that bias for a low number of bins is removed.
   - a) for the bins, my intuition is that you want both the delta_t and t_min bins so that each bin has the same expected number of events.
   - b) this will probably need detailed discussion

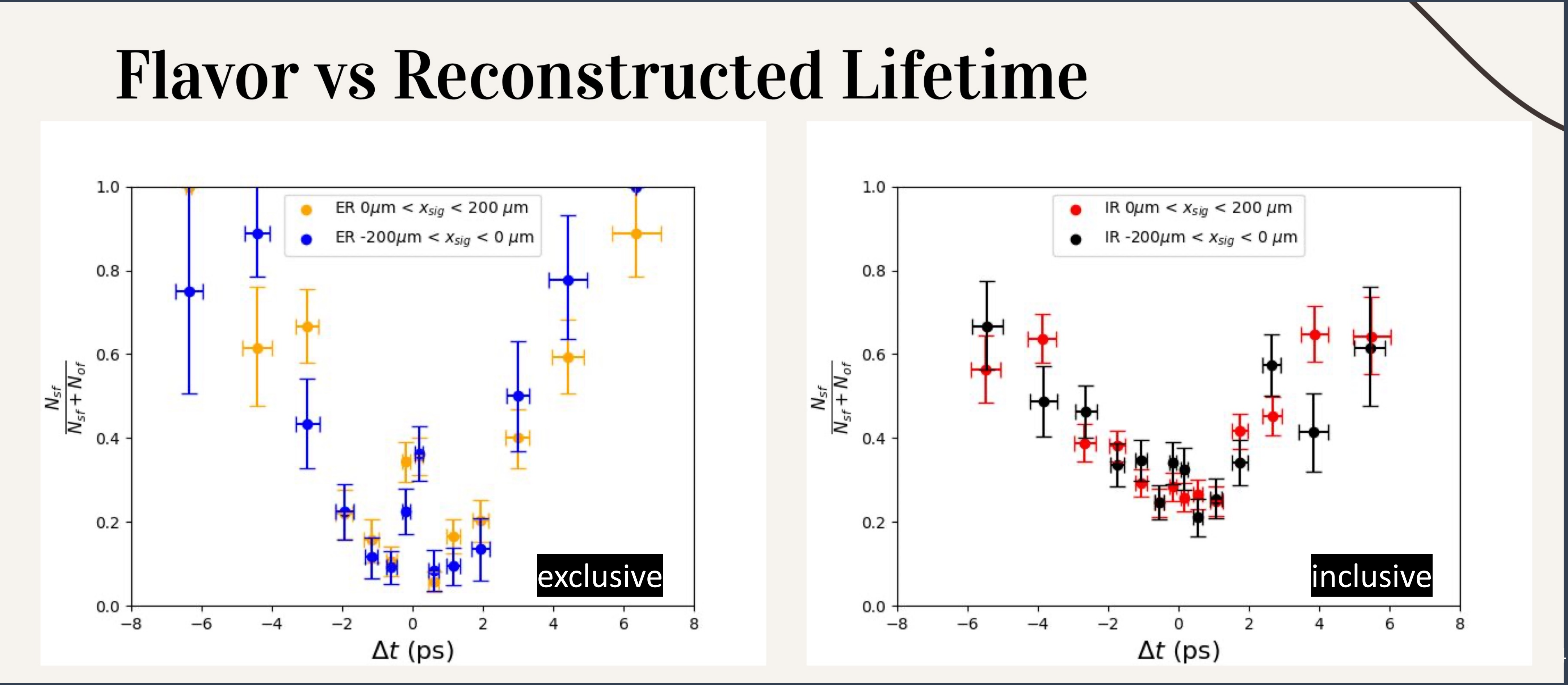
Aleczander



- Fix problem at delta t~0 for exclusive reconstruction of two B mesons.
- Suspect that tracks are shared among the B mesons. Can be fixed by explicitly checking this and vetoing such eents.
- [A less direct method would use a tighter cut on vertex (p-value > 0.5 or 0.9) cut also work, but might not be needed. Requiring istruth==1 might also work, but can not be used on experimental data.)]

Alexei

- We need the Lindblad decoherence model in EvtGen to work with ALIAS, so that we can test $\lambda\,!=0$ for inclusive reconstruction



Other open questions and some next tasks

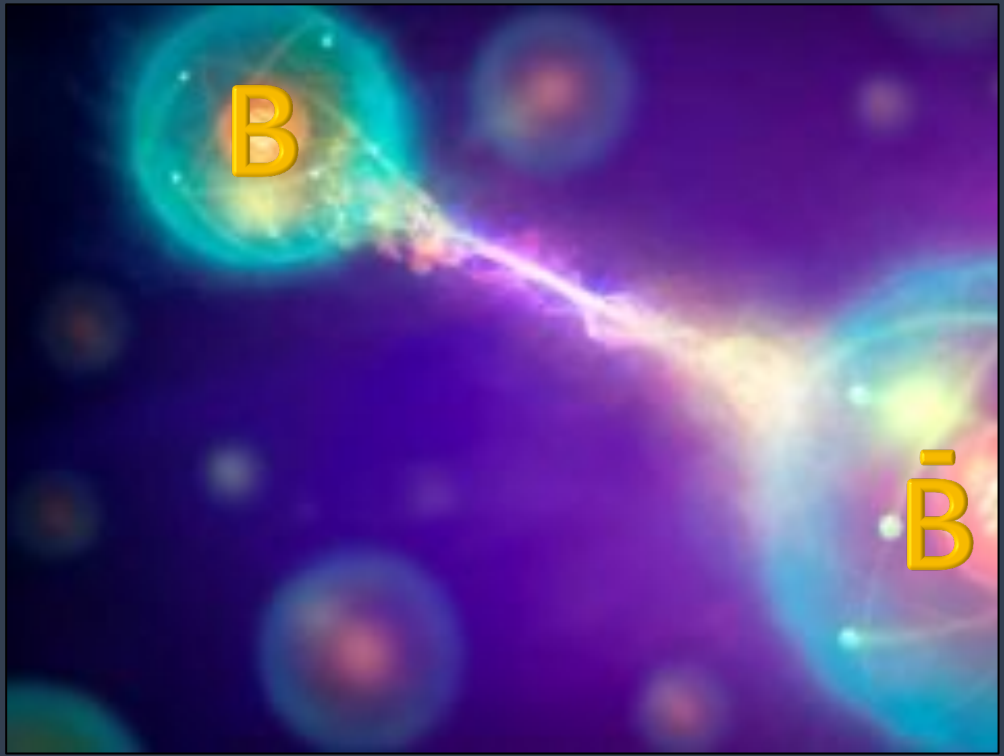
- The limit λ → infinity does not reproduce spontaneous diss-entanglement. Should it?
- What is the measured size of the beam-spot in *x* now, and versus time, in Belle II data recorded to date?
- Rather than using *x* as a proxy for absolute decay time, can we improve t_{min} sensitivity by using all available (*x,y,z*) vertex info for both B-mesons and the measured beam spot size
- We may want to calibrate the t_{min} measurement by building a resolution function. That would then allow us to fit models in the 2d space of (t_{min} *vs* Δt) [or equivalently, $t_{min}+t_{max}$ *vs* Δt]
    - Perhaps we can validate the *x* resolution by measuring the B lifetime, similarly to Tim's ongoing Δt resolution calibration

Recent Quantum Decoherence Activities

TDCPV meeting

June 2024 B2GM

Sven Vahsen, U. Hawaii



QM Decoherence Team at U. Hawaii

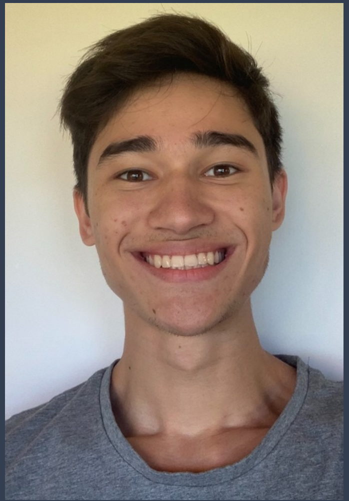
Sven Vahsen (group leader)

Alexei Sibidanov (postdoc)

Timothy Mahood (grad student)

Lucas Stötzer (grad student)

Aleczander Paul (undergrad)



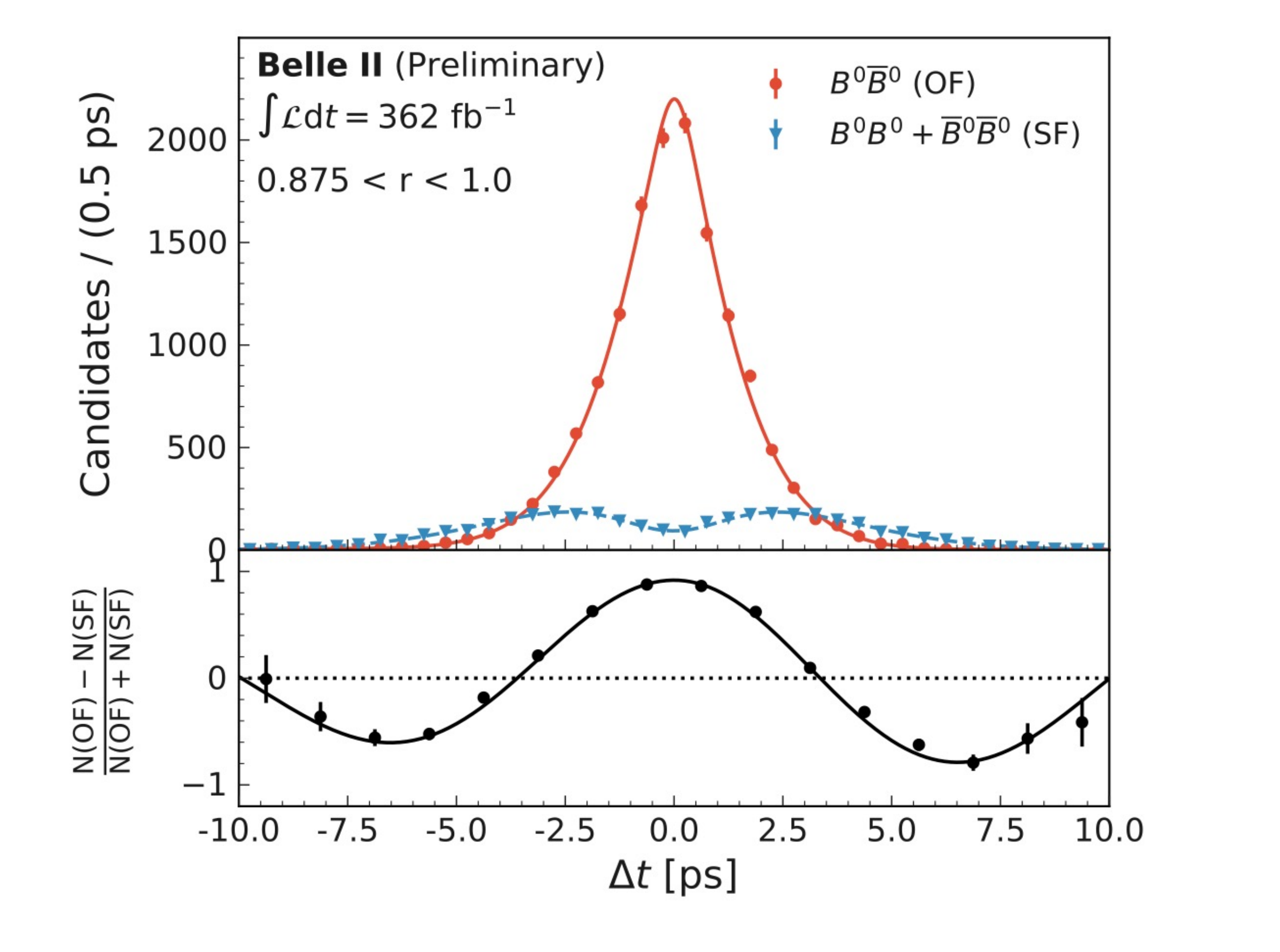
Hershel Weiner (undergrad)

- Today, mainly reporting outcomes of year-long undergraduate honors thesis projects by Hershel and Aleczander
- MPI and IPMU groups working on related subjects, MPI and UH starting to coordinate.

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

- Non-local flavor entanglement is assumed “perfect” in analyses of B-mixing and TDCPV
  - Expect all B mesons to have opposite flavor at delta t=0.
- 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

https://arxiv.org/abs/2402.17260



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. $\sin 2\emptyset_1$) ✅ Bread and butter of B factories
2. BSM Symmetry violations (CPTV, Lorentz symmetry violation) ✅ Belle, Babar, (D0, LHCb,…)
3. Search for evidence of hidden variable theories (alternatives to QM) ✅ Belle (PRL 99, 131802 – 2007)
4. Collapse theories (augmentations of QM) ?
5. Quantum Decoherence ← This talk.

Spontaneous versus environmental decoherence

Measurement of Einstein-Podolsky-Rosen-Type Flavor Entanglement in $\Upsilon(4S)\rightarrow BB$ Decays
A. Go *et al.* (Belle Collaboration), PRL **99** (2007)

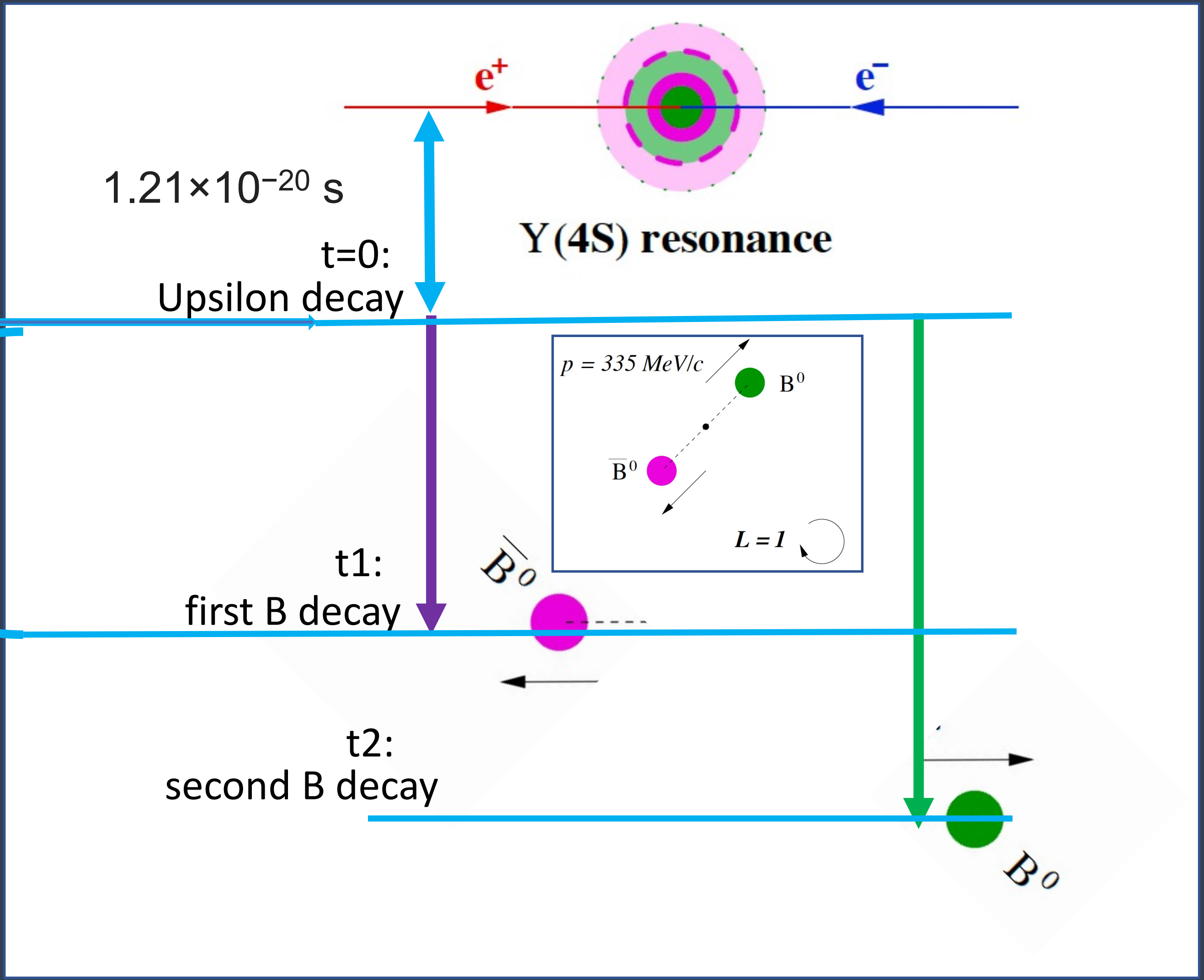
Spontaneous disentanglement or non-coherent production

Lindblad type decoherence

Model for decoherence of entangled beauty
R. A. Bertlmann and W. Grimus, PRD **64** (2001)

Measurement not attempted to date!

time



The Belle PRL on EPR

A. Go et al. used deconvolved Δt *distribution*, excluded

- "Pompili-Selleri" hidden variable model

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

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

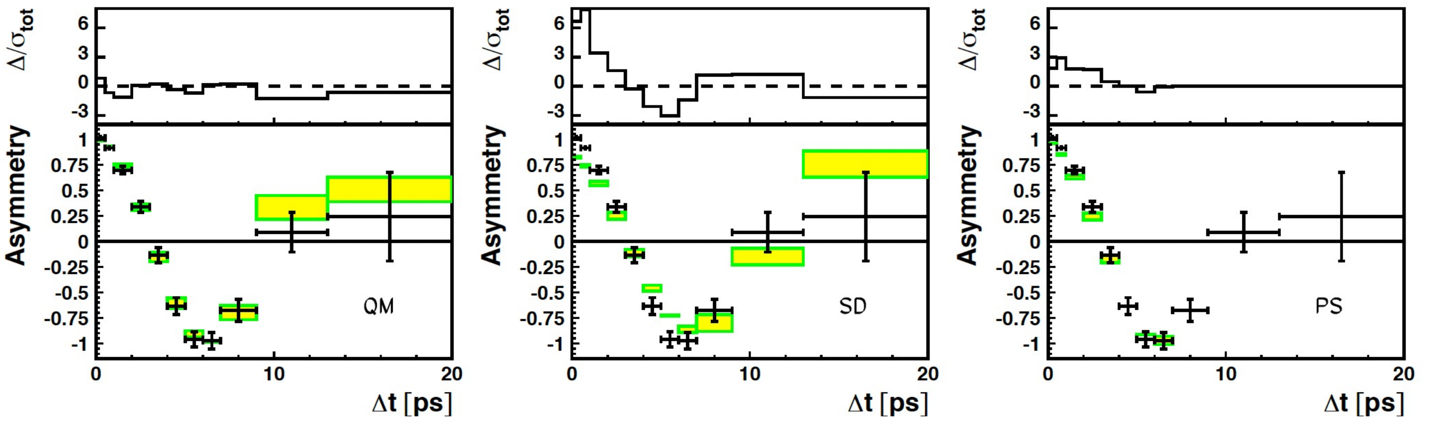
$$\Psi = \{1+\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{min}) - \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{min}). \quad (5)$$

- "Spontaneous Disentanglement" of all BB pairs

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

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

A. Go *et al.* (Belle Collaboration), PRL **99** (2007)



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

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

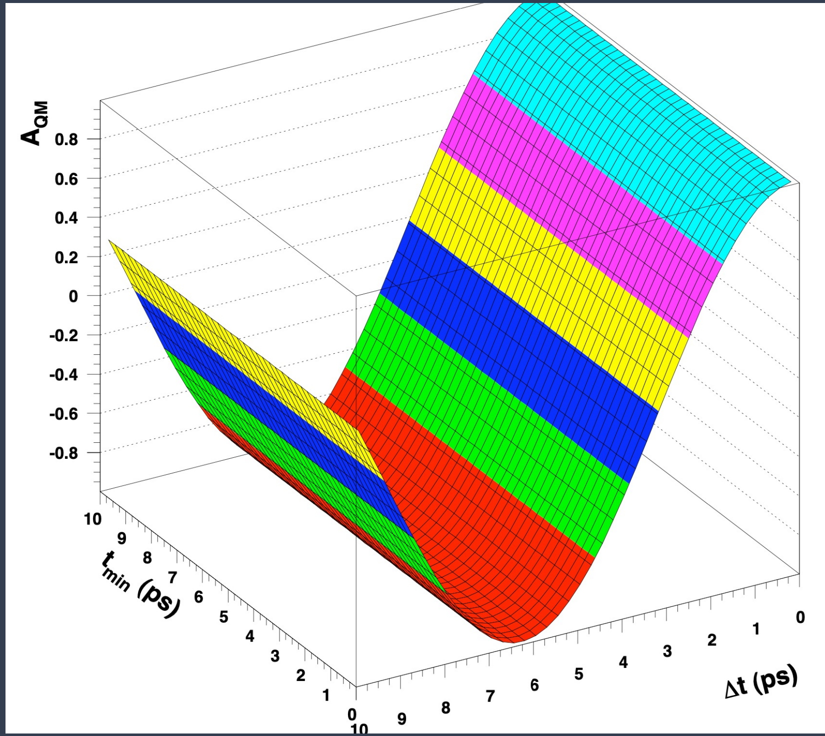
PS disfavoured: 5.1σ, $\chi^2/n_{dof} = 31/11$

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 increase sensitivity

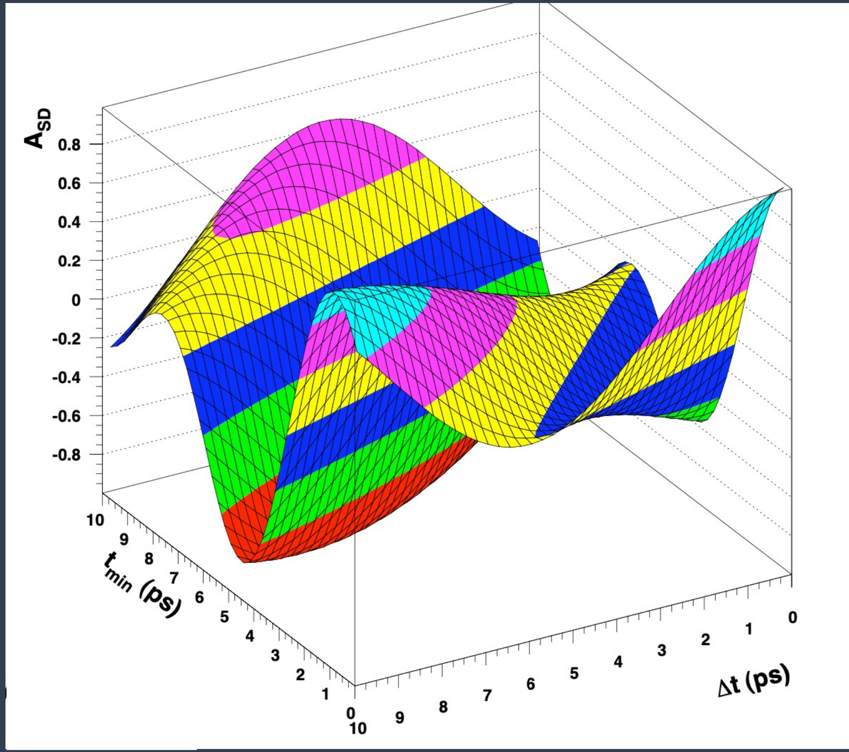
Asymmetry for QM



Entanglement: depends only on Δt

B. Yabsley

Asymmetry for Spontaneous Disentanglement



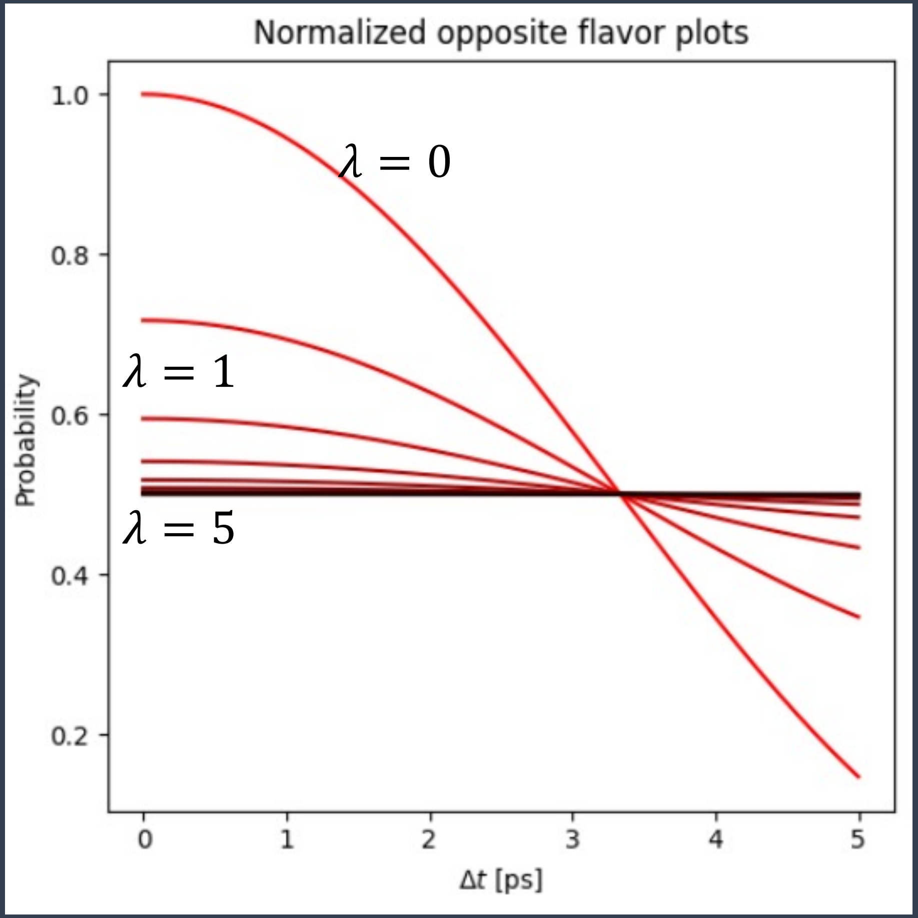
Disentanglement and decoherence: depends on t_1 and Δt

Lindblad Type Decoherence

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

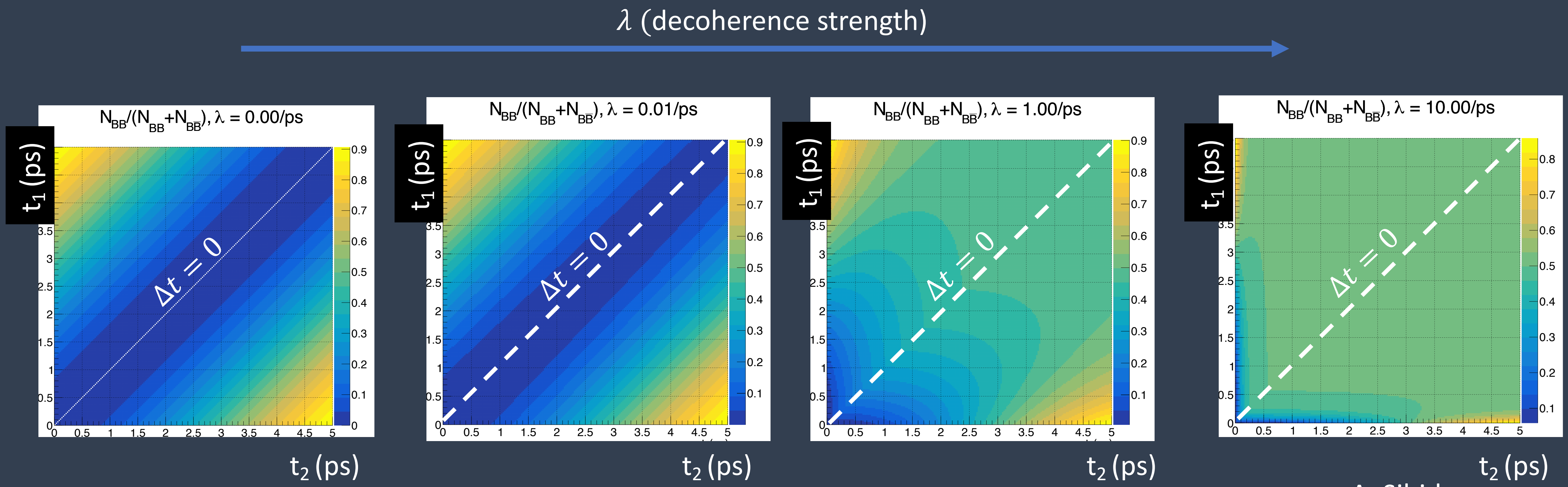
$$N = \frac{1}{4}e^{-\Gamma(t_1+t_2)}[\cosh(\frac{\Delta\Gamma\Delta t}{2}) - \mu e^{-\lambda t_1}\cos(\Delta m \Delta t)]$$

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



A. Sibidanov

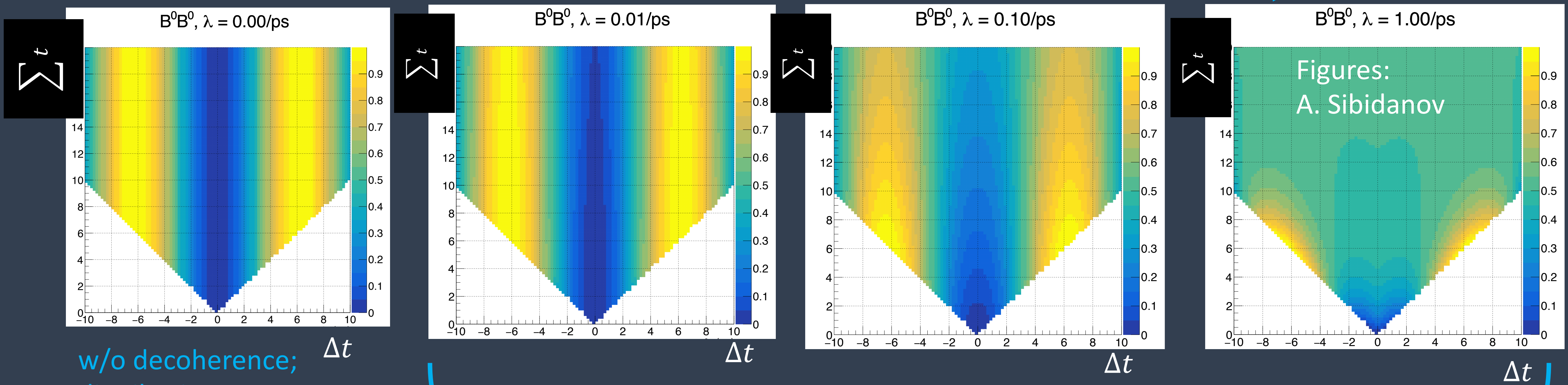
- As decoherence strength parameter λ increases
- Number of same-sign B meson pairs at $\Delta t = 0$ increases
- In this 2d plane, pattern distinct from miss-tagging (assigning wrong b-flavor in reconstruction)

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 $\sum t$

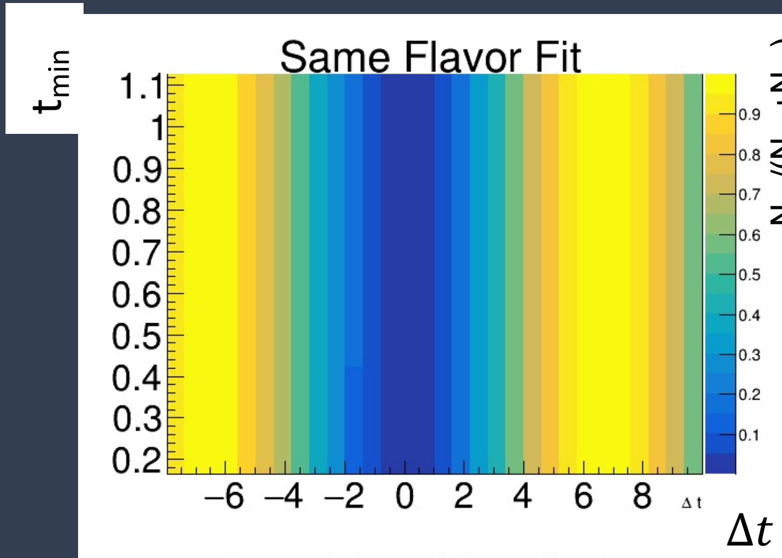
Measuring $\sum t$ (or equivalently; just t_1) in addition to Δt should enhance sensitivity to decoherence, and the difference between miss-tagging and decoherence

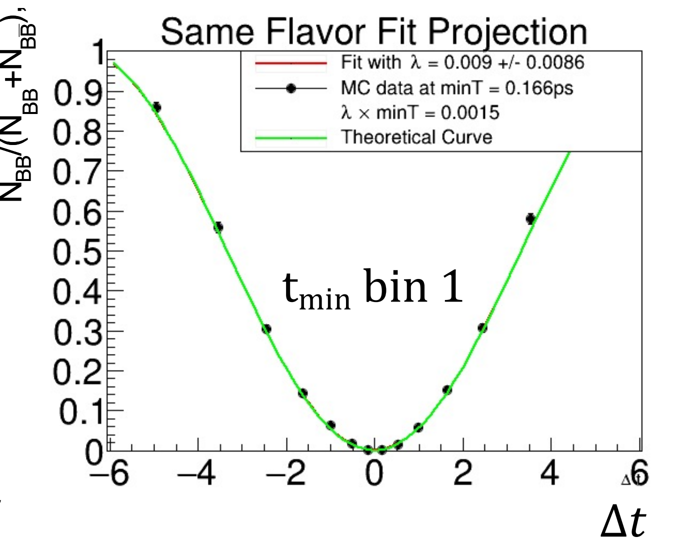
Fitting for Lindblad Decoherence Parameter λ using truth-level decay times and flavor

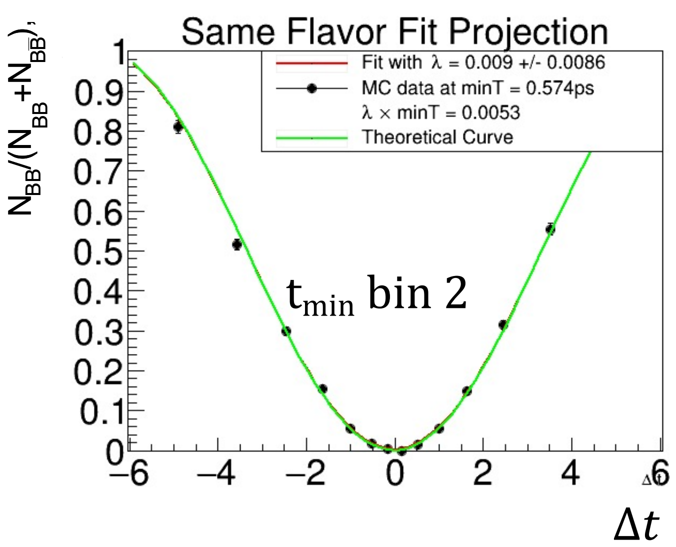
Hershel

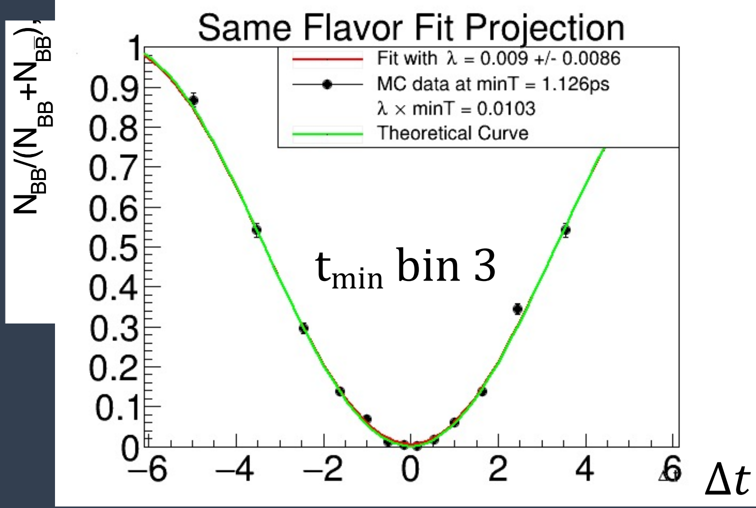
2d binned fit: 10 Δt bins and 3 t_{min} bins .

100k events per fit









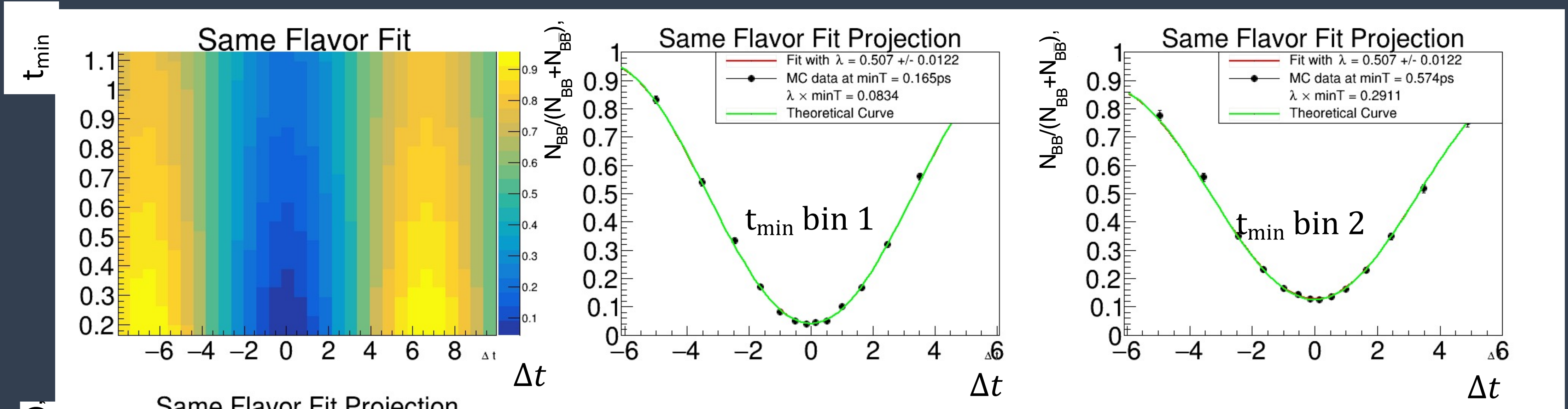
Fitted pdf matches data and theory curve

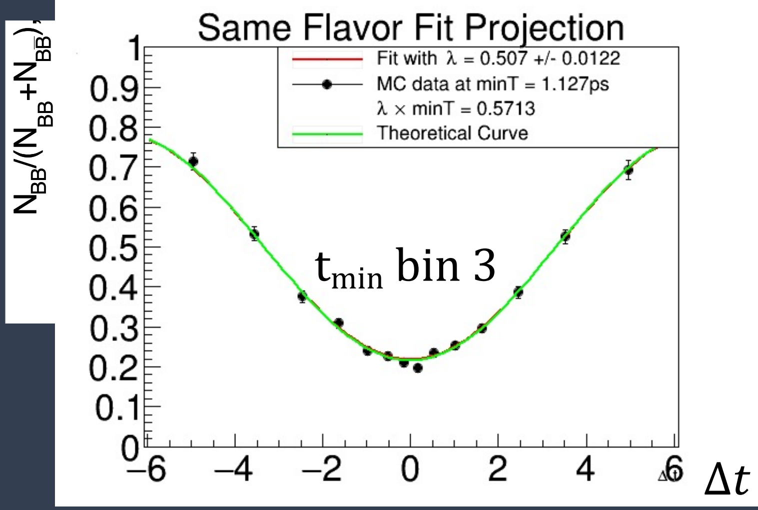
λ=0: flavor oscillation identical in three t_{min} bins

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

2d binned fit: 10 Δt bins and 3 t_{min} bins .

100k events per fit





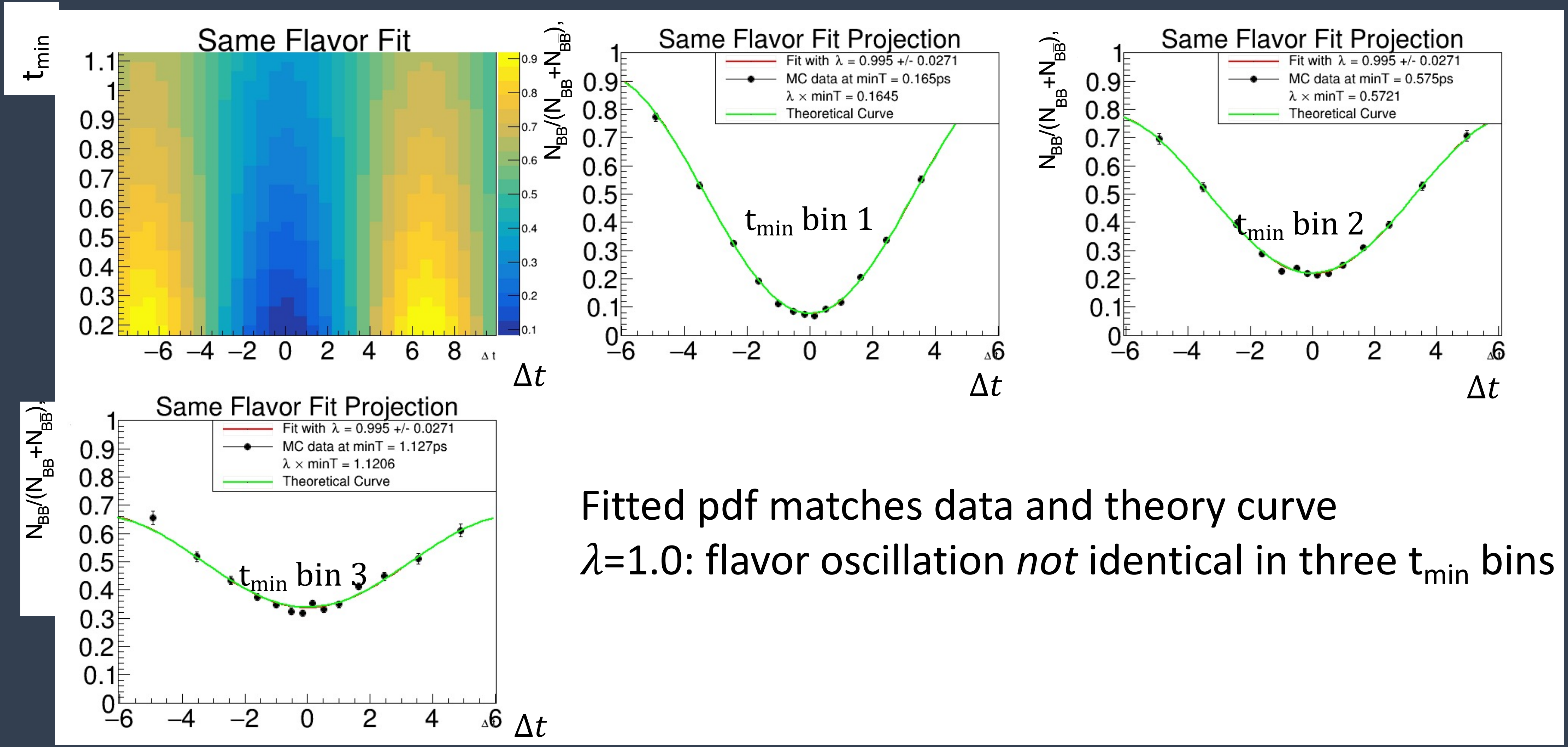
Fitted pdf matches data and theory curve

λ=0.5: flavor oscillation *not* identical in three t_{min} bins

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

2d binned fit: 10 Δt bins and 3 t_{min} bins .

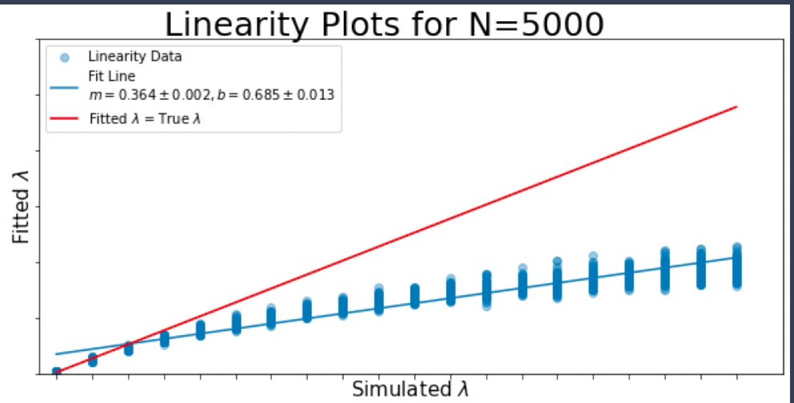
100k events per fit



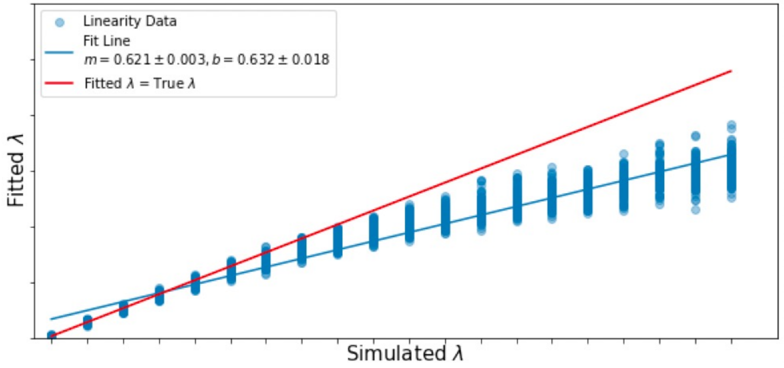
Fitted pdf matches data and theory curve

λ=1.0: flavor oscillation *not* identical in three t_{min} bins

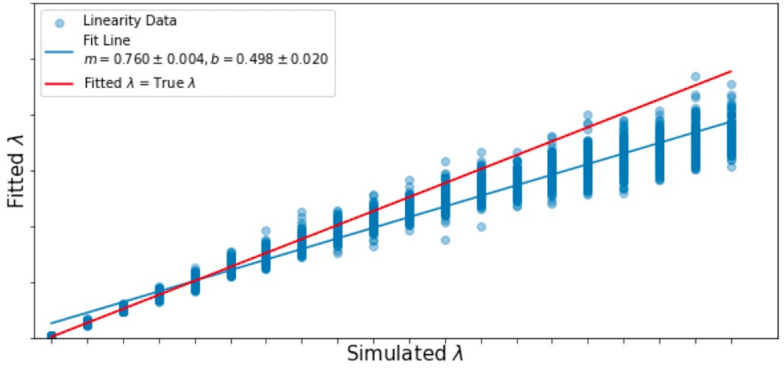
Linearity and Sensitivity at truth-level for 5k events



dtbins = 10, tmin bins = 1,
number of simulations = 100

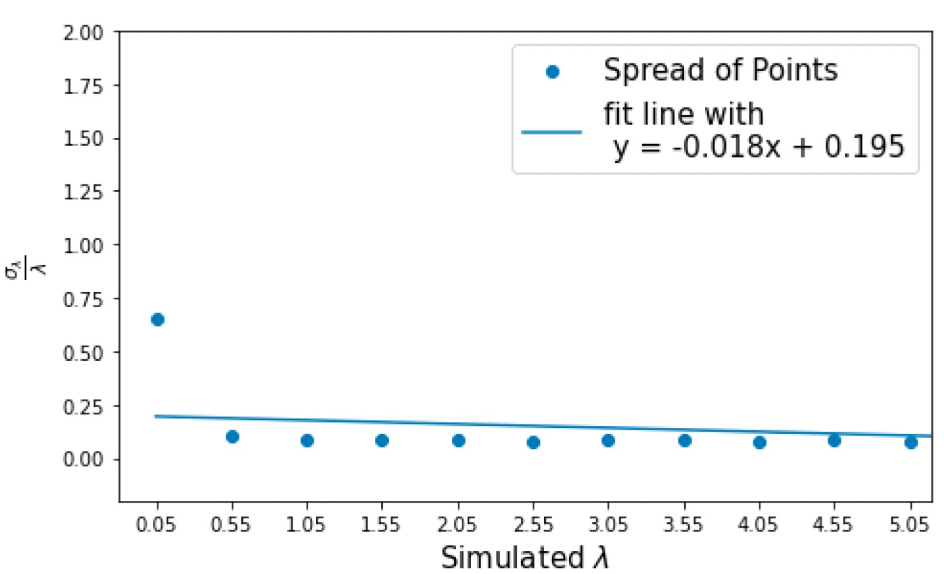


dtbins = 10, tmin bins = 2,
number of simulations = 100



dtbins = 10, tmin bins = 3,
number of simulations = 100

Sensitivity

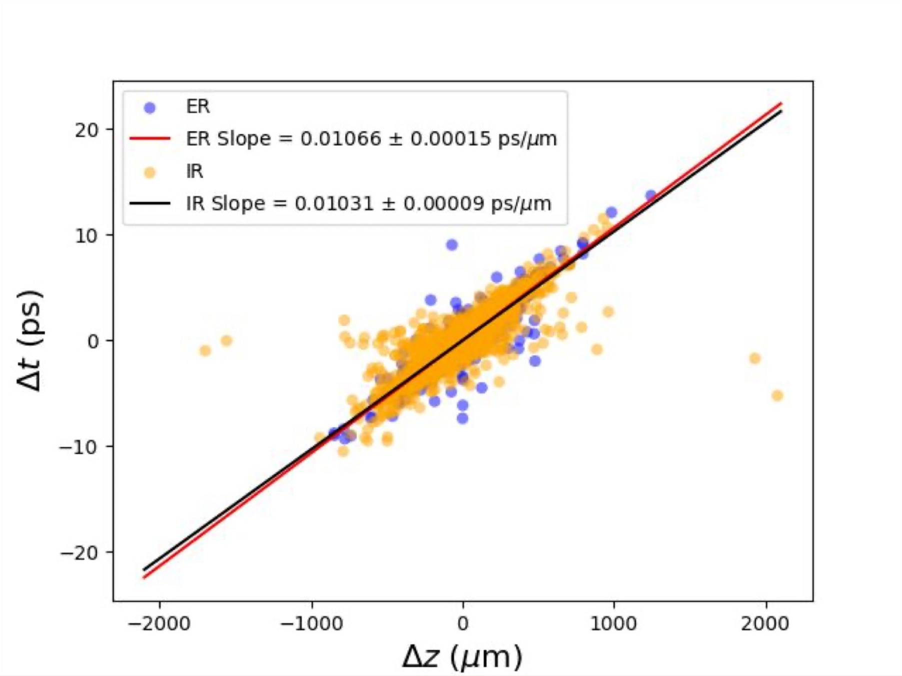


dtbins = 5, tmin bins = 4,
number of simulations = 100

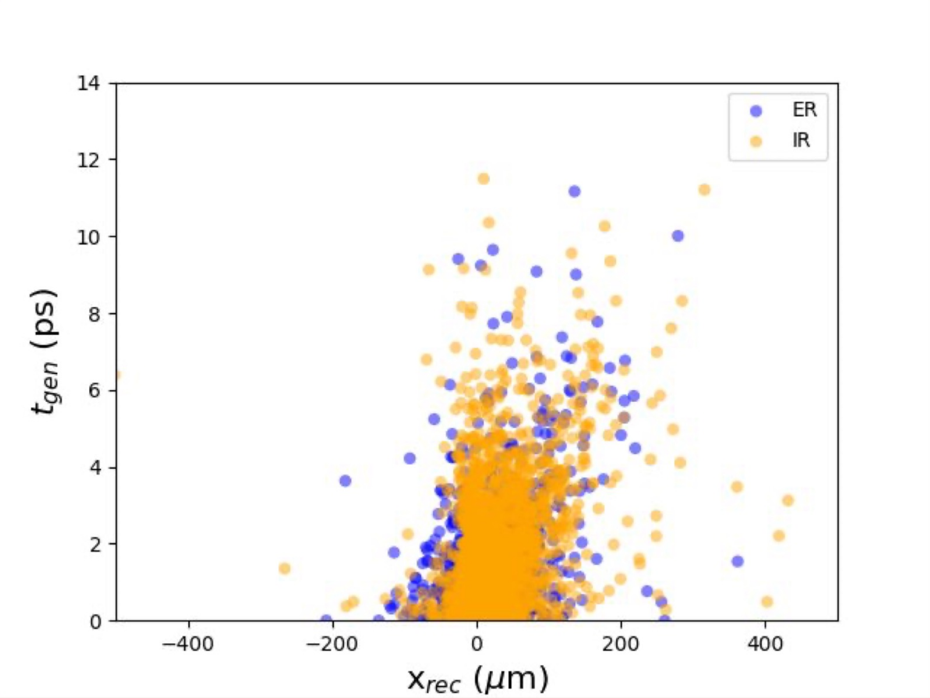
Sensitive to true λ
Fitter less bias with more bins
At truth-level >5 sigma sensitivity w/5k event for λ>~0.5

Aleczander

Obtaining Δt, t_{min} from *reconstructed* quanties



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

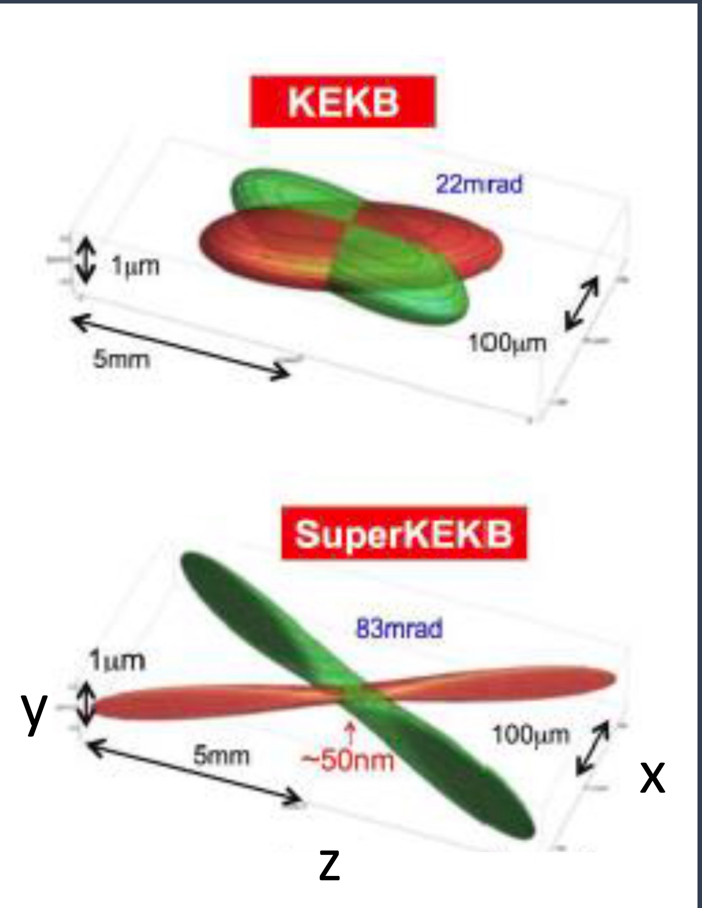


Discovered correlation between t and x, found proxy for absolute B meson lifetime!

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



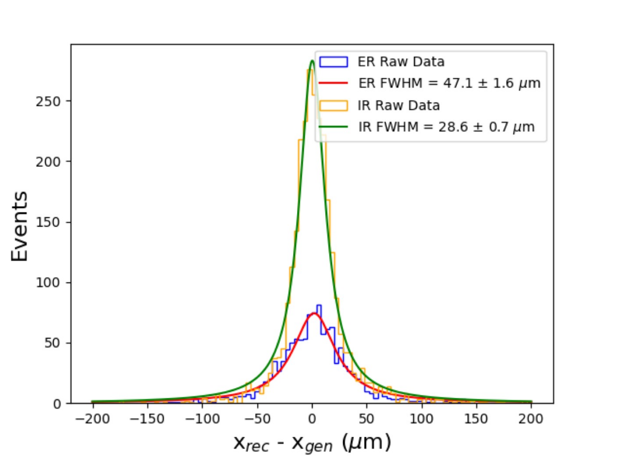


Figure 8: Decay vertex accuracy distributions with best fit Lorentzian for signal decays (left) and generic decays overlaid with signal decays (right) along each coordinate axis of the detector. "ER" refers to exclusive reconstruction B mesons, and "IR" refers to inclusive reconstruction B mesons.

	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

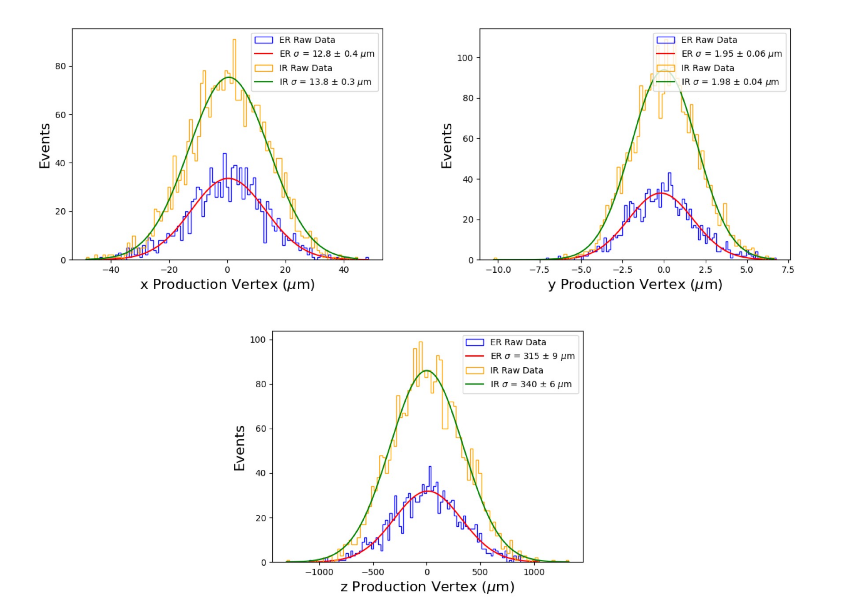
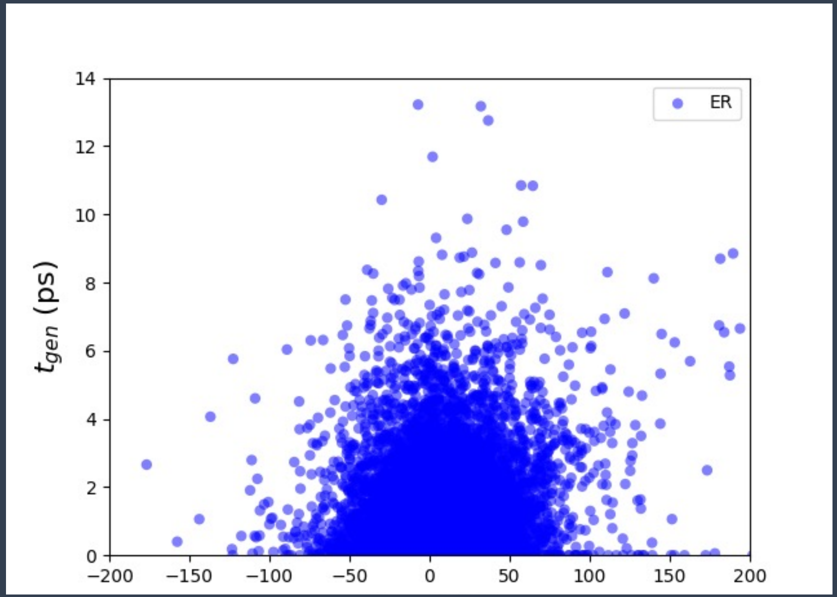


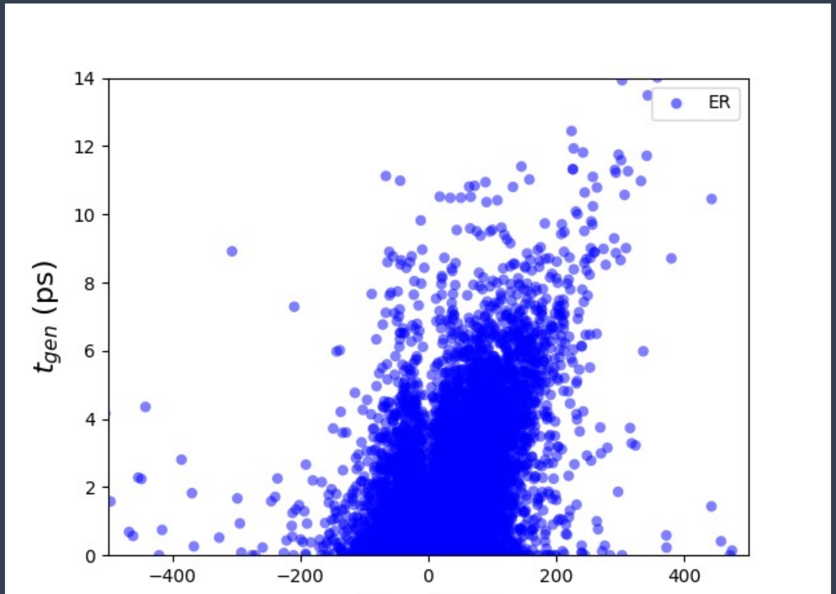
Figure 11: Distribution of the truth level production vertex of the B mesons. "ER" refers to exclusive reconstruction B mesons, and "IR" refers to inclusive reconstruction B mesons.

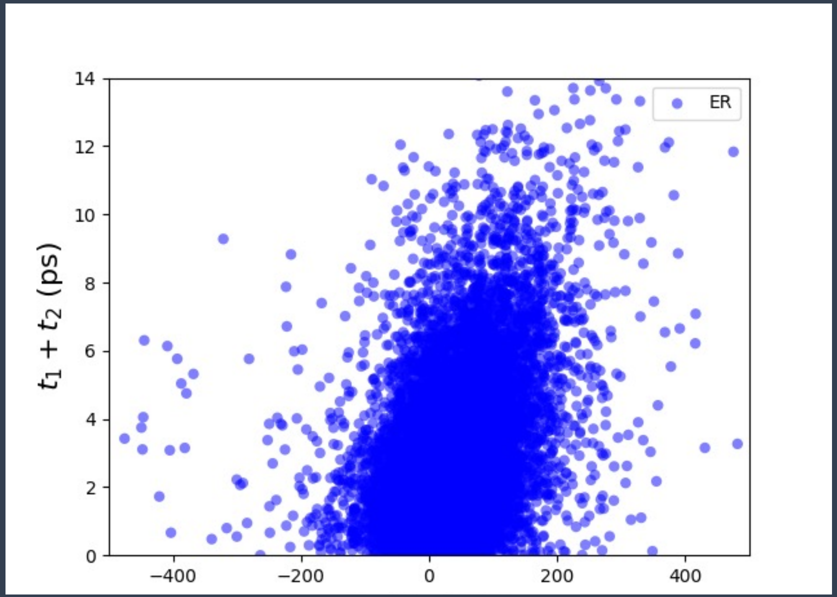
Look like IP shape in simulation is based on SuperKEKB design --> should switch to run-dependent MC. Not fully sure if yellow table (from machine group) is fully accurate. But, σ_x appears to be small even before beams are fully focused! Lucky for us! Measurement looks feasible already now!

Aleczander

A closer look: which x_B coordinate works best?







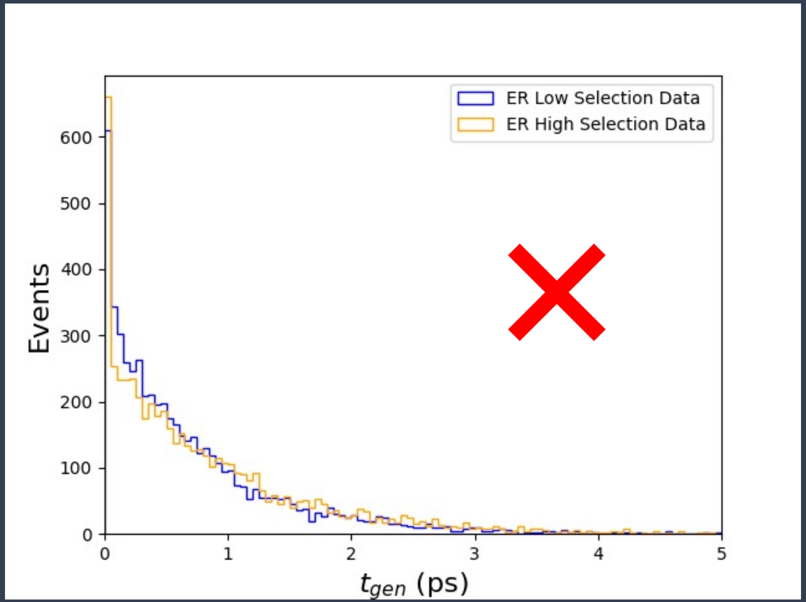
x_{min} ✗

x_{max} ✓

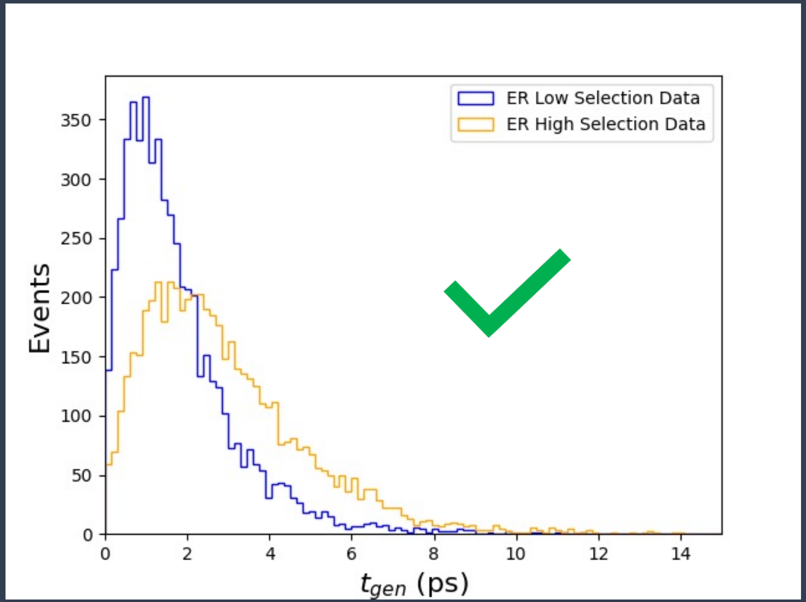
$x_{min}+x_{max}$ ✓

Aleczander

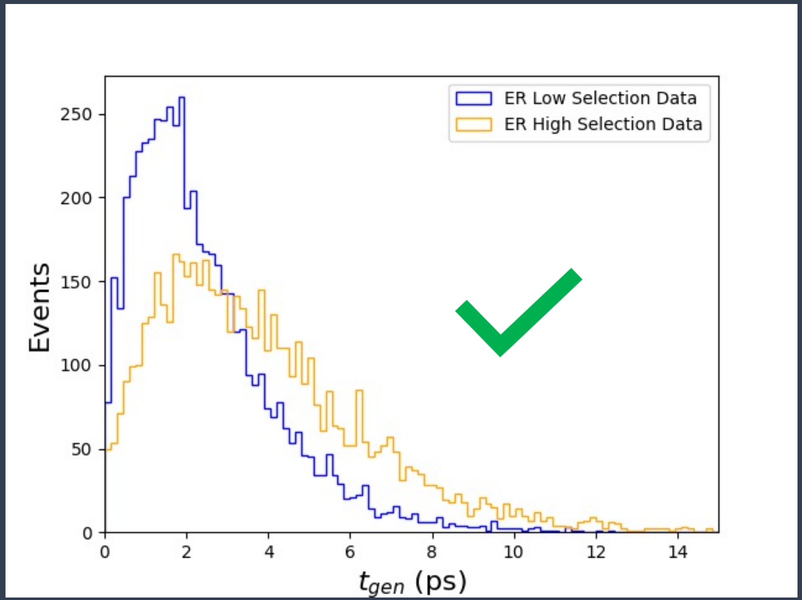
Separate reconstructed events into two x_B bins…



using x_{min}



using x_{max}

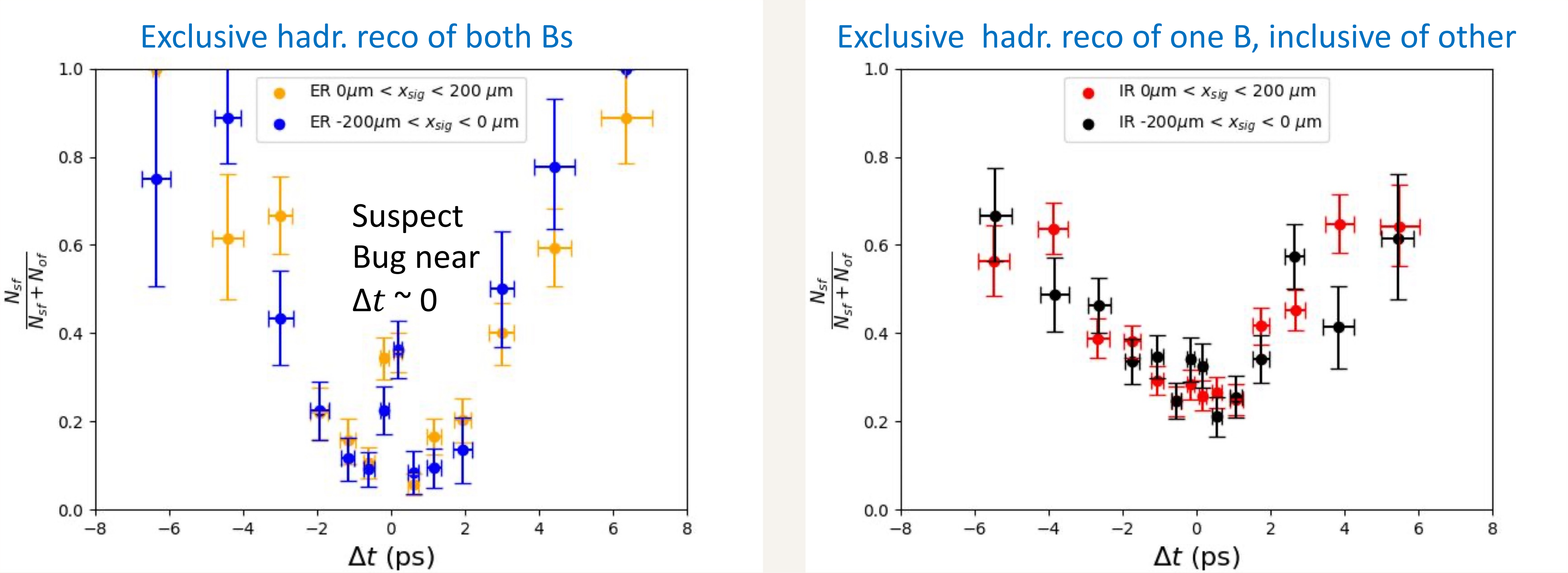


using $x_{min}+x_{max}$

- We obtain two different t distributions if we use x_{max} or $x_{min}+x_{max}$
- We have access to two bins of absolute B meson decay time
- This is after reconstruction – i.e. technique appears experimentally feasible!

Reconstructed Δt distributions, λ =0

Flavor vs Reconstructed Lifetime

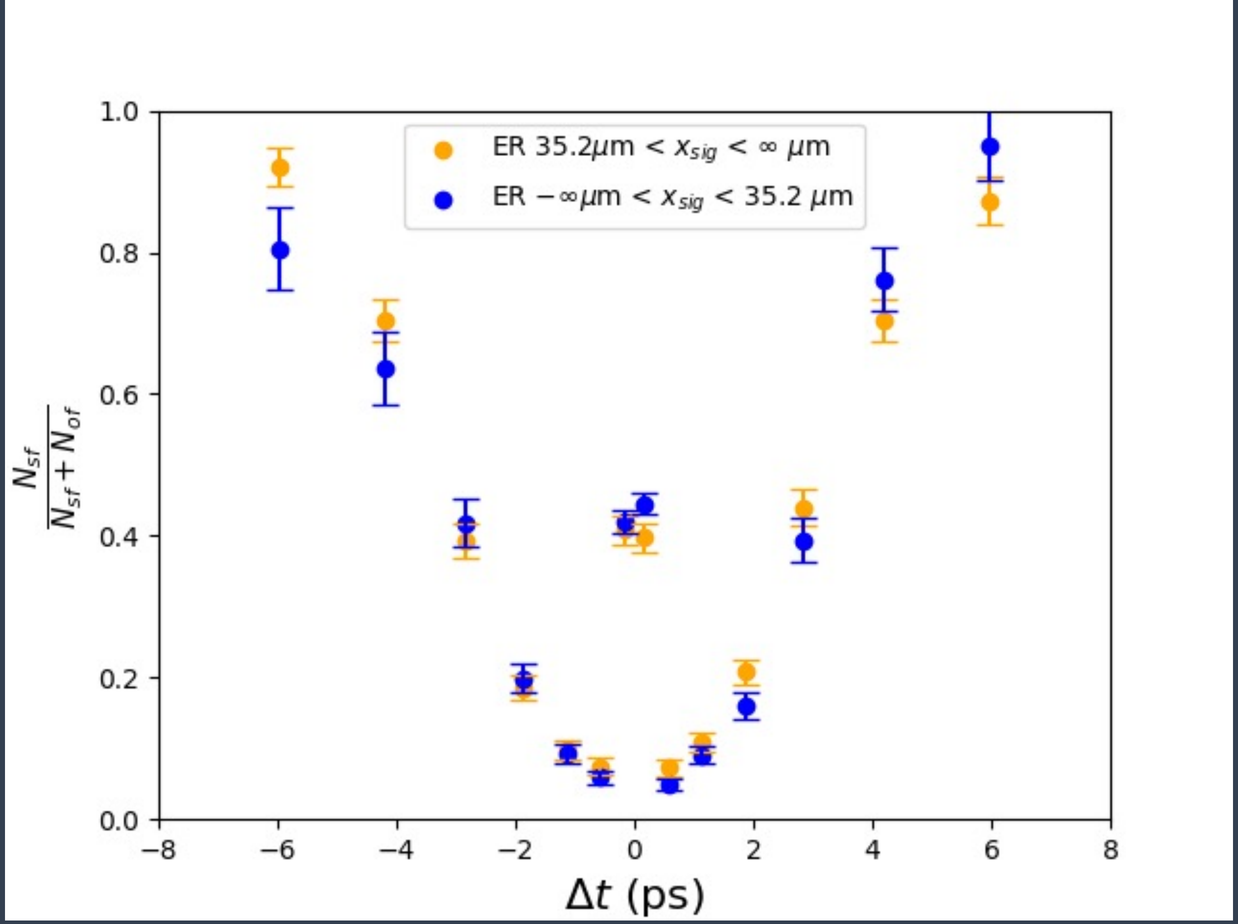


This is with default EvtGen (λ =0, no decoherence). Alexei Sibidanov has implemented decoherence (any λ) into EvetGen, but can only be used with exclusive case *for now*.

Aleczander

Reconstructed Δt distributions, λ =0

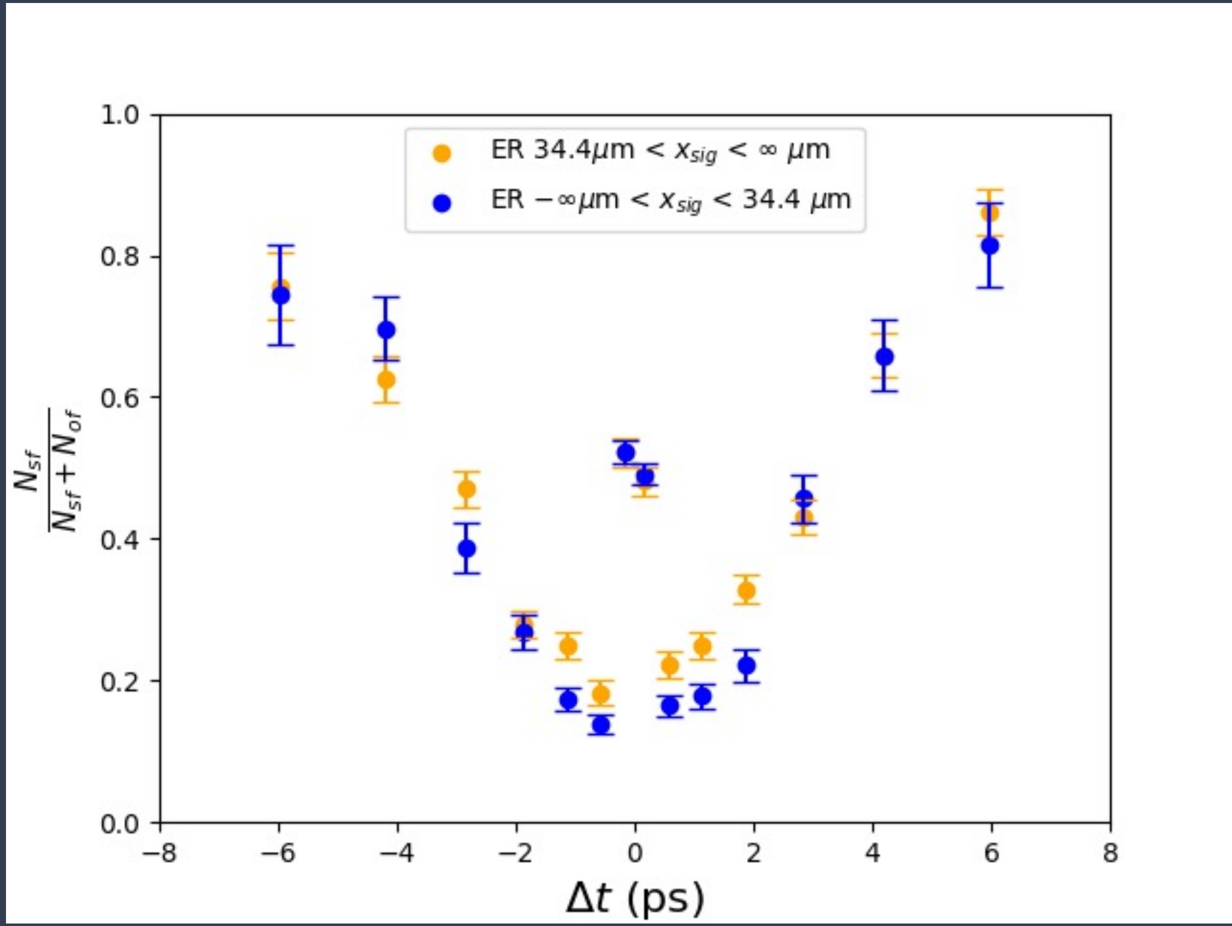
Exclusive reconstruction of both Bs. Data binned using x_{max}. Custom EvtGen. 33k events



Aleczander

Reconstructed Δt distributions, λ =0.5

Exclusive reconstruction of both Bs. Data binned using x_{max}. Custom EvtGen. 33k events

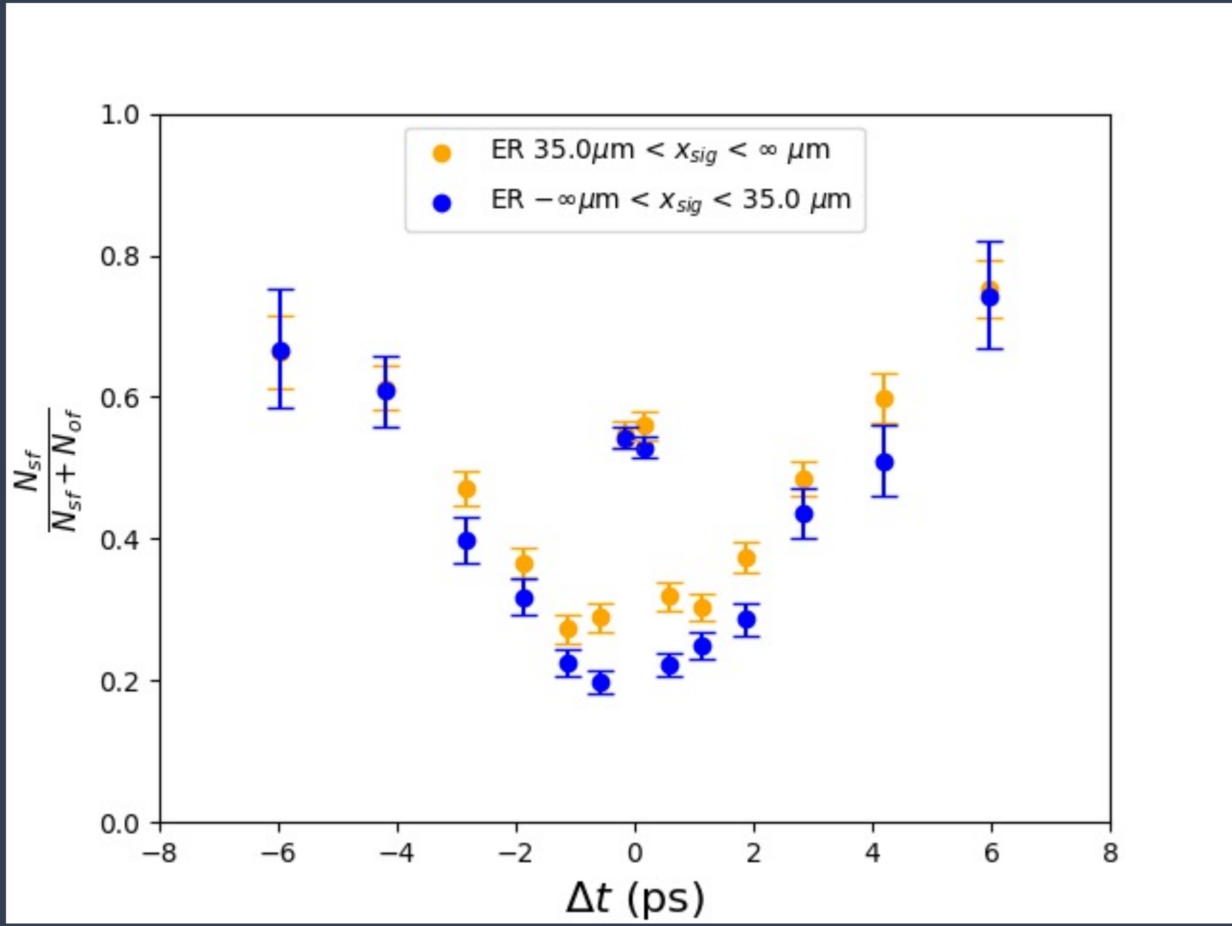


Clearly observe decoherence signature using only reconstructed quantities

Aleczander

Reconstructed Δt distributions, λ =1.0

Exclusive reconstruction of both Bs. Data binned using x_{max}. Custom EvtGen. 33k events



Clearly observe decoherence signature using only reconstructed quantities

Summary & Further Plans

- Two U. Hawaii undergrads (Hershel and Aleczander) developed
  - Proof-of-concept truth-level binned fits sensitive to Lindblad decoherence.
  - A first, straightforward experimental strategy to obtain absolute t_B!
- This work is being continued by two Hawaii PhD students
  - Tim: “Lindblad” environmental decoherence, hadronic decays
  - Lucas: fractional spontaneous decoherence, hadronic decays

- Searches for Lindblad decoherence and other models appear feasible!
- Exploit nano-beam scheme to obtain absolute B meson decay times
- Only possible w/ SuperKEKB & Belle II

BACKUP

ϵ exclusive (both Bs hadronic): 15.23%
ϵ inclusive (one B hadronic): 28.18%
BF hadronic: 0.07%

Preliminary, need to check numbers

For 1 ab-1

1.1*1E9*(.0007)^2*0.15 = 80 exclusive events
2*0.5*1.1*1E9*(.0007)*0.28= 215600 inclusive events

1. $B^0 \to (D^- \to K^+\pi^-\pi^-)\pi^+$
2. $B^0 \to (D^{*-} \to \overline{D^0}\pi_s^-)\pi^+$ where $\overline{D^0} \to K^+\pi^-$
3. $B^0 \to (D^{*-} \to \overline{D^0}\pi_s^-)\pi^+$ where $\overline{D^0} \to K^+\pi^-\pi^0$
4. $B^0 \to (D^{*-} \to \overline{D^0}\pi_s^-)\pi^+$ where $\overline{D^0} \to K^+\pi^-\pi^+\pi^-$

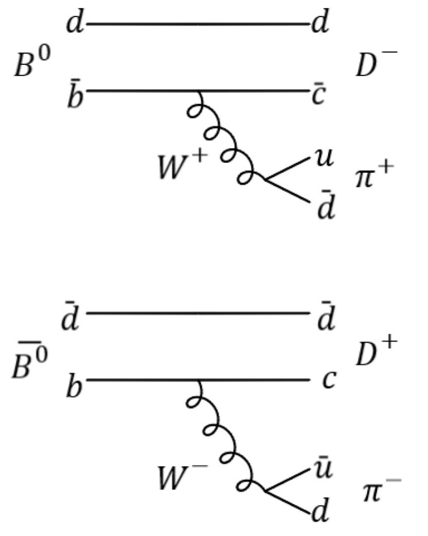


Figure 4: Feynman diagram of $B^0 \to D^-\pi^+$ and $\overline{B^0} \to D^+\pi^-$.

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

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

- $\Upsilon(4S) \rightarrow B^0\overline{B^0}$ decays via strong interaction; initial state C=-1 charge conjugation eigen-value must be conserved
- Hence, $B^0\overline{B^0}$ pair is flavor entangled (Eq. 1)
- If one B decays into a flavor specific final state at time t_1…
  - …then the other meson collapses into a state of opposite flavor instantaneously
  - … but it will keep undergoing flavor oscillations until it, too, decays
- “EPR-style” entanglement
  - non-local, quantum super-position state

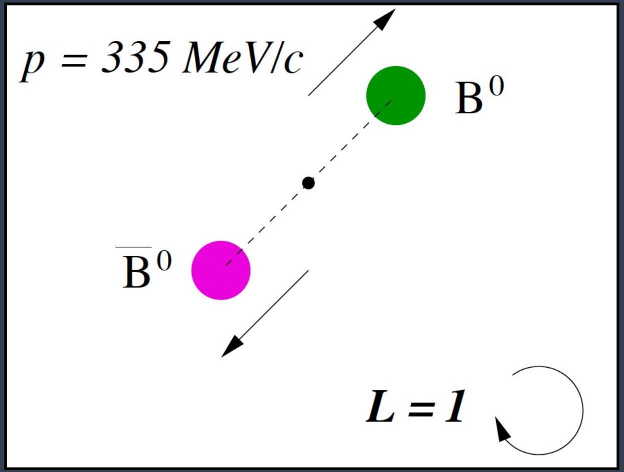
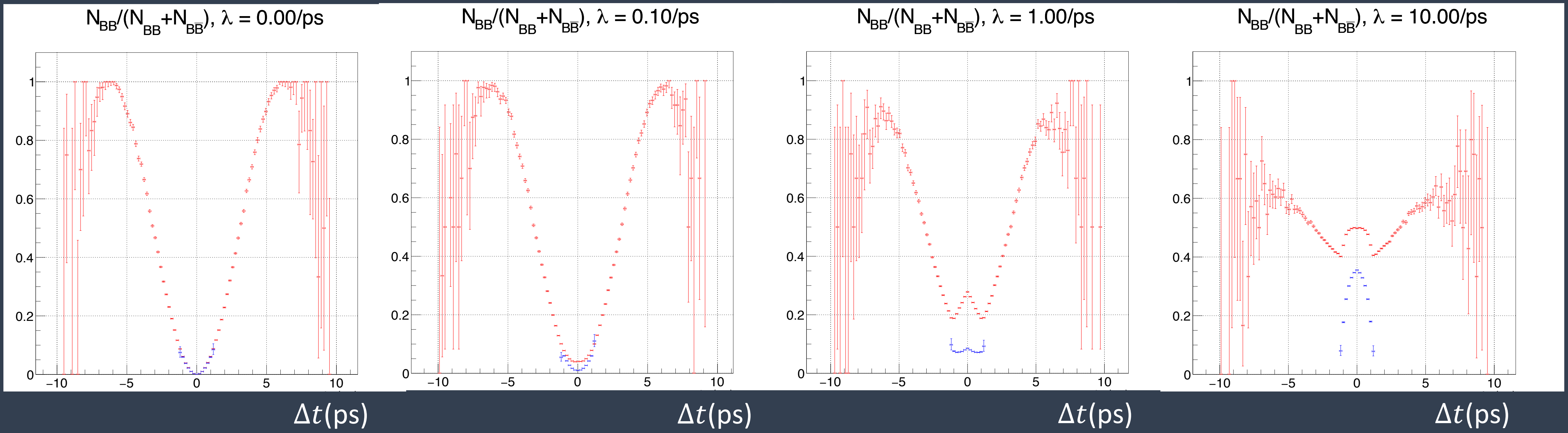


Figure by Bruce Yabsley

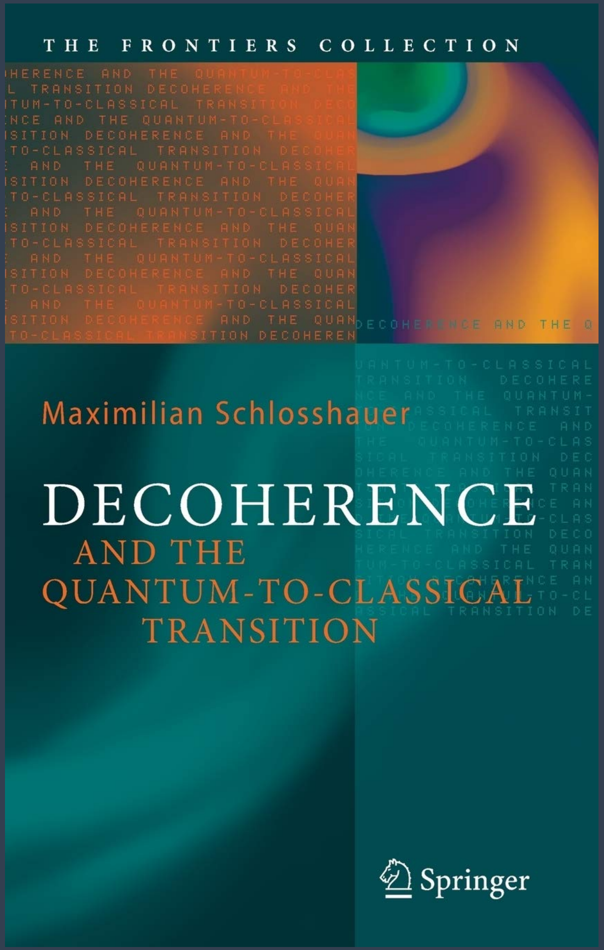
Example: weak sensitivity to $\sum t$ → two bins only



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

A. Sibidanov

Quantum Decoherence



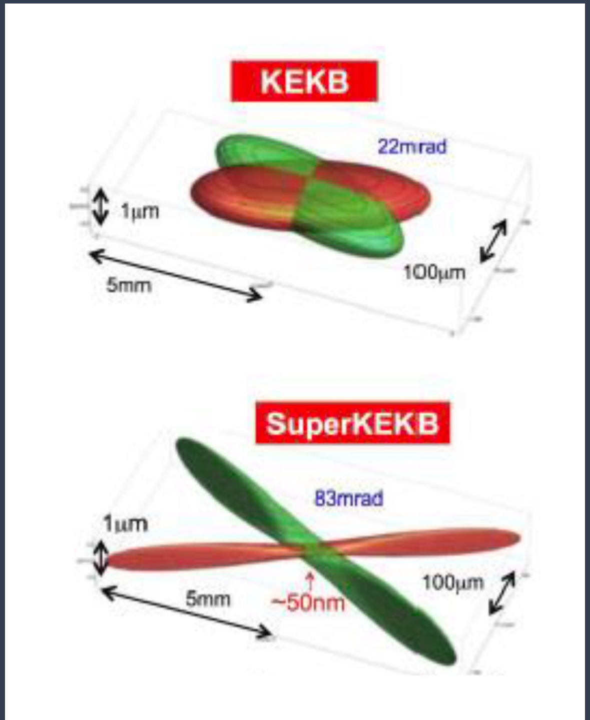
- Interaction of entangled states with environment can explain appearance of classical behavior at macroscopic scales
- Not an extension of QM, but rather a consequence of QM that was not previously appreciated
- Entangled states decohere over time
- Limits quantum computers
- SM decoherence
  - Our $B\overline{B}$ 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

Plans @ Belle II (Hawaii/MPI/IPMU)

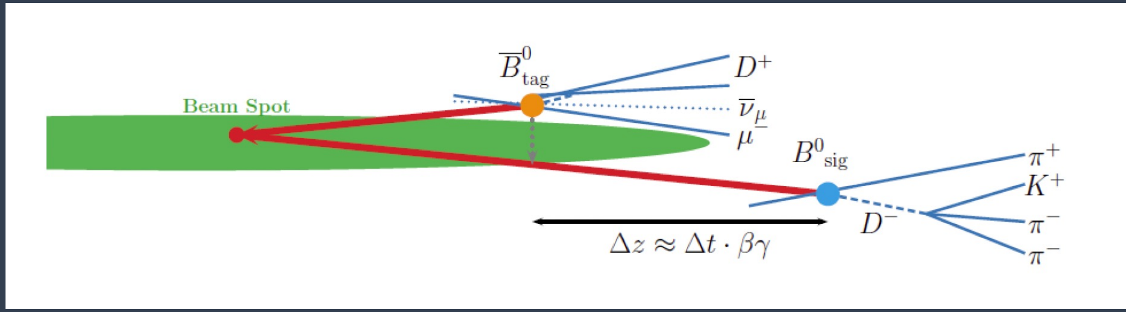
1. Repeat Belle analysis, but with higher statistics, more channels, better resolution

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

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



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



$\gamma\beta\tau c = 0.125$ 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)