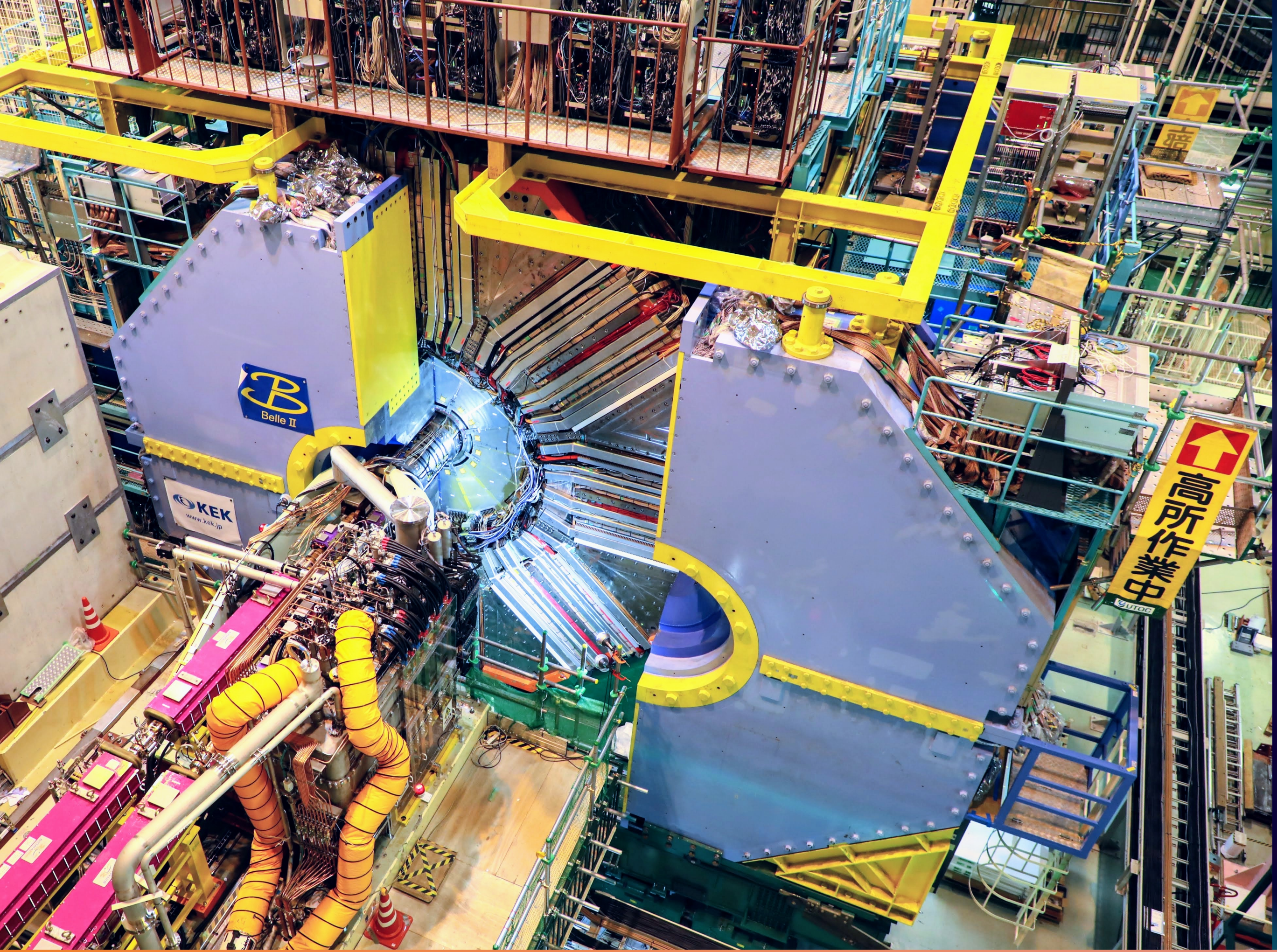


University of Hawaiʻi Mānoa

BELLE

Belle II

2024 Workshop on Quantum tests in Collider Physics @ Merton College, Oxford University

Quantum tests with entangled B meson pairs at the Belle and Belle II Experiments

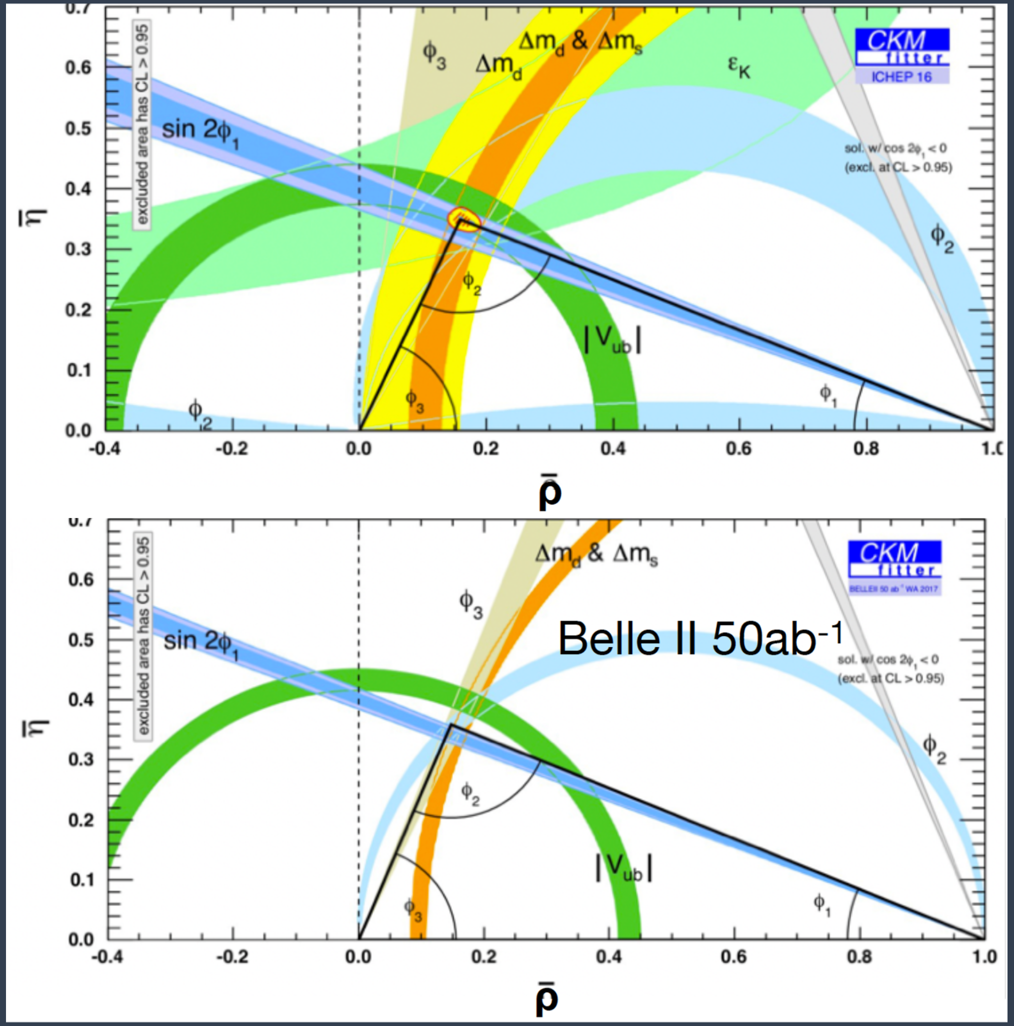
Sven Vahsen, for the Belle and Belle II collaborations

Outline

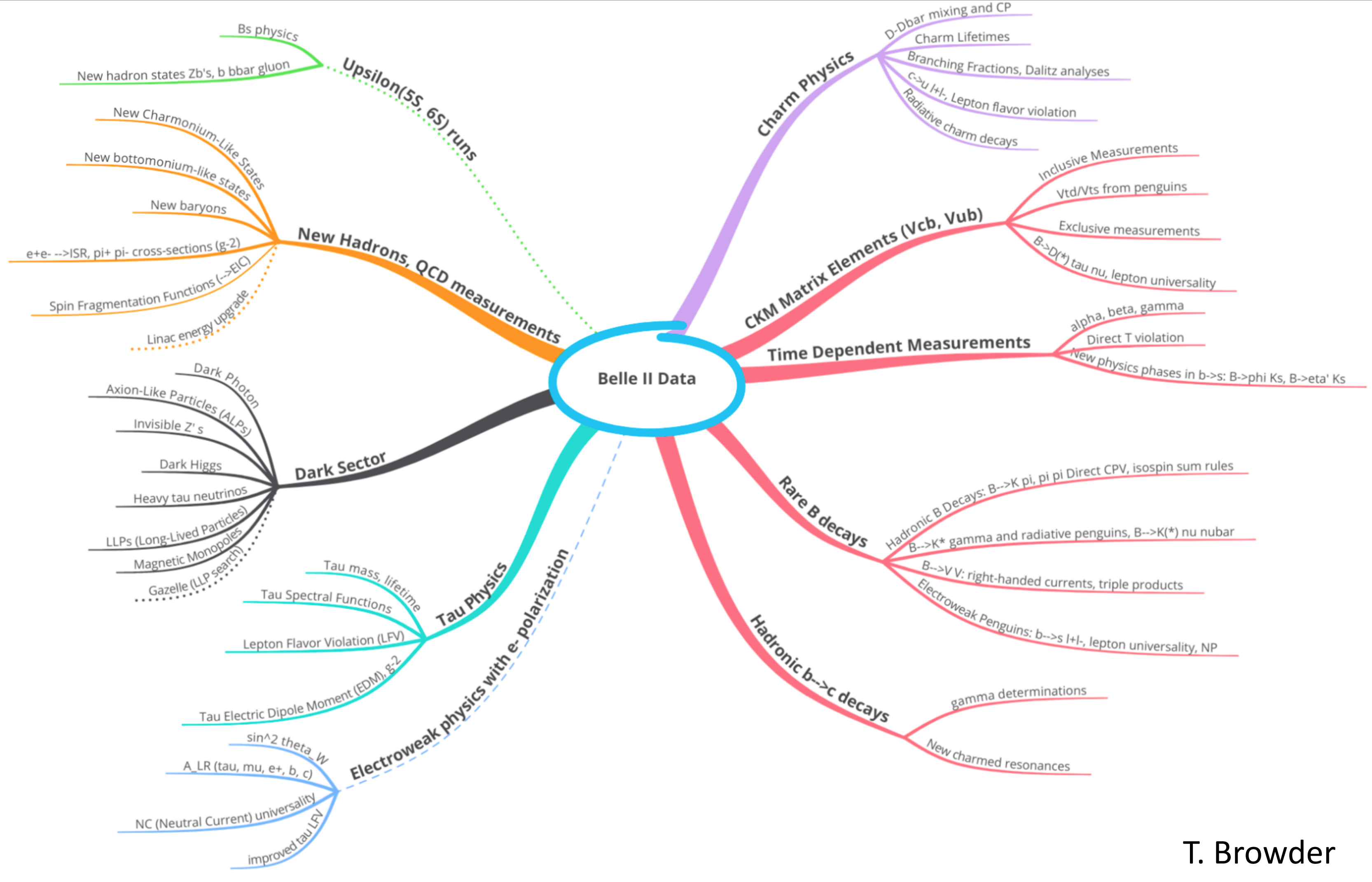
- B-factory basics
- Belle II @ SuperKEKB
- $\Upsilon(4S) \rightarrow B^0\overline{B^0}$: a quantum laboratory
- Tests of entanglement
- Conclusion

The Original B factory Experiments

- BaBar @ PEPII (1999-2008): 433 fb^{-1} (470M BB)
- Belle @ KEKB (1999-2010): 711 fb^{-1} (771M BB)
- Confirmed the Kobayashi-Maskawa Mechanism
  - A single complex CKM phase can explain all CPV observed in the quark sector to date
  - This is now a validated part of the SM
- Belle II @ SuperKEKB (2018-): aims to collect 50ab^{-1} (>50 x 10^9 BB) to look for deviations from this picture (BSM physics)



The Belle II physics program

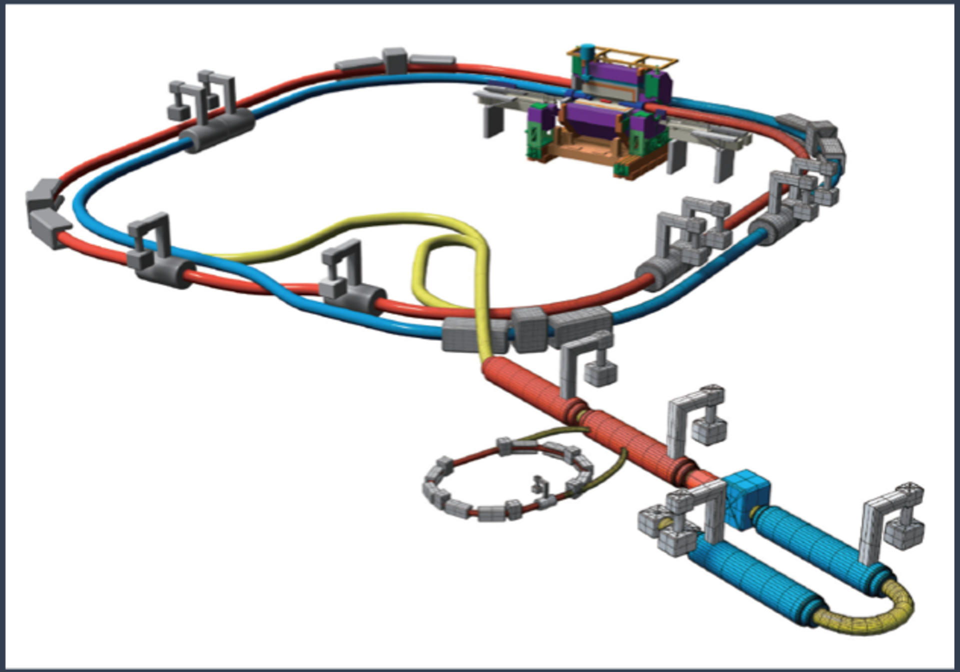


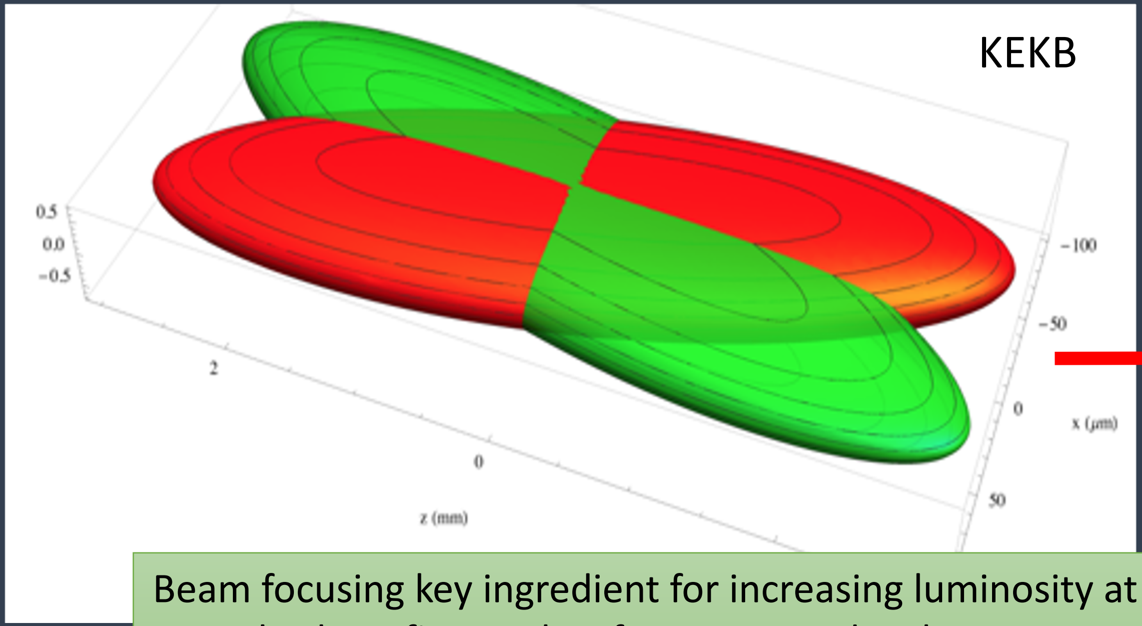
The Belle II physics scope extends far beyond B physics and CPV: Charm, tau, precision EW, quarkonium physics, dark sector searches, and more
See *The Belle II Physics Book*, arXiv:1808.10567, 689 pages
Note: quantum tests with Tau mesons proposed (arXiv:2311.17555), but won't be discussed today.

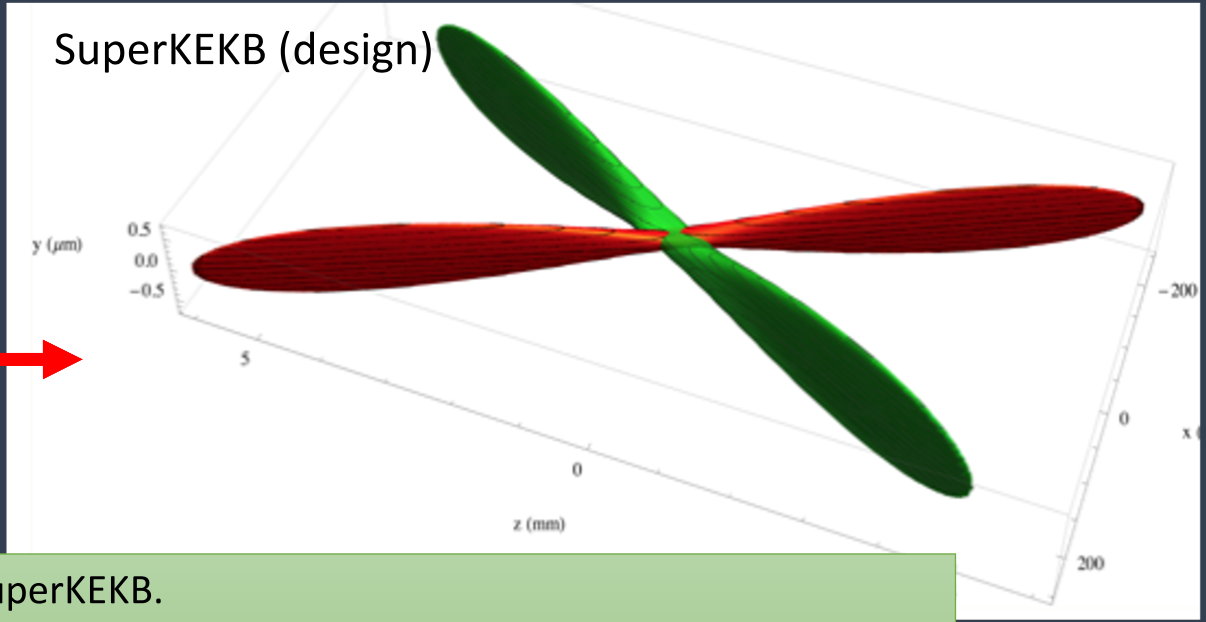
Process	σ (nb)
bb	1.1
cc	1.3
Light quark qq	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

Belle II @ SuperKEKB

- Upgrade of Belle @ KEKB
- Asymmetric e^+e^- collider at 10.58 GeV [$\Upsilon(4S)$]
- Increase instantaneous luminosity by factor 30
- Largely accomplished via nanobeam scheme
  - σ_y^*: 940 → ~50 nm

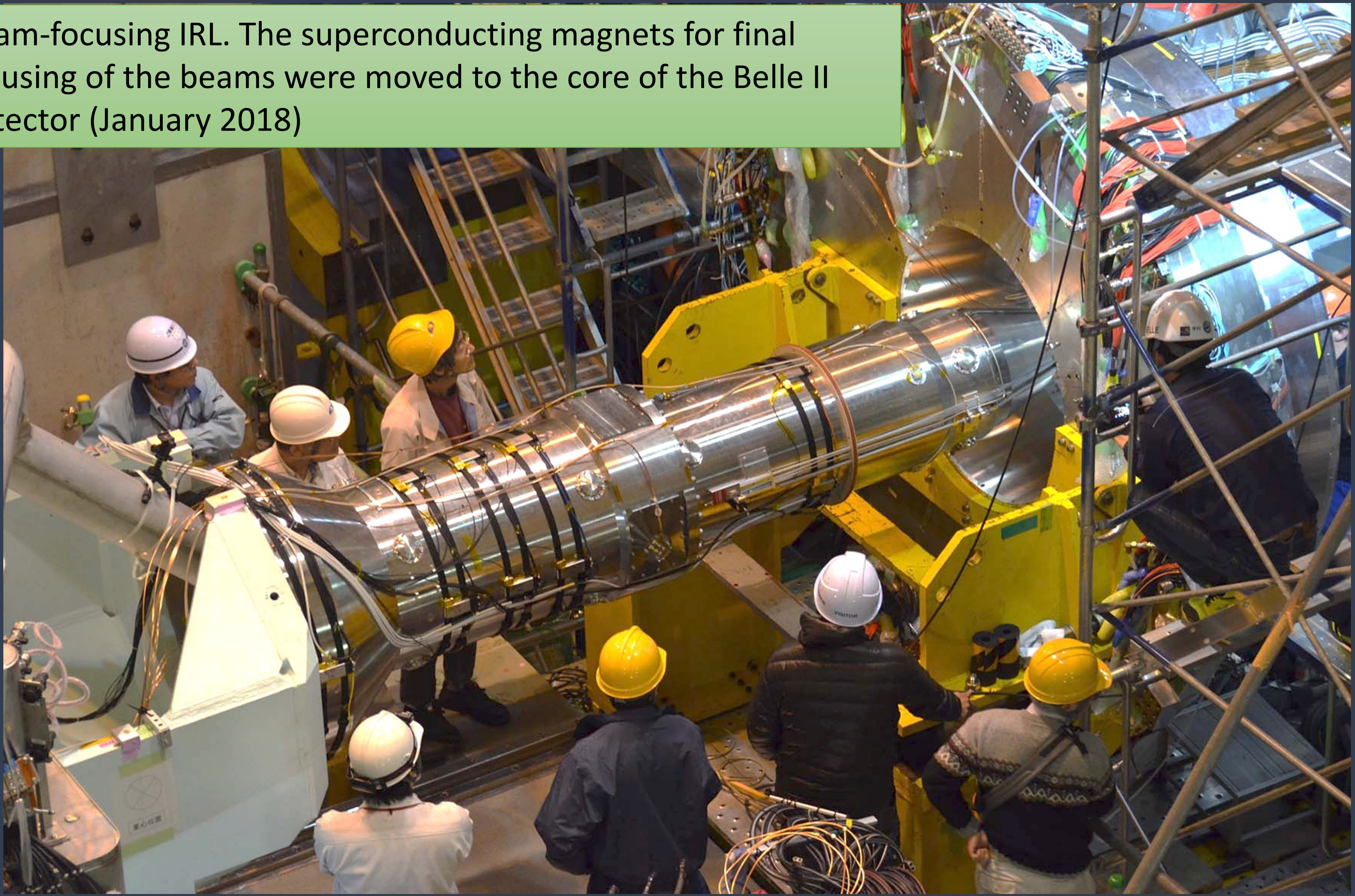






Beam focusing key ingredient for increasing luminosity at SuperKEKB.
May also benefit searches for quantum decoherence: once interaction region becomes sufficiently small, we should be able to estimate individual B meson decay times; t1, t2

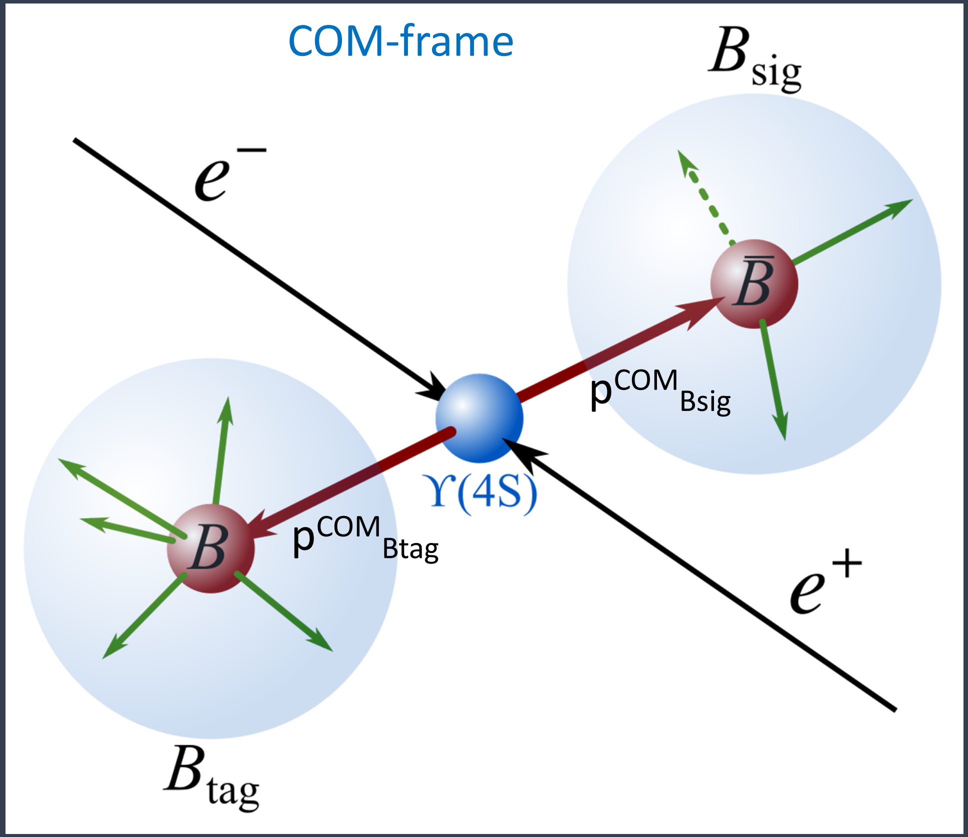
Beam-focusing IRL. The superconducting magnets for final focusing of the beams were moved to the core of the Belle II detector (January 2018)



B factory basics

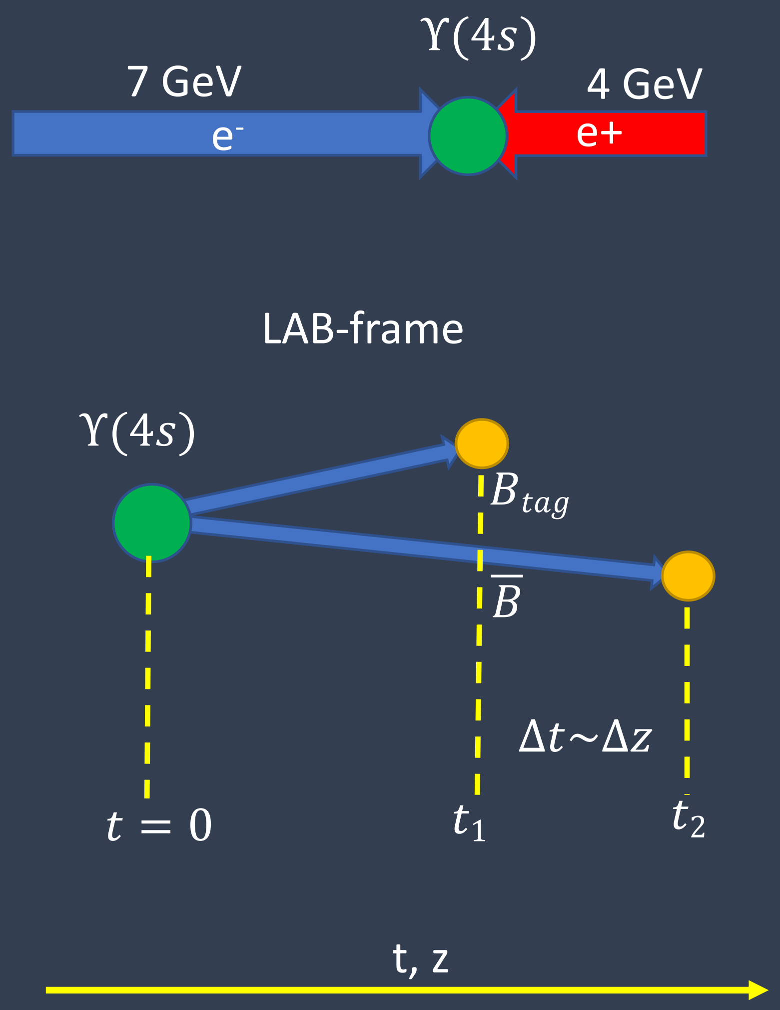
Clean events with tightly constrained kinematics

- Unlike hadron colliders
  - Single collision per event
  - e^+e^- are elementary → initial state four-vector known and static: $p_{\Upsilon(4S)} = p_{e-}+p_{e+}$
- BB pair produced just above threshold
  - Insufficient energy to produce additional particles
- BB fly back-to-back in COM frame (p_T exaggerated in figure), but B frame is not a priori known
  - p^{COM}_B ~ 335 MeV/c
  - Full kinematic reconstruction of a single neutrino is possible on ”signal side” by fully reconstructing the “tag side”
- Flavor tagging: determine if B or anti-B
  - Exclusive reconstruction: low reconstr. efficiency, probability of correct flavor tag very high
  - Inclusive reconstruction: high reconstr. efficiency, but only medium-high probability of correct flavor tab



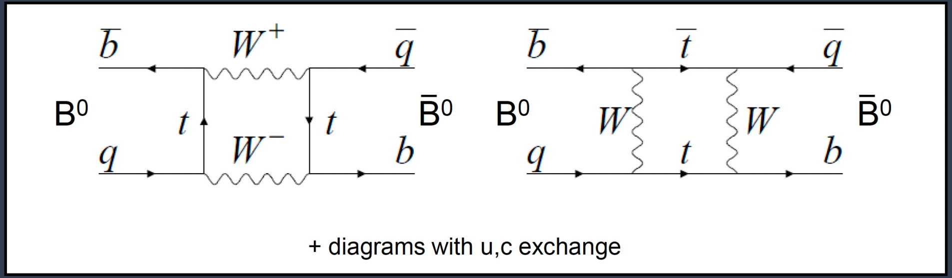
B factory basics: decay times from vertices

- e^+e^- beam energies are asymmetric
- Resulting $\Upsilon(4s)$ boost allows for identification of displaced B vertices
    - B-decay-time-difference $\Delta z = \gamma\beta c\Delta t \sim 200\ \mu\text{m}$
    - measurable with silicon strip and pixel detectors
- Δz provides decay time *difference*, order ps!
- However: *Absolute* decay positions / *absolute* decays times inaccessible *at Belle and Babar*, due to size of e^+e^- interaction region…



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

- B^0 and $\overline{B^0}$ are not mass-eigenstates
  → a single B^0 undergoes flavor oscillations
- $\Upsilon(4S) \to B^0\overline{B^0}$ decays via strong interaction; initial state C=-1 charge conjugation eigen-value must be conserved
- Hence, $B^0\overline{B^0}$ pair ends up flavor entangled:



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

- 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

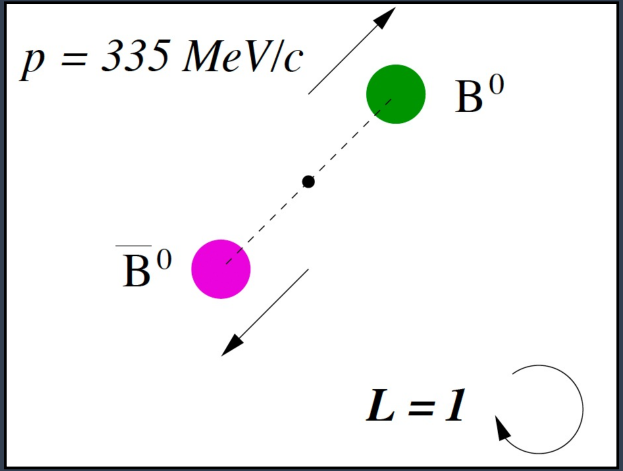
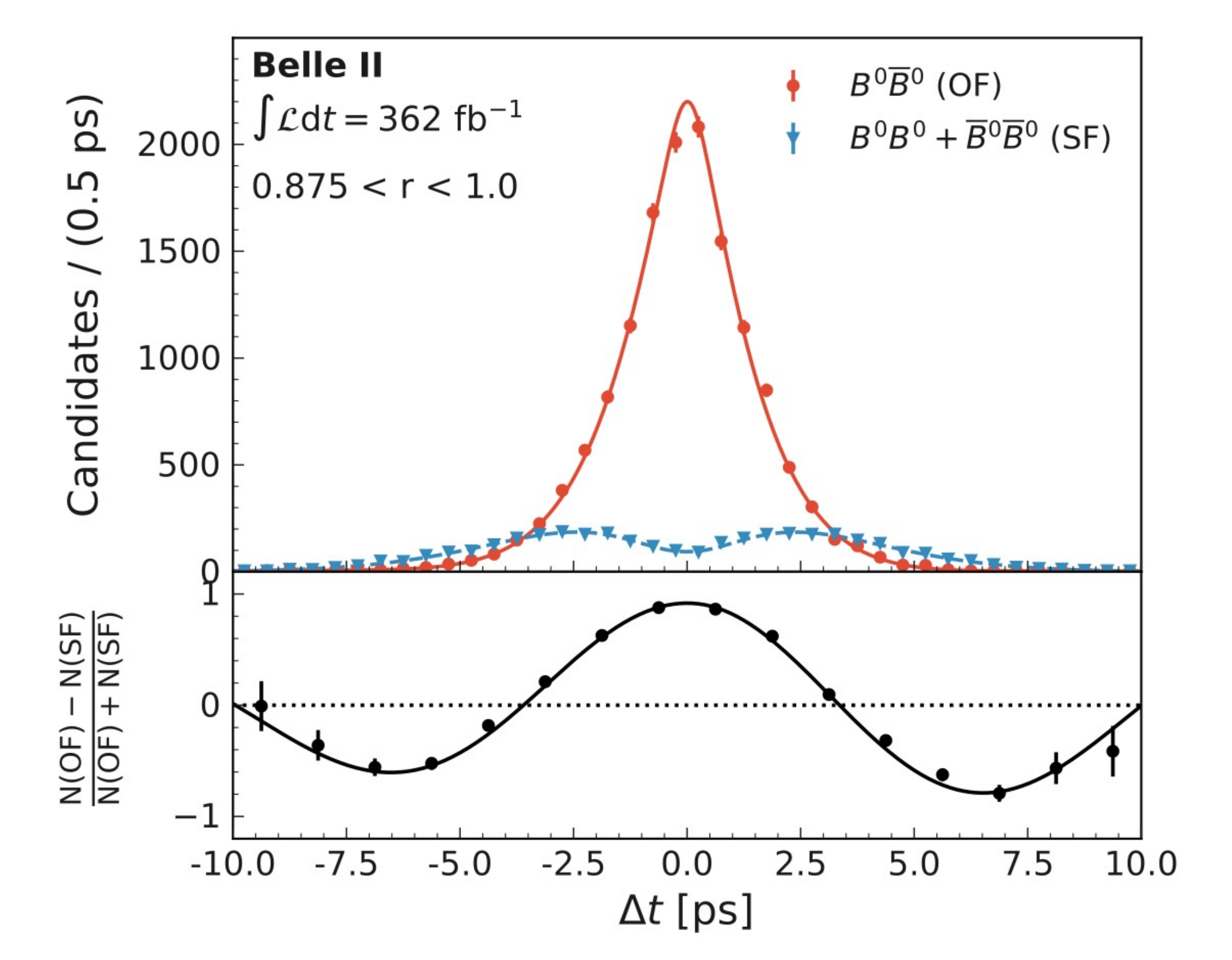


Figure by Bruce Yabsley

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

https://arxiv.org/abs/2402.17260

- Non-local flavor entanglement is assumed "perfect" in analyses of B-mixing and TDCPV
  - 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



What can we probe in this Quantum Laboratory?

<u>Six broad categories</u>

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 (augment QM)
5. QM Decoherence of B meson pair entanglement
6. Statistical tests of entanglement

(4–6:) not attempted?
(except for spontaneous decoherence,
included in 2007 Belle PRL)

Spontaneous versus environmental decoherence

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

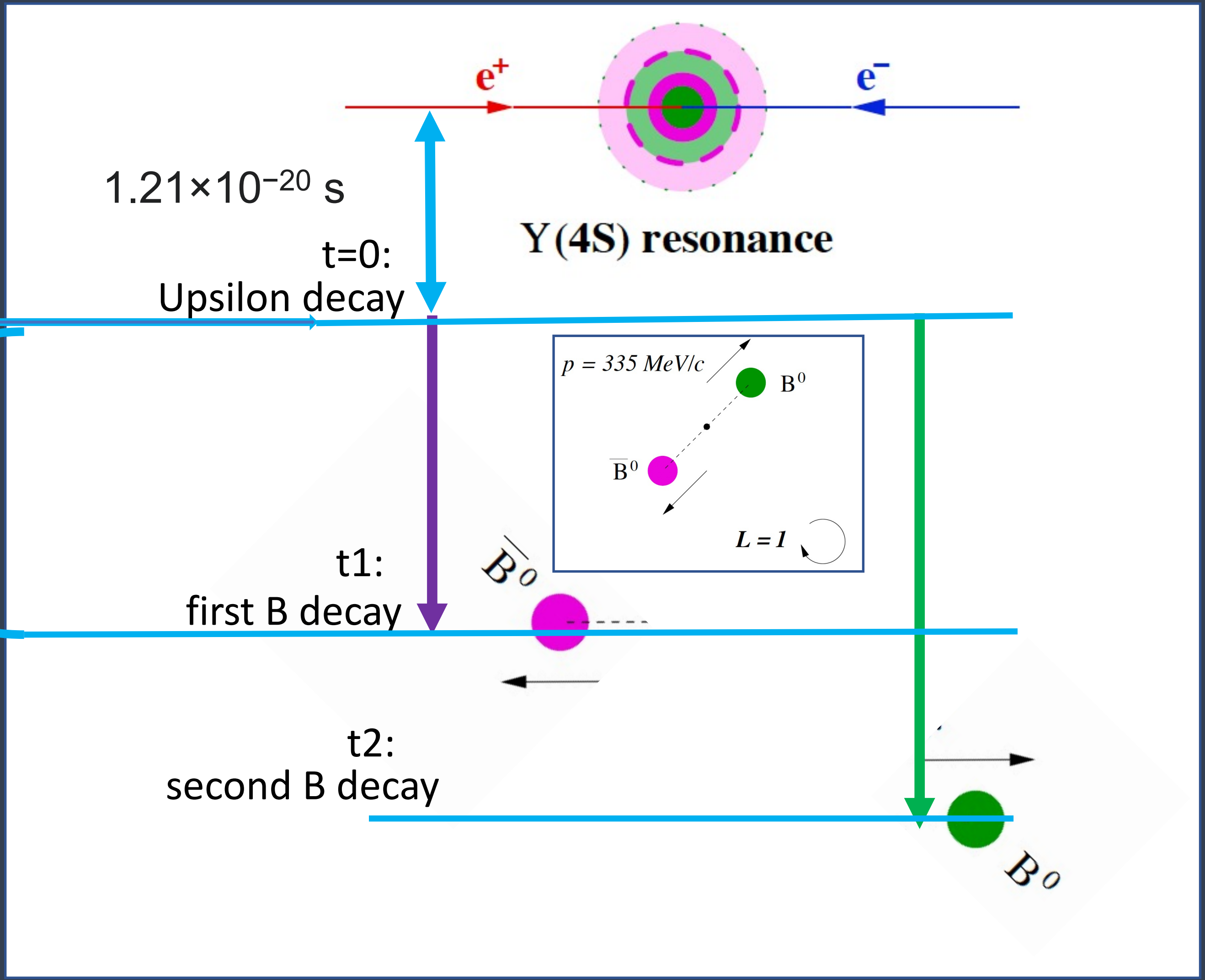
Spontaneous disentanglement or non-coherent production

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

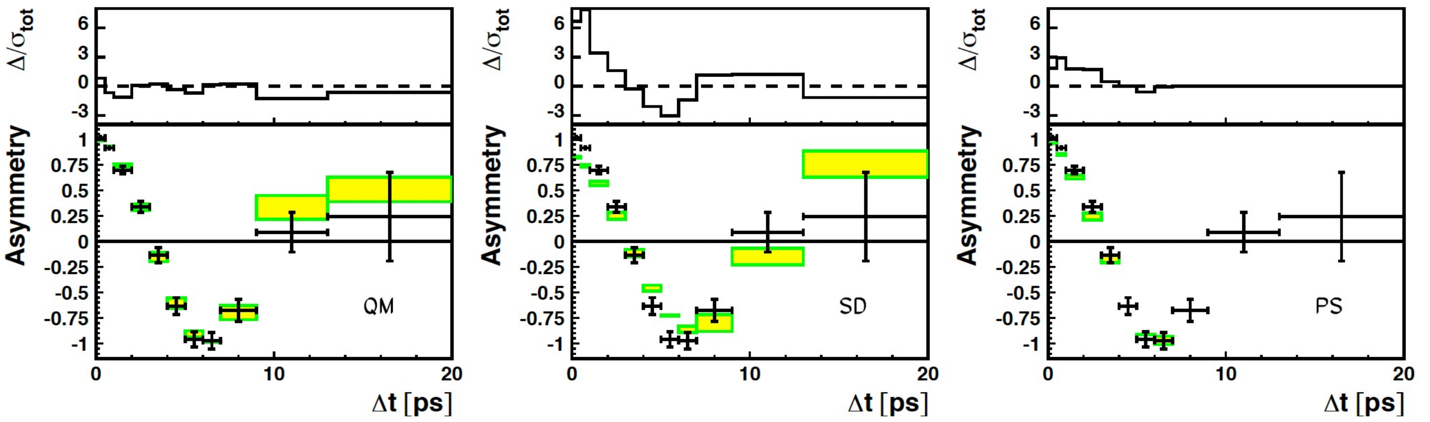
$$\begin{aligned} \mathrm{A}_{\mathrm{PS}}^{\max}(t_1,t_2) &= 1 - |\{1-\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\min}) \\ &\quad + \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\min})|, \text{ and} \qquad (3) \\ \mathrm{A}_{\mathrm{PS}}^{\min}(t_1,t_2) &= 1 - \min(2+\Psi,\, 2-\Psi), \text{ where}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

- "Spontaneous Disentanglement" of all BB pairs

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

- Fractional Spontaneous Disentanglement
  - 3% +/- 6% ; possibly a systematic error on sin $2\phi_1$ measurement, not studied

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



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

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

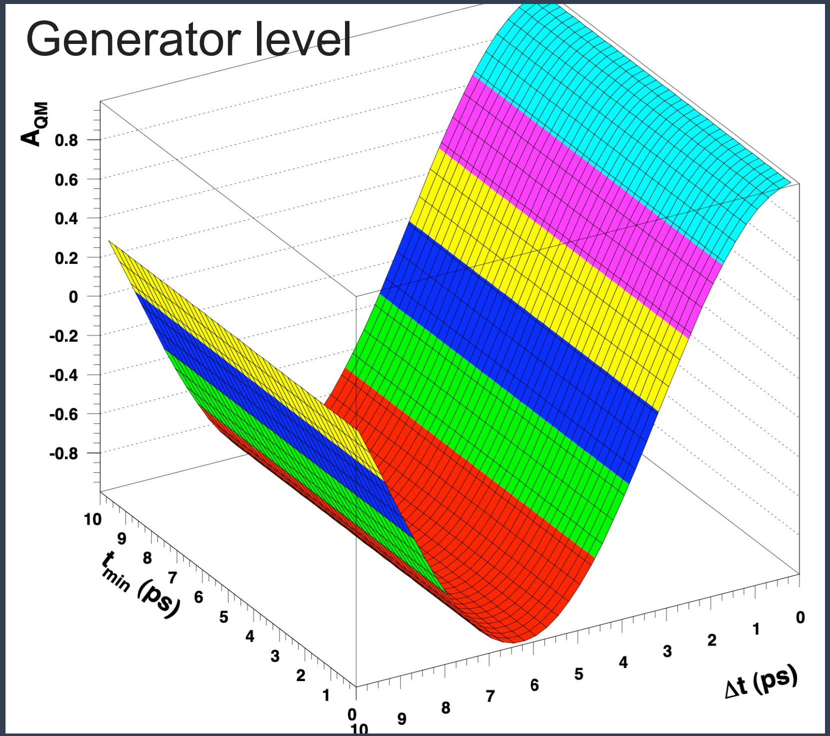
PS disfavoured: 5.1σ $\chi^2/n_{dof} = 31/11$

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

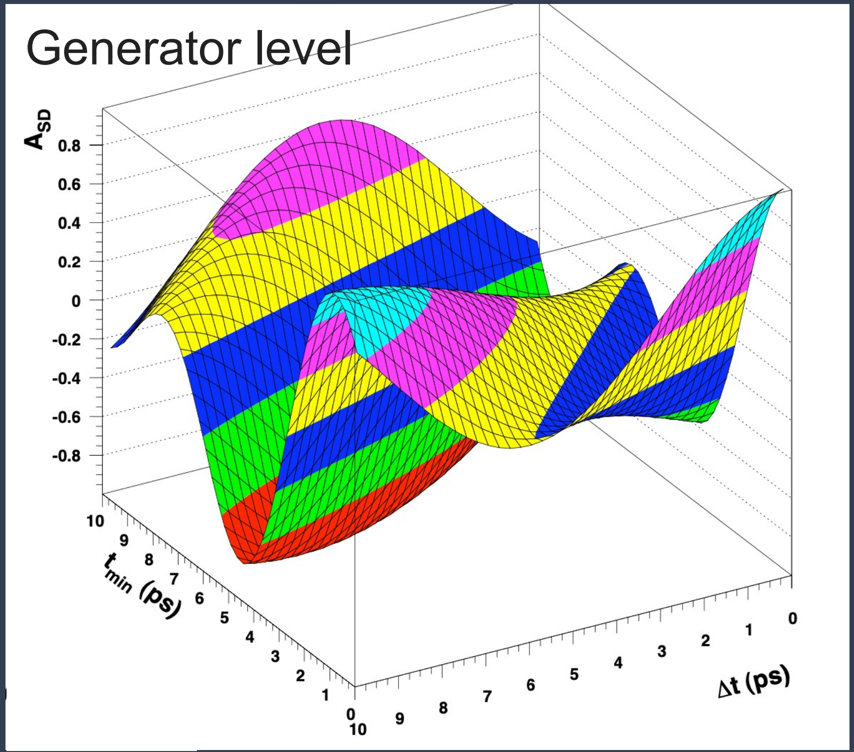
Access to t_1 generally adds a new dimensions and should increase sensitivity

Asymmetry for QM



Entanglement: depends only on Δt

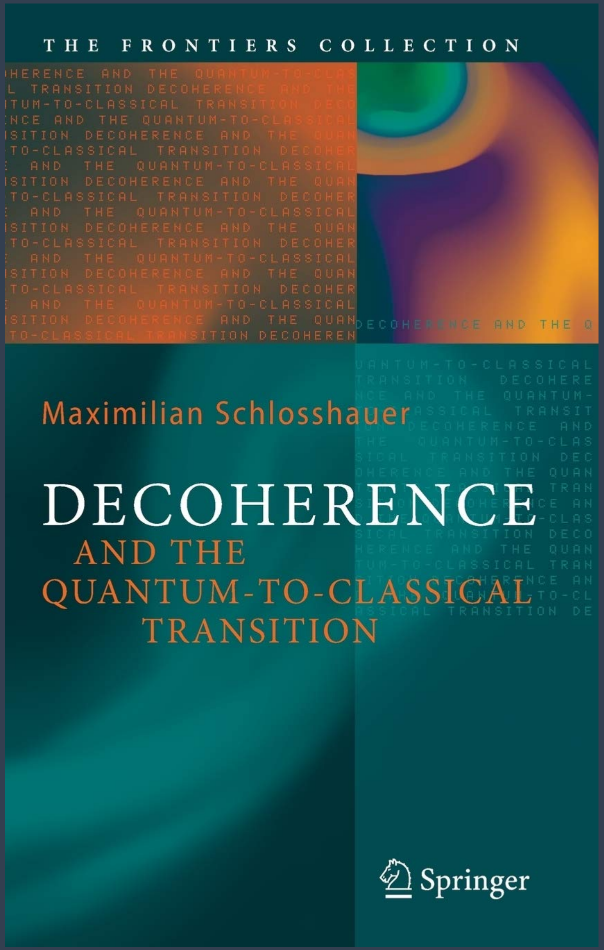
Asymmetry for Spontaneous Disentanglement



B. Yabsley

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: infrared photons, cosmological neutrinos, Higgs condensate…
- BSM decoherence
  - Energy density components that we do not fully understand, yet, may also contribute: dark matter & energy

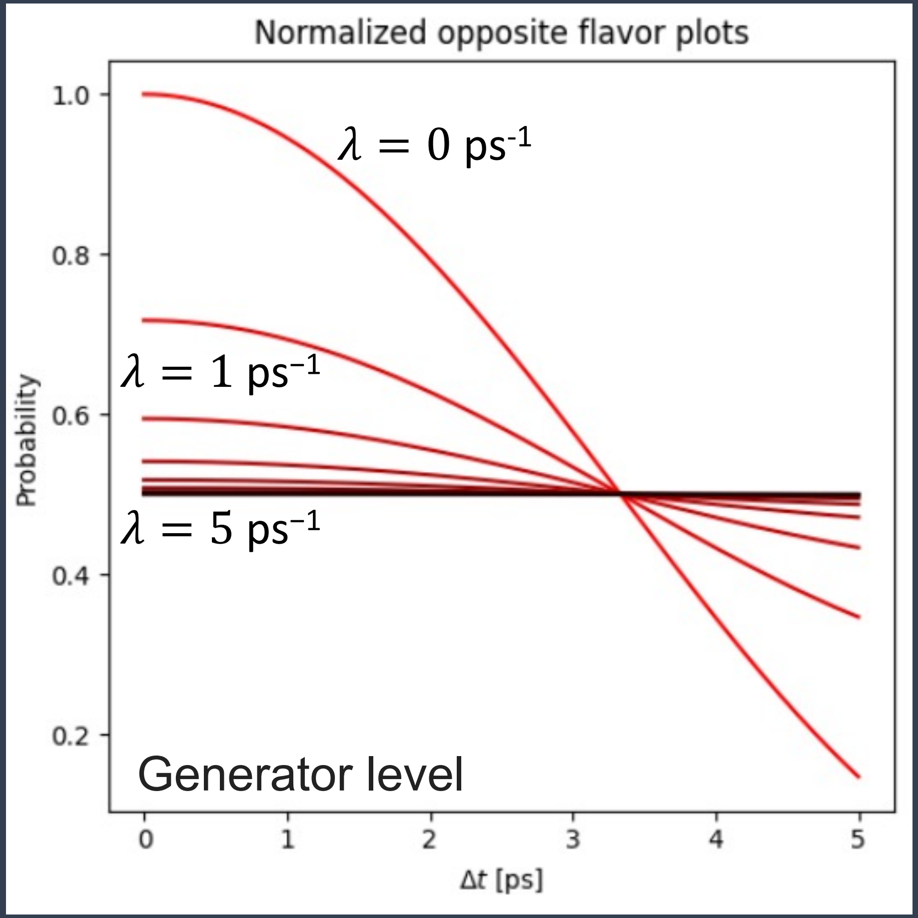
Lindblad Type Decoherence of B meson entanglement

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

- Decoherence effect in this model: entanglement of the B meson pair becomes imperfect with time
- Begins after $\Upsilon(4S)$ decay and ends at first B meson decay
- Parameter $\lambda \in [0, \infty)$ characterizes strength of decoherence growth
- Theory predictions for Belle II:

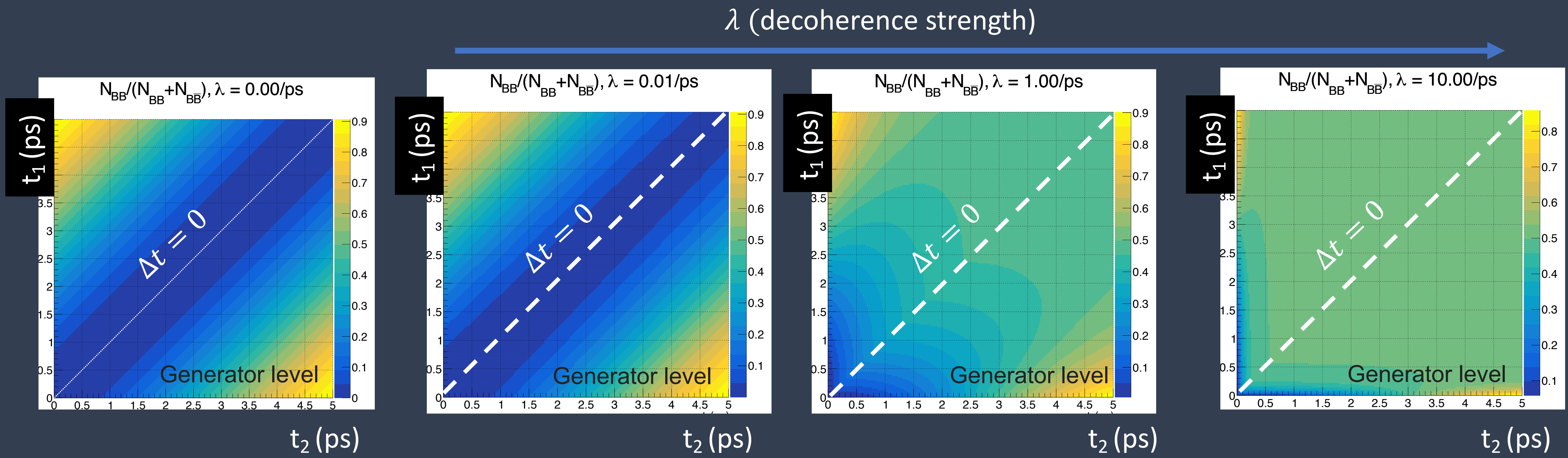
$$N = \frac{1}{4} e^{-\Gamma(t_1+t_2)} [\cosh(\frac{\Delta\Gamma\Delta t}{2}) - \mu e^{-\lambda t_1} \cos(\Delta m \Delta t)]$$

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



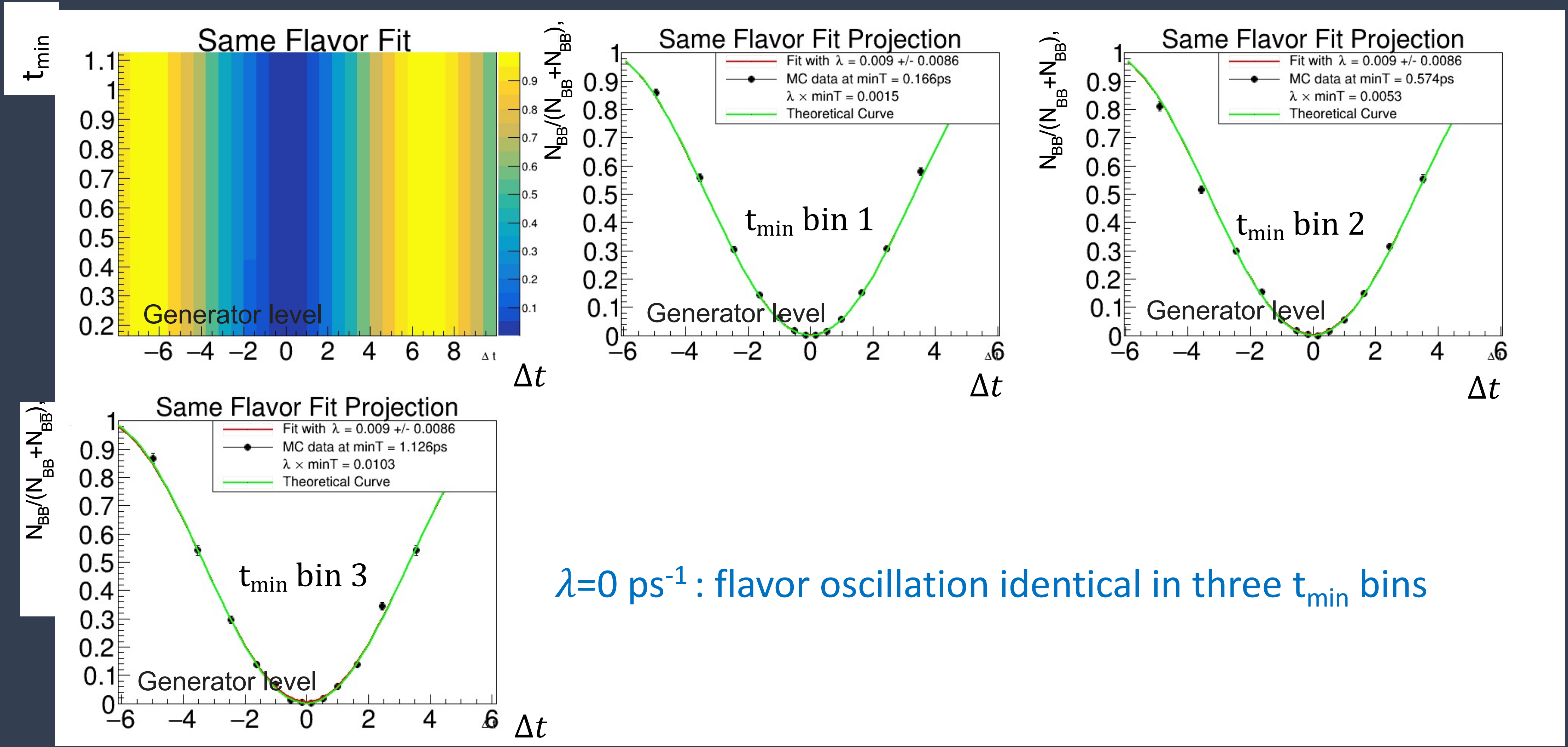
- As decoherence strength λ increases, number of same-sign B meson pairs at $\Delta t = 0$ increases
- In this 2d plane, decoherence distinct from miss-tagging (assigning wrong b-flavor in reconstruction)
- Experimentally access to coordinate orthogonal to Δt (t_{min} , t_{max} or $\sum t$) should enhance sensitivity to decoherence, and the difference between miss-tagging and decoherence

$$\Delta t = t_2 - t_1 \quad ; \quad \sum t = t_1 + t_2.$$

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

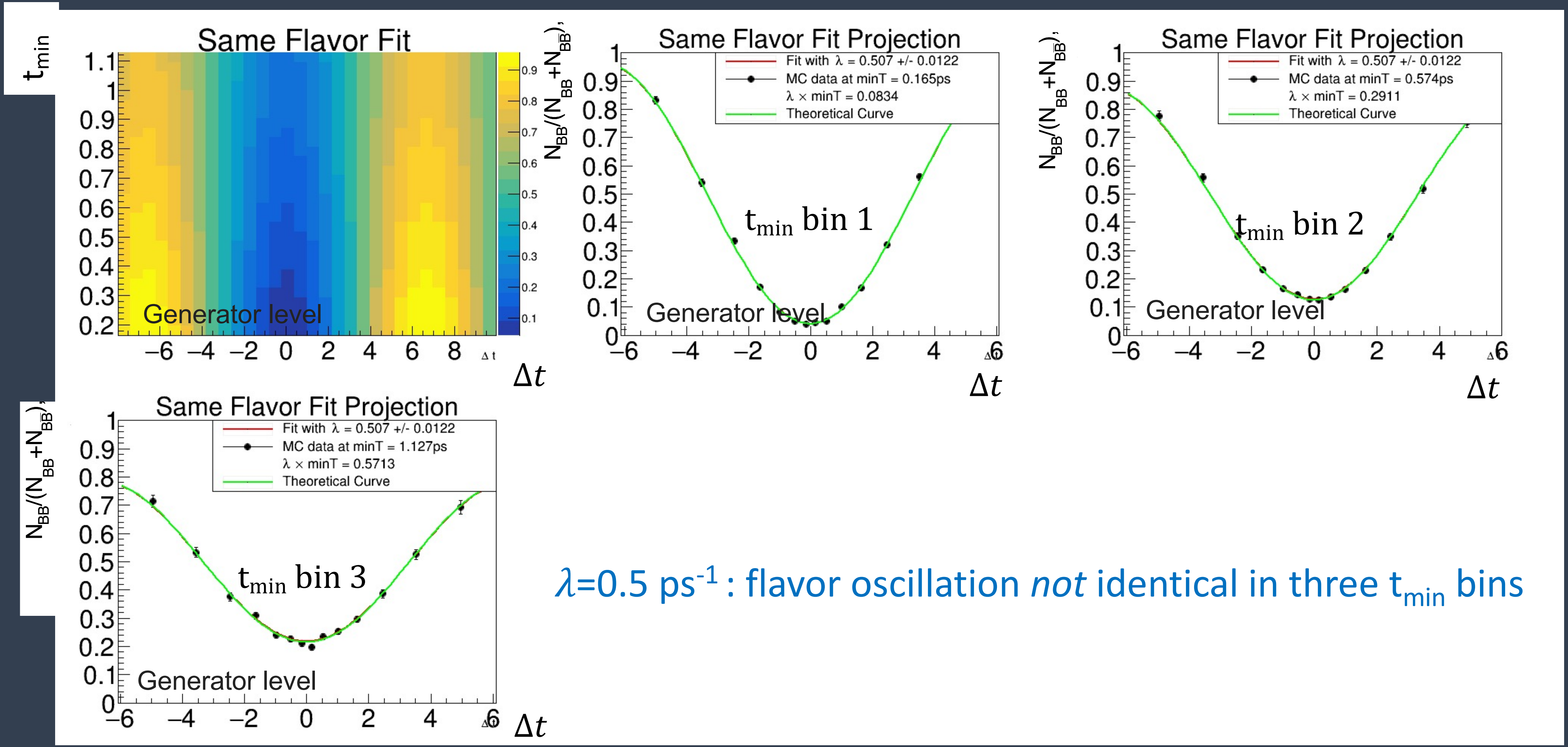


λ=0 ps^{-1} : flavor oscillation identical in three t_{min} bins

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

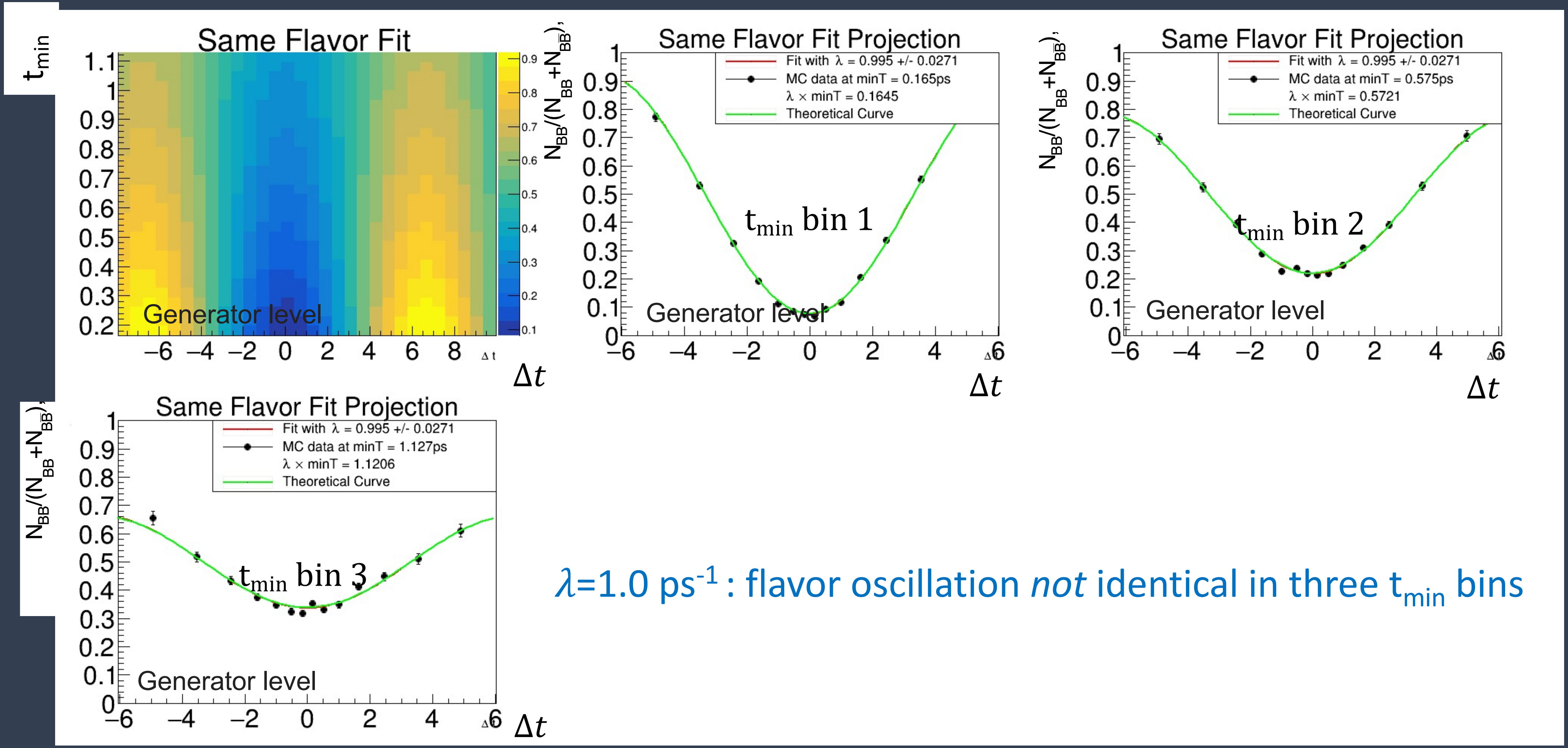


λ=0.5 ps^{-1} : flavor oscillation *not* identical in three t_{min} bins

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

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

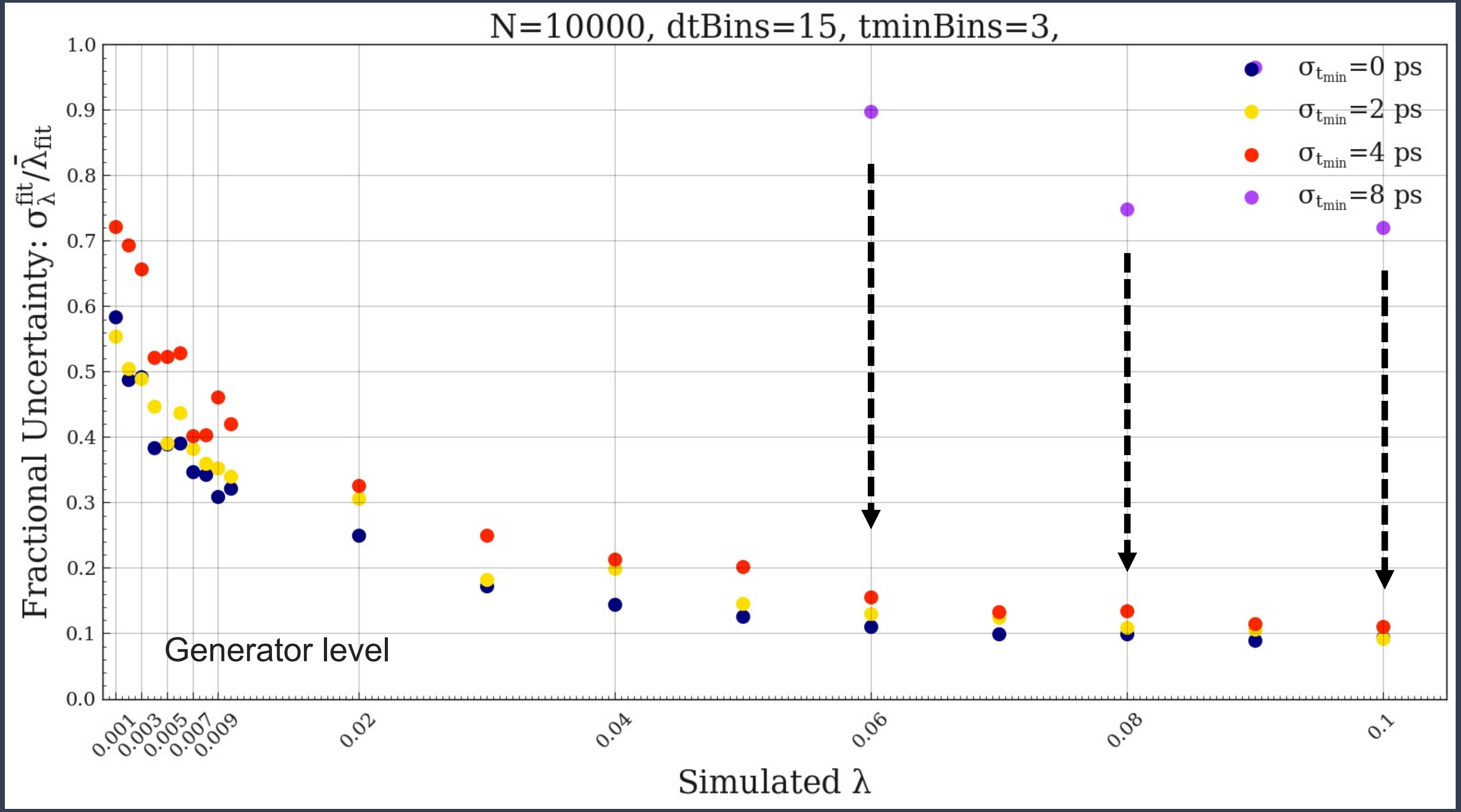
100k events per fit



λ=1.0 ps^{-1} : flavor oscillation *not* identical in three t_{min} bins

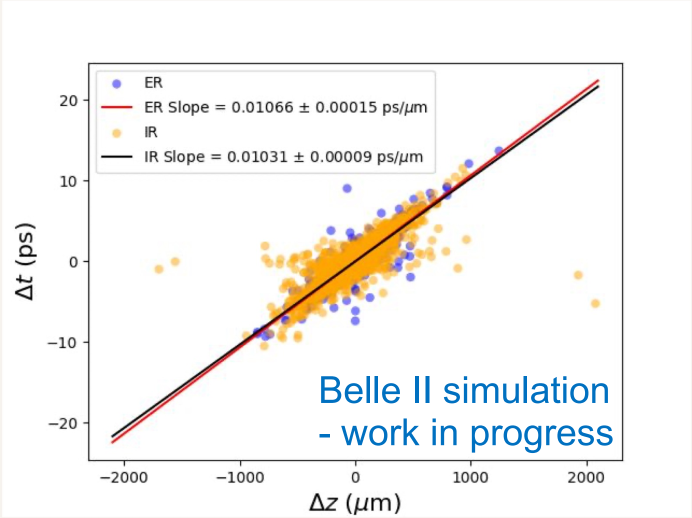
Sensitivity to decoherence parameter λ

simplistic binned fit at truth level (10k events, 15 Δt bins and 3 t_{min} bins)
smearing of absolute decay time = $\sigma_{t_{min}}$

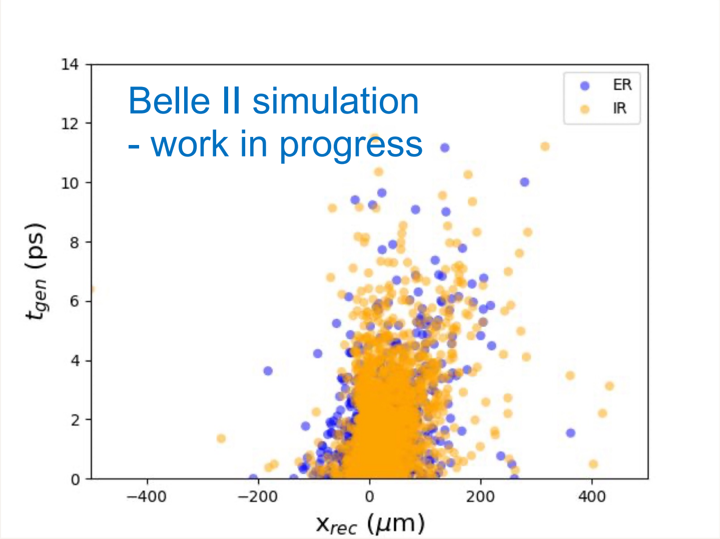


Sensitivity improves with smaller $\sigma_{t_{min}}$ - illustrating importance of measuring t_{min}
At truth-level >5 sigma sensitivity w/10k reconstructed events for λ>~0.04

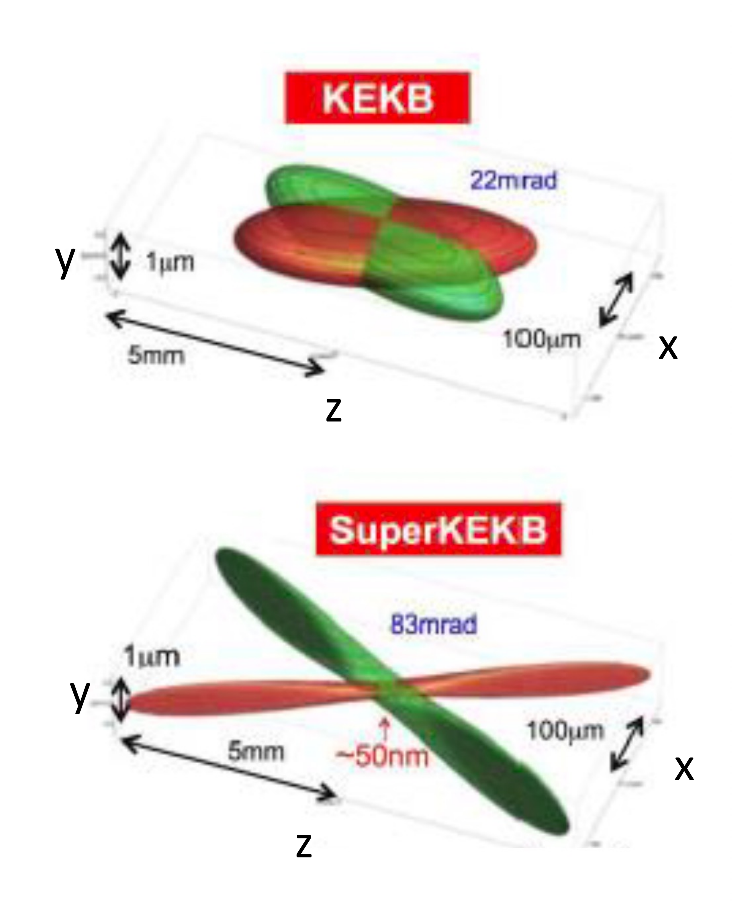
Obtaining Δt, t_{min} from *reconstructed* quantities



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



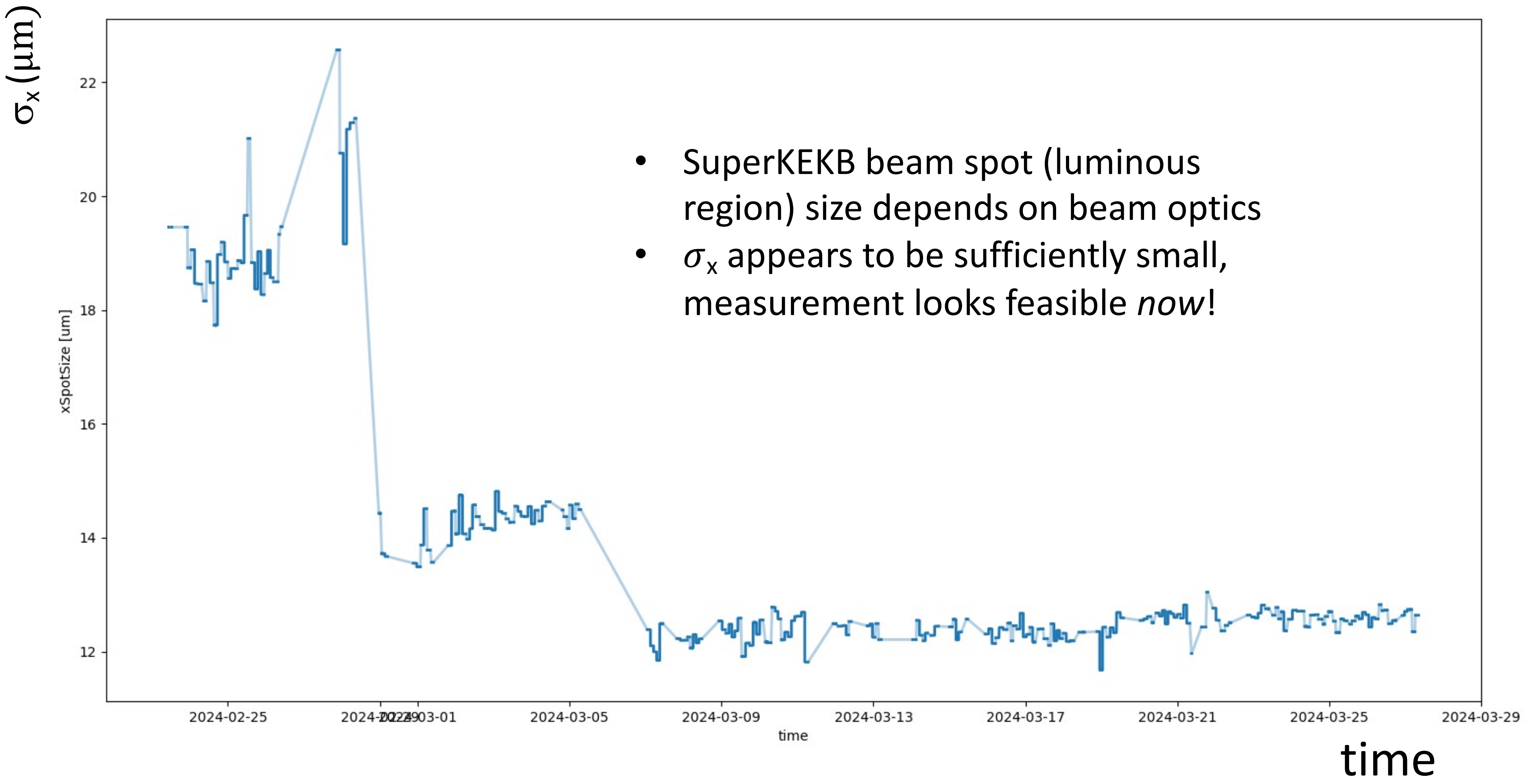
Discovered correlation between t and x, found proxy for absolute B meson lifetime!



Non-zero correlation due to beam-crossing angle!

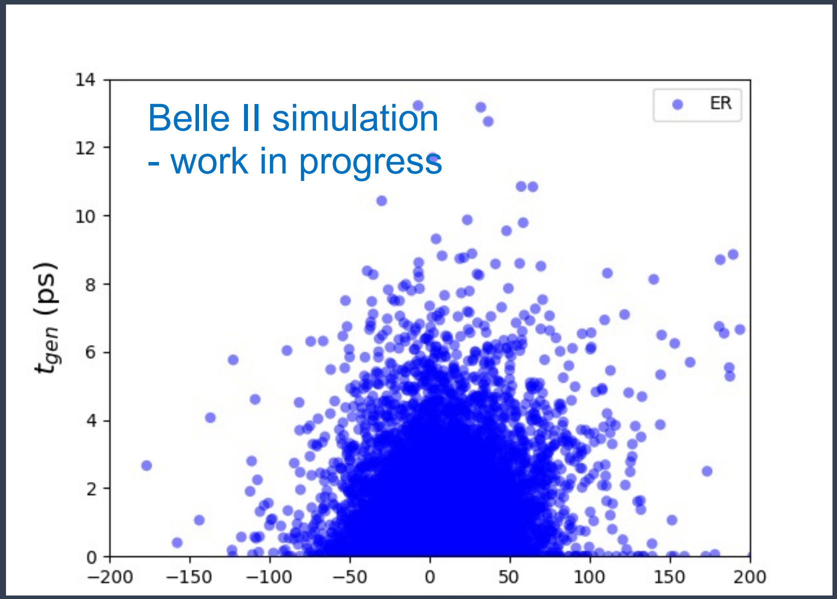
Beam spot size	KEKB	SuperKEKB *design*
σ_x	150 μm	10 μm
σ_y	940 nm	50 nm
σ_z, eff	7 mm	0.25 mm

Recent measurements of the beam spot size in *x*

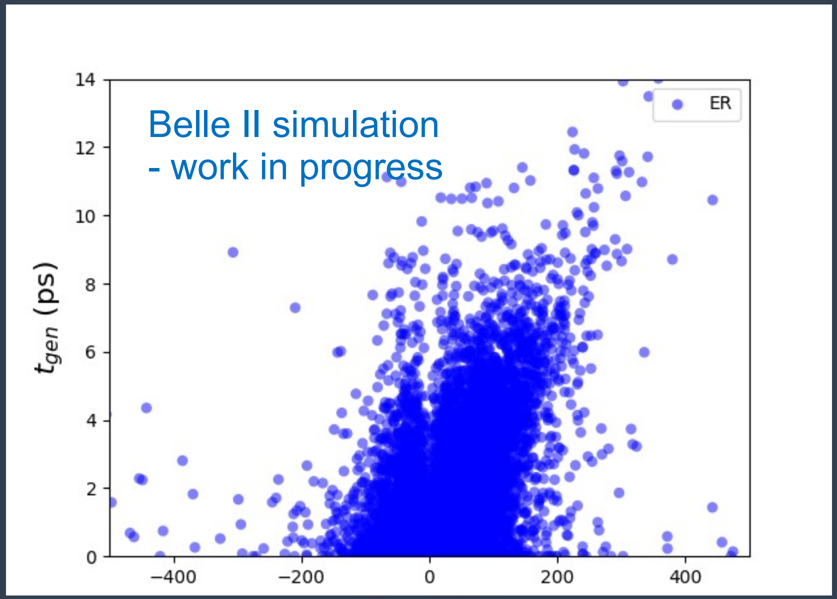


- SuperKEKB beam spot (luminous region) size depends on beam optics
- σ_x appears to be sufficiently small, measurement looks feasible *now*!

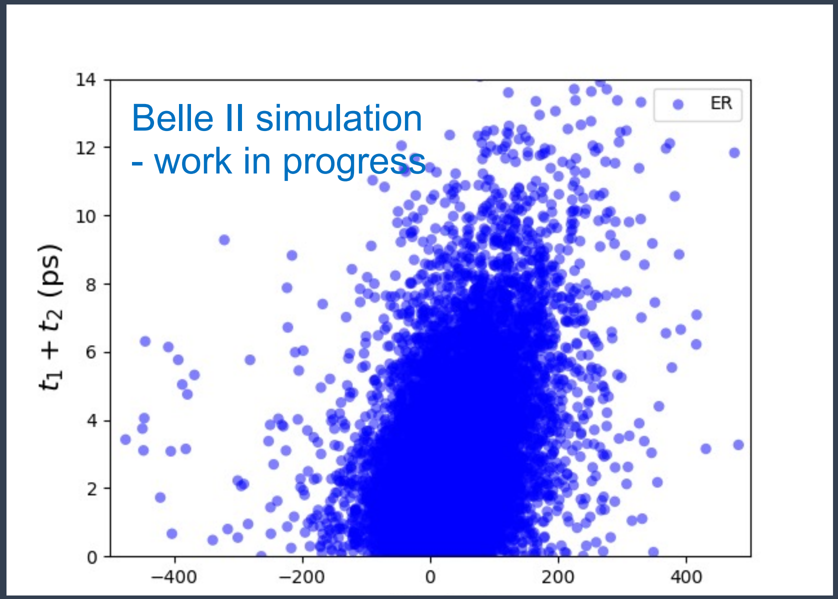
A closer look: which x_B coordinate works best?



x_{min} ✗

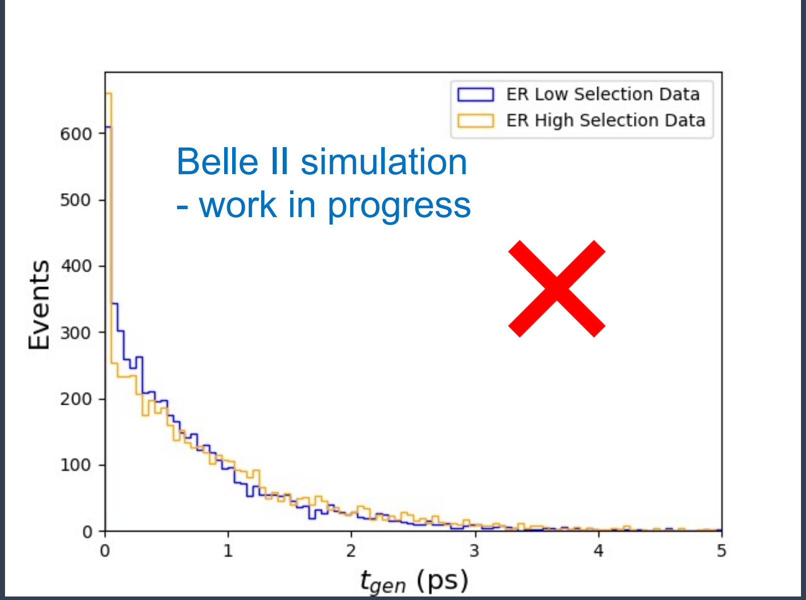


x_{max} ✓

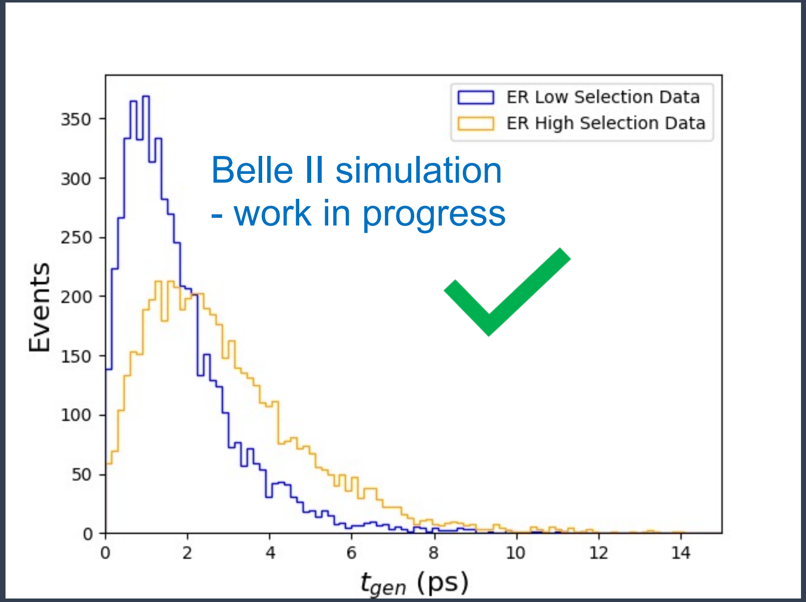


$x_{min}+x_{max}$ ✓

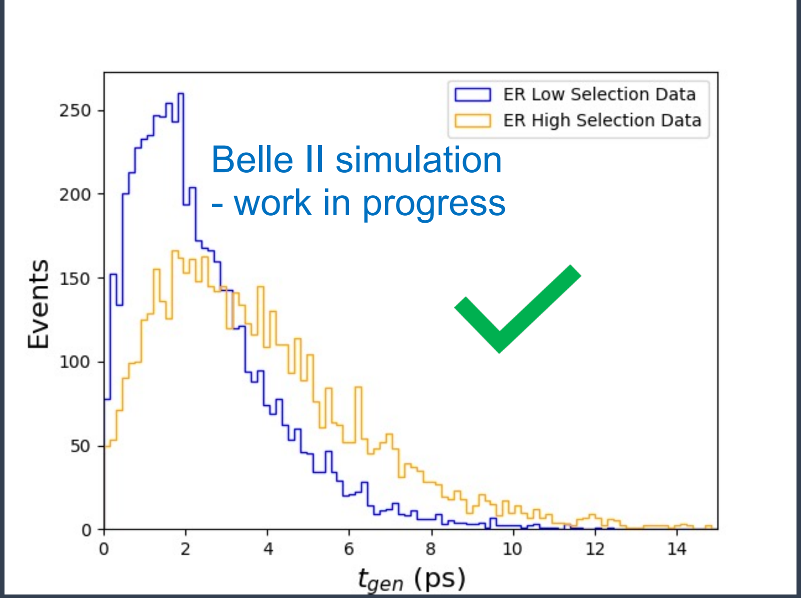
Separate reconstructed events into two x_B bins…



using x_{min}



using x_{max}



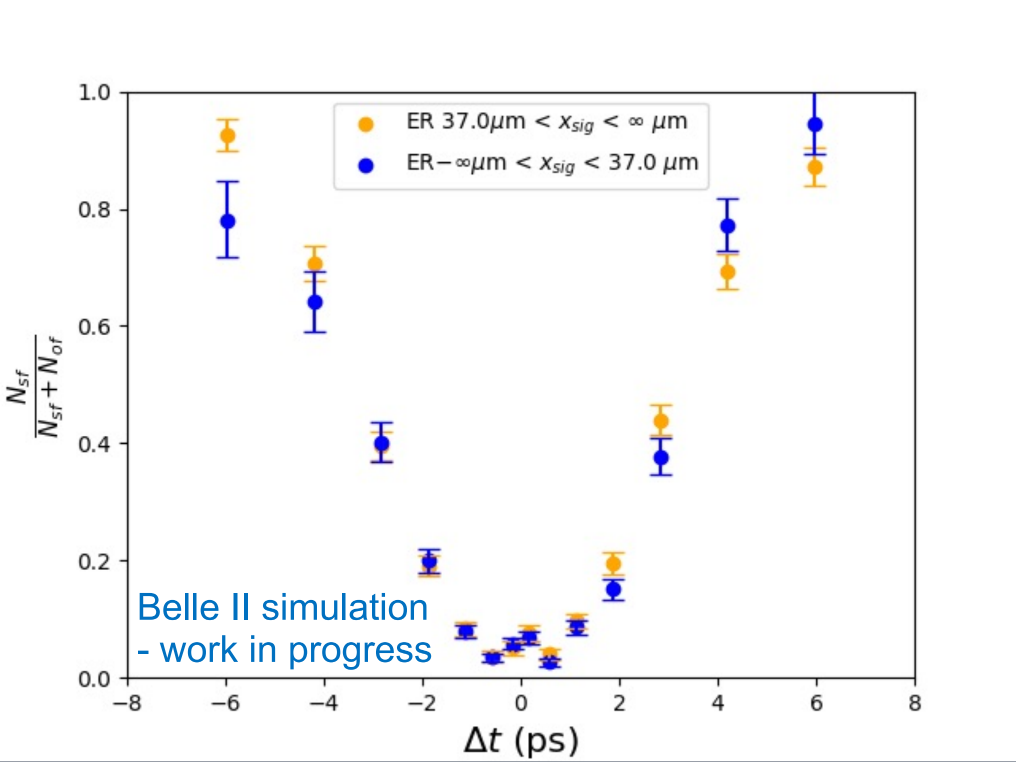
using x_{min}+x_{max}

- 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!

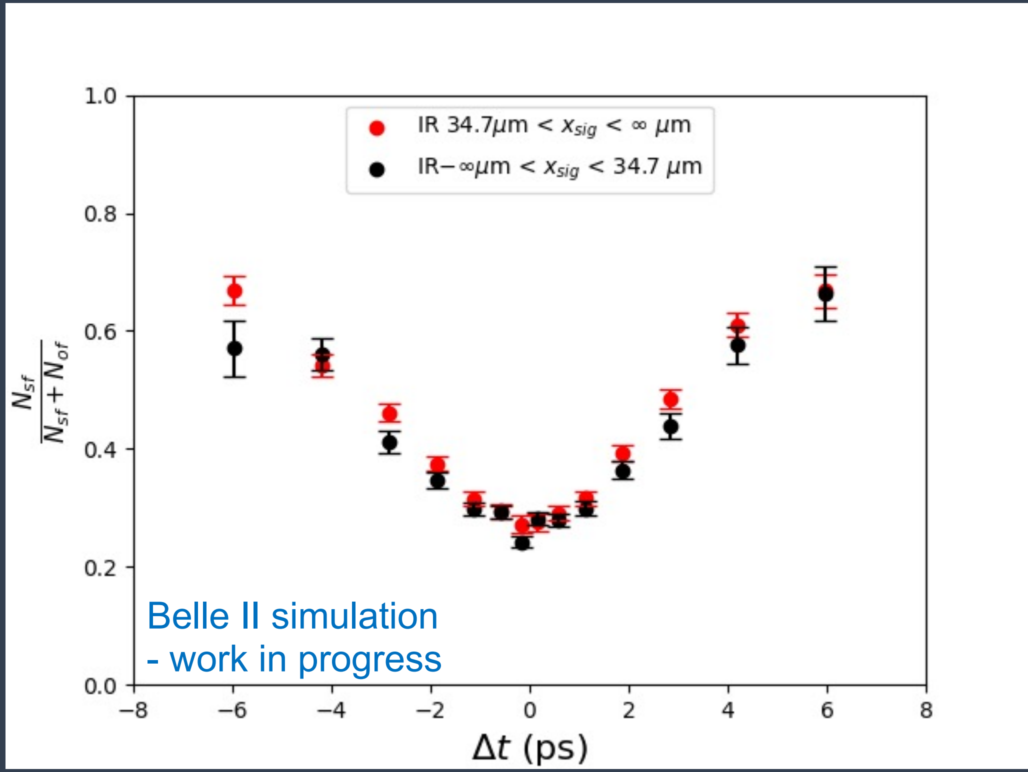
Reconstructed Δt distributions, $\lambda = 0\ ps^{-1}$

Data binned using x_{max}. 100k events

Exclusive hadronic reconstruction of both Bs



Exclusive hadr. reconstruction of one B, other inclusive

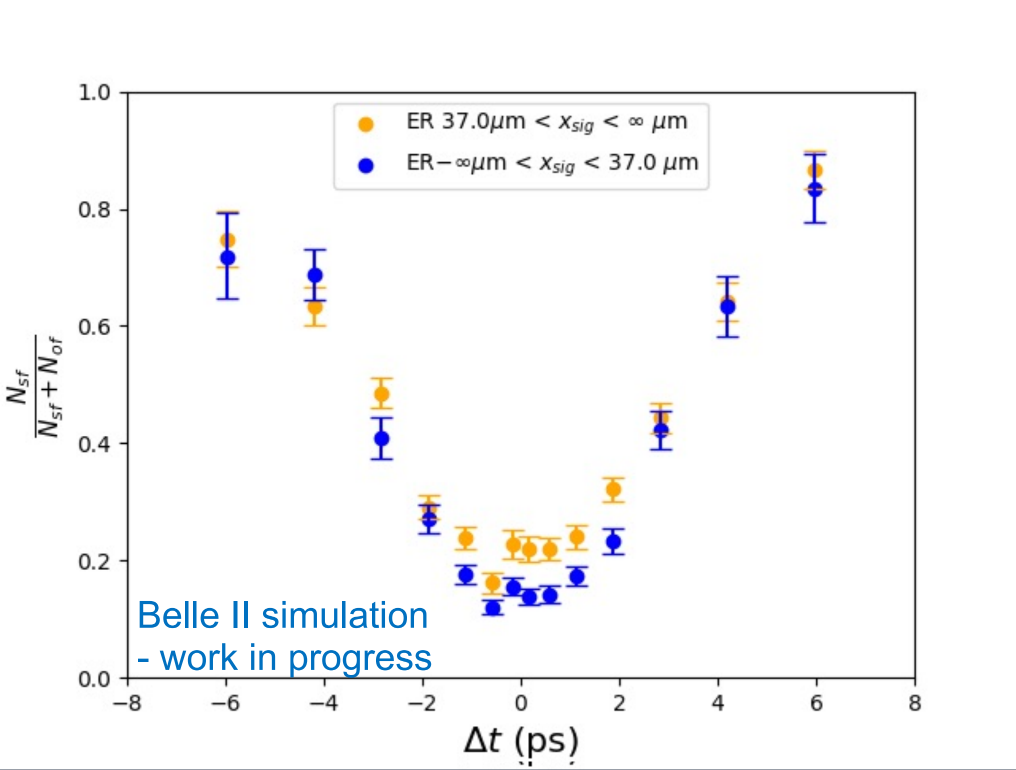


λ =0, no decoherence, default Standard Model physics in EvtGen

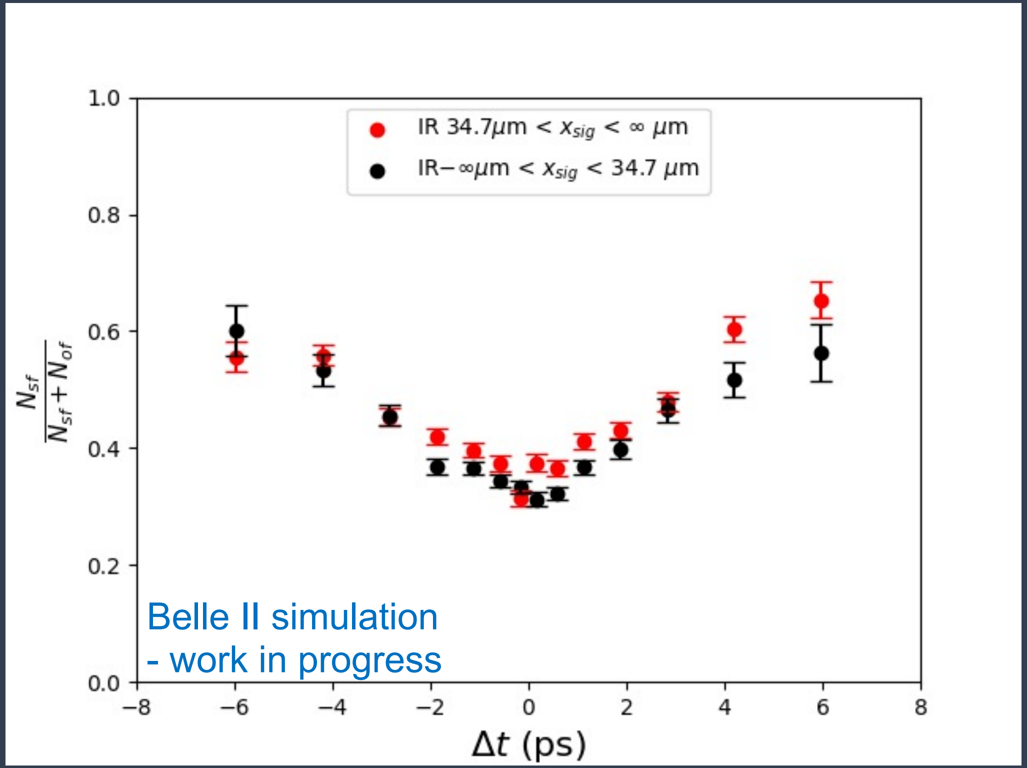
Reconstructed Δt distributions, λ = 0.5 ps^{-1}

Data binned using x_{max}. 100k events

Exclusive hadronic reconstruction of both Bs



Exclusive hadr. reconstruction of one B, other inclusive

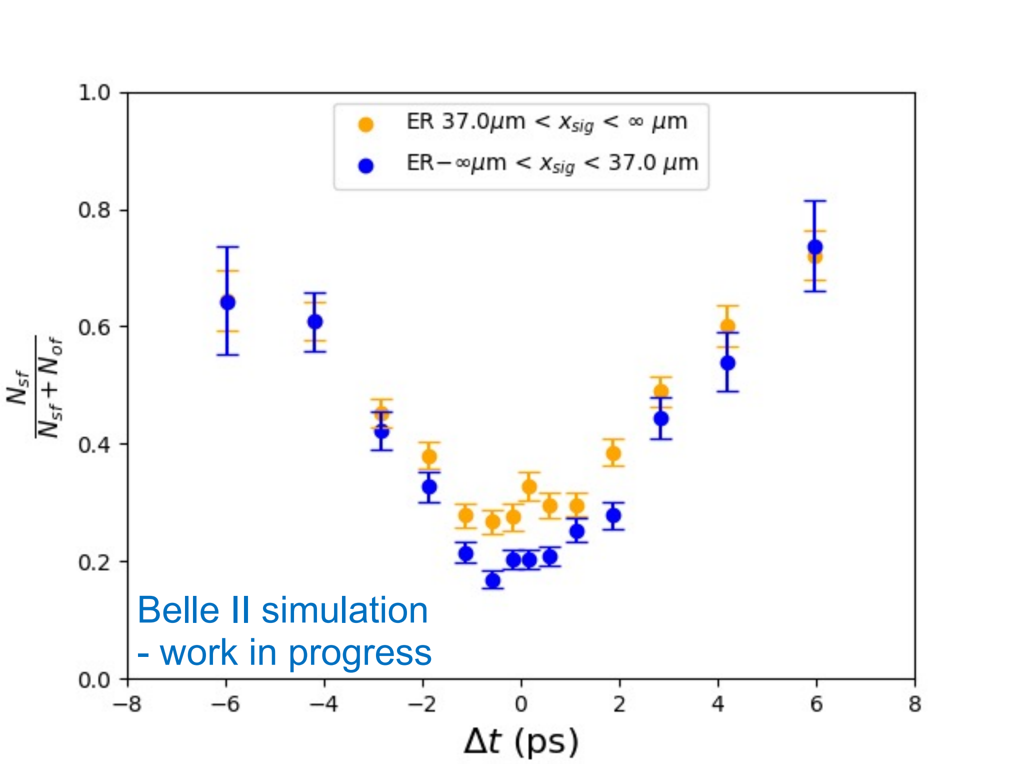


Clearly observe decoherence signature using only reconstructed quantities

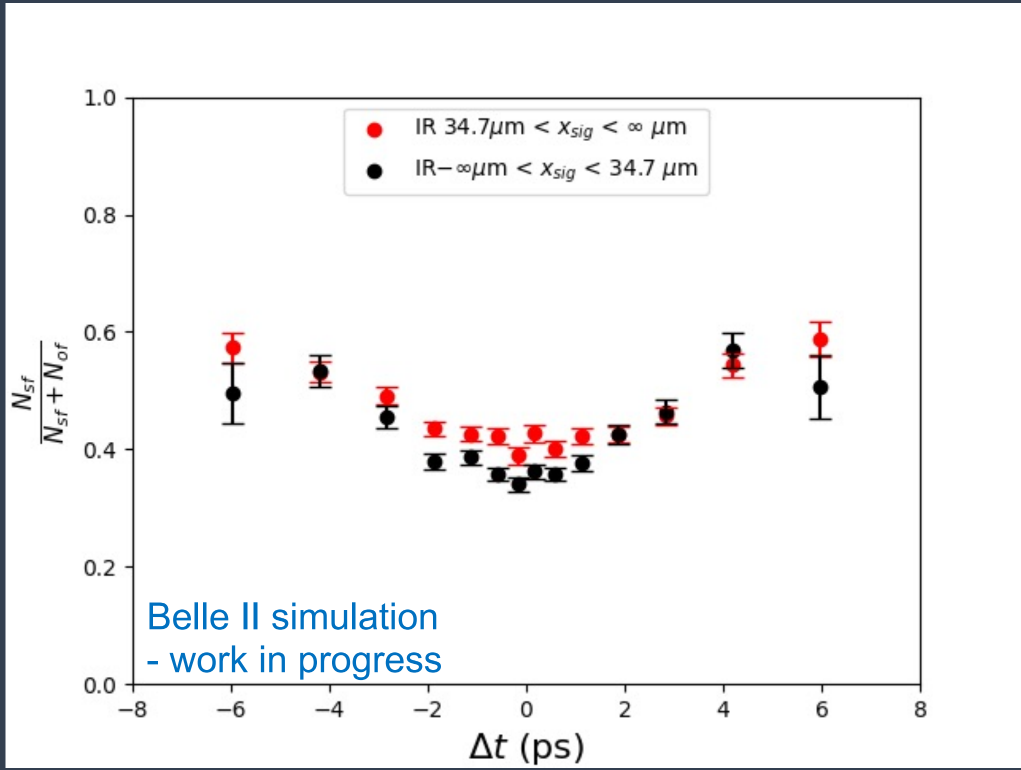
Reconstructed Δt distributions, λ = 1.0 ps^{-1}

Data binned using x_{max}. 100k events

Exclusive hadronic reconstruction of both Bs



Exclusive hadr. reconstruction of one B, other inclusive



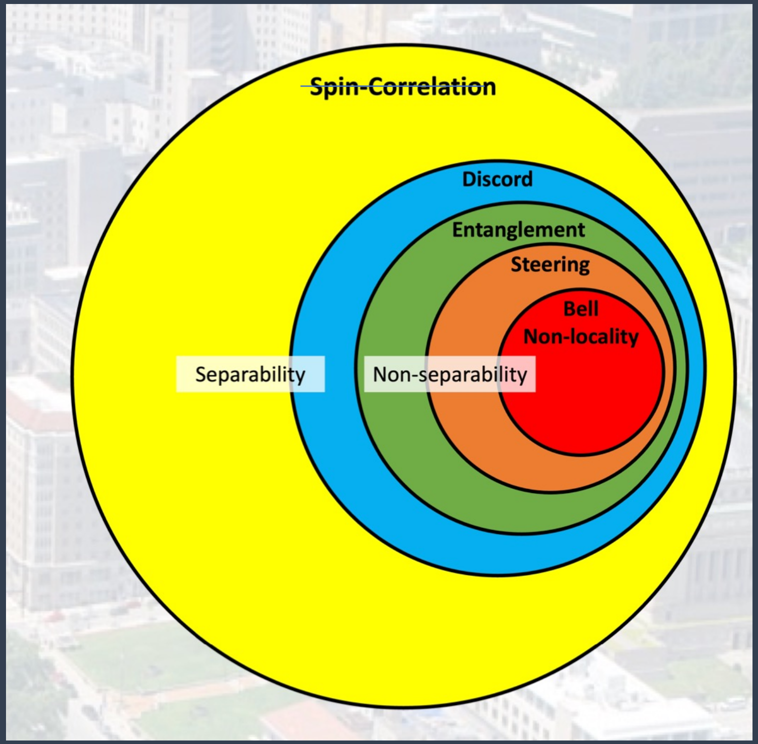
Clearly observe decoherence signature using only reconstructed quantities

Summary

- Υ(4S) $\rightarrow BB$ system constitutes an exciting Quantum Laboratory, sensitive to many classes of SM and BSM physics effects
- Setting limits on decoherence of entanglement (e.g. Lindblad parameter λ, and non-coherent production fraction) would allow us to
  - provide a systematic uncertainty for IDCPV analyses
  - compare against SM theory predictions (⇦ needed!)
  - set limits on various BSM contributions to decoherence
- New experimental techniques, unique to SuperKEKB & Belle II, are in development
  - Exploit nano-beam scheme to obtain absolute B meson decay times
  - First proof-of-concept with reconstructed simulation shown today!

Looking for input from theorists

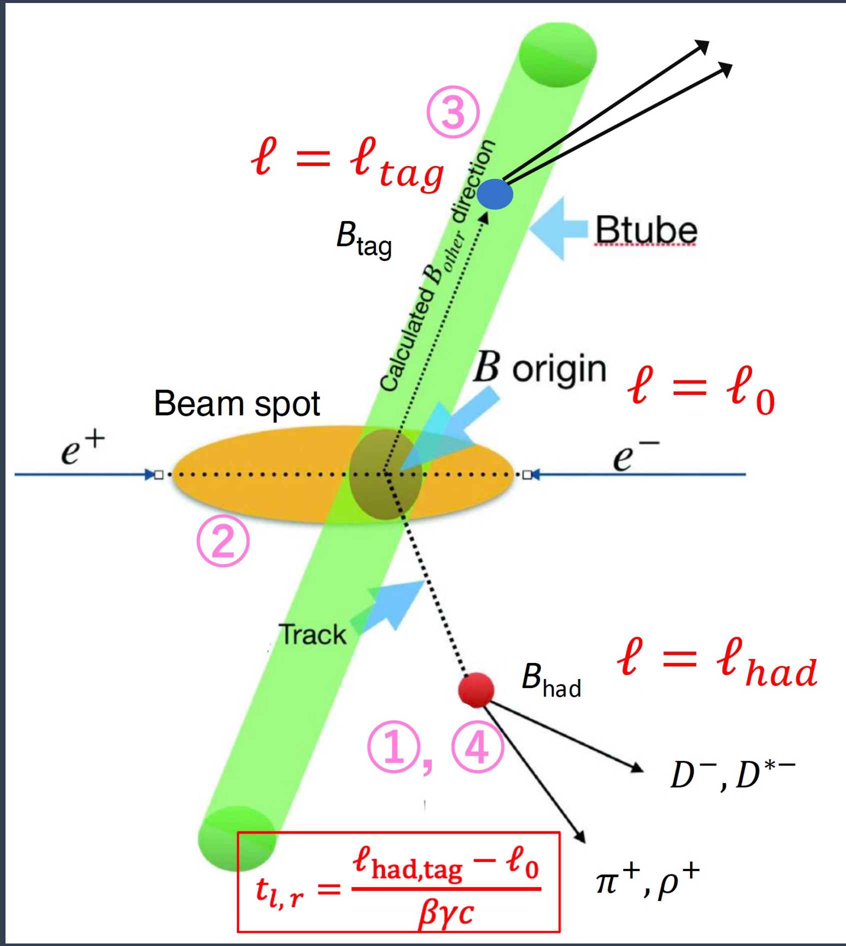
- Lindblad decoherence of BB entanglement
  - Apparently the predicted is basis dependent: https://arxiv.org/abs/hep-ph/9710236
  - Does the form of the decoherence depend on the coupling of the environmental interaction?
  - Need predictions of SM and BSM decoherence strength λ
- Other B-meson types (B_s, B^*)available at higher beam energies. What are the most interesting opportunities?
- Generic Quantum Information tests using BB system and flavor correlations, despite collider loopholes.
- Quantum tests with Tau mesons, proposed in arXiv:2311.17555
- We welcome new ideas from theorist, please get in touch.



Yoav Afik (University of Chicago)

BACKUP

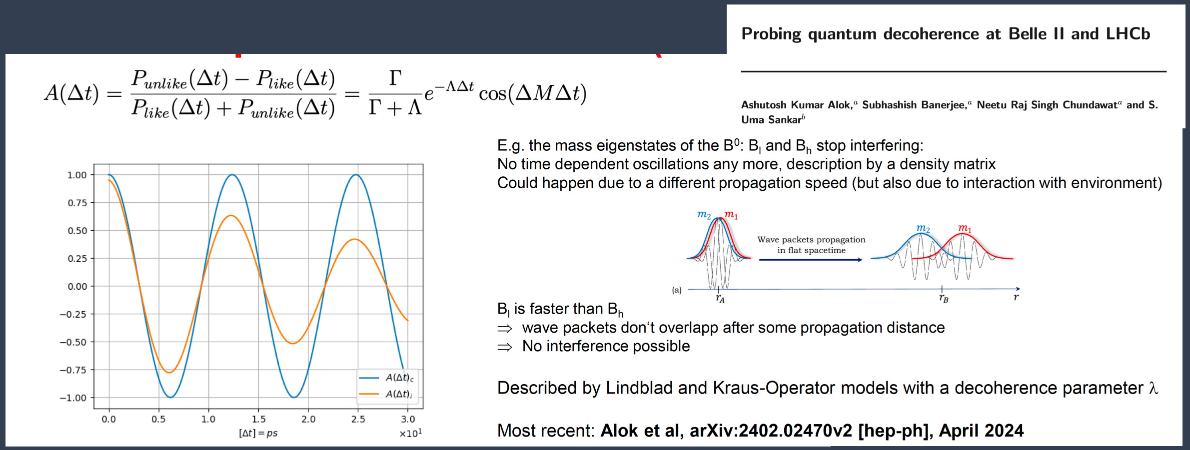
Future directions

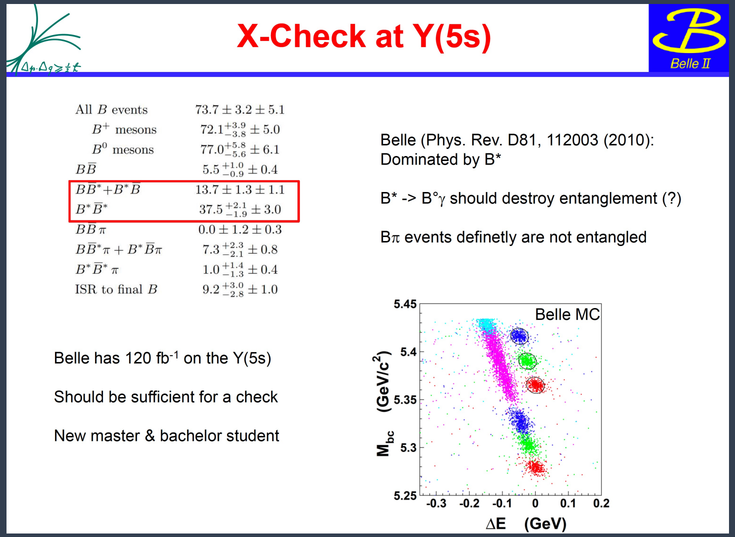


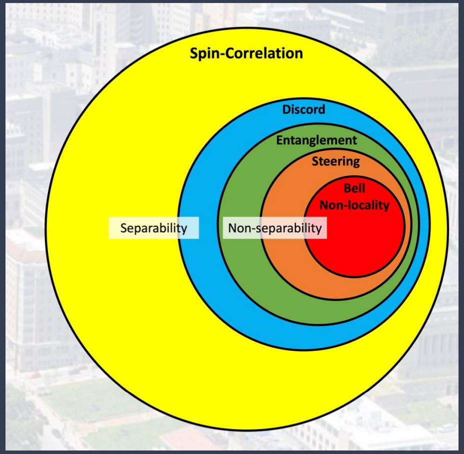
- While the simple B-meson x-vertex positions already appear sensitive to the absolute B decay times…
- …A full 3D treatment that maximally exploits all available information should do even better, and work on this has started

Other models and ideas

- Decoherence at the *single*-B-meson level. Also also affects observed flavor oscillation.
- Other B-meson types available at higher beam energies.
- Generic Quantum Information tests, despite loopholes.
- Quantum tests with Tau mesons, proposed in arXiv:2311.17555
- We welcome new ideas from theorist, please get in touch.





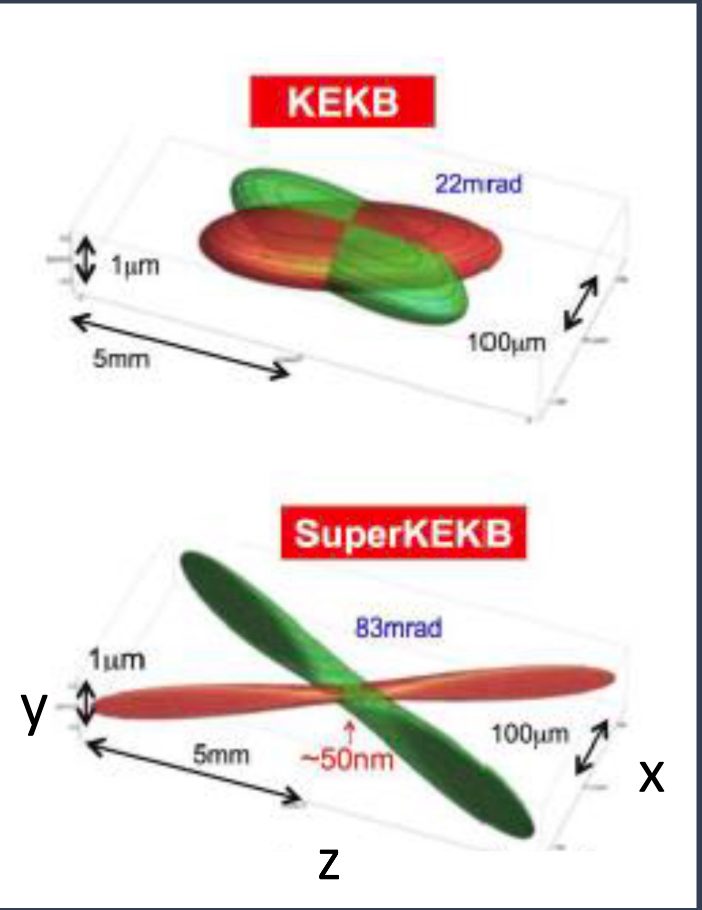


Yoav Afik (University of Chicago)

Critical issue: Size of Beam Spot

	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



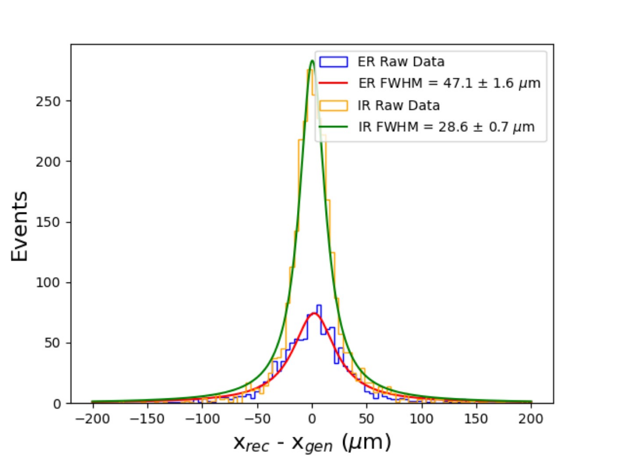


Figure 8: Decay vertex accuracy distributions with best fit Lorentzian for signal decays (left) and generic decays overlaid with signal decays (right) along each coordinate axis of the detector. "ER" refers to exclusive reconstruction B mesons, and "IR" refers to inclusive reconstruction B mesons.

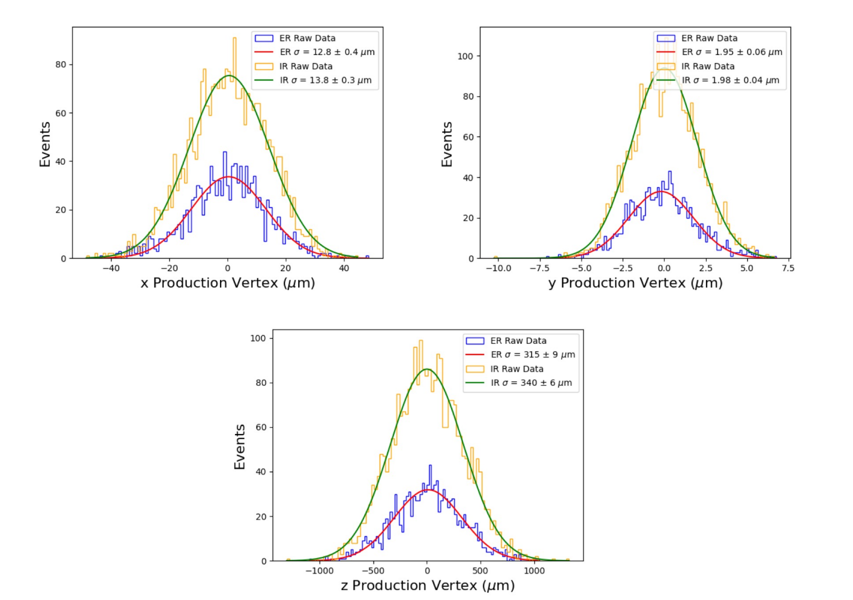


Figure 11: Distribution of the truth level production vertex of the B mesons. "ER" refers to exclusive reconstruction B mesons, and "IR" refers to inclusive reconstruction B mesons.

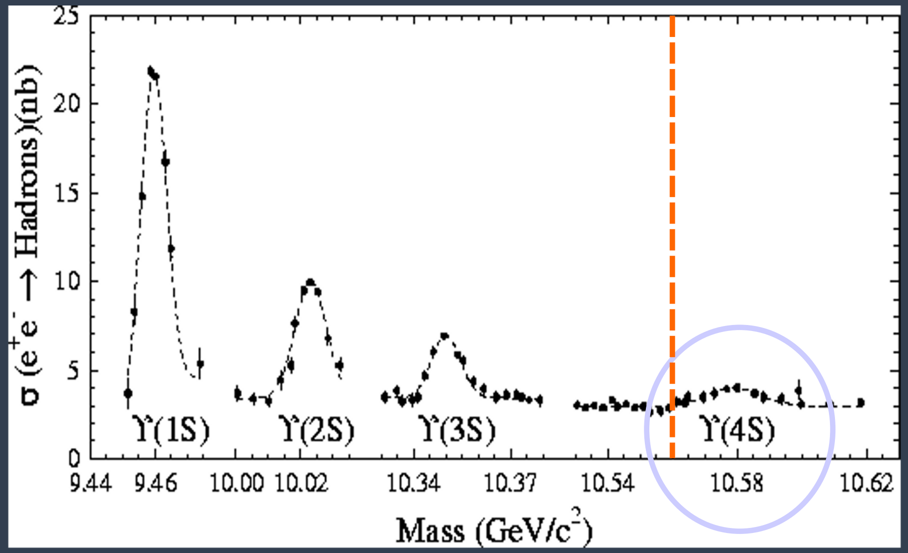
SuperKEKB beam spot (luminous region) size depends on beam optics

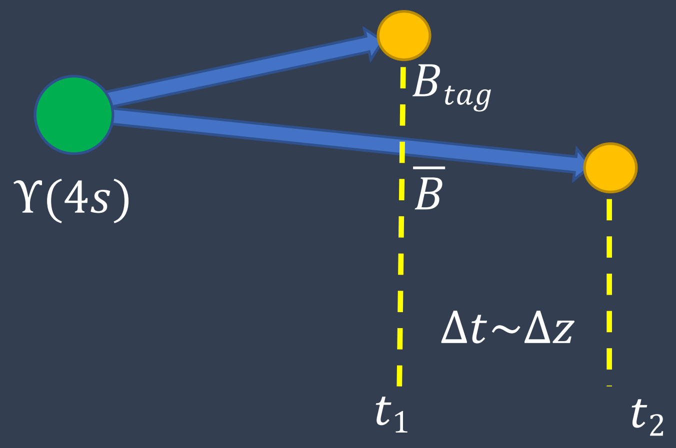
σ_x appears to be sufficiently small, our measurement looks feasible already now!

(see backup slides for recent time dependence)

B-factories as Quantum Laboratories

- At B factories, high statistics (>1 Bn) of cleanly produced B meson pairs
  - $e^+e^- \to \Upsilon(4S) \to \overline{B^0}B^0\ ,\ B^+B^-$
- Neutral B mesons
  - Undergo flavor oscillations
  - Flavors of neutral B mesons in pair: quantum-entangled
- Decay-time-difference (Δt) + flavor measurements enable precise probes of EW interaction
  - Most analyses *assume* perfect entanglement / coherence



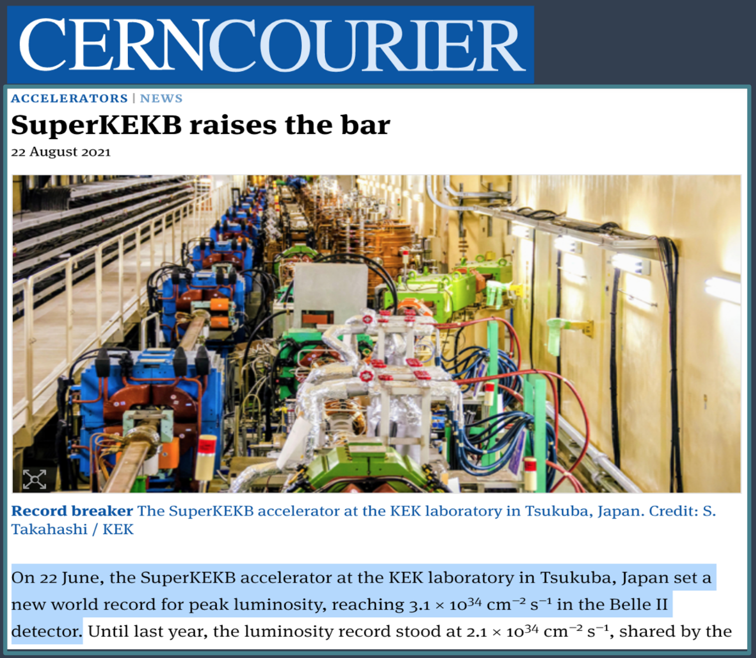


We plan to experimentally probe this entanglement,
e.g. by searching for quantum decoherence in the $\overline{B^0}B^0$ system

SuperKEKB Luminosity

Ran Belle II and SuperKEKB *through the global pandemic*.
Broke many accelerator world records for luminosity.

- Goal: $50ab^{-1}$ integrated (>50Bn BB)
- Operating since 2018
- L_{peak}= 4.7 x 10^{34}/cm^2/sec
- This is 3.9 x PEP-II at SLAC
- More than 2 x KEKB
- But still a long way to go!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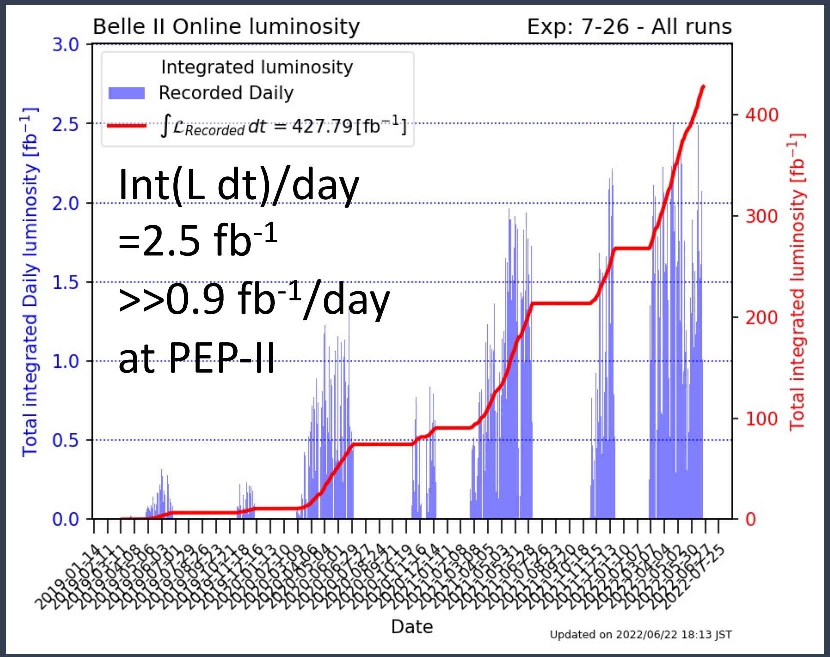
ACCELERATORS | NEWS

SuperKEKB raises the bar

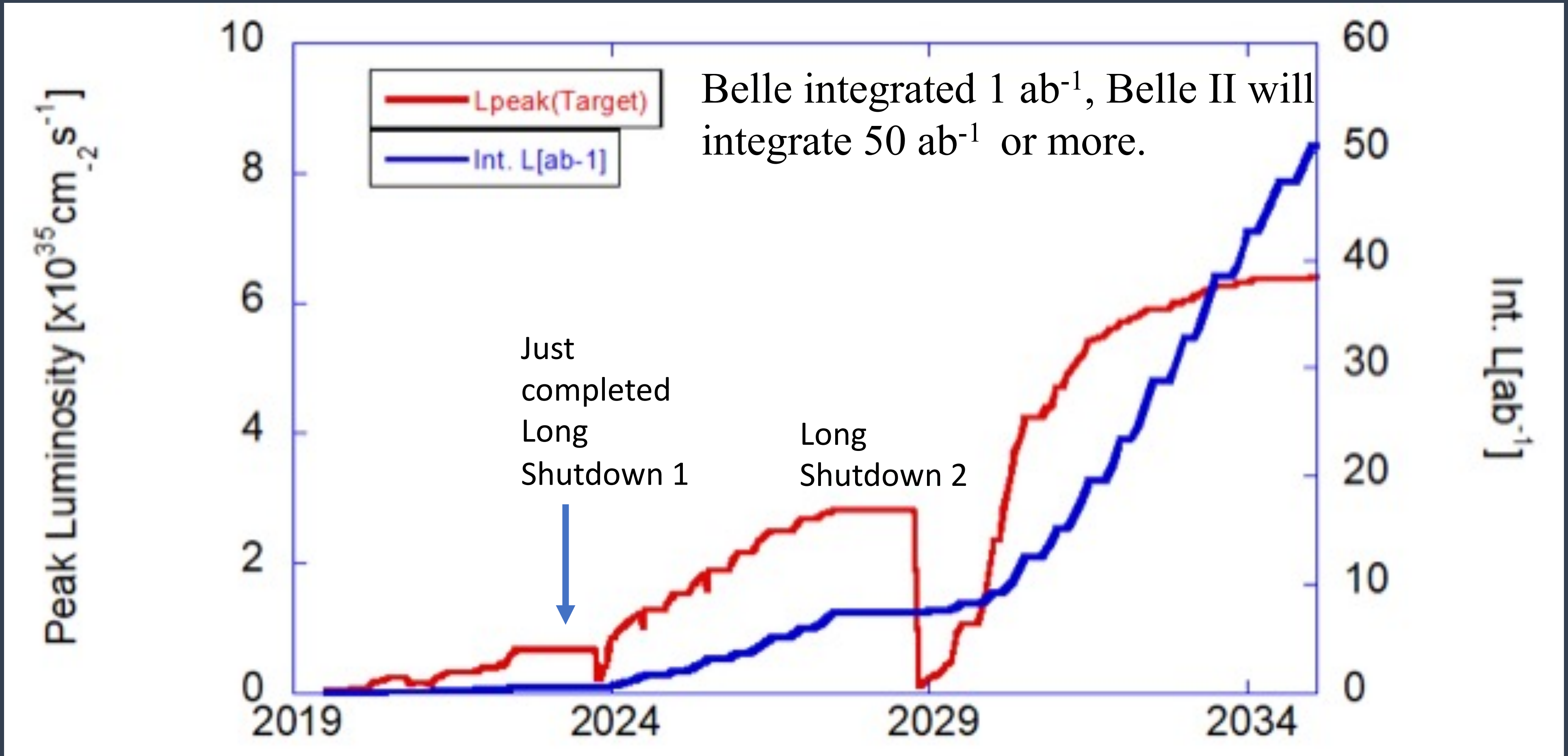
22 August 2021

Record breaker The SuperKEKB accelerator at the KEK laboratory in Tsukuba, Japan. Credit: S. Takahashi / KEK

On 22 June, the SuperKEKB accelerator at the KEK laboratory in Tsukuba, Japan set a new world record for peak luminosity, reaching 3.1 × 10^{34} cm^{-2} s^{-1} in the Belle II detector. Until last year, the luminosity record stood at 2.1 × 10^{34} cm^{-2} s^{-1}, shared by the



Luminosity Plan



Current beam spot is 200nm high.

- About one order of magnitude from design instantaneous luminosity
- About two orders of magnitude from goal integrated luminosity

Belle → Belle II upgrade

Central beam pipe: decreased diameter from 3cm to 2cm (Beryllium)

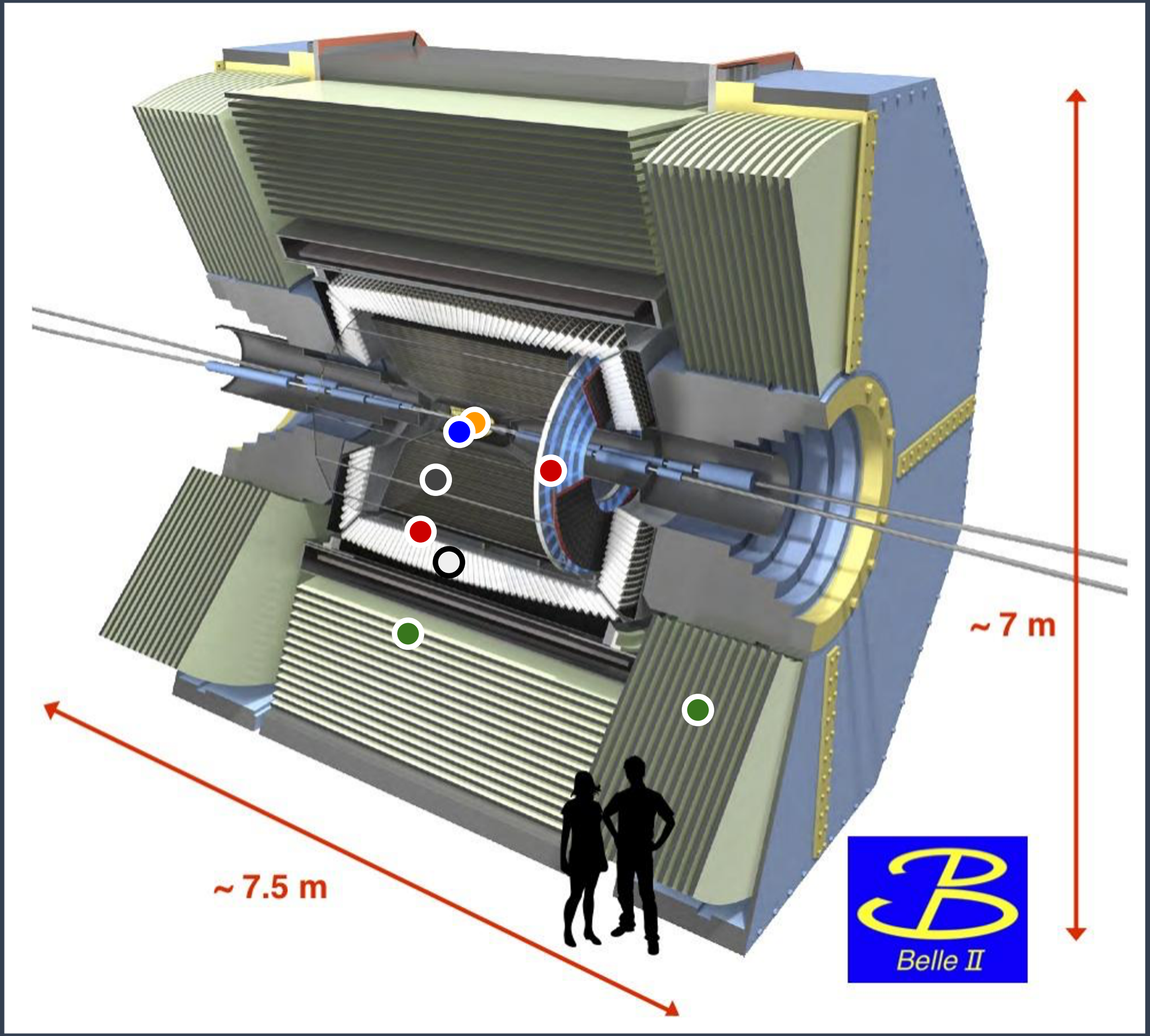
Vertexing: new 2 layers of pixels, upgraded 4 double-sided layers of silicon strips

Tracking: drift chamber with smaller cells, longer lever arm, faster electronics

PID: new time-of-propagation (barrel) and proximity focusing aerogel (endcap) Cherenkov detectors

EM calorimetry: upgrade of electronics and processing with legacy CsI(Tl) crystals

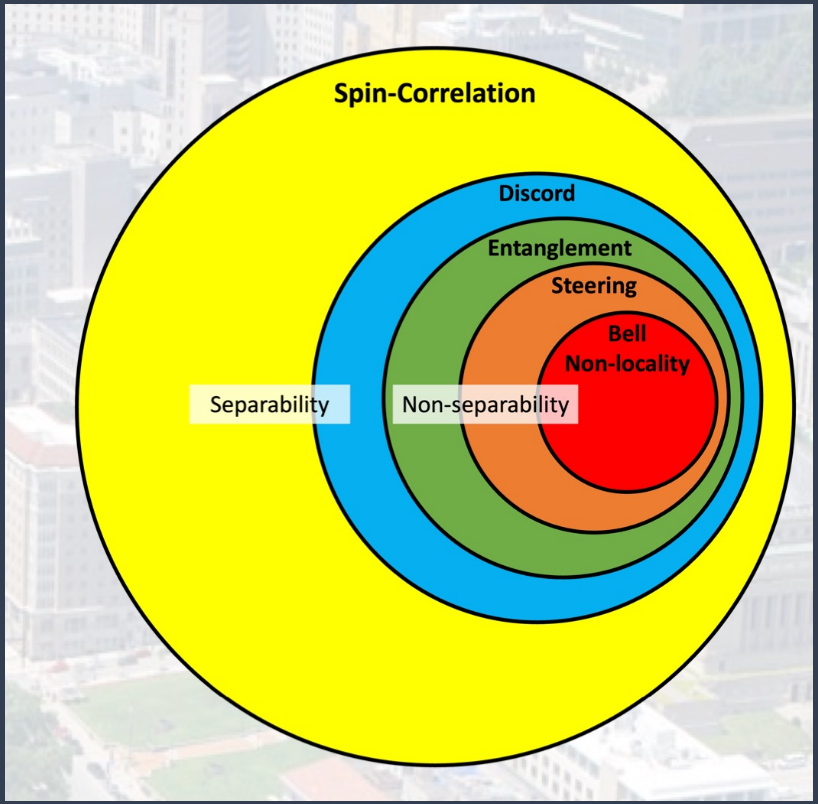
K_L and μ: scintillators replace RPCs (endcap and inner two layers of barrel)



Upgraded Belle II vertex detector benefits decay-time measurements.
Spring 2024 run was first with complete pixel detector.

Questions that arose at this workshop

- How would the figure on the right look for time-dependent flavor correlations in $\Upsilon(4S) \to \overline{B^0}B^0$?
- The short B_d meson life-time compared to mixing frequency seems to prevent establishing Bell non-locality.
  - How about Steering, Discord?
- How to best quantify the non-separable properties for $\Upsilon(4S) \to \overline{B^0}B^0$?
- Does the Belle II sensitivity to time dependence open up any new possibilities, compared to spin correlations?



Yoav Afik (University of Chicago)

D^0 and D^+ lifetimes

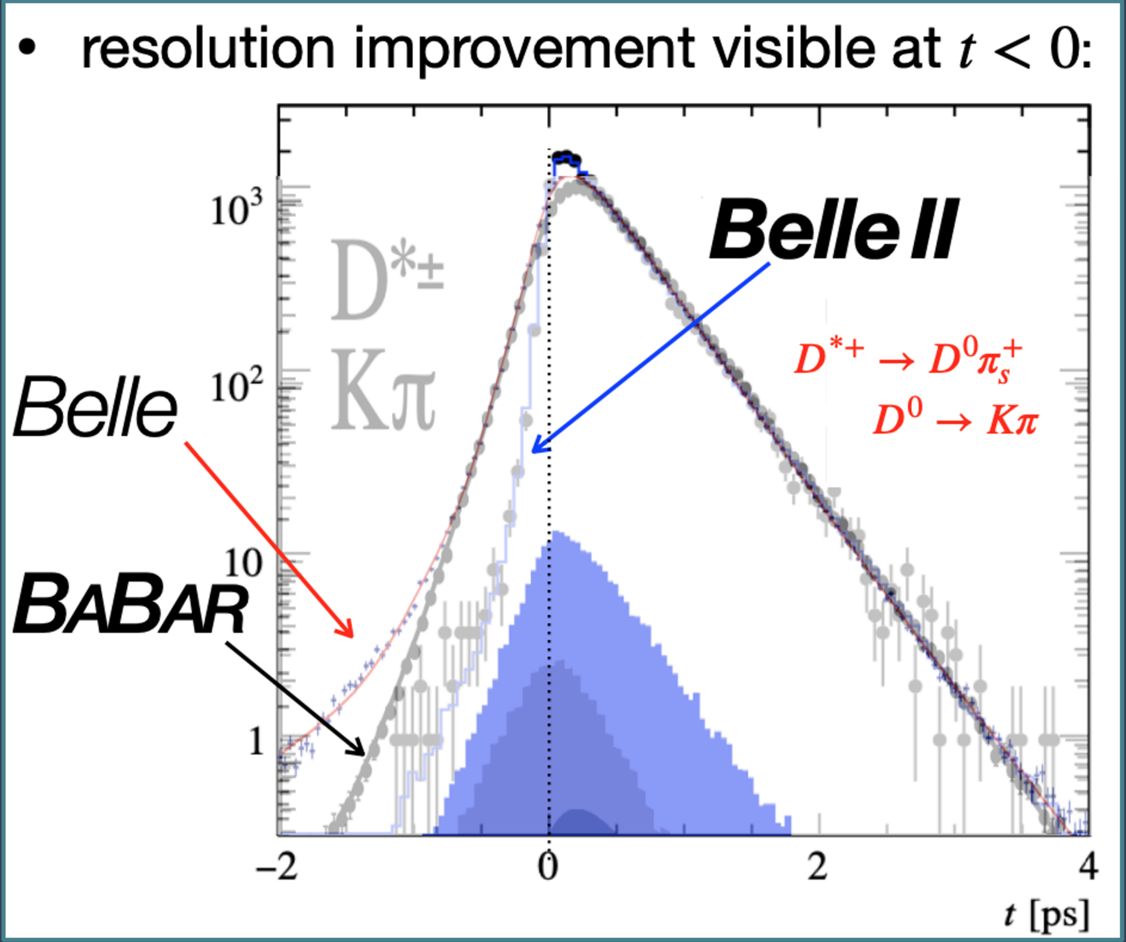
arXiv: 2108.03216

Precise measurement of the D^0 and D^+ lifetimes at Belle II

F. Abudinén,[31] I. Adachi,[21,18] K. Adamczyk,[66] L. Aggarwal,[73] H. Ahmed,[76] H. Aihara,[112] N. Akopov,[2] A. Aloisio,[88,25] N. Anh Ky,[40,13] D. M. Asner,[3] H. Atmacan,[99] V. Aushev,[81] V. Babu,[11] S. Bacher,[66] H. Bae,[112]

Results

- Proper time resolution at Belle II is a **factor of 2** better than Belle and BaBar due to better vertexing



arXiv:2402.17260 (hep-ex)

[Submitted on 27 Feb 2024]

A new graph-neural-network flavor tagger for Belle II and measurement of $\sin 2\phi_1$ in $B^0 \to J/\psi K_S^0$ decays

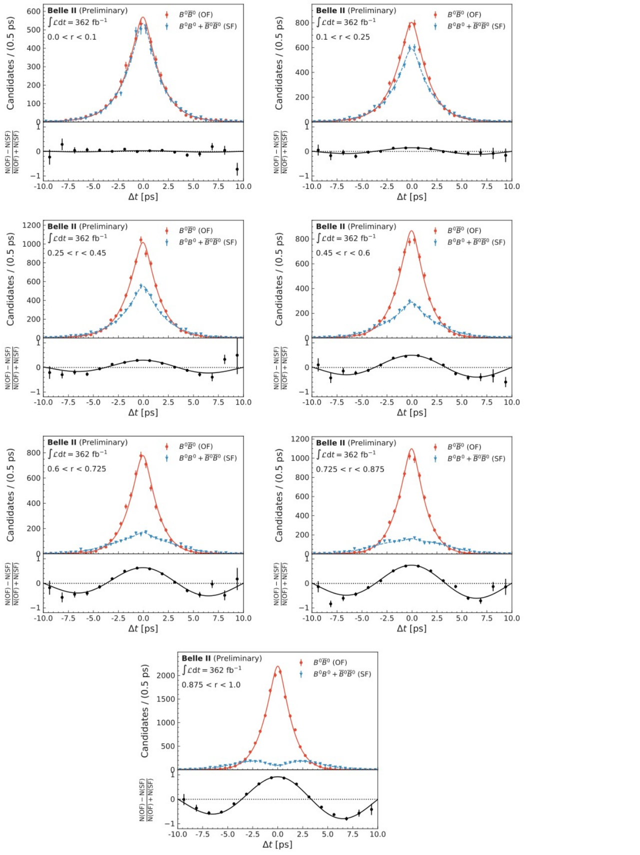


Figure 4. Background-subtracted Δt distributions of $B^0 \to D^{(*)-}\pi^+$ reconstructed in data in each of the seven r intervals (points) and the best-fit functions (lines) for opposite- and like-flavor B pairs with the corresponding asymmetries.

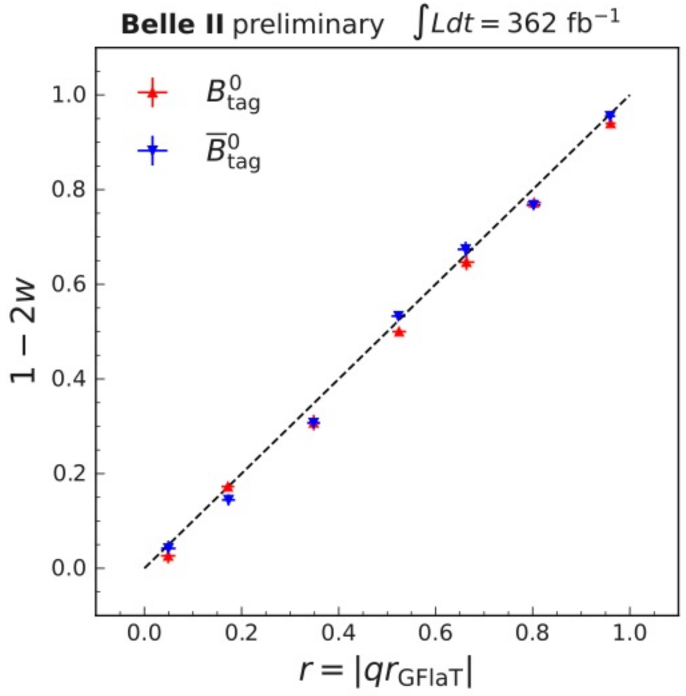


Figure 6. Dilution factors $1 - 2w$ of $B^0 \to D^{(*)-}\pi^+$ as functions of their GFlaT predictions, r for $B^0_{\rm tag}$, $1 - 2\bar{w} - \Delta w$, and $\bar{B}^0_{\rm tag}$, $1 - 2\bar{w} + \Delta w$; the dashed line shows $r = 1 - 2w$.

data and determine an effective tagging efficiency of

$$\varepsilon_{\rm tag} = (37.40 \pm 0.43 \pm 0.36)\%, \qquad (8)$$

where the first uncertainty is statistical and the second is systematic. For comparison, using the same data, we determine $\varepsilon_{\rm tag} = (31.68 \pm 0.45)\,\%$ for the Belle II category-based flavor tagger.[4] The GFlaT algorithm thus has an 18% better effective tagging efficiency.

Hidden variable theories

- Hidden variable theories are attempts to explain non-intuitive QM effects, such as entanglement, with deterministic and/or local theories
- Bell-test: statistical test that can rule out local deterministic alternative descriptions to QM
- Can Belle (II) perform Bell-tests? This questions has a fraught history!

- *Most likely* answer: no for $\overline{B^0}B^0$ *mixing*
- See talk by B. Yabsley for detailed discussion

With hypothetical active flavor measurement, could a Bell test be performed?

- B-meson sample decreases with Δt
- crucial parameter $x_d = \Delta m_d / \Gamma_d$: rate of oscillation relative to decay
- Bell test impossible if $x < 2.0$:

system	x
$B^0/\overline{B}^0$	0.77
$K^0/\overline{K}^0$	0.95
$D^0/\overline{D}^0$	< 0.03
$B_s^0/\overline{B}_s^0$	~ 26

- May still be possible in Tau-pair events or B *decays*; e.g. arXiv 2305.04982 claims

Bell inequality is violated in $B^0 \to J/\psi\, K^\star(892)^0$

If Bell-test impossible, instead fit specific hidden variable models to data