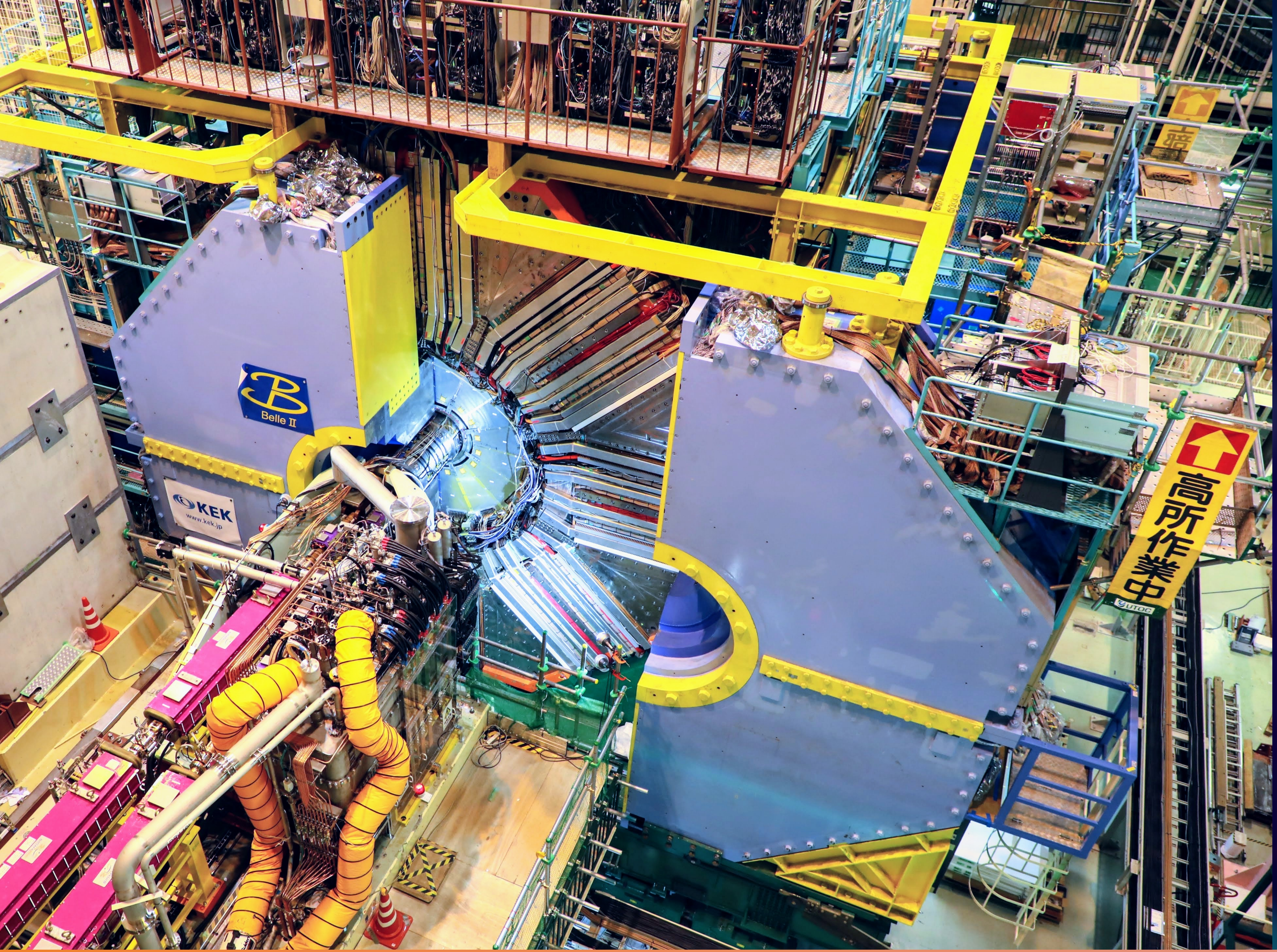
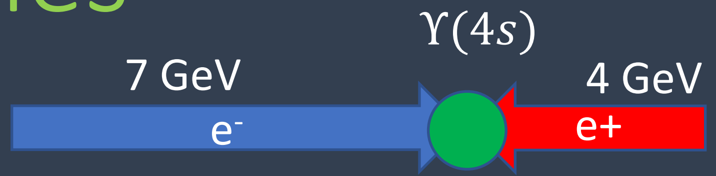


2024 PITT PACC Workshop: Exploring Quantum Mechanics in High Energy Physics

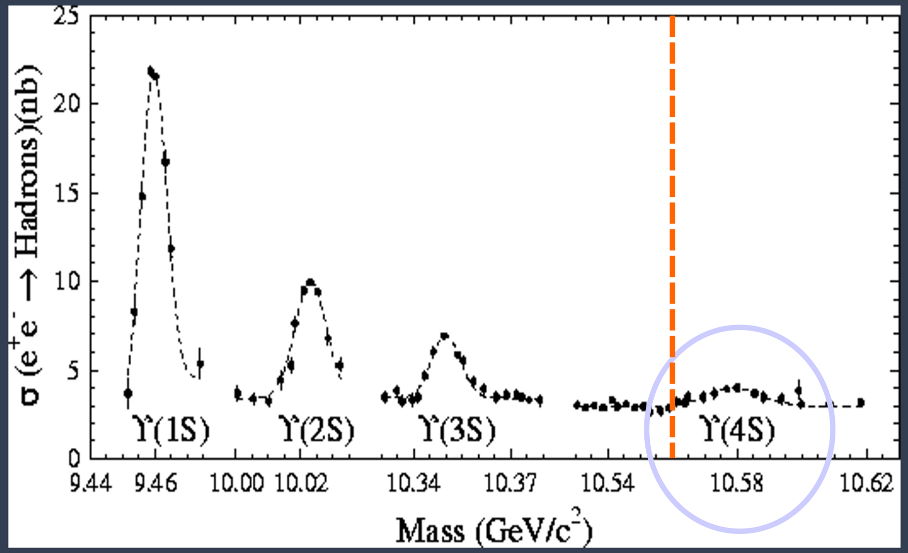
Quantum tests with entangled B meson pairs at the Belle and Belle II Experiments

Sven Vahsen, for the Belle and Belle II collaborations

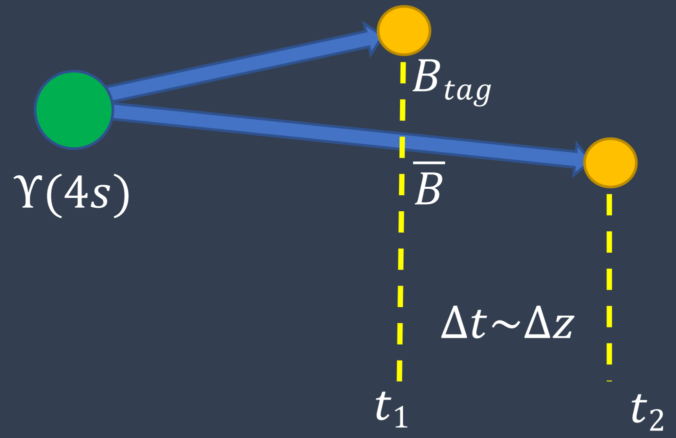
B-factories as Quantum Laboratories



- At B factories, high statistics (>1 Bn) of cleanly produced B meson pairs
  - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow \overline{B^0}B^0, B^+B^-$
- 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

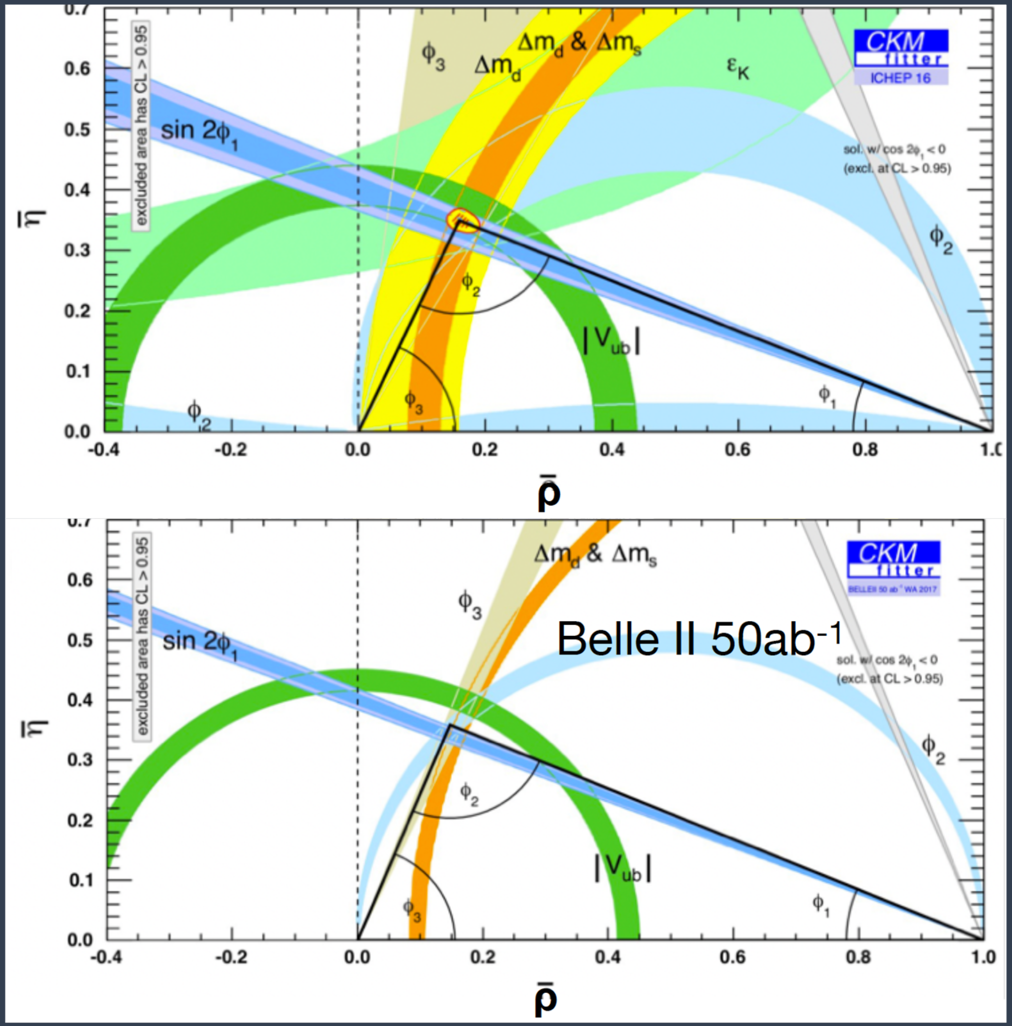


Outline

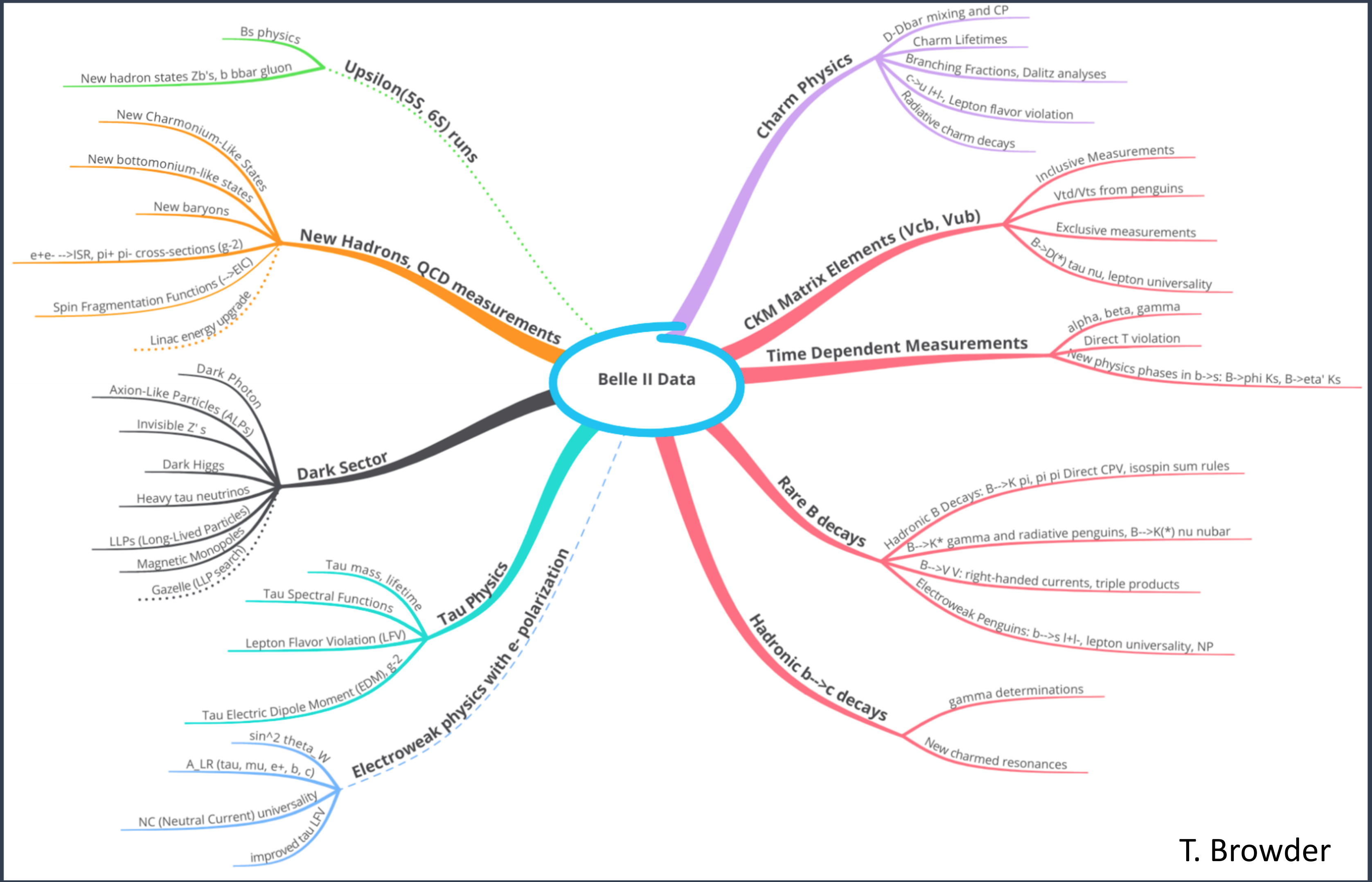
- B-factory basics
- Belle II @ SuperKEKB
- $\Upsilon(4S) \to B^0\overline{B^0}$: a quantum laboratory
- Tests of symmetry violation and entanglement
- Conclusion

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, irreducible, 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 $50ab^{-1}$ (>50Bn BB) to look for deviations from this picture (BSM physics)



The Belle II physics program



But 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.

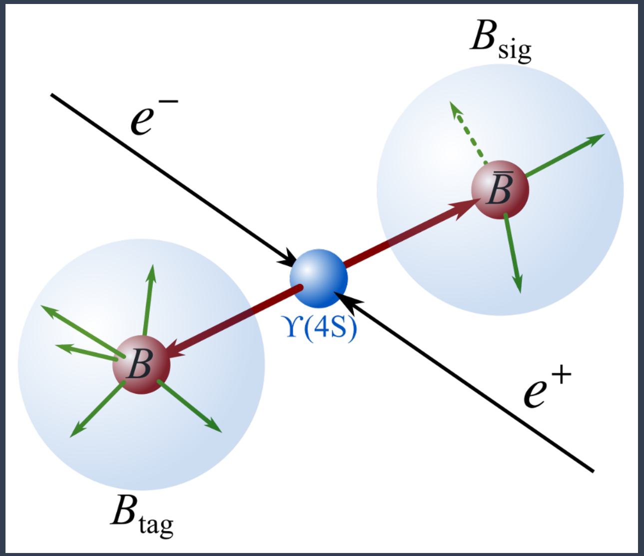
Process	σ (nb)
bb	1.1
cc	1.3
Light quark qq	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

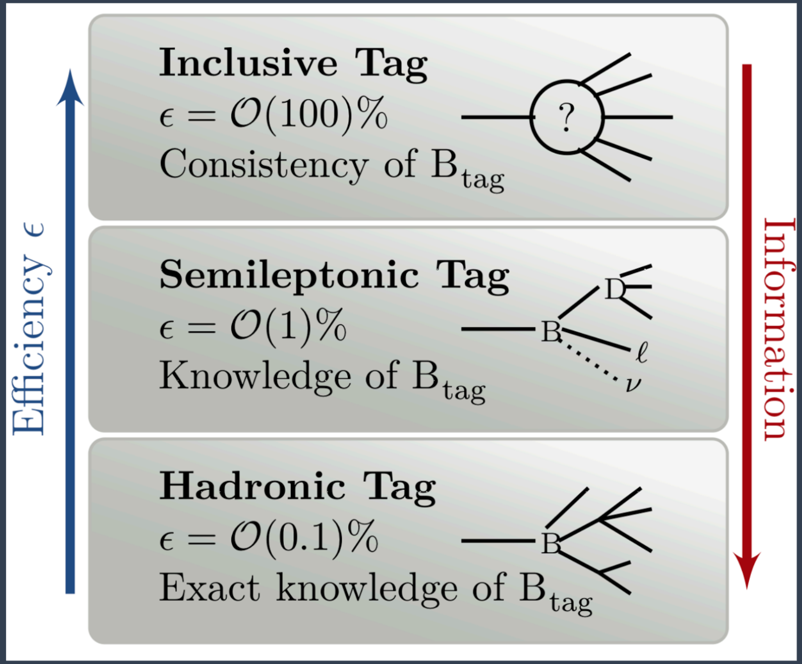
B factory basics

- 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
  - Full kinematic reconstruction of a single neutrino is possible on "signal side" by fully reconstructing the "tag side"
- In Belle II, Full Event Interpretation (FEI):
  - Hierarchical reconstruction of ~10,000 decay modes. Extensive use of machine learning

Clean events with tightly constrained kinematics

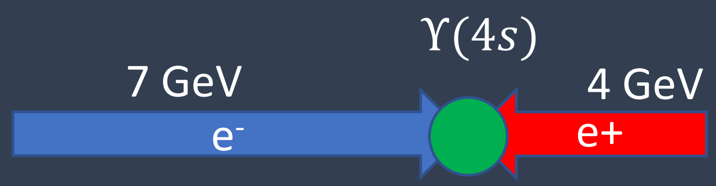
COM-frame

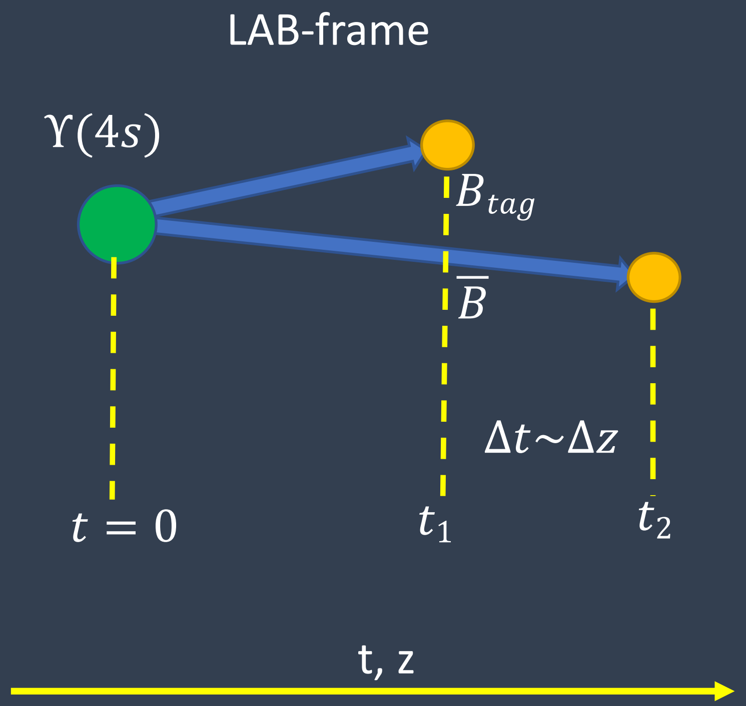




B factory basics: decay times

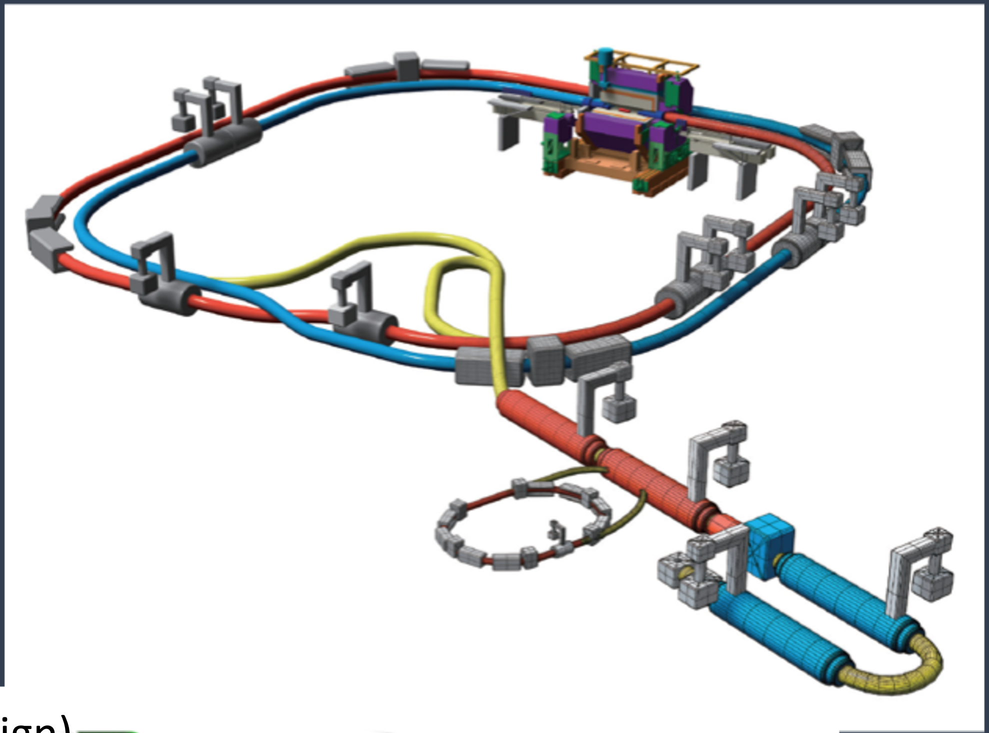
- e^+e^- beam energies are asymmetric
- Resulting $\Upsilon(4s)$ boost allows for identification of displaced B vertices
  - B-decay-time-difference $\Delta t \approx \Delta z/\gamma\beta c$
  - $\Delta z \sim 200\ \mu\text{m}$
  - measurable with silicon strip or pixel detectors
- Δz provides decay time *difference,* order ps!
- Absolute decay positions / absolute decays times not accessible *at Belle and Babar*, due to size of e^+e^- interaction region…

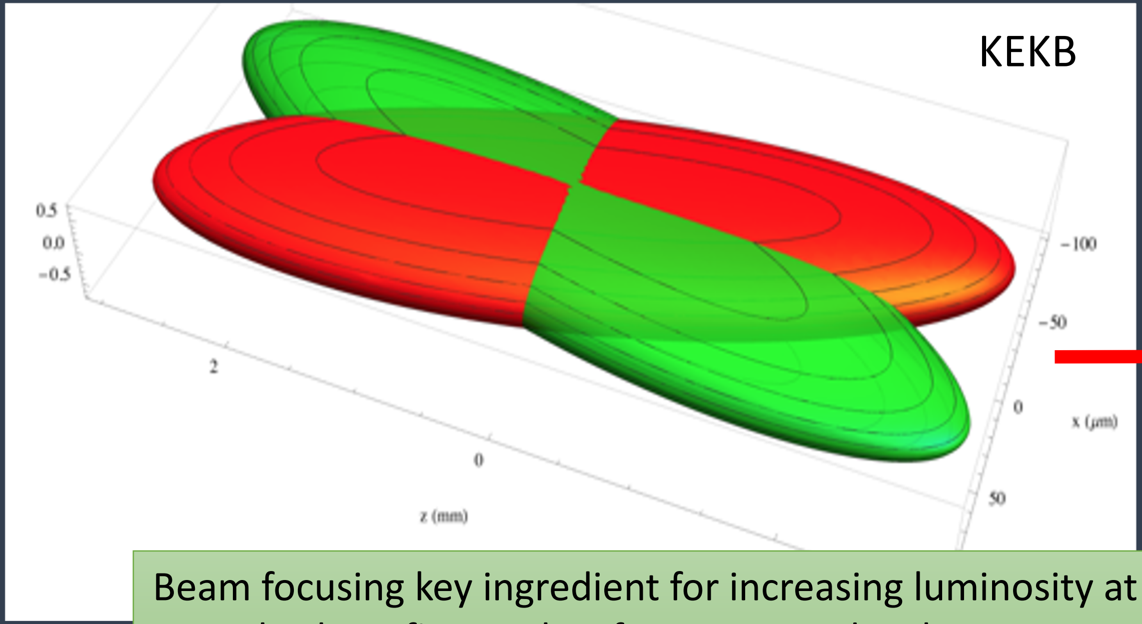


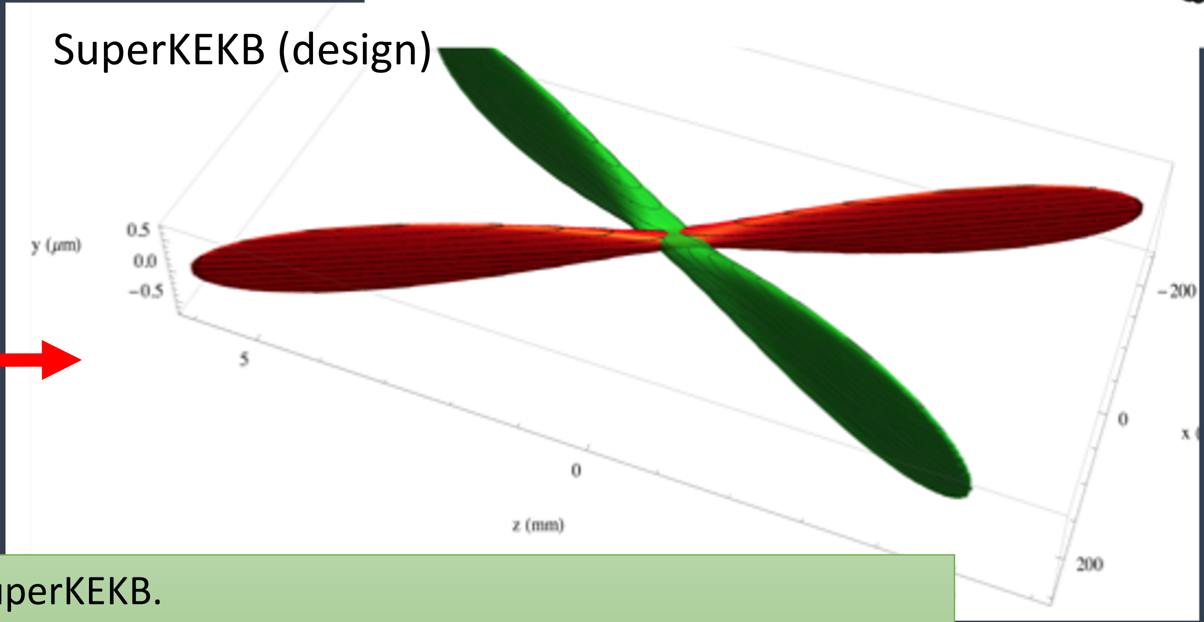


SuperKEKB

- Upgrade of 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

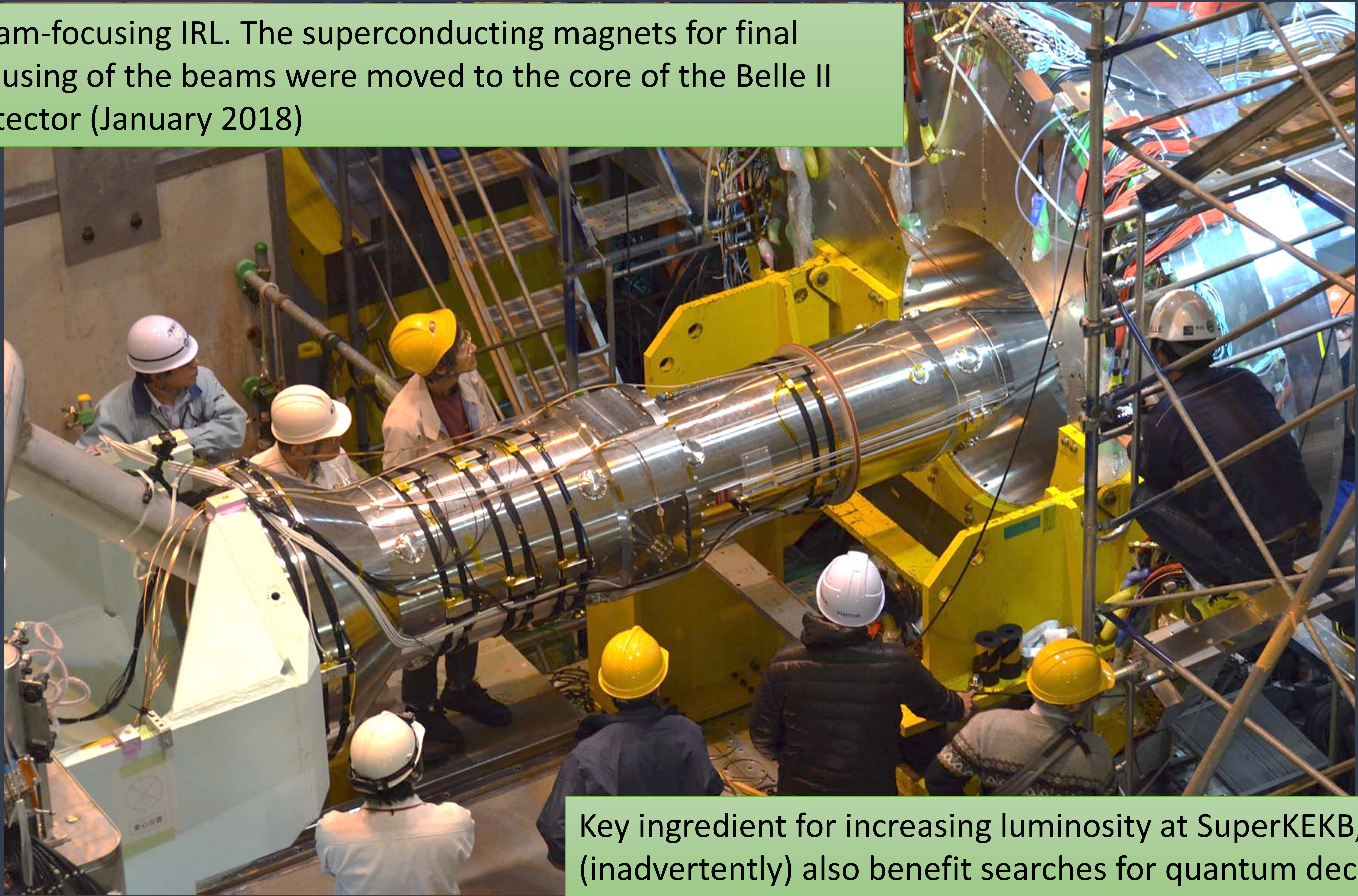






Beam focusing key ingredient for increasing luminosity at SuperKEKB.
May also benefit searches for quantum decoherence: once interaction region becomes sufficiently small, we should be able to estimate individual B meson decay times; t1, t2

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



Key ingredient for increasing luminosity at SuperKEKB, but may (inadvertently) also benefit searches for quantum decoherence!

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!

CERNCOURIER

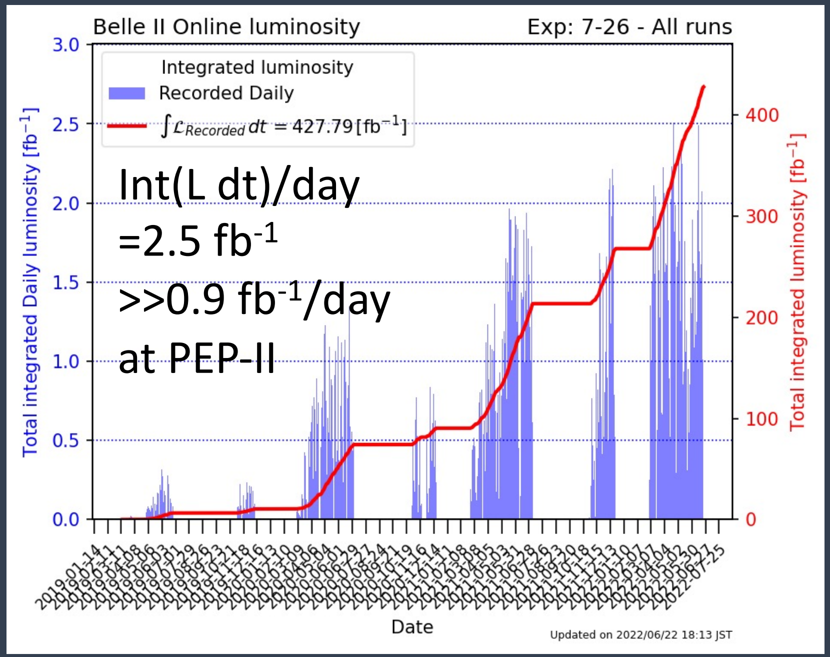
ACCELERATORS | NEWS

SuperKEKB raises the bar

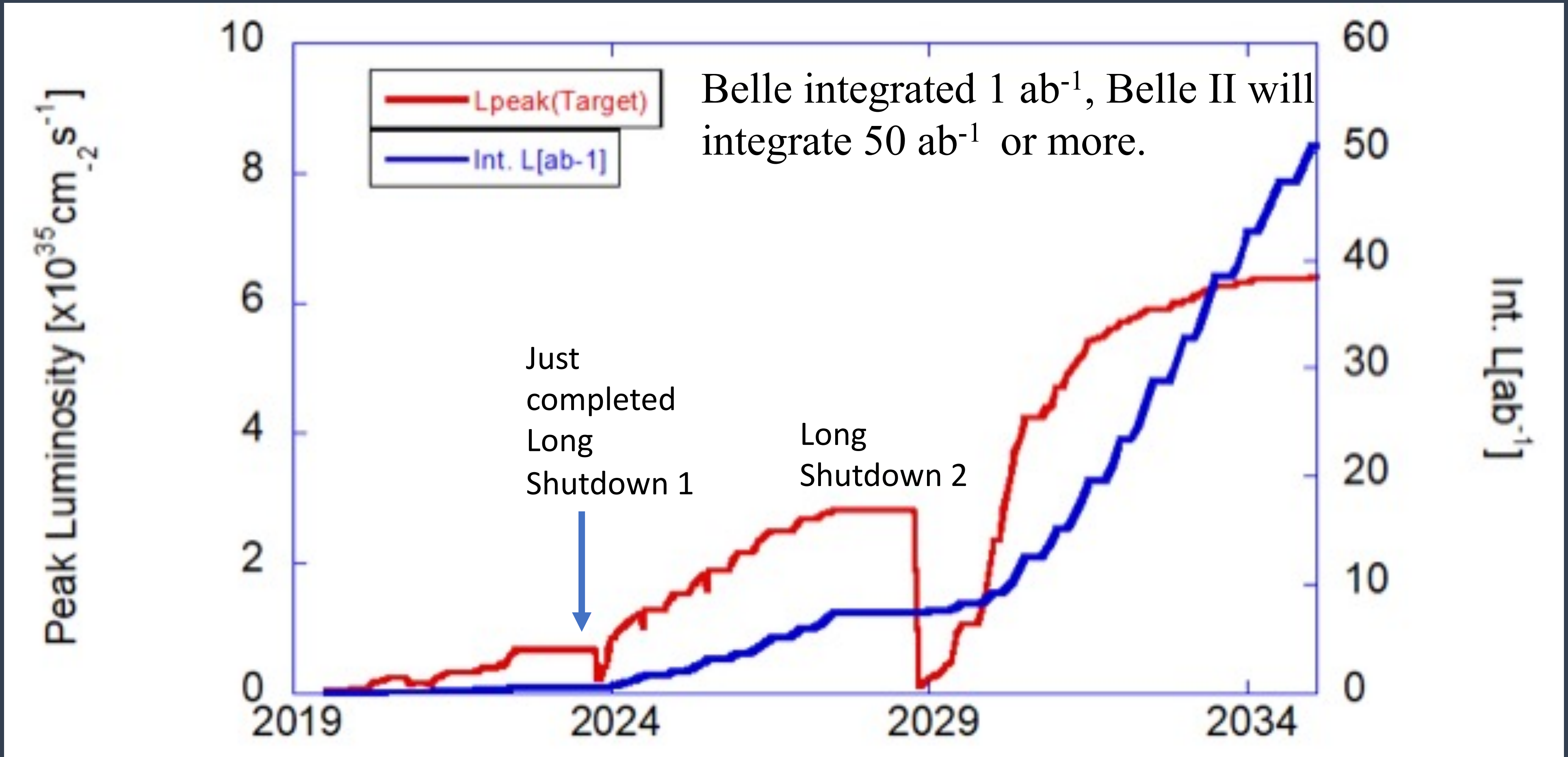
22 August 2021

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)

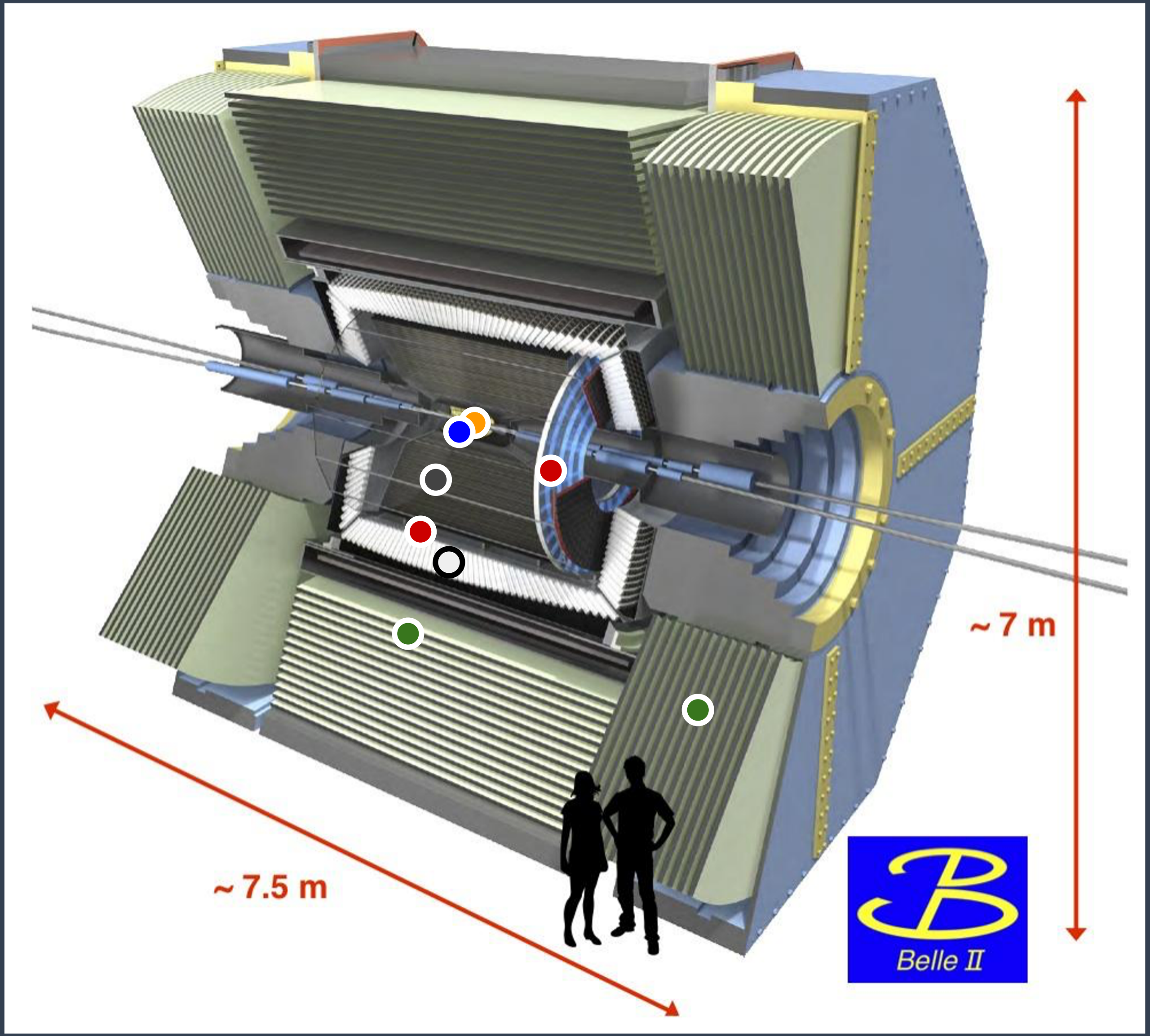
Vertexing: new 2 layers of pixels, upgraded 4 double-sided layers of silicon strips

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)

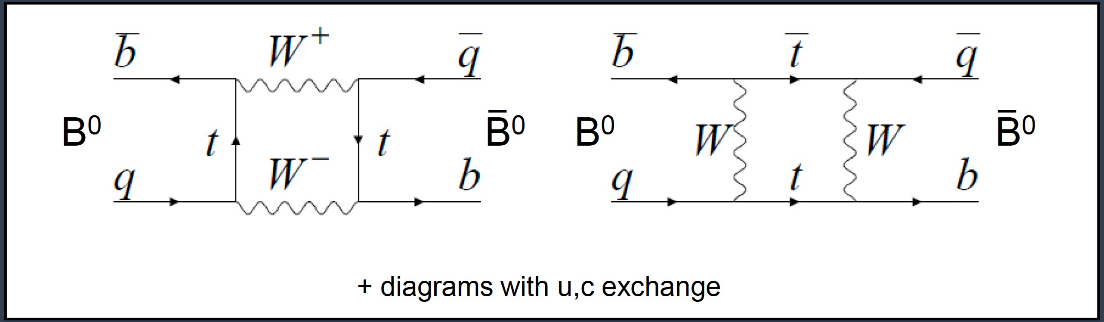


Upgraded Belle II vertex detector benefits decay-time measurements. Spring 2024 run is first with complete pixel detector.

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

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

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



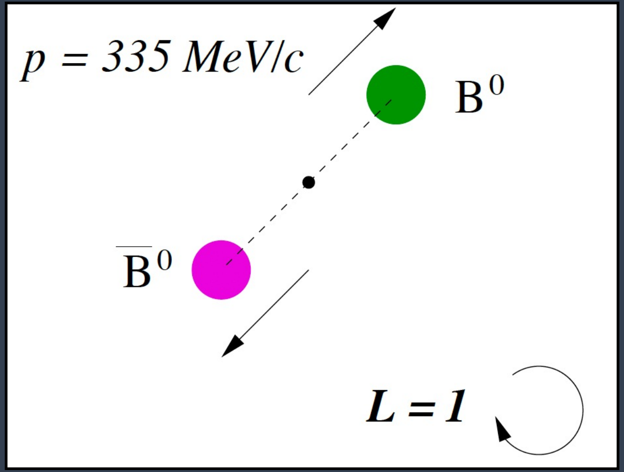
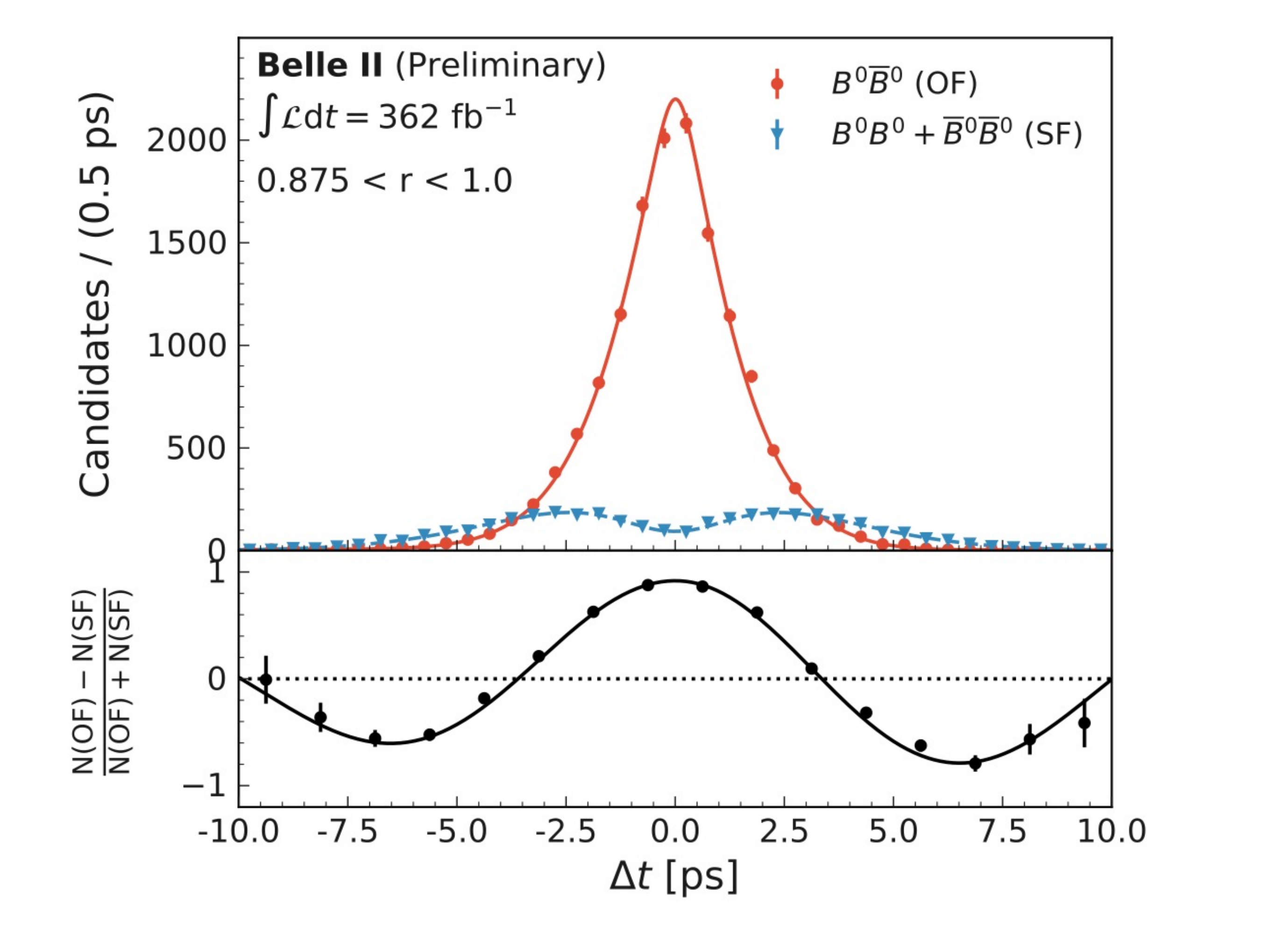


Figure by Bruce Yabsley

$\Upsilon(4S) \rightarrow B^0\overline{B^0}$: 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 $2\emptyset_1$) ✅ 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) (p. 16-18) ✅ Belle (PRL 99, 131802 – 2007)
4. Collapse theories (augmentations of QM) (p. 19)
5. Quantum Decoherence (p. 20-26)
6. Quantify Separability (p.27)

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

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

The Belle PRL on EPR

This was the approach of A. Go et al., who excluded

- "Pompili-Selleri" hidden variable model

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

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

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

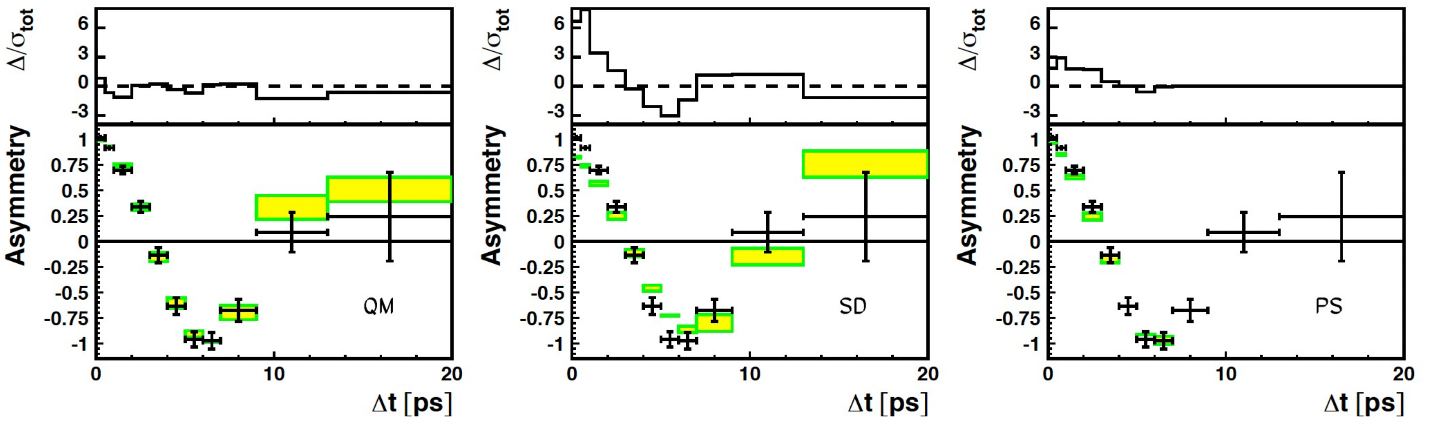
- "Spontaneous Disentanglement" of all BB pairs

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

- 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 $\chi^2/n_{dof} = 174/11$

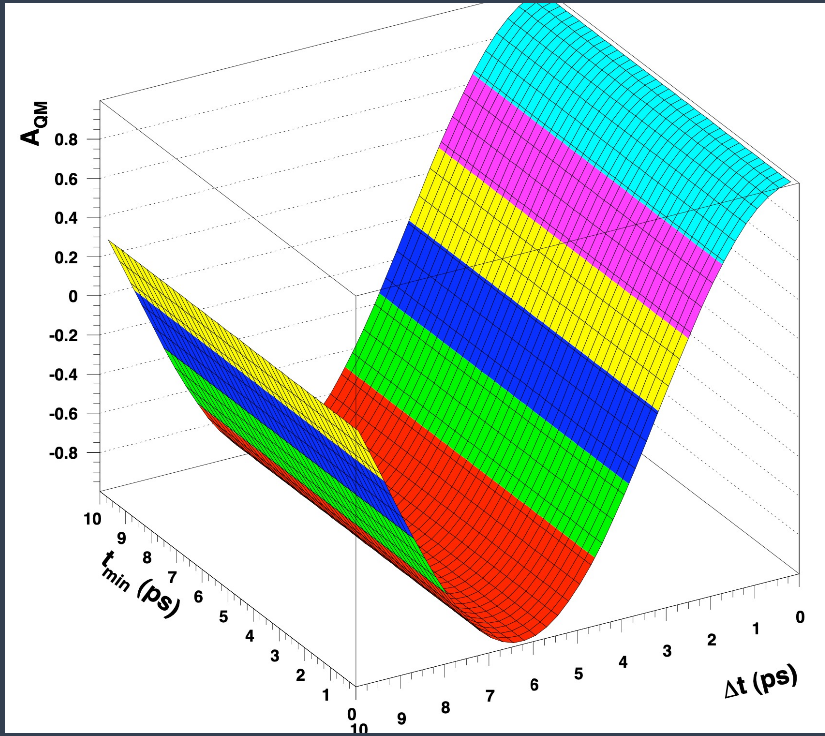
PS disfavoured: 5.1σ $\chi^2/n_{dof} = 31/11$

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

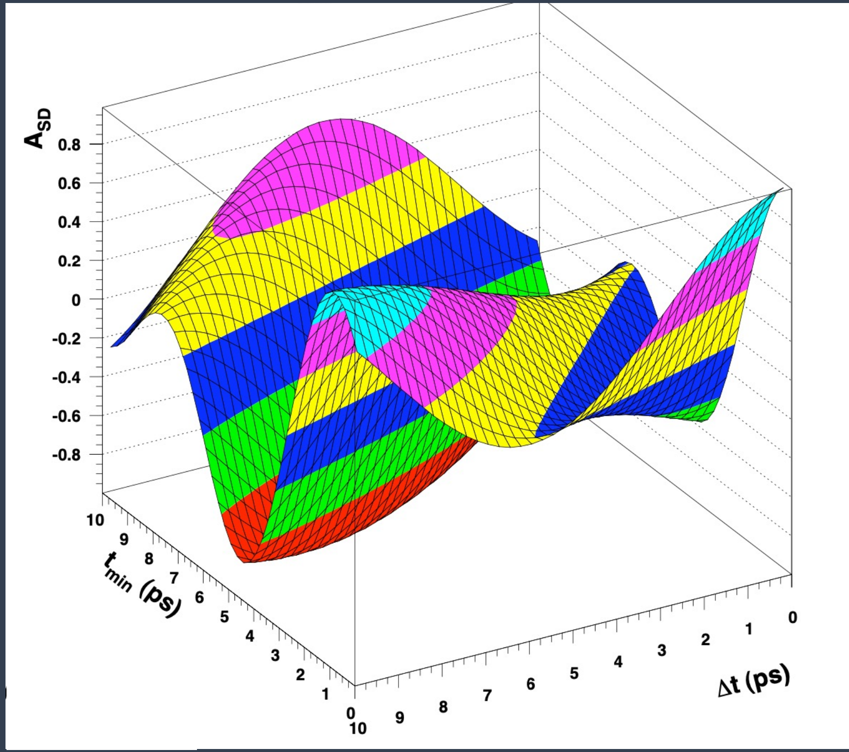
Access to t_1 generally adds a new dimensions and should result higher sensitivity

Asymmetry for QM



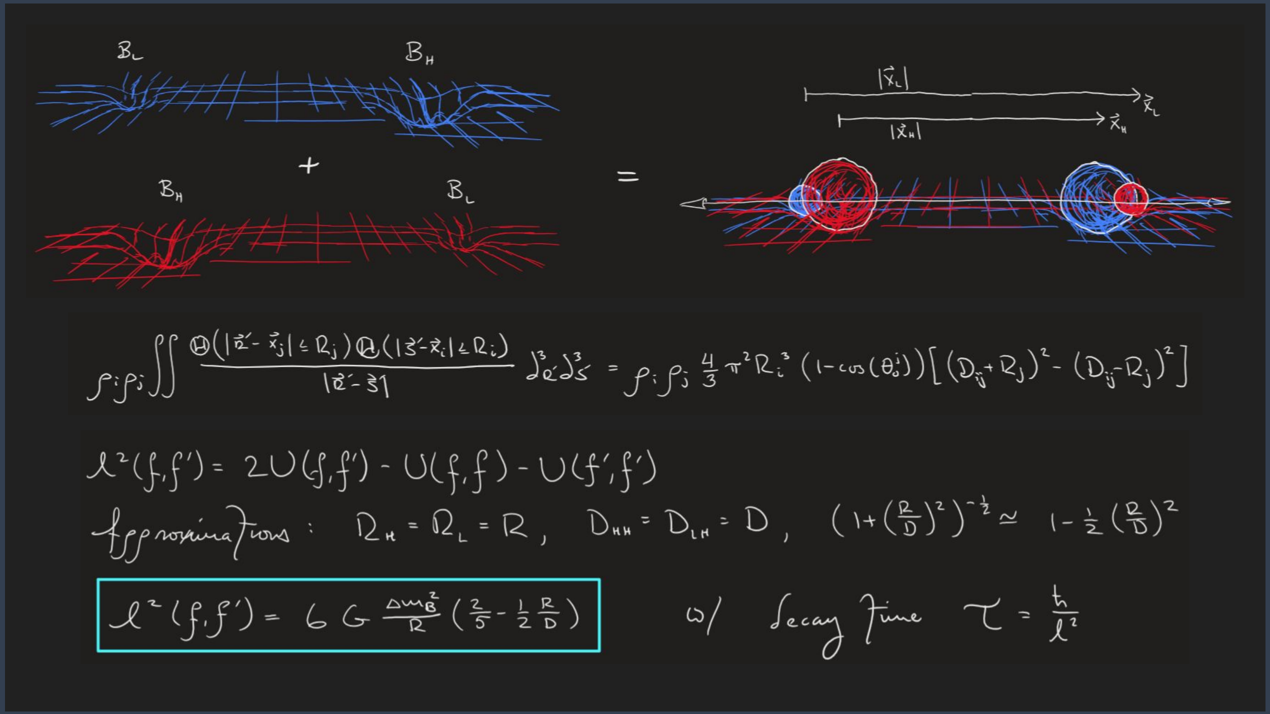
Entanglement: depends only on Δt

Asymmetry for Spontaneous Disentanglement



Disentanglement and decoherence: depends on t_1 and Δt

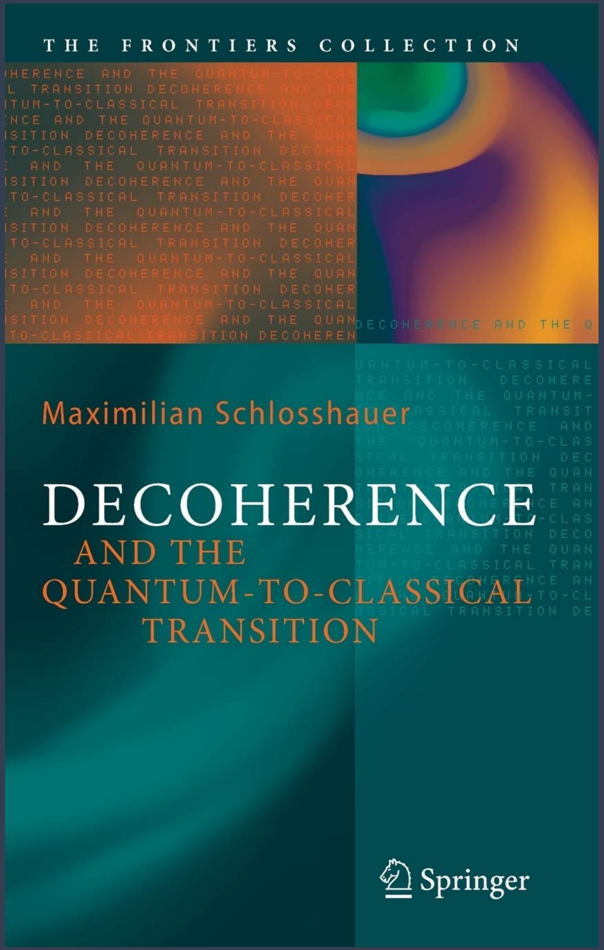
Collapse Theories



- Extensions of QM that predict macroscopic states will spontaneously collapse
- The **Diósi–Penrose model** was introduced as a possible solution to the measurement problem, where the wave function collapse is related to gravity.

Tim Mahood (Hawaii grad student) performed theory calculation.
Suggests a $B\overline{B}$ collapse time of order 10^{23}s — i.e., not measurable

Quantum Decoherence



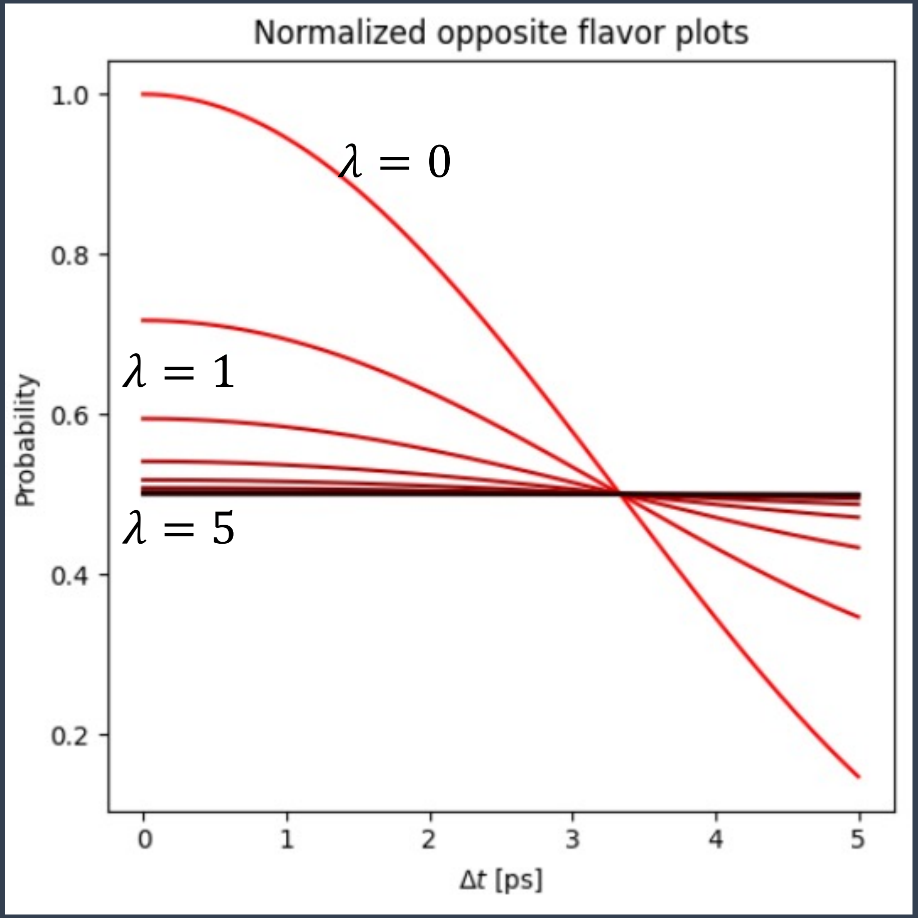
- Interaction of entangled states with environment can explain appearance of classical behavior at macroscopic scales
- Not an extension of QM, but rather a consequence of QM that was not previously appreciated
- Entangled states decohere over time
- Limits quantum computers
- SM decoherence
  - Our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

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:

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

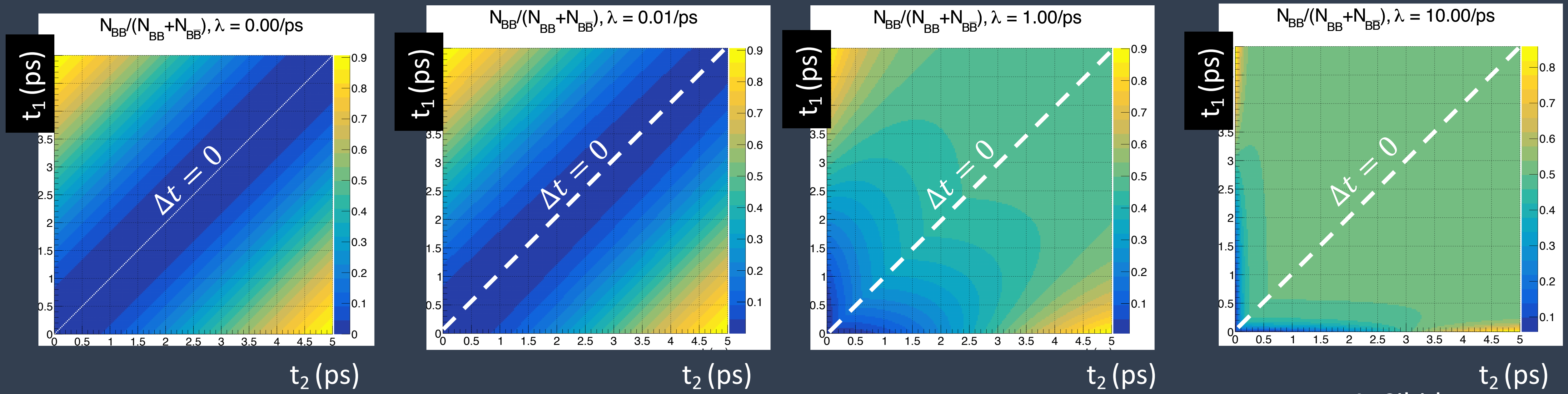
μ=+1: same flavor decays, -1: opposite flavor decays



- 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

λ (decoherence strength)



A. Sibidanov

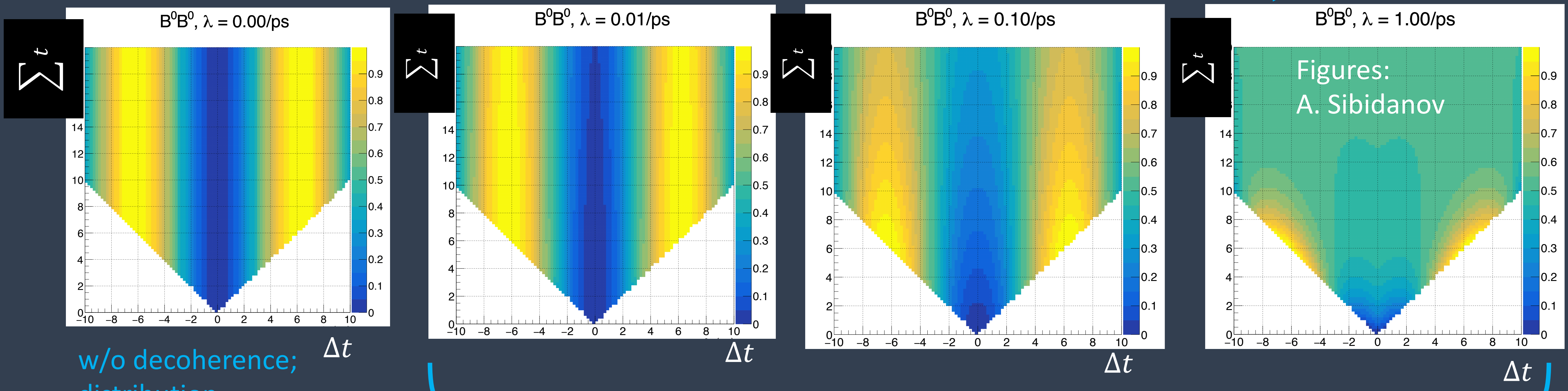
- As decoherence strength parameter λ increases
- Number of same-sign B meson pairs at $\Delta t = 0$ increases
- In this 2d plane, pattern distinct from miss-tagging (assigning wrong b-flavor in reconstruction)

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

$\sum t = t_1 + t_2$

$\Delta t = t_2 - t_1$

λ (decoherence strength)

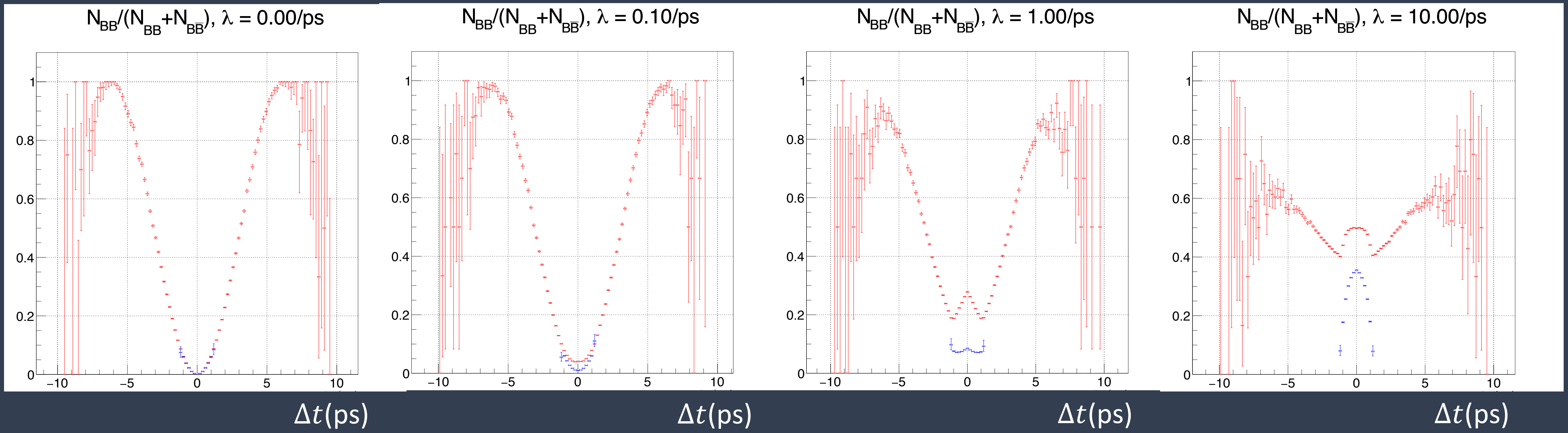


w/o decoherence; distribution independent of $\sum t$

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 $\sum t$ $\rightarrow$ two bins only



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

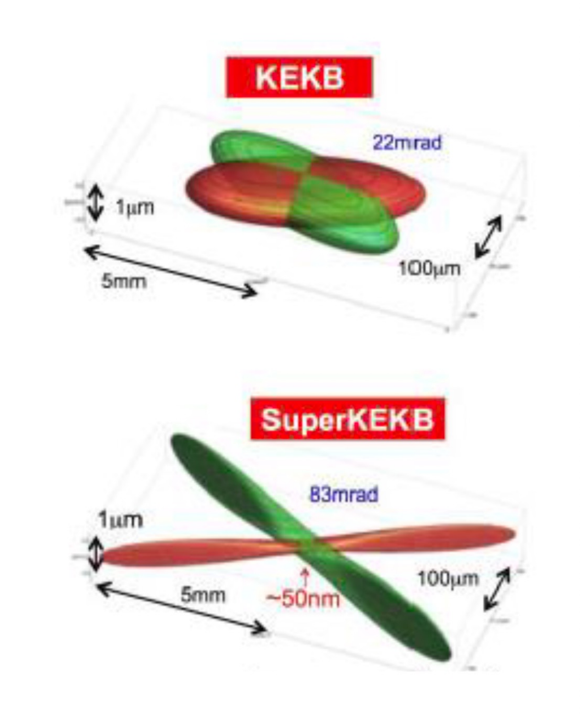
A. Sibidanov

Plans @ Belle II

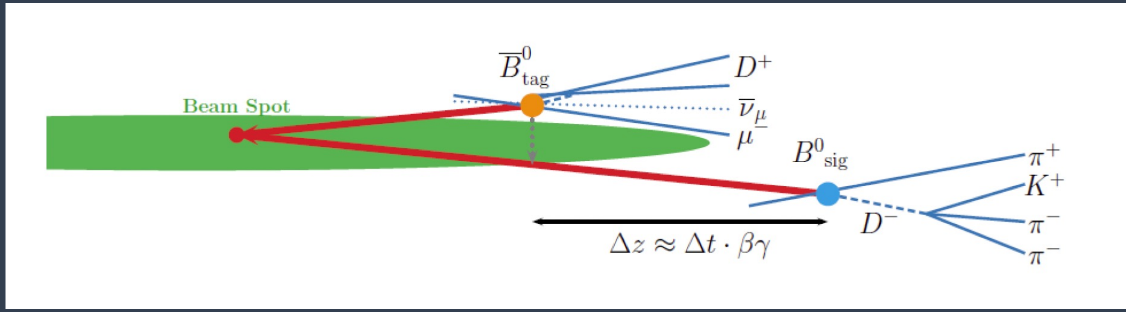
1. Repeat Belle analysis, but with higher statistics, more channels, better resolution

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

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



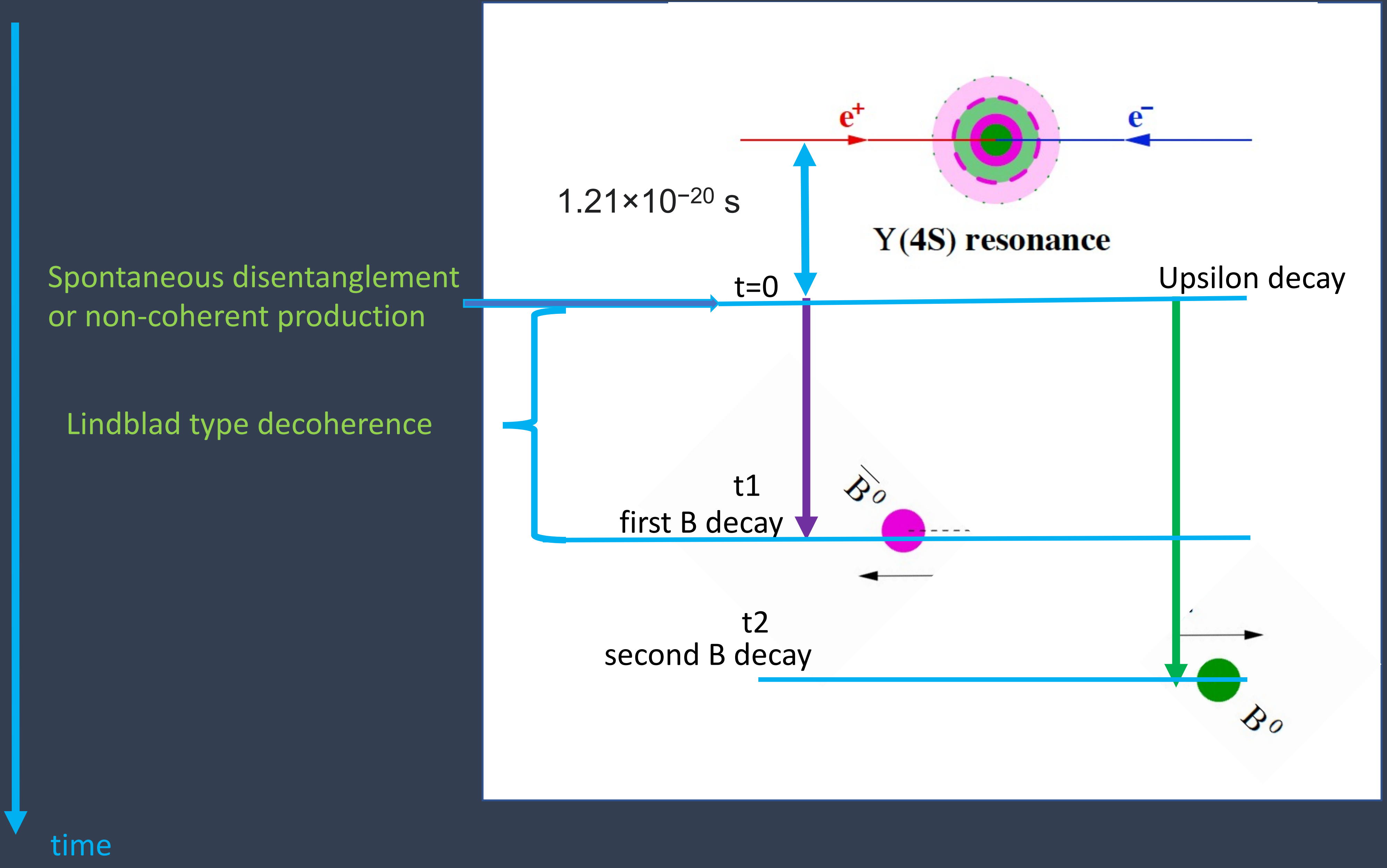
$\gamma\beta\tau c$ = 0.125 mm

Not ideal, but some sensitivity to t_1 should be achievable

Transverse separation ~50 µm

Vertex resolution σ_{res} ~20 µm

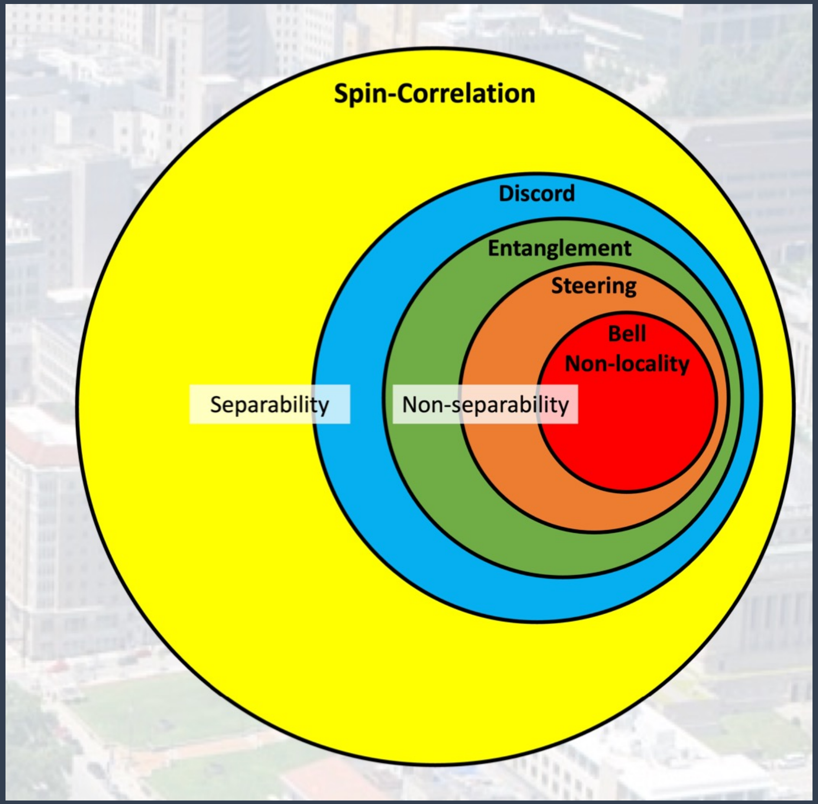
3. Probe more general decoherence models (such as Lindblad)
4. Work with theorists to estimate SM and BSM decoherence times
5. Understand possible systematics from unconstrained decoherence in other Belle II measurements (see talk by H.G. Moser)



Spontaneous disentanglement
or non-coherent production
Lindblad type decoherence
time
1.21×10^{-20} s
e^+
e^-
Y(4S) resonance
t=0
Upsilon decay
t1
first B decay
$\bar{B}^0$
t2
second B decay
B^0

Questions that arose at this workshop

- How would the figure on the right look for time-dependent flavor correlations in $\Upsilon(4S) \rightarrow \overline{B^0}B^0$?
- 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 $\Upsilon(4S) \rightarrow \overline{B^0}B^0$?
- Does the Belle II sensitivity to time dependence open up any new possibilities, compared to spin correlations?



Yoav Afik (University of Chicago)

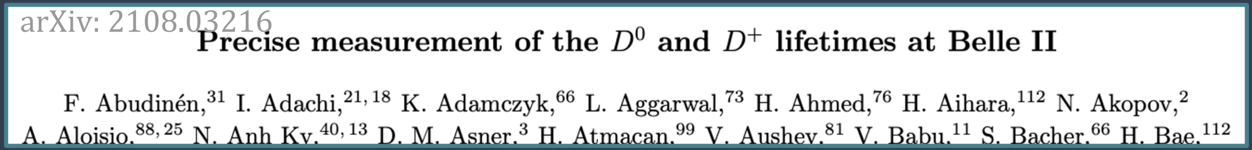
Summary

- $\Upsilon(4S) \rightarrow \overline{B^0}B^0$ system constitutes an interesting Quantum Laboratory
- Many classes of SM and BSM physics can be searched for
- Can probe entanglement versus time
- Studies of quantum decoherence appear particularly attractive
  - SM decoherence is expected — at some level
- Setting limits on decoherence (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
- SuperKEKB + Belle II appears particularly suitable
- Work has started within Belle II. We welcome your input and suggestions.

With contributions from
Hans-G. Moser (MPI)
A. Sibidanov, T. Mahood, H. Weiner,
A. Paul, L. Stötzer, P. Lewis (Hawaii)
Bruce Yabsley (Sidney)
Fumiaki Otani, Takeo Higuchi (IPMU)

BACKUP

D^0 and D^+ lifetimes

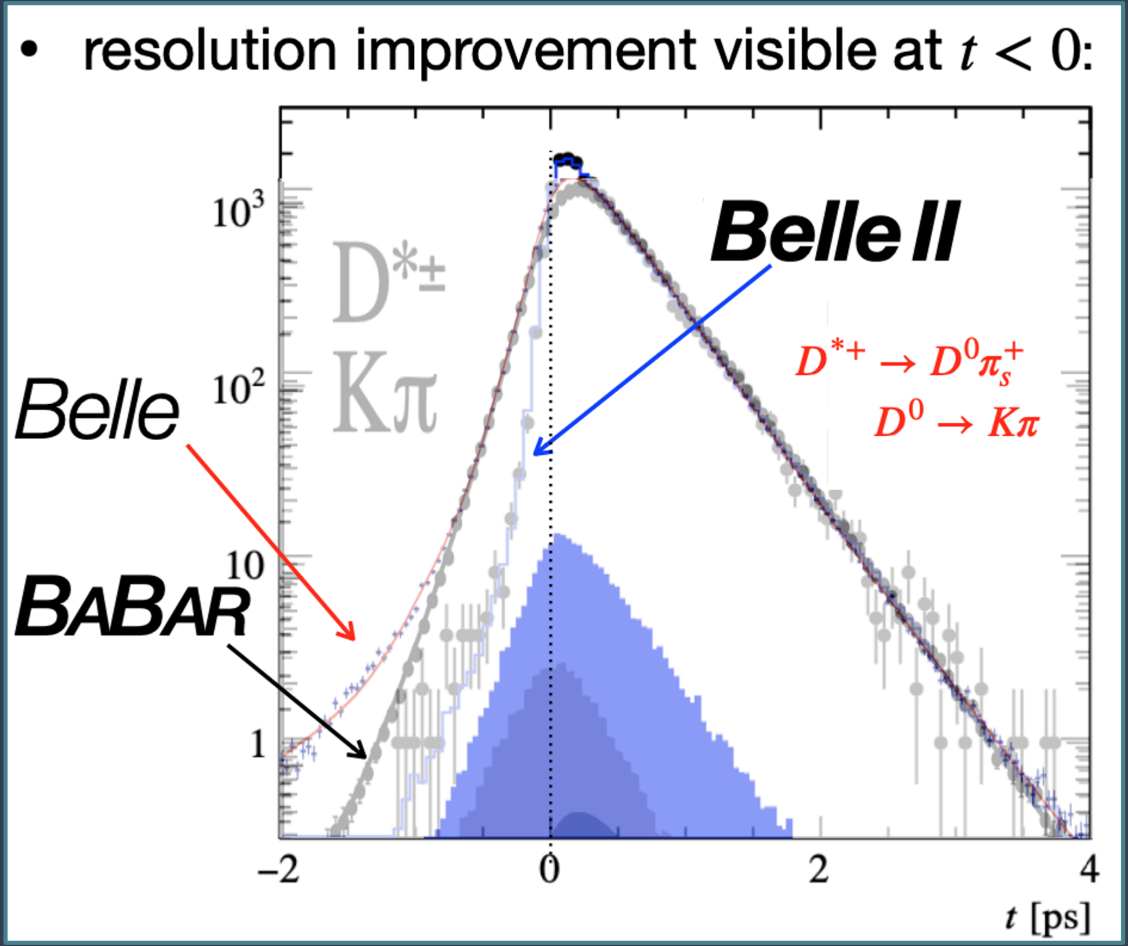

arXiv: 2108.03216

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

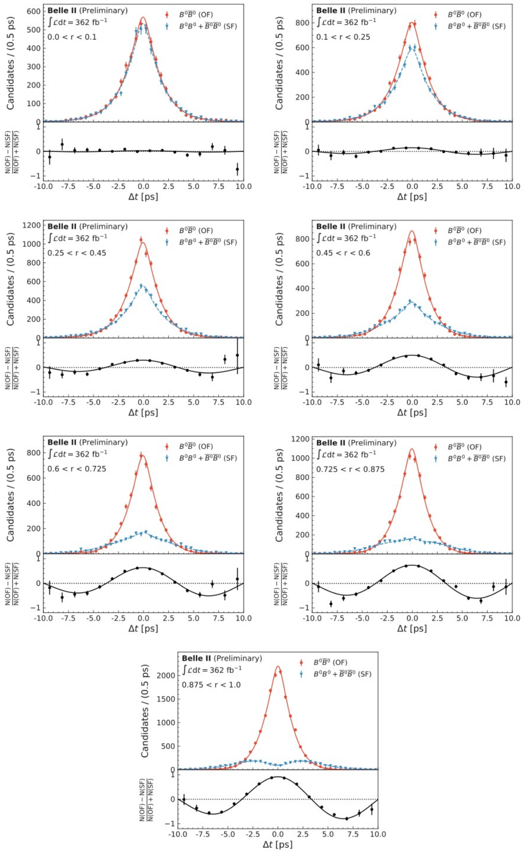


Figure 4. Background-subtracted Δt distributions of $B^0 \to D^{(*)-}\pi^+$ reconstructed in data in each of the seven r intervals (points) and the best-fit functions (lines) for opposite- and like-flavor B pairs with the corresponding asymmetries.

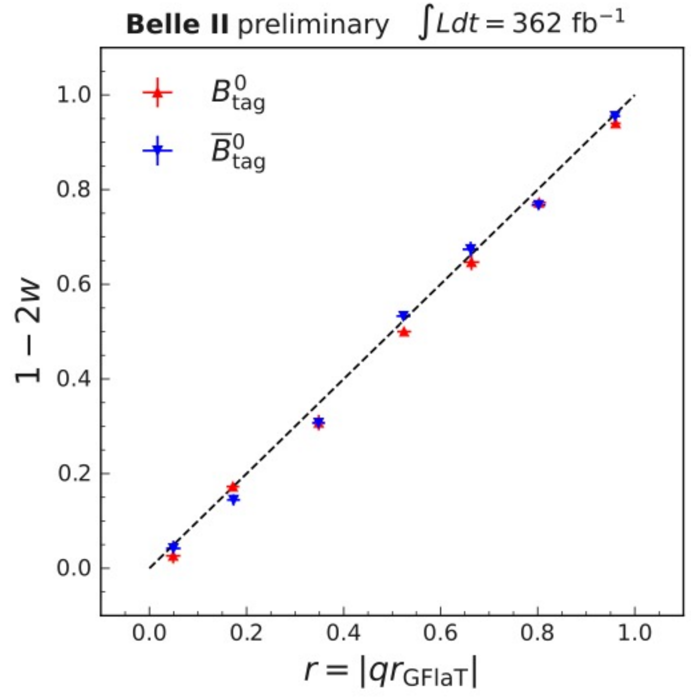


Figure 6. Dilution factors $1-2w$ of $B^0 \to D^{(*)-}\pi^+$ as functions of their GFlaT predictions, r for $B^0_{\rm tag}$, $1-2\bar{w}-\Delta w$, and $\overline{B}^0_{\rm tag}$, $1-2\bar{w}+\Delta w$; the dashed line shows $r = 1-2w$.

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.