Search for decoherence of $B\bar{B}$ quantum entanglement at Belle II

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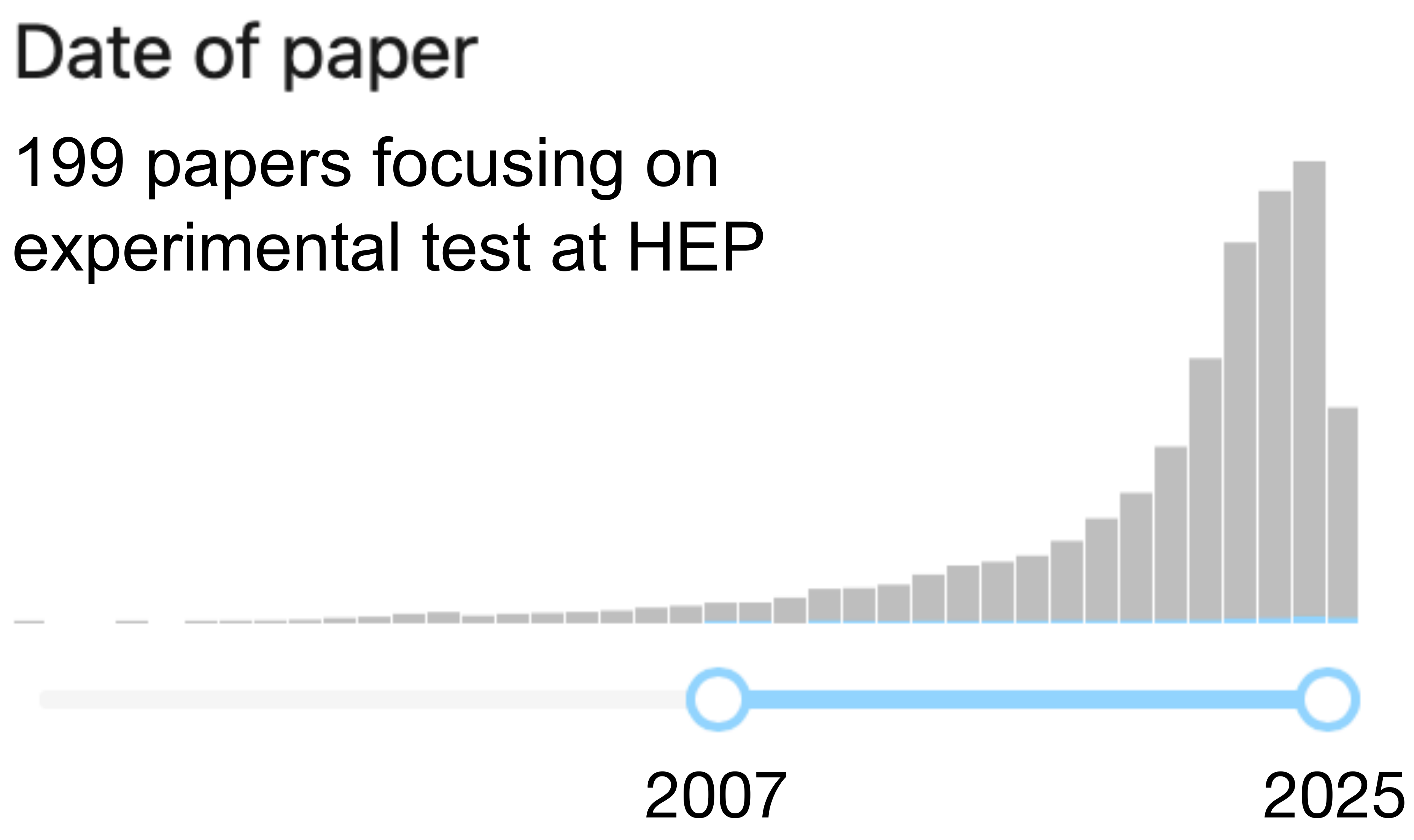
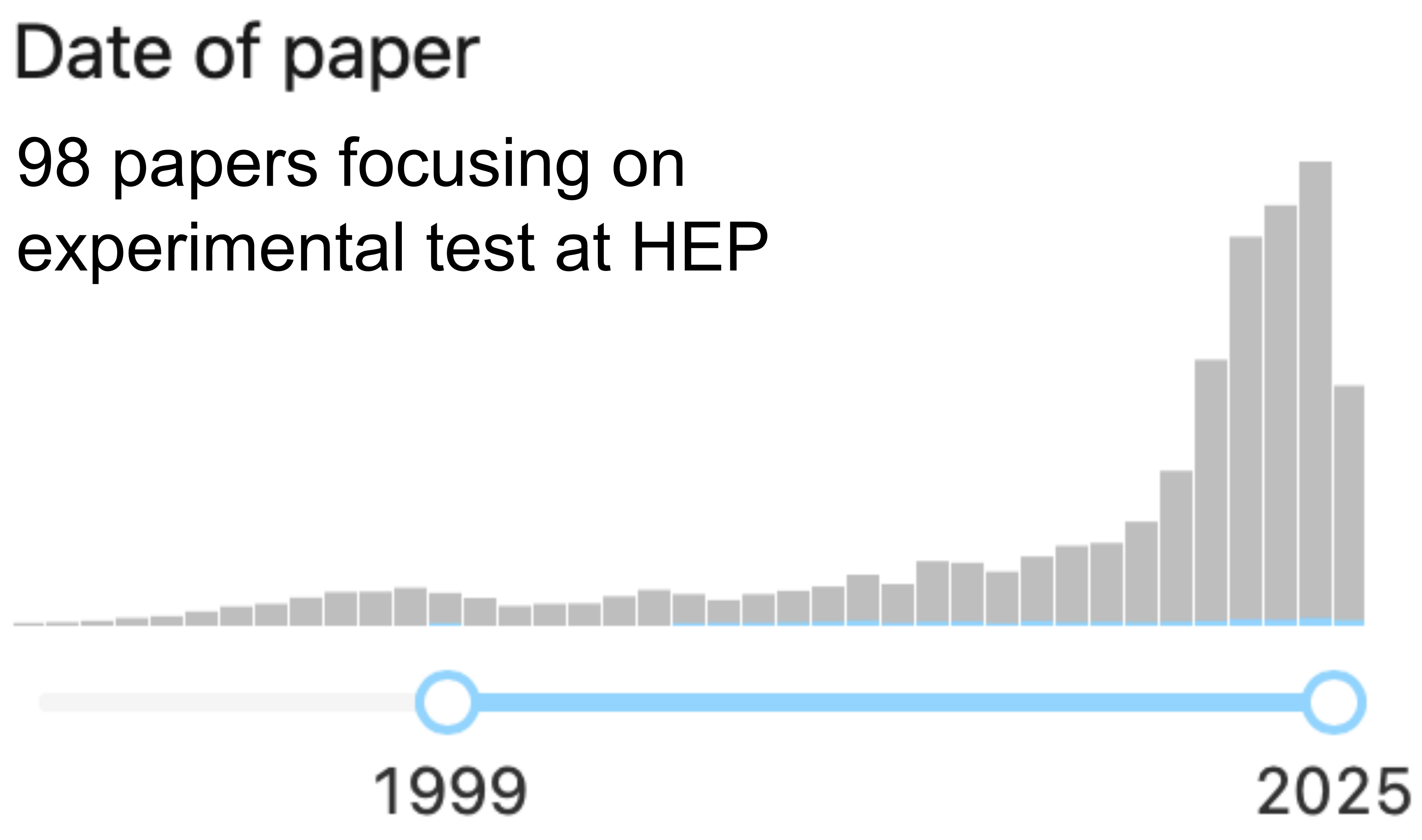
Entanglement and decoherence in HEP Collider experiments

Tests of quantum entanglement



Tests of quantum decoherence



- Emerging new field in HEP collider experiments in the recent years (ATLAS, CMS, Belle, Belle II, KLOE-2 etc.)
- ATLAS/CMS ⇒ Entanglement of top pair $(t\bar{t})$ spins (ATLAS 2024: https://arxiv.org/pdf/2311.07288 , CMS 2024: https://arxiv.org/pdf/2406.03976)
- KLOE-2 ⇒ Decoherence in entangled neutral Kaon systems (2022, https://arxiv.org/pdf/2111.04328, Conference Talk)

Source: InspireHEP

Entanglement and Decoherence at $\Delta t = 0$

Entanglement → Only opposite flavor events

$$B^0 \longleftarrow \Upsilon(4S) \longrightarrow \bar{B}^0$$

$$\bar{B}^0 \longleftarrow \Upsilon(4S) \longrightarrow B^0$$

Decoherence → Both opposite and same flavor events

$$B^0 \longleftarrow \Upsilon(4S) \longrightarrow B^0$$

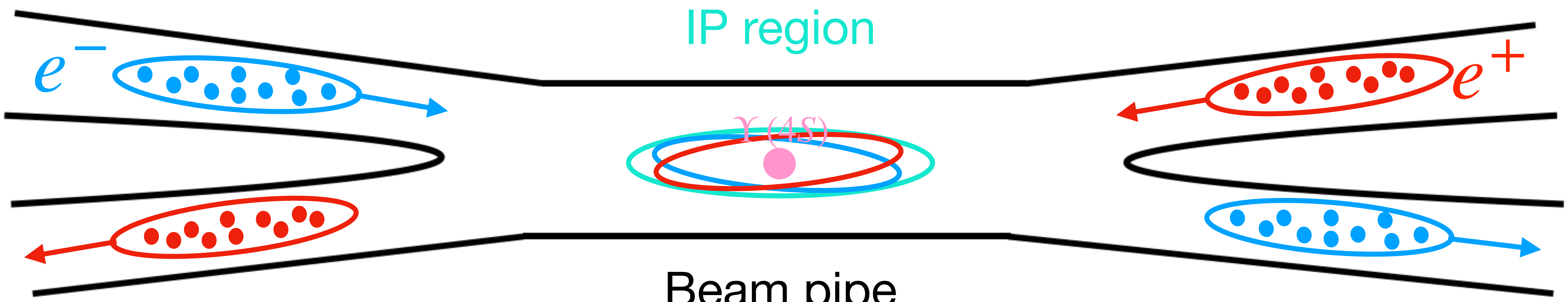
$$\bar{B}^0 \longleftarrow \Upsilon(4S) \longrightarrow \bar{B}^0$$

$$B^0 \longleftarrow \Upsilon(4S) \longrightarrow \bar{B}^0$$

$$\bar{B}^0 \longleftarrow \Upsilon(4S) \longrightarrow B^0$$

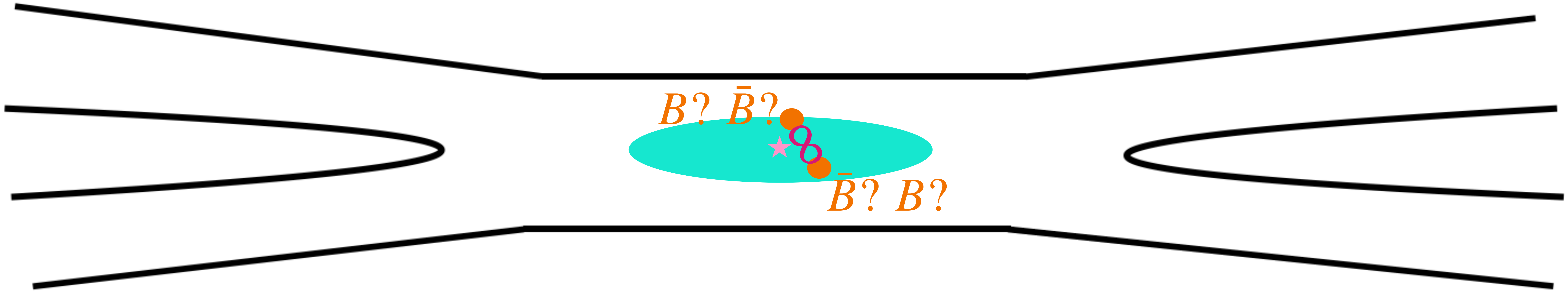
- When the $B\bar{B}$ decay at the same time (Δt=0), one is tagged to be the B, which makes the other instantaneously the $\bar{B}$
- Decoherence would allow same flavor → Interesting to test!

Creation of the $\Upsilon(4S)$ state



- $\Upsilon(4S)$ is created in the interaction point (IP) region by colliding e^- and e^+
- In the beam pipe we achieve pressures of 10^{-7} Pa

Production of flavor entangled $B\bar{B}$ pair



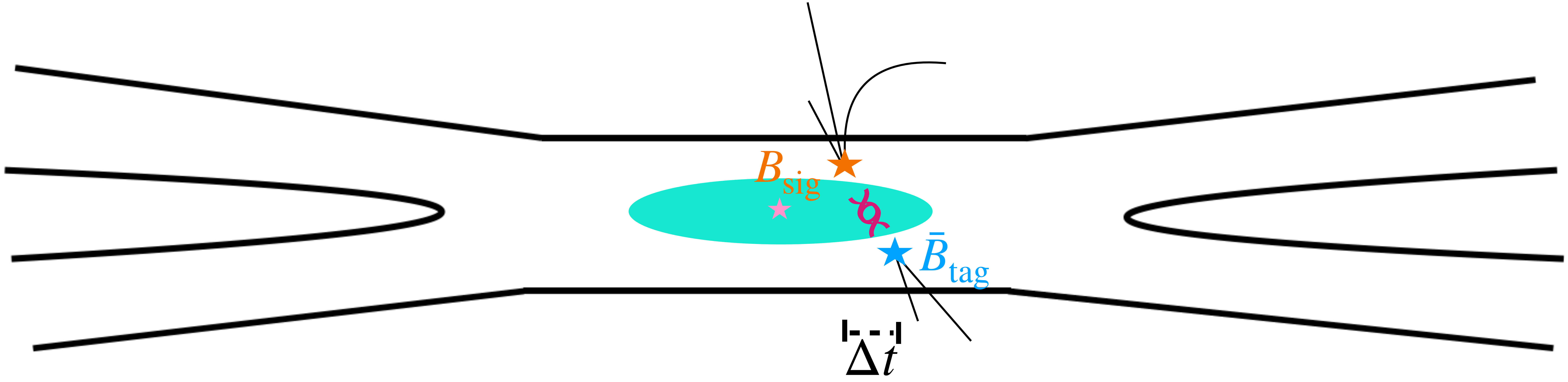
$$|\Psi\rangle = \frac{e^{-t/\tau_B}}{2}\left[\,|B^0(\vec{p})\,\bar{B}^0(-\vec{p})\rangle - |\bar{B}^0(\vec{p})\,B^0(-\vec{p})\rangle\right]$$

- $\Upsilon(4S)$ decays instantly in two neutral $B\bar{B}$ mesons
- $\Upsilon(4S) \to B^0\bar{B}^0$ via strong interaction

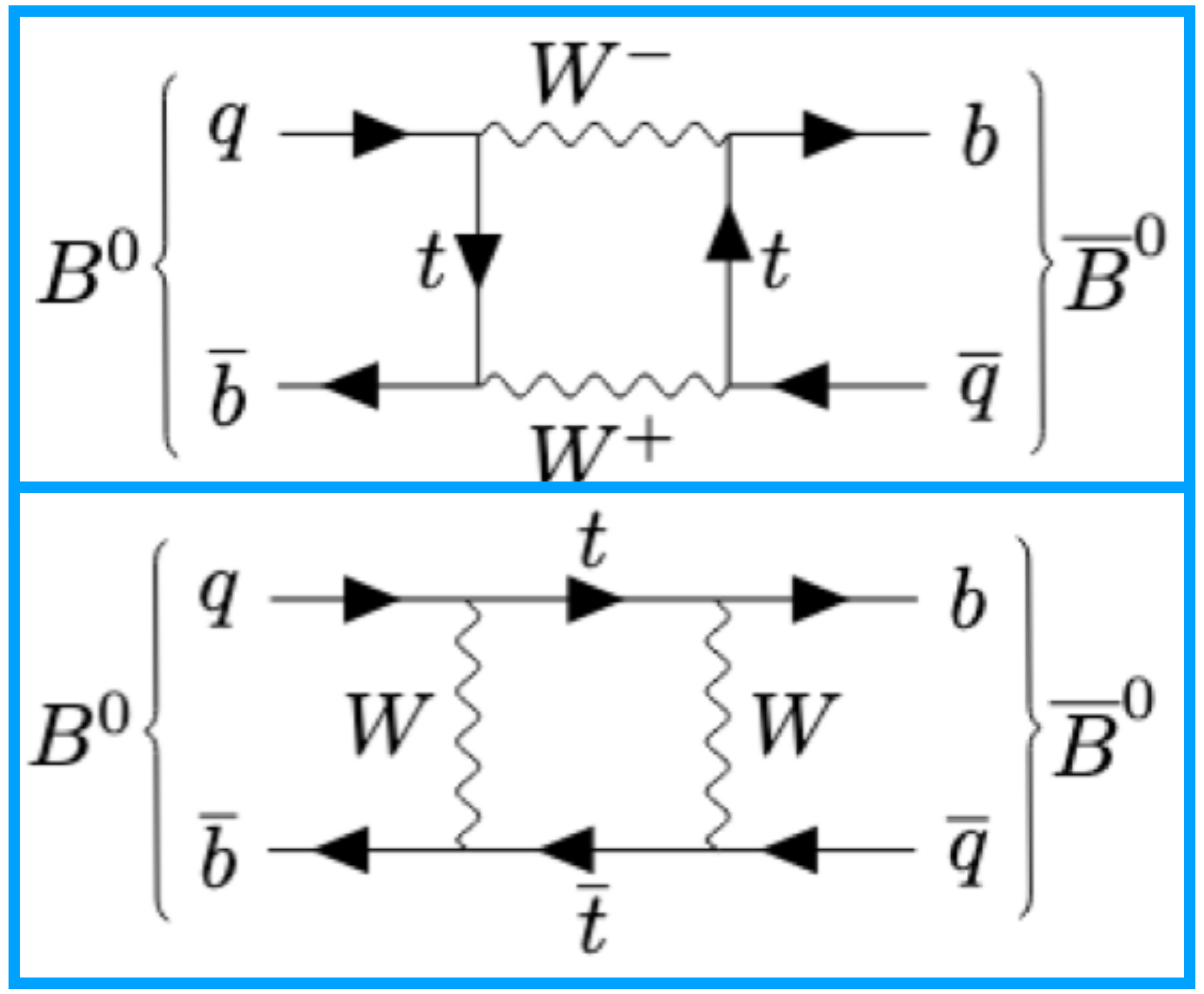
➡ $\Upsilon(4S)$ is a $C = -1$ charge conjugate eigenstate $\Rightarrow$ conserved in strong interaction

➡ $B^0\bar{B}^0$ will be flavor entangled

B meson decay and flavor tagging

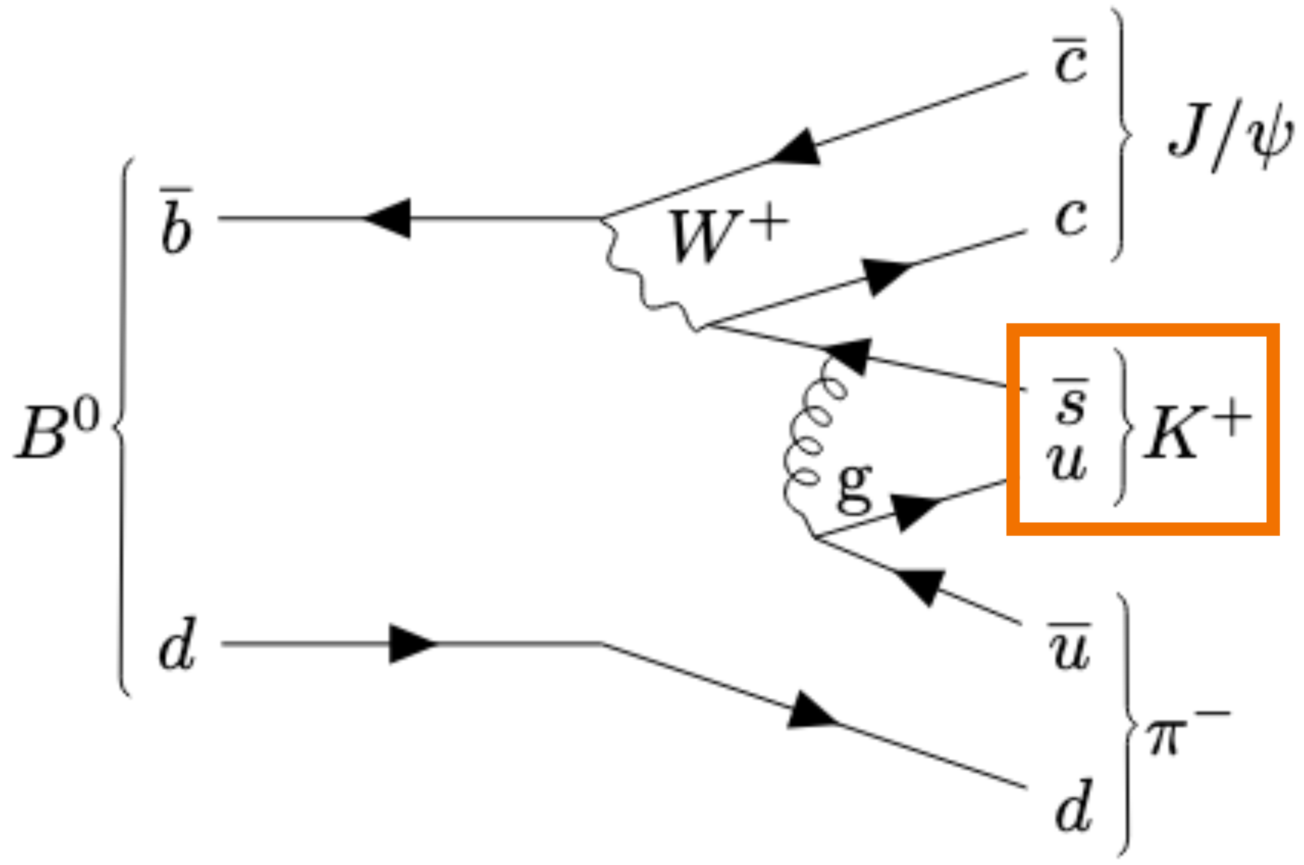


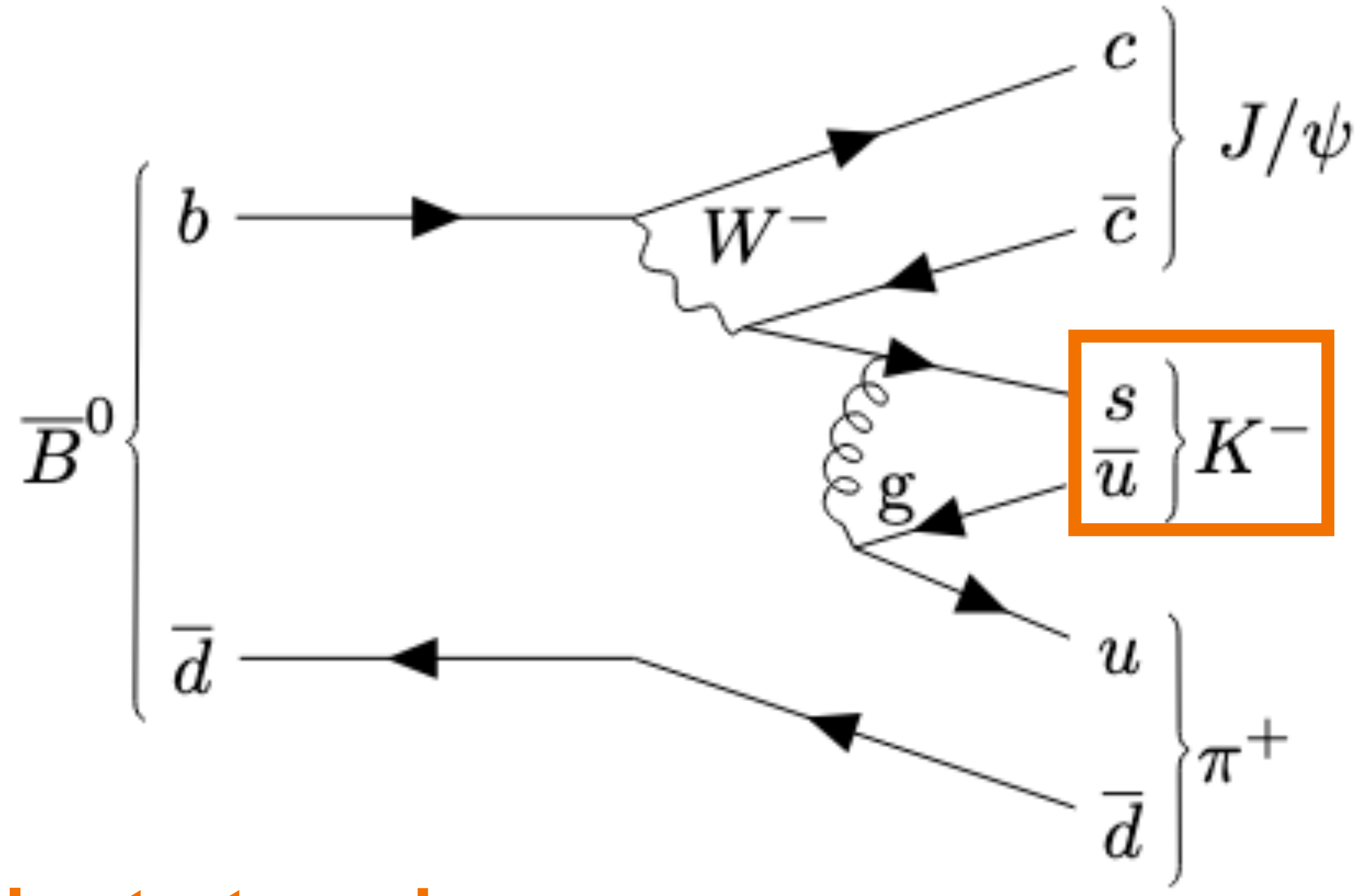
- First B meson decays and the entanglement is broken
  - ➡ The first B decays into one flavor specific eigenstate at time t_1
    - The second meson will instantaneously collapse into the opposite flavor state
    - But now (after first B decayed), undergoes flavor oscillation until it decays
- Reconstruct B_{sig} decay exclusively: Get flavor from charge of final state particles (self tagging)
- Reconstruct other B (B_{tag}) inclusively via flavor tagger neural network algorithm → not perfect will observe wrong tagging



Self tagging decay modes and expected #Events in $385\ \mathrm{fb}^{-1}$

Decay modes			Branching ratio	Expected # of Events
$B^0 \to J/\psi K^+ \pi^-$			$1.15 \cdot 10^{-3}$	
	$J/\psi \to \ell^+ \ell^-$		0.12	
$B^0 \to J/\psi K^0\,(1270)$			$1.30 \cdot 10^{-3}$	$\sim 88k$
	$J/\psi \to \ell^+ \ell^-$		0.12	
	$K^0\,(1270) \to K^*\,(892)\,\pi^0$		0.21	
		$K^*\,(892) \to K^+ \pi^-$	0.999	No reconstruction efficiencies known
	$K^0\,(1270) \to K^*\,(1430)\,\pi^0$		0.28	
		$K^*\,(1430) \to K^+ \pi^-$	0.930	
$B^0 \to D^- \pi^+$			$2.51 \cdot 10^{-3}$	
	$D^- \to K^+ \pi^- \pi^-$		$9.38 \cdot 10^{-2}$	
$B^0 \to D^{*-} \pi^+$			$2.74 \cdot 10^{-3}$	$\sim 72k$
	$D^{*-} \to \bar{D}^0 \pi_s^-$		0.677	
		$\bar{D}^0 \to K^+ \pi^-$	$3.95 \cdot 10^{-2}$	
		$\bar{D}^0 \to K^+ \pi^- \pi^0$	0.144	Reconstruction efficiencies known
		$\bar{D}^0 \to K^+ \pi^- \pi^+ \pi^-$	$8.22 \cdot 10^{-2}$	





- Self tagging means we can identify the flavor of the B via the final state charges
- Run 1 data set $\sim 385\ \mathrm{fb}^{-1}$, expect ~ 164755 entangled $B\bar{B}$ events

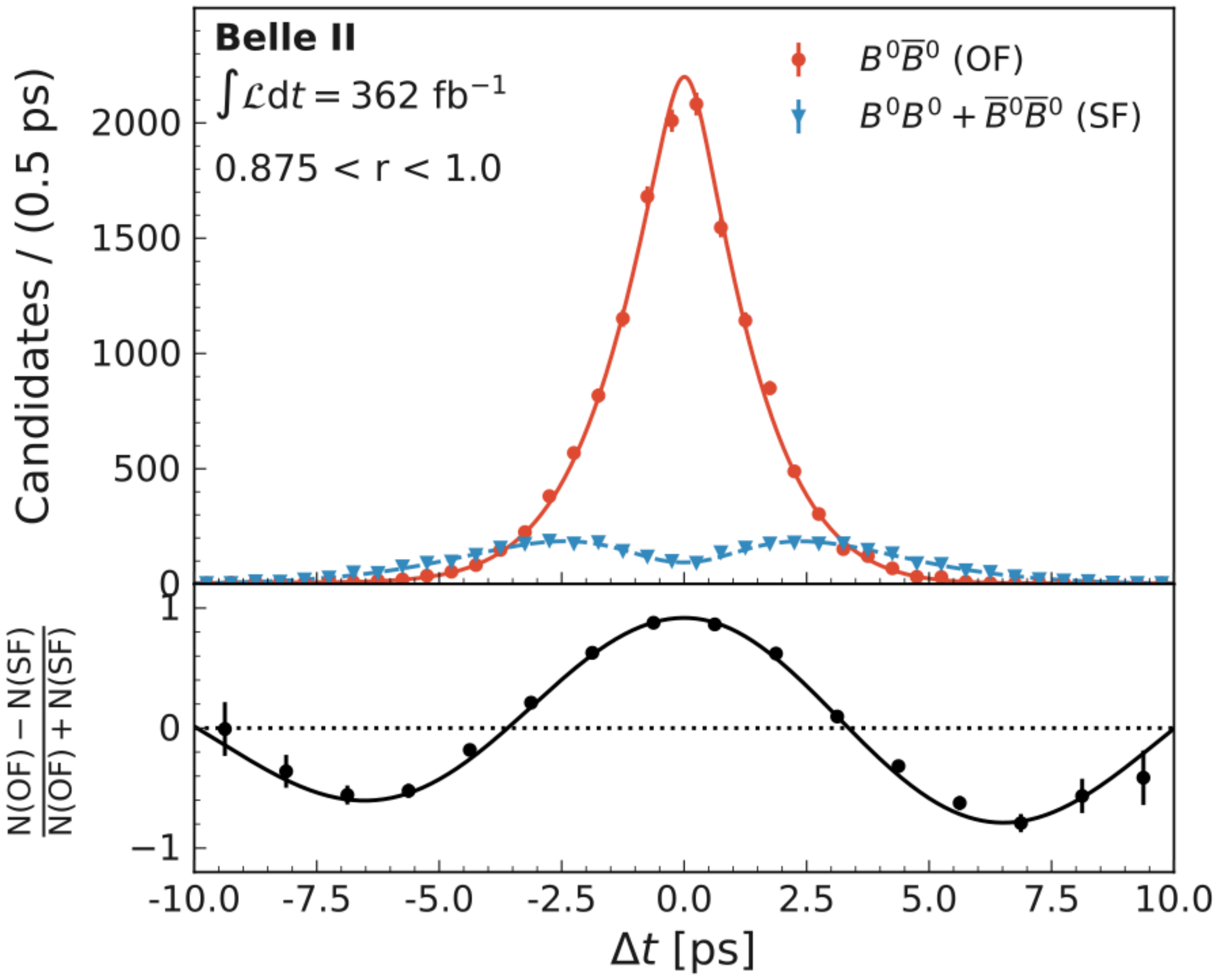
$B\bar{B}$ quantum entanglement at Belle II

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

- So far flavor entanglement assumed "perfect" in $B\bar{B}$ mixing analysis
- If there is decoherence, would observe decrease in amplitude of flavor oscillation (especially at $\Delta t = 0$)

➡ Belle II will be especially well suited:

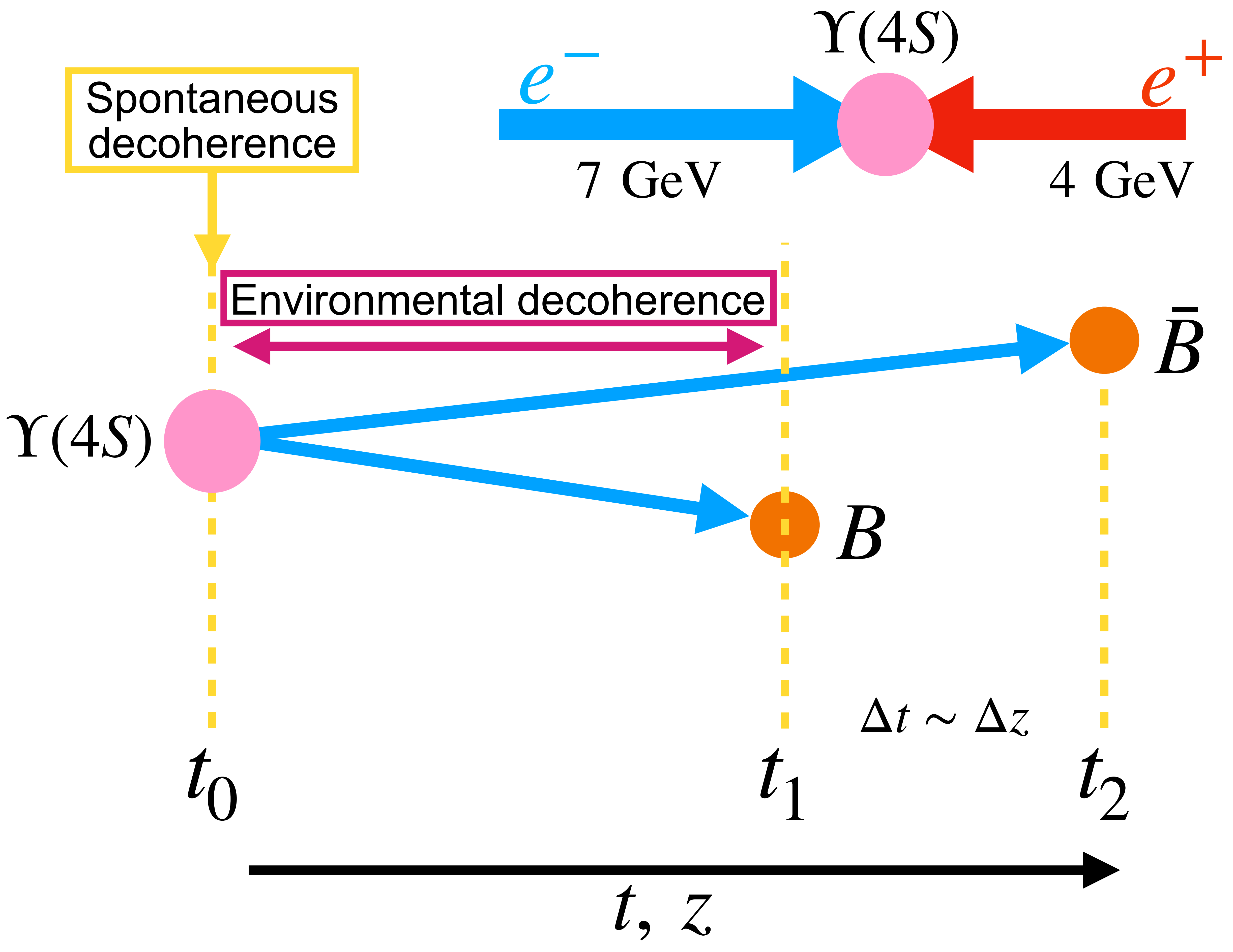
- More data than Belle
- Smaller interaction point (IP) region $\Rightarrow$ access to absolute decay times of the B mesons



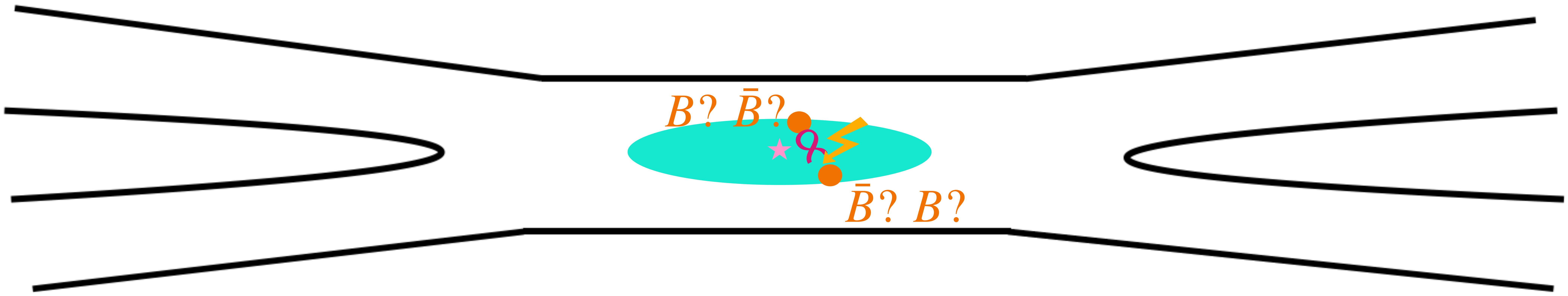
Spontaneous and environmental decoherence

- Spontaneous decoherence/ disentanglement $\Rightarrow B$ states evolve independently from their production on
  - ➡ Searched for in Belle[†] but no significant evidence
- Environmental decoherence $\Rightarrow B\bar{B}$ system interacts with environment, leading to disentanglement
  - ➡ e.g. Linblad Decoherence*
  - ➡ No search performed yet, in quantum entangled $B\bar{B}$ system!

† A. Go et al, https://arxiv.org/pdf/quant-ph/0702267
* https://arxiv.org/pdf/hep-ph/0101160



Environmental decoherence effects



- Environment interacts with the $B\bar{B}$ system and breaks the entanglement before first B decays
- Can get "Same Flavor" (SF) events when decaying simultaneously ($\Delta t = 0$)

Environmental Effect	Timescale for... (in picoseconds)		
	Dust Grain size $a = 10^{-3}$ cm	Molecule size $a = 10^{-6}$ cm	Particle size $a = 10^{-13}$ cm
Cosmic background radiation	10^{12}	10^{36}	10^{92}
Photons at room temperature	10^{-6}	10^{18}	10^{74}
Best laboratory vacuum	10^{-2}	10^{10}	10^{38}
Air at normal pressure	10^{-19}	10^{-7}	10^{21}
Other e^-/e^+ in the colliding bunch	???	???	???
Dark matter	???	???	???
Quantum Gravity	???	???	???

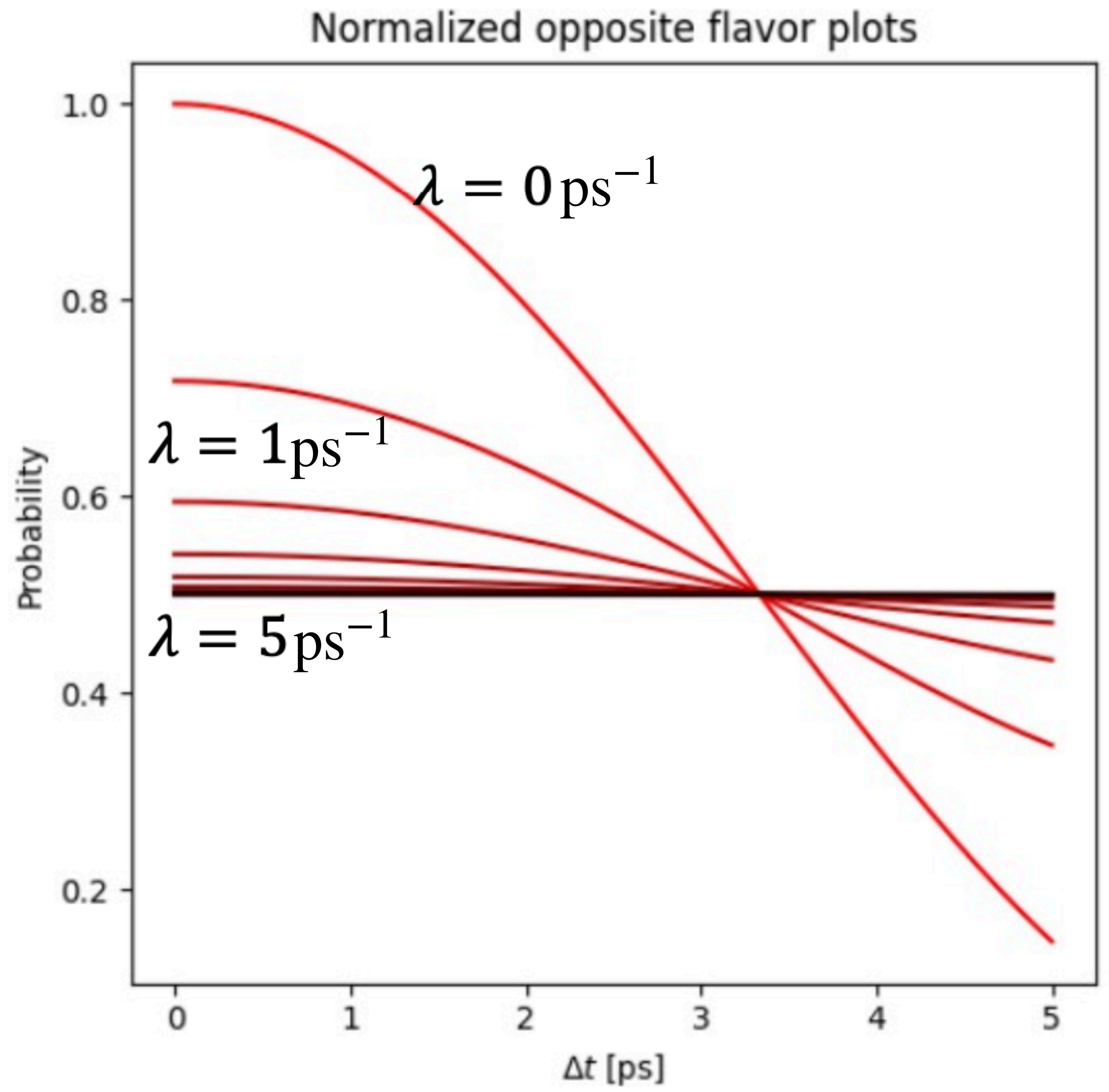
Table from: Maximilian Schlosshauer, Decoherence And The Quantum - To - Classicasl Transition, Springer 2010, p. 135

Lindblad type decoherence

- λ characterizes how strong the decoherence is in the system
- Former UH undergrad, Hershel Weiner, started developing a binned fitter that I inherited

$$N = \frac{\exp\left(-\Gamma \boxed{(t_1 + t_2)}\right)}{4}\left[\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) - q \boxed{\exp\left(-\lambda t_{\min}\right)} \cos\left(\Delta m \Delta t\right)\right]$$

- No absolute decay time $\Rightarrow$ Lindblad decoherence difficult to distinguish from wrong tagging in Δt projection only



Lindblad decoherence: B flavor vs $t_1,\ t_2$

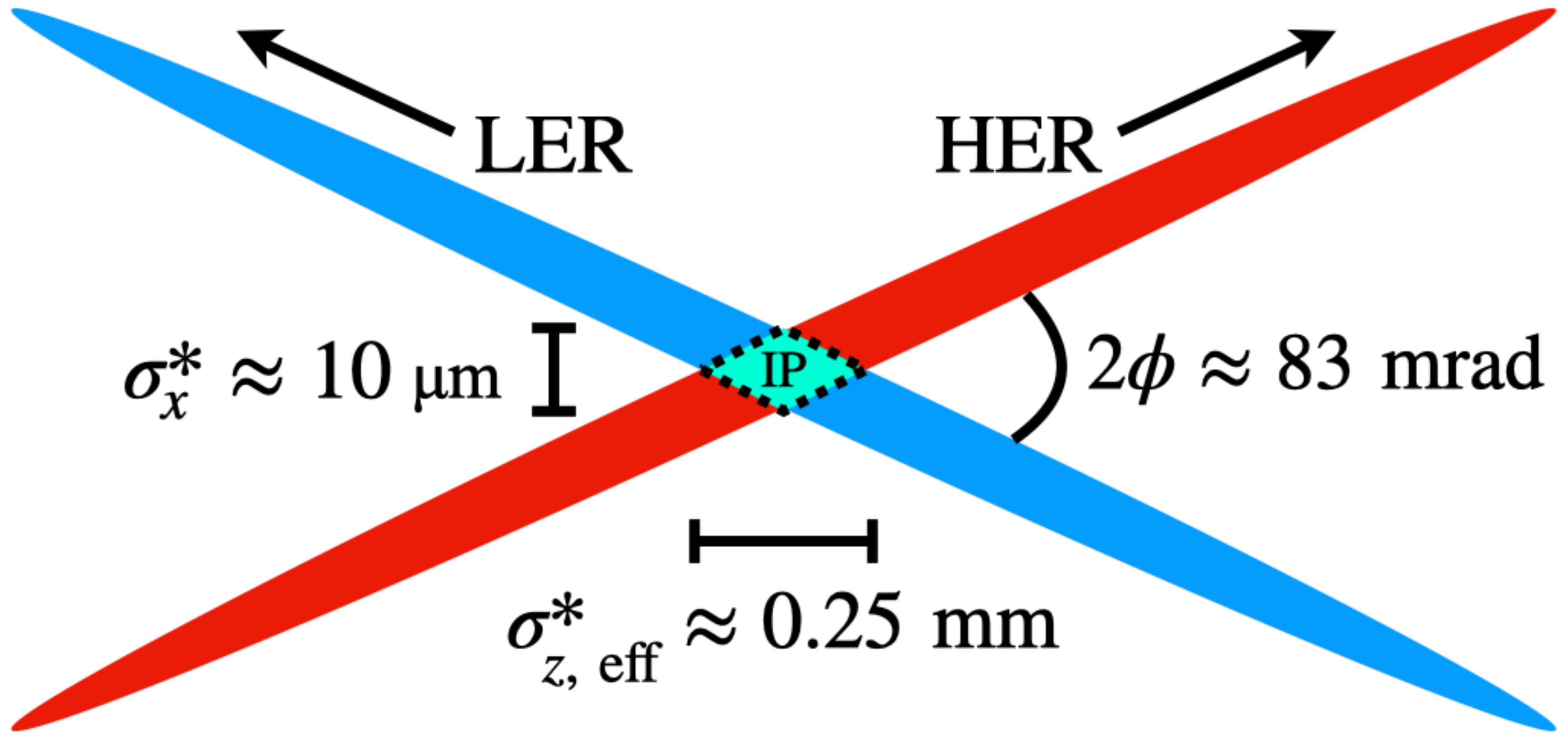
- Increasing decoherence parameter λ, increases same-sign B meson pairs at $\Delta t = 0$

Lindblad decoherence: B flavor vs $t_1,\ t_2$ with wrong tagging

- Observe wrong tagging is a constant effect in $t_1 \sim t_2$ plane

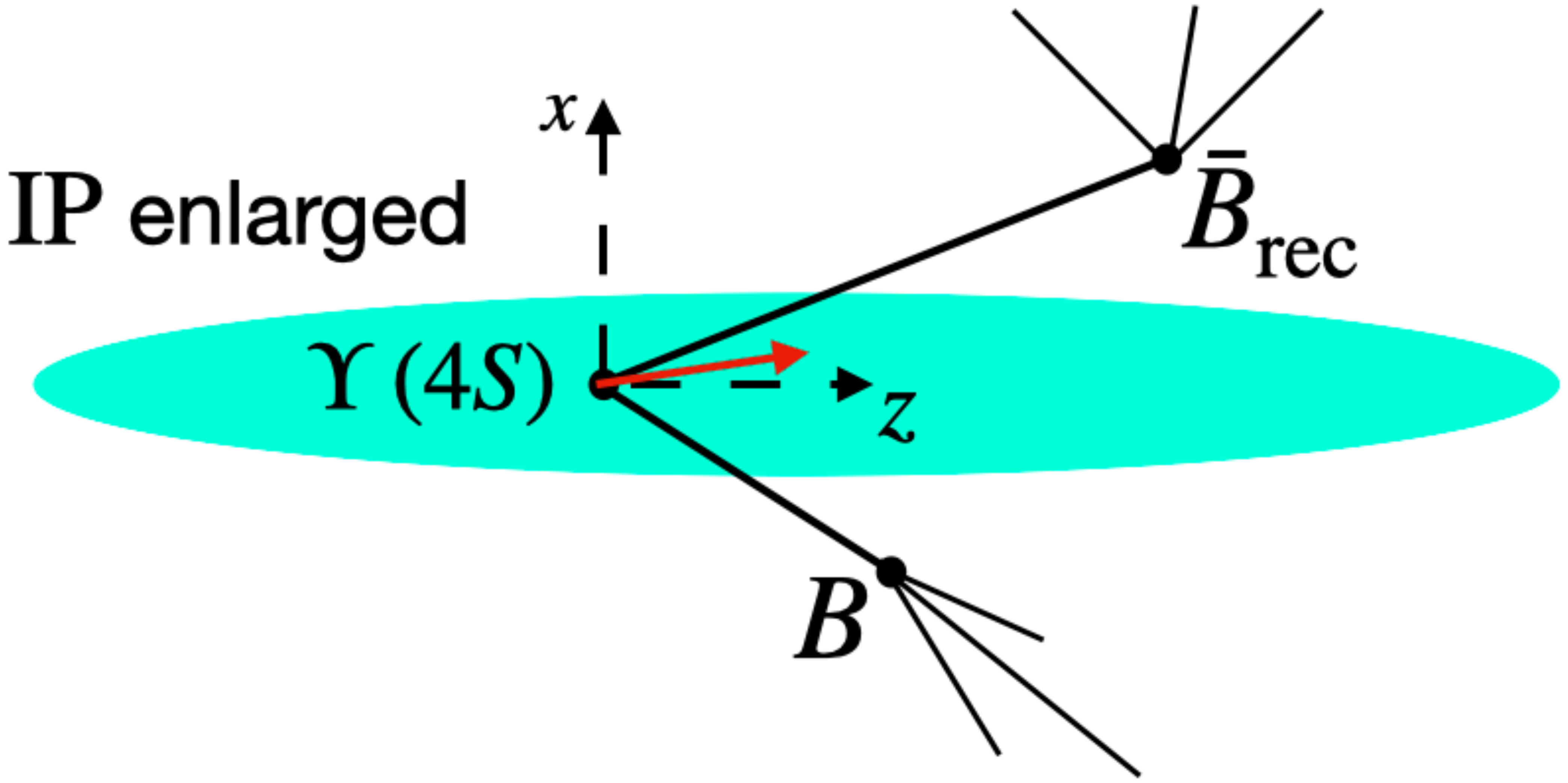
➡ t_1 and t_2 reveal a decoherence pattern, distinct from wrong tagging

Size of the beam spot, asymmetric beam energies and crossing angle!



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

Boost mainly in z direction, but also non negligible in x direction!

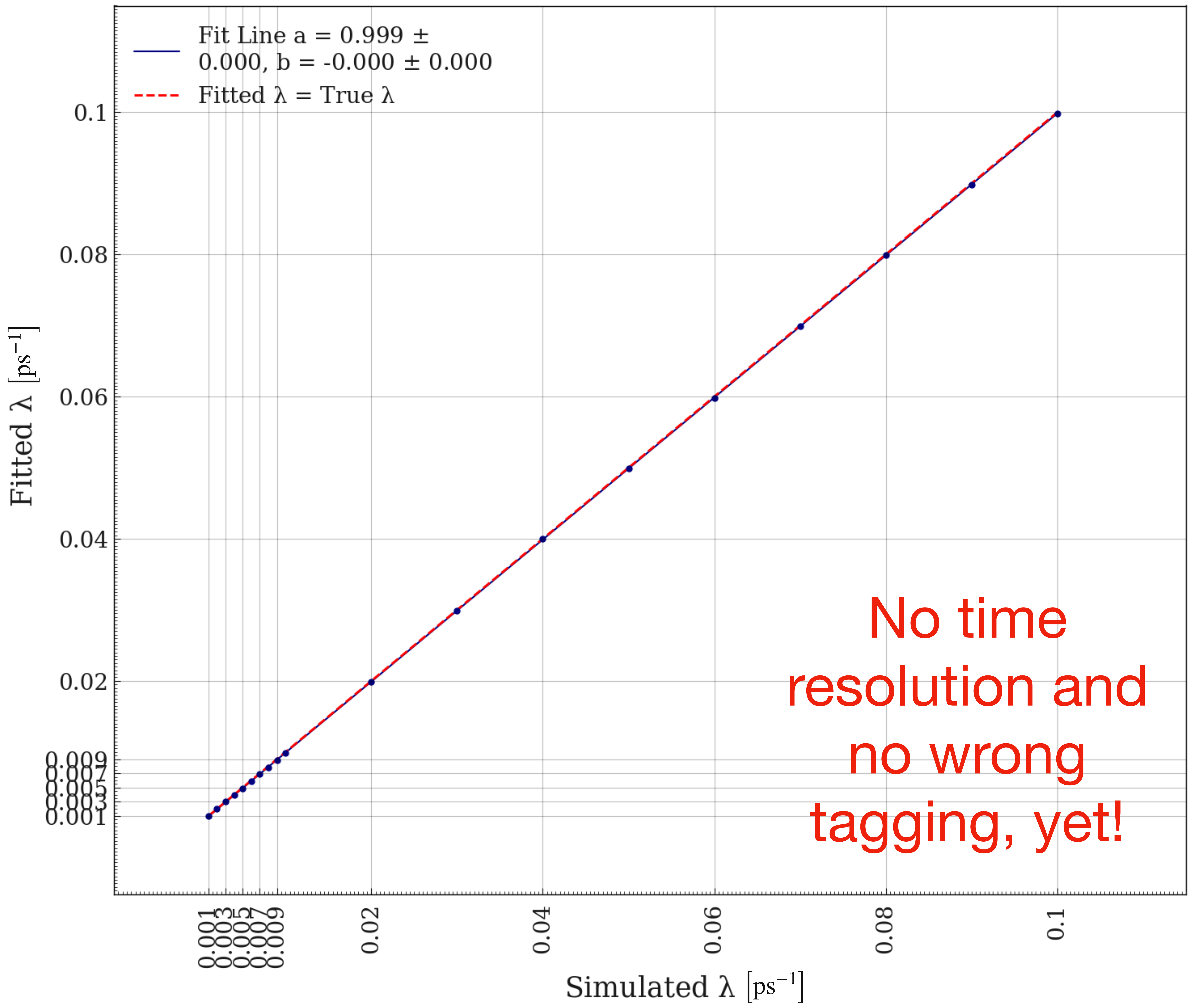


- Boost, not only in z, but also in x direction enables B mesons to leave the interaction point (IP) region
- Therefore, we can use the Btube fitting method determine the individual decay times!

Generating toy MC in semi-realistic conditions

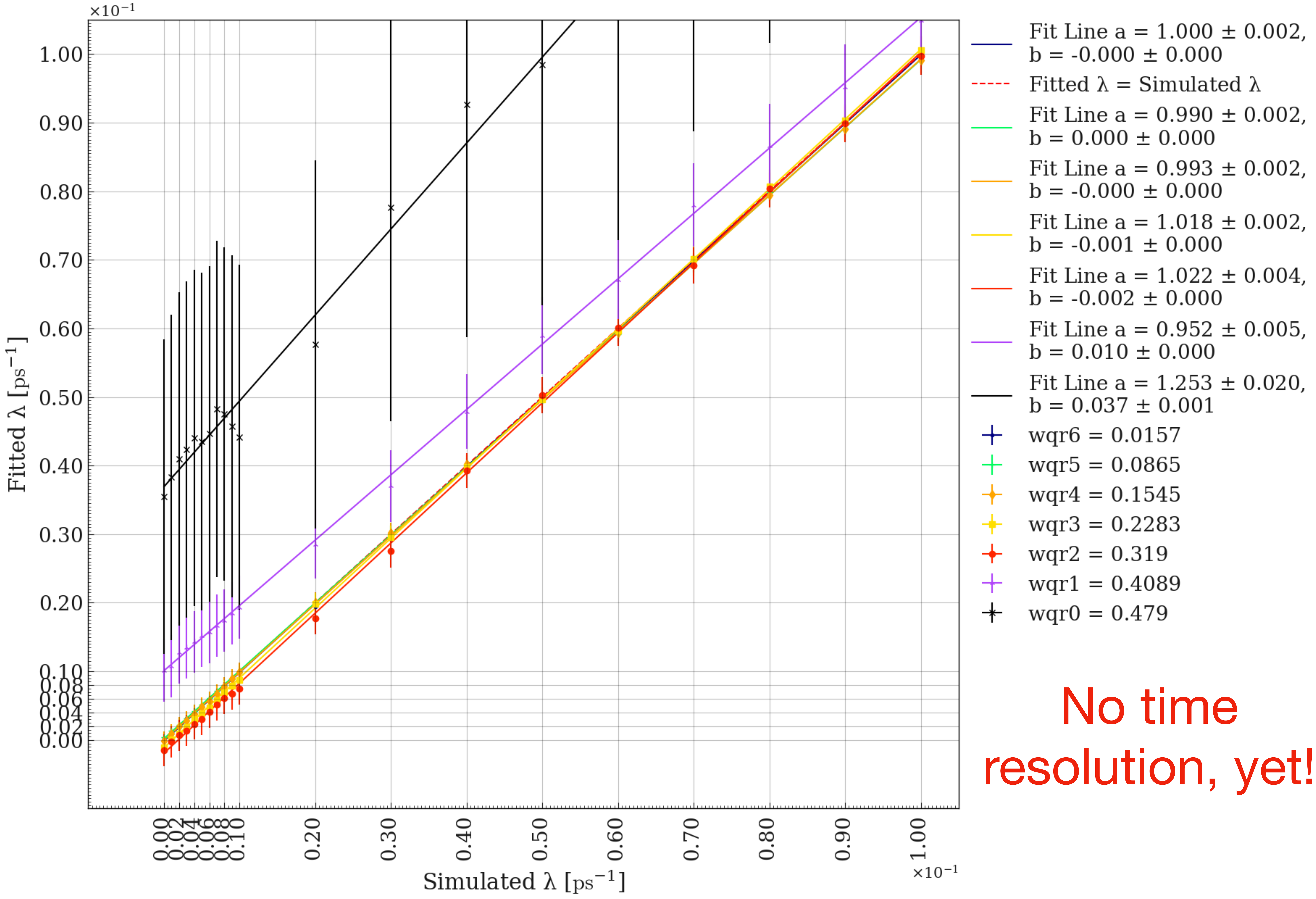
- We want to generate multiple toy MC data sets to test low and high λ values (low: $\lambda \leq 0.01\ \text{ps}^{-1}$; high: $\lambda > 0.01\ \text{ps}^{-1}$)
- For each λ value generate 100 toy experiments
  ➡ Each toy experiment consists of 72k events
  $$\left(72k/\ \text{toy exp.} \sim \mathscr{L}_{\text{int}} = 385\ \text{fb}^{-1}/\ \text{toy exp.}\right)$$
  ➡ Use random exponential to create t_1 and t_2 pairs
- To make the toy MC study semi-realistic introduce two major effects
  (1) Wrong tagging
  (2) Resolution effects

Linearity Test Unbinned Fitter without wrong tagging



- On truth level toy MC the unbinned fitter performs well
- However, we need to incorporate wrong tagging and resolution effects to obtain the total picture

Linearity Test Unbinned Fitter with wrong tagging



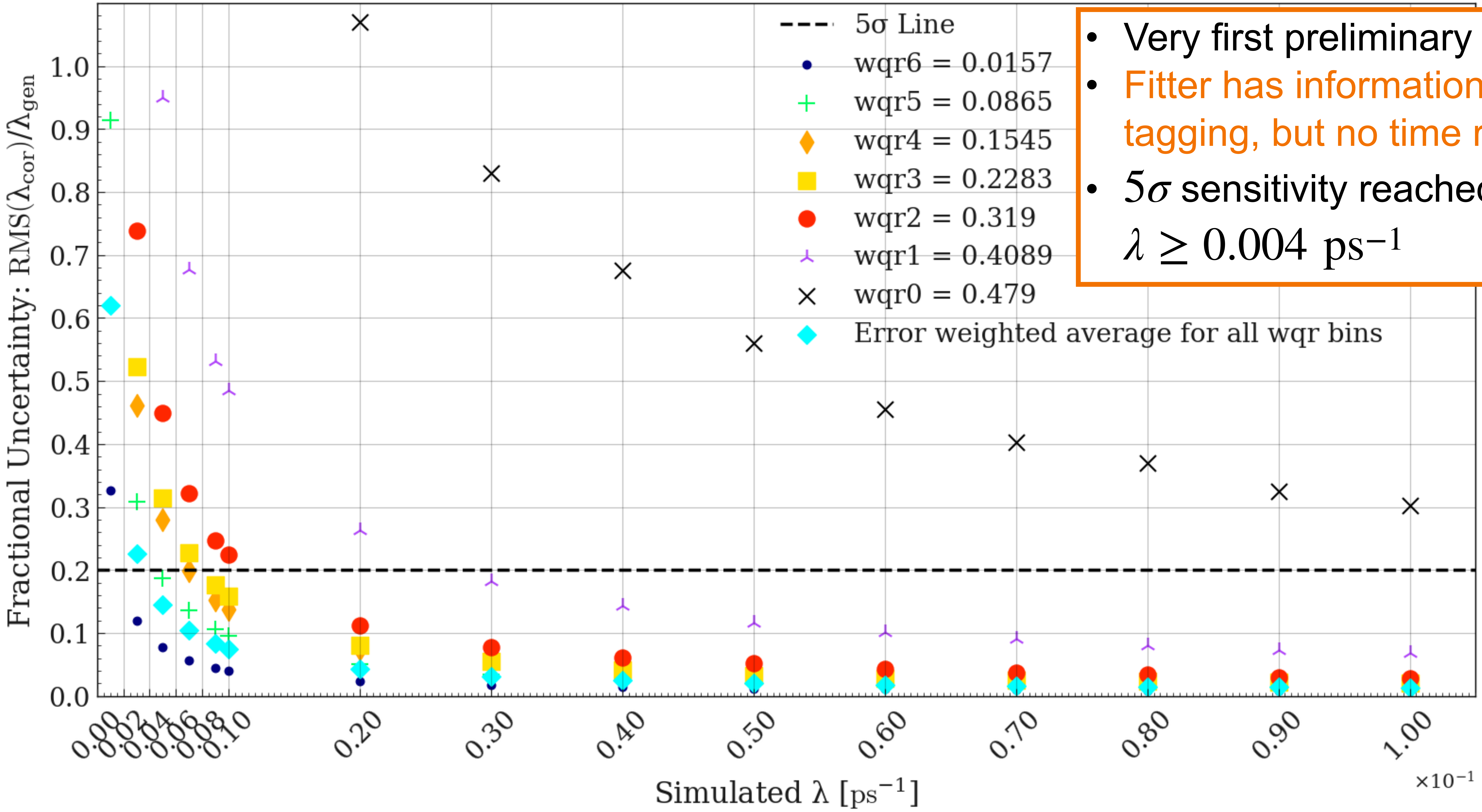
No time resolution, yet!

- Take wrong tagging ratio into account for each w_{qr} bin
- Observe large bias for the two highest wrong tagging bins (black and purple)
- Bias comes from low MC statistics!

➡ Correct fitting bias:

$$\lambda_{\text{cor}} = \frac{\lambda_{\text{fit}} - b}{a}$$

Sensitivity Test Unbinned Fitter with wrong tagging



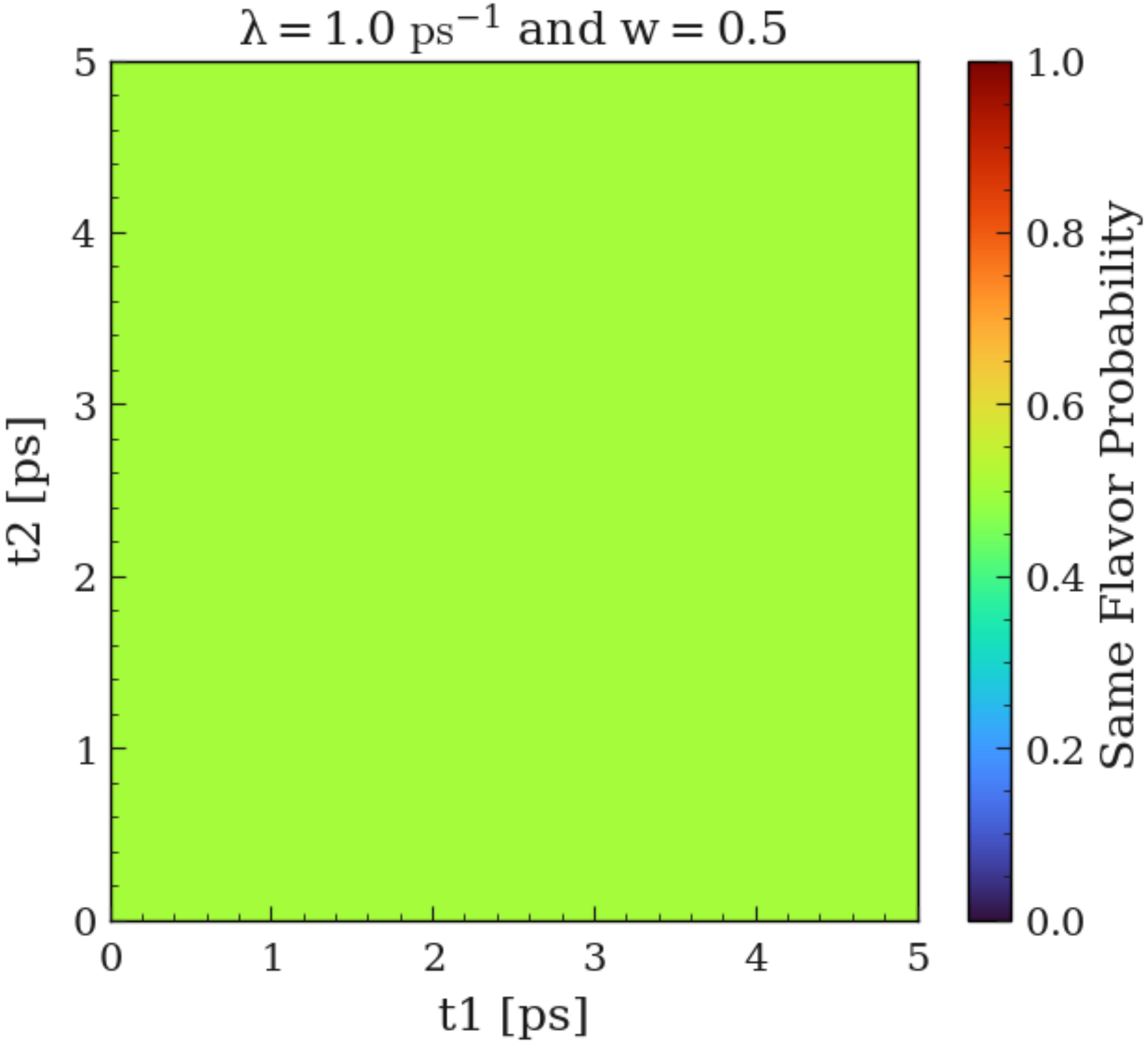
- Very first preliminary sensitivity plot
- Fitter has information about wrong tagging, but no time resolution
- 5σ sensitivity reached at $\lambda \geq 0.004\ \mathrm{ps}^{-1}$

Summary

- Search for quantum decoherence of flavor entangled B mesons
- Absolute decay times distinguish decoherence from wrong tagging
- We have access to the absolute decay times in Belle II
- Exploring measurement only using the absolute decay times (not Δt)
- Developing a new unbinned fitter
- Preliminary: Observe 5σ sensitivity for $\lambda \geq 0.004\ \mathrm{ps}^{-1}$ in $385\ \mathrm{fb}^{-1}$ of toy MC

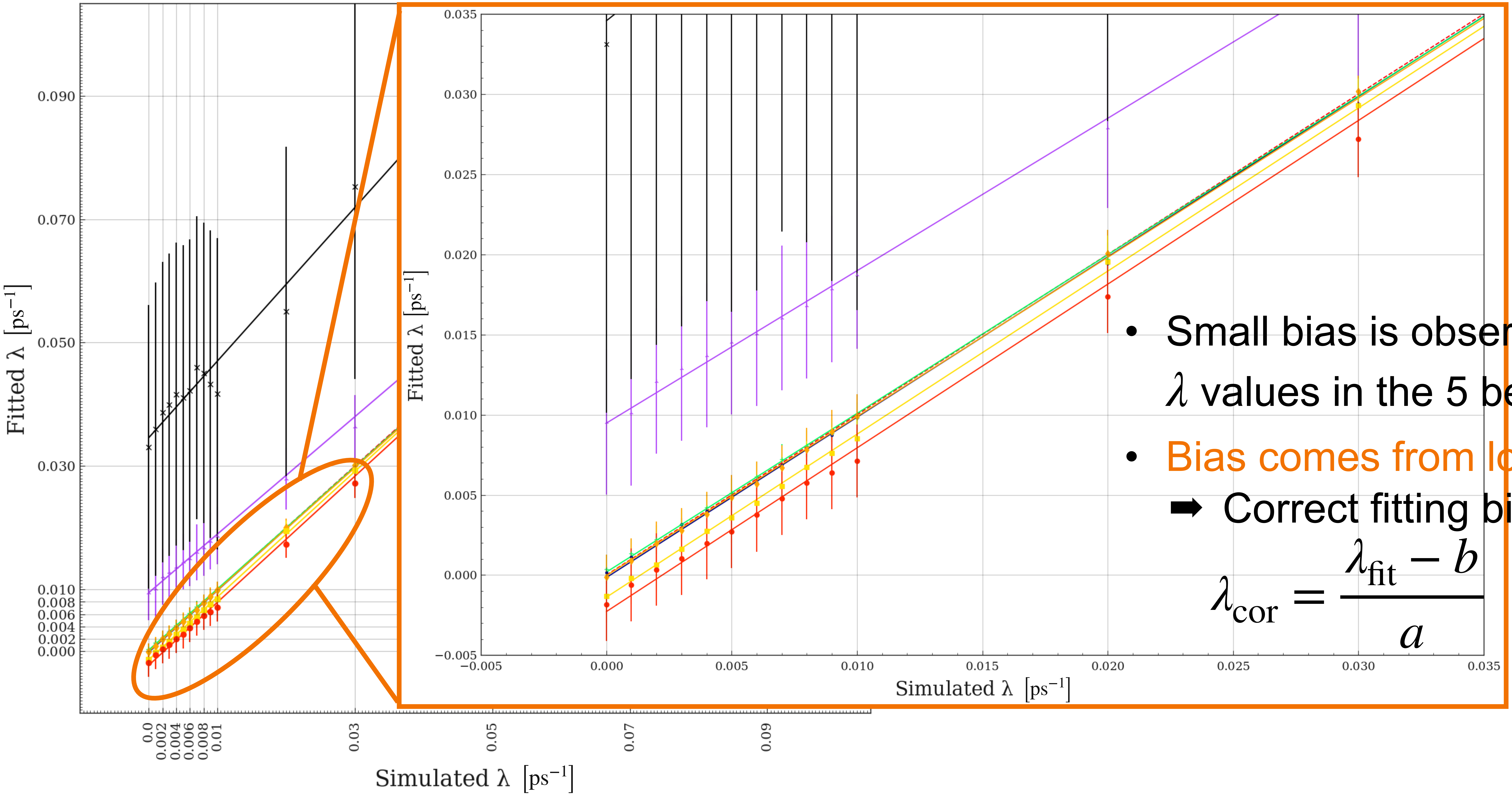
Thank you for your attention!

Backup: B flavor vs $t_1,\ t_2$ with wrong tagging



- If wrong tagging ratio reaches $50\,\%$ no hints of decoherence can be observed
  - ➡ The closer we get to $50\,\%$ wrong tagging the fitter will get more and more problems fitting for λ

Backup: Linearity Test Unbinned Fitter with wrong tagging

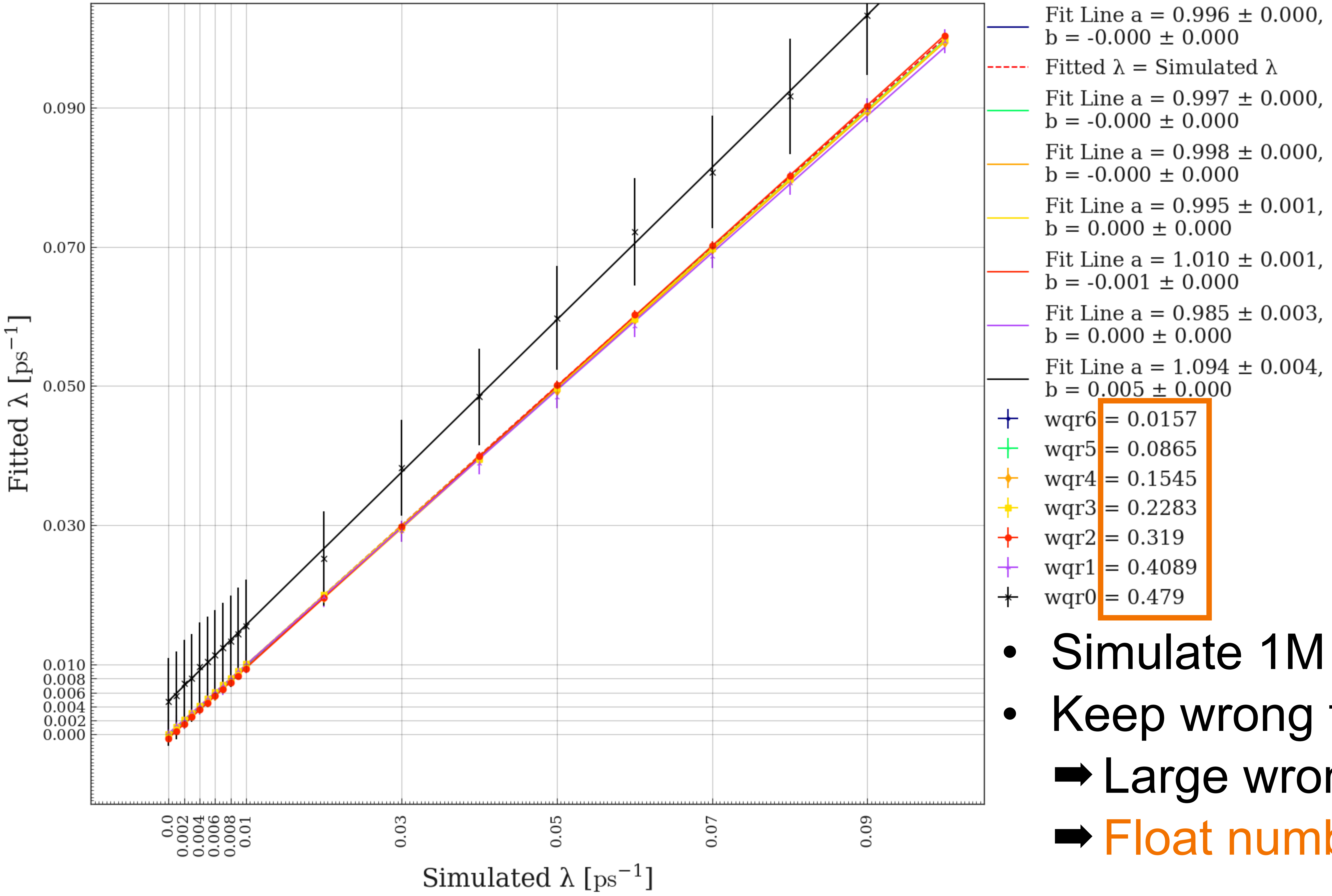


- Small bias is observed for small λ values in the 5 best w_{qr} bins
- Bias comes from low statistics!

➡ Correct fitting bias:

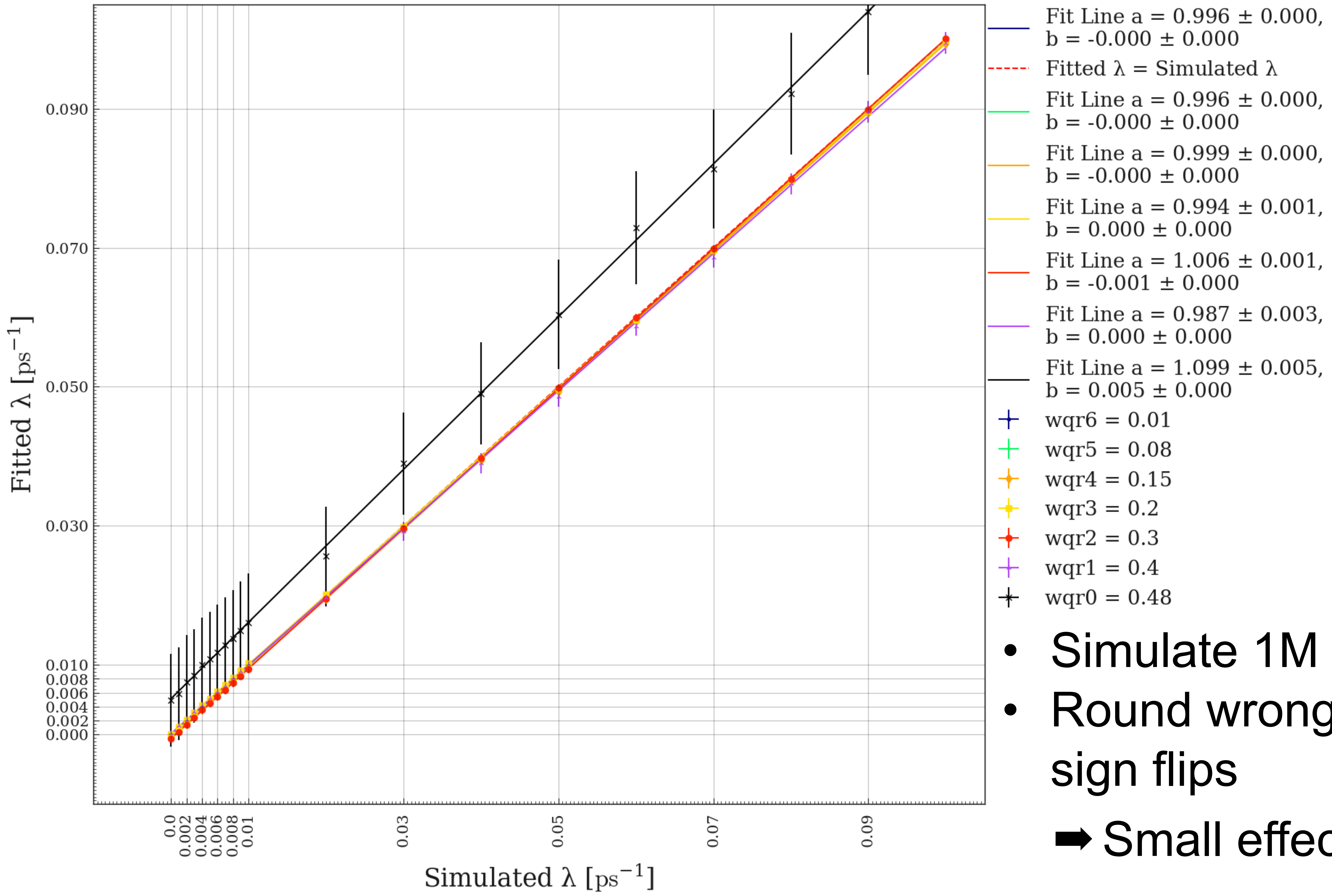
$$\lambda_{\mathrm{cor}} = \frac{\lambda_{\mathrm{fit}} - b}{a}$$

Backup: Bias study



- Simulate 1M events
- Keep wrong tag ratio the same
  - ➡ Large wrong tag ratio = Large bias
  - ➡ Float numbers causing a small bias?

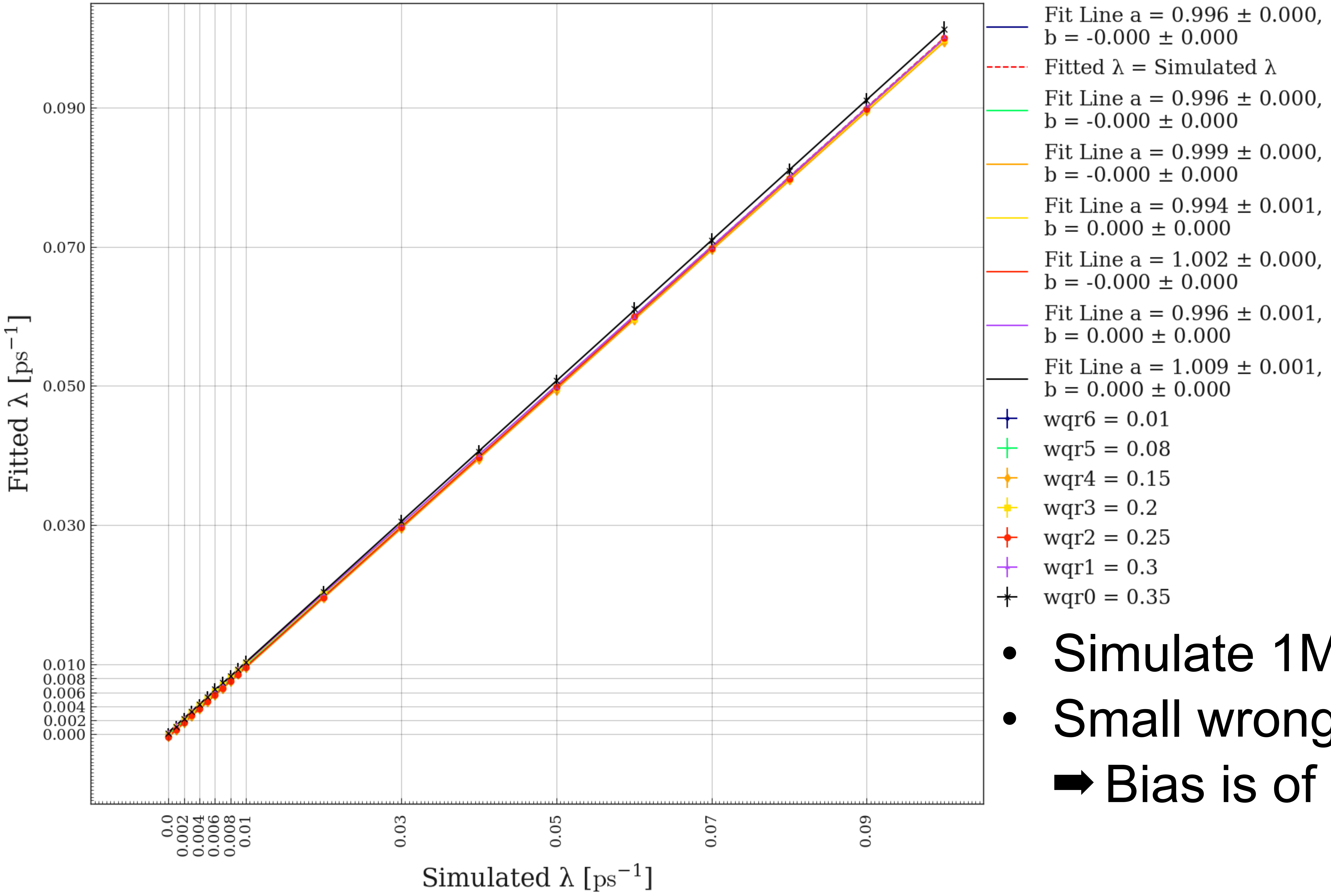
Backup: Bias study



- Simulate 1M events
- Round wrong tag ratio that we get integer sign flips

➡Small effect on the scale of $\sim 1\,\%$

Backup: Bias study



- Simulate 1M events
- Small wrong tag ratio
  ➡ Bias is of statistical nature

Backup: Bias study

100k events Gen $\lambda = 0.002\ \text{ps}^{-1}$		Wrong tagging bins (fraction of data)						
		w_{qr0} (15.5%)	w_{qr1} (15.8%)	w_{qr2} (16.5%)	w_{qr3} (13.4%)	w_{qr4} (11.6%)	w_{qr5} (11.0%)	w_{qr6} (16.2%)
Wrong tag ratio	Normal	0.0372 ± 0.0217	-0.0007 ± 0.0038	0.0069 ± 0.0018	0.0016 ± 0.0013	0.0007 ± 0.0011	0.0022 ± 0.0007	0.0021 ± 0.0003
	All 5%	0.0020 ± 0.0005	0.0021 ± 0.0005	0.0029 ± 0.0005	0.0020 ± 0.0005	0.0015 ± 0.0005	0.0018 ± 0.0005	0.0018 ± 0.0005
	All 25%	0.0028 ± 0.0013	0.0023 ± 0.0013	0.0052 ± 0.0013	0.0024 ± 0.0015	-0.0014 ± 0.0017	0.0019 ± 0.0015	0.0004 ± 0.0014
	All 30%	0.0018 ± 0.0016	0.0010 ± 0.0016	0.0062 ± 0.0017	0.0018 ± 0.0020	-0.0032 ± 0.0023	0.0002 ± 0.0020	-0.0002 ± 0.0019
	All 32%	0.0003 ± 0.0018	0.0004 ± 0.0018	0.0069 ± 0.0018	0.0015 ± 0.0022	-0.0044 ± 0.0026	0.0023 ± 0.0023	0.0002 ± 0.0021
	All 33%	0.0011 ± 0.0019	-0.0001 ± 0.0019	0.0075 ± 0.0019	0.0018 ± 0.0022	-0.0055 ± 0.0028	0.0017 ± 0.0025	0.0000 ± 0.0022
	All 40%	0.0030 ± 0.0034	-0.0001 ± 0.0035	0.0129 ± 0.0031	0.0016 ± 0.0038	-0.0116 ± 0.0049	0.0017 ± 0.0043	0.0012 ± 0.0036

- Small wrong tag ratios observe good fit precision
- Lager wrong tag ratios observe larger fit bias
- Larger wrong tag ratio, bias can switch from positive to negative bias → quantization effect in choosing how many events go into each wrong tag bin?

100k events Gen $\lambda = 0.002\ \text{ps}^{-1}$		Wrong tagging bins (fraction of data)						
		w_{qr0} ($\sim 14.3\%$)	w_{qr1} ($\sim 14.3\%$)	w_{qr2} ($\sim 14.3\%$)	w_{qr3} ($\sim 14.3\%$)	w_{qr4} ($\sim 14.3\%$)	w_{qr5} ($\sim 14.3\%$)	w_{qr6} ($\sim 14.3\%$)
Wrong tag ratio	Normal	0.0003 ± 0.0204	0.0072 ± 0.0043	0.0014 ± 0.0019	0.0011 ± 0.0014	0.0024 ± 0.0009	0.0017 ± 0.0007	0.0019 ± 0.0003
	All 5%	0.0014 ± 0.0005	0.0014 ± 0.0005	0.0020 ± 0.0005	0.0023 ± 0.0005	0.0021 ± 0.0004	0.0019 ± 0.0005	0.0023 ± 0.0005
	All 25%	0.0020 ± 0.0013	0.0033 ± 0.0013	0.0024 ± 0.0012	0.0012 ± 0.0015	0.0043 ± 0.0012	0.0012 ± 0.0014	0.0038 ± 0.0014
	All 30%	0.0030 ± 0.0016	0.0026 ± 0.0018	0.0019 ± 0.0017	0.0018 ± 0.0020	0.0041 ± 0.0017	0.0013 ± 0.0019	0.0044 ± 0.0017
	All 32%	0.0030 ± 0.0018	0.0039 ± 0.0020	0.0016 ± 0.0019	0.0010 ± 0.0023	0.0050 ± 0.0019	0.0012 ± 0.0020	0.0049 ± 0.0019
	All 33%	0.0029 ± 0.0019	0.0041 ± 0.0020	0.0021 ± 0.0020	0.0008 ± 0.0024	0.0050 ± 0.0020	0.0010 ± 0.0021	0.0052 ± 0.0020
	All 40%	0.0029 ± 0.0038	0.0058 ± 0.0039	0.0032 ± 0.0035	0.0019 ± 0.0046	0.0119 ± 0.0035	0.0013 ± 0.0039	0.0075 ± 0.0037

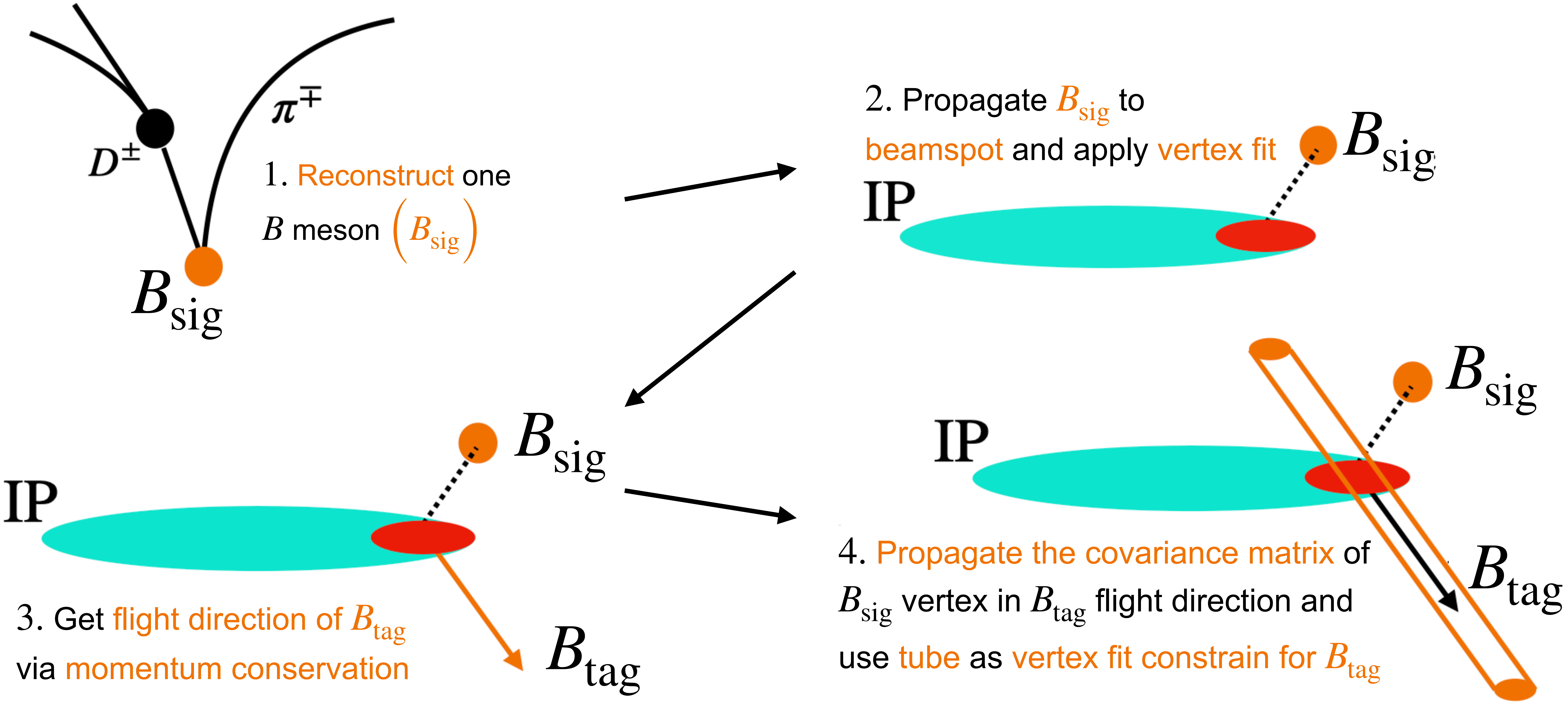
Backup: Bias study

1M events Gen $\lambda = 0.002\ \mathrm{ps}^{-1}$	Wrong tagging bins (fraction of data)						
Wrong tag ratio	w_{qr0} (15.5%)	w_{qr1} (15.8%)	w_{qr2} (16.5%)	w_{qr3} (13.4%)	w_{qr4} (11.6%)	w_{qr5} (11.0%)	w_{qr6} (16.2%)
Normal	0.0073 ± 0.0063	0.0021 ± 0.0014	0.0015 ± 0.0006	0.0021 ± 0.0004	0.0016 ± 0.0003	0.002 ± 0.0002	0.0019 ± 0.0001
All 5%	0.0021 ± 0.0002	0.0021 ± 0.0001	0.0021 ± 0.0002	0.0019 ± 0.0002	0.0016 ± 0.0002	0.0018 ± 0.0002	0.0018 ± 0.0002
All 25%	0.0025 ± 0.0004	0.0018 ± 0.0004	0.0017 ± 0.0004	0.0019 ± 0.0005	0.0014 ± 0.0005	0.0015 ± 0.0005	0.0017 ± 0.0004
All 30%	0.0023 ± 0.0006	0.0022 ± 0.0006	0.0014 ± 0.0005	0.0021 ± 0.0006	0.0015 ± 0.0007	0.0013 ± 0.0007	0.0020 ± 0.0006
All 32%	0.0022 ± 0.0006	0.0019 ± 0.0006	0.0014 ± 0.0006	0.0023 ± 0.0007	0.0014 ± 0.0008	0.0011 ± 0.0008	0.0023 ± 0.0006
All 33%	0.0022 ± 0.0007	0.0019 ± 0.0007	0.0012 ± 0.0006	0.0023 ± 0.0007	0.0016 ± 0.0008	0.0013 ± 0.0008	0.0023 ± 0.0007
All 40%	0.0030 ± 0.0012	0.0021 ± 0.0013	0.0014 ± 0.0010	0.0032 ± 0.0013	0.0031 ± 0.0015	0.0016 ± 0.0013	0.0032 ± 0.0012

1M events Gen $\lambda = 0.002\ \mathrm{ps}^{-1}$	Wrong tagging bins (fraction of data)						
Wrong tag ratio	w_{qr0} ($\sim$ 14.3%)	w_{qr1} ($\sim$ 14.3%)	w_{qr2} ($\sim$ 14.3%)	w_{qr3} ($\sim$ 14.3%)	w_{qr4} ($\sim$ 14.3%)	w_{qr5} ($\sim$ 14.3%)	w_{qr6} ($\sim$ 14.3%)
Normal	0.0022 ± 0.0064	0.0035 ± 0.0014	0.0023 ± 0.0007	0.0021 ± 0.0004	0.0019 ± 0.0003	0.0020 ± 0.0002	0.0019 ± 0.0001
All 5%	0.0020 ± 0.0002	0.0022 ± 0.0002	0.0022 ± 0.0002	0.0021 ± 0.0002	0.0018 ± 0.0002	0.0020 ± 0.0002	0.0019 ± 0.0002
All 25%	0.0019 ± 0.0005	0.0020 ± 0.0004	0.0025 ± 0.0005	0.0020 ± 0.0005	0.0017 ± 0.0005	0.0016 ± 0.0004	0.0020 ± 0.0005
All 30%	0.0017 ± 0.0007	0.0024 ± 0.0005	0.0023 ± 0.0006	0.0022 ± 0.0006	0.0021 ± 0.0006	0.0013 ± 0.0005	0.0022 ± 0.0006
All 32%	0.0020 ± 0.0007	0.0026 ± 0.0006	0.0023 ± 0.0007	0.0018 ± 0.0006	0.0026 ± 0.0007	0.0015 ± 0.0006	0.0023 ± 0.0007
All 33%	0.0021 ± 0.0008	0.0027 ± 0.0007	0.0024 ± 0.0007	0.0016 ± 0.0007	0.0027 ± 0.0008	0.0016 ± 0.0007	0.0022 ± 0.0008
All 40%	0.0018 ± 0.0013	0.0033 ± 0.0012	0.0023 ± 0.0012	0.0013 ± 0.0012	0.0035 ± 0.0013	0.0009 ± 0.0011	0.0025 ± 0.0013

- With more data we observe fit values in same fraction of data agree with each other within its errors
- Bias seems to have statistic nature!

Backup: Btube algorithm



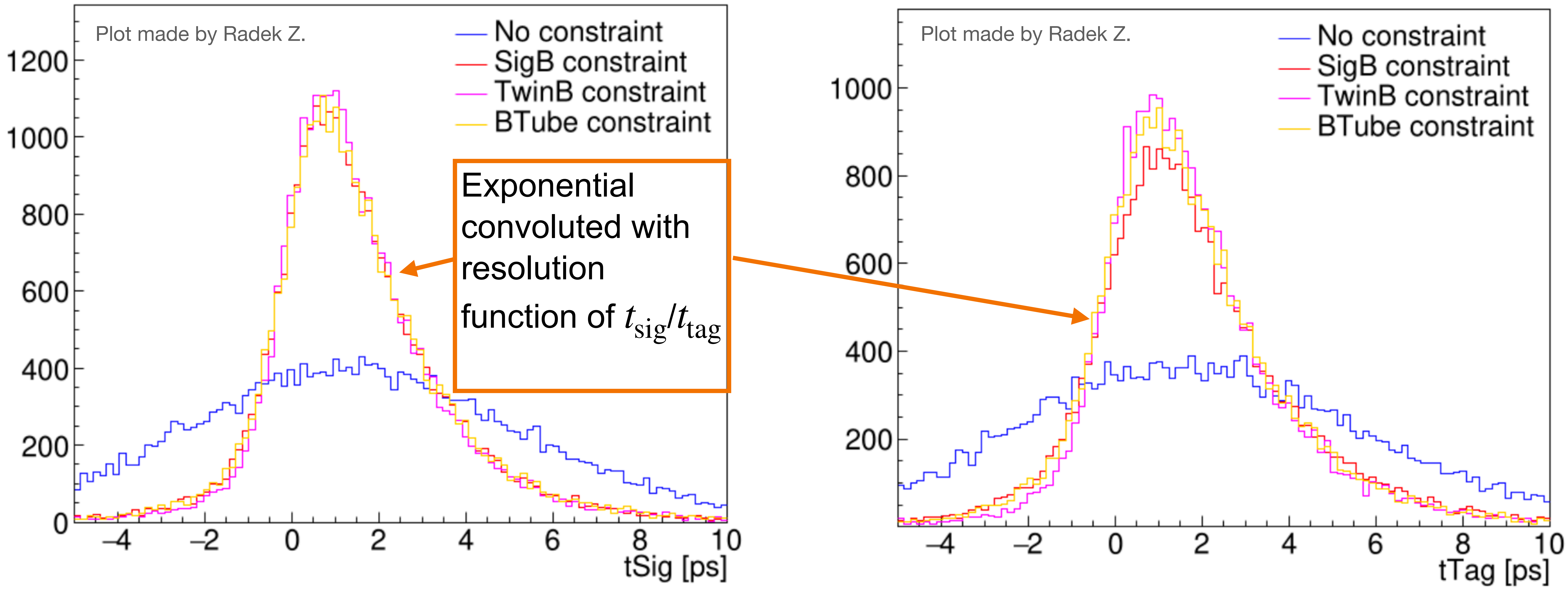
1. Reconstruct one B meson $\left(B_{\text{sig}}\right)$

2. Propagate B_{sig} to beamspot and apply vertex fit

3. Get flight direction of B_{tag} via momentum conservation

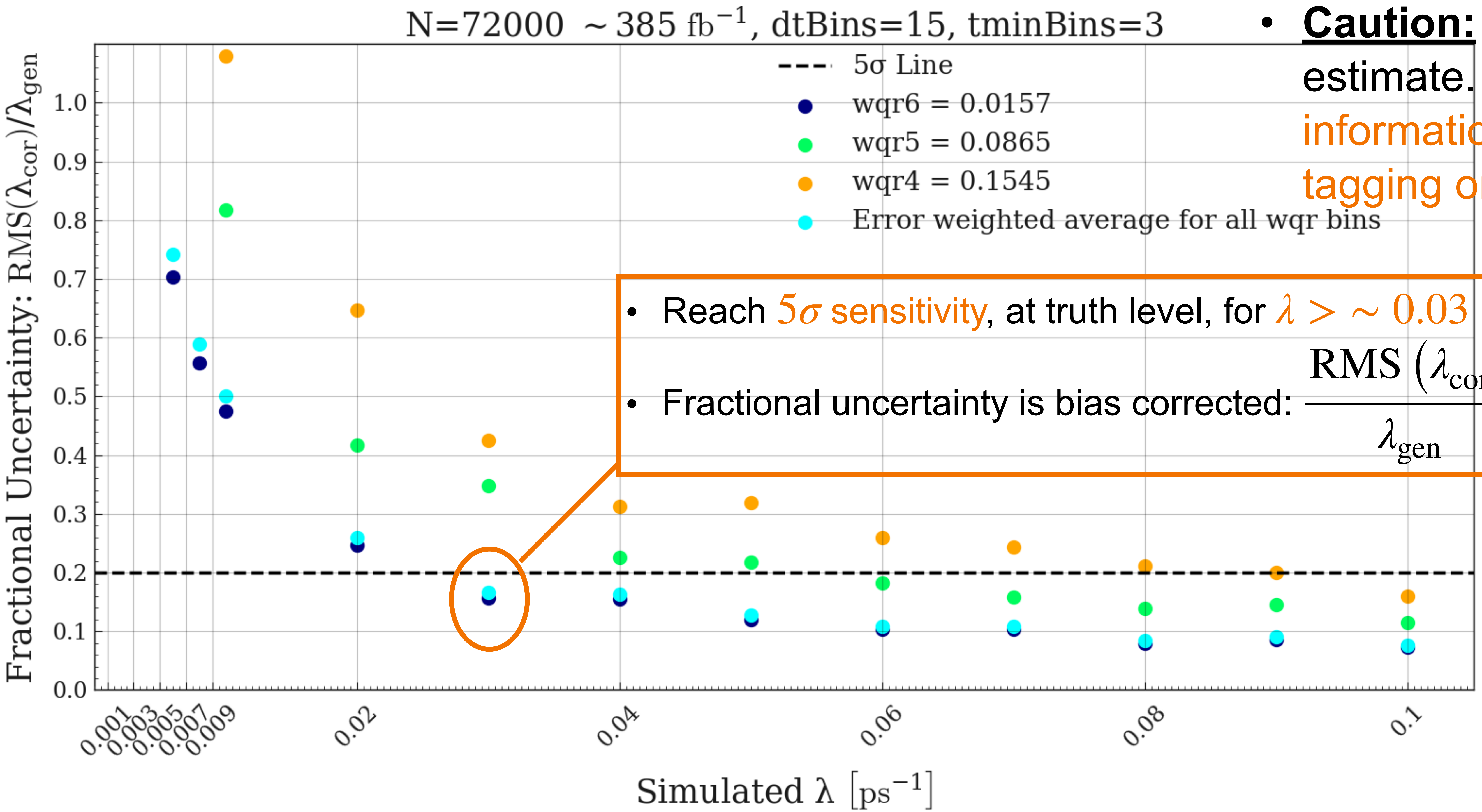
4. Propagate the covariance matrix of B_{sig} vertex in B_{tag} flight direction and use tube as vertex fit constrain for B_{tag}

Backup: Absolute times using the Btube method



- Reconstruction of the absolute times of B_{sig} and B_{tag} is working!

Backup: Sensitivity to Lindblad decoherence parameter λ in binned fitter



- **Caution:** This is a very first estimate. The fitter has no information about wrong tagging or resolutions!

- Reach 5σ sensitivity, at truth level, for $\lambda > \sim 0.03\ \mathrm{ps}^{-1}$
- Fractional uncertainty is bias corrected: $\dfrac{\mathrm{RMS}\left(\lambda_{\mathrm{cor}}\right)}{\lambda_{\mathrm{gen}}} = \dfrac{\mathrm{RMS}\left(\lambda_{\mathrm{fit}}\right)}{\lambda_{\mathrm{gen}} \cdot a}$