Quantum Entanglement in $B^{0(*)}\overline{B}^{0(*)}$ Pairs from $\Upsilon(5S)$ Decays using Belle Monte Carlo Data

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KEKB and Belle

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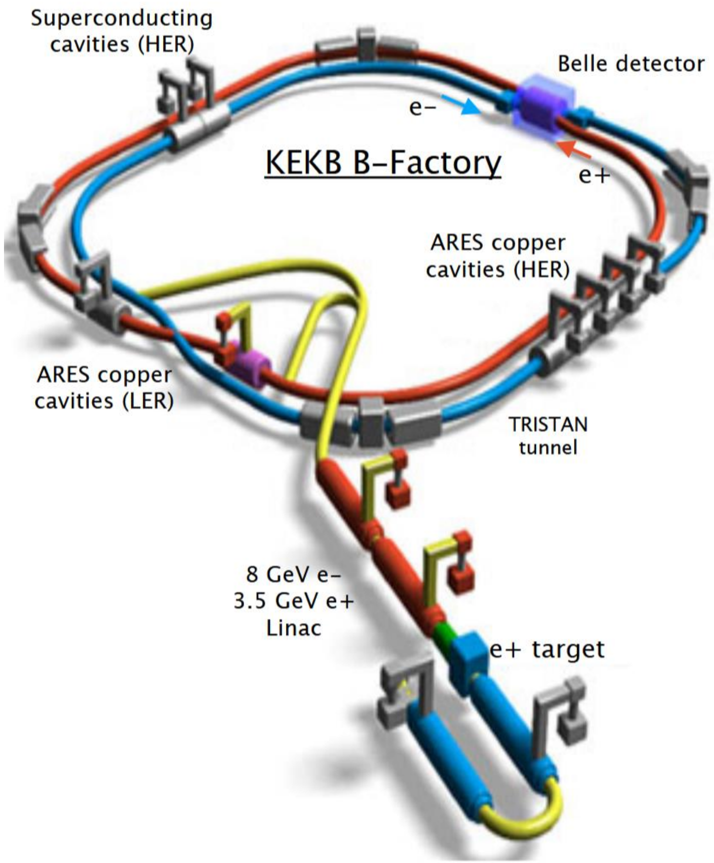
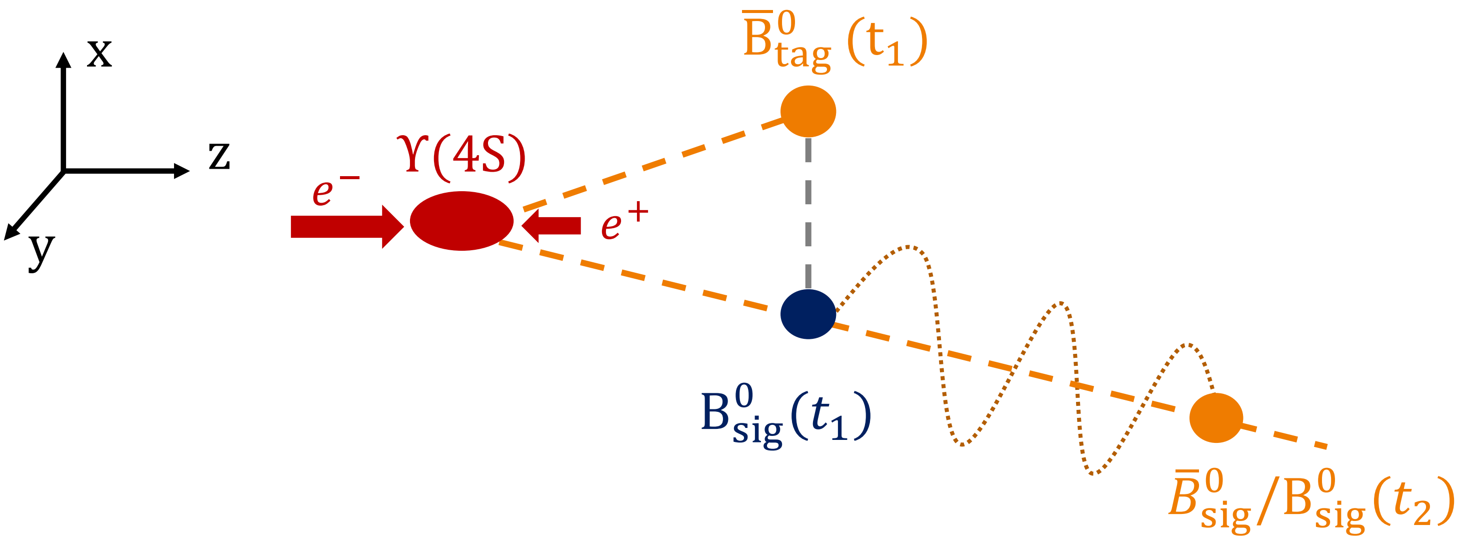


- Belle experiment from 1999-2010
- Located at KEK in Tsukuba, Japan
- High-energy electron-positron collider
- Designed to operate at the $\Upsilon(4S)$ resonance (10.58 GeV) for B-meson studies
  - $\Upsilon(5S)$ (10.89 GeV) was also measured → Only by Belle
- Two-ring asymmetric collider
  - High-energy electron beam
  - Low-energy positron beam
  - Belle detector located at beam collision point

Entanglement in B physics

Entanglement in B physics



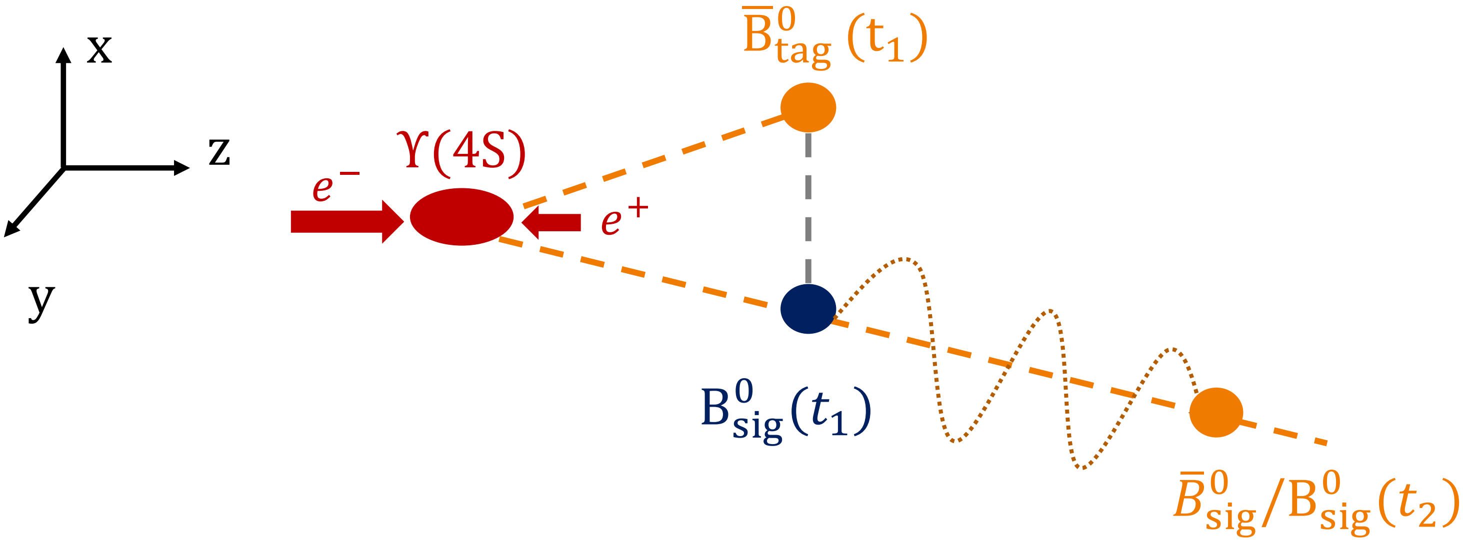
- Quantum phenomenon where two particles become correlated

→ They share a common wavefunction

- B meson pairs after $\Upsilon(5S)$ decay are entangled
- When one B meson decays at time t_1, the shared quantum state collapses

→ The second B meson oscillates independently until its own decay

Entanglement in B physics



- If the B mesons weren‘t entangled, the flavor of the B^0_{sig} at time t_1 couldn‘t be determined
- Measure time dependent Asymmetry $A = \frac{P_{OF} - P_{SF}}{P_{OF} + P_{SF}}$

→ Entanglement property needed for flavor information

Theory

Motivation for $\Upsilon(5S)$

- Rich physics → Production of different quantum states due to $B^{*0} \to \gamma B^0$:
  - $C = -1$: $\frac{1}{\sqrt{2}}\left[\left|B_1^0\right\rangle \otimes \left|\bar{B}_2^0\right\rangle - \left|\bar{B}_1^0\right\rangle \otimes \left|B_2^0\right\rangle\right]$ (antisymmetric wavefunction)
  - $C = +1$: $\frac{1}{\sqrt{2}}\left[\left|B_1^0\right\rangle \otimes \left|\bar{B}_2^0\right\rangle + \left|\bar{B}_1^0\right\rangle \otimes \left|B_2^0\right\rangle\right]$ (symmetric wavefunction)

  → Different forms of entanglement
  - Possible disentangled states arising from mixture of C = ± 1 states

- Wavefunctions for disentangled case:

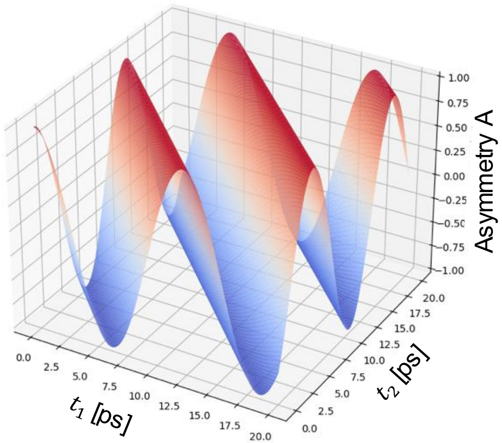
$$|\Psi_1(t_1, t_2)\rangle = [|B^0(t_1)\rangle \otimes |\bar{B}^0(t_2)\rangle] \quad |\Psi_2(t_1, t_2)\rangle = [|\bar{B}^0(t_1)\rangle \otimes |B^0\,(t_2)\rangle]$$

each with probability $1/2$

Entanglement of the $\bar{B}^0 B^0$ pairs after $B^{*0} \to \gamma B^0$ transition

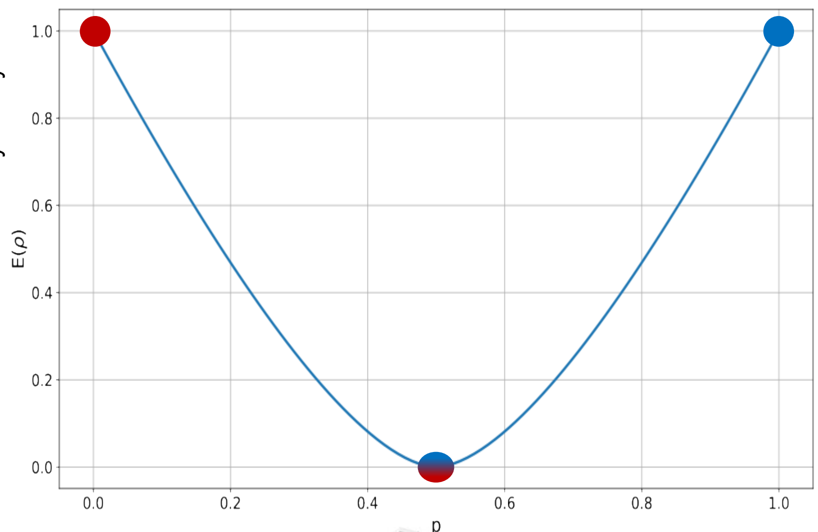
Quantum state	C	Time-dependent PDF
$\Upsilon(5S) \to \bar{B}^0 B^0$	-1	$P^{C=-1} \propto e^{\Gamma(t_1+t_2)}[1 \pm \cos \Delta m(t_1 - t_2)]$
$\Upsilon(5S) \to \bar{B}^{0*} B^{0*}$		
$\Upsilon(5S) \to \bar{B}^0 B^{0*} + c.c.$	+1	$P^{C=+1} \propto e^{\Gamma(t_1+t_2)}[1 \pm \cos \Delta m(t_1 + t_2)]$
Disentangled	–	$P^{dis} \propto \frac{1}{2} e^{\Gamma t_2}(1 \pm \cos(\Delta m t_2)) \cdot \frac{1}{2} e^{\Gamma t_1}(1 \pm \cos(\Delta m t_1))$

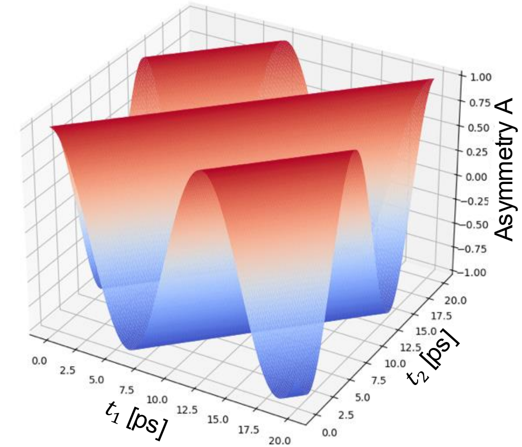
Entanglement of formation $E(\rho)$ (quantum information)



$C = -1$: $A = \cos(\Delta m \Delta t)$

$\Delta t = t_1 - t_2$

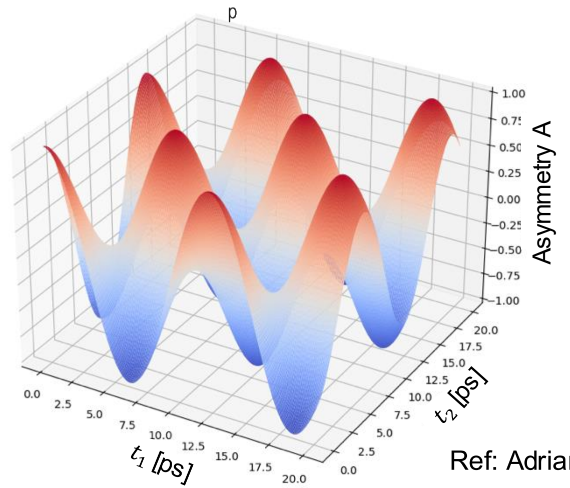




$C = +1$: $A = \cos(\Delta m \Sigma t)$

$\Sigma t = t_1 + t_2$

$$A_{\text{dis}} = \cos(\Delta m t_1)\cos(\Delta m t_2)$$
$$= \frac{1}{2}\cos(\Delta m \Delta t) + \frac{1}{2}\cos(\Delta m \Sigma t) = A_{mix}$$



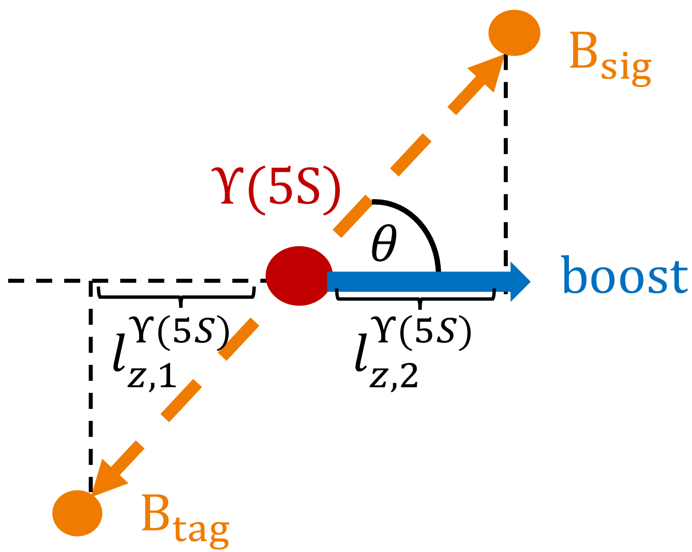
Ref: Adrian Liese

Obtaining time variables

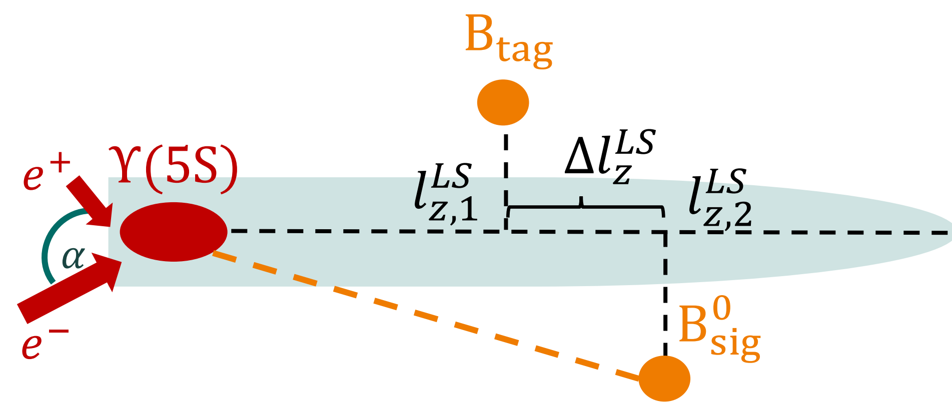
Kinematics

Motivation: Obtaining Δt as well as $t_1 + t_2$

Rest frame $\Upsilon(5S)$:

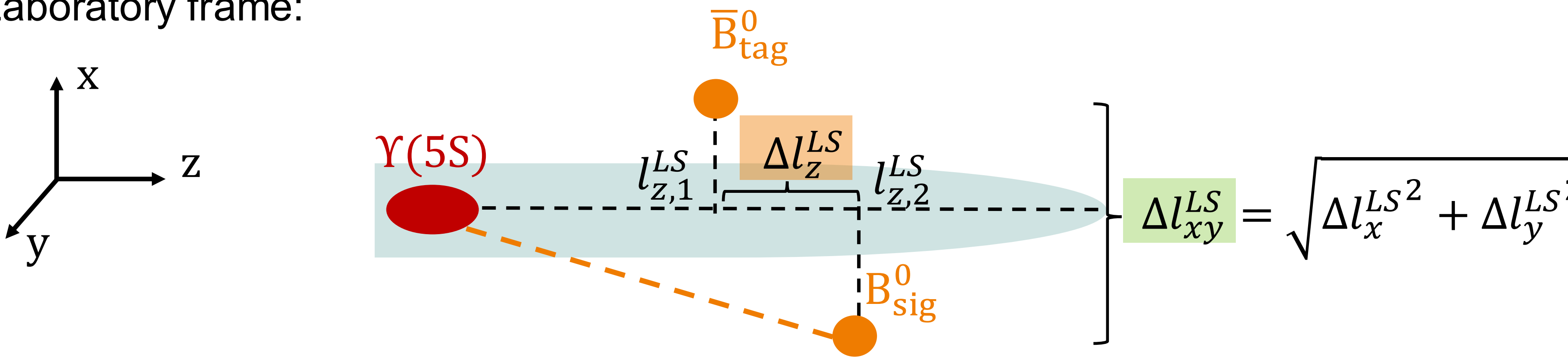


Laboratory frame:



Kinematics: Laboratory frame

Laboratory frame:



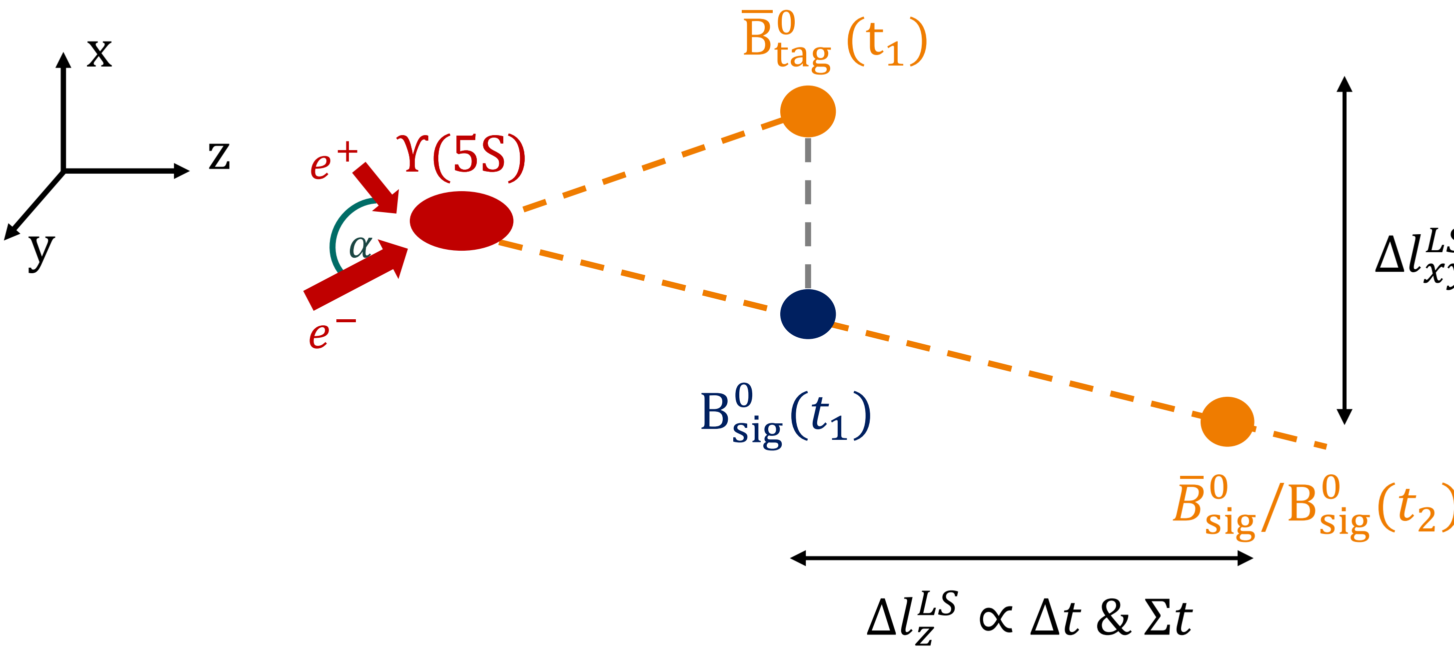
$\beta^B\gamma^B = \frac{p_B}{m(B^0)} = 0.24$: Boost of the B meson in $\Upsilon(5S)$ rest frame

$\beta\gamma = 0.425$: Boost in the LS

$$\Delta t = \frac{\Delta l_z^{LS}}{\gamma^B\gamma\beta c} - \frac{\cos\theta_{cms}}{\sin\theta_{cms}}\frac{\Delta l_{xy}^{LS}}{\gamma^B\gamma\beta c}$$

$$\Sigma t = \frac{\Delta l_{xy}^{LS}}{c\beta^B\gamma^B\sin\theta_{cms}}$$

Goal of the analysis



- Set framework for entanglement studies of the $\Upsilon(5S)$ system
- Reconstruct B^0_{sig} and $\overline{B}^0_{tag}$ vertices

→ Obtain Δt and Σt

- Analyzing entanglement via propagation in time of the B mesons

Analysis strategy

Reconstruction

- Reconstructed decays:

$$B^0 \to D^-\pi^+ \quad D^- \to K^+\pi^-\pi^-$$

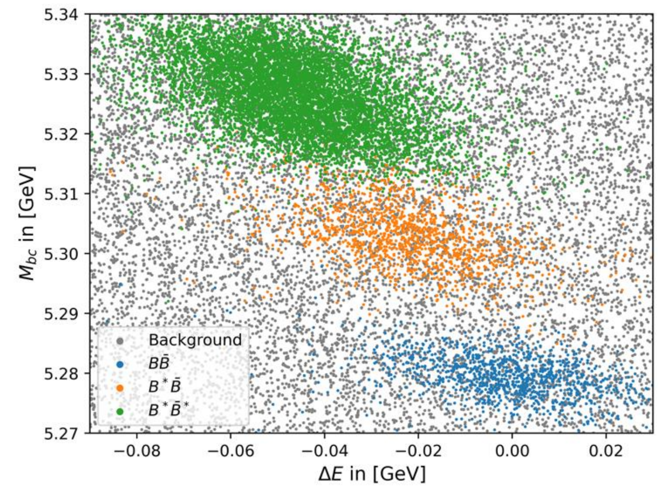
$$B^0 \to D^{*-}\pi^+ \quad D^{*-} \to \bar{D}^0\pi_s^- \quad \bar{D}^0 \to K^+\pi^- \quad \bar{D}^0 \to K^+\pi^-\pi^+\pi^-$$

- Separate between:

$$\Upsilon(5S) \to \bar{B}^0 B^0 \ (5.5^{+1.0}_{-0.9} \pm 0.4\%)$$

$$\Upsilon(5S) \to \bar{B}^{*0} B^0 + c.c. \ (13.7 \pm 1.3 \pm 1.1\%)$$

$$\Upsilon(5S) \to \bar{B}^{*0} B^{*0} \ (37.5^{2.1}_{-1.9} \pm 3.0\%)$$



- Energy of the photon in B rest frame: 45 MeV → cannot be reconstructed
- Goal: Differentiate these channels using M_{bc} and ΔE
  - $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_{B^0}^2}$, $\Delta E = E_{B^0} - E_{\text{beam}}$ momentum and energy conservation

Obtaining variables and simulating MC

Problem:

- No correct Δt and MC flavor of the other B variable available
- Limited amount of Belle $\Upsilon(5S)$ MC

Solution:

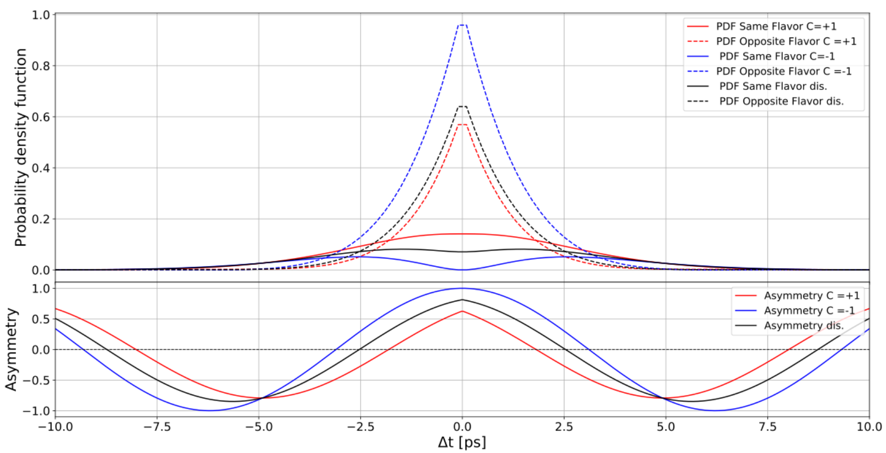
- Generation of new MC samples using EvtGen to model $\Upsilon(5S)$ decays
- Applied Belle detector simulation for detector effects
- Conversion of old Belle data formats to be compatible with new reconstruction software
- Ensured availability of key analysis variables (time, flavor)

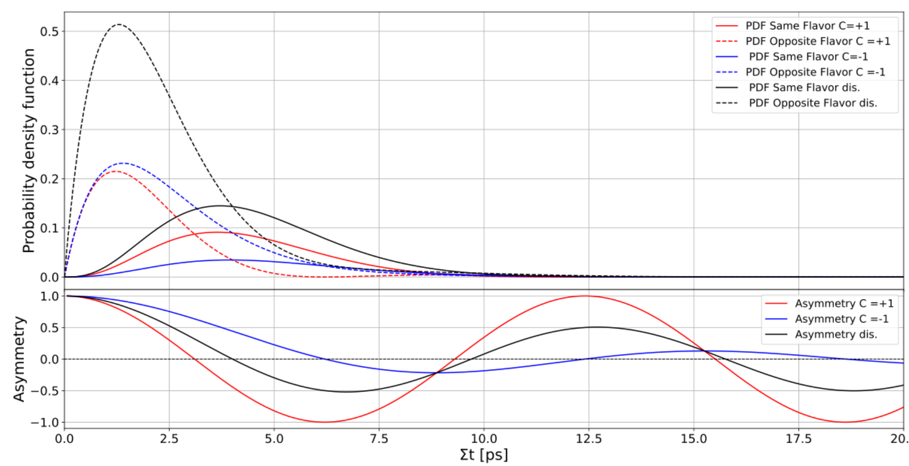
Validating with MC data

- Goal: Fit partial spontaneous disentanglement model (PSD) to the MC data

$$P_{\mathrm{PSD}} = \zeta P_{dis} + (1-\zeta) P_{C=-1}$$

- The model introduces the ζ parameter, quantifying the level of entanglement in the sample
- ζ close to 0 indicates a pure $C = \pm 1$ sample, mixture of both should be interpreted as a disentangled sample → ζ close to 1





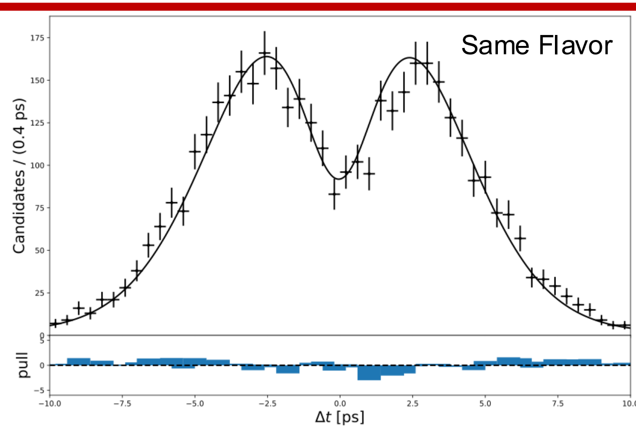
Δt-fit on MC

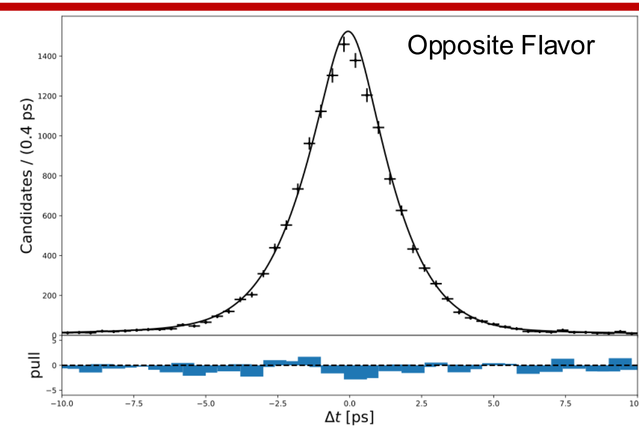
- Implemented $\Upsilon(4S)$ fit-framework to $\Upsilon(5S)$ case
- Detector effects and measurement uncertainties are now included in the fit
- We run **residual fits** using MC-truth Δt versus reconstructed Δt to extract the resolution parameters
- The PDFs are convolved with a **resolution function** to account for detector response
- The resolution function consists of:
  - **Core** component: 2 Gaussians + 1 Gaussian with exponential tails
  - **Outlier (OL)** component: 1 wide Gaussian

$$\mathrm{R}(\delta\Delta t;\sigma_{\Delta t}) = (1-\mathrm{f}_{OL})\mathrm{R}_{\mathrm{core}}(\delta\Delta t;\sigma_{\Delta t}) + \mathrm{f}_{\mathrm{OL}}\mathrm{R}_{\mathrm{OL}}(\delta\Delta t;\sigma_{\Delta t})$$

Δt-fit on MC: $C = -1$ case

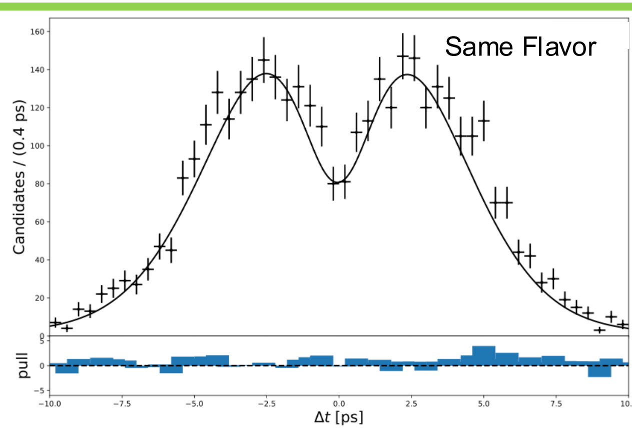
Δt distribution for $C = -1$ entangled states

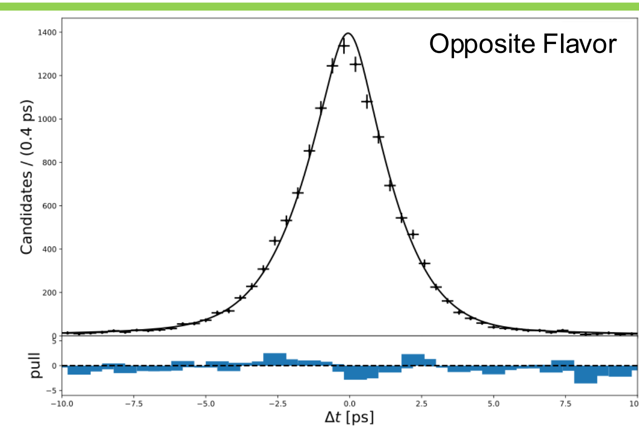




$\zeta = 0.054 \pm 0.0128$

$\Upsilon(5S) \to B^0\overline{B}^0$

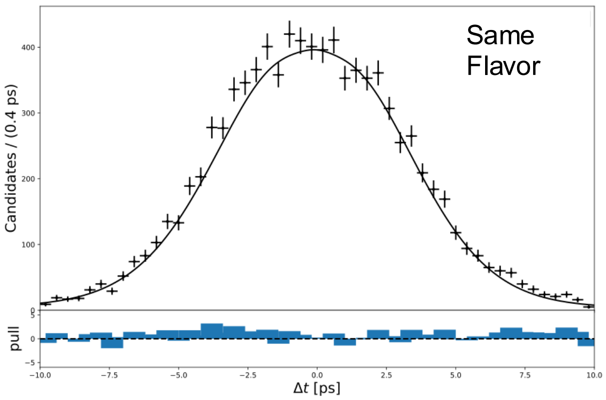


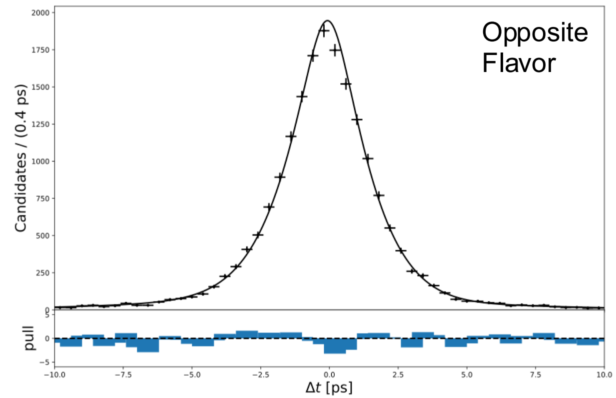


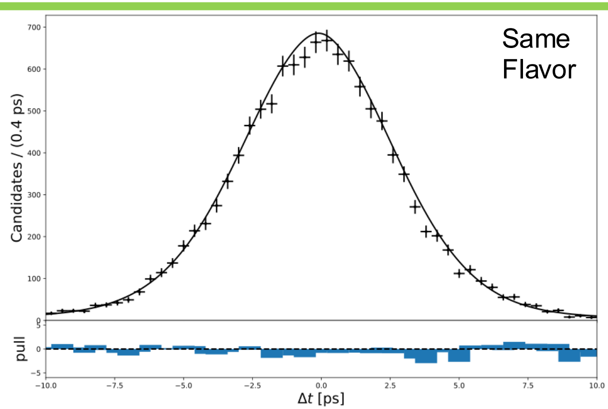
$\zeta = 0.0493 \pm 0.0139$

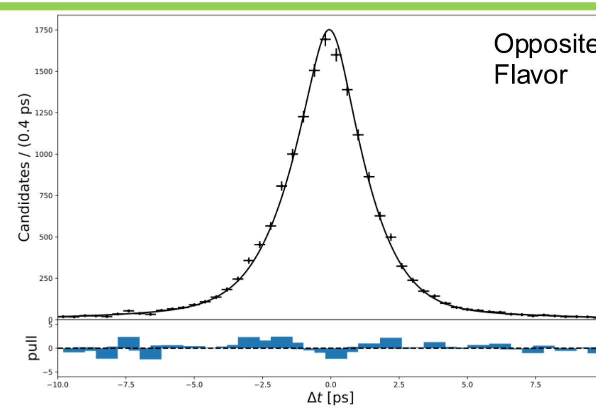
$\Upsilon(5S) \to B^{*0}\overline{B}^{*0}$

Δt-fit on MC









Disentangled case

$\zeta = 1.0155 \pm 0.0150$

50/50 mixture of $C = \pm 1$ entangled states

$C = +1$ case

$\zeta' = 0.0037 \pm 0.0149$

$\Upsilon(5S) \rightarrow B^0 \bar{B}^{*0} + c.c.$

Conclusion

- Studied entanglement of neutral B-meson pairs produced at the $\Upsilon(5S)$ resonance
- Analyzed quantum numbers of the different decay channels
- Derived symmetric ($C = +1$) and antisymmetric ($C = -1$) wavefunctions and computed time-dependent probabilities and asymmetries to distinguish $C = \pm 1$ and disentangled states
- Developed reconstruction of Δt and Σt
- Generated MC samples, created disentangled samples by mixing $C = \pm 1$ states
- Adapted the $\Upsilon(4S)$ fit-framework to $\Upsilon(5S)$

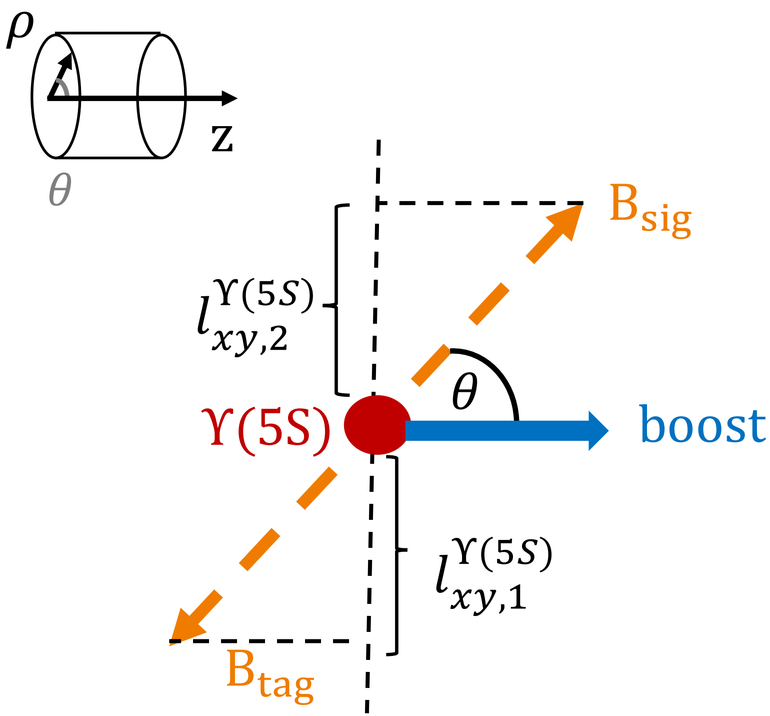
Outlook:

- Include Σt dependence $\rightarrow$ full 2D fit in $(\Delta t, \Sigma t)$

Backup

Kinematics: X-Y-direction

Restframe $\Upsilon(5S)$:



$$l_{xy,2}^{\Upsilon(5S)} = \beta^B c t_2^{\Upsilon(5S)} \sin\theta \qquad t_{xy,1/2}^{\Upsilon(5S)} = \gamma^B t_{1/2}^B$$

$$l_{xy,1}^{\Upsilon(5S)} = -\beta^B c t_1^{\Upsilon(5S)} \sin\theta$$

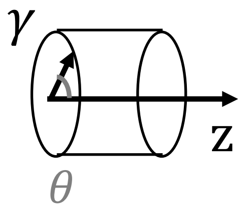
$$l_{xy,1}^{\Upsilon(5S)} = -\beta^B c \gamma^B t_1^{\mathrm{B}} \sin\theta$$

$$l_{xy,2}^{\Upsilon(5S)} = \beta^B c \gamma^B t_2^{\mathrm{B}} \sin\theta$$

$$\Delta l_{xy,2}^{\Upsilon(5S)} = \Delta l_{xy}^{LS} = c\beta^B \gamma^B (t_2^{\mathrm{B}} + t_1^{\mathrm{B}}) \sin\theta$$

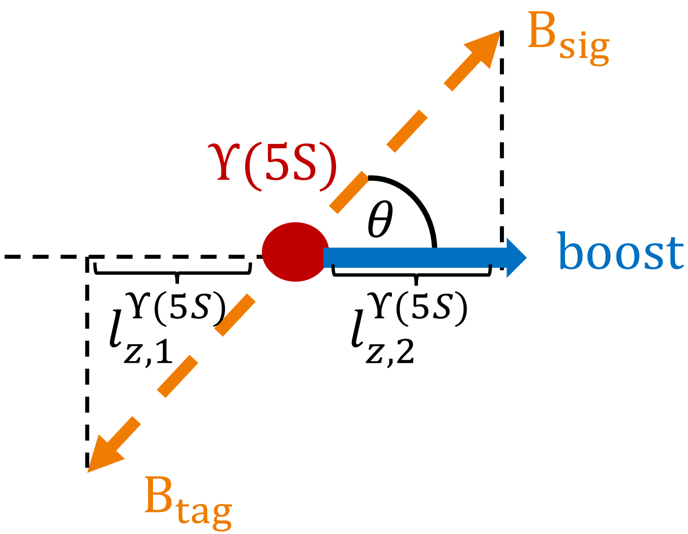
Kinematics: Z direction

Restframe $\Upsilon(5S)$:



Motivation: Obtaining Δt as well as $t_1 + t_2$

$\beta^B \gamma^B = \frac{p_B}{m(\mathrm{B}^0)} = 0.24$: Boost of the B meson in $\Upsilon(5S)$ restframe



$$l_{z,1}^{\Upsilon(5S)} = -\beta^B c t_1^{\Upsilon(5S)} \cos\theta_{cms}$$

$$l_{z,2}^{\Upsilon(5S)} = \beta^B c t_2^{\Upsilon(5S)} \cos\theta_{cms}$$

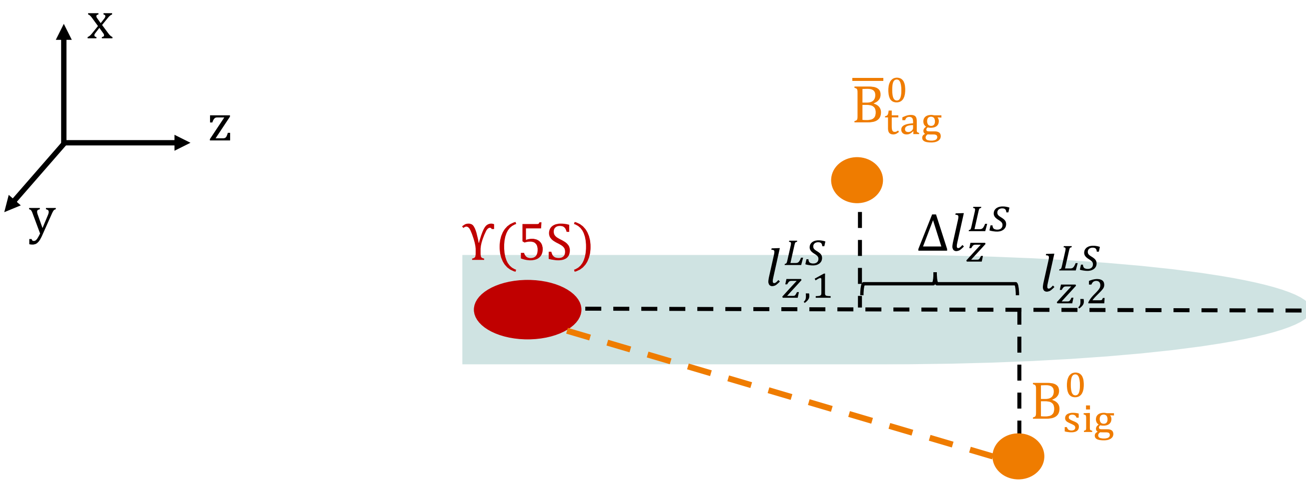
$$t_{z,1/2}^{\Upsilon(5S)} = \gamma^B t_{1/2}^B$$

$$l_{z,1}^{\Upsilon(5S)} = -\beta^B c \gamma^B t_1^{\mathrm{B}} \cos\theta$$

$$l_{z,2}^{\Upsilon(5S)} = \beta^B c \gamma^B t_2^{\mathrm{B}} \cos\theta$$

Kinematics: Z direction

Laboratory frame: $\gamma\beta = 0.425$: boost on particles in LS



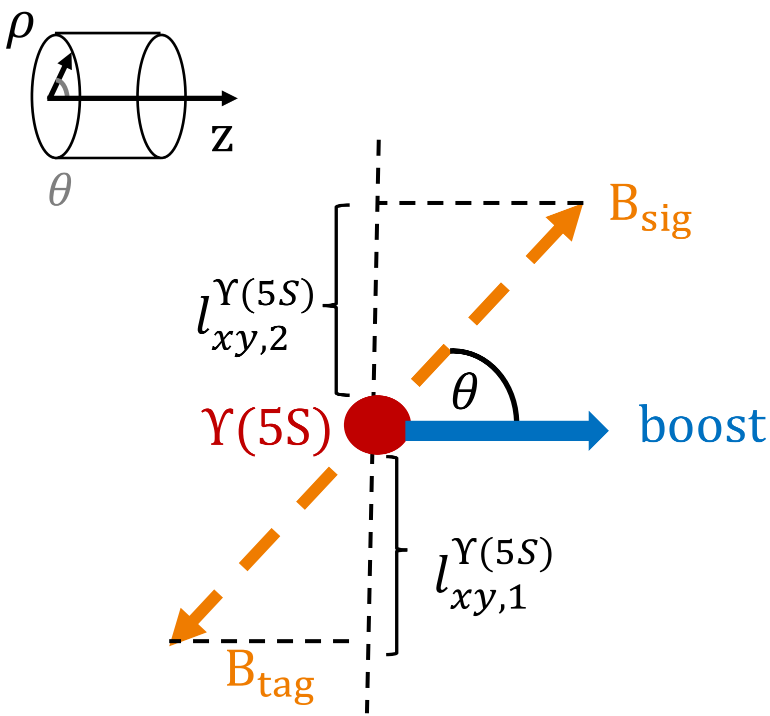
$$l^{\mathrm{LS}}_{z,1} = \gamma(-c\beta^B\gamma^B t^B_1 \cos\theta_{cms} + \beta c\gamma^B t^B_1)$$

$$l^{\mathrm{LS}}_{z,2} = \gamma(c\beta^B\gamma^B t^B_2 \cos\theta_{cms} + \beta c\gamma^B t^B_2)$$

$$\Delta l^{LS}_{z} = \gamma\gamma^B\beta^B c(t^B_2 + t^B_1)\cos\theta_{cms} + \gamma^B\gamma\beta c(t^B_2 - t^B_1)$$

Kinematics: x-y-direction

Restframe $\Upsilon(5S)$:



$$l_{xy,2}^{\Upsilon(5S)} = \beta^B c t_2^{\Upsilon(5S)} \sin\theta_{cms} \qquad t_{xy,1/2}^{\Upsilon(5S)} = \gamma^B t_{1/2}^B$$

$$l_{xy,1}^{\Upsilon(5S)} = -\beta^B c t_1^{\Upsilon(5S)} \sin\theta_{cms}$$

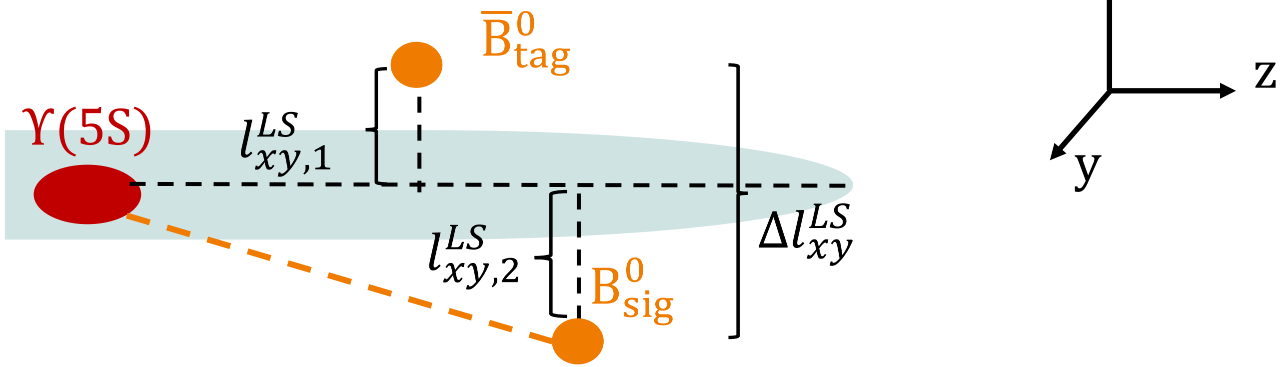
$$l_{xy,1}^{\Upsilon(5S)} = -\beta^B c\gamma^B t_1^{\mathrm{B}} \sin\theta_{cms}$$

$$l_{xy,2}^{\Upsilon(5S)} = \beta^B c\gamma^B t_2^{\mathrm{B}} \sin\theta_{cms}$$

Kinematics: x-y-direction

Laboratory frame:

- Only boost in z-direction
  → No contribution in x- and y- direction



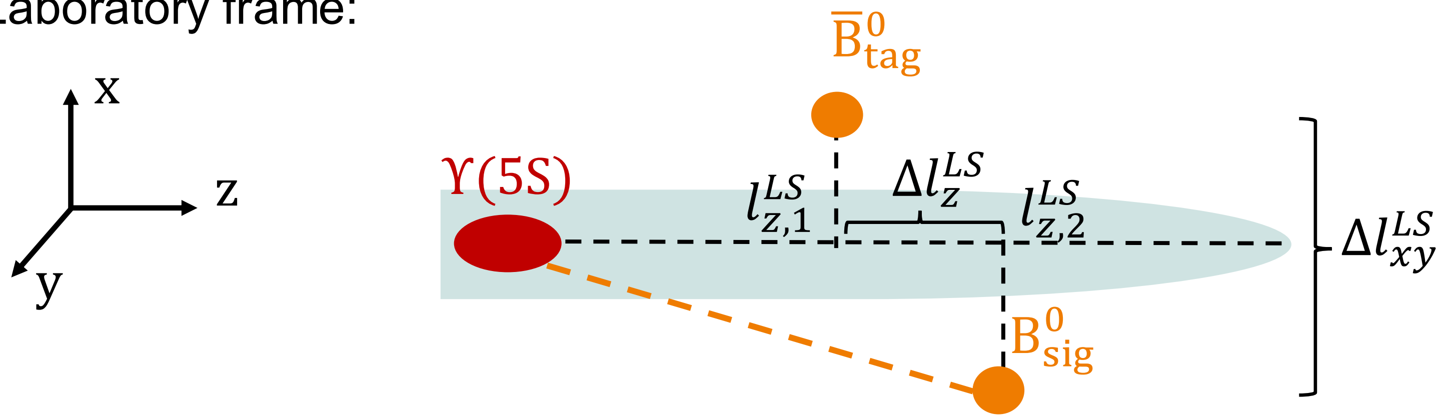
$$l^{\mathrm{LS}}_{xy,1} = -c\beta^B\gamma^B t^{\mathrm{B}}_1 \sin\theta_{cms}$$

$$l^{\mathrm{LS}}_{xy,2} = c\beta^B\gamma^B t^{\mathrm{B}}_2 \sin\theta_{cms}$$

$$\Delta l^{LS}_{xy} = c\beta^B\,\gamma^B (t^{\mathrm{B}}_2 + t^{\mathrm{B}}_1) \sin\theta_{cms}$$

Kinematics: Laboratory frame

Laboratory frame:



$$l^{LS}_{z,1} = \gamma(-c\beta^B\gamma^B t^B_1 \cos\theta + \beta c\gamma^B t^B_1)$$

$$l^{LS}_{z,2} = \gamma(c\beta^B\gamma^B t^B_2 \cos\theta + \beta c\gamma^B t^B_2)$$

$$l^{\Upsilon(5S)}_{xy,2} = \beta^B c t^{\Upsilon(5S)}_2 \sin\theta$$

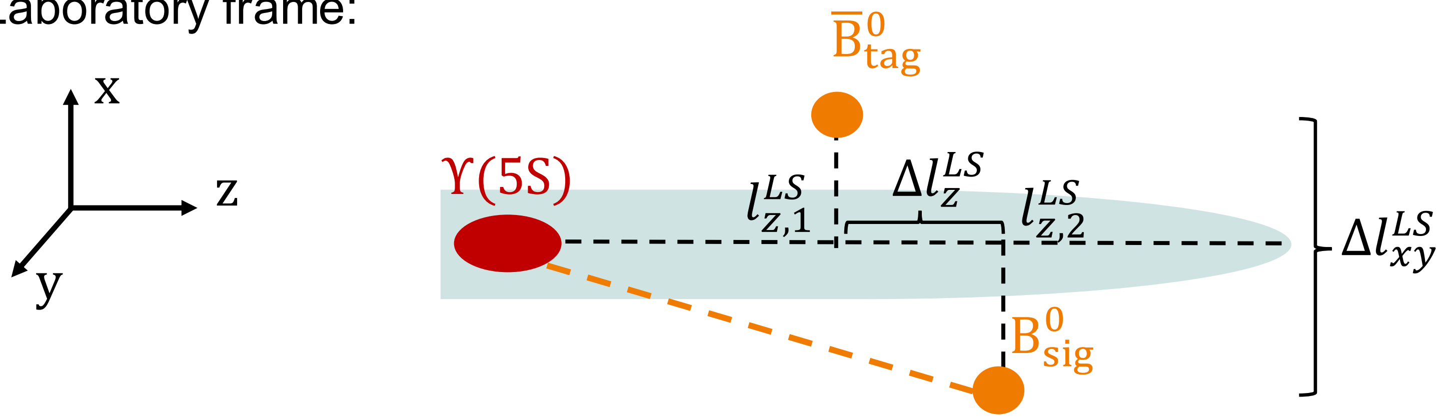
$$l^{\Upsilon(5S)}_{xy,1} = -\beta^B c t^{\Upsilon(5S)}_1 \sin\theta$$

$$\Delta l^{LS}_z = \gamma\gamma^B\beta^B c(t^B_2 + t^B_1)\cos\theta + \gamma^B\gamma\beta c(t^B_2 - t^B_1)$$

$$\Delta l^{LS}_{xy} = c\beta^B\gamma^B(t^B_2 + t^B_1)\sin\theta$$ (no contribution in xy-direction)

Kinematics: Laboratory frame

Laboratory frame:



$\beta^B\gamma^B = \frac{p_B}{m(B^0)} = 0.24$: Boost of the B meson in $\Upsilon(5S)$ restframe

$\beta\gamma = 0.425$: Boost in the LS

$$\Delta l_z^{LS} = \gamma\gamma^B\beta^B c(t_2^B + t_1^B)\cos\theta_{cms} + \gamma^B\gamma\beta c(t_2^B - t_1^B)$$

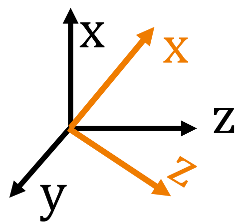
$$\Delta l_{xy}^{LS} = c\beta^B\gamma^B(t_2^B + t_1^B)\sin\theta_{cms}$$

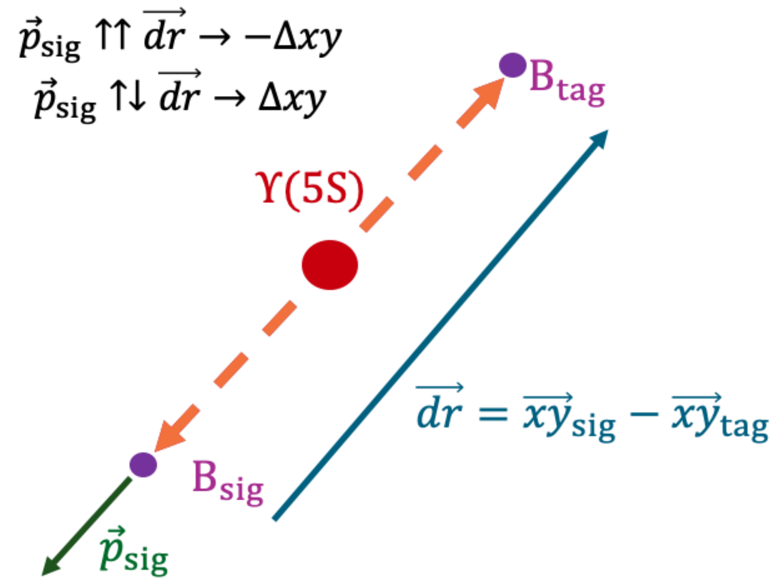
Kinematics: Note on deriving Δl_z and Δl_{xy}

Laboratory frame:

- Rotate laboratory frame
  by $\alpha = 11$ mrad (beam crossing)

→ Boost purely along the **z-direction**





$$\Delta l_z^{LS} = \cos\alpha\, \Delta l_z^{\mathrm{measured}} + \sin\alpha\, \Delta l_x^{\mathrm{measured}}$$

$$\Delta l_x^{LS} = \cos\alpha\, \Delta l_x^{\mathrm{measured}} - \sin\alpha\, \Delta l_z^{\mathrm{measured}}$$

$$\Delta l_{xy}^{LS} = \pm\sqrt{{\Delta l_x^{LS}}^2 + {\Delta l_y^{LS}}^2}$$

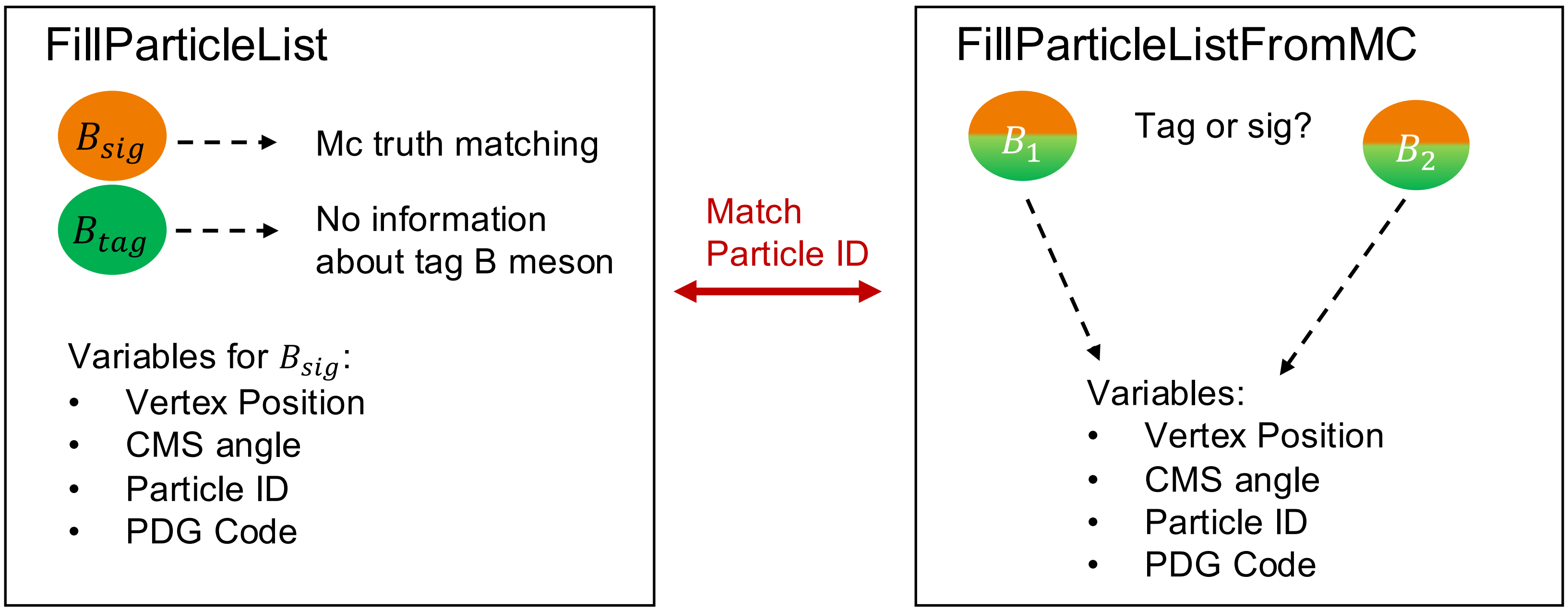
Obtaining variables

Problem:

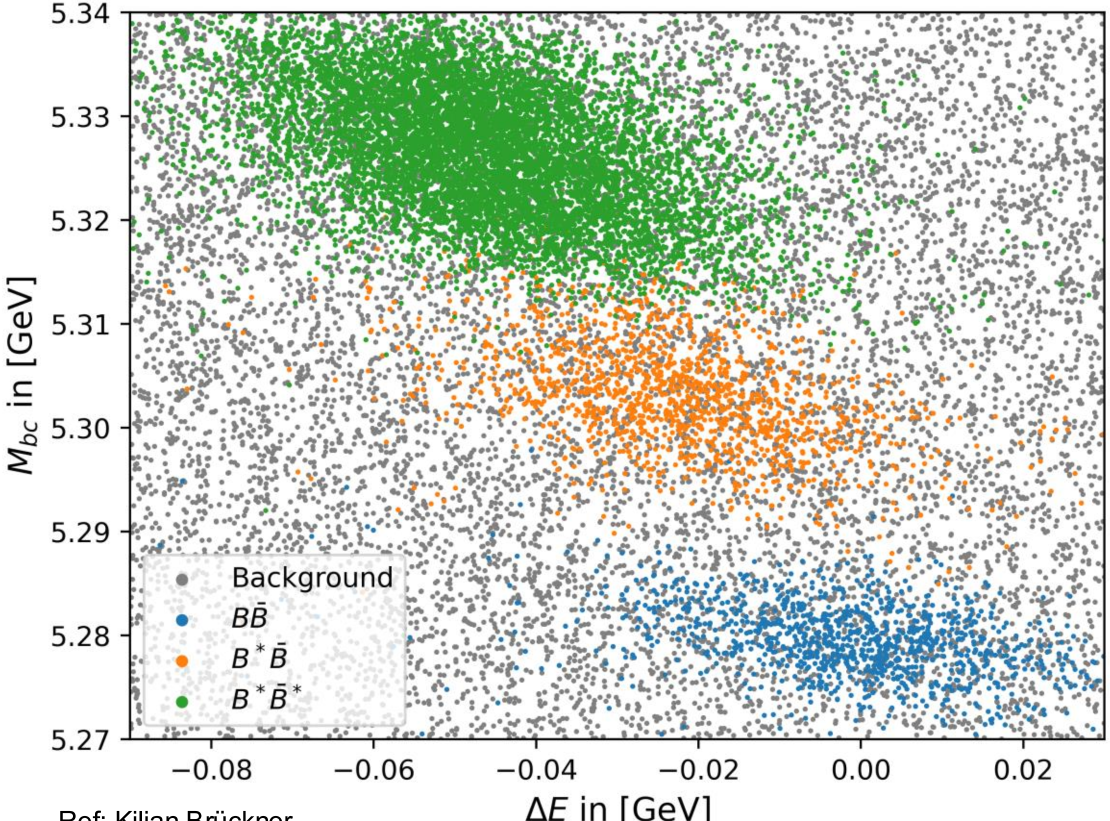
- No correct Δt and MC flavor of the other B variable available

Solution:

- In addition to the reconstructed B meson list, also extract B mesons from FillParticleListFromMC



Separation



Ref: Kilian Brückner

- Attempting to improve the separation using a BDT
- Background consists of:
  - Combinatorial background
  - Continuum background

true decay	prediction $B\bar{B}$	prediction $B^*\bar{B}$	prediction $B^*\bar{B}^*$	prediction background	Total:
$B\bar{B}$	214	2	0	48	264
$B^*\bar{B}$	1	586	25	97	709
$B^*\bar{B}^*$	0	9	1821	129	1959
Background	124	238	455	1736	2553
Total:	339	835	2301	2010	5485

Table 5.5 Events of the test sample separated by the BDT with p_t

Entanglement of formation $E(\rho)$ (quantum information)

Consider 2-qubit state in 'magic basis':

$$|e_1\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle) \quad |e_2\rangle = \frac{i}{\sqrt{2}}(|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle)$$
$$|e_3\rangle = \frac{i}{\sqrt{2}}(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle) \quad |e_4\rangle = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle)$$

- Density Matrix: $\rho = p_i \Sigma_i |e_i\rangle\langle e_i|$
- Spin flip operator: $\tilde{\rho}_{mb} = (\sigma_y \otimes \sigma_y)\rho^*_{sb}(\sigma_y \otimes \sigma_y) = \rho_{mb}$
- Hermitian Operator $R = \sqrt{\sqrt{\rho}\rho^*\sqrt{\rho}}$ with eigenvalues $\lambda_i \;\; i \in \{1,2,3,4\}$
- Concurrence $C(\rho)\,\max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\}$:
  - measure of entanglement
  - System is fully disentangled (C = 0) or max. entangled (C = 1)
- Entanglement of formation $E(\rho) = H\left(\frac{1+\sqrt{1-C(\rho)^2}}{2}\right)$
- Where $H = -x\log_2 x - (1-x)\log_2 1 - x$ is the binary Entropy function

Entanglement of formation $E(\rho)$ (quantum information)

Form of measuring entanglement in a system:

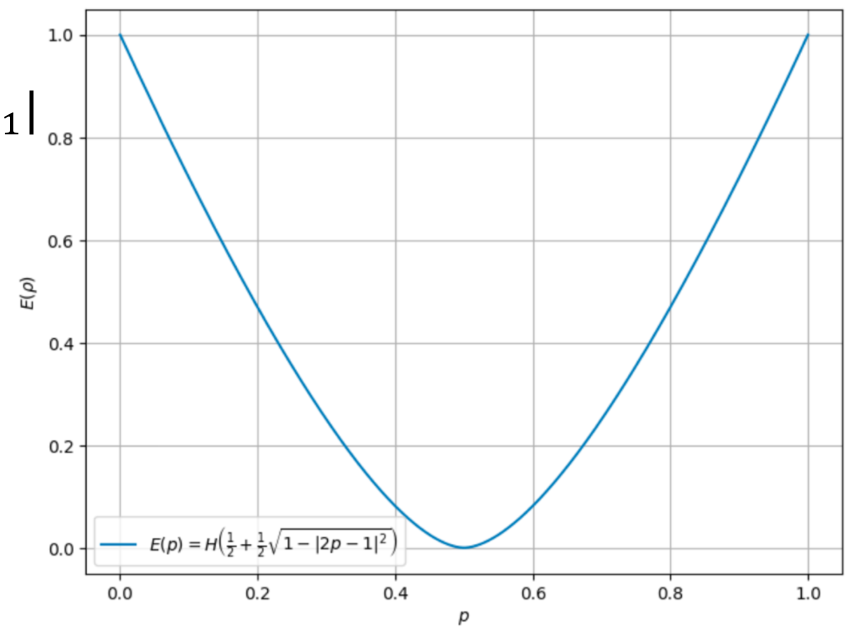
Concurrence $\mathfrak{C}(\rho)$ and Entanglement of formation $E(\rho)$:

- Measure of entanglement
- System is fully disentangled ($\mathfrak{C}, E = 0$) or max. entangled ($\mathfrak{C}, E = 1$)

Our case:

- $\rho = p|\psi_{C=+1}\rangle\langle\psi_{C=+1}| + (1-p)|\psi_{C=-1}\rangle\langle\psi_{C=-1}|$
- $\mathfrak{C} \; = |2p-1|$
- $E(p) = H\left(\frac{1}{2} + \frac{1}{2}\sqrt{1-|2p-1|}\right)$

Ref: Sam A. Hill & William K. Wootters
arXiv:quant-ph/9703041



Ref: Adrian Liese

Entanglement of formation $E(\rho)$

- In our case:

$$|e_3\rangle = \frac{1}{\sqrt{2}}\left[\left|B_1^0\right\rangle \otimes \left|\bar{B}_2^0\right\rangle + \left|\bar{B}_1^0\right\rangle \otimes \left|B_2^0\right\rangle\right] = |\Psi_{C=+1}\rangle$$

$$|e_4\rangle = \frac{1}{\sqrt{2}}\left[\left|B_1^0\right\rangle \otimes \left|\bar{B}_2^0\right\rangle - \left|\bar{B}_1^0\right\rangle \otimes \left|B_2^0\right\rangle\right] = |\Psi_{C=-1}\rangle$$

- $\rho = p|e_3\rangle\langle e_3| + (1-p)|e_4\rangle\langle e_4|$ (mixture)
- $C = \max\{0, \max(p, 1-p) - \min(p, 1-p)\} = |2p-1|$
- $E(p) = H\left(\frac{1}{2} + \frac{1}{2}\sqrt{1-|2p-1|}\right)$

p	$C(p)$	$E(p)$
0	1	$H(1/2) = 1$
1	1	$H(1/2) = 1$
½	0	$H(1) = 0$

Asymmetry

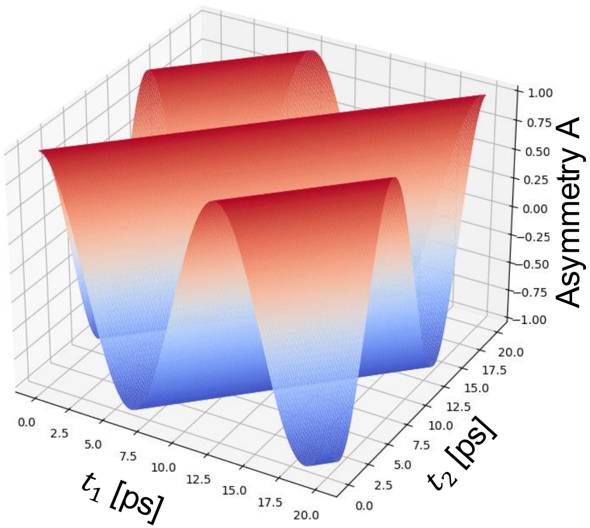
Entangled case

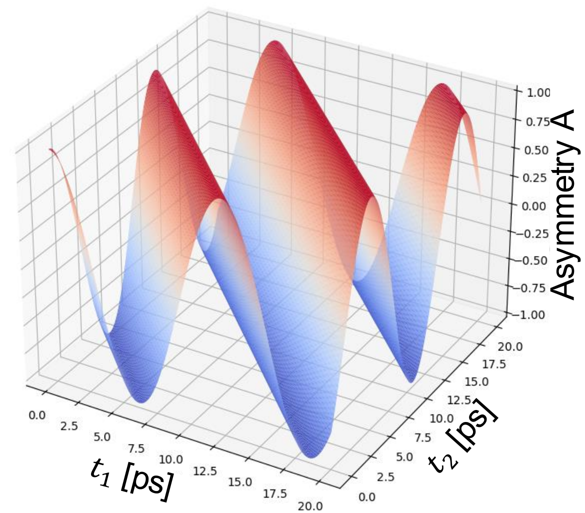
$$C = \pm 1$$

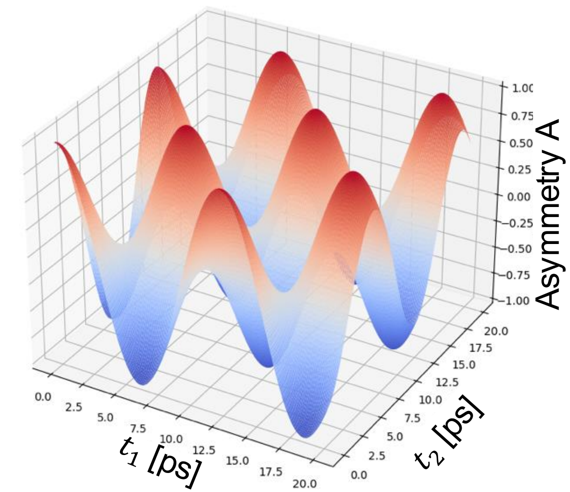
$$A = \frac{P_{OF} - P_{SF}}{P_{SF} + P_{OF}} = \cos \Delta m (t_1 \pm t_2)$$

Disentangled case:

$$A(t_1, t_2) = \cos \Delta m t_1 \cos \Delta m t_2$$







Ref: Adrian Liese

Problems with Signal MC

- Generating with basf:
  - mcproduzh package → simulation based on evtgen and gsim
  - Procedure for evtgen:

```
./runEvtgen nBB.txt [decaytablefile.dec] [evtgenModuleParamatersConfigFile] [TotalNumberOfEvents]
[EventsPerJob]
```

  - Problem with evtgen run scripts:
    - Able to generate $\overline{B}^0 B^0$ and $\overline{B}^{*0} B^0 + c.c.$ events but not $\overline{B}^{*0} B^{*0}$
    - Reason: CMS energy didn‘t correspond to the $\Upsilon(5S)$ CMS energy

    → Not enough energy to produce $\overline{B}^{*0} B^{*0}$ events

    → Tried to set the beam energies correctly in config file for $\Upsilon(5S)$

    → Did not work

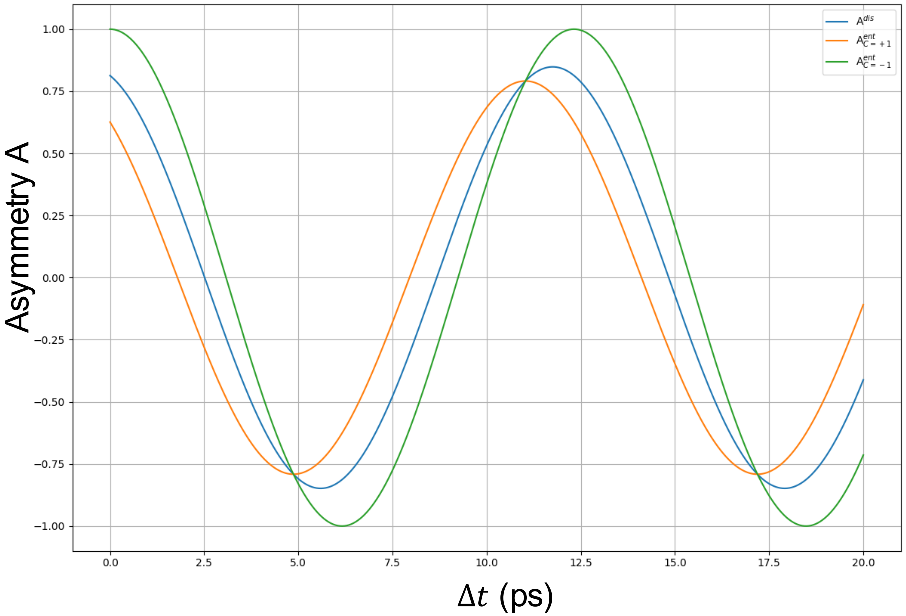
Problems with Signal MC

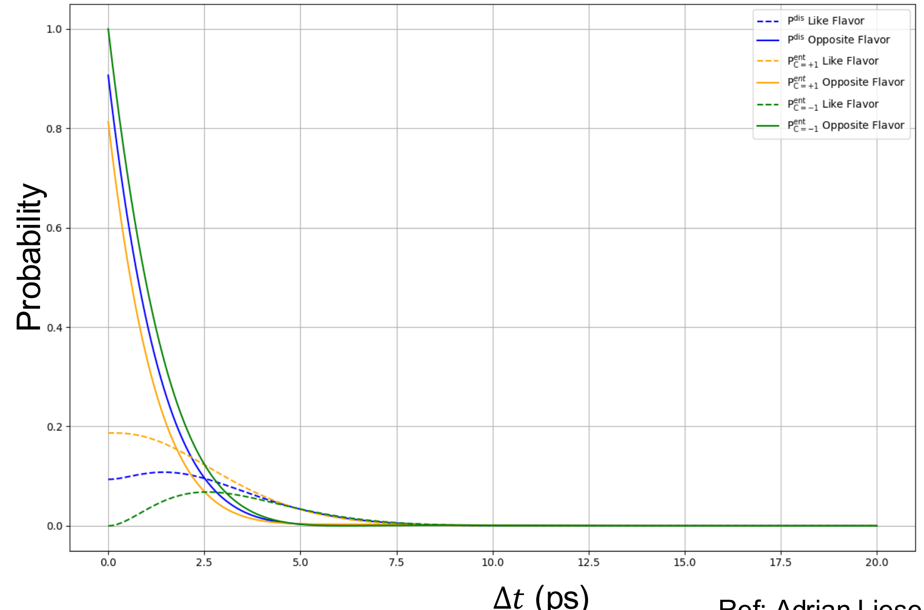
- Generating with basf2:
  - Idea: generate events with basf2 and use Belle detector simulation
  - Model: PHSP_BB_MIX
    - New particles: B0heavy B0long → propagate
    - Requires setting B0 lifetime to 0
    → This should be done in the evt.pdl
  - Problem:
    - EvtGen sources a central PDL for predefined particles
    - The B meson lifetime defined in the local evt.pdl is overwritten
    → Incorrect time evolution of the B mesons
  - Temporary solution: Define a new particle B0_test with zero lifetime
    → No overwritting

Integrating over t_1

For comparison: Method used at $\Upsilon(4S)$ analysis

- Only measuring Δt instead of t_1 and t_2
  → Need to integrate over time
- As a result the time integrated probabilities and the asymmetries depend only on Δt





Ref: Adrian Liese

→ Less differentiation power

Overview of Belle $\Upsilon(5S)$ Data and Simulation

- Lorentz boost at Belle $\beta\gamma = 0.425$
- Integrated luminosity on-resonance $\Upsilon(5S)$ $L = 121\ \mathrm{fb}^{-1}$
- Generic Monte Carlo on Belle $\Upsilon(5S)$ data
  - In total six times more MC data than real data ($L = 726\ \mathrm{fb}^{-1}$MC)
- Simulated Signal Monte Carlo:

Signal MC	$\int Ldt$	N_{Signal}
$\bar{B}^0 B^0$	$\sim 6.5 \cdot 10^{11}\ \mathrm{fb}^{-1}$	$\sim 2.2 \cdot 10^5$
$\bar{B}^{*0} B^0 + c.c.$	$\sim 8.8 \cdot 10^{11}\ \mathrm{fb}^{-1}$	$\sim 3.0 \cdot 10^5$
$\bar{B}^{*0} B^{*0}$	$\sim 7.8 \cdot 10^{11}\ \mathrm{fb}^{-1}$	$\sim 2.7 \cdot 10^5$
Equal mixture of $C = \pm 1$ states	$\sim 8.8 \cdot 10^{11}\ \mathrm{fb}^{-1}$	$\sim 3.0 \cdot 10^5$

PDF as a function of Δt and Σt for each case

Δt

$C=-1$:

- $$P^{\text{ent}}_{\substack{\text{SF}\\ \text{OF}}}(\Delta t)=\frac{1}{4\Gamma}e^{-\Gamma|\Delta t|}[1\mp\cos\Delta m\Delta t]$$

$C=+1$:

- $$P^{\text{ent}}_{\substack{\text{SF}\\ \text{OF}}}(\Delta t)=\frac{1}{8}e^{-\Gamma|\Delta t|}\left[\frac{1}{\Gamma}\mp\frac{\Gamma\cos\Delta m\Delta t}{\Gamma^2+\Delta m^2}\pm\frac{\Delta m\sin\Delta m\Delta t}{\Gamma^2+\Delta m^2}\right]$$

Disentangled:

- $$P^{\text{dis}}_{\substack{\text{SF}\\ \text{OF}}}(\Delta t)=\frac{1}{16\Gamma}e^{-\Gamma|\Delta t|}\left[2\mp\frac{\cos\Delta m\Delta t}{2\Gamma^2+\Delta m^2}\pm\frac{\Gamma\Delta m\sin\Delta m\Delta t}{2\Gamma^2+\Delta m^2}\right]$$

Σt

$C=-1$:

- $$P^{\text{ent}}_{\substack{\text{SF}\\ \text{OF}}}(\Sigma t)=\frac{1}{4}e^{-\Gamma\Sigma t}\left[\Sigma t\mp\frac{\sin\Delta m\Sigma t}{\Delta m}\right]$$

$C=+1$:

- $$P^{\text{ent}}_{\substack{\text{SF}\\ \text{OF}}}(\Sigma t)=\frac{\Gamma^2}{4}e^{-\Gamma\Sigma t}\left[1\mp\frac{\sin\Delta m\Sigma t}{\Delta m}\right]\Sigma t$$

Disentangled:

- $$P^{\text{dis}}_{\substack{\text{SF}\\ \text{OF}}}(\Sigma t)=\frac{\Sigma t}{4}e^{-\Gamma\Sigma t}\left[2\mp\cos\Delta m\Sigma t\pm\frac{\sin\Delta m\Sigma t}{\Sigma t}\right]$$

Simulating Signal Monte Carlo data

- Generating with basf2:
  - Idea: generating events: basf2 & detector simulation: Belle
  - Model: PHSP_BB_MIX
    - New particles: B0heavy B0long → propagate
    - Requires setting B0 lifetime to 0
    → This should be done in the evt.pdl
  - Problem:
    - EvtGen sources a central pdl
    - Locally defined B meson lifetime gets overwritten
    → Incorrect time evolution
  - Solution: Define a new particle B0_test with zero lifetime
    → No overwriting

Reconstruction

- Seperate between:

$$\Upsilon(5S) \rightarrow \overline{B}^0 B^0$$

$$\Upsilon(5S) \rightarrow \overline{B}^{*0} B^0 + c.c.$$

$$\Upsilon(5S) \rightarrow \overline{B}^{*0} B^{*0}$$

- Goal: Seperating via M_{bc} and ΔE

Cuts:

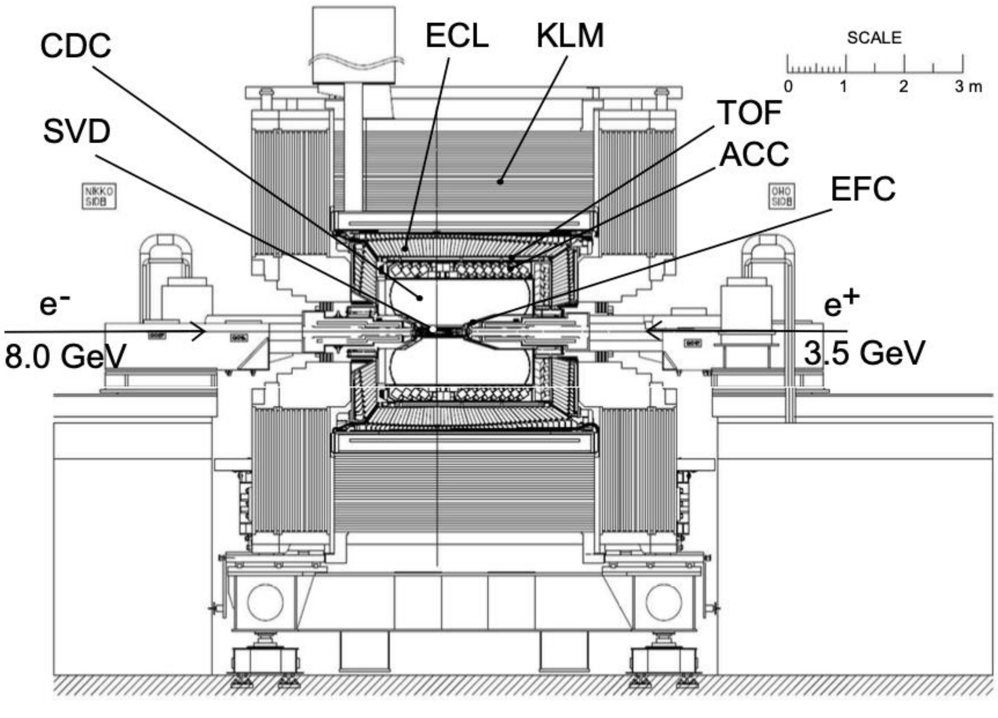
- $dr < 0.5$
- $abs(dz) < 3.0$
- $thetaInCDCAcceptance$
- $atcPIDBelle(3,2) > 0.6\ (K^+) / < 0.4\ (\pi)$
- $1.8597 < InvM < 1.8797\ D^-$

- Reconstructed decays:

$$B^0 \rightarrow D^- \pi^+$$
$$D^- \rightarrow K^+ \pi^- \pi^-$$

$$B^0 \rightarrow D^{*-} \pi^+$$
$$D^{*-} \rightarrow \overline{D}^0 \pi_s^-$$
$$\overline{D}^0 \rightarrow K^+ \pi^-$$
$$\overline{D}^0 \rightarrow K^+ \pi^- \pi^0$$
$$\overline{D}^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$$

KEKB and Belle Detector: Subsystems



- SVD = Silicon Vertex Detector
- CDC = Central Drift Chamber
- ECL = Electromagnetic Calorimeter

Overview of Belle $\Upsilon(5S)$ Data and Simulation

- Lorentz boost at Belle $\beta\gamma = 0.425$
- Integrated luminosity on-resonance $\Upsilon(5S)$ $L = 121\ \mathrm{fb}^{-1}$
- Generic Monte Carlo on Belle $\Upsilon(5S)$ data
  - In total six times more MC data than real data ($L = 726\ \mathrm{fb}^{-1}$MC)
- Simulated Signal Monte Carlo

Entangled case

Antisymmetrical wavefunction: $|\Psi\rangle = \frac{1}{\sqrt{2}}\left[\left|B_1^0\right\rangle \otimes \left|\bar{B}_2^0\right\rangle - \left|\bar{B}_1^0\right\rangle \otimes \left|B_2^0\right\rangle\right]$

- $C = -1,\ l = 1,\ s = 0$
- Probabilities: $P^{\text{ent}}(\phi_1\phi_2) = |\langle\phi_1\phi_2|\Psi\rangle|^2$
  - $P^{\text{ent}}(|B^0B^0\rangle) = \frac{1}{4}e^{-\bar{\Gamma}(t_1+t_2)}[1 - \cos\Delta m(t_1 - t_2)] = P^{\text{ent}}(|\bar{B}^0\bar{B}^0\rangle)$
  - $P^{\text{ent}}(|\bar{B}^0B^0\rangle) = \frac{1}{4}e^{-\bar{\Gamma}(t_1+t_2)}[1 + \cos\Delta m(t_1 - t_2)] = P^{\text{ent}}(|B^0\bar{B}^0\rangle)$

Entangled case

Symmetrical wavefunction: $$|\Psi\rangle = \frac{1}{\sqrt{2}}\left[\left|B_1^0\right\rangle \otimes \left|\bar{B}_2^0\right\rangle + \left|\bar{B}_1^0\right\rangle \otimes \left|B_2^0\right\rangle\right]$$

- $C = +1,\ l = 0,\ s = 0$
- Probabilities: $P^{\text{ent}}(\phi_1\phi_2) = |\langle\phi_1\phi_2|\Psi\rangle|^2$
  - $P^{\text{ent}}(|B^0B^0\rangle) = \frac{1}{4}e^{-\bar{\Gamma}(t_1+t_2)}[1 - \cos\Delta m(t_1 + t_2)] = P^{\text{ent}}(|\bar{B}^0\bar{B}^0\rangle)$
  - $P^{\text{ent}}(|\bar{B}^0B^0\rangle) = \frac{1}{4}e^{-\bar{\Gamma}(t_1+t_2)}[1 + \cos\Delta m(t_1 + t_2)] = P^{\text{ent}}(|B^0\bar{B}^0\rangle)$

Disentanglement

- Wavefunctions $\overline{B}^0 B^0$system:

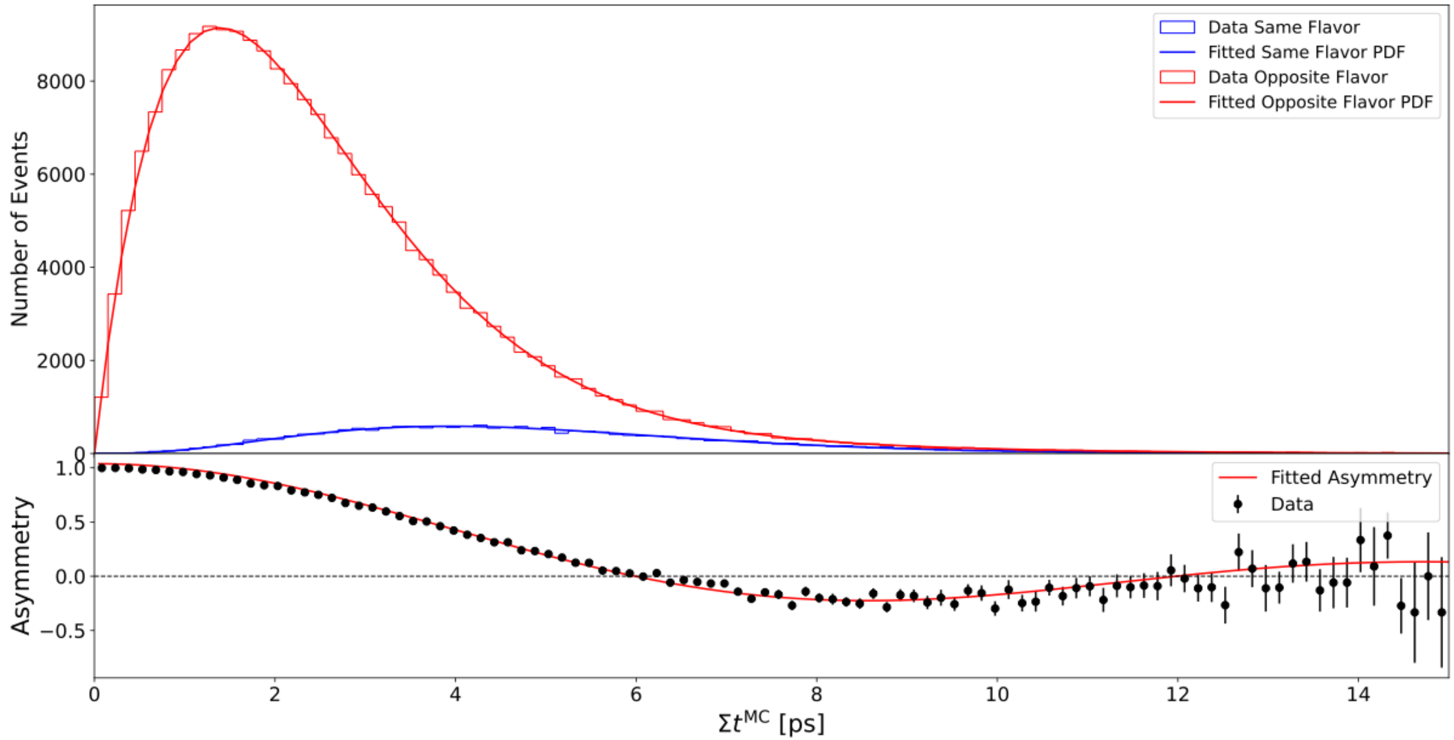
$$|\Psi_1(t_1,t_2)\rangle = [|B^0(t_1)\rangle \otimes |\overline{B}^0(t_2)\rangle] \quad |\Psi_2(t_1,t_2)\rangle = [|\overline{B}^0(t_1)\rangle \otimes |B^0\ (t_2)\rangle]$$

each with probability $1/2$

- Probabilities: $P^{\mathrm{dis}}(\phi_1\phi_2) = |\langle\phi_1\phi_2|\Psi\rangle|^2$

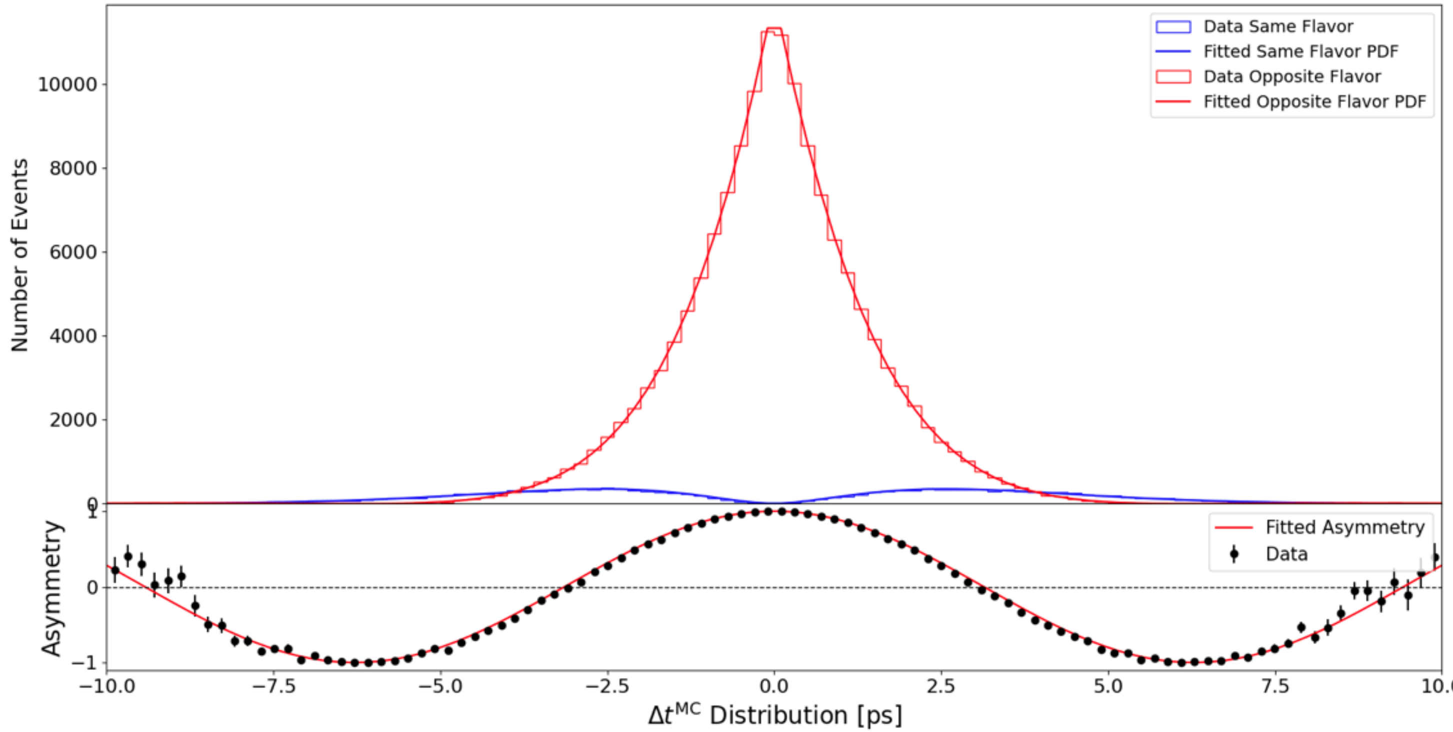
  - $P^{\mathrm{dis}}(|B^0 B^0\rangle) = \frac{1}{4} e^{-\overline{\Gamma}(t_1+t_2)}[1 - \cos\Delta m t_1 \cos\Delta m t_2] = P^{\mathrm{dis}}(|\overline{B}^0\overline{B}^0\rangle)$
  - $P^{\mathrm{dis}}(|\overline{B}^0 B^0\rangle) = \frac{1}{4} e^{-\overline{\Gamma}(t_1+t_2)}[1 + \cos\Delta m t_1 \cos\Delta m t_2] = P^{\mathrm{dis}}(|B^0\overline{B}^0\rangle)$

Simulating Signal Monte Carlo data
$\bar{B}^{*0}B^{*0}$ $C = -1$ case



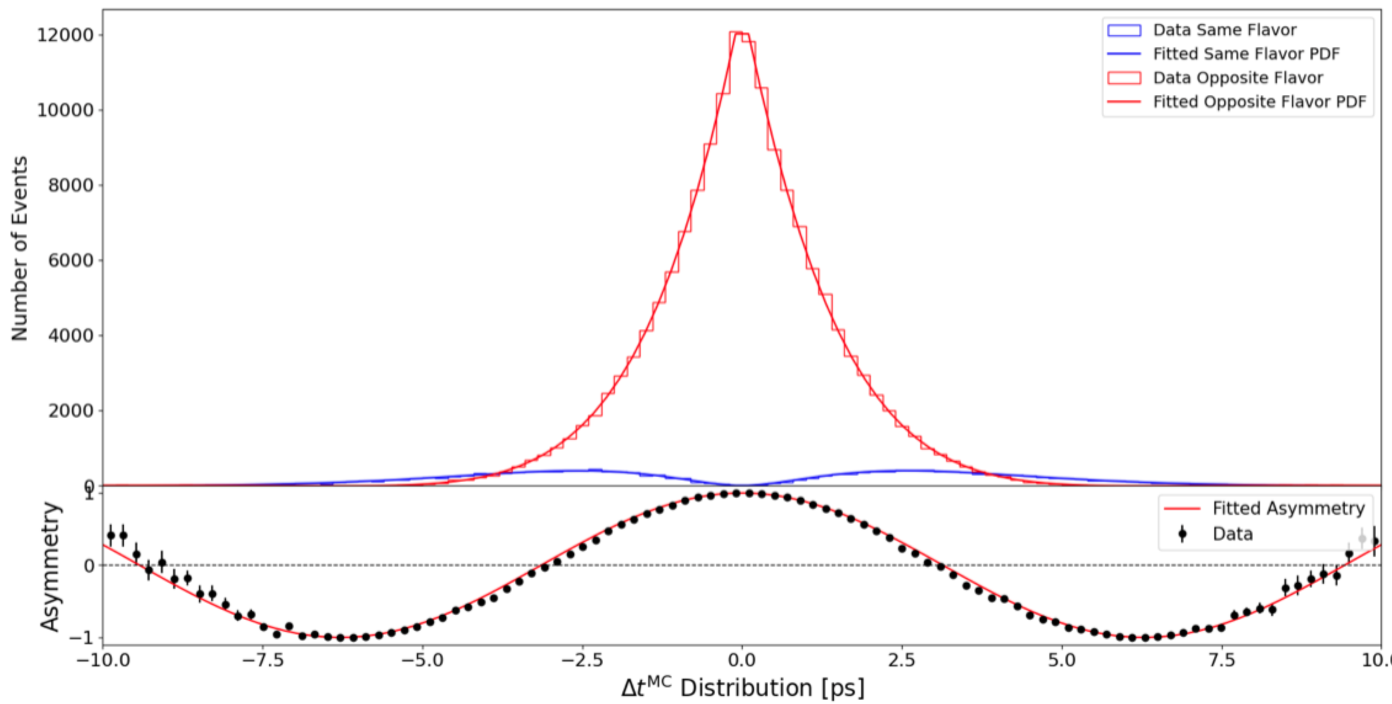
- MC-reconstructed B mesons from $B^0 \rightarrow D^-\pi^+$ channel
- $\omega = (0.524 \pm 0.002)\mathrm{ps}^{-1}$ $\zeta = 0.034 \pm 0.007$

Validating Signal Monte Carlo data
$\overline{B}^{*0}B^{*0}$ $C = -1$ case



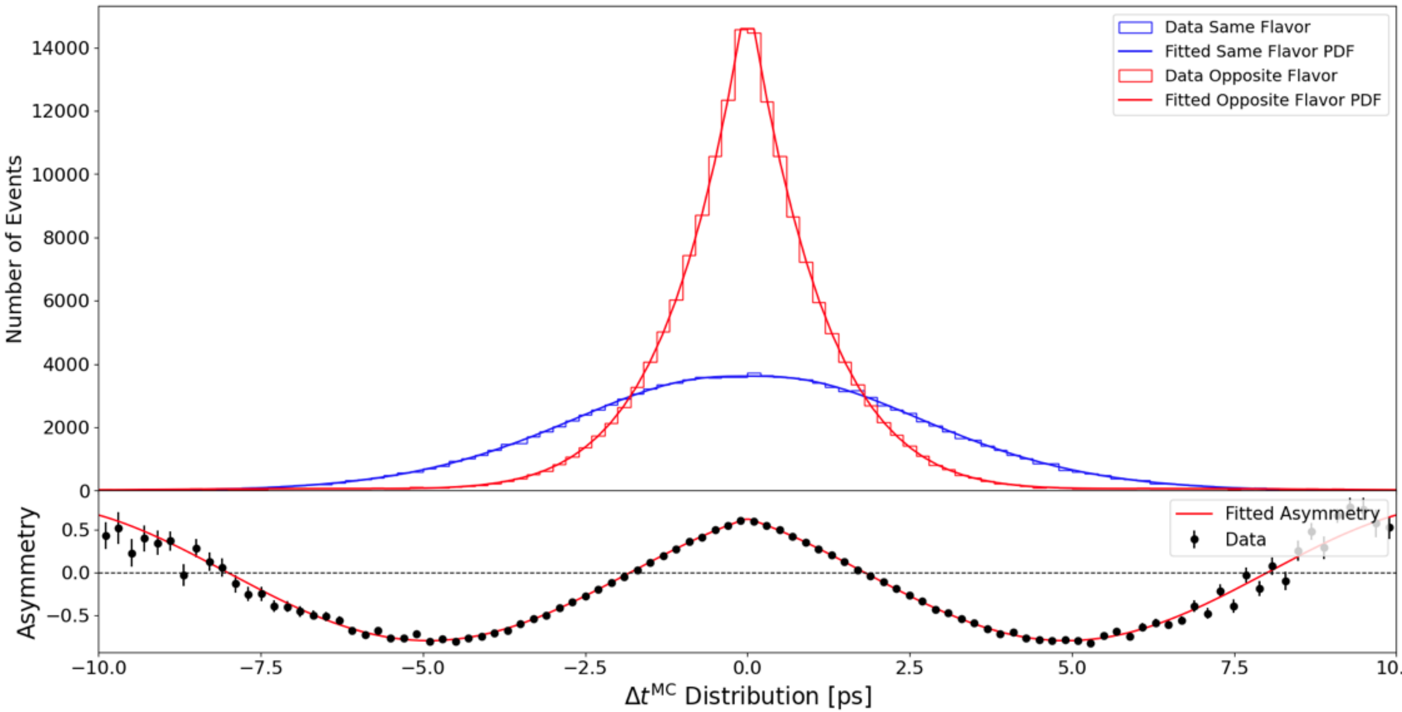
- MC-reconstructed B mesons from $B^0 \rightarrow D^-\pi^+$ channel
- $\omega = (0.510 \pm 0.001)\mathrm{ps}^{-1}$ $\zeta = 0.00 \pm 0.01$

Validating Signal Monte Carlo data $\bar{B}^0 B^0$ $C = -1$ case



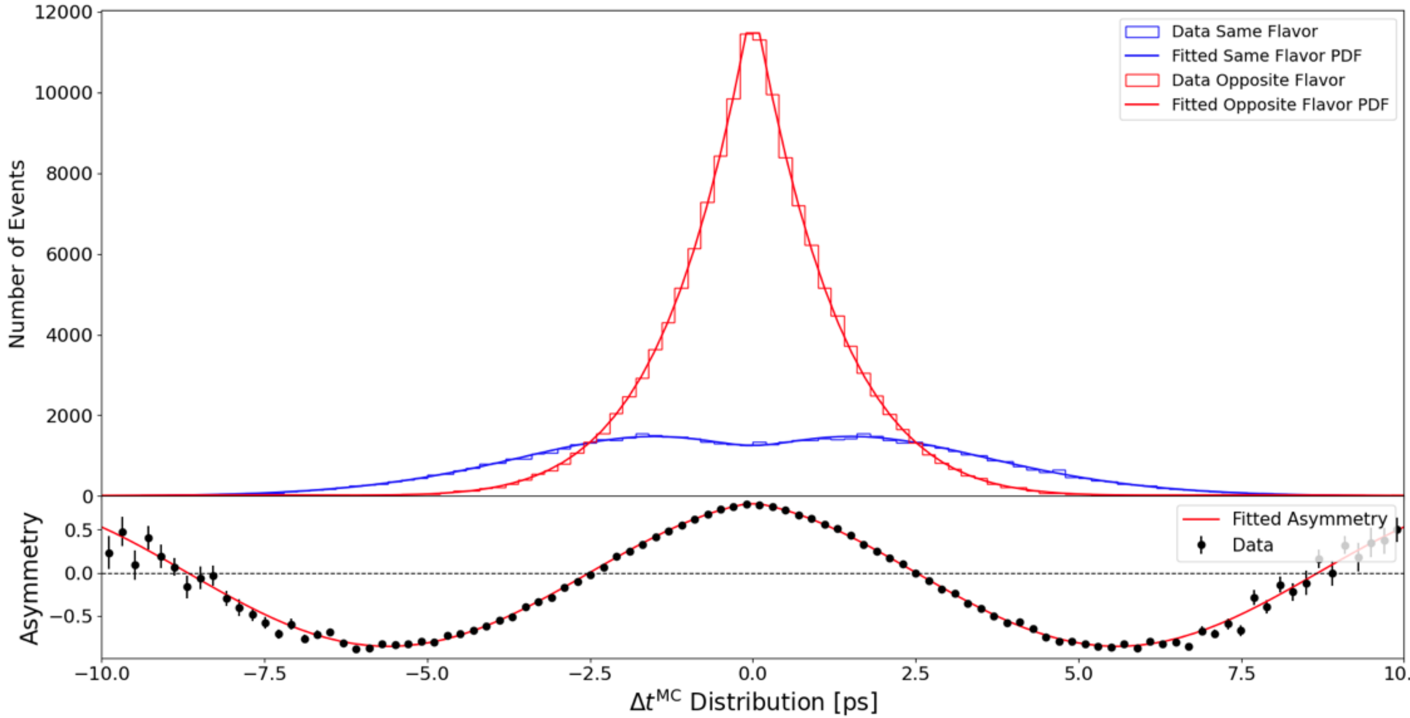
- MC-reconstructed B mesons from $B^0 \rightarrow D^-\pi^+$ channel
- $\omega = (0.510 \pm 0.001)\text{ps}^{-1}$ $\zeta = 0.00 \pm 0.01$
- In MC generation: $\omega = 0.5065\ \text{ps}^{-1}$

Validating Signal Monte Carlo data
$\bar{B}^{*0}B^{0}$ $C = +1$ case



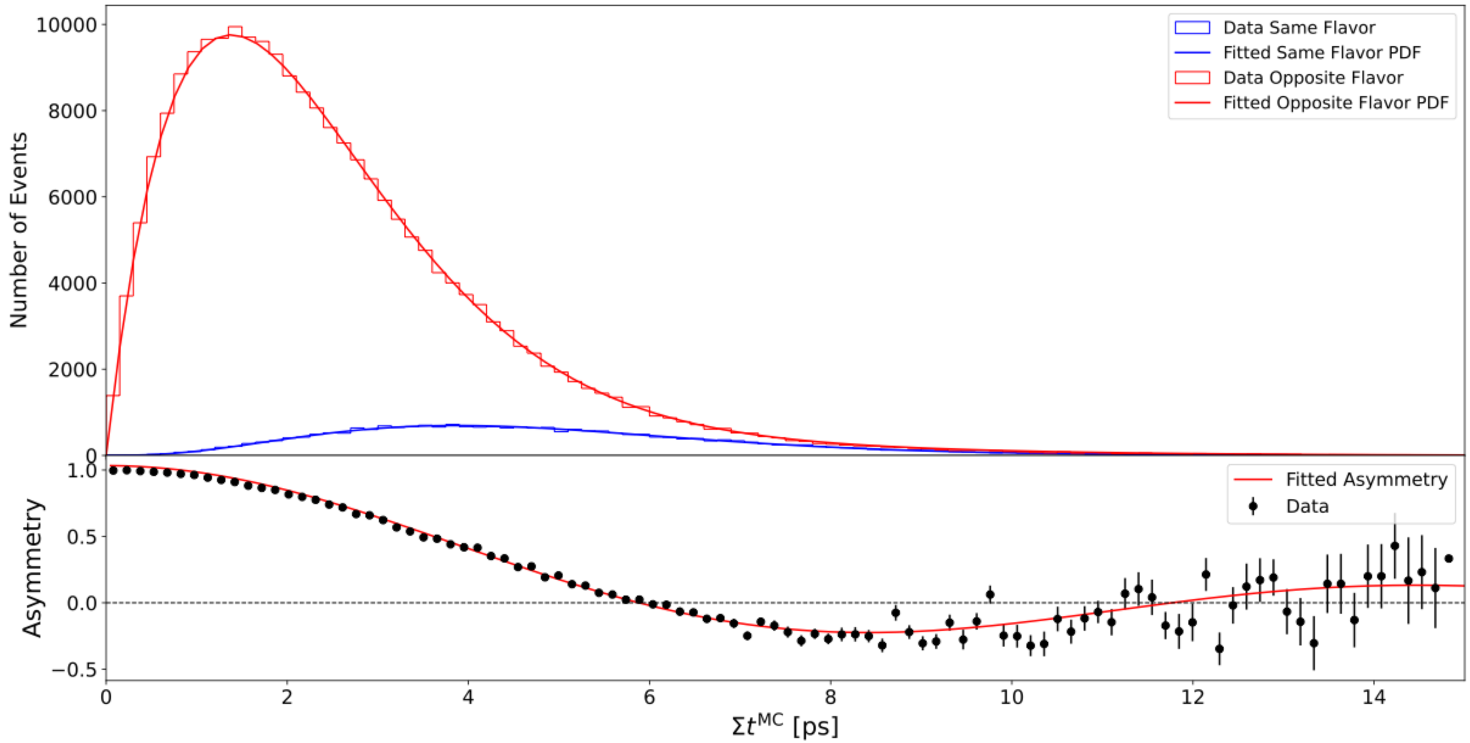
- MC-reconstructed B mesons from $B^0 \rightarrow D^-\pi^+$ channel
- $\omega = (0.506 \pm 0.001)\text{ps}^{-1}$ $\zeta = 0.00 \pm 0.07$

Validating Signal Monte Carlo data
Equal mixture of $C = \pm 1$ states



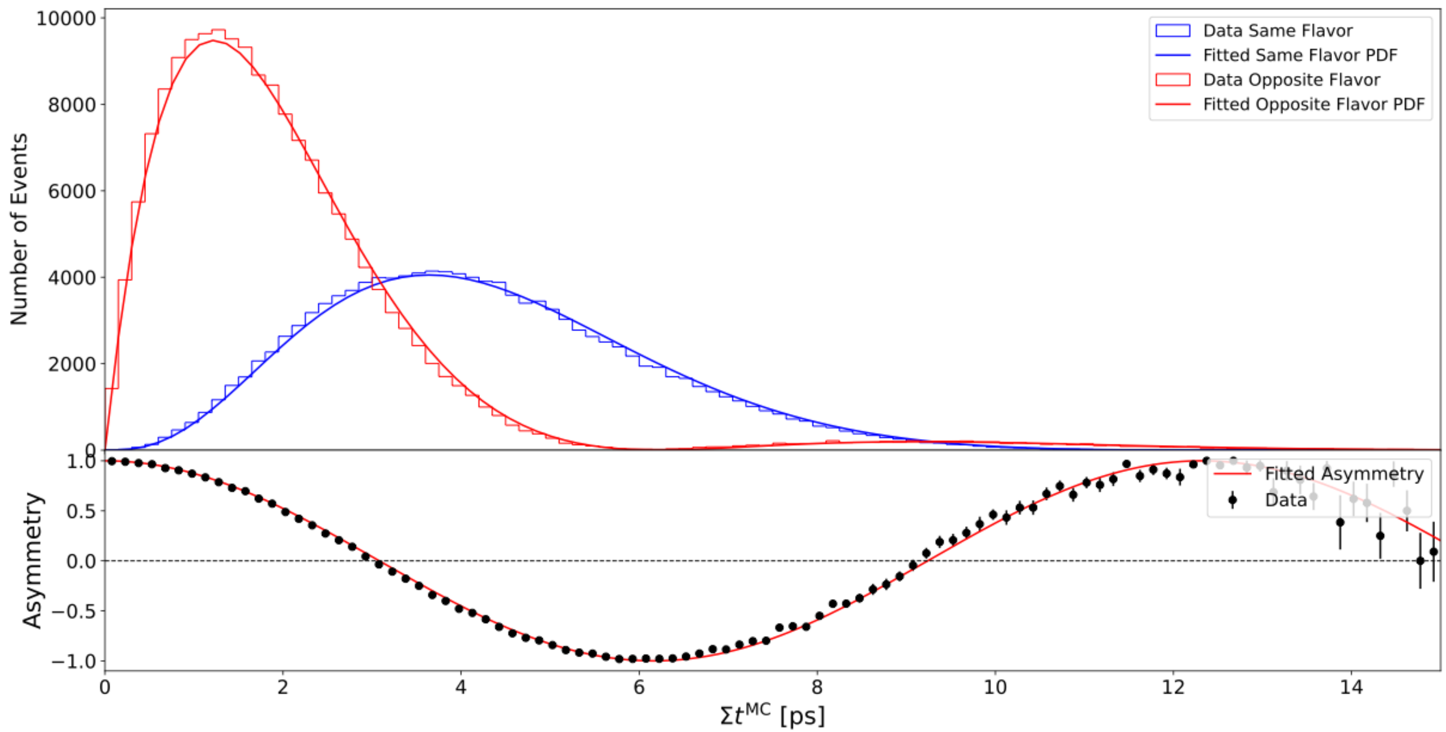
- MC-reconstructed B mesons from $B^0 \to D^- \pi^+$ channel
- $\omega = (0.510 \pm 0.001)\mathrm{ps}^{-1}$ $\zeta = 1.00 \pm 0.12$

Simulating Signal Monte Carlo data
$\bar{B}^0 B^0$ $C = -1$ case



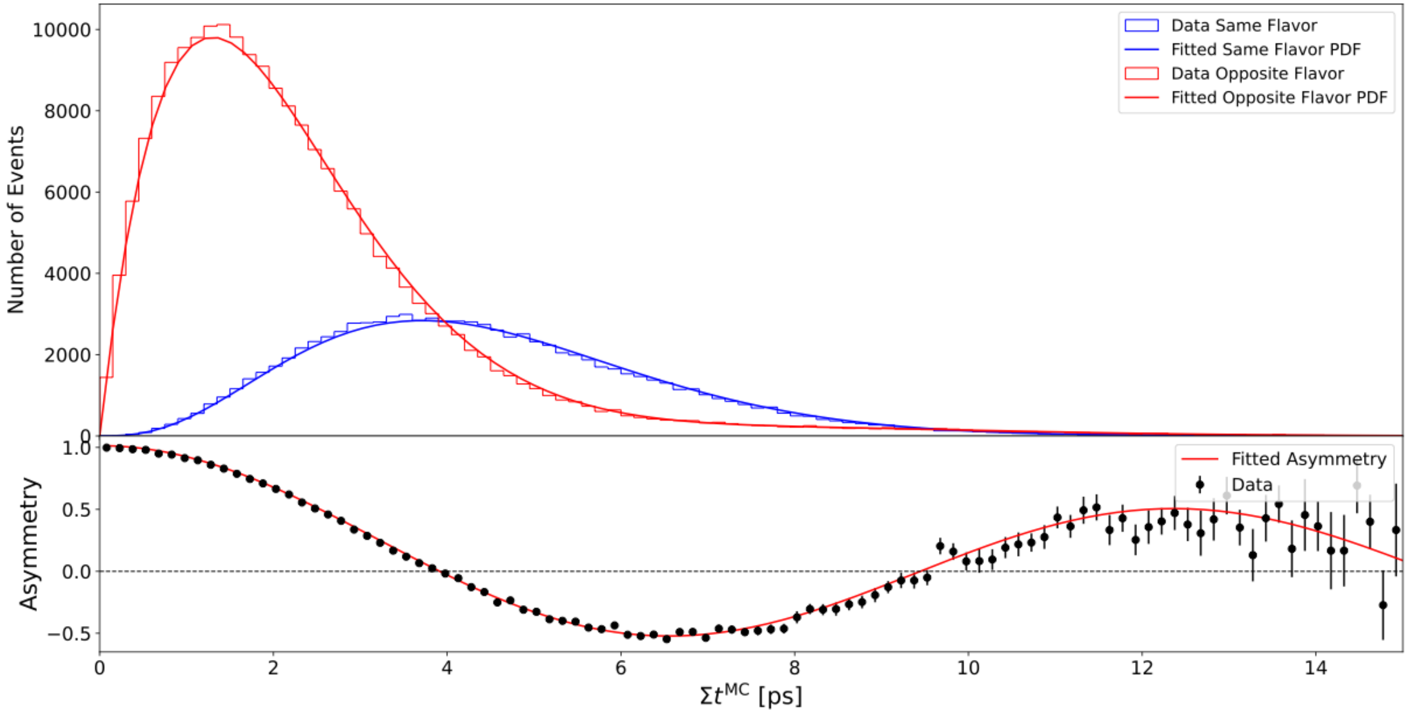
- MC-reconstructed B mesons from $B^0 \rightarrow D^- \pi^+$ channel
- $\omega = (0.534 \pm 0.002)\text{ps}^{-1}$ $\zeta = 0.068 \pm 0.007$
- In MC generation: $\omega = 0.5065\ \text{ps}^{-1}$

Simulating Signal Monte Carlo data
$\bar{B}^{*0}B^0$ $C = +1$ case



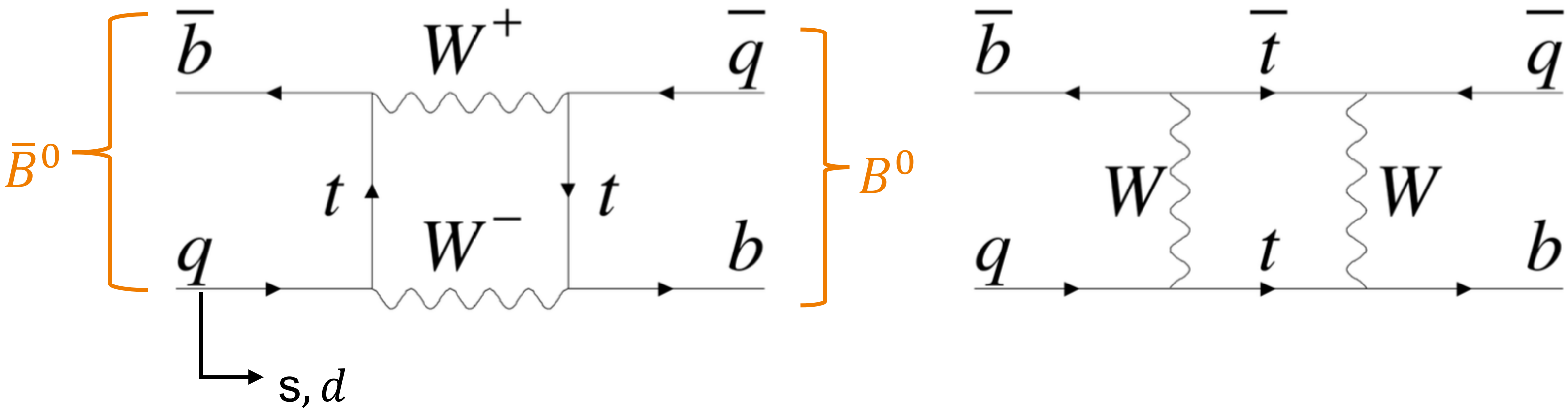
- MC-reconstructed B mesons from $B^0 \rightarrow D^-\pi^+$ channel
- $\omega = (0.517 \pm 0.006)\mathrm{ps}^{-1}$ $\zeta = 0.003 \pm 0.001$

Simulating Signal Monte Carlo data
Equal mixture of $C = \pm 1$ states



- MC-reconstructed B mesons from $B^0 \to D^-\pi^+$ channel
- $\omega = (0.520 \pm 0.001)\text{ps}^{-1}$ $\zeta = 1.00 \pm 0.19$

Entanglement in B physics: $\bar{B}^0 B^0$ mixing



- Mass eigenstates $|B_L\rangle, |B_H\rangle$ are linear combinations of weak eigenstates

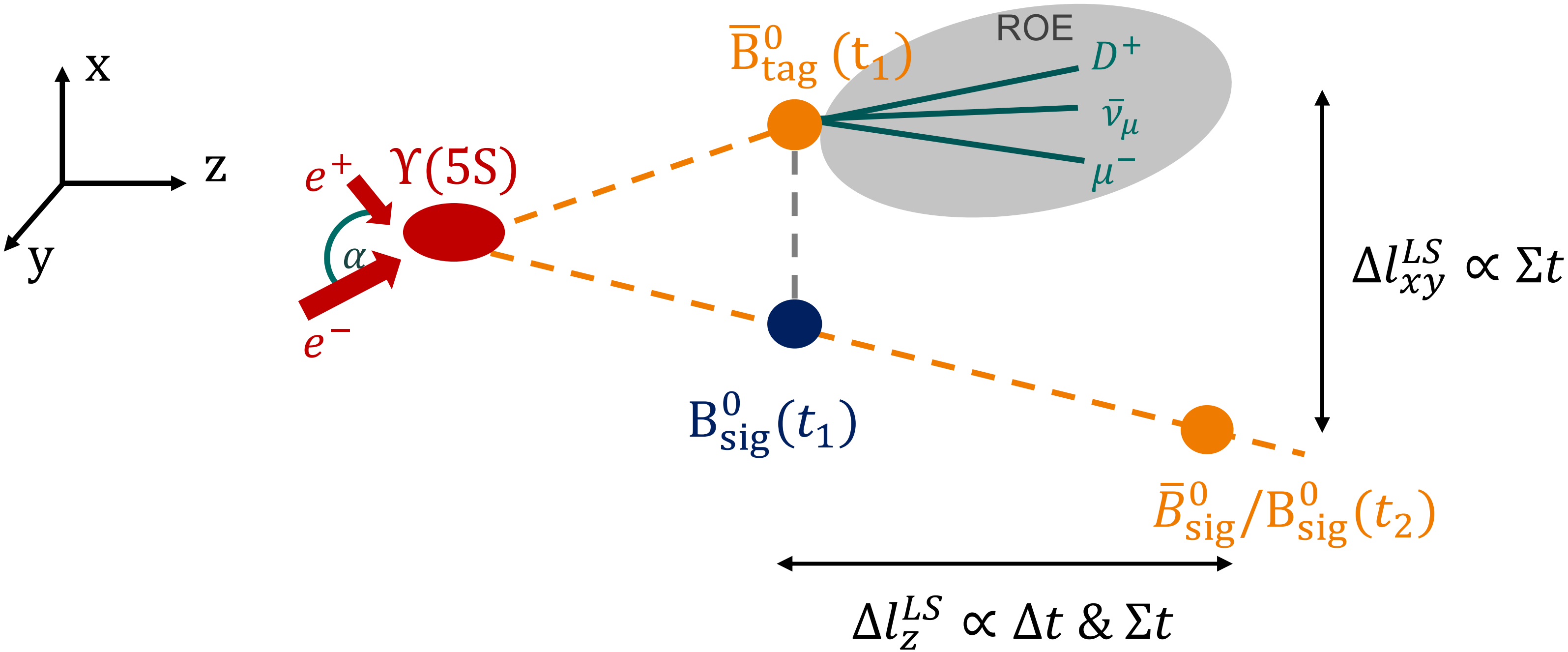
$$|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle \quad |B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$

→ describe decay and propagation in time

→ Resulting in the mixing/oscillation of the B meson flavors in time

- Approximation: $\left|\frac{p}{q}\right| \approx 1$

Goal of the analysis



- Set framework for entanglement studies of the $\Upsilon(5S)$ system
- Reconstruct B^0_{sig} and $\overline{B}^0_{tag}$ vertices

→ Obtain Δt and Σt

- Analyzing entanglement via propagation in time of the B mesons

Quantum numbers of the $\bar{B}^0 B^0$ system after $B^{*0} \rightarrow \gamma B^0$ transition

Decay	C	L	J	Wavefunction
$\Upsilon(4S) \rightarrow \bar{B}^0 B^0$	-1	1	1	p
$\Upsilon(5S) \rightarrow \bar{B}^0 B^0$	-1	1	1	p
$\Upsilon(5S) \rightarrow \bar{B}^0 B^{0*} + c.c.$	1	0	0	s
$\Upsilon(5S) \rightarrow \bar{B}^{0*} B^{0*}$	-1	1	1	p

- Antisymmetric wavefunction for $\bar{B}^0 B^0$ and $\bar{B}^{0*} B^{0*}$ decays
- $C = -1$ antisymmetric
- Symmetric wavefunction for $\bar{B}^0 B^{0*} + c.c.$ decay
- $C = +1$ symmetric (after $B^{*0} \rightarrow \gamma B^0$ transition)

Obtaining variables and simulating Signal MC

Problem:

- No correct Δt and MC flavor of the other B variable available

Solution: Determine Δt via vertex positions

Matching MC generator level particles

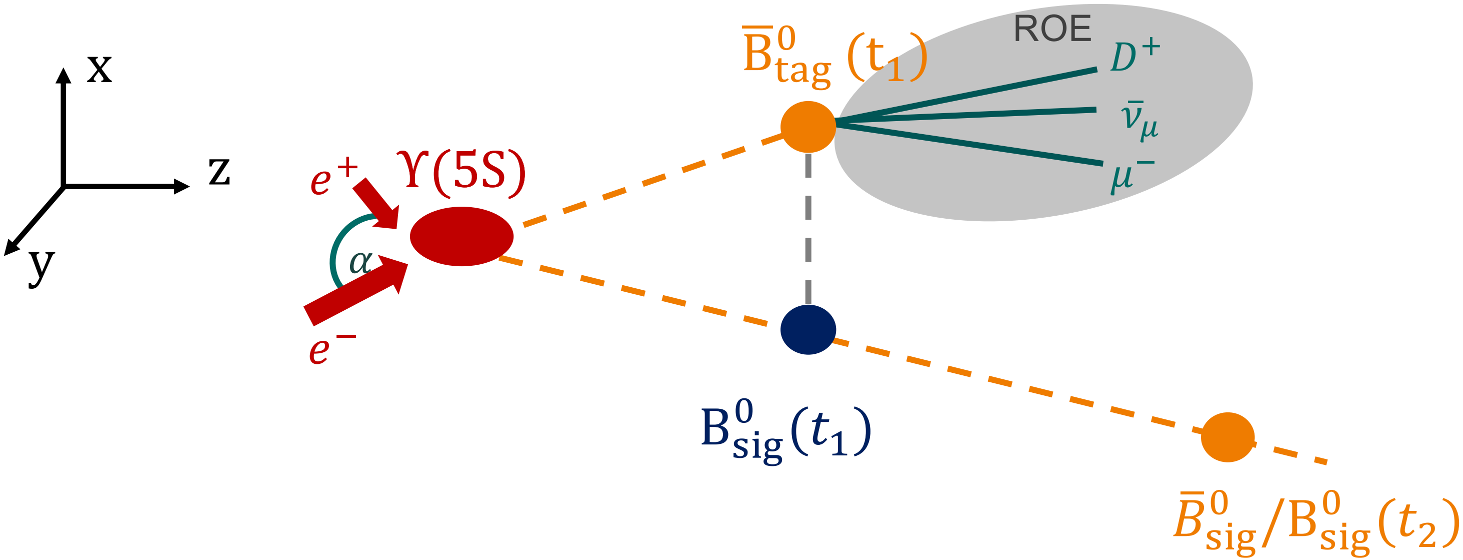
- Simulated signal MC data for increasing statistics:

Signal MC:
Only decays of the B mesons in the reconstruction channels

Generic MC:
Already simulated MC from Belle collabration, B mesons decay in all allowed channels → less B signal events

- New particle definiton for simulation signal MC
- Using old Belle detector simulation for signal MC

Flavor Tagger



- Determine the flavor of the tag B meson using the Flavor Tagger a multivariate algorithm
- Input: kinematic, track-hit, PID information out of Rest of Events (ROE)
- Output: Product $q \cdot r$ with q as flavor of the B and r as the dilution factor
- $r = 1$ indicates a perfectly tagged flavor

Δt-fit on signal MC for the $C = +1$ case

- Fit model expects $C = -1$ case PDF as entangled function:

$$P_{PSD} = (1-\zeta)P_{C=-1} + \zeta P_{dis}$$

- Write diesentangled PDF as mixture of fully entangled $C = \pm 1$ states:

$$P_{dis} = \frac{1}{2}P_{C=-1} + \frac{1}{2}P_{C=+1}$$

  - Plug new diesentangled PDF in fit model to make it also dependent on the $C = +1$ case PDF :

$$P_{PSD} = (1-\zeta)P_{C=-1} + \frac{1}{2}\zeta P_{C=-1} + \frac{1}{2}\zeta P_{C=+1} = \left(1 - \frac{1}{2}\zeta\right)P_{C=-1} + \frac{1}{2}\zeta P_{C=+1}$$

$\Rightarrow$ $P_{PSD} = P_{C=+1}$ for $\zeta = 2$