Korea Institute of Science and Technology Information

The Automatic Particle Reconstruction with Machine Learning at e^+e^- Collider

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Contents

Introduction: e^+e^- Collider

e^+e^- Collider & B Meson Analysis

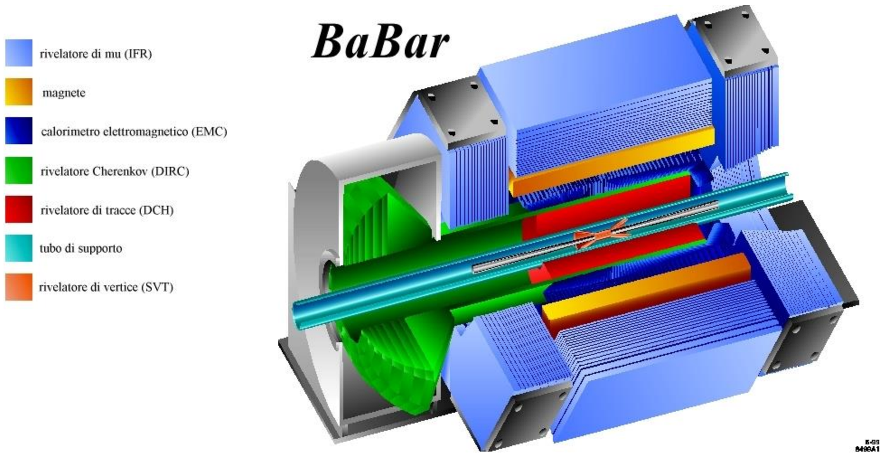
Characteristics of e^+e^- colliders for B meson analysis

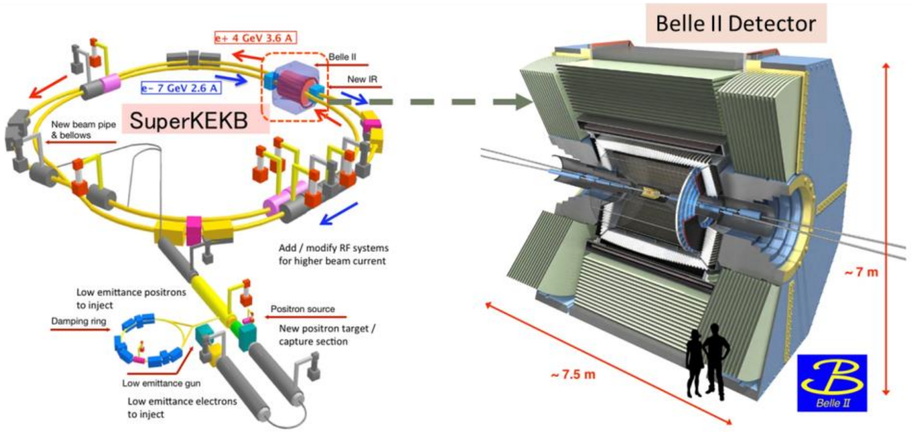
- Focusing e^+e^- beams that CM energy goes near 10.58GeV, the mass of $Y(4S)$ (Upsilon 4S)

Experiment	Location	e- beam energy	e+ beam energy
BaBar[1]	SLAC, USA	9.0 GeV	3.1 GeV
Belle[2]	KEK, Japan	8.0 GeV	3.0 GeV
Belle II[3]	KEK, Japan	7.0 GeV	4.0 GeV

- Upsilon(4S) creation from e^+e^- collision : decays to $B\bar{B}$ with 96% branching ratio
- Clean event : Only 2 B mesons (and background particles like cosmic ray) are in the event

$\Rightarrow$ The best condition to study B mesons

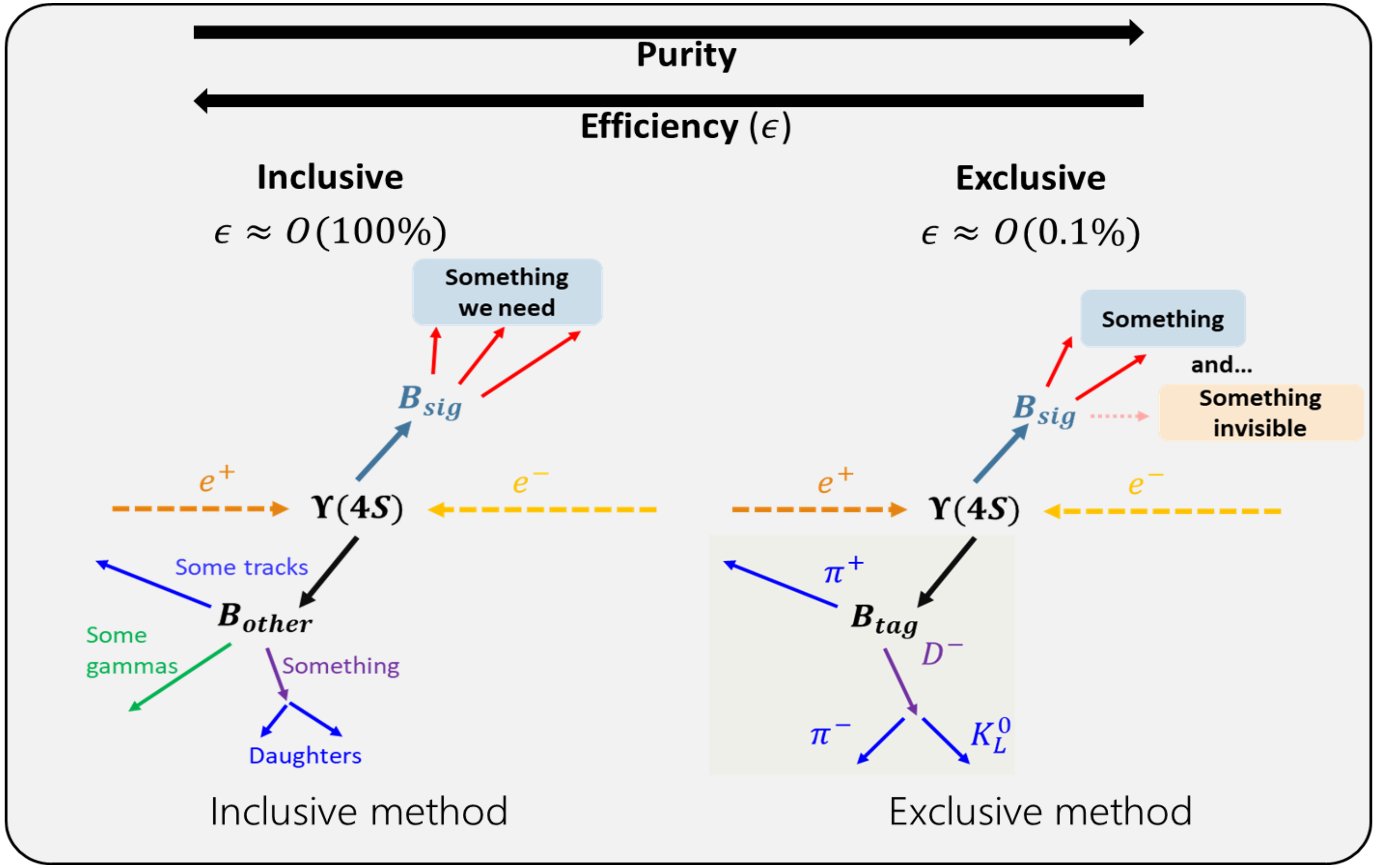




How to Reconstruct B?

B meson analysis : reconstructing B inclusively or exclusively

- B meson decays to final state particles $: e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, \gamma$
  - Reconstruction of B meson should be done.
- Inclusive : signal-side B reconstruction only
- Exclusive : 1) tag-side (B_{tag}) 2) signal-side B reconstruction
- It is possible because B decay events from $e^{+}e^{-}$ and $\Upsilon(4S)$ are 'clean'



Large statistics
Large background (and candidates!)

Cleaner sample and signal kinematics
Lower tag-side efficiency

Difficulties of B Tagging

There are many B meson decays.

- 500 for B^+, B^0 each
- Since not tagged decay channels are excluded, the selection of tagging mode is important.
  - **Signal efficiency** is always important!

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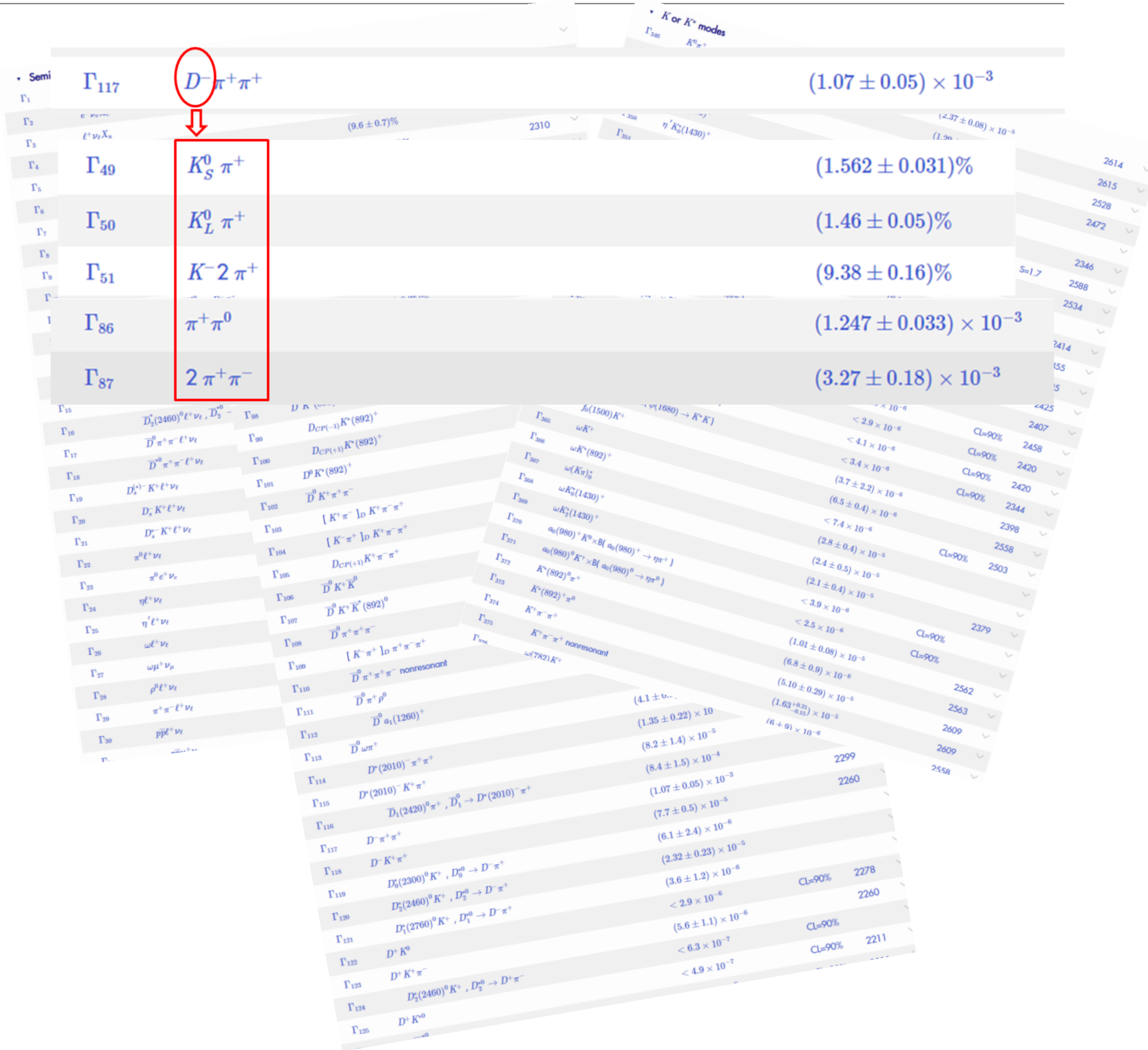
B daughters can be decayed with various channels.

- Need to consider for daughter's decay mode to reconstruct

More work for reconstruction of tagged B

- Decay channel: (seems) determined on collaboration group
- Anyway, reconstructing manually is not so easy..
- Not finished: quality control of tagged B

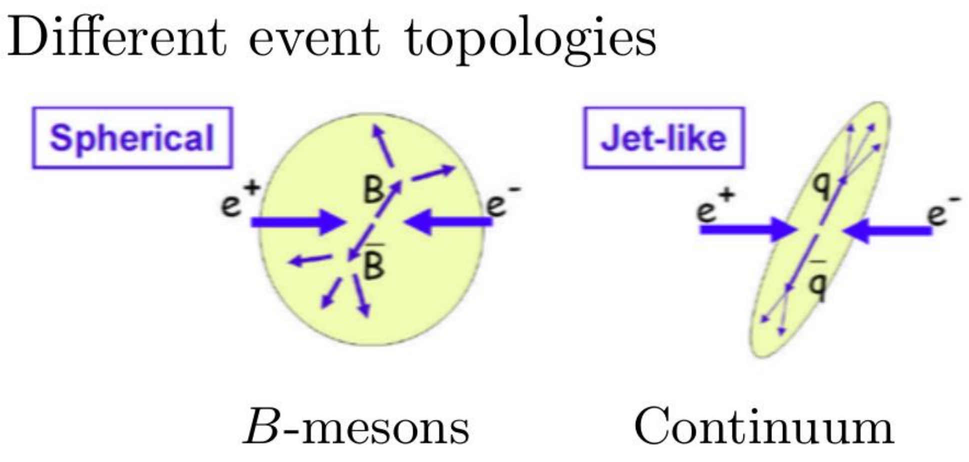


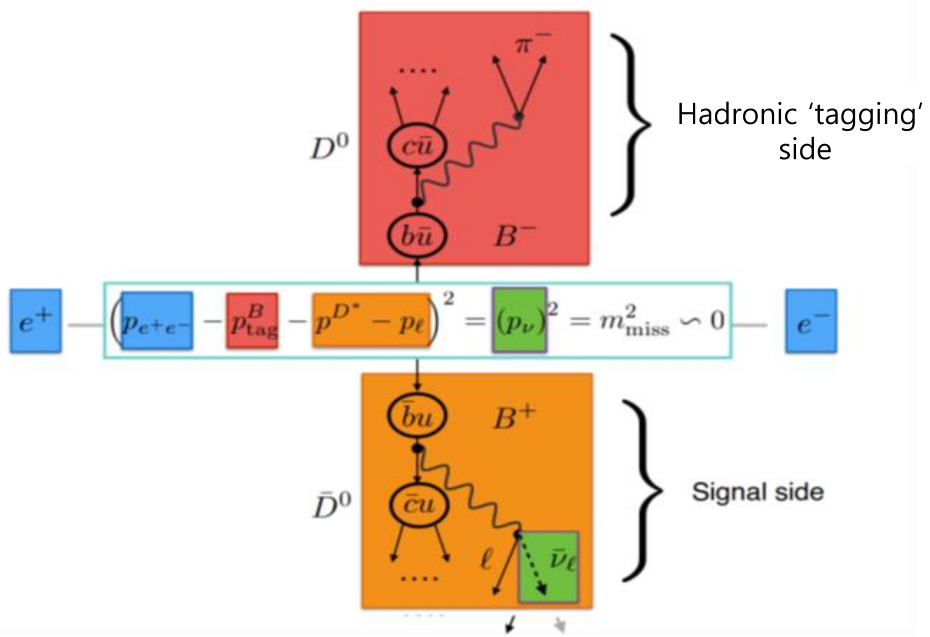
Then why doing exclusive B study?

Advantages of *B* Tagging

Advantages of exclusive *B* tagging

- Effective continuum suppression due to different event topologies
- Requiring no additional particles in event (Completeness)
- Accessing tagged *B* information and additional information for quality control
  : optimized to research that invisible particles are included in the decay channel.





Calcultaion of m^2_{miss} using information of p^B_{tag}

Automatic B Tagging with MVA

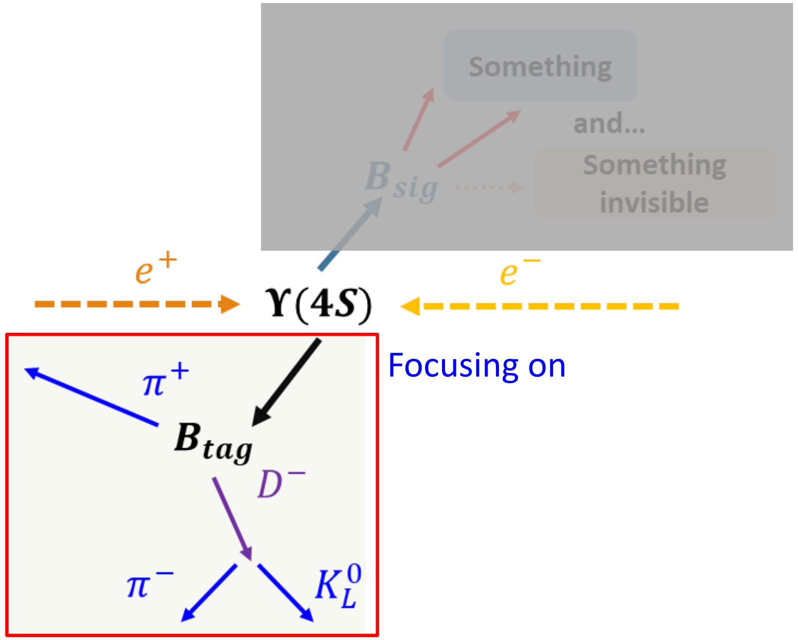
Reconstructing B with Machine Learning

B tagging with MVA (MultiVariate Analysis)

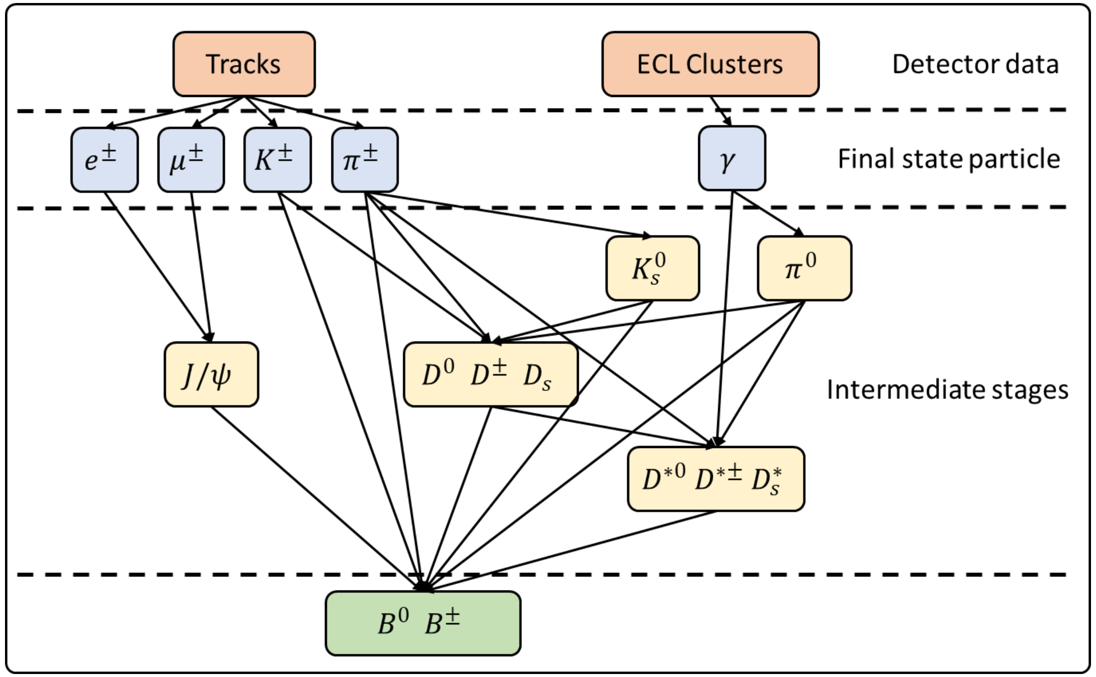
- Automatically reconstructing tagged B mesons
- Applied at each particle reconstruction & identification
- Assigning a classifier to each decay channel →
- Used MVA tools: BDT(for Belle II) and ANN(for Belle, Babar)

1. $D^+ \to K^-\pi^+\pi^+$
2. $D^+ \to K^-\pi^+\pi^+\pi^0$
3. $D^+ \to K^-K^+\pi^+$
4. $D^0 \to K^-K^+\pi^+\pi^0$

4 D+ channel
- Each decay channel takes its classifier



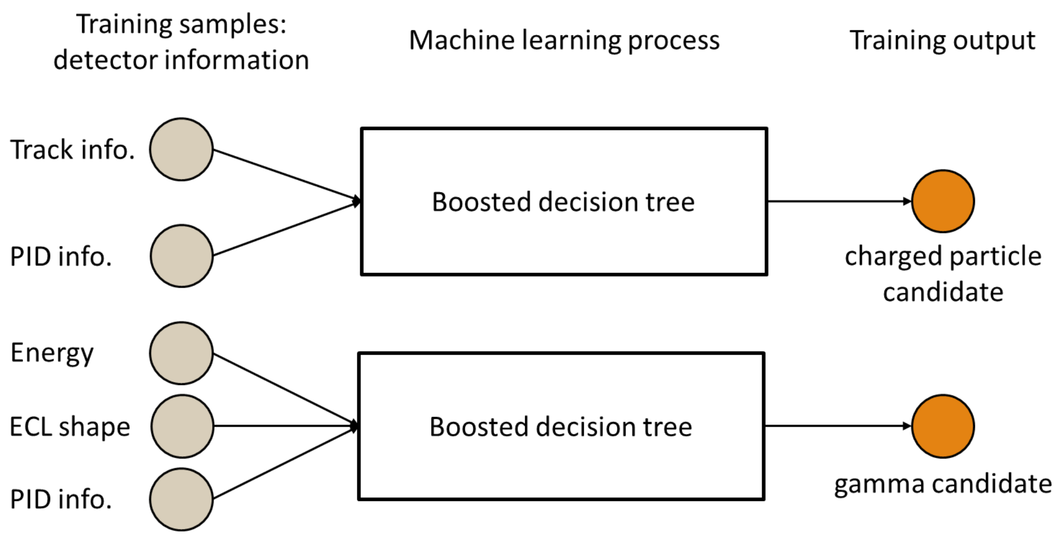
Schematic view of B tagging via $B \to D\pi$ channel

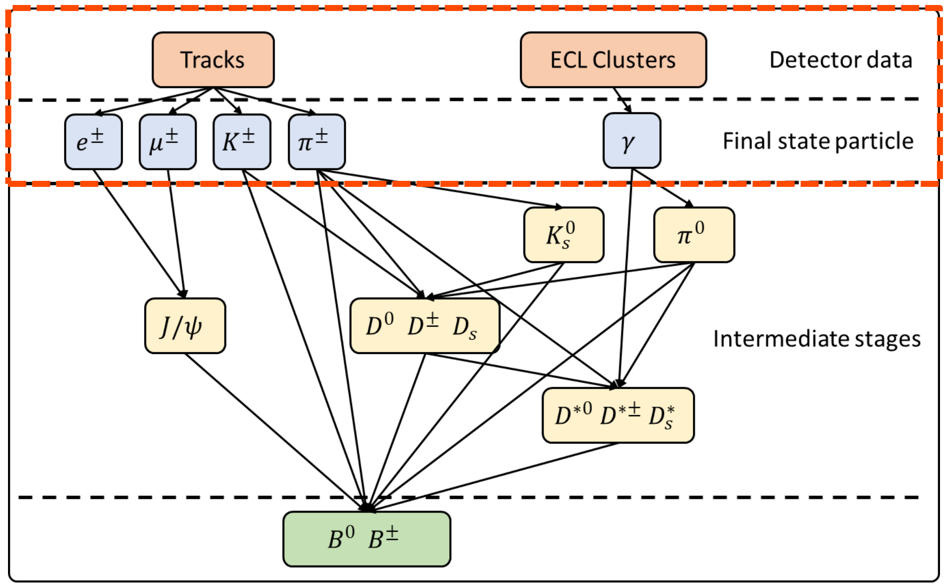


Training a Classifier for Final State Particle

Final state particles : 4 charged particles (e, μ, π, K) and gamma

- Reconstructed with subdetector information
- Charged particle (e, μ, π, K) : track information + PID information
- Photon : deposited energy, shape information from calorimeters + PID information
- Training sample condition
  - Precut: PID information (track) or energy (cluster)
  - Postcut: probability(>0.01) and rank (10 for charged, 20 for photon) of particle classifier

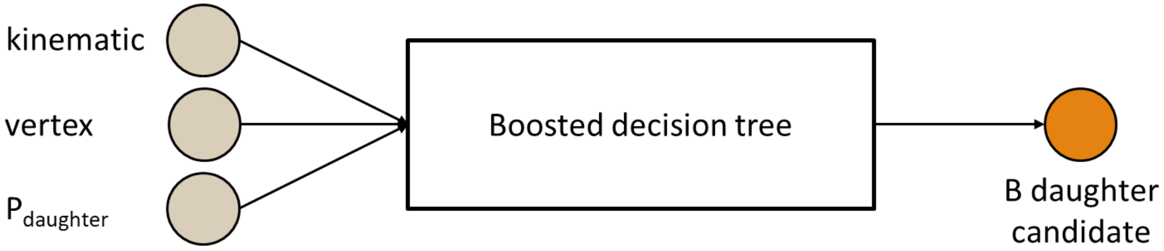


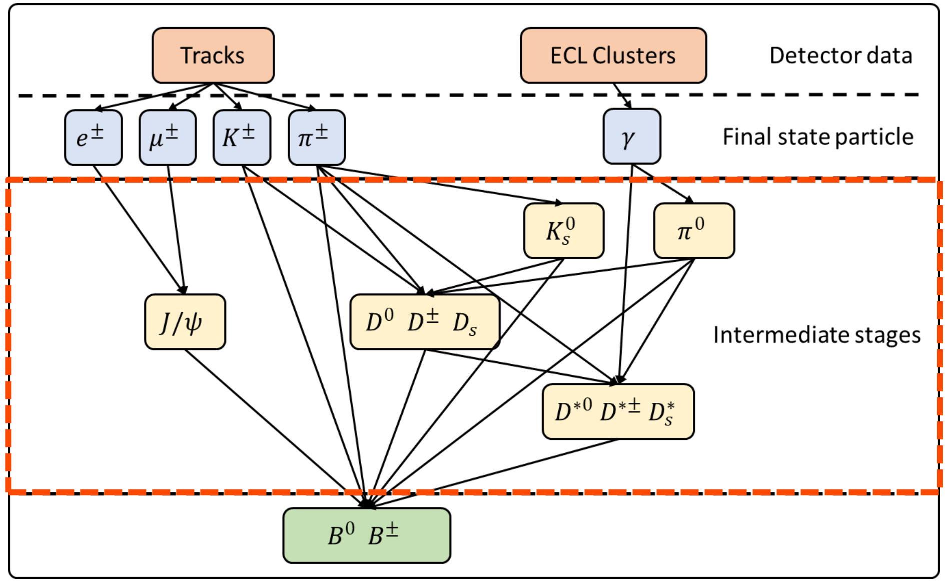


Training a Classifier for Intermediate Particles

Training for particles as a part of B_{tag}

- Particle type : $\pi^0, K_S^0, J/\psi, D^0, D^+, D_S^+, D^{0*}, D^{+*}, D_S^{+*}$
- Training variable : kinematic variables + vertex variables + classifier probabilities of the daughters
- Training sample condition
  - Precut : $P_{daughter}$ product, mass difference (*ΔM*), released energy (for *D**)
  - Postcut : probability (> 0.001) and rank (10) of particle classifier

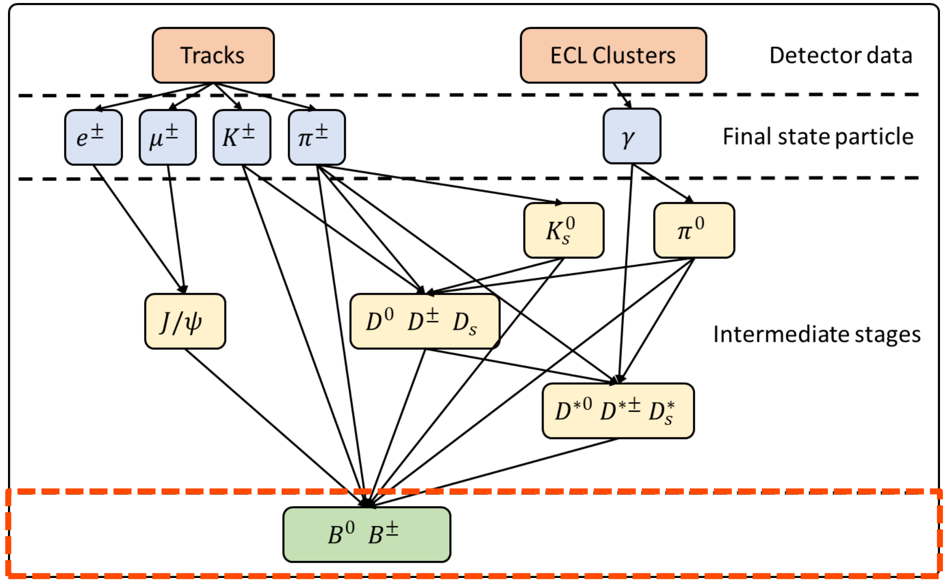




Training a Classifier for B Mesons

Final training for B mesons

- Training variables : kinematic variables + vertex variables + MVA probabilities of the daughters
- Not using an invariant mass (hadronic) or angular variables (semileptonic) for training
  - Avoiding high correlation of M_{bc} (hadronic) and $\cos\theta_{B,D^{(*)}\ell}$ (semileptonic)
- Training sample condition
  - Precut : $P_{daughter}$ product
  - Postcut : B candidates with 20 highest probabilities



Applying to $B^0 \to \ell^{\pm}\tau^{\mp}$ Decay

Properties & Processes of $B^0 \rightarrow \ell^{\pm}\tau^{\mp}$ Decay

Lepton flavor violation in $B^0 \rightarrow \ell^{\pm}\tau^{\mp}$

- Forbidden in the Standard Model
- Predicted to occur in 'beyond the Standard Model' theories

The properties of the signal B

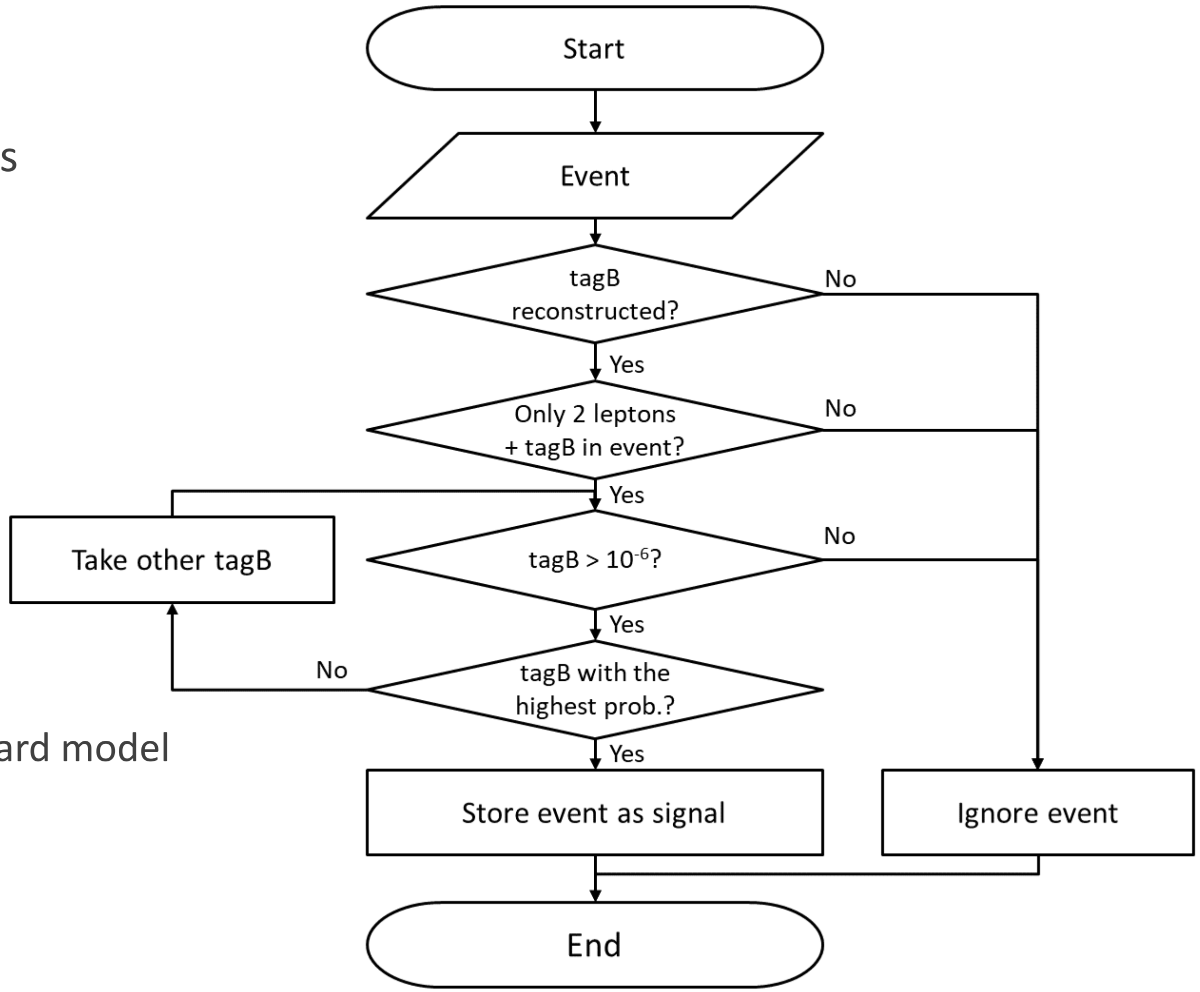
- Invisible particles (neutrino) from τ decay
- Lack of signal mode for B reconstruction

Sample condition

- Signal: Belle MC samples,
  - One B meson should be decayed to $\ell^{\pm}\tau^{\mp}$
- Background: Belle generic background MC
  - Generated events of B pair or quark jet pair based on the Standard model

Best candidate selection of tagB

- tagB with the highest classifier output



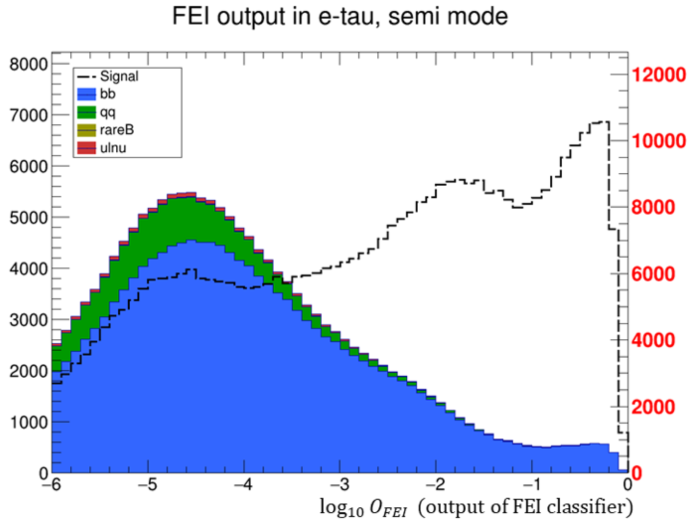
Event selection after B tagging

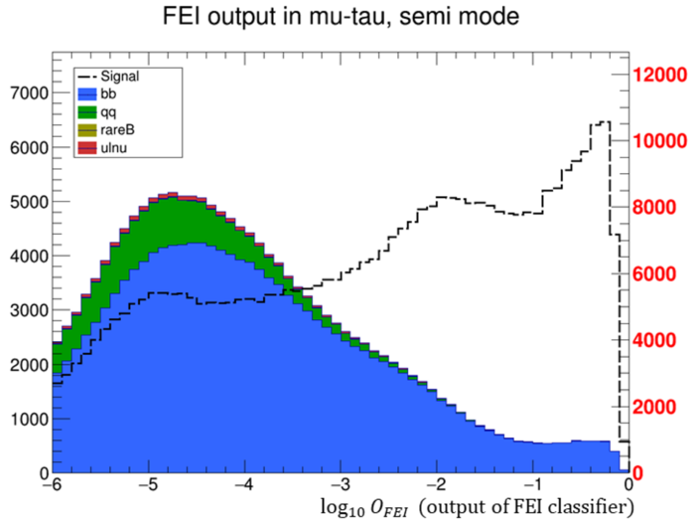
Application of B Tagging: Results

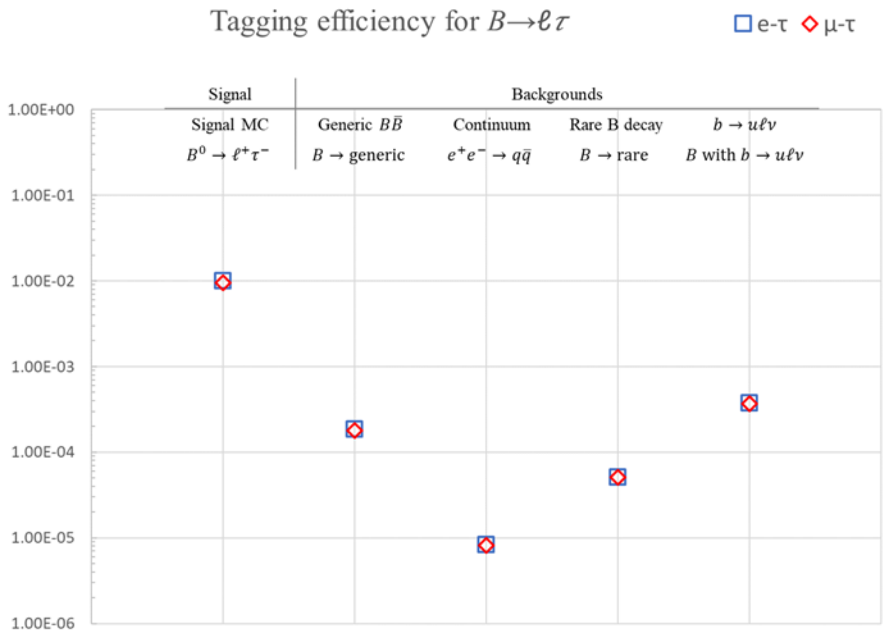
Result of B tagging[6] application

- 1% signal tagging efficiency
- 0.04% or lower background efficiency
- Tagging works:
  - High continuum suppression
  - Additional signal/background separation with classifier output

Class		Signal	Backgrounds			
Type		$B^0 \to \ell^\pm\tau^\mp$	generic B	$e^+e^- \to q\bar{q}$	rare B	$b \to u\ell\nu$
Before tagging		40×10^6	754×10^6	2350×10^6	5.66×10^6	5.47×10^6
After tagging	$B^0 \to e^\pm\tau^\mp$	400,980	138,820	19,657	287	2,050
	$B^0 \to \mu^\pm\tau^\mp$	380,315	135,908	19,068	290	2,007







Summary

e^+e^- colliders: the best condition to study B mesons

- Precise construction of $\Upsilon(4S)$ and B pair production makes the best condition for analysis.
- Suitable to apply B tagging due to clean event.
- Using B tagging can take the advantage of continuum suppression, signal/background separation with completeness, and additional variables for quality control.

The steps and processes of automatic particle reconstruction are shown.

- Training with classifiers at each steps and each particles are done.
- Application to $B^0 \to \ell^\pm \tau^\mp$ decay channel shows remarkable background suppression and signal/background separation.

Thank you!

for listening my presentation!

References

[1] BABAR Collaboration, Nucl. Instrum. Meth. A, **479**, 1 (2002).

[2] Belle Collaboration, Nucl. Instrum. Meth. A, **479**, 117 (2002).

[3] Belle II collaboration, arXiv:1011.0352 [physics.ins-det] (2010).

[4] B. Aubert et al., BaBar Collaboration, Phys. Rev. D, **77**, 091104 (2008).

[5] H. Atmacan et al., Belle Collaboration, Phys. Rev. D, **104**, L091105 (2021).

[6] T. Keck et al., Comput Softw Big Sci, **3**, 6 (2019).

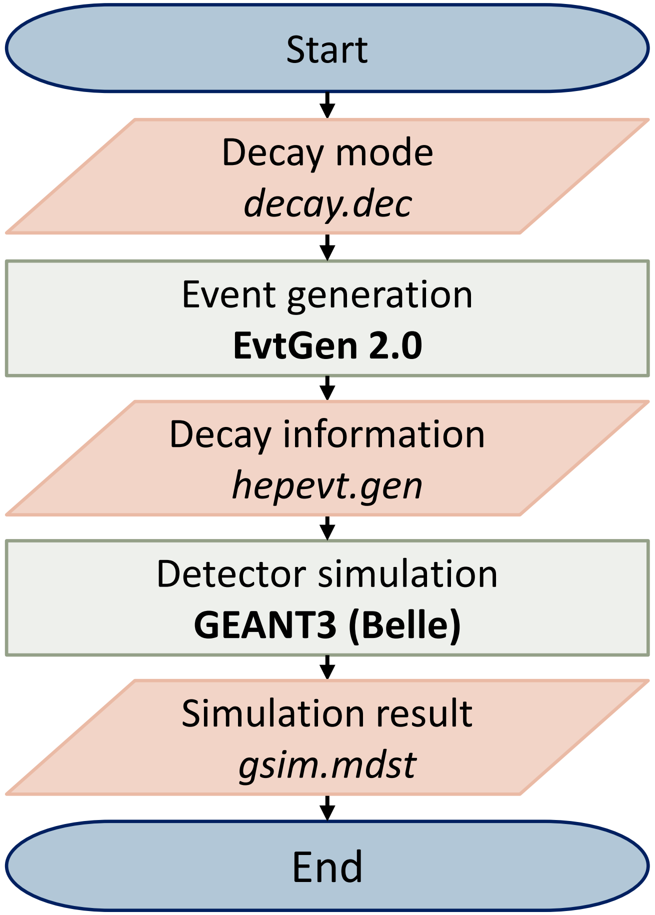
Steps for Event Simulation

B meson decay at collider

- *B* mesons will be decayed to various decay channel.
- Usually *B* daughters will be decayed to other particles.
  - π^0 meson: mean lifetime $8.43 \times 10^{-17} s$, decay to 2 γ with 98.82% probability
- Any particle will be decayed to stable particle: $e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, \gamma$

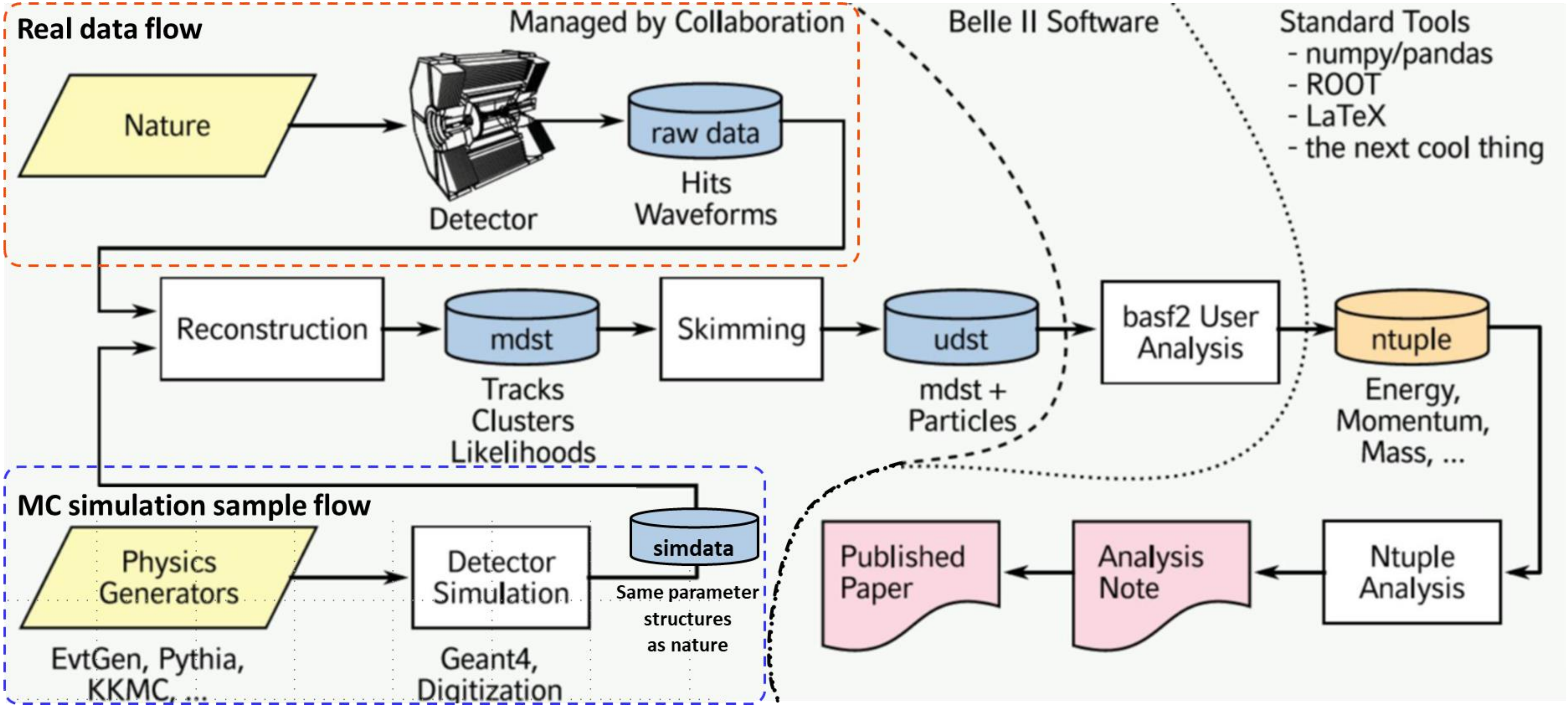
Simulation of detector-based *B* meson analysis (at Belle)

- Decay mode information is used to randomly generate tables (.gen) with event generation toolkit (EvtGen[4]).
- From the generation table, detector simulation with GEANT3[5] calculates the interaction between particles and variables.
- Simulation result (.mdst) is constructed from detector simulation.
  - Simulation results are saved same form as the data detected from detector.
  - Particles will be reconstructed from simulation results.



Particle type		Training input	Training condition
Final state particles	Charged particles (e, μ, π, K)	track information, PID information	(pre) PID information (post) P > 0.01, rank 10
	Gamma	deposited energy, shape information from calorimeters, PID information	(pre) deposited energy (post) P > 0.01, rank 20
Intermediate state particles	$\pi^0, K_S^0, J/\psi, D^0, D^+, D_s^+,$ D^{0*}, D^{+*}, D_s^{+*}	kinematic variables, vertex variables, $\prod P_{daughter}$	(pre) $\prod P_{daughter}$, $\triangle$M (pre) released energy (D*) (post) P > 0.001, rank > 10
B meson	B_{hadronic}, $B_{\text{semileptonic}}$	kinematic variables, vertex variables, $\prod P_{daughter}$ (excluding invariant mass or angular variables)	(pre) $\prod P_{daughter}$ (post) P rank 20

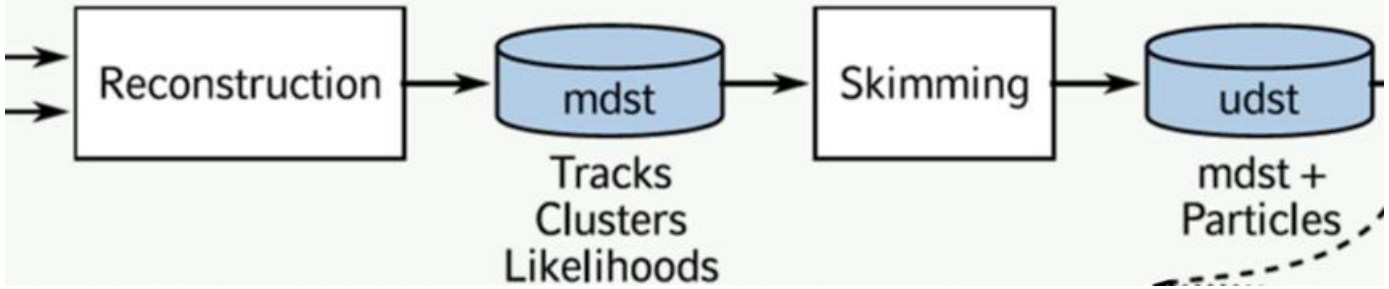
Data Flow Overview (Belle II)

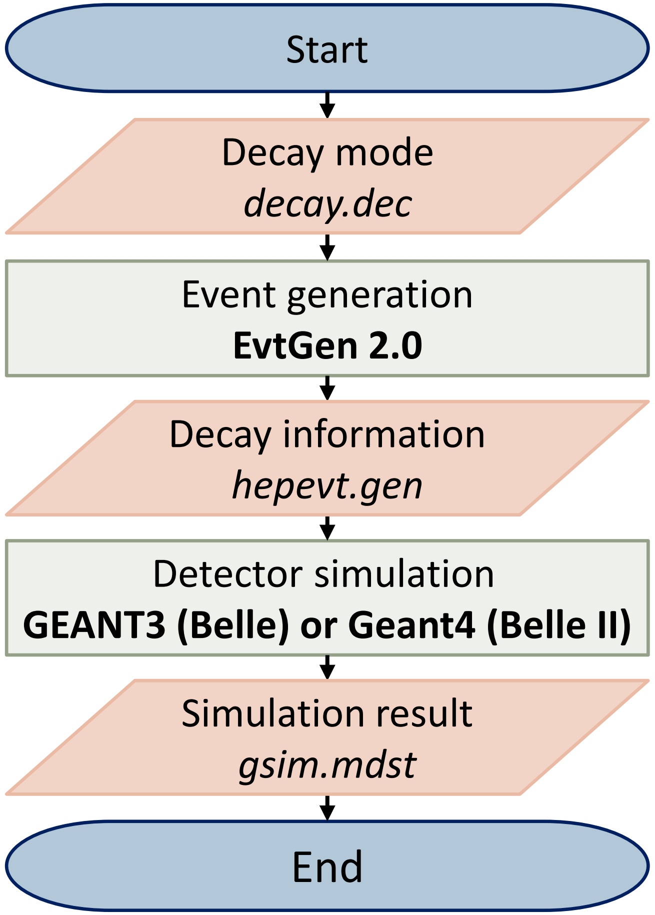


Steps for Simulation

Steps for simulation of detector-based B meson analysis

- Decay mode information is used to randomly generate tables(.gen) with event generation toolkit(EvtGen[4]).
- From the generation table, detector simulation with GEANT3[5] (or Geant4[6]) calculates the interaction between particles and variables.
- Simulation result(.mdst) is constructed from detector simulation.
  - Particles will be reconstructed from simulation results.





Introduction of $B^0 \to \ell^\pm\tau^\mp$ Decay

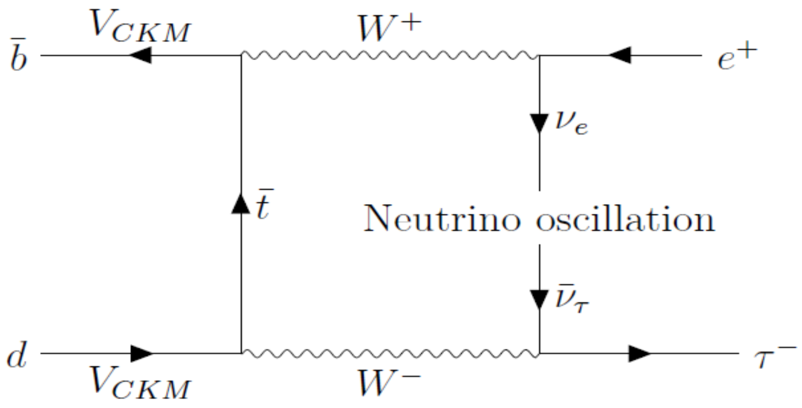
Lepton flavor violation in $B^0 \to \ell^\pm\tau^\mp$

- Forbidden in the Standard Model
- Predicted to occur in 'beyond the Standard Model' theories

Research for $B^0 \to \ell^\pm\tau^\mp$

- BaBar collaboration (2008)[4]
  - Using hadronic tagging method with 378×10^6 $B\bar{B}$ pairs
  - $\Gamma(B^0 \to e^\pm\tau^\mp) < 2.8 \times 10^{-5}$
  - $\Gamma(B^0 \to \mu^\pm\tau^\mp) < 2.2 \times 10^{-5}$
- Belle collaboration (by Hulya Atmacan, 2021)[5]
  - Using hadronic tagging method(FR) with 771×10^6 $B\bar{B}$ pairs
  - $\Gamma(B^0 \to e^\pm\tau^\mp) < 1.6 \times 10^{-5}$
  - $\Gamma(B^0 \to \mu^\pm\tau^\mp) < 1.5 \times 10^{-5}$
- My research
  - using semileptonic tagging method(FEI) with 771×10^6 $B\bar{B}$ pairs, ongoing

	B^0	$\to$	e^-	τ^+
e lepton number	0	$\neq$	1	0
τ lepton number	0	$\neq$	0	-1
	B^0	$\to$	μ^-	τ^+
μ lepton number	0	$\neq$	1	0
τ lepton number	0	$\neq$	0	-1



Feynman diagram of $B^0 \to e^+\tau^-$ with neutrino oscillation