Master thesis internship

Flavour tagging

Primary Vertex identification

using advanced deep machine learning techniques

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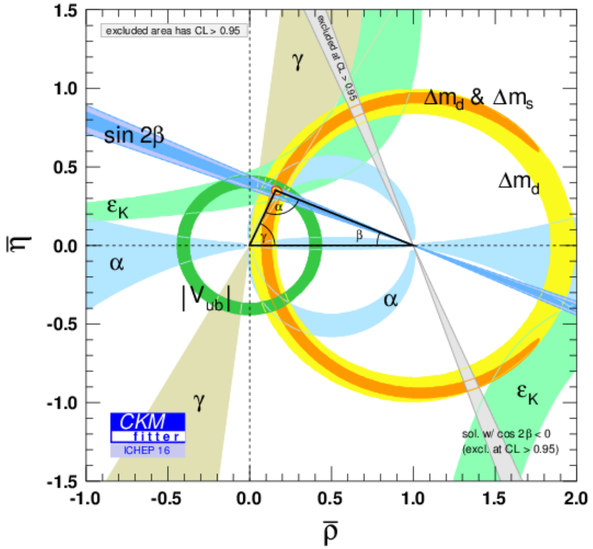
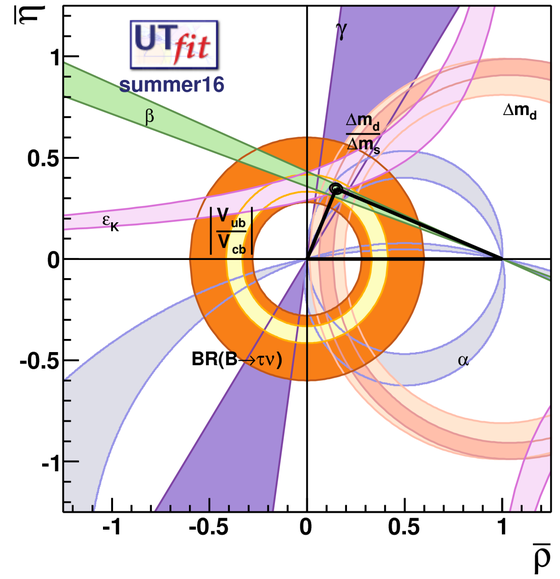
Time-dependent *CP* violation

- **CKM mechanism introduces *CP* violation and neutral meson mixing phenomena**
  - The presence of new heavy particles exchanged in virtual loops could introduce additional phases altering the corresponding measurements
  - Constraining these phases put stringent limits on a large range of NP models
- ***CP* violation is needed to explain baryon asymmetry in the Universe**
  - Discovered in 1964 in the kaons, 2004 in the *B* and each time awarded with Nobel Prizes
  - Still missing 10 orders of magnitudes!
- **Experimentally, *CP* violation observables accessed through ratios of measured quantities**
  - Cancelation of many experimental systematics
  - Flagship measurements for LHCb and Belle II





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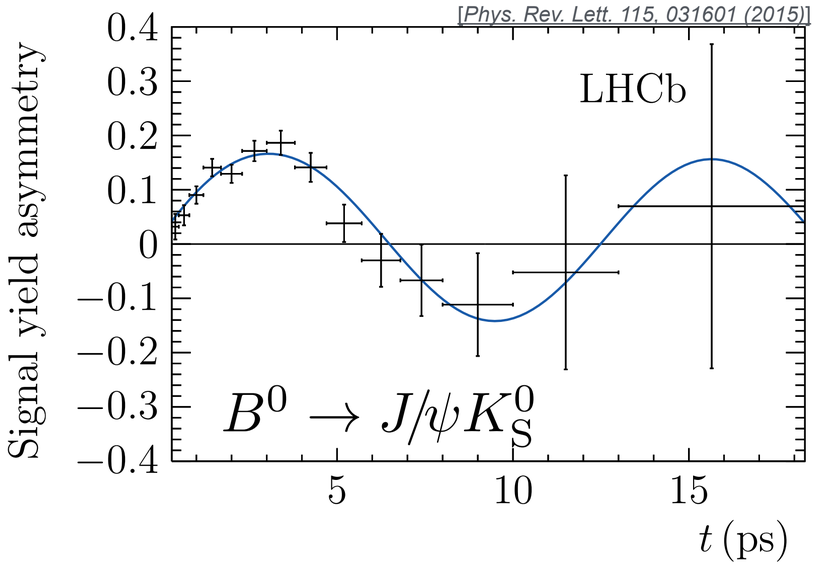

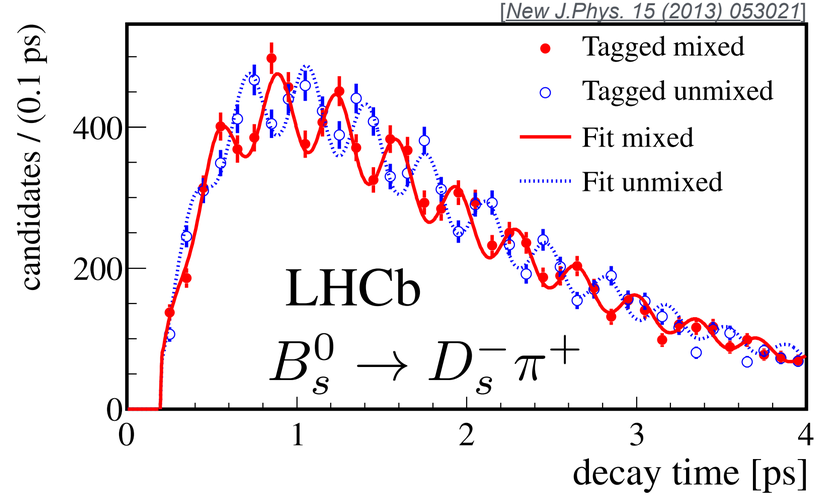

- **Time-dependent *CP* asymmetry:**

$$\mathcal{A}_{CP}(t) = \frac{\Gamma\left(\overline{B}^0_q(t) \to f\right) - \Gamma\left(B^0_q(t) \to f\right)}{\Gamma\left(\overline{B}^0_q(t) \to f\right) + \Gamma\left(B^0_q(t) \to f\right)} = \frac{\mathcal{S}_f \sin\left(\Delta m t\right) - \mathcal{C}_f \cos\left(\Delta m t\right)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

Measurements of time-dependent asymmetries and decay rates require knowledge of ***B* flavour at the production time (*t* = 0)**

Flavour tagging algorithms tag the candidate as ***B*** or $\overline{\boldsymbol{B}}$ (tag decision) with some ***efficiency*** and ***mistag probability***

Flavour tagging

- **Motivation : <u>essential</u> ingredient for <u>ALL</u> time dependants analyses**

$$\sigma^{\text{stat}}(CP \text{ asym}) \propto \frac{1}{\sqrt{\varepsilon_{\text{eff}} N}}$$

Flavour tagging

- **Motivation : <u>essential</u> ingredient for <u>ALL</u> time dependants analyses**
- **Goal & challenges :**
  Develop algorithms that exploit the charge correlations of particles produced together with B mesons in order to determine their production flavour (tagging)

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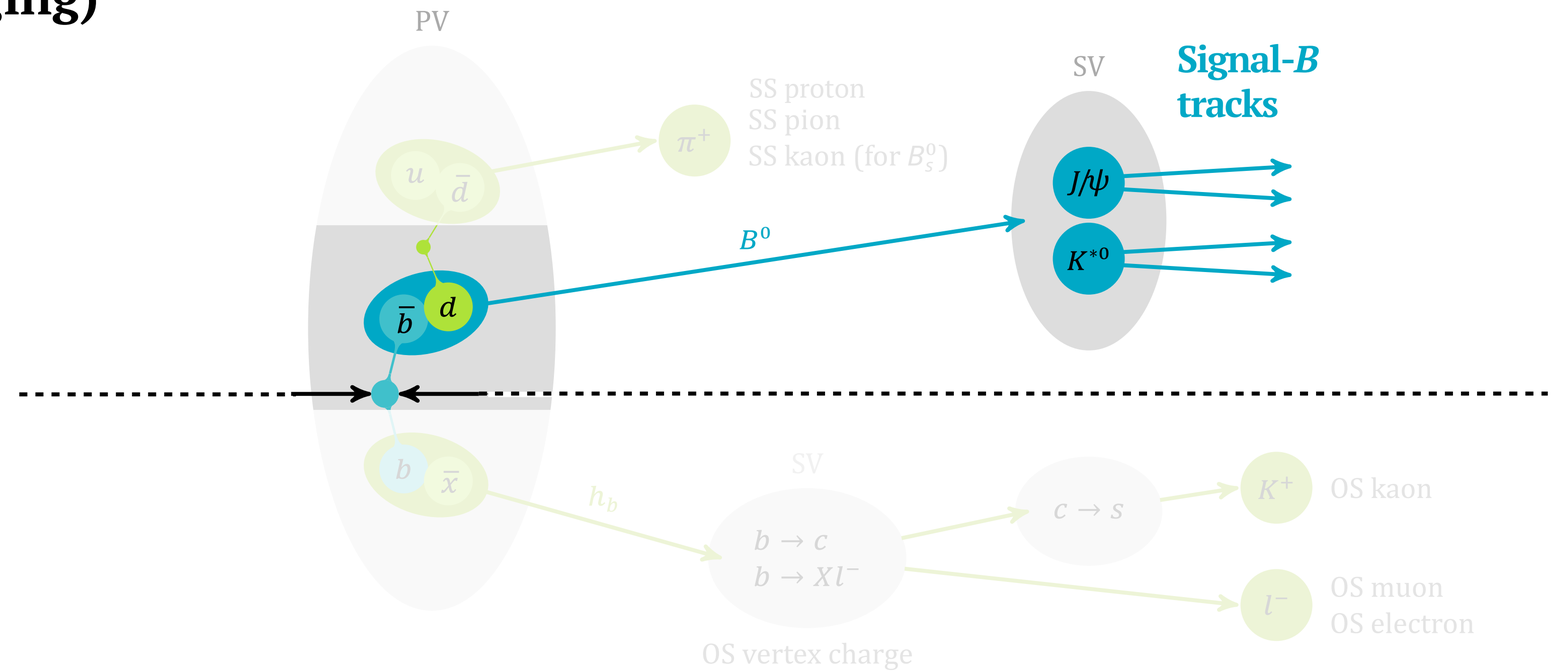

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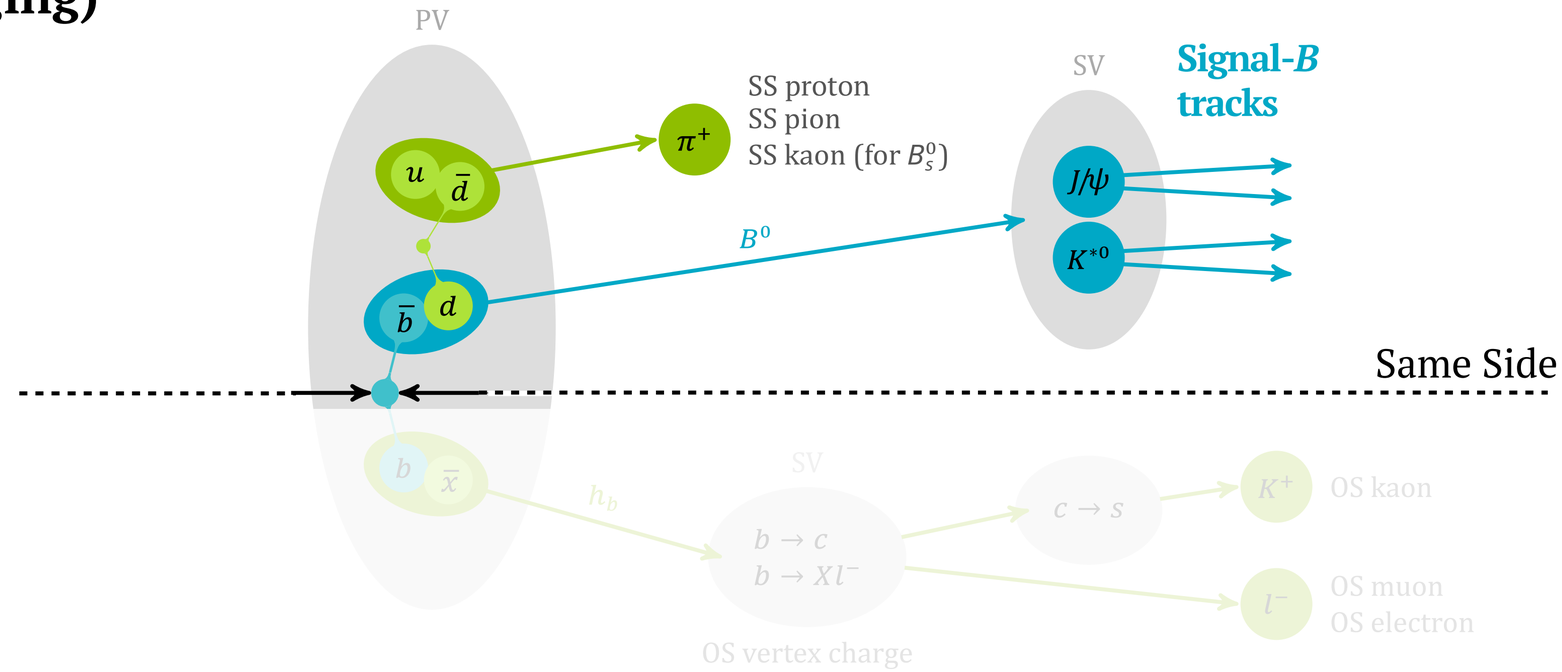

Opposite Side (OS) : particles originating from the secondary vertex of the other b hadron **<5%> tracks**

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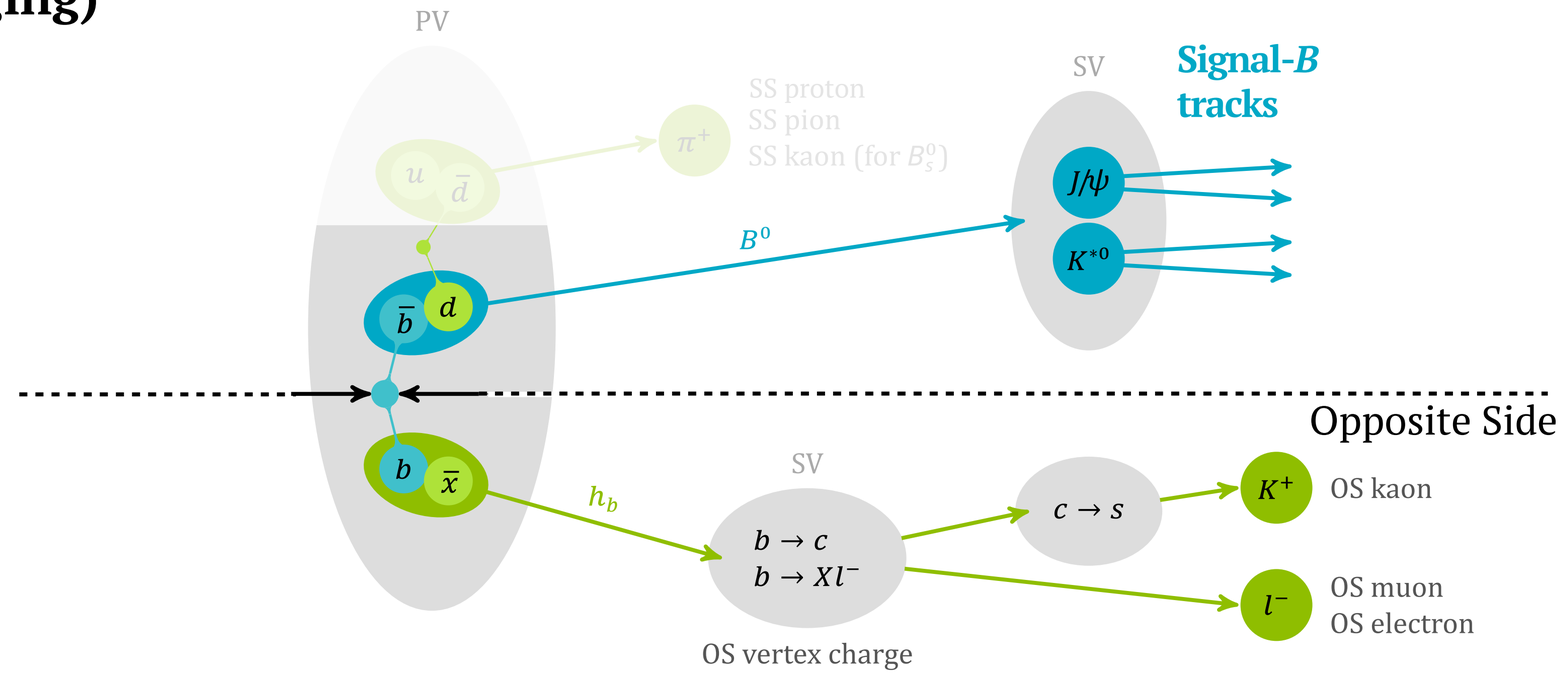

Opposite Side (OS) : particles originating from the secondary vertex of the other b hadron **<5%> tracks**
Same Side (SS) : particles produced in the hadronisation/fragmentation process **<7%> tracks**

Flavour tagging with advanced deep machine learning techniques

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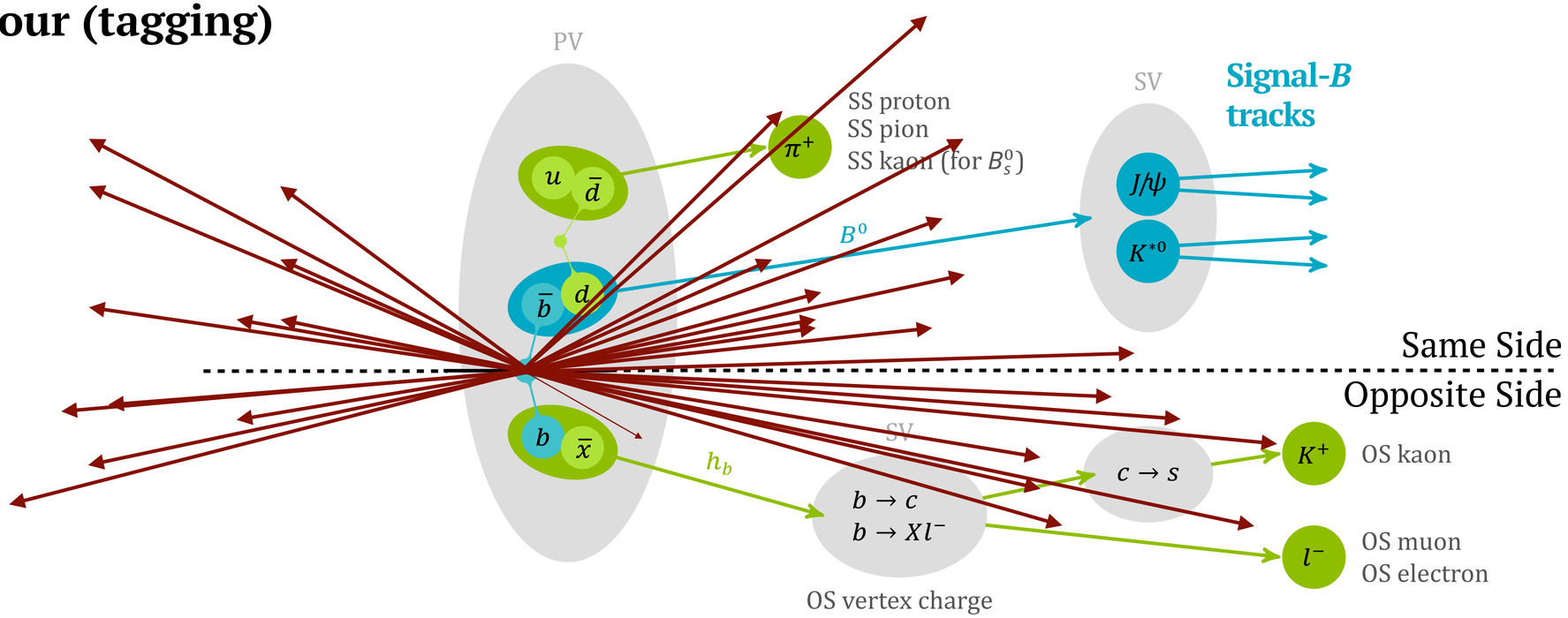
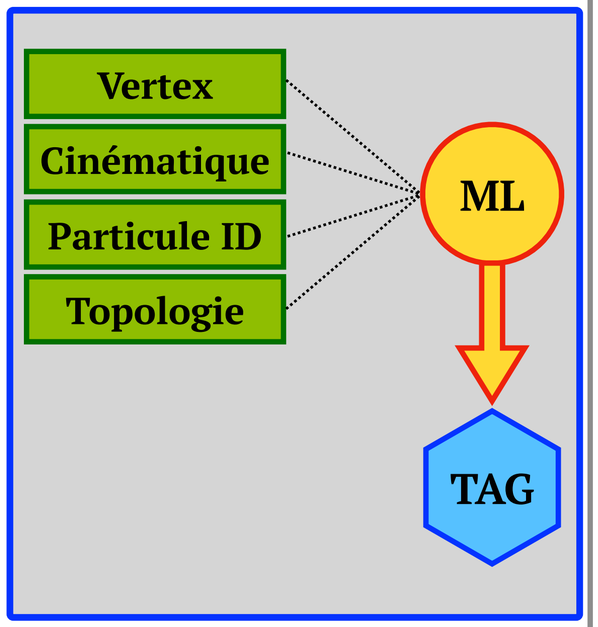
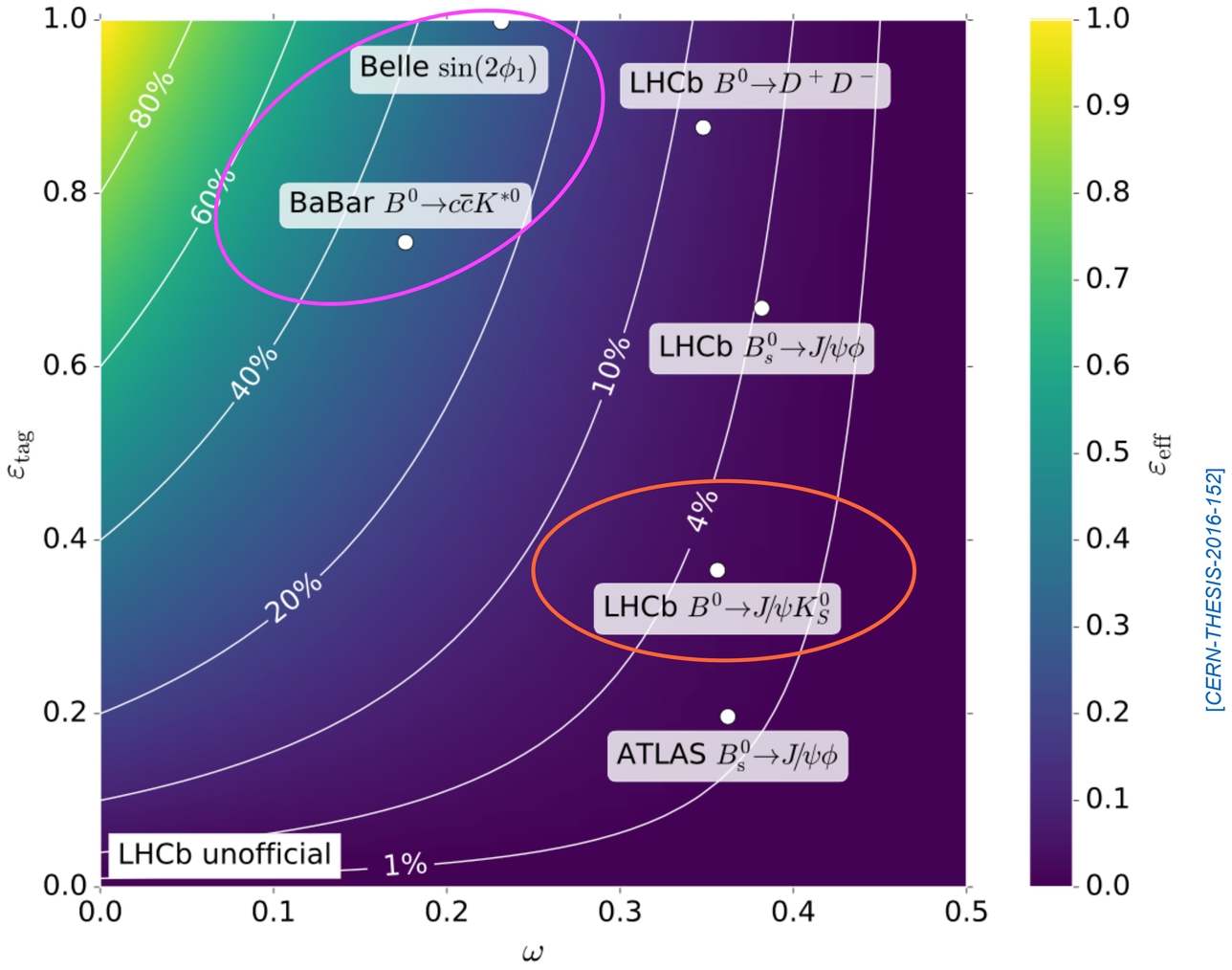




Opposite Side (OS) : particles originating from the secondary vertex of the other b hadron **<5%> tracks**
Same Side (SS) : particles produced in the hadronisation/fragmentation process **<7%> tracks**
Background : particles from soft-QCD pp interactions **<83%> tracks**

Flavour tagging



$$\sigma^{\text{stat}}(CP \text{ asym}) \propto \frac{1}{\sqrt{\varepsilon_{\text{eff}} N}}$$

An ambitious **two-fold improvement** in flavour-tagging performance is equivalent to having "**collected twice as much data**"

This would have a strong impact on the LHCb collaboration!

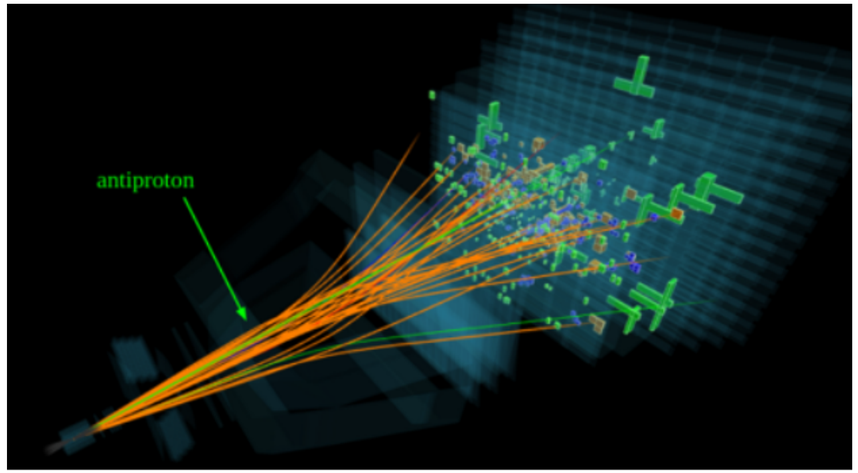
Primary vertex identification

- **Motivations :**
  - Over the next years, the LHC detectors will face significantly increased luminosities
  - One of main challenges in this high pile-up environment will be the ability to perform efficient vertexing
- **Goals :**
  - **train realistic algorithms (in terms of fidelity and throughput) to find Primary Vertexes with high efficiency while producing false positives at low rates**
  - **understand how the results depend on underlying model architectures and input features**

Primary vertex identification

What is Primary Vertex finding?

- When two beams collide inside a detector, we observe the collision through the particles it produces
- The trajectories (tracks) of particles produced by the collision are reconstructed by an existing algorithm and encoded though **POCA** (point of closest approach) values



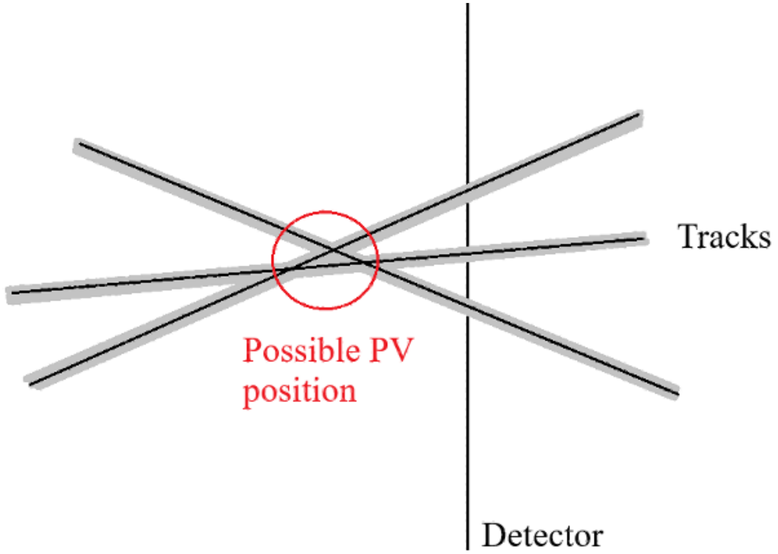
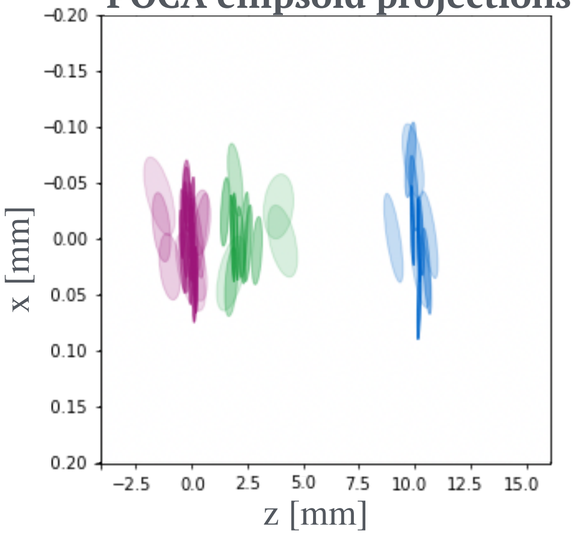
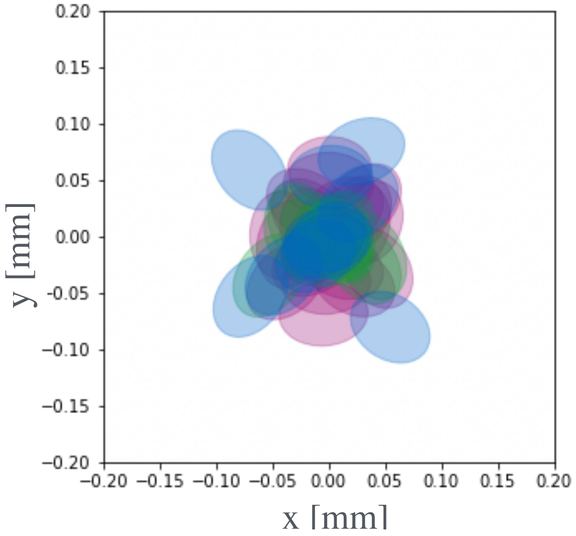


Illustration:
POCA ellipsoid projections

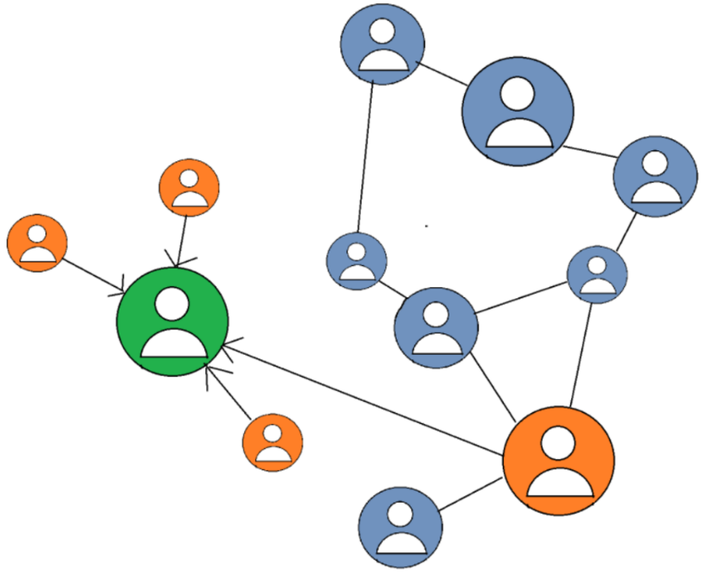




Primary vertex identification

Graph Neural Networks (GNN):

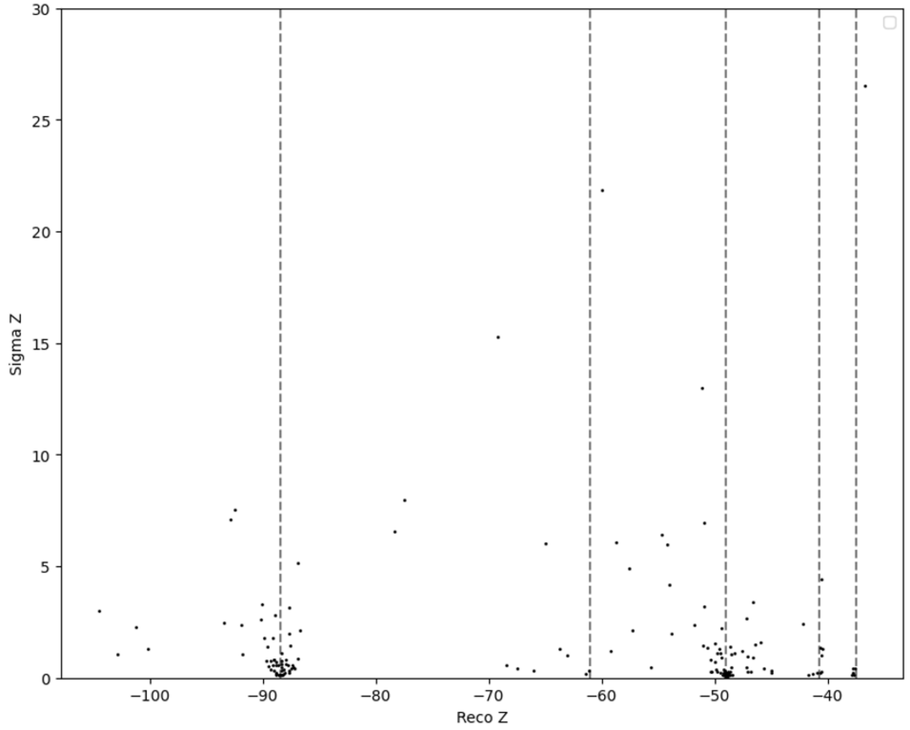
- Type of Artificial Intelligence Algorithm
- Data is represented by a graph with nodes and edges
- Data that can be represented by a graph examples:
  - Social Networks (nodes = people, edges = friendship)
  - Transportation Systems (nodes = cities, edges = roads)
  - Collision events (nodes = tracks, edges connect close tracks)
- The graphs are then used as the information the Neural Network is trained on, the GNN than makes prediction for a node based or edge based value
- Message passing step allows information from nearby nodes (connected by an edge) to influence node prediction

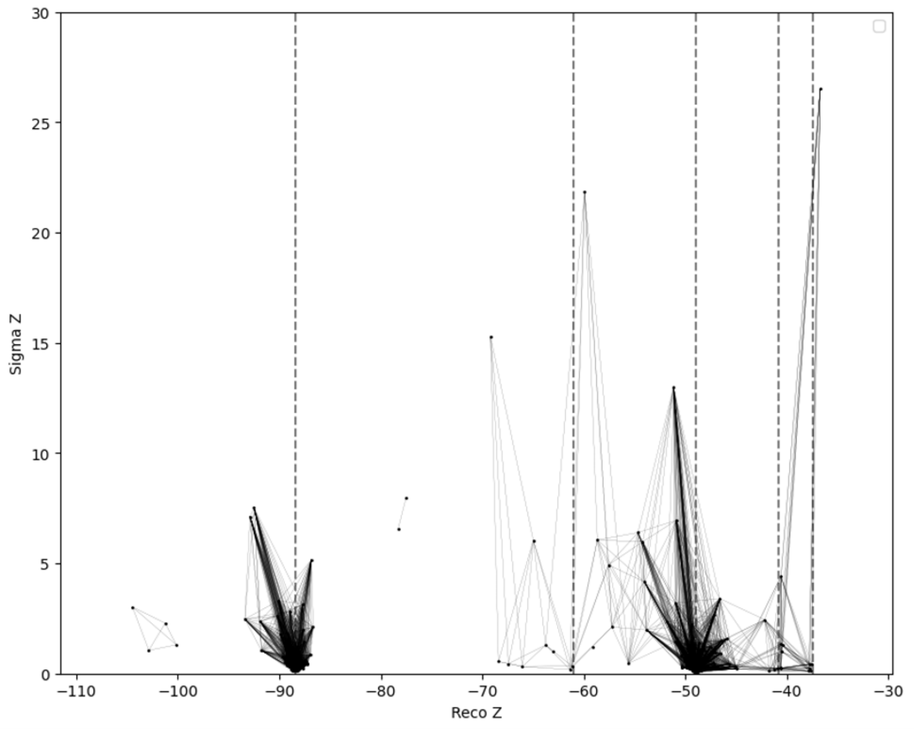


Primary vertex identification

GNN algorithm:

- Group tracks (build edges) from "distances"

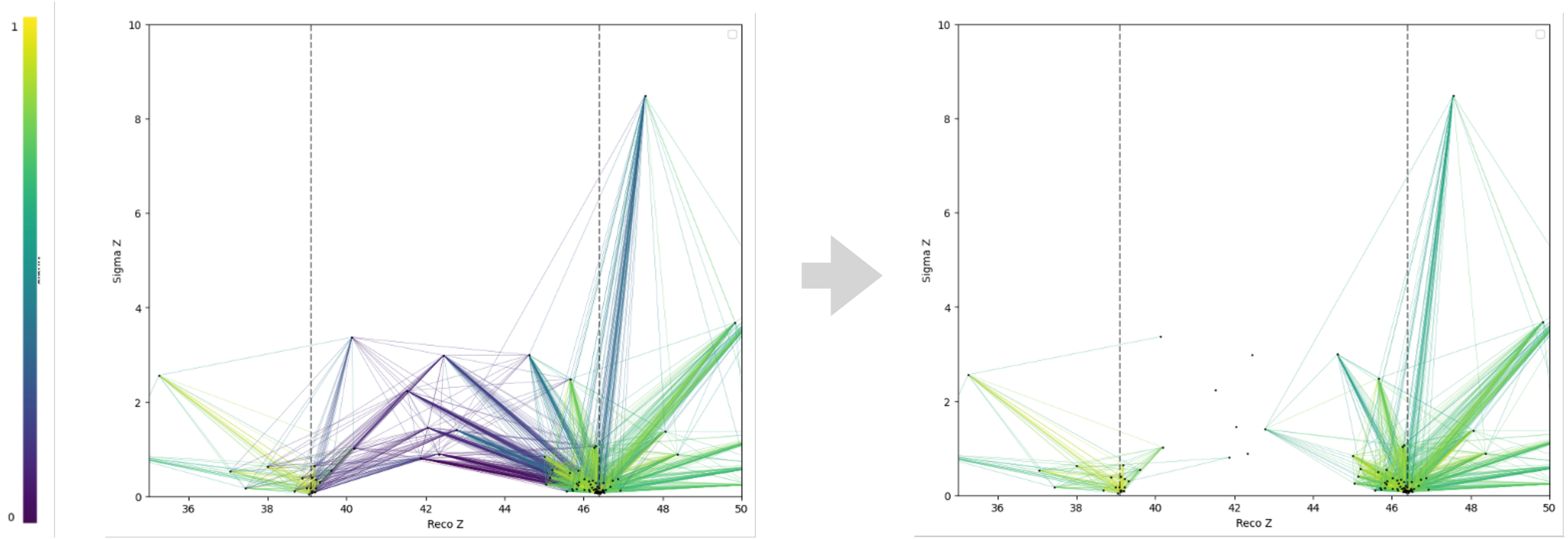




Primary vertex identification

GNN algorithm:

- Group tracks (build edges) from "distances"
- Train GNN to best identify which tracks are likely to originate from same interaction point



Summary

- **Flavour tagging**
  - Participate in the improvement of flavour tagging at LHCb
- **Primary vertex identification**
  - Participate in the improvement of vertex identification at LHCb
  - **In both cases develop expertise in advanced ML tools: Graph Neural Network, Transformer…**