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FSP LHCb
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Flavour Tagging at the LHCb experiment

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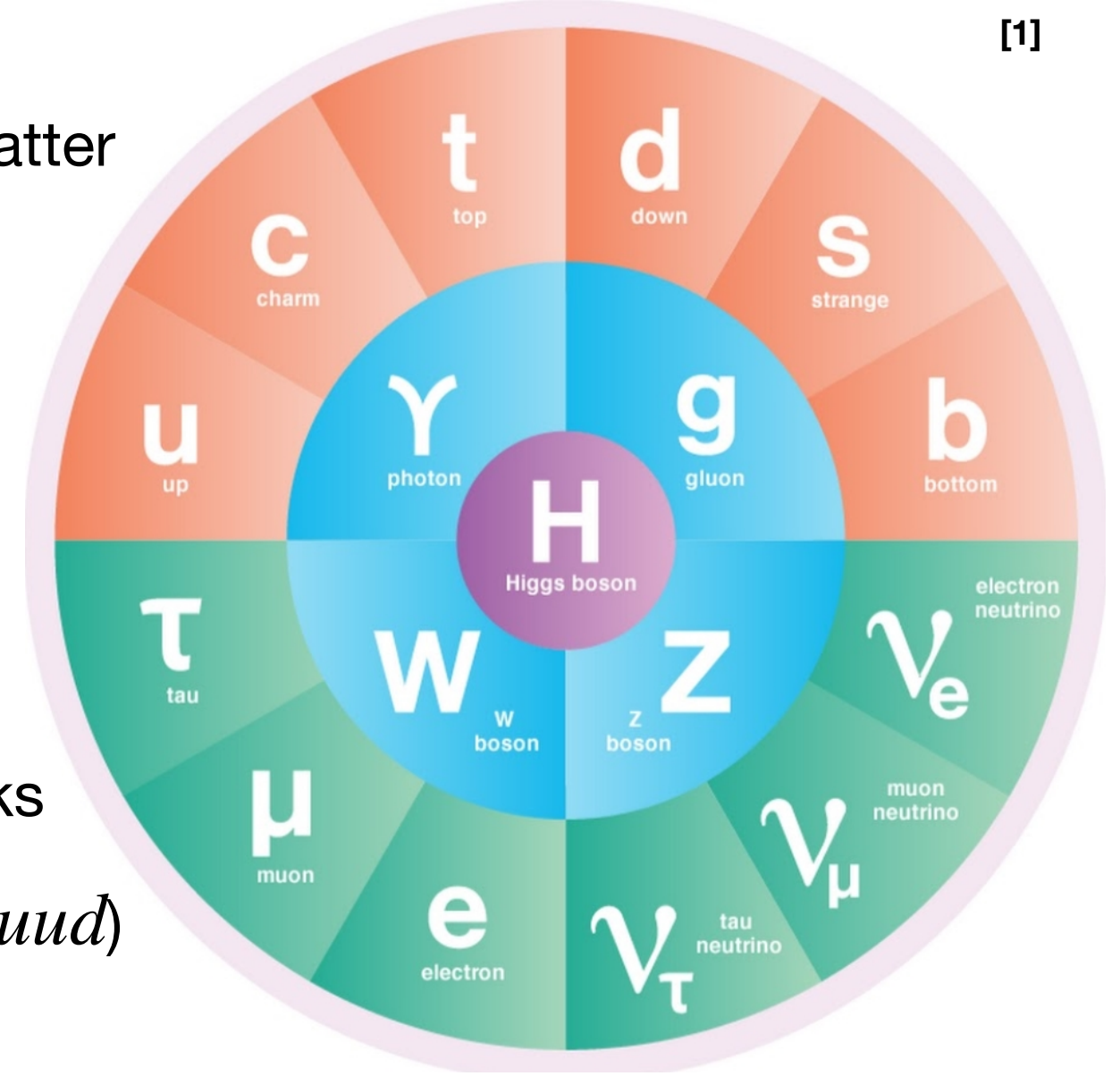
Quarks & Hadrons

Quarks:

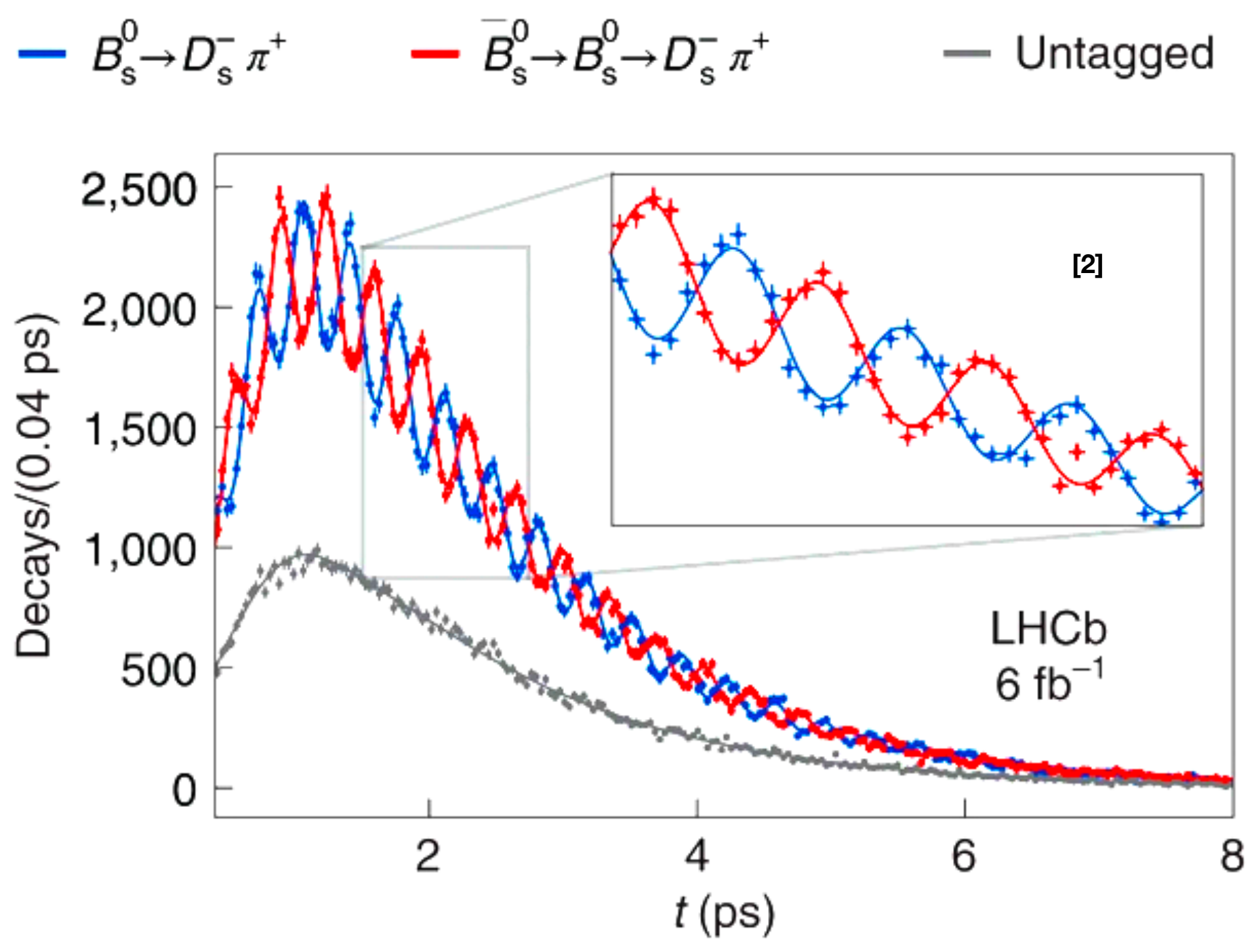
- Fundamental building blocks of visible matter in the universe
- 3 generations of particles
- Carry colour charge (RGB)
  → not observable as free states



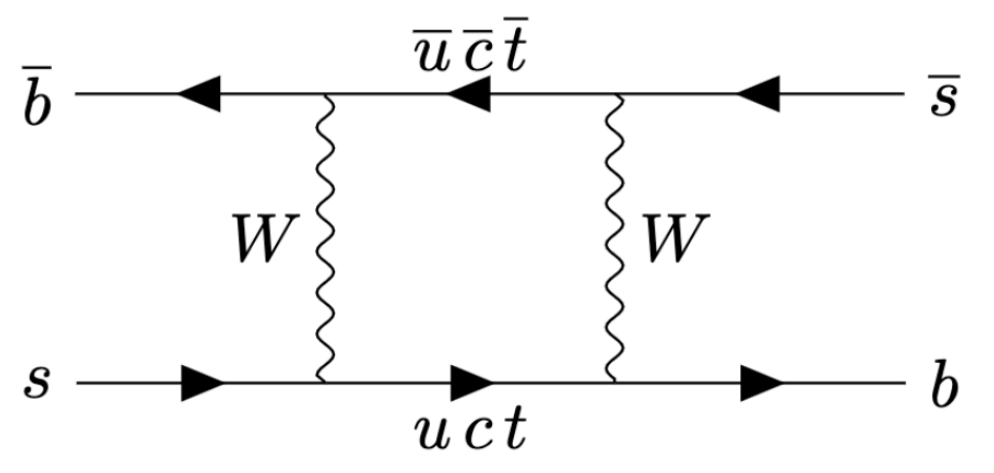
Hadrons:

- Colour-neutral bound states of (anti)quarks
- Baryons made of qqq ($\bar{q}\bar{q}\bar{q}$), e.g. proton (uud)
- Mesons made of $q\bar{q}$, e.g. $B_s^0/\bar{B}_s^0$ ($\bar{b}s/b\bar{s}$)

Neutral B meson mixing & CPV



- Matter & antimatter connected via **C**harge & **P**arity (CP) transformation
- Baryons & charged mesons are fixed to (anti)particle state
- Neutral mesons constantly oscillate between states ("flavour")



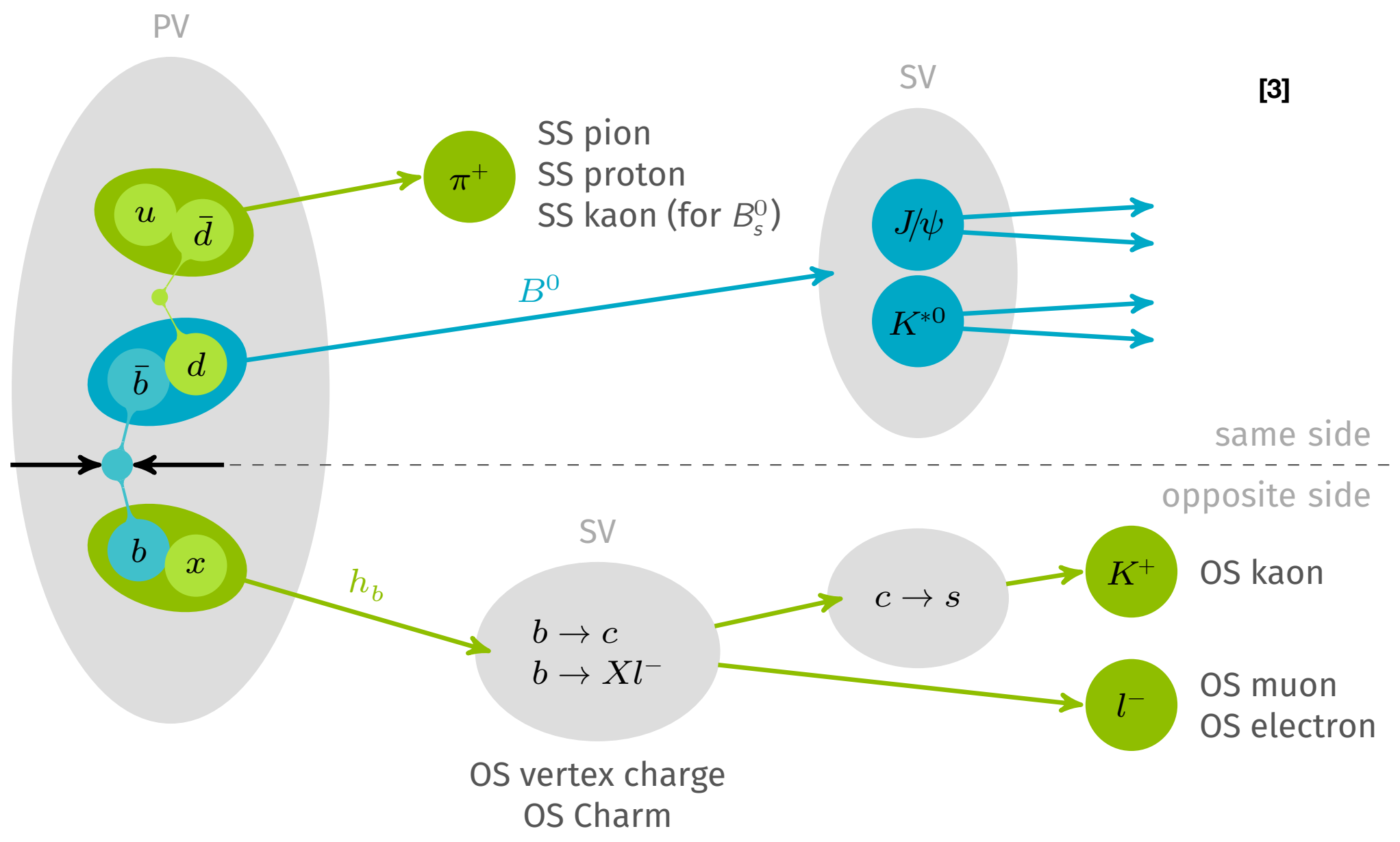
- CP symmetry violated (CPV) → difference between matter and antimatter
- Neutral (B) mesons: time-dependent CPV measurement possible due to oscillation
- Correct knowledge of flavour at decay needed to determine asymmetry in mixing and decay

A method is needed to identify state of particle at production.

Current Flavour Taggers at LHCb

Same Side (SS) taggers:

- Use charged particles produced alongside the signal $B^0_{(s)}$ meson (**Frag**mentation) to directly identify the signal flavour
  - SS Kaon for B_s^0 identification
  - SS Pion/Proton for B^0 identification



Opposite Side (OS) taggers:

- Use properties of non-signal b hadron decay coming from the initial $b\bar{b}$ pair → independent of signal meson type (B^0/B_s^0)
  - OS Vertex Charge: measures average charge of OS tracks
  - OS Charm: uses $\Lambda_c^\pm/D^\pm$ from $b \to c$ transition
  - OS Kaon: uses charged kaon in the final state
  - OS Muon/Electron: use lepton from semi-leptonic B decay

Tagging outputs:

- Tag decision d: prediction of initial signal B flavour
- Mistag estimate η: per event prediction of how likely the wrong d was assigned

Flavour Tagging characteristics:

- Tagging efficiency: fraction of successfully tagged events

$$\varepsilon_{tag} = \frac{N_{right} + N_{wrong}}{N_{right} + N_{wrong} + N_{untagged}}$$

- Average mistag probability: fraction of events with wrong tag decision
- Mistag prediction does not necessarily match the true mistag: calibrate η on flavour specific decays of real mesons using a linear function

$$\omega(\eta) = p_0 + p_1(\eta - \langle\eta\rangle)$$

- Effective tagging power: reduced efficiency due to dilution $D = 1 - 2\omega$ of mistaged events

$$\varepsilon_{eff} = \varepsilon_{tag} D^2$$

All tagging algorithms use a selection based approach as well as multivariate analysis.
The selection process depends on good particle identification and specific domain knowledge.
Good performance therefore requires a trade-off between tag quality and tagging efficiency.

The Inclusive Flavour Tagger (IFT)

The goal is to find a more general approach for LHCb to determine the production flavour of a decaying meson. Using advanced Machine Learning techniques the IFT aims to increase the performance and potentially replace the current ensemble of tagging algorithms.

The idea:

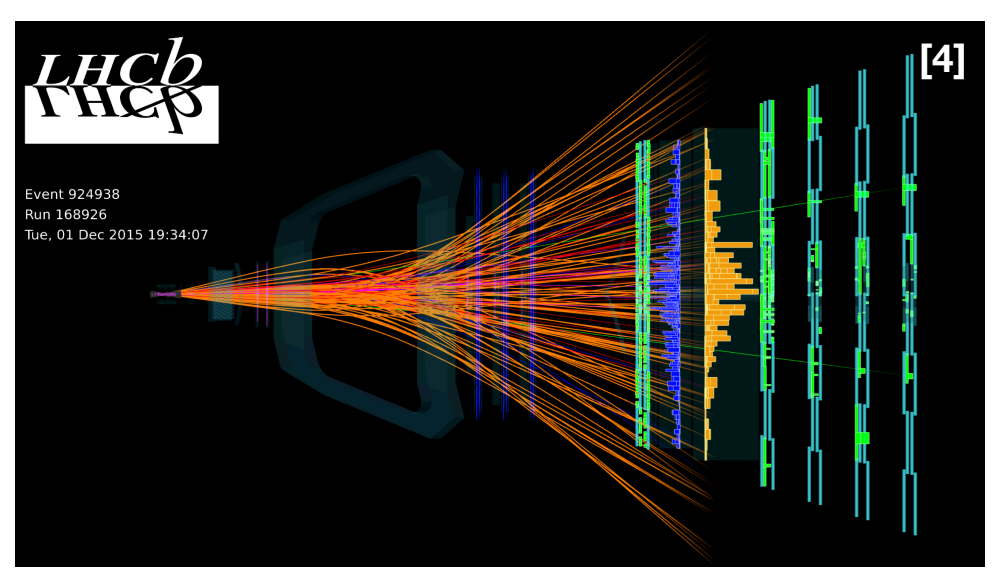
- Use all reconstructed tracks & vertices in an event not related to signal decay chain
  → not rely on specific segments and physics assumptions
- Apply only a loose selection to achieve high $\varepsilon_{tag} \lesssim 100\,\%$
  → let the neural network (NN) learn to recognise important information

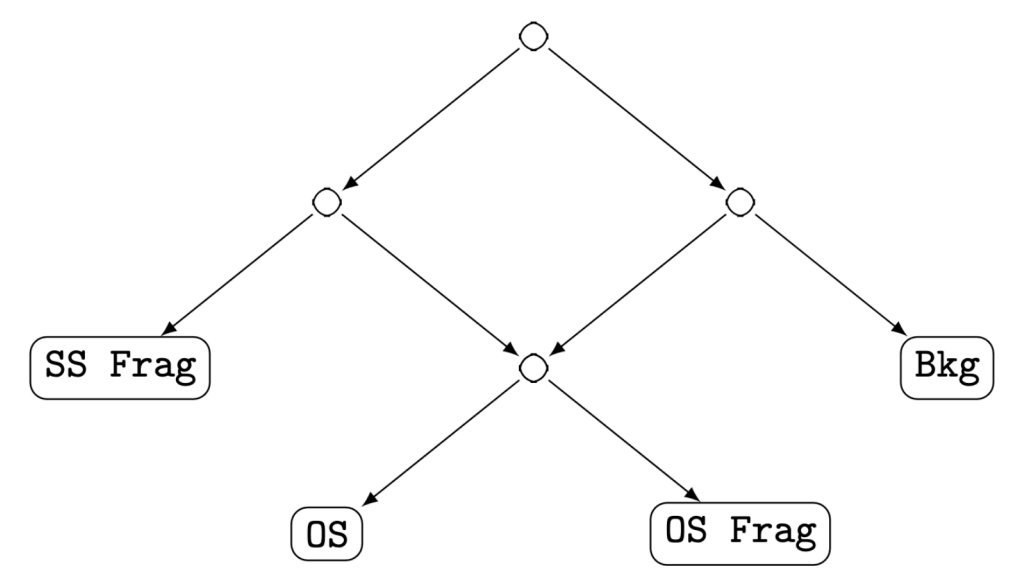
First implementations:

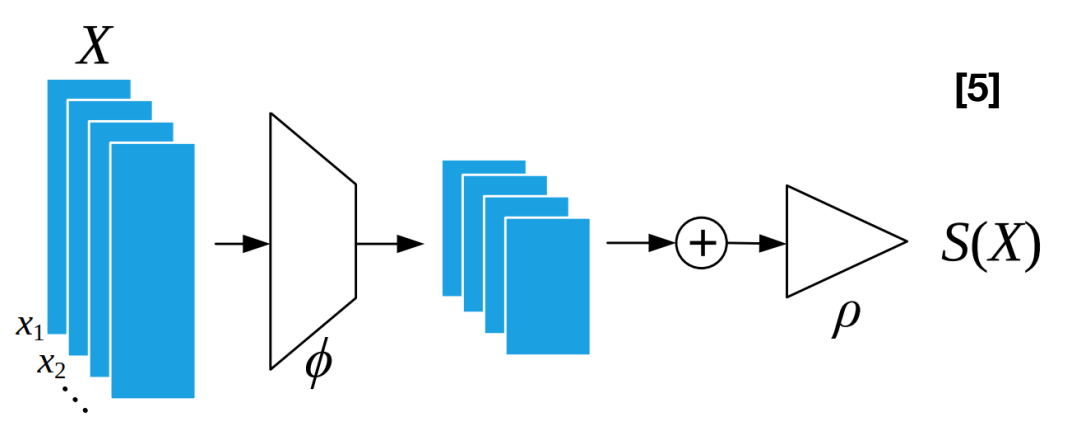
- Categorise tracks based on topology (SS Frag, OS, OS Frag)
  → multiclass Boosted Decision Tree (BDT) output as extra input for NN
- Number of tracks/vertices varies from event to event
  → DeepSet for fast training & to adapt for different input sizes

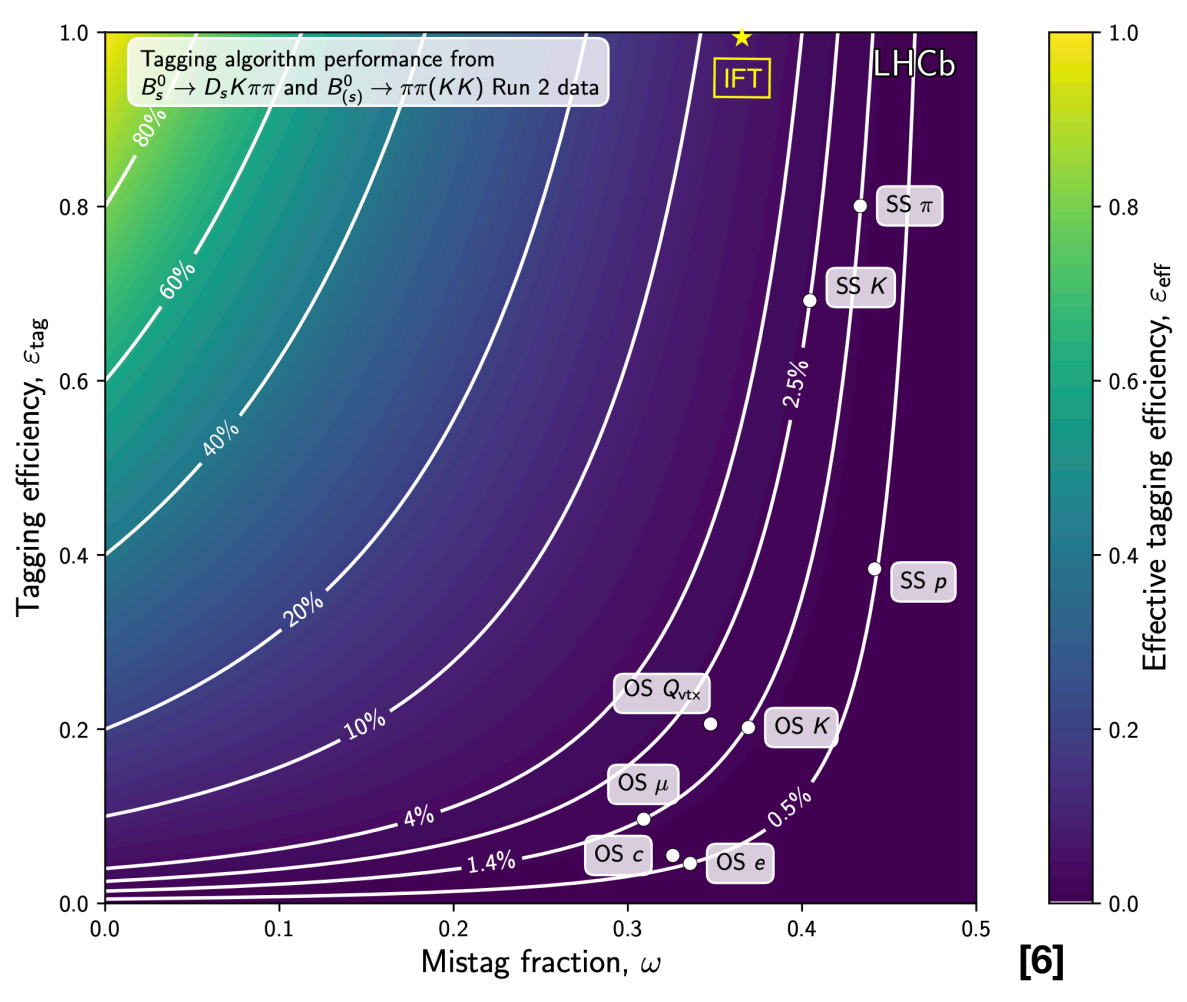
Training data:

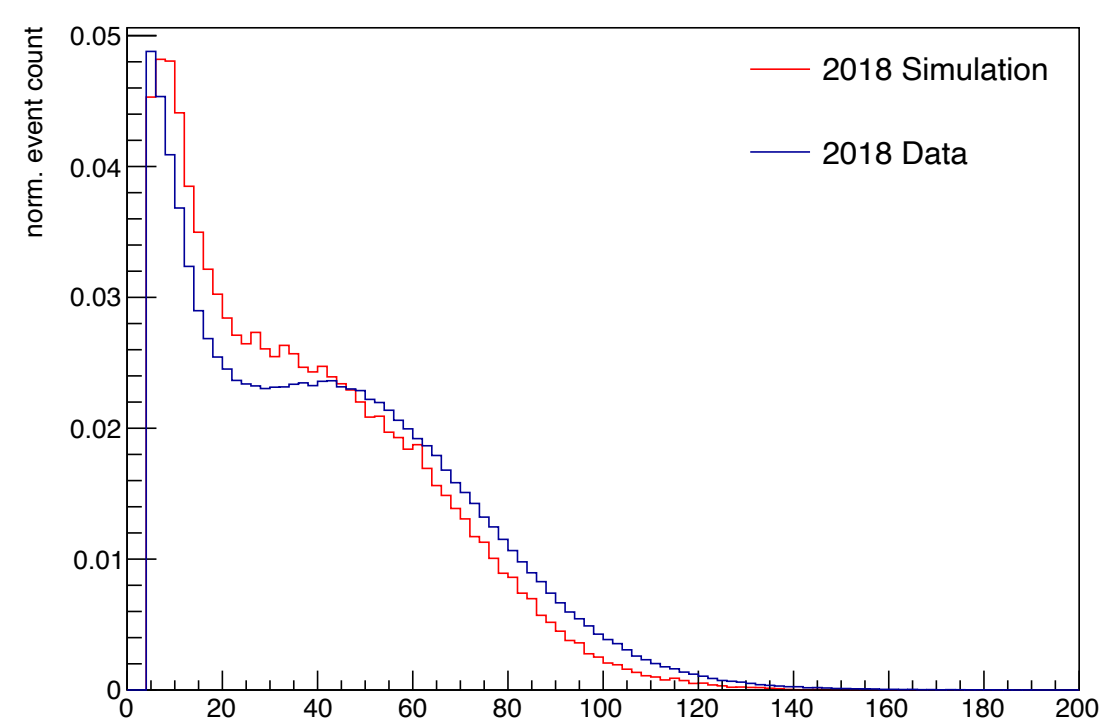
- Real data:
  - Background contamination
  - Limited statistics for specific decay channels
  - Difficult labelling in neutral meson decays
- Simulation:
  - Not a perfect description of reality
  - Pure signal samples
  - Truth information available
- Idea: train two separate taggers & combine their predicted tag decisions
  - SS tracks dependent on signal decay type: train SS-IFT on individual simulated samples for different decays
  - Train OS-IFT using real "self-tagging" $B^\pm \to J/\psi K^\pm$ decays
    → can be cross-applied on other channels











The IFT as the future of flavour tagging:

- Benefits:
  - Increased tagging power & high tagging efficiency
  - Simple framework: only one tagger needs to be trained the same way for different channels
- Challenges:
  - Complete event information used → sensitive to differences between simulation and real data
  - Background contribution have to be accounted for during training with real self-tagging decays
  - Real data training SS tagger not feasible for neutral meson decays due to oscillation
  - NN structure is a "black box" → hard to interpret compared to classical taggers
- Plans:
  - Test using detector output directly as input features instead of/in addition to reconstructed high level variables
  - Optimisation of training procedure & network architecture
  - Validate performance on different channels in real data

[1] https://www.energy.gov/science/doe-explainsthe-standard-model-particle-physics
[2] LHCb collaboration. Precise determination of the B_s^0–$\bar{B}_s^0$ oscillation frequency. *Nat. Phys.* 18, 1–5 (2022)
[3] https://twiki.cern.ch/twiki/bin/view/LHCb/FlavourTaggingConferencePlots
[4] https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015
[5] Manzil Zaheer et al. *Deep Sets*. 2017 https://arxiv.org/abs/1703. 06114
[6] Comparison of Flavour Tagging performances displayed in the ω-$\varepsilon_{\mathrm{tag}}$-plane LHCB-FIGURE-2020-02

CS & Physics Meet-Up by Lamarr & B3D, 29.11. - 01.12.23