GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

AGENCIA ESTATAL DE INVESTIGACIÓN

Inclusive flavour tagging at LHCb

Borja Sevilla Sanjuan PhD student

laSalle
UNIVERSITAT RAMON LLULL

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LHCb

Contents

1. CP Violation and time dependent CP asymmetries

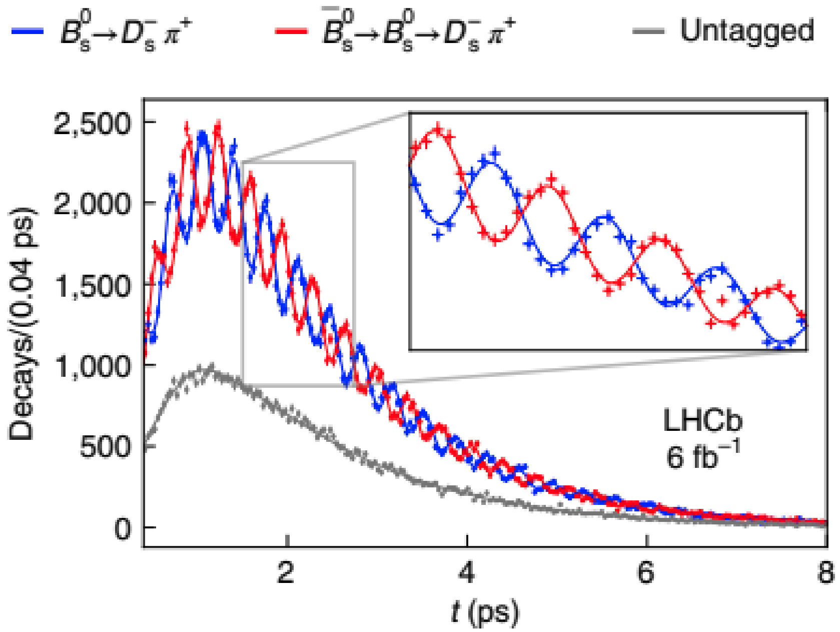
- CP violation and mixing measurements of neutral B mesons decays require the flavour at production of the reconstructed B meson, i.e. whether it contained a b or $\bar{b}$ quark at production time

  - Time dependent CP asymmetry

$$A_{CP}(t) = \frac{\Gamma(B_q^0 \to f)(t) - \Gamma(\bar{B}_q^0 \to f)(t)}{\Gamma(B_q^0 \to f)(t) + \Gamma(\bar{B}_q^0 \to f)(t)}$$

  - Measuring B-mixing Δm(s)

$$A_{CP} = \frac{\Gamma(B_q^0 \to f) - \Gamma(\bar{B}_q^0 \to \bar{f})}{\Gamma(B_q^0 \to f) + \Gamma(\bar{B}_q^0 \to \bar{f})}$$



arXiv:2104.04421

[2]

[1Tellarini, G. (2017). B-flavour tagging calibration for CP violation measurement in K decays at LHCb

[2] 2021. LHCb. Precise determination of the B0s-B0sbar oscillation frequency

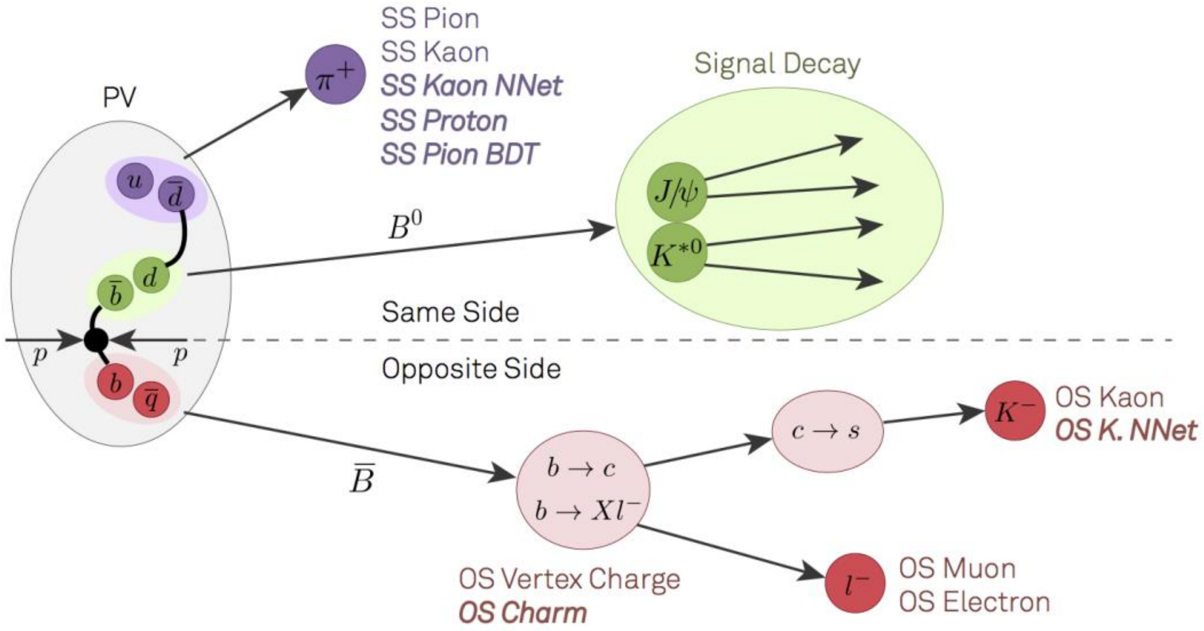
2. Classical Flavour tagging in LHCb

Flavour tagging: all techniques that allow to determine if a given B signal decay contains a b or an $\bar{b}$ quark at production time

CLASSICAL TAGGERS

- **Same Side taggers** aim to select charged particles that are produced in the same hadronization process of the signal B meson

- **Opposite Side taggers**
exploit the decay of the other b-hadron to infer the flavour of the signal B meson



[1Tellarini, G. (2017). B-flavour tagging calibration for CP violation measurement in K decays at LHCb

2. Flavour tagging in LHCb and challenges

Common challenges for FT algorithms in LHCb are:

- Untagged events : **tagging efficiency** $\varepsilon_{tag}(\%)$

$$\boldsymbol{\varepsilon} = \frac{Ntagged}{Ntotal}$$

- Wrong tagging decisions. This compromise the **mistag probability ω** (0-0.5).

$$\boldsymbol{\omega} = \frac{N\,wrong\,tagged}{N\,wrong\,tagged + N\,correct\,tagged}$$

- The figure of merit that measures the performance of flavour tagging algorithms is the tagging power.

Dilution to the yields

$$\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}}\langle D^2\rangle = \varepsilon_{\text{tag}}\langle\underbrace{(1-2\omega)^2}\rangle$$

3. Inclusive flavour tagging

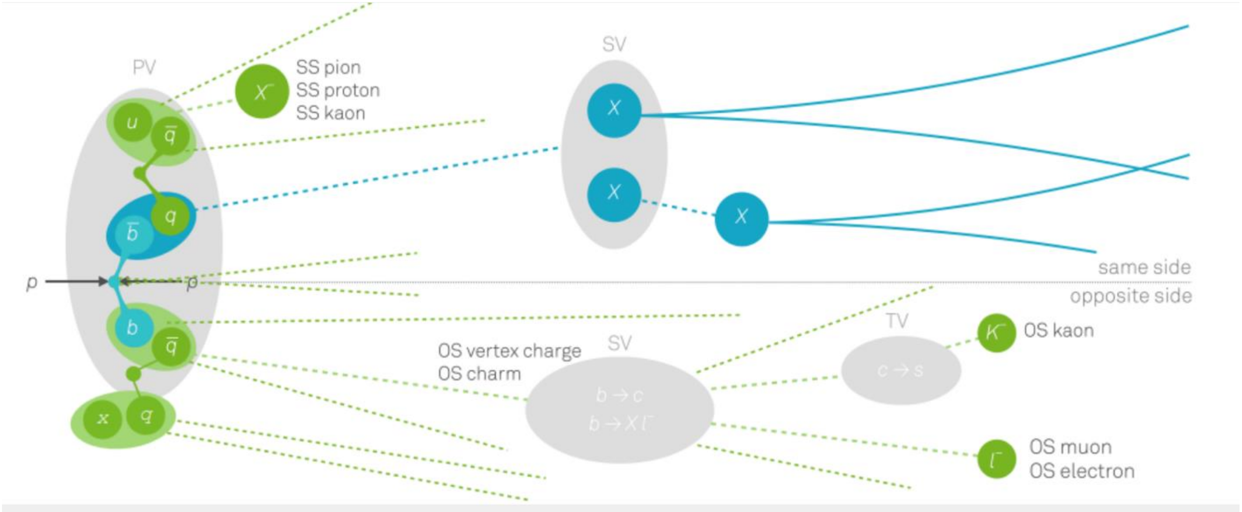
UNIVERSIDADE DA CORUÑA

IFT Deepset presented by 2024 John Wendel CPAN 2024

INCLUSIVE FLAVOUR TAGGING

- **Use all tracks in the event** except for the signal decay tracks

- Make flavour tagging predictions based on patterns and correlations between all tracks in high-dimensional feature space



Architecture good choice

3. Inclusive flavour tagging: Deepset

IFT Deepset presented by 2024 John Wendel CPAN 2024

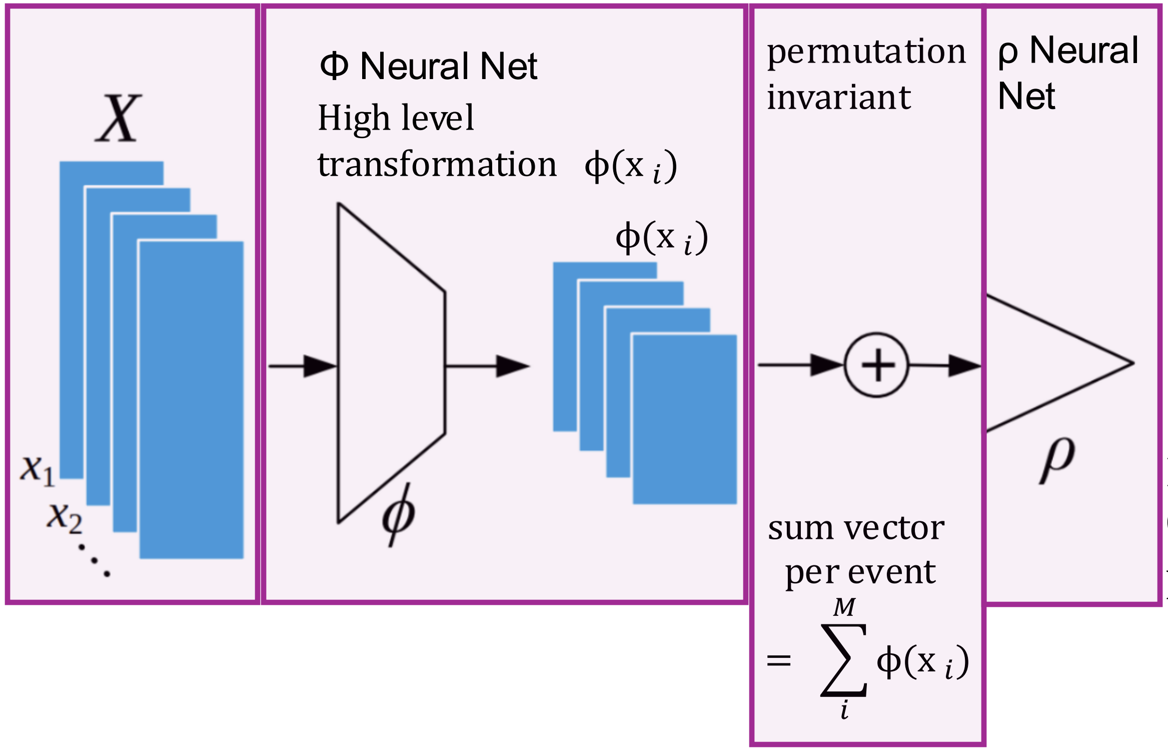
- [4] Zaheer et al. 2018. Deepsets] Deepset can take inputs of different lengths, and its predictions are permutation invariant.
- 1 hour to train on a statistically significant sample and 7µs to evaluate per event

[5]*2024. Prouve et all. Fast Inclusive Flavour Tagging at LHCb]*

INPUT

The event collision is a set $X = \{ x_1, \dots, x_M \}$

- set of vectors $x_i \in \mathbb{R}^d$
- vector xi are charged particles with d features
- X can take variable sizes.



$$S(X) = \rho(\sum_i^M \phi(x_i))$$

$S(X)$

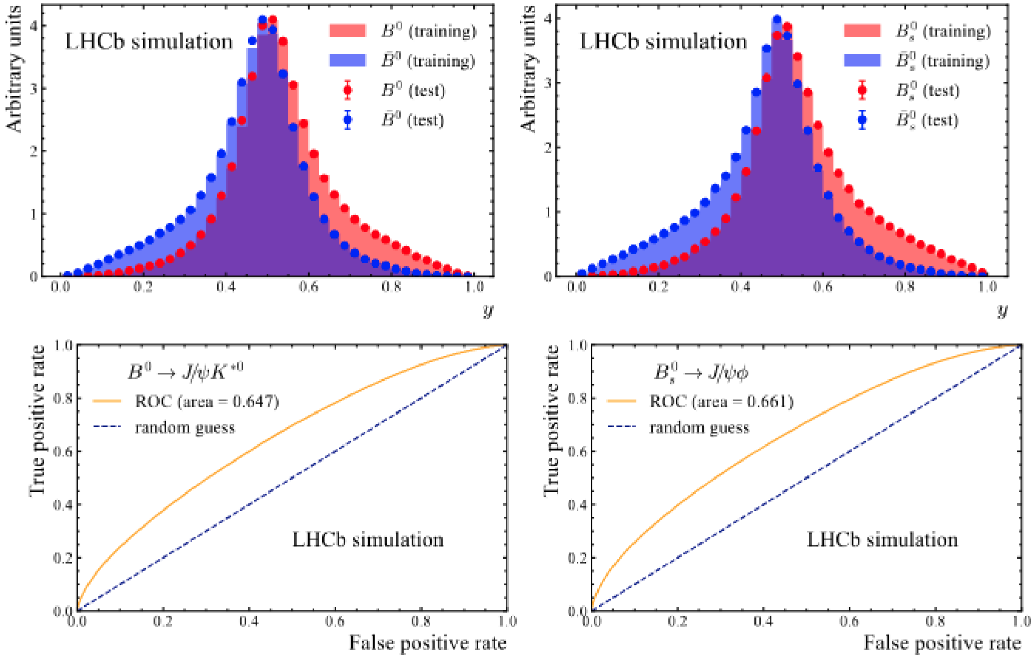
Loss function BCE
Output flavour tagging prediction , $\bar{b}$ b

[6] JHEP11(2025)041

NEW [6] JHEP11(2025)041. Inclusive B-meson flavour-tagging algorithm at LHCb

3. Inclusive flavour tagging Deepset Run2 published results

- Trained MC simulation Run2 conditions from 2016-2018. ($\sim 1.5\ M\ Events$) using 23 input features including SS and OS tagger decisions. [6] JHEP11(2025)041



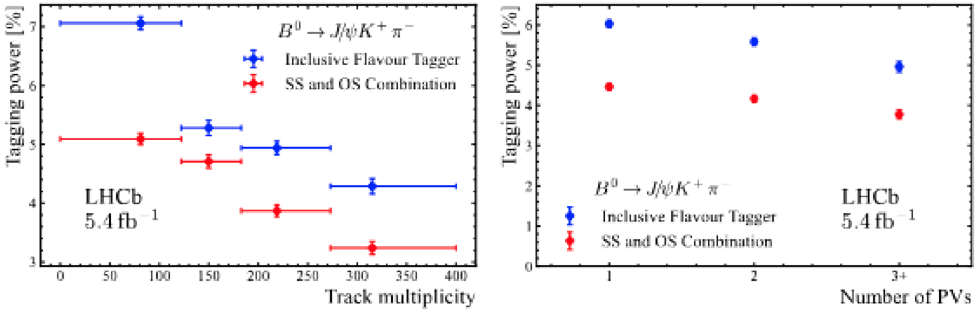
meson	*training MC*	*calibration data*	*validation studies*
B^0	$B^0 \to J/\psi K^*(892)^0$	$B^0 \to J/\psi K^+\pi^-$	$B^0 \to J/\psi K^0_S$, $B^0 \to J/\psi K^+\pi^-$
B^0_s	$B^0_s \to J/\psi\phi(1020)$	$B^0_s \to D^-_s\pi^+$	$B^0_s \to D^-_s\pi^+$, $B^0_s \to J/\psi K^+K^-$

GOOD NEWS:

- ✓ The IFT algorithm provides a **tagging power that is greater than the combination of SS and OS taggers by a relative 35% for B0 mesons and 20% for B0 s mesons.**
- ✓ This translates into **a reduction of 15% and 10% statistical uncertainty on the CP-violating parameters**.
- ✓ Tagging power around **5.5% to 7.5% across different validation decays**

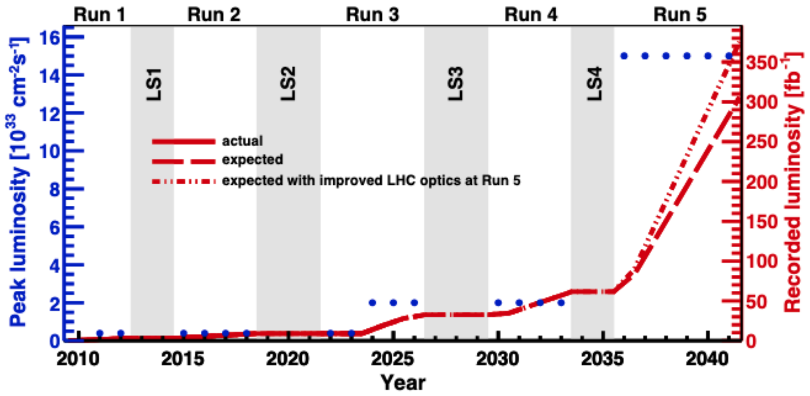
4. Inclusive flavour tagging Run3 challenges - multiplicity

- SS&OS and IFT Deepset with Run2 conditions shown that higher track or PV´s multiplicities lead to tagging power performance as a consequence of higher mistag rate.



[6] JHEP11(2025)041

- LHCb Upgrade II Scoping Document projected luminosity, will significantly increase pile up challenges.
- Robustness against track and PV´s multiplicity must be a central design requirement for future IFT models



- Run1 and 2, 9 fb-1 integrated luminosity collected

nº PV´s ~ 1 Run2

- Run3 >22 collected fb-1

nº PV´s ~ 5 Run3

- Run5 aiming for 300 fb-1

nº PV´s ~ 50 Run5

[7] LHCb Upgrade II Scoping Document

4. Inclusive flavour tagging in Run3 - New work ahead

- Deepset IFT for new Run3 detector conditions. Lower tagging power than in Run2. (Refactoring code, run3 features..)
- **Transformer architecture for IFT - why transformers?**
- **Track isolation for IFT**

[7] ParticleTransformer for Jet Tagging. Qu et al 2024.

4. Transformers in HEP : jet tagging and Inclusive Flavour Tagging

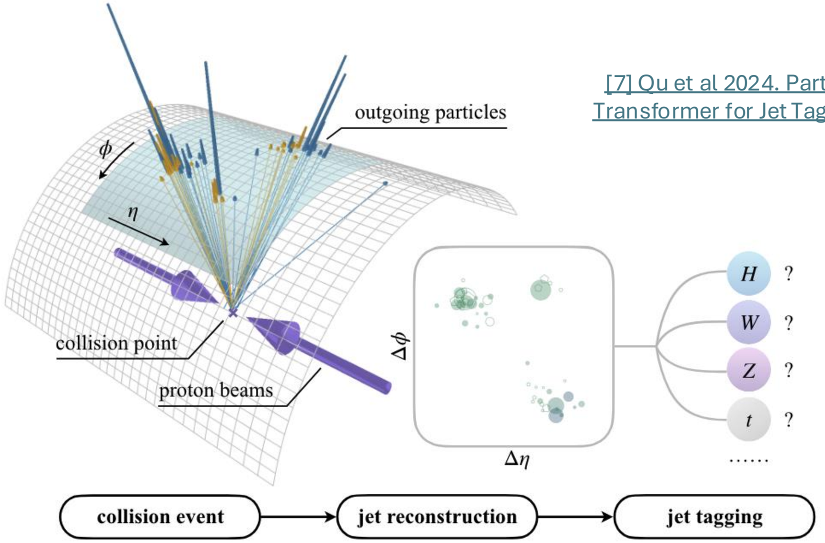
- **Inspired**: very successful for Jet Tagging.

[7] Qu et al 2024. Particle Transformer for Jet Tagging]

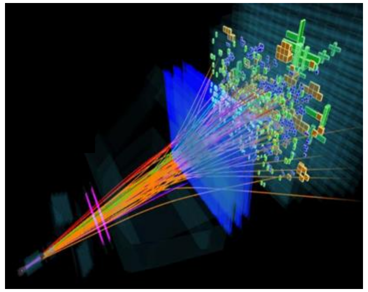
[8] W.Esmail et al 2025 IAFormer Interaction-Aware Transformer network for collider data analysis]

Particle Transformer:

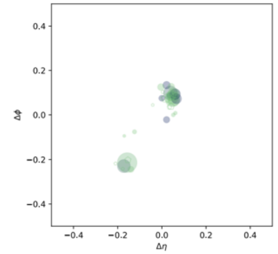
1. Outperformed NN Deep Sets on JetTagging problem
2. *Attention* mechanism between particles
3. Point clouds data input. Keep the unordered & permutational-invariant characteristic.
4. No ad-hoc positional encoding.



[7] Qu et al 2024. Particle Transformer for Jet Tagging]



LHCb reconstructed event



Pointcloud representation

b $\bar{b}$

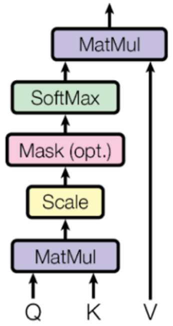
Flavour tagging prediction

[7]ParticleTransformer. [Qu et al 2024. Particle Transformer for Jet Tagging].

4. Transformers IFT University of Chinese Academy of Sciences , EPFL, La Salle Barcelona URL , Heidelberg University

$$\text{Attention}(Q, K, V) = \text{softmax}(\frac{QK^T}{\sqrt{d_k}})V$$

[9] *2017 Attention is all you need.* arXiv:1706.03762

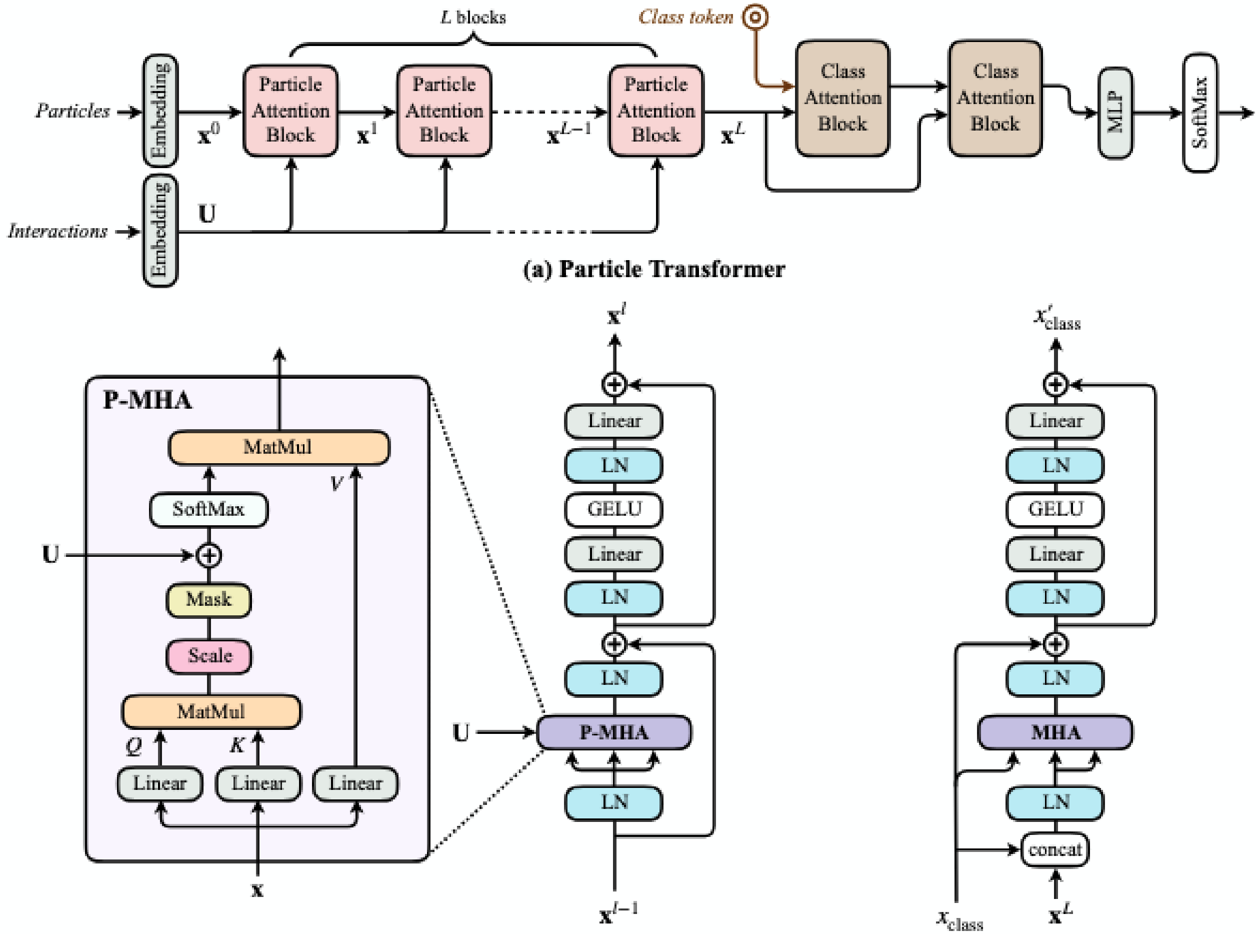


Input pairwise **particle interaction matrix U** (Na, Nb, C')

$$\text{P-MHA}(Q, K, V) = \text{SoftMax}(QK^T/\sqrt{d_k} + \mathbf{U})V,$$

$$U = \begin{aligned} \Delta &= \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2}, \\ k_T &= \min(p_{T,a}, p_{T,b})\,\Delta, \\ z &= \min(p_{T,a}, p_{T,b}) / (p_{T,a} + p_{T,b}), \\ m^2 &= (E_a + E_b)^2 - \|\mathbf{p}_a + \mathbf{p}_b\|^2. \end{aligned}$$

[7] Qu et al 2024. Particle Transformer for Jet Tagging]



(a) Particle Transformer

(b) Particle Attention Block

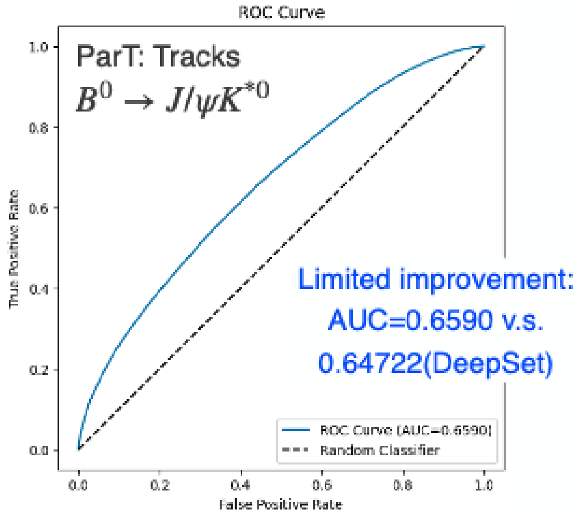
(c) Class Attention Block

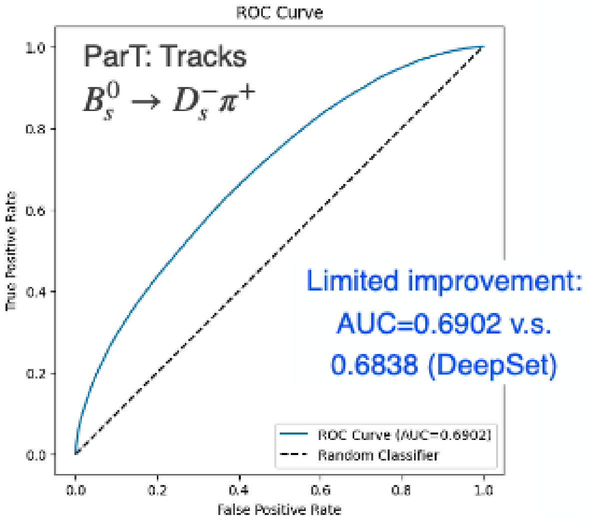
Training : PRELIMINARY RESULTS

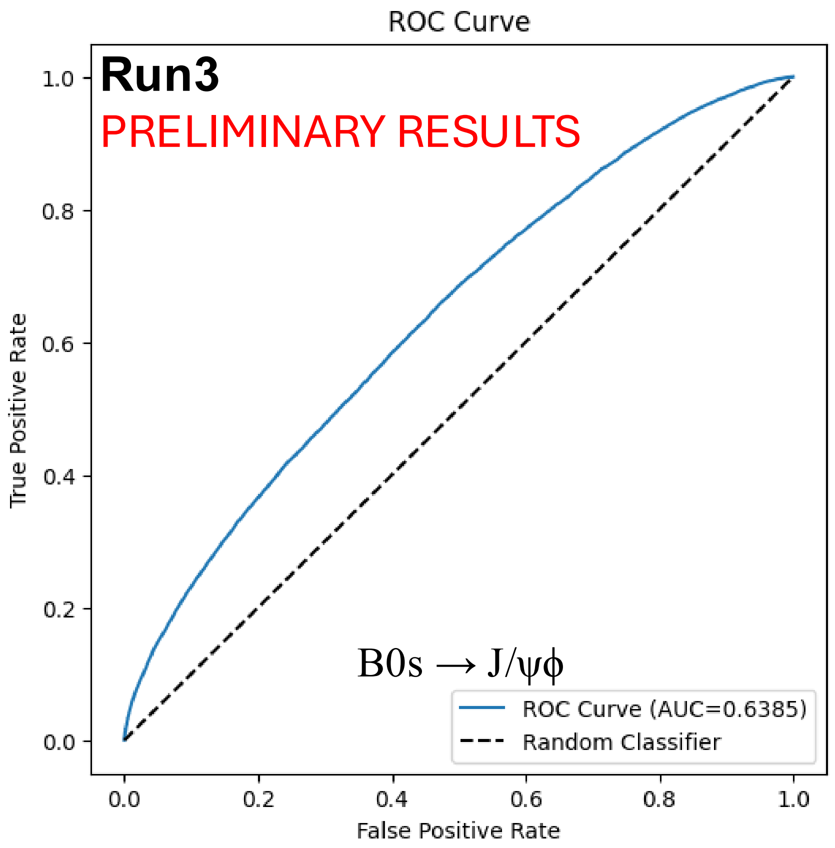
4. Global Transformer IFT Run2 and Run 3

Run2

PRELIMINARY RESULTS





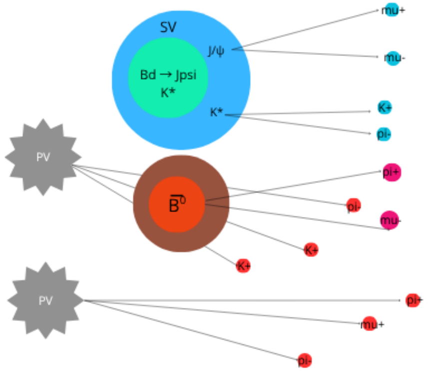


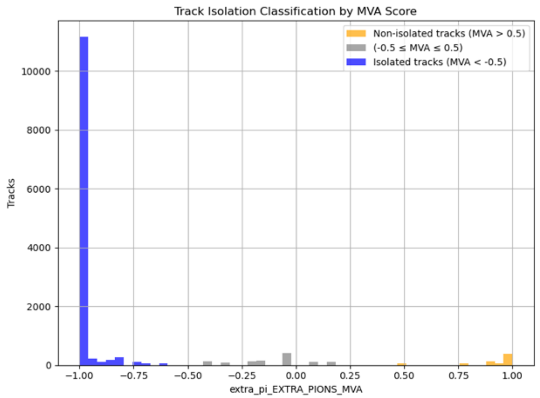
- ➢ Positive validation preliminary results in Run2
- ➢ Expected drop in performance in Run3 compared to Run2 due to track and PV multiplicity

Preliminary [LHCB-PAPER Inclusive Particle Isolation for LHCb's Run III]

4. Isolation information for flavour tagging in Run3 :

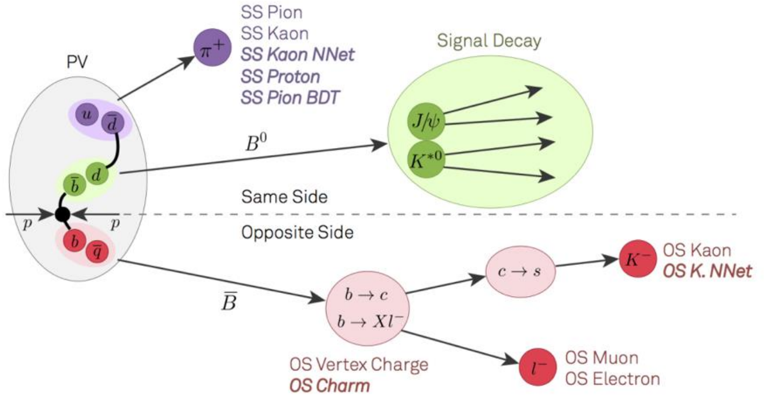
- Currently studying if isolation information could increase tagging power in inclusive flavour tagging models.





- Opposite Side taggers exploit correlated tracks with other B will be **Isolated tracks = displaced from B signal secondary vertex**.

- Same Side taggers aim to select charged particles that are produced in the same hadronization process. These are also **isolated charged tracks displaced from B signal secondary vertex**



5. Future work

- Other IFT models, transformers approach and Graph neural networks IFT based on DFEI (Deep Full Event interpretation) promising results for PV association

[10] Pardiñas et al. – 2023 GNN for Deep Full Event Interpretation and hierarchical reconstruction of heavy-hadron decays in proton-proton collisions

borja.sevilla@salle.url.edu
borja.sevilla@cern.ch