Jet Flavour Tagging and Physics Case Studies at UZH/VUB

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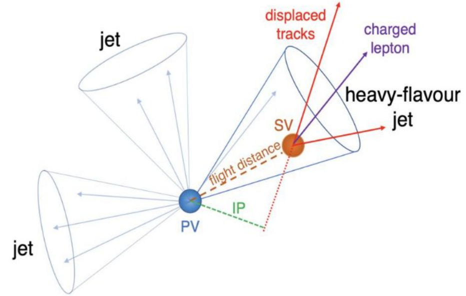
Flavour Tagging

Identification of hadronic final states is an essential ingredient in exploiting the physics potential of collider experiments

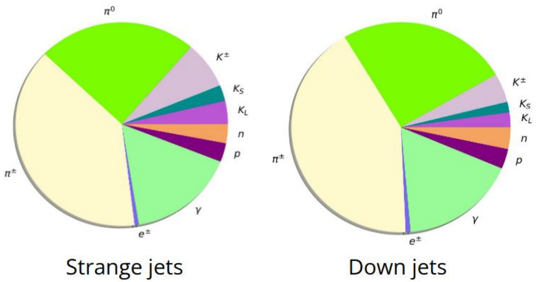
Future lepton collider such as FCC-ee offer much cleaner environment than hadronic collisions (Initial state kinematics known, no PDFs, no QCD ISR, …) => expect to do much better

Distinguishing features have historically been used to discriminate jets

- Differing colour factors for q vs g $C_A/C_F = \frac{9}{4}$
- Displaced SVs for b/c's
- Kaon excess for s
- Jet charge for up/down

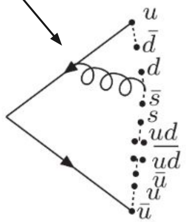


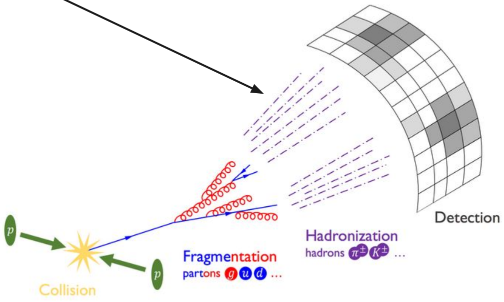
$$Q_\kappa = \frac{1}{p^\kappa_{T,jet}} \Sigma_j q_j (p^j_T)^\kappa$$



The Feedback Loop

ML approaches uniquely suited for task where underlying dynamics poorly understood, but there is an abundance of training data





Goal: Study the dependence on detector requirements of physics potential

$$\text{Sensor perf.} \xrightarrow[\text{sim.}]{\text{detector}} \text{vertexing perf.} \xrightarrow[\text{analysis}]{\text{sample}} \text{physics perf.} \xrightarrow[\text{input}]{\text{theory}} \text{sensor specification}$$

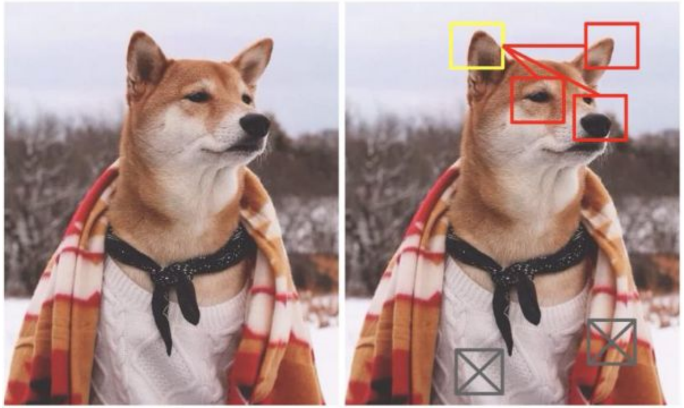
Transformers

Recent advances in Natural Language Processing have come from the implementation of Attention Mechanisms

Model exploiting an attention mechanism are typically dubbed “Transformers” and some examples exist in the realm of jet flavour tagging and have achieved state-of-the-art performance

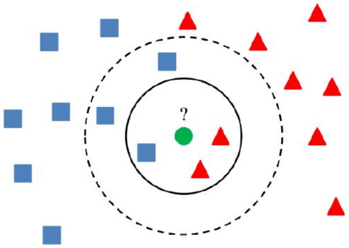
- ABCNet
- PointCloud transformer
- ParT

These architectures calculate attention on graph representations of data and can be computationally expensive



~200k + KNN

~2M + KNN



DeepJetTransformer

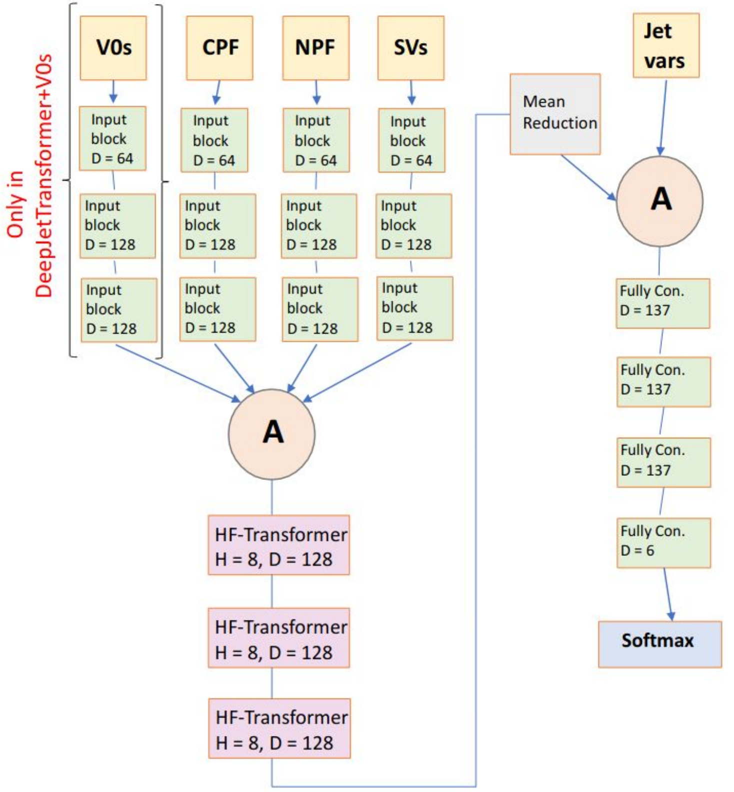
DeepJetTransformer is an architecture likewise achieving state-of-the-art performance, but using an encoder-decoder architecture

- More lightweight/still performant (~1M trainable weights, only 65k per encoder layer)

Set up pipeline for training the network using FCCAnalyses framework centrally produced FCC-ee Spring2021 samples

Required

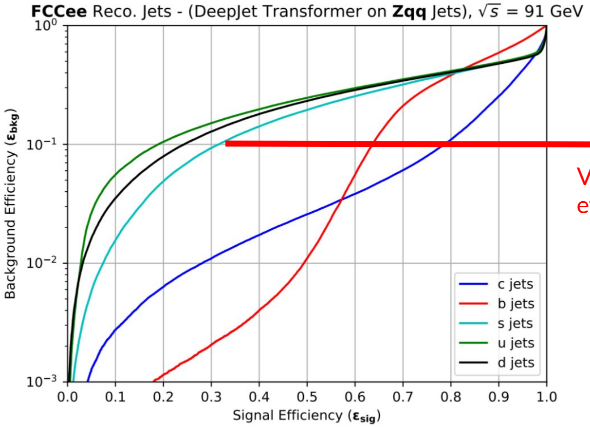
- Restructuring of jet-constituent input vars
- Secondary Vertexing code
- V0 reconstruction



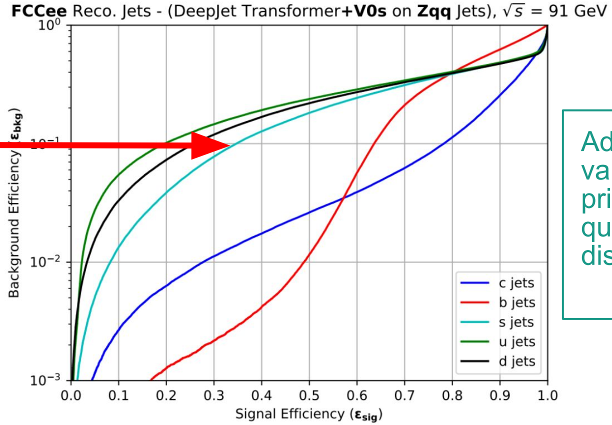
Results

Performance strongest for b quark jets

Weakest for up quark jets

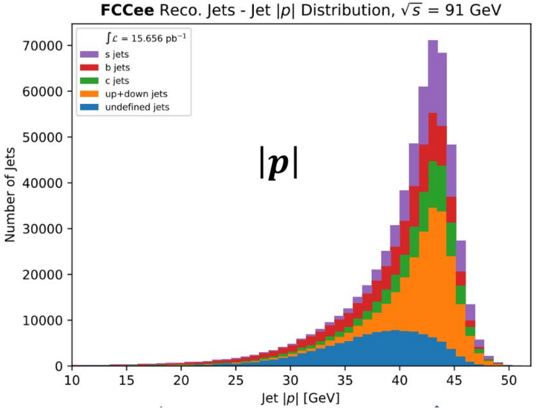


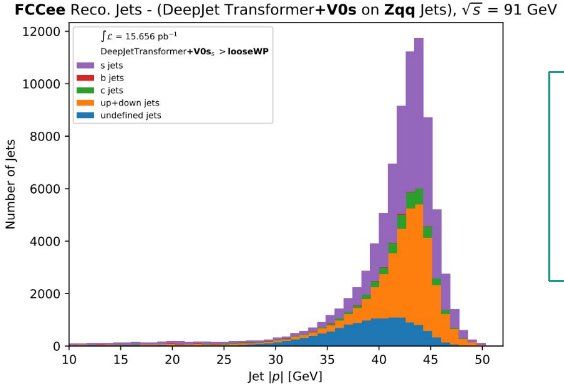
V0 improves efficiency by 3%



Addition of V0 variables improves primarily strange quark discrimination

Bkg to s quark jets almost exclusively up+down quark jets





Up+down quark jet bkg relatively insensitive to V0 variables

SVs & V^{0}s for FCC

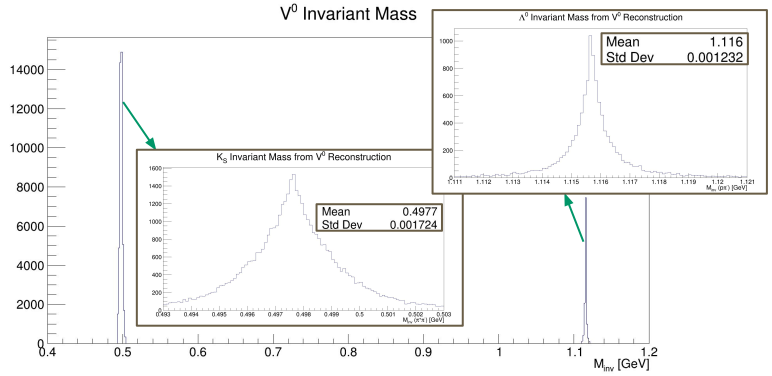
Implementation of the vertexing module from LCFIPlus

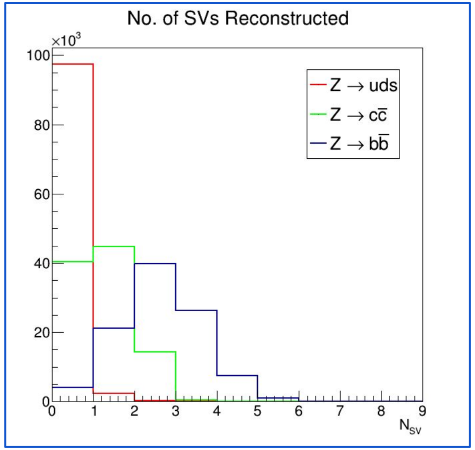
V^0 Reconstruction

- Three processes considered: $K^0_S \rightarrow \pi^+\pi^-$; $\Lambda^0 \rightarrow p\pi^-$; $\gamma_{conv} \rightarrow e^+e^-$
- Fit all possible pairs of tracks with opposite charge and constrain their invariant mass, distance from the interaction point and direction

SV Reconstruction

1. Find primary vertex and remove all tracks forming the PV
2. Remove tracks forming any V^{0}s
3. Find a two-track vertex (seed) that by applying a set of constraints
4. Add tracks to the seed until the resulting vertex doesn't pass the set of constraints
5. Repeat step 4&5 until no more seeds can be found





Case Studies

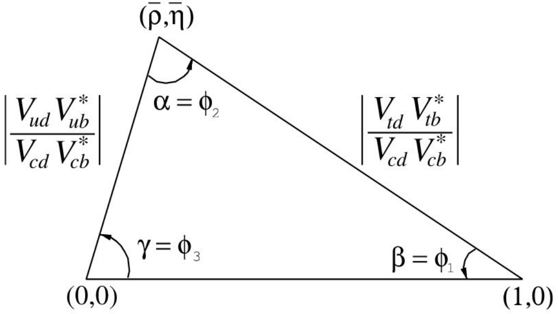
About to be started…

V_cs/V_cb from hadronic W decays: Motivation

Precise determinations of CKM elements offer some of the most stringent SM tests

V_cb appears in the normalization of the unitarity triangle sides, sensitivity to departure from SM will become limited by |V_cb| [1]

=> Presently most precise determinations from semileptonic B decays



Precision of unitarity constraints in second row (& column) dominated by |V_cs|

=> currently best determinations from D_(s) decays

V_cs in particular was extracted directly at LEP using hadronically decaying W->cs [2] achieving

$$|V_{cs}| = 0.94^{+0.32}_{-0.26} \pm 0.13$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.001 \pm 0.012 \text{ (2nd row)}$$

$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1.004 \pm 0.012 \text{ (2nd column)}$$

With the 2·10^3 times LEP statistics at the WW* threshold (and above) + Vastly improved jet tagging algorithms (like DJT)

Expect to push the precision boundary for both V_cb and V_cs at the FCC-ee

Goal → Perform realistic FullSim studies, and study impact of different detector configurations on physics potential

H->ss, cc : Motivation and Status

Higgs programme one of the leading motivations for a future collider

Deviations from SM couplings hint at BSM physics

Higgs coupling to second generation quarks not measured yet

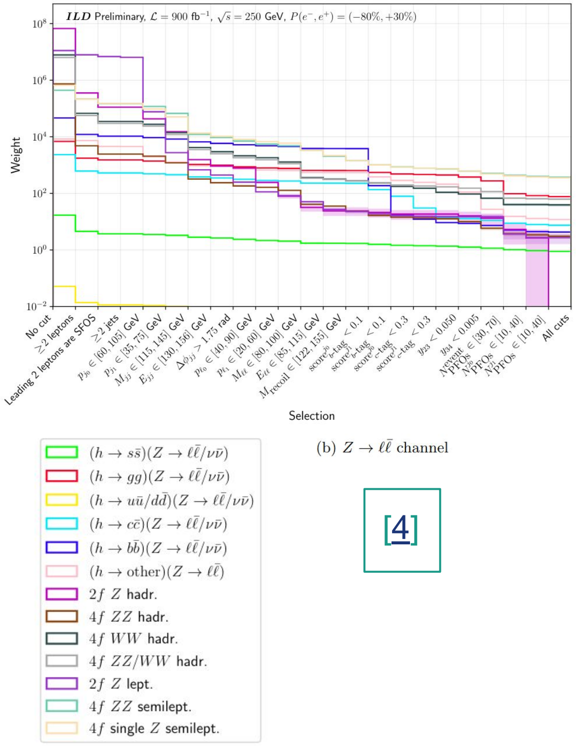
FCC-ee has highest e+e- integrated luminosity at 240 GeV (Higgsstrahlung)

1.7% error on Hcc coupling expected at FCC-ee (240 GeV) [3]

No expected measurement of Hss as of CDR, strong limits given a well performing s-tagger

Other attempts - (sensitivities a few times SM assessed by Duarte-Campderros et al., being attempted for ILC by Cairo et al.)

Goal → Perform realistic FullSim studies, and study impact of different detector configurations on physics potential



(b) $Z \to \ell\bar{\ell}$ channel

[4]

b/c+s-tagging : Detector Requirements

- b/c-tagging:
  - Accurate reconstruction of the decay chain, i.e. good SV reconstruction to remove background from *b*-jets
  - V^0 rejection to remove *s*-jet background
  - Need excellent resolution for VXD & tracker
- s-tagging:
  - Background from c-jets: requires good vertex reconstruction
  - Background from light jets: requires an excellent PID strategy to significantly improve tagging performance
  - V^0 reconstruction to identify K^0_S and Λ^0
  - Cluster counting + ToF seem to provide a good K/π separation in the momentum range of interest
- Jet clustering:
  - Irregularly shaped jets, so need a good jet definition and flavour assignment
  - Highly granular calorimeters for efficient jet reconstruction

Summary

Look at a Transformer based jet flavour tagger DeepJetTransformer in context of FCC-ee

- Lightweight (relatively) yet performant
- Trained & evaluated on Spring2021 samples
- Further training with different processes underway
- Inclusion of PID variables/estimates to address s vs u/d

=> Paper under construction

Case Studies (W→cs/cb, H→ ss/cc) getting started

Hardware development also starting

Backup