Optimisation of the ATLAS HL-LHC Trigger Menu for Improved diHiggs (bbtautau) Measurement

CERN Openlab Lightning Talks

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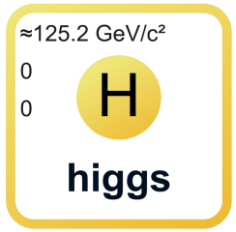
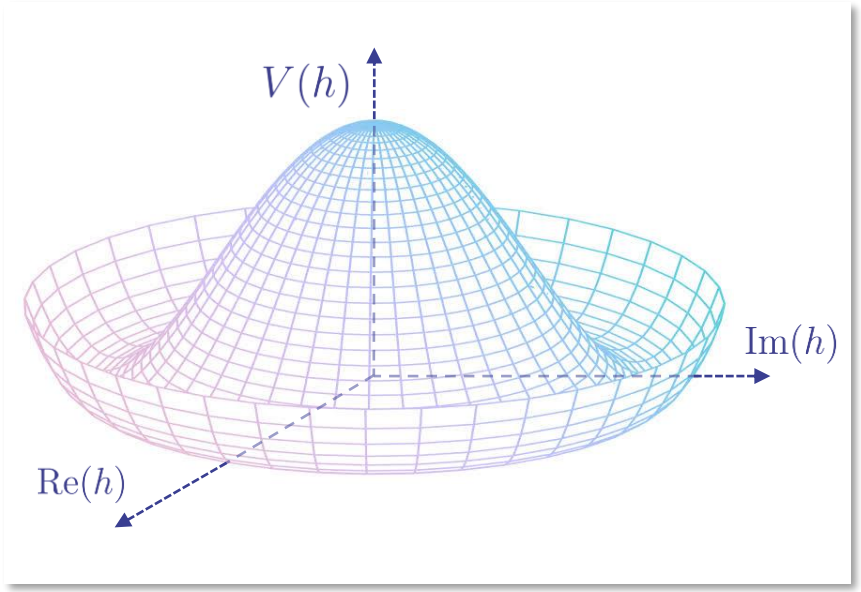
11 / 08 / 2026

1. Motivation: Higgs Pair-Production



- Discovered in 2012 by ATLAS and CMS
- Great progress in understanding its properties, but...

Shape of the Higgs potential



Higgs mass (precisely measured)

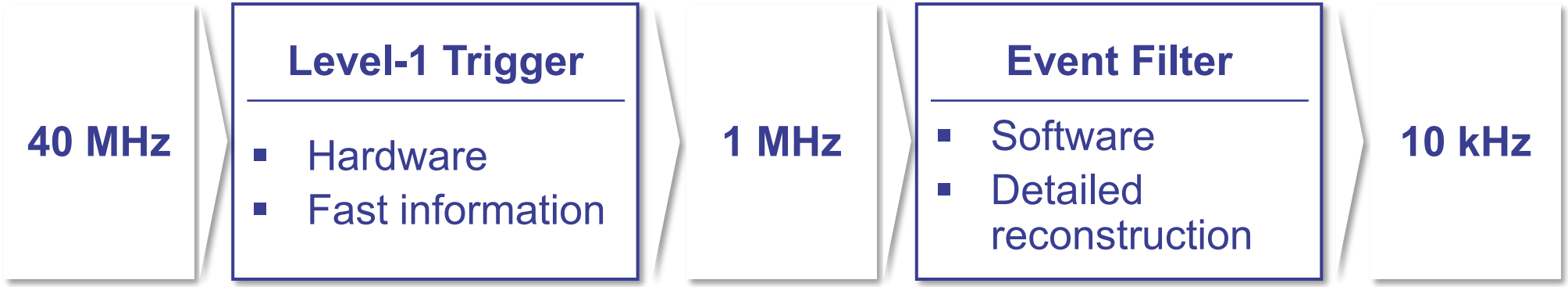
$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda v h^3 + \lambda h^4 + \cdots$$

Higgs self-coupling (poorly constrained): $\kappa_\lambda = \dfrac{\lambda}{\lambda_{\mathrm{SM}}}$

Study processes in which two Higgs bosons are produced!

2. The HL-LHC Trigger

$40 \cdot 10^6$ collisions / s ----> Impossible to store every event ----> **Trigger system**

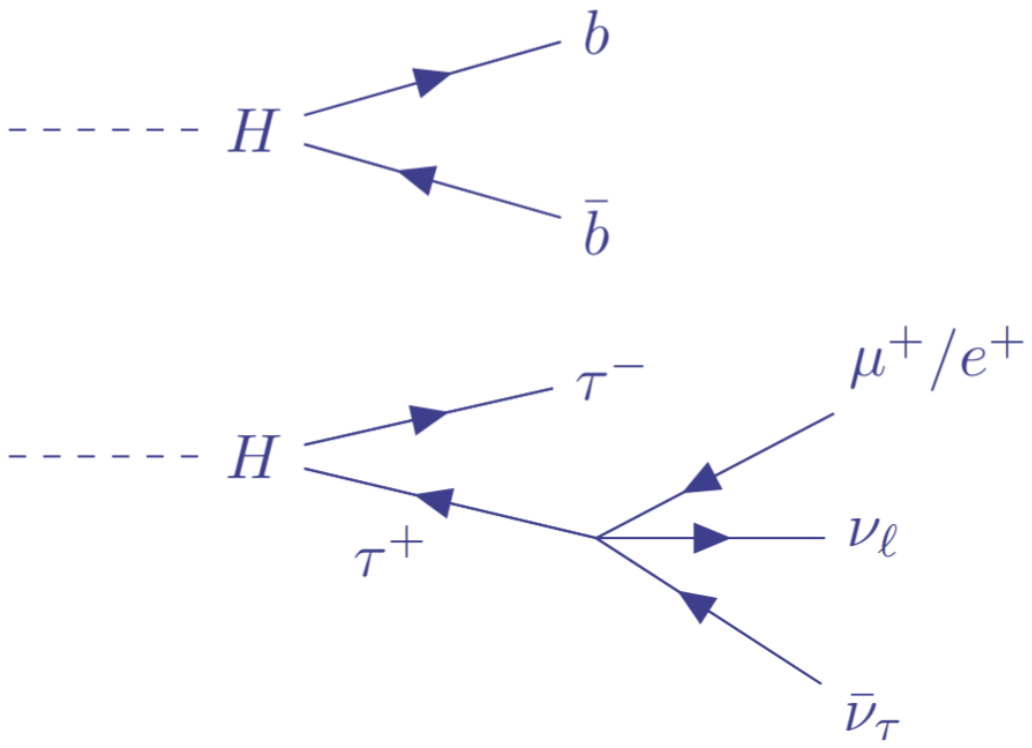


Trigger Menu

- Rate allocated in each channel
- Trigger strategies that retain as much signal as possible (within the budget)

3. My Target: $HH \rightarrow b\bar{b}\tau_{\mathrm{had}}\tau_{\mathrm{lep}}$

Higgs-pair production



Characteristic final state

Goal

Design trigger strategies to identify this topology as efficiently as possible (within the available budget)

4. Optimisation Strategy

Quantify trigger performance: Signal efficiency $\varepsilon_{\text{signal}}(\kappa_\lambda) = \frac{N_{\text{signal}}^{\text{pass}}}{N_{\text{signal}}^{\text{total}}}$

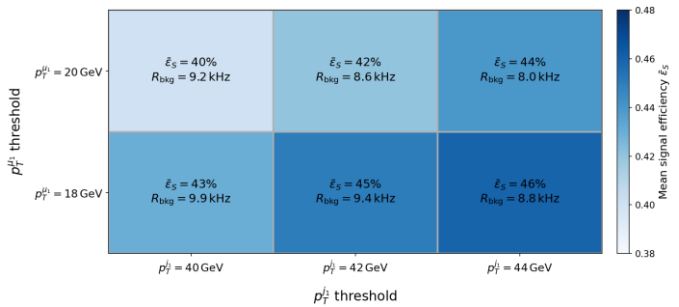
$\kappa_\lambda = 0, 1, 5 \xrightarrow{\text{QFT}} \kappa_\lambda \in [-1, 8]$

Constraint: Rate budget for this channel

35 MHz → L1 → 10 kHz → EF → 0.1 kHz

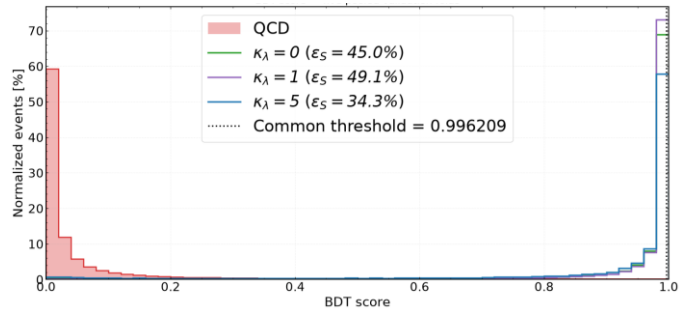
Optimisation strategies

Large grid scans



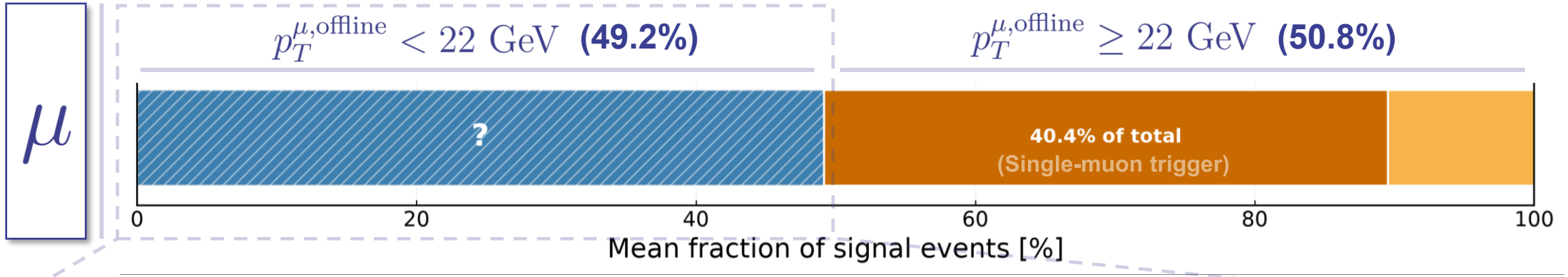
- Simple cut-based selections
- Guided by final topology

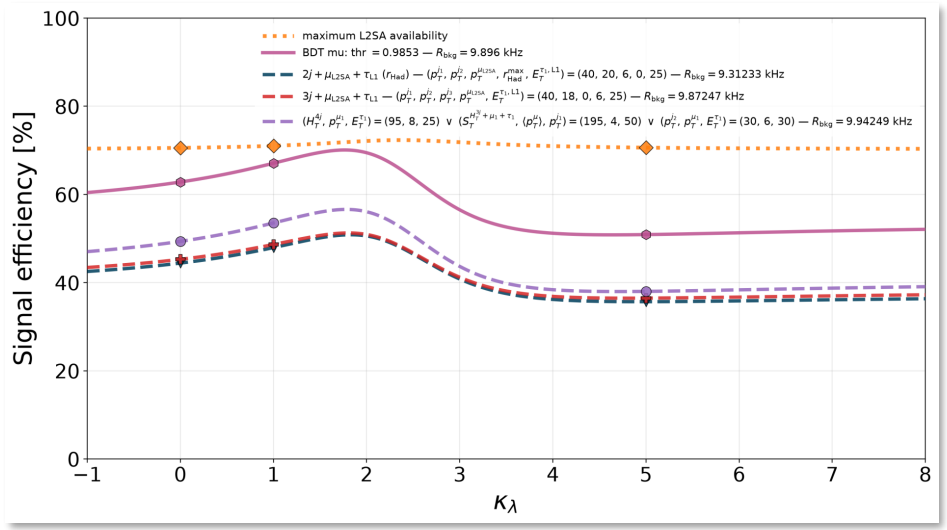
Machine learning



- Best achievable performance
- Identify useful patterns

5. Results: Muon Channel at Level-1

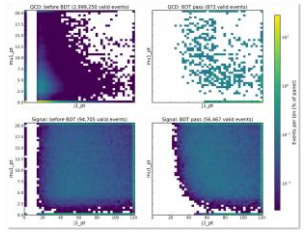




- Efficiency limited by **muon reconstruction**: 70%
- **Boosted Decision Trees**: 60%
- **Cut-based selections**: 47%

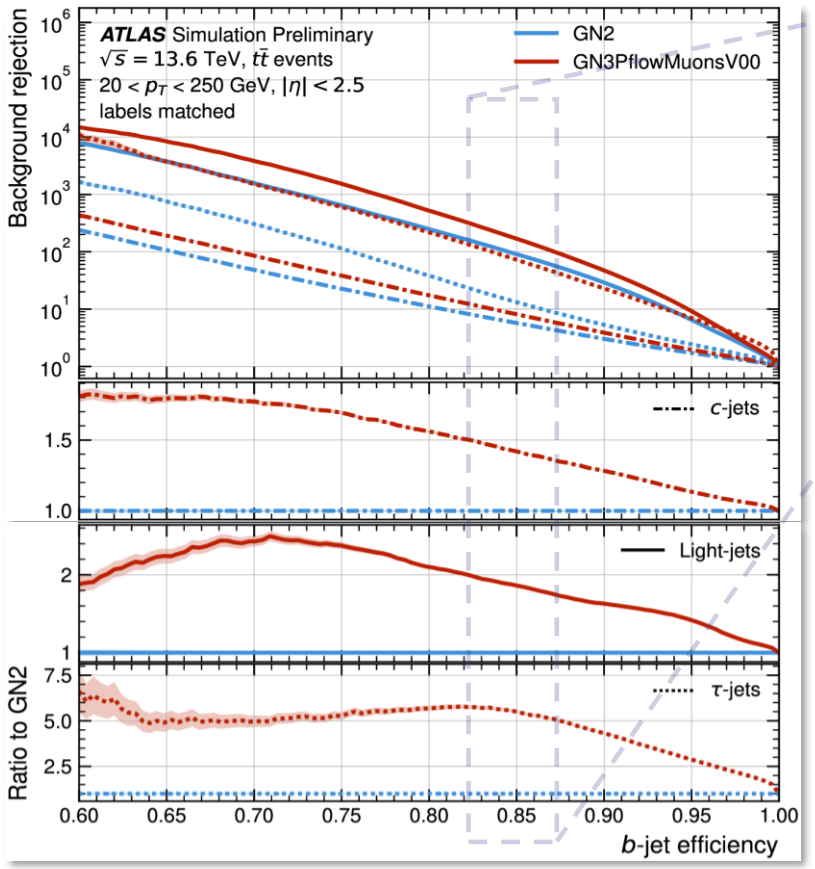
Variables and patterns

- 2D correlations
- Stronger tau quality requirements



5. Results: Efficiency in the Event Filter

b-tagging: Strong background rejection



ATLAS flavour-tagging algorithm

b-tagging efficiency: 85%

- **Background rejection factor**: 100
- **Signal efficiency**: 98% (only 1 *b*-jet)

Current inclusive efficiency

μ	65.13%

6. Conclusions & Next Steps

Conclusions

- di-Higgs production is a key part of ATLAS physics programme for the HL-LHC
- di-Higgs events have several possible final states: $HH \rightarrow b\bar{b}\tau_{\text{had}}\tau_{\text{lep}}$
- Study the channel separately: muons (65.13%) and electrons (TBD)

Next steps

- Improve the cut-based selections using 2D correlations from the BDT
- Include stronger tau- and electron-identification requirements
- Validate the full trigger strategy using *b*-tagging at the EF

Thank you for your attention!
Any questions?

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Back-up Slides

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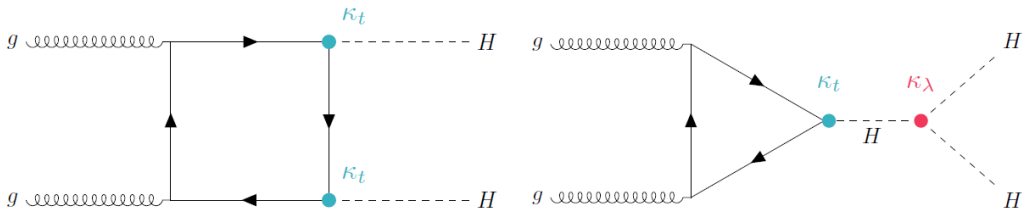
4. Optimisation Strategy

Signal samples

- **Simulation conditions:**
  - Run 4 at $\sqrt{s} = 13.6$ TeV
  - $\langle\mu\rangle = 140$
- Only **gluon fusion production**: $gg \rightarrow HH$



- **Semileptonic final state:** $HH \rightarrow b\bar{b}\tau_{\mathrm{had}}\tau_{\mathrm{lep}}$
- **Higgs self-coupling benchmarks:**

κ_λ	$\sigma(gg \rightarrow HH)$ [fb]
0	65.85
1	29.88
5	83.84

Background samples

- **Simulation conditions:**
  - Run 4 at $\sqrt{s} = 14$ TeV (updating)
  - $\langle\mu\rangle = 140$
- **QCD dijet production:** $pp \rightarrow jj$
- **Dijet slice:** JZ0 (low-p_T)

4. Optimisation Strategy

Channel Split

$HH \rightarrow b\bar{b}\tau_{\text{lep}}\tau_{\text{had}}$ → $\tau_\mu\tau_{\text{had}}$ | $\tau_e\tau_{\text{had}}$

Classification of $\tau_\mu\tau_{had}$

Truth leptons from a τ-lepton decay

- $\tau_\mu\tau_{\text{had}}$: $N_\mu^\tau > 0 \ \wedge \ N_e^\tau = 0$
- $\tau_e\tau_{\text{had}}$: $N_\mu^\tau = 0 \ \wedge \ N_e^\tau > 0$

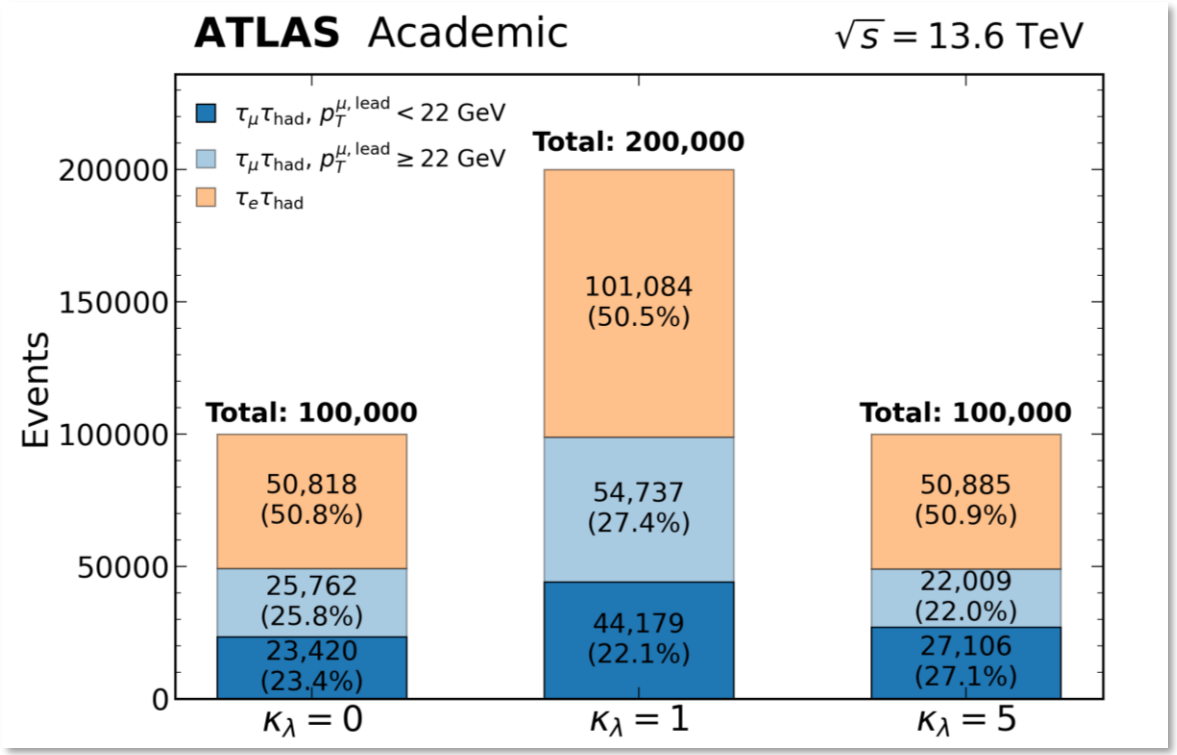
Mutually exclusive and exhaustive

Low-p_T muon region

Recover events not covered by the standard single-muon trigger

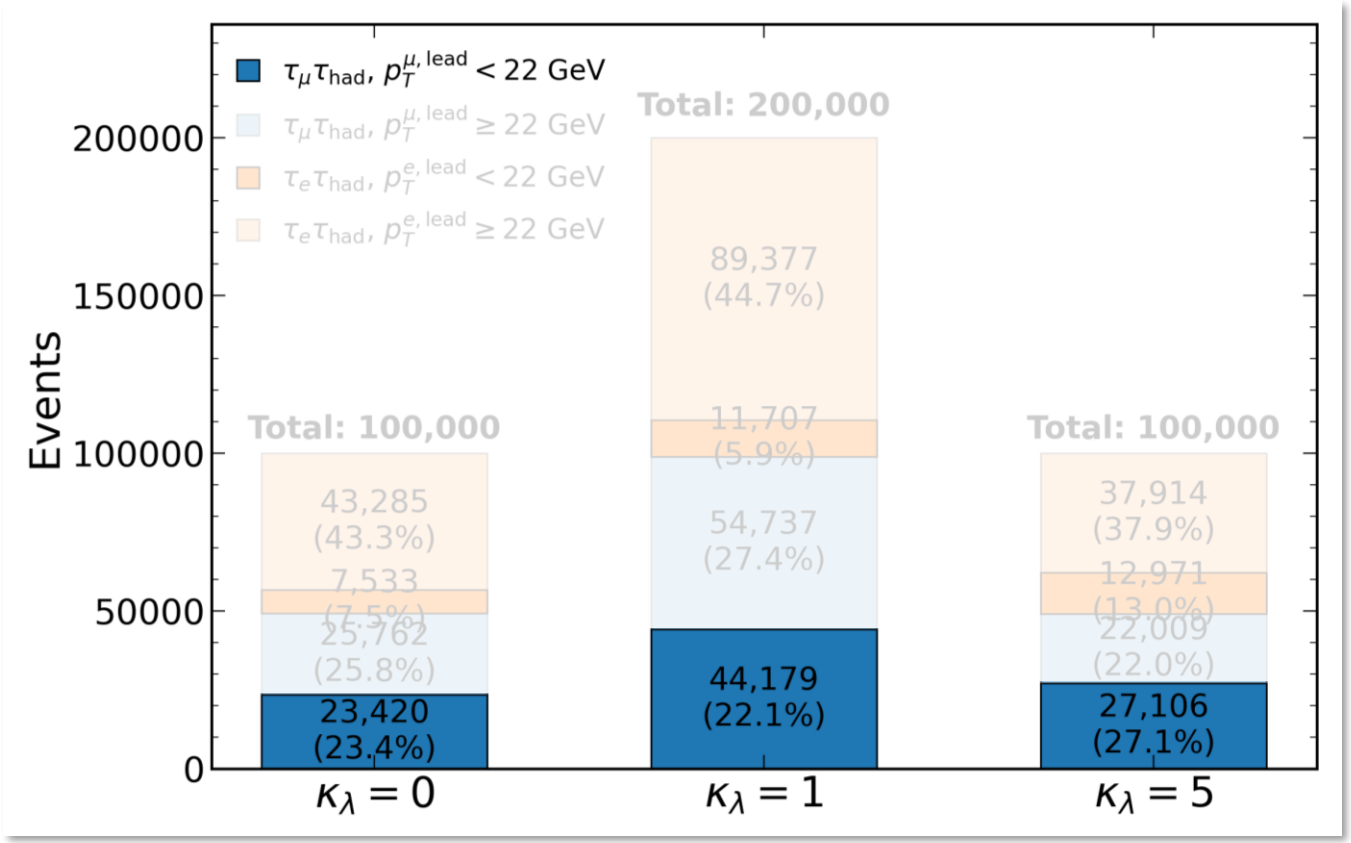
All offline muons from the event

- $N_\mu = 0 \ \vee \ p_T^{\mu,\text{lead}} < 22\,\text{GeV}$



4. Optimisation Strategy

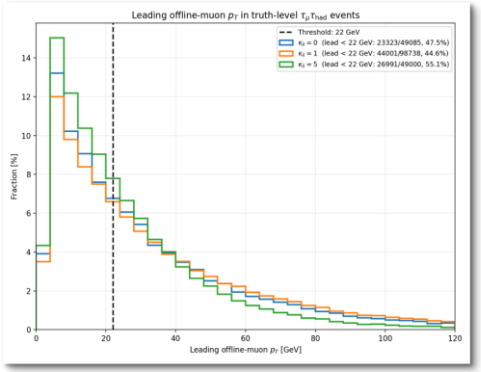
Data Samples



- Self-coupling modifier: $\kappa_\lambda = 0, 1, 5$
- Leptonic channels: e, μ
  - Electrons_Pt : $p_T^{\text{lead } e} < 22$ GeV
  - Muons_Pt : $p_T^{\text{lead } \mu} < 22$ GeV

31.73 % signal events:

15.88% of $\tau_e\tau_{had}$



48.02% of $\tau_\mu\tau_{had}$

4. Optimisation Strategy

Inputs: 31 variables

Object	ROOT collection	Branched used	Variables
Jets	AntiKt4EMTopo422Jets	Pt, Eta, Phi	njets, j1_pt, j2_pt, j3_pt, j4_pt, ht3, ht4, dr_j1j2, deta_j1j2, dphi_j1j2, j2_over_j1, j3_over_j1
Muons	HLT_MuonL2SAInfo	Pt, Eta, Phi	n_l2sa_muons, has_l2sa_muon, mu1_pt, mu2_pt,
Electrons	L1_eEMRoI	Et, Eta, Phi	n_eem, has_eem, eem1_et, eem2_et
Taus	L1_eTauxRoI	Et, Eta, Phi, rHadNumerator, rHadDenominator	n_etaux, has_etaux, etaux1_et, etaux2_et, etaux1_rhad, etaux2_rhad

Fully redundant

Potentially redundant

Object-topology

dr_mu_tau, dphi_mu_tau, mvis_mu_tau, dr_e_tau, dphi_e_tau, mvis_e_tau, min_dr_mu_jet4, min_dr_e_jet4, min_dr_tau_jet4

4. Optimisation Strategy

Training Strategy

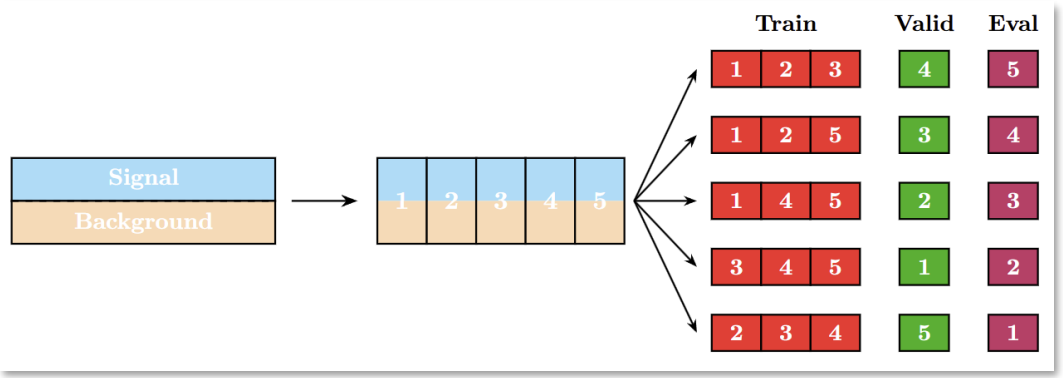
Training Weights

$$\omega_i^{\text{train}} = \begin{cases} \dfrac{N_{\text{tot}}}{2N_{\text{QCD}}}, & i \in \text{QCD} \\ \dfrac{N_{\text{tot}}}{6N_k}, & i \in \text{signal } k \end{cases}$$

Used hyperparameters

- **n_estimators**: 3000
- **learning_rate**: 0.03
- **max_depth**: 3
- **min_child_weight**: 5.0
- **gamma**: 0.0
- **reg_alpha**: 0.0
- **reg_lambda**: 1.0

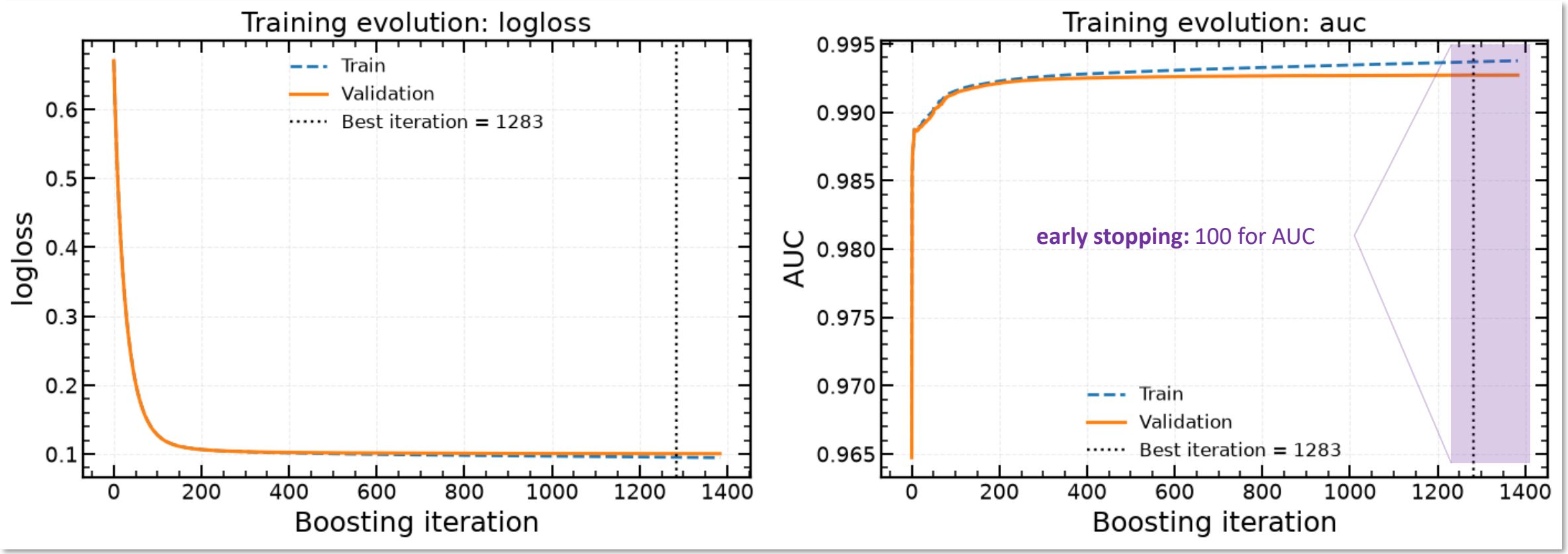
Stratified 5-fold cross-validation




```
================================================================================================================
STRATIFIED FOLD CONTENT
================================================================================================================
class       type        channel      fold00 fold01 fold02 fold03 fold04     total
----------------------------------------------------------------------------------------------------------------
background  background  inclusive   599,792  600,008  599,746  599,729  599,975 2,999,250
signal      kl0         electron      1,506    1,470    1,536    1,558    1,463     7,533
signal      kl0         muon          4,708    4,634    4,674    4,555    4,849    23,420
signal      kl1         electron      2,314    2,341    2,427    2,310    2,315    11,707
signal      kl1         muon          8,910    8,811    8,744    8,891    8,823    44,179
signal      kl5         electron      2,616    2,611    2,563    2,567    2,614    12,971
signal      kl5         muon          5,395    5,431    5,363    5,456    5,461    27,106
================================================================================================================
```

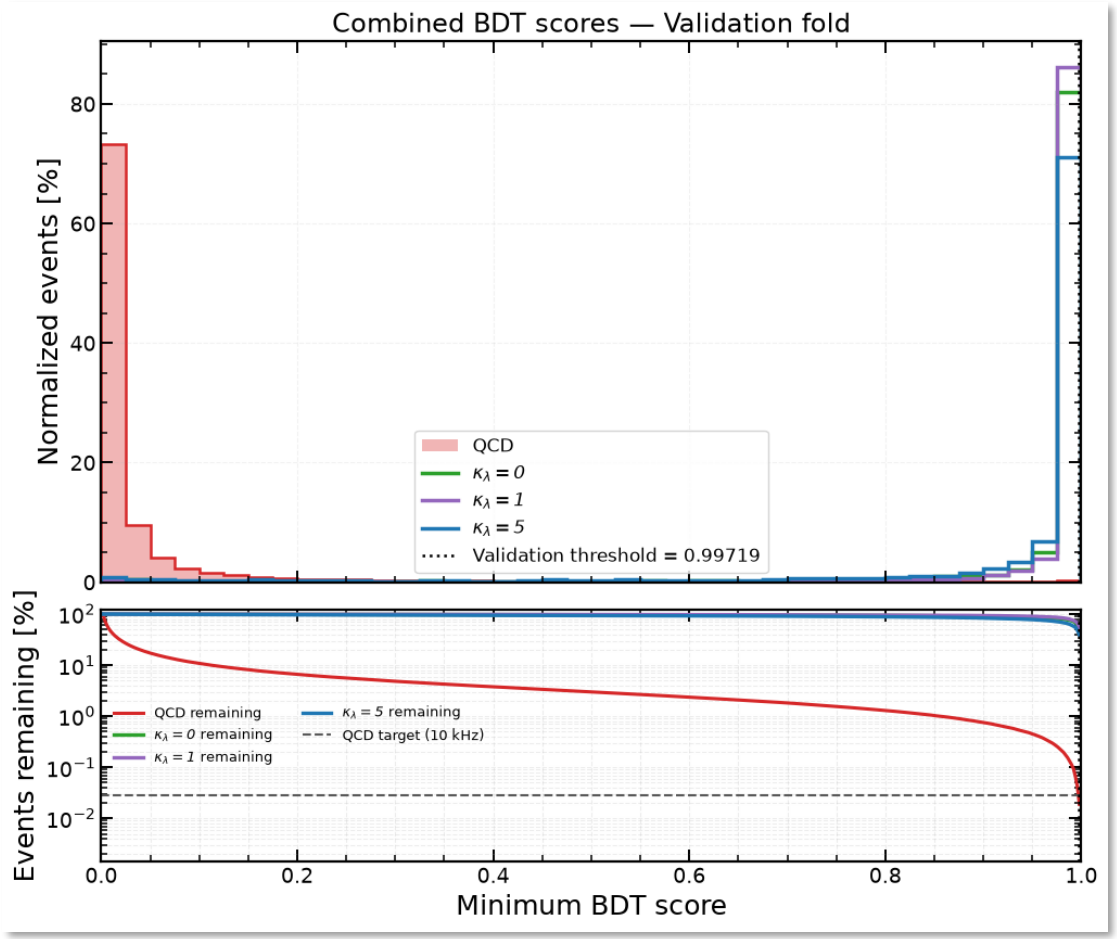
4. Optimisation Strategy

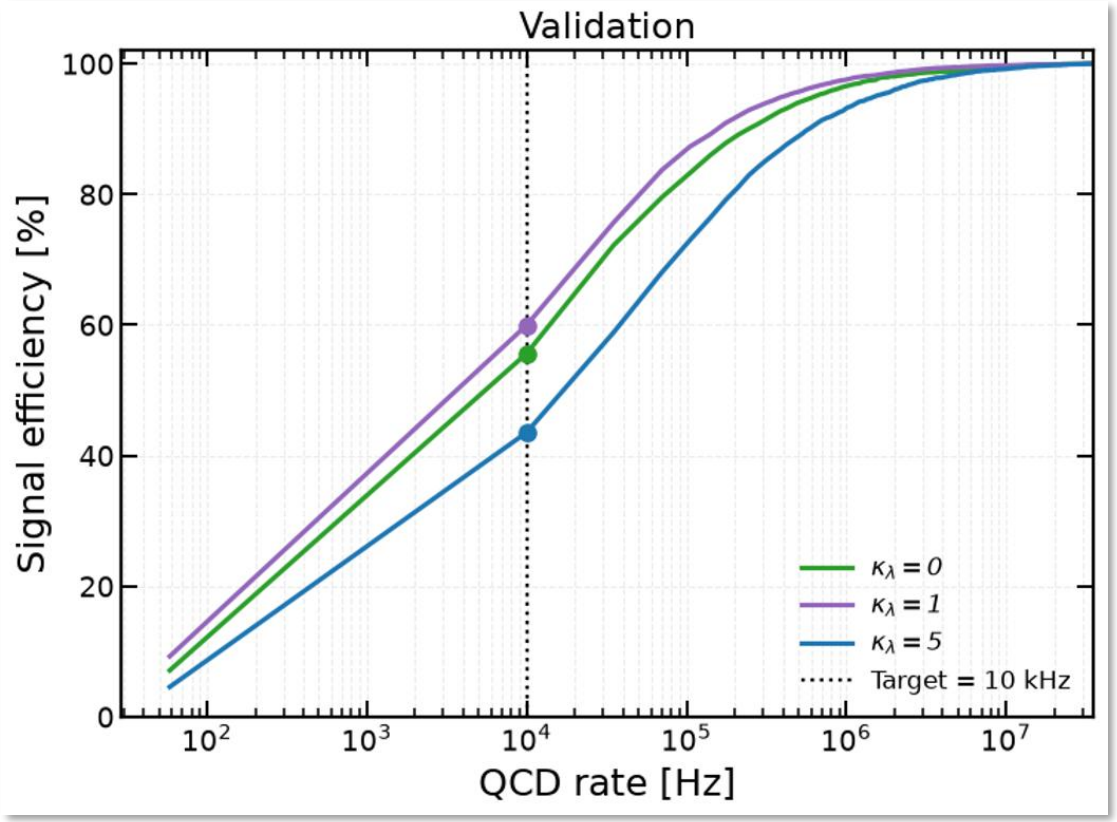
Diagnostic Plots: Training



4. Optimisation Strategy

Diagnostic Plots: Discriminating Power

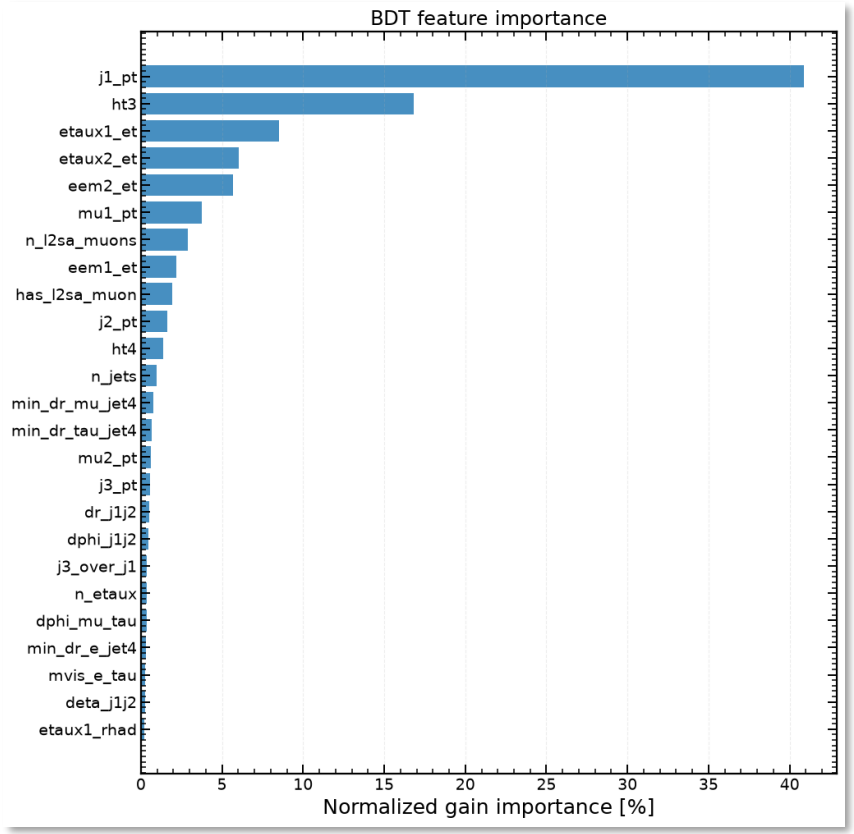




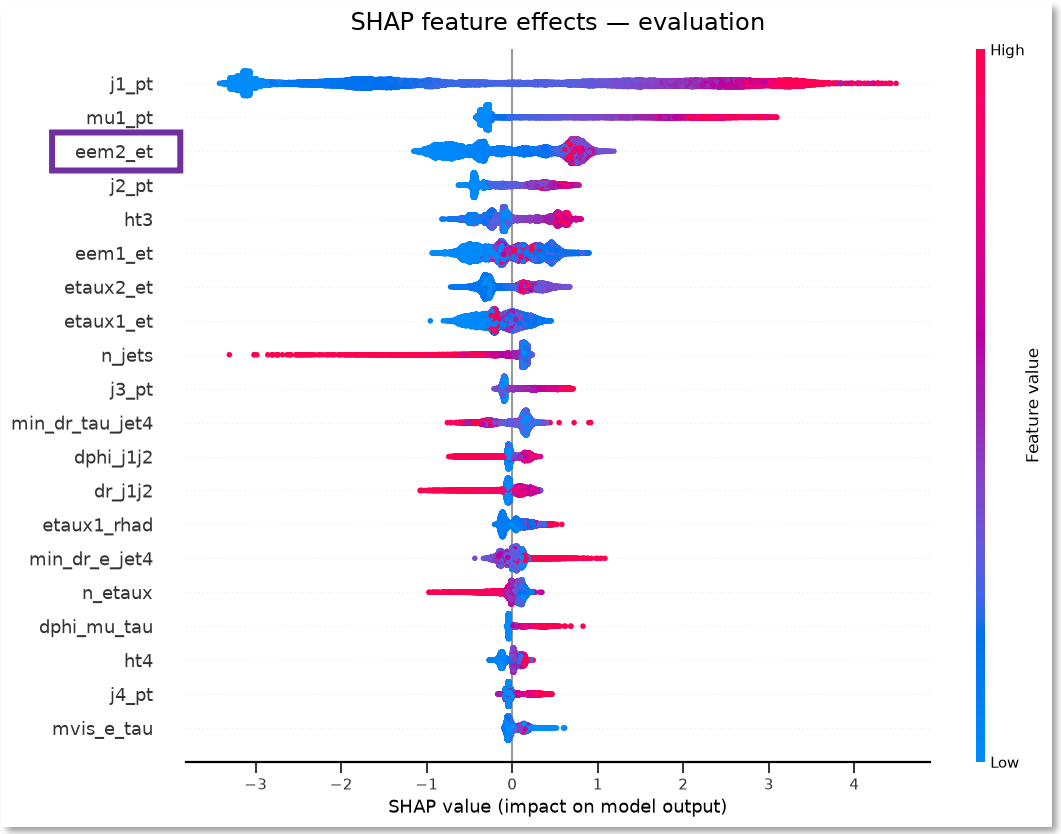
4. Optimisation Strategy

Diagnostic Plots: Feature Importance

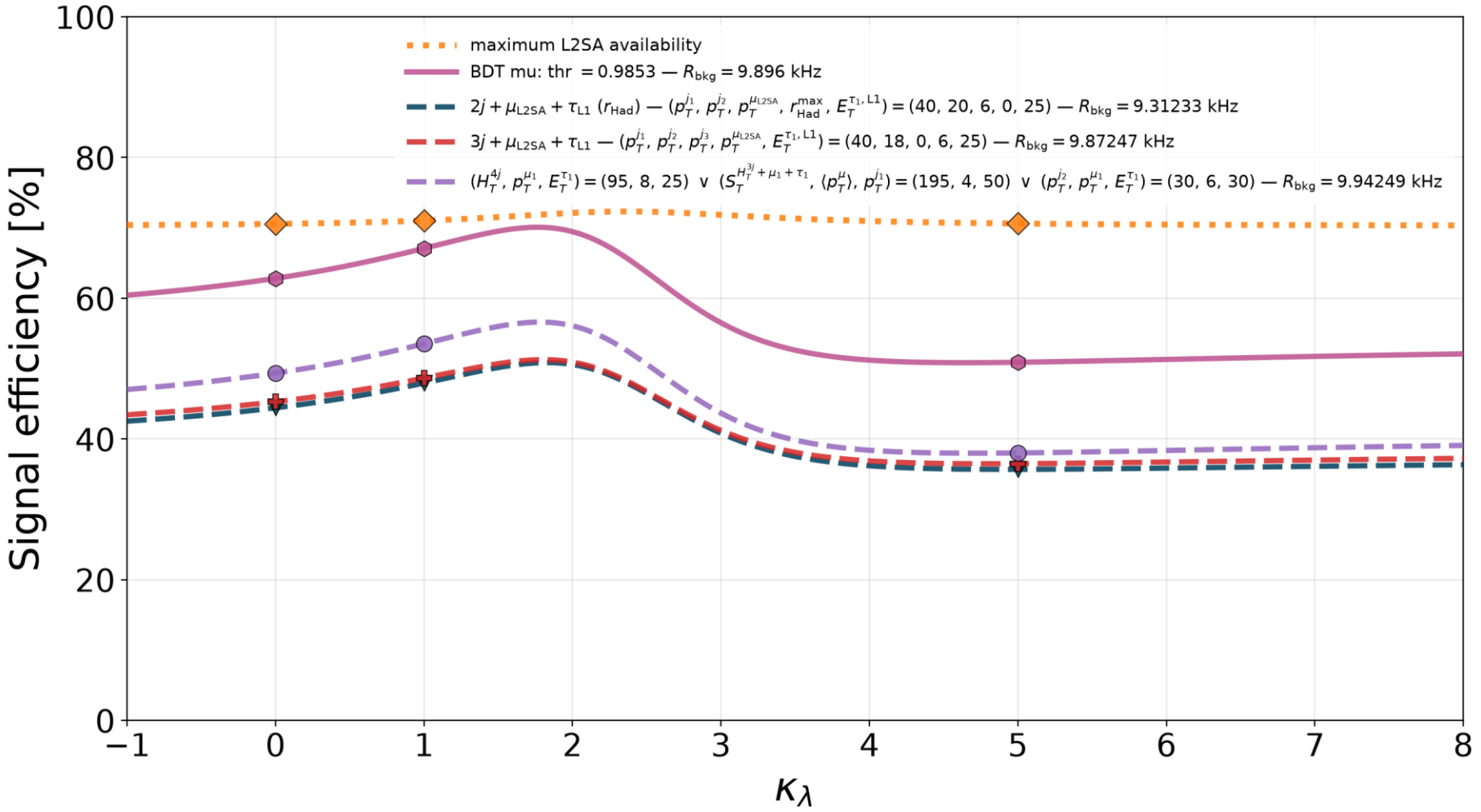
Gain Importance



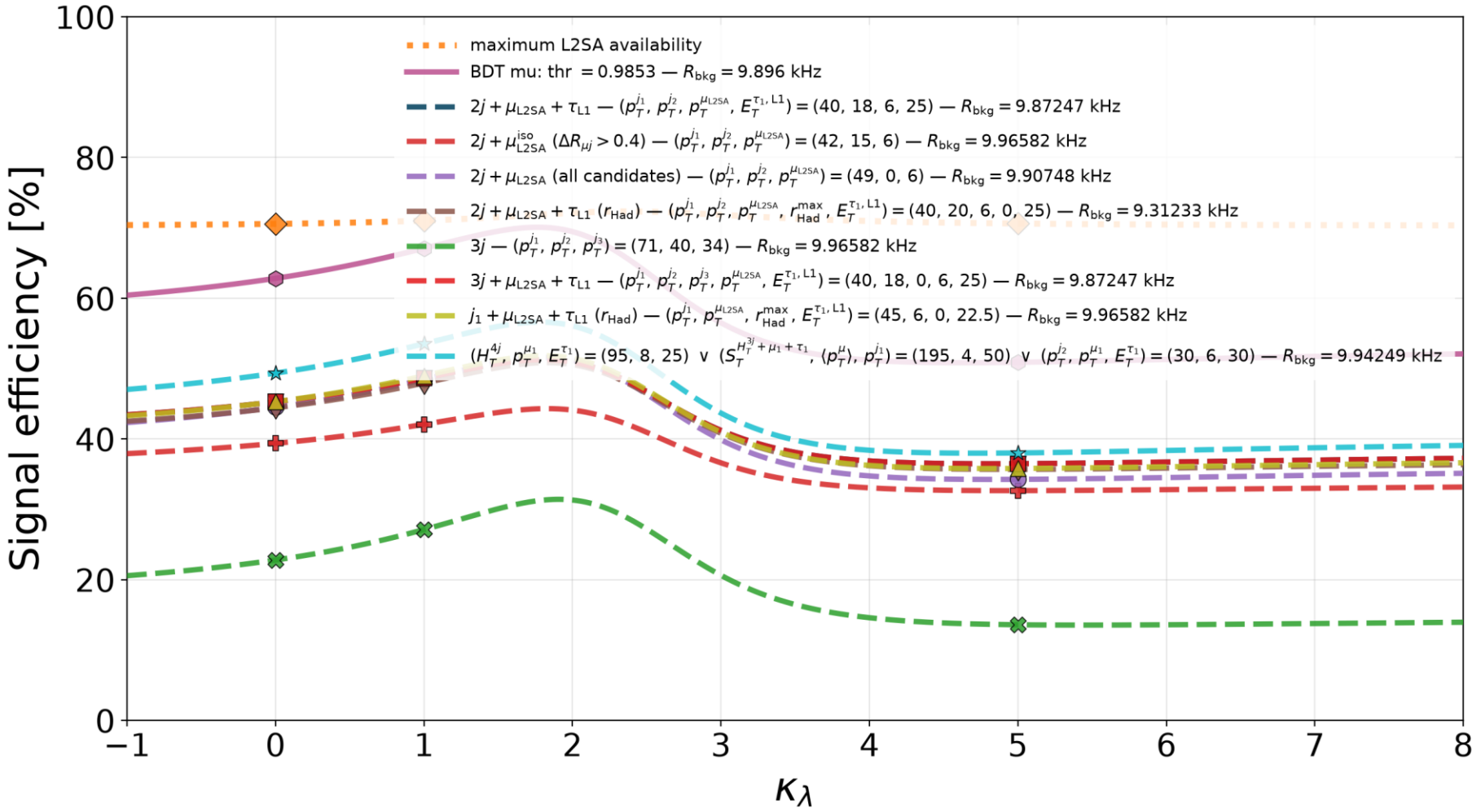
SHAP



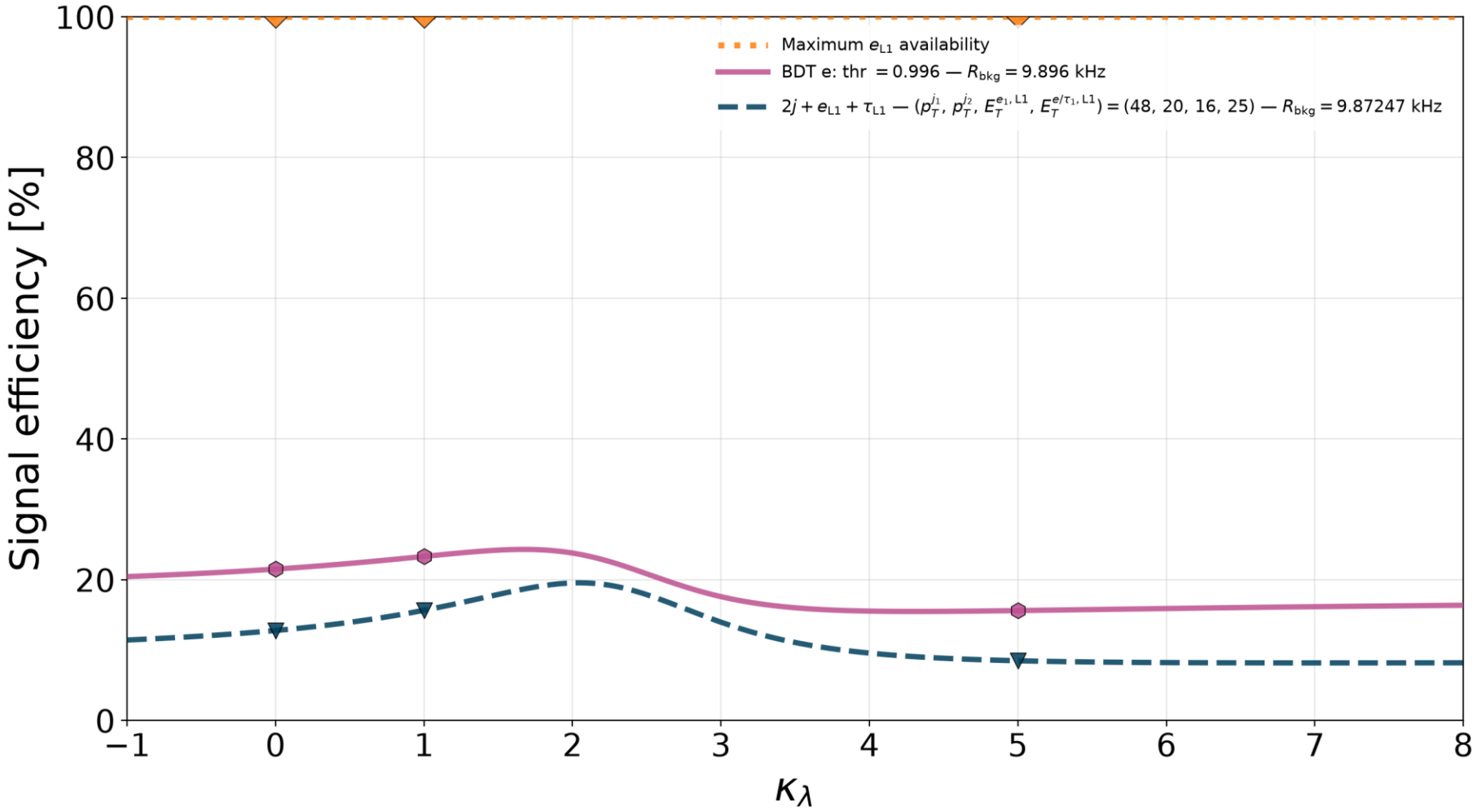
5. Results


maximum L2SA availability
BDT mu: thr = 0.9853 — R_{bkg} = 9.896 kHz
$2j + \mu_{L2SA} + \tau_{L1}$ (r_{Had}) — ($p_T^{j_1}$, $p_T^{j_2}$, $p_T^{\mu_{L2SA}}$, r_{Had}^{max}, $E_T^{\tau_1,L1}$) = (40, 20, 6, 0, 25) — R_{bkg} = 9.31233 kHz
$3j + \mu_{L2SA} + \tau_{L1}$ — ($p_T^{j_1}$, $p_T^{j_2}$, $p_T^{j_3}$, $p_T^{\mu_{L2SA}}$, $E_T^{\tau_1,L1}$) = (40, 18, 0, 6, 25) — R_{bkg} = 9.87247 kHz
(H_T^{4j}, $p_T^{\mu_1}$, $E_T^{\tau_1}$) = (95, 8, 25) ∨ ($S_T^{H_T^{3j}+\mu_1+\tau_1}$, $\langle p_T^{\mu} \rangle$, $p_T^{j_1}$) = (195, 4, 50) ∨ ($p_T^{j_2}$, $p_T^{\mu_1}$, $E_T^{\tau_1}$) = (30, 6, 30) — R_{bkg} = 9.94249 kHz
Signal efficiency [%]
κ_λ

5. Results


maximum L2SA availability
BDT mu: thr = 0.9853 — R_{bkg} = 9.896 kHz
$2j + \mu_{L2SA} + \tau_{L1}$ — ($p_T^{j_1}$, $p_T^{j_2}$, $p_T^{\mu_{L2SA}}$, $E_T^{\tau_1,L1}$) = (40, 18, 6, 25) — R_{bkg} = 9.87247 kHz
$2j + \mu_{L2SA}^{iso}$ ($\Delta R_{\mu j} > 0.4$) — ($p_T^{j_1}$, $p_T^{j_2}$, $p_T^{\mu_{L2SA}}$) = (42, 15, 6) — R_{bkg} = 9.96582 kHz
$2j + \mu_{L2SA}$ (all candidates) — ($p_T^{j_1}$, $p_T^{j_2}$, $p_T^{\mu_{L2SA}}$) = (49, 0, 6) — R_{bkg} = 9.90748 kHz
$2j + \mu_{L2SA} + \tau_{L1}$ (r_{Had}) — ($p_T^{j_1}$, $p_T^{j_2}$, $p_T^{\mu_{L2SA}}$, r_{Had}^{max}, $E_T^{\tau_1,L1}$) = (40, 20, 6, 0, 25) — R_{bkg} = 9.31233 kHz
$3j$ — ($p_T^{j_1}$, $p_T^{j_2}$, $p_T^{j_3}$) = (71, 40, 34) — R_{bkg} = 9.96582 kHz
$3j + \mu_{L2SA} + \tau_{L1}$ — ($p_T^{j_1}$, $p_T^{j_2}$, $p_T^{j_3}$, $p_T^{\mu_{L2SA}}$, $E_T^{\tau_1,L1}$) = (40, 18, 0, 6, 25) — R_{bkg} = 9.87247 kHz
$j_1 + \mu_{L2SA} + \tau_{L1}$ (r_{Had}) — ($p_T^{j_1}$, $p_T^{\mu_{L2SA}}$, r_{Had}^{max}, $E_T^{\tau_1,L1}$) = (45, 6, 0, 22.5) — R_{bkg} = 9.96582 kHz
(H_T^{4j}, $p_T^{\mu_1}$, $E_T^{\tau_1}$) = (95, 8, 25) ∨ ($S_T^{H_T^{3j}+\mu_1+\tau_1}$, $\langle p_T^{\mu}\rangle$, $p_T^{j_1}$) = (195, 4, 50) ∨ ($p_T^{j_2}$, $p_T^{\mu_1}$, $E_T^{\tau_1}$) = (30, 6, 30) — R_{bkg} = 9.94249 kHz
Signal efficiency [%]
κ_λ
0
20
40
60
80
100
−1
0
1
2
3
4
5
6
7
8

5. Results

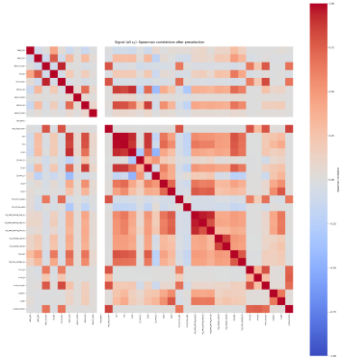

Maximum e_{L1} availability
BDT e: thr = 0.996 — R_{bkg} = 9.896 kHz
$2j + e_{L1} + \tau_{L1}$ — ($p_T^{j_1}$, $p_T^{j_2}$, $E_T^{e_1,L1}$, $E_T^{e/\tau_1,L1}$) = (48, 20, 16, 25) — R_{bkg} = 9.87247 kHz
Signal efficiency [%]
100
80
60
40
20
0
−1
0
1
2
3
4
5
6
7
8
K_λ

6. Conclusions & Next Steps

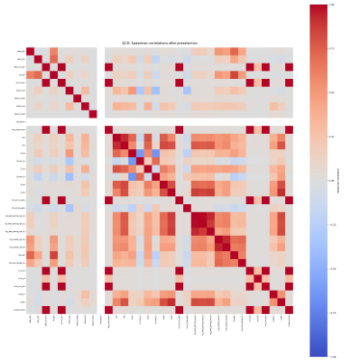
Next steps

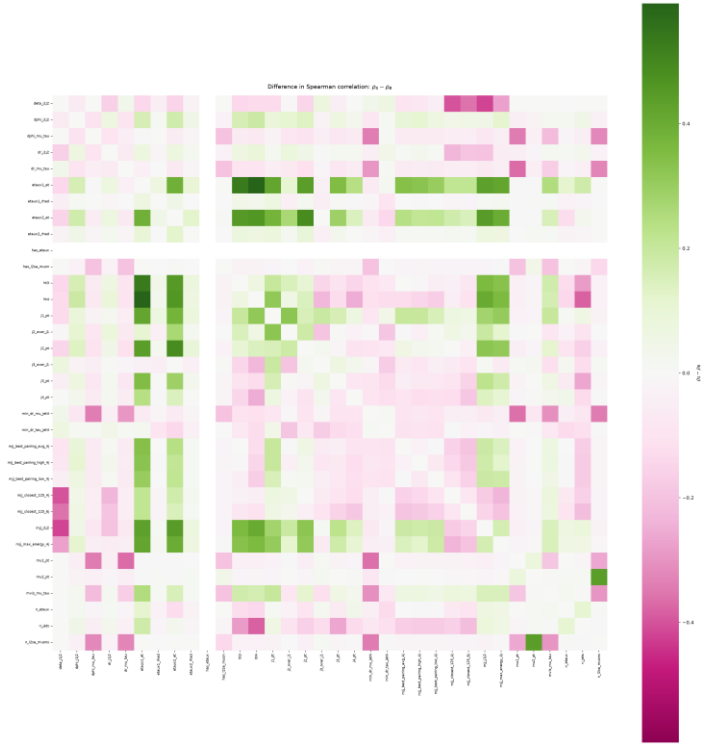
- Improve the cut-based selections using 2D correlations from the BDT

Signal



Bkg

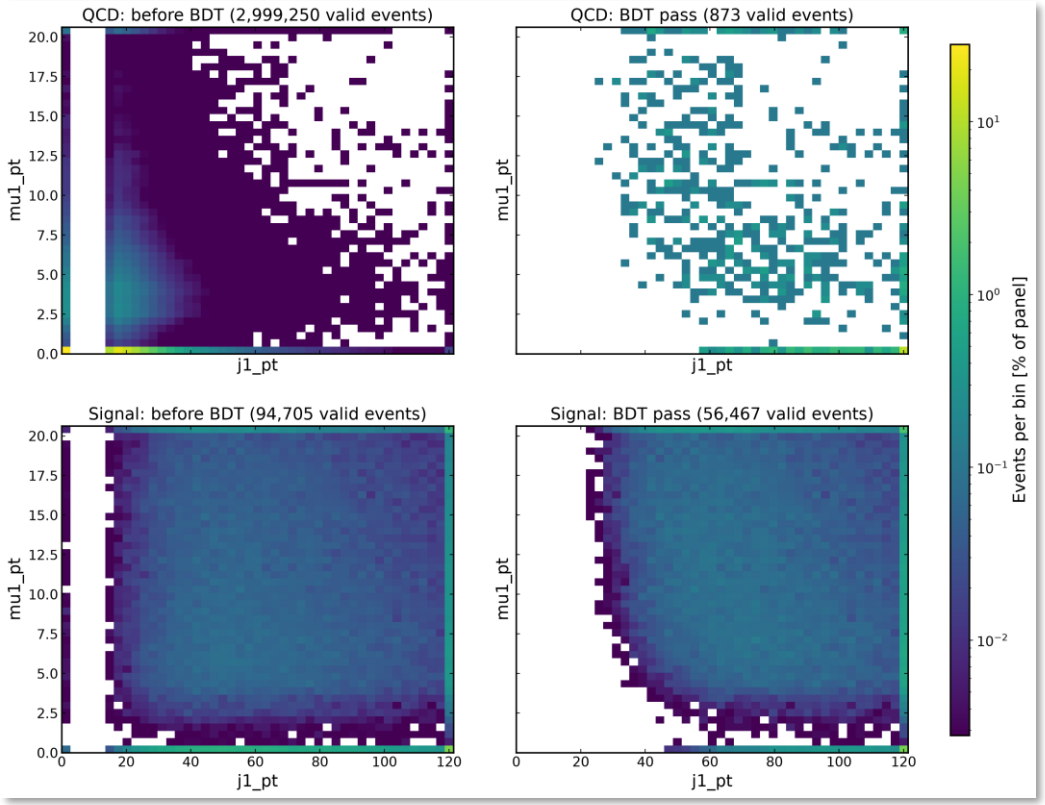




6. Conclusions & Next Steps

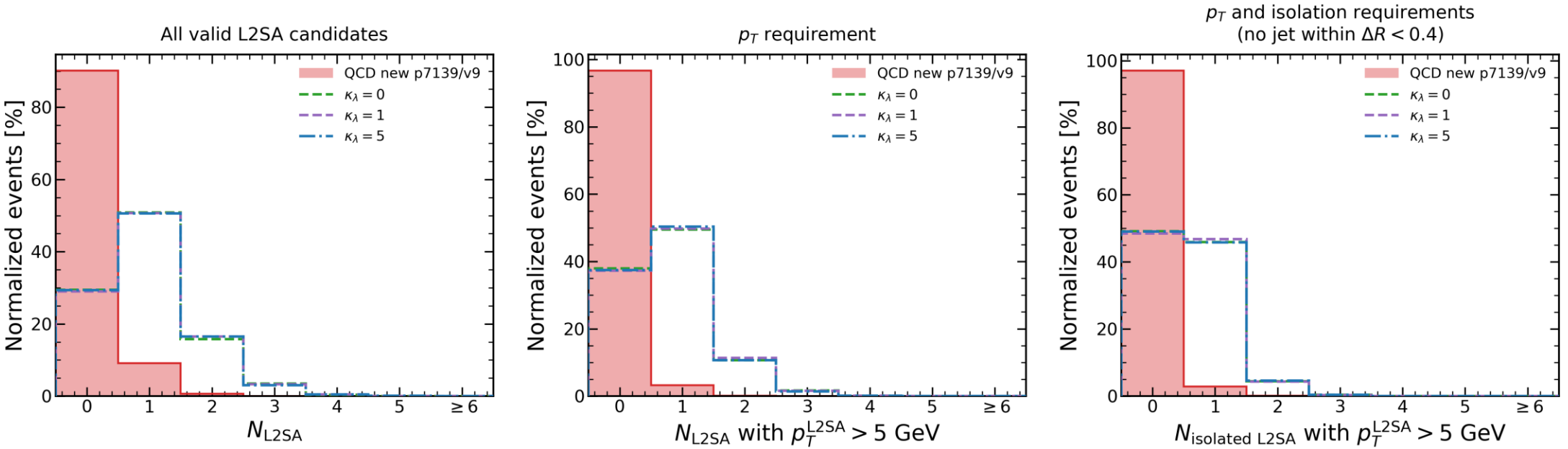
Next steps

- Improve the cut-based selections using 2D correlations from the BDT



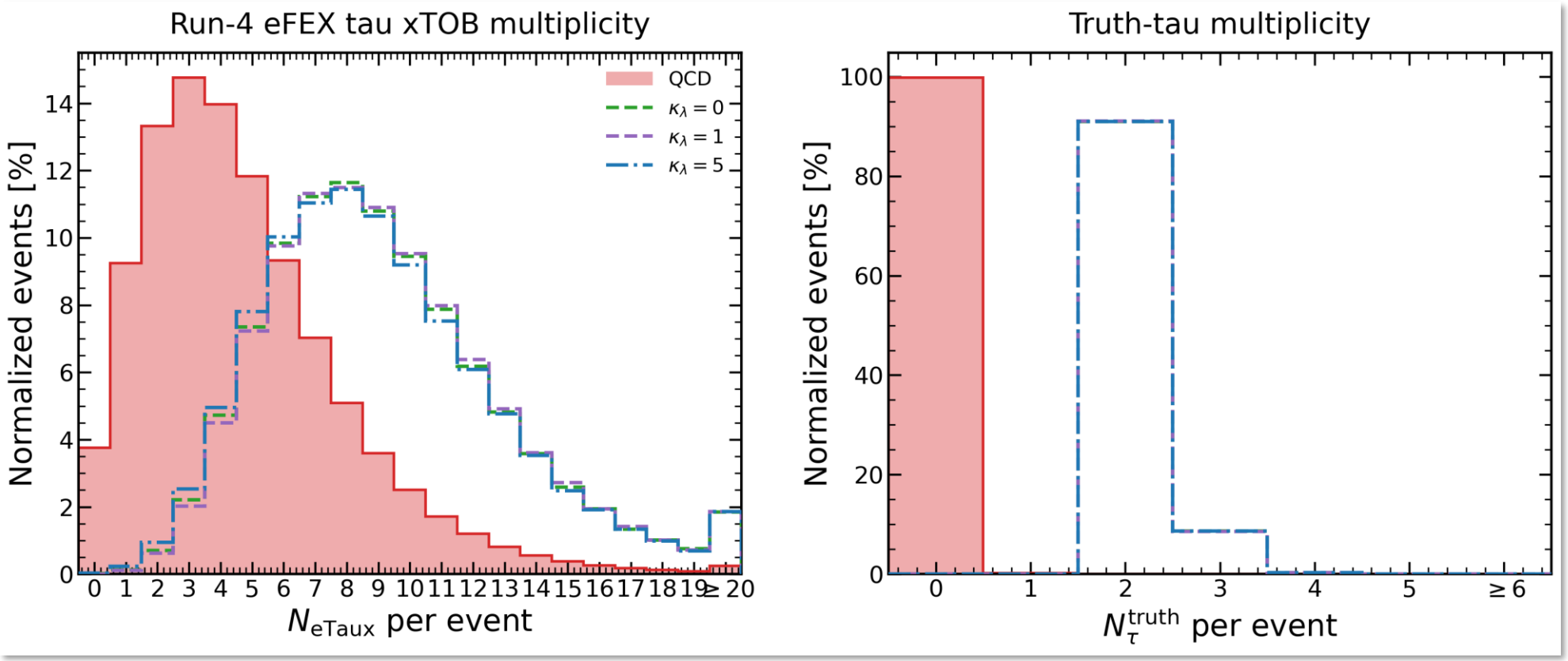
7. Others

Muon isolation



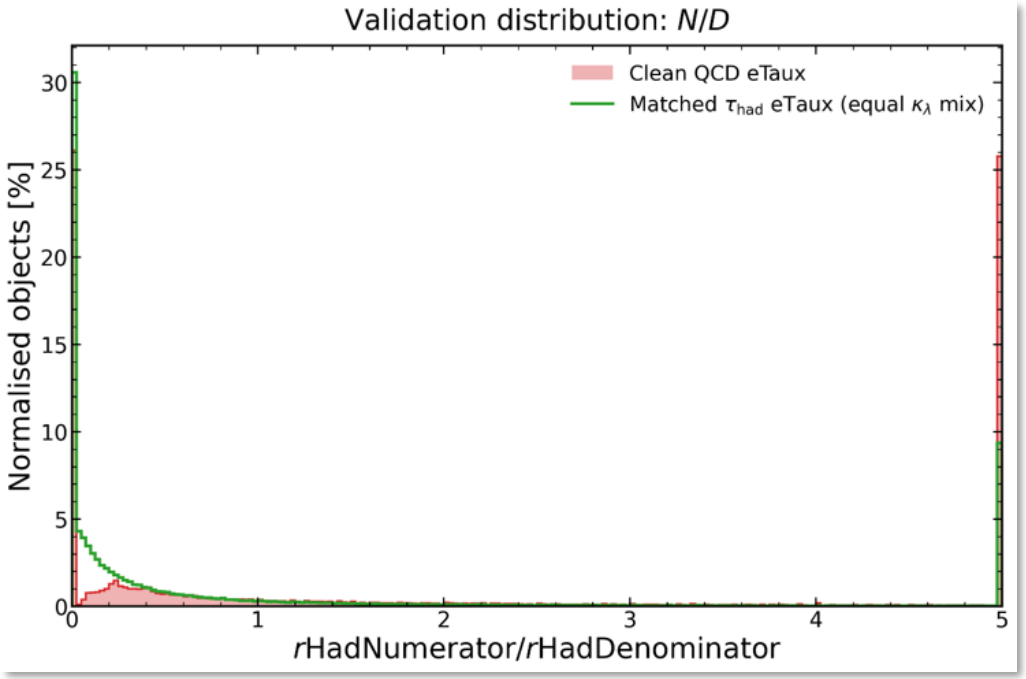
7. Others

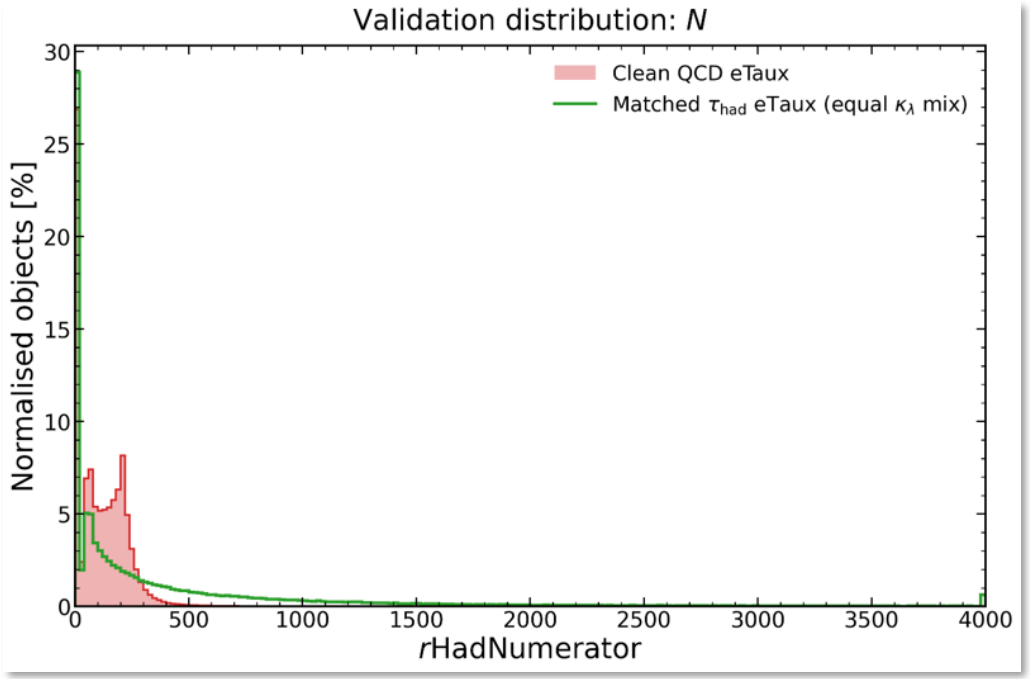
Tau quality requirement



7. Others

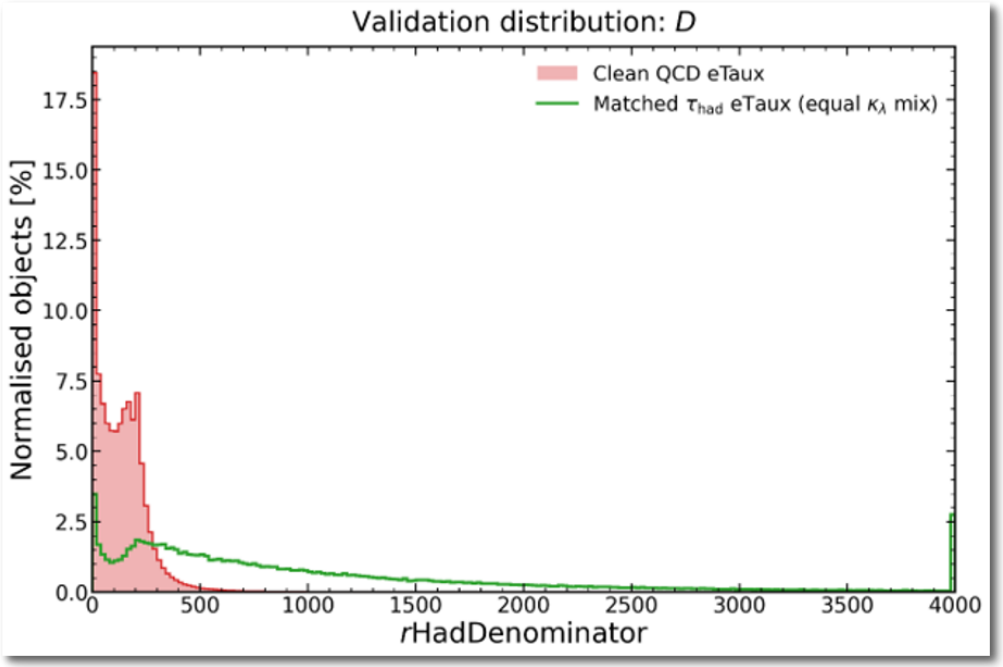
Tau quality requirement

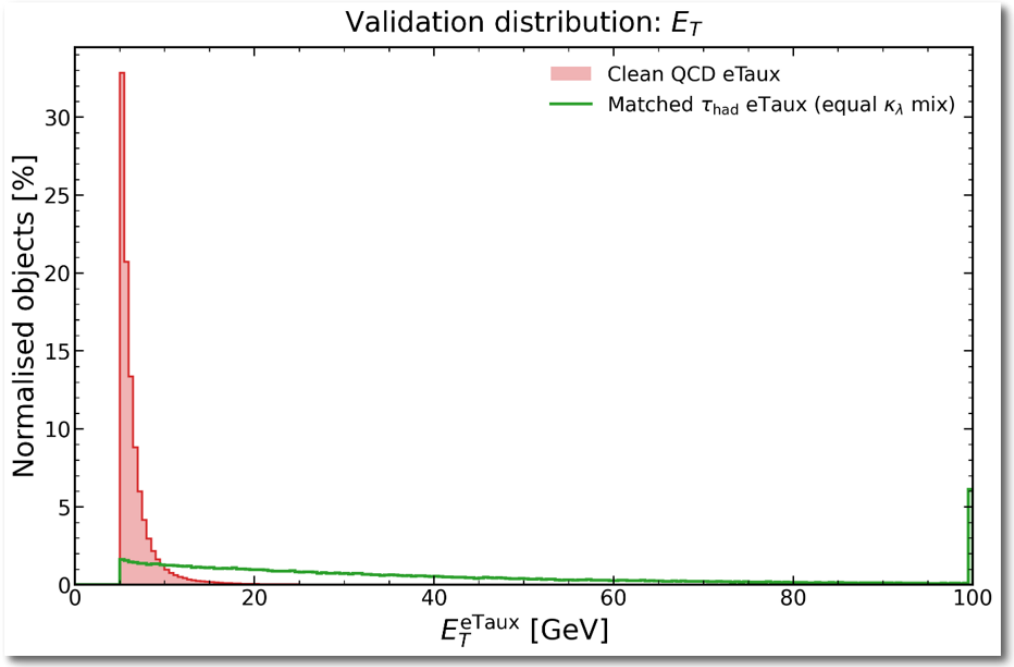


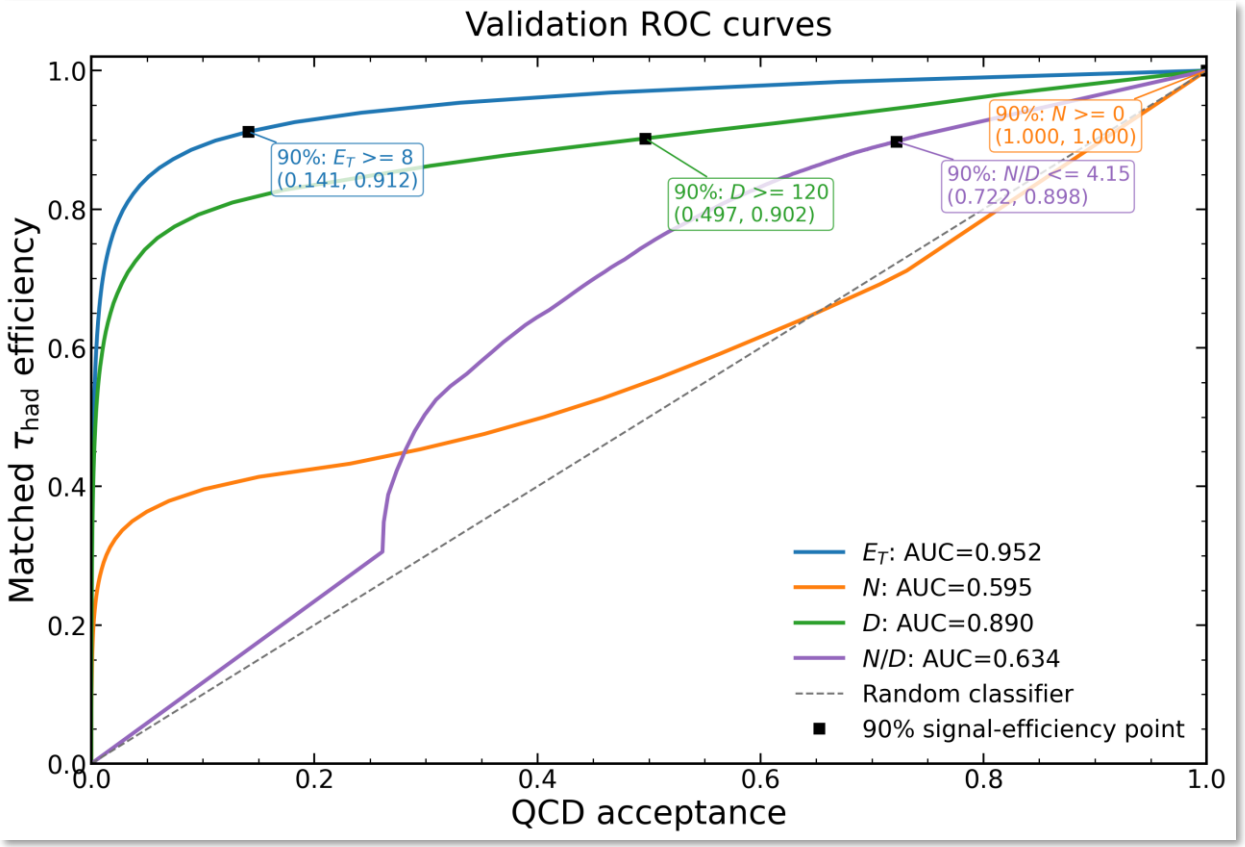


7. Others

Tau quality requirement





7. Others

Tau quality requirement