b-jet Trigger at ATLAS

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On behalf of the ATLAS b-jet trigger group
HHH workshop Dubrovnik 2023
• b-jets are important in many physics searches (e.g. $HH \rightarrow b\bar{b}b\bar{b}$)
• b-tagging algorithms exploit the b-hadron decay properties to identify b-jets
  o Used in multiple stages in the b-jet trigger preselection
  o With many updates in Run 3!
• $HH \rightarrow b\bar{b}b\bar{b}$ trigger strategy update
  o Gain in efficiency from delayed stream
• Challenges in HL-LHC and HHH searches
  o Specific kinematic phase space currently not within reach?
  o More final-state specific triggers?

Bunch crossings
40 MHz
L1 trigger
< 100 kHz
HLT
~100 Hz

Data for physics analysis
(b-jet trigger)
• Precision b-tagging requires precise tracking information to reconstruct secondary vertices → CPU intensive!
  o Can utilize b-tagging at earlier stages for pre-select candidates for full scan tracking
• Significant improvement in the ability to reject background from b-tagging
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Calorimeter topo clusters → Fast ROI tracking → fastDIPS

Trained on jets from calorimeter without PV

Level 1 trigger seed → Full scan tracking → Primary vertex finding → Particle flow → Precision tracking → GN1

Trained on Particle flow jets + PV + precision tracking

Trigger level analysis

Precision b-tagging requires precise tracking information to reconstruct secondary vertices → CPU intensive!
  o Can utilize b-tagging at earlier stages for pre-select candidates for full scan tracking
• Significant improvement in the ability to reject background from b-tagging
b-tagging exploits the b-hadron decay properties:

- Hard $b$-quark fragmentation
  - $\sim 70\%$ of the $b$-quark energy goes to the B-hadron
- Relatively long lifetime: $\sim 1.5\text{ps}$
- Displaced secondary vertex
- Large transverse impact parameter ($d_0$) in B-hadron decay tracks
- Large decay multiplicity

**Objective:**

- Classify jets originating from $b$-quarks, $c$-quarks and light-flavour quarks
Update to GN1

DNN $\rightarrow$ GNN (represents jets with variable number of unordered tracks naturally)

- **Previously:** DL1d relies on "low-level" algorithms
- **Now:** GN1 – a single algorithm
  - Uses auxiliary tasks to learn jet substructure
    1. Group tracks from common vertices
    2. Predict physics origins of tracks
- **Benefits:**
  - Better background rejection
  - No "low-level" algorithms to retune/maintain
  - Useful auxiliary tasks outputs
Combine the GNN outputs $p_b$, $p_c$, $p_{\text{light}}$ into a single discriminant:

$$D_b = \log\left(\frac{p_b}{(1 - f_c) \cdot p_{\text{light}} + f_c \cdot p_c}\right)$$

$f_c$ - effective charm fraction

Define working points for b-jet efficiency:

Evaluate background rejection:

**GN1 performance**

**GN1 public results**
Higher background rejection means lower trigger rates!

- Rates estimated by rerunning the Run 3 HH4b trigger on Run 3 Enhanced Bias data
- Replacing DL1d with GN1 in the same trigger
- At most a 20% reduction in readout rate → highly relevant in HL-LHC
Rejecting $bb$-jets from $g \to b\bar{b}$ splitting can further reduce readout rates

- Currently $bb$-jets are identified as $b$-jets by GN1
- DL1dbb – a dedicated DNN to separate $b$-jets and $bb$-jets
Combining GN1 + DL1dbb:

- Higher background rejection while maintaining HH4b signal efficiency
- Most significantly at tighter GN1 b-tagging working points
- Reduce readout rates, and maintain high signal purity for final states with multiple b-jets
• Run 3 triggers use full scan tracking to reconstruct PFlow objects
  - Better reconstruction but CPU intensive
• Fast track finding + fastDIPS: reduces tracking to high-energetic jets only

FastDIPS algorithm – deep sets network

\[
D_b = \log \left( \frac{p_b}{(1 - f_c) \cdot p_{\text{light}} + f_c \cdot p_c} \right)
\]

DIPS paper

**Features**
- Track 1
- Track 2
- \ldots
- Track N

**Calorimeter topo clusters**
- Fast track finding
- FastDIPS
- Full scan tracking
- Level 1 trigger seed
FastDIPS pre-selection

RoI width for fast track finding – 0.5 to 0.3
Track $p_T$ threshold – 0.5 to 1 GeV

Fast tracking finding + FastDIPS – 30% of CPU cost

Smaller RoI width + higher track $p_T$ cut:
no large degradation in light-jet rejection
Impact on $HH \rightarrow b\bar{b}b\bar{b}$ signal acceptance:

- From tightening the working point on fastDIPS from 85% to 80%
  - Very small impact on $HH \rightarrow b\bar{b}b\bar{b}$ signal trigger acceptance (-2%)
  - But reduces the rates of event-wide tracking significantly

- CPU reduction will be highly relevant in HL-LHC data-taking

**ATLAS Preliminary**

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Run 3 $HH \rightarrow 4b$ trigger strategy

- $HH \rightarrow 4b$ is challenging due to all-hadronic final state
  - Analysis operates on trigger turn-on region
  - Several multi-jet triggers for acceptance across $m_{HH}$

**Non-resonant analysis:**

- $2b2j$ – 2 35GeV $b$-tagged jets
  - + 1 35GeV extra jet
- $2b1j$ – 2 55 GeV $b$-tagged jets
  - + 1 100-150 GeV extra jet
Run 3 $HH \rightarrow 4b$ trigger strategy

Changes in L1:

Run 2:
- Sensitivity limited by requiring 4 jets with $p_T > 15$ GeV
- Plateaus at 65 GeV in offline $\rightarrow$ low acceptance for the 4$^{th}$ soft jet

Run 3:
- Pre-selection upgrade allows for more L1 accept rates $\rightarrow$ requiring 2 jets $p_T > 15$ GeV, 1 jet $p_T > 45$ GeV
- lower L1 threshold for 4$^{th}$ soft jet
Run 3 $HH \rightarrow 4b$ trigger strategy

Changes in HLT:

Run 2:
- Symmetric triggers: same $p_T$ cut on triggered jets ($p_T > 35$ GeV)

Run 3:
- Asymmetric trigger: different $p_T$ cuts on triggered jets ($p_T > 80$ GeV, 55 GeV, 28 GeV, 20 GeV)
  → reduces trigger rates
- Delayed stream – events stored for later reconstruction

Run 3 expected HH4b trigger performance

Largest improvement in the low $m_{HH}$ region
Conclusion & HHH trigger challenges

- Upgrades to reduce readout rates and maintain signal purity are highly relevant for HL-LHC, where HHH signatures might become accessible.
- Upgrades in $HH \rightarrow 4b$ trigger strategies also relevant for HHH.
- However HHH signatures are more challenging:
  - More $b$-quarks in the final states ($HHH \rightarrow 6b$).
  - Softer $b$-quarks in the final states in many BSM models
  → Tania will give an overview on a range of models.

Challenges to consider:
- Challenges to calibrate $b$-tagging for $b$-jets at very low $p_T$.
- How much can we rely on delayed stream in HL-LHC?
- More final-state-specific trigger strategies for more complex signatures?
Backup
bb-jet features

Compared to $b$-jets:

- Contains 2 $b$-hadrons instead of 1
- Larger track multiplicity within the jet cone
- Lower fraction of energy carried by tracks from $b$-hadron decay
- Larger jet width
DL1d discriminant

**ATLAS** Simulation Preliminary
- $t\bar{t}$ and multijet events, $\sqrt{s} = 13$ TeV
- Trigger PFlow Jets
- $p_T > 20$ GeV, $|\eta| < 2.5$
- $f_c = 0.018$

- $b$-jets
- $c$-jets
- $bb$-jets
- light-flavour jets
- stat. unc.

-77%
DL1dbb discriminant

ATLAS Simulation Preliminary
$t\bar{t} +$ multijet events, $\sqrt{s} = 13$ TeV
Trigger PFlow Jets
$p_T >$ 20 GeV, $|\eta| < 2.5$

77%
fastDIPS performance

fastDIPS | EMTopo jets is not trained with any primary vertex info
- However still decent performance in light-jet rejection compared to precision b-tagging algorithms
L1 jet turn-on

3J15 at L1 plateaus at 65 GeV for offline jet
- L1 jet energy resolution is low, therefore jet $E_T$ at L1 spreads more widely at offline jet $p_T$
- The 65 GeV threshold limits the acceptance of the 4$^{th}$ soft jet in the HH4b signal