Development and performance of track reconstruction algorithms at the energy frontier with the ATLAS detector

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Introduction

The ATLAS inner detector

- ATLAS: general purpose detector at the CERN LHC
- At center: inner detector
- TRT: Drift tube detector
- SCT: silicon strip detector
- PIXEL: silicon pixel detector
Introduction

Dense environments

- Charged particles typically deposit charge in $\geq 1$ pixel or strip per layer
- **dense environments**: distance between particles close to detector granularity
  - e.g. high-\(p_T\) \(b\)-hadron, \(\tau\) decays or top quark jets
- Charge clusters can merge
- High $\sqrt{s}$ $\rightarrow$ more dense environments $\rightarrow$ difficult tracking!
- figures: [STDM-2014-17], [1406.7690]
Outline

Tracking in ATLAS
  Track finding
  Ambiguity solving
  Track fitting

Performance
  Track reconstruction
  Lost tracks

Conclusion
Tracking in ATLAS
First step: track finding

- Detector measures **space-points** $\equiv$ 3D coordinates of hits
- Next, define **seeds**: sets of 3 space-points passing $p_T$, impact-parameter cuts
- Use **Combinatorial Kalman Filter** to produce **Track candidates**
  - Get track parameters from seed (position, angle, charge)
  - Predict probability distribution of parameters for next hit
  - Use compatible space-points to update/create track candidate
Tracking finding can create an excess of track candidates

Score tracks according to holes, fit $\chi^2$, $\log(p_T)$, ... 

If cluster used by multiple tracks, use neural network to decide if correct or not
  - Clusters identified as merged (i.e., multi-particle): no penalty $\rightarrow$ shared
  - Clusters not identified as merged are penalized

Neural networks estimate probability that cluster comprises 1, 2 or $\geq 3$ particles
Tracking in ATLAS

Clustering neural network

- Inputs:
  - 7x7 discretized charge matrix centered on charge centroid
  - 7D vector of pixel pitches
  - Angles of incidence of track candidate
  - Layer number and detector region (barrel or endcap)

- Output: 3D vector of class probabilities
  - 1-particle, 2-particles, \( \geq 3 \)-particles

- Trained using the Keras python library
  - [https://keras.io/](https://keras.io/)

- Trained on 12 million clusters from high-\( p_T \) dijet sample
  - 22% 1-particle clusters
  - 26% 2-particle clusters
  - 52% \( \geq 3 \)-particle clusters
Finally fit all tracks and measure final parameters
Problem: shared clusters assigned only one hit position
Use another set of neural networks to estimate the correct positions and improve track resolution

- ●: position obtained with linear interpolation
- ■: true hit position
- ★: Position obtained with neural network
Neural network trained separately for 1, 2 and 3 particle cases

- > 3 particle not considered
- Inputs: same as number neural network
- Output: 1/2/3 × 2D position vectors
- Regression task: network has linear activation at output layer

Truth hit residuals [mm]
Tracking in ATLAS
Track fitting

Also estimate error on measurement using neural networks

6 neural networks: one for each number/direction pair

Inputs: same as before + position estimation

Output: 1, 2 or 3 binned probability distributions on residual

Actually a classification task over the bins!

Point estimate of error: rms of distribution
Performance

Track reconstruction

ATLAS Preliminary
Simulation, $\rho \rightarrow \pi^+ \pi^-$

- Ideal, merged
- TIDE, shareable
- Baseline, split

[Pixel Clusters]

- measure average multiplicity of shared clusters in simulation
- True distribution in black
- Measured distribution with algorithms optimized for dense environment in red
- Measured distribution before optimization in green
- Optimized selection follows much more closely the true distribution

[ATL-PHYS-PUB-2015-006]
Performance
Lost tracks

- dE/dX of MIP \sim Landau
- Shifted if > 1 charge-particle fit to a Landau
- **Blue**: dE/dX of single-track clusters *away* from jet core
- **Green**: dE/dX of merged clusters *inside* jet core
- Select single-track clusters *inside* jet core, fit to weighted sum of both single and merged clusters templates

- If multiple-charged-particles cluster not split: used by one track only
- Merged clusters template will then be needed in dE/dX fit
  - Measures the inefficiency of tracking in dense environments
Performance

Lost tracks

Zoom:

- Left: Fit in $1 < p_T^{jet} < 1.2$ TeV range. $F_{lost} \approx 0.03$
- Right: $F_{lost}$ value in all $p_T^{jet}$ bins
- Good agreement between data and simulation (up to 25%)
Conclusion

- The ATLAS track reconstruction has been optimized for dense environments that are more and more frequent at energy frontier.
- Notably: now use three sets of neural networks to estimate number of particles contributing to clusters and to measure the true hit positions.
- Performance very good: never lose more than 4\% of tracks in high-$p_T$ jet core for tracks up to $\approx 1.5$ TeV measured by dE/dX fit.
- All done without increasing CPU time.
Thank you!
Backup slides
Truth hit resolution with/without neural network

ATLAS Simulation
\( \sqrt{s} = 7 \text{ TeV} \)

- CCA Clustering
- NN Clustering

4-pixel wide clusters

Arbitrary Units

Local x resolution [\( \mu \text{m} \)]
Tracking efficiency vs $p_T$

![Graph showing tracking efficiency vs $p_T$]

**ATLAS** Preliminary
Simulation, $\sqrt{s}=13$ TeV, $Z'(3$ TeV)
Shared cluster multiplicity, $\tau \rightarrow \nu 3\pi^{\pm}$

ATLAS Preliminary

Simulation, $\tau \rightarrow \nu 3\pi^{\pm}$

- Ideal, merged
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[ATL-PHYS-PUB-2015-006]
dE/dX templates definitions

Sample

Event Selection
Jet Selection
Track Selection

0 < |η^{trk}| < 1.2
Track p_T > 10 GeV
1 pixel hit per layer
B-layer dE/dx

Multiply Used

Not Multiply Used

ΔR(jet,trk) < 0.05
Jet p_T cut

Inside Jet Core

Inside Jet Core

Outside Jet Core

ΔR(jet,trk) > 0.1

Multiple-track template

Data distribution

Single-track template

[ATL-PHYS-PUB-2016-007]
\(F_{\text{lost}}:\) data & simulation agreement

\[ \int \text{[GeV]} T \text{Jet } p \text{ lost} \]

\[ \text{Sim.} / \text{Data} \]

ATLAS Preliminary

\[ L dt = 2.8 \text{ fb}^{-1}, \sqrt{s} = 13 \text{ TeV} \]

Simulation, \(\sqrt{s} = 13 \text{ TeV} \)

Pythia8
Herwig++
Sherpa

[ATL-PHYS-PUB-2016-007]