FATRAS —
A Novel Fast Track Simulation Engine for the ATLAS Experiment

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on behalf of the ATLAS Collaboration

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Outline

1. Introduction
   - The ATLAS detector
   - Fast detector simulations – Why?

2. Simulation strategies
   - Track simulation in FATRAS
   - Digitisation
   - Combined simulation: Tracking and calorimetry
   - Comparison to other simulation strategies

3. Performance
   - Comparison with full simulation
   - Comparison with collision data
   - Special use-cases and applications

4. Summary
The ATLAS detector

Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
TRT
Pixel/SCT
Tracking System
Solenoid

Muon Spectrometer
Hadronic Calorimeter
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The ATLAS Inner Detector

- **TRT drift tubes**
  - $\approx 300\,000$ straw tubes
  - $130\,\mu\text{m}$ resolution ($R_\phi$)
  - Xe/CO$_2$/O$_2$
  - about 30 measurements per track

- **SCT silicon strips**
  - $\approx 6$ million Si strips
  - resolution:
    - $17\,\mu\text{m}$ ($R_\phi$)/$580\,\mu\text{m}$ ($Z$)
  - 4 (double) measurements / track

- **silicon Pixel**
  - $\approx 80$ million Si pixels
  - resolution:
    - $10\,\mu\text{m}$ ($R_\phi$)/$115\,\mu\text{m}$ ($Z$)
  - 3 measurements / track

- **2 T solenoidal field**
Why do we need fast detector simulations?

- Monte Carlo simulation of detector response is needed to compare theoretical predictions (by Monte Carlo event generators) to data
- Detailed simulation of particles penetrating the detector material is CPU-time consuming
  - Simulation of a single $t\bar{t}$ event in full Geant4 simulation takes about 30 kSI2K minutes
- Fast simulation techniques can increase the amount of simulated events
Track simulation strategies

EVENT GENERATION
Primary Interaction, Decay, Fragmentation

4-momentum, particle type (PDG ID)

Geant4
Detector Simulation, Full physics list

FATRAS
Track Simulation
Material effects
Particle decay
Photon conversions
Digitisation

ATLFAST
Track representation smearing

detector simulation
simulates passage of particles through the detector, charge deposition in sensitive detectors, showers, material interactions

digitisation
emulates readout

reconstruction
pattern recognition, track finding, track fitting

standard high energy physics libraries (e.g. PYTHIA)
The simulation scheme of \texttt{fatras} uses the component model of the ATLAS software

- take extrapolation engine of the ATLAS track reconstruction
- reconstruction modules, such as the estimation of energy loss, are replaced by Monte Carlo implementations
- event data objects identical to full simulation or real data

- Where feasible, Geant 4 modules are used, such as particle decays
- Nearly all effects are estimated from first principles (Bethe-Bloch, etc.)
- no parametrisations used, despite hadronic interactions
Track reconstruction in ATLAS uses greatly simplified detector description
  - Sensitive elements identical to full Geant 4 description!
  - Uses the same!
Track simulation in FATRAS

MC Event Generator

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Track simulation in FATRAS

MC Event Generator

- Particle unstable? ⇒ Simulate decay length
- Extrapolation to next surface
- Material Effects
  - Decay point reached? Create decay products yes no
  - secondaries, brems photons, conversion electrons

\[ e^{-} \to \gamma \gamma \pi^+ e^{-} K^0 S \mu^- \]
Track simulation in FATRAS

MC Event Generator

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Track simulation in \texttt{fatras}

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Track simulation in FATRAS

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Track simulation in **fattas**

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**MC Event Generator**

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Track simulation in \textit{fatisas}
Track simulation in **FATRAS**

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MC Event Generator

Material Effects
- secondaries, brem photons, conversion electrons

Extrapolation to next surface

Particle unstable? ⇒ Simulate decay length
Track simulation in \textit{fatras}

- **MC Event Generator**
- **Material Effects**
  - secondaries, bremsstrahlung photons, conversion electrons
  - Extrapolation to next surface
  - Particle unstable? \(\Rightarrow\) Simulate decay length
  - Decay point reached?

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MC Event Generator

Material Effects

Extrapolation to next surface

Particle unstable? ⇒ Simulate decay length

Decay point reached?

Material Effects

spectators, brem photons, conversion electrons

Secondary, conversion electrons, bremsstrahlung

Particle unstable? ⇒ Simulate decay length

Decay point reached?

Outcomes:
- Yes: Create decay products
- No: Extrapolation to next surface

MC Event Generator

γ γ π⁺ e⁻ K± μ

Secondary, brem photons, conversion electrons
Track simulation in \( \text{atlas} \)

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**MC Event Generator**

- Particle unstable? \( \Rightarrow \) Simulate decay length
- Extrapolation to next surface
- Material Effects
- Decay point reached?

- secondaries, brems photons, conversion electrons
Track simulation in FATRAS

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Track simulation in **FATRAS**

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  - Material Effects
    - secondaries, brem photons, conversion electrons

**Decay point reached?**
- yes
- no

**Create decay products**

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Track simulation in *fattas*

Postprocessing

Outline

Introduction

Simulation strategies

Performance

Summary

Backup
Extract measurements from simulated tracks
Track simulation in FATRAS

Postprocessing

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Extract measurements from simulated tracks
Extract measurements from simulated tracks

Add noise
Track simulation in FATRAS
Postprocessing

1. Extract measurements from simulated tracks
2. Add noise and merge clusters
Digitisation in \textit{FATRAS}

Silicon clusterisation with geometric approach

Without Lorentz angle:

\begin{align*}
\theta_{L,1} & \quad \text{Lorentz Angle} \\
\theta_{1} & \quad \text{Lorentz Angle}
\end{align*}

With Lorentz angle:

\begin{align*}
\theta_{L,1} & \quad \text{Lorentz Angle} \\
\theta_{1} & \quad \text{Lorentz Angle}
\end{align*}

- intersection with surface
- exit of sensor material
- \( \mathbf{X} \) pixel position (vetoed)
- \( \star \) cluster position
**Combined Simulation**

FATRAS and FastCaloSim interfaced:

- **FATRAS** simulates the Inner Detector including secondaries
- Calorimeter deposits simulated by FastCaloSim
- Muon System simulated by FATRAS
# The Fast and the Furious

<table>
<thead>
<tr>
<th>ID</th>
<th>Atlfast I</th>
<th>Atlfast II</th>
<th>Geant4/full</th>
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<tbody>
<tr>
<td></td>
<td>parameterised track perigee</td>
<td>FatrasID</td>
<td>full simulation digitisation reconstruction</td>
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<tr>
<td>Calo</td>
<td>parameterised clusters</td>
<td>FastCaloSim</td>
<td>full/frozen G4 digitisation reconstruction</td>
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<td>MS</td>
<td>parameterised track perigee's</td>
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<td>full simulation digitisation reconstruction</td>
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<td>rel. gain</td>
<td>~ 1000</td>
<td>~ 100</td>
<td>~ 10</td>
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<tr>
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<td>-</td>
</tr>
</tbody>
</table>
Material effects
Comparison of FATRAS and Geant4

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FATRAS
Sebastian Fleischmann

Multiple scattering

Energy loss

Radiation of brems photons

Hadronic interactions

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- Pixels and SCT clusterisation tuned by adapting
  - minimal required path length in the Pixels cell
  - strength of Landau smearing

- Tuning can be done within 24h

Cluster width in Pixels

Measurement residual in Pixels
Track parameter resolutions

- Single muon events with $p_T = 1$ GeV, 5 GeV, 100 GeV
- In general good agreement, but still some parameters to tune in the digitisation
- In particular tails better described than in ultra-fast sim
Reconstructed tracks in minimum bias events at $\sqrt{s} = 900$ GeV

- Reconstructed tracks in minimum bias Monte Carlo (Pythia) at the center of mass energy $\sqrt{s} = 900$ GeV
- Still some discrepancies, but not yet tuned to data and misalignments of detector modules in data
Reconstructed tracks in minimum bias events
Average number of Pixels hits per track

“sinoidal structure” due to inactive Pixels modules in b-layer folded with the z-position of the primary vertex

- Detector conditions like inactive modules automatically taken into account
- Precise description of the detector geometry
Cluster size depends on incident angle, because of sensor thickness

Mean cluster size (in $\eta$ direction) vs incident angle ($\eta$) on the Pixel module

Very sensitive test of the clusterisation model
Reconstructed tracks in minimum bias events at $\sqrt{s} = 900\text{GeV}$

- Position and size of the beam spot in the simulation taken from detector conditions database
FATRAS was used for SLHC upgrade studies of the ATLAS tracker.

- Allows easy testing of various geometries at a reasonable time scale.
- Detector occupancies can be derived reliably.
- Reconstruction effects are included in momentum resolutions, etc.
Stress tests for track fitters

Simulation with high noise levels

- Detailed truth information by allows to evaluate performance of track fitters
- Quick simulation of arbitrary noise levels

5 GeV single muon events

- Example: Study of adaptive track fitter (Deterministic Annealing Filter)
- High detector occupancy
- Solution of left-right ambiguities in the TRT
Conclusions

- Fattas is a new track simulation concept between full Geant4 simulation and conventional fast detector simulations
  - The full reconstruction chain can be run on output
  - Speed improvement mostly due to simplified Tracking Geometry and extrapolation
  - (Nearly) no parametrisations needed
  - All important physics effects included, like multiple scattering, brem, conversions, particle decays, hadronic interactions
  - Allows studies to be performed that cannot easily be done either with full simulation or conventional fast simulations

- Currently in the tuning phase
- Validation with collision data has started
Acknowledgements

- Special thanks to Andreas Salzburger (CERN), Sharka Todorova (Tufts University) and Simone Zimmermann (Bonn)

- and
The ATLAS Muon System

- Monitored Drift Tubes (MDT)
  - \( \approx 354k \) straw tubes
  - barrel and forward region
  - 80 \( \mu \)m straw resolution (\( Z \))
  - 20 measurements / track

- Resistive Plate Chambers (RPC)
  - barrel region
  - chamber resolution:
    - 10 mm (\( Z \))/10 mm (\( \phi \))
  - 6 measurements / track
  - trigger (+ 2\(^{nd}\) coordinate)

- Thin Gap Chambers (TGC)
  - end-cap
  - chamber resolution:
    - 2 - 6 mm (\( R \))/3 - 7 mm (\( \phi \))
  - 9 measurements / track
  - trigger (+ 2\(^{nd}\) coordinate)

- Cathode-Strip Chambers (CSC)
  - forward region
  - multi-wire prop. chambers
  - plane resolution:
    - 60\( \mu \)m (\( R \))/5mm (\( \phi \))
  - 4 measurements / track

- barrel toroid: 1.5 – 5.5 Tm bending power,
  end-cap toroids: 1 – 7.5 Tm

Muons with momenta of 4 GeV and 20 GeV in the bending plane of the barrel muon spectrometer.
### Simulation strategies

<table>
<thead>
<tr>
<th>Simulation time/event, kSI2Kseconds</th>
<th>Minimum Bias</th>
<th>$t\bar{t}$</th>
<th>Jets</th>
<th>$W^\pm \rightarrow e^\pm \nu_e$</th>
<th>Heavy Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Sim</td>
<td>551</td>
<td>1990</td>
<td>2640</td>
<td>1150</td>
<td>56,000</td>
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<tr>
<td>Fast G4 Sim</td>
<td>246</td>
<td>757</td>
<td>832</td>
<td>447</td>
<td>21,700</td>
</tr>
<tr>
<td>ATLFAST-II</td>
<td>31.2</td>
<td>101</td>
<td>93.6</td>
<td>57.0</td>
<td>3050</td>
</tr>
<tr>
<td>ATLFAST-IIIF</td>
<td>2.13</td>
<td>7.41</td>
<td>7.68</td>
<td>4.09</td>
<td>203</td>
</tr>
<tr>
<td>ATLFAST-I</td>
<td>0.029</td>
<td>0.097</td>
<td>0.084</td>
<td>0.050</td>
<td>6</td>
</tr>
</tbody>
</table>

- Hard to estimate how much $CO_2$ is emitted for one CPU second by the grid

- Taking 0.01 grams/s: Simulating 100k $t\bar{t}$ events with ATLFAST-IIIF (``fattas`` + FastCaloSim) instead of Full Simulation saves about 2 tons of $CO_2$
Digitisation in FATRAS
Simulation of hits with transition radiation in the Transition Radiation Tracker

- Transition radiation in the TRT produces hits with stronger signal and is used for particle ID.
- Probability of transition radiation depends on relativistic $\gamma$ factor.
- Measured with test beams and cosmic ray data.
- Fit of turn-on curve has been fed into FATRAS.

![Graph showing the relationship between $P_{HT}$ and $\gamma$ factor with data points for pions, electrons, and muons.](image)
Combined simulation
Comparison of reconstructed muon $p_T$ resolution

- central muons ($|\eta| < 1.2$) in $Z \rightarrow \mu^+ \mu^-$ events
Reconstruction efficiencies

- Single electrons and muons with transverse momentum $p_T = 5$ GeV
- Shape roughly reproduced, but "too perfect" for electrons
  - Needs some extra fudge factors