Simulation of hadronic showers in Geant4

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Outline

Simulation of hadronic showers in Geant4 for high-energy collider particle physics

- Hadronic interactions
- Hadronic showers and calorimeter observables

- Hadronic physics in Geant4
  - Geant4 Physics Lists, QGSP_BERT

- Validation with the LHC calorimeter test-beams
- Transition between hadronic models

- Future of validation: LHC data and CALICE
- Summary and outlook
I

Hadronic interactions
Hadronic showers in calorimeters
Hadronic interactions (1/2)

- Most of what I’ll discuss in this talk is related to hadronic interactions.

For hadronic interaction we mean here the collision of a hadron (e.g. $\pi^+$, $\pi^-$, $K^+$, $K^-$, $K^0_L$, $K^0_S$, $p$, $n$, $\alpha$, etc.) on a nucleus (e.g. H, C, Ar, Si, Al, Fe, Cu, W, Pb, etc.) i.e. the reaction:

$$h + A \rightarrow \text{anything}$$

- “anything” can be:

  - $h + A$: elastic (coherent scattering of the whole nucleus)
  - $h + A^*$: quasi-elastic (elastic on single nucleons)
  - $h + X$, $A + X$: diffraction (target, projectile, double) inelastic
  - all the rest: deep inelastic
Hadronic interactions (2/2)

- Hadronic interactions were studied a lot in the past 50 years, but they are still relevant in modern high-energy particle physics. In fact, $e^+ e^-$, $e^- p$, $p - p\bar{p}$, $p - p$ colliders produce hadrons that pass through detectors, therefore the simulation has to be able to describe hadronic interactions.

- In principle, QCD is the theory that describes all hadronic interactions; in practice, pertubative calculations are available only for a tiny phase-space region (the hard scattering at high transverse momentum), whereas for the rest, i.e. most of the phase space (soft primary scattering, re-scattering, and nucleus de-excitation) only approximate models, valid for limited combinations of particle type, energy, and target material are available.
Jets & $\tau$ leptons

How hadrons are produced in high-energy colliders?

- **Jets**
  - “sprays” of hadrons, coming from the hadronization of partons (partons produced in the “hard scattering” and showering)
  - Jets are fundamental in most physics analyses in modern colliders (Tevatron, HERA, LHC, ILC) either as signal or as background
  - Missing $E_T$ (e.g. important for SUSY) rely also on jet measurements
  - A good simulation of jets is essential: this involves
    - Monte Carlo Event Generator
    - Simulation of hadronic showers

- **$\tau$ leptons**
  - About 2/3 of $\tau$ decays produce hadrons
  - $\tau$ leptons are produced in several models beyond SM
  - They look like isolated narrow jets
    - Simulation of hadronic showers play an important role
Hadronic showers

- A single hadron impinging on a large block of matter (e.g. a hadron calorimeter) produces secondary hadrons (and $\gamma$) of lower energies, which in turn can produce other hadrons, and so on. $e^-/e^+/\gamma$ (electromagnetic component) are also produced copiously because of $\pi^0 \rightarrow \gamma + \gamma$ and ionization of charged particles. The ensemble of these particles constitute a hadronic shower.

- The development of a hadronic shower involves many energy scales, from hundreds of GeV down to thermal energies.

- Most of hadronic calorimeters are non-compensating, e.g. an electron of a given energy produces a different (usually higher) response than a hadron of the same energy:
  - Hadronic calibration is needed
  - Fluctuations in the electromagnetic component of hadronic showers are the main limitation of the energy resolution
The simulation of hadronic showers can be validated with calorimeter test-beam set-ups, with pion and proton beams of various energies, considering the following observables:

- **Energy response**: $E_{\text{rec}} / E_{\text{beam}}$
- **$e/\pi$**: $E_{\text{rec}}(e^- \text{ beam}) / E_{\text{rec}}(\pi^- \text{ beam})$
- **Energy resolution**: $\Delta E_{\text{rec}} / E_{\text{rec}}$
- **Shower profile**
  - **Longitudinal**: $E_{\text{rec}}(z) / E_{\text{rec}}$
  - **Lateral (transverse, or radial)**: $E_{\text{rec}}(r) / E_{\text{rec}}$

Note that we can test directly only single-hadron showers in calorimeter test-beam set-ups, whereas for a collider experiment (e.g. ATLAS and CMS) jets are measured.

Once again, the simulation of jets involves:
1. the Monte Carlo Event Generator
2. the convolution of the showers for each constituent hadron
II

Geant4
Hadronic physics
Physics Lists
QGSP_BERT
**Geant4**

- It is an object-oriented toolkit, in C++, for the simulation of particle transport in matter. Very flexible and powerful.

- Useful in several application domains:
  - High-energy particle physics (BaBar, HARP, ATLAS, CMS, LHCb, ILC)
  - Space science
  - Medical physics
  - Underground physics
  - Nuclear physics

- The user must specify:
  1) geometry
  2) primary particle(s)
  3) physics: particles and their processes

- Compared with its competitors (e.g. FLUKA, MARS, MCNPX), Geant4 is easier to customize and adapt, but at the price of writing some C++ code. Being younger than other codes, it has been less validated in some aspects of hadronic physics, like isotope production (activation).
Physics processes in Geant4

- **Electromagnetic physics**
  - “standard” processes valid from $\approx 1$ keV to $\approx$ PeV
  - “low-energy” processes valid from $\approx 250$ eV to $\approx$ PeV
  - optical photons

- **Weak physics**
  - decay of subatomic particles
  - radioactive decay of nuclei

- **Hadronic physics**
  - pure hadronic processes valid from 0 to $\approx$ TeV
  - $\gamma$, $e^-$, $\mu^-$ nuclear valid from $\approx 10$ MeV to $\approx$ TeV

- Parameterized physics for “fast simulation”
Hadronic physics in Geant4

- Geant4 offers a choice of hadronic processes, models and cross-sections
  - No model matches the requirements for all application domains

- Models are divided in 3 categories
  - **Theory-driven** (phenomenological) models
    - QGS, FTF, Bertini, Binary, CHIPS, Preco, etc.
  - **Parameterized** models
    - Use data and physical meaningful extrapolations: LEP, HEP
  - **Data-driven** models
    - HP (neutron $E_{\text{kin}} < 20$ MeV), radioactive decay, coherent elastic n-n

- Applicability of models is limited
  - Range of energies
  - Incident particle types
  - Range of nuclei (only for few models)
Hadronic Process/Model Inventory sketch, not all shown

- At rest
  - Absorption
  - \( \mu, \pi, K, \) anti-\( p \)

Radioactive Decay

High precision neutron

- Evaporation
- Fermi breakup
- Multifragment
- \( \gamma \) de-excitation

Pre-compound

- Binary cascade
- Bertini cascade

FTF String

QG String

CHIPS

- Fission
- HEP
- LEP

1 MeV  10 MeV  100 MeV  1 GeV  10 GeV  100 GeV  1 TeV
The members of the Geant4 hadronic physics group are responsible of the tuning & validation of the models, using published thin-target results.

Tuning of model parameters should not be done by users. But users are welcome to perform validation, especially with data relevant for their use-cases, and give feedback to the developers.

Tuning of the model parameters should not be done with calorimeter test-beam data, because too many processes and effects contribute to the observables.

Simplified calorimeter set-ups are used to understand which hadronic models could have an impact on a given observable (e.g. longitudinal pion shower shape), and then the developers of these models try to improve them...
Validation of String models

- **QGS**: Pi+ production in scattering of protons (400 GeV/c) off Tantalum: invariant cross section $d2\sigma/d\Omega/dT$

- **FTF**: pi+/ production in scattering of protons (158 GeV/c) off Carbon: invariant cross section $d2\sigma/dp_T/dx_F$
Validation of Bertini cascade
Validation of Binary cascade
Validation of Precompound & de-excitation

Isotope production at 1000 MeV in inverse kinematics

**Before** 9.2p01  **Now** 9.3

Isotope production (mb) $\text{Pb + H \rightarrow X at 1000 MeV}$

**Includes GEM (corrected)**
Physics Lists in Geant4

- Each Geant4 application must specify a **Physics List**
  - which **particle types** can be simulated
  - which **physics interactions** can have each of these particles

- Nature has just one “physics”: so why Geant4 does not provide a complete and unique set of particles and physics processes that everyone can use? Because there are many **different physics models**, corresponding to a variety of approximations of the real phenomena
  - One model can be better than another for a given application
  - Comparing different models one can estimate the systematic err.
  - A user can prefer a less accurate, but faster model

- For users’ convenience Geant4 provides a set of pre-packaged **Reference Physics Lists** for some use-cases. These are best guesses, intended as starting point, to be eventually modified/extended and validated by users.
Let’s give a look to the Reference Physics List QGSP_BERT which is the most used one in high-energy physics

- used in production by ATLAS and CMS
- very similar also to the one used by BaBar and ILC

Various hadronic models are utilized for different particles and in certain kinetic energy ranges:
QGSP_BERT (2/2)

- **QGS** (Quark Gluon String) model [12 GeV, 10 TeV] for pions, kaons, protons and neutrons
- **LEP** (Low Energy Parameterized) model [9.5 GeV, 25 GeV]
- **BERT** (Bertini cascade) model [0, 9.9 GeV] for pions, kaons, protons and neutrons

- Nucleus de-excitation: Precompound + evaporation
- Neutron capture and fission: parameterized models
- Other hadrons (hyperons, anti-baryons, light ions): parameterized model
- CHIPS: capture of negative hadrons; elastic for protons and neutrons; quasi-elastic, gamma-nuclear, electron-nuclear
- Standard electromagnetic physics
III

Validation of Geant4 hadronic physics with LHC calorimeter test-beams
Set-ups

The main LHC calorimeter test-beam set-ups that we are considering here are the following:

- **ATLAS Tile**: Fe-Sci
- **ATLAS HEC**: Cu-LAr
- **ATLAS combined barrel**: Pb-LAr (EM) + Fe-Sci (HAD)
- **CMS combined**: PbWO4 crystals (EM) + Brass-Sci (HAD)

Note: an extensive validation of the Geant4 electromagnetic physics has been undertaken before the validation of hadronic physics (remember that there is always an electromagnetic component in a hadronic shower). We concentrate here only on the validation of hadronic physics.
A long journey...

Once you have collected data from a calorimeter test-beam set-up with hadron beams, there is a long work needed before drawing conclusions on the hadronic simulation:

- Cleaning/selection cuts to have the purest possible sample
- Model beam composition and spread
- Check material composition, geometry, dead material
- Model quenching effects (Birks' law), photo-statistics, etc.
- Include noise, cross-talk, DAQ time-window, and digitization

To help on these steps:

- Special triggers
- Muon beam
- Electron beam (also needed for the electromagnetic calibration)
Energy Response
Bertini cascade increases response for *Tile* and *HEC* by 4–5%.

In *Tile* and *HEC* response ~2% too high with QGSP_BERT.
Pion energy response in ATLAS barrel combined test-beam

Bertini cascade model increases the response.

QGSP_BERT shows the best overall performance for the linearity (within 4%).

2% above 10 GeV
4% below 10 GeV
Pions and protons energy response in CMS combined test-beam

Agreement between data and simulation on energy response is within systematic uncertainty.
Energy response vs. beam energy

Problem of matching models:

FTF_BIC is more smooth
QGSP_BERT is in better agreement to data

FTF_BIC:
- 0-5 GeV binary cascade model (BIC)
- 0-5 GeV LEP for capture and fission processes
- >5 GeV Fritiof model (FTF)

QGSP_BERT:
- 0-9.9 GeV Bertini intra-nuclear cascade (BERT)
- 9.5-25 GeV low energy parameterised model (LEP)
- >12 GeV QGSP

ATLAS Tile

FTF_BIC is more smooth
QGSP_BERT is in better agreement to data

Effect of transition between models?
Energy Resolution
Bertini cascade makes resolution better:
in Tile: better agreement with data ($\pm 10\%$)
in HEC: MC resolution too good by $-10\%$
Pion resolution in ATLAS barrel combined test-beam

Bertini cascade makes resolution better
MC predicts too good resolution -5 ÷ -10%

G4 9.0
Pions and protons energy resolution in CMS combined test-beam

Resolution is too good in the simulation
Longitudinal shower shape
Pion longitudinal shower profile in stand-alone ATLAS TileCal test-beam at 90°

MC within ~ ±10% up to 10 \( \lambda \)
Proton longitudinal shower profile in stand-alone ATLAS TileCal test-beam at 90°

MC -20% ÷ -40% at 10 λ
Pion longitudinal shower profile in stand-alone ATLAS HEC test-beam

G4 9.0

QGSP starts/ends too early, QGSP_BERT with ±10 % (still a bit too early)
Problem at 10 GeV
Pion longitudinal shower profile in ATLAS barrel combined test-beam

G4 9.0

E = 5 GeV

- Pion data
- QGSP_BERT
- QGSP

\( \frac{1}{E_{\text{tot}}} \frac{dE}{dl} [1/\lambda] \)

\( \frac{MC}{Data} \)

E = 100 GeV

- Pion data
- QGSP_BERT
- QGSP

\( \frac{1}{E_{\text{tot}}} \frac{dE}{dl} [1/\lambda] \)

\( \frac{MC}{Data} \)

QGSP_BERT describes data within ±10%
Pion longitudinal shower profile in CMS combined test-beam

- QGSP produces shorter showers than data
- QGSP_BERT showers are as long as in the data
- Similar trend at all energies
Lateral shower shape
Bertini cascade makes shower wider, which is in better agreement with data, but data are still a bit wider.

Pion lateral spread in stand-alone ATLAS TileCal test-beam @90°
Transition between hadronic models
Energy response in a simplified Cu-LAr calorimeter for $\pi^-$ beam vs. beam energy.

Unphysical discontinuity in QGSP_BERT corresponding to the transition between LEP and BERT models.

It can affect the simulation of jets, and the hadronic calibration based on simulation.
Study of models

- 3 ways to make smoother the transition between models
  1. Improve the models; extend their applicability region
  2. Optimize the choice of the transition region between models
  3. Create novel combinations of models in new Physics Lists

- This requires the study of hadronic models (instead of Physics Lists) for single interactions as a function of the kinetic energy of the primary
  - $\pi^-$ - Fe inelastic interactions
  - 1 - 20 GeV primary kinetic energy
  - Fraction of the final state energy for each particle type: $\pi^0$, $\pi^-$, $\pi^+$, $p$, $n$, ion, all
    - these variables are more directly correlated to calorimeter observables, such as energy response and resolution, than the more common multiplicity, spectrum and angular distributions
\( \pi^- \text{ Fe inelastic collisions} \)
Improvements

- **Models:**
  - **Fritiof**: improved and re-tuned, based on thin-target data; FTF is now coupled to a 2-dimensional reggeon cascade + Precompound.
  - **CHIPS**: extended to all particles, energies, and materials. New CHIPS Physics List available in G4 9.3
  - **BERTini cascade**: improved cross-sections; higher multiplicity final-states; strange hadron production.

- **Optimization of the transition region:**
  - **FTFP_BERT_TRV**: transition between BERT and FTFP in the range 6 - 8 GeV (instead of 4 - 5 GeV)

- **Novel combinations of models:**
  - **QGSP_FTFP_BERT**: as QGSP_BERT, but with FTFP replacing LEP and transition between BERT and FTFP in the range 6 - 8 GeV (instead of 9.5 - 9.9 GeV for the LEP-BERT transition)
Energy response in a simplified Cu-LAr calorimeter for $\pi^-$ beam vs. beam energy.

In 9.3, FTFP_BERT and QGSP_FTFP_BERT are smooth and close to QGSP_BERT, which we know is close to the LHC test-beam data.

CHIPS is also interesting, but needs some tuning.
Hadronic physics validation in the next future: LHC data and CALICE
LHC collision data

- **Isolated tracks** pointing to calorimeter clusters can be used for hadronic calibration and validation of hadronic showers
  - Minimum-bias sample

- **Jets** can be used for hadronic calibration and validation of hadronic showers
  - Not easy to decouple from Monte Carlo Event Generator effects

- **Interactions in the Tracker** sub-detectors can be used for validation of single hadronic inelastic interactions
  - Similar to thin-target benchmarks: cross-sections, multiplicities, momentum and angular spectra
  - LHCb can identify kaons, so we can test hadronic interactions of these particles, which has not yet been done extensively in Geant4
3 goals:
1. Develop highly granular calorimeters for Particle Flow
2. Establish technologies for ILC
3. Validation of hadronic interaction models in simulation

For ILC multi-jet physics, it is essential to separate $W \rightarrow \text{jet} + \text{jet}$ and $Z \rightarrow \text{jet} + \text{jet}$.
This appears impossible with traditional calorimetry.
A promising solution seems to be the Particle Flow:

- Use the Tracker for charged particles ($\approx 60\%$)
- Use the ECAL for gammas ($\approx 30\%$)
- Use the HCAL for neutral hadrons ($\approx 10\%$)

Highly granular calorimeters are needed to separate the various contributions and find tracks inside showers.
CALICE Imaging calorimeter

ECAL prototype
- materials: Silicon – Tungsten
- cell size: $1 \times 1 \text{ cm}^2$
- channels: 9760
- size: $20 \times 20 \times 30 \text{ cm}^3$
- interaction length: $1 \lambda_I$

HCAL prototype
- materials: Iron – Scintillator
- cell size: $3 \times 3 / 6 \times 6 / 12 \times 12 \text{ cm}^2$
- channels: 7608
- size: $90 \times 90 \times 120 \text{ cm}^3$
- interaction length: $5 \lambda_I$
CALICE : 2D shower profiles in HCAL

- It allows to study the transverse shower profile as a function of the longitudinal depth (not only the integrated transverse profile as for the LHC calorimeter set-ups).

- It is possible to look at the longitudinal shower profile from the start of the shower (instead from the start of the calorimeter as for the LHC calorimeter set-ups): more sensitive to the shape (avoid smearing with the position of the first interaction).

![Image showing 80 GeV π⁺ standard profile and 80 GeV π⁺ from shower start](image-url)
CALICE: hadronic showers in ECAL

- Although hadronic showers are not contained in the ECAL, its extreme granularity allows to probe features of the **first hadronic interaction** (e.g. total energy in ECAL; energy in the first few layers after the first interaction)
- Transverse profile in the first part of the shower
- Separation of e, π, p from the longitudinal profile
Summary & Outlook

- The simulation of hadronic showers is a key aspect of the simulation of jets and $\tau$, and therefore it is important for physics analyses and detector design & optimization. A better modelling of hadronic interactions would be very useful also in several other fields and applications.

- Significant progress in Geant4 hadronic physics has been achieved in the last few years. Validation with LHC test-beam data has been essential to drive and confirm such improvements (e.g. hadronic shower shapes; discontinuities in the energy response vs. $E_{\text{beam}}$).

- QGSP_BERT Physics List should provide reasonable simulations for first LHC data analyses. Interesting alternative Physics Lists are FTFP_BERT and CHIPS.

- We expect that further progress in Geant4 hadronic physics in the next future will be driven mostly by LHC collision data, and from ILC test-beam data (CALICE).
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