Recent improvements on the description of hadronic interactions in Geant4

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Overview

- Introduction
- Status of the simulation of hadronic interactions for HEP experiments
- Recent developments
  - FTF based physics lists improvements
  - CHIPS one model physics list
- Results: comparison of different physics lists of calorimetric quantities
Introduction

“Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science”


http://www.cern.ch/geant4

Hadronic physics in Geant4:

- cross sections and models for hadron-nucleus interaction up to TeV
- For neutrons from thermal energies to TeV

Models are tuned with thin target data (not calorimeters test-beam)

Models are assembled in physics lists: stable configurations (few billions of events simulated)

- Example: QGSP_BERT (used at LHC since 3-4 years)

Experiments compare physics lists with test-beam data

We use simplified calorimeters to study the impact of hadronic models on calorimeter observables
**Bertini** cascade: low energy intra-nuclear cascade (best agreement with data up to $E_{\text{kin}} \approx 5$ GeV) \cite{Bertini1968, Bertini1966}.

**Quark-Gluon-String, “QGS”:** $p,n,k,\pi$ of high energy (agreement with data from $E_{\text{kin}} \approx 10$-15 GeV) \cite{QGS1966}.

**Parameterized models** (derived from GHEISHA as first hadronic model mid-90): all $E$ and particles. **Goal:** replace with more accurate models. Still used in most physics lists for hyperons and antibaryons.

**Chiral Invariant Phase Space Decay, “CHIPS”** (new developments): all $E$ and particles. \cite{CHIPS2000, CHIPS2001}.

**Fritjof, “FTF”** (new developments): $p,n,k,\pi$ of high energy (valid from $E_{\text{kin}} \approx 4$-5 GeV) \cite{FTF1987}.
Thin Target Tuning: Example

- Tuning is done at model level:
  - Thin target data
  - Several tests are run routinely to follow evolution of model code

- BERT and FTF predictions for HARP-CDP data: double differential cross sections in pA interactions
- BERT and FTF describe data reasonably well

FTF and BERT can be used together in the 4-5 GeV region
A Physics List is a set of consistent physics models for each particle in application.

LHC tested several options: most challenging requirements on hadronic interactions come from ATLAS and CMS calorimeters.

- After detailed validation with test-beam: QGSP_BERT (2007)

For a given physics list when a hadronic interaction occurs a model, depending on primary type and energy, is sampled.

Models
- BERT
- LEP
- QGSP
- FTFP

Physics Lists
- QGSP_BERT
- FTFP_BERT
- CHIPS
- LHEP
- HEP
- LEP

Theory driven

CHIPS components used by other PL for capture of negative hadrons at rest and γ-Nuclear and Lepto-Nuclear interactions.
Status Of Simulation

Need for precise simulation of observables for LHC (CERN-LCGAPP-2004-02):

- **Response** (e/\pi), resolution, shower shapes

Results from ATLAS & CMS test beam:

- best description obtained with QGSP_BERT physics list
  - G4 9.3 under validation by experiments
  - Response: good agreement, within 3%
  - Resolution: simulation is a bit too narrow, within 10%
  - Showers still a bit shorter and narrower than data:
    - pions within 10% up to 10\(\lambda\)
    - protons within 30% up to 10\(\lambda\)

See: JoP Conf. Series 160 (2009) 012073; CALOR08 Contribution by G. Folger
CMS, and then ATLAS, observed unphysical steps in response as a function of beam energy

- Confirmed with simplified setups

We have investigated in detail the source of this:

- Related to transitions between models
- Use of parametrized models (LEP) in medium (10-25GeV) energy range

This has been one of the main area of activity in Geant4 hadronic

FTF Physics Lists Improvement

- Based on Fritiof model: string model with LUND fragmentation

- Why FTF? Geant4 QGS is valid from $E_{\text{kin}} \approx 10-15$ GeV, FTF is promising alternative: valid from $E_{\text{kin}} \approx 4-5$ GeV

- Hadron-hadron interactions are modeled as binary reactions: $a + b \rightarrow a' + b' \ ; \ m_{a'} > m_a, \ m_{b'} > m_b$
  - $a'$ and $b'$ are excited states of the initial hadrons $a$ and $b$

- FTF model in Geant4: simulation of single diffraction, simulation of binary reactions, Reggeon cascading

- Recent improvements (quark exchange introduction, Reggeon cascading) allow for a smooth coupling with Bertini cascade models at 4-5 GeV: removing discontinuities

- FTF is also implemented in HIJING, UrQMD, ART, HSD codes

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Original FTF

Quark-exchange (new)

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New CHIPS Physics List

CHIPS model of inelastic nuclear interactions:
- High energy: 1-D Parton Multi String (PMS), soft part of it absorbed by target nucleus creating quasmons
- Low energy: 3-D decay of a quasmon (parton plasma) with final CHIPS evaporation

CHIPS physics list (released as experimental PL in Dec. 2009) very smooth: melds the HE and LE approaches

CHIPS can be used for all particles (including kaons, anti-baryons, hyperons)

CHIPS provides also:
- Revised cross sections for all hadrons
- At rest nuclear capture processes for negative hadrons
- Neutrino-nuclear, electron-, muon-, tau-nuclear and photo-nuclear reactions
- Elastic scattering for all hadrons
- Quasi-elastic scattering

EPJ A 8 (2000), 217
EPJ A 9 (2000), 411
EPJ A 9 (2000), 421
Simplified Fe/Sci Calorimeter

FTFP_BERT and CHIPS: smooth response.
FTFP_BERT agrees with QGSP_BERT, where this one agrees with data

What about other observables (resolution, shower shapes)?

QGSP_BERT stable since G4 8.3 (May 2007)
FTFP_BERT smooth response (improved in G4 9.3)
CHIPS (new in G4 9.3) higher response

π beam geant4 9.3.ref02 (development version)
Resolution \( \sigma(\text{Evis})/\langle\text{Evis}\rangle \) is not a good observable: \( \langle\text{Evis}\rangle \) has steps, prefer to show \( \sigma(\text{Evis})/E_{\text{beam}} \)

- CHIPS smaller width
- QGSP_BERT: step at 10 GeV

FTFP_BERT and CHIPS: smooth.
Bertini model (low energy) increases dimensions of showers

Small steps at 10 GeV (QGSP_BERT) and at 5 GeV (FTFP_BERT) are visible

CHIPS predicts longer showers at high energy

Feedback from experiments: agreement (QGS_BERT) with test-beam data has improved in the last years, models predicting longer and wider showers should be preferred (G4 still 10-30% shorter)
Lateral Shower Shape

- QGSP_BERT is smooth
- FTFP_BERT has a step at 4-5 GeV (transition between BERT and FTFP): can be improved increasing transition region (under investigation)

Compared with data (E>20GeV): FTFP_BERT and CHIPS better agreement with data
- FTF and CHIPS predicts wider showers at high energy and more compact at low energy
- Cascading is a fundamental ingredient to increase shower size and thus improve agreement with test-beam data
Thin target experiments are the primary source of data for tuning models

Agreement with test-beam data for response and resolution is $O(\text{few } \%)$

Agreement for shower shapes have much improved but still a bit shorter and narrower with respect to test-beam data (worst case: shower length for protons -30\% at $10\lambda$),

Recent major improvements:

- Fritiof model (available in FTFP_BERT physics list)
- Extension of CHIPS components (available in CHIPS physics list)

Main concern is discontinuities in response

- Studied in detail during 2009, origin tracked down to use of parametrized model (LEP) in intermediate region: now providing option with reduced or no dependence on this (FTFP_BERT, CHIPS)
- FTFP_BERT is smooth and agrees with QGSP_BERT for $E_{\text{kin}} < 9$ GeV and $E_{\text{kin}} > 25$ GeV
Challenges And Future Work

At the moment two physics lists show the most promising results to solve these issues:

- **FTFP_BERT physics list** (Bert < 5 GeV ; FTF > 4 GeV). Transition effect to be corrected in shower dimension. Very similar results to QGSP_BERT at high and low energies.

- **CHIPS physics list**: very smooth. Response is too high, results should be considered preliminary: still “experimental” physics list, ongoing validation and tuning with thin target data.

Expect further improvements in next months thanks to new data:

- First comparison with LHC collisions
- CALICE test-beams

Other challenges: improve simulation of hadronic interactions for kaons, anti-p, hyperons.

Other possibilities being explored: example **QGSP_FTFP_BERT** (use of FTF instead of LEP)
Thank you!
BACKUP SLIDES
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Hadronic Inelastic Interactions Models

At rest absorption
anti-p, K, μ, π

CHIPS 3-D quasmon decay

CHIPS string

Evaporation

Fermi breakup

Multifragment

γ de-excitation

Pre-Compund

Binary Cascade

FTF String

Photo-nuclear, lepto-nuclear (CHIPS)

Rad. Decay

Fission

Bertini Cascade

QGS String

Evaporation

HEP

LEP

1 MeV 10 MeV 100 MeV 1 GeV 10 GeV 100 GeV 1 TeV

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anti-p, K, μ, π

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LEP

1 MeV 10 MeV 100 MeV 1 GeV 10 GeV 100 GeV 1 TeV
Simplified Calorimeter

- Simulation of a cylindrical calorimeter 10 $\lambda_I$ long

- All LHC calorimeters technologies are implemented: Pb/Sci, Fe/Sci, Cu/LAr, PbWO4

- Energy in active material is collected

proton shower with $E_{\text{kin}}=50$ GeV
There are two effects introducing a systematic error in the simulation of energy response: late energy deposits (slow neutrons) and finite dimension of simplified calorimeter.

A time cut at 50 ns (typical read-out timing of scintillator calorimeters) have been introduced: deposited energy depends softly from this cut (3% varying from 20 to 200 ns).

Most important correction is leakage (front and longitudinal): O(1%), error on leakage is a fraction of stat error.

At low energy correction for (front)leakage becomes important.

Neutrino and muon included! Effect on visible energy is reduced to less than half.
Resolution Vs Width

Response and width extracted from iterative gaussian fit around response peak of visible energy

\[ \sigma/E = \sqrt{\frac{a}{E_{\text{beam}}} + b} \]

NIMA606: \( a = (52.9 \pm 0.9)\% \); \( b = (5.7 \pm 0.2)\% \)

Modulation of residuals following transition regions: is this a problem in \( \sigma \) or in \(<E>\)? Need to look at both independently.
Shower Shape

1. Define “mesh” of voxels: pseudo-cells
2. Accumulate quantity for each voxel (energy deposit, energy density)
3. If an observable O can be defined for each voxel (e.g. energy, density, position) the n-th moment in O can be calculated:
   \[ <O^n> = \frac{\sum_v E_v \cdot O^n_v}{\sum_v E_v}, \forall v \in \text{voxels} \]
4. Moments are often calculated w.r.t. shower center (\(<x>,<y>,<z>\)) and shower axis (principal component analysis)

Original Idea from:
T. Barillari et al. ; Local Hadron Calibration; 2008 (CERN); ATL-LARG-PUB-2009-001
Shower Shape

Shower moments can be used to “summarize” the shower shape in few numbers:

- $\lambda_{\text{center}}$: depth of the shower “maximum” w.r.t. calorimeter front-face
- $\lambda^2$: shower dimension along shower axis
- $r, r^2$: shower dimension in plane orthogonal to shower axis

- Long shapes depend weakly from mesh size (<10%)
- Lateral shower shape depends weakly (<10%) from mesh size only for $1\text{cm} < \text{size} < 10 \text{ cm}$. Prefer $r^2$ over $r$: less dependency on mesh size

Systematic error $O(5\%)$ on shower shapes due to choice of a particular mesh size
Shower moments distributions present a long tail...

...however they are regular w.r.t. beam energy...

Stat. Errors x3

...stat. errors are small: plot mean and error on the mean Vs beam energy
Additional Physics Lists

Response

\[
\frac{E_{\text{vis}}}{E_{\text{beam}}} \quad \text{vs} \quad E_{\text{kin}}^\text{beam} \quad \text{(GeV)}
\]

- QGSP\_FTFP\_BERT
- LHEP
- QGSP\_BERT
- FTFP\_BERT
- QGSP\_BIC
- CHIPS
Additional Physics Lists
Additional Physics Lists
Additional Physics Lists

Longitudinal shower shape

$\langle d^2 \rangle$ (cm$^2$)

$E_{\text{beam}}$ (GeV)

QGSP, FTFP_BERT
LHEP
QGSP_BERT
FTFP_BERT
QGSP_BIC
CHIPS
Additional Physics Lists

**Lateral shower shape**

The graph shows the lateral shower shape for different physics lists, with the y-axis representing the shower size in cm² and the x-axis representing the beam energy in GeV. The different physics lists are represented by various symbols and colors:

- **GGSP_FTPF_BERT** (diamonds, blue)
- **LHEP** (red stars)
- **GGSP_BERT** (black circles)
- **FTFP_BERT** (blue triangles)
- **GGSP_BIC** (green diamonds)
- **CHIPS** (black asterisks)

The graph illustrates how the lateral shower size changes with increasing beam energy for each physics list, allowing for a comparative analysis of their performance.