Hadronic Physics: Test Coverage

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Testing What ? (1/2)

- For Hadronic Physics, we have to **test 3 things**
  - Individual cross sections
    - Gheisha, Chips, Barashenkov, Glauber-Gribov, *etc.*
    - Quite stable, not much tested directly
  - Individual final-state models
    - FTF, QGS, BERT, BIC, INCLXX, Preco/de-excitation, QMD, RDM, ParticleHP, lepto-nuclear, elastic, *etc.*
    - Active development for many of these, dedicated tests are used
  - Physics Lists (set of cross sections and models + framework)
    - FTFP_BERT + variants, QGSP_BERT + QGS-variants, QBBC, Shielding, NuBeam, LBE, *etc.*
    - Extensively tested by us in simple set-up, and much more thoroughly by our users, in particular the LHC experiments

Testing What ? (2/2)

- 3-dimensional **input**: projectile type , energy , target
- **Output**:
  - Cross sections: simple, one single value
  - Physics Lists: generally a few, integrated observables
    - e.g. like energy response, energy resolution, shower shapes
  - Models: multi-dimensional observables: the number of secondaries produced, their particle types and 4-momenta
    - but in practice, inclusive single differential (e.g. multiplicity, spectra, y or xF distributions) or double differential (e.g. spectra in particular angular regions) are generally considered and sometimes measured experimentally
- Our Geant4 tests:
  - In most tests, run a few events and check that it runs to the end
  - In fewer cases, we do “regression”, i.e. compare the output of two simulations to see if they are statistically compatible or not
  - In even fewer cases, we compare the output with experimental data

What can we improve ?

- Needless to say, we could and should test much more, even with reasonable contraints of the CPU available
  - An crucial part is the human effort to write new tests and to automatize them as much as possible
- I am focusing here mostly of testing coverage
  - See later an overview of tests as in G4 10.3.ref08
  - But many considerations can be applied to physics validation as well. The main suggestion here is to enlarge as much as possible with medium (*e.g.* **Fe** & **Cu**) and heavy targets (*e.g.* **W** & **Pb**) that are relevant for calorimetry, whereas most available thin-target data are with **H** or **C** targets...
- In the next slide, a few, personal, biased and incomplete suggestions for improving our testing coverage

A few suggestions for improvement (1/2)

- Expand lepton-nuclear tests
  - More below ~GeV , something in the range: ~GeV – ~10 TeV
- Process-level FTF & QGS tests of hadron-nucleus interactions at very high energies: 0.5 – 30 TeV
  - Particularly relevant for FCC, although an important physics component is missing (gluon/jet production)
- Expand the cross sections tests
  - More combinations projectile-energy-target
    - on-going progress with hadr00 in geant-val.cern.ch
  - Consistency checks between expected cross section and what observed in physics lists
- Process-level FTF tests of nucleus-nucleus interactions
- Radioactive Decay: planned work to expand the testing...

A few suggestions for improvement (2/2)

- Add SATIF to our regular tests
  - 2.83 and 24 GeV proton on thick-target (Hg, Concrete, Iron, Bi)
- Add TARC to our regular tests
  - 2.5 GeV/c proton on Pb thick-target, looking a neutron fluence
- Add a few CALICE simplified calorimeters

Quick Summary of our Tests of Hadronic Physics (as of G4 10.3.ref08)

Nightlies tests (1/4)

- **test02** : reference P.L. FTFP_BERT; Air, Al, Pb (large box); N_{evt} = 1 (20 for largeN);
  @100 GeV: π±, kaons, p ; @500 MeV: p, n ; @100 MeV: n, d, t, α
- **test04** : home-made P.L. with FTFP, BERT + ParticleHP + thermal neutrons;
  C, Al, Fe, Ag, Pb, U (thick box); N_{evt} = 1 (20 for largeN);
  @1-20 MeV p, n, d, t, He3, α
- **test11** : home-made P.L. with FTFP, BERT + ParticleHP + thermal neutrons;
  many materials (thick box), including thermal ones (Water_TS, Al_TS,
  Fe_TS, etc.); N_{evt} = 1 (20 for largeN); @0.001 eV - 10 MeV neutrons
- **test12** : reference P.L. FTFP, FTF_BIC, QGS_BIC, and QGSP_FTFP_BERT;
  Air, Al, Pb (large box); N_{evt} = 100 (2000 for largeN);
  @10 and 100 GeV π±, kaons, p, n, light anti-ions
- **test13** : home-made P.L. with QMD + G4BinaryLightIonReaction + BERT + FTFP +
  QGSP only for p & n (BERT used up to 20 GeV, FTFP and QGSP starting
  from 19 GeV); Air, Al, Pb (large box); N_{evt} = 100 (2000 for largeN);
  @100, 400, 1000 GeV proton
- **test16** : home-made P.L. for p & n inelastic cross sections tests (with BERT used up
  to 25 GeV, and G4BinaryLightIonReaction up to 10 GeV for light ions);
  Air, Al, Pb (large box); N_{evt} = 10 (100 for largeN);
  @1, 10, 20 GeV proton, neutron

Nightlies tests (2/4)

- **test18** : home-made P.L. with RadioactiveDecay (and BERT used up to 25 GeV, and G4BinaryLightIonReaction for light ions);
  huge (r > 100 km) spheres of Al and quartz; N_{evt} = 1 (1000 for largeN);
  @0 MeV radioactive ions (Ne, F, Al, Cr, Po)

- **test22** : for nightlies, **test22_NA49** : 100'000 collisions of 158 GeV p C with model-level FTFP
  for validation: string models (FTF & QGS) suite covering 3 – 400 GeV

- **test24** : home-made P.L. to test of Binary Cascade (for p, n, π±, and light ions, with the rest BERT up to 20 GeV, FTFP above 19 GeV, and also QMD for light ions); H, Be, C, Si, Cu, U (large box); N_{evt} = 20; @10 GeV π±, p, n

- **test25** : home-made P.L. to test of BERT (up to 20 GeV, with transition to PRECO between 65-70 MeV only for p & n; with the rest FTFP above 19 GeV, and G4BinaryLightIonReaction); H, Si, Cu, U (large box); N_{evt} = 100;
  @50, 100, 500, 800, 1500, 3000 MeV p, n

- **test27** : home-made P.L. for testing of G4BinaryLightIonReaction (below 20 GeV) (BIC below 10 GeV only for p & n ; BERT below 20 GeV, QGSP above 19 GeV, FTFP for anti-baryons); H, H2O, Si, Pb, U (large box);
  N_{evt} = 2000; @30, 200, 1000 MeV d, α, ion

Nightlies tests (3/4)

- **test28** : home-made P.L. for testing of G4WilsonAbrasionModel (for ions below 10 GeV) and G4EMDissociation (from 0 up to 100 TeV)
  (G4BinaryLightIonReaction below 20 GeV; BIC below 10 GeV only for p & n; BERT below 20 GeV, QGSP above 19 GeV, FTFP for anti-baryons);
  H, H2O, Si, Pb, U (large box); N_{evt} = 20; @200, 1000 MeV d, α, ion

- **test30** : test of single interactions of hadronic generators;
  for nightlies, 10 collisions of 22.2 MeV p on Zr using BIC, BERT, and INCL;
  for validation: neutron production by 100 MeV – 3 GeV protons on various targets; 9 – 65 MeV neutron-induced reactions on various targets; 11 – 600 MeV/n ion reactions on various targets

- **test35** : test of single interactions of hadronic generators:
  for nightlies, 100 collisions of 3 GeV p C using BERT and FTFP;
  for validation: HARP experimental data (3 – 12 GeV p, π± on Be, C, Al, Cu, Sn, Ta, Pb)

- **test45** : reference P.L. FTFP_BERT;
  for nightliest, 100'000 collisions of 50 MeV p C (1.5 cm thick target)

- **test46** : reference P.L. FTFP_BERT_EMV; CMS combined ECAL+HCAL calorimeter;
  N_{evt} = 100; 15 GeV π-

- **test48** : single interactions of stopping particles;
  for nightlies: 100'000 π- at rest on Pb, with BERT;
  10'000 μ- at rest on Si, with G4MuonVDNuclearModel

Nightlies tests (4/4)

- **test61 :** home-made P.L. to test QMD (90 MeV/n - 10 GeV/n)
  (G4BinaryLightIonReaction below 100 MeV/n , BERT + FTFP for the rest)
  @200, 1000 MeV/nucleon C(6,12)++ on H, Water, Si, U (thick box);
  N_{evts} = 4 or 16

- **test62** : reference P.L. QGSP_INCLXX to test for the INCL/ABLA;
  N_{evt} = 20; @1 GeV π±, p, n on C, Si, Cu, Pb, U, Th (thick box);
  @1 GeV/n d on Pb; @500 MeV/n α on Pb; @290 MeV/n 12C on C;
  @500 MeV/n 12C on Pb

- **test64** : generator-level test for BERT & FTFP nuclear capture at rest; N_{evt} = 1000;
  BERT: π-, K-, Σ- ; FTFP: p̲, Σ̲+̲ ; on He, Be, C, Al, Ar, Fe, Cu, W, Pb

- **test65** : home-made P.L. to test LEND (with G4BinaryLightIonReaction, BERT and FTFP for the rest); N_{evt} = 1 (20 for largeN);
  @10 GeV π±, kaons, p, n on Air, Al, Lead (thick target);
  @1, 10, 100 eV, 1, 10, 100 keV, 1, 10 MeV neutron on H, He, Li, Be, ... U (thick target)

- **test69** : test of INCLXX physics lists: reference P.L. QGSP_INCLXX, FTFP_INCLX, QGSP_INCLXX_HP, and FTFP_INCLXX_HP;
  N_{evt} = 20; @1, 2, 40 GeV π±, p, n, d, α, 12C on C, Si, Cu, Pb, U, Th (thick box)

Nightlies benchmarks

- **bench-calo-FullCMS** : reference P.L. FTFP_BERT and QGSP_BERT of the full CMS detector (via GDML);
  benchmarks/calorimeter/FullCMS/ ; N_{evt} = 1;
  random hadron of random energy [1, 100] GeV
  in random direction from (0, 0, 0)

- **bench-calo-ParFullCMS** : reference P.L. FTFP_BERT and QGSP_BERT of the MT-version of the FullCMS;
  benchmarks/calorimeter/ParFullCMS/ ; N_{evt} = 100

- **bench-calo-HadCalCMS** : reference P.L. FTFP_BERT, FTFP_BERT_HP, FTFP_BERT_TRV, FTF_BIC, QGSP_FTFP_BERT, QGSP_BERT, QGSP_BERT_HP, QGS_BIC, QGSP_INCLXX, QGSP_BIC, QGSP_BIC_EMY, QGSP_BIC_HP, QBBC, and Shielding
  benchmarks/calorimeter/HadCalCMS/ ; N_{evt} = 100;
  30 GeV π^- on Cu-LAr simplified calorimeter with B=2T

Nightlies extended examples (1/4)

- **example-ext-hadronic-hadr00** : use of G4PhysListFactory to build P.L. and how to use G4HadronicProcessStore to access cross sections;
  examples/extended/hadronic/Hadr00/ ; N_{evt} = 10;
  nightly: 20 GeV proton on Al (semi-thick) target with FTFP_BERT

- **example-ext-hadronic-hadr01** : generic P.L. inherited from G4VModularPhysicsList using physics constructors (allows to specify the P.L. via macro command); dedicated to simulation of proton or ion beam interaction with a water target
  examples/extended/hadronic/Hadr01/ ; N_{evt} = 100;
  nightly: 3 GeV proton on Al (semi-thick) target with QBBC

- **example-ext-hadronic-hadr02** : using G4PhysListFactory for the P.L. ; dedicated to simulation of ion beam interaction with different targets, and interfaces with external ion generators (UrQMD and HIJING);
  examples/extended/hadronic/Hadr02/ ; N_{evt} = 100;
  nightly: 200 GeV on S(16, 32) (i.e. 6.25 GeV/n) on Al (semi-thick) target with QBBC and FTF ion physics

Nightlies extended examples (2/4)

- **example-ext-hadronic-hadr03** : P.L. inherited from G4VModularPhysicsList using physics constructors (implementing something similar to the reference P.L. QGSP_FTFP_BERT); dedicated to compute total cross section from the direct evaluation of the mean free path and how to identify nuclear reactions;
  examples/extended/hadronic/Hadr03/ ;
  N_{evt} = 10'000;
  nightly: 10 MeV proton on Mo (thick) target
- **example-ext-hadronic-hadr04** : nice home-made P.L. with only neutronHP physics including thermal scattering;
  examples/extended/hadronic/Hadr04/ ;
  N_{evt} = 1000;
  nightly: 2 MeV neutron on water_ts (thick) target
- **example-ext-hadronic-hadr05** : example of usage of G4GenericPhysicsList to build the concrete P.L. at run time; based on Hadr00;
  examples/extended/hadronic/Hadr05/ ; N_{evt} = 10;
  nightly: 20 GeV proton on Al (semi-thick) target with FTFP_BERT-like P.L.

Nightlies extended examples (3/4)

- **example-ext-hadronic-hadr06** : survey energy deposition and particle's flux from a hadronic cascade; use PhysicsConstructor objects rather than reference P.L. (building something similar to FTFP_BERT_HP + RDM);
  examples/extended/hadronic/Hadr03/ ;
  N_{evt} = 10'000;
  nightly: 14.1 MeV neutron on Li7 (semi-thick) target

- **example-ext-hadronic-hadr07** : similar to the previous one...

- **example-ext-hadronic-FissionFragment** : how to use the fission fragment model in NeutronHP; using reference P.L. QGSP_BIC_HP;
  ...*extended/hadronic/FissionFragment/*
  N_{evt} = 50;
  nightly: 4.5 MeV neutron on subcritical assembly (with U *et al.*)

- **example-ext-hadronic-NeutronSource** : neutron production (together with RDM); use PhysicsConstructor objects rather than reference P.L. (building something similar to QGSP_BIC_HP + RDM)
  ...*extended/hadronic/NeutronSource/*
  N_{evt} = 10'000;
  nightly: at rest Am(95, 241) ion in BeO&Fe

Nightlies extended examples (4/4)

- **example-ext-radioactivedecay-activation** : activity and time-evolution of species; use PhysicsConstructor objects rather than reference P.L. (building something similar to FTFP_BERT_HP + RDM)
  ...*extended/radioactivedecay/Activation/*
  N_{evt} = 1000;
  nightly: 25 meV neutron on 1 cm (semi-thick) of Co

- **example-ext-radioactivedecay-rdecay01** : home-made P.L. with little more than RDM
  ...*extended/radioactivedecay/rdecay01/*
  N_{evt} = 100'000;
  nightly: at rest Co(27, 60) in Air

- **example-ext-radioactivedecay-rdecay02** : use PhysicsConstructor objects rather than reference P.L. (building something similar to FTFP_BERT_HP + RDM)
  ...*extended/radioactivedecay/rdecay02/*
  N_{evt} = 10'000;
  nightly: at rest Ne(10, 24) in CsI-Ge (semi-thick) set-up

Nightlies advanced examples

- **example-adv-composite_calorimeter-build** : for nightly: only built, not run
- **example-adv-radioprotection** : diamond microdosimeter; with nice home-made P.L. using PhysicsConstructor objects (building something like QGSP_BIC_HP_EMY); *examples/advanced/radioprotection/* ; N_{evt} = 1000; nightly: cosmic ray spectrum of protons on diamond thin-target
- **example-adv-lArCal** : reference P.L FTFP_BERT for ATLAS FCAL (EM+HAD) sim; *examples/advanced/lAr_calorimeter/* ; N_{evt} = 18; nightly: 20 GeV e-
- **example-adv-hadrontherapy** : example with nice home-made P.L. using PhysicsConstructor objects (building something like QGSP_BIC_HP_EMZ + RDM); *examples/advanced/hadrontherapy/* ; N_{evt} = 500; nightly: 62 MeV proton on water phantom (semi-thick)
- **example-adv-underground_physics** : underground dark matter experiment with Lxe; home-made P.L. with rich physics (low-energy EM + optical photons, FTFP_BERT_HP like with also RDM); ...underground_physics/ ; N_{evt} = 1000 nightly: 60 keV gamma

Other tests used only for Validation

- **test19** : process-level test of FTFP and QGSP from 31 GeV/c (NA61) up to 158 GeV/c (NA49), including SASM6 Barton's at 100 GeV/c
- **test23** : physics-list (home-made by using builders) test similar to test19 for HARP, NA61, and NA49
- **test45** : reference P.L. FTFP_BERT for validation of thick target data for stopping of low-energy proton and ion beams, e.g. 50 MeV p on C (thick target)
- **test47** : ITEP (1.4-7.5 GeV), BNL (14.6 GeV) and MIPP (56 & 120 GeV) model-level tests for validation of hadronic models (BERT, FTFP, QGSP)
- **test75** : gamma-nuclear model-level test (BERT)
  @300 MeV gamma on Cu target;
  @668 MeV gamma on Cu and Pb target
- **iaea** : official spallation IAEA benchmarks; similar to test30 but with special IAEA data formats; more emphasis to light-ion and isotope production than test30

Simplified Calo test (run on the Grid)

- Mostly π- and e- , but sometimes also p, n, π+, K+, K-, $\underline{p}$, $\underline{n}$
- Energies: 1 – 500 GeV
- Calorimeters: ATLAS TileCal (Fe-Sci) , ATLAS HEC (Cu-LAr) ,
  ATLAS FCAL (W-LAr) , ATLAS ECAL (Pb-LAr) ,
  CMS ECAL (PbWO4) , LHCb (Pb-Sci)
- Physics Lists: FTFP_BERT , FTFP_BERT_ATL , FTFP_BERT_HP ,
  FTFP_BERT_TRV , QGSP_FTFP_BERT ,
  QGSP_BERT , QGSP_BERT_HP ,
  QGSP_BIC , QGSP_INCLXX
- Number of events: 5'000 per combination

- To-do : add a few CALICE simplified calorimeters