FERMILAB-SLIDES-21-013-SCD

Status of hadronic calorimetry in GEANT4

Hans Wenzel, Adam Para, Sunanda Banerjee, Julia Yarba

Fermilab

CPAD Instrumentation Frontier Workshop

18-22 March 2021, Stony Brook, NY

This document was prepared by GEANT4 Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

Outline

- Motivation
- Geant4 hadronic physics
- Validation
  - Thin target tests
  - Calorimeter setups
  - The Geant4 validation portal
- Geant4 as a predictive tool
  - Identifying particles of interest
  - utilizing the time structure of hadronic showers
  - Dual readout total absorption Calorimetry: hadron shower development
- Conclusions

Motivation

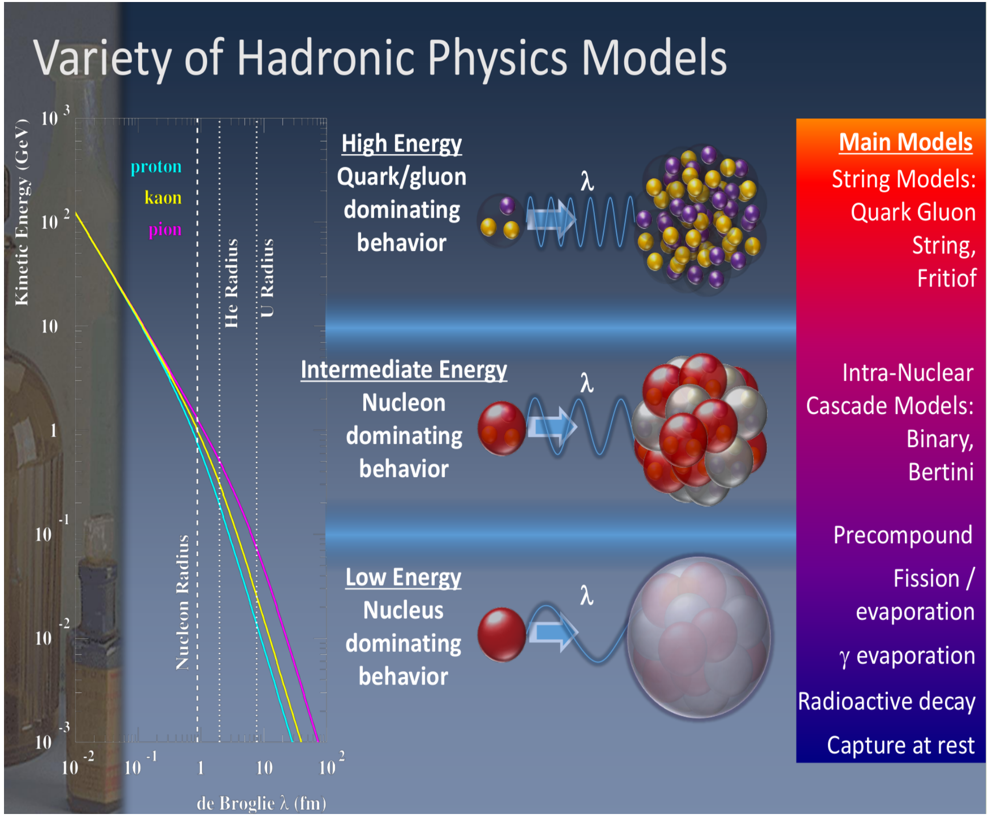
Proposed Lepton collider projects: ILC, CLIC, FCCee, CEPC, muon Collider for different energy regimes: 91 GeV (Z-factory), 250 GeV (Higgs-factory), and multi TeV for linear/muon colliders.
Precision frontier: measurement of Higgs couplings, W, Z and top properties, searches for BSM physics.
Many of the physics channels of interest involve hadronic jets in the final state → hadronic calorimetry paramount for extracting the physics!
Typical benchmark: to distinguish di-jets from W and Z decaying into hadrons → Goal: 3-4% jet energy resolution requiring much better hadron calorimeters.

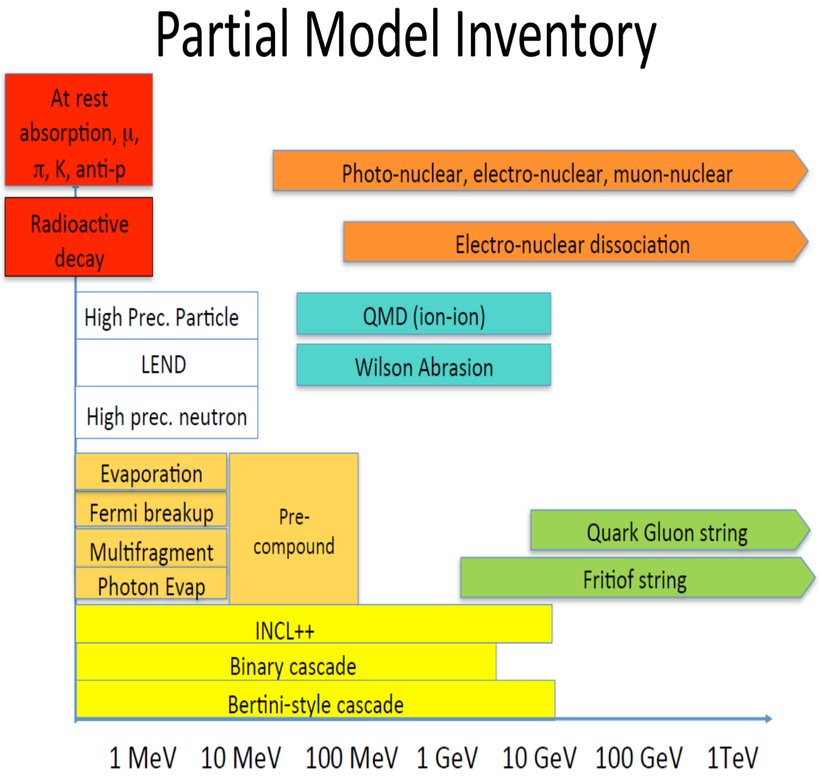
Many ideas and concepts to improve the performance of hadronic calorimeters. Exploring this ideas requires more than just modeling of global observables in hadron calorimeters (response, resolution, longitudinal center of gravity, shower radius etc.). We will rely on the Simulation to make predictions and to identify the most relevant contributions on calorimeter performance. This ideas include:

- **dual readout calorimetry[1]:** uses Cerenkov light produced by light relativistic particles (β>1/n) in the shower to correct energy response. This requires good description of particle content of hadronic showers, good description of the velocity distribution of produced particles to predict the amount of Cerenkov light.
- **Temporal structure of hadronic showers:** this requires the detailed knowledge of the spatial and temporal development of hadronic showers and requires the detailed treatment of neutrons.
- **Particle flow algorithms[2]:** combines tracking of charged particles with imaging, highly segmented calorimeters (CALICE). It relies on the possibility to disentangle contributions from particles within jets and identify the sub structure of showers.

1) see e.g.: M. Demarteau: "Total Absorption Calorimetry, a path to superior jet energy resolution ", this conference.
2) see e.g.: S. Chekanov: "Calorimeter performance studies using Monte Carlo simulations for future collider detectors", this conference.

Geant4 hadronic physics





https://groups.lal.in2p3.fr/ED-geant4/

Factories allow to customize physics

Achieve higher precision when and where you need it. Speed up processing time when less precision is sufficient.

Be aware of transition regions between models. Be aware model might not apply to particle of interest.

Useful:
C++: phys->DumpList();
Will list all models attached to particles and energy ranges.

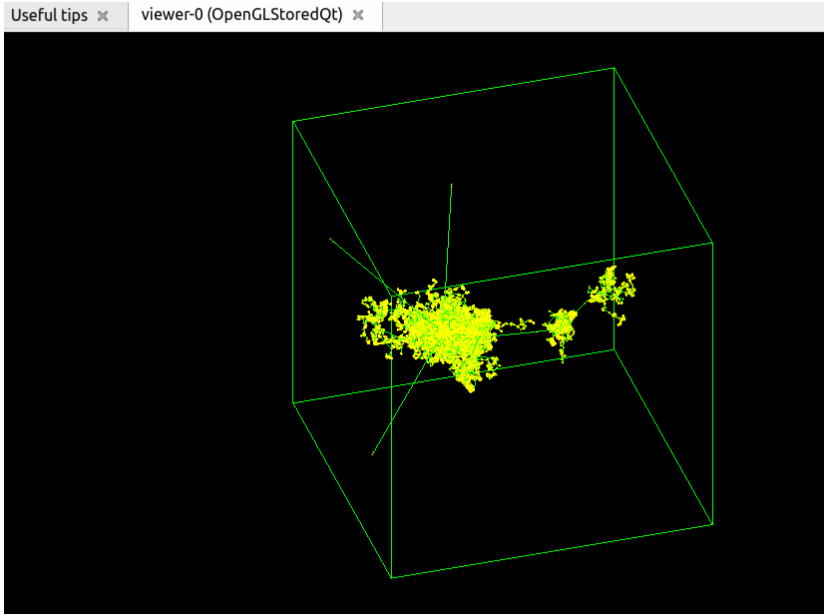
Reference physics list:	Em Option:	Physics Constructor:
FTFP_BERT	""	G4OpticalPhysics
FTFP_BERT_HP	_EMV	G4NeutronTrackingCut
FTFP_BERT_TRV	_EMX	G4StepLimiterPhysics
FTFP_BERT_ATL	_EMY	…
FTFP_INCLXX	_EMZ	
FTFP_INCLXX_HP	_LIV	
FTF_BIC	_PEN	
QGSP_BERT	__GS	
QGSP_BERT_HP	__SS	
QGSP_BIC	_EM0	
QGSP_BIC_HP	_WVI	
QGS_BIC	__LE	
QGSP_INCLXX		
QGSP_INCLXX_HP		
QBBC		
Shielding(M)		
ShieldingLEND		
NuBeam		

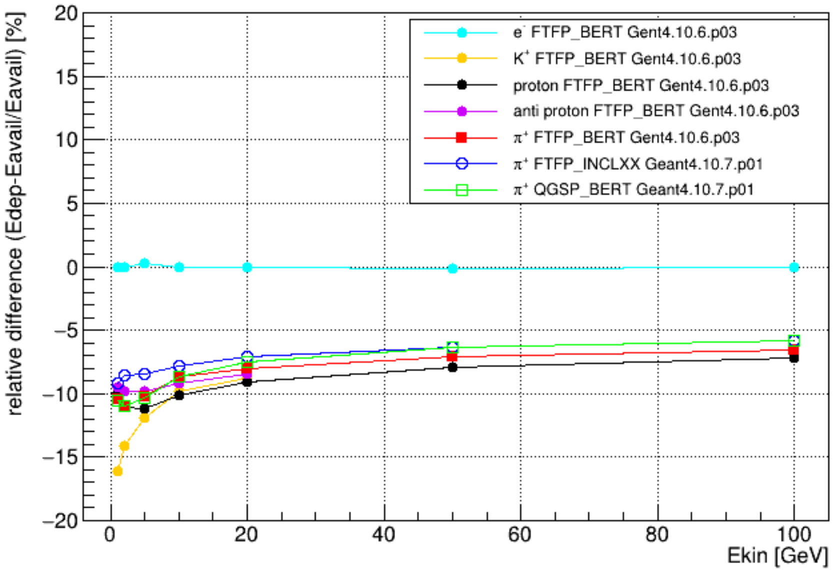
+ you can register your own custom physics list!

Energy response for various particles and physics lists

Very simple geometry: 5 x 5 x 5 m^3 cube of PbWO
Particle Gun located inside the volume
Below is the shower created by a π^+ with 20 GeV kinetic Energy

Available Energy Eavail:
e^-, p : Ekin
π^+ : Ekin + $m\pi^+$
K^+ : Ekin + mK^+
pbar : Ekin + 2 x mp





Fermilab

Validation

It’s a continuous effort leading to continuous improvement of models and providing of alternative models.

1. There are mainly two types of validation tests:
    1. **Simple benchmarks:** typical thin-target setups with simple Geometry. They test a single interaction and a specific physics model. (often limited by the availability and quality of experimental data). But experimentalists should feel some responsibility to identify particles and processes of interest, do their own tests and provide feed back to the Geant4 collaboration (so put your students to work ☺).
    2. **Full Calorimeter setups:** e.g. test-beams. The observables are the convolution of many effects and interactions. Mostly performed by the experiments.
2. A subset of test results are collected in the Geant4 Validation Portal (https://geant-val.cern.ch/). This is an active development. New tests and experimental data are added continuously (labor intense process).
3. Regression testing: keep track of changes.
4. Regular validation work shops: see e.g.: https://indico.cern.ch/event/964486
5. Publications see: https://geant4.web.cern.ch/publications

Example of thin-target validation:

Bertini:

D.H. Wright and M.H. Kelsey,
Nucl. Instrum. Meth. 1 804 (2015) 175-188

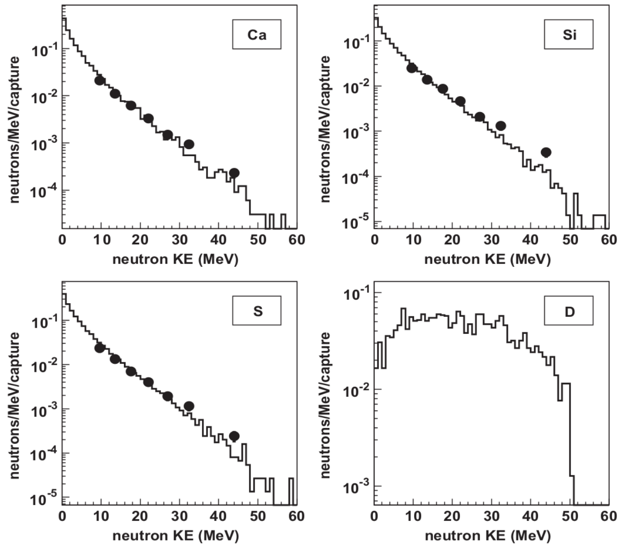


Fig. 6. Neutron kinetic energy spectrum from μ^- capture on Ca, Si, S and deuterium. The histograms represent the Bertini model predictions and the data (dots) are from Sundelin and Edelstein [30].

INCLXX:

J.-C. David et al., Eur. Phys. J. Plus (2018) 133: 253

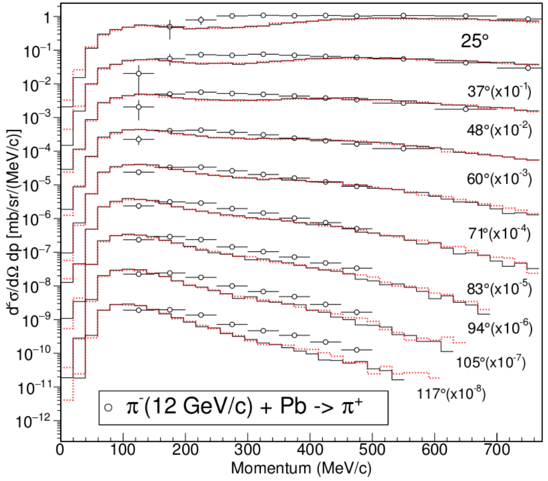
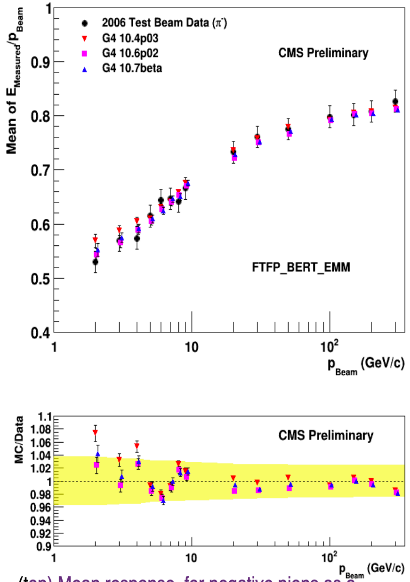


Fig. 13: π^+ spectra with (dotted red lines) or without (solid black lines) η and ω mesons in the intranuclear cascade code INCL. Experimental data are taken from [54] for the reaction $\pi^-(12\ \mathrm{GeV/c}) + \mathrm{Pb} \to \pi^+ + \mathrm{X}$. A scaling factor (power of 10) is applied for each angle for sake of clarity.

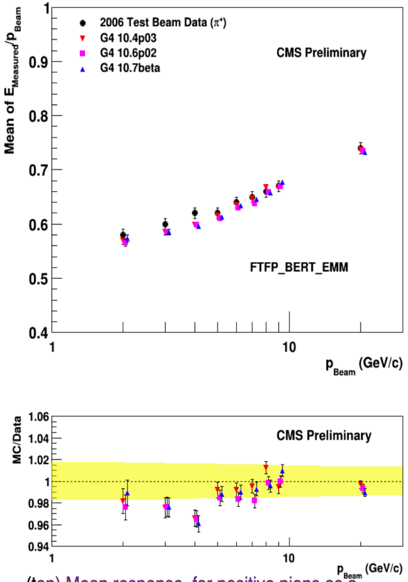
Full Calorimeter setups: e.g. CMS Test beam:

Π^{+-}: Good agreement

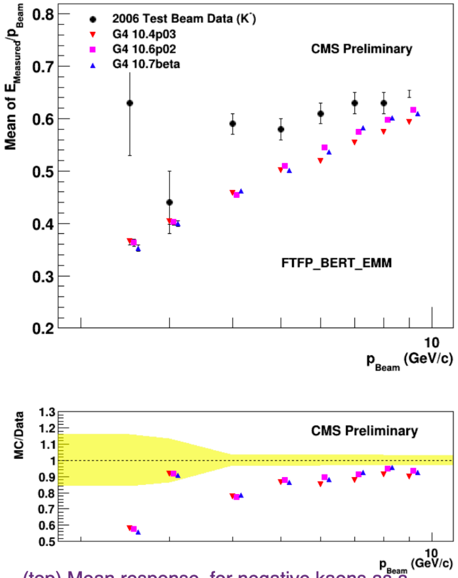
K^{+-} : underestimation of the response



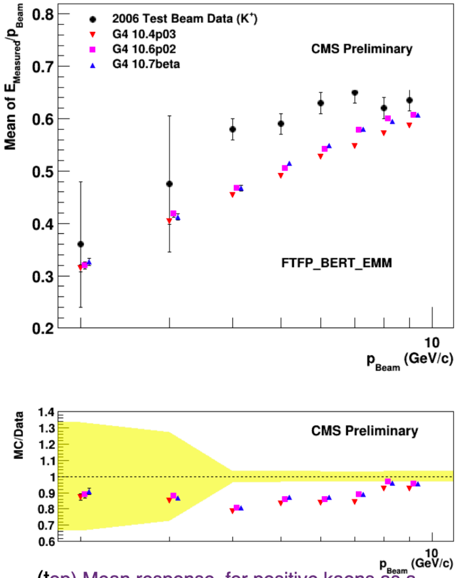
(top) Mean response for negative pions as a function of momentum compared to MC predictions; (bottom) Ratio of MC to data for negative pions as a function of momentum



(top) Mean response for positive pions as a function of momentum compared to MC predictions; (bottom) Ratio of MC to data for positive pions as a function of momentum



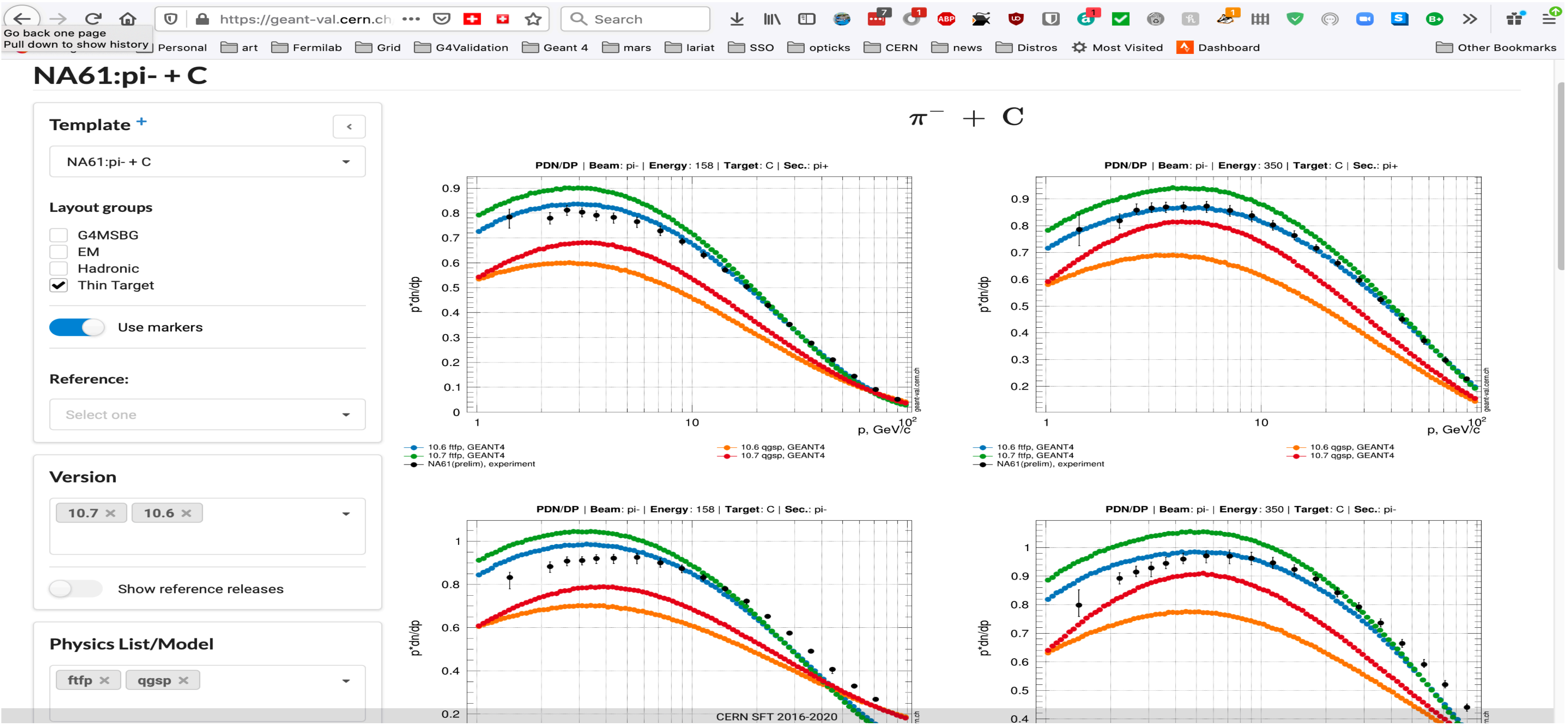
(top) Mean response for negative kaons as a function of momentum compared to MC predictions; (bottom) Ratio of MC to data for negative kaons as a function of momentum



(top) Mean response for positive kaons as a function of momentum compared to MC predictions; (bottom) Ratio of MC to data for positive kaons as a function of momentum

4th LPCC Detector Simulation Workshop, CERN (Geneva), 2-3 November 2020. https://indico.cern.ch/event/964486

Geant4 Validation Portal: https://geant-val.cern.ch/



See: https://doi.org/10.1051/epjconf/201921405002

Fermilab

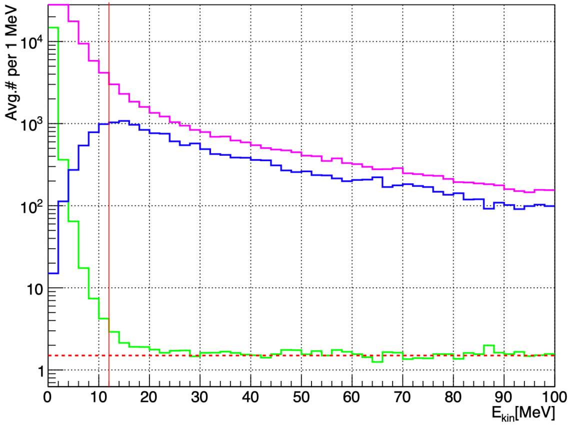
Geant4 as a predictive tool

- Very powerful and flexible tool to
  - identify the most important contributions, variables and particle types,
  - develop and test new concepts and ideas and make predictions with high confidence,
  - Identify observables that can be tested in small experimental test setups,
  - learn and teach physics ☺.

Particles of interest: neutrons and protons

Neutrons:

- Neutrons are abundantly produced they are typically the 3rd most produced particle (after electrons and gammas)
- Mostly "soft" neutrons, produced by the de-excitation of nuclei.
- Before a neutron "disappears" via an inelastic interactions (or decays or exits the world volume), it can have many elastic scatterings with nuclei, and eventually can "thermalize" in the environment.
- Assuming a long integration time (> 10μs) for a 5 *GeV* π^- shower in a dual readout total absorption *PbF* calorimeter one observes that ≈ 17% of the Scintillation signal and ≈ 23% the Cerenkov signal are due to γ's from neutron capture.
- For typical high-energy applications very often a simple treatment is enough. But as we will see neutrons are critical to get the details (e. g. temporal development) in hadronic calorimetry right.



Kinetic Energy of neutrons (magenta) and protons(blue) created in Pb^{208} and the ratio thereof (green) as predicted by Geant4 (Bertini Cascade). The vertical line represents the energy of the Coulomb barrier (≈ 12*MeV*). The horizontal line represents the ratio in which neutrons and protons are present in the target nucleus (≈ 1.54).
(H. Wenzel CHEF2013)

Topics to discuss with students: nuclear binding forces, nuclear potential, difference for n and p, Coulomb barrier, tunneling ….

Fermilab

Particles of interest: neutrons and protons (cont.)

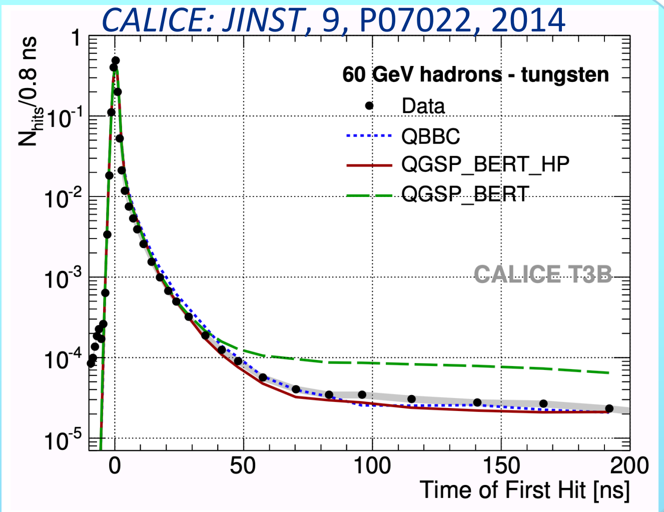
- For low energy neutrons kinetic energies Ekin < 20 MeV down to thermal energies a high precision, data-driven and isotope-specific treatment is available. NEUTRON_HP is based on evaluated neutron scattering data libraries. It includes 4 types of interactions: elastic scattering, radiative capture, fission, inelastic scattering. It is precise, but slow (expensive)!
  Concerning calorimetry energy conservation needs special attention!

protons:

- Range of spallation protons is very short (~ 1 mm).
- in a sampling calorimeter these energies are not observable (part of the 'nuclear effects').
- In a total absorption dual read out calorimeter these protons contribute significantly to the observed ionization signal (~23% for 5 GeV π^{+-} showers).
- These protons don't contribute to Cerenkov signal.

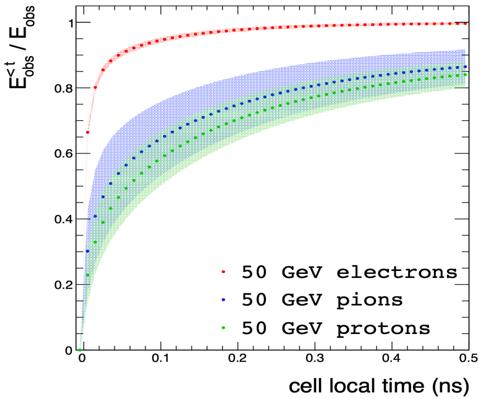
Physics list	sec/evt (20GeV π+)
QGSP_BERT	1.8
FTFP_BERT	4.2
FTFP_INCLXX	15.4
FTFP_BERT_HP	24.8

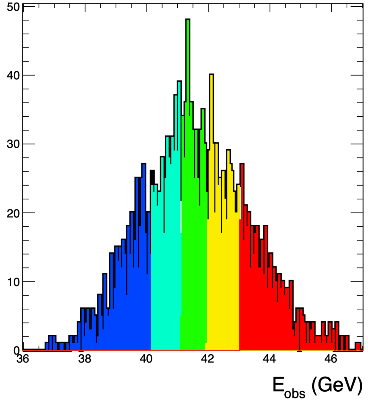
utilizing the time structure of hadronic showers

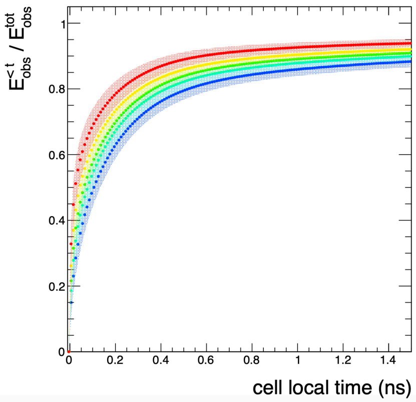


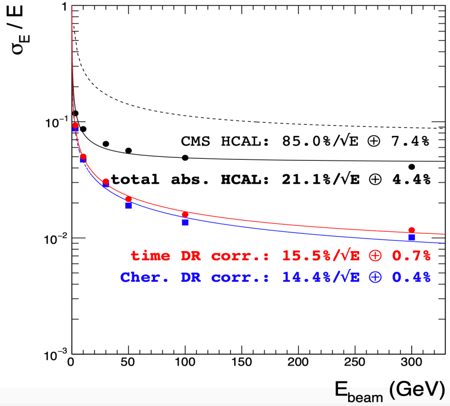
requires the detailed knowledge of spatial and temporal development of hadronic showers and specifically requires the precise treatment of neutrons (QBBC, _HP).

Monte Carlo study (FERMILAB-PUB-16-407-CD)
GEANT4 10.1.p01,
Physics list: QGSP_BERT_HP,
Geometry: 3000 x 1m x 1m x 1mm Iron







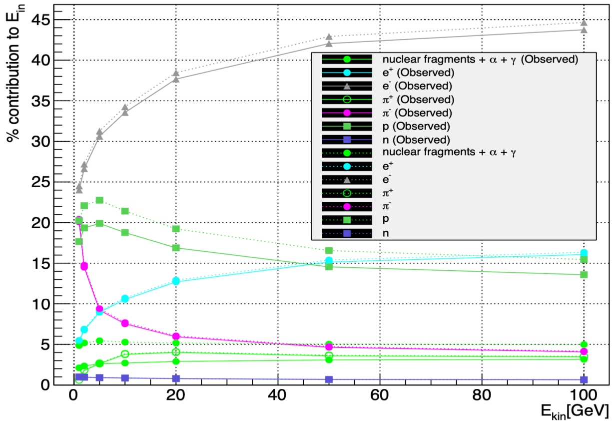


Fermilab

Dual readout total absorption Calorimetry: hadron shower development

- Scintillation response: requires good understanding of particle content and momentum distribution of hadronic showers.
- Cerenkov response: requires good understanding of the velocity distribution of produced particles.
- Full simulation of the creation and tracing of optical photons is critical to address:
  - how the directionality of Cerenkov light affects the response,
  - how to separate Cerenkov from Scintillation light

  → great application for G4Opticks (see: https://doi.org/10.1051/epjconf/201921402027) which offloads the creation and tracing of optical photons to GPU's.



from

H. Wenzel CHEF2013

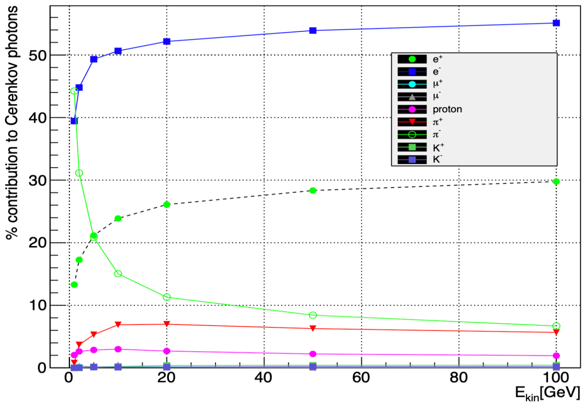


Figure 2: Comparison of the per-particle contributions to ionization (dotted line) and scintillation (continuous line, Observed) signals in a π^- shower for a PbF_2 calorimeter. Saturation effects (Birks suppression) have been taken into account to convert deposited energy to scintillation light.

Figure 3: Per-particle contributions to the Čerenkov signal for a π^- shower in a PbF_2 calorimeter. One observes that the Čerenkov signal is not only due to e^- and e^+ but the contribution of pions (incident particle or produced in nuclear reactions) is significant. Especially the leading incident π^- contributes significantly to the Čerenkov signal at low energy.

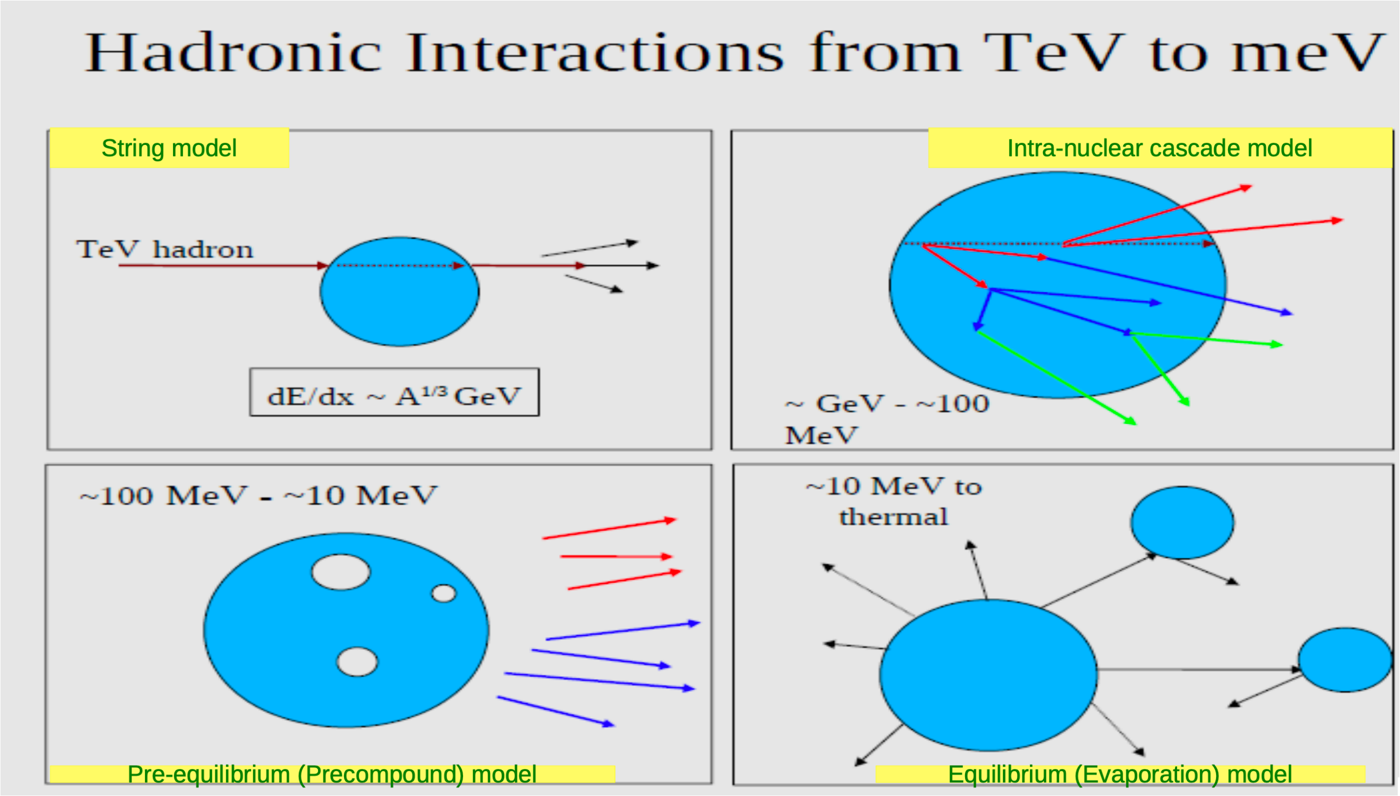
Conclusion

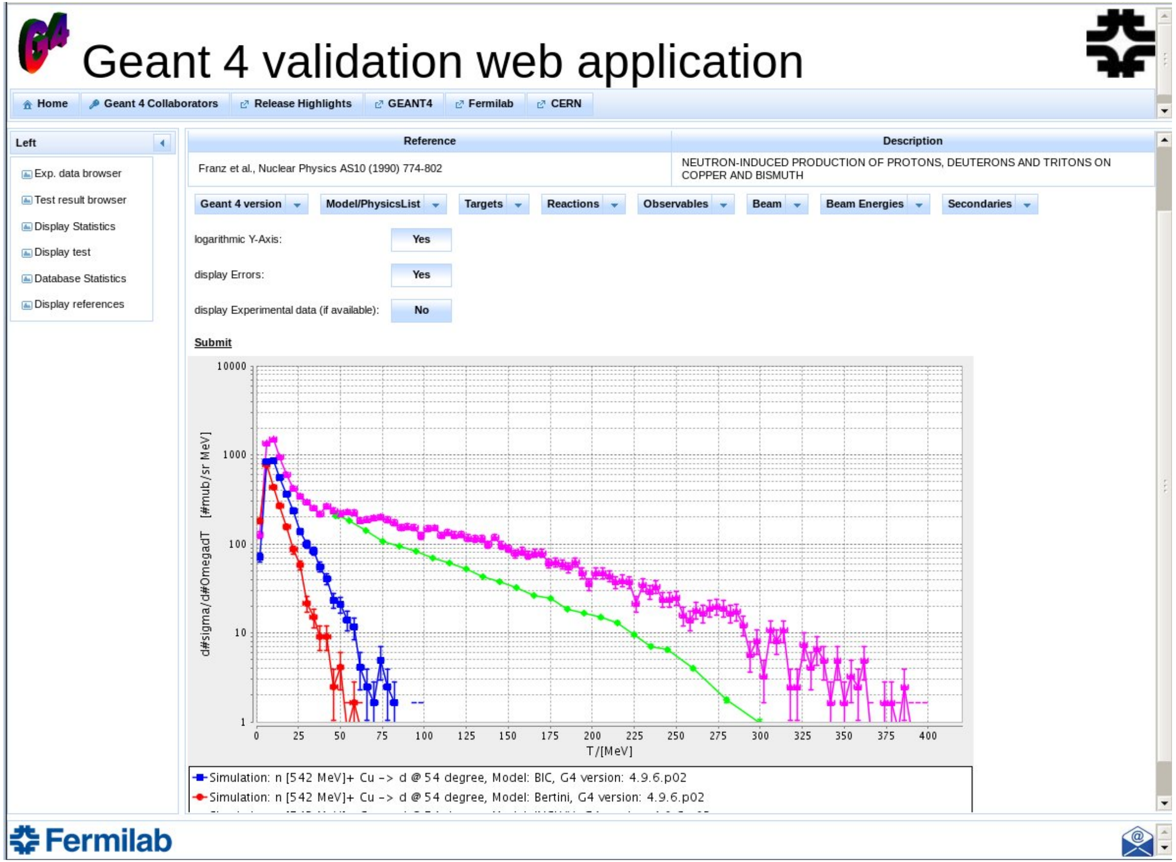
- Many ways to configure and customize Geant4 physics to meet your requirements.
- Validation is a continuous effort.
- Geant4 under active development, it's continuously being improved.
- Geant4 is very well documented, open source, provides many excellent examples and tutorials and has very active user community.
- Very good tool to learn and teach physics ☺.
- Geant4 needs user feed back to identify shortcomings and bugs.
- We need a program to systematically study the dynamics of hadronic showers. Geant4 is a very powerful predictive tool that allows to:
  - Identify the most important contributions, variables and particle types,
  - Develop and test new concepts and ideas and make predictions with high confidence,
  - Identify observables that can be tested in small experimental test setups.
  - …
- Simulation is important. The US community needs to stay actively involved (funded).

Resources

- Tutorials
  - Ecole Geant4 de l'IN2P3 et PHENIICS, 23 – 27 November 2020 https://groups.lal.in2p3.fr/ED-geant4/
  - Geant4 Advanced Course @ CERN, 28 September - 2 October 2020. https://indico.cern.ch/event/866056/
- Workshops and Conferences
  - 4th LPCC Detector Simulation Workshop, CERN (Geneva), 2-3 November 2020. https://indico.cern.ch/event/964486
  - Simulation of total absorption dual readout calorimetry - INSPIRE-HEP https://old.inspirehep.net/record/1846890
- Geant4 main web page:
  - https://geant4.web.cern.ch/node/1
- LXR source code browser:
  - https://geant4.kek.jp/LXR/
- Geant4 examples:
  - https://geant4.kek.jp/lxr/source/examples/
- Physics Reference Manual:
  - https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsReferenceManual/html/index.html
- Guide for Physics Lists:
  - https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsListGuide/html/index.html
- Geant4 on-line forum:
  - https://geant4-forum.web.cern.ch/
- Geant4 technical forum:
  - https://geant4.web.cern.ch/collaboration/technical_forum
- Geant4 validation portal
  - https://geant-val.cern.ch/

Backup Slides


Hadronic Interactions from TeV to meV
String model
TeV hadron
dE/dx ~ A^1/3 GeV
Intra-nuclear cascade model
~ GeV - ~100 MeV
~100 MeV - ~10 MeV
Pre-equilibrium (Precompound) model
~10 MeV to thermal
Equilibrium (Evaporation) model



Geant 4 validation web application
Home
Geant 4 Collaborators
Release Highlights
GEANT4
Fermilab
CERN
Left
Exp. data browser
Test result browser
Display Statistics
Display test
Database Statistics
Display references
Reference
Description
Franz et al., Nuclear Physics AS10 (1990) 774-802
NEUTRON-INDUCED PRODUCTION OF PROTONS, DEUTERONS AND TRITONS ON COPPER AND BISMUTH
Geant 4 version
Model/PhysicsList
Targets
Reactions
Observables
Beam
Beam Energies
Secondaries
logarithmic Y-Axis:
Yes
display Errors:
Yes
display Experimental data (if available):
No
Submit
d#sigma/d#OmegadT [#mub/sr MeV]
T/[MeV]
Simulation: n [542 MeV]+ Cu -> d @ 54 degree, Model: BIC, G4 version: 4.9.6.p02
Simulation: n [542 MeV]+ Cu -> d @ 54 degree, Model: Bertini, G4 version: 4.9.6.p02
Fermilab