Status of Geant4 Hadronic Physics

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Outline

- Highlights of Geant4 10.5
- Status of development
  - In preparation for the December release, G4 10.6
- Selected topics of interest for JLab
  - Gamma- and lepton-nuclear interactions in Geant4

Hightlights of G4 10.5

String models

- **FTF** (Fritiof) & **QGS** (Quark Gluon String)
  - Released the latest development version - developed since G4 10.2 but not included in 10.3 and 10.4, to keep hadronic showers stable
    - Note that snapshots of these developments have been made available in previous beta releases: G4 10.3.beta, 10.4.beta and 10.5.beta
    - Development driven to improve the desciption of thin-target data
    - No problems found in the $\pi°$ production which could explain the observed higher energy response of hadronic showers in calorimeters
    - Reviewed Birks quenching : inconsistent use of Birks coefficient taken from publications where no-delta-ray emissions were assumed...

Intra-nuclear Cascade models

- Bertini-like (BERT)
  - Extended strange pair production channels to multibody final states
    - 6,7,8 and 9 bodies
  - A few important fixes (affecting the physics results)

- Binary (BIC)
  - Stable, no developments

- Liege (INCLXX)
  - Improved strangeness and the few-nucleon-removal
  - Fixed various bugs
  - New data-set : G4INCL**1.0**

Precompound / de-excitation models

- Coherent use of the same parameterisation of level density and pairing correction between all models in de-excitation and precompound
- Several code improvements
- New data-set : PhotonEvaporation**5.3**

Radioactive Decay model

- Improved electron capture
- New data-set : RadioactiveDecay**5.3**

ParticleHP & LEND models

- Bug fixes, no new development

Others

- ABLA
  - Extended to hypernuclei
  - Can be used as an alternative de-excitation model for INCLXX
- Elastic scattering
  - Extended the high-energy applicability of G4DiffuseElastic and G4NuclNuclDiffuseElastic up to 100 TeV
- *"Extensions"*
  - Made easier to change the high-energy limit of applicability of hadronic physics (which is still 100 TeV by default)
    - Requested by a cosmic ray experiment (DAMPE)
  - Possible to run Geant4, in the whole energy range of applicability, for transuranic elements
    - Interest from an ADS (Accelerator Driven System) project (MYRRHA)

Physics Lists & Validation

- Both QGSP_BIC_HP and QGSP_BIC_AllHP use EM Opt4
  - Instead of EM Opt0 as before

- **geant-val.cern.ch**
  - Our validation and regression testing tool which we rely on for all Geant4 releases (public, patches, development)
  - Started with the hadronic showers in SimplifiedCalo, and then extended to many other applications, such as:
    - Thin-target testing-suite for string models, cross sections, TARC, FragTest (hadron-therapy), simplified CMS ECAL+HCAL, *etc.*
    - Many EM tests : fluctuation, bremsstrahlung, electron scattering, dE/dx, multiple scattering, attenuation, Bragg peak, Fano cavity, medical physics, simplified EM calorimeters, *etc.*

Hadronic showers

- Hadronic showers in G4 **10.5** changed significantly
  - Few per-cent higher energy response
  - Smaller fluctuations of energy response
  - Wider lateral shapes

  mostly due to the **development in string models** (improved description of thin-target data)
- The first two aspects (energy response – mean and fluctuations) are affected by the **Birks quenching** : we recommend a new treatment
  - Fit the Birks coefficient from the test-beam data on the ratio h/e, at one beam energy arbitrarily chosen

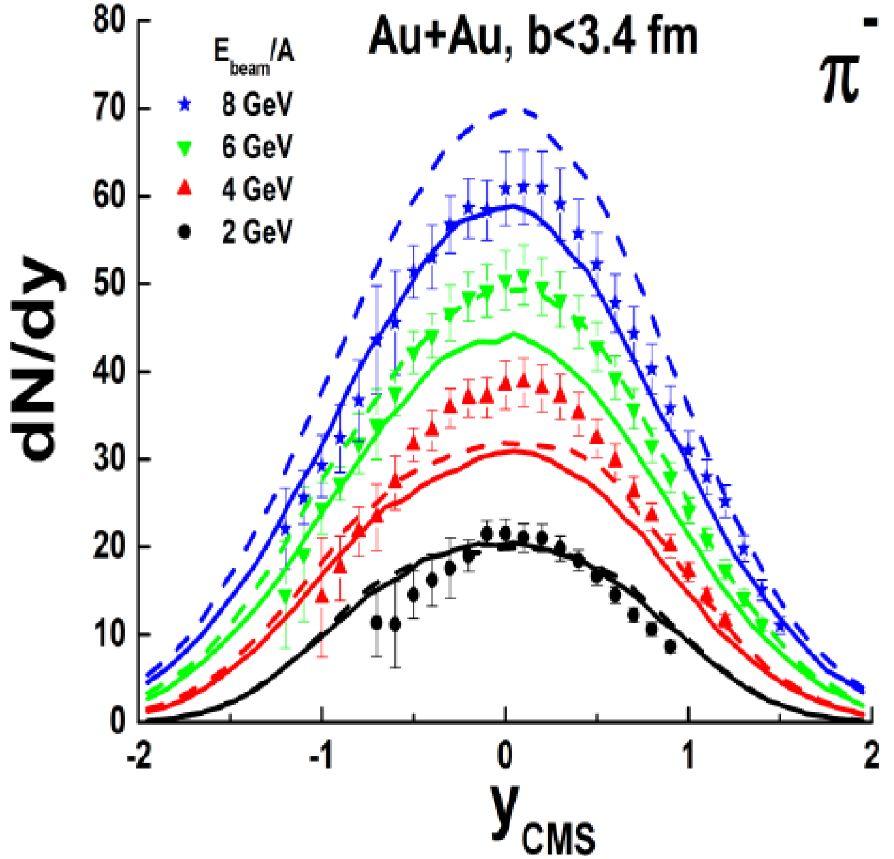
Current Developments

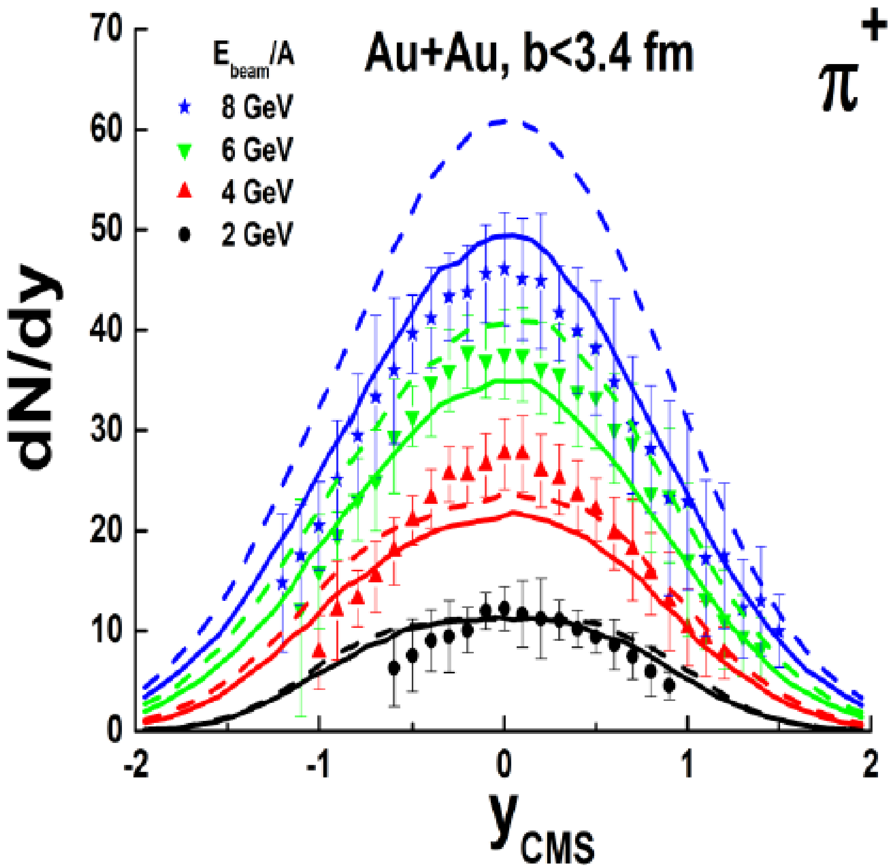
String models

- Changes on FTF after G4 10.5
  - Validation and refinement of nucleus-nucleus interactions *(see an example in the next page)*
  - Improved annihilation at rest of light anti-ions
  - Extended configuration interface for pion projectile parameters
  - Fixed a memory leak
- Changes on QGS after G4 10.5
  - Further validation
  - On-going code review
  - Fixed a bug in the computation of the transverse mass

Results of the improvements for E895 exp.

J. L. Klay et al., Phys. Rev C 68, 054905 (2003)
Charged pion production in 2A to 8A GeV central Au+Au Collisions,





Dashed lines are previous calculations, solid ones – current results.

Results become better for high energies, T > 6 GeV.

FTF *vs.* QGS

- In Geant4 version 10.5, from thin-target data, we can generally conclude that QGS becomes **competitive** with FTF roughly above **~ 15 – 20 GeV** (lab. projectile E_{kin}) whereas below this energy FTF is better
  - In the QGS-based physics lists, the transition between FTF and QGS is currently in the region [12 , 25] GeV
- QGS model is more theory-based than FTF, therefore QGS is expected to be more reliable at high energies
  - Above about ~0.5 TeV, where there are no clean thin-target data
  - But both models cannot be valid above few TeV
    - Because of the lack of gluon-jet production
    - Likely acceptable for LHC experiments, but not for FCC...
- QGS hadronic showers are narrower and with higher energy response than those of FTF
  - FTF hadronic showers expected to agree better with test-beam data

String models for G4 10.6

- Started the activity to **extend the string models to charm and bottom hadrons** i.e. transporting and producing heavy hadrons
  - Interest in FCC (as well as LHC) experiments to simulate hadronic interactions of highly boosted charmed and bottom hadrons in the beam pipe and first layers of the silicon tracker
  - Geant4 Glauber-Gribov nuclear cross sections for heavy hadrons will be available in the coming release G4 10.6
    - Unfortunately, no experimental data is available !
- This extension will be common for FTF and QGS for the **string fragmentation** part, whereas the **string formation** part will be done separately for FTF and QGS
  - Starting first with FTF ; not yet clear how much will go in G4 10.6
  - Plan to collect available data on charm production

Intra-nuclear Cascade models

- Bertini-like (BERT)
  - A few bug fixes
  - Investigating possible improvements in multi-body phase generation
- Binary (BIC)
  - Stable, no developments
- Liege (INCLXX)
  - MT-irreproducibility fixed in the patch, G4 10.5.p01
  - No new development expected for G4 10.6
    - Due to lack of man-power
    - Pending fixes on memory leaks
  - FTFP_INCLXX is the preferred physics list for ALICE
    - It gives the best description of light ion production (d, t, 3He, α) by ~GeV pion and nucleon interactions on the beam pipe & tracker
    - But it is CPU costly (see later...)

Hadronic models per Region

- Geant4 physics list is defined globally, not per region
- Sometimes users would like to use a reference physics list, e.g. FTFP_BERT, but replacing a hadronic physics model in a region with a more precise model
  - Recent request from ALICE : to be able to use INCLXX in the Tracker region, while using BERT elsewhere
    - INCLXX describes better the production of light ions by primary pions and nucleons interacting in the beam pipe and silicon tracker
    - The overhead in CPU time for ALICE of using FTFP_INCLXX instead of FTFP_BERT if about a factor of 2
- An elegant and efficient solution is provided by the "**Generic Biasing**" capability of Geant4
  - It naturally allows a treatment per-region and per-particle
  - No "occurrence" biasing, only "final-state operation" biasing
    - Kept the natural cross sections, but changed final-state hadronic model
    - It is "biasing" but with weight = 1.0 (as in analogous simulations)

String and Cascade cross-over

- Transition region between FTFP and BERT in FTFP_BERT physics list
  - **[3 , 12] GeV** in G4 10.3, 10.4, 10.5
    - The main motivation was to use more BERT and less FTFP to have lower energy response and wider hadronic showers
    - But thin-target data (HARP) prefer FTFP to BERT above ~ 5 GeV
  - **[3 , 6] GeV** new in G4 10.6 (scheduled for December)
    - Requested by CMS and supported by thin-target experimental data
    - Took the occasion to set consistently the same transition region for all hadrons (i.e. also for hyperons and light ions)
    - Reviewed also the transition for **BIC** (Binary Cascade model)
      - **[3, 6] GeV** between FTFP and BIC for proton and neutron
      - For pions, **BIC < 1.5 GeV** , 1 GeV < BERT < 6 GeV , FTFP > 3 GeV
    - Left unchanged the transition region QGSP − FTFP : **[12, 25] GeV**
    - Left unchanged the transition region in these 4 special physics lists : **FTFP_BERT_ATL** , **INCLXX**-based P.L. , **NuBeam** , **ShieldingM**

Interface to Fortran EPOS

- The hadronic extended example **Hadr02** in G4 **10.5** includes an interface to **CRMC** (Cosmic Ray Monte Carlo) − which offers the possibility to use generators like **EPOS** for final-state hadron-nucleus (and nucleus-nucleus) inelastic collisions at very high energies − and created a (local) physics list which uses this interface
  - The Physics List is called CRMC_FTFP_BERT and the transition between CRMC and FTFP is currently set to be [100, 110] GeV
  - Main interest for **FCC**, to simulate **jets above ~ 10 TeV**
    - Hadron-nucleus interactions up to at least ~ 1 TeV (projectile kinetic energy in the Lab frame) are expected to be well described by the Geant4 string models (FTF & QGS); above this, missing gluon-jet production
  - Currently under testing in the context of FCC
    - At model-level we see fewer and more energetic secondaries in G4 FTF & QGS with respect to EPOS due to the lack of gluon-jet emissions
  - Needs a special version of CRMC adapted for Geant4 use...

De-excitation models: Fermi Breakup

- For disintegration of light nuclei ($Z < 9$, $A < 17$)
- Breakup into 2- , 3- and 4-body final states
- Implementation
  - G4 10.4 and earlier: hard-coded data to precompute decay probabilities
    - 260 final states from data files and 399 reactions
  - G4 10.5 and later: new version G4FermiBreakupVI
    - 380 final states and 991 reactions
    - Fully based on data in G4GAMMALEVELDATA
    - Only binary decay chains considered, with standard Coulomb barrier calculation
    - Slightly slower than the old version

De-excitation models: Evaporation

- G4Evaporation
  - Simplified integration of inverse cross sections and final state sampling
    - Some speed-up
  - Optimized initialization, reduced memory churn

- G4PhotonEvaporation
  - If no transition data is found in database for a level, go to the nearest level
    - Was ground state in past
  - Corrected internal conversion probability for some isotopes

De-excitation models: Level Density

- For high nuclear excitation values, nuclear levels are too many and too close together to deal with them separately, therefore the level density is parameterized
  - Before G4 10.5 , $\rho_L = 0.1 * A$
  - New parameterization
    - Based on fits to data (A. Mengoni, Yu. Nakajima JNST 31 (1994) 151)
    - $\rho_L = \alpha * A * (1 + \beta / A^{1/3})$
    - Same parameterization must be used for fission, evaporation and photon evaporation to get reasonable results
  - New option in G4DeexPrecoParameters to get/set LevelDensityFlag
    - New default $\rho_L = 0.075 * A$

ParticleHP (1/3)

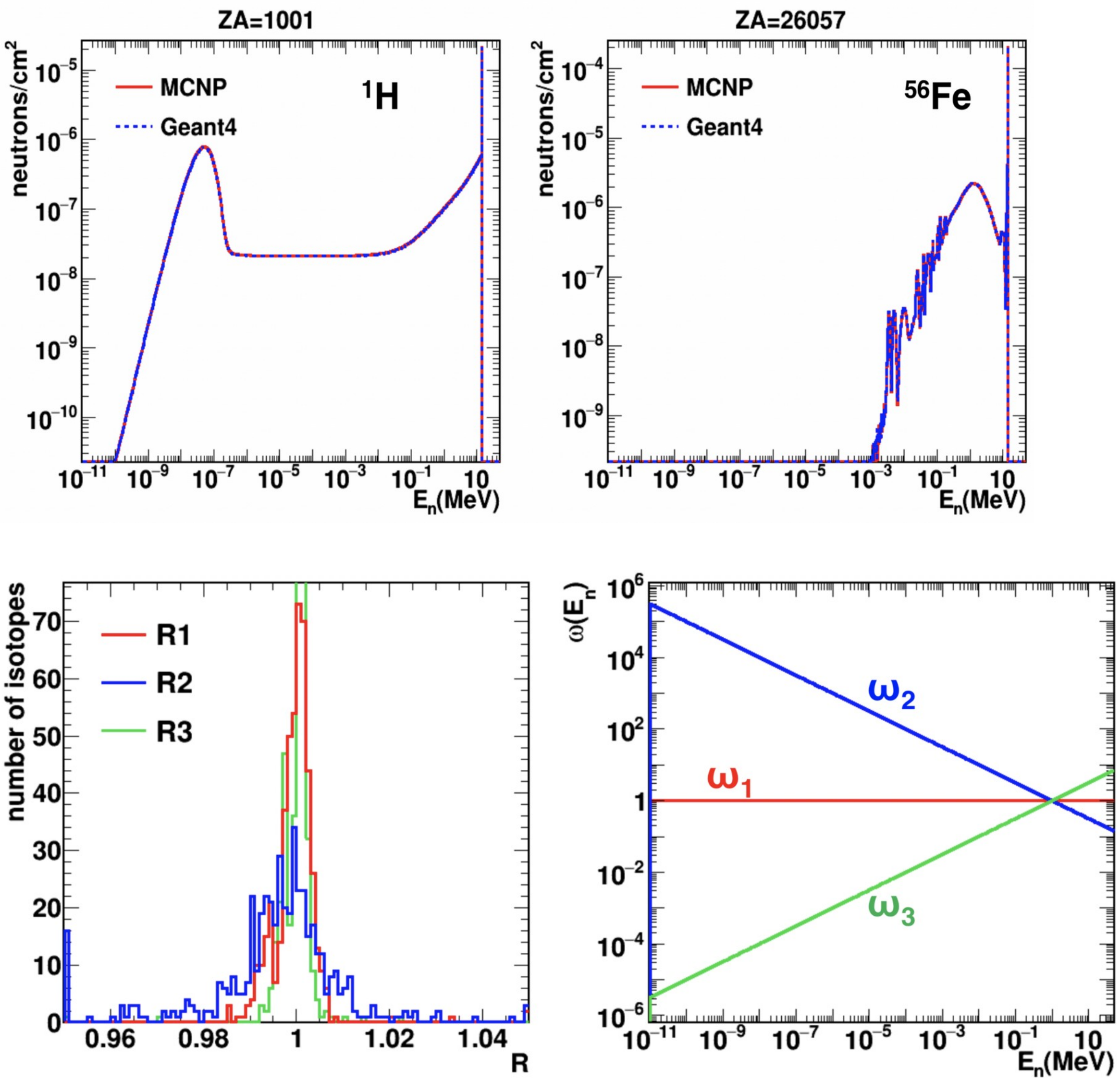
- By default tries to conserve energy-momentum event-by-event
  - Works sometimes, but not in general
- Current ParticleHP code often makes common sense modifications to get energy conservation, but this often destroys agreement with ENDF energy distributions
  - ENDF database rules deal only with distributions
  - Violating these rules can cause unexpected results (like extra gammas) which make validation difficult
  - Environmental variables exist to “fix up” ENDF
- Quick and dirty fix:
  - export G4NEUTRONHP_DO_NO_ADJUST_FINAL_STATE = 1
  - export G4PHP_DO_NOT_ADJUST_FINAL_STATE = 1

ParticleHP (2/3)

- Better idea:
  - Remove environmental variables
  - Refactor code for two modes of operation
    - ENDF mode: no event-by-event energy-momentum conservation is forced
    - Energy-momentum conservation forced – do not use ENDF data for final state, use a final-state model instead
- This choice follows ENDF rules
  - Better validation results and cross-code (MCNP) comparisons
- Methods for ENDF mode fairly easy to do
- Significant work to add new methods for modeling the final state in energy conservation mode

ParticleHP (3/3)

Verification (E. Mendoza & D. Cano-Ott)



$C_1 = \int \Phi(E)\, dE$

$C_2 = \int \Phi(E)/\sqrt{E}\, dE$

$C_3 = \int \Phi(E) \cdot \sqrt{E}\, dE$

$R_1 = C_1(\text{MCNP})/C_1(\text{Geant4})$

$R_2 = C_2(\text{MCNP})/C_2(\text{Geant4})$

$R_3 = C_3(\text{MCNP})/C_3(\text{Geant4})$

Radioactive Decay

- Spontaneous fission channel added
  - Competes with all other channels: α , β , IC , IT
  - Gets branching ratio from ENSDF database (RadioactiveDecay5.3)
  - Uses the Livermore spontaneous fission model already in Geant4
    - G4fissionEvent : currently valid only for Cf isotopes
    - Neutrons and gammas generated in final-state
      - Not fragments, but could be added in the future
- Electron capture
  - N-shell capture added to G4ECDecay
    - Machinery is there for all nuclides; but, currently, data for only a few are included in RadioactiveDecay5.3
  - Subshell capture ratios added
    - Tables of PL2/PL1, PM2/PM1 and PN2/PN1 added to RadioactiveDecay5.3
    - Based on bound electron radial wave amplitude from Bambynek (1977)
    - Partial probabilities of subshell capture calculated from above tables

Neutrino Interactions

- Progress in modelling neutrino interactions inside Geant4
  - Alternative to the interface to external GENIE package
- Neutrino – electron interactions included in G4 10.5
  - Neutral- and charged-current for neutrinos and anti-neutrinos of all 3 flavours (ν_e , ν_μ , ν_τ)
  - Included in the gamma-lepto-nuclear physics constructor G4EmExtraPhysics (present in all physics lists); it can be activated and steered via UI commands
- ν_μ – nuclear interactions will be included in G4 10.6
  - Including also "anti_nu_mu"
  - Included in the gamma-lepto-nuclear physics constructor G4EmExtraPhysics (present in all physics lists); it can be activated and steered via UI commands
  - In the future (after G4 10.6), can be extended to electron and tau neutrinos (and anti-neutrinos)

Selected Topics

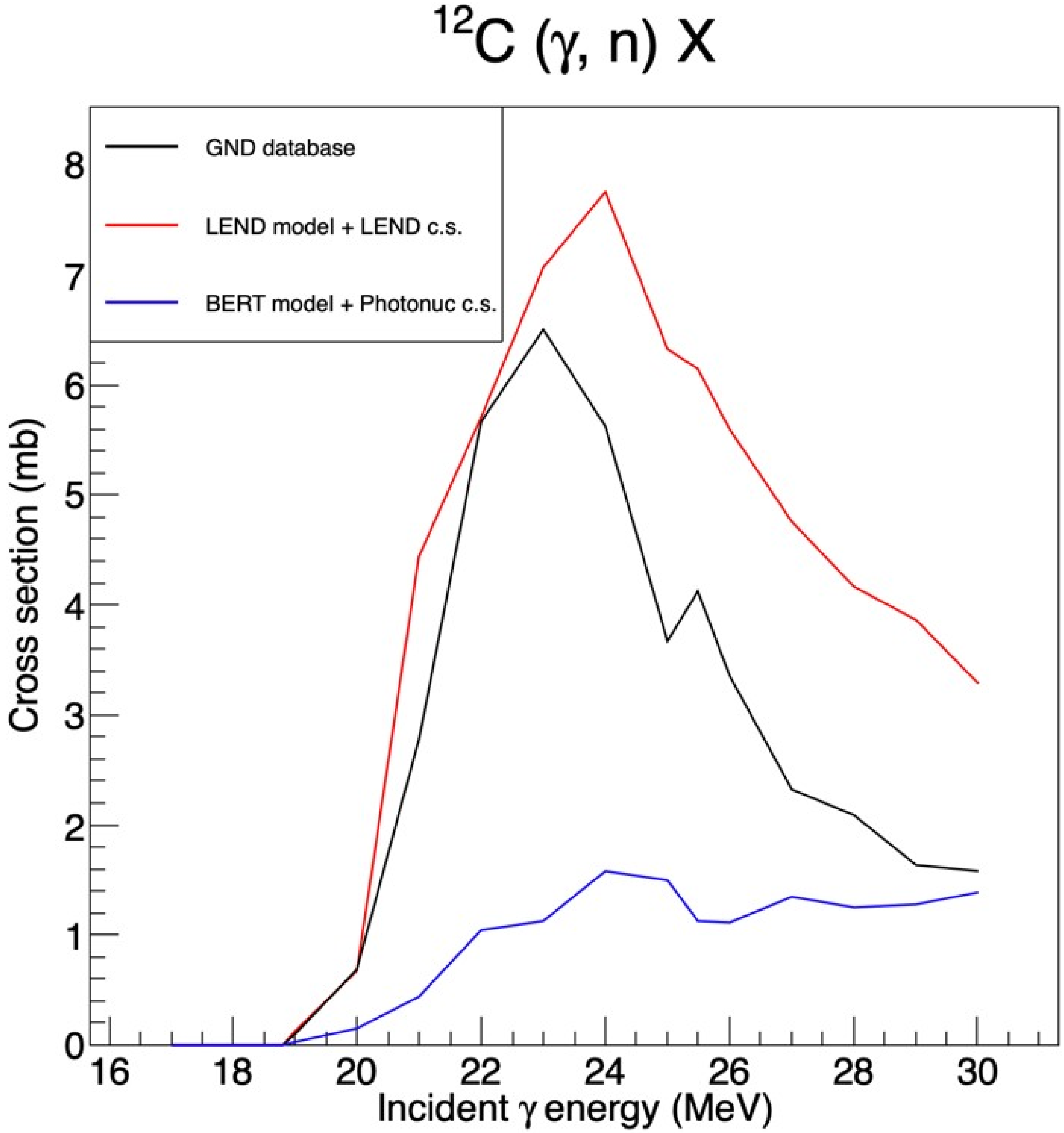
Gamma- and Lepton-Nuclear interactions in G4

- Gamma-nuclear
  - BERT < 3.5 GeV
    - For all reference physics lists, except for ShieldingLEND, where LENDorBERT model is used below 20 MeV (see next slide)
  - QGSP > 3 GeV
- Electro-nuclear
  - Kossov model of EM cross section and virtual photon generation
  - Weizsacker-Williams conversion of virtual to real gamma
  - For $E\gamma < 10$ GeV , direct interaction with nucleus using BERT
  - For $E\gamma > 10$ GeV , conversion of γ to π^o , then interaction with nucleus using FTFP
- Muon-nuclear
  - Kokoulin model of EM cross section and virtual photon generation
  - All else identical to electron-nuclear

LENDorBERT model (1/3)

- Recent gamma-nuclear model introduced in G4 10.4
  - Use LEND (GND-based hadronic model) below 20 MeV
  - Use Bertini (BERT) above 20 MeV
    - Bertini is also used when no appropriate data is found in GND
- Started the verification of gamma-nuclear reactions
  - Is the combination model correctly designed?
  - Can the GND data be reproduced with G4 process-level tests?
  - Test by using pure BERT and pure LEND, then comparing
- Validation to follow
  - GND data cover many isotopes from 1 MeV to 150 MeV
    - Also covers several reactions
  - Lots of data for **(γ, n)**

LENDorBERT model (2/3)



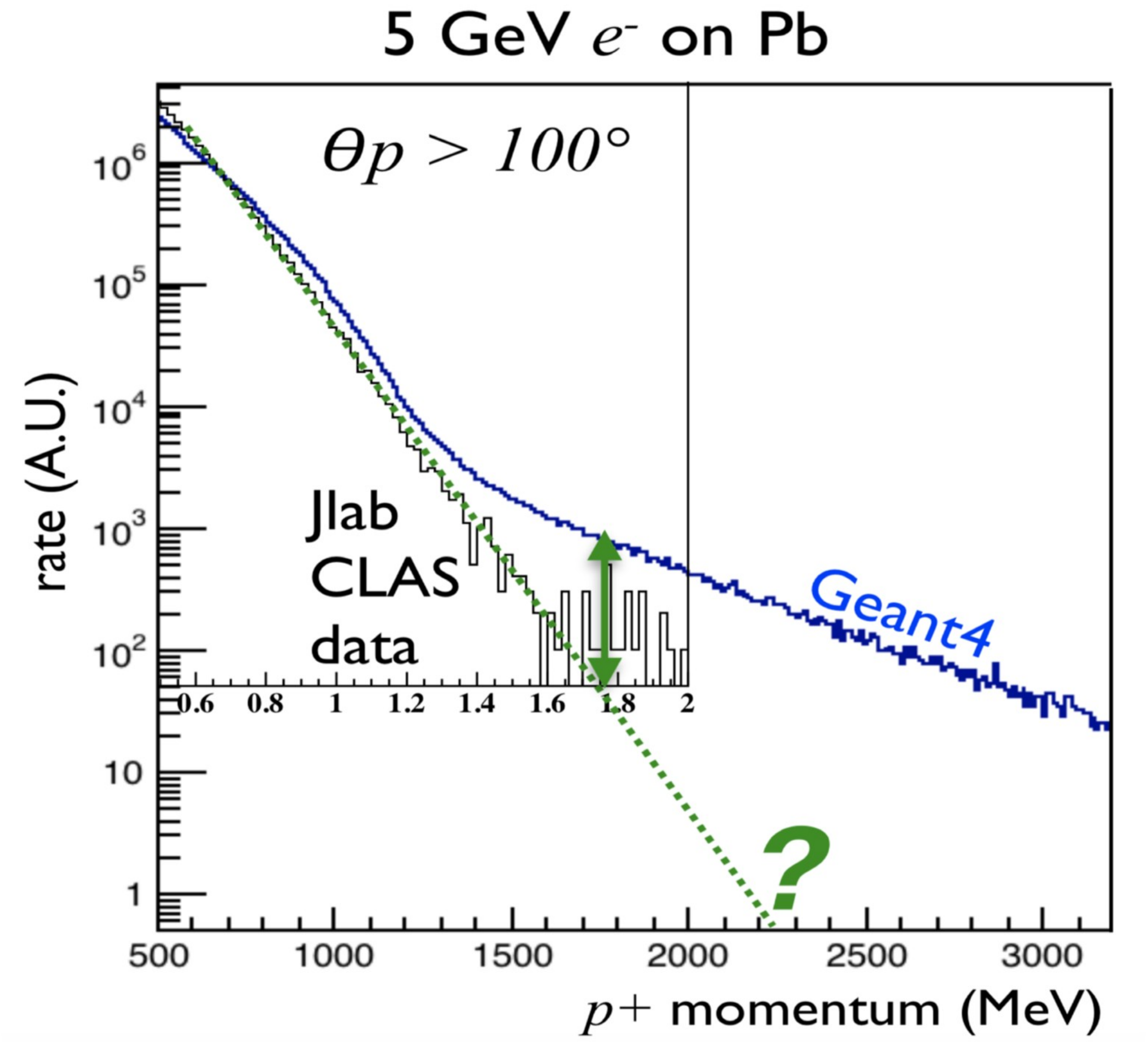
LENDorBERT model (3/3)

- Early conclusions for 12C
  - LEND much better than BERT in Giant Dipole region
  - LEND overestimates data
    - Protons being produced below threshold is part of the reason
    - But Precompound/de-excitation models are apparently not called
- General findings for G4LENDorBERT gamma-nuclear
  - Bug in code causes BERT to always be selected
  - 20 MeV cross-over from LEND to BERT seems to be too low
    - 30 MeV or higher looks better
  - Large number of energy non-conservation warnings
- Plans
  - Understand why pure LEND does not exactly reproduce GND data
  - Look at many other target nuclei to see where to set the LEND-BERT cross-over

Electro-nuclear Validation

- Initial validation against JLab data mentioned last year
- For 5 GeV e- on Pb, Geant4 over-produces protons
  - *See next slide*
  - High energy quasi-deuteron cross section may be the cause
    - Recently fixed in Bertini
  - Validation plot with new quasi-deuteron cross section not yet produced

Electro-nuclear Problem in Geant4



Improved Quasi-deuteron Photo-disintegration Cross Section