Updates on Hadronic Physics

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Outline

- Since August 2015 (the last Space Users Workshop)
  - Ions, isomers, nuclides
  - Radioactive Decay
  - Nuclear de-excitation
  - High precision particle code
  - Cascade models
  - High energy models
- In progress
  - Neutrino scattering
  - Hadronic model parameter variations
- Coming attractions

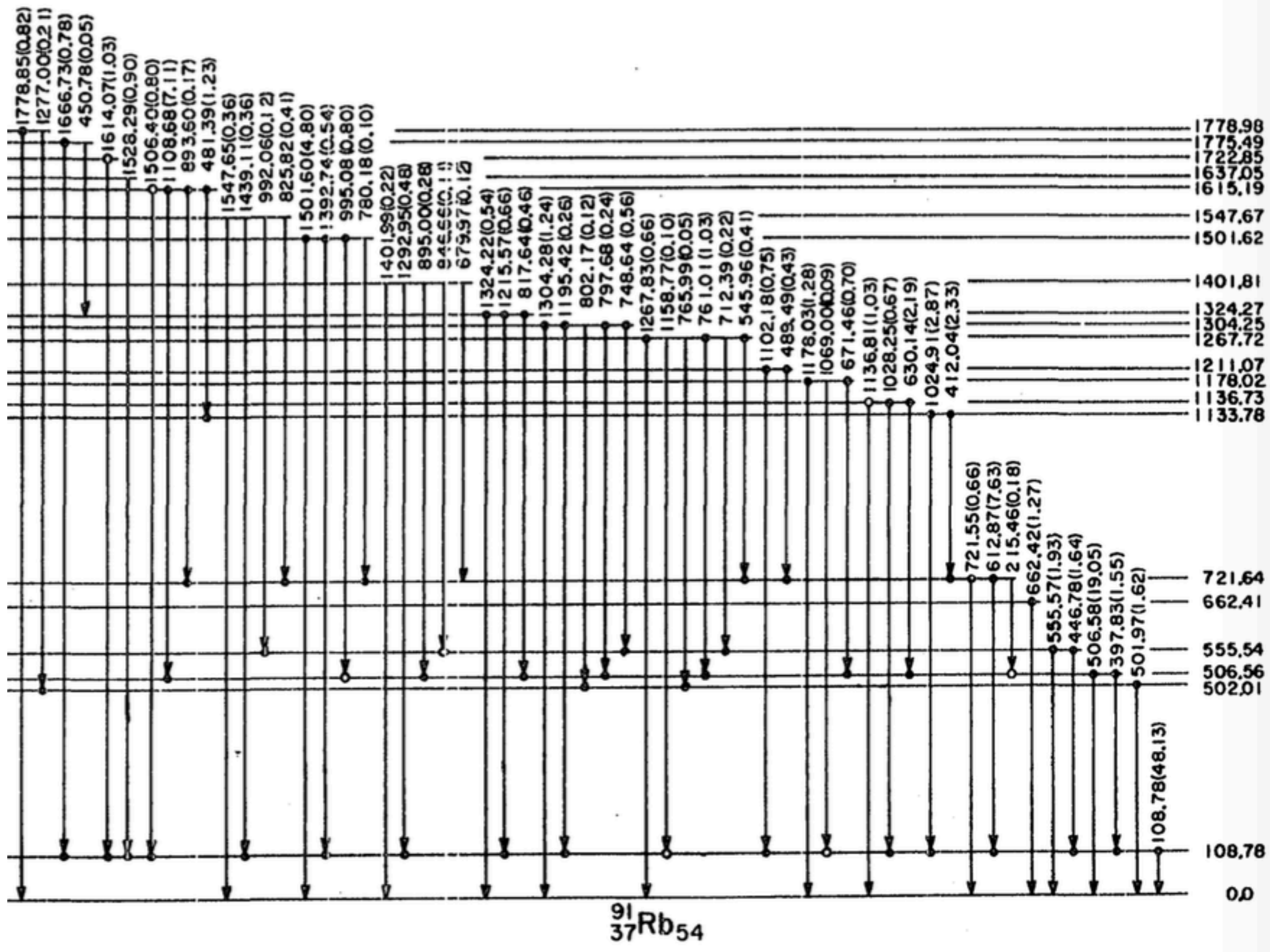
Ions, Isomers and Nuclides (1)

- “Floating levels”
  - ~hundreds of nuclear levels are either known or expected to exist but do not have well-determined energies
  - decay chains are sometimes built on these levels with well measured transition energies
  - these levels previously represented by adding a very small energy (e.g. 0.000004 keV) to the expected level energy → Pa234[73.920004]
- Now implemented as distinct nuclides and propagated as such by Geant4
  - represented now as Pa234[73.92+X]
  - if more than one floating level per nucleus use Y, Z, W, …

Ions, Isomers and Nuclides (2)

- Modifications of G4IonTable, G4PhotonEvaporation, G4RadioactiveDecay, etc. were required
- Three databases providing this information were rationalized → shared data now consistent
  - RadioactiveDecay5.1.1
  - PhotonEvaporation4.3.2
  - G4ENSDFSTATE2.1
- Working on easier access by compressing data sets or offering more data in fewer files
- Data exists for resolving some of the floating levels → less of a problem in future

Typical Nuclear Level Scheme



Radioactive Decay Improvements

- Improved energy conservation
  - down to ~ 30 eV for decays by electron capture and isomeric transition (< 1 eV for alpha, beta)
  - used Zoglauer approximate model of outer shell energies
  - could do better with more sophisticated atomic de-excitation model

- Switched from G4UAtomicDeexcitation to G4VAtomicDeexcitation (as in EM code)
  - more general
  - better treatment of fluorescence and Auger emission
  - de-excitation parameters now set by G4NuclearLevelData

Radioactive Decay and Photon Evaporation

- Correlated Gamma Emission
  - Now fully implemented
  - Previous photon evaporation code could emit multiple gammas during de-excitation, but they were isotropic and not correlated with each other
  - New code (Jason Detwiler) makes use of J^{π} data to calculate the Legendre polynomials corresponding to the multipolarity of the gamma transition

- This required still more additions to the photon evaporation database (thanks, Laurent!)
  - nuclear spin (J), parity (π), multi-polarity (E0, E1, M1, etc.)
  - PhotonEvaporation 4.3.2

But Still Some Problems ….

- Correlations have not yet been validated and several warnings appear
- Reproducibility
  - addition of gamma correlation to radioactive decay re-introduces irreproducibility
  - reproducibility recovered when correlations turned off
  - caching of successive nuclides in decay chain the likely suspect

- Radioactive decay code still does not take full advantage of multithreading
  - working on improved RDM database file access

Nuclear De-excitation

- Evaporation, Fermi Breakup and Photon Evaporation models all re-written to use common nuclear level data
- Customizable parameters for precompound and de-excitation models – set in physics list builder

- Improved treatment of Coulomb barrier led to some improvement in final state neutron and proton spectra at low energy (< 100 MeV)
- Increased use of C++11 features
- Changes resulted in some slow-down for calorimetry applications

ParticleHP

- NeutronHP has been merged with its analogue for high precision charged particle interactions, ParticleHP
  - now handles n, p, d, t, α
  - new code is ParticleHP, but NeutronHP kept for backward compatibility
  - mostly for E < 20 MeV, but some data up to 200 MeV

- Database
  - G4NDL4.5 now required
  - to reduce size data files stored in zlib format
  - code automatically unpacks this, but to get human readable data, you need to run zlib (http://www.zlib.net)

ParticleHP – Problems Solved

- Reproducibility now restored in multithreaded running
  - Release 10.2

- Large memory consumption problem solved
  - Release 10.3

GND/GIDI/LEND

- Generalized Nuclear Data (GND)
  - new low energy particle database with more modern, rationalized format
  - includes all ENDF/B-VII data
  - upgrade of Generalized Interaction Data Interface (GIDI) used to access new GND format
    - to be delivered late 2015/ early 2016

- Can already try the new data
  - use G4LEND neutron models
  - or G4HadronElasticPhysicsLEND physics constructor
  - need to download data from ftp: //gdo-nuclear.ucllnl.org/pub

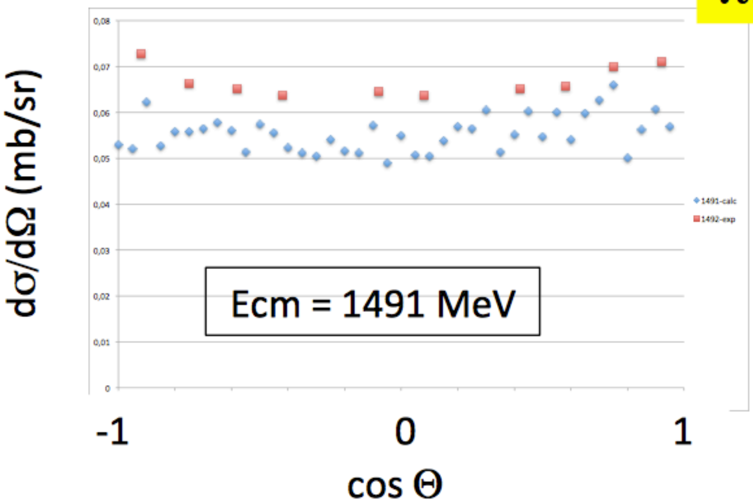
Cascade Models

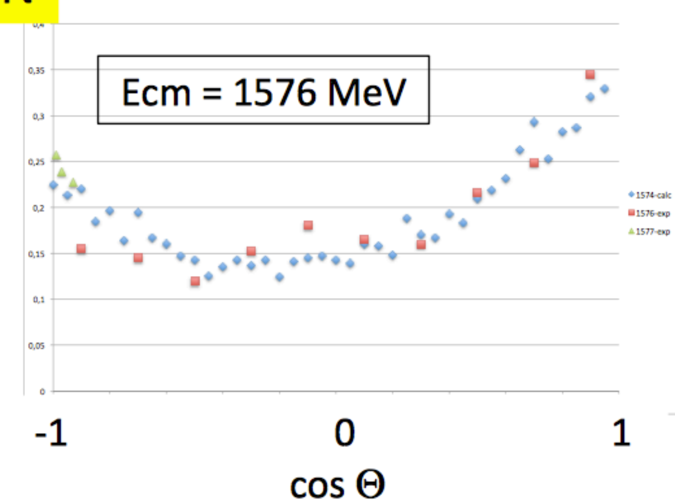
- INCL++
  - extended to include production of η and ω mesons
  - several INCL-based physics lists now available (as alternative to Bertini)

- Bertini
  - Evaporation code improved to use Dostrovsky model correctly
    - long-time over-simplification resulted in neutron over-production at low energies

η Production with INCL++

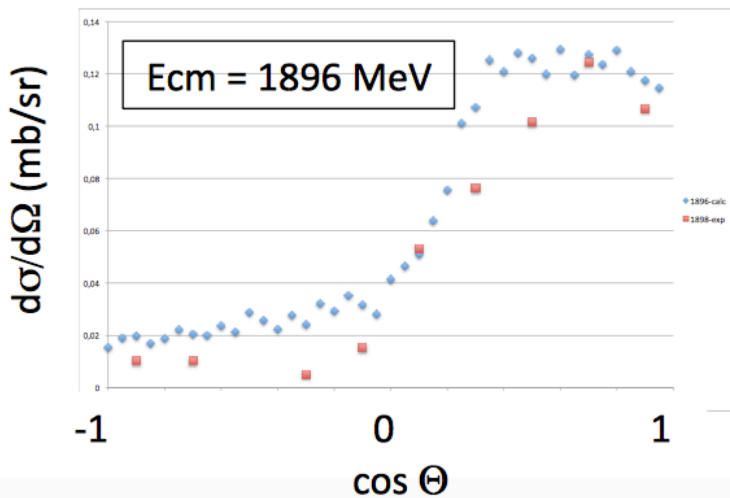
$\pi N \rightarrow \eta N$





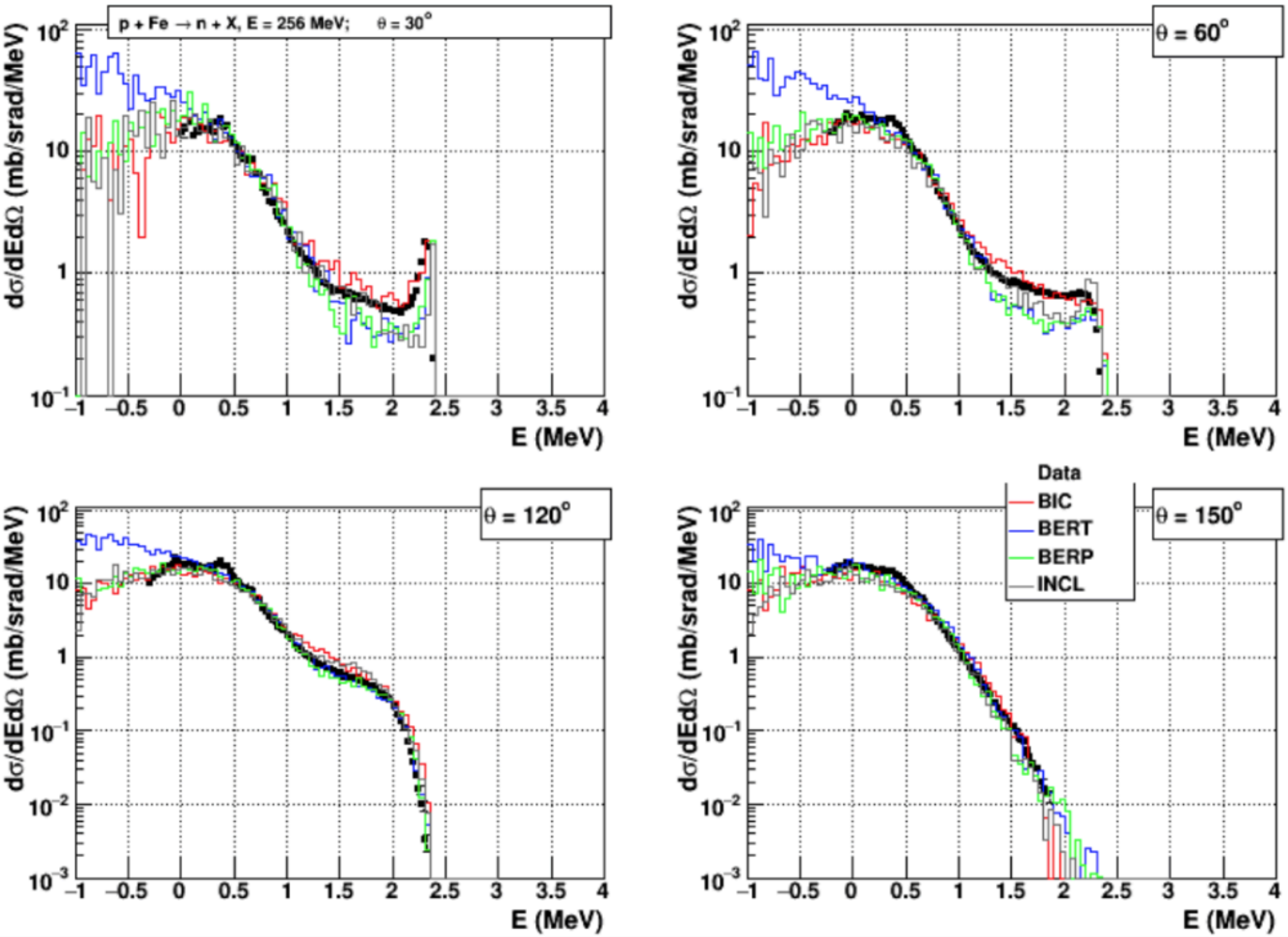
Exp. data

INCL++ formula

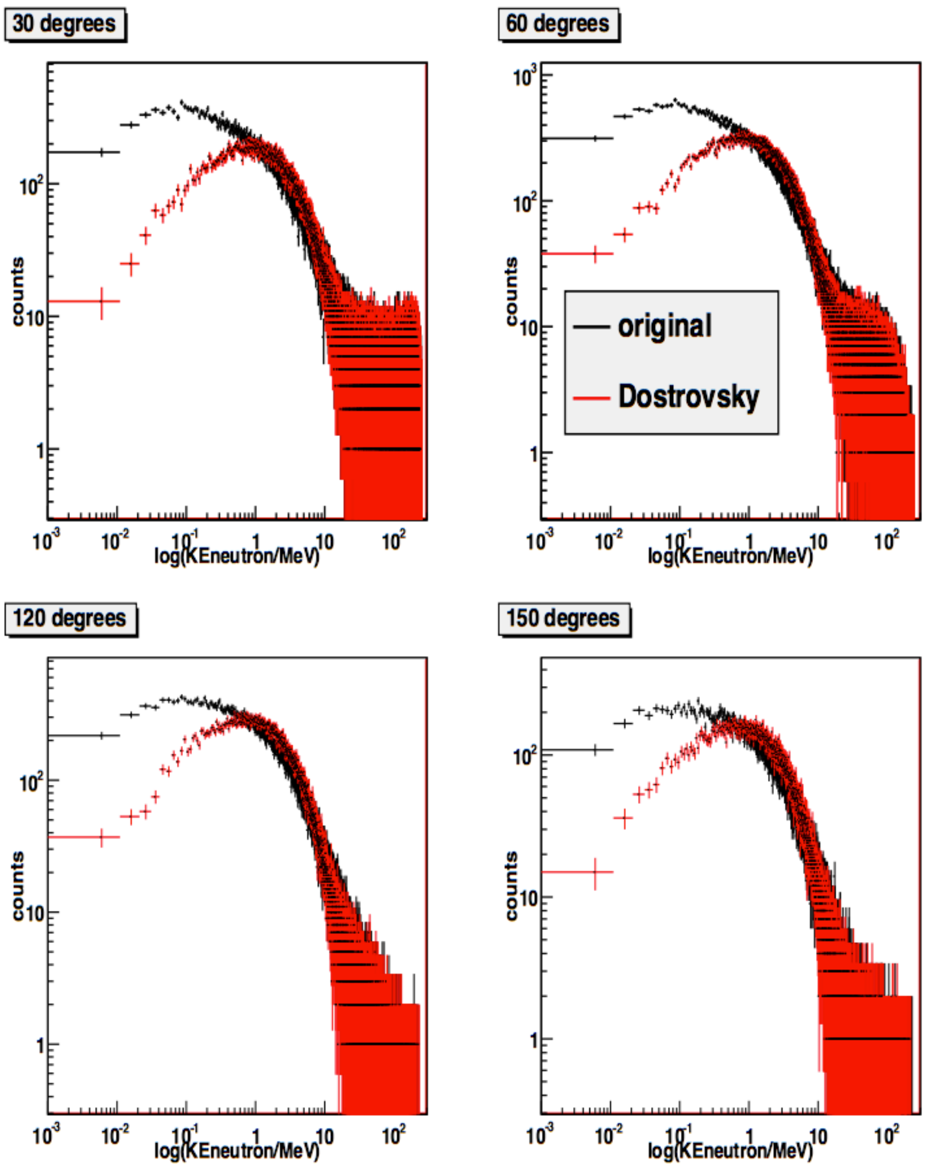


Not too bad at all..

Low Energy Neutron Production in Bertini (old)



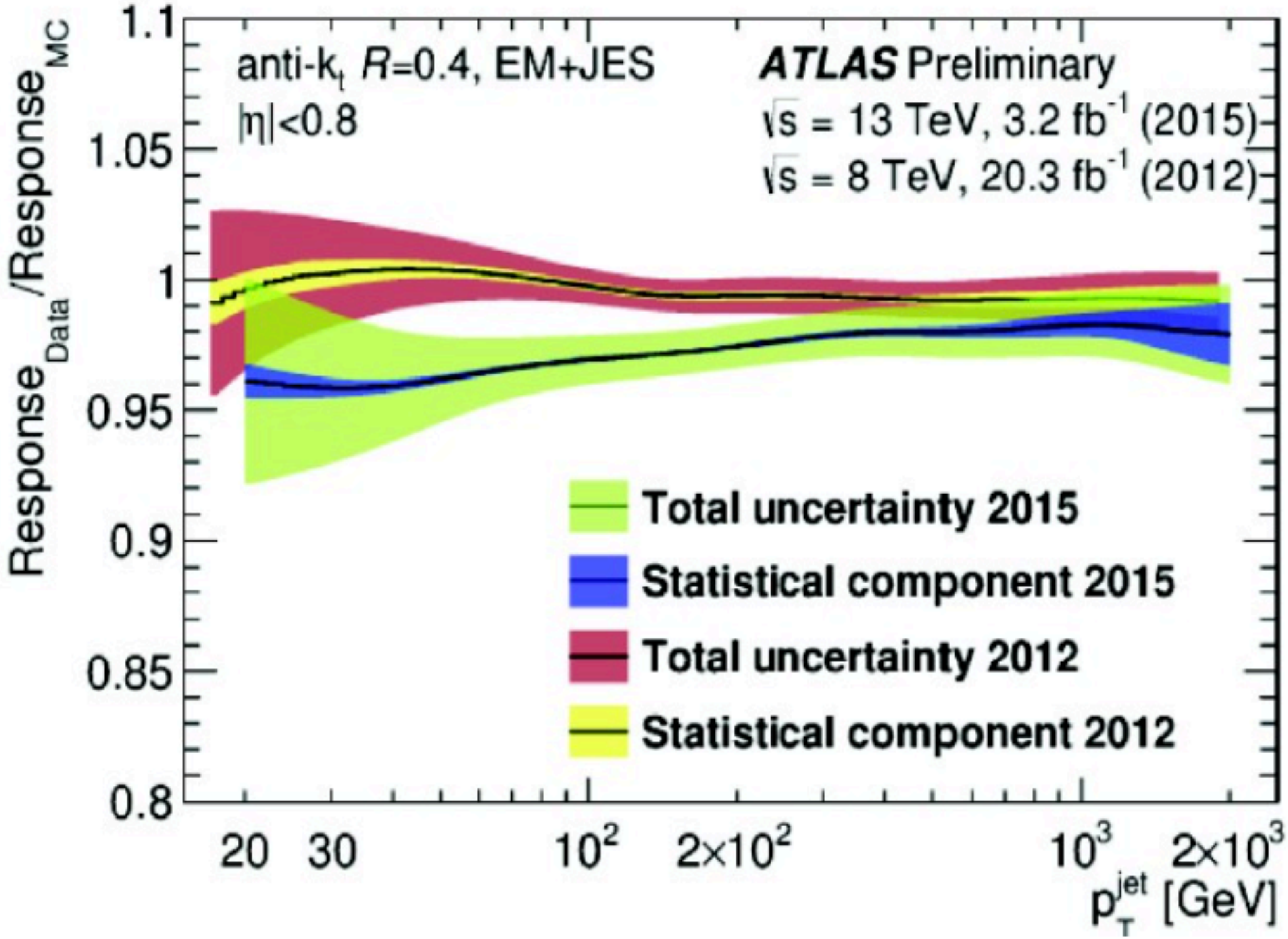
Low Energy Neutron Production in Bertini (new)



High Energy Models

- Recent analysis by ATLAS and CMS has shown a shift in ratio of simulated to measured response at jet energy scale
  - between Run 1 (8 TeV) with G4 9.4
    and Run 2 (13 TeV) with G4 9.6
- FTF and Bertini used by both ATLAS and CMS physics lists
  - despite many changes to Bertini, little effect on showers
  - FTF is now the suspect
- Created new physics list for ATLAS
  - transition from BERT to FTF moved from [4–5] GeV to [9-12] GeV
  - restores some lost shower width
  - wait to see results of new ATLAS analysis

Problem at the Jet Energy Scale



FTF Model

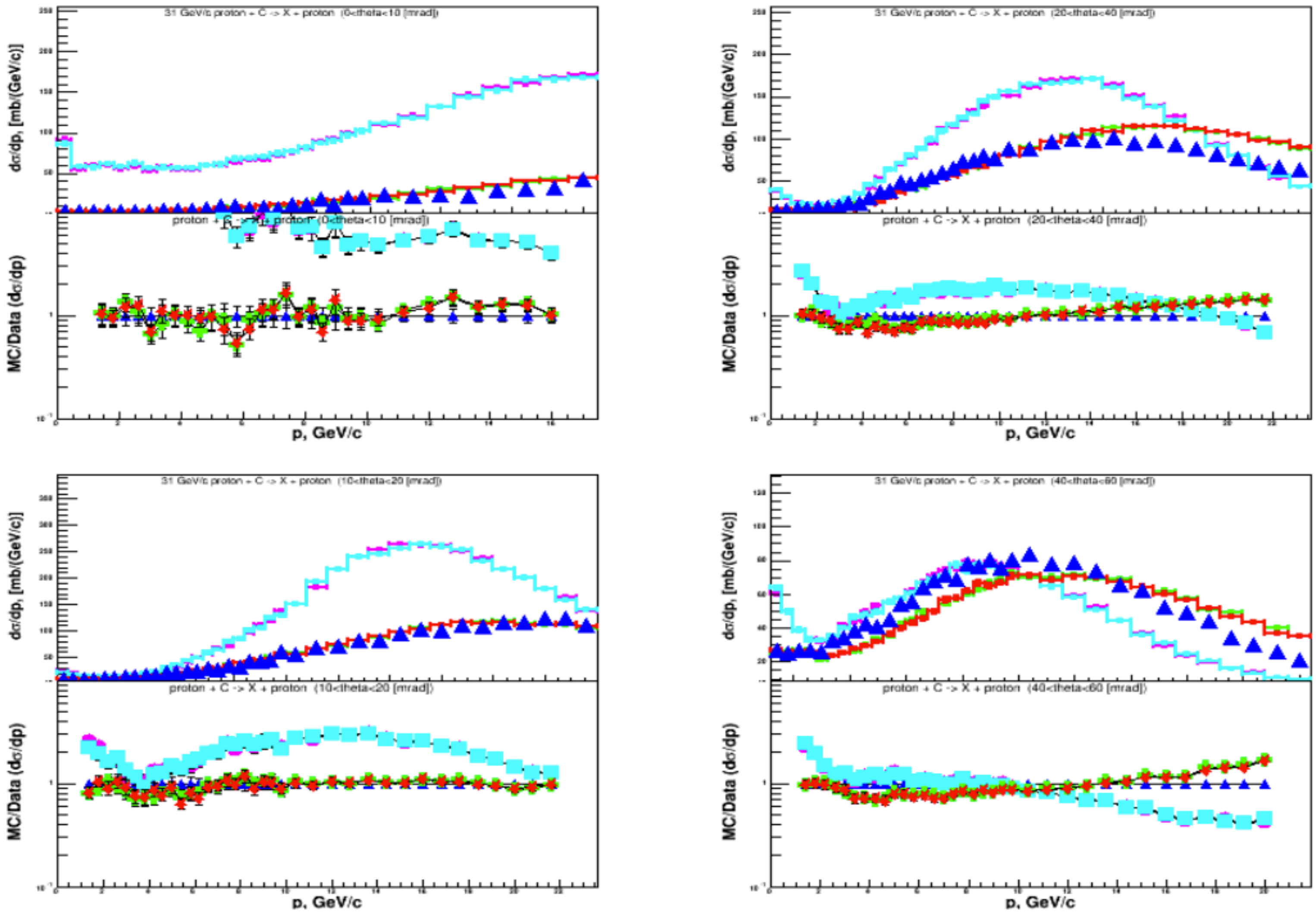
- Has been the “go-to” model for high energies
- Work continues by Vladimir Uzhinsky and Alberto Ribon
  - new hadron fragmentation functions, other physics improvement
  - parameter tuning, such as mean P_t

- However, may have reached point of diminishing returns
  - still small improvements in agreement with thin target data
  - but departures from calorimeter data
  - now using Bertini at higher energies (up to 12 GeV) to get better agreement with hadronic showers
  - time to go to a more theory-driven model?

QGS Improvements

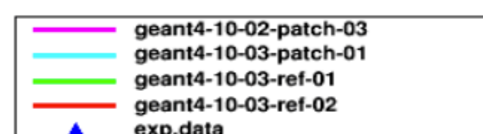
- QGS has lain dormant for many years
- Work resumed (by Vladimir Uzhinsky) because
  - model is more theoretically based
  - can be extended to much higher energies (multi-Tev)
  - FTF model may be reaching its limits
- Changes
  - use constituent quark masses (instead of massless)
  - Pomeron and Reggeon parameters set up according to Kaidalov and Poghosyan
  - quark exchange improved
  - some parameter tuning

QGSPP: 31GeV/c p+C -> p



qgsp vs NA61 Data; χ^2/NDF calculated over ALL theta bins

χ^2/NDF = 155.851 for geant4-10-02-patch-03
χ^2/NDF = 156.461 for geant4-10-03-patch-01
χ^2/NDF = 13.1912 for geant4-10-03-ref-01
χ^2/NDF = 13.0215 for geant4-10-03-ref-02



In Progress

Neutrino Interactions

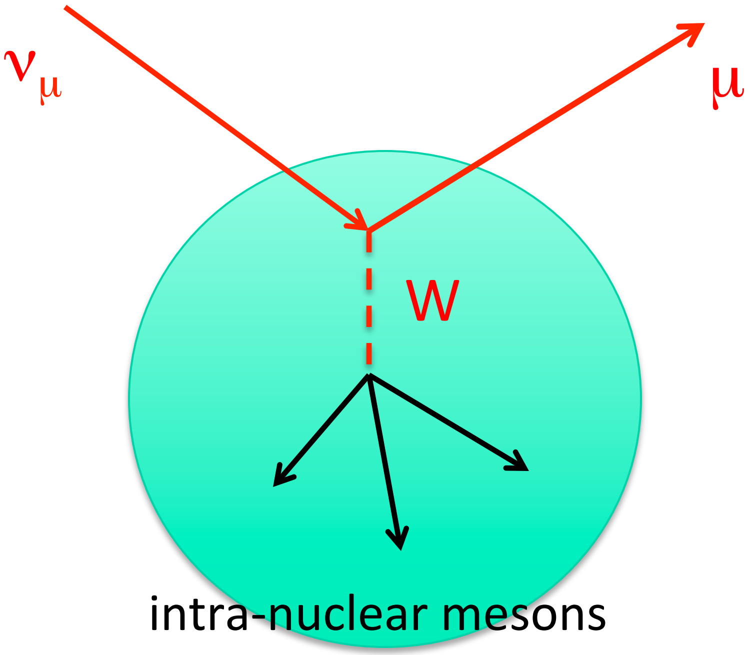
- Began work two years ago on interface of Geant4 to GENIE
  - goal: allow GENIE neutrino generator to use Geant4 hadronic models for fragmentation and final state interactions within nucleus following initial interaction
    - will allow greater variety of models than now available in GENIE
    - interface to Bertini precompund model completed
    - interface to full Bertini nearly ready

- Second step: interface of GENIE to Geant4
  - goal: allow Geant4 to use GENIE's neutrino-nucleus interactions in a Geant4 neutrino process
    - planned for late 2017

- Third step: once neutrino scattering processes are in place, use new Geant4 biasing techniques to do neutrino propagation

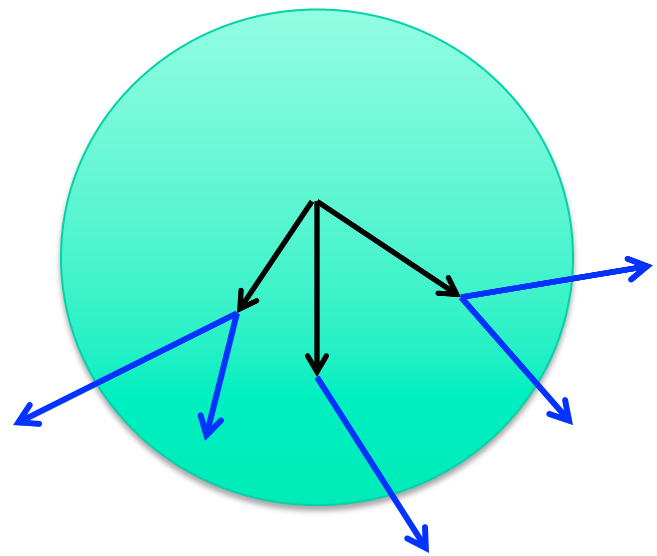
Geant4-Genie Interface

Neutrino interaction with nucleon in nucleus (Genie)



intra-nuclear mesons and nucleons

Geant4 model for propagation and re-scattering (Bertini)



final state mesons and nucleons

User Variation of Model Parameters

- Requested by several user communities
  - most notably for studies of neutrino production targets

- A means of establishing systematic errors for some models and allowing parameter space to be searched for best agreement with data

- Prototype interface now ready
  - Bertini cascade first model to be tested
  - Only two parameters allowed to be varied in test
    - nuclear radius, intra-nuclear cross section scaling
  - Other models to follow later

- Interface to be offered on a restricted basis
  - only users working with model developers

Coming Attractions

“High Precision” Gamma-nuclear Model

- G4LEND model can access gamma-induced reactions in Generalized Nuclear Data (GND) database
  - up to 100 MeV
  - large number of targets

- Perfect solution to current problem of poor agreement of Bertini gamma reactions at low energy
  - Bertini not really intended for such low energies, but with GND data–driven solution nuclear structure feature can be simulated
  - can envision a hybrid model with G4LEND below 100 MeV and Bertini above

Low Energy Gamma-nuclear (GDR and below)

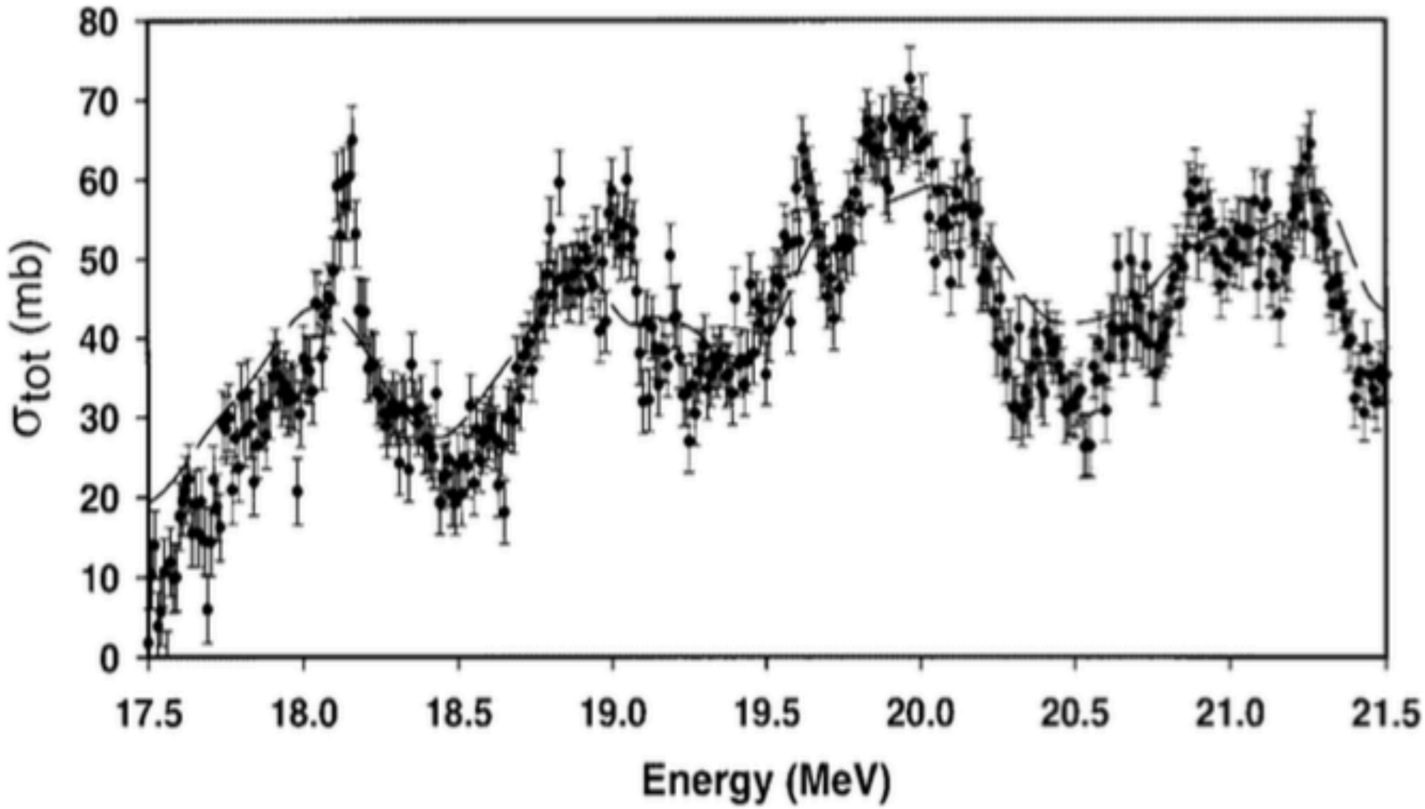


Fig. 2 The observed $^{28}Si(\gamma, abs)$ cross section (•) in the energy range 17.5–21.5 MeV

Improved Electro-nuclear Models

- Increasing need for better virtual photon exchange models
  - from BNL, SLAC, Jefferson Lab, heavy photon search experiments, future electron-ion colliders

- Current Geant4 models are approximate
  - assume exchanged virtual photon can be converted to real photon before interaction with nucleus
  - OK at low and medium energies but not for deep inelastic scattering

- Will need to develop full 4-momentum transfer of virtual photons
  - and deal with off-shell nuclear targets

Validation and Testing

- Work proceeding on new validation framework
  - using latest web technology
  - with on-demand generation of plots
  - also to be used for EM

- Development of infrastructure to allow generation of MC predictions with error band

- New test suite for hadronic cross sections with data

- TARC experiment simulation to be converted to Geant4 test15 for system testing
  - for low to medium energy neutrons