Geant4 Hadronic Physics Performance: Recent Validation and Developments

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Outline

- Performance Issues
- Key Validation Results
- Successes and Challenges
- Key Developments
- Summary

Performance Issues

- Physics performance: agreement of model predictions with data
  - validation
  - accesibility
- Computing performance
  - CPU Speed: cost per interaction improved by code review
  - Efficiency use of memory (allocations per interaction)
    - Goal to improve a model with no change in physics.
- Code usability
  - docs, guidelines
  - modularity
  - ease of use

Validation Efforts and Accessibility

- Our goal is to provide extensive validation of every active Geant4 hadronic model and cross section set
  - Against thin-target data (primarily)
  - And make the results easily accessible to users
- Most results are regenerated with each major Geant4 release and are linked to the Geant4 web page
  - During the past two years much effort has been devoted to improving Geant4 hadronic validation
    - according to the January 2009 Review of the Geant4 project: "An impressive program of systematic physics validation has been carried out."

Survey of Validation Efforts (1)

- Stopped particles
  - M. Kossov (CERN), J. Yarba (FNAL)
  - μ^-, π^-, K^-, anti-p
  - geant4.cern.ch/results/validation_plots/thin_target/hadronic/stopped
- Heavy ions
  - P. Cirrone, F. Romano, G. Cuttone (INFN, Catania)
  - T. Koi (SLAC)
  - E < 10 GeV/N
  - target: 12 < A < 208, projectile: 12 < A < 56
  - web pages under construction

Nucleus-nucleus model validation

Catania group (LNS-INFN) is involved on nucleus-nucleus models validation at intermediate-low energy (10-400 MeV/n). This energy range is of interest for medical applications, in which the group is involved on (hadrontherapy).

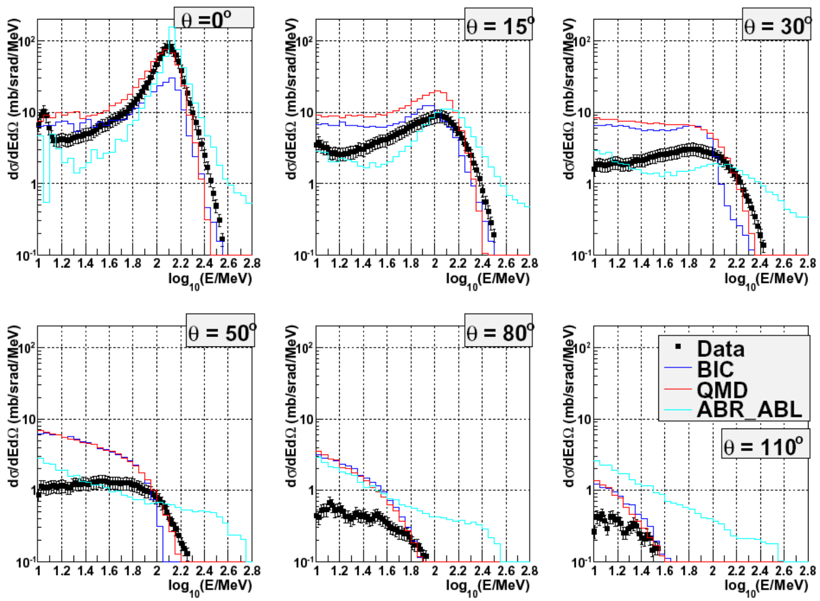
Nucleus-nucleus interaction models available in Geant4:

- ***Binary Light Ion Cascade***
- ***Quantum Molecular Dynamics (QMD)***
- ***Abrasion Ablation***
- ***G4QLowEnergy***

few experimental data published for <u>thin targets</u> at low energy!

(most of them → secondary <u>neutron</u> production)

C + C → n + X



incident beams: He, C, Ne, Ar

targets: C, Al, Cu, Pb

Comparison of experimental neutron double differential cross sections production at different angles and those predicted by different models

Reference: H.Sato et al., *Measurements of double differential neutron production cross sections by 135 AMeV He, C, Ne, and 95 AMeV Ar ions* Phys. Rev. C, 64, 054607 (2001)

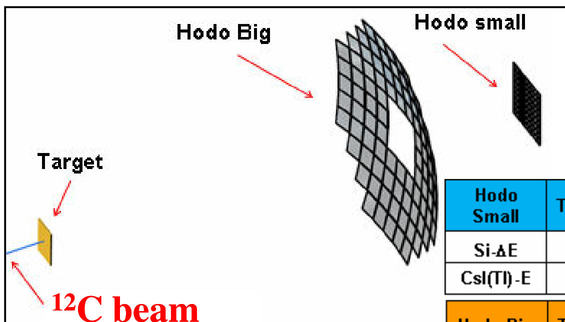
Nucleus-nucleus models validation (cont.)

Experiment at LNS-INFN in Catania for fragments production

$^{12}C + ^{197}Au$ @ 62 MeV/n → p, d, t, ^{3}He, α, ^{6}He, ^{6}Li, ^{7}Li, ^{7}Be, ^{9}Be, ^{10}B, ^{11}B , ^{11}C

Experimental apparatus: Two hodoscopes with different granularity ("Hodo big" and "Hodo small") composed by ΔE-E telescope detectors, able to identify the different isotopes detected.

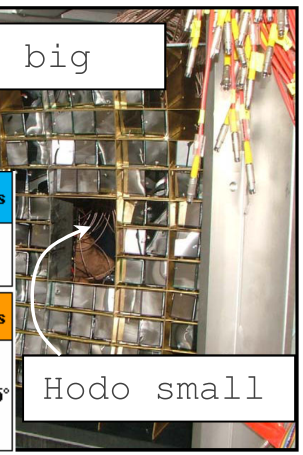
Double differential cross sections for charged fragments production have been compared



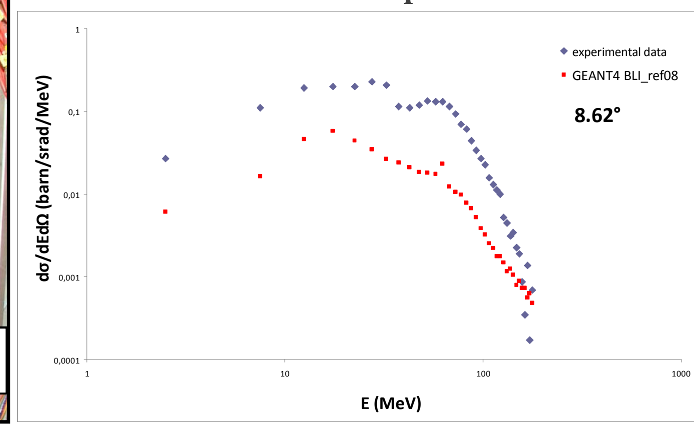
Scheme of the experimental apparatus

Hodo Small	Thickness	Active area	Covered angles
Si-ΔE	300 μm	1x1 cm²	$\theta_{lab} = \pm5°$
CsI(Tl)-E	10 cm	1x1 cm²	

Hodo Big	Thickness	Active area	Covered angles
Si-ΔE_1	50 μm	3x3 cm²	$\pm5° \le \theta_{lab} \le \pm21.5°$
Si-ΔE_2	300 μm	3x3 cm²	
CsI(Tl)-E	6 cm	3x3 cm²	



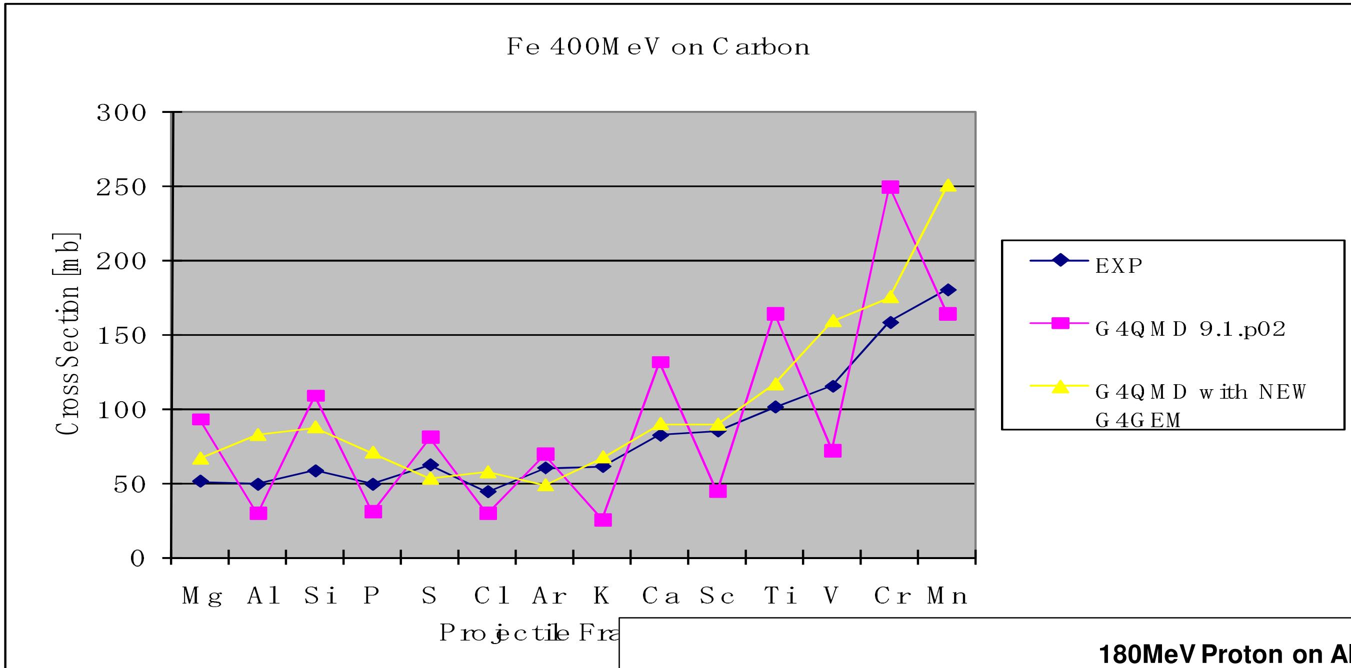
C + Au → p + X

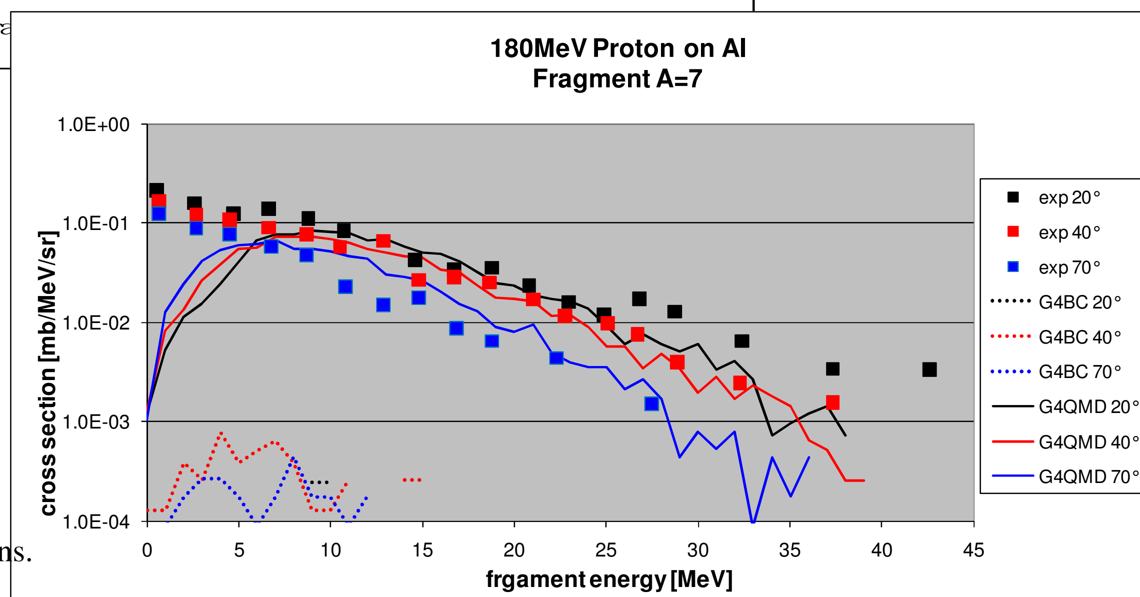


Future plan

- Measurements at low energy (C + C @ 62 MeV/n) → already performed at LNS Catania in April 2009 (analysis still in progress)
- New measurements at higher energy at GSI (Germany) → approved for 2010
- Intercomparison with other Monte Carlo codes (Fluka)

Nucleus-nucleus: G4QMD vs data





Energy deposition in intermediate-energy nucleon–nucleus collisions," *Kwiatkowski* et al., *Phys. Rev. Lett., vol. 50*, no. *21*, pp. 1648–1651, *1983*

This result includes some but not all recent corrections.

Survey of Validation Efforts (2)

- Cascade energy
  - p, n on various targets, 20 MeV – 3 GeV (labelled test30)
    - cern.ch/vnivanch/tests.shtml (V. Ivanchenko, A. Ivanchenko - CERN)
- Transition region
  - p on various targets, 3-12 GeV (labelled test35)
    - cern.ch/vnivanch/tests.shtml (V. Ivanchenko, A. Ivanchenko - CERN)
  - proton and pion double-differential cross sections for various targets
    - Covers100 MeV – 20 GeV
    - geant4.fnal.gov/hadronic_validation/validation_plots/thin_target/hadronic/medium_energy/index1.shtml
      - S. Banerjee, J. Yarba, D. Elvira (FNAL)

Survey of Validation Efforts (3)

- High(est) energy
  - 100 – 400 GeV protons, pions on various nuclei
    - geant4.fnal.gov/hadronic_validation/validation_plots/thin_target/hadronic/high_energy
      - G. Folger
- CHIPS
  - test49
  - M. Kossov

CPU performance

- **Speed:** efforts to improve it as LHC running approaches
- **Memory use:** addressing problems reported by ATLAS (memory *churn* = allocate+free in 1step)

Code usability

- **Documentation:** a task force is working on improving documentation of physics lists and model usage.
- **Easy of use:** we continue to be concerned with improving ease of use of hadronic models.

IAEA benchmark of spallation data

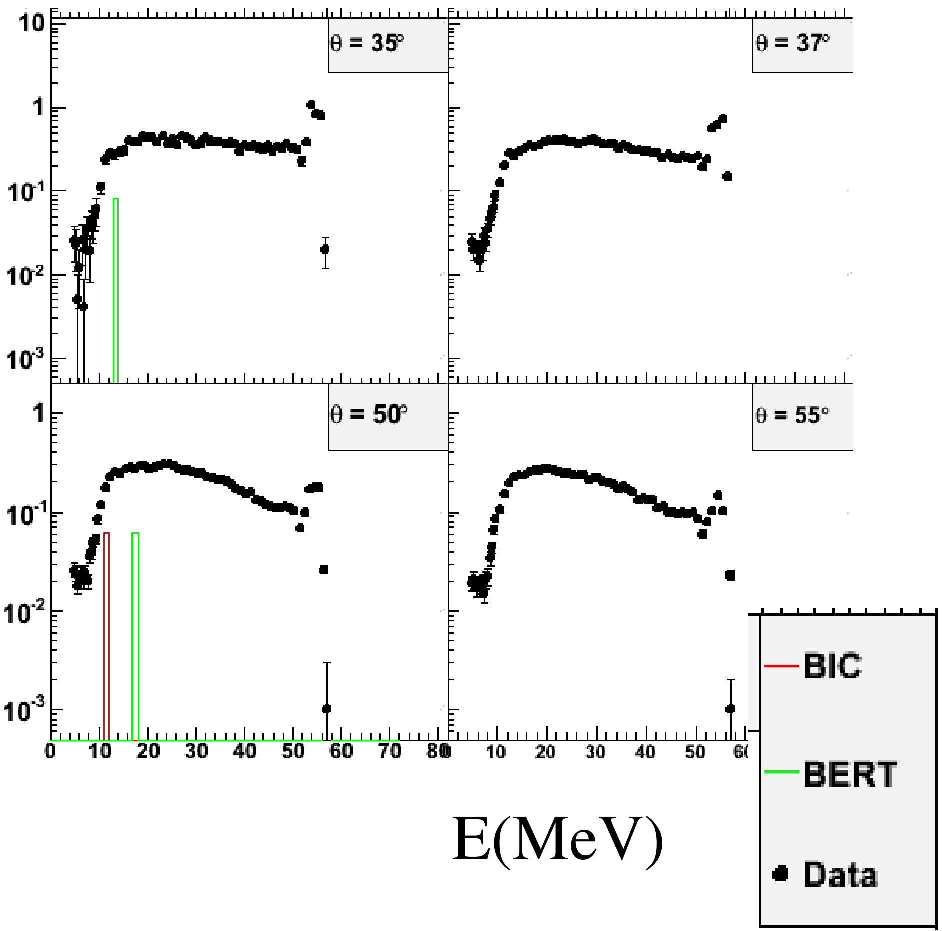
- The benchmark includes nucleon-induced reactions on nuclei from carbon to uranium
  - Energy range: 20 MeV to 3 GeV
- Geant4 has participated in benchmarking
  - In parallel with intensive model improvement,
- This benchmarking has triggered a series of critical model improvements
  - in pre-compound & de-excitation models in Geant4

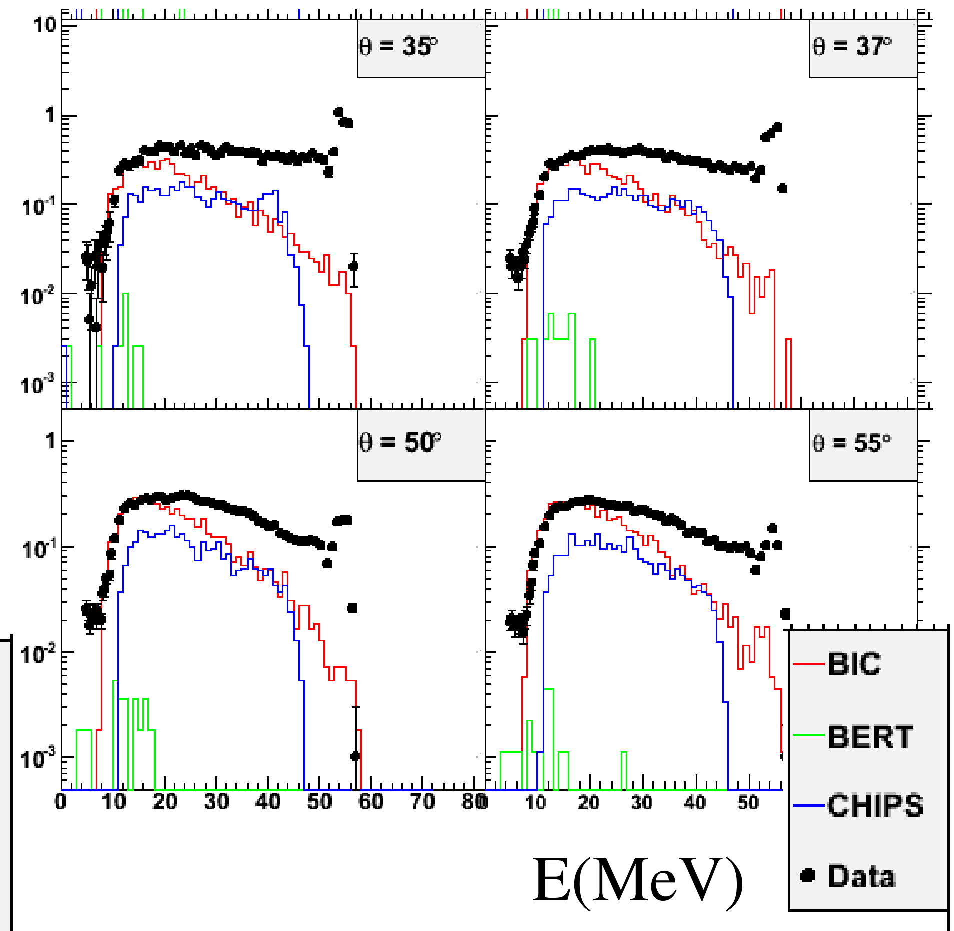
Light cluster emission: improvement

Pb (p, d) at 63 MeV

BEFORE 9.2

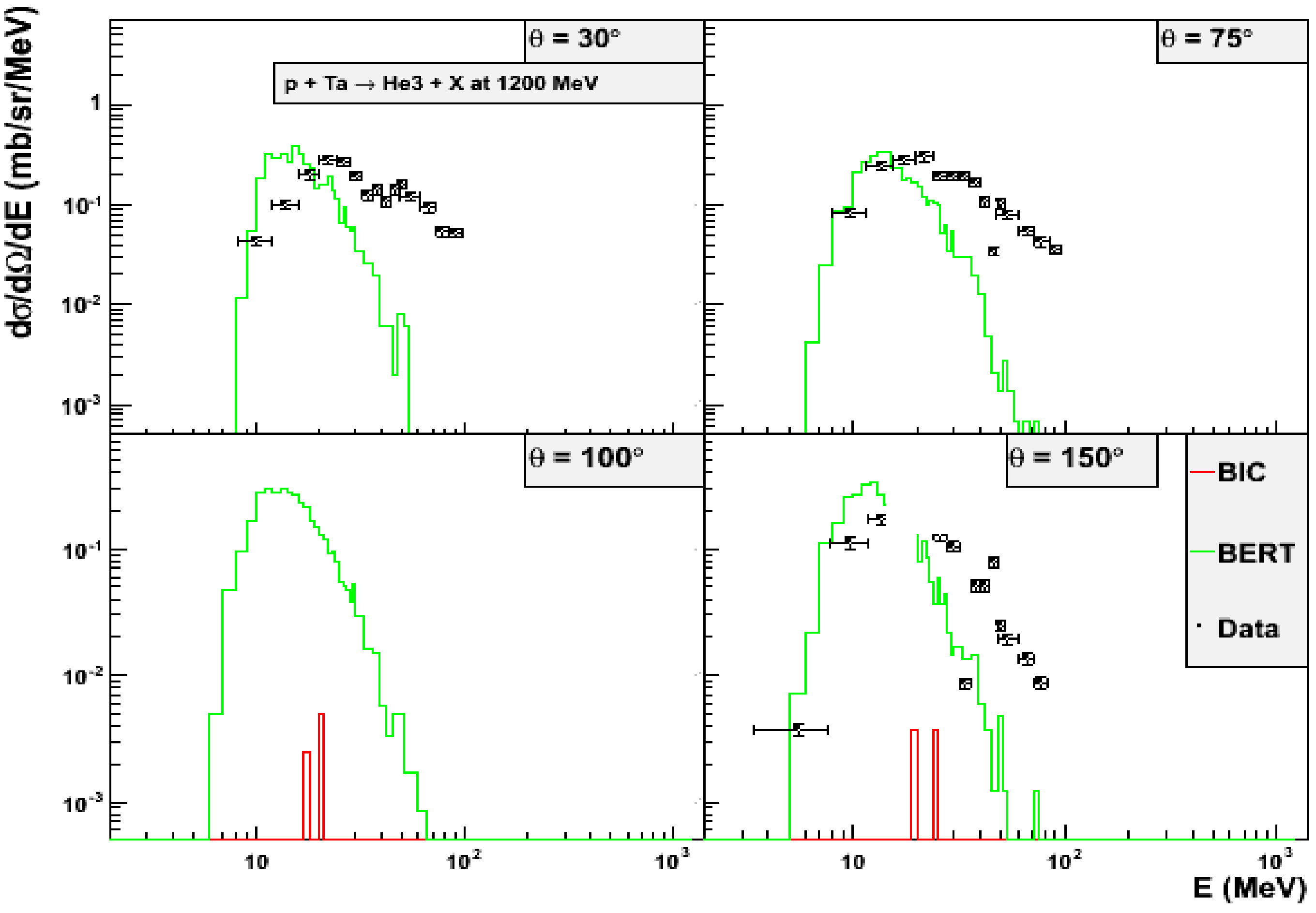
NOW 9.2p01





Light cluster emission

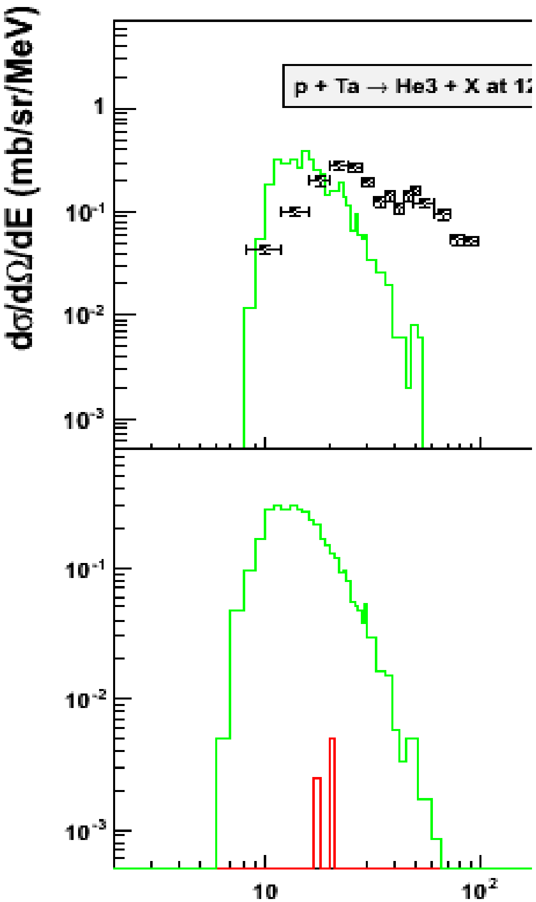
BEFORE 9.2

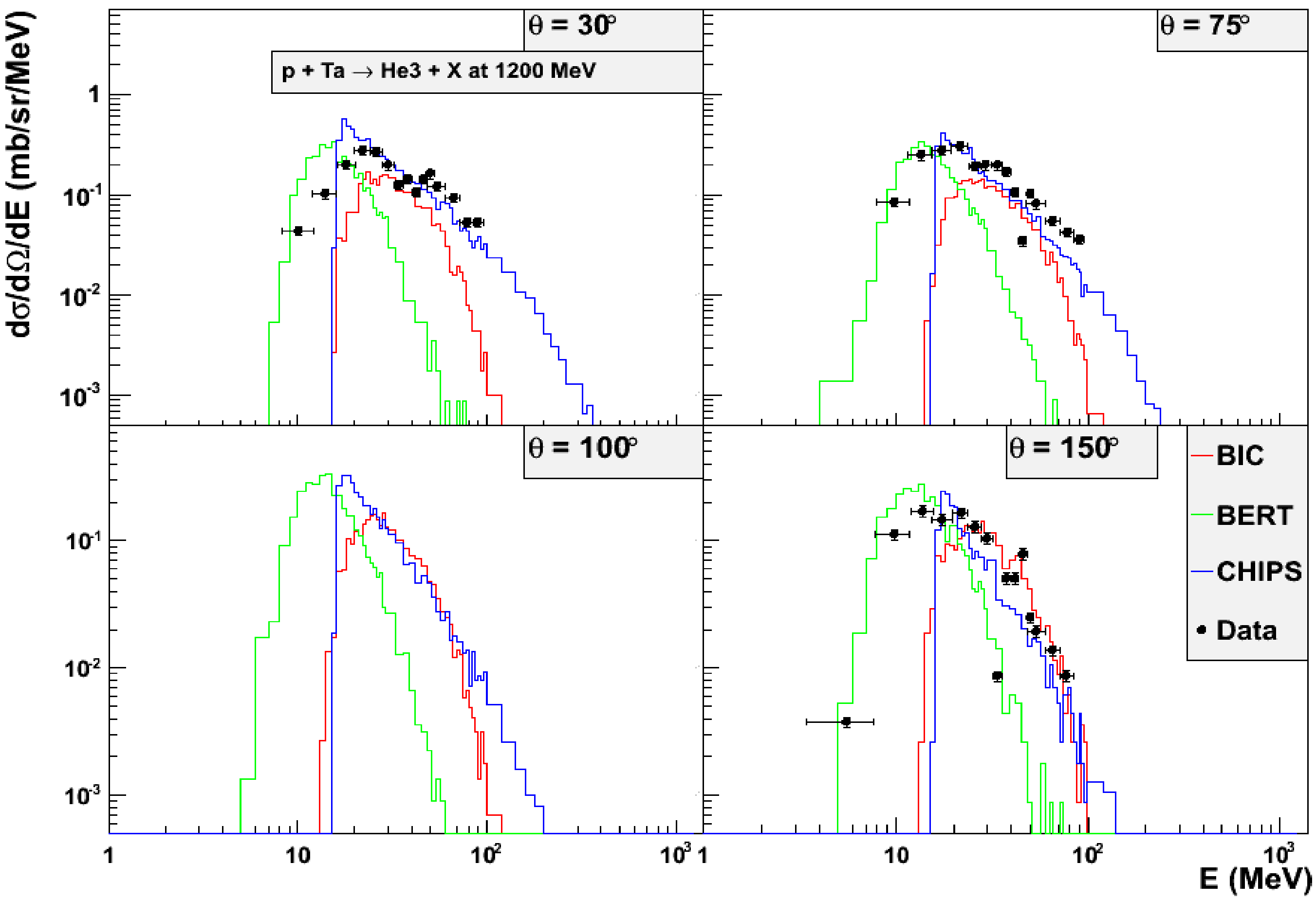


Light cluster emission

BEFORE 9.2

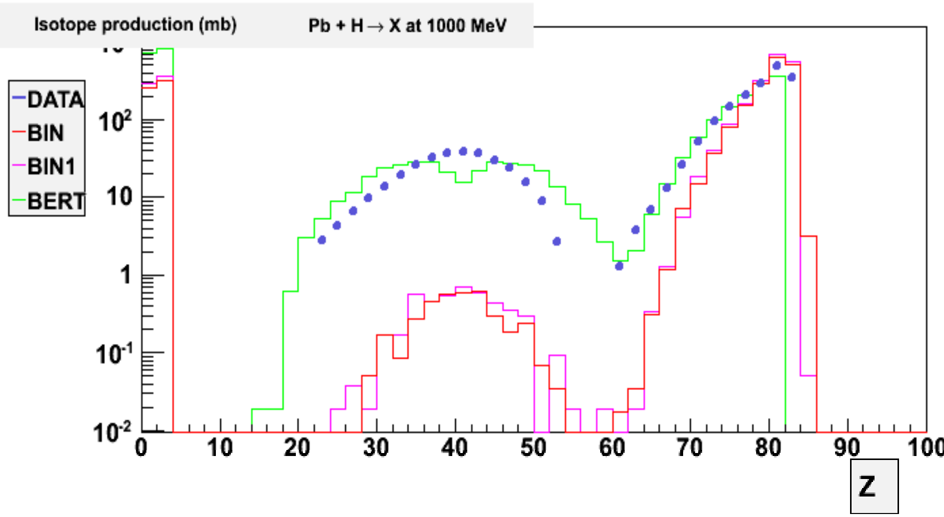
NOW 9.2p01

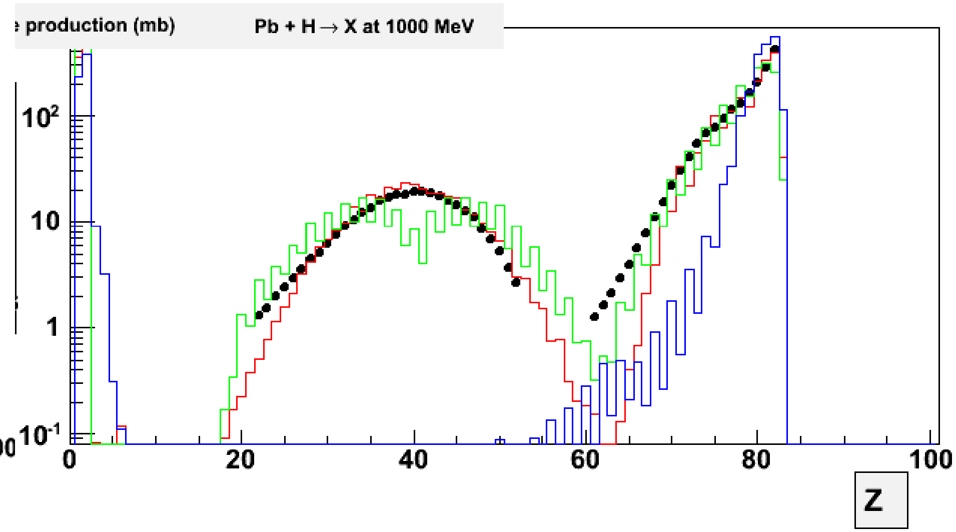


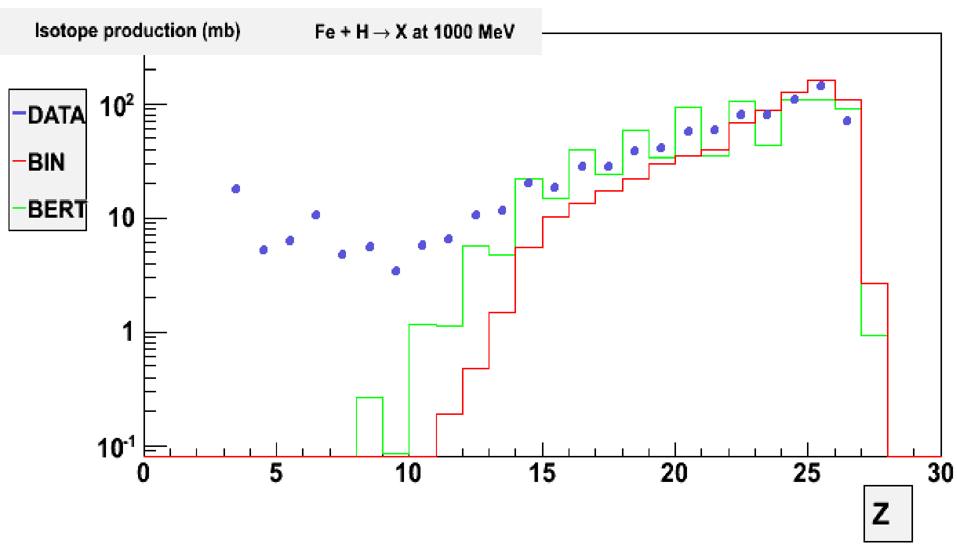


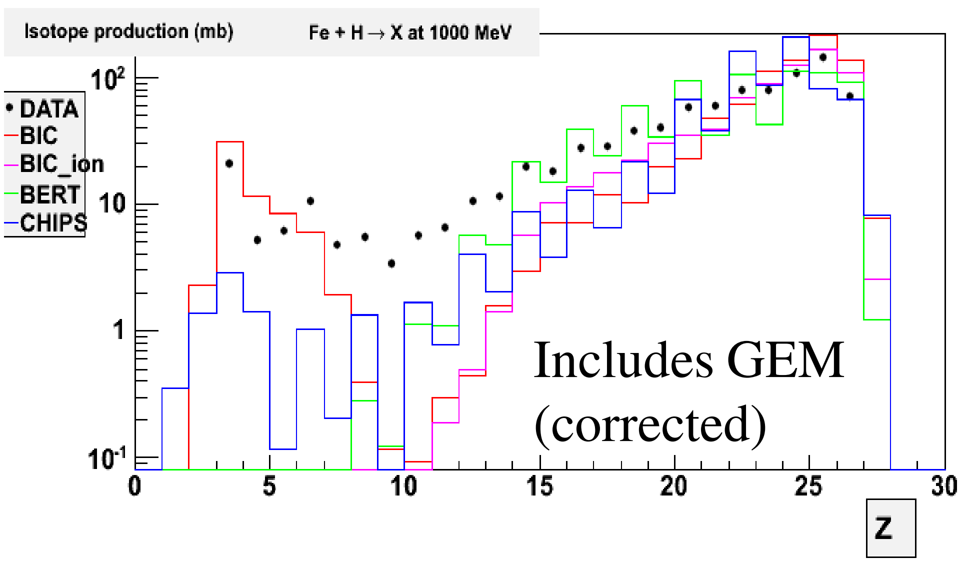
Isotope production at 1000 MeV in inverse kinematics

BEFORE 9.2p01 NOW 9.3









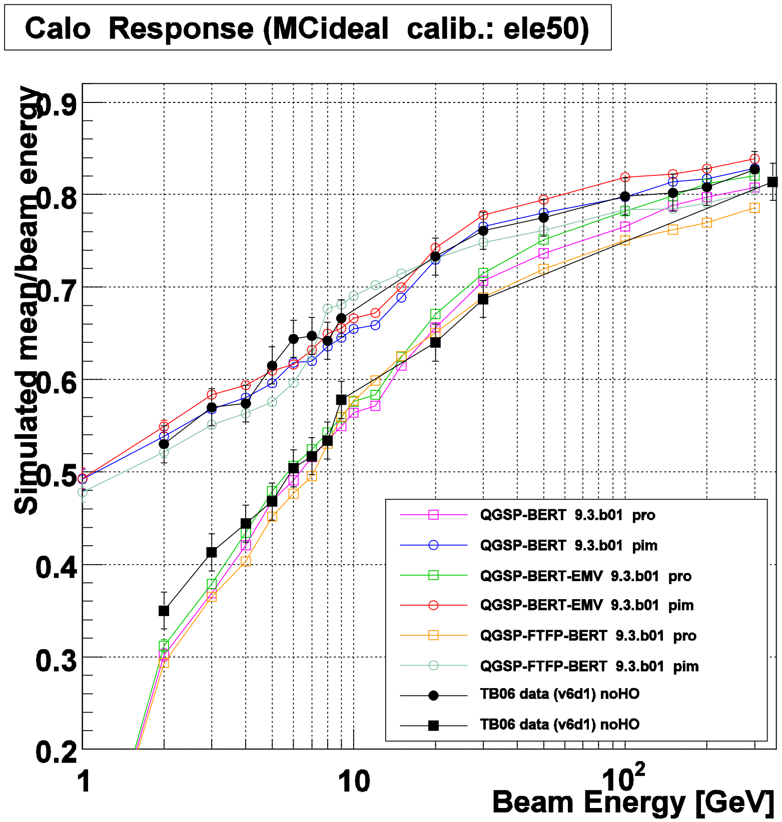
Progress (1)

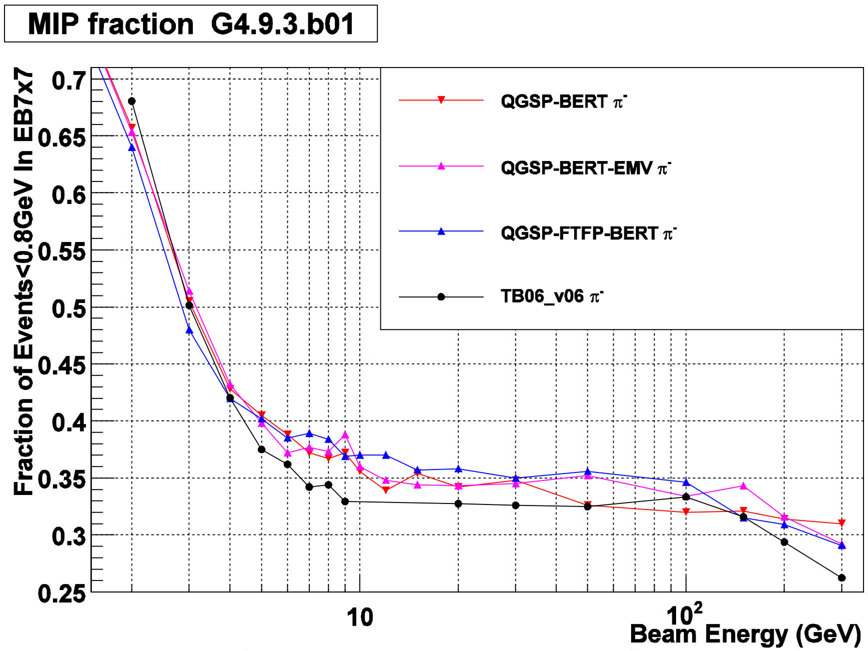
- IAEA spallation validation exercise
  - was very helpful in identifying and fixing problems with G4Precompound, Binary and Bertini cascade models
    - improved low energy behavior (< 200 MeV)
- Shower shapes
  - improved treatment of quasi-elastic scattering in nuclei has solved most problems with shower shapes
- Comparison with other codes
  - A measure of progress in this area
    - Some Geant4 hadronics members becoming Fluka users and learning to use code;
    - Preliminary comparisons with Dubna Cascade, UrQMD.

Progress (2)

- Model transition region
  - we now have a much better understanding of what is going on in the energy regions between models in a physics list
    - simplified calorimeter studies of energy partition among particle types
  - we are beginning to understand how to extend cascade models higher in energy, string models lower in energy
    - using Binary, Bertini and CHIPS models as “back-ends” for string models
    - shutting off Bertini cascade at high energies
    - => will allow the removal of the energy non-conserving LEP models from some physics lists

Validation with CMS TB Data





Test done with Geant4 9.3.beta01 for 3 physics lists: QGSP_BERT, QGSP_BERT_EMV, QGSP_FTFP_BERT

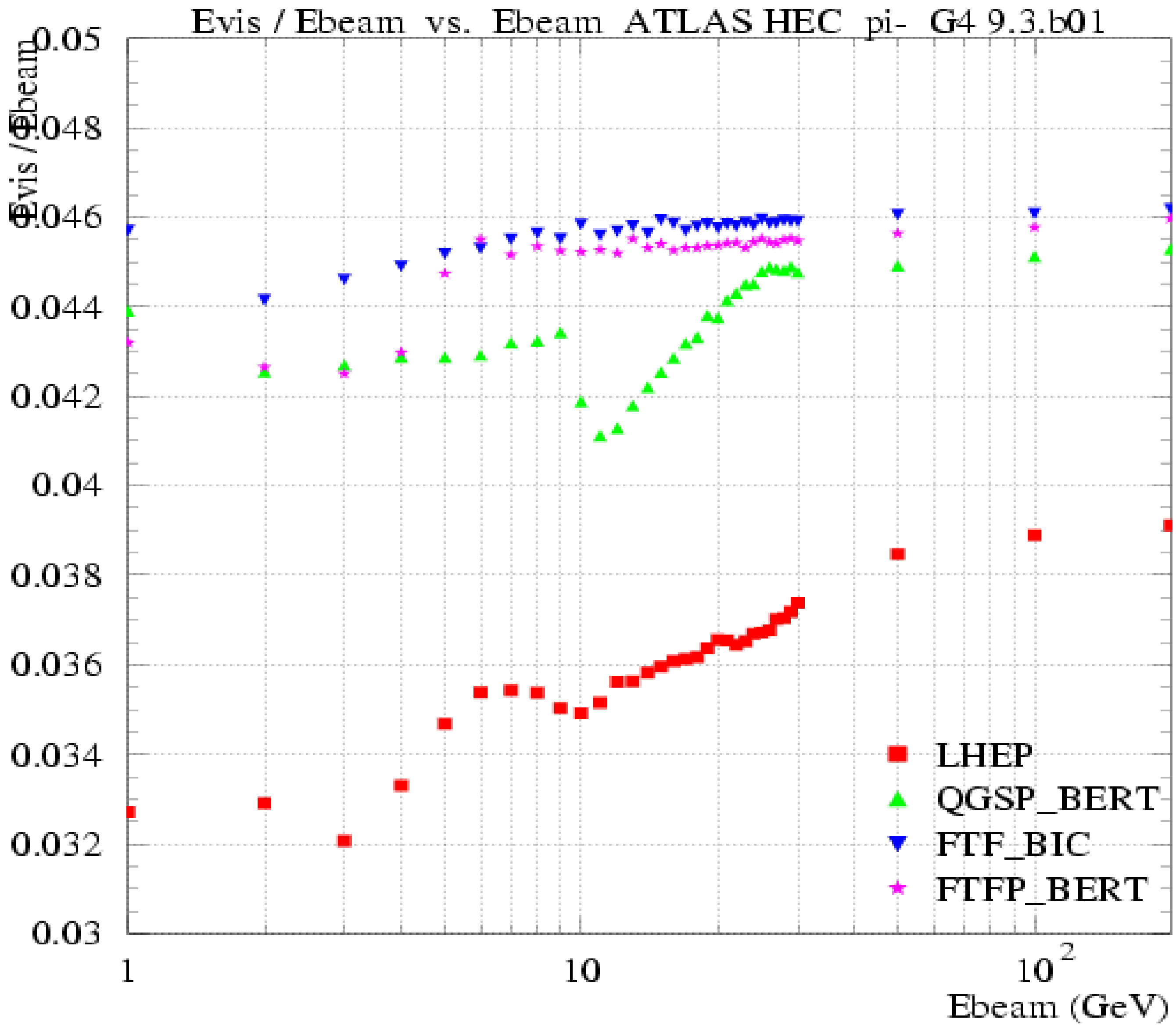
- CMS measured response of the combined calorimeter with identified pion and proton beams of momenta between 2 and 350 GeV/c
- Measures mean response and resolutions separately with all events and MIP like signal in the ECAL
- Also measures the fraction of MIP events as a function of beam energy

Challenges (1)

- Energy non-conservation in some physics lists
  - LEP, HEP models used in cases where no other physics list applies
    - these models do not conserve energy – even on average
- Model transition region
  - discontinuities as one moves in energy from one model domain to another
    - multiplicity
    - mean energy per particle type
    - angular distributions
  - energy response & resolution affected
    - important for calibration, jets, energy scale
      - For LHC and ILC calorimeters

Model transition region

Energy response in a simplified **Cu-LAr** calorimeter

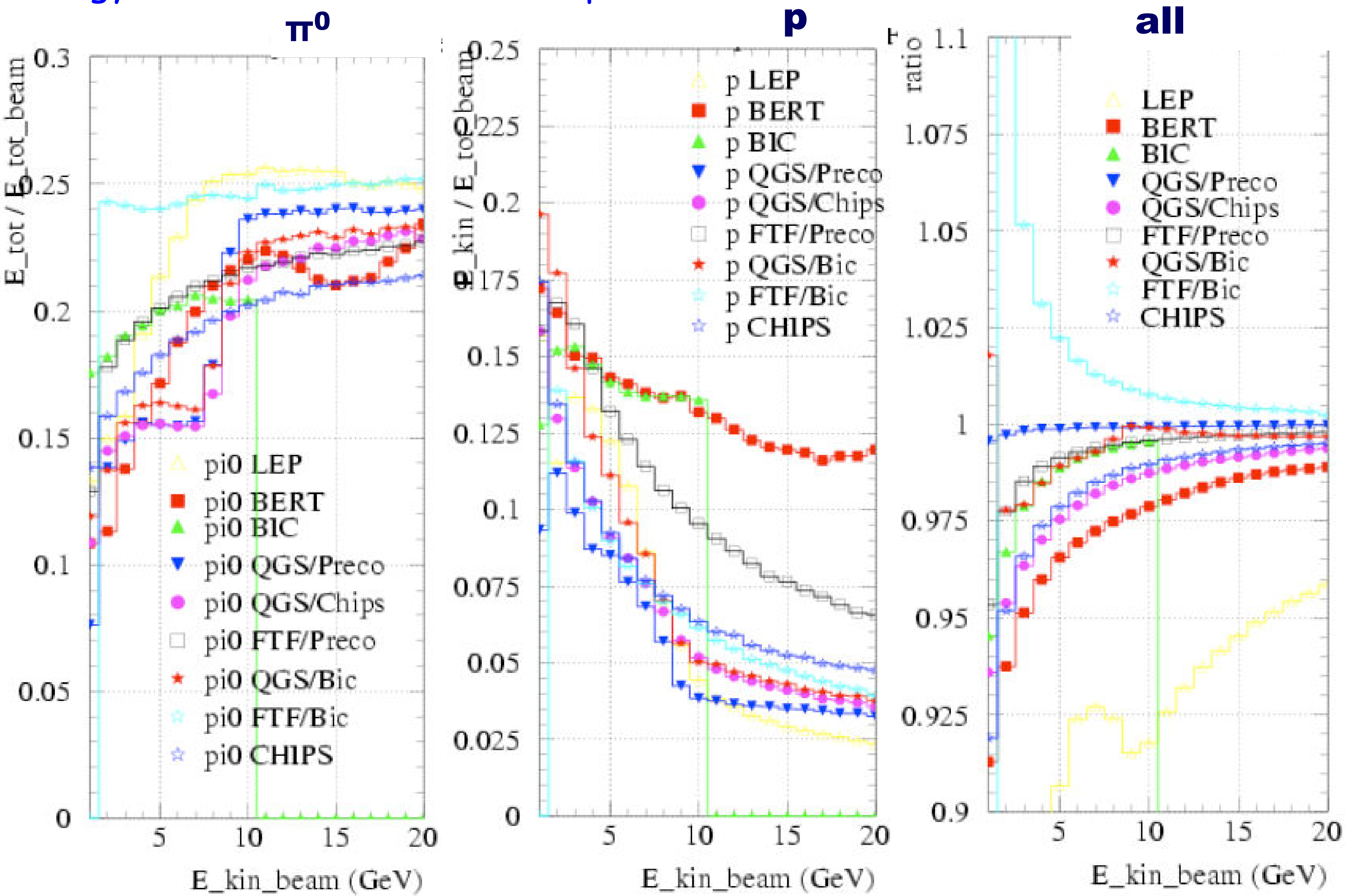


QGSP_BERT uses (in GeV)

- Bertini: 0-9.9
- LEP: 9.5-25
- QGS/P: 12+

Origin of the problem

Energy fractions of secondaries produced in π^- Fe inelastic interactions



Challenges (2)

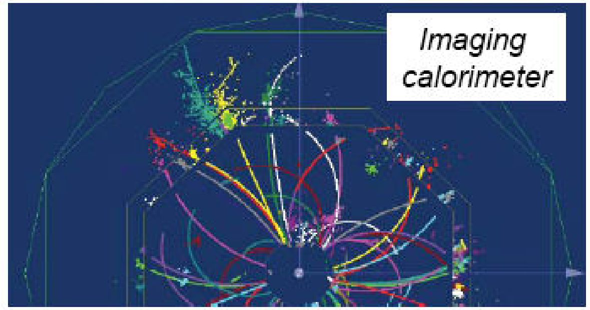
- Low energy behaviour
  - Incident p and n below 200 MeV
    - large differences between models in number of these particles predicted
    - more work required on low energy end of cascade and nuclear physics
- New aspects important for ILC calorimeter
  - High granularity requires good lateral profile, ..
- Comparison with other codes (MCNP, Fluka, ...)
  - has been a challenge in the past
    - few people expert in more than one code => difficult to do comparisons
    - not many opportunities for head-to-head comparisons

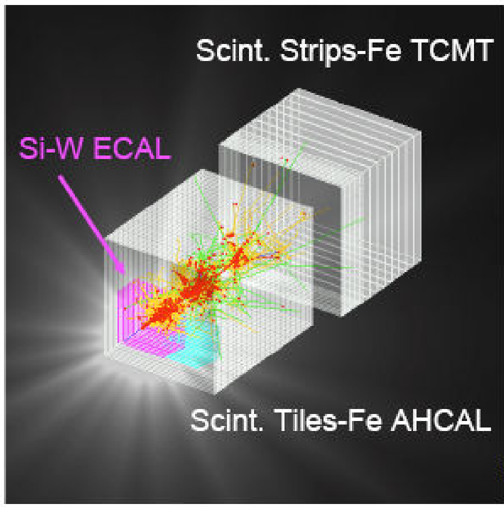
CALICE: from MC to reality

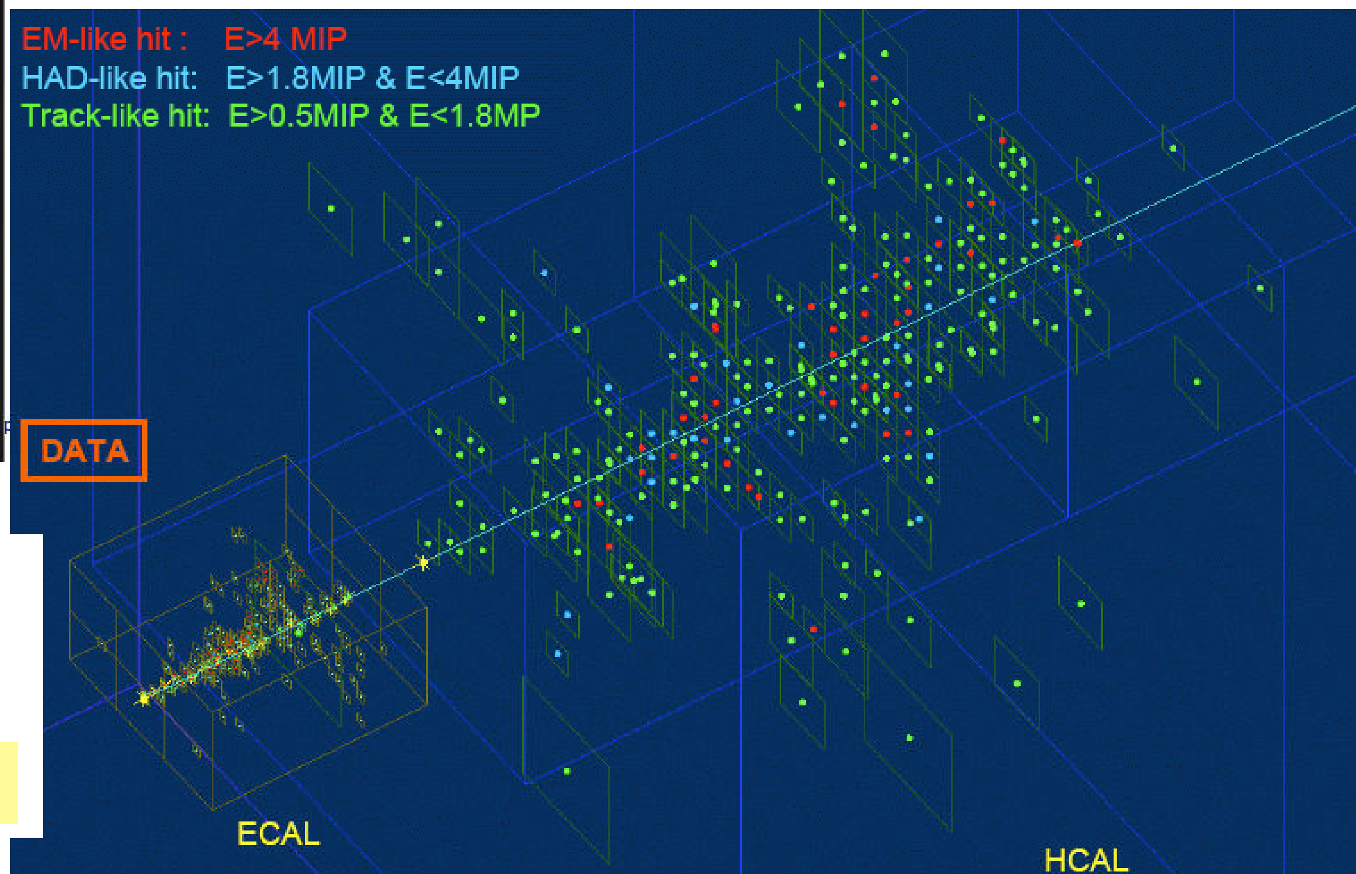
CAlorimeter for the LInear Collider Experiment

Final goal:

A high granularity calorimeter optimised for the Particle Flow measurement of multi-jets final state at the International Linear Collider







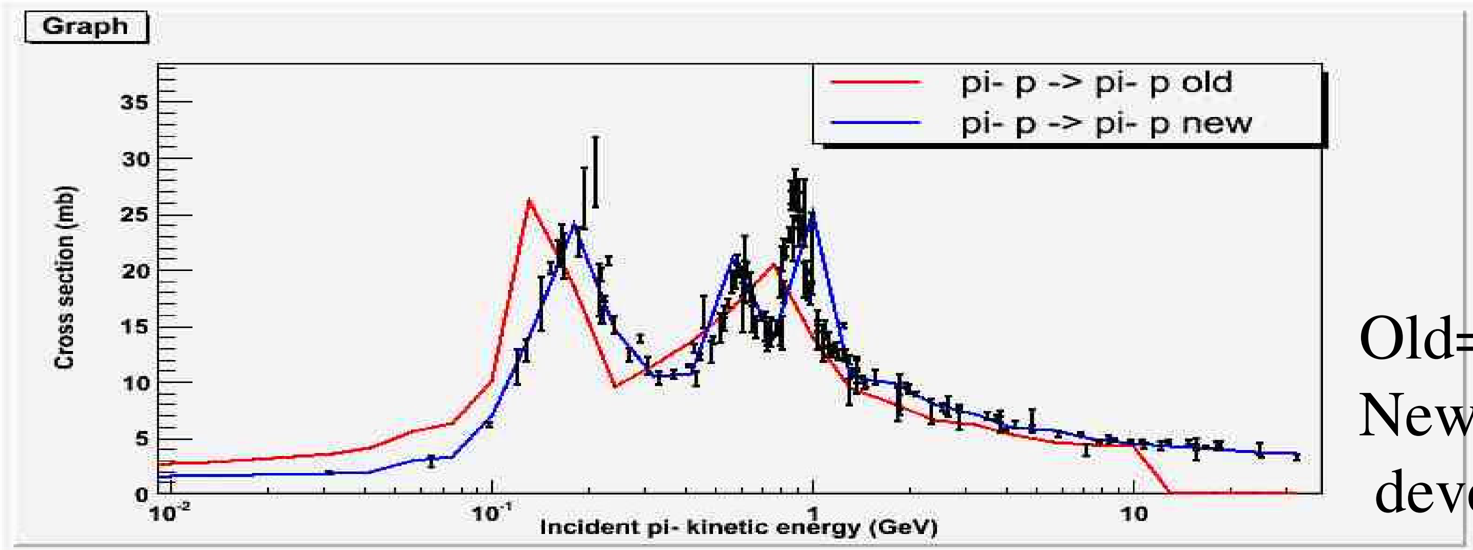
Intermediate task:

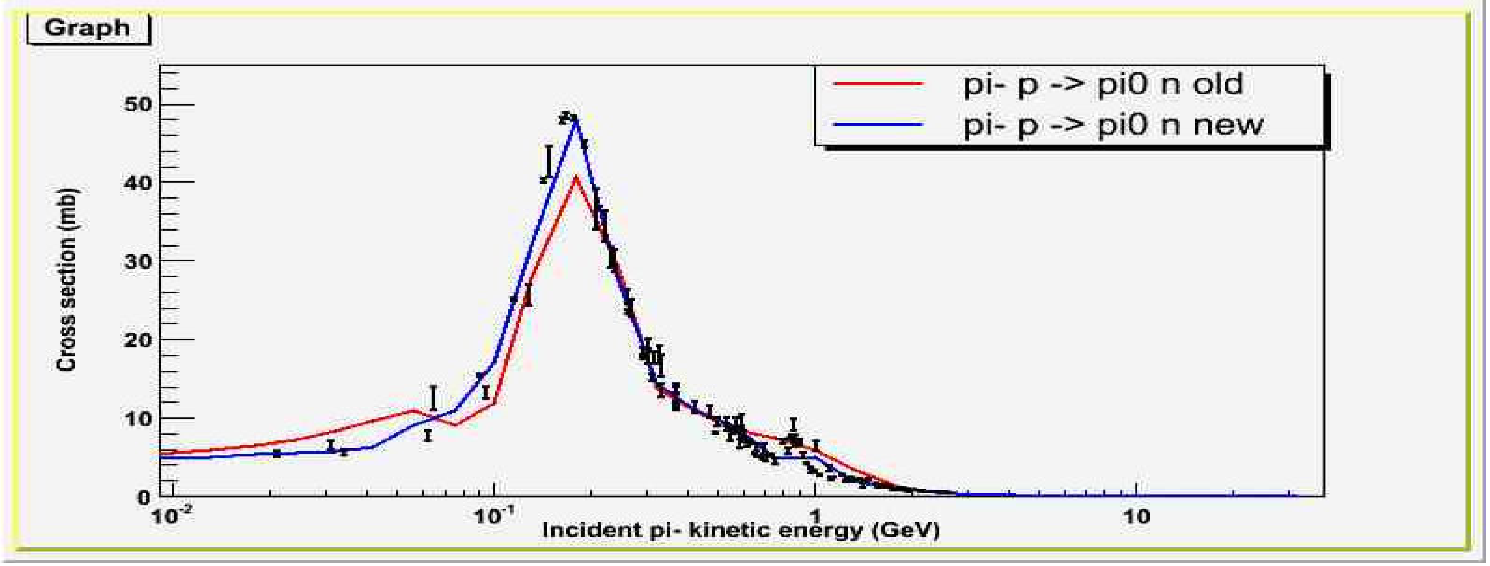
Build prototype calorimeters to
- Establish the technology
- Collect hadronic showers data with unprecedented granularity to
  - tune reconstruction algorithms
  - validate existing MC models

Developments in Bertini Cascade

- Coulomb barrier added in cascade and precompound phases
- Completed review and correction of total and partial cross sections used in intra-nuclear cascade
  - nucleon-nucleon, pion-nucleon
  - 95 cross sections reviewed from 0 to 30 GeV
- Added partial cross sections for production of strange particle pairs from p-p and π-p interactions
  - ΛK, ΣK, KK
- Investigating “shutting off” cascade at energies above 3 GeV
  - using trailing effect, formation length

Corrected Bertini Cross Sections: $\pi^- p$ -> 2 body, before and after



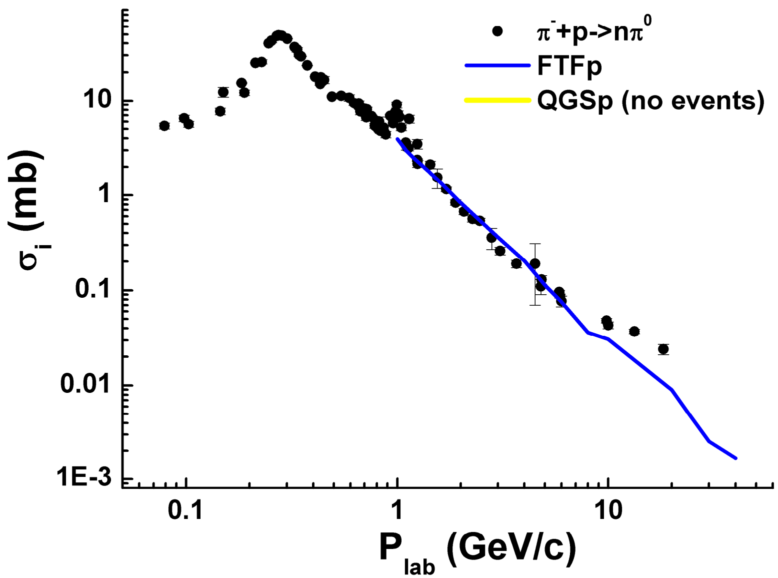


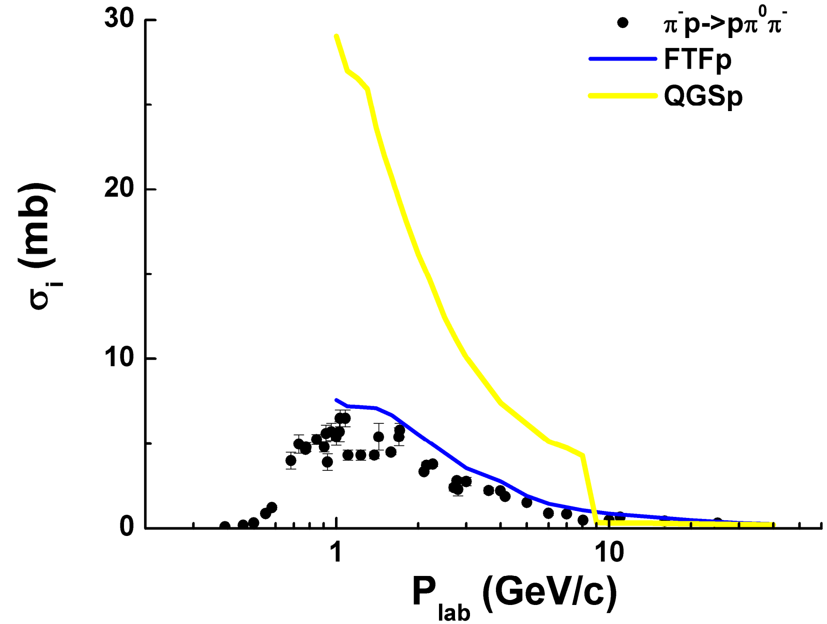
Old=9.3 beta
New= recent development

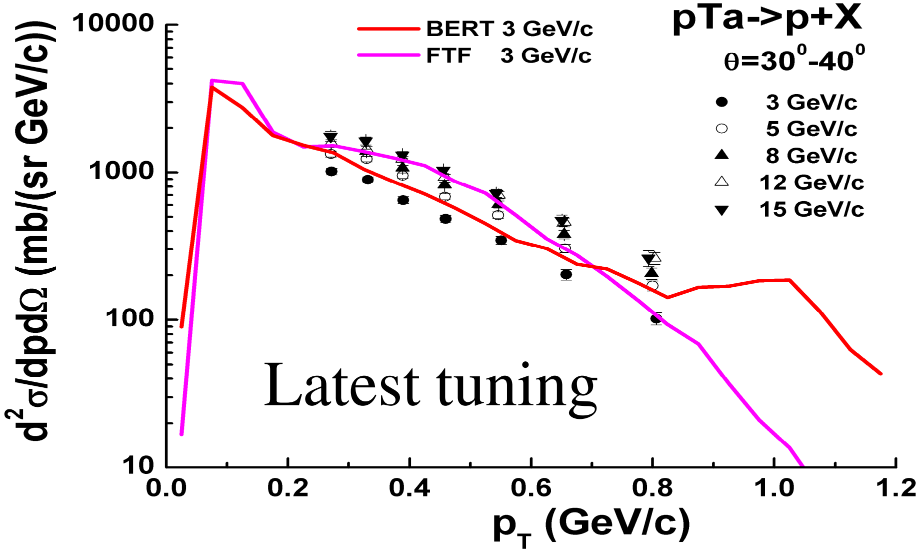
FTF: The FRITIOF Model Implementation in Geant4

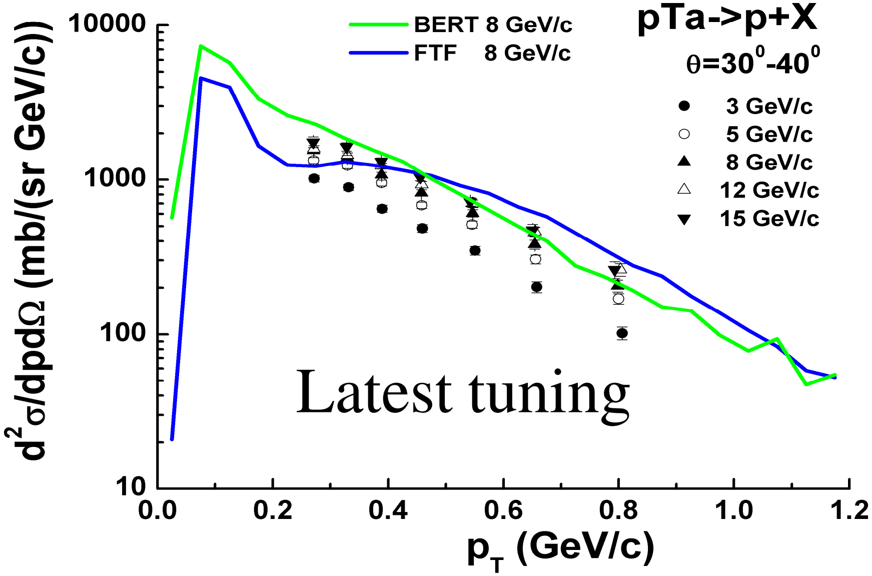
- Alternative string model starting at ~3 GeV
  - Potential to improve transitions
- Can be coupled with the Binary model (= FTF_BIC)
  - provides a smoother transition to cascade models in the most problematic energy region (3-20 GeV)
    - (Simple transition from Bertini to FTF still has bump 3-5 GeV)
- Key model details:
  - Hadron-hadron interactions are modelled as binary reactions
  - Multiple collisions are calculated in Glauber approach
    - including elastic re-scatterings of hadrons.
  - Excited states are considered as QCD-strings
    - the LUND model is used for their fragmentation.

The FRITIOF Model: validation & tuning









Model improvements in pre-equilibrium and de-excitation models

- Fixed errors in pre-equilibrium
  - in the widths of light cluster emission

- Fixed errors in equilibrium de-excitation
  - fission widths
  - excitation energies of fragments in Fermi Break-Up.
  - emission widths in Generalized Evaporation Model (GEM).

- Tuned parameters of fission.

- New “hybrid “ model :
  - Weisskopf-Ewing for n,p,d,t,^{3}He, ^{4}He
  - GEM for heavier ejectiles (A<29,Z<13).

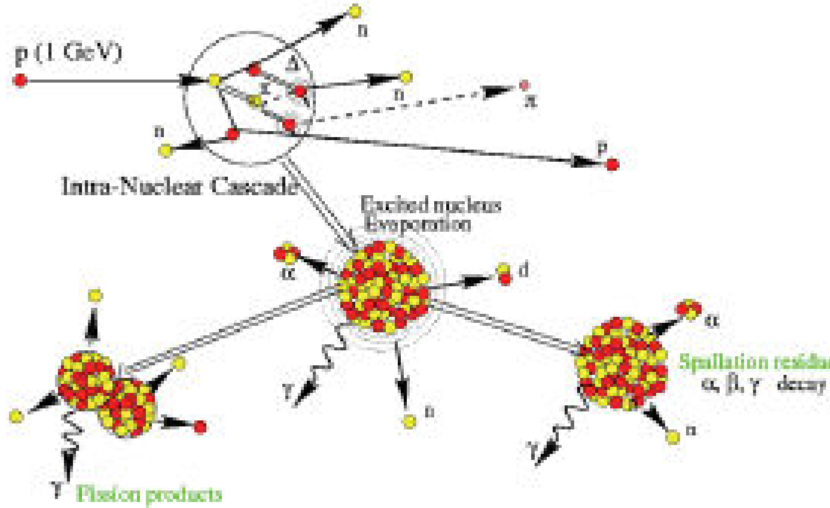
Improvements in G4QMD

- Improved nuclear fragment creation
  - Using detailed GEM de-excitation model (via physics list)
    - Default is now G4GEM
  - Option of FRAG mode in cascade phase in order to obtain best fragment production
    - Default is OFF, i.e. optimized for energy spectra of secondary nucleons
- Corrected meson absorption in reaction phase
  - Used to break (E,p) conservation at high energy
    - Corrected in V9.2 patch 2.
- Extended for use in additional reactions
  - proton, neutron and pion incident
- Used first corrections of GEM

INCL intra-nuclear cascade and ABLA de-excitation

Projectile	p, n, π, deuteron, triton, He3, alpha
Energy range	150 MeV - 3 GeV
Target nuclei	Carbon - Uranium

Table: Model validity range



Interactions (isospin dependence):

NN ⟶ NN

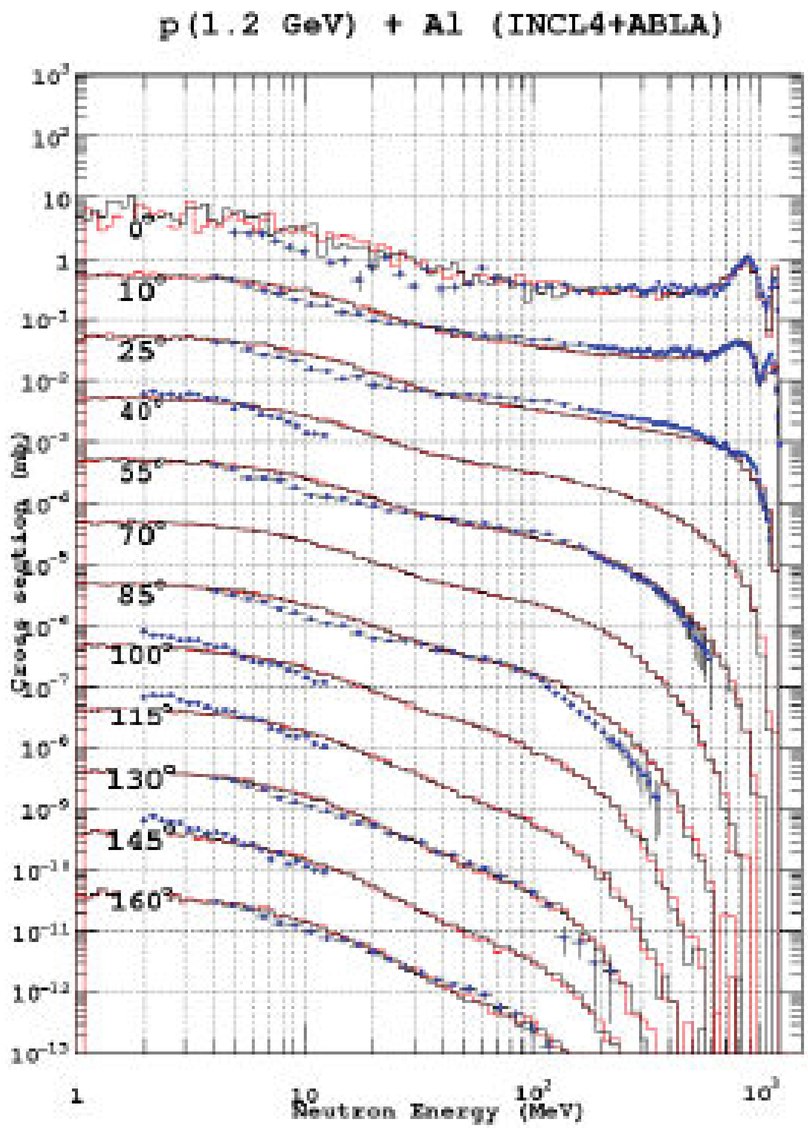
NN ⟶ NΔ

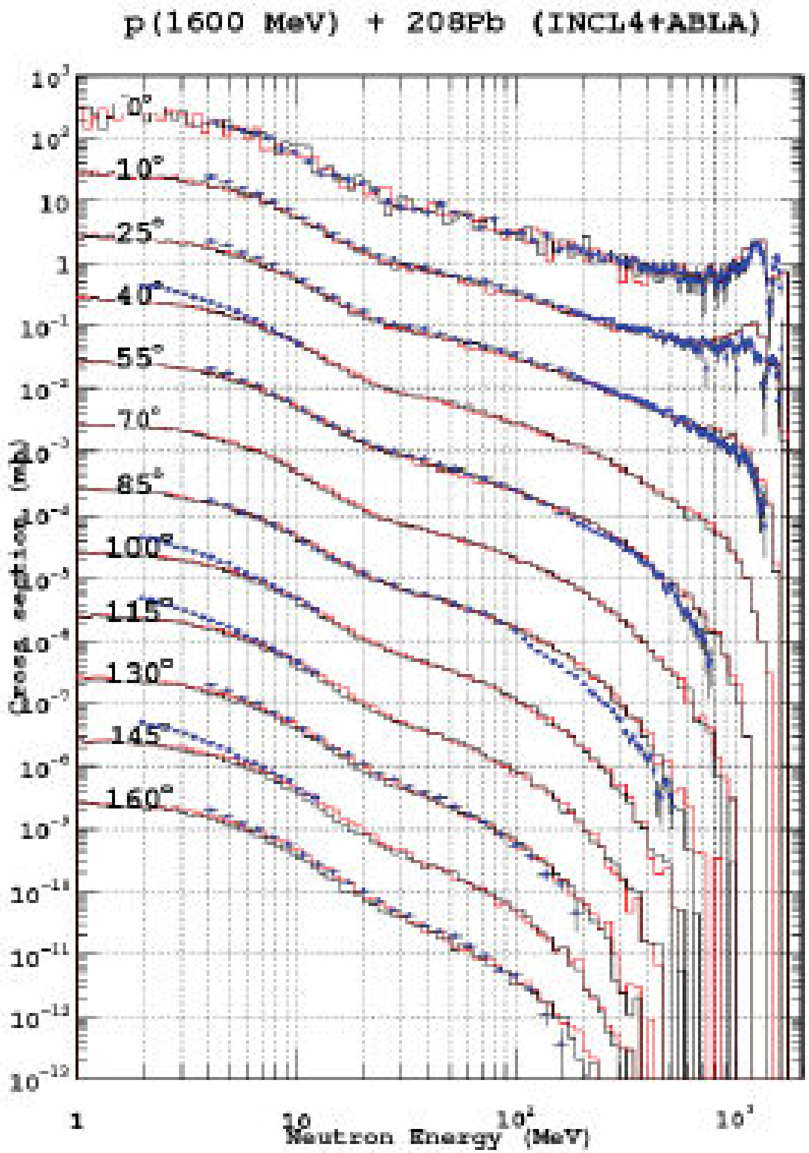
NΔ ⟶ NN
NΔ ⟶ NΔ
ΔΔ ⟶ ΔΔ

No NΔ ⟶ ΔΔ
Δ = Δ33 (1232 MeV)
(No other baryonic resonances)
No πN ⟶ πN
No πN ⟶ 2πN,
but Δ ⇄ πN

- INCL tracks particles (p, n, π, Δ) and their binary collisions.
- Stop the cascade when stopping time is reached and treat the remnant nucleus with ABLA de-excitation (evaporation of p, n, α or fission).

INCL/ABLA: Double-differential neutron energy spectra





SUMMARY

- Systematic validation effort carried out.
  - Extensions undertaken and ongoing.
- Deficiencies due to transitions between model
  - Found and being investigated
  - Different approaches to address them are underway.
- Model improvements being carried out
  - Fixes made and retuning of some models
  - Further improvements under way.
- Thin target comparisons are benchmarks for models
  - Thick target, e.g. calorimeter studies used to confirm
- New challenge(s)
  - Next generation (high granularity) calorimeter data (CALICE)