Granular Calorimeters for Geant4 Validation

Dennis Wright (SLAC)

IAS Workshop

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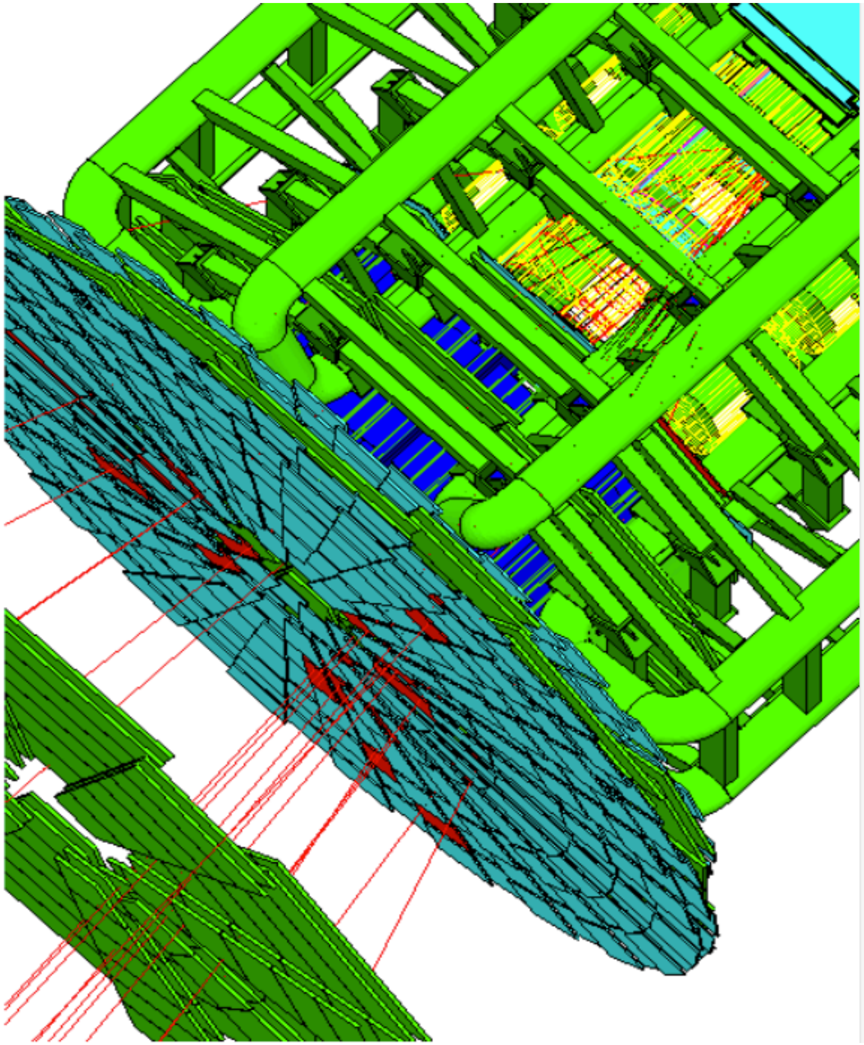
Introduction to Geant4

Geant4 Simulation Toolkit

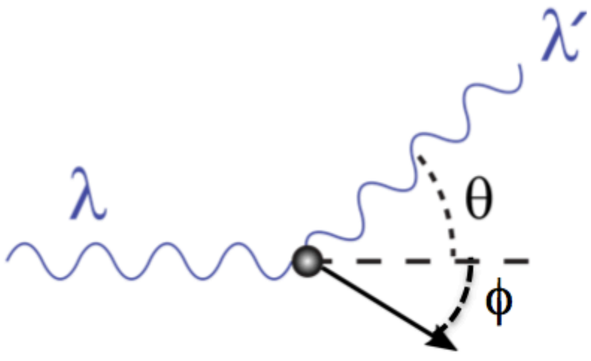
- A general purpose radiation transport code developed originally for use in HEP
  - also used extensively for space, medical and nuclear applications
- Offers most, if not all, functionality required for Monte Carlo simulations
  - kernel
  - geometry and navigation
  - physics processes
  - GUI and visualization drivers
- Flexible and extensible



Geant4 is a Toolkit; You Must:

- Build your own application using Geant4 components
  - Geant4 does not provide a main()
- Define your geometrical set-up
  - materials, volumes
- Define the physics you need
  - particles, physics processes
  - production thresholds
- Define how an event starts
  - primary track generation
- Extract the information you need from the simulation
- As well as, among other things
  - visualization of detectors, trajectories, physics output
  - use or extension of the User Interface

Geant4 is a Monte Carlo Code: Example



- Compton scattering

  $e^- \gamma \rightarrow e^- \gamma$

- Distance traveled before Compton scattering, l, is a random value

  Cross section per atom : $\sigma(E,z)$

  Number of atoms per volume : $n = \rho N_A / A$

  ρ : density, N_A : Avogadro number, A : atomic mass

  Cross section per volume : $\eta(E, \rho) = n\,\sigma$

- η is the probability of Compton interaction per unit length. $\lambda(E, \rho) = \eta^{-1}$ is the mean free path associated with the Compton scattering process.
- The probability density function $f(l)$

$$f(l) = \eta \exp(-\eta l) = \frac{1}{\lambda} \exp\left(-\frac{l}{\lambda}\right)$$

- With a uniformly distributing random number r on [0,1), One can sample the distance l.

$$l = -\lambda \ln(r) \qquad 0 \leq r < 1$$

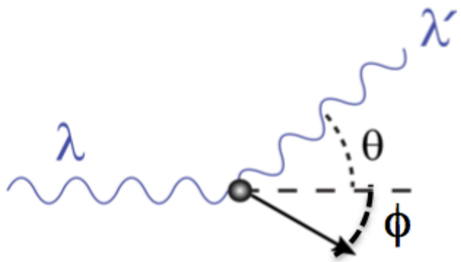
Geant4 is a Monte Carlo Code: Example

- The relation between photon deflection (θ) and energy loss for Compton scattering is determined by the conservation of momentum and energy between the photon and recoiled electron.

$$h\nu = \frac{h\nu_0}{1 + \left(\frac{h\nu_0}{m_e c^2}\right)(1 - \cos\theta)},$$

$$E = h\nu_0 - h\nu = m_e c^2 \frac{2(h\nu_0)^2 \cos^2\phi}{(h\nu_0 + m_e c^2)^2 - (h\nu_0)^2 \cos^2\phi},$$

$$\tan\phi = \frac{1}{1 + \left(\frac{h\nu_0}{m_e c^2}\right)} \cot\frac{\theta}{2},$$



hν : energy of incident photon
hν₀ : energy of scattered photon
E : energy of recoil electron
mₑ : rest mass of electron
c : speed of light

- For unpolarized photon, the Klein-Nishina angular distribution function per steradian of solid angle Ω

$$\frac{d\sigma_c^{KN}}{d\Omega}(\theta) = r_0^2 \frac{1+\cos^2\theta}{2} \frac{1}{[1 + h\nu(1-\cos\theta)]^2} \left\{1 + \frac{h\nu^2(1-\cos\theta)^2}{(1+\cos^2\theta)[1+h\nu(1-\cos\theta)]}\right\}$$

$$= \frac{1}{2} r_0^2 \left(\frac{k}{k_0}\right)^2 \left(\frac{k}{k_0} + \frac{k_0}{k} - \sin^2\theta\right) \qquad (cm^2 sr^{-1} electron^{-1}),$$

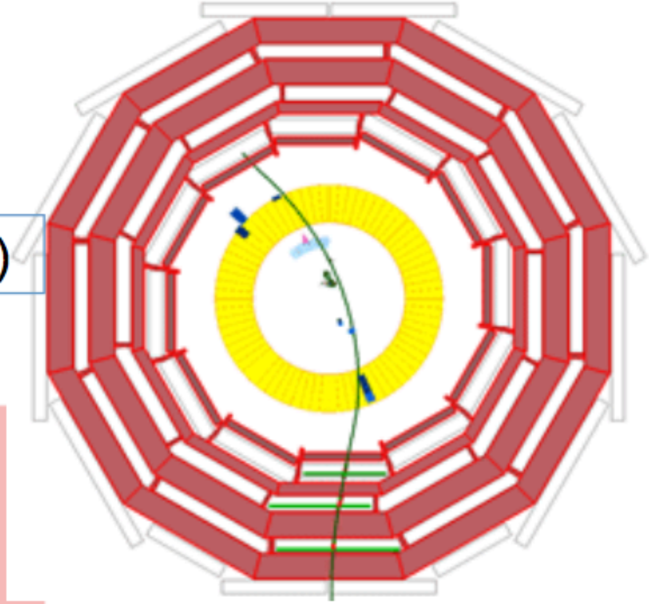
- One can use acceptance-rejection method to sample the distribution.

$$k_0 = \frac{h\nu_0}{m_e c^2}, \qquad k = \frac{h\nu}{m_e c^2}$$

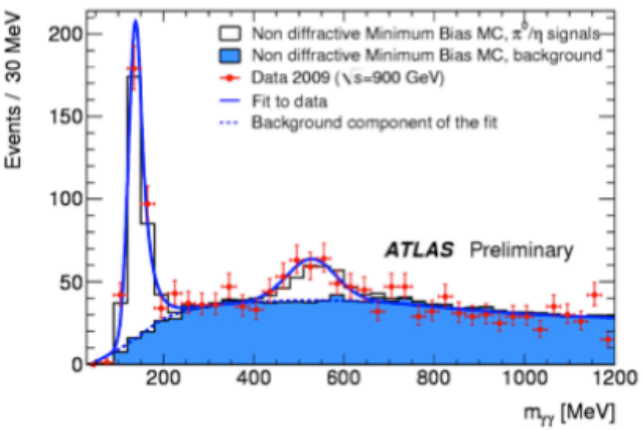
Geant4 has been successfully employed for

- Detector design
- Calibration / alignment
- First analyses

T. LeCompte (ANL)



GEANT4 Comparisons with the Calorimeters



Invariant mass of pairs of well-isolated electromagnetic clusters.

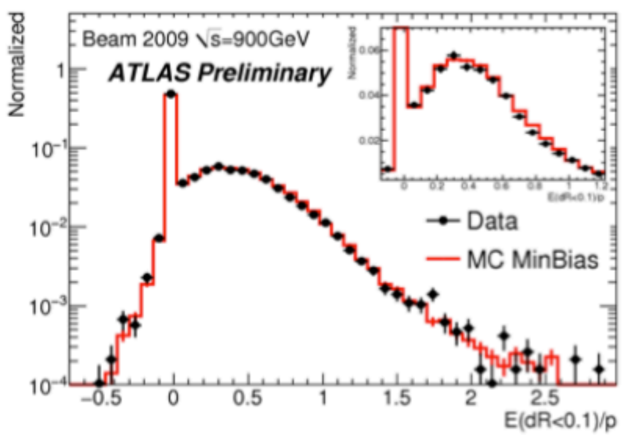
The π^0 mass is within 0.8 ± 0.6% of expectations.

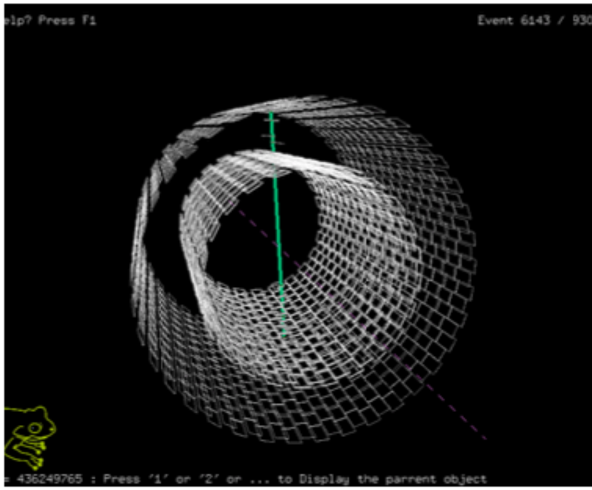
The η^0 mass is within 3 ± 2% of expectations.

The detector uniformity is better than 2%.

Response of the calorimeter to single isolated tracks. To reduce the effect of noise, topological clusters are used in summing the energy.

This plot agreed better than we ever expected. (I sent the student who made it back to make sure that they didn't accidentally compare G4 with G4.

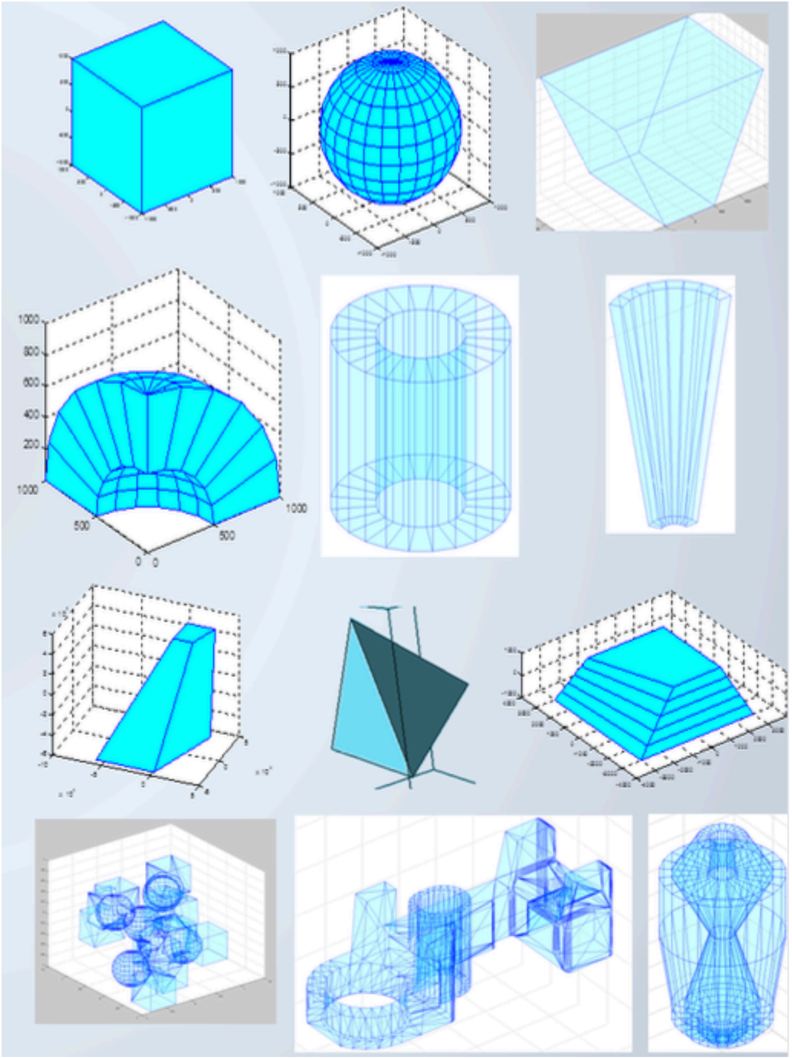




Figures from CMS

Geometry

- Large number of geometry primitives available
    - G4Box, G4Tubs, G4Cons, G4Trd, etc.
- Specific solids
    - G4Polycone, G4Hype, …
- Tessellated solid
- Boolean solids
- User builds detector by combining, filling with materials and placing these solids in a mother volume
    - certain volumes can then be made sensitive



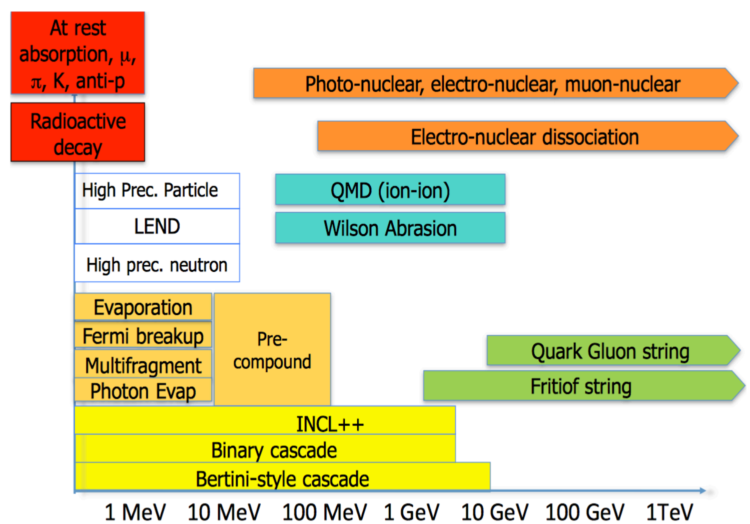
Physics

- In Geant4 there is not just one all-purpose set of physics
  - user may customize
- Geant4 offers electromagnetic, hadronic and decay physics
  - for almost every physics process, alternative cross section sets and physics models are offered
- User must validate combination he chooses
  - Geant4 validates the components and some combinations

EM

- Standard
  - γ, e± up to 100 TeV
  - hadrons up to 100 TeV
  - ions up to 100 TeV
- Muons
  - up to 1 PeV
  - energy loss propagator
- X-rays
  - X-ray and optical photon production proc.
- High-energy
  - processes at high energy (E>10GeV)
  - physics for exotic particles
- Polarisation
  - simulation of polarized beams
- Optical
  - optical photon interactions
- Low-energy
  - Livermore library γ, e- from 10 eV up to 1 GeV
  - Livermore library based polarized processes
  - PENELOPE code rewrite , γ, e- , e+ from 100 eV up to 1 GeV (2008 version)
  - hadrons and ions up to 1 GeV
  - atomic de-excitation (fluorescence + Auger)
- Geant4-DNA
  - microdosimetry models for radiobiology (Geant4-DNA project) from 0.025 eV to 10 MeV
- Adjoint
  - New sub-library for reverse Monte Carlo simulation from the detector of interest back to source of radiation
- Utils
  - general EM interfaces

HAD



Physics Lists

Where physics models are collected and assigned to particles

Custom designed for each application

Two main components:

Electromagnetic and hadronic

For most calorimeter applications "standard" EM physics is chosen

Main difference comes with choice of hadronic models

"Backbone" of hadronic component

FTFP_BERT physics list (original)

In order to get agreement with measured shower shapes, transition between models is changed (ATLAS)

Other physics lists add other models

QGS, BIC, etc.

Geant4 Validation Strategy

Thin target scattering data

Most of our validation depends on this

Models are tuned on it, since it mostly tests single interactions

Lots of this kind of data available, but significant gaps in coverage

Thick target scattering data

A tougher test as it depends on multiple interactions

Data are often not as reliable as thin target due to systematic errors

Calorimeter data most stringent test of all

Effectively thick target

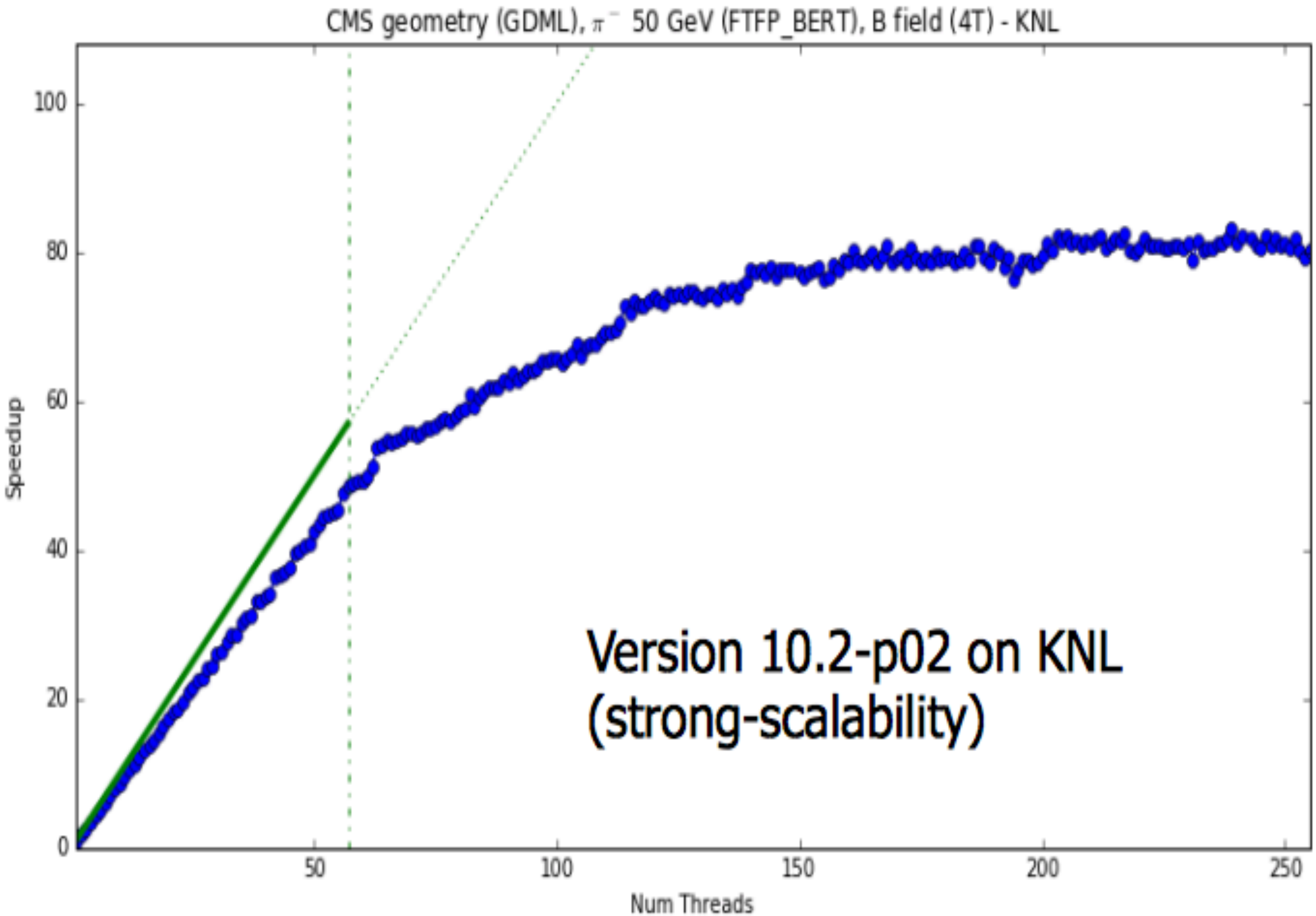
Shower shapes!

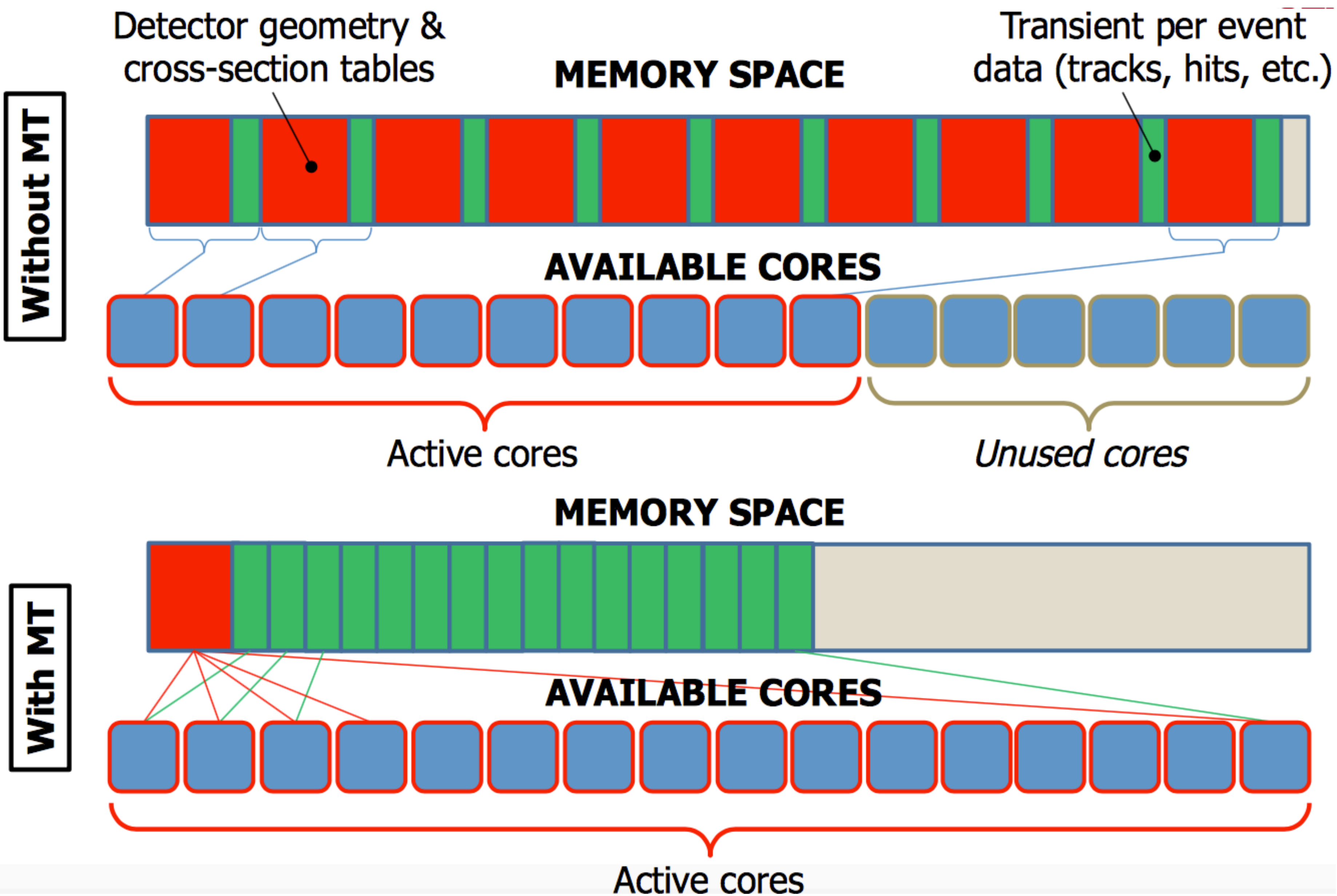
Physics lists are tuned on this data

Test beam data

Very useful calorimeter data relies on single-particle, mono-energetic beams on segments of calorimeters

Geant4 is Multithreaded




Without MT
Detector geometry & cross-section tables
MEMORY SPACE
Transient per event data (tracks, hits, etc.)
AVAILABLE CORES
Active cores
Unused cores
With MT
MEMORY SPACE
AVAILABLE CORES
Active cores

Geant4 General Paper (2016)

ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 835, 1 November 2016, Pages 186–225

Recent developments in GEANT4

J. Allison[a, b], K. Amako[c, a], J. Apostolakis[d], P. Arce[e], M. Asai[f], T. Aso[g], E. Bagli[h], A. Bagulya[i], S. Banerjee[j], G. Barrand[k], B.R. Beck[l], A.G. Bogdanov[m], D. Brandt[n], J.M.C. Brown[o], H. Burkhardt[d], Ph. Canal[j],

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https://doi.org/10.1016/j.nima.2016.06.125

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Recent Calorimeter Results

Collision Data

- The level of disagreement between data and MC is between 2 to 5% depending on the region of the detector as well as the physics list used

Mean level of disagreement between MC and data

	$(E_{7x7}+H_{3x3})/p$ 10.0.p02	$(E_{7x7}+H_{3x3})/p$ 10.2.p02	$(E_{11x11}+H_{5x5})/p$ 10.0.p02	$(E_{11x11}+H_{5x5})/p$ 10.2.p02
Barrel 1	(1.1±0.4)%	(2.4±0.4)%	(2.5±0.4)%	(2.6±0.4)%
Barrel 2	(3.4±0.4)%	(3.6±0.4)%	(1.9±0.4)%	(2.2±0.4)%
Transition	(3.7±0.5)%	(4.9±0.5)%	(1.6±0.5)%	(2.2±0.5)%
Endcap	(1.1±0.3)%	(4.1±0.5)%	(4.7±0.4)%	(1.6±0.5)%

EM Models: Energy Loss Fluctuations

ALICE TPC Benchmark

measures energy deposit in 7.5 mm gap by 1 GeV/c incident protons

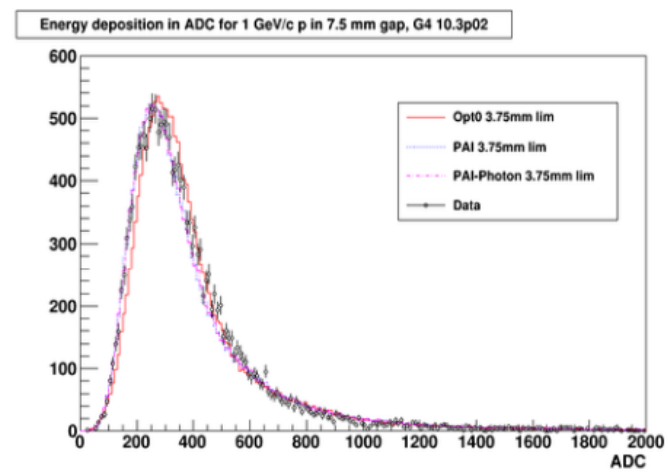
Two Geant4 models compared

- PAI
- Urban

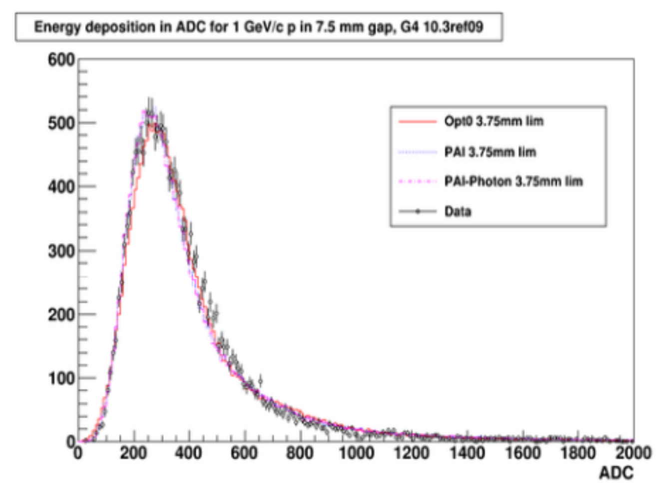
Recent improvements in Urban model lead to

- better agreement with data
- agreement with more precise PAI

10.3p02

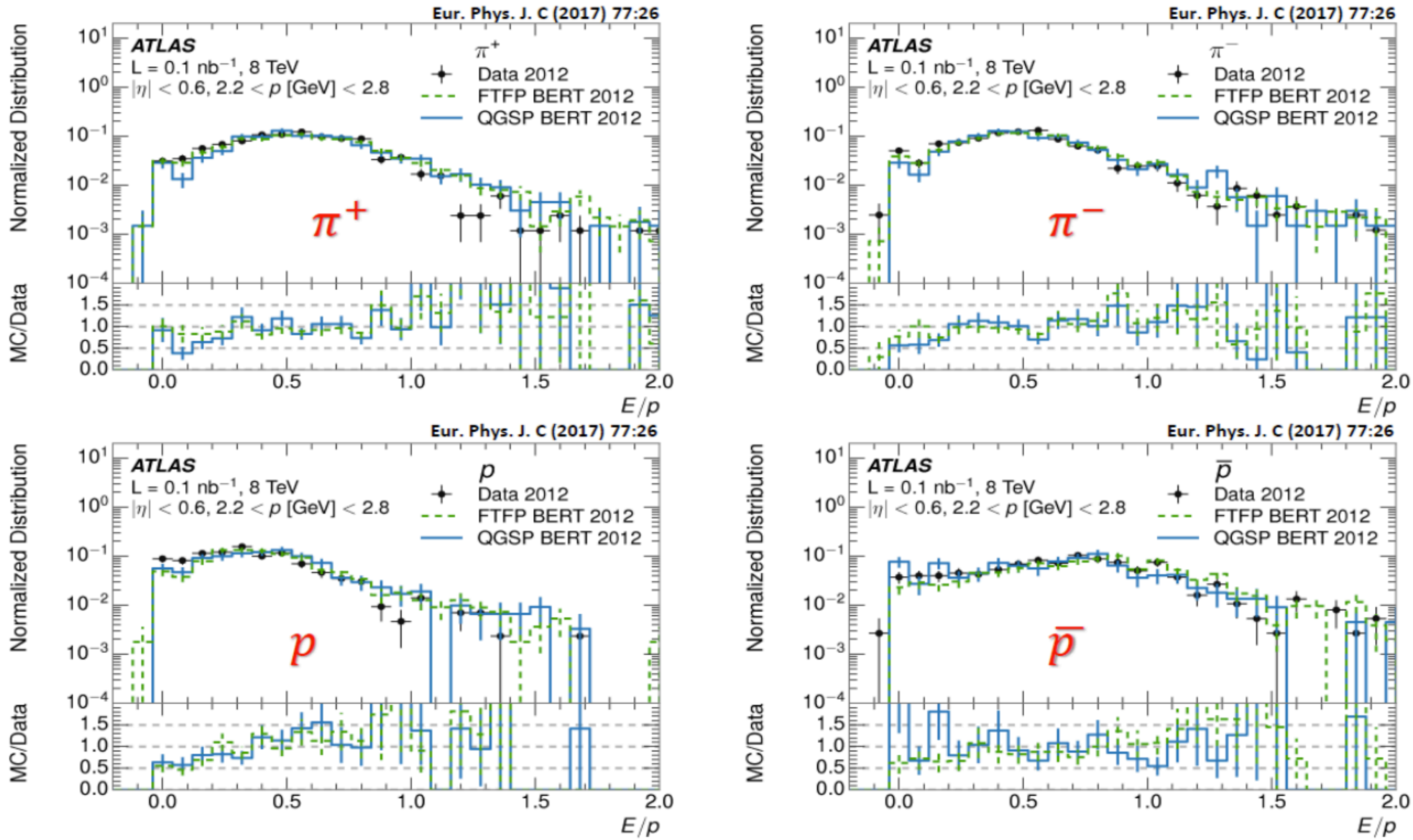


10.4



E/p for Identified Particles

Peter Loch
UAPhysics
THE UNIVERSITY OF ARIZONA
College of Science



Hadronic Cross Sections

LHCb Asymmetry Measurements

looked at amount of anti-matter vs. matter produced in $D^{+/-}$ decays

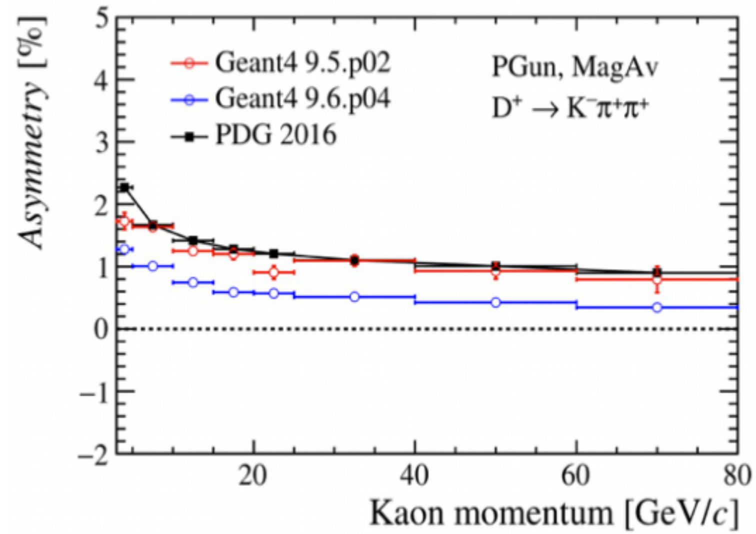
Showed a problem in our cross sections

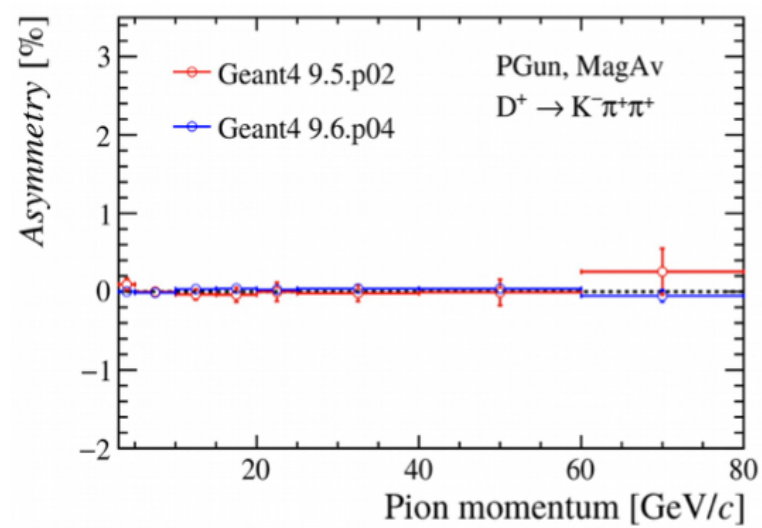
kaon asymmetry became too small

pion asymmetry OK

Problem due to error in kaon-nuclear cross sections

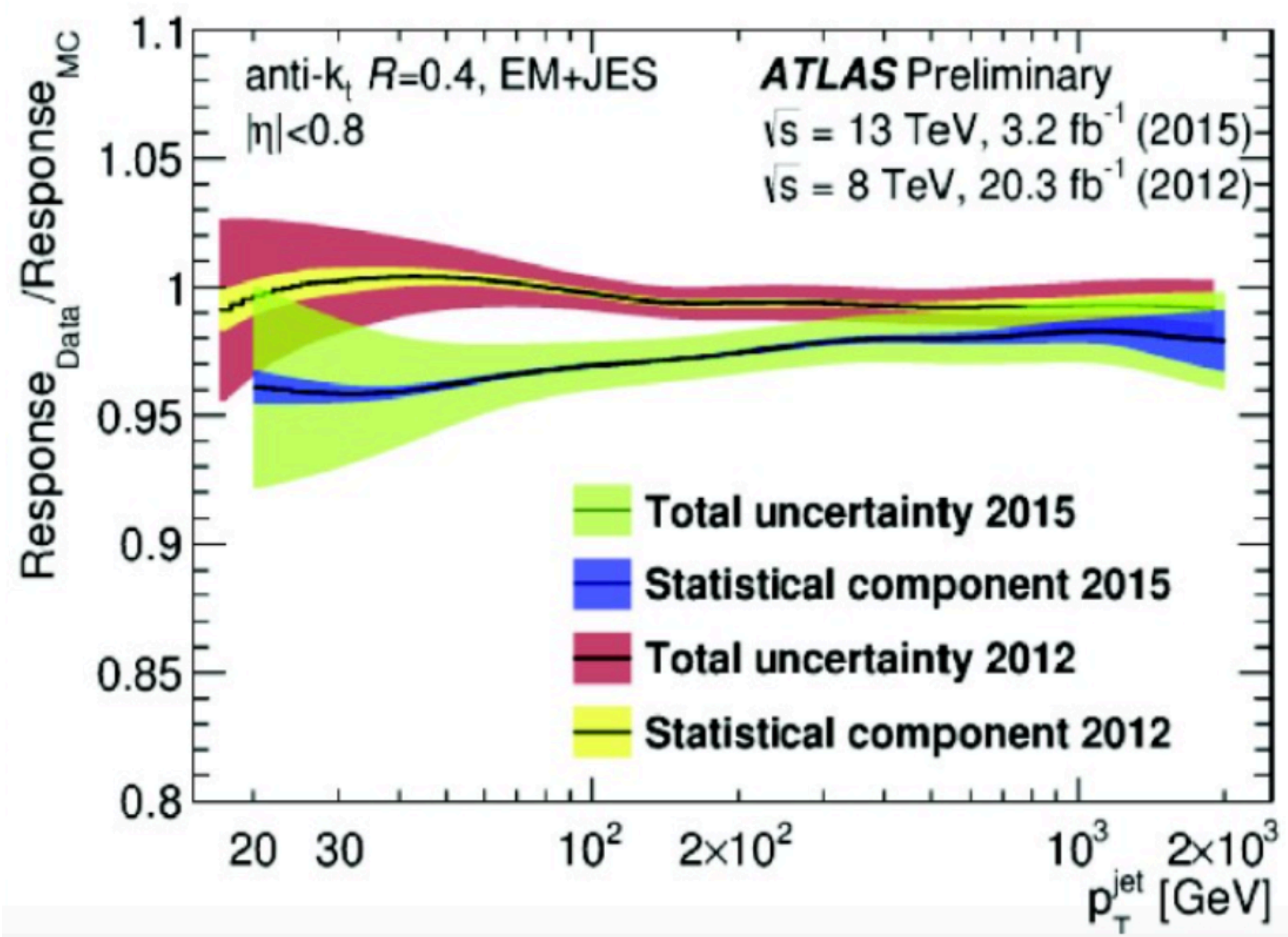
fixed in 10.1





Jet Energy Scale

Unexpected difference between FTFP_BERT and QGSP_BERT physics lists was due to transition region



Shower Depth and Hadronic Models

Example of how thin target tuning can diverge from calorimeter data

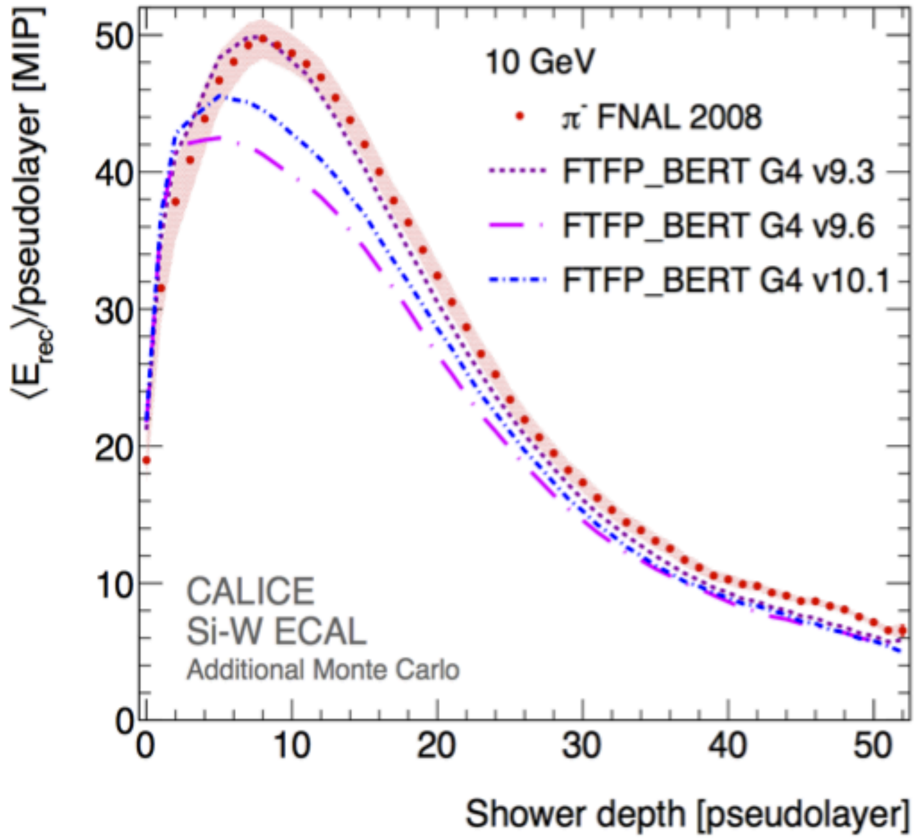
Continuous FTF model improvement through Geant4 version 10.3 according to thin target data

V9.3: good (fortuitous?) agreement

V9.6: significantly worse

V10.1: getting better again

V10.4: ?



Granular Calorimeters and Geant4

Problem: Hadron-Nuclear Physics

- At medium and low energies (< 20 GeV) simulation of hadron-nuclear interactions leaves something to be desired
  - models (factor of two errors considered good!)
  - cross sections (somewhat better but still problems at lower energies)

- High energy models are better, but..
  - still a significant number of free parameters

- How can we do better?
  - improve the theory
  - go to data-driven models

Needed: Single Interactions

- Wide range of nuclear targets
  - or at least a few spread over a wide range of A

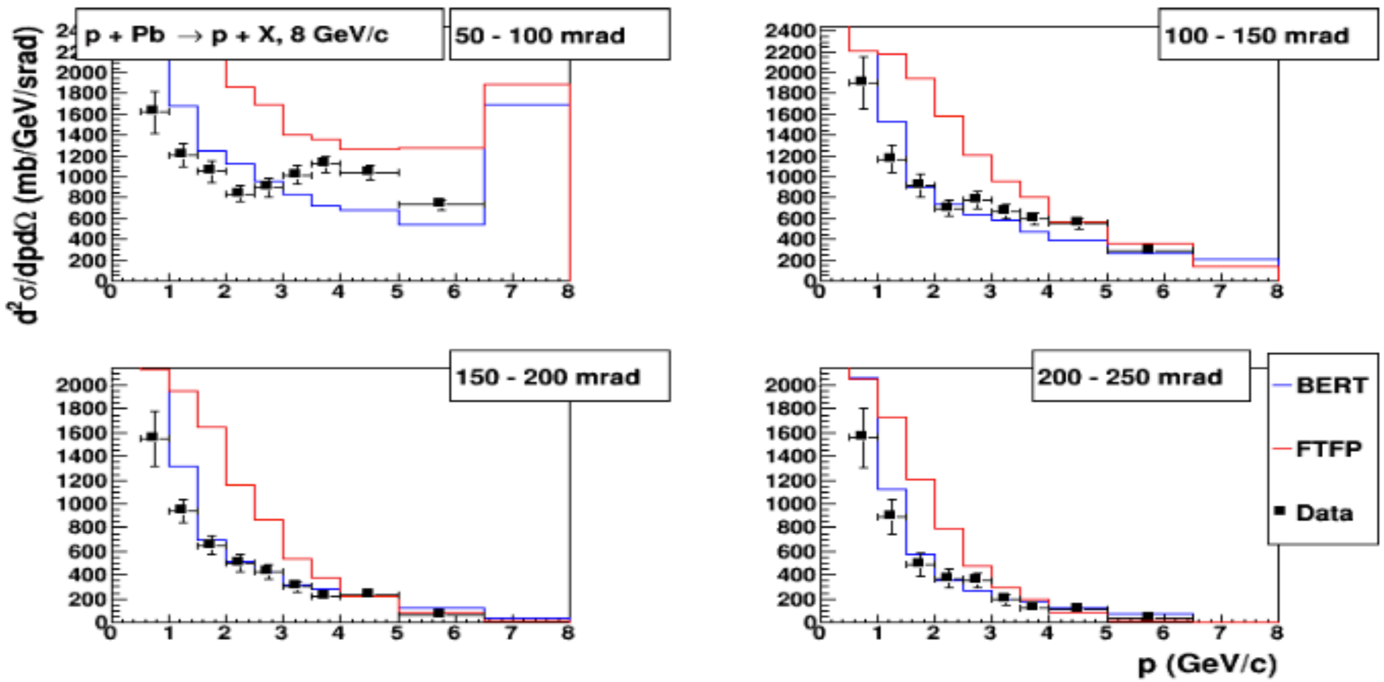
- Initial state
  - nearly mono-energetic projectile
  - good particle ID
  - well-defined initial direction

- Final state
  - multiplicity
  - angular distribution
  - good particle ID

Problem: Thin Target and Thick Target Validations Often Disagree

- We rely heavily on thin-target data to tune models
  - more control over incident beam, target
  - usually single interaction
  - more reliable than thick target
- However, improving agreement with thin-target data often reduces agreement with thick target or calorimeter data
  - lately the case with FTF (energy response, shower shapes)
  - but also with Bertini (shielding experiments)
- Reasons?
  - models are faulty
  - measured double differential cross sections do not cover enough phase space

Forward Scattering: A Clue?



- HARP data (above) goes to 12.9, 10.0, 7.1 and 4.3 degrees
  - character of spectrum changes going to small angles
  - could this account for part of the problem connecting thin and thick target data – overestimating the forward scattering?

Granular Calorimeters Can Help

Isolated hadronic interactions

Number of tracks

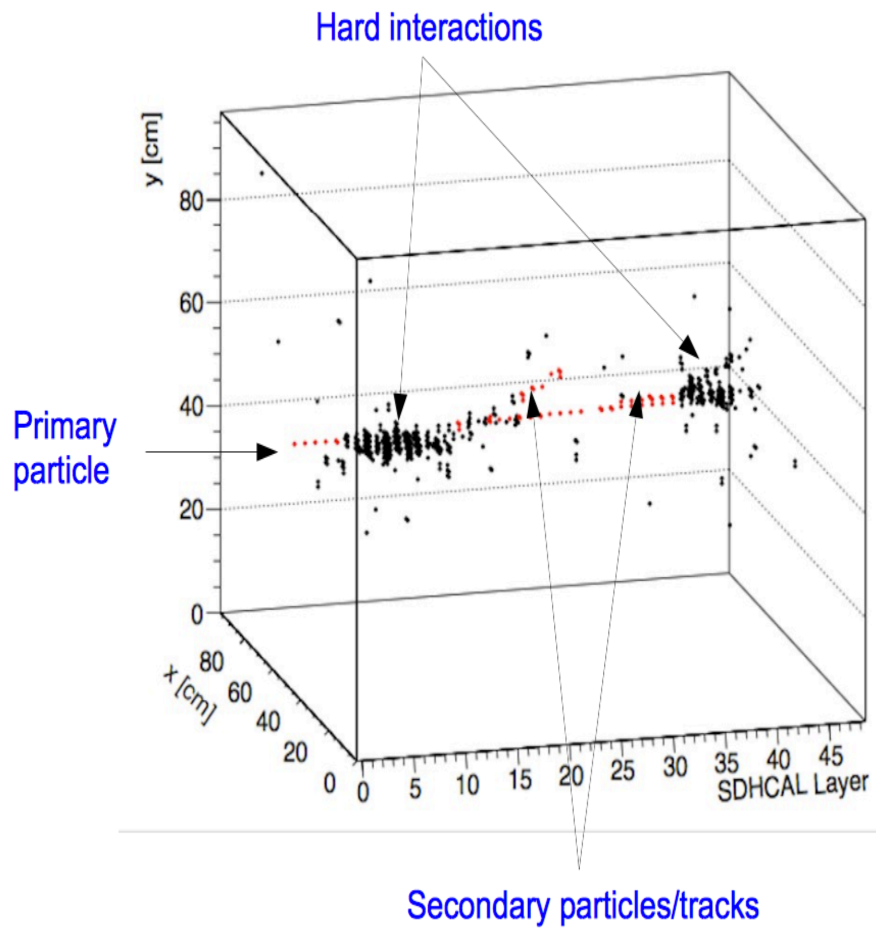
Angular distributions

Target

Neutral tracks?

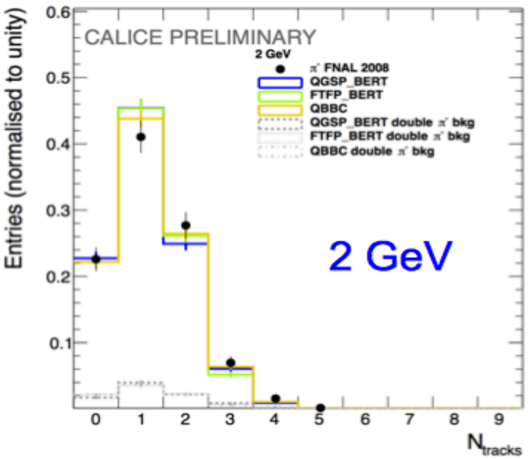
Recoil nucleus?

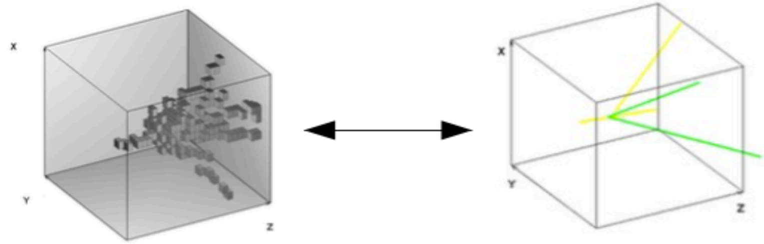
For the first time we have observables other than the “bulk” values from conventional calorimeters



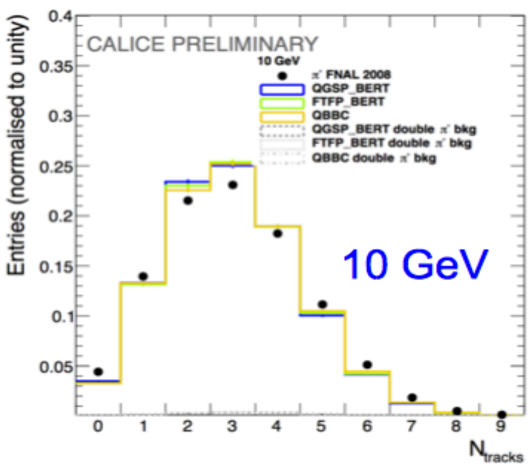
Si Ecal - Number of tracks

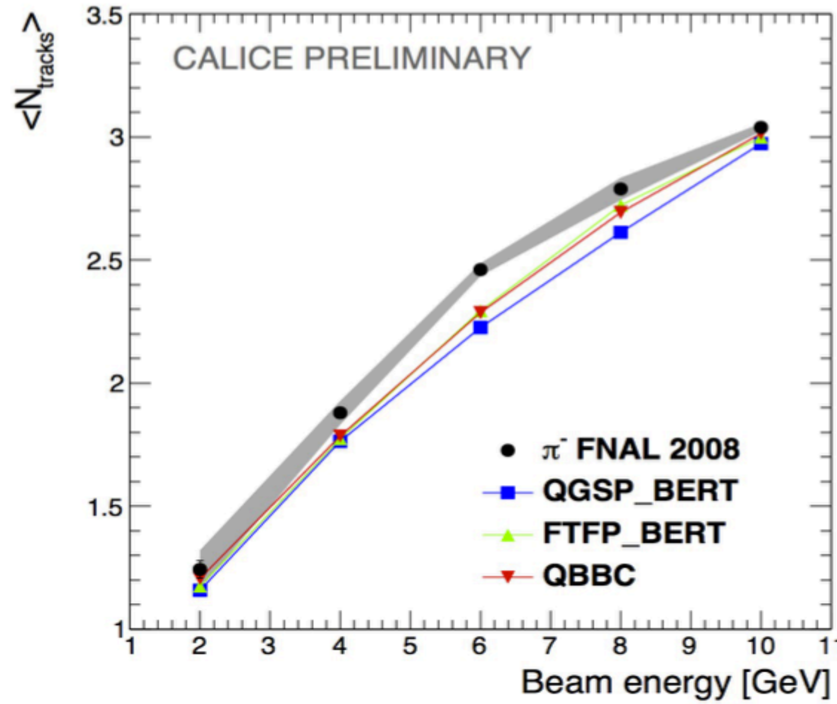
CAN-055





- active material: Si
- absorber: tungsten
- Geant4 10.01



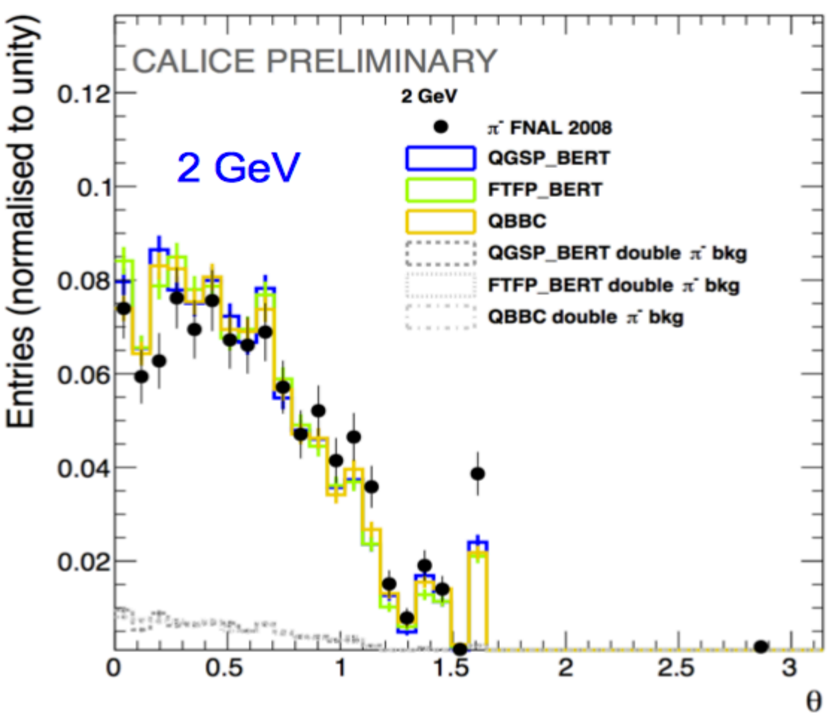


- Mean number of secondary tracks increases with beam energy
- Surprisingly good reproduction of data by Geant4

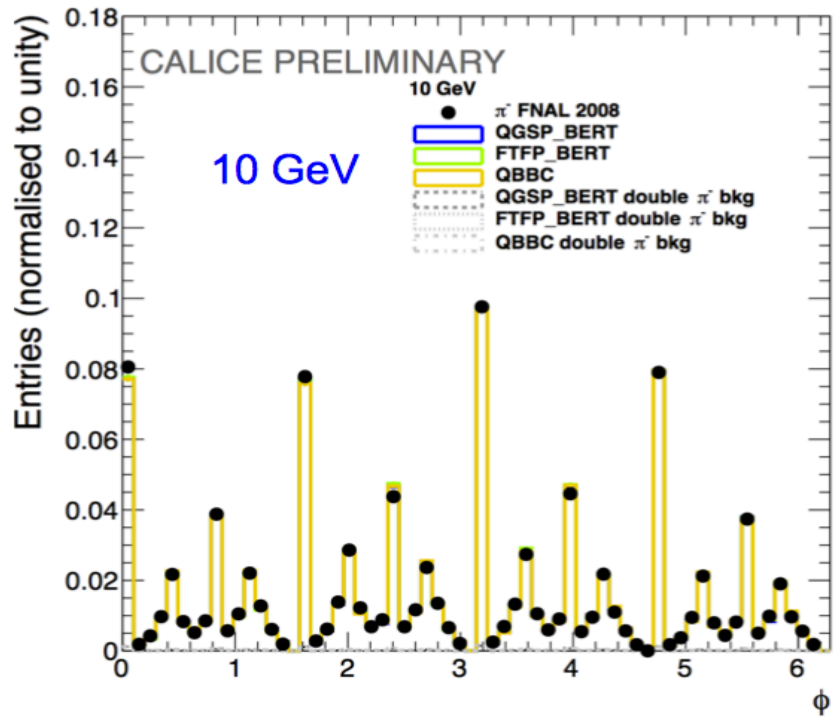
Si ECAL - Angular distributions

- active material: scintillator
- absorber: tungsten
- Geant4 10.01

Polar Angle



Azimuthal Angle



- Observables available due to high granularity of detector
- Good reproduction of data by MC even at this high level of detail

What Else Can Granular Calorimeters Give Us?

- Can they act as modern day “bubble chambers”?
- Forward angle hadronic scattering
  - looks like angles down to 0 degrees may be possible
  - impossible for most thin target experiments (limited by beam/ target geometry)
  - HARP data a big improvement, but not enough
- Low momentum secondaries
  - what is smallest energy secondary that can be seen?
  - what about neutral hadrons?
- Can EM and hadronic vertexes be cleanly separated?

Simplified Calorimeter

- A Geant4 tool for regression testing
  - compare one Geant4 version against another
  - alter physics model parameters and observe changes (quickly)
  - several statistical tests used (χ^2 , K.S., etc.)

- Geometry is a box containing layers of absorbers and active materials
  - can choose number, thickness and material of layers to approximate real calorimeters
  - can also choose lateral shower bin size
  - there is enough detail to make meaningful comparisons to real data

Simplified Calorimeter

- All LHC calorimeter material combinations are supported
  - Fe-Scint, Cu-Scint, Cu-LAr, W-LAr, Pb-Scint, Pb-LAr, $PbWO4$
- Particle types tested:
  - $\pi^{+/-}$, $K^{+/-}$, K_L^0, p, n, e^-
- Beam energies used:
  - 1, 2, ⋯ , 10, 20, 30, 40, 50, 60, 80, 100, 120, 150, 180, 200, 250, 300, 1000 GeV
- Observables:
  - total energy deposit all active layers
  - total energy deposit whole calorimeter
  - energy deposit in each active layer (longitudinal shower profile)
  - energy deposit in each radial bin (lateral shower profile)

A Simplified Calorimeter for Calice

- New effort to extend simplified calorimeters to highly granular detectors
  - Katalin Nikolics, Witold Pokorski (CERN)
- A challenge
  - how much simplification can be made without sacrificing too much detailed response?
  - first target could be SiW ECAL → most detailed shower shapes
  - maybe DHCAL eventually?
- Good opportunity to tune model parameters and get fast turn-abound on angular distributions, number of tracks, etc.

Calorimeters and Better Hadronic Models

- Geant4 EM physics already in good shape
  - sufficiently well understood that we can attribute changes in shower shape to hadronic models
  - use width and depth of shower to choose models and transition range
- FTF vs. QGS
  - FTF is a more phenomenological model
  - QGS more theory-based, and is valid at higher energies
- Bertini
  - measuring number of hadronic secondaries is crucial
  - number of secondaries as a function of incident energy
- Precompound/deexcitation
  - can we identify nuclear fragments?

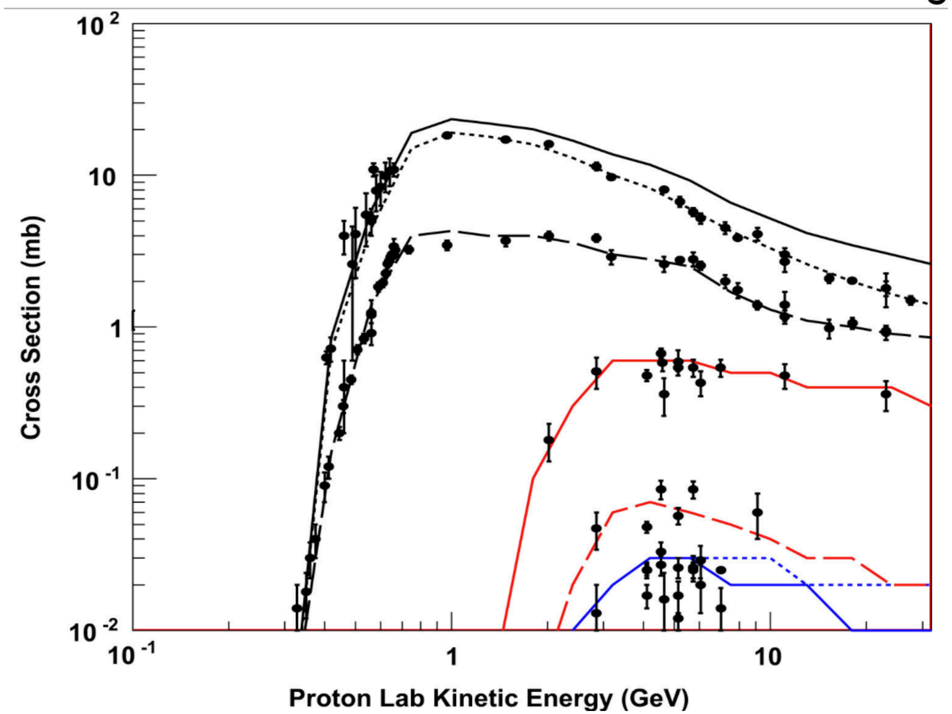
Bertini Cascade (Low to Medium Energy)

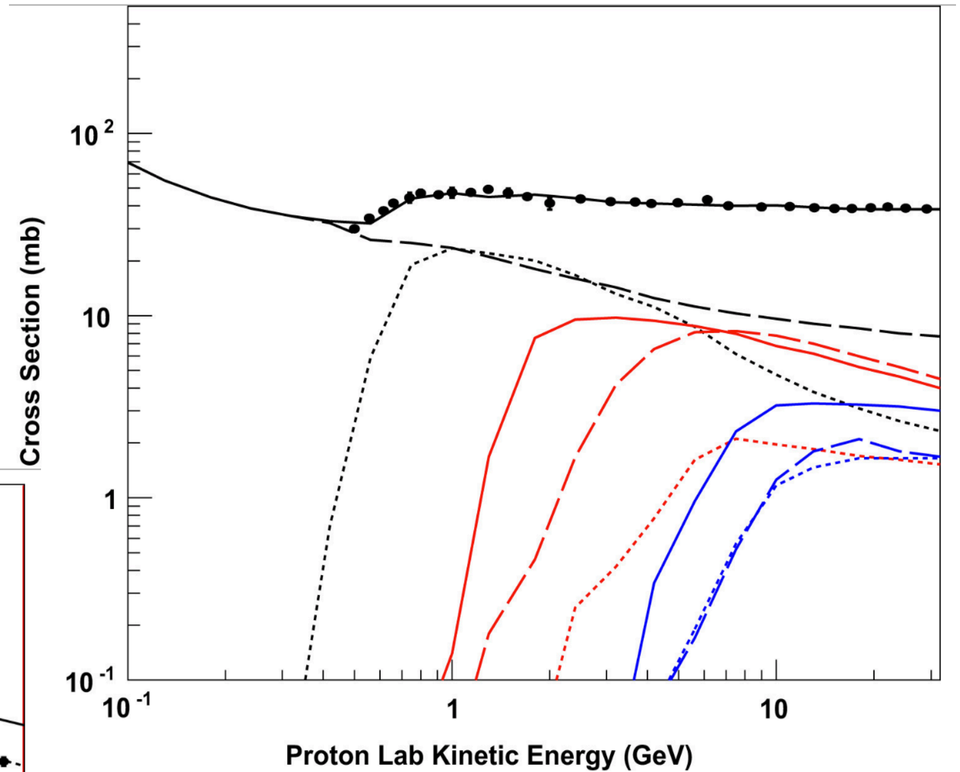
- Depends on free-space hadron-nucleon cross sections embedded in nuclear medium
  - thousands of partial cross sections as function of energy and final state multiplicity
  - some of these well-measured, many not
  - use measured final state number of tracks to constrain poorly measured particle cross sections (among other nuclear parameters)

- Only have good angular distributions for two-body final states
  - n-body states rely on phase space
  - isolate a few low multiplicity final states , parameterize model angular distributions for 3-, 4-body, then fit calorimeter data

Bertini Partial p-p Cross Sections

Final state multiplicity cross sections (2 - 9)





3-body final state cross sections

FTF/QGS Models (High Energy)

- Both FTF and QGS models on much better theoretical footing than Bertini
  - but they still have a number of free parameters
  - coarse-grained calorimeters gave been essential in tuning these
  - can fine-grained detectors data help?

- Can still learn something from track multiplicity
  - best hadron fragmentation function to use still unknown -> effects multiplicity
  - as in Bertini, embedded hadron-nucleon reactions still important
  - nuclear physics less relevant

- Probably not much from angular distributions – too forward
  - can tracks be resolved at > 20 GeV?

Summary

- Geant4 has been and continues to be used by all HEP experiments
  - feedback from test-beams and calorimeters has been essential for tuning of Geant4 models
- While coarse-grained calorimeter data has been useful, detailed model tuning has depended on thin target data
  - single interaction assumed
  - but discrepancies with thick target data seen
- Granular calorimeters hold the promise of single interaction data in a thick-target environment
  - final state multiplicity
  - angular distribution
  - detailed model tuning possible