Geant4 ASSOCIATES INTERNATIONAL
Experts in Radiation Simulation

CERN

GEANT4 MODELS FOR HADRON PRODUCTION

Nuclear physics for Galactic Cosmic Rays in the AMS-02 era

Grenoble, France, 3-4 December 2012

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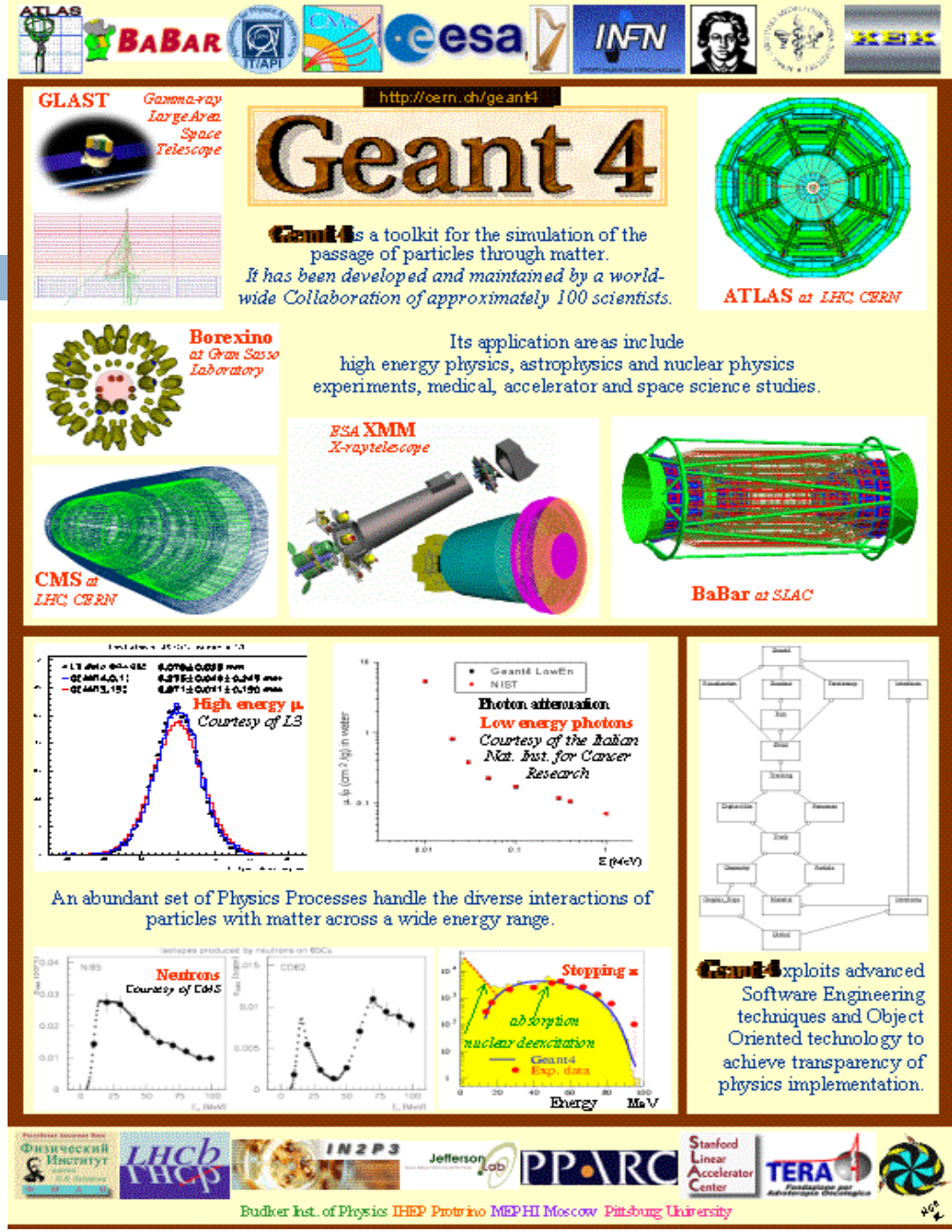
For Geant4 Collaboration

Outline

- General introduction
- Geant4 Physics List
- Highlights on Geant4 hadronic models
- Geant4 9.6 validation results



Geant4: General introduction

- Dec 1994 - Project starts
- Dec 1998 - First Geant4 public version 1.0
- Dec 17th, 2010 - Geant4 version 9.4 – today production version for ATLAS and CMS
  - Very good agreement with LHC data
- Dec 2th, 2011 - Geant4 version 9.5 release
- Nov 30th, 2012 - Geant4 version 9.6 release
  - Last release of 9.X series
- 2013 – plan to provide version 10
  - Significant update in all Geant4 components
  - Multi-threading capabilities

- Geant4 is a toolkit
  - Consists of 17 categories which are mantained by different working groups
- Kernel categories
  - Run, event, track, hit, trajectory
- Flexible geometry
  - Transportation in EM fields
- Physics
  - Particle types
  - Physics processes
    - Transportation
    - Decay
    - Electromagnetic
    - Hadronic
    - Optical
  - Physics Lists
- User interface
- Visualisation

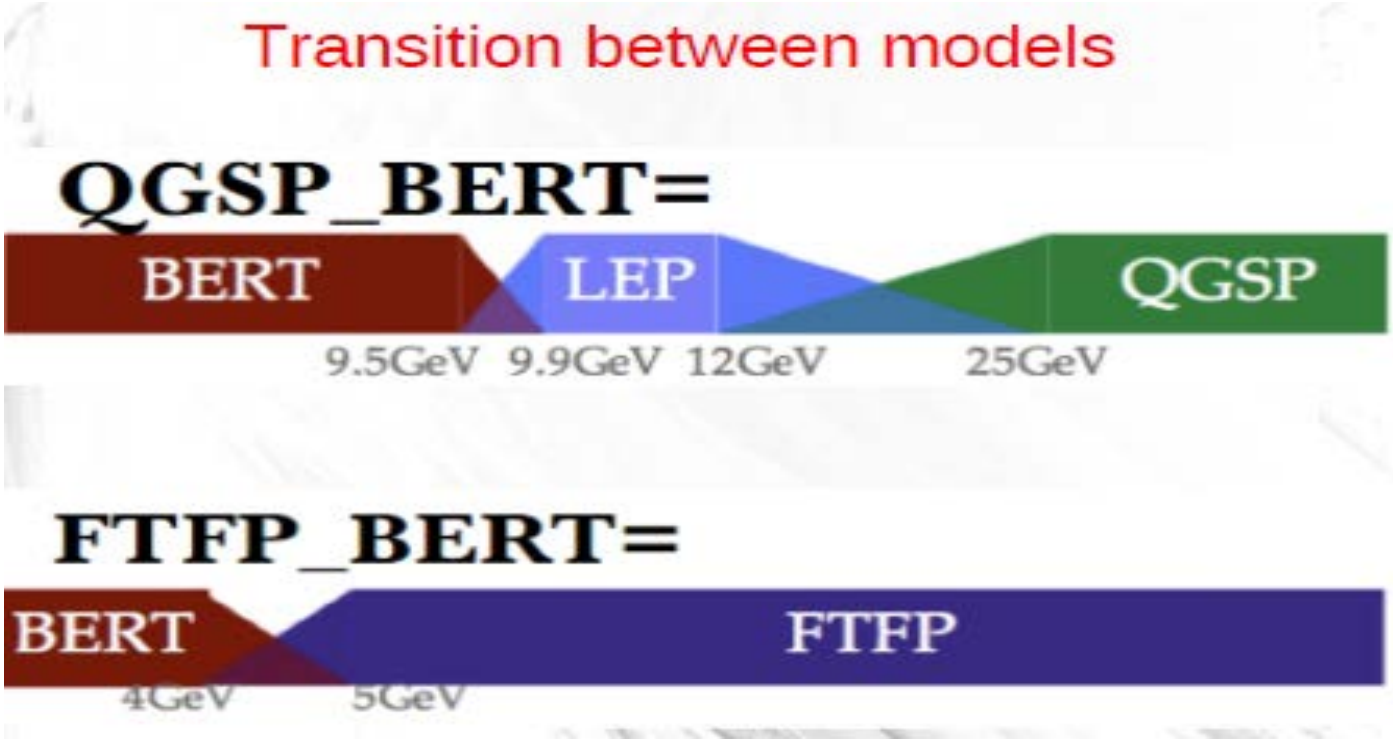
Geant4 Physics

- Geant4 philosophy: competitive models within toolkit
  - We try to keep production models stable
  - Old models may become obsolete and even be removed
  - New model may be included even if it has limited applicability
  - In Geant4 hadronics secondary generation and cross section are independent
- Geant4 model and cross section configuration is done via Physics List
  - Reference Physics List distributed with Geant4
  - Custom Physics Lists may be created by users
- Reference Physics Lists use modular constructors (builders):
  - EM (default is standard EM)
  - Extra EM (gamma- and electro- nuclear processes)
  - Decay
  - Hadron elastic scattering
  - Stopping
  - Hadron inelastic Interaction
  - Ion-nuclear interactions
  - User can add extra physics constructor – StepLimiter, Optical…

Reference Physics Lists

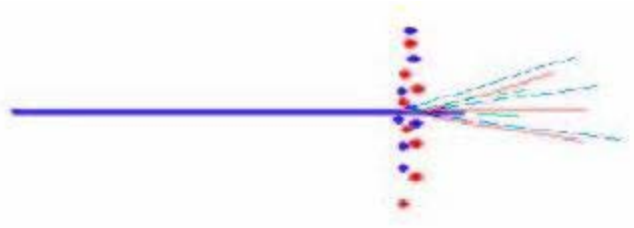
- Reference Physics Lists are part of Geant4 distribution
  - The best method to communicate with user communities
- Extensive validation by LHC experiments
  - QGSP_BERT currently used by ATLAS
  - QGSP_FTFP_BERT_EML currently used by CMS
  - QGSP_BERT_EMV currently used by LHCb
- Geant4 9.6 provides
  - Physics defined from zero to 100 TeV
  - We favour Physics List FTFP_BERT for LHC
  - Interest of space users may be also to FTFP_BERT_TRV, FTF_BIC, QBBC....
  - Additionally electromagnetic physics options may be selected
  - In total 33 reference Physics Lists in Geant4 9.6
    - Part are obsolete but kept for users for backward compatibility
- Let us discuss hadronic models in production Physics Lists

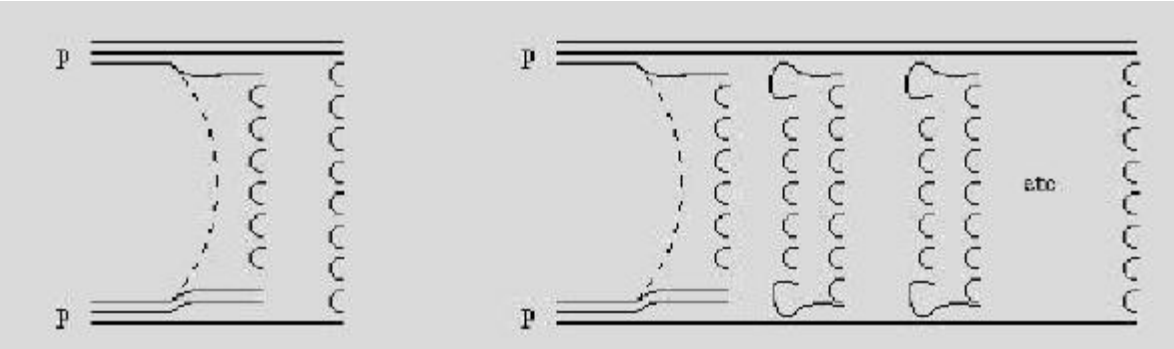
Different hadronic inelastic models are combined in Physics List



- Physics at high energy and at low-energy is too different for one universal model to serve complete energy range
- For hadron/ion inelastic process several models are combined
- Below we will discuss the most important models for hadronic interactions

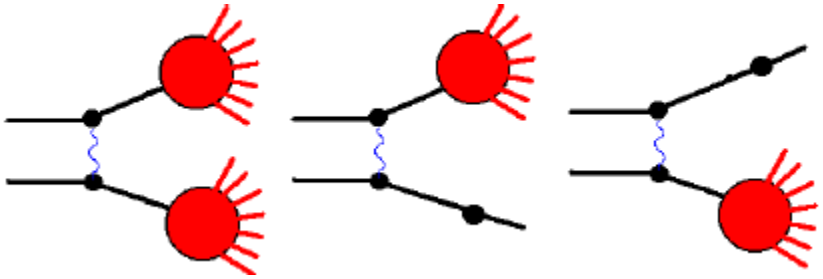
Quark-Gluon String Model





- Classical string models
  - Proposed by A.Kaidalov and A.Capella
  - Implemented in Sibul, EPOS, DPMJET, Venus
  - In this model, two or more strings are stretched between the partons (quarks or gluons) within the hadrons
- Geant4 QGS model is stable for many years
  - Applicable for p, n, $\pi^{\pm}$, kaons
  - Valid from 12 GeV - 1TeV

Fritiof fragmentation model: today Geant4 recommended



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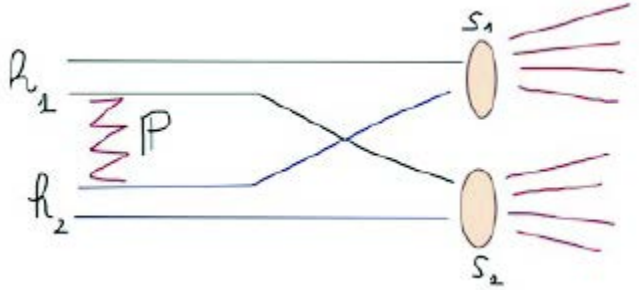
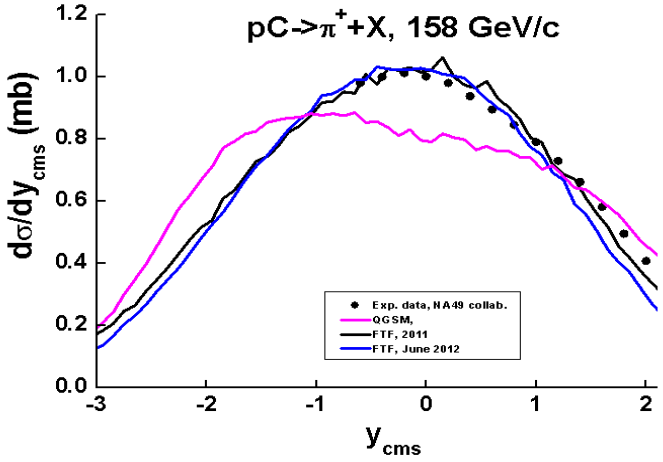
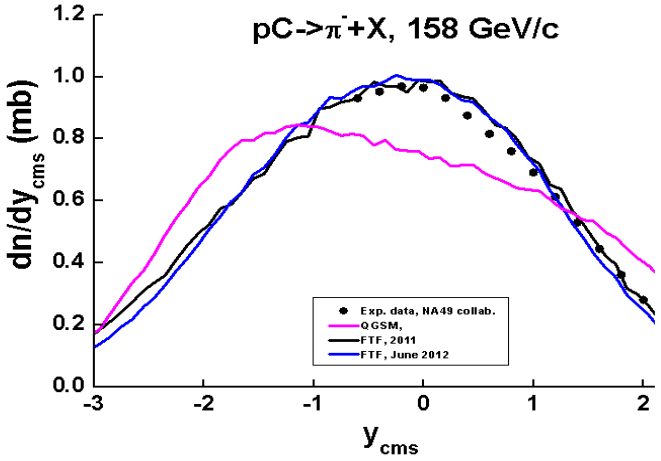


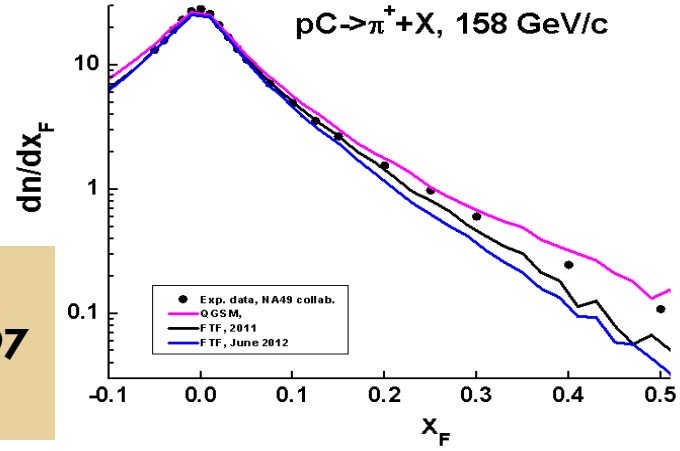
- Alternative string model initially proposed by Bo Anderssen
- Geant4 FTF model
  - Valid from 3 GeV - low limit provides a smooth transition to the cascade model
  - Applicable for all «stable» hadrons, ions and light anti-ions
  - Geant4 developer Vladimir Uzhinskiy (JINR, Dubna, Russia & CERN)
- Specifics of Geant4 implementation of FTF
  - Uses a different set of fragmentation functions and relies more on fitted parameters than QGS
  - Ability to handle lower string masses
  - Reggeon cascade for re-scattering
  - Natural introduction of diffraction processes
  - Anti-nucleus/nucleus interactions
  - Multi-fragmentation of projectile nucleus (recently added)

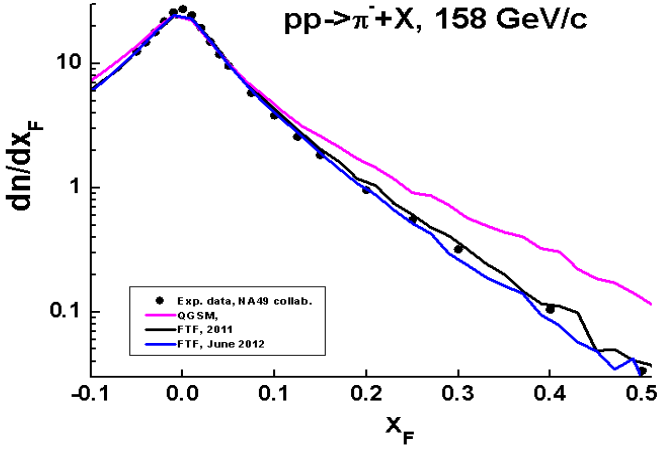
Today FTF is compatible or more accurate than QGS

Pion production at high energy









NA 49 data:
Eur. Phys. J. C49 (2007) 897
courtesy of V. Uzhinskiy

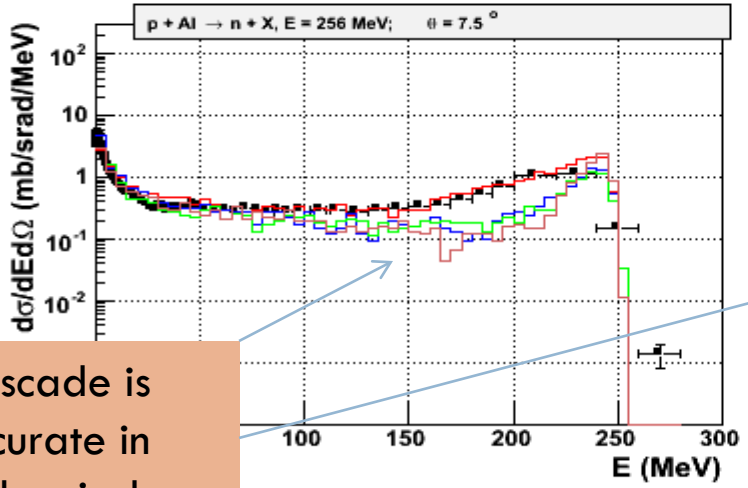
Bertini Cascade:
Today Production Model for LHC

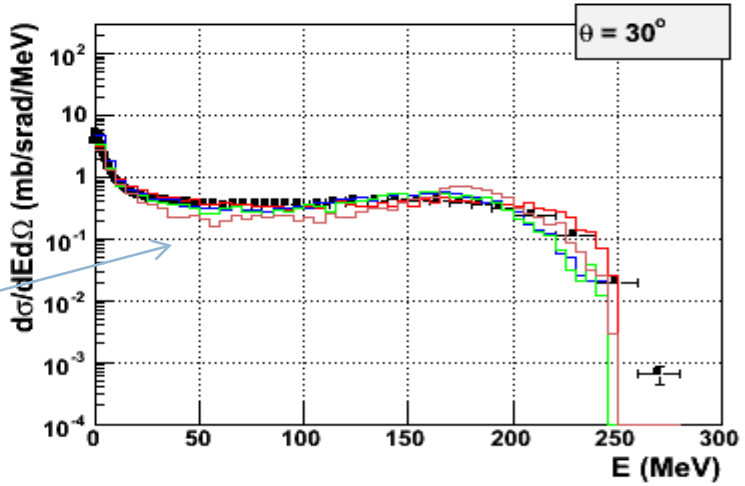
- The Bertini model is a classical intra-nuclear cascade model:
  - Proposed by Bertini (1960), further developed by V.Barashenkov and S.Mashnik at JINR, Dubna
  - Implemented in GEM95, MCMPX, LAQGSM, MARS....
  - Geant4 implementation by Stepanov (ITEP, Moscow)
  - Current developers Mike Kelsey and Dennis Wright (SLAC, Stanford, CA)
    - Code was significantly re-written last years
- Geant4 implementation:
  - Elementary particle collider: uses modified free-space cross sections to generate secondaries
  - Cascade in nuclear medium
  - Pre-equilibrium and equilibrium decay of residual nucleus
    - Internal Bertini model or Geant4 native Pre-compound model
  - 3-D model of nucleus consisting of shells of different nuclear density
- In Geant4 the Bertini model is currently used for γ, p, n, π, K^+, K^-, K^0_L, K^0_S, Λ, Σ^+, Σ^-, Ξ^-, Ξ^0, Ω^-
  - Valid for incident energies of 0 – 10 GeV
  - More accurate for A > 10
  - Significantly faster than other intra-nuclear cascade models of Geant4

Alternative Geant4 Cascade Models

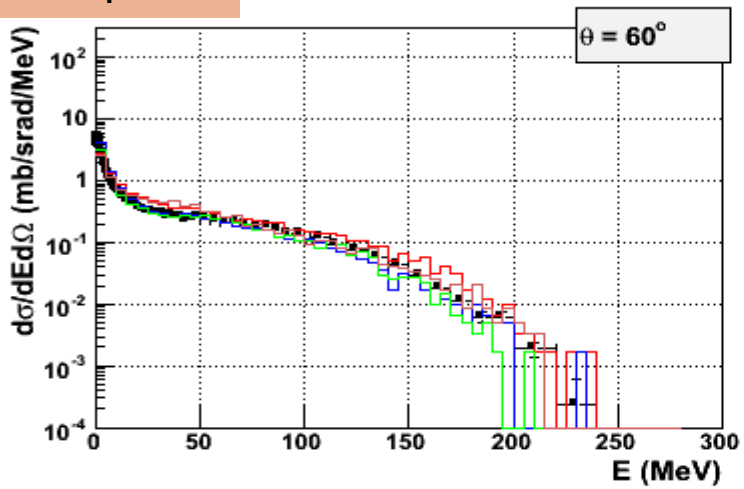
- Binary Cascade is original C++ model, no FORTRAN analog
  - Valid for incident p, n from 0 to 10 GeV
  - Valid for incident π^+, π^- from 0 to 1.3 GeV
  - Valid for ions up to 5 GeV/u
  - Current developer Gunter Folger (CERN)
- Specifics of the Binary cascade model
  - Nucleus consists of nucleons
  - Hadron-nucleon collisions
    - Handled by forming resonances which then decay according to their quantum numbers
    - Elastic scattering on nucleons
  - Particles follow curved trajectories in nuclear potential
  - Geant4 native Pre-Compound/de-excitation models are used after cascading
- QMD (Tatsumi Koi, SLAC) - may be recommended for light media
  - Complete quantum theory – JQMD FORTRAN code rewrite
  - Very CPU intensive
- INCL++ - see previous talk of Alain BOUDARD (CEA-IRFU/SPhN)

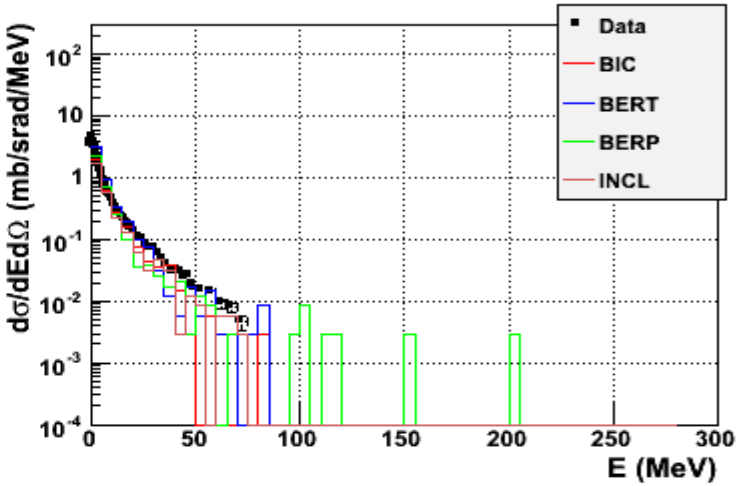
Double differential cross section of neutron production by 256 MeV protons off Al target, Geant4 9.6





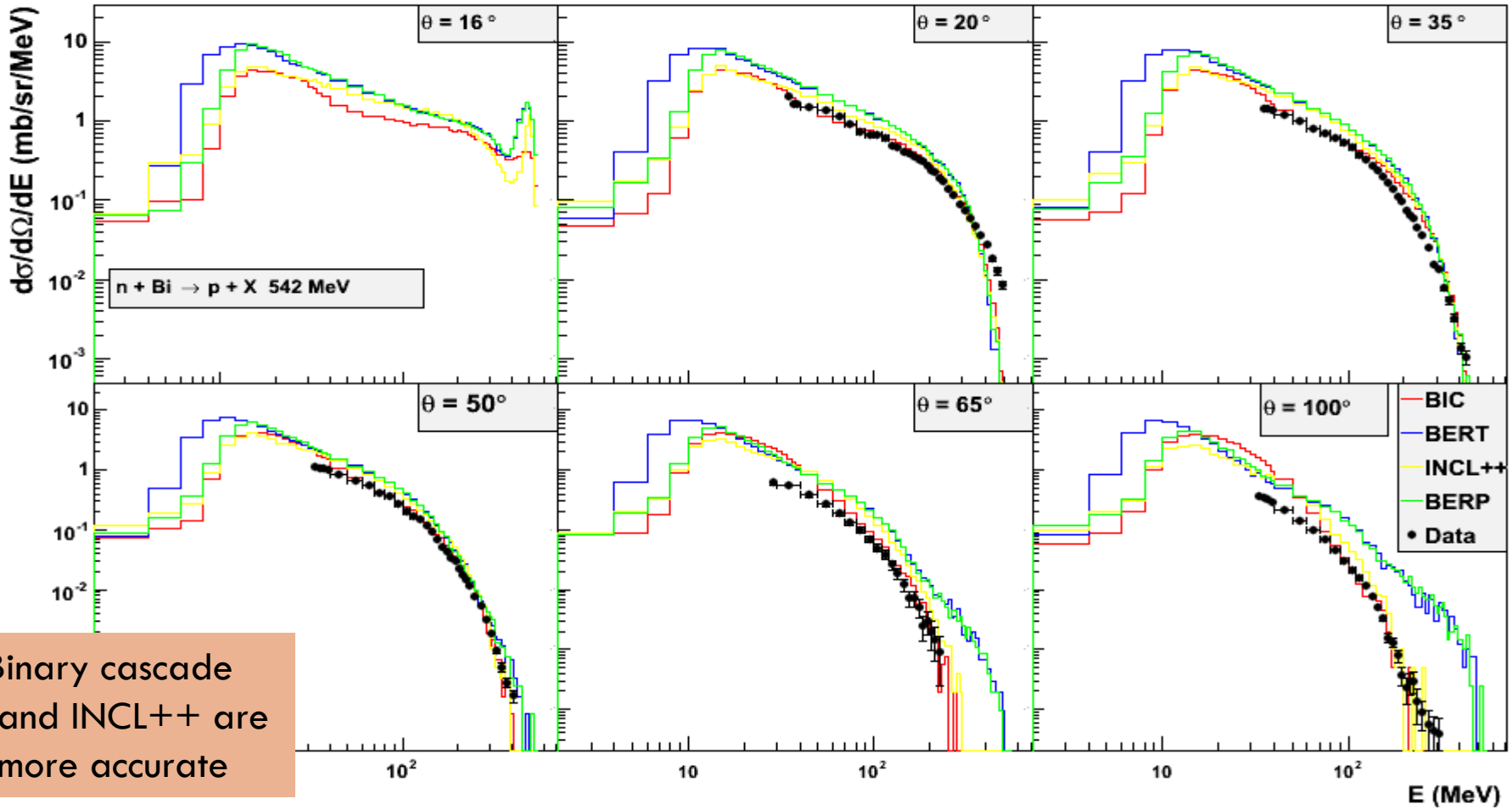
Binary cascade is more accurate in forward hemisphere





Nucl. Sci. Eng. 110 (1992) 289

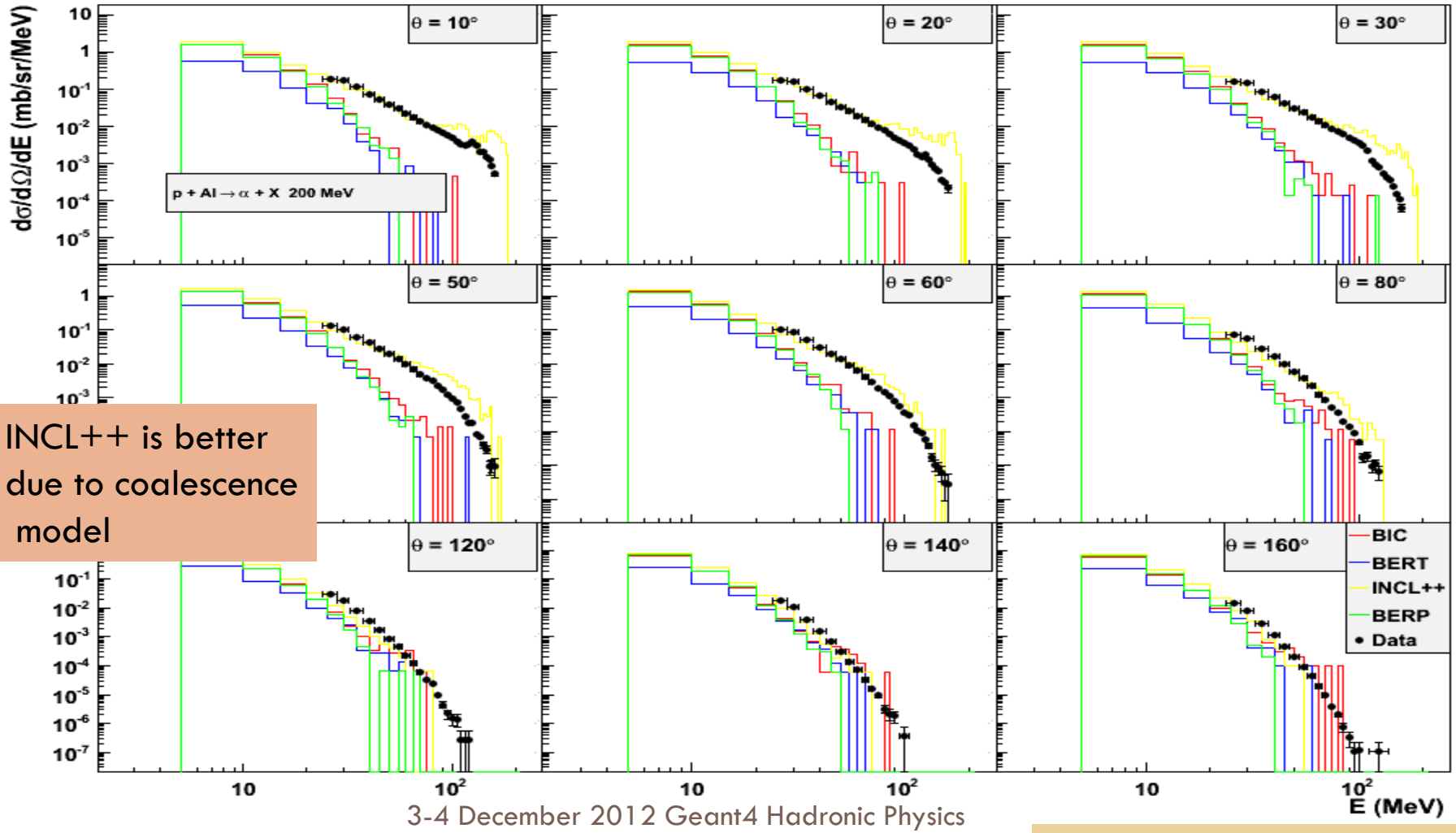
Double differential cross section of proton production, Geant4 9.6



Binary cascade and INCL++ are more accurate

IAEA Spallation benchmark

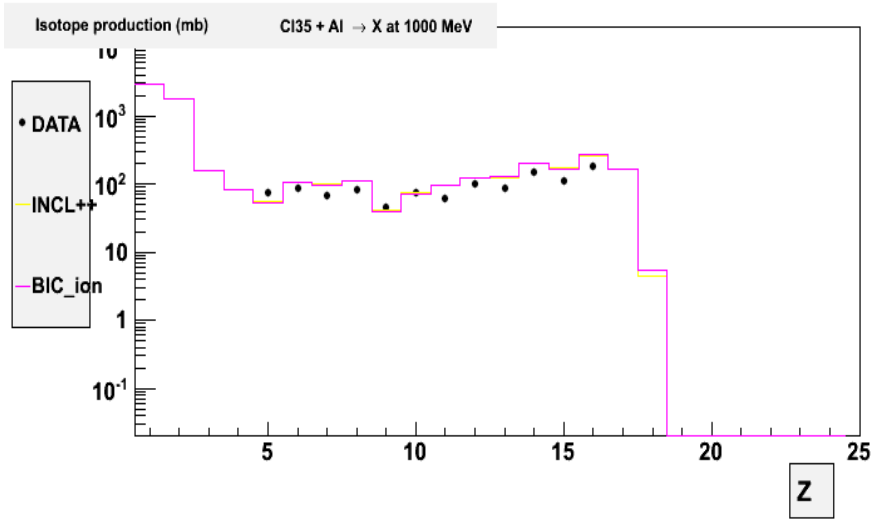
Double differential cross section of alpha production by 200 MeV proton off Al, Geant4 9.6



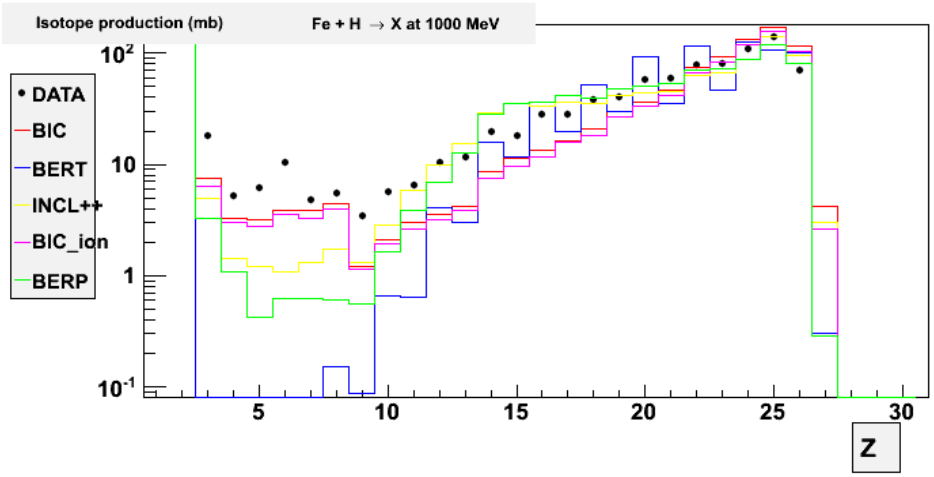
INCL++ is better due to coalescence model

IAEA Spallation benchmark

Nuclear fragmentation of 1 GeV/u ion beams, Geant4 9.6

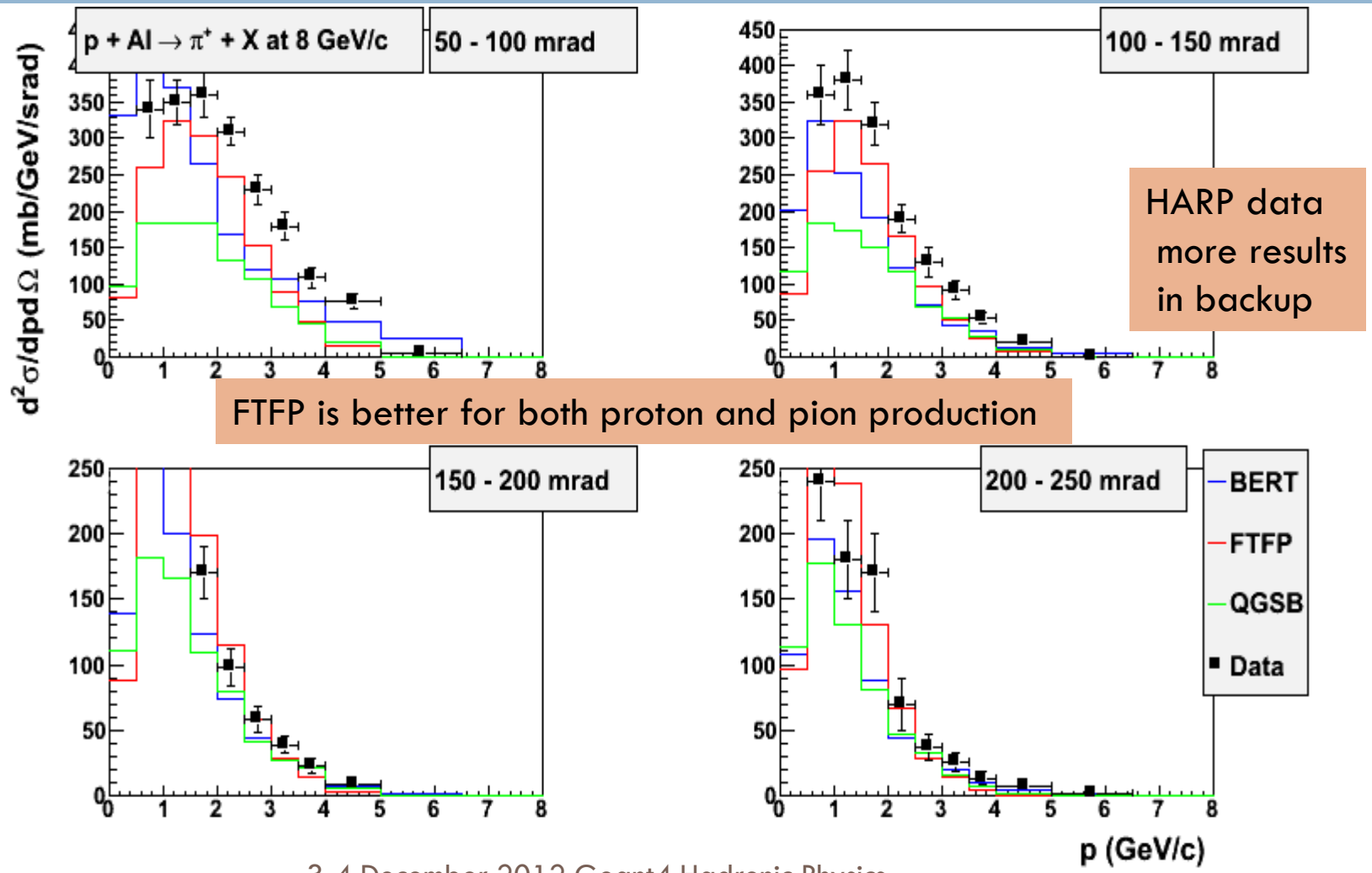


- Forward fragmentation of ion beam
- Reasonable agreement with the data both for INCL++ and the Binary cascade



- Isotope production in inverse kinematic
- INCL++ and Bertini cascades better describe high-Z fragment yield
- The Binary cascade better describes low-Z fragment yield

Forward pion production by protons in Aluminum target, Geant4 9.6



HARP data more results in backup

FTFP is better for both proton and pion production

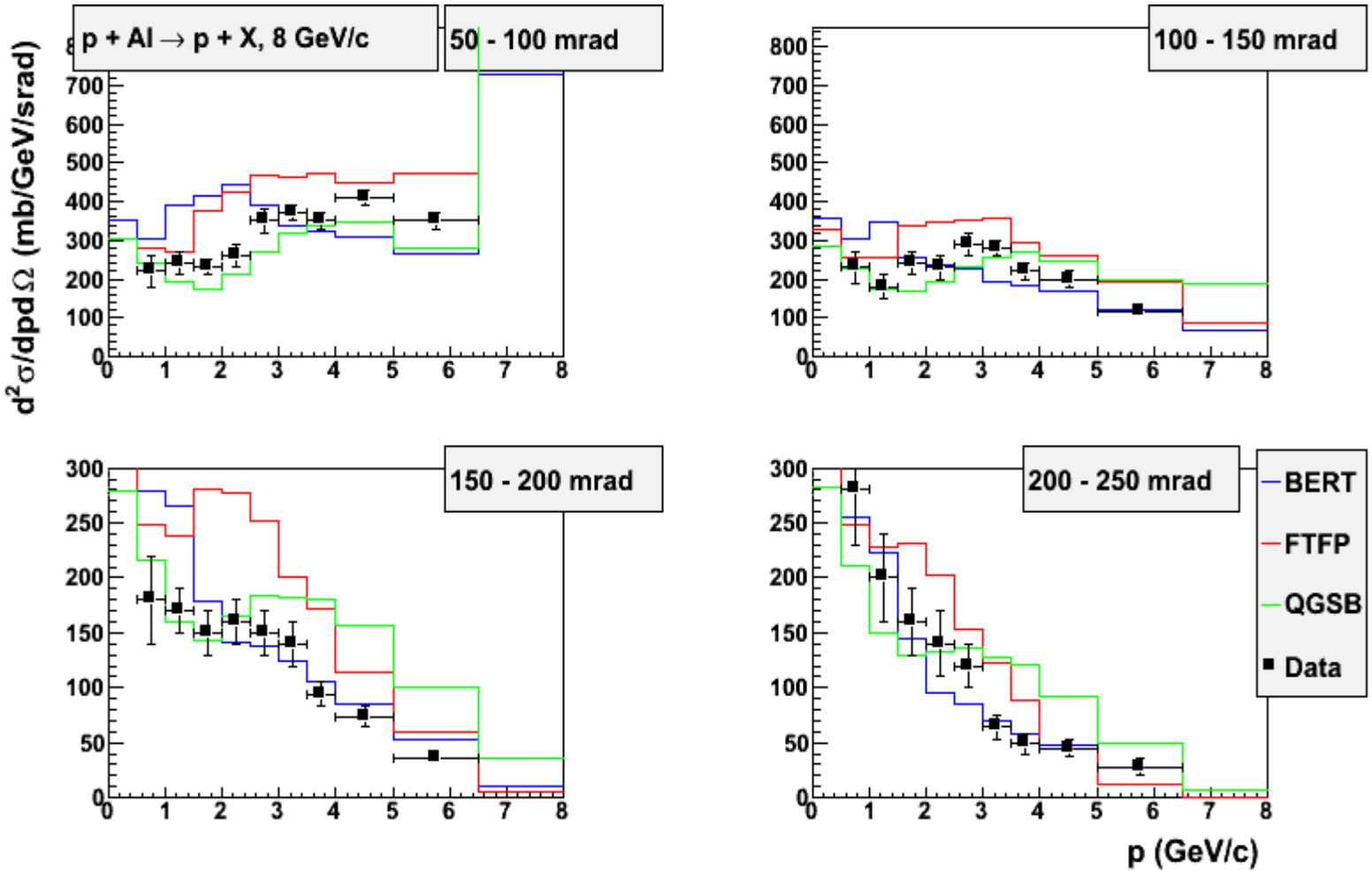
Phys. Rev. C80 (2009) 035280

Summary

- New Geant4 version 9.6 is released last Friday
  - FTFP_BERT is recommended Physics List for LHC
  - Several reference Physics Lists are recommended for space users
    - FTFP_BERT, FTFP_BERT_TRV, FTF_BIC, QBBC
  - Several hadronic models are recommended:
    - FTF, QGS for high energy
    - Bertini, Binary, INCL++, QMD cascades for intermediate/low energies
  - It is possible to configure custom Physics List using available physics constructors
- Geant4 plan to make a significant update in 2013 providing version 10
  - Multi-treading capabilities will be available
  - LHEP and CHIPS hadronic models will be removed
  - Refinement of FTF ion fragmentation
  - Revision of QGS model
  - Revision of de-excitation/photon evaporation

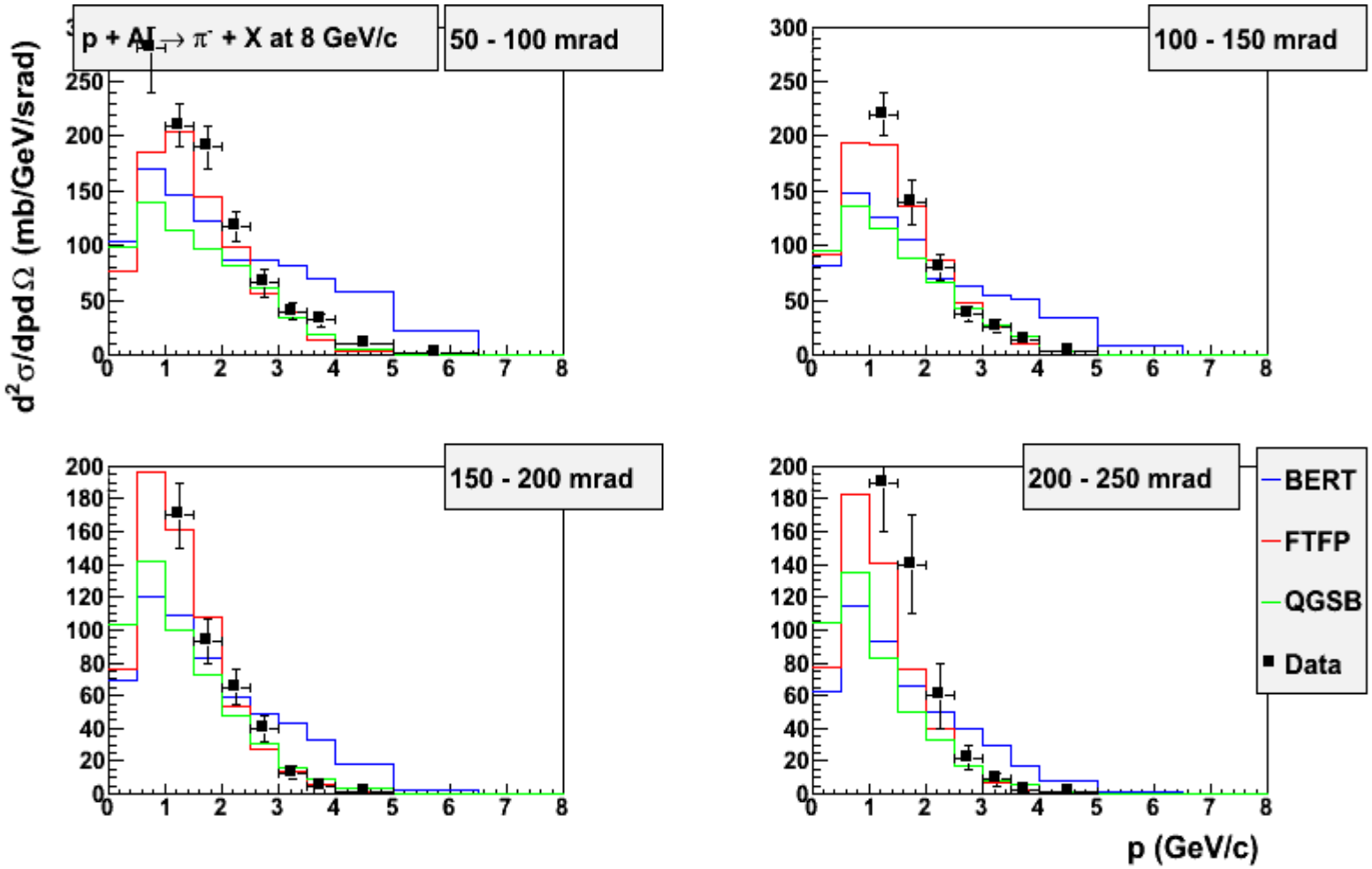
BACKUP SLIDES

HARP Data: Forward Protons



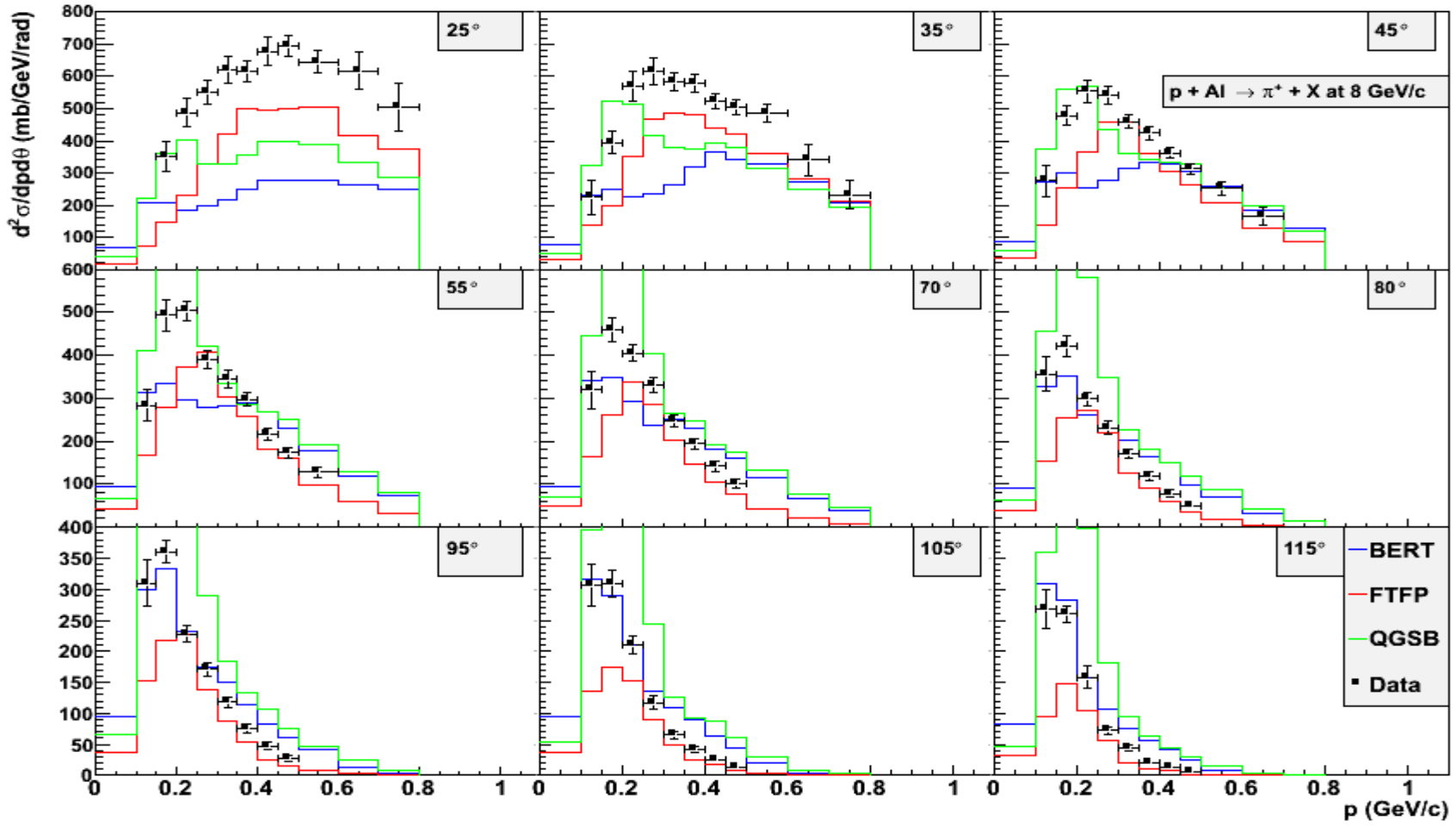
Phys. Rev. C82 (2010) 045208

HARP Data: Forward π^-



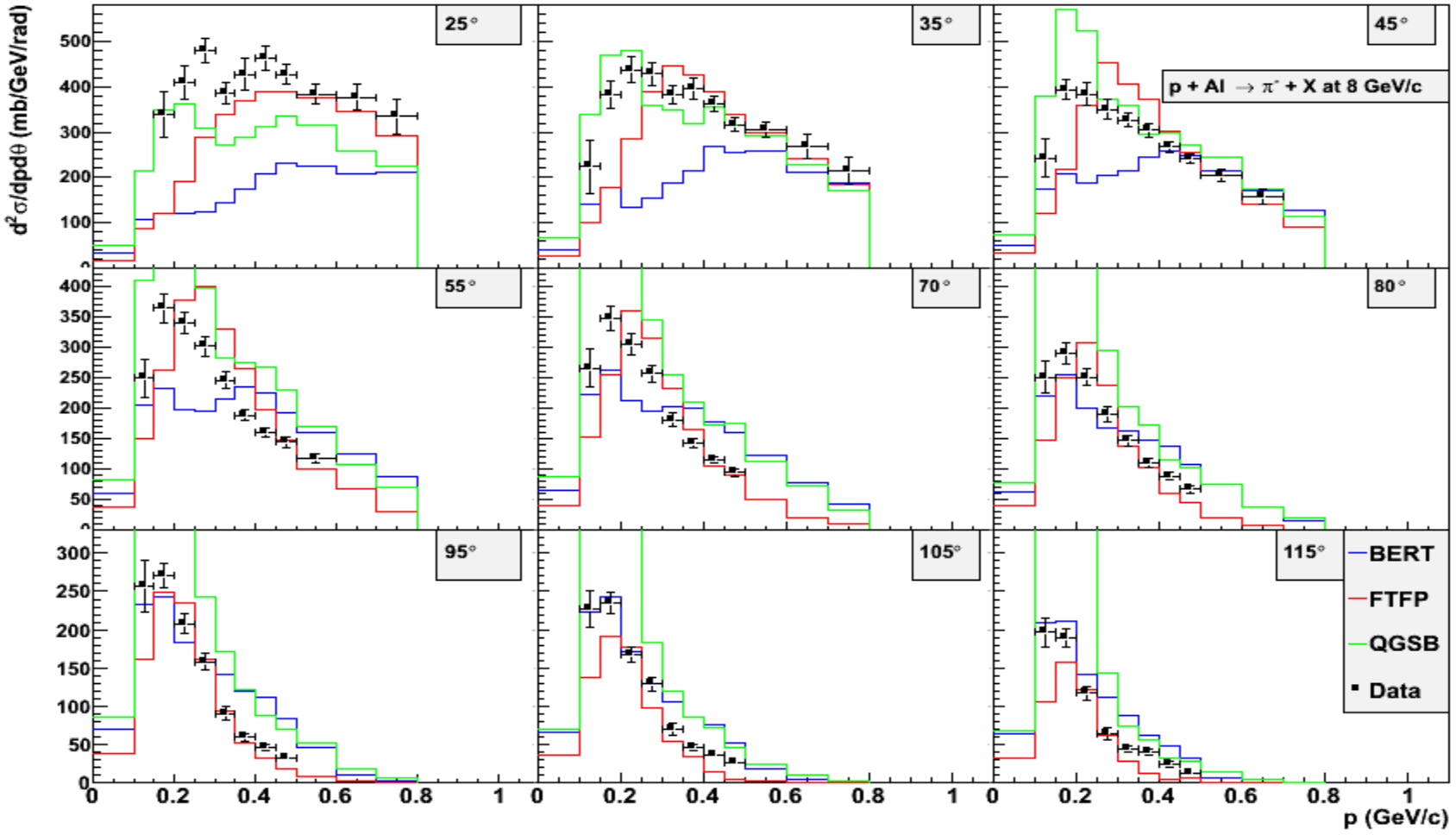
Phys. Rev. C80 (2009) 035280

HARP Data: Large Angle π^+



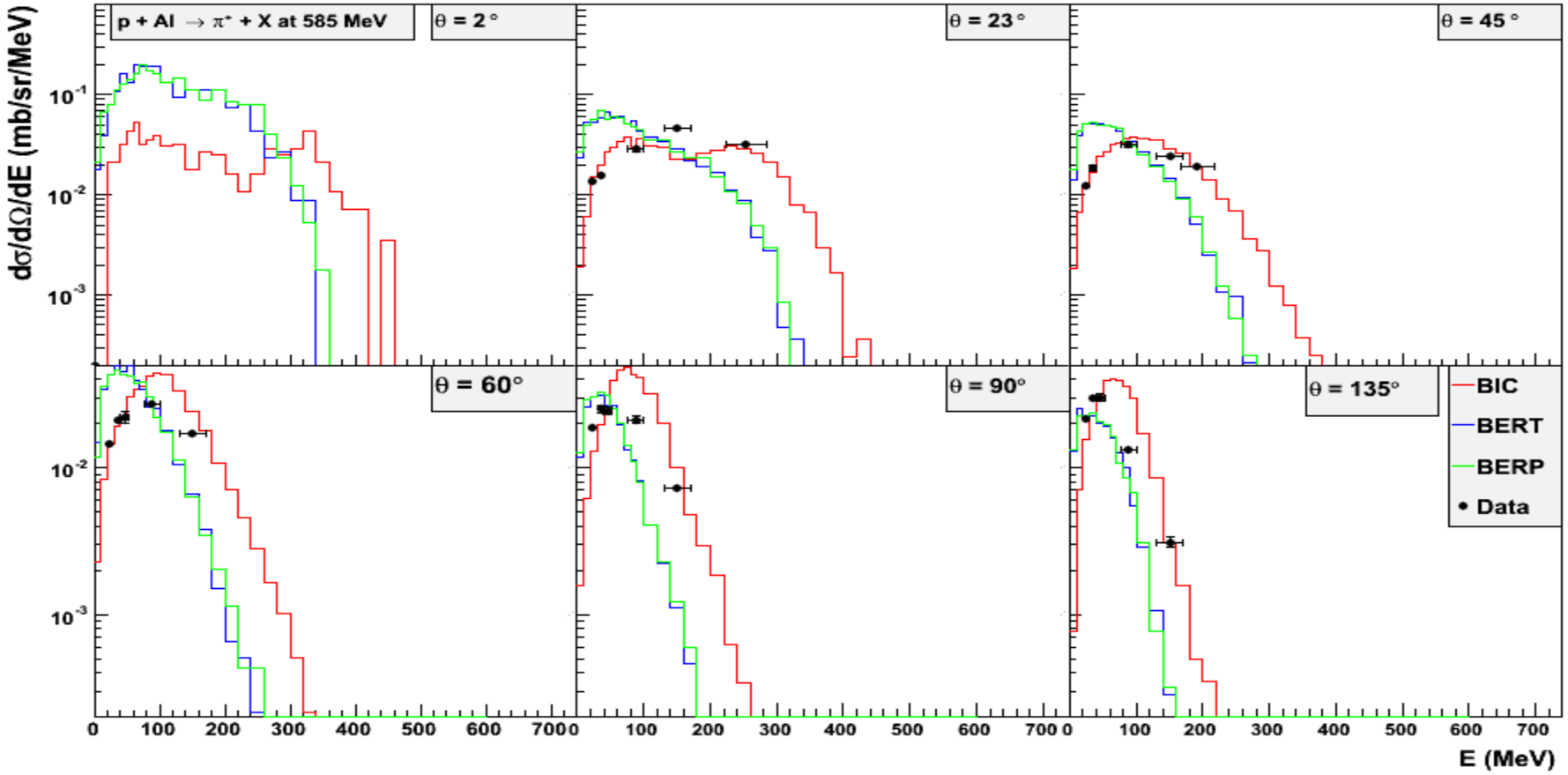
Phys. Rev. C82 (2010) 045208

HARP Data: Large Angle π^-

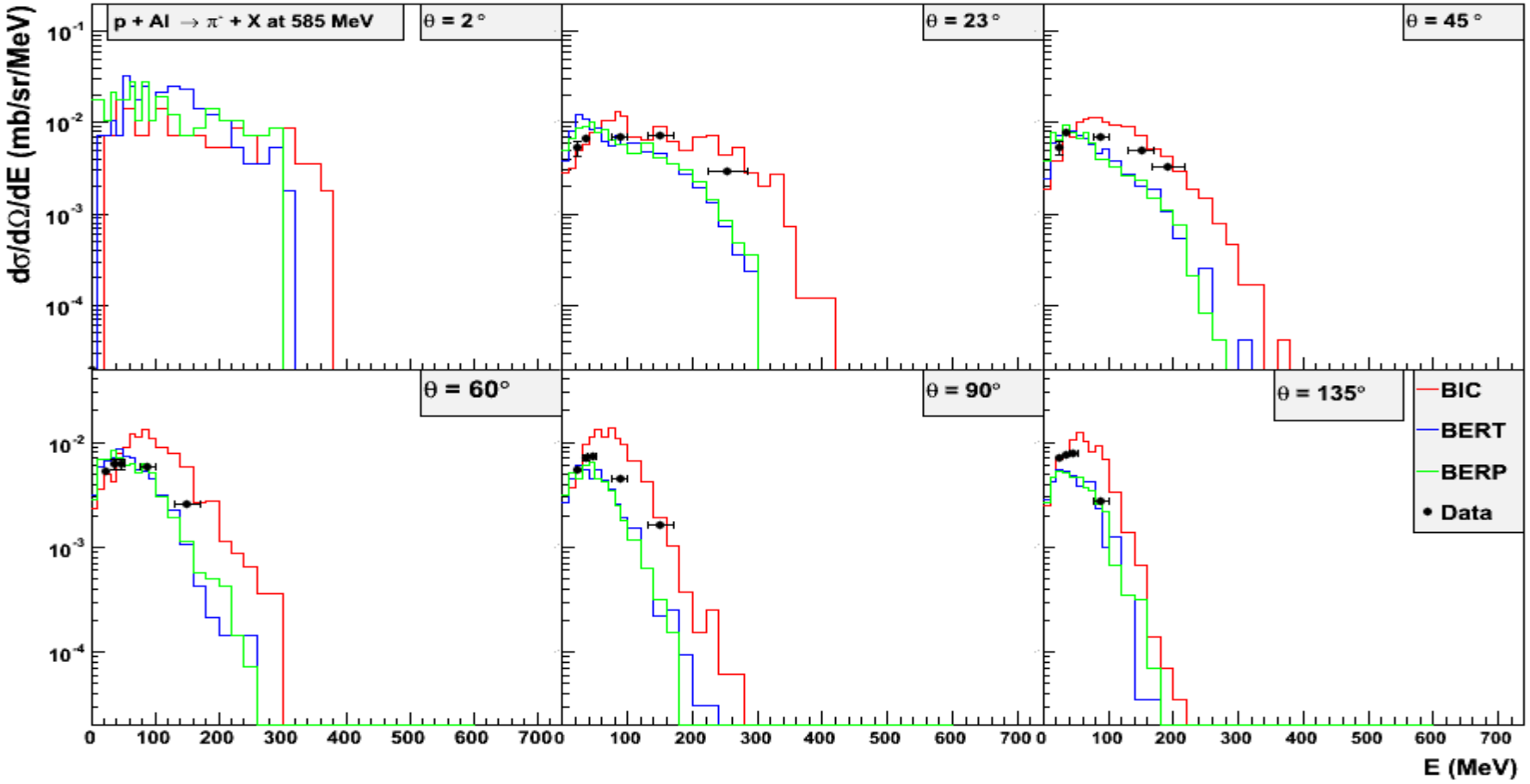


Phys. Rev. C82 (2010) 045208

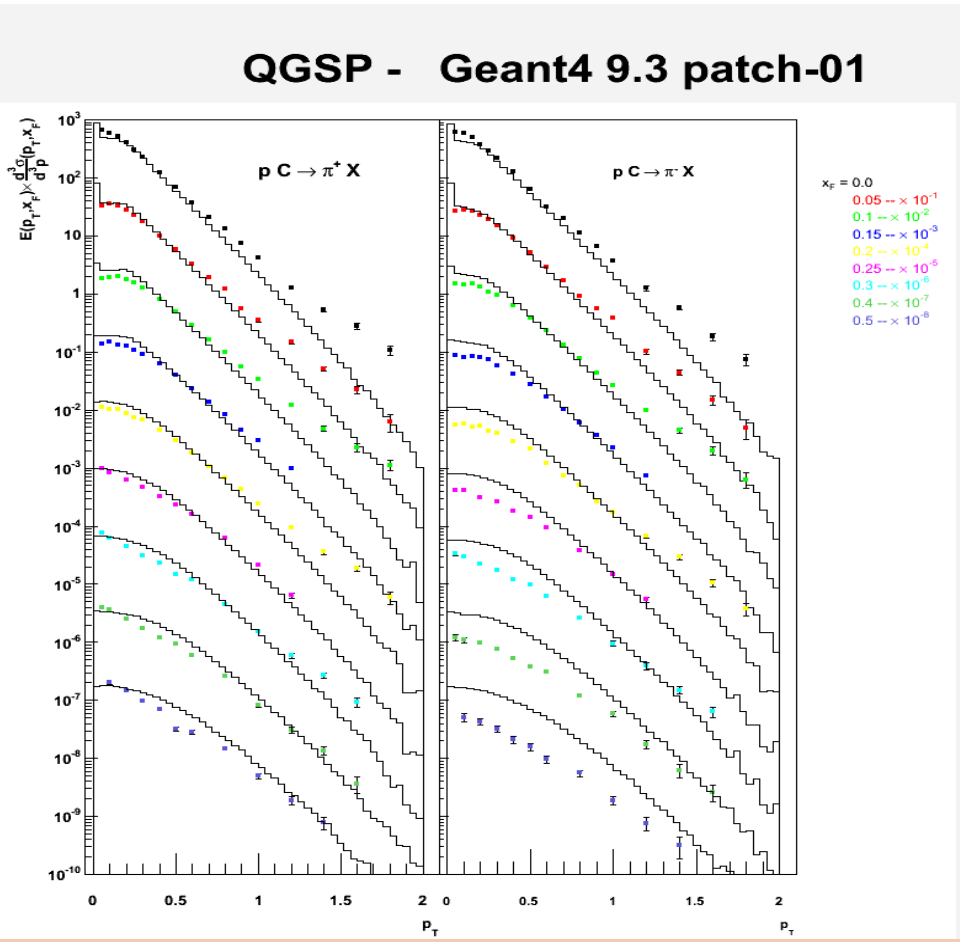
Large Angle π^+

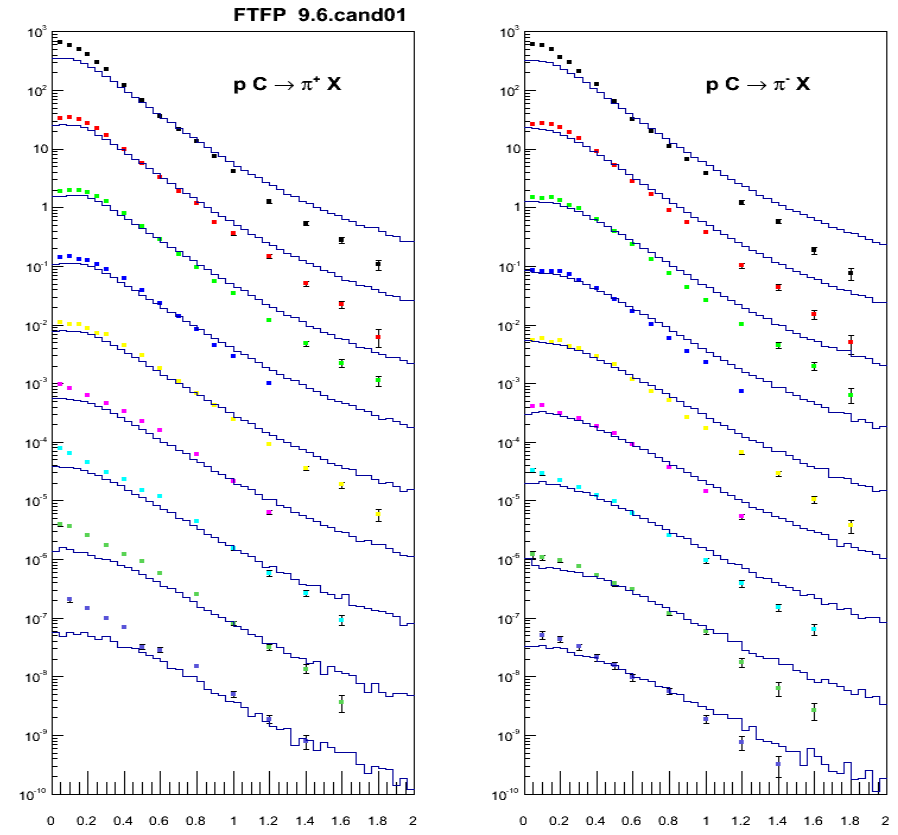


Large Angle π^-



Transfer momentum for different bins in y QGS versus FTF



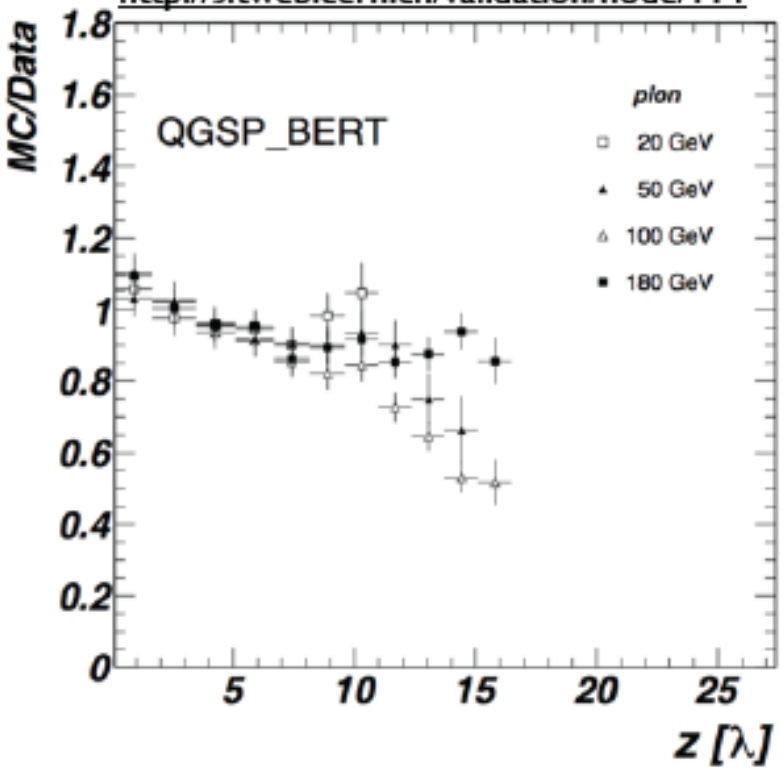


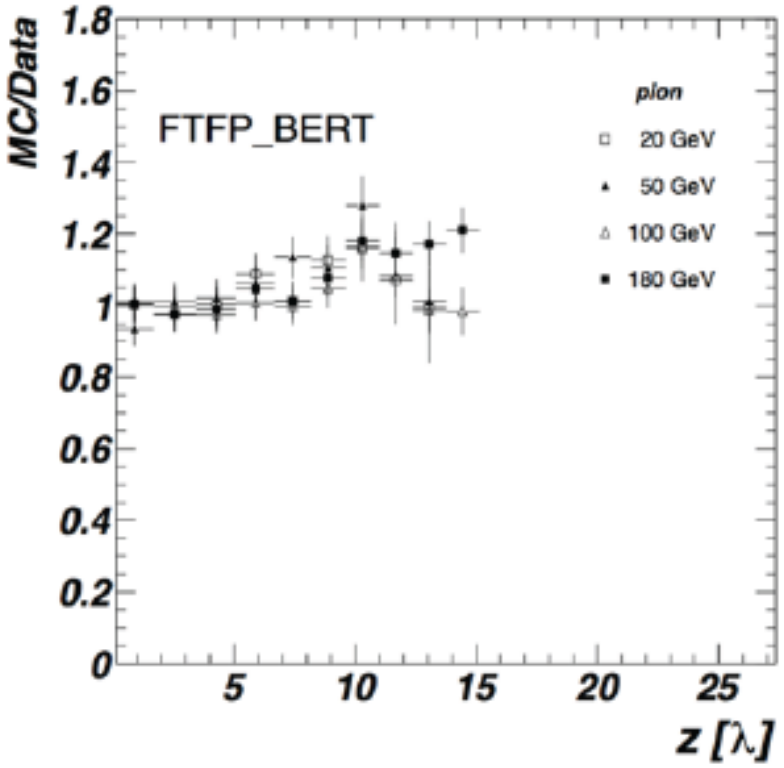
http://geant4.cern.ch/results/validation_plots/thin_target/hadronic/high_energy/index.shtml

Longitudinal TileCal

Geant4 9.6

http://sftweb.cern.ch/validation/node/114



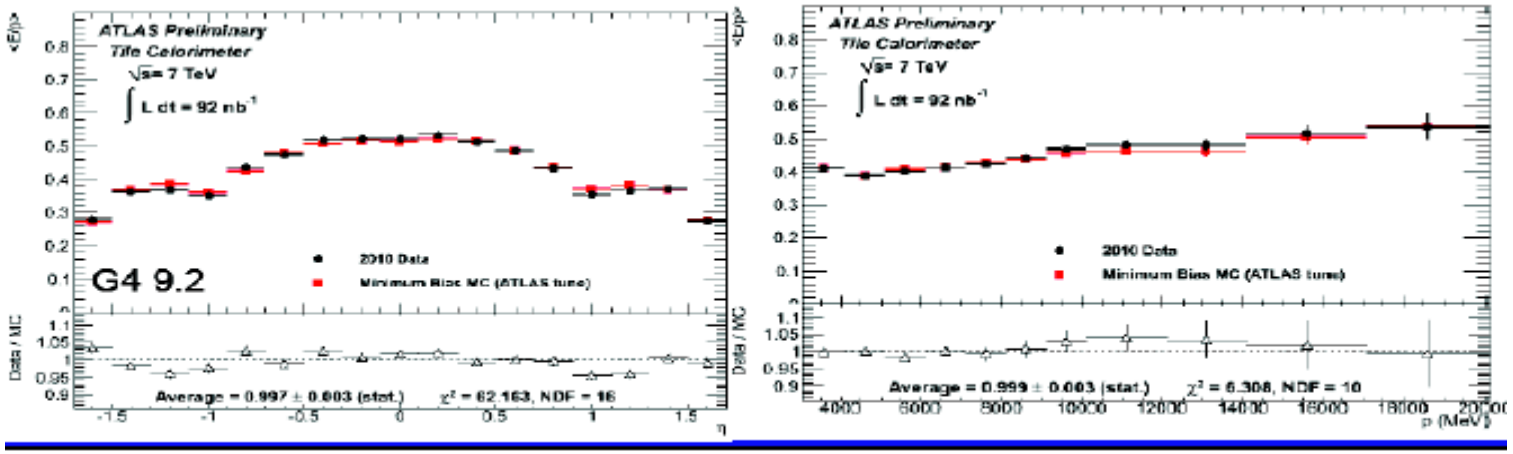


http://sftweb.cern.ch/validation

ATLAS data/Monte Carlo Comparisons

Energy Response (III)

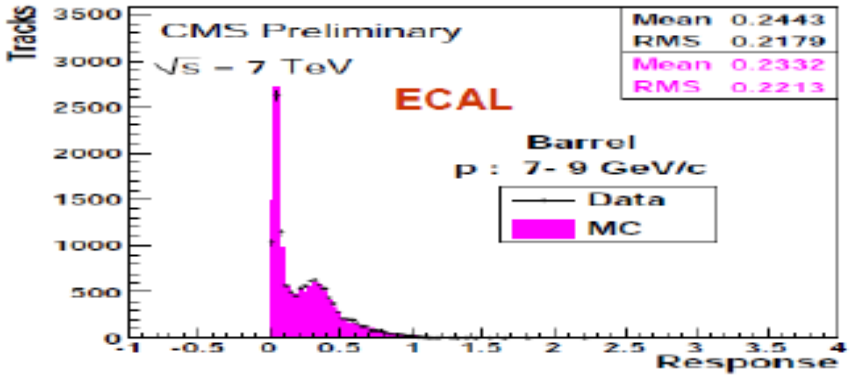
- Also measured in the tile calorimeter in situ using particles that deposit only minimal energy in the EM calorimeter
  - Background is largely caught by the EM calorimeter, so this should really be measuring isolated hadron response in the tile calorimeter
- Excellent agreement with the MC simulation
  - Note: no statement about the fraction of hadrons not interacting in

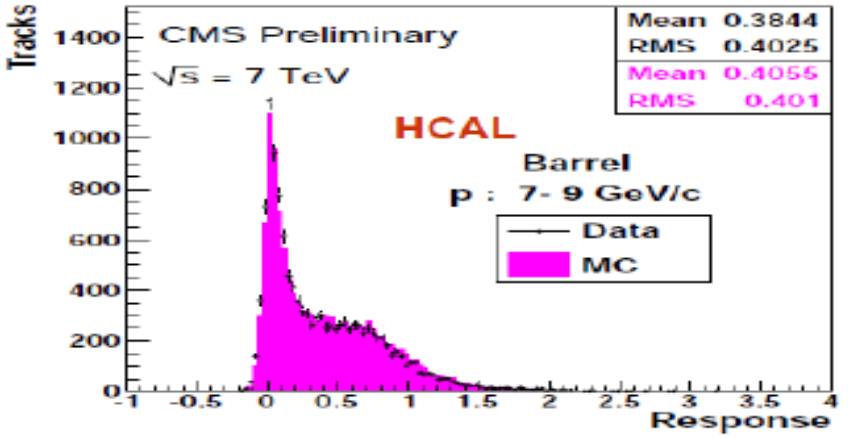


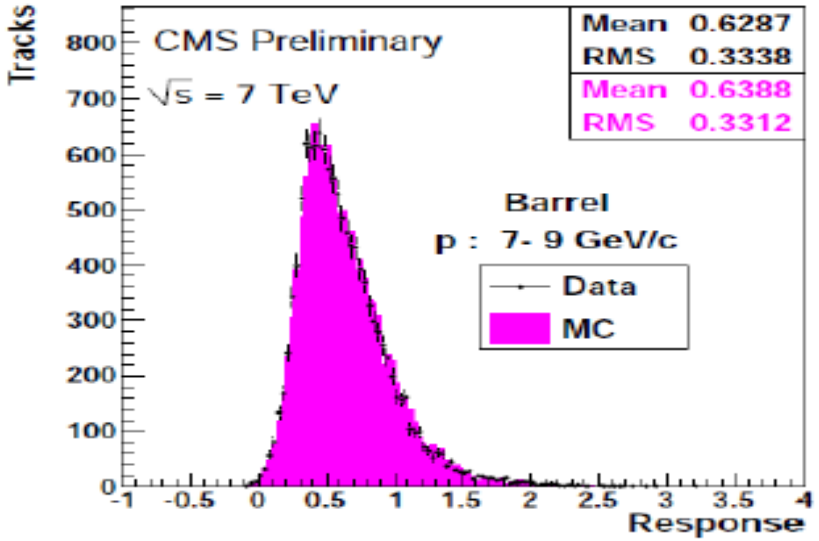
6 Oct 2011 Z Marshall - Data/MC Comparisons in Hadronic Physics 9

CMS data/Monte Carlo Comparisons

Barrel Region (I)







- Overall agreement is quite reasonable: small difference in individual contributions

Results for CMS Calorimeters S. Banerjee 26