Hadronic Shower Shape studies in Geant4

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Outline

- Motivation
- Strategy
- Simplified calorimeter setup
- Observables
- Results
- Summary

Motivation

From comparisons between data from calorimeter test-beams of LHC experiments (ATLAS HEC, ATLAS TileCal, CMS HCAL) with Geant4 simulations with LHEP and QGSP Physics Lists, it has been concluded that:

- σ_E/E is described well by LHEP and even better by QGSP;
- e/π is described very well by LHEP and even better by QGSP;
- hadronic shower shapes at high energies (≥ 100 GeV) are shorter and narrower than data for QGSP, whereas LHEP looks better.
  At lower beam energies, both QGSP and LHEP describe better the hadronic showers.

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Strategy

The goal is to understand the impact of the various physics processes on the development of hadronic showers, in order to improve the longitudinal (and lateral) shower profiles.

To tackle this complex problem we use two complementary approaches:

1. "microscopic" : study single physics processes, using thin-target data;
2. "macroscopic" : monitor the observables of a sampling calorimeter setup to compare different physics simulations.

This talk is devoted only to the latter approach!

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Strategy (cont.)

For the first approach, we start from those physics aspects that we suspect have a major impact on calorimeter observables:

- elastic scattering
- neutron production and transportation
- pion inelastic cross-sections
- multiplicity and spectra.

For the second approach, we start comparing some of the Physics Lists available in Geant4:

- LHEP, QGSP, QGSC, FTFP
- QGSP_BIC, QGSP_BERT
- QGSP_HP, QGSP_BERT_HP.

Simplified Calorimeter setup (1)

Ultimately, the LHC calorimeter test-beam data will validate any improvement in the hadronic shower shapes.

However, it is useful to compare different physics simulations, between themselves without real data, in simplified calorimeter setups:

- to avoid to repeat, each time, long and laborious analyses, which can be done (currently) only by the experimentalists;
- to look to many other variables, even not measurable, but still interesting;
- to decouple pure physics effects from instrumental details (beam composition, beam profile, complex geometry, noise, cross-talk, digitization, and reconstruction).

Simplified Calorimeter setup (2)

- It reproduces, in a simplified way, all the LHC calorimeters: Fe-Sci , Cu-Sci , Cu-LAr , W-LAr
  Pb-Sci , Pb-LAr , PbWO4 .

- Beam particle type: π^+ , π^- , k^+ , k^- , k_L^0 , p , n , e^- .

- Beam energy: 1, 2, 3, ..., 10, 20, 30, 40, 50, 60, 80, 100, 120, 150, 180, 200, 250, 300 (1000) GeV.

- The calorimeter is a tube. The user can choose:
  - the total thickness of the absorber (in [mm] or λ)
  - the radius of the tube (in [mm] or λ)
  - the thickness of the active layer
  - the number of layers
  - the number and the size (in [mm] or λ) of the rings for the lateral shower profile.

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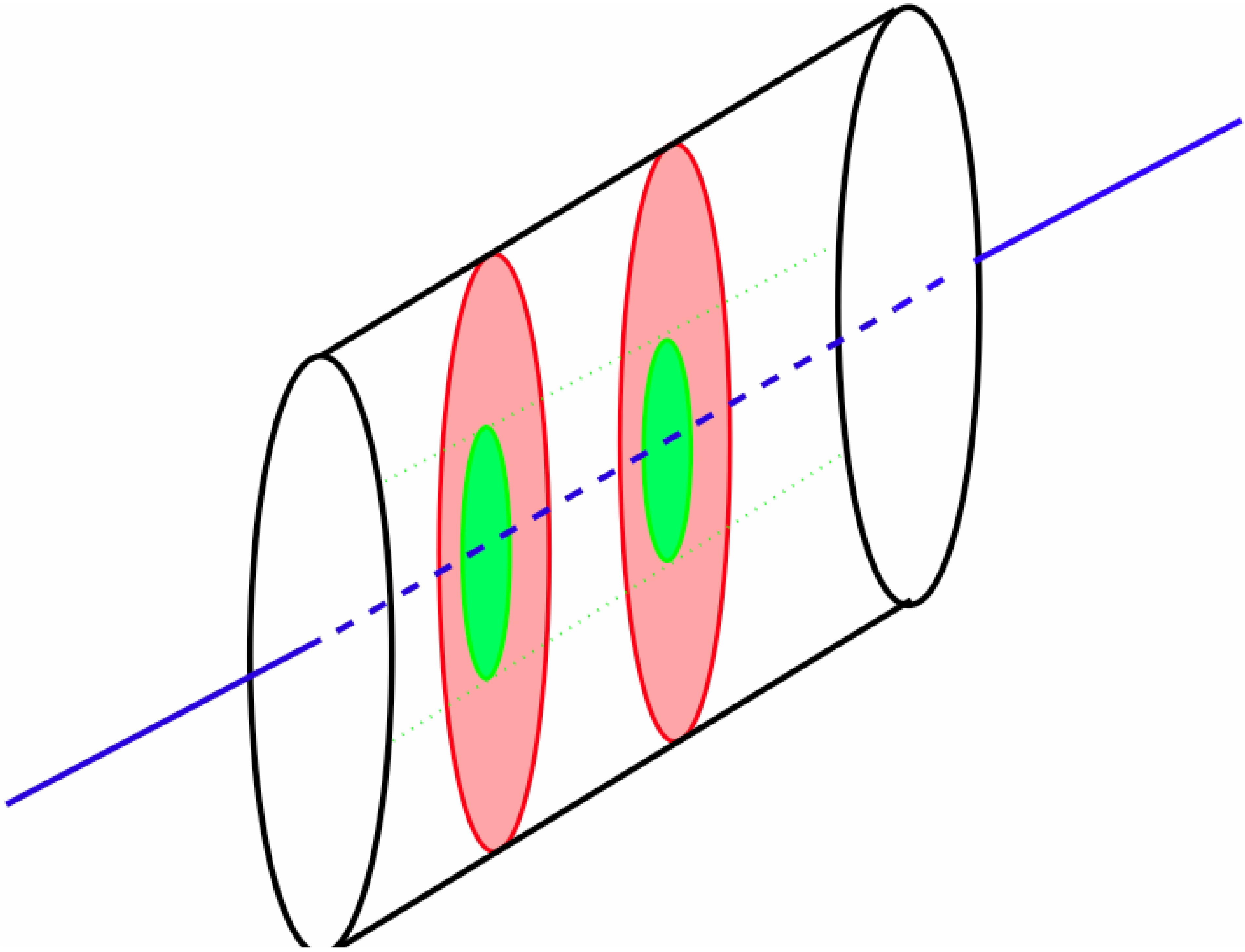

“Observables”

- total energy deposit in all active layers
- total energy deposit in the whole calorimeter
- energy deposit in each active layer
  (longitudinal shower profile)
- energy deposit in each ring (i.e. radial bin)
  (lateral shower profile)
- \- average number of steps and tracks per event;
  \- average track and step length;
  \- average number and Ekin of exiting tracks;
  \- kinetic energy spectra of tracks entering some active layers;
  each of these is done for different particle types and also for all particle tracks;
  \- contributions to the visible energy and shower shapes for different particle types.

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Configurations used

- Geant4 8.0.ref04 (so, rough hadronic elastic!)
- default production range cut: 0.7 mm
  (but we made some tests also with 10 μm)
- Primary beam particle: 30, 100, 300 GeV π^-
- Main setup: simplified ATLAS HEC
  60 layers Cu (25 mm) - LAr (8.5 mm)
  (about 10 lambda), with 20 readout layers.

NB) We studied also the simplified CMS HCAL
25 layers Cu (60 mm) - Sci (4 mm)
but it is too sensitive to the elastic scattering...

Beam energy **30 GeV**

Normalized shower shapes
per Physics List

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Beam energy **100 GeV**

Normalized shower shapes
per Physics List

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Beam energy **300 GeV**

Normalized shower shapes
per Physics List

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Some observations

- For both the longitudinal and lateral profiles:
  QGSP ≤ QGSP_BIC ≤ QGSP_BERT ≤ QGSP_BERT_HP

- The effect of _HP is mainly outside the "bulk" of the shower (in the longitudinal and lateral tails).

- LHEP produces the longest showers at 100 and 300 GeV; at 30 GeV it is the shortest (but close to QGSP); for the lateral profile, LHEP is always wider than QGSP and QGSP_BIC, and narrower than QGSP_BERT_HP; with respect QGSP_BERT, it is slightly narrower at 30 GeV, and slightly wider at 100 and 300 GeV.

- QGSC and FTFP are very similar to QGSP (not shown here!)

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E_{vis} , σ_E/E , e/π

In these comparisons between different Geant4 Physics Lists, we concentrate only on the hadronic shower shapes, but of course there are other important observables to consider, such as the visible energy, energy resolution, and e/π.
Briefly:

- For the visible energy
  LHEP ≤ QGSP ≤ QGSP_BIC ≤ QGSP_BERT
  ≤ QGSP_BERT_HP
- For the the energy resolution and the ratio e/π
  LHEP ≥ QGSP ≥ QGSP_BIC ≥ QGSP_BERT
  ≥ QGSP_BERT_HP

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Particle contributions

- We want to study how much different particle types contribute to the visible energy, and which is shower shape (longitudinal and transverse) for each of them.

- We consider the following particle types
  1. e^-/e^+
  2. p/pbar
  3. π^+/π^-
  4. nuclei (PDG code = 0)

  NB) The contribution of kaons and muons is negligible (<1%).

  We consider always a primary beam of π^- .

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Beam energy **30 GeV**

Normalized shower shapes per Particle type

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Beam energy **100 GeV**

Normalized shower shapes
per Particle type

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Beam energy **300 GeV**

Normalized shower shapes
per Particle type

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Some observations

- The relative contribution to the visible energy per particle type is: $e \gg p > \pi > pdg0$
  and the electron dominance grows as the beam energy increases.

- For both longitudinal and lateral shower shapes
  $e \ll \pi < pdg0 < p$

- Comparing QGSP with respect to LHEP :
  - QGSP has larger electron contribution, especially for higher beam energies;
  - QGSP has shorter and narrower electron shape;
  - QGSP has similar shapes for the others (only slightly narrower, and slightly longer at 30 and 300 GeV, for protons and pdg0).

Number of tracks

Let's compare the average number of tracks per event of LHEP with respect QGSP:

	30 GeV	100 GeV	300 GeV
# EM	-10%	-11%	-12%
# $\pi^{+/-/0}$	+16%	+19%	+24%
# p	+12%	+17%	+23%
# n	+12%	+17%	+22%
# pdg0	+13%	+18%	+24%

The ratio π^0/π is the same for LHEP and QGSP!
Consistent with results with 1 km production cut...

Let's look at the particle spectra...

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Beam energy **30 GeV**

Particle ($\pi^{\pm}$, p, n) spectra after 5 λ

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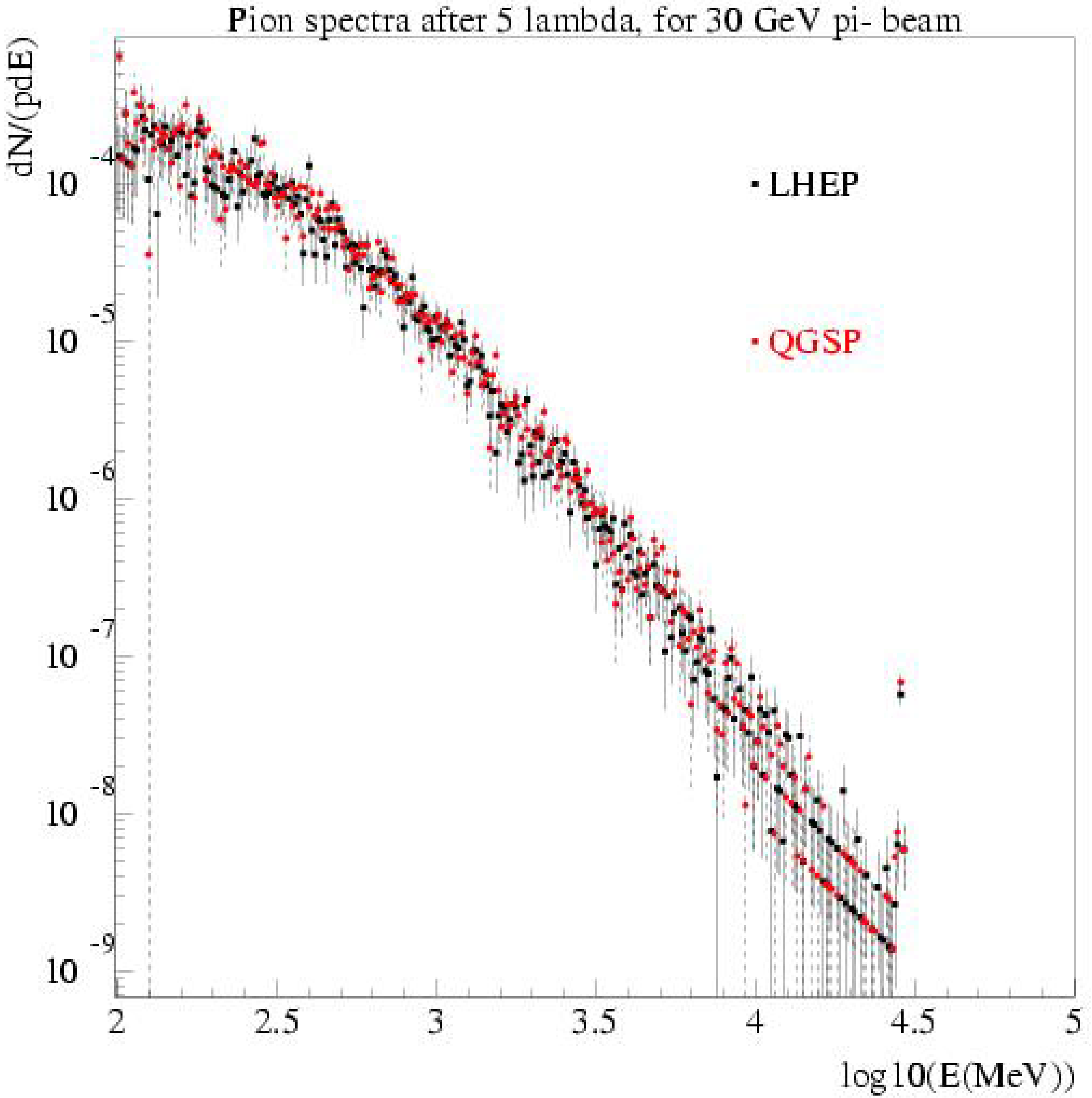

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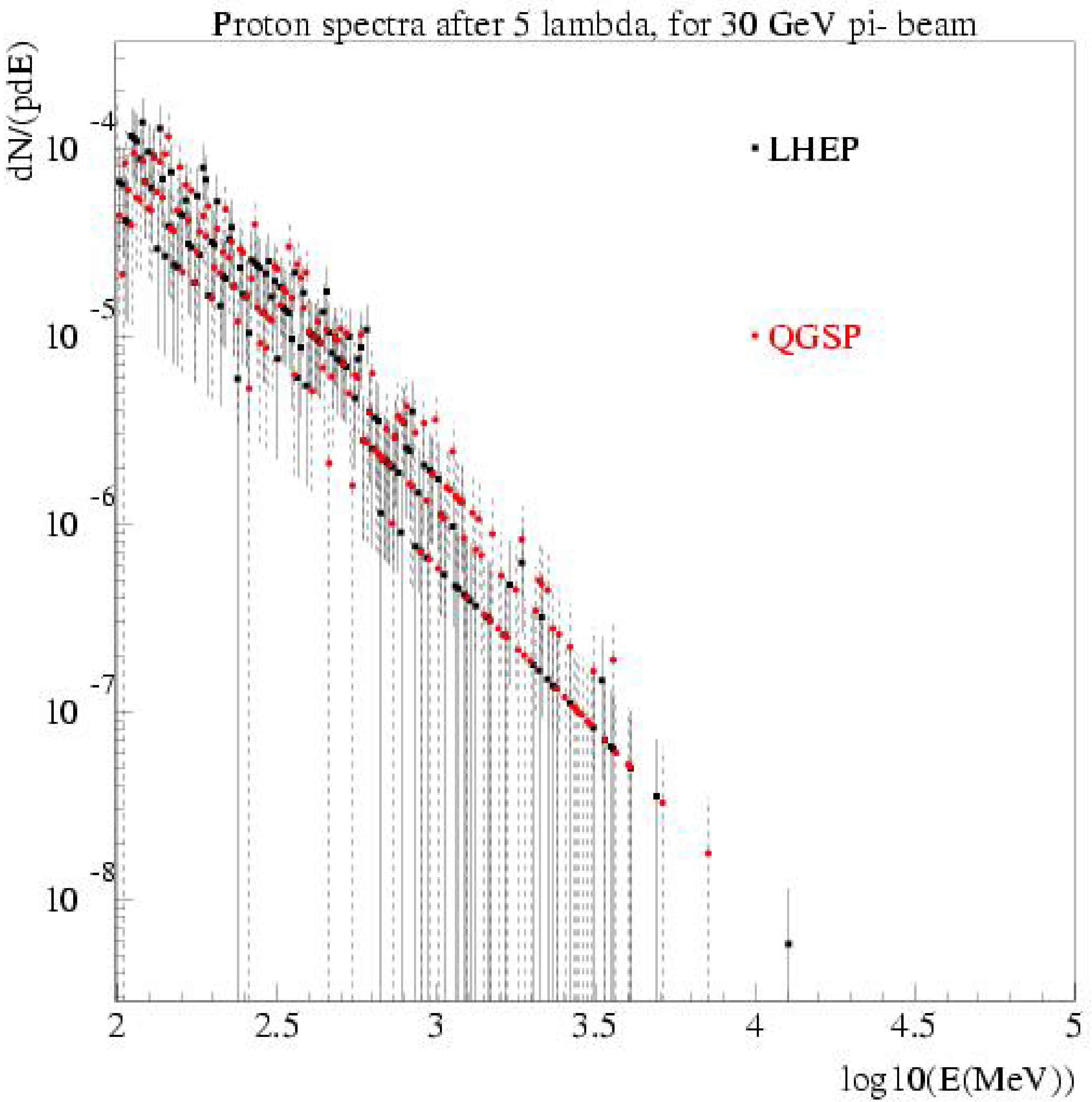

Proton spectra after 5 lambda, for 30 GeV pi- beam
dN/(pdE)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
LHEP
QGSP
2
2.5
3
3.5
4
4.5
5
log10(E(MeV))

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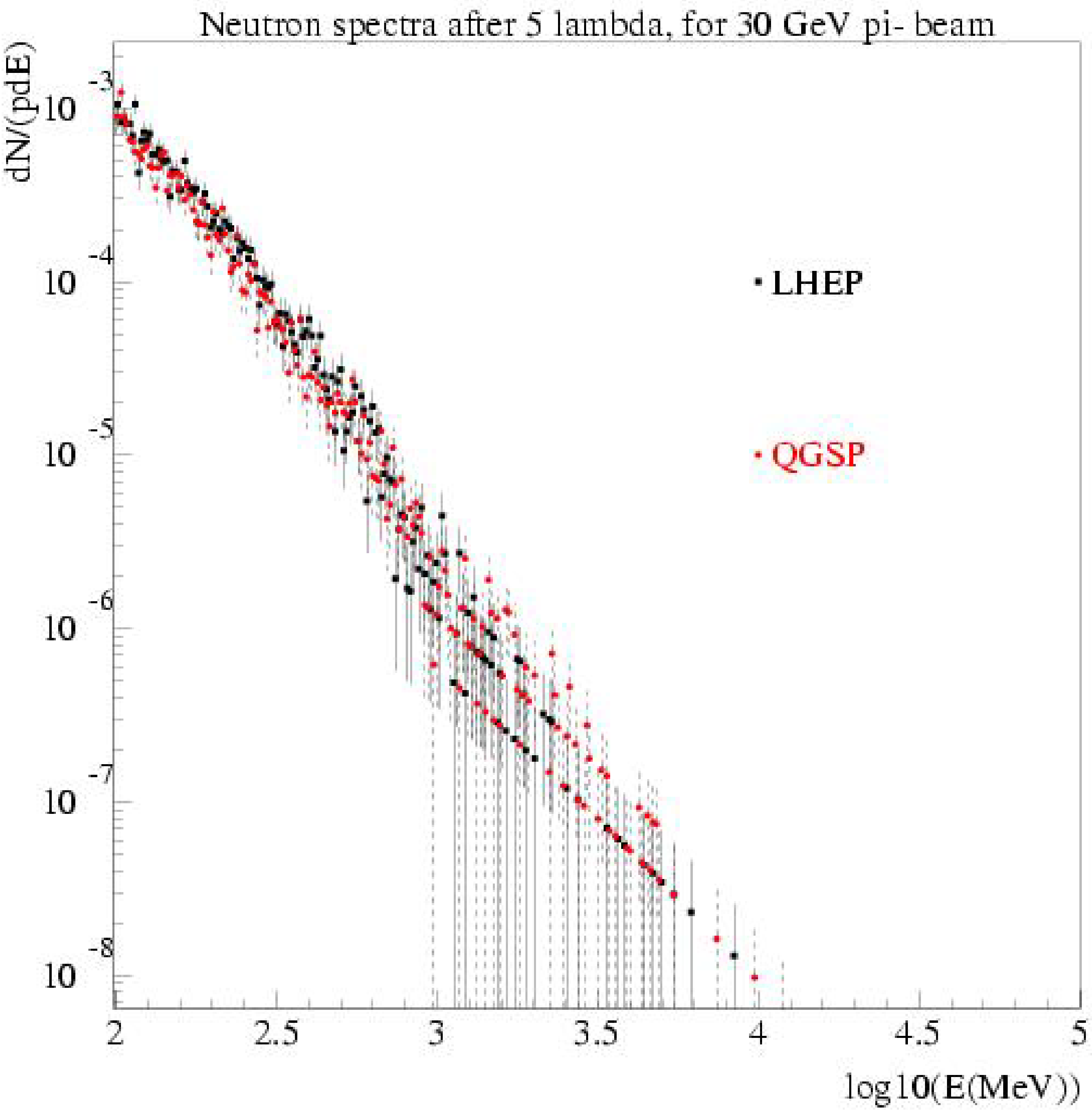

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Beam energy **100 GeV**

Particle ($\pi^{\pm}$, p, n) spectra after 5 λ

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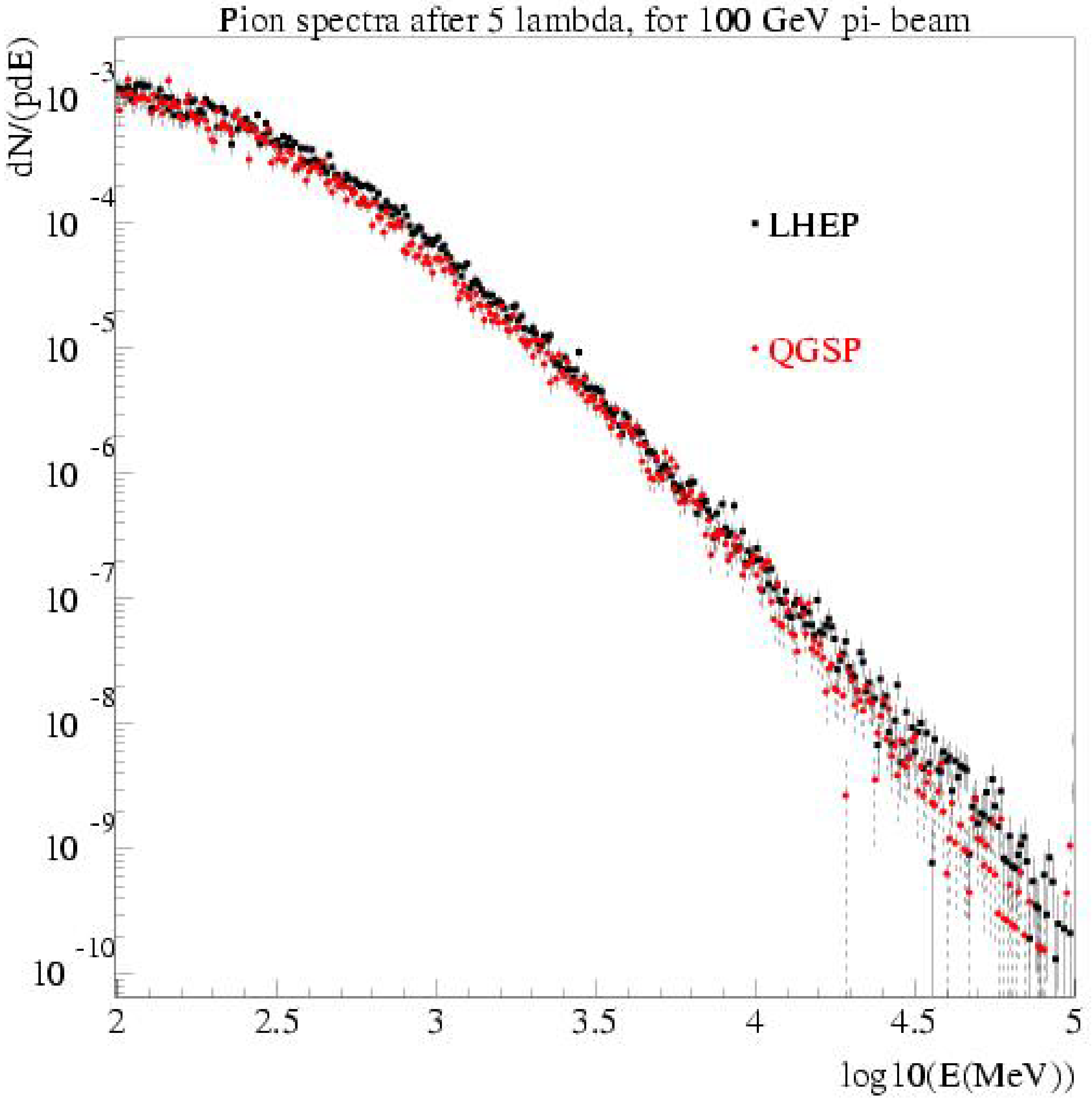
Pion spectra after 5 lambda, for 100 GeV pi- beam
dN/(pdE)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
LHEP
QGSP
2
2.5
3
3.5
4
4.5
5
log10(E(MeV))

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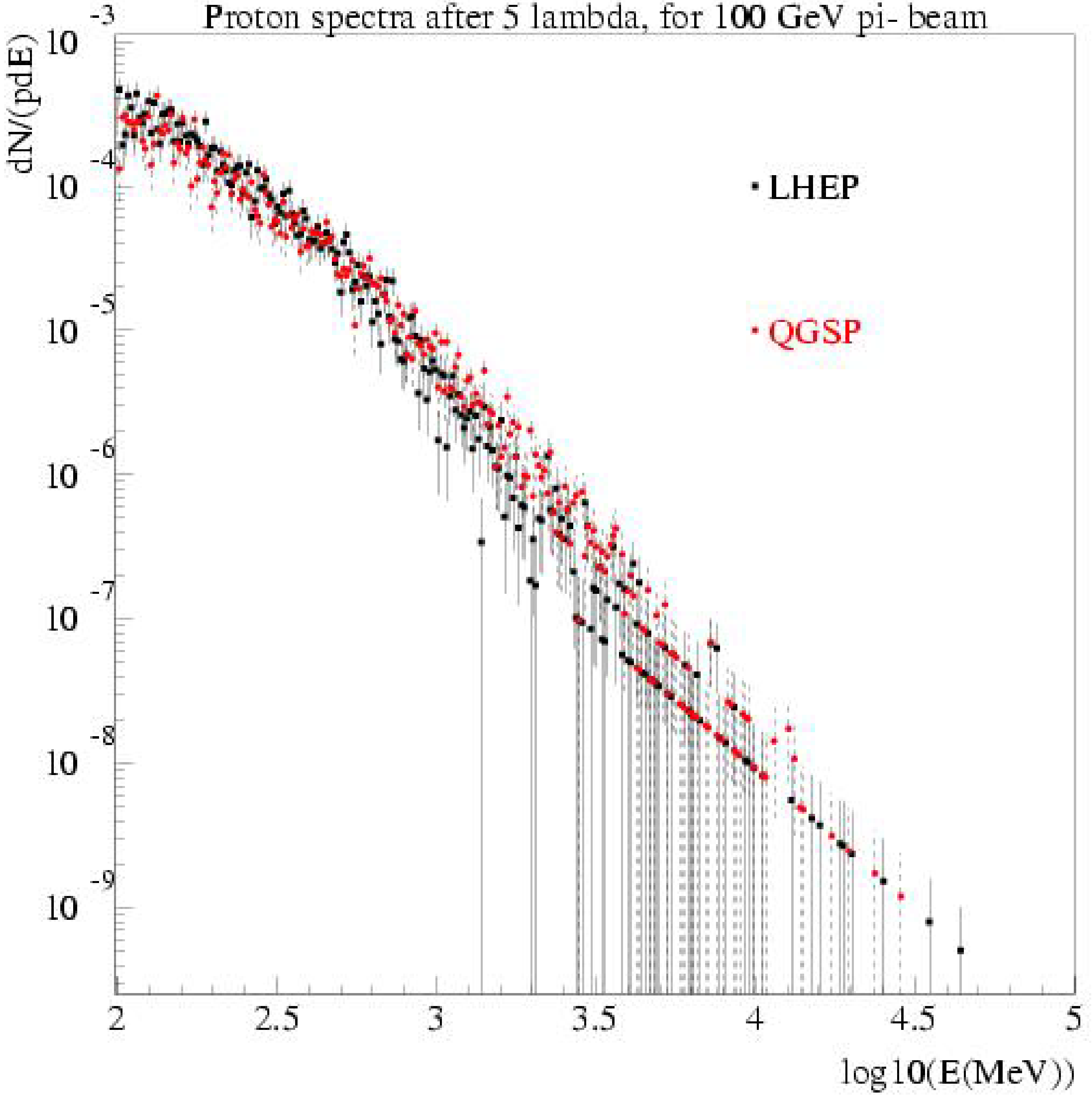
Proton spectra after 5 lambda, for 100 GeV pi- beam
dN/(pdE)
LHEP
QGSP
log10(E(MeV))
2
2.5
3
3.5
4
4.5
5

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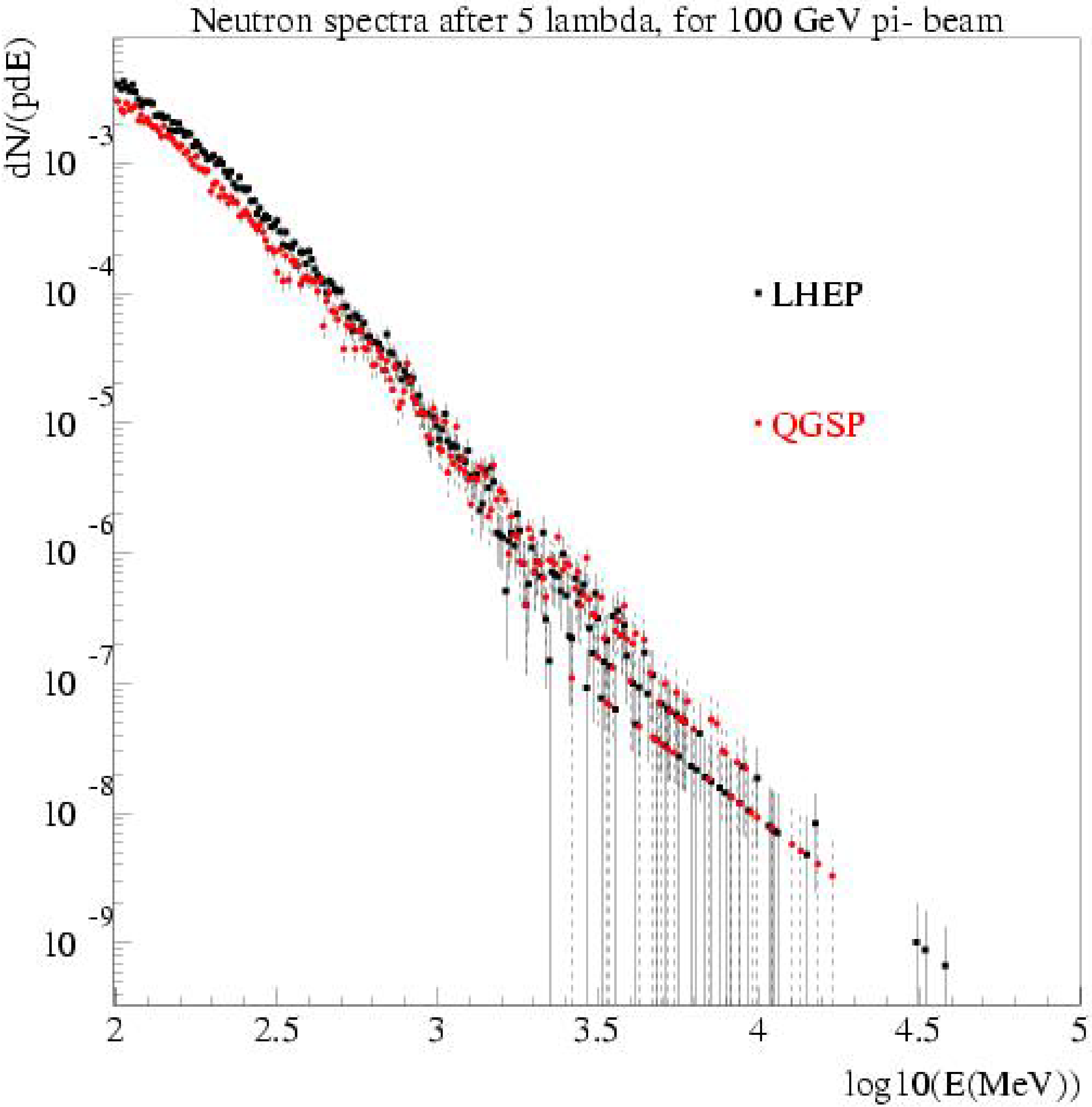
Neutron spectra after 5 lambda, for 100 GeV pi- beam
dN/(pdE)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
LHEP
QGSP
2
2.5
3
3.5
4
4.5
5
log10(E(MeV))

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Beam energy **300 GeV**

Particle ($\pi^{\pm}$, p, n) spectra after 5 λ

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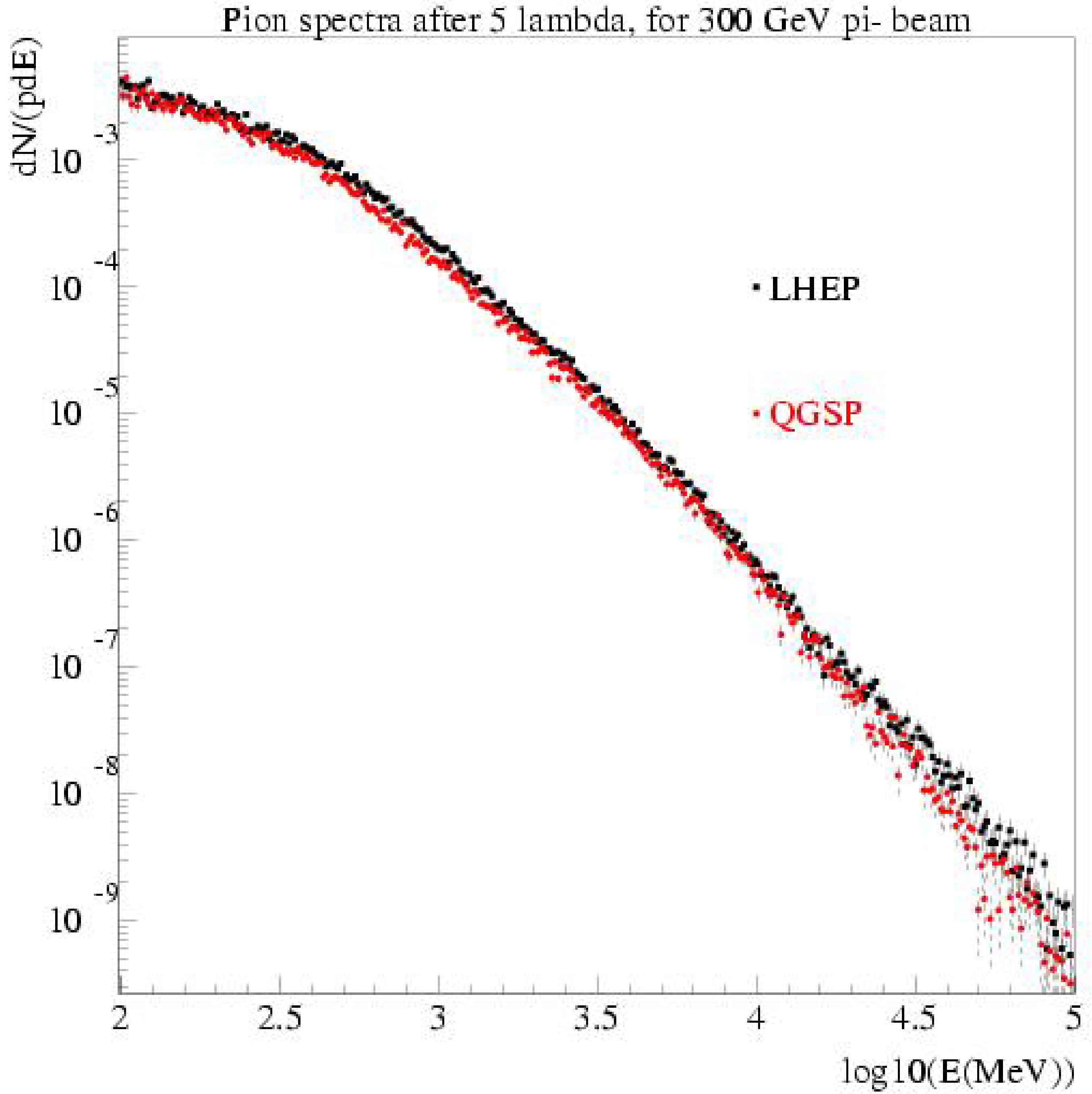
Pion spectra after 5 lambda, for 300 GeV pi- beam
dN/(pdE)
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
2
2.5
3
3.5
4
4.5
5
log10(E(MeV))
LHEP
QGSP

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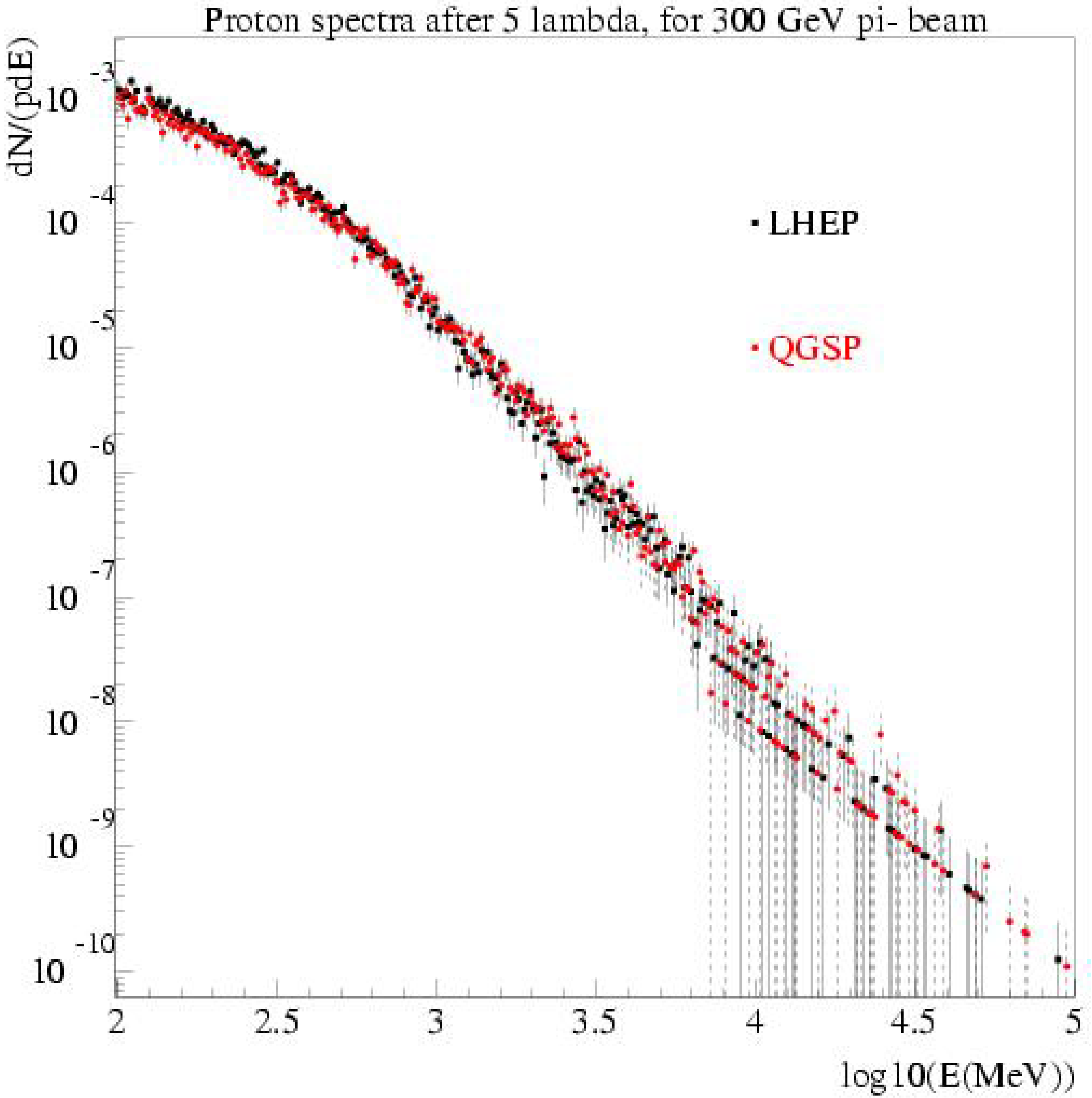

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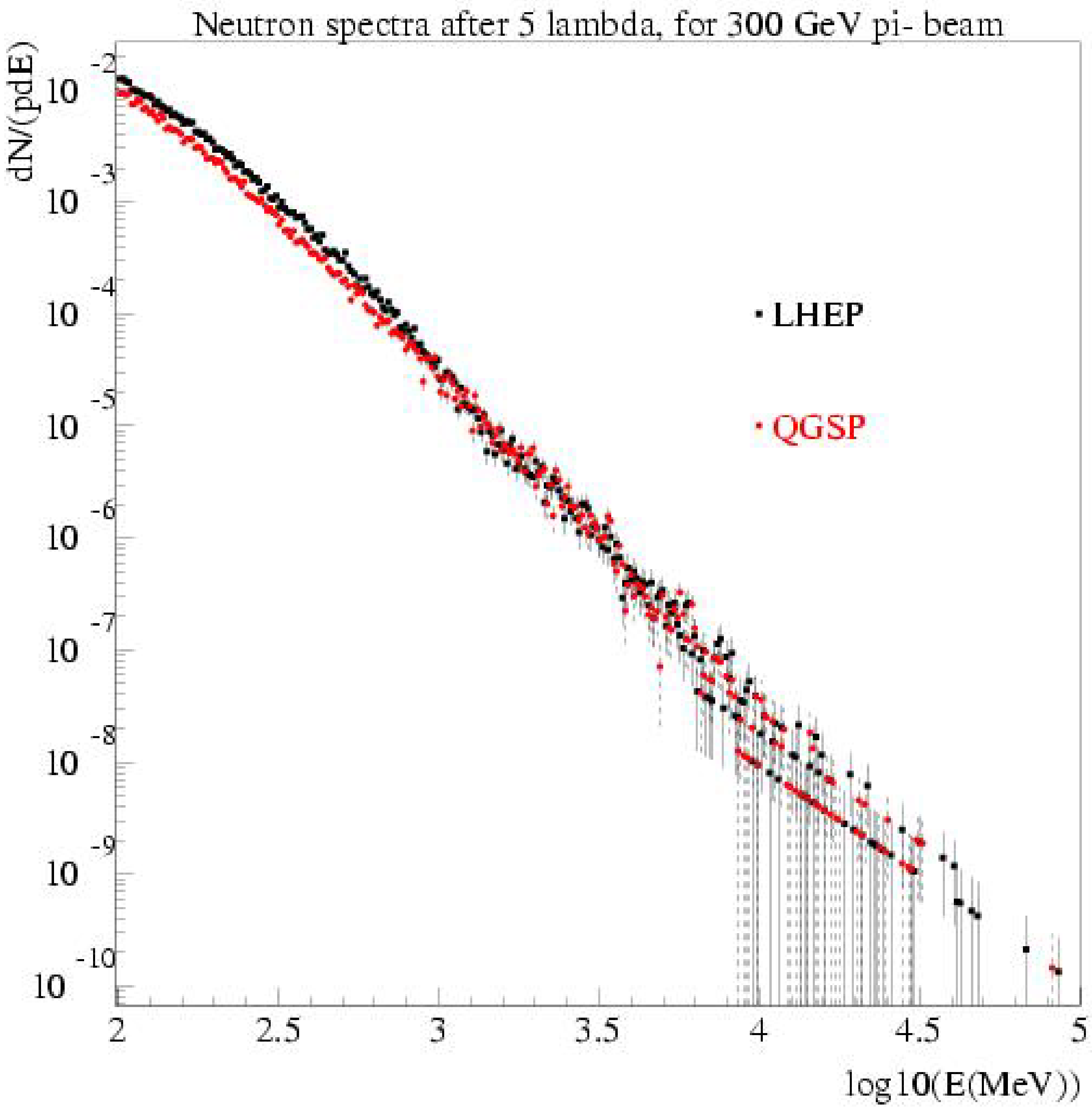

Neutron spectra after 5 lambda, for 300 GeV pi- beam
dN/(pdE)
log10(E(MeV))
LHEP
QGSP

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Summary

We have compared the hadronic showers for some Geant4 Physics Lists. Although we do not have yet a complete understanding of the differences, some useful information have been collected:

- adding cascade models (Bertini, Binary) the hadronic showers get a bit longer and wider;
- adding a precise transportation of low-energy neutrons (HP) does not affect the bulk of the hadronic showers but contribute to larger tails;
- the parametrized physics list (LHEP) has a reduced, longer and wider EM component,

  a harder spectrum of high-energy $\pi^{\pm}$, and

  more 100 MeV - 1 GeV neutrons.