Physics of shower simulation at LHC, at the example of GEANT4.

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The Monte Carlo Roadmap

- Part 1: Introduction
  - LHC related use cases - LCG.
  - Analyzing showers and their development in matter.
  - Brief overview of hadronic models in geant4
- Part 2: Hadronic showers in bulk matter.
  - Selected topics on hadronic shower simulation:
    - Theory driven modeling of inelastic reactions.
- Part 3: ghad – how good is it really?
- Part 4: Modeling electromagnetic showers.
  - Examples of electromagnetic showers.
  - Selected topics on electromagnetic shower physics.

The cases considered for LHC (LCG)

- Detector design and physics studies
  - Calorimeter test-beam
  - Tracker test-beam
  - Full detector simulation
  - Hadronic interactions in trackers
  - Nucleon penetration

The use-cases

- Radiation studies:
  - Shield optimization
  - Neutron fluences
  - Deep penetration
  - Back-splash
  - Radiation damage
  - Etc..

The basic question: How to simulate a Calorimeter ?

- What makes signal?
- What reacts?
- What defines the shower topologies?
- What processes are happening?
- What defines the em contents of a hadronic shower?
- What is invisible energy?
- How different are different calorimeters?
- How about combined calorimetry?
- Etc..

Analyzing showers

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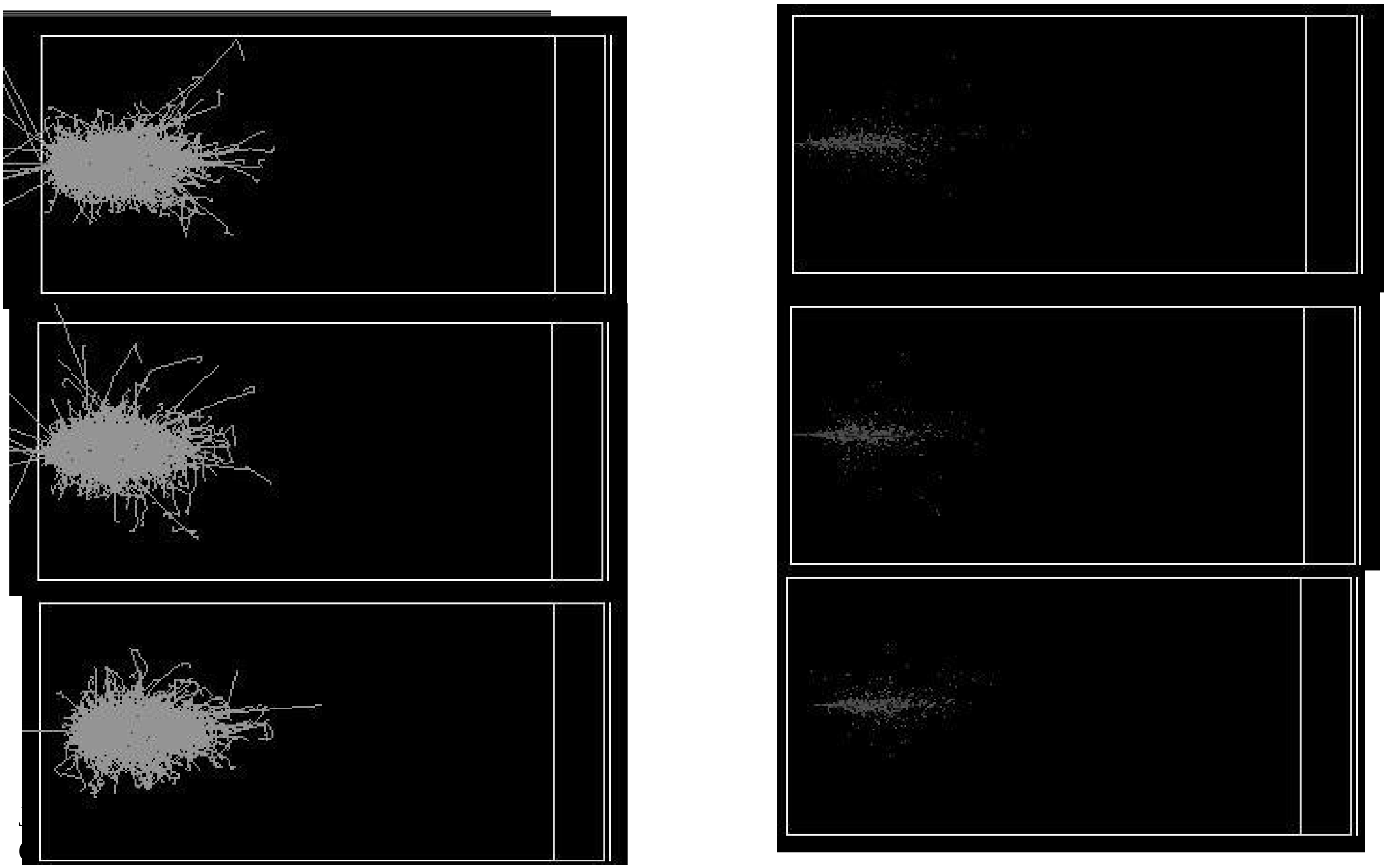
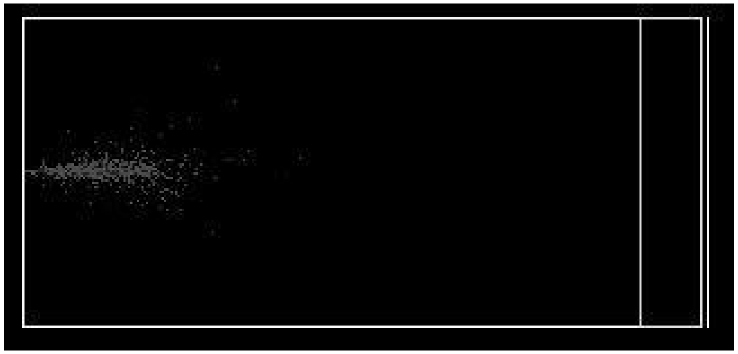
20 GeV gammas in copper (right, charged particles only, left complete)



Modeling electromagnetic showers

- Physics processes involved:
  - Photo effect
  - Compton scattering
  - Pair production
  - Ionization
  - Multiple coulomb scattering
  - Bremsstrahlung
  - Annihilation



- For more detail, please see the complete lecture notes by Michel Maire (LAPP) on the geant4 WWW site, or the geant4 physics reference manual.

A bracket on electromagnetic shower physics in geant4

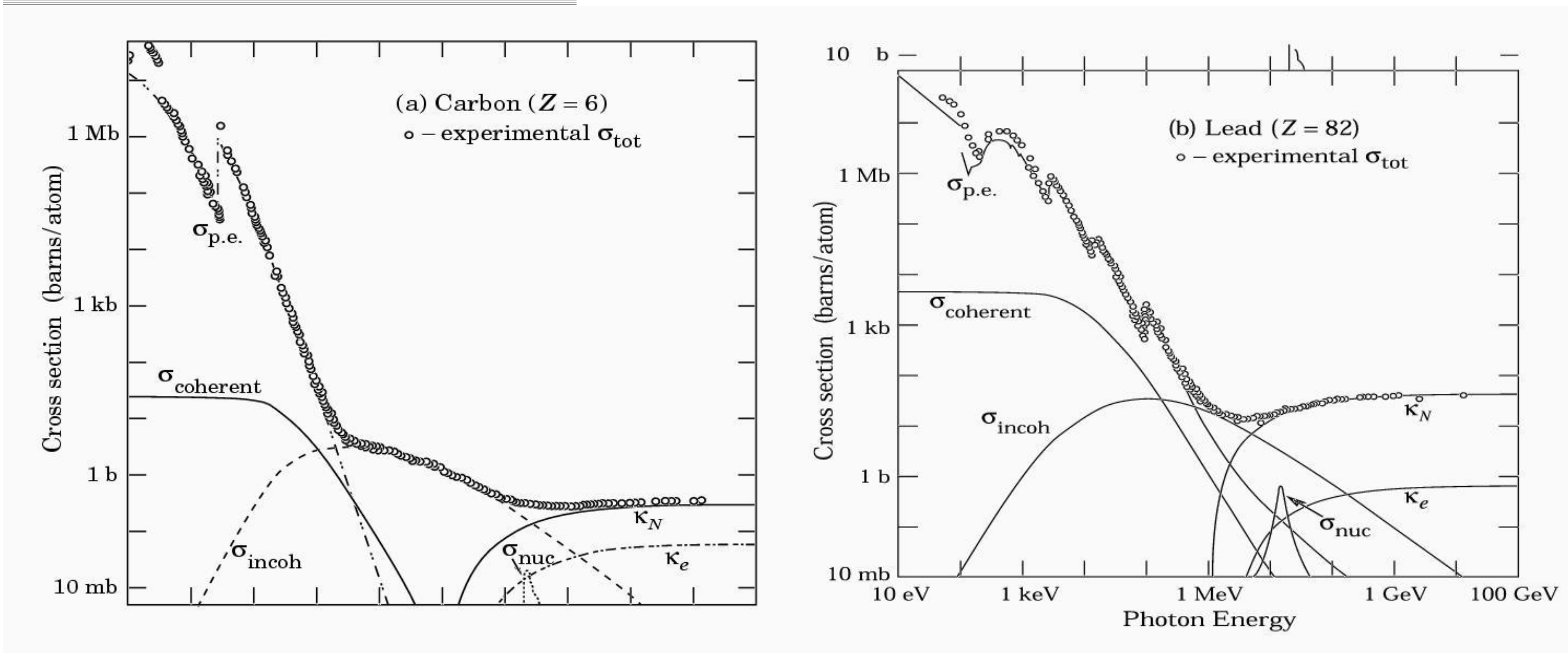
- In geant4, for HEP applications, it is simulated using the 'standard' electromagnetic physics package.
  - All charged particles:
    - Ionization (including delta rays)
    - Multiple coulomb scattering
  - Electrons and positrons
    - Bremsstrahlung
    - Annihilation (e+)
  - Gammas
    - Photo effect
    - scattering (incoherent and coherent, I.e. Compton and Reyleigh)
    - Conversion

It also contains

- Muons
  - Bremsstrahlung
  - Direct pair production (for muons)
  - Muon-nuclear leptonic vertex
- All charged particles:
  - Cerenkov effect
  - Scintillation
  - Transition radiation
- Optical photons
  - Reflection and refraction
  - Absorption
  - Reyleigh scattering

Assumptions:

- Relevant particle energies > 1 keV
- Scattering of a particle in a material is off quasi-free electrons (except for photo effect).
- Doppler broadening (due to bound electron velocities) can be neglected.
- The material is homogeneous and amorphous.



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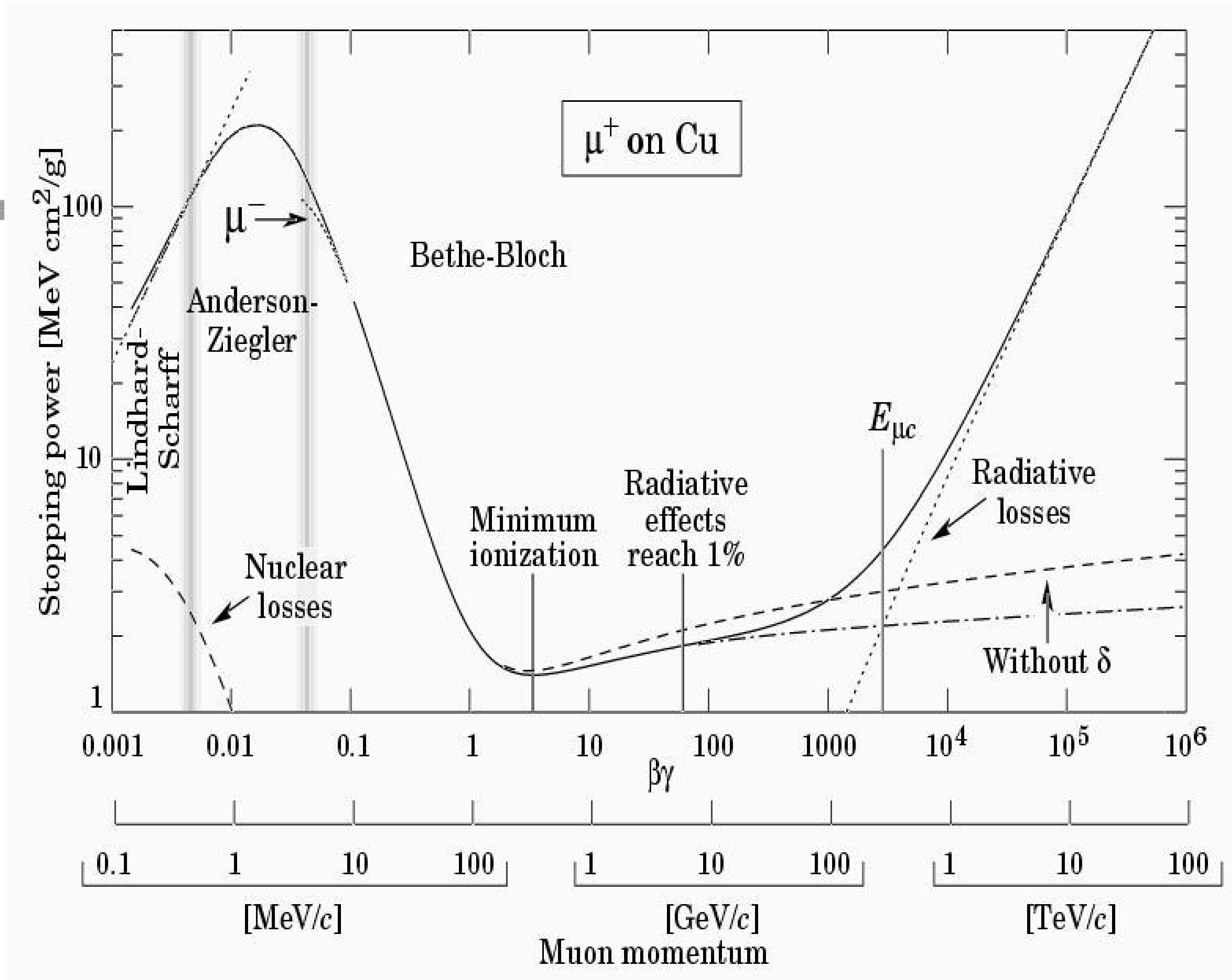

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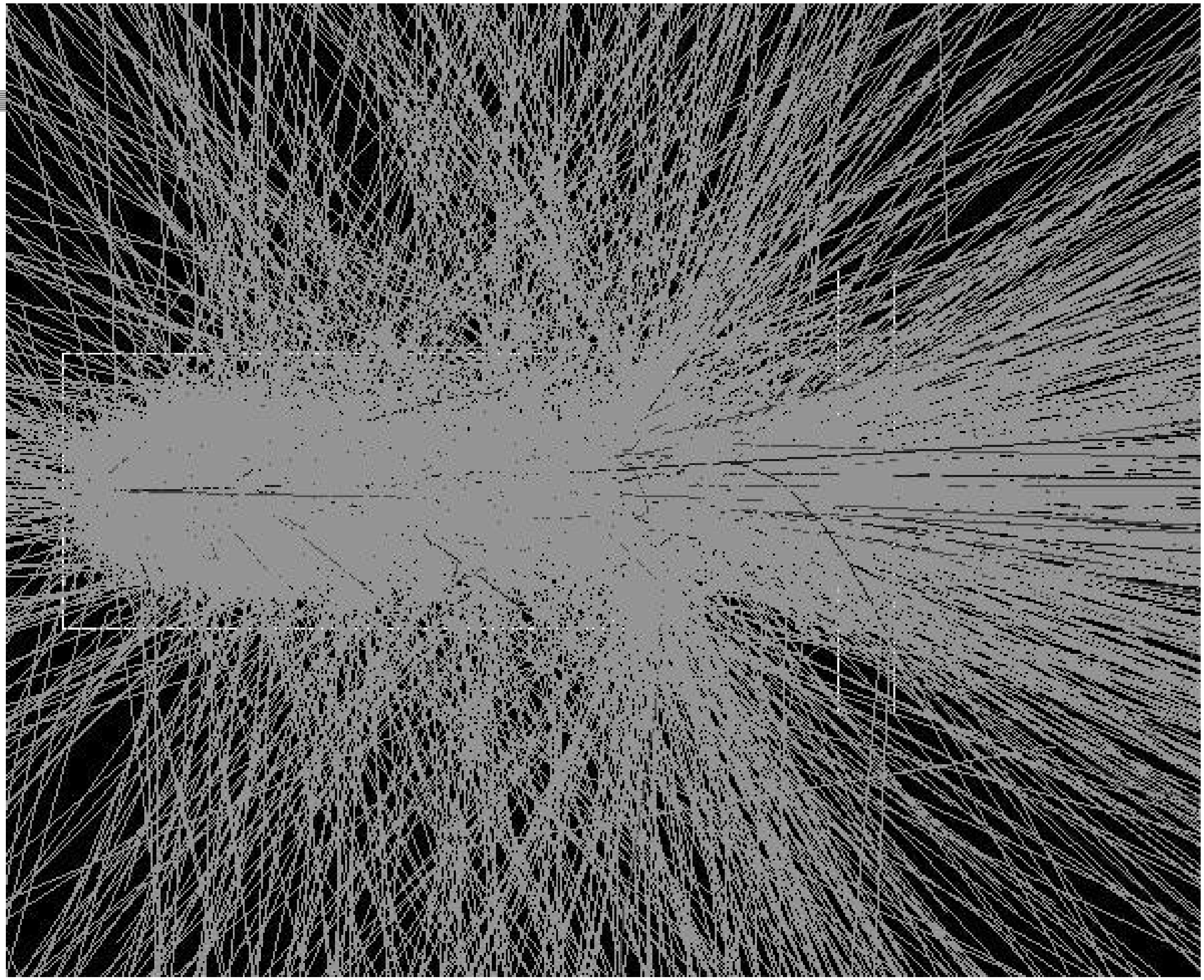
2 TeV pi- in copper



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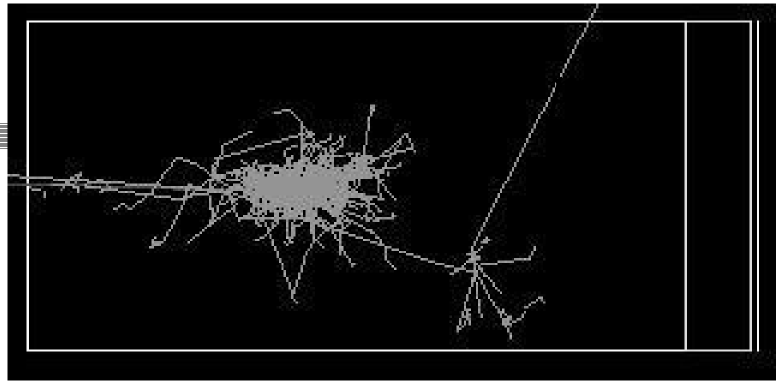
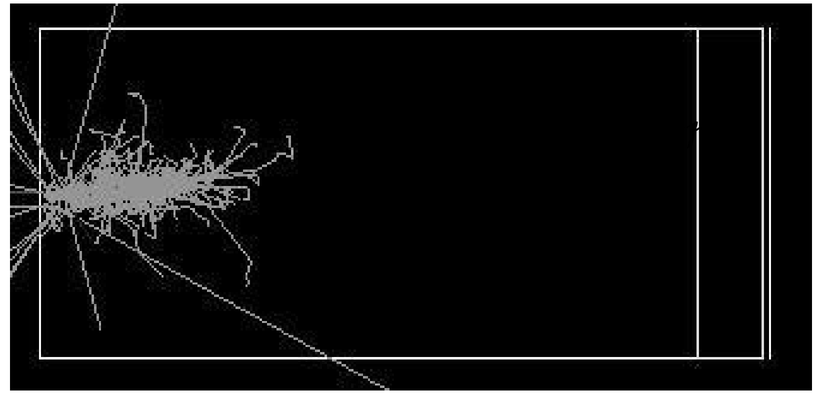
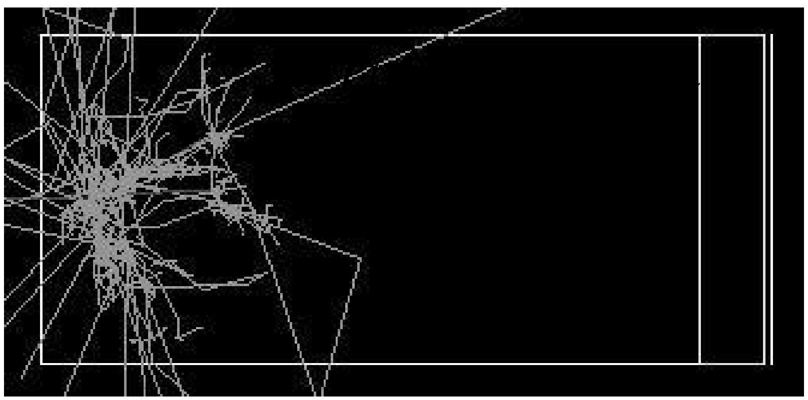
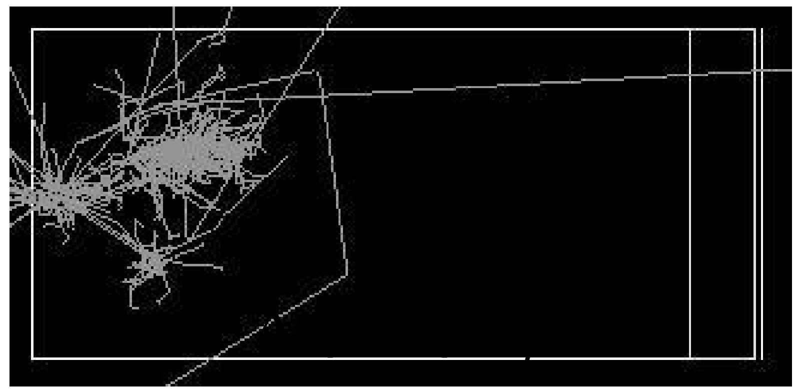
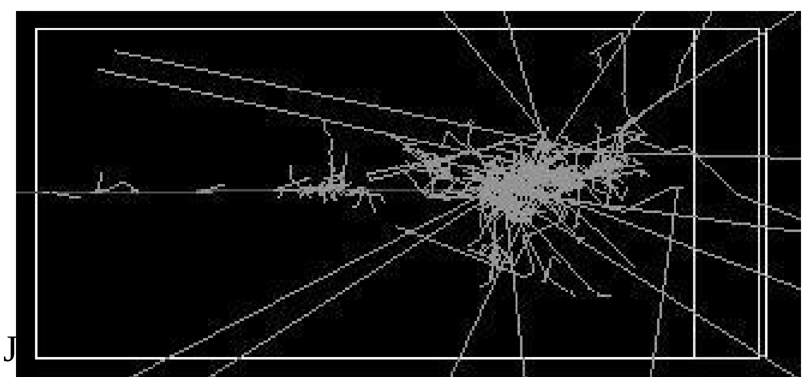
5 GeV pi- in copper

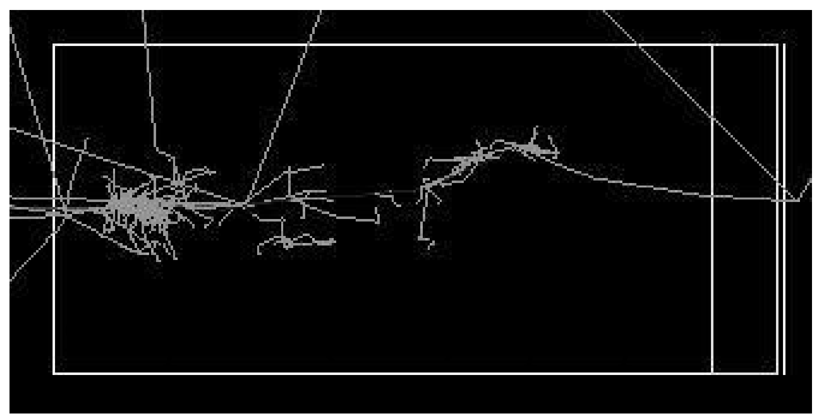




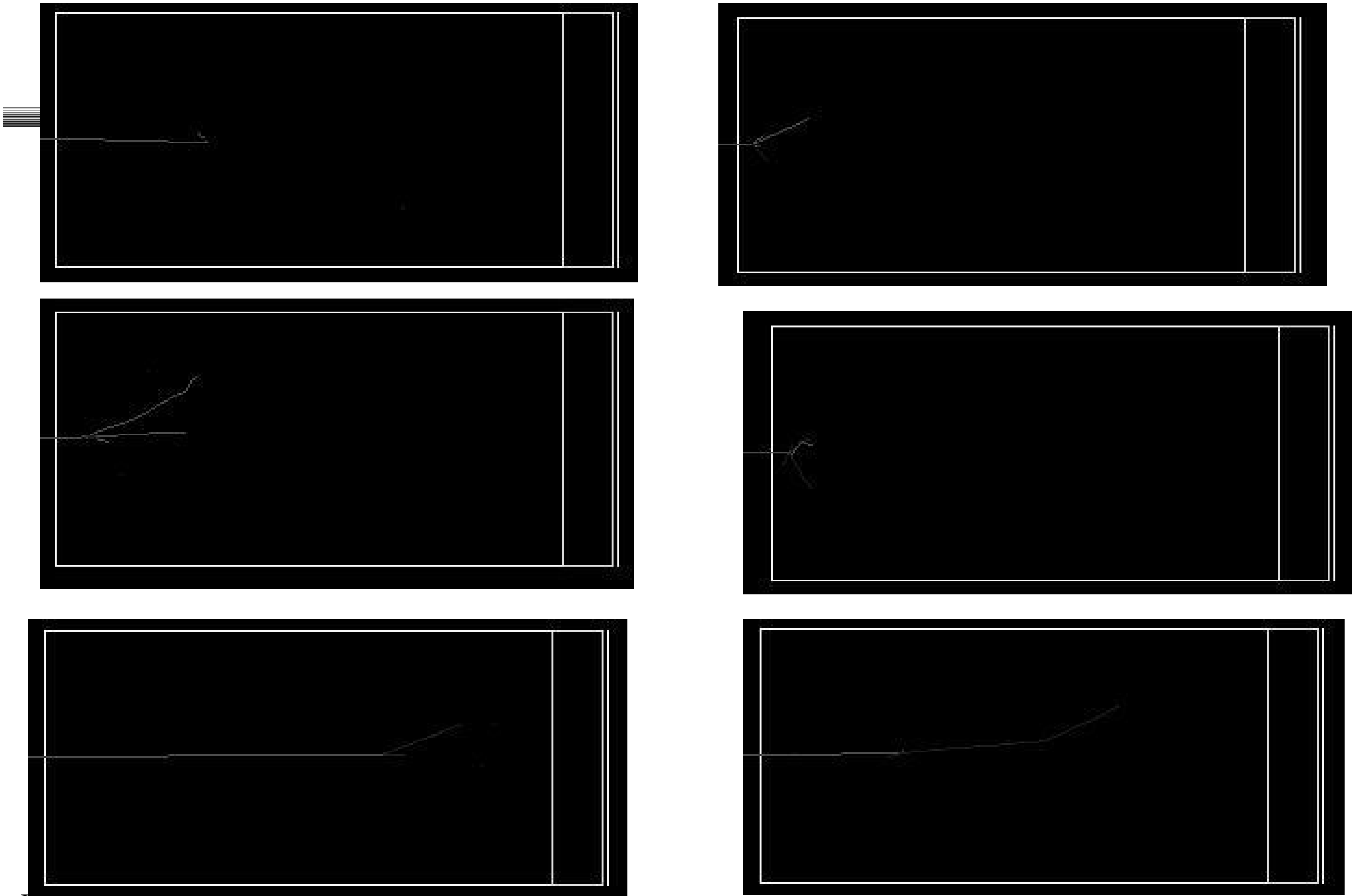




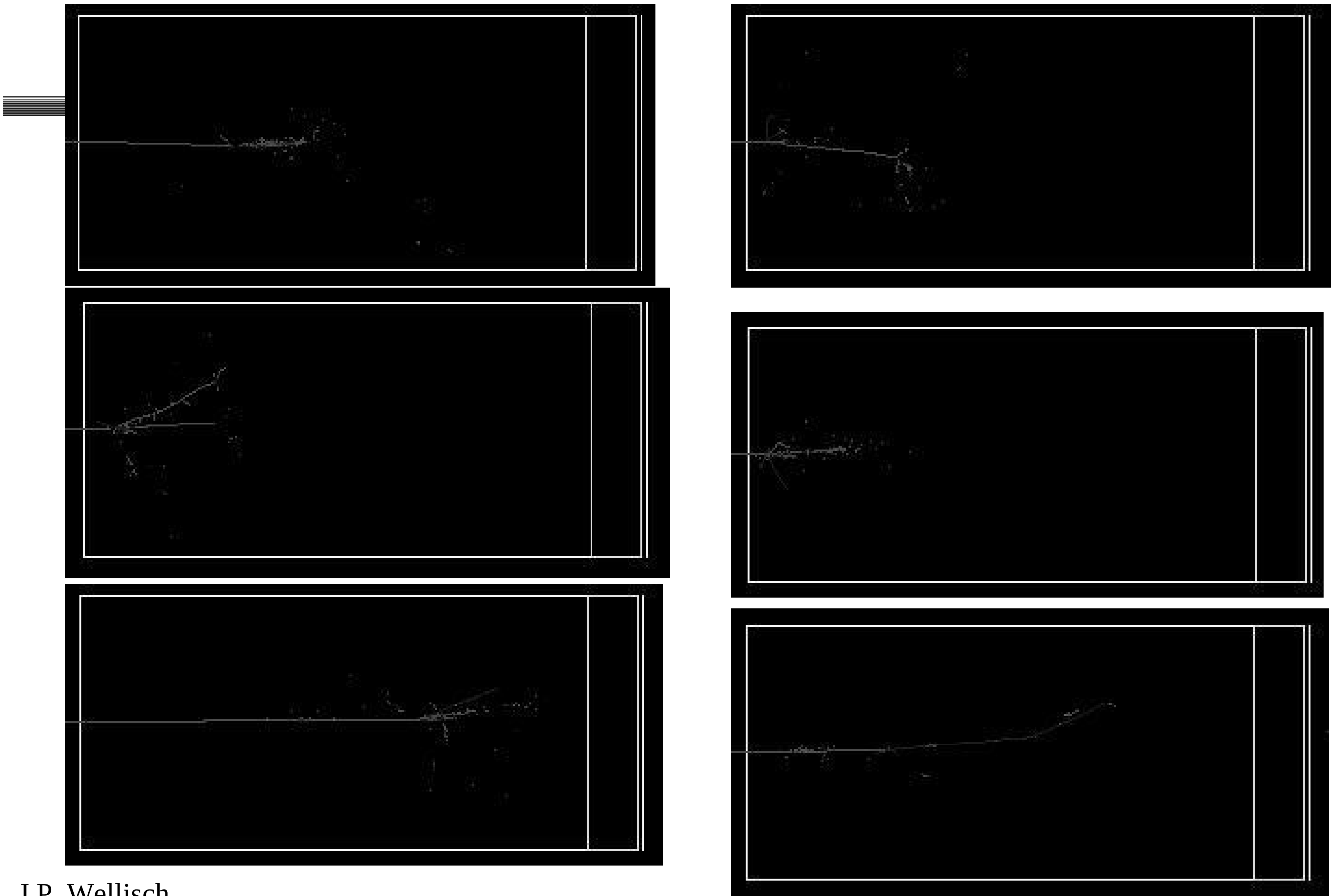




5 GeV pi- in copper (only charged hadrons shown)



5 GeV pi- in copper (all charged particles)



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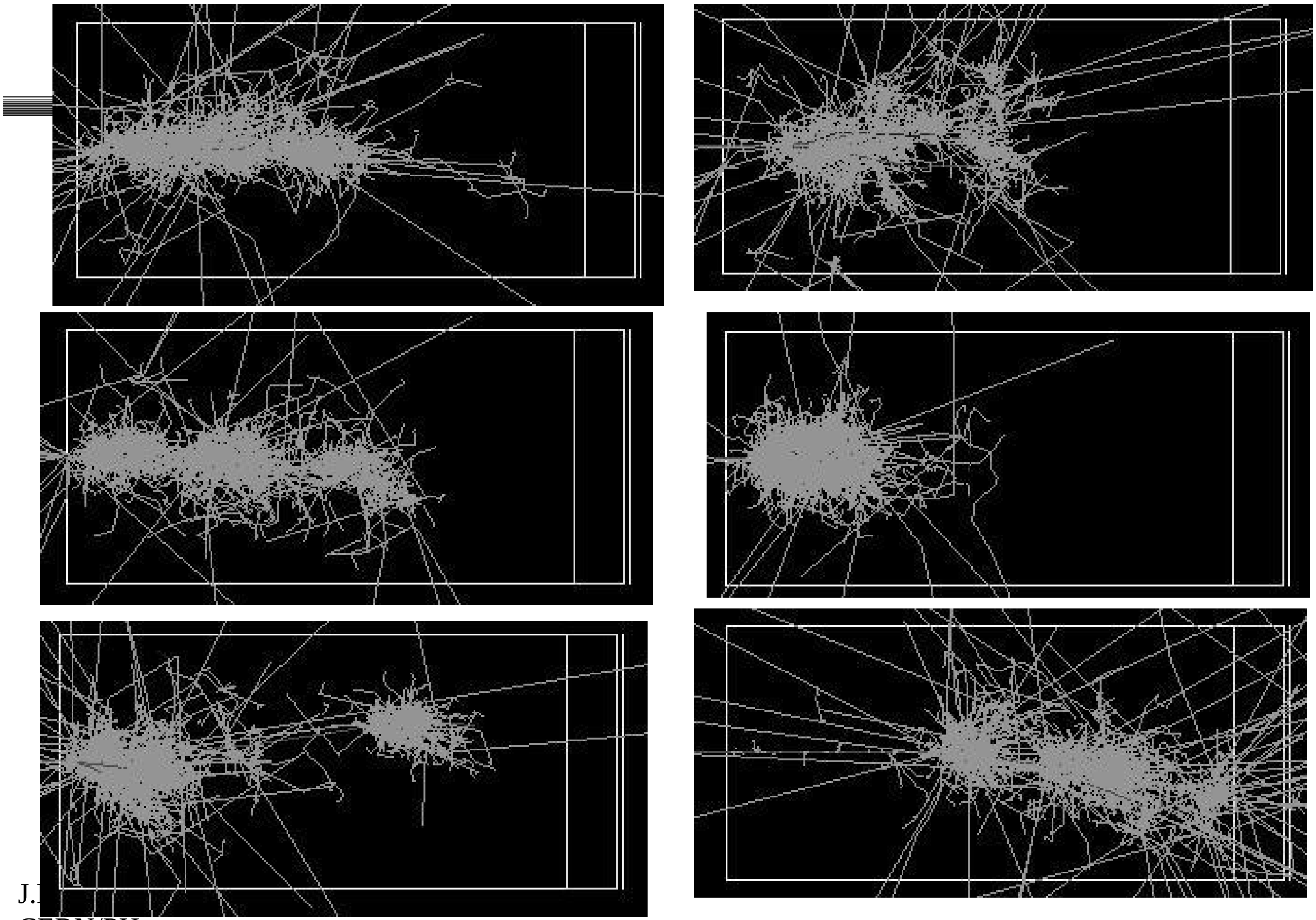
20 GeV pi- in copper



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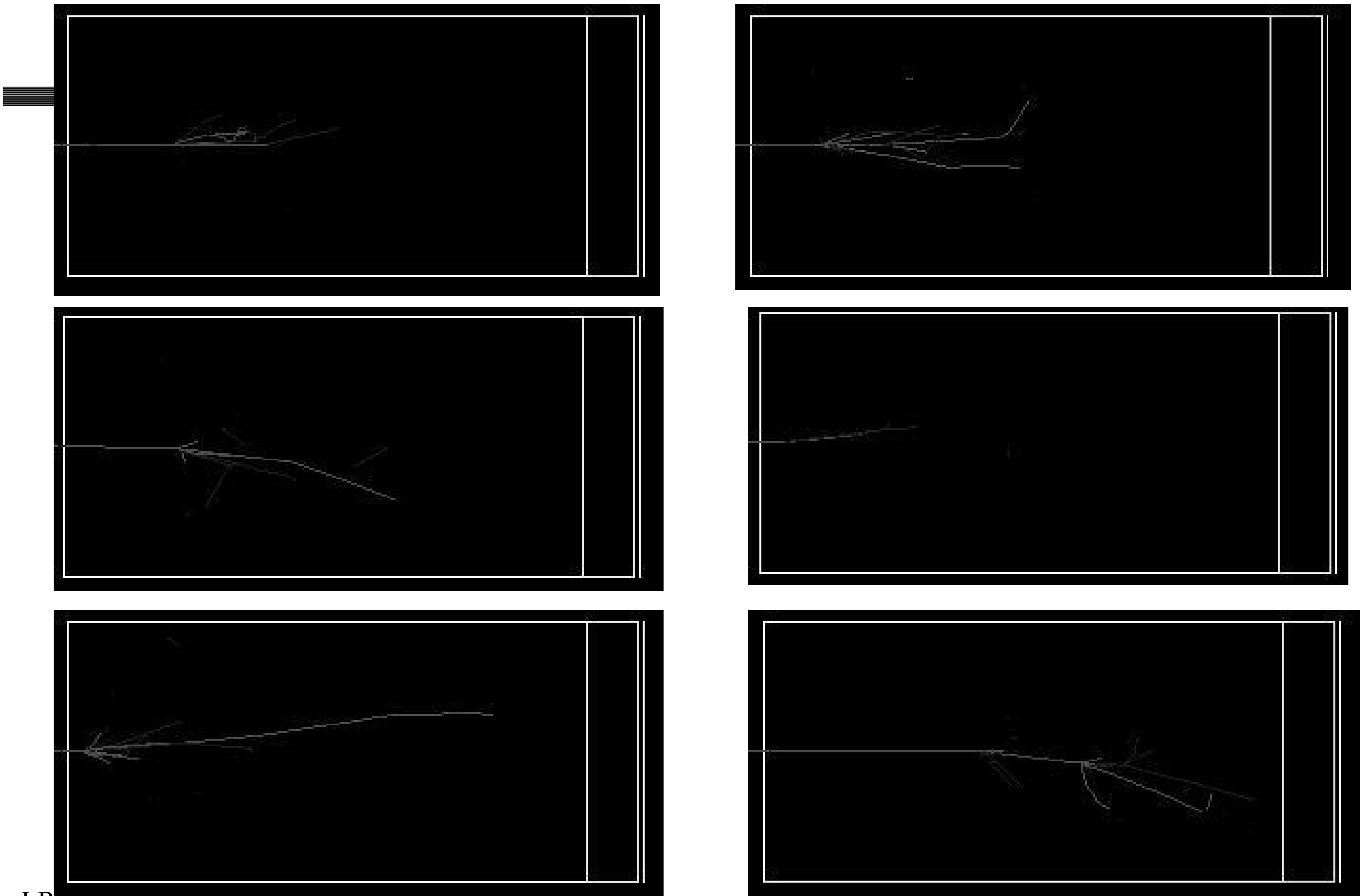

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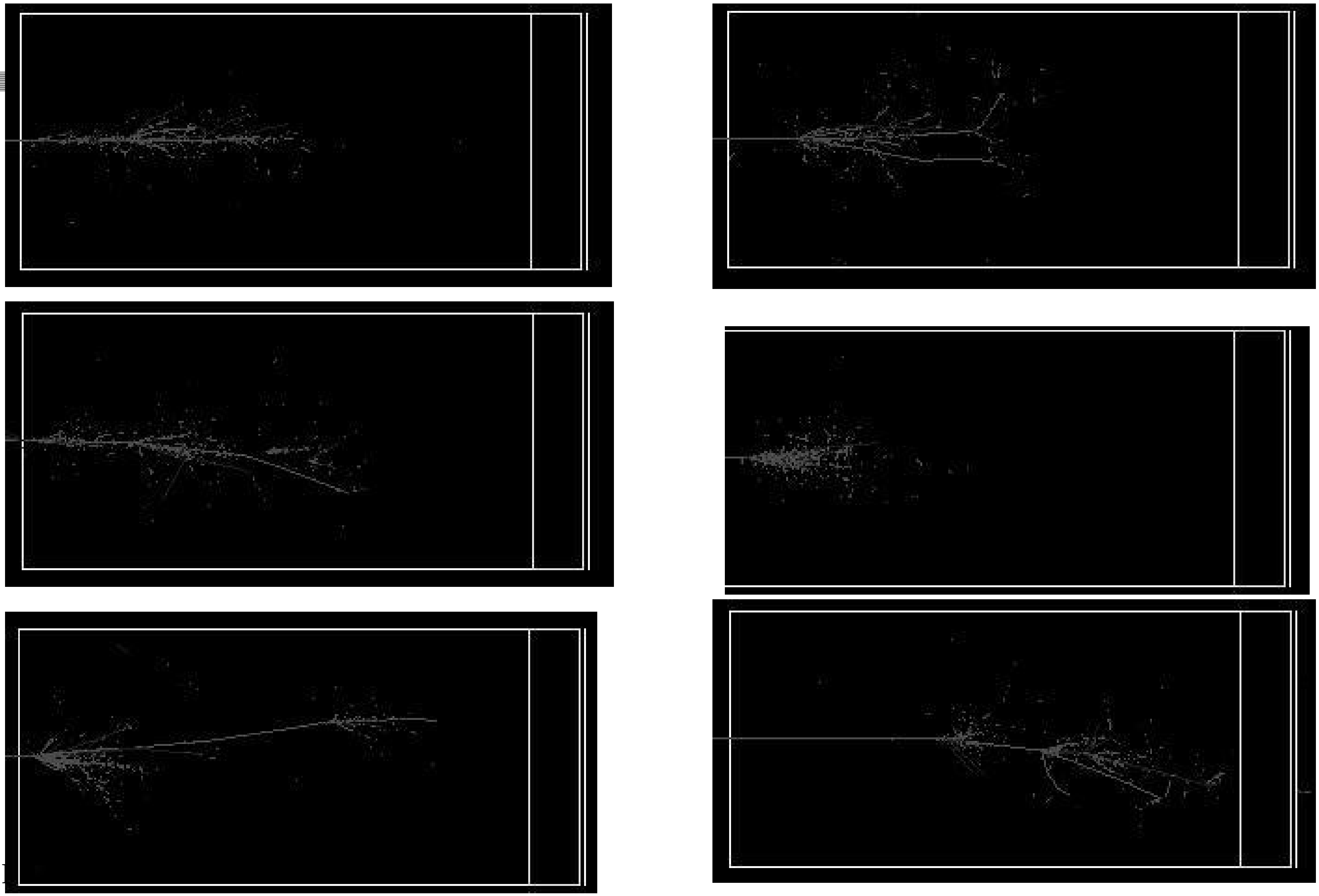

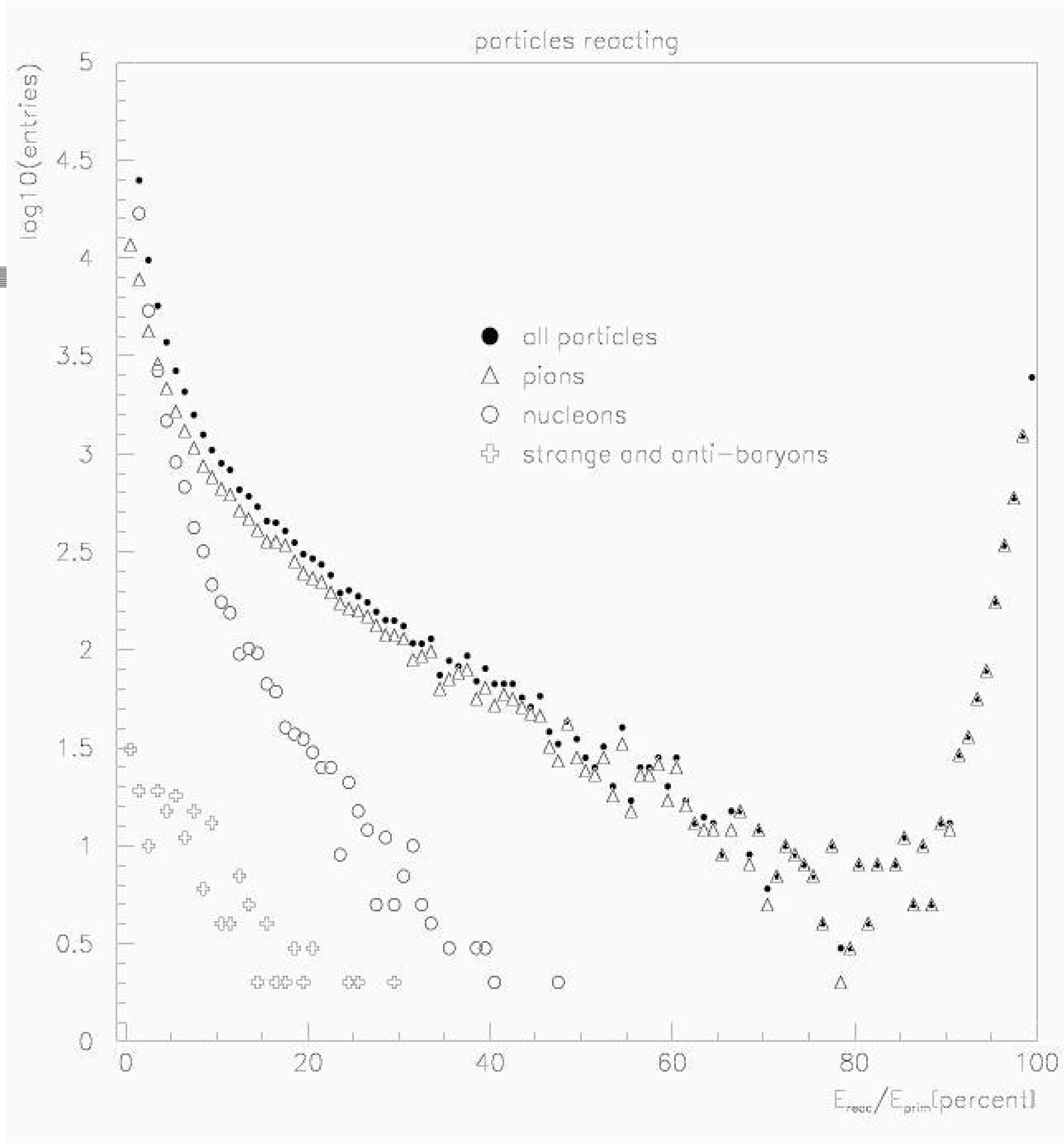

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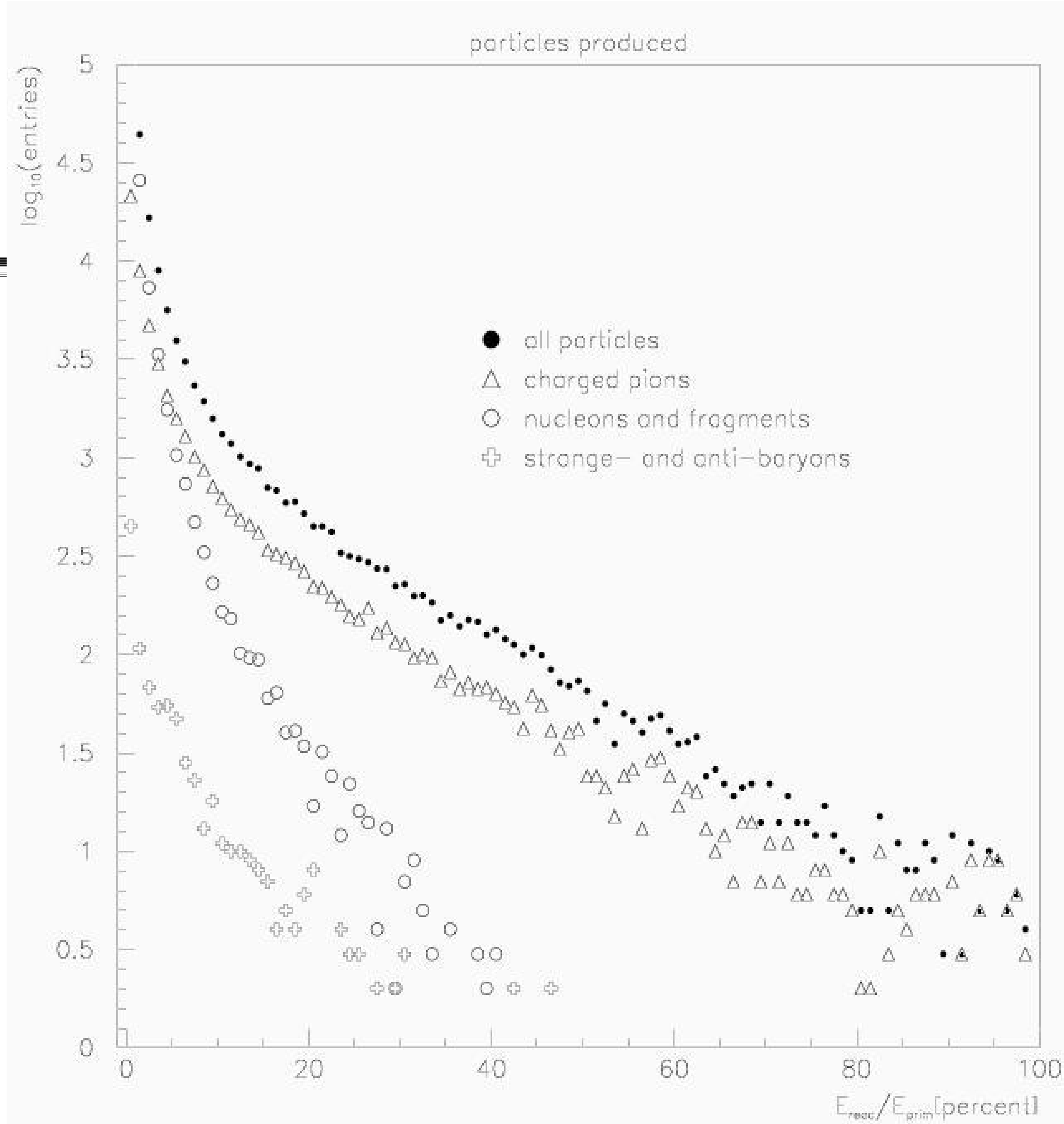

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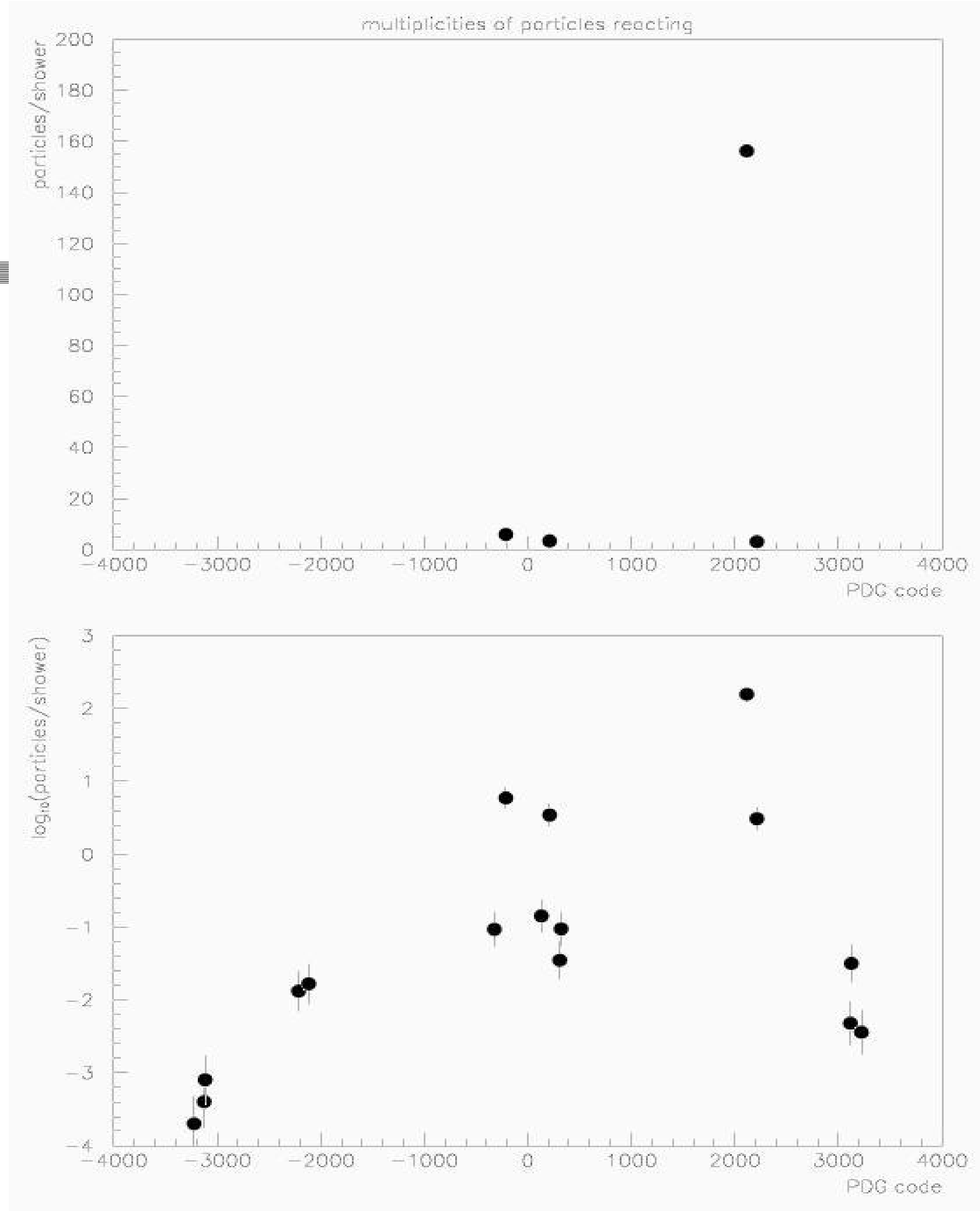

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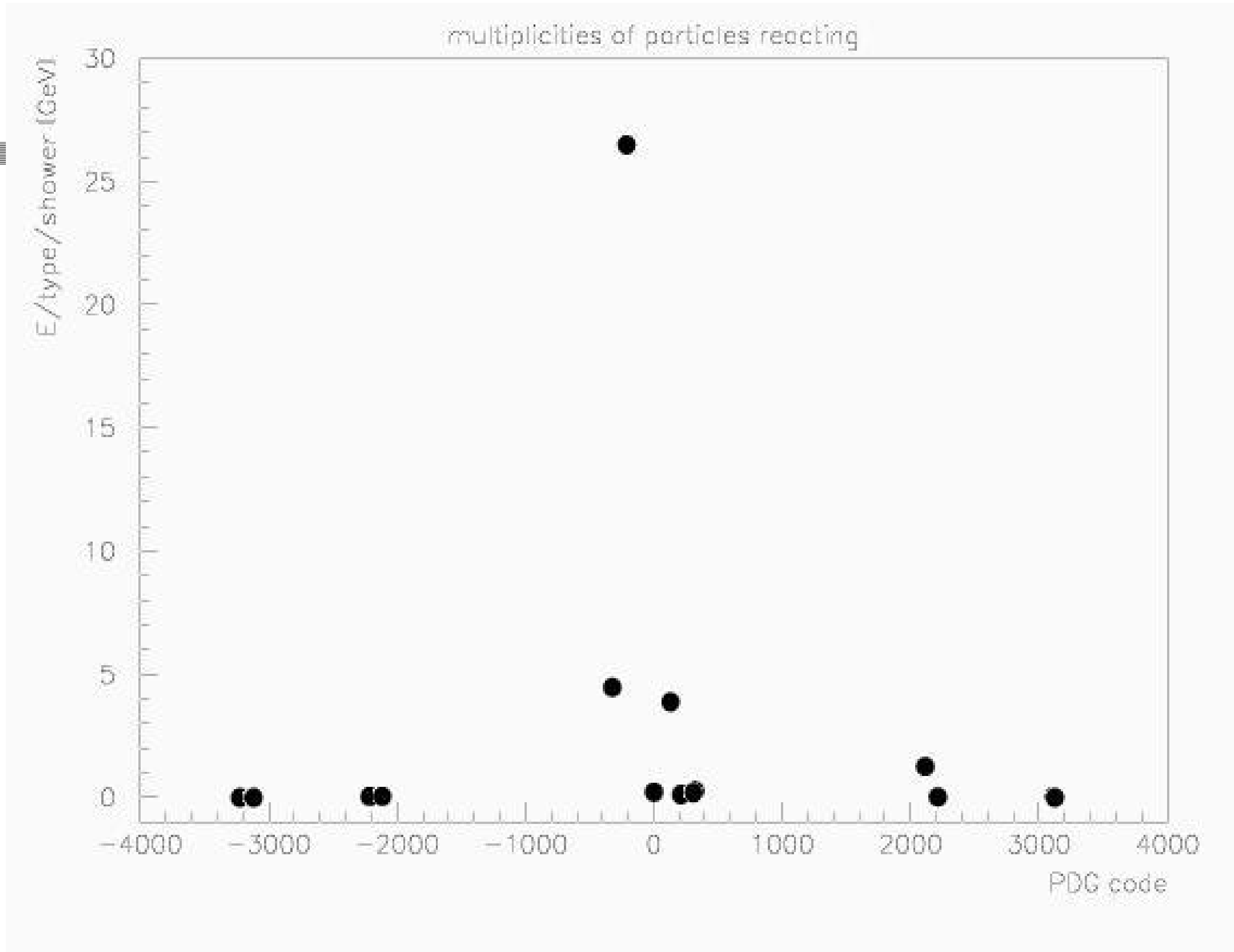

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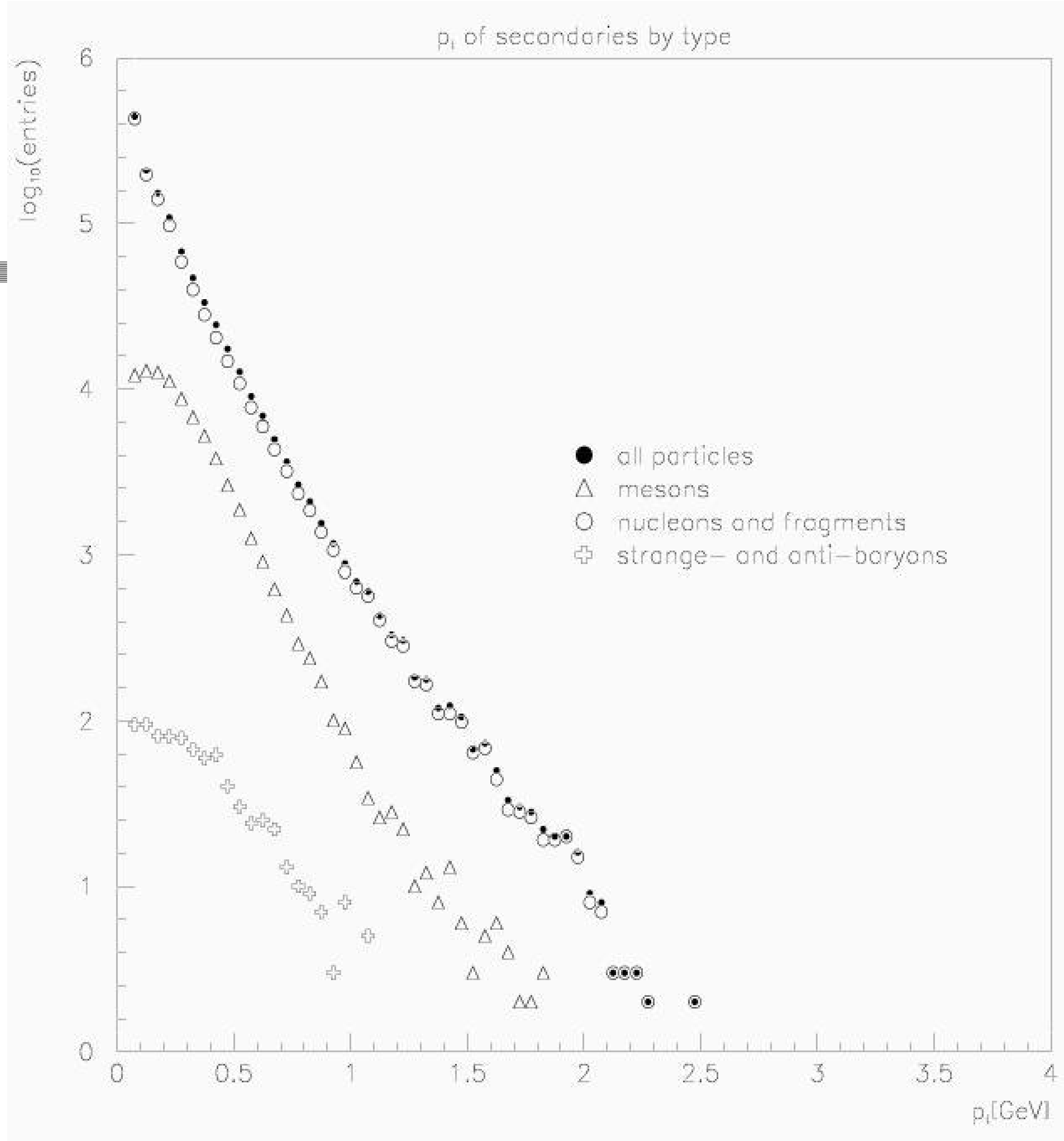

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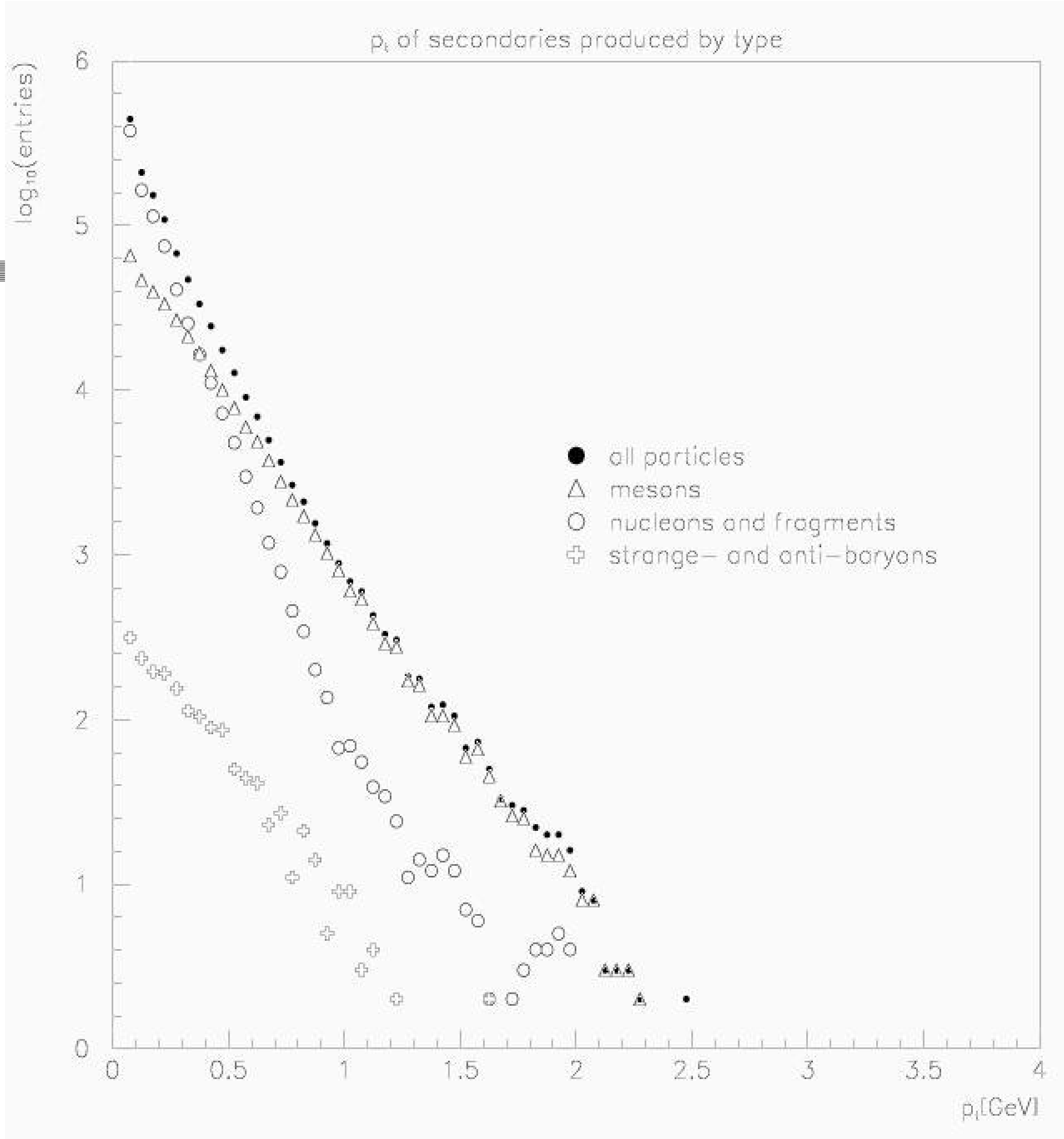

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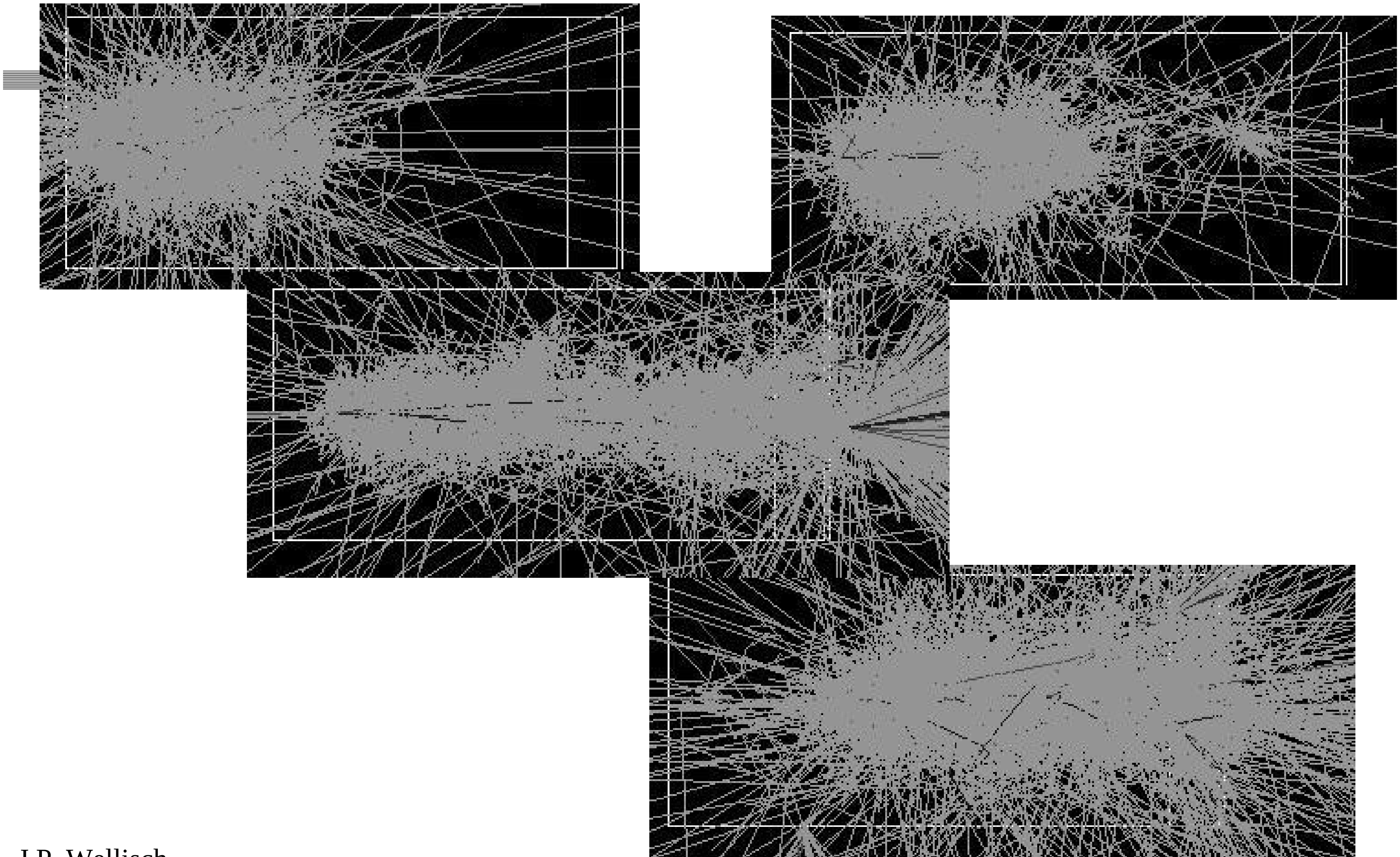
200 GeV pi- in copper



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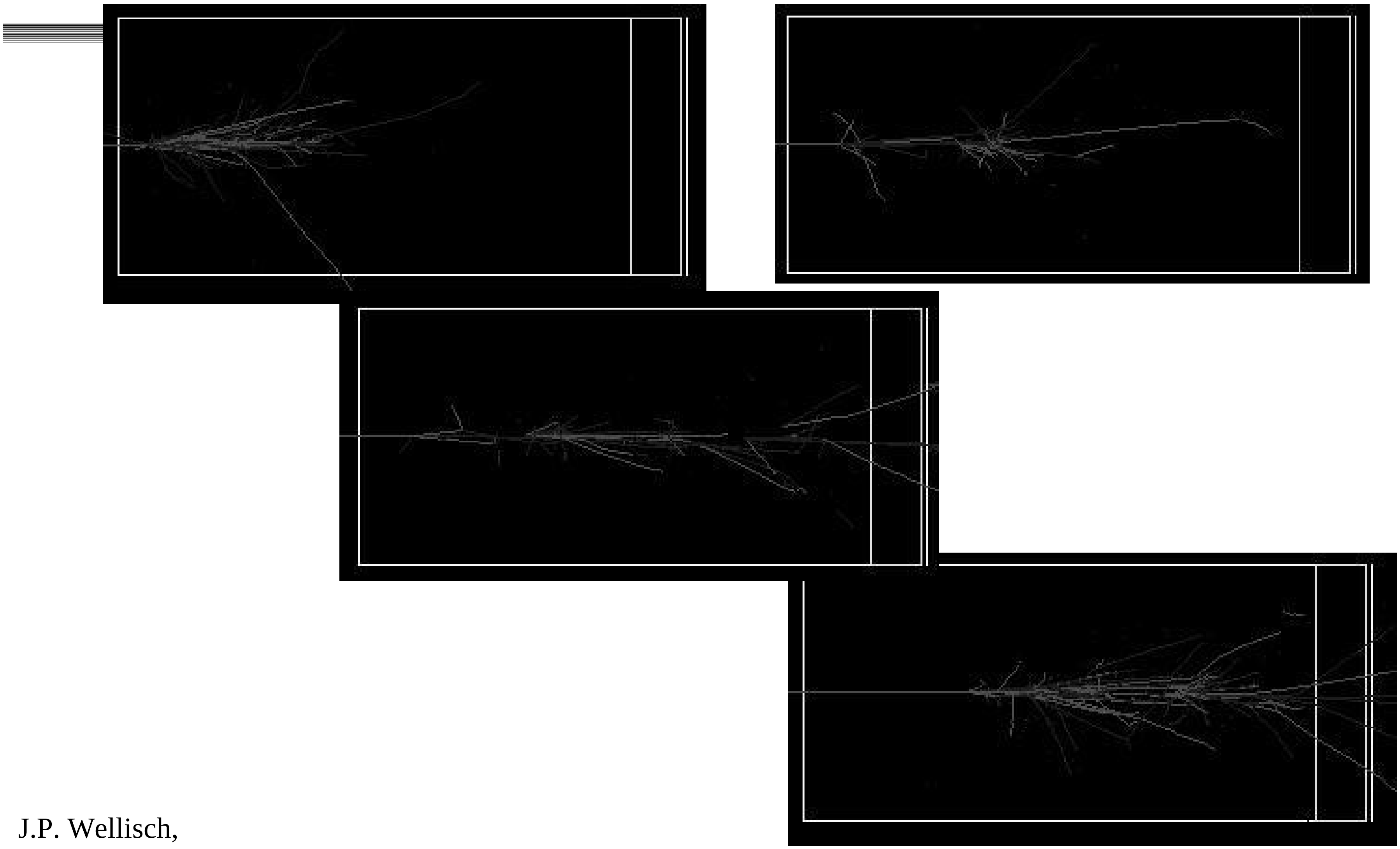

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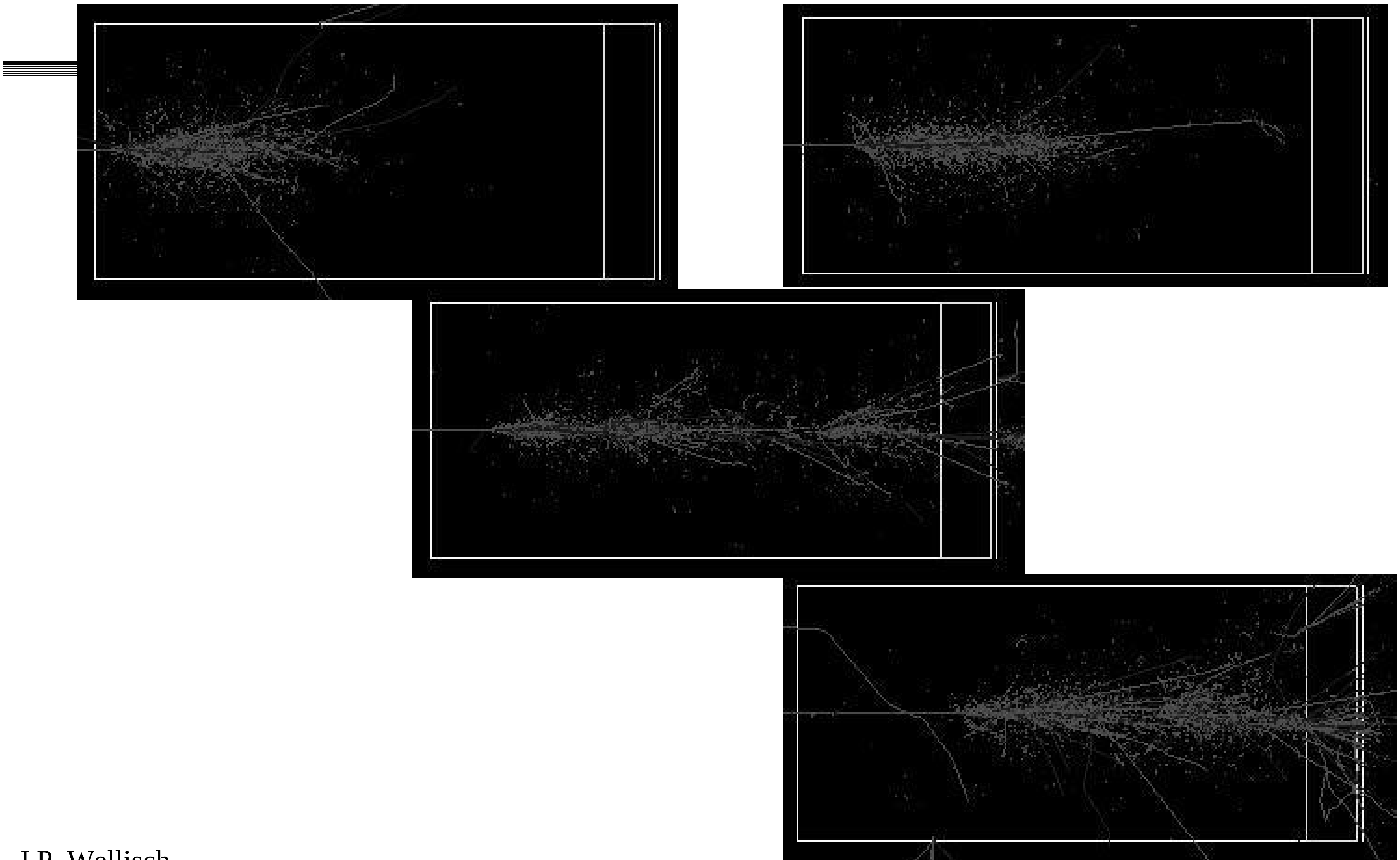

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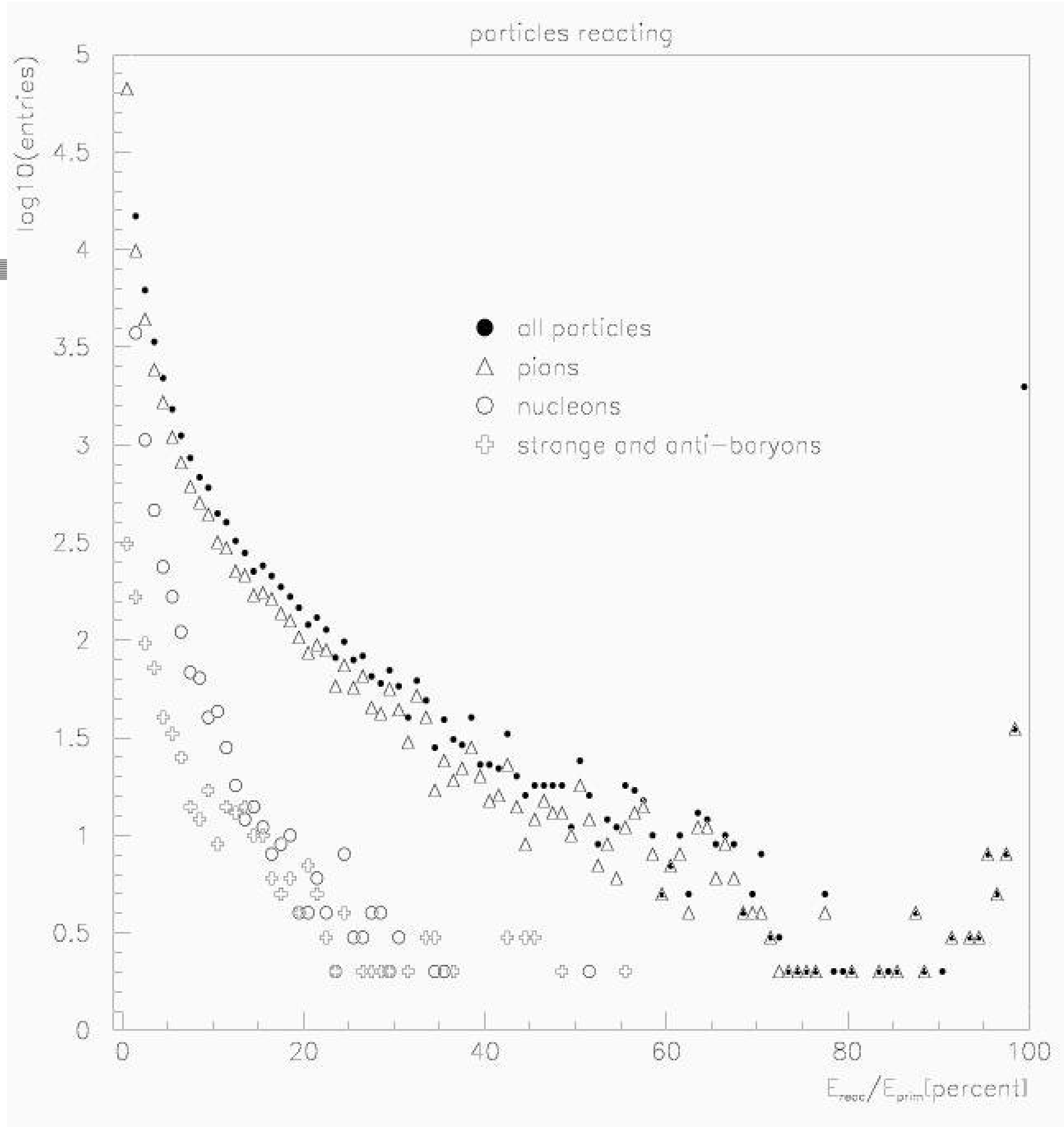

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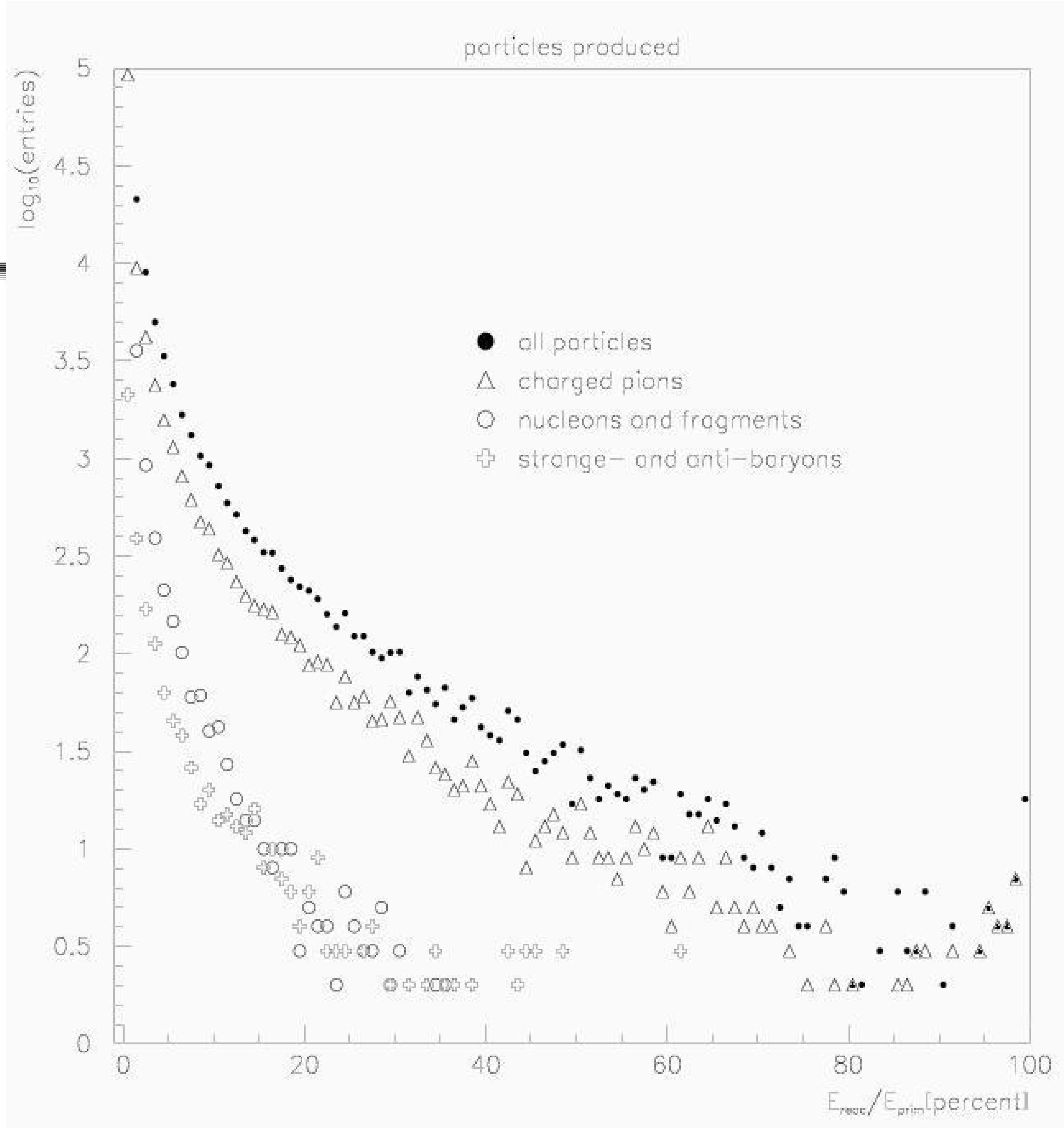

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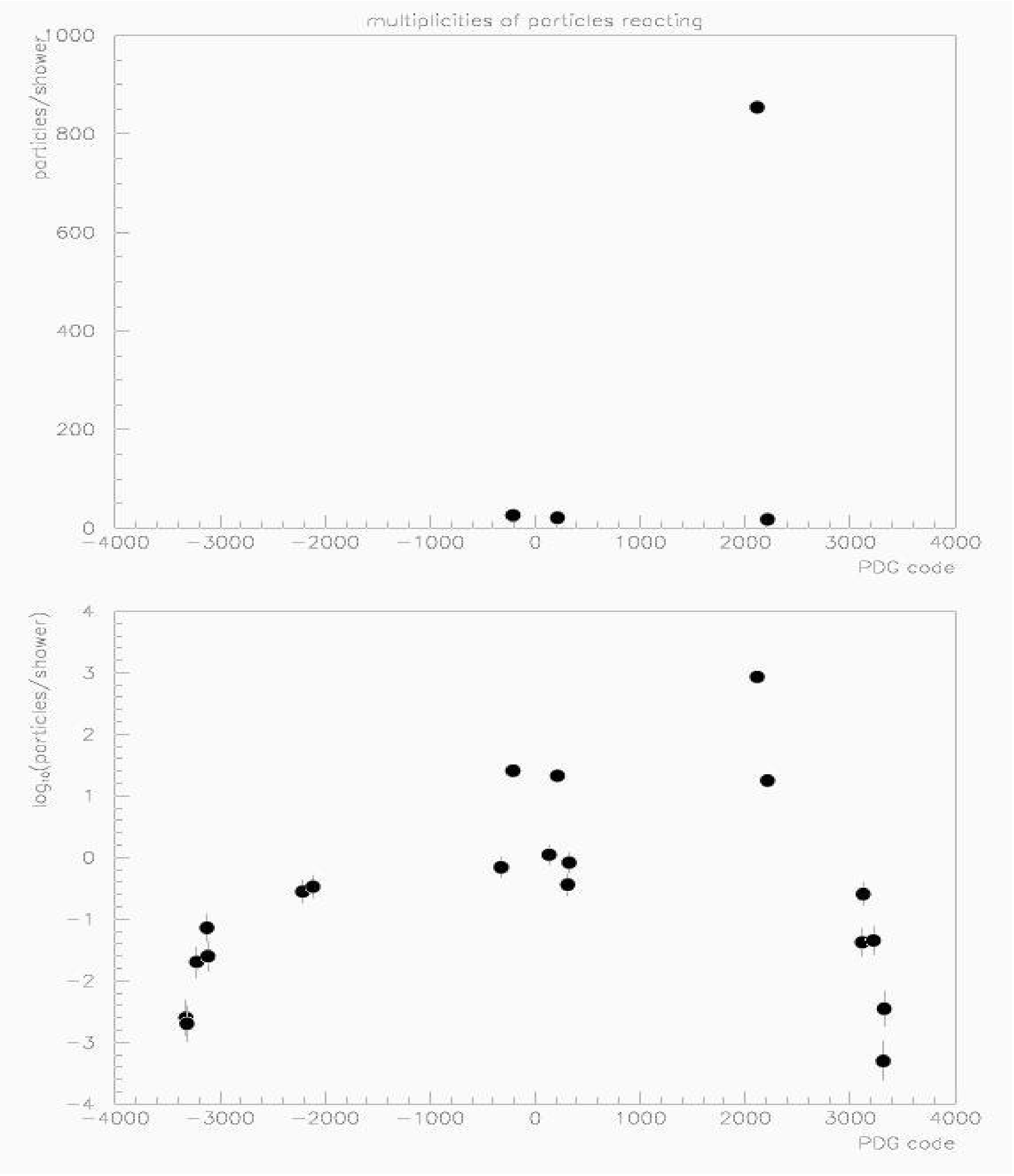
150 GeV pi- in Copper



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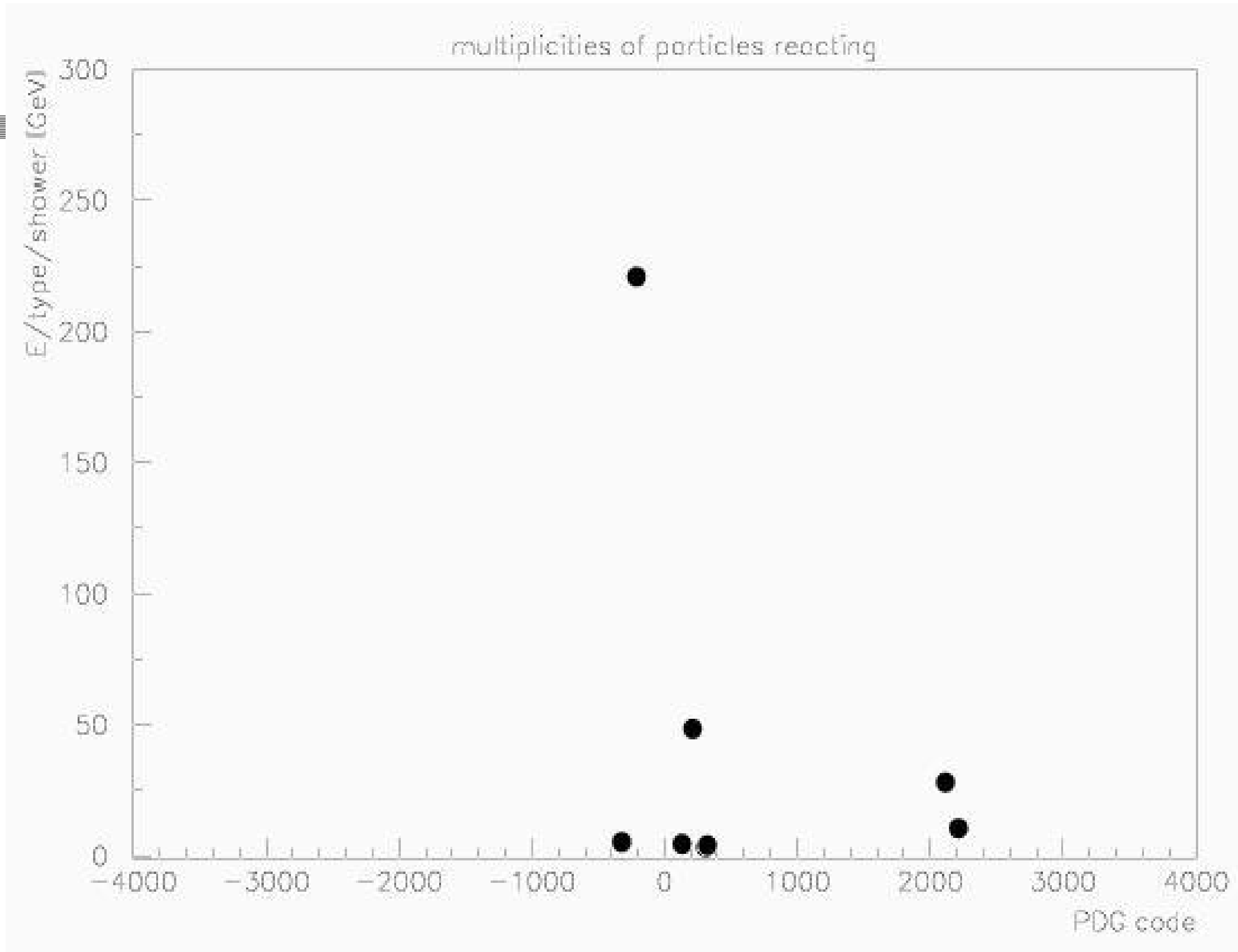
150 GeV pi- in Copper



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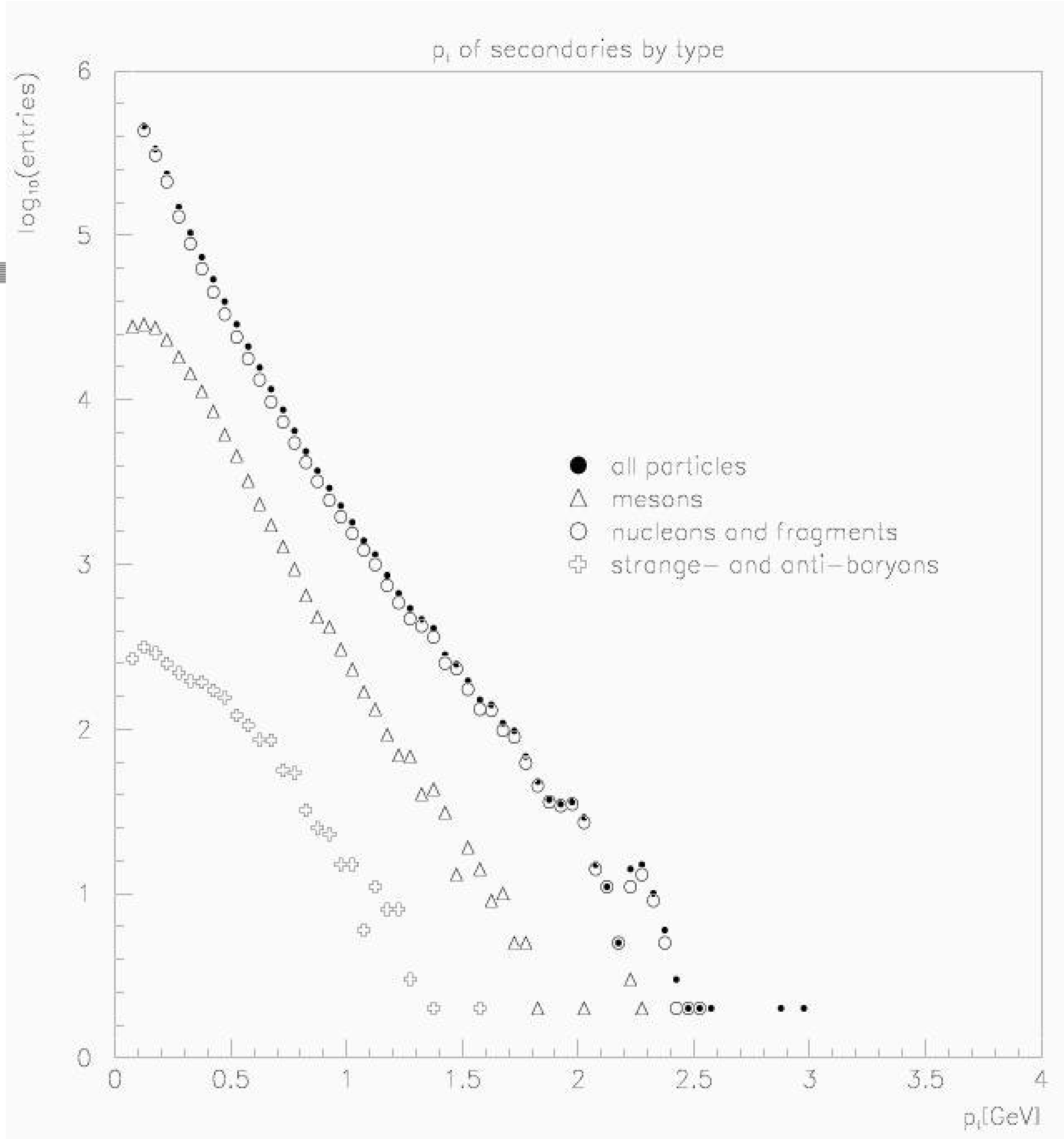

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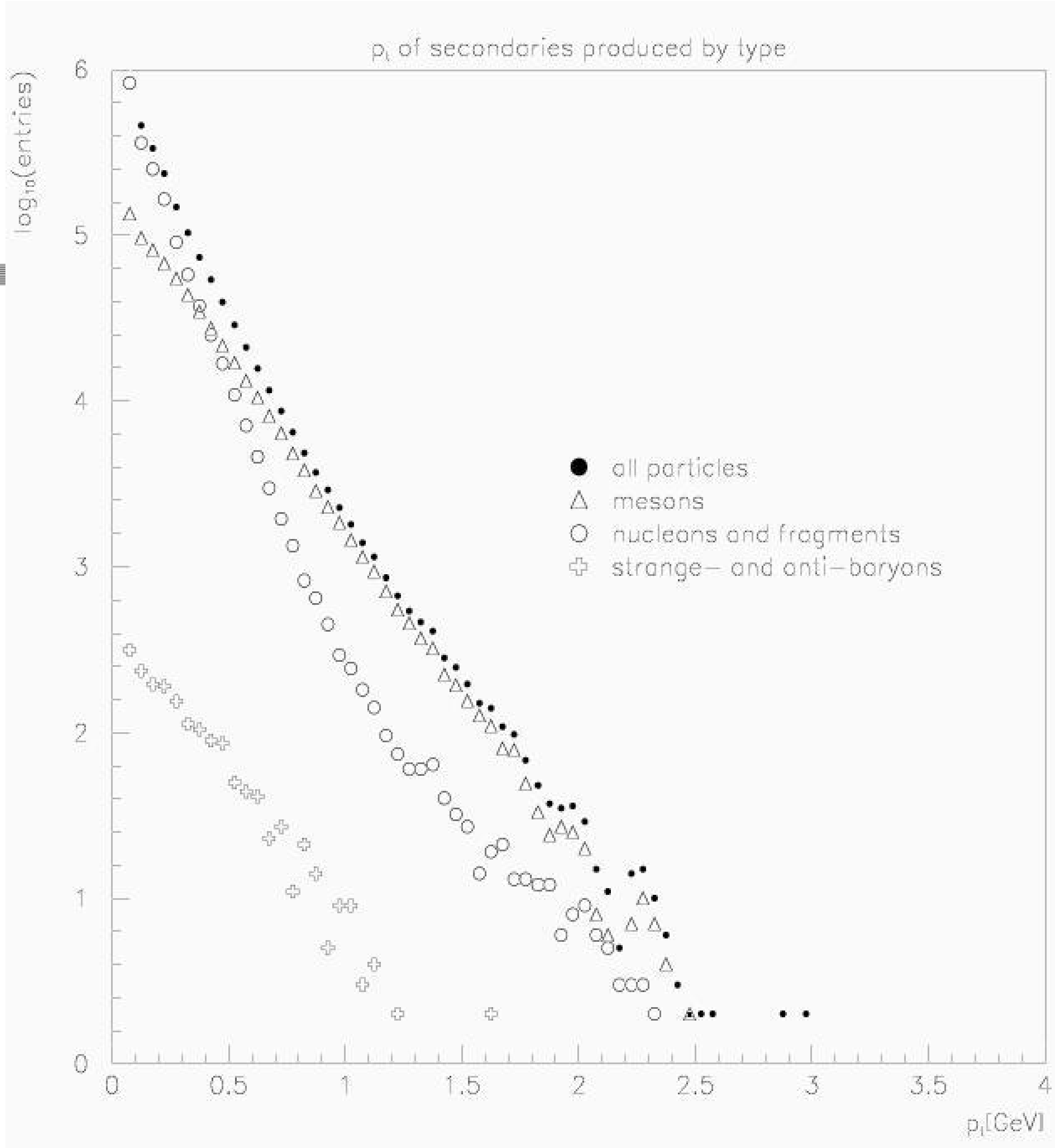

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Conclusions:

- Energetic particles are close to the original particle axis.
  - They define the shower core, and the initial reaction needs much attention in the modeling.
  - This also contains most of the electromagnetic fraction of the shower.
  - They define the longitudinal shower shape, with multiple interactions of leading particles. Hence leading particle effects are of much interest.

Conclusions continued

- The energy going towards secondary proton reactions is very small in hadronic showers
  - Reaction rates should be modeled correctly
  - Final states do not need detailed modeling (unless we have low energy protons as primaries).
  - In sampling calorimetry, most secondary protons will not reach the active medium.

Conclusions continued

- Neutrons:
  - There is a large number of them, and they induce many reactions.
  - They spend a significant share of the invisible energy.
    - O(15MeV)/20GeV * O(150) = 11.25%
    - O(15MeV)/150GeV * O(900) = 9%
  - Reactions cross-sections and produced multiplicities need to be precise.
  - They carry most of the long range transverse momentum, and hence their reactions are expected to contribute significantly to the transverse shower shape.
  - As there are many neutron reactions in each shower, the final states need reasonable average description.

Conclusions continued

- Other particles:
  - Pi0 carry a substantial fraction of the energy of a hadronic shower.
    - They are created close to the shower core.
    - They decay immediately, and generate much of the electromagnetic contents of a hadronic shower.
  - We need to model their production, including its fluctuations, and the sub-sequent electromagnetic showers in great detail.
  - Other particles have peripheral importance as shower particles.

On hadronic shower physics

- In geant4 it is simulated using the components from the hadronic physics category.
  - Inelastic reactions
  - Coherent elastic scattering
  - Capture of neutral hadrons
  - Fission
  - Absorption of particles at rest (π^-, K-, p-bar, μ^-)
- The goal is to describe both the interaction cross-sections, and exclusive final states in their natural probability of occurrence.

Three categories of modeling approaches are realized in geant4

- Data driven modeling
  - For some situations, there are enough dada or evaluated data available to create a complete description of cross-sections and/or exclusive final states
- Parameterization driven modeling
  - In some cases it is advantageous to parameterize part of a response function, like the inelasticity of a inelastic reaction.
- Theory driven modeling
  - Microscopic modeling at various levels of detail.

Examples of data driven modeling in geant4:

- Radioactive decay, photon evaporation, internal conversion (ENSDF), elastic scattering (SAID), etc..
- Low energy neutron
  - Based on evaluated data: G4NDL, derived from ENDF, Jef, JENDL, CENDL, ENSDF, Brond, IRDF, FENDL, MENDL,...
  - Sampling codes for ENDF-B VI derived data formats
  - Use the file-system to ensure granular and transparent access/usage of data sets
  - Doppler broadening not static on input data, but on the fly from 0K data.

Parameterization driven models in geant4

- Total cross-sections.
- Final state generators - two domains:
  - high energy inelastic (Aachen, CMS)
  - low energy inelastic, elastic, fission, capture (TRIUMF, UBC, CERN)
  - Partial MARS rewrite (Kyoto, in collaboration with UVic. and FNAL)
- Stopping particles
  - base line (TRIUMF, CHAOS)
  - pi- (INFN, CERN, TRIUMF)
  - K- (Crystal Barrel, TRIUMF)
  - anti-protons (JLAB, CERN)
  - Electromagnetic transitions of the exotic atom prior to capture; effects of atomic binding. (Novosibirsk, ESA)

Theory driven models in geant4

- Ultra-high energy models
  - Parton transport model (in discussion)
- High energy models
  - 'Fritjof' type string model (CERN)
  - Quark gluon String (CERN)
  - Pythia(7) interface (Lund, CERN)
- Intra-nuclear transport models (or replacements)
  - Bertini cascade (HIP, CERN)
  - Binary cascades (CERN, U.Frankfurt)
  - QMD (CERN, Inst.Th.Phys. Frankfurt)
  - Chiral invariant phase-space decay (JLAB, CERN, ITEP)
- De-excitation
  - Exciton preequilibrium model,
  - Evaporation, fission, multi-fragmentation, fermi-break-up (Valencia)

The END ?

Tomorrow

- Theory driven modeling of hadronic interactions.

The END.