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Comparison of cosmic ray models with PYTHIA at energies near the 2nd "knee" of the cosmic ray spectrum

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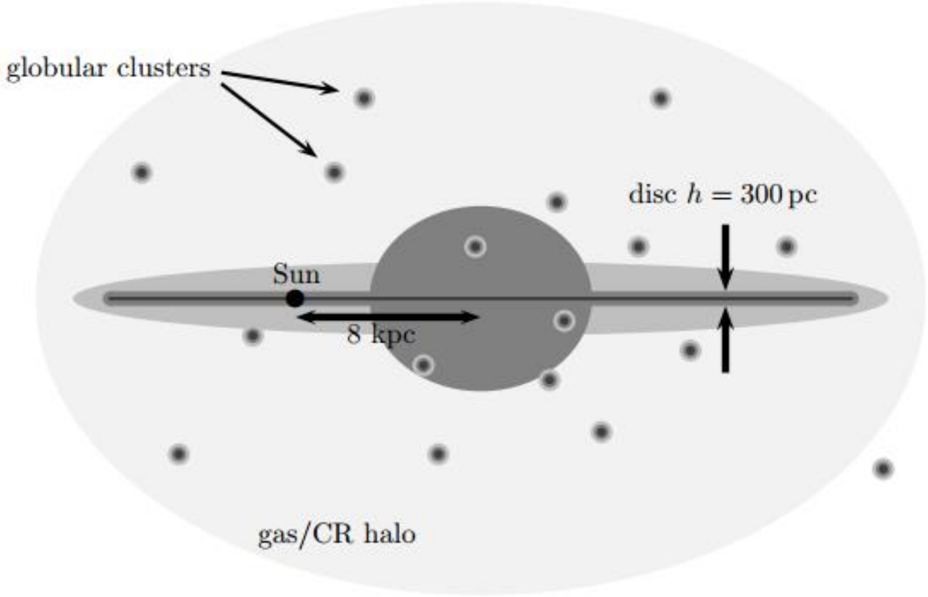
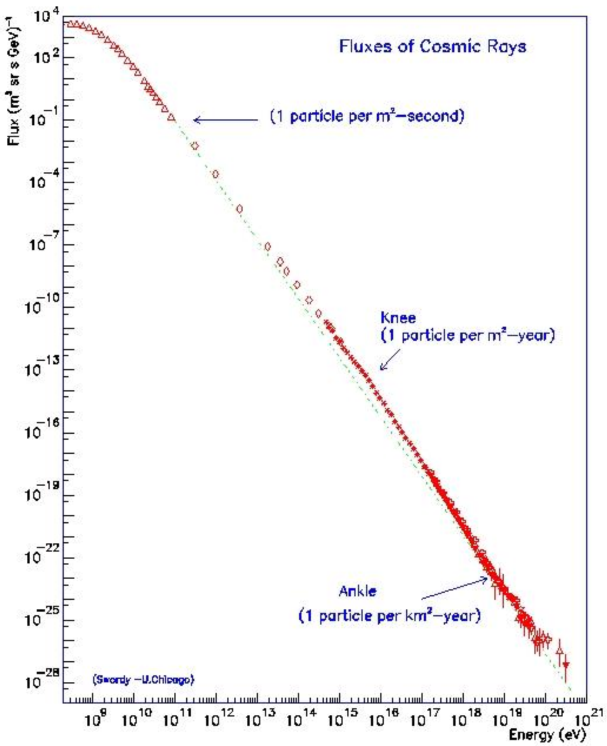
Introduction

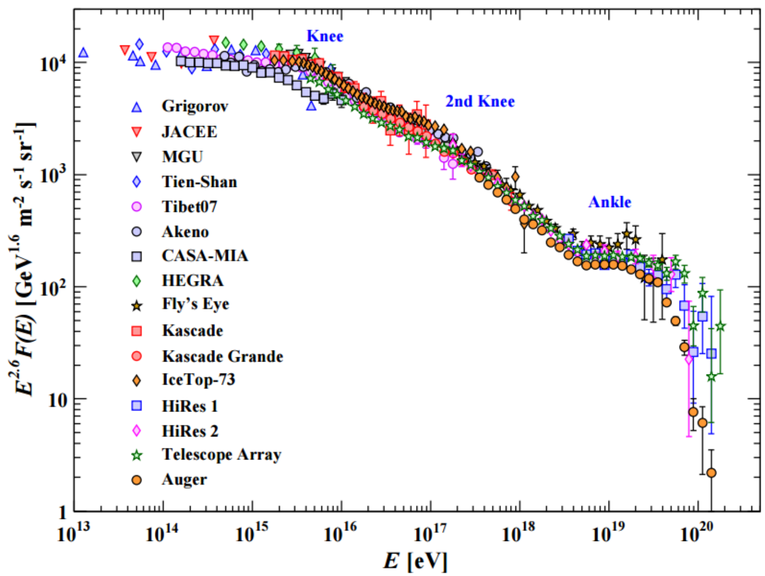
- 1912 – discovery of cosmic rays – Victor Hess;
- 1929 – Bothe and Kolhorster, tracks are curved by magnetic fields;
- 1932 – Milikan and Compton – gamma rays → cosmic rays;
- 1934 – cosmic ray primaries are positively charged;
- 1934-1938 – Rossi, Auger – coincidence measurements – extensive air showers (EAS);
- 1934 – Bethe and Heitler – electromagnetic cascade theory;
- 1949 – Fermi acceleration (galactic magnetic clouds);
- 1952-1954 – Accelerators over 1 GeV – decoupling of cosmic ray and high energy physics;
- 1954 – first measurements of high energy cosmic rays (EAS);

- Stable charged particles and nuclei $\tau \sim 10^6\ yrs$
- Primaries – accelerated at astrophysical sources – e^- (2%), p (87%), He (12%), C, O, Fe (1%) – synthesized in stars, γ, ν;
- Secondaries – produced in interactions of primaries with interstellar gas – Li, Be, B ($\bar{p}$ and e^+);
- Solar modulation;



Cosmic ray spectrum

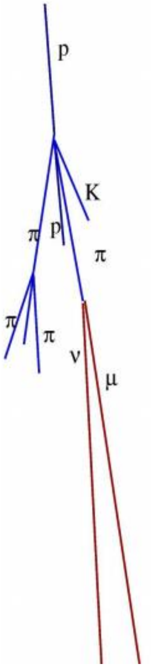


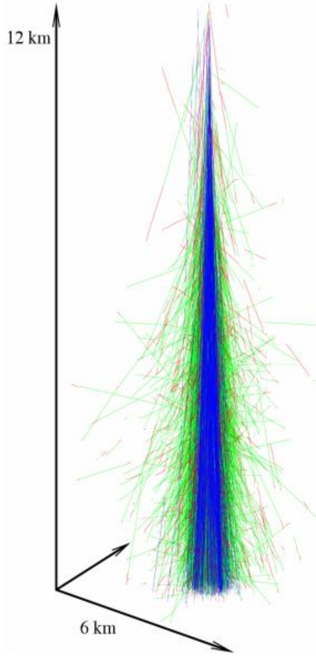


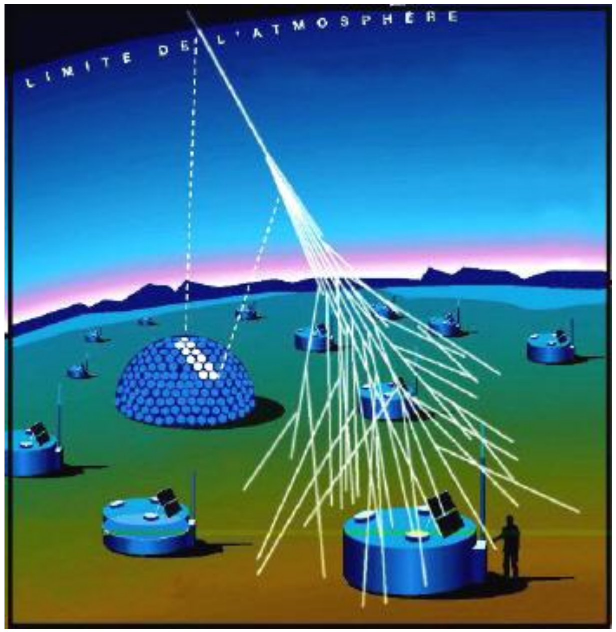
- 2 main sources – Galactic and extragalactic;
- Supernova remnants – SNe II, Pulsars, Active galactic nuclei (AGN), Gamma Ray Bursts;
- Shock acceleration (1st order Fermi acceleration)
- 2nd order Fermi acceleration (scattering on a moving magnetic clouds)

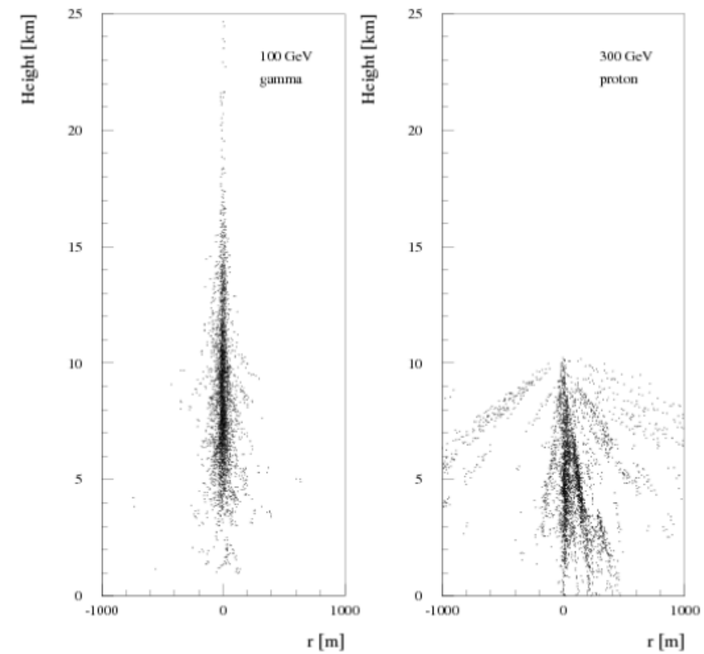
- Knee – $\sim 10^{15} - 10^{16}\ eV$ → maximum energy for galactic accelerators (supernovae $\sim 10^{15}\ eV$, confinement in the galaxy);
- 2nd knee – $\sim 8 \times 10^{16}\ eV$ accompanied by a transition to heavy primaries;
- Ankle – $\sim 10^{18.5}\ eV$, GZK effect (high σ for protons on CMB), photodisintegration (nuclei)

Extensive air showers (EAS)









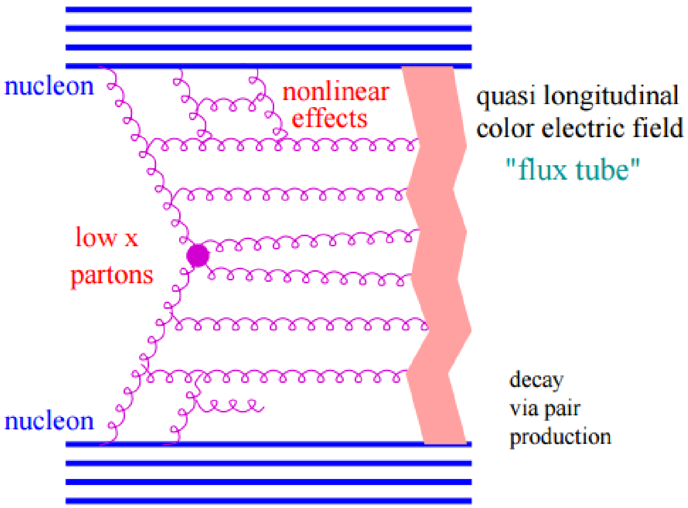
- High enough energy for its cascade to be detected at the ground
- Hadronic core – source of em. subshowers – $\pi^0 \rightarrow \gamma\gamma$
- Electrons, positrons – most numerous
- Muons – decays of charged mesons – an order of magnitude lower
- Large ground area

- Array of detectors (Sparse as possible – large aperture) on the ground for secondaries
  - Scintillation detectors;
  - Cherenkov detectors;
- Timing information – reconstruction of arrival direction and core of the shower;
- Fluorescence light method – Electrons excite nitrogen molecules – isotropic fluorescence light – shower evolution – the energy of the primary.

Cosmic ray models

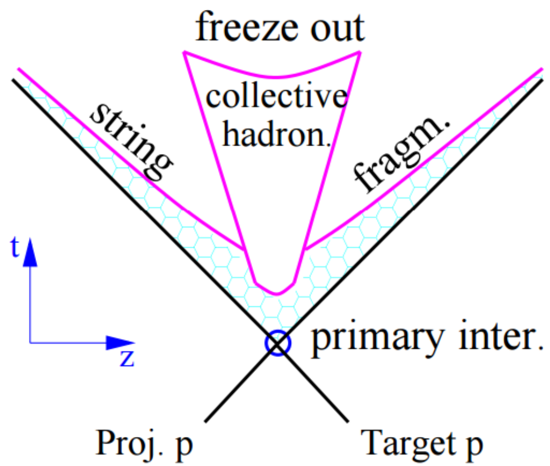
EPOS

- Minimum bias event generator;
- Heavy ion and cosmic ray interactions;
- Parton ladder (cut Pomeron);
- "flux tube" – relativistic string (which fragments);
- Core-corona model (unique);
- Effects not present in other models;
- The core – a region with a high density of string segments
  - the hadronization is treated collectively;
- Corona – a region with low density of string segments.



QGSJET

- Extensive air shower simulations;
- Quark-Gluon string model;
- Also nucleus-nucleus interactions and semihard processes;
- Semihard "Pomeron" approach;
- QGSJET-II non-linear effects (enhanced Pomeron diagrams);
- Gribov's reggeon approach – multiple scattering processes;
- Pomeron exchanges – microscopic parton cascades
  - "Soft" and "semihard" Pomerons.



PYTHIA

1. PDF – Parton distribution functions;
2. Hard process – interaction between the most energetic partons;
3. *Initial State Radiation*, ISR

→ parton branching on hard process ingoing partons;

4. *Final State Radiation*, FSR

→ parton branching on hard process outgoing partons;

5. *Multiple Parton Interactions*, MPI

→ interactions between the other partons;

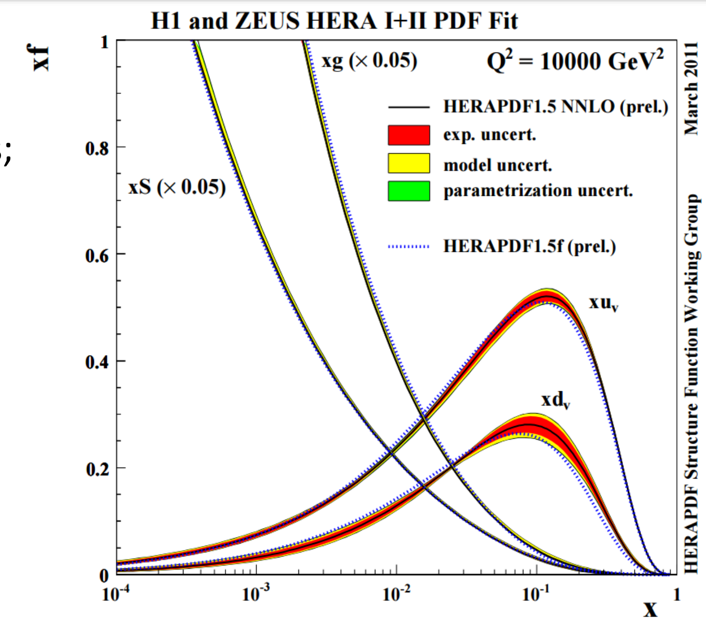
6. Hadronization

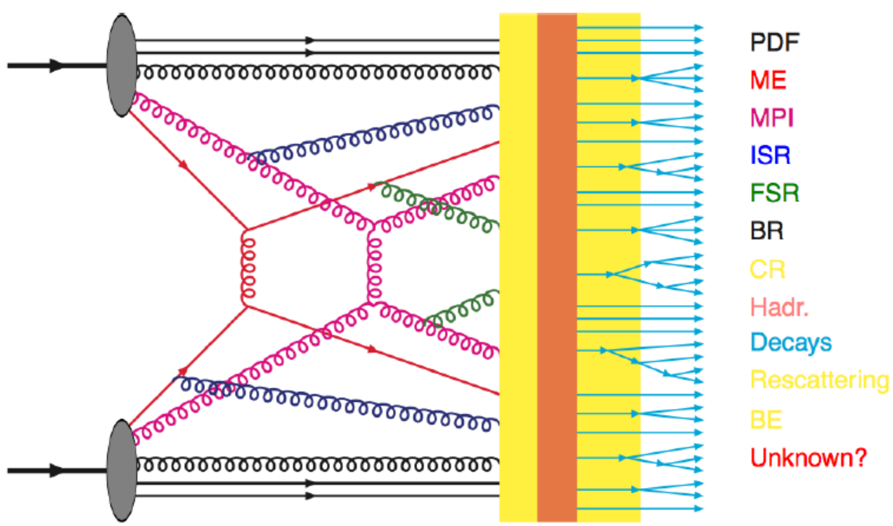
→ Independent fragmentation;

→ String fragmentation;

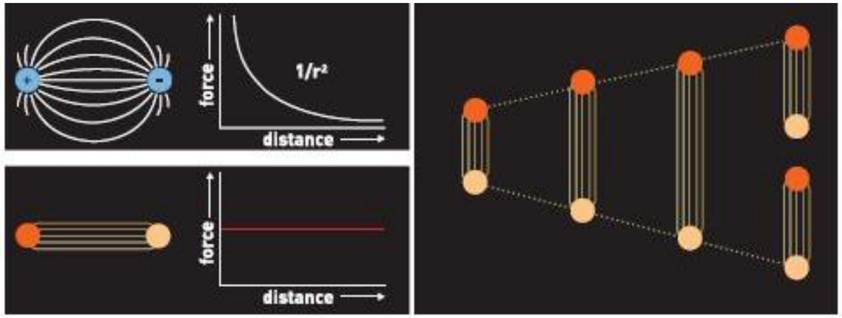
→ Cluster fragmentation.

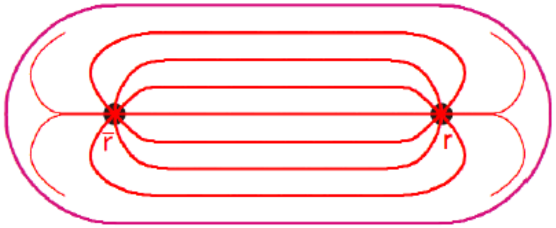
7. Decay.





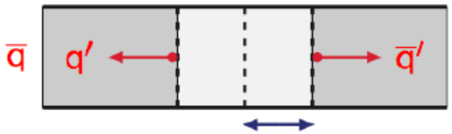
Lund string model





Field lines compressed to tubelike regions: **strings**!
Linear confinement:
$V(r) \approx \kappa r$, $\kappa \approx 1$ GeV/fm
Lorentz invariant.

String breaking by tunneling:
$\mathcal{P} \propto \exp(-\pi m_{\perp q}^2/\kappa)$
with adjacent pairs forming mesons (and baryons).

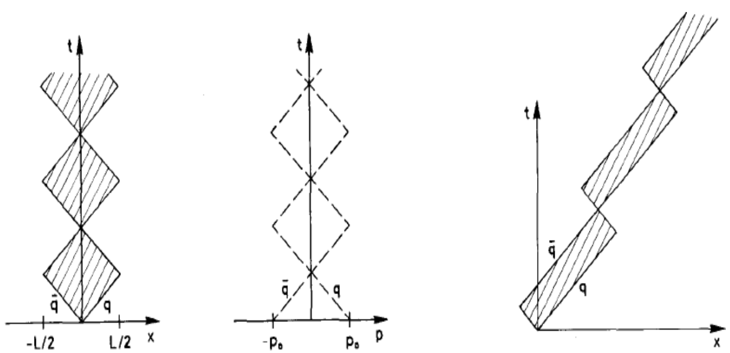


$d = m_{\perp q}/\kappa$

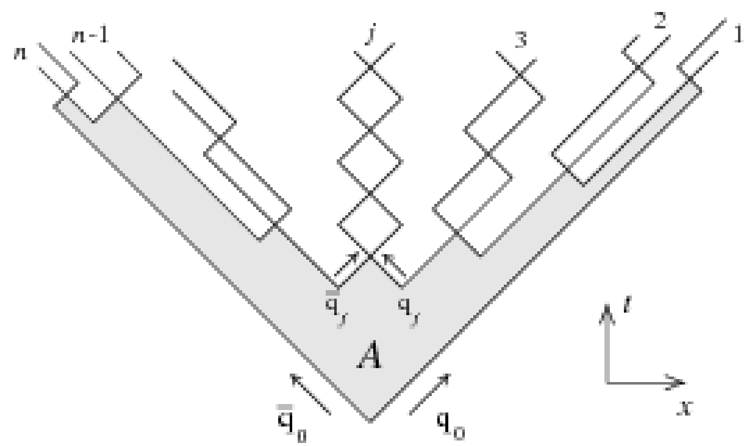
- Bound state:

  $\rightarrow \frac{dp}{dt} = \pm k;$

  → "yo-yo" system.



- Fragmentation:



Observables

Rapidity: $y = \frac{1}{2}\ln\left(\frac{E+p_z c}{E-p_z c}\right) \rightarrow y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$

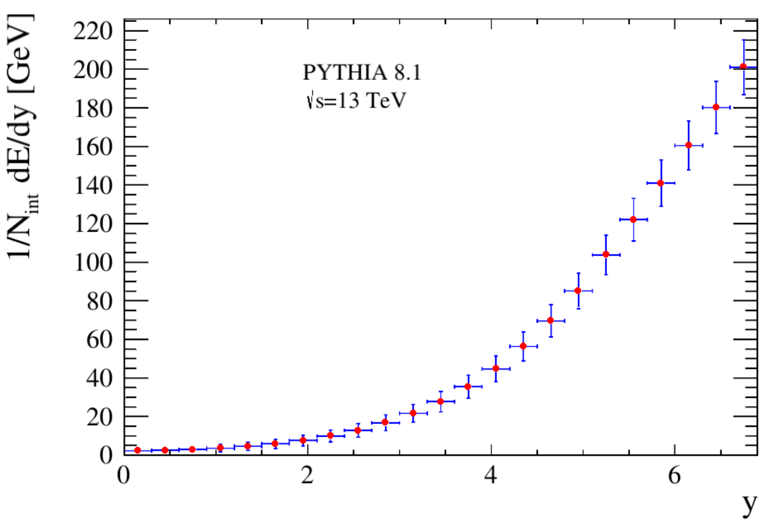
Pseudorapidity: $\eta = -\ln\tan\frac{\theta}{2}$ or $\eta = \frac{1}{2}\ln\left(\frac{|p|+p_L}{|p|-p_L}\right)$

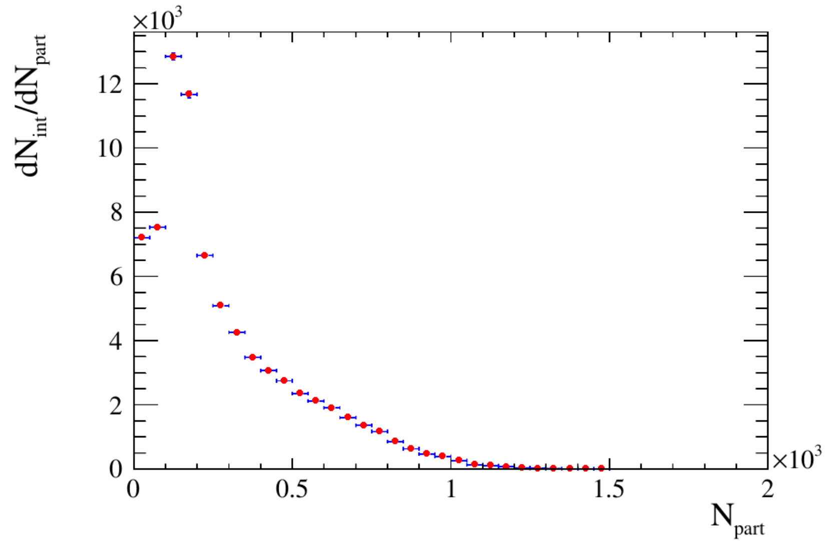
Beam rapidity: $y_{beam} = \ln\left(\frac{2E_{beam}}{m_p}\right)$

Rapidity loss: $\Delta y = y_{beam} - y \rightarrow Lorentz\ invariant$

Energy flow: $\frac{dE}{dy}, \frac{dE}{d\theta}, \frac{dE}{d\omega}$ etc.

Transverse momentum: $p_T = \sqrt{p_x^2 + p_y^2}$





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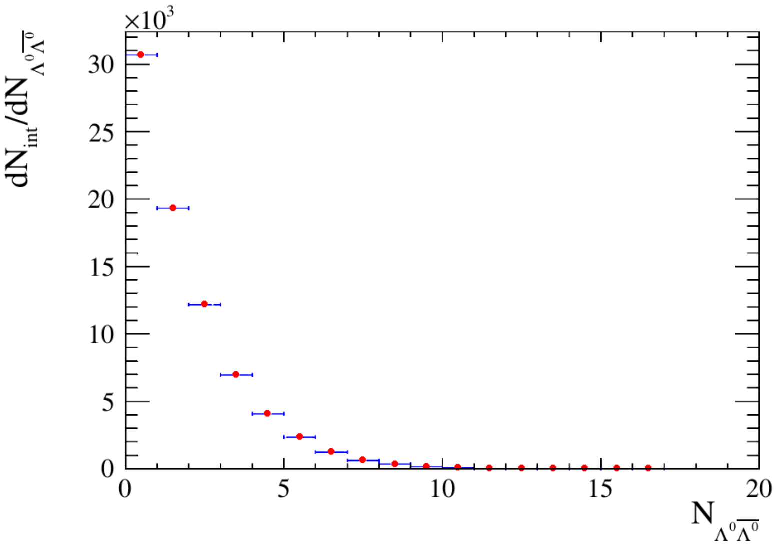

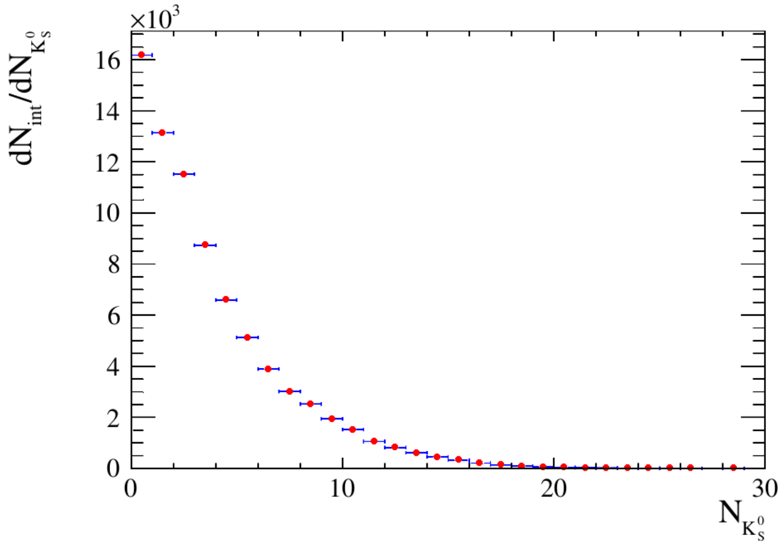

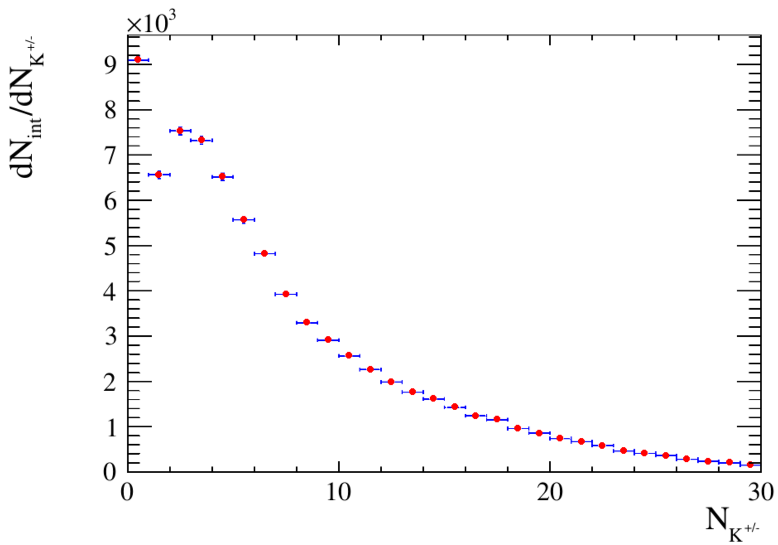

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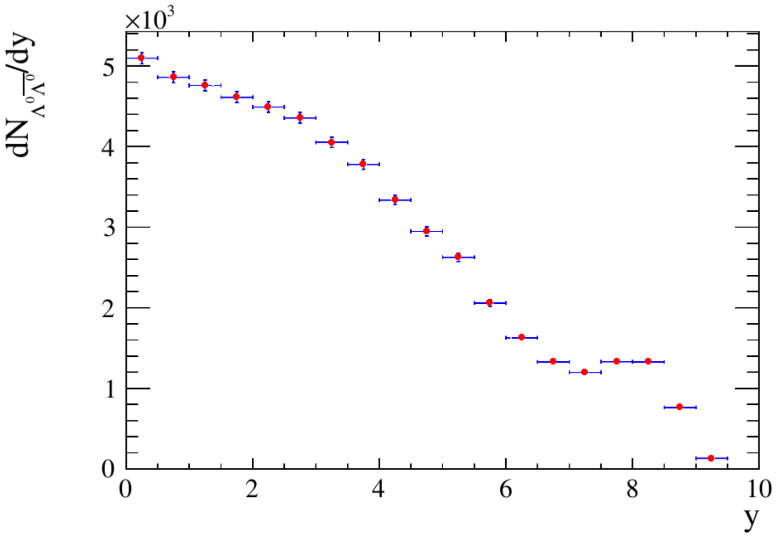

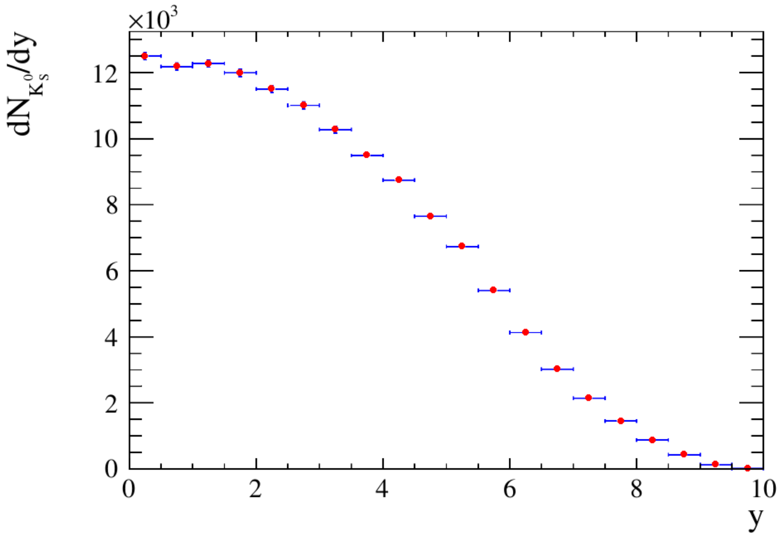

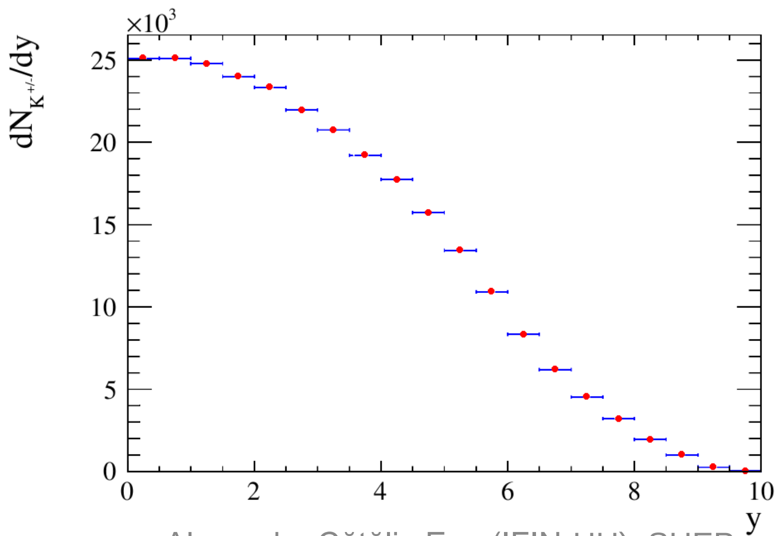

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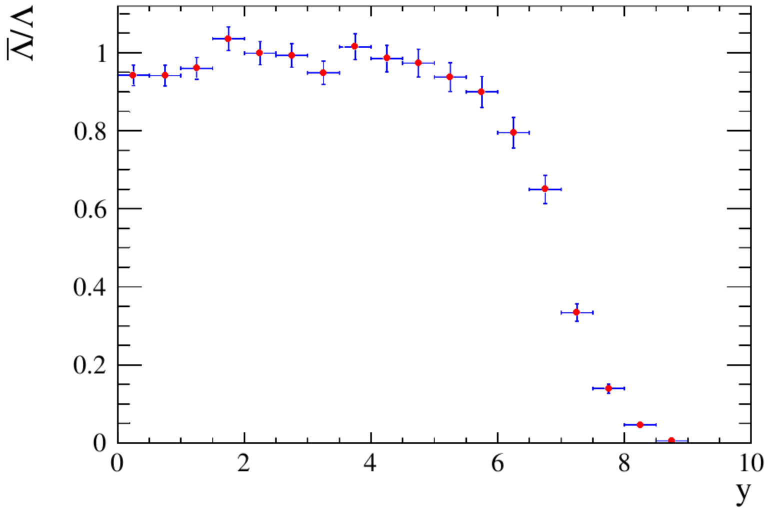

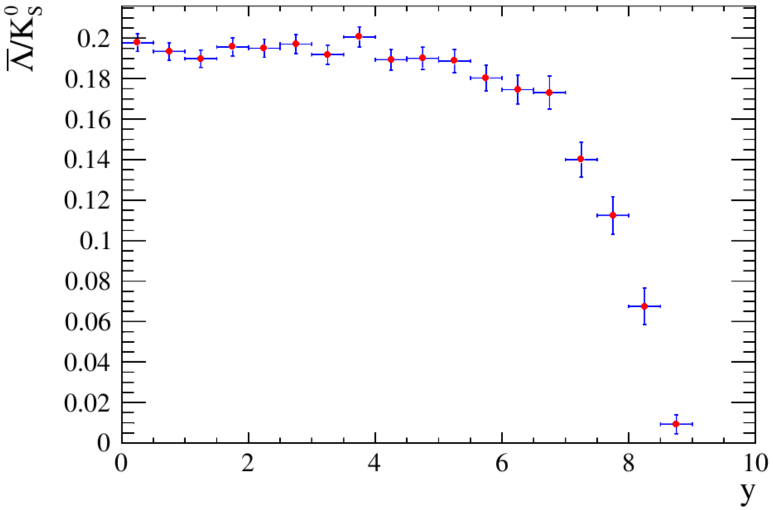

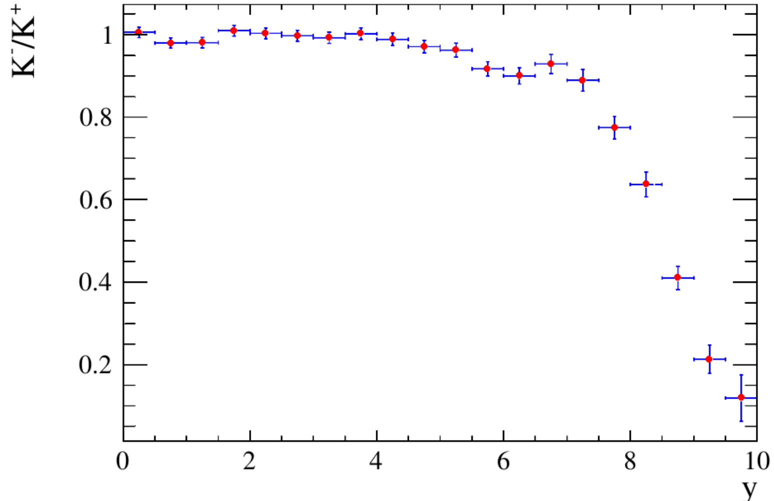

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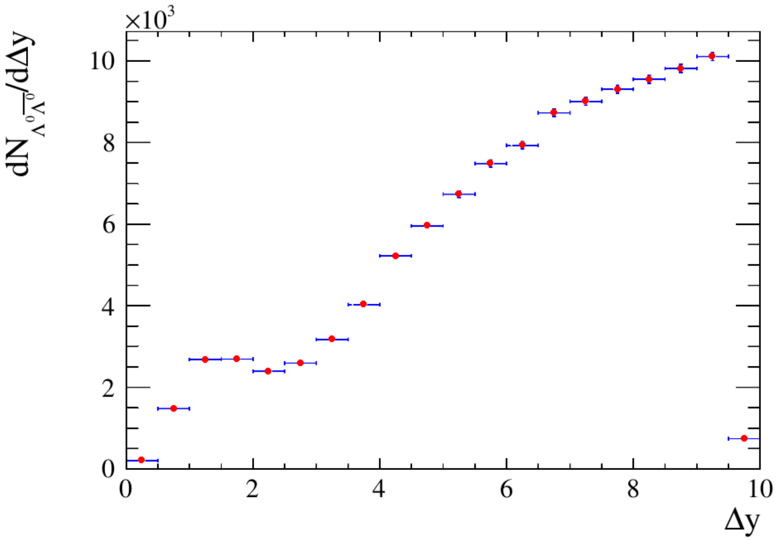

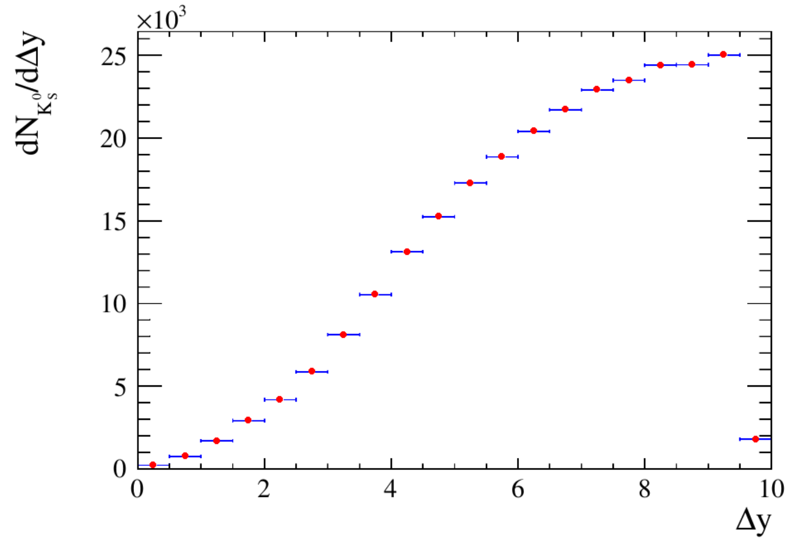

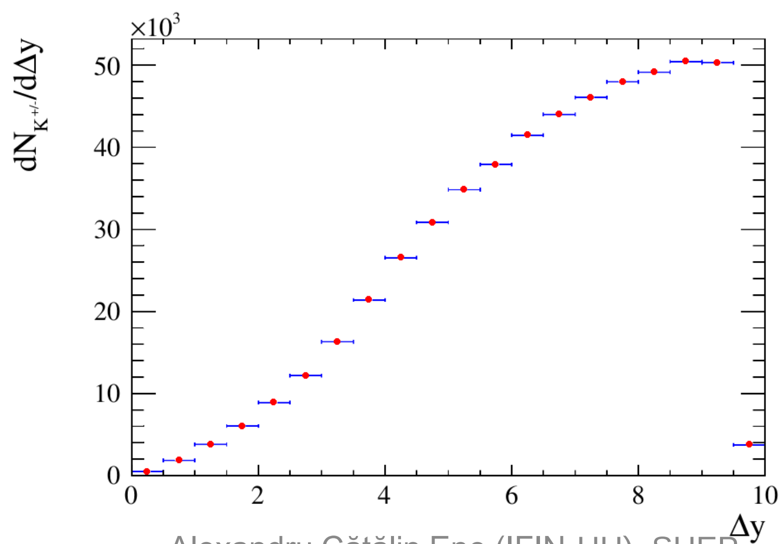

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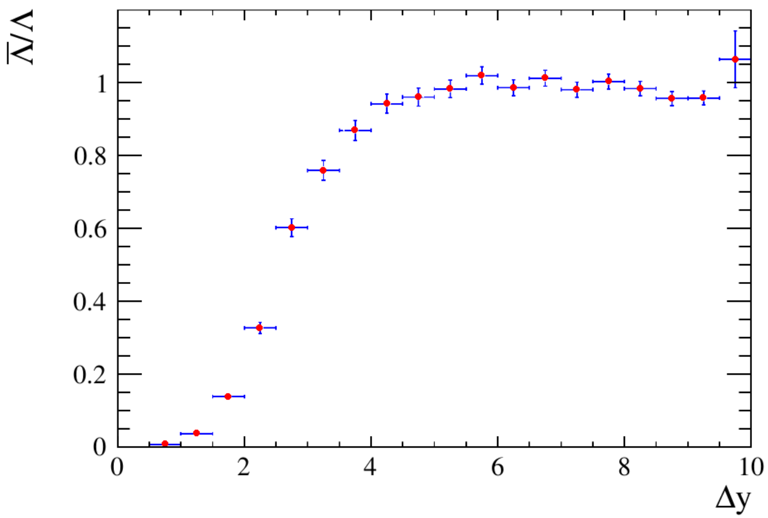

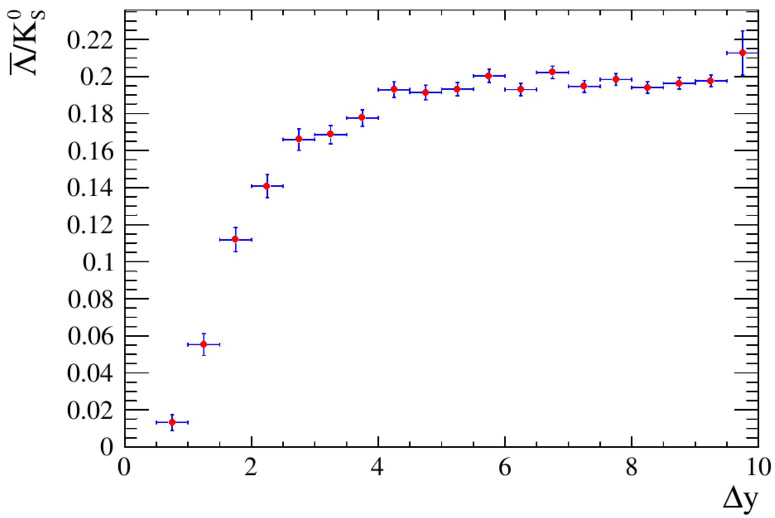

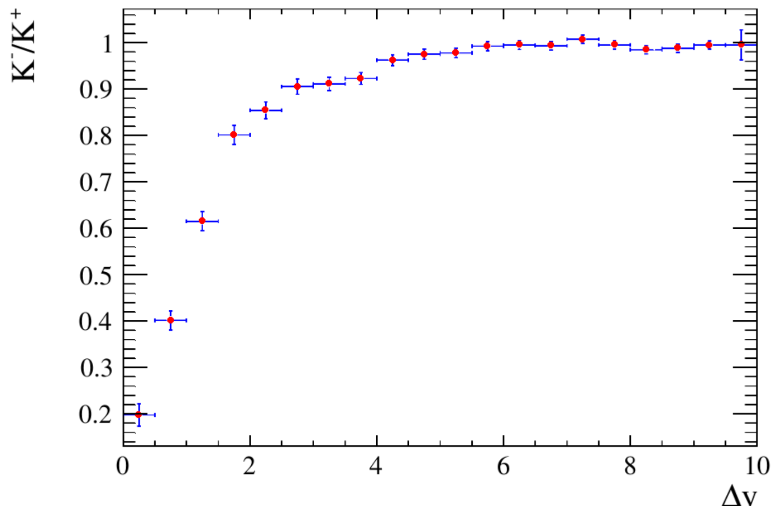

Future plans

We will compare the output from PYTHIA with the one from the cosmic ray models and try to explain the differences.

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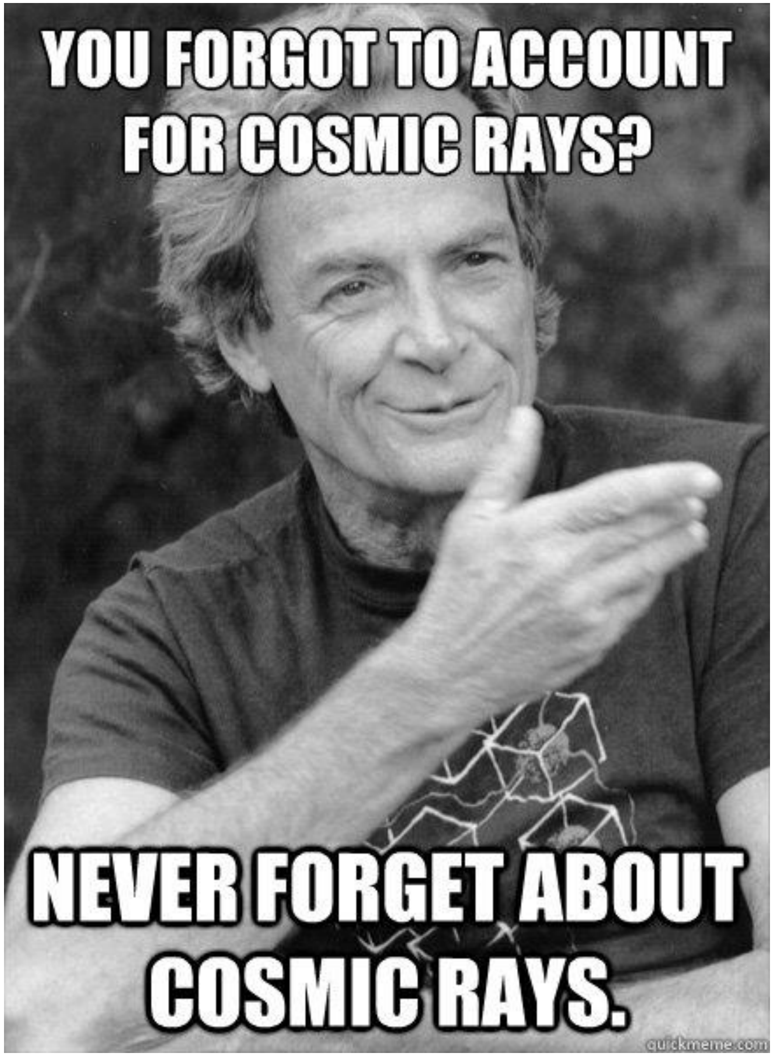


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