Ultra-High Energy Proton-Proton Collisions as the Source of Proton, Neutrino and Gamma Spectra in Astrophysics

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Abstract

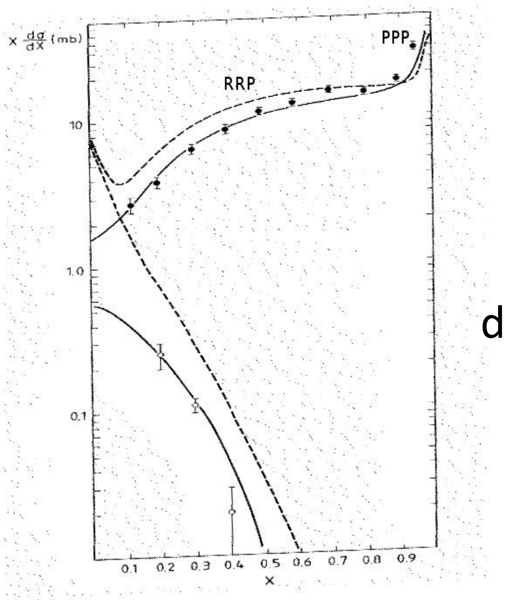
Production of ultra-high-energy (UHE) particles in astrophysics should not be different from the hadron production at the contemporary proton colliders. LHC experiments are providing us with the proton spectra at very-high energy (VHE) that are measured in center-of-mass system (c.m.s.). The proton spectrum in c.m.s. has two special features that are important at HE collisions: **the growing central-rapidity part with hadron-antihadron pair production** and the **valuable diffractive peak in the region of leading proton due to the triple-pomeron exchange**. The QCD phenomenological studies of previous years gave us the Quark-Gluon String Model for the calculations of baryon and meson production spectra in full kinematical range of rapidities. The collider proton production spectrum was recalculated to the laboratory system of coordinates, which is natural for the astrophysical observations. The specifics of collider distributions of protons are reflected in astrophysical spectra **as the knee of cosmic proton spectrum** and as **the spectrum enhancement at the UHE area in cosmic spectra of protons, neutrinos, and gamma-photons**. They help us to conclude that baryon interactions play an important role in the production of UHE cosmic particles. The remarkable result of this approach is **the estimation of maximal energy (Emax) of initial protons (and antiprotons) from the energy of knee in proton spectrum: Emax = 6*10^12 GeV.}**

Outline

- The form of proton spectra within the Quark-Gluon Model :
  the components of proton spectrum in c.m.s. at $\sqrt{s}$ = 540 GeV:
  central rapidity table, diquark contribution and triple-pomeron
  peak
- The procedure of spectrum transfer from c.m.s. to laboratory system
- The specifics of proton spectrum in laboratory system: the “knee” and a bump at the very-high energy
- Entire-range gamma radiation and an enhancement at the edge of spectrum
- Expectations for the spectra of neutrinos – recent measurements at UHE
- Conclusions

Components of proton spectrum in the collider p-p collision at $\sqrt{s}$ = 540 GeV

A.B. Kaidalov and O.Piskunova,
Zeit. Phys. C30 (1986), 145

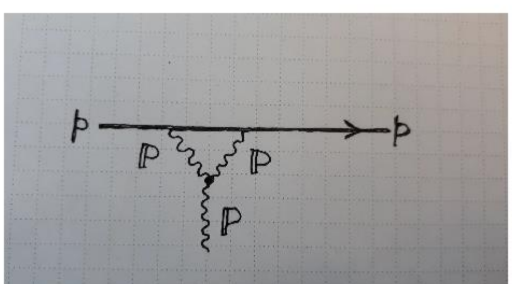


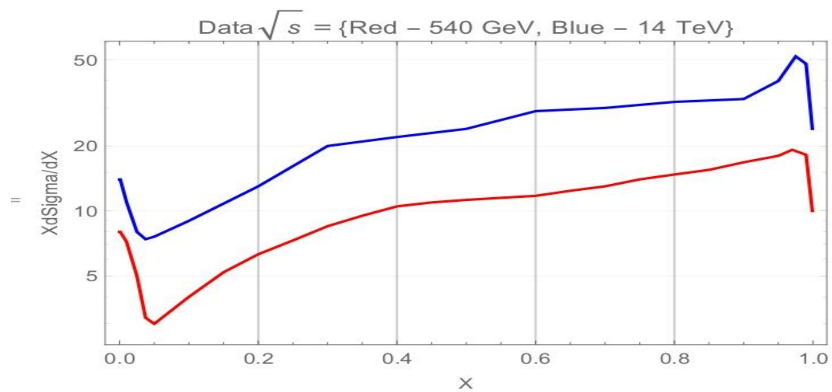
Proton production at x = 0
from vacuum diquark - antidiquark pairs
is growing with energy

Triple-Pomeron peak (**PPP** term)
is the diffractive reflexion of beam
proton

$d\sigma/dY = x\, d\sigma/dx \rightarrow d\sigma/dE = E^{-1} d\sigma/dY$

The contribution of walking diquark from
beam proton (**RRP** term) should decrease
with energy

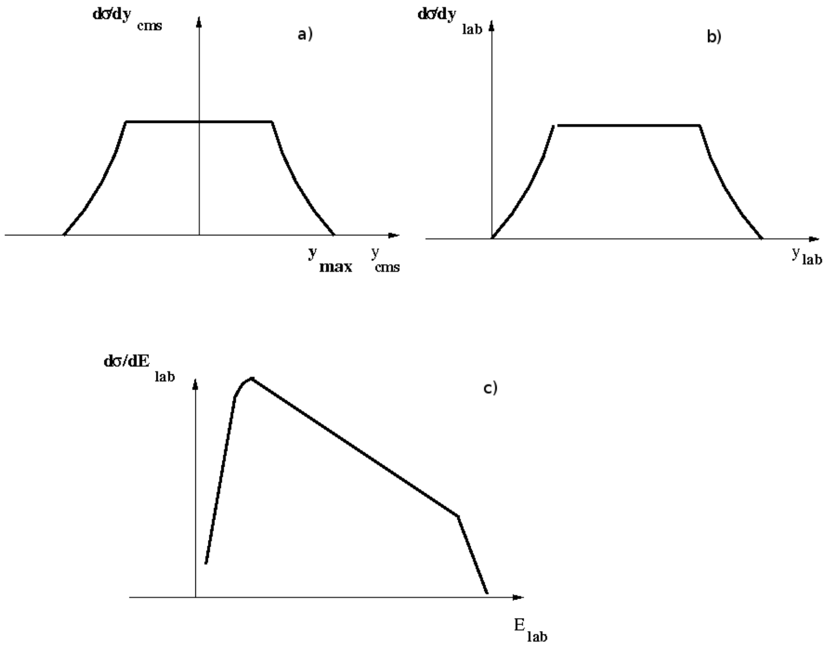




Theoretical background and achievements for QGSM

- Regge theory, trajectories and string behavior of strong interaction (1959)
- Pomeron vacuum trajectory and triple-pomeron diffraction (1963)
- Duality (1966)
- Baryonium (1968)
- Topological expansion (1974)
- Factorization of distributions, multi pomeron exchanges, supercritical intercept of pomeron trajectory, cross sections and spectra that are growing with energy(1984)
- String Junction and baryon asymmetry at LHC (2007)

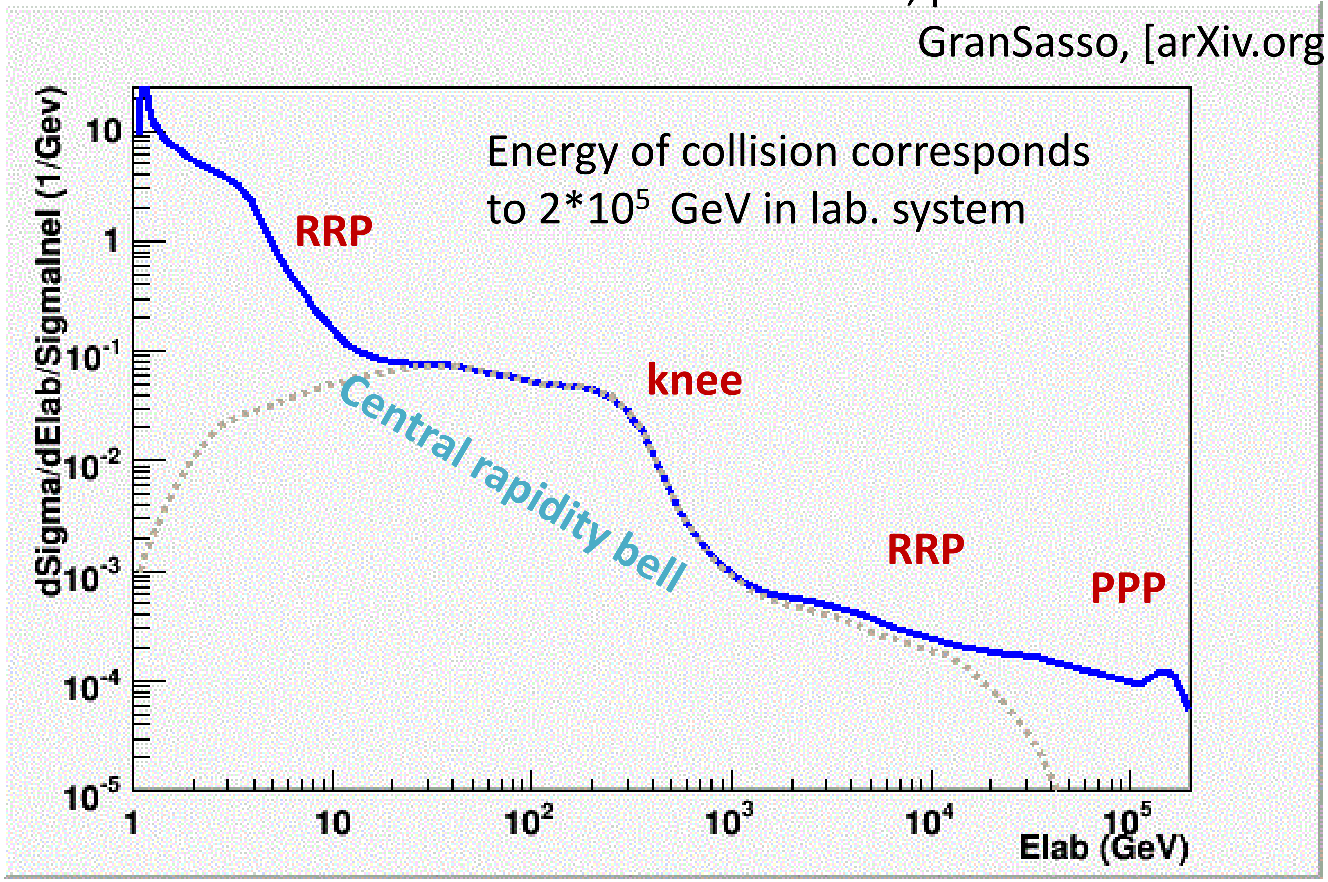
The procedure of spectrum transfer from c.m.s. to laboratory system



$d\sigma/dY = x\, d\sigma/dx$ ⇒ $d\sigma/dE = E^{-1}\, d\sigma/dY$

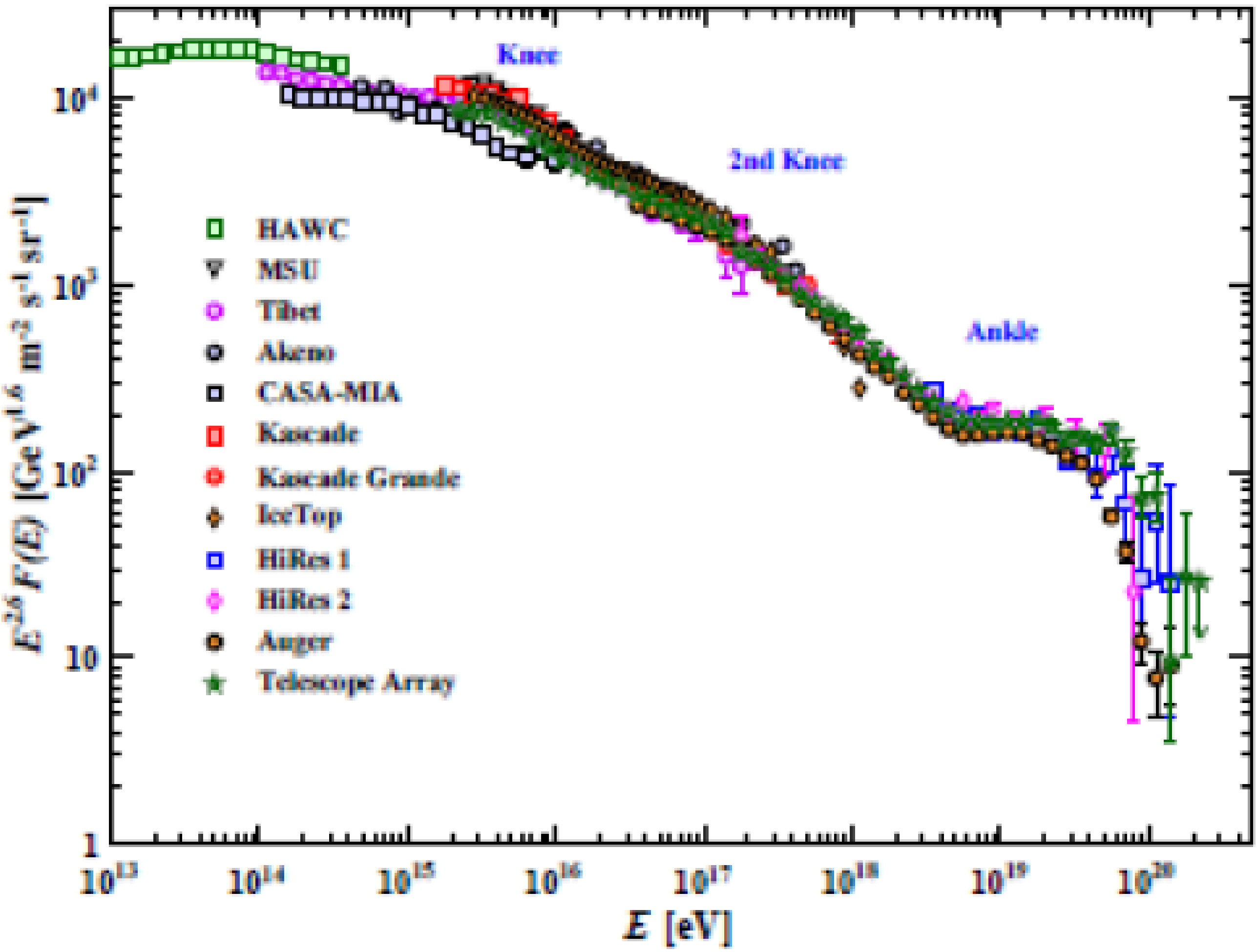
The specifics of proton spectrum in laboratory system: the “knee” and a bump at the very-high energy

O.I. Piskounova , presentation at UHECR 22, GranSasso, [arXiv.org:2110.13618]



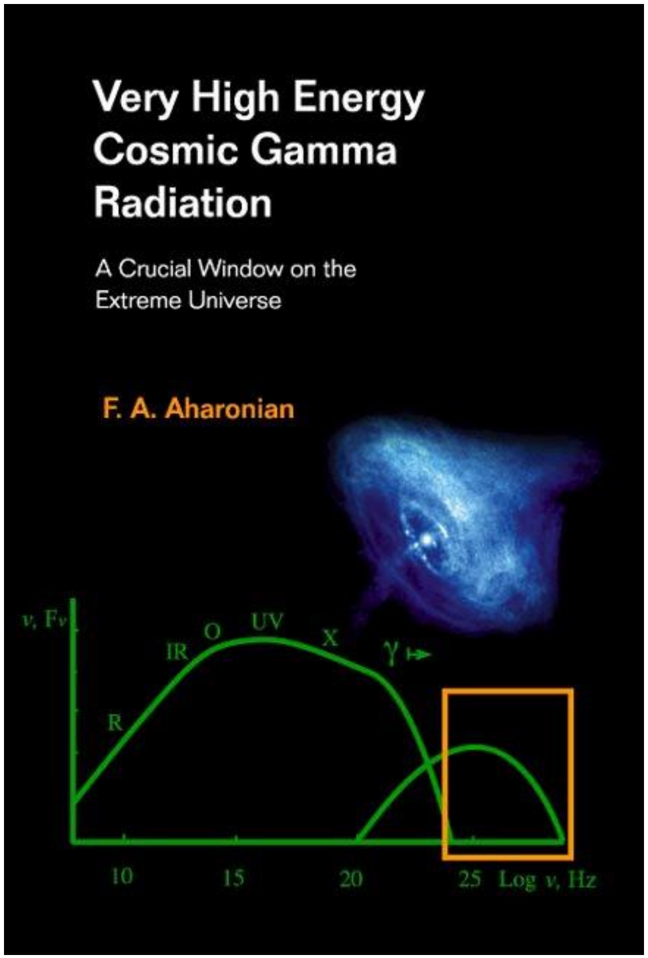
Cosmic ray spectrum

Particle Data 19: spectrum-cosmic-rays.pdf

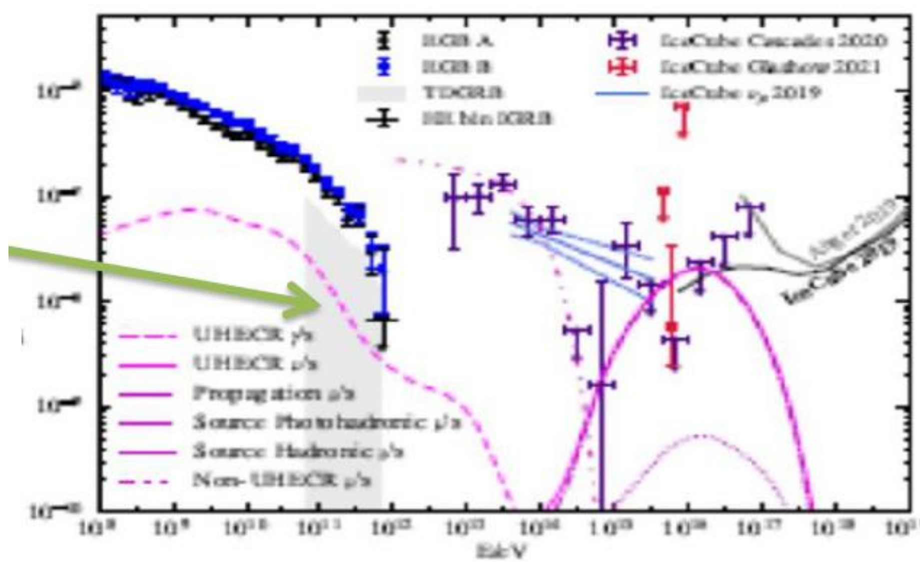


The all-particle spectrum as a function of E (energy per nucleon)

Entire-diapason of gamma radiation and an enhancement at the edge of spectrum

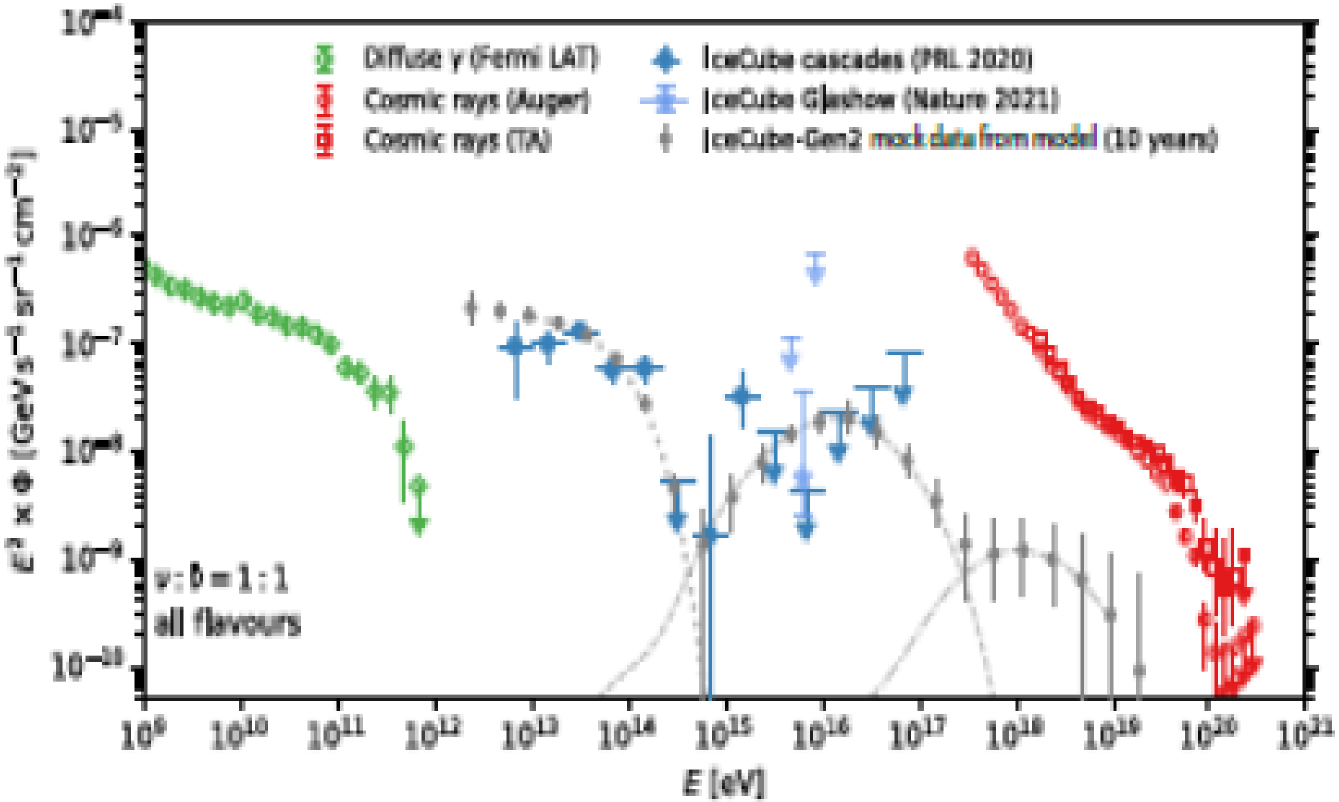


M.S. Muzio, G.R. Farrar, and M. Unger, Phys. Rev. D **105**, 023022 (2022), [arXiv.org:2108.05512]



The expectations for spectra of neutrinos – recent measurements at UHE

Snow Mass Review of Ultra-High-Energy Cosmic Rays, 2022, p. 106, [arXiv.org: 2205.05845]



Extremal energy of CR proton spectrum

- Rapidity of knee for laboratory system is maximal rapidity in c.m.s.
- The end of lab.sys. spectrum corresponds to doubled rapidity in c.m.s.
- Energy spectrum is the invariant rapidity distribution divided per energy. Each next collision or decay adds -1 to the slope of spectrum

$$d\sigma/dY = x\, d\sigma/dx \rightarrow d\sigma/dE = E^{-1}\, d\sigma/dY$$

- The energy of protons that are producing the cosmic particle spectra is of order $6 * 10^{12}$ GeV

Conclusions

- Protons and antiprotons are the fundamental matter in the Universe. Their interactions are the source of many other particles in space: secondary protons and antiprotons, positrons and electrons, gamma-photons, and neutrinos .
- The UHE protons and antiprotons are injected from the most powerful sources , Super Massive Black Holes (SMBH), and initiate particle spectra with distinctive signatures. If injected symmetrically about baryon charge, spectra of HE antiprotons from antiproton interaction should have the same features as in proton-proton case. The interaction does not produce baryon asymmetry.
- If c.m.s. spectrum has transferred into laboratory system, the central rapidity bell converts into the knee of laboratory spectrum, and the triple-pomeron peak corresponds to the bump at the end of cosmic particles: protons, neutrinos, gamma, and others.
- Within of this approach we can estimate the initial energy of protons (antiprotons) from the source. Since the knee corresponds to rapidity center in c.m.s., the maximal rapidity in astrophysical proton spectrum is a doubled rapidity of the knee. In such a way, the maximal energy of spectra is approximately Emax = 6*10**12 GeV.