LHC experiments: Exercises[0]

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Exercise 1: Higgs observation. The Compact Muon Solenoid (CMS) experiment measures a peak in the invariant-mass photon-photon spectrum at $m = 120.$ GeV/c^2 with a width of 6 GeV/c^2. The signal has S = 25 counts on top of B = 100 counts from the residual QCD diphoton background. In this mass range, the CMS electromagnetic calorimeter has a mass resolution for a $\gamma\,\gamma$ resonance of $\Delta m/m = 1\%$.

(a) What is the signal significance ? Usually, "evidence" ("discovery") for a new particle is claimed when the Gaussian probability that a local fluctuation generates such a signal is below 0.27% (5.7 10^{-5}%). Does the CMS observation qualify as evidence/discovery for a new resonance ? For the same luminosity, ATLAS observes the same peak with a signal-to-background ratio of S/B = 36/206. Assuming completely uncorrelated measurements, does the *combined* ATLAS+CMS signal qualify as "evidence" or "discovery" of a new 120-GeV/c^2 resonance ?
(b) What is the error in the mass of the measured particle ?
(c) Explain why the decay channel indicates that such a resonance could be the Standard Model Higgs. Given the measured width, is this resonance consistent with this assumption ?

Exercise 2: Cosmic rays and Greisen-Zatsepin-Kuzmin cutoff. The LHCf experiment (and other forward detectors in ALICE/ATLAS/CMS) aims at studying (neutral) particle production at zero degrees to constrain Monte Carlo models of relevance for cosmic-rays (CR) physics. Very high-energy hadronic CRs can lose energy through collisions with the cosmic microwave background (CMB) photons (black-body radiation with T = 2.72 K) in the process $p\,\gamma \to p\,\pi$ with a cross section peaked at the Δ resonance $\sigma_{p\gamma\to\Delta} \approx 0.5\times A^{2/3}$ mb, where A is the mass-number of the CR.

(a) Give a short intuitive explanation for the mass-number dependence of the nuclear pion photoproduction cross section: $\sigma \propto A^{2/3}$.
(b) Determine the threshold energy ("GZK cutoff") for a CR proton and ^{56}Fe ion to photoproduce a pion in its way through the universe. $[m_p = 0.938\,\mathrm{GeV}/c^2,\, m_\pi = 0.140\,\mathrm{GeV}/c^2]$.

[0]Most (if not all) relevant material to answer the questions can be found in the presentation slides.

(c) Determine the (black-body) CMB photon number density n_γ and the corresponding mean free path length l of a CR proton and a ^{56}Fe ion in the universe.
(d) Assuming the same accelerating/magnetic settings as the LHC today, what should be the radius of a proton-proton collider to deliver center-of-mass energies equal to the GZK cut-off ? In such a hypothetical collider, where (around which rapidity) should one install zero-degree detectors ?

Exercise 3: Collider kinematics, pileup probability.

(a) Prove that under a boost to a frame that moves with velocity β in the z-direction, the rapidity transforms as: $y \to y - y_\beta$. Show that at very high energies ($\beta \to \infty$ and/or $m \to 0$), the rapidity y of a particle can be approximated by its pseudorapidity η (is that true for very low angles too ?). What is the relation between $d\sigma/dy$ and $d\sigma/d\eta$ for a particle of mass m ? (Find the Jacobian). Usually $d\sigma/dy$ is a Gaussian-like distribution peaked at $y = 0$. What about $d\sigma/d\eta$?
(b) The production cross section of a particle expressed as $E\, d^3\sigma/d^3p$ (where E is the particle energy and $d^3p = dp_x dp_y dp_z$ its 3-momentum in Cartesian coordinates) is Lorentz invariant. Find the corresponding Jacobians, and write the invariant cross section as a function of (p_T,y,ϕ) and (p,θ,ϕ).
(c) The number of simultaneous proton-proton inelastic interactions ("pileup") taking place in the ATLAS and CMS interaction points is given by a Poisson distribution with an average of $\langle n \rangle = \mathcal{L}\sigma_{\rm inel}\, t\,/\, f \;\approx 25$ per bunch crossing at design luminosity ($\mathcal{L} = 10^{34}$ cm^{2}s^{-1}). The focusing magnets at the LHCb interaction point are tuned to run at $\mathcal{L} = 4{\cdot}10^{32}$ cm^{2}s^{-1}, and yield $\langle n \rangle = 1$ to minimize pileup. What is the probability of having a bunch-crossing at LHCb with two pileup collisions ? and with zero collisions (empty bunch) ?