The Study of Events Observed in Cosmic Rays through the Comparison with the prediction of Monte Carlo Event Generators

DOCTORAL QUALIFYING EXAM

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Outline

1. Introduction
   - Cosmic Rays Physics
2. Cosmic Rays Experiment
   - Events Observed by the CBJ (C-jets Events)
3. Kinematic Variables
   - LAB Frame
   - CM Frame
4. Analysis Methodology
   - C-jets Events, Monte Carlo Event Generations
5. Results and Discussion (Preliminary)
   - Experiment / Simulation

Introduction

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- **Objectives**:
  - **General**: Study hadronic interactions produced by particles of cosmic radiation $E_{LAB} = 10^2$ TeV (CBJ) - 10^9 TeV (Pierre Auger Observatory[1]), and compare it with the results obtained by Monte Carlo event generators (like PYTHIA 82[2] and EPOS LHC[3]).
  - **Specific**: Event generators for searching by characteristics of diffractive phenomena, jet production or other asymmetries of the Standard Model for the energy of $E_{LAB} \sim 100$ TeV (CBJ) and $\sim 10^9$ TeV (Auger) in the forward region of cosmic rays[4].

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[2] T. Sjöstrand et al., Comput. Phys. Commun. **191**, 159–177 (2015).
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  - **Specific**: Comparison of cosmic rays data (CBJ and Auger) to acelerator data[5].
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Cosmic Rays: Definition, Origin, Properties

- Cosmic Rays are high-energy radiation, mainly originating outside the Solar System and even from distant galaxies[7].

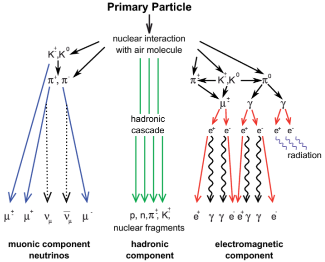

Figure: Cosmic Ray[8]. https://www.auger.org/

[7] A. Aab et al., Nucl. Instrum. Meth. **A798**, 172–213 (2015), A. Aab et al., Science **357**, 1266–1270 (2017).

[8] A. Haungs et al., J. Phys. Conf. Ser. **632**, 012011 (2015).

Cosmic Ray History

- In August 1912, Victor Hess made the historic balloon flight that was set to open a new window on matter in the universe. (CERN Courier, Jul 18, 2012)
- 9 September 1932, Carl Anderson discovers the positron.
- 1 September 1933, Bruno Rossi: Cosmic Rays are positive charged particles.
- 18 July 1938, Pierre Auger and colleagues demonstrate extensive air showers[9].
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  - Mt. Chacaltaya (5220m, Bolivia),
  - CBJ(1962) the experiments through the exposures of emulsion chambers to cosmic radiation,
  - Phase 1: Emulsion Chamber (Type simple) (1962-70),
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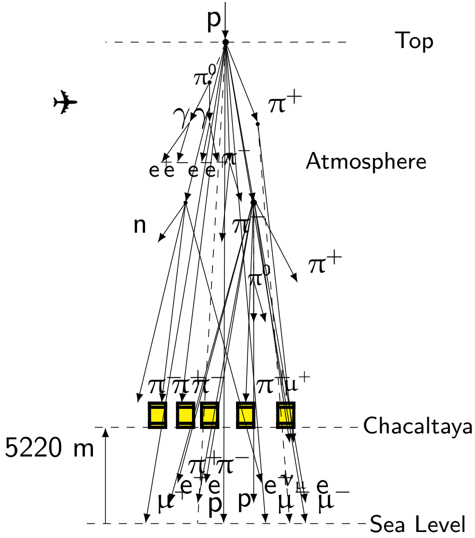
Extensive Air Shower (EAS)



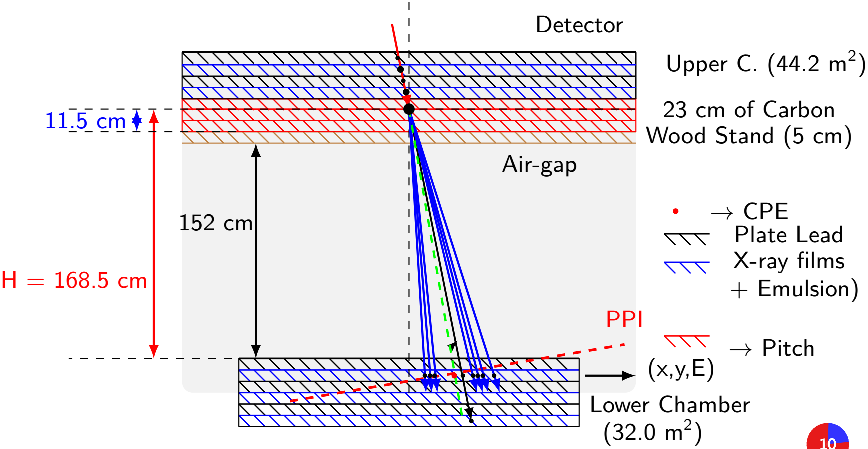
Detector of the CBJ

- Cosmic Rays are highly energetic particles, atomic nuclei or radiation that can produce particle showers ($\pi^0, \pi^\pm$, n, p, γ, $e^\pm$, η^0, $K^\pm$, ...) in the earthly atmosphere, through hadronic interactions,
- To study the hadronic interactions using cosmic radiation as a source of particles, the CBJ used nuclear emulsion chambers.

Chacaltaya Two-Storey Chamber (LAB Frame)

1. Upper Chamber ($\sim$ 7 cm Pb)
2. Carbon Layer (Target) ($\sim$ 23 cm)
3. Air-gap ($\sim$ 152 cm)
4. Lower Chamber ($\sim$ 7 cm Pb)

Emulsion Chamber



C-jets

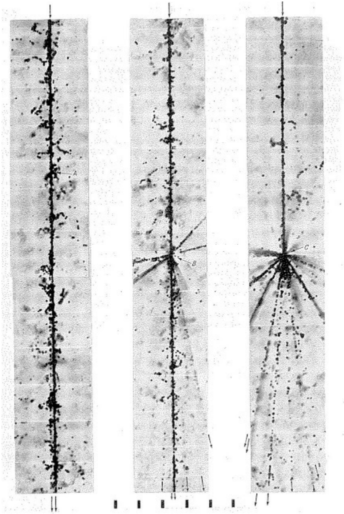
- **C-jets** (CBJ): Events observed in the Lower Chamber are products of the interaction of the incident particle with Carbon (target) in the Upper Chamber.
- $\sum E_\gamma \sim E_0/3$, E_0 is the total energy of the cosmic radiation incident (γ, hadron) in the two-storey chamber.
  $E_\gamma \equiv$ Energy deposited in the calorimeter

82 events (x,y,E) (total 1334 shower) (Lower Chamber)

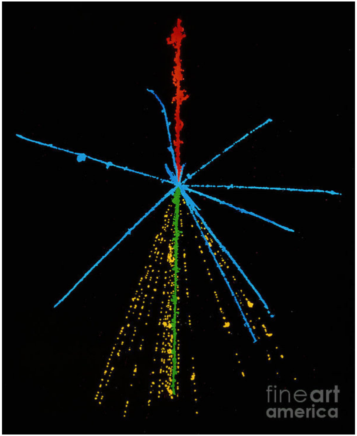
$$20 \text{ TeV} \lesssim E_\gamma \lesssim 123 \text{ TeV} \rightarrow 60 \text{ TeV} \lesssim E_0 \lesssim 370 \text{ TeV}$$

- $\langle E_\gamma \rangle \sim 37$ TeV, $\langle E_0 \rangle \sim 130$ TeV (CBJ Data/Simulation).
- Simulation: PYTHIA 8.226, PYTHIA 8.230, EPOS LHC.

Cosmic Rays Detected in an Emulsion Film



Nuclear Emulsion Film (vertical position) with track of the one particle(or shower γ) that come from cosmic rays [C. Powell, P. Fowler & D. Perkins].



Cosmic Ray is a photograph by C. Powell, P. Fowler & D. Perkins which was uploaded on September 29th, 2014

Experimental Characteristics of the C-jets Events

- Detection efficiency is higher for particles with energies greater than 0.5 TeV (0.2 TeV).
- The energy in the range of 20 - 123 TeV, LAB Frame.
- Particle flow(or Luminosity) is low, so the signal-to-noise ratio is very favorable (Low Pileup [11]).
- Detector (CBJ) observed C-jets Events: The secondary particles are scattered at low angles.
- LAB Frame: In the events (energy ∼ TeV) with low transverse momentum (below 1 GeV)[12] is an evidence to compare with diffractive events in hadronic interactions softQCD predicted by the PYTHIA 82[13] or EPOS LHC[14].

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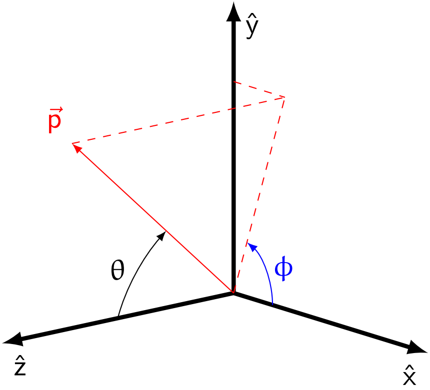

Spherical Coordinate System. $\phi = [-\pi, \pi]$ and $\theta = [0, \pi]$

Definitions

LAB Frame (Observables)

- 4-momentum: (E, p_x, p_y, p_z), $p_T = \sqrt{p_x^2 + p_y^2}$.
- $y \equiv \frac{1}{2} \ln \left[\frac{E+p_z}{E-p_z}\right]$, $\phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$ $\theta = \tan^{-1}\left(\frac{p_T}{p_z}\right)$.
- Highly Relativistic Particles, $y \simeq \eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$, LHC or Cosmic Rays. Natural units $\hbar = c = 1$.

- LORENTZ INVARIANT $\Delta\eta$: Lorentz Transformation.
- Cosmic Rays: $\theta \lesssim 10^{-3}$ rad[15] (High $\eta \gtrsim 7.6$) (LHC)[16].

[15] H. Kumano, Prog. Theor. Phys. Suppl. **76**, 51–82 (1983).
[16] D. G. d'Enterria, in Proceedings, 15th International Workshop on Deep-inelastic scattering and related subjects (DIS 2007). Vol. 1 and 2: Munich, Germany, April 16-20, 2007 (2007), pp. 1141–1152.

Definitions

LAB Frame (Observables)

- $\vec{\beta}_{\mathrm{CM}} = \frac{\sum_i^N \vec{p_z}}{\sum_i^N E_i}, \quad |\vec{\beta}_{\mathrm{CM}}| = \beta, \quad \gamma_{\mathrm{CM}} = \frac{1}{\sqrt{1-\beta^2}},$
- $\sqrt{s} = \sqrt{2mE_{\mathrm{LAB}}}, \quad E_{\mathrm{LAB}} = \sum_i^N E_i$

Lorentz Transformation (LT): LAB $\rightarrow$ CM*

$$\begin{bmatrix} E^* \\ p_x^* \\ p_y^* \\ p_z^* \end{bmatrix} = \begin{bmatrix} \gamma & 0 & 0 & -\beta\gamma \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\beta\gamma & 0 & 0 & \gamma \end{bmatrix} \begin{bmatrix} E \\ p_x \\ p_y \\ p_z \end{bmatrix}$$

Definitions

CM Frame (Observables)

- $p_T^* = \sqrt{(p_x^*)^2 + (p_y^*)^2}$, $\phi^* = \tan^{-1}\left(\frac{p_y^*}{p_x^*}\right)$,
- $\theta^* = \tan^{-1}\left(\frac{p_T}{p_z^*}\right)$, $\eta_{CM} = -\ln\left[\tan\left(\frac{\theta^*}{2}\right)\right]$,
- $\eta_{CM} = \eta_{LAB} - \frac{1}{2}\ln\left[\frac{1+\beta}{1-\beta}\right]$,
- $p_T = p_T^*$, $\phi = \phi^*$, $\sum_{i=1}^{N} \vec{p}_i^{\,*} = \vec{0}$ and $\sum_{i=1}^{N} E_i^* = \sqrt{s}$,
- $dN/d\eta$ (Multiplicity or Particle Flow) (Normalized),
- $dE/d\eta$ (Energy Flow) (Normalized).

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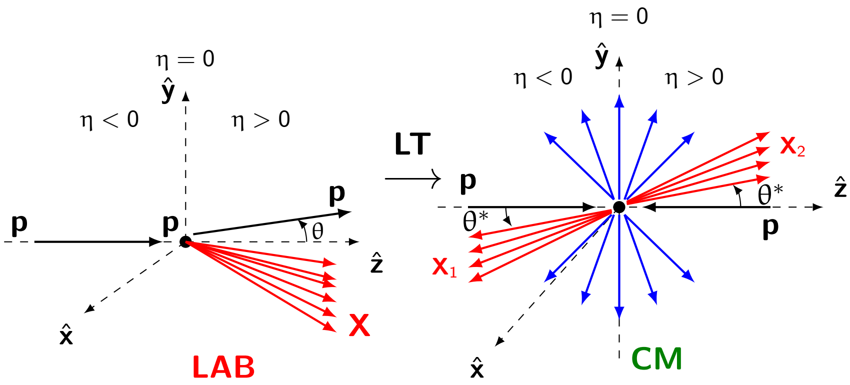
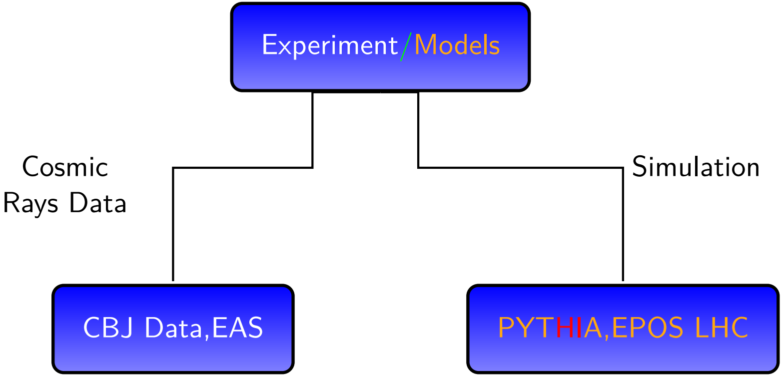


(a) (b)

General Description



General Description

- Treatment of the C-jets Events (CBJ Data).
  - $(x, y, \mathrm{E}) \rightarrow$ Kinematic Variables,
  - Multiplicity and Energy Distribution in the Phase Space (η, ϕ).
- Monte Carlo Event Generations:
  - Collisions: pp, pA and AA, A = Pb, C, ... HI - Heavy Ions,
  - PYTHIA 8.226 (pp), PYTHIA 8.230 (pp, pA, AA) (Collider),
    - softQCD (Diffractive and Non-Diffractive (Low-p_T)),
    - hardQCD (High-p_T),
  - EPOS LHC (pA and AA) (Cosmic Rays),
  - Output: Particle Production, Kinematic Variables, PDGid, Multiplicity and Energy Distribution in the Phase Space (η, ϕ),
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1. An event with N shower (x_i, y_i, E_i), x_i,y_i [cm] and E [TeV],
2. (x_i, y_i, E_i) already is in the PPI,
3. Weighted Center of Energy (CPE) is $(x_{\mathrm{CPE}}, y_{\mathrm{CPE}})$, LAB frame:

$$x_{\mathrm{CPE}} = \frac{\sum_i^N x_i \mathrm{E}_i}{\mathrm{E_T}} \text{ [cm]}, \quad y_{\mathrm{CPE}} = \frac{\sum_i^N y_i \mathrm{E}_i}{\mathrm{E_T}} \text{ [cm]},$$

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Kinematic Variables of the C-jets Events

4. Azimuth Angle: $\phi_i = \tan^{-1}\left(\frac{y_i'}{x_i'}\right)$,
5. Angle Scattering (or polar angle): $\theta_i = \tan^{-1}\left(\frac{\sqrt{x_i'^2+y_i'^2}}{h}\right)$, being $h = H/\cos\theta_Z$ is the height between the half of the Carbon target (C) and the PPI.
6. Pseudo-rapidity :$\eta_i = -\ln\left[\tan\left(\frac{\theta_i}{2}\right)\right]$.
7. Approximation $E \approx |\vec{p}|$:

$$\begin{cases} p_{T_i} = E_i \sin\theta_i, \\ p_{xi} = p_{T_i}\cos\phi_i, \\ p_{yi} = p_{T_i}\sin\phi_i, \\ p_{zi} = E_i\cos\theta_i. \end{cases}$$

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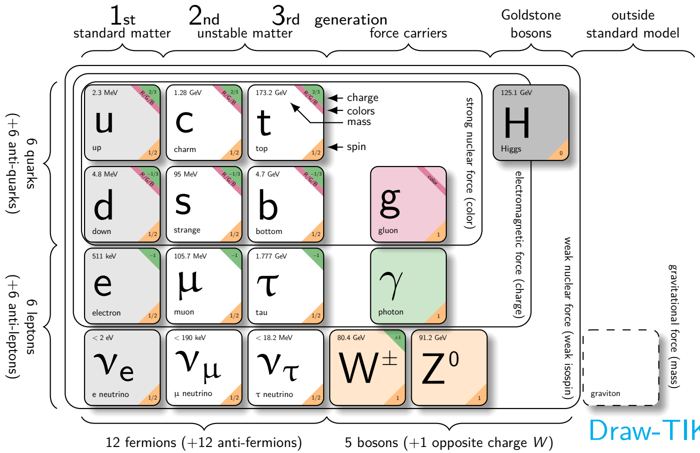
Overview: The Standard Model of Particle Physics

- The Standard Model explains how the basic building blocks of matter interact, governed by three fundamental forces.



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Quantum Chromodynamics (QCD)

- QCD: Quantum field theory of strong interactions[17],
  - interaction carried by gluons acting on quarks and gluons.
- QCD running coupling strength α_s depends on energy,[18]
  - Low energy (= long distance or time)
    $\rightarrow$ α_s is large (confinement): non-perturbative regime of QCD (non-pQCD),
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- Two beams of partons (quarks, gluons) initiate the parton-level interaction[19],
- Particles produced in high-energy are described by Phenomenological models together with pQCD that do predictions for high-p_T processes to obtain an almost complete description of the final states,
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  - hard QCD treated by pQCD (high-p_T)[20], $\sigma_{hard} \sim 10^{-3}$ mb ($\sqrt{s}$ = 475 GeV),
  - soft processes such as diffractive and Non-Diffractive events. Phenomenology of soft hadronic processes based on Gribov-Regge theory[21] has been employed to describe these processes at high energies, e.g, EPOS LHC.

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- PYTHIA $\rightarrow$ total cross section ($\sigma_{\text{Tot}}(s)$), cross section elastic ($\sigma_{\text{el}}(s)$) and cross section for diffractive and Non-Diffractive topologies ($\sigma_{\text{inel}}(s)$)[22]:

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$$\sigma_{\text{inel}}(s) = \sigma_{\text{ND}}(s) + \sigma_{\text{SD}}(s) + \sigma_{\text{DD}}(s) + \sigma_{\text{DC}}(s),$$

where $\sigma_{\text{ND}}(s)$: Non-Diffractive, $\sigma_{\text{SD}}(s)$: Single-Diffractive, $\sigma_{\text{DD}}(s)$: Double-Diffractive and $\sigma_{\text{DC}}(s)$: Central-Diffractive[23].

- Diffractive processes are caracterised by rapidity gaps ($\Delta\eta$) in the final state of multiplicity and energy distribuition[24].

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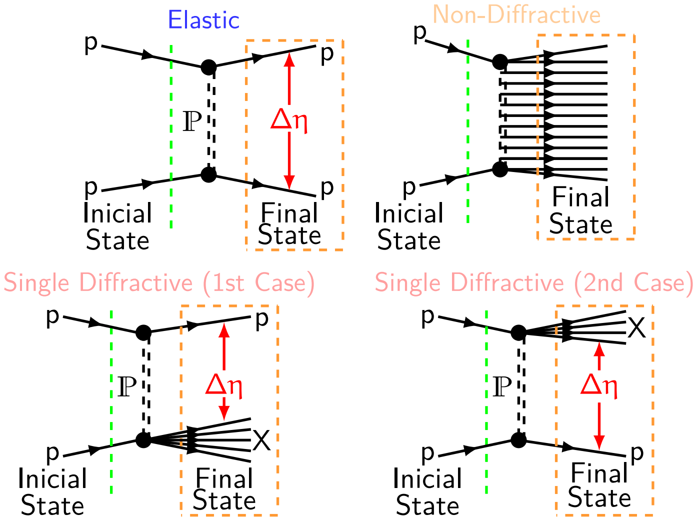
Diffractive and Non-Diffractive Topologies



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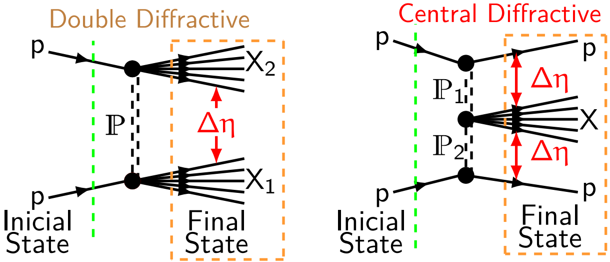

- **SoftQCD**: Low-$p_T \leq 1$ GeV^2 (Minimum Bias). Most of the events observed in the LHC are due to low-p_T collisions or non-pQCD (only phenomenological models).
- The rapidity gap ($\Delta\eta$) is defined as the absence of charged particle tracks above a certain p_T threshold.

Configurations: Beams for Event Generators

- Incident particle (hadron = p, n or $\pi^{\pm}$) in upper chamber (p, Pb or C):
  - PYTHIA: pp, pPb, pC, nPb, nC, π^{+}C, π^{-}C.
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  Some more likely combinations
  - PYTHIA: pp, pC, pPb, nPb, nC, π^{+}C, π^{-}C.
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CORSIKA[25] (Chacaltaya) Average of particles per Event:

p = 1.4 %, $\bar{\text{p}}$ = 1.1 %, n = 1.2 %, = 1.0 %, γ = 17.8 %, e^{+} = 5.4 %, e = 5.5 %, μ^{+} = 6.4 %, μ^{-} = 6.6 %, π^{0} = 0.0 %, π^{+} = 12.6 %, π^{-} = 12.5 %, K_{0L} = 2.7 %, K_{0S} = 0.1 %, K^{+} = 1.5 %, K^{-} = 2.1 %.

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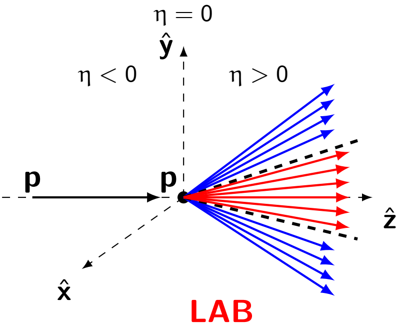
Physical Interpretation after the energy cut: E_{cut}



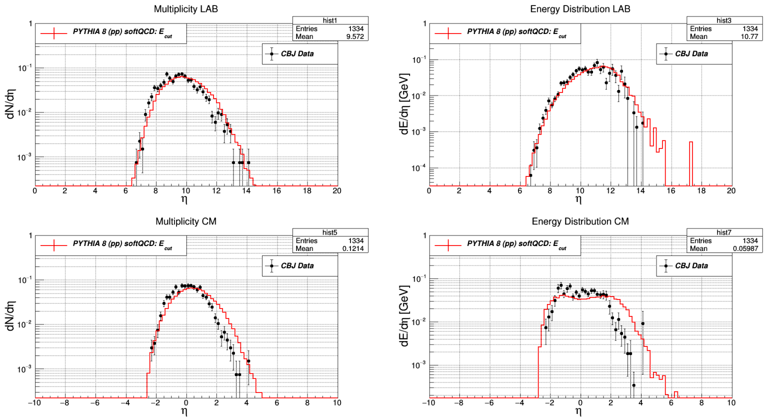
PYTHIA 8.226: Physics Processes, Kinematics ...

- **SoftQCD**: Non-Diffractive, Elastic, Single Diffractive, Double Diffractive and Central Diffractive (neglected in the PYTHIA),
- $\mathrm{E_{LAB}} = 130$ TeV $\rightarrow \sqrt{s} = 493.92$ GeV,
- 10^4 Collisions pp LAB Frame, $\mathrm{E_{cut}} = 0.5$ TeV,
- Beam 1 ($\mathrm{E_{Beam\ 1}} = 130$ TeV), Beam 2 ($\mathrm{E_{BEAM\ 2}} = \mathrm{m_p}$),
- **Only γ are selected in each event (lower chamber detects the electromagnetic component)**.

PYTHIA Events and Cross Section Statistics: **SoftQCD**

Subprocess	events	sigma
ND	5515	32.68 mb
p p -> p p (E)	1906	11.31 mb
p p -> X p (SD)	864	5.09 mb
p p -> p X (SD)	838	5.09 mb
p p -> X X (DD)	877	5.17 mb
sum	10000	59.33 mb

CBJ Data/PYTHIA 8.226



Multiplicity and Energy Distribution of the CBJ data and generated by PYTHIA 8.226 (pp): $E_{LAB} = 130$ TeV, $E_{cut} = 500$ GeV.

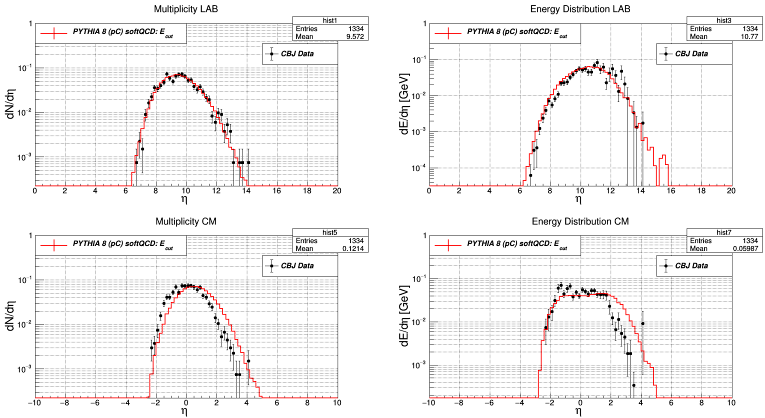
PYTHIA 8.230: Physics Processes, Kinematics ...

- **SoftQCD**: Non-Diffractive, Elastic, Single Diffractive, Double Diffractive and Central Diffractive (neglected in the PYTHIA),
- $E_{LAB} = 130$ TeV $\rightarrow \sqrt{s} = 493.92$ GeV,
- 10000 Collisions pC LAB Frame, $E_{cut} = 0.5$ TeV,
- Beam 1 ($E_{Beam\ 1} = 130$ TeV), Beam 2 ($E_{BEAM\ 2} = m_C$),
- **Only γ are selected in each event (lower chamber detects the electromagnetic component)**.

PYTHIA Events and Cross Section Statistics: **SoftQCD**

```
*--HeavyIon fitting of SubCollisionModel--*
|            to cross sections             |
|                 Total:  62.996 mb        |
|       non-diffractive:  34.672 mb        |
|        XX diffractive:   5.582 mb        |
|    wounded target (B):  45.513 mb        |
| wounded projectile (A): 45.513 mb        |
|       AXB diffractive:   0.000 mb        |
|               elastic:  12.225 mb        |
*------------------------------------------*
```

CBJ Data/PYTHIA 8.230



Multiplicity and Energy Distribution of the CBJ data and generated by PYTHIA 8.230 (pC): $E_{LAB} = 130$ TeV, $E_{cut} = 500$ GeV.

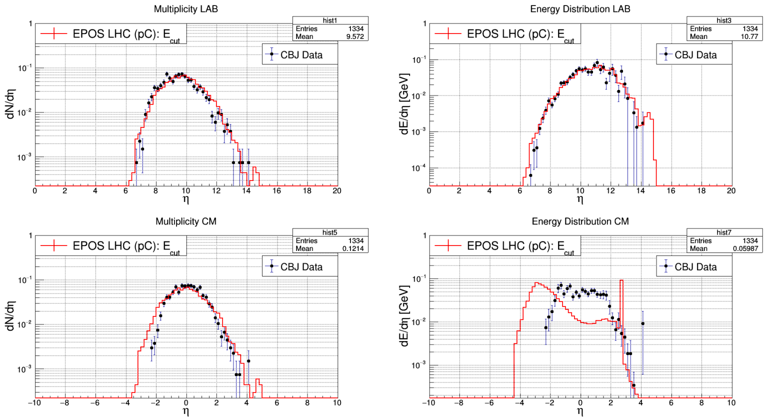
EPOS LHC: Physics Processes, Kinematics ...

- $E_{LAB} = 130$ TeV $\rightarrow \sqrt{s} = 493.92$ GeV,
- 10000 Collisions pC LAB Frame, $E_{cut} = 0.5$ TeV,
- Beam 1 ($E_{Beam\ 1} = 130$ TeV), Beam 2 ($E_{BEAM\ 2} = m_C$),
- **Only γ are selected in each event (lower chamber detects the electromagnetic component)**.

EPOS LHC Events and Cross Section Statistics: **SoftQCD**

```
*---------- HeavyIon CRMC: EPOS LHC -----*
|             Cross Sections             |
|                     Total: 400.00  mb  |
|                Inelastic:  301.50  mb  |
|                   Elastic:  98.99  mb  |
|  projective-Nucleon(Tot):   56.88  mb  |
| projective-Nucleon(Inel):   45.68  mb  |
|   projective-Nucleon(El):   11.21  mb  |
*----------------------------------------*
```

CBJ Data/EPOS LHC



Multiplicity and Energy Distribution of the CBJ data and generated by EPOS LHC (pC): $E_{LAB} = 130$ TeV, $E_{cut} = 500$ GeV.

Outlook

- EPOS LHC and PYTHIA 8.230 show some evidence of the type of interacting particles (pp, pC) that give rise to the products observed in the lower chamber,
- χ^2: Testing for goodness of fit.
- PYTHIA: nC, π^+C, π^-C,
- EPOS LHC: nC, π^+C, π^-C,
- PYTHIA: Select specific processes (Non-Diffractive, Elastic, Single Diffractive and Double Diffractive)

Thank you!

UNICAMP

IFGW
Instituto de Física Gleb Wataghin

CAPES

DRCC-IFGW

BACKUP

High-Energy-Physics Event Generation with PYTHIA 8.2

- The PYTHIA program is a standard tool for the generation of events in high-energy collisions.
  - Physics models for the evolution from a few-body hard-scattering process to a complex multiparticle final state,
  - Collisions: (e^+e^-), (pp), ($p\bar{p}$), ($\pi^+\bar{p}$) or ($\pi^-\bar{p}$)
  - Simulation of the detector is not included in PYTHIA,
  - Based on phenomenological models (QCD-inspired),
  - $\sqrt{s} = 100$ TeV (pp fixed-target beam energy 10^7 TeV),
  - The task of a Monte Carlo event generator is to calculate everything that happens in a high-energy collision, from the hard short-distance physics to the long wavelengths of hadronisation and hadron decays[26].

[26] A. Buckley et al., Phys. Rept. **504**, 145–233 (2011), P. Skands, in *Proceedings, Theoretical Advanced Study Institute in Elementary Particle Physics: Searching for New Physics at Small and Large Scales (TASI 2012): Boulder, Colorado, June 4-29, 2012*, [,63(2107)] (2013), pp. 341–420.

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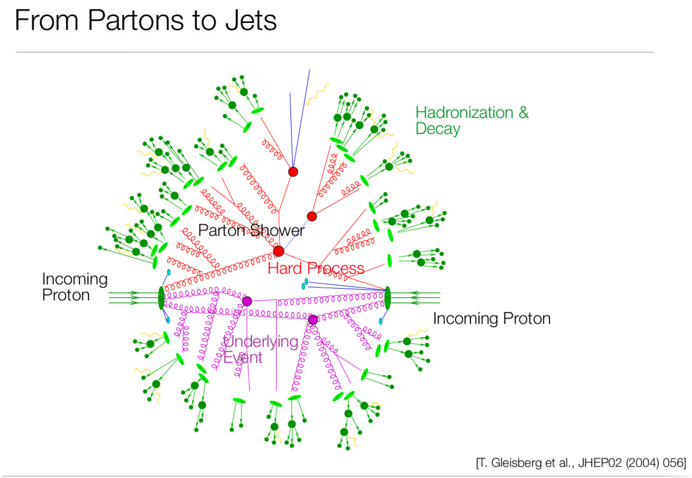
High-Energy-Physics Event Generation with PYTHIA 8.2



Description of the stage of an event generation.[27]

High-Energy-Physics Event Generation with PYTHIA 8.2

- Theoretical tools that simulate events at colliders,
- Extensively used to simulate signal and background processes, to help us understand our data and enable us to make measurements,
- Soft-QCD processes use phenomenological models with theoretical motivation that must be validated against data (using RIVET)[28],
- These models contain parameters that must be tuned to the data,
- It is therefore necessary to make measurements of softQCD processes.

[28] A. Buckley et al., Comput. Phys. Commun. **184**, 2803–2819 (2013).

- **SoftQCD**: Diffractive and Non-Diffractive events with low-p_T (Minimum Bias). Most of the events observed in the LHC are due to low-p_T collisions or nonperturbative QCD (only phenomenological models).
  - Diffractive scattering in more peripheral pp interactions, where one or both protons survive the interaction and/or are excited into a low-mass state in pp inelastic cross section[29].
  - An experimental signature for diffraction is given by rapidity gaps[30].
  - The particle multiplicity produced in these processes is modeled phenomenologically in the existing Monte Carlo event generators of hadronic interactions, experimental results provide an important input for tuning of the models[31].

[29] B. Abelev et al., Eur. Phys. J. **C73**, 2456 (2013).
[30] G. Aad et al., Eur. Phys. J. **C72**, 1926 (2012).
[31] S. Chatrchyan et al., Eur. Phys. J. **C74**, 3053 (2014).

High-Energy-Physics Event Generation with PYTHIA 8.2

- Forward region, where diffractive interactions contribute and where most of the interaction energy is going, all the models are fairly close together[32]. This is the motivation to study and analysis the events from cosmic rays observed by the CBJ and compared with predicted hadronic interaction models.
- Measured hadronic total cross sections have become crucial instruments to probe the so called soft part of QCD physics, where quarks and gluons are confined, and have led to test and refine Regge behavior and a number of diffractive models[33].

[32] R. D. Parsons et al., Astropart. Phys. **34**, 832–839 (2011).

[33] G. Pancheri and Y. N. Srivastava, Eur. Phys. J. **C77**, 150 (2017).

- **Hadronisation and Soft Hadron-Hadron Physics**
  - soft QCD that are relevant for hadron-hadron collisions, such as hadronisation, minimum-bias and soft-inclusive physics, and the so-called underlying event.
  - In the event generators, hadronisation denotes the process by which a set of coloured partons (after showering) is transformed into a set of colour-singlet primary hadrons, which may then subsequently decay further.
  - This non-perturbative transition takes place at the hadronisation scale $Q_{had} \sim 1$ GeV, which by construction is identical to the infrared cutoff of the parton shower. In the absence of a first-principles solution to the relevant dynamics, event generators use QCD-inspired phenomenological models to describe this transition.

- colour-singlet (i.e., confined) hadronic states. MC models do this in three steps:
  - Map the partonic system onto a continuum of high-mass hadronic states (called "strings" or "clusters").
  - Iteratively map strings/clusters onto discrete set of primary hadrons (via string breaks/cluster splittings/cluster decays).
  - Sequential decays into secondaries ($\rho \to \pi\pi$, $\Lambda \to n\pi$, $\pi^0 \to \gamma\gamma$, ...).
- The physics governing this mapping is non-perturbative.

- **Minimum Bias:**
  - Minimum bias adj. experimental term, to select events with the minimum possible requirements that ensure an inelastic collision occurred.
  - Minimum Bias includes a diverse mixture of both soft and hard processes, though the fraction that is made up of hard high-p_T processes is only a small tail compared to the total minimum-bias cross section.
  - In theoretical contexts, the term "minimum-bias" is often used with a slightly different meaning; to denote specific (classes of) inclusive soft-QCD subprocesses in a given model.

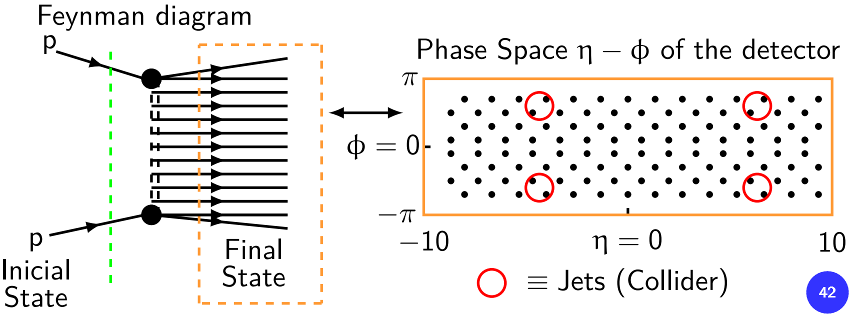
- **Underlying Event and Multiple Parton Interactions**
  - The physics of multiple parton interactions (MPI) as a theoretical basis for understanding both inelastic, Non-Diffractive processes (minimum-bias), as well as the so-called underlying event,
  - hadrons are composite, multi-parton interactions (several distinct parton-parton interactions in one and the same hadron-hadron collision) will always be there — but how many, and how much additional energy and tracks do they deposit in a given measurement region. The first detailed Monte Carlo model for perturbative MPI was proposed by Sjöstrand and Zijl[34].

[34] A. Buckley et al., Phys. Rept. **504**, 145–233 (2011), T. Söjstrand and M. van Zijl, Phys. Rev. **D36**, 2019 (1987).

- **SoftQCD**: Non-Diffractive

Theoretical and Experimental Description

$$\mathrm{p}(p_1) + \mathrm{p}(p_2) \longrightarrow \mathrm{X}(p_\mathrm{X}), \quad p_i \text{ 4-momentum, } i = 1,2,\mathrm{X}.$$



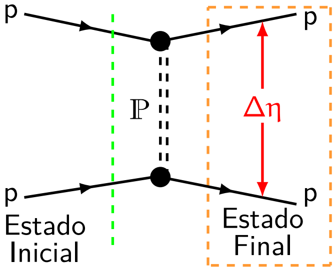
High-Energy-Physics Event Generation with PYTHIA 8.2

- **SoftQCD**: Elastic

Theoretical and Experimental Description

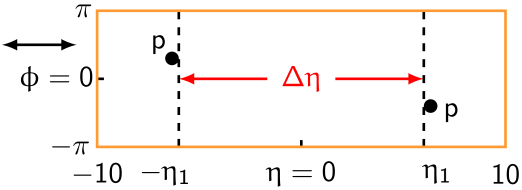
$$p(p_1) + p(p_2) \longrightarrow p(p_1') + \Delta\eta + p(p_2'), \quad p_i \text{ 4-momentum}, \; i = 1,2,1',2'.$$

Feynman diagram



$\Delta\eta \equiv$ Rapidity Gap

Phase Space $\eta - \phi$ of the detector



- **SoftQCD**: Single Diffractive

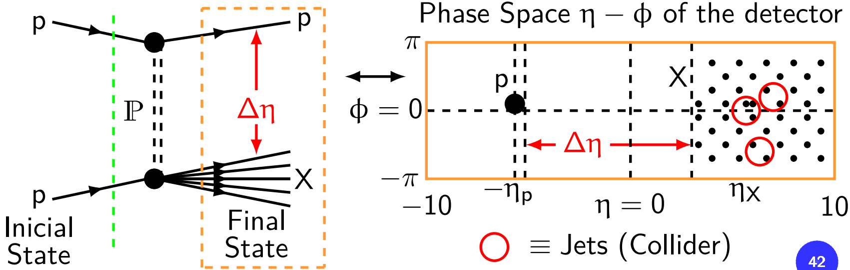
Theoretical and Experimental Description (1st Case)

$$\mathrm{p}(p_1) + \mathrm{p}(p_2) \longrightarrow \mathrm{p}(p_3) + \Delta\eta + \mathrm{X}(p_\mathrm{X}), \quad p_i \text{ 4-momentum}, \; i = 1,2,3,\mathrm{X}.$$

Feynman diagram

$\Delta\eta \equiv$ Rapidity Gap

Phase Space $\eta - \phi$ of the detector



- **SoftQCD**: Single Diffractive

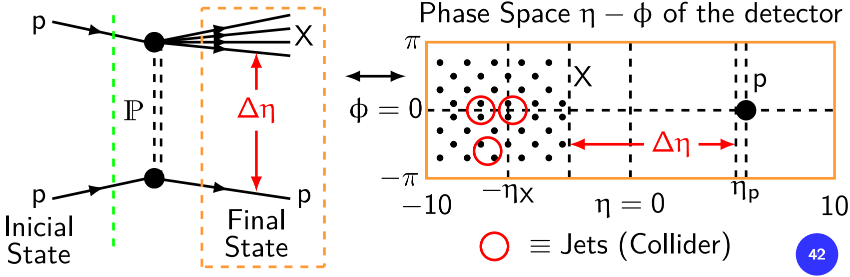
Theoretical and Experimental Description (2nd case)

$$\mathrm{p}(p_1) + \mathrm{p}(p_2) \longrightarrow \mathrm{X}(p_{\mathrm{X}}) + \Delta\eta + \mathrm{p}(p_4), \quad p_i \text{ 4-momentum, } i = 1,2,\mathrm{X},4.$$

Feynman diagram

$\Delta\eta \equiv$ Rapidity Gap

Phase Space $\eta - \phi$ of the detector



- **SoftQCD**: Double Diffractive

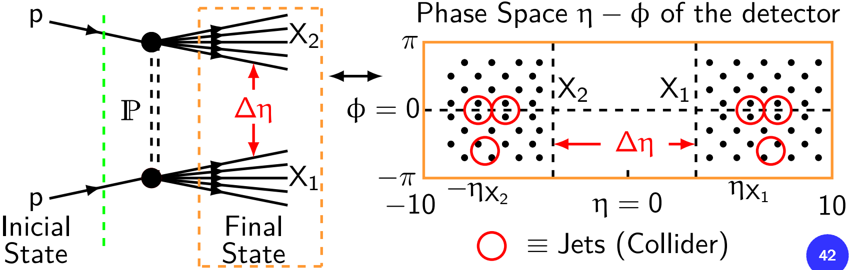
Theoretical and Experimental Description

$$\mathrm{p}(p_1) + \mathrm{p}(p_2) \longrightarrow \mathrm{X}_1(p_{\mathrm{X}_1}) + \Delta\eta + \mathrm{X}_2(p_{\mathrm{X}_2}), \ \Delta\eta \equiv \text{Rapidity Gap}$$

p_i 4-momentum, $i = 1,2,\mathrm{X}_1,\mathrm{X}_2$.

Diagrama de Feynman

Phase Space $\eta - \phi$ of the detector



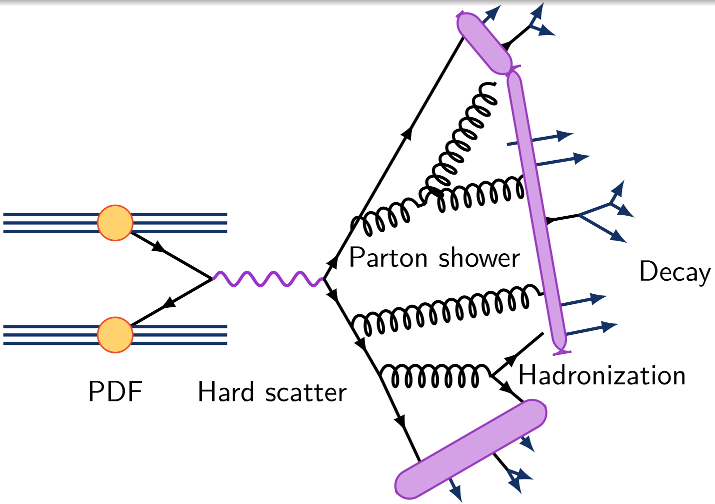
- **HardQCD**: QCD at high-energy scales, $Q \gg \Lambda_{QCD} \sim 200$ MeV is perturbative quantum field theory, the starting point for which is Matrix Elements (MEs) which can be calculated systematically at fixed orders (FO) in the strong coupling α_s,
- PYTHIA8 contains the **jet production (QCD)** above a minimum threshold of p_T. This is because the shock section of the pQCD is divergent for p_T in the range of 0.1 - 1 GeV[35],

Jet Definition:

Jets are the collimated sprays of hadrons that result from the fragmentation of a high-energy quark or gluon.

[35] R. K. Ellis et al., (Cambridge university press, 2003), S. Sapeta, Prog. Part. Nucl. Phys. **89**, 1–55 (2016), K. Rabbertz, Springer Tracts Mod. Phys. **268**, pp.1–214 (2017), M. Kaur and R. Gupta, (2016).

High-Energy-Physics Event Generation with PYTHIA 8.2



A pictorial representation of a collision with the hard interaction and the resulting fragmentation, hadronization, and decay [Kira Grogg].

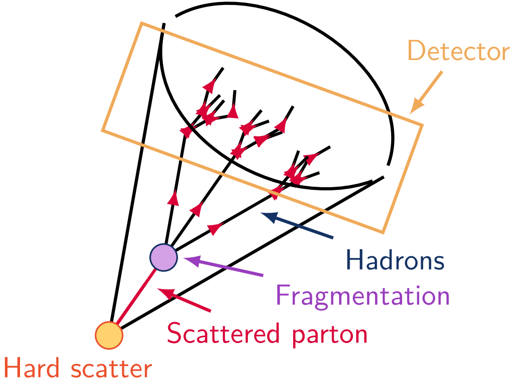


Illustration of the evolution from the hard scattering parton to the jet in the detector [Kira Grogg].

High-Energy-Physics Event Generation with PYTHIA 8.2

- LHC - jet production is the dominant high-p_T processes[36].
- Jet cross sections serve as one of the main observables in high-energy particle physics, providing precise information on the structure of the proton.
- Naturally, any measurement of jet energy and momenta leads to a close estimation of the dynamical properties associated with partons.
- In QCD studies, jets are basically the transformed states of partons to hadrons through the hadronization process with produces a collection of spray of particles[37].

[36] V. Khachatryan et al., Phys. Rev. D **92**, 112001 (2015).
[37] M. Cacciari et al., JHEP **04**, 063 (2008), S. Ganguly and M. Guchait, Int. J. Mod. Phys. **A28**, 1330030 (2013).

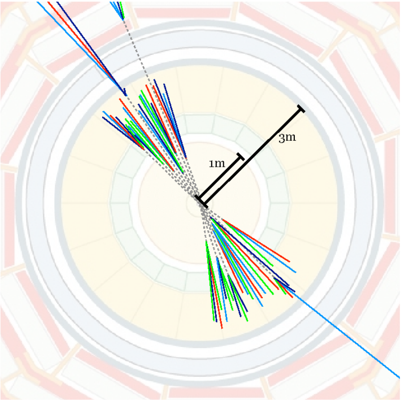
- PYTHIA 8.230 (6 October 2017)[38] A new Heavy Ions machinery has been added, that allows PYTHIA to generate pA and AA collisions within a simple model. The new capabilities are pp, pPb, PbPb and pC and among others collisions. Extending the Multiparton Interactions framework with Glauber model[39].

---

[38] http://home.thep.lu.se/~torbjorn/Pythia.html.

[39] C. Loizides, Phys. Rev. C **94**, 024914 (2016), G. Aad et al., Eur. Phys. J. **C76**, 199 (2016), C. Bierlich et al., JHEP **10**, 139 (2016).

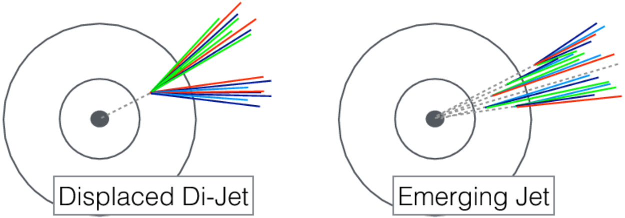
Emerging Jets into the detector (LHC)



A schematic depiction of jet production from quarks and gluons forming two emerging jets[40].

[40] P. Schwaller et al., JHEP **05**, 059 (2015).

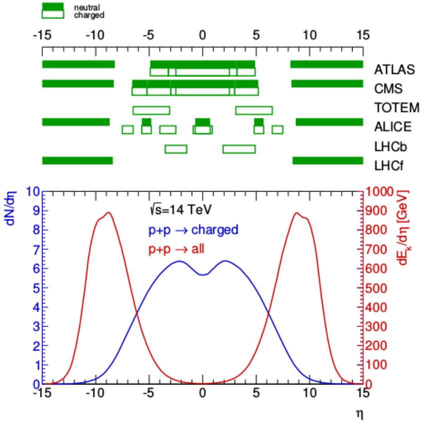
Jets



Difference between a displaced dijet signature from the decay of a heavy long-lived particle and the emerging jet signature.[41].

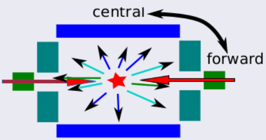
[41] P. Schwaller et al., JHEP **05**, 059 (2015).

Cosmic Ray and LHC Interactions



Angular Acceptance of LHC experiments [Ralf Ulrich, Measurements at LHC an their relevance for cosmic ray physics, TeVPA 2016, CERN]

Cosmic Ray and LHC Interactions



- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

- How relevant are specific detectors at LHC for air showers?

$\rightarrow$ Simulate parts of shower individually.

Phase space coverage at LHC [Ralf Ulrich, Measurements at LHC an their relevance for cosmic ray physics, TeVPA 2016, CERN]

Data of the Events Observed by CBJ (C-jets)

- < 20 TeV $\rightarrow$ 8 Events.
- 20 - 30 TeV $\rightarrow$ 36 Events (44 %).
- 30 - 40 TeV $\rightarrow$ 16 Events.
- 40 - 50 TeV $\rightarrow$ 5 Events.
- 50 - 60 TeV $\rightarrow$ 4 Events.
- 60 - 70 TeV $\rightarrow$ 4 Events.
- 70 - 80 TeV $\rightarrow$ 1 Event.
- 80 - 90 TeV $\rightarrow$ 1 Event.
- 90 - 100 TeV $\rightarrow$ 3 Events.
- 110 - 123 TeV $\rightarrow$ 4 Events.

TOTAL 82 Events (Total 1334 Shower (γ))

CBJ Data

ICR-Report-91-81-7

COSMIC-RAY OBSERVATION OF MULTIPLE PION PRODUCTION AT AROUND 100 TEV

Brasil-Japan Emulsion Chamber Collaboration

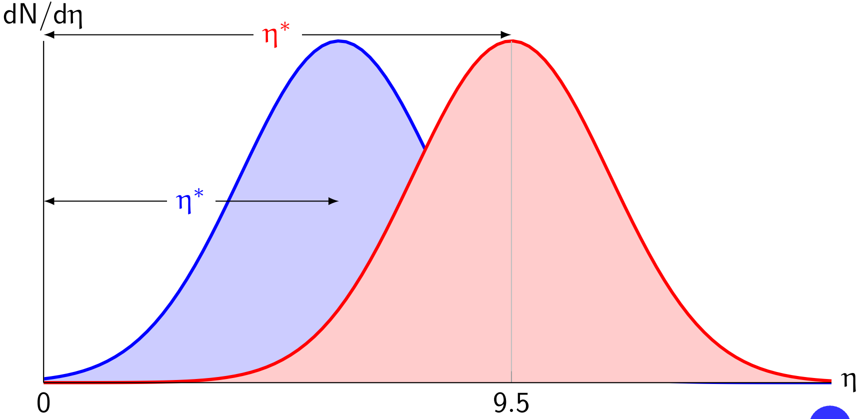
(July 1, 1981)

(Submitted to "Pysical Review")

Institute for Cosmic Ray Research
University of Tokyo
Tanashi, Tokyo, Japan

http://inspirehep.net/record/166385?ln=en

Kinematics: Lorentz Factor change with energy cut: E_{cut}



Kinematics: Lorentz Factor change with energy cut: E_{cut}

$$\eta_{LAB} = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right], \quad \eta_{LAB} = \eta_{CM} + \eta^{*}$$

- Blue curve: without energy cut, E_{cut}.
  $E_1^2 = \vec{p}_1^{\,2} + m_1^2$
  $\theta = \tan^{-1}\left(\frac{p_T}{p_z}\right) \rightarrow \theta_1 \rightarrow \eta_{LAB1}$
- Red curve: with energy cut, E_{cut}.
  $E \geq E_{cut}$, $E_2^2 = \vec{p}_2^{\,2} + m_2^2$
  $\theta = \tan^{-1}\left(\frac{p_T}{p_z}\right) \rightarrow \theta_2 \rightarrow \eta_{LAB2}$

$$E \geq E_{cut} \rightarrow p > p \rightarrow \theta_2 < \theta_1 \Rightarrow \boxed{\eta_{LAB2} > \eta_{LAB1}}$$

$$\beta > \beta \Rightarrow \gamma > \gamma$$

RIVET (Like ROOT)

- RIVET: toolkit for robust comparison of physics models to experimental data,
- Object-oriented C++ framework for analysis algorithms,
- Ever-increasing collection of analyses, more than 400 so far...
- Python interface and suite of user-friendly data handling scripts,

RIVET (Like ROOT)

- Large collection of generator-independent event analysis tools,
- Automatic caching of expensive calculations, for efficiently running many analyses on each event,
- Flexible system for fast detector effect simulation in BSM analyses,
- Close matching of standard observables to experimental analysis definitions,
- Reference data connection to HEPDATA - High Energy Physics Data Repository, avoid hard-coding

RIVET (Like ROOT)

rivet –list-analyses (a few)

```
ALICE:  Eur.Phys.J. C68 (2010) 345-354
ATLAS:  JHEP 1512 (2015) 105
CMS:    Eur.Phys.J. C72 (2012) 2216
CMS:    Eur.Phys.J. C73 (2013) no.12, 2674
CMS:    Phys.Rev. D92 (2015) no.1, 012003
CMS:    JHEP 1708 (2017) 046
LHCb:   Eur. Phys. J. C 73 (2012) 2421
```

Cosmic Ray Models: EPOS LHC

- EPOS is a Monte-Carlo event generator for minimum bias hadronic interactions, used for both heavy ion interactions and cosmic ray air shower simulations.

EPOS LHC

E : Energy conserving quantum mechanical multiple scattering approach,

P : Partons Ladders,

O : Off-shell remnants, and

S : Splitting of parton ladders.

Hadronic Interaction Models

- **Theoretical Basis**:
  - EPOS is based on the Parton-Based Gribov Regge Theory (cross section with multiple scattering).
  - pQCD (large p_T), Cosmic Rays physics dominated by soft interactions
- **Phenomenology (models)** :
  - string fragmentation,
  - beam remnants,
  - diffraction (Good-Walker, ...), Need Parameters !
  - higher order effects. From Experiments !

Cosmic Ray Models

EPOS-LHC model

CRMC

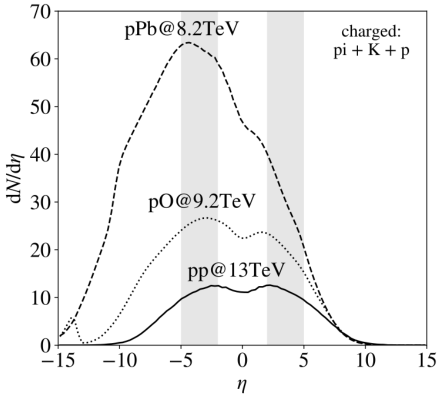


Figure: [Collisions for cosmic Ray physics at the LHC (LHCb)]