1. Introduction

2. Phenomenology of Ultra High Energy Cosmic Rays

3. The total and elastic pp cross section

4. Properties of particle production

5. Learn about hadronic interactions with Cosmic Rays?

6. Conclusions
Structure in the energy spectrum

Importance of a mass composition measurement.
EXTREMELY ENERGETIC COSMIC-RAY EVENT

John Linsley, Livio Scarsi,† and Bruno Rossi
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received April 12, 1961)

~50 years of UHECR

Energy

it follows on any reasonable shower model that the energy of the primary particle was about $10^{19}$ ev. Taking the usual estimate $3 \times 10^{-6}$ gauss for the galactic magnetic field, one finds the radius of curvature of the path of a proton of such energy to be about $10^4$ light years. Since, according to current estimates, the radius of the galactic halo is only about five times this value, while the thickness of the galactic disk is about five or ten times smaller, it seems certain that the primary particle acquired its energy outside our galaxy.

An important question is whether the primary particle was a proton or a heavier nucleus.

Hadronic interaction Modeling

Mass A
EXTREMELY ENERGETIC COSMIC-RAY EVENT

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An important question is whether the primary particle was a proton or a heavier nucleus.

Hadronic interaction Modeling

MUONS

Measure a single slice of the shower at the ground

Mass A
Energy measurement problem “solved”: “Fly's Eye”
Observed Light \rightarrow \text{Emitted Photons} \rightarrow \text{Shower Size}

L(\Omega) \rightarrow F_\gamma(X) \rightarrow N_{e\pm}(X)
$E \propto \int \frac{dE}{dX} \, dX$

\[ E_{\text{ionization}} = \int dX \ N_e(X) \left\langle -\frac{dE}{dX} \right\rangle \]

\[ E_{\text{tot}} = E_{\text{ionization}} + E_\nu + E_\mu + E_{\text{ground}} \]
Area $\propto$ Energy

Shape depends on:
• Primary Identity
• Interaction Model

$E \propto \int \frac{dE}{dX} \, dX$
“Calorimetric” energy measurement

Area = ENERGY

Shape = Mass + Model
\[ E \approx 10^{20} \text{ eV} \]

NOT an IRON nucleus
IF model is approximately correct
Proton showers: Deeper, larger fluctuations
Shower fluctuations

[Graph showing RMS($X_{max}$) vs. Energy (eV) for different masses and models.]
Mass Composition becoming heavy at very high energy?

Significance would be very important! Constraints on the structure and properties of the astrophysical sources.

Observational controversy NON confirmation of HiRes

Correlation with sources Small deviation in magnetic Fields (Z < 3?)
HIRES 2009

Fluctuations on $X_{\text{max}}$

![Graph showing fluctuations on $X_{\text{max}}$](image)

- **σ_x (g/cm²)**
- **log(E(eV))**

- **HiRes Stereo Data**
- **QGSJET-II Protons**
- **QGSJET-II Iron**
Overall comparison of Xmax data with QGSJET02 p and FE HIRES

Fig. 11. — Top: $X_{max}$ overlay of HiRes data (points) with QGSJET02 proton Monte Carlo airshowers after full detector simulation. Bottom: $X_{max}$ overlay of HiRes data (points) with QGSJET02 iron Monte Carlo airshowers after full detector simulation.
Proton Shower

\[ \pi^0 \rightarrow \gamma \gamma \]

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]
One proton Shower: $E_0 = 10^{19}$ eV

50 highest energy individual sub-showers
100 photons  \sim 50\% \text{ of energy}
1000 photons  \sim 70\% \text{ of energy}

Approximately 100 photons
In 30-40 interaction vertices
Control the structure of the Shower:  x \sim 0.1
Muons do not reach the ground
Pions that generate muons

Vertical (0°)

60° inclination
Source of Muons

- Kaons
- Pions

$E_x$ (GeV) vs $\rho_0$ (g cm$^{-2}$) in the vertical direction.
Source of Muons

Muons are produced by particles of few – to few hundred GeV. Much softer in the shower. Precise calculation is difficult.
Toy Model

\[ p + \text{air} \rightarrow \binom{n}{2} \pi^0 \rightarrow n \gamma \]

Energy equally divided among \( n \) photons.

\[ E_\gamma \approx \frac{E_0}{n} \]

\[ \frac{dN_\gamma}{dz} = \sum_n P_n \delta \left[ z - \frac{1}{n} \right] \]
Electromagnetic Showers

\[ E_{e^+} = E_\gamma \ u \quad \psi(u) \]

\[ E_\gamma = E_e \ \nu \quad \varphi(\nu) \]

Radiation Length (Energy independent)

Vertices : theoretically understood (and scaling)
Average longitudinal development of a photon shower well understood.

\[ X_{\text{max}}(E) \approx \lambda_{\text{rad}} \ln \left( \frac{E}{\varepsilon} \right) \]

\[ N_{\text{max}}(E) \approx \frac{E}{\varepsilon} \frac{1}{\sqrt{\ln(E/\varepsilon)}} \]

Elongation Rate

85 (g/cm²)/decade
Photon Shower:

\[ \langle X^{(\gamma)}_{\text{max}} \rangle \approx X_{\text{rad}} \log \left[ \frac{E_\gamma}{\varepsilon} \right] \]

\[ \langle X^{(p)}_{\text{max}} \rangle = \langle X_{1\text{st}} \rangle + X_{\text{rad}} \left\langle \log \left( \frac{E_0}{n_\gamma \varepsilon} \right) \right\rangle \]

\[ \langle X^{(p)}_{\text{max}} \rangle = \lambda_p + X_{\text{rad}} \log \left[ \frac{E_0}{\varepsilon} \right] - X_{\text{rad}} \left\langle \log n_\gamma \right\rangle \]

\[ \frac{d\langle X^{(p)}_{\text{max}}(E) \rangle}{d \log E} = X_{\text{rad}} + \frac{d\lambda_p(E)}{d \log E} - X_{\text{rad}} \frac{d\langle \log n_\gamma(E) \rangle}{d \log E} \]
\( \langle X_{\text{max}}^{(p)} \rangle = \lambda_p + X_{\text{rad}} \log \left[ \frac{E_0}{\varepsilon} \right] - X_{\text{rad}} \langle \log n_\gamma \rangle \)

Interaction length

“Softness”
$$\langle X_{\text{max}}^{(p)} \rangle = \lambda_p + X_{\text{rad}} \log \left[ \frac{E_0}{\varepsilon} \right] - X_{\text{rad}} \langle \log n_\gamma \rangle$$

Interaction length

"Softness"

$$\frac{d\langle X_{\text{max}}^{(p)}(E) \rangle}{d \log E} = X_{\text{rad}} + \frac{d\lambda_p(E)}{d \log E} - X_{\text{rad}} \frac{d\langle \log n_\gamma(E) \rangle}{d \log E}$$

Evolution with Energy of the Interaction length

Evolution with energy of the "softness" of the spectrum
"softness"

Inclusive Pion Energy spectrum.

1\textsuperscript{st} order approximation

\[
\frac{dN_\pi}{dz} \propto \frac{(1 - z)^p}{z}
\]

Position of peak \(1/(p+1)\)
Scaling model: 85 (g/cm²)/decade

Increasing cross sections

Softer spectra

Elongation Rate
For protons
Elongation Rate for protons.

\[
\frac{d\langle X_{\text{max}}^{(p)}(E) \rangle}{d \log E} = X_{\text{rad}} + f_1 \frac{d\lambda_p(E)}{d \log E} - f_2 X_{\text{rad}} \frac{\log[1 + p(E)]}{d \log E} \\
+ g_1 \frac{d\lambda_\pi(E)}{d \log E} - g_2 X_{\text{rad}} \frac{\log[1 + p_\pi(E)]}{d \log E}
\]

\[f_1, f_2, g_1, g_2 \sim 1\]

Significance of Pion Cross section
And particle production properties.
Charged pion spectrum

$E_0 = 10^{13}, 10^{15}, 10^{17}, 10^{19}$ eV

**Sibyll**

**Montecarlo code**
FLUCTUATIONS on $X_{\text{max}}$

\[ X_{\text{max}} = X_{\text{1st}} + Y_{\text{max}} \]

\[ \sigma_{X_{\text{max}}}^2 = \sigma_{X_{\text{1st}}}^2 + \sigma_{Y_{\text{max}}}^2 \]

\[ \left( \frac{\sigma_{\text{proton}}}{\langle X_{\text{max}} \rangle} \right)^2 \approx \lambda_p^2 + \sigma_{Y_{\text{max}}}^2 \]

**Toy model**
\[ \left( \frac{\sigma_{\text{proton}}}{\langle X_{\text{max}} \rangle} \right)^2 \approx \lambda_p^2 + X_{\text{rad}}^2 \left[ \langle (\ln n_\gamma)^2 \rangle - \langle \ln n_\gamma \rangle^2 \right] \]
\[
\left(\sigma_{\text{proton}}^{X_{\text{max}}}\right)^2 \approx \lambda_p^2 + \sigma_{Y_{\text{max}}}^2 \\
\left(\sigma_{\langle X_{\text{max}}\rangle}^A\right)^2 \approx f(A) \lambda_p^2 + \frac{\sigma_{Y_{\text{max}}}^2}{A}
\]

\[A = 56\]
\[\frac{1}{\sqrt{A}} = 0.13\]
\[\sqrt{f(A)} \approx 0.4\]

Nuclear interaction.
Several Nucleons
Interact at same point.
$^56\text{Fe}$ interactions. $E_{\text{tot}} = 10^{19}$ eV

$\lambda_p = 48.5 \text{ g cm}^{-2}$

$\sigma\langle X_{1\text{st}} \rangle \approx \frac{\lambda_p}{\sqrt{A}} \approx 6.5 \text{ g cm}^{-2}$

$\sigma\langle X_{1\text{st}} \rangle \approx 20.5 \text{ g cm}^{-2}$
LEARNING from ACCELERATORS
Important potential of LHC

Vue d'ensemble des expériences LHC.

7 + 7 TeV PP collider
Event rate

Level-1

On tape

Higgs discovery golden channel
$\sigma_{\text{dihadronic}}$

$\sigma_{FD} \quad \sigma_{BD} \quad \sigma_{DD}$

$$\frac{d^2 \sigma_{\text{diff}}}{dt \ dM_X^2}$$
Total, Elastic, Diffractive Cross Sections:
Cross section Measurements

**Tevatron:**

E710:

1.8 TeV: \( \sigma_{\text{tot}} = 72.8 \pm 3.1 \text{ mb} \)

E811:

1.8 TeV: \( \sigma_{\text{tot}} = 71.42 \pm 2.41 \text{ mb} \)

CDF:

546 GeV: \( \sigma_{\text{tot}} = 61.26 \pm 0.93 \text{ mb} \)  
(agrees with UA4)

1.8 TeV: \( \sigma_{\text{tot}} = 80.03 \pm 2.24 \text{ mb} \)

Prediction for LHC at \( \sqrt{s} = 14 \text{ TeV} \)
Total, Elastic, Diffractive Cross Sections:

1 minute of "19th century physics": The OPTICAL ANALOGY.

Absorption and Scattering of light from an Opaque screen
Black Disk Of radius $R$.

Diffraction Pattern

$$\sigma_{el} = \sigma_{abs} = \pi R^2$$
\[ \sigma_{\text{abs}} = \int d^2 b \ P_{\text{abs}}(\vec{b}) \]

\[ P_{\text{abs}}(\vec{b}) = 1 - e^2 \chi(\vec{b}) \]

\[ 0 \leq P_{\text{abs}} \leq 1 \]
\[ A_{\text{tra}}(\vec{b}) = \sqrt{1 - P_{\text{abs}}(\vec{b})} \]

\[ 1 - A_{\text{tra}}(\vec{b}) \equiv \Gamma(b) = 1 - e^{\chi(\vec{b})} \]

\[ \frac{d\sigma_{el}}{dt} = \pi \left| i \int d^2b \ e^{i \vec{q} \cdot \vec{b}} \left[ 1 - A_{\text{tra}}(\vec{b}) \right] \right|^2 \]

\[ \sigma_{el} = \int dt \ \frac{d\sigma_{el}}{dt} = \int d^2b \ \left| 1 - e^{-\chi(\vec{b})} \right|^2 \]
Black Disk

Gray Disk [Opacity 0.5]
Identical absorption

\[ g \leq 1 \quad \text{opacity} \]

\[ \sigma_{\text{abs}} = g \pi R^2 \]

\[ \sigma_{\text{el}} = g^2 \pi R^2 \]
Elastic scattering distributions

\[ \sigma_{el} = \frac{\sigma_{\text{tot}}^2 (1 + \rho^2)}{16\pi B_{el}} \]
\[ B_{el}(s) = \left[ (\frac{d\sigma_{el}}{dt})^{-1} \frac{d}{dt} \left( \frac{d\sigma_{el}}{dt} \right) \right]_{t=0} \]

\[ B_{el}(s) = \left\{ \int d^2b \frac{b^2}{2} \Gamma_{el}(b, s) \right\} \times \left\{ \int d^2b \Gamma_{el}(b, s) \right\}^{-1} \]

\[ = \frac{\langle b^2 \rangle}{2} \]
Elastic Cross section has essentially no Phenomenological significance for the development Of Cosmic Ray Showers.

[Very small angle scattering]

But conceptually it is of great importance Because it can lead to a deeper understanding Of the dynamics of the hadron-hadron interaction.
Absorption profiles

Elastic scattering
ISR 62.3 GeV
CERN UA4 546 GeV

![Graph showing logarithmic dependence of dσ/dt on t (GeV⁻²). The graph includes data points and fitted curves, representing the reaction rate as a function of momentum transfer.]
“Absorption profile”
Obtained from the elastic scattering of pp

ISR
CERN SpS (UA4)
CDF

\[ \chi(b, s) \]
Hadronic Interactions

Composite (complex) Objects
Multiple interaction structure

QCD
Parton Distribution Function

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ x f(x, Q^2) \]
QCD $2 \rightarrow 2$

$q q' \rightarrow q q'$
$q \bar{q} \rightarrow q' \bar{q}'$
$q \bar{q} \rightarrow g g$
$q g \rightarrow q g$
$g g \rightarrow g g$
$g g \rightarrow q \bar{q}$

\[ \frac{d\sigma}{dp^2} \approx \frac{1}{p^4} \text{ for } p_\perp \rightarrow 0. \]
Typically 2 – 3 interactions/event at the Tevatron, 4 – 5 at the LHC, but may be more in “interesting” high-$p_{\perp}$ ones.

Most particles in Fragmentation Regions Described by the “beam remnants strings”
Estimate of the average number of Elementary interactions per pp scattering

“Spatial Distribution” [proton spin] (Transverse coordinates) of the partonic constituents.

Fluctuations of the “parton configuration” of an interacting hadron.

Beyond PDF's
Parton Distribution Functions
Hadrons crossing time short

"Snapshot" of the Parton Configuration.
Diffraction

$h_1 h_2 \rightarrow h_1^* h_2$ (beam diffraction),

$h_1 h_2 \rightarrow h_1 h_2^*$ (target diffraction),

$h_1 h_2 \rightarrow h_1^* h_2^*$ (double diffraction).
“Good-Walker ansatz” for inelastic diffraction.

[Extension of the optical analogy]

Scattering of polarized light from a “polarimeter”

\[ |x\rangle \]

Incident beam:

\[ |x\rangle \]

Absorption of

\[ |x\rangle \]

Out scattered light

In polarizations

\[ |x\rangle \]

\[ |y\rangle \]

\[ |x\rangle = \cos \varphi |x\rangle + \sin \varphi |y\rangle, \]

\[ |y\rangle = -\sin \varphi |x\rangle + \cos \varphi |y\rangle \]

Elastic scattering

“inelastic diffraction”
\[ |x'\rangle = \cos \varphi |x\rangle + \sin \varphi |y\rangle, \]
\[ |y'\rangle = -\sin \varphi |x\rangle + \cos \varphi |y\rangle \]

\[ |x\rangle \quad |y\rangle \quad \ldots \quad = p, \, \Delta, \, \ldots \]

\[ |x'\rangle \quad |y'\rangle \quad \ldots \quad = \text{different} \]

“Parton configurations”
Phenomenological Significance of Pion Cross section In Cosmic Ray Showers.

Theoretical interest: Range of predictions:

\[ \sigma_{\pi p}(\sqrt{s}) \simeq \sigma_{pp}(\sqrt{s}) \]

\[ \sigma_{\pi p}(\sqrt{s}) \simeq \frac{2}{3} \sigma_{pp}(\sqrt{s}) \]
Nuclear Effects

Possibility to study proton-nucleus interactions at LHC

Heavy in program
Properties of Particle Production.

From the modeling of the total cross section
To the description of particle production

Need of additional assumptions.
Electron - Positron Results

Quark-gluon structure + Hadronization. Excellent agreement
Field - Feynman : Quark - Fragmentation
The (iterative) Fragmentation of one COLOR STRING produces a SCALING SPECTRUM of HADRONS

\[ q_0, p_{\perp 0}, p_+ \rightarrow q_0 q_1, p_{\perp 0} - p_{\perp 1}, z_1 p_+ \]
\[ q_1 q_2, p_{\perp 1} - p_{\perp 2}, z_2 (1 - z_1) p_+ \]
\[ q_2 q_3, p_{\perp 2} - p_{\perp 3}, z_3 (1 - z_2) (1 - z_1) p_+ \]

and so on until joining in the middle of the event.

\[ \frac{dn}{dy} \]

\[ \langle n_{ch} \rangle \approx c_0 + c_1 \ln E_{cm}, \sim \text{Poissonian multiplicity distribution} \]
Charged particle rapidity distribution : qq system
Basic Structure of a NON diffractive PP interactions is made of TWO STRINGS

hard/semihard interactions result in additional strings

Color Structure

\[ 3 \otimes 3 = \bar{3} \oplus 6 \]
\[ 3 \otimes \bar{3} = 1 \oplus 8 \]
\( \sqrt{s} = 1.8 \text{ TeV} \)
PROBLEM of PHASE SPACE COVERING
Kinematical Variables:

\[ dy = \frac{dp_z}{E} \]

\[ d\eta = \frac{dp_z}{p} \]

\[ dE_{\text{lab}} \quad d\ln z = \frac{dE_{\text{lab}}}{E_0} \]

\[ dy \sim d\eta \sim d\ln E = d\ln z \]
$E_0 = 10^{15} \text{ eV}$
PROTON Spectra  (elasticity spectra)

\[ E_{\text{beam}} = 10^{19}, 10^{17}, 10^{15}, 10^{13} \text{ eV} \]

\[ z = \frac{E_{\text{lab}}}{E_{\text{beam}}} \]
$E_0 = 10^{15}$ eV
NUCLEAR effects:  \( pp \) vs \( p^{-12}C \)
Growth Of the rapidity "plateau"

\[ E^* \approx \sqrt{m_p E_0} \]
Charged pion spectrum

$E_0 = 10^{13}, 10^{15}, 10^{17}, 10^{19}$ eV
"METHODOLOGY"

Can you learn about hadronic Interactions studying High Energy Cosmic Rays?

Problem: Poor knowledge of the beam!
Proton Showers

\[ X^p_{\text{max}}(E) = X^p_{\text{max}}(E^*) + Dp(E^*) \ln \left( \frac{E}{E^*} \right) \]

Logarithmic growth of average \( X_{\text{max}} \) with energy

\[ X^A_{\text{max}}(E) \sim X^p_{\text{max}} \left( \frac{E}{A} \right) \]

Mass dependence
$X_{\text{max}}$ and the Composition of Cosmic Rays

Proton Showers

$$X^p_{\text{max}}(E) = X^p_{\text{max}}(E^*) + D_p(E^*) \ln \left( \frac{E}{E^*} \right)$$

Logarithmic growth of average $X_{\text{max}}$ with energy

$$X^A_{\text{max}}(E) \sim X^p_{\text{max}} \left( \frac{E}{A} \right)$$

Mass dependence

$$\langle X_{\text{max}}(E) \rangle \sim X^p_{\text{max}}(E) - D_p(E) \langle \ln A \rangle$$
Obtain the average mass and its variation with energy

\[ \langle \ln A \rangle_E = \frac{\sum_A \phi_A(E) \ln A}{\sum_A \phi_A(E)} \]

\[ \langle \ln A \rangle_E = \frac{\langle X_{\text{max}}(E) \rangle - X_p(E)}{D_p} \]

\[ \frac{d\langle \ln A \rangle_E}{d \ln E} = 1 - \frac{D_{\text{exp}}}{D_p} \]
Obtain the average mass and its variation with energy

\[
\langle \ln A \rangle_E = \frac{\sum_A \phi_A(E) \ln A}{\sum_A \phi_A(E)}
\]

\[
\langle \ln A \rangle_E = \frac{\langle X_{\text{max}}(E) \rangle}{D_p} - X_p(E)
\]

\[
\frac{d\langle \ln A \rangle_E}{d \ln E} = 1 - \frac{D_{\text{exp}}}{D_p}
\]
From Accelerator Data + Theory → Astrophysics

C.R. DATA

Astrophysical Information

Hadronic Interactions
From Cosmic Ray Data → Hadronic Interactions

C.R. DATA

Astrophysical Information

"Astrophysical Composition Methods"

Hadronic Interactions
“Astrophysical Composition Methods”

- Energy Spectrum
  “imprints” of Energy Loss

- “Cosmic Magnetic Spectrometer”
Features in the Cosmic Ray Energy Spectrum can in principle give information on the nature of the particle.

Interpreted as the effect of energy loss during propagation from their extragalactic sources.

Known target: 2.7 K CMBR radiation field

Energy Thresholds for protons:

\[ p \gamma \rightarrow p\pi^0 \]
\[ p \gamma \rightarrow n\pi^+ \]

“GZK”

\[ p \gamma \rightarrow p e^+ e^- \]

Pair Production
Inject Smooth power law Spectrum.

Let propagation leave its "imprint" on the shape of the spectrum.

"ANKLE"

--> "DIP"

e+e- production
“COSMIC MAGNETIC SPECTROMETER”

Correlations of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects (AGN)

Constraint on: $B, Z$

AUGER RESULT

Protons are preferred [....? ....]
Deviation in GALACTIC Magnetic Field

\[ \delta \simeq 2.7^\circ \frac{60 \text{ EeV}}{E/Z} \left| \int_0^D \left( \frac{\text{d}x}{\text{kpc}} \times \frac{B}{3 \mu \text{G}} \right) \right| \]

Deviation in EXTRA-GLACTIC Magnetic Field

\[ \delta_{rms} \approx 4^\circ \frac{60 \text{ EeV}}{E/Z} \frac{B_{rms}}{10^{-9} \text{G}} \sqrt{\frac{D}{100 \text{ Mpc}}} \sqrt{\frac{L_c}{1 \text{ Mpc}}} \]
IF one accepts (at least for the sake of discussion) the astrophysical hints of a proton dominated composition....
IF one assumes [for the sake of discussion] the astrophysical hints of a proton dominated composition....

Proton Line!! (?)

Showers Need to be Shorter!
IF one assumes [for the sake of discussion] the astrophysical hints of a proton dominated composition....

Ambiguities:
Different way to obtain The same curve.
“Play” with: interaction lengths Spectrum softening

Proton Line (! ?)
AUGER
Fluctuations result.

Sufficient [after experimental confirmation] to establish That the highest particle Mass is close to iron?
Fluctuations result.

Sufficient [after experimental confirmation] to establish
That the highest particle Mass is close to iron?

But then also in
This case one should change the interaction model.

In the “opposite direction”: Longer showers
The importance of “CORNERS”

(when real)

\[ \chi^2 / \text{Ndf} = 9.7 / 9 \]

\[ D_1 = 106 \pm 35 \]
\[ D_2 = 24 \pm 3 \]
\[ \lg(E_b/eV) = 18.2 \pm 0.1 \]
Naive 2-component model

\[ \phi(E) = \phi_p(E) + \phi_{Fe}(E) \]

\[ \phi(E) \propto r \left( \frac{E}{E^*} \right)^{-\alpha_p} + \left( \frac{E}{E^*} \right)^{-(\alpha_p+\beta)} \]

\[ E^* = 10^{19} \text{ eV} \]

Consistent picture
Of composition evolution
And spectral features
Conclusions
Conclusions

1. Many important open questions.
   [....which make life interesting....]
Conclusions

1. Many important open questions.
   [....which make life interesting....]

2.a Crucial moment for
   Particle Physics and accelerators.

2.b Very exciting moment for
   Cosmic Ray science and
   High Energy Astrophysics

3. Possibility [in fact need] for communication
Anderson discovery of positron

Particle Physics

Cosmic Ray Physics

Occhialini, Powell