Recent status of LHCf to improve the cosmic-ray air shower modeling

Takashi SAKO (KMI/STEL, Nagoya University) for the LHCf Collaboration
Outline

- Standard Scenario of the Cosmic-Ray Spectrum
- LHCf
  - Experiment
  - Results
  - Future
- Summary
Standard Scenario of the Cosmic-Ray Spectrum

Electro-magnetic process => Same rigidity spectrum for different nuclei

Acceleration limit of SNR approx. $4 \times 10^{15}$ V
In term of ‘Energy,’ heavier particles have $Z$ times higher energy than protons.
Over GCR max energy, Extra-galactic CRs appear.
Standard Scenario of the Cosmic-Ray Spectrum

Questions
- End of GCR
- Turn over from GCR to EGCR
- Cutoff (acc. Limit, proton GZK, ion GZK)
Standard Scenario of the Cosmic-Ray Spectrum

- Mass vs. Energy
  - Light < knee
  - Light to heavy over knee
  - Heavy to light around ankle
  - Light or light to heavy around cutoff (GZK) cutoff

![Diagram showing the standard scenario of the cosmic-ray spectrum with specific energy and mass distributions.](image-url)
Mass vs. Energy

- Light (< knee)
- Light to heavy (knee)
- Heavy to light (ankle)
- Light or light to heavy around (GZK) cutoff

Energy flux:
- Light (proton)
(Kampert and Unger, Astropart. Phys., 2012)
① Inelastic cross section

If large \( s \)
- rapid development
If small \( s \)
- deep penetrating

② Forward energy spectrum

If softer
- shallow development
If harder
- deep penetrating

③ Inelasticity \( k = 1 - \frac{p_{\text{lead}}}{p_{\text{beam}}} \)

If large \( k \)
- \( (p^0\)'s\) carry more energy
  - rapid development
If small \( k \)
- (baryons carry more energy)
  - deep penetrating

④ Secondary interactions

nucleon, \( p \)
2ry particle flow at colliders
multiplicity and energy flux at LHC 14TeV collisions
pseudo-rapidity; \( \eta = -\ln(\tan(\theta / 2)) \)

Most of the energy flows into very forward...
Large Hadron Collider forward (LHCf)
The LHC forward experiment

Two independent detectors at either side of IP1 (Arm#1, Arm#2)

- All charged particles are swept by dipole magnet
- Neutral particles (photons and neutrons) arrive at LHCf
- 0 degree is covered
LHCf Detectors

- Imaging sampling shower calorimeters
- Two calorimeter towers in each of Arm1 and Arm2
- Each tower has 44 r.l. of Tungsten, 16 sampling scintillator and 4 position sensitive layers

Arm#1 Detector
20mmx20mm+40mmx40mm
4 XY SciFi+MAPMT

Arm#2 Detector
25mmx25mm+32mmx32mm
4 XY Silicon strip detectors
LHCf Status

- **Done**
  - 0.9, 2.76, 7 TeV pp collision, 5 TeV pPb collision data taking
  - Photon spectra at 0.9 and 7 TeV published
  - Pi0 spectra at 7 TeV published
  - Performance at 7 TeV published

- **On going**
  - Neutron spectra at 7 TeV
  - Pi0 and UPC spectra at 5 TeV pPb
  - Detector upgrade for 13 TeV pp

- **Plan**
  - 13 TeV pp collision in 2015 (operation plan in discussion)
  - 0.5 TeV pp at RHIC (LOI submitted)
  - Discussion for light ion collision at RHIC and LHC
Photon spectra @ 7TeV (Data vs. Models)
Adriani et al., PLB, 703 (2011) 128-134

Around 0 degree (On axis)

Off axis

DPMJET 3.04 QGSJET II-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145
Photon spectra @ 900GeV

Adriani et al., PLB, 715 (2012) 298-303
900 GeV vs. 7 TeV

LHCf coverage in $X_F p_T$ plane
($X_F = E/E_{beam}$)

- Normalized by # of events $X_F > 0.1$
- Statistical error only

Data 2010 at $\sqrt{s} = 900$ GeV
(Normalized by the number of entries in $X_F > 0.1$)
Data 2010 at $\sqrt{s} = 7$ TeV ($\eta > 10.94$)

Good agreement of $X_F$ spectrum shape between 900 GeV and 7 TeV.
**π⁰ analysis**

- π⁰ candidate
- 599GeV & 419GeV photons in 25mm and 32mm tower, respectively
- \( M = \sqrt{E_1 \times E_2} \)

### Lateral development
- **Silicon X**
- **Silicon Y**

### Longitudinal development
- **Small Cal.**
- **Large Cal.**

### Diagram:
- \( \theta = \frac{R}{140 \text{ m}} \)
- \( Y_1(E_1) \)
- \( Y_2(E_2) \)
- \( I.P.1 \)

### Acceptance for π⁰ at LHCf–Arm1
- Events / (1 MeV)
- Reconstructed \( m_{\gamma\gamma} \) [MeV]
- Energy [GeV]

\[ y = 9.0, y = 9.2, y = 9.4, y = 9.6, y = 10.0 \]
π^0 p_T distribution in different rapidity (y) ranges

Adriani et al., PRD, 86, 092001 (2012)
Cosmic-ray spectrum & Colliders

Knee: end of galactic proton CR
End of galactic CR and transition to extra-gal CR
Ankle (GZK) cutoff: end of CR spectrum

Perfect (or best at least) understanding up to $10^{17}\text{eV}$ helps CR physics
$x_F$ scaling: a key for extrapolation

LHC single gamma data
(900GeV pp / 7TeV pp)

Expected from models
(5TeV, 14TeV and 50TeV)

Preliminary

But this comparison done in very limited phase space..
RHICf 500GeV
Similar phase space to LHCf 7TeV
Next Step of LHCf

Analysis

- Impact on air shower calculation / CR physics
- Photon spectra at $\sqrt{s} = 0.9$ TeV in analysis
- $\pi^0$ spectra in analysis
- $p_T$ spectra
- Hadron spectra (photon/hadron ratio)
- Test for LPM effect
- Correlation with central production (joint analysis with ATLAS)

Measurements

- LHC $\sqrt{s} = 14$ TeV pp
- LHC p-Pb in study
- Possibility in the other colliders
- Dream: N-p, N-N, N-Fe (N; Nitrogen) in future
Next Step of LHCf

**Analysis**
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**Measurements**
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Summary

- Analysis ongoing using existing data
- Preparation for the highest energy operation in progress
- Discussion for future experiment
  - RHIC; validation of Feynman scaling
  - RHIC; first light ion collision
  - LHC; highest energy light ion collision
Backup
KML International Symposium 2013
on “Quest for the Origin of Particles and the Universe”
(KMI2013)

Sakata-Hirata Hall, Nagoya University
December 11 - 13, 2013

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- Lattice Gauge Theory
- Physics at LHC
- Flavor Physics
- Theory of Standard Model and Beyond
- QCD Matter
- M Theory and AdS/CFT Correspondence
- Cosmology and Gravity
- Neutrino Physics
- Dark Matter and Astroparticle Physics
- Observational Astrophysics

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