Highlight: Forward Physics (LHCf + FASER)

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on behalf of the LHCf and FASER collaboration

LHCP 2021
June 7th-12th 2021
Scientific motivation

Determination of **mass composition of Ultra High Energy Cosmic Rays** by indirect measurements are limited by the large uncertainty coming from the ability of hadronic interaction models to simulate the Extensive Air Showers (EASs).

\[ \text{EAS}_{\text{max}} \]

\[ \begin{align*}
\text{HiRes-MIA} & \quad \text{HiRes (2005)} \\
\text{HiRes (2005)} & \quad \text{Yakutsk 2001} \\
\text{Fly’s Eye} & \quad \text{Yakutsk 1993} \\
\text{Auger (2013)} & \quad \text{EPOS LHC} \\
\text{SIBYLL 2.3} & \quad \text{QGSJETII-04}
\end{align*} \]

T. Pierog, UHECR2016
The LHCf experiment

EAS Input from LHC:
- Inelastic cross section
- Multiplicity

TOTEM, ATLAS, CMS, ...

- Forward energy spectrum
- Inelasticity $k = 1 - \frac{p_{\text{lead}}}{p_{\text{beam}}}$
- Nuclear effects
- Extrapolation to $E > 10^{17}$ eV

LHCf

Neutrons, photons, $\pi^0$ in $\eta > 8.4$

Forward region: high energy and low multiplicity of collision products

Two detectors installed in the TAN regions of IP1

IP2 ..... TAN
(absorber for neutrals)

D1 dipole magnet

ATLAS INTERACTION REGION

D1 dipole magnet

140 m

Arm1

Arm2

IP1

IP8

TAN
## The LHCf detectors

<table>
<thead>
<tr>
<th>Arm1</th>
<th>Arm2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Towers Size:</strong></td>
<td><strong>Towers Size:</strong></td>
</tr>
<tr>
<td>20 x 20 and 40 x 40 mm²</td>
<td>25 x 25 and 32 x 32 mm²</td>
</tr>
<tr>
<td><strong>Imaging layers:</strong></td>
<td><strong>Imaging layers:</strong></td>
</tr>
<tr>
<td>4 x-y 1mm GSO bars</td>
<td>4 x-y 160μm Si microstrip</td>
</tr>
<tr>
<td><strong>Position resolution:</strong></td>
<td><strong>Position resolution:</strong></td>
</tr>
<tr>
<td>&lt; 200 μm (photons)</td>
<td>&lt; 40 μm (photons)</td>
</tr>
<tr>
<td>&lt; 1 mm (hadrons)</td>
<td>&lt; 800 μm (hadrons)</td>
</tr>
</tbody>
</table>

### Two sampling calorimeters

- **Two towers:** 22 tungsten and 16 GSO scintillators layers
- **Depth:** 21 cm, $44 X_0$, $1.6 \lambda_i$
- **Energy resolution:**
  - < 2% (photons)
  - ~ 40% (hadrons)
LHCf in Run III
p-p @ 14 TeV

DAQ readout will be faster by a factor of 10 thanks to the new Arm2 silicon electronics based on Gb-Ethernet (~1 Gbps) instead of FOXI-Chip (~100 Mbps) protocol.

In addition, it will be possible to detect ~5000 events of η->2γ and ~500 events of K_{0s}->4γ.

Operating at $L = 10^{29}$ cm$^{-2}$s$^{-1}$, in a couple of days LHCf will collect $L_{\text{int}} = 20$ nb$^{-1}$, i.e. a statistics 10 times larger than the one obtained from p-p collisions @ 13 TeV.

GOAL: significantly reduce the uncertainty on measurement of forward π$^0$ production, allowing for a better discrimination between different models.

In addition, it will be possible to detect ~5000 events of η->2γ and ~500 events of K_{0s}->4γ.
LHCf in Run III

**p-O @ 9.9 TeV (Z*7 TeV)**

LHCf cannot operate after Run III: it is the (first and) last chance to **measure forward production in p-light nucleus collisions**!

**Forward photon production in \( \eta > 10.94 \)**

**GOAL 1**: measure forward production in a configuration very similar to the first interaction of UHECR with an atmospheric nucleus (N or O)

**GOAL 2**: measure the effect of the target nucleus on forward production without a large contribution from UltraPeripheral Collisions

In p-O, UPC is negligible respect to QCD, thus strongly reducing the effect of this theoretical uncertainty respect to the p-Pb case.

Operating at \( L = 10^{28} \text{ cm}^{-2}\text{s}^{-1} \), in a couple of days LHCf will collect \( L_{\text{int}} = 0.7 \text{ nb}^{-1} \)
In Run II, the LHCf and ATLAS experiments had **common operations** in p-p collisions @ 13 TeV so that, exploiting the information in the central region, it is possible to study forward production from different contributions, non-diffractive and diffractive \((M_X<50\text{GeV})\).

In Run II, the LHCf and ATLAS common data taking was not effective in p-Pb collisions because of the large UPC contribution (which has no activity in the central region).

In Run III, it will be possible to extend the LHCf-ATLAS joint analysis to p-O collisions, thanks to the negligible UPC contribution in case of p-O respect to p-Pb.

In Run III, this common operation will be extended including two ATLAS subdetectors:
- **ALFA roman pots**, for the identification of single diffractive events and measurements of \(\Delta\) resonance \((p+p \rightarrow p+\Delta \rightarrow p+p+\pi^0)\) and bremsstrahlung \((p+p \rightarrow p+p+y)\) contributions
- **ZDC**, in order to increase the depth of the combined calorimeter from 1.6 to 6.2 \(\lambda_I\) and consequently improve the hadronic energy resolution from about 40% to about 20%
Scientific motivation

**Strongly interacting Heavy Particles**, mainly produced at high $p_T$, are only accessible to central experiments.

**Weakly Interacting Light Particles**, mainly produced at small $p_T$, are only accessible to forward experiment.

In the forward region, a large amount of $\pi$, $K$, $D$ and $B$ mesons are produced.

These mesons could decay in BSM particles, e.g. a dark photon $A'$ with mass $m_{A'}$ and coupling constant $\varepsilon$.

Being weakly interacting, $A'$ travels large distances before decaying in $e^+e^-$. 

A detector in the forward region, at a reasonable distance from interaction point and with a proper shielding from SM particles, can search for new physics.
The FASER experiment

Located in the **Ti12 tunnel** that connected SPS to LEP, at a distance of 480 m from the interaction point and shielded by 100 m of rock and concrete.

**SM Background** assuming $L_{\text{int}} \sim 150$ fb$^{-1}$ in Run III (estimated by simulation and confirmed by *in situ* measurements):
- $2 \times 10^9$ muons above 10 GeV
- $10^4$ interacting neutrinos

Despite FASER covers $2 \times 10^{-8}$ of the solid angle ($\eta > 9.1$), 2% of $\pi^0$ above 10 GeV from p-p collisions at 14 TeV are inside its acceptance (for a total of $10^{17}$ assuming $L_{\text{int}} \sim 150$ fb$^{-1}$ in Run III).
A' → e^+e^- candidate event:
- Veto and Trigger Scintillators
- Two tracks from vertex in Spectrometer
- Electromagnetic-like event in Calorimeter
The FASER experiment

In HL-LHC ($L_{\text{int}} \approx 3 \text{ ab}^{-1}$), FASER will have a good sensitivity to a large range of BSM particles. After Run III, a possible upgrade is FASER2, with an increase of the decay volume from 1.5 to 5 m and of the aperture from 20 to 200 cm. In Run III ($L_{\text{int}} \approx 150 \text{ fb}^{-1}$), FASER will have a good sensitivity to some BSM particles, like dark photons.

**FASERν:** emulsion/tungsten detector with a 1 t target mass

Thanks to FASERν, FASER will measure neutrino production cross sections at TeV collision energies.

First ever detection of neutrinos at a collider using 2018 pilot run: 6 candidates coming from forward region!

**arXiv:** 2105.06197
Run III will be the **last Run** for LHCf!

In Run III the LHCf experiment will reach its **main scientific goals**:
- **p-p collisions @ 14 TeV**: Measurements of forward production with large statistics at the highest energy available at a collider
- **p-O collisions @ 9.9 TeV**: Measurements of forward production in a configuration similar to UHECR interaction with atmospheric nucleus

**LHCf-ATLAS joint operations** will shed new light on different processes responsible for forward production.

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Run III will be the **first Run** for FASER!

In Run III ($L_{int} \sim 150 \text{ fb}^{-1}$), FASER will search for a limited range of particles from **BSM physics**, like dark photons. **Neutrino production cross sections** will be measured (thanks to FASER$\nu$ detector) at a collider for the first time.

After Run III, a possible upgrade is **FASER2**, which will have good sensitivity to a large range of BSM particles, including dark photons, dark Higgs, heavy neutral leptons and axion-like particles in HL-LHC ($L_{int} \sim 3 \text{ ab}^{-1}$).
Thank you for the attention!

In case you have more questions:
https://cern.zoom.us/j/5606239122?pwd=MElpWU9jdHhSOVlIxRFJud3pDNFhVdz09
LHCf in Run III

$x_F$-$p_T$ coverage in p-O collisions

Leading to the maximum coverage in the $x_F$-$p_T$ plane, Operations @ 7 Z TeV are strongly supported by LHCf.
On the **proton remnant** side in p-O collisions, multiplicity is very limited and LHCf can operate at nominal detector position.

On the **oxygen remnant** side in p-O or O-O collisions, multiplicity is too high to operate at the nominal position and the detector must be shifted higher by 15 mm.

At a price of not covering the most forward region, LHCf can still measure production in $8.4 < \eta < 11$. 

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**LHCf in Run III**

Detector position in p-O and O-O operations
LHCf in Run III
Ideal Beam Conditions

Beam conditions are currently under discussion with LPC

Ideal beam condition for \( p-p \) @ 14 TeV:
- \( N_{\text{bunch}} = 500 \)
- \( \Delta t_{\text{bunch}} = 500 \) ns
- \( L < 10^{30} \text{ cm}^{-2}\text{s}^{-1} \)
- \( \theta_{\text{crossing}} = 290 \) μrad
- \( \mu = 0.01-0.02 \)
- \( \beta^* = 19 \) m

Ideal beam condition for \( p-O \) @ 9.9 TeV:
- \( N_{\text{bunch}} = 43 \)
- \( \Delta t_{\text{bunch}} = 2 \) μs
- \( L < 10^{29} \text{ cm}^{-2}\text{s}^{-1} \)
- \( \theta_{\text{crossing}} = 290 \) μrad
- \( \mu = 0.01-0.02 \)
- \( \beta^* = 10 \) m
## LHCf in Run III
### Trigger Scheme

<table>
<thead>
<tr>
<th>Trigger Type</th>
<th>Prescale Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Shower&quot; trigger</td>
<td>14</td>
<td>Photons (efficiency ~100% for $E &gt; 100$ GeV) Neutrons (efficiency ~70% for $E &gt; 1$ TeV)</td>
</tr>
<tr>
<td>&quot;Type I&quot; trigger</td>
<td>1</td>
<td>$\pi^0$ with one photon in each calorimeter (efficiency ~98%)</td>
</tr>
<tr>
<td>&quot;High EM&quot; trigger</td>
<td>1</td>
<td>High energy photons ($E &gt; 1$ TeV) $\pi^0$ with both photons in the calorimeter (efficiency ~97%)</td>
</tr>
</tbody>
</table>
LHCf in Run III
Arm2 DAQ Upgrade

Arm2 (LHC tunnel): «electronic crate»

Underground control room (USA15)
The LHCf detectors are designed to operate in the TAN region, so its size is constrained by the space in TAN internal walls. After Run III, the distance between the TAN internal walls will be strongly reduced, with this number changing from 9.2 to 5 cm. The current LHCf detector cannot fit this space, so that it would be necessary to build a new detector to continue operations.
### Acquired data and published results

<table>
<thead>
<tr>
<th></th>
<th>Proton equivalent energy in LAB (eV)</th>
<th>$\gamma$</th>
<th>$n$</th>
<th>$\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>p+p 2.76 TeV</strong></td>
<td>$4.1 \times 10^{15}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>p+Pb 5.02 TeV</strong></td>
<td>$1.4 \times 10^{16}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>p+Pb 8.1 TeV</strong></td>
<td>$3.6 \times 10^{16}$</td>
<td>Data taking completed in November 2016</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thanks to information in the central region it is possible to distinguish between diffractive and non-diffractive events.

ATLAS-LHCf common data taking
Photons $d\sigma/dE$

$p$-p $\sqrt{s} = 13$ TeV

QGSJET II-04 is in good agreement for $\eta>10.94$, otherwise softer.

EPOS-LHC is in good agreement below 3-5 TeV, otherwise harder.
In $\eta > 10.76$ no model agrees with peak structure and production rate. Among all models, SIBYLL 2.3 and EPOS-LHC have the best overall agreement in $8.99 < \eta < 9.22$ and $8.81 < \eta < 8.99$, respectively.
Analyses for p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

**Data set**
- Fill # 5538
- 25 Nov 9.22-11.28
- $\int L dt = 8.1 \mu b^{-1}$
- $\mu = 0.01$

**Preliminary Ultra Peripheral Collisions (UPC)** simulated using STARLIGHT + SOPHIA/DPMJET and added to hadronic collisions simulations

QGSJET II-04 and EPOS-LHC in good agreement for $\eta > 10.94$. No model has good agreement in $8.81 < \eta < 8.99$. 
Diffractive and non diffractive events

$LHCf - ATLAS$ joint analysis

$LHCf$ measures the total production rate in the forward region

$\sqrt{s} = 13 \text{ TeV} - \eta > 10.94$

Different models lead to different contributions to **diffractive** and **non-diffractive** events

How it is possible to separate diffractive and non-diffractive contributions?

$LHCf$-ATLAS joint analysis
LHCf-ATLAS joint analysis

After a preliminary test in 2013, in 2015 and 2016 LHCf and ATLAS had common operations.

Diffractive events can be distinguished from non-diffractive events by ATLAS veto: tracks=0 at \(|\eta|<2.5\).

According to simulation studies the ATLAS veto can identify diffractive events with an efficiency of about 50% and a purity of almost 100%.
LHCf detection efficiency for single diffraction

Efficiency
- about 5% for $\log_{10} \xi_x \sim -6.5$
- about 40% for $\log_{10} \xi_x \sim -8$

Central veto
selection of very low mass diffraction

$\xi_x = M_x^2/s$
LHCf-ATLAS combined analysis
Photons production at p-p $\sqrt{s} = 13$ TeV

EPOS-LHC is the model in best agreement with data

Analysis in progress for publication
LHCf-ATLAS combined analysis

\( N_{\text{ch}} = 0 / N_{\text{inclusive}} \) photons energy spectra

\( p-p \sqrt{s} = 13 \) TeV

EPOS-LHC is the model in best agreement with data
Acceptance extension

Arm1 only

SIBYLL 2.3 and EPOS-LHC have the best agreement with data for $\eta < 9.22$

This may suggest that UHECRs have light but not protonic composition.

Preliminary
Acceptance extension
Arm1 only

For $\eta < 9.22$ the dominant contribution is coming from the low energy region.
FASER Magnets

- The FASER magnets are **0.55T permanent dipole magnets** based on the Halbach array design
  - Thin enough to allow the LOS to pass through the magnet center with minimum digging to the floor in T112
  - Minimize needed services (power, cooling etc.)

- Designed and to be constructed by TE-MSC group at CERN
  - Main order released in Dec 2019, magnetic blocks for first magnet produced at CERN.
FASER Tracker

- Made up of semi-conductor strip (SCT) modules
  - ATLAS donated spare SCT modules

- Each module two pairs of silicon strip detectors glued back-to-back: 768 read-out channels/side
  - Precision measurements in bending plane

- 8 SCT modules give a 24cm x 24cm tracking layer

- 3 tracker stations, each with 3 layers
  - $3 \times 3 \times 8 = 72$ SCT modules for the full tracker
  - $10^5$ channels in total

- Efficiently separate very closely spaced tracks
FASER Calorimeter

- FASER EM calorimeter for:
  - Measuring the EM energy in the event
  - Electron/photon identification
  - Triggering
- 4 outer ECAL modules donated by LHCb
- 66 layers of lead/scintillator (allows detection of photons)
- Readout by PMT (no longitudinal shower information)
  - Only 4 channels in full calorimeter
- Provides \( \sim 1\% \) energy resolution for 1 TeV electrons
- Cosmic ray test stand used for testing calorimeter response and to calibrate PMTs
Scintillators used for:
- Vetoing incoming charged particles
  - Very high efficiency needed \( (O(10^8)) \) incoming muons in 150/fb
- Triggering
  - Expected trigger rate: ~500 Hz (muons)
- Timing measurement
  - ~1ns resolution
- Simple pre-shower for Calorimeter
FASER$\nu$ detector

- **FASER$\nu$:** tungsten emulsion detector in front of FASER
- 3D tracking detector, 50 nm precision, no timing
- Total mass 1.2 tons, $285 \times 0.1 \times 10^3$ $\lambda_{\text{int}}$
- Needs to be exchanged every $\sim$3 months (during technical stops) to control track density $\lesssim 1 \times 10^6$ tracks/cm$^3$
- To be installed before data taking in 2021.
- 10 emulsion detectors in total needed 2021-2024 data.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Interactions</th>
<th>Mean energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e + \bar{\nu}_e$</td>
<td>1300</td>
<td>830 GeV</td>
</tr>
<tr>
<td>$\nu_\mu + \bar{\nu}_\mu$</td>
<td>20400</td>
<td>630 GeV</td>
</tr>
<tr>
<td>$\nu_\tau + \bar{\nu}_\tau$</td>
<td>21</td>
<td>965 GeV</td>
</tr>
</tbody>
</table>

Assumptions: tungsten emulsion detector (25 cm x 25 cm x 100 cm), 14 TeV, 150 fb$^{-1}$, E. $>$ 100 GeV

Total 1000 emulsion films interleaved with 1-mm-thick tungsten plates

Emulsion film

Cross-sectional view

AgBr crystal

Track in emulsion film

dispersed in gelatin media
**FASER\(\nu\) detector**

- Global reconstruction possible with interface to FASER spectrometer:
- Muon charge identification → distinguish neutrino/anti-neutrino
- Momentum of charged tracks → improve neutrino energy reconstruction
- Timestamp of events and identify additional activity → background rejection
- Interface detector would be installed in 2021-22 YETS.