LHCf Run II physics results in proton-proton collisions at $\sqrt{s} = 13$ TeV

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on behalf of the LHCf collaboration

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Ultra-high-energy cosmic rays

- **Direct measurements** limited by low flux of particles at high energies
- Only **indirect measurements** (with ground based experiments) are possible above $\sim 10^{14}$ eV

Observation of air showers of secondary particles

Detailed MC simulations are fundamental
Contribution from accelerators

First CR interaction

- Inelastic cross section
- Multiplicity
- Elasticity = $p_{\text{lead}} / p_{\text{beam}}$
- Forward energy spectrum
- Nuclear effects

Other effects:
- Neutrons
- Photons
- $\pi^0, \eta$
- p-Pb collisions (p-O in 2023/24!)

LHCf

$\sqrt{s} = 13$ TeV

$E_{\text{CR}} = 0.9 \cdot 10^{17}$ eV
Why forward?

Maximum multiplicity in the central region

\( \eta = -\ln\left[ \tan\left( \frac{\theta}{2} \right) \right] \)

\[ \sqrt{s} = 13 \text{ TeV} \]

Peak of energy flow around \( \eta \approx 9 \) (\( \theta \approx 0.25 \text{ mrad} \))
Experimental setup

Arm 1

Charged particles deflected by D1 dipole magnets

Neutral particles (photons and neutrons) detected

Arm 2

Zero degree particles!
Coverage: $\eta > 8.4$ (with 140 $\mu$rad beam crossing angle)
Neutrons in p-p at \( \sqrt{s} = 13 \) TeV

- Models do not reproduce the peak structure at \( \eta > 10.75 \) and underestimate the total cross section in this region.

- For \( 8.65 < \eta < 10.75 \), either EPOS-LHC or SIBYLL 2.3 has the best agreement with data, depending on the pseudorapidity region.
Inelasticity in p-p at $\sqrt{s} = 13$ TeV

- Neutron elasticity distribution is not well reproduced by any model (SIBYLL 2.3 better than others)
- Average neutron inelasticity is well reproduced with QGSJet II-04 and not far from the prediction of other models, except PYTHIA 8.212

$k_n \equiv$ elasticity in events where the leading particle is a neutron
Good agreement between Arm1 and Arm2 data and between “Type I” and “Type II” events.

Arm2 acceptance covers the gaps in Arm1 data for $X_F < 0.6$ and extends the low-\(p_T\) coverage for $X_F > 0.6$, while Arm1 extends the acceptance to higher \(p_T\).
$\eta$ in p-p at $\sqrt{s} = 13$ TeV (preliminary)

Better agreement with QGSJET, but still a factor $\sim 2$ difference at low $X_F$
ATLAS-LHCf combined analysis

- The number of tracks in the central region gives information on the type of collision.
- Requiring no charged tracks in ATLAS for $|\eta| < 2.5$ a sample of low-mass diffractive events can be selected.

$\xi_X = \frac{M_X^2}{s}$


**Figure**: QGSJET-II-04 p-p, $\sqrt{s} = 13$ TeV

**Graph**: $d\sigma / d \log_{10}(\xi_X)$ for SD(pp -> pX) and SD w/ central-veto.
Combined analysis with ATLAS (photons in p-p at $\sqrt{s} = 13$ TeV)

- Good agreement with EPOS-LHC for $\eta > 10.94$

- Best agreement with EPOS-LHC and PYTHIA 8.212DL for $8.81 < \eta < 8.99$
The fraction of diffractive-like events differs between models.

Best agreement with EPOS-LHC for $\eta > 10.94$.

Best agreement with PYTHIA 8.212DL for $8.81 < \eta < 8.99$. 

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Combined analysis with ATLAS: ongoing analysis

- Study of **multi parton interaction (MPI)**, as proposed in S. Ostapchenko *et al.*, *Phys. Rev. D* 94, 114026

- Study of the correlation between the energy of a neutron detected by LHCf and the number of charged tracks detected by ATLAS in the central region
Future prospects

- Operation in proton-proton collisions at $\sqrt{s} = 13.6$ TeV
  - Increase of $\pi^0$ and $\eta$ statistics thanks to the upgrade of the readout electronics and a dedicated trigger scheme
  - Allow the $K^0$ analysis thanks to the increased statistics
  - Joint acquisition with ATLAS planned
    - operation with roman pots (ALFA and AFP): hadronization of single diffractive events and $\Delta$ resonance ($p+\pi^0$)
    - operation with ATLAS ZDC: improve hadron resolution from ~40% to ~20% (measurements of $p-\pi$ cross section via one-pion exchange process)
- Operation in proton-oxygen and oxygen-oxygen collision (2023 or 2024)
  - best configuration to probe CR-atmosphere collision
  - direct measurement of nuclear modification factor (no background from ultra peripheral collisions as in p-Pb collisions)
backup
Detectors performance

- Two sampling and position sensitive calorimeters
- Tungsten + **GSO scintillators**
- Depth: 44 $X_0$, 1.6 $\lambda$
- Energy resolution:
  - $< 3\%$ (photons, $E > 200\text{ GeV}$)
  - $\sim 40\%$ (neutrons)

Arm 1

- Transverse size: 20 x 20 mm$^2$ and 40 x 40 mm$^2$
- 4 x-y **GSO bars** layers
- Position resolution: 100 $\mu$m (photons, $E > 200\text{ GeV}$)

Arm 2

- Transverse size: 25 x 25 mm$^2$ and 32 x 32 mm$^2$
- 4 x-y **silicon $\mu$strip** layers
- Position resolution: 40 $\mu$m (photons, $E > 200\text{ GeV}$)
Event categories

- **Responsible for air shower core (elasticity)**
  - Leading baryon (neutron)
  - LHCf calorimeters
  - Single hadron event

- **Multi meson production**

- **Responsible for air shower EM particles (inelasticity)**
  - $\pi^0$
  - Photon
  - Single photon event
  - Pi-zero event (photon pair)
$X_{\text{max}}$ vs parameters

**SIBYLL 2.1**

Proton $10^{19.5}$ eV

Iron $10^{19.5}$ eV
$N_\mu$ vs parameters

**SIBYLL 2.1**

- **Proton:** $10^{19.5}$ eV
- **Iron:** $10^{19.5}$ eV
Photons in p-p at $\sqrt{s} = 13$ TeV

- Best agreement with QGSJET and EPOS-LHC for $\eta > 10.94$

- Good agreement with EPOS-LHC and PYTHIA 8.212 for $8.81 < \eta < 8.99$ at energies below 3 TeV
Diffraction mass distribution

\[ \xi_X = \frac{M^2_X}{s} \]

\[ \Delta \eta \approx - \ln \big( \xi_X \big) \]

$\pi^0$ geometrical acceptance

Arm2 geometrical acceptance

$\sqrt{s} = 14$ TeV
Trigger logic

- **“Shower” trigger**
  - prescale factor: 14
  - ~100% efficiency for photons (E > 200 GeV)
  - ~70% efficiency for neutrons (E > 1 TeV)

- **“Type I” trigger**
  - prescale factor: 1
  - $\pi^0$ with one photon in each calorimeter (efficiency ~98%)
  - $\eta$

- **“High EM” trigger**
  - prescale factor: 1
  - high energy photons (E > 1 TeV)
  - $\pi^0$ with both photons in the same calorimeter (efficiency ~97%)
Arm2 DAQ upgrade

- Replace aged electronics
  - lack of replacements for FOXI optical transmitters/receivers, control ring boards, ...

- Speed-up the readout by a factor ~10
  - Arm2 silicon DAQ gives the main contribution to dead time (~1 ms)
  - GbEthernet (~1 Gbps) protocol will be used instead of FOXIchip protocol (~100 Mbps)
Arm2 DAQ upgrade

Arm2 (LHC tunnel): «electronic crate»

Underground control room (USA15)

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