Measurements of hadron production in p-Pb collisions at LHCf

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on behalf of the LHCf collaboration

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Outline

• Introduction and Physics motivation
• Very forward $\pi^0 p_T$ spectra in p-Pb at 5.02 TeV (Neutron energy spectra in p-p at 7 TeV)
• (Preparation towards the 13 TeV operation)
• Summary
The LHCf collaboration involves ~30 members from 10 institutions.

Calibration of GSO plates at HIMAC

**Purpose**

Make the position maps of light yield of GSO for all GSO plates before assembling the detector.

**Experiment**

HIMAC: An Ion accelerator in Chiba, Japan.

Beam: 400MeV/n $^{12}$C

Beam Time: 23rd & 25th July 2013 (3 nights)
Two independent detectors (Arm1 and Arm2) are located in TAN to measure the **very forward particles**:
- $\eta>8.7$ w/o crossing angle and $\eta>8.4$ with crossing angle
- $p_T<1.0$GeV at $\sqrt{s}=7$TeV.

- Sampling calorimeter + position sensitive detector.
- Charged particles are swept away due to the D1 magnet, so we can only observe neutral particles (photon and neutron).
- Same detectors have been used since 2009.
Detector performances

Hadronic shower (MC)
- Position resolution
- Energy resolution

EM shower (MC)
- Position resolution
- Energy resolution

PID technique
- 400 GeV photon
- 1 TeV neutron
Identification of incoming particle by shower shape

π^0 reconstruction
- M_{\gamma\gamma} \sim M_{\pi^0}
Physics motivation (cosmic ray point of view)

1. **Charge ratio** (e.g. NA61)
   - number of muons in air shower sensitive to mass composition

2. **Multiplicity**
   - number of muons in air shower sensitive to mass composition

3. **Inelastic cross section**
   - large → rapid development
   - small → deep penetrating

4. **Inelasticity**
   - $k = 1 - \frac{p_{\text{lead}}}{p_{\text{beam}}}$
   - large → rapid development
   - small → deep penetrating

5. **Forward energy spectrum**
   - softer → rapid development
   - harder → deep penetrating

6. **Nuclear effects**

7. **Extrapolation to high energy**
   - precise measurements at lower energies are crucial

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**Development of cosmic-ray air showers**

Primary particle (e.g. iron nucleus)

1. First interaction
2. Second interaction

- Pion-nucleus interaction
- Pion decay

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**Figure 8.** Example of a longitudinal air shower development as measured with non-imaging Cherenkov detectors (Tunka 132, HiRes, CASA-BLANCA, MIA, Yakutsk, Tunka, Tunka, Auger).

**Table**

- TA, preliminary, $\langle \Delta \rangle = 17 \text{ g/cm}^2$
- HiRes, $\langle \Delta \rangle = 26 \text{ g/cm}^2$
- HiRes/MIA
- CASA-BLANCA
- Yakutsk
- Tunka
- Auger

**Legend**

- Proton
- Iron
- LHC $\sqrt{s} = 7 \text{ TeV}$
- QGSJetII
- Sibyll2.1
- EPOSv1.99

**Graph**

- $X_{\text{max}}$ vs. $E$ [GeV]

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(Kampert and Unger, Astropartphys. 35, 660, (2012))
## Physics and test beam analysis at LHCf

<table>
<thead>
<tr>
<th></th>
<th>Photon (EM shower)</th>
<th>Neutron (hadron shower)</th>
<th>(\pi^0) (EM shower)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-Pb at 5.02TeV</td>
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</table>

- LHC’s analysis activity was first directed to the EM shower events for its simplicity.
- We show the analysis result of forward \(\pi^0\)s in p-Pb collisions.
- Note we have extended the activity to neutron event analysis based on improved tools.

Analysis on the other parts are ongoing.
**π₀ event categories in p-Pb collisions**

(Soft) QCD:
- Central and peripheral collisions

Ultra peripheral collisions:
- Virtual photon from rel. Pb collides a proton.

Momentum distribution of the UPC induced secondary particles is estimated as
1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation.
2. photon-proton collisions are simulated by the SOHIA model (E_γ > pion threshold).
3. produced mesons and baryons by γ-p collisions are boosted along the proton beam.

Dominant channel to forward π₀ is
\[ \gamma + p \rightarrow \Delta(1232) \rightarrow p + \pi^0 \]

About half of the observed π₀ may originate in UPC, another half is from soft-QCD.

Comparison with soft-QCD

π⁰ event reconstruction in p-Pb collisions

1. Search for two photons

Large Tower

γ₂(E₂, P₂)

Small Tower

γ₁(E₁, P₁)

θ

R

travel in beam pipe (140m)

IP1

2. BG subtraction by sideband

3. Unfolding the smeared p_T spectra and correction for geometrical inefficiency

π⁰ detection efficiency

p-Pb √s=5.02TeV

4. Subtraction of the UPC component

LHCf √s=5.02TeV π⁰

-9.4 > y_{lab} > -9.2

LHCf data

UPC MC (x0.5)
Derivation of $\pi^0$ $p_T$ spectra in p-p at 5.02TeV

1. Thermodynamics (Hagedron model)

\[
\frac{1}{\sigma_{\text{inel}}} \frac{1}{E} \frac{d^3 \sigma}{dp^3} = A \cdot \exp\left(-\sqrt{p_T^2 + m_{\pi^0}^2 / T}\right)
\]

\[
\langle p_T \rangle = \sqrt{\frac{\pi m_{\pi^0} T}{2}} K_2(m_{\pi^0} / T) K_{3/2}(m_{\pi^0} / T)
\]

2. Gauss distribution

\[
\frac{1}{\sigma_{\text{inel}}} \frac{1}{E} \frac{1}{\pi \sigma_{\text{Gauss}}^2} \frac{d^3 \sigma}{dp^3} = A \cdot \exp\left(-\frac{p_T^2}{\sigma_{\text{Gauss}}^2}\right)
\]

\[
\langle p_T \rangle = \frac{\sqrt{\pi}}{2} \sigma_{\text{Gauss}}
\]

The $p_T$ spectra in “p-p at 5.02TeV” are obtained by the Gauss distribution with the above $\langle p_T \rangle$ and absolute normalization.
The LHCf data in p-Pb (filled circles) show good agreement with DPMJET and EPOS.

The LHCf data in p-Pb are clearly broadened than the LHCf data in p-p at 5.02TeV (shaded area). The latter is interpolated from the results at 2.76TeV and 7TeV.
Nuclear modification factor in p-Pb at 5.02TeV

- Both LHCf and MCs show strong suppression.
- LHCf grows as increasing $p_T$, which is understood by the softer $p_T$ spectra in p-p at 5TeV than those in p-Pb.

$$R_{pPb}(p_T) \equiv \frac{\sigma_{\text{inel}}^{pp}}{\langle N_{\text{coll}} \rangle \sigma_{\text{inel}}^{pPb}} \frac{Ed^3 \sigma^{pPb}}{Ed^3 \sigma^{pp}} / dp^3$$

$$\langle N_{\text{coll}} \rangle = 6.9$$
Inclusive neutron energy spectra in p-p at 7TeV

- In $\eta>$10.76 huge amount of neutron exists. Only QGSJET roughly reproduces the LHCf result.
- In other rapidity regions, the LHCf results are enclosed by the variation of models.
- These results may indicate small inelasticity in very forward region.
Towards the next operation at 13TeV

The LHCf detectors will be upgraded giving a priority to high energy operation.

1. Radiation damage will be more severe; $0.2\text{Gy/nb}^{-1}$ at 7TeV $\rightarrow 2-3\text{Gy/nb}^{-1}$ at 13TeV.
   - All of plastic scintillators were replaced with GSO scintillators in both Arm1 and Arm2.
     GSO scintillator can survive up to $10^6\text{Gy}$.
   - Scintillation fibers (SciFi, position detector in Arm1) were replaced with GSO bars.
2. Old silicon detector would be saturated for $>1.5\text{TeV}$ photon (Arm2).
   - New wire bonding scheme to avoid saturation effects, pulse height was reduced $\sim 60\%$
   - Rearrangement of the Si detector position for effectively catching EM/hadron showers.

All parts except for new Si modules are ready and their properties were tested by the test beams at HIMAC (HI beam facility in Japan) and SPS.
Construction of GSO calorimeters
Summary

- Very forward \( \pi^0 \) production in p-Pb collision was measured at LHCf.
- Soft-QCD component of the measured \( \pi^0 \) production overall agree with DPMJET 3.04 and EPOS 1.99.
- Strong suppression of \( \pi^0 \) production is found in p-Pb collision which is consistent with predictions of DPMJET, EPOS and QGSJET II-03.
- Huge amount of neutron exists in very forward region, leading to small inelasticity.
- Detector upgrade is ongoing smoothly.
Backup
Prediction of $X_{\text{max}}$ with retuned models

- Difference of $<X_{\text{max}}>$ in p-air among pre LHC models is about 50g/cm$^2$ at $10^{20}$eV, although a difference between p-air and Fe-air is about 100g/cm$^2$.
- Retuned models with the the LHC data are somehow converged into pre-LHC model SIBYLL 2.1.
- Difference between p and Fe is reduced to 20g/cm$^2$. 

(T. Pierog)
Measurement of cosmic rays

- Direct* measurement (e.g. balloon, AMS etc.) of cosmic rays is quite severe above $E_{\text{lab}}=10^{14}\text{eV}$.
- Instead, indirect measurement observing cascade showers of daughter particles (extensive air-shower, EAS) is the best way to increase statistics.
- Largest systematic uncertainty of indirect measurement is caused by a finite understanding of the hadronic interaction of cosmic ray in atmosphere (because very high energy and very forward).

*Direct measurement refers to methods that measure cosmic rays directly, such as balloon flights, AMS, etc., while indirect measurement involves observing cascades of daughter particles from extensive air showers.
Neutron event reconstruction

**Neutron energy reconstruction**

- Neutron energy is reconstructed by a sum of energy deposits.
- Detector simulation based on QGSJET2 for hadronic shower reproduces the test beam data better than that on DPMJET3.
- Difference between QGSJET2 and the test beam data is taken into account as a systematic error in the latter analysis.

**Particle identification**

- With two variables, L90% and L20%, PID performance is improved to reduce the photon contamination in neutron events.
- PID efficiency and purity are >90%.
- Energy spectra are corrected for PID inefficiency and BG contamination.
Results at the LHC: diffraction

Number of charged particles

![Graphs showing number of charged particles for Proton and Iron with different models: SIBYLL, QGSJET, and SIBYLL (ND).](graph1)

Number of muons

![Graphs showing number of muons for Proton and Iron with different models: SIBYLL, QGSJET, and SIBYLL (ND).](graph2)

$X_{\text{max}}$ of charged particles (dominantly electron) is insensitive to diffraction.

Muons are more sensitive to diffraction (i.e. leading baryon production): small multiplicity leading to less pions and less muons.

<table>
<thead>
<tr>
<th>Model</th>
<th>Cross Section (mb) or (µb)</th>
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<tbody>
<tr>
<td>TOTEM Preliminary</td>
<td>$\sigma_{SD} = 6.5 \pm 1.3 \text{mb}$</td>
</tr>
<tr>
<td>PYTHIA8</td>
<td>$\sigma_{DD}(4.7&lt;</td>
</tr>
<tr>
<td>PHOJET</td>
<td>$\sigma_{DD}(4.7&lt;</td>
</tr>
<tr>
<td>TOTEM (PRL101,262001)</td>
<td>$\sigma_{DD}(4.7&lt;</td>
</tr>
</tbody>
</table>
Results at the LHC: cross section

- There is no drastic change from EPOS 1.99 to EPOS LHC.
- Better agreement with TOTEM is found in QGSJET II-04 compared with QGSJET II-03.
- Post LHC models show overall good agreement with data up to the LHC energy.
- They are converged into similar values even at $10^6\text{GeV}$.  

(T. Pierog)

![Graph showing cross sections before and after LHC](image-url)
Extrapolation and scaling

- Feynman scaling of forward photon energy and $\pi^0$ $p_T$ distributions are found at LHCf.
- More precise extrapolation to ultrahigh energy.
  - LHC at 13 TeV
  - Extension to lower energy (e.g. RHIC at $\sqrt{s}=510$GeV).
The idea for the new silicon planes

In the original scheme one strip over two was connected to the front-end electronics and the other strips were floating.

Silicon sensor

OLD

80 µm implant pitch
160 µm readout pitch

NEW

Readout
Floating
Readout

Readout
GND
Readout

Loosing some part of the released energy

Histogram of peak values

SPS2012, 200GeV/c e⁻

#Events

0 100 200 300 400 500 600 700

ADC Counts @ Peak

Normal Silicon

New Silicon
Assembling of new silicon planes

Gluing of NEW type hybrid circuits to old type kapton fanout

Gluing of silicon layers to the NEW kapton fanout (with GND pads for charge loss)

µ-strip fanout

Bias pad
(to be connected to the silicon back-plane)
Glue deposition on the new kapton fanout cable

Plane with vacuum system

Thin layer of kapton tape for insulation

Thin layer of siliconic glue (not hard)

GND large pad

Electrically-conductive (Ag) glue deposited on a bent strip of golden kapton film for sensor biasing
Modification of the manipulators

Only one manipulator has been modified and tested. The modification was necessary because the beam dumping procedure in 2013 went faster than in 2010. It lasted about 5 min. So the target of this modification was 5 min for 12 cm movement (from the operation position to the garage position it took about 12 min before the modification).

Replacement of the gear box (decreased the gear ratio from 30 to 12.5)

Test with the weight corresponding to the LHCf detector was successful.

Final vertical speed: 12 cm / 4 min

Power consumption is well below the limits of the engine.