LHCf forward physics results

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and on behalf of the LHCf collaboration

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The LHCf collaboration

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~30 physicists from 5 countries
The LHCf detectors

- 16 tungsten + pl.scinti. layers
  - 25mmx25mm + 32mmx32mm
- 4 Silicon strip tracking layers
- 4 SciFi tracking layers

16 tungsten + pl.scinti. layers
- 20mmx20mm + 40mmx40mm
- 4 SciFi tracking layers
What LHCf measures

- Inelastic cross section
  - If large $\sigma$
    - rapid development
  - If small $\sigma$
    - deep penetrating

- Forward energy spectrum
  - If softer
    - shallow development
  - If harder
    - deep penetrating

- Inelasticity $k = 1 - \frac{p_{lead}}{p_{beam}}$
  - If large $k$
    - $\pi^0$s carry more energy
    - rapid development
  - If small $k$
    - (baryons carry more energy)
    - deep penetrating
    
(relevant to $N_\mu$)
Impact of forward spectra on shower development

Half of shower particles comes from large $X_F \gamma$

$X_F = E/E_{tot}$
LHCf $p_T$ acceptance

Projected edge of beam pipe
Y. Itoy, LHCf Forward physics results

LHCf single $\gamma$ spectra at 7TeV

DPMJET 3.04  QGSJETII-03  SIBYLL 2.1  EPOS 1.99  PYTHIA 8.145

Gray hatch: Sys+stat errors
Magenta hatch: Stat errors of MC

None of the models agree with data
Data within the range of the model spread

PLB 703 (2011) 128-134

$0.68 \pm 0.53 \text{nb}^{-1}$ on 15May2010
LHCf single $\gamma$ spectra at 900 GeV

May 2010 900 GeV data (0.3 nb$^{-1}$, 21% uncertainty not shown)

DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145
Comparison of Data/MC ratio at two energies

DPMJET 3.04  QGSJETII-03  SIBYLL 2.1  EPOS 1.99  PYTHIA 8.145
$X_F$ spectra for single $\gamma$: 900GeV/7TeV comparison

\[
\frac{1}{\sigma_{\text{inel}} \frac{dX}{dX_F}} \frac{d\sigma_{\gamma}}{dX_F} \bigg\rvert_{\eta<\text{limited}} \propto \frac{1}{\sigma_{\text{inel}} p_T dp_T dX_F} \langle p_T \rangle dp_T
\]

(syst error not included)

- Comparing $X_F$ for common $P_T$ region at two collision energies.
- Less root-$s$ dependence of $P_T$ for $X_F$?
LHCf 7TeV $\pi^0$ analysis

Type-I

$\sigma_M = 3.7\%$

Type-II

Type-I sample

Type-II sample

LHCf-Arm1

Data 2010

Preliminary

LHC-CRS2013 @ 11Feb 2013
LHCf $\pi^0$ $P_T$ spectra at 7 TeV

DPMJET 3.04  QGSJETII-03  SIBYLL 2.1  EPOS 1.99  PYTHIA 8.145

PRD 86 (2012) 092001
LHCf $\pi^0$ $P_T$ spectra at 7TeV (data/MC)

DPMJET 3.04  QGSJETII-03  SIBYLL 2.1  EPOS 1.99  PYTHIA 8.145

EPOS gives the best agreement both for shape and yield.
7TeV π⁰ analysis

- Photon analysis and π⁰ analysis compensate each missing information.
  - High energy photon originates from large \( P_T \) π⁰ events.
  - Photon spectrum includes a contribution from other hadrons/baryons.

Photon \( P_T \) analysis can connect each measurement.
**Average P_T of π^0**

![Graph](image)

1. Thermodynamics

\[
\frac{1}{\sigma_{\text{inel}}} E \frac{d^3 \sigma}{dp^3} = A \cdot \exp(-\sqrt{p_T^2 c^2 + m_{\pi^0}^2 c^4 / T})
\]

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

- Comparison w/ UA7@630GeV
- Extend to higher η regions
- Less energy dependence of <PT>?
Current and future activity

- Forward neutron spectra
  - Inelasticity
- Cold nuclear effect
  - LHC p-Pb
- Energy dependence
  - 14TeV at LHC, 0.5TeV pp at RHIC
- Nuclear dependence
  - p-A, A-A at RHIC, and future LHC?
- Feedback to air showers
Nuclear effects for very forward region

- Air showers take place via p-N or Fe-N collisions!
  - Nuclear shadowing, final state interaction, gluon saturations
  - Nuclear modification factor at 0 degree may be large.


\[
R_{dAu}^Y = \frac{\sigma_{pp}^{inel}}{\langle N_{bin}\rangle \sigma_{had}^{dAu}} \cdot \frac{E d^3\sigma/dp^3(d + Au \to Y + X)}{E d^3\sigma/dp^3(p + p \to Y + X)}
\]

\[\sqrt{s_{NN}} = 200 \text{ GeV}\]

\[\eta^0(\eta > 4.00)\]
\[h^-(\eta = 3.2)\]
\[h^-(\eta = 2.2)\]

\[\eta < 8.99\]
\[\eta > 10.94\]

\[\text{Courtesy of S. Ostapchenko}\]
LHCf p – Pb runs at $\sqrt{s_{NN}} = 4$ TeV (Jan 2013)

- 2013 Jan / a month of p-Pb opportunity.
  - Install only Arm2 at one side (Si good for multiplicity)
  - Data both at p-side and Pb-side
  - Common pre-scaled trig. w/ ATLAS $\gamma$ for centrality tagging

![Graph showing number of events over time]

- #Events (Millions)
  - p-remnant side
  - Pb-remnant side
  - Beam reversal

- 20 Jan
- 27 Jan.
- 01 Feb.
LHCf p-Pb runs

Shower incident position at p-side

A high multiplicity event at Pb-side
Future p-N and Fe-N in LHC?

- LHC 7TeV/Z p-N and N-N collisions realize the laboratory energy of $5.2 \times 10^{16}$eV and $3.6 \times 10^{17}$eV, respectively (N: Nitrogen)

- Suggestions from the CERN ion source experts:
  - LHC can in principle circulate any kind of ions, but switching ion source takes considerable time and manpower
  - Oxygen can be a good candidate because it is used as a ‘support gas’ for Pb ion production. This reduces the switching time and impact to the main physics program at LHC.
  - According to the current LHC schedule, the realization is not earlier than 2020.
  - New ion source for medical facility in discussion will enable even Fe-N collisions in future
Summary

- LHCf provides dedicated measurements of neutral particles at 0 deg to cover most of collision energy flow.
  - $E_\gamma$ spectra for single gamma at 7TeV and at 900GeV. Agreement is “so-so”, but none of models really agree.
  - $p_T$ spectra for 7TeV $\pi^0$. EPOS gives nice agreement.
  - Forward neutron analysis is under going.
  - 2004 LHC p-Pb run successfully (almost ) done to study cold nuclear effect at 0 degree.

- Future
  - Revisit “14TeV” at ~2014 with a rad-hard detector.
  - Possible future RHIC run is under discussion.
  - Possible LHC light ion runs is under discussion.
International Workshop on
“High-energy scattering at zero degree"

2nd - 4th March, 2013
KMI, Nagoya University

http://www.gcoe.phys.nagoya-u.ac.jp/hesz2013

Organizing committee
Yoshitaka Itow (Nagoya)
Kazunori Itakura (KEK)
Yuji Goto (Riken)
Takashi Sako (Nagoya)
Kenta Shigaki (Hiroshima)
Kiyoshi Tanida (SNU)
Yuji Yamazaki (Kobe)

- Diffraction and very forward p-p and p-A scatterings
- Forward and ultra peripheral A-A scatterings
- Spin asymmetry at very forward in polarized p-p scatterings
- High energy cosmic ray interaction models
- QCD aspects in very forward scattering
Backup
Calorimeter performance

- Gamma-rays ($E>100\text{GeV}$, $dE/E<5\%$)
- Neutral Hadrons ($E>a$ few $100\text{ GeV}$, $dE/E\sim30\%$)
- Neutral Pions ($E>700\text{GeV}$, $dE/E<3\%$)
- Shower incident position ($170\mu\text{m} / 40\mu\text{m}$ for Arm1/Arm2)

\[\begin{align*}
\text{Gamma-rays (E>100GeV, dE/E<5\%)} \\
\text{Neutral Hadrons (E>a few 100 GeV, dE/E~30\%)} \\
\text{Neutral Pions (E>700GeV, dE/E<3\%)} \\
\text{Shower incident position (170\mu m / 40\mu m for Arm1/Arm2)}
\end{align*}\]
Very forward: Majority of energy flow ($\sqrt{s}=14$ TeV)

Most of the energy flows into very forward (Particles of $X_F > 0.1$ contribute 50% of shower particles)
LHCf calorimeters

Arm#2 Detector

Arm#1 Detector

290mm

90mm
Setup in IP1-TAN (side view)

BRAN-Sci
ZDC type1
ZDC type2
LHCf Calorimeter
BRAN-IC
LHCf Front Counter
Beam pipe
Distance from center
Neutral particles
IP1

Pseudo-Rapidity

8.7 - 47mm
9.6 - 19mm
0mm

Calorimeter
Event sample \( (\pi^0 \rightarrow 2\gamma) \)

Longitudinal development measured by scintillator layers

- 25mm Tower ➔ 600GeV photon
- 32mm Tower ➔ 420GeV photon

Lateral distribution measured by silicon detectors

- Total Energy deposit ➔ Energy Shape ➔ PID
- Hit position, Multi-hit search.

\( M_{\pi^0} = \sqrt{E_{\gamma_1}E_{\gamma_2}} \cdot \theta \)

\( \Box^0 \) mass reconstruction from two photon.

Systematic studies
Parent $\pi^0$ pseudorapidity producing ground muons
The single photon energy spectra at 0 degree at 7TeV

(O.Adriani et al., PLB 703 (2011) 128-134)

**DATA**
- 15 May 2010 17:45-21:23, at Low Luminosity $6 \times 10^{28}\text{cm}^{-2}\text{s}^{-1}$, no beam crossing angle
- 0.68 nb$^{-1}$ for Arm1, 0.53 nb$^{-1}$ for Arm2

**MC**
- DPMJET3.0 4, QGSJETII03, SYBILL2.1, EPOS1.99
- PYTHIA 8.145 with the default parameters.
- $10^7$ inelastic p-p collisions by each model.

**Analysis**
- Two pseudo-rapidity, $\eta > 10.94$ and $8.81 < \eta < 8.99$.
- No correction for geometrical acceptance.
- Luminosity by FrontCounter (VdM scan)
- Normalized by number of inelastic collisions with assumption as $\sigma_{\text{inela}} = 71.5\text{mb}$. (c.f. $73.5 \pm 0.6^{+1.8}_{-1.3}\text{mb}$ by TOTEM)
New 900 GeV single $\gamma$ analysis

- 0.3nb$^{-1}$ data (44k Arm1 and 63k Arm2 events ) taken at 2,3 and 27 May, 2010
- Low luminosity ($L \sim 10^{28}$ typical, 1 or 4 xing), negligible pile up (0.05 int./xing).
- Relatively less $\eta$-dependence in the acceptance. Negligible multi-incidents at a calorimeter ($\sim 0.1\gamma (>50\text{GeV})$/int.)
- Higher gain operation for PMTs. Energy scale calibration by SPS beam, checked with $\pi^0$ in 7TeV data.
LHCf type-I \( \pi^0 \) analysis

- Low lumi (L\( \sim \)5e28) on 15-16May, 2.53(1.91) nb\(^{-1}\) at Arm1 (Arm2). About 22K (39K) \( \pi^0 \) for Arm1(Arm2) w/ 5\%BG.
- For \( E_\gamma > 100 \text{GeV} \), PID (\( \gamma \) selection), shower leakage correction, energy rescaling (-8.1\% and -3.8\% for Arm1&2).
- \((E, P_T)\) spectra in +-3\( \sigma \) \( \pi^0 \) mass cut w/ side band subtracted.
- Unfolding spectra by toy \( \pi^0 \) MC to correct acceptance and resolution.
Next target: Inelasticity ~ 0 degree neutrons

- Important for $X_{\text{max}}$ and also $N_{\mu}$
- Measurement of inelasticity at LHC energy

Neutral hadrons at 14 TeV
(LHCf acceptance, no resolution)

Neutral hadrons at 14 TeV
(LHCf acceptance, 30% resolution)
“RHICf” : $\eta$ acceptance for 100GeV/n d-N MC

$\eta > 5.8$ is covered

No acceptance for $\phi^0$ at 900GeV
Expct’d E spectra (p-remnant side)

Small tower

- $\gamma$-rays, small tower
  - DPMJET III
  - EPOS

- Neutrons, small tower
  - DPMJET III
  - EPOS

Large tower

- $\gamma$-rays, big tower
  - DPMJET III
  - EPOS

- Neutrons, big tower
  - DPMJET III
  - EPOS
LHCf future plan

- Analysis ongoing for 2010 data
  - Neutron energy spectra → inelasticity
- Reinstall Arm1+2 for 14TeV in 2014
  - Now upgrading detectors w/ rad-hard GSO.
- A new measurement at RHIC 0 degree
  - Under discussions for 500GeV p+p and d + light-A.
- Far future (>2020?) p-N and N-N collisions at LHC?