Status of the LHCf experiment

- Physics background
- Experiment and current results
- LHC 13 TeV run and future

STE Lab. / Kobayashi-Maskawa Inst., Nagoya University
Yoshitaka Itow
ICRC2015
30th Jul 2015
$10^{17}$ eV: Crossroad of accelerators and UHECRs

- LHC covers $10^{14} - 10^{17}$ eV cosmic rays
- LHCf measures forward particle spectra relevant to air showers.
The LHCf experiment


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The LHCf experimental setup

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

44\times X_0, 1.6 \lambda_{int}

16 tungsten + pl.scinti. layers
20mmx20mm+40mmx40mm
4 SciFi tracking layers
Calorimeter performance

- Gamma-rays ($E>100\,\text{GeV}$, $dE/E<5\%$)
- Neutral Hadrons ($E>a\,\text{few}\,100\,\text{GeV}$, $dE/E\sim40\%$)
- Neutral Pions ($E>700\,\text{GeV}$, $dE/E<3\%$)
- Shower incident position ($170\mu m / 40\mu m$ for $\gamma$, Arm1/Arm2)
  (1mm for hadron showers)

\[\gamma\]-like

\[\pi^0\]

\[\text{Had-like}\]
Brief history of LHCf

- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved

- Jul 2006 construction
- Aug 2007 SPS beam test

- Jan 2008 Installation
  Sep 1st LHC beam

- Jul 2006 construction
- Aug 2007 SPS beam test

- Dec- Jul 2010
  0.9TeV & 7TeV pp
  Detector removal

- Dec 2012 - Feb 2013
  5TeV/n pPb, 2.76TeV pp
  (Arm2 only)
  Detector removal

- May-June 2015
  13 TeV pp
  Detector removal
Y. Itow "Status of LHCf"

**LHCf published results**

- **7 & 0.9 TeV pp photon**
  - \( \eta > 10.94 \)
  - Gamma-ray like
  - \( \eta > 10.94, \Delta \phi = 360^\circ \)
  - Published:
    - PLB 703 (2011) 128-134
    - PLB 735 (2012) 298-303

- **7 TeV pp neutron**
  - Preliminary

- **7 TeV pp**
  - \( \pi^0 \)
  - \( 8.9 < y < 9.0 \)
  - \( \int Ldt = 2.53 + 1.90 \)
  - Published:
    - PRD 86 (2012) 092001

- **5 TeVn pPb**
  - \( \pi^0 \)

- **\( \eta > 10.76 \)**
  - \( d\sigma/dE \) (mb/GeV)
  - Data 2010, Stat. + Syst. error
  - DPMJET 3.04, EPOS 1.99, QGSJET II-03, SIBYLL 2.1, PYTHIA 8.145

- **5TeV p-p at 5.02 TeV (x5)**

- **-9.0 > y_{lab} > -9.2**

- **PRC 89 (2014) 065209**

- **PLB 715 (2012) 298-303**

- **Submitted PLB**

- **PLB 703 (2011) 128-134**

- **PRD 86 (2012) 092001**
**Very forward neutron at 7TeV p-p**

- $\eta > 10.76$: QGSJET03 good, $8.99 < \eta < 9.22$: DPMJET3 good
- Larger neutron / gamma ratio than expected

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<th>n / $\gamma$ ratio</th>
<th>Data</th>
<th>$3.05 \pm 0.19$</th>
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<td>SYBILL 2.1</td>
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40% E res. unfolded

Submitted to PLB
LHCf Type-I and Type-II $\pi^0$ analysis

Type-I

Type-II

(a) LHCf $\sqrt{s} = 7$ TeV
Type-II $\pi^0$ at Small Tower

(b) LHCf Arm1 $\sqrt{s} = 7$ TeV
$9.0 < y < 9.2$

(c) Arm2 Type-I

(d) Arm2 Type-II
$P_z$ spectra Type-I + Type-II $\pi^0$

LHCf $\sqrt{s}=7$TeV

$\int Ldt=2.64+2.85\text{nb}^{-1}$

To be submitted PRD

Preliminary
LHCf $\pi^0$ yields vs collision energies

- DPMJET 3.0.6 ($\sqrt{s}=7\text{TeV}$)
- QGSJET II-04 ($\sqrt{s}=7\text{TeV}$)
- LHCf ($\sqrt{s}=7\text{TeV}$)
- LHCf ($\sqrt{s}=2.76\text{TeV}$)
- UA7 ($\sqrt{s}=630\text{GeV}$)

RHICf 510GeVpp planned

To be submitted PRD
LHC 13TeV LHCf run 2015

- Week24, Jun 9~13, LHCf dedicated low-lumi run
- Total 26.6 hrs w/ $L=0.5\sim1.6\times10^{29}\text{ cm}^2\text{s}^{-1}$
- $\sim39$ M showers, 0.5 M $\pi^0$ obtained
- Trigger exchange with ATLAS
- Detector removal on Jun 15$^{th}$ during TS1
First look from 13 TeV data

LHCf photon pair invariant mass (preliminary)
LHCf Arm2 detector
LHC 13TeV p-p collisions (fill 3855)

Preliminary
ATLAS-LHCf trigger exchange

- Non-diffraction tagging by $N_{\text{trk}} \geq 2$ in ALTAS $|\eta| < 2$ ($P_T > 100$ MeV/c)
- Diffraction: 10% of LHCf data
Future prospects

• RHICf (LHCf detector at RHIC zero degree)
  – Participate Run-17 510 GeV pp at the STAR site
  – Comparison to 7&13TeV data with same $p_T$ coverage

• And also LHC p-Pb run, and future LHC p-Oxygen ...

RHICf E_{π0} expected
510 GeV pp
6.36<y<6.70

η>5.8
18m
Summary

• The LHCf: particles spectra at very forward of LHC
  • $\eta > 8.4$, with nice performance for PID, EM energy and PT
  • So far $\gamma, \pi^0, n$ from 0.9, 2.76 and 7 TeV p-p, and $\pi^0$ 5TeV p-Pb

• Energy spectra for very forward neutron
  • Bump at large $X_F$, data shows more neutron yield than models

• New $\pi^0$ analysis
  • Add Type-II $\pi^0$, complete acceptance coverage
  • Comparison of 7 TeV and 2.76 TeV p-p

• LHC 13 TeV pp and Future
  • 13 TeV run successfully done in Jun 2015, analysis on-going
  • RHICf 510 GeV pp in 2017, LHC p-Pb, and more
Backup
LHCf average $P_T$ of Type-I + Type-II $\pi^0$

- LHCf ($s=7$ TeV)
- LHCf ($s=2.76$ TeV)
- LHCf ($s_{NN}=5.02$ TeV)
- UA7 ($s=630$ GeV)

To be submitted PRD

$\langle p_T \rangle$ [MeV]

RHICf planned

$y_{beam} - y$

DPMJET 3.0.6 (p+p)
DPMJET 3.0.6 (p+Pb)
QGSJET II-04 (p+p)
QGSJET II-04 (p+Pb)
Rapidity vs Forward energy spectra

Gamma-rays @ $\sqrt{s}=7\text{TeV}$

- $\eta=5.99$
- $\eta=6.91$
- $\eta=7.60$
- $\eta=8.40$
- $\eta=8.77$

$\eta=8.7$

$\eta=\infty$

Projected edge of beam pipe

Gamma-rays @ $\sqrt{s}=14\text{TeV}$

- $460\mu\text{rad}$
- $310\mu\text{rad}$

Viewed from IP1 (red:Arm1, blue:Arm2)

Projected edge of beam pipe
Rapidity vs Forward energy spectra

**Gamma-rays @ \( \sqrt{s}=7 \text{TeV} \)**

- **Neutral Hadrons @ \( \sqrt{s}=7 \text{TeV} \)**

- \( \eta = 8.7 \)
- \( \eta = \infty \)

**Projected edge of beam pipe**

Viewed from IP1 (red:Arm1, blue:Arm2)
LHCf single $\gamma$ spectra at 7TeV

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

$\eta > 10.94$

$8.81 < \eta < 8.99$

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

0.68 (0.53)nb$^{-1}$ on 15May2010
Y. Itoh “Status of LHCf”

LHCf single $\gamma$ spectra at 900 GeV

$\eta > 10.15$ ($<$\it{\theta}$>$ = 39 $\mu$rad)

$\eta > 10.15$

$8.77 < \eta < 9.46$ ($<$\it{\theta}$>$ = 234 $\mu$rad)

May 2010, 0.3 nb$^{-1}$

(21\% normalization uncertainty)

DPMJET 3.04
QGSJETII-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145

PLB 715 (2012) 298-303
LHCf $\pi^0$ $p_T$ spectra at 7TeV

PRD 86 (2012) 092001

Type-I sample
Type-I at large tower
Type-II at small tower

LHCf $\sqrt{s}=7$TeV $\pi^0$

$8.9 < y < 9.0$

$\int L dt = 2.53 \pm 1.90 \text{nb}^{-1}$

$1/\alpha_{\text{inel}} \times E d^3 \sigma/dp^3$ [GeV$^2$]

$p_T$ [GeV]

LHCf $\sqrt{s}=7$TeV $\pi^0$

$9.4 < y < 9.6$

$\int L dt = 2.53 \pm 1.90 \text{nb}^{-1}$

$1/\alpha_{\text{inel}} \times E d^3 \sigma/dp^3$ [GeV$^2$]

$p_T$ [GeV]
LHCf nuclear modification factor ($-11.0 > \eta > -8.9$)

- Very large suppression ($\sim 0.1$) at $P_T \sim 100\text{MeV}$ region
- Models also show similar large suppression, but PT dependence?

$$R_{ppPb} \equiv \frac{\sigma_{pp}^{\text{inel}}}{\langle N_{\text{coll}} \rangle \sigma_{\text{inel}}^{pp}} \frac{E d^3 \sigma_{ppPb} / dp^3}{E d^3 \sigma_{pp} / dp^3} \quad \langle N_{\text{coll}} \rangle = 6.9 \pm 0.7$$
LHCf $\text{EM}(\pi^0)$ energy flow vs rapidity (7TeV)

Plot by N. Sakurai
LHCf neutron energy flow vs rapidity

Plot by N. Sakurai
ATLAS ND Tagged LHCf $\gamma$ and neutrons
13 TeV pp MC (PYTHIA)
XF scaling of very forward neutron


RHIC PHENIX (200 GeV),
ISR (30.6-62.7 GeV)

LHCf 7 TeV neutron (Arm1 only)
0 < P_T < 0.11 x_F GeV/c
PT\(_{\pi^0}\) spectra Type-I + Type-II \(\pi^0\)

To be submitted PRD

![Graphs showing PT\(_{\pi^0}\) spectra for different \(y\) ranges from 8.8 to 10.8.](image)

**Legend**
- LHCf (stat.+syst.)
- DPMJET 3.06
- QGSJET II-04
- SIBYLL 2.1
- PYTHIA 8.185
- EPOS LHC

**Note:** Preliminary
Feynman scaling in $\pi^0$ production

- LHCf $\pi^0$ spectra at $\sqrt{s} = 2.76$ and 7 TeV (preliminary)
- Soon compared w/ LHC 13 TeV, and future RHICf (510GeV)

To be submitted PRD
Detector performance

Energy Resolution

\[ \frac{\sigma_{E}}{E} = \frac{31.3 \pm 2.8}{E} \]

**E\(_{\gamma}\) resolution**

**Energy resolution**

**Number of event**

\[ \sigma_{x} = 172 \, \mu m \]

**Position resolution**

**For hadron, \( \Delta x \approx 2.5 \, mm \)**

**E\(_{\text{had}}\) resolution**

- Black dots: Small tower
- Red dots: Large tower

**200 GeV electrons**

- 100 GeV
- 200 GeV

**350 GeV protons**

- Energy [GeV]
- Number of event

- X-pos [mm]
Y. Itoh “Status of LHCf"

**EM shower (SPS)**
NIM, A671 (2012) 129-136
JINST, 5, P01012, 2010

**Hadronic shower (LHC MC)**
JINST, 9, P03016 (2014)

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**PID (SPS energy)**

**Energy Resolution (arm2)**
- SP5207 25mm cal. with 800V
- SP5207 32mm cal. with 800V
- MC 25mm cal.
- MC 32mm cal.
  - 800V (High Gain)

**Energy resolution (%)**

**Position Resolution for electron showers (X Side)**
- Data
- Simulation

**Position resolution (µm)**
Hadron shower reconstruction

Check by SPS 350GeV p beam

- Experiment
- MC DPM3
- MC QGS2

\( \chi^2 = 31.5/28 \text{(NDF)} \)
Expected Results (single photons)

- Photon spectra at 4 rapidity samples
- 12 hours statistics (12 nb\(^{-1}\) effective luminosity; 360nb\(^{-1}\) delivered)
- Statistical error is almost negligible except at the highest energy bins
Expected Results (single neutrons)

- Neutron spectra at 4 rapidity samples
- 12 hours statistics (12 nb\(^{-1}\) effective luminosity; 360nb\(^{-1}\) delivered)
  - RHICf resolution not considered; true spectra
  - Statistical error is almost negligible
Possible future p-Oxygen run

- Important missing information; nuclear shadowing
- Large suppression 0.1 for p-Pb for very forward $\pi^0$ at low PT
- Less expected for p-Light Ion, but model dependent (~25%)
- Oxygen beam is technically feasible in LHC