# LHCf and UHECR

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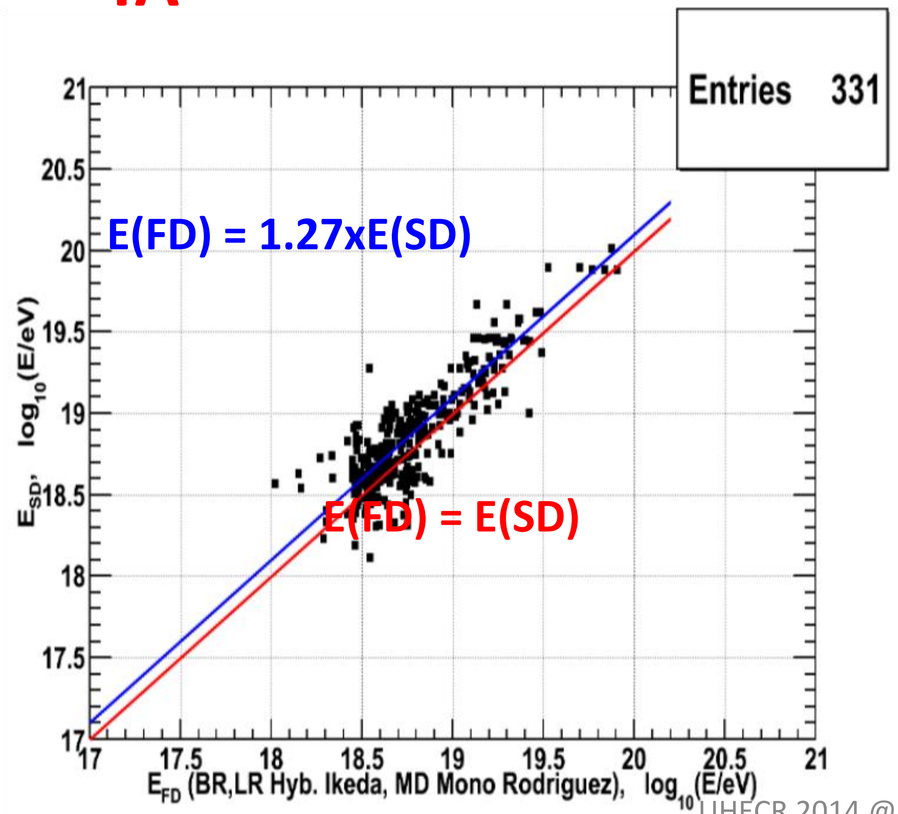
# Outline

- Introduction
  - Difference b/w UHECR data and simulation results
  - Collider data and EAS observables
- LHCf experiment
  - Instruments
  - Results ($\pi^0$, neutron, nuclear modification factor)
- Energy flux analysis using LHCf results
  - Modification of QGSJET-II-04
  - Results
- Summary & prospects

# Difference b/w UHECR data and MC

- Muon deficit in MC (Auger)
- Secondary particle on the ground observed by TA is larger than the expected.

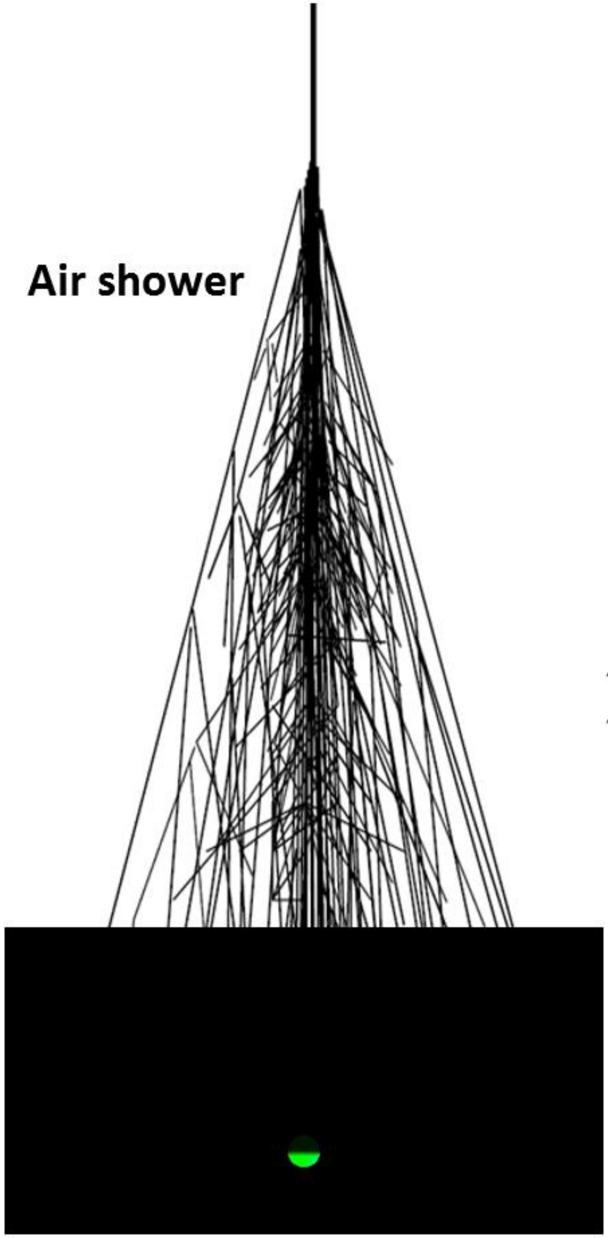
**TA**

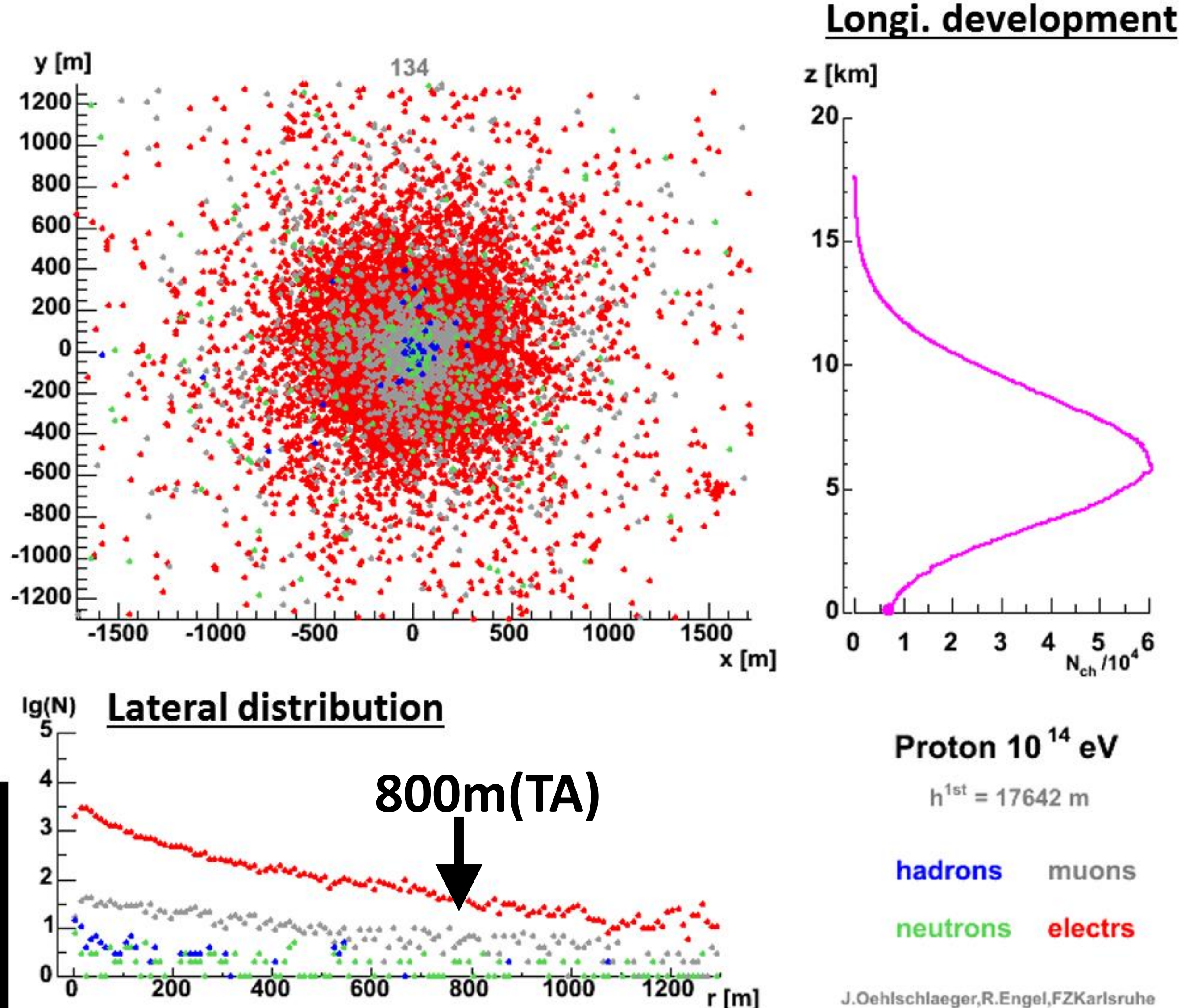



TA-SD is the thin (1.2cm) scintillator.
→**Most of the signal is due to EM component**.

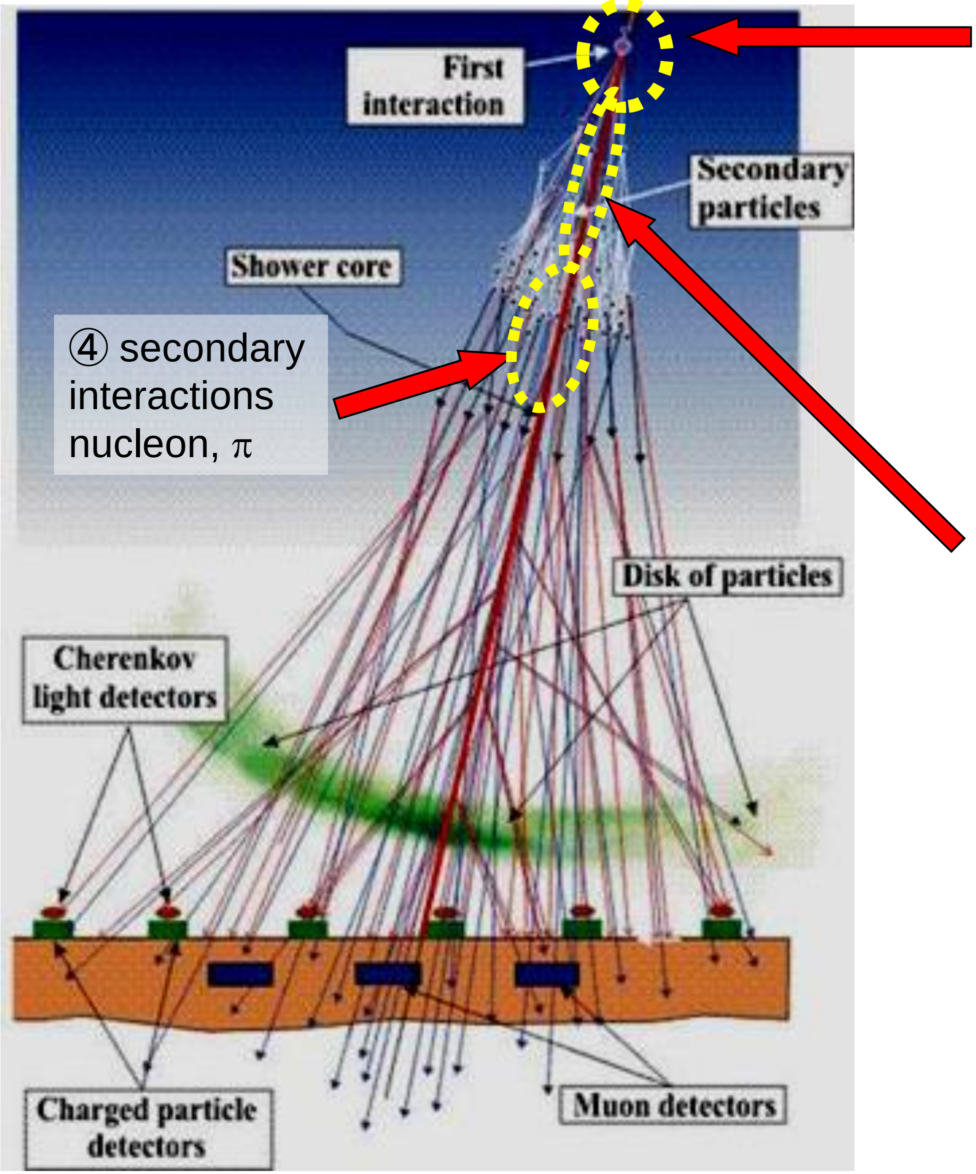
Muon surplus reported by Auger is one of the candidate of the source of this difference.
I consider the lateral distribution of EM component as a candidate too.

# Difference b/w E(FD) and E(SD)



# Air Shower study using collider




① Inelastic cross section

If large σ: rapid development
If small σ: deep penetrating

**② Forward energy spectrum**

Softer → shallow development
Harder → deep penetrating

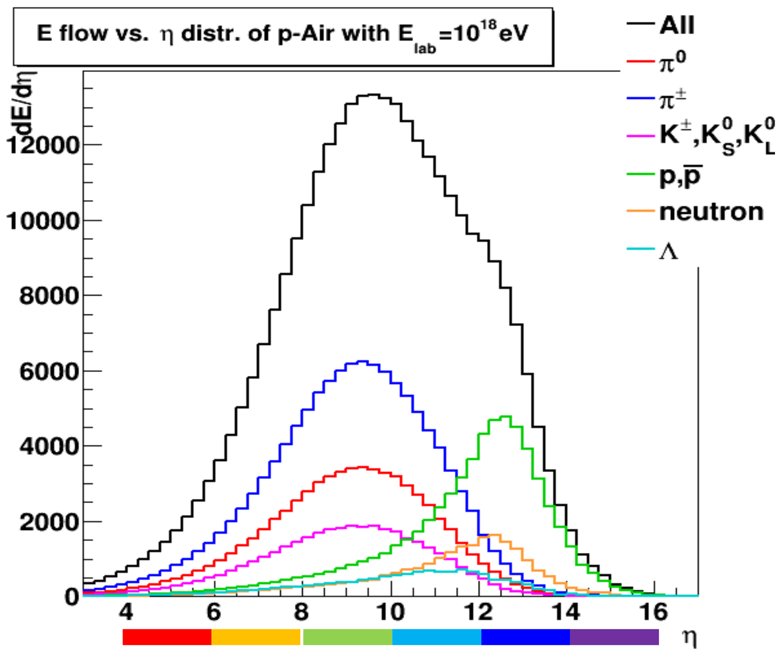
**③ Inelasticity $k = 1 - {E_{lead}}/{E_{avail}}$**

Large ***k*** ($\pi^0$s carry more energy)
→ rapid development

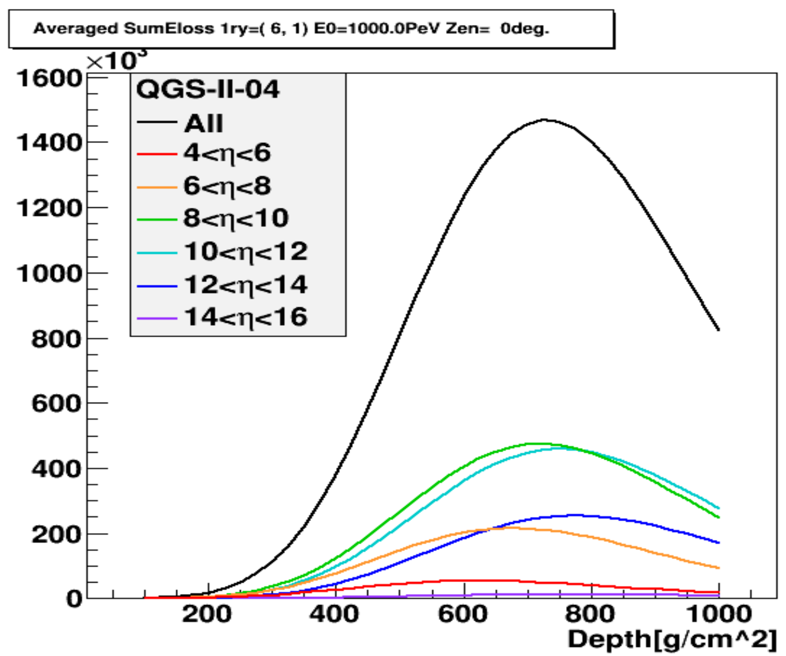
Small ***k*** (baryons carry more energy)
→ deep penetrating

# Very forward hadron energy flow & extensive air shower

**Energy flow @ Elab = 10^18eV**



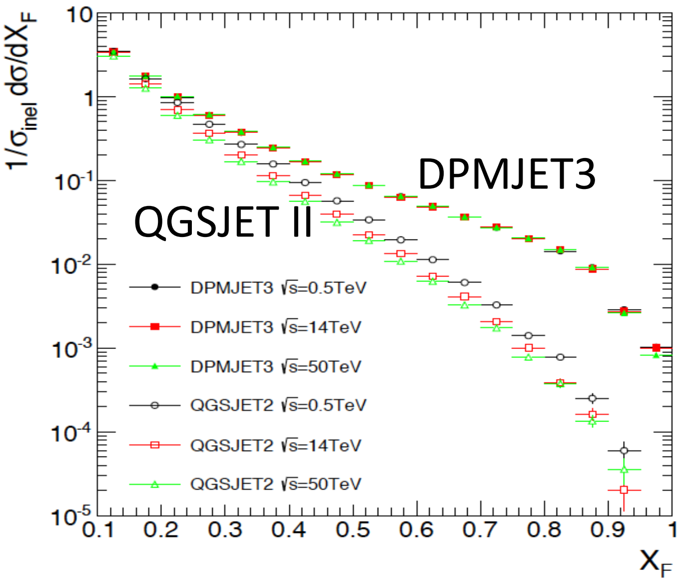

**Long. development @ Elab = 10^18eV**



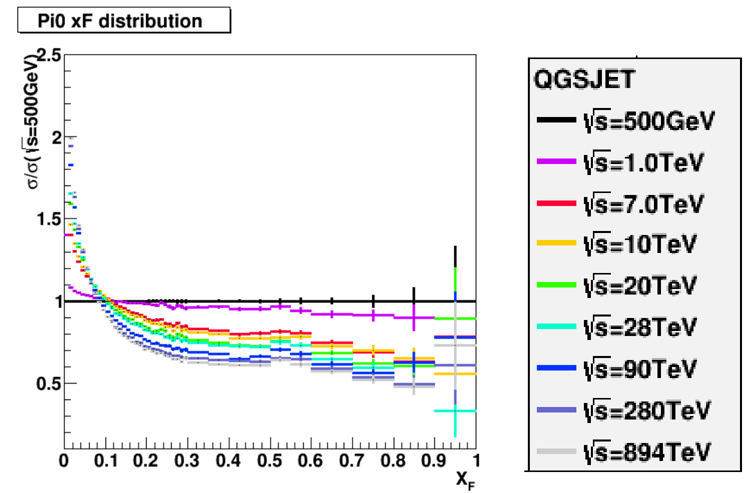

Neutron energy flow @ high pseudo-rapidity region (η>12) increase
→ Larger Xmax

# $\sqrt{s}$ scaling of $x_F$ and EAS

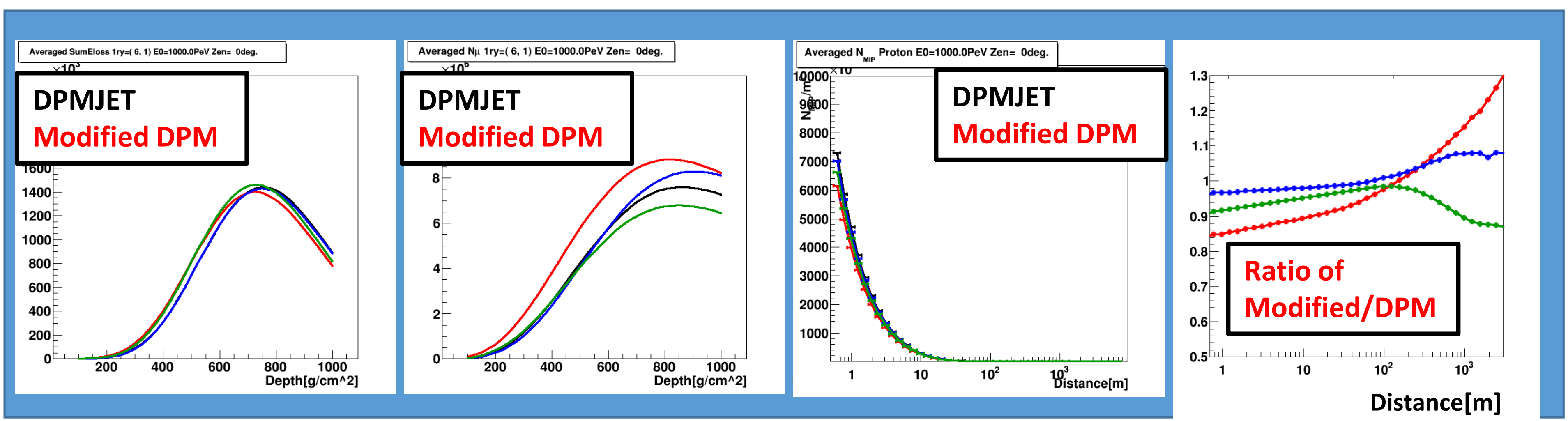
**All $\pi^0$ expected from models (0.5TeV, 14TeV and 50TeV)**




**$\sqrt{s}$ scaling of xF from QGSJET-II-04**




**Apply "$\sqrt{s}$ scaling" to DPMJET3 & Run MC of EAS w/ 1EeV proton**



# Large Hadron Collider (LHC)

**p-p $\sqrt{s} = 0.9\text{TeV}$ → $E_{lab}$ = 0.2PeV 2009, 2010**

**p-p $\sqrt{s} = 7\text{TeV}$ → $E_{lab}$ = 26PeV 2010 - 2011**

**p-p $\sqrt{s} = 13\text{TeV}$ → $E_{lab}$ = 90PeV 2015 -**

p-p $\sqrt{s} = 2.76,8\text{TeV}$

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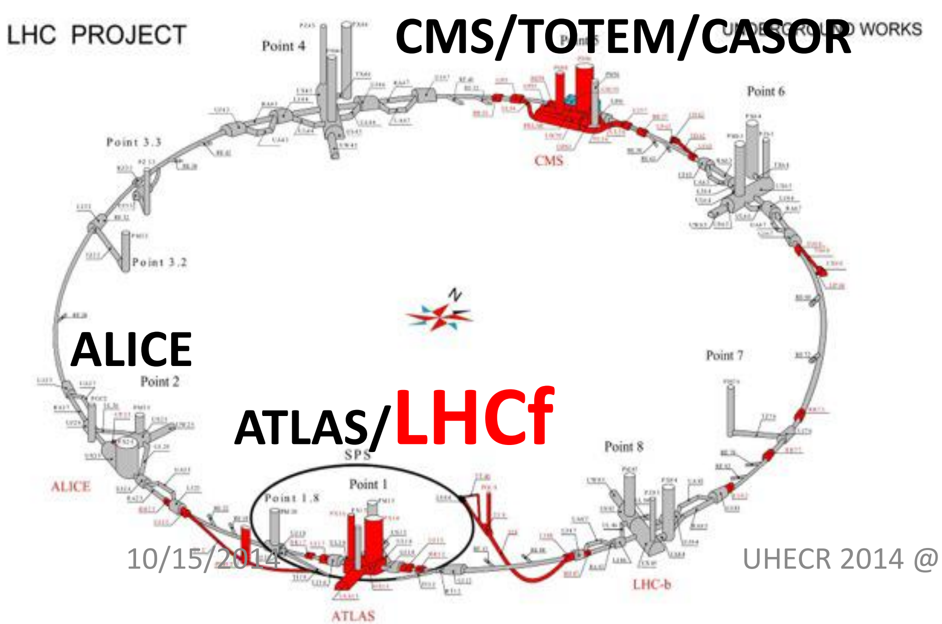
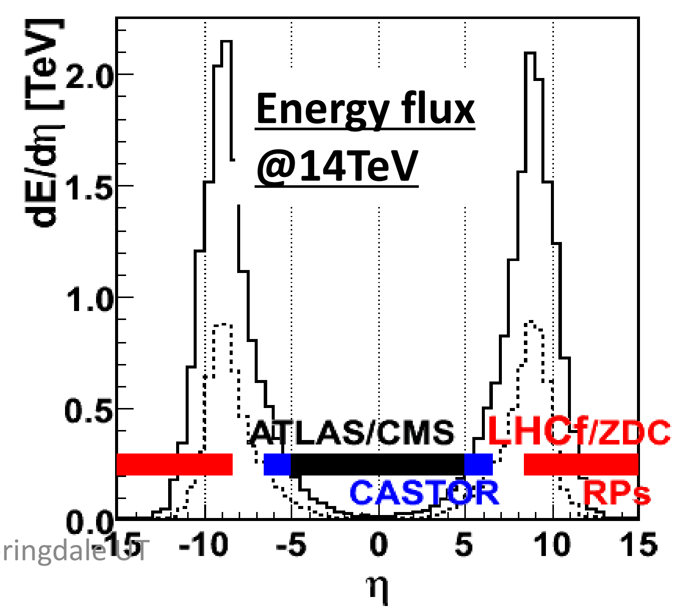
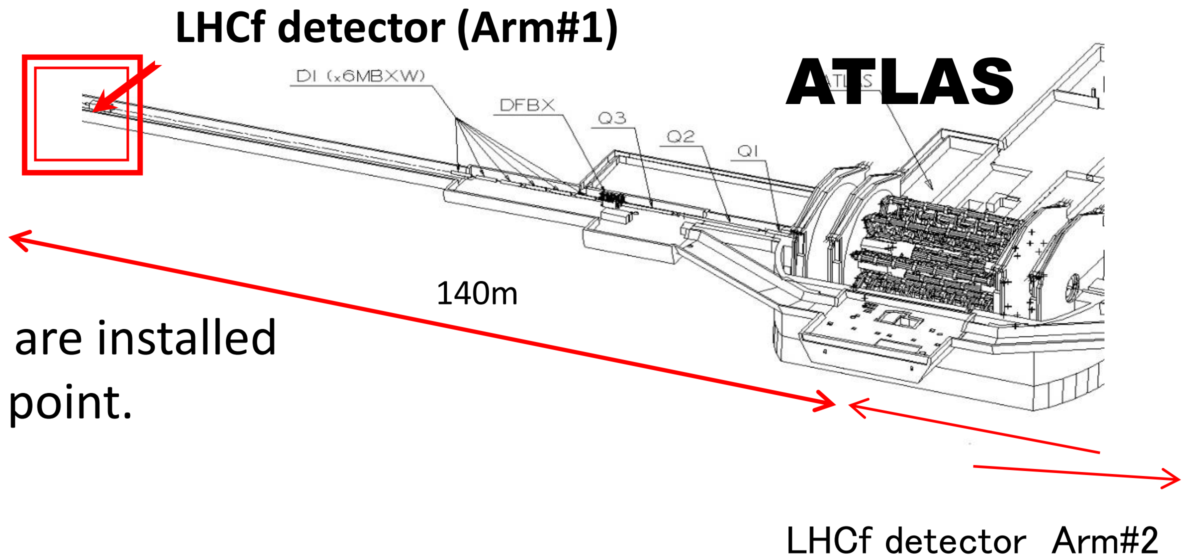
Pb-Pb $\sqrt{S_{NN}} = 2.76\text{TeV}$ 2011

**p-Pb $\sqrt{S_{NN}} = 5\text{TeV}$ 2013**

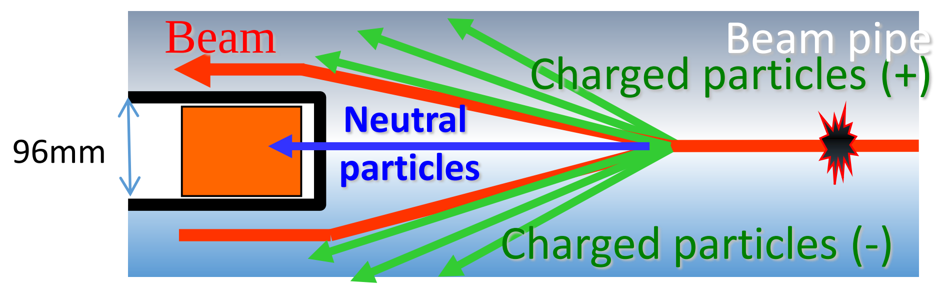


# The LHC forward (LHCf) experiment

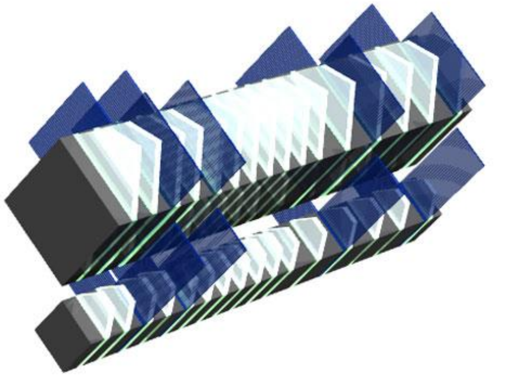



Two independent detectors are installed at either side of interaction point.




- All charged particles are swept by dipole magnet
- Neutral particles (photons and neutrons) arrive at LHCf
- 0 degree is covered

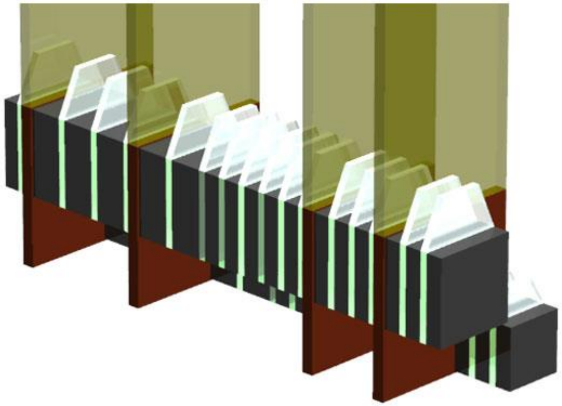
# LHCf detectors



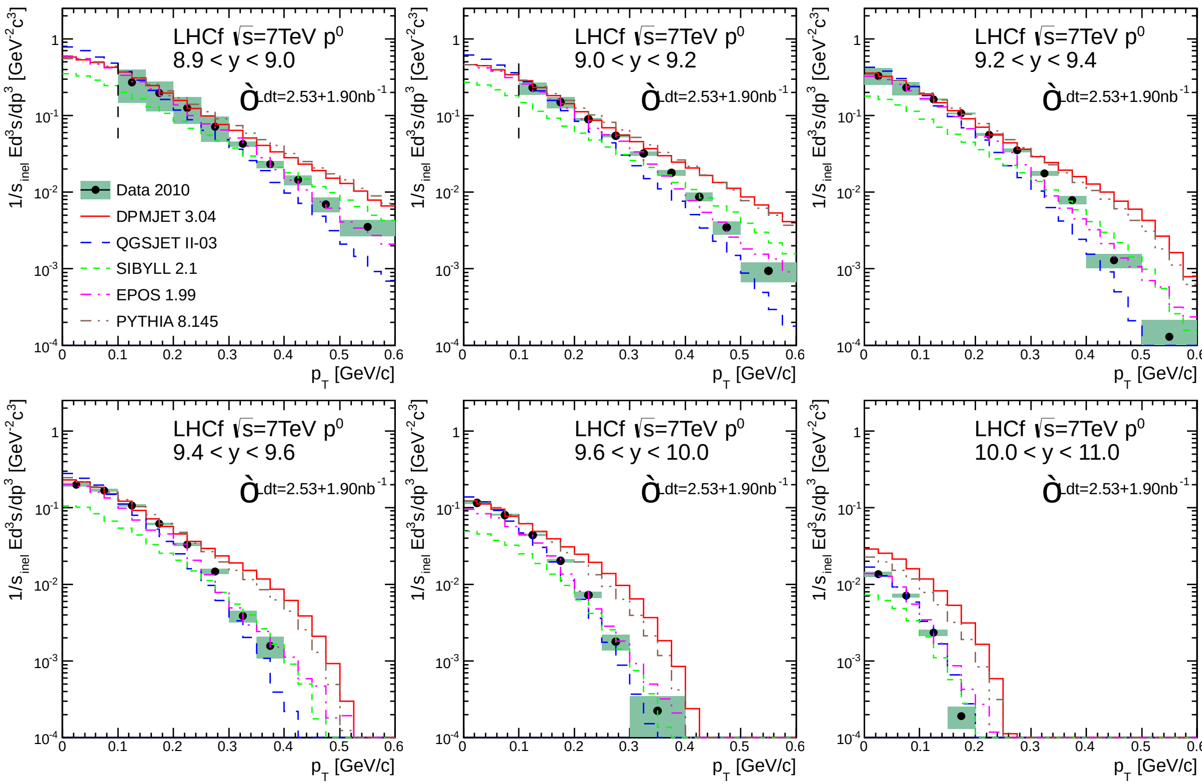
- Imaging/Sampling shower calorimeter
  - 2 different detectors (ARM1 & ARM2)

**ARM1** : 20mmx20mm & 40mmx40mm
XY position : 4 layers of SciFi (1mm pitch)
Calorimeter : tungsten & 16 layers of plastic scinti.
→ 44 r.l.

**ARM2** : 25mmx25mm & 32mmx32mm
XY position: 4 layers of Silicon micro-strip (0.16mm)
Colorimeter : tungsten & 16 layers of plastic scinti.



# Comparison of $\pi^0$ data @ $\sqrt{s} = 7\mathrm{TeV}$ w/ hadronic interaction models

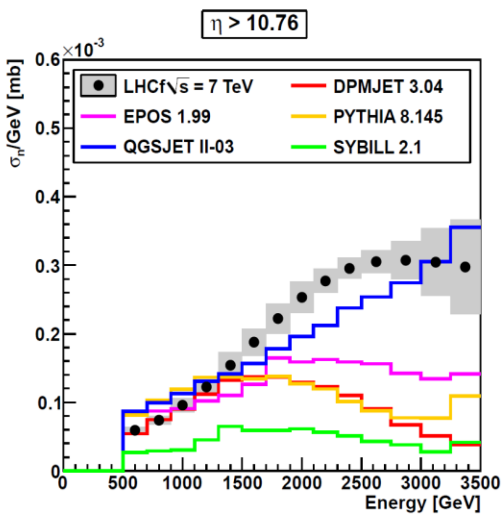


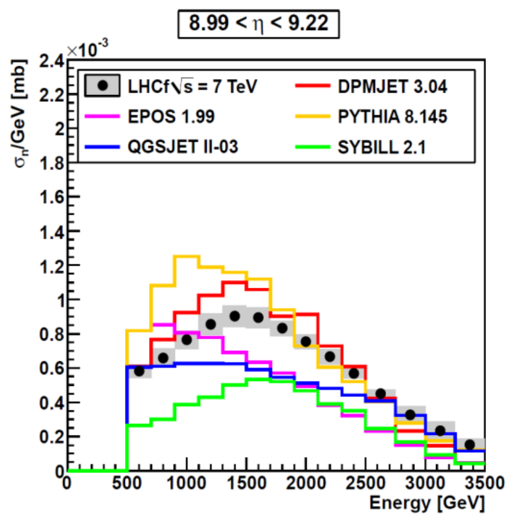

**Data**
**DPMJET3.04**
**QGSJET-II-03**
**SIBYLL2.1**
**EPOS1.99**
**PYTHIA8.145**

**"$\sqrt{s} = 7\mathrm{TeV}$"→ CR energy of 26PeV**

- **EPOS1.99** shows the best agreement with data in the models.
- **DPMJET** and **PYTHIA** have harder pt spectra than data.
- **QGSJET** has softer pt spectrum than data.

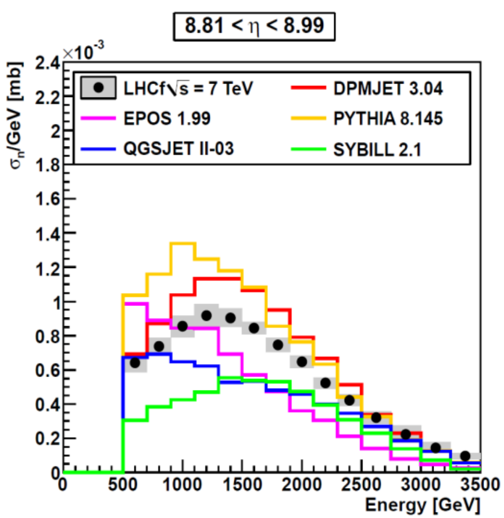
# Comparison of n data @ $\sqrt{s} = 7\text{TeV}$ w/ hadronic interaction models



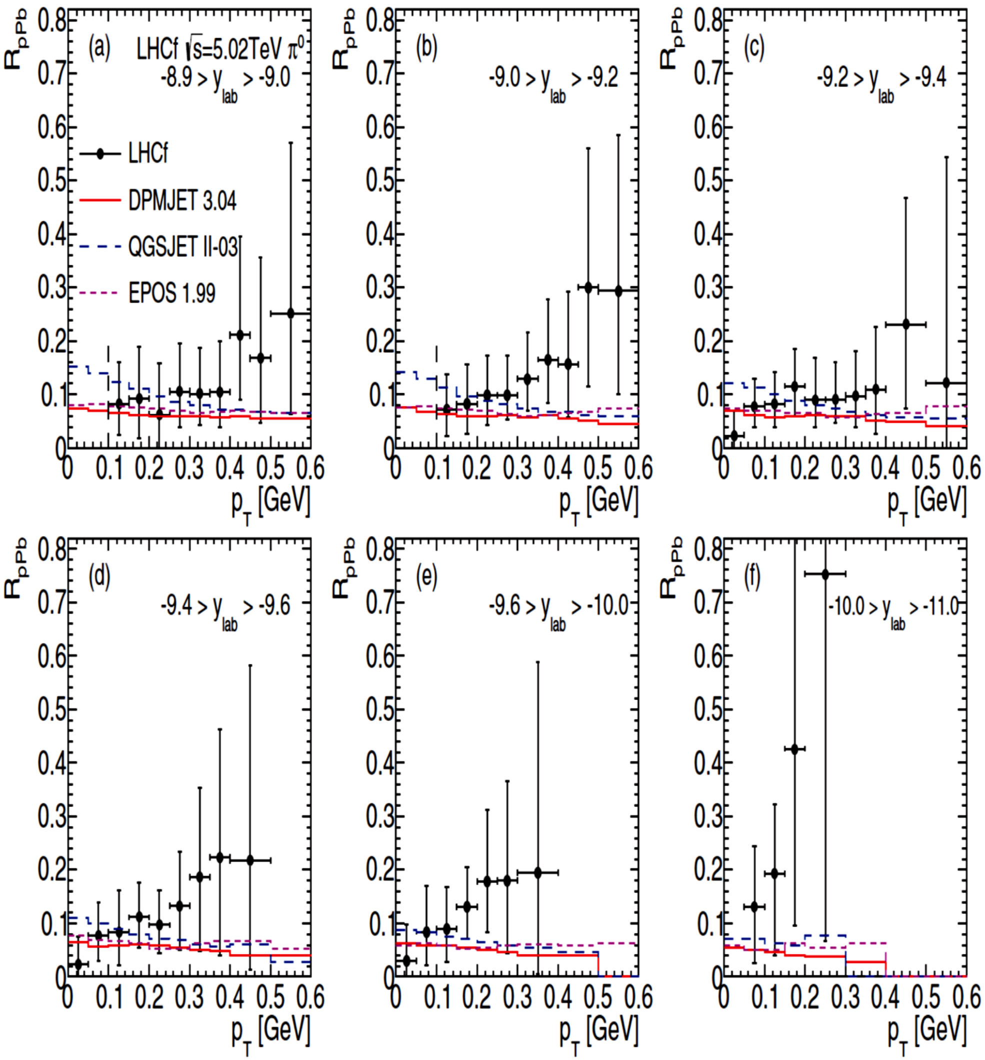

**Data**
**DPMJET3.04**
**QGSJET-II-03**
**SIBYLL2.1**
**EPOS1.99**
**PYTHIA8.145**

**"$\sqrt{s} = 7\text{TeV}$"→ CR energy of 26PeV**




- **QGSJET-II-03** predicts a high neutron production at the highest pseudo-rapidity region.
- **DPMJET3** is similar with data at the lower pseudo-rapidity region.
- No model completely explains the experiment results.

# Nuclear modification factor




**Data**
**DPMJET3.04**
**QGSJET-II-03**
**EPOS1.99**

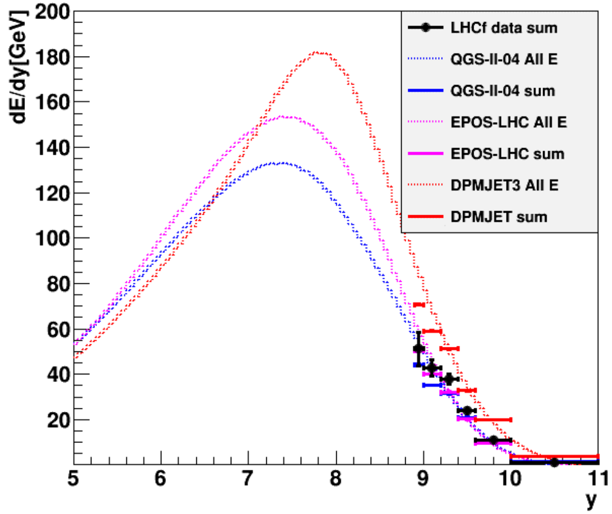
- $\pi^0$ $p_T$ spectra in p-Pb@$\sqrt{s_{NN}} = 5\text{TeV}$
- Very large suppression (~ 0.1)
  @ $p_T$>0.1GeV/c in proton-side.
- Models well reproduce the large suppression.
- LHCf pT spectra in p-Pb seems harder than one in p-p@5TeV expected from LHCf 7TeV & 900GeV results. (but not clear)

$$R_{pPb} \equiv \frac{d^2N^{pPb}_{\pi^0}/dydp_T}{\langle N_{coll}\rangle d^2N^{pp}_{\pi^0}/dyddp_T}$$

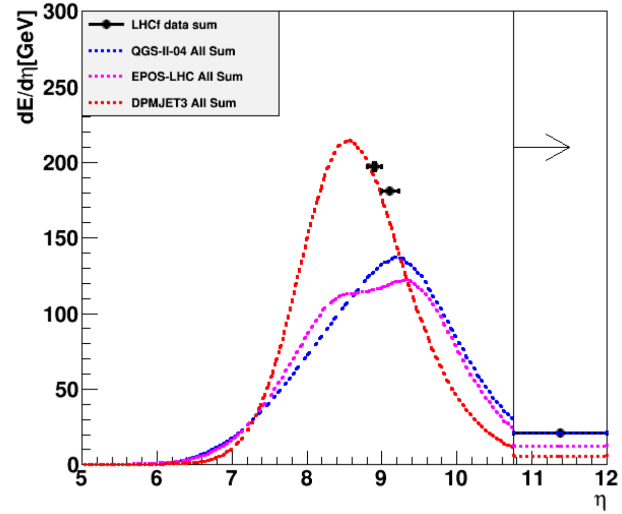
$$\langle N_{coll}\rangle = 6.9$$

# Energy flux by LHCf (very preliminary)

## $\pi^0$ (vs rapidity)




## neutron (vs pseudo-rapidity)



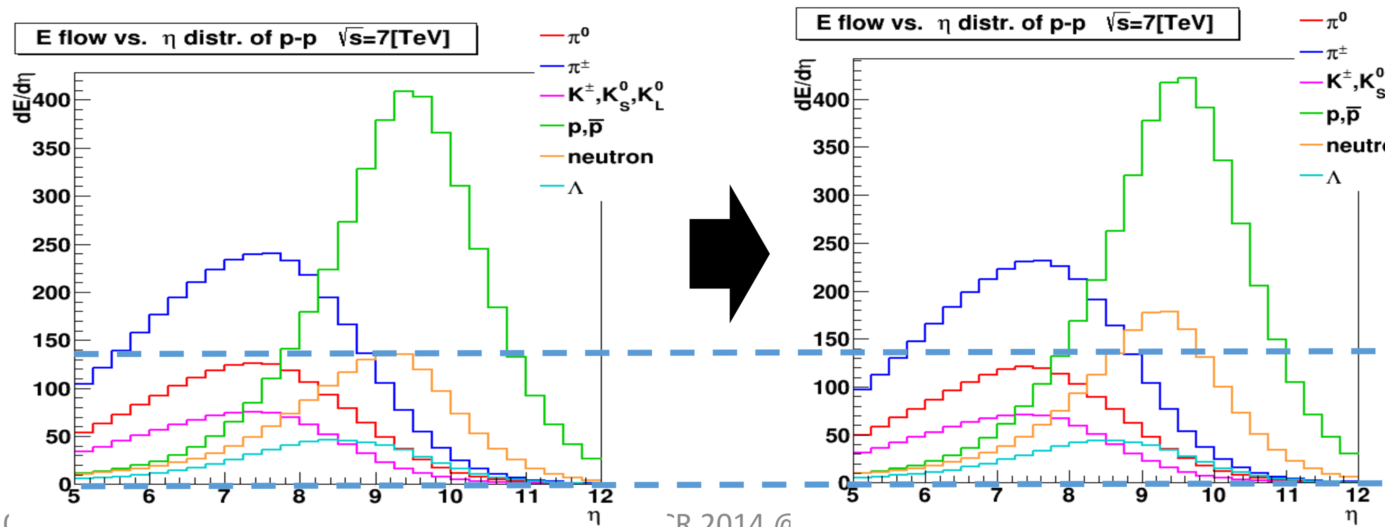

**$\pi^0$ energy flux is consistent with Post-LHC models.**

**Neutron energy flux is much larger than the predictions by post-LHC models.**
**(Shape of distribution or amplitude of production rate?)**

I start from the QGSJET-II-04 and try to modify so that the forward energy flux of neutron increase. But this modification should not change pions so much.

# Modification method

- In order to increase energy flow of neutron at very forward region, the interaction in which the leading particle is neutron is increased.
  1. Select Non-diffractive events whose leading particles are not neutrons.
  2. 10% of selected events are converted to Single diffractive events or Double diffractive events whose leading particles are neutrons.

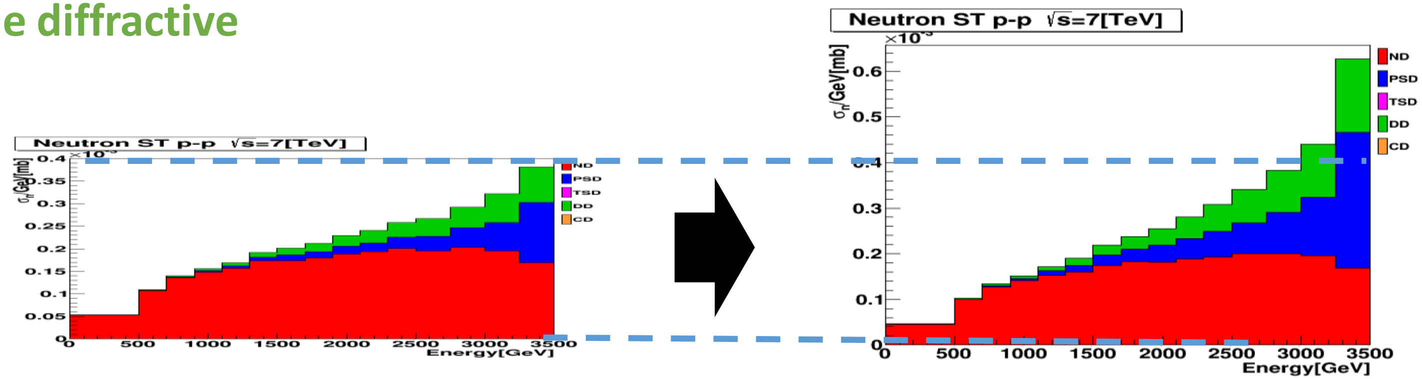



**neutron : +30%**
**proton : +2%**
**Charged π : -4%**
**π0 : -4%**

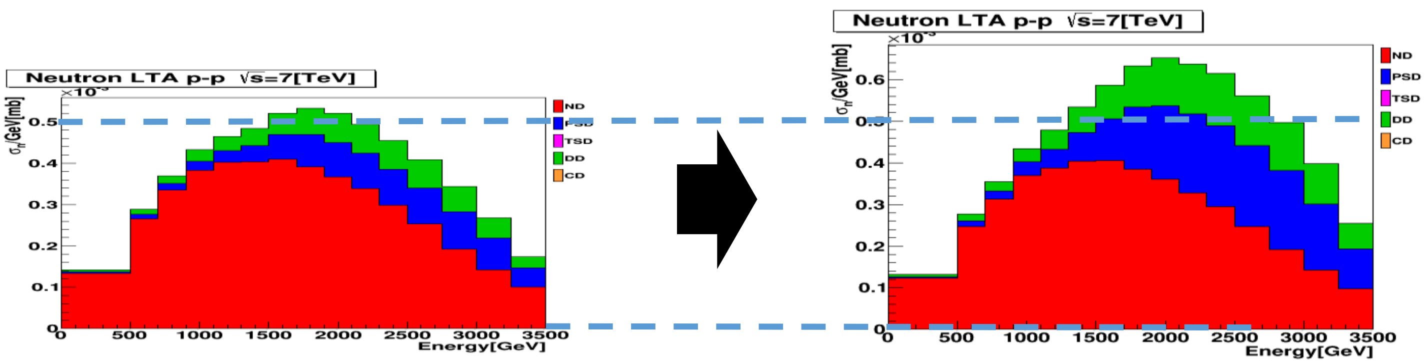
# Results of modification (1)

Non diffractive
Projectile single diffractive
Double diffractive

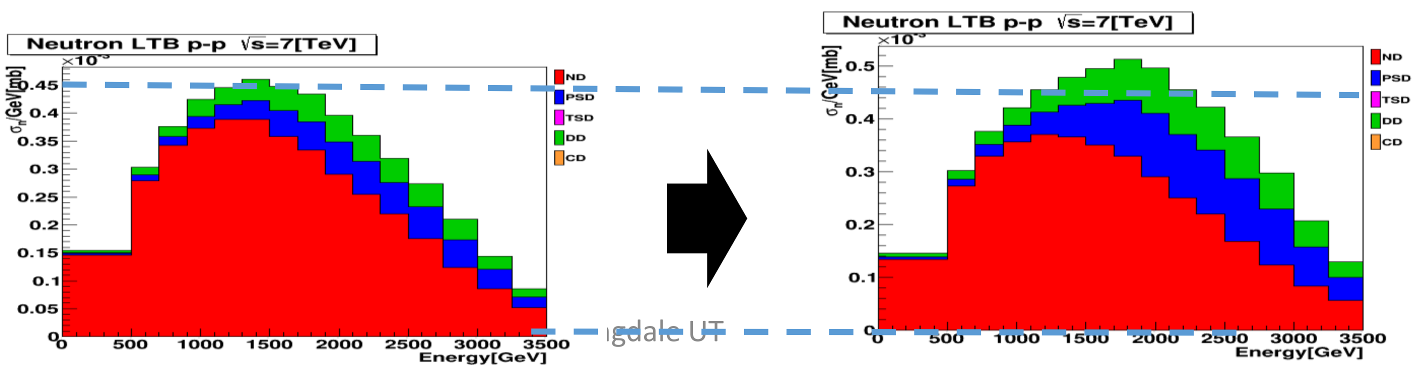
**η > 10.76**




**9.76>η> 8.99**

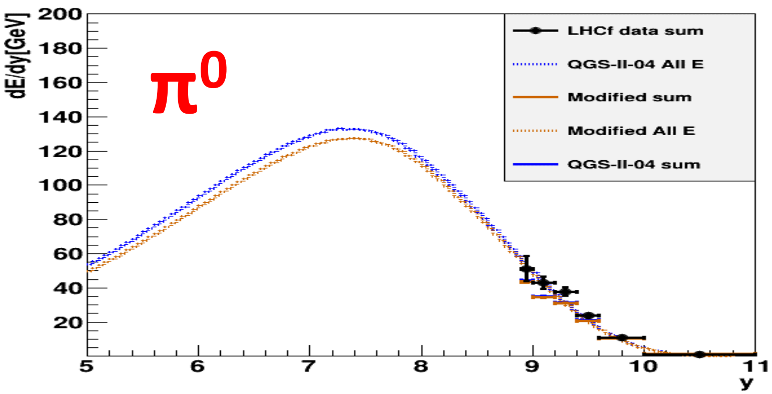


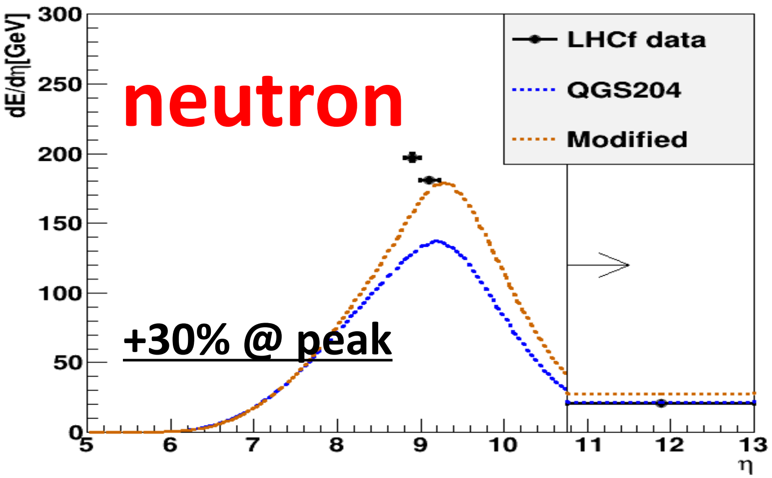

**8.99>η> 8.81**



# Results of modification (2)

## Energy flow plots



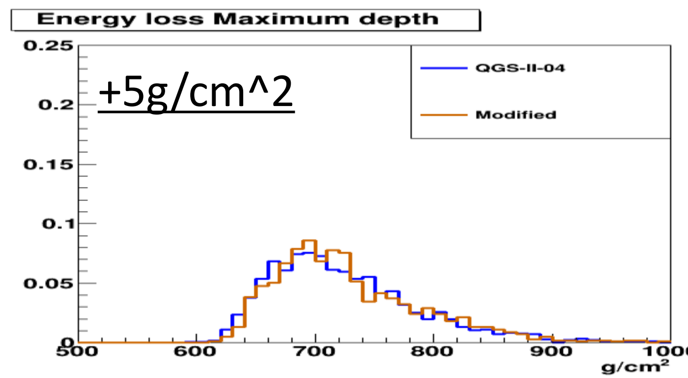




Inelasticity → Down
Multiplicity → Down
Neutron spectrum → Hard

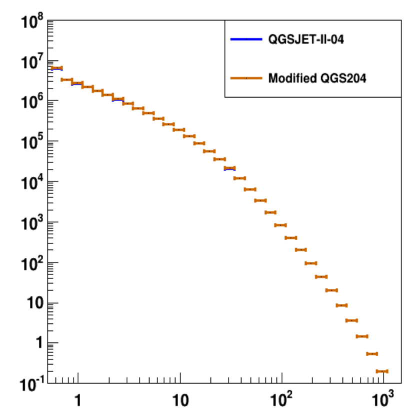
## Air shower simulation

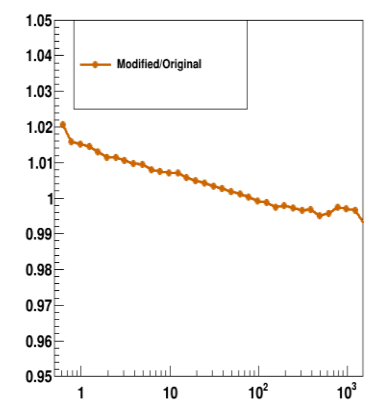
10EeV proton shower is simulated using **COSMOS** air shower simulator.

### Longitudinal development




### Lateral distribution of E.M component



# Future prospects

- LHC p-p collision @ $\sqrt{s} = 13$ TeV (~ 10^17eV)
  - 1 week operation in May 2015 w/ low luminosity.

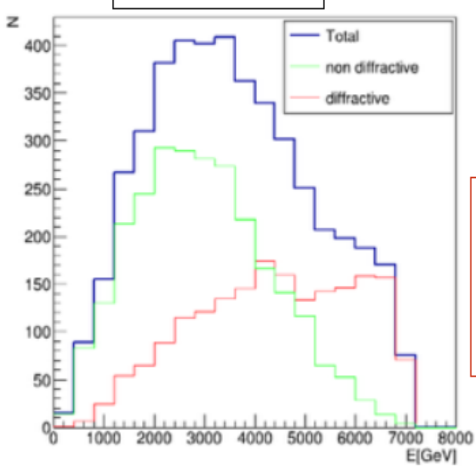
    → Test of energy scaling of xF & pT distributions.

    → Enlarge the LHCf acceptance

    → Common operation w/ ATLAS gives us data of 99% pure diffractive events.

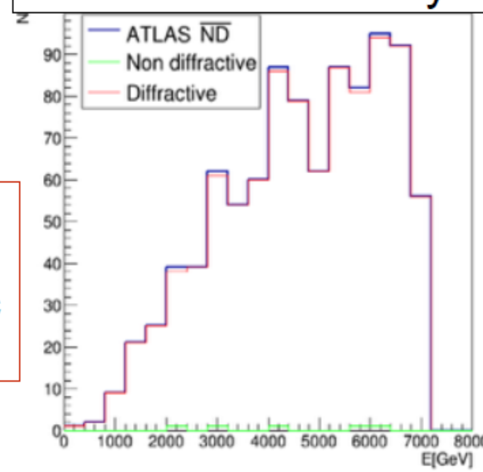
**n @ Arm1-TS**

All Events




0 charged particle with > 100MeV/c in |η| < 2.5

w/ Event selection by ATLS

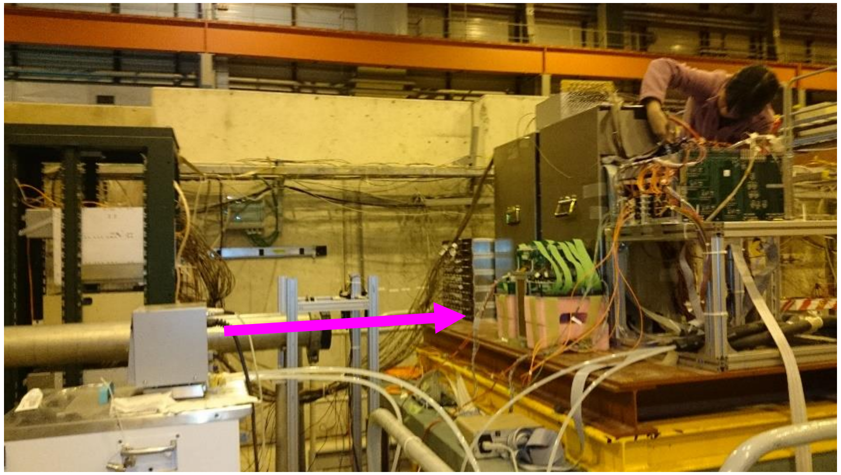



99% Pure diffractive events with ~40% eff.

# Preparation of 13TeV operation

**Assemble @ Nagoya**
**July 2014**

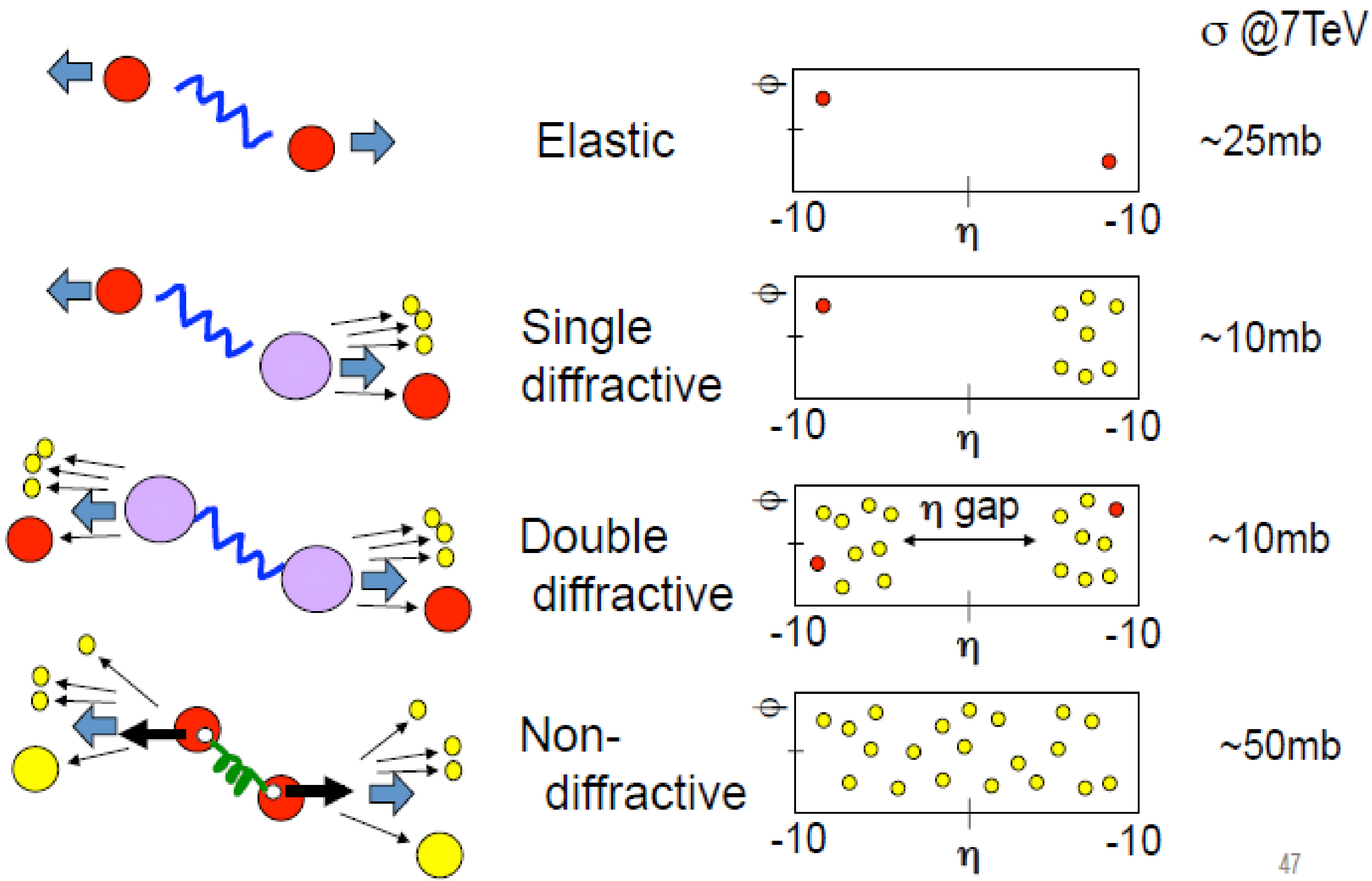
**Beam test @ CERN-SPS**
**Until tomorrow. It goes very well so far.**



# Summary

- LHCf measures the very forward hadron production to improve the models used in EAS simulations.
- LHCf had operations at p-p @$\sqrt{s} = 0.9,7\ \mathrm{TeV}$ and w/ p-Pb @$\sqrt{s_{NN}} = 5\ \mathrm{TeV}$ .
- Photons & π0 (EM component) in LHCf acceptance seems to be good agreement with EPOS1.99 model.
- Energy spectra of very forward neutron is not well described by models.
- QGSJET-II-04 output is modified to increase the leading neutron.
  - Neutron spectra at LHCf acceptance become harder than the observation results.
  - Xmax becomes larger (+5g/cm^2) .

# pseudorapidity and interactions



# Future Operations

- **LHC p-p √s = 13 TeV**
  - Operation for about 1 week in **May 2015** with low luminosity collisions.
    - **Test of Energy scaling**
    - **Enlarge the LHCf acceptance**