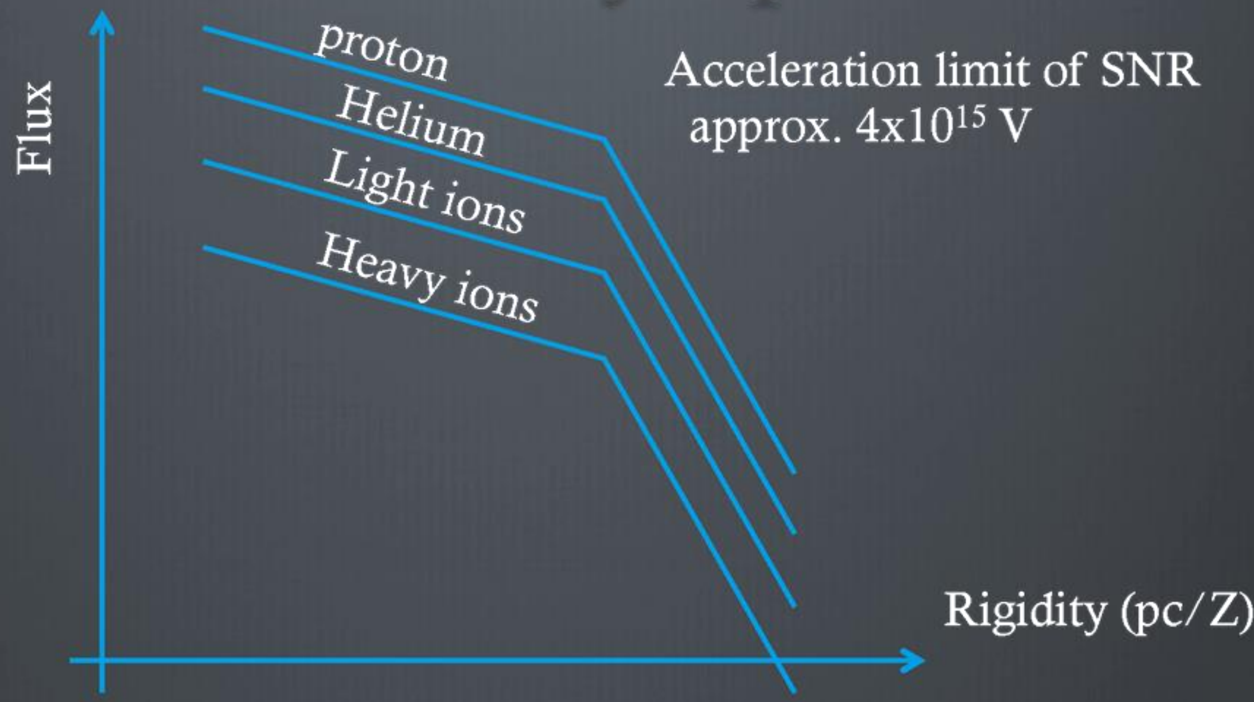
# Cosmic-ray physics at LHC: the LHCf experiment

Massimo Bongi, for the LHCf collaboration

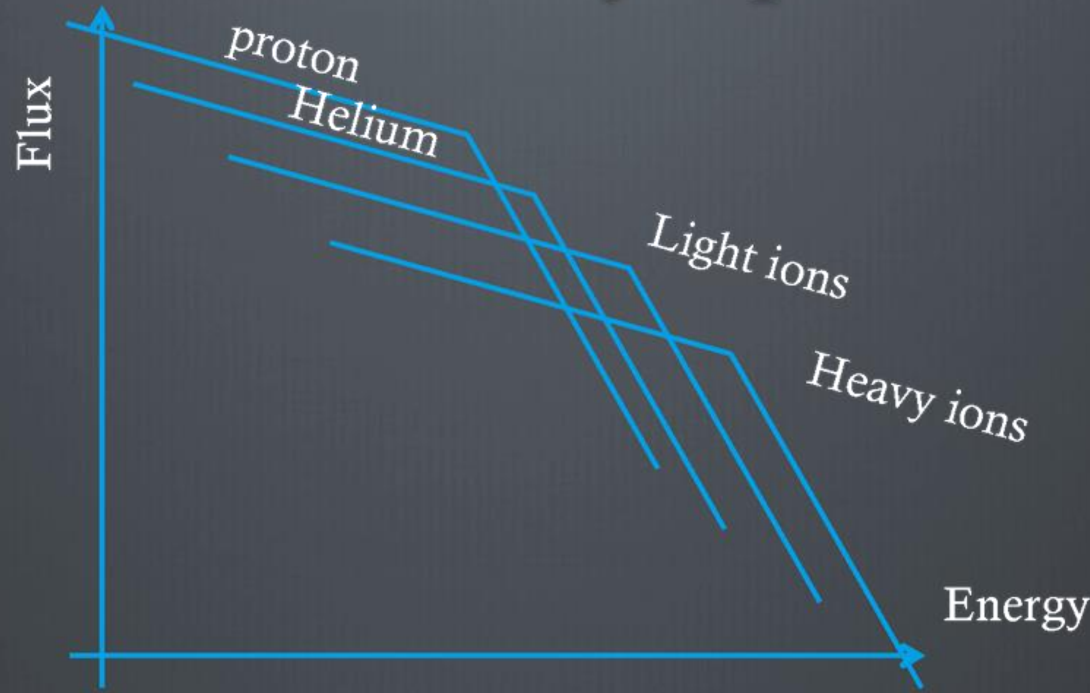
INFN Florence, $16^{th}$ Dec 2013

# Standard Scenario of the Cosmic-Ray Spectrum



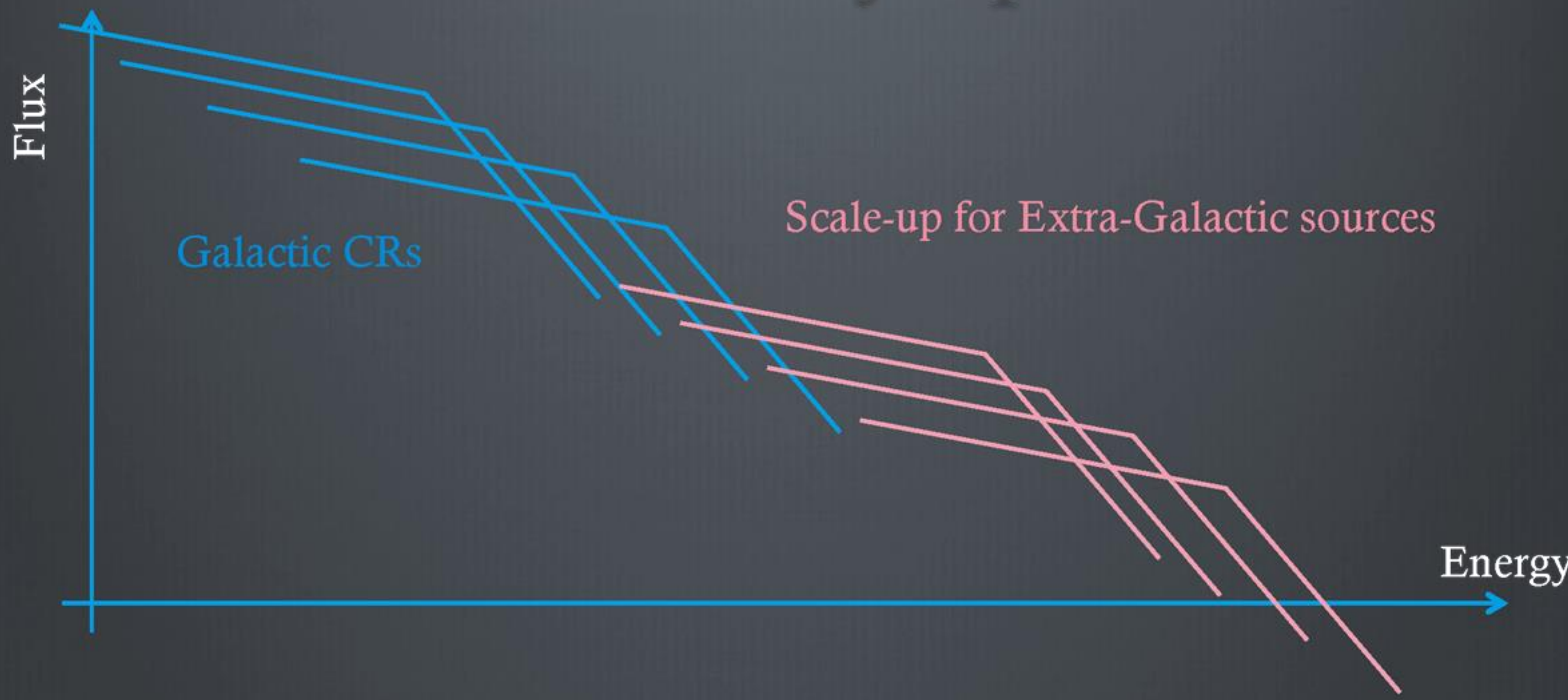

- Electro-magnetic process => Same rigidity spectrum for different nuclei

# Standard Scenario of the Cosmic-Ray Spectrum



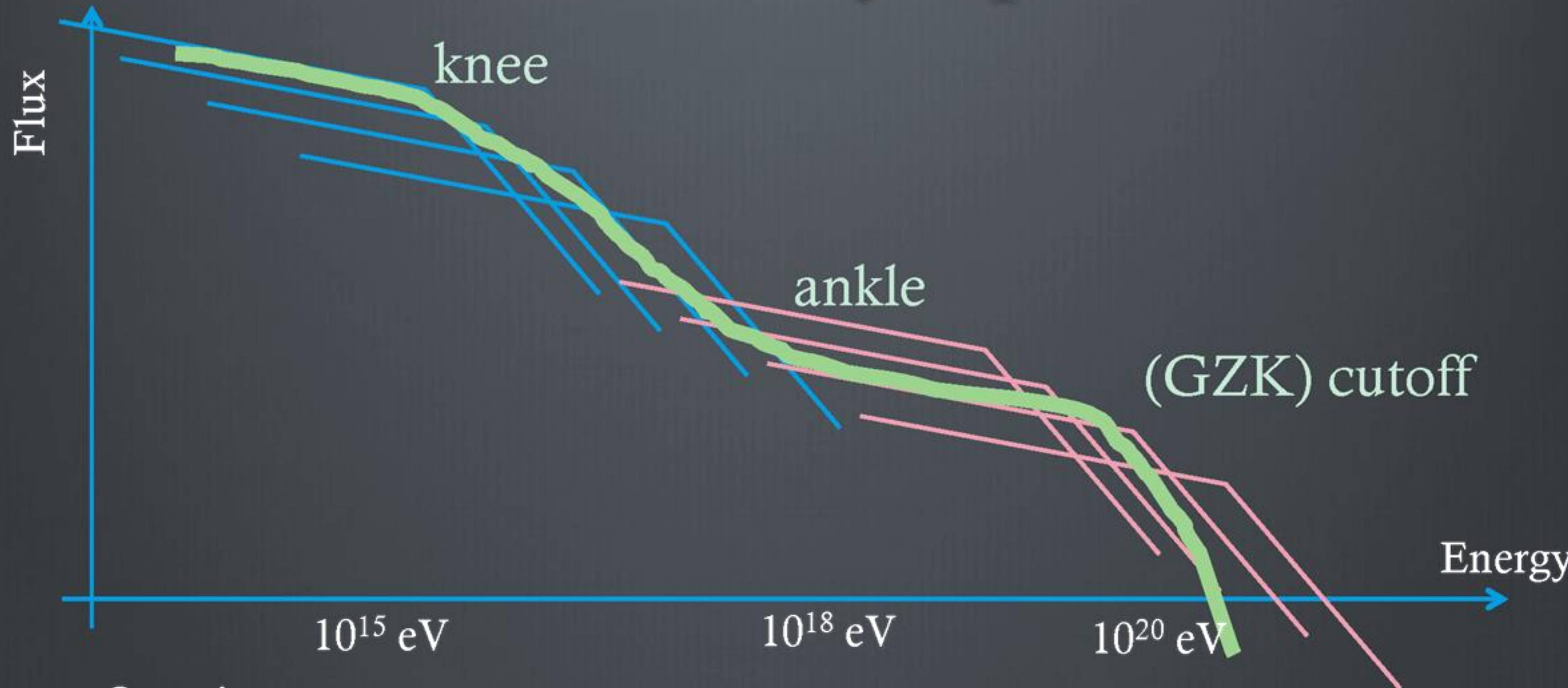

- In term of 'Energy,' heavier particles have Z times higher energy than protons

# Standard Scenario of the Cosmic-Ray Spectrum



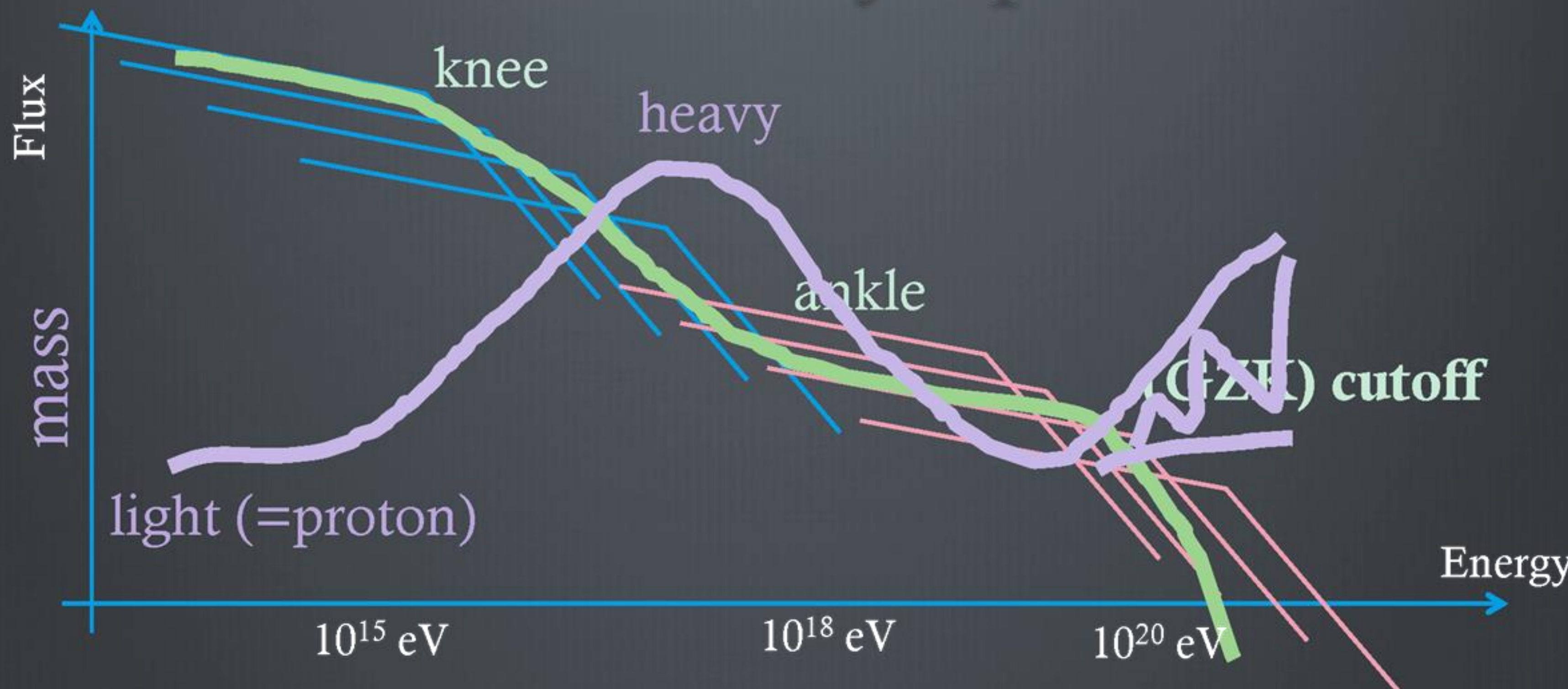

- Over GCR max energy, Extra-galactic CRs appear

# Standard Scenario of the Cosmic-Ray Spectrum

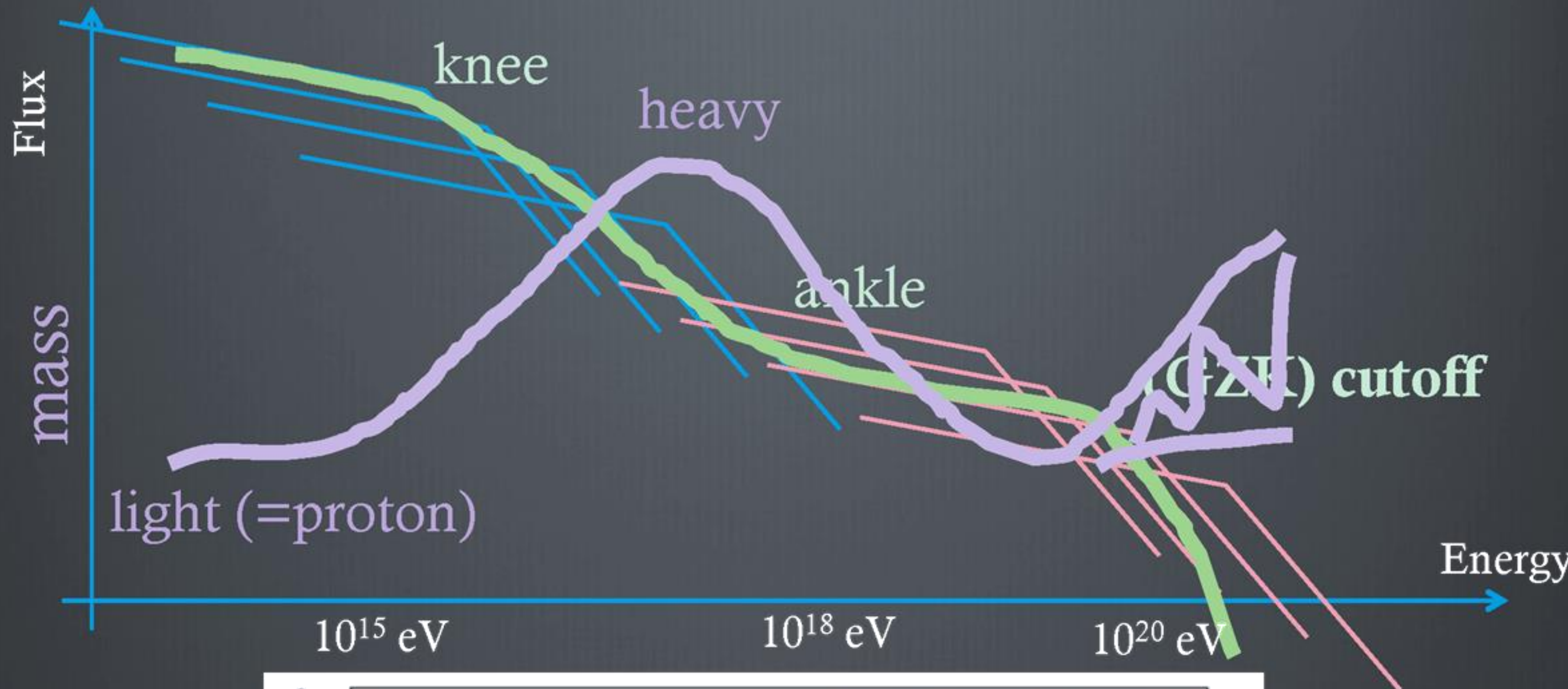


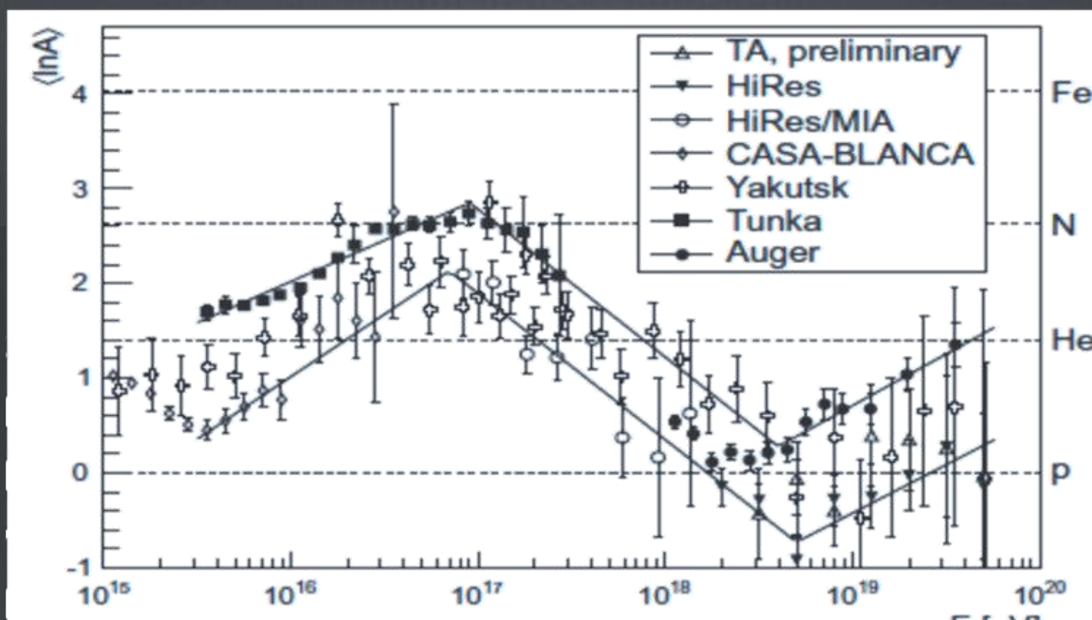

- Questions
  - End of GCR
  - Turn over from GCR to EGCR
  - Cutoff (acc. Limit, proton GZK, ion GZK)

# Standard Scenario of the Cosmic-Ray Spectrum

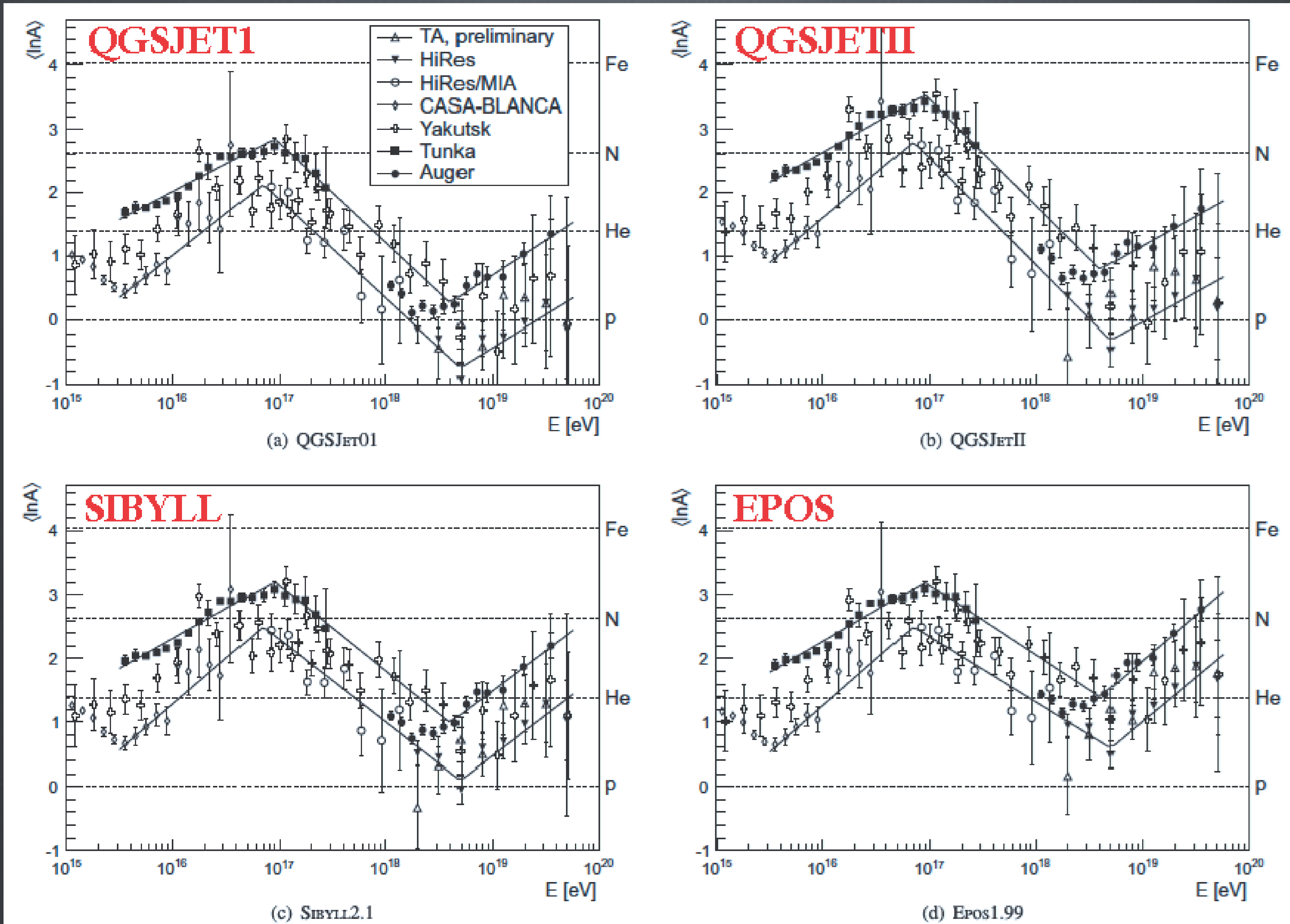



- Mass vs. Energy
  - Light < knee
  - Light to heavy over knee
  - Heavy to light around ankle
  - Light or light to heavy around cutoff


Flux
mass
knee
heavy
ankle
cutoff
light (=proton)
Energy
$10^{15}$ eV
$10^{18}$ eV
$10^{20}$ eV

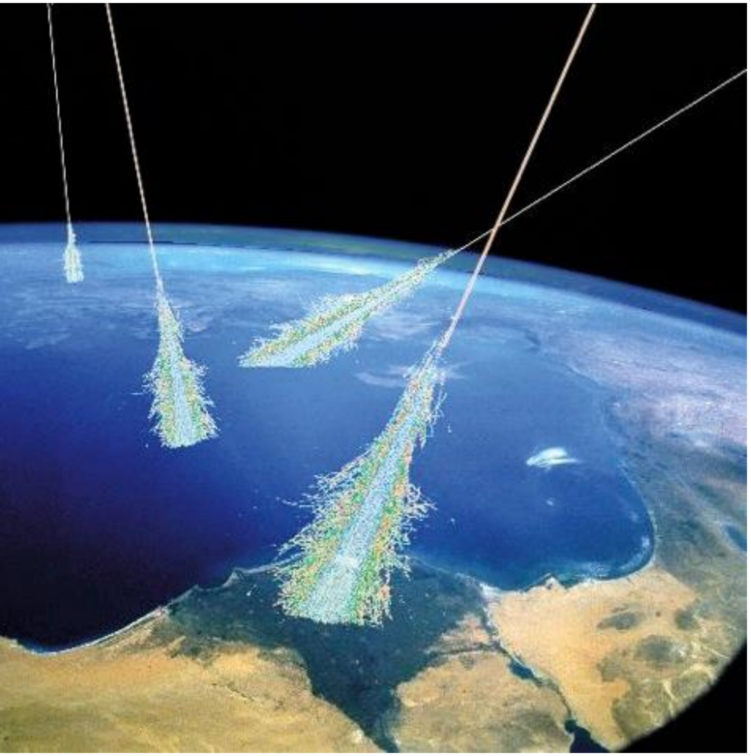

⟨lnA⟩
4
3
2
1
0
-1
$10^{15}$
$10^{16}$
$10^{17}$
$10^{18}$
$10^{19}$
$10^{20}$
E [eV]
TA, preliminary
HiRes
HiRes/MIA
CASA-BLANCA
Yakutsk
Tunka
Auger
Fe
N
He
p

(a) QGSJET01




(Kampert and Unger, Astropart. Phys., 2012)

# *High Energy Cosmic Rays*



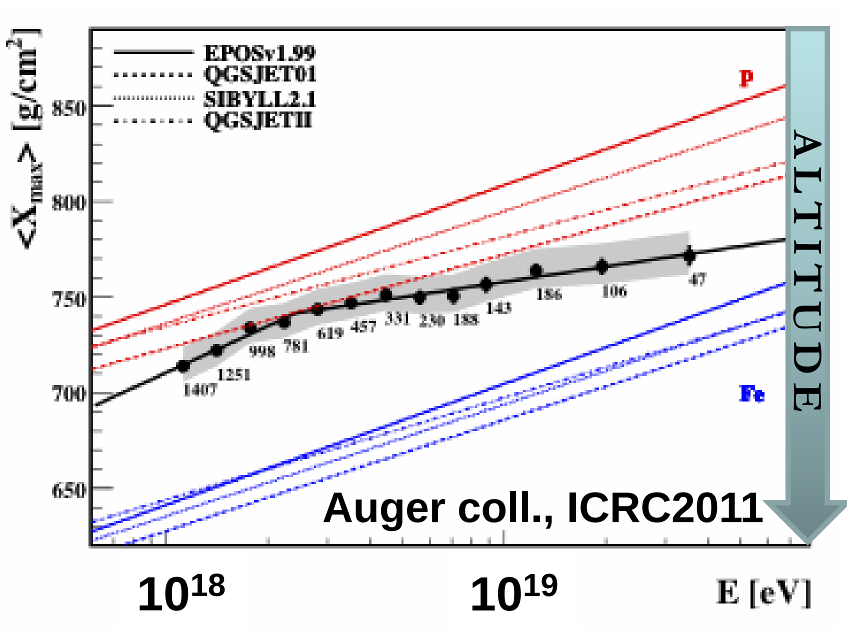
**Extensive air shower (EAS) observation**

- longitudinal distribution
- lateral distribution
- arrival direction

**(air shower development)**

**Astrophysical parameters**

- spectrum
- composition
- source distribution




- $X_{max}$: depth of shower maximum in the atmosphere
- $<X_{max}>$ gives information on the CR composition

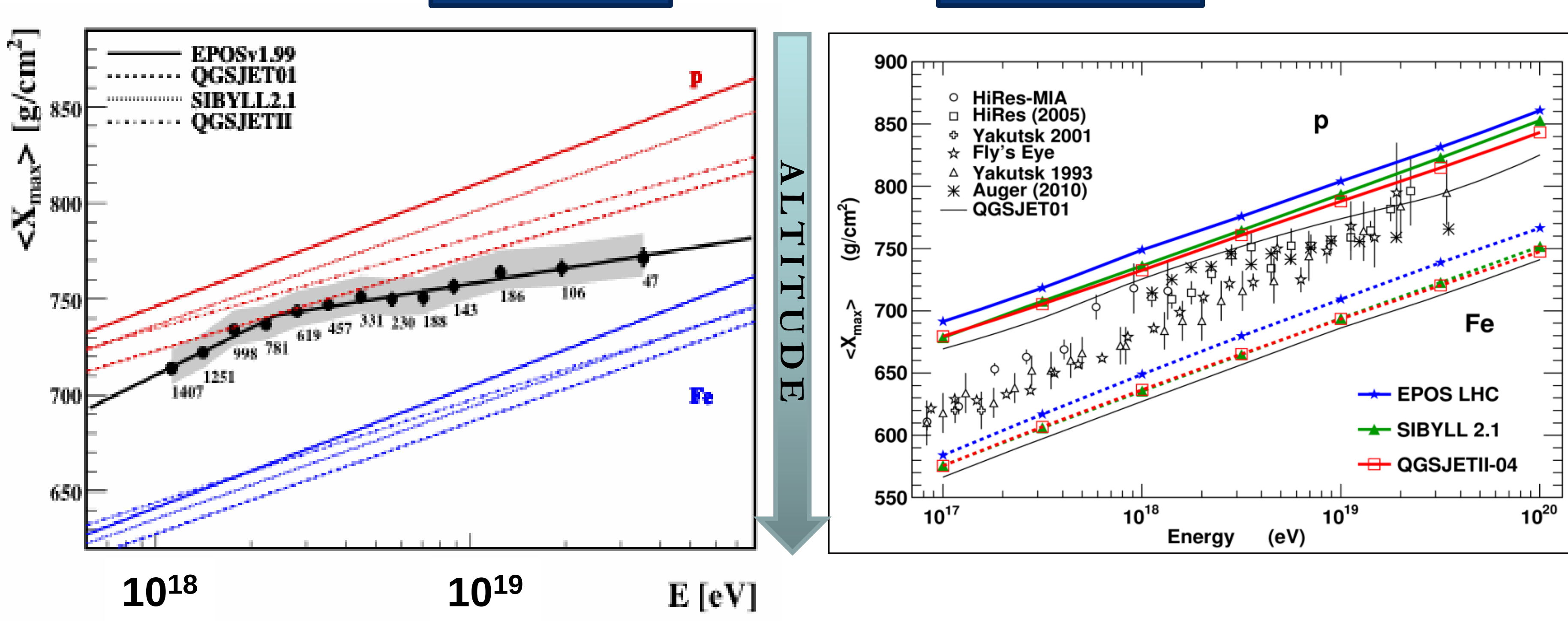
Uncertainty of hadron interaction models

Uncertainty in the interpretation of $<X_{max}>$

# *Tuning of hadron interaction models after the first LHC data*

pre LHC

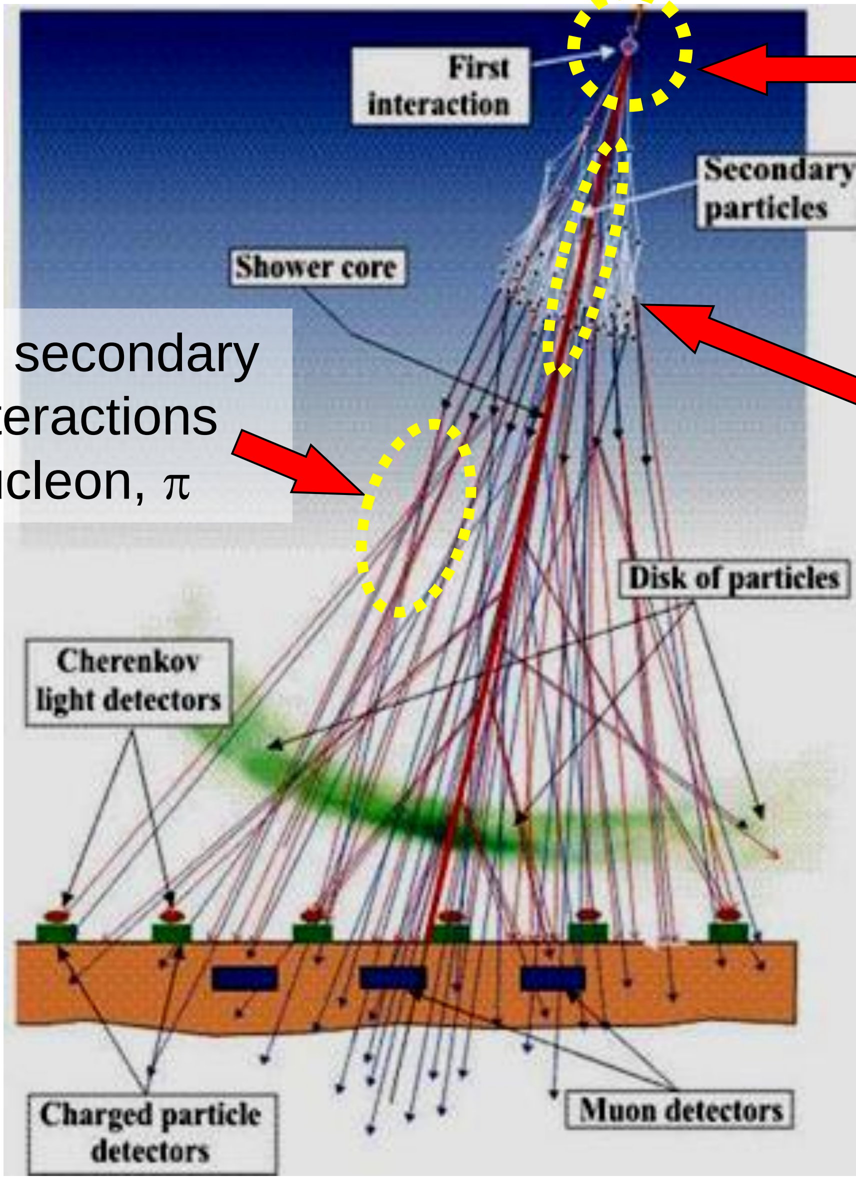
post LHC




Auger coll., ICRC2011

T. Pierog, Cosmic QCD 2013

# How accelerator experiments can contribute?




④ secondary interactions nucleon, π

① Inelastic cross section

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

**② Forward energy spectrum**

If softer rapid development
If harder deep penetrating

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

If large k ($\pi^0$s carry more energy)
rapid development
If small k (baryons carry more energy)
deep penetrating

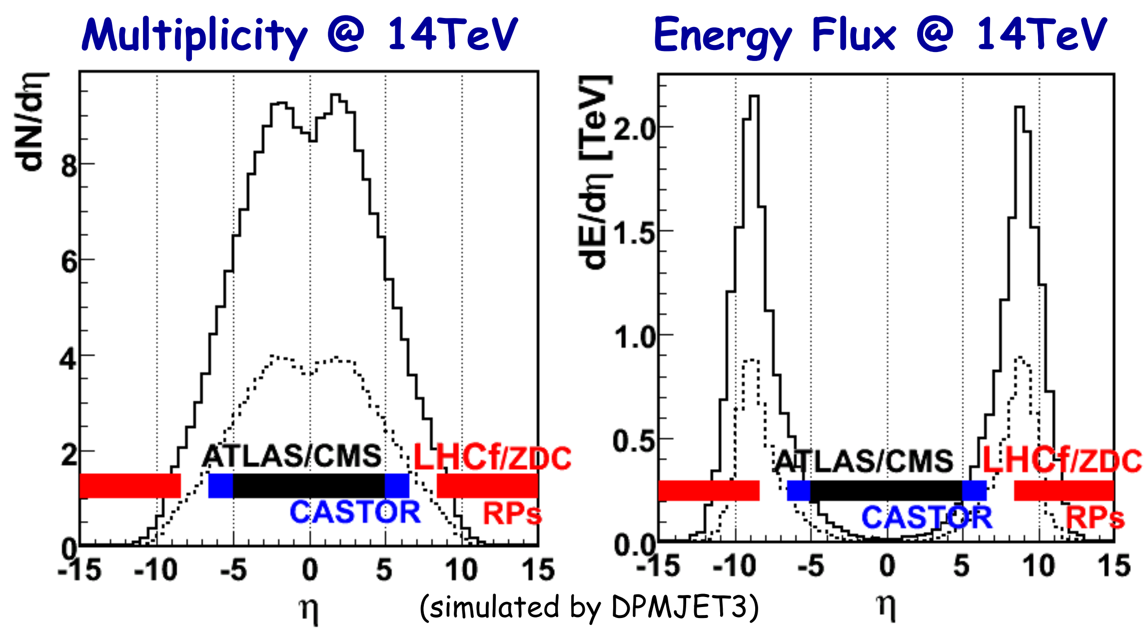
# *Calibration of hadron interaction models at LHC*

**p-p 450 GeV + 450 GeV → $E_{lab} \sim 4 \cdot 10^{14}$ eV**

**p-p 3.5 TeV + 3.5 TeV → $E_{lab} \sim 3 \cdot 10^{16}$ eV**

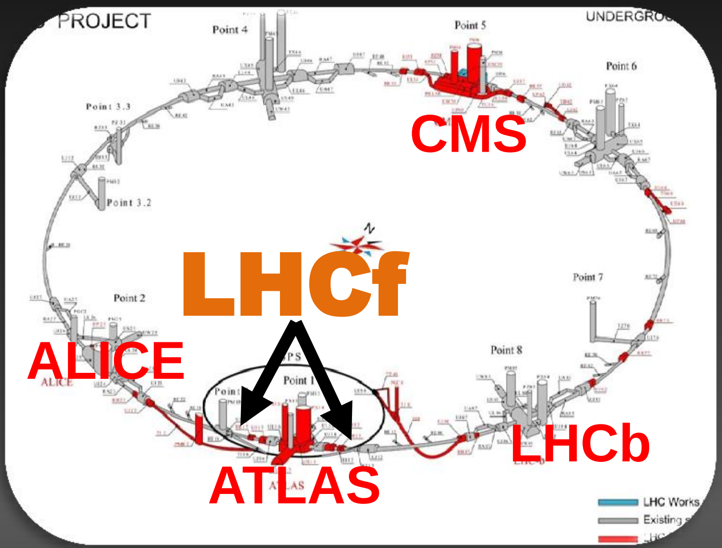
**p-p 6.5 TeV + 6.5 TeV → $E_{lab} \sim 9 \cdot 10^{16}$ eV**

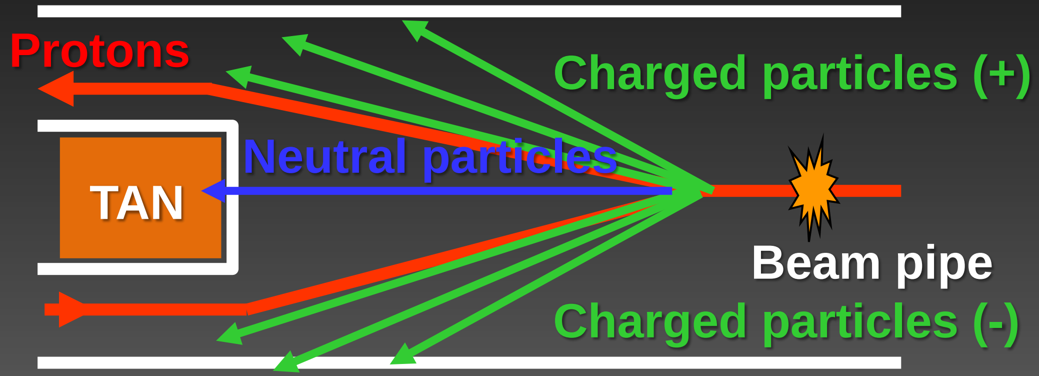
- Total cross section ↔ TOTEM, ATLAS, CMS
- Multiplicity ↔ Central detectors
- Inelasticity/Secondary spectra ↔ Forward calorimeters (**LHCf**, ZDCs)

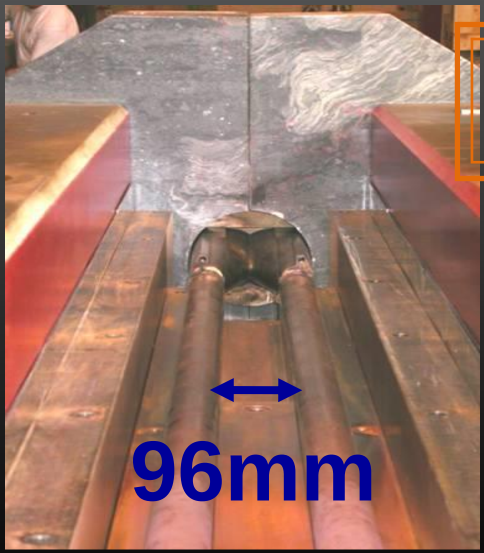


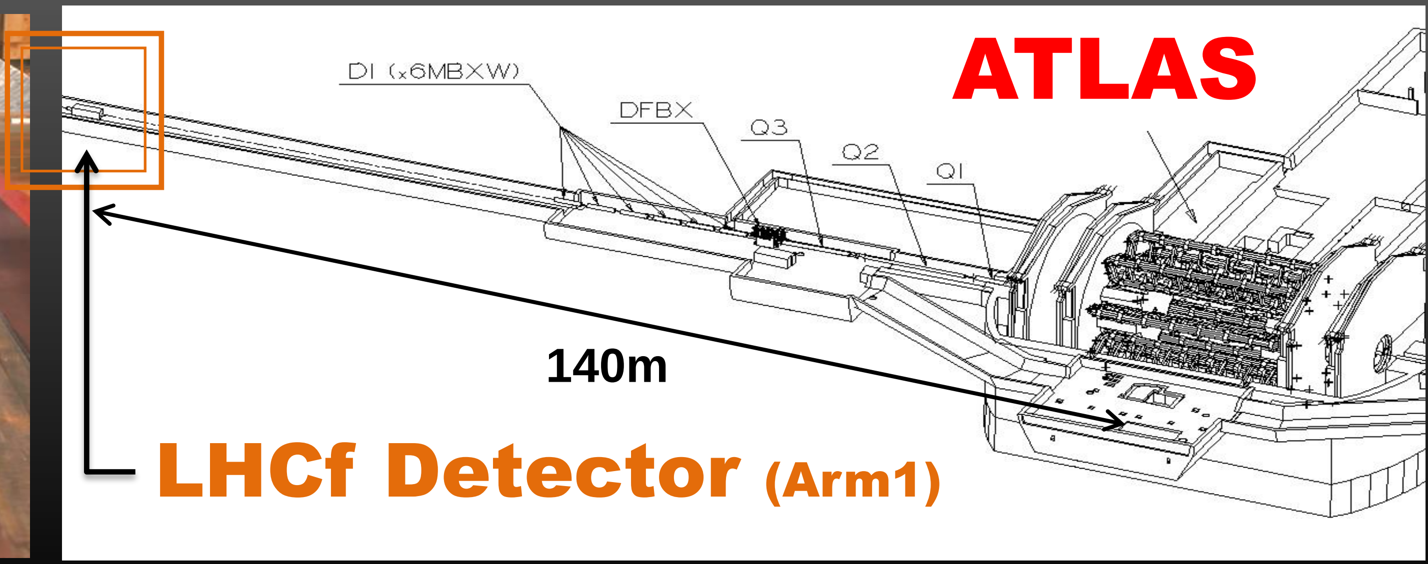

pseudo-rapidity $\eta = -\ln(\tan(\theta/2))$

# LHCf experimental set-up



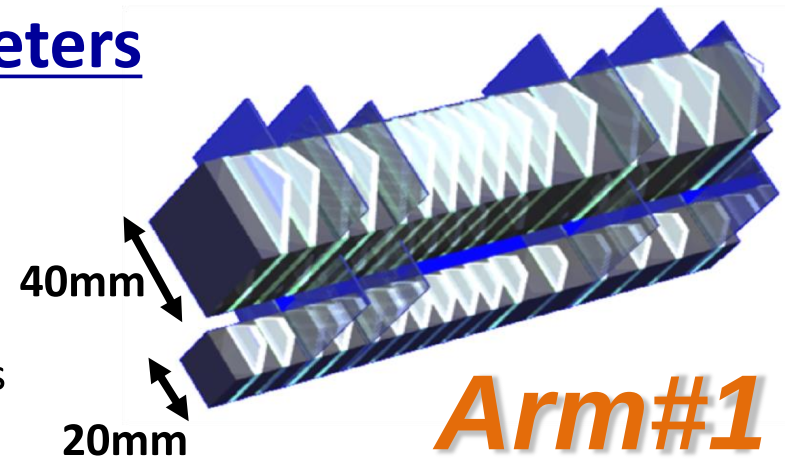



# *LHCf detectors and performances*

## Sampling and imaging E.M. calorimeters

- **Absorber**: W layers (44 r.l , 1.55 $\lambda_I$ in total)
- **Energy measurement**: plastic scintillator tiles
- **4 tracking layers** for imaging:
  XY-SciFi (Arm#1) and XY-Silicon $\mu$-strip (Arm#2)
- Each detector has two independent calorimeter towers

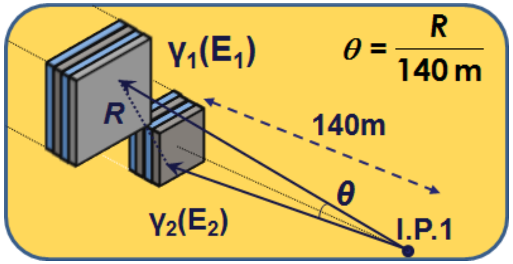
→ **reconstruction of $\pi^0 \to \gamma\gamma$ events**

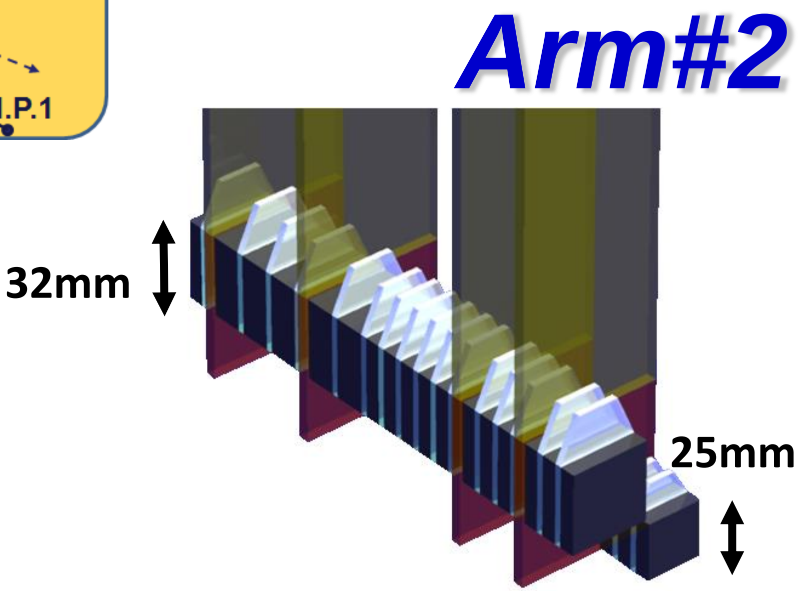



## Performance

**Energy resolution** (> 100GeV)
< 5% for $\gamma$ and ~ 30% for **n**

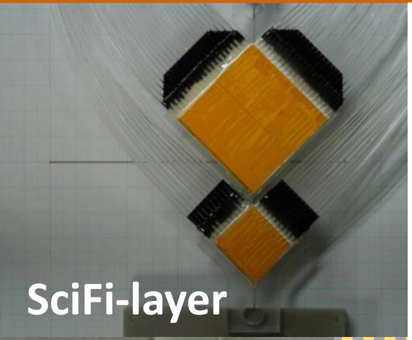
**Position resolution**
< 200μm (Arm#1) and ~ 40μm (Arm#2)

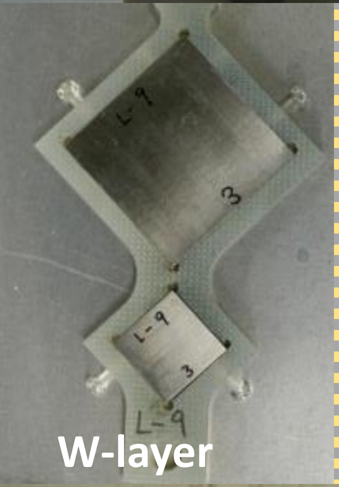



## Front Counters

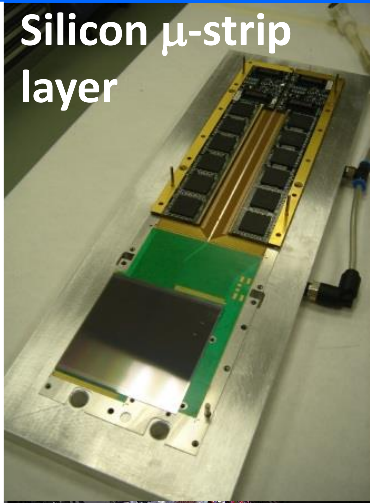
- thin scintillators 80x80 mm$^2$
- **monitoring of beam condition**
- **background rejection**
- **Van der Meer scan**

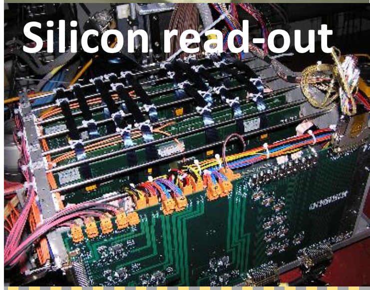

SciFi-layer


W-layer


Arm#1 Detector


Arm#2 Detector


Silicon μ-strip layer

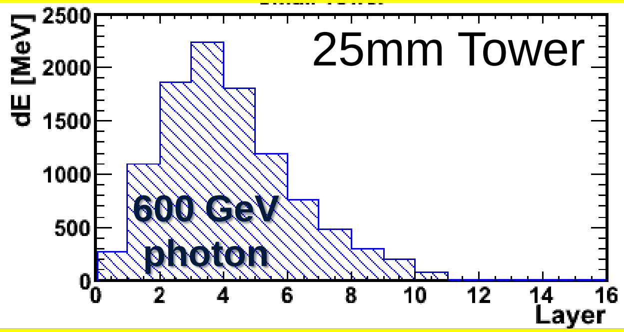

Silicon read-out

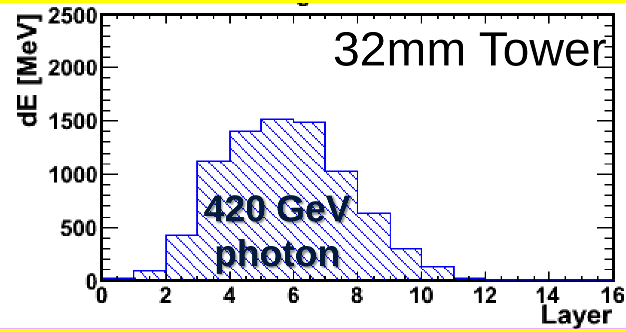

Arm#1 in the TAN


Arm#2 in the TAN

# Detection of a $\pi^0$ in Arm#2

**Longitudinal development measured by scintillator layers**

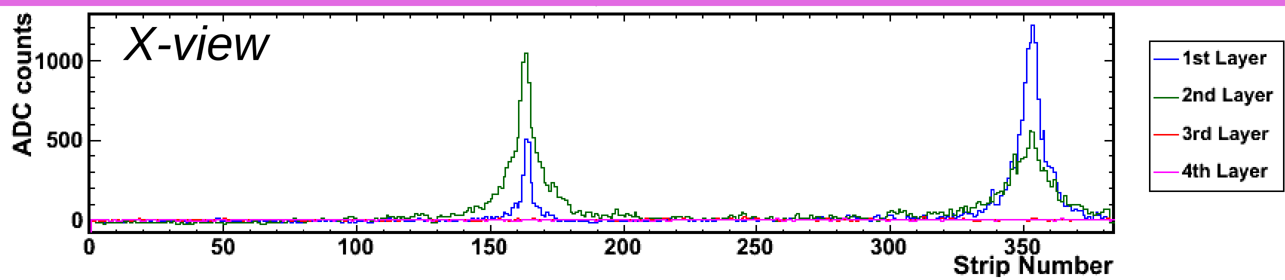


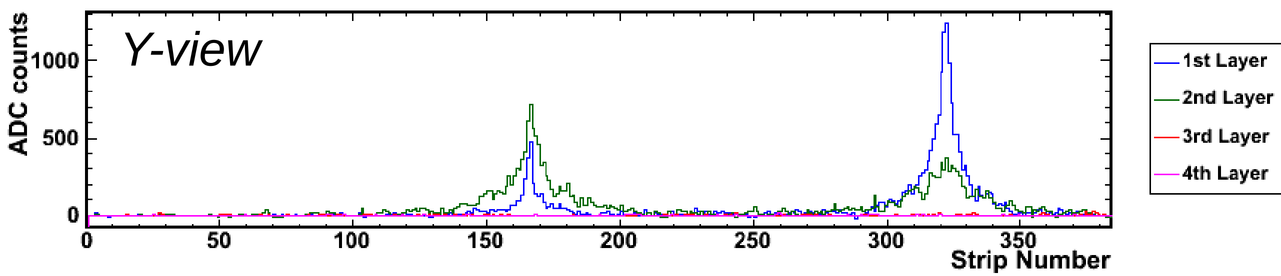




Determination of **energy** from total energy release

**PID** from shape

**Transverse profile measured by silicon μ–strip layers**




Determination of the **impact point**

Measurement of the **opening angle** of gamma pairs

Identification of **multiple hit**

Reconstruction of $\pi^0$ mass $M_{\pi 0} \cong \sqrt{E_{\gamma 1} E_{\gamma 2}} \cdot \theta$

# LHCf Status

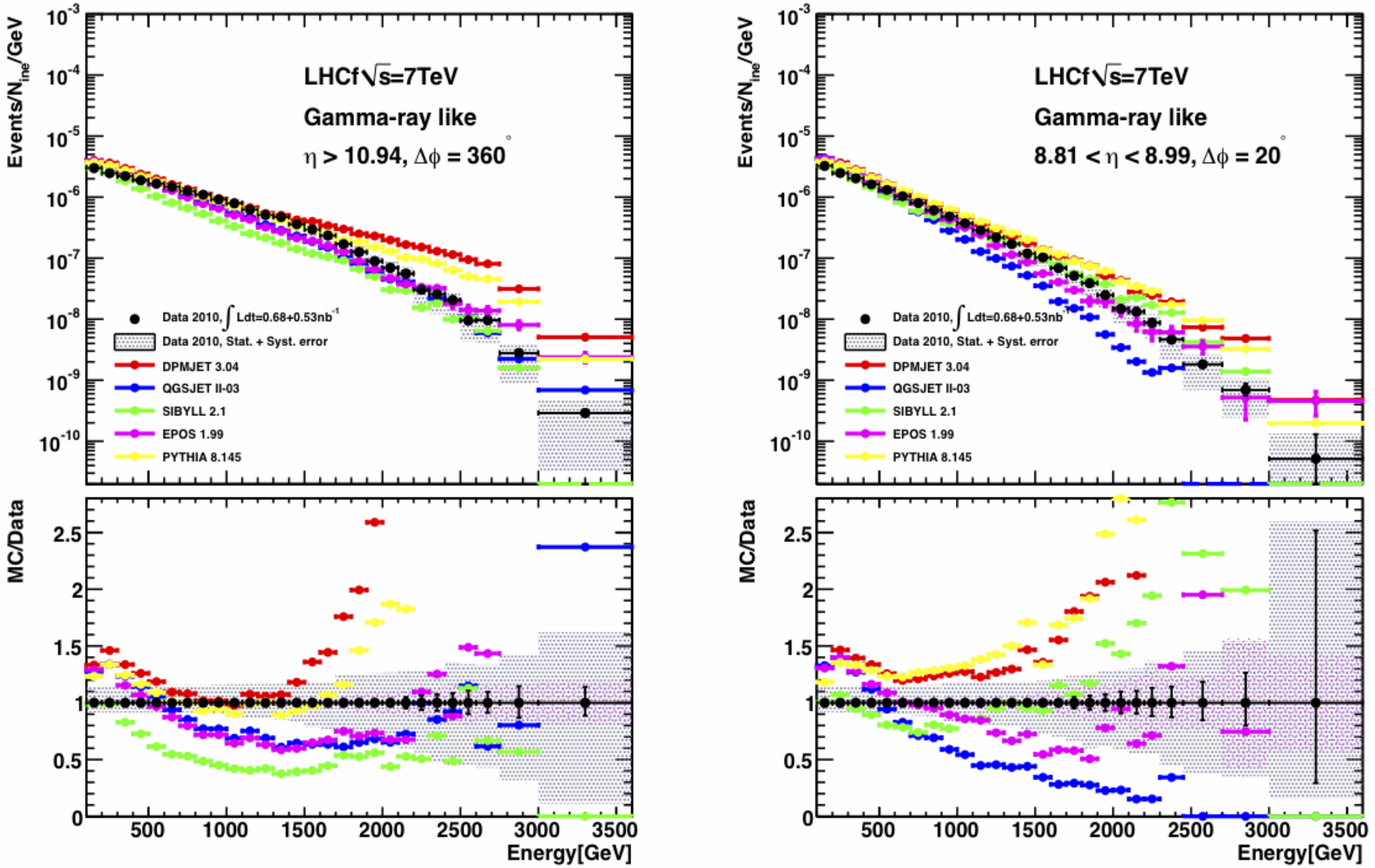
- Done
  - 0.9, 2.76, 7 TeV pp collision, 5 TeV pPb collision data taking
  - Photon spectra at 0.9 and 7TeV published
  - Pi0 spectra at 7 TeV published
  - Performance at 7TeV published

- **PLB 715 (2012) 298**
- **PLB 703 (2011) 128**
- **PRD 86 (2012) 092001**
- **IJMPA 28 (2013) 1330036**

- On going
  - Neutron spectra at 7TeV
  - Pi0 and UPC spectra at 5TeV pPb
  - Detector upgrade for 13 TeV pp

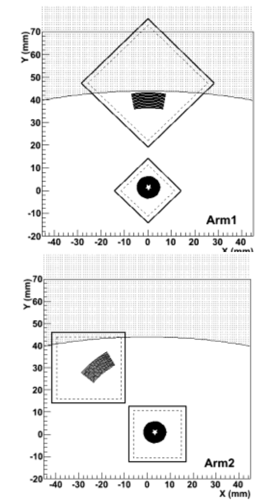
- Plan
  - 13TeV pp collision in 2015 (operation plan in discussion)
  - 0.5TeV pp at RHIC (LOI submitted)
  - Discussion for light ion collision at RHIC and LHC

# Comparison of **single γ** data at **√s = 7 TeV** with hadronic interaction models (pre-LHC versions)




**DATA**
**DPMJET 3.04**
**QGSJET II-03**
**SIBYLL 2.1**
**EPOS 1.99**
**PYTHIA 8.145**

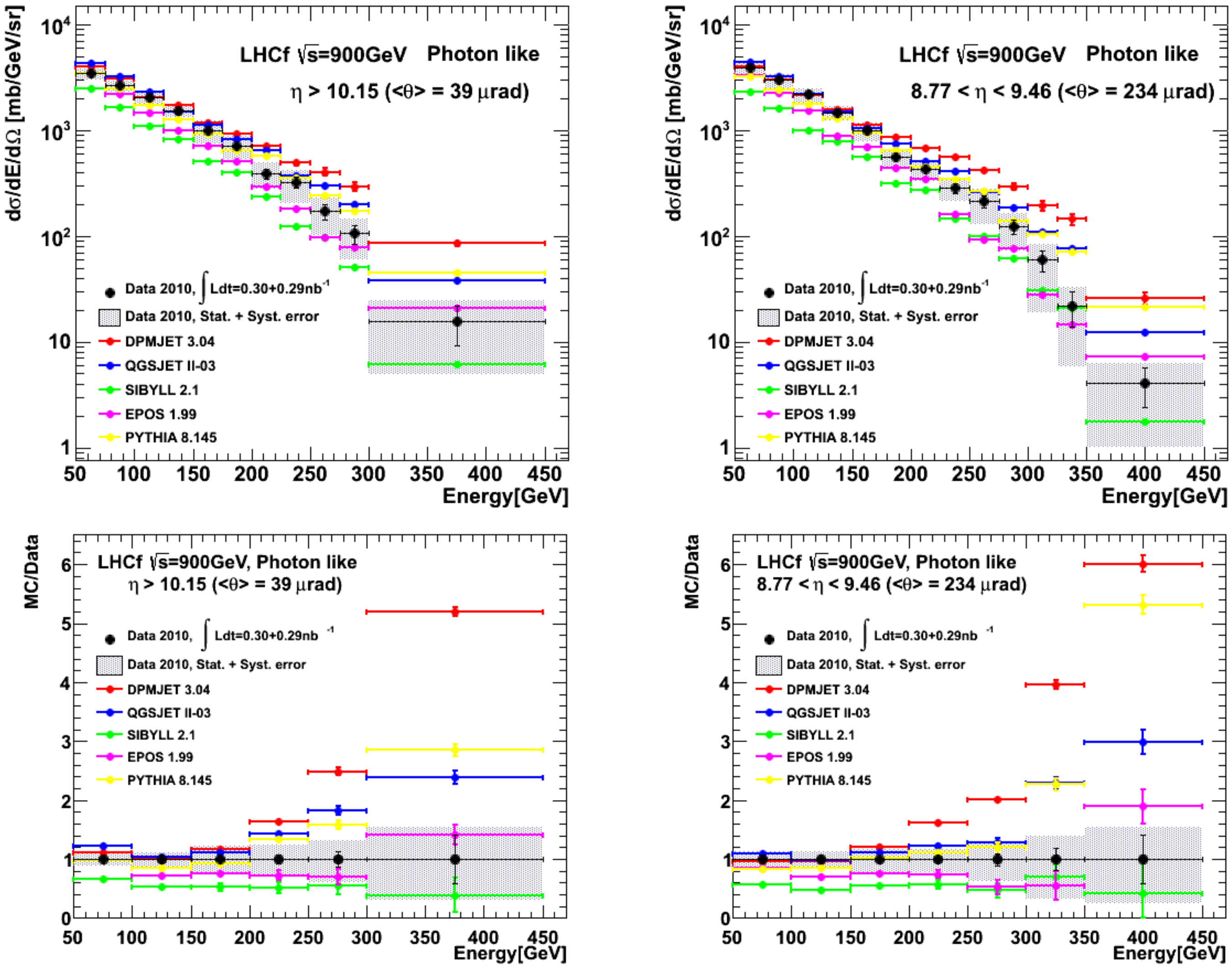
Syst.+Stat.




- No model can reproduce the **LHCf data** perfectly
- **DPMJET**, **PYTHIA** are in good agreement at high-η for 0.5<$E_\gamma$<1.5TeV, but harder for E>1.5TeV
- **QGSJET**, **SIBYLL**, **EPOS** show reasonable agreement of shape for high η, but not for low η

**O. Adriani et al., PLB, Vol.703-2, p.128-134 (09/2011)**

# Comparison of **single γ** data at **√s = 900 GeV** with hadronic interaction models (pre-LHC versions)



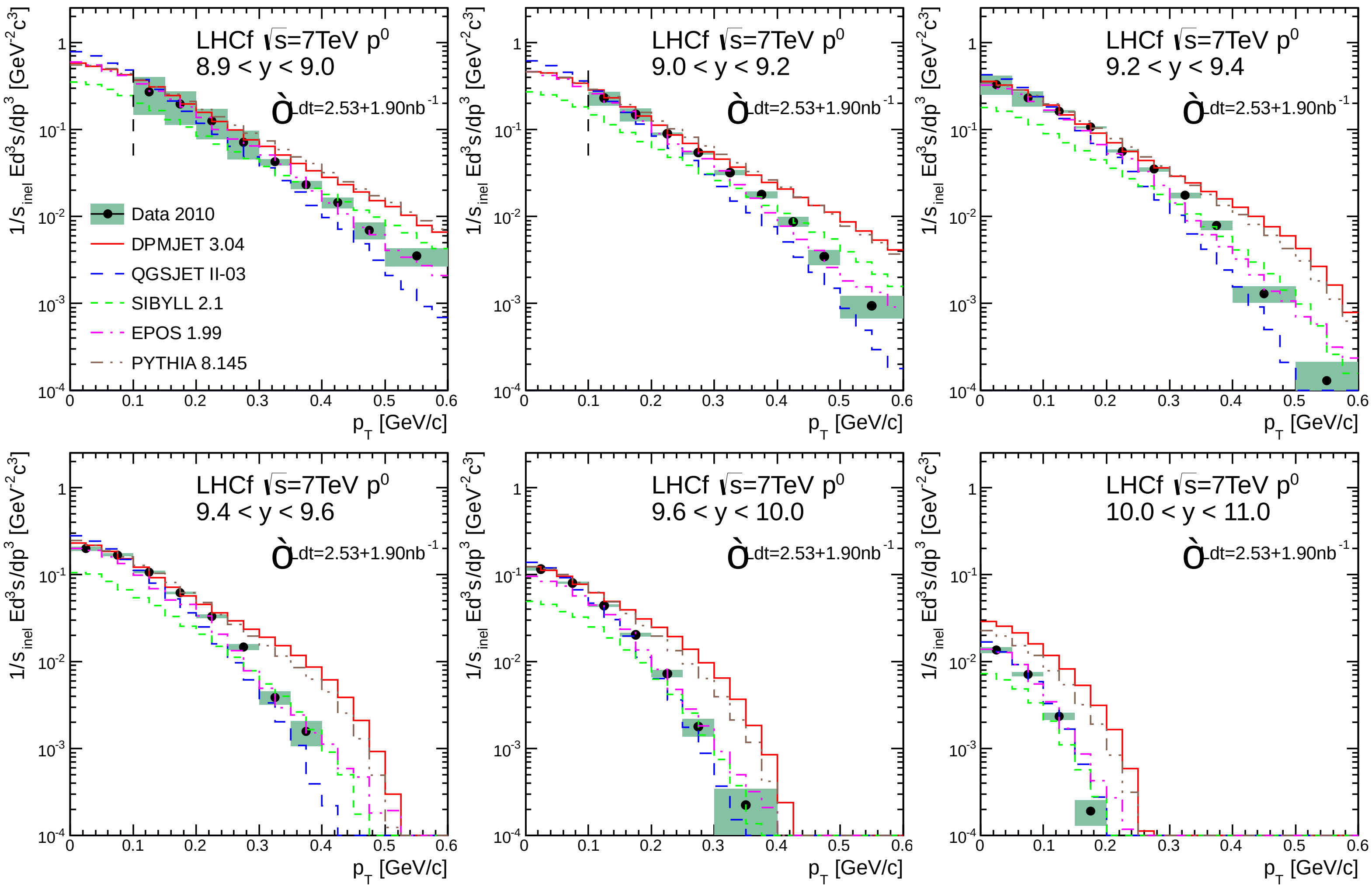

**DATA**
**DPMJET 3.04**
**QGSJET II-03**
**SIBYLL 2.1**
**EPOS 1.99**
**PYTHIA 8.145**

Syst.+Stat.

- No strong evidence of η-dependence
- **SYBILL** and **EPOS** show reasonable agreement of shape
- None of the models reproduces **LHCf data** within the error bars

**O. Adriani et al., PLB, 715, p. 298-303 (2012)**

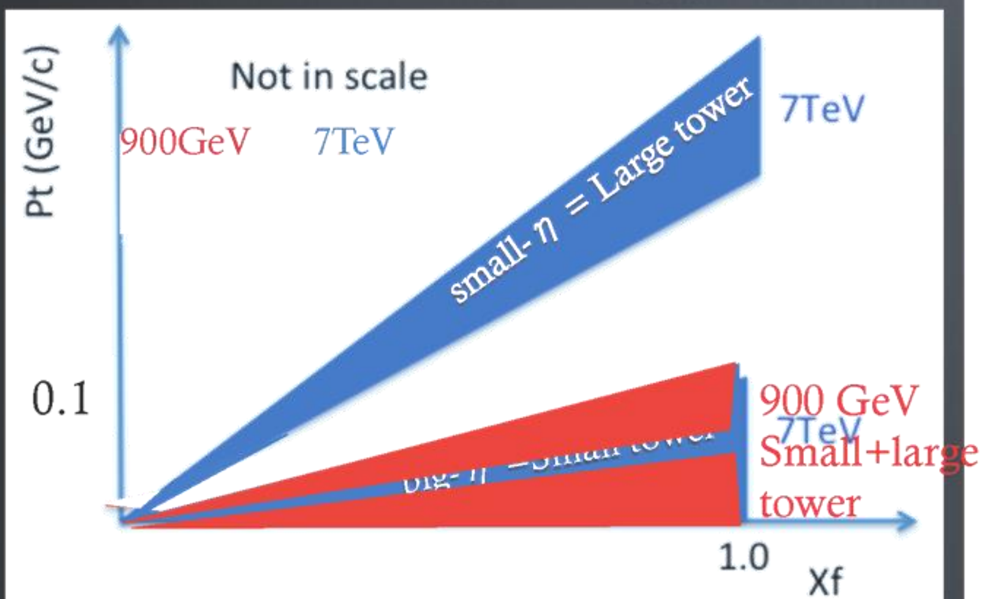
# Comparison of $\pi^0$ data at $\sqrt{s}$ = **7TeV** with hadronic interaction models (pre-LHC versions)

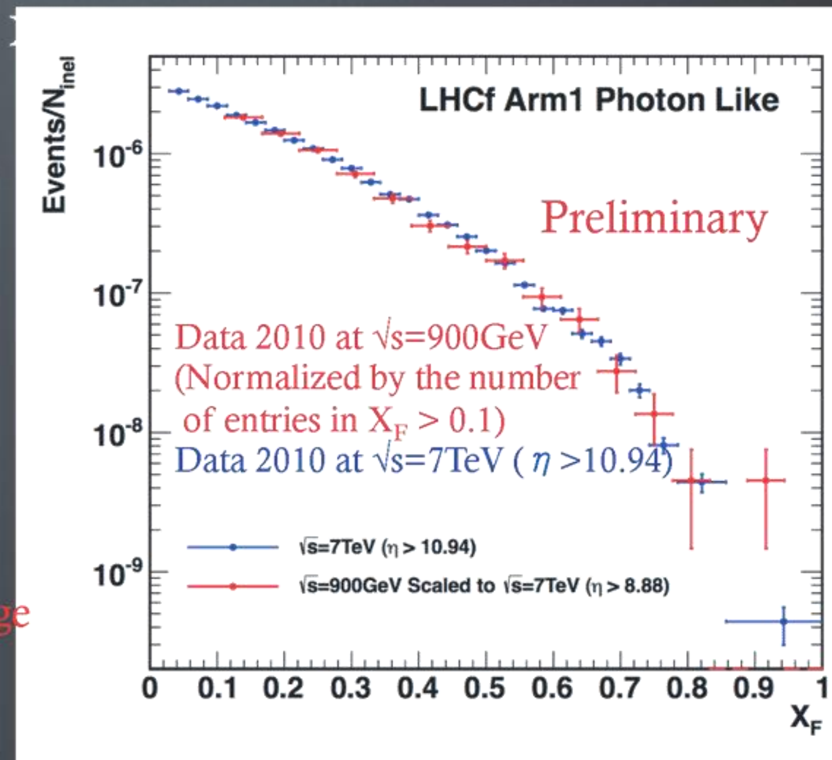



- **EPOS** shows the best agreement with data
- **DPMJET** and **PYTHIA** have harder spectra than data
- **QGSJET** has softer spectrum than data

# 900GeV vs. 7TeV

*LHCf coverage in $X_F$-$p_T$ plane*
*($X_F = E/E_{beam}$)*

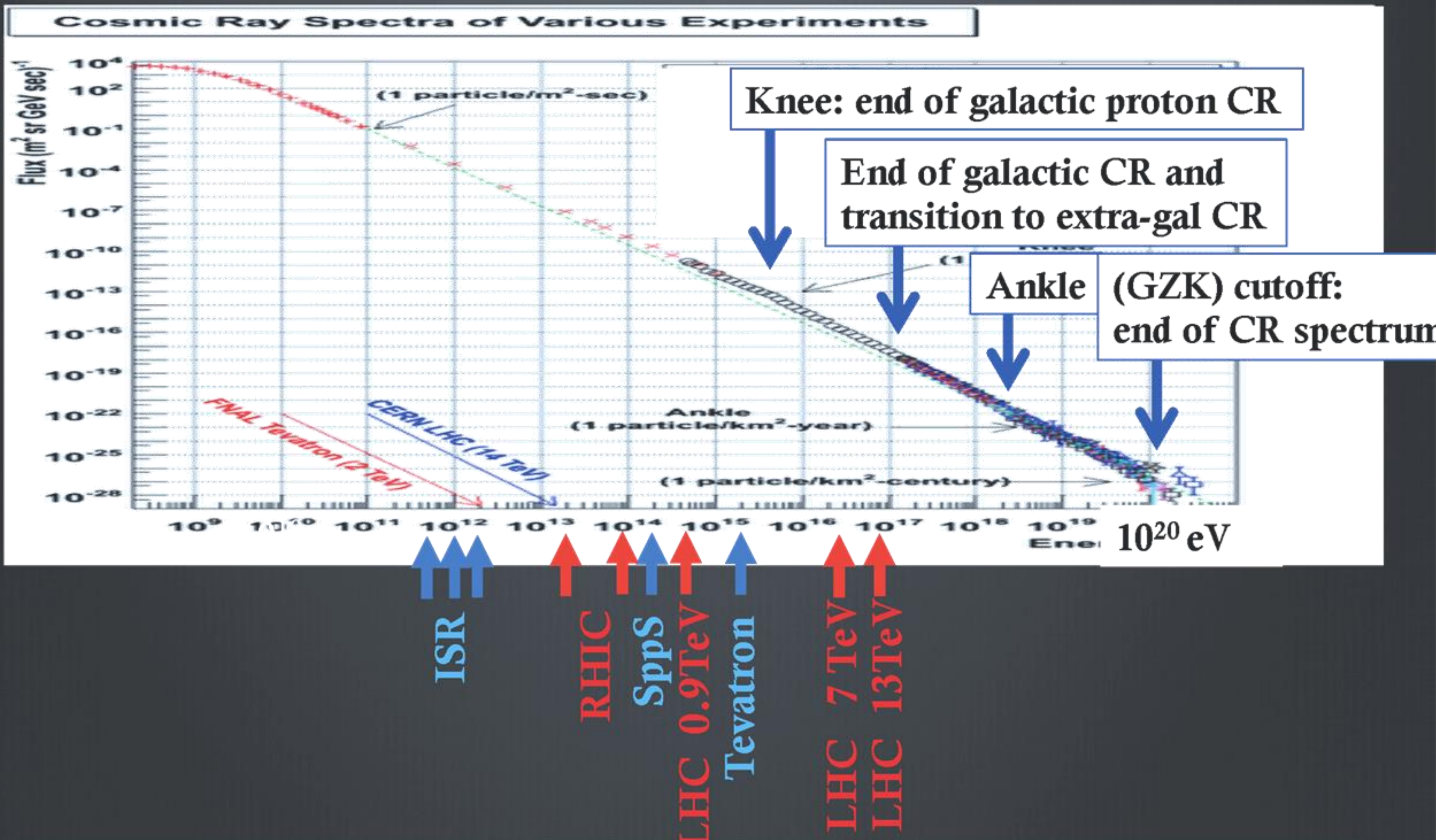



- ✓ normalized by the number of entries in $X_F > 0.1$
- ✓ statistical errors only

**Good agreement of $X_F$ spectrum shape between 900 GeV and 7 TeV**

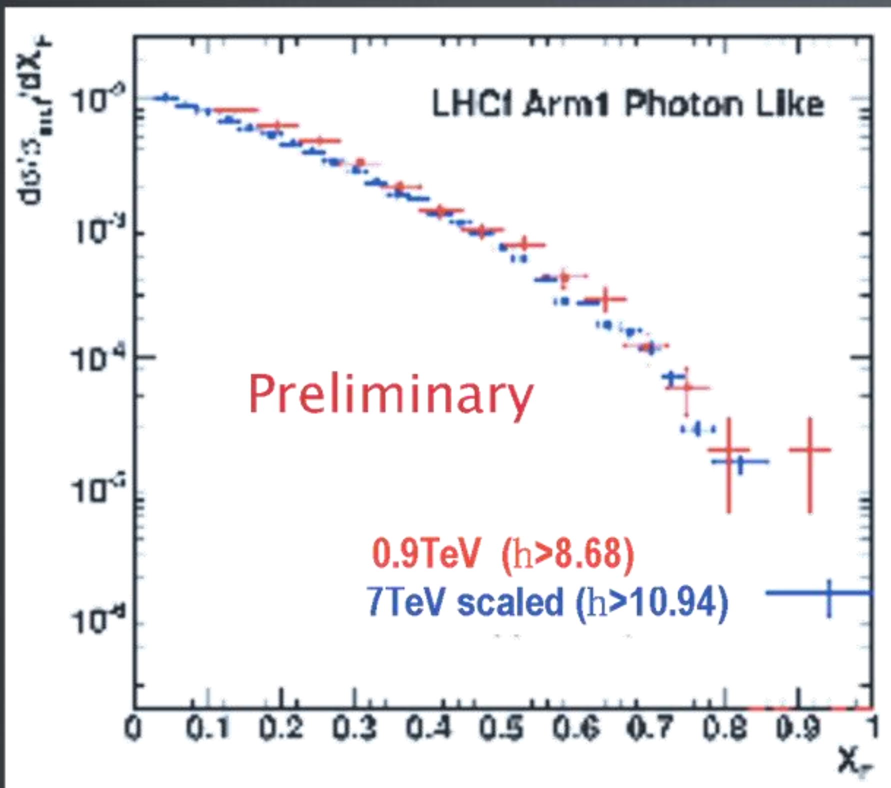
# Cosmic-ray spectrum & Colliders



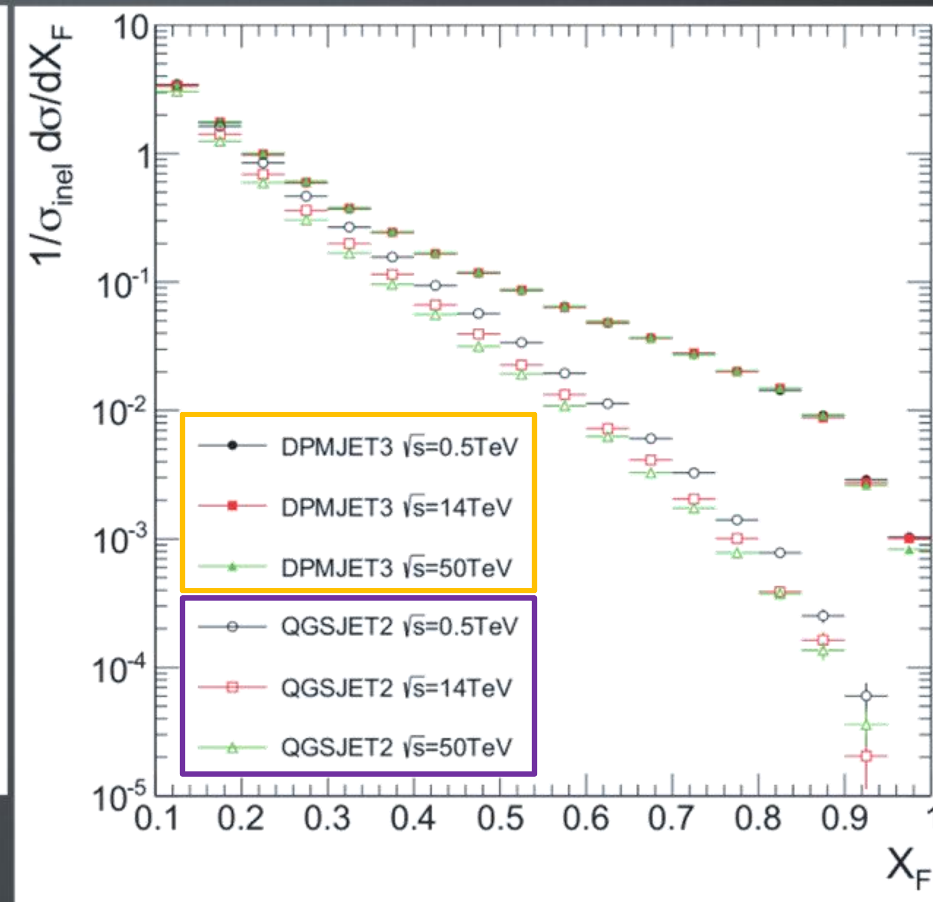

**Perfect (or best at least) understanding up to $10^{17}$eV helps CR physics**

# $x_F$ scaling : a key for extrapolation

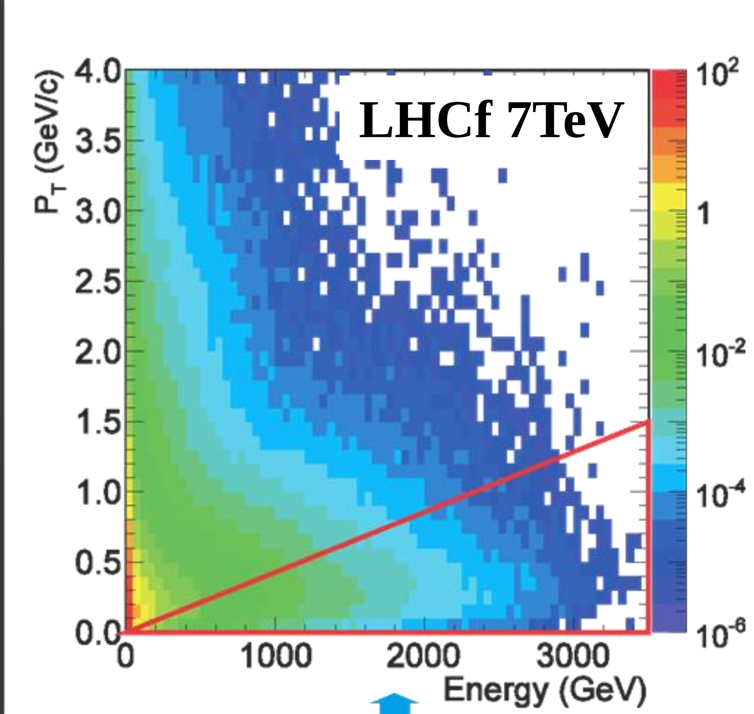
**LHC single gamma data (900GeV pp / 7TeV pp)**



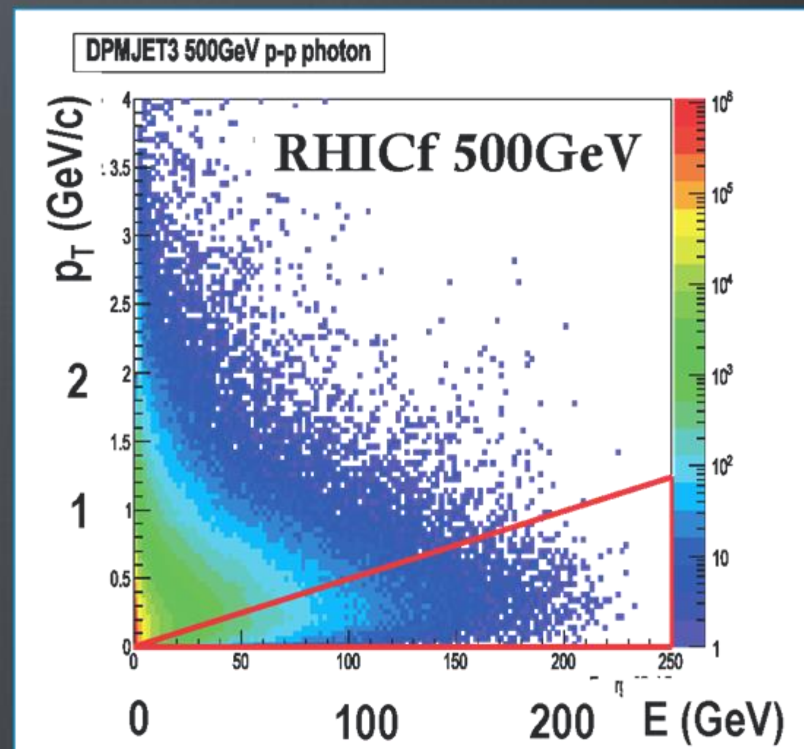

**Expected from models (5TeV, 14TeV and 50TeV)**

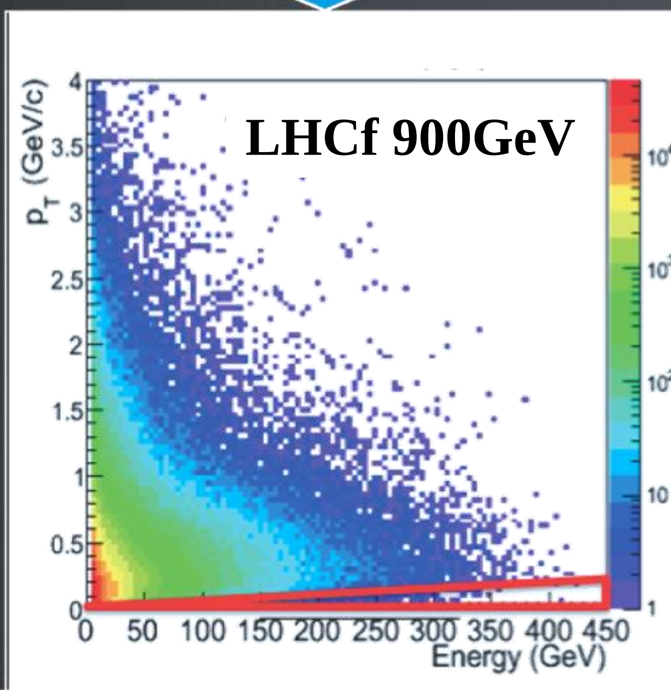



But this comparison done in very limited phase space..




# RHICf 500GeV Similar phase space to LHCf 7TeV



# *LHCf: future plan*

***<u>p-p √s = 13TeV at LHC</u>*** *<u>(2015)</u>*

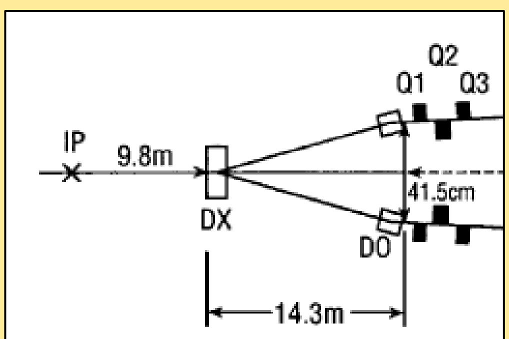
Main target: measurement at the LHC design energy.
Study of energy scaling by comparison with √s = 900 GeV and 7 TeV data.
Upgrade of the detectors for radiation hardness.

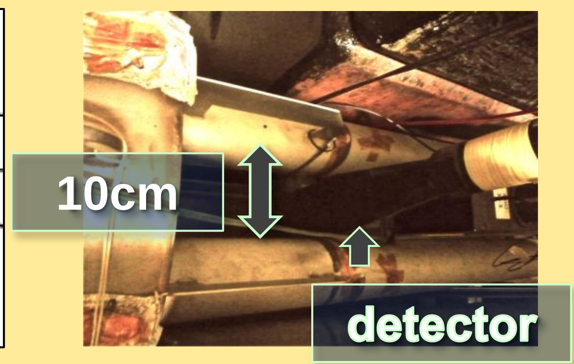
***<u>p-light ions</u>*** *<u>(O, N)</u>* **<u>at the LHC</u>** *<u>(2019?)</u>*

It allows studying HECR collisions with atmospheric nuclei.

***<u>RHICf experiment at RHIC</u>*** *(Relativistic Heavy Ion Collider @ Brookhaven)*

Lower collision energy, ion collisions.
LOI to the RHIC committee submitted.




<u>p-p collisions</u>:
- Max. √s = 500 GeV
- Polarized beams

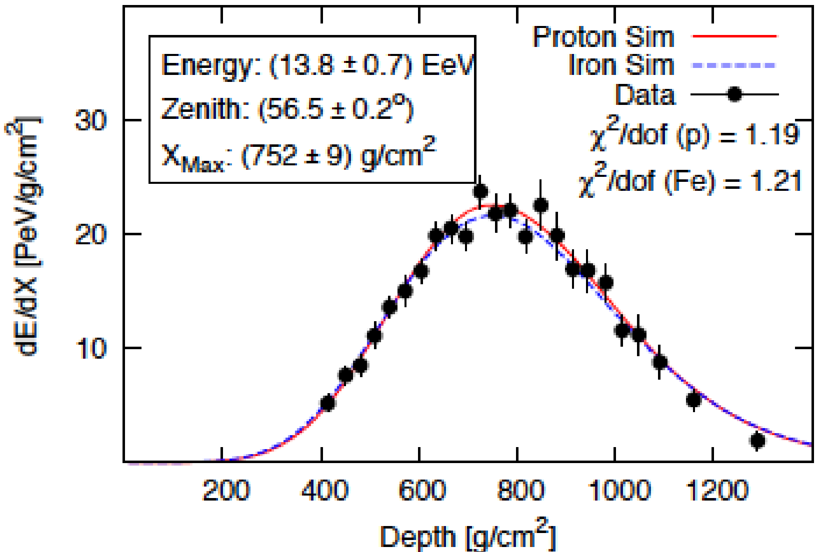
<u>Ion collisions</u>:
- Au-Au, d-Au
- Max. √s = 200 GeV
- Possible, d-O,N (p-O,N)
  ➔ Cosmic ray – Air @ knee energy

# Conclusions

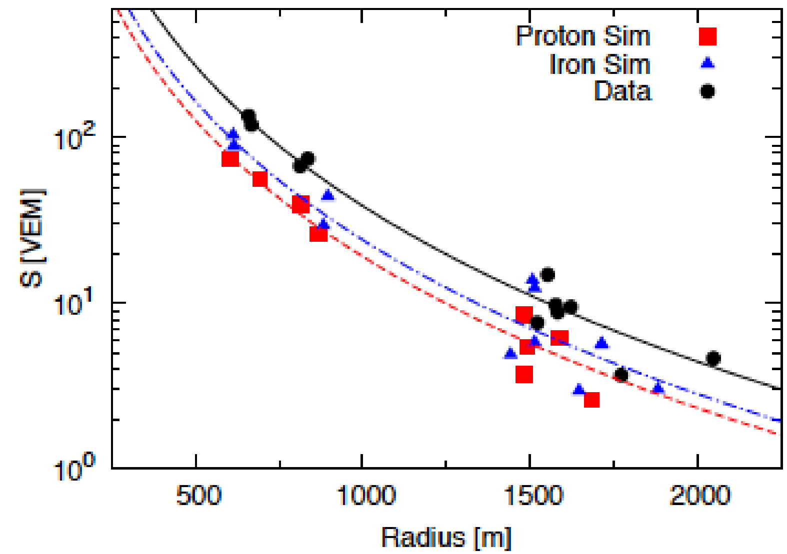
- LHCf is a small experiment at LHC dedicated to **forward physics**
  - Important for High Energy Cosmic-Ray Physics
- We have published **spectra of photons and neutral pions** for p-p interactions at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 900 GeV
  - None of the hadron interaction models that we have considered can reproduce the data within the errors, but data lie anyway between the models
  - On-going data analysis for the hadron component (neutrons)
- p-Pb run at the beginning of 2013
  - Successful data taking in p-remnant and Pb-remnant side
  - Common operations with ATLAS
  - On-going data analysis
- Future plan
  - Complete the **upgrade of the detectors** for radiation hardness
  - Data taking for **p-p collisions at $\sqrt{s}$ = 13 TeV** (2015)
  - Run **p-light ions** at LHC (2019?)
  - Operations at **RHIC** (p-O or p-N at lower energies)

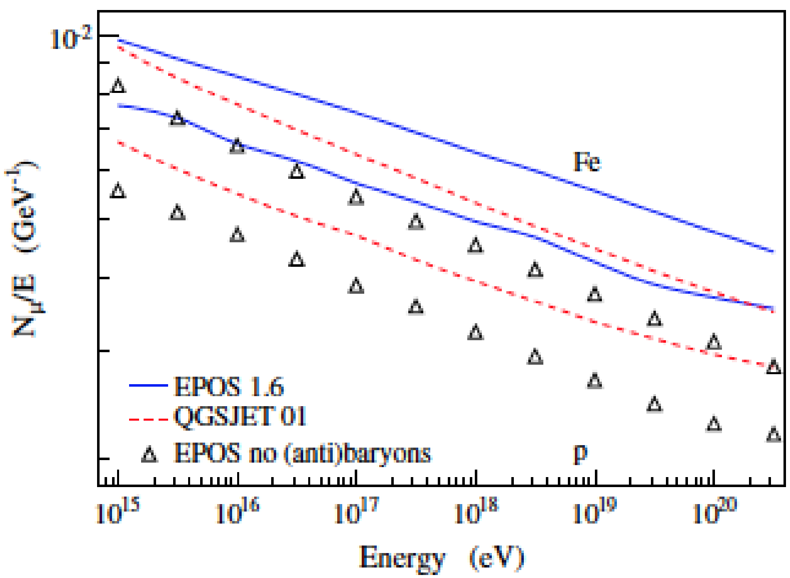
# BACKUP SLIDES

# Muon excess at Pierre Auger Obs.




Pierre Auger Collaboration, ICRC 2011 (arXiv:1107.4804)




**Auger hybrid analysis**

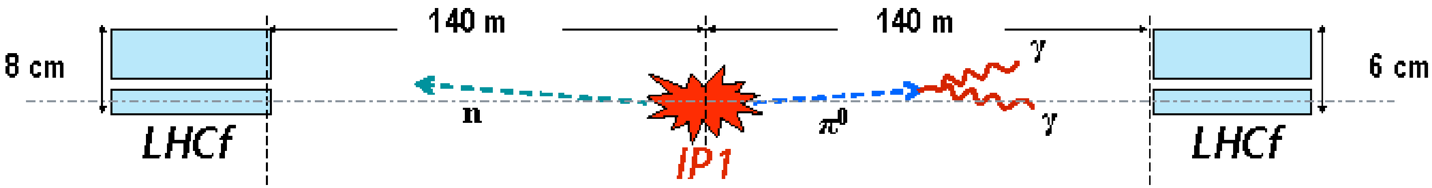
- event-by-event MC selection to fit FD data (top-left)
- comparison with SD data vs MC (top-right)
- muon excess in data even for Fe primary MC

EPOS predicts more muon due to larger baryon production

=> importance of baryon measurement

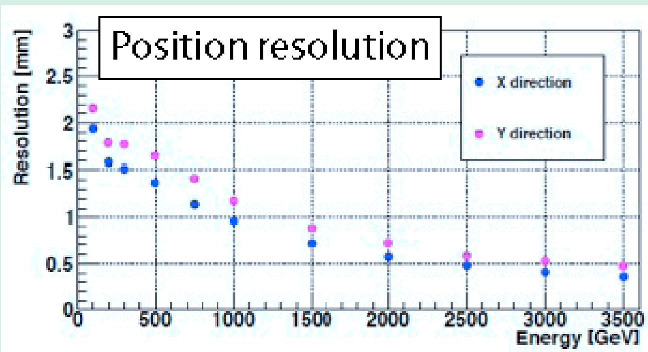
Pierog and Werner, PRL 101 (2008) 171101

# Detector performances

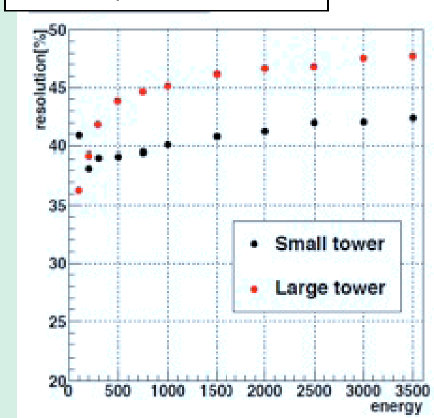



## Hadronic shower (MC)

Position resolution

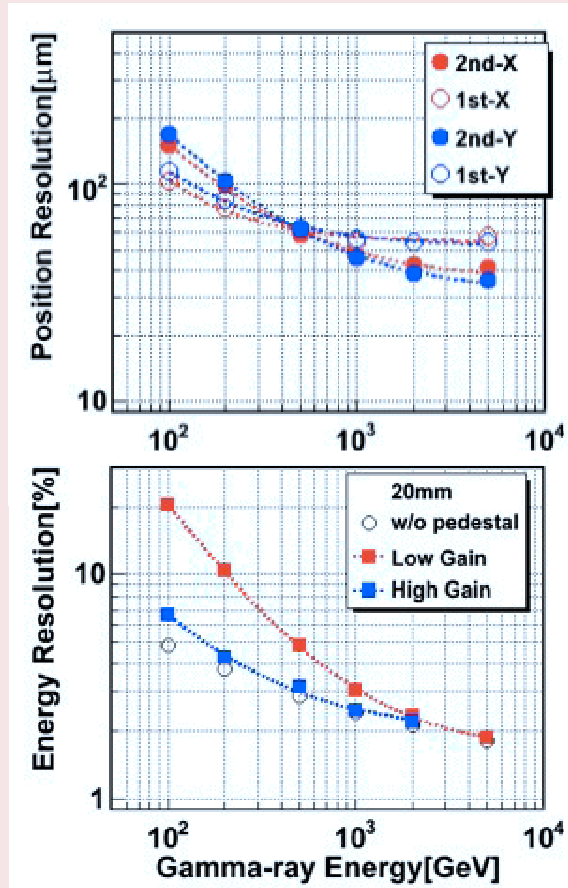



Energy resolution




$\sigma_E/E > 40\%$ because of $1.6\lambda$

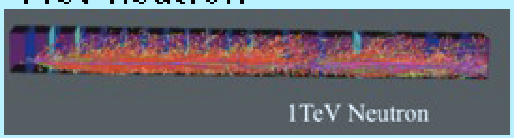
## EM shower (MC)




## PID technique

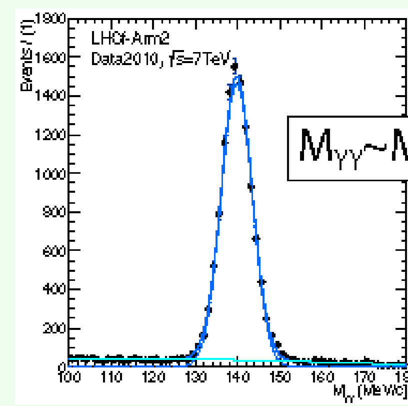
400GeV photon


1TeV neutron




Identification of incoming particle by shower shape

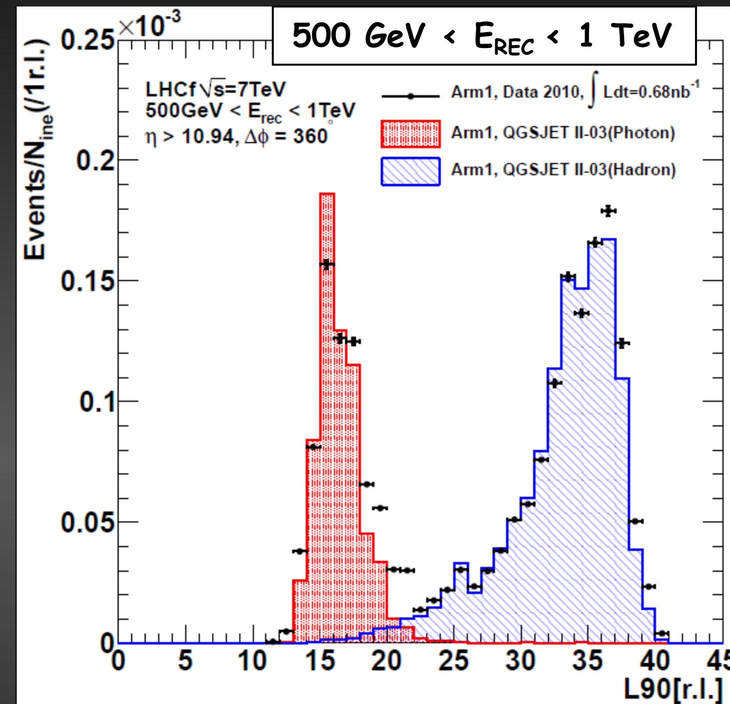
## $\pi^0$ reconstruction

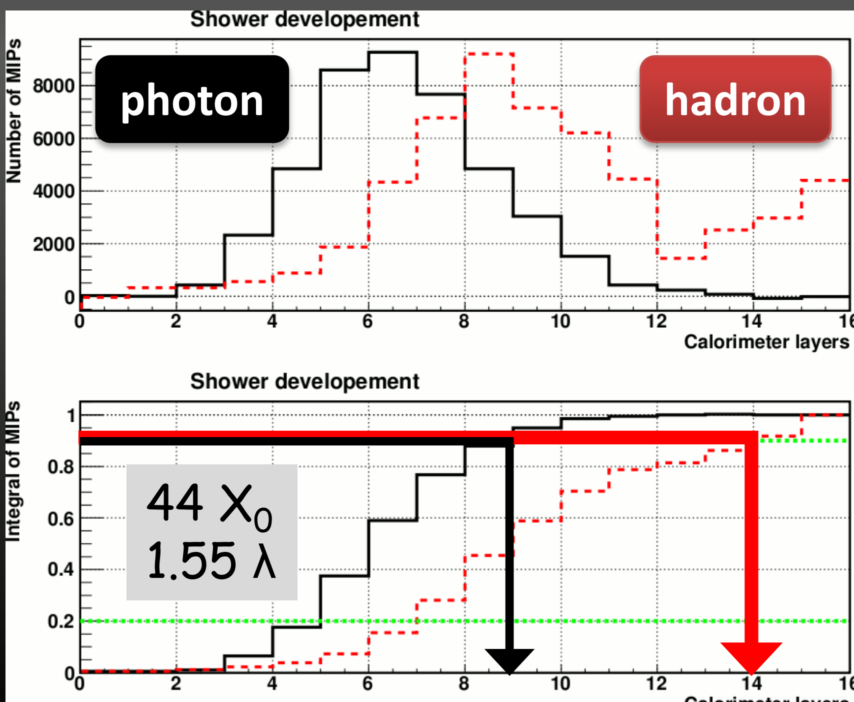



$M_{\gamma\gamma} \sim M_{\pi 0}$

# Particle identification

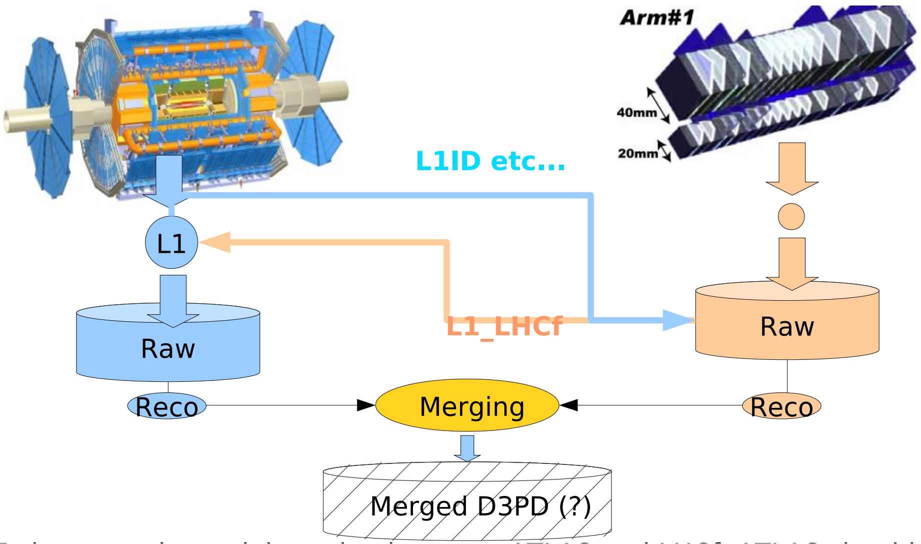
- $L_{90\%}$: longitudinal position containing 90% of the shower energy
- Photon selection based on $L_{90\%}$ cut
- Energy dependent threshold in order to keep constant efficiency $\varepsilon_{PID}$ = 90%
- Purity $P = N_{phot}/(N_{phot}+N_{had})$ estimated by comparison with MC
- Event number in each bin corrected by $P/\varepsilon_{PID}$

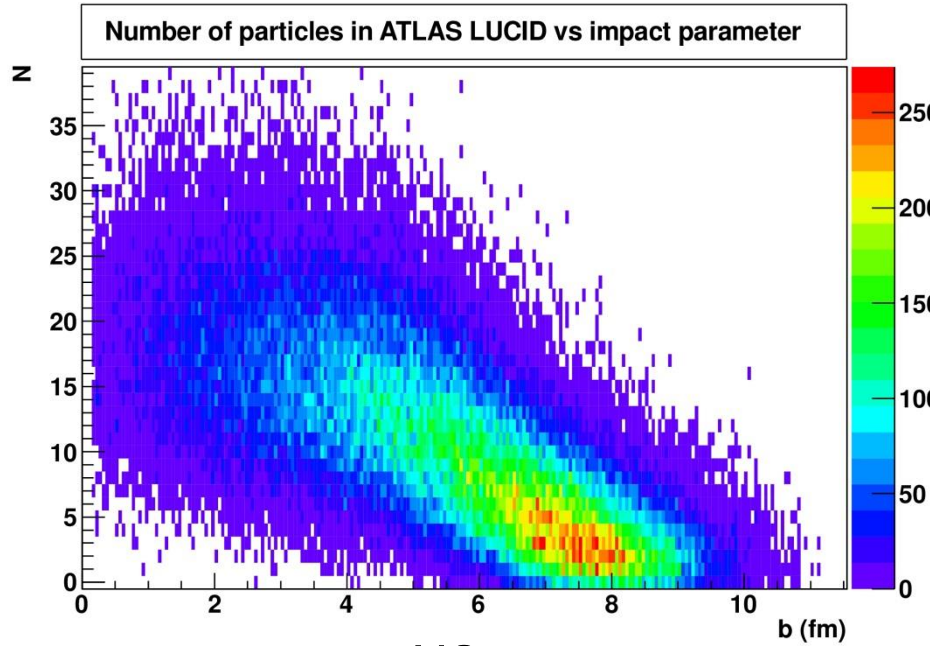



- MC photon and hadron events are independently normalized to data
- Comparison done in each energy bin
- LPM effect is switched on

# Common trigger with ATLAS




MC
impact parameter vs. # of particles in ATLAS LUCID

- LHCf signal has been used to trigger ATLAS
- Impact parameter may be determined by ATLAS
- Identification of forward-only events