Test of hadronic interaction models by a LHC forward experiment; LHCf

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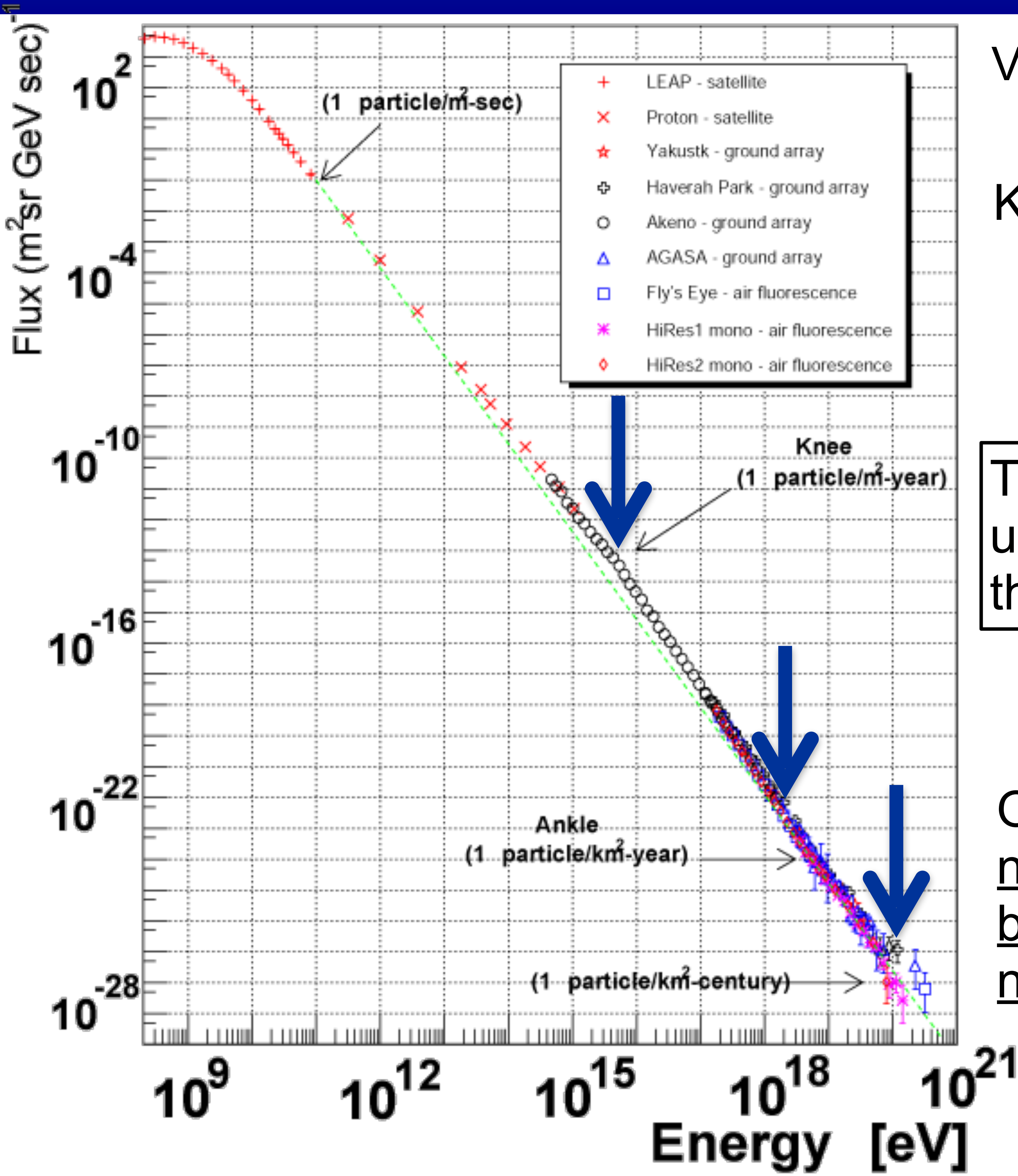
Hadronic Interactions

- Lots of hadronic interaction models were developed.

  For studies of universe
  For detector simulations
  For Cosmic-rays

  Wide energy range from 10^9 to 10^{20} eV
  All processes
  p-A, π-A as well as p-p

Energy Spectrum of Cosmic-rays



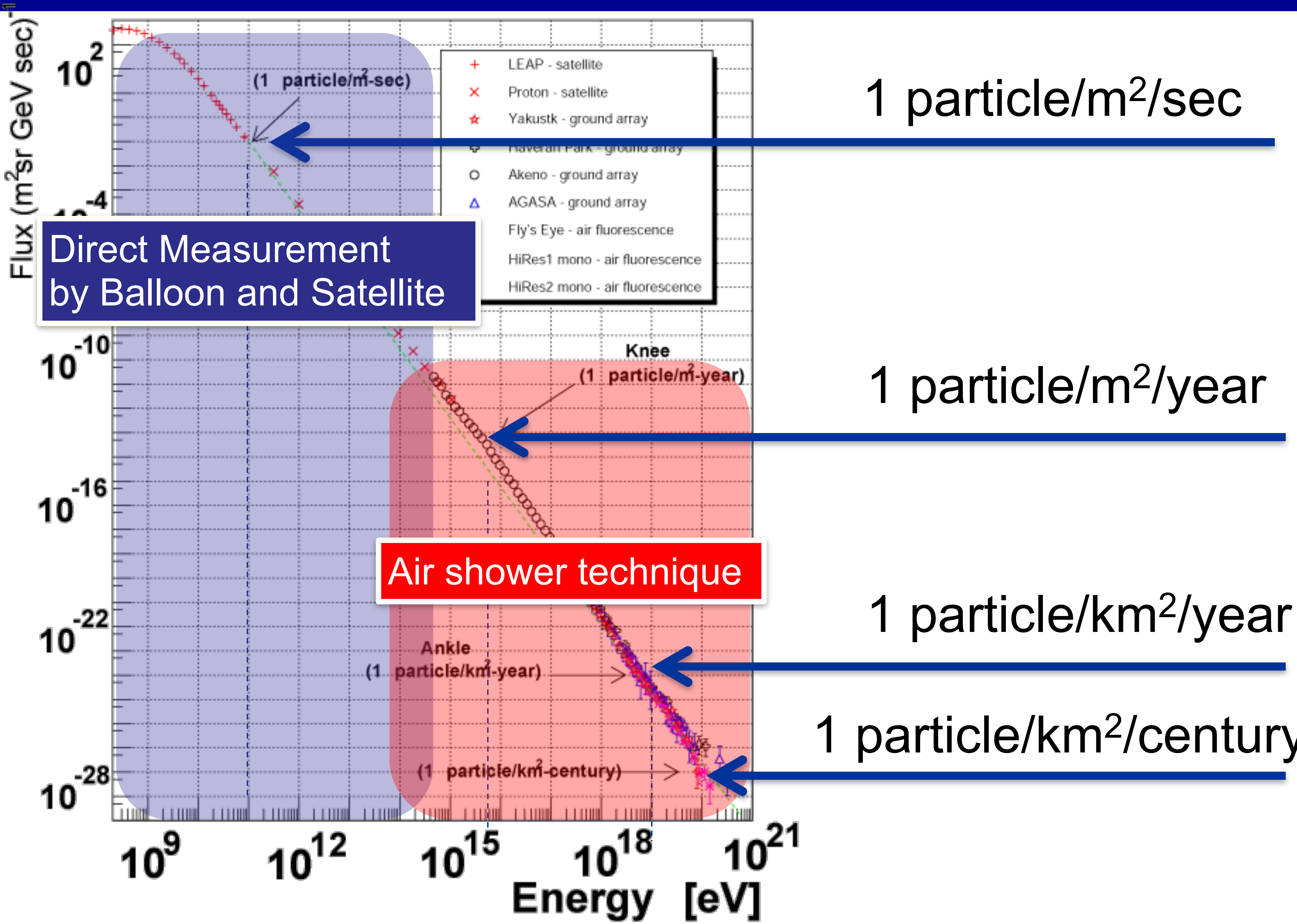
Very wide energy range
$10^9 \sim 10^{20}$ eV

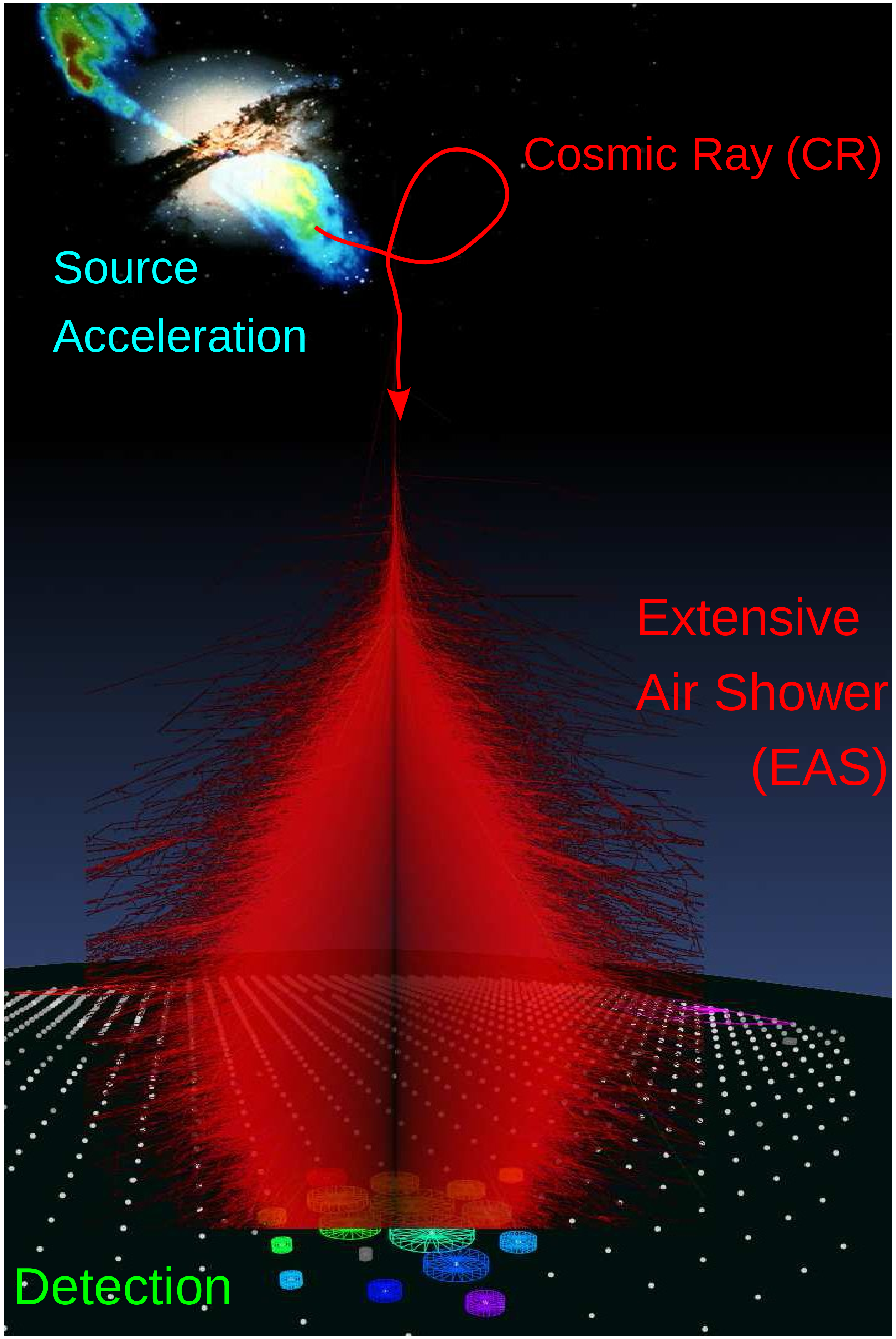
Kinks in the spectra
Knee ~10^{15}eV
Ankle ~10^{18}eV
Cut-off ~$10^{19.5}$eV

The goal of CR-studies is to understand the **sources** and the **acceleration mechanism**.

Observation of
not only "charged" cosmic-rays but also X-rays/gamma-rays and neutrinos

Observation of CRs





From R. Ulrich (KIT)

Air Shower Technique

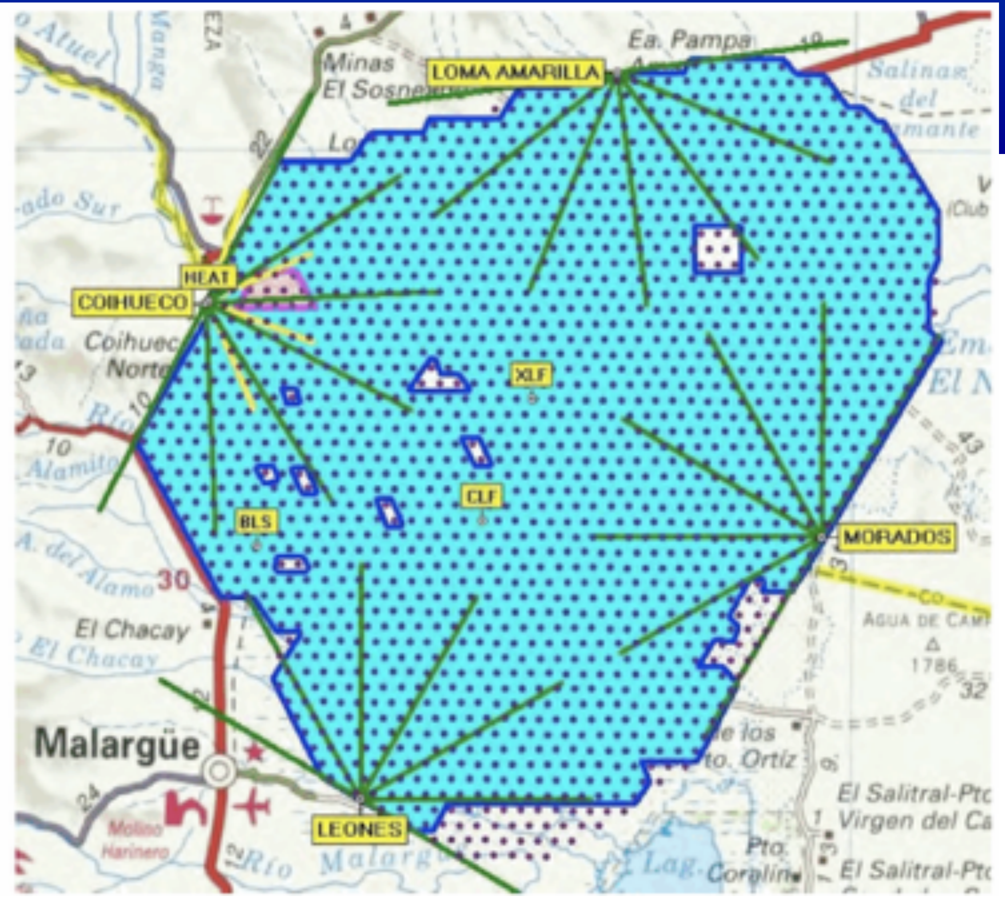
Air showers are observed by
- Particle detector array (SD)
- Florescence telescopes (FD)

Extensive air shower observation
- longitudinal distribution
- lateral distribution
- Arrival direction

Air shower development

Astrophysical parameters
- Spectrum
- Composition
- Source distribution

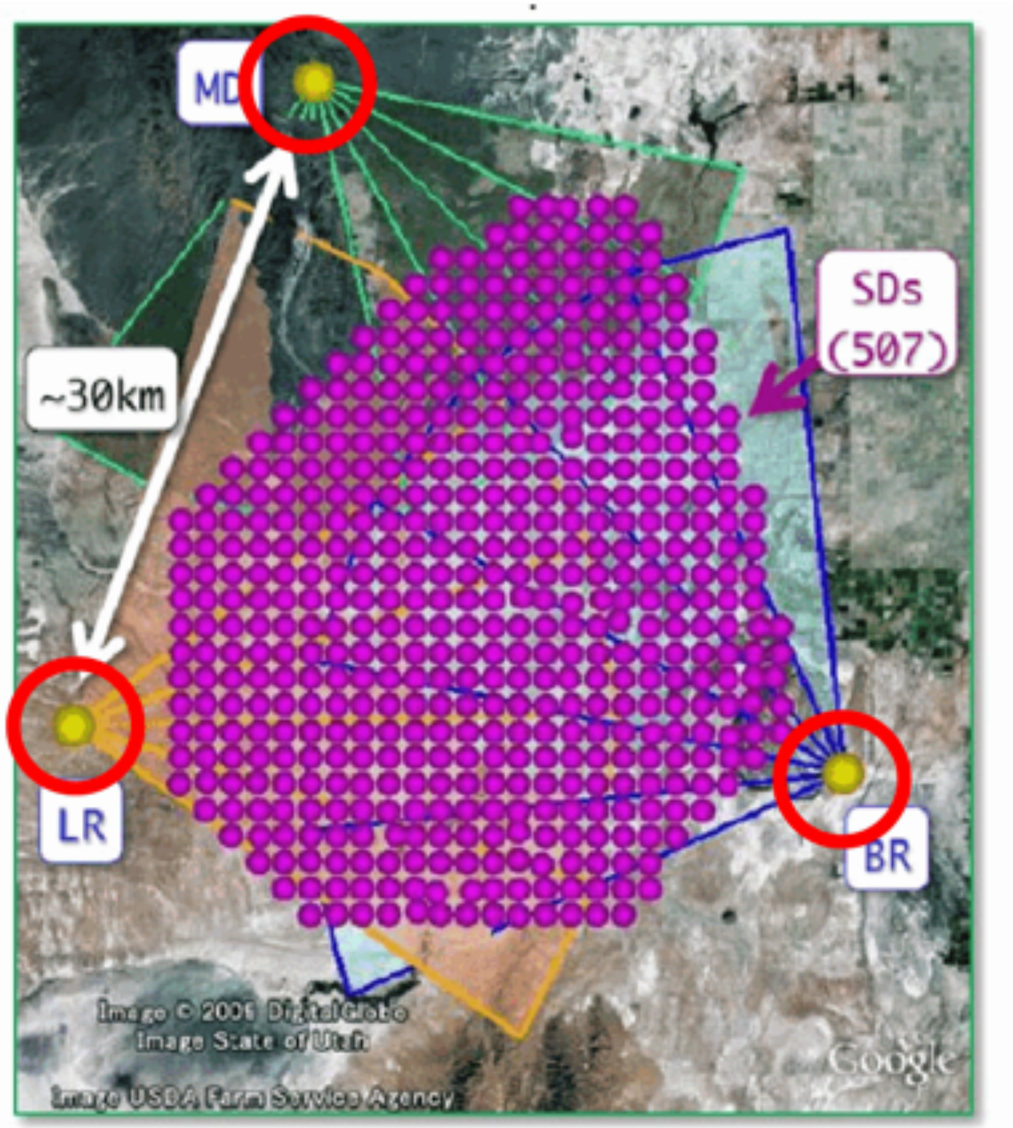
UHECR experiments



Pierre Auger Observatory

SD + FD

3,000km^2 in Argentina



Telescope Array

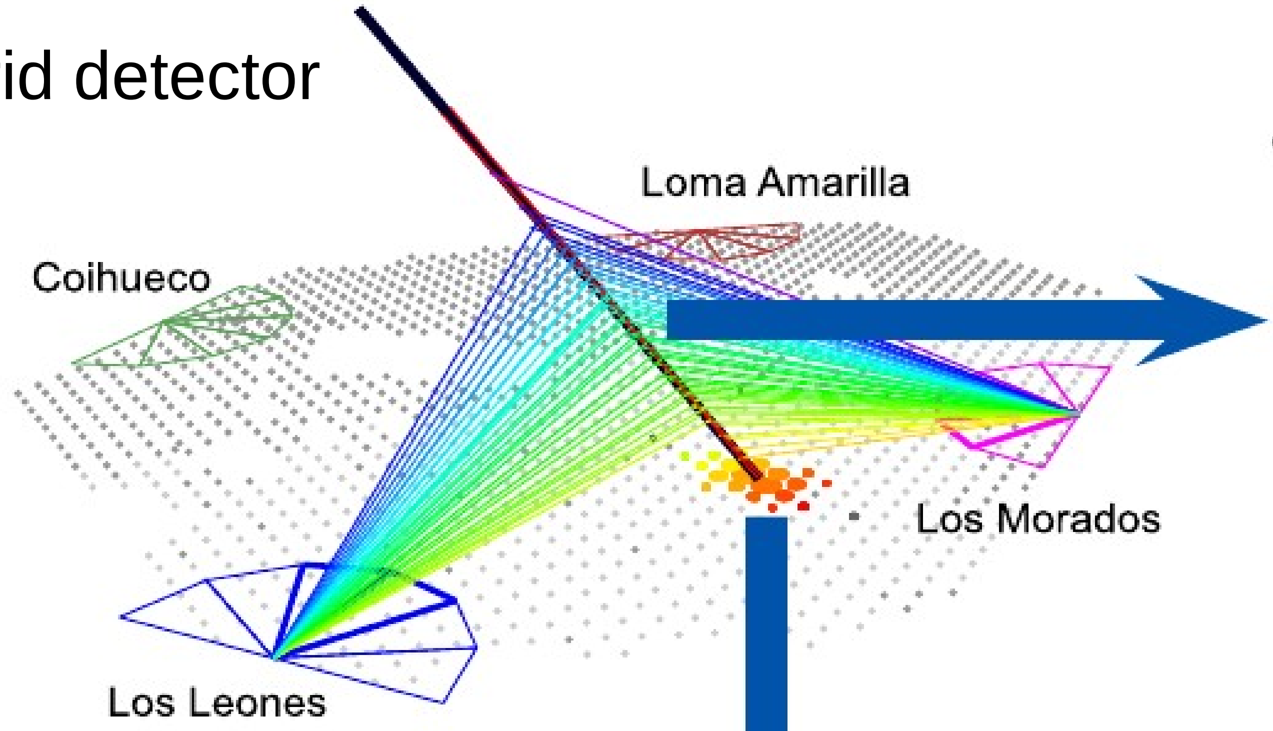
SD+FD

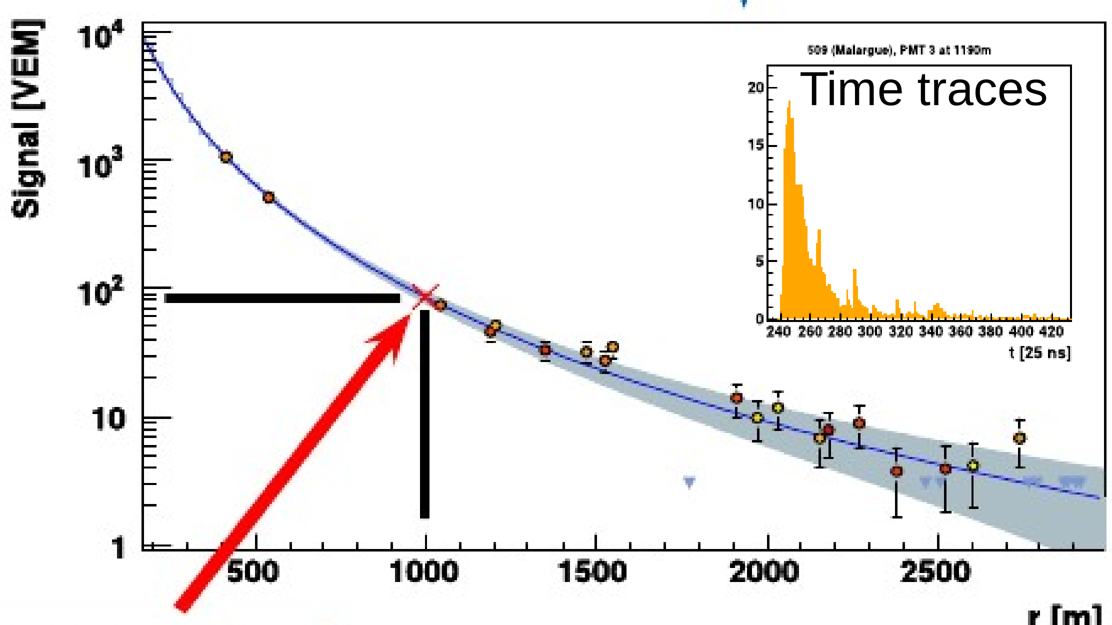
700km^2 in USA

AGASA, HiRes and JEM-EUSO

A PAO hybrid event

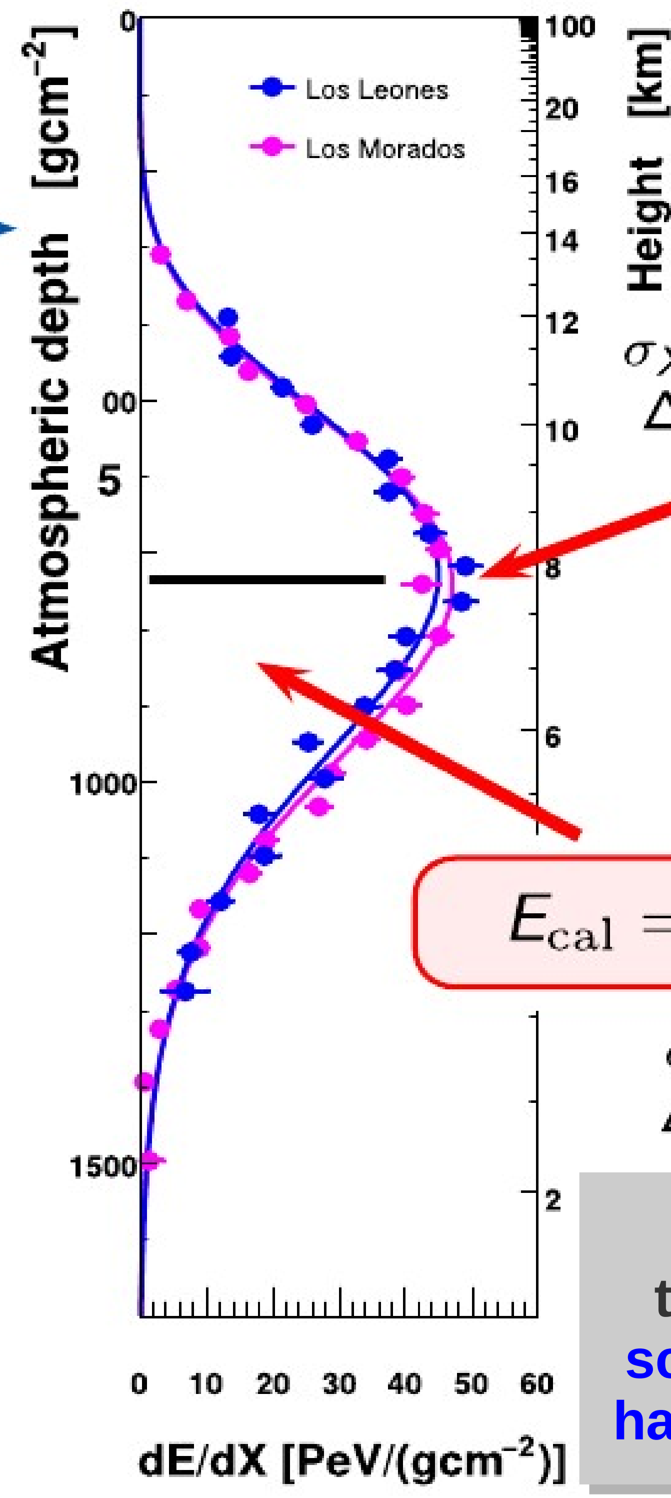
Hybrid detector





S_{1000}

$E_{\mathrm{surface}} = f(S_{1000}, \theta)$



$\sigma X_{\mathrm{max}} < 20\,\mathrm{g/cm}^2$
$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm}^2$

X_{max}

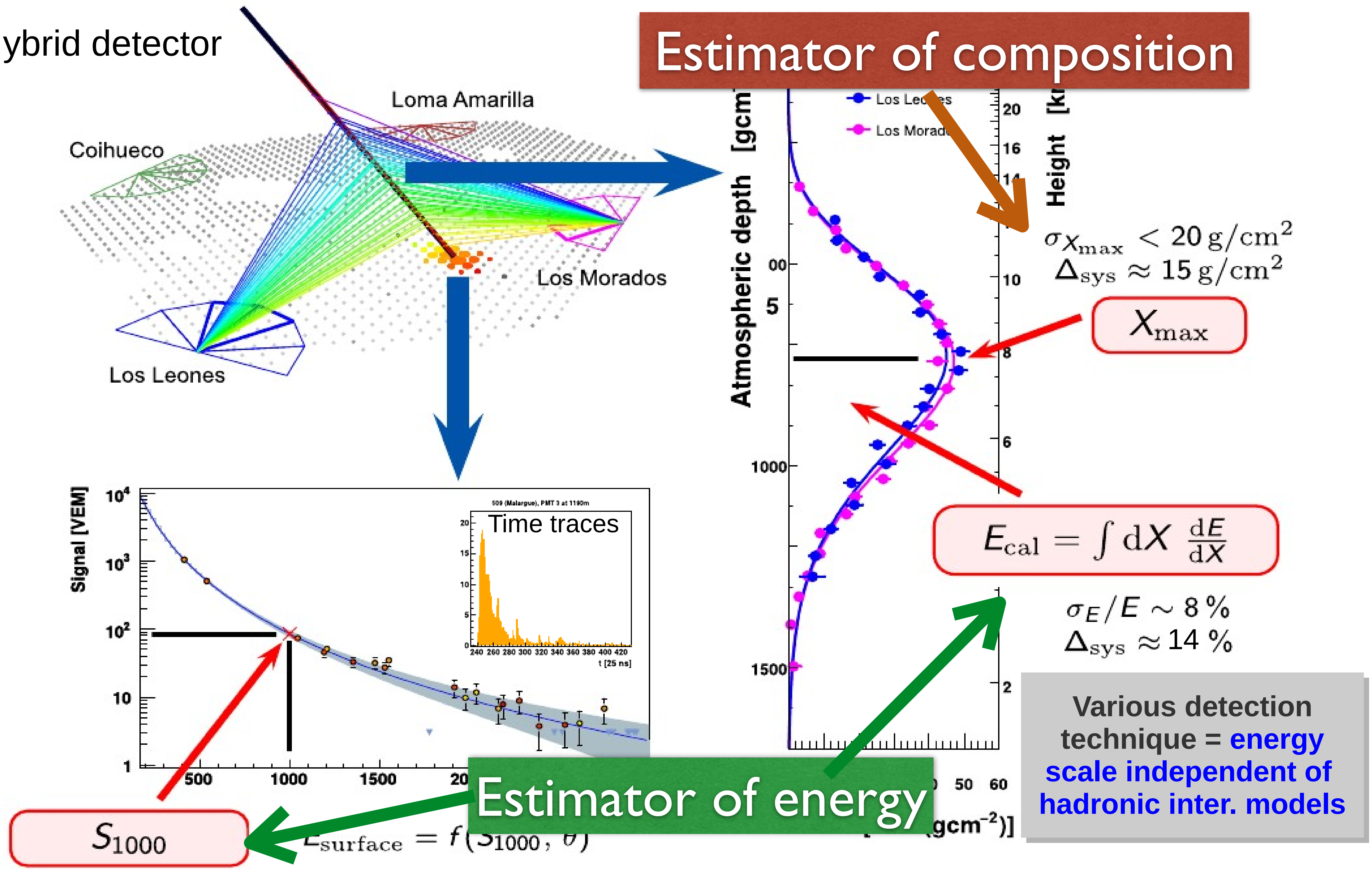
$E_{\mathrm{cal}} = \int \mathrm{d}X \, \frac{\mathrm{d}E}{\mathrm{d}X}$

$\sigma_E / E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 14\,\%$

Various detection technique = energy scale independent of hadronic inter. models

From R. Ulrich (KIT)

A PAO hybrid event

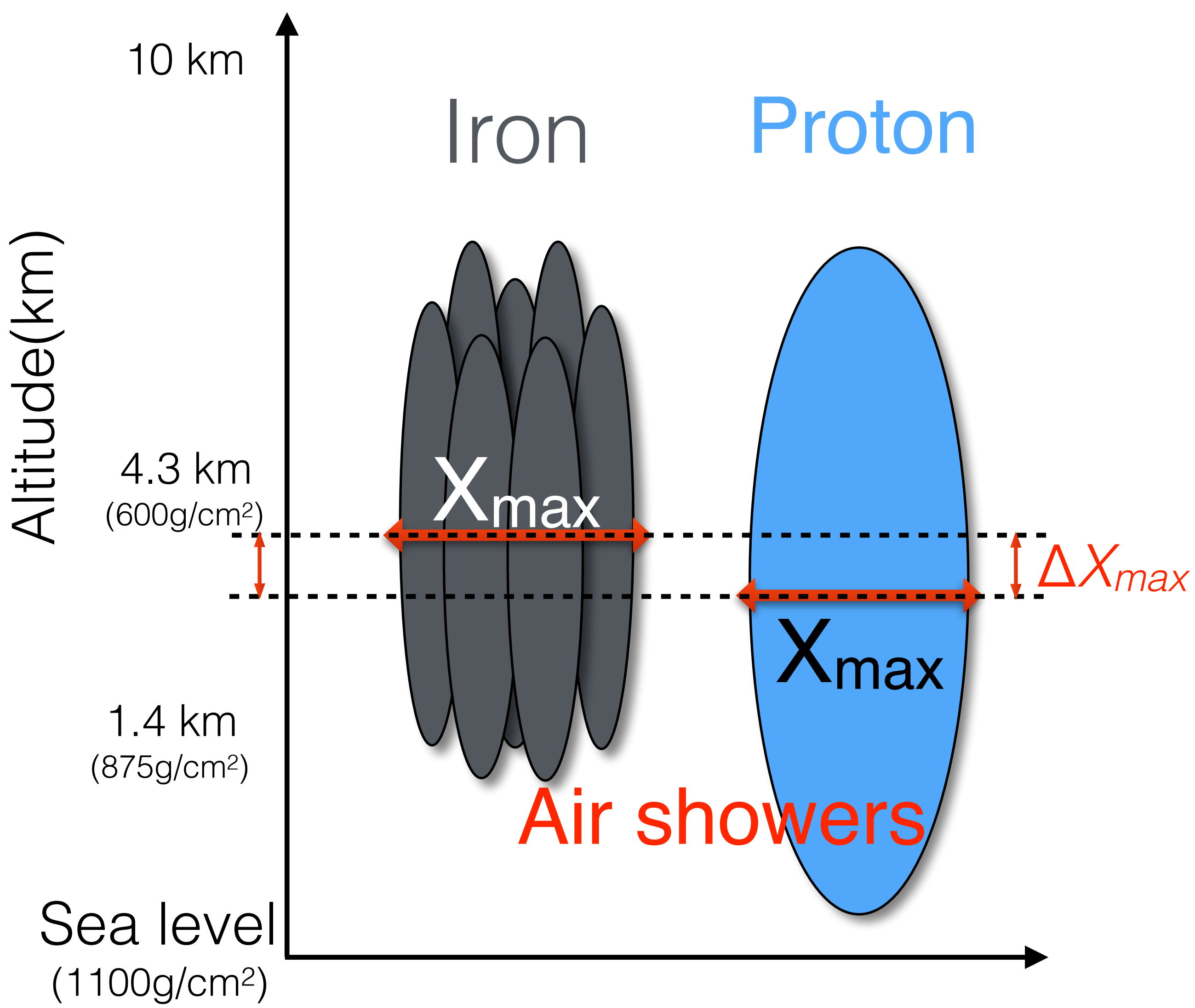


From R. Ulrich (KIT)

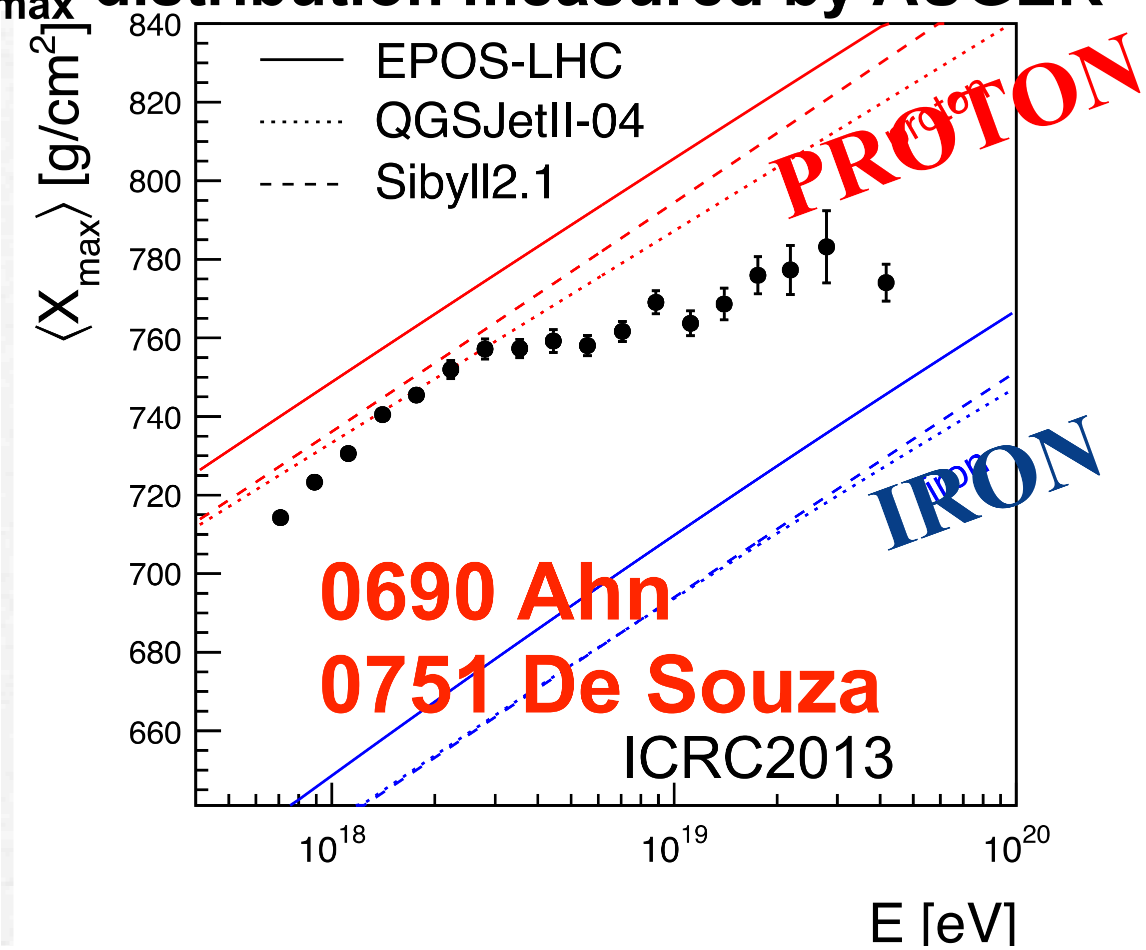
Composition measurement of UHECRs

Composition of UHECRs is one of important observable.

ΔX_{max} indicates the different primary mass composition



X_{max} distribution measured by AUGER

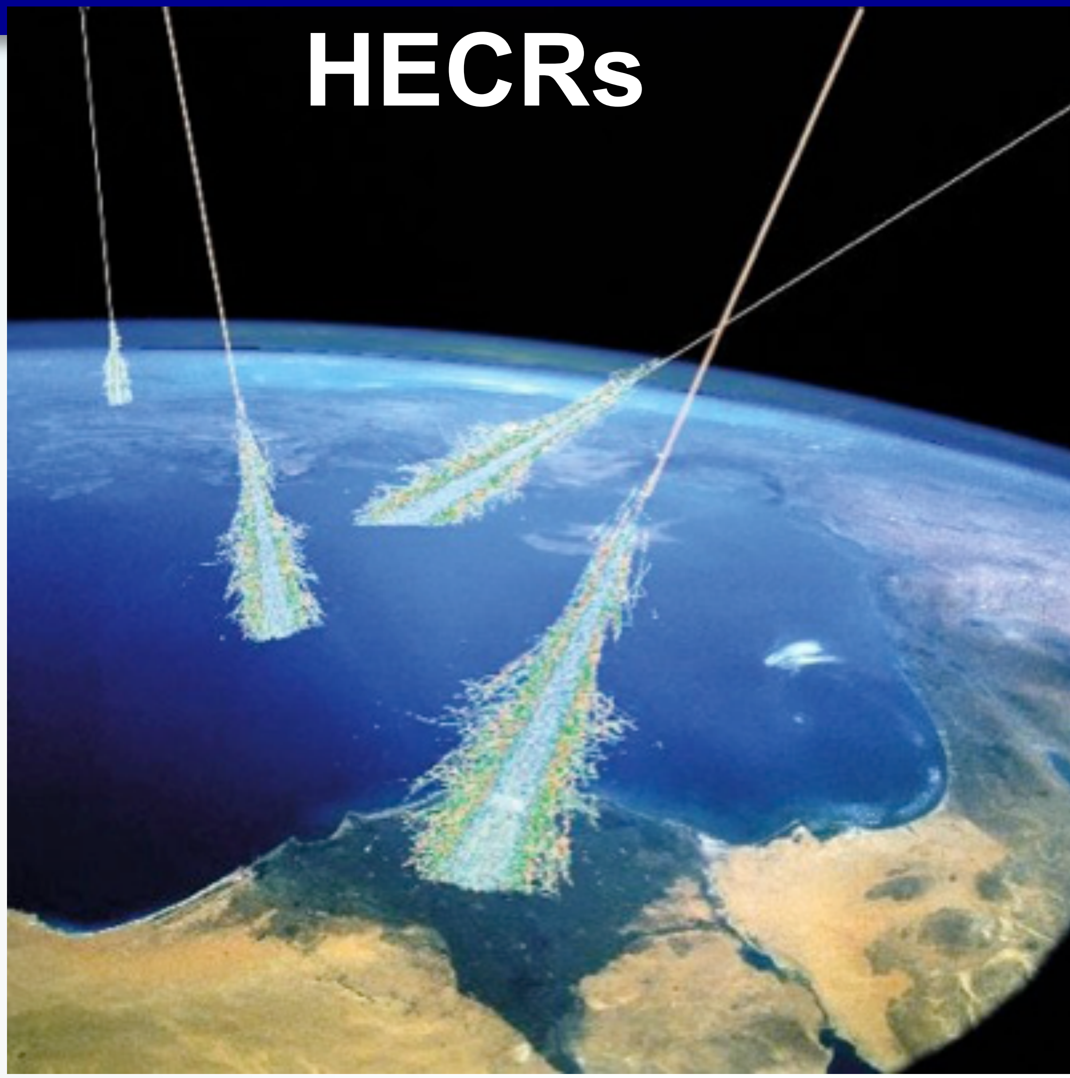


Uncertainty of hadron interaction models

V

Error of <X_{max}> measurement

Measurement of HECR



Extensive air shower observation

- longitudinal distribution
- lateral distribution
- Arrival direction

Air shower development

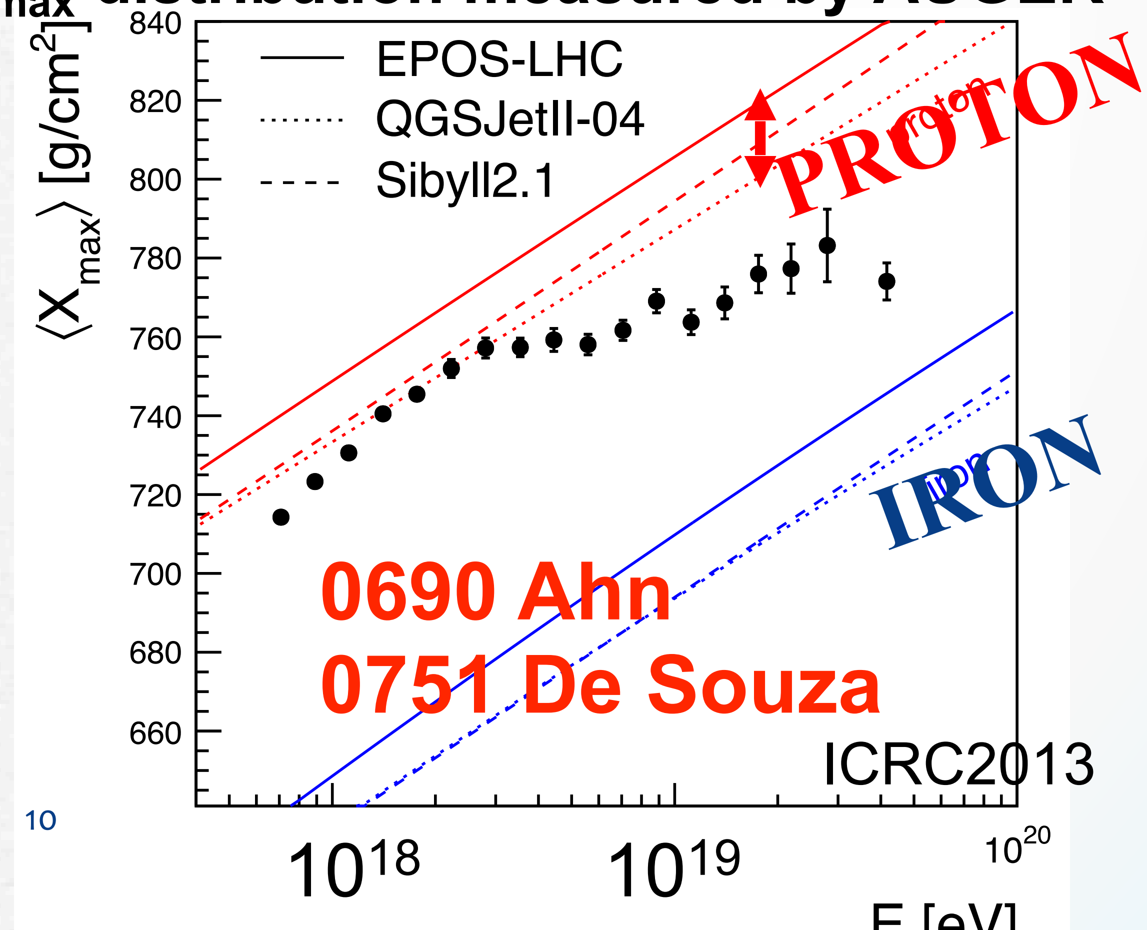
Astrophysical parameters

- Spectrum
- Composition
- Source distribution

X_{max}
the depth of air shower maximum.
An indicator of CR composition

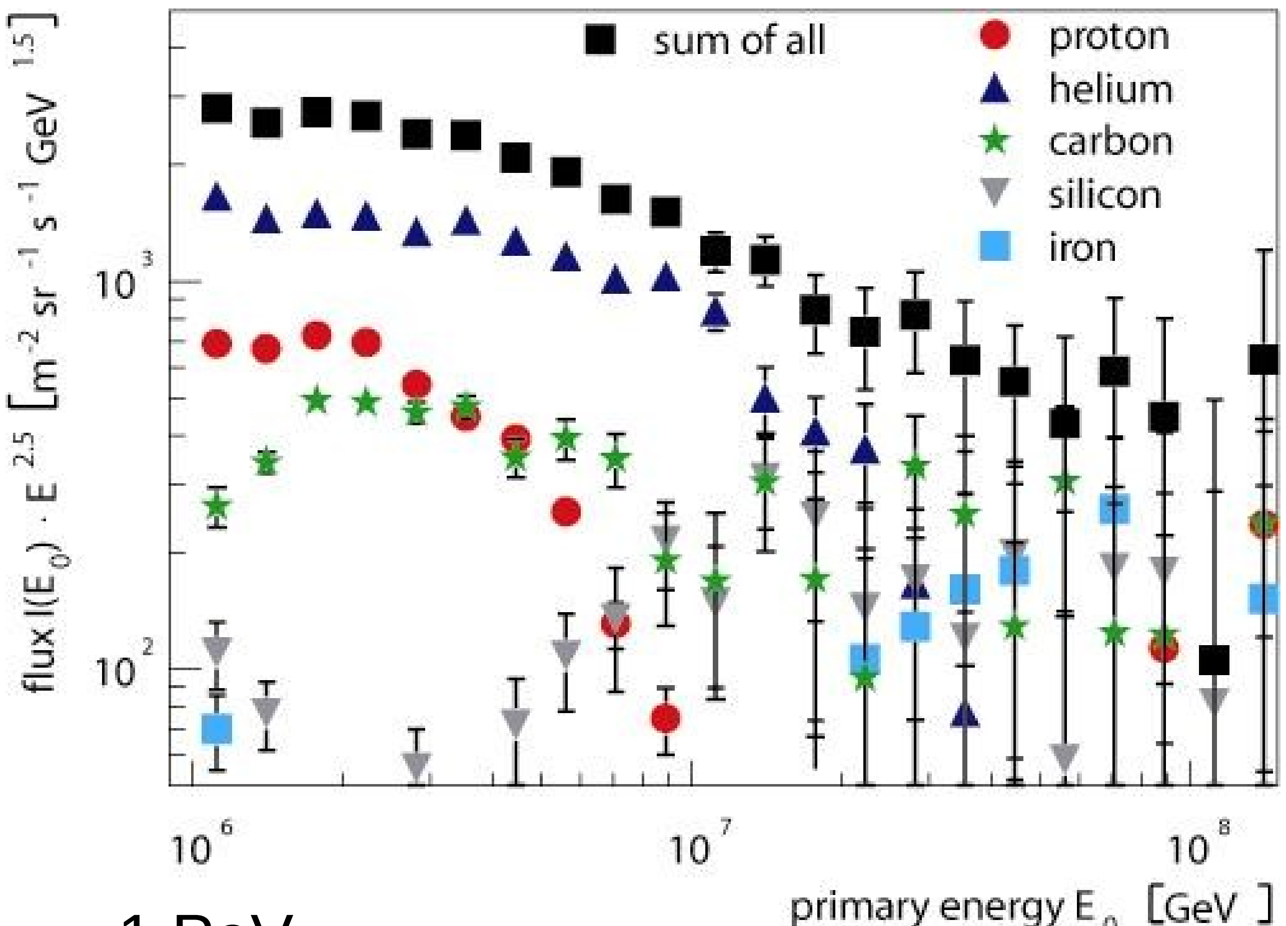
Uncertainty of hadron interaction models
V
Error of $<X_{max}>$ measurement

X_{max} distribution measured by AUGER



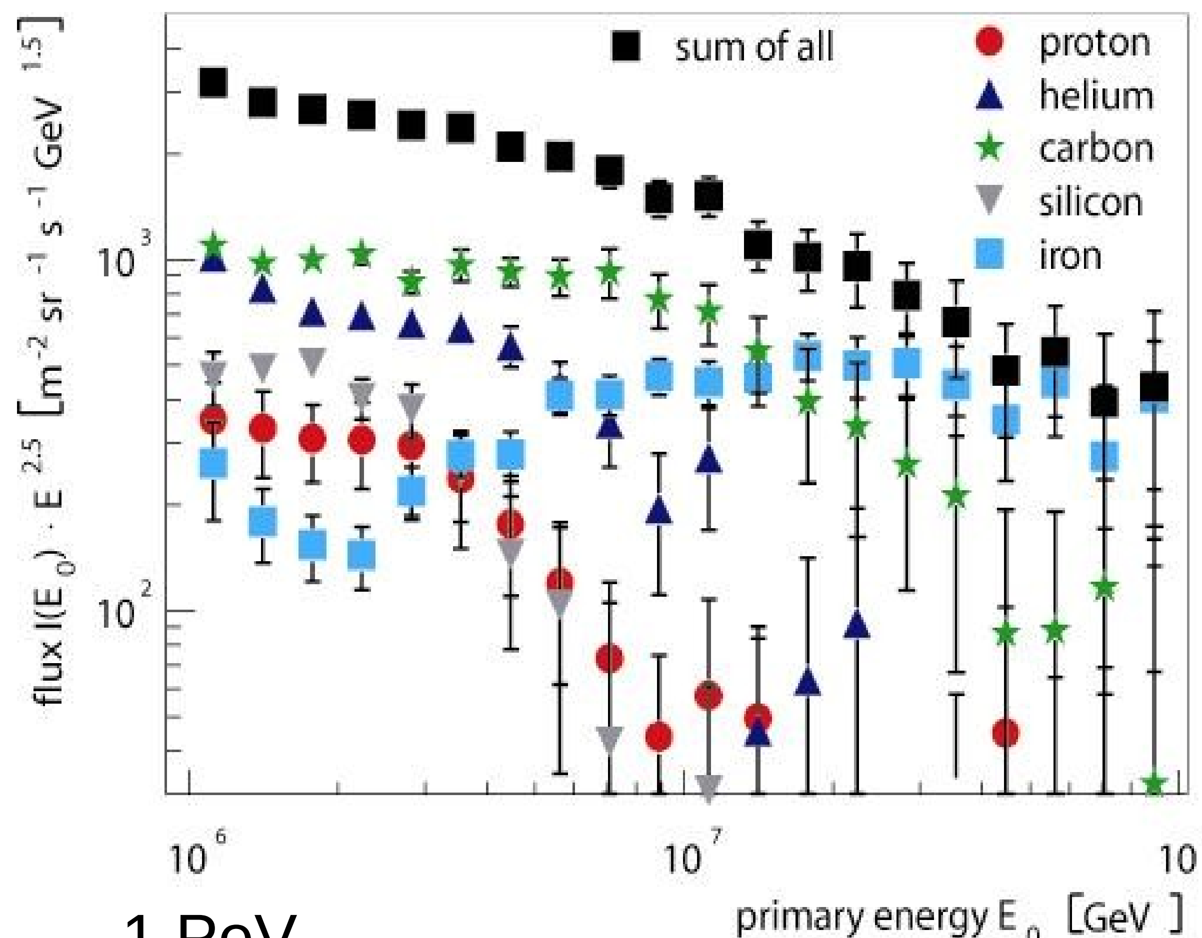
Composition at Knee (10^{15-16}eV)

- **Spectrum mass decomposition by KASCADE collaboration :**



1 PeV

QGSJET 01



1 PeV

SIBYLL 2.1

Change in spectrum slope due to mass composition (large uncertainties due to models) or change in hadronic interactions.

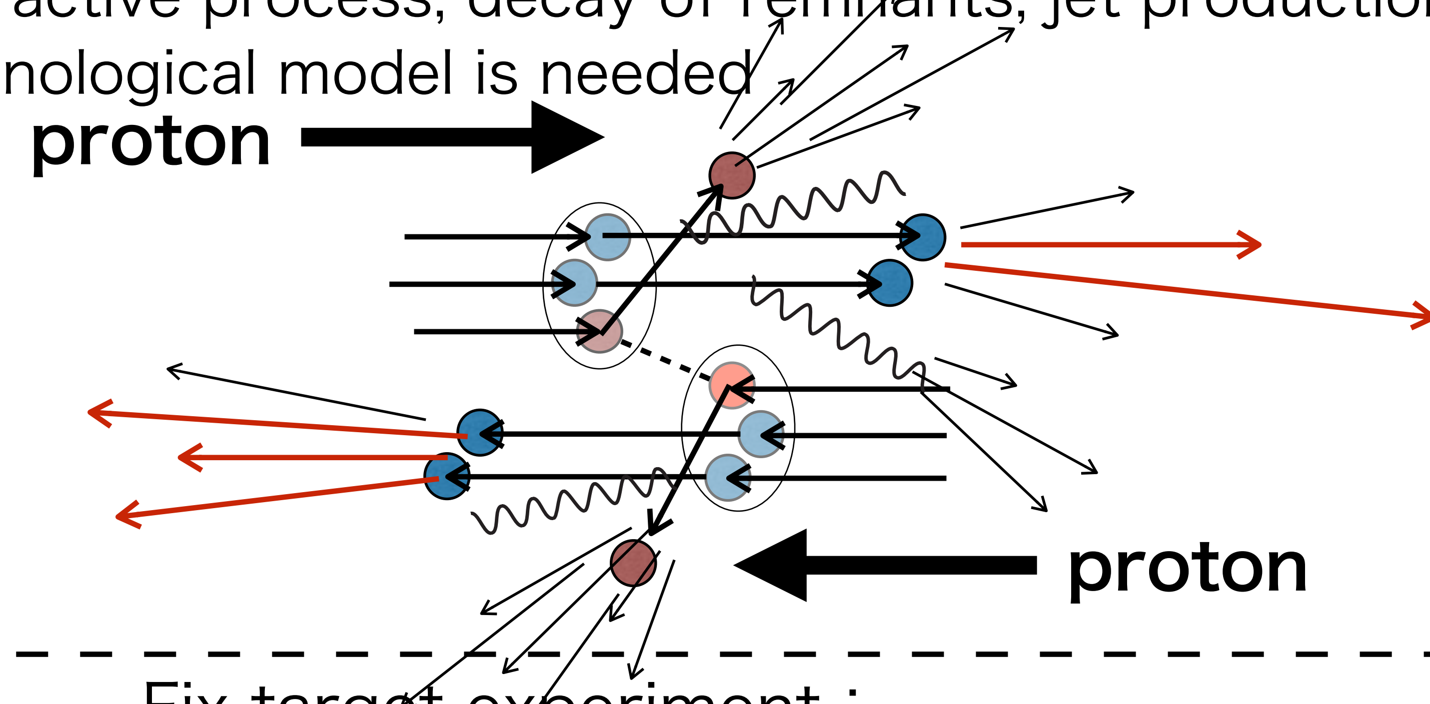
KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25, astro-ph/0505413
ref. T.Pierog in HESZ2015

Hadronic interaction

QCD theory can calculate well all process

pQCD can caluclate only the process with the hard interaction (high Q^2). For other processes, exp., diffractive process, decay of remnants, jet production., phonological model is needed

NO



The model has been checked very well with collider data.

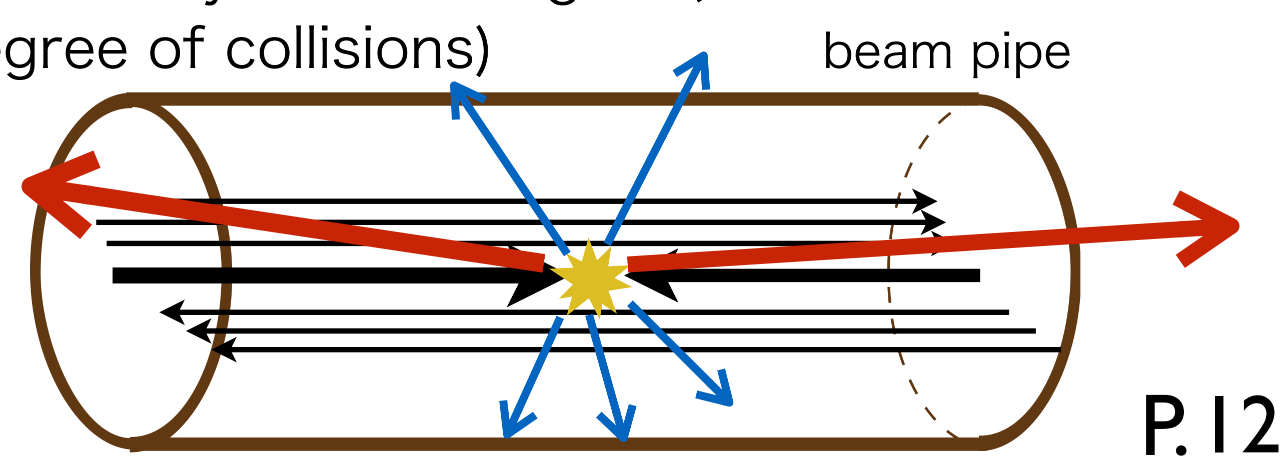
Fix target experiment：

E_{CR}<450GeV

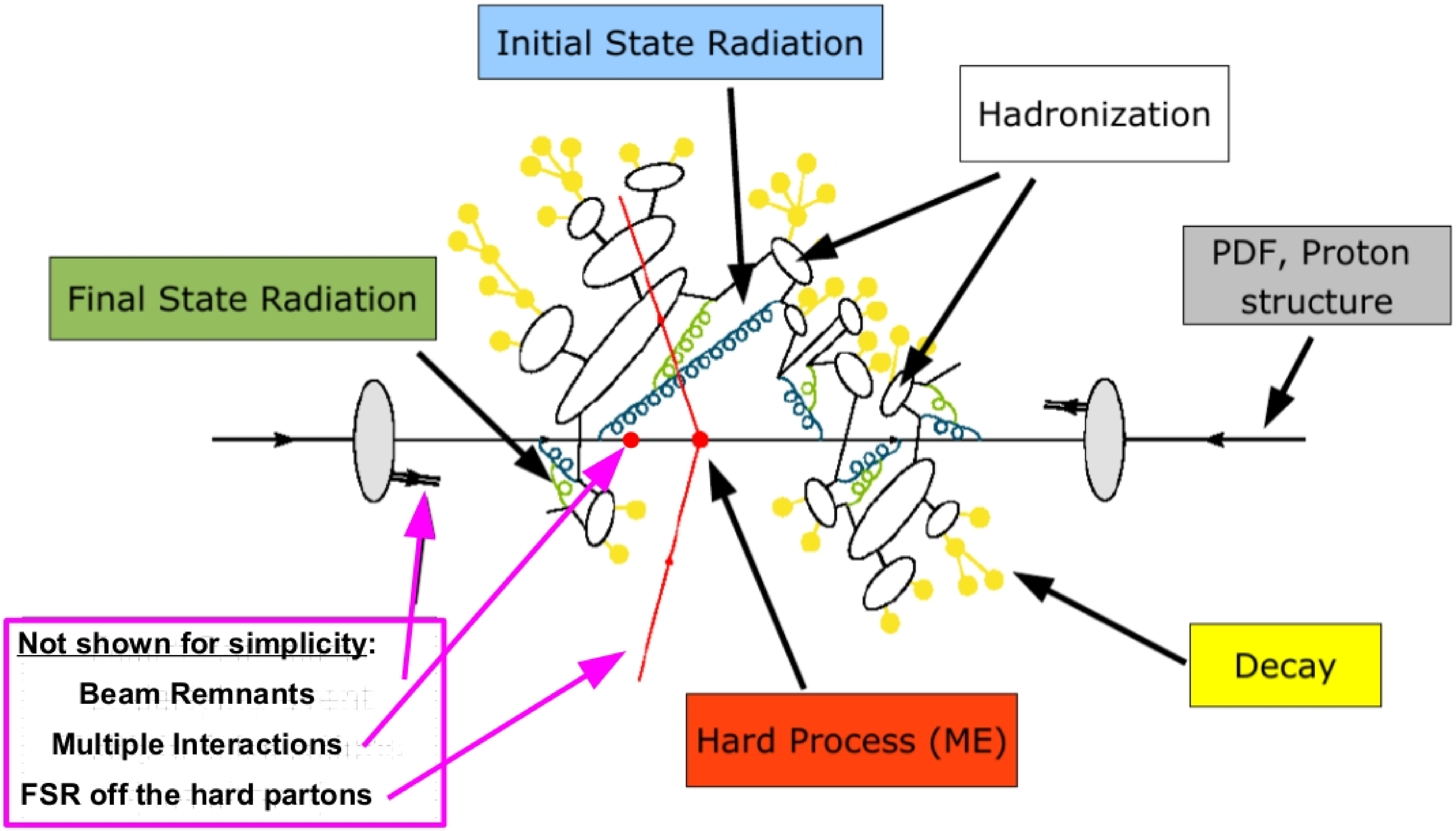
Collieder experiment：

Very difficult to have a measurement at the very forward region (close to zero degree of collisions)

Yes, but few data in the very forward region

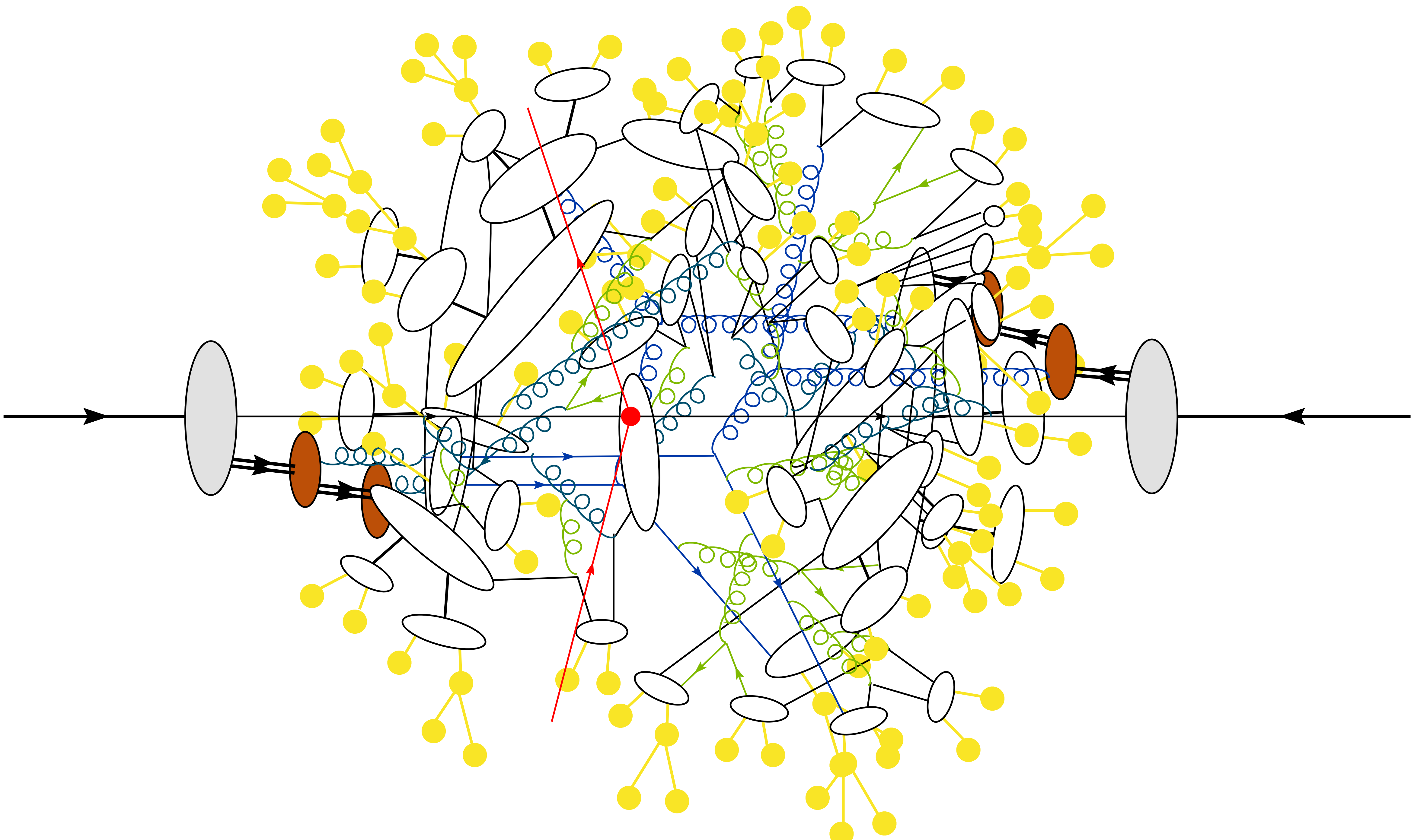


Hadronic interaction

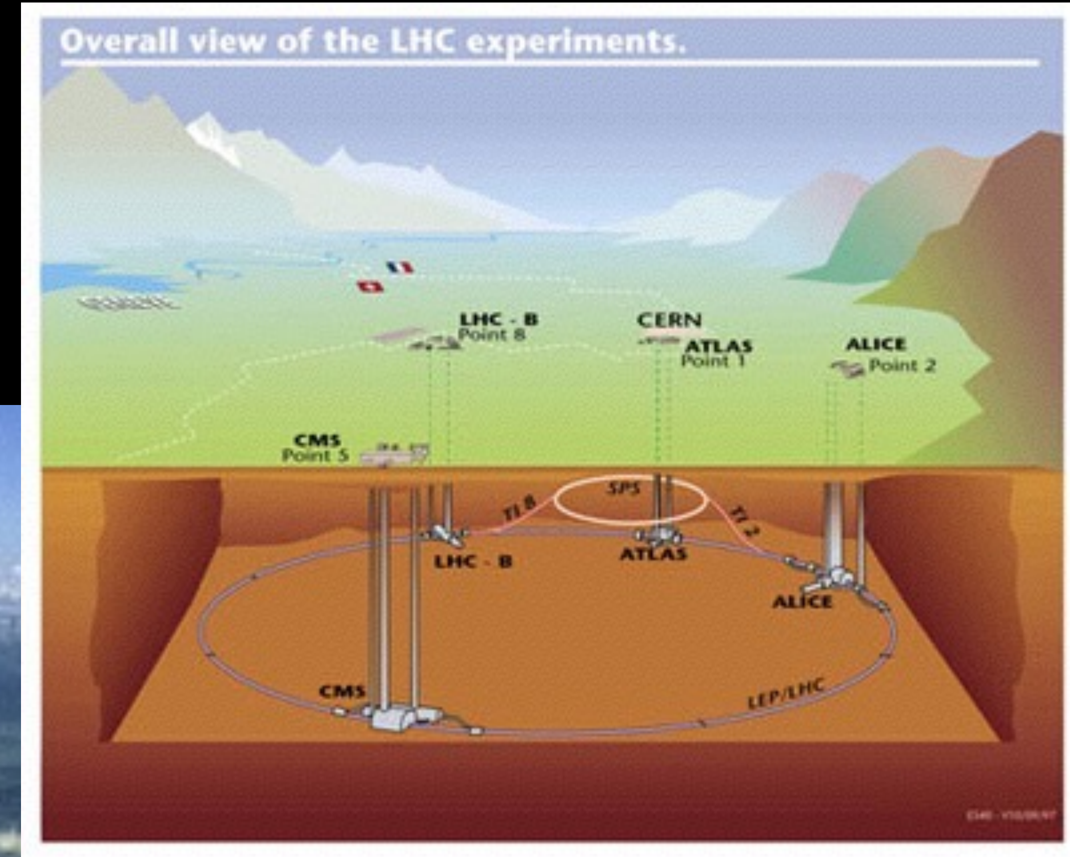


taken from Stefan Gieseke©

Hadronic interaction

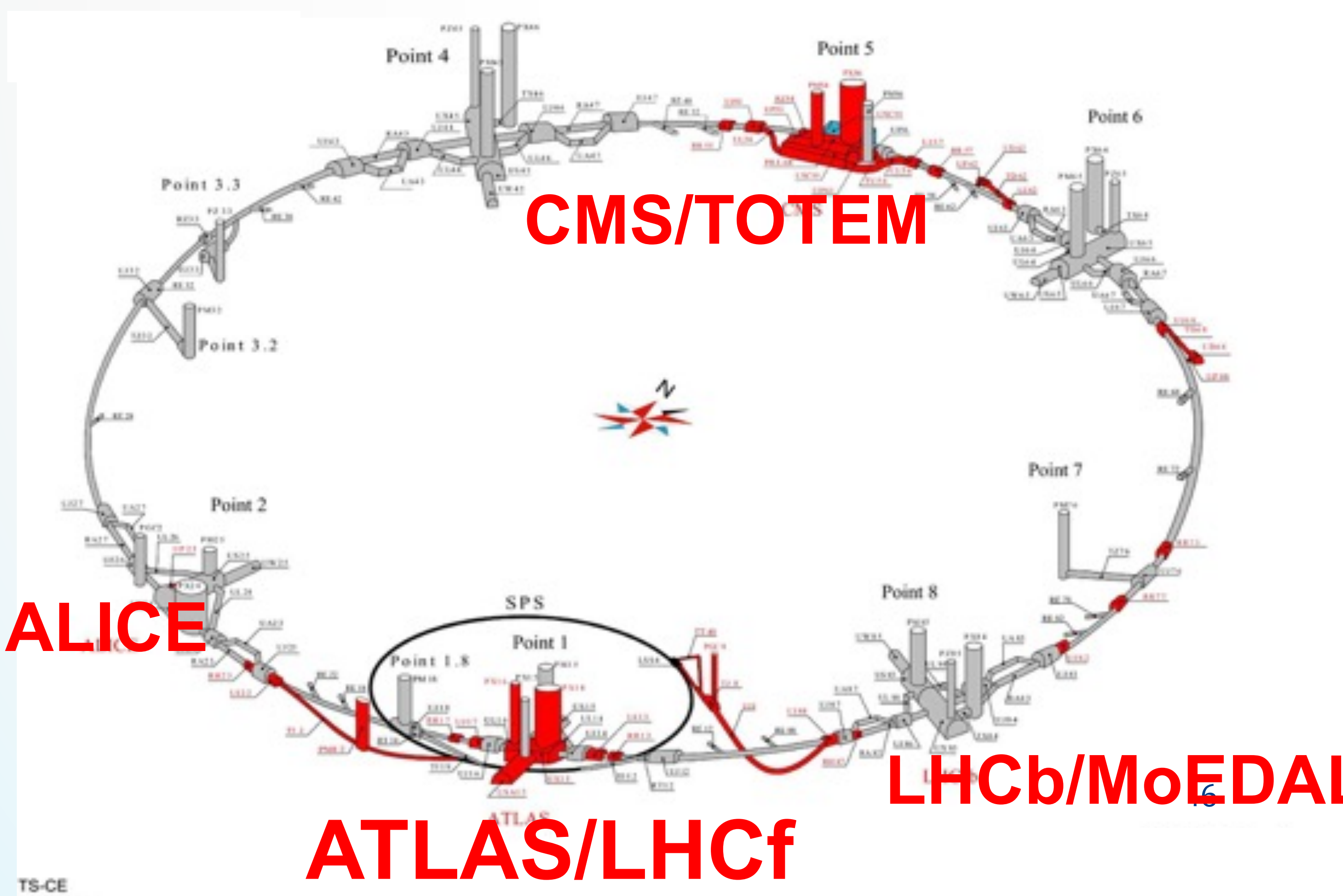


Large Hadron Collider



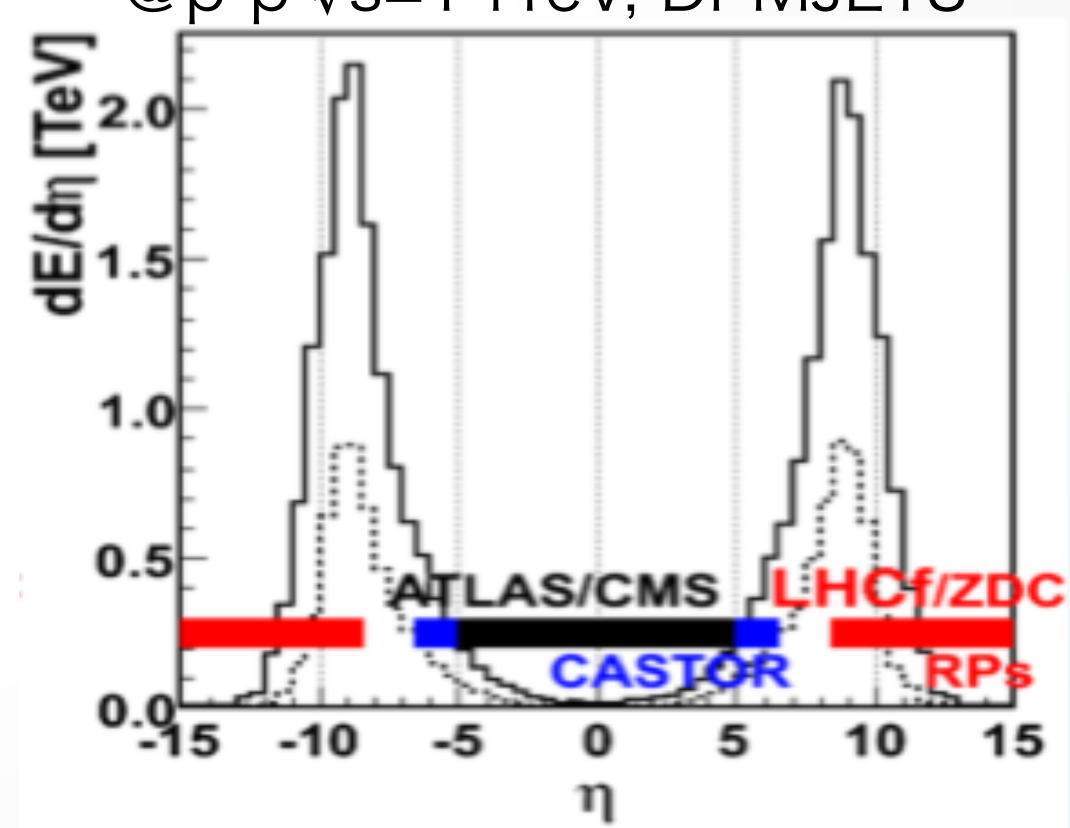
The Large Hadron Collider (LHC)

pp 6.5TeV+6.5TeV	→ $E_{lab} = 9\times10^{16}$eV	**2015-**
pp 3.5TeV+3.5TeV	→ $E_{lab} = 2.6\times10^{16}$eV	2010-2011
pp 450GeV+450GeV	→ $E_{lab} = 2\times10^{14}$eV	2009,2010
+ $\sqrt{s}$=2.76TeV, 8TeV		
A-A/p-A PbPb $\sqrt{s_{NN}}$=2.76TeV		2011-
p-Pb $\sqrt{s_{NN}}$=5TeV		2012-



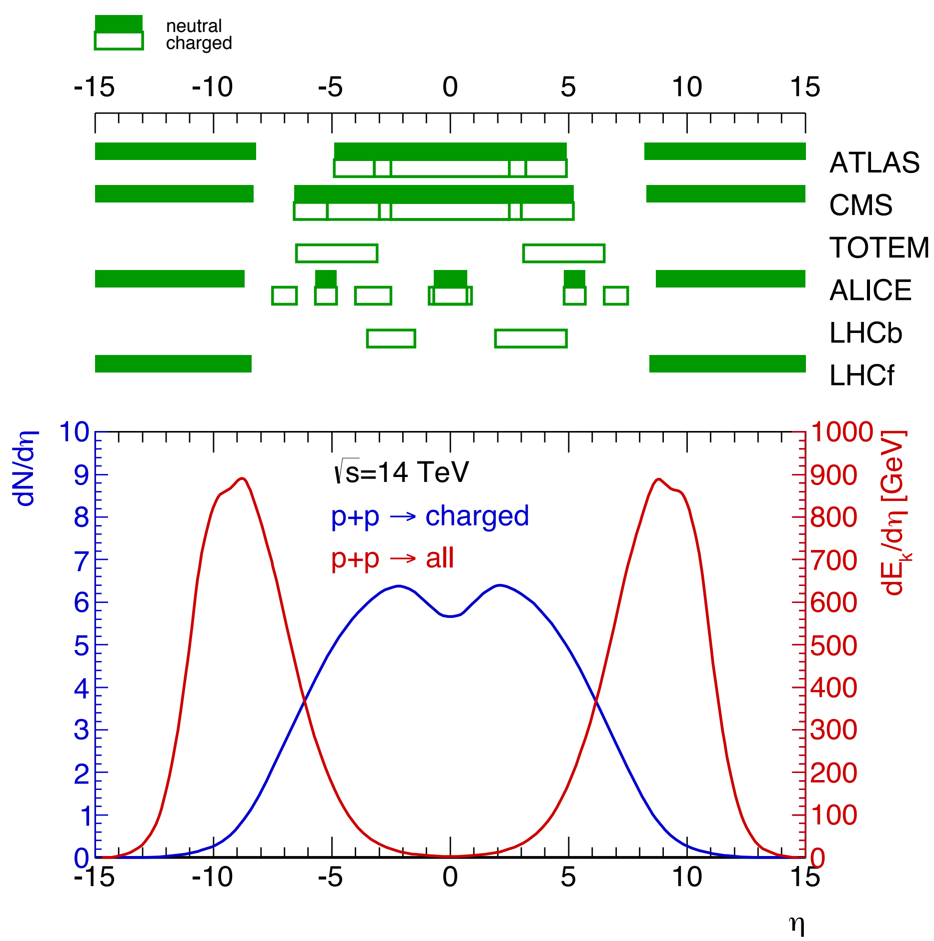
Energy Flux

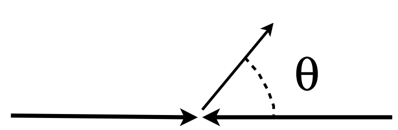
@p-p $\sqrt{s}$=14TeV, DPMJET3



Energy Flow in the forward region

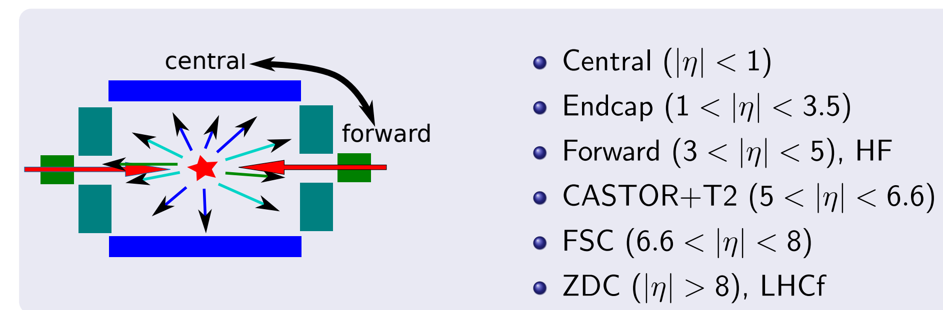
Challenge of limited phase space coverage

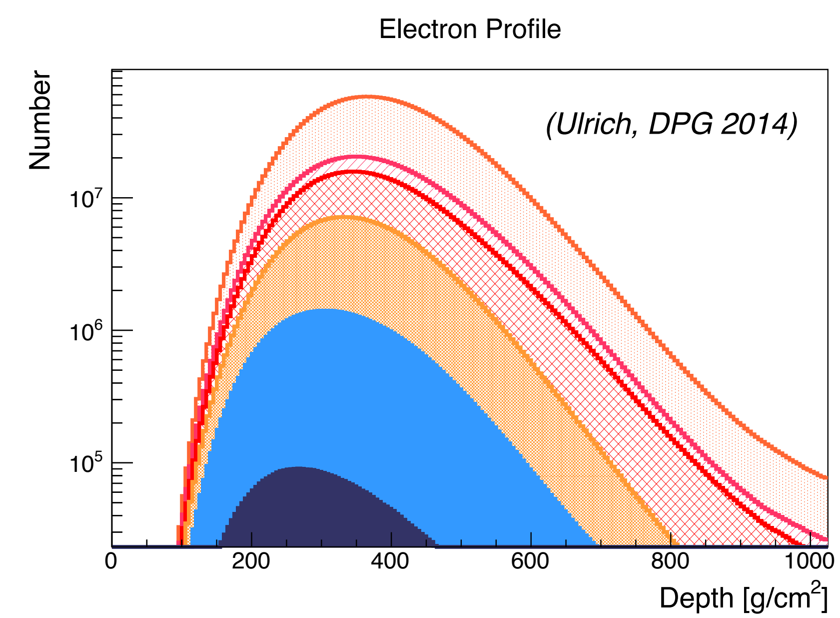




$$\eta = -\ln \tan \frac{\theta}{2}$$

η	deg.	mrad.
3	5.7	97
5	0.77	10
8	0.04	0.7
10	0,005	0,009





More than 50% of shower from η > 8

Salek et al., 2014)

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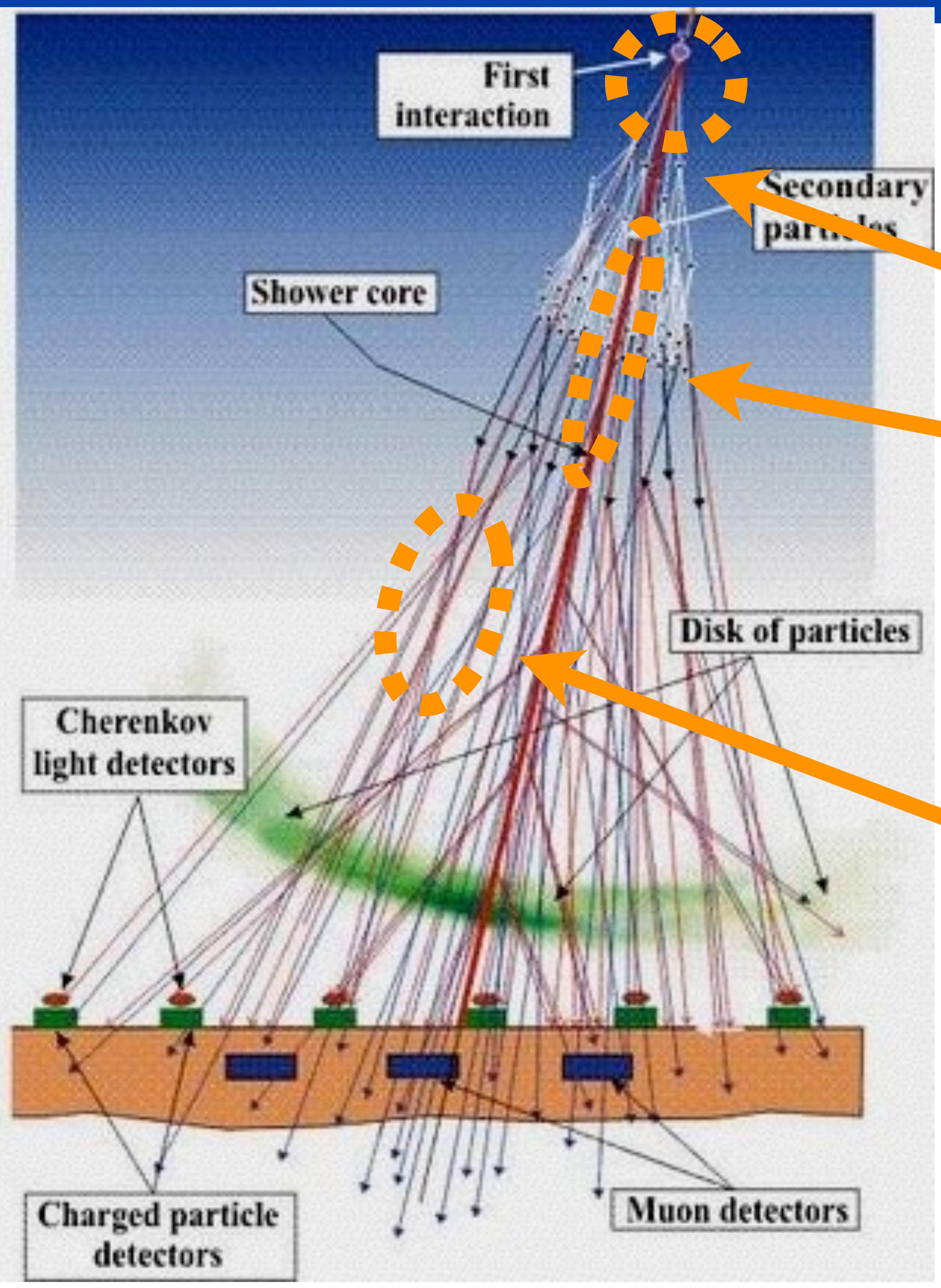
[REMINDER] 空気シャワーのキーパラメータ



Key Parameters

- Inelastic Cross Section
  →TOTEM, ATLAS, CMS,ALICE
- Forward Energy Spectrum
  →LHCf, ZDC and etc.
- Inelasticity $k = 1 - p_{lead}/p_{beam}$
  →LHCf, ZDC and etc.
- Secondary interactions

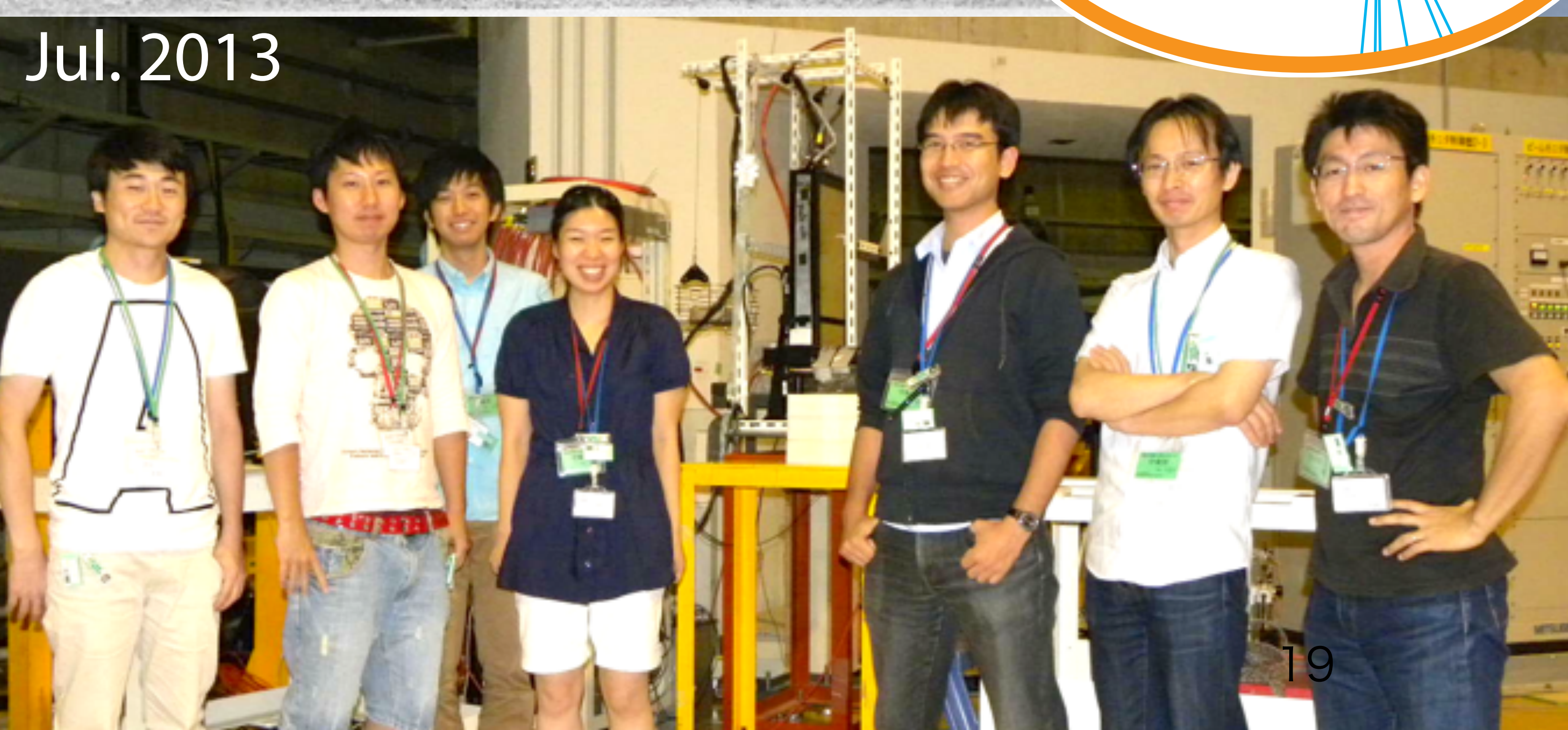
+Nuclear Effect @ CR-Air

The LHCf collaboration

The LHCf collaboration involves ~30 members at 10 institutions.

Feb. 2009

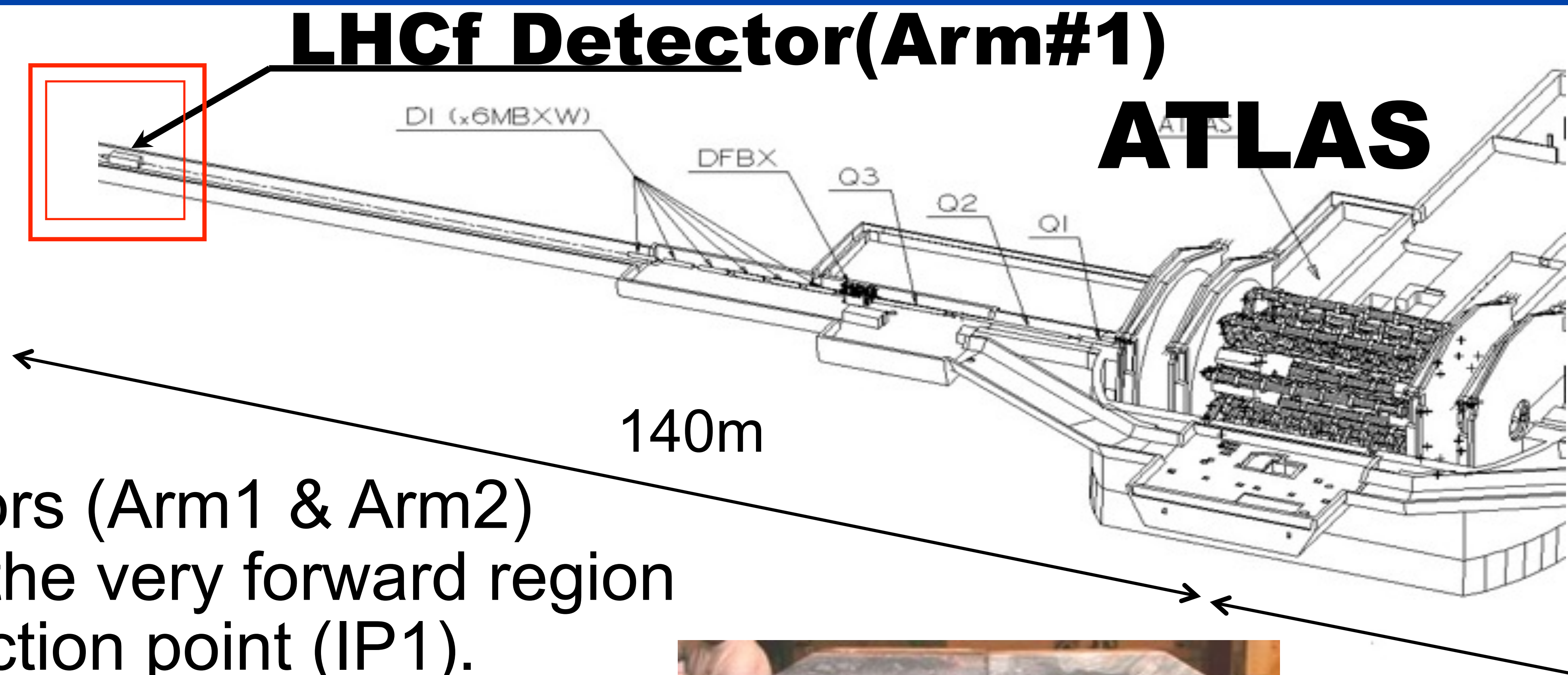
Jul. 2011



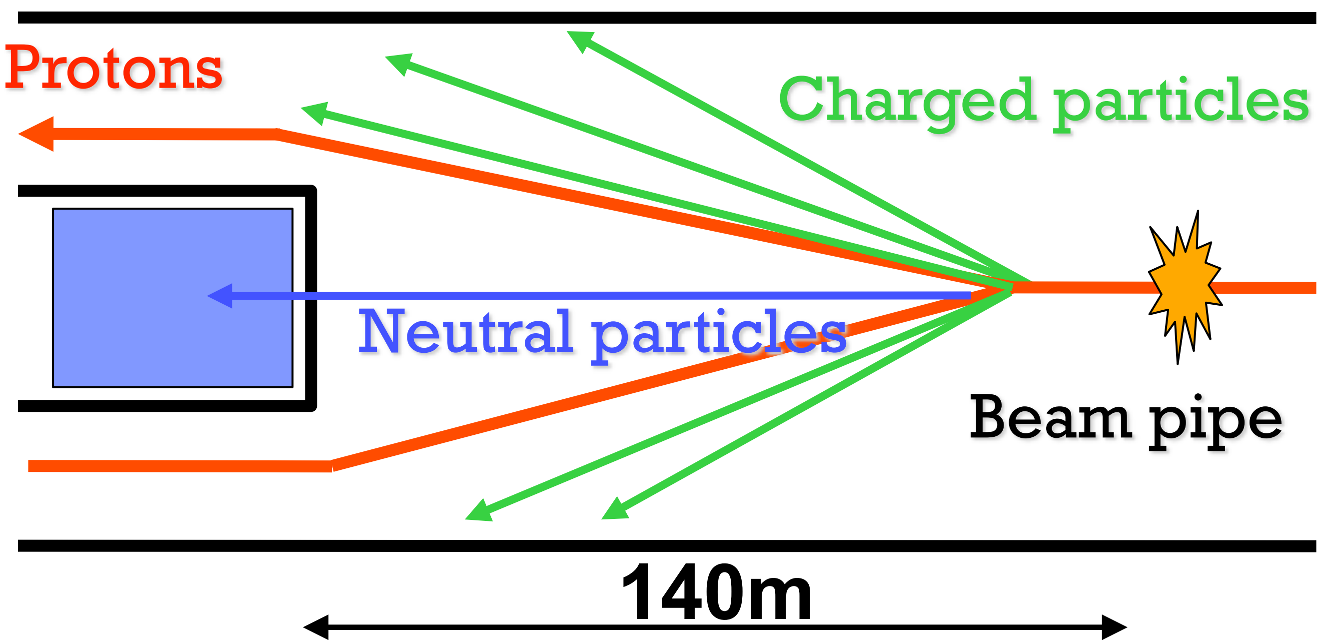
Jul. 2013

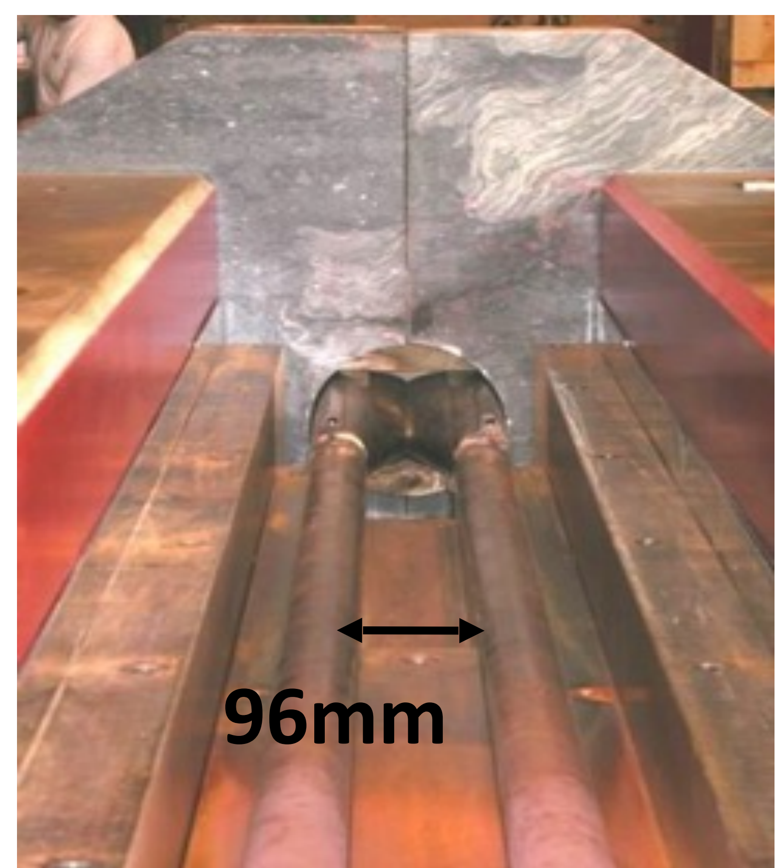
Apr. 2013

Experimenta Setup



Two LHCf detectors (Arm1 & Arm2) are installed into the very forward region of the LHC interaction point (IP1). LHCf can measure neutral particles (γ, n) at the rapidity range **η > 8.4.**

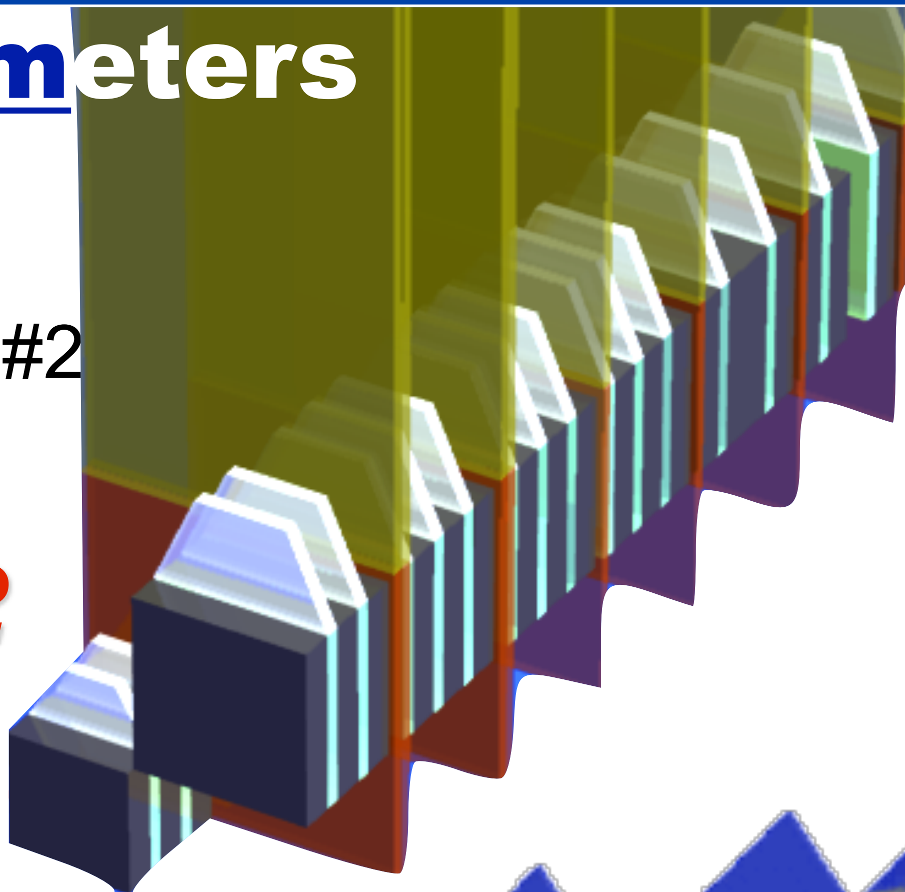




The LHCf detectors

Sampling and Positioning Calorimeters

- W (44 r.l , $1.7\lambda_I$) and Scintillator x 16 Layers
- Four positioning sensitive layers
  XY-Scintillator bars (Arm1) and XY-Silicon strip(Arm#2
- **Each detector has two calorimeter towers, which allow to reconstruct π^0**



Arm2

Expected Performance

Energy resolution (> 100GeV)

< 5% for Photons

40% for Neutrons

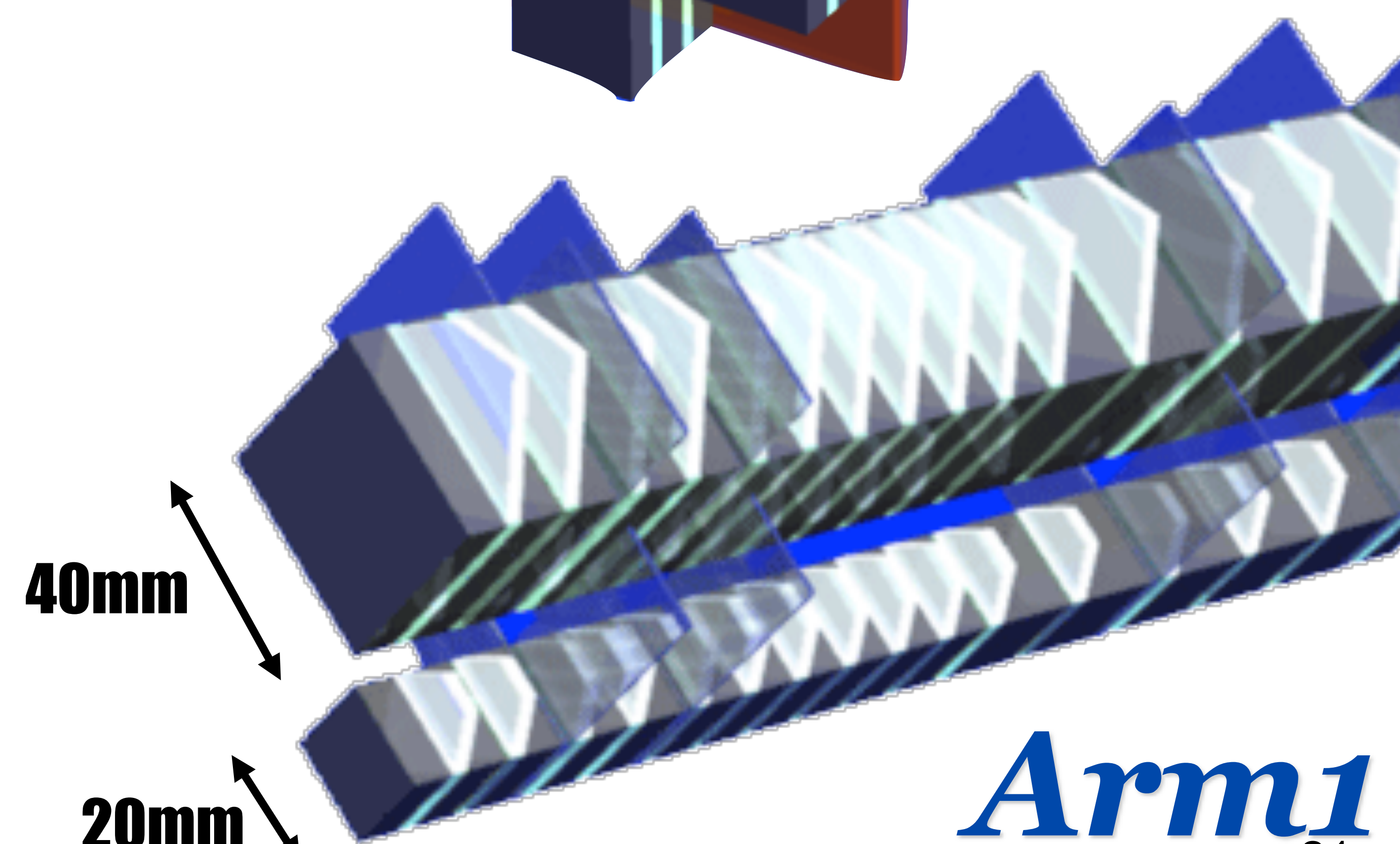
Position resolution

< 200μm for Photons

a few mm for Neutrons

Front Counter

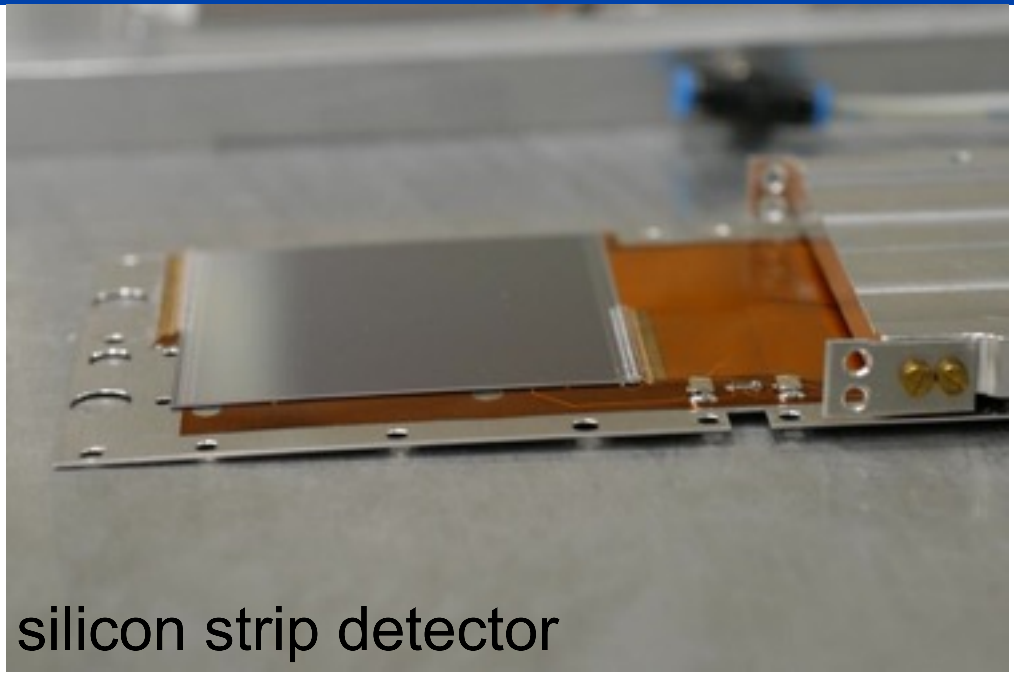
- thin scintillators with $80x80mm^2$
- **To monitor beam condition.**
- **For background rejection of beam-residual gas collisions by coincidence analysis**

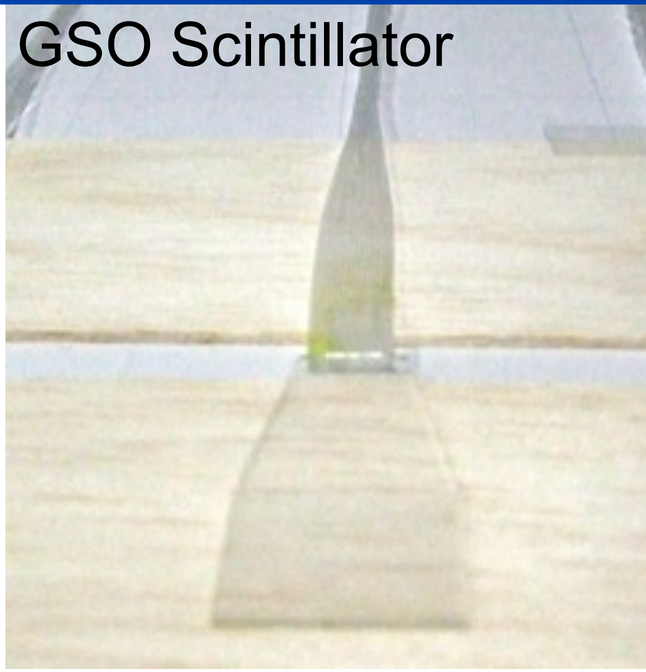


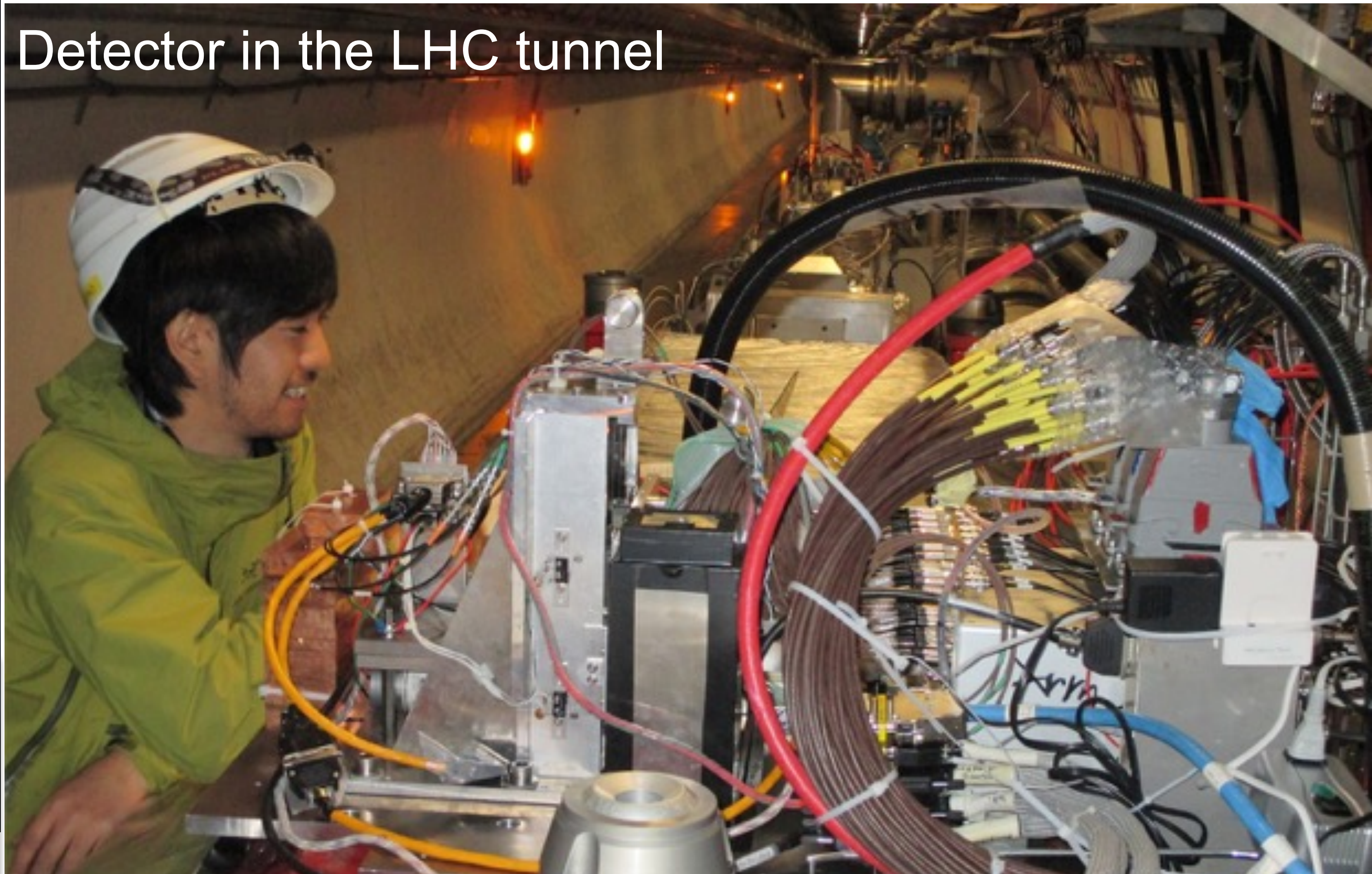
Arm1

The LHCf detectors


Arm1 Detector


silicon strip detector


GSO Scintillator


Detector in the LHC tunnel

Operation in 2015

- LHCf physics operation with pp √s=13TeV has been completed !!
  - LHCf detectors were installed in Nov. 2014
  - Special physics operation with low pile-up in 9 - 13 June 2015.
  - After the operation, LHCf detectors were removed on 15 June during TS1.

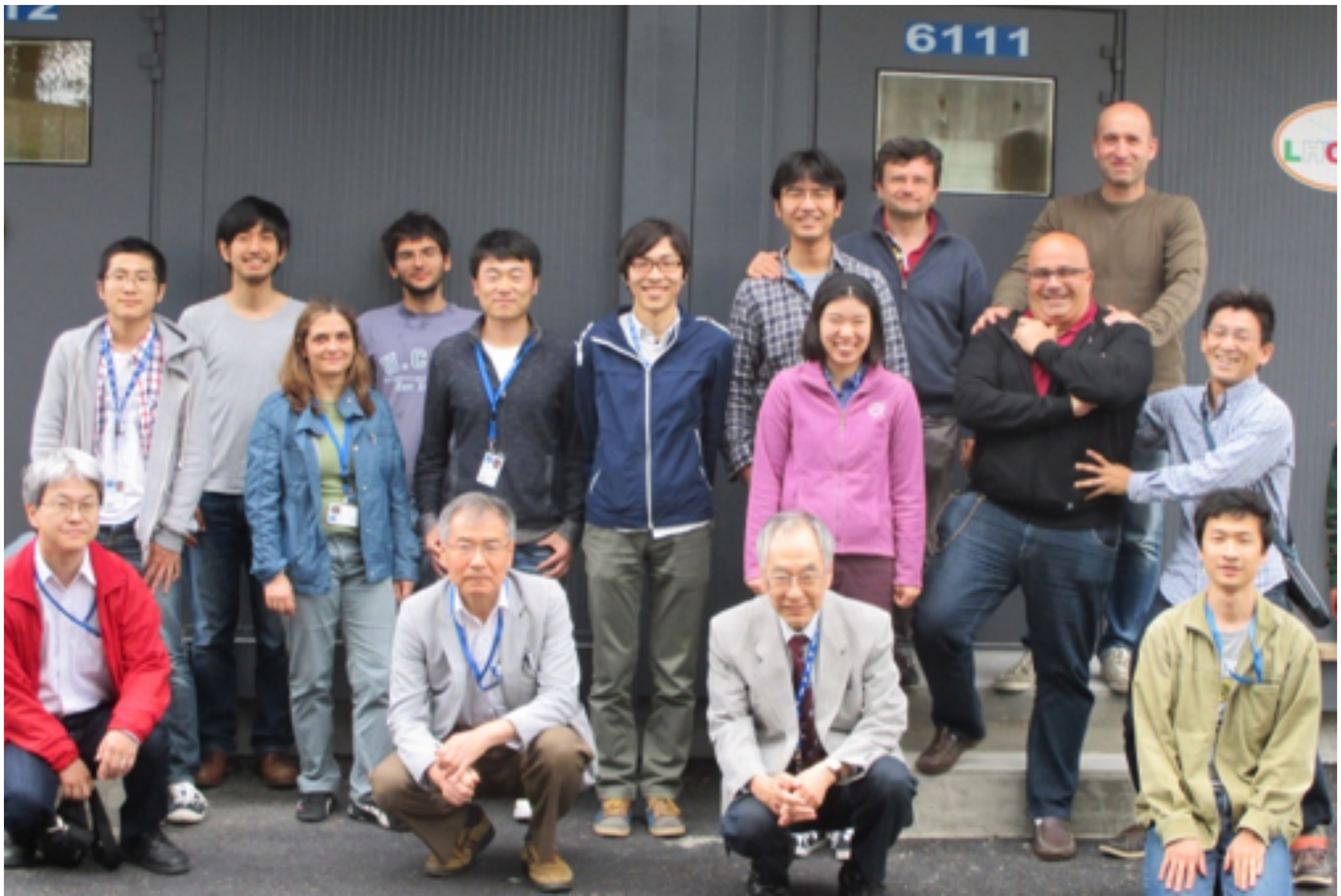


Photo @ CERN
Most of collaborators were in the front of the LHCf control room.

Operation in Run II

- 26.6 hours of operation with DAQ rate of 200 - 500 Hz
- 39 M shower events and 0.53 M π^0 events were obtained.
- The final triggers of LHCf were sent to ATLAS for common operation.

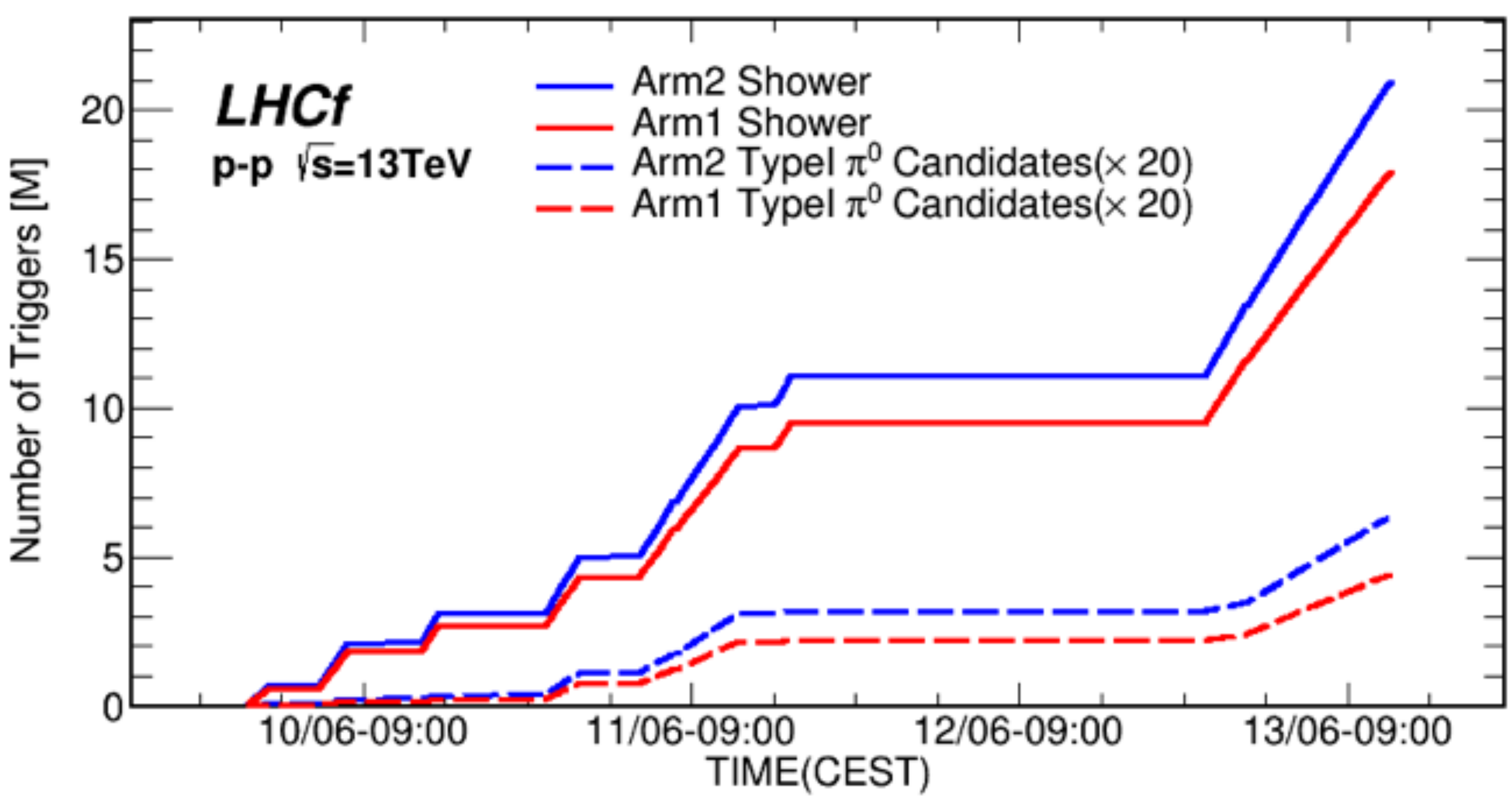


Table of Statistics

	Arm1	Arm2
Shower Events	18 M	21 M
π^0 Events	0.22 M	0.31 M

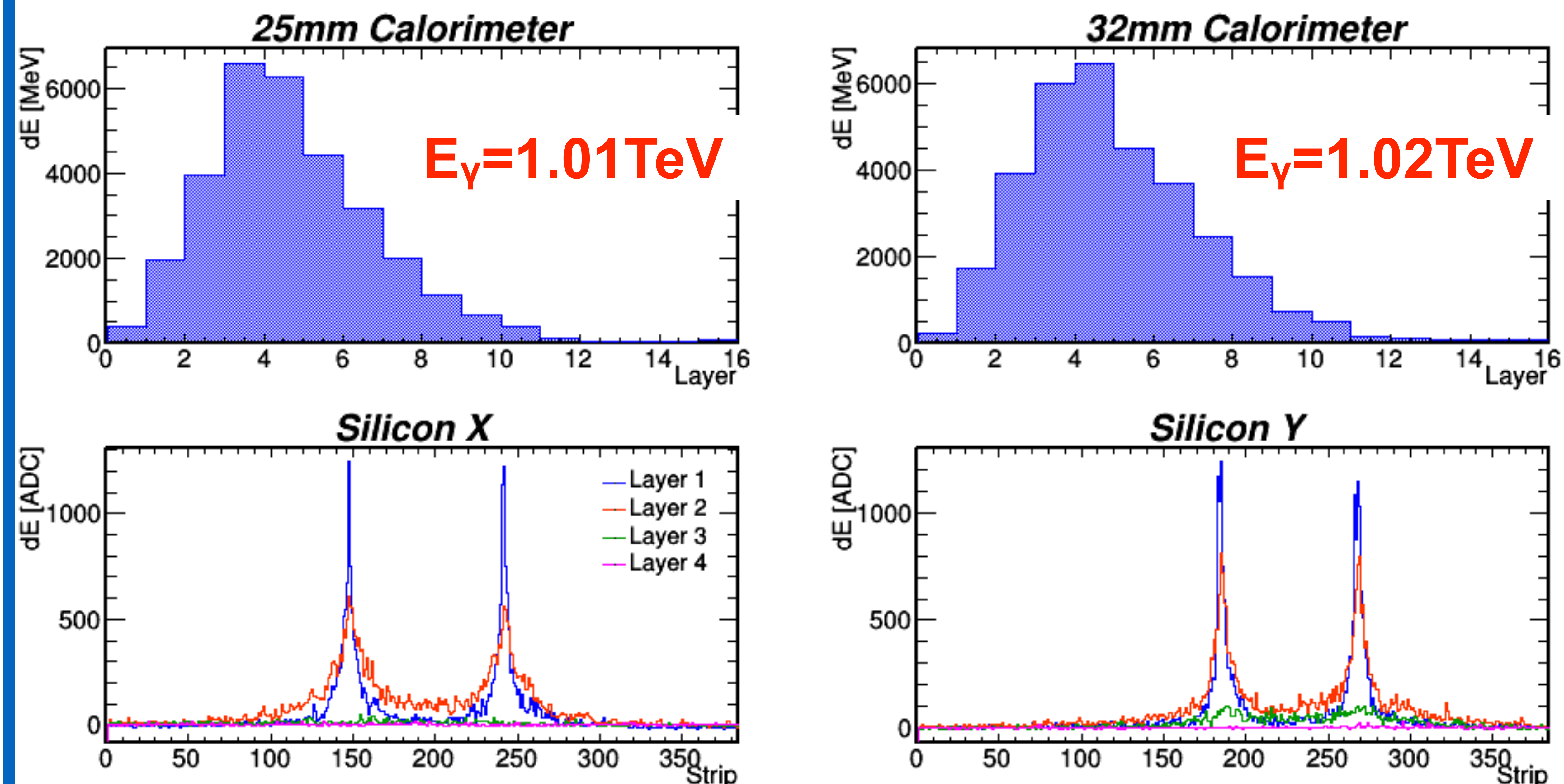
Arm2 Event Display

LHCf Arm2 Detector

π^0 Candidate Event

LHC p-p, $\sqrt{s}$ = 13 TeV Collisions

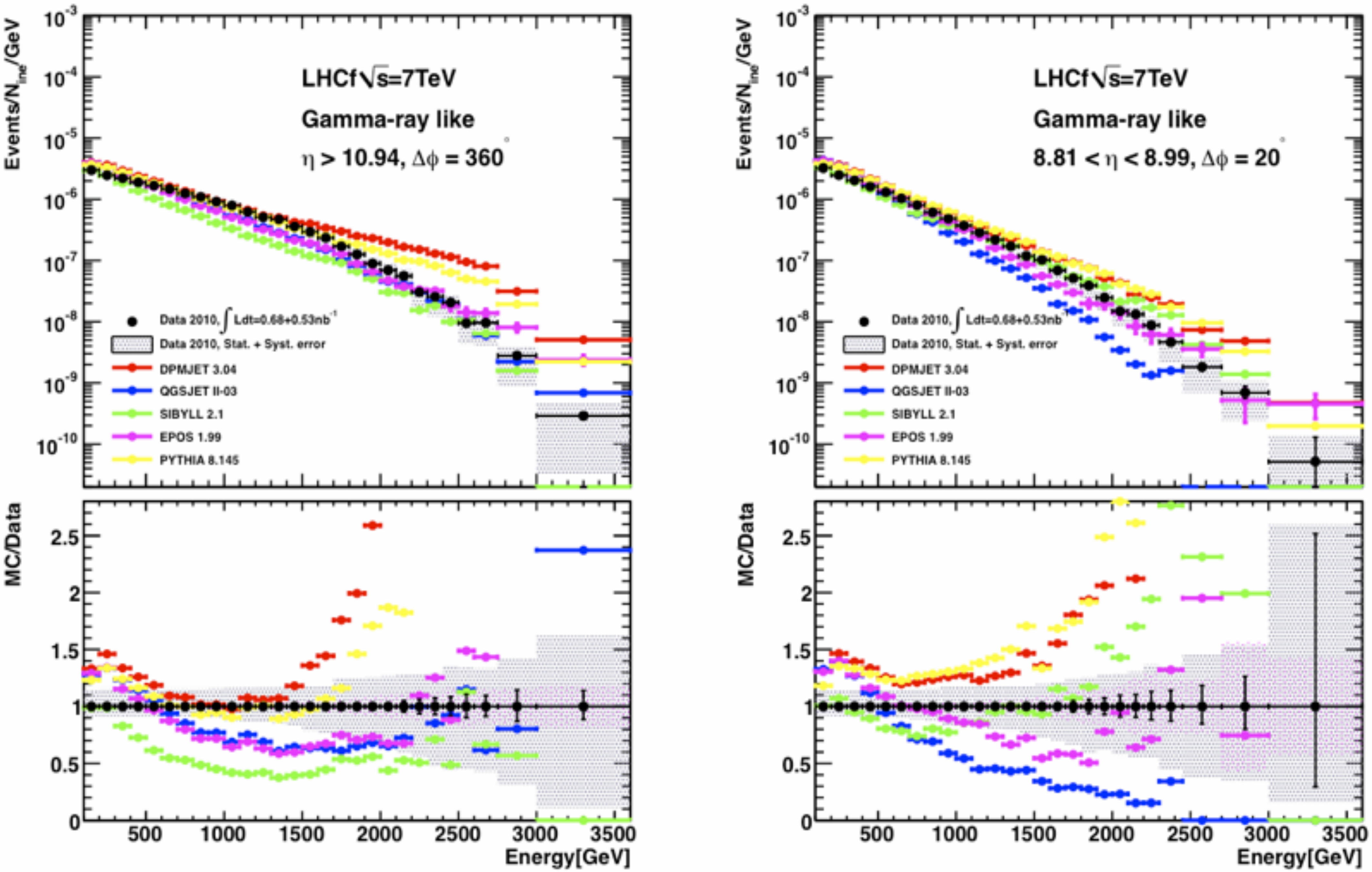
RUN:	44484
NUMBER:	3010
TIME:	1434152507
FILL:	3855
E_{25mm}:	1014 GeV
E_{32mm}:	1021 GeV
$M_{\gamma\gamma}$:	147 MeV



LHCf Results

	Photon	π^0	Neutron
p-p √s=0.9TeV	PLB 715 (2012) 298-303	-	
p-p √s=2.7TeV		arXiv:1507.08764	
p-p √s=7 TeV	PLB 703 (2011) 128-134	PRD86(2012)092001 arXiv:1507.08764	PLB 750 (2015) 360-366
p-p √s=13 TeV	Preparing		On-going
p-Pb √s=5TeV		PRC 89 (2014) 065209	
(p-Pb √s=8TeV)			

Photons, p-p $\sqrt{s}$=7TeV



Data

Sys.+Stat.

DPMJET 3.04

QGSJETII-03

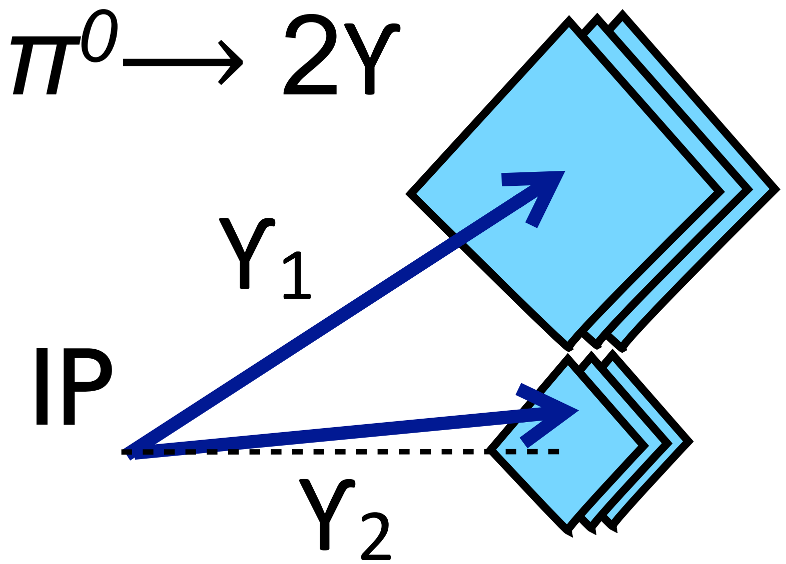
SIBYLL 2.1

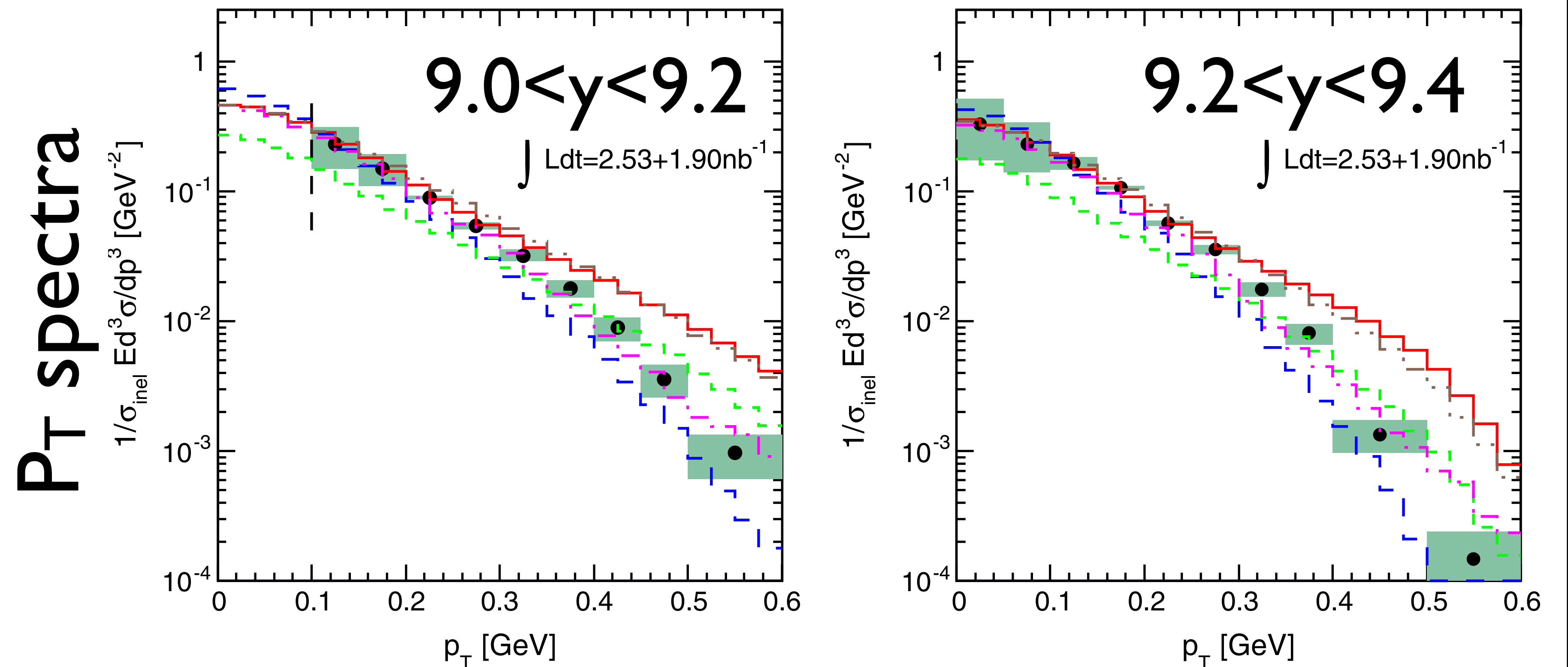
EPOS 1.99

PYTHIA 8.145

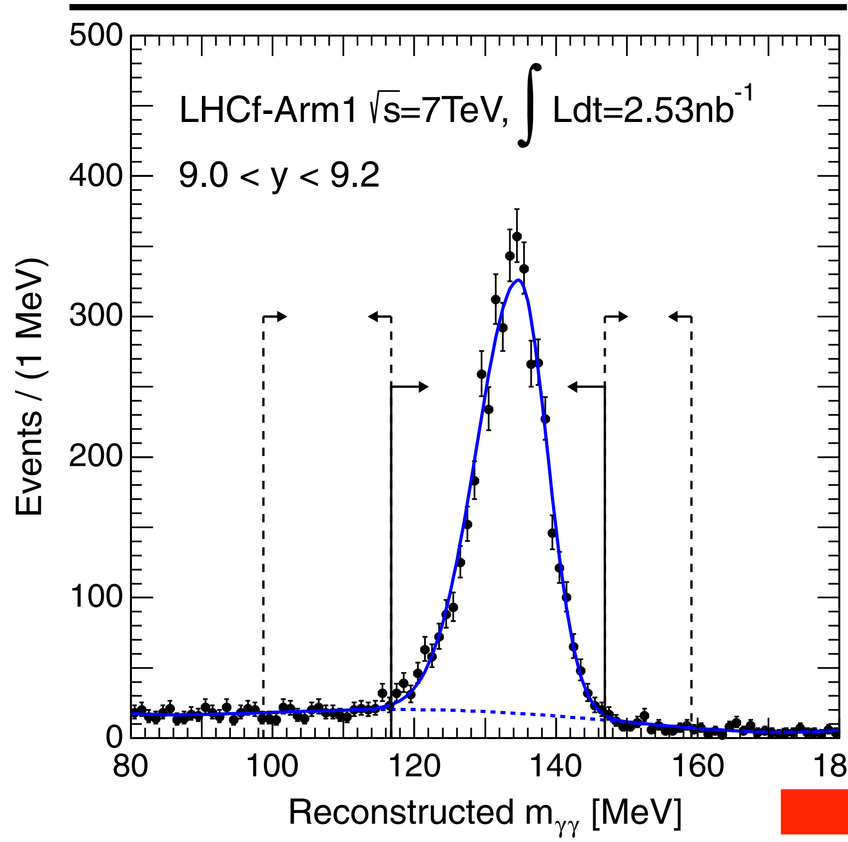
- No model can reproduce the LHCf data perfectly.
- Data points are on the middle of MC predictions except E < 500GeV.

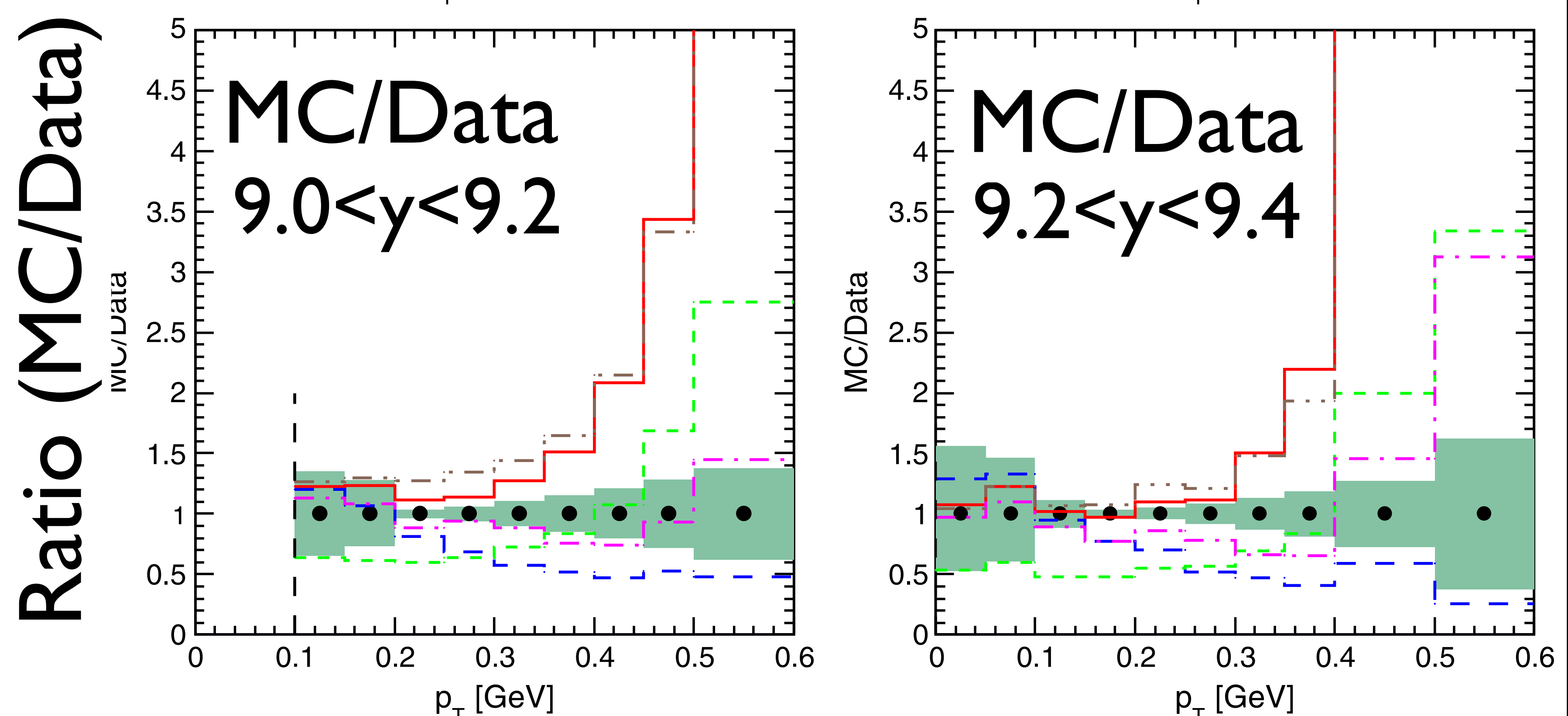
Neutral Pions at 7TeV p-p





Reconstructed Mass

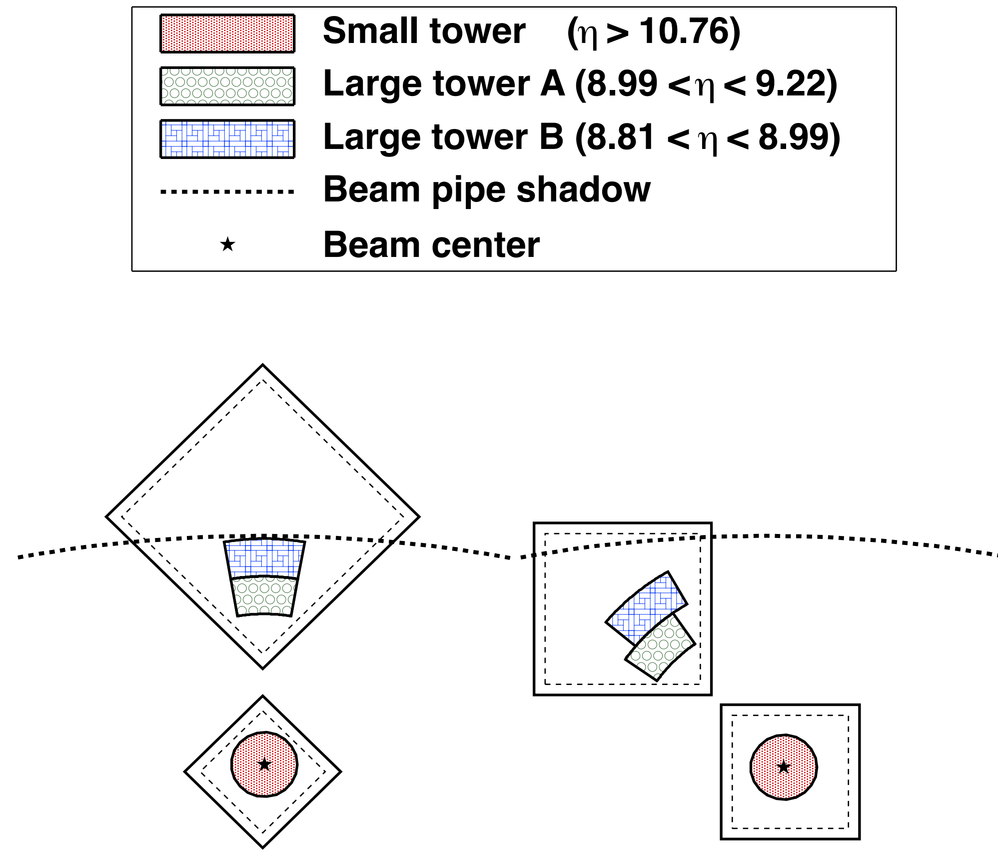




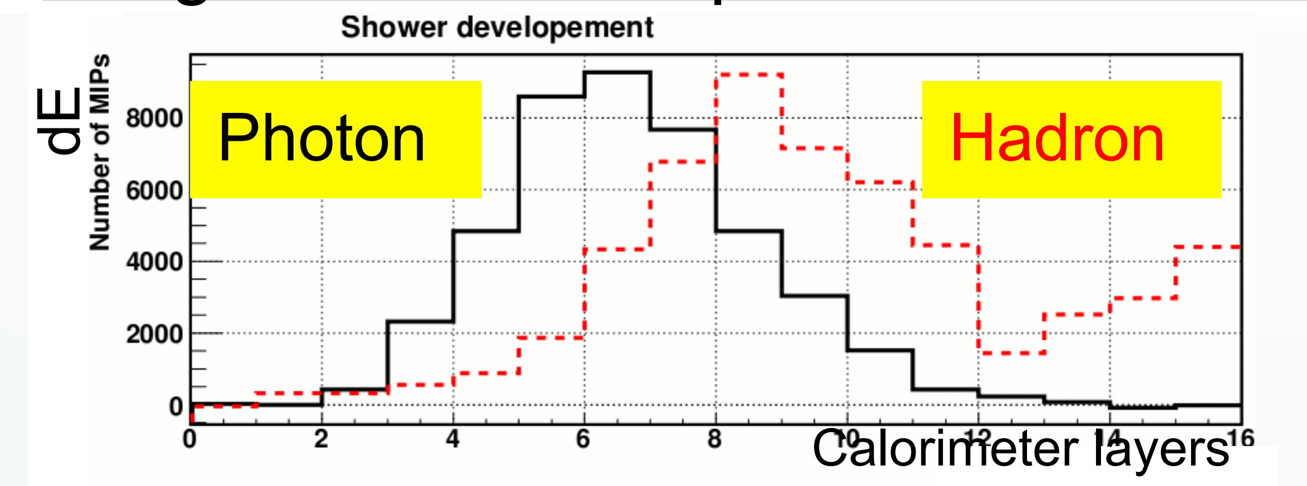
Consistent with Photon results

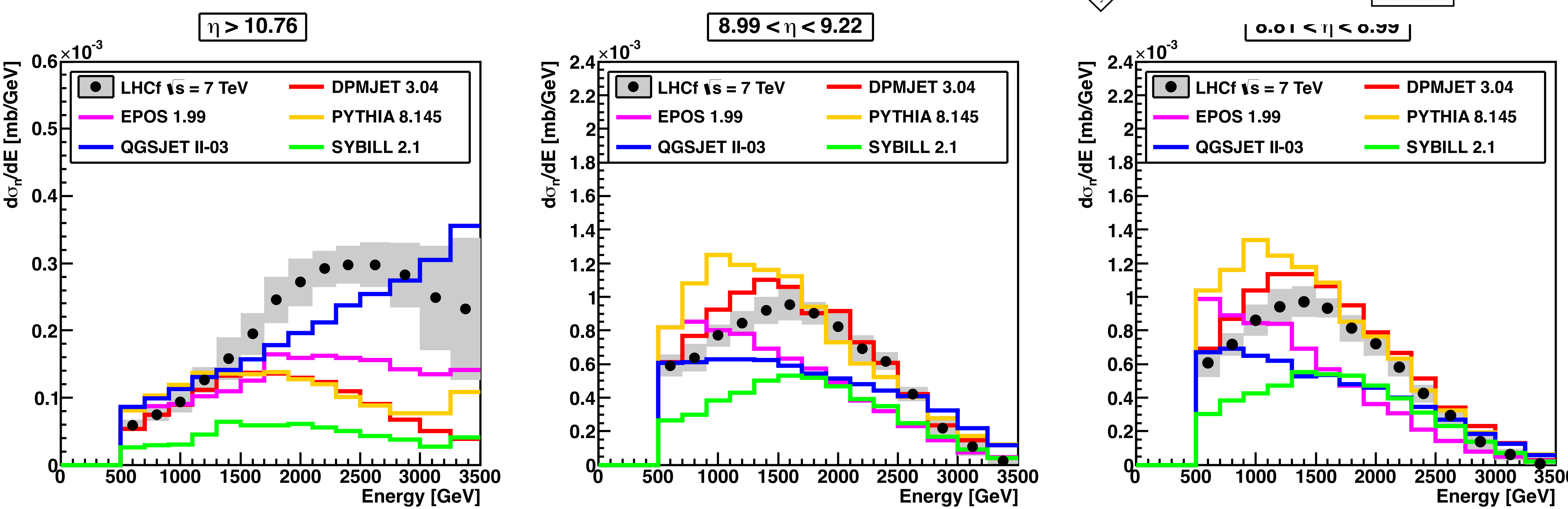
Neutron at √s=7TeV, p-p

For neutron analysis, the events with deeply developed showers were used.



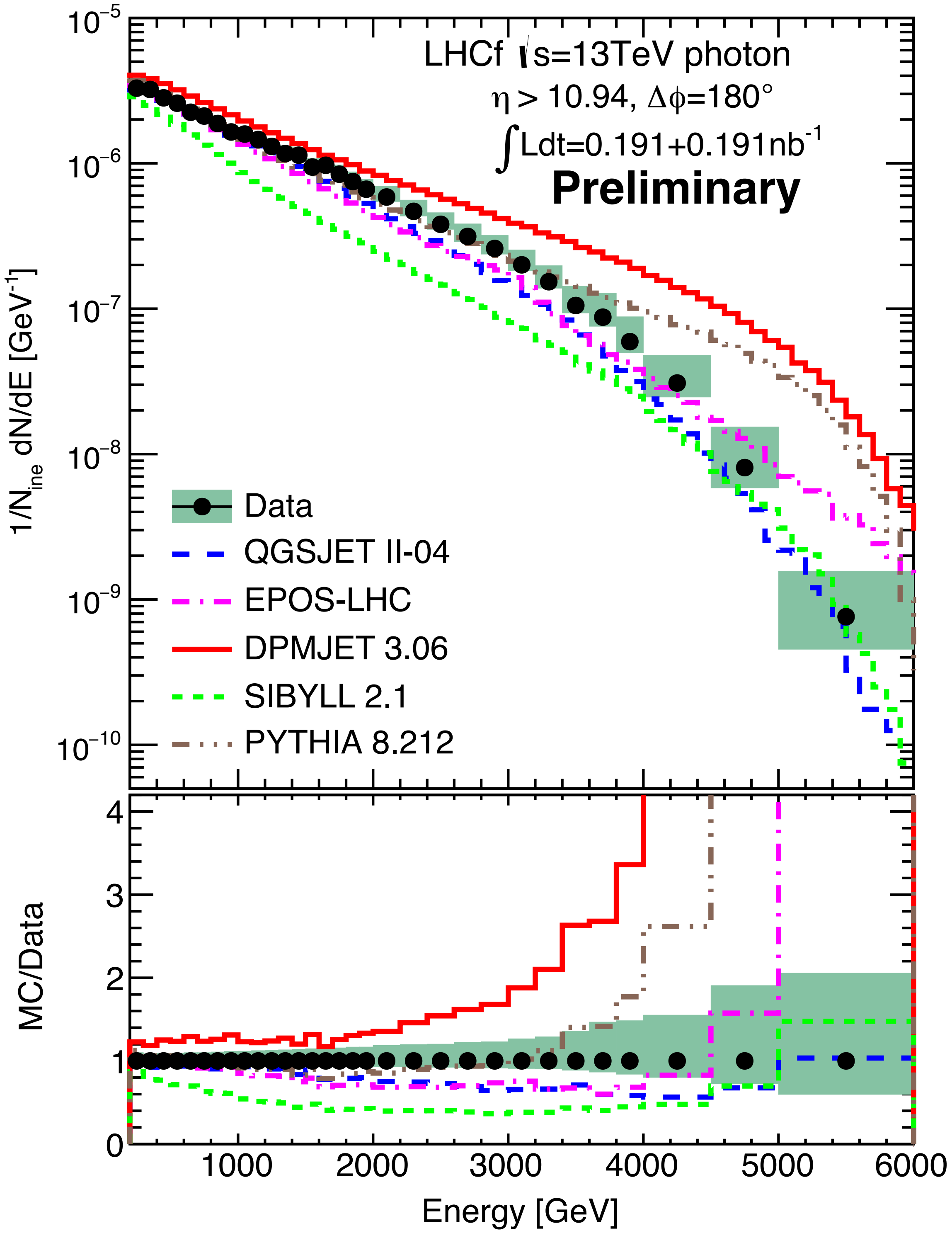
<u>Longitudinal development of showers</u>



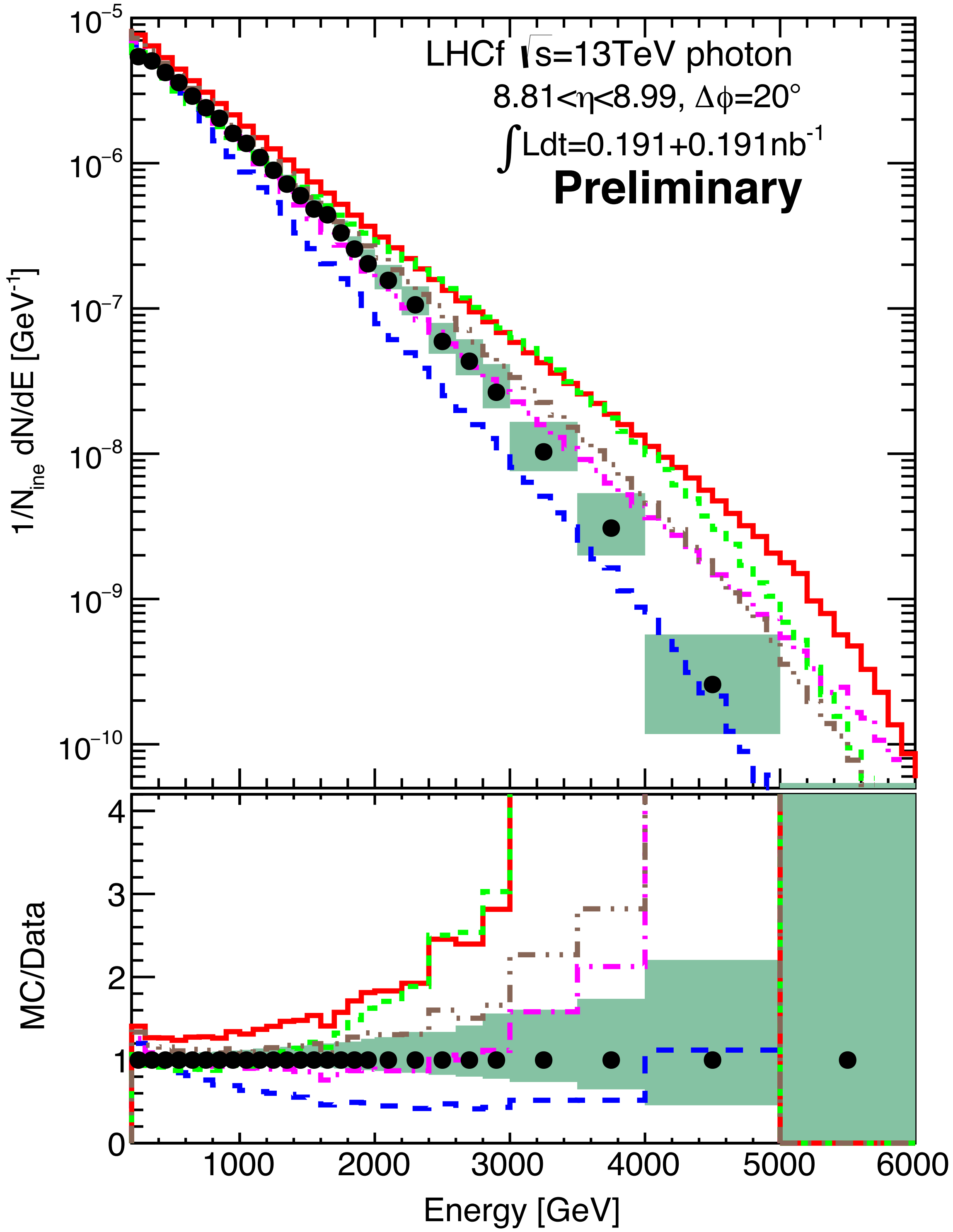


Photons, p-p √s=13TeV

η > 10.94, $\Delta\phi$=180°



8.81<η<8.99, $\Delta\phi$=20°

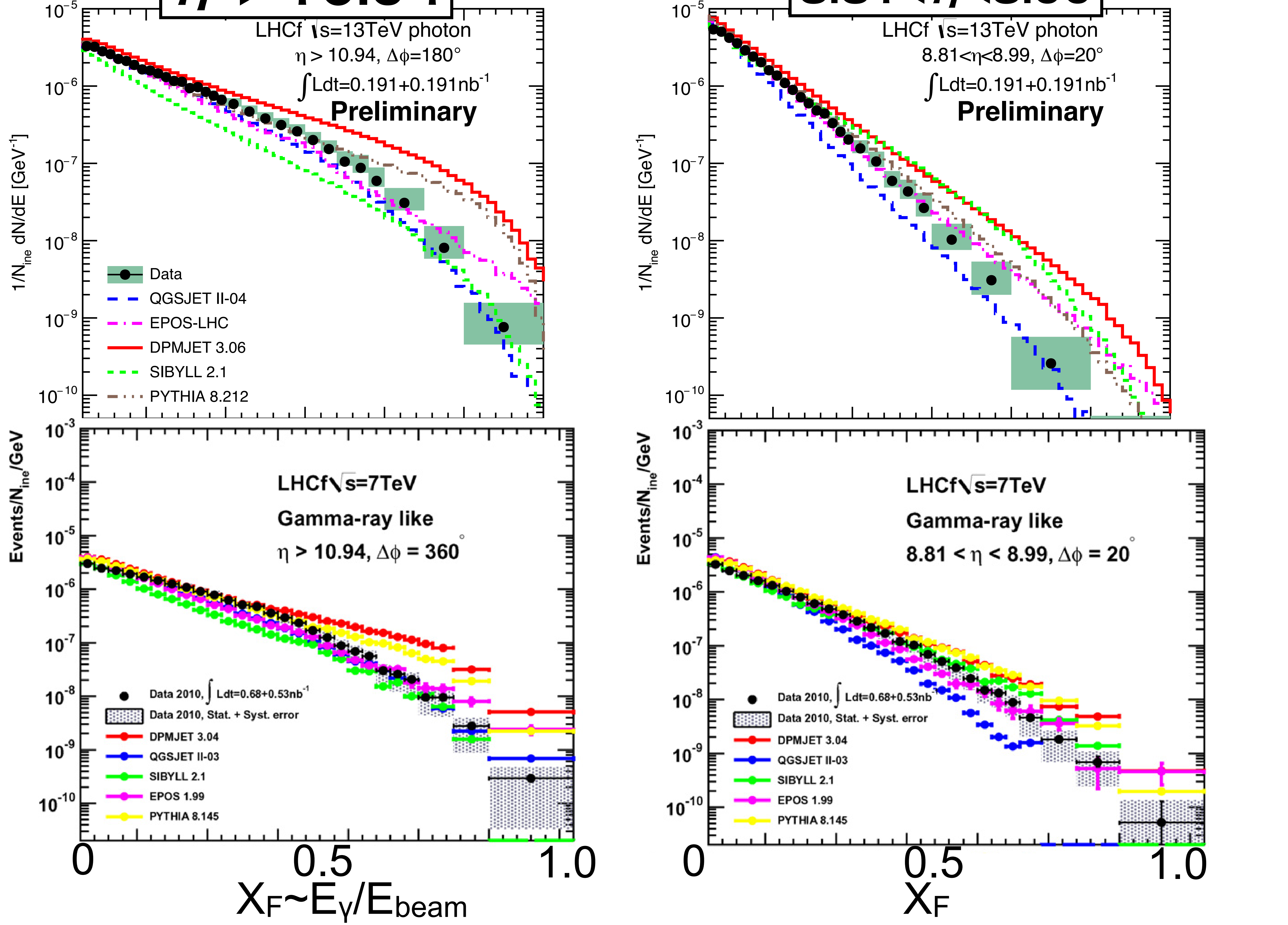


Comparison with 7TeV result

η > 10.94 | 8.81<η<8.99

√s=13TeV

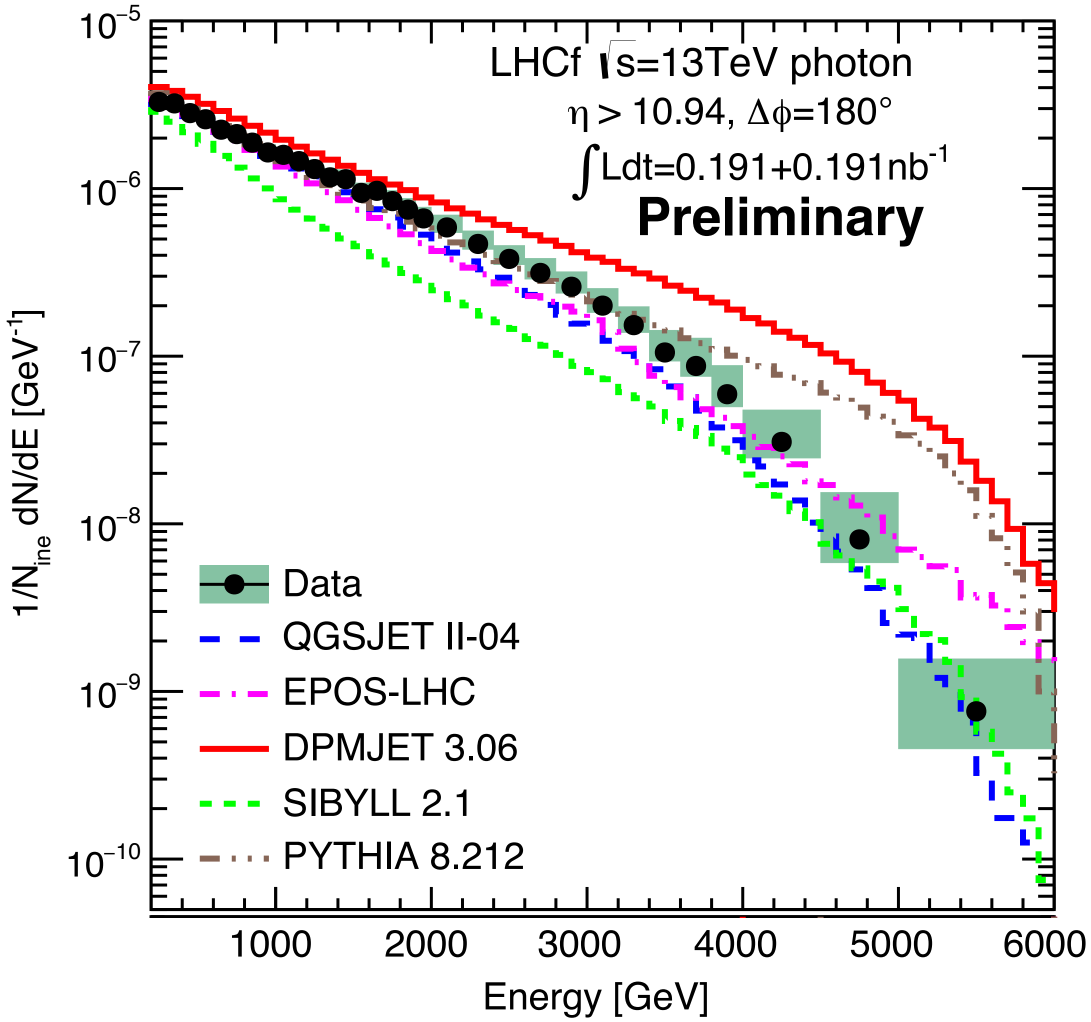
√s=7TeV



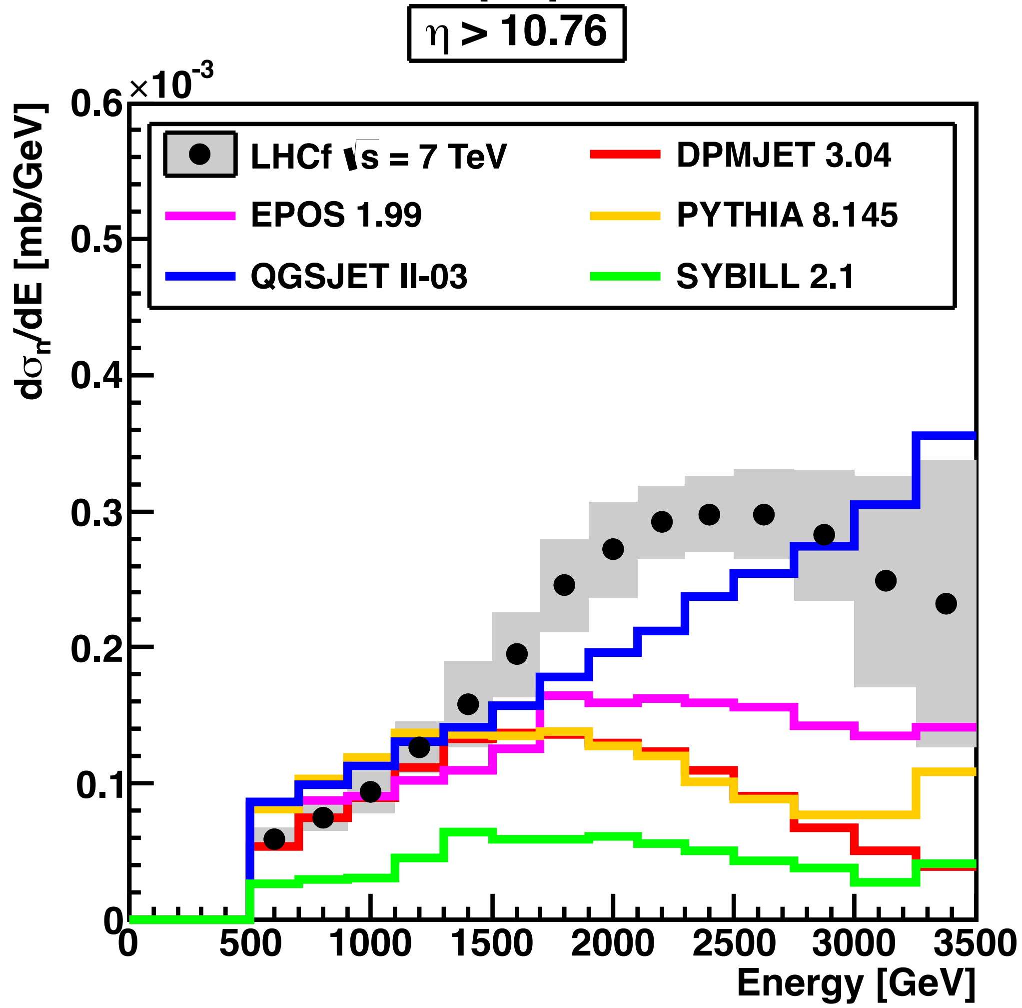
Short summary of results

- LHCf results (comparison with model predictions)
  ⇒ **No model can reproduce data perfectly.**
  - γ,π^0: data is located in the band of model predictions.
  - n: higher flux at zero degree than any models.

photons, p-p √s=13TeV



neutrons, p-p √s=13TeV



What's the next ?

What are sources of discrepancies between data and models predictions ?

The LHCf data, inclusive spectra of photons, π^0, neutrons, clearly requires the tuning/modification of models. To understand the discrepancy, process-related data are really helpful for the model developers

- ☑ Diffractive / non-diffractive selection by ATLAS information.

What data are additionally needed to test/tune the models ?

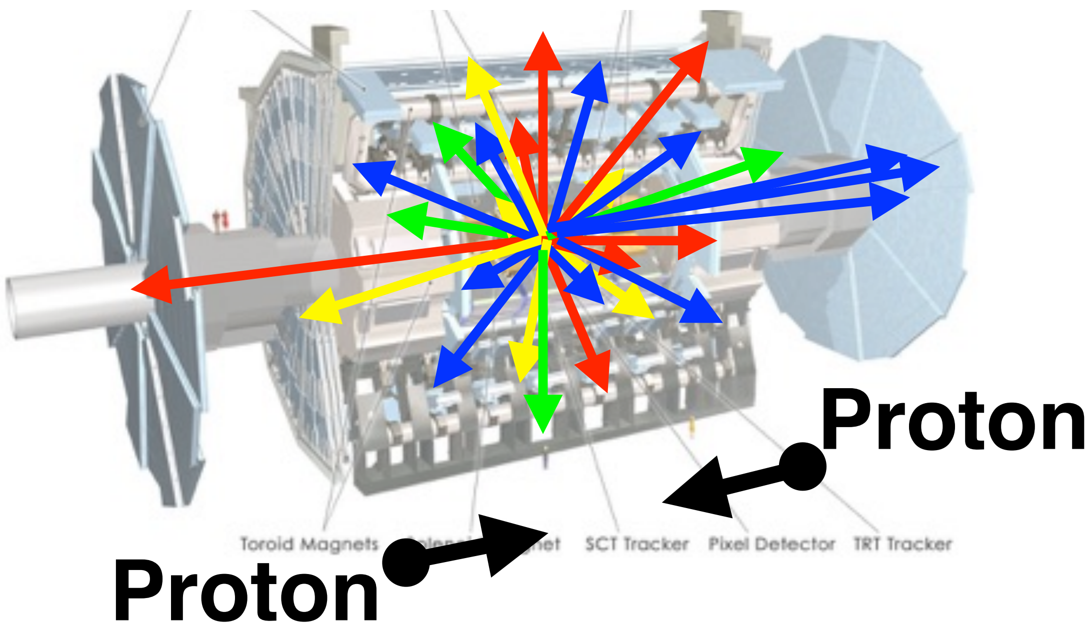
QGSJET2 and EPOS has been tuned with several data taken at p-p $\sqrt{s}$=7TeV. However issues related to UHECRs are not solved yet.
=> Additional data are needed.

- ☑ Production cross section of other mesons, η, ρ, K and etc.
  LHCf can access the production cross section of η in the forward region.
- ☑ p−π interaction in the air-shower development.
  LHCf+ATLAS can measure p-π collisions **at LHC**
- ☑ Test of models at a lower collision energy
  LHCf goes to RHIC(p-p $\sqrt{s}$=500GeV) at BNL

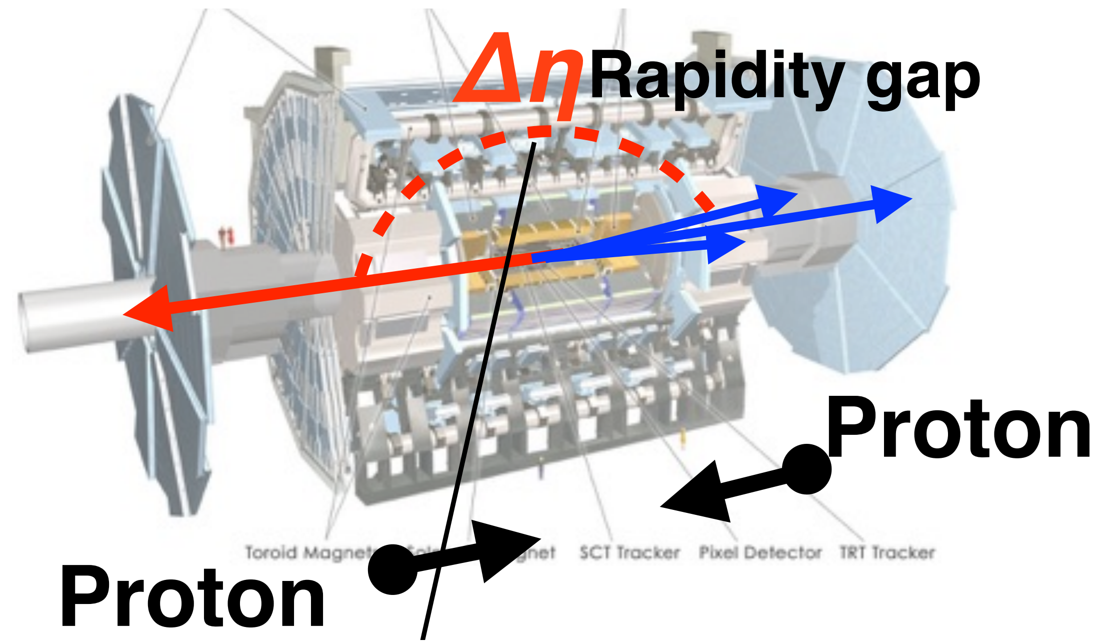
Diffractive collisions

Event categorization with non-diffractive and diffractive collisions.

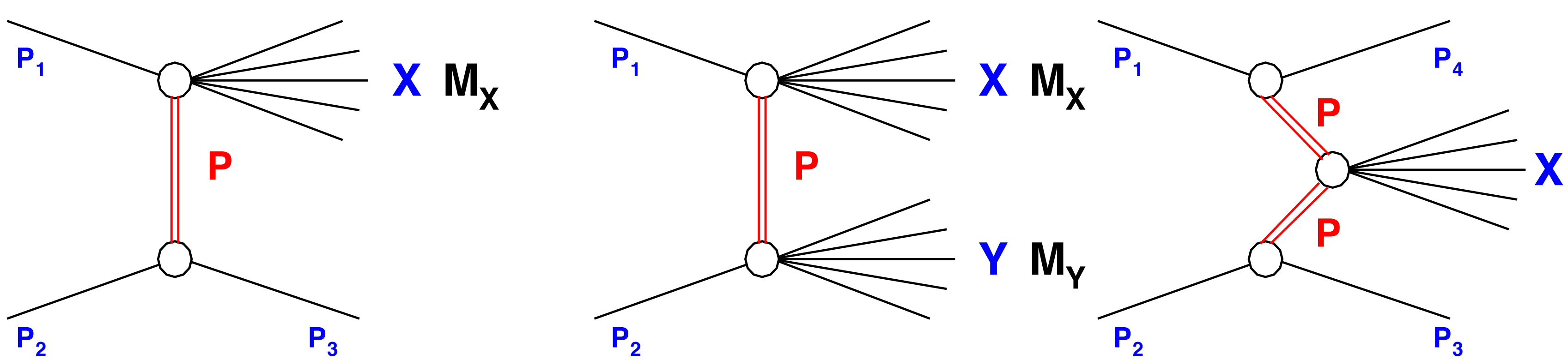
Non-diffraction



Diffraction



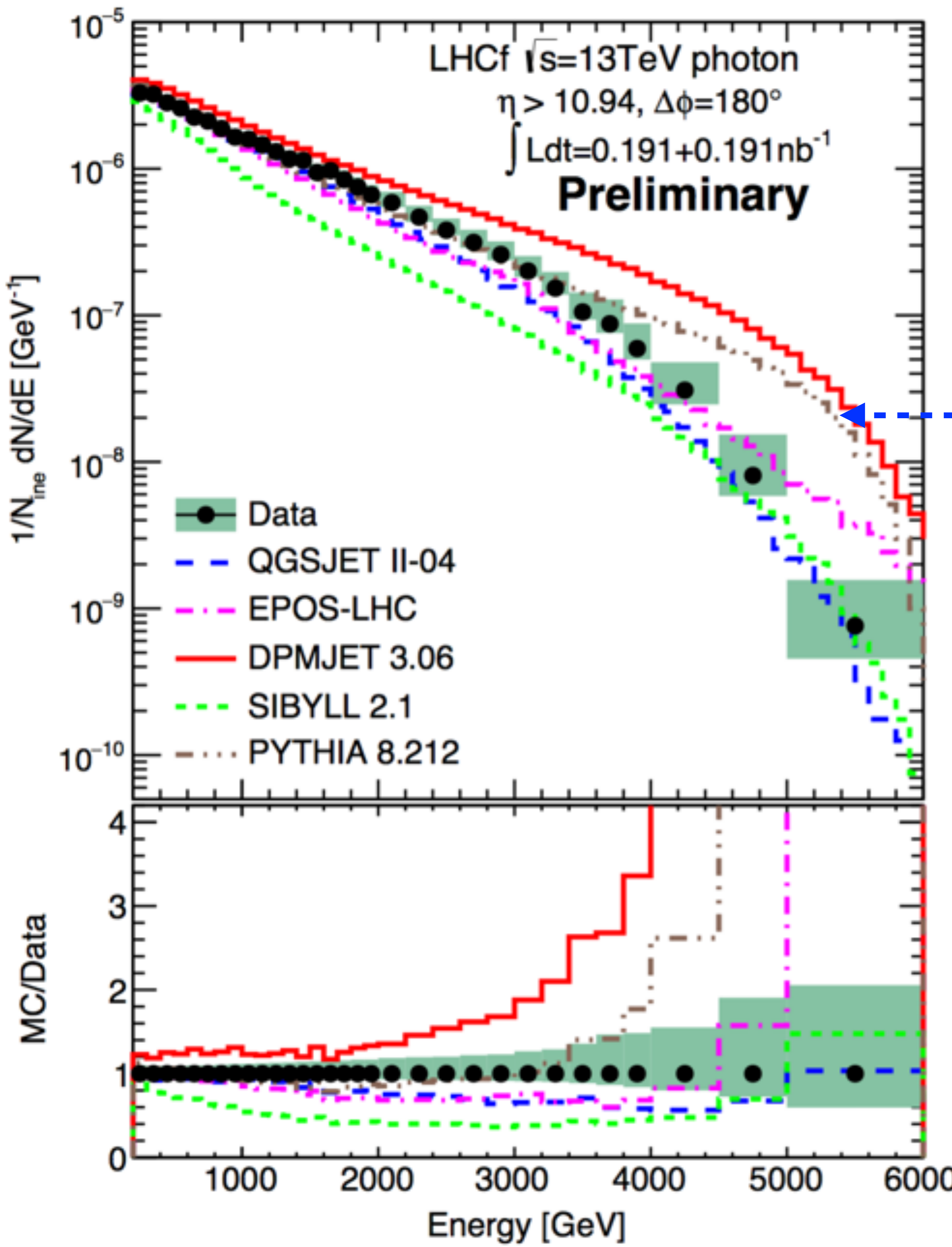
Diffractive processes

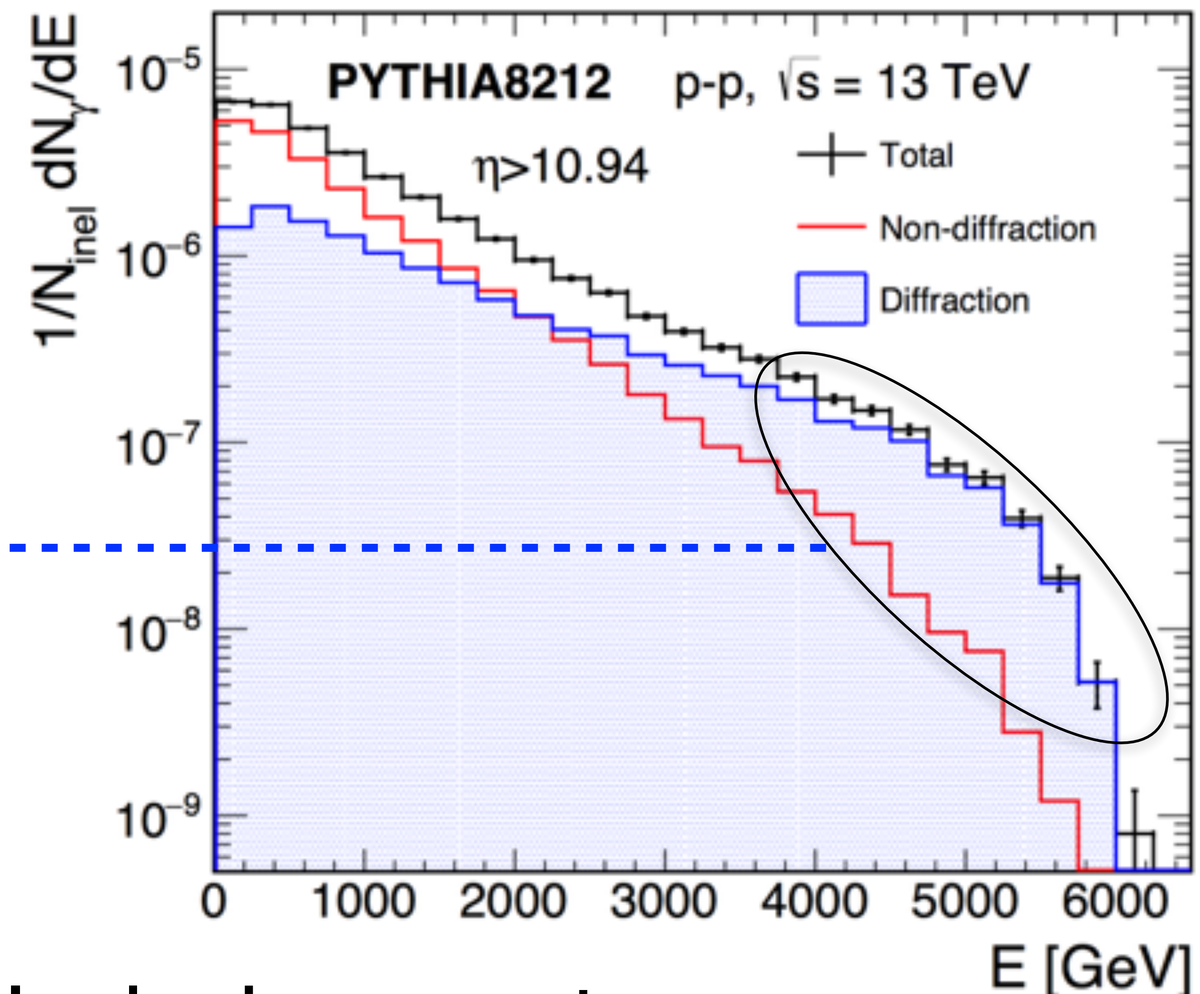


(a) (b) (c)

Single-diffraction Double-diffraction Central-diffraction

Investigation of photon spectrum





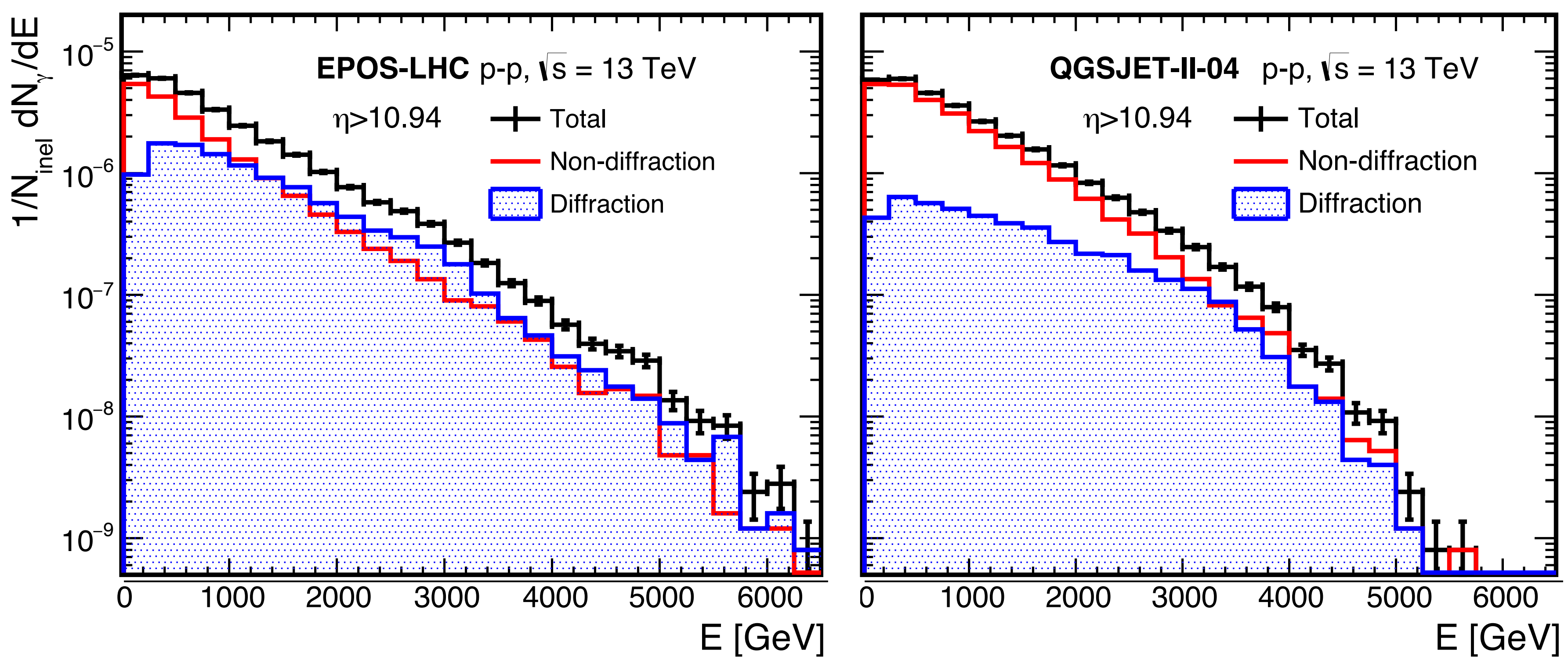
Inclusive spectrum: contribution from diffraction + non-diffraction

The excess of PYTHIA8 at E>3TeV due to over contribution from diffraction

Slides from Q.Zhou @ Low-X 2016

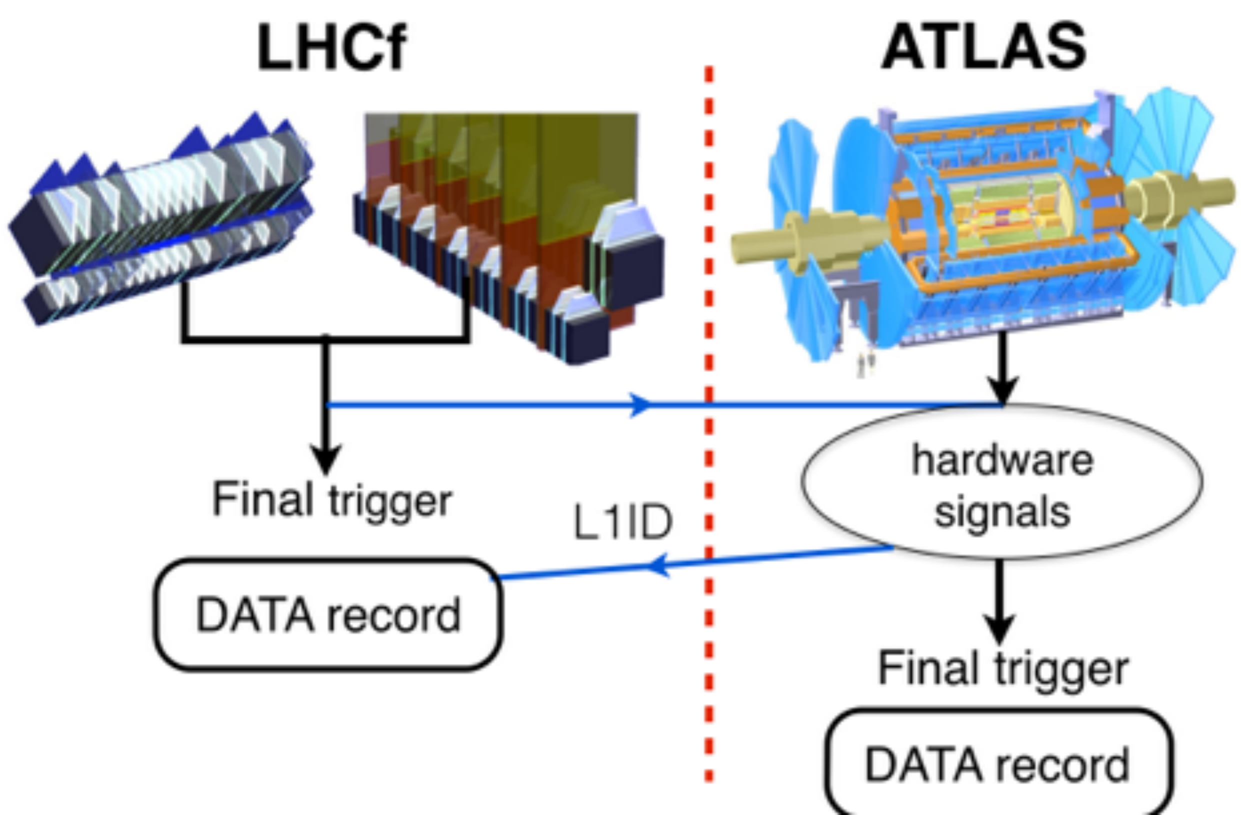
Contribution of diffractive collisions

Photon, p-p √s=13TeV, η>10.94



Inclusive spectra:
QGSJET2 ~ EPOS-LHC

Contribution of Diffraction
QGSJET2 < EPOS-LHC

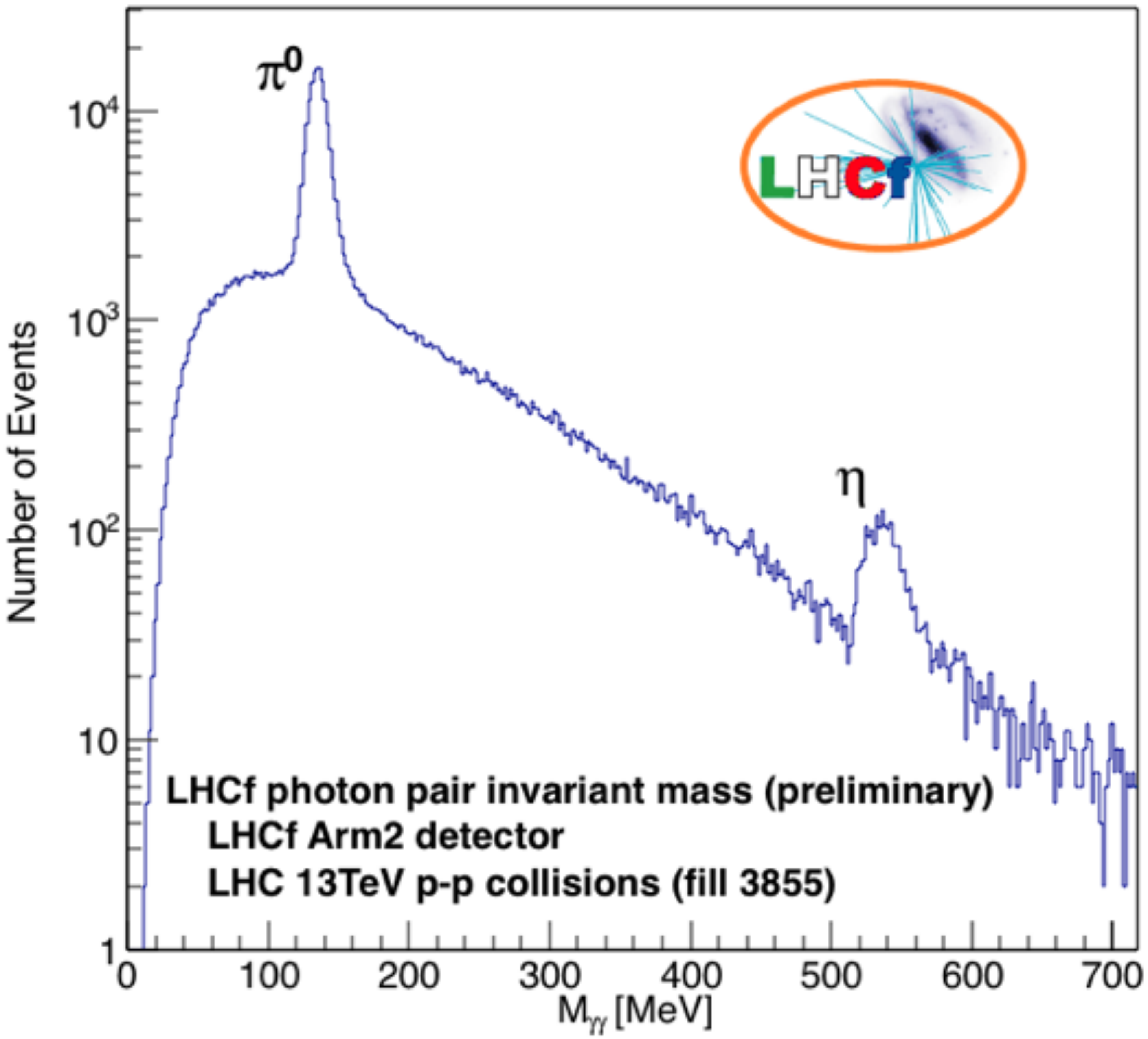


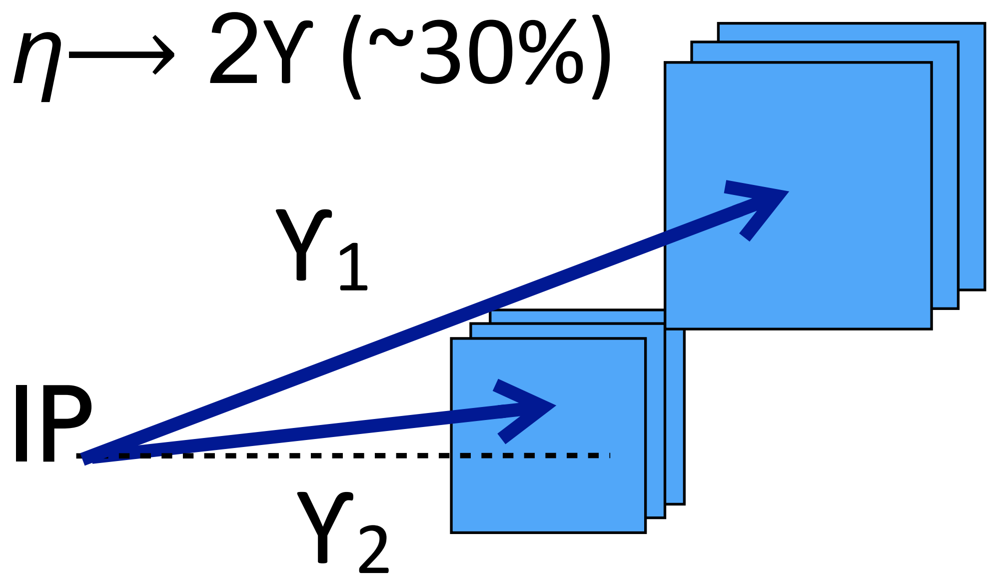
The common operation with ATLAS has been successfully done in 2015.
The event selection by using number of tracks measured by ATLAS is a powerful tool to identify diffractive or non-diffractive events

Common analysis is on-going

η measurement

Peaks corresponding to π^0, η



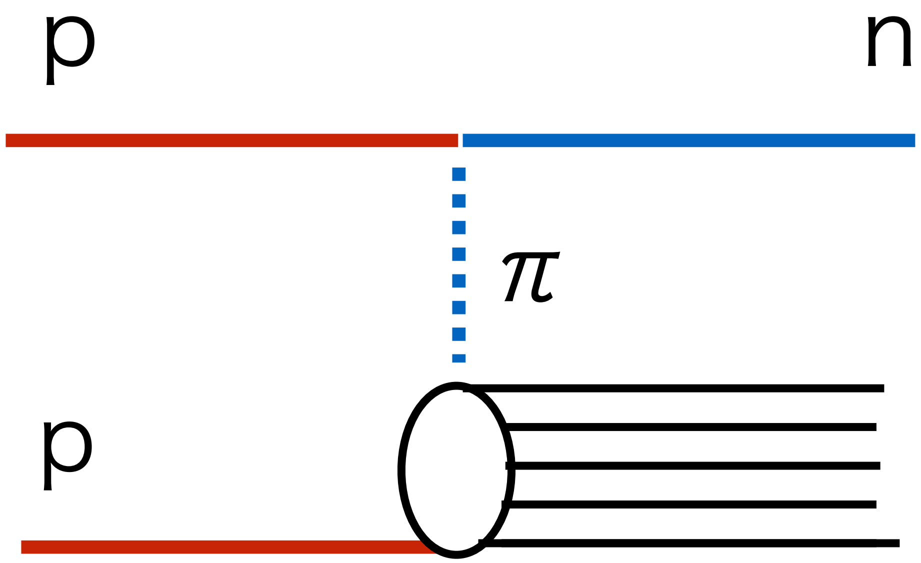


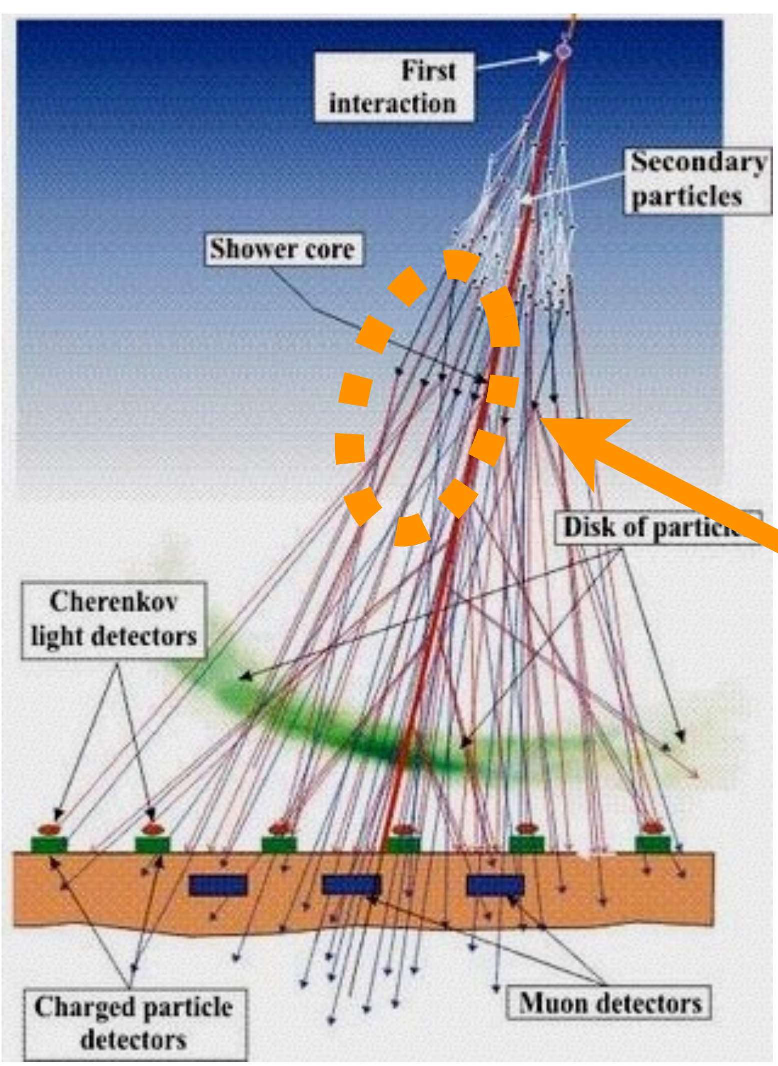
Energy thresholds for π^0 and η detections

For π^0 : $E_{\pi 0} > 600$GeV

For η : $E_{\eta} > 2.2$ TeV

Measurement of p-π^0 collisions





<u>LHC is p-π collider also ?</u>

proton may collide the pion cloud around coming proton. The pion-exchange events are tagged with the detection of one high energy neutron in the very forward region.

$$p+p \rightarrow n + (\pi^{+} + p) \rightarrow n + X$$
$$p: 6.5\ \text{TeV},\ \pi:\sim 1.0\text{TeV} \rightarrow \sqrt{s_{p\pi}} = 6\ \text{TeV}$$

Measurement of π+p interactions is very important as the hadronic interaction of secondaries in Air showers

Summary

- Hadronic interaction models is one of the keys for precise measurement of UHECRs
- LHCf is a forward experiment of LHC. LHCf published the results of photons, π^0 and neutrons at p-p with several collision energies of 0.9, 2.76, 7 and 13TeV.
- New data from LHCf, diffractive studies, p-π^0 collisions, measurement at RHIC, will be provided and hadronic interaction models will be improved.

Measurement at RHIC