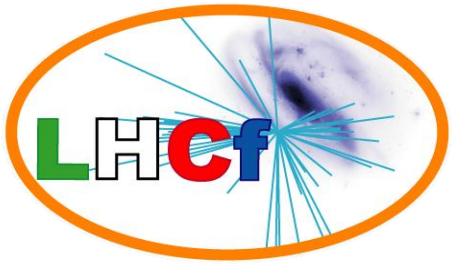
Forward physics with the LHCf experiment:
a contribution of LHC to the cosmic-ray physics

Lorenzo Bonechi
INFN section of Firenze (Italy)

on behalf of the LHCf Collaboration

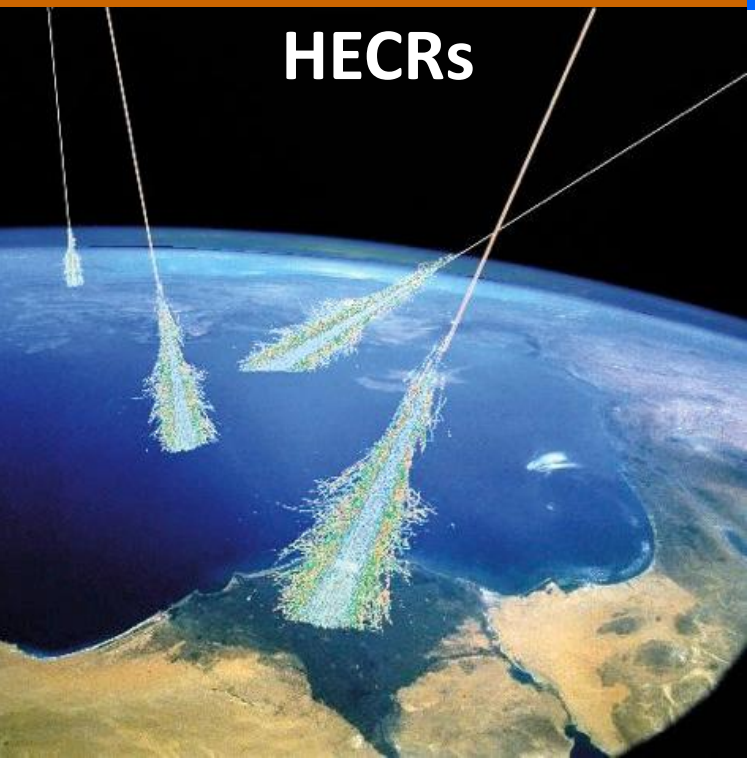


International Conference on New Frontiers in Physics
28 August 2013 – 05 September 2013 Kolymbari (Crete)

Outline

- Introduction
  - The physics framework of LHCf
  - Overview of the detectors and their location at the LHC
- Data taking and published results
  - Energy spectra of forward photons in 900 GeV and 7 TeV pp collisions
  - Spectra of forward-emitted π^0s in 7 TeV pp collisions
- On-going analysis
  - Study on the neutron component in 7 TeV pp collisions
  - The 2013 p-Pb run at $\sqrt{s_{NN}} = 5\ \mathrm{TeV}$
- Future plan

High Energy Cosmic Rays



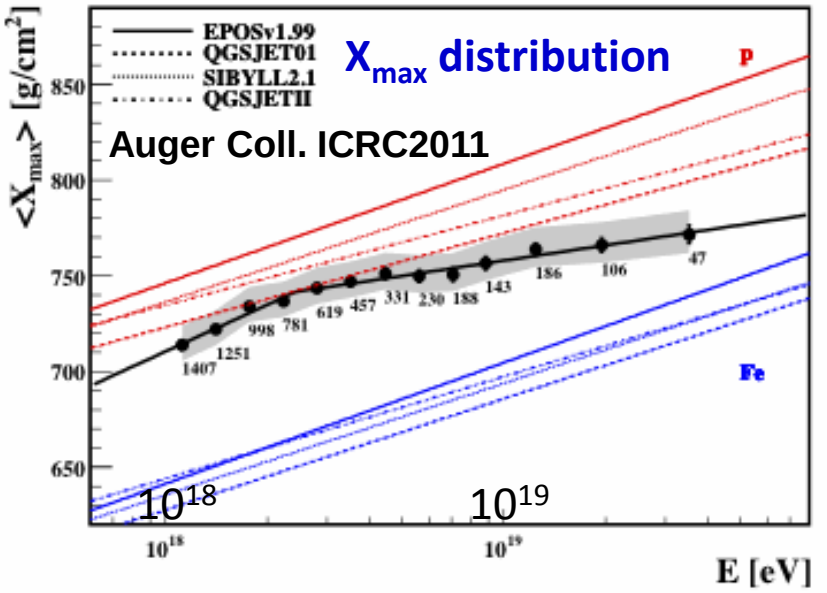
Extensive air shower observation

- longitudinal distribution
- lateral distribution
- Arrival direction

⇓ **Air shower development**

Astrophysical parameters

- Spectrum
- Composition
- Source distribution



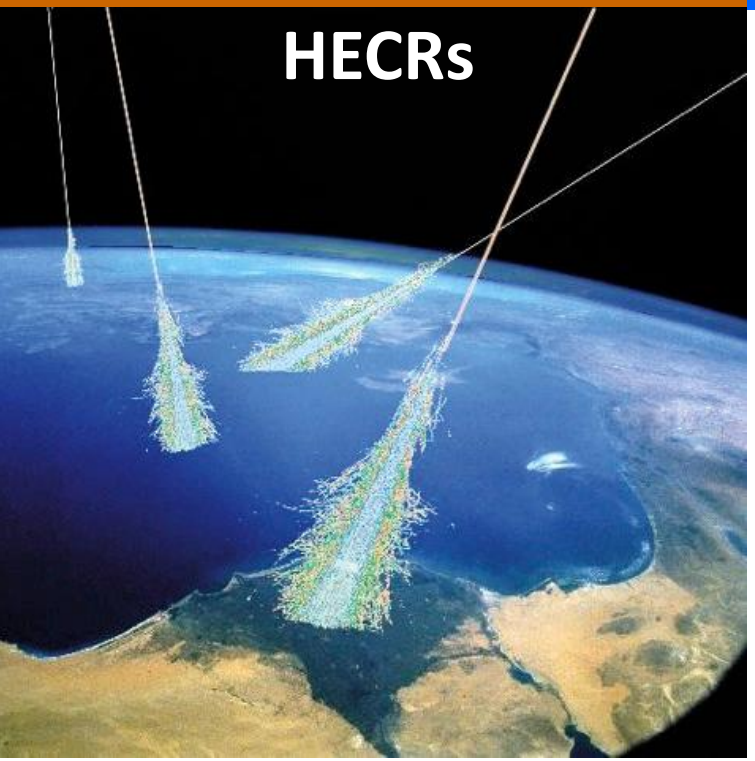
X_{max} is the depth of air shower maximum in the atmosphere. An indicator of CR composition.

Uncertainty of hadron interaction models

⇓

Uncertainty in the interpretation of $\langle X_{max} \rangle$

High Energy Cosmic Rays



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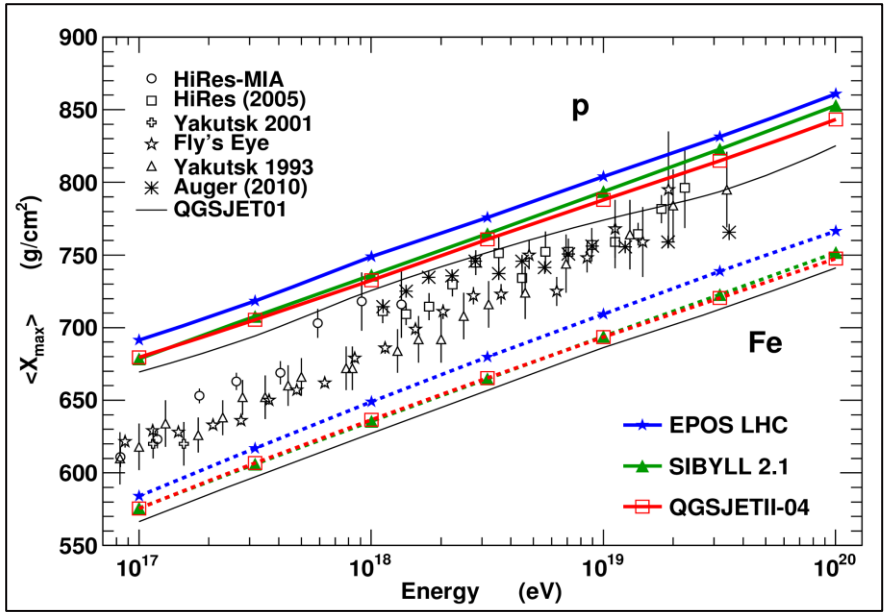
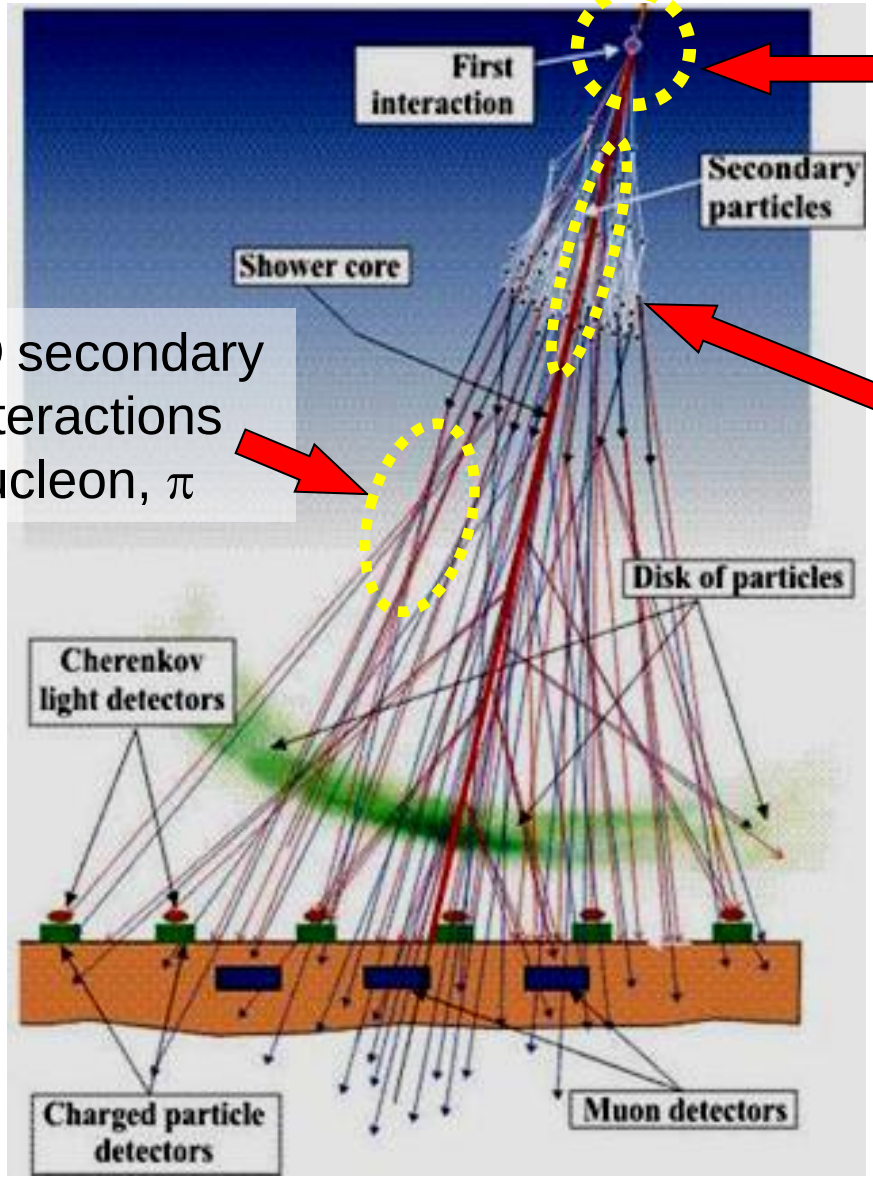


After newest LHC data

(P. Tanguy's presentation at the *Cosmic QCD 2013* conference in Paris)

Atmospheric Showers



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 shallow development
If harder deep penetrating

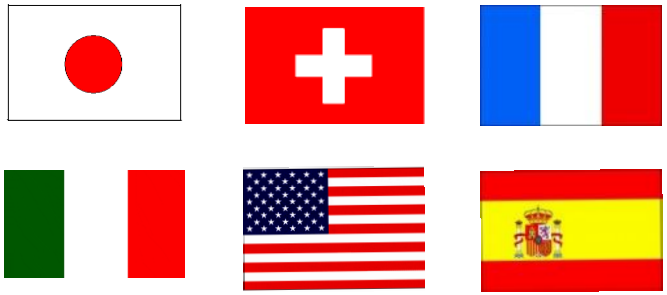
③ **Inelasticity** $k = 1 - \frac{E_{lead}}{E_{avail}}$

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

The LHCf international collaboration

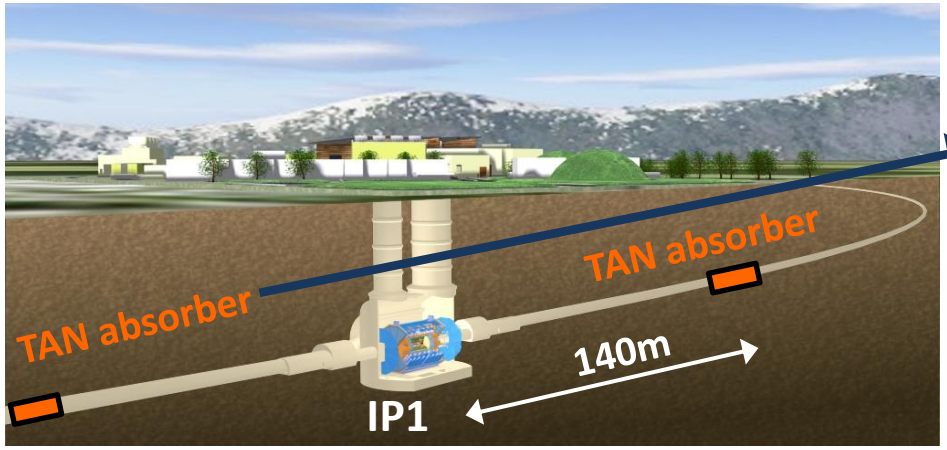
O.Adriani[a,b], L.Bonechi[b], M.Bongi[a], G.Castellini[c,b], R.D'Alessandro[a,b], A.Faus[d], M.Grandi[b], M.Haguenauer[e], Y.Itow[f,g], K.Kasahara[h], K. Kawade[g], Y.Makino[g], K.Masuda[g], Y.Matsubara[g], E.Matsubayashi[g], H.Menjo[i], G.Mitsuka[g], Y.Muraki[g], P.Papini[b], A.-L.Perrot[j], D.Pfeiffer[j], S.Ricciarini[c,b], T.Sako[g], Y.Shimitsu[h], Y.Sugiura[g], T.Suzuki[h], T.Tamura[k], S.Torii[h], A.Tricomi[l,m], W.C.Turner[n], J.Velasco[d], K.Yoshida[o], Q.Zhou[g]

a) University of Florence, Italy
b) INFN Section of Florence, Italy
c) IFAC-CNR, Florence, Italy
d) IFIC, Centro Mixto CSIC-UVEG, Spain
e) Ecole Polytechnique, Palaiseau, France
f) Kobayashi Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya, Japan
g) Solar-Terrestrial Environment Laboratory, Nagoya University, Japan
h) RISE, Waseda University, Japan
i) Graduate School of Science, Nagoya University, Japan
j) CERN, Switzerland
k) Kanagawa University, Japan
l) University of Catania, Italy
m) INFN Section of Catania, Italy
n) LBNL, Berkeley, California, USA
o) Shibaura Institute of Technology, Japan



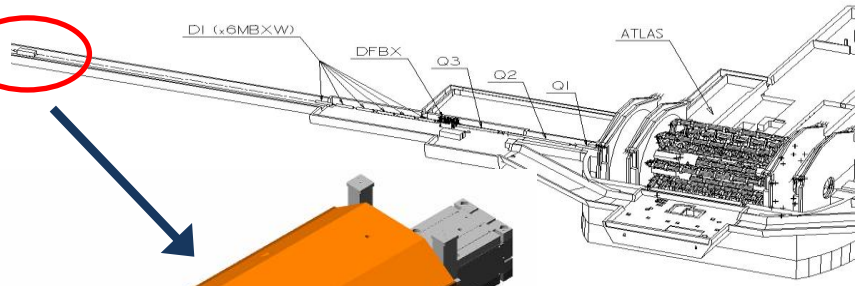
The LHCf international collaboration

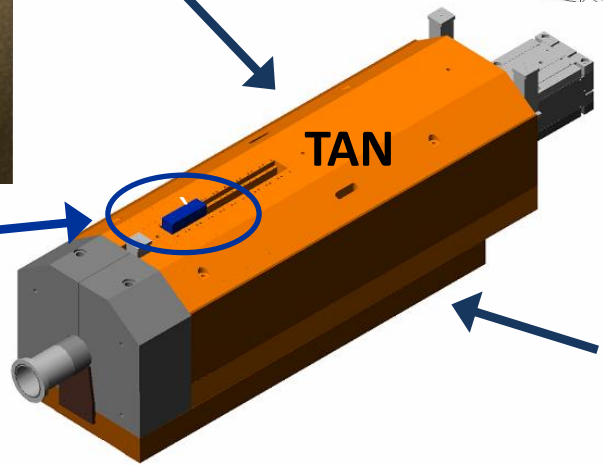
Overview of the experiment



Forward Physics region

ATLAS





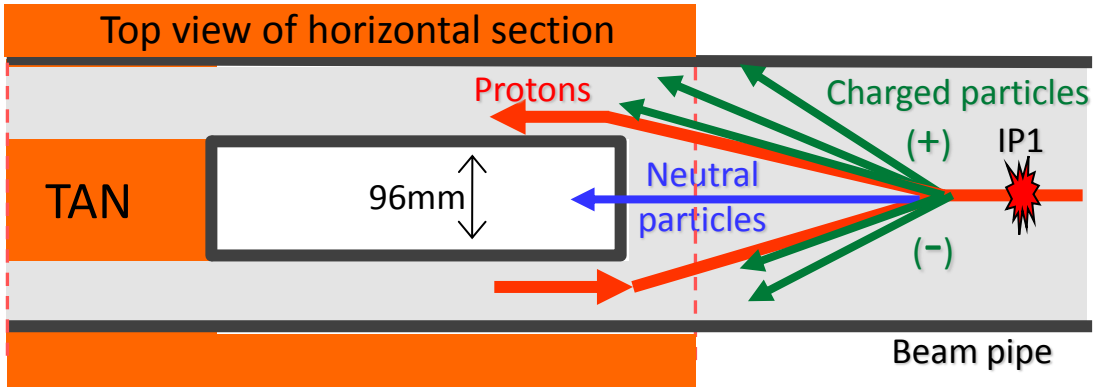
Detectors are located Inside the TAN, absorber for neutral particles

Detectors measure energy and impact point of γ from π^0 decays

→ **e.m. calo + tracking layers**

Two independent detectors on both sides of IP1

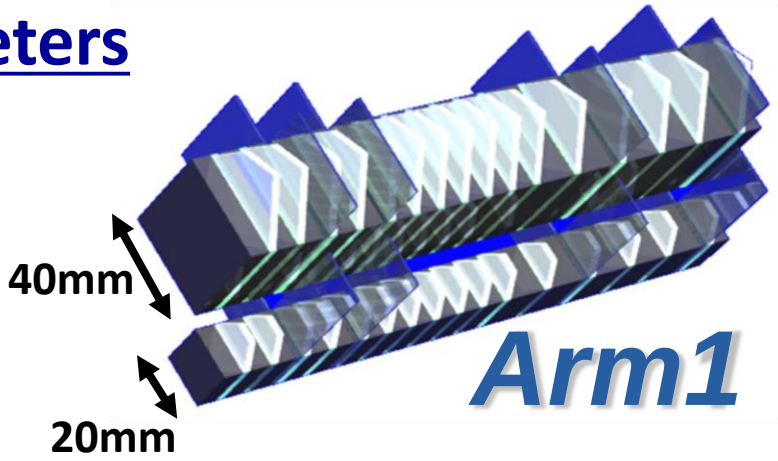
- ✓ Redundancy
- ✓ Background rejection (esp. beam-gas)

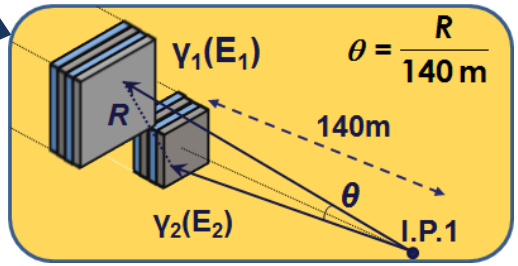


Sampling and imaging E.M. calorimeters

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

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

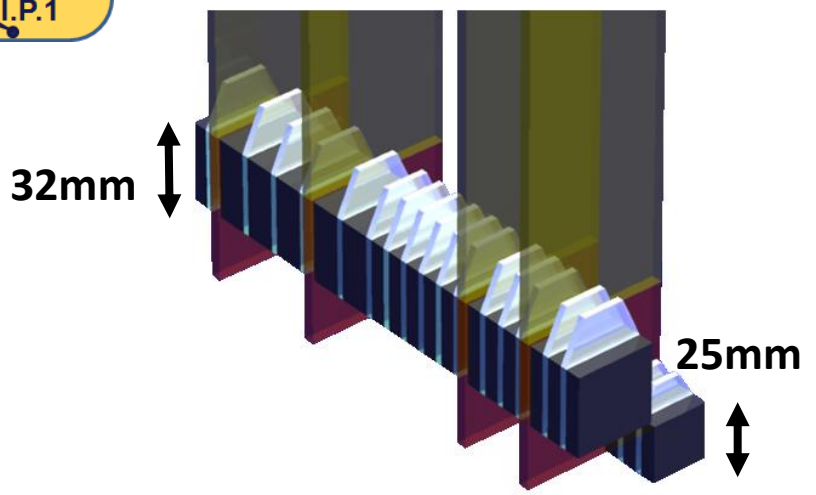




Performance

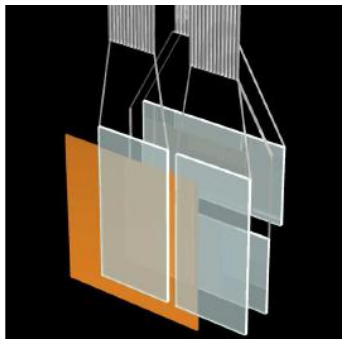
Energy resolution (> 100GeV)
< 5% for γ and ~ 30% for **n**

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

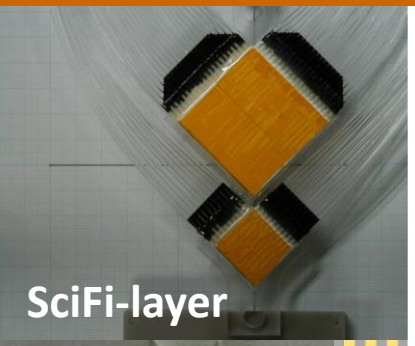


Front Counters

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



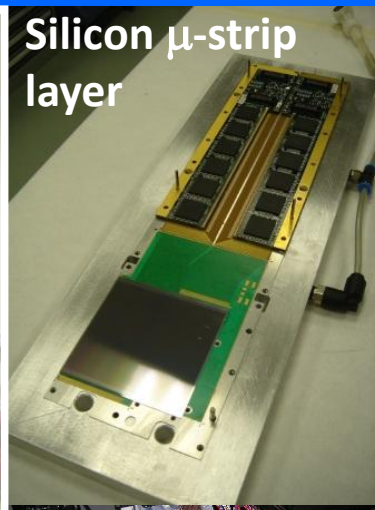
Some photos


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

Physics program

Year	Beams	Beam energy	Proton equivalent energy in the LAB (eV)	Setup
2009	p - p	450+450 GeV	$4.3\ 10^{14}$	Arm1+Arm2
2009/2010	p - p	3.5+3.5 TeV	$2.6\ 10^{16}$	Arm1+Arm2
2013	p – Pb	4 TeV proton	$1.3\ 10^{16}$	Arm2
2013	p - p	1.38+1.38 TeV	$4.1\ 10^{16}$	Arm2
2015	p - p	6.5+6.5 TeV	$9\ 10^{16}$	Arm1+Arm2 upgraded
?	p – light ions	?	?	?

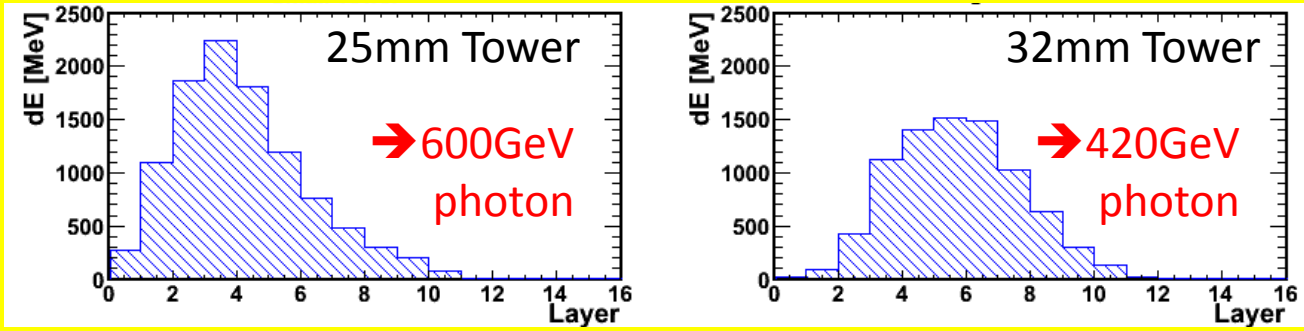
- *"Measurement of zero degree inclusive photon energy spectra for √s = 900 GeV proton-proton collisions at LHC"*, **O. Adriani et al., PLB, 715, p. 298-303 (2012)**

- *"Measurement of zero degree single photon energy spectra for √s = 7 TeV proton-proton collisions at LHC "*, **O. Adriani et al., PLB, Vol.703-2, p.128-134 (09/2011)**

- *"Measurement of forward neutral pion transverse momentum spectra for √s = 7TeV proton-proton collisions at LHC"*, **O. Adriani, et al., PRD 86,092001 (2012)**

How we see one event in Arm#2

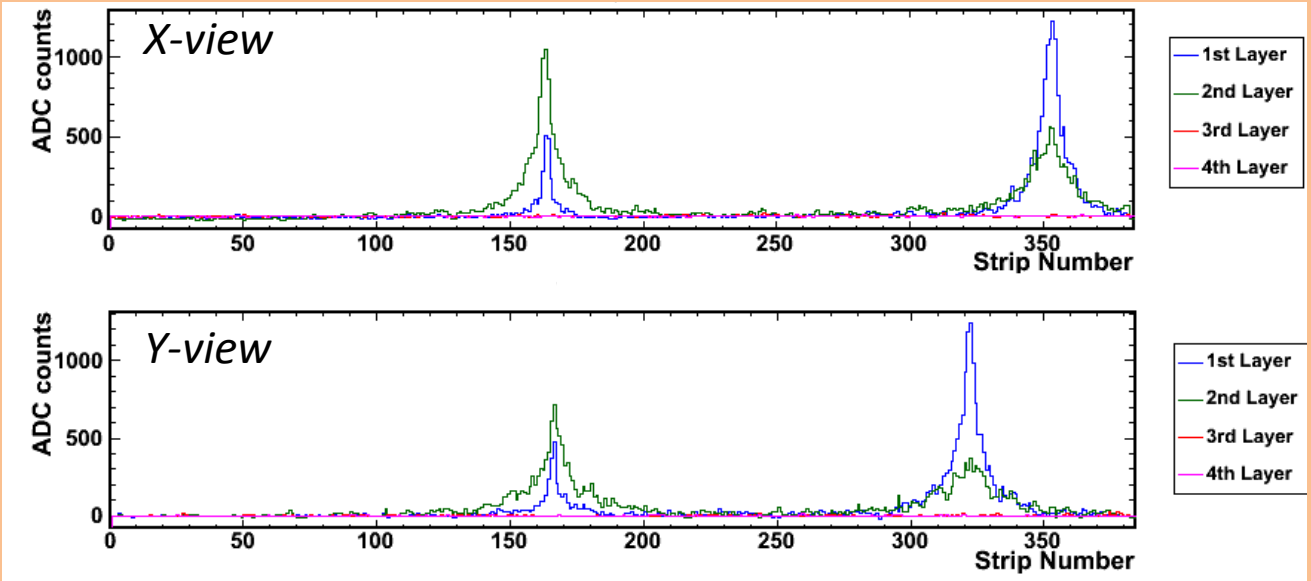
Longitudinal development measured by scintillator layers



Determination of **energy** from total energy release

PID from shape

Transverse profile measured by silicon μ–strip layers



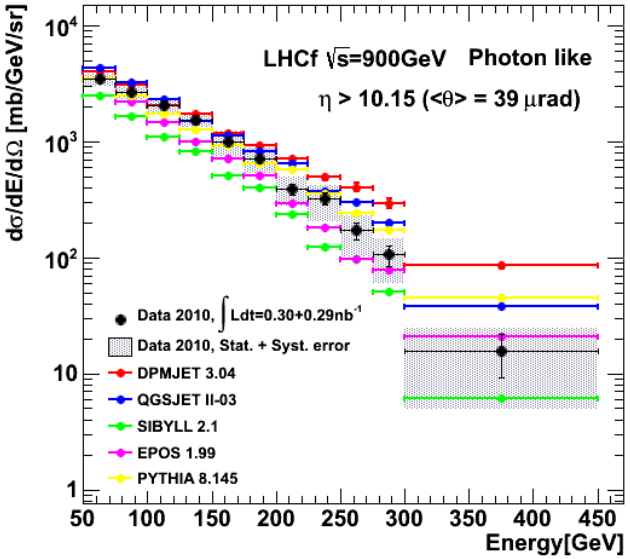
Determination of the **impact point**

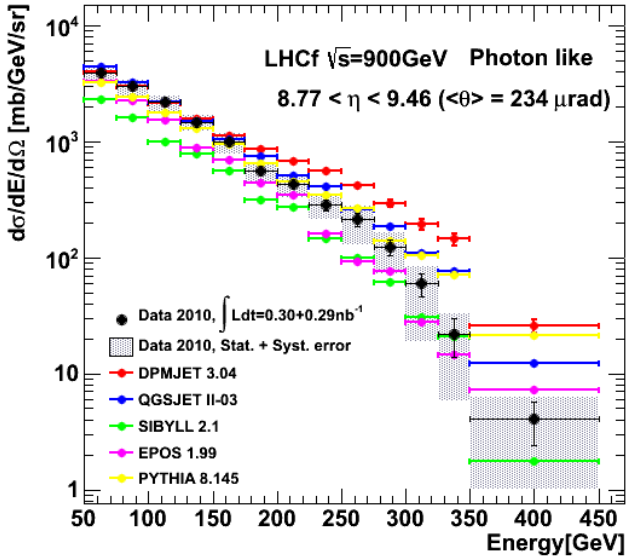
Measurement of the **opening angle** of gamma pairs

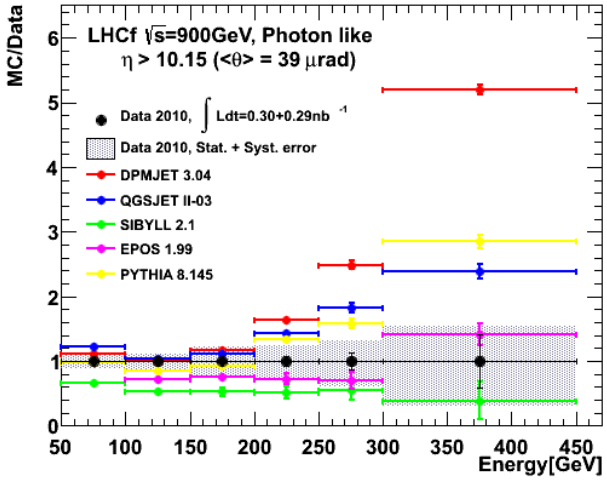
Identification of **multiple hit**

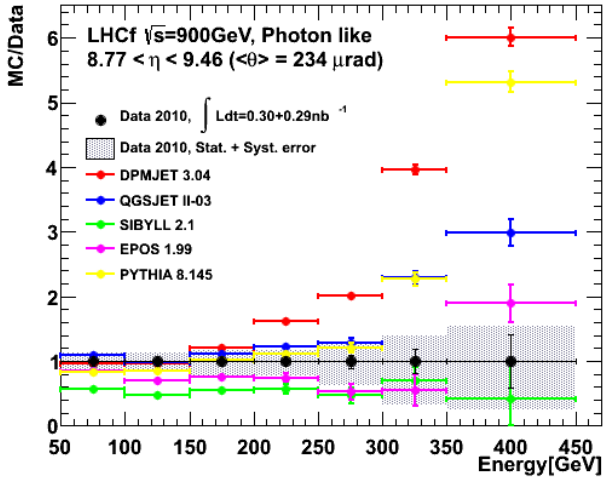
Reconstruction of π^0 mass: $M_{p0} = \sqrt{E_{g1}E_{g2}} \times q$

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

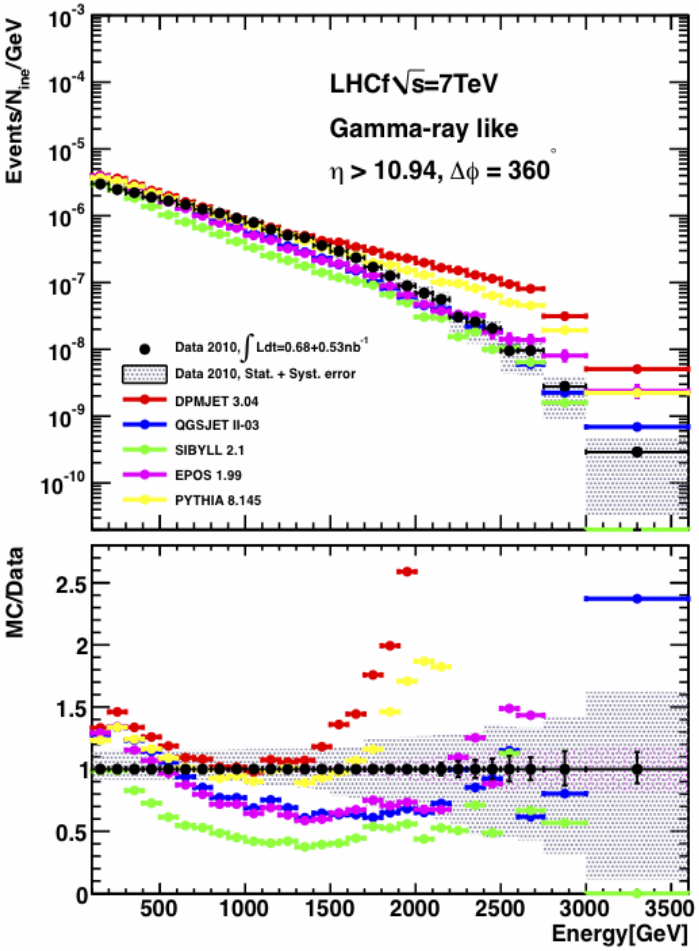
Syst.+Stat.

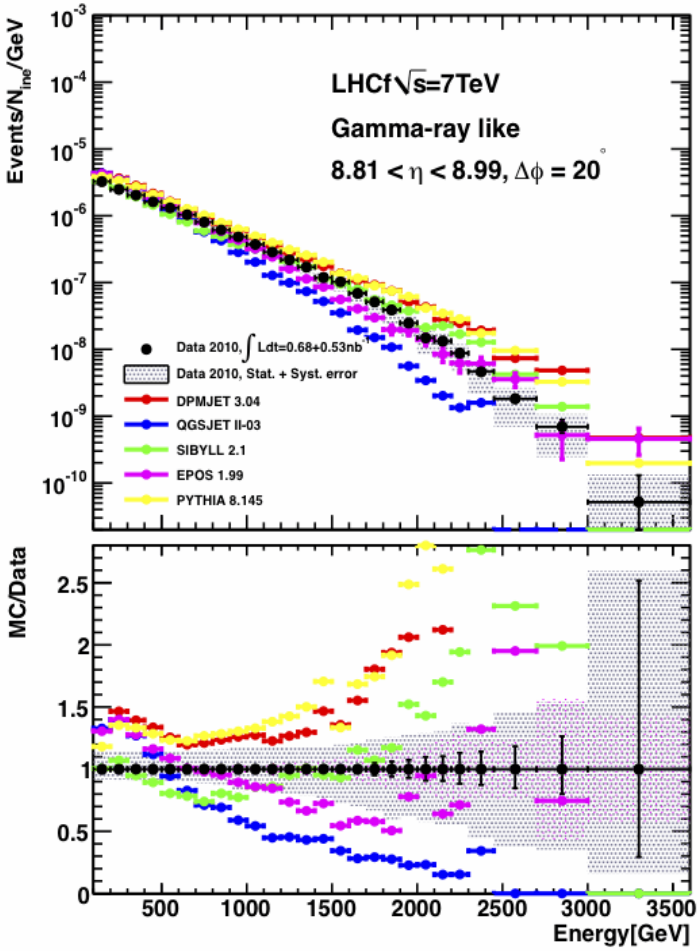
No strong evidence of η-dependence

DPMJET and **SYBILL** show reasonable agreement of shape

None of the models reproduces the data within the error bars

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





DATA
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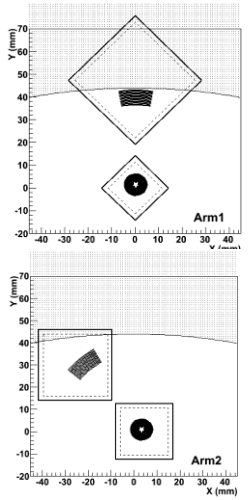
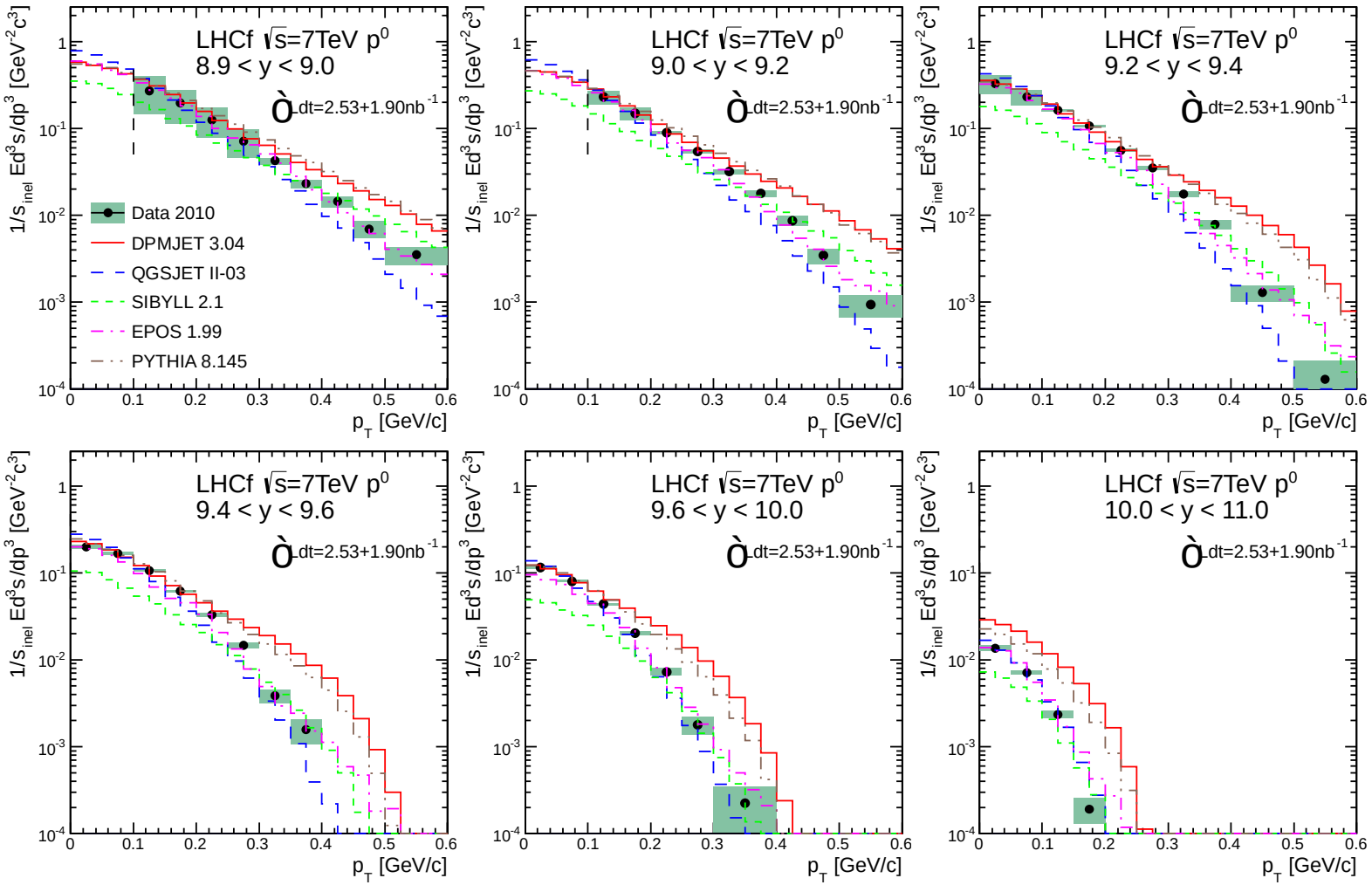
Syst.+Stat.



- No model can reproduce the **LHCf data** perfectly.
- **DPMJET** and **PYTHIA** are in good agreement at high-η for E_γ<1.5TeV, but harder in E>1.5TeV.
- **QGSJET** and **SIBYLL** shows reasonable agreement of shapes in high-η but not in low-η
- **EPOS** has less η dependency against the LHCf data.

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



- **EPOS1.99** show the best agreement with data in the models.
- **DPMJET** and **PYTHIA** have harder spectra than data (“popcorn model”)
- **QGSJET** has softer spectrum than data (only one quark exchange is allowed)

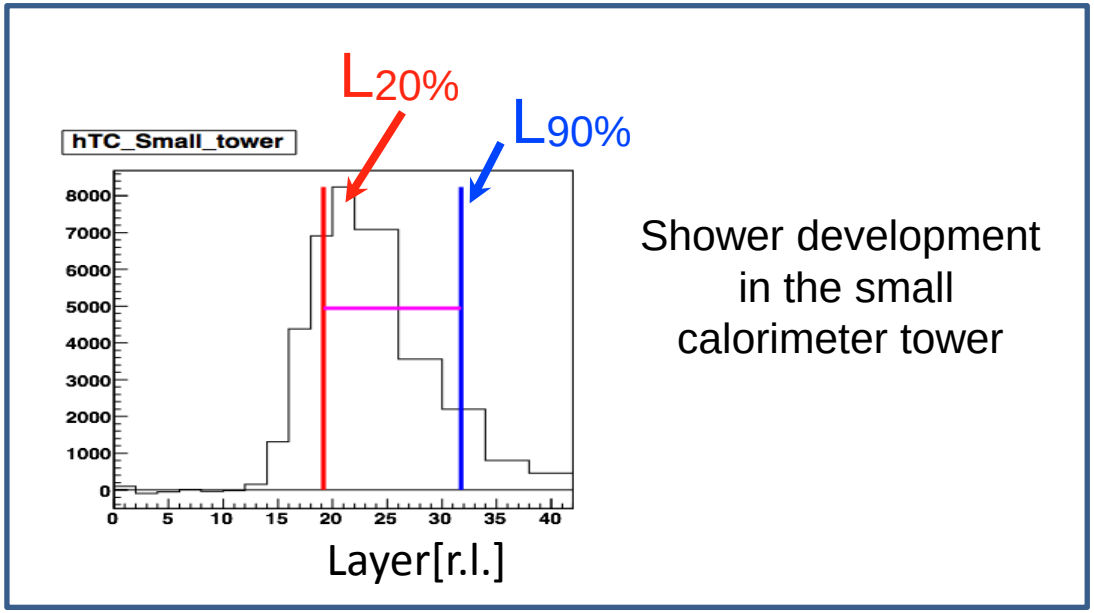

On-going analysis:
1) Neutrons for 7 TeV pp collisions
2)The 2013 p-Pb run

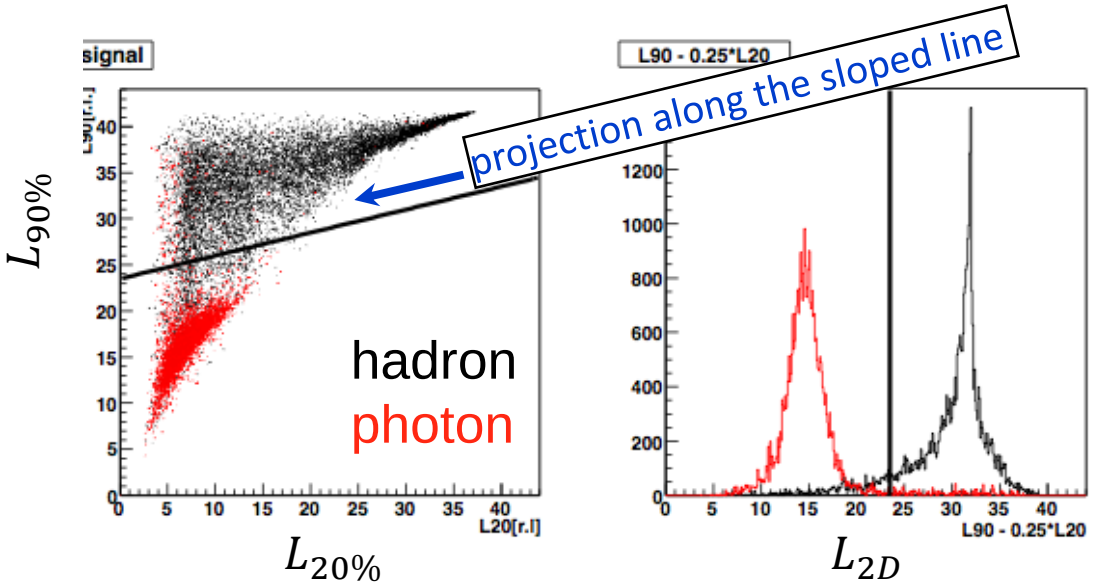
Neutron identification (7 TeV pp collisions)

Neutron analysis for pp at $\sqrt{s}$ = 7 TeV

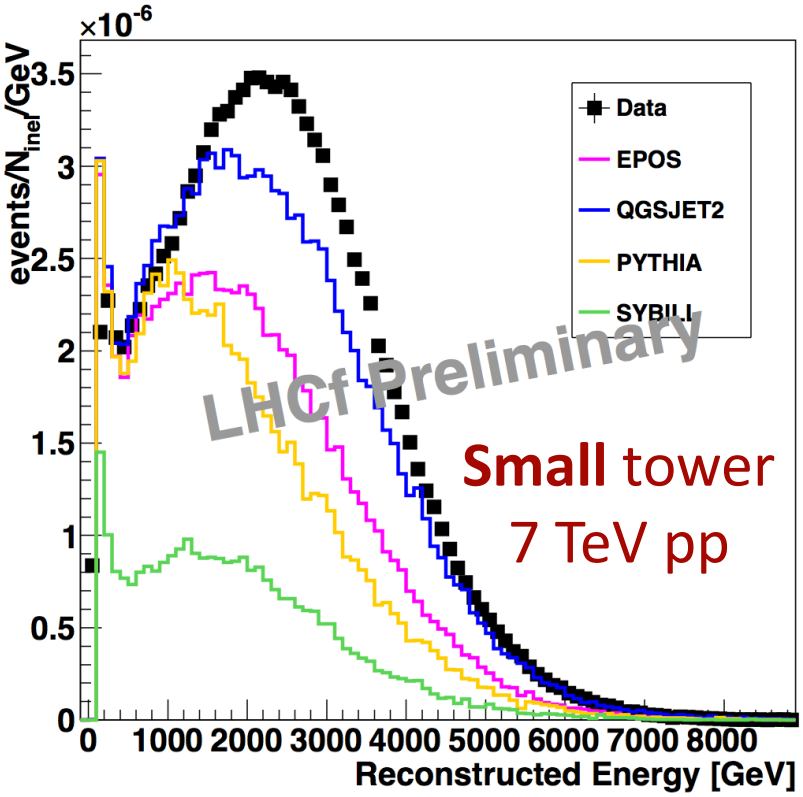
- To perform **PID** with higher efficiently and less contamination is essential
- 2D method using $L_{20\%}$ and $L_{90\%}$ are used for PID in this study
- $L_{20\%}$ ($L_{90\%}$) is the depth containing 20% (90%) of total deposited energy
- 2D cut parameter L_{2D} is obtained as below
  - $L_{2D} = L_{90\%} - \frac{1}{4} L_{20\%}$
- Mean **purity** of selected sample, estimated by simulation, over the entire energy range (0 – 10 TeV) is 95% with a mean selection efficiency of 97%

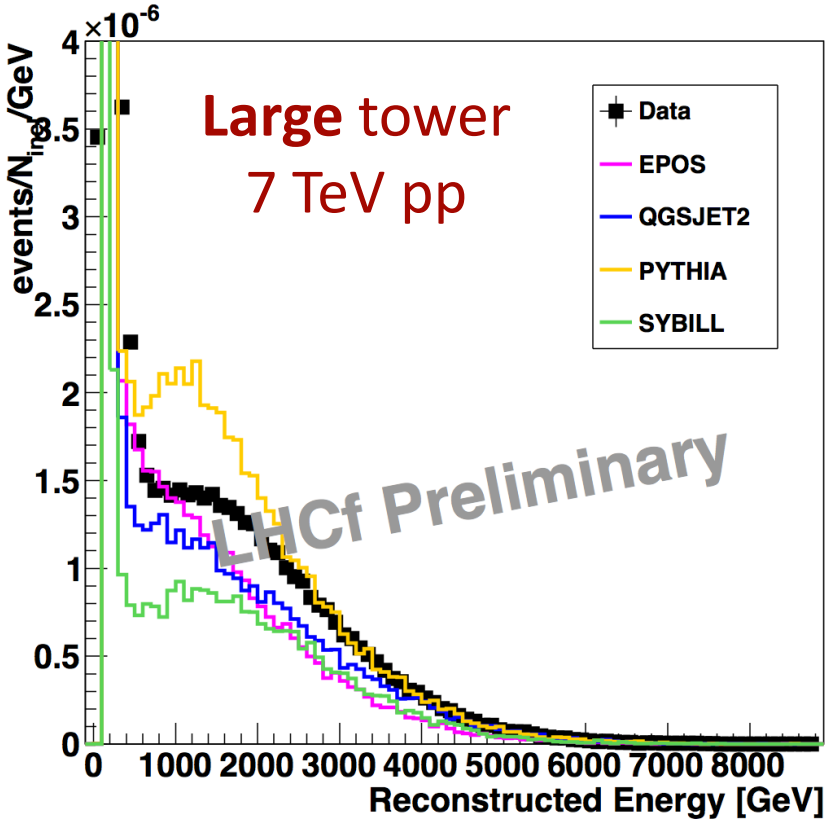
Courtesy of K. Kentaro





PRELIMINARY neutron spectrum (7 TeV pp)



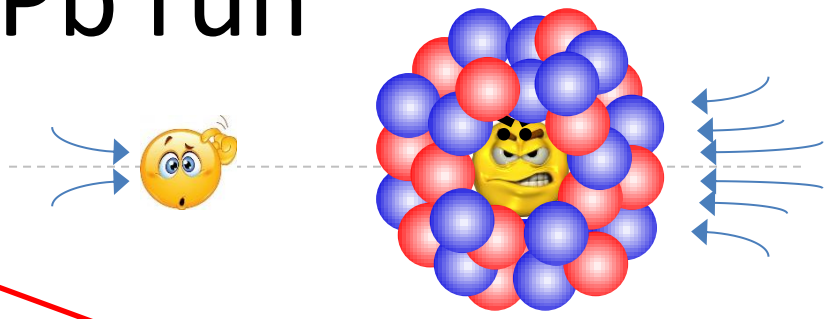


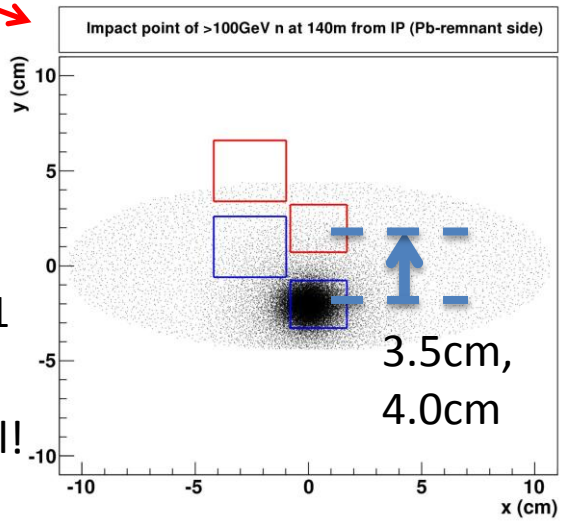
No rapidity selection
No efficiency correction
Only statistical error

Courtesy of K. Kentaro

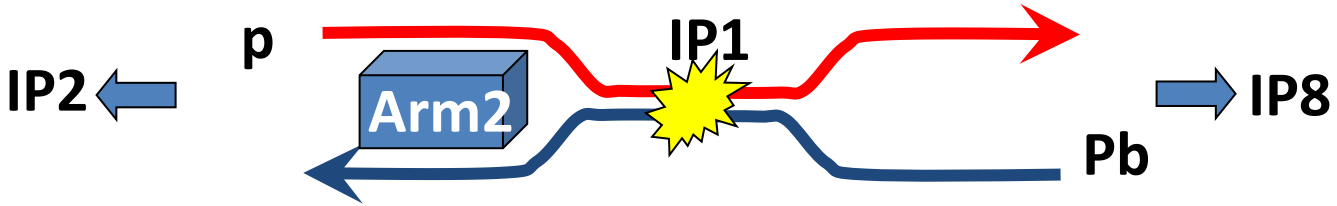
The 2013 p-Pb run

- 2013 Jan-Feb for p-Pb/Pb-p collisions
  - Installation of the **only Arm2** at one side (silicon tracker good for multiplicity)
  - Data both at **p-side** (20Jan-1Feb) and **Pb-side** (1fill, 4Feb), thanks to the **swap of the beams**

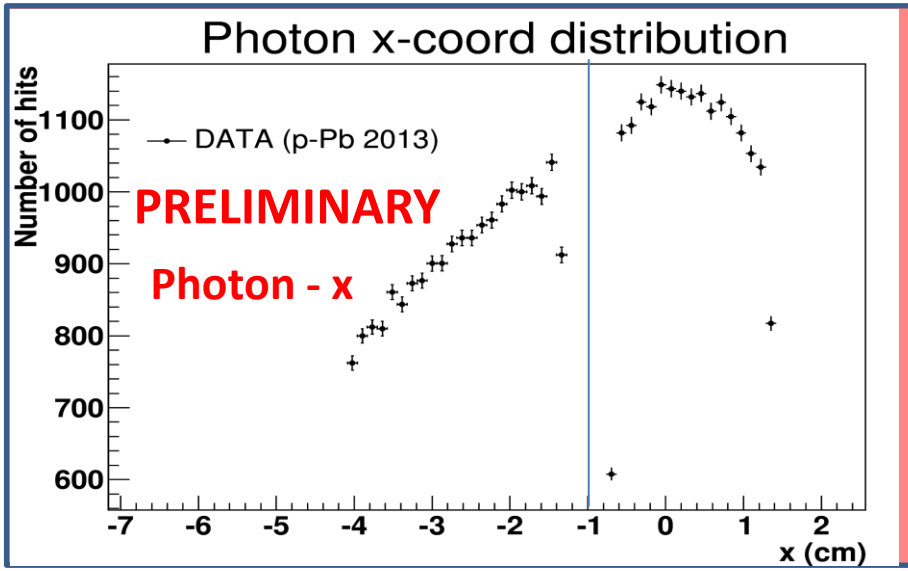


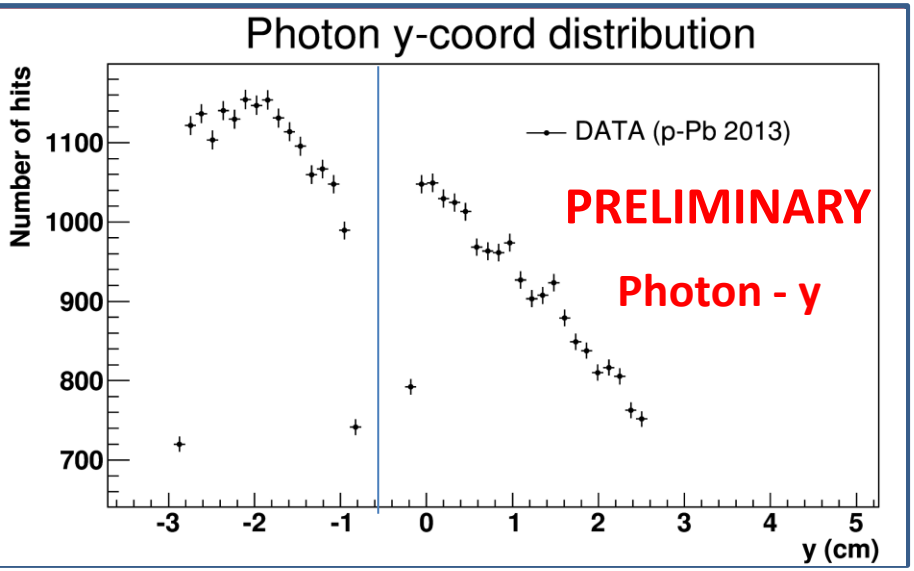


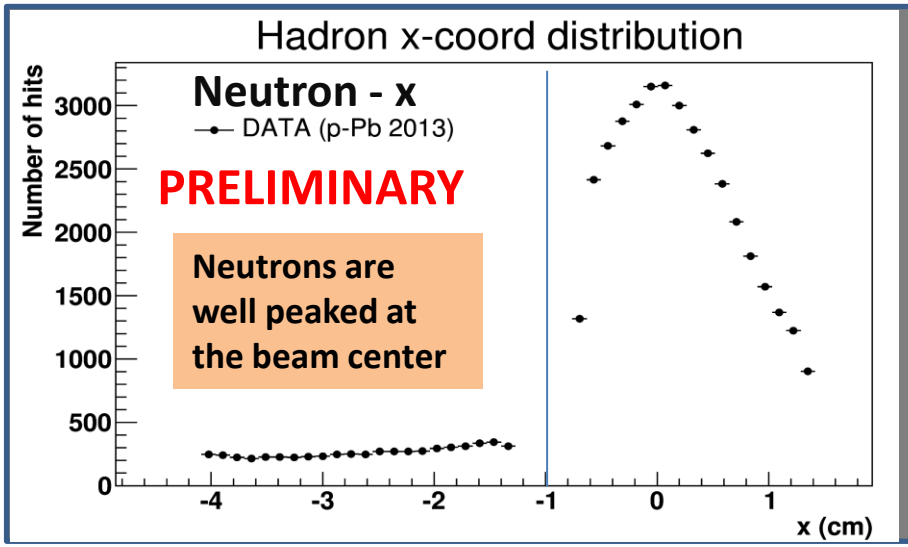
- Details of beams and DAQ
  - L = $1x10^{29}$ – $0.5x10^{29}cm^{-2}s^{-1}$
  - β^* = 0.8 m, 290 μrad crossig angle
  - 338p+338Pb bunches (min.ΔT = 200 ns), 296 colliding at IP1
  - 10-20 kHz trig rate downscaled to approximately 700 Hz
  - 20-40 Hz ATLAS common trig. Coincidence seems successful!

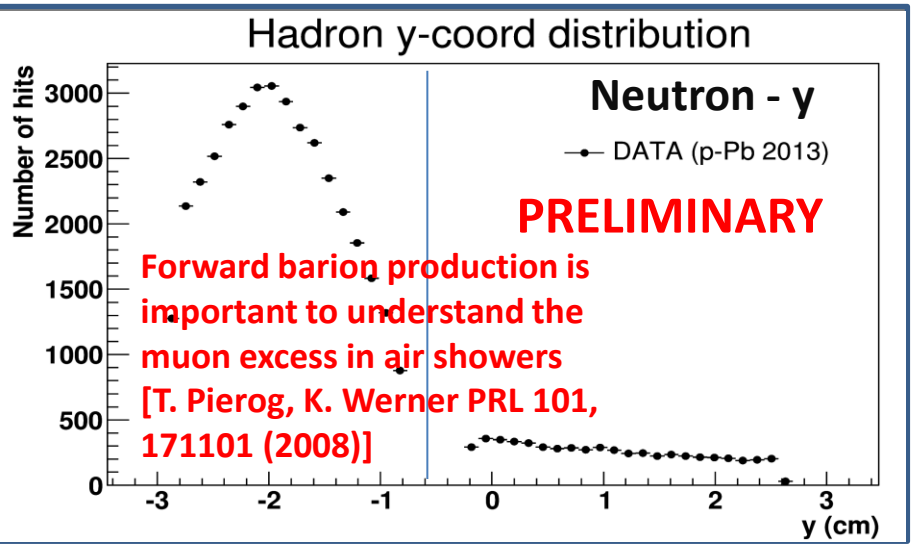


The p-Pb run in 2013: photon and neutrons impact point distributions (p-remnant)



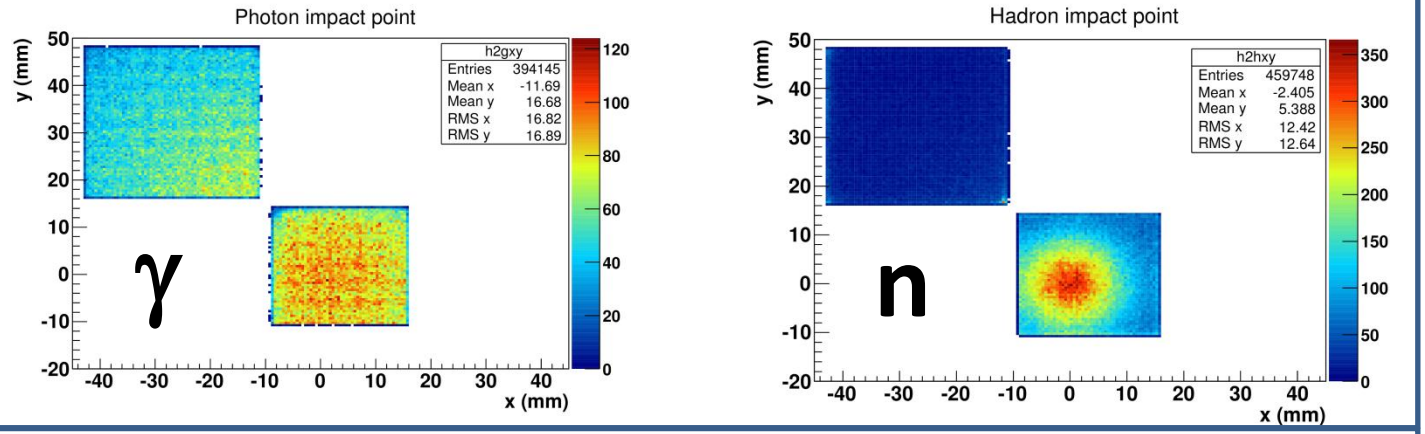






p-Pb run in 2013: impact points and beam center

2d distribution of impact point: neutrons are more peaked

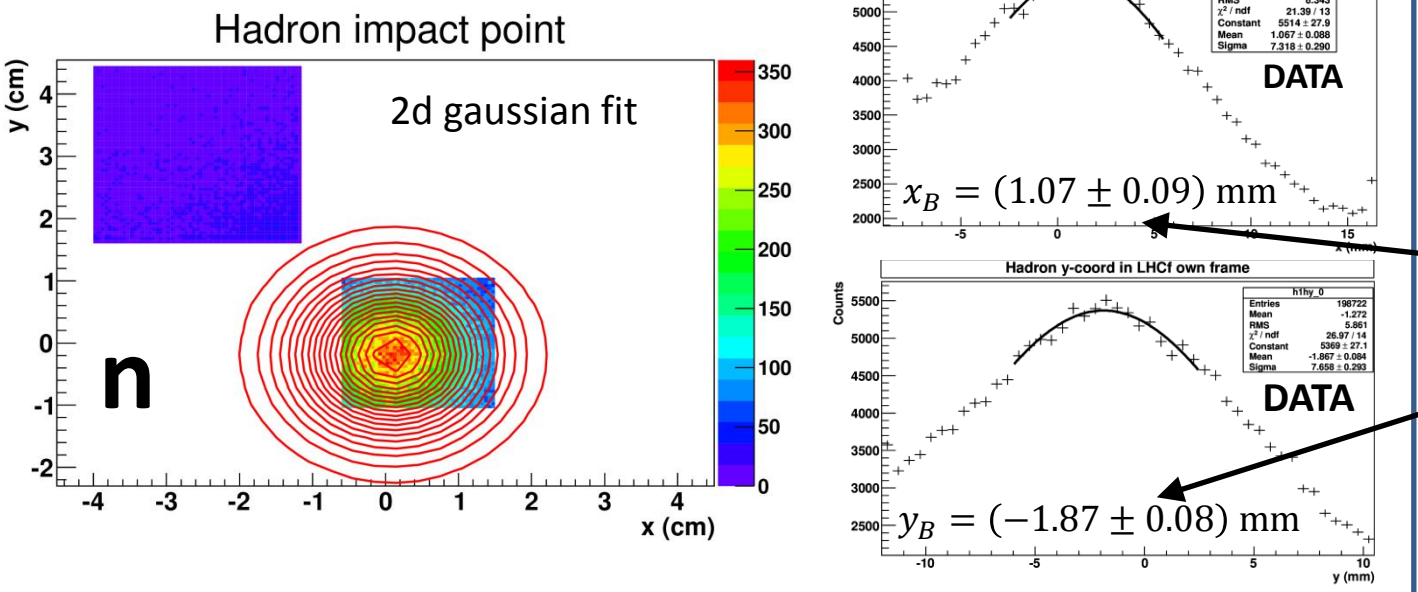


2013 p-Pb run

p-remnant side

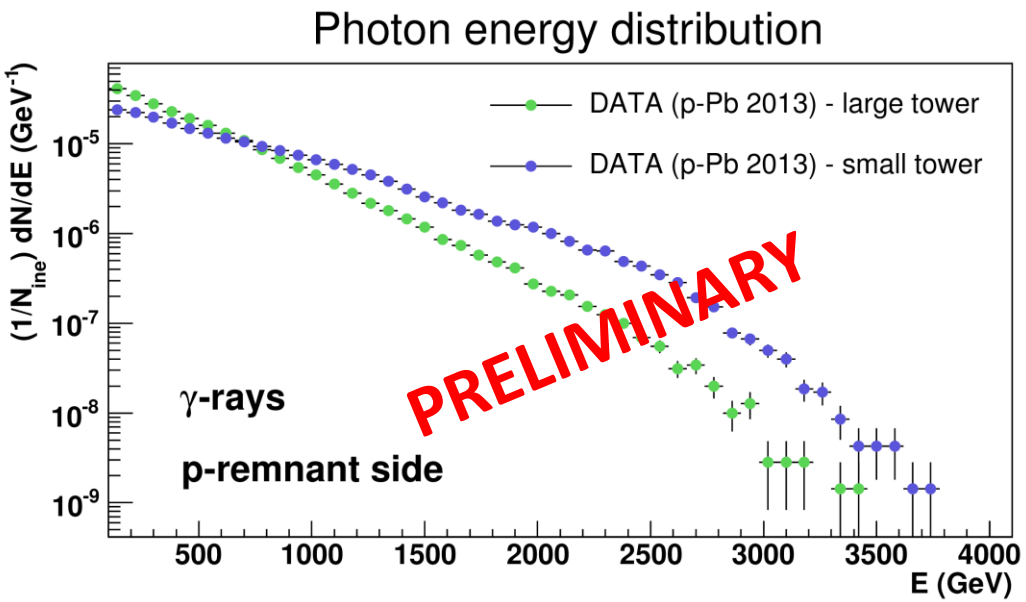
DATA

Determination of the beam center (BC)



Coordinates of the beam center with respect to the expected beam center

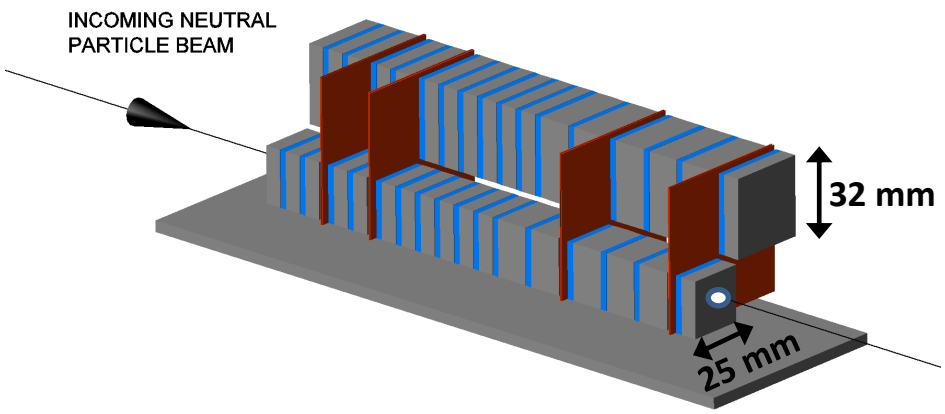
The p-Pb run in 2013: single γ-ray spectra

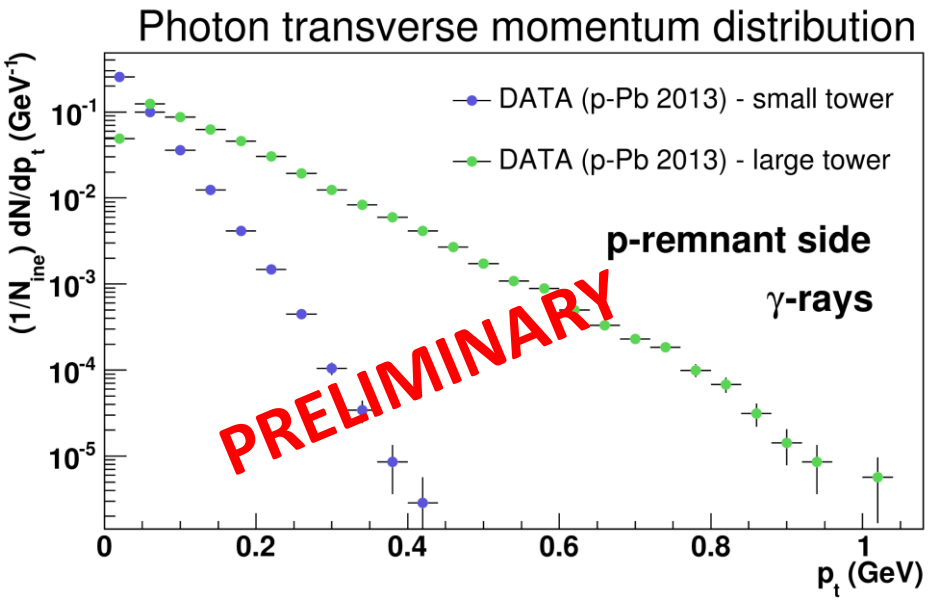


Detailed **simulations** with the available hadronic interaction models are on-going for a comparison with data

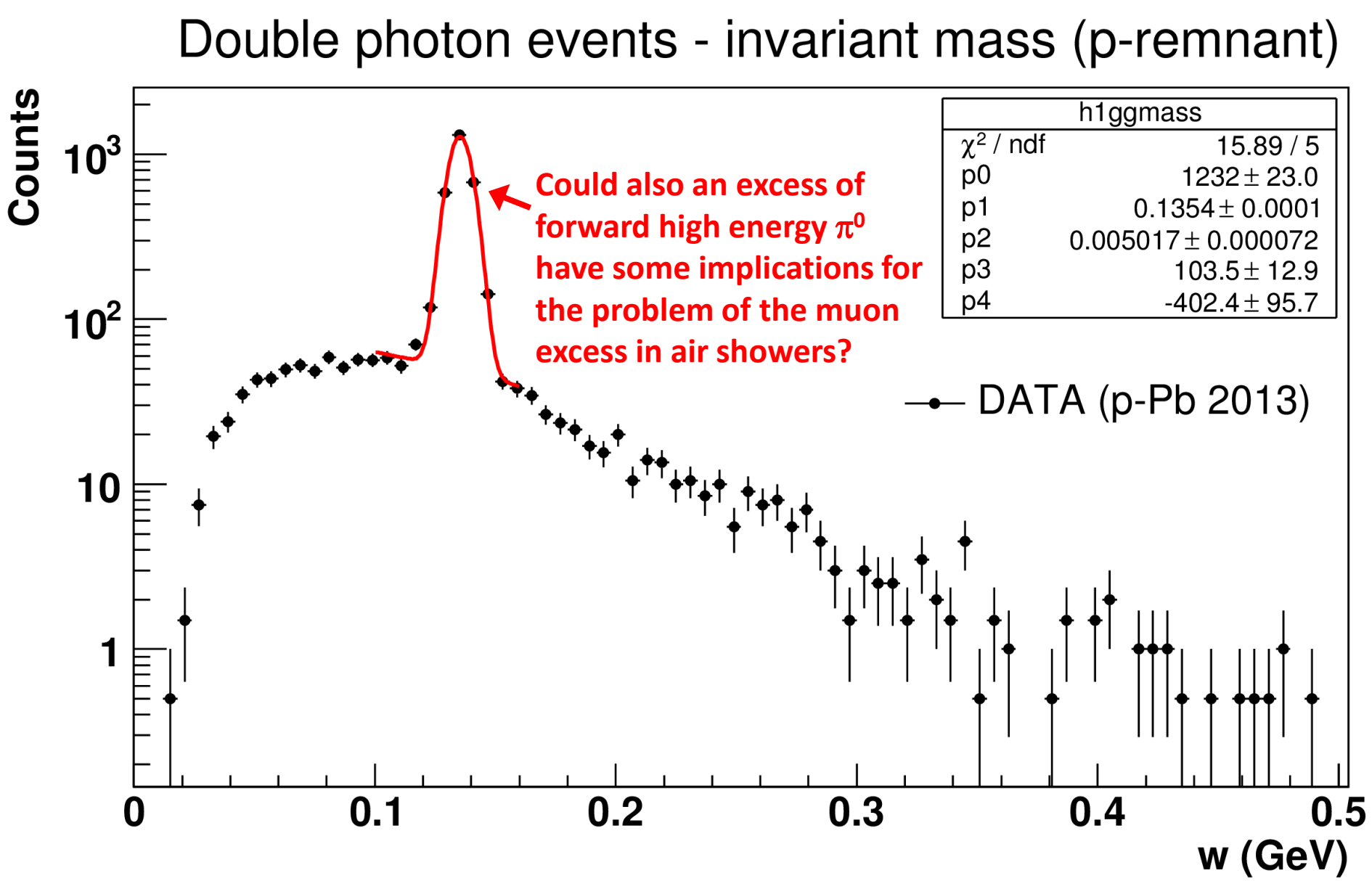
- Transportation of secondary particles from IP to detector, beam pipe structure, magnetic fields along the path and detector's response will be taken into account

Vertical bars on data points are only the statistical errors





The p-Pb run in 2013: invariant mass of γ-ray pairs



LHCf: future plan

p-p at 13TeV (2015)

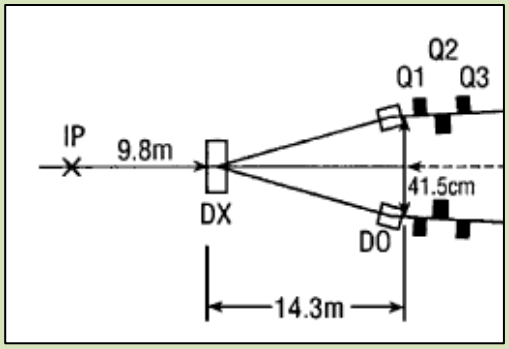
Main target: measurement at the LHC design energy.
Study of energy scaling by comparison with √s = 900 GeV and 7 TeV data
Upgrade of the detectors for radiation hardness.

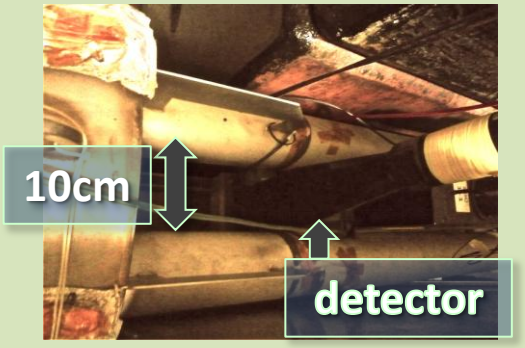
***p-light ions** (O, N)* **at the LHC** *(2019?)*

It allows studying high energy cosmic-rays collisions with atmospheric nuclei.

***RHICf** experiment at RHIC*

Lower collision energy, ion collisions.
LOI to the RHIC committee has been submitted on ….





p-p collisions:
- Max. √s = 500 GeV
- Polarized beams

Ion collisions:
- 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 Very High Energy Cosmic-Ray (VHECR) Physics
- We have published **spectra of photons and neutral pions** for pp interactions at $\sqrt{s}$ = 900 GeV and $\sqrt{s}$ = 5 TeV
  - None of the hadronic 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 hadronic component (neutrons)
- p-Pb run at the beginning of 2013
  - Successful data taking in p-remnant and Pb remnant side
  - Common operations with ATLAS (trigger exchange)
  - On-going data analysis (some hints for interesting results!!!)
- Future plan
  - Continue and finalize the on-going data analysis (start also ATLAS/LHCf common analysis)
  - Complete the upgrade of the detectors for radiation hardness
  - Data taking for pp 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)