Cosmic rays and accelerators: future

Oscar Adriani
University of Florence & INFN Firenze

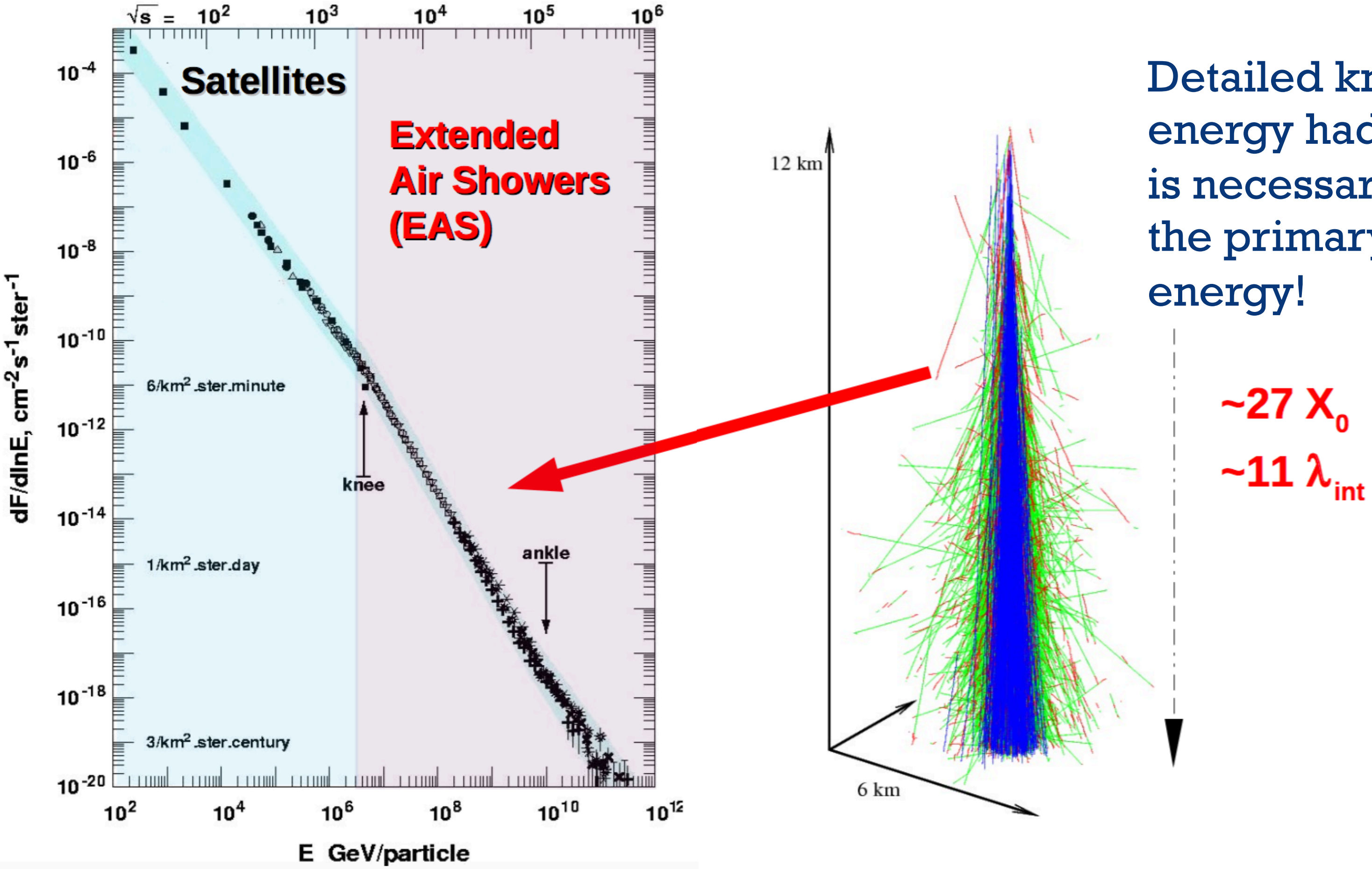
NPQCD 2015
Cortona, April 21st, 2015

+ Contents

Introduction

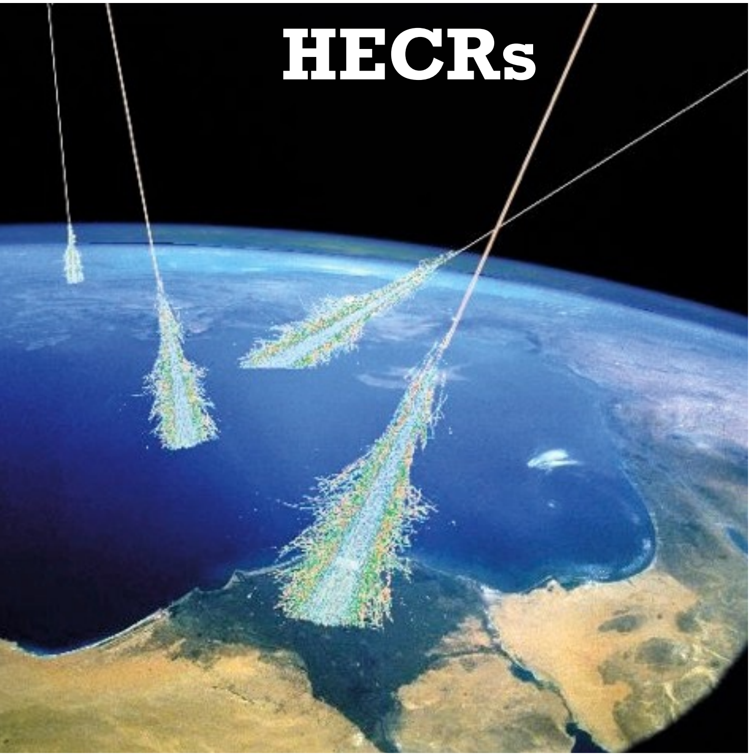
+ The High Energy cosmic ray spectrum

- The spectrum falls very rapidly with energy ($\sim E^{-2.7}$)
- No direct measurements are possible for $E > 10^{15}$ eV (Flux< $1/m^2$/year)
- We have to rely on the atmospheric showers measurements



Detailed knowledge of high energy hadronic interactions is necessary to reconstruct the primary CR type and energy!

High Energy CR Showers main Observables



- X_{max} : depth of air shower maximum in the atmosphere
- RMS(X_{max}): fluctuations in the position of the shower maximum
- N_{μ}: number of muons in the shower at the detector level

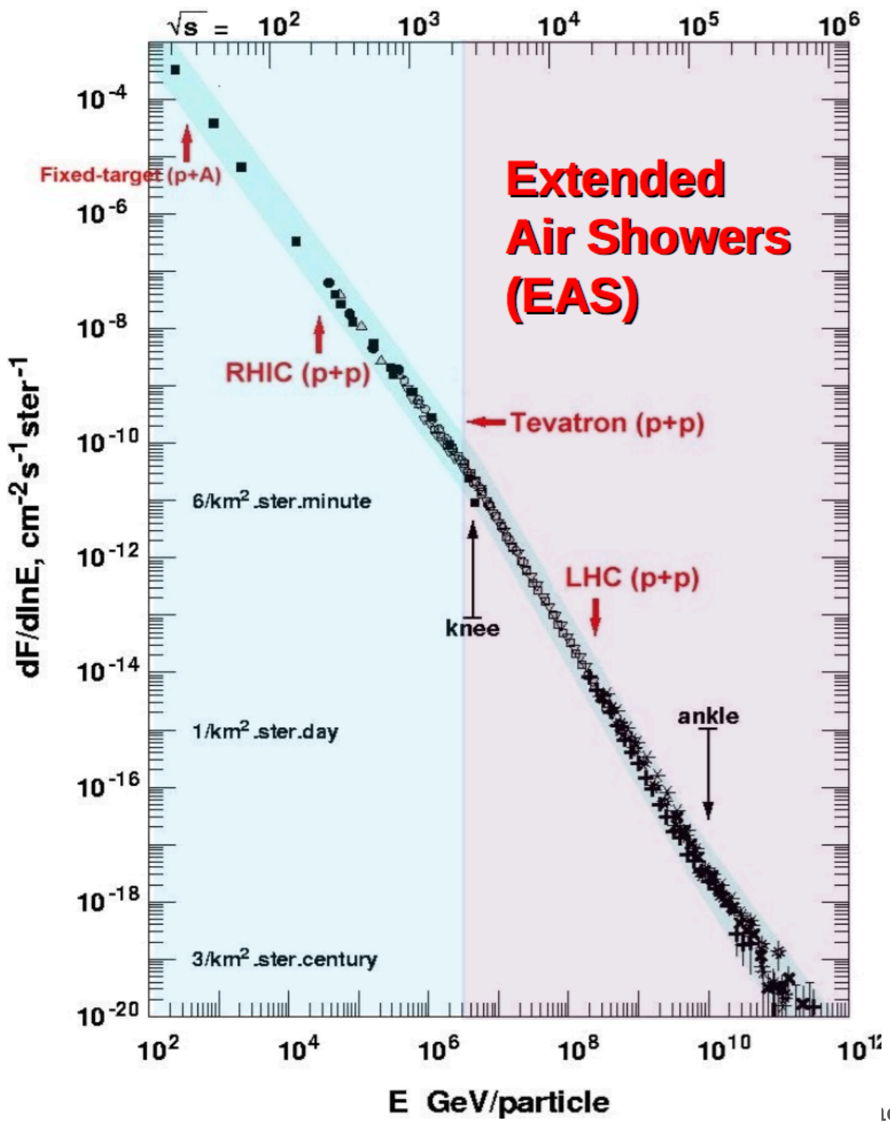
- To go from these observables to the CR composition and energy determination passing through the hadronic interaction models is mandatory

Uncertainty of hadron interaction models

↓

Uncertainty in the interpretation of the observables

The role of the accelerators experiments

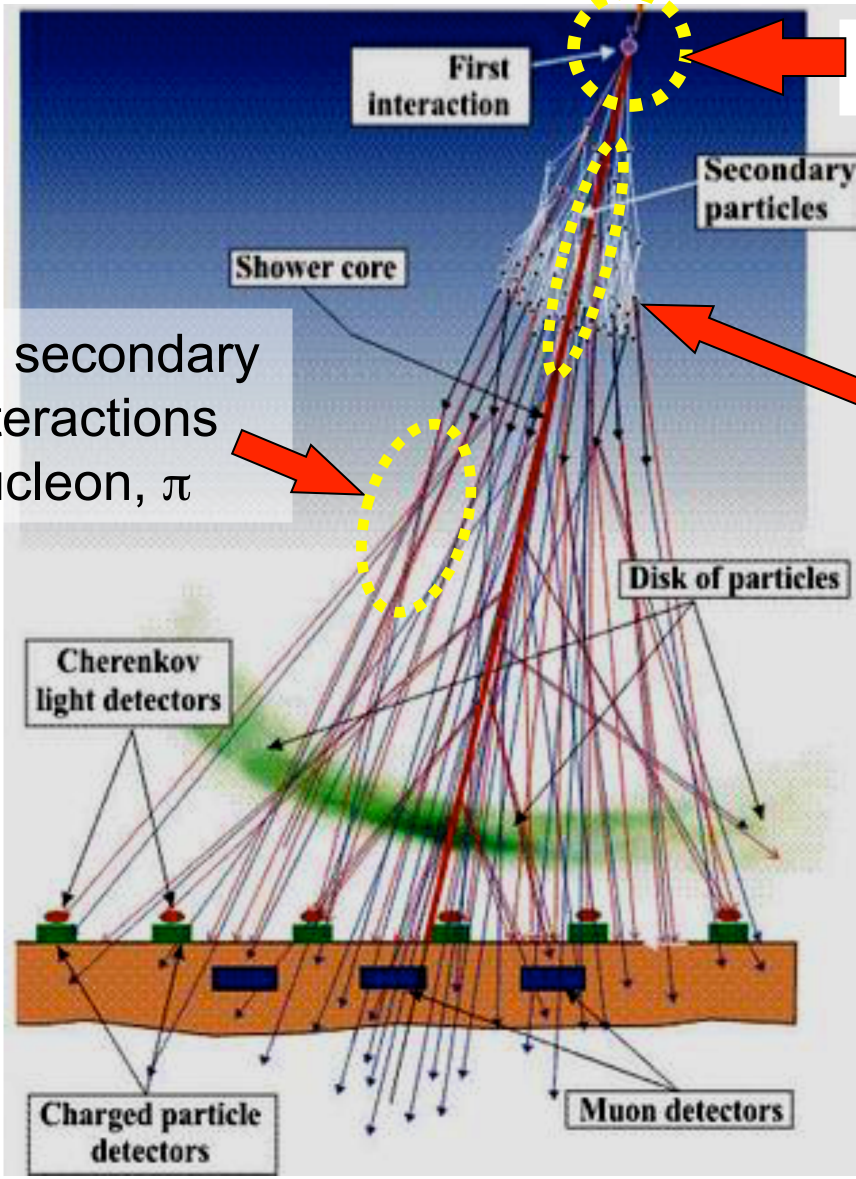


Accelerator based experiments are the most powerful available tools to determine the high energy hadronic interactions characteristics

→ Hadronic interactions models tuning

LHC 13 TeV →9.10^{16} eV
Unique opportunity to calibrate the models in the 'above knee' region

How accelerator experiments can contribute?



④ secondary interactions nucleon, π

① Inelastic cross section

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

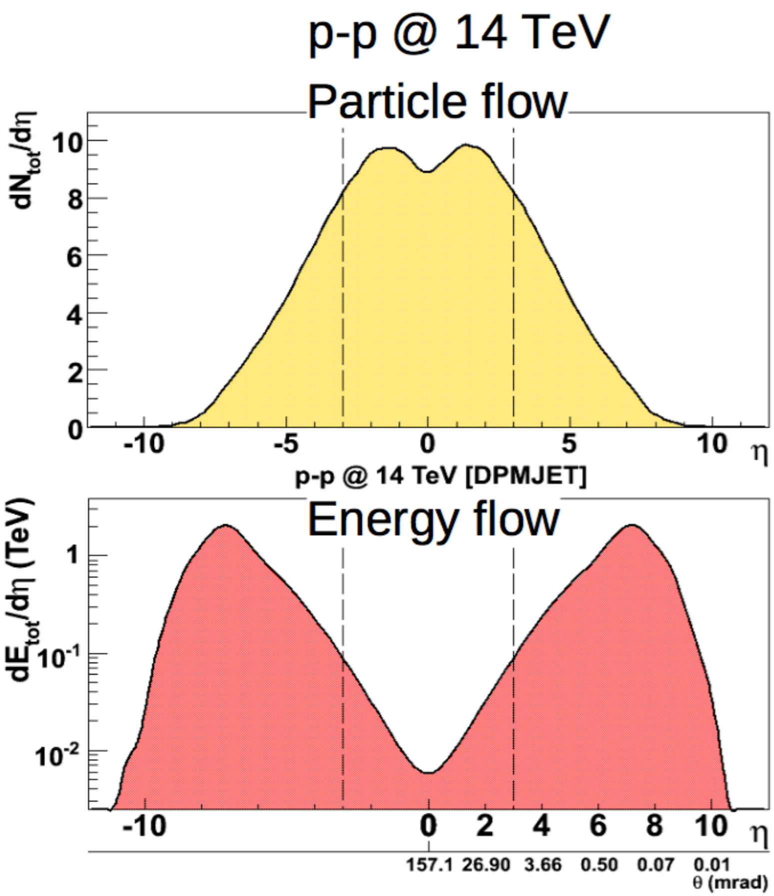
② **Forward energy spectrum**

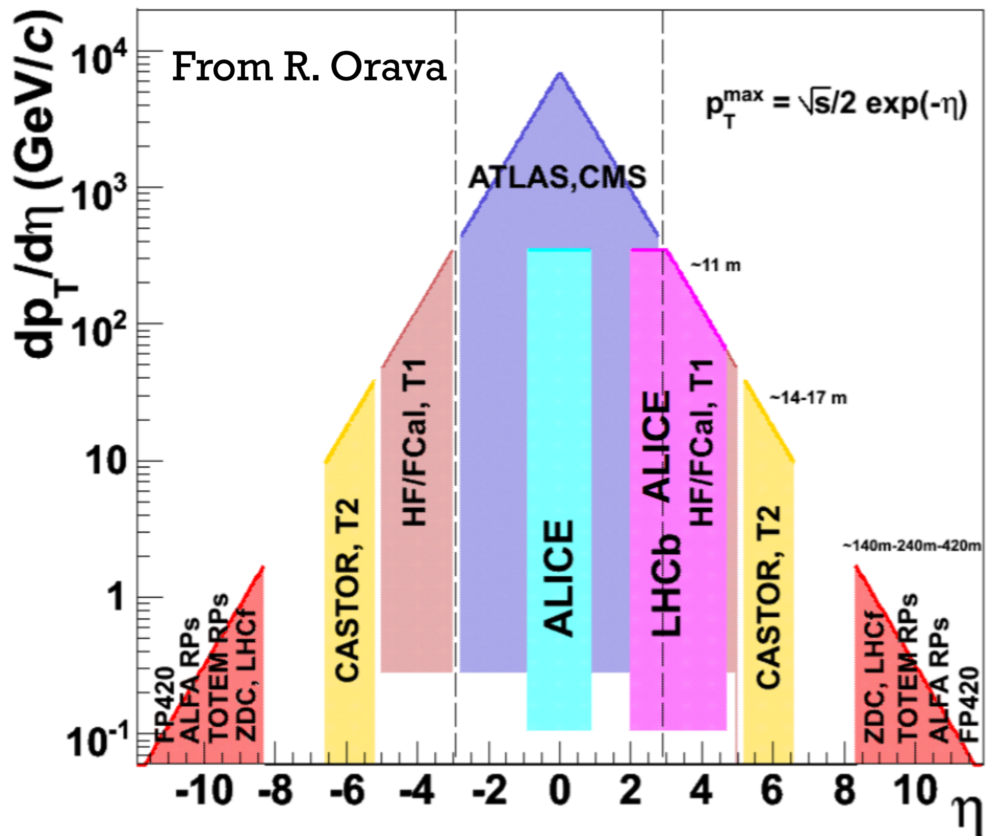
If softer shallow development
If harder deep penetrating

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

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

+ LHC phase space coverage

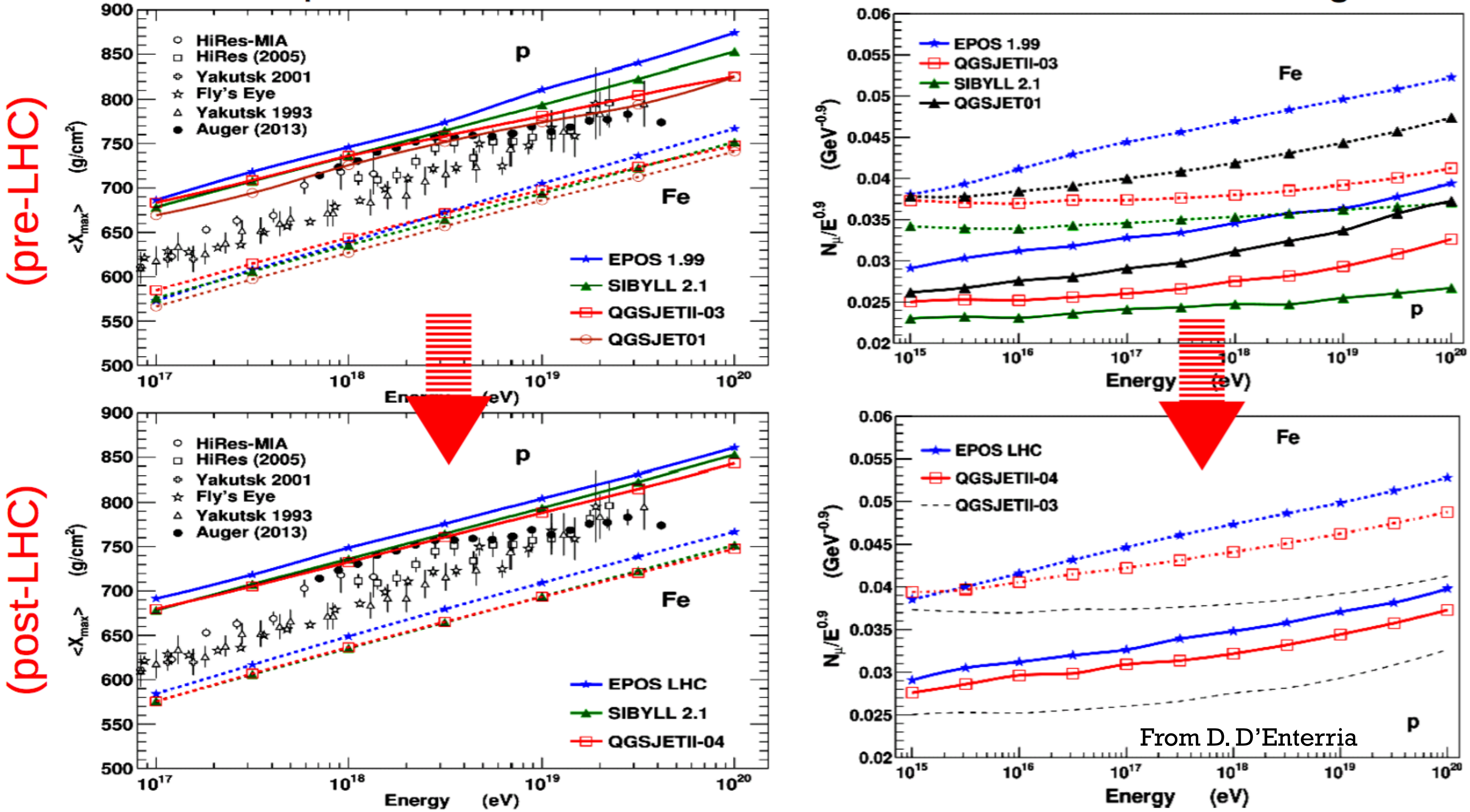




We may profit (and we are profiting) of the very broad coverage!
Dedicated forward detectors for a better measurement of the energy flow

Models tuning after the first LHC data (EPOS and QGSJET) (See talk by Engel)

Mean depth of shower maximum: Number of muons on ground:



Significant reduction of differences btw different hadronic interaction models!!!

LHC @ 13 TeV

Charged multiplicity

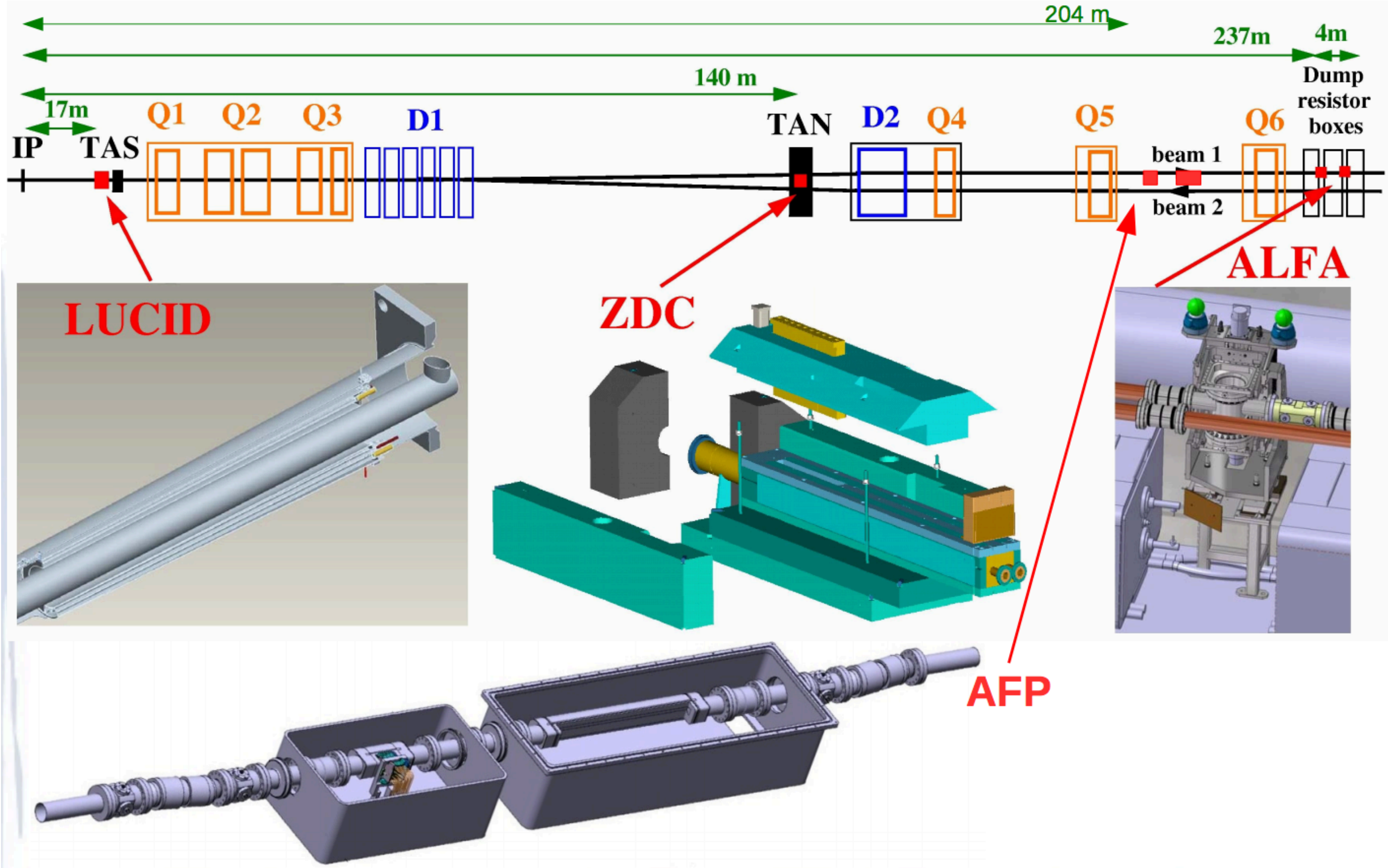
Energy flow

Forward neutral particles spectra

What is new in the detectors/ triggers/analysis?

- LHCf completed an upgrade to improve radiation hardness
- Very forward proton tag to identify the event topology
  - ATLAS/Alfa
  - CMS/TOTEM
- ATLAS-LHCf combined data analysis
  - LHCf trigger will be used by ATLAS to trigger the detector
  - Offline synchronization of the events will be possible
- Some improvements in the trigger algorithms by big experiments

ATLAS upgraded forward region



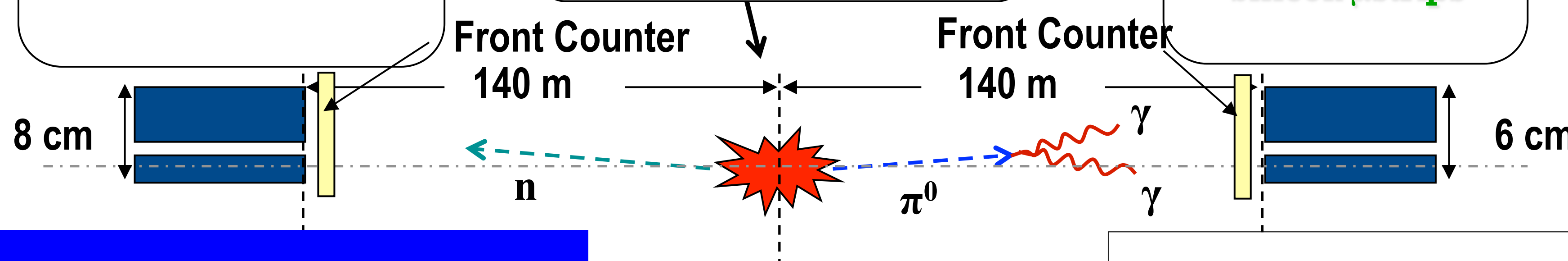
LHCf: location and detector layout

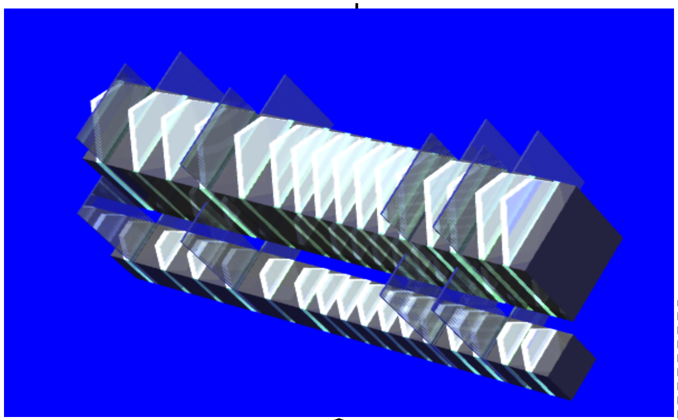
Detector I
Tungsten
GSO
GSO bars

INTERACTION POINT

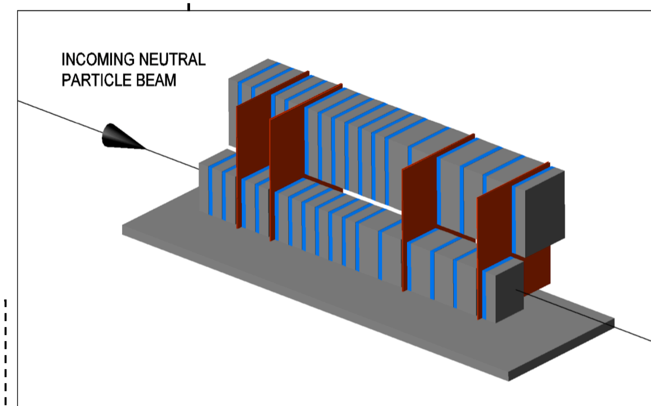
IP1 (ATLAS)

Detector II
Tungsten
GSO
Silicon μstrips





$44X_0$,
$1.6\ \lambda_{int}$



Arm#1 Detector
20mmx20mm+40mmx40mm
4 X-Y GSO Bars tracking layers

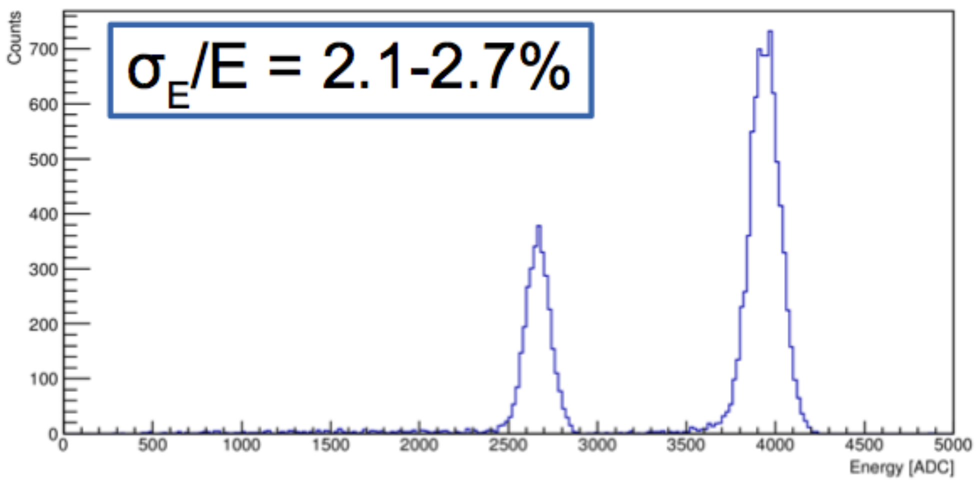
Energy resolution:
- < 5% for photons
- 30% for neutrons

Position resolution:
- < 200 μ m (Arm#1)
- 40 μ m (Arm#2)

Pseudo-rapidity range:
- η > 8.7 @ zero Xing angle
- η > 8.4 @ 140urad

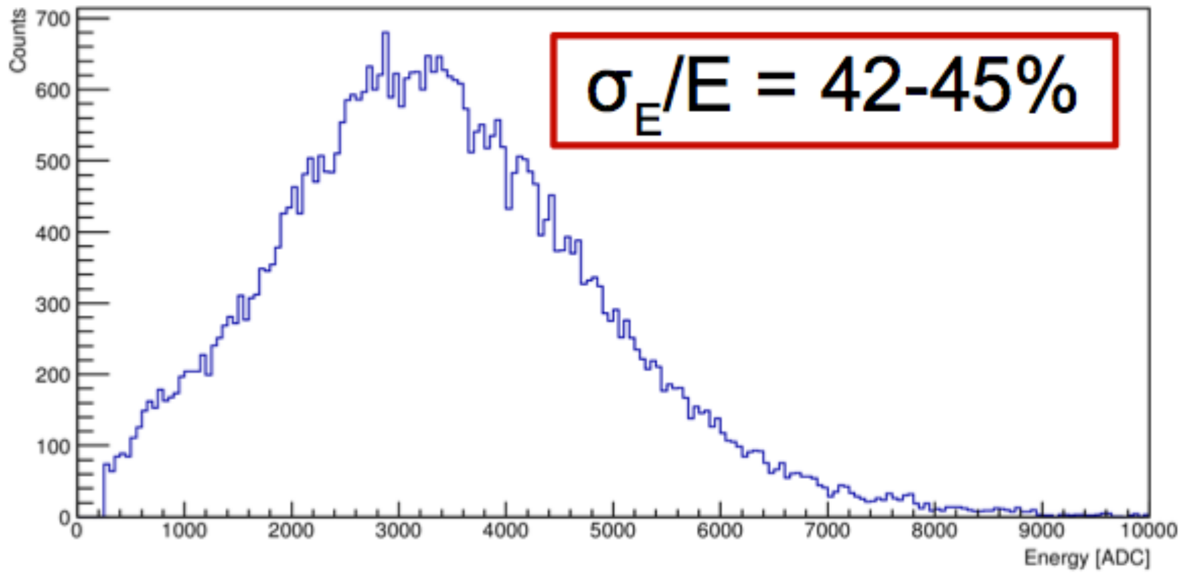
Arm#2 Detector
25mmx25mm+32mmx32mm
4 X-Y Silicon strip tracking layers

Arm2 Energy Reconstruction



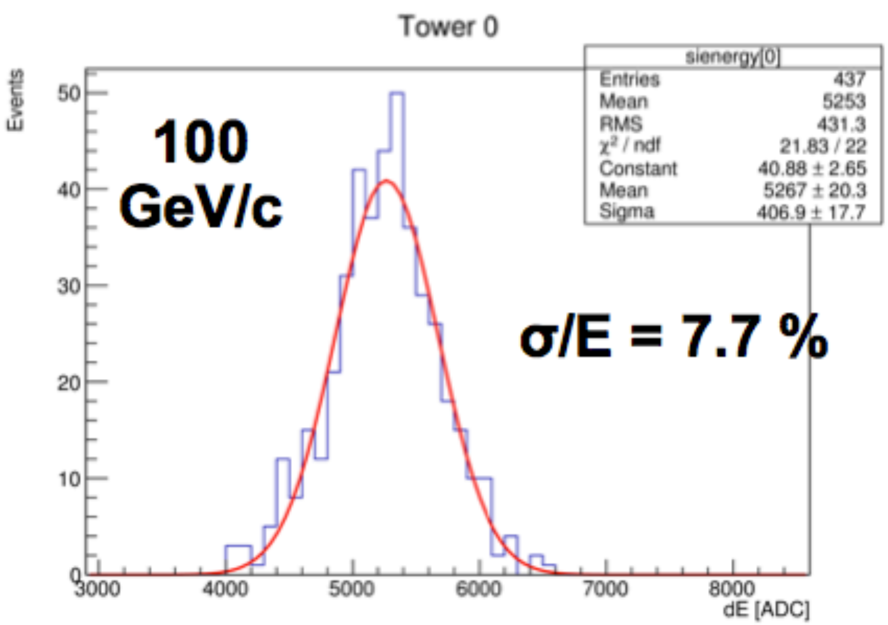
100 & 150 GeV electron beam on small tower center

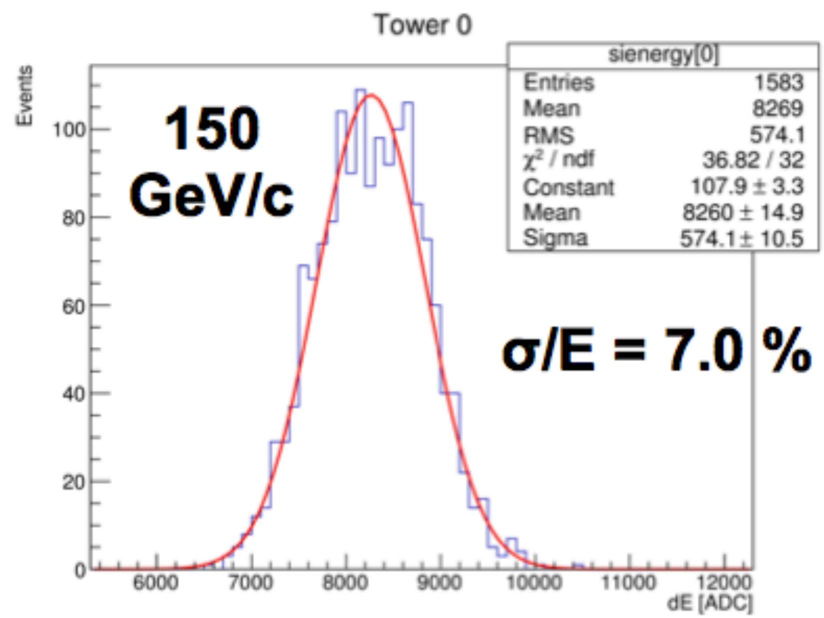
300 GeV proton beam on small tower center



+ Arm2 silicon energy measurement (small tower)

- Sum of energy releases over all silicon layers
- Only strips with signal > 3σ are considered
- Central events (5 mm x 5 mm square)





- Resolution with old configuration: 8.4 % @100 GeV
  8.2 % @150 GeV

+ LHCf/ATLAS common operation strategy

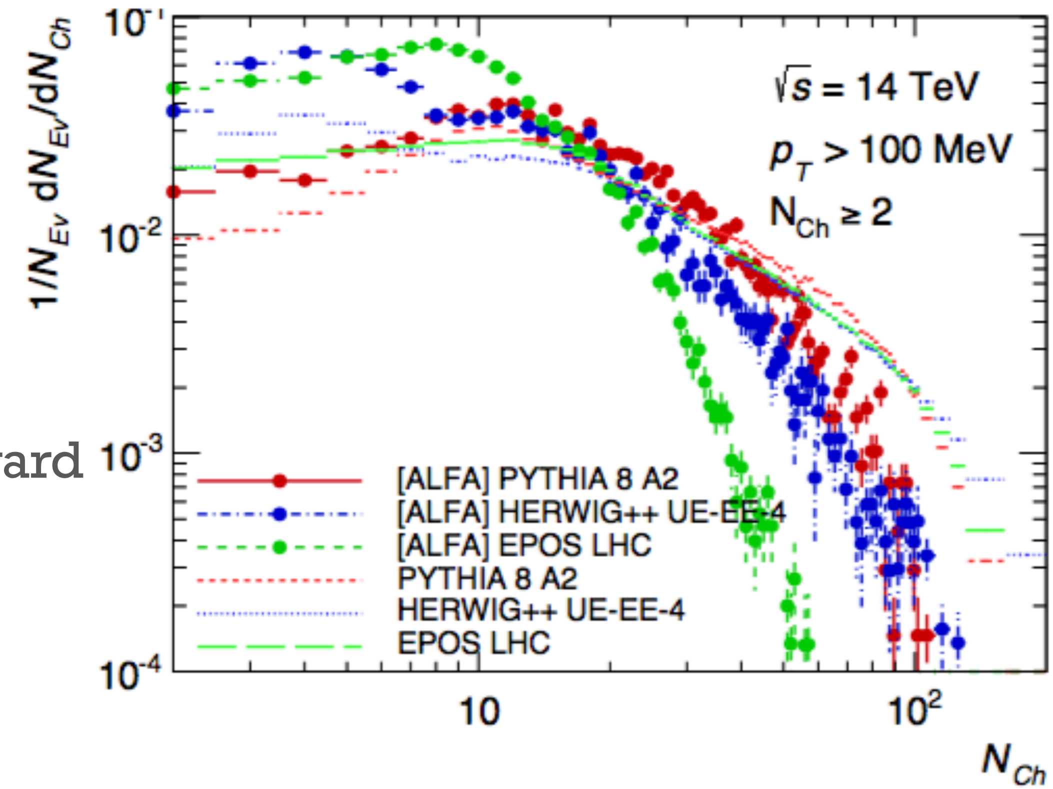
- Beam conditions:
- Low luminosity ($L<6.10^{28}$ $cm^{-2}s^{-1}$), low pileup ($\mu<0.03$) at the beginning of the LHC run
- Very clean beam conditions
- LHCf trigger delivered to ATLAS + Offline matching of the events
- $>50.10^6$ commonly triggered events
- Excellent statistics for clean measurements of:
  - γ
  - Neutrons
  - π^0

for different conditions of central activity

+ Charged particles multiplicity

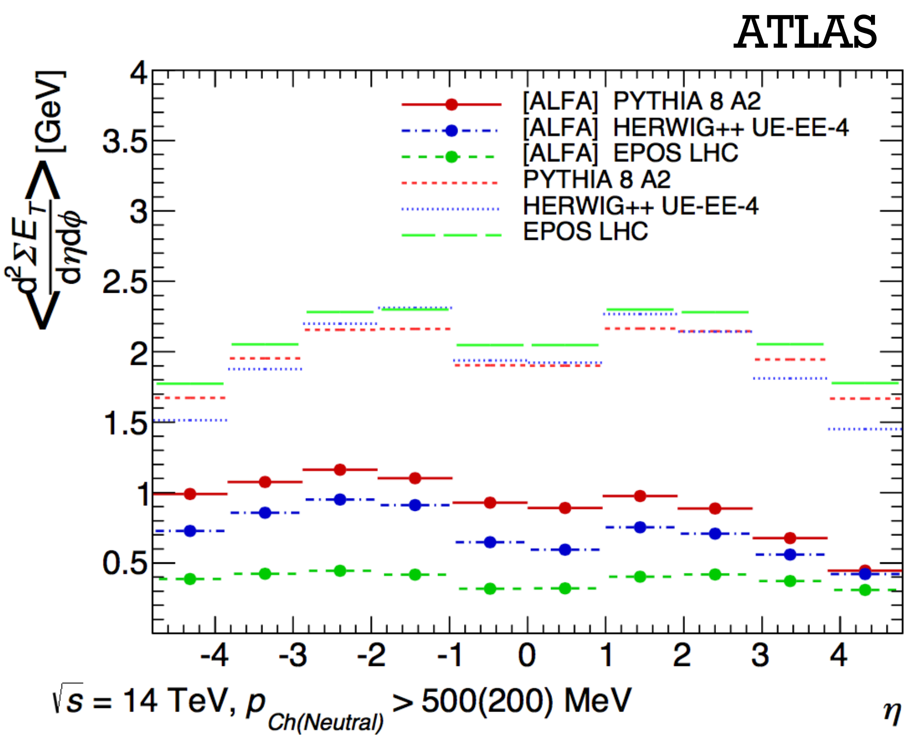
- Important for the longitudinal dependence of the showers → X_{max}
- 'Standard measurements' will be done at 13 TeV
  - $|\eta|<2.5$ (Atlas, CMS, Alice)
  - $2<|\eta|<4.5$ (LHCb)
  - $3.1<|\eta|<6.5$ (TOTEM)
- For the first time the measurement could be correlated with the very forward proton tag!

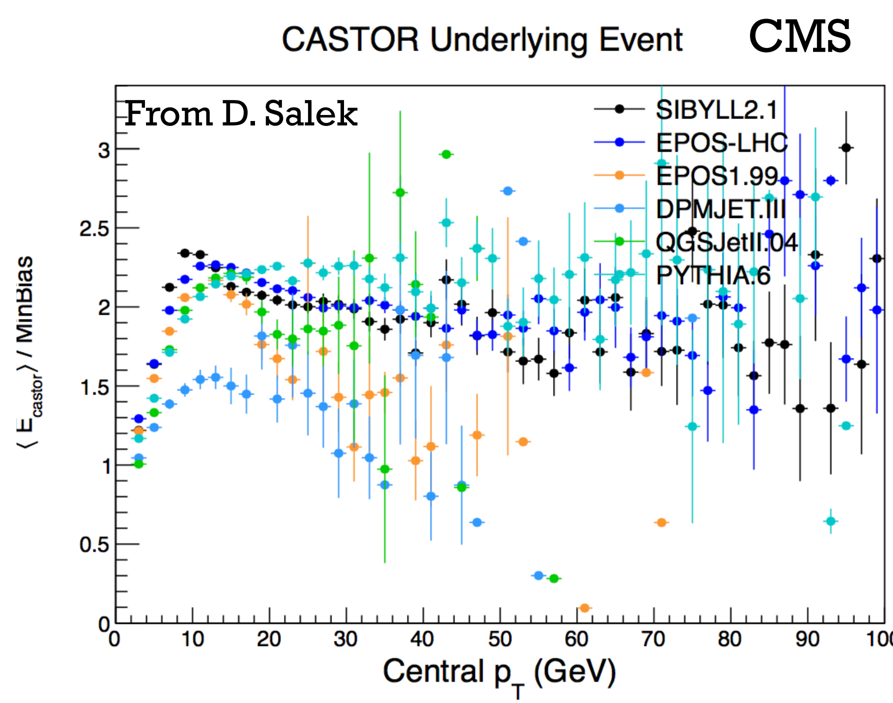
From D. Salek



Energy flow

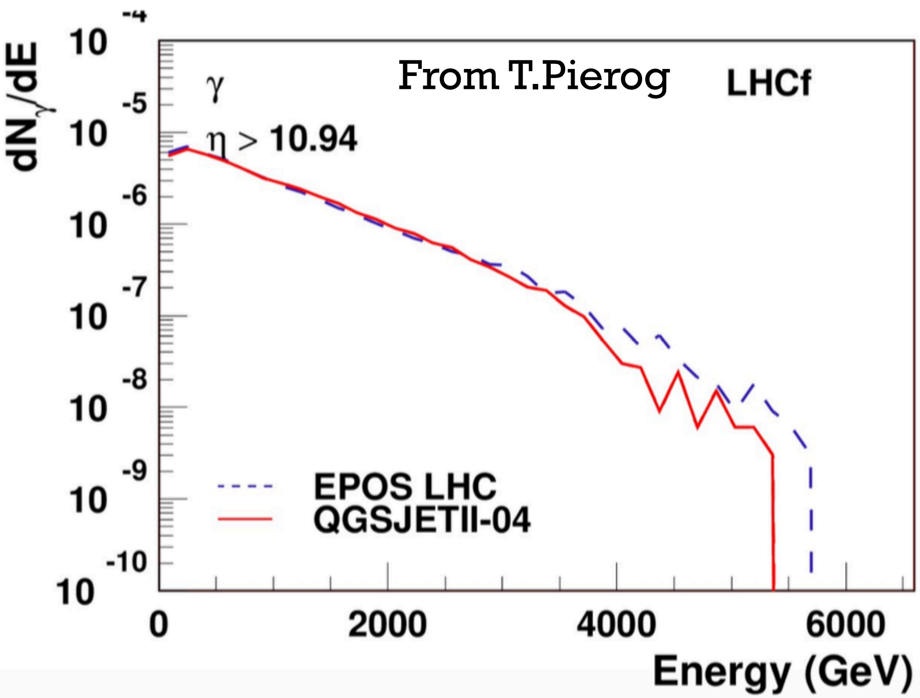
- Energy flow is the most important ingredient for the air shower development
- This measurement can greatly profit of the forward proton tag
  - Energy flow is significantly affected by the presence of a leading very forward high energy particle

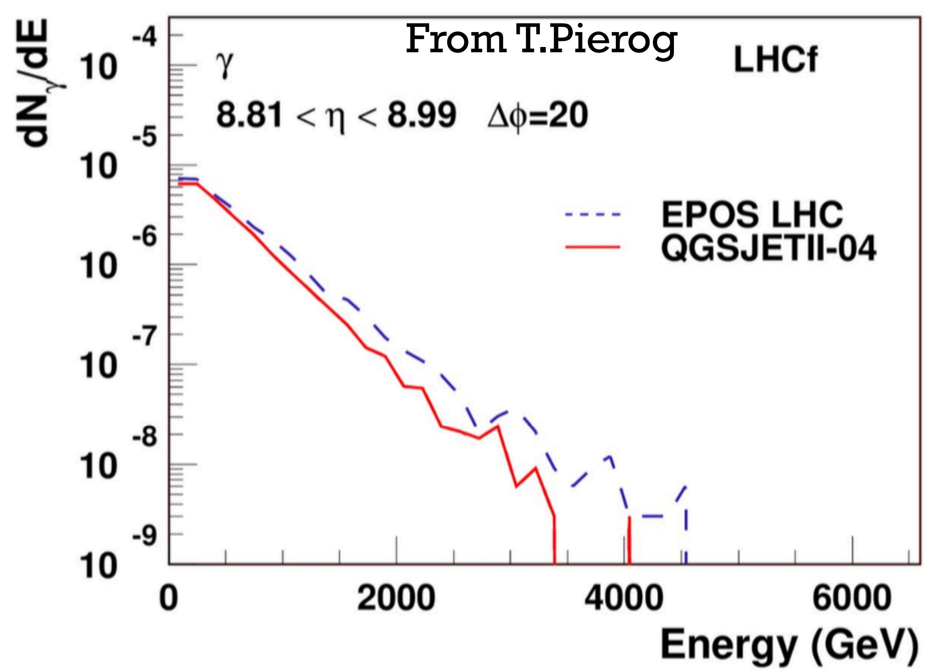




+ Very forward neutral particle spectra I: photons

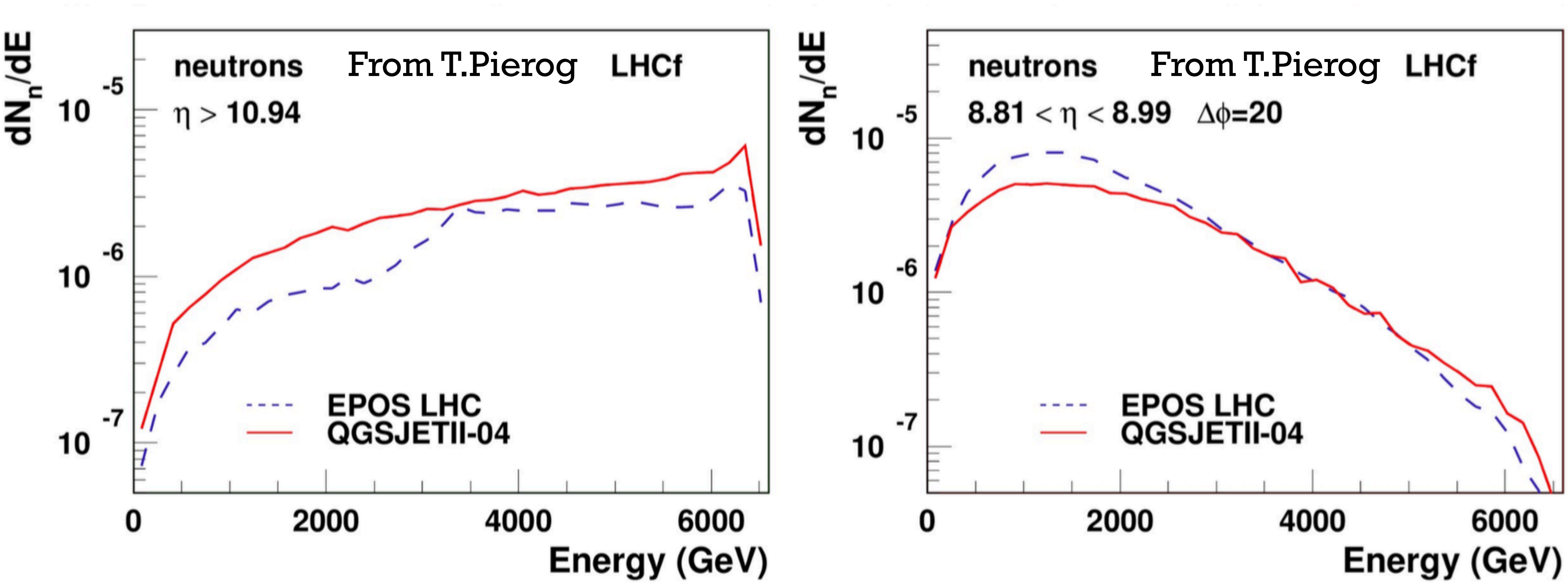
- LHCf is optimized for the very forward neutral particle detection
- $|\eta| > 8.4$
- Excellent performances in the γ measurement (~2%)
- Large difference even with tuned models





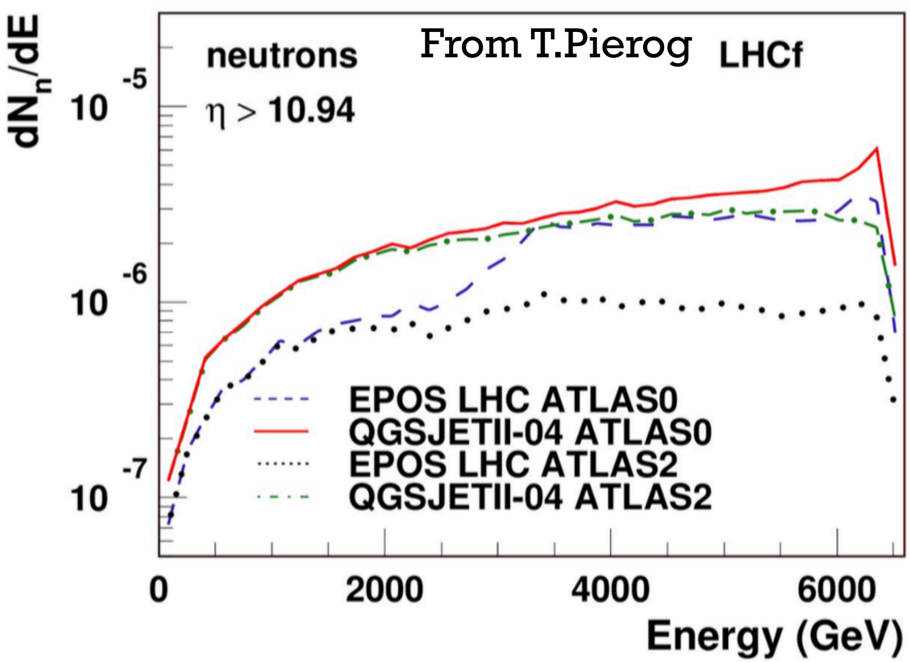
Very forward neutral particle spectra II: neutrons

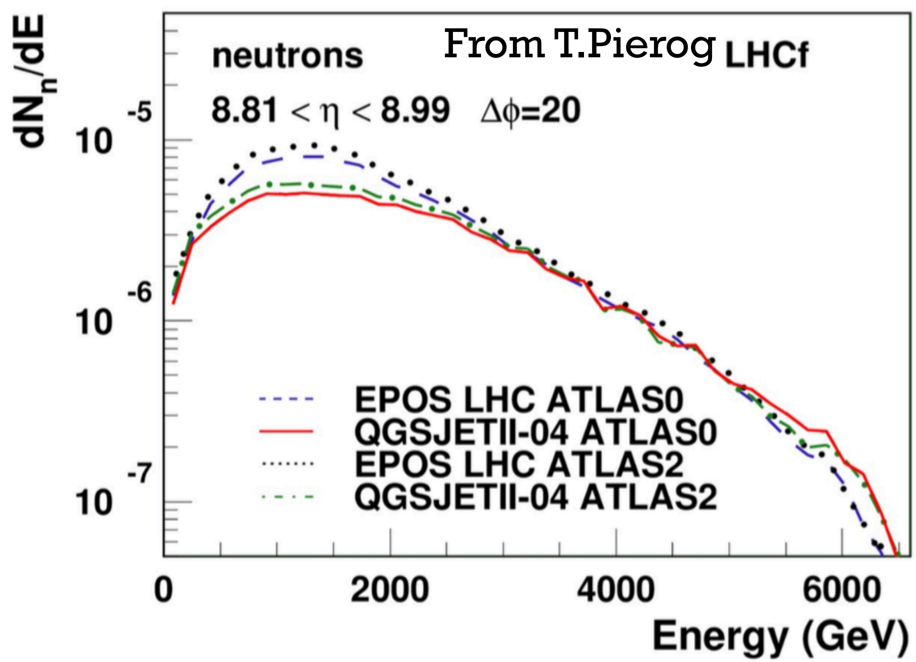
- Even larger differences wrt γ!
- 30% energy resolution is not taken into account
- …. But unfolding works well! (See Bonechi's talk)



What happens if we off-line combine ATLAS and LHCf?

- ATLAS0: no charged particles in the $|\eta|<2.5$ and $p_t>0.1$ GeV/c
- ATLAS2: >1 charged particles in the $|\eta|<2.5$ and $p_t>0.1$ GeV/c
- Central activity selection enhance the differences btw models
- Could be used to tune different components of the models

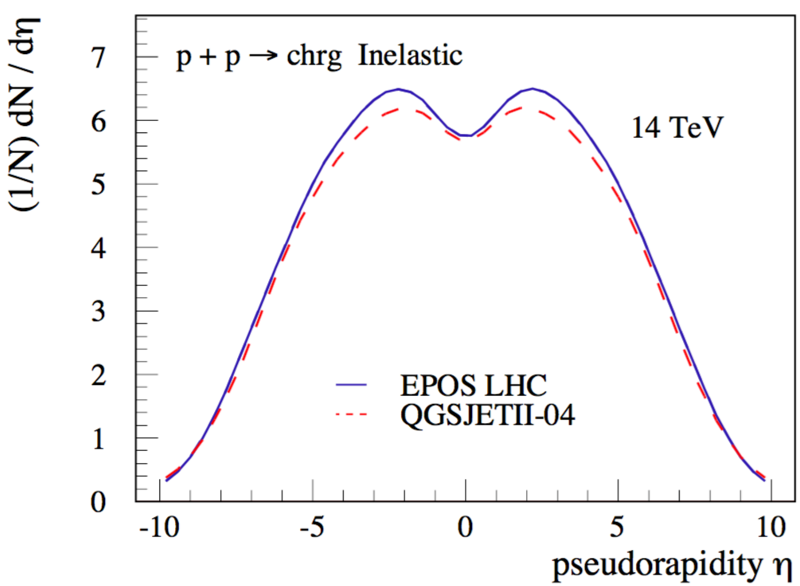


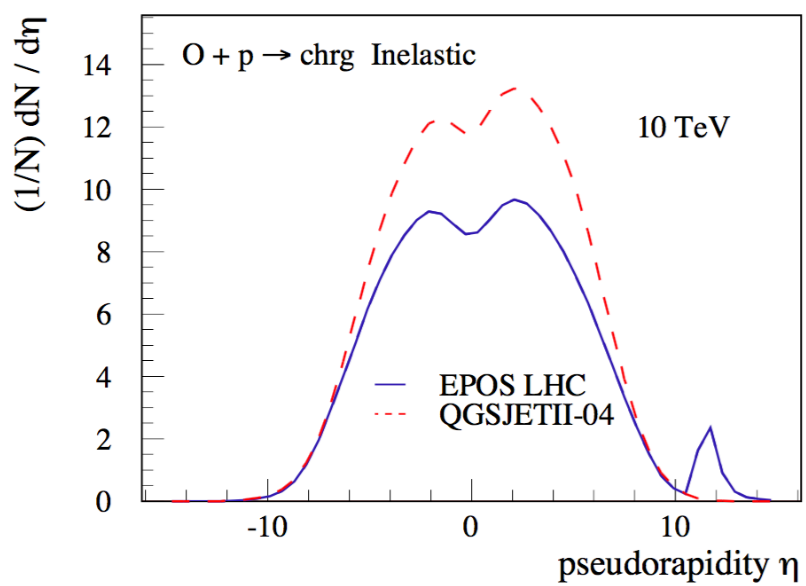


The future….

The far future @ LHC

- The most promising future at LHC involve the proton-light ions collisions
- To go from p-p to p-Air is not so simple….
  - Comparison of p-p, Pb-Pb and p-Pb is useful, but model dependent extrapolations are anyway necessary
- Direct measurements of p-O or p-N could significantly reduce some systematic effects

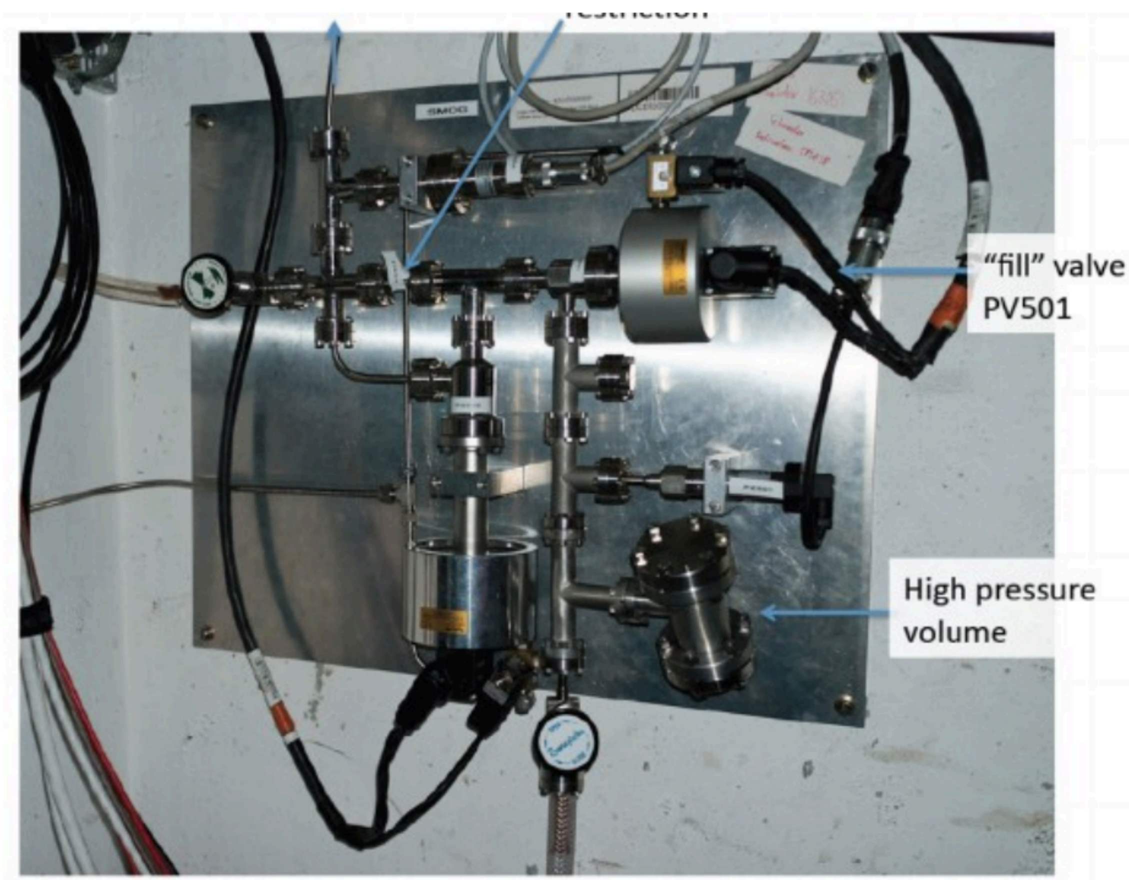




A new idea!

- After the talk of F. Donato yesterday a new idea came to my mind
- The SMOG system has already been tested in 2012 in LHCb
  - Injection of noble gas atoms inside the beam pipe to:
    - Measure the beam profile
    - Measure the luminosity
- Why don't use SMOG to measure cross section relevant for Cosmic Ray Physics???
  - P-He→Antiprotons+X
- We could make use of 'perfect' Particle Identification Detectors
- We could make use of the highest possible energies
  - Direct access to protons in the most interesting energy region

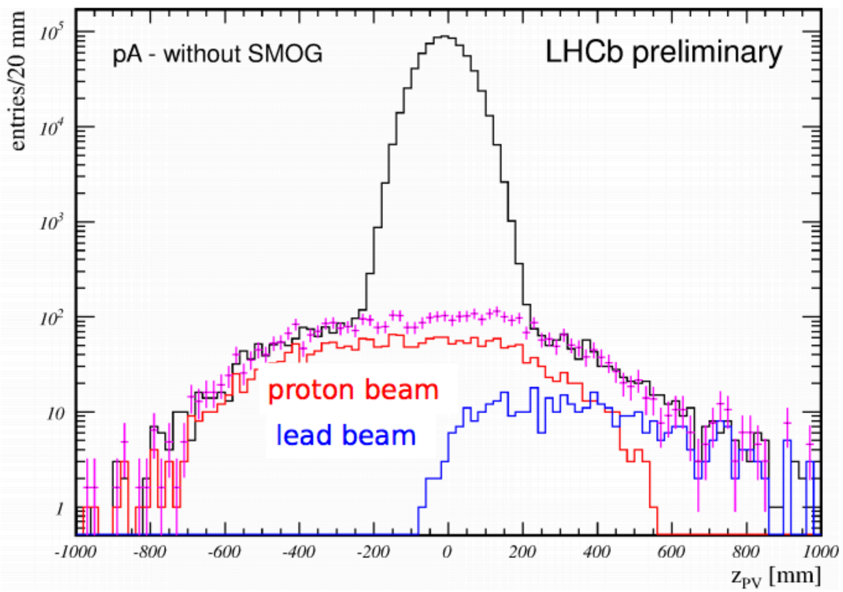
SMOG: System for Measuring Overlap with Gas



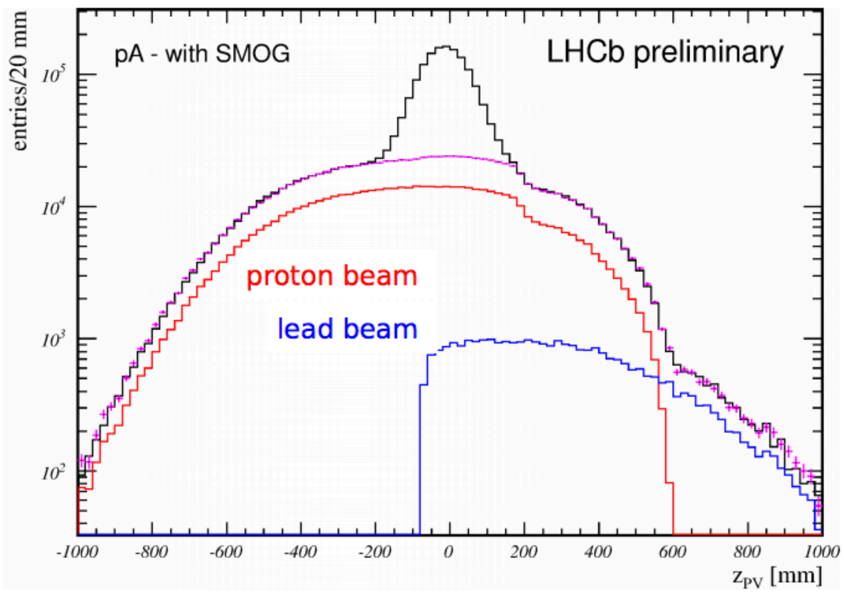
→ injection of Ne gas into interaction region

→ injection of Ne gas into interaction region

no SMOG



with SMOG



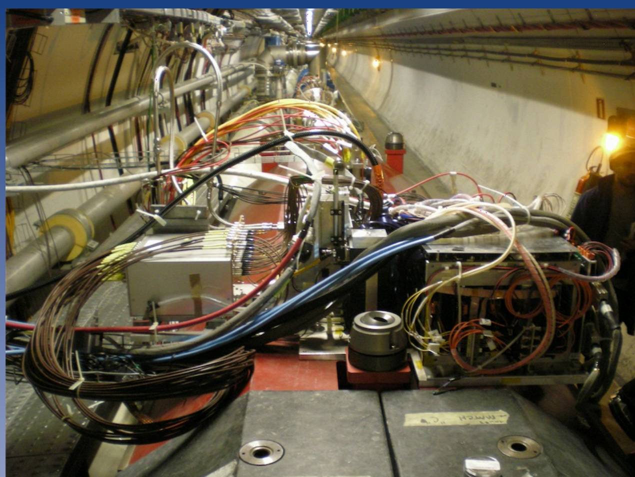
z-distribution of primary vertex

- increase of beam-gas interaction rate by two orders of magnitude
- accurate measurement of beam profile → precise luminosity determination

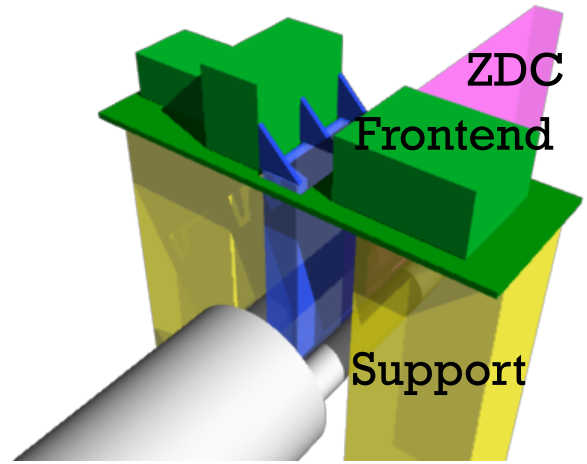
→ also allows to study pNe interactions at √s=87 GeV
shift of cm system by 4.5 units in rapidity in proton direction
→ LHCb is a central detector for fixed target collisions

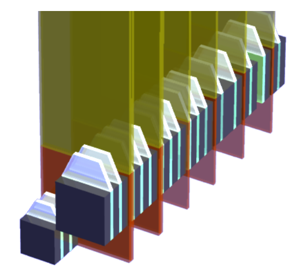
+ The future @ RHIC: From the Large Hadron Collider to the Longisland Hadron Collider

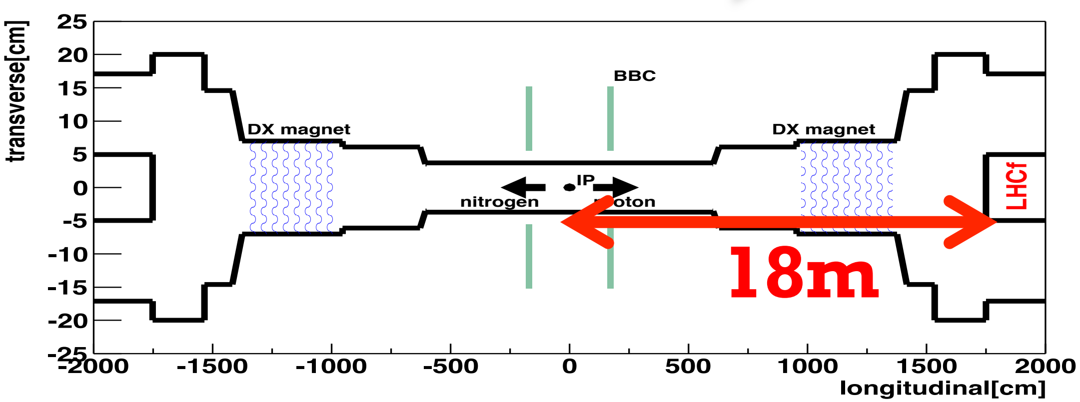
LHCf Arm2 detector in the LHC tunnel

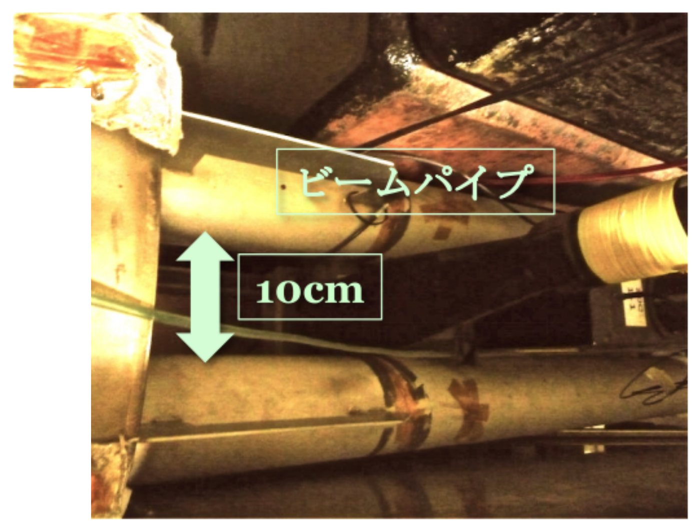


Schematic view of the RHICf installation



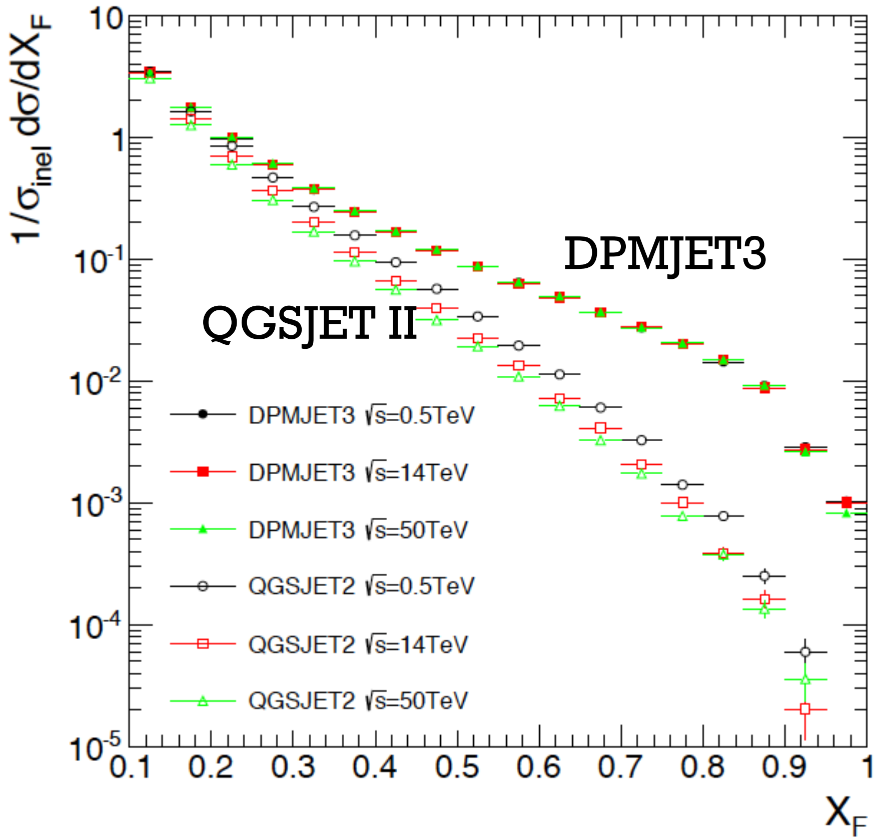




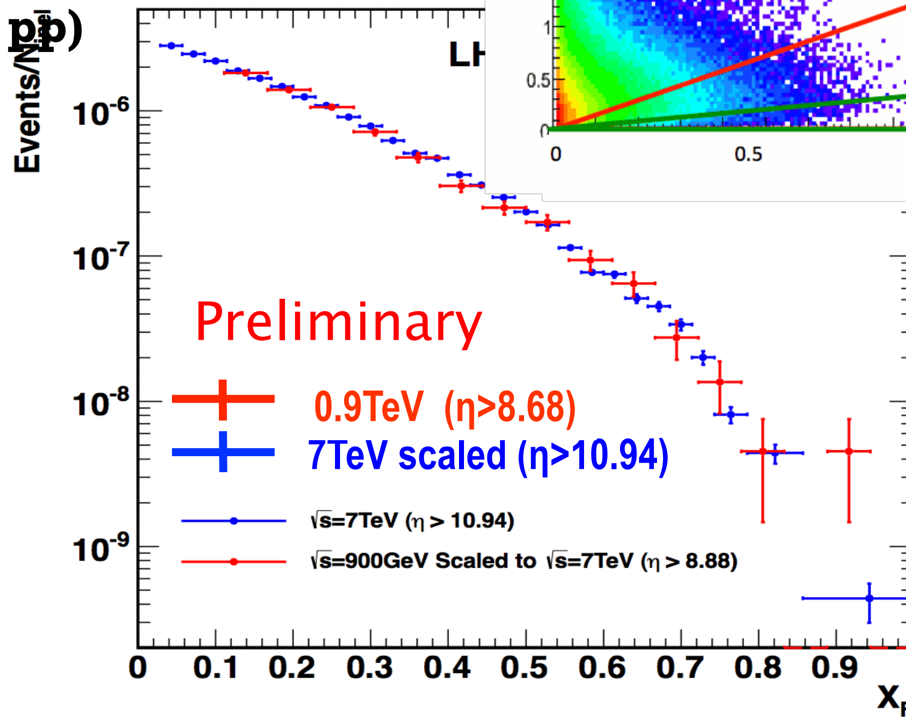


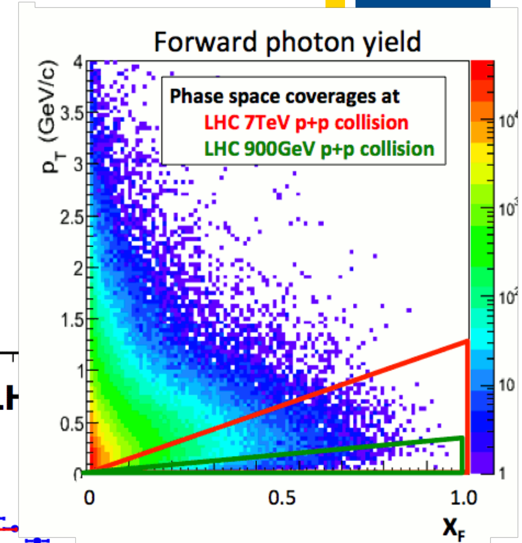
+ √s scaling : a key for extrapolation beyond the LHC

All π⁰ expected from models (0.5TeV, 14TeV and 50TeV)



LHCf single photon data (900GeV pp , 7TeV pp)



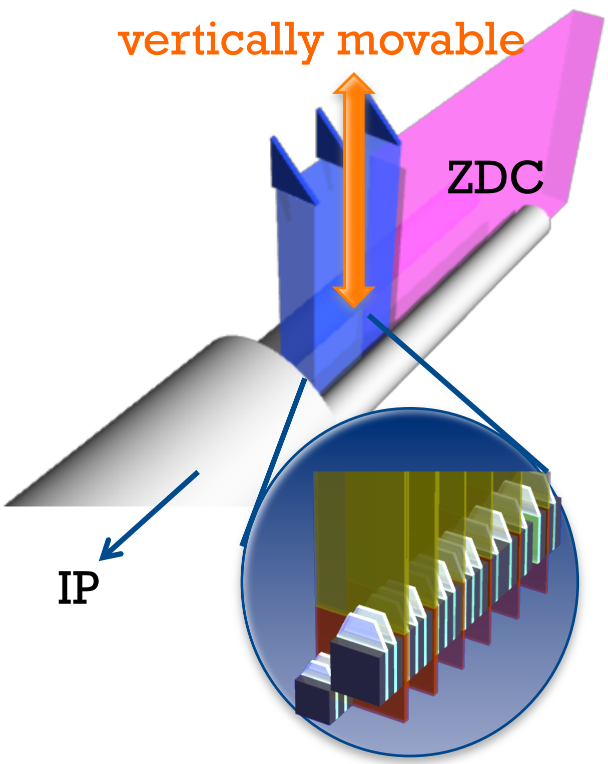


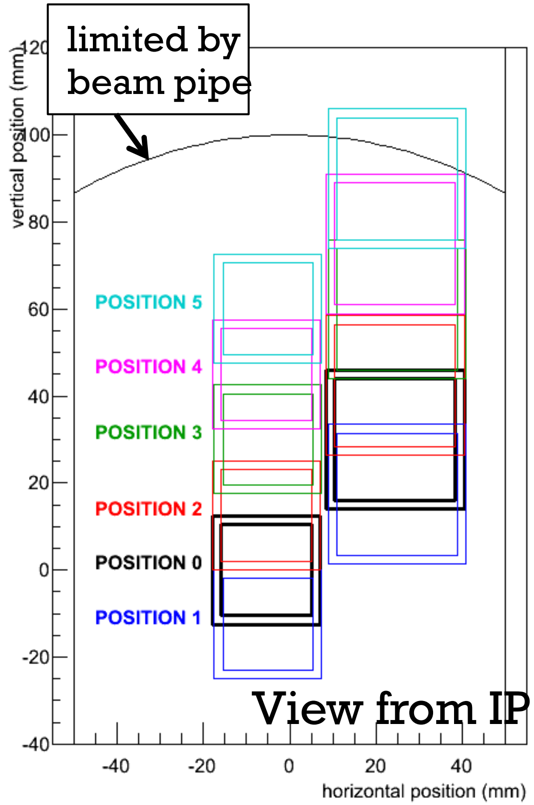
Comparison done in the <u>very limited phase space</u> of 900GeV collisions

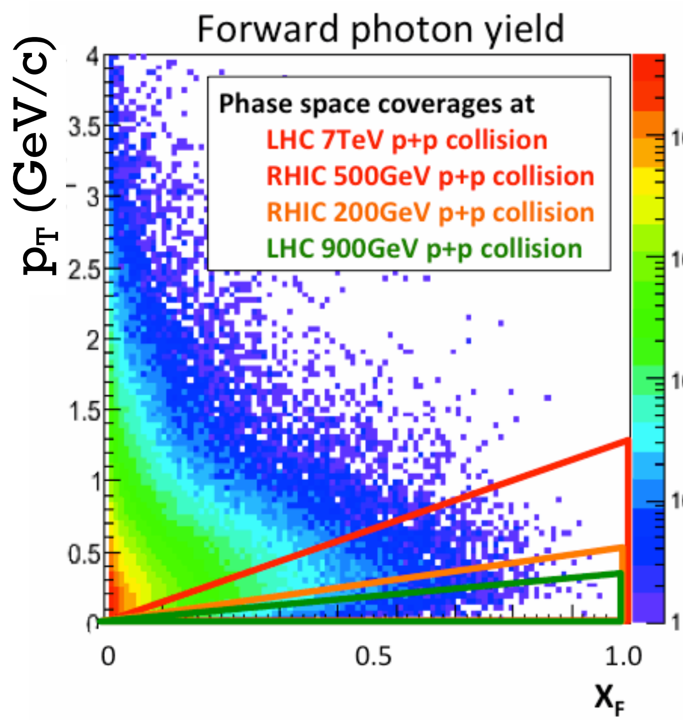
(green triangle in the phase space plot)

+ RHICf coverage

Installing the LHCf Arm2 detector at RHIC (PHENIX IP)

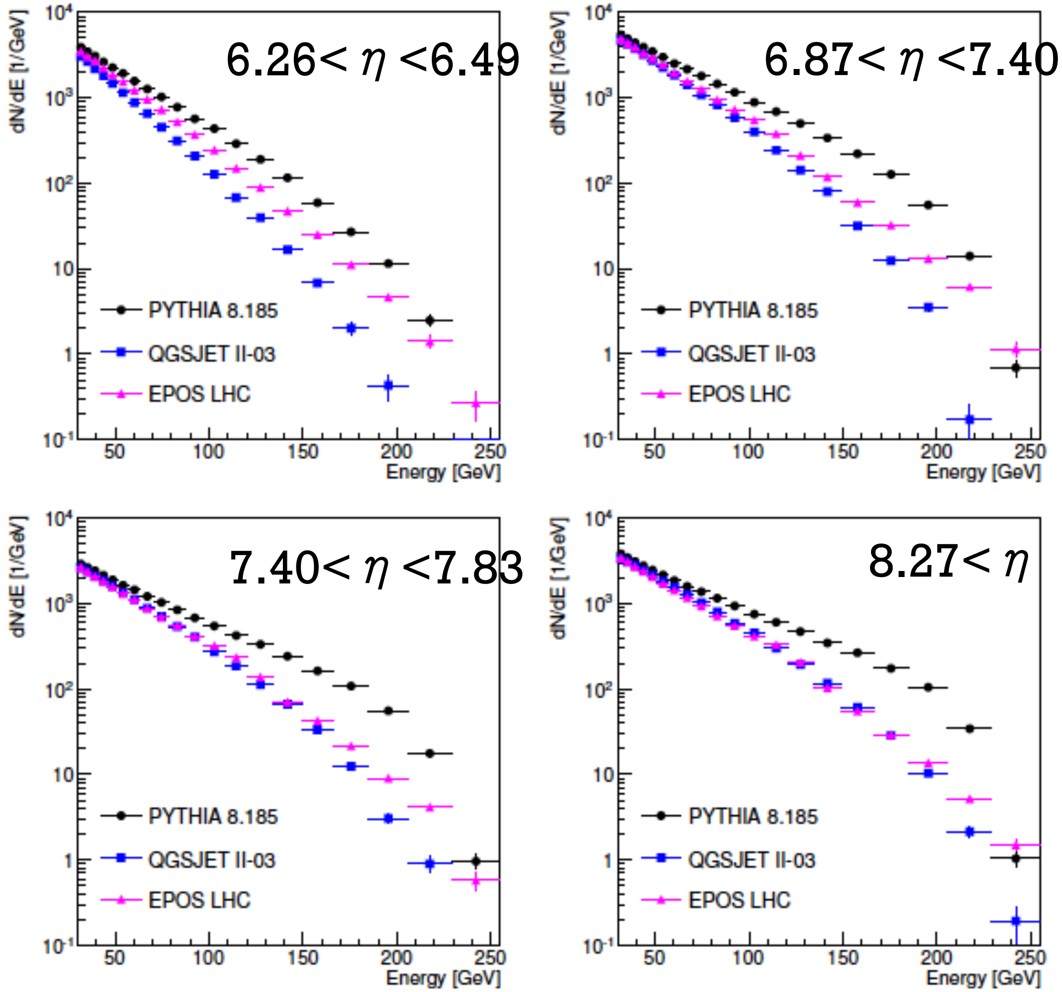






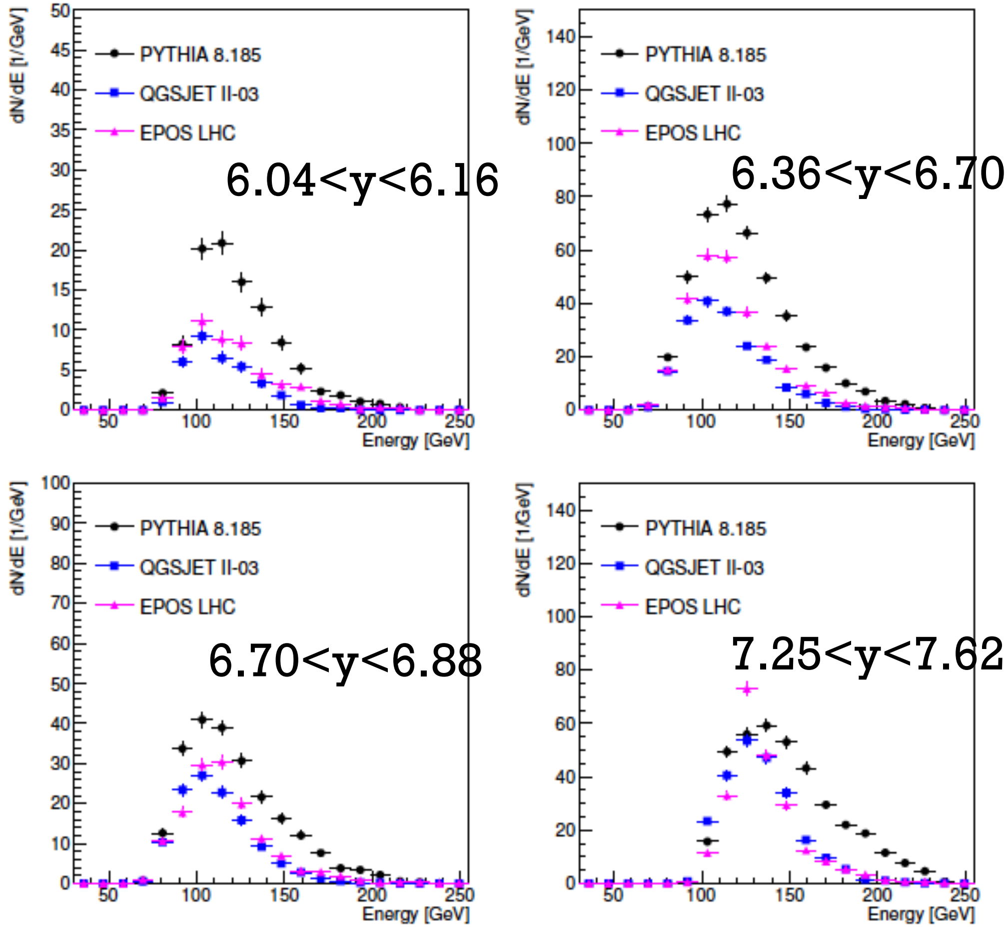
- Detector is moved up-down; wide p_T coverage
- x_F-p_T coverage identical to LHC 7 TeV collision
- Wider coverage and higher resolution in p_T than PHENIX ZDC+SMD measurements (joint analysis between ZDC and RHICf)

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 (π^0)



- π^0 spectra at 4 rapidity samples
- <60GeV not detectable due to large opening angle of $\gamma\ \gamma$
- 24 min statistics (12 nb^{-1} effective luminosity; 12 nb^{-1} delivered)
- Statistical error will be negligible with a reasonable run time

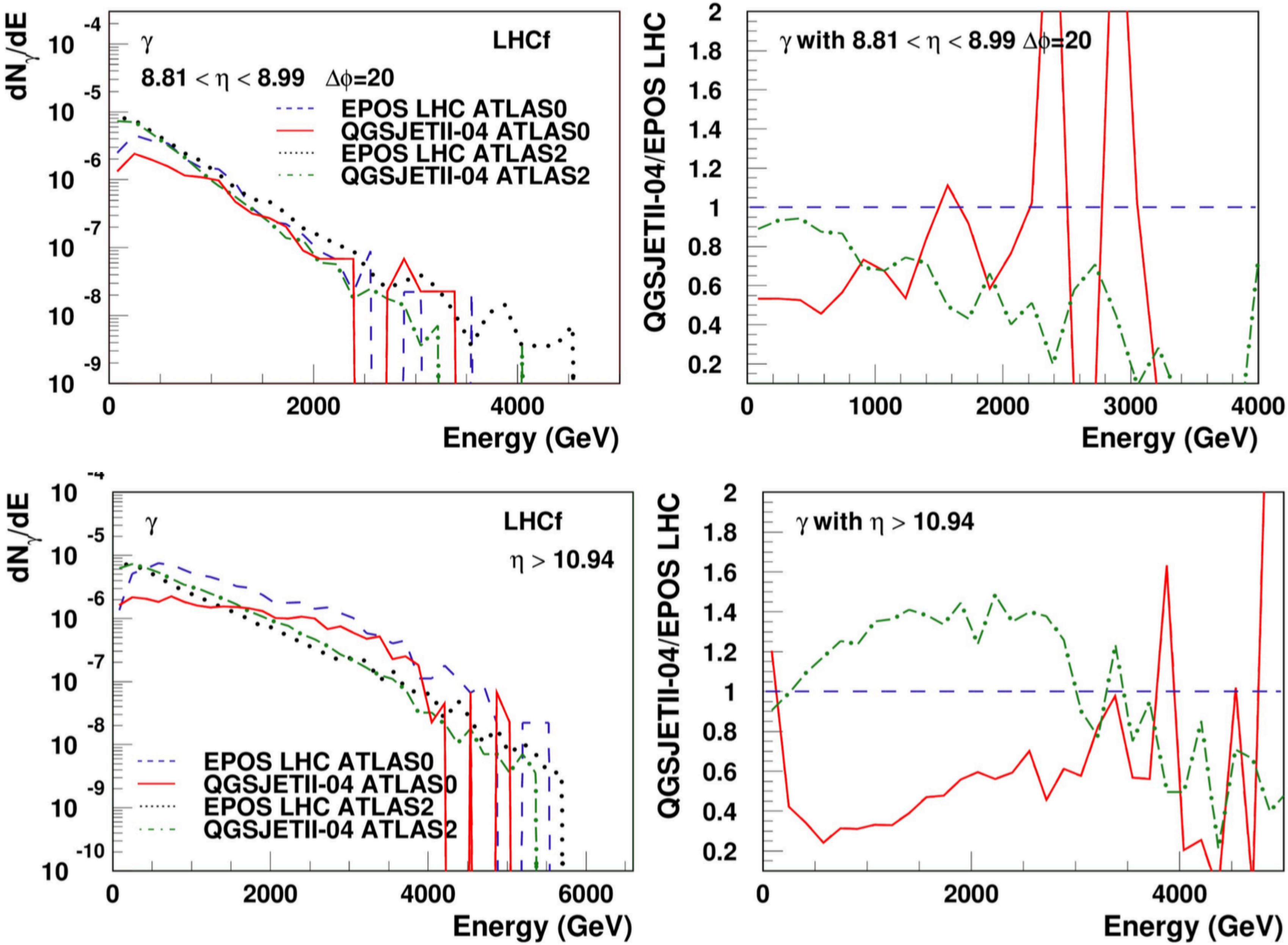
Conclusions

- In the last few years the importance of accelerator based measurements useful for Cosmic Ray physics came up very clearly
- LHC is the ideal laboratory for these studies
- Many important measurements have already been done
  - Significant improvement of EPOS_LHC and QGSJET-04 hadronic interaction models
- Synergies between dedicated forward detectors and large acceptance central detectors are coming up
  - Next generation measurements, profiting of these synergies, will be soon performed, allowing further improvements of the models in their different components

+

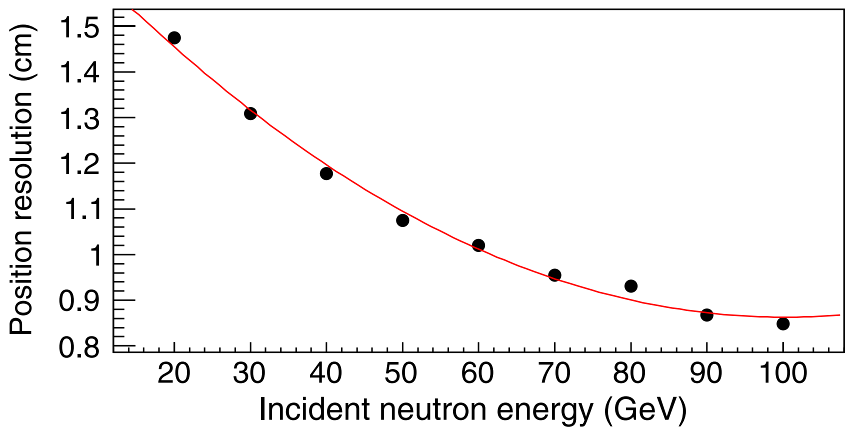
Backup slides

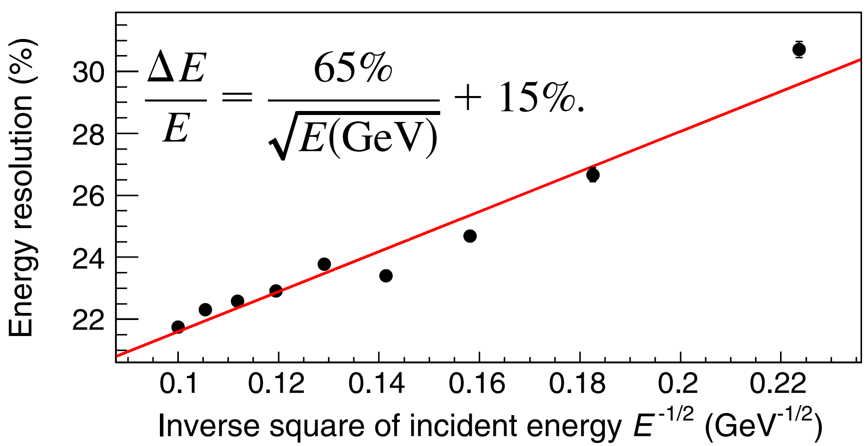
+ LHCf-Atlas: photons



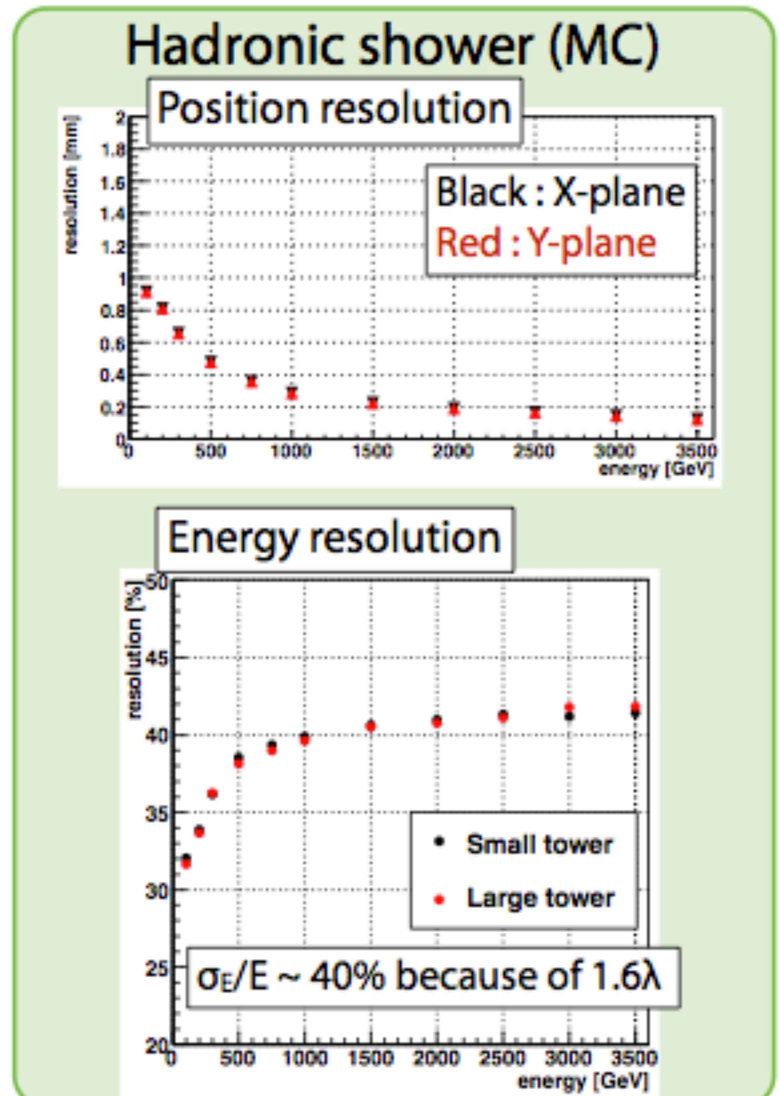
+ ZDC resolution @PHENIX vs RHICf

PHENIX ZDC





RHICf



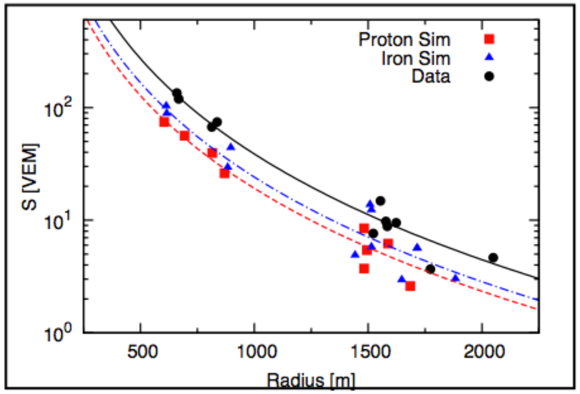
+ RHICf beam condition proposal

- Constraints
  - RHICf DAQ speed is limited to 1kHz
  - Collision pile up cannot be resolved
  - Small angular dispersion is preferred
- Beam Proposal
  - 510GeV p+p collisions
  - $\beta^* = 10m$
  - Radial (horizontal) polarization; 0.4-0.5
  - ε = 20mm mrad, $I_b = 2\times10^{11}$, $n_{b\text{-colliding}} = 100$, $n_{b\text{-noncolliding}} = 20$ (nominal)
  - Luminosity=$1.1\ 10^{31}\ cm^{-2}s^{-1}$
- Operation
  - Few days for physics and few days for contingency
  - π^0 (double tower event) enhanced and single shower prescaled triggers are used simultaneously
  - Trigger exchange with PHENIX
  - Stay at the garage position not to interfere ZDC when RHICf does not take data

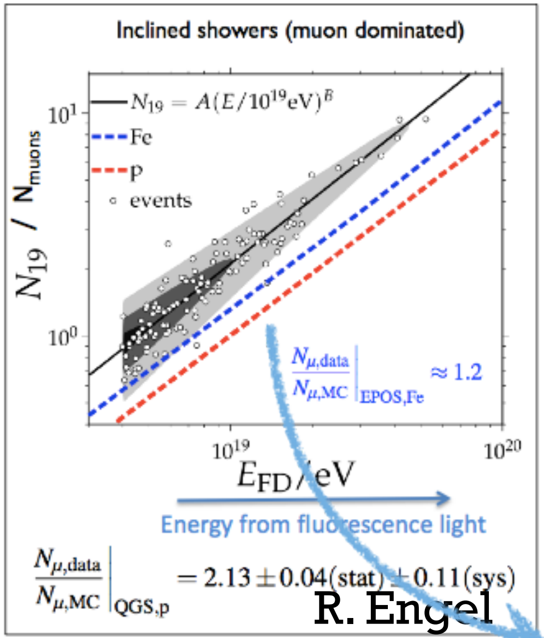
LHCf @ pp 7 TeV: neutron analysis

Motivations:

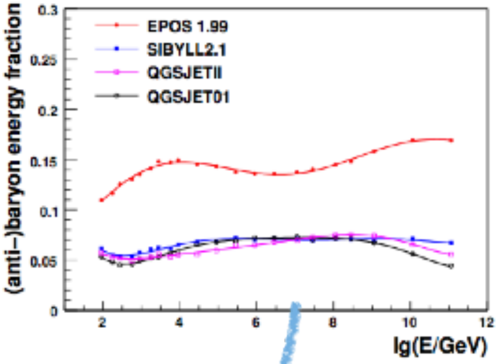
- Inelasticity measurement $k=1-p_{leading}/p_{beam}$
- Muon excess at Pierre Auger Observatory
  - Cosmic rays experiment measure PCR energy from muon number at ground and florescence light
  - 20-100% more muons than expected have been observed

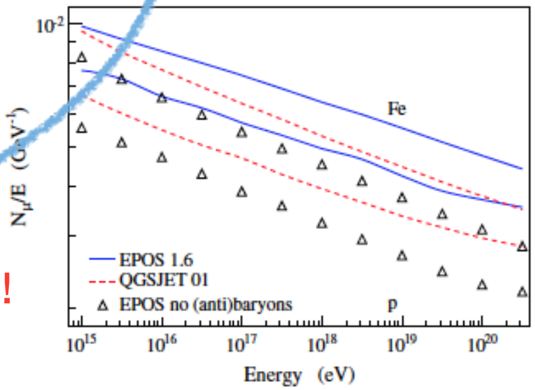


[J.Allen, et al. ICRC2011 Proceedings]



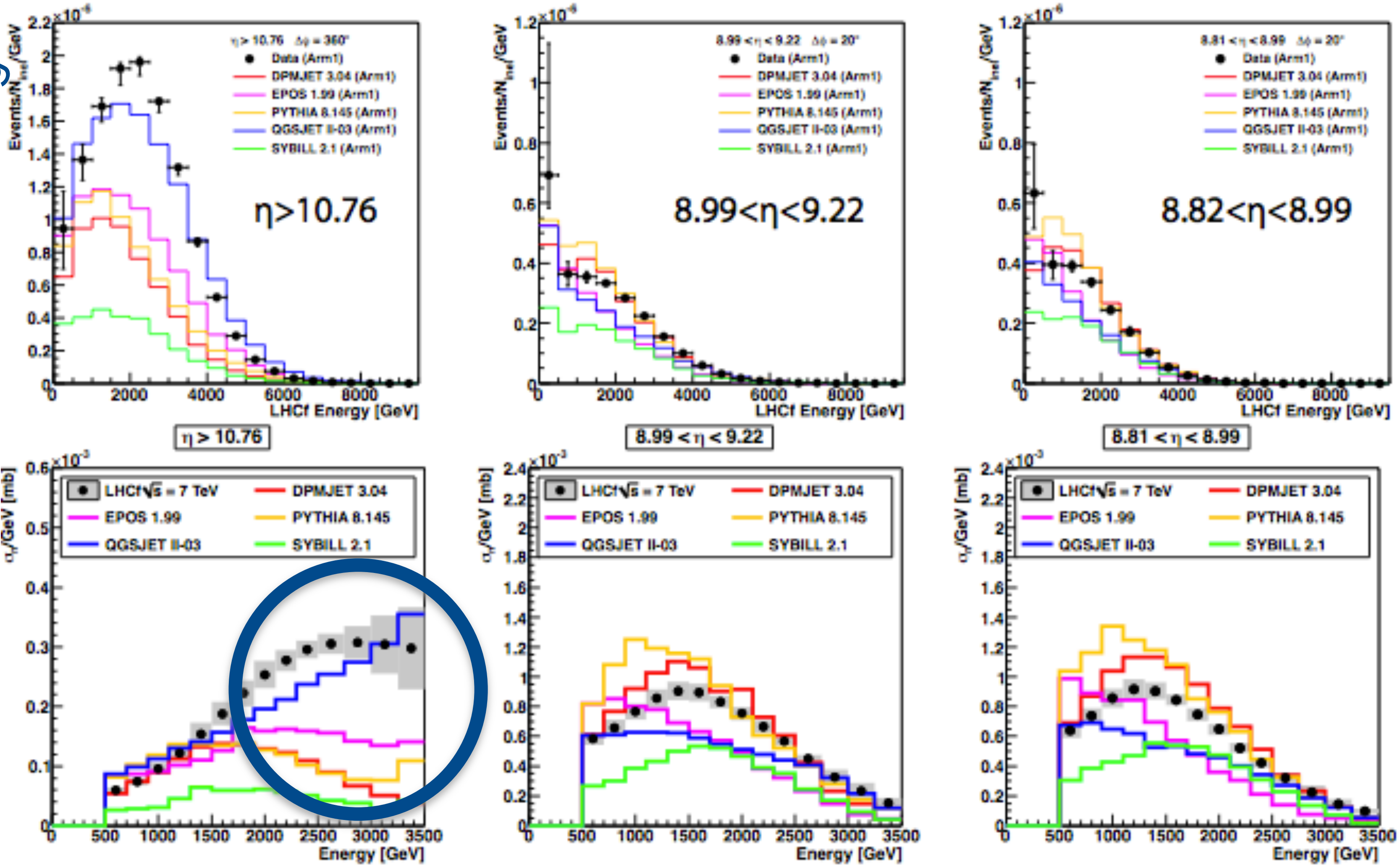
- Number of muons depends on the energy fraction of produced hadron
- Muon excess in data even for Fe primary MC!!!!
- EPOS predicts more muons due to larger baryon production, even if it is not sufficient to reproduce the experimental data





importance of baryon measurement!!!

+ Inclusive neutron spectra (7 TeV pp)

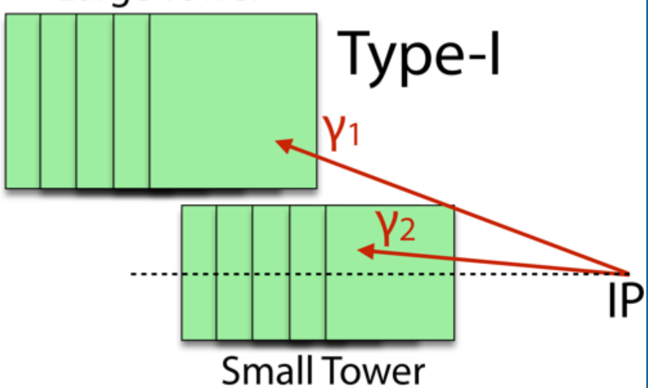


Very large high energy peak in the η>10.76 (predicted only by QGSJET)

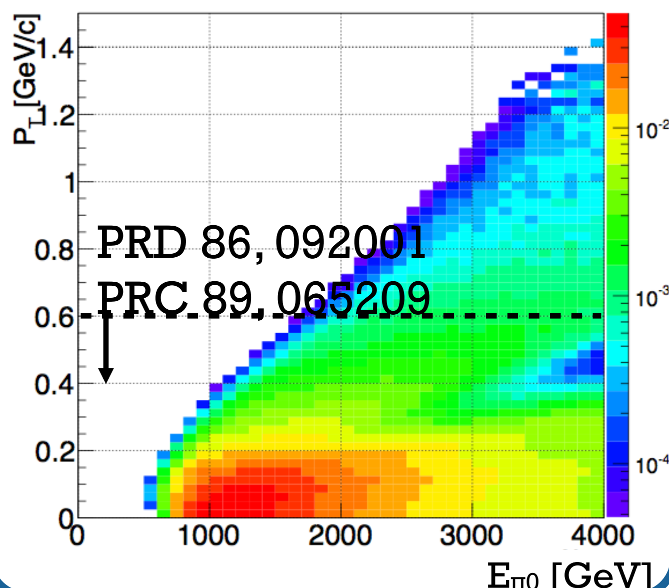
→ Small inelasticity in the very forward region!

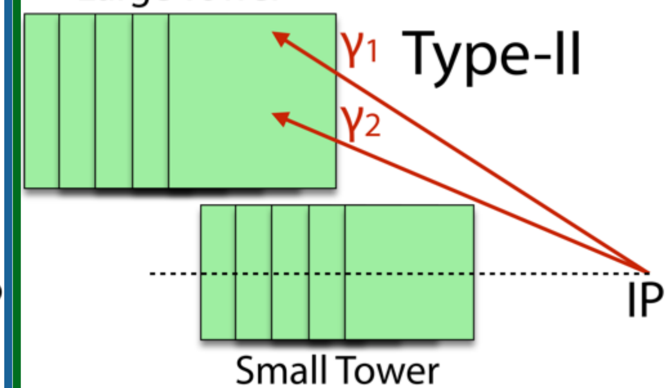
+ Type II π^0 in pp 7 TeV collisions

Present LHCf results are based on the Type-I π^0 events.
Improved π^0 reconstruction, Type-II, is now ready for use in analysis.

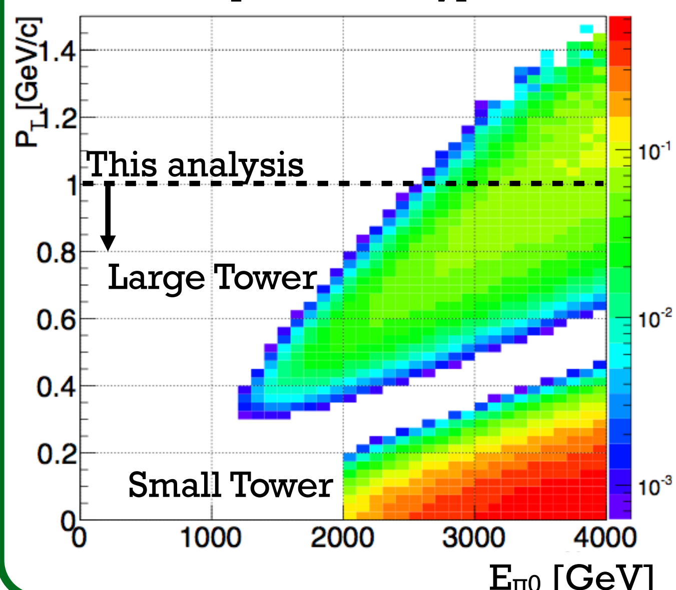


Arm2 acceptance for Type-I π^0

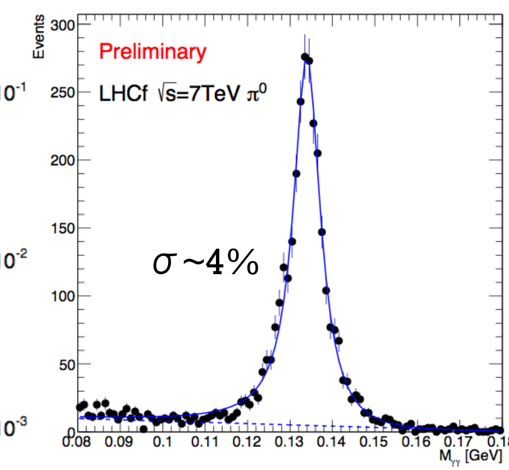




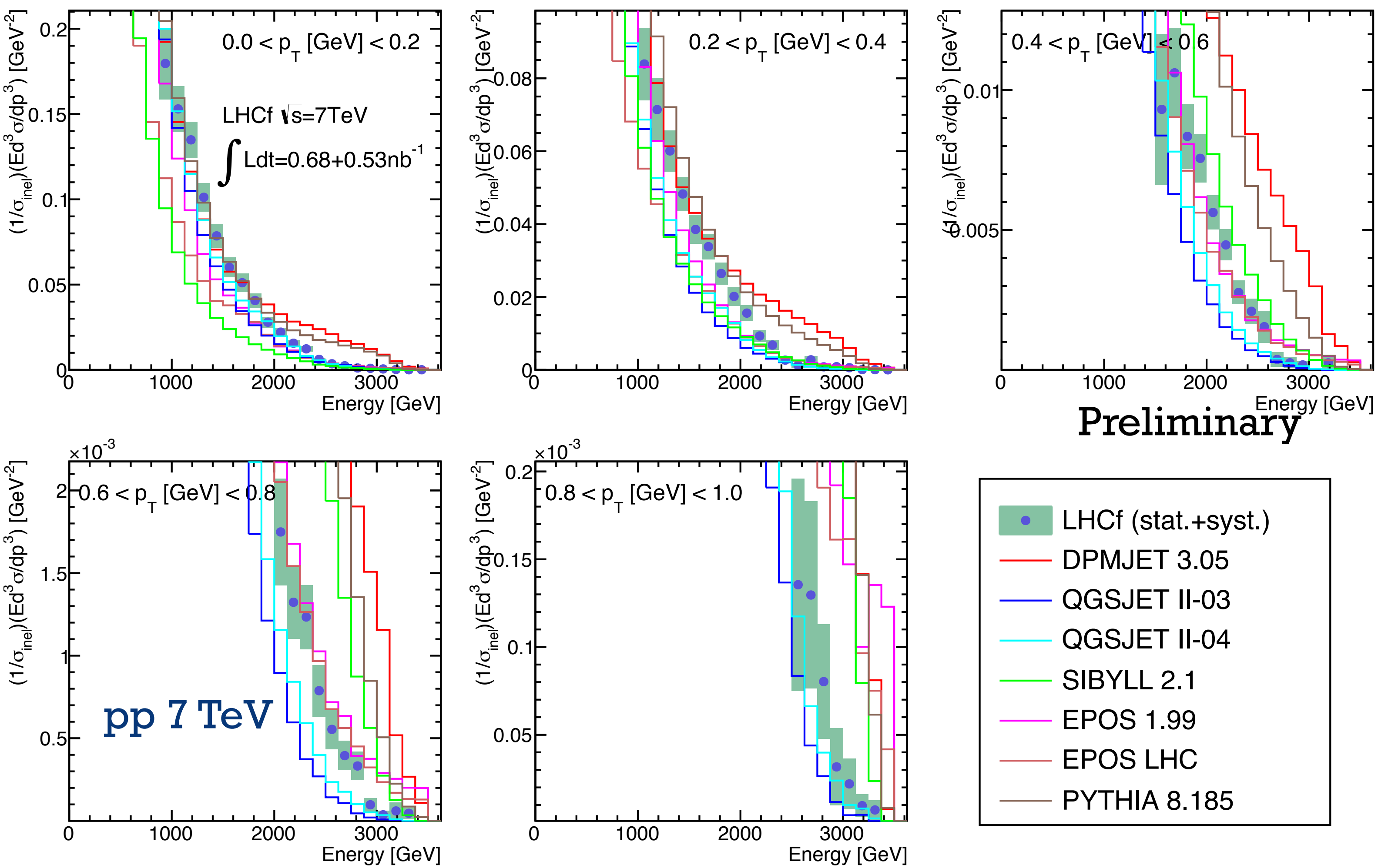
Arm2 acceptance for Type-II π^0



Motivation of Type-II
- extended p_T range
- applicable to Λ and K
- di-hadron.

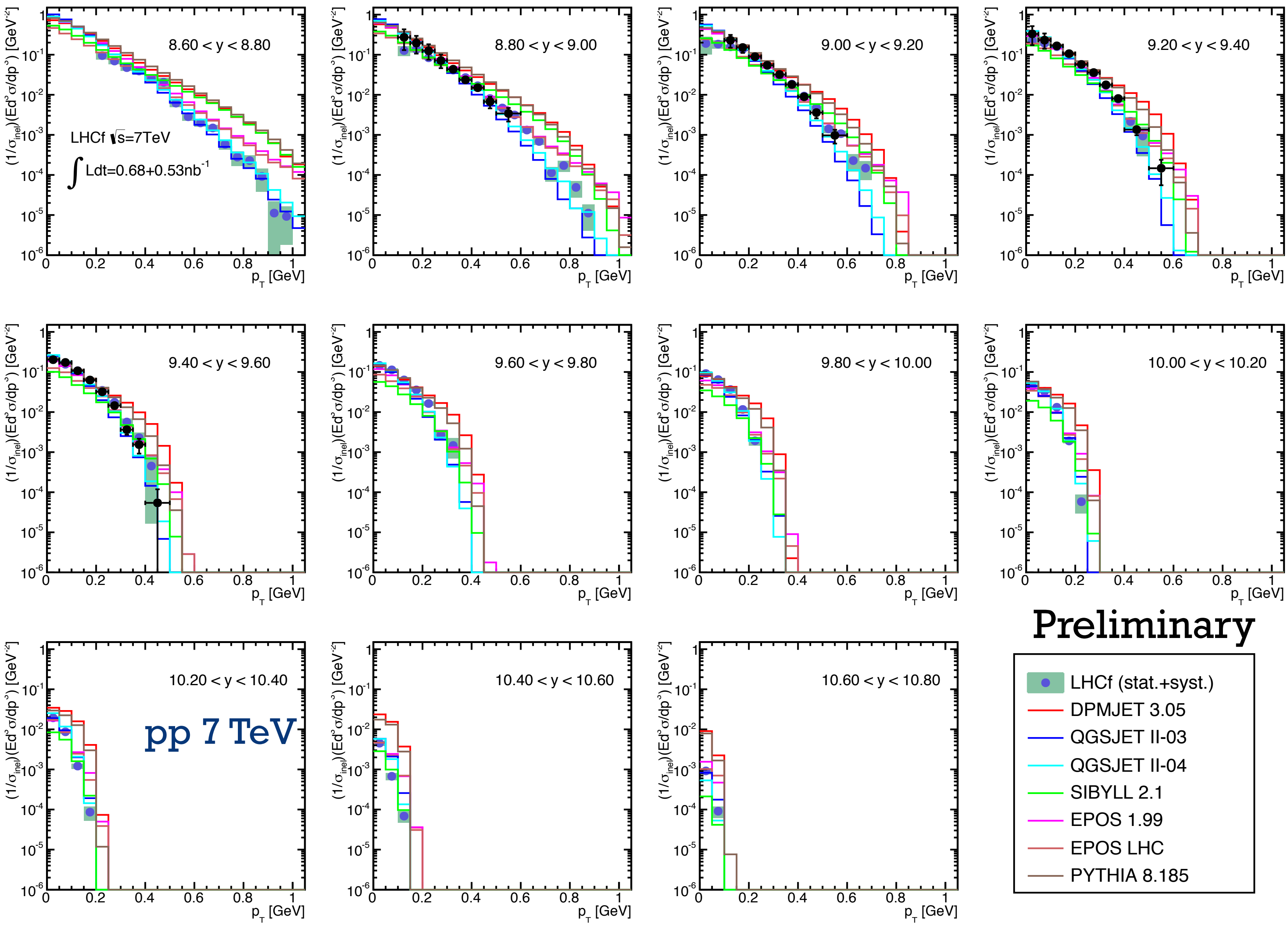


+ π^0 energy spectra (for different p_T bins)

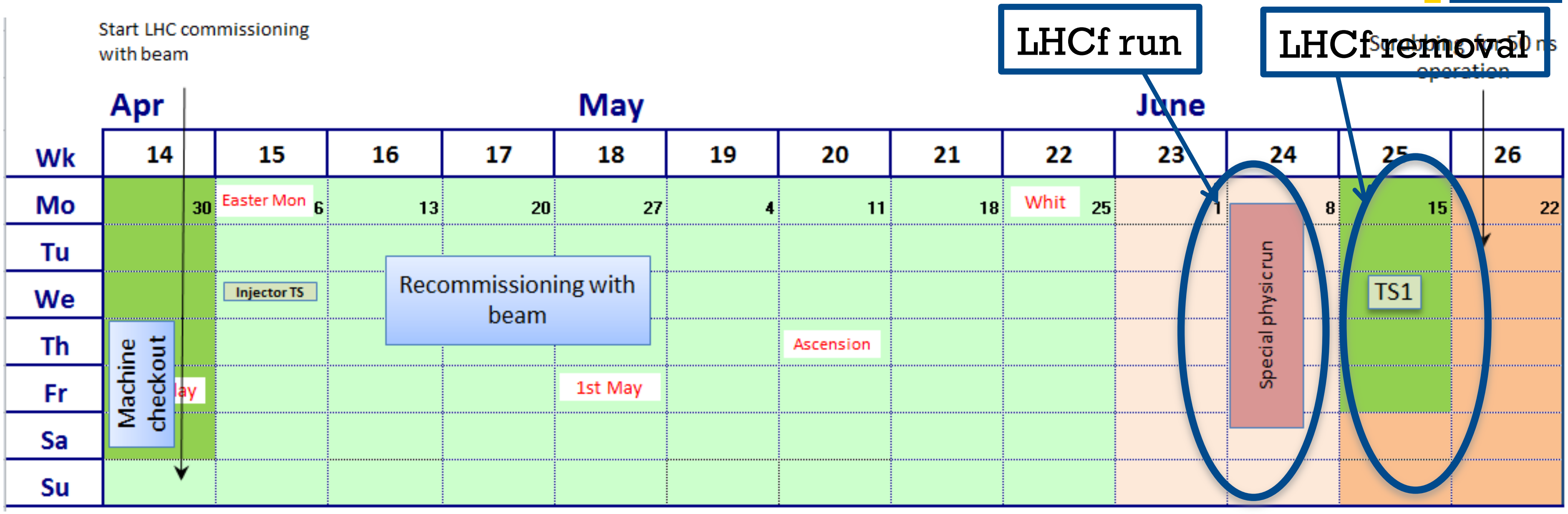


- DPMJET and PYTHIA are harder than LHCf $p_T < 1.0$ GeV, although compatible at low p_T and low E.
- QGSJET II gives good agreement at $0 < p_T < 0.2$ GeV and $0.8 < p_T < 1.0$ GeV.
- EPOS 1.99 agrees with LHCf at $0.4 < p_T < 0.8$ GeV. LHCf prefers EPOS 1.99 than EPOS LHC.

π^0 p_T spectra (for different rapidity bins)



+ 2015 updated LHC operation schedule



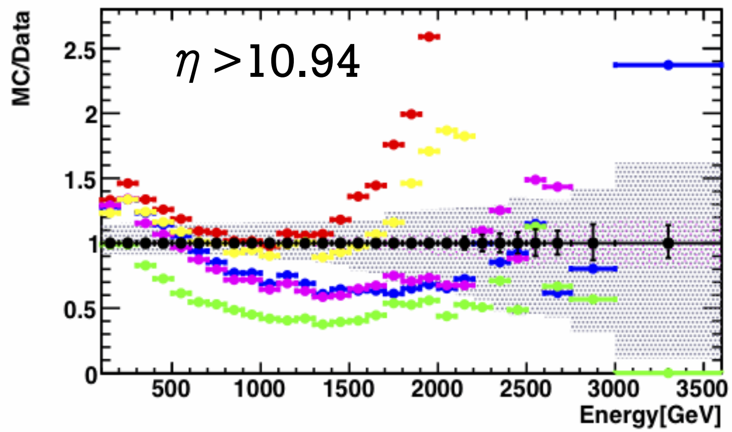
From M. Lamont, LMC Meeting, 15/04/15

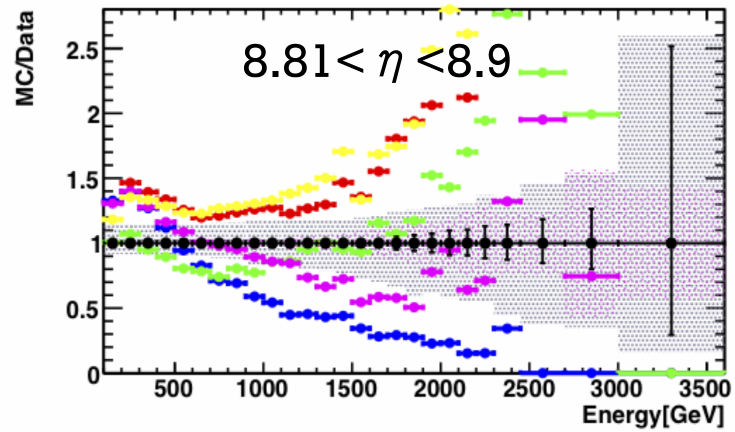
- 8 weeks beam commissioning
- 5 days special physics at beta* = 19 m (VdM, LHCf, TOTEM & ALFA)
- Start TS1 – 15th June. 24 hour technical stop in SPS in parallel followed by SPS scrubbing.

+ DATA vs MC : comp. 900GeV/7TeV

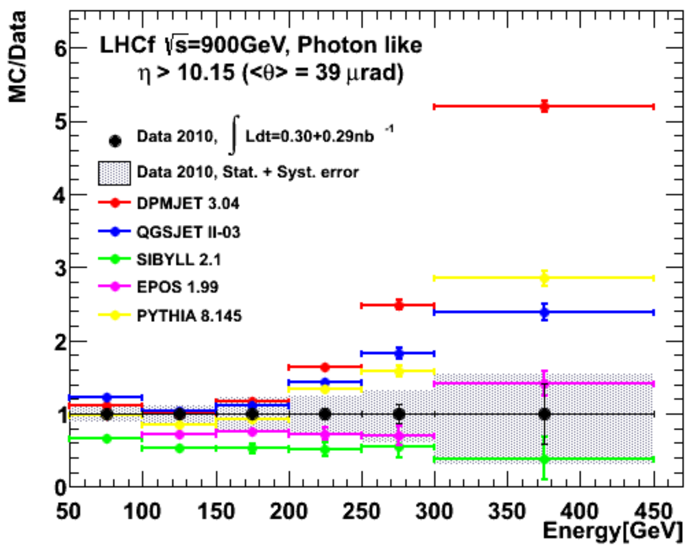
- None of the model nicely agrees with the LHCF data
- Here we plot the ratio MC/Data for the various models
- > Factor 2 difference

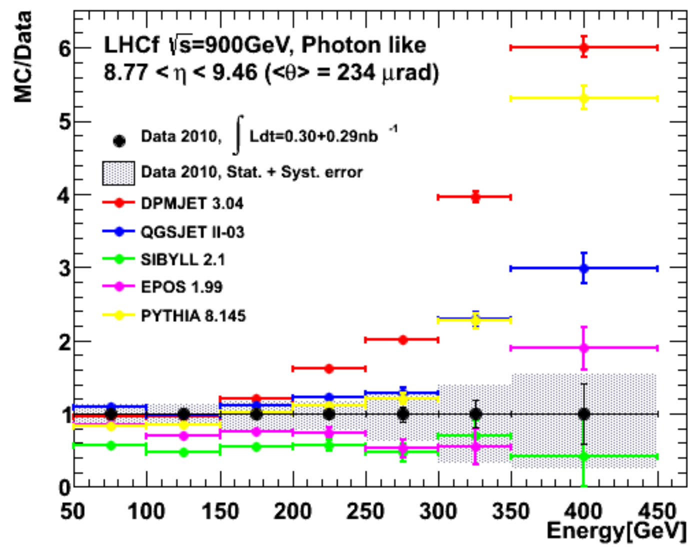
7TeV





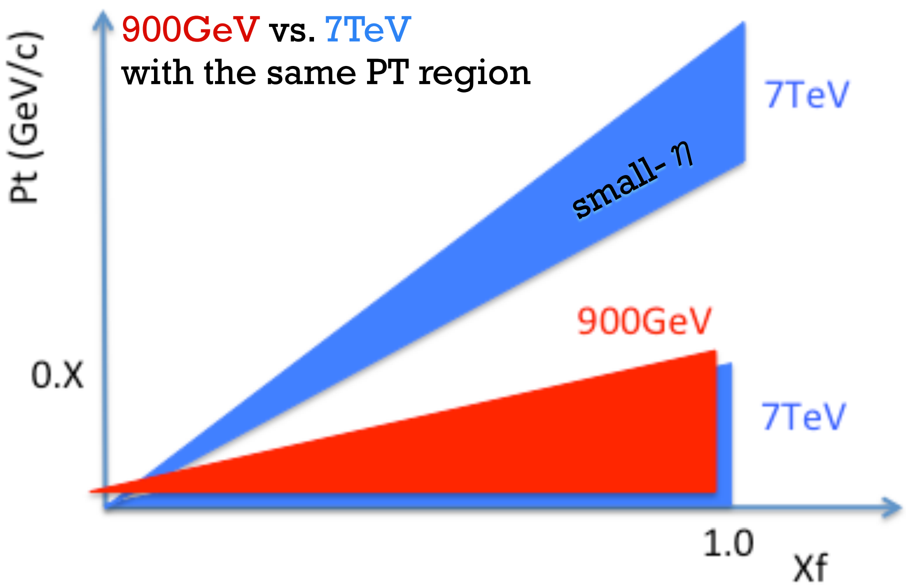
900GeV



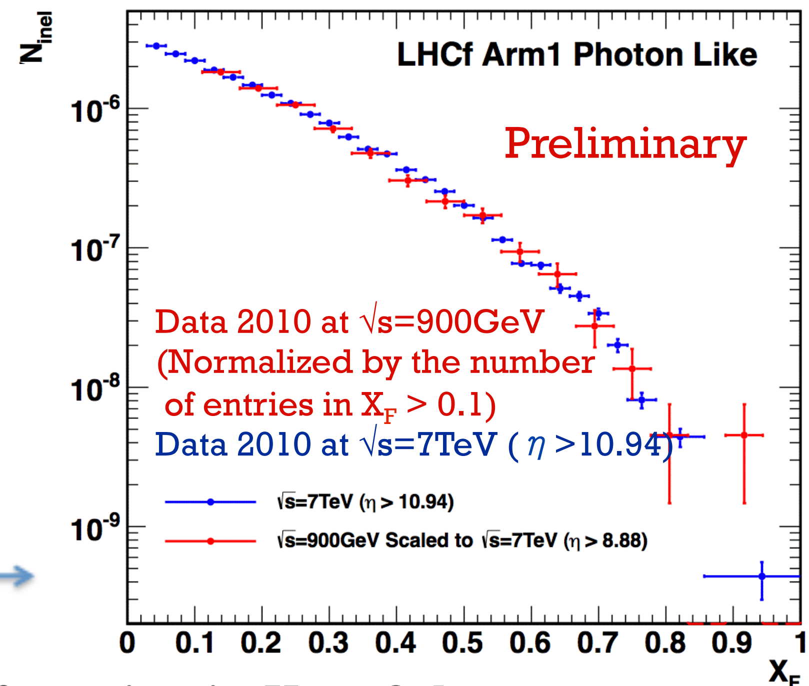


+ DATA : 900GeV vs 7TeV

Coverage of 900GeV and 7TeV results in Feynman-X and P_T



X_F spectra : 900GeV data vs. 7TeV data



- ✓ Normalized by the number of entries in $X_F > 0.1$
- ✓ No systematic error is considered in both collision energies.

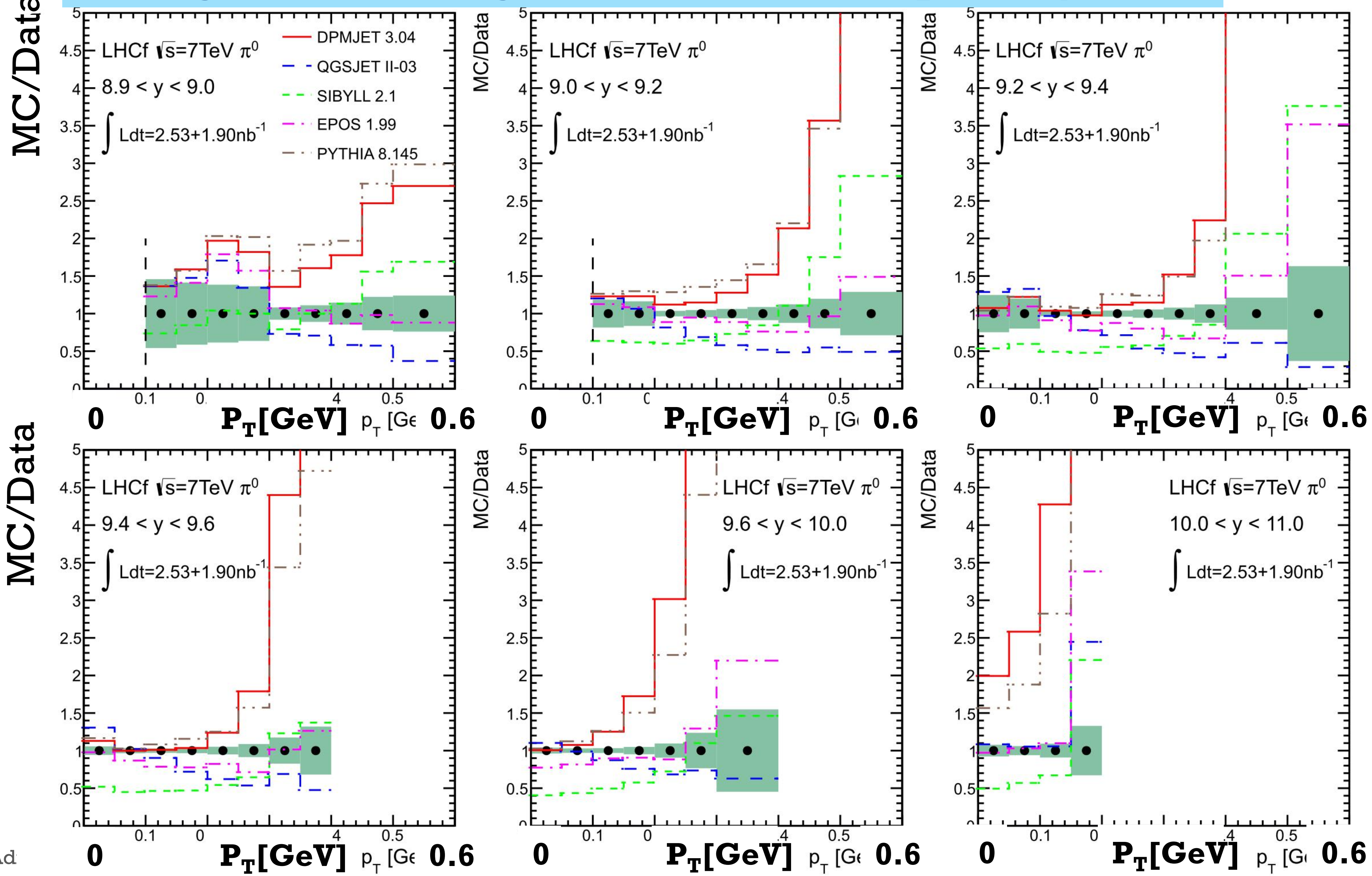
Good agreement of X_F spectrum shape between 900 GeV and 7 TeV.
➔weak dependence of $\langle p_T \rangle$ on E_{CMS}

$$\frac{1}{\sigma_{\rm inel}} \frac{d\sigma_\gamma}{dX_{\rm F}}\bigg|_{\eta<\text{limited}} \propto \frac{1}{\sigma_{\rm inel}} \frac{d\sigma_\gamma}{p_{\rm T} dp_{\rm T} dX_{\rm F}} \langle p_{\rm T} \rangle dp_{\rm T}$$

π^0 P_T spectra for various y bin: MC/data

DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

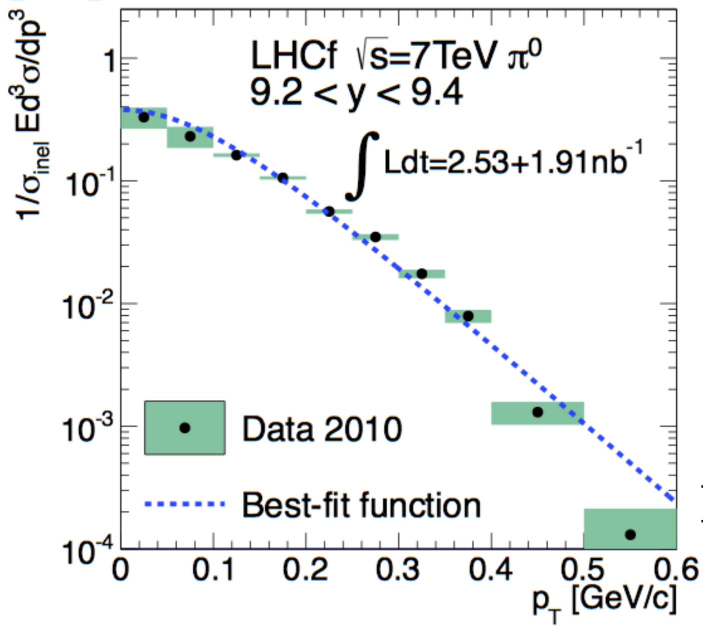
EPOS gives the best agreement both for shape and yield.



+ π^0 analysis at $\sqrt{s}$=7TeV

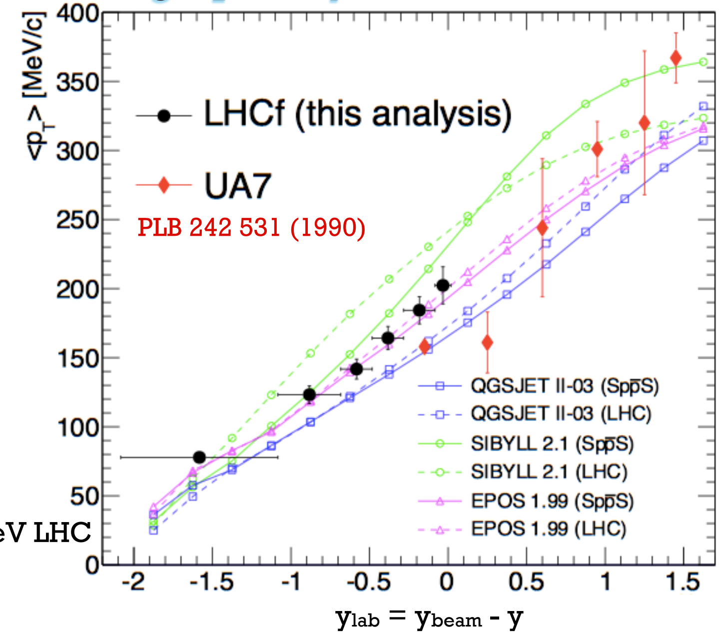
1205.4578).

p_T spectra vs best-fit function



Y_{Beam}=6.5 for SPS
Y_{Beam}=8.92 for7 TeV LHC

Average p_T vs y_{lab}



1. Thermodynamics
(Hagedron, Riv. Nuovo Cim. 6:10, 1 (1983))

$$\frac{1}{\sigma_{\rm inel}} E \frac{d^3\sigma}{dp^3} = A \cdot \exp(-\sqrt{p_{\rm T}{}^2 c^2 + m_{\pi^0}^2 c^4}/T)$$

$$\langle p_{\rm T} \rangle = \sqrt{\frac{\pi m_{\pi^0} c^2 T}{2}} \frac{K_2(m_{\pi^0} c^2/T)}{K_{3/2}(m_{\pi^0} c^2/T)}$$

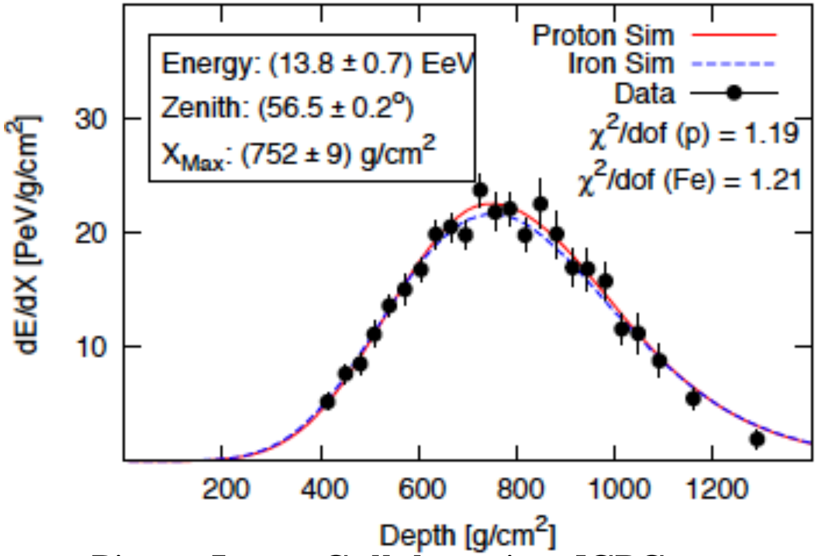
2. Numerical integration

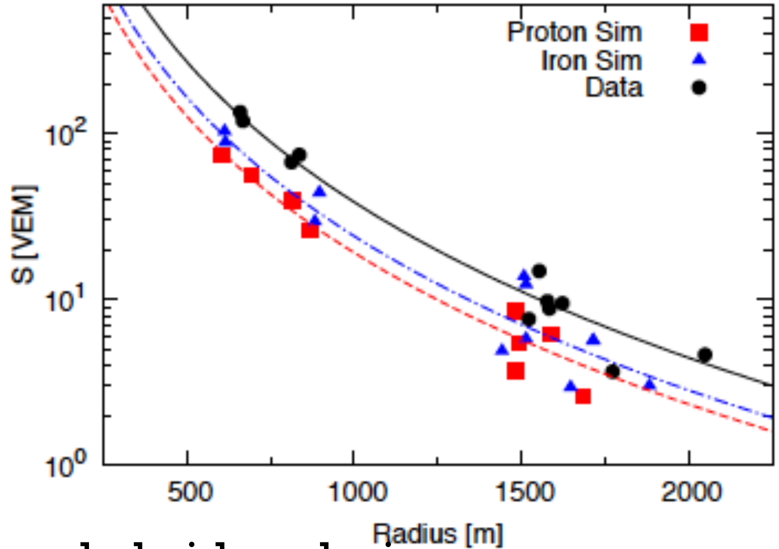
$$\langle p_{\rm T} \rangle = \frac{\int_0^\infty 2\pi p_{\rm T}^2 f(p_{\rm T}) dp_{\rm T}}{\int_0^\infty 2\pi p_{\rm T} f(p_{\rm T}) dp_{\rm T}}$$

actually up to the upper bound of histogram

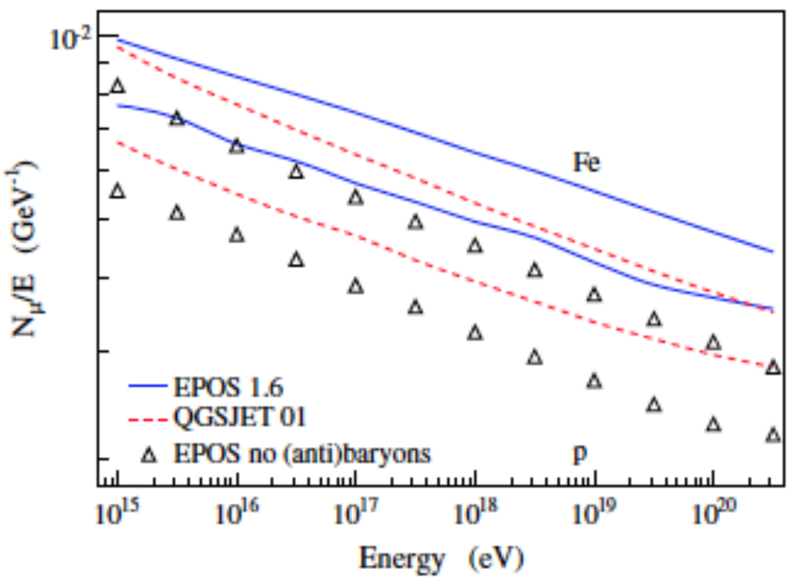
- Systematic uncertainty of LHCf data is 5%.
- Compared with the UA7 data ($\sqrt{s}$=630GeV) and MC simulations (QGSJET, SIBYLL, EPOS).
- Two experimental data mostly appear to lie along a common curve
  → no evident dependence of $\langle p_T \rangle$ on E_{CMS}.
- Smallest dependence on E_{CMS} is found in EPOS and it is consistent with LHCf and UA7.
- Large E_{CMS} dependence is found in SIBYLL

+ 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

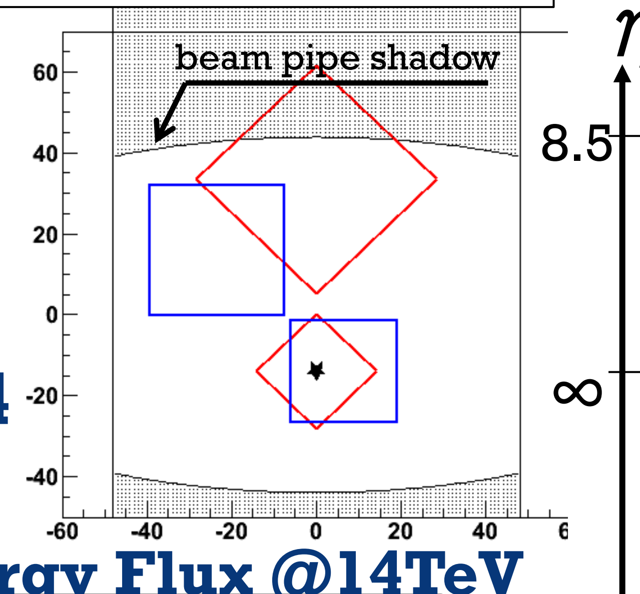
EPOS predicts more muon due to larger baryon production

=> importance of baryon measurement

Pierog and Werner, PRL 101 (2008) 171101

What LHCf can measure

Front view of calorimeters
@ 100 μ rad crossing angle

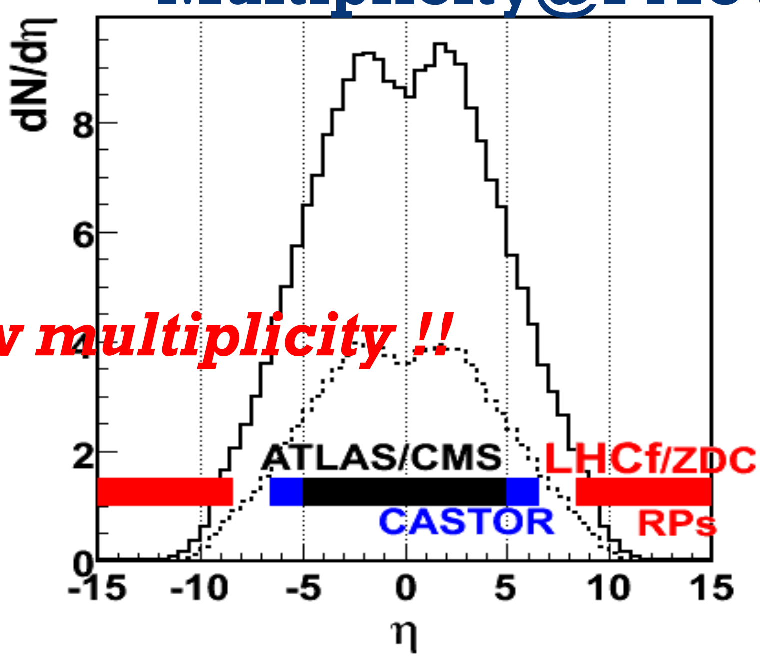


Energy spectra and
Transverse momentum distribution of

- **Gamma-rays (E>100GeV,dE/E<5%)**
- **Neutral Hadrons (E>a few 100 GeV, dE/E~30%)**
- **π^0 (E>600GeV, dE/E<3%)**

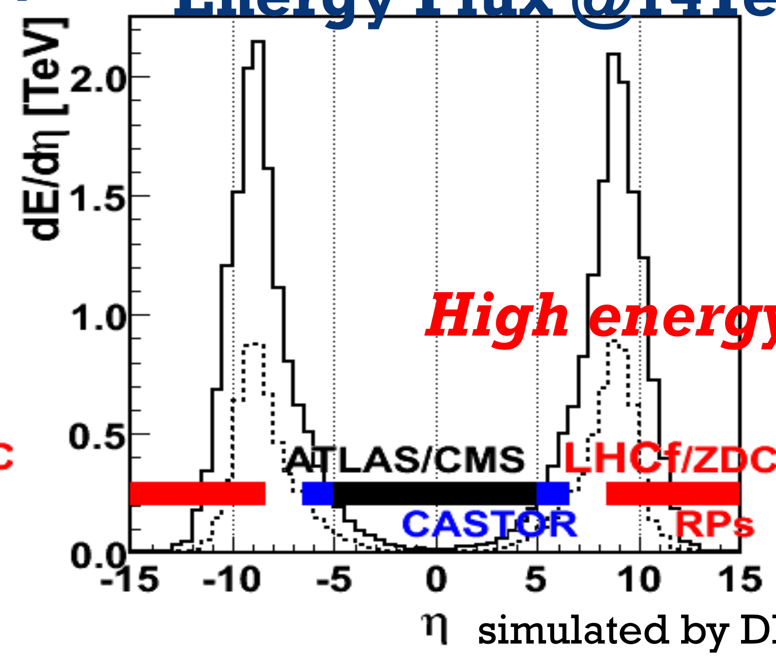
at pseudo-rapidity range >8.4

Multiplicity@14TeV



Low multiplicity !!

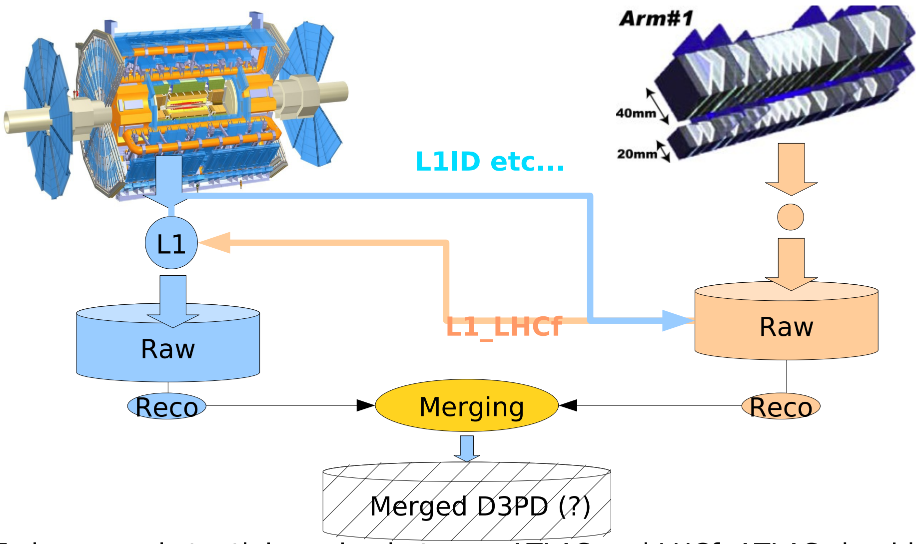
Energy Flux @14TeV

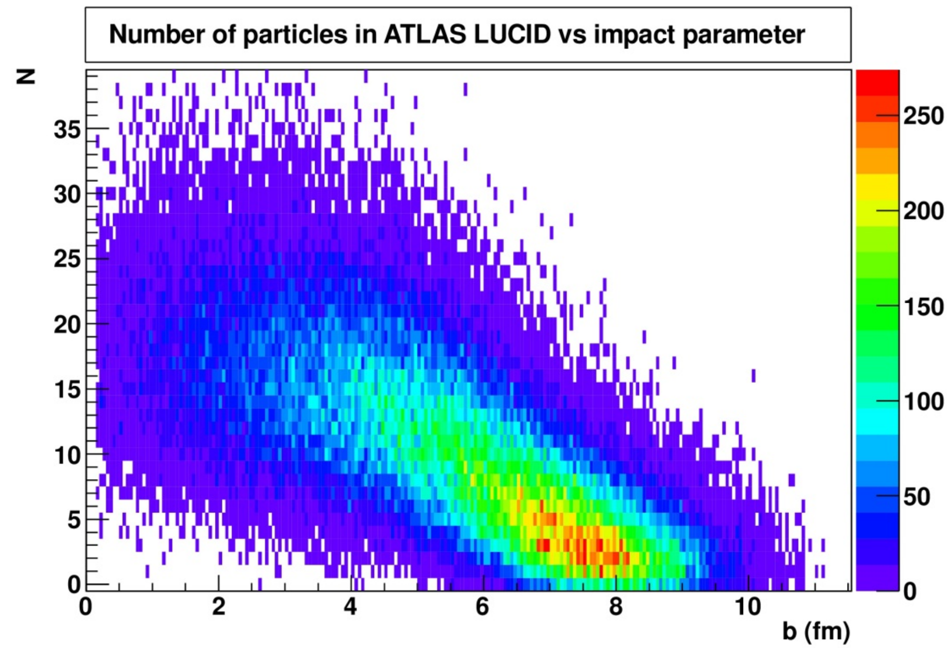


High energy flux !!

simulated by DPMJET3

Common trigger with ATLAS





MC
impact parameter vs. # of particles in ATLAS LUCID

- LHCf forced to trigger ATLAS
- Impact parameter may be determined by ATLAS
- Identification of forward-only events