123rd LHCC Meeting
Geneva, September 23th, 2015

LHCf Status Report

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- Where we are with the analysis
- The 13 TeV data taking
- Ongoing activities
- Future plans

+ A new milestone in LHCf history

- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved

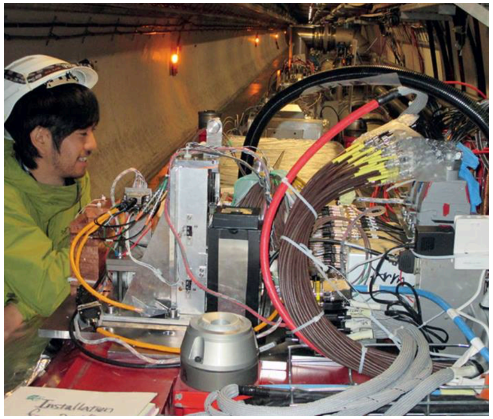
Jul 2006 construction

Aug 2007 SPS beam test

Jan 2008 Installation
Sept 1st LHC beam

Dec- Jul 2010
0.9TeV& 7TeV pp
Detector removal

Dec 2012- Feb 2013
5TeV/n pPb, 2.76TeVpp
(Arm2 only)
Detector removal



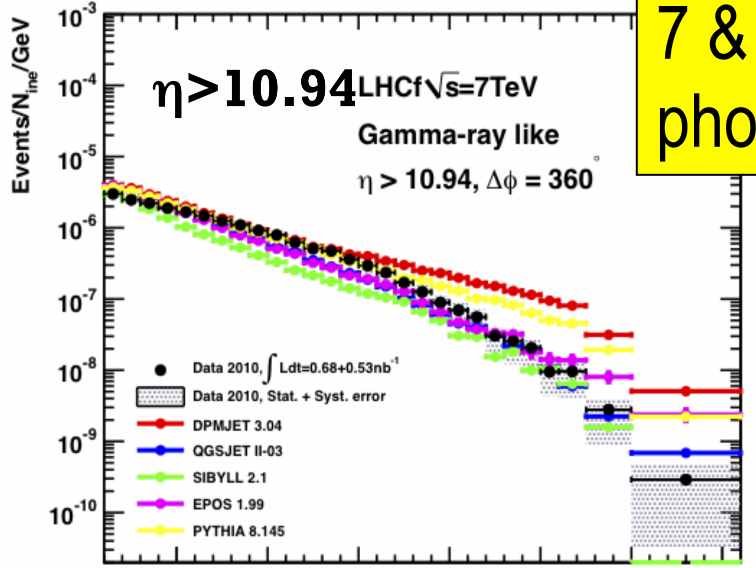
May-June 2015
13 TeV dedicated pp
Detector removal

Status of the analyses

+ LHCf 'analysis matrix'

	Proton equivalent energy in the LAB (eV)	γ	Neutrons	π^0
SPS Test beam		NIM A, 671, 129 (2012)	JINST 9 P03016 (2014)	
p-p 900 GeV	4.3×10^{14}	Phys. Lett. B 715, 298 (2012)		
p-p 7 TeV	2.6×10^{16}	Phys. Lett. B 703, 128 (2011)	Accepted in PLB	Phys. Rev. D 86, 092001 (2012) + Submitted (Type II)
p-p 2.76 TeV	4.1×10^{15}			Phys. Rev. C 89, 065209 (2014) + Submitted (Type II)
p-Pb 5.02 TeV	1.3×10^{16}			
p-p 13 TeV	9.0×10^{16}	Data taken in June 2015 after the LHC restart! Analysis activities just started…		

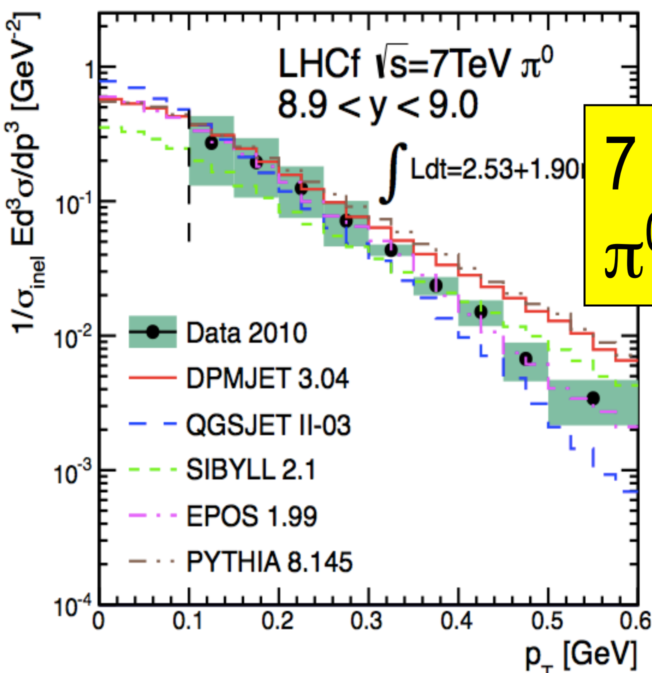
'Old' LHCf published results



7 & 0.9 TeV pp photon

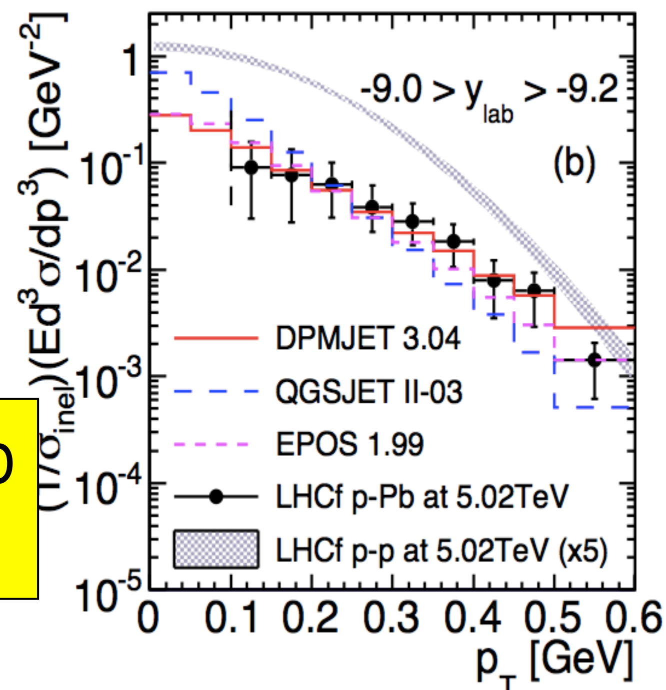
A simple sketch of what we have done:

- Comparison btw data and expectation from different models
- Inclusive energy spectra
- P_T spectra in different rapidity bins

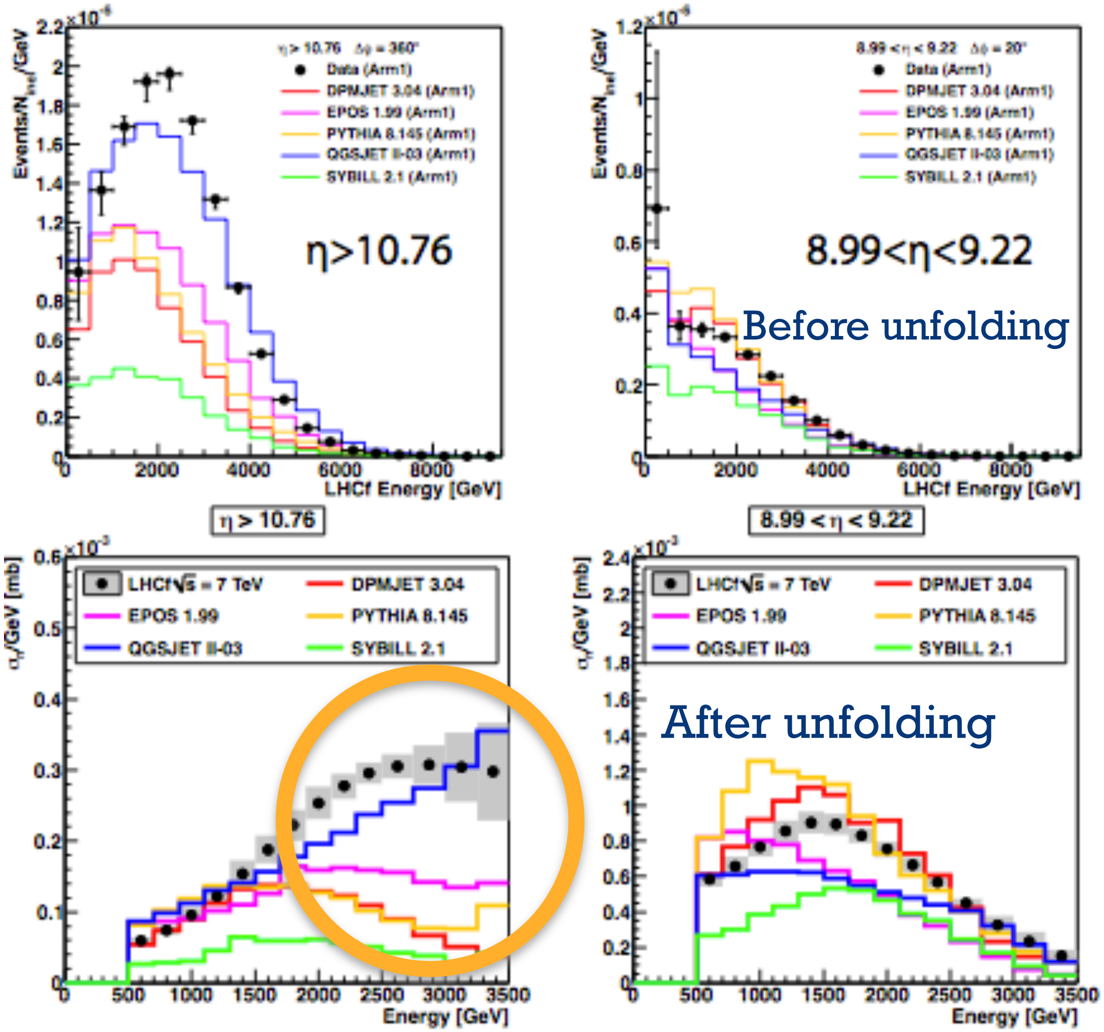


7 TeV pp π^0

5 TeV/n pPb π^0



+ Inclusive neutron spectra (7 TeV pp)



Accepted on PLB

n / γ ratio

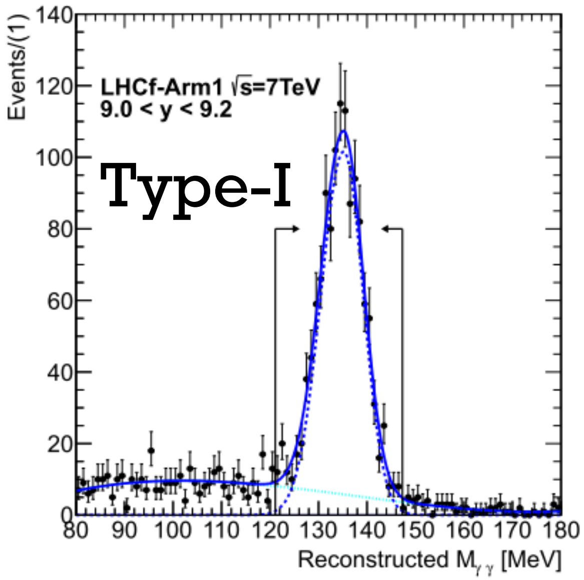
Data (η>10.76)	3.05±0.19
DPMJET3.04	1.05
EPOS 1.99	1.80
PYTHIA 8.145	1.27
QGSJET II-03	2.34
SYBILL 2.1	0.88

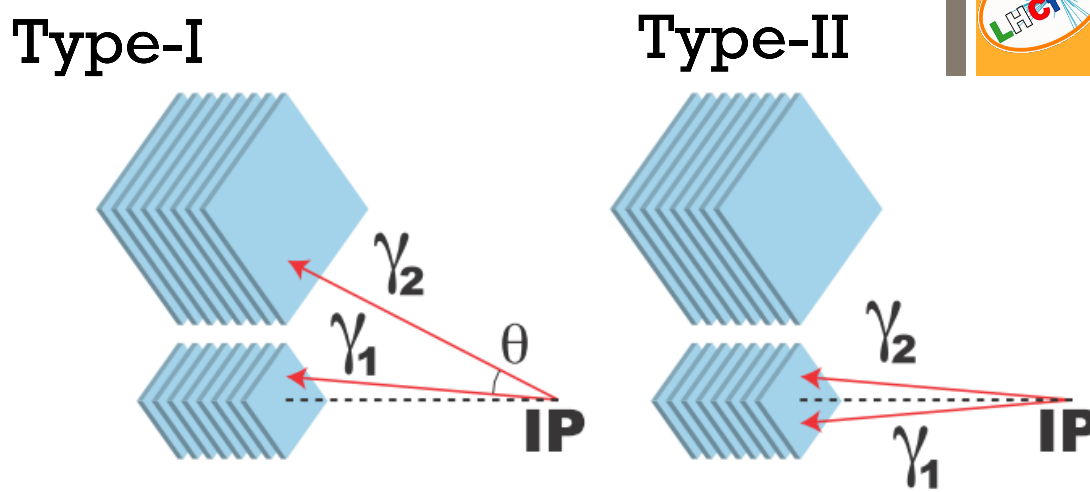
n / γ ratio

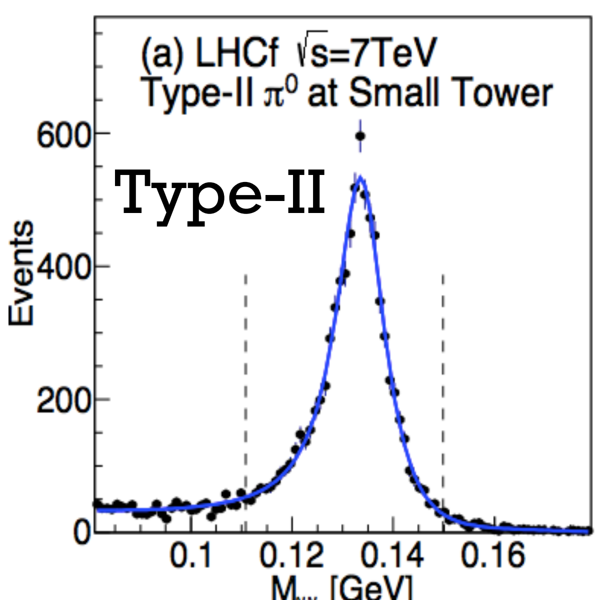
Data (8.99<η<9.22)	1.26±0.08
DPMJET3.04	0.76
EPOS 1.99	0.69
PYTHIA 8.145	0.82
QGSJET II-03	0.65
SYBILL 2.1	0.57

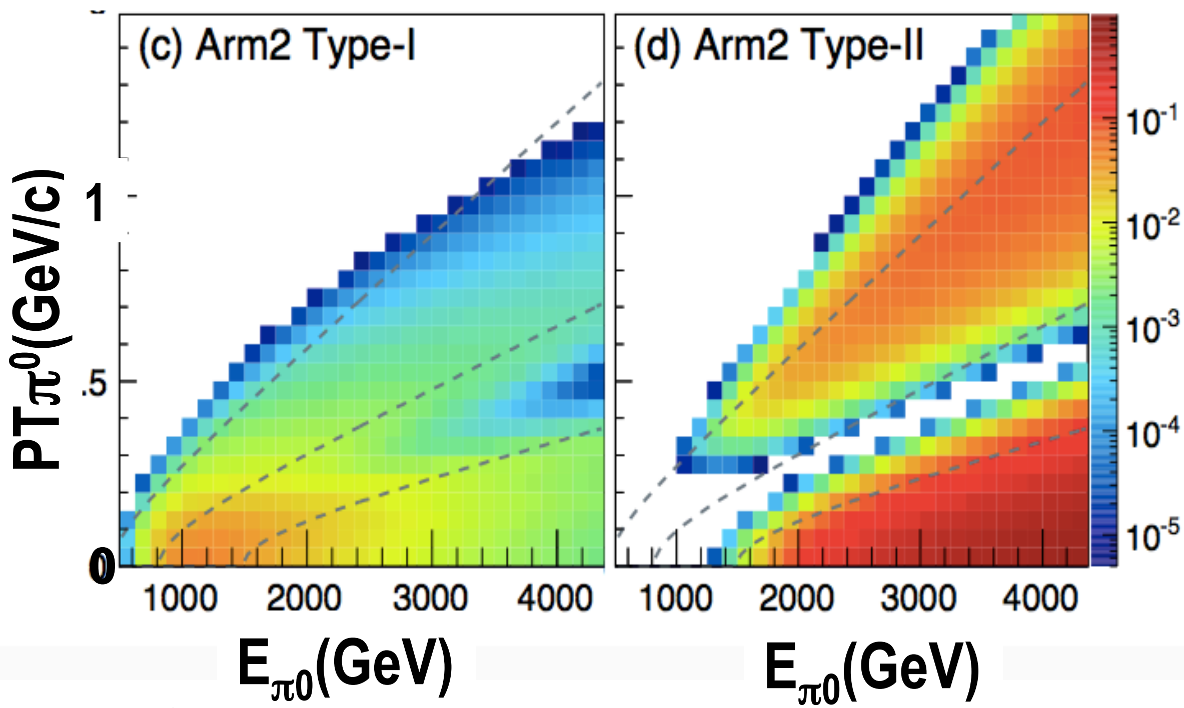
Very large high energy peak in the η>10.76 (predicted only by QGSJET)
→ Small inelasticity in the very forward region!

+ LHCf Type-I and Type-II π^0 analysis

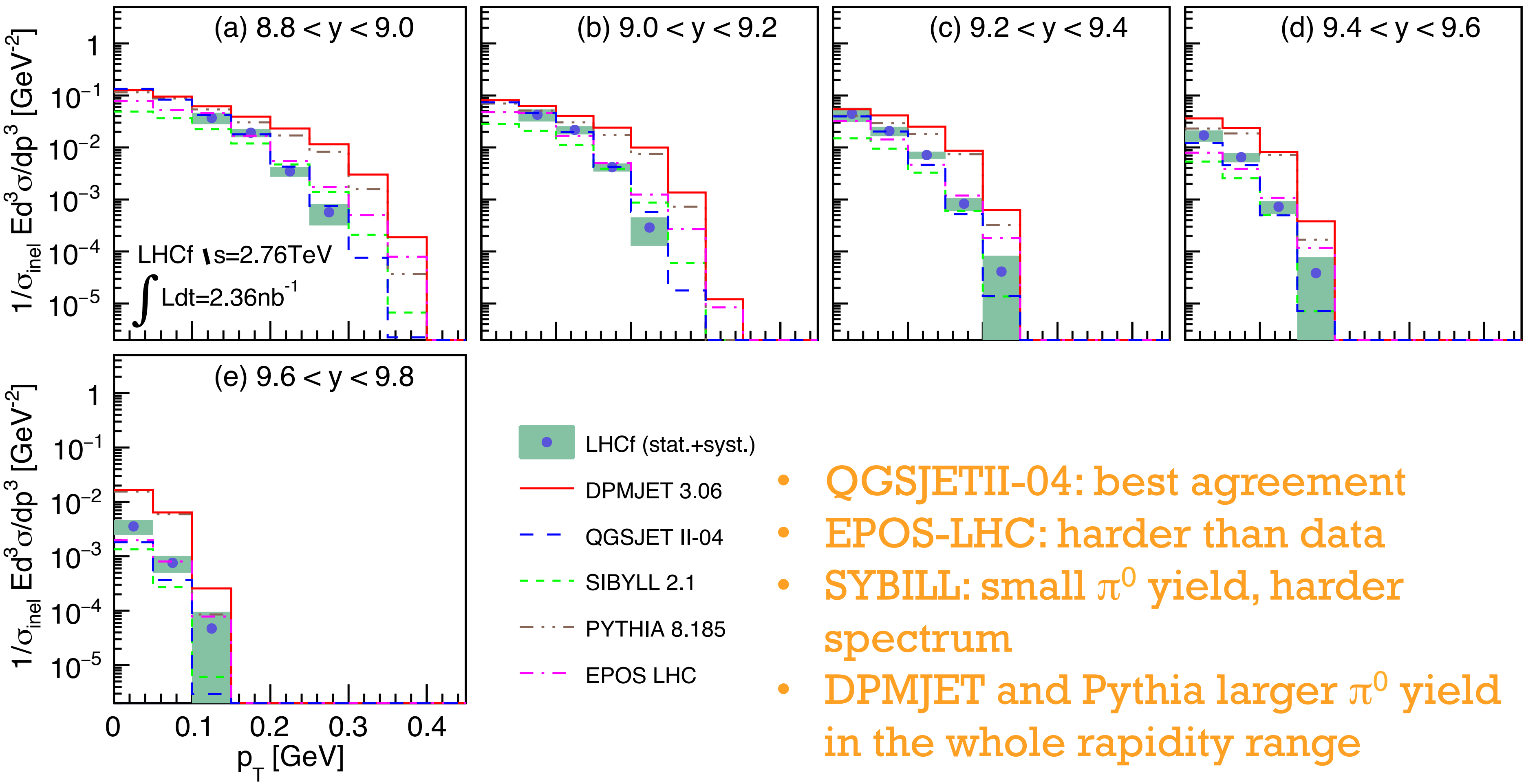






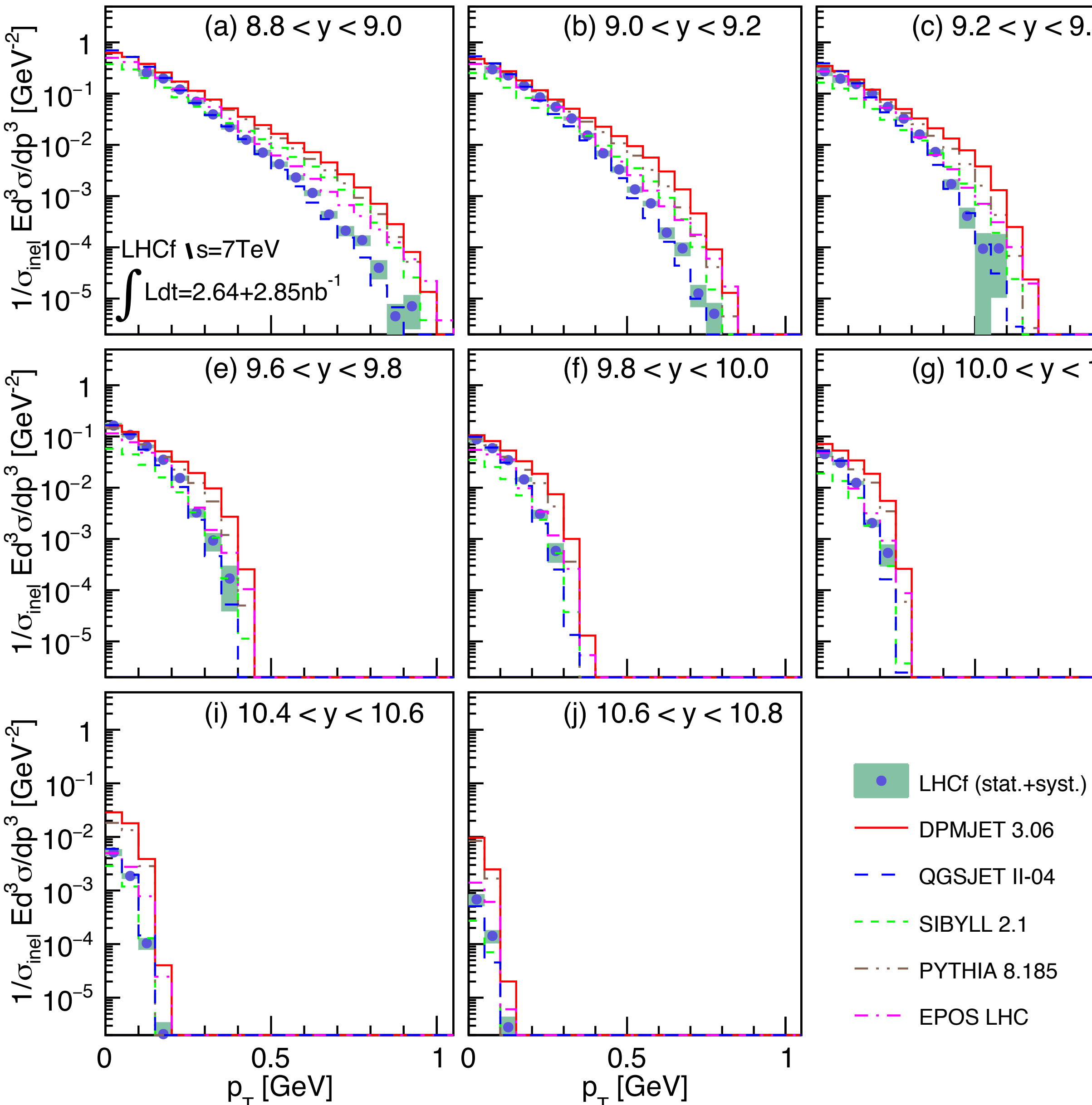


+ π^0 p_T spectra in 2.76 TeV pp collisions (Type I & Type II)



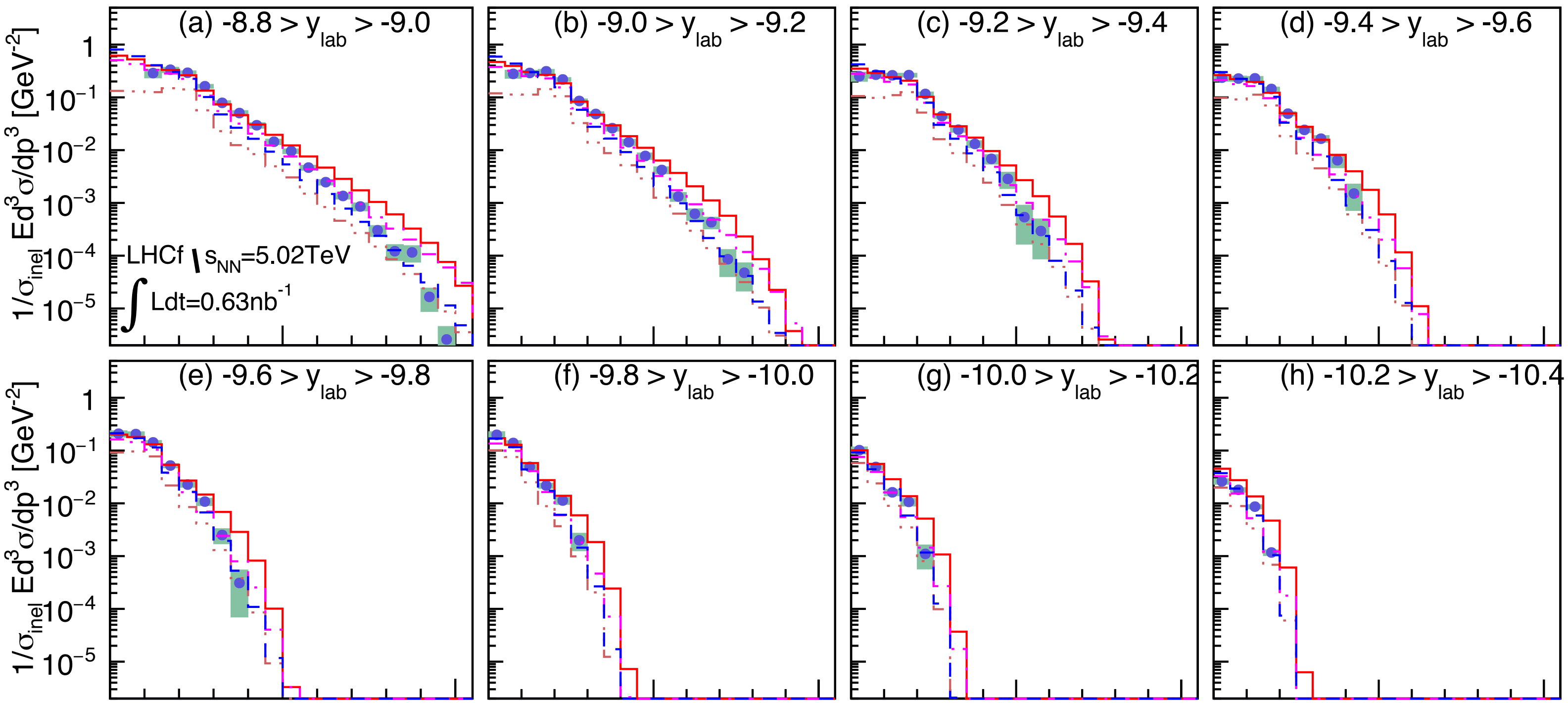
- QGSJETII-04: best agreement
- EPOS-LHC: harder than data
- SYBILL: small π^0 yield, harder spectrum
- DPMJET and Pythia larger π^0 yield in the whole rapidity range

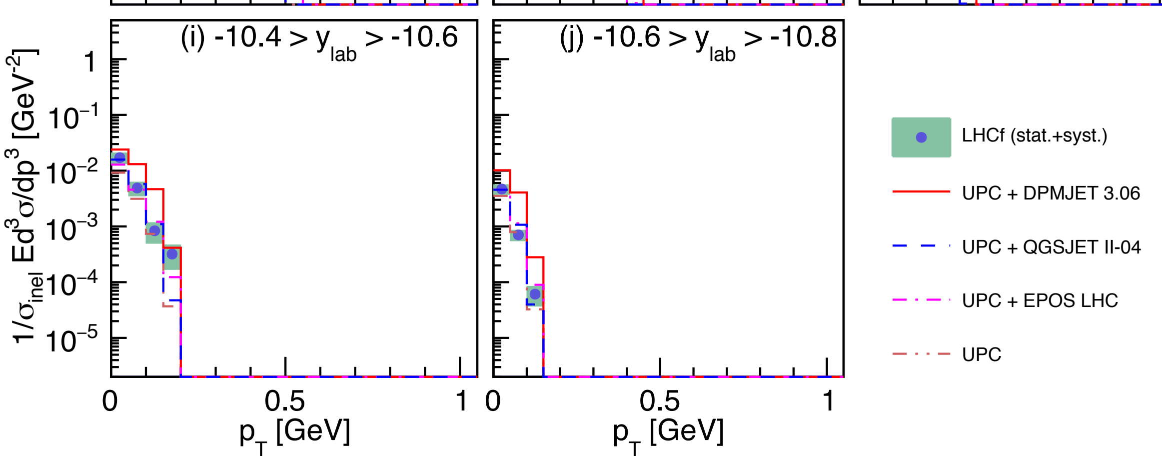
π^0 p_T spectra in 7 TeV pp collisions



- QGSJETII-04: best agreement
- EPOS-LHC: harder than data for large p_T
- SYBILL: good agreement only for small y

+ π^0 p_T spectra in 5.02 TeV p-Pb collisions

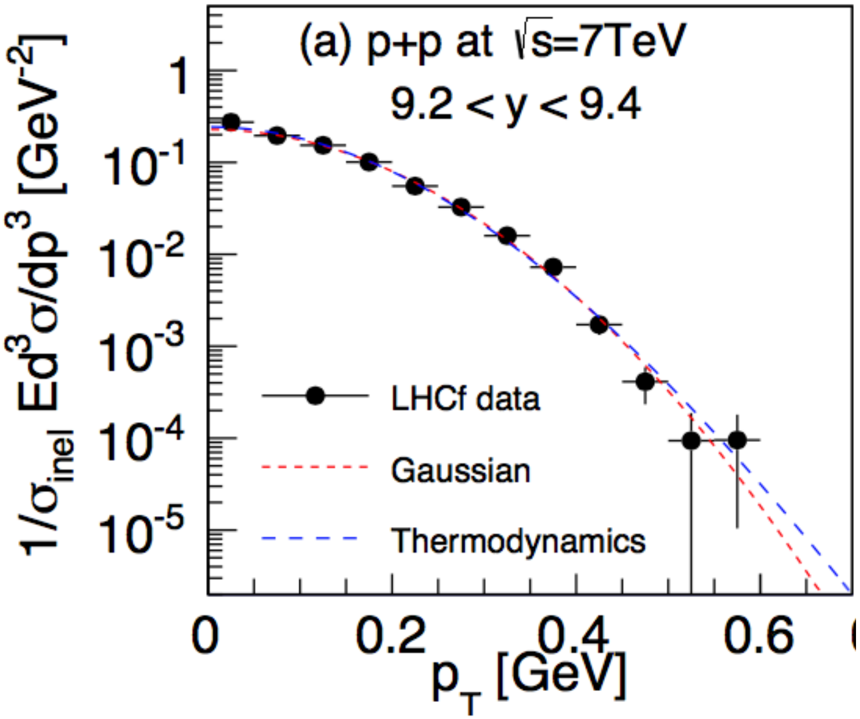




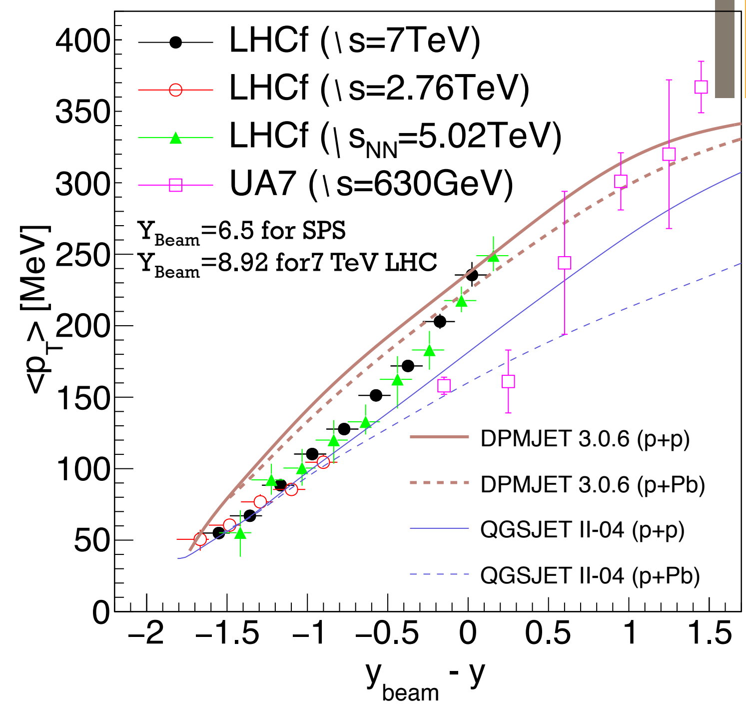
- QGSJETII-04 and EPOS-LHC: similar, good agreement for pT>0.4 GeV
- DPMJET: good agreement for −8.8 > ylab > −10.0 and p_T < 0.3 GeV
- Characteristic bump at y > −9.6 and p_T ~ 0.2GeV: Ultra Peripheral Collisions

+ π^0 average p_T for different cm energies

p_T spectra vs best-fit function



Average p_T vs y_{lab}



$y_{lab} = y_{beam} - y$

$<p_T>$ is inferred in 3 ways:

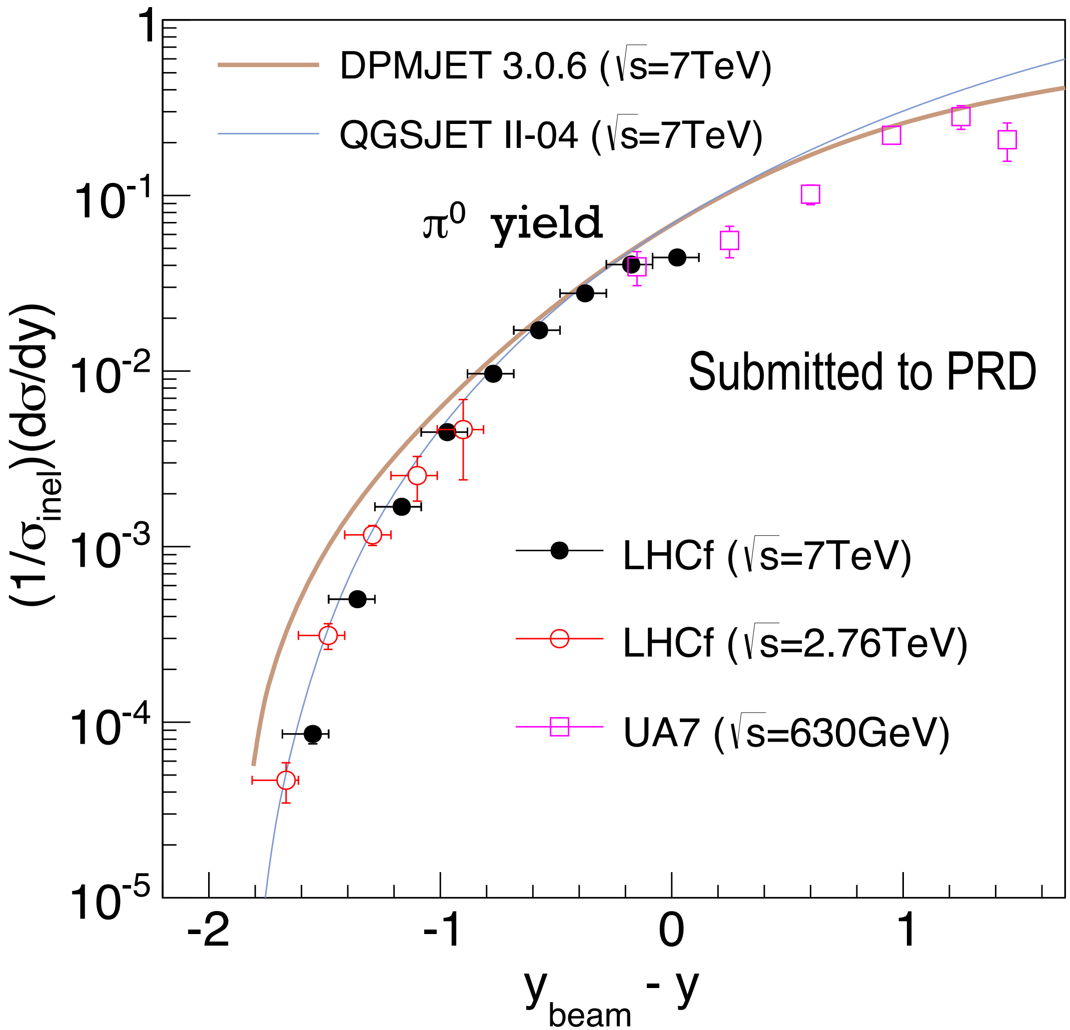
1) Thermodynamical approach
2) Gaussian distribution fit
3) Numerical integration up to the histogram upper bound

- From scaling considerations (projectile fragmentation region) we can expect that $<p_T>$ vs rapidity loss should be independent from the c.m. energy
- Reasonable scaling can be inferred from the data

Limiting fragmentation in forward π^0 production

Limiting fragmentation hypothesis:
rapidity distribution of the secondary particles in the forward rapidity region (target's fragment) should be independent of the center-of-mass energy.

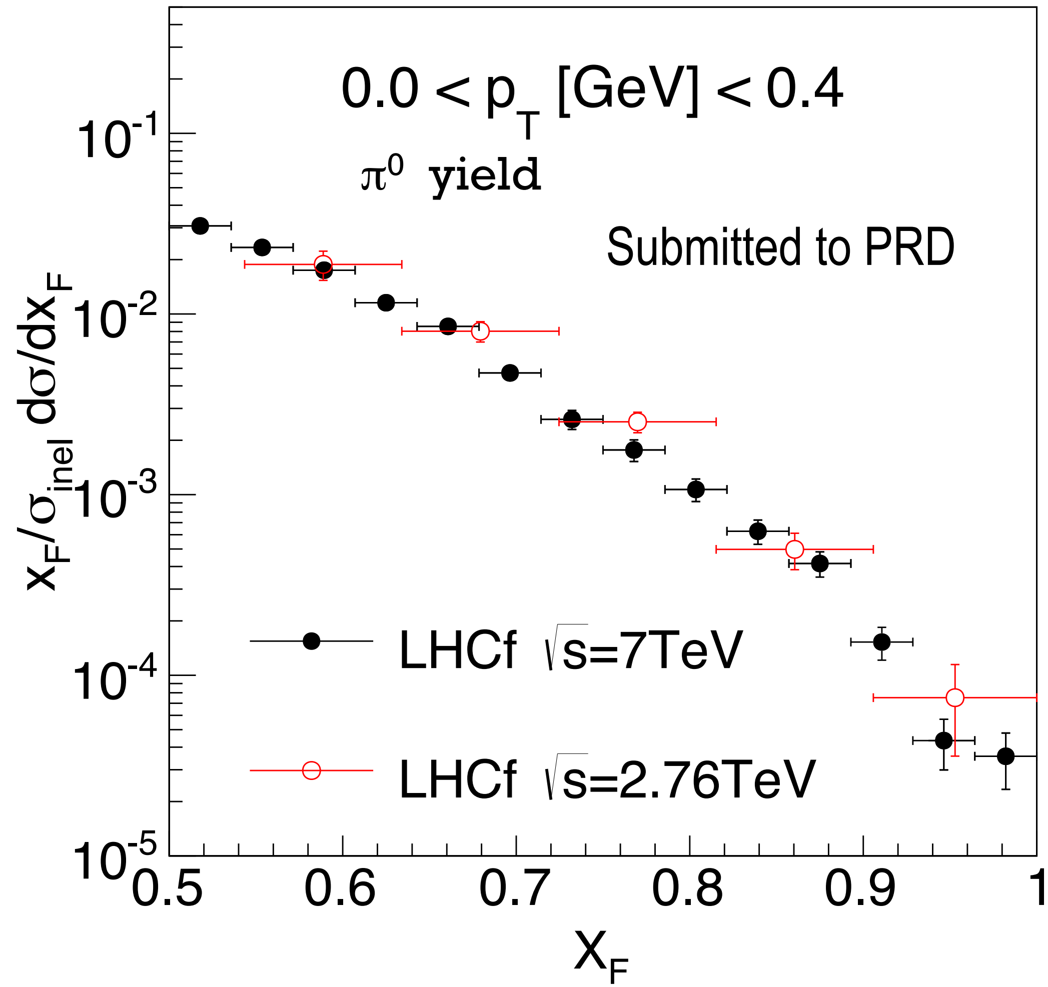
This hypothesis for π^0 is true at the level of ±15%



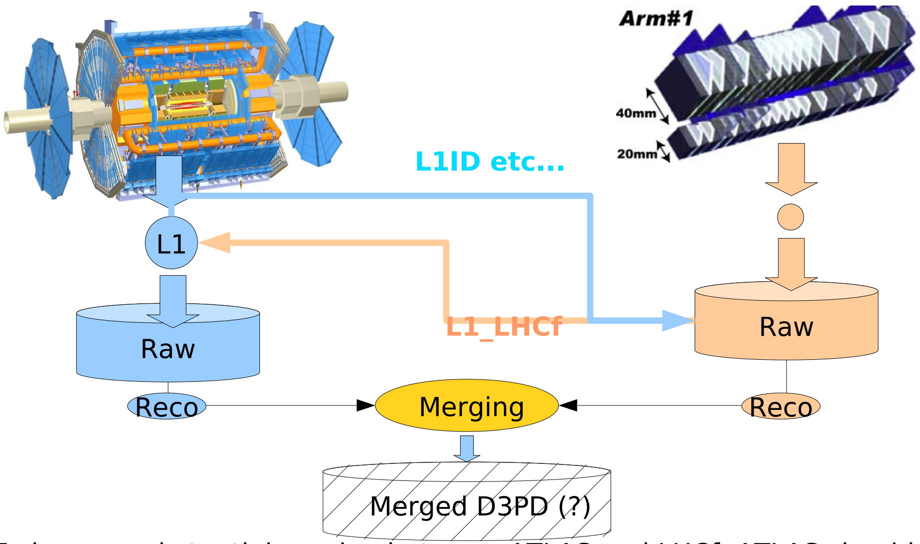
Feynman scaling in forward π^0 production

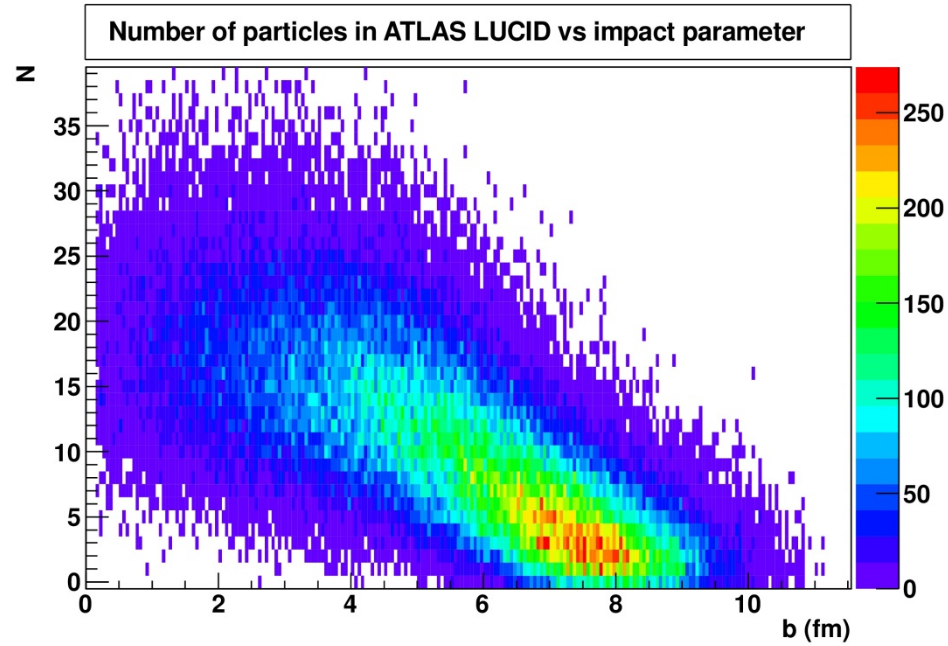
Feynman scaling hypothesis:
cross sections of secondary particles as a function of $x_F \equiv 2p_z/\sqrt{s}$ are independent from the incident energy in the forward region ($x_F > 0.2$).

This hypothesis for π^0 is true at the level of ±20%



Common trigger with ATLAS in p-Pb operation





MC
impact parameter vs. # of particles in ATLAS LUCID

- LHCf trigger sent to ATLAS
- Impact parameter may be determined by ATLAS
- Central activity in ATLAS can be used to select diffractive events
- Identification of forward-only events

+ A commonly triggered event

ATLAS LHCf NOTE

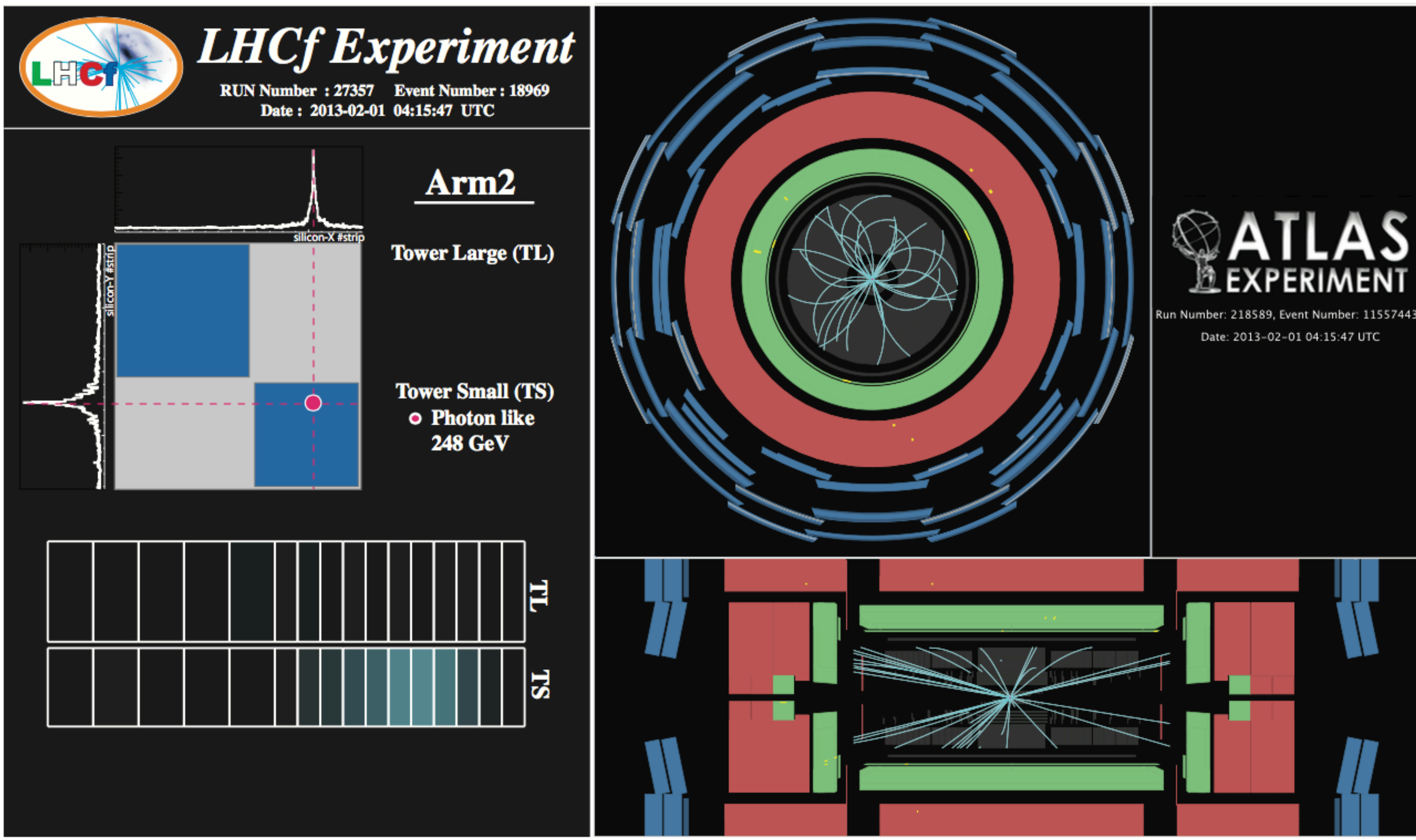
August 26, 2015

ATL-PHYS-PUB-2015-038

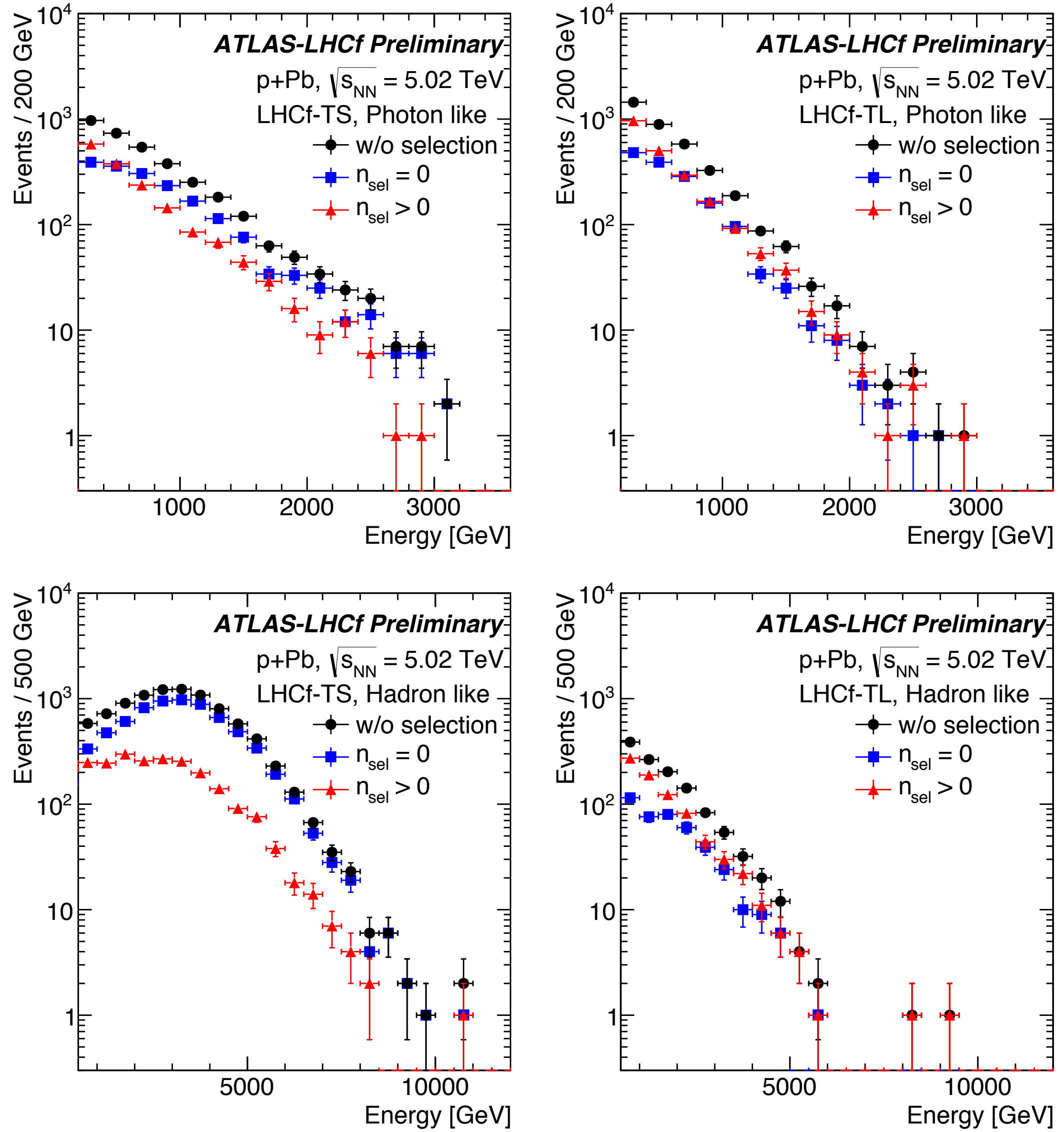
30 August 2015

Classification of Events in the Combined ATLAS-LHCf Data Recorded During the p+Pb Collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

The ATLAS and the LHCf Collaborations



LHCf spectra in p-Pb collisions with Atlas tagging on tracks



N_{sel}:
number of good charged ATLAS tracks

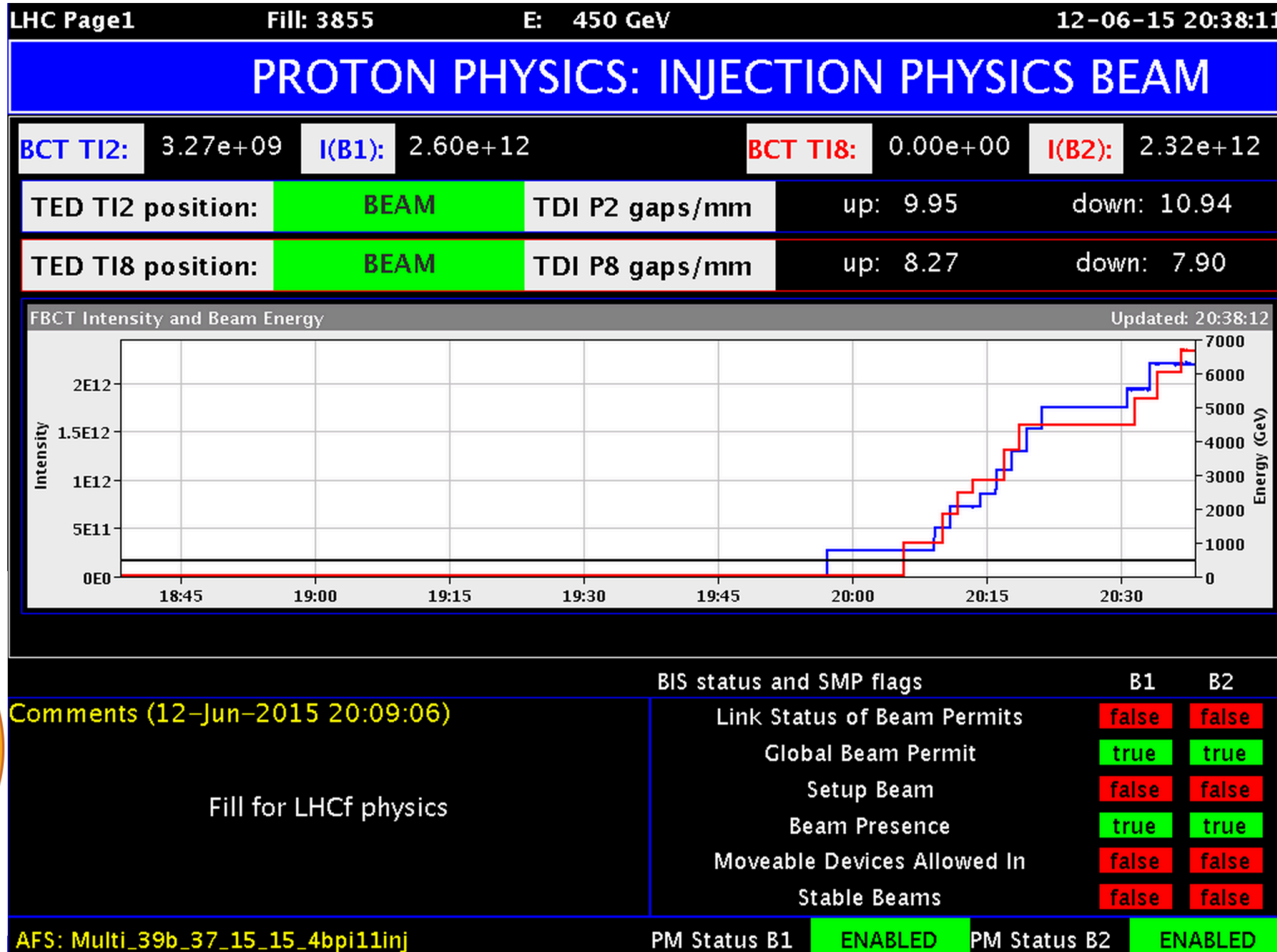
- p_T > 100 MeV
- vertex matching
- $|\eta| < 2.5$.

Significant UPC contribution in the very forward region with N_{sel}=0

The 2015 13 TeV run

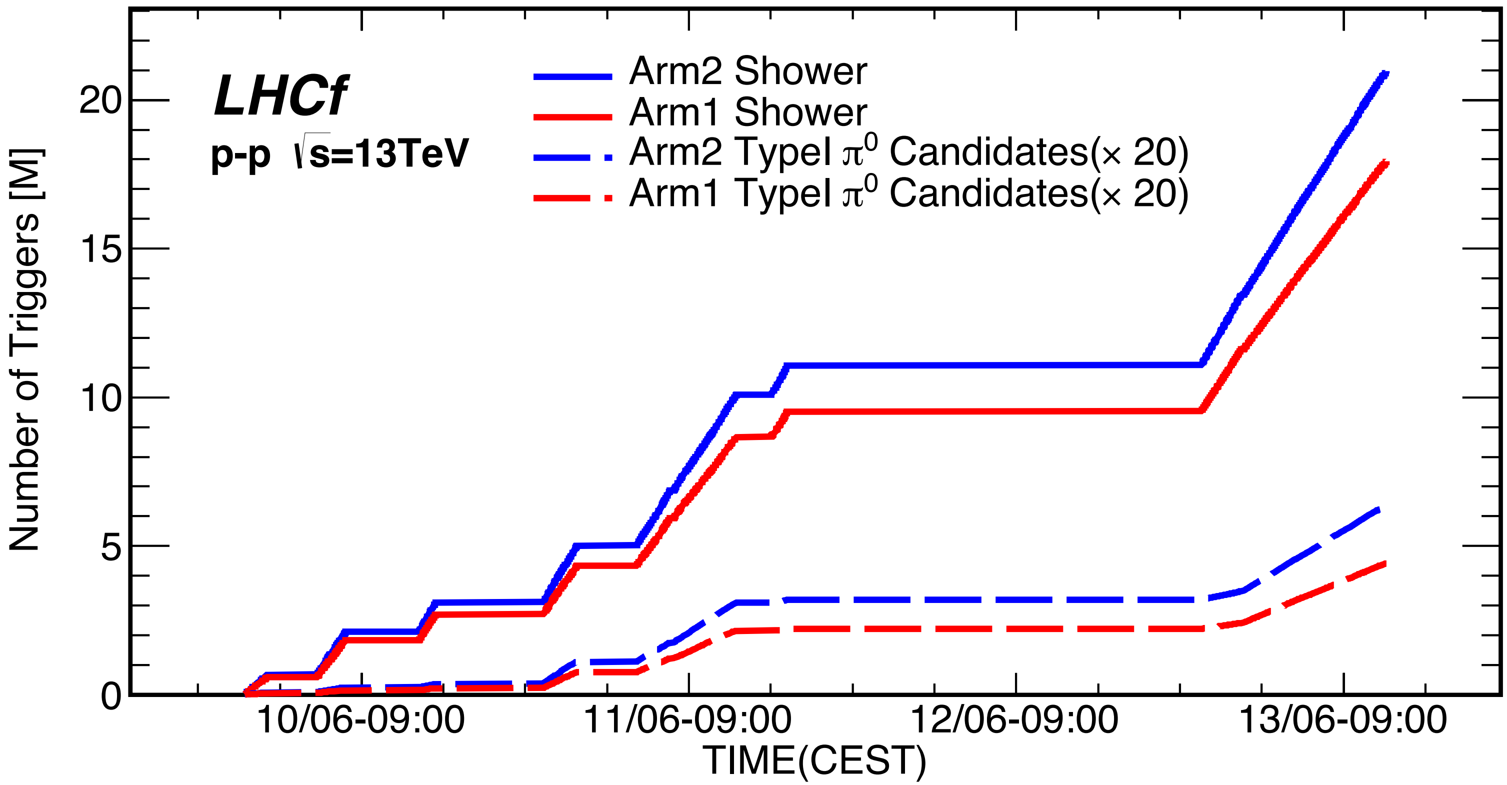
LHC 13 TeV run in 2015

- During Week 24, June 9-13, LHCf dedicated low-lumi run



+ LHC 13 TeV run in 2015

- During Week 24, June 9-13, LHCf dedicated low-lumi run
- Total 26.6 hrs with L=0.5~1.6.10[29] $cm^{-2}s^{-1}$ (16 nb^{-1})
- ~39 M showers, 0.5 M π^0 obtained
- Trigger exchange with ATLAS
- Detector removal on June 15th during TS1
- Run was very successful!!!!



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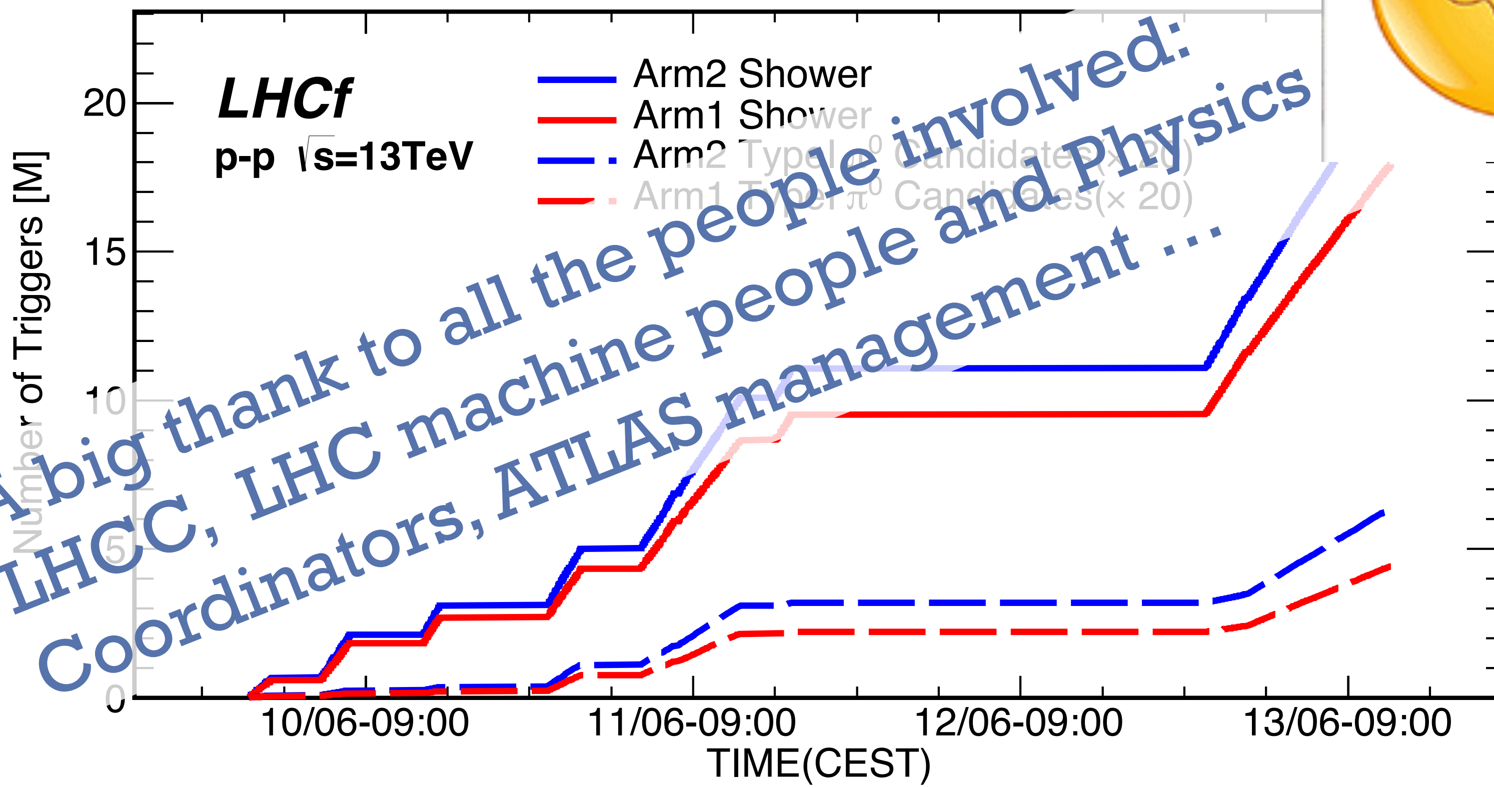
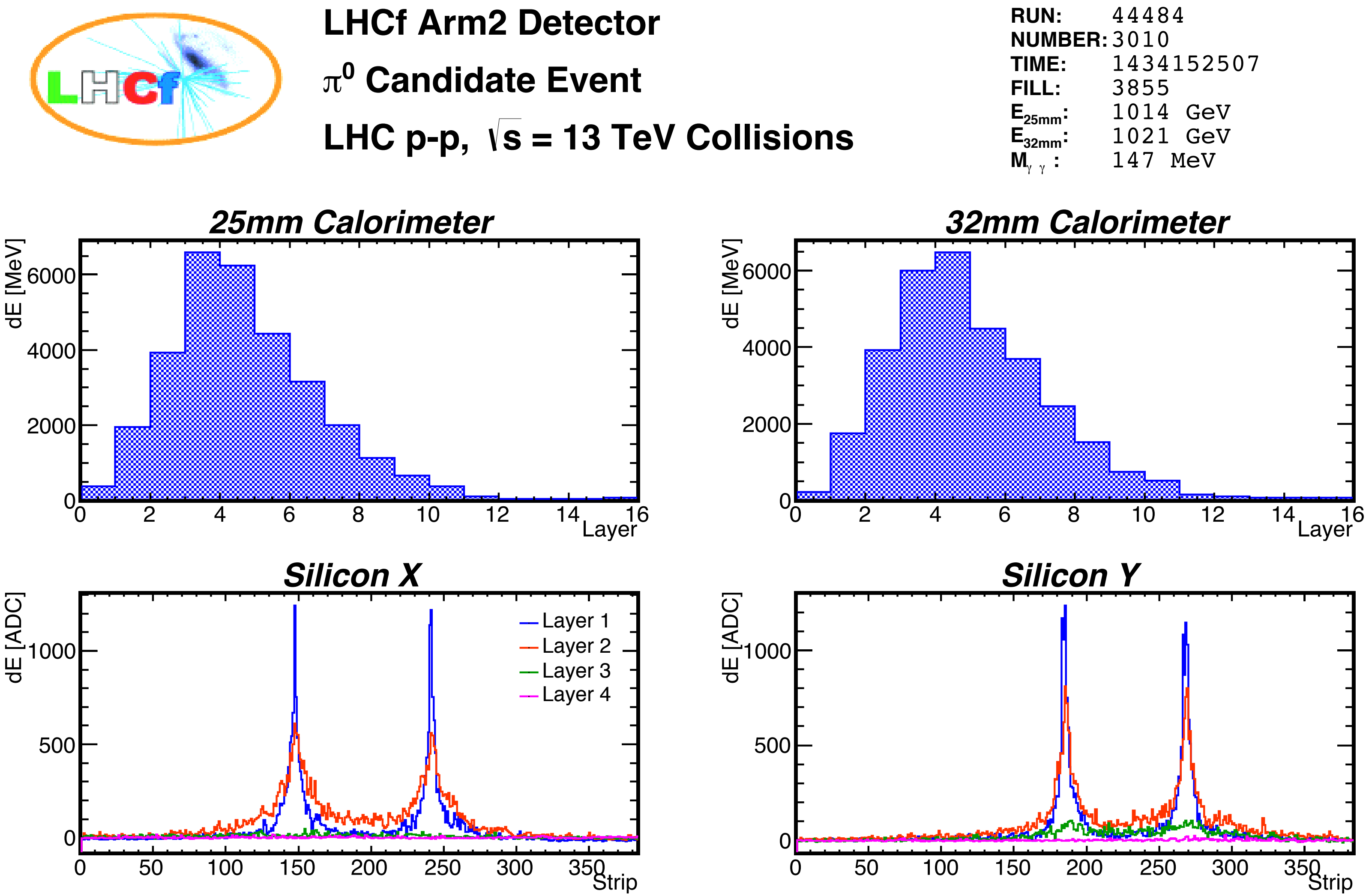
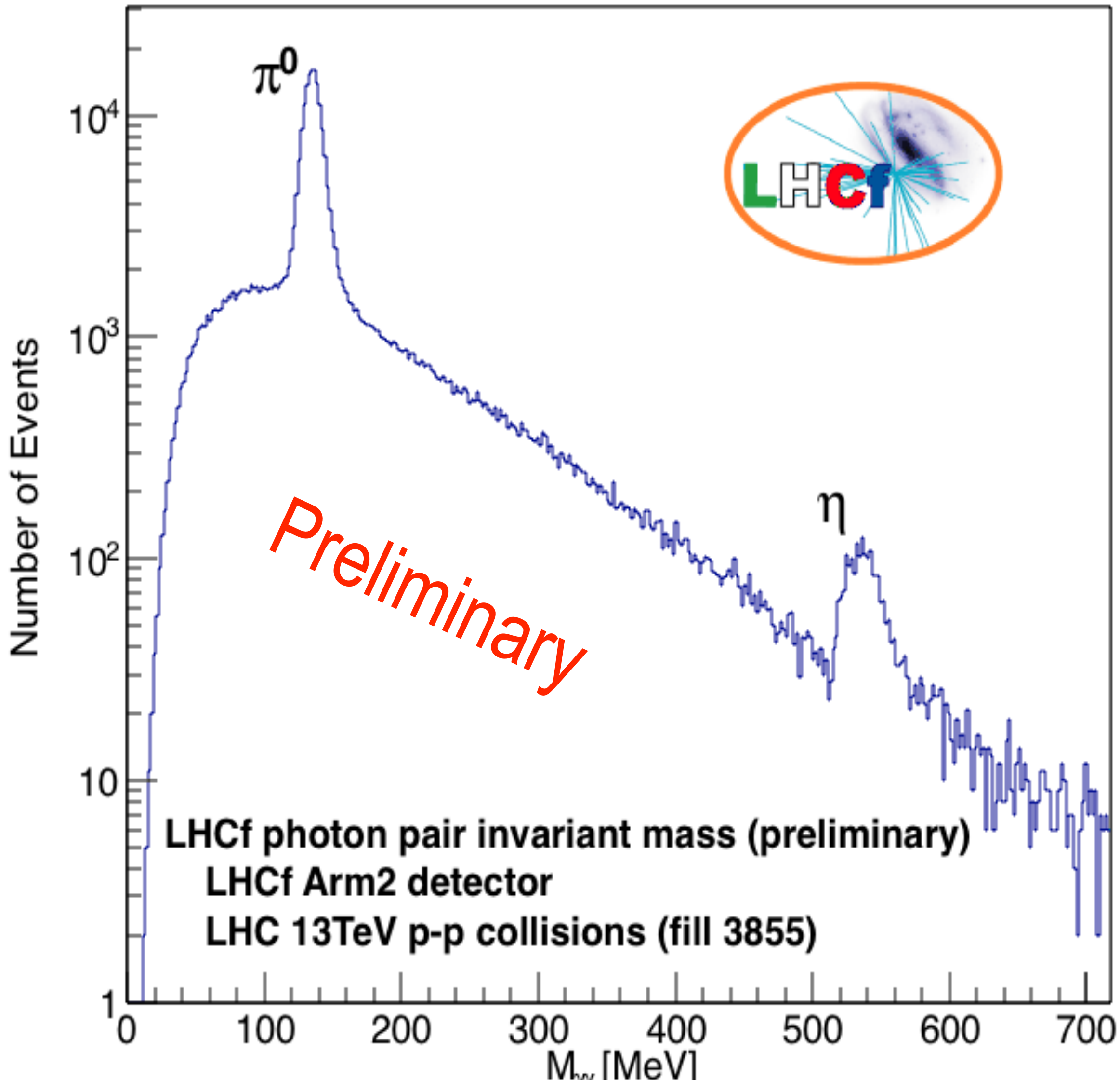


A big thank to all the people involved:
LHCC, LHC machine people and Physics
Coordinators, ATLAS management ...

+ An impressive high energy π^0

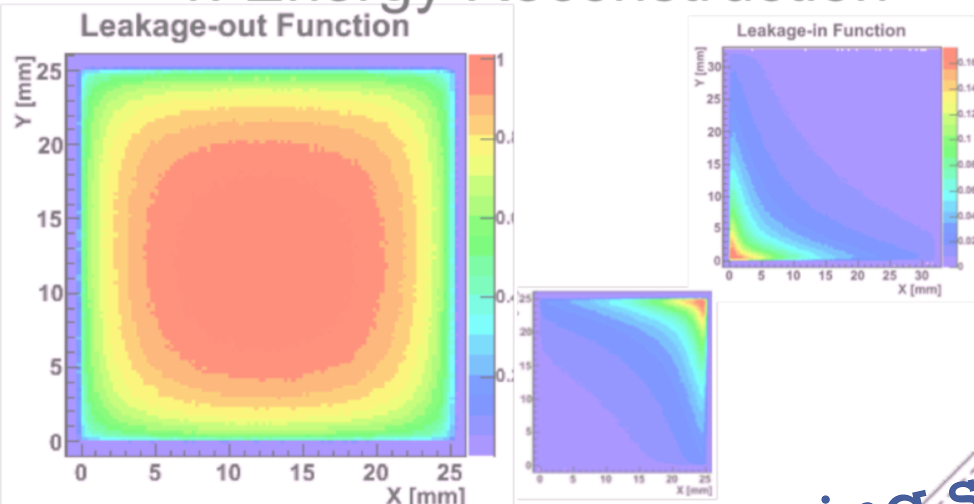


+ First look at 13 TeV data

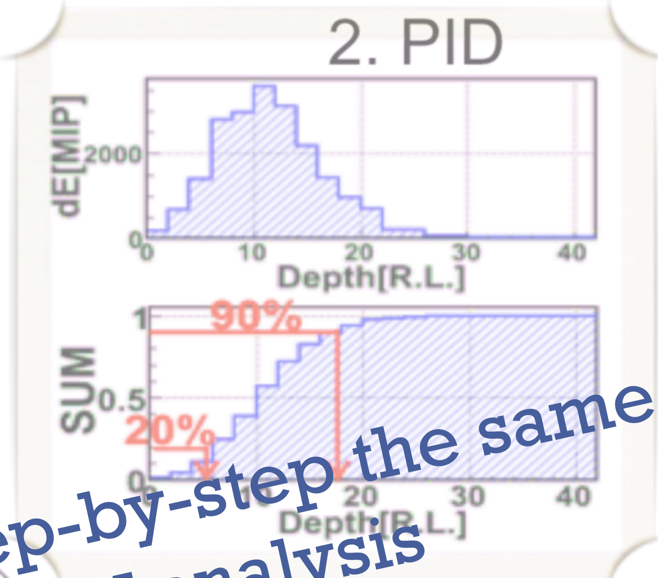


+ Analysis WORKFLOW at 7 TeV

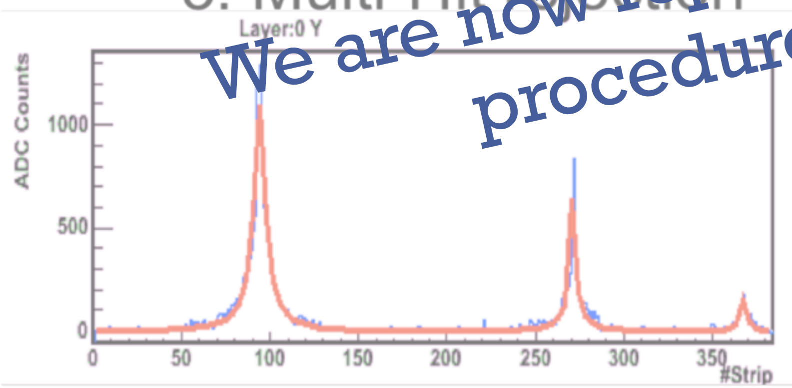
1. Energy Reconstruction



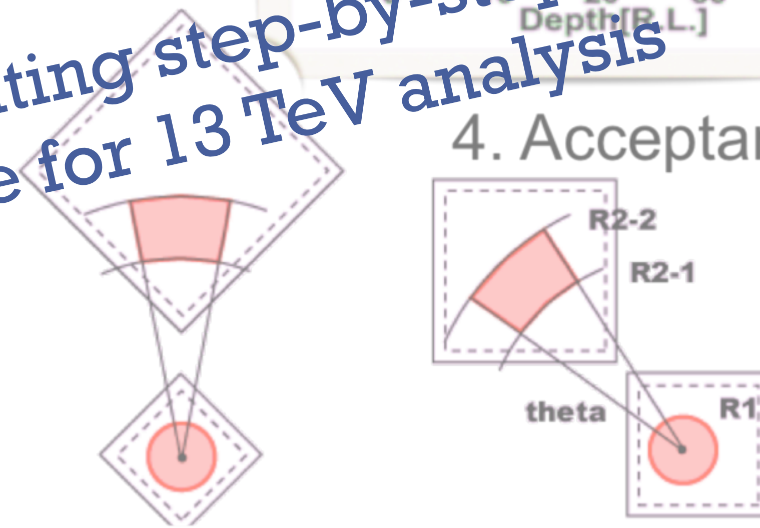
2. PID



3. Multi-Hit rejection



4. Acceptance cut

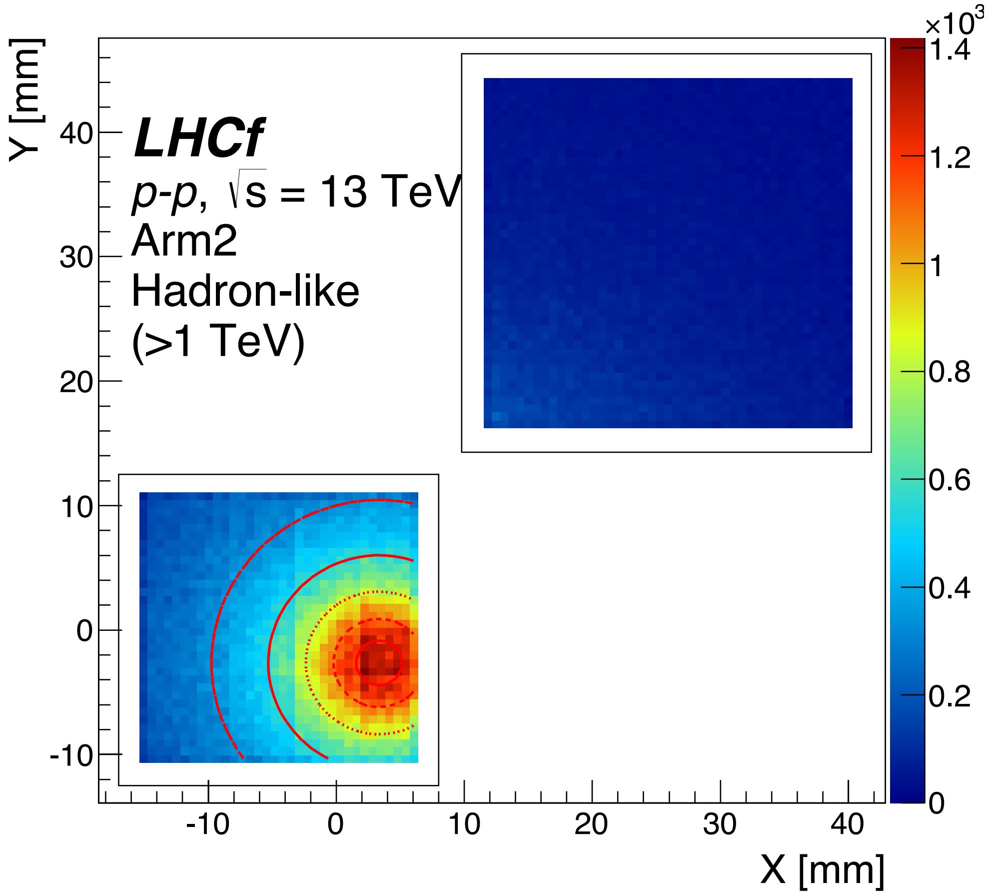


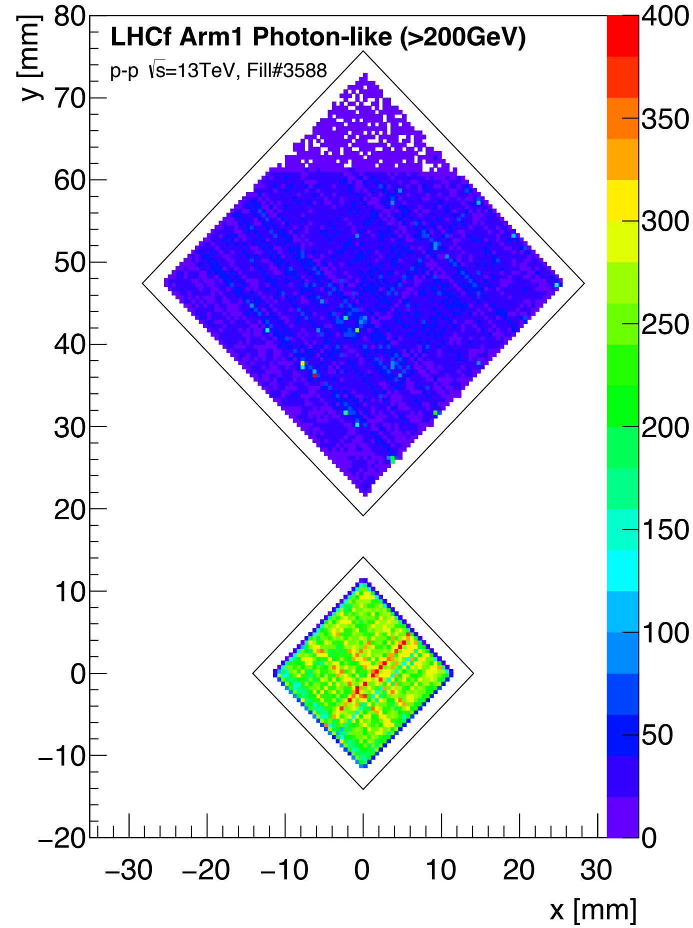
Small Tower
$\eta > 10.94$
Large Tower
$8.81 < \eta < 8.99$

5. Systematic uncertainties

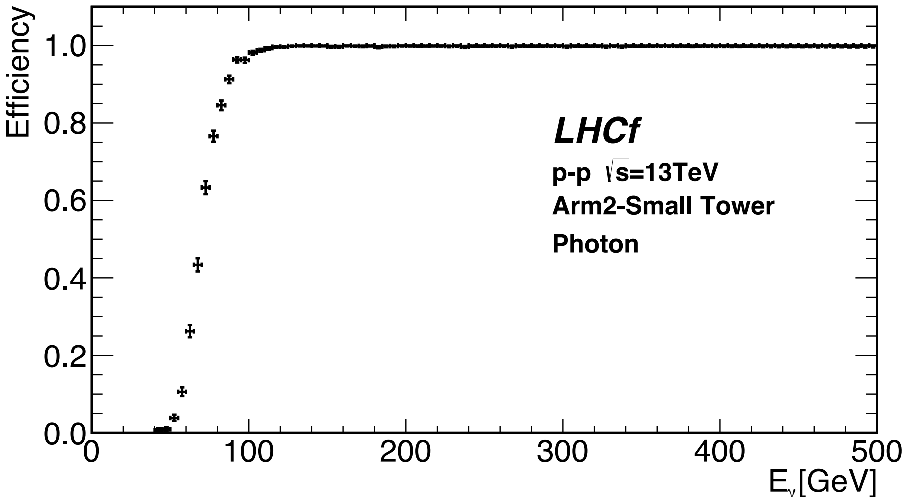
We are now repeating step-by-step the same procedure for 13 TeV analysis

Analysis workflow: determination of the beam center

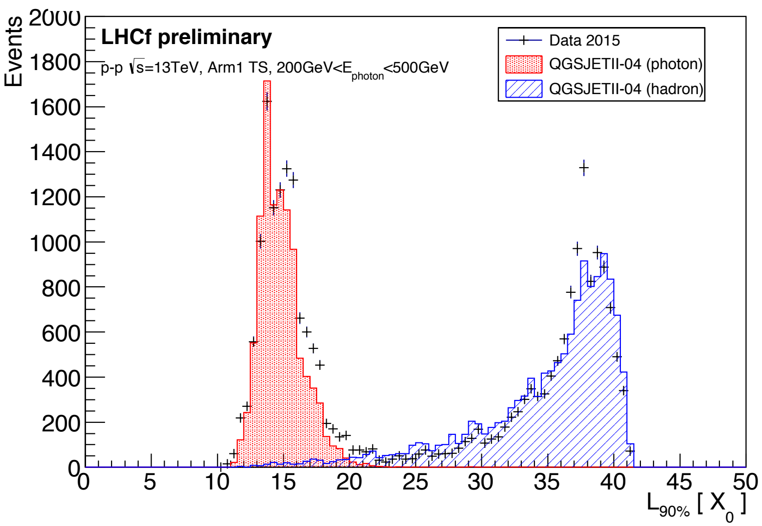




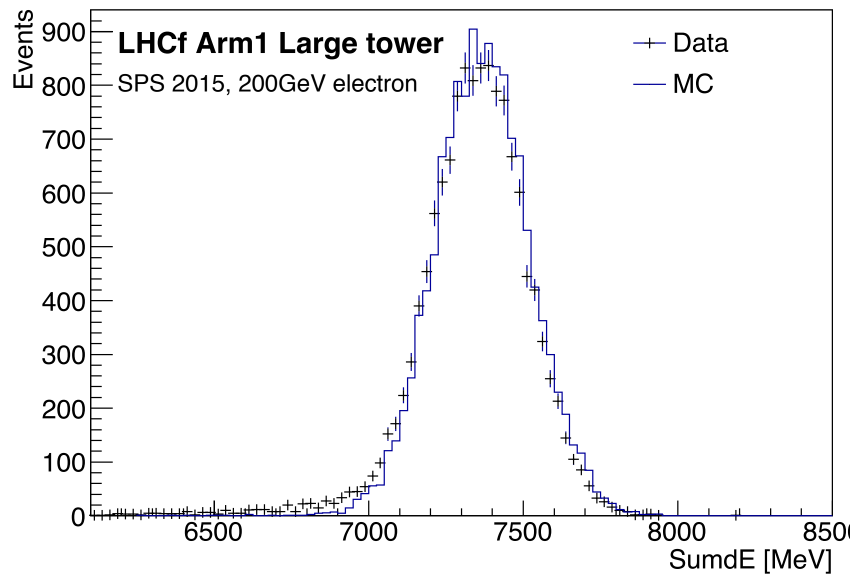
Analysis workflow: selections and reconstructions



Trigger efficiency:
Fully efficient for E>100 GeV

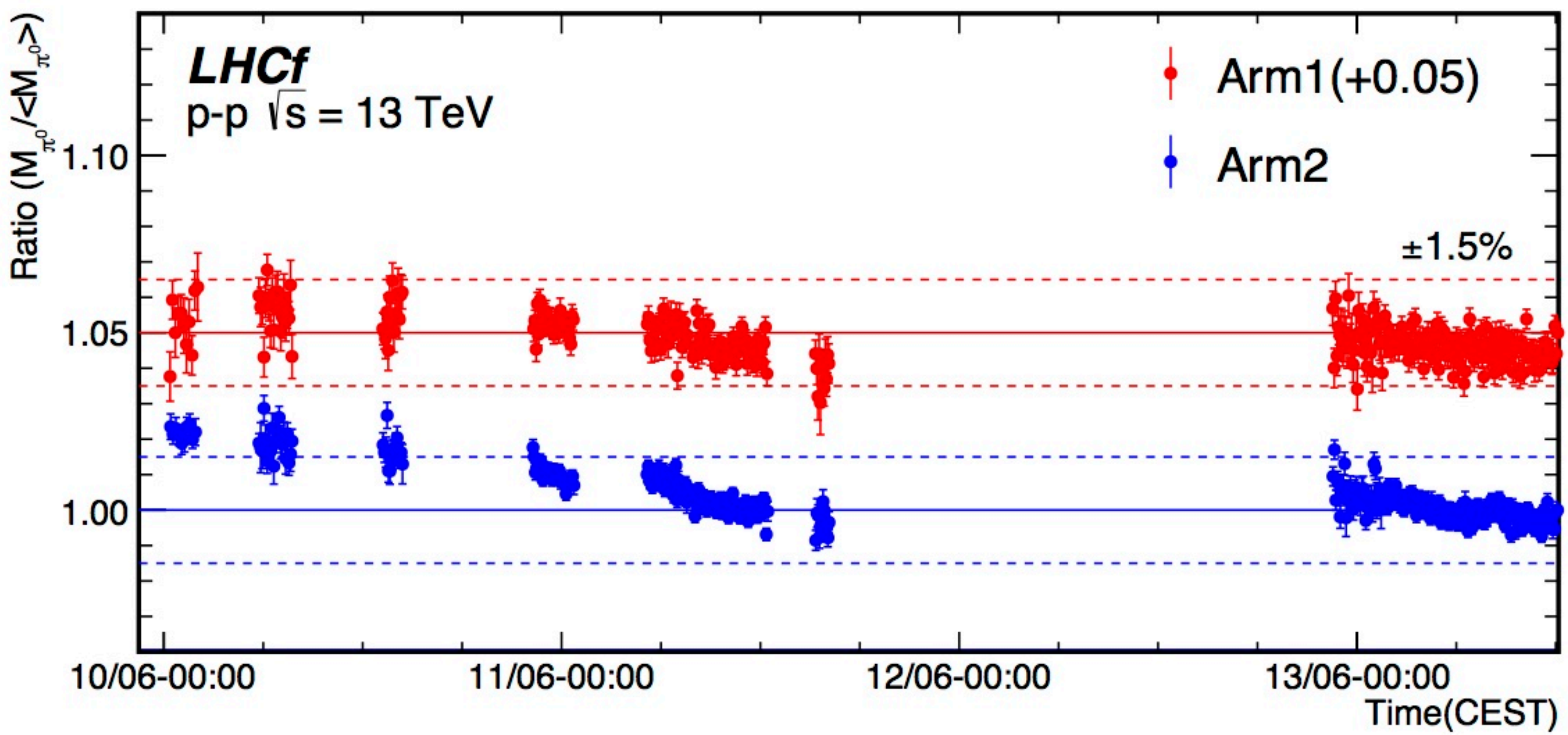


PID based on longitudinal profile distribution ($L_{90\%}$)



Energy calibration based on SPS beam test

+ π^0 mass stability



Future perspectives

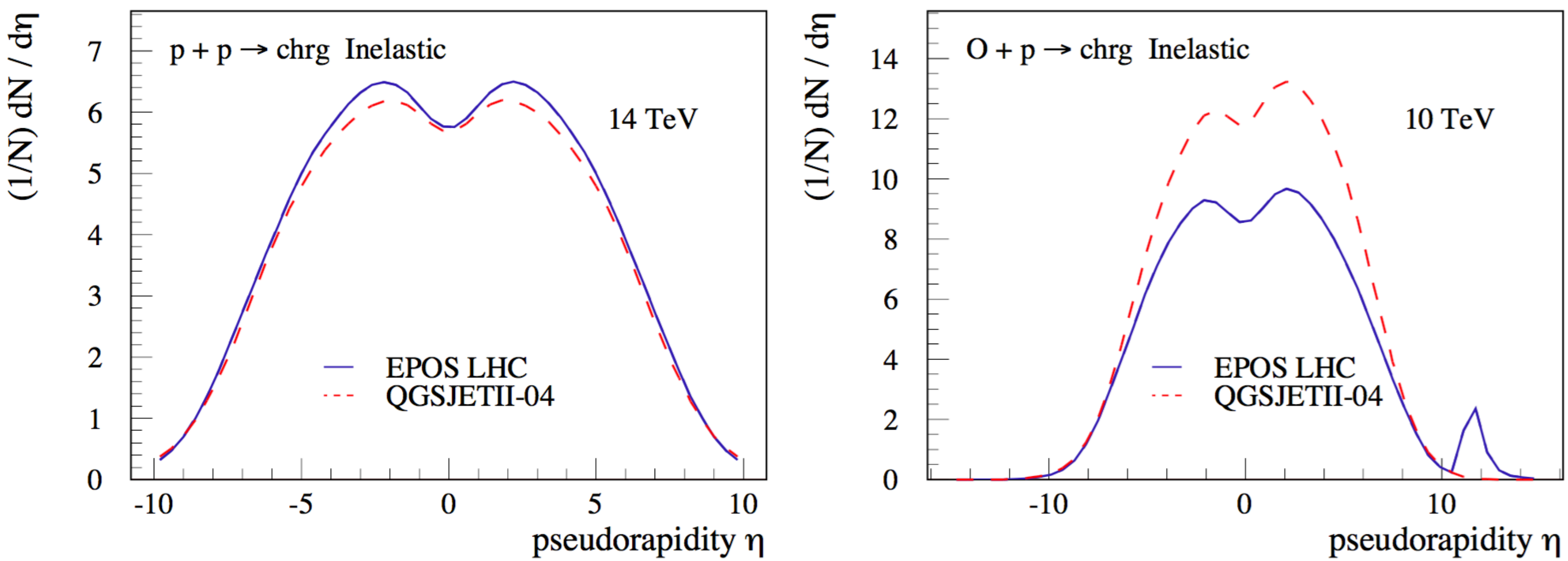
What's next? Let's start from p-Pb

- LHCf is certainly very interested in a possible high energy p-Pb run (2016-2017?)
  - Physics simulations are ongoing
    - We plan to present soon a LoI
  - Nuclear Modification factor can be measured at the highest energies

  - Installation issues should be very carefully investigated
    - ☹ TAN activation at the end of the long high luminosity pp run
    - ☺ Remote handling system works very efficiently
    - ☺ Past experience from the 2012 re-installation helped us and the RP team to better understand the modeling of the radioactive activation

The far future @ LHC

- The most promising future at LHC for LHCf 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



+ Conclusions

- Very forward γ, n and π^0 production in p-p and p-Pb collision have been precisely measured by LHCf at $E_{CM} \leq 7$ TeV
- Very successful 13 TeV pp run has been done in June 2015
  - Analysis is on going
- Trigger exchange with Atlas significantly improve the LHCf physics capabilities
  - ATLAS-LHCf joint physics note on the p-Pb operation has been released
- For the future we are certainly interested in:
  - Higher energy p-Pb collisions in 2016-2017
  - p-Light ions at LHC in the far future

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THANKS TO EVERYBODY FOR THE CONTINOUS SUPPORT TO OUR SMALL BABY!

Backup slides

The LHCf Collaboration

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f) KMI, Nagoya University, Nagoya, Japan
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h) RISE, Waseda University, Japan
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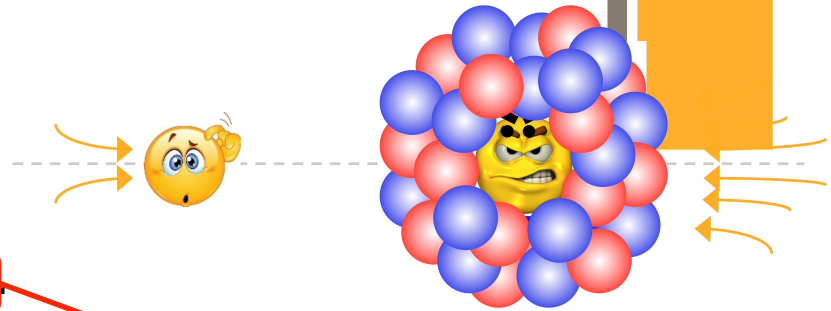
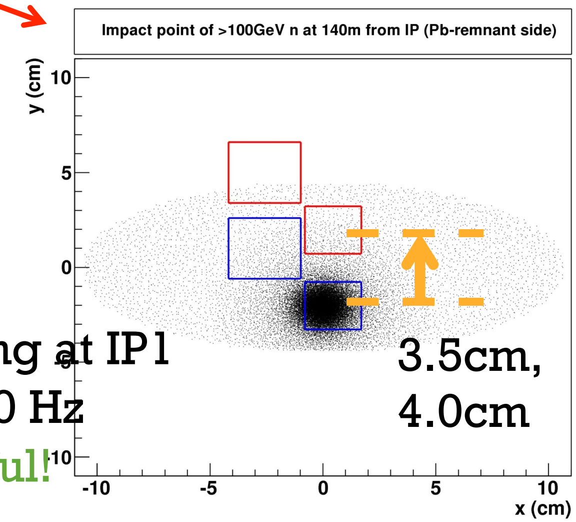
j) CERN, Switzerland
k) Kanagawa University, Japan
l) University of Catania, Italy
m) INFN Section of Catania, Italy
n) LBNL, Berkeley, California, USA
o) Shibaura Institute of Technology, Japan

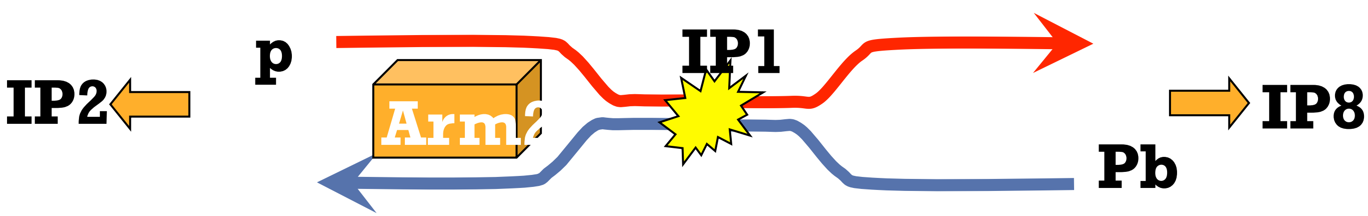
+ The 2013 p-Pb run at $\sqrt{s_{NN}}$ = 5.02 TeV



- 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**



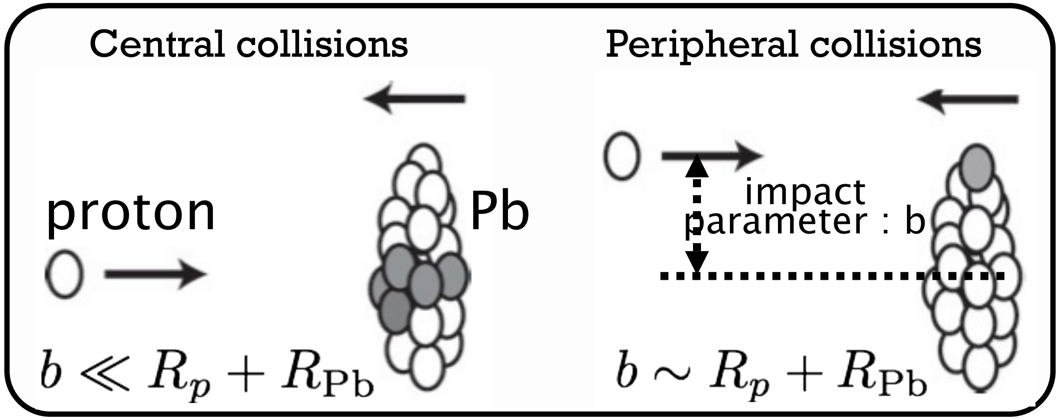
- Details of beams and DAQ
  - $L = 1x10^{29} – 0.5x10^{29} cm^{-2}s^{-1}$
  - ~200.10^{6} events
  - β^{*} = 0.8 m, 290 μrad crossing angle
  - 338p+338Pb bunches (min.ΔT = 200 ns), 296 colliding at IP1
  - 10-20 kHz trig rate downscaled to approximately 700 Hz
  - 20-40 Hz ATLAS common trig. Coincidence successful!
  - p-p collisions at 2.76 TeV have also been taken

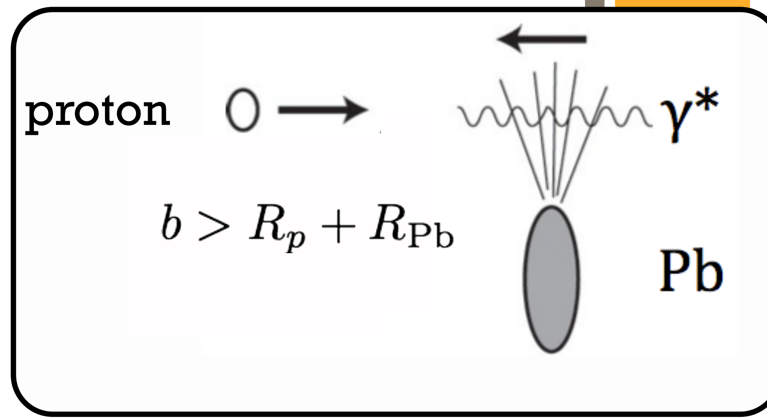


LHCf @ pPb 5.02 TeV: π^0 analysis

(Soft) QCD :
central and peripheral collisions

Ultra peripheral collisions :
virtual photons from rel. Pb collides a proton



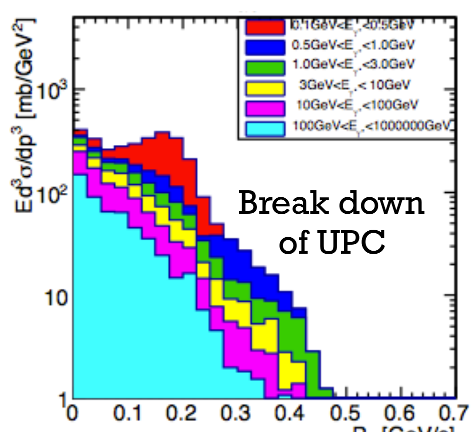


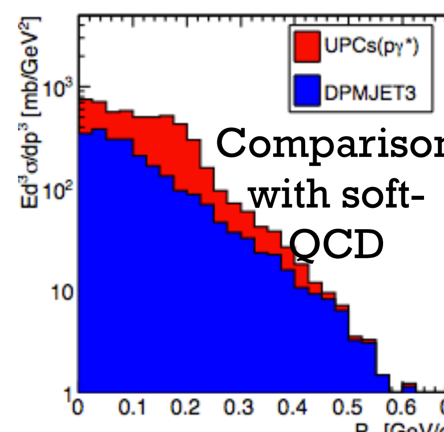
Estimation of momentum distribution of the UPC induced secondary particles (Lab frame+Boost):
1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation
2. photon-proton collisions are simulated by the SOPHIA model (E_γ > pion threshold)

Dominant channel to forward π^0 is

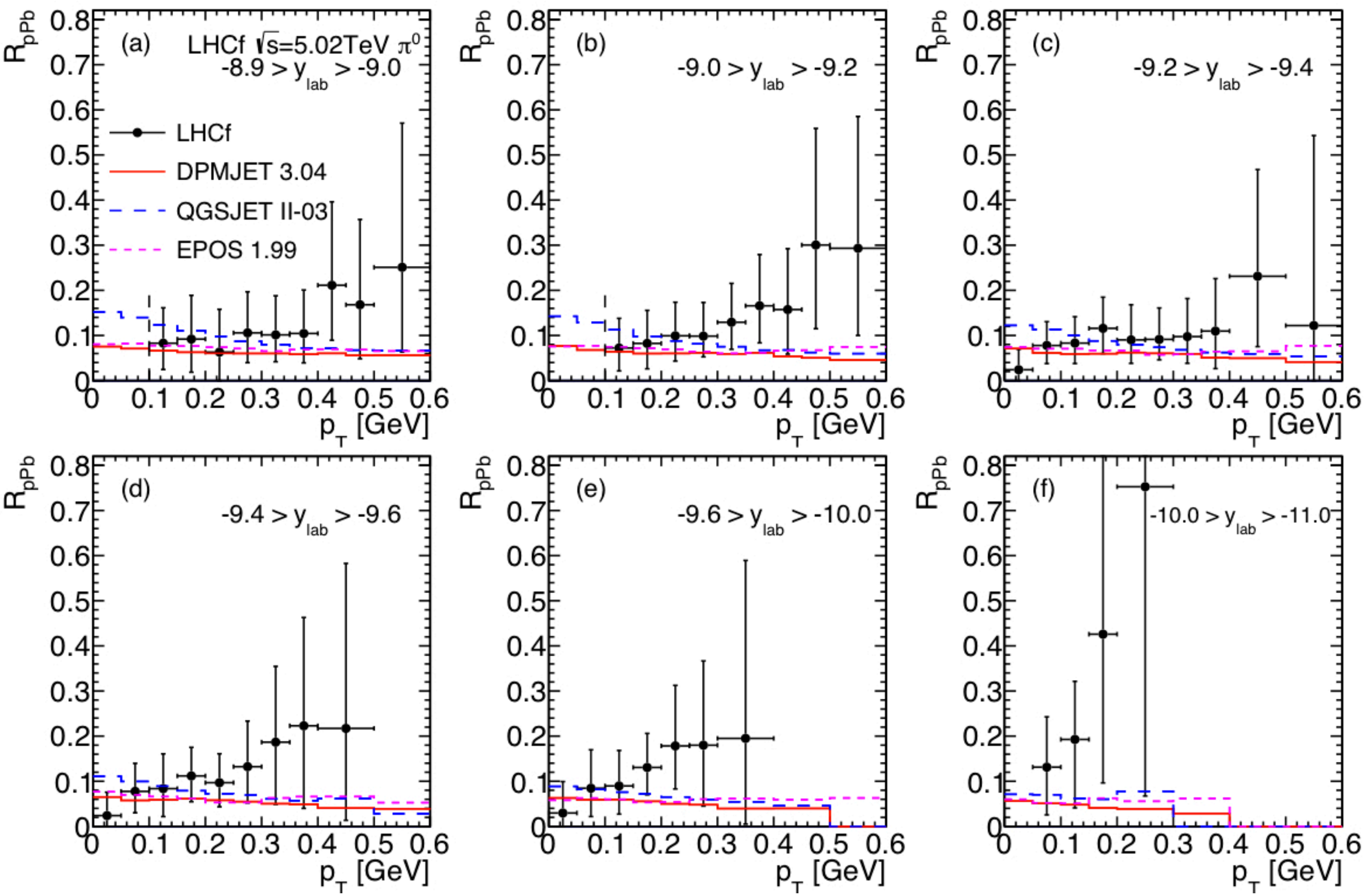
$$\gamma + p \to \Delta(1232) \to p + \pi^0$$

About half of the observed π^0 originate from UPC
About half is from soft-QCD
Need to subtract UPC component





Nuclear modification factor in p-Pb at 5.02 TeV

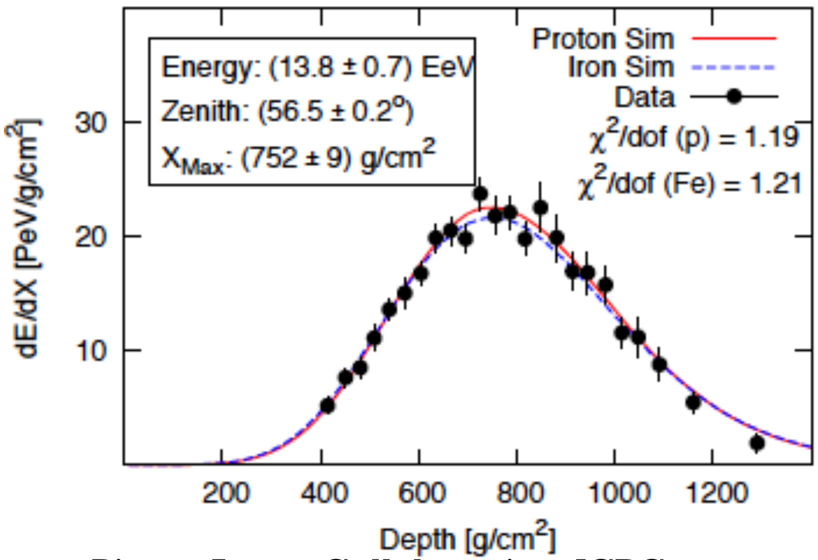


$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) \equiv \frac{\sigma_{\mathrm{inel}}^{\mathrm{pp}}}{\langle N_{\mathrm{coll}}\rangle \sigma_{\mathrm{inel}}^{\mathrm{pPb}}} \frac{E d^3\sigma^{\mathrm{pPb}}/dp^3}{E d^3\sigma^{\mathrm{pp}}/dp^3}$$

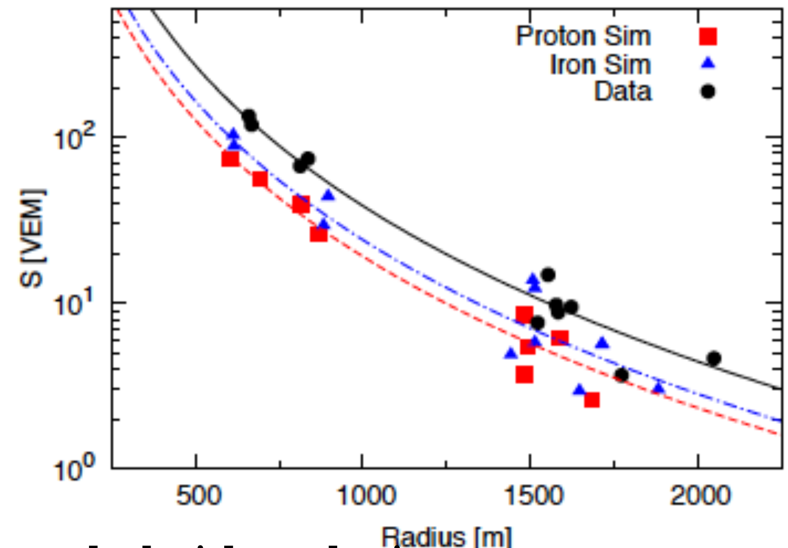
$$\langle N_{\mathrm{coll}}\rangle = 6.9$$

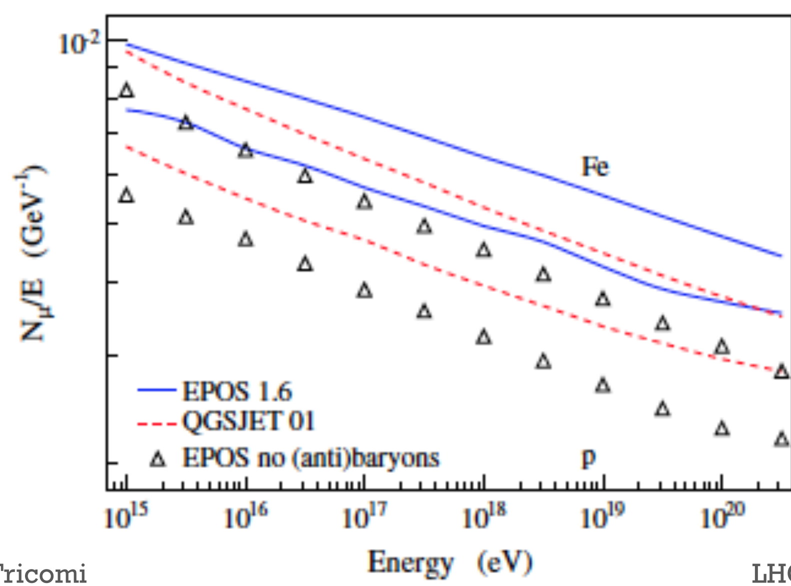
- Both LHCf and MCs show strong suppression.
- NMF grows with increasing p_T, as can be expected by the p_T spectrum that is softer in p-p 5 TeV than in p-Pb 5 TeV collisions

+ 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

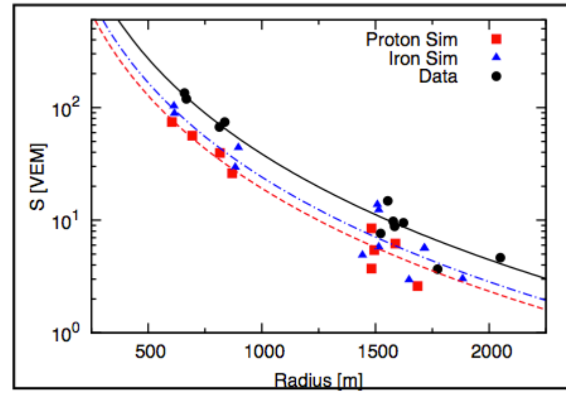
=> importance of baryon measurement

Pierog and Werner, PRL 101 (2008) 171101

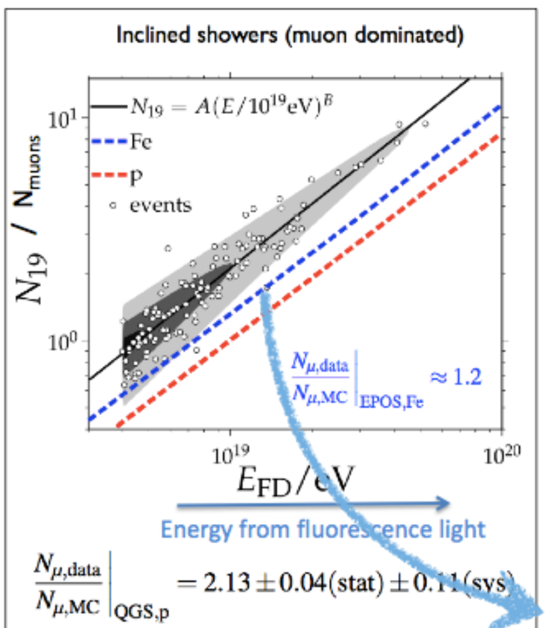
The importance of neutrons in the very forward region

Motivations:

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

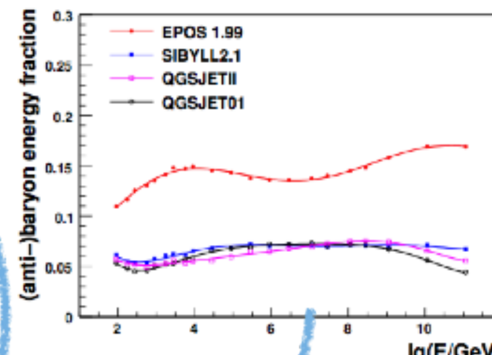


[J.Allen, et al. ICRC2011 Proceedings]

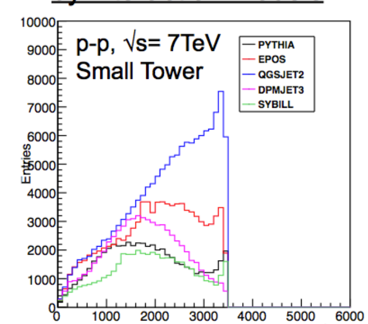


R. Engel

- Number of muons depends on the energy fraction of produced hadron
- Muon excess in data even for Fe primary MC
- EPOS predicts more muon due to larger baryon production



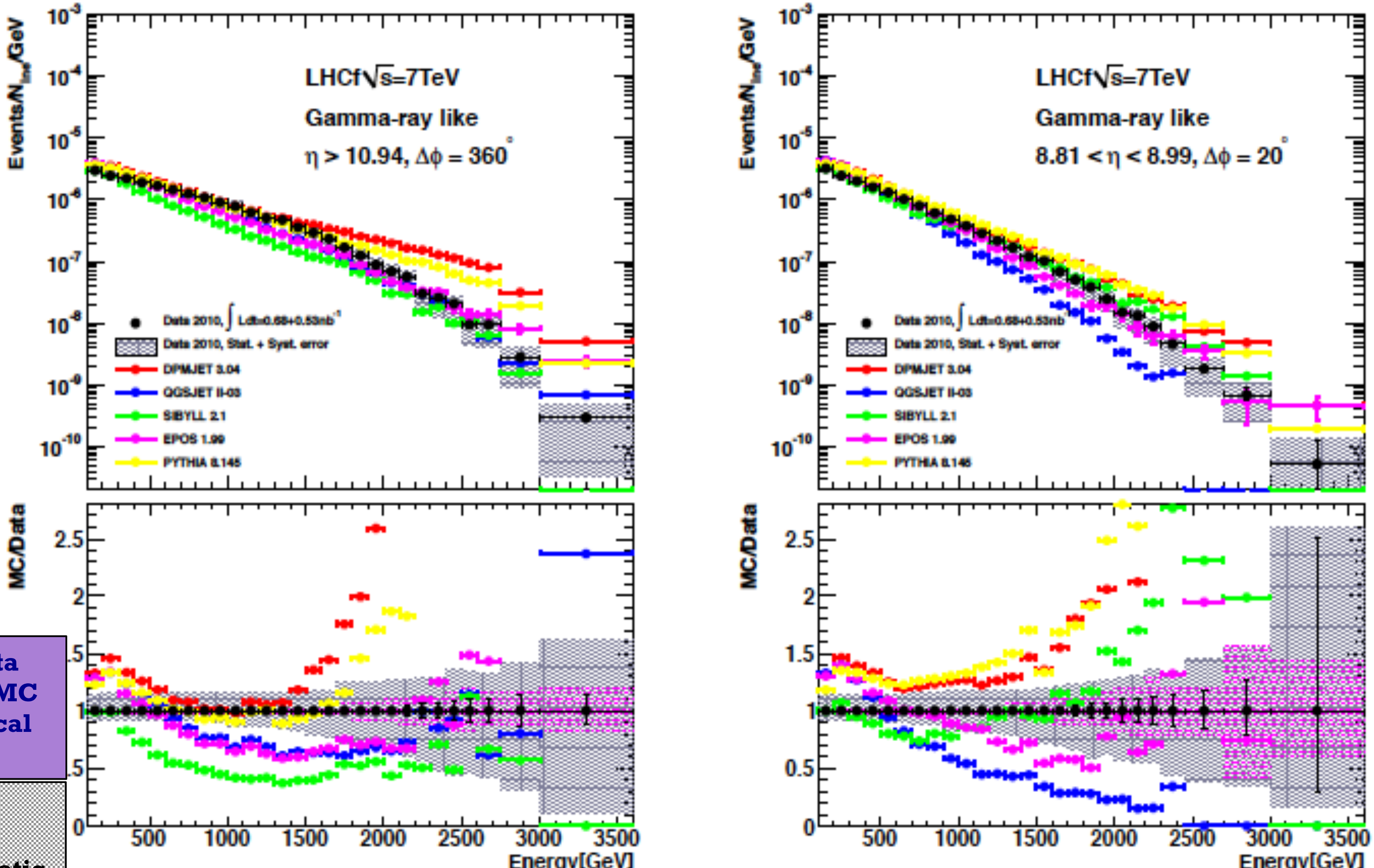
Neutron spectra predicted by interaction models



importance of baryon measurement

+ Comparison wrt MC Models at 7 TeV

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



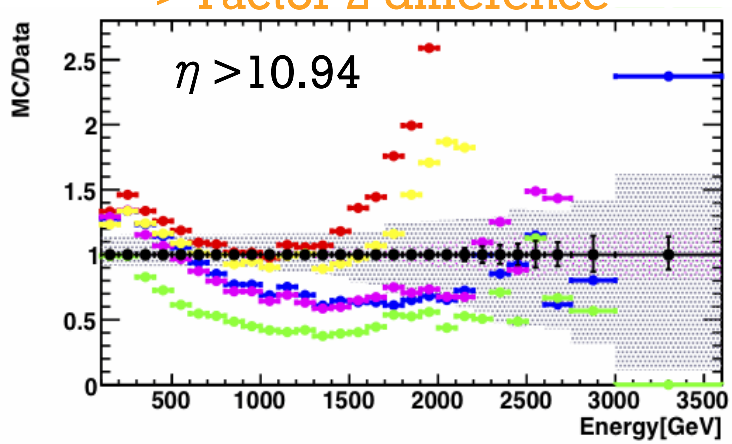
Magenta hatch: MC Statistical errors

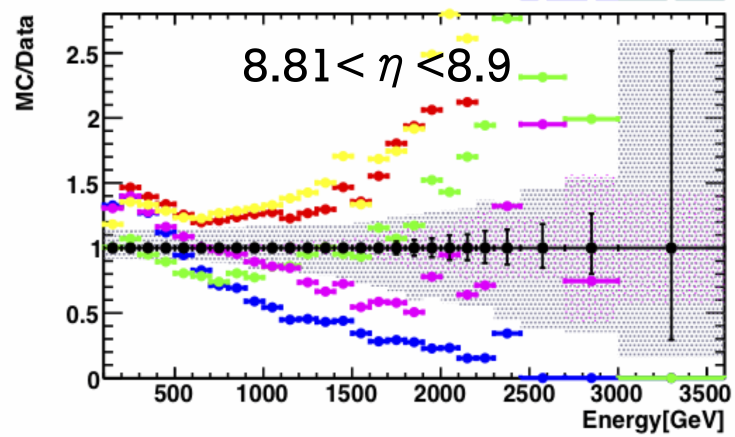
Gray hatch : Systematic Errors

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

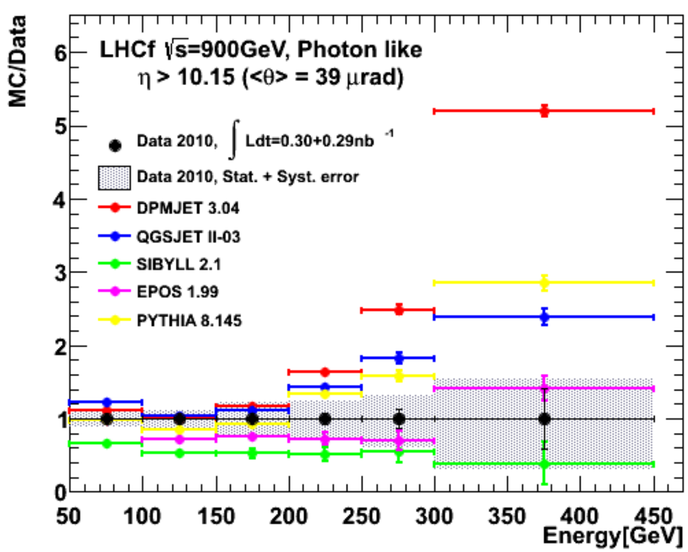
- None of the model nicely agrees with the LHCF data
- Here we plot the ratio MC/Data for the various models
- > Factor 2 difference

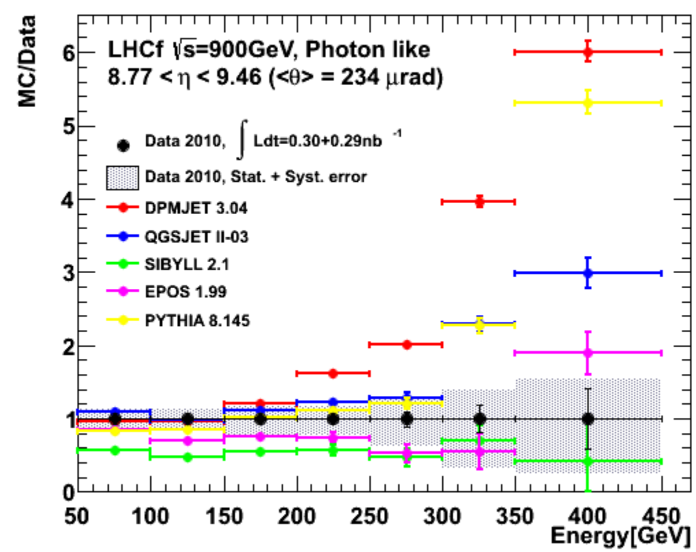
7TeV





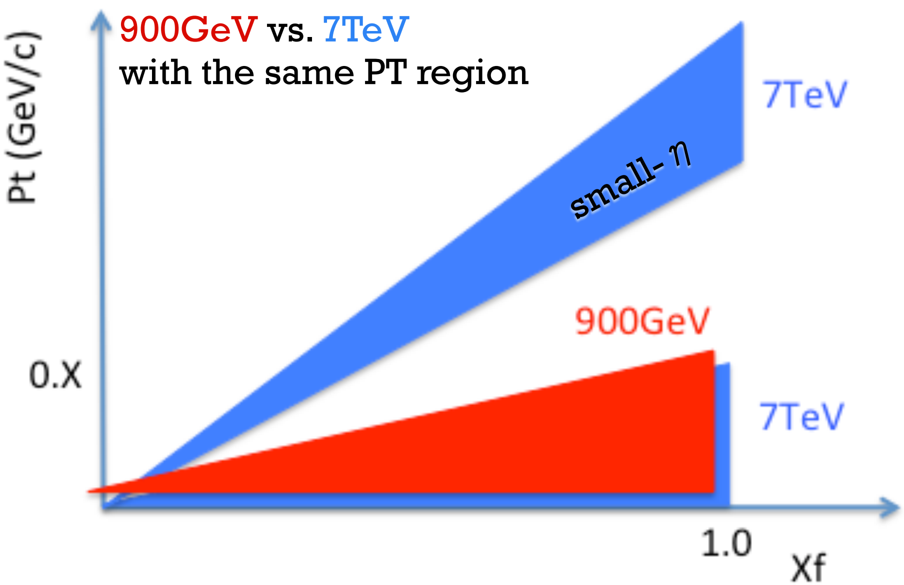
900GeV



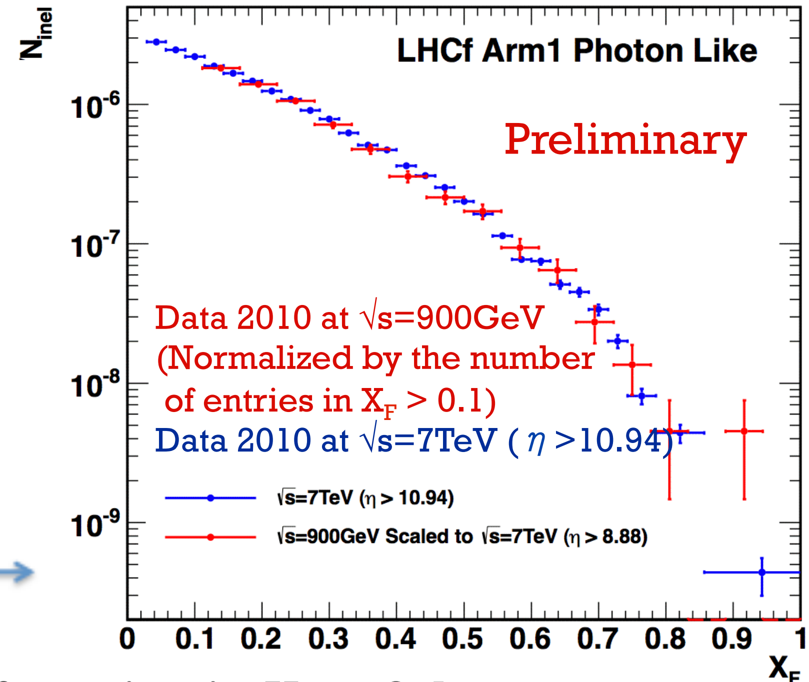


+ DATA : 900GeV vs 7TeV

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



X_F spectra : 900GeV data vs. 7TeV data

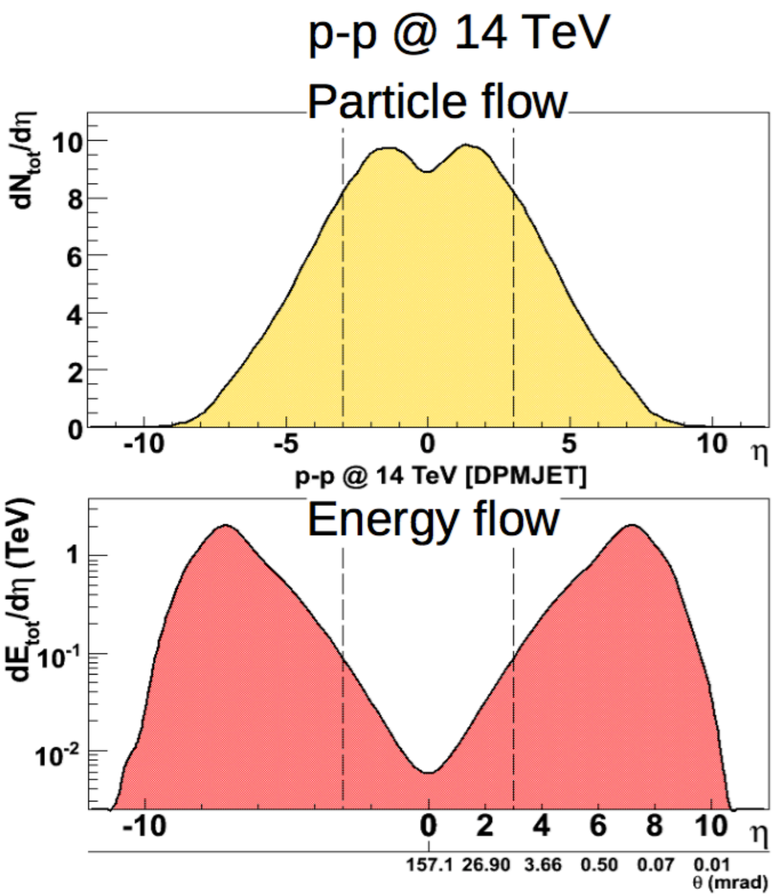


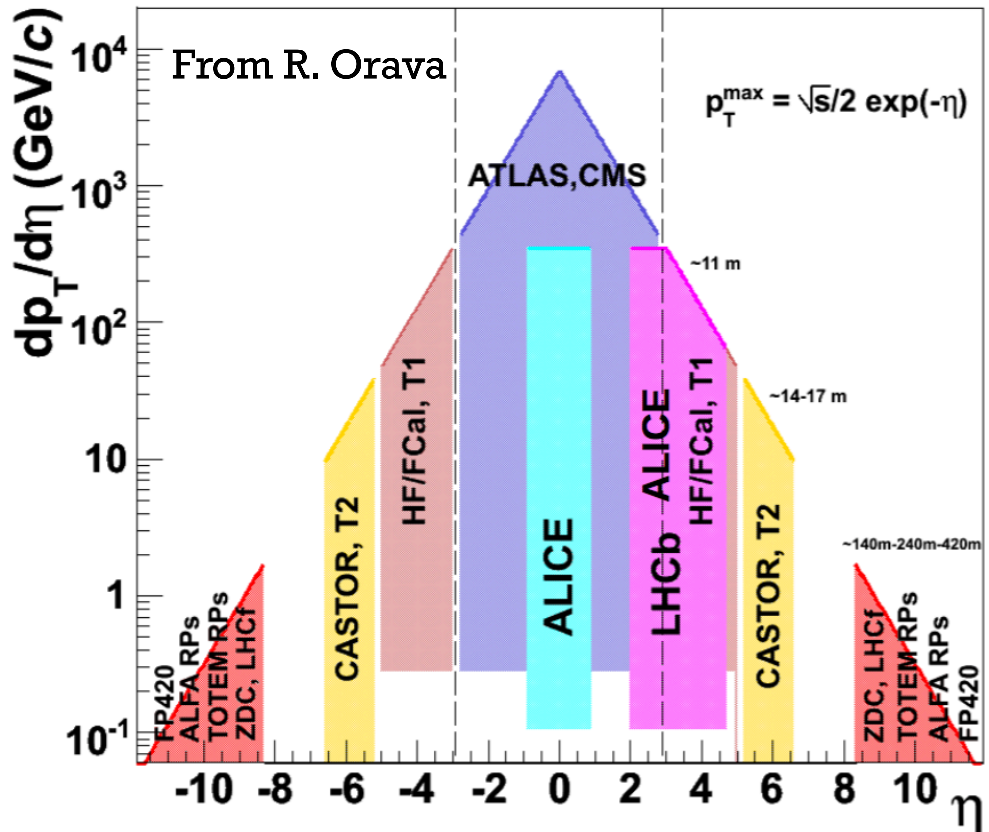
- ✓ Normalized by the number of entries in $X_F > 0.1$
- ✓ No systematic error is considered in both collision energies.

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

$$\frac{1}{\sigma_{\mathrm{inel}}}\frac{d\sigma_\gamma}{dX_F}\Big|_{\eta<\mathrm{limited}} \propto \frac{1}{\sigma_{\mathrm{inel}}}\frac{d\sigma_\gamma}{p_T dp_T dX_F}\langle p_T\rangle dp_T$$

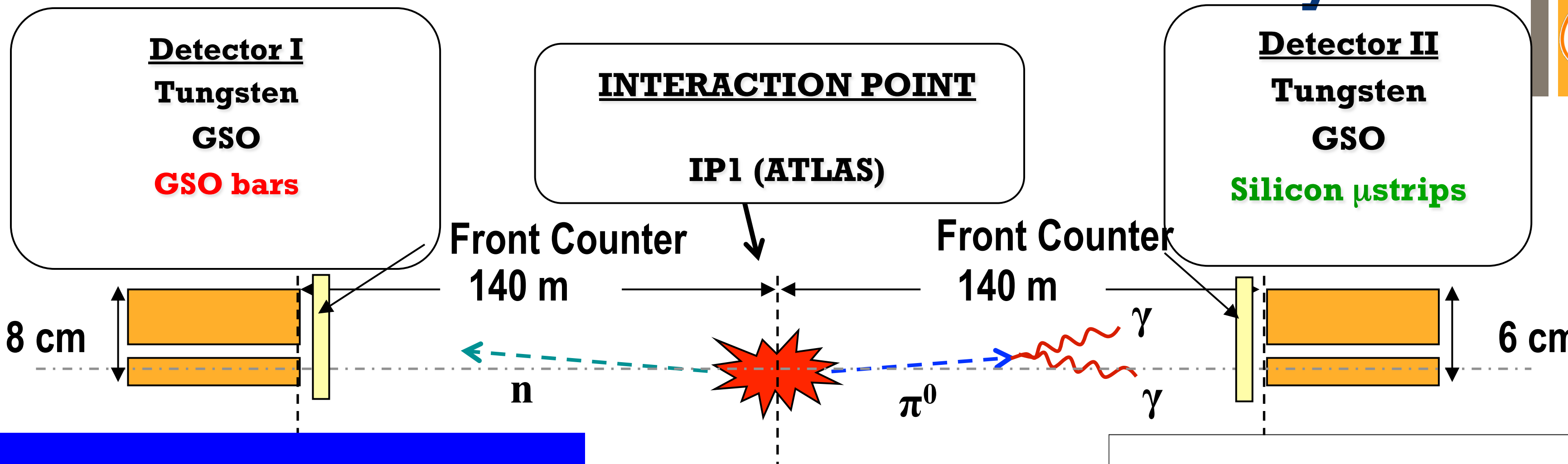
LHC phase space coverage

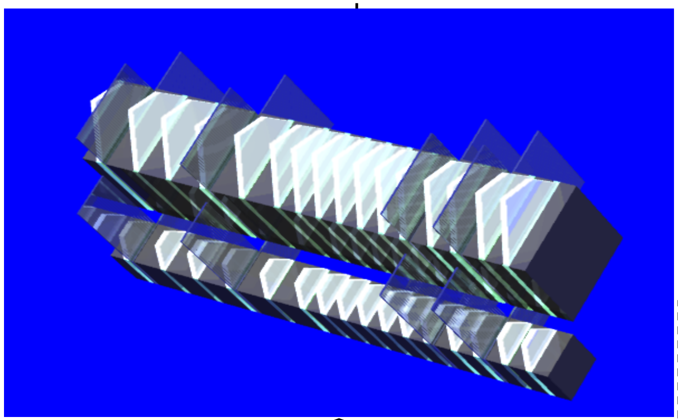




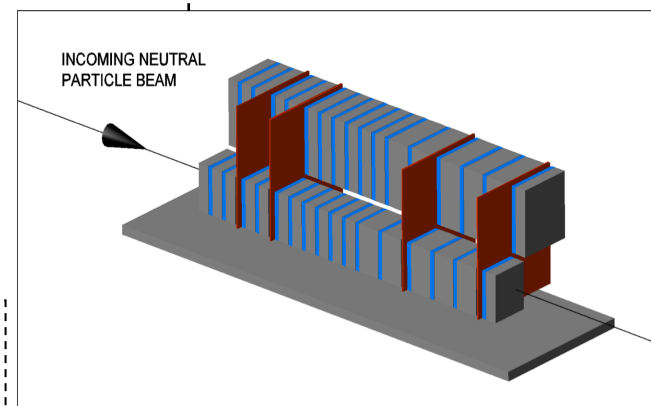
We may profit (and we are profiting) of the very broad coverage!
LHCf is a dedicated forward detectors for a better measurement of the energy flow

LHCf: location and detector layout





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



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

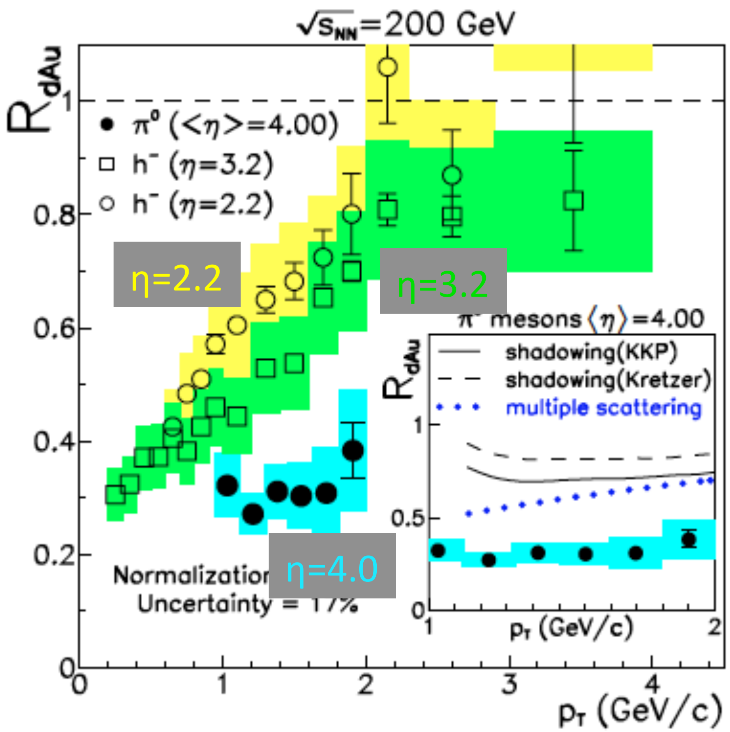
Arm#2 Detector
25mmx25mm+32mmx32mm
4 X-Y Silicon strip tracking layers

+ Physics of RHICf

- Physics of RHICf
  - Energy Scaling of Very Forward at p-p √s=500GeV
  - Measurement at p-light ion collisions (p-O) $\sqrt{s_{NN}}$=200GeV
  - Asymmetry of Forward Neutron with polarized beams

- LOI submitted to the RHIC committee and nicely appreciated
  - More news soon

Nuclear modification factor at d-Au 200GeV

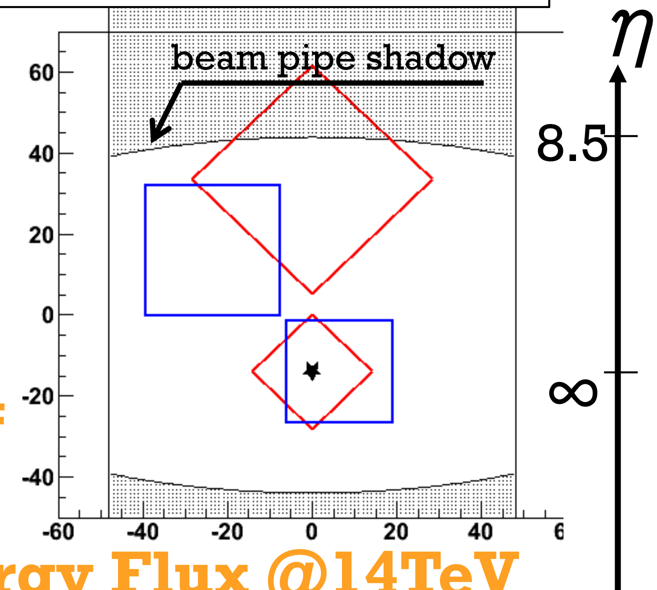


The STAR Collaboration, PRL 97 (2006) 152302

Y. Fukao et al., PLB 650 (2007)

+ *What LHCf can measure*

Front view of calorimeters
@ 100 μ rad crossing angle

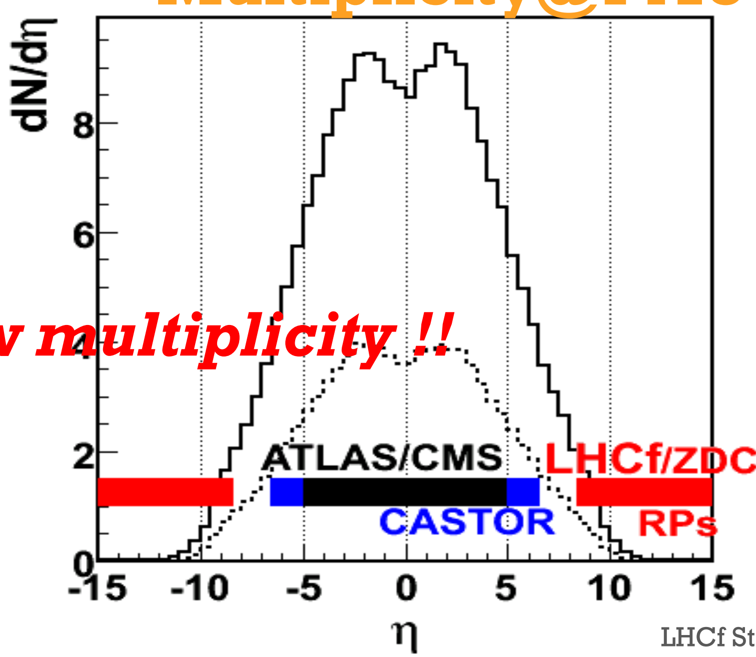


Energy spectra and
Transverse momentum distribution of

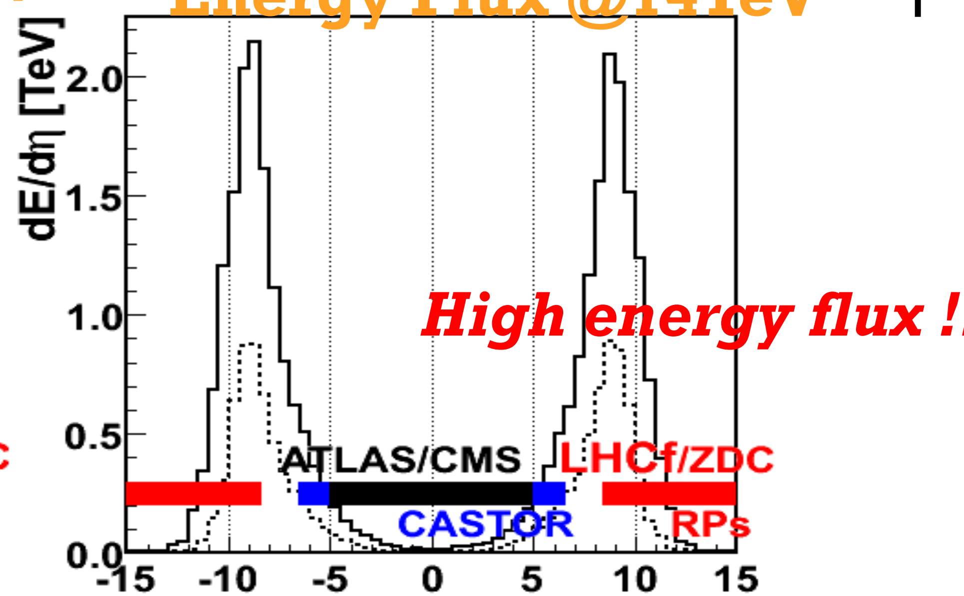
- **Gamma-rays (E>100GeV,dE/E<5%)**
- **Neutral Hadrons (E>a few 100 GeV, dE/E~30%)**
- **π^0 (E>600GeV, dE/E<3%)**

at pseudo-rapidity range >8.4

Multiplicity@14TeV

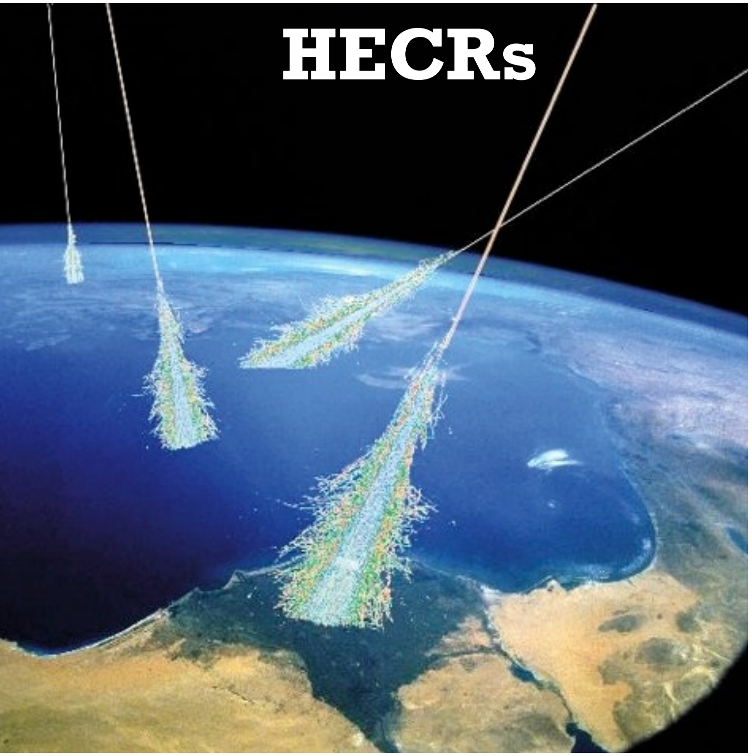


Energy Flux @14TeV



simulated by DPMJET3

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

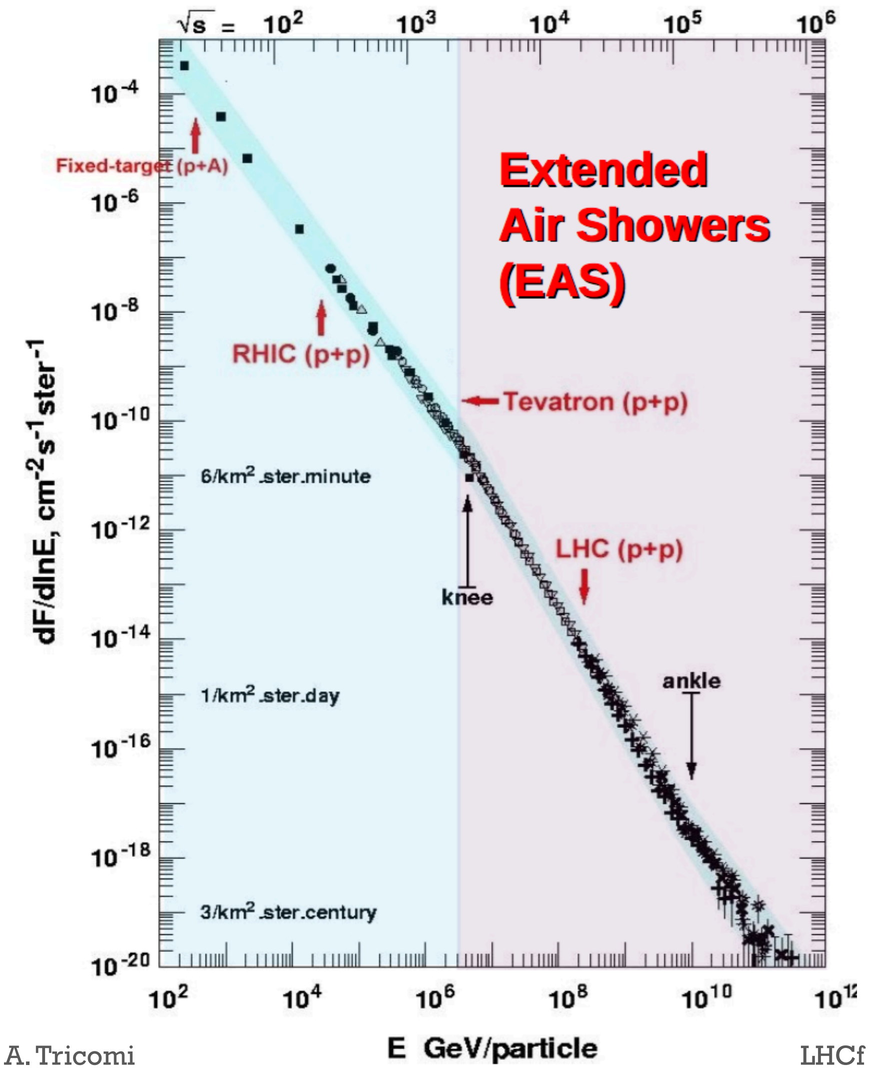
Uncertainty of hadron interaction models

↓

Uncertainty in the interpretation of the observables

+ The 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!

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

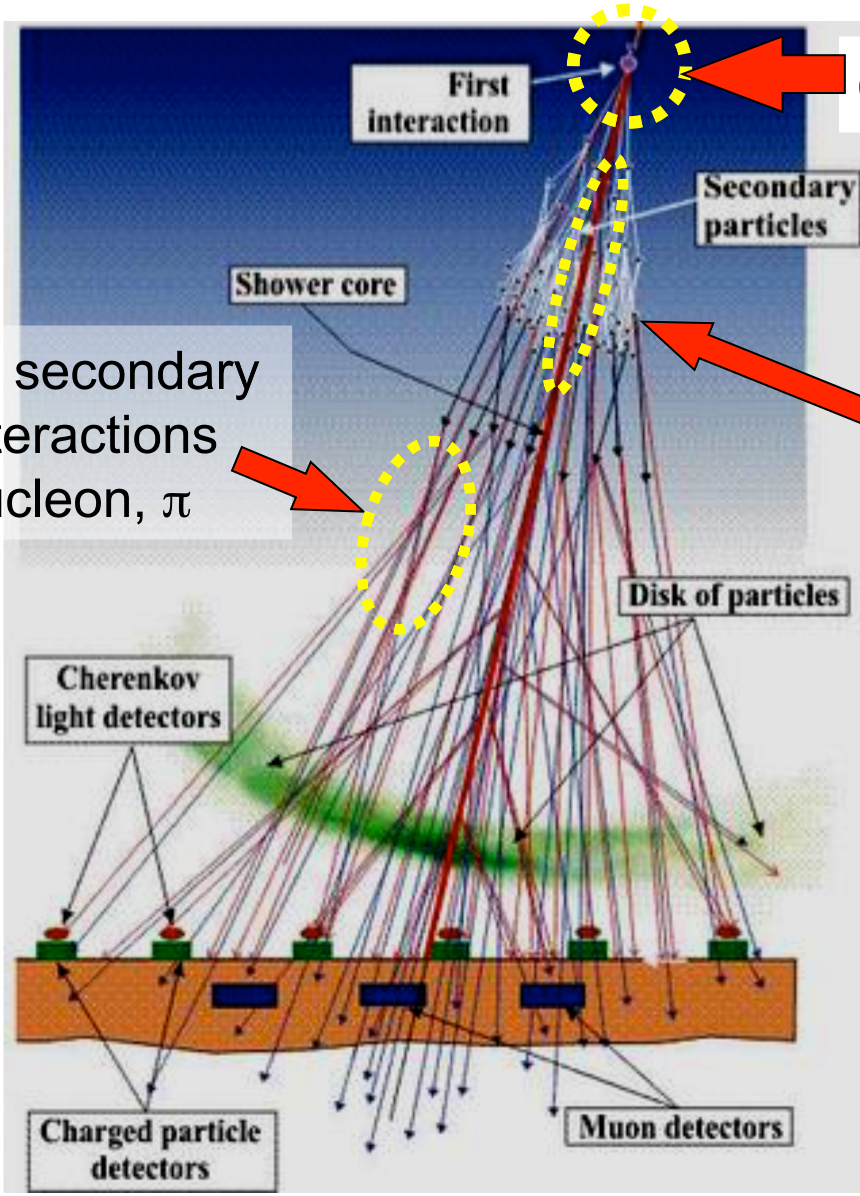
Uncertainty of hadron interaction models

↓

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

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

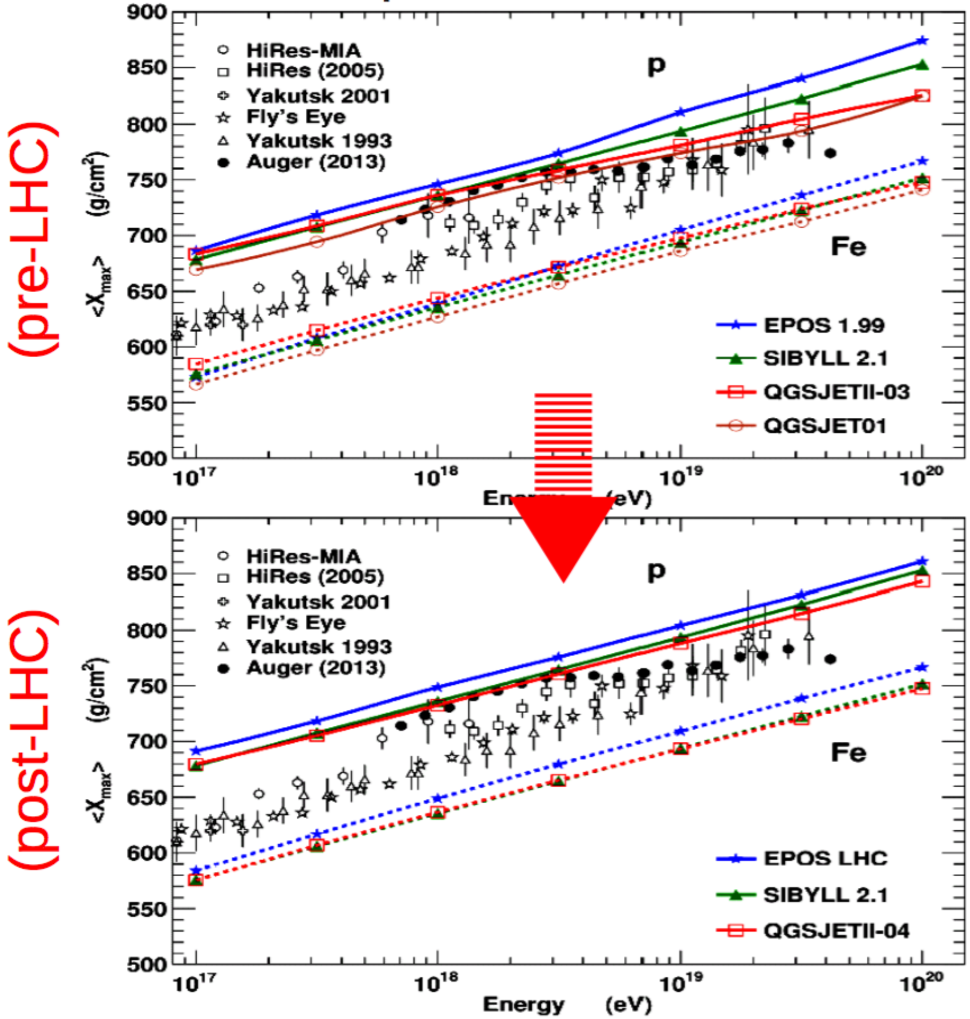
If softer shallow development
If harder deep penetrating

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

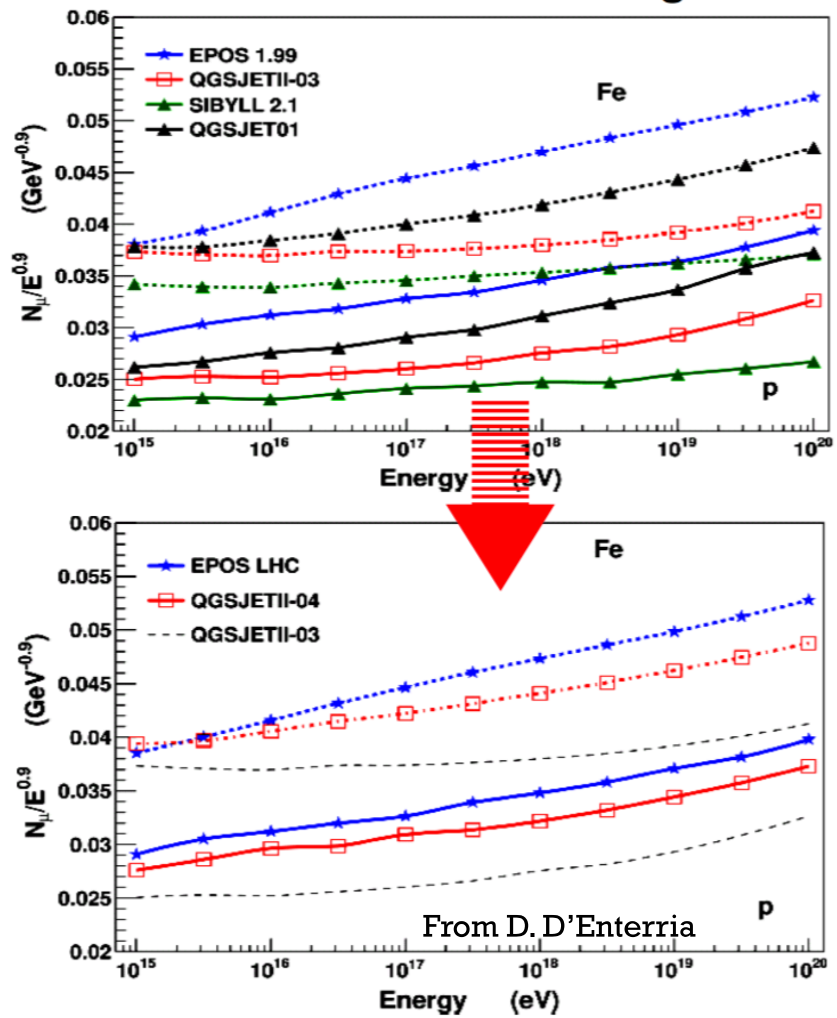
If large k (π^0s carry more energy)
rapid development
If small k (baryons carry more energy)
deep penetrating

Models tuning after the first LHC data (EPOS and QGSJET)

Mean depth of shower maximum:



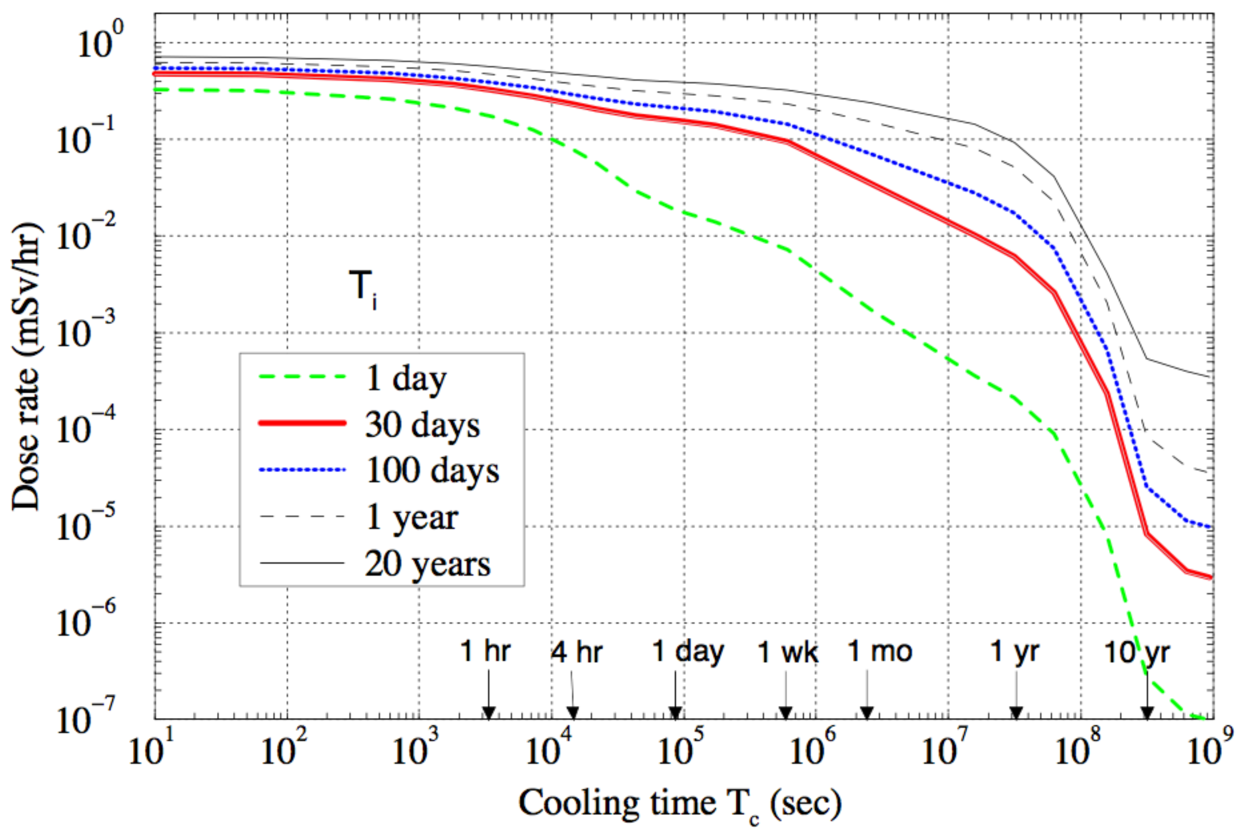
Number of muons on ground:



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

Dose rate in the TAN region

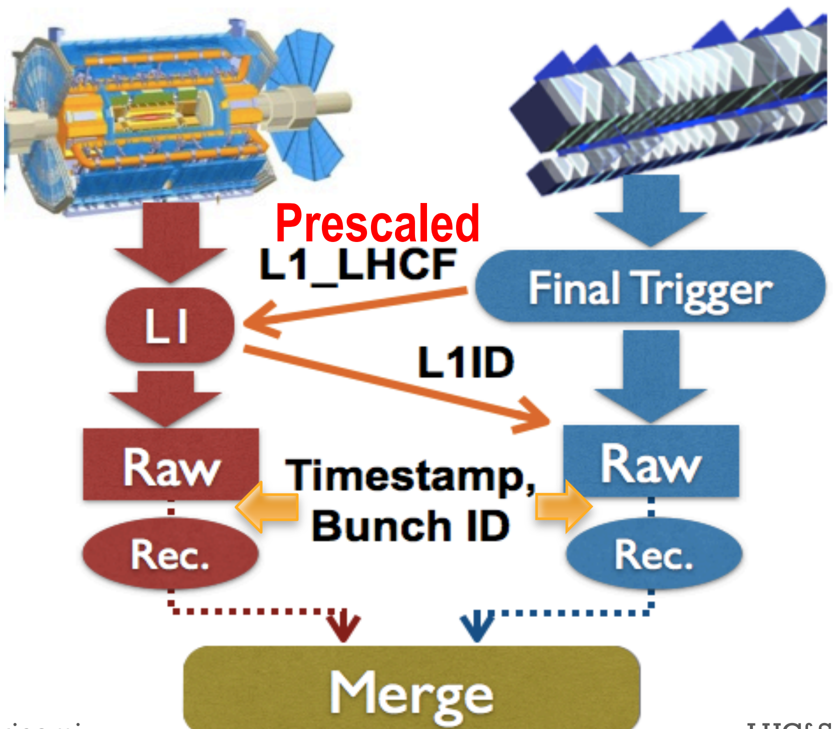
- https://cds.cern.ch/record/613167
- 100 days of operation with L=10^34 and cooling of a few days, the residual dose of the aisle side of the TAN is 100-200 uSv/h.

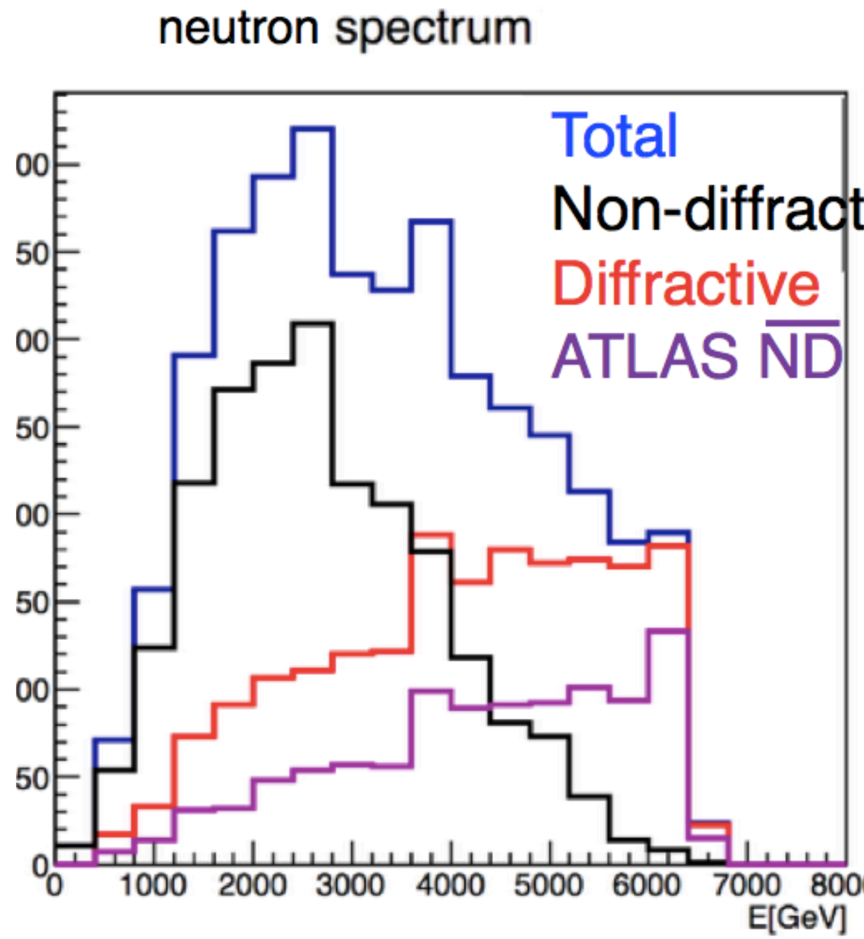


+ ATLAS-LHCf trigger exchange

- Non-diffraction tagging by N_{trk}>=2 in ATLAS | η |<2 (P_T>100 MeV/c)

- Diffraction : 10 % of LHCf data





Hadron(neutron)
MC by PYHITA