# Cosmic rays and accelerator physics at LHCf

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    - Contribution to forward physics
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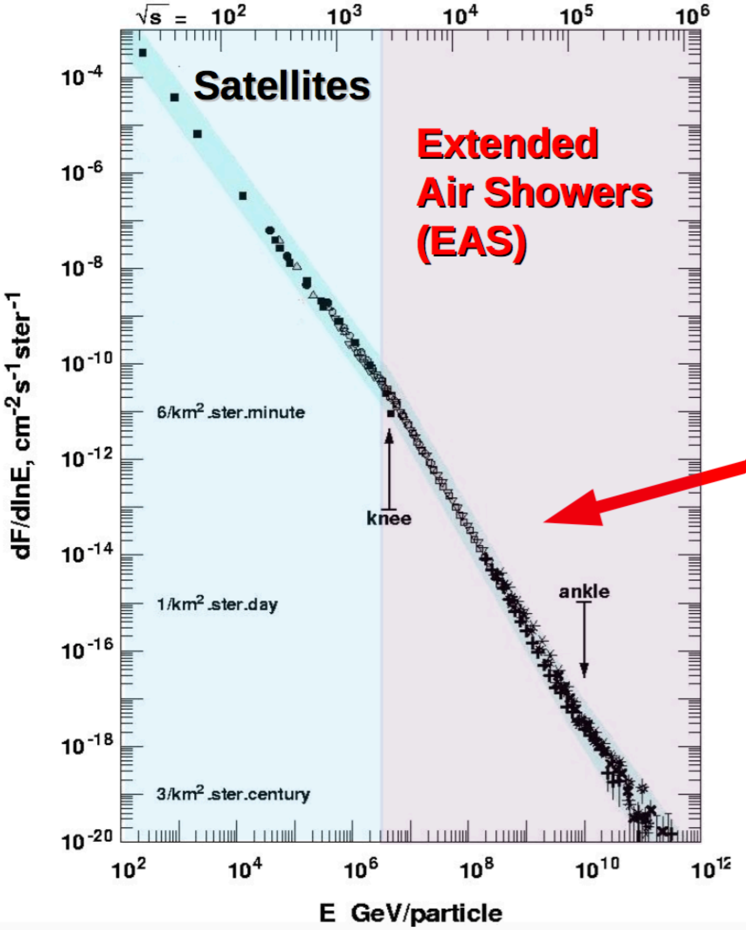
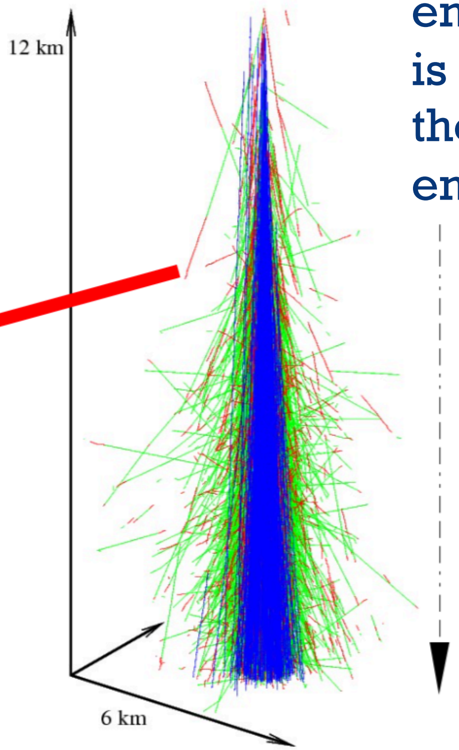
+

# Introduction

# + The High Energy cosmic ray spectrum

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



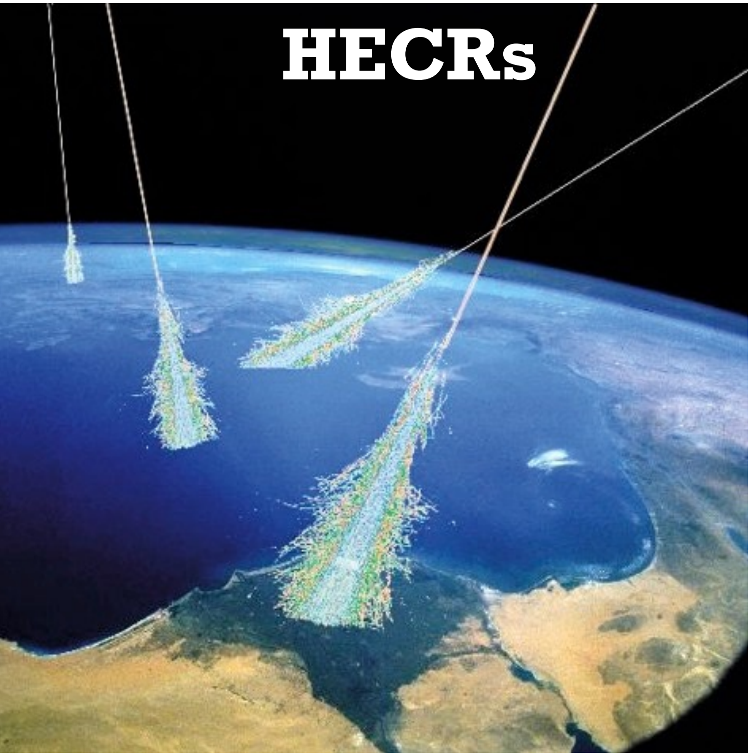


Detailed knowledge of high energy hadronic interactions is necessary to reconstruct the primary CR type and energy!

~27 $X_0$

~11 $\lambda_{int}$

# 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
- **$N_\mu$**: number of muons in the shower at the detector level

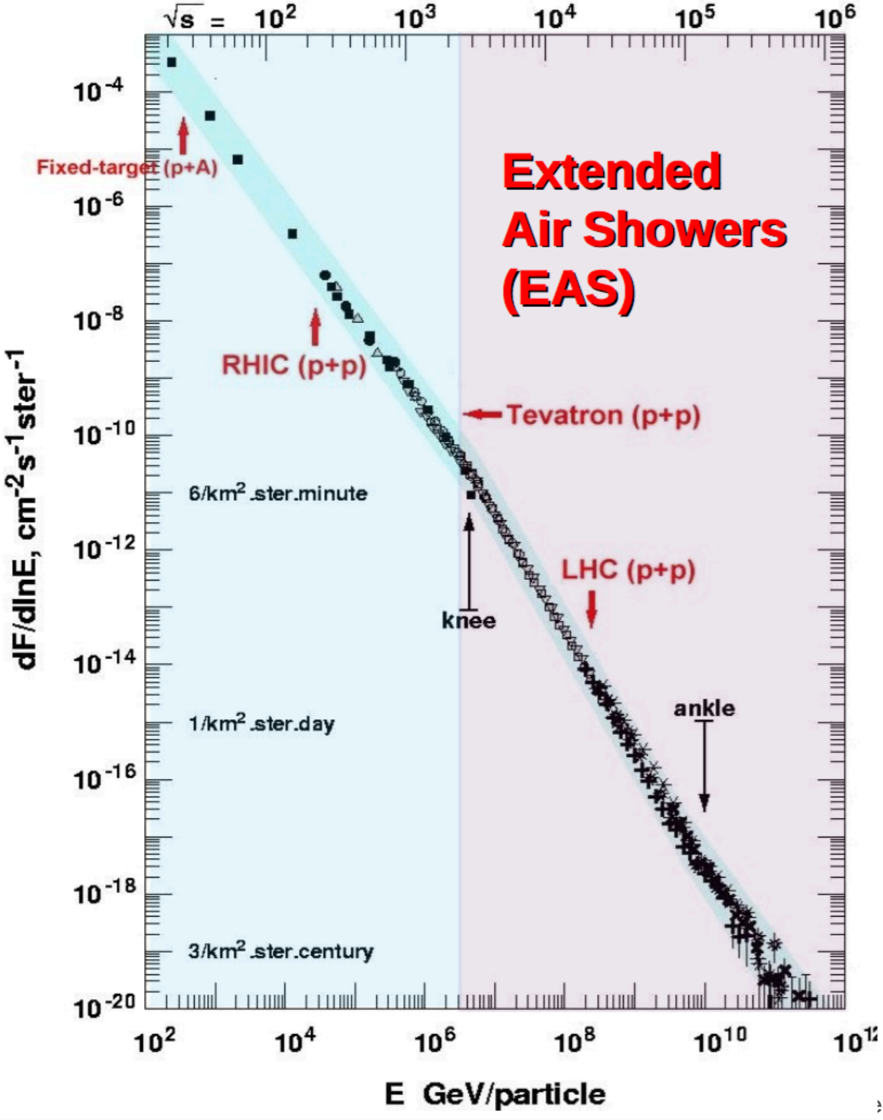
- To go from these observables to the CR composition and energy determination passing through the hadronic interaction models is mandatory

Uncertainty of hadron interaction models

↓

Uncertainty in the interpretation of the observables

# + The role of the accelerators experiments

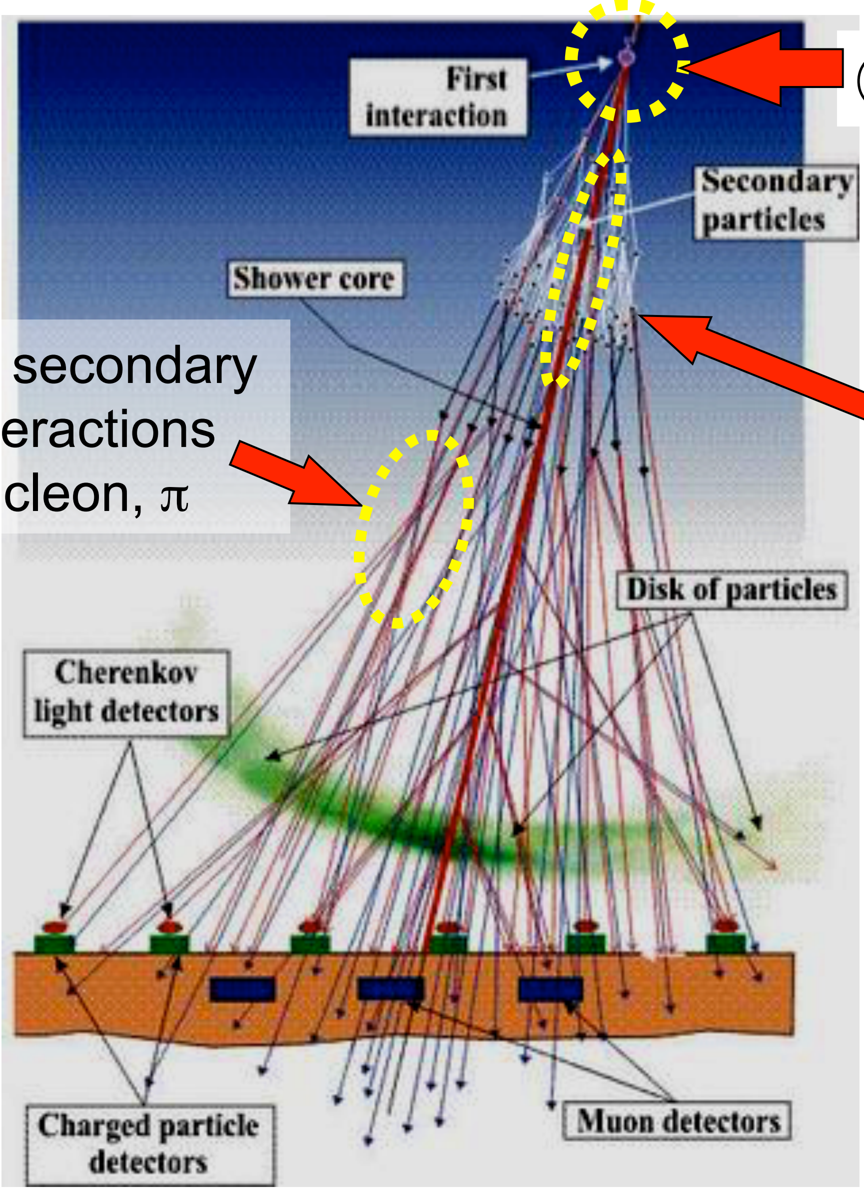


Accelerator based experiments are the most powerful available tools to determine the high energy hadronic interactions characteristics

→ 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?



① Inelastic cross section

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

② **Forward energy spectrum**

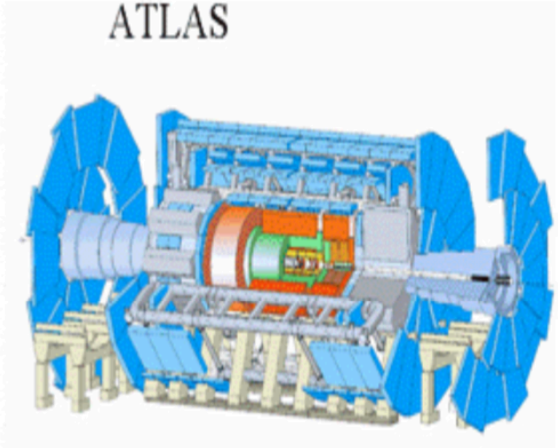
If softer shallow development
If harder deep penetrating

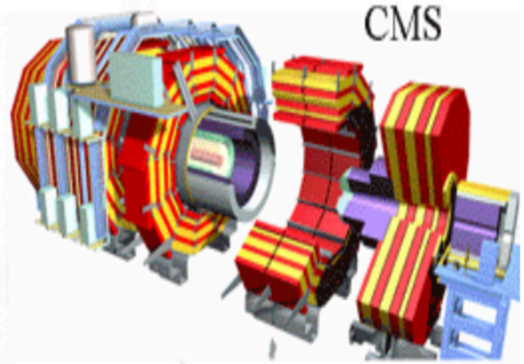
③ **Inelasticity** **k=1-$E_{lead}/E_{avail}$**

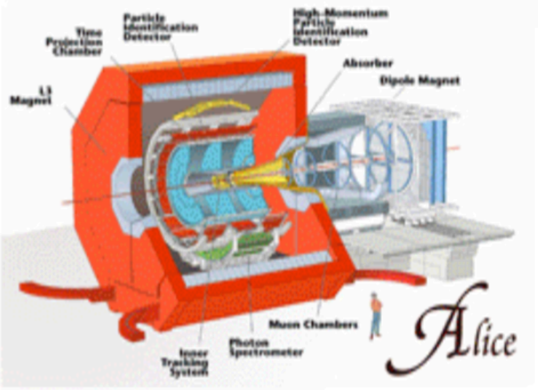
If large k ($\pi^0$s carry more energy)
rapid development
If small k (baryons carry more energy)
deep penetrating

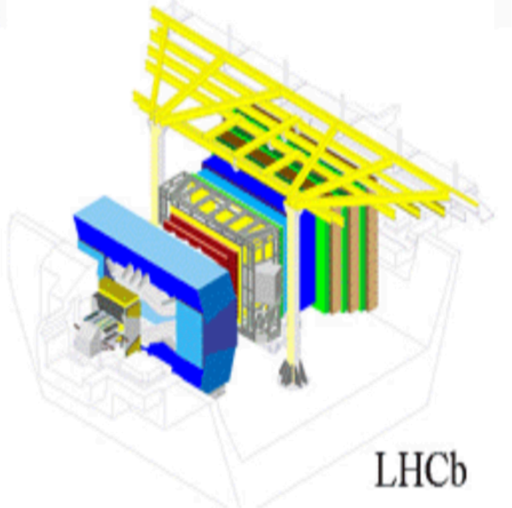
④ secondary interactions nucleon, π

# + Impressive coverage of the central region

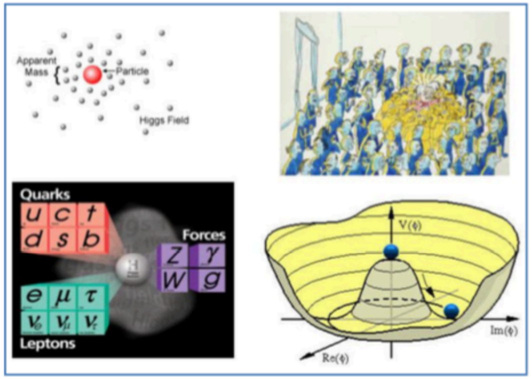








- The largest detectors for particle physics
- Surrounding the LHC Interaction Points
- Covering many fundamental physics items
- Designed for discoveries!



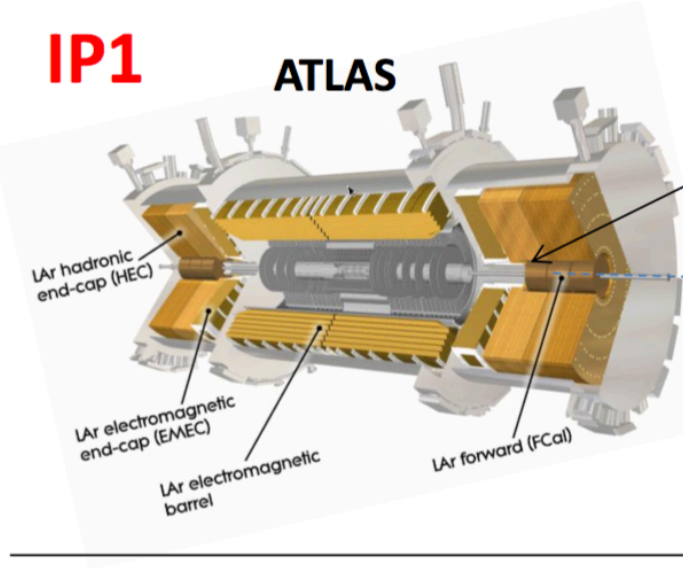
General purpose detectors (ATLAS, CMS,...) cover the spatial region at low rapidity.

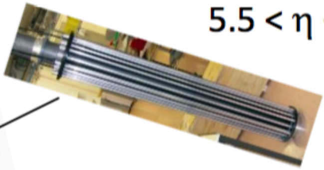
Special detectors to access forward particles are necessary!

# And also of the forward region!

**IP1**

**ATLAS**



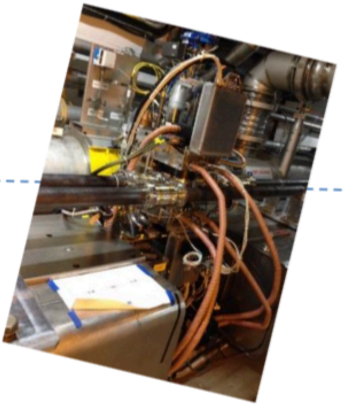


ATLAS LUCID
5.5 < η < 6

ATLAS
FCAL
3 < η < 5

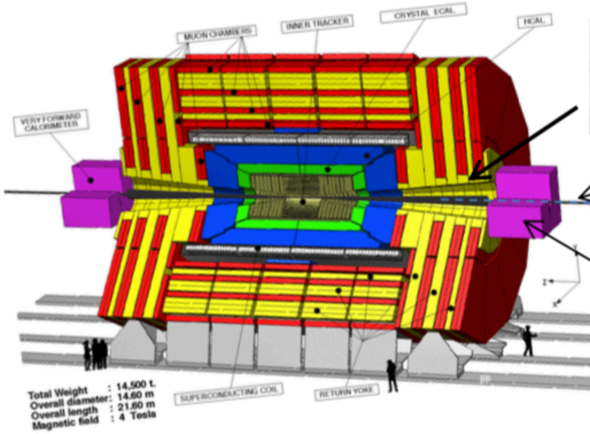
LHCf and ATLAS ZDC
( ± 140 m); |η| > 8

ATLAS ALFA RPs ( ± 240 m)
10.6 < η < 13.5

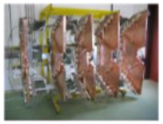


**IP5**

**CMS**



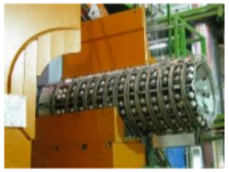
TOTEM T1
3.1 < |η| < 4.7



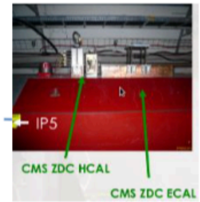
TOTEM T2
5.3 < |η| < 6.5

CMS HF
2.9 < |η| < 5.2

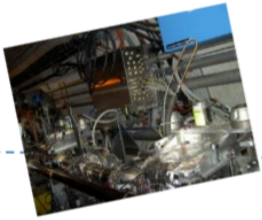
CMS CASTOR
5.1 < |η| < 6.6



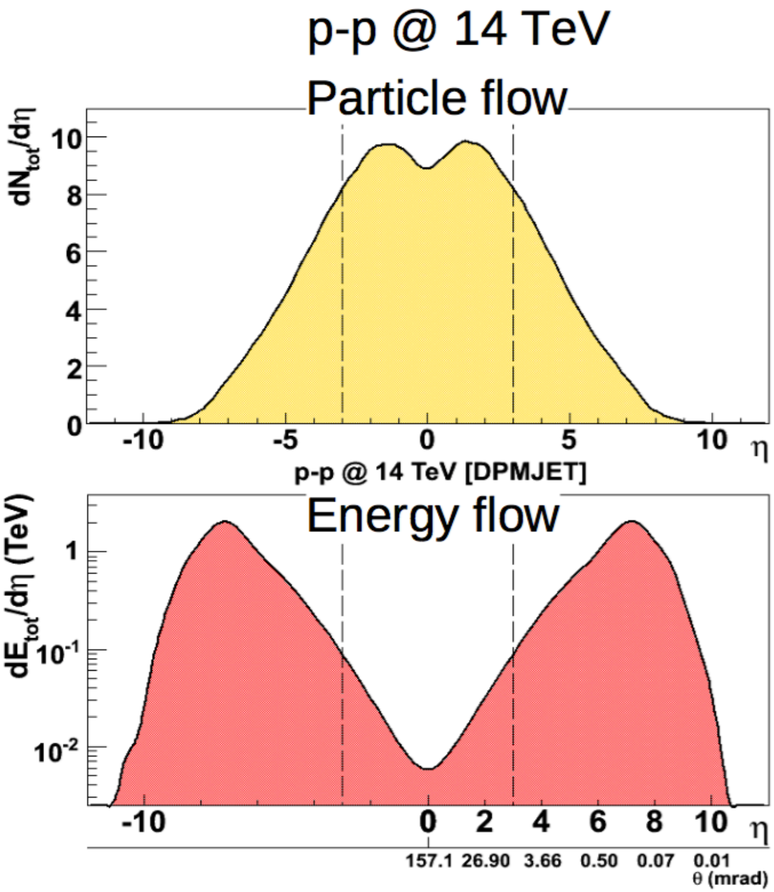
CMS ZDC (±140 m)
|η| > 8

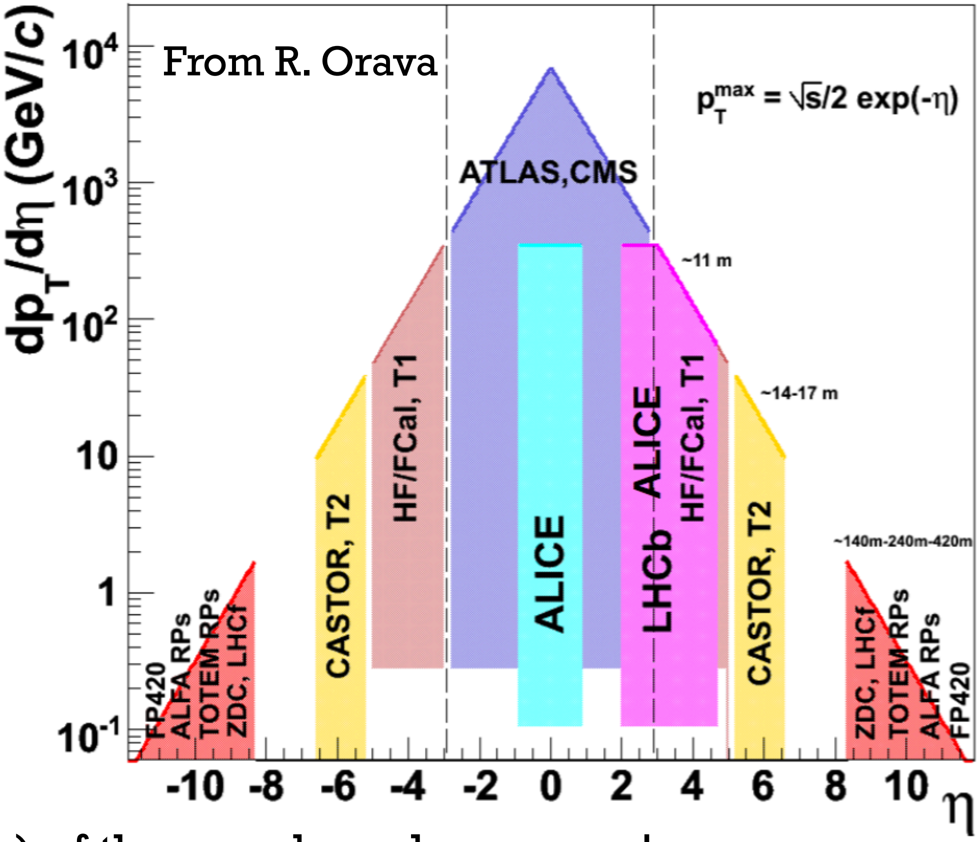


TOTEM RPs
(±150 and ±220 m)



# + LHC phase space coverage

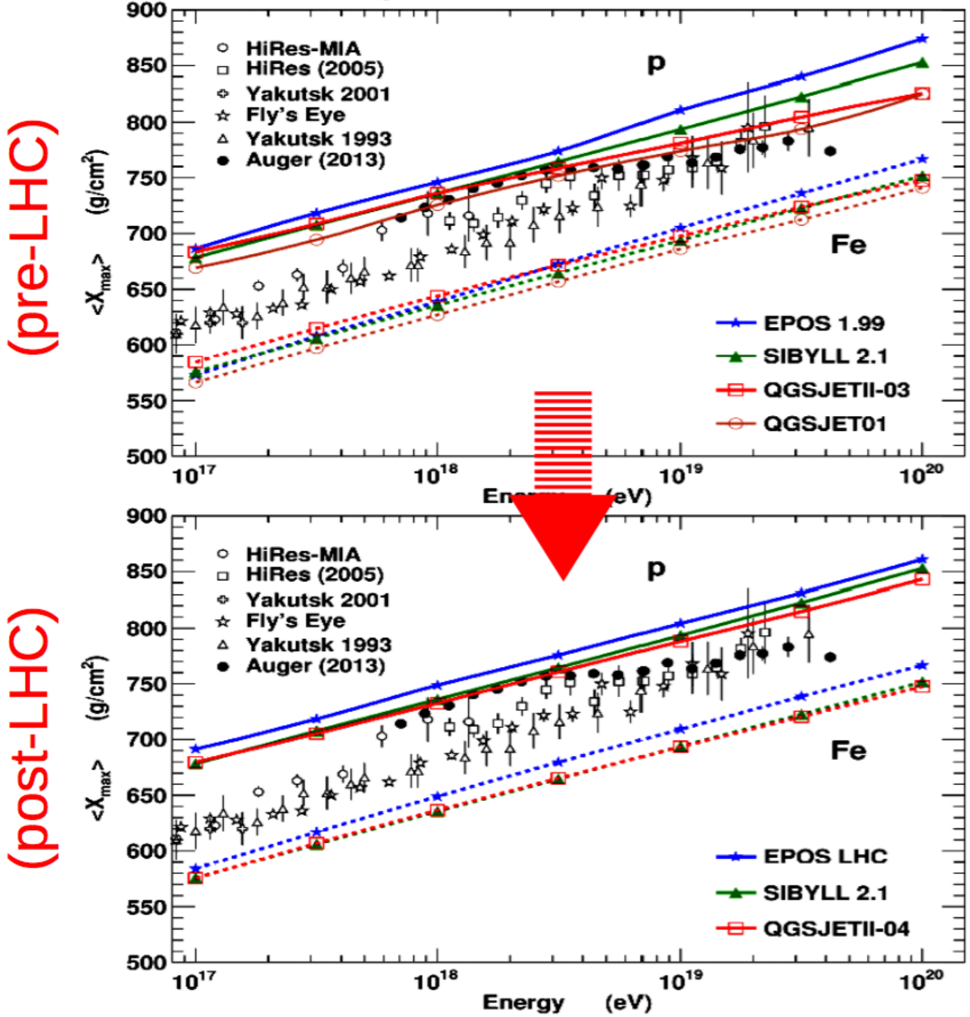



From R. Orava

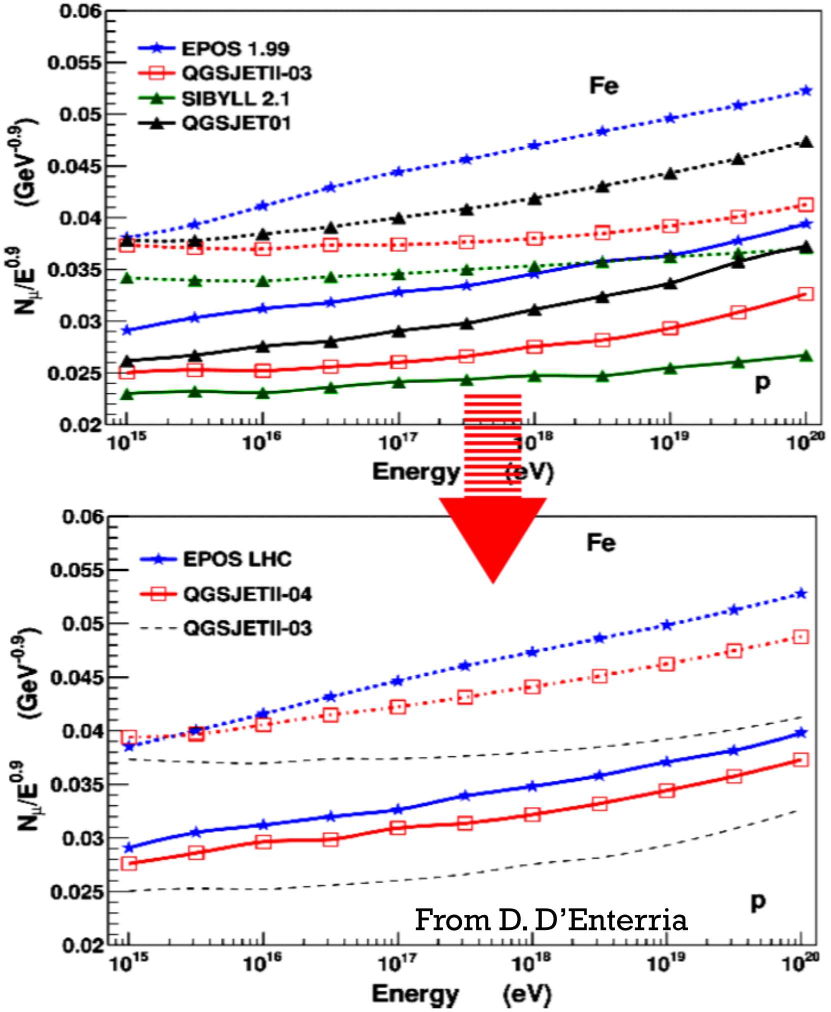
We may profit (and we are profiting) of the very broad coverage!
Dedicated forward detectors for a better measurement of the energy flow

# First models tuning after the first LHC data (EPOS and QGSJET)

Mean depth of shower maximum:



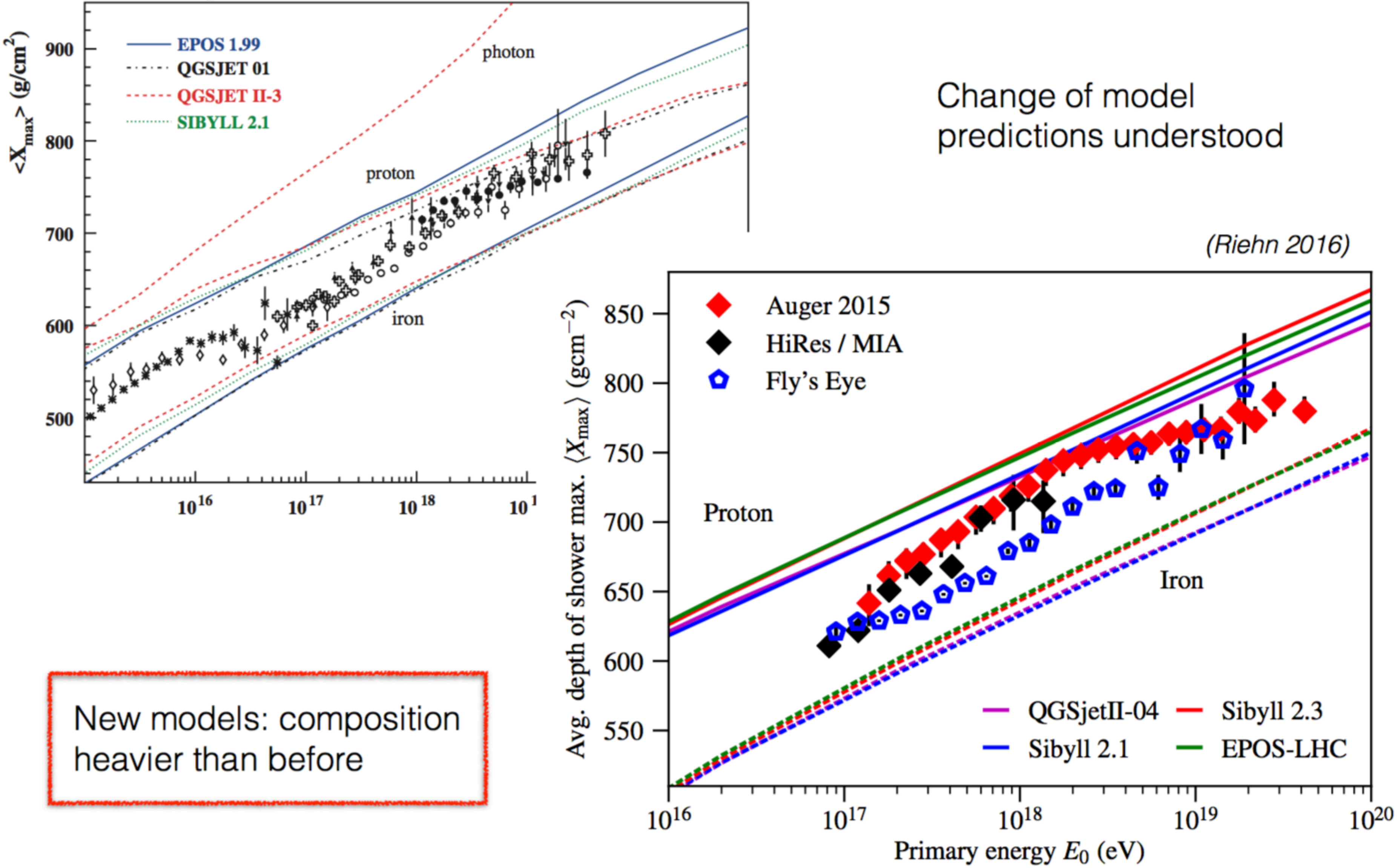
Number of muons on ground:



From D. D'Enterria

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

# + Second models tuning after the first LHC data (Sibyll 2.3)



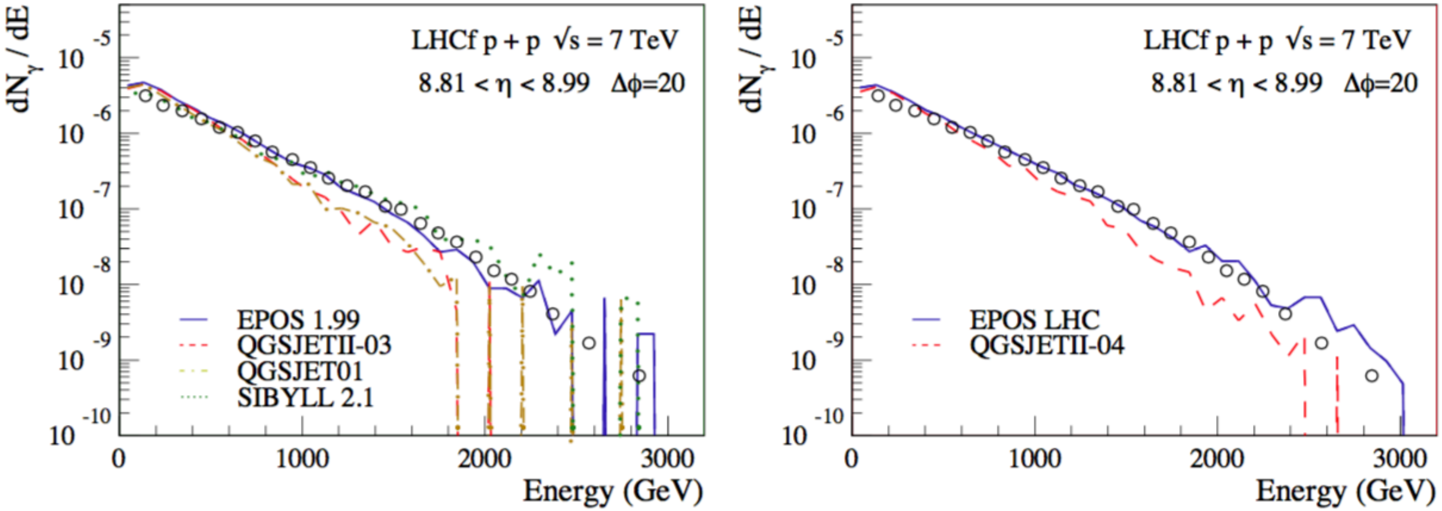
*(RE, Pierog, Heck, ARNPS 2011)*

*(Riehn 2016)*

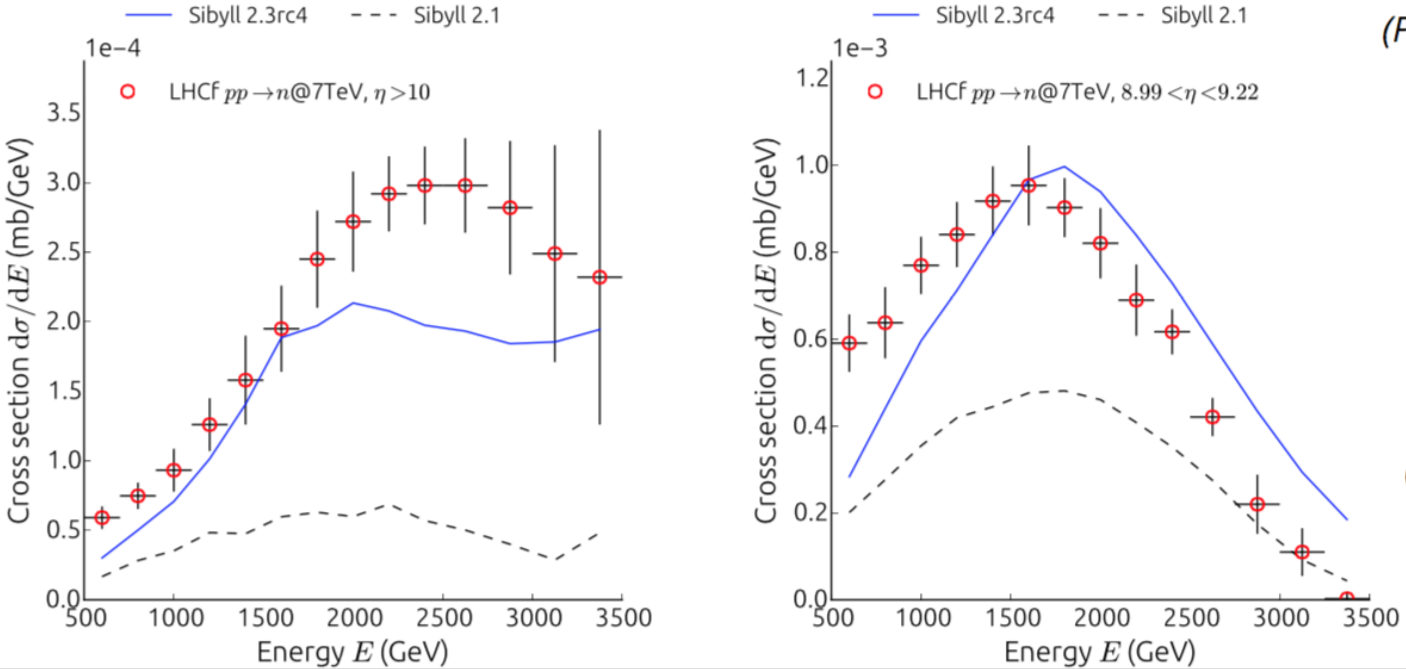
Change of model predictions understood

New models: composition heavier than before

# + But not everything is perfect….



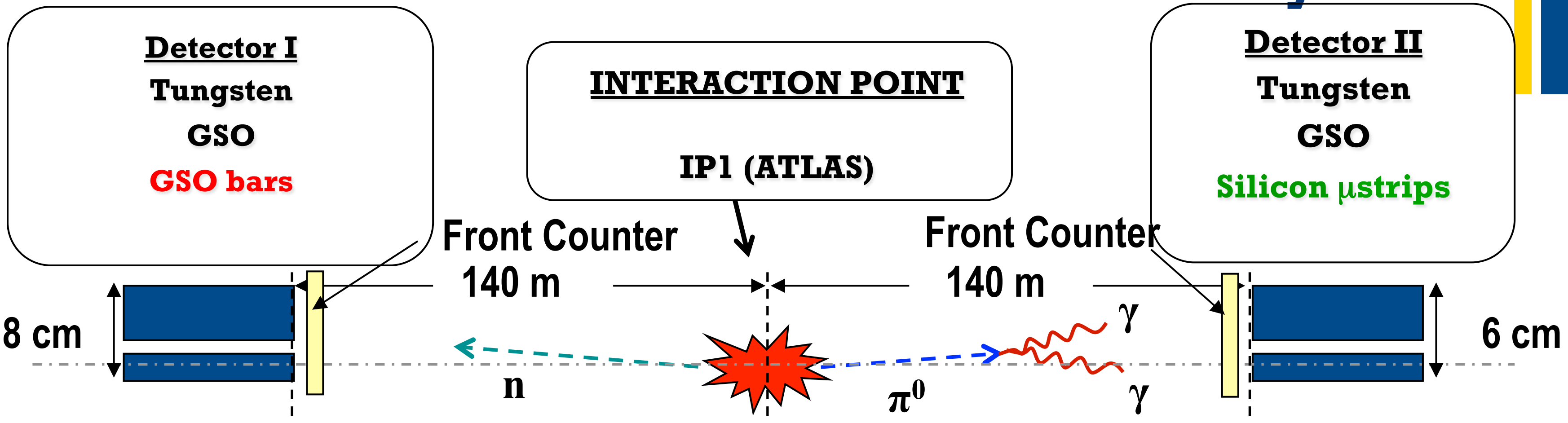
(Pierog 2014)



(Riehn 2015)

# + LHCf detector and performances

# + LHCf: location and detector layout

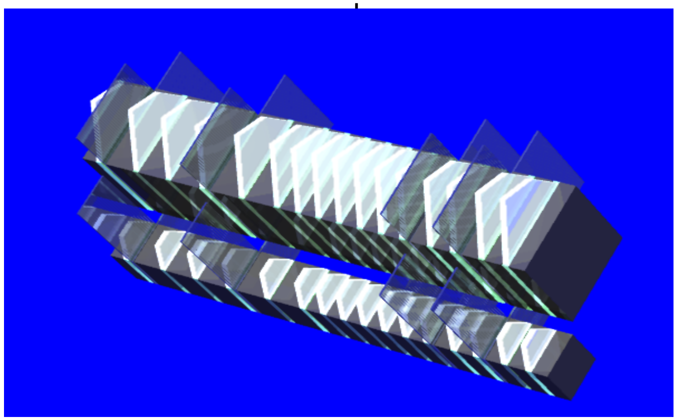


**Detector I**
Tungsten
GSO
GSO bars

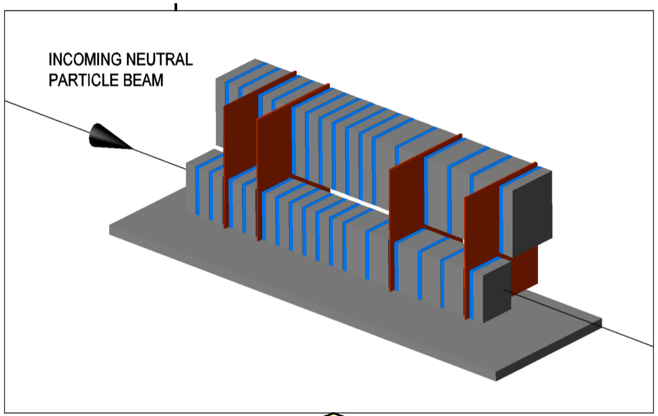
**INTERACTION POINT**

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 μm (Arm#1)
40 μm (Arm#2)
Pseudo-rapidity range:
$\eta$ > 8.7 @ zero Xing angle
$\eta$ > 8.4 @ 140urad

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

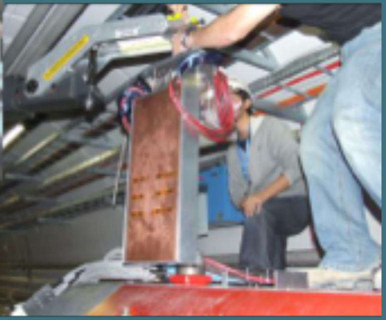
# + A brief LHCf photo-history

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

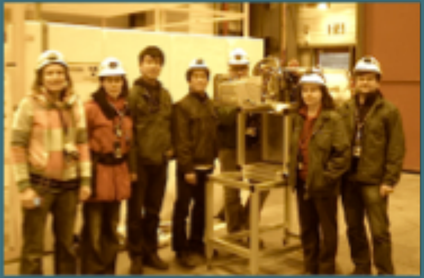
Jul 2006
construction

Aug 2007
SPS beam test

Jan 2008
Installation
Sept
1st LHC beam

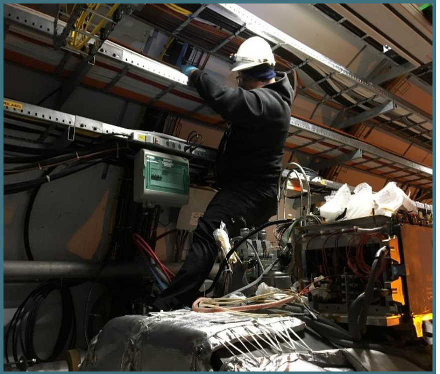


Dec- Jul 2010
0.9TeV& 7TeV pp
Detector removal



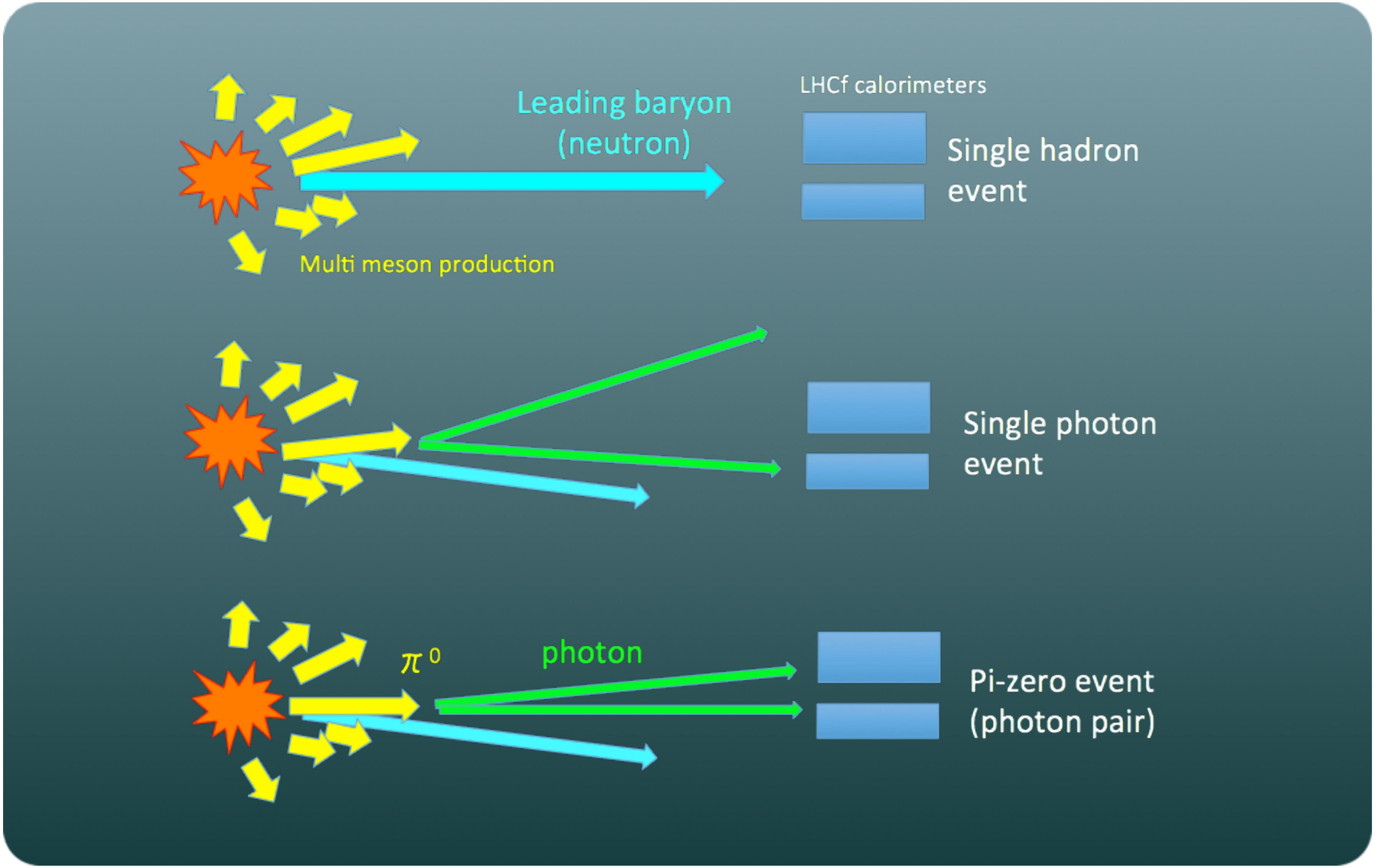
Dec 2012- Feb 2013
5TeV/n pPb, 2.76TeVpp
(Arm2 only)
Detector removal

May-June 2015
13 TeV dedicated pp
Detector removal

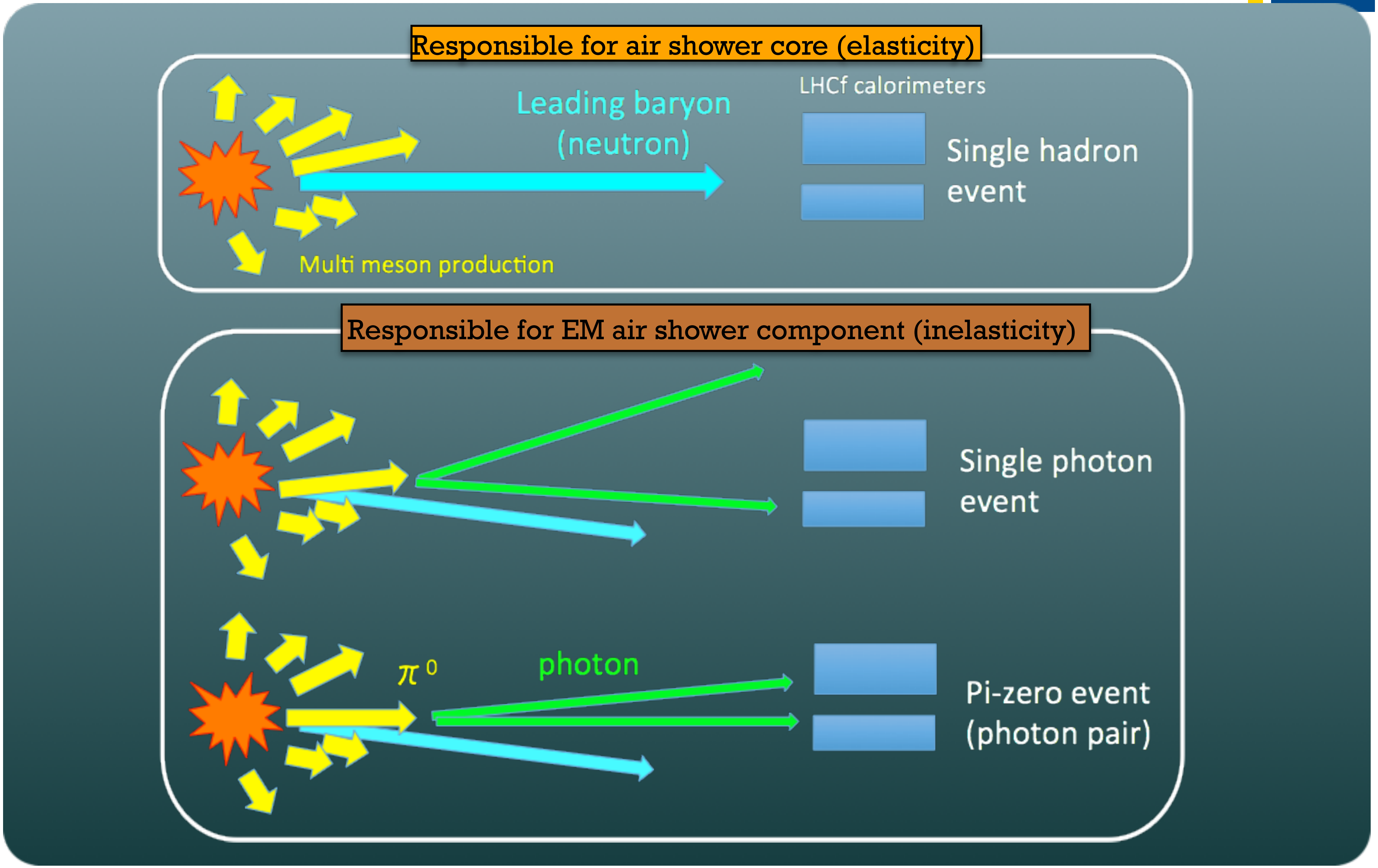


November 2016
8 Tev p-Pb

# + Event category in LHCf

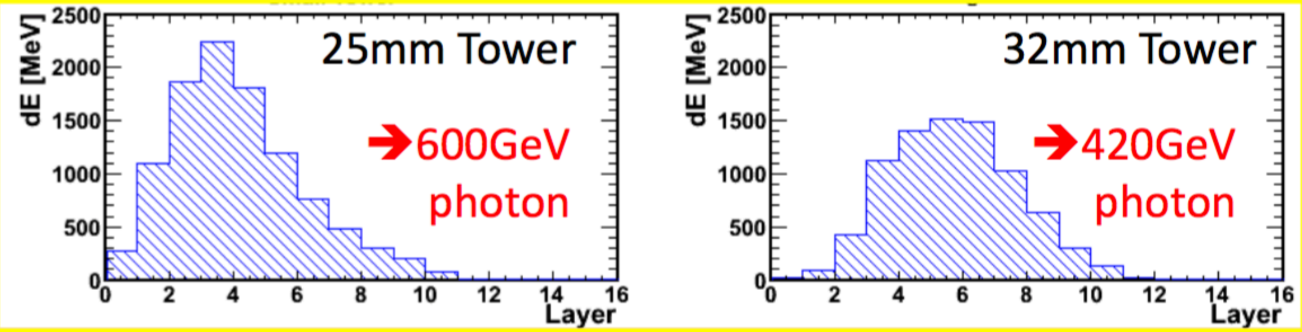


# Event category in LHCf



# + $\pi^0$ reconstruction

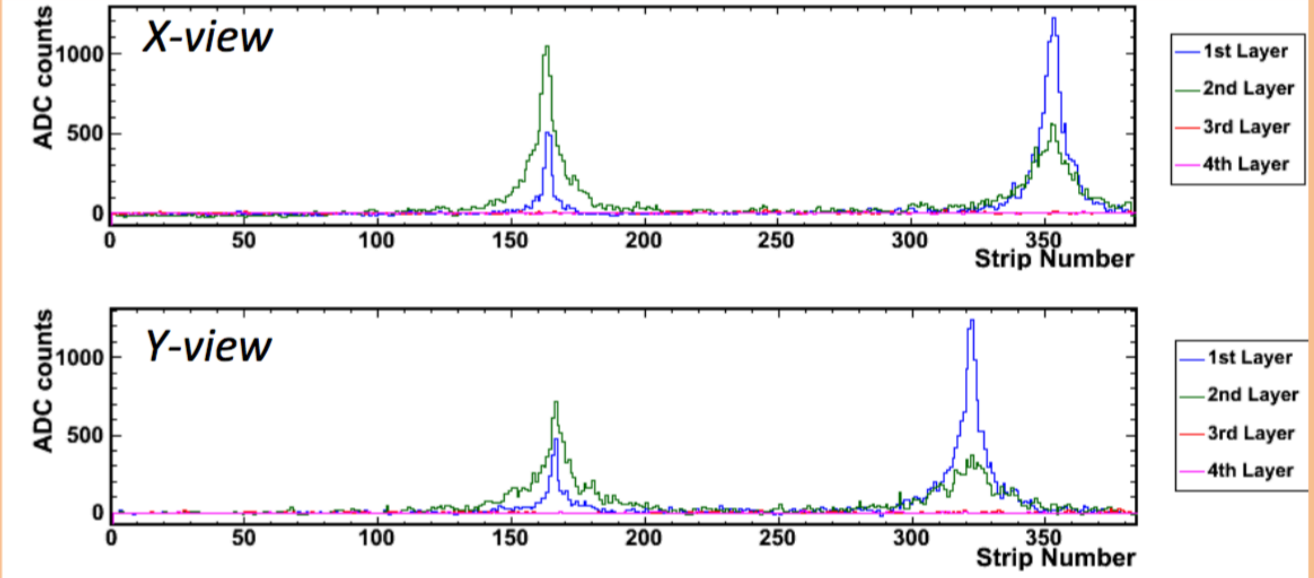
Longitudinal development measured by scintillator layers



Determination of **energy** from total energy release

**PID** from shape

Transverse profile measured by silicon $\mu$–strip layers



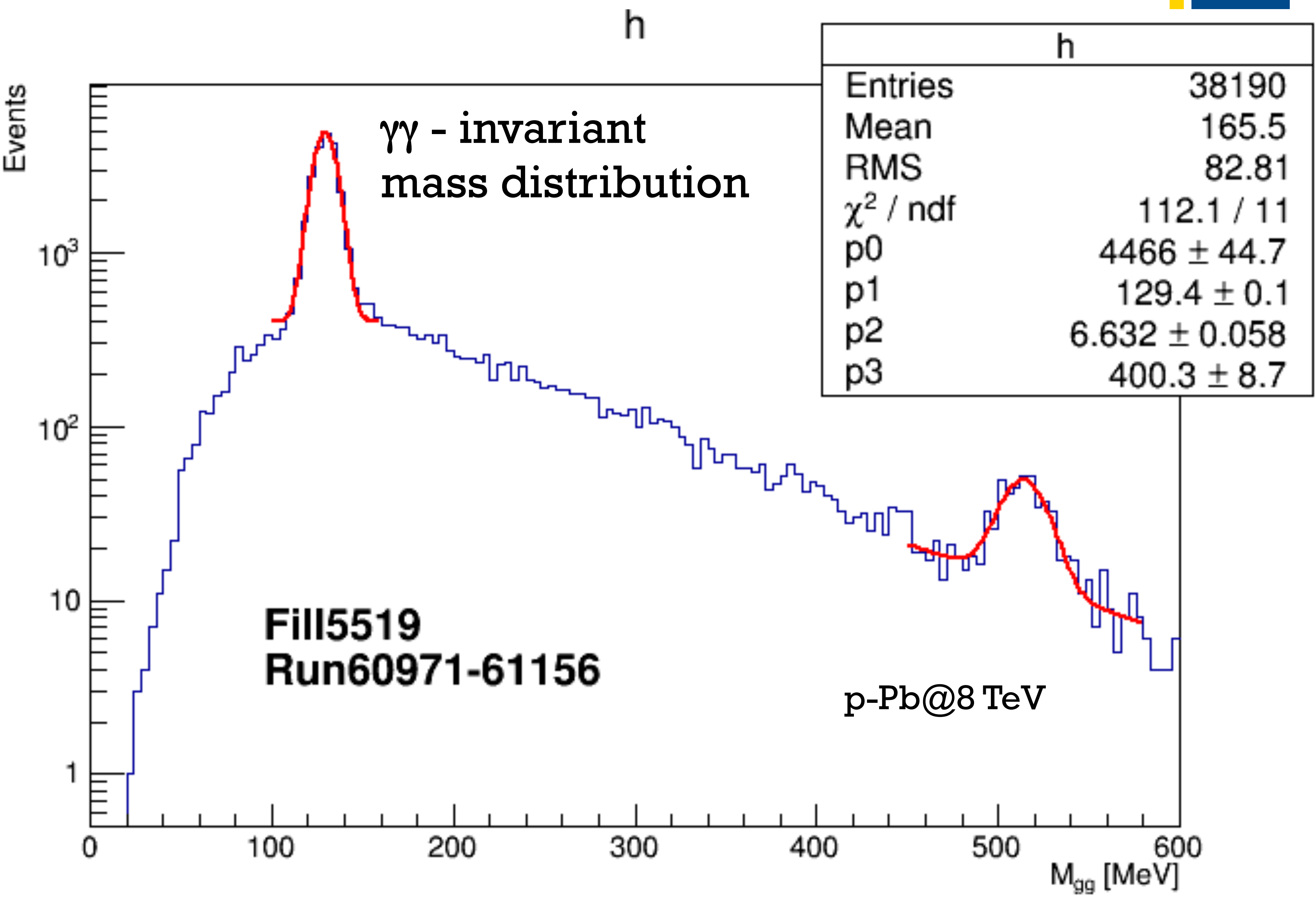
Determination of the **impact point**

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

Identification of **multiple hit**

Reconstruction of $\pi^0$ mass: $M_{0} = \sqrt{E_1 E_2} \times$

# + γγ invariant mass distribution



γγ - invariant mass distribution

**Fill5519**
**Run60971-61156**

p-Pb@8 TeV

+

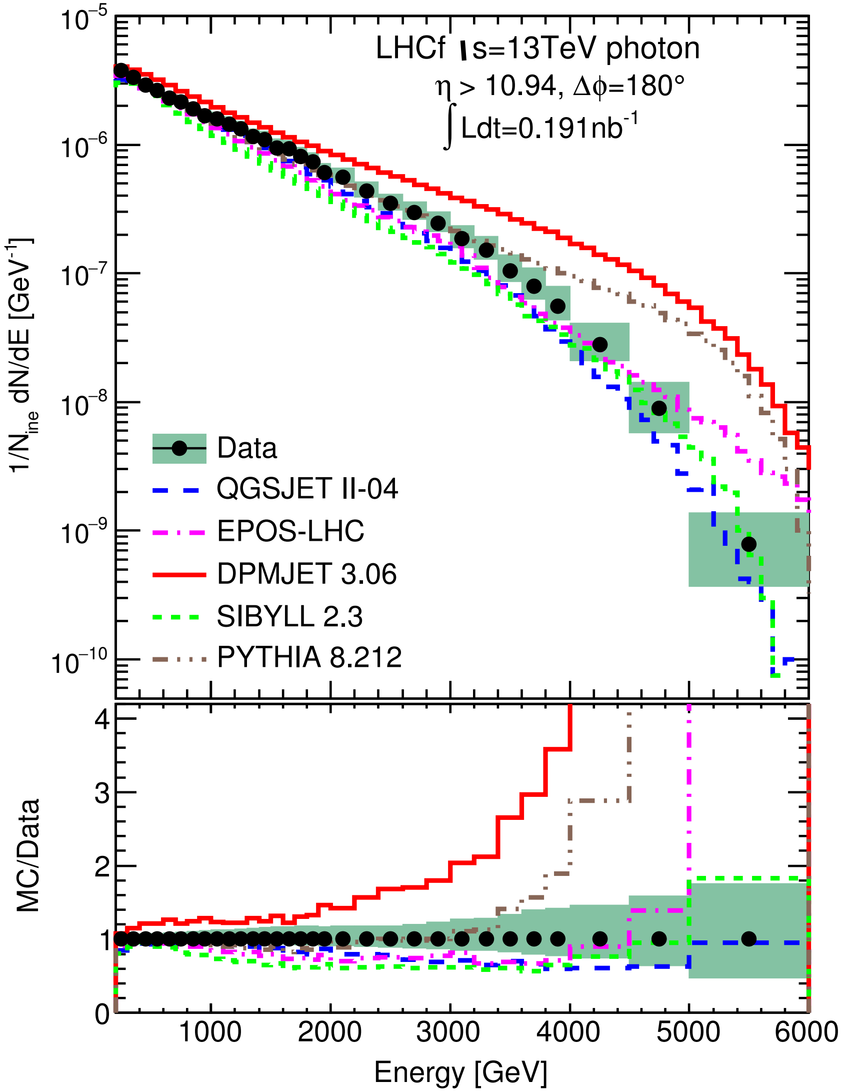
# LHCf physics results

# LHCf Data Taking and Analysis matrix

| | Proton $E_{LAB}$ (Ev) | Photon (EM shower) | Neutron (hadron shower) | $\pi^0$ (EM shower) | |
|---|---|---|---|---|---|
| Test beam at SPS | | NIM. A 671, 129–136 (2012)<br>**JINST 12P03023(2017)** | JINST 9 P03016 (2014) (2014)P03016 | | |
| p-p at 900GeV | $4.3\text{x}10^{14}$ | Phys. Lett. B 715, 298-303 (2012) | | | Run1 |
| p-p at 7TeV | $2.6\text{x}10^{16}$ | Phys. Lett. B 703, 128–134 (2011) | Phys. Lett. B 750, 360-366 (2015) | Phys. Rev. D 86, 092001 (2012)+<br>Phys. Rev. D 94, 032007(2016) Type II | |
| p-p at 2.76TeV | $4.1\text{x}10^{15}$ | | | Phys. Rev. C 89, 065209 (2014)+<br>Phys. Rev. D 94, 032007(2016) Type II | Run2 |
| p-Pb at 5.02TeV | $1.3\text{x}10^{16}$ | | | | |
| p-p at 13TeV | $9.0\text{x}10^{16}$ | **Submitted to PLB** | **Preliminary results** | | Run3 |
| p-Pb at 8.1 TeV | $3.6\text{x}10^{16}$ | Run completed in November 2016 | | | Run4 |

# $\gamma$ energy spectra at 13 TeV

**$\eta$ >10.94**



**QGSJET II-04**: overall good agreement

**EPOS-LHC**: overall good agreement

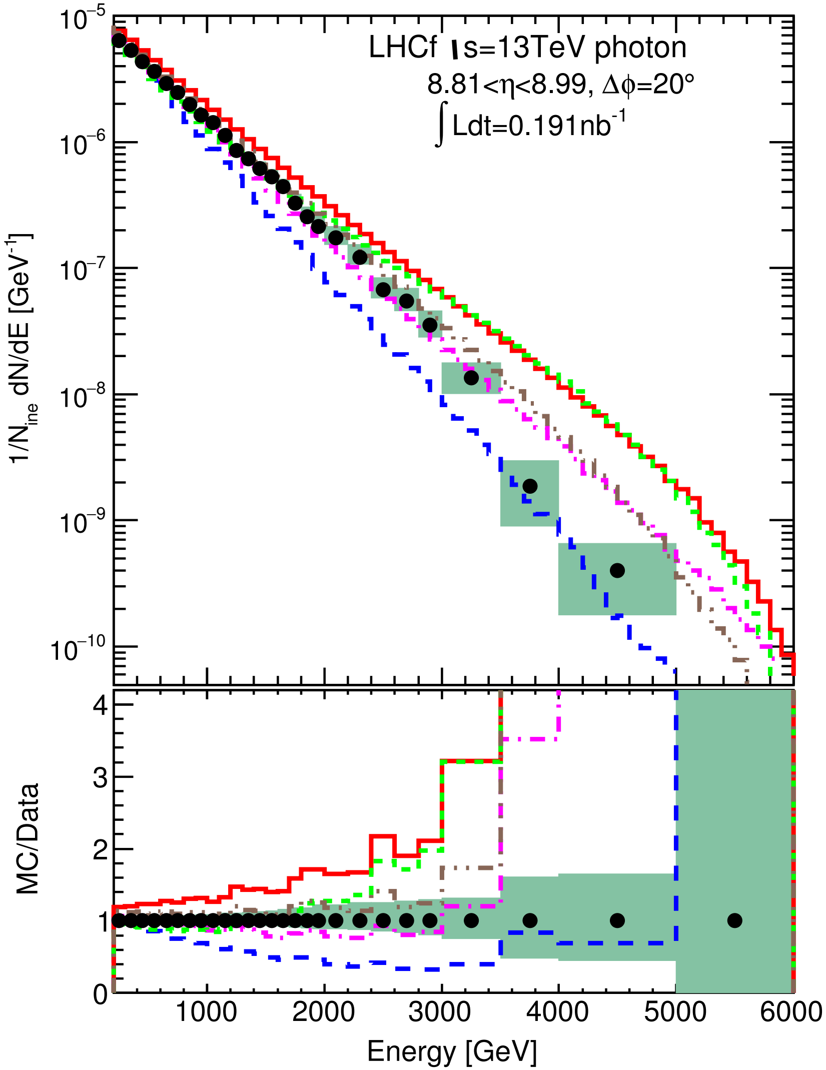
**DPMJET 3.06**: overall higher flux

**SIBYLL 2.3**: overall lower flux

**PYTHIA 8.212**: higher flux above 3 TeV

# + $\gamma$ energy spectra at 13 TeV

**$8.81< \eta <8.99$**



**QGSJET II-04**: overall lower flux

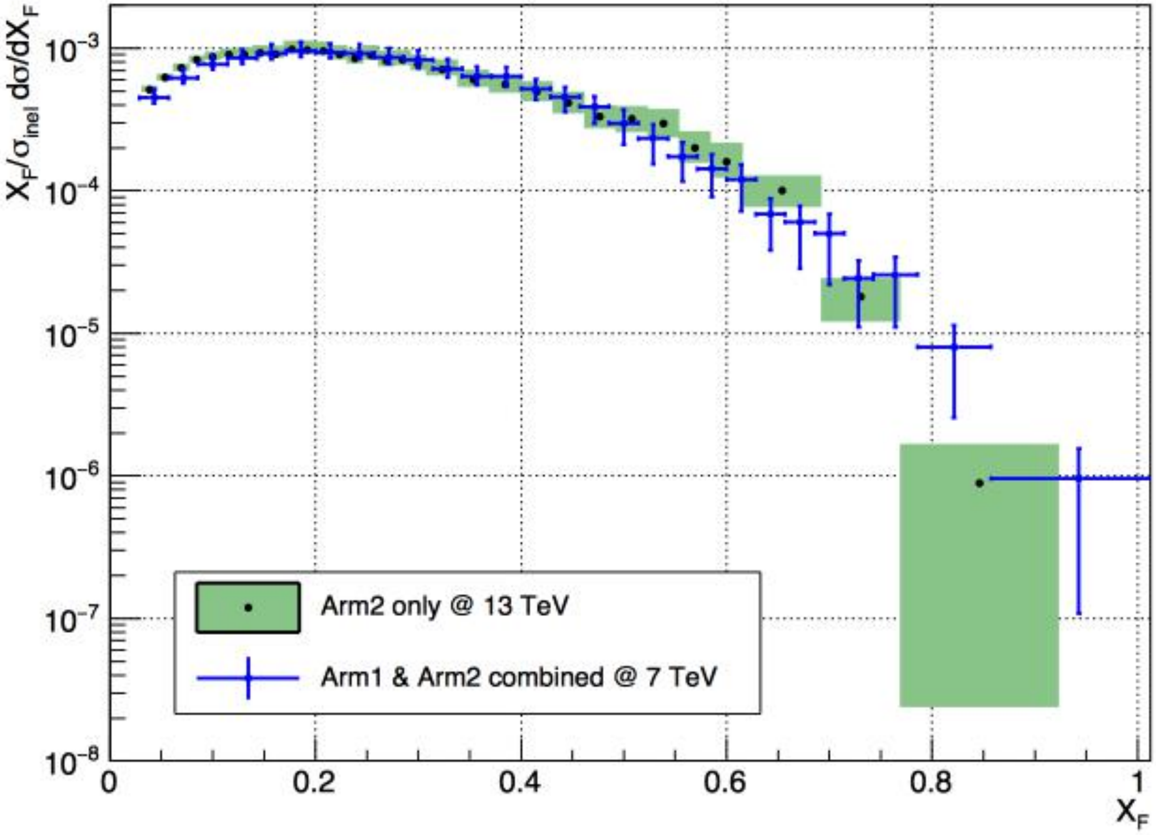
**EPOS-LHC**: higher flux above 3-4 TeV

**DPMJET 3.06**: overall higher flux

**SIBYLL 2.3**: higher flux above 2 TeV

**PYTHIA 8.212**: higher flux above 3 TeV

# + Photon spectra – Feynman Scaling



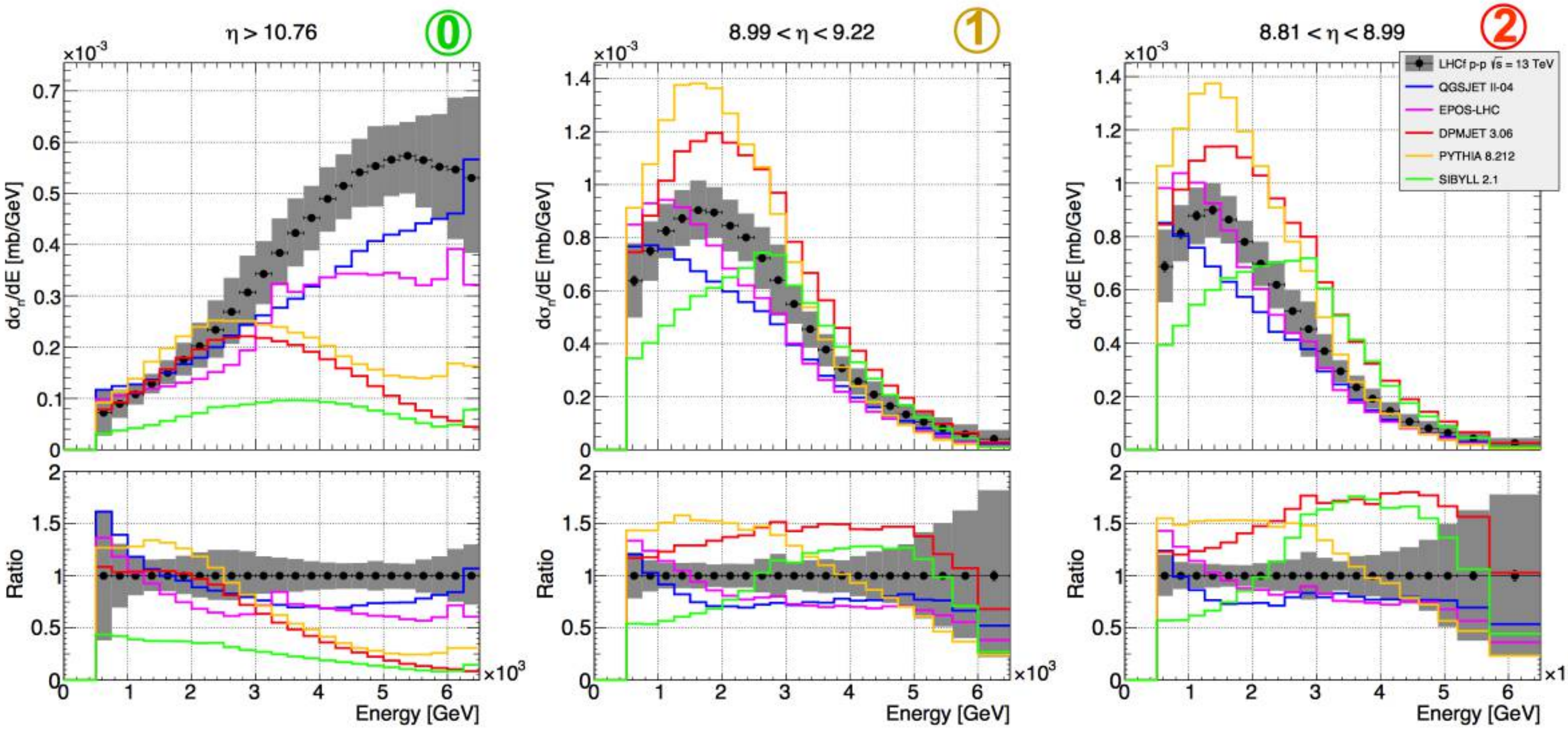
Feynman scaling: differential cross section as a function of $X_F$ independent of √s for $X_F$

Feynman scaling holds within systematic uncertainties

# + Preliminary ARM2 unfolded neutron spectra @ 13 TeV

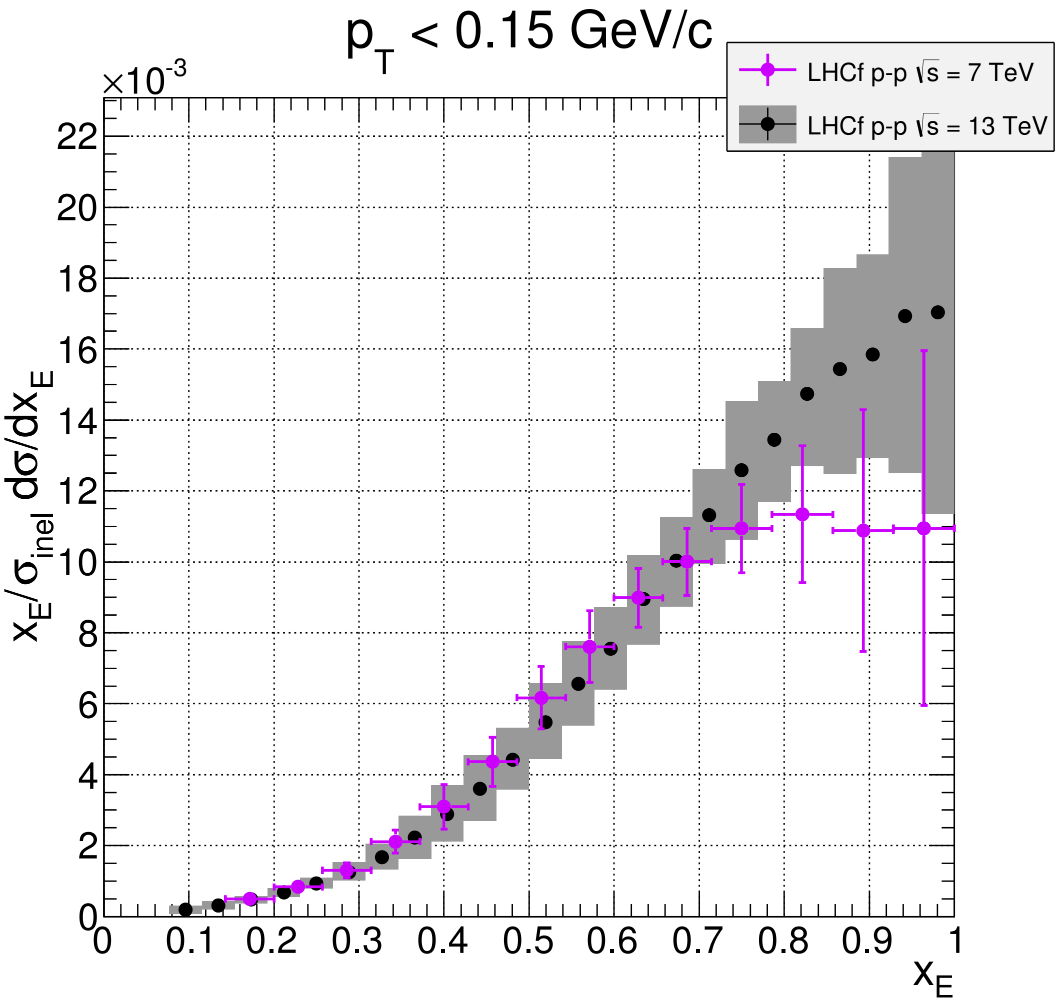
Differential production cross section

$$d\sigma_n/dE = \frac{dN(\Delta\eta,\Delta E)}{E}\,\frac{1}{L} \times \frac{2\pi}{d\varphi}$$



Only **QGSJET II-04** qualitatively reproduces behavior of data in η > 10.76
**EPOS-LHC** has similar shape in 8.81 < η < 9.22, but lower yield

# Feynman scaling in neutron production cross-section

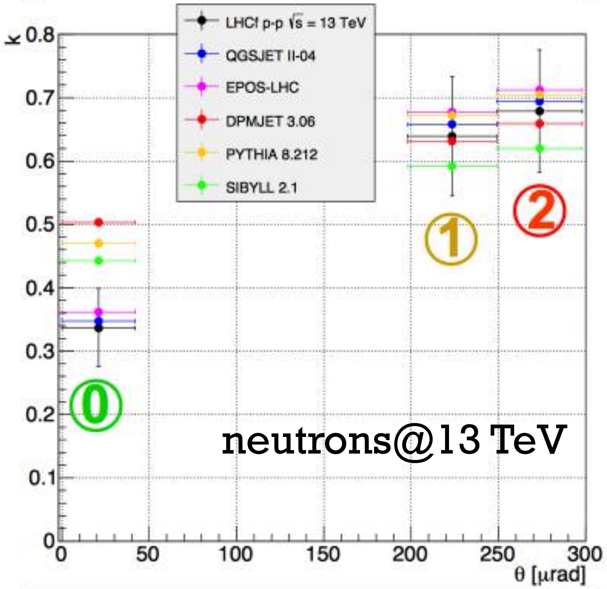


Feynman scaling hypothesis holds within the error bars

Consistency is good especially in the region $0.2 < x_F < 0.75$

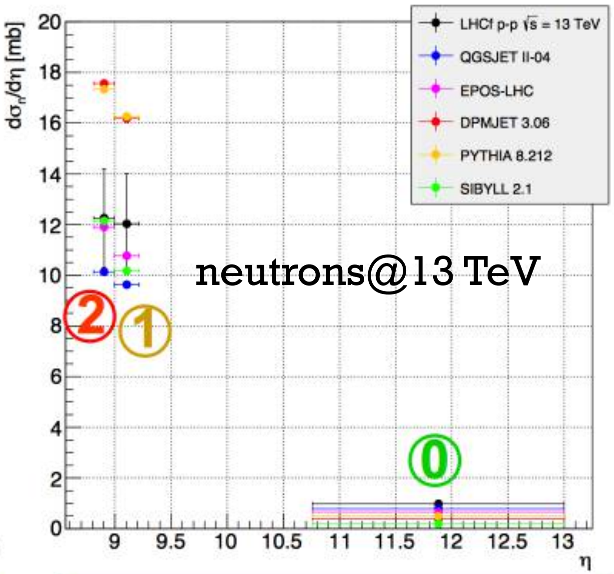
# + Measurement of interesting quantities for CR Physics

## Inelasticity VS θ



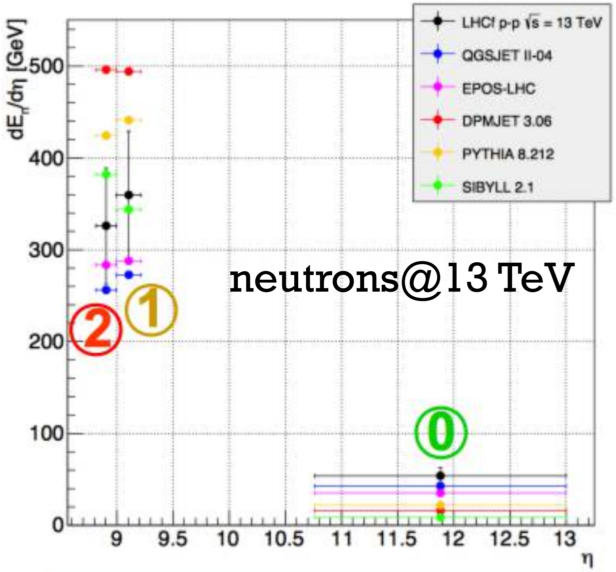
All models overestimate inelasticity in the most forward region even if **QGSJET II-04** and **EPOS-LHC** are consistent within the error bars

## dσ/dη VS η



**EPOS-LHC** and **SIBYLL 2.1** reproduce enough well the measured total differential cross section except in the most forward region

## dE/dη VS η

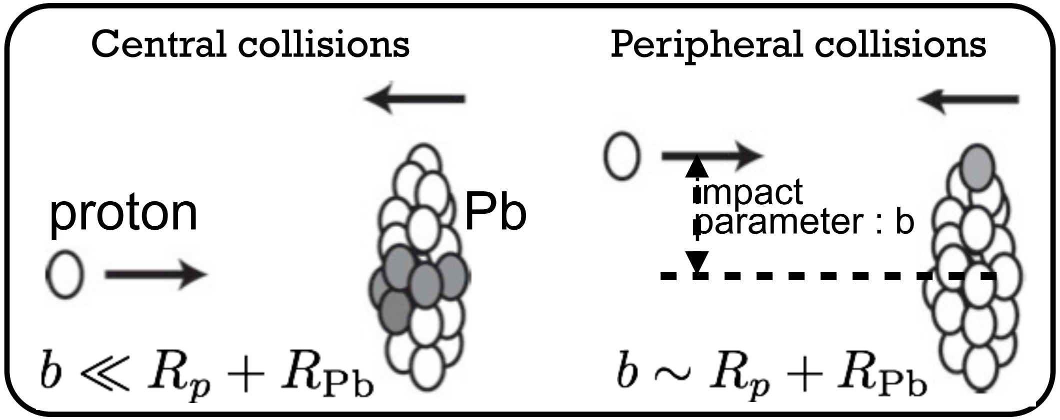


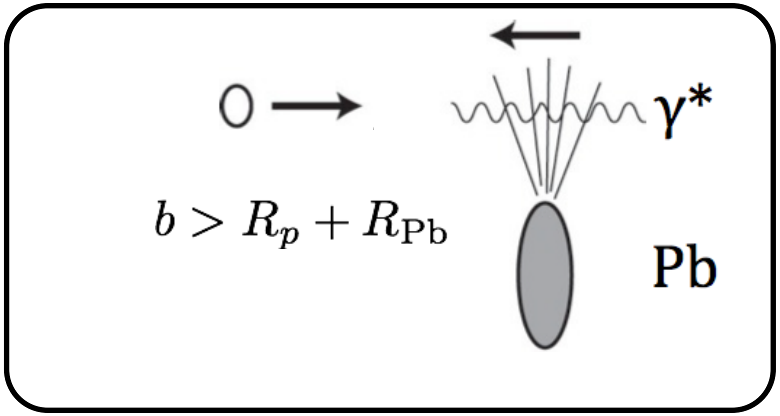
Where the energy flux is high, the agreement between experimental measurements and **SIBYLL 2.1**/**EPOS-LHC** is quite good

# LHCf @ pPb 5.02 TeV: $\pi^0$ analysis

**(Soft) QCD :**
central and peripheral collisions

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





proton
rest frame

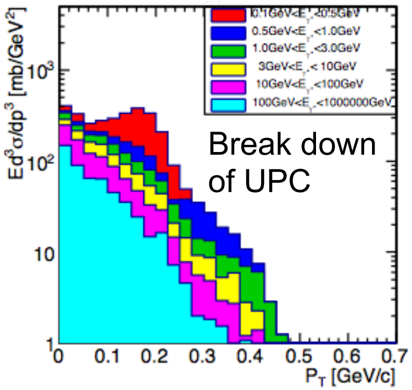
Momentum distribution of the UPC induced secondary particles is estimated as

1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation.
2. photon-proton collisions are simulated by the SOHIA model ($E_\gamma$ > pion threshold).
3. produced mesons and baryons by $\gamma$-p collisions are boosted along the proton beam.

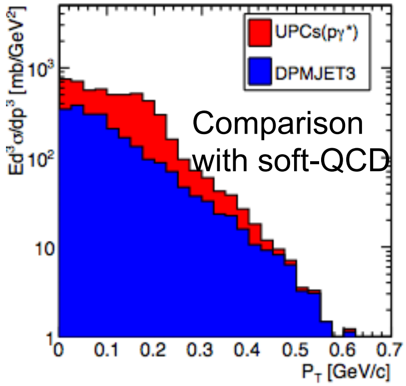
Dominant channel to forward $\pi^0$ is

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

About half of the observed $\pi^0$ may originate in UPC, another half is from soft-QCD.

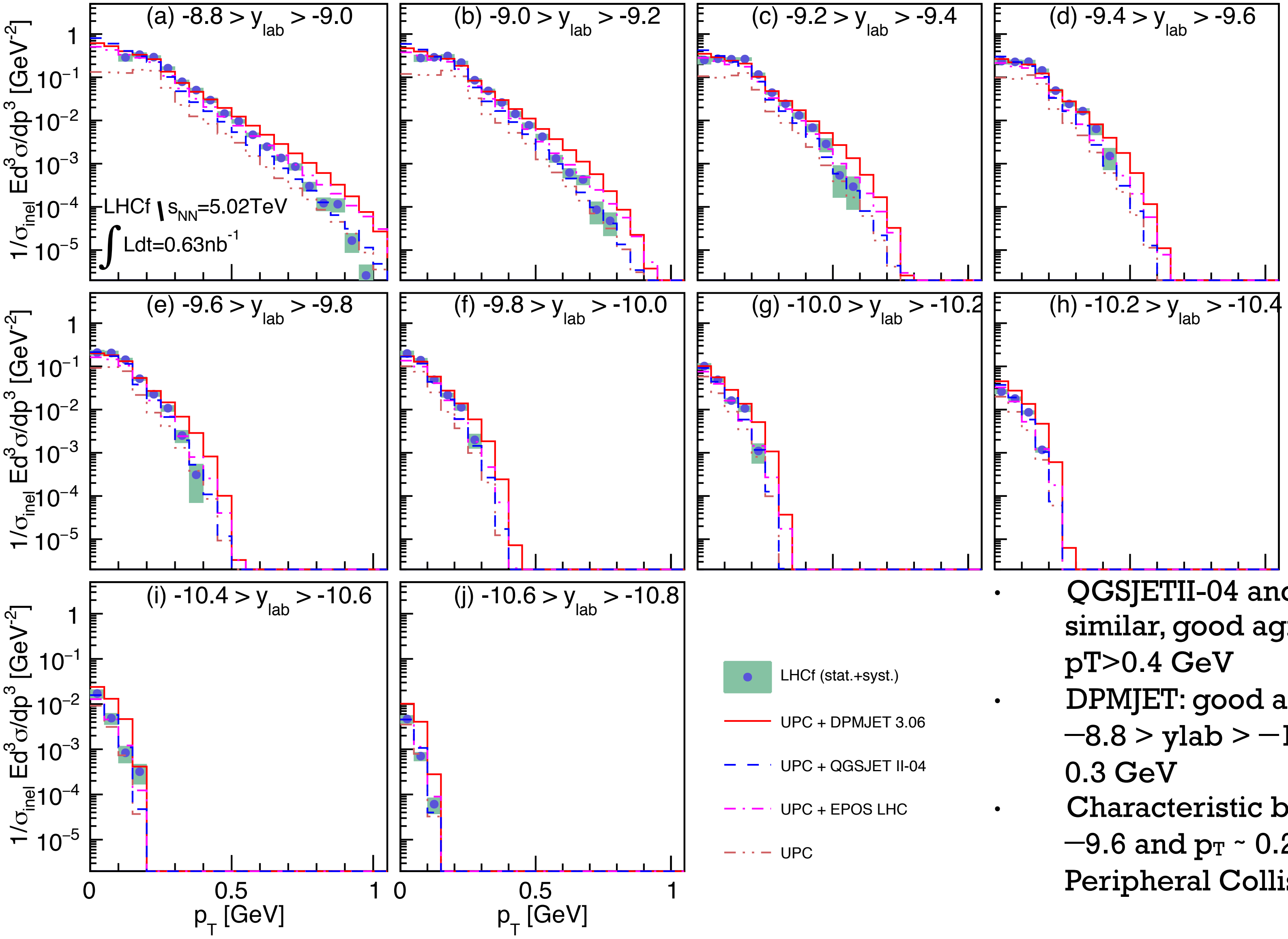


Break down of UPC



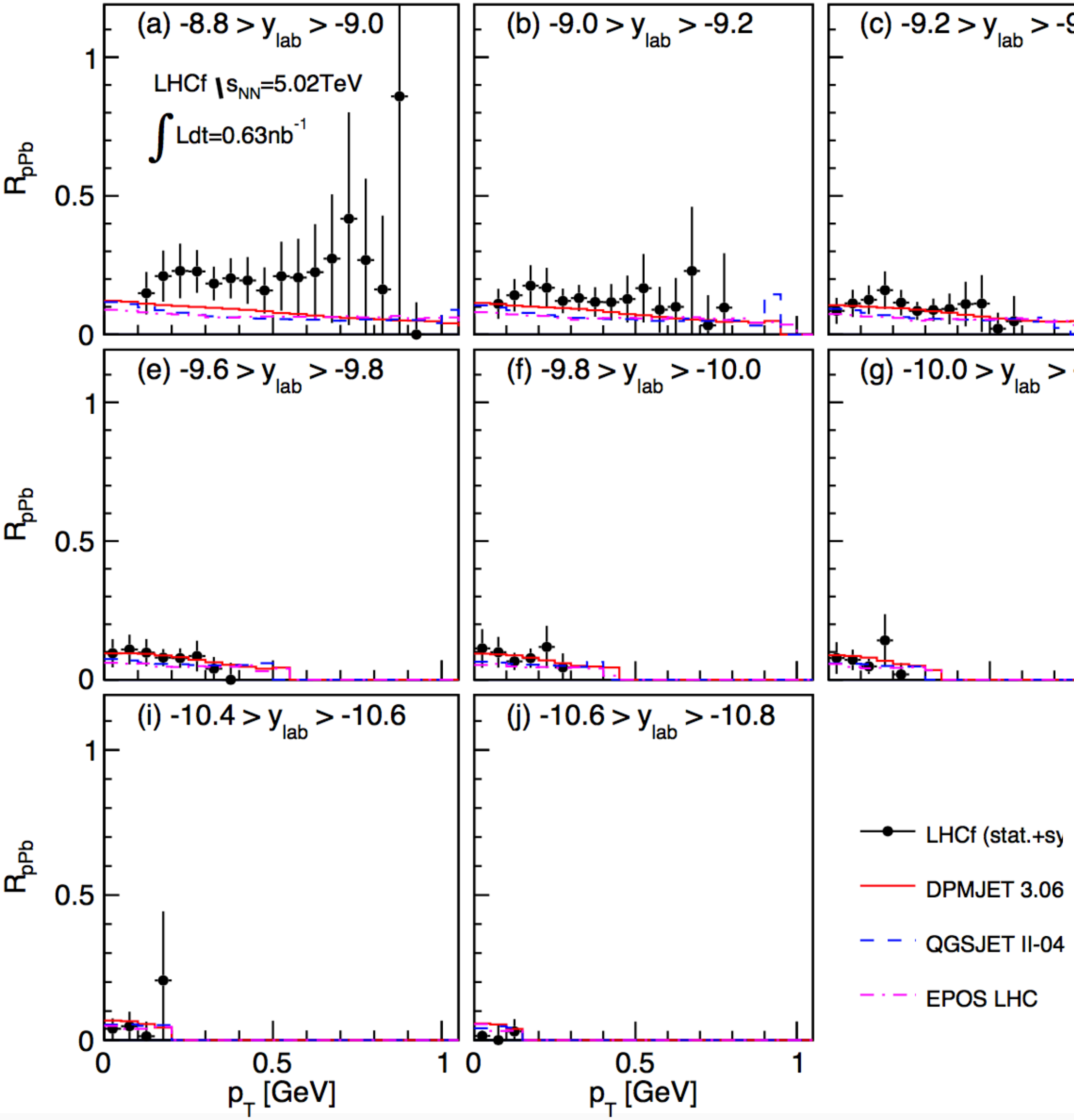
Comparison with soft-QCD

# + LHCf @ pPb 5.02 TeV: $\pi^0$ $p_T$ spectra



- 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

# + Nuclear modification factor



$$R_{\mathrm{pPb}} \equiv \frac{\sigma_{\mathrm{inel}}^{\mathrm{pp}}}{\langle N_{\mathrm{coll}} \rangle \sigma_{\mathrm{inel}}^{\mathrm{pPb}}} \frac{Ed^3\sigma^{\mathrm{pPb}}/dp^3}{Ed^3\sigma^{\mathrm{pp}}/dp^3},$$

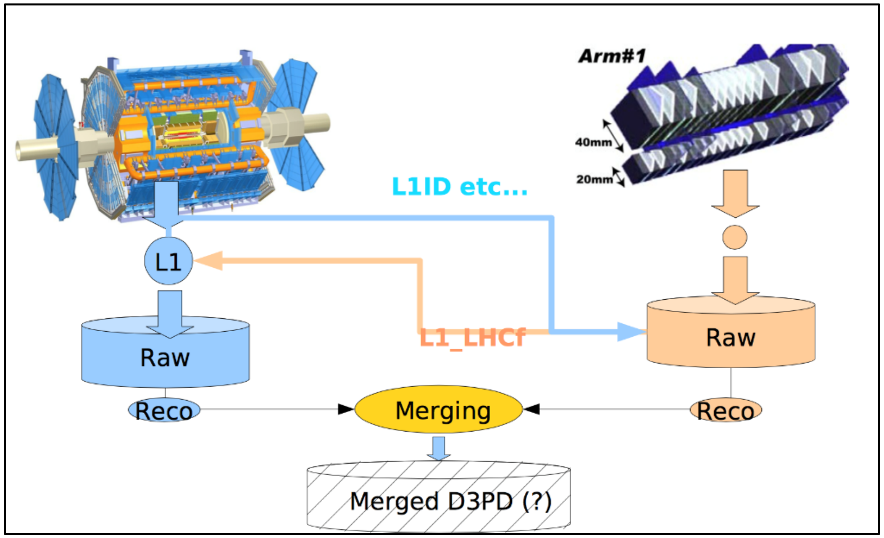
Strong suppression of the $\pi^0$ production from the nuclear target relative to that from the nucleon target.

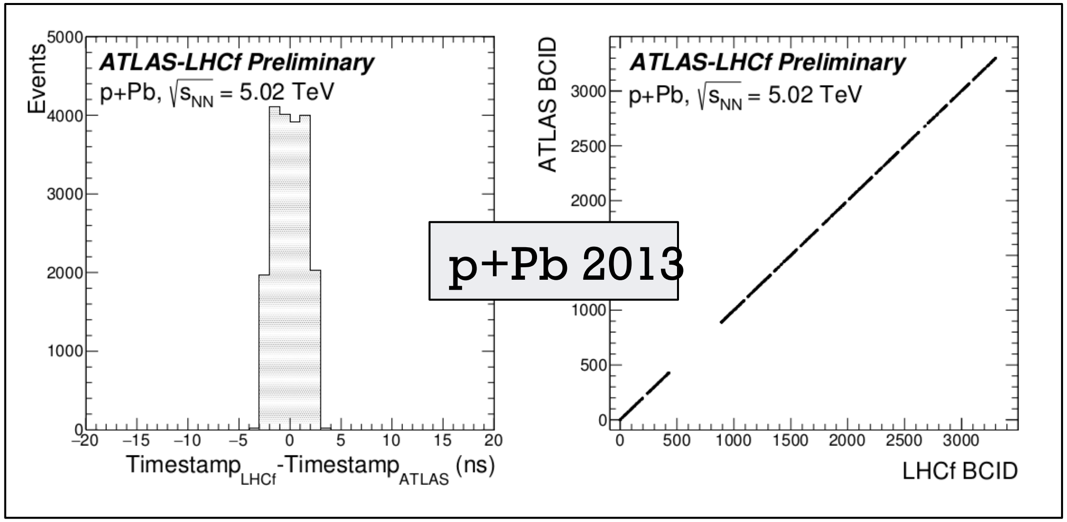
+

# LHCf & ATLAS

# + ATLAS-LHCf combined data taking

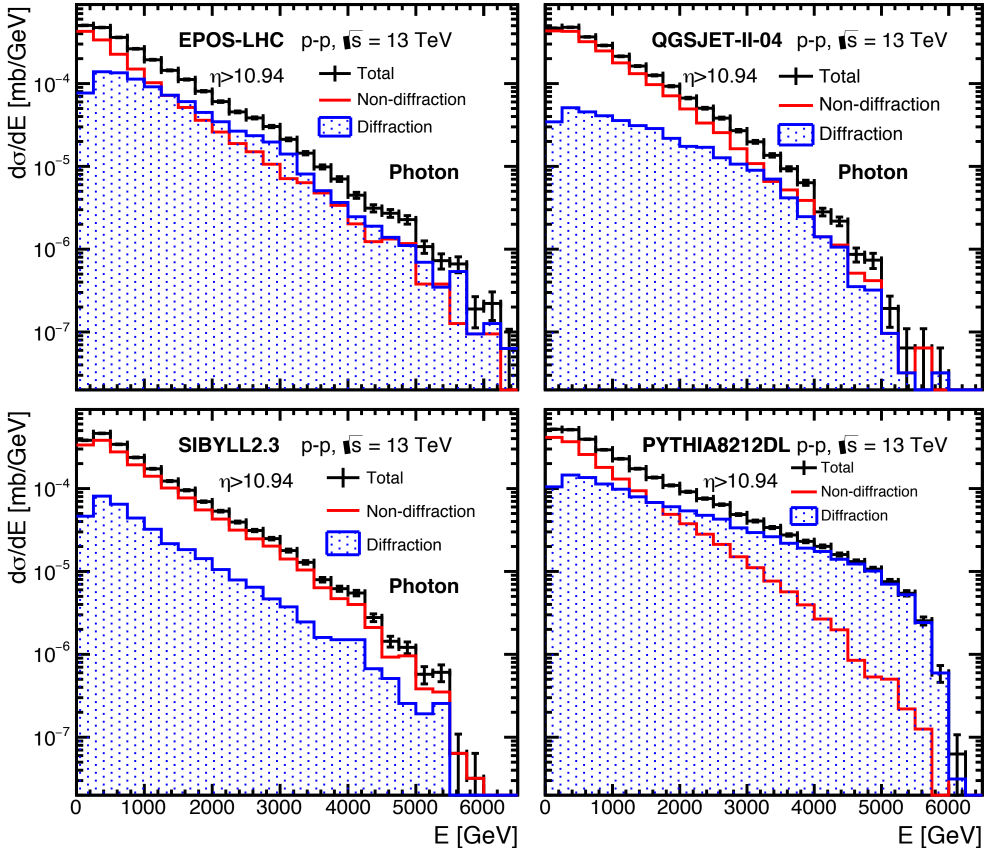
- Trigger sharing with ATLAS at ~100-500 Hz in p+p (500 Hz in 2016 p+Pb)
- Off-line event matching
- Internal note (p+Pb 2013)
  - **ATL-PHYS-PUB-2015-038**
- Important to separate the contributions due to diffractive and non-diffractive collisions
  - It makes more easy improving the hadronic interaction models





# + Diffractive studies

- MC studies
  - Contributions on forward photon/neutron spectra from diffractive/non-diffractive collisions.
  - Event-selection by the central particle production to separate these events



Very forward photon energy spectra predicted by four models with **total**/**diffractive**/**non-diffractive**

- Total: Very similar spectra in EPOS, QGSJET and SIBYLL (LHCf alone)
- Diffractive/Non-diffractive: Very big difference between models (ATLAS-LHCf)

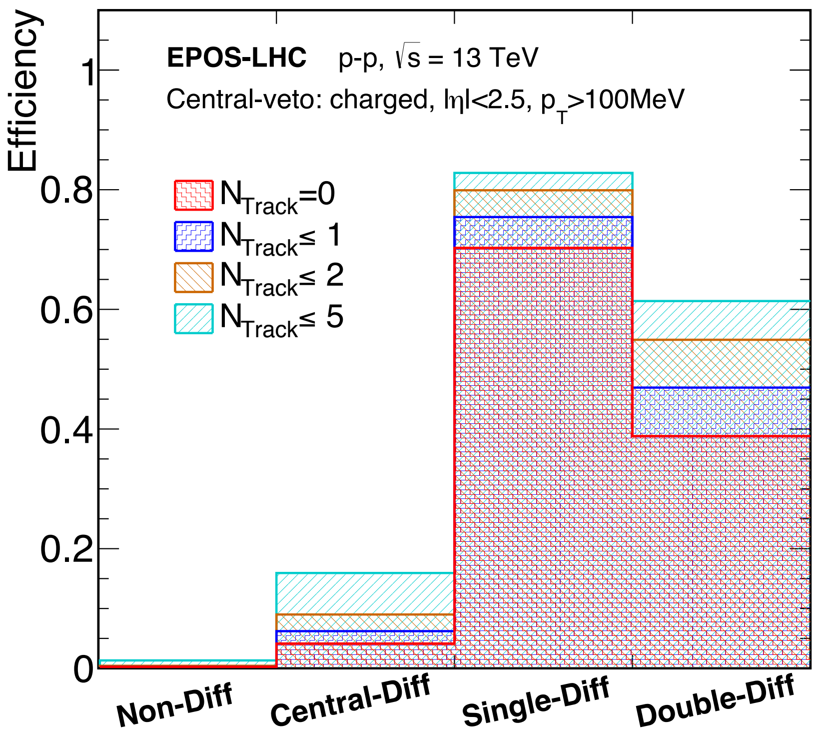
Zhou et al., Eur.Phys.J. C77 (2017) no.4, 212

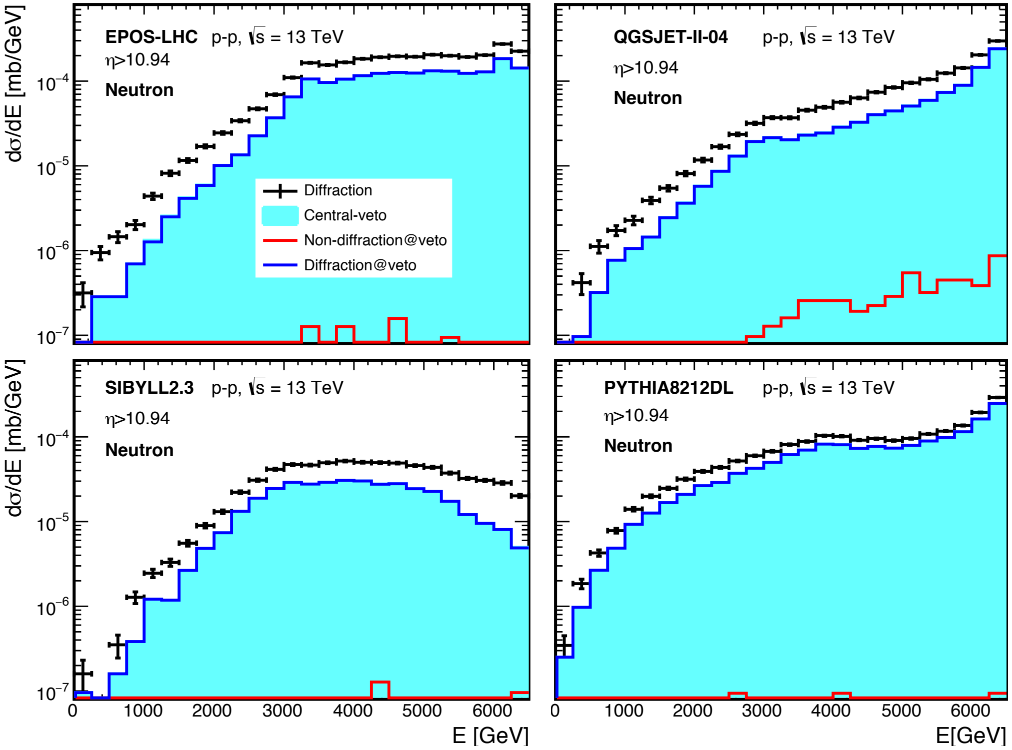
# Diffractive studies

- Event selection for Diffractive/Non-diffractive by using $N_{\text{charged}}$ with $p_T$>100MeV in $|\eta|$<2.5

By using ATLAS-tracker information,
We can separate diffractive/non-diffractive events with high efficiency and purity

Expected efficiencies

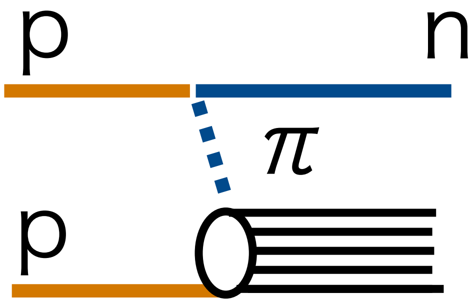




# + Physics cases with Atlas jointly taken data

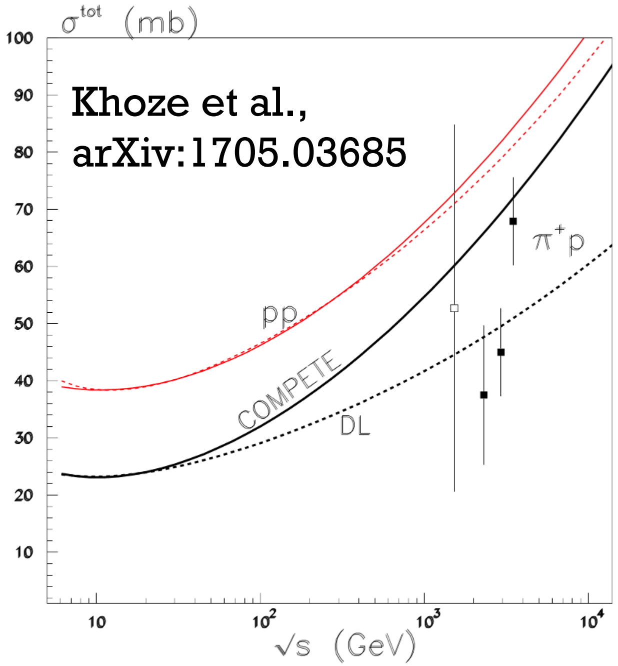
- In p+p collisions
  - Forward spectra of Diffractive/ Non-diffractive events
  - Measurement of proton-π collisions

Both are important for precise-understanding of CR air shower development



*p-π measurement at LHC*

Leading neutron can be tagged by LHCf detectors
-> total cross section
multiplicity measurement



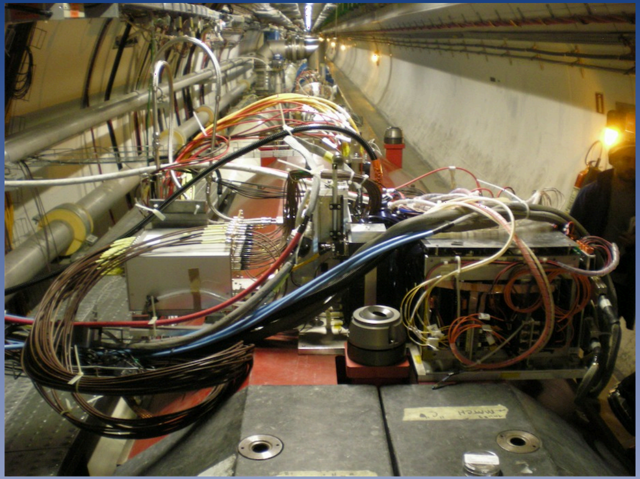
Khoze et al., arXiv:1705.03685

- In p+Pb collisions
  - Measurement of UPC in the forward region.

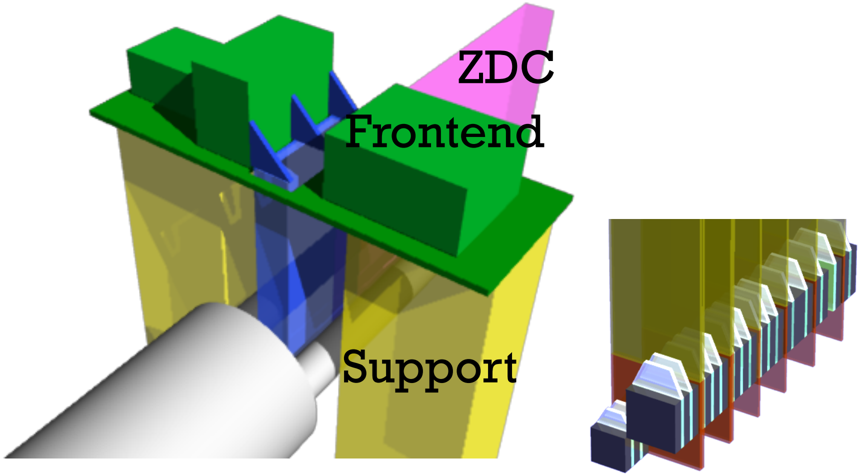
# The future….

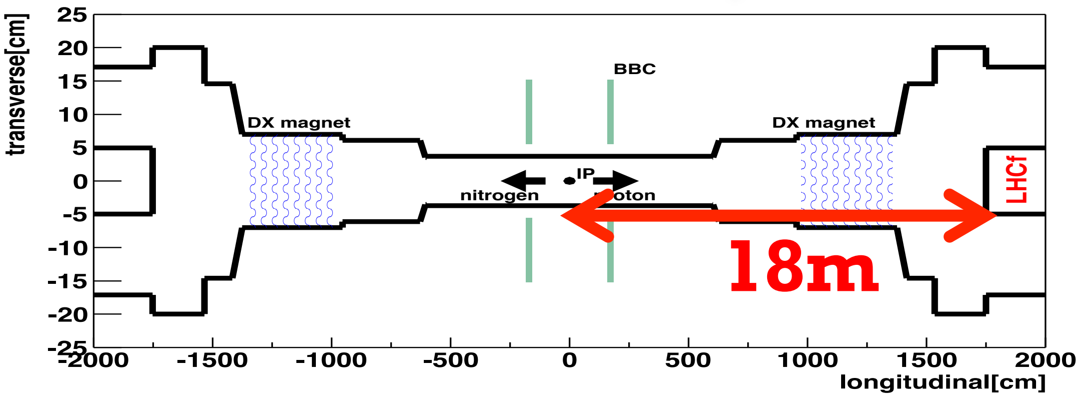
# + The future @ RHIC: From the Large Hadron Collider to the Longisland Hadron Collider

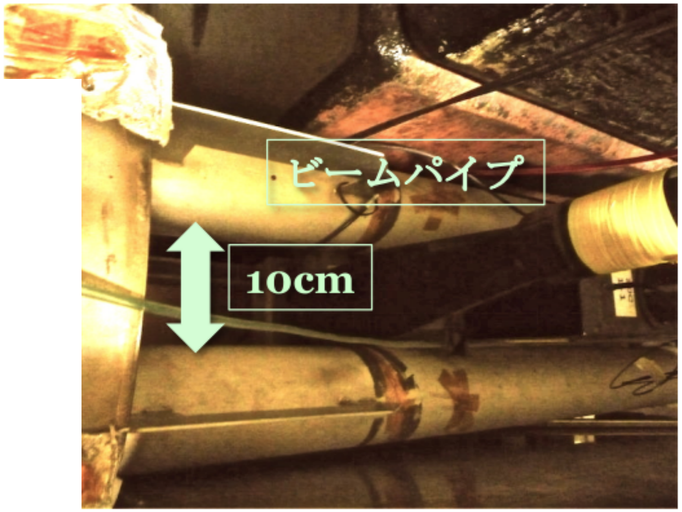
LHCf Arm2 detector in the LHC tunnel



Schematic view of the RHICf installatio

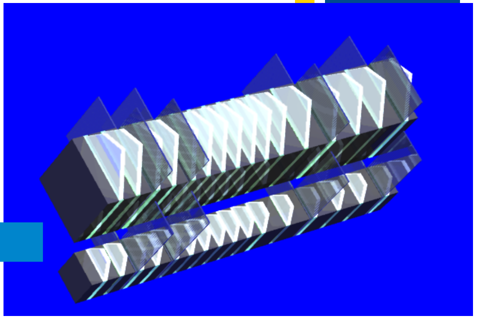




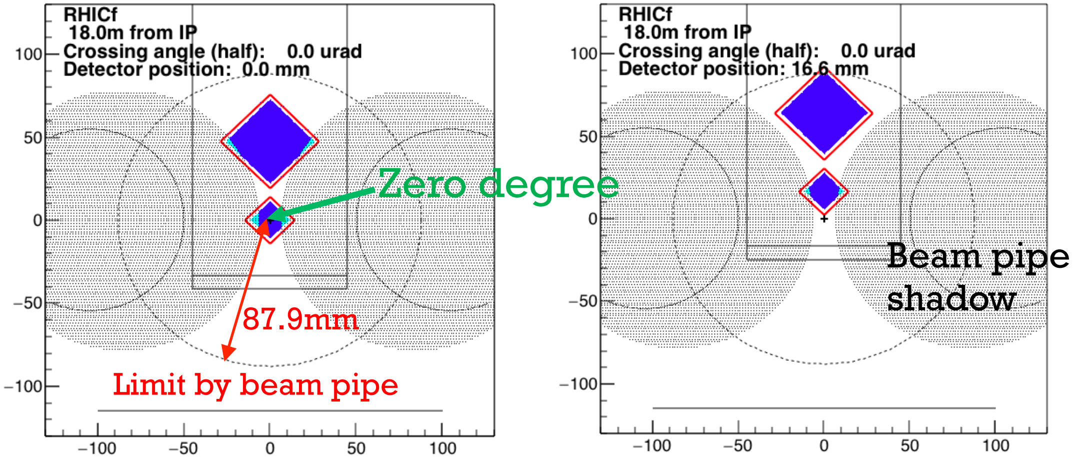


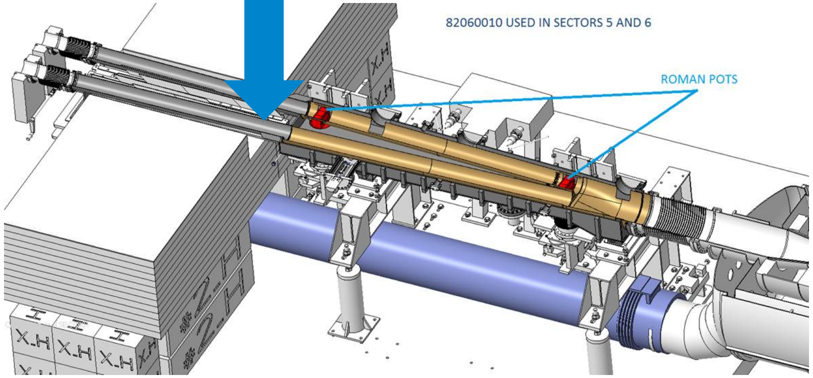
# + RHICf detector acceptance STAR IP

Compact double calorimeters (20mmx20mm and 40mmx40mm)

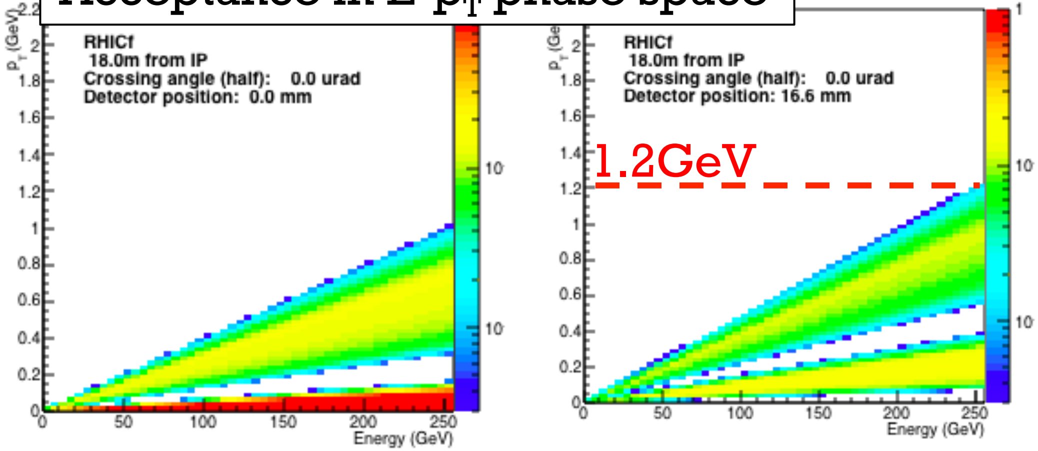


Cross section view from IP





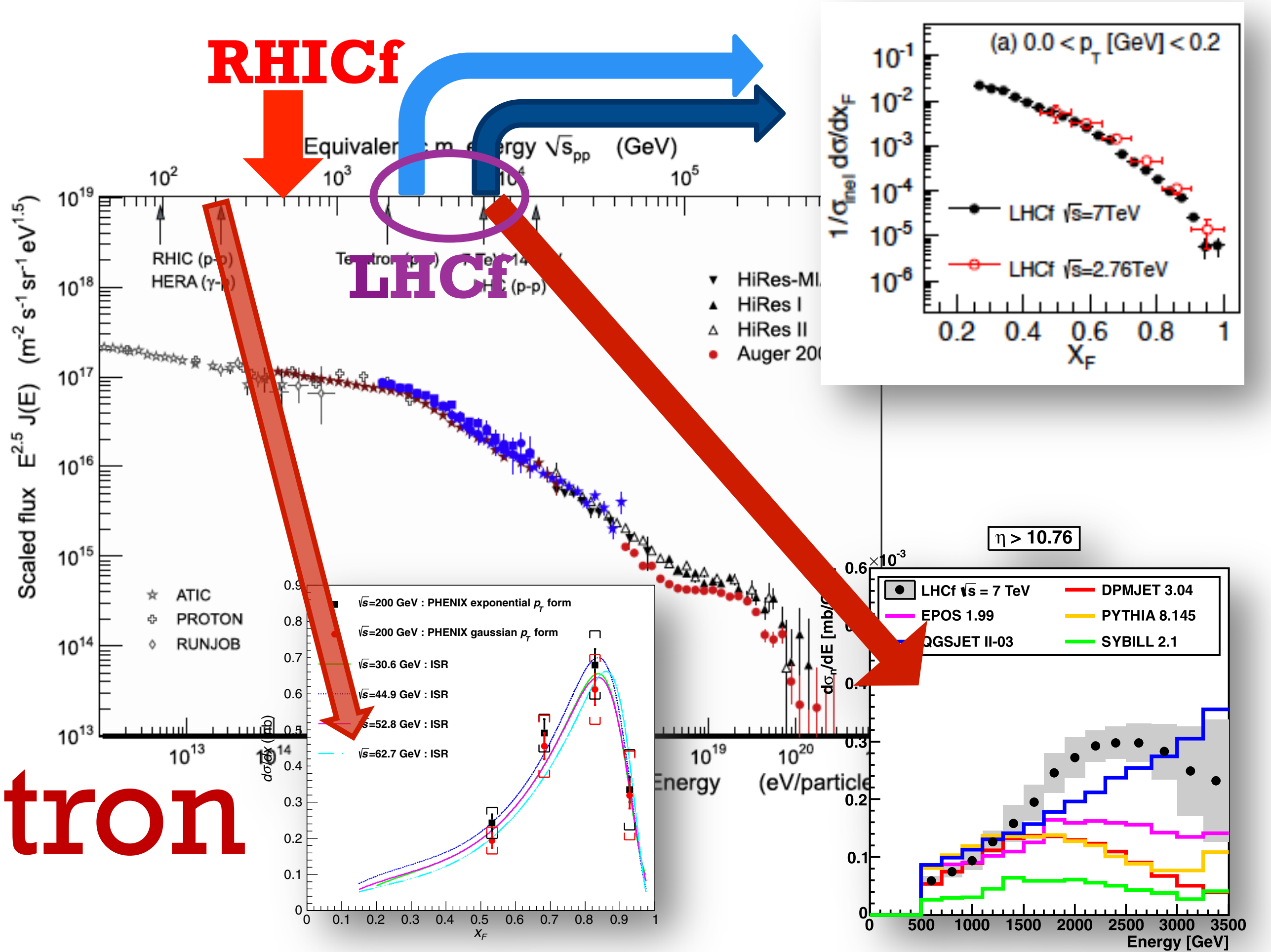
Acceptance in E-$p_T$ phase space



- ✓ Widest and gapless $p_T$ coverage is realized by moving the vertical detector position.
- ✓ Beam pipes obscure photons but not neutrons.

# + √s scaling, or breaking?

LHCf 2.76TeV and 7TeV data shows scaling of forward $\pi^0$



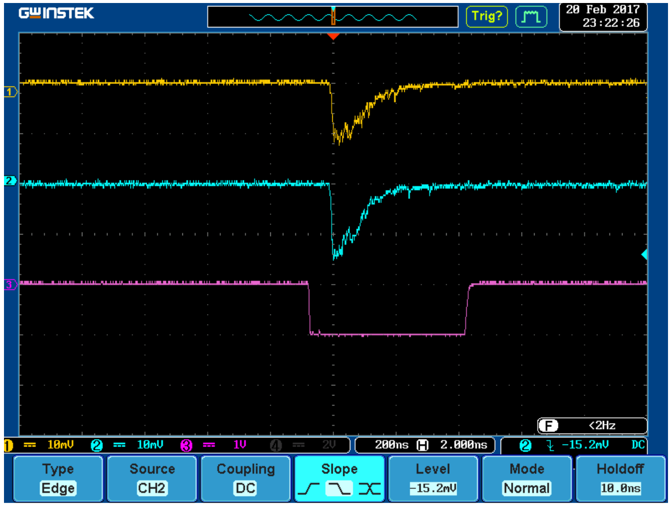
$\pi^0$

neutron

ISR (30-60GeV), PHENIX (200GeV) and LHCf (7TeV) data indicate scaling ***breaking*** of forward neutrons

# + RHICf commissioning

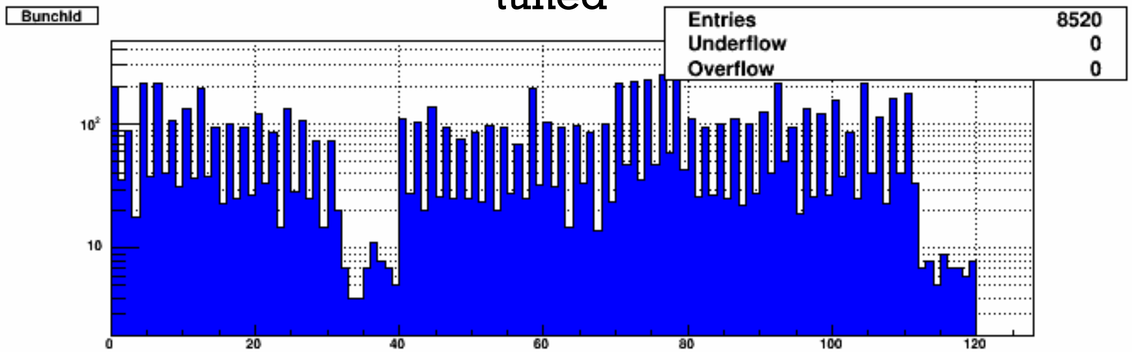
- RHIC starts first RUN2017 collision on 20-Feb
- RHICf observed shower signal (PMT coincidence) and tuned timing
- Common operation (RHICf triggers STAR) tested and common data successfully recorded at STAR (analysis of physics correlation on going)
- Data taking: last week of June



1 10mV 2 10mV 3 1V 4 2V
200ns 2.000ns
2 -15.2mV DC

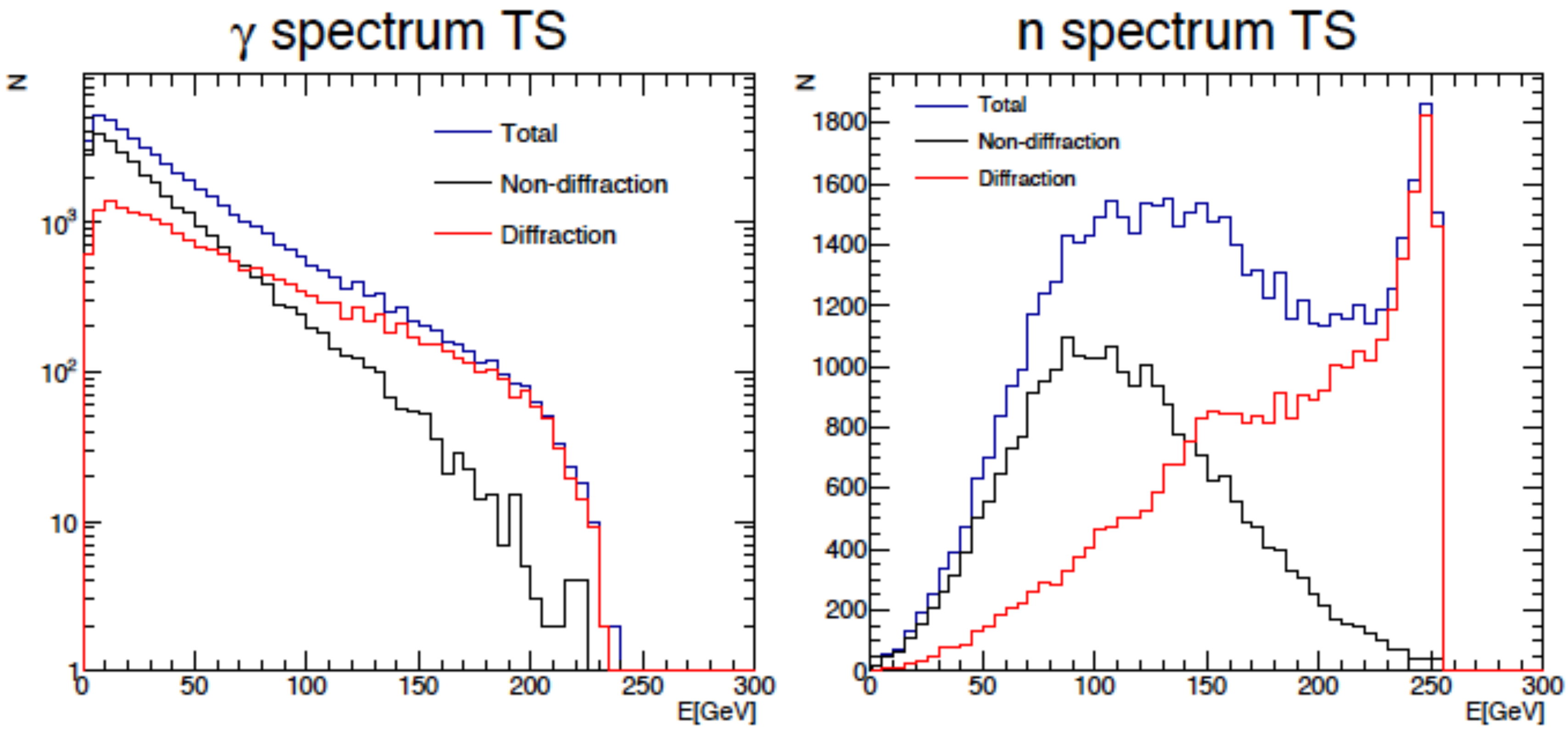
Type: Edge
Source: CH2
Coupling: DC
Slope
Level: -15.2mV
Mode: Normal
Holdoff: 10.0ns

RHICf calorimeter PMT signals and ADC Gate after timing tuned



Bunch ID of RHICf trigger recorded at "STAR"
Two abort gaps correctly identified

# + Diffractive vs. non diffractive at $\eta$ >8.2 with √s=510GeV p+p collisions



**PYTHIA 8 simulation**

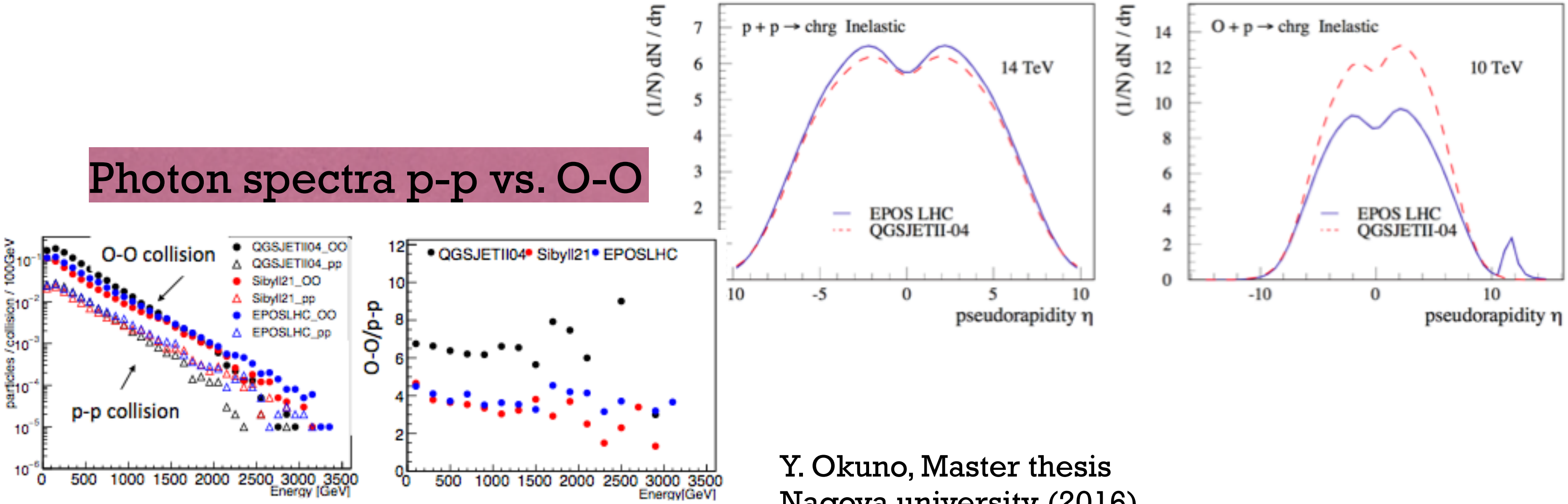
**BLUE: inclusive spectra expected by RHICf only**

**RED: diffractive only ("RHICf + no central track in STAR" will be similar => TBC)**

**BLACK: non diffractive ("RHICf + >=1 central track in STAR" => TBC )**

# + The Near-Far Future at LHC

- The most promising future at LHC for LHCf involve the proton-light ion 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
- Still make sense to take data if intermediate ion (like Ar) will be available



Photon spectra p-p vs. O-O

Y. Okuno, Master thesis
Nagoya university (2016)

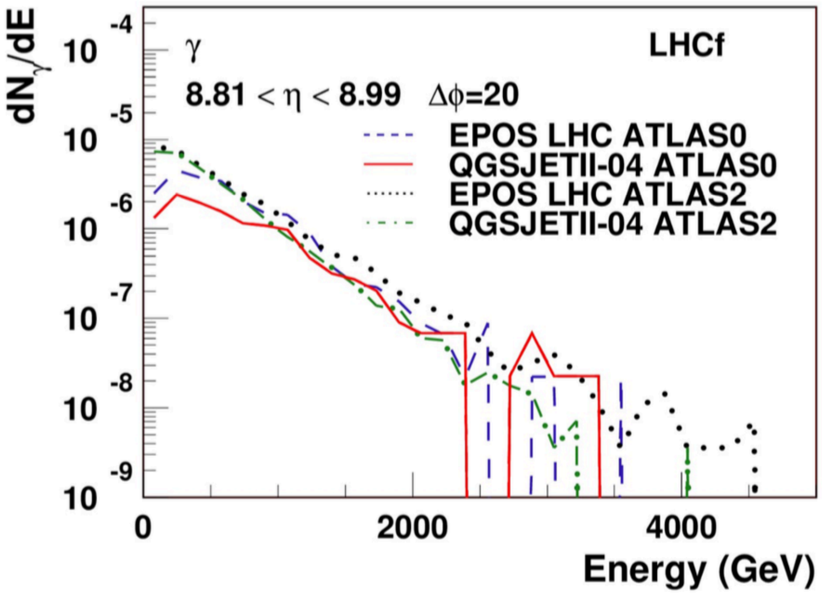
# Conclusions

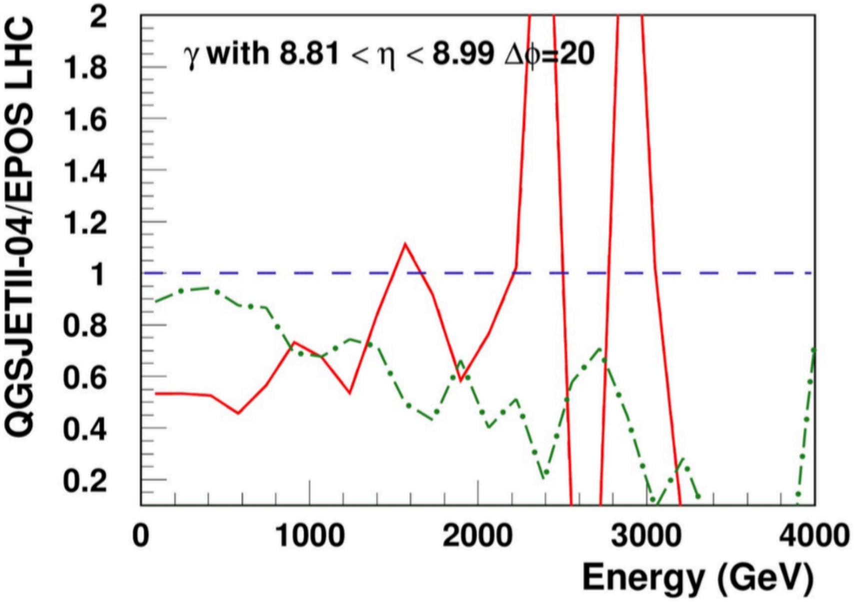
- In the last few years the importance of accelerator based measurements useful for Cosmic Ray physics came up very clearly, in addition to the ‘standard’ physics case
- LHC is the ideal laboratory for these studies
- Many important measurements have already been done
  - Significant improvement of EPOS_LHC, QGSJET-04 and Sibyll_2.3 hadronic interaction models
- LHCf provided many precise results on forward $\gamma$, n and $\pi^0$ with different collision’s conditions
- Joint analysis with Atlas is on-going for diffractive/non diffractive events selection
- RHICf will take data next month

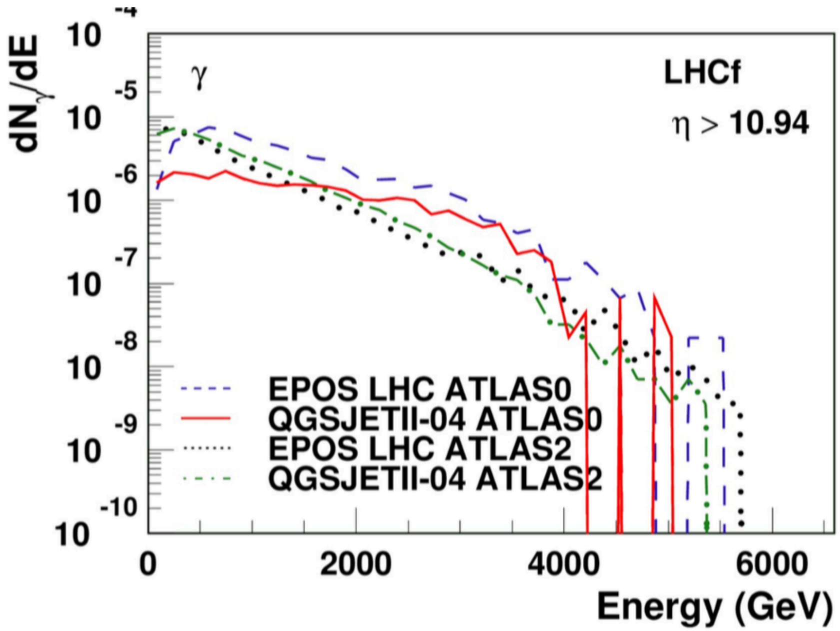
+

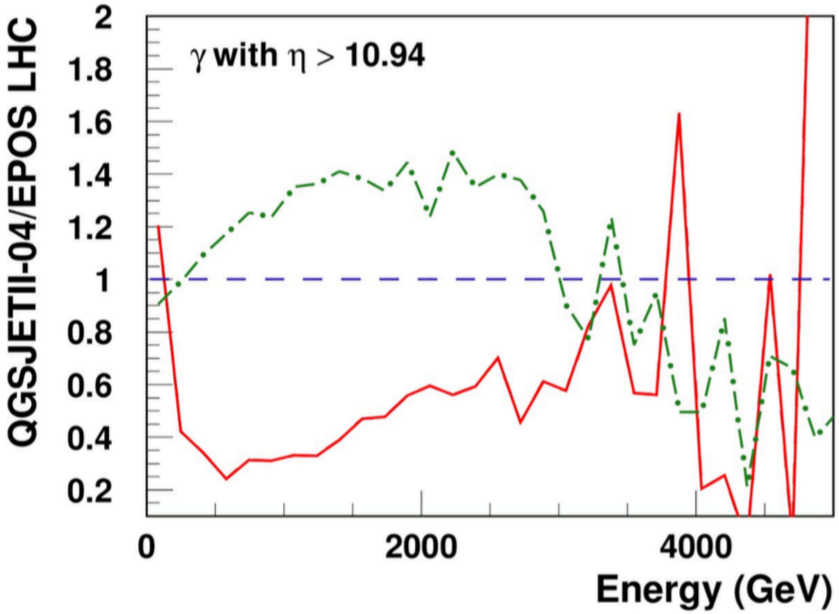
# Backup slides

# + LHCf-Atlas: photons



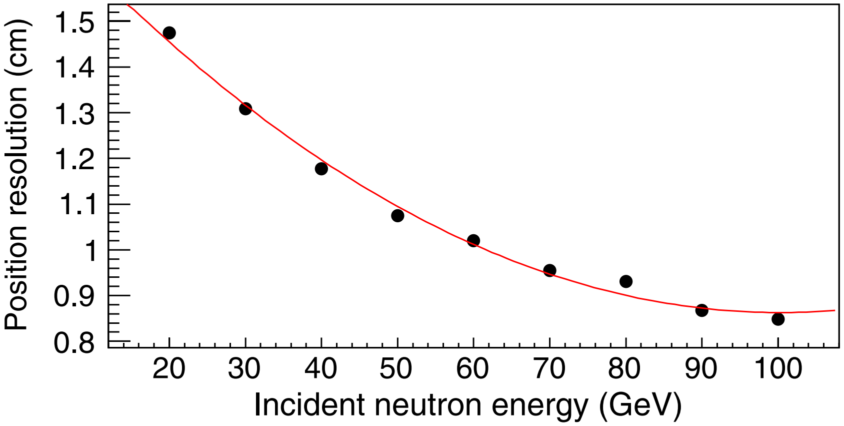


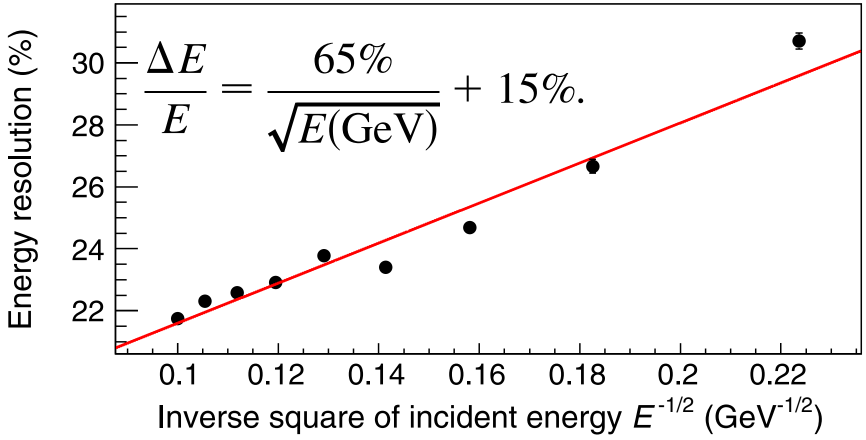




# + ZDC resolution @PHENIX vs RHICf

PHENIX ZDC

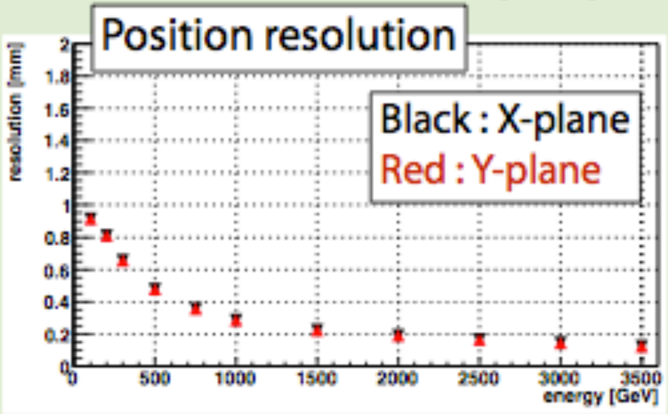




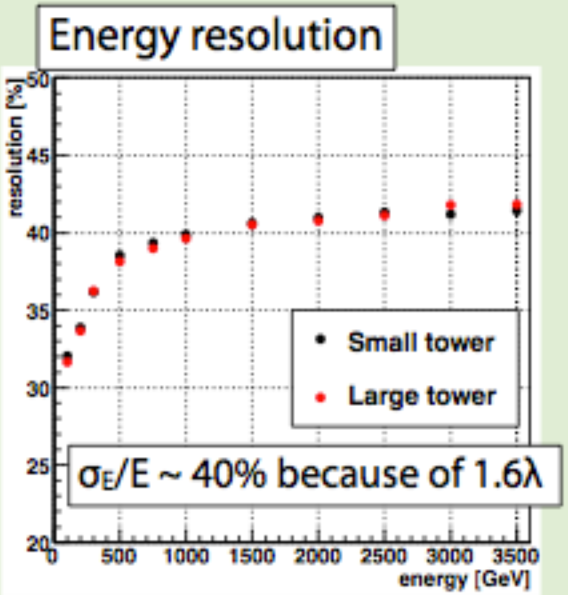
$$\frac{\Delta E}{E} = \frac{65\%}{\sqrt{E(\mathrm{GeV})}} + 15\%.$$

RHICf

Hadronic shower (MC)


Position resolution

Black : X-plane
Red : Y-plane


Energy resolution

$\sigma_E/E$ ~ 40% because of 1.6λ

# + RHICf beam condition proposal

- Constraints
  - RHICf DAQ speed is limited to 1kHz
  - Collision pile up cannot be resolved
  - Small angular dispersion is preferred

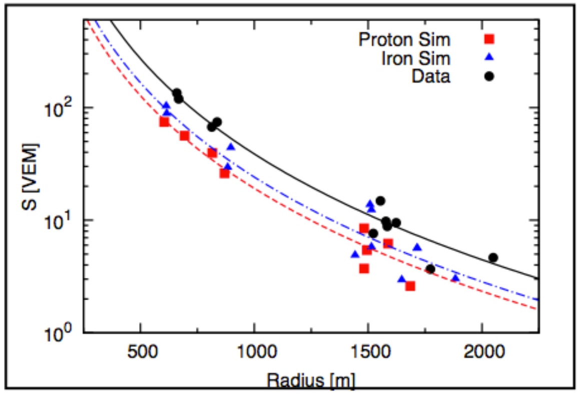
- Beam Proposal
  - 510GeV p+p collisions
  - $\beta^* = 10$m
  - Radial (horizontal) polarization; 0.4-0.5
  - $\varepsilon = 20$mm mrad, $I_b = 2\times10^{11}$, $n_{b\text{-colliding}} = 100$, $n_{b\text{-noncolliding}} = 20$ (nominal)
  - Luminosity=$1.1\ 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

- Operation
  - Few days for physics and few days for contingency
  - $\pi^0$ (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

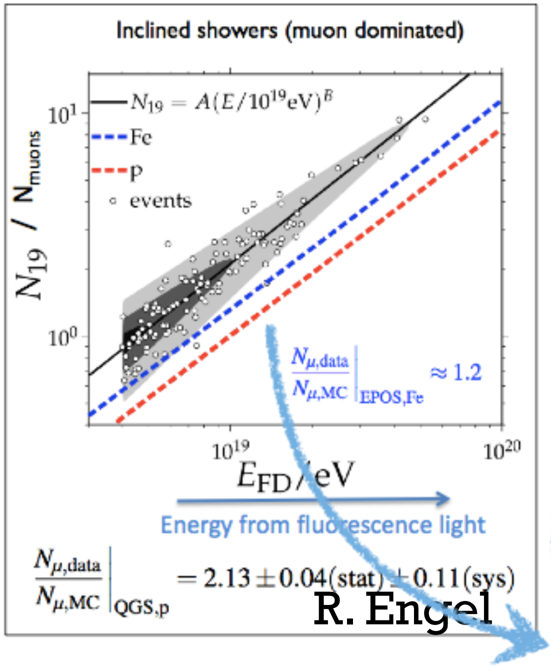
# LHCf @ pp 7 TeV: neutron analysis

## Motivations:

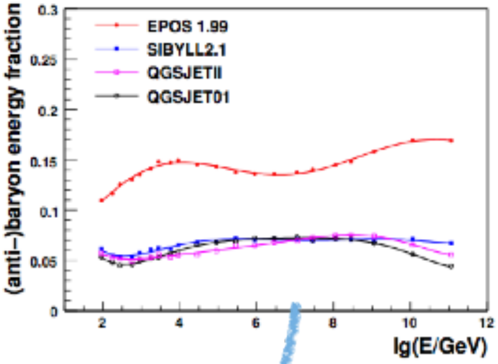
- Inelasticity measurement k=1-$p_{leading}/p_{beam}$
- Muon excess at Pierre Auger Observatory
  - Cosmic rays experiment measure PCR energy from muon number at ground and florescence light
  - 20-100% more muons than expected have been observed

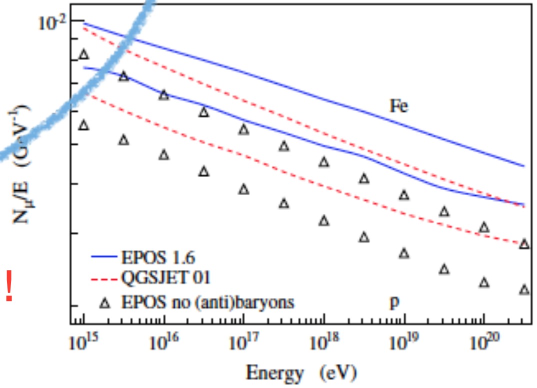


[ J.Allen, et al. ICRC2011 Proceedings]



- 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



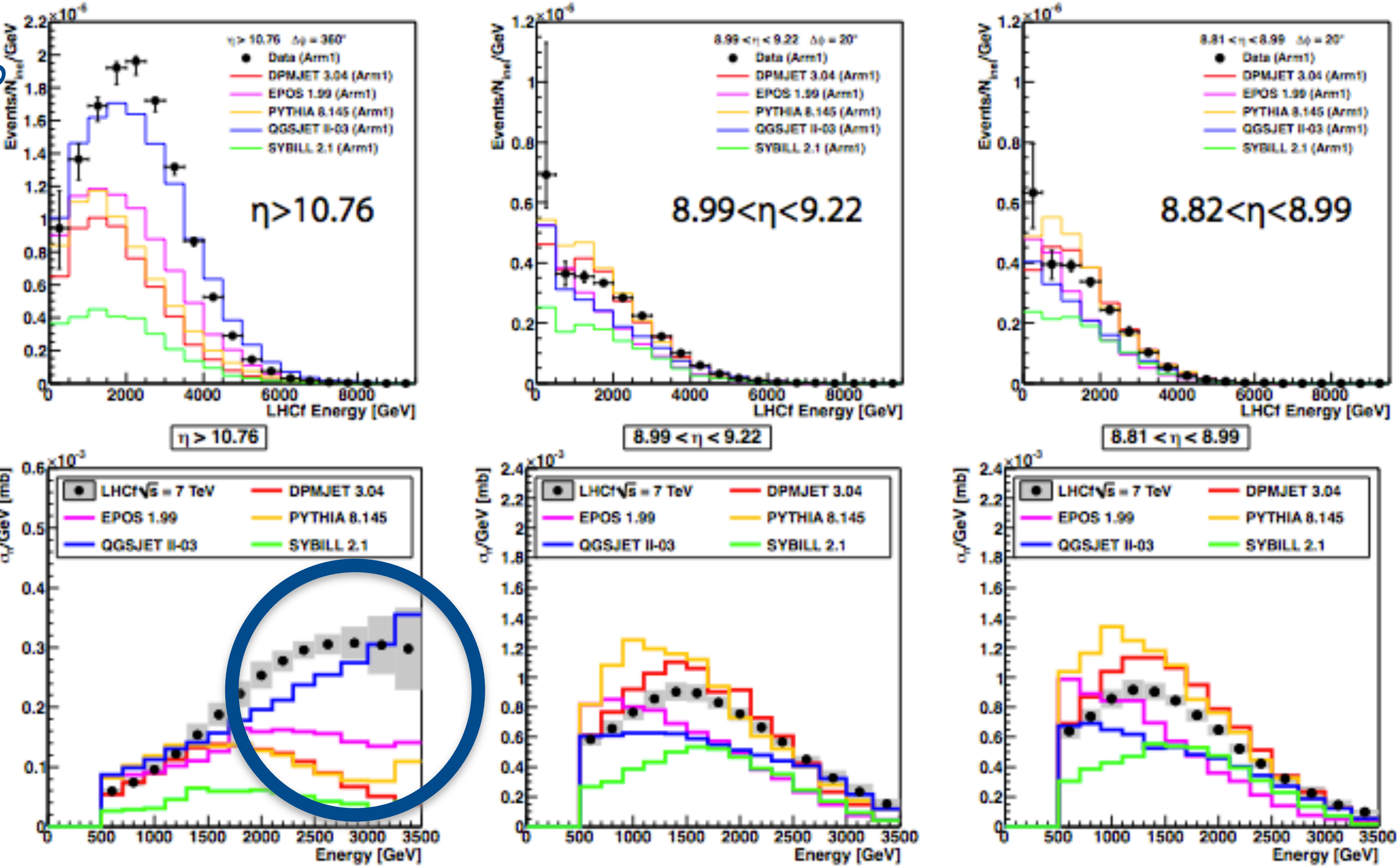


importance of baryon measurement!!!

# + Inclusive neutron spectra (7 TeV pp)

Before unfolding

After unfolding

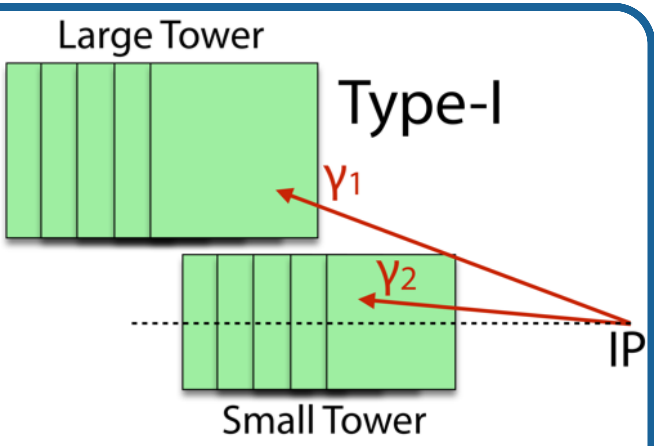


Very large high energy peak in the η>10.76 (predicted only by QGSJET)

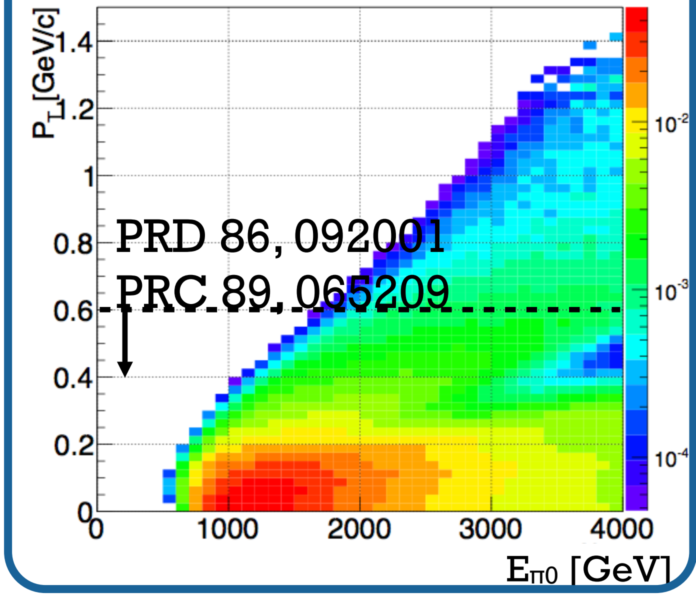
→ Small inelasticity in the very forward region!

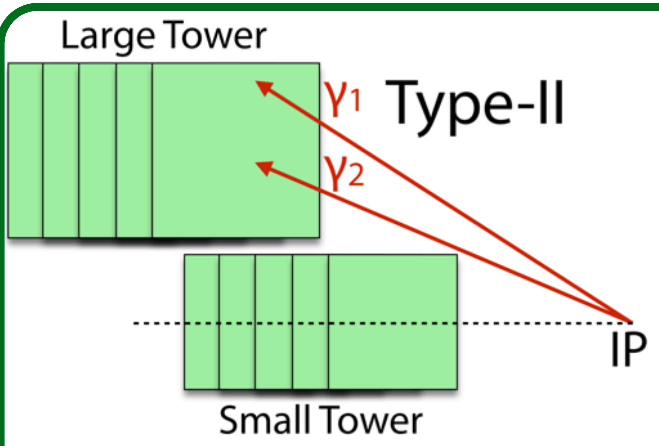
# + Type II $\pi^0$ in pp 7 TeV collisions

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



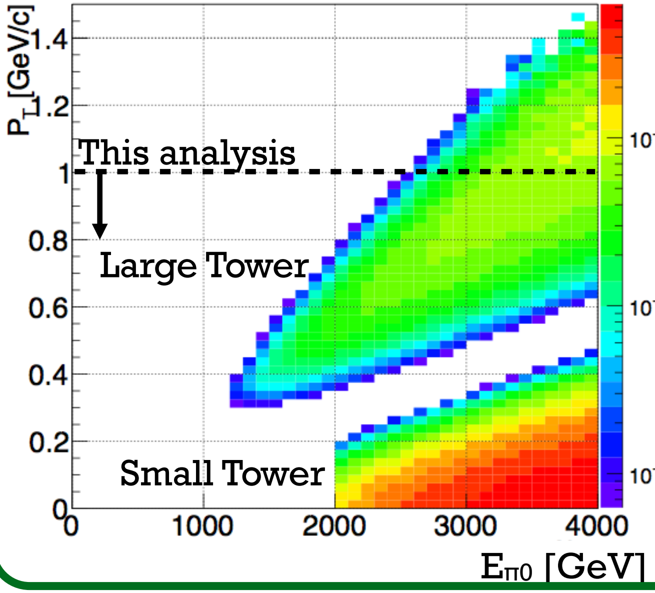
Arm2 acceptance for Type-I $\pi^0$

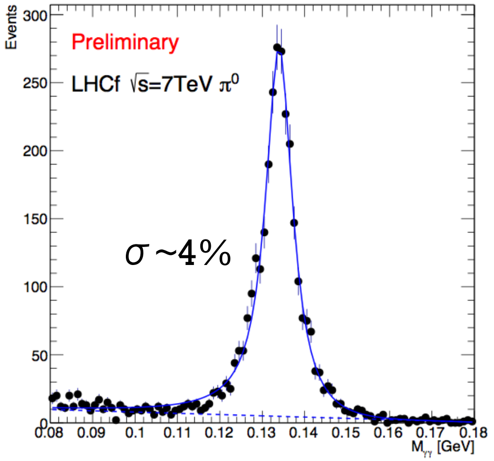




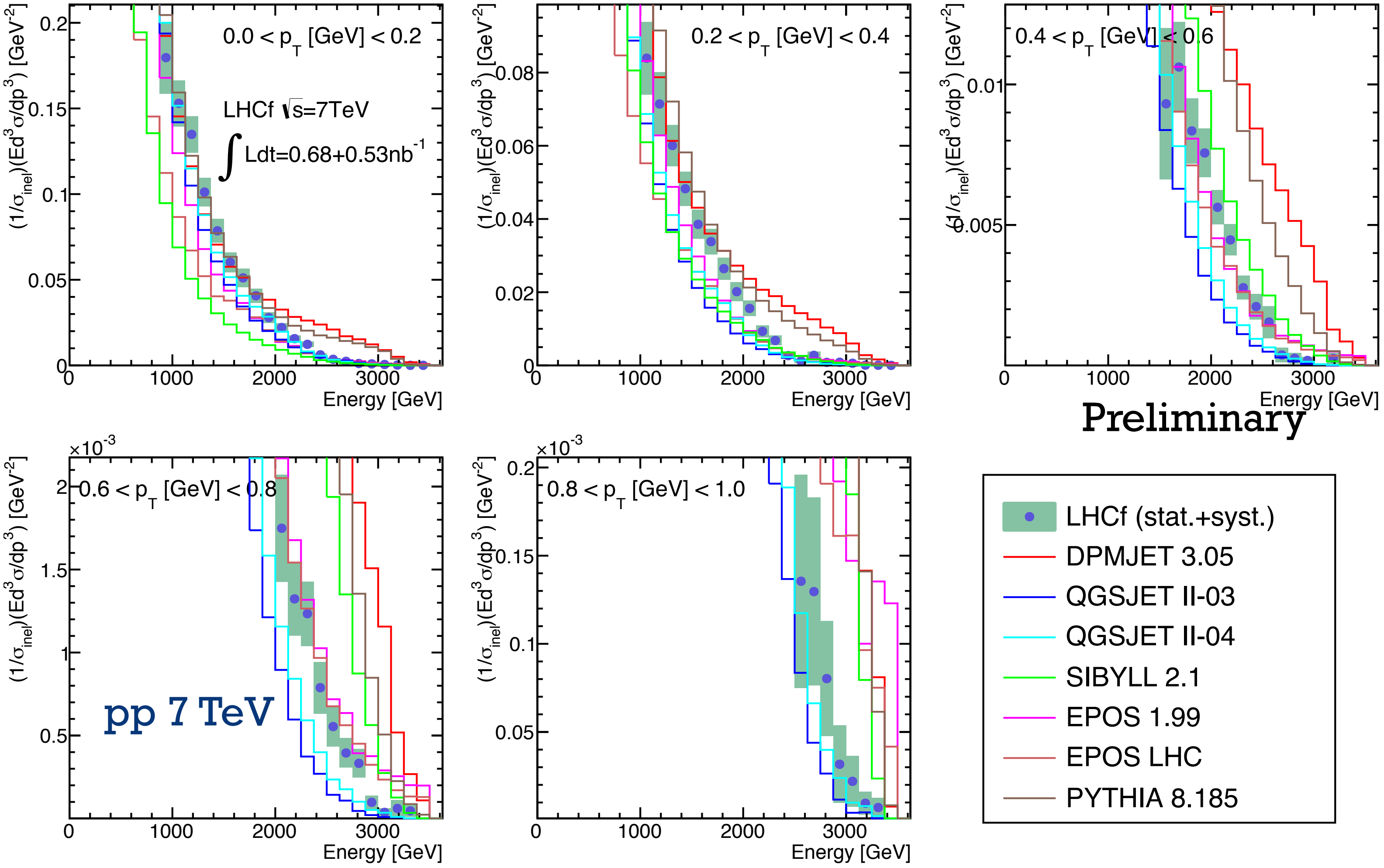
Motivation of Type-II
- extended $p_T$ range
- applicable to Λ and K
- di-hadron.

Arm2 acceptance for Type-II $\pi^0$



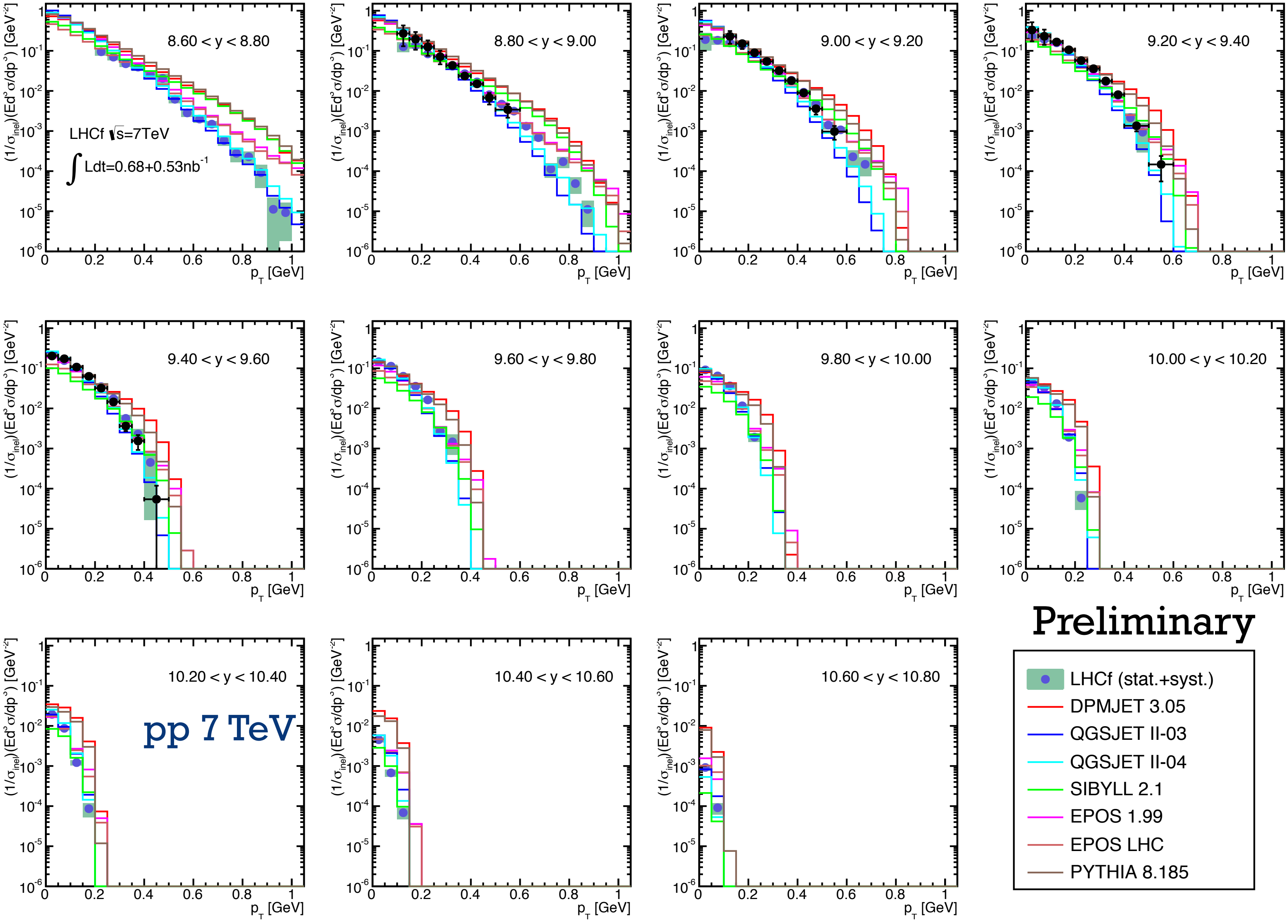


# + $\pi^0$ energy spectra (for different $p_T$ bins)



- 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.

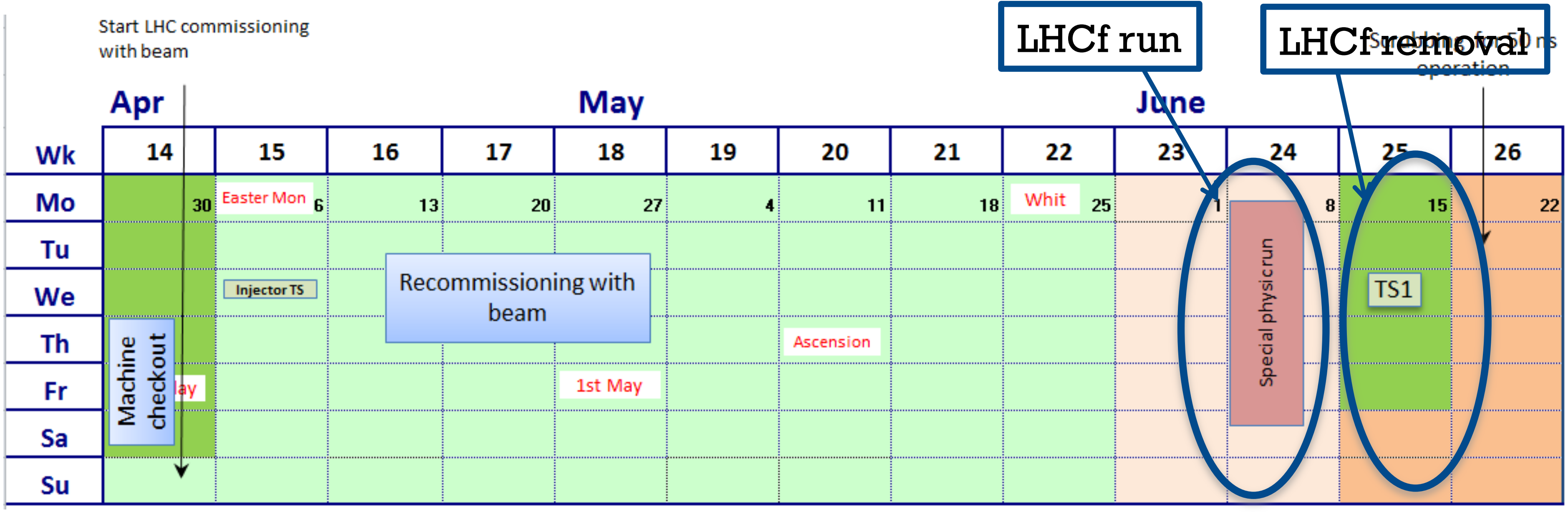
# + $\pi^0$ $p_T$ spectra (for different rapidity bins)



**pp 7 TeV**

**Preliminary**

# + 2015 updated LHC operation schedule



Start LHC commissioning with beam

LHCf run

LHCf removal

Scrubbing for 50 ns operation

| Wk | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Apr |  |  |  | May |  |  |  |  | June |  |  |  |
| Mo | 30 | Easter Mon 6 | 13 | 20 | 27 | 4 | 11 | 18 | Whit 25 | 1 | 8 | 15 | 22 |
| Tu |  |  |  |  |  |  |  |  |  |  | Special physics run |  |  |
| We |  | Injector TS |  | Recommissioning with beam |  |  |  |  |  |  |  | TS1 |  |
| Th | Machine checkout |  |  |  |  |  | Ascension |  |  |  |  |  |  |
| Fr | lay |  |  |  | 1st May |  |  |  |  |  |  |  |  |
| Sa |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Su |  |  |  |  |  |  |  |  |  |  |  |  |  |

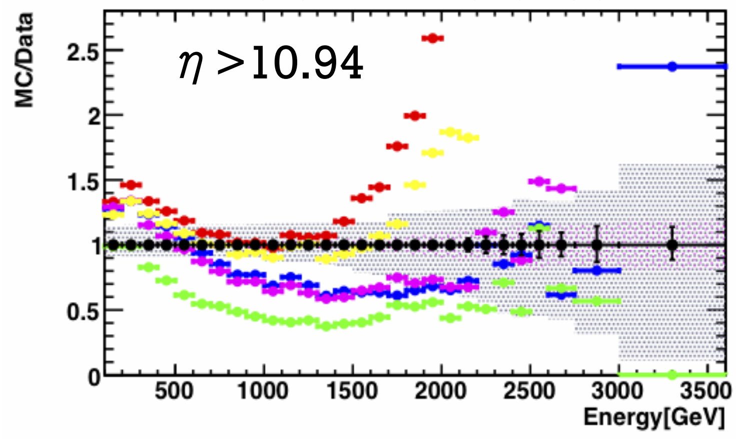
From M. Lamont, LMC Meeting, 15/04/15

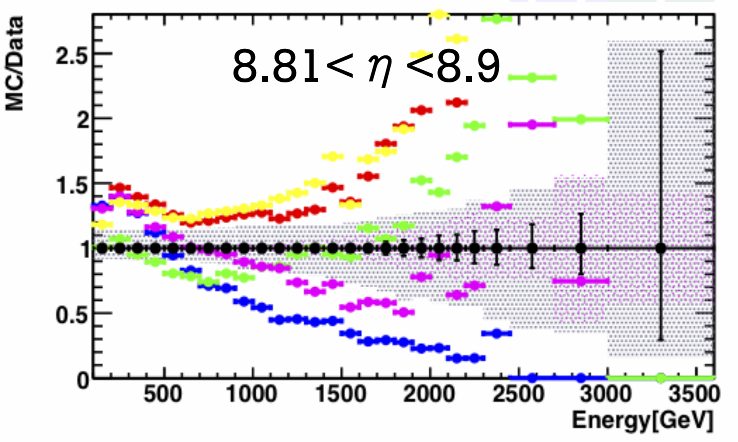
- 8 weeks beam commissioning
- 5 days special physics at beta* = 19 m (VdM, LHCf, TOTEM & ALFA)
- Start TS1 – 15th June. 24 hour technical stop in SPS in parallel followed by SPS scrubbing.

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

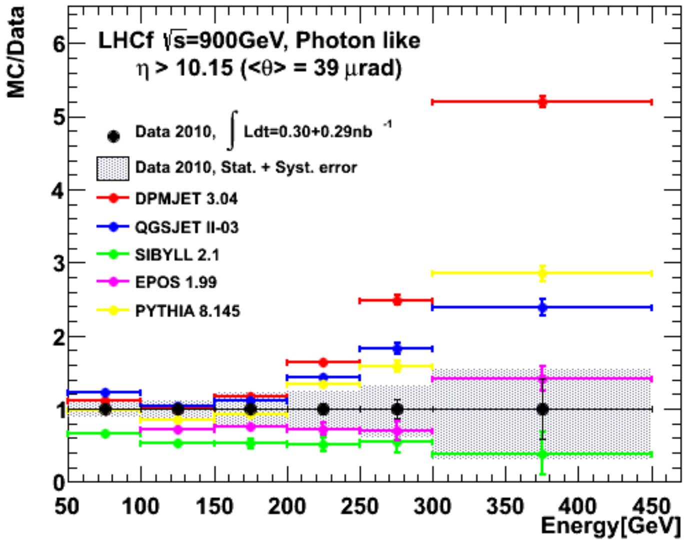
- None of the model nicely agrees with the LHCF data
- Here we plot the ratio MC/Data for the various models
- > Factor 2 difference

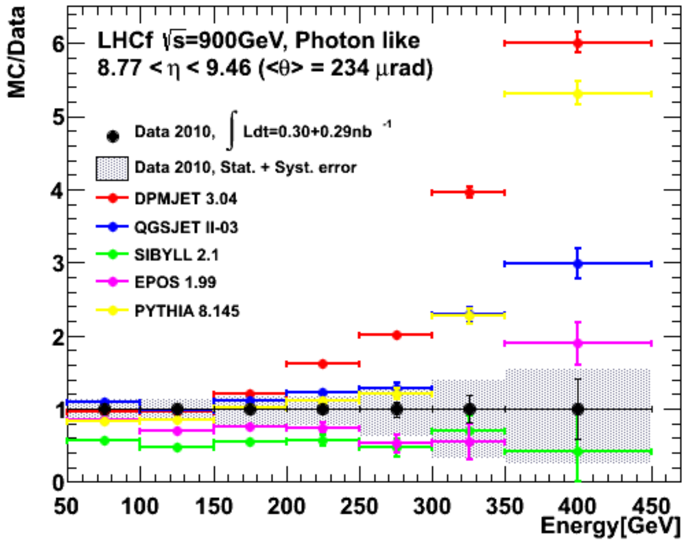
7TeV





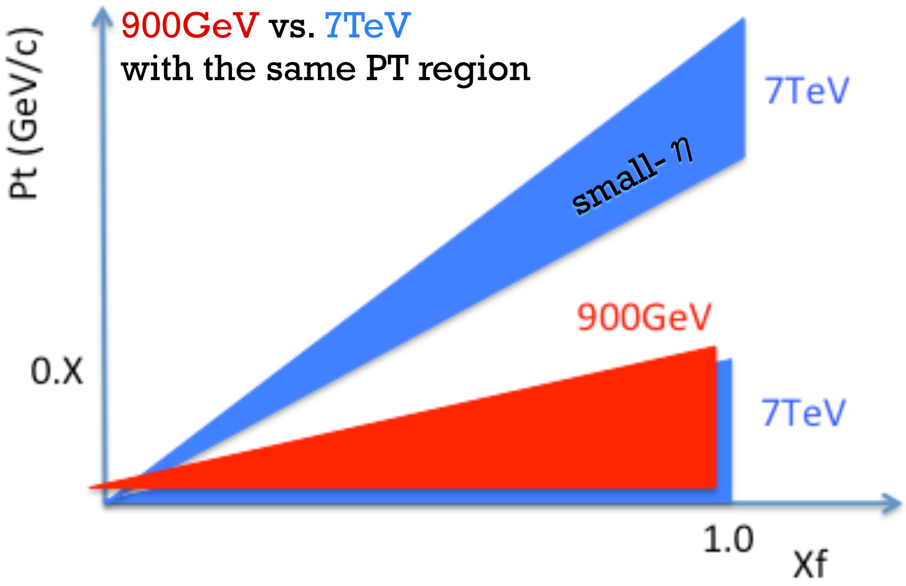
900GeV



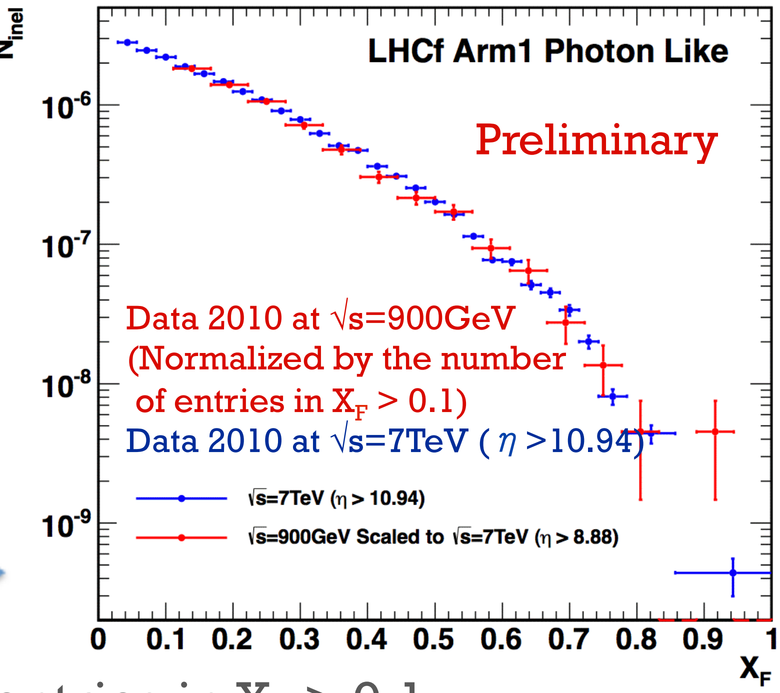


# + DATA : 900GeV vs 7TeV

*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.

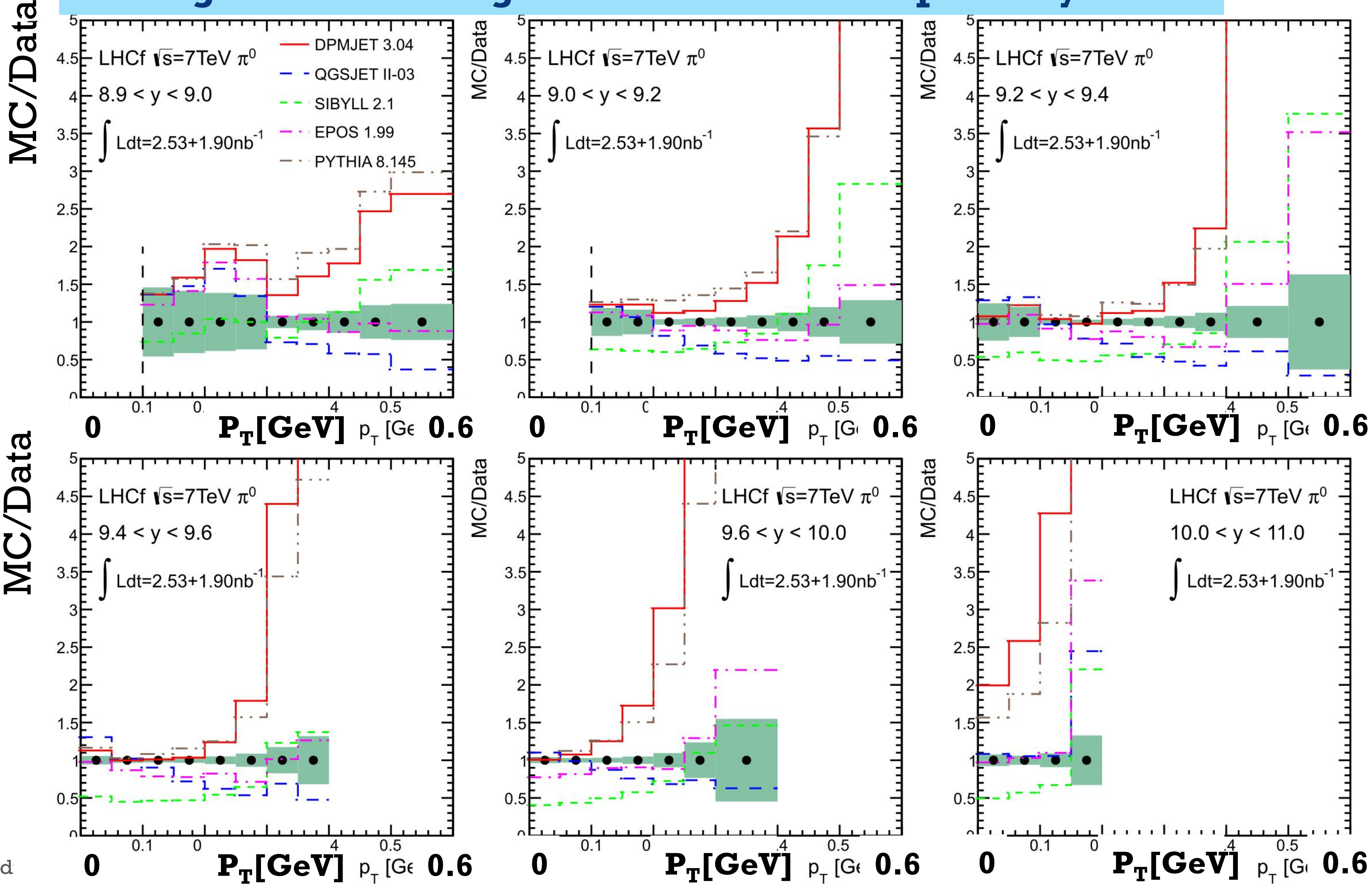
Good agreement of $X_F$ spectrum shape between 900 GeV and 7 TeV.
➔weak dependence of $<p_T>$ on $E_{CMS}$

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

# + $\pi^0$ $P_T$ 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.**

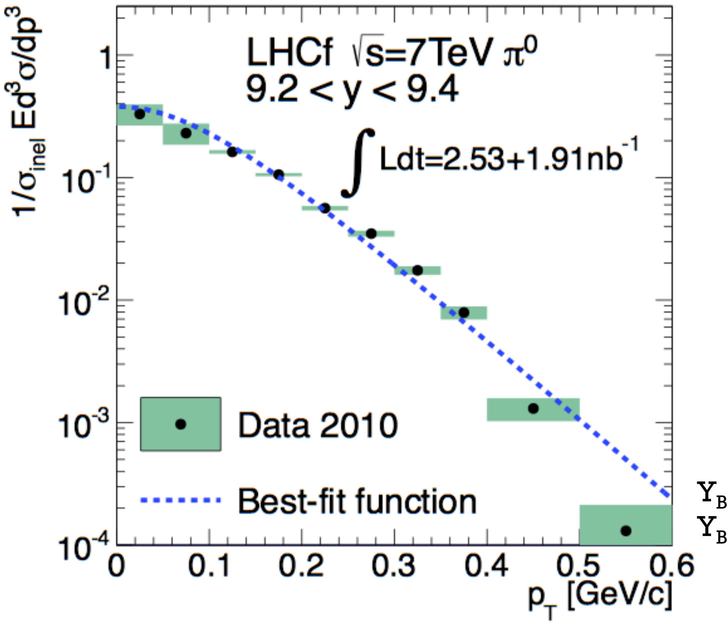


O. Ad

# + $\pi^0$ analysis at $\sqrt{s}$=7TeV

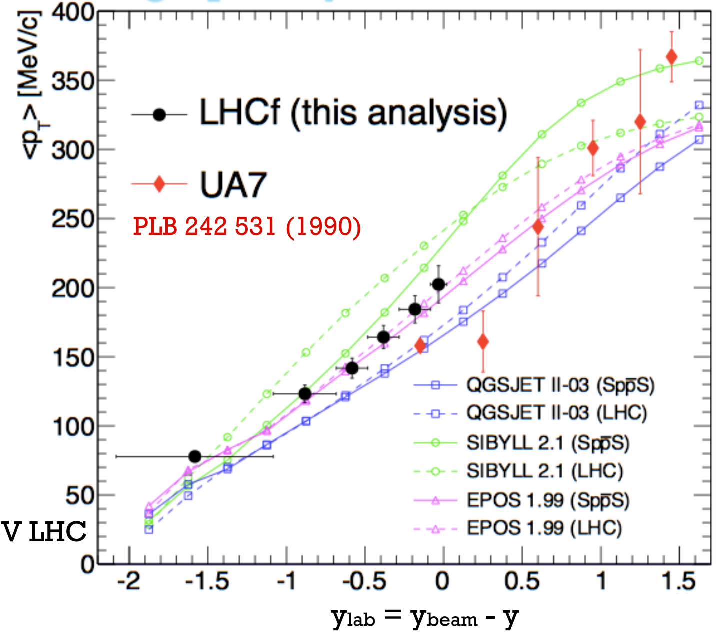
1205.4578).

## $p_T$ 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))

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

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

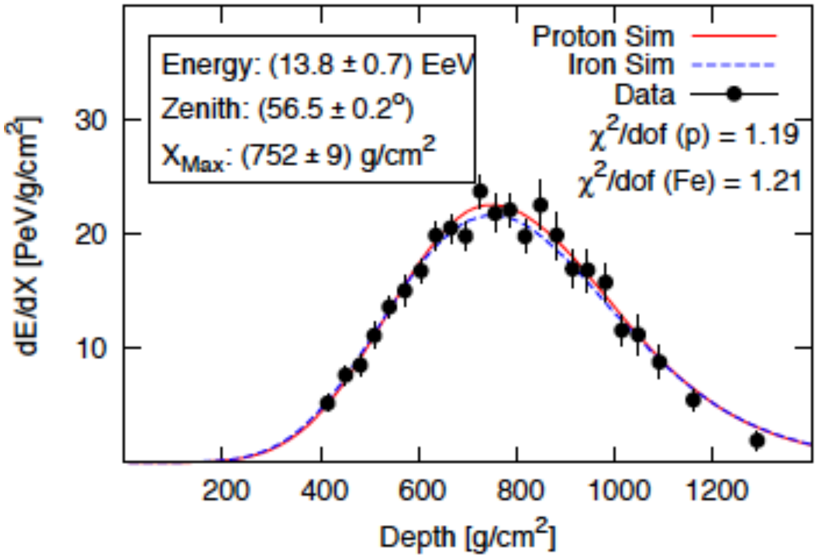
2. Numerical integration

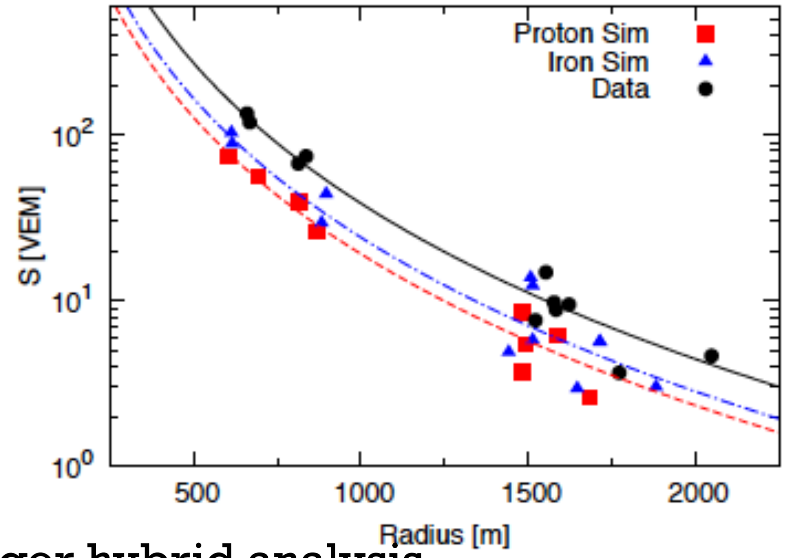
$$\langle p_{\rm T}\rangle = \frac{\int_0^\infty 2\pi p_{\rm T}^2 f(p_{\rm T})dp_{\rm T}}{\int_0^\infty 2\pi p_{\rm T} f(p_{\rm T})dp_{\rm T}}$$

actually up to the upper bound of histogram

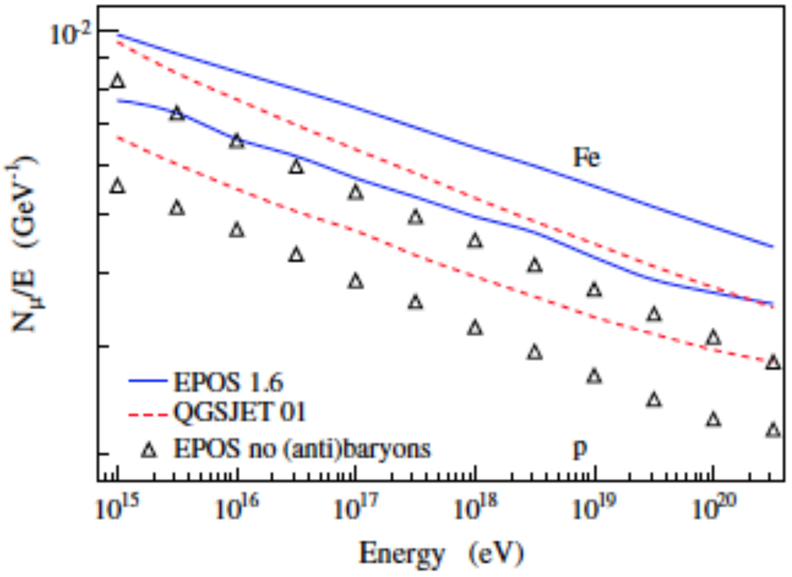
- Systematic uncertainty of LHCf data is 5%.
- Compared with the UA7 data ($\sqrt{s}$=630GeV) and MC simulations (QGSJET, SIBYLL, EPOS).
- Two experimental data mostly appear to lie along a common curve
  → no evident dependence of $<p_T>$ on $E_{CMS}$.
- Smallest dependence on $E_{CMS}$ is found in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

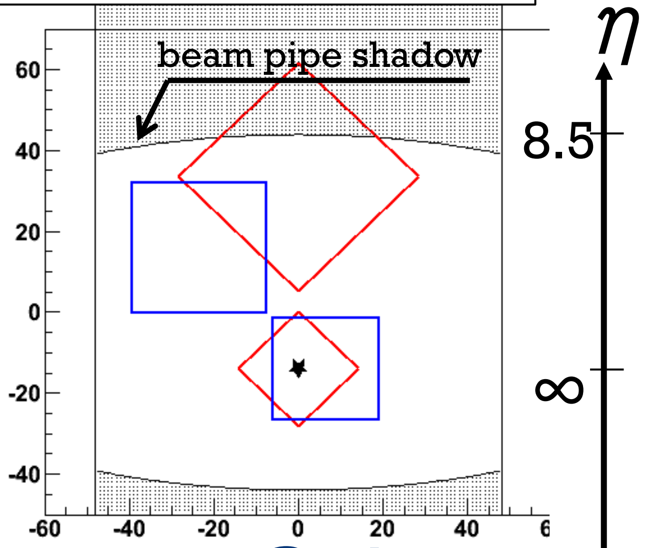
EPOS predicts more muon due to larger baryon production

=> importance of baryon measurement

Pierog and Werner, PRL 101 (2008) 171101

# +What LHCf can measure

Front view of calorimeters
@ 100 $\mu$ rad crossing angle

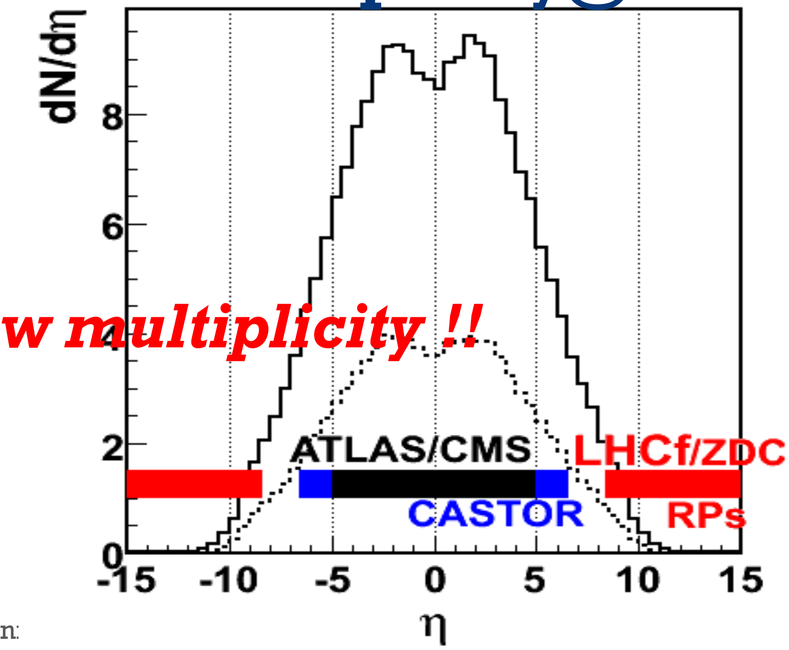


**Energy spectra and Transverse momentum distribution of**

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

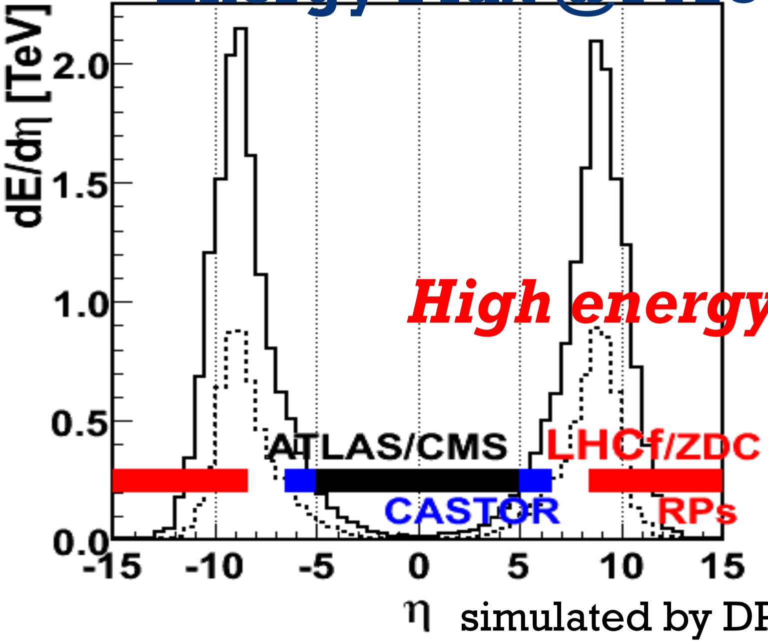
**at pseudo-rapidity range >8.4**

## Multiplicity@14TeV



*Low multiplicity !!*

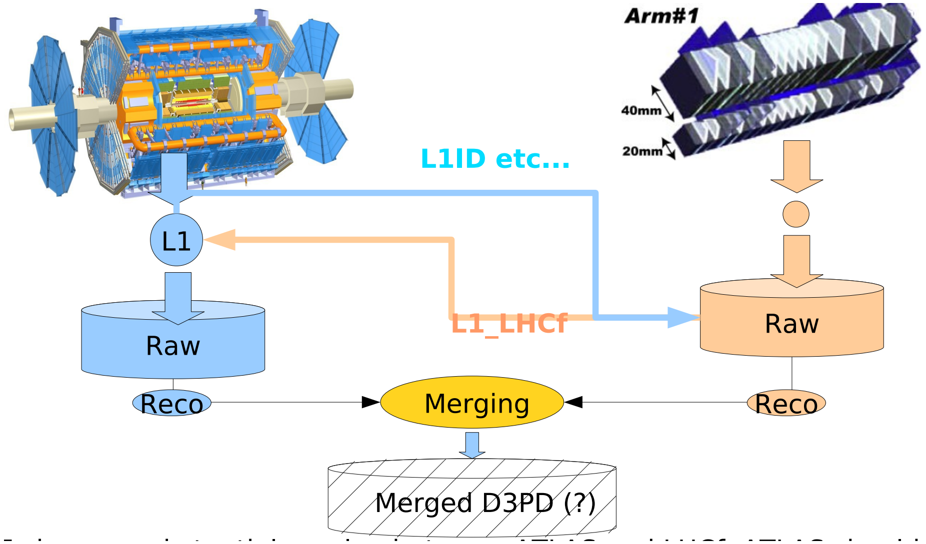
## Energy Flux @14TeV

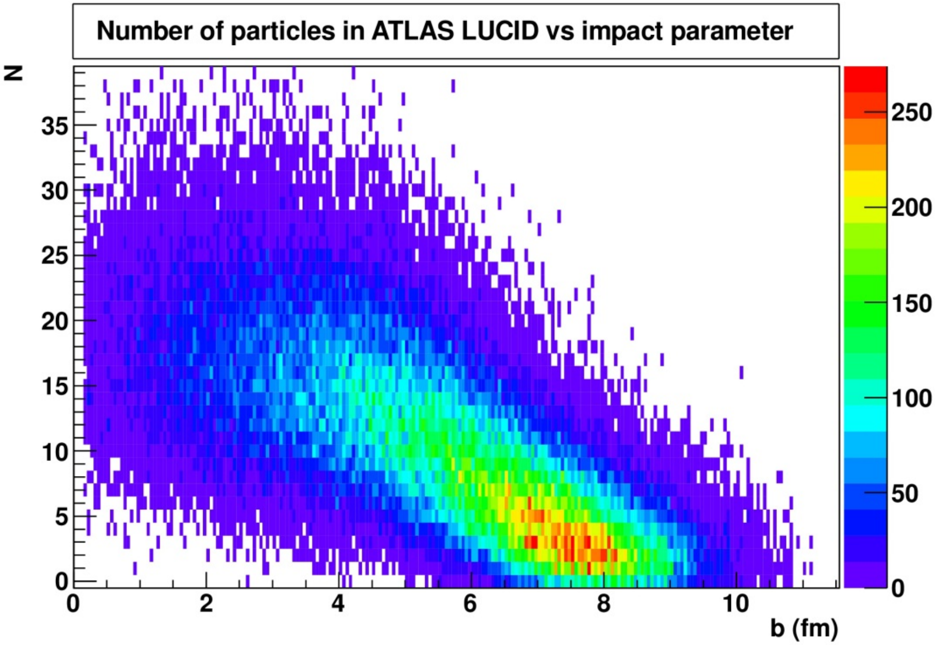


*High energy flux !!*

simulated by DPMJET3

# + Common trigger with ATLAS





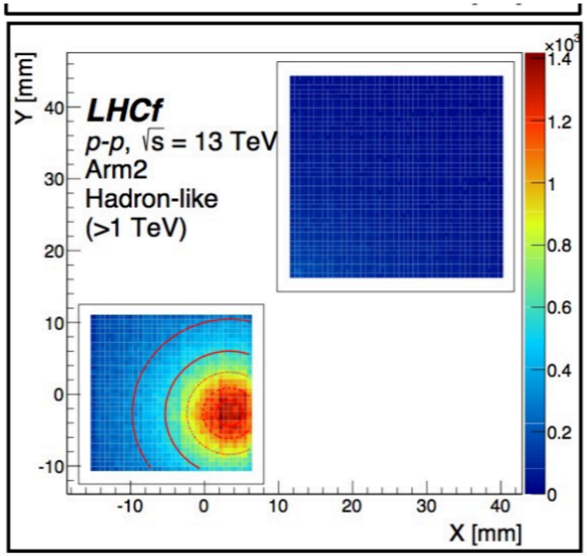
MC
impact parameter vs. # of particles in ATLAS LUCID

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

# + Analysis of hadron production in p-p collisions at 13 TeV

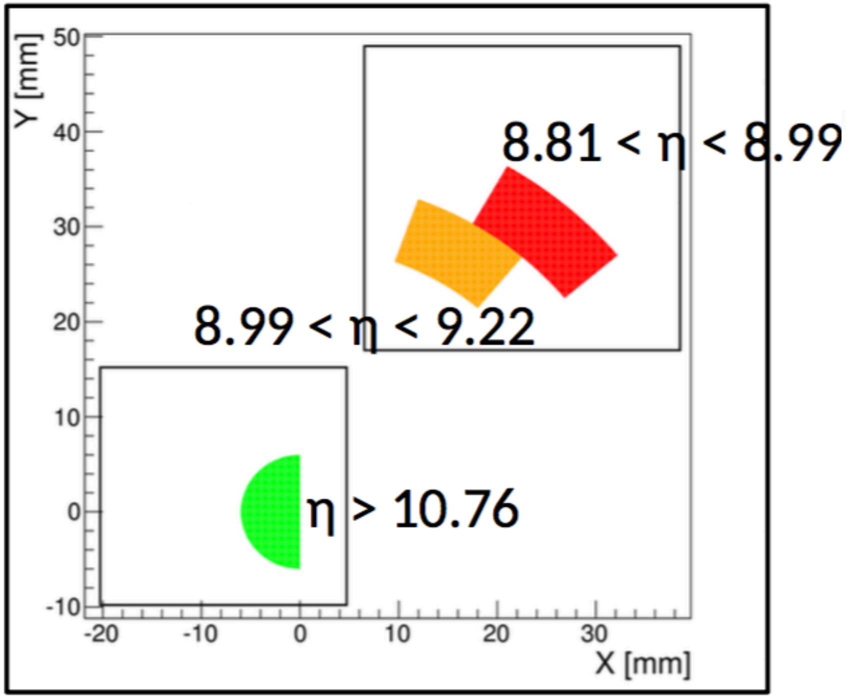
**Data set**

12 July 2015, 22:32-1:30 (3 hours)
Fill # 3855
$\mu = 0.01$
$\int L dt = 0.19\ \mathrm{nb}^{-1}$
$\sigma_{ine} = 78.53\ \mathrm{mb}$



**Beam Center**

Estimated using 2 D fit on high energy hadron hitmap distribution



Same as 7 TeV analysis
PLB 750 (2015) 360-366

**Event selection criteria:**

**software trigger**

at least 3 consecutive layers with deposit above threshold $dE > dE^{thr}$

**PID selection**

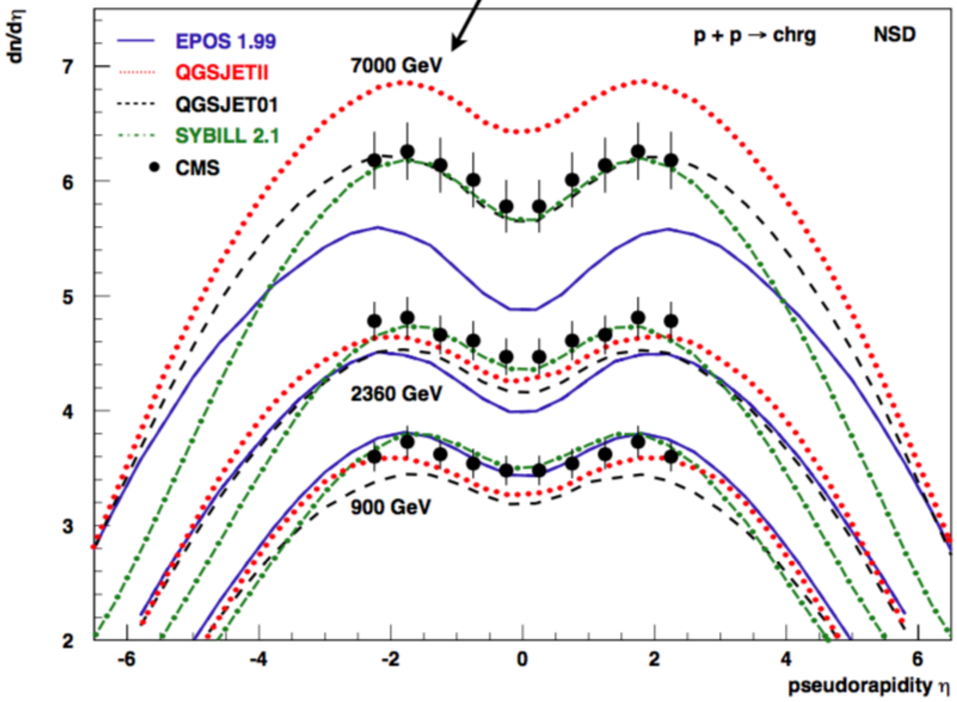
$L_{2D} > L_{2D}^{thr}$ where $L_{2D}$ is a variable related to shower longitudinal profile

**pseudorapidity acceptance**

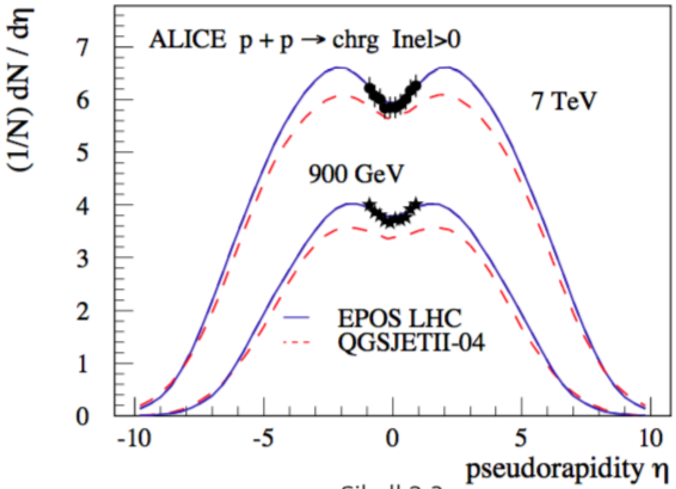
3 different pseudorapidity regions

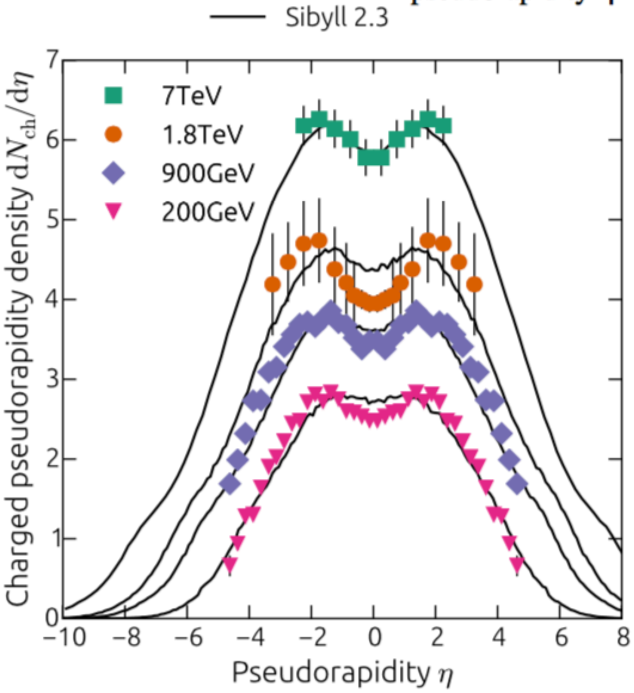
# Charged particle distribution in pseudorapidity

*Protons: $E_{lab} = 3 \times 10^{16}$ eV*



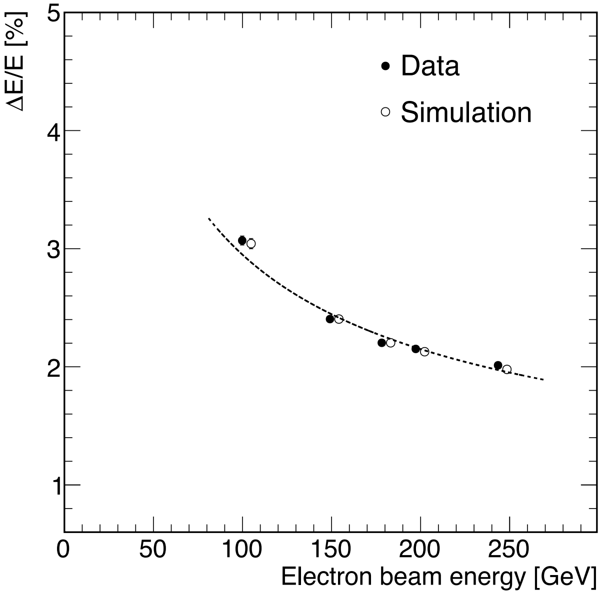
*(data exist from all LHC experiments)*



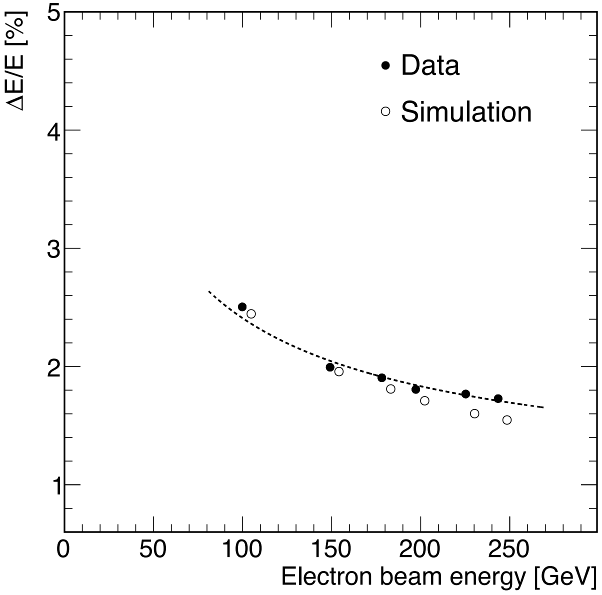


Feb. 2016: tuned version of Sibyll (v2.3)

# + Photon reconstruction



**Arm1 20 mm cal.**

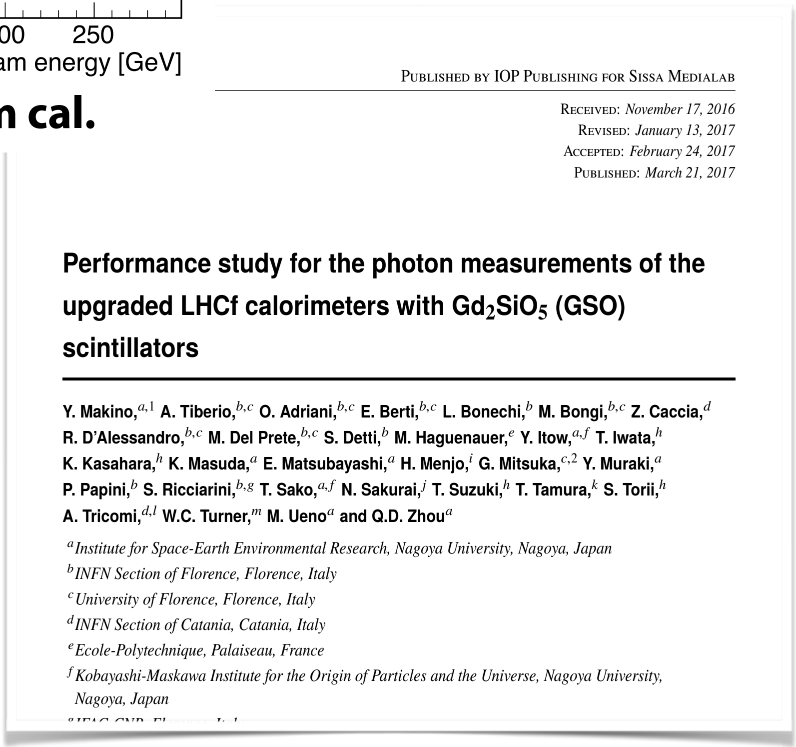


**Arm2 25 mm cal.**

$\Delta E/E < 2\%$

$\Delta x < 0.2$ mm

JINST 12 P030023 (2017)



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**Performance study for the photon measurements of the upgraded LHCf calorimeters with $Gd_2SiO_5$ (GSO) scintillators**

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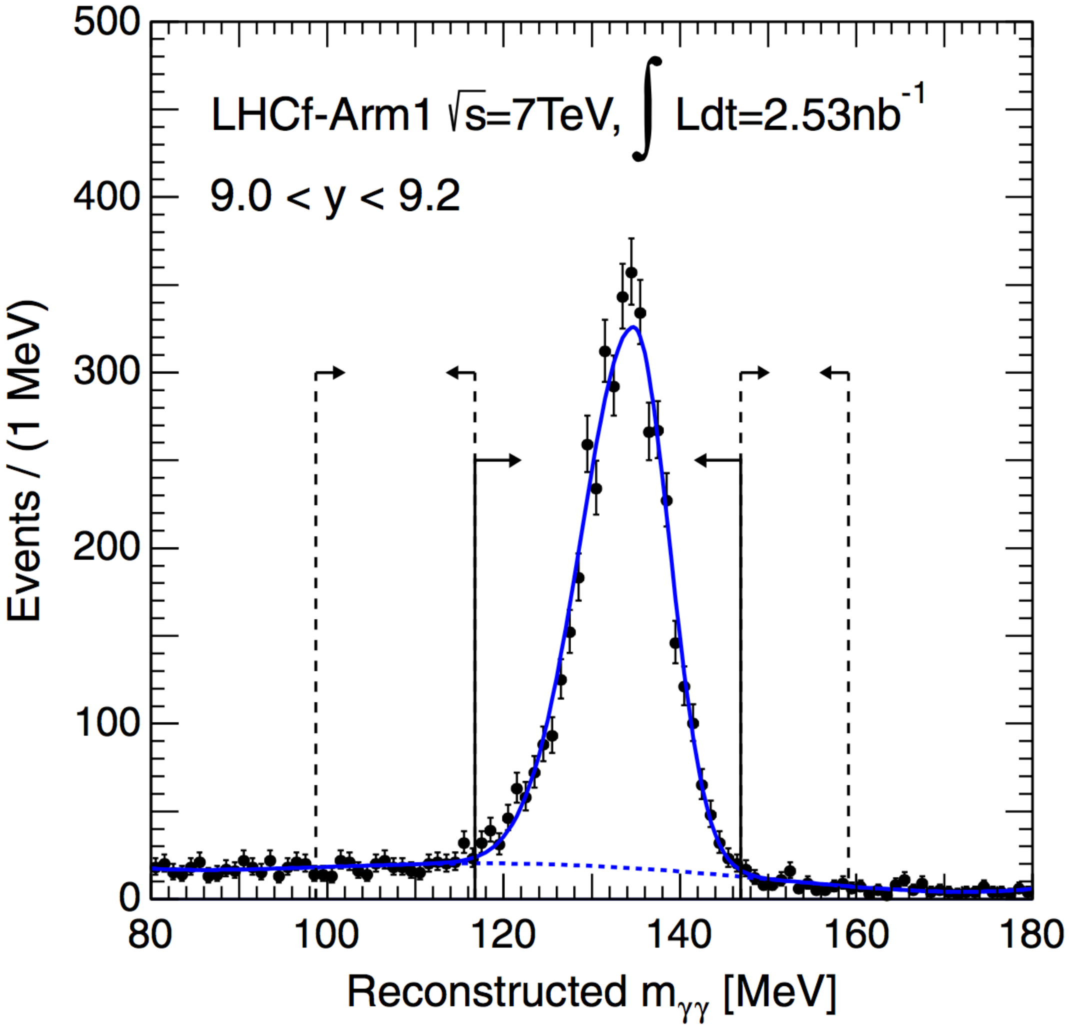
# + $\pi^0$ mass peak

$\Delta m_{\gamma\gamma}/m_{\gamma\gamma} \sim 3.5\%$



# + Neutron reconstruction

Performance for 1.5 TeV neutrons:

$\Delta E/E$ ~35%-40%

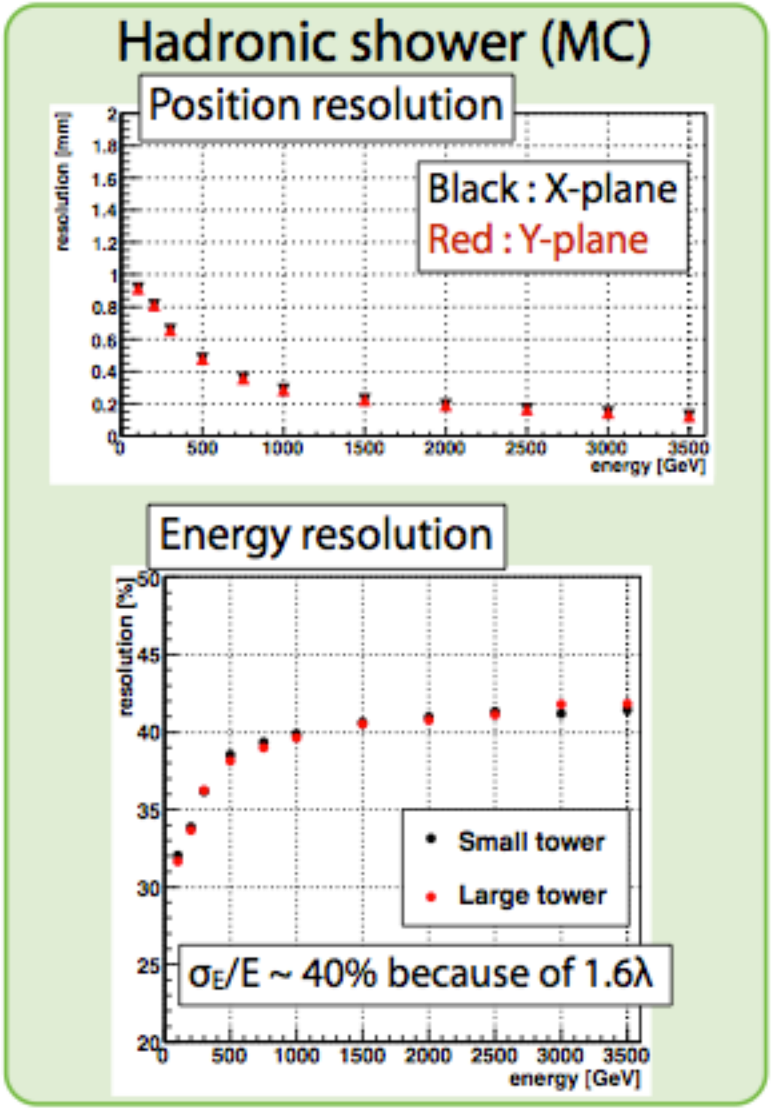
$\Delta x \sim 1$mm

And….

Detector performance is also interaction model dependent!

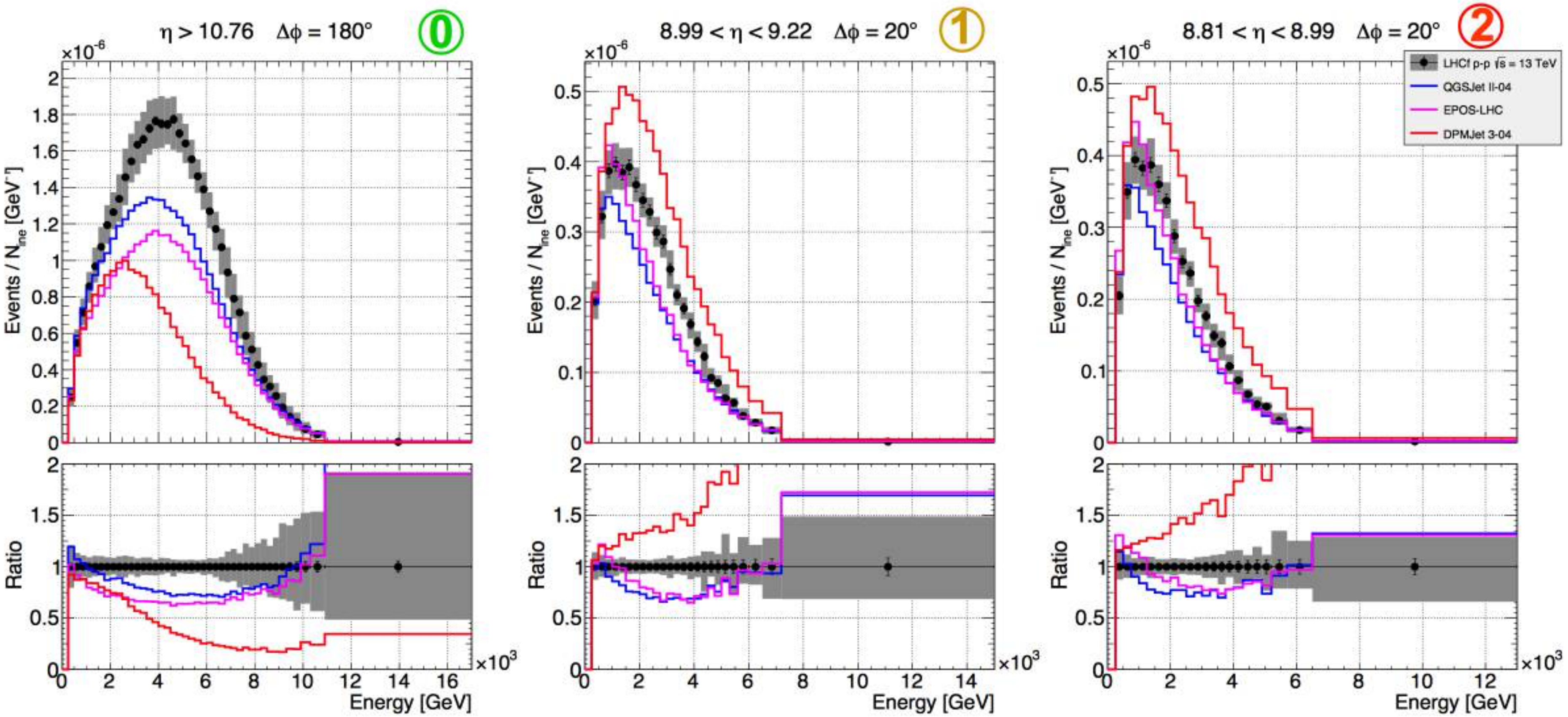
Unfolding is essential to extract physics results from the measured spectra

Physics measurement important to try to solve the 'Muon ecess' observed from the ground based HECR experiments



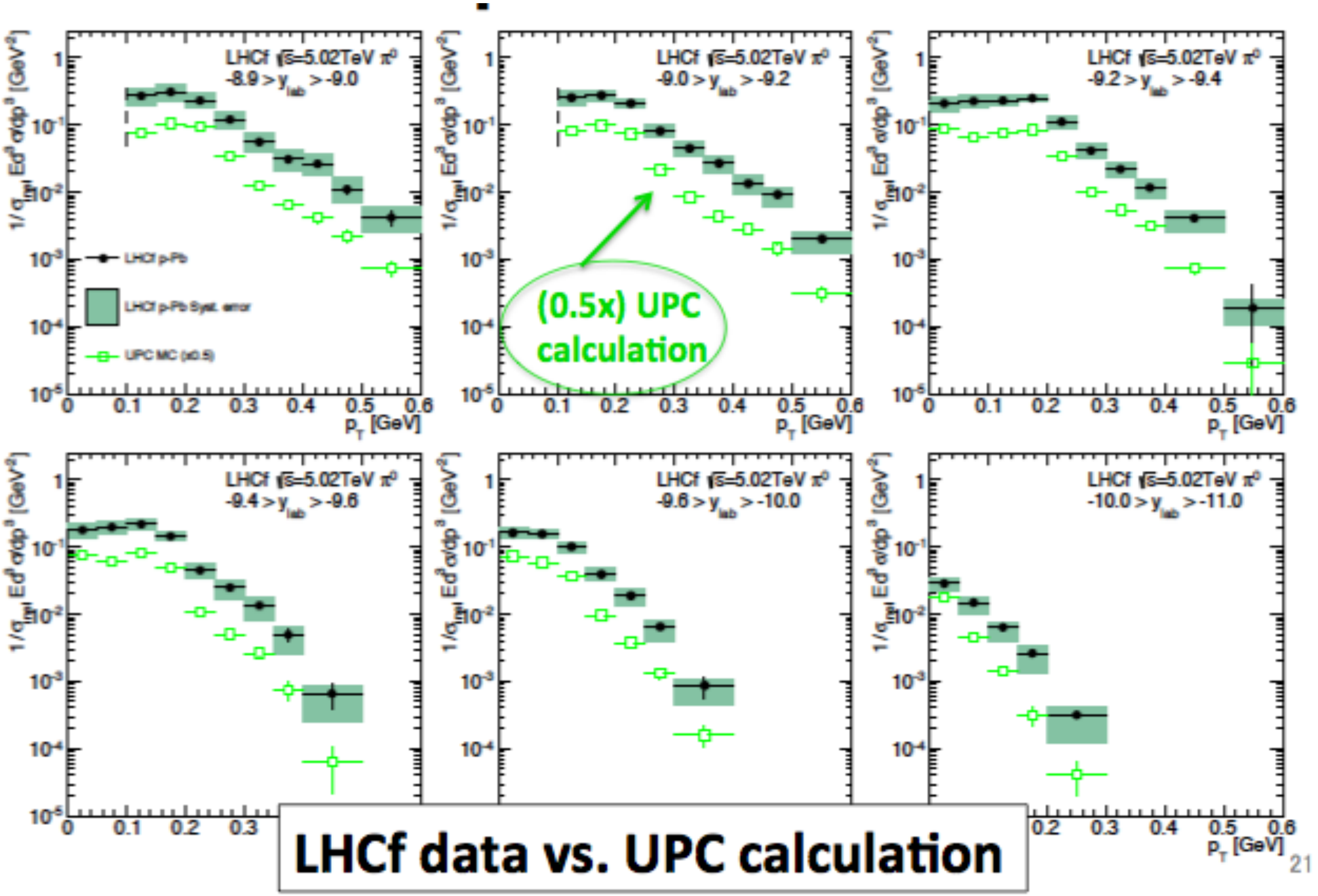
# Reconstructed ARM2 hadron energy spectra @ 13 TeV

Events / $N_{ine}$ / dE



**QGSJET II-04** and **EPOS-LHC** have similar shape but lower yield
**DPMJET 3.04** have very different shape and yield

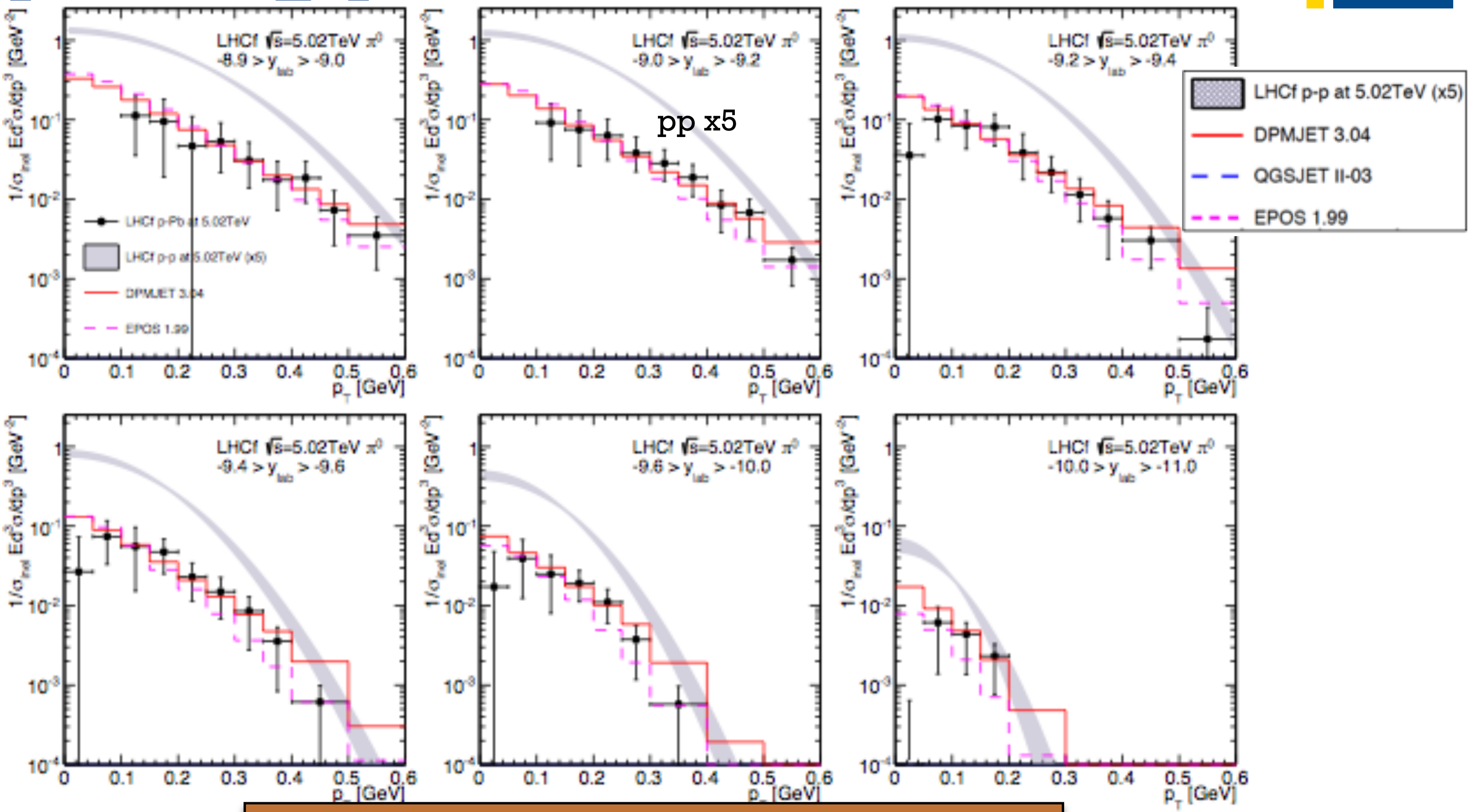
# + LHCf @ pPb 5.02 TeV: $\pi^0$ spectra @ p-remnant side



(0.5x) UPC calculation

**LHCf data vs. UPC calculation**

# LHCf @ pPb 5.02 TeV: $\pi^0$ spectra @ p-remnant side

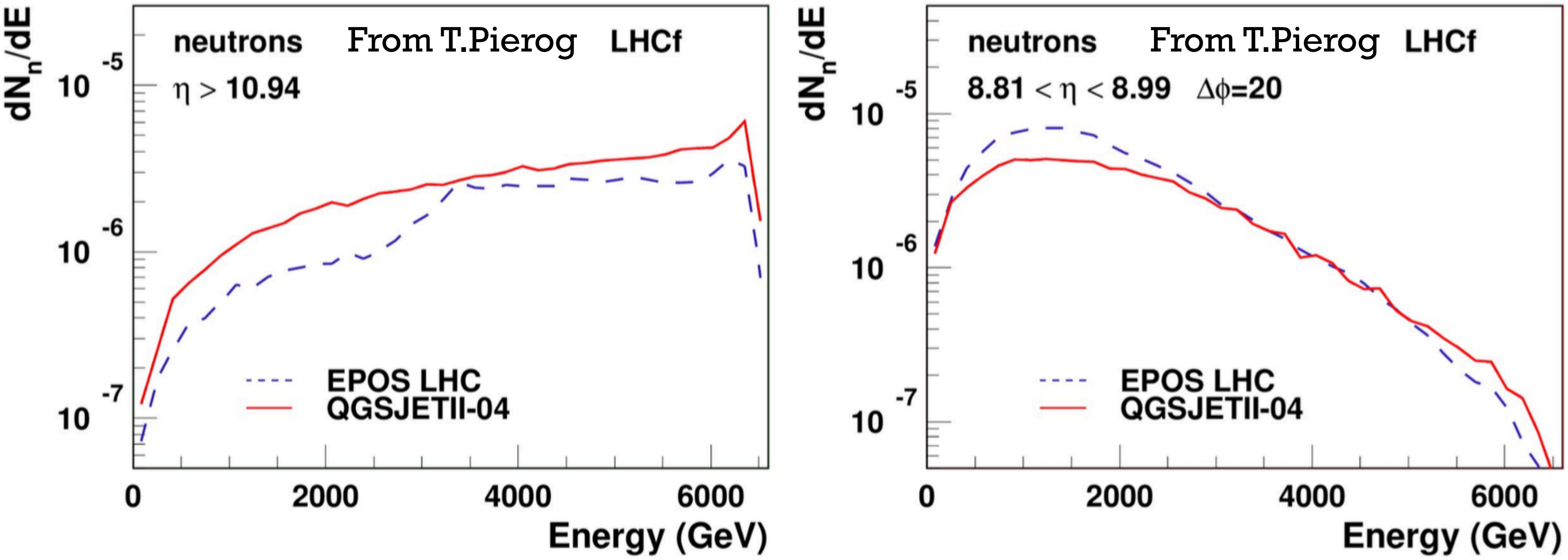


LHCf Data (UPC subtracted) vs Models

- The LHCf results in p-Pb (filled circles) show good agreement with DPMJET and EPOS.
- The LHCf results in p-Pb are clearly harder than the LHCf results in p-p at 5.02TeV (shaded area) which are interpolated from the results at 2.76TeV and 7TeV.

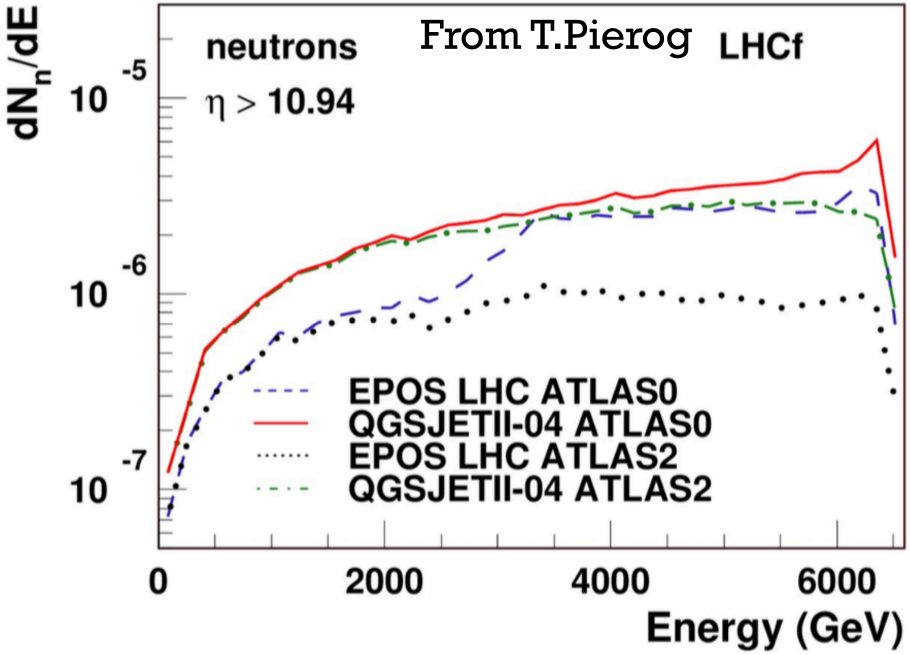
# + Very forward neutral particle spectra: neutrons

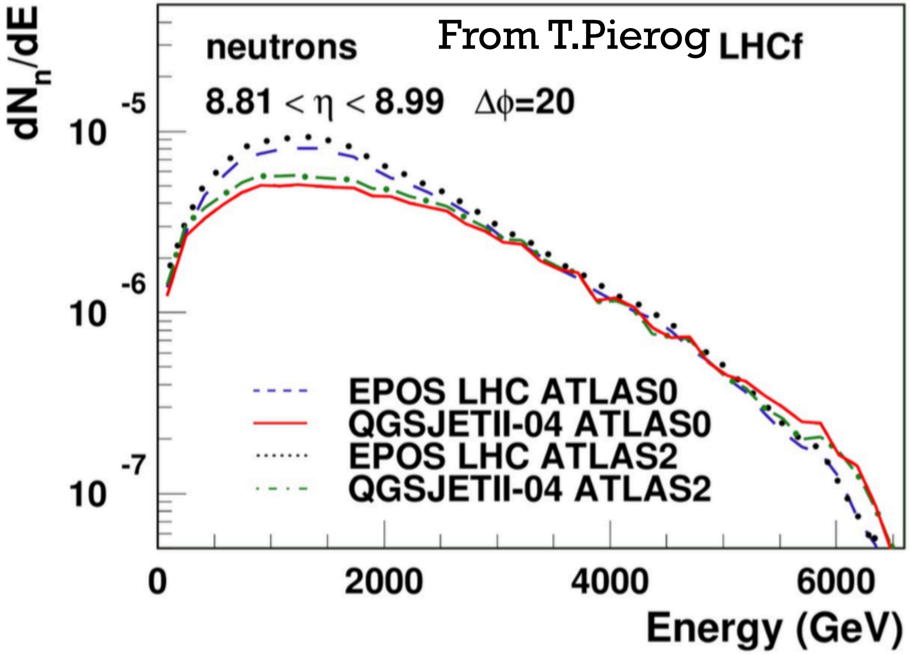
- Even larger differences wrt $\gamma$!
- 30% energy resolution is not taken into account
- …. But unfolding works well!



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

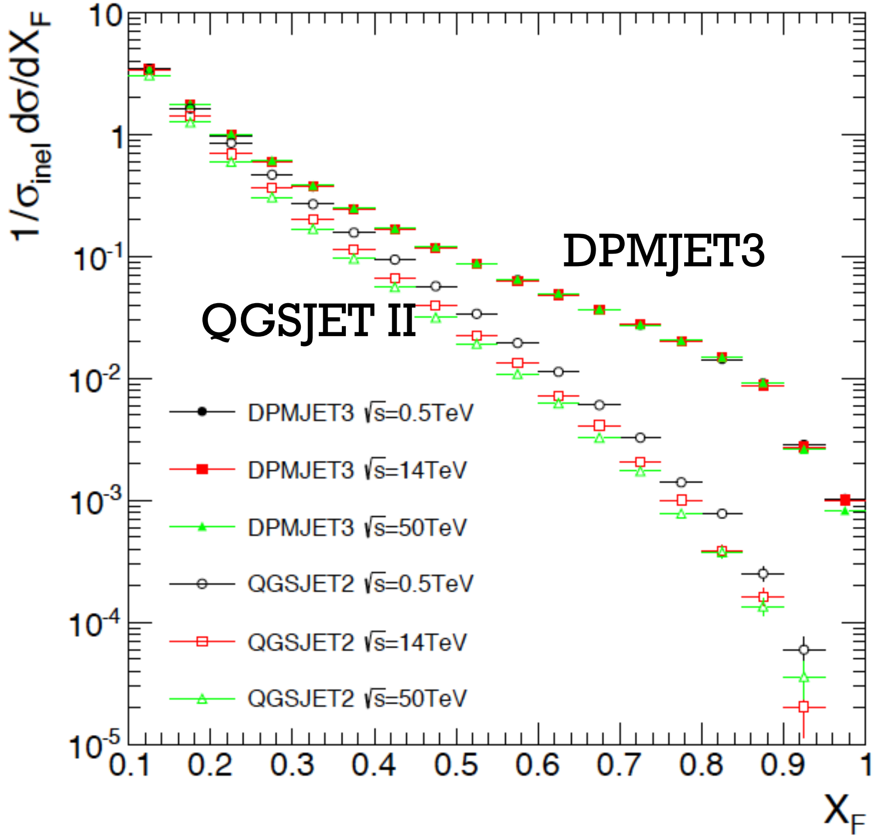
- ATLAS0: no charged particles in the $|\eta|<2.5$ and $p_t>0.1$ GeV/c
- ATLAS2: >1 charged particles in the $|\eta|<2.5$ and $p_t>0.1$ GeV/c
- Central activity selection enhance the differences btw models
- Could be used to tune different components of the models


From T.Pierog

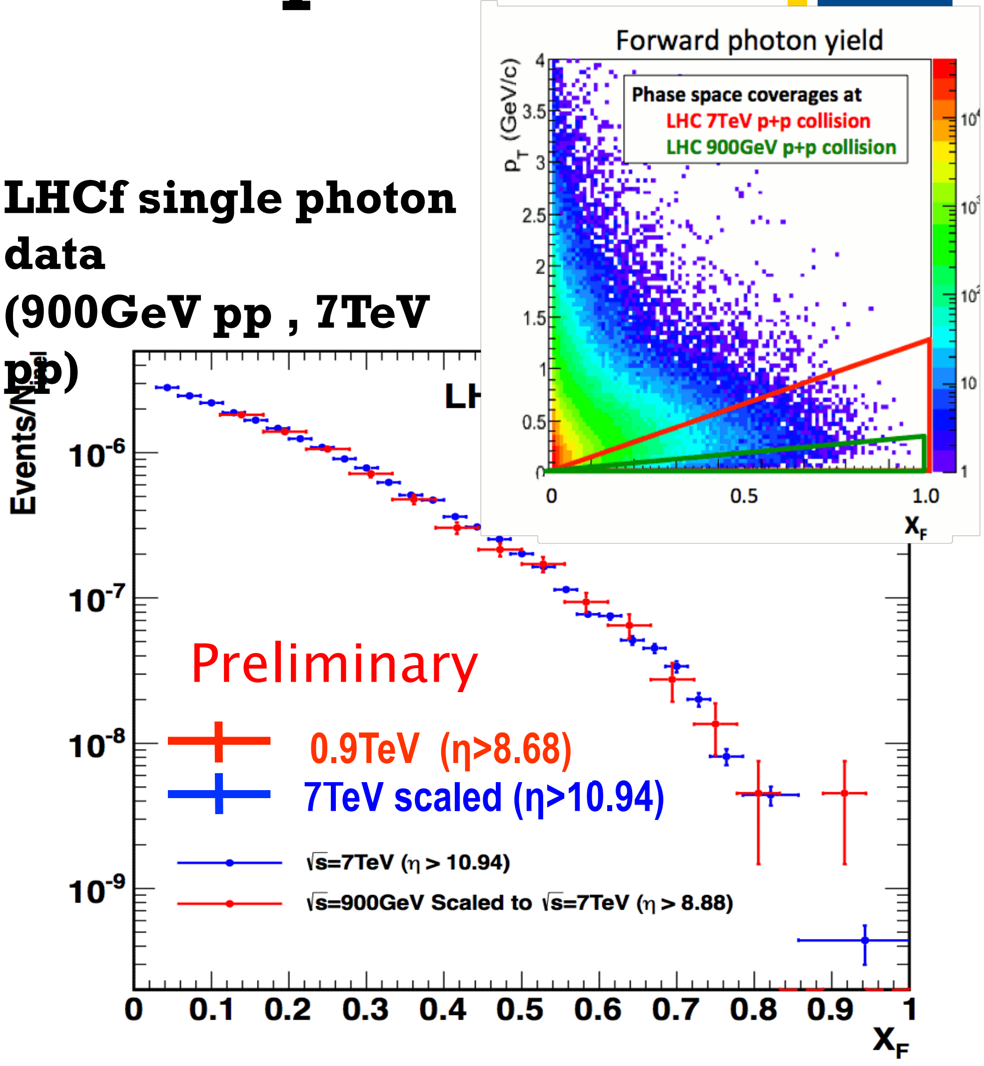

From T.Pierog

# $\sqrt{s}$ scaling : a key for extrapolation beyond the LHC

**All $\pi^0$ expected from models (0.5TeV, 14TeV and 50TeV)**

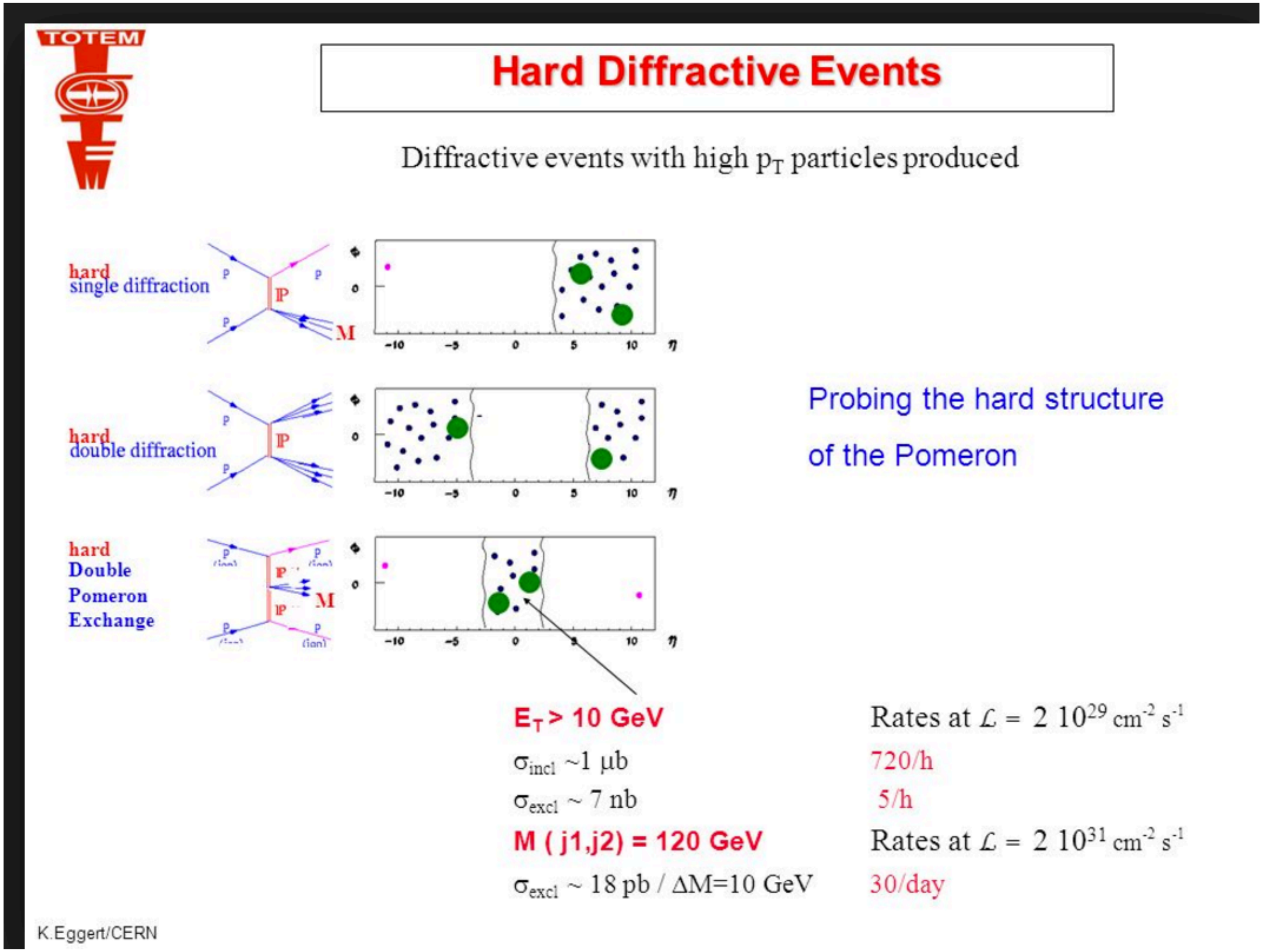


**LHCf single photon data (900GeV pp , 7TeV pp)**



Comparison done in the very limited phase space of 900GeV collisions

(green triangle in the phase space plot)



# Hard Diffractive Events

Diffractive events with high $p_T$ particles produced

hard single diffraction

hard double diffraction

hard Double Pomeron Exchange

Probing the hard structure of the Pomeron

**$E_T > 10$ GeV**

$\sigma_{incl} \sim 1\ \mu b$

$\sigma_{excl} \sim 7$ nb

**M ( j1,j2) = 120 GeV**

$\sigma_{excl} \sim 18$ pb / $\Delta M = 10$ GeV

Rates at $\mathcal{L} = 2\ 10^{29}\ cm^{-2}\ s^{-1}$

720/h

5/h

Rates at $\mathcal{L} = 2\ 10^{31}\ cm^{-2}\ s^{-1}$

30/day

K.Eggert/CERN