LHCf Status Report

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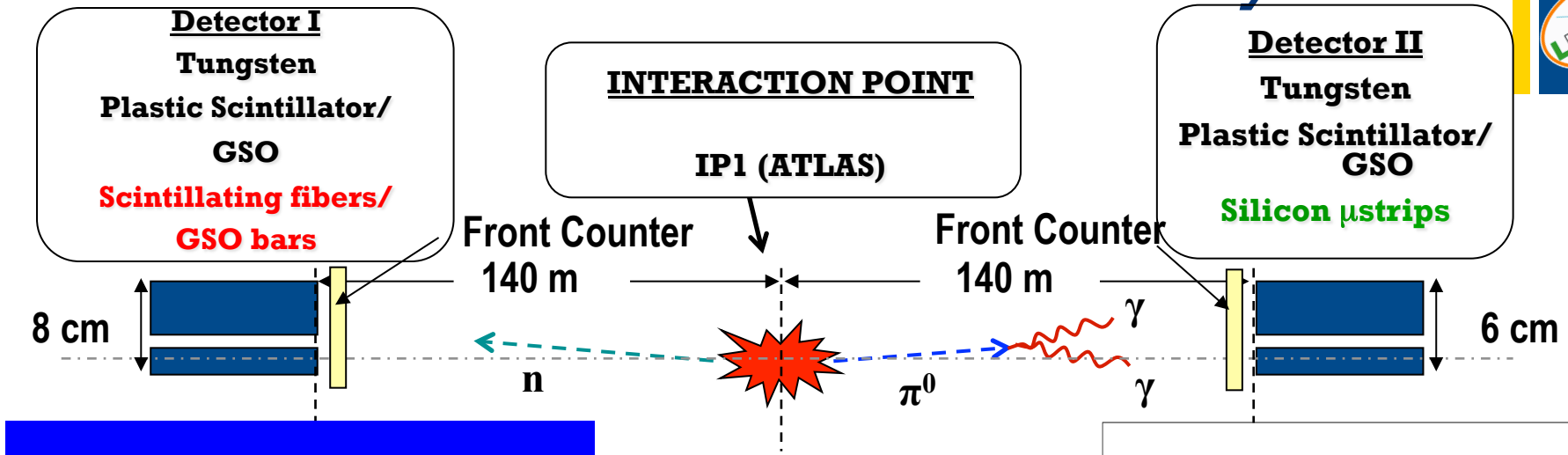
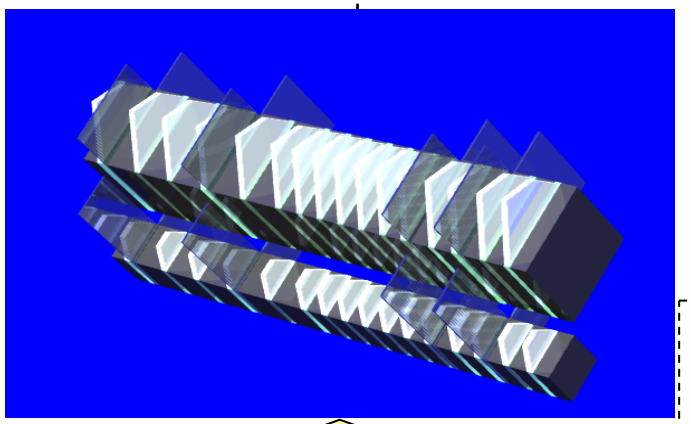
120th LHCC Meeting
CERN, November 19th, 2014

Contents

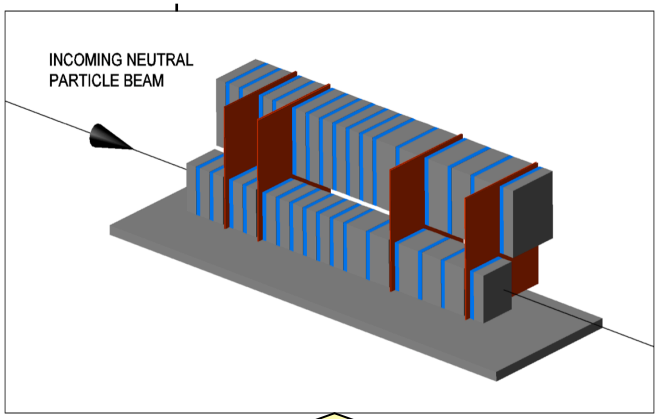
- Summary of LHCf physics results
  - Neutrons
  - Type II π^0
- Upgrade of the detectors
- Test Beam
- Installation in the tunnel
- 2015 Run

LHCf: location and detector layout





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



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

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

LHCf Physics Program

Year	Beams	Beam energy	Proton equivalent energy in the LAB (eV)	Setup
2009/2010	p - p	450+450 GeV	$4.3\ 10^{14}$	Arm1+Arm2
2010	p - p	3.5+3.5 TeV	$2.6\ 10^{16}$	Arm1+Arm2
2013	p – Pb	4 TeV proton	$1.3\ 10^{16}$	Arm2
2013	p - p	1.38+1.38 TeV	$4.1\ 10^{15}$	Arm2
2015	p - p	6.5+6.5 TeV	$9\ 10^{16}$	Arm1+Arm2 upgraded
>2020?	p–light ions@LHC	?	?	?

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)	Ready to be submitted	Phys. Rev. D 86, 092001 (2012)
p-p 2.76 TeV	4.1×10^{15}			Phys. Rev. C 89, 065209 (2014)
p-Pb 5.02 TeV	1.3×10^{16}			
p-p 7 TeV	9.0×10^{16}	Waiting for LHC restart!		

Latest analysis

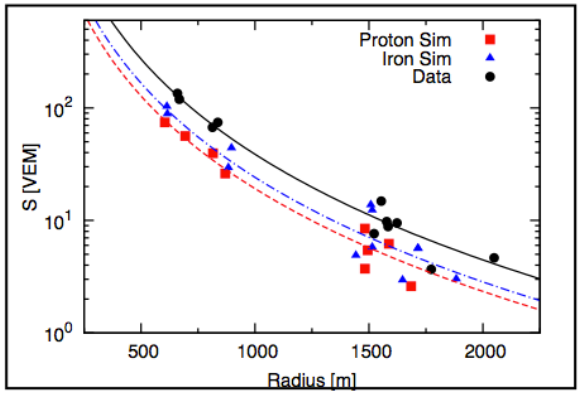
Neutrons in 7 TeV pp collisions

Type II π^0 in 7 TeV pp collisions

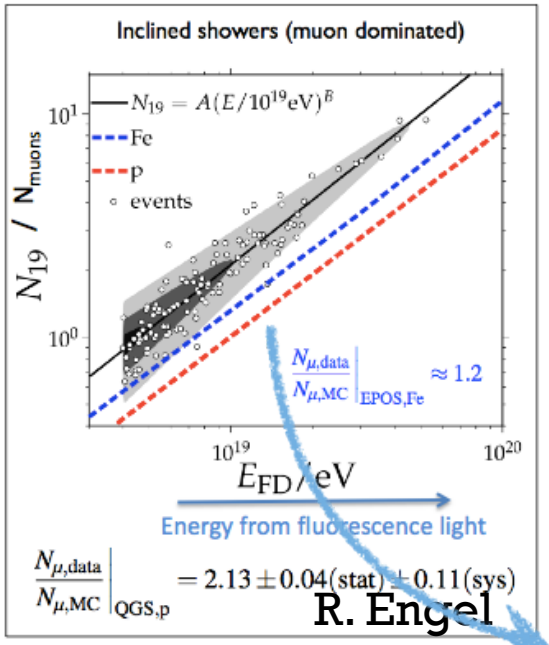
LHCf @ pp 7 TeV: neutron analysis

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

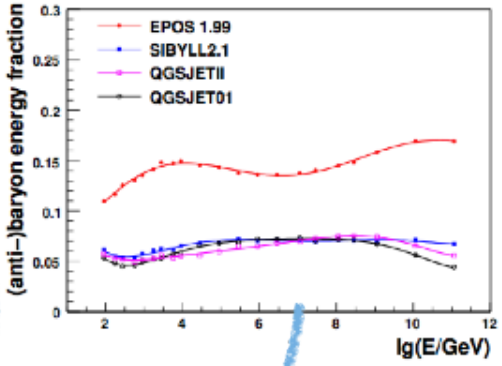


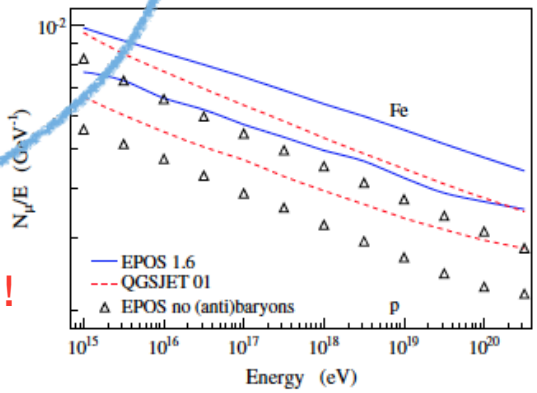
[J.Allen, et al. ICRC2011 Proceedings]



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 muons due to larger baryon production, even if it is not sufficient to reproduce the experimental data

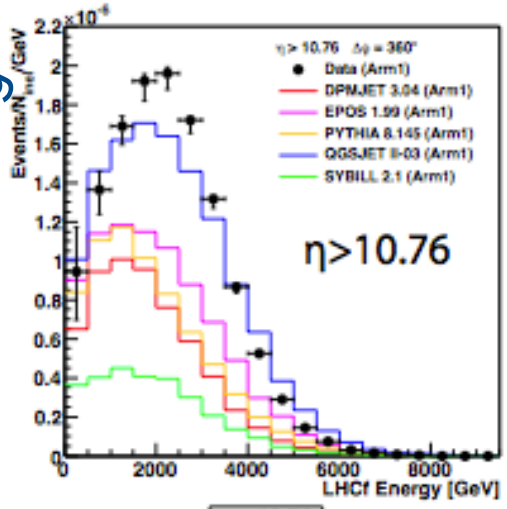


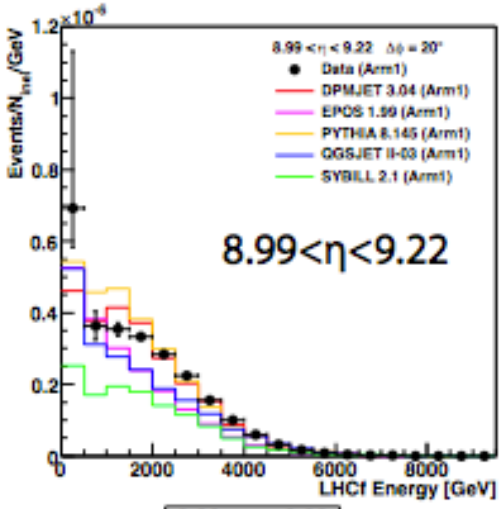


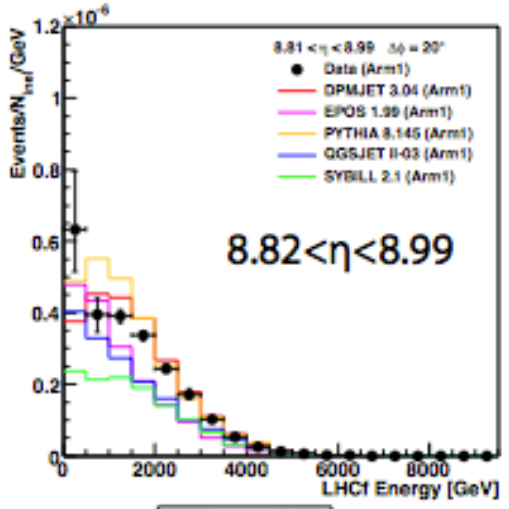
importance of baryon measurement!!!

Inclusive neutron spectra (7 TeV pp)

Before unfolding

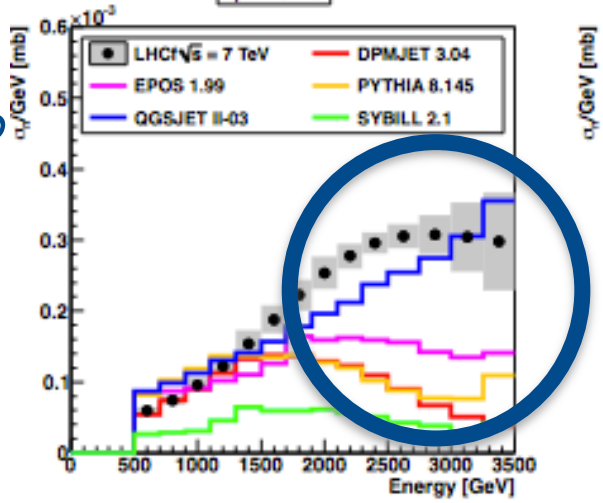


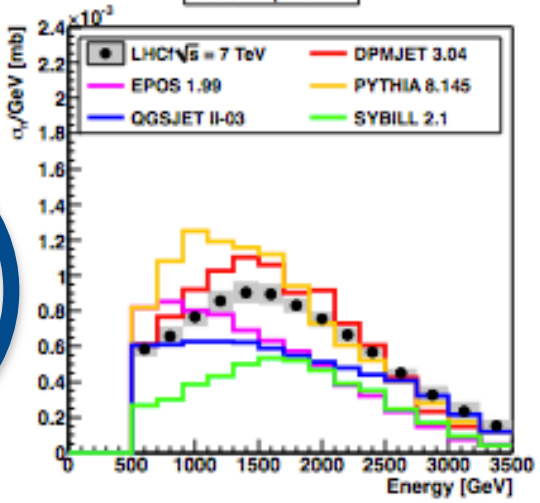


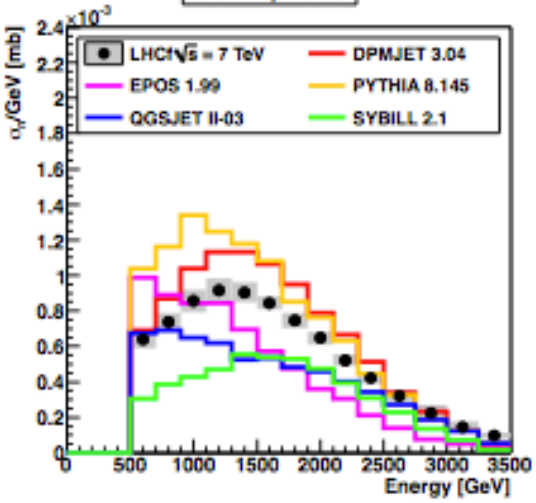


η > 10.76 | 8.99 < η < 9.22 | 8.81 < η < 8.99

After unfolding



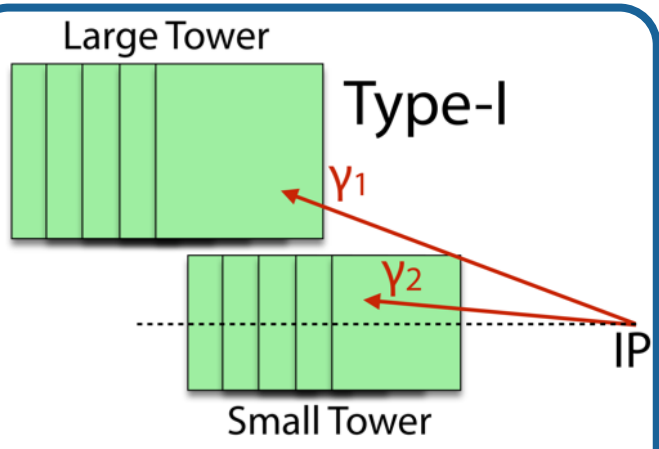


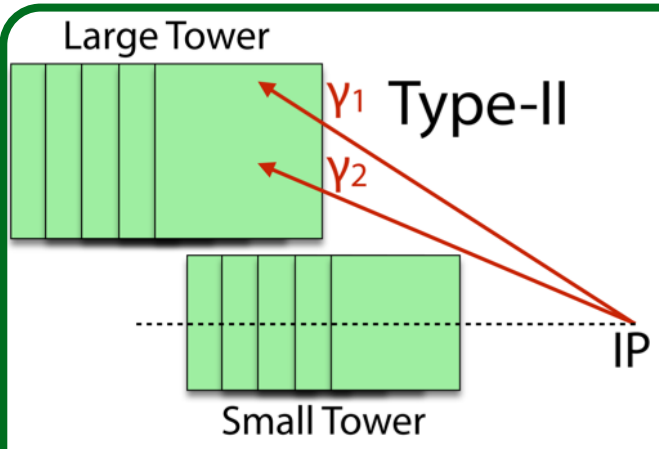


Very large high energy peak in the η>10.76 (predicted only by QGSJET)
→ Small inelasticity in the very forward region!

+ Type II π^0 in pp 7 TeV collisions

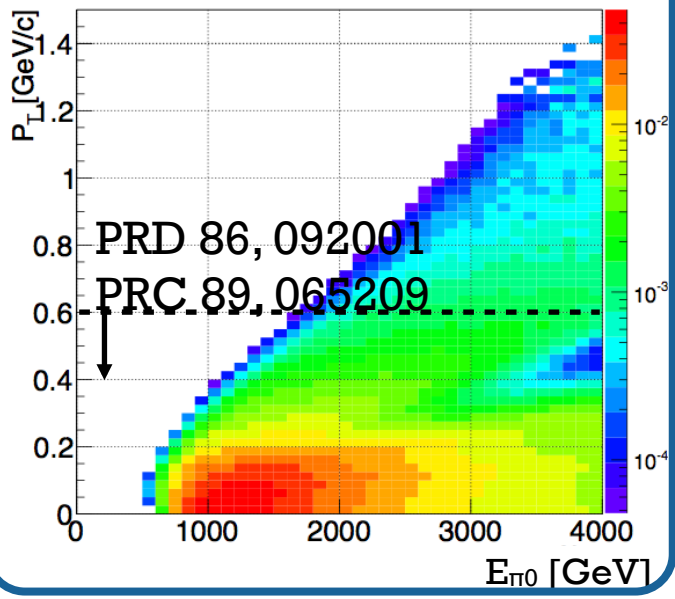
Present LHCf results are based on the Type-I π^0 events.
Improved π^0 reconstruction, Type-II, is now ready for use in analysis.



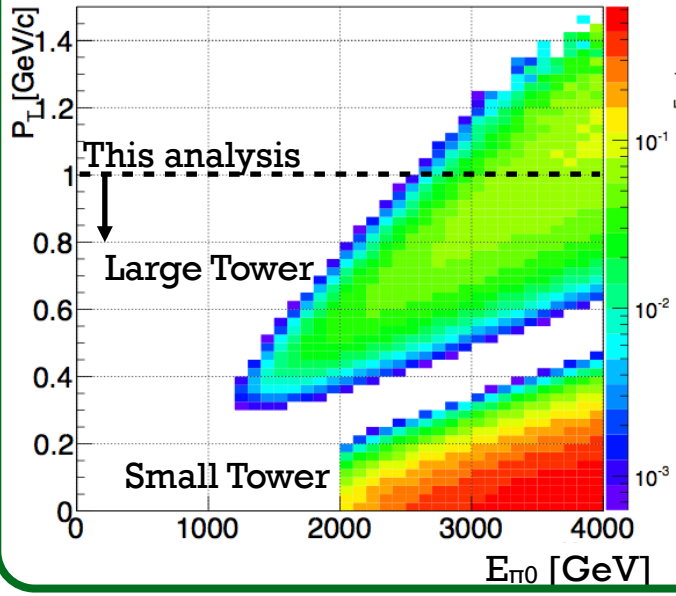


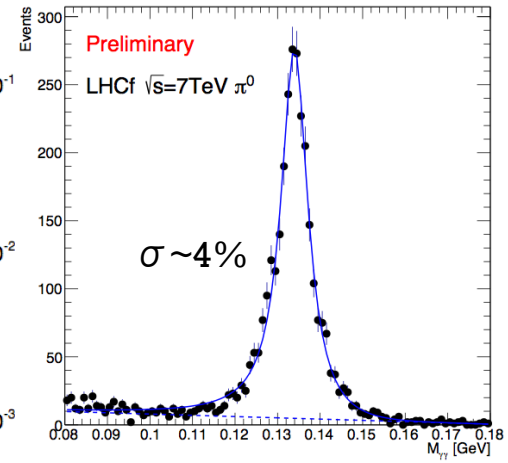
Motivation of Type-II
- extended p_T range
- applicable to Λ and K
- di-hadron.

Arm2 acceptance for Type-I π^0

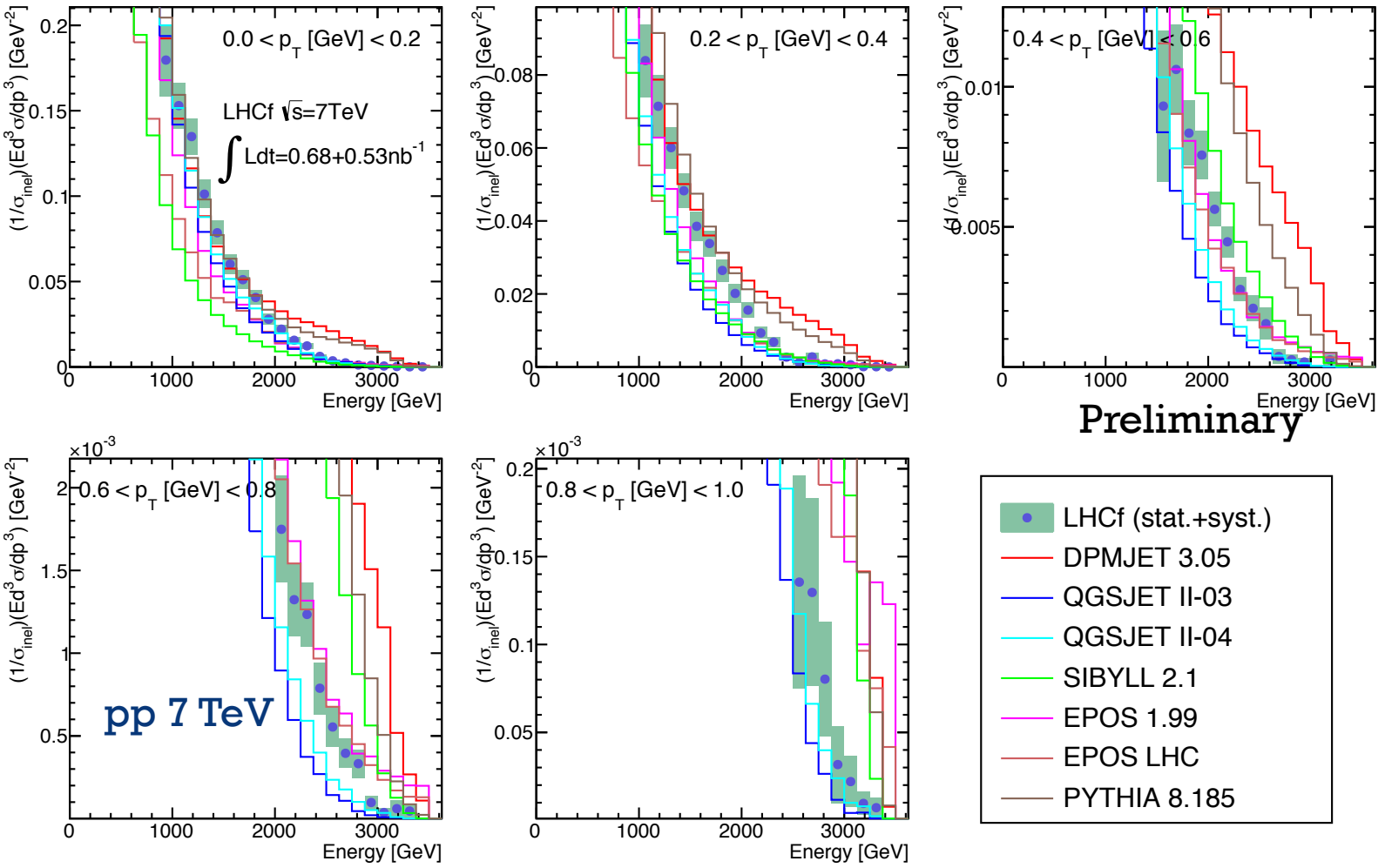


Arm2 acceptance for Type-II π^0



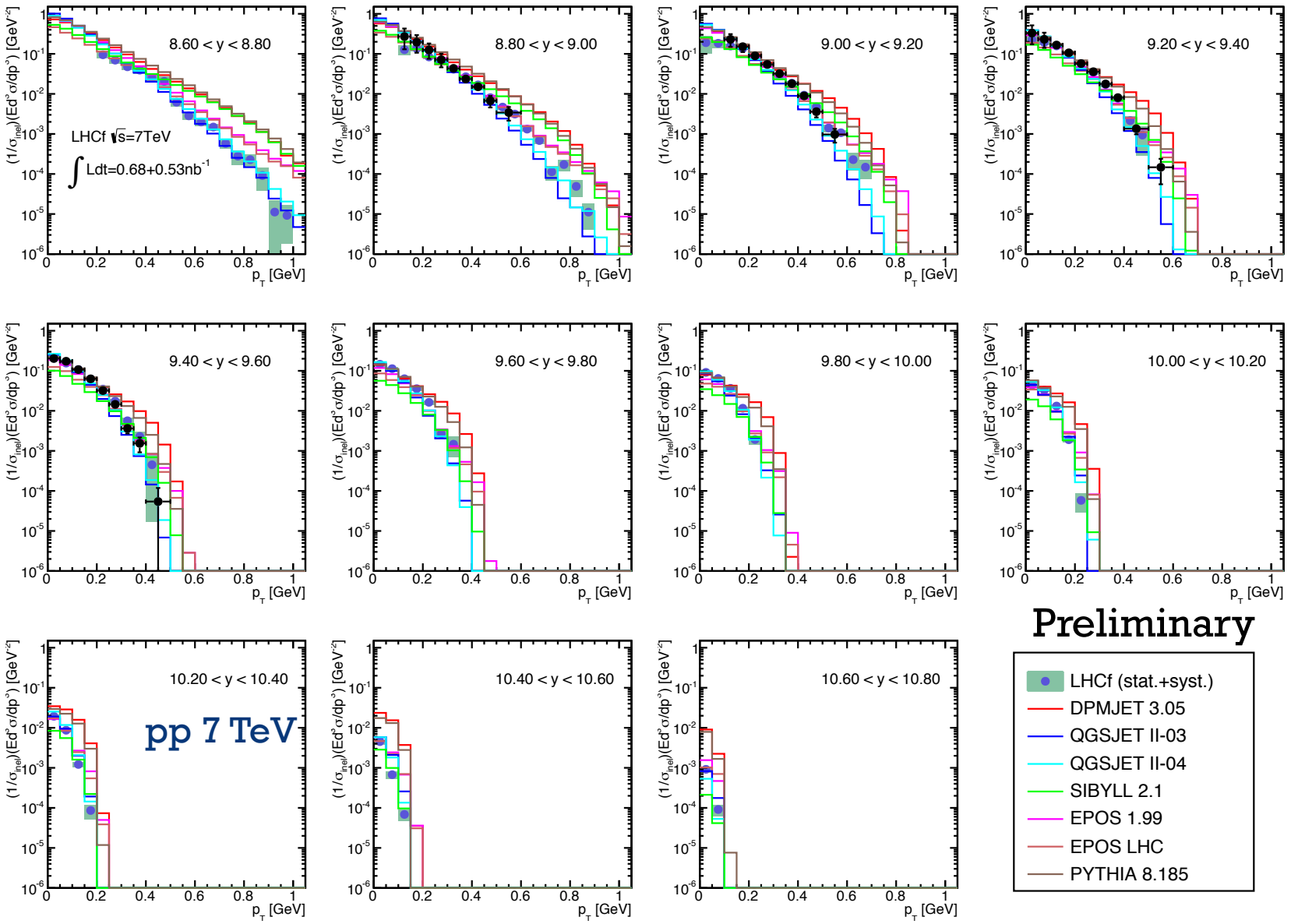


+ π^0 energy spectra (for different p_T bins)



- 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)



Detectors upgrade
October 2014 SPS Test Beam
Installation in the LHC tunnel

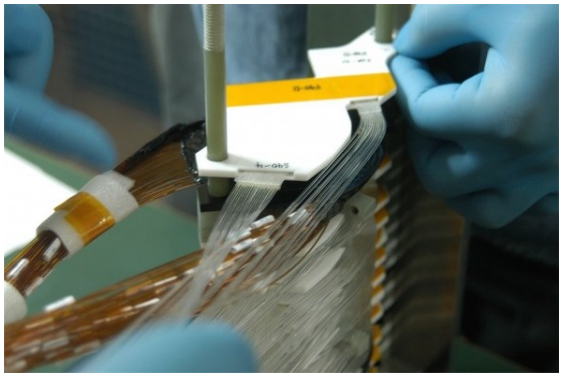
Status of detectors

- Both Arm1 and Arm2 have been upgraded to optimize the 13 TeV operation

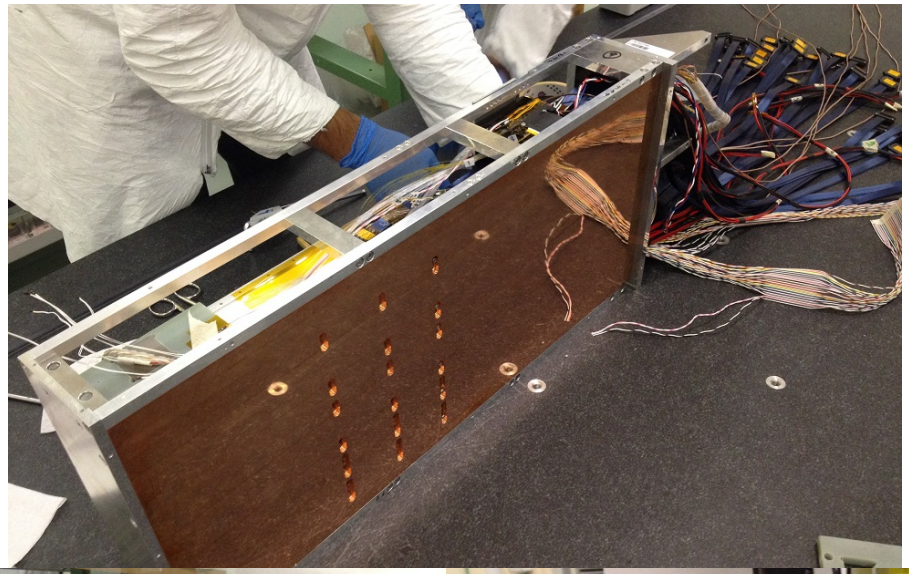
- Upgrade of the scintillator measuring system in Arm1 by replacing plastic scintillating fibers with GSO small bars (1 mm^2)
- Upgrade of the silicon positioning measurement system in Arm2:
  - Rearranging Silicon layers for independent precise energy measurement
  - Increase the dynamic range to reduce saturation effects (new silicon sensors and new hybrid circuits)
- Calorimeter radiation hardening both in Arm1 and Arm2 by replacing plastic scintillator with GSO
- Particular care has been used for the temperature monitoring because of the observed π^0 mass peak shift correlated with temperature during LHC operation

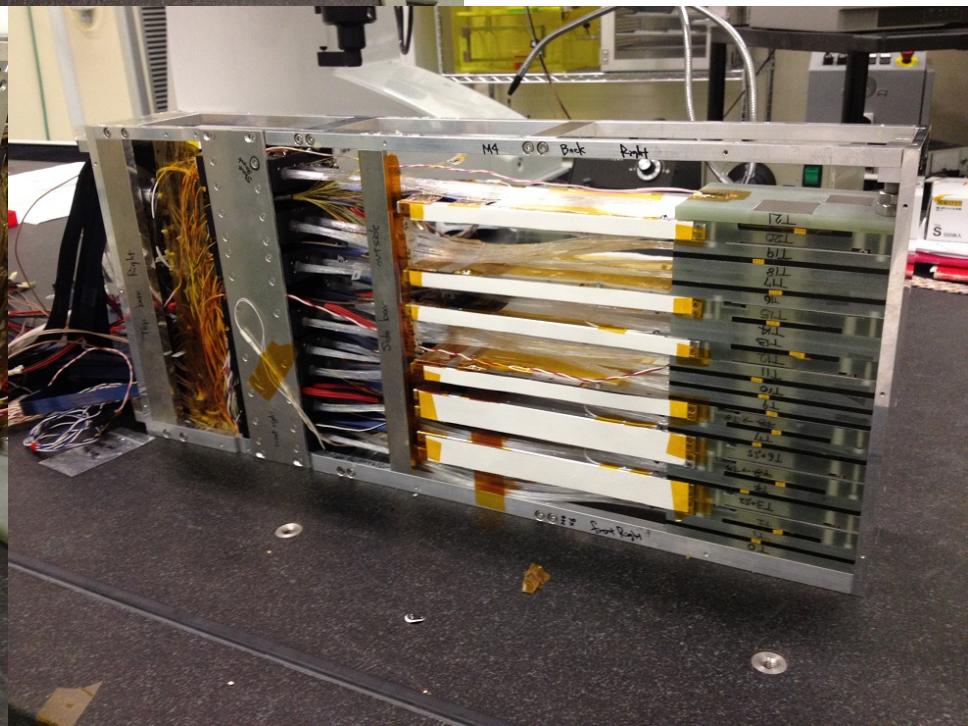
- Production, assembly and laboratory tests have been completed both for Arm1 and Arm2

Full Assembling of Upgraded Arm1



Full Assembling of Upgraded Arm2



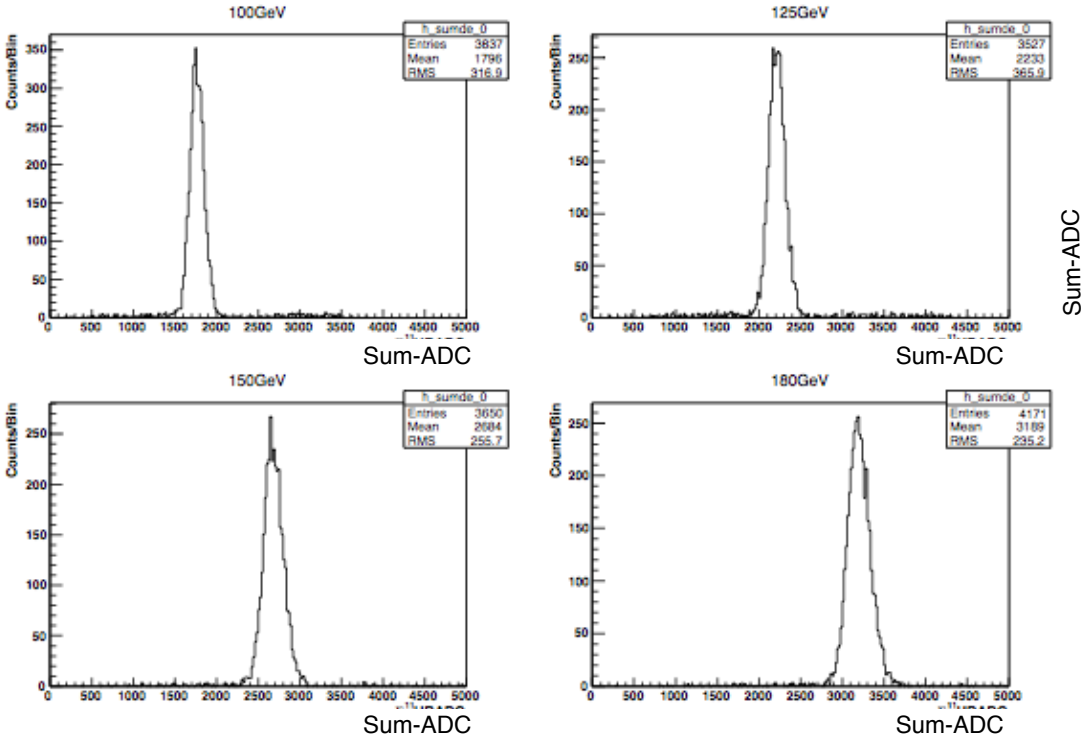


Preparation for test beam

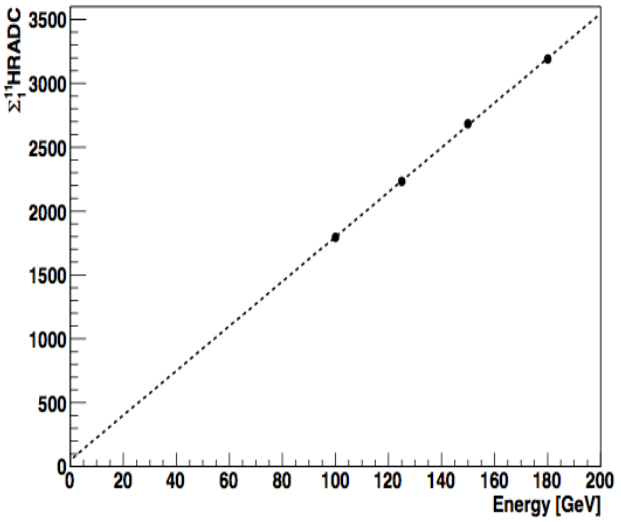
- Test beam in the H4 area @SPS from October 6th, to 15th, 2014
- Purpose of the test:
  - Final precise calibration of the GSO absolute energy scale both for Arm1 and Arm2
  - Final precise calibration of the silicon part for the energy measurement
  - Measurement of the shower position resolution for the upgraded silicon part
  - Measurement of the temperature dependence of the energy calibration (chillers are used to change Temperature)
- Test beam was very successful!
  - Thanks to the SPS coordinator for the nicely timing of the test (at the very beginning of the SPS operation)

Arm1 e.m. energy measurement

Sum-ADC (2nd-12th)

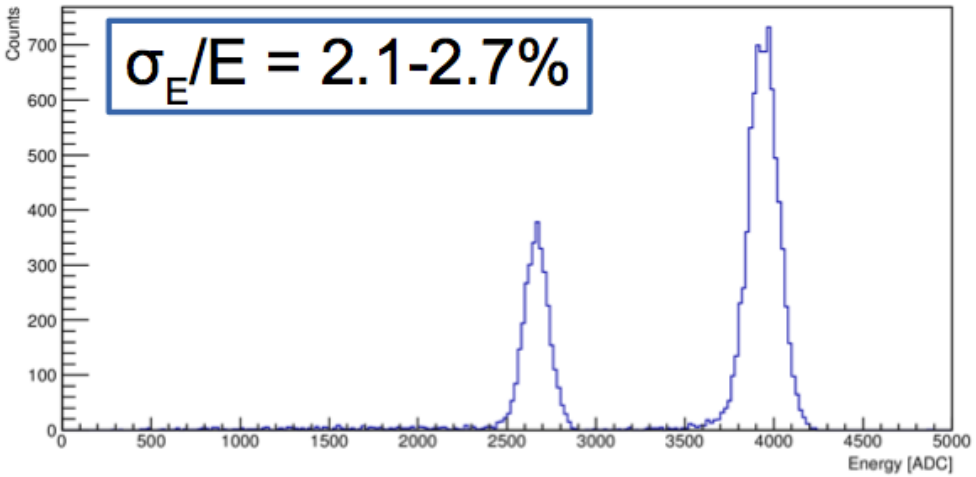


Linearity



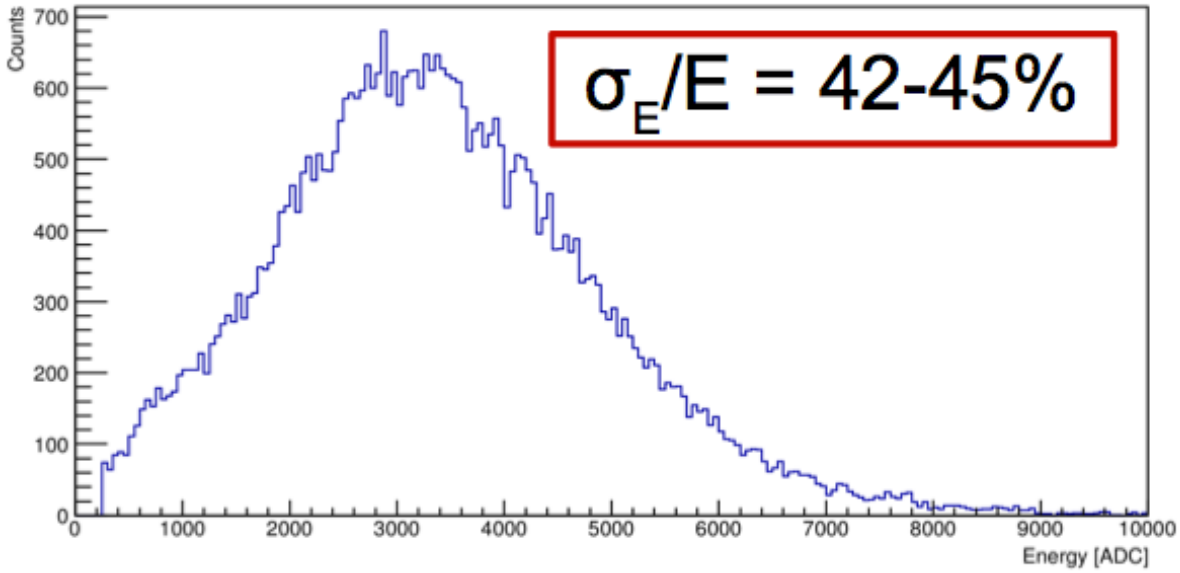
- Sum-ADC distribution
- Sharp peak in each energy, good energy resolution
- Good linearity

Arm2 Energy Reconstruction



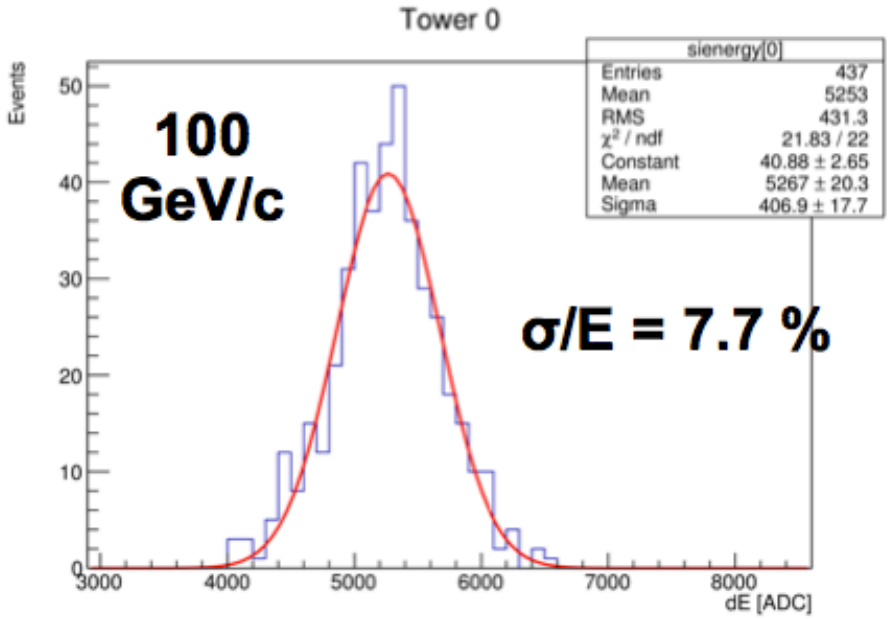
100 & 150 GeV electron beam on small tower center

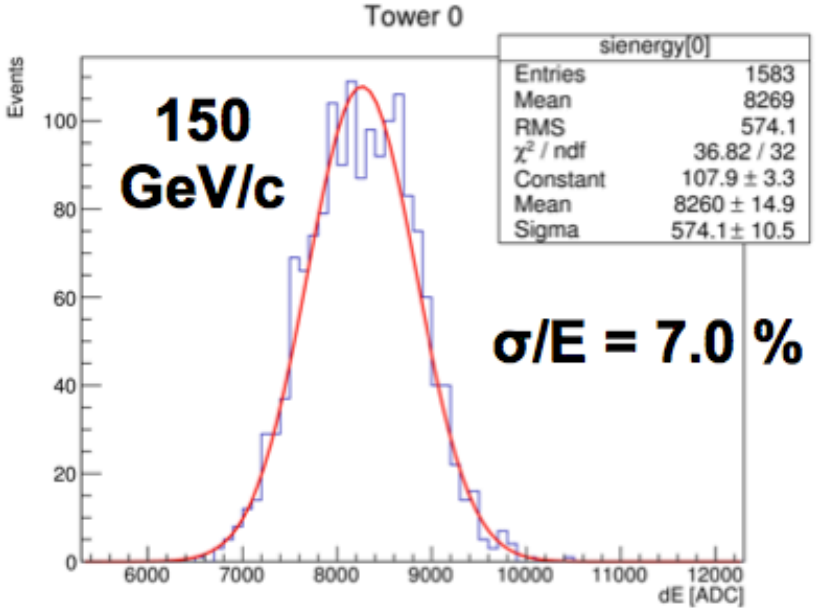
300 GeV proton beam on small tower center



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)

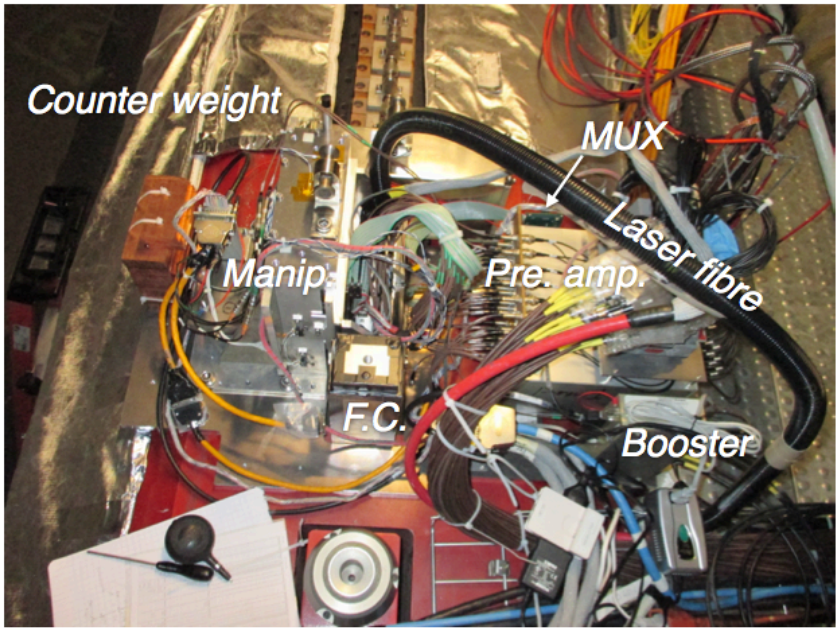


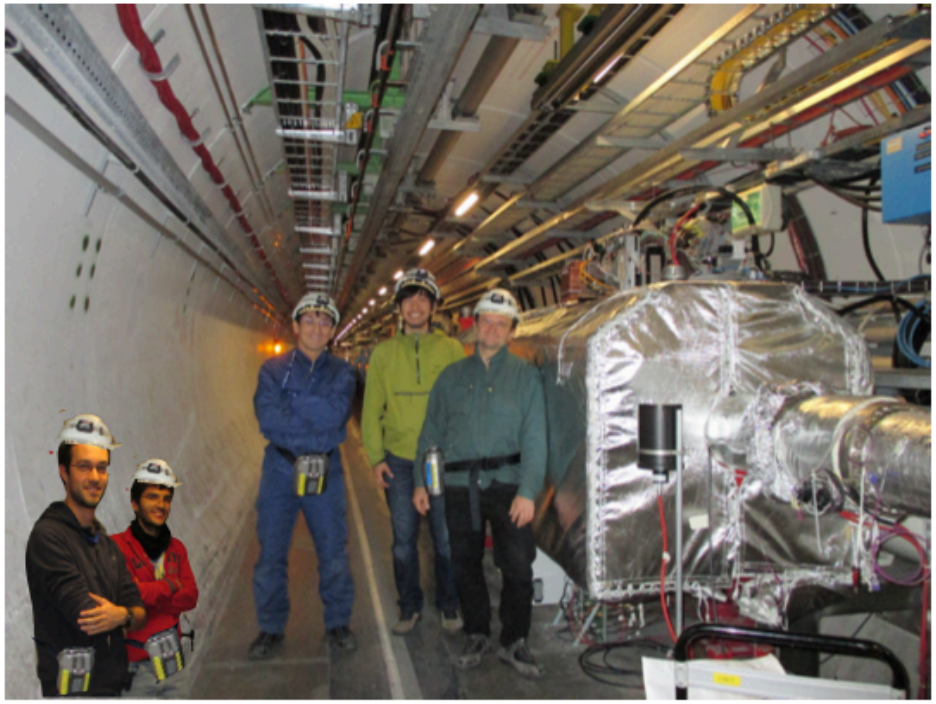


- Resolution with old configuration: 8.4 % @100 GeV
  8.2 % @150 GeV

Installation in LHC

- The installation in LHC is currently under way!
  - This week for Arm1
  - Next week for Arm2
- Remote handling system used to install the detector
- Commissioning of the detectors
  - Pedestal runs
  - Check with Laser
- Arm1 installation was successfully completed on Monday, November 17th


Counter weight
MUX
Laser fibre
Manip.
Pre. amp.
F.C.
Booster



The 2015 p-p run

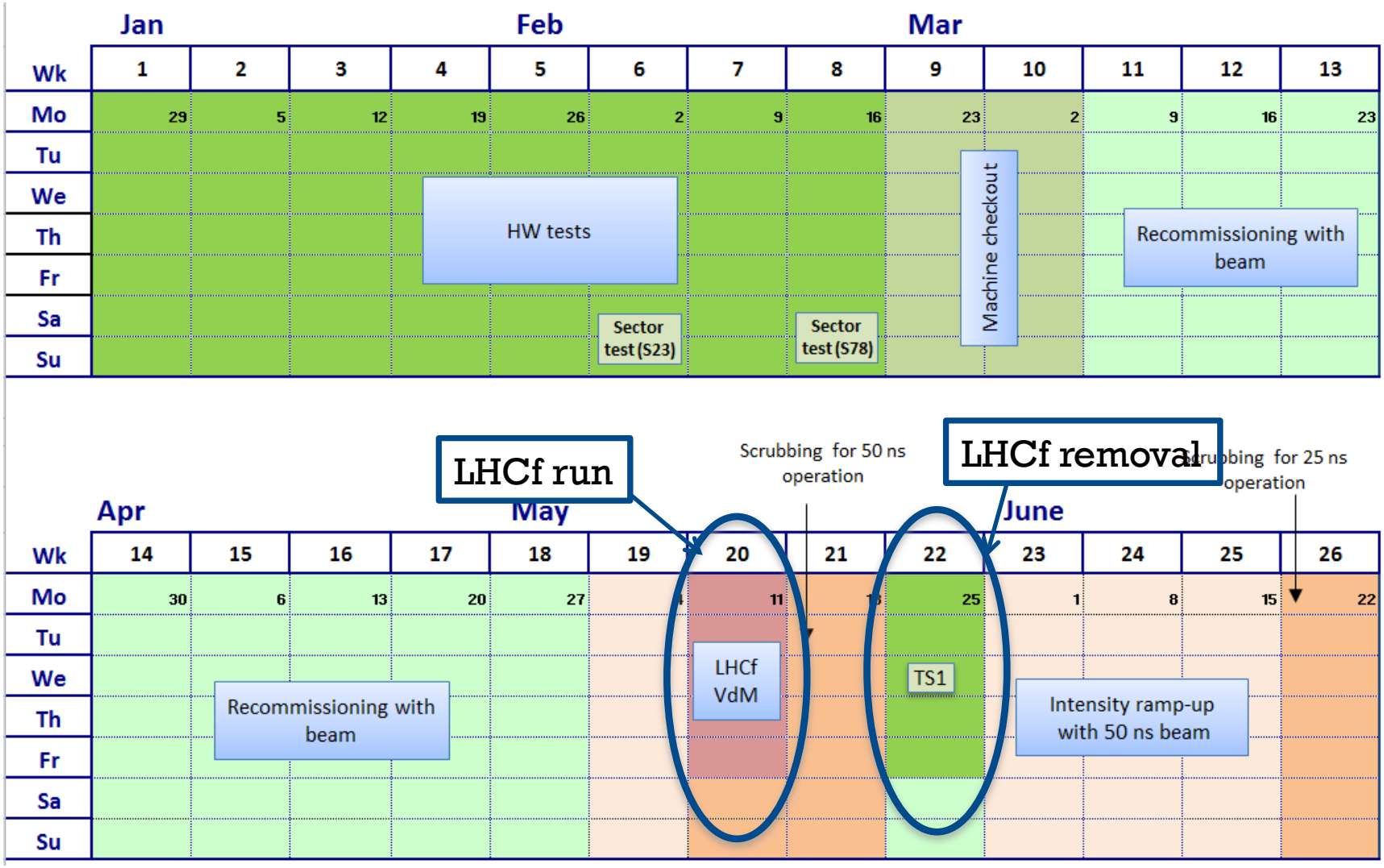
- Long discussions in the previous years to have the possibility of an optimized run for LHCf
- Our requests have been nicely considered and taken into account → Thanks to the LHC Program Coordinators!!!!

LHCf run

- Ideal beam conditions:
  - $\beta^* = 19m$, optics commissioned for VdM scan as well
  - Half crossing angle of 145 urad
  - isolated bunches with some non-colliding (no trains)
  - very low pileup
  - $L \sim 5x10^{28}\ cm^{-2}s^{-1}$
  - Goal: collect 5-20 nb^{-1}
- Constraints:
  - The run must be taken before 500 pb^{-1} of delivered luminosity in IP1
    - Beyond that LHCf will suffer from radiation damage even it is kept in garage position

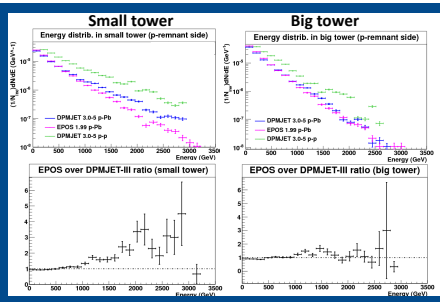
From E. Meschi, Experiment's expectation for 2015, LHC Performance workshop, Chamonix 2014

2015 operation schedule



Conclusions

- Most of the 'classic' 7 TeV p-p and 5.02 TeV p-Pb analysis have been completed and published
- Some 'more exotica' analyses are under way
  - Type II π^0 preliminary results
- The p-Pb analysis of the data jointly taken with Atlas is starting
  - On December 11th we will have a jointly Atlas-LHCf meeting dedicated to the analysis of p-Pb data and to the future joint operations
- Detectors have been upgraded and tested at the SPS, and we are installing them in the tunnel
- Ready for the 2015 13 TeV p-p run!


Small tower
Big tower
Energy distrib. in small tower (p-remnant side)
Energy distrib. in big tower (p-remnant side)
DPMJET 3.0-5 p-Pb
EPOS 1.99 p-Pb
DPMJET 3.0-5 p-p
Energy (GeV)
EPOS over DPMJET-III ratio (small tower)
EPOS over DPMJET-III ratio (big tower)

Backups

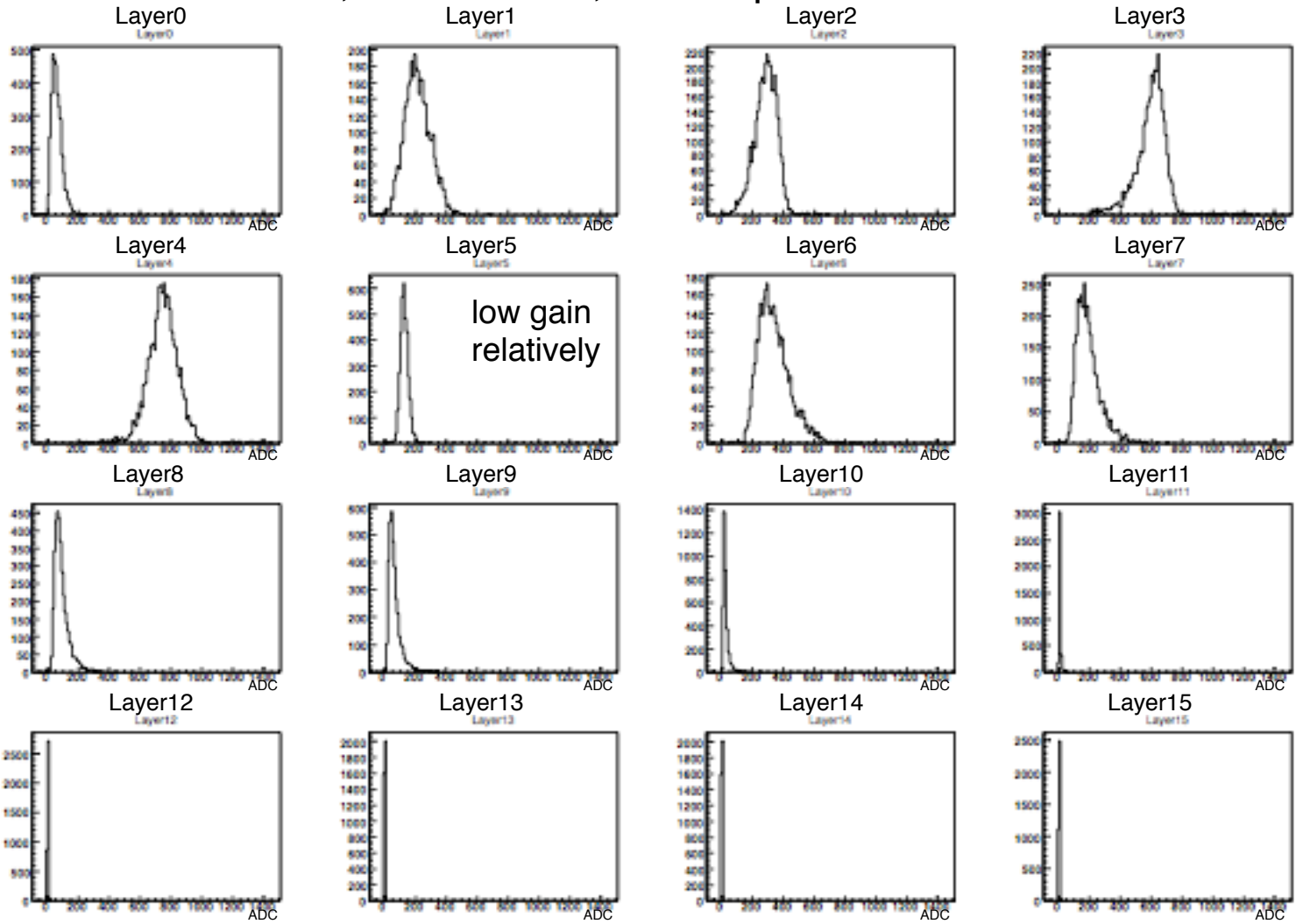
Future-Future plans….
p-Light ions collisions

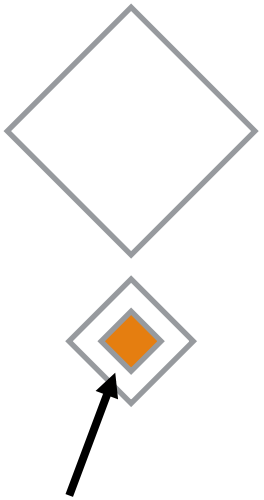
- Possible run with light ions @ LHC?
  - >2020? We are in touch with the working groups discussing these items (Yellow Book)

- Possible run with light ions @RHIC?
  - It depends on the RHIC programs after the long >2016 shutdown
  - RHIC will be possibly upgraded to increase luminosity and polarization
  - Some rumors that p-light ions could be brought to collisions

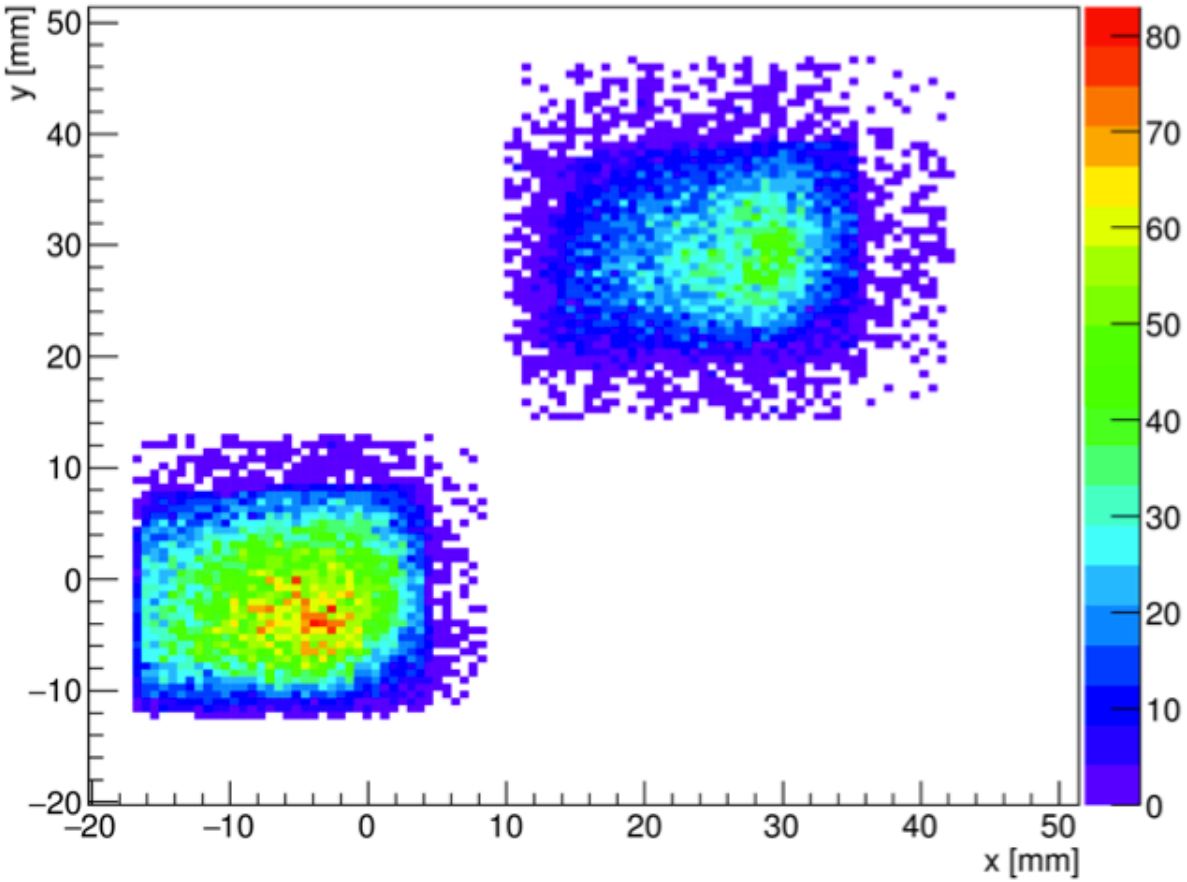
Arm1 Longitudinal development of e.m. shower

150GeV electron, 20mm tower, central position





Arm2 Position Reconstruction



- 100 GeV electron beam on towers center

The challenge of neutron analysis

Performance for 1.5 TeV neutrons:

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

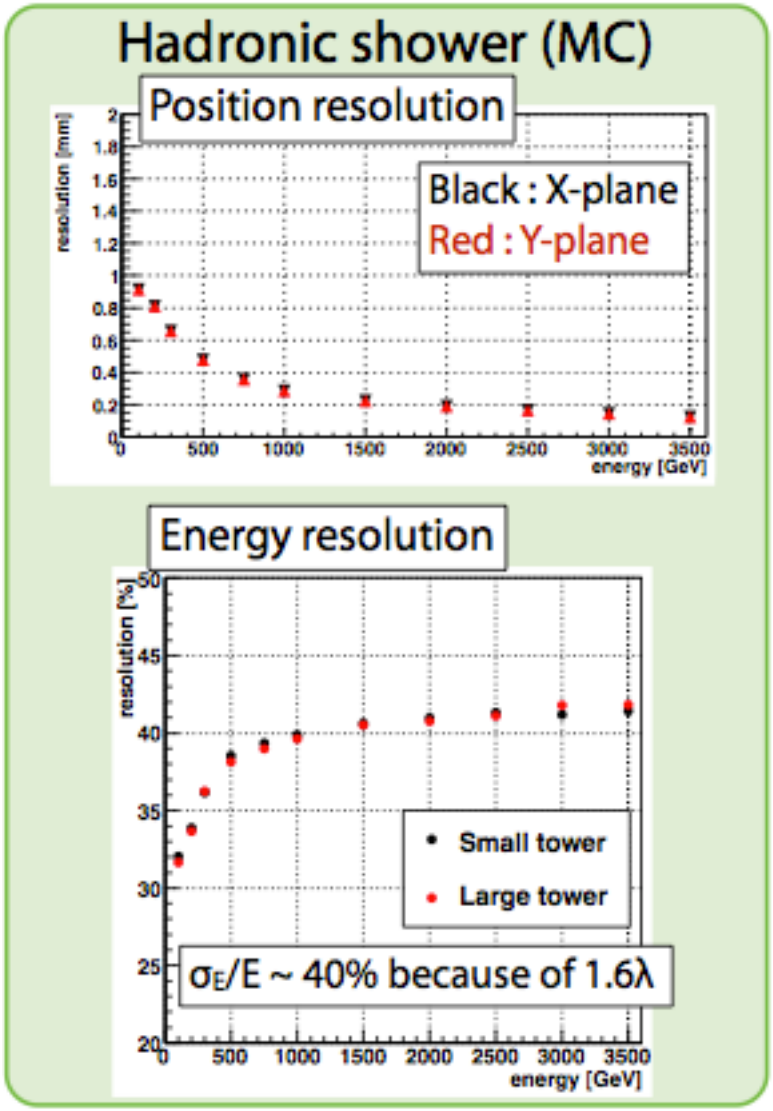
Δx ~ 1mm

And….

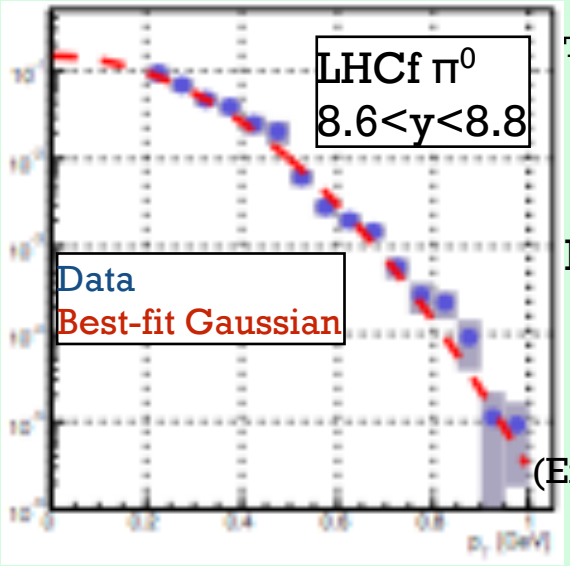
Detector performance is also interaction model dependent!

Unfolding is essential to extract physics results from the measured spectra

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



+ Average p_T and limiting fragmentation



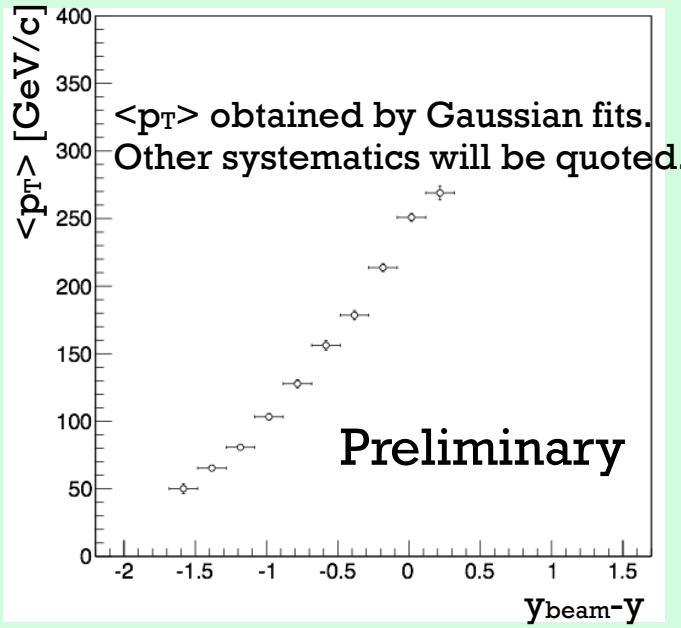
p_T spectra can be fitted by a Gaussian shape:

$$\frac{1}{\sigma_{inel}} E \frac{d^3\sigma}{dp^3} = A \frac{\exp(-p_T^2/\sigma_{Gauss}^2)}{\pi \sigma_{Gauss}^2}.$$

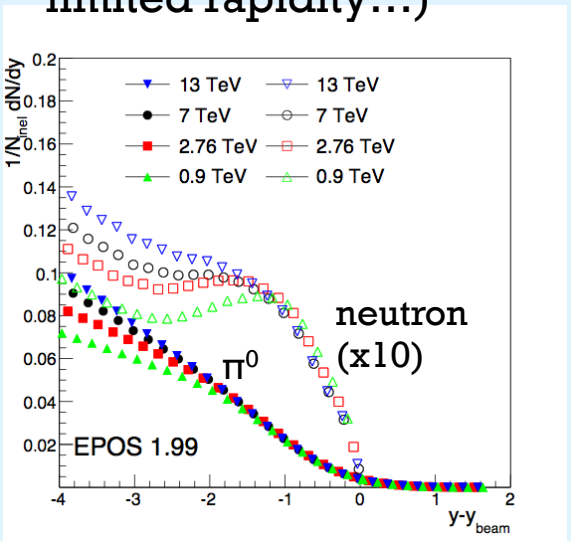
hen the average p_T $\langle p_T \rangle$is obtained by

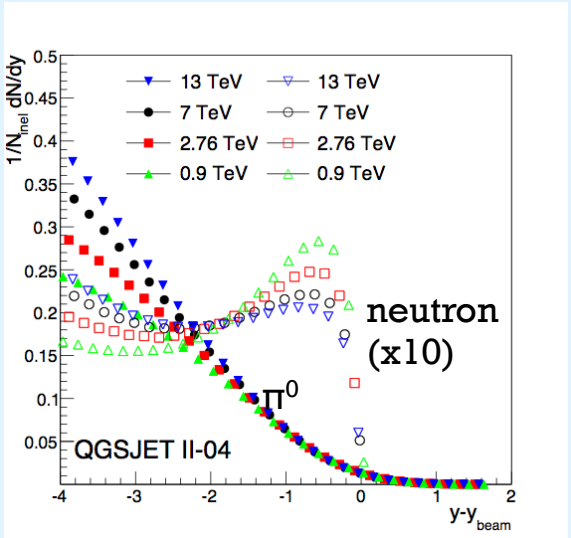
$$\langle p_T \rangle = \frac{\int 2p_T^2 f(p_T) dp_T}{\int 2p_T f(p_T) dp_T} = \frac{\sqrt{\pi}}{2} \sigma_{Gauss},$$

(Exponential and Tsallis fail to fit the LHCf data.)

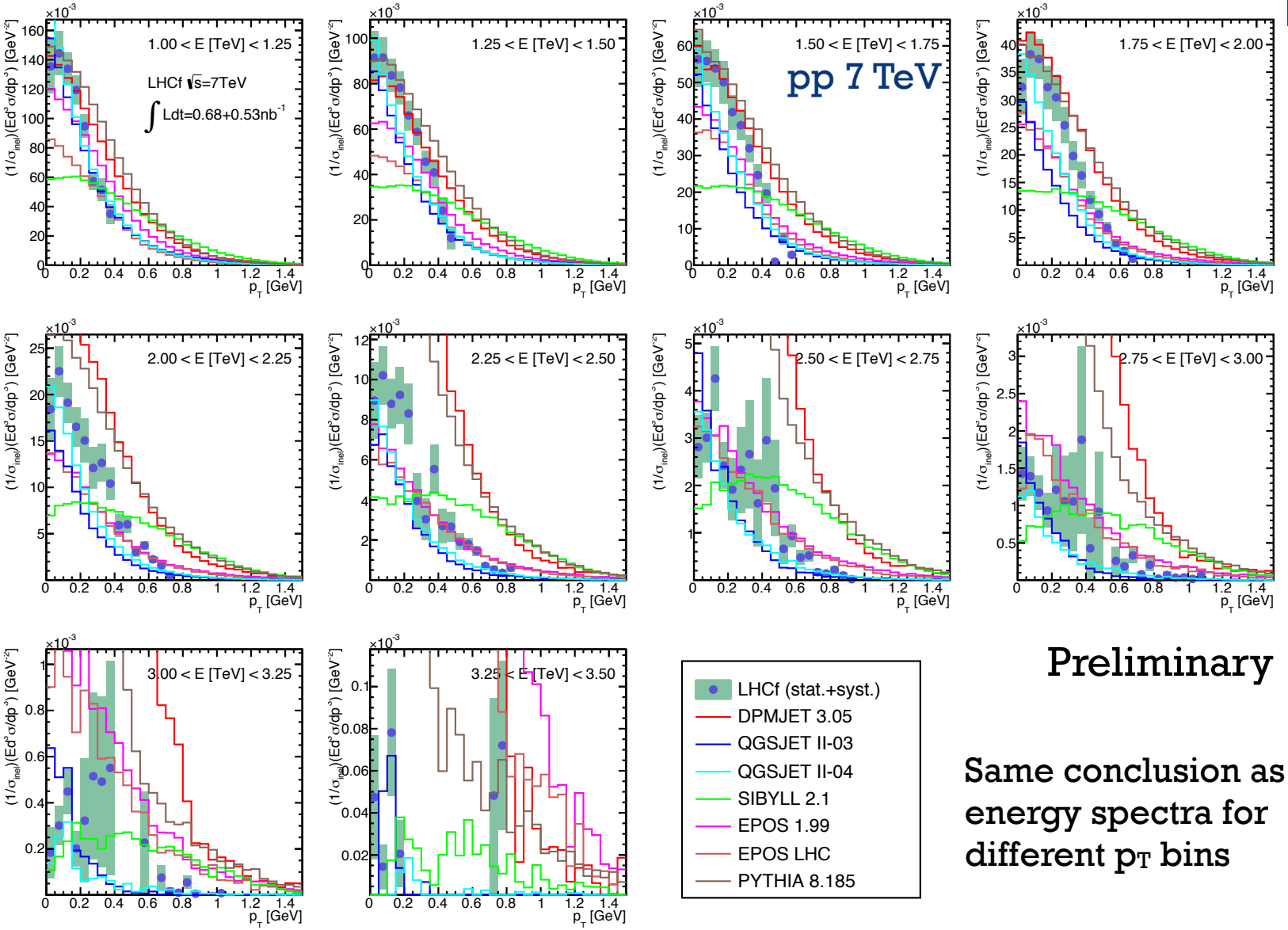


LHCf provides a unique opportunity to test a limiting fragmentation (analysis ongoing but limited rapidity…)





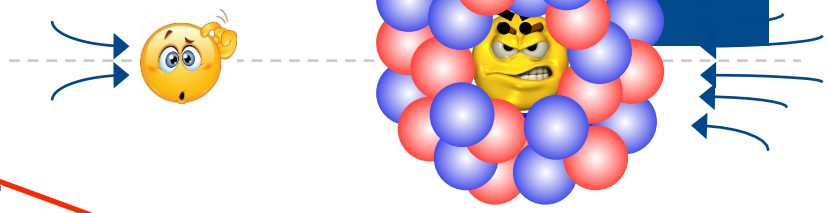
π^0 p_T spectra (for different Energy bins)



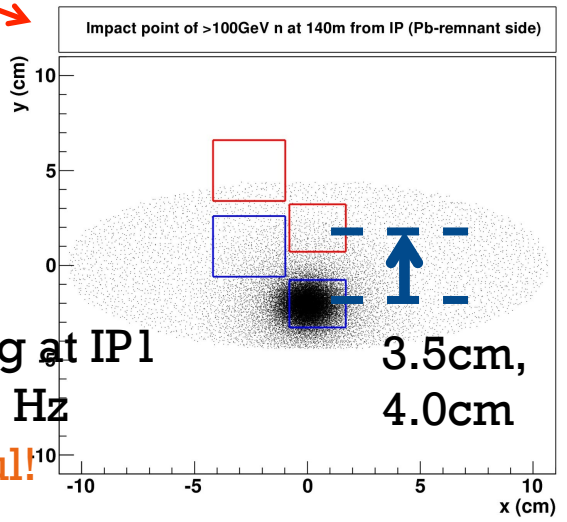
Preliminary

Same conclusion as energy spectra for different p_T bins

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

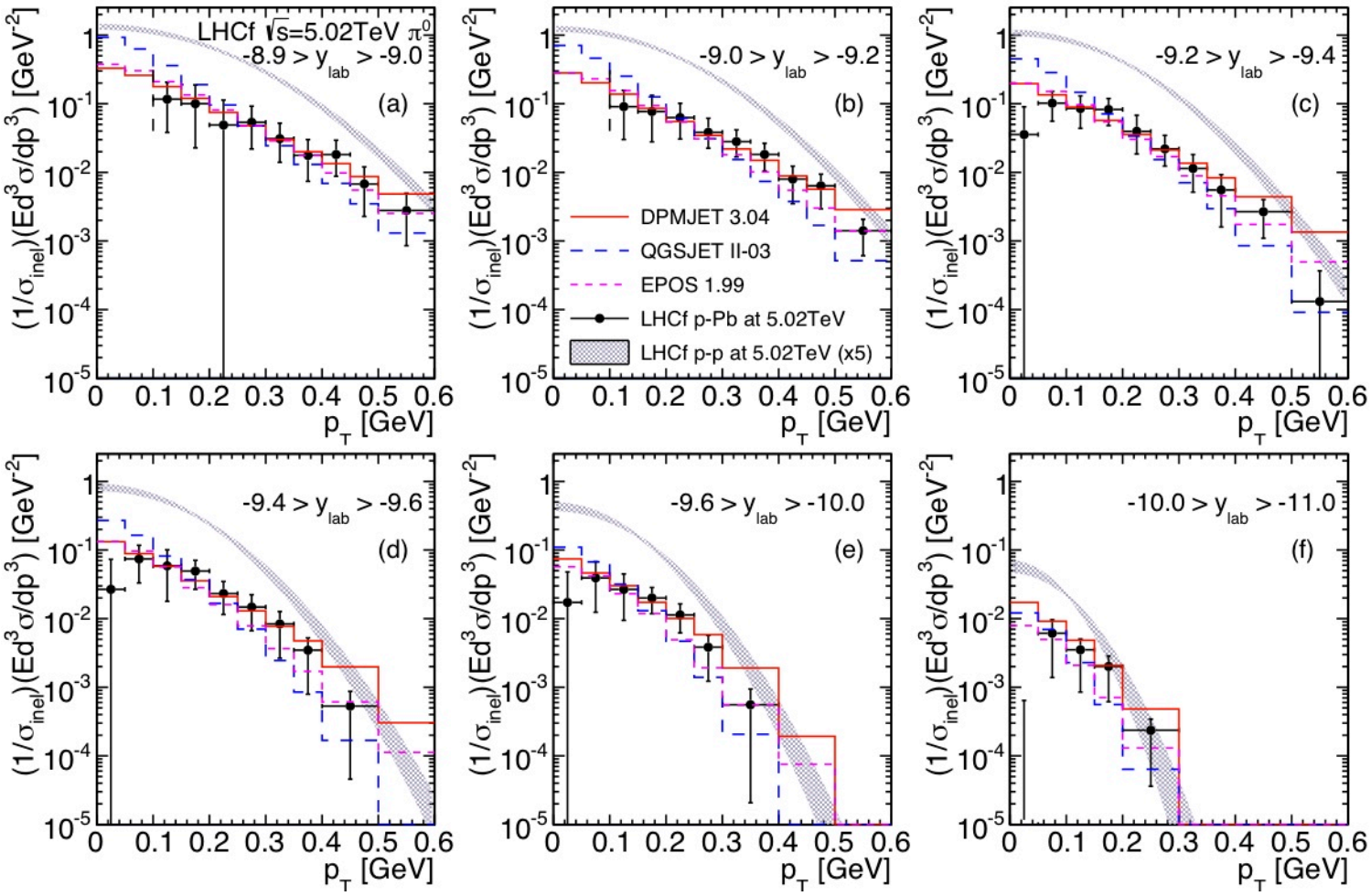


- 2013 Jan-Feb for p-Pb/Pb-p collisions
  - Installation of the **only Arm2** at one side (silicon tracker good for multiplicity)
  - Data both at **p-side** (20Jan-1Feb) and **Pb-side** (1fill, 4Feb), thanks to the **swap of the beams**



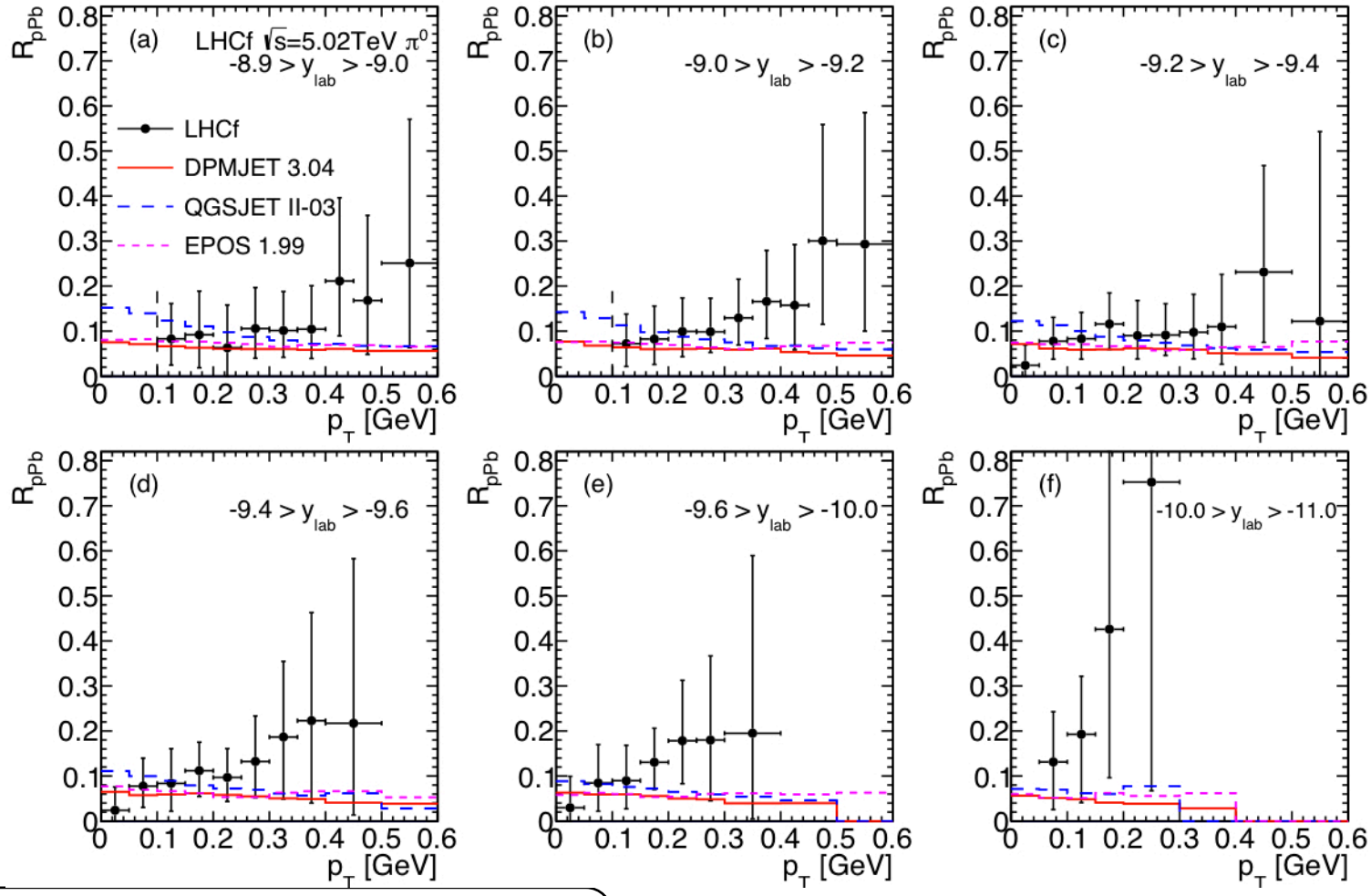
- Details of beams and DAQ
  - L = $1 \times 10^{29} - 0.5 \times 10^{29} cm^{-2} s^{-1}$
  - ~200.10^6 events
  - $\beta^* = 0.8$ m, 290 μrad crossing angle
  - 338p+338Pb bunches (min.ΔT = 200 ns), 296 colliding at IP1
  - 10-20 kHz trig rate downscaled to approximately 700 Hz
  - 20-40 Hz ATLAS common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

Inclusive π^0 p_T spectra in p-Pb at 5.02 TeV



- LHCf data in p-Pb (filled circles) show good agreement with DPMJET and EPOS.
- LHCf spectra in p-Pb are clearly harder than the LHCf data in p-p at 5.02 TeV (shaded area, spectra multiplied by 5). The latter is interpolated from the results at 2.76 TeV and 7 TeV.

Nuclear modification factor in p-Pb at 5.02 TeV

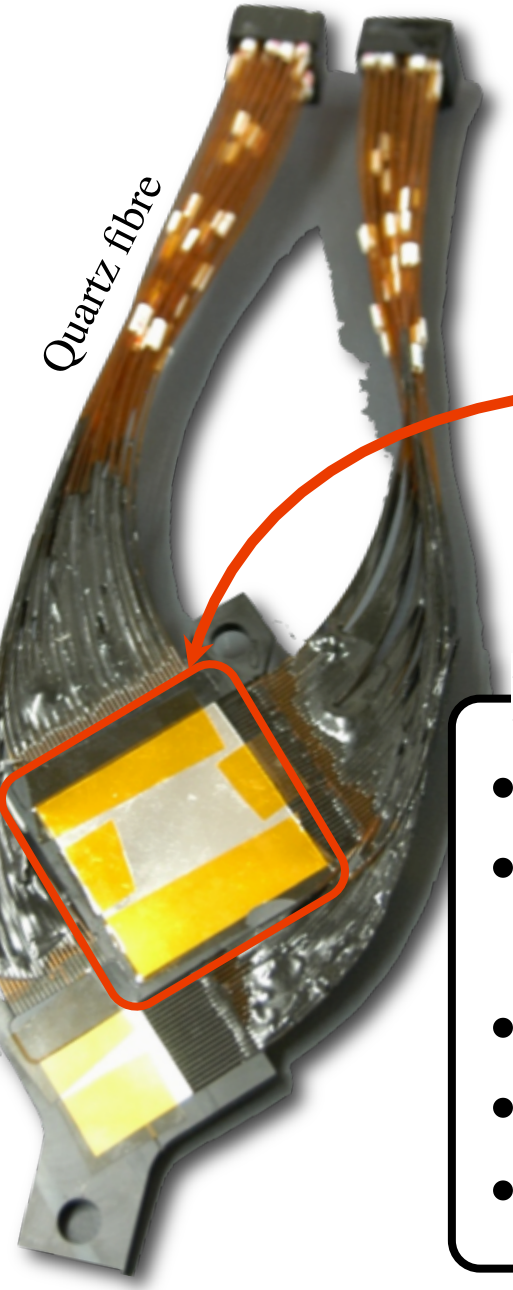


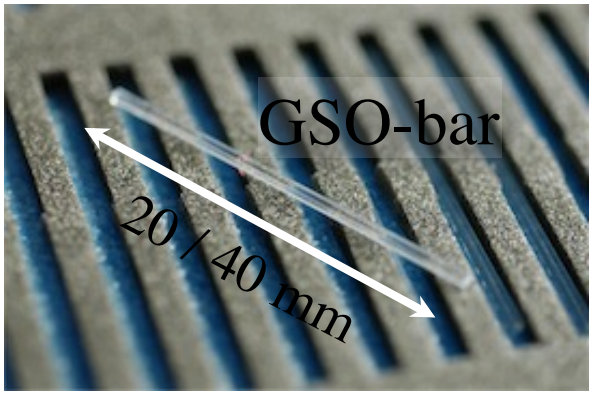
$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) \equiv \frac{\sigma_{\mathrm{inel}}^{\mathrm{pp}}}{\langle N_{\mathrm{coll}} \rangle \sigma_{\mathrm{inel}}^{\mathrm{pPb}}} \frac{Ed^3\sigma^{\mathrm{pPb}}/dp^3}{Ed^3\sigma^{\mathrm{pp}}/dp^3}$$

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

- 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

GSO-bar hodoscope



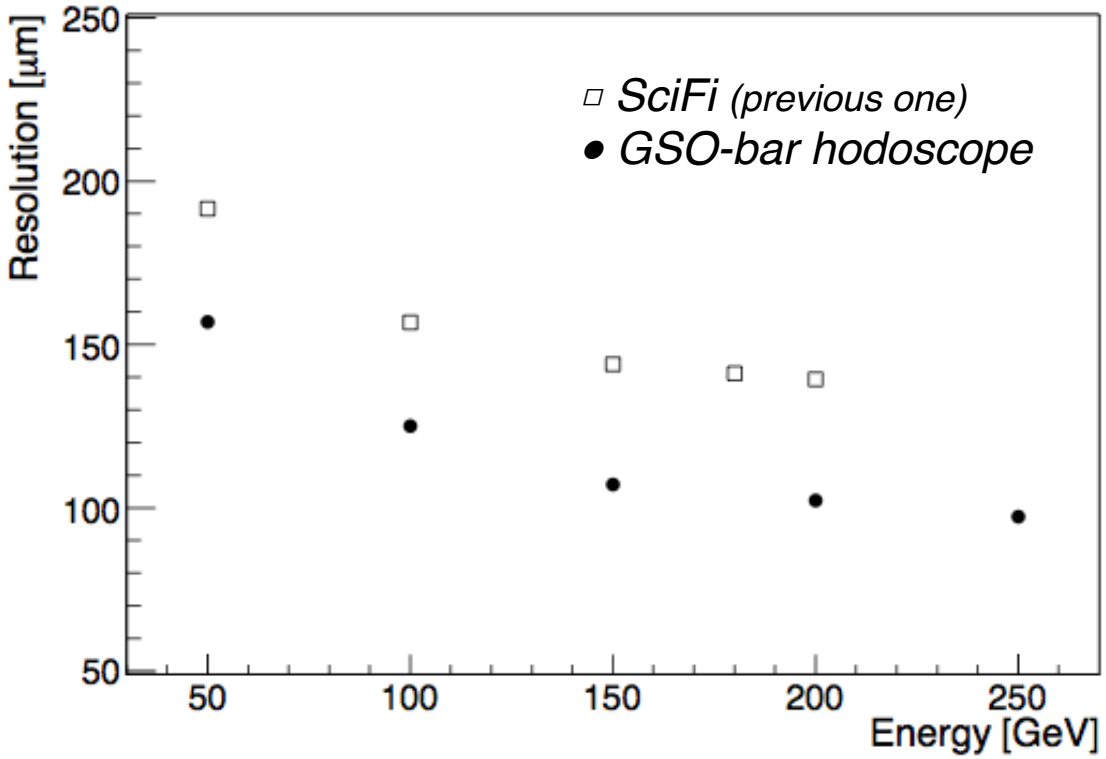


Design

- Shower-imaging layers
- 1mm x 1mm x 20(40) mm long and thin GSO scintillator (**GSO-bar**) --> Radiation-hard
- GSO-bars have no cladding materials
- GSO-bars have no coating
- MAPMT with 64 anodes (HAMAMATSU H7546)

Position Resolution: Energy Dependence

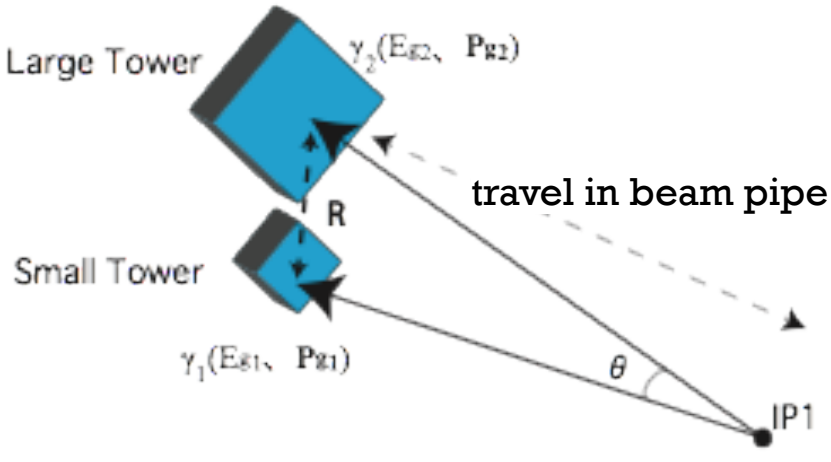
Energy dependence of position resolution and the comparison with previous imaging layer (SciFi).



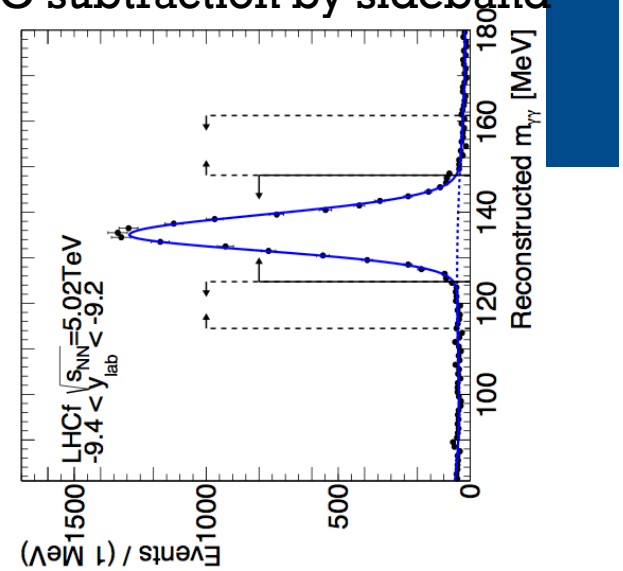
GSO-bar shows better results than that of SciFi among all energy ranges

π^0 event reconstruction in p-Pb collisions

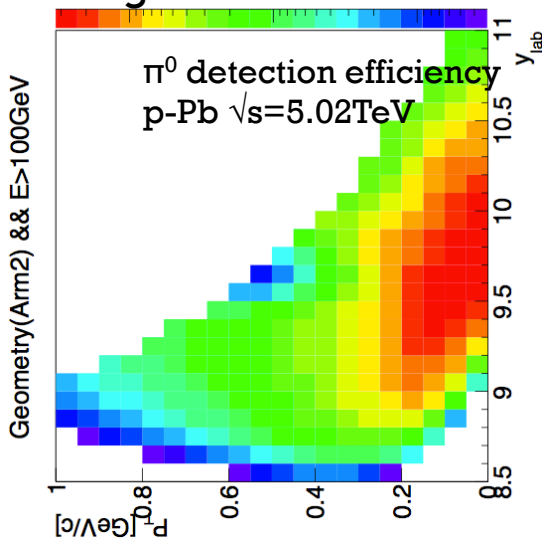
1. Search for two photons



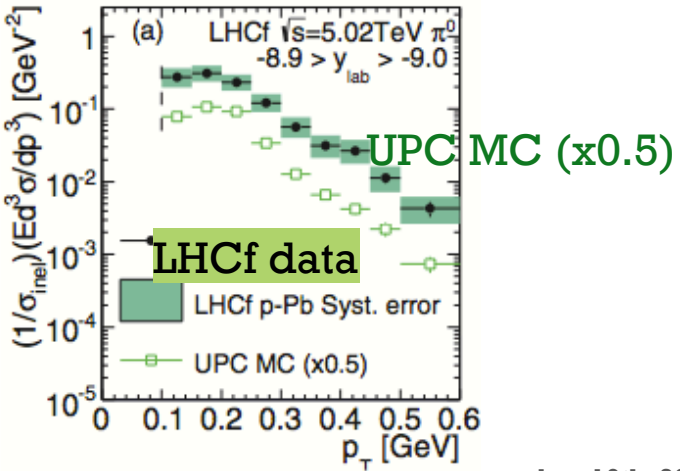
2. BG subtraction by sideband



3. Unfolding the smeared p_T spectra and correction for geometrical inefficiency



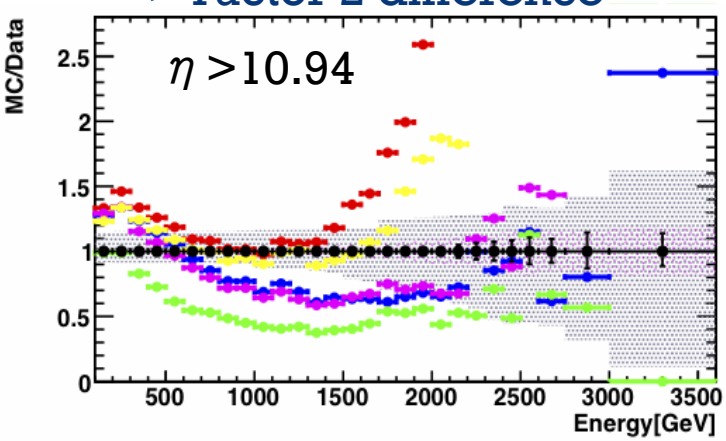
4. Subtraction of the UPC component

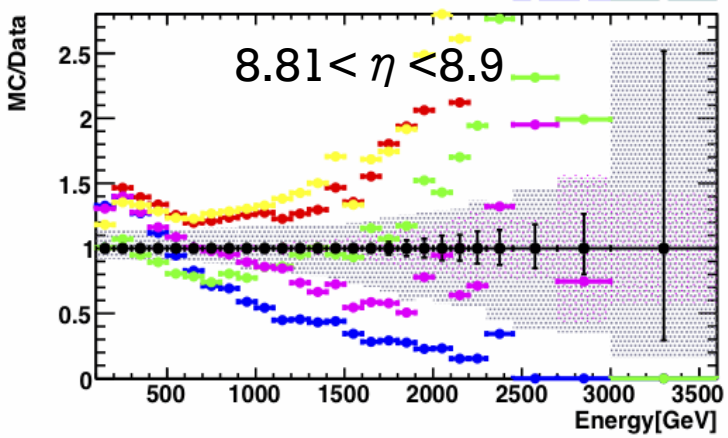


DATA vs MC : comp. 900GeV/7TeV

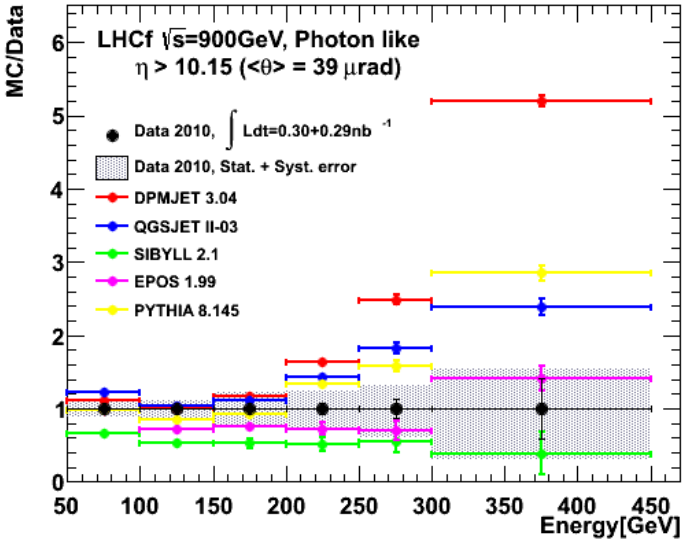
- None of the model nicely agrees with the LHCF data
- Here we plot the ratio MC/Data for the various models
- > Factor 2 difference

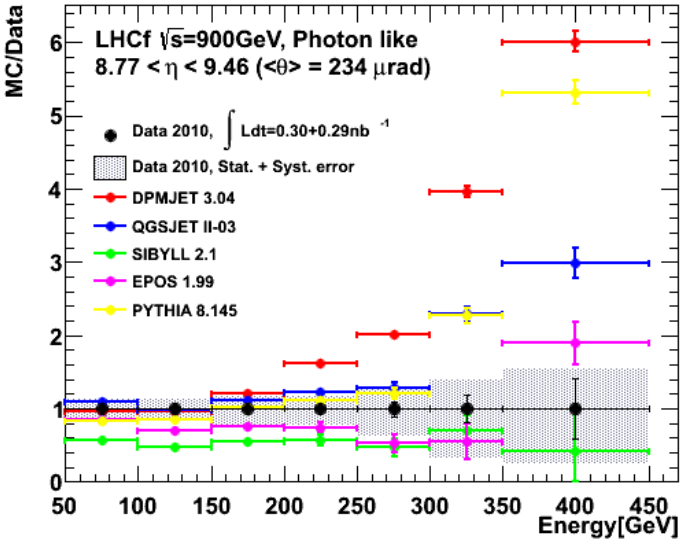
7TeV





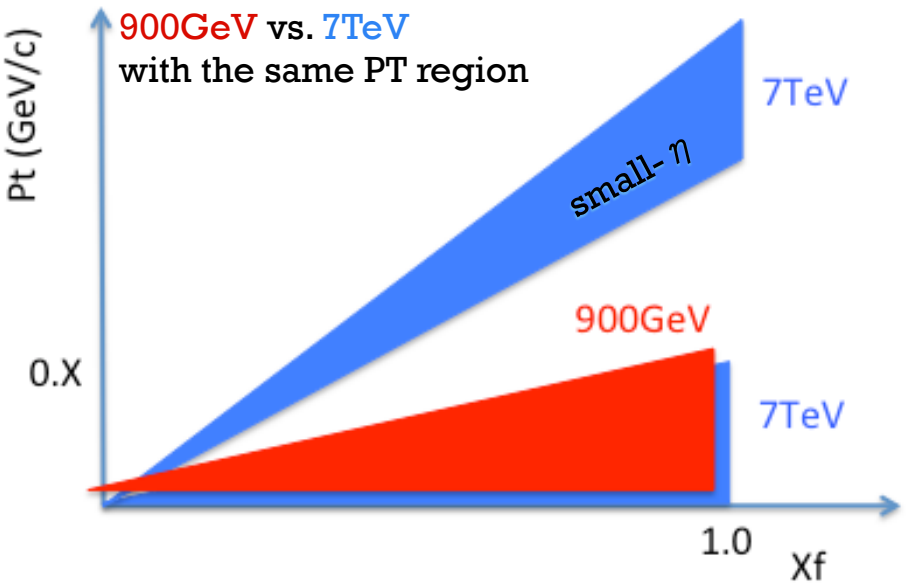
900GeV



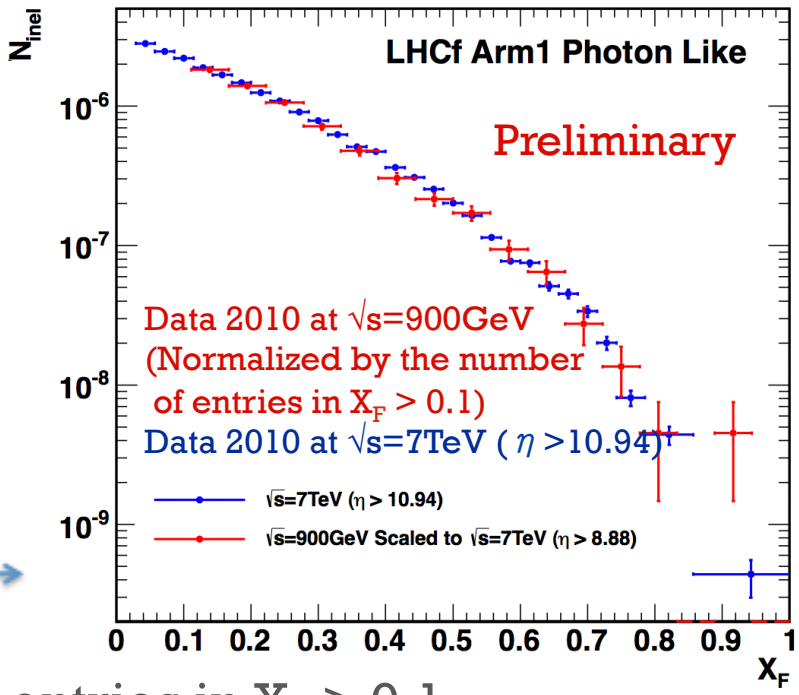


+ DATA : 900GeV vs 7TeV

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.

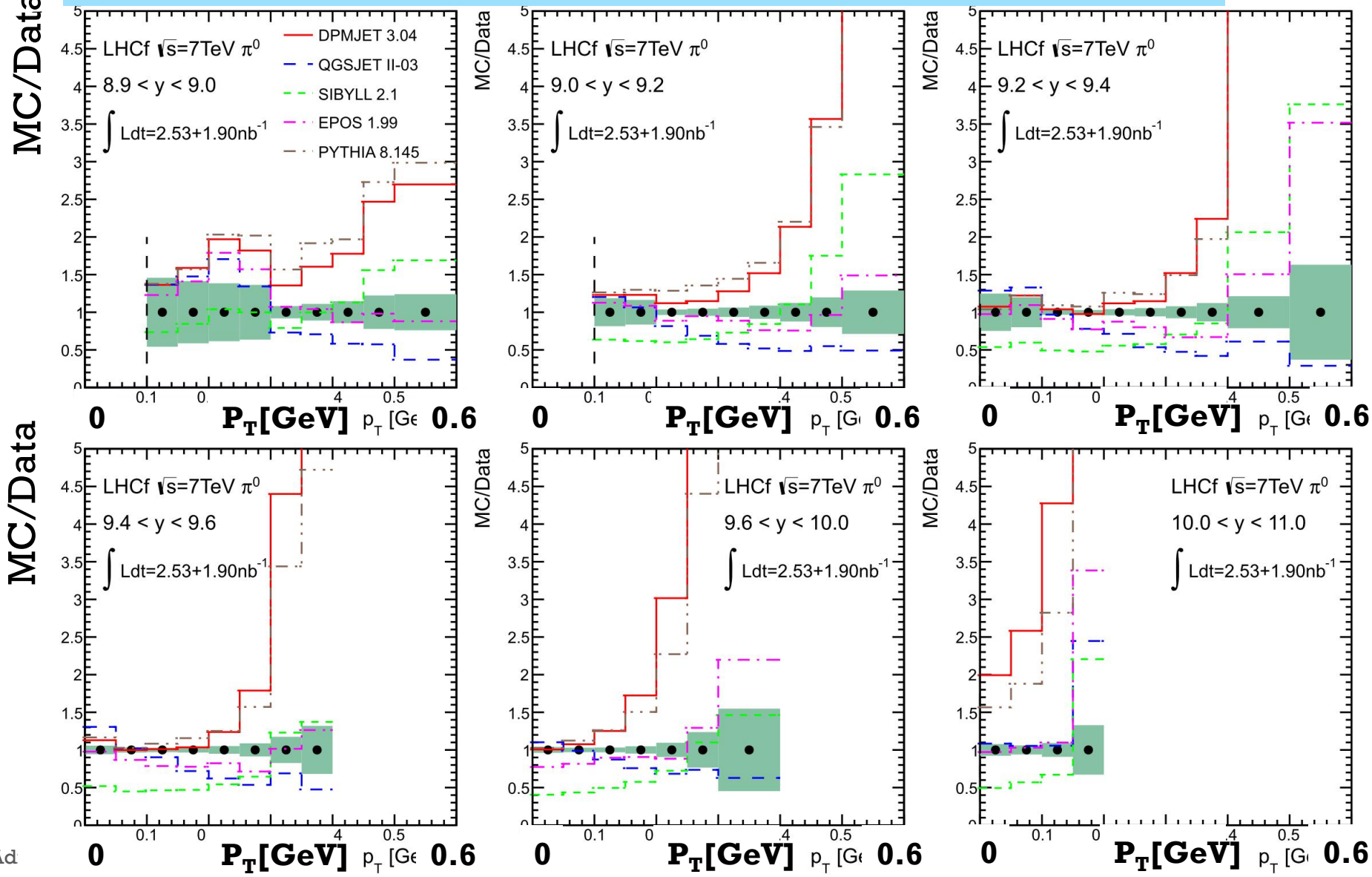
Good agreement of X_F spectrum shape between 900 GeV and 7 TeV.
➔weak dependence of $\langle p_T \rangle$ on E_{CMS}

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

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

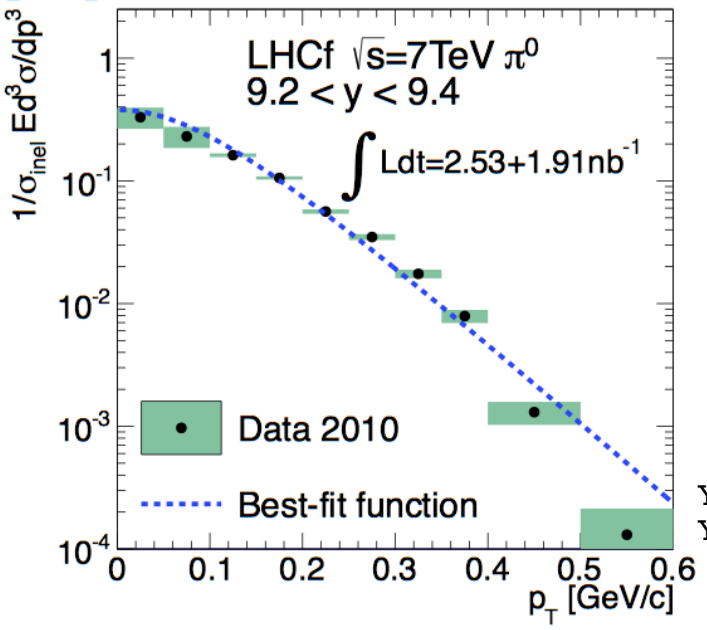
DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

EPOS gives the best agreement both for shape and yield.

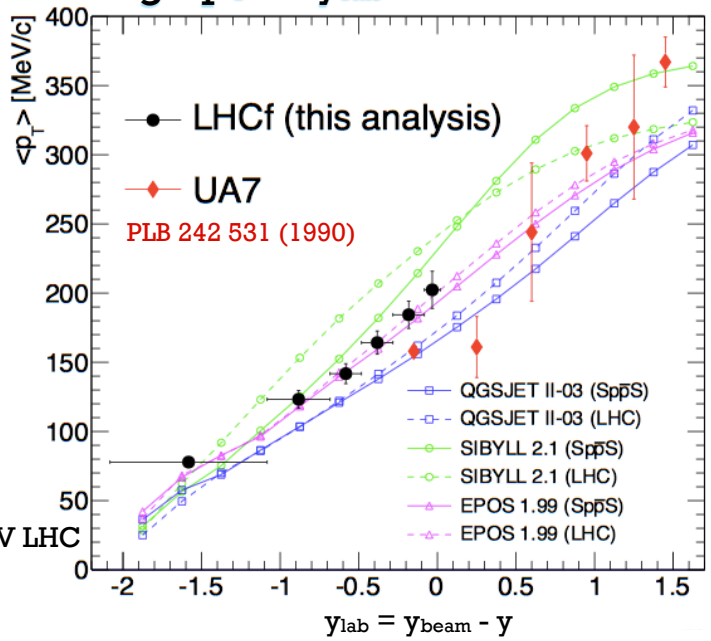


π^0 analysis at $\sqrt{s}$=7TeV

p_T spectra vs best-fit function



Average p_T vs y_{lab}



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

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

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

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

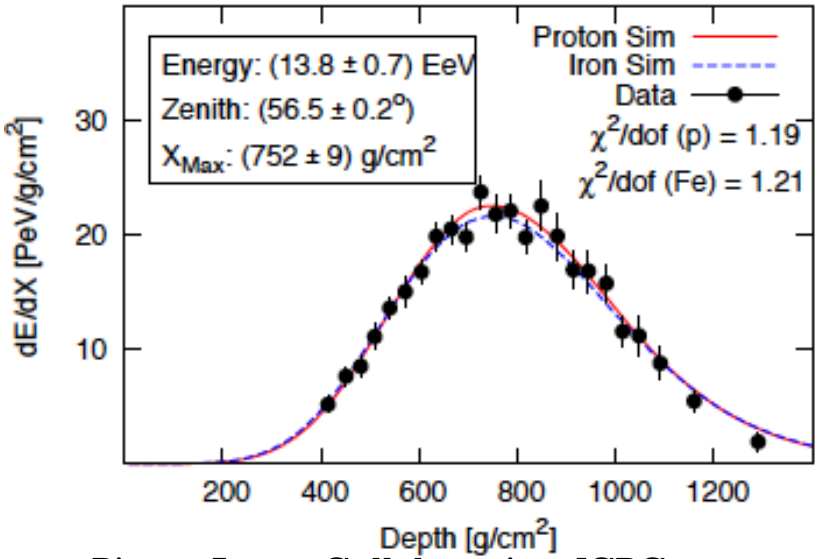
2. Numerical integration

$$\langle p_T \rangle = \frac{\int_0^\infty 2\pi p_T^2 f(p_T) dp_T}{\int_0^\infty 2\pi p_T f(p_T) dp_T}$$

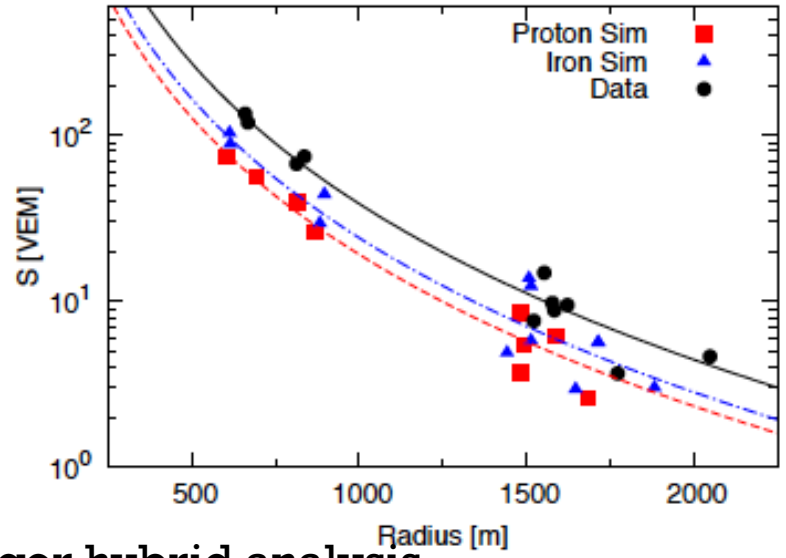
actually up to the upper bound of histogram

- 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)

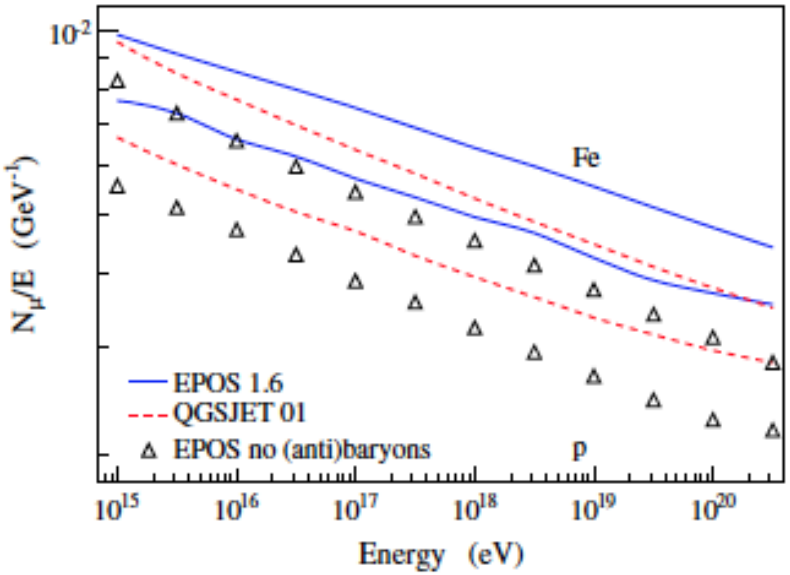


Auger hybrid analysis

- 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

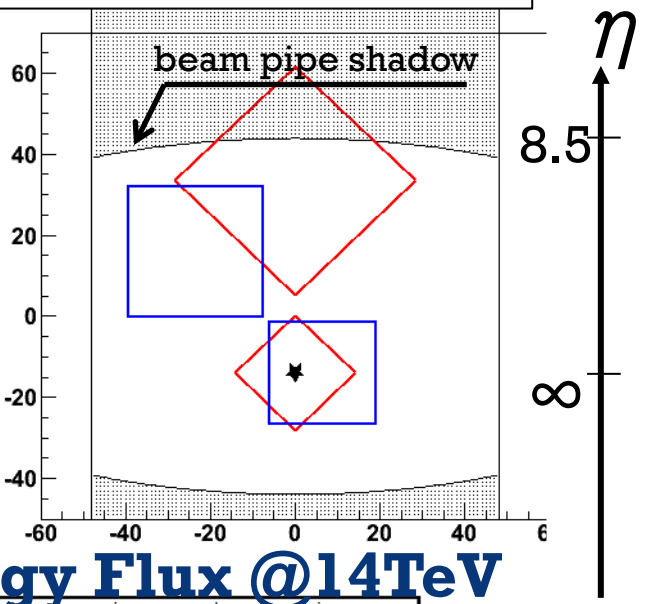
=> importance of baryon measurement



Pierog and Werner, PRL 101 (2008) 171101

+ What LHCf can measure

Front view of calorimeters
@ 100 μ rad crossing angle

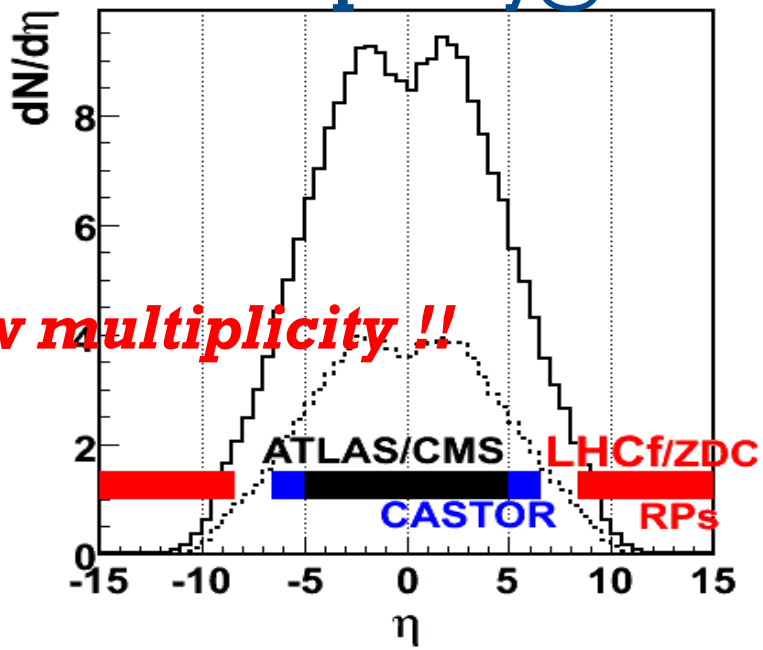


Energy spectra and
Transverse momentum distribution of

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

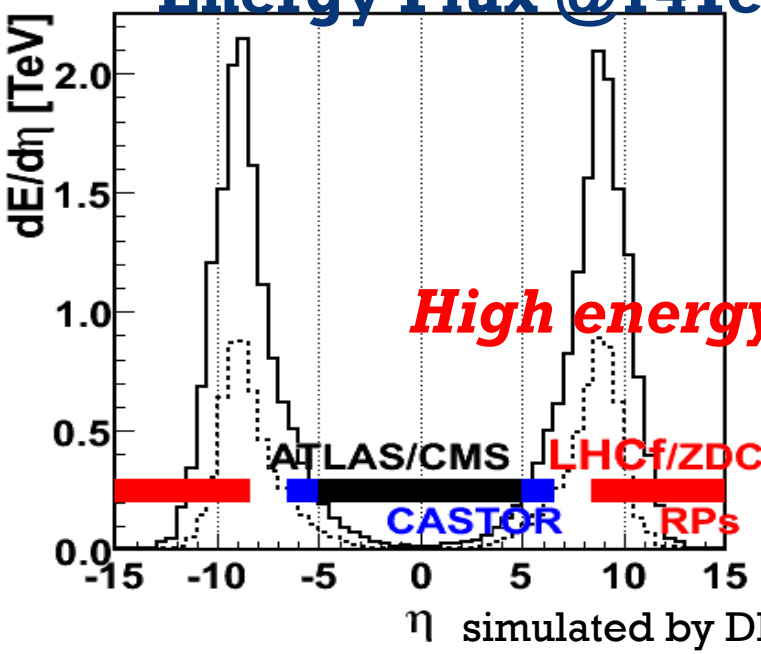
at pseudo-rapidity range >8.4

Multiplicity@14TeV



Low multiplicity !!

Energy Flux @14TeV



High energy flux !!

simulated by DPMJET3

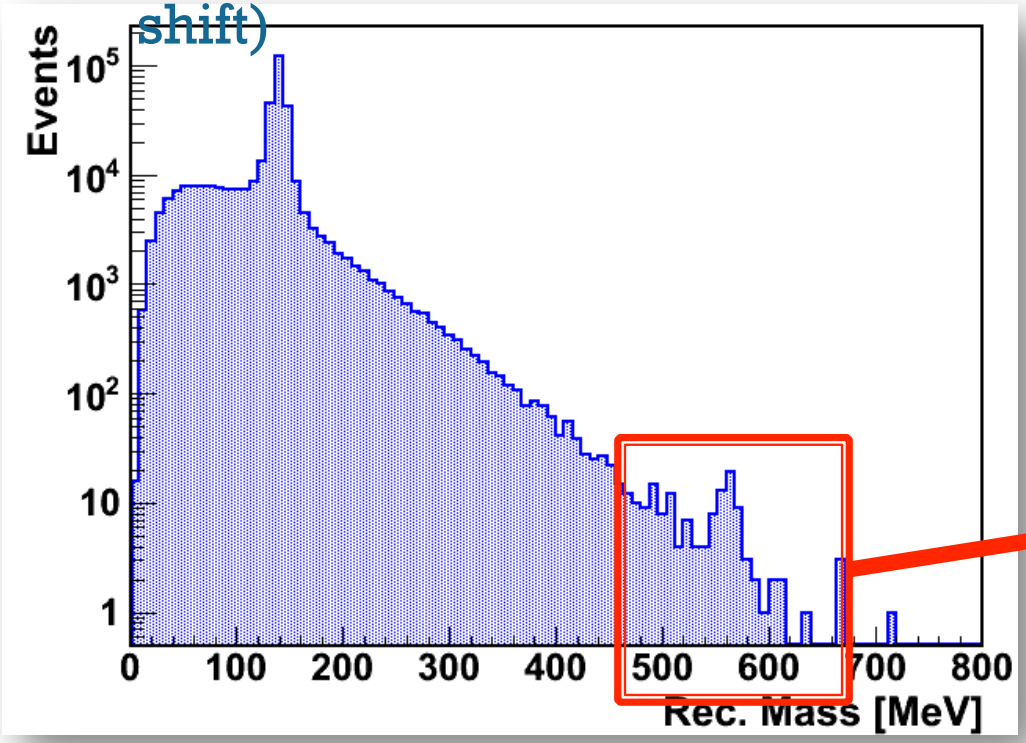
η Mass

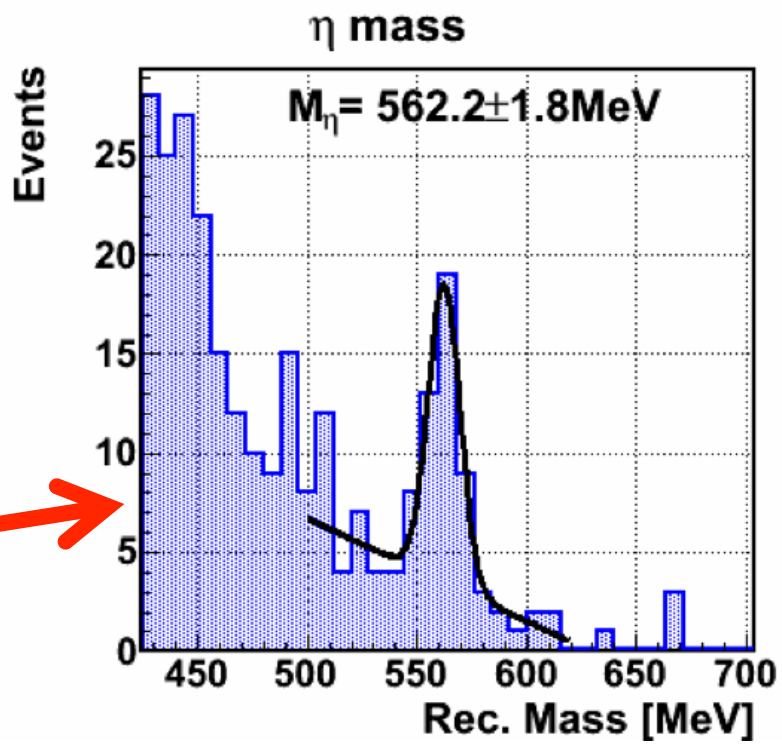
Arm2 detector, all runs with zero crossing angle

True η Mass: 547.9 MeV

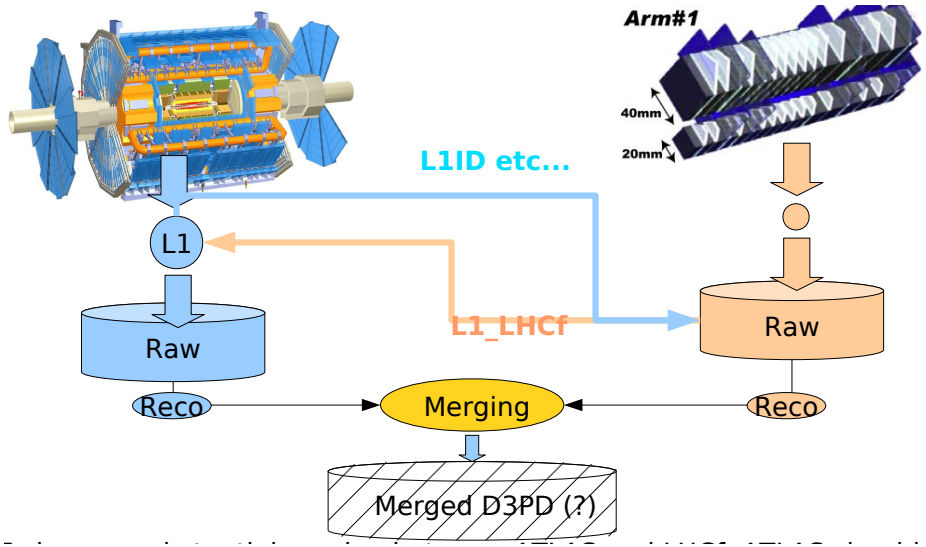
MC Reconstructed η Mass peak: 548.5 ± 1.0 MeV

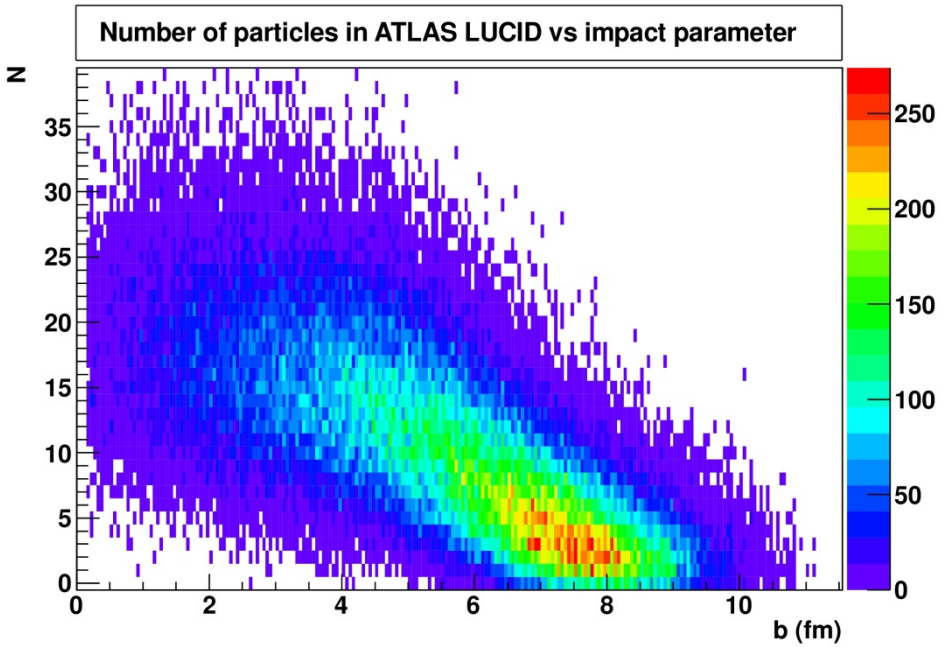
Data Reconstructed η Mass peak: 562.2 ± 1.8 MeV (2.6% shift)





Common trigger with ATLAS

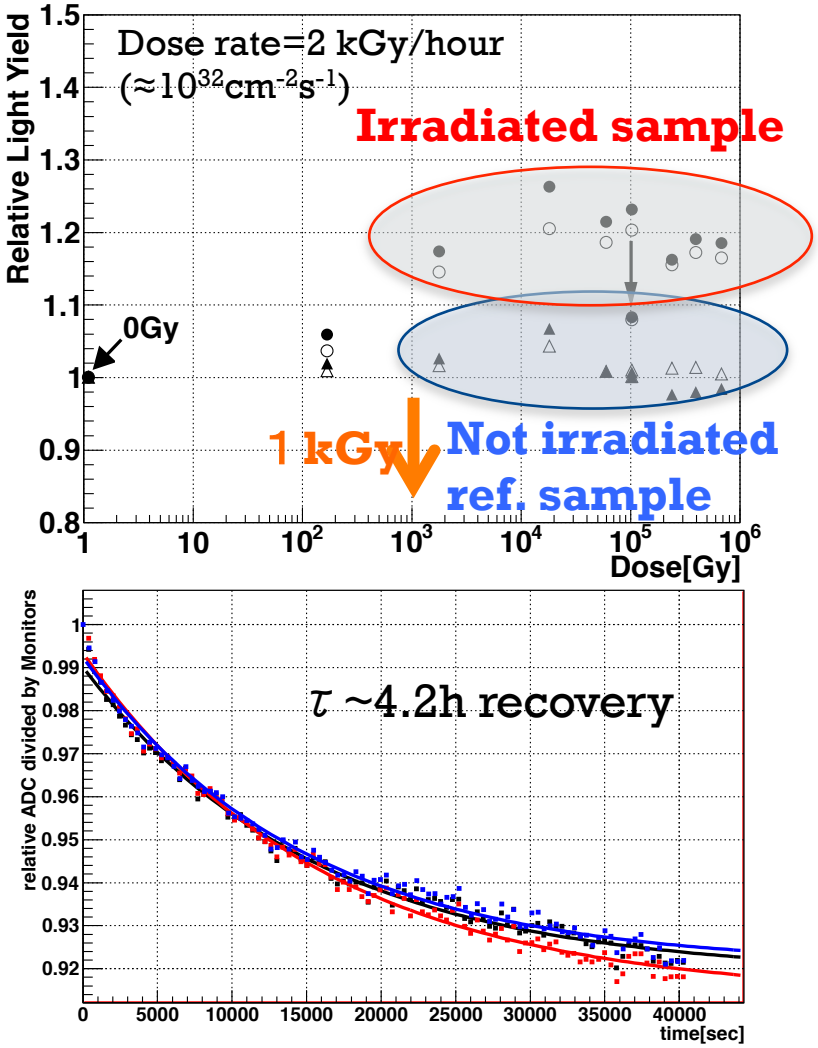


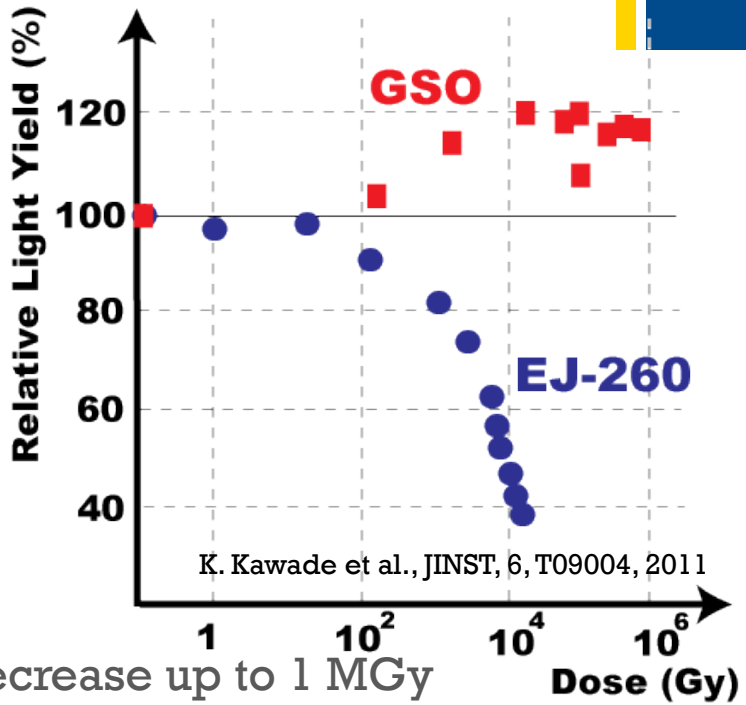


MC
impact parameter vs. # of particles in ATLAS LUCID

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

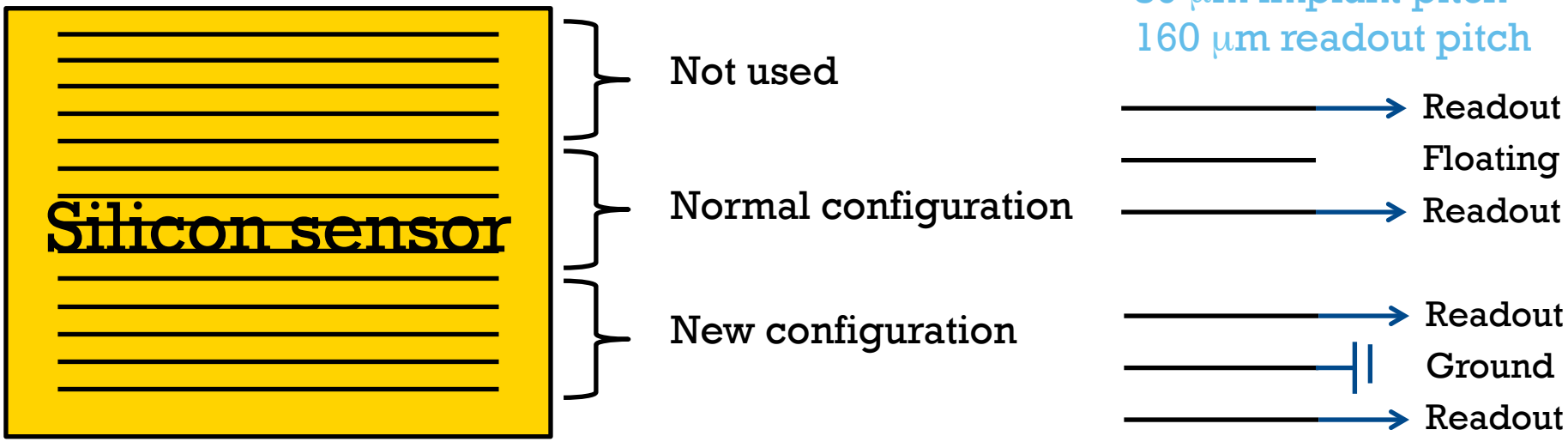
Radiation hardness of GSO

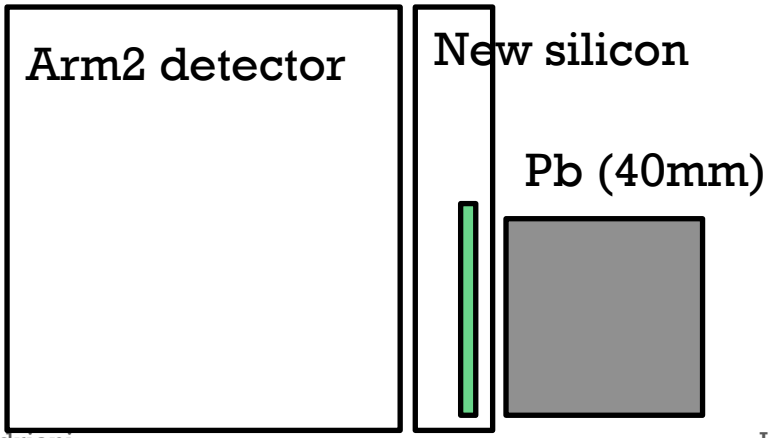




- No decrease up to 1 MGy
- +20% increase over 1 kGy (τ =4.2h recovery)
- 2 kGy is expected for 350nb^{-1} @ 14TeV pp)

Different silicon bonding scheme





The beam test setup

e-, 200 GeV/c