Results from LHCf

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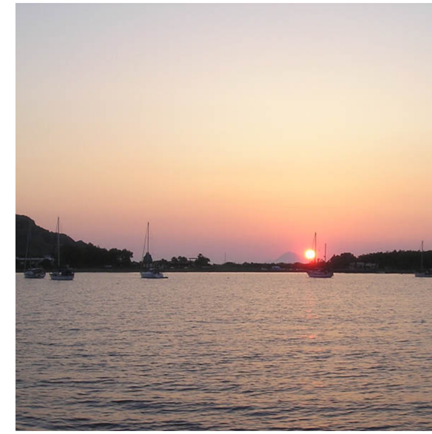
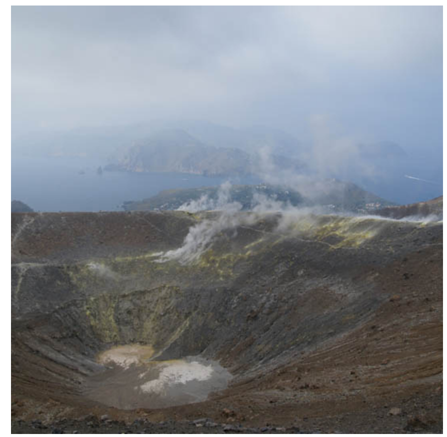
Vulcano Workshop 2012
Frontier Objects in Astrophysics and Particle Physics
Vulcano 28 May – 2 June 2012

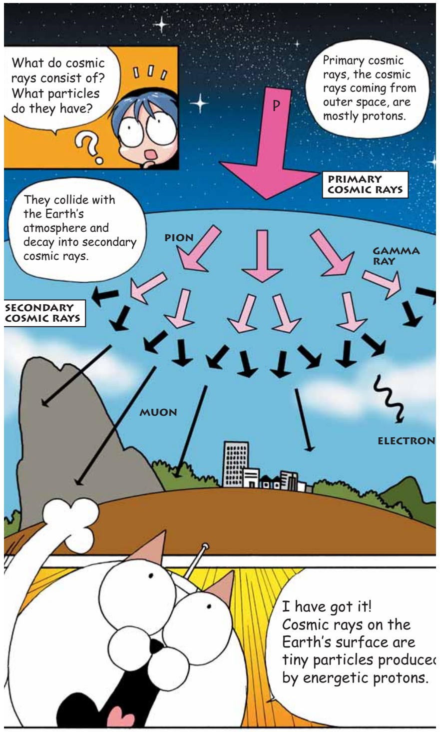




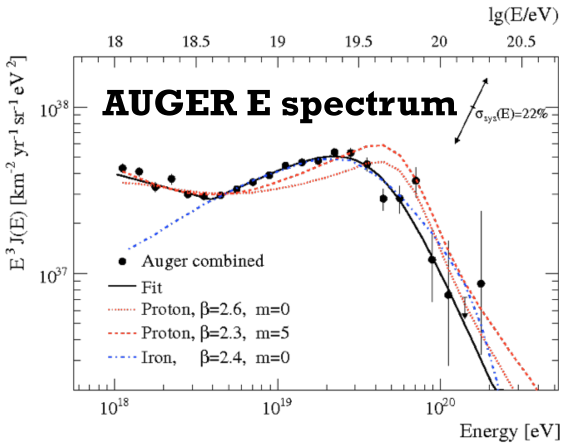
- Forward photon energy spectrum at $\sqrt{s}$ = 7 TeV and 900 GeV p-p collisions
- π^0 p_T spectra
- Prospects for new data taking
- Detector upgrade
- Prospects for new analyses

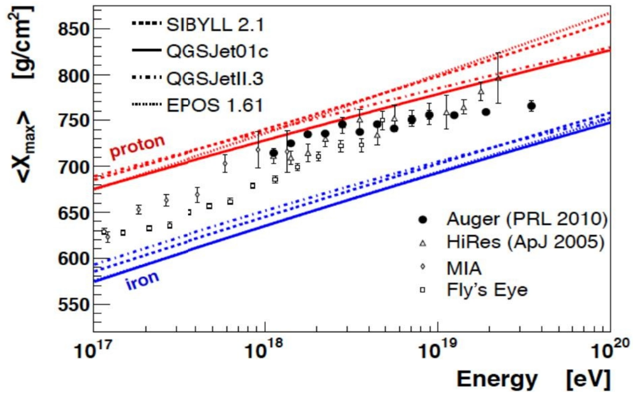
Physics Motivations

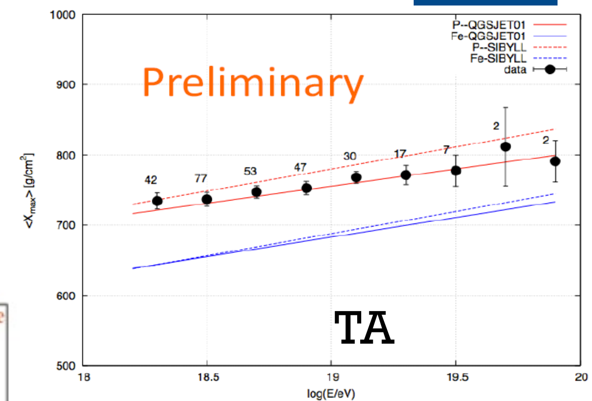
Impact on HECR Physics

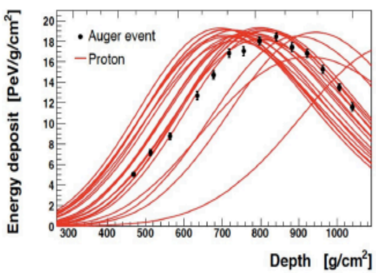


+ HECR Open questions (E/X_{max})

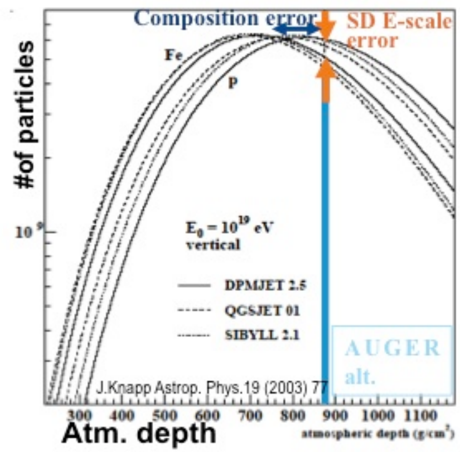


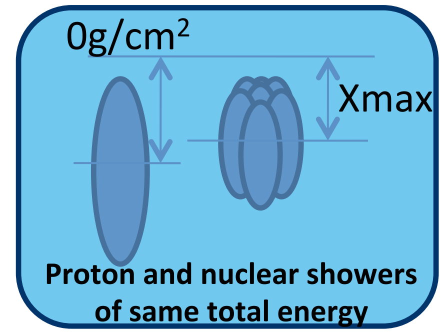




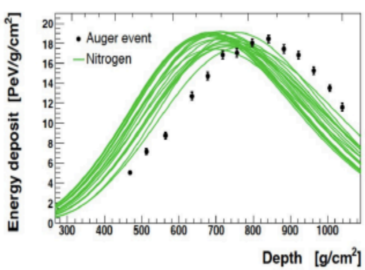


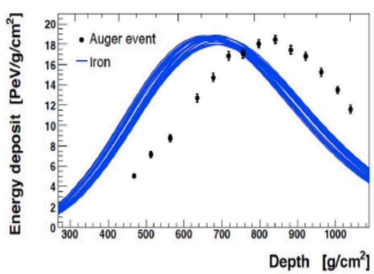
$$E \simeq 10^{20}\ \mathrm{eV}$$





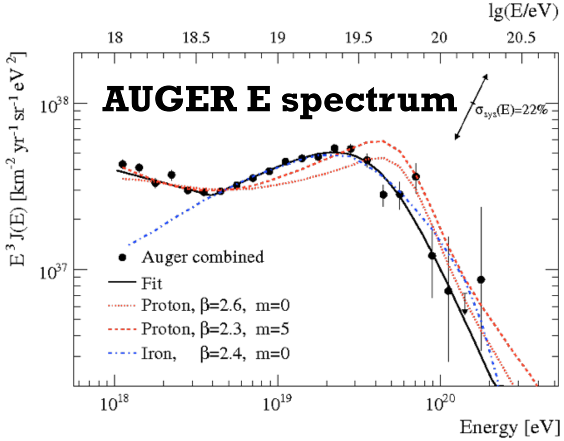
Courtesy P. LIPARI

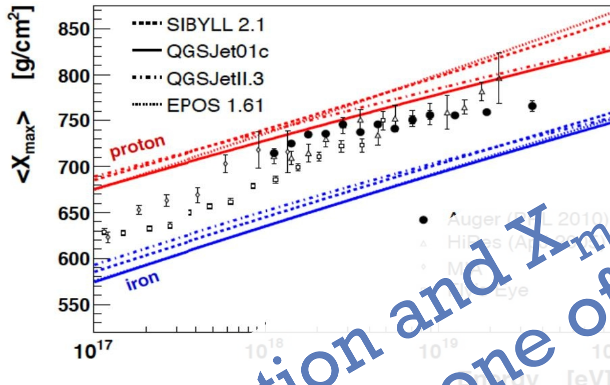


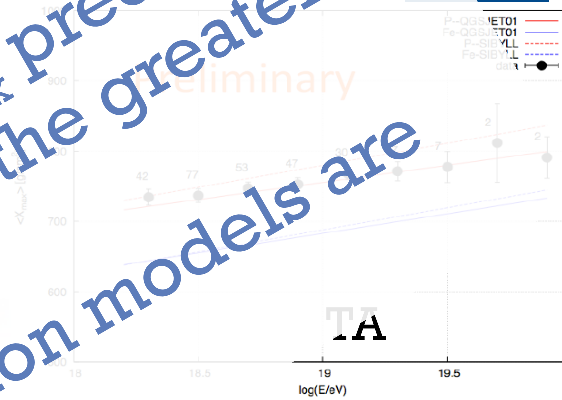


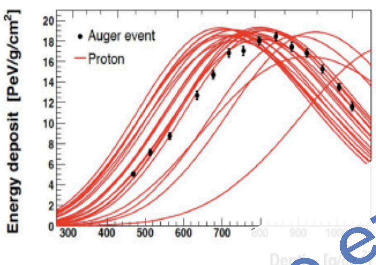
- ✓ X_{max} gives information on the primary particle
- ✓ Results are different between experiments both for E spectra and composition measurements
- ✓ Interpretation relies on the MC prediction and has quite strong model dependence

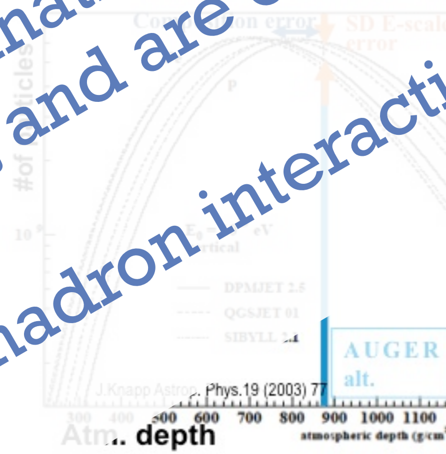
+ HECR Open questions (E/X_{max})

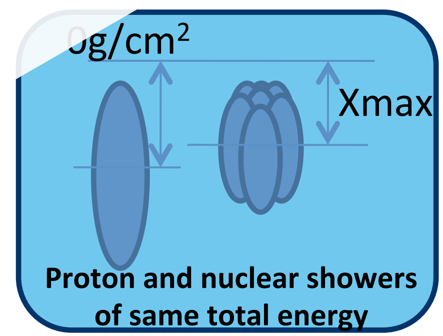












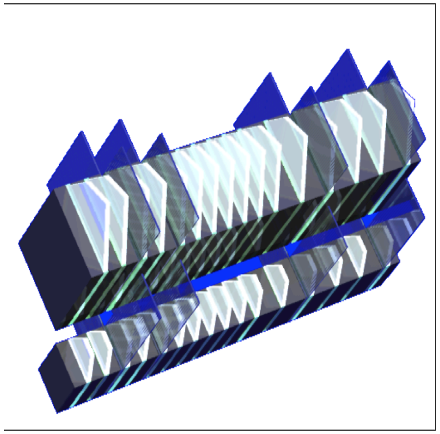
Both in the energy determination and X_{max} prediction MC simulations are used, and are one of the greater sources of uncertainty.

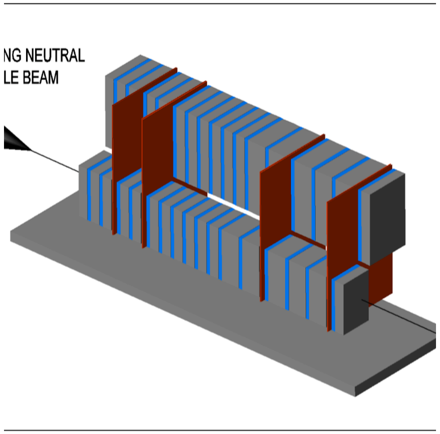
Experimental tests of hadron interaction models are necessary! → LHCf

- ✓ X_{max} gives information on the primary particle
- ✓ Results are different between experiments both for E spectra and composition measurements
- ✓ Interpretation relies on the MC prediction and has quite strong model dependence

LHCf @ LHC

The experimental set-up





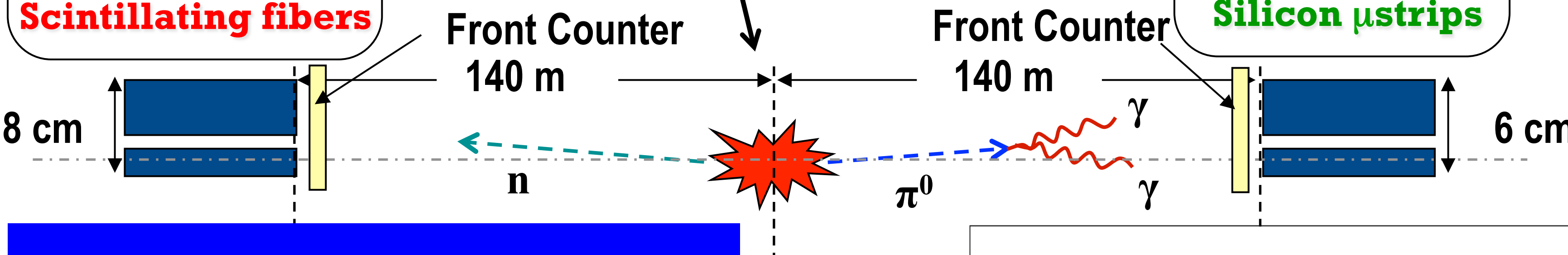
LHCf: location and detector layout

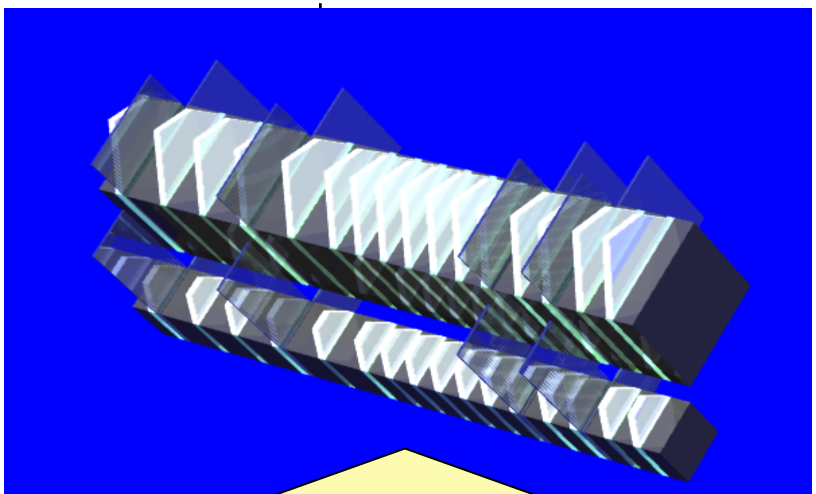
Detector I
Tungsten
Scintillator
Scintillating fibers

INTERACTION POINT

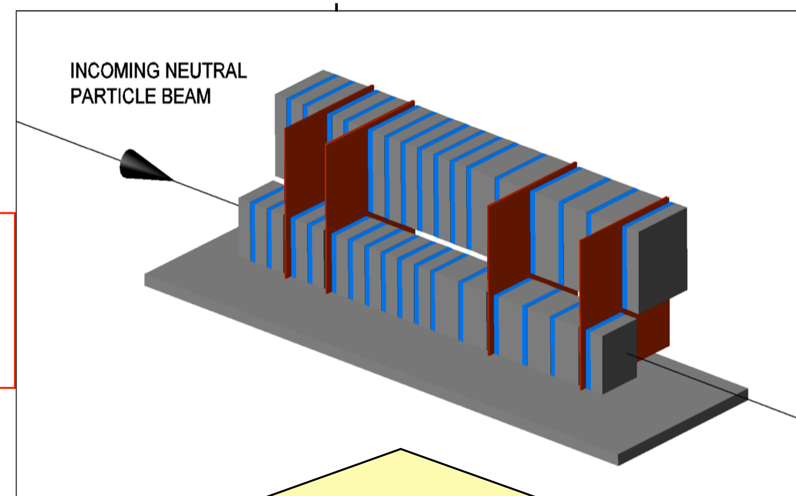
IP1 (ATLAS)

Detector II
Tungsten
Scintillator
Silicon μstrips





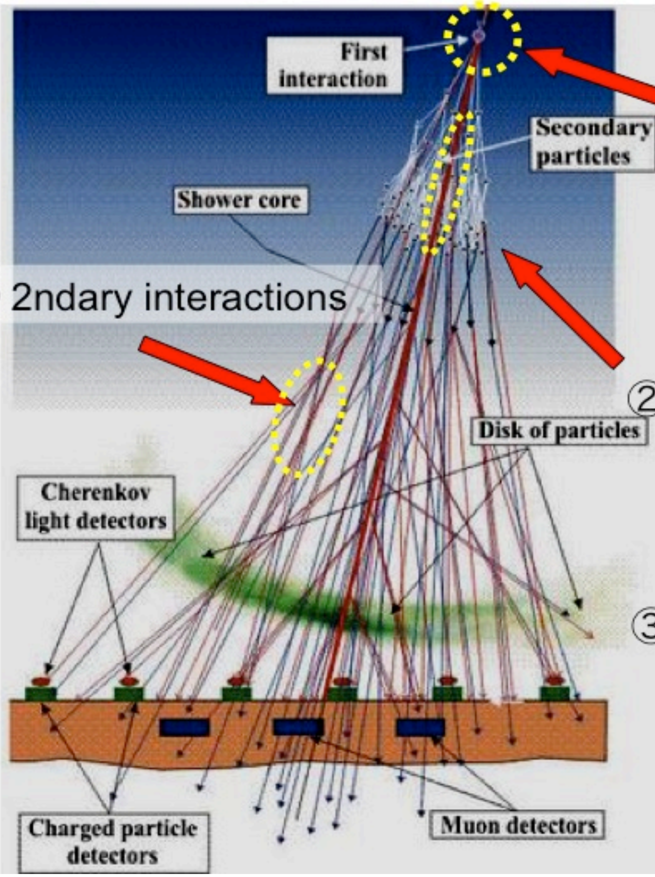
$44X_0$,
$1.6\ \lambda_{int}$



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

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

+ How LHCf can contribute?



④ 2ndary interactions

① Inelastic cross section

If large σ
rapid development
If small σ
deep penetrating

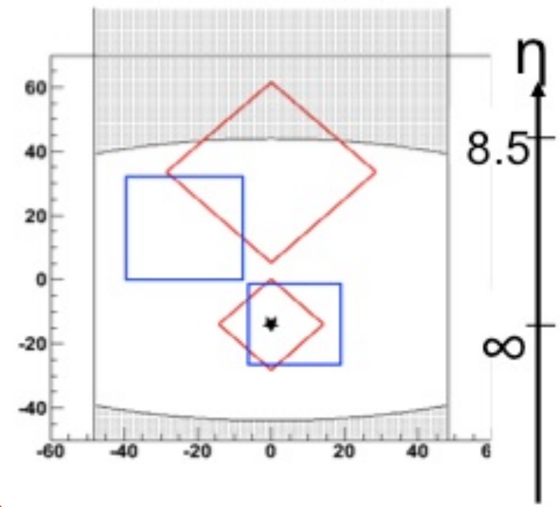
σ_{inela} =73.5±0.6 mb (TOTEM)

② Forward energy spectrum

If softer
shallow development
If harder
deep penetrating

③ Inelasticity k

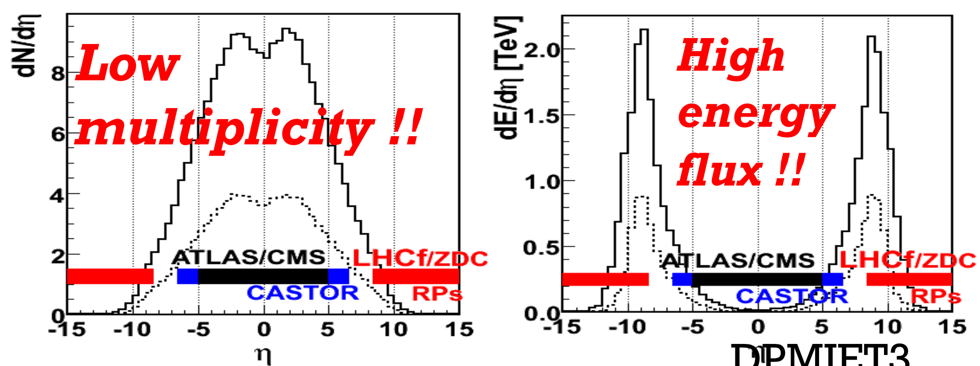
If large k
rapid development
If small k
deep penetrating



➔ Forward region is very effective on air shower development

LHC gives a unique opportunity to measure hadronic interactions at 10^{17} eV

7TeV+7TeV	$\longrightarrow E_{lab} = 10^{17}$eV
3.5TeV+3.5TeV	$\longrightarrow E_{lab} = 2.6\times10^{16}$eV
450GeV+450GeV	$\longrightarrow E_{lab} = 2\times10^{14}$eV



+ Brief LHCf photo-story

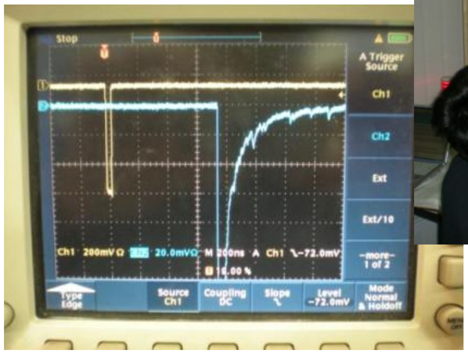
- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved

Jul 2006 construction

Aug 2007 SPS beam test

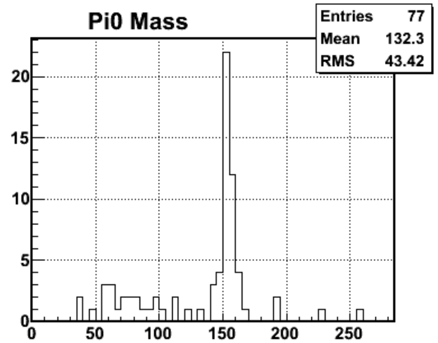
Jan 2008 Installation

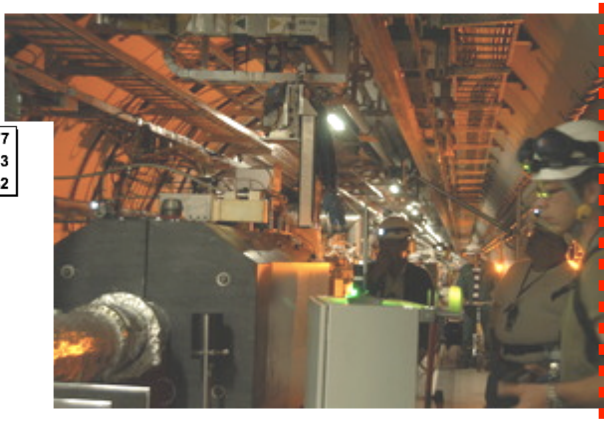
Sep 2008 1st LHC beam



Dec 2009 1st 900GeV run

Mar 2010 1st 7TeV run



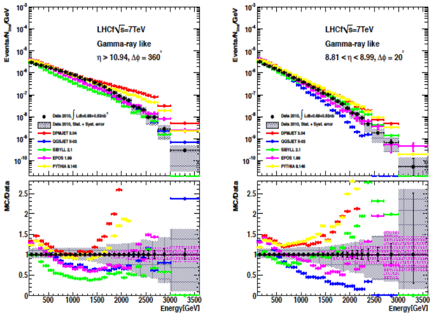


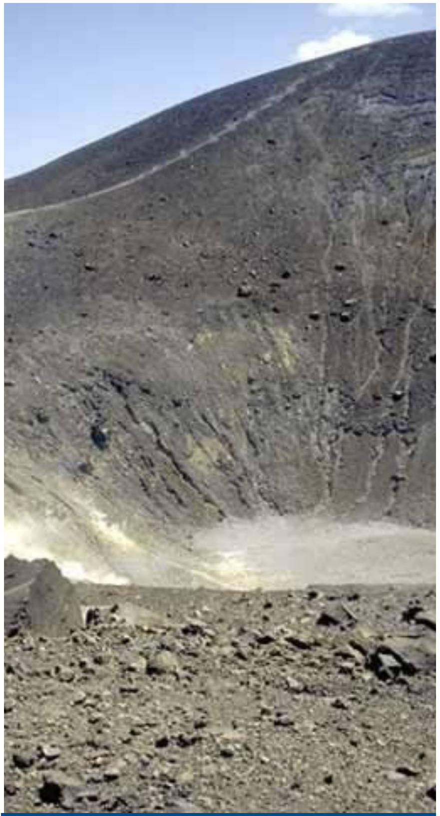
Jul 2010 Detector removal

Inclusive photon spectrum analysis

“Measurement of zero degree single photon energy spectra for $\sqrt{s}$ = 7 TeV proton-proton collisions at LHC“

PLB 703 (2011) 128





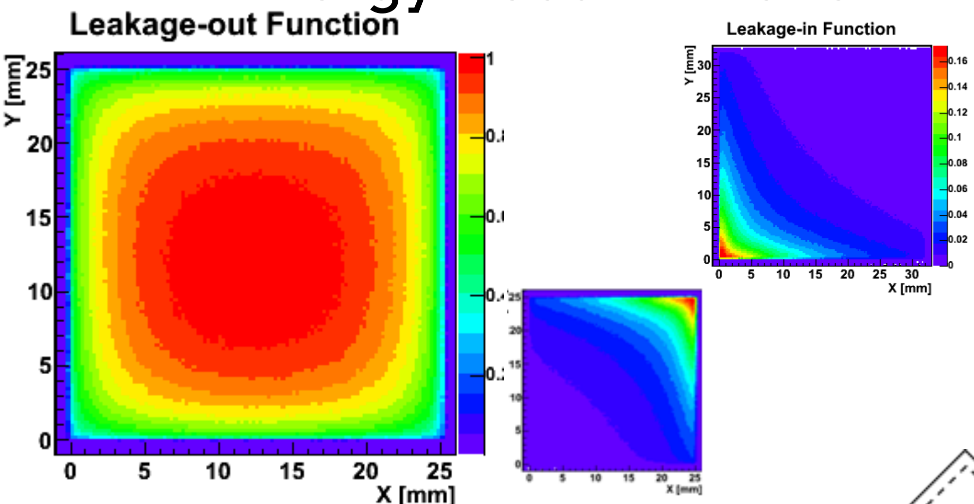
Data Set for inclusive photon spectrum analysis at 7 TeV

- Data
  - Date : 15 May 2010 17:45-21:23 (Fill Number : 1104) except runs during the luminosity scan.
  - Luminosity : $(6.5\text{-}6.3)\times10^{28}\,cm^{-2}s^{-1}$,
  - DAQ Live Time : 85.7% for Arm1, 67.0% for Arm2
  - Integrated Luminosity : 0.68 nb^{-1} for Arm1, 0.53nb^{-1} for Arm2
  - Number of triggers : 2,916,496 events for Arm1
    3,072,691 events for Arm2
  - Detectors in nominal positions and Normal Gain

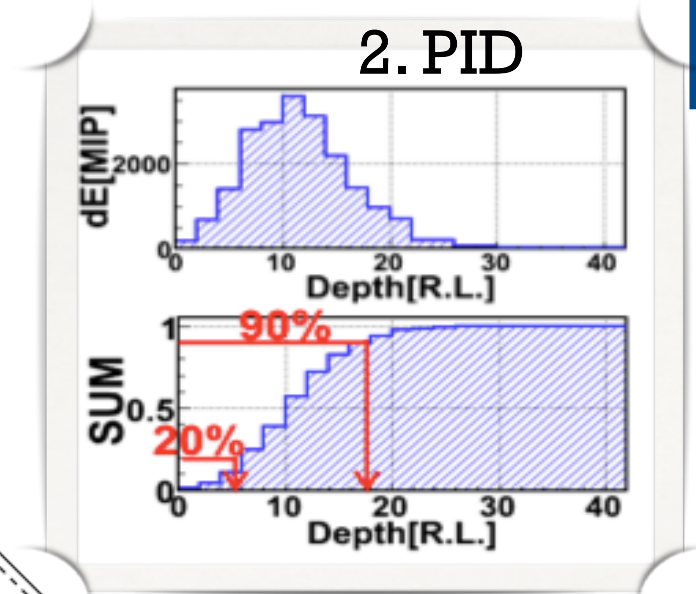
- Monte Carlo
  - QGSJET II-03, DPMJET 3.04, SYBILL 2.1, EPOS 1.99 and PYTHIA8.145: about 10^7 pp inelastic collisions each

+ Analysis WORKFLOW at 7 TeV

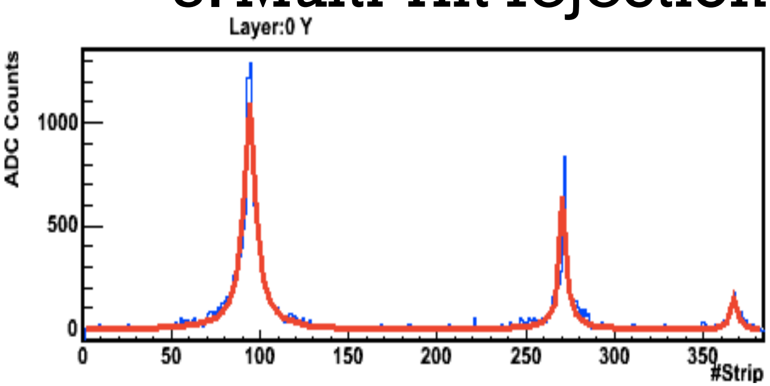
1. Energy Reconstruction

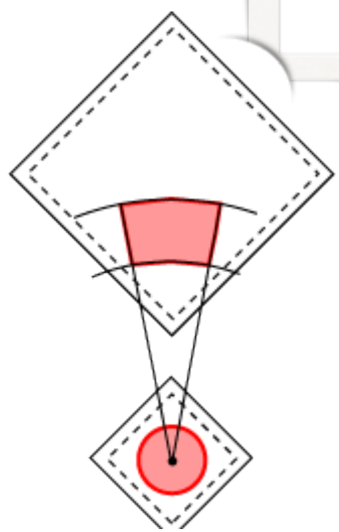


2. PID

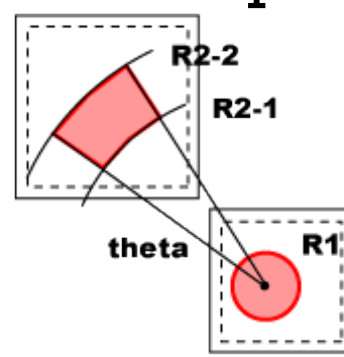


3. Multi-Hit rejection





4. Acceptance cut

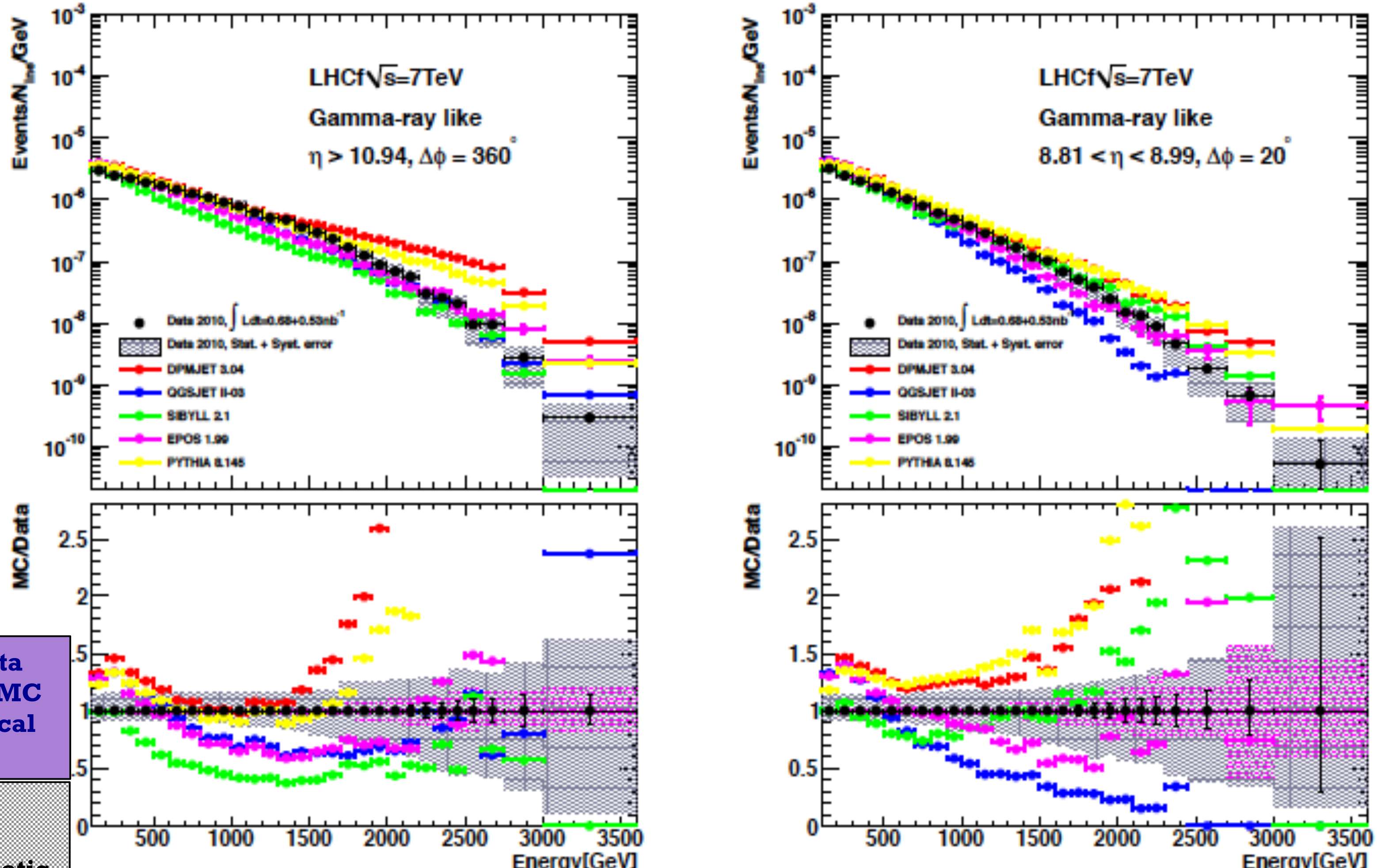


Small Tower
$\eta > 10.94$
Large Tower
$8.81 < \eta < 8.99$

5. Systematic uncertainties

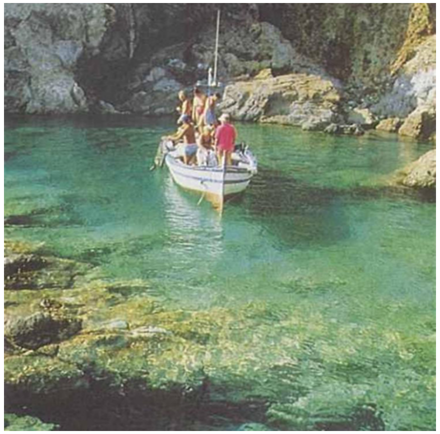
+ Comparison wrt MC Models at 7 TeV

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



Magenta hatch: MC Statistical errors

Gray hatch : Systematic Errors

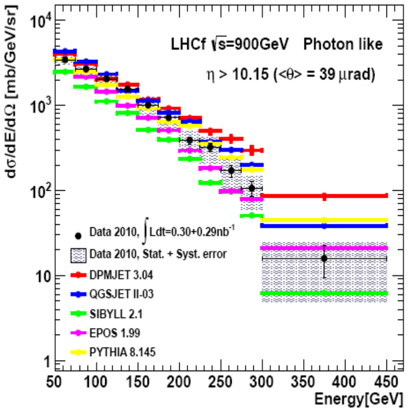


Inclusive photon spectrum analysis at 900 GeV

“Measurement of zero degree single photon energy spectra for $\sqrt{s}$ = 900 GeV proton-proton collisions at LHC“

Submitted to PLB

CERN-PH-EP-2012-048



Data Set for inclusive photon spectrum analysis at 900 GeV

Data

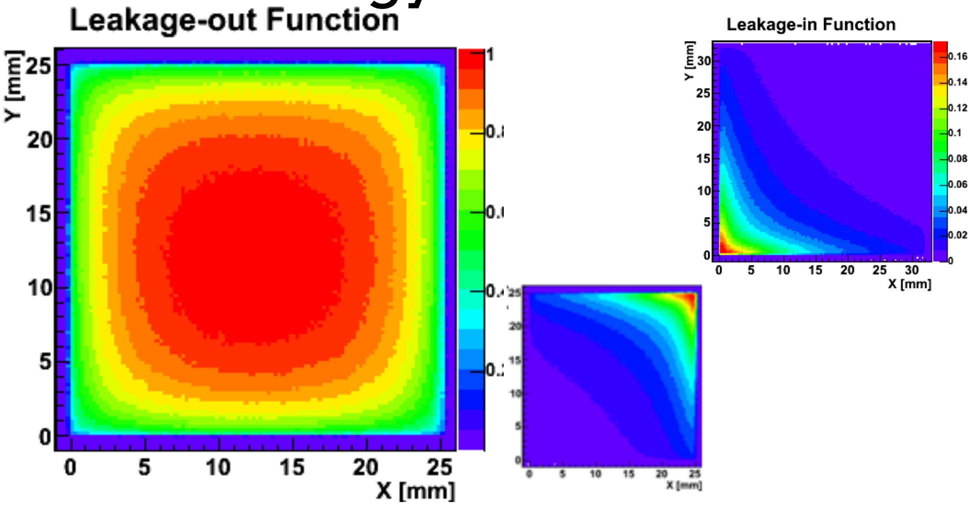
- Date : 2,3 and 27 May 2010
  - Luminosity : $(3\text{-}12)\times 10^{28} cm^{-2}s^{-1}$,
  - DAQ Live Time : 99.2% for Arm1, 98.0% for Arm2
  - Integrated Luminosity : 0.30 nb^{-1}

Monte Carlo

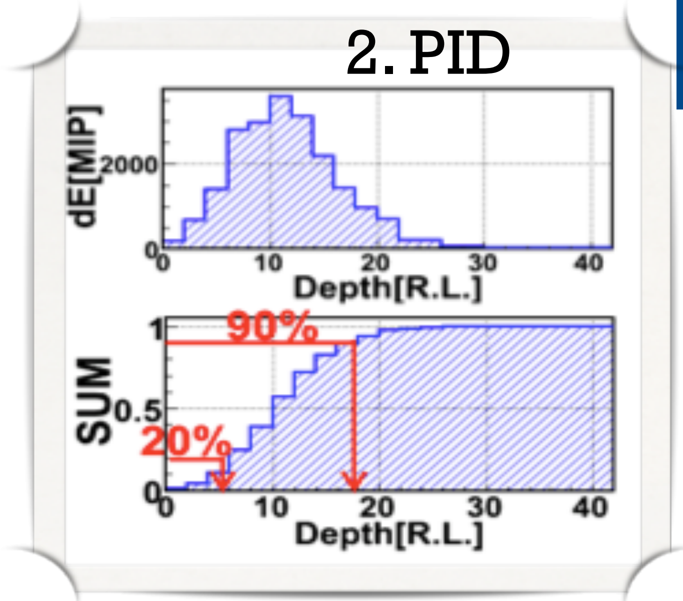
- QGSJET II-03, DPMJET 3.04, SYBILL 2.1, EPOS 1.99 and PYTHIA 8.145: about ~$3*10^7$ pp inelastic collisions each with default parameters

Analysis WORKFLOW @ 900 GeV

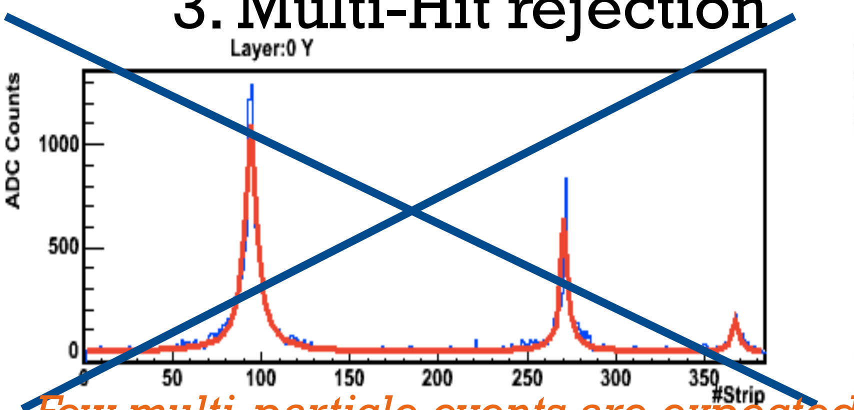
1. Energy Reconstruction



2. PID

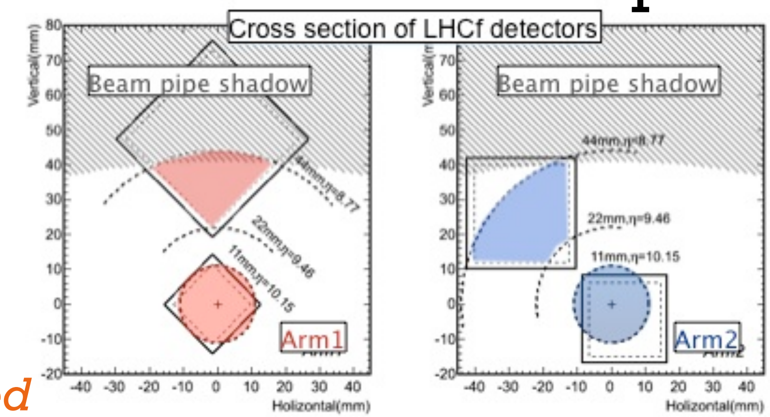


3. Multi-Hit rejection



Few multi-particle events are expected

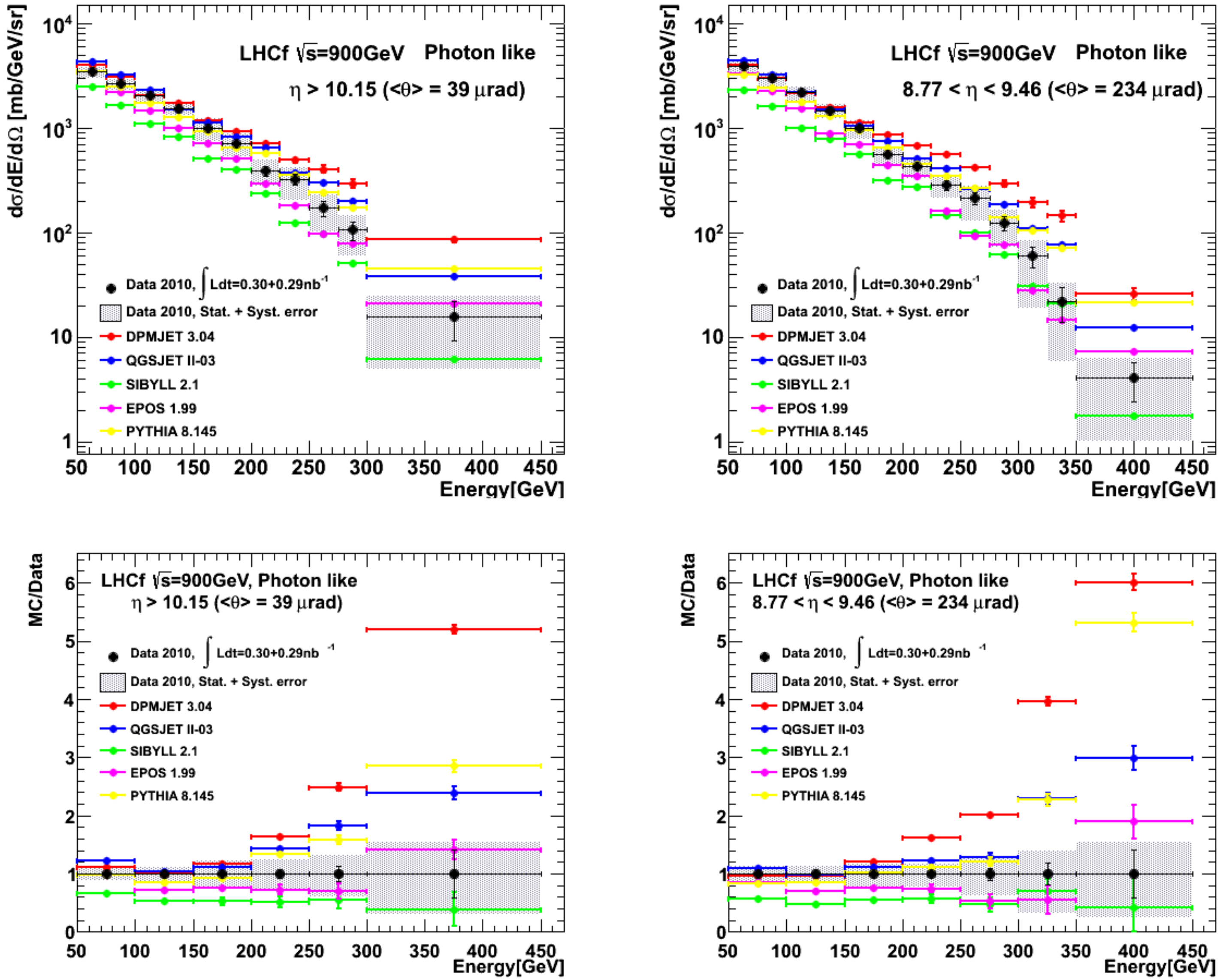
4. Acceptance cut



Small Tower
$\eta > 10.15$
Large Tower
$8.77 < \eta < 9.46$

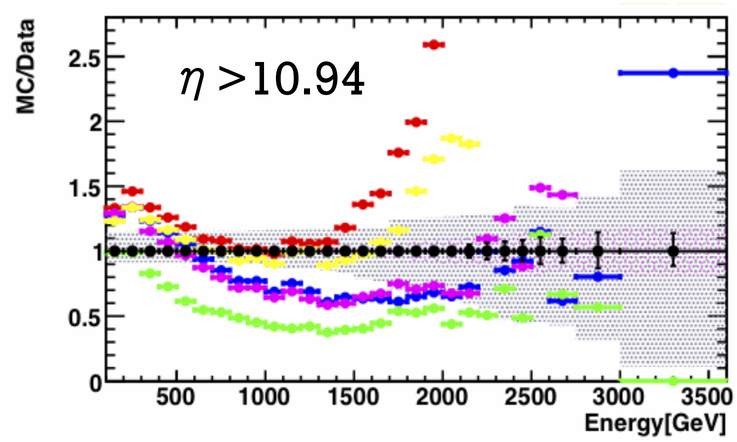
5. Systematic uncertainties

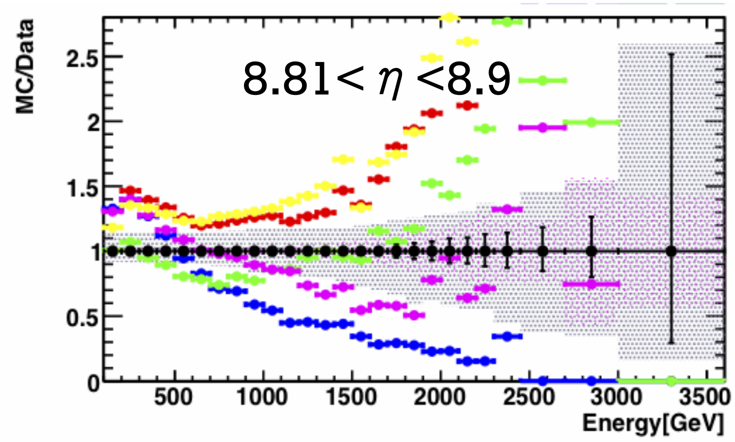
+ Comparison wrt MC Models at 900 GeV



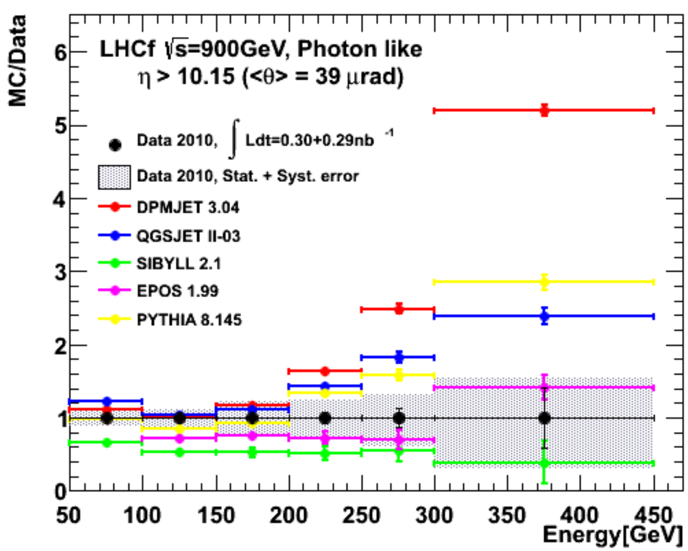
+ DATA-MC : comp. 900GeV/7TeV

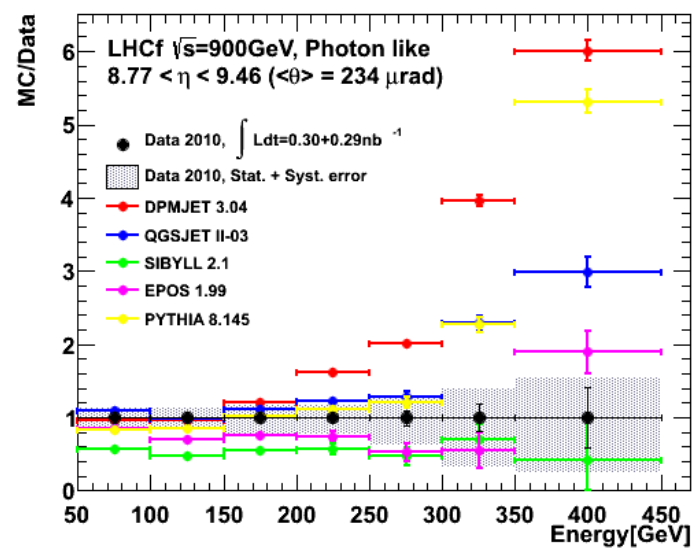
7TeV





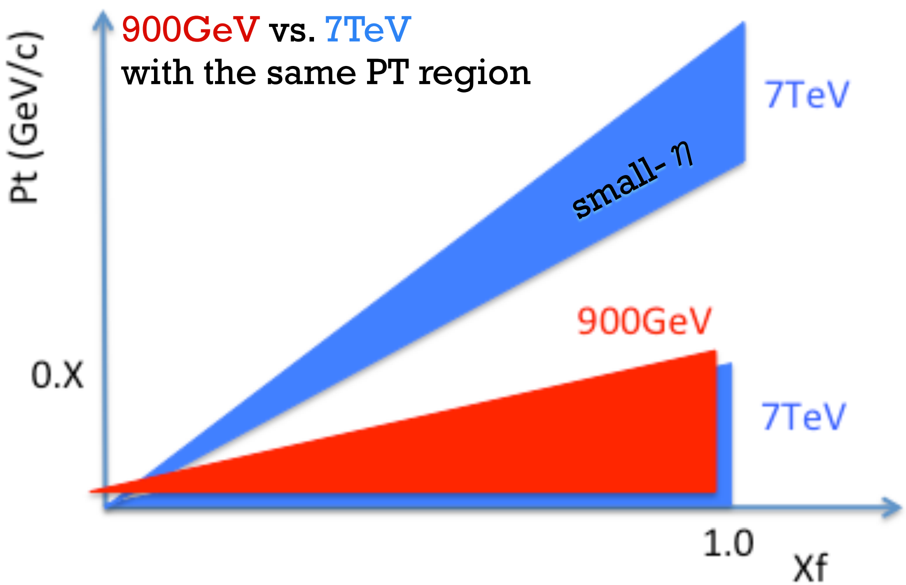
900GeV



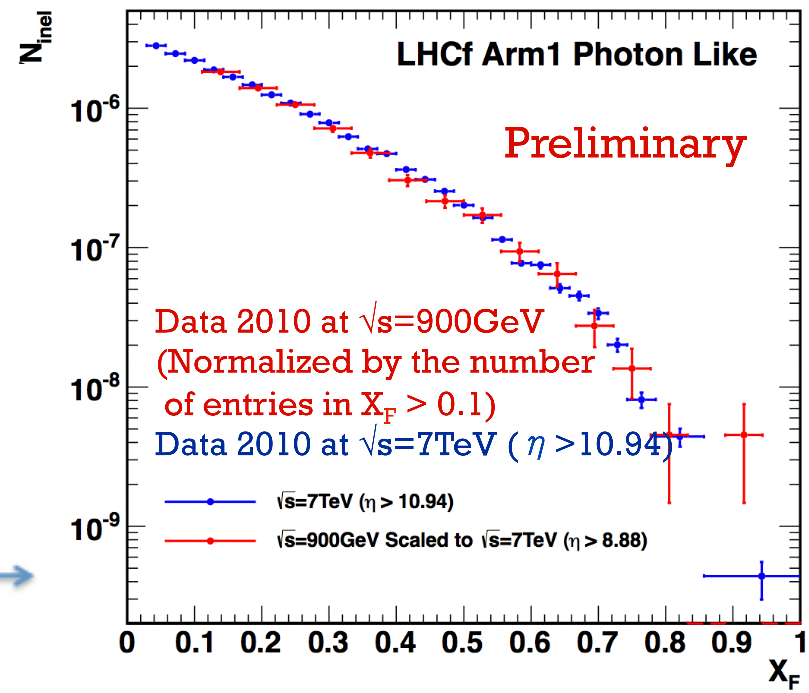


+ DATA : Comp. 900GeV/7TeV

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.

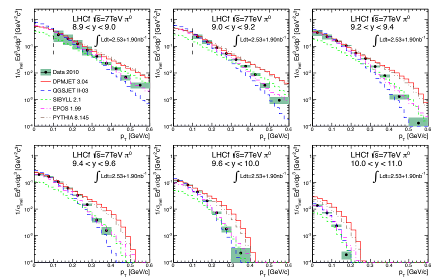
Good agreement of X_F spectrum shape between 900 GeV and 7 TeV.
➔Checking more for the Feynman scaling now.

Forward π^0 spectra at 7 TeV

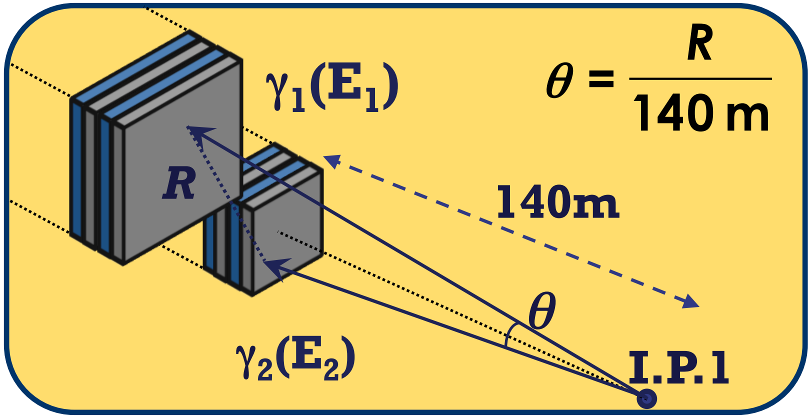
"Measurement of forward neutral pion transverse momentum spectra for $\sqrt{s}$ = 7TeV proton-proton collisions at LHC"

Submitted to PRD

CERN-PH-EP-2012-145



+ 7 TeV π^0 analysis

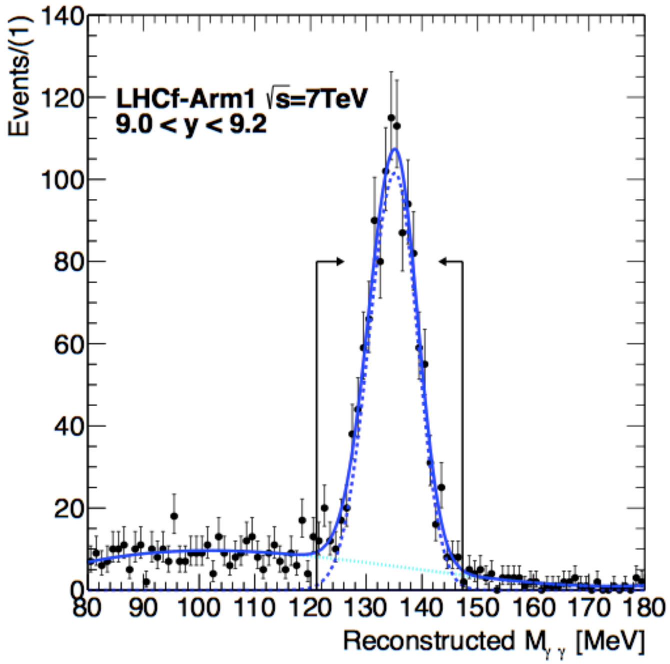


Mass, energy and transverse momentum are reconstructed from the energies and impact positions of photon pairs measured by each calorimeter

$$M_{\pi^0} = \sqrt{E_{\gamma 1} E_{\gamma 2} \theta^2},$$

$$E_{\pi^0} = E_{\gamma 1} + E_{\gamma 2},$$

$$P_{T\pi^0} = P_{T\gamma 1} + P_{T\gamma 2}$$



Analysis Procedure

- Standard photon reconstruction
- Event selection
  - one photon in each calorimeter
  - reconstructed invariant mass
- Background subtraction
  by using outer region of mass peak
- Unfolding for detector response.
- Acceptance correction.

Dedicated part for π^0 analysis

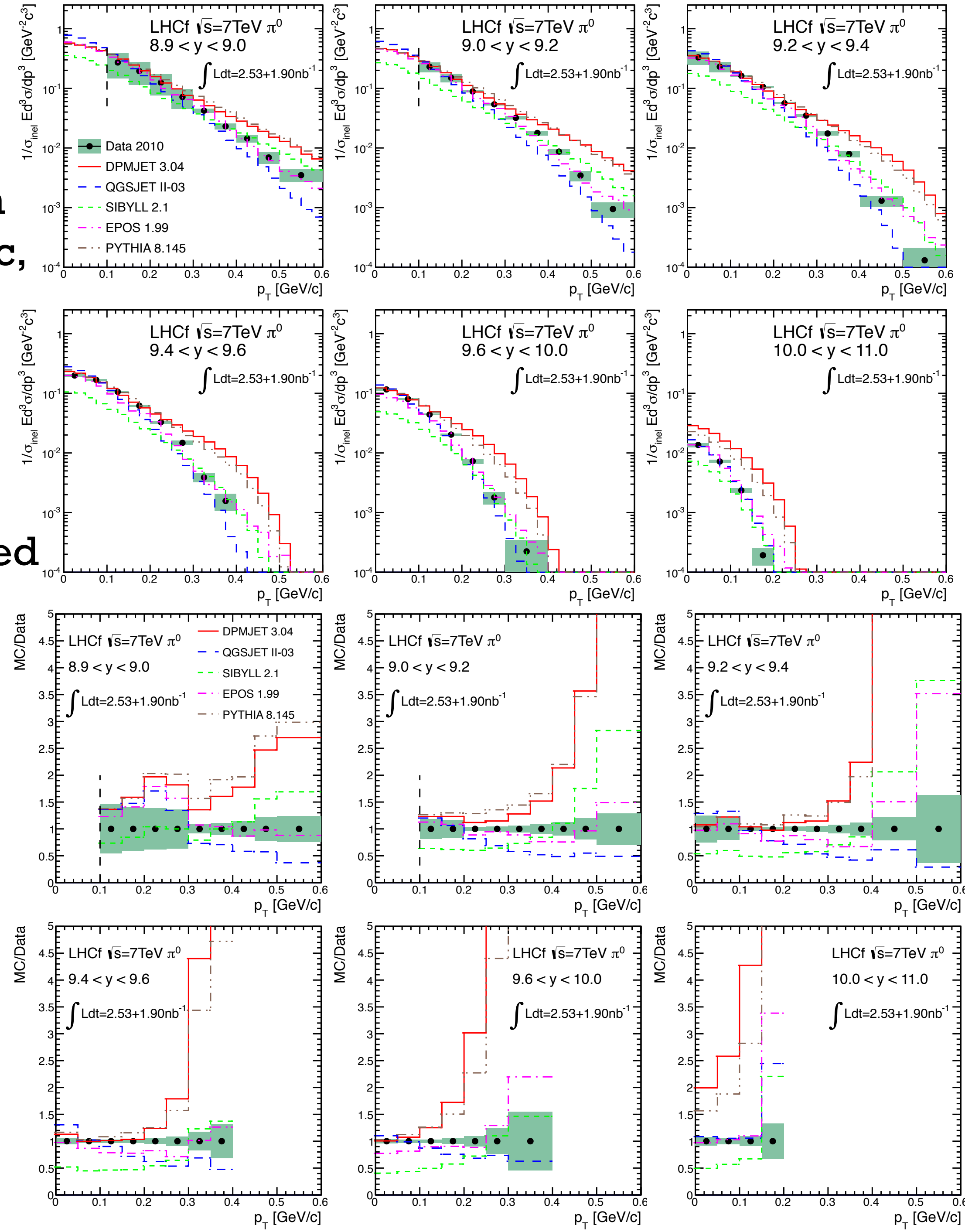
π^0 Data vs MC

- dpmjet 3.04 & pythia 8.145 show overall agreement with LHCf data for 9.2<y<9.6 and p_T <0.25 GeV/c, while the expected π^0 production rates by both models exceed the LHCf data as p_T becomes large

- sibyll 2.1 predicts harder pion spectra than data, but the expected π^0 yield is generally small

- qgsjet II-03 predicts π^0 spectra softer than LHCf data

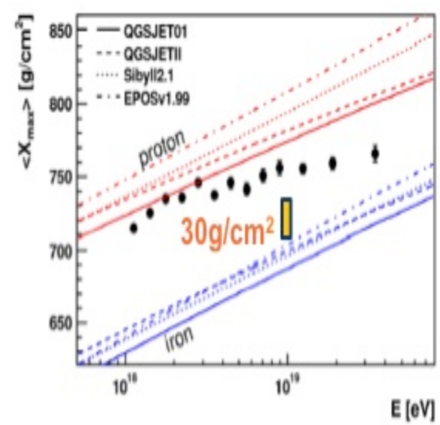
- epos 1.99 shows the best overall agreement with the LHCf data.
  - behaves softer in the low p_T region, p_T < 0.4GeV/c in 9.0<y<9.4 and p_T <0.3GeV/c in 9.4<y<9.6
  - behaves harder in the large p_T region.



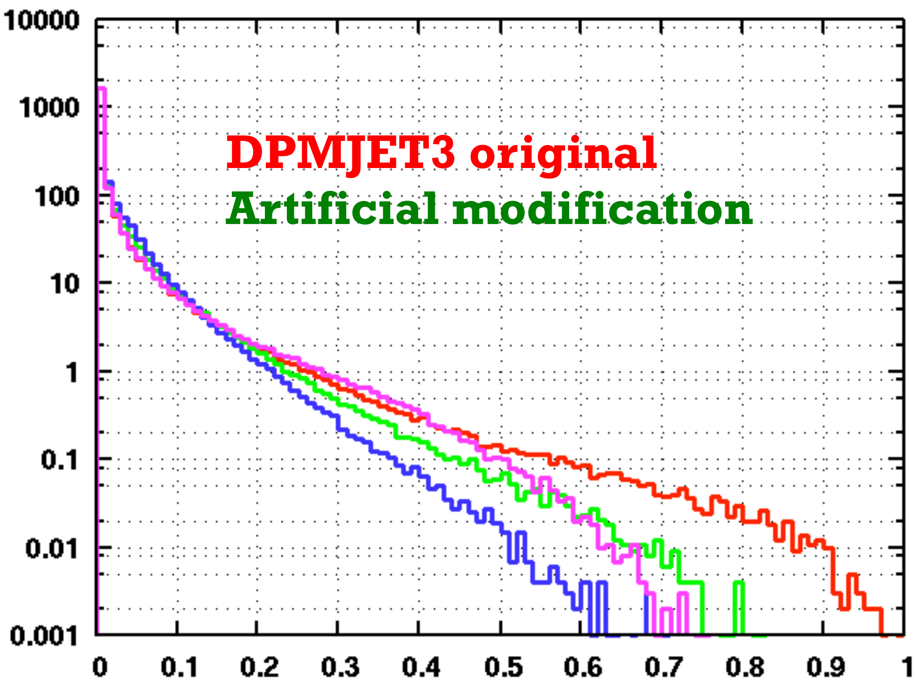
Alessia Tricomi

Impact on HECR Physics

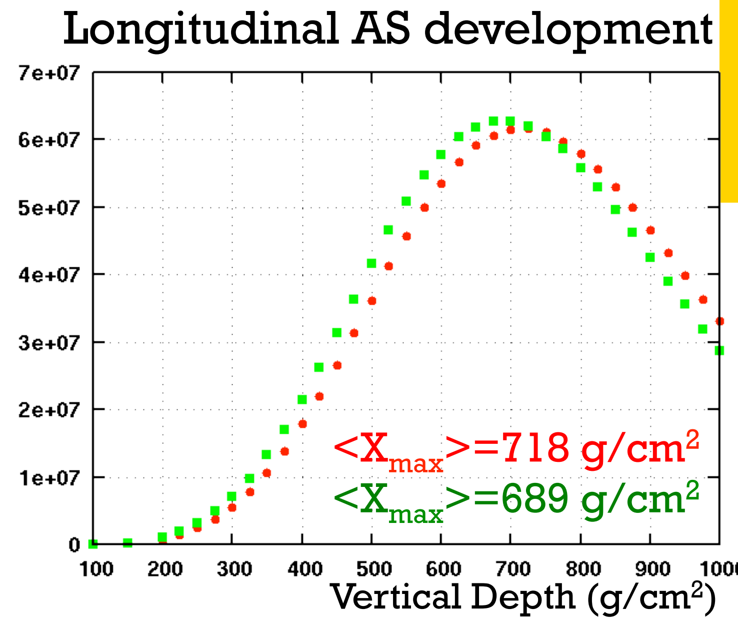
Understanding the impact of our measurements

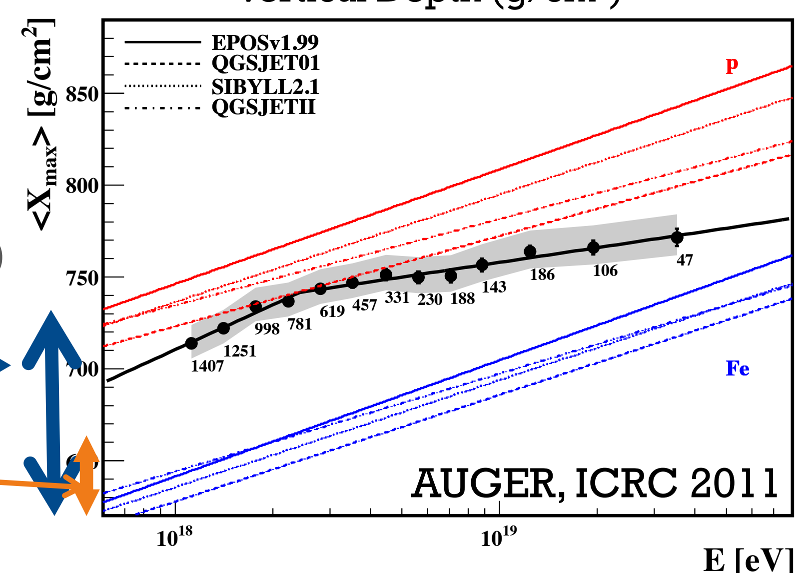


π^0 spectrum and air shower



π^0 spectrum at $E_{lab} = 10^{17}$eV



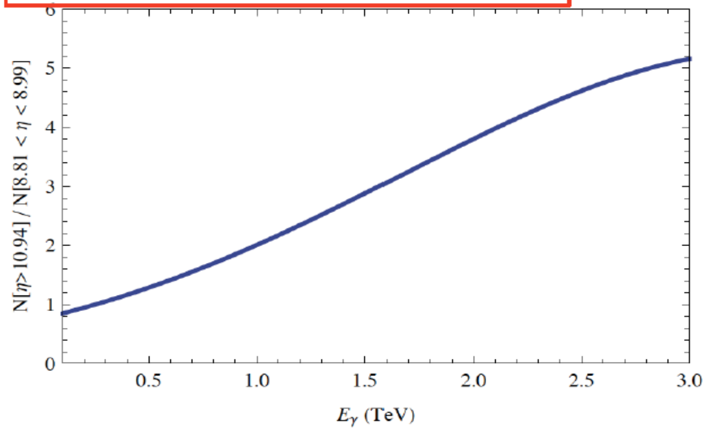


- ✓ Artificial modification of meson spectra (in agreement with differences between models)
- ✓ $\Delta\langle X_{max}(p\text{-}Fe)\rangle \sim 100$ g/cm^2
- ✓ Effect to air shower ~ 30 g/cm^2

+ p_T distribution dependence

Ratio [High Rapidity] / [Low Rapidity]

for LHCf DATA



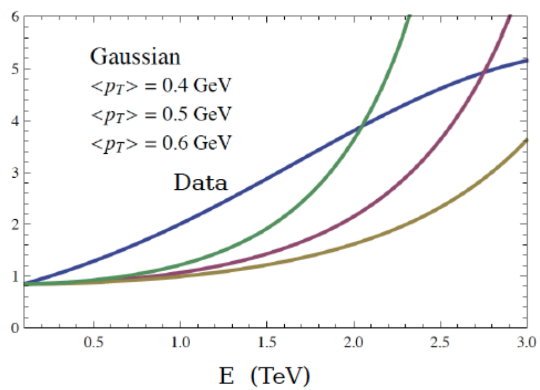
$$\left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\right]_{8.81\le\eta\le 8.99} = \frac{dN_\gamma}{dE_\gamma}(E_\gamma)\times\frac{dN_\gamma[8.81\le\eta\le 8.99]}{dN_\gamma[\text{all }\eta]}$$

$$\left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\right]_{\eta>10.94} = \frac{dN_\gamma}{dE_\gamma}(E_\gamma)\times\frac{dN_\gamma[\eta>10.94]}{dN_\gamma[\text{all }\eta]}$$

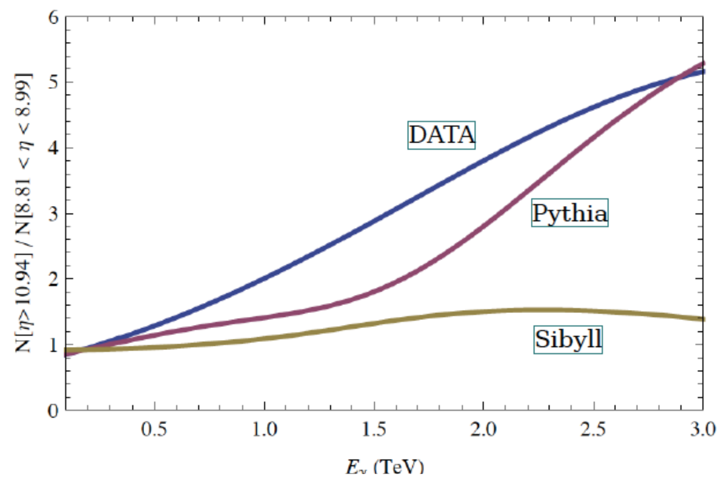
Directly relevant for UHECR shower development

pT distribution dependence

The pT distribution a sqrt[s] = 7 TeV is not a Gaussian of energy independent width.



Courtesy P. LIPARI
Interplay of LHCf data with HECR Physics Workshop,
Catania, July 6 2011



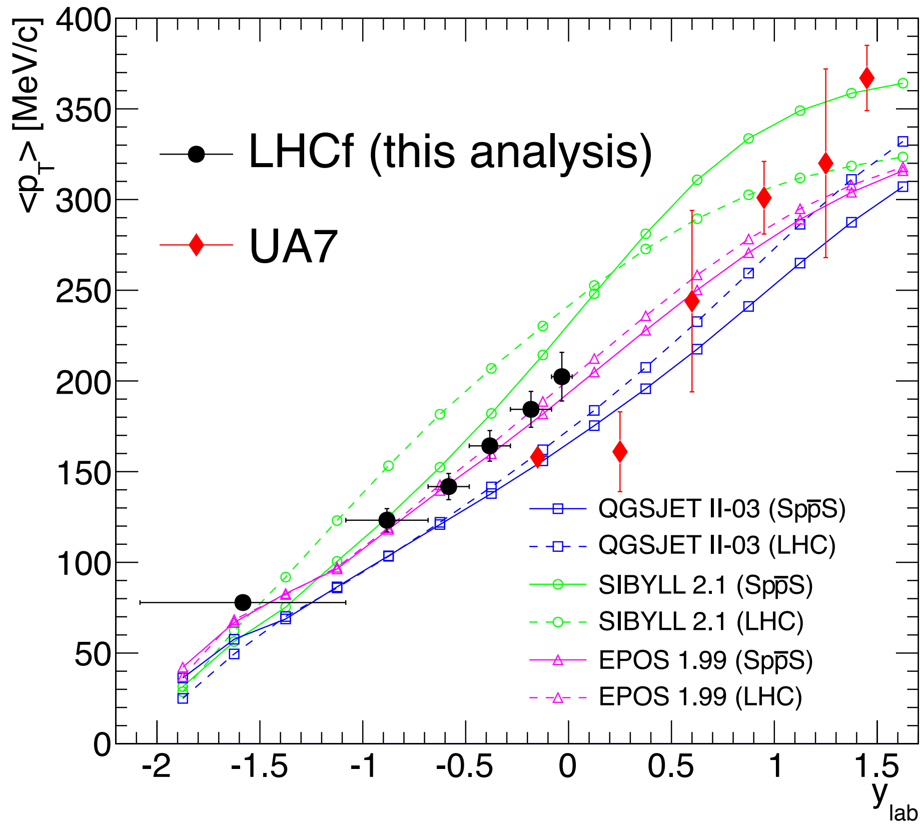
LHCf <p_T> distribution

Two different approaches used to derive the average transverse momentum, ⟨pT⟩

1. by fitting an empirical function to the p_T spectra in each rapidity range (exponential distribution based on a thermodynamical approach)

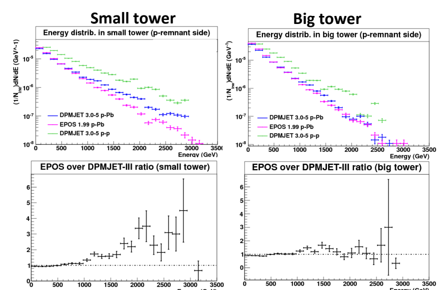
2. by simply numerically integrating the p_T spectra

Results of the two methods are in agreement and are compared with UA7 data and hadronic model predictions

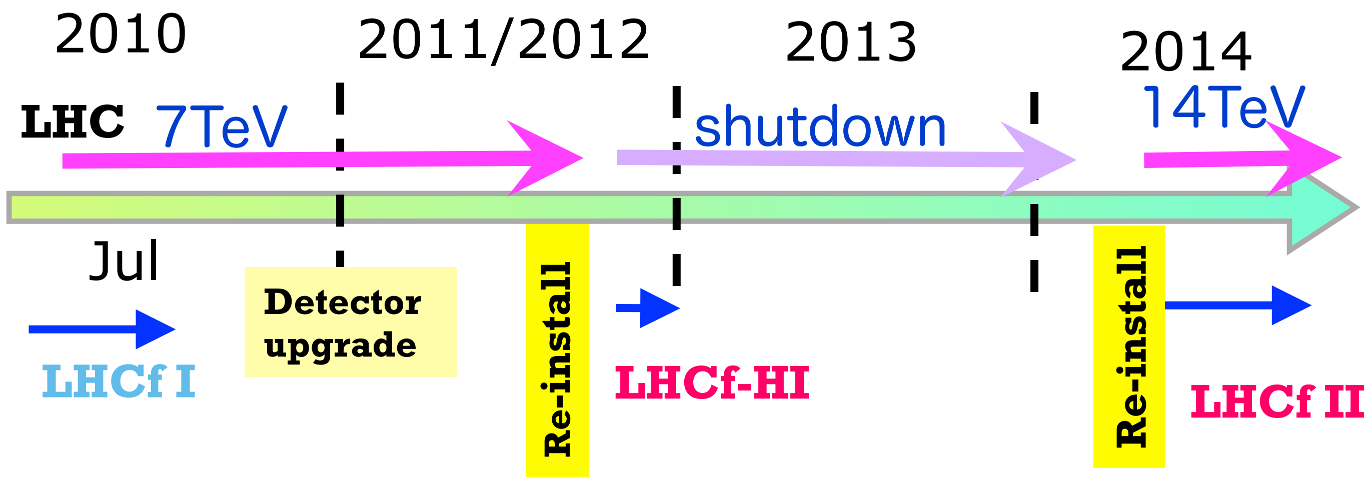


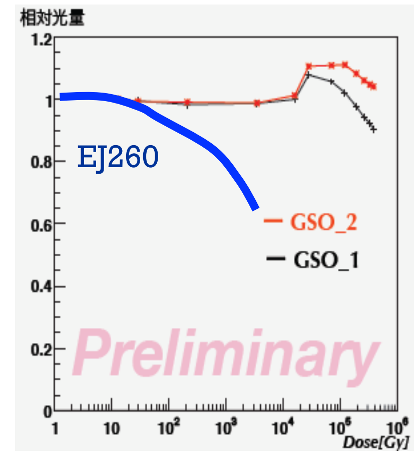
What's next

Detector upgrade, ion runs, future analyses



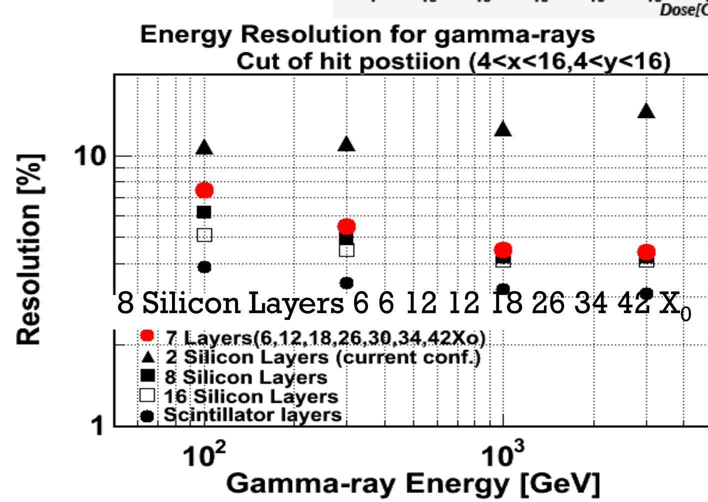
+ LHCf Future PLANS (I)



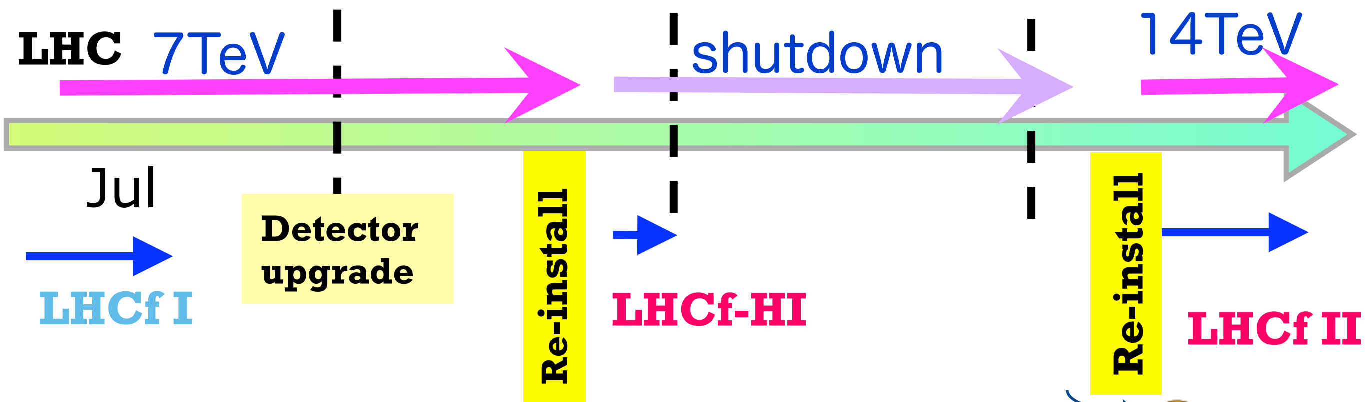


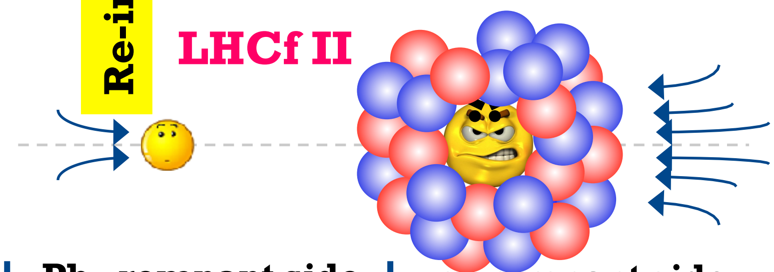
2012: Detector upgrade for 14 TeV run

- Replace plastic scintillators with Rad Hard GSO
  - Test beam at HIMAC end of last year
- Modify the silicon layers positions to improve silicon-only energy resolution
- Test beam at SPS to calibrate Arm1&Arm2
- Improve the dynamic range of silicon

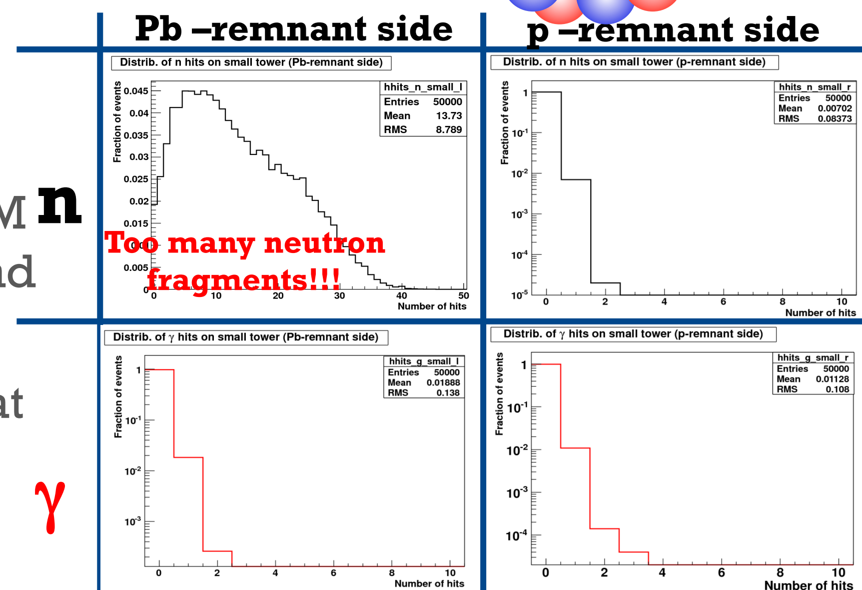


LHCf Future PLANS (II): Ion runs





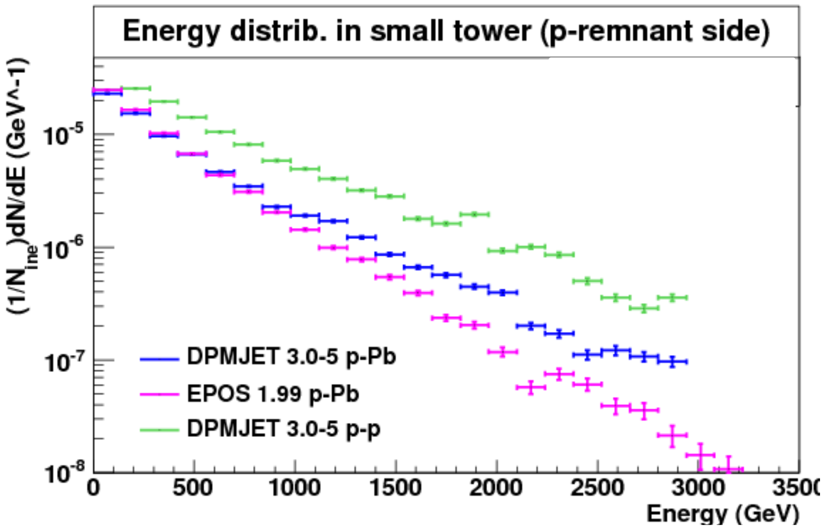
- 2012-(2013): p-Pb runs
  - Interest in Ion runs
  - Physics case study well motivated
  - LHC Ion run and RHIC (2015?)
    - Approved by LHCC to reinstall one ARM on p-remnant side during p-Pb run (end of 2012)
    - Discussion about possible data taking at RHIC



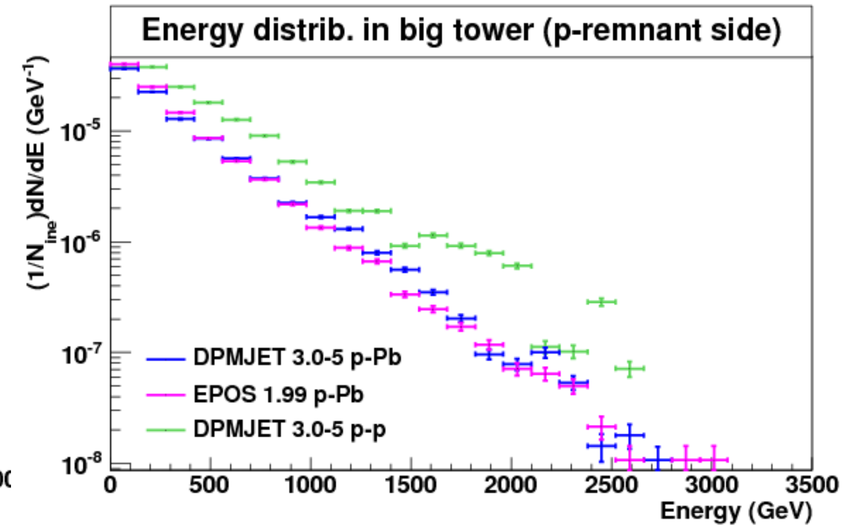
LHCf Future PLANS (II): p-Pb run

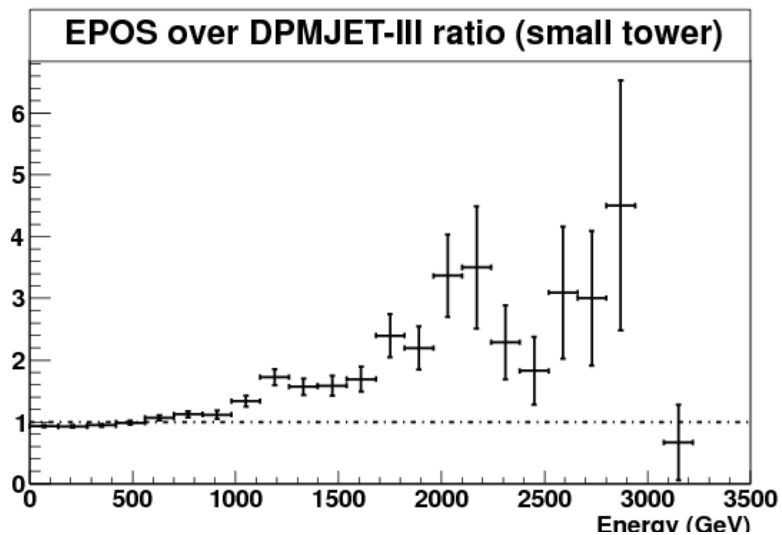
Photon spectra

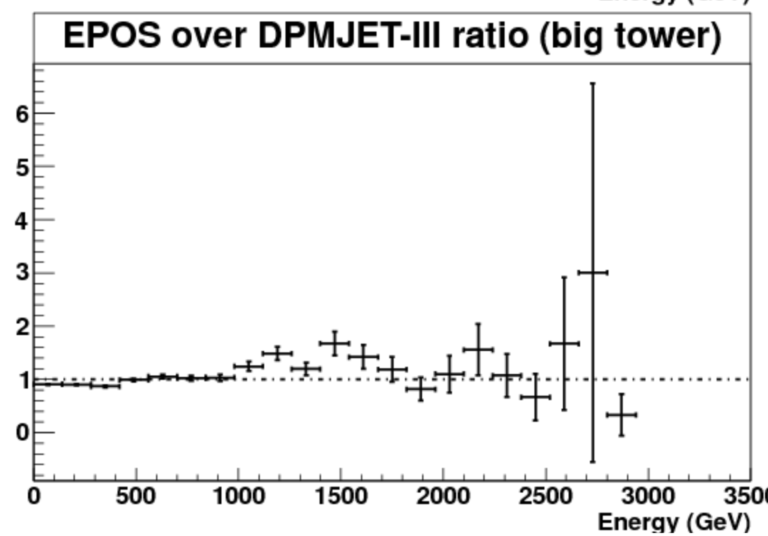
Small tower



Big tower



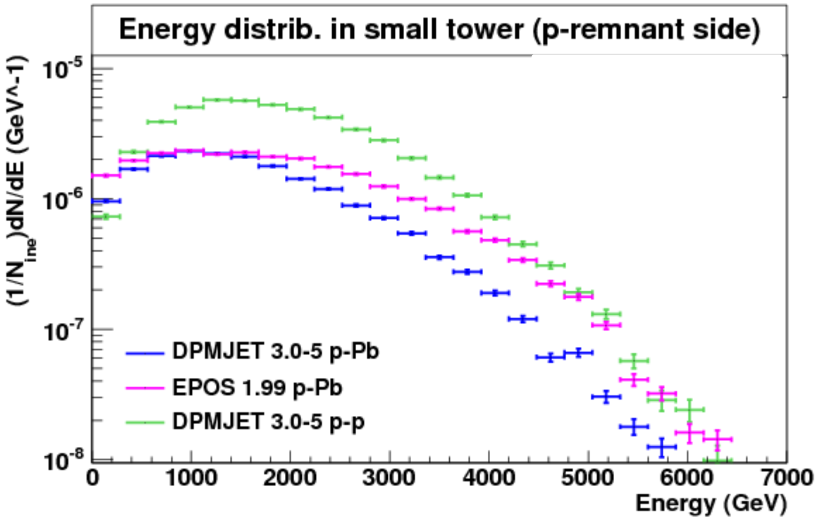


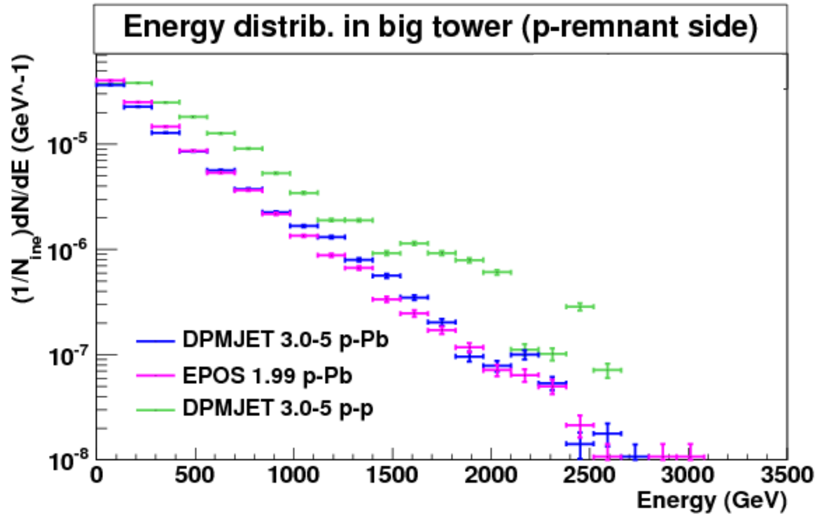


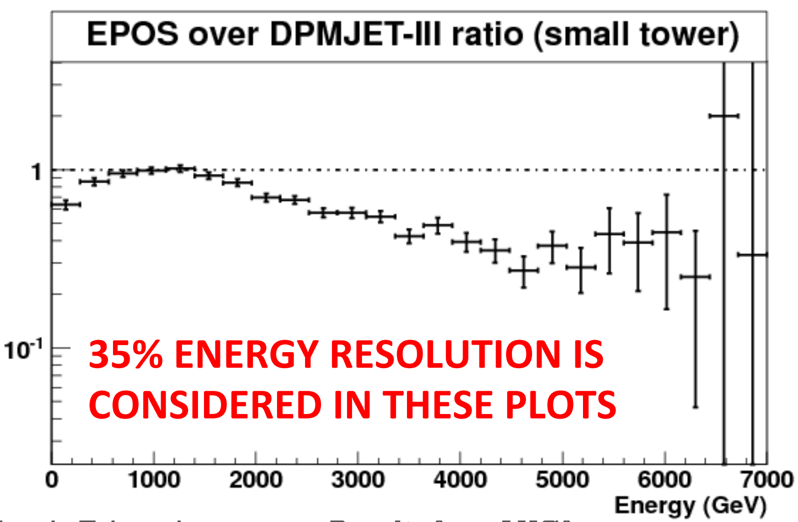
+ LHCf Future PLANS (II): p-Pb run

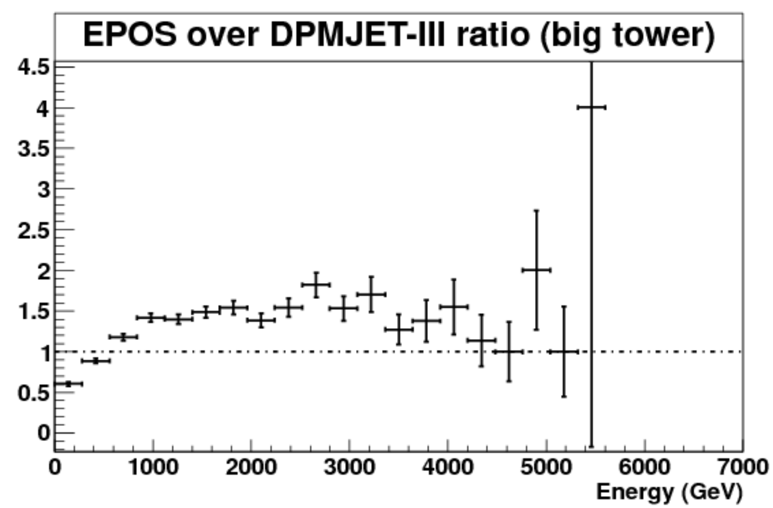
Neutron spectra

Small tower | **Big tower**



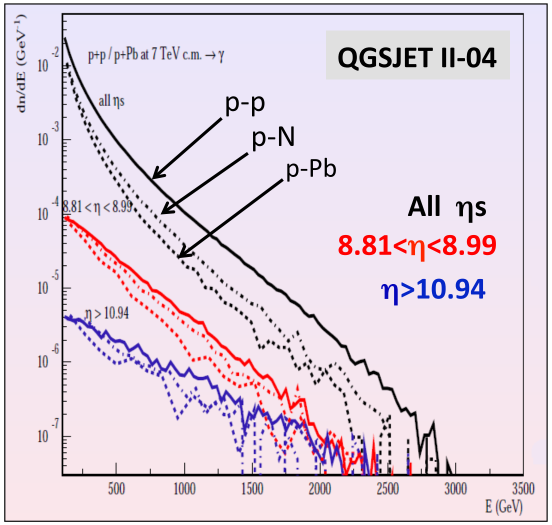


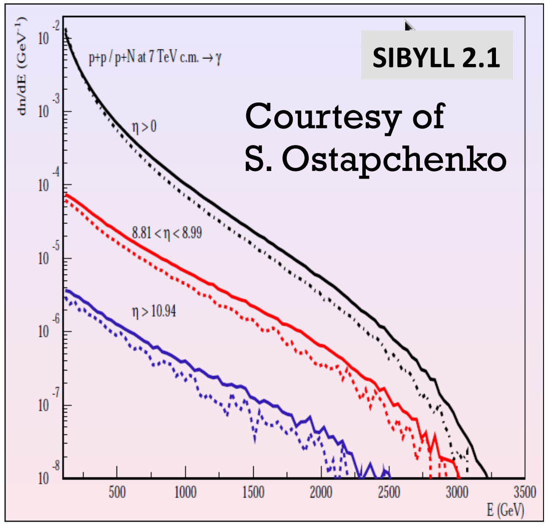




+ LHCf Future PLANS (II): p-Pb run

Additional motivations





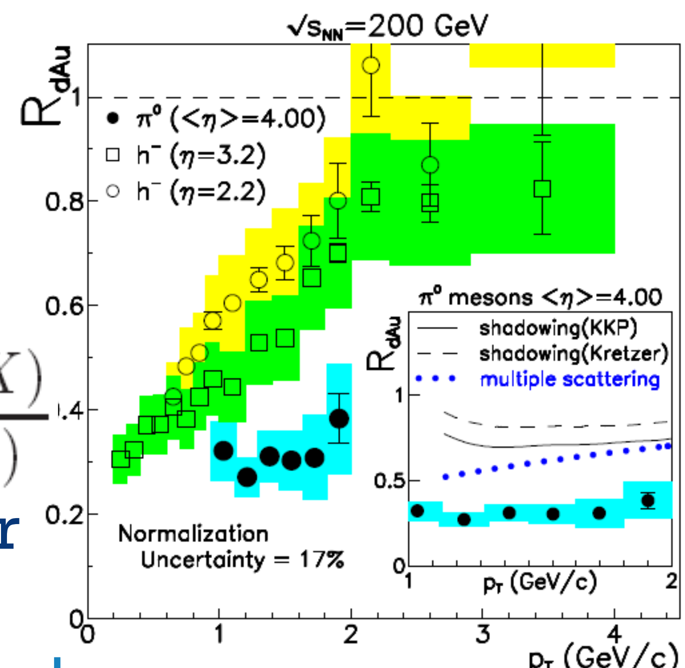
Photon energy distrib. vs η intervals at $\sqrt{s_{NN}} = 7$ TeV

Comparison of p-p/p-N/P-Pb

Enhancement of suppression for heavier nuclei case

Nuclear Modification Factor measured at RHIC (production of π^0): strong suppression for small p_T at $<\eta>=4$

$$R^{Y}_{\mathrm{dAu}} = \frac{\sigma^{pp}_{\mathrm{inel}}}{\langle N_{\mathrm{bin}}\rangle \sigma^{dAu}_{\mathrm{hadr}}} \frac{E\, d^3\sigma/dp^3(d+Au \to Y+X)}{E\, d^3\sigma/dp^3(p+p \to Y+X)}$$



Phys. Rev. Lett. 97 (2006) 152302

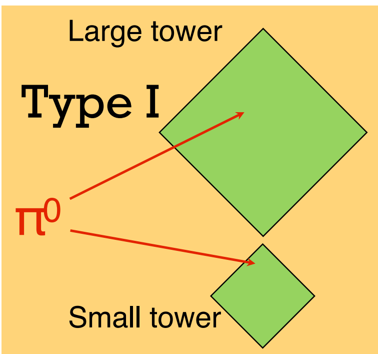
LHCf can extend the measurent at higher energies and for $\eta>8.4$

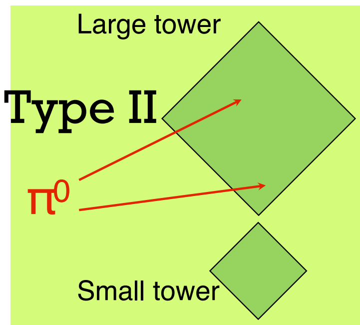
Important measurement for HECR Physics!

LHCf on going activities: new analyses

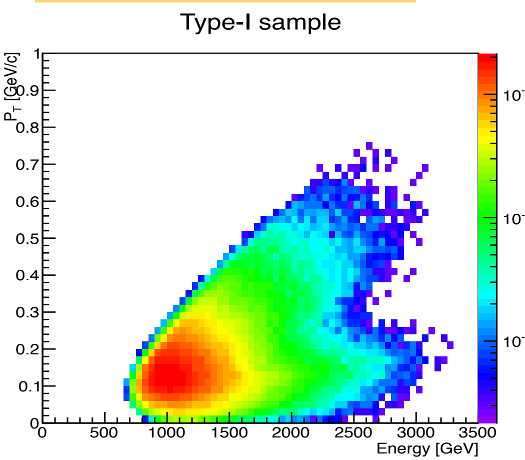
2012-2013: New analyses

- Hadron spectra
- π^0 type II measurement
- η, K^0, Λ ?

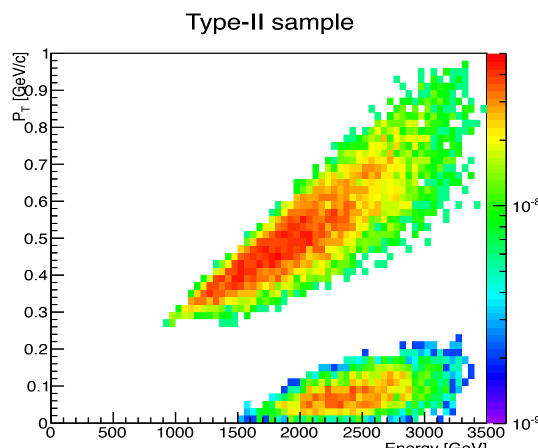




Excellent performance of position sensitive detectors give us the possibility to reconstruct multi-hit event in the same tower



Wide opening angle
Dominate at lower energy



Tight opening angle
Dominate at high energy

Extend our acceptance

Conclusions

- LHCf analysis activity is progressing well
  - 7 TeV Inclusive photon analysis published
    - First comparison of various hadronic interaction models with experimental data in the most challenging phase space region ($8.81 < \eta < 8.99$, $\eta > 10.94$)
    - Large discrepancy especially in the high energy region with all models
  - 900 GeV spectra submutted
    - Comparison with 7 TeV in agreement
  - π^0 p_T spectra just released
    - Comparisons with models gives important hints for HECR and soft QCD Physics
  - Implications on UHECR Physics under study in strict connection with relevant theoreticians and model developer
  - Stay tuned for new results
- We are upgrading the detectors to improve their radiation hardness (GSO scintillators and rearrange silicon layers) for 14 TeV run
- We will reinstall ARM2 detector for the p-Pb run at the and of 2012
  - Physics case well motivated
- We are also thinking about a possible run at RHIC with lighter ions
- Last but not least…We are also working for the 14 TeV run with upgraded detector!!!

Backup slides

Some additional material

LHCf operations @900 GeV & 7 TeV

With Stable Beam at 900 GeV Dec 6th – Dec 15th 2009

With Stable Beam at 900 GeV May 2nd – May 27th 2010

	Shower	Gamma	Hadron
Arm1	46,800	4,100	11,527
Arm2	66,700	6,158	26,094

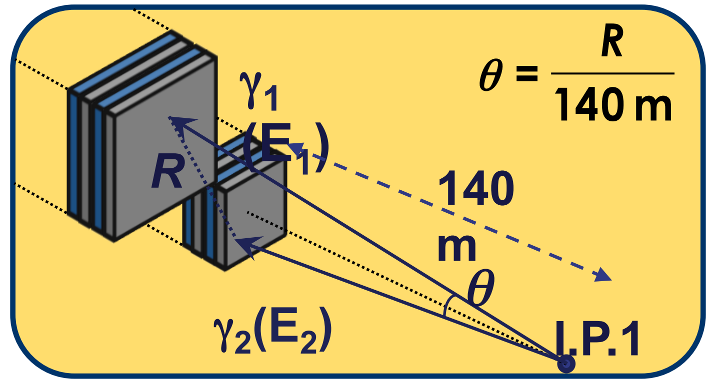
- With Stable Beam at 7 TeV March 30th - July 19th 2010

  We took data with and without 100 μrad crossing angle for different vertical detector positions

	Shower	Gamma	Hadron	π^0
Arm1	172,263,255	56,846,874	111,971,115	344,526
Arm2	160,587,306	52,993,810	104,381,748	676,157

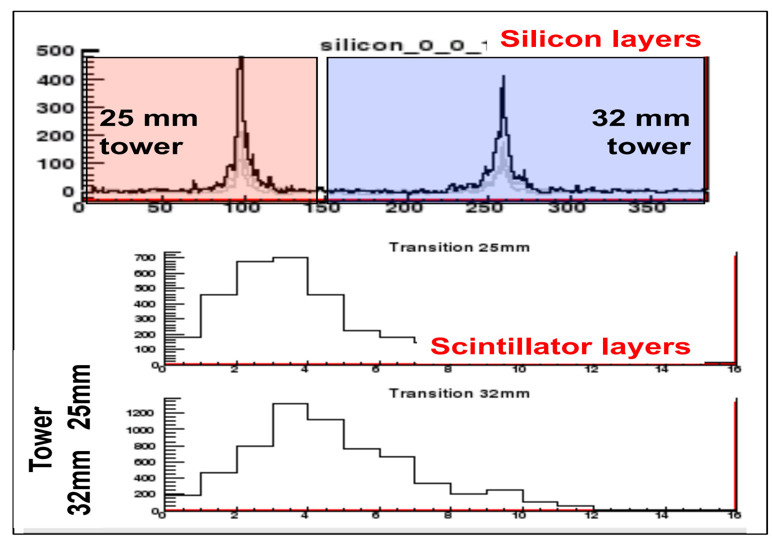
+ Systematic Uncertainties

- Main systematic uncertainty due to energy scale
  - ✓ Energy scale can be checked by π^0 identification from two tower events.
  - ✓ Mass shift observed both in Arm1 (+7.8%) and Arm2 (+3.7%)
  - ✓ **No energy scaling** applied, but shifts assigned in the systematic error in energy



$$M = \theta \sqrt{(E_1 x E_2)}$$

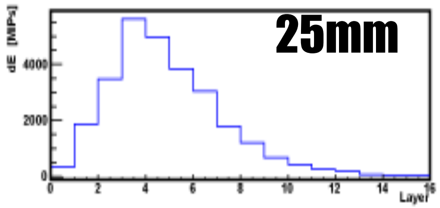
- Uncorrelated uncertainties between ARM1 and ARM2
  - Energy scale (except π^0 error)
  - Beam center position
  - PID
  - Multi-hit selection

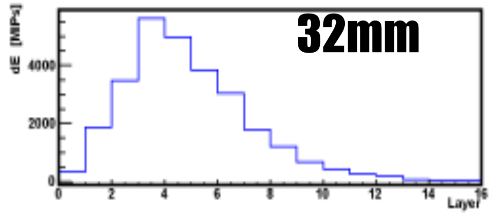


- Correlated uncertainty
  - Energy scale (π^0 error)
  - Luminosity error

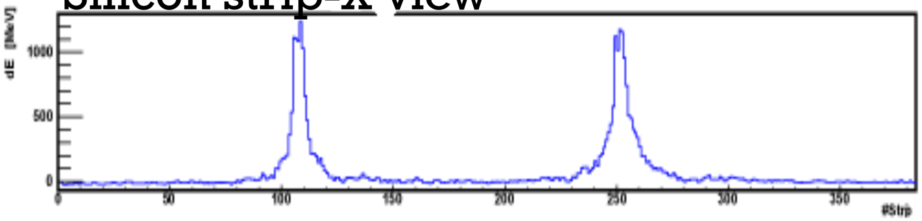
π^0 reconstruction

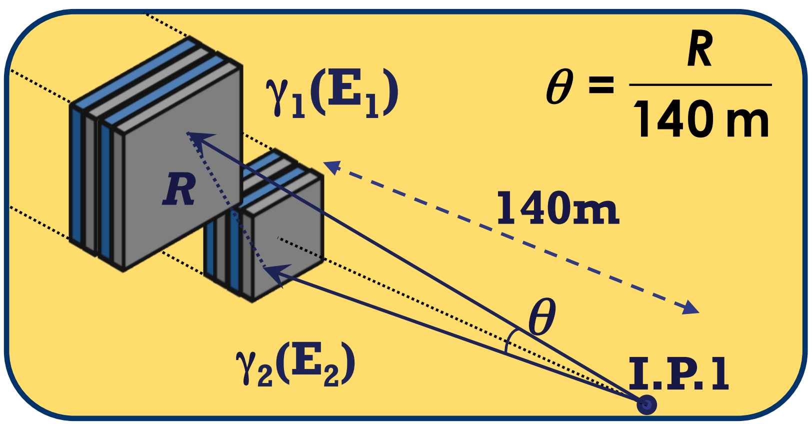
An example of π^0 events





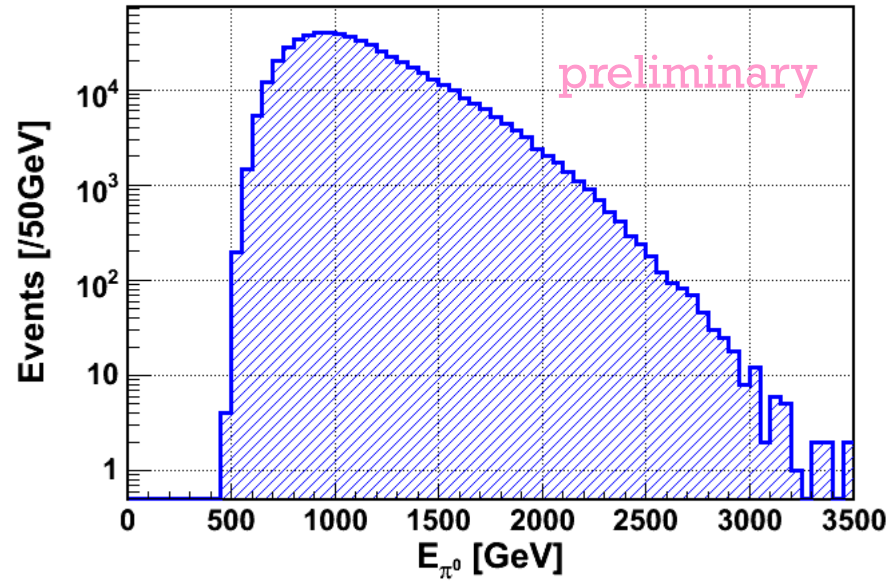
Silicon strip-X view



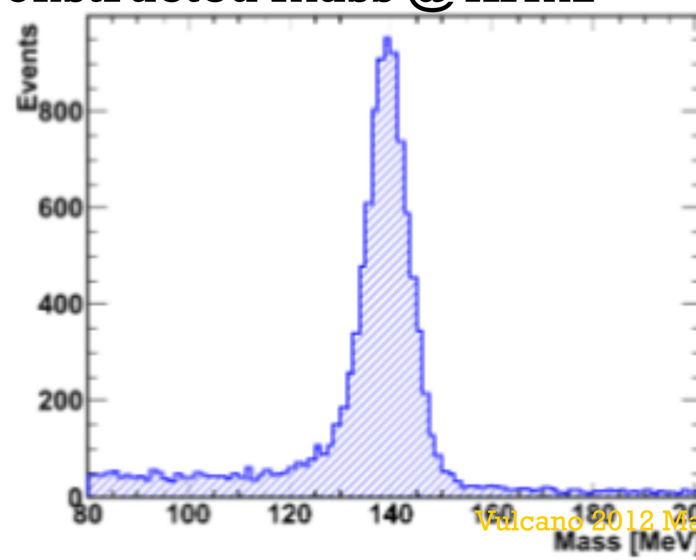


- π^0' s are the main source of electromagnetic secondaries in high energy collisions.
- The mass peak is very useful to confirm the detector performances and to estimate the systematic error of energy scale.

measured energy spectrum @ Arm2

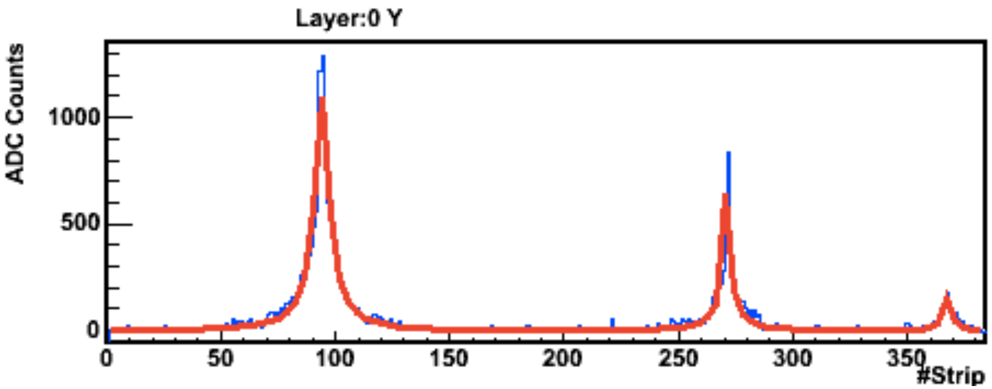


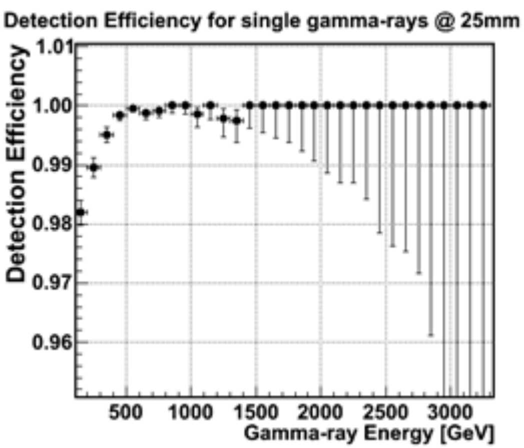
Reconstructed mass @ Arm2



Analysis 3. -Multi-hit identification

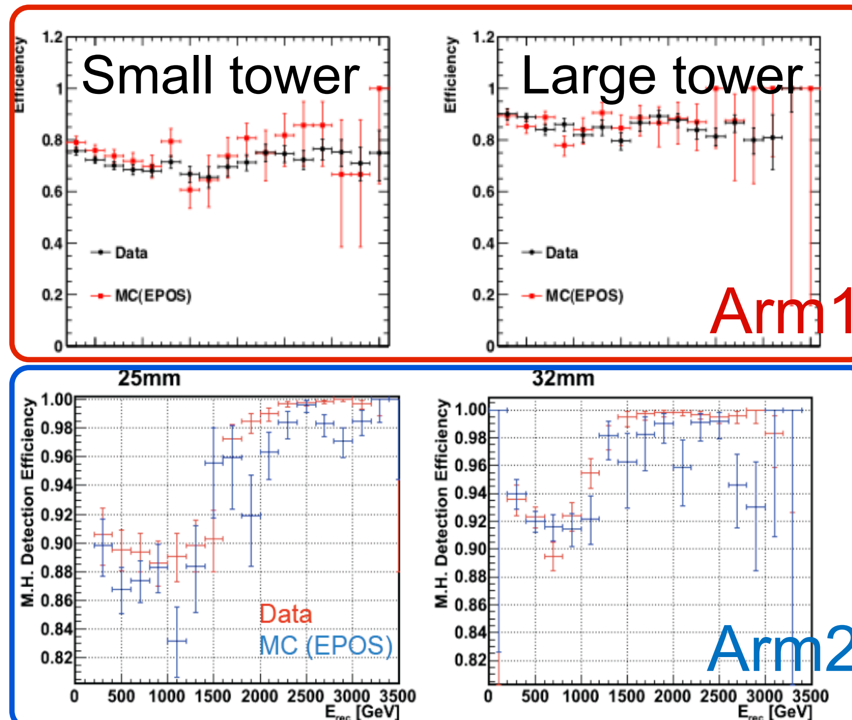
- Reject events with multi-peaks
  - Identify multi-peaks in one tower by position sensitive layers.
  - Select only the single peak events for spectra.



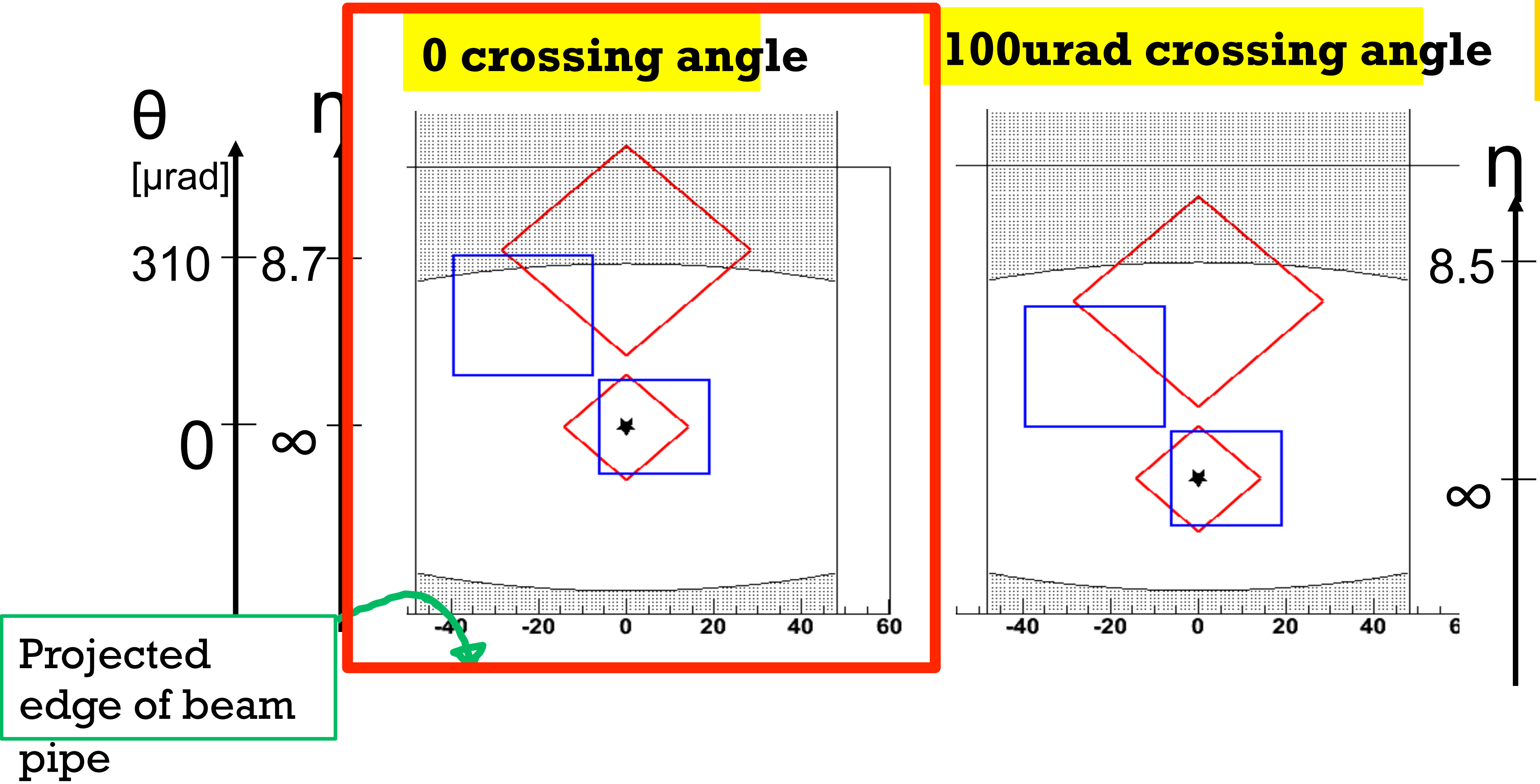


Single hit detection efficiency

Double hit detection efficiency



Calorimeters viewed from IP



- Geometrical acceptance of Arm1 and Arm2
- Crossing angle operation enhances the acceptance

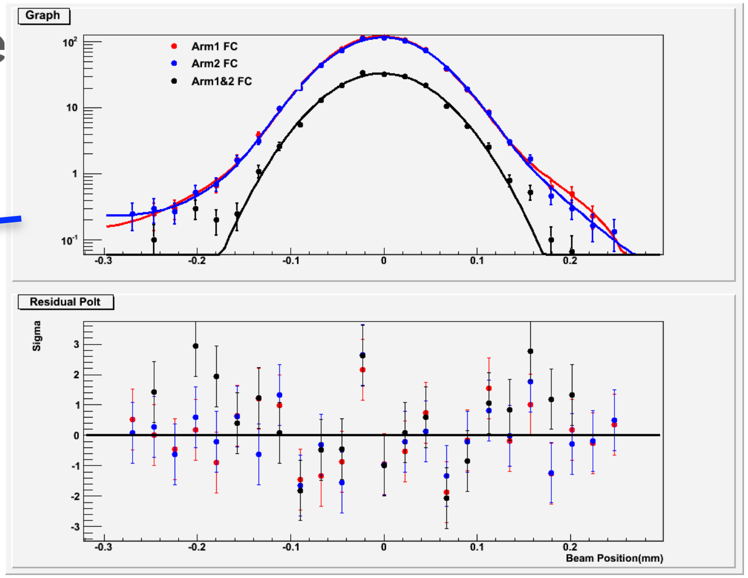
+ Luminosity Estimation

- Luminosity for the analysis is calculated from Front Counter rates:

$$L = CF \times R_{\mathrm{FC}}$$

- The conversion factor CF is estimated from luminosity measured during Van der Meer scan

$$L_{\mathrm{VDM}} = n_b f_{\mathrm{rev}} \frac{I_1 I_2}{2\pi \sigma_x \sigma_y}$$



Beam sizes σ_x and σ_y measured directly by LHCf

BCNWG paper

https://lpc-afs.web.cern.ch/lpc-afs/tmp/note1_v4_lines.pdf

+ Estimation of Pile up

When the circulated bunch is 1x1, the probability of N collisions per Xing is

$$P(N) = \frac{\lambda^N \exp[-\lambda]}{N!}$$

$$\lambda = \frac{L \cdot \sigma}{f_{\mathrm{rev}}}$$

The ratio of the pile up event is

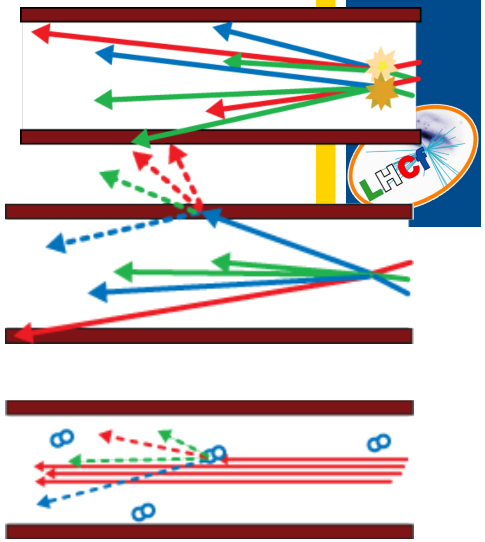
$$R_{\mathrm{pileup}} = \frac{P(N \geq 2)}{P(N \geq 1)} = \frac{1-(1+\lambda)e^{-\lambda}}{1-e^{-\lambda}}$$

The maximum luminosity per bunch during runs used for the analysis is 2.3×10^{28} cm^{-2}s^{-1}

So the probability of pile up is estimated to be 7.2% with σ of 71.5mb

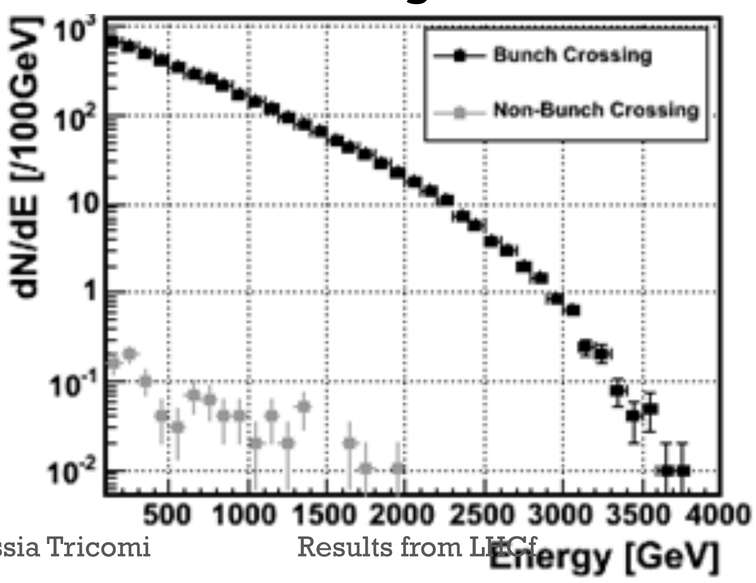
Taking into account the calorimeter acceptance (~0.03) only 0.2% of events have multi-hit due to pile-up. It does not affect our results

+Backgrounds

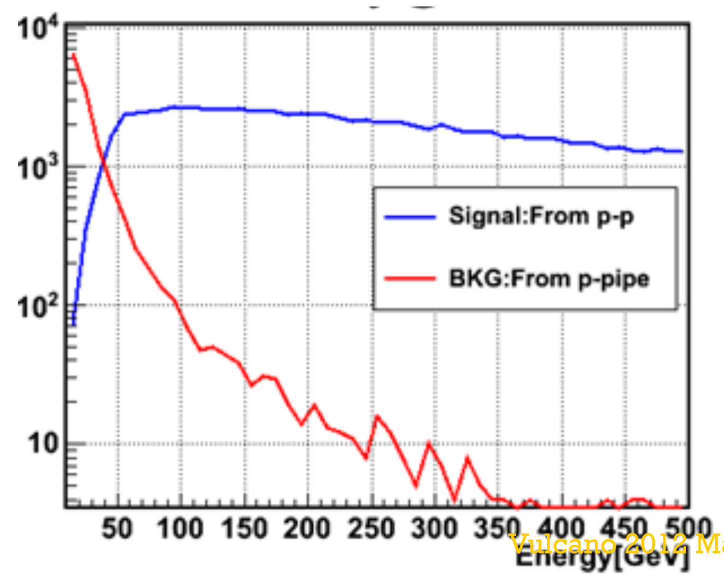


1. Pileup of collisions in one beam crossing
   - Low Luminosity fill, L=6x10[28]cm[-2]s[-1]
     ➔ 7% pileup at collisions, 0.2% at the detectors.
2. Collisions between secondary's and beam pipes
   - Very low energy particles reach the detector (few % at 100GeV)
3. Collisions between beams and residual gas
   - Estimated from data with non-crossing bunches.
     ➔ <0.1%

Beam-Gas backgrounds



Secondary-beam pipe backgrounds

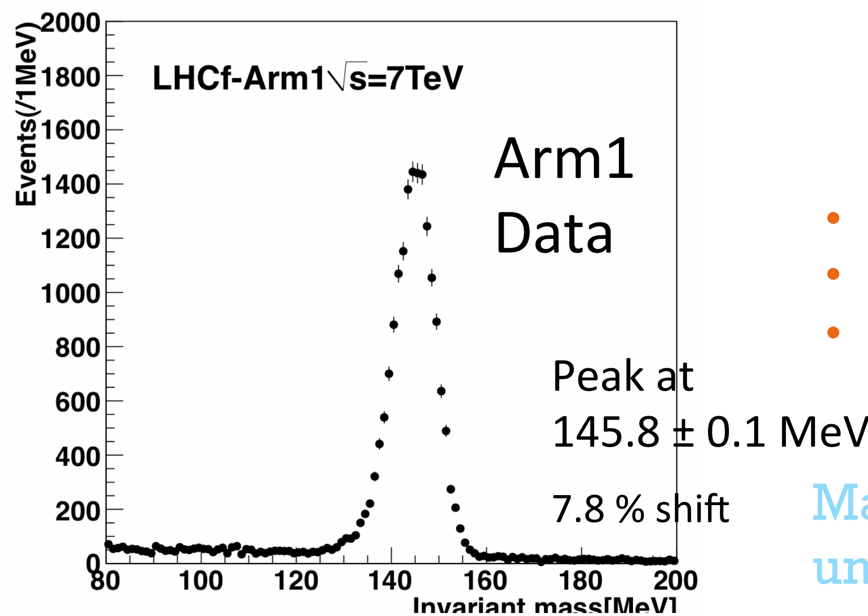


Systematic error from Energy scale

- Two components:
  - Relatively well known: Detector response, SPS => 3.5%
  - Unknown: π^0 mass => 7.8%, 3.8% for Arm1 and Arm2.
- Please note:
- - 3.5% is symmetric around measured energy
- - 7.8% (3.8%) are asymmetric, because of the π^0 mass shift
- - No 'hand made' correction is applied up to now for safety
- Total uncertainty is
  - -9.8% / +1.8% for Arm1
  - -6.6% / +2.2% for Arm2

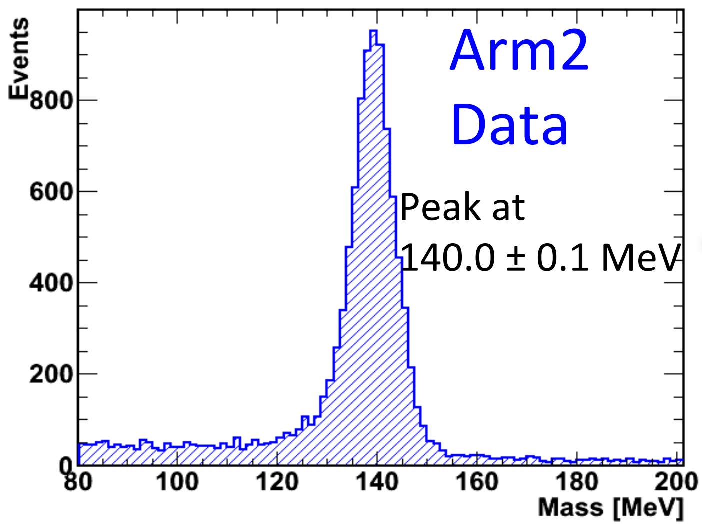
Systematic Uncertainty on Spectra is estimated from difference between normal spectra and energy shifted spectra.

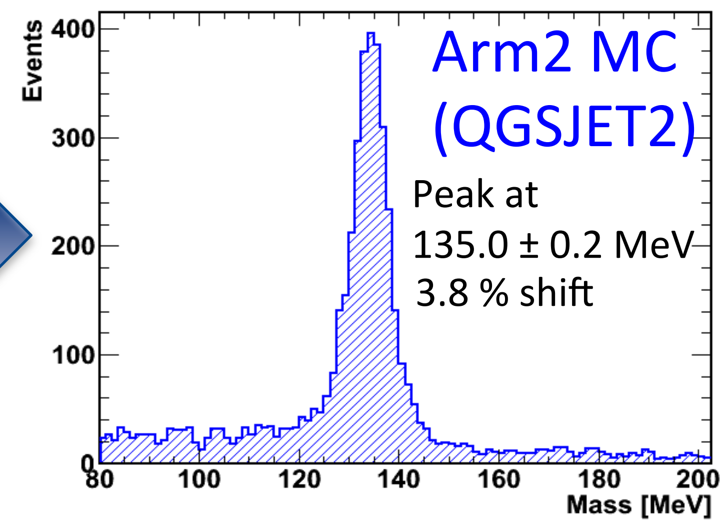
π^0 Mass



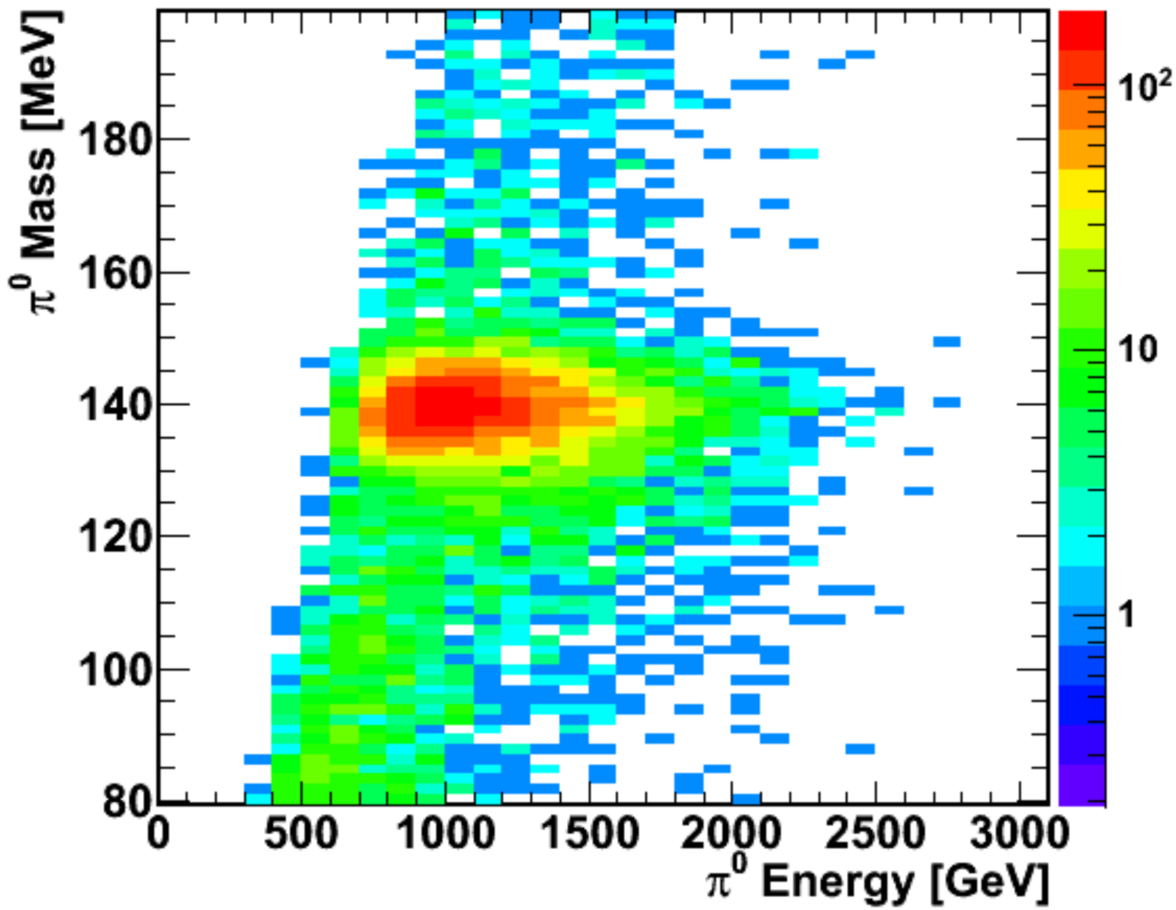
- Disagreement in the peak position
- No 'hand made correction' is applied for safet
- Main source of systematic error → see later

Many systematic checks have been done to understand the energy scale difference





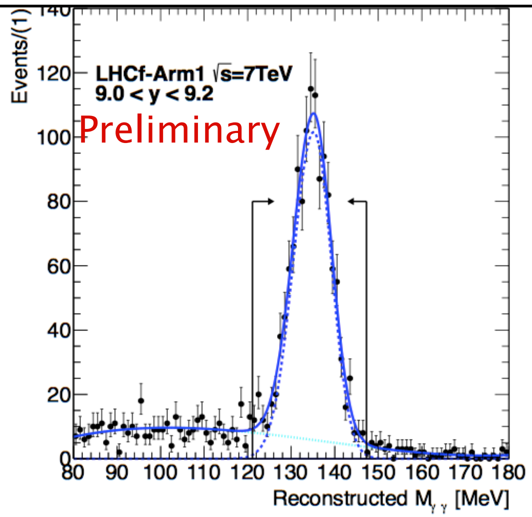
π^0 mass vs π^0 energy



Arm2 Data
No strong energy dependence of reconstructed mass

+ 7 TeV π^0 analysis

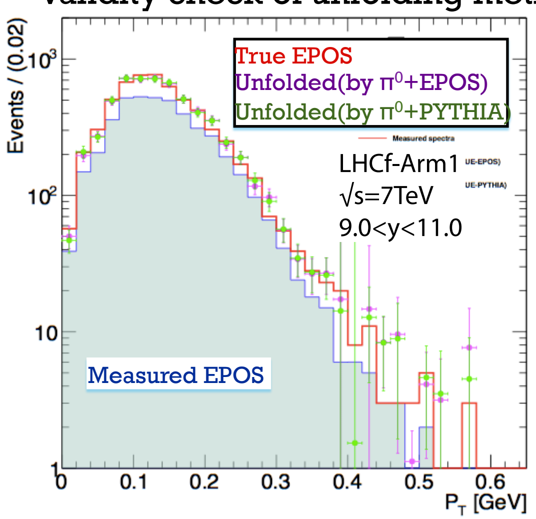
Signal window : [−3σ, +3σ]
Sideband : [−6σ, −3σ] and [+3σ, +6σ]



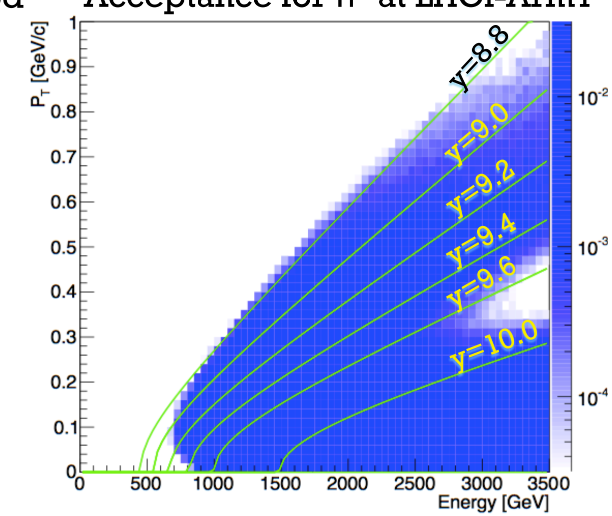
Remaining background spectrum is estimated using the sideband information, then the BG spectrum is subtracted from the spectrum made in the signal window.

$$Signal = f(E, P_T)^{signal} - f(E, P_T)^{BG} \frac{\int_{\hat{M}-3\sigma_l}^{\hat{M}+3\sigma_u} \mathcal{L}_{BG} dM}{\int_{\hat{M}-6\sigma_l}^{\hat{M}-3\sigma_l} \mathcal{L}_{BG} dM + \int_{\hat{M}+3\sigma_u}^{\hat{M}+6\sigma_u} \mathcal{L}_{BG} dM}$$

Validity check of unfolding method



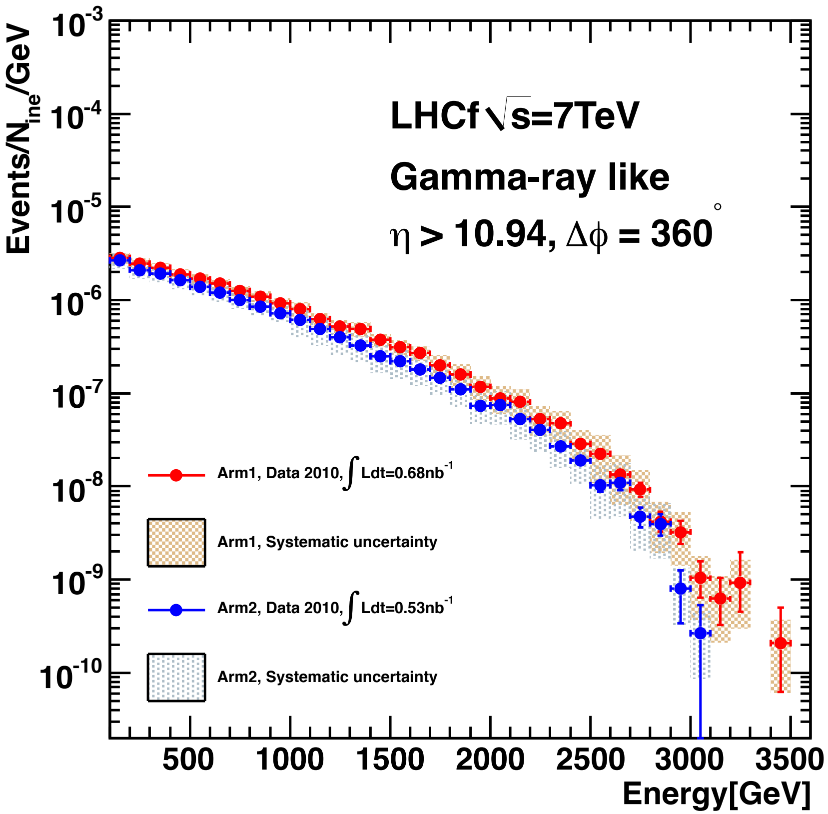
Acceptance for π^0 at LHCf-Arm1

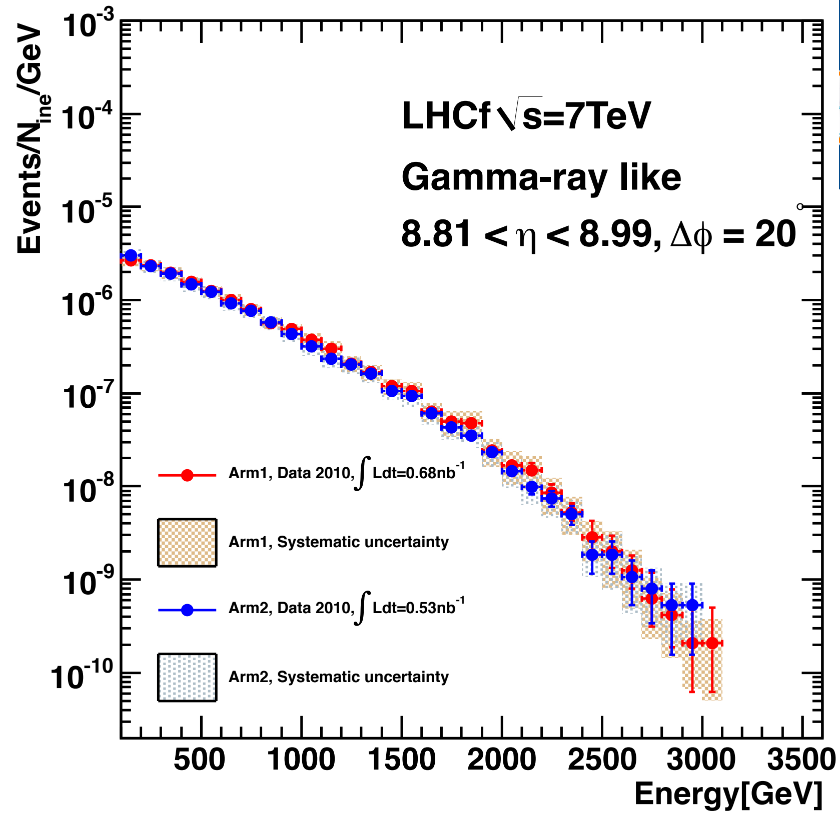


Detector responses are corrected by an unfolding process that is based on the iterative Bayesian method.
(G. D' Agostini NIM A 362 (1995) 487)

Detector response corrected spectrum is proceeded to the acceptance correction.

comparison of arm1 and arm2 spectra





- Multi-hit rejection and PID correction applied
- Energy scale systematic not considered due to strong correlation between Arm1 and Arm2

Deviation in small tower: still unclear, but within systematic errors

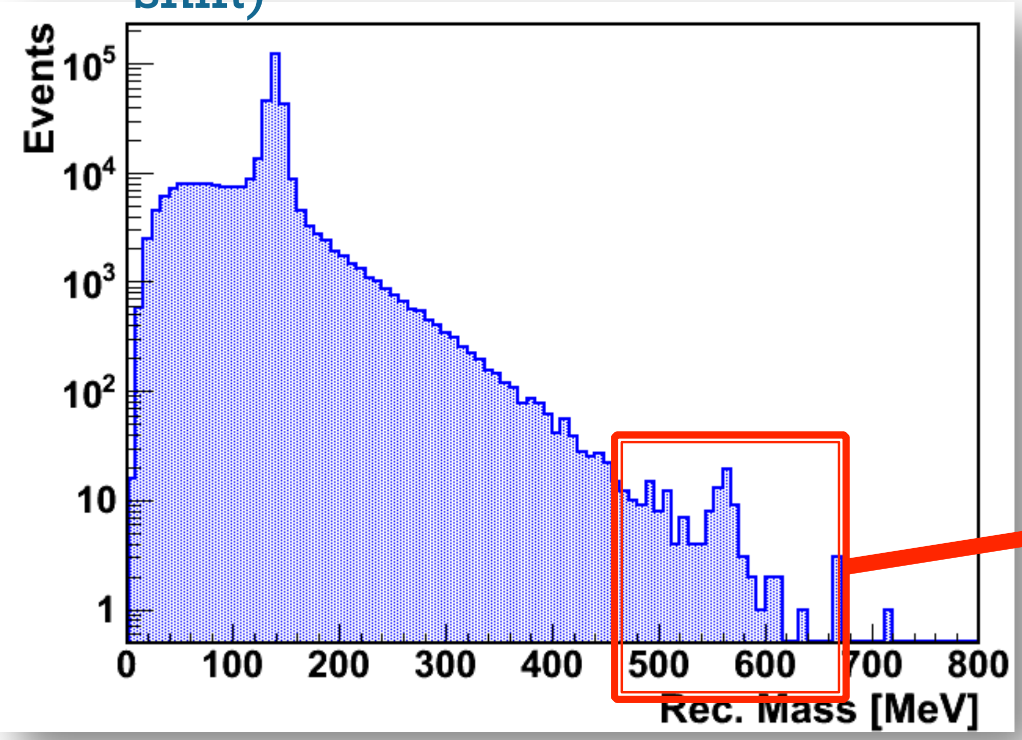
+ η Mass

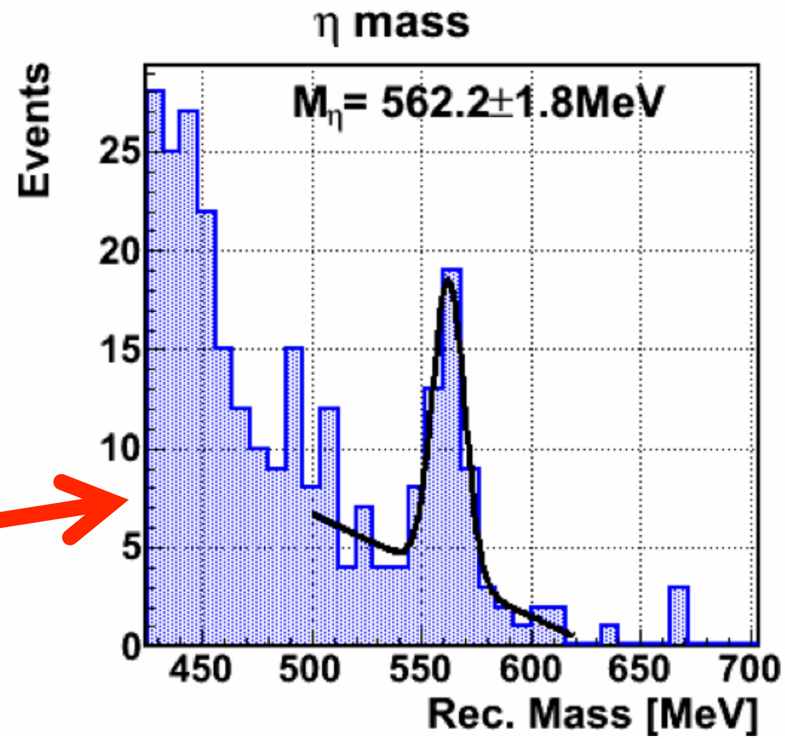
Arm2 detector, all runs with zero crossing angle

True η Mass: 547.9 MeV

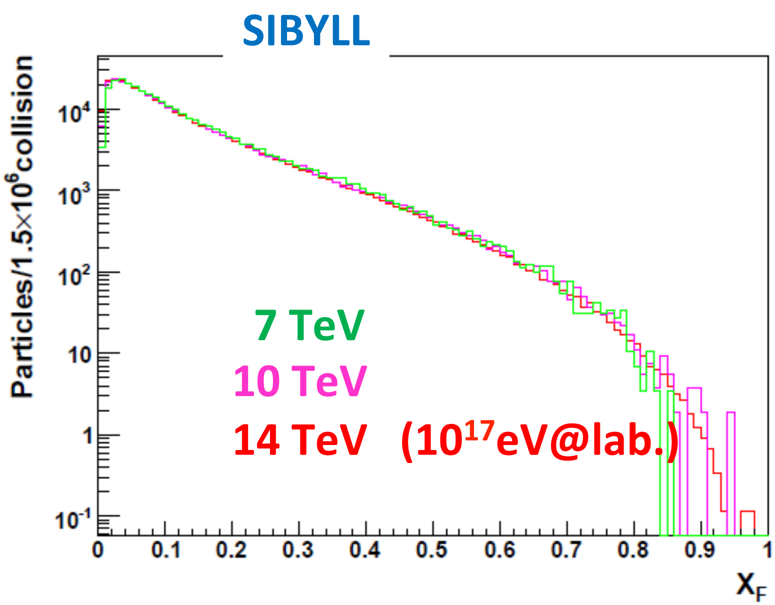
MC Reconstructed η Mass peak: 548.5 ± 1.0 MeV

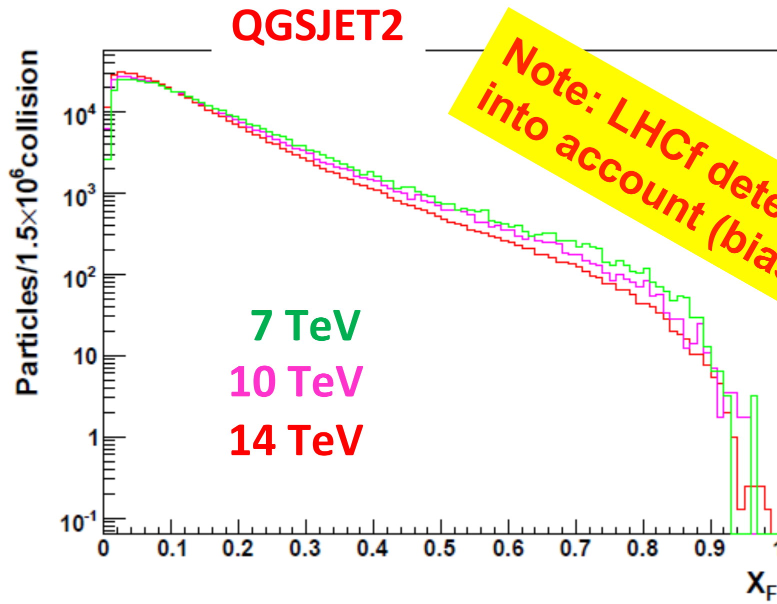
Data Reconstructed η Mass peak: 562.2 ± 1.8 MeV (2.6% shift)



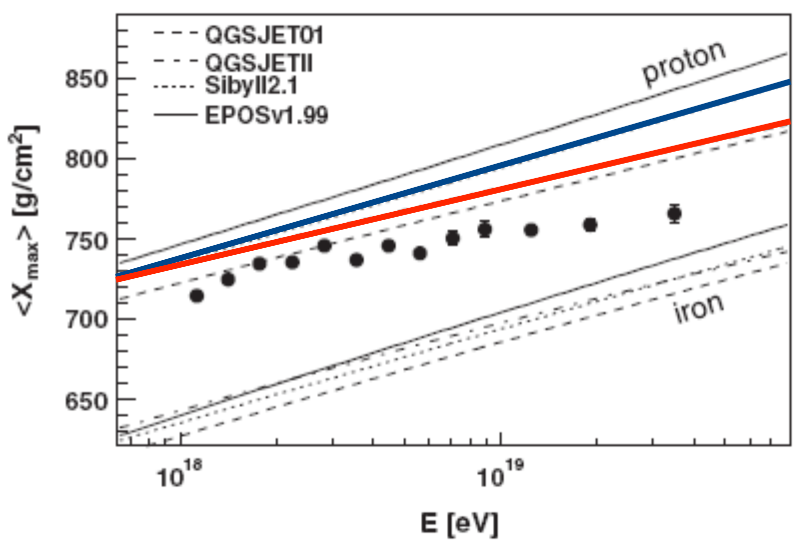


14TeV: Not only highest energy, but energy dependence…





Note: LHCf detector taken into account (biased)



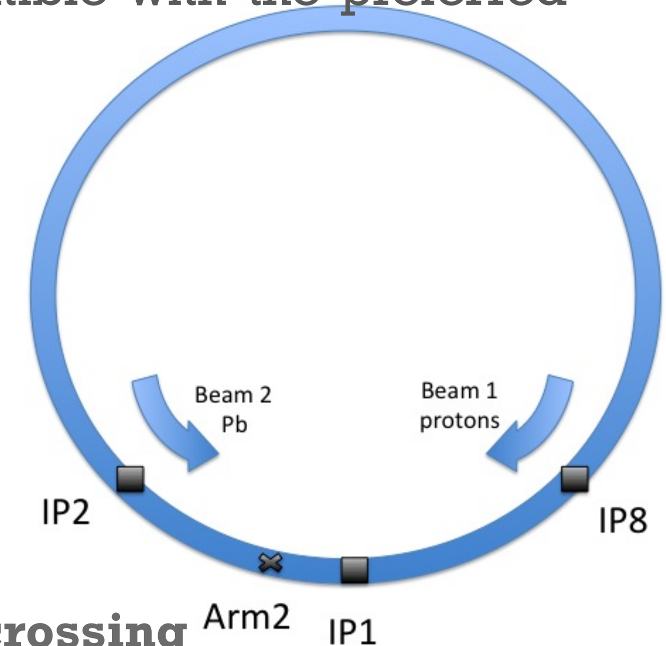
Secondary gamma-ray spectra in p-p collisions at different collision energies (normalized to the maximum energy)

SIBYLL predicts perfect scaling while QGSJET2 predicts softening at higher energy

Qualitatively consistent with Xmax prediction

Requirements and conclusions…

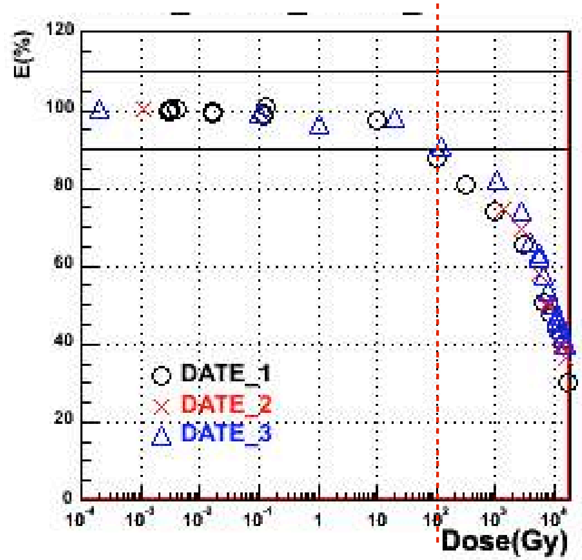
- We require to run with **only one detector**
  - Arm2 (W/scint. e.m. calorimeter + μ-strip silicon)
  - Only on one side of IP1 (on P2 side, compatible with the preferred machine setup: Beam1=p, Beam2=Pb)
- Considering machine/physics params:
  - Number of bunches, **n = 540** (100 ns spacing)
  - Luminosity up to **10^{28} cm^{-2}s^{-1}**
  - Interaction cross section **2.15 b**

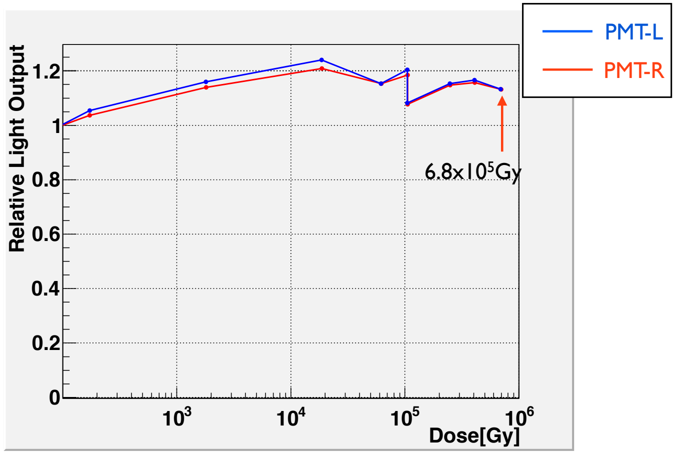


- **PILE-UP** effect
  - Around **3.6×10^{-3} interactions per bunch crossing**
  - **2%** probability for one interaction in five successive beam crossing (typical time for the development of signals from LHCf scintillators ~500 ns) → **NOT AN ISSUE**
  - Some **not interacting bunches** required for beam-gas subtraction

Comparison of EJ260 and GSO -Radiation Hardness-

- EJ260 (HIMAC* Carbon beam)
  10% decrease of light yield after exposure of 100Gy
- GSO (HIMAC Carbon beam)
  No decrease of light yield even after 7*10^5Gy exposure,
  BUT increase of light yield is confirmed
- The increase depend on irradiation rate (~2.5%/[100Gy/hour])





*HIMAC : Heavy Ion Medical Accelerator in Chiba