High Energy Hadronic Interactions and Cosmic Ray Physics

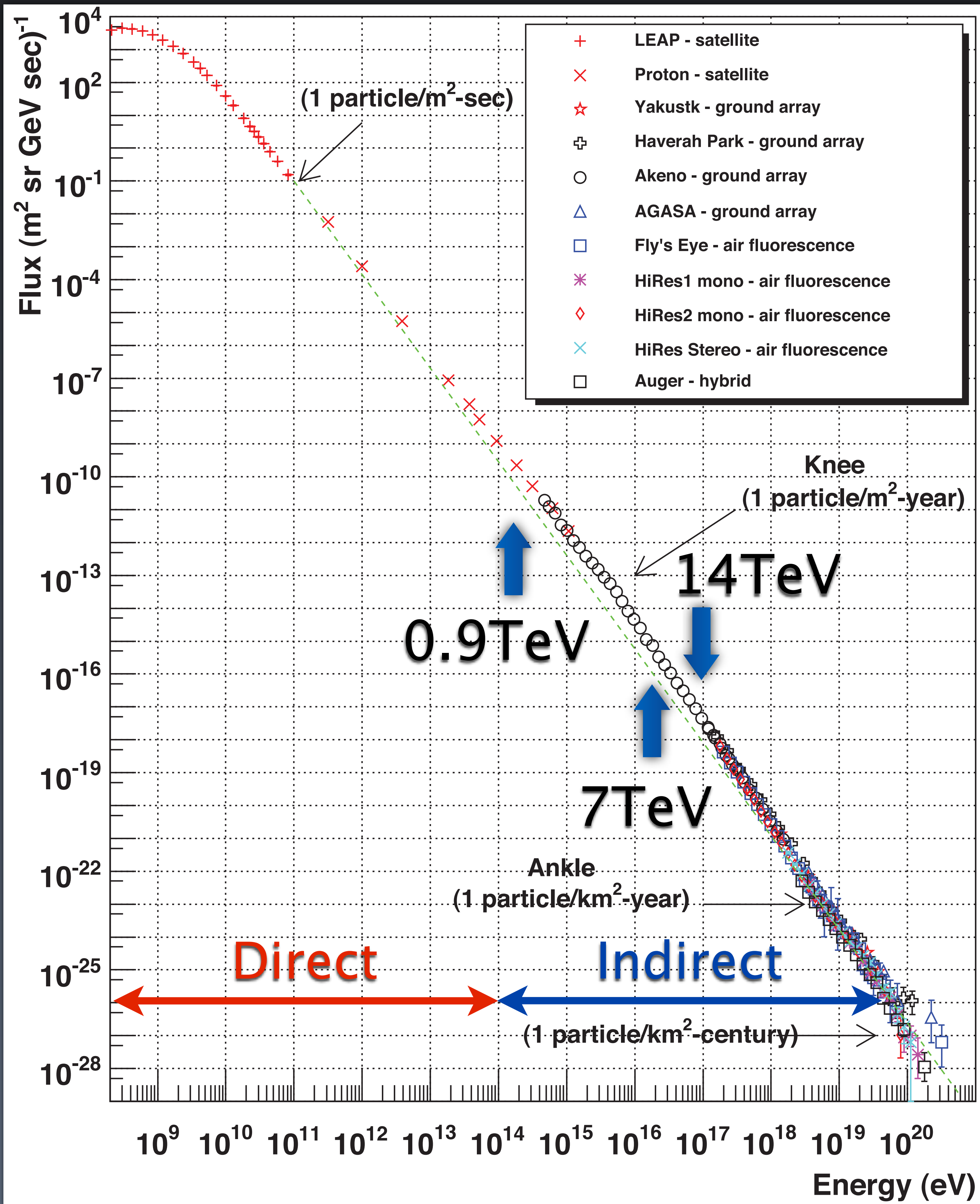
G. Mitsuka (Nagoya University)

14th Workshop on Elastic and Diffractive Scattering
(EDS Blois Workshop)
Dec. 15-21, 2011   Qui Nhon, Vietnam

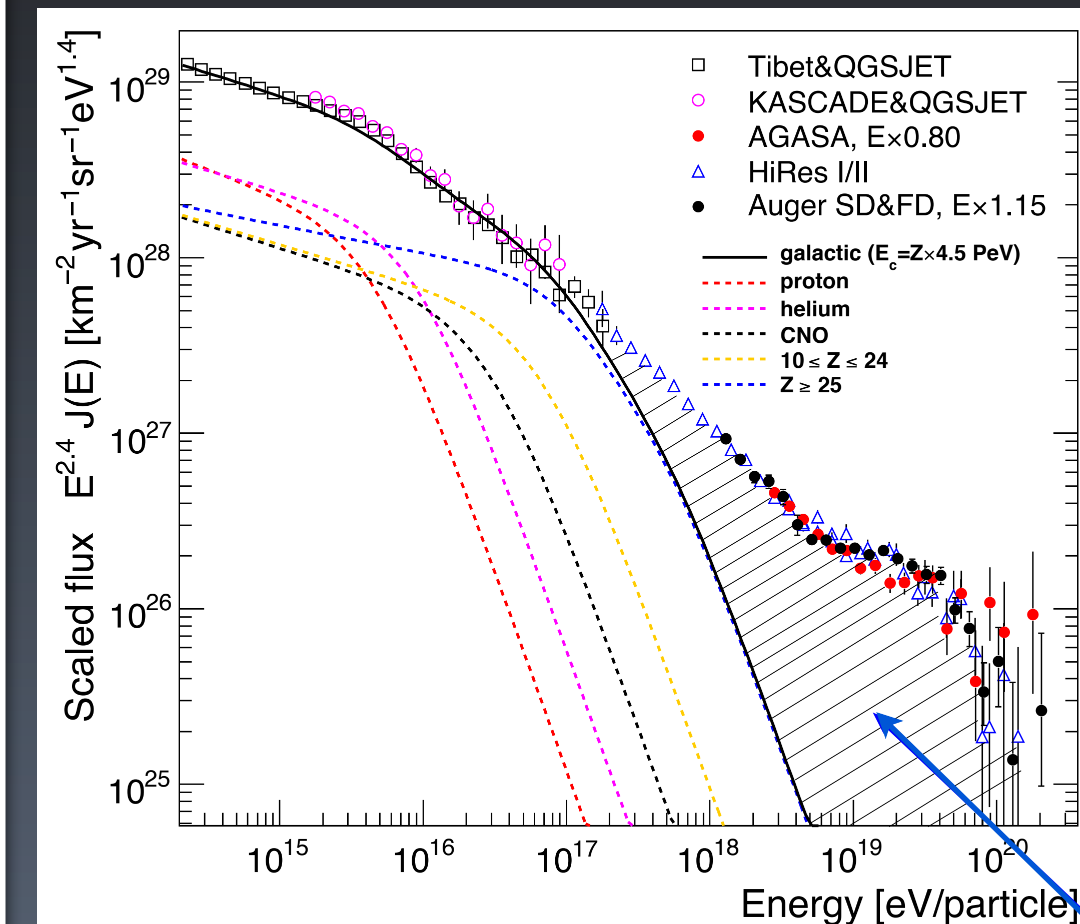
Outline

- An introduction to the high energy hadronic interactions in cosmic ray physics
- Hadronic interaction models
- High energy hadronic interaction data
  - Total cross section
  - Nuclear effects
  - Inclusive scattering (TeV scale)
  - Forward photon in DIS
  - Diffractive scattering
  - Inclusive scattering (GeV scale)
- Summary

Energy spectra of high energy cosmic rays



Standard (i.e. widely believed) model



(M. Unger ECRS 2008)

Extragalactic source

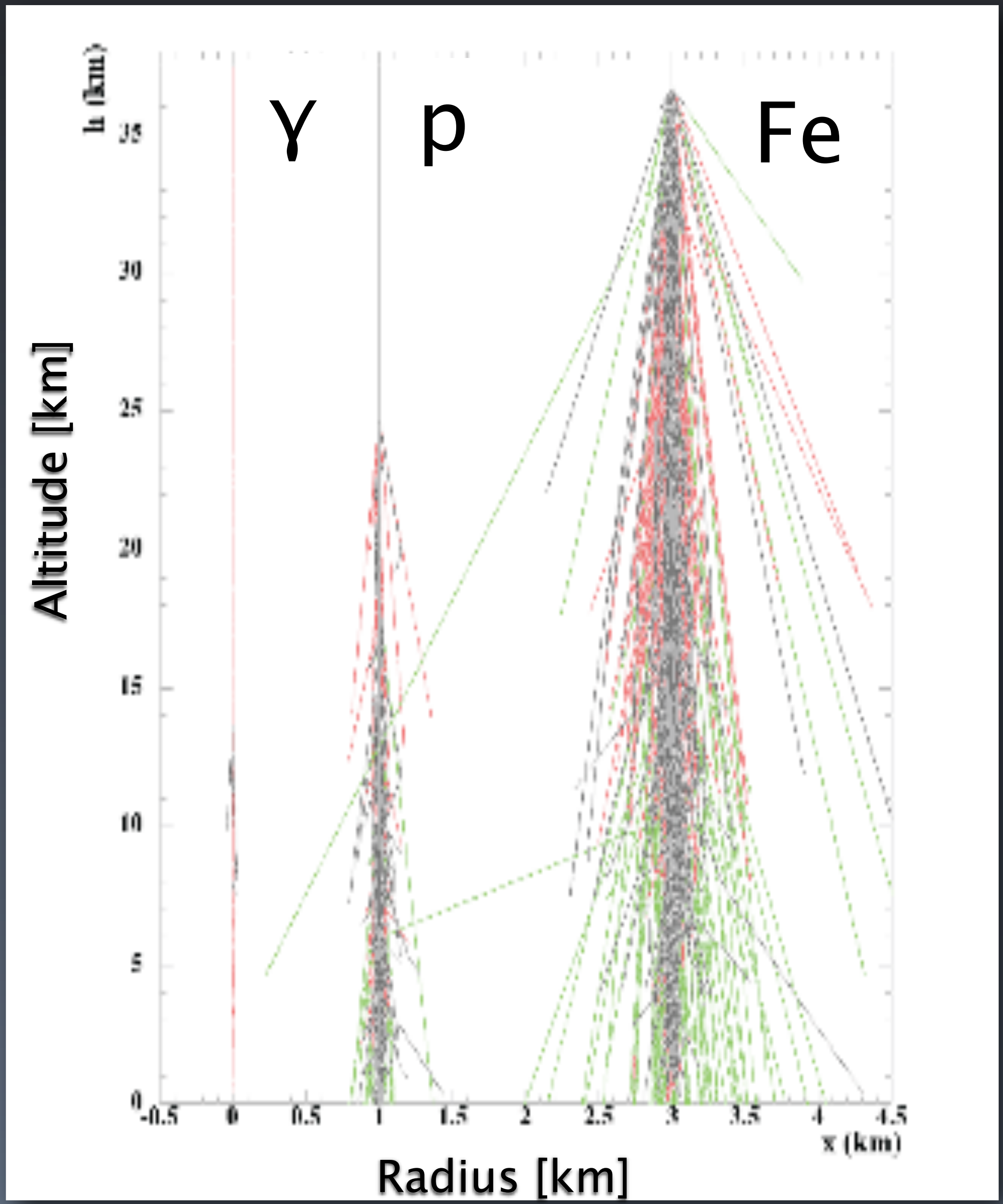
Energy, Composition, & direction

→Source of cosmic ray

→Structure of the universe (goal)

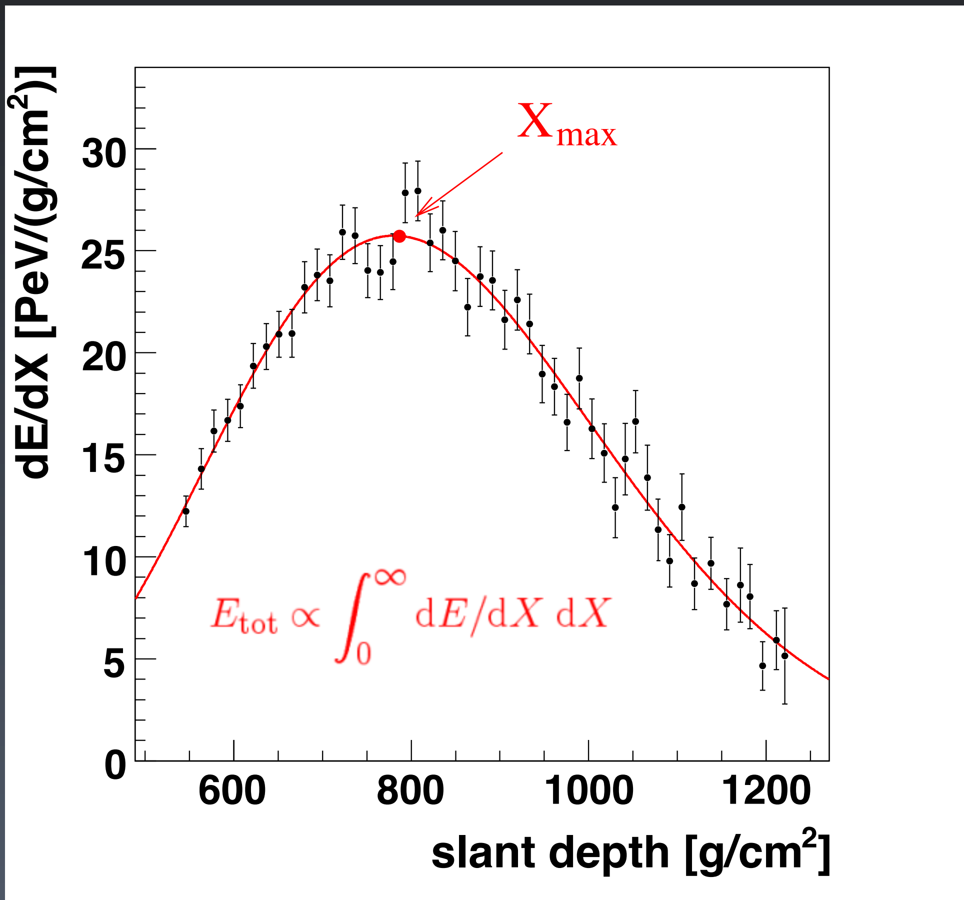
Indirect measurement of cosmic rays

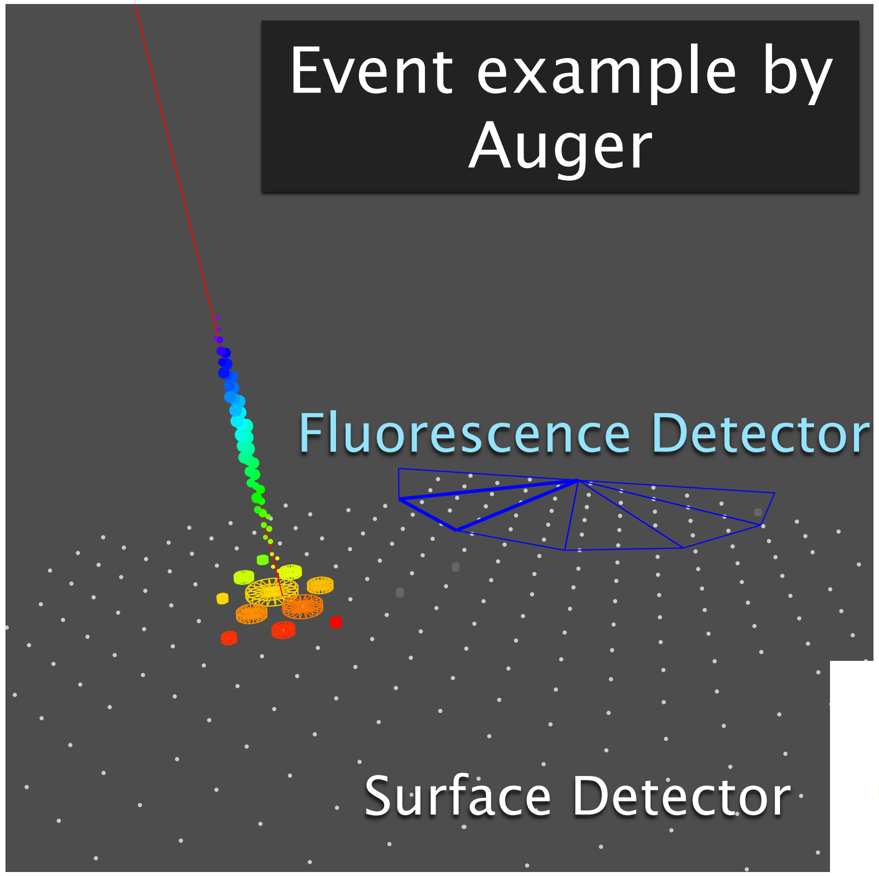
- It is not possible to directly* measure cosmic rays above 10^{14}eV, but possible indirectly using the cascade shower of daughter particles, Extensive Air-Shower(EAS).
- Composition and energy of cosmic rays affect the generation of EAS.
- Understanding of high-energy cosmic ray also owes to the indirect technique: comparison between the simulation of EAS and observation.
- Largest systematic uncertainty of indirect measurement is caused by the hadronic interaction of cosmic ray in atmosphere.

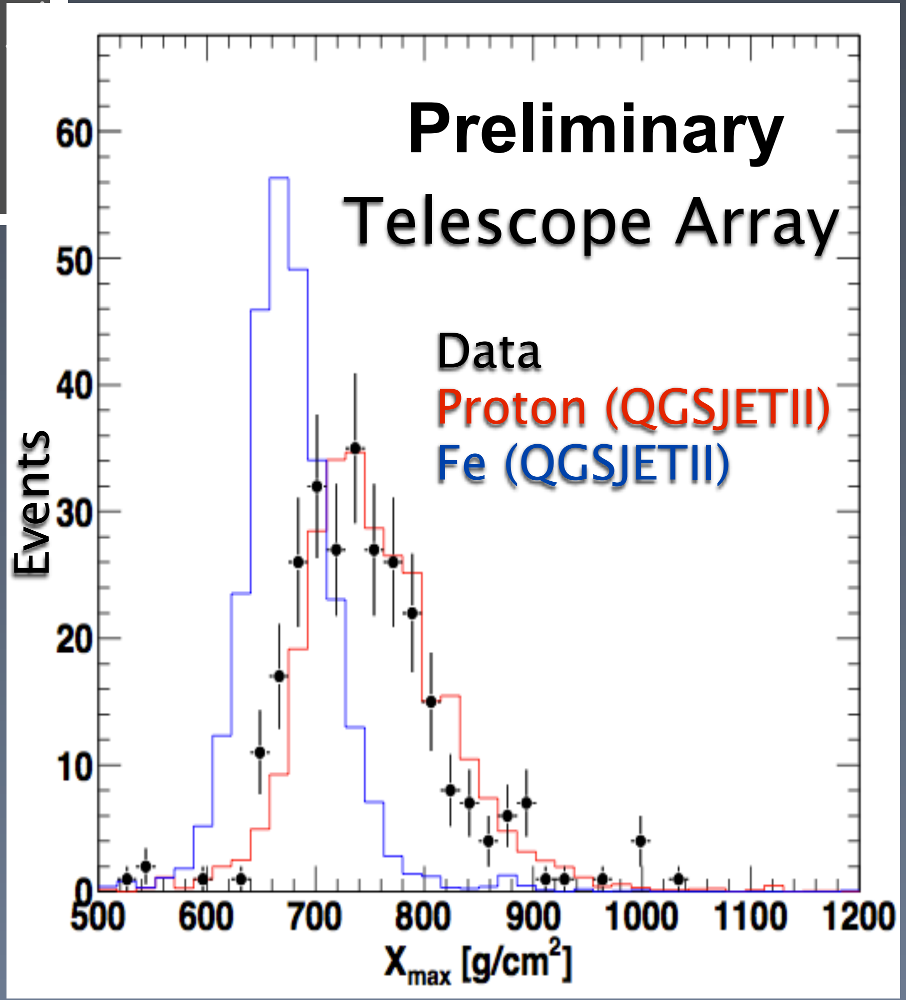


* direct measurement of cosmic ray <10^{14}eV is done by balloon, satellite, and ISS.

Indirect measurement of cosmic rays





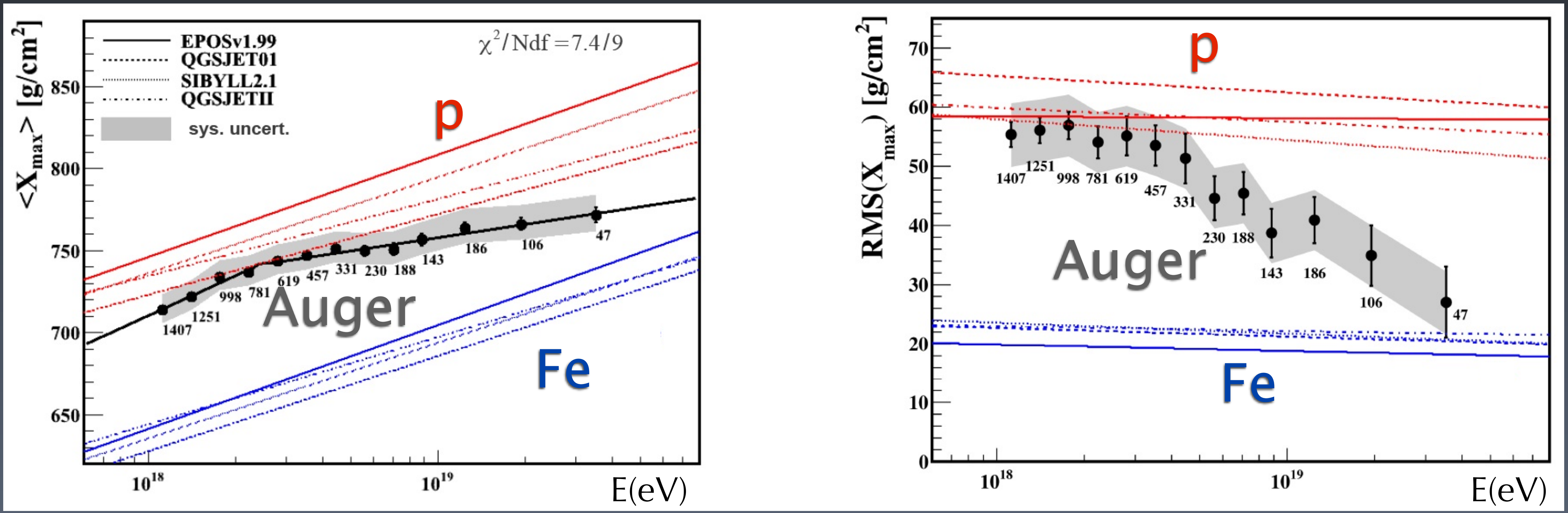


Y. Tameda, ICRC 2011

Generally two methods are used to measure cosmic rays:

- by surface detector, high efficiency(~100%) but largely suffer from systematic uncertainty of hadronic interactions
- by fluorescence detector, low efficiency but strong sensitivity to mass composition and less model dependent energy reconstruction

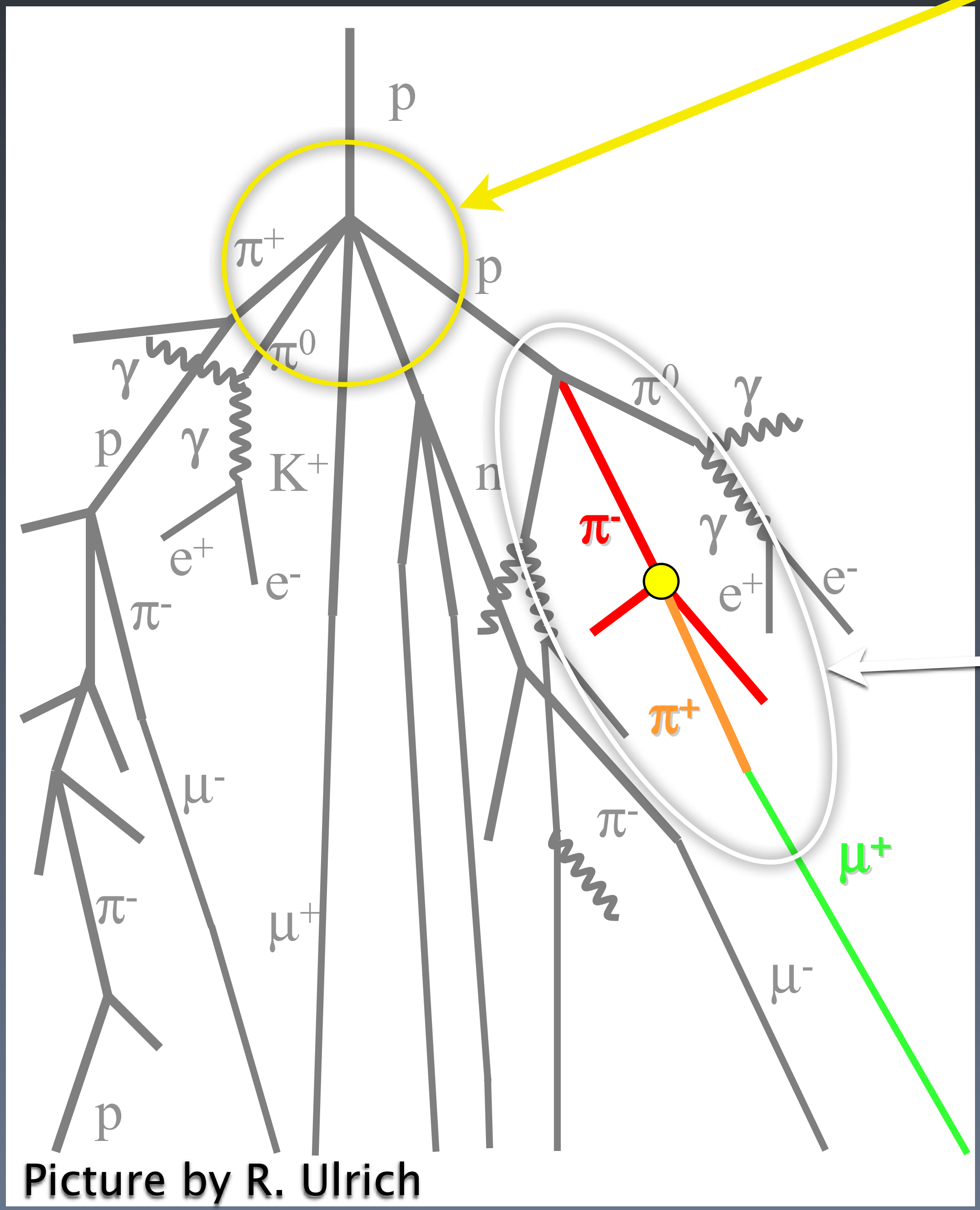
Indirect measurement of cosmic rays



P.Facal-Luis, ICRC 2011

- Transition towards heavier composition
- Break in $<X_{max}>$ seems to occur around the Ankle
- Break in RMS(X_{max}) roughly at the same energy

Hadronic interaction models (CR view)



High-energy

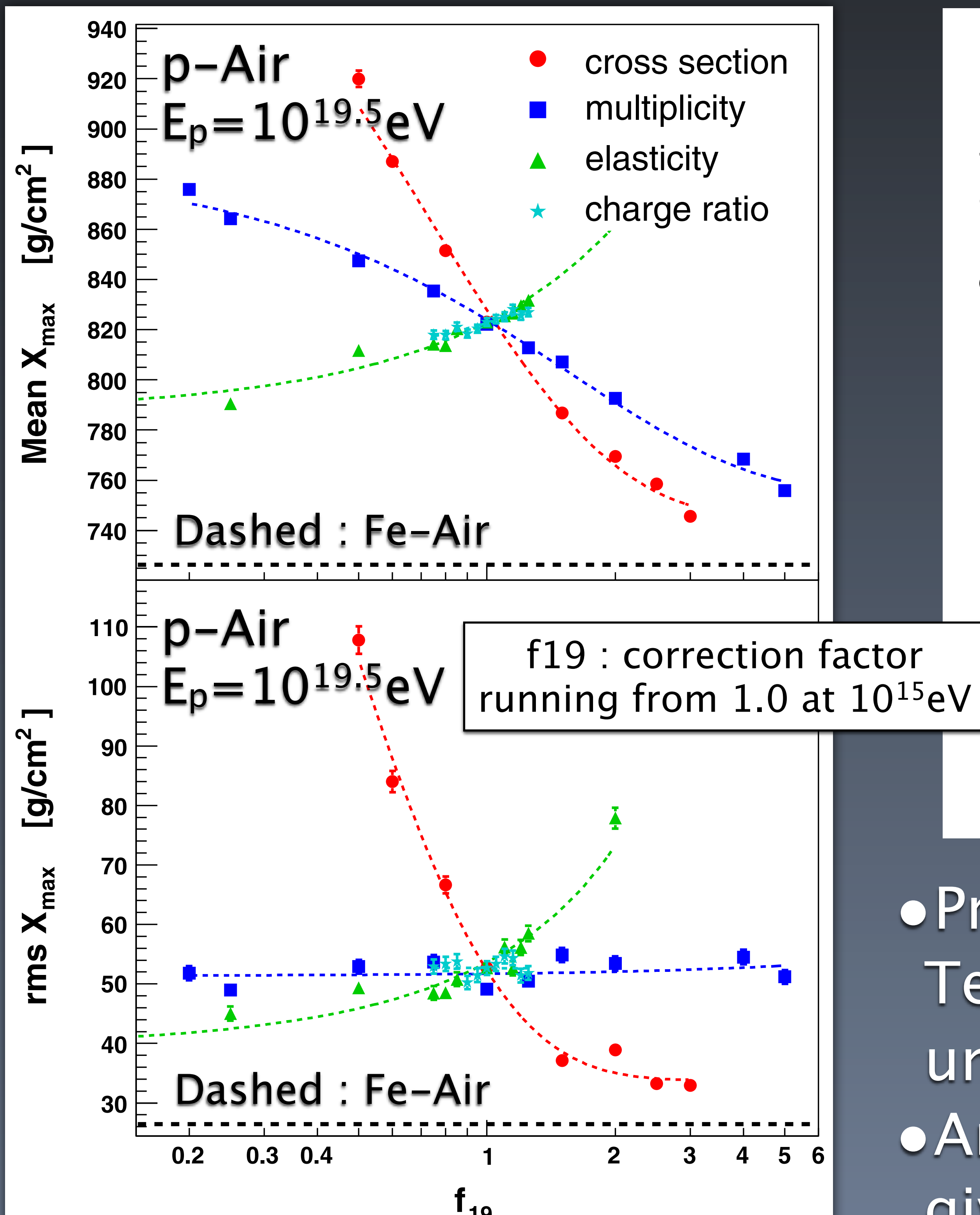
- DPMJET 3.04
- QGSJET 01 & II-03
- SIBYLL 2.1
- EPOS 1.99
- ....

Low/intermediate-energy

- GHEISHA
- FLUKA
- UrQMD
- ....

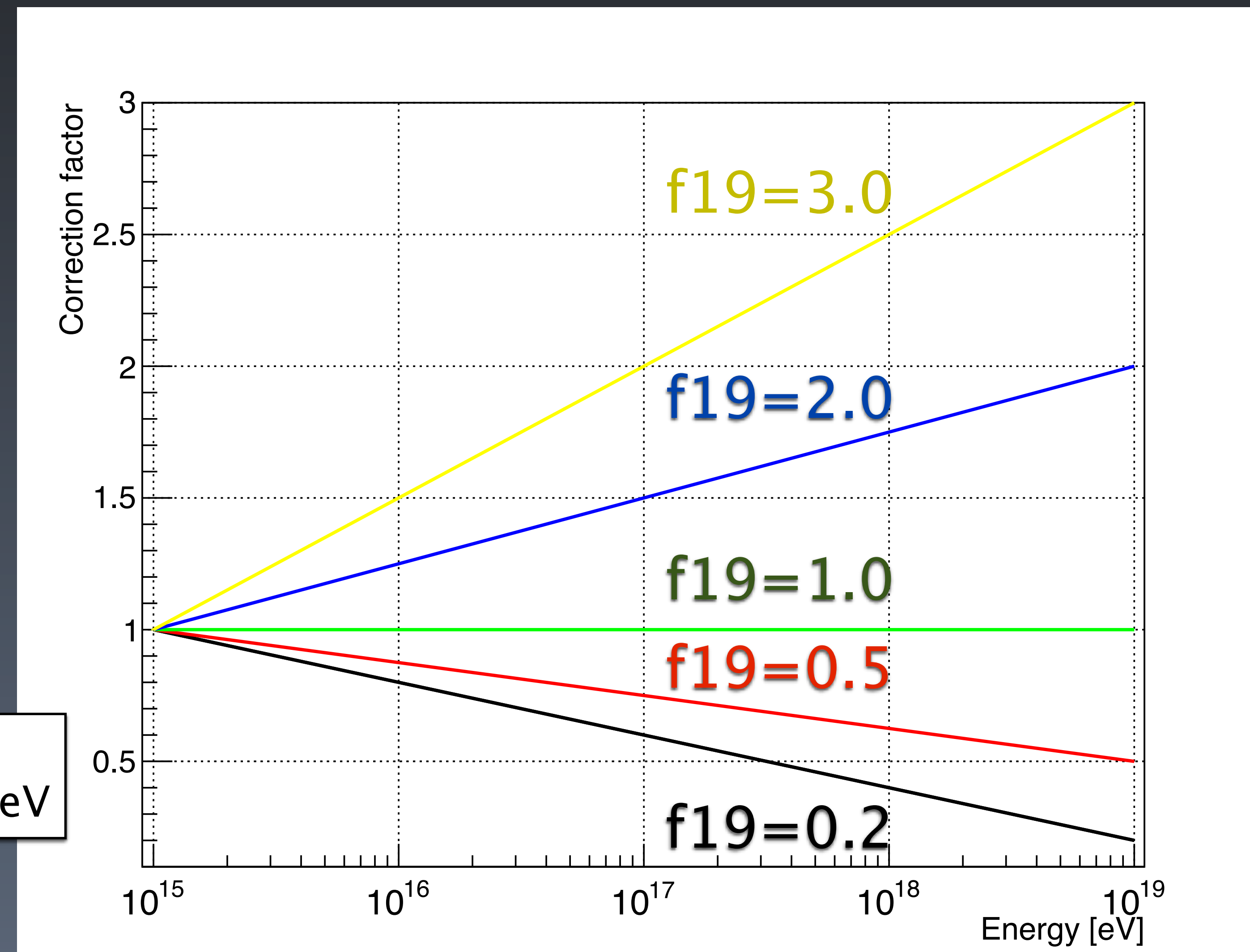
Total cross section

Effects on CR observation



R. Ulrich et al, Phys. Rev. D 83, 054026 (2011)

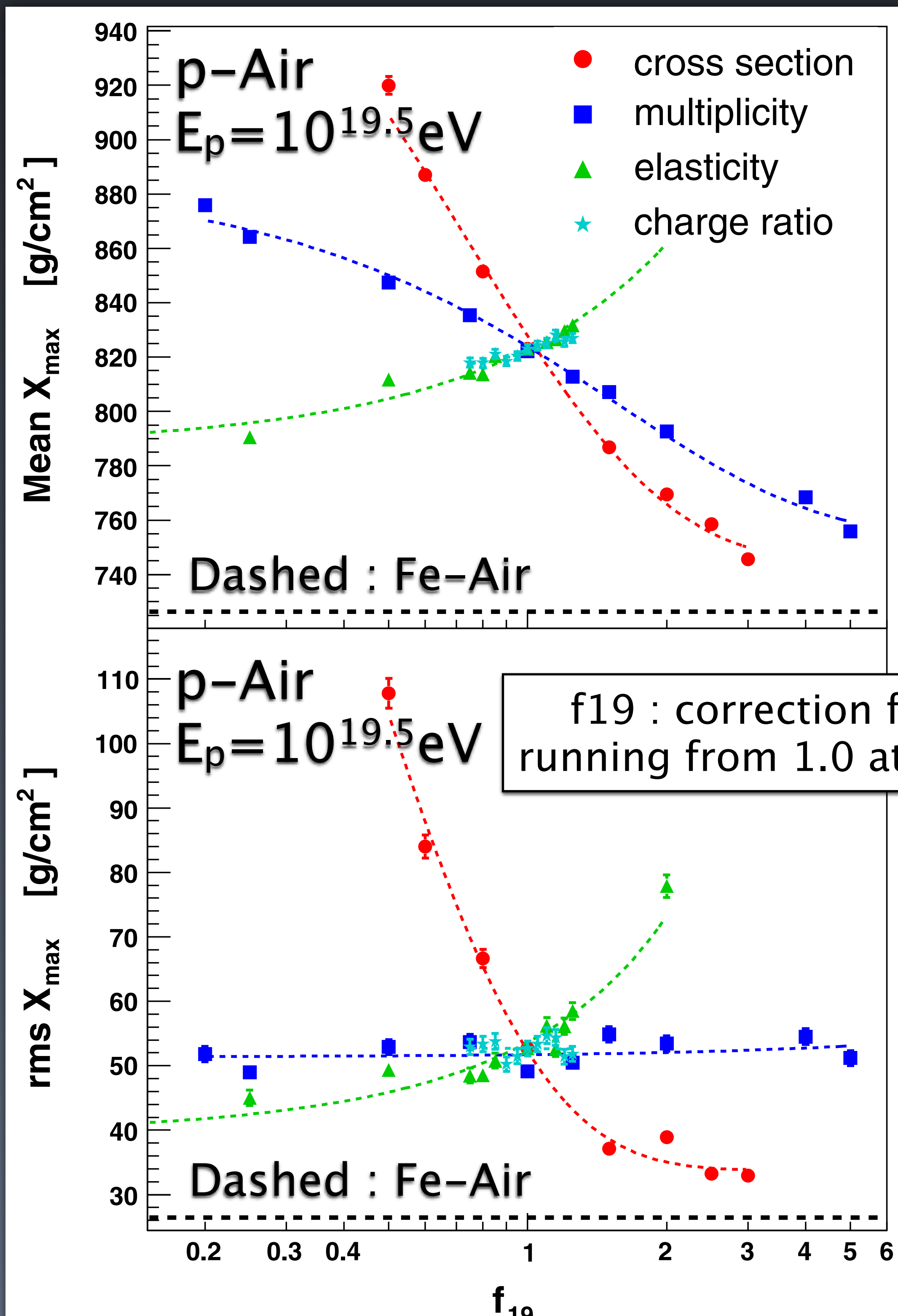
Correction factor(f19) vs. Energy



- Proton-proton cross section above the TeV scale involves a large systematic uncertainty.
- Artificially enhanced cross section may give resemble phenomena as Fe-Air.

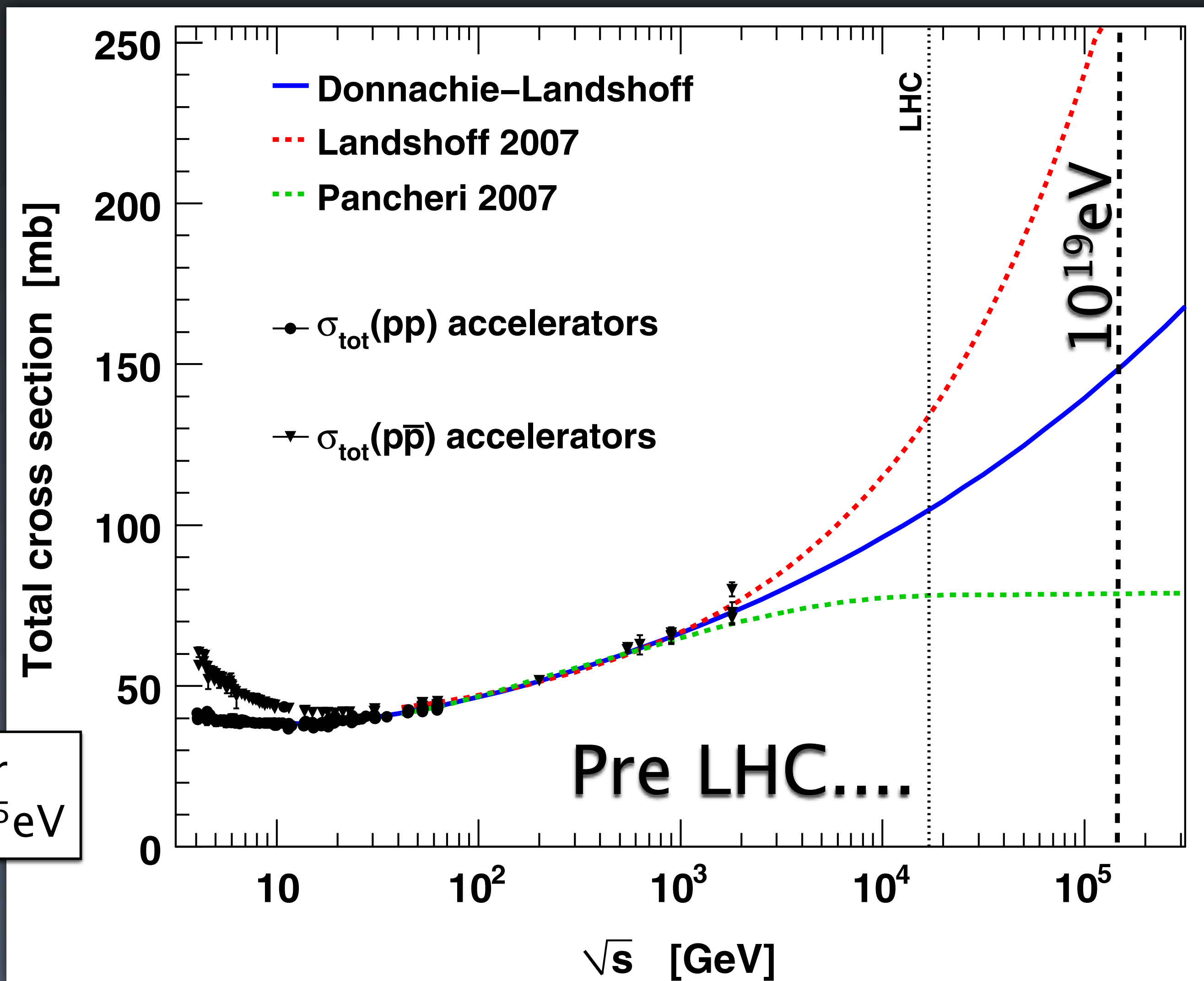
Total cross section

Effects on CR observation



R. Ulrich et al, Phys. Rev. D 83, 054026 (2011)

Total/inelastic cross sections

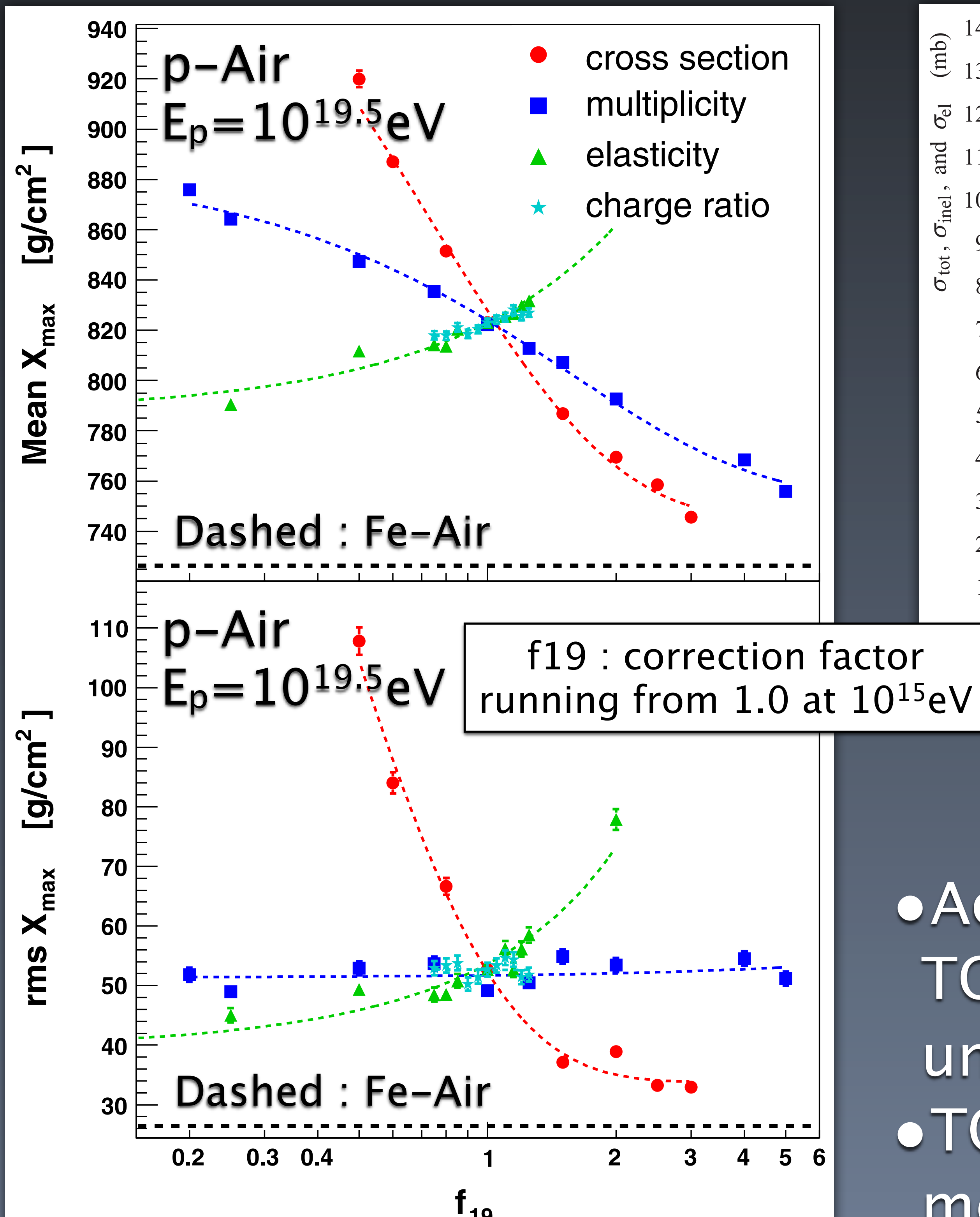


R. Ulrich et al, Phys. Rev. D 83, 054026 (2011)

- Artificially enhanced cross section may give resemble phenomena as Fe-Air.
- It's not surprising the enhancement is still within the theoretical expectation tuned to the pre-LHC data.

Total cross section

Effects on CR observation



R. Ulrich et al, Phys. Rev. D 83, 054026 (2011)

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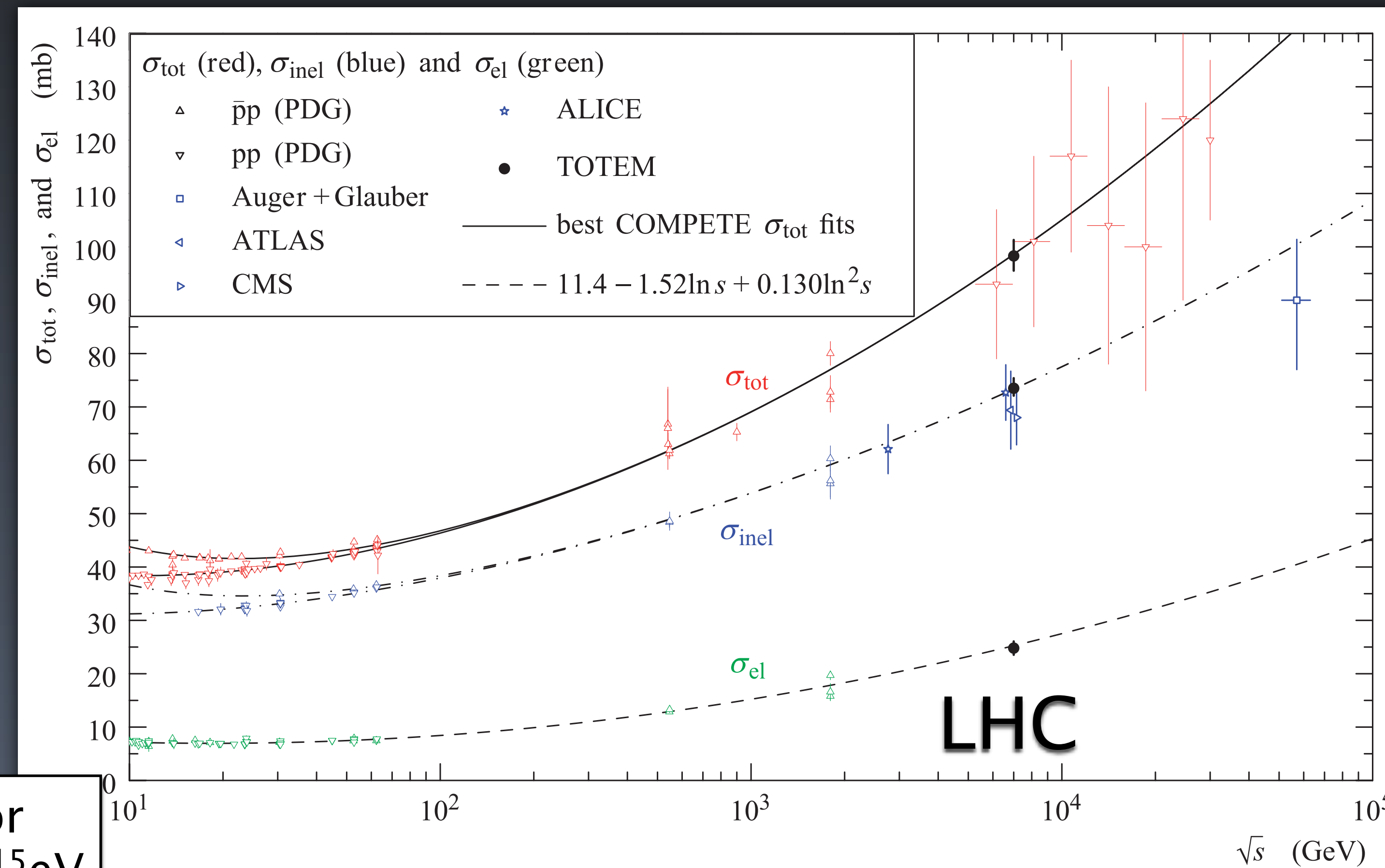
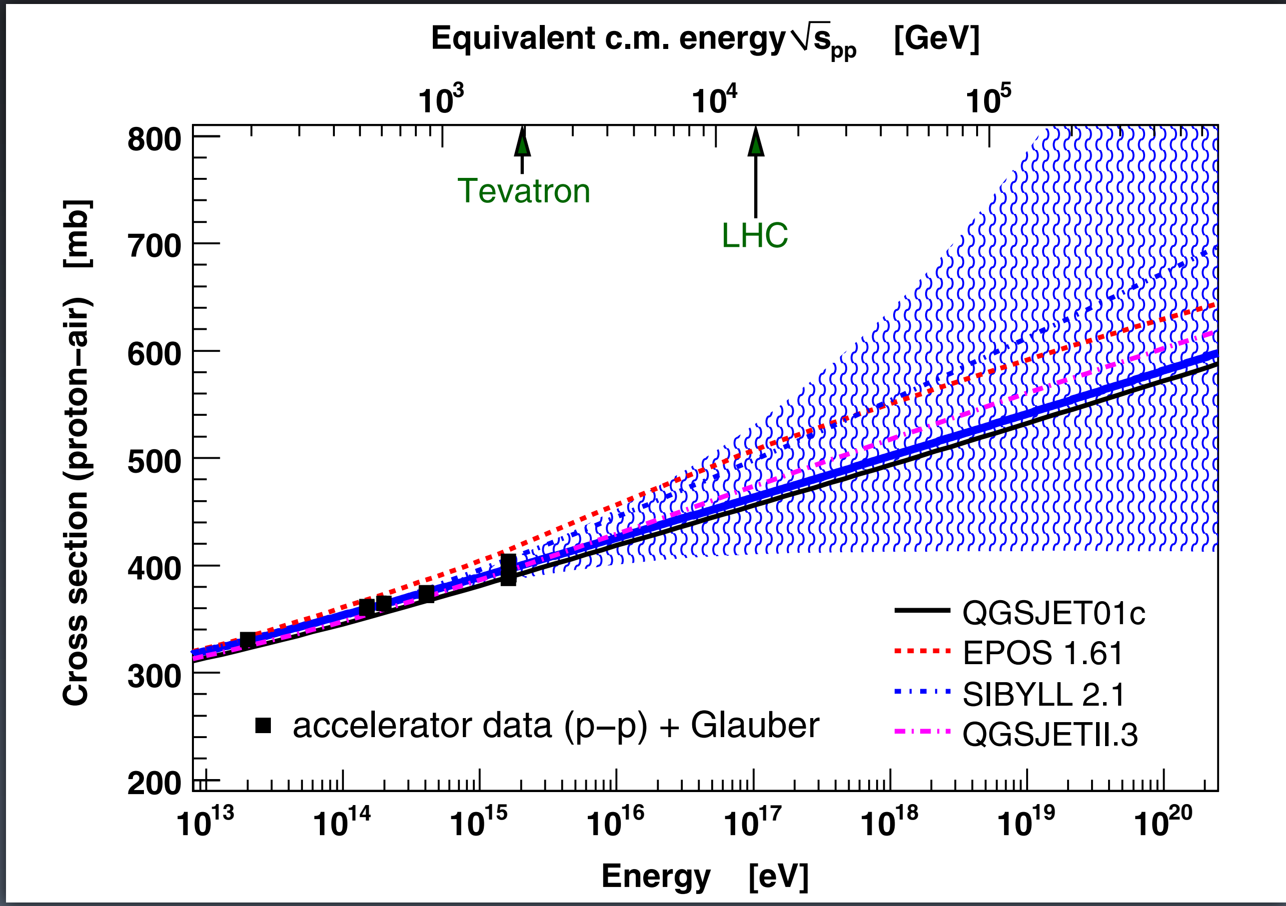


The TOTEM collaboration,
EPL 95 41001 & 96 (2011) 21002

- Accelerator based anchor point by TOTEM tightly constrains systematic uncertainty.
- TOTEM results@$\sqrt{s}$=14TeV will have more strong constraints.

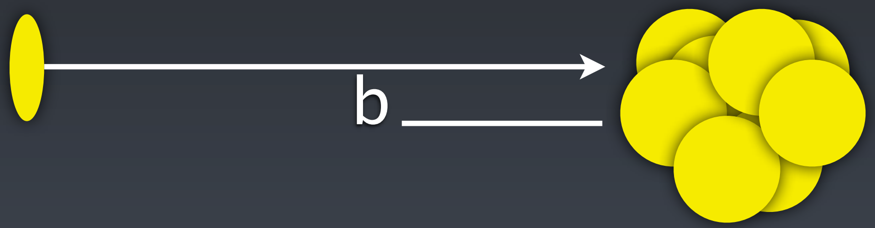
Nuclear effects

Atmosphere = Nitrogen & Oxygen (!=proton)



R. Ulrich et al, Phys. Rev. D 83, 054026 (2011)

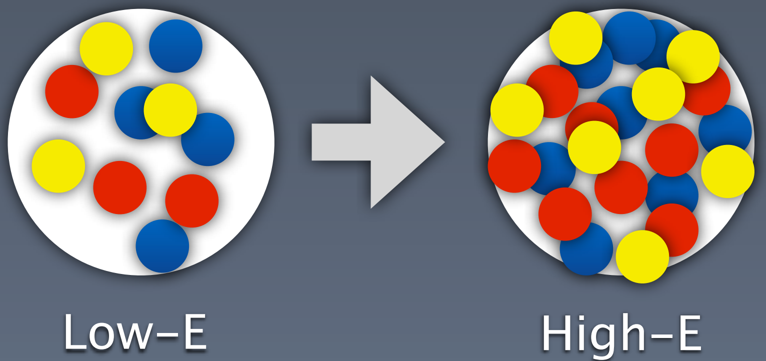
Glauber theory



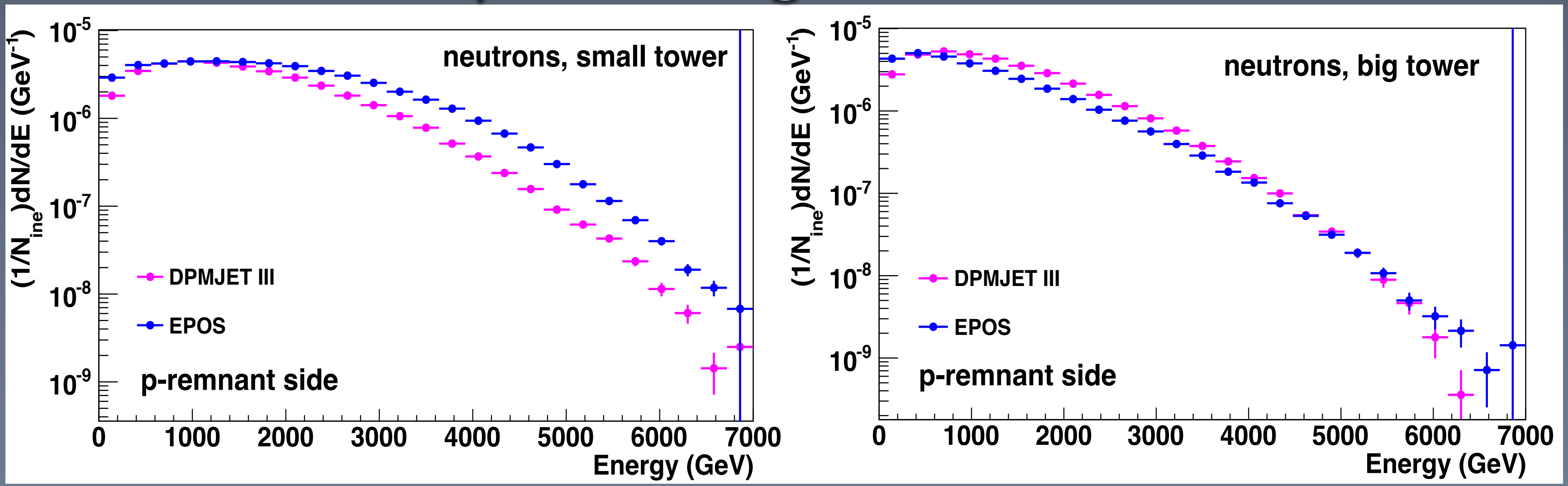
Used in many hadronic interaction models

Saturation effects

Non-linear parton density
Multi-pomeron interactions
Color glass condensate



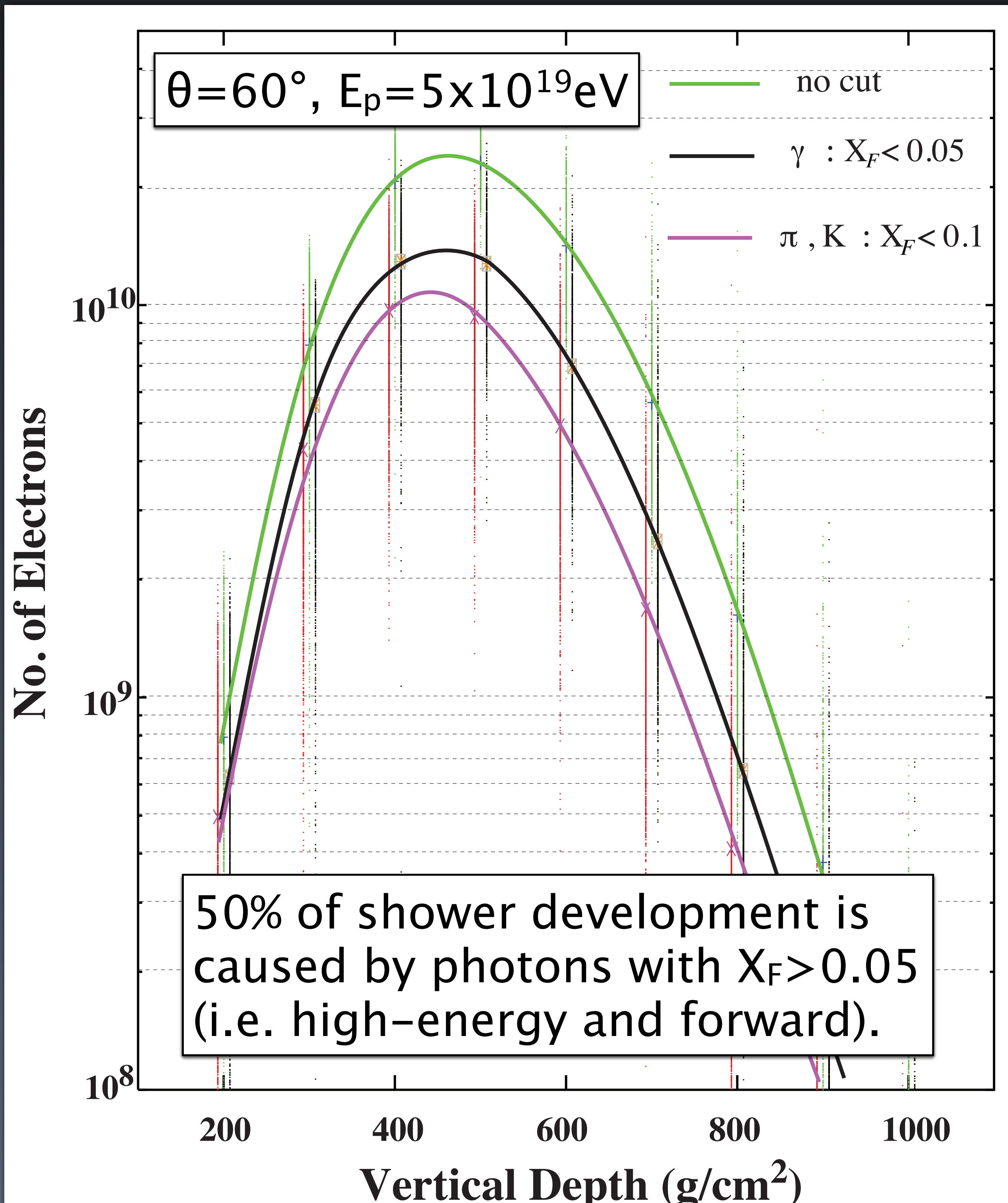
Expected signal in LHCf



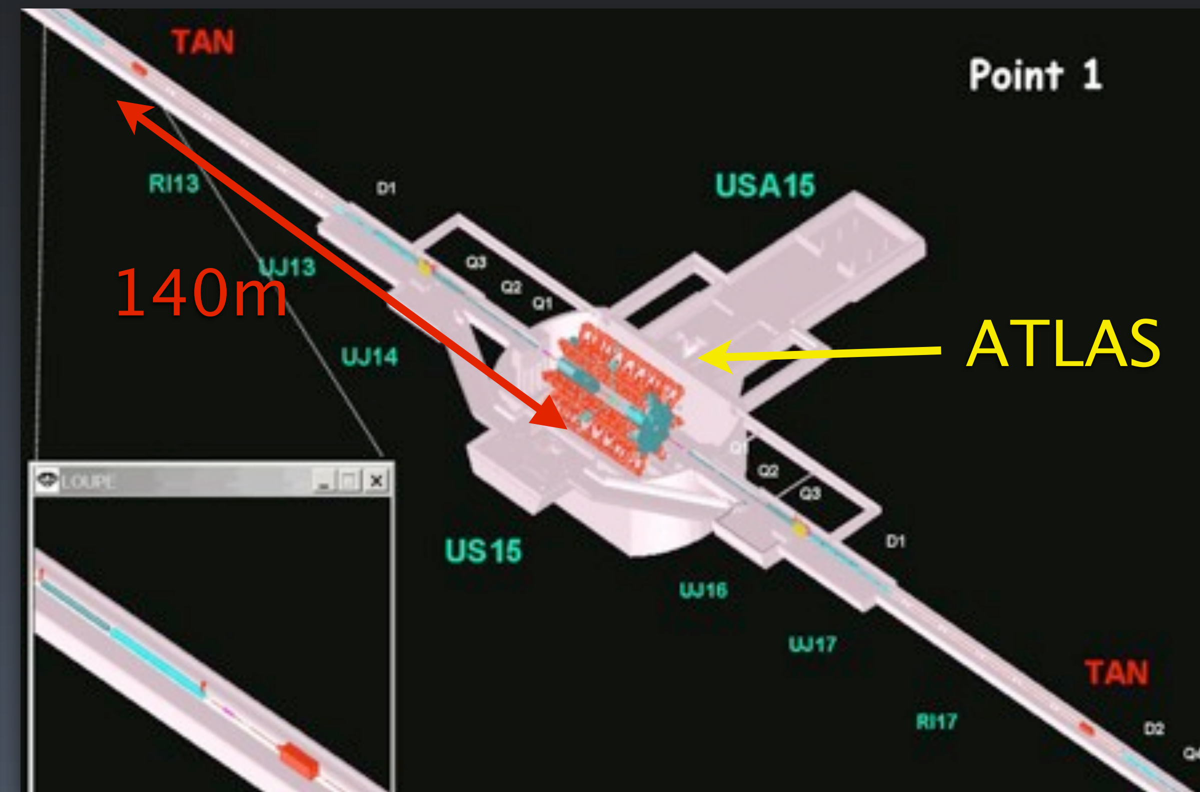
LOI of LHCf for p-Pb run, CERN-LHCC-2011-015 / LHCC-I-021

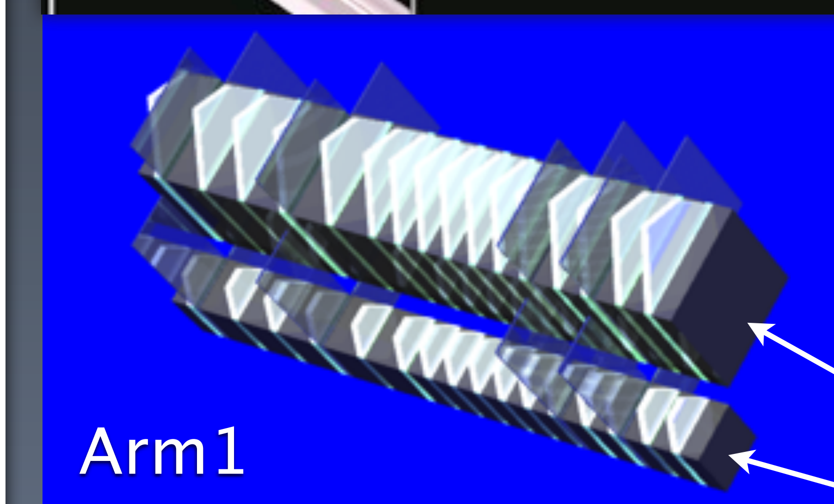
- See Itakura's talk.
- p-Pb run in 2012@LHC is under discussion.

Inclusive photon spectra (LHCf)



LHCf TDR, CERN-LHCC-2006-004



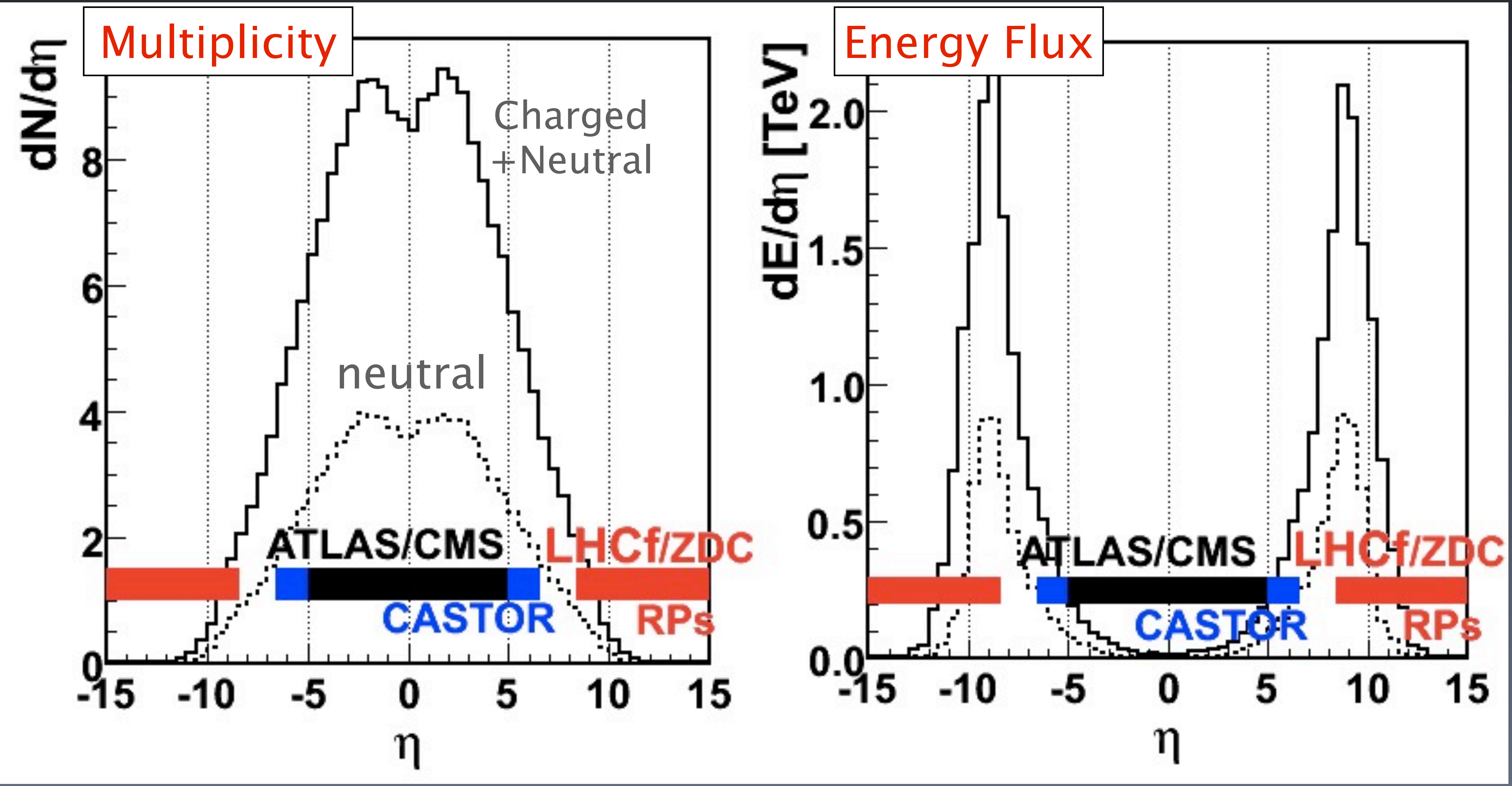


$\eta > 8.7(8.4)$

Charged particles
- swept away by D1 magnet

Neutral particle
- photon, neutron, π^0, etc..

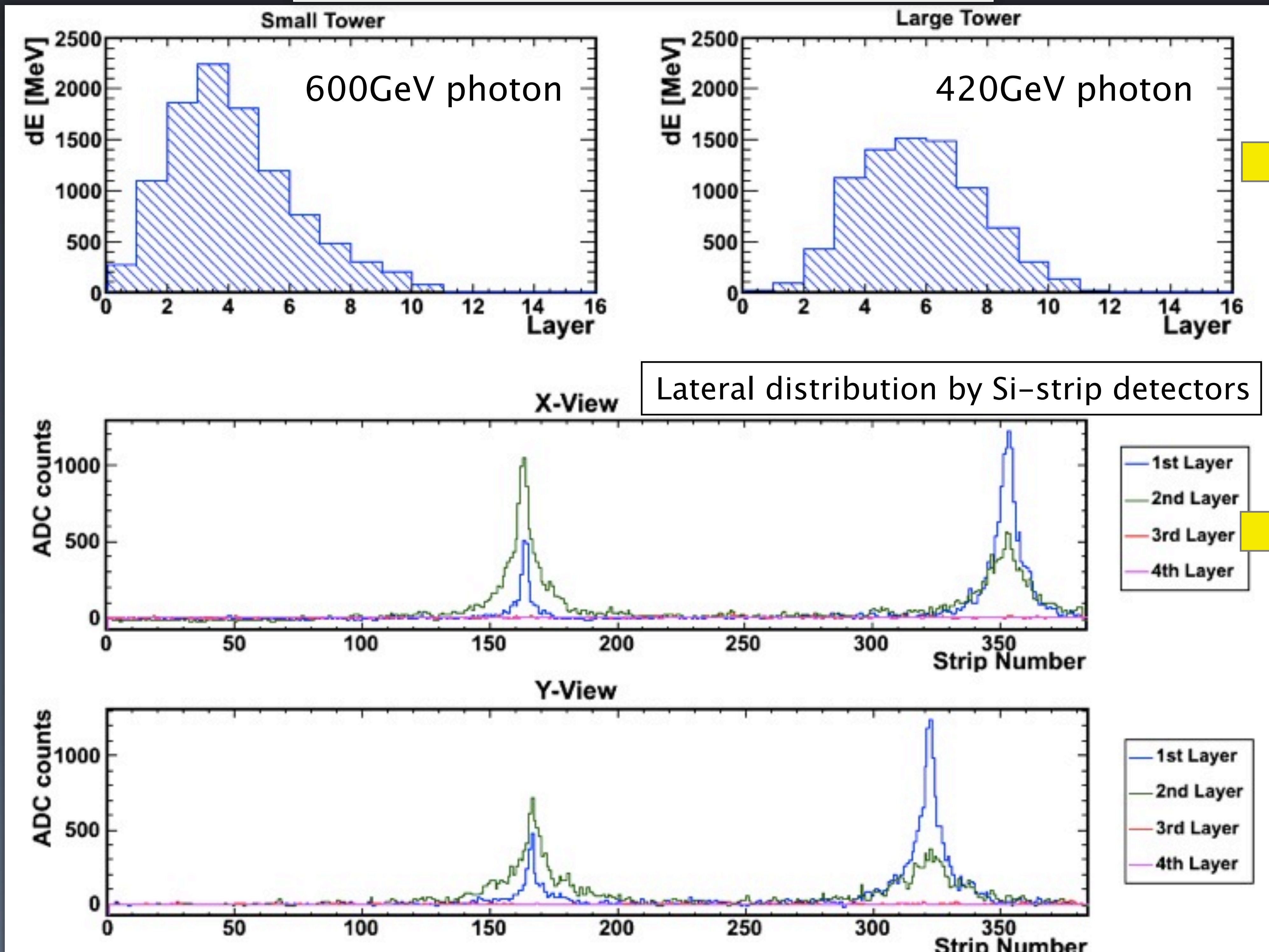
Inclusive photon spectra (LHCf)



- LHCf can cover the large fraction of energy flow.
- Soft-QCD dominates forward region.
- Note : LHCf's π^0 and hadron analysis still ongoing (open soon).

Inclusive photon spectra (LHCf)

Longitudinal distribution by scintillator layers



Lateral distribution by Si-strip detectors

Energy deposit
→ Energy
Shower shape
→ EM/hadron ID

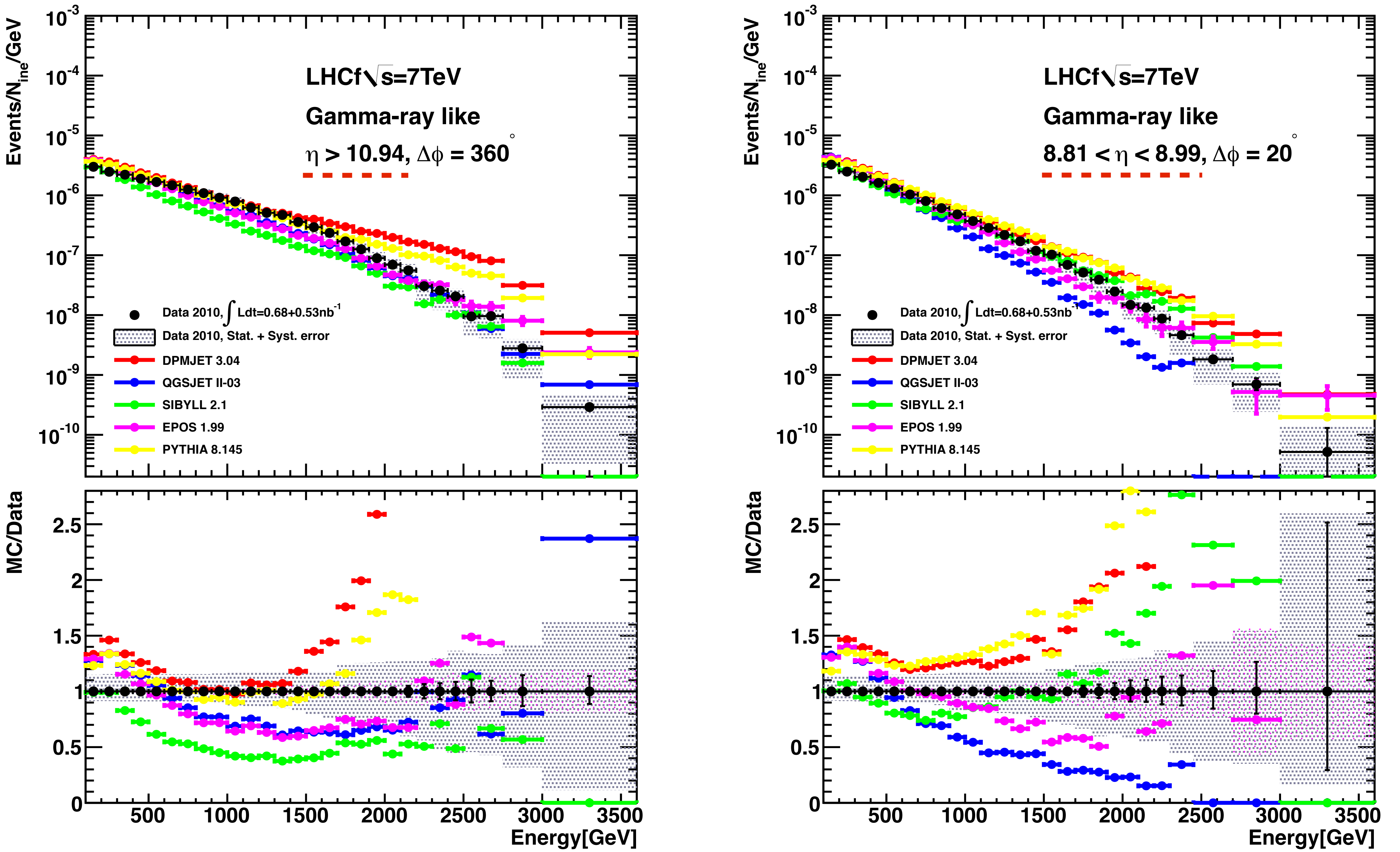
Hit position
→ Multi-hit cut
→ π^0 reconst.
→ P_T

$M_{\gamma\gamma}$ ~ opening angle$\sqrt{(E_1 E_2)}$ → Systematic error estimation

The LHCf Collaboration, Phys. Lett. B 703 (2011) 128-134

Inclusive photon spectra (LHCf)

The LHCf Collaboration, Phys. Lett. B 703 (2011) 128-134

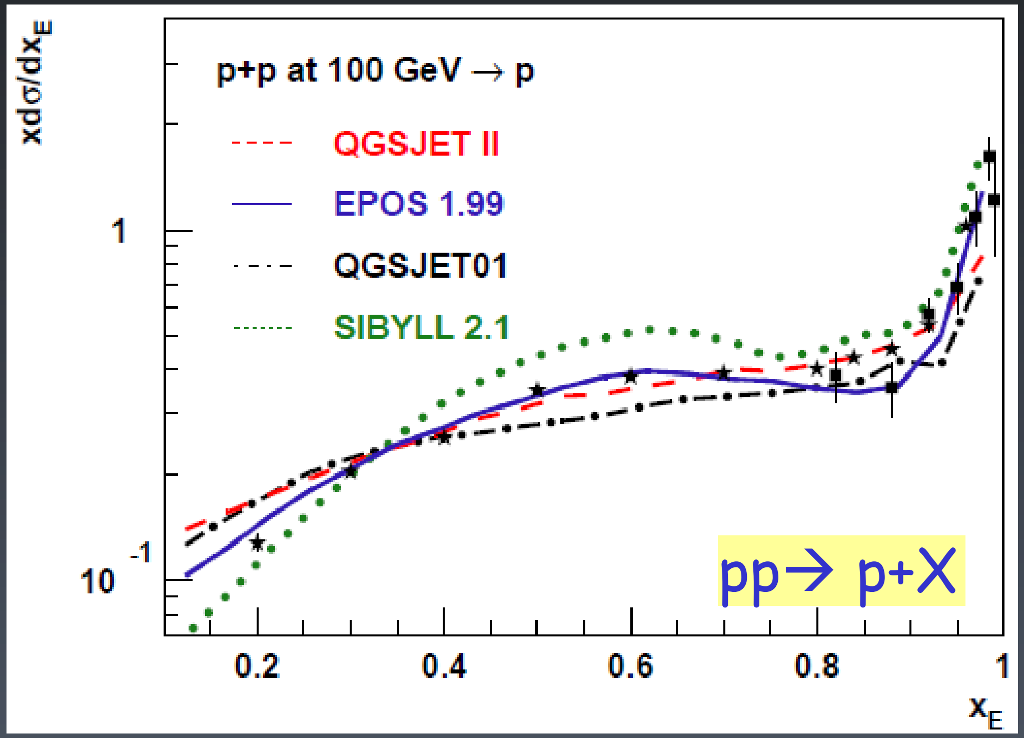


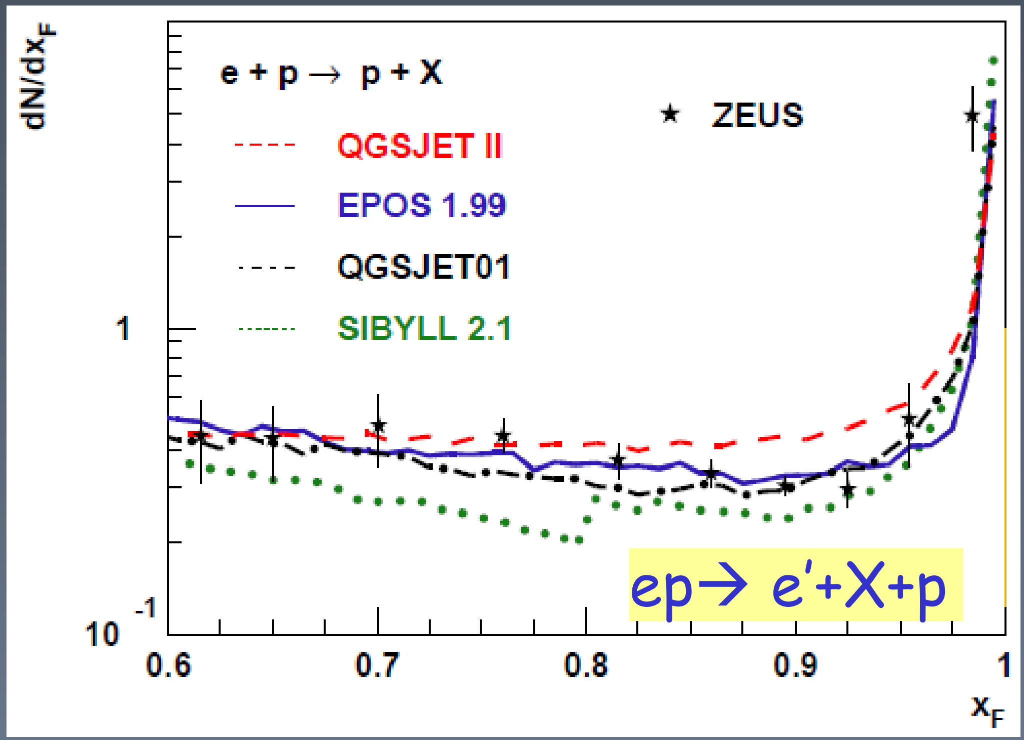
By checking the ratio plots more in detail...

- Pt dependence is indicated in DPMJET, PYTHIA, and SIBYLL.
- Is Pt independent found in EPOS above 1.5TeV ?

Diffractive scattering

- The leading particle from the cosmic ray-air interaction transports a large fraction of the total energy.
- It goes the primary particle in the next interaction of the air shower.
- The elasticity $K = E_{lead}/E_{proj}$ also affects
  - multiplicity
  - speed of shower development.
- Overall good agreement except SIBYLL.

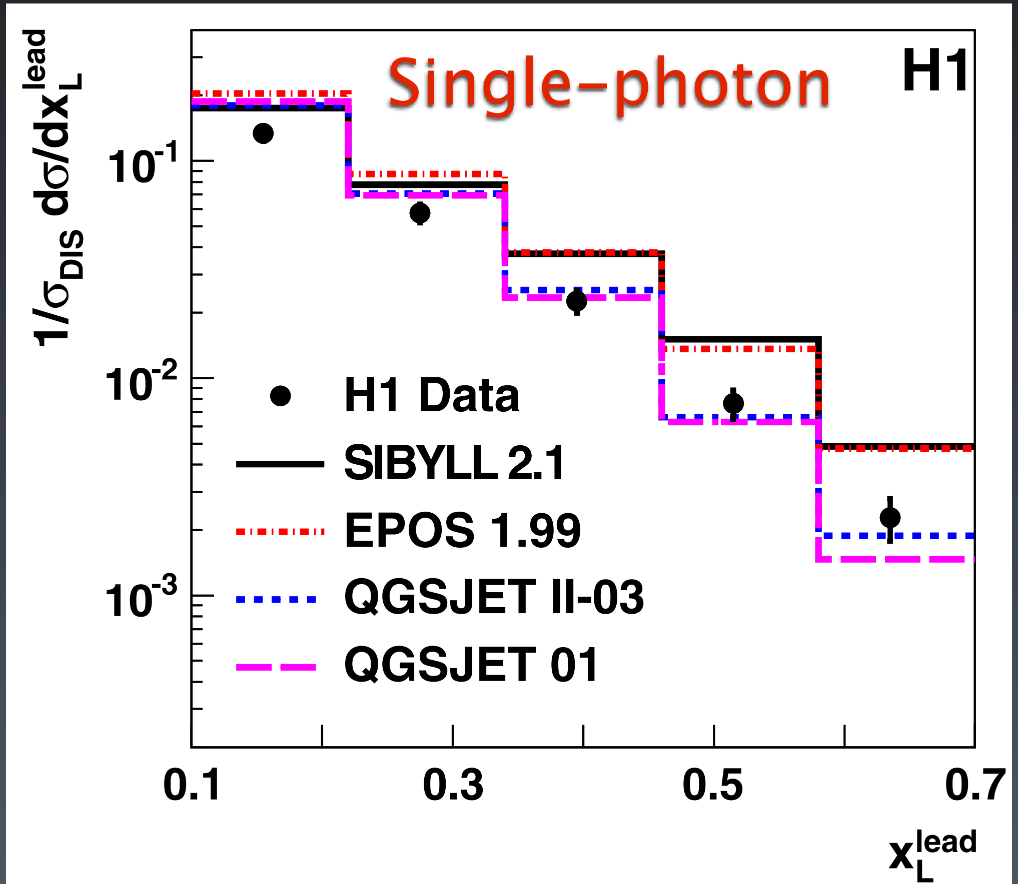


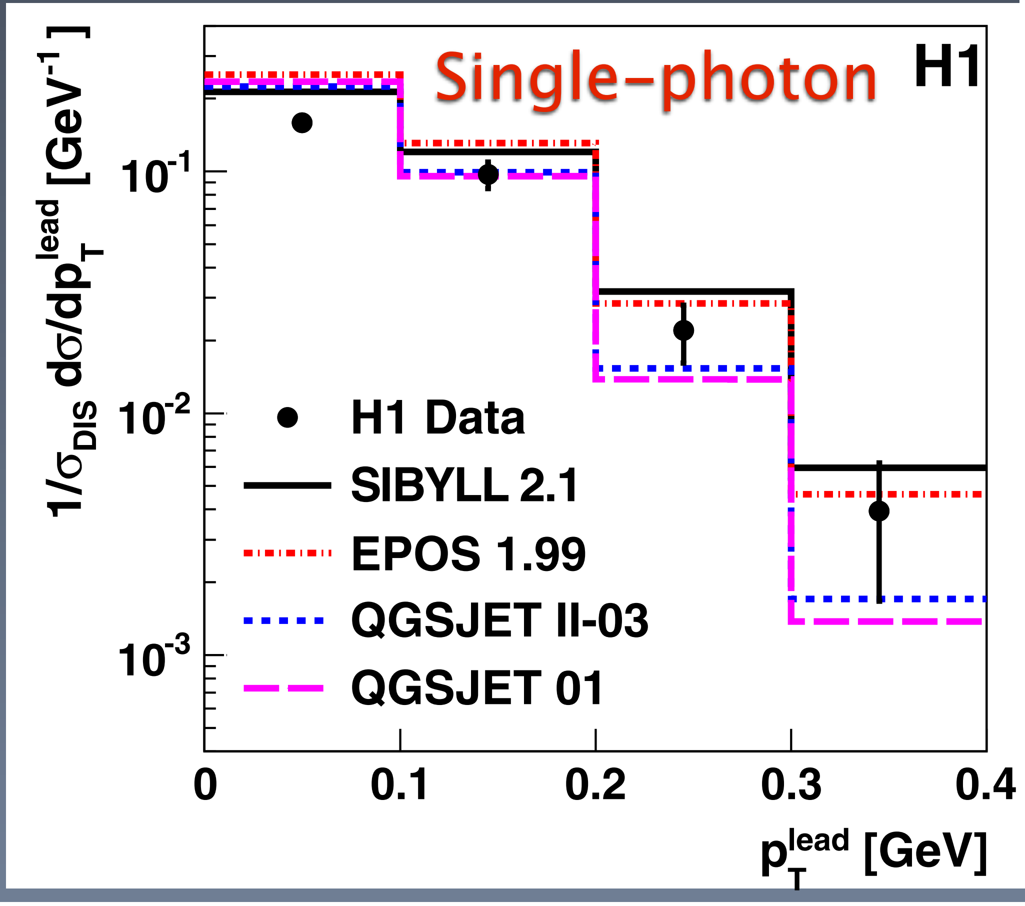


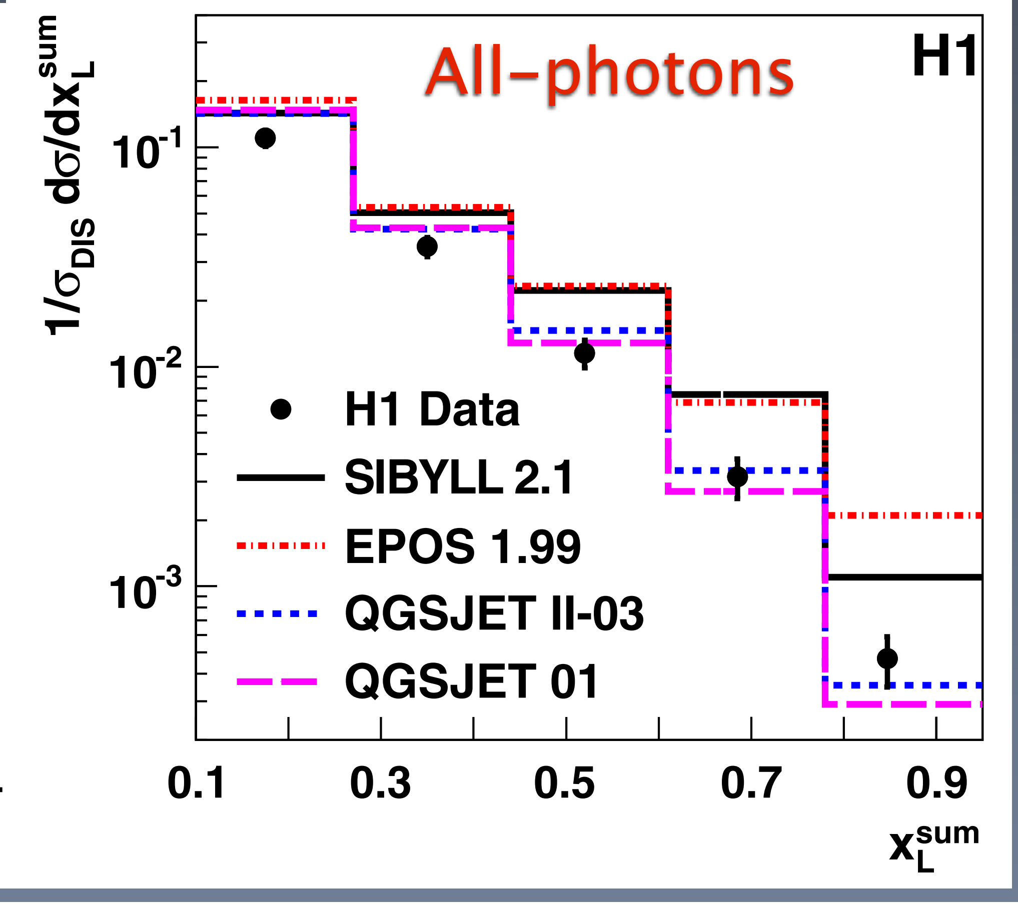
Armen Bunyatyan, 13th EDS, 2009
Analysis by T.Pierog & R.Engel

Forward photon in DIS

- First measurement of very forward ($\eta > 7.9$) photon production in DIS e^+p collision by H1.
- Provided new input to the understanding of proton fragmentation.
- Both single-photon ($X_L < 0.7$) and all-photon ($X_L < 0.9$) spectra are obtained.

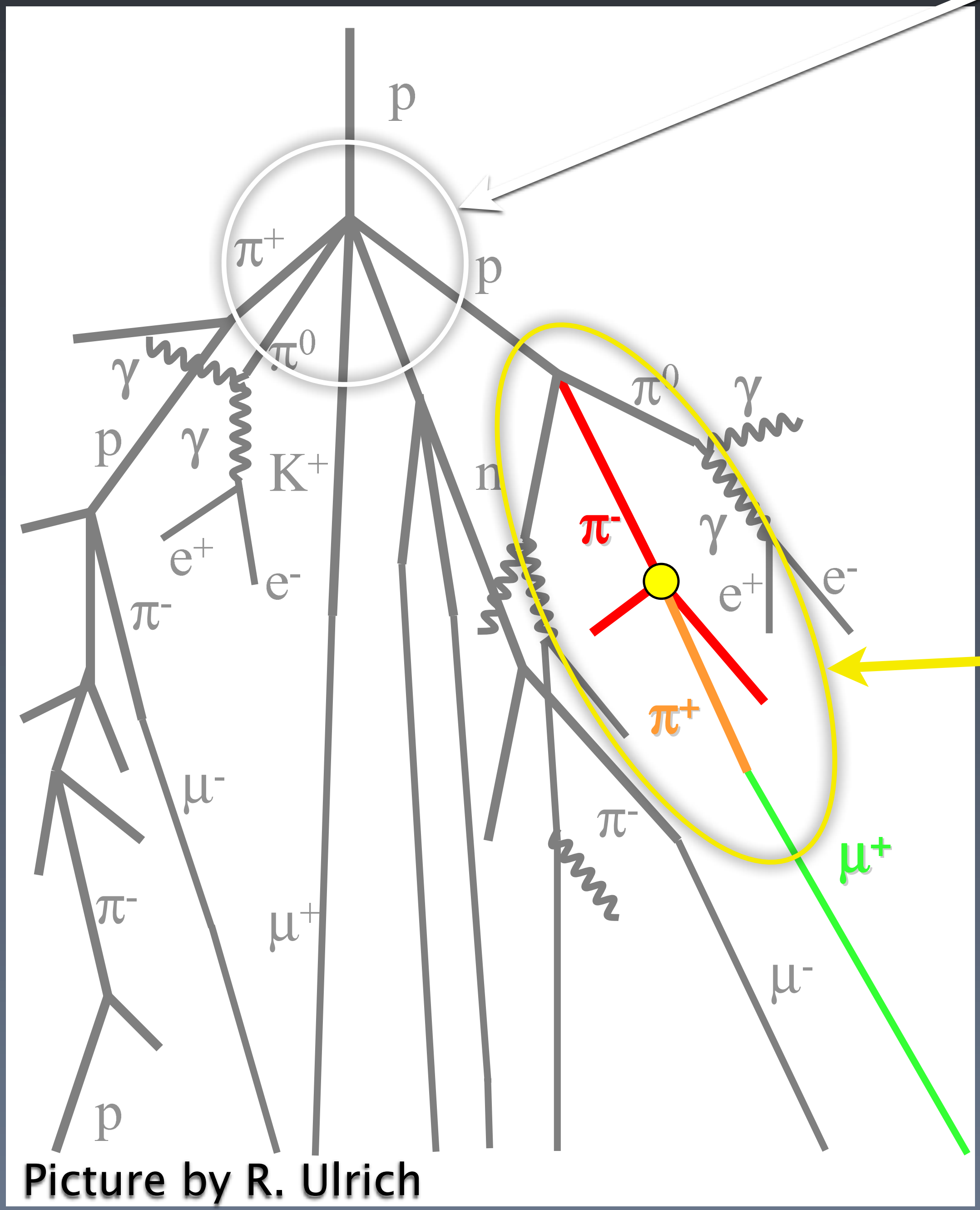






The H1 Collaboration
Eur. Phys. J. C (2011) 71:1771

Hadronic interaction models (CR view)



High-energy

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- QGSJET 01 & II
- SIBYLL 2.1
- EPOS 1.99
- ....

Low/intermediate-energy

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- FLUKA
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Inclusive pion spectra (NA61)

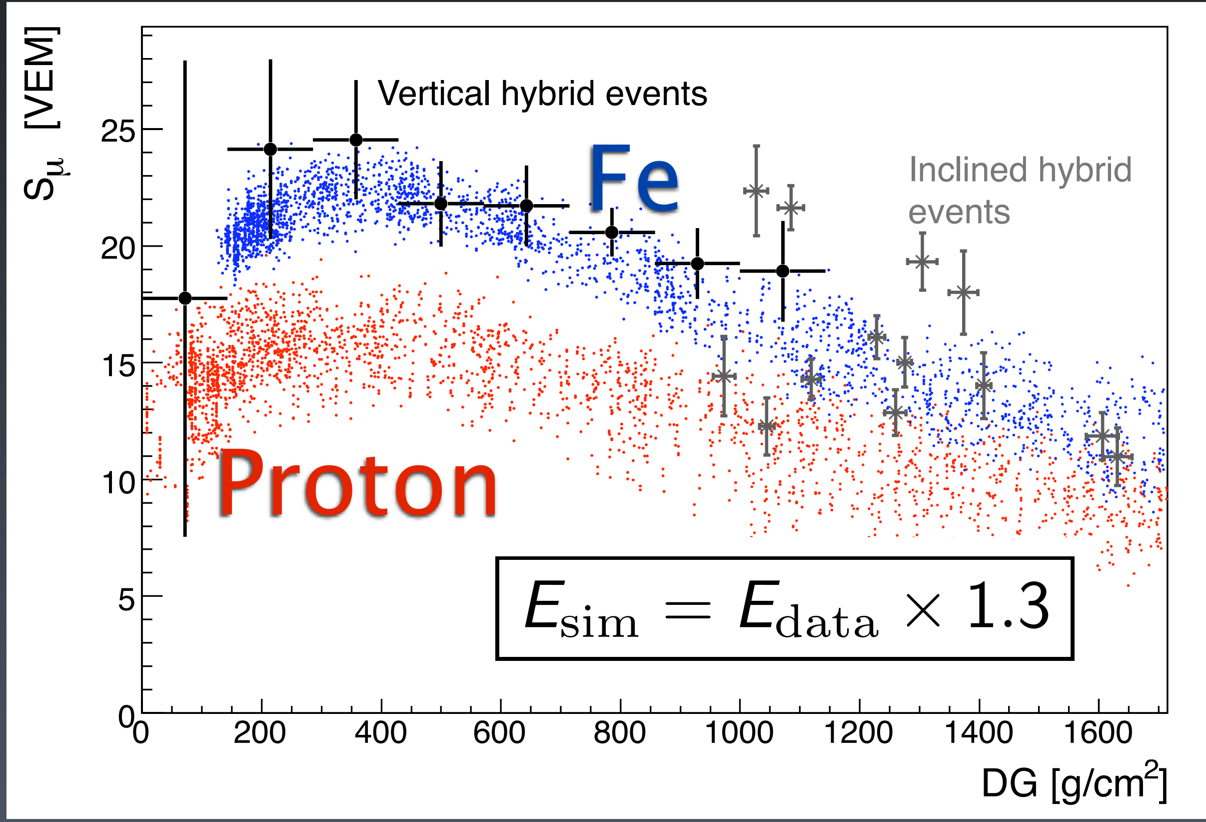
- The Pierre Auger surface detector relies on the number of muons at ground to reconstruct the primary cosmic ray energy.

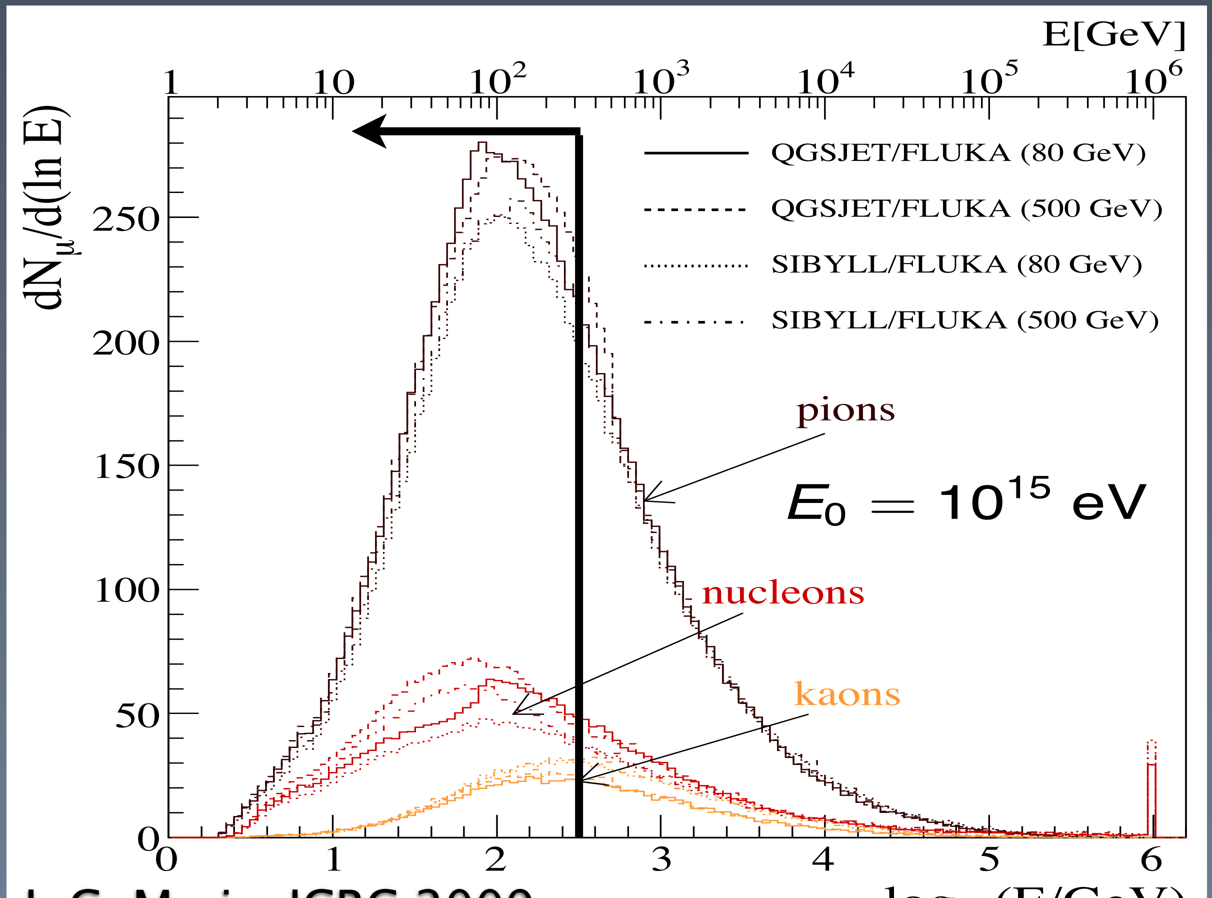
$$N_\mu \propto \left(\frac{E_0}{E_c^\pi}\right)^{1+\ln(N_{had}/N_{tot})/\ln N_{tot}}$$

E_0 : Primary energy
E_c^π : Critical energy of π decaying to μ before int.
N_{had} : Number of hadrons leading to hadronic shower
N_{tot} : Total number of particles.

T. Pierog and K. Werner,
Phys. Rev. Lett. 101 (2008), 163 171101

- Secondary pions, kaons, and baryons are distributed from 10GeV to 1TeV.
- Fraction of baryons in air-shower highly affects the number of muon at ground.





I. C. Maris, ICRC 2009

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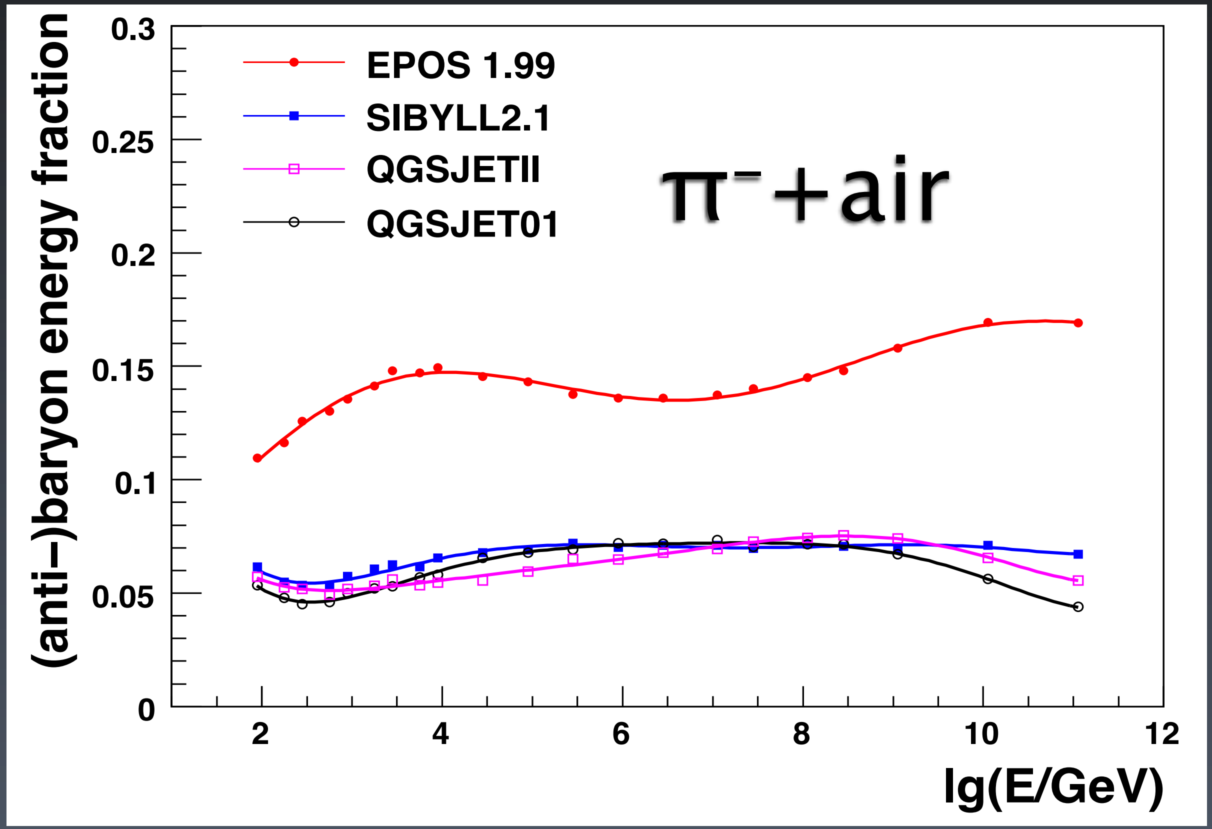
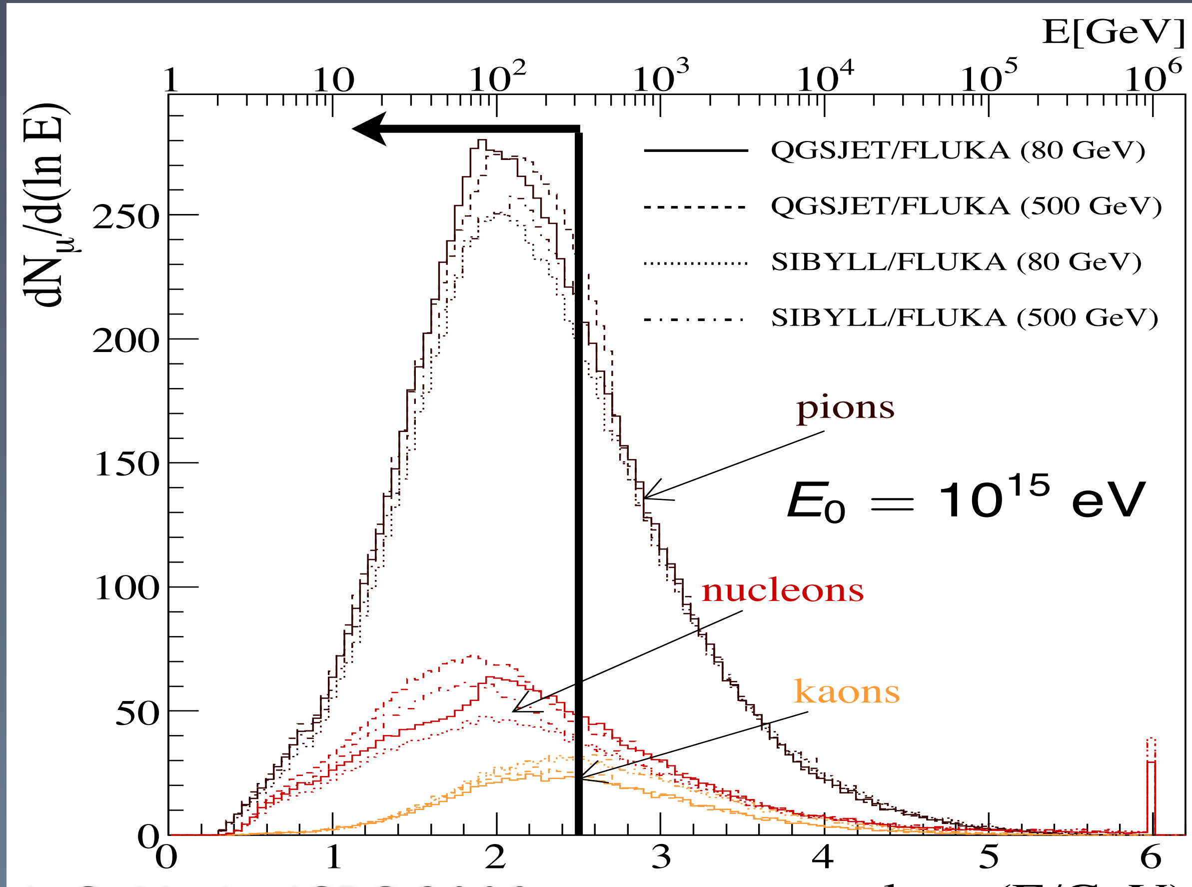
T. Pierog and K. Werner,
Phys. Rev. Lett. 101 (2008), 163 171101

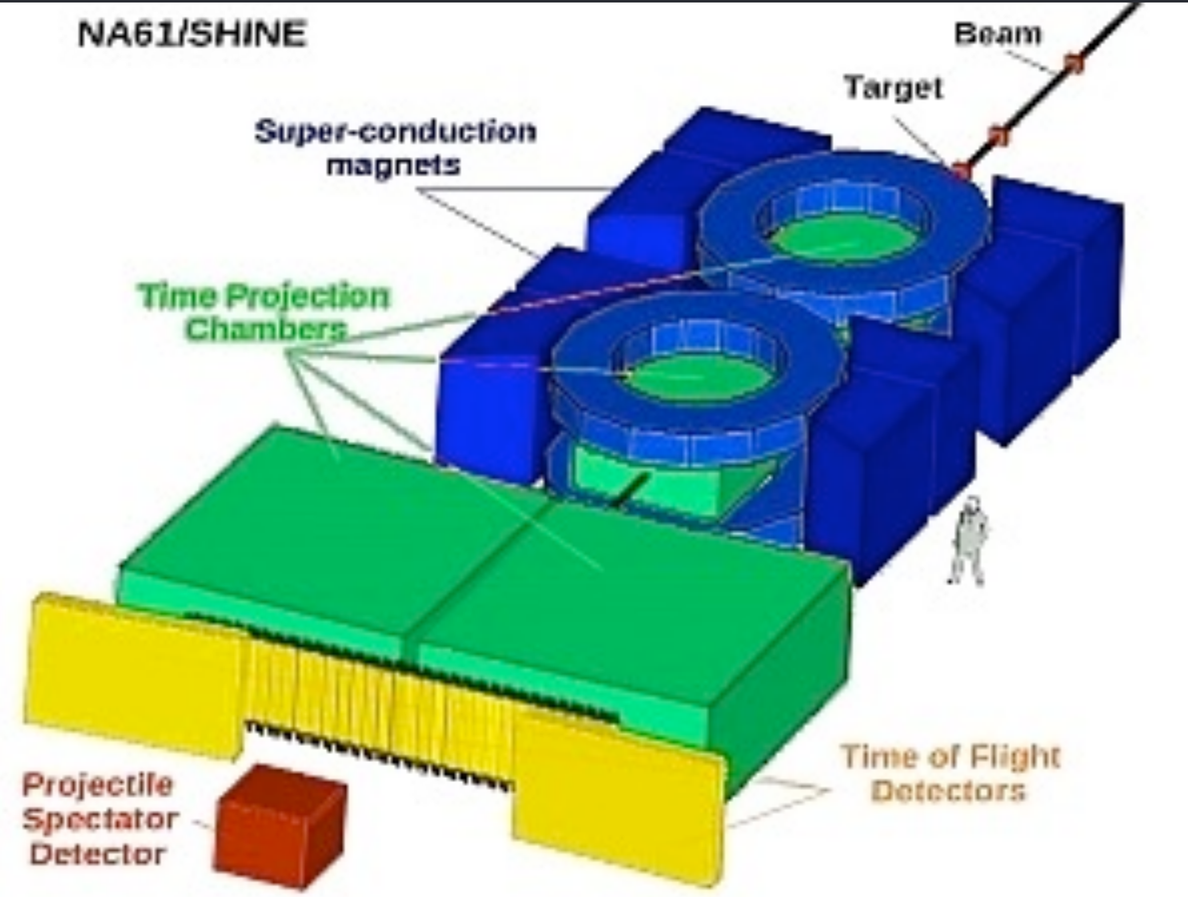
- Enhancement of (anti-)baryon production gives large number of muon.
  - less EM component and more hadronic component
    - →more charged pion
    - →more muon at ground



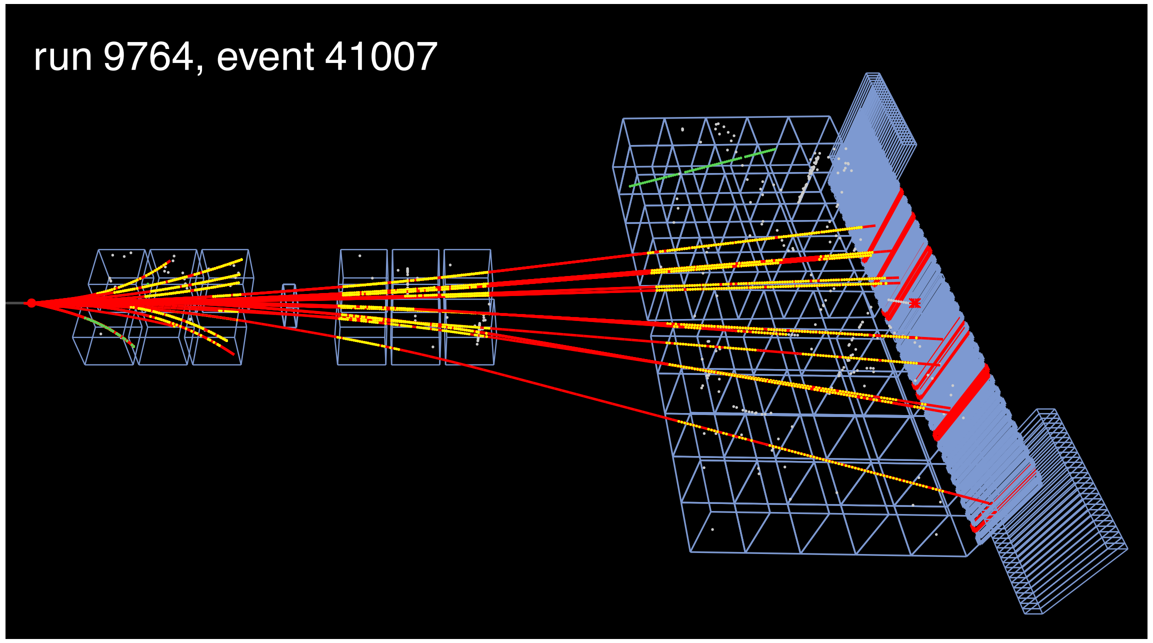


I. C. Maris, ICRC 2009

Inclusive pion spectra (NA61)



π^-+C interaction at 350 GeV/c



Basically inherited from the NA49 detectors.

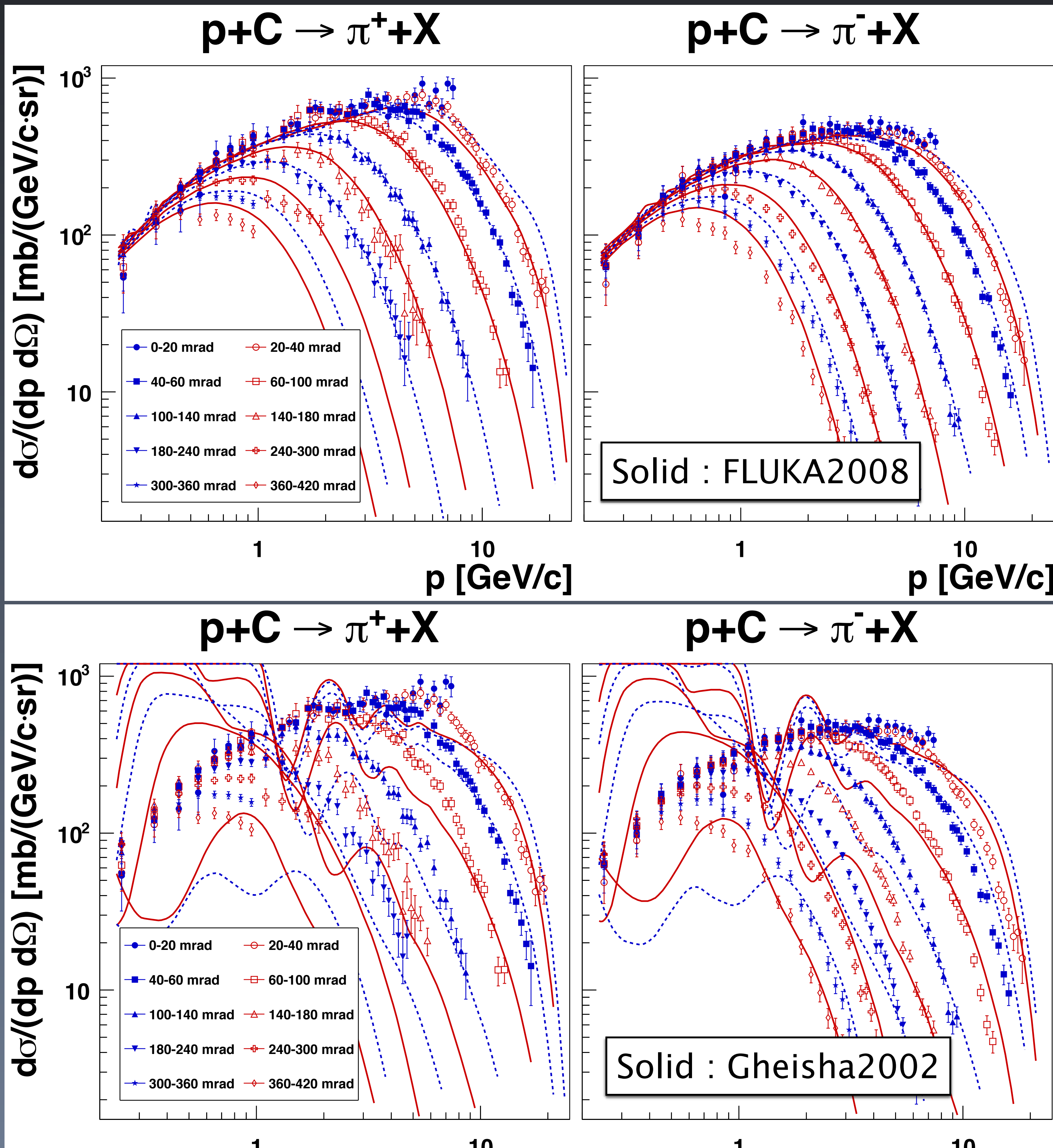
Good detector performances:
- Covering large acceptance~P_T<2.5GeV/c
- $\sigma(p)/p^2 \sim 10^{-4}(\mathrm{GeV/c})^{-1}$
- Tracking efficiency>95%

Well suited for many physics program:
- Cosmic ray physics
- Neutrino flux prediction (suited to T2K)
- Heavy ions

	p	yr	N_{trig} [x10^6]
π^-C	158	2009	5.5
π^-C	350	2009	4.6
pC	31	2007	0.7
pC	31	2009	5.4
pp	13	2010	0.7
pp	13	2011	2*
pp	20	2009	2.2
pp	31	2009	3.1
pp	40	2009	5.2
pp	80	2009	4.5
pp	158	2009	3.5
pp	158	2010	44
pp	158	2011	30*

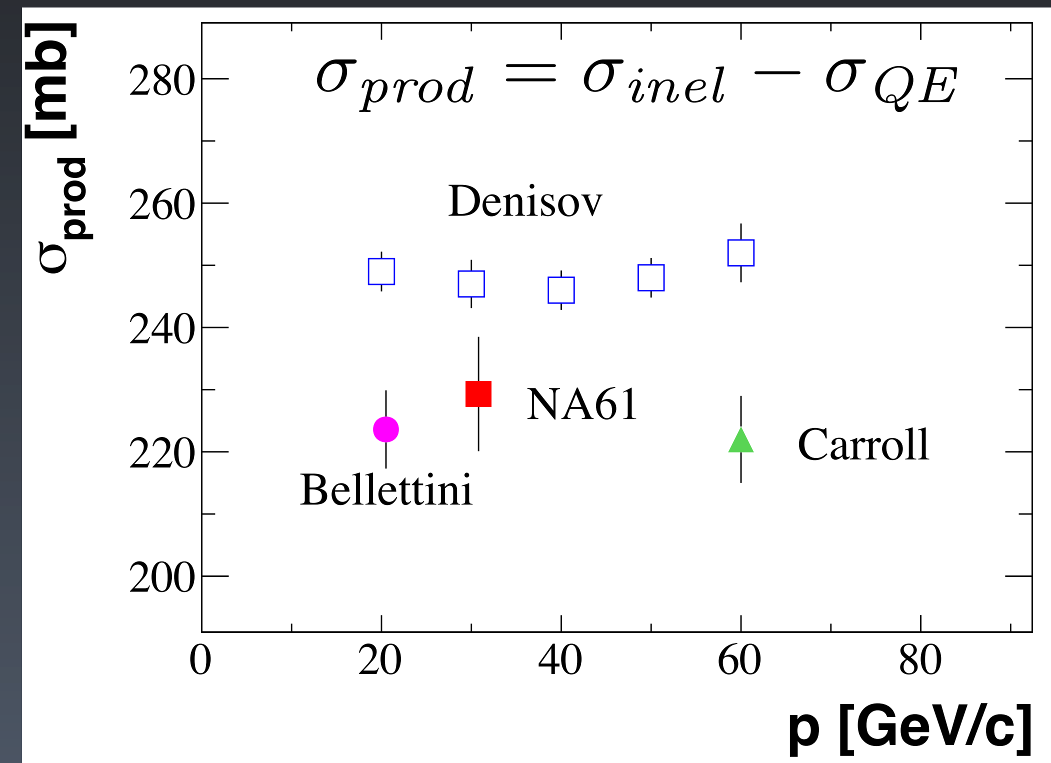
(M. Unger, ICRC2011)

Inclusive pion spectra (NA61)



(M. Unger, ICRC2011)

p+C production cross section



(The NA61/SHINE Collaboration
Phys. Rev. C 84, 034604 (2011))

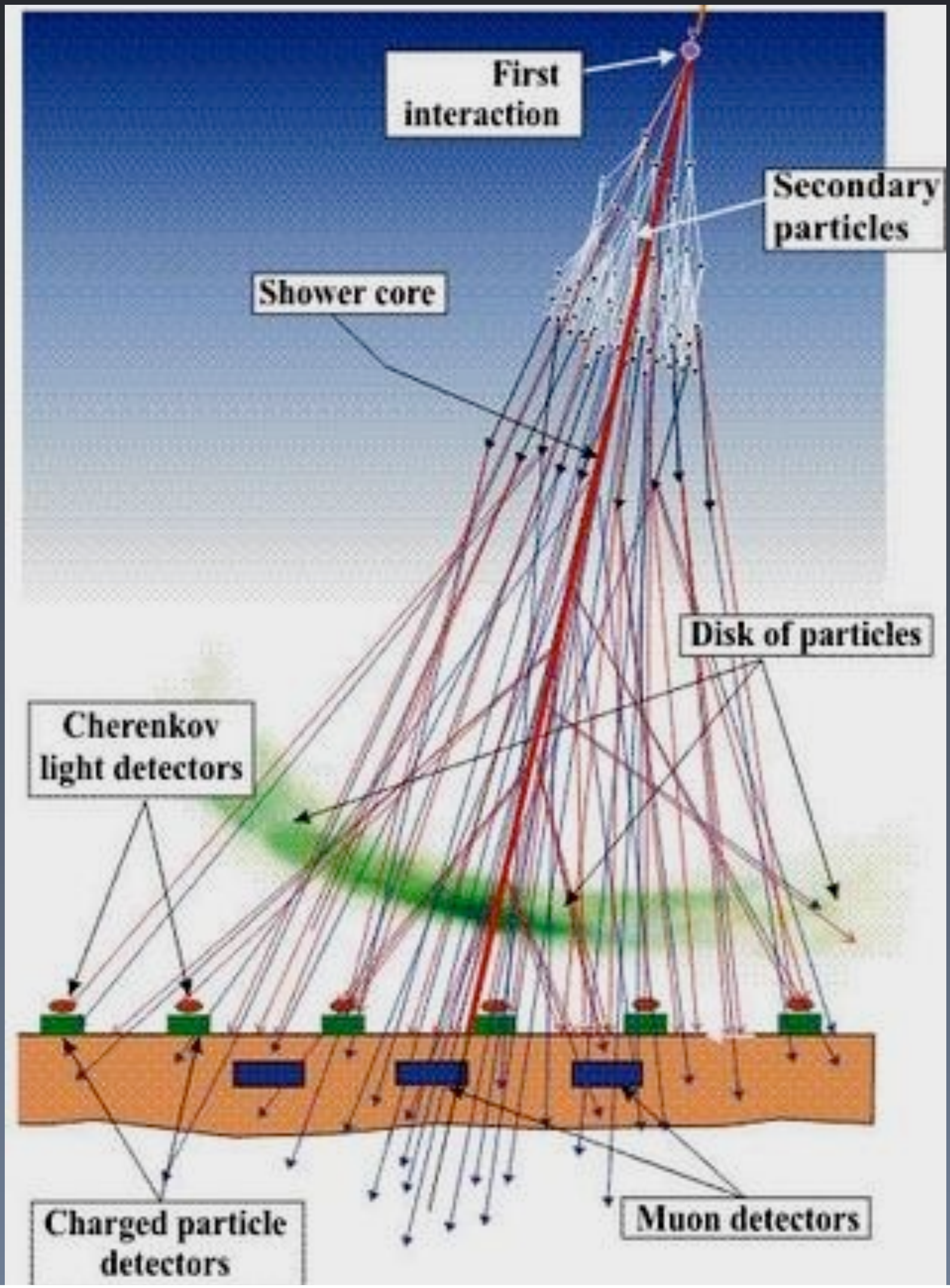
- Total syst. error ~ 5%.
- Best agreement with data is obtained from FLUKA2008.
- Analyses of other data set/ particles (p, K, Λ etc.) are ongoing.

Summary

- Understanding of hadronic interactions, both of soft and hard process, is necessary for the "correct" interpretation of the cosmic ray observations.
- Many rooms are left to be improved in the existing hadronic interaction models even at the GeV scale, as well as the TeV scale.
- LHC-generation model can tightly reduce the systematic uncertainty related to cosmic ray interaction.

Backup

Cosmic ray scattering in atmosphere



- Cosmic ray scattering off atmosphere
  → Total/inelastic xsec.
  → Nuclear effects(p⇄Fe)

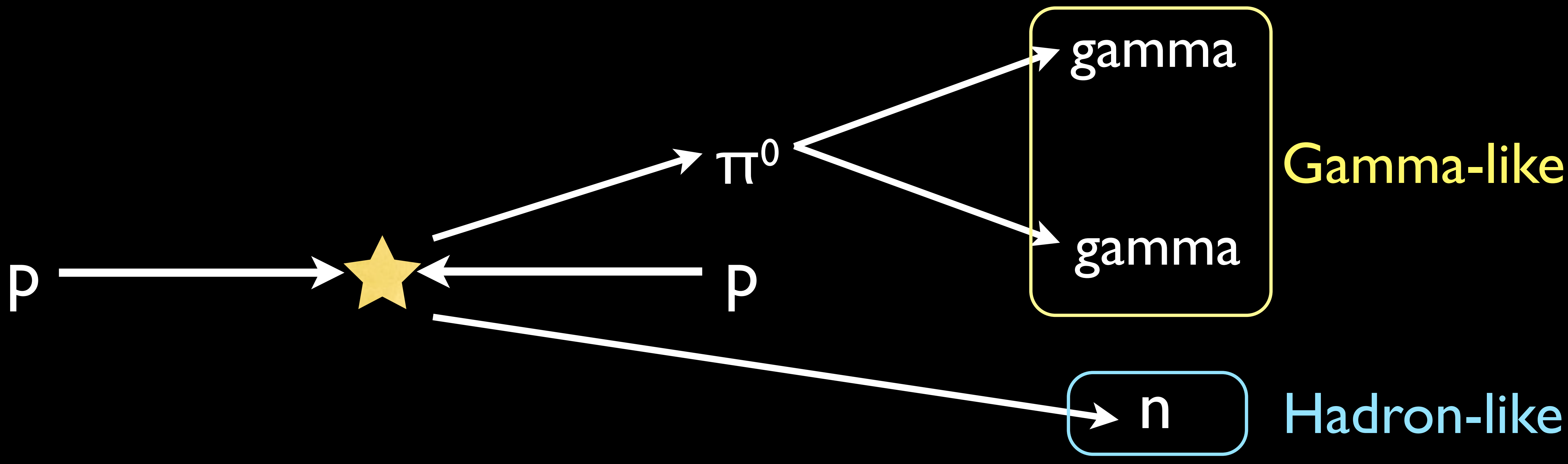
- Secondary particle flux
  → EM/Hadron production
  → Charged/Neutral ratio
  → Proton fragmentation

- Energy fraction
  → Diffractive scattering

Multiplicity and P_T have been discussed in Tanguy Pierog's talk (Dec. 18).

Introduction

- Run at 7TeV is able to detect π^0 events since an opening angle is enough small to be covered by the acceptance of the LHCf calorimeter.
  - energy scale calibration is possible by π^0 mass
  - photon events are first focused on for simplicity

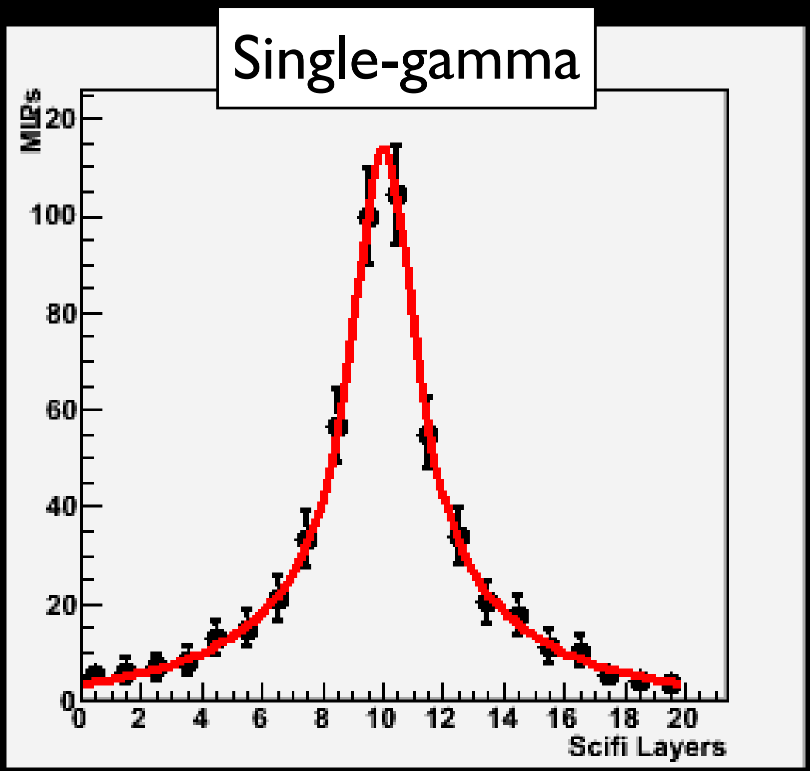


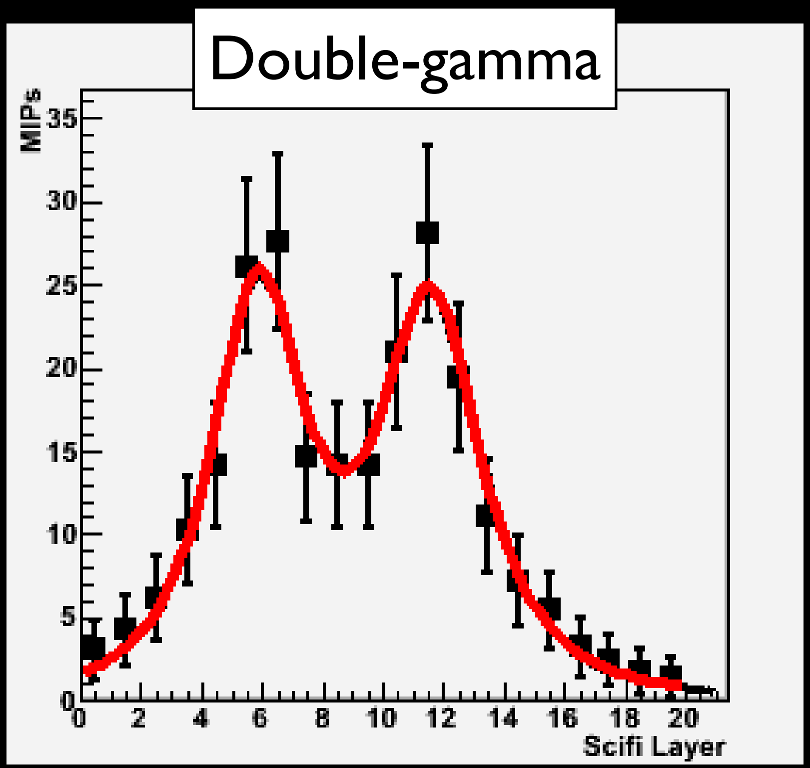
- Other analyses are on going (π^0 spectra, hadron events and data at 900GeV), would be presented in this winter.

Data sets

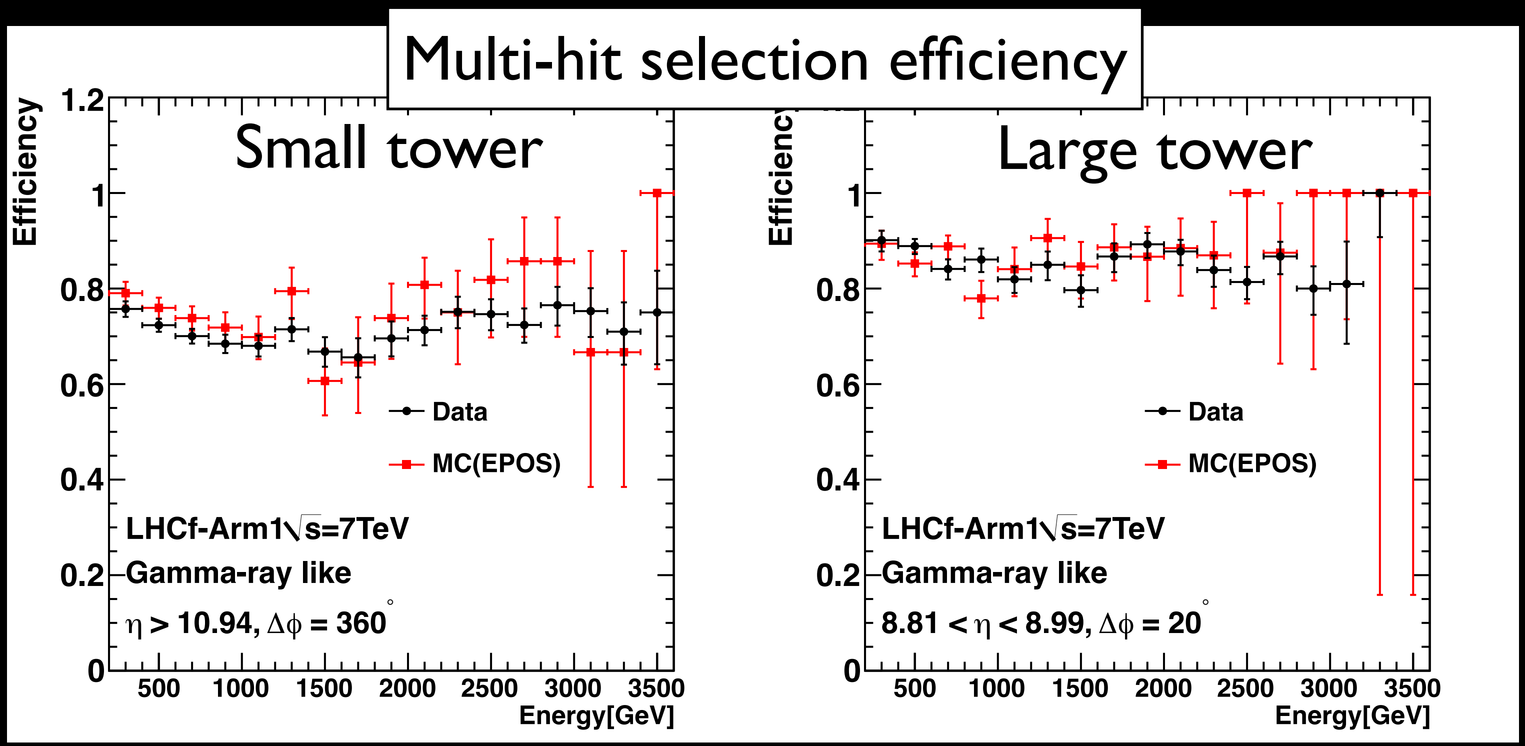
- Experimental data
  - 2010 May 15, 17:45-21:23 (Fill# 1104, except for Lumi-scan data)
  - No crossing angle, pile up is negligibly small ~ 0.2%
  - Luminosity : (6.3-6.5)x10^{28}cm^{-2}s^{-1}
  - DAQ Live Time : 85.7% (Arm1), 67.0% (Arm2)
  - Integrated luminosity : 0.68 nb^{-1} (Arm1), 0.53nb^{-1} (Arm2)
- Monte Carlo simulations
  - DPMJET 3.04, QGSJET II-03, SYBILL 2.1, EPOS 1.99 and PYTHIA8.145 are used to simulate the proton-proton collisions at $\sqrt{s}$=7TeV.
  - Transportation in beam pipe and detector response are correctly treated based on the survey and calibration data.
  - Number of simulated collisions are 10^7s for each hadronic interaction model.

Single-hit selection

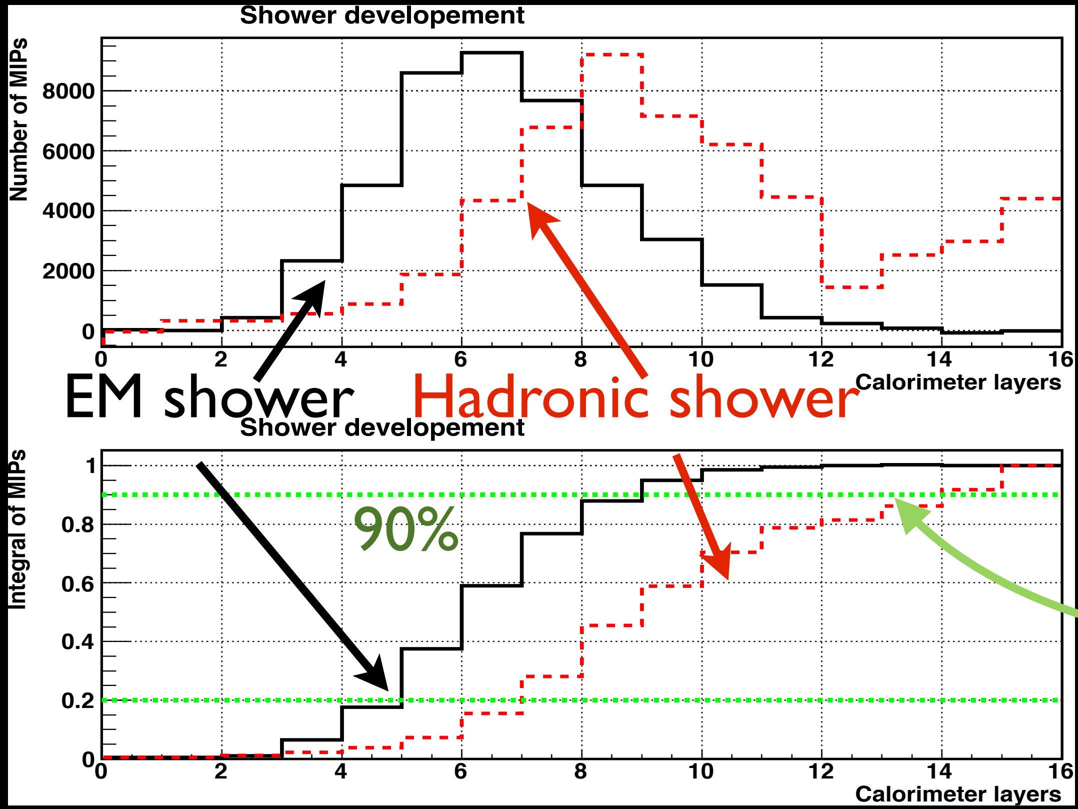


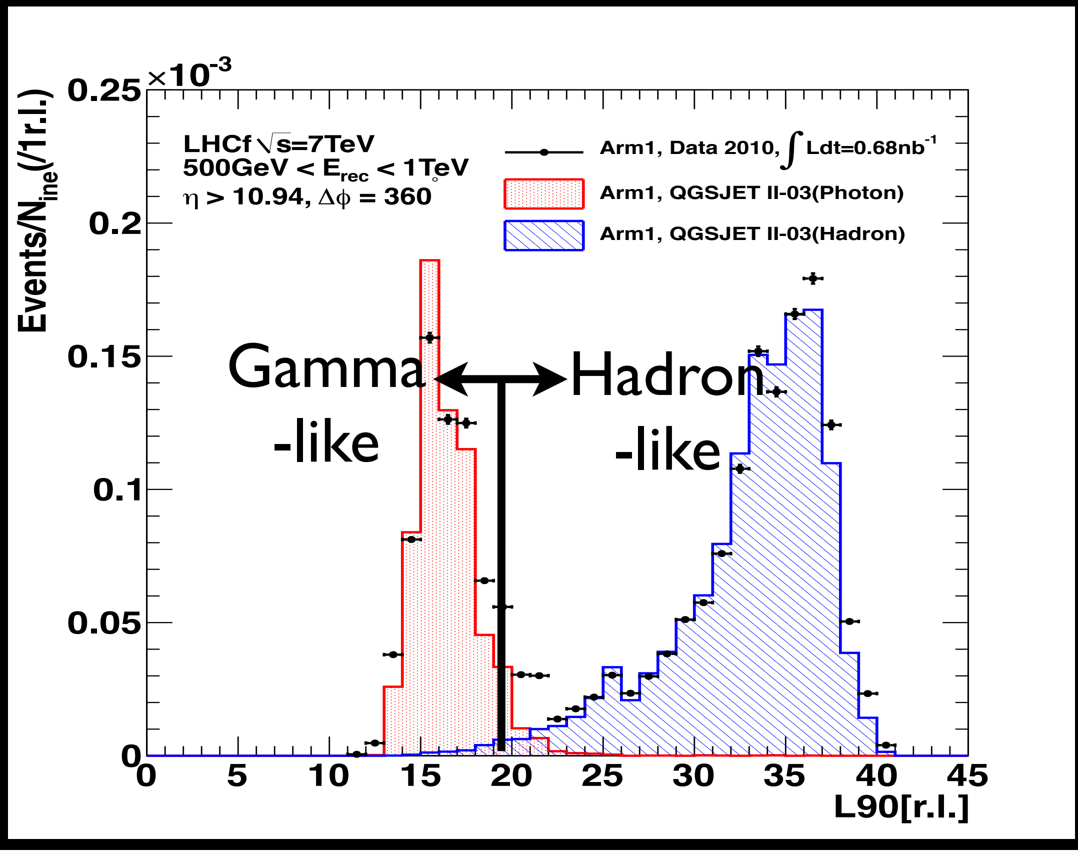


- SIngle-hit/Multi-hit separation by the number of showers.
- Transverse shower development is fitted by a superimpose of a Lorentzian spectra.
- Incident position(X,Y) of neutral particle is used to estimate an amount of shower leakage and to cut events by the fiducial volume.
- Deviation of "multi-hit selection" efficiency btw. data and MC is assigned to a systematic uncertainty.



Particle Identification





- EM and hadronic showers can be discriminated by a difference of longitudinal shower development in calorimeter.
- L90%(in units of r.l.) is introduced to parametrize a longitudinal development.

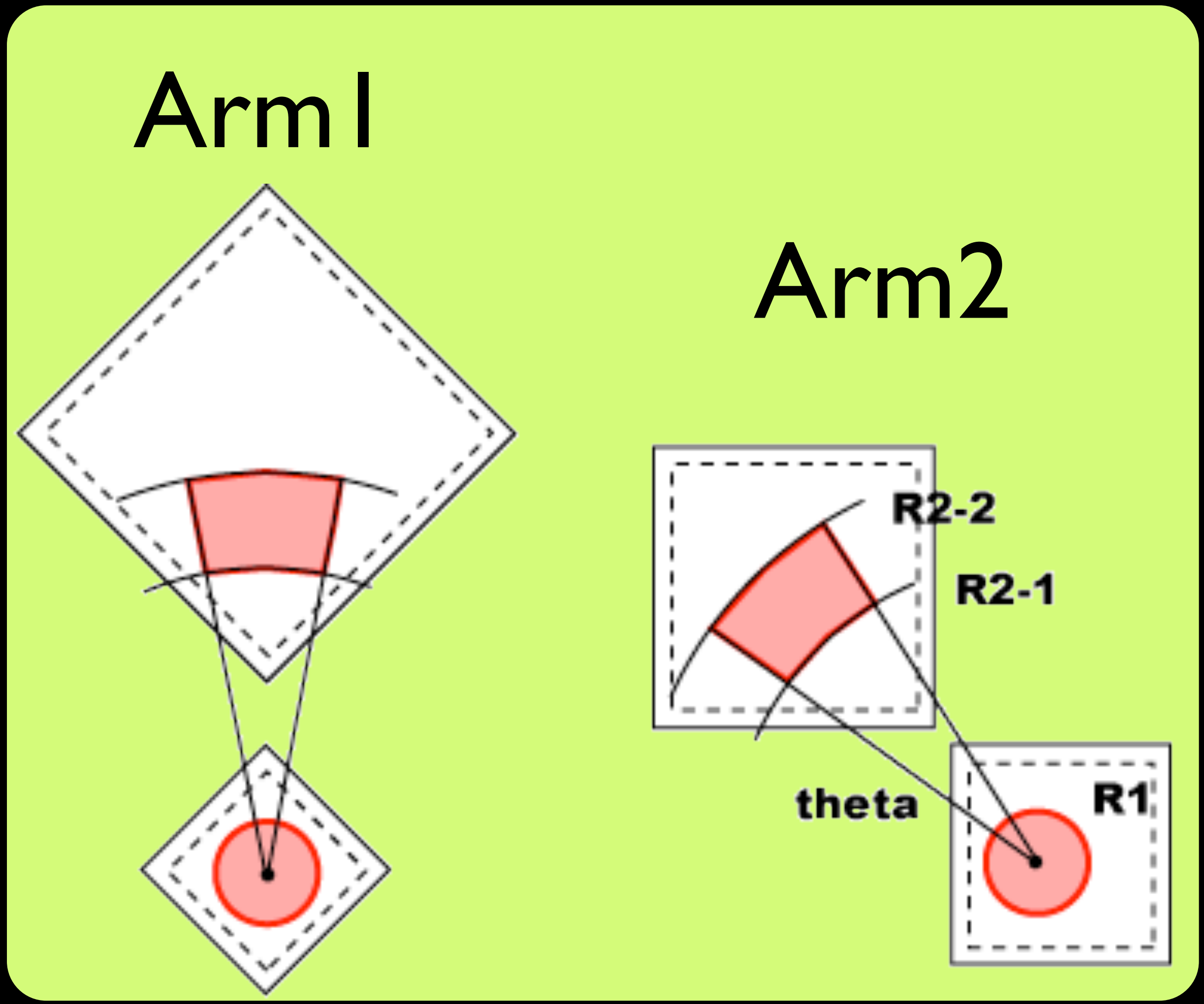
$$\frac{\int_0^{L90\%} E_{dep}}{\int_0^{44r.l.} E_{dep}} = 90\%$$

- ~90% efficiency and >80% purity for gamma-like events. Inefficiency and impurity are corrected to be compared with theoretical expectations.
- Imperfect agreement of MC simulations with data is considered as a systematic uncertainty.

Event selection

- Reconstructed energy > 100GeV
  - Trigger efficiency for EM shower achieves >99% above 100GeV.

- Fiducial volume
  - Events hitting in the following regions are selected so that Arm1 and Arm2 have the common rapidity and azimuthal areas.
  1. Small tower : η>10.94、$\Delta\varphi$=360.0°
  2. Large tower : 8.99>η>8.81、$\Delta\varphi$=20.0°



- Single-hit sample
  - For simple energy reconstruction and better resolution.

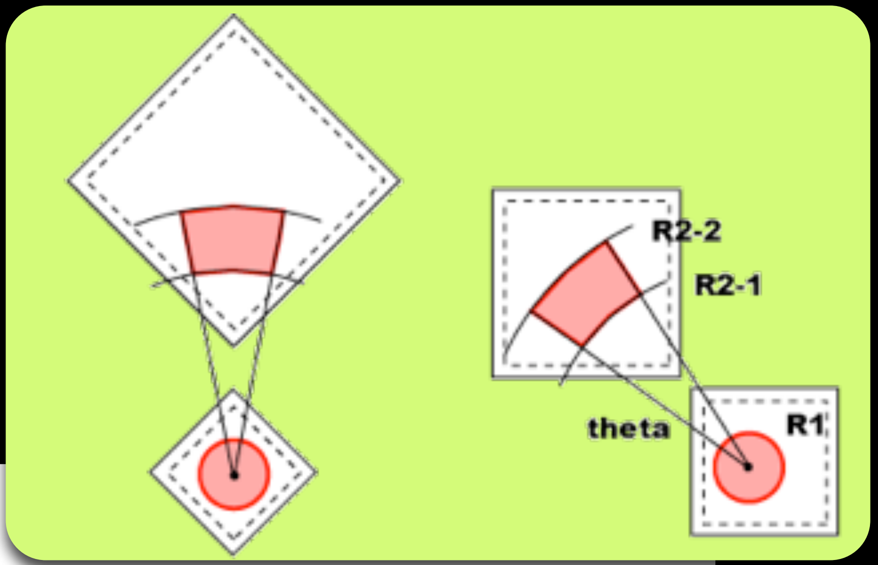
- Gamma-like sample
  - Reconstruction of hadron-like events is still under investigation.

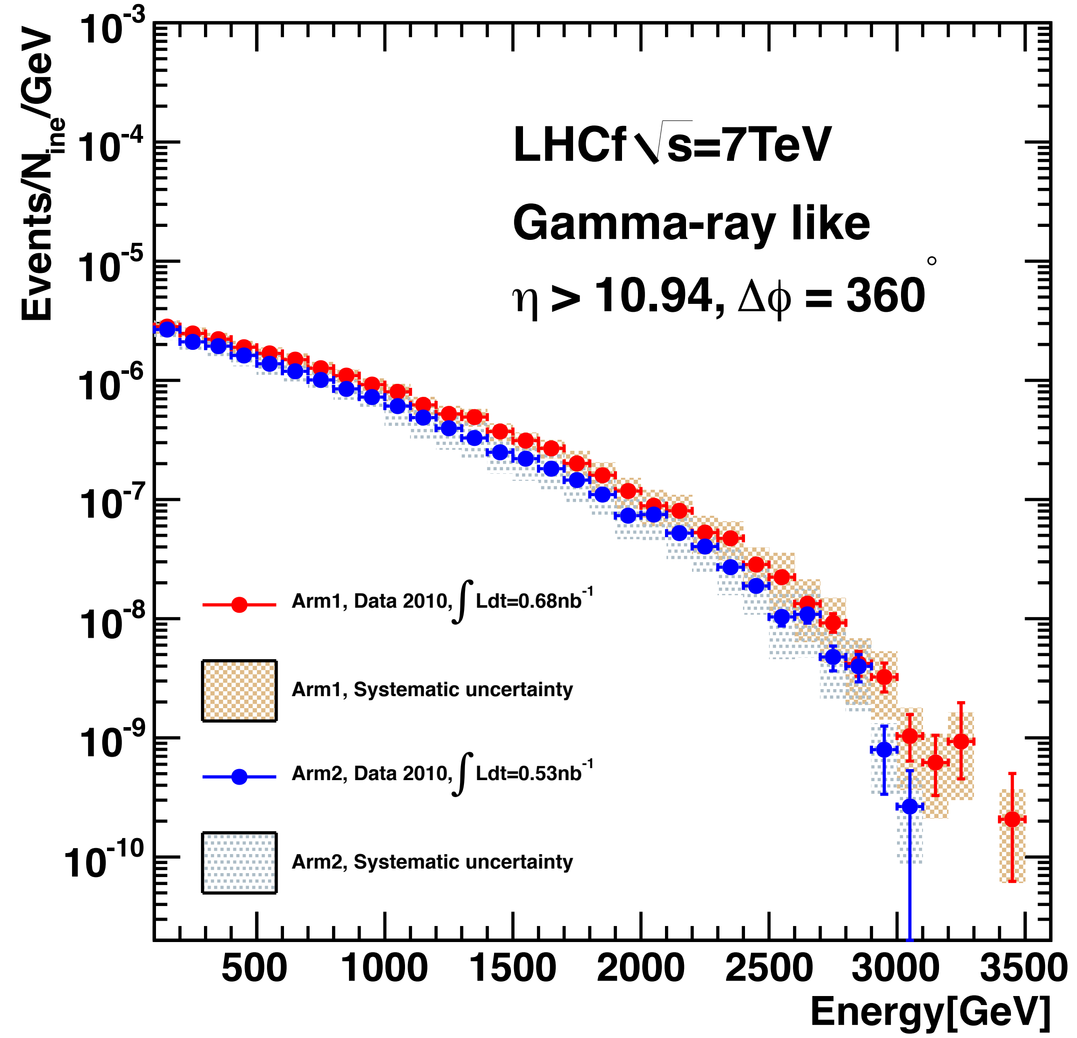
Systematic uncertainties

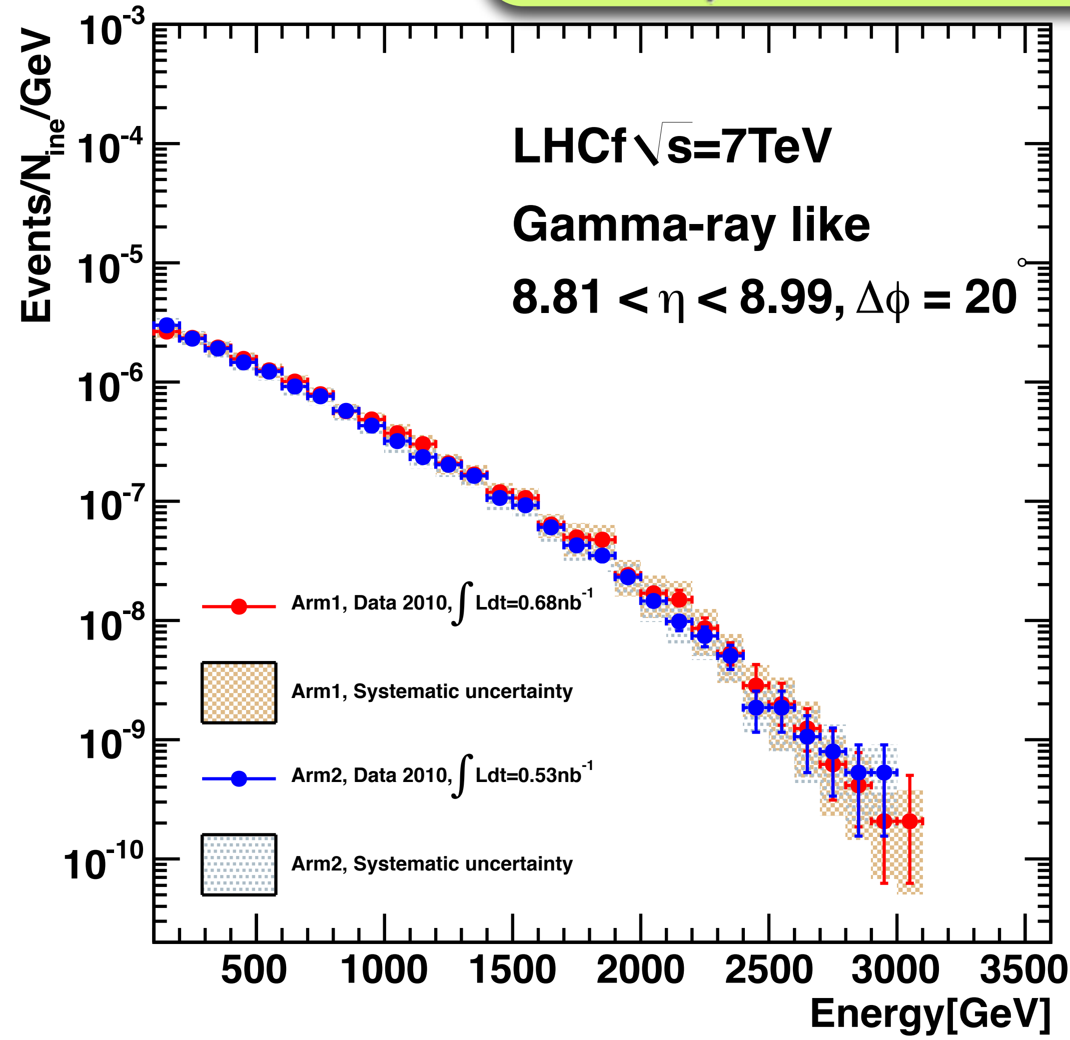
- Energy scale
  - Estimated by MC simulations vs. the SPS beam test and a π^0 mass shift.
  - Dominant error source above 2TeV (2-10% to energy axis).
- Beam center
  - May cause a distortion of energy spectra, especially sensitive in large tower.
  - +/-5% at small tower and over 10% at large tower.
- Particle ID
  - Slight disagreement of the L90% distribution between data and MC simulations gives a different PID efficiency, and this could be systematics.
  - 5% at E<2TeV and 20% at E>2TeV.
- Single-hit/Multi-hit separation
  - Difference of separation efficiency between data and MC simulations.
  - 1% at E<2TeV and grows up to 20% as energy.

Photon spectra

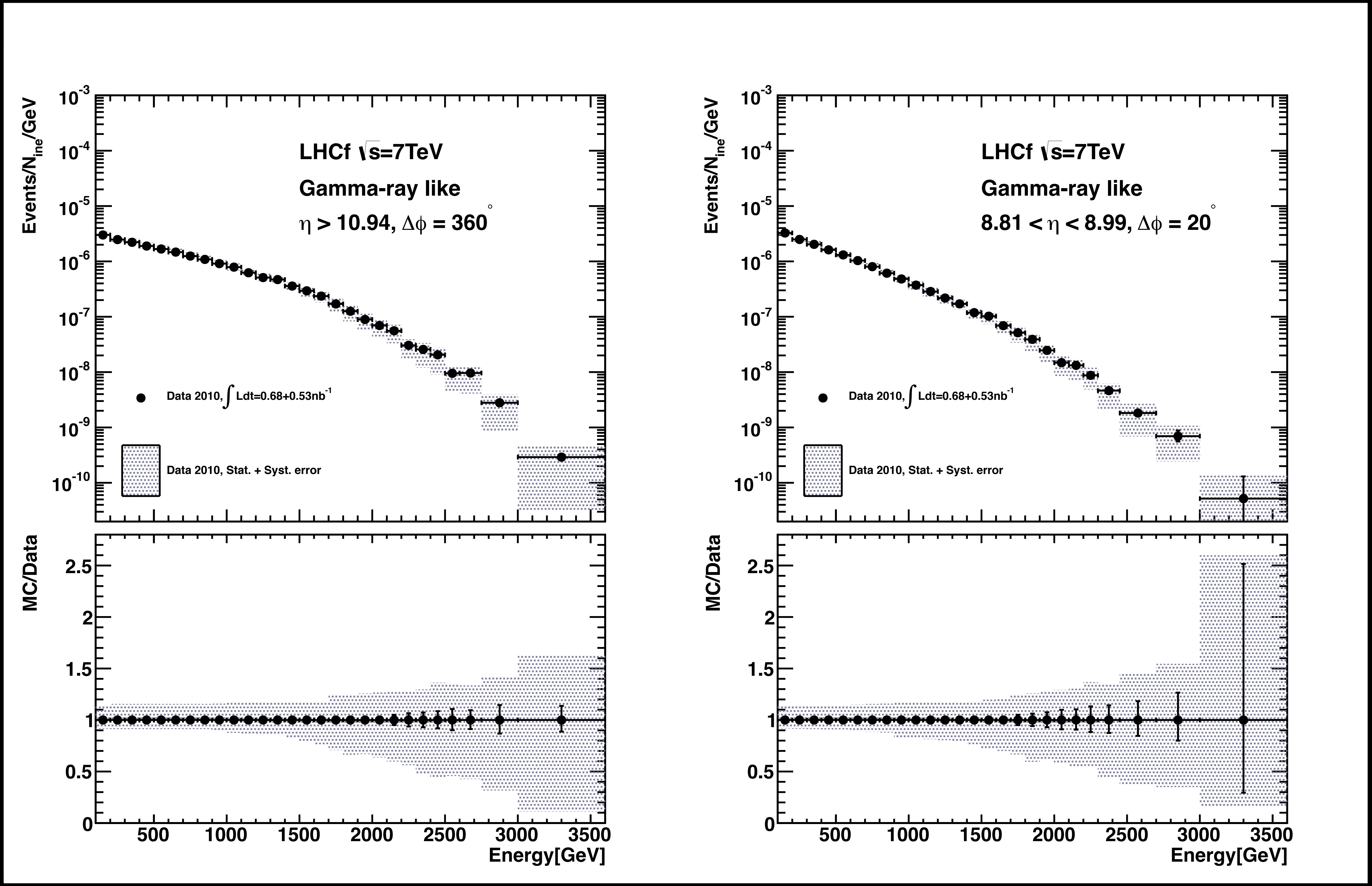
- Correlated syst. uncertainties are removed in the figures.
- Deviation btw. Arm1 and Arm2 is recognized in small tower, while it is within syst. uncertainty.
- Consistent each other in large tower.



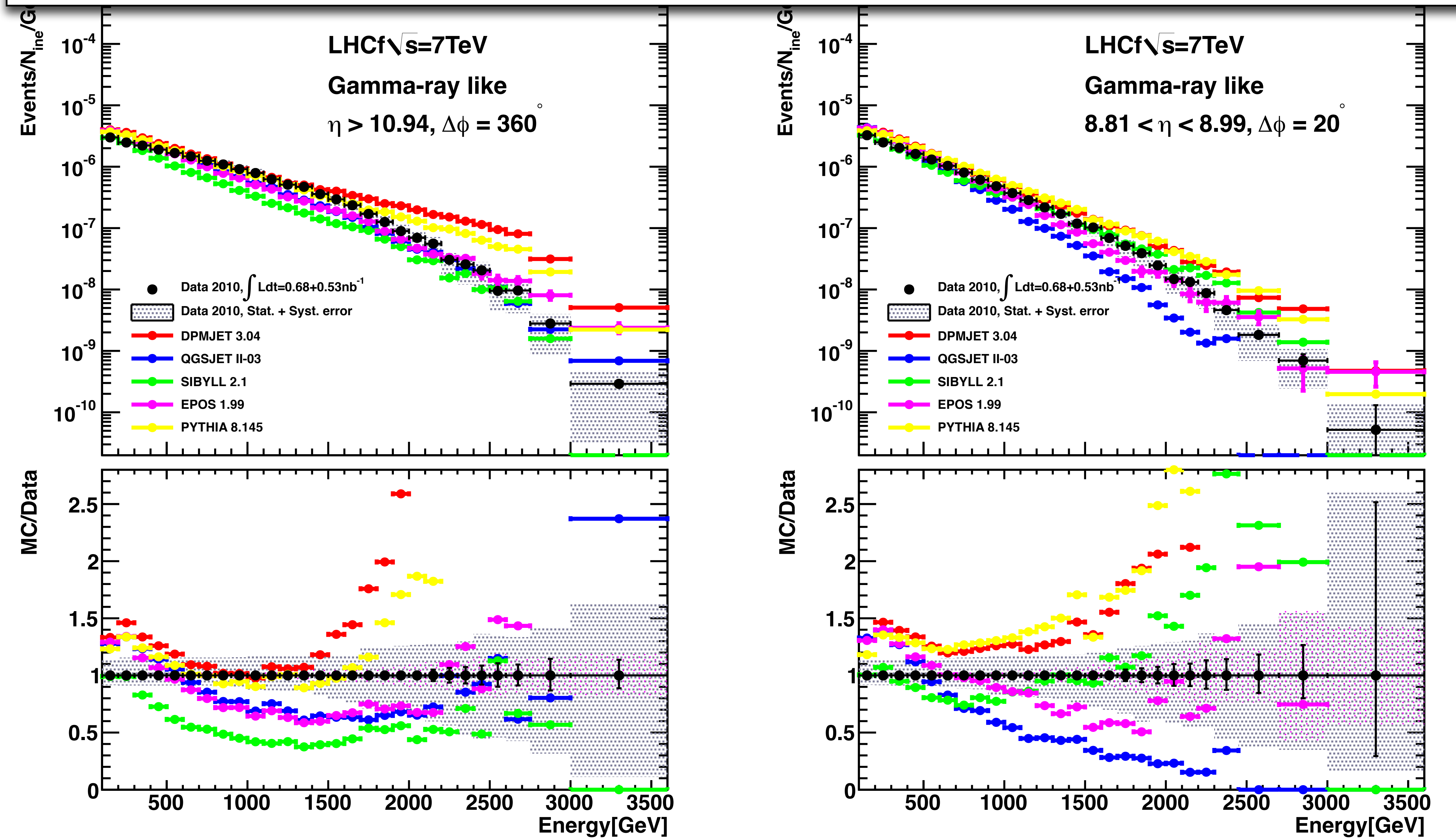




Combined analysis



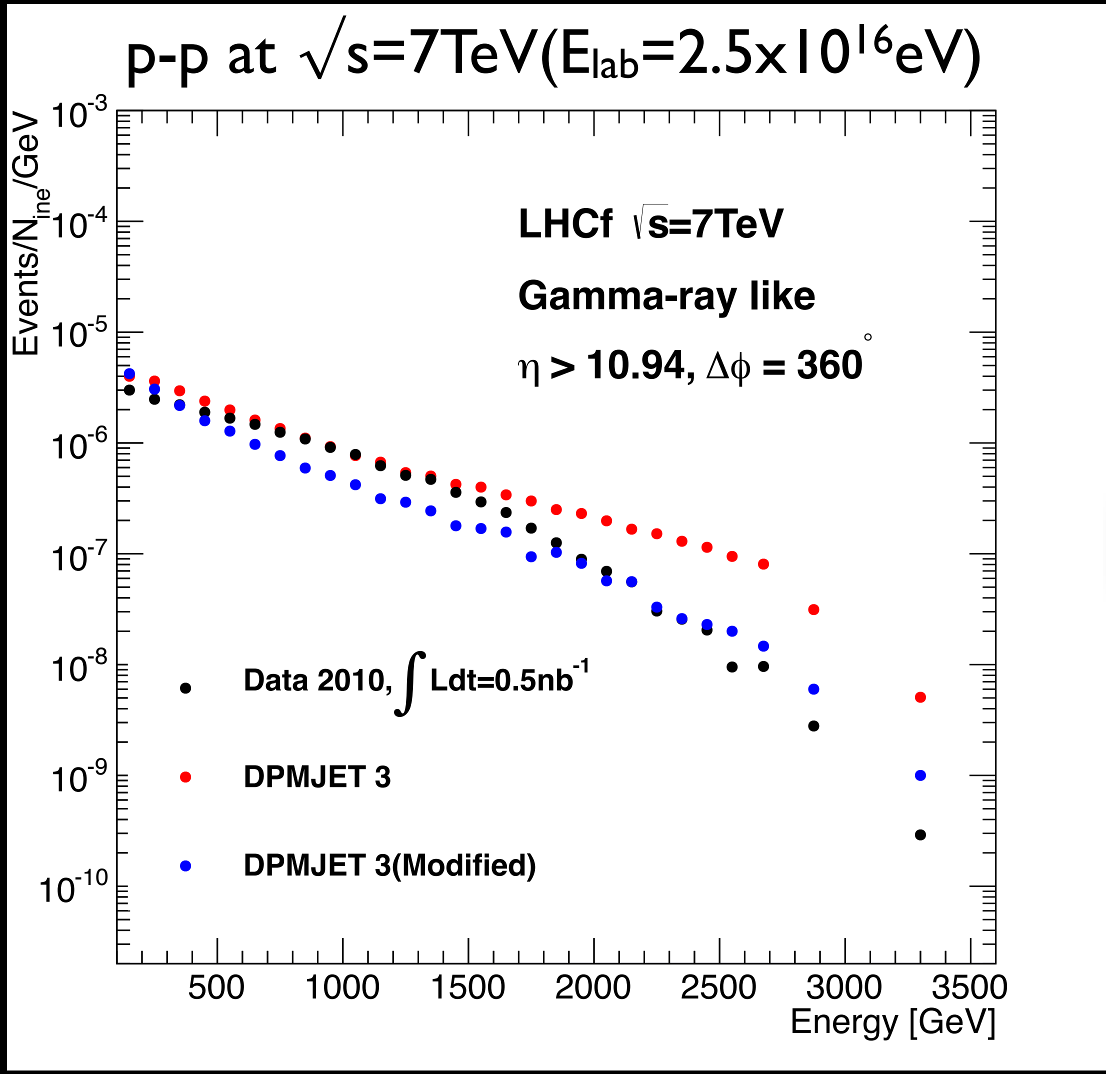
- DPMJET 3.04, PYTHIA 8.145
  - Good agreement in small tower at 0.5-1.5TeV, but too ample flux above 2TeV.
- SIBYLL 2.1
  - Similar behavior at small tower above 0.5TeV, although almost half flux.
- QGSJET II-03, EPOS 1.99
  - Similar tendency each other in small tower. QGSJET II-03 is softest in large tower.

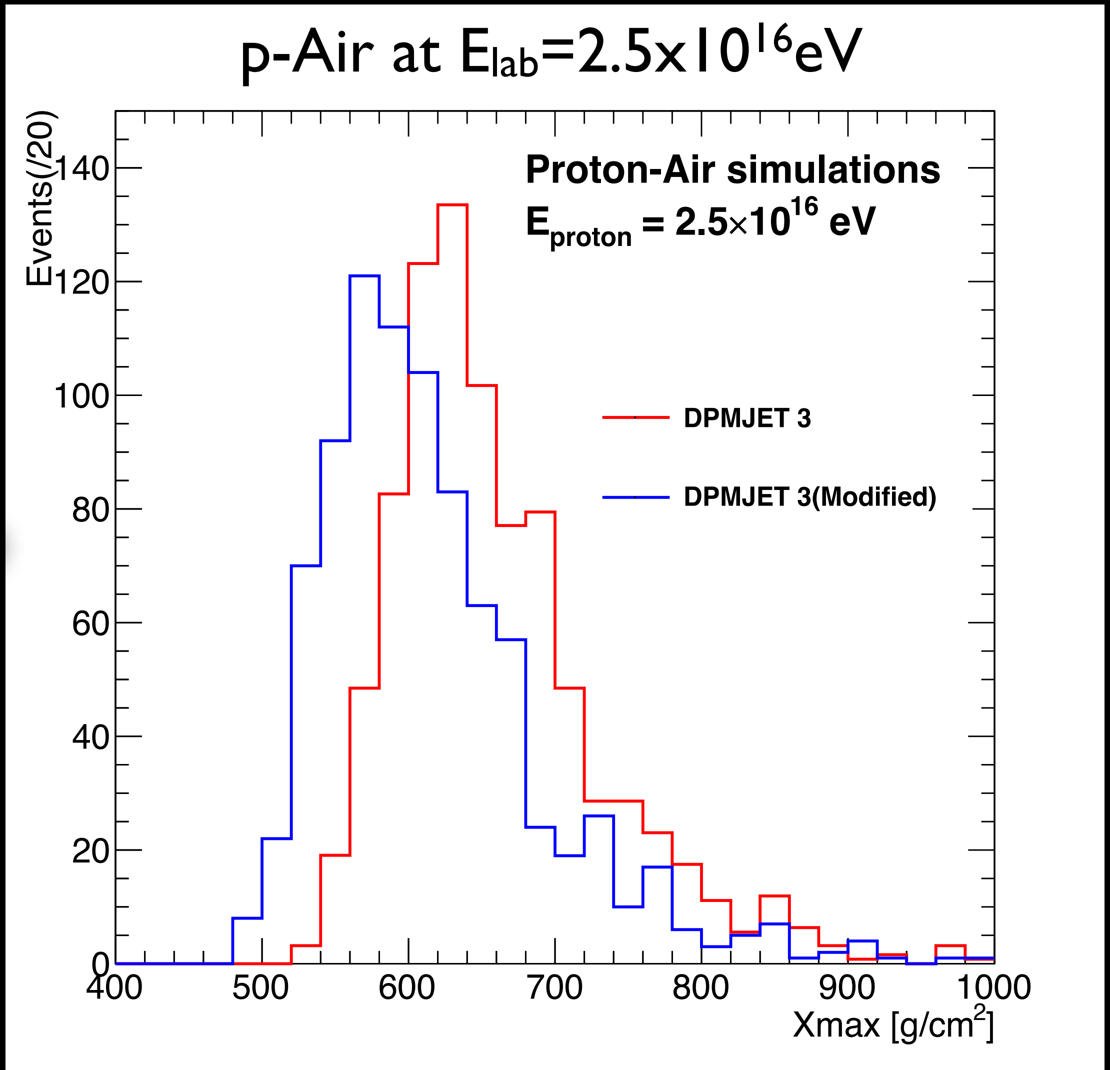


DPMJET 3.04 QGSJET II-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

Constraints to CR observation

- Constraint of the LHCf results to CR observations is estimated by proton-air simulations:
  - Proton-proton collisions are generated by DPMJET3
  - DPMJET3 outputs are artificially modified to be parallel to the LHCf spectra (split a high-energy π^0 to two low-energy π^0s)
  - Modification factor is applied to simulations of the proton-air collision.
  - E_{Proton} is 2.5×10^{16}eV, equivalent to the energy in lab frame of p-p collision at $\sqrt{s}$=7TeV
- Results in decrease of ~40 g/cm^2.

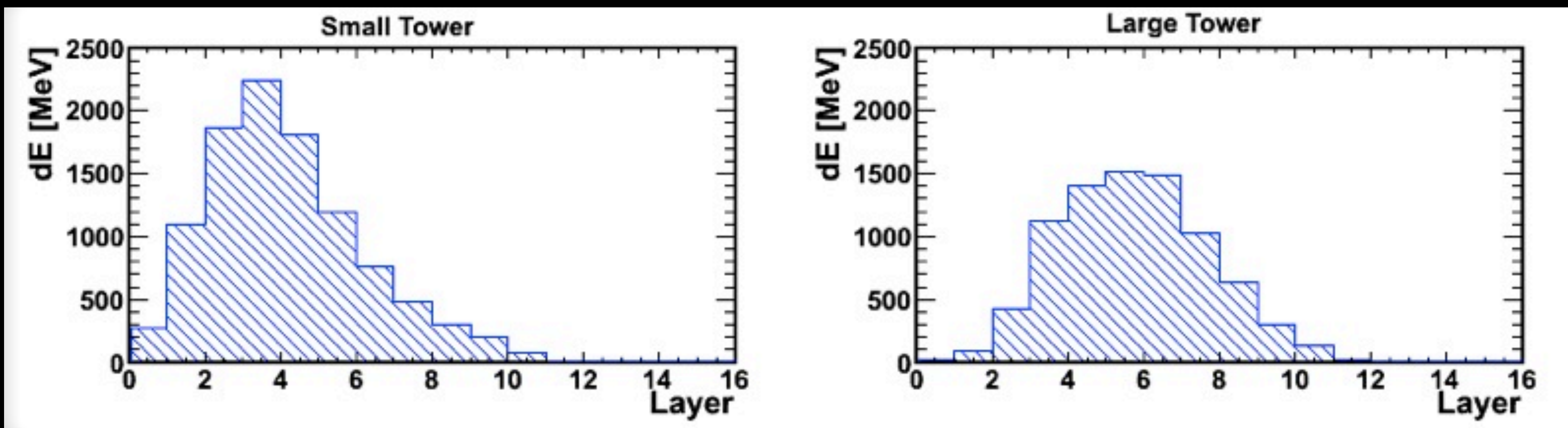




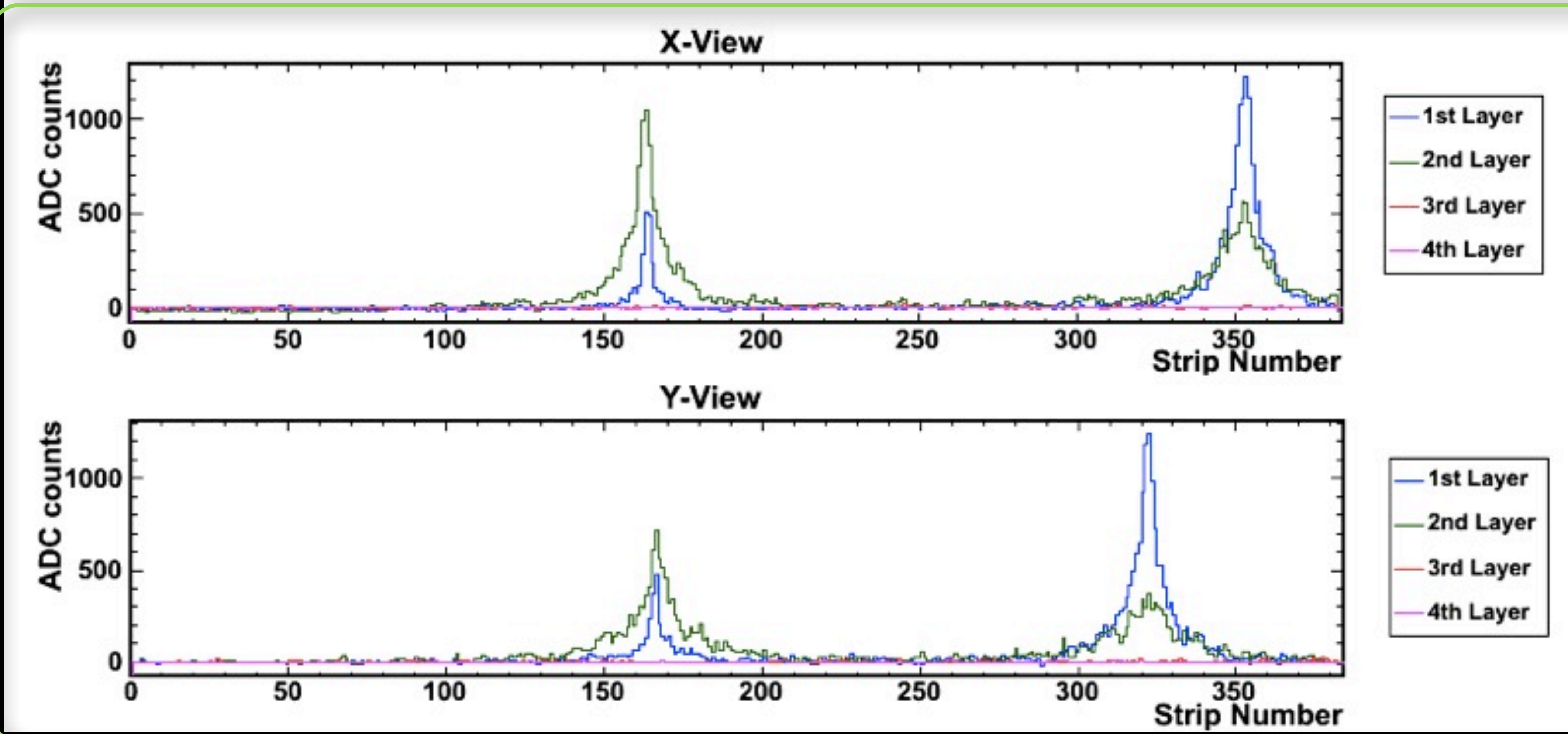
Conclusions

- The 1st phase data at $\sqrt{s}$=7TeV was analyzed in which gamma-like events are focused on.
- Overall good agreement in spectra btw. two independent detectors and analyses.
- Combined photon spectra concluded no hadronic interaction model perfectly reproduce the LHCf measurement.

Event example(Arm2)



Longitudinal development

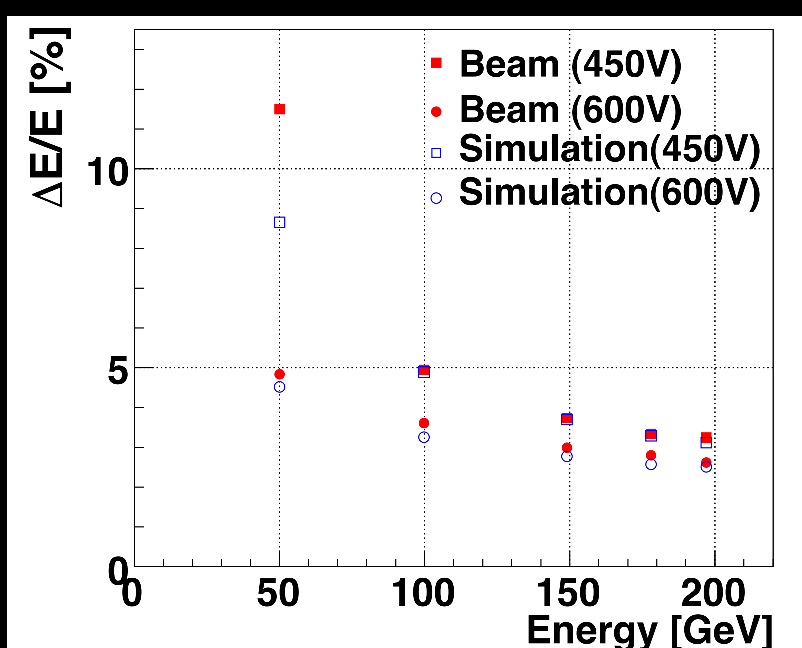


Transverse development

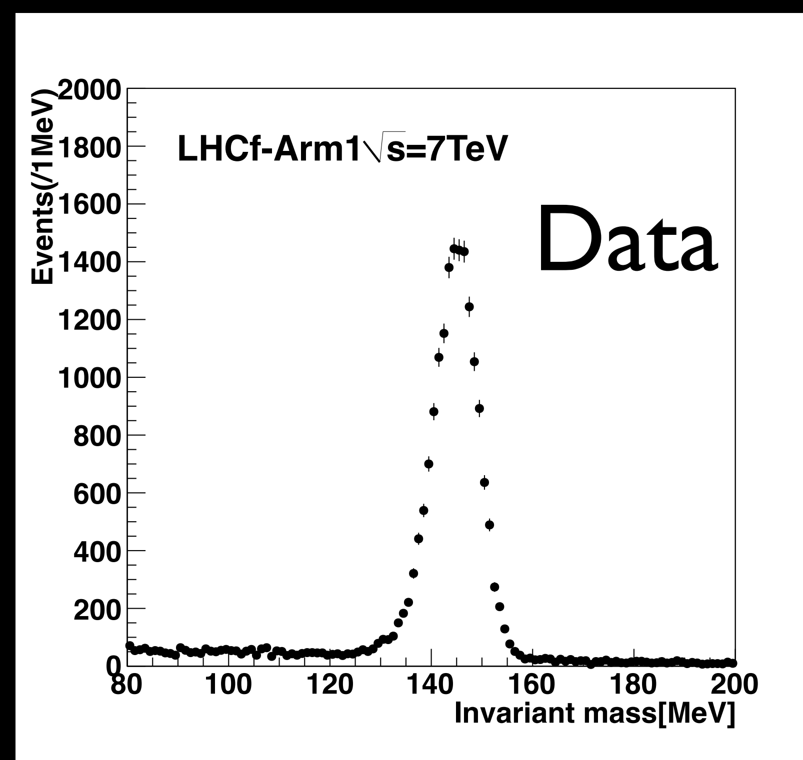
SYST. ERROR(ENERGY SCALE)

Syst. Error (Energy scale)

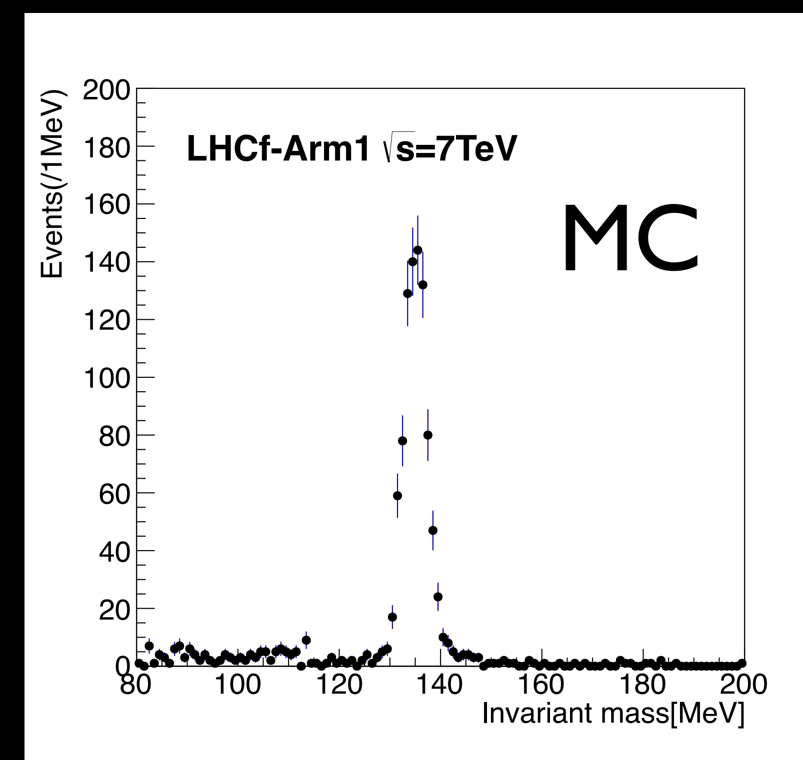
= Detector response + π^0 mass



Total : +/-3.5%



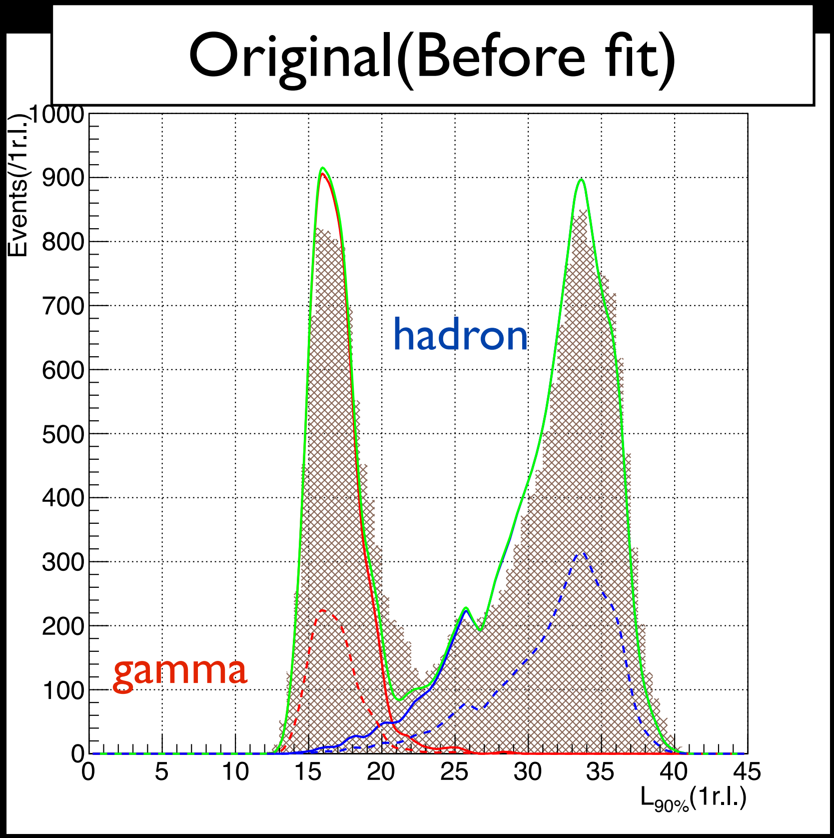
$\langle M_{\pi 0} \rangle$ = 145.8MeV



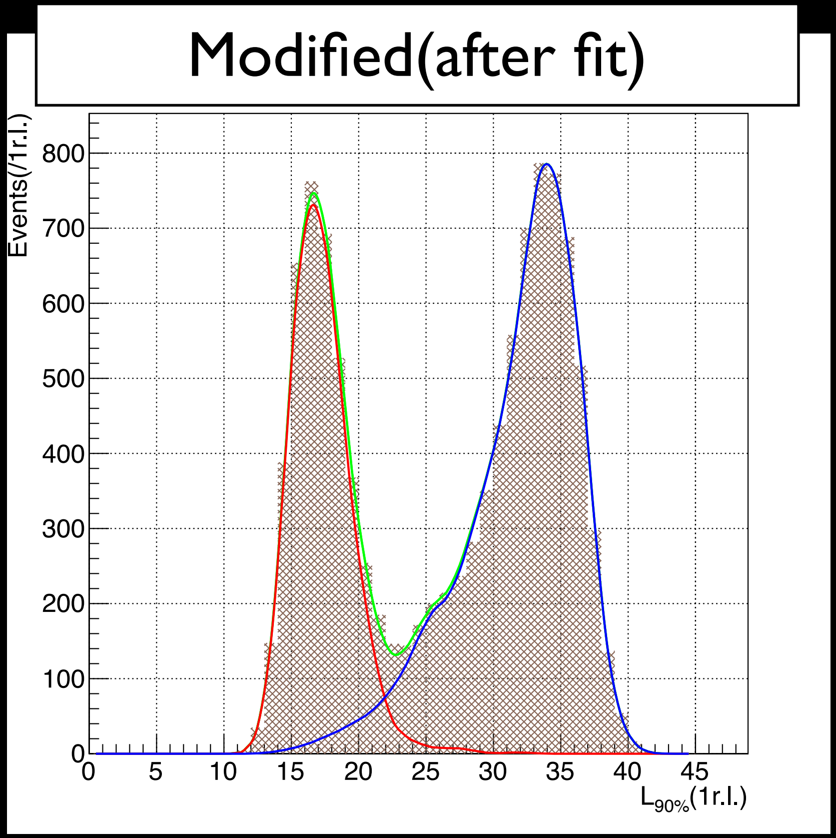
$\langle M_{\pi 0} \rangle$ = 135.2MeV

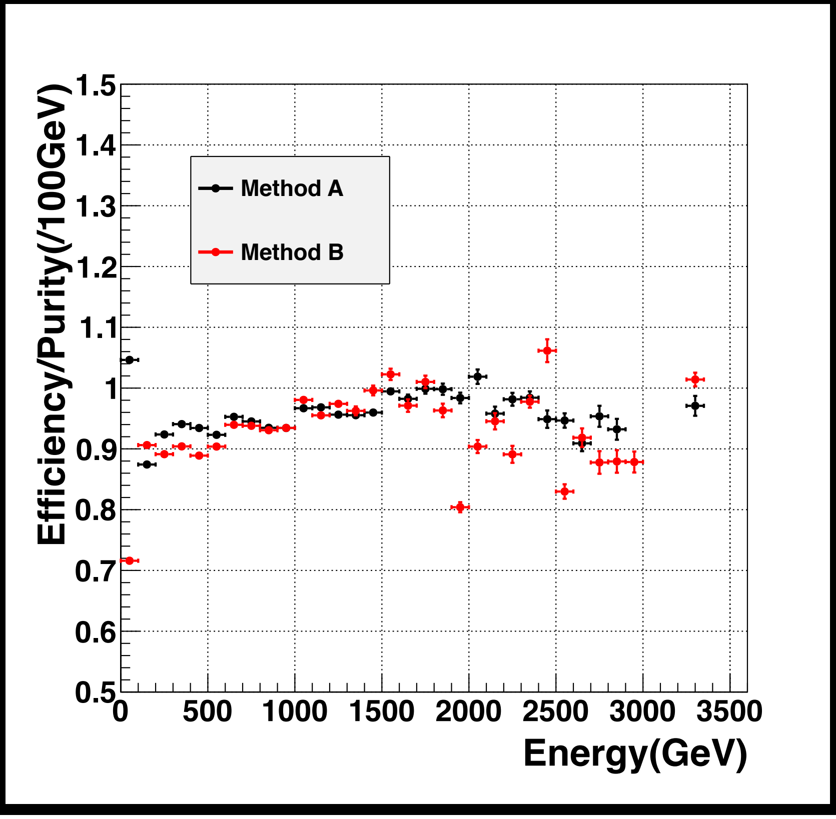
145.8/135.2 = 7.8%(Arm1)
140.0/135.0 = 3.7%(Arm2)

SYST. ERROR (PID)



Fit the template MC (poor man's PDF) to data to get free parameters

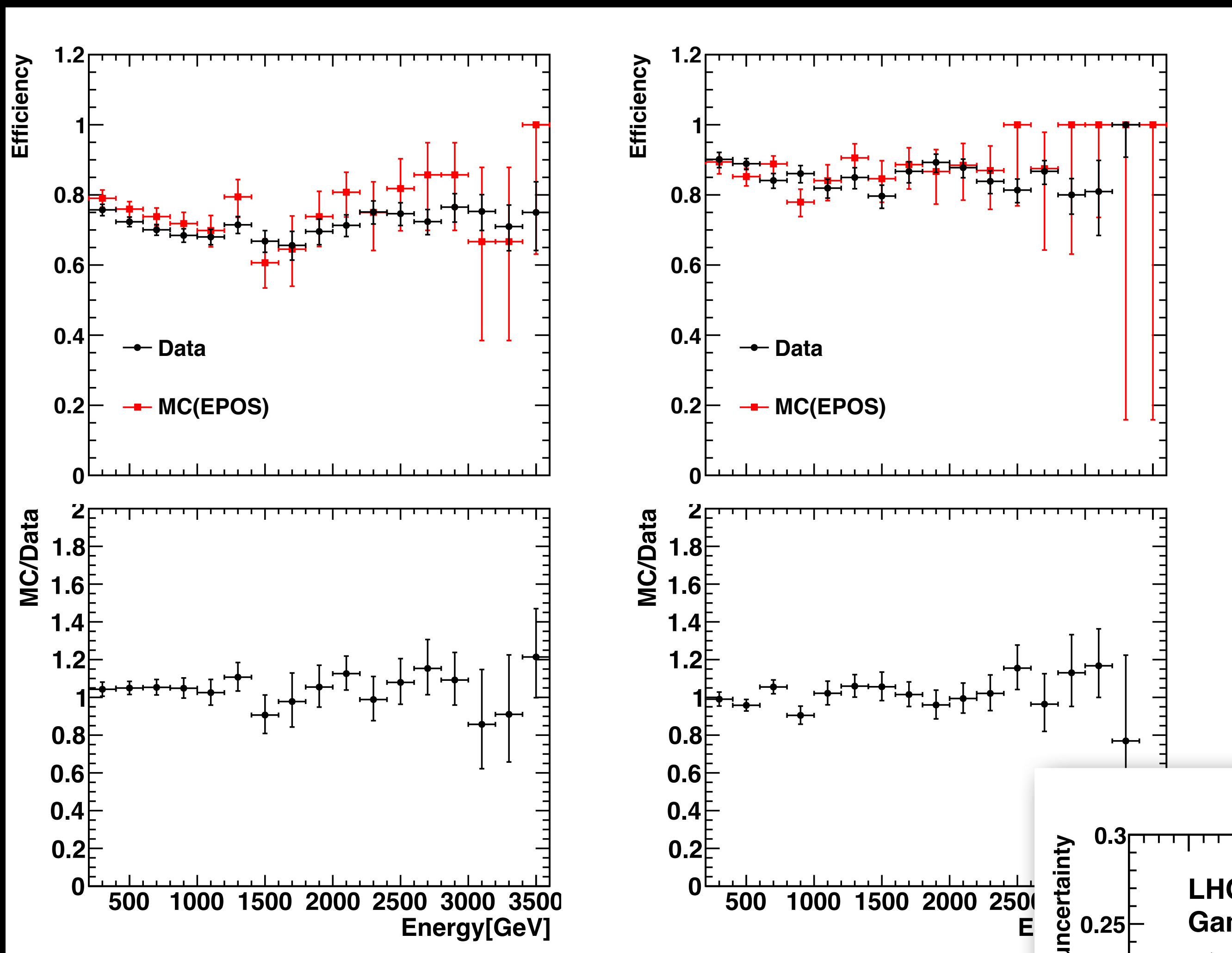




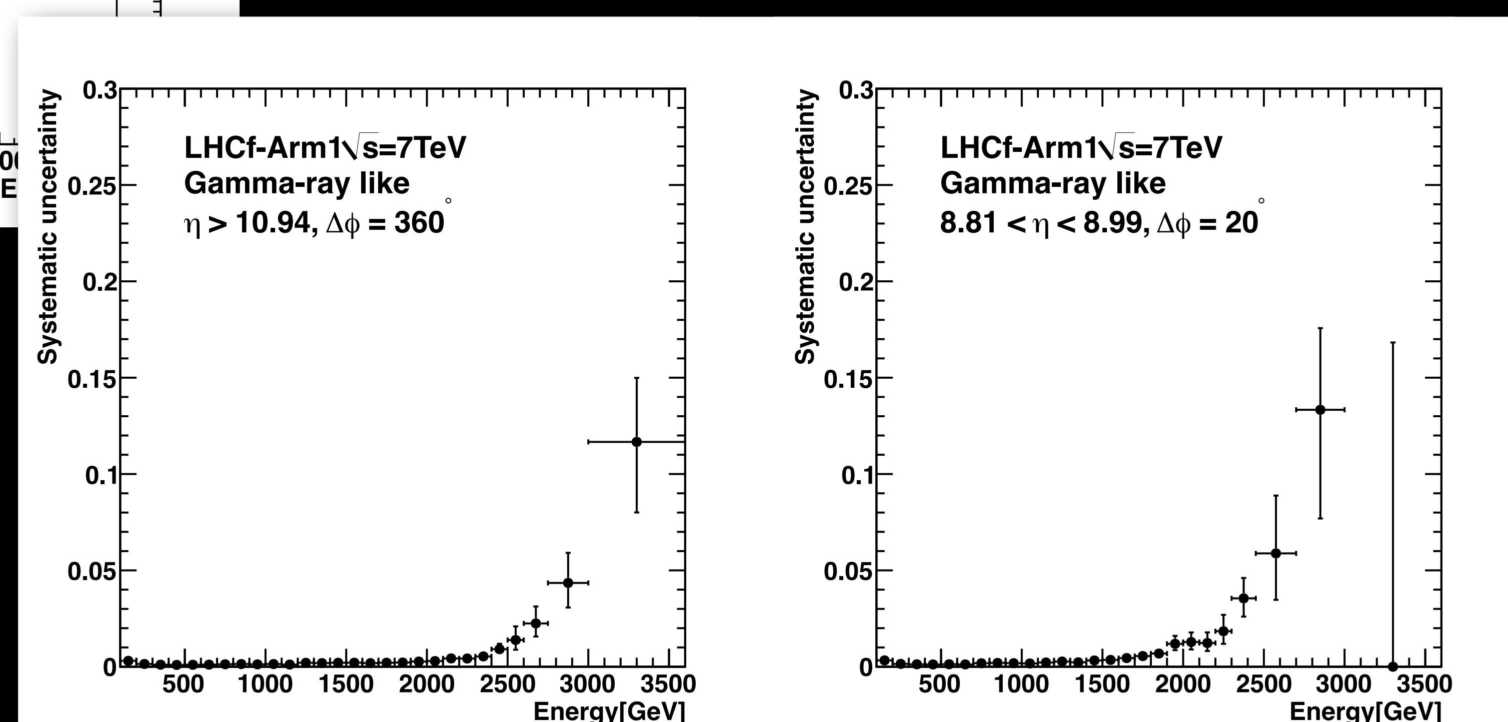
Difference of efficiency/purity between before and after fit => syst. error.

E<2TeV : 5%
E>2TeV : 20%

SYST. ERROR (SINGLE-HIT SELECTION)



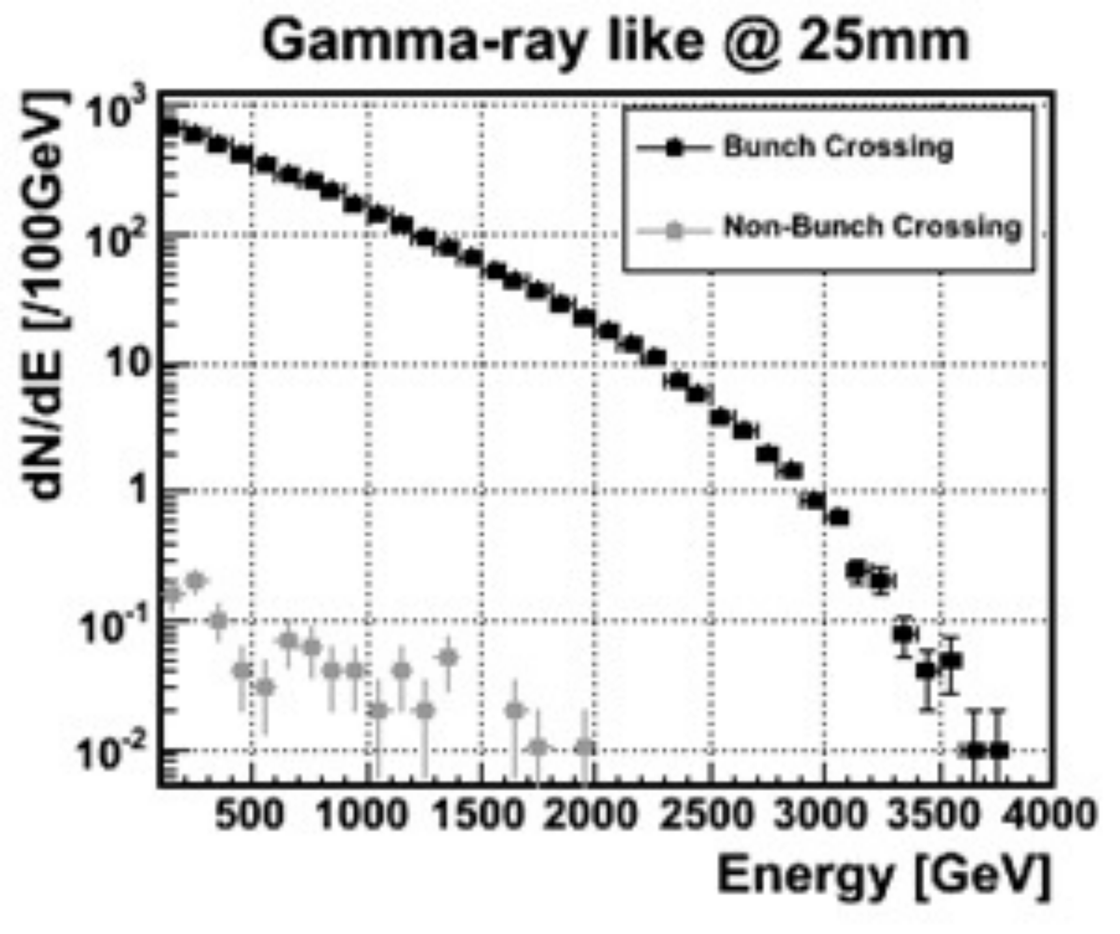
Multi-hit selection efficiency difference btw. data and MC = syst. error for multi-hits



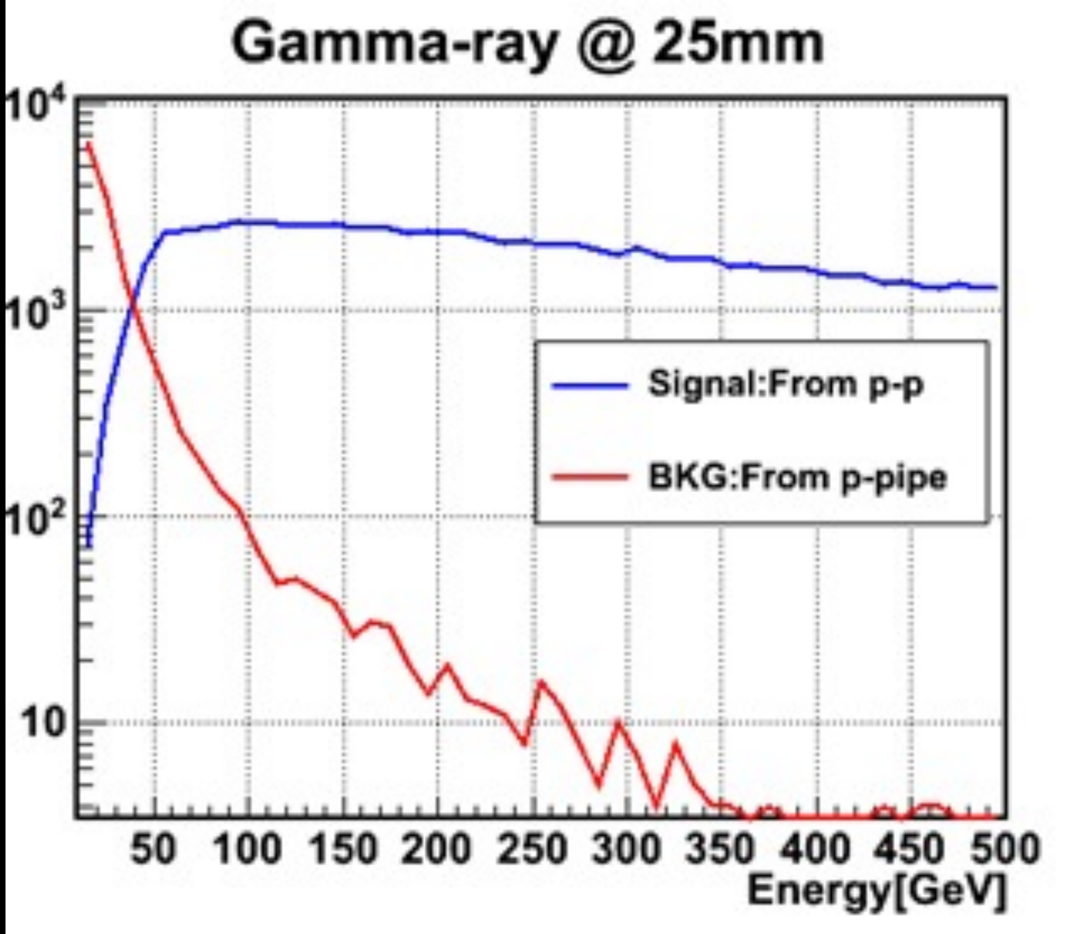
Syst. error for single-hits = syst. error for multi-hits x N_{multi}/N_{total}.

PILEUP/BEAM-PIPE/GAS

Crossing vs. non-crossing bunches

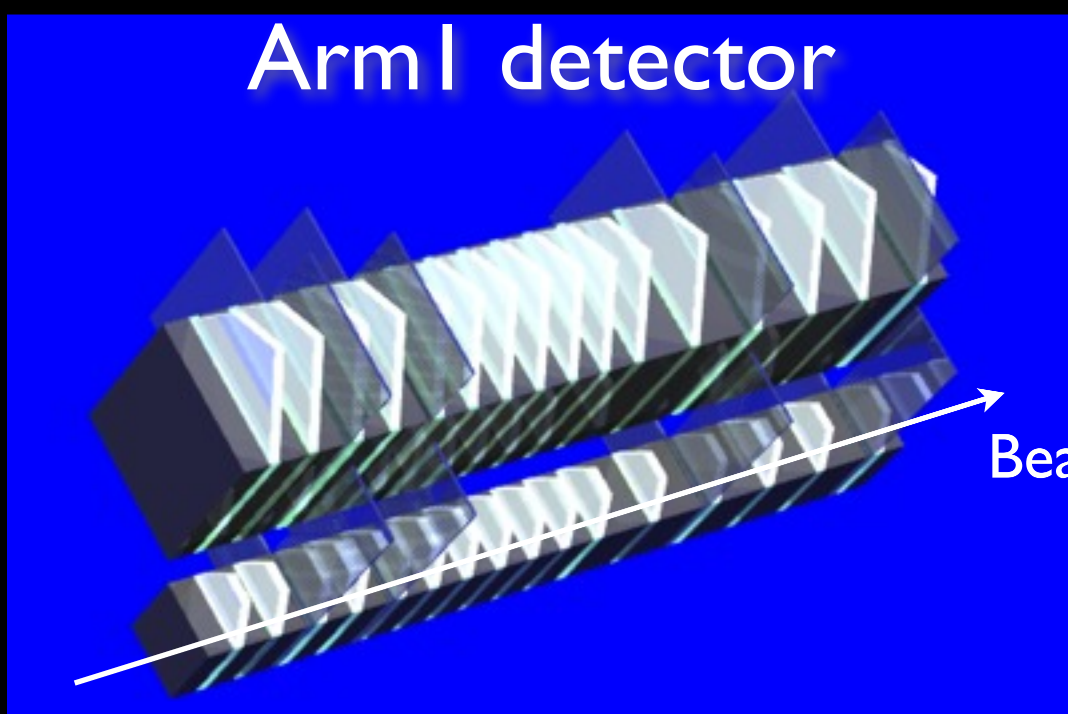


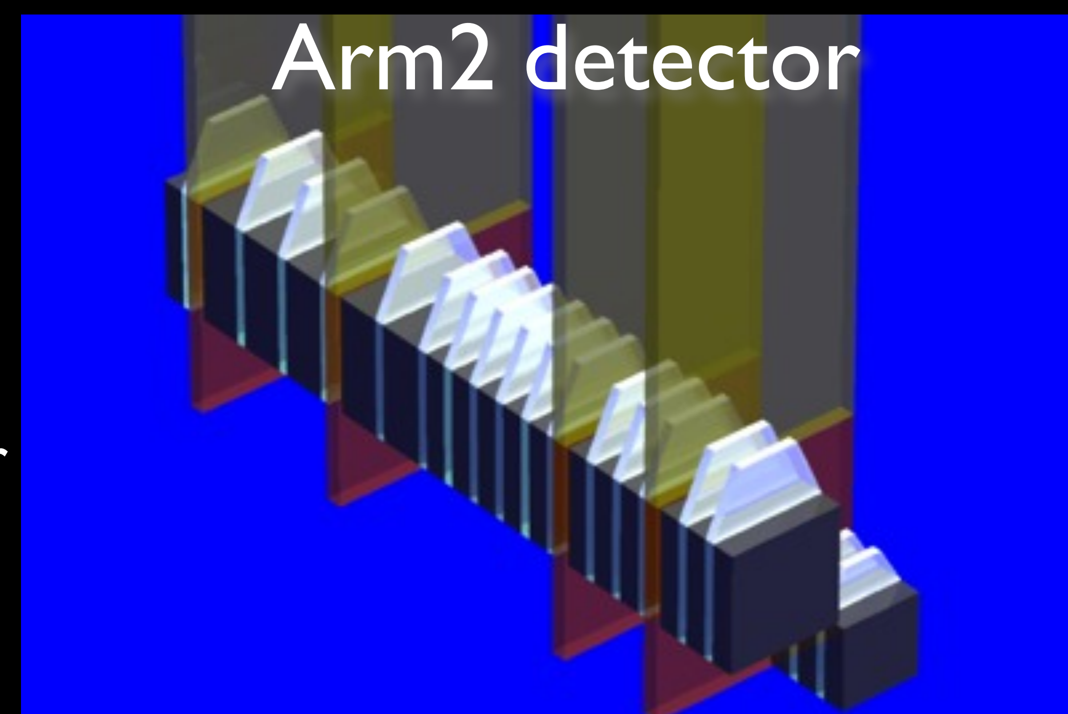
Direct vs beam-pipe photons



The LHCf detector

- Sampling & imaging calorimeters either side of IP1.
- Two compact towers in both detectors.
  - Tungsten absorbers: 44r.l., 1.7λ
  - 16 plastic scintillator sampling layers
  - 4 position sensitive layers





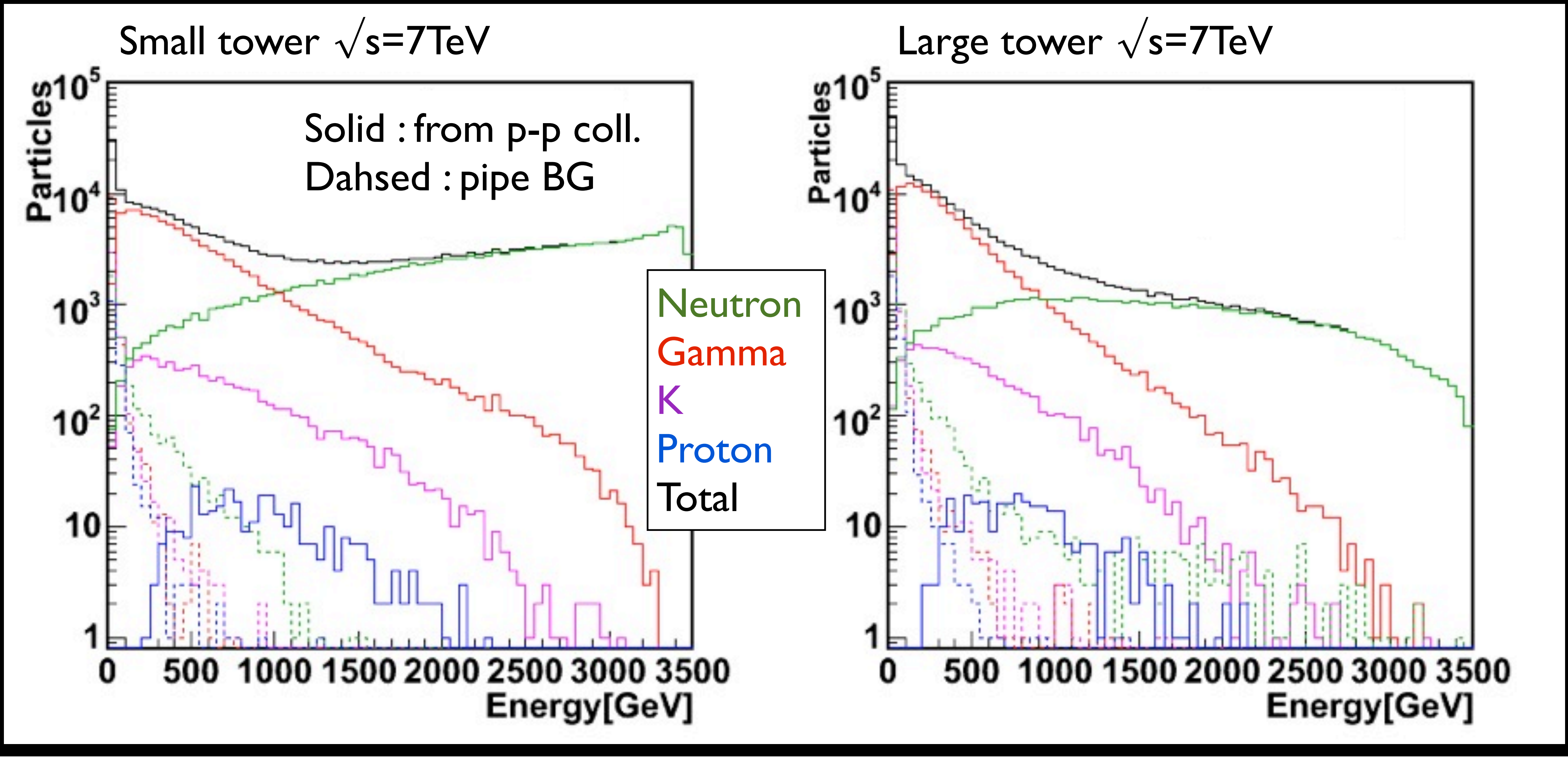
20mmx20mm + 40mmx40mm
Consists of scintillation fibers
Located at 6, 10, 30, 42 r.l.

25mmx25mm + 32mmx32mm
Consists of silicon strip detector
Located at 6, 12, 30, 42 r.l.

Expected spectra

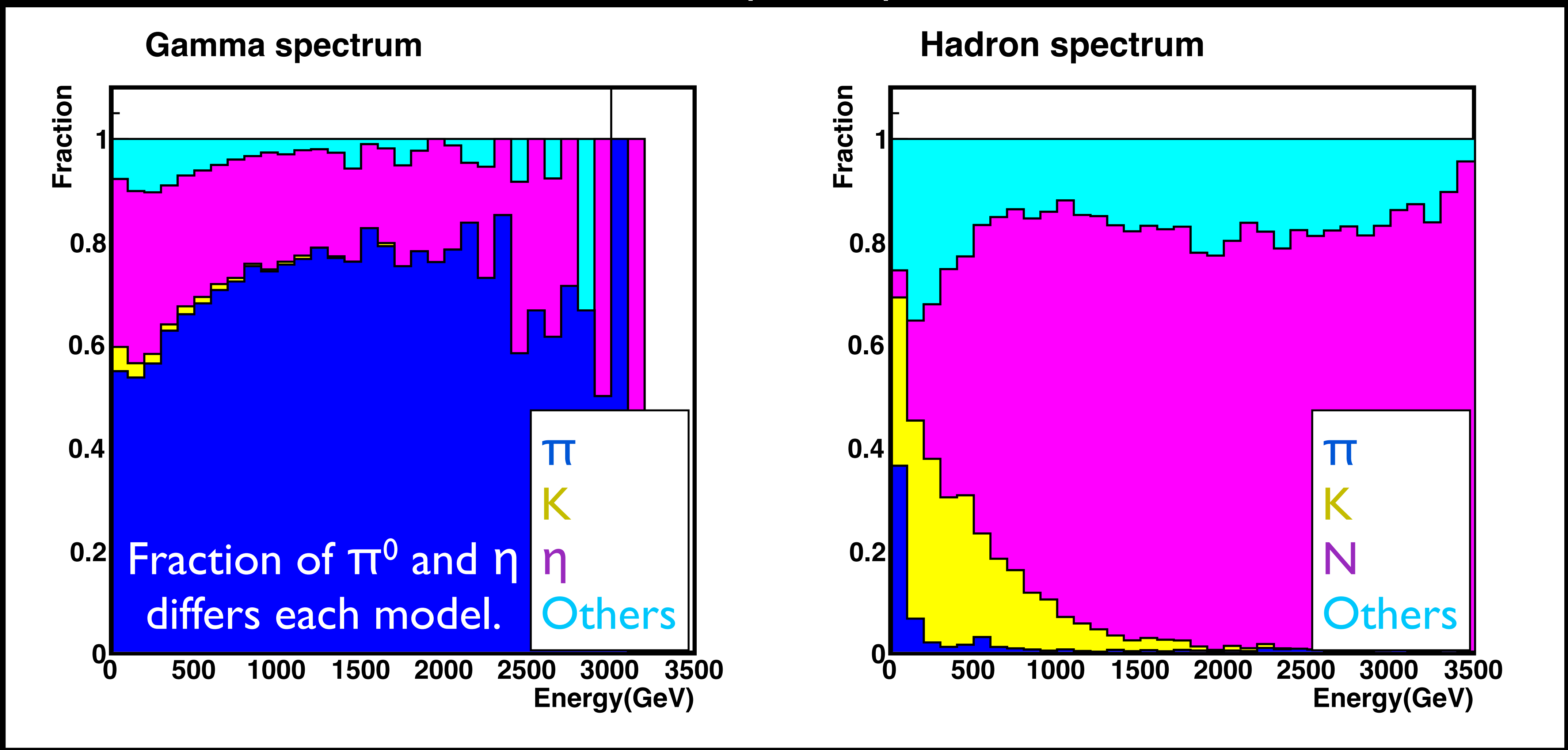
All figures assume
10^7 collisions@$\sqrt{s}$=7TeV

- Spectrum in the forward region at 140m away from IP1 (i.e. LHCf site).
- No detector simulation is applied.
- Neutron/Gamma ratio is also important from the cosmic-ray point of view.

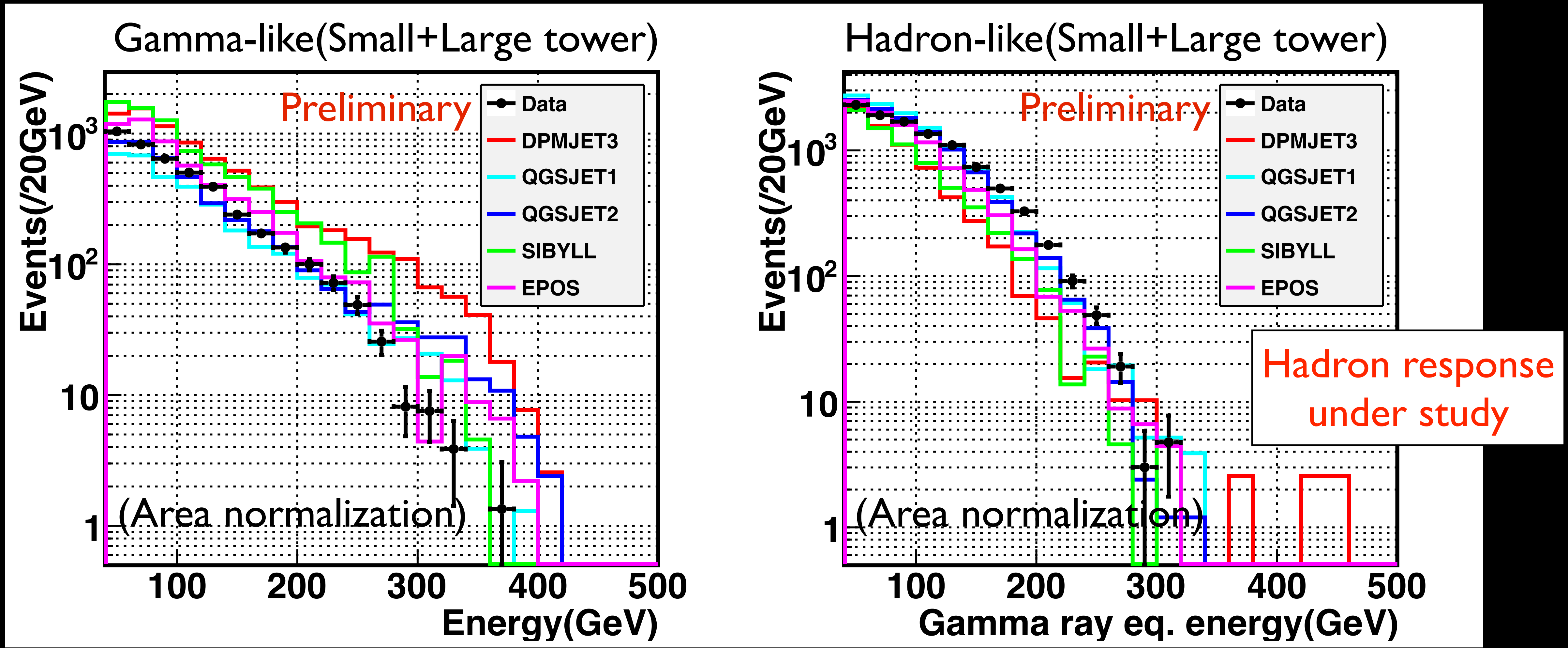


Description in Sibyll

Fraction of parent particles

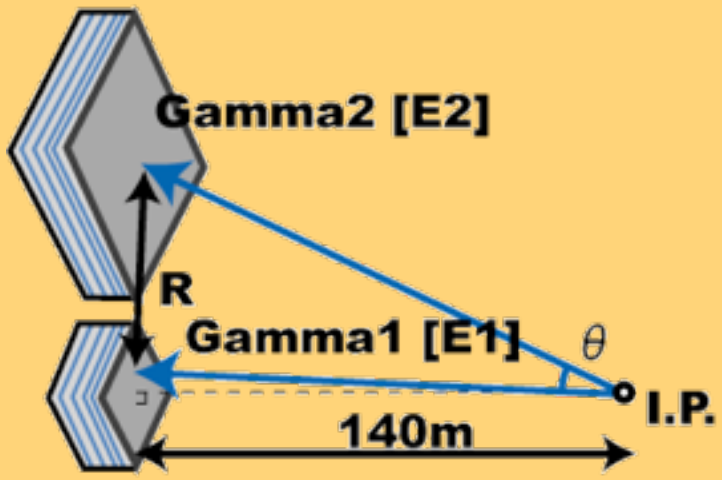


Spectra at $\sqrt{s}$=900GeV



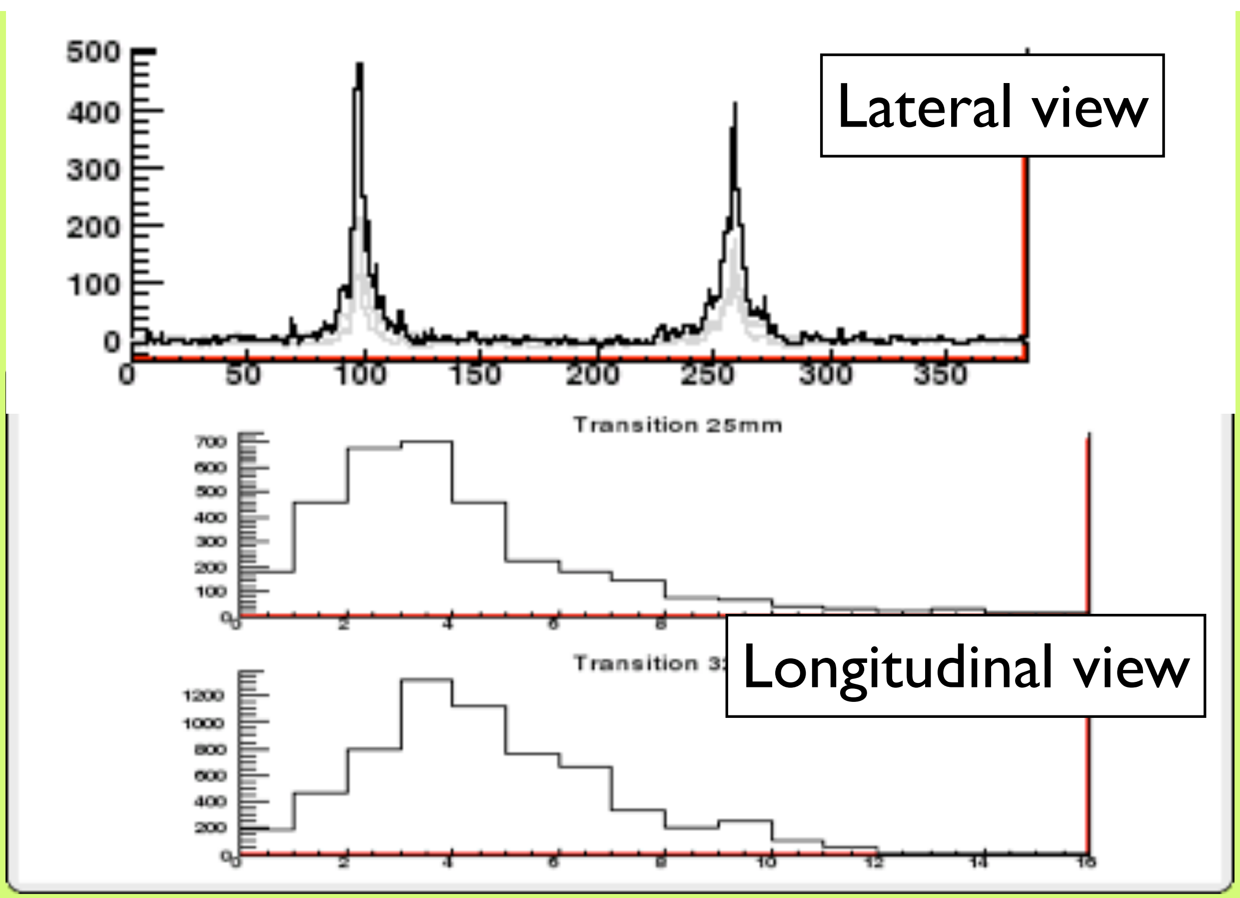
- Focusing on only shape Sibyll seems better agreement, while QGSJET2 has similar gamma/hadron ratio with data.
- For the moment very conservative systematic uncertainty must be taken into account for energy scale +10%-2% both for gamma and hadron-like events.
- We'll soon back to $\sqrt{s}$=900GeV data analysis.

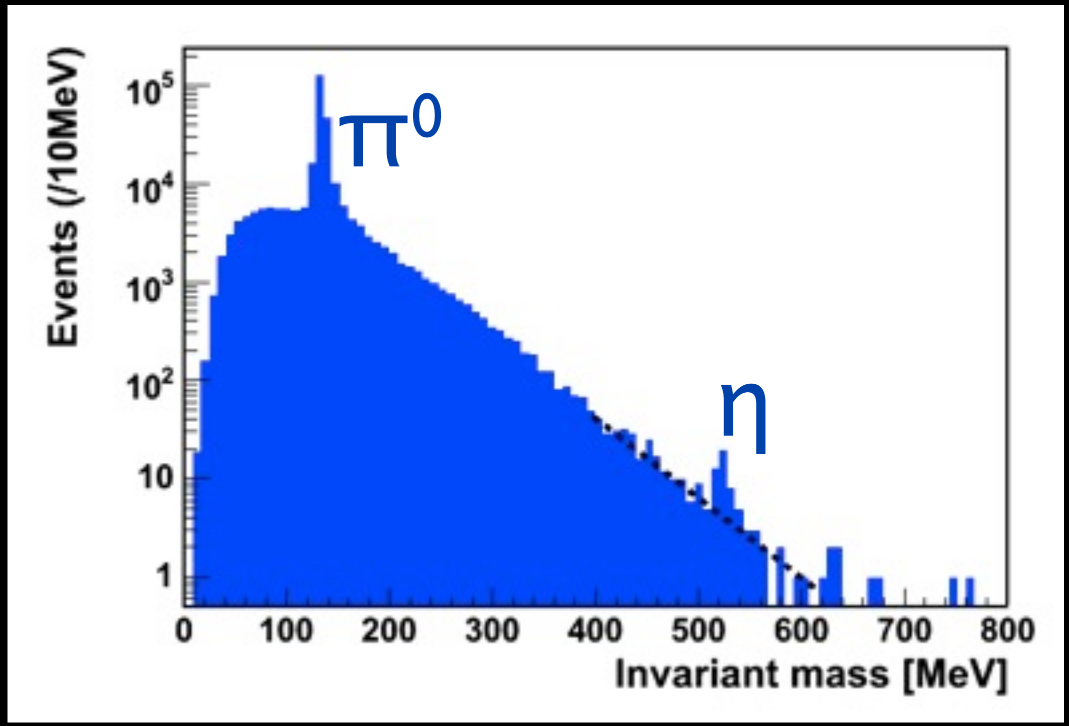
π^0 measurement

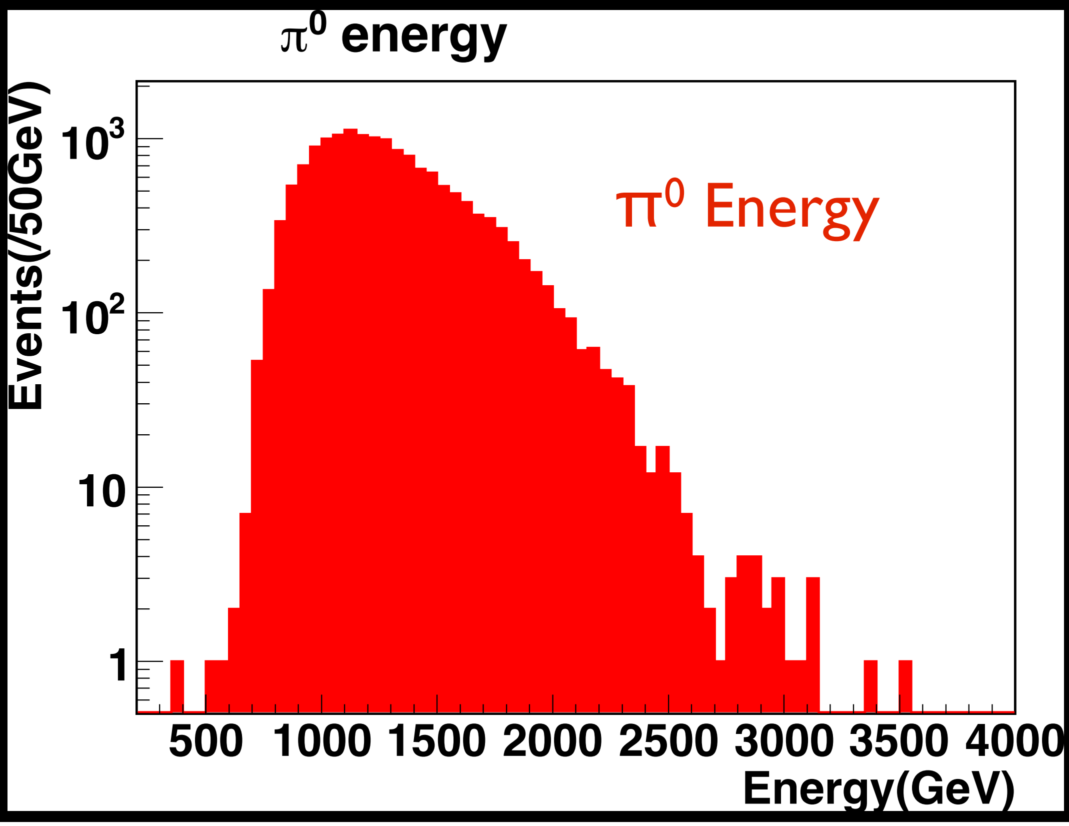


$$\theta = \frac{R}{140\text{m}}$$

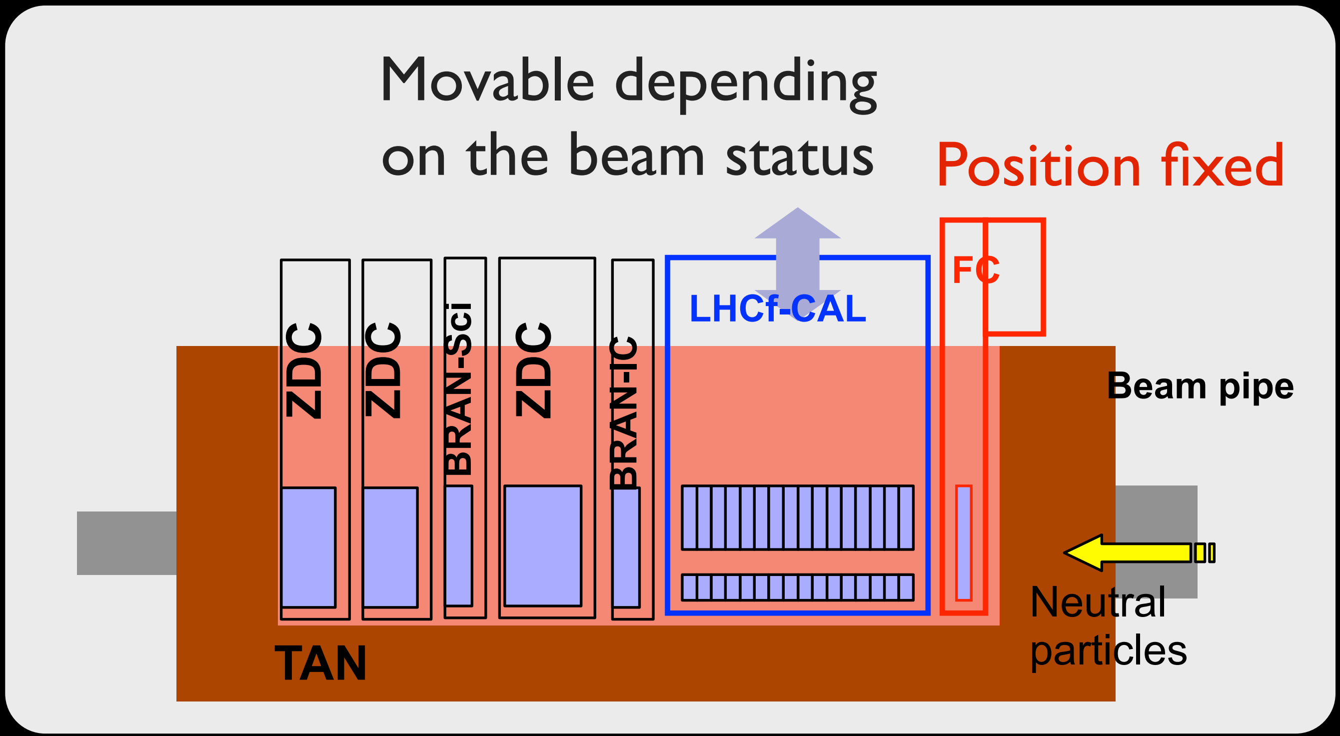
Event display of π^0(2-gamma)





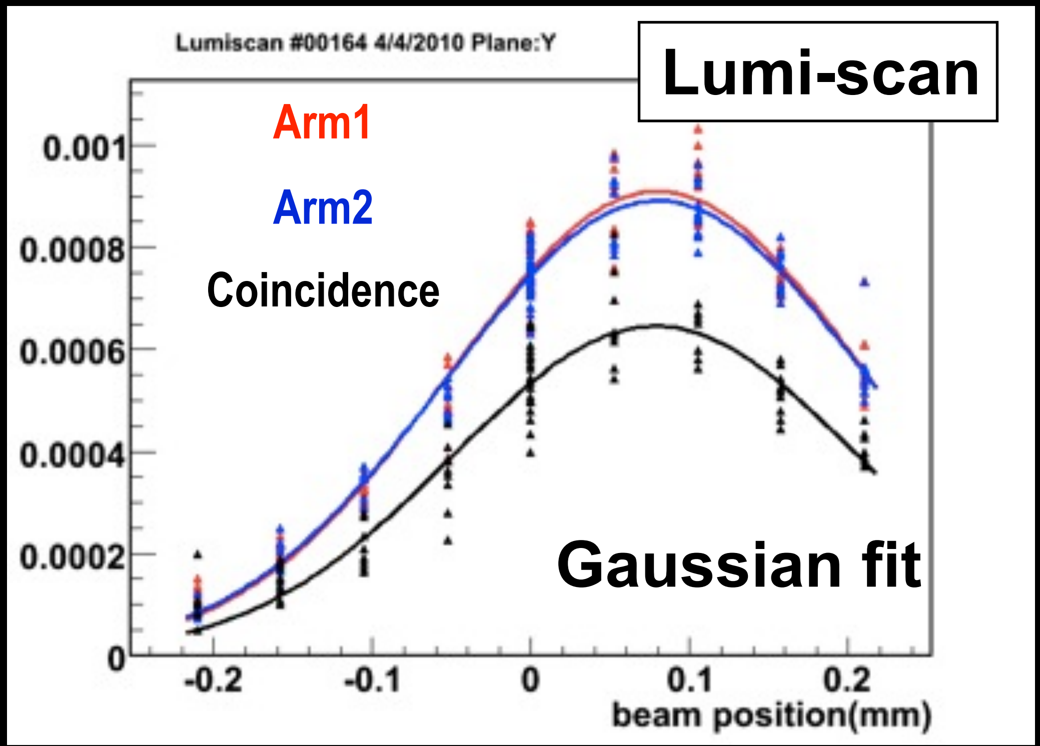


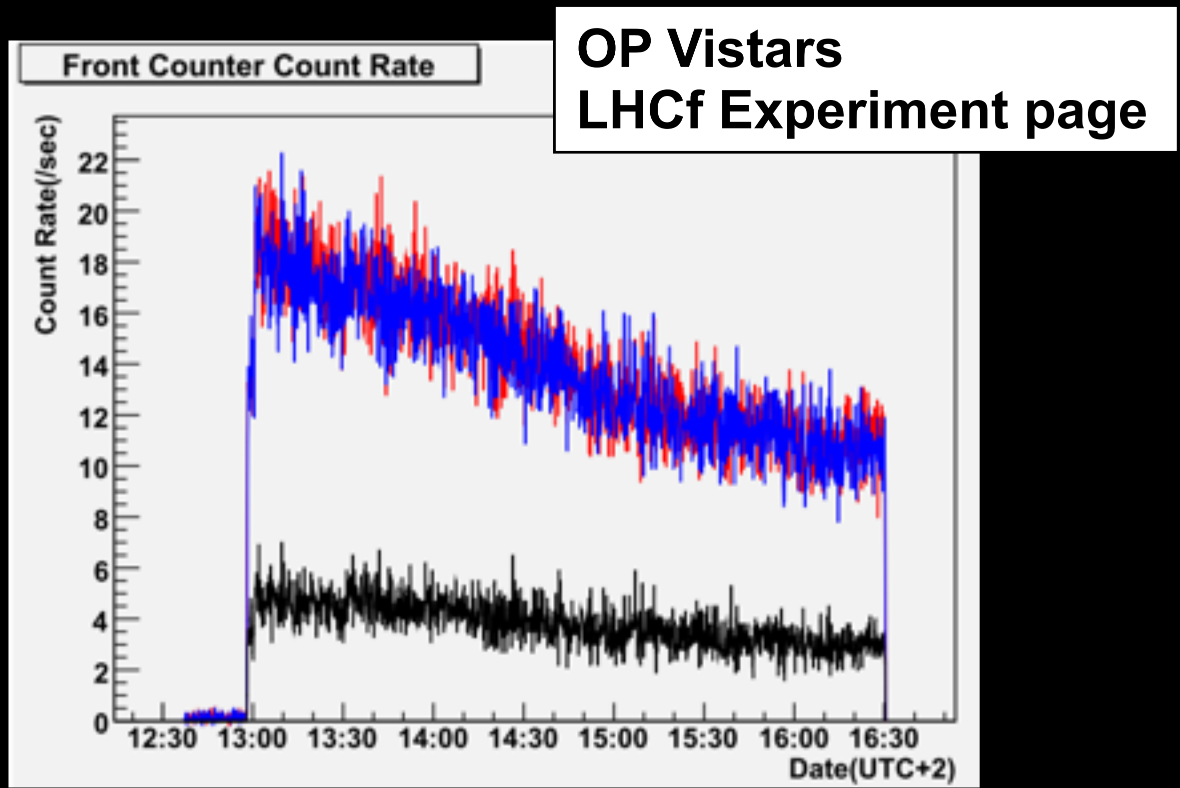
Front Counter



Front counter...

- consists of 4 scintillation counters, 2 for X and 2 for Y.
- has large aperture(80mmx80mm).
- can work prior to the stable beam declaration.
- acts as the luminosity monitor and beam-gas BG monitor.

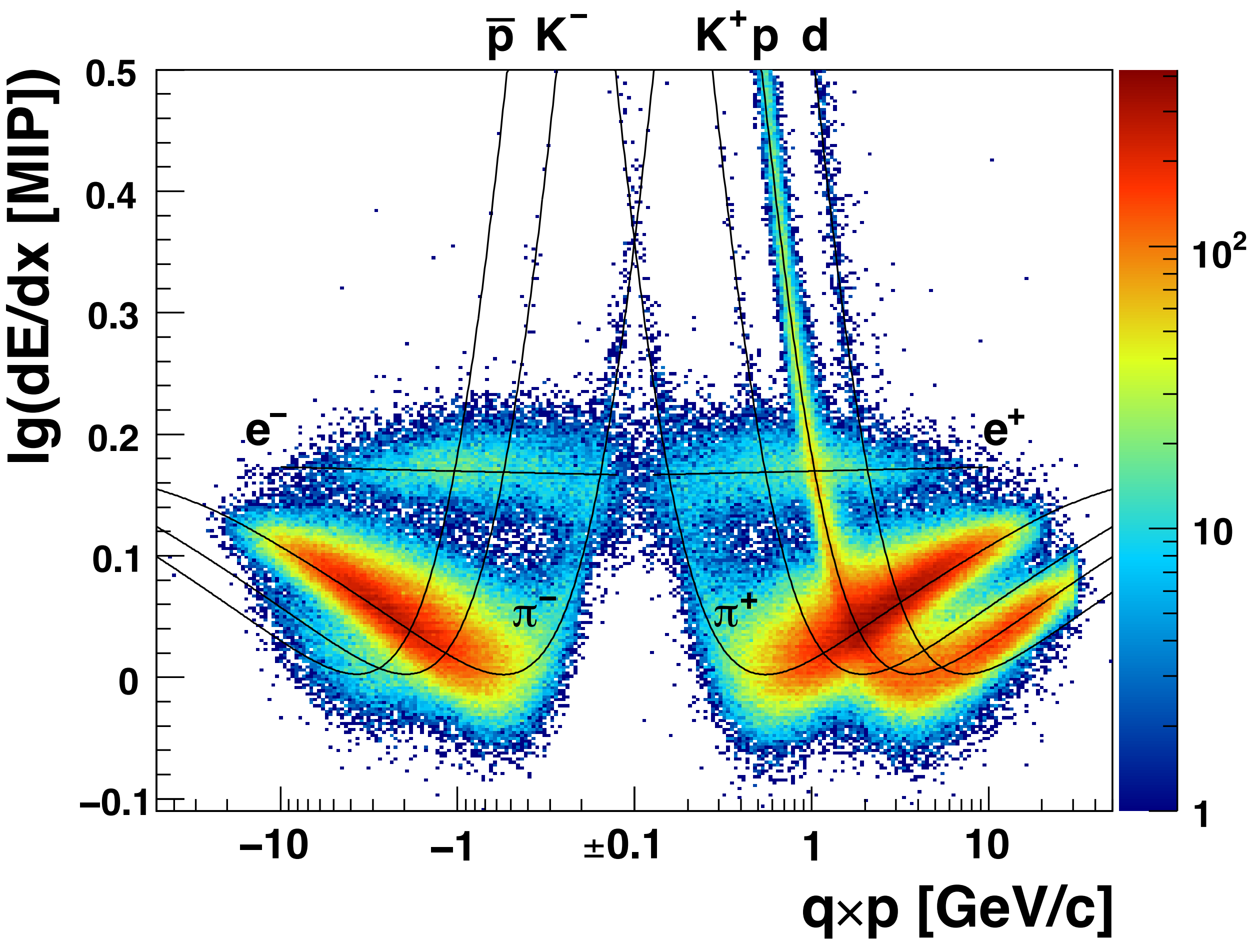




NA61

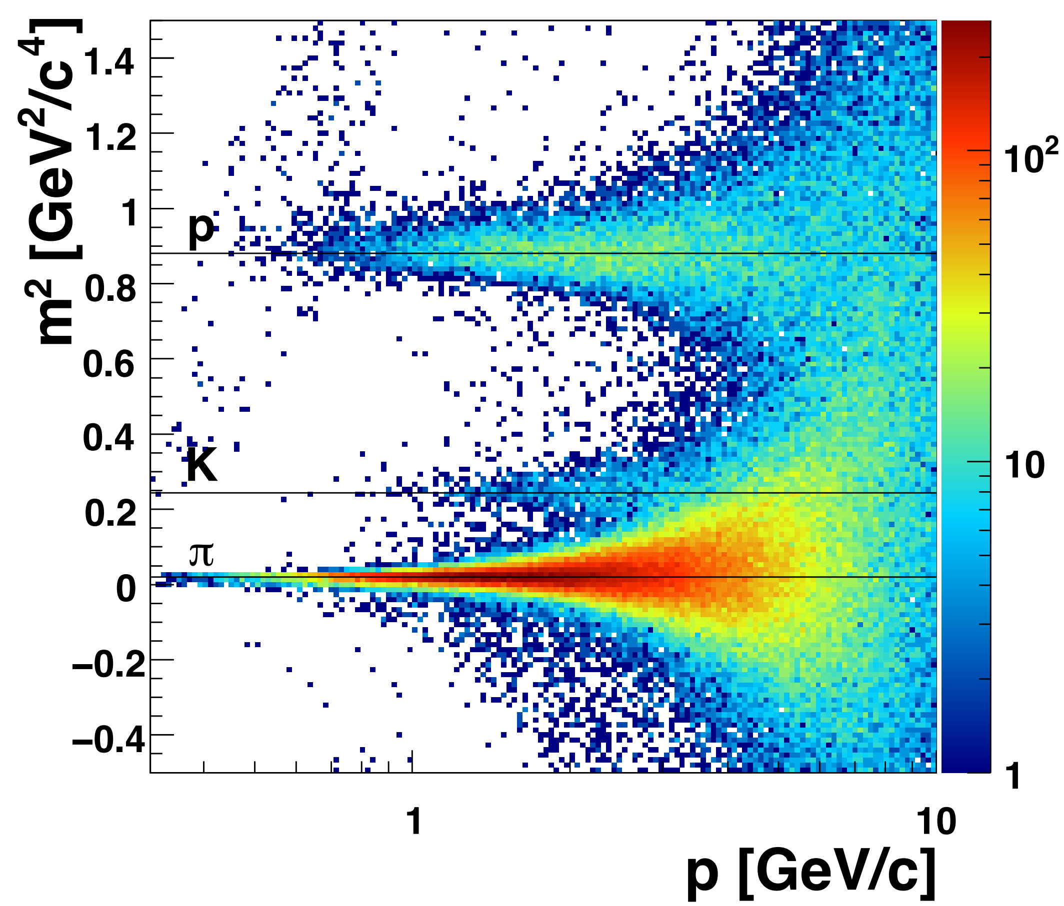
Particle Identification

energy deposit in TPC:



$\sigma\left(\frac{dE}{dx}\right)/\frac{dE}{dx} \approx 4\%$

time of flight:

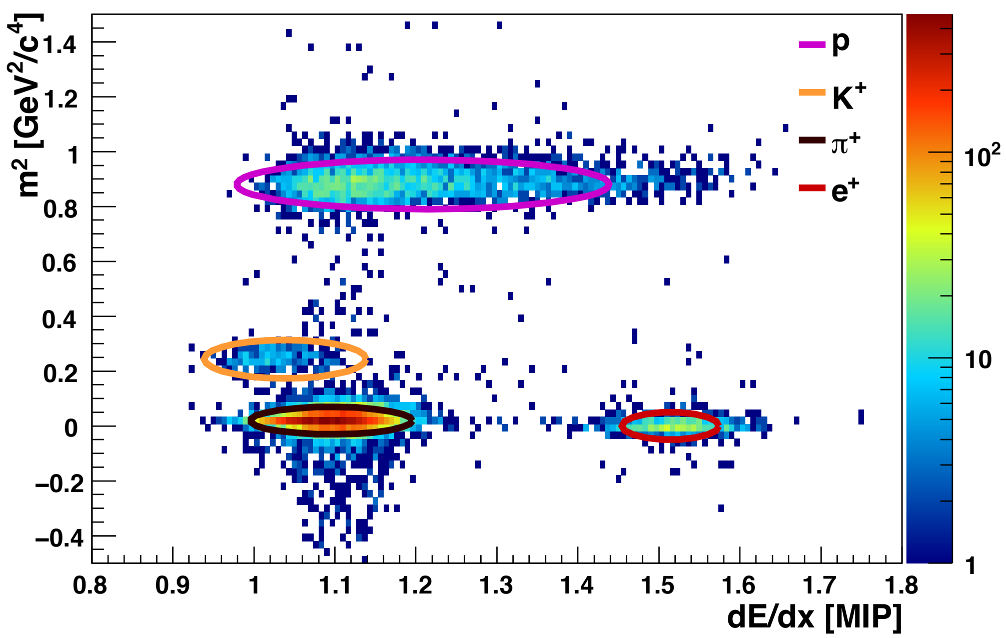


$\sigma(t) \approx 100\,\mathrm{ps}$

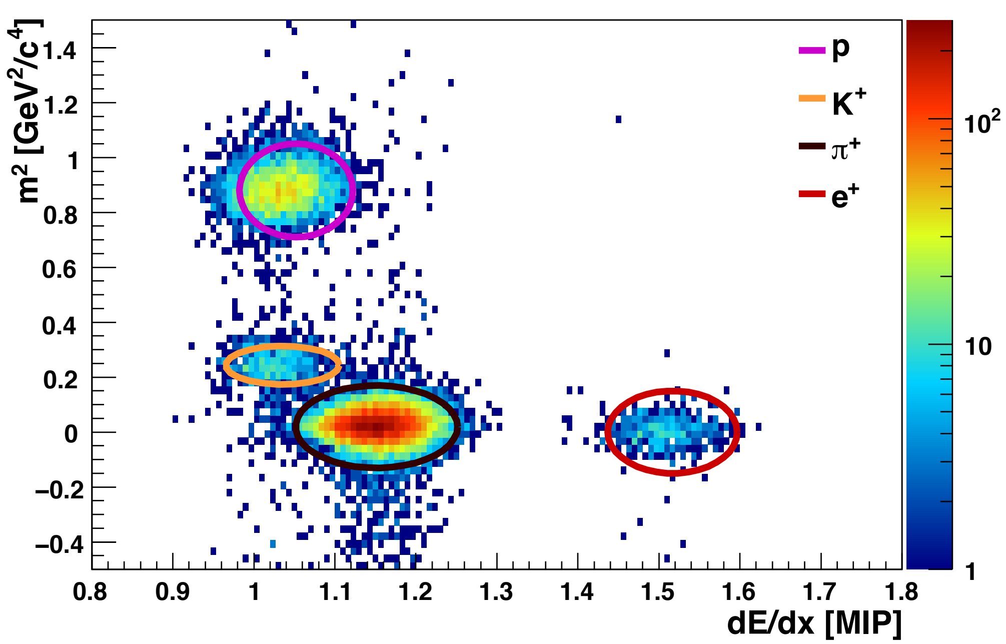
data from 2007 NA61 pilot run (p+C at 31 GeV/c)

Particle Identification

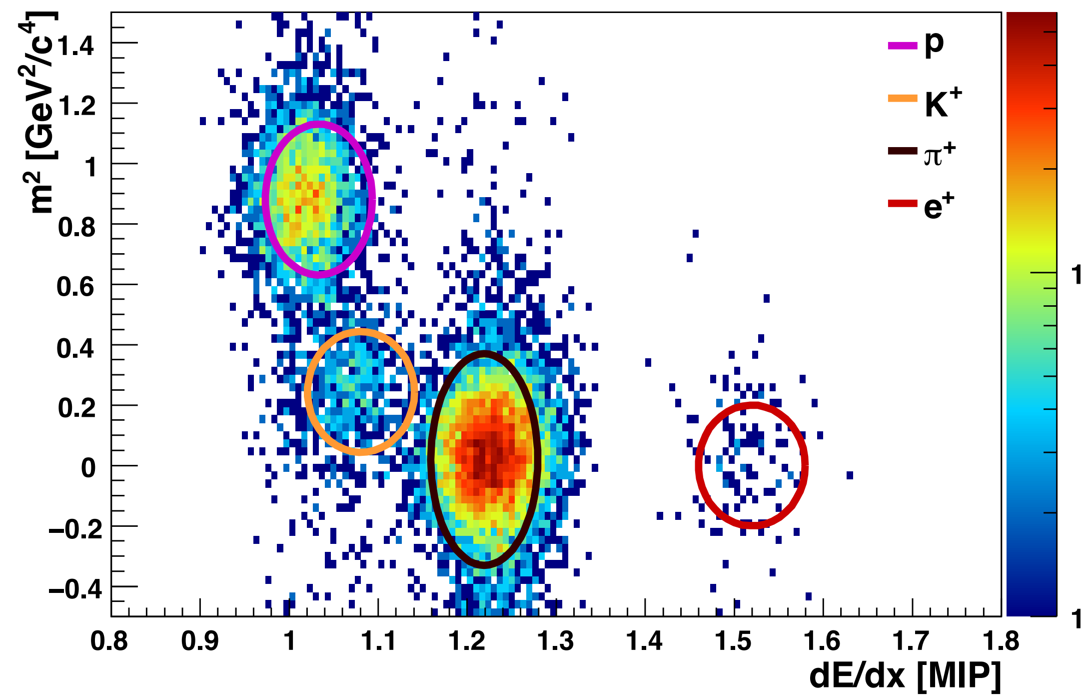
1 GeV/c < p < 2 GeV/c

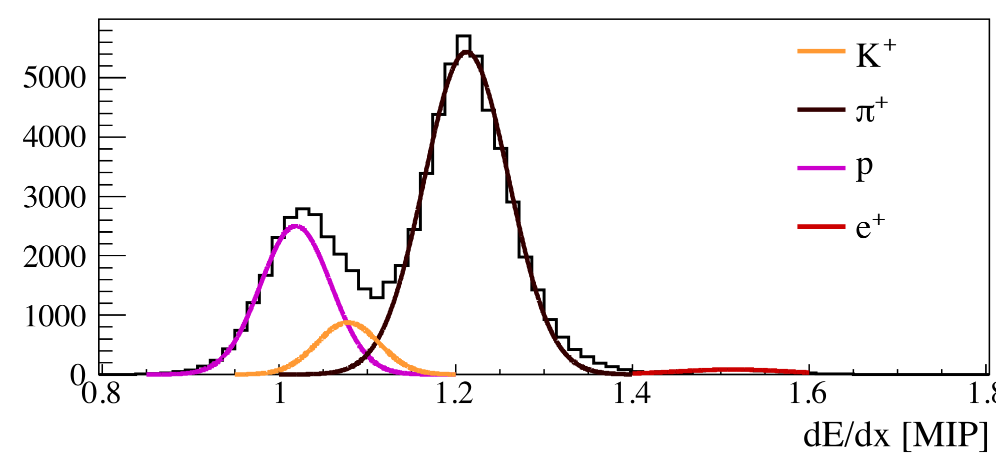


2 GeV/c < p < 3 GeV/c



4 GeV/c < p < 5 GeV/c





NA61

Analysis of 2007 data (p + C at 31 GeV/c)

three independent analyses:

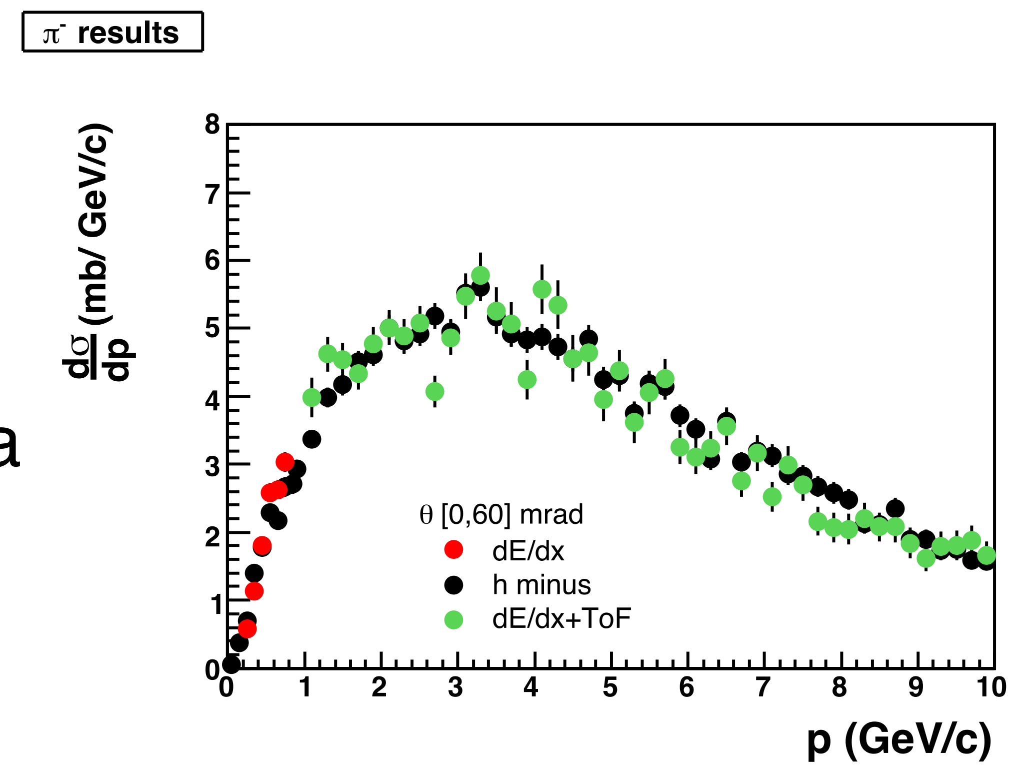
- negative hadrons (model corrected)
- dE/dx-only at low momentum
- dE/dx and TOF at medium momenta

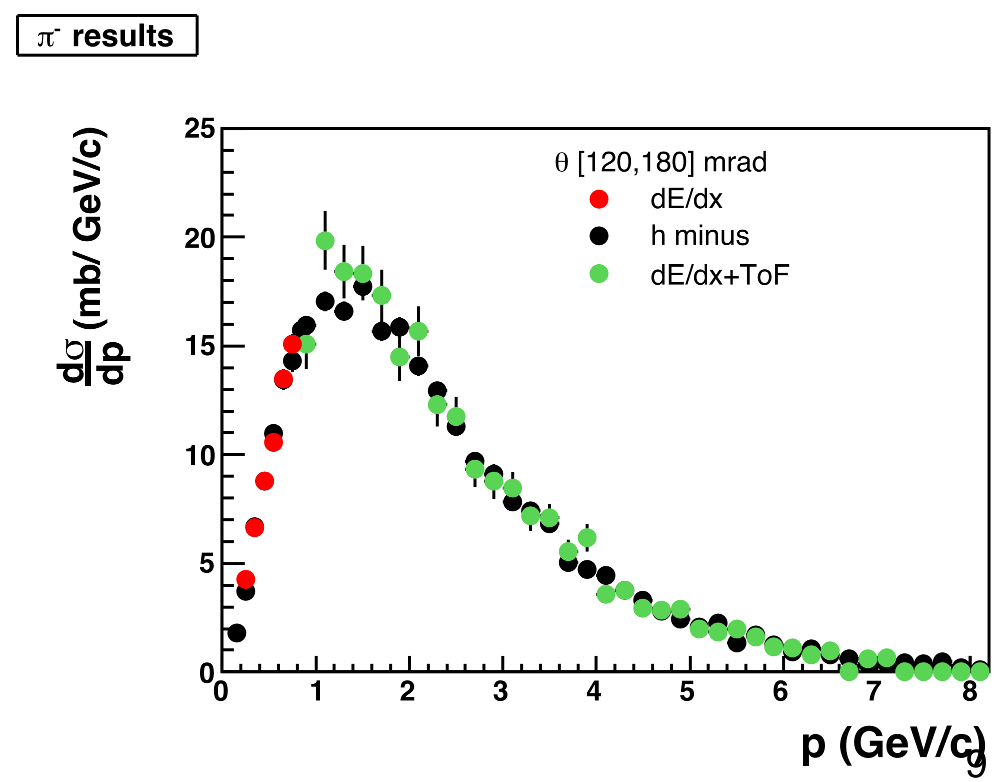
spectrum corrections

- acceptance $\geq$ 99%
- reconstruction efficiency $\geq$ 96%
- pion decay $\leq$ 10%
- feed-down $\leq$ 10%

production cross section:

$$\sigma_{\mathrm{prod}} = 229.3 \pm 1.9 \pm 9.0 \ \mathrm{mb}$$





NA61

Summary

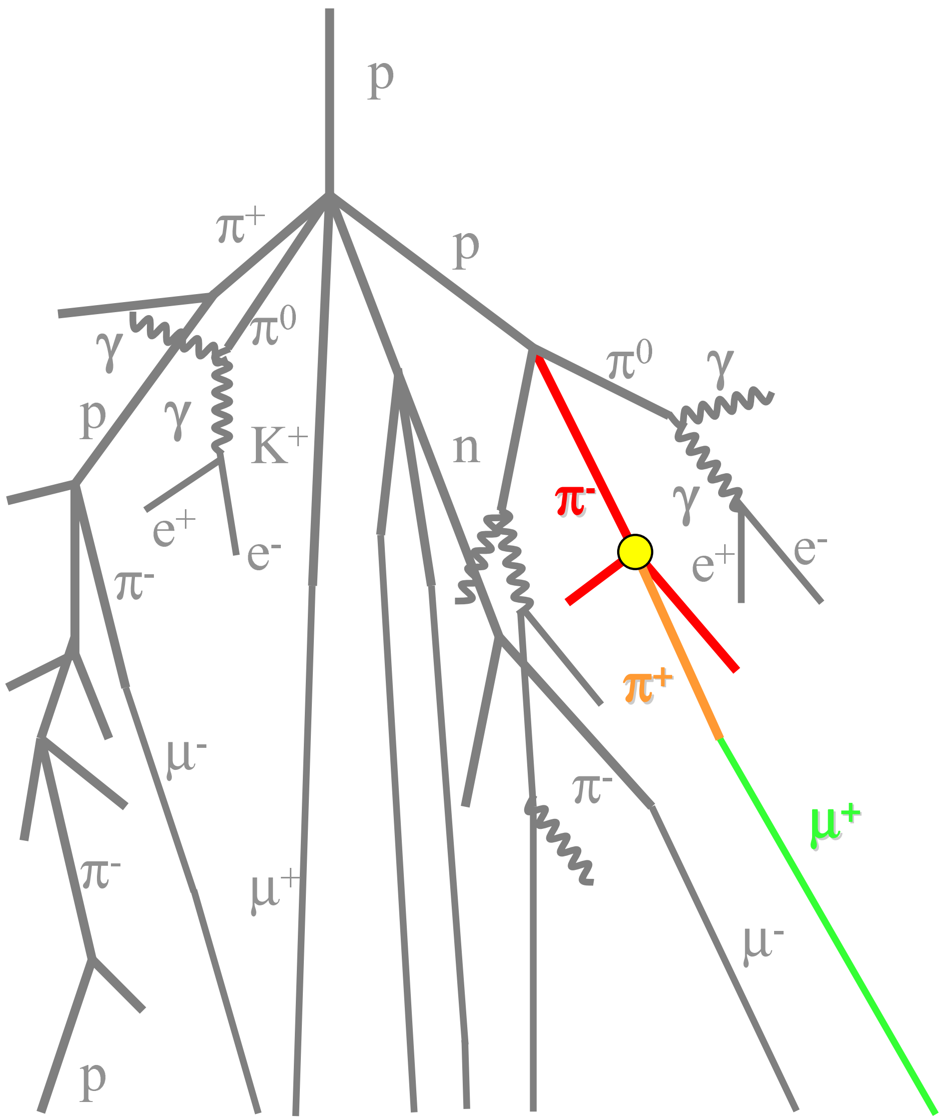
muons in UHE air showers

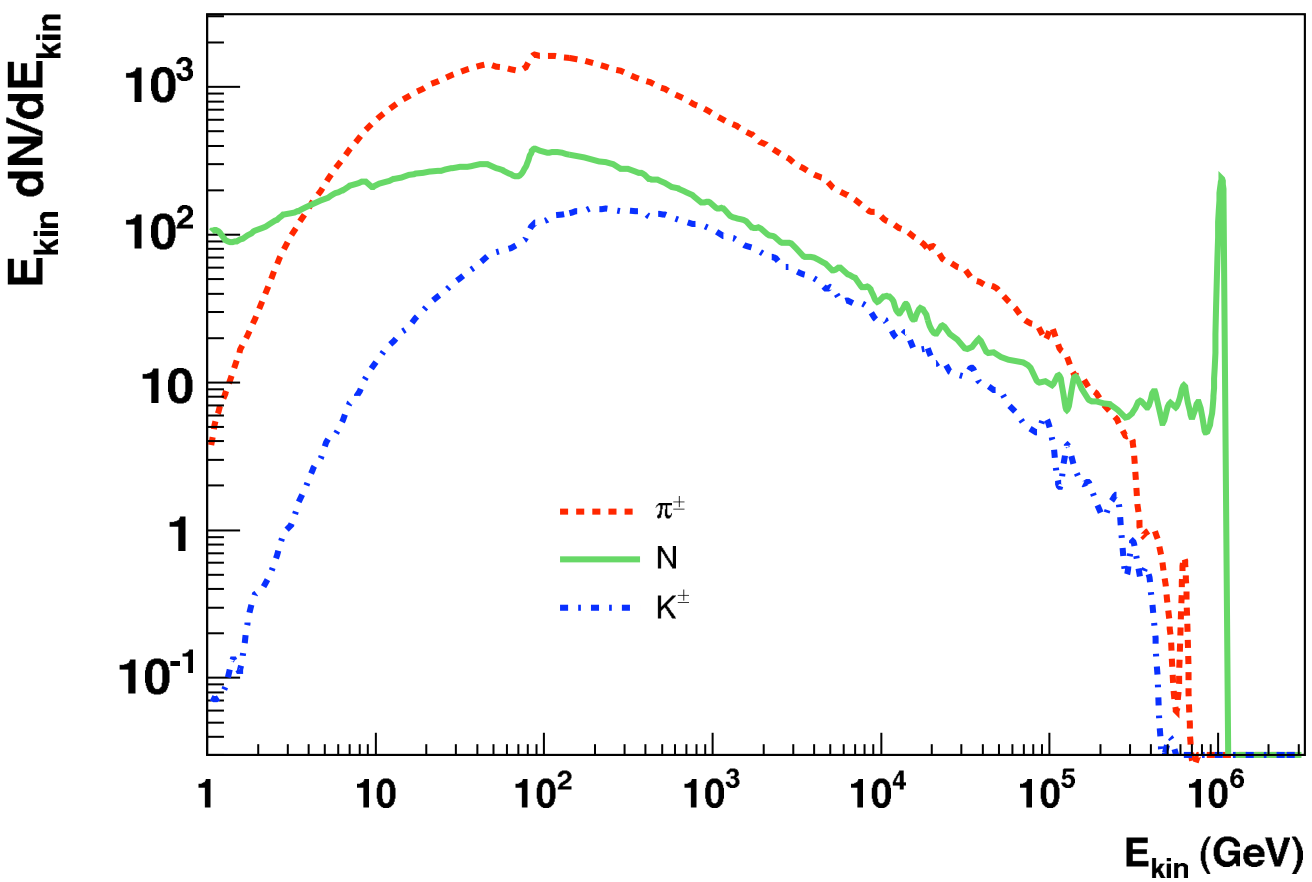
- last interactions at SPS fixed target energies, dominated by pions
- theoretical uncertainties from baryon production

NA61/SHINE

- large acceptance spectrometer with particle ID
- measurement of particle production spectra
- special ’cosmic runs’: π^-+C at 158 and 350 GeV/c
- p+C at 31 and 158 GeV/c
- p+p scan from 13 to 158 GeV/c
- first p+C $\rightarrow \pi^{\pm}$+X spectra at 31 GeV/c
  FLUKA2008 best overall agreement ($\leq$ 20%)
- p+C $\rightarrow$ K$^+$+X at 31 GeV/c publication in preparation

Relevant Interactions in Air Showers for Muon Production

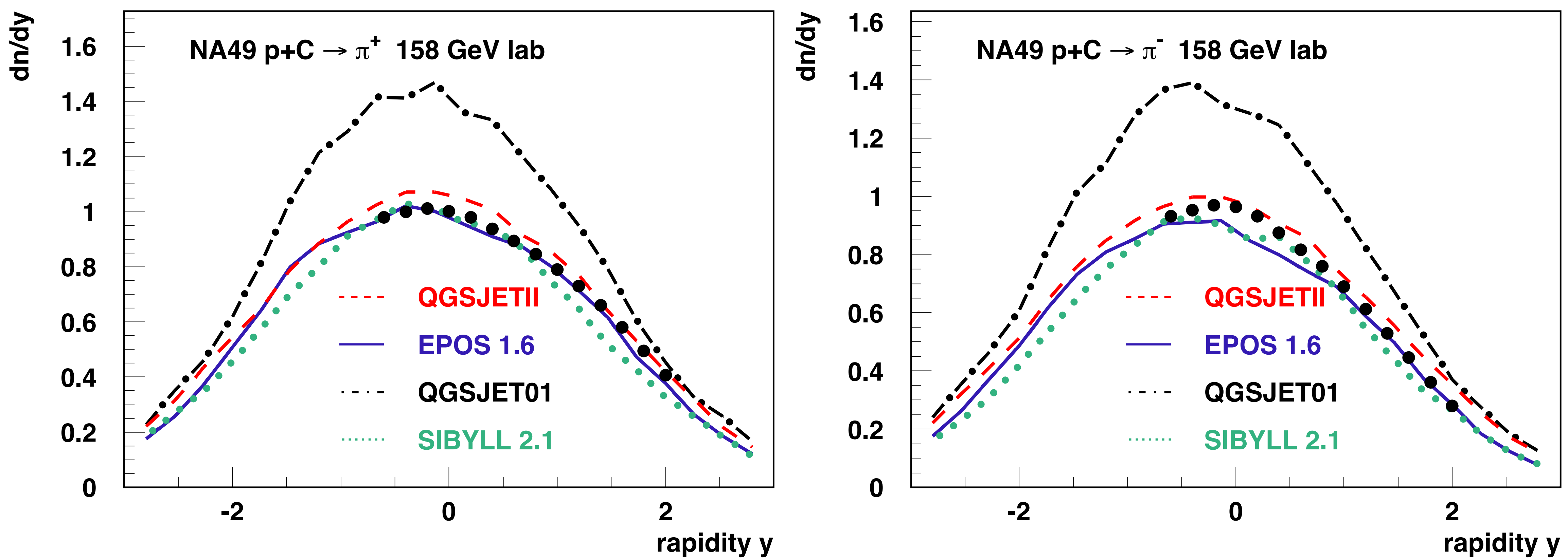




Important energies: **10 - 1000 GeV**

	beam particle	secondary
pion	**72.3 %**	**89.2 %**
nucleon	**20.9 %**	
kaon	**6.5 %**	**10.5 %**

Comparison of NA49 Data to Models



(Tanguy Pierog)