LHCf and p-A forward at RHIC

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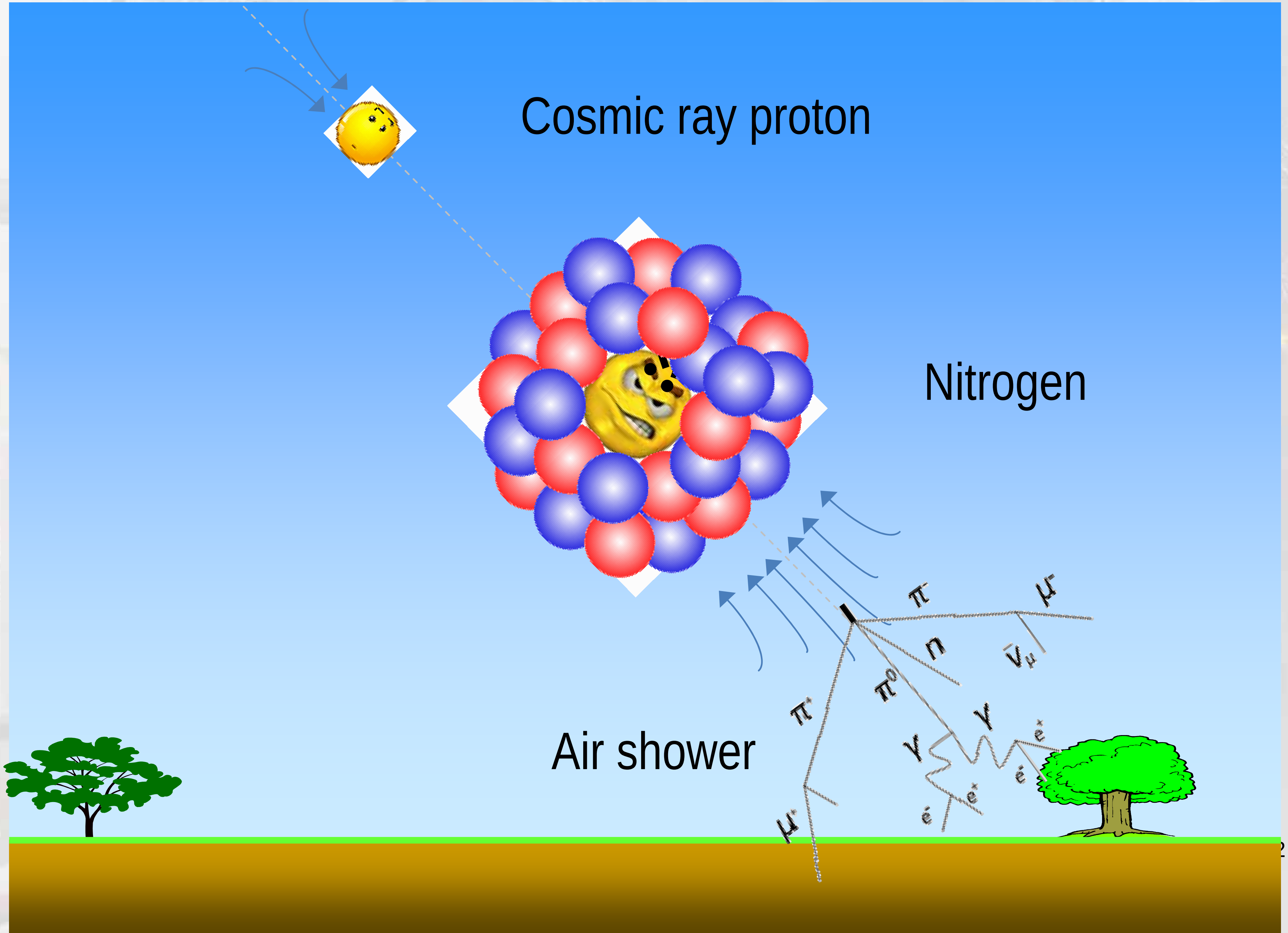
STE Lab / Kobayashi-Maskawa Inst.
Nagoya University
and on behalf of the LHCf collaboration

“pA@RHIC”
Jan 7-9, 2013, BNL

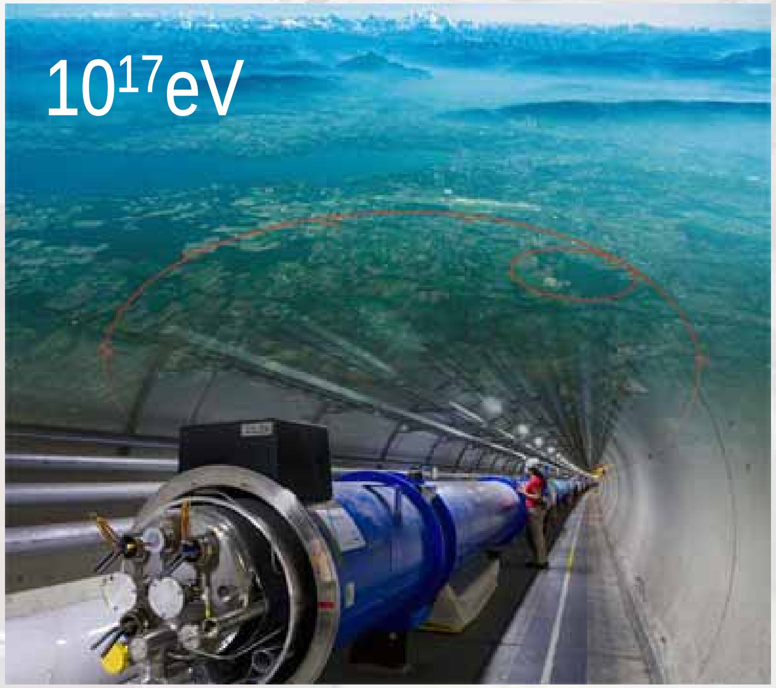
Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

Very high energy p-A collisions above our heads



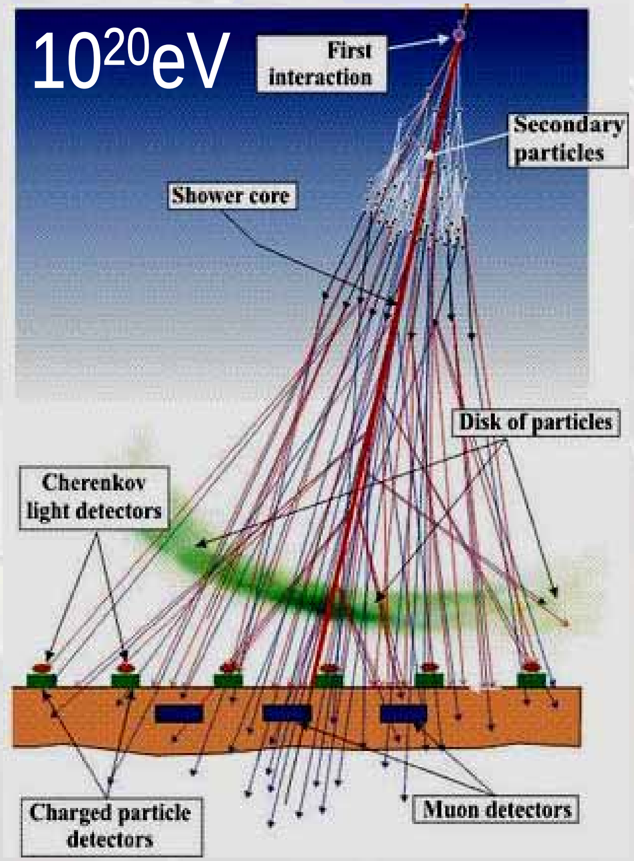
Hadron interactions at ultra high energy

Accelerator ⇔ Cosmic rays



Hadron interaction data

Hint for interactions at ultra-ultra high energy



$$E_{CM} \sim (2 \times E_{lab} \times M_p)^{1/2}$$

$\sqrt{s}$=14 TeV ⇔ 10^{17}eV cosmic rays (pp)

$\sqrt{s}$=447TeV ⇔ 10^{20}eV cosmic rays (pp)

10^{17} eV :Crossroad of accelerators and UHECRs

TA

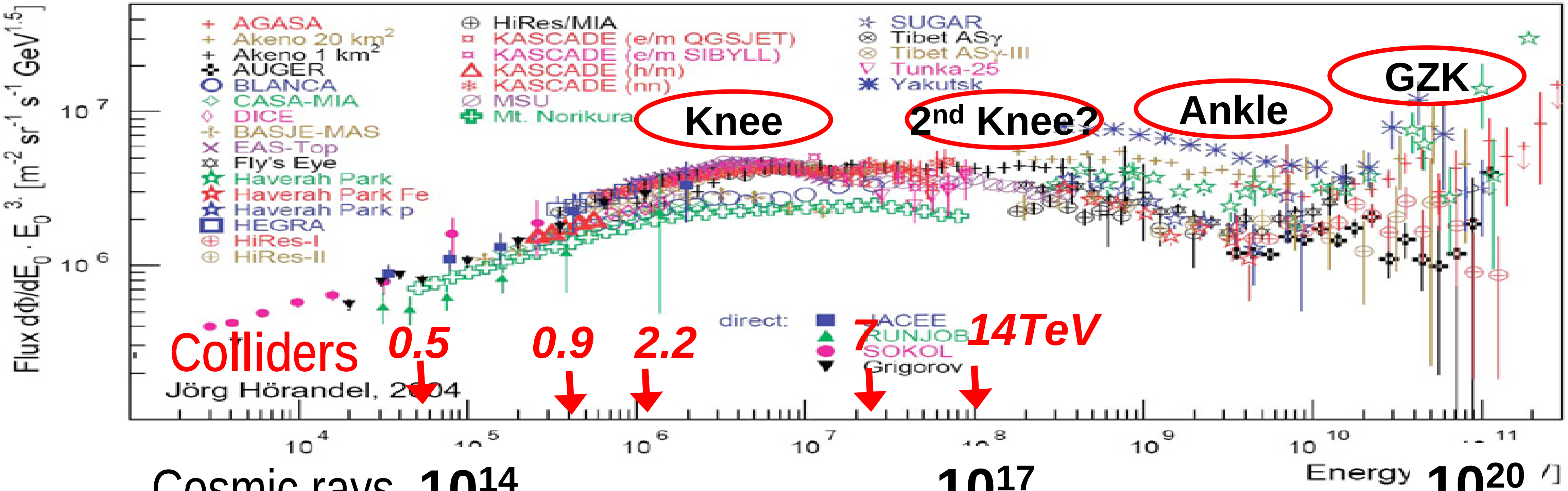
AUGER

Air shower experiments

HEAT

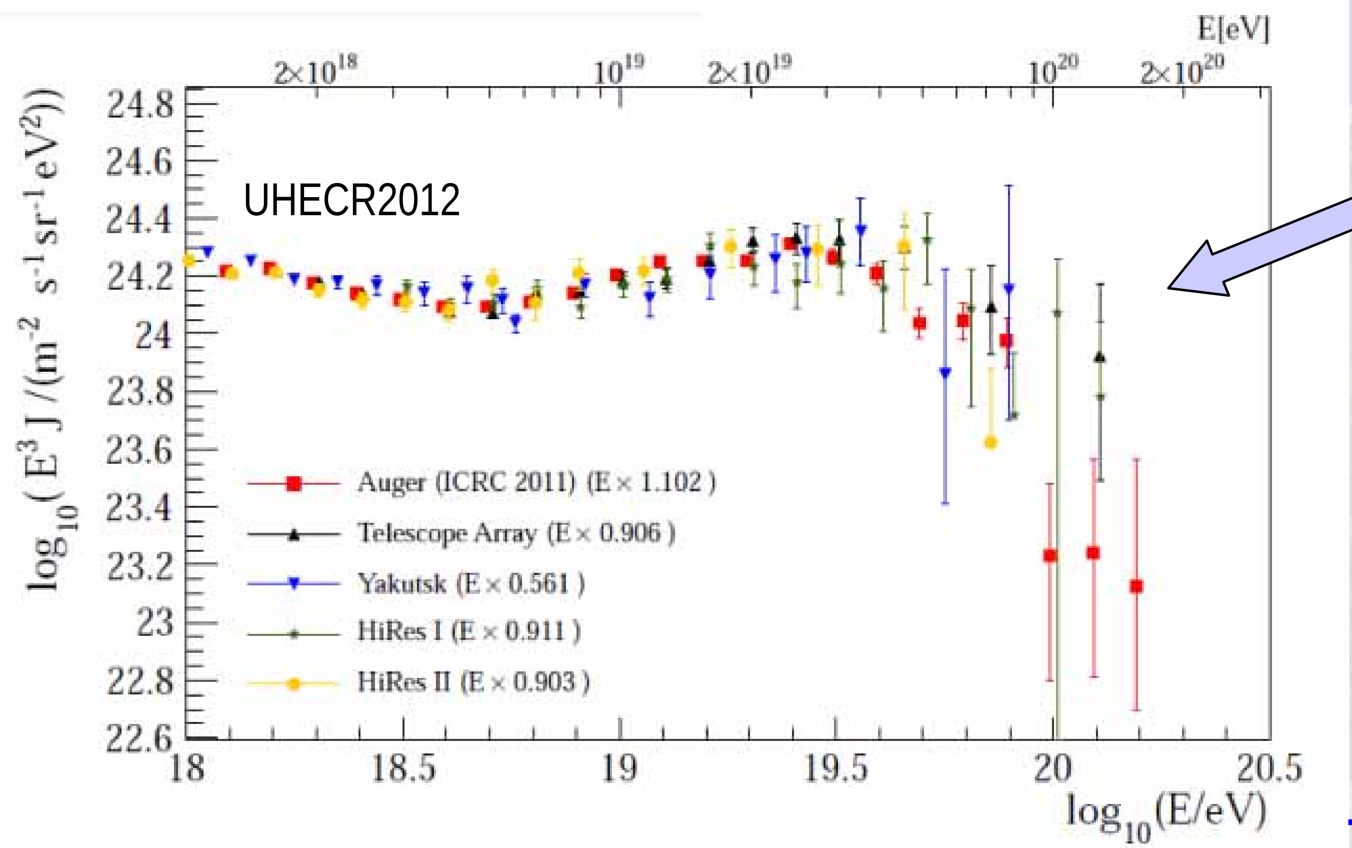
TALE

AUGER, TA



- LHC, Tevatron, SppS and RHIC can verify interactions at 10^{14} ~ 10^{17} eV
- Low E extension (TALE, HEAT) plan can verify 10^{17}eV shower

GZK cut-off confirmed ? But…

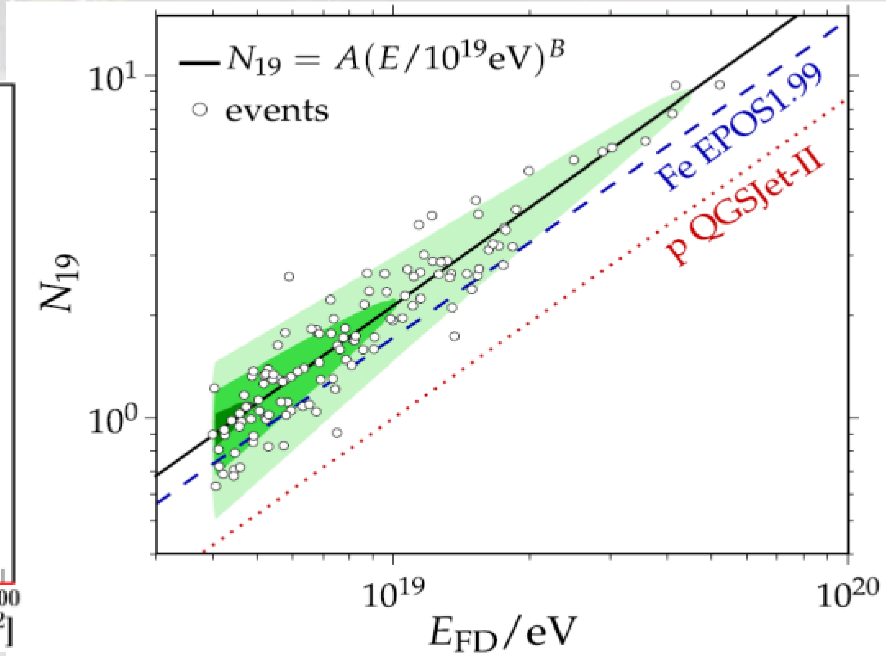


GZK cut off ?

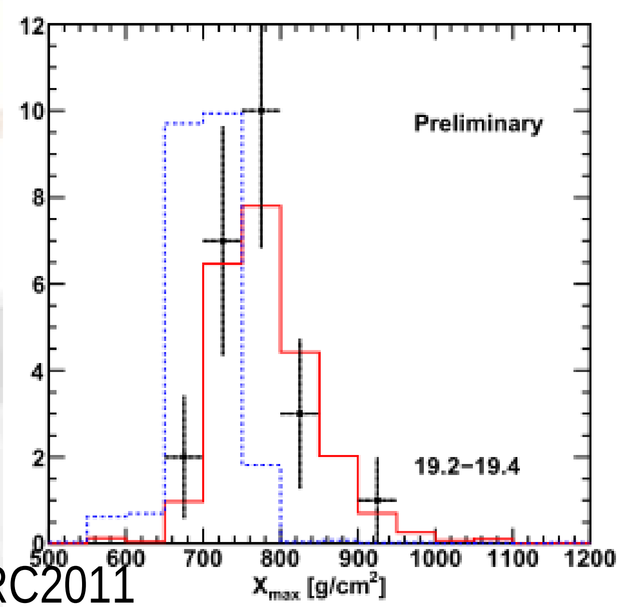
$$p + CMB\gamma \rightarrow \Delta$$

Need identify UHECR is "proton"

Too many μs @ Auger, if proton

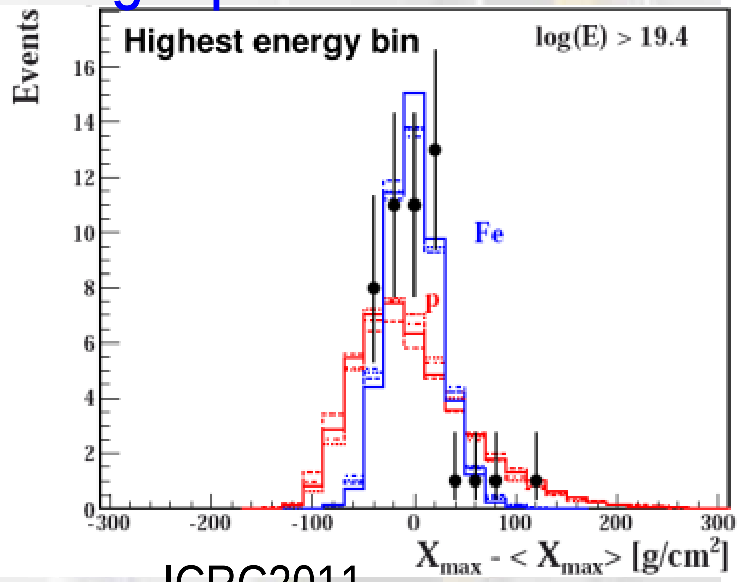


TA prefers proton

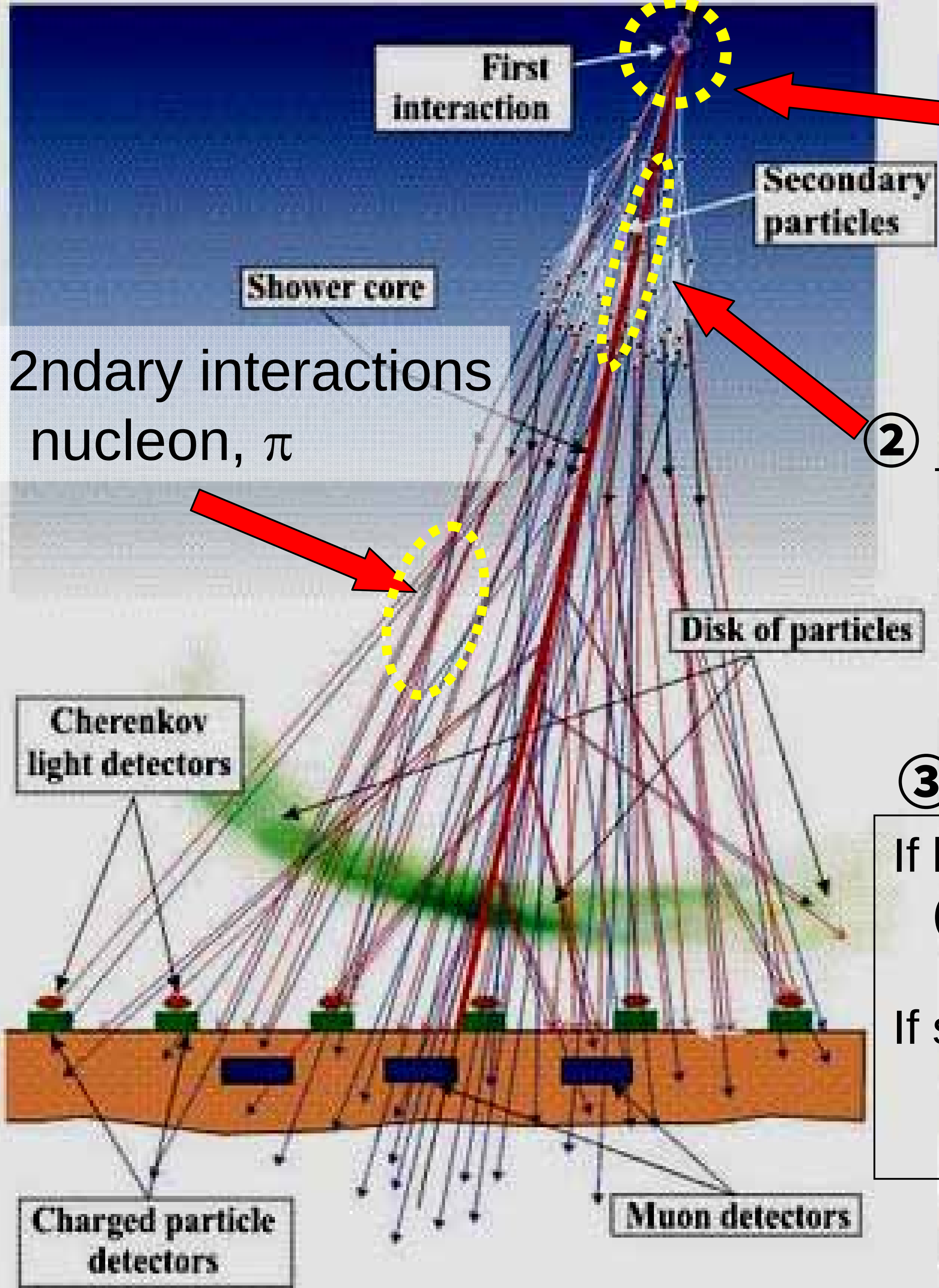


ICRC2011

Auger prefers Fe



ICRC2011



④ 2ndary interactions
nucleon, π

① Inelastic cross section

If large σ
rapid development
If small σ
deep penetrating

② Forward energy spectrum

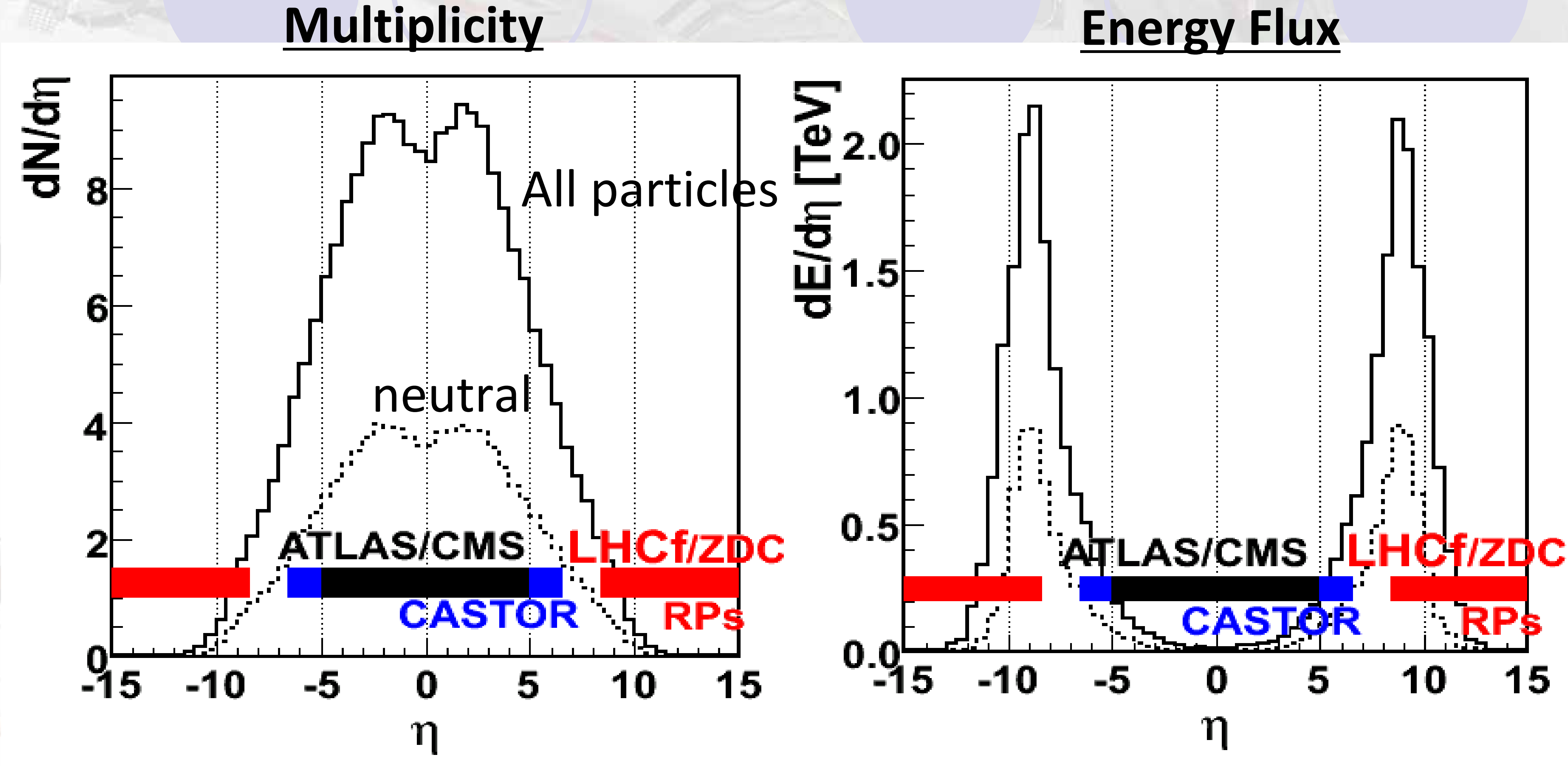
If softer
shallow development
If harder
deep penetrating

③ Inelasticity $k = 1 - p_{lead}/p_{beam}$

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

(relevant to N_μ)

Very forward : Majority of energy flow ($\sqrt{s}$=14TeV)



Most of the energy flows into very forward

(Particles of X_F > 0.1 contribute 50% of shower particles)

Need to measure EM component at η~8

The LHCf collaboration

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M.Haguenauer *Ecole Polytechnique, France*

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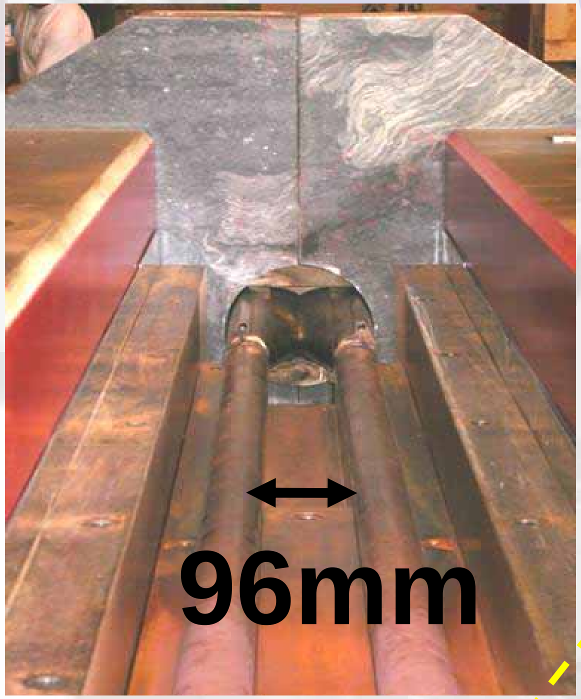
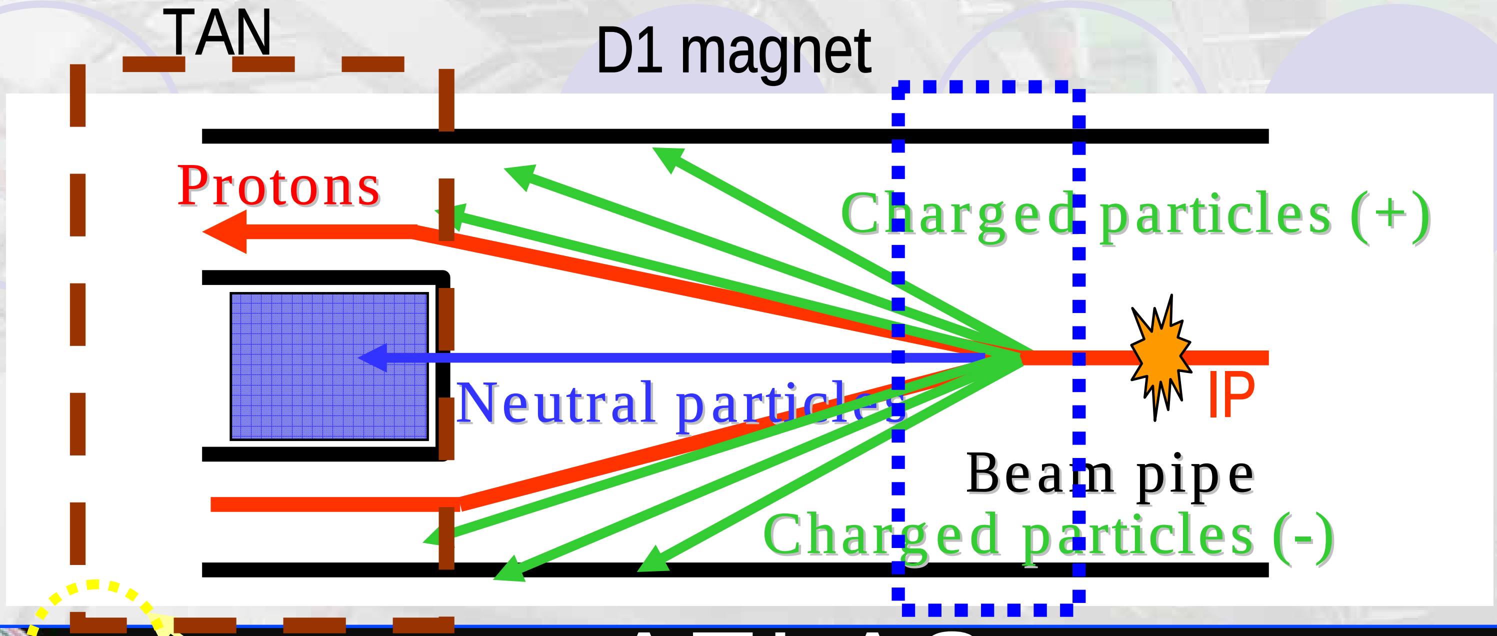
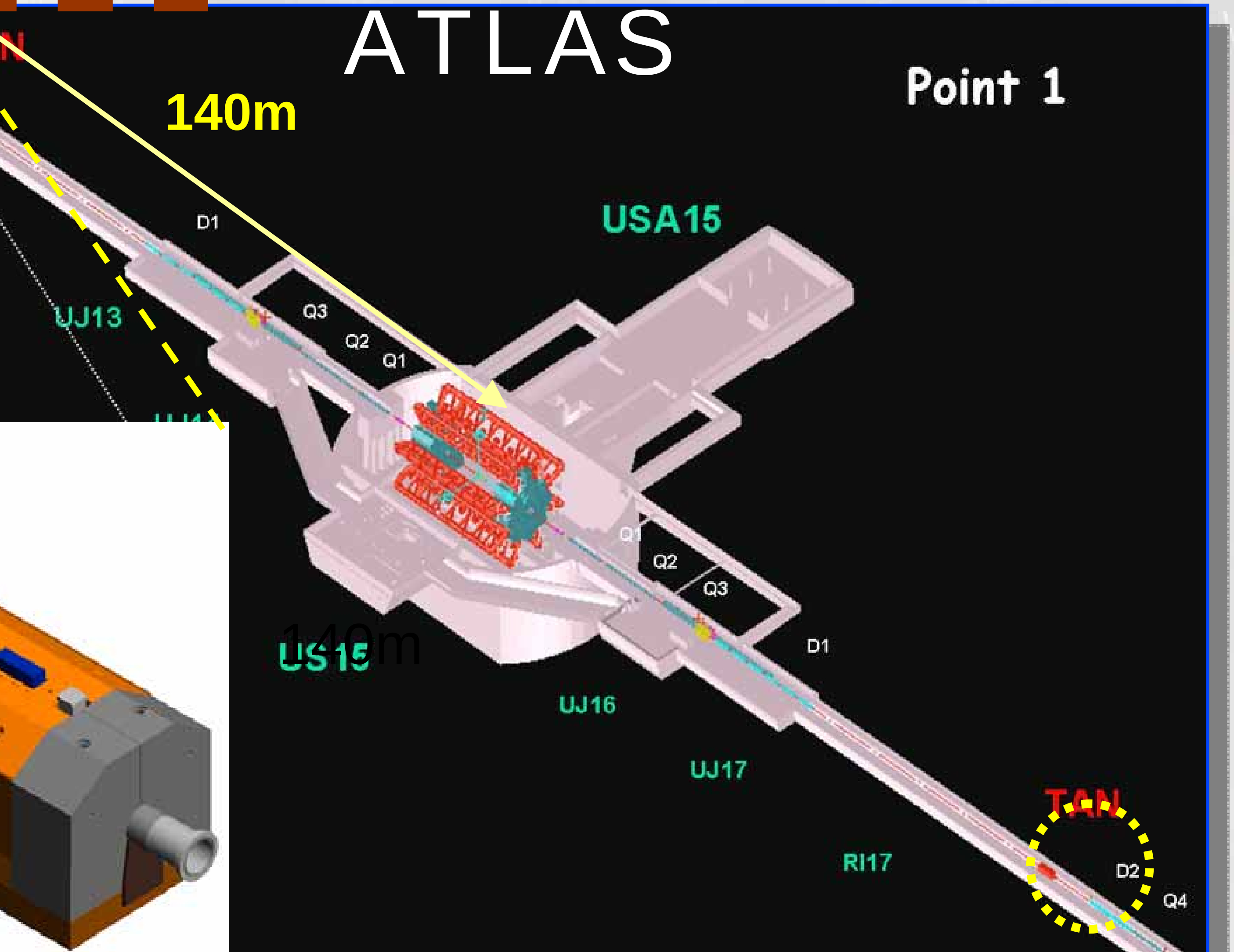
A-L.Perrot *CERN, Switzerland*

~30 physicists from 5 countries

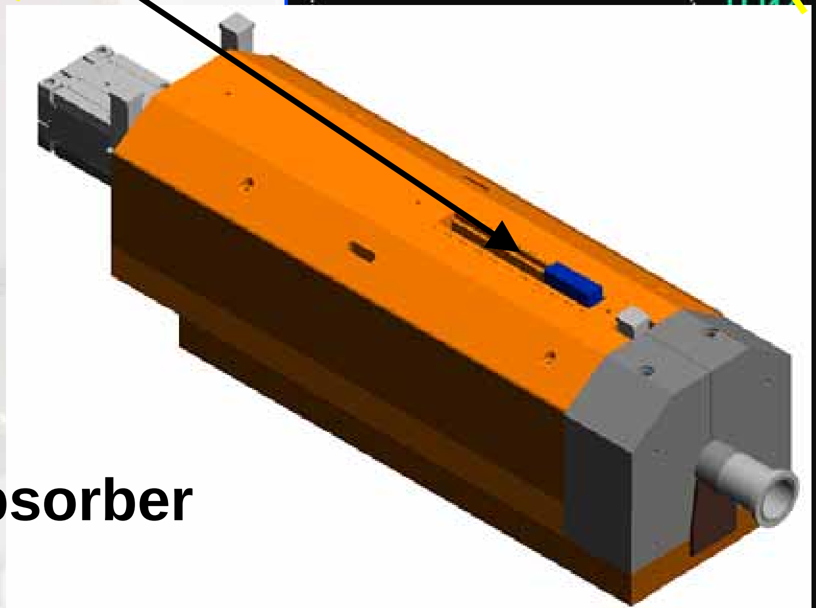
LHCf site





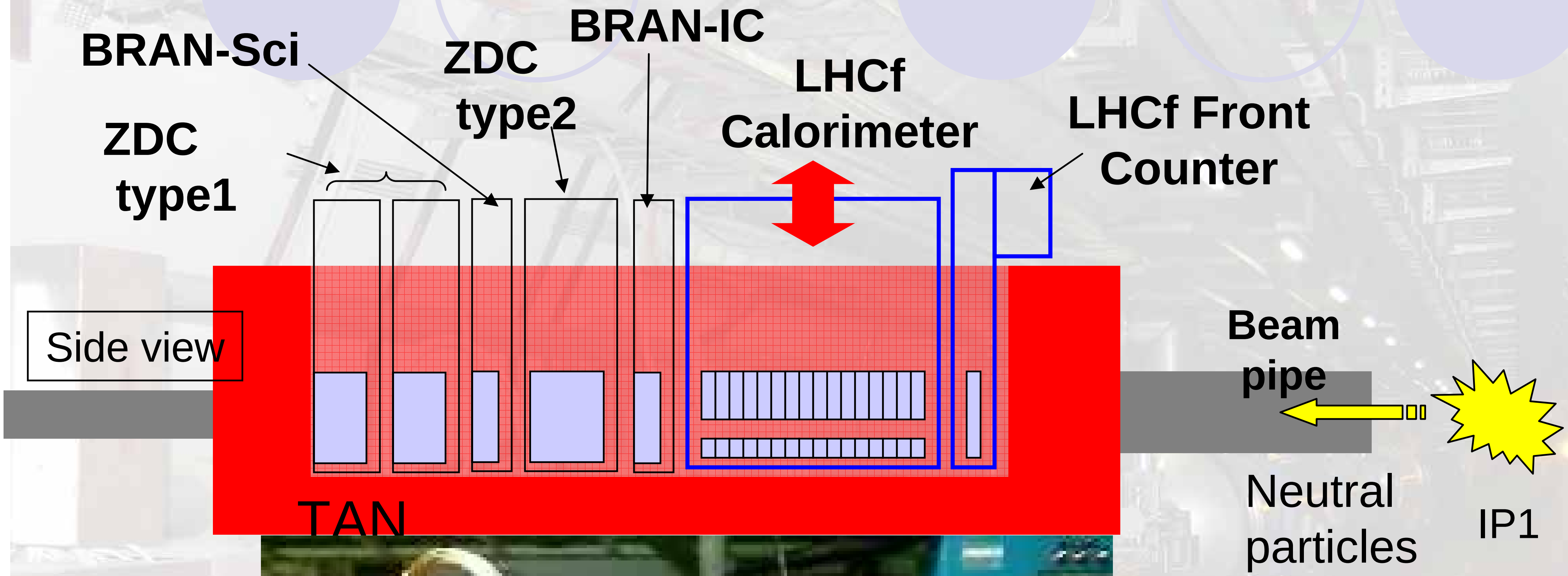


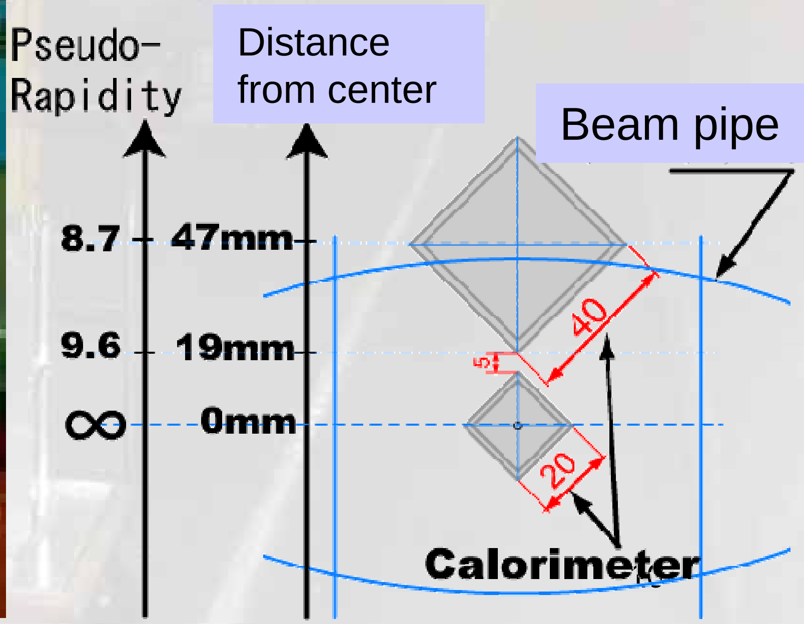
LHCf/ZDC



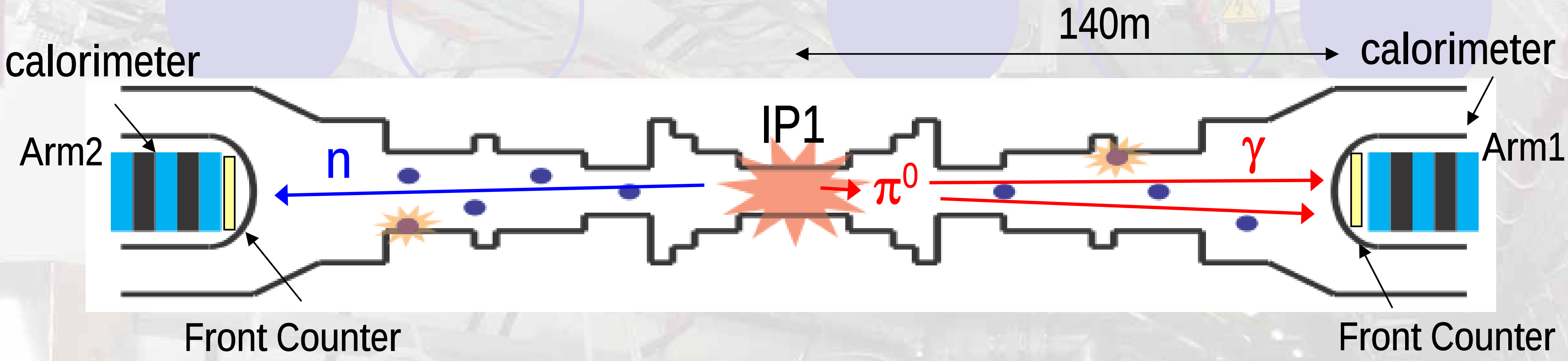
TAN absorber

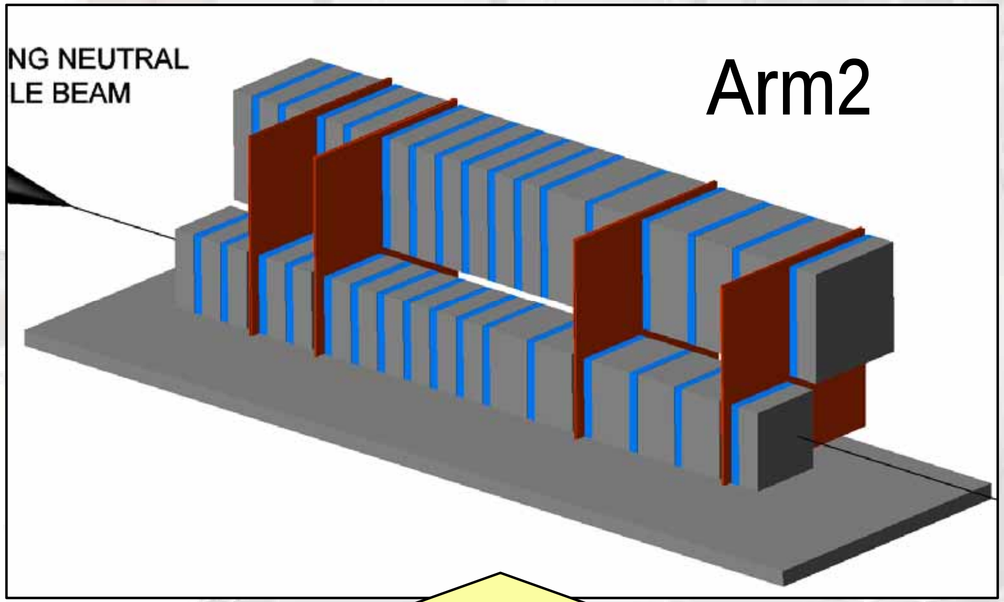
Setup in IP1-TAN (side view)



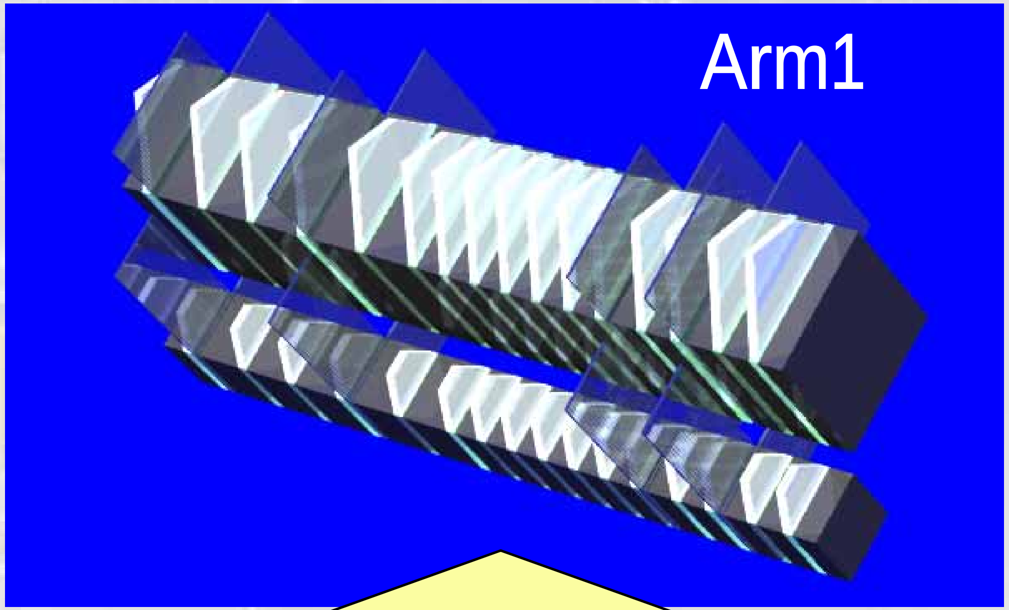


The LHCf detectors





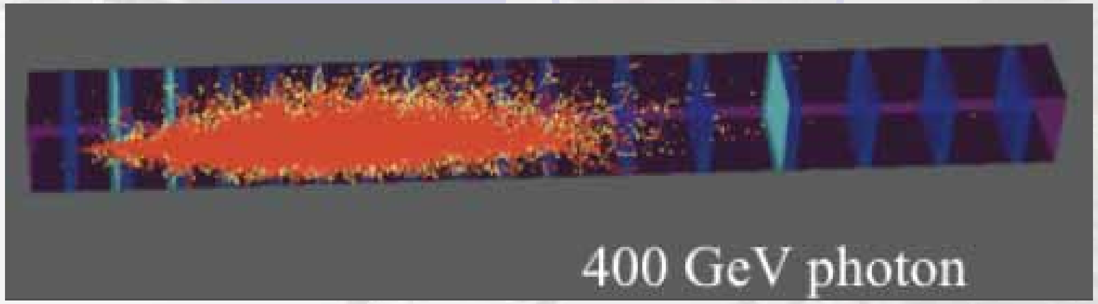
$44X_0$,
$1.6\ \lambda_{int}$

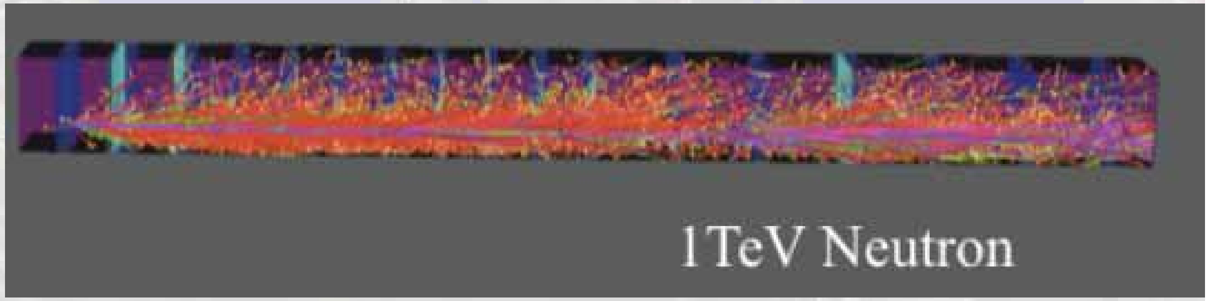


16 tungsten + pl.scinti. layers
25mmx25mm+32mmx32mm
4 Silicon strip tracking layers

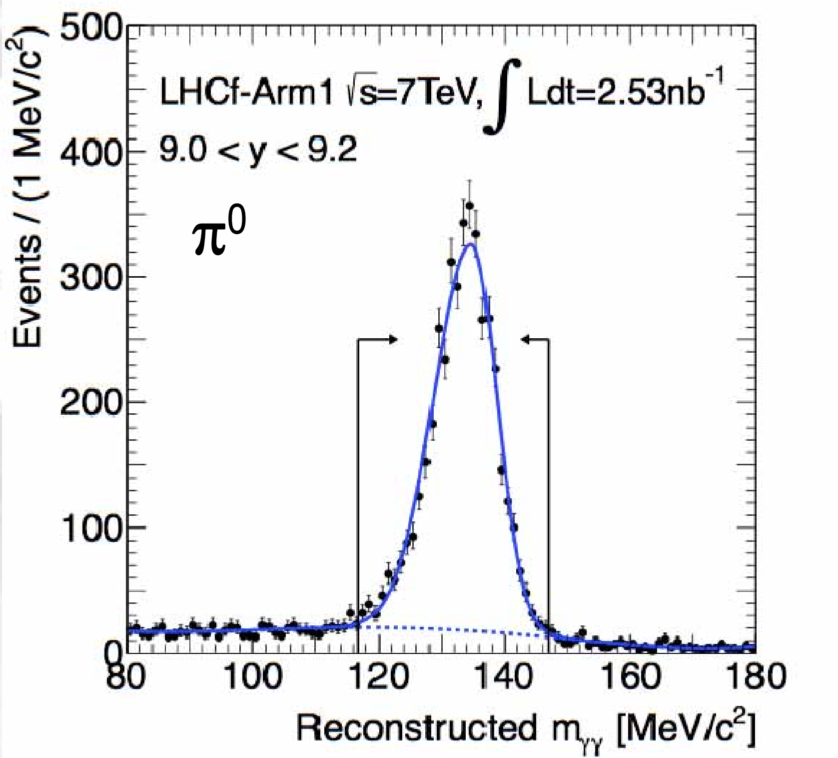
16 tungsten + pl.scinti. layers
20mmx20mm+40mmx40mm
4 SciFi tracking layers

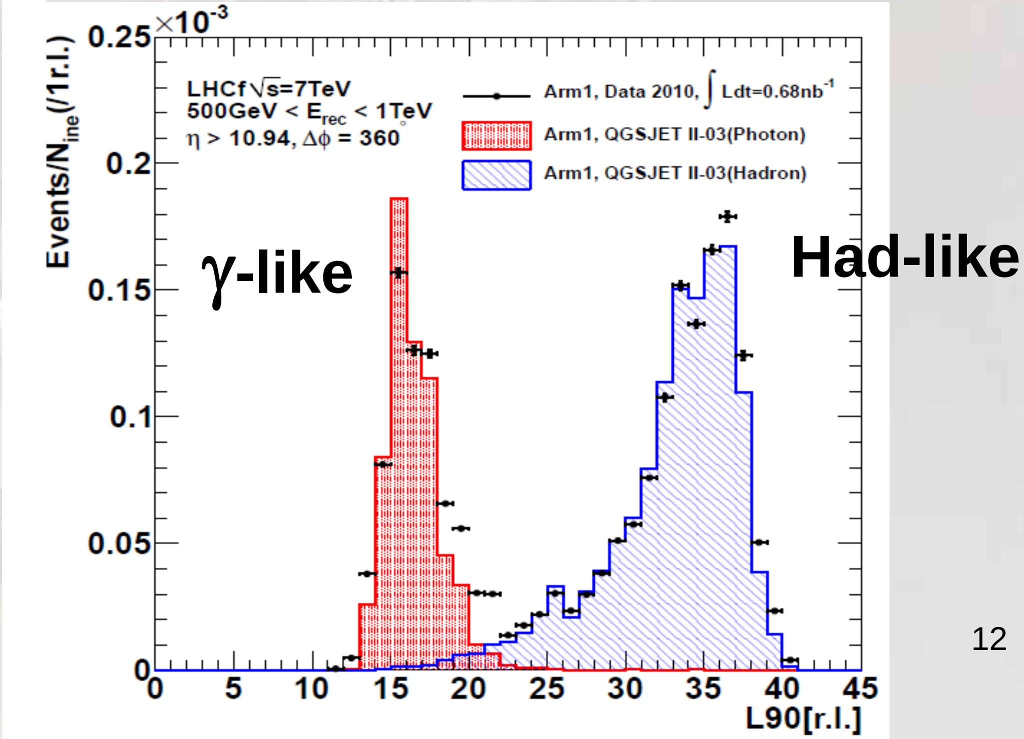
Calorimeter performance





- Gamma-rays (E>100GeV, dE/E<5%)
- Neutral Hadrons (E>a few 100 GeV, dE/E~30%)
- Neutral Pions (E>700GeV, dE/E<3%)
- Shower incident position (170μm / 40μm for Arm1/Arm2)





Brief history of LHCf

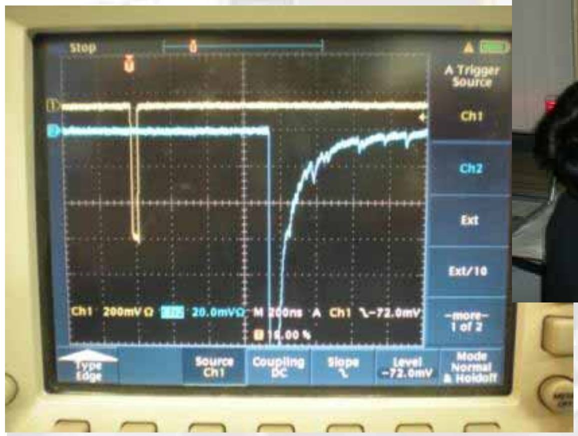
- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved

Jul 2006 construction

Aug 2007 SPS beam test

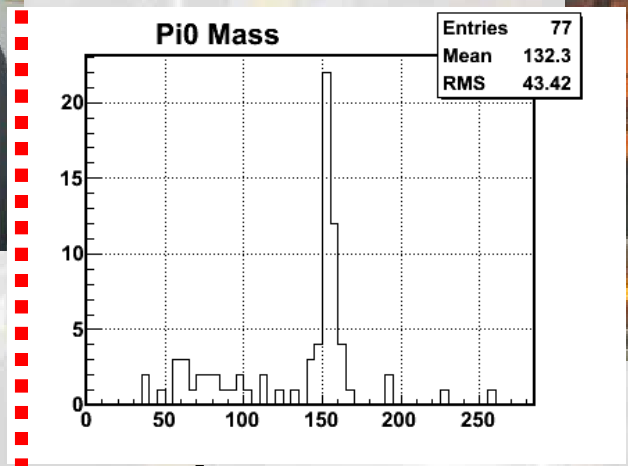
Jan 2008 Installation

Sep 2008 1st LHC beam



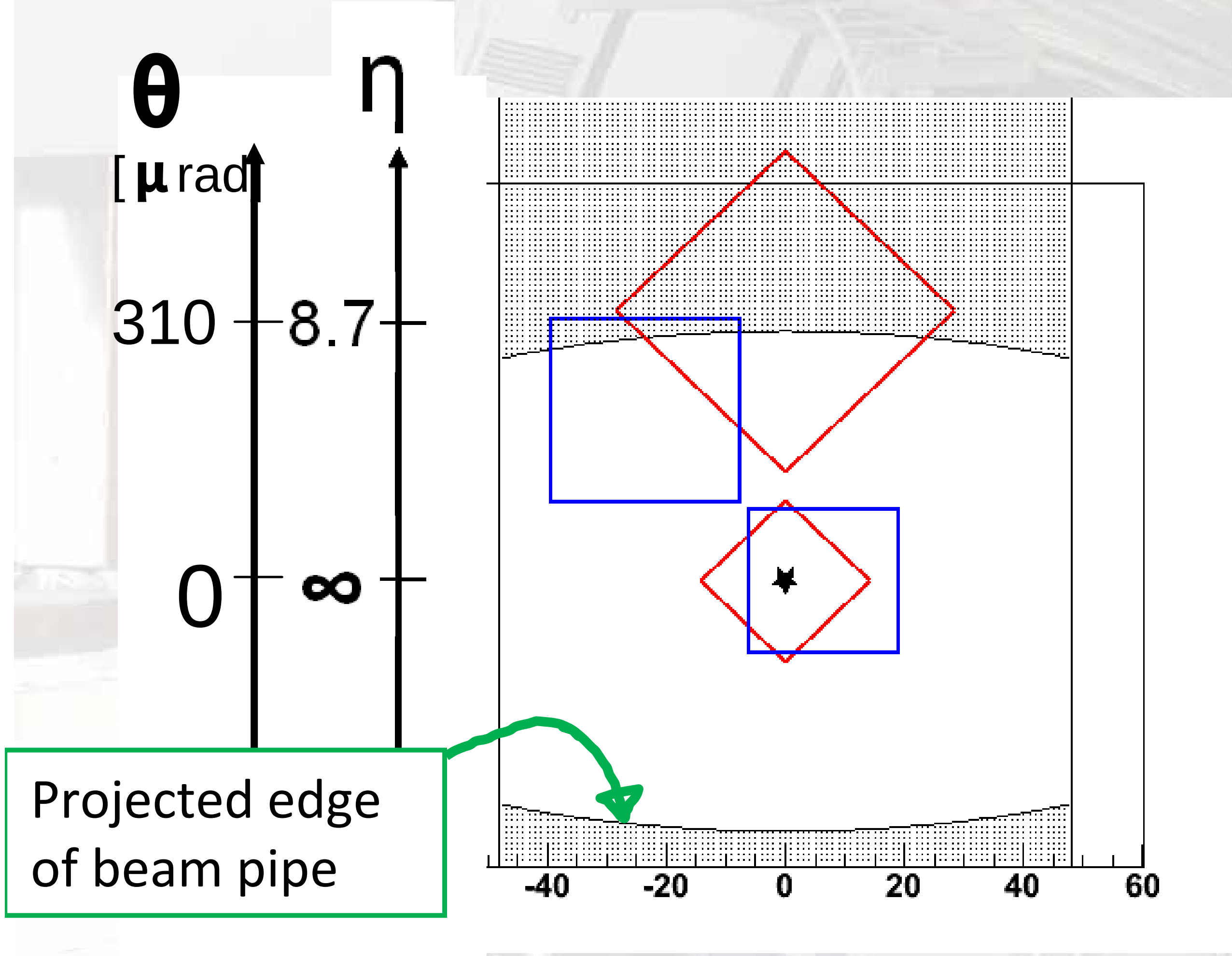
Dec 2009 1st 900GeV run (2nd 900GeV in May2010)

Mar 2010 1st 7TeV run

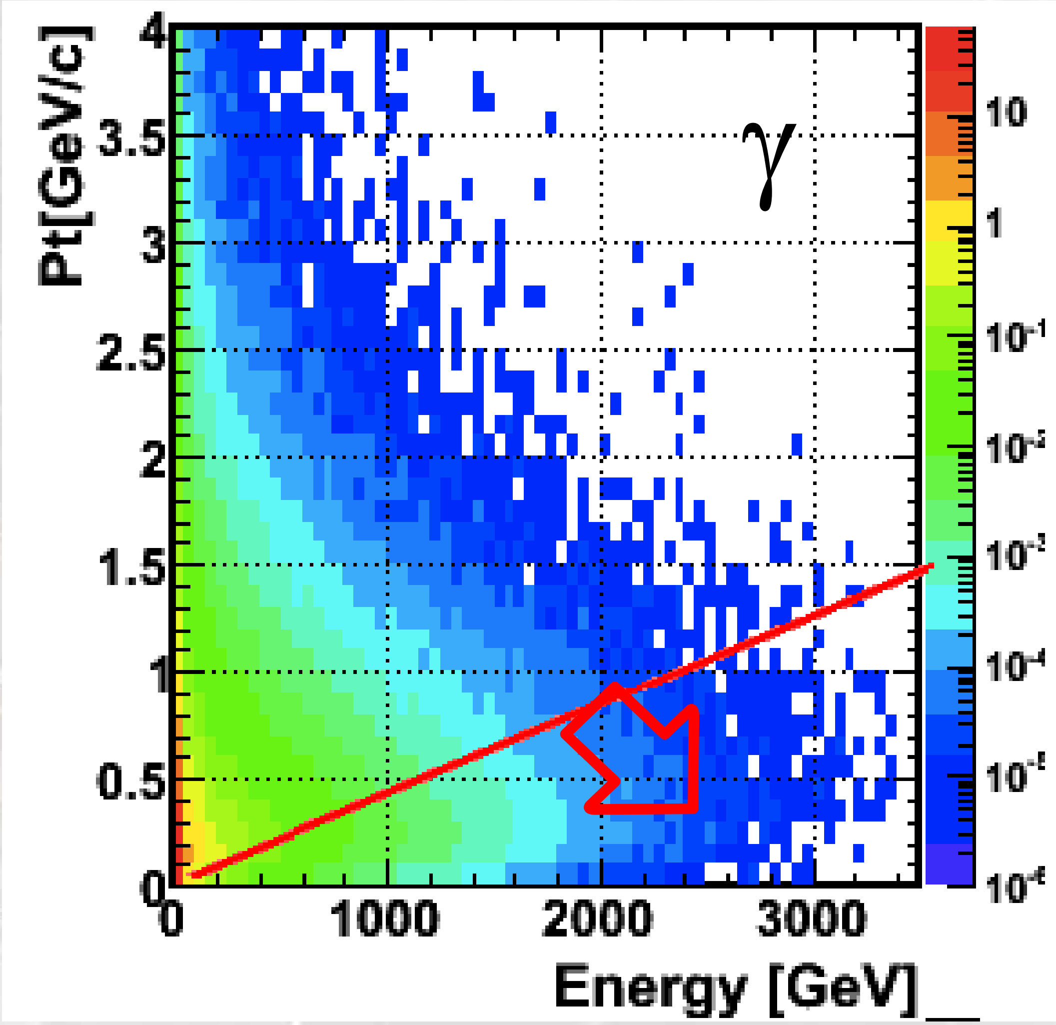


Jul 2010 Detector removal

Acceptance of LHCf



Viewed from IP1
(red:Arm1, blue:Arm2)



pp 7TeV, EPOS

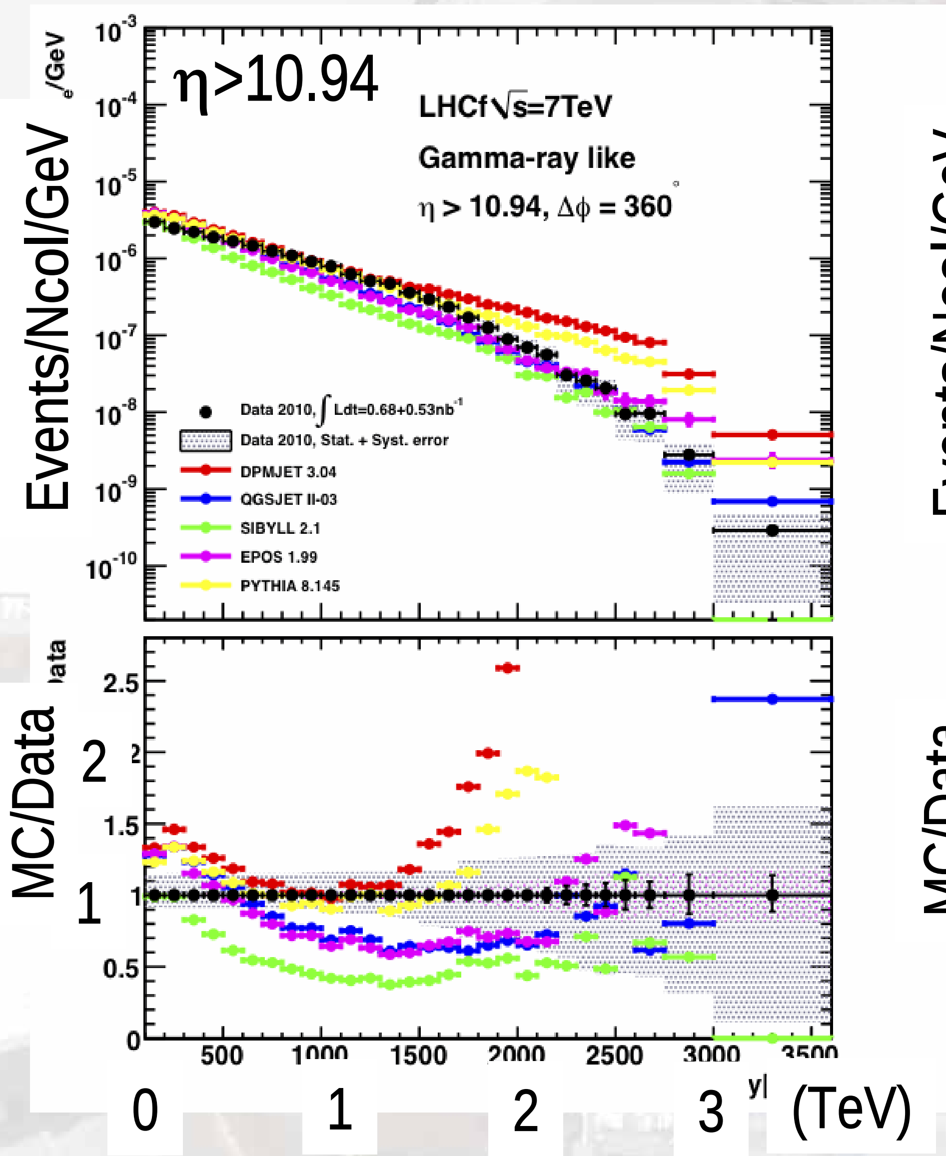
LHCf single γ spectra at 7TeV

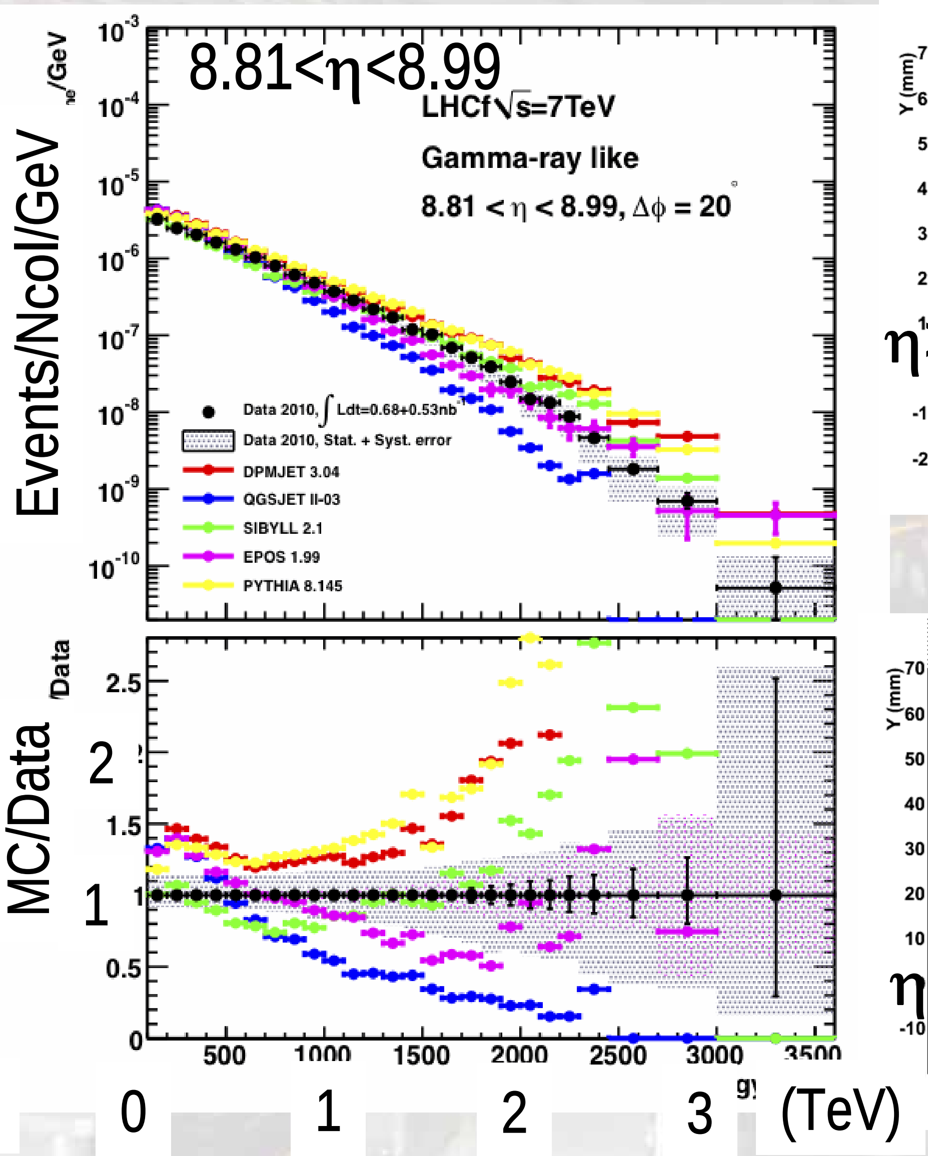
PLB 703 (2011) 128-134

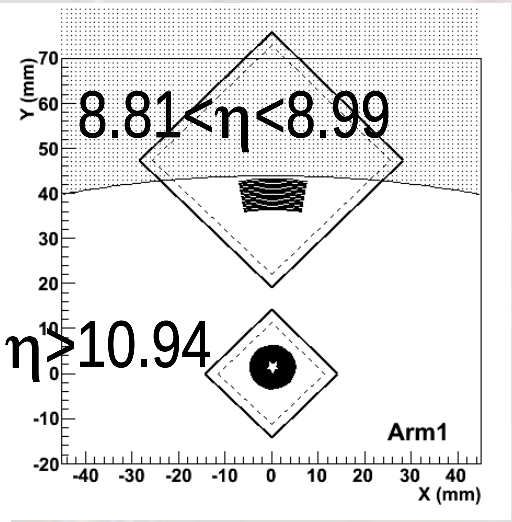
DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

Gray hatch : Sys+stat errors

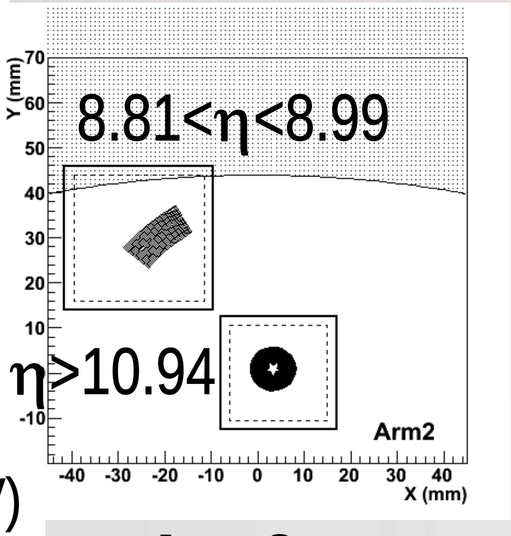
Magenta hatch: Stat errors of MC







Arm1



Arm2

- None of the models agree with data
- Data within the range of the model spread

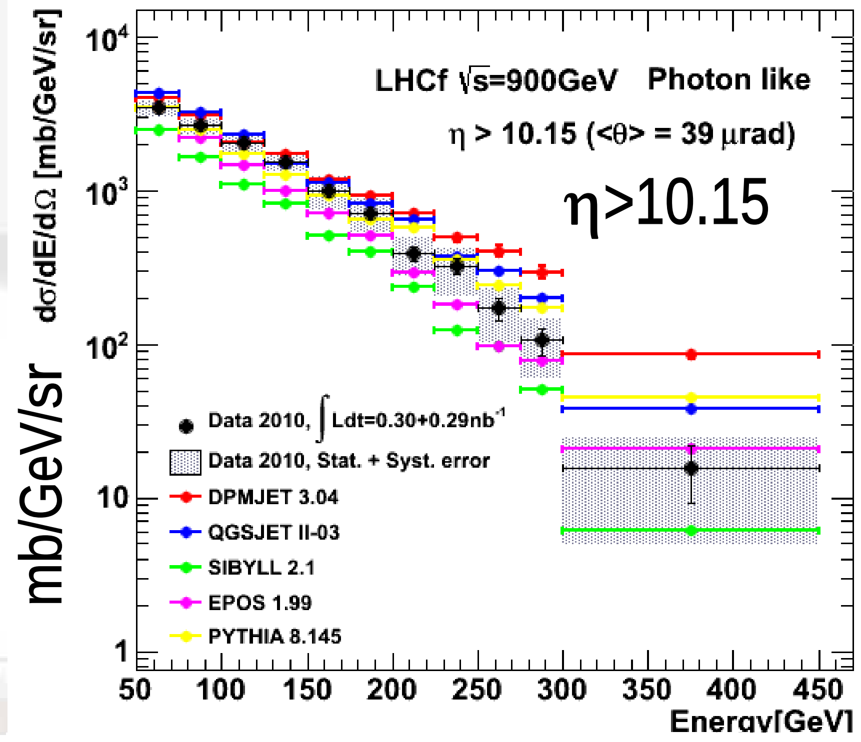
0.68 (0.53)nb^{-1} on 15May2010

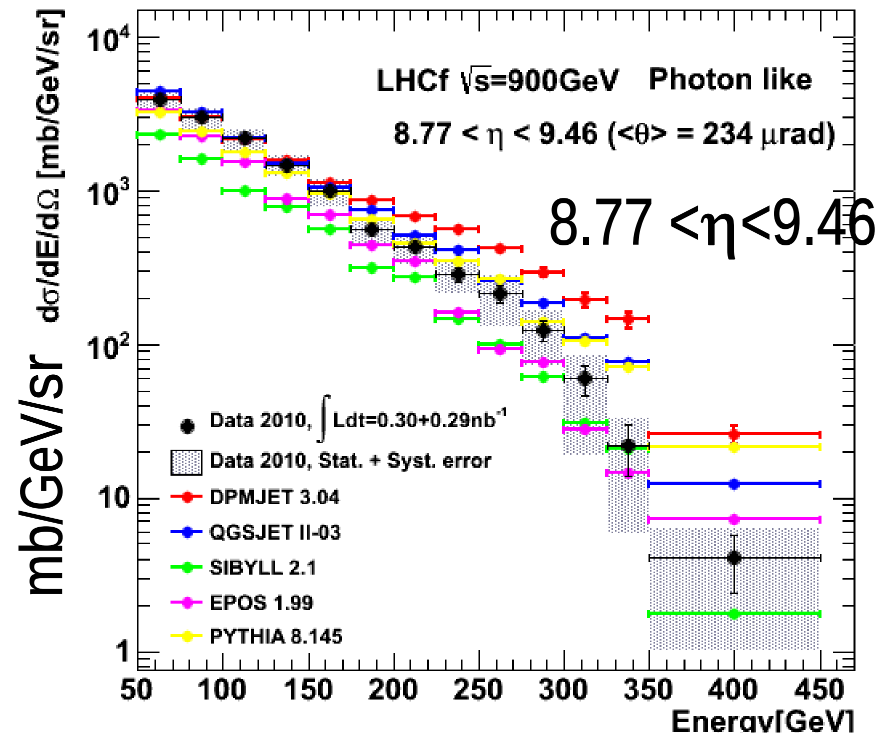
LHCf single γ spectra at 900 GeV

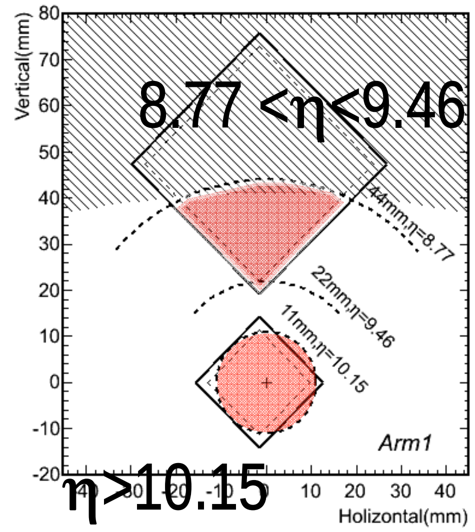
PLB 715 (2012) 298-303

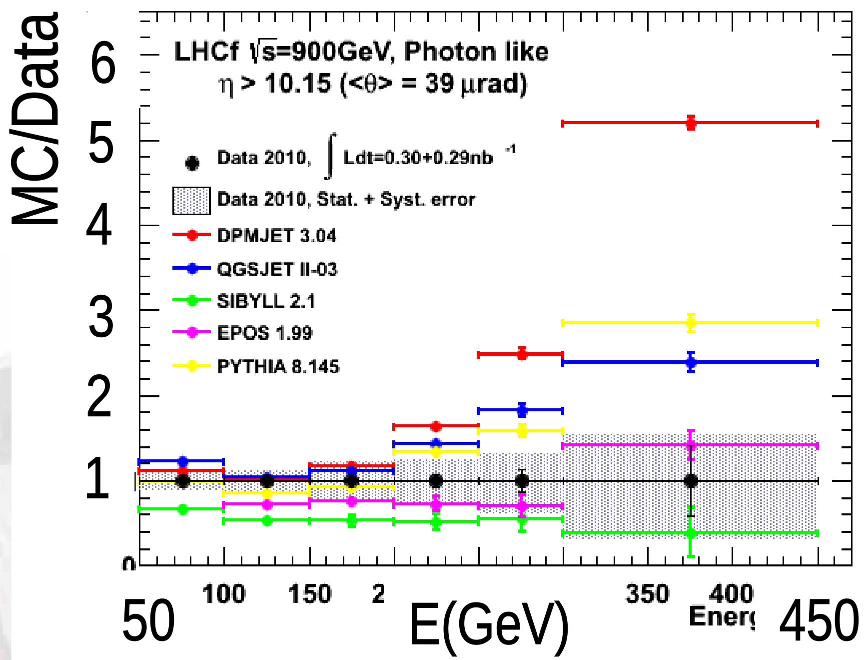
May2010 900GeV data (0.3nb-1 , 21% uncertainty not shown)

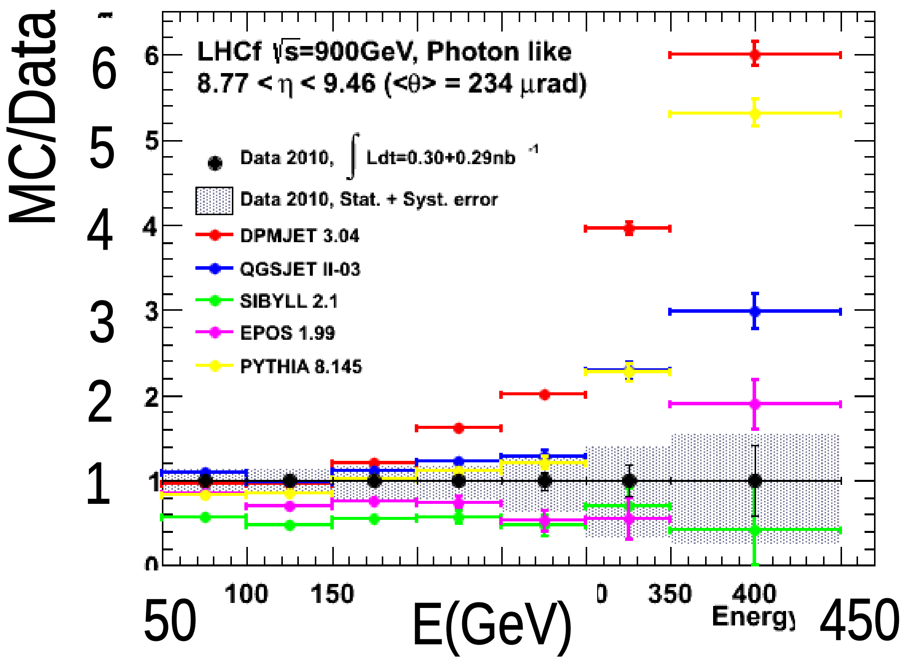
DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

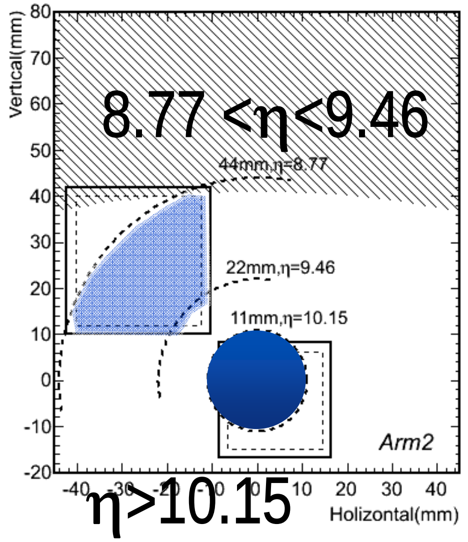






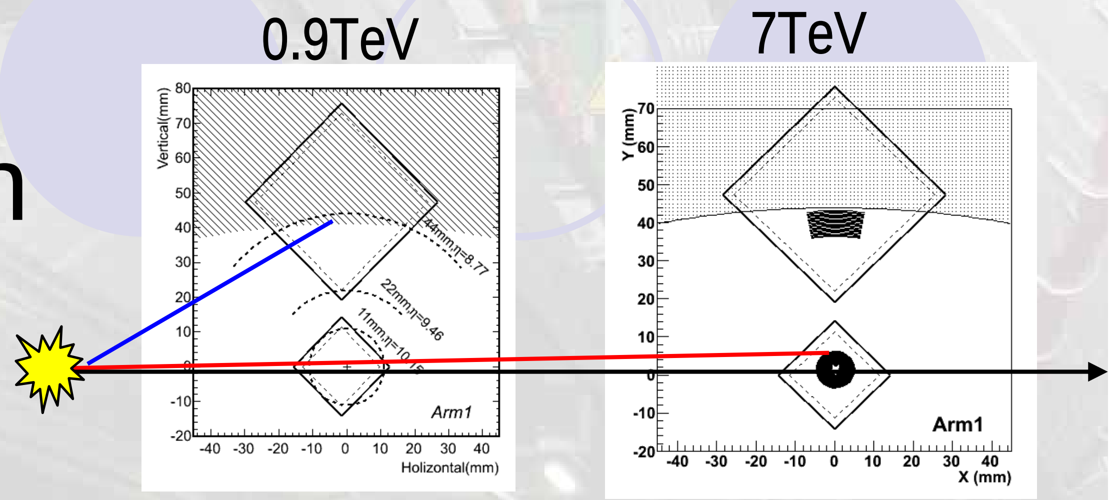




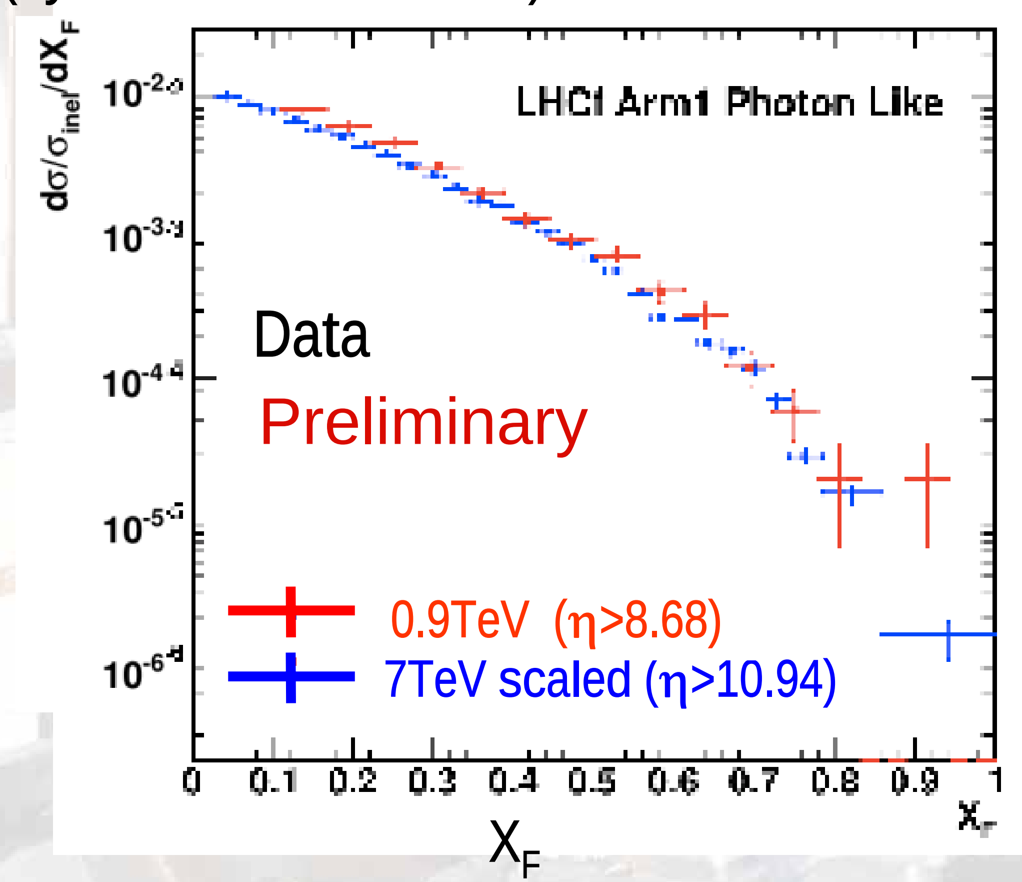


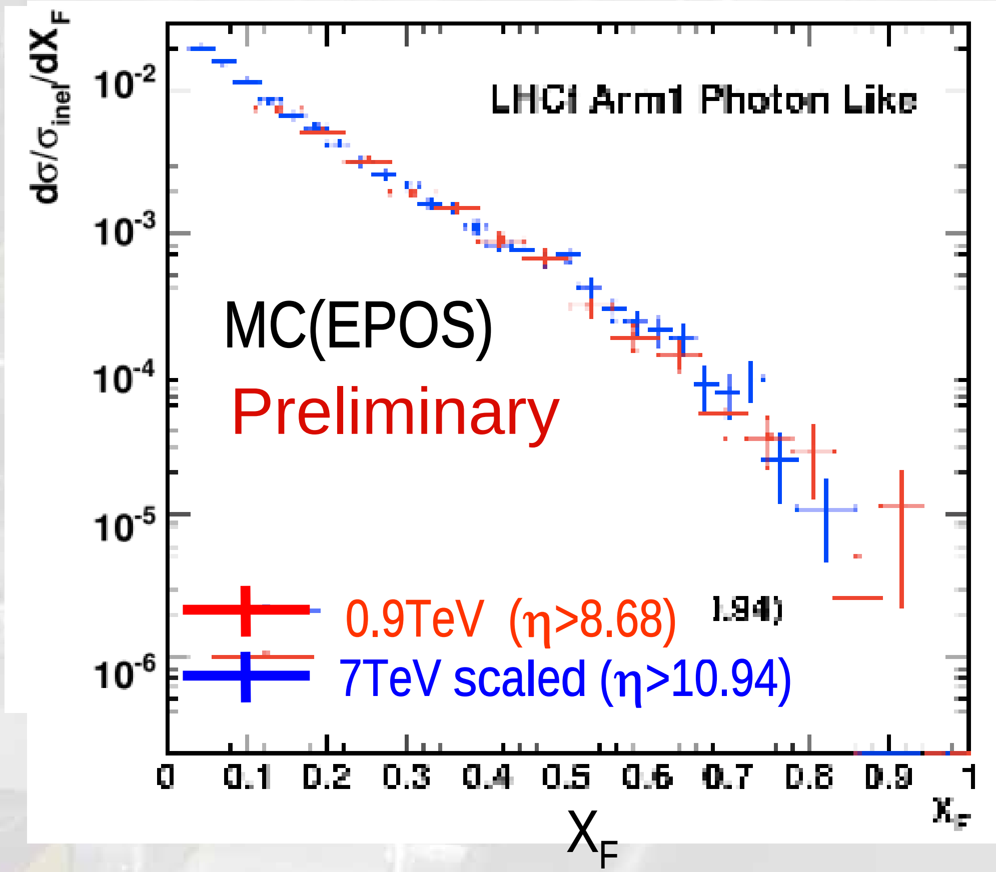
X_F spectra for single γ: 900GeV/ 7TeV comparison

$$\frac{1}{\sigma_{\rm inel}}\frac{d\sigma_\gamma}{dX_{\rm F}}\bigg|_{\eta<\rm limited} \propto \frac{1}{\sigma_{\rm inel}}\frac{d\sigma_\gamma}{p_{\rm T}dp_{\rm T}dX_{\rm F}}\langle p_{\rm T}\rangle dp_{\rm T}$$



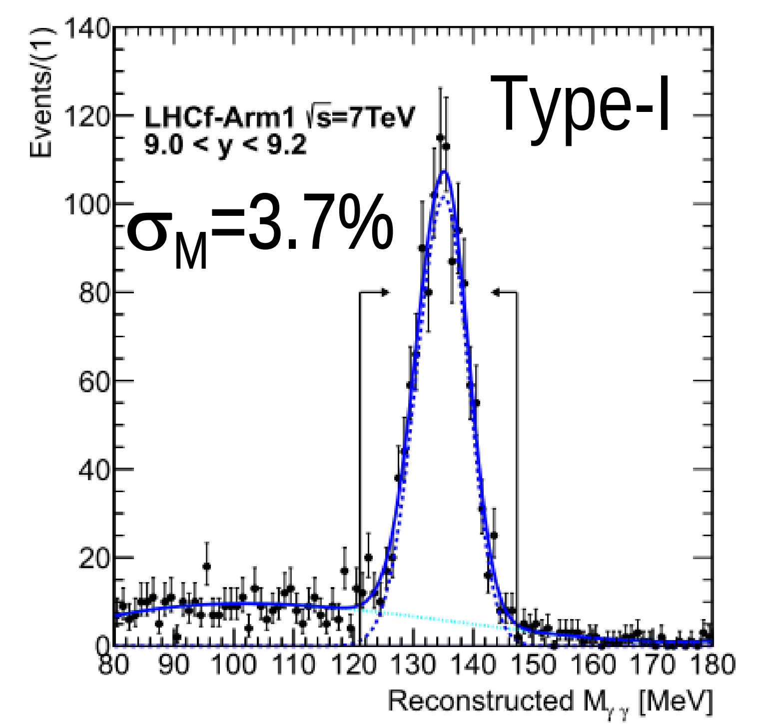
(sys error not included)

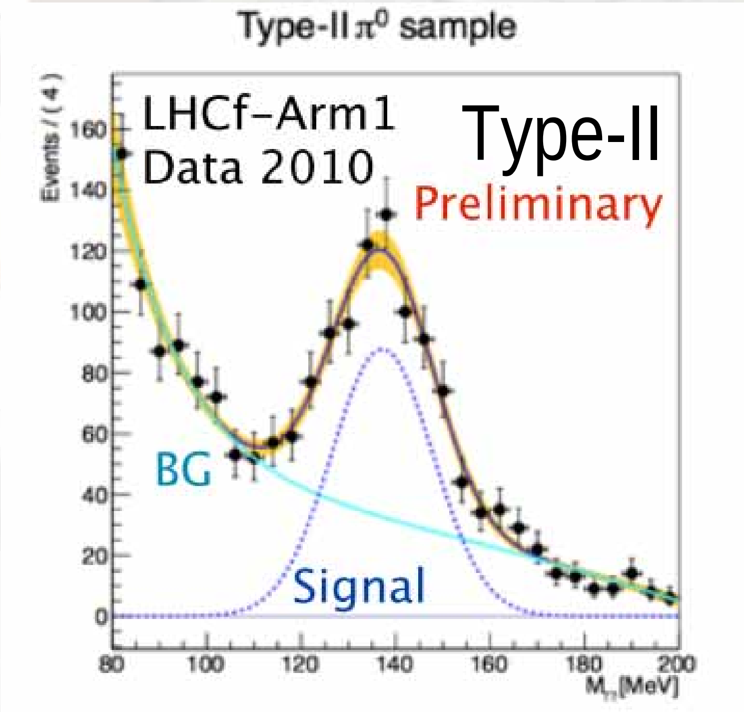




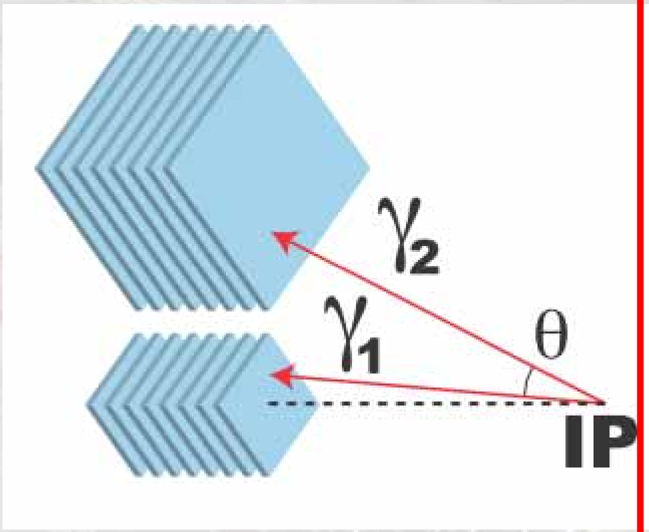
- Comparing X_F for common P_T region at two collision energies.
- Less root-s dependence of P_T for X_F ?

LHCf 7TeV π^0 analysis

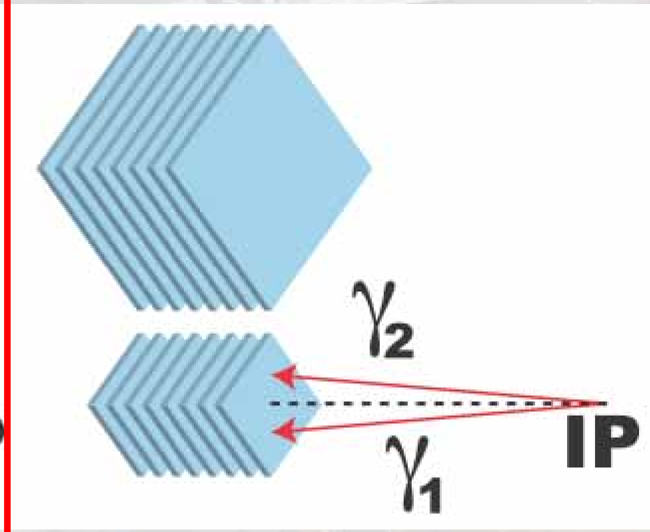


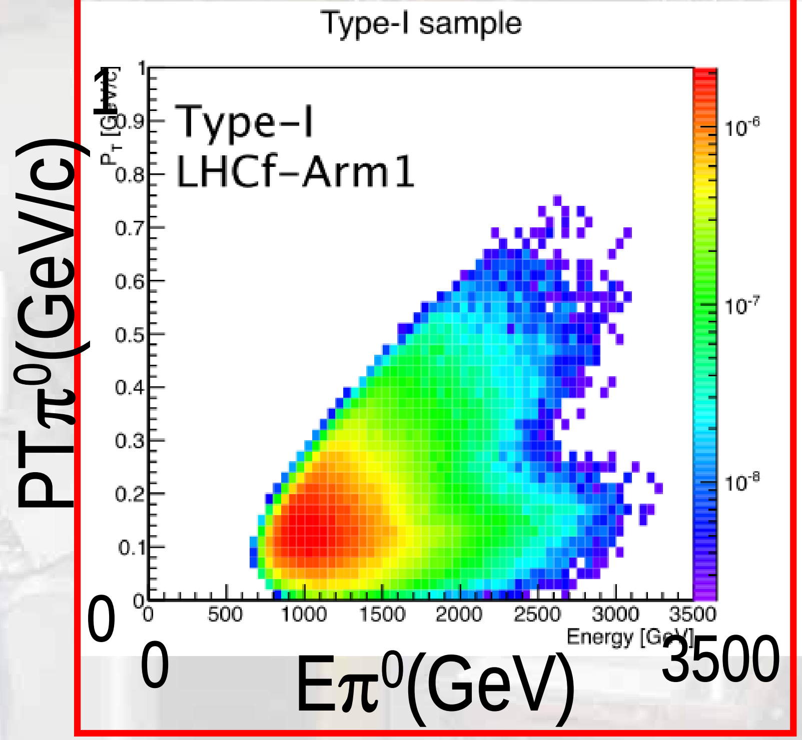


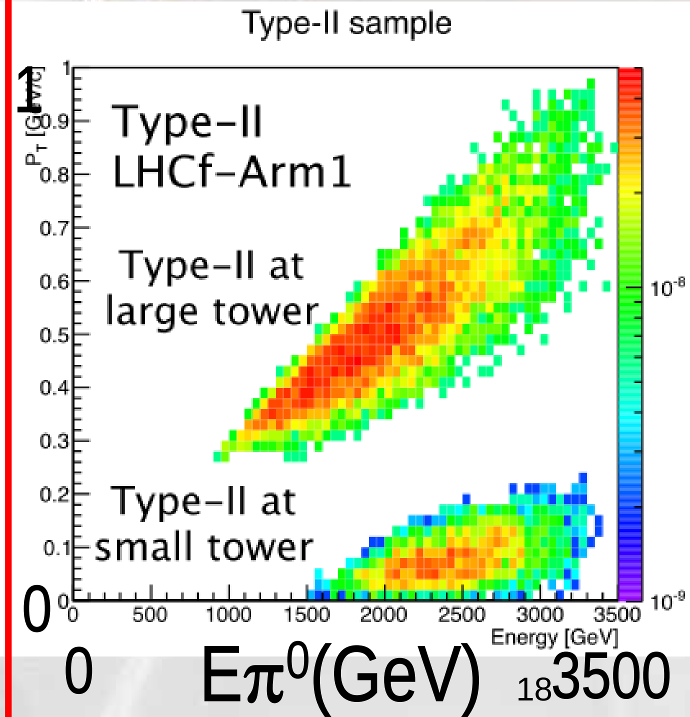
Type-I



Type-II



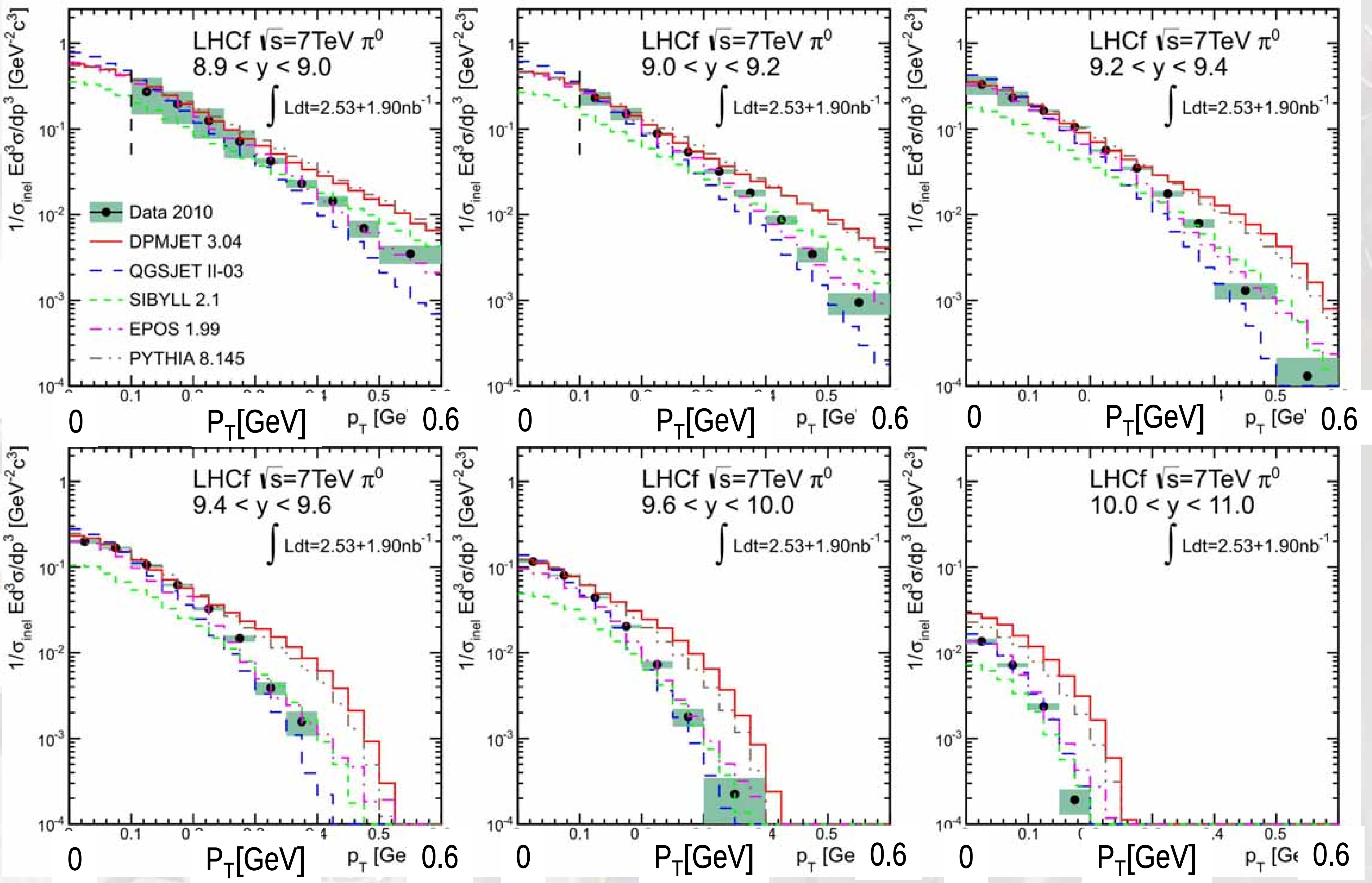




LHCf π^0 P_T spectra at 7TeV

PRD 86 (2012) 092001

DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

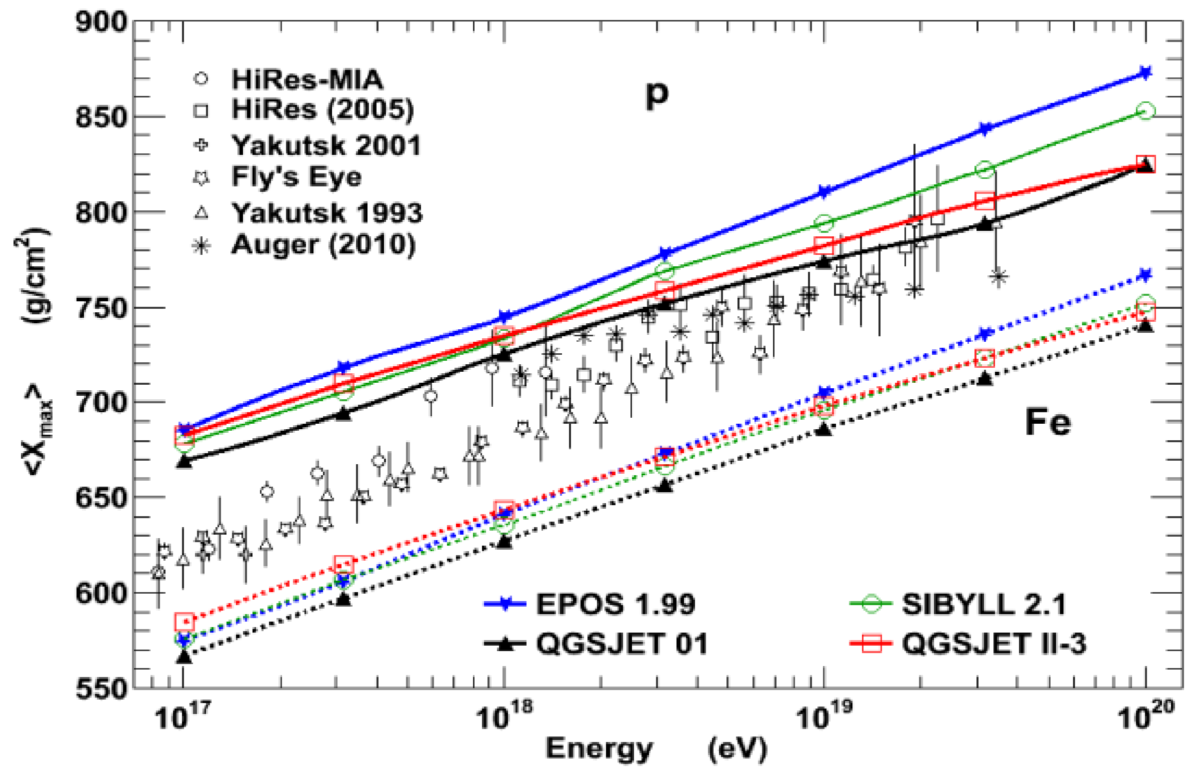


Feed back to UHECR composition

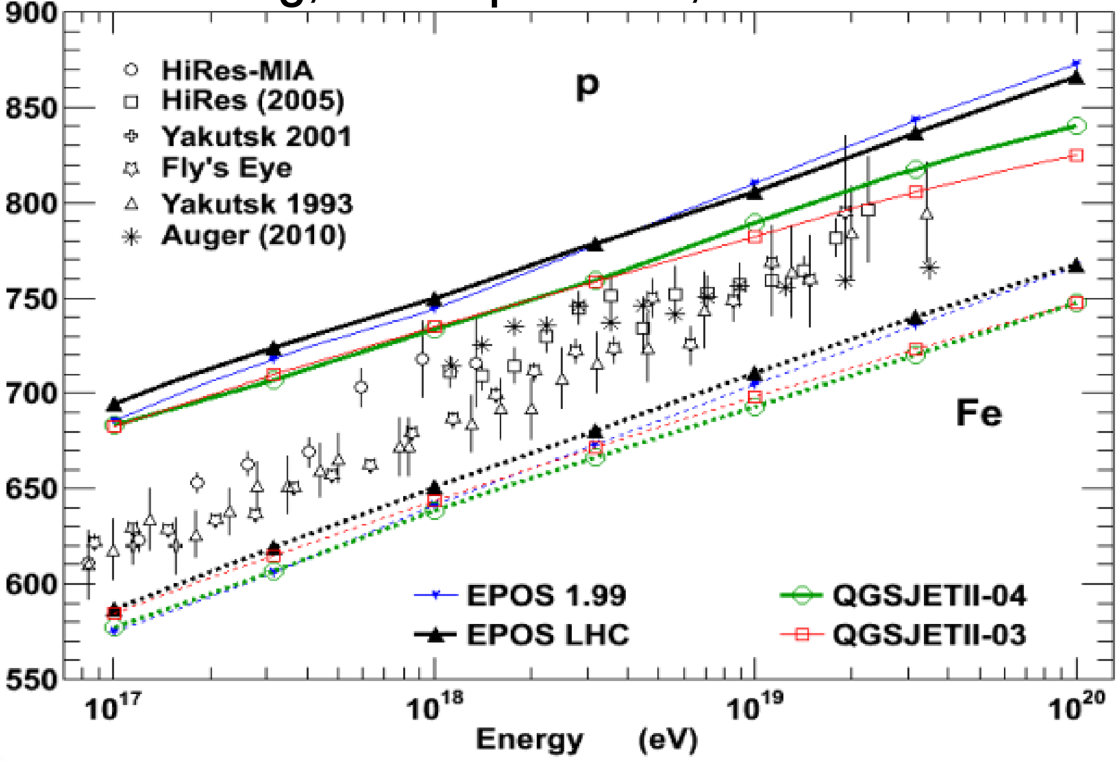
- Retune done for cosmic ray MC (EPOS, QGSJET II) with all the LHC input. (cross section, forward energy flow, LHCf, etc.)
- Uncertainty reduced from 50 gcm^2 to 20gcm^2 (p-Fe difference is 100gcm^2)

Detal reanlaysis of UHECR is also needed for conclusion.

T.Pierog, S.Ostapchenko, ISVHECRI2012



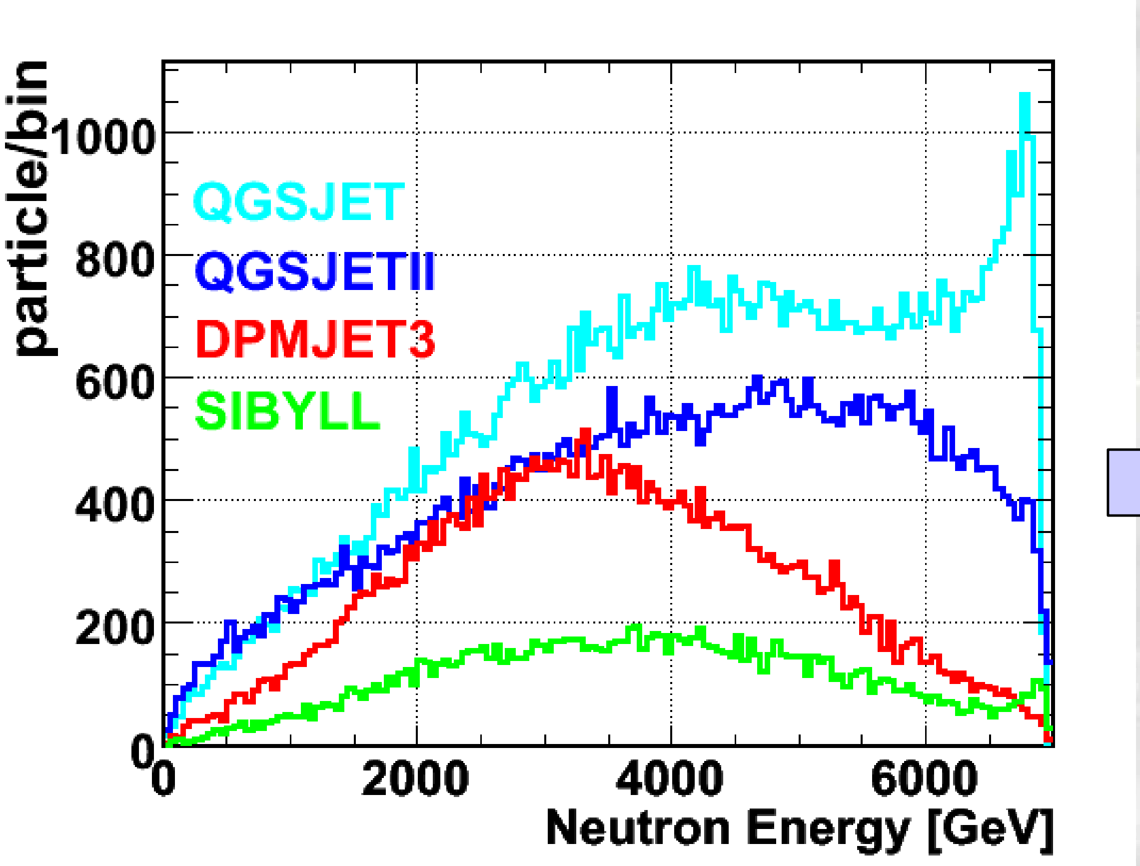
Before LHC



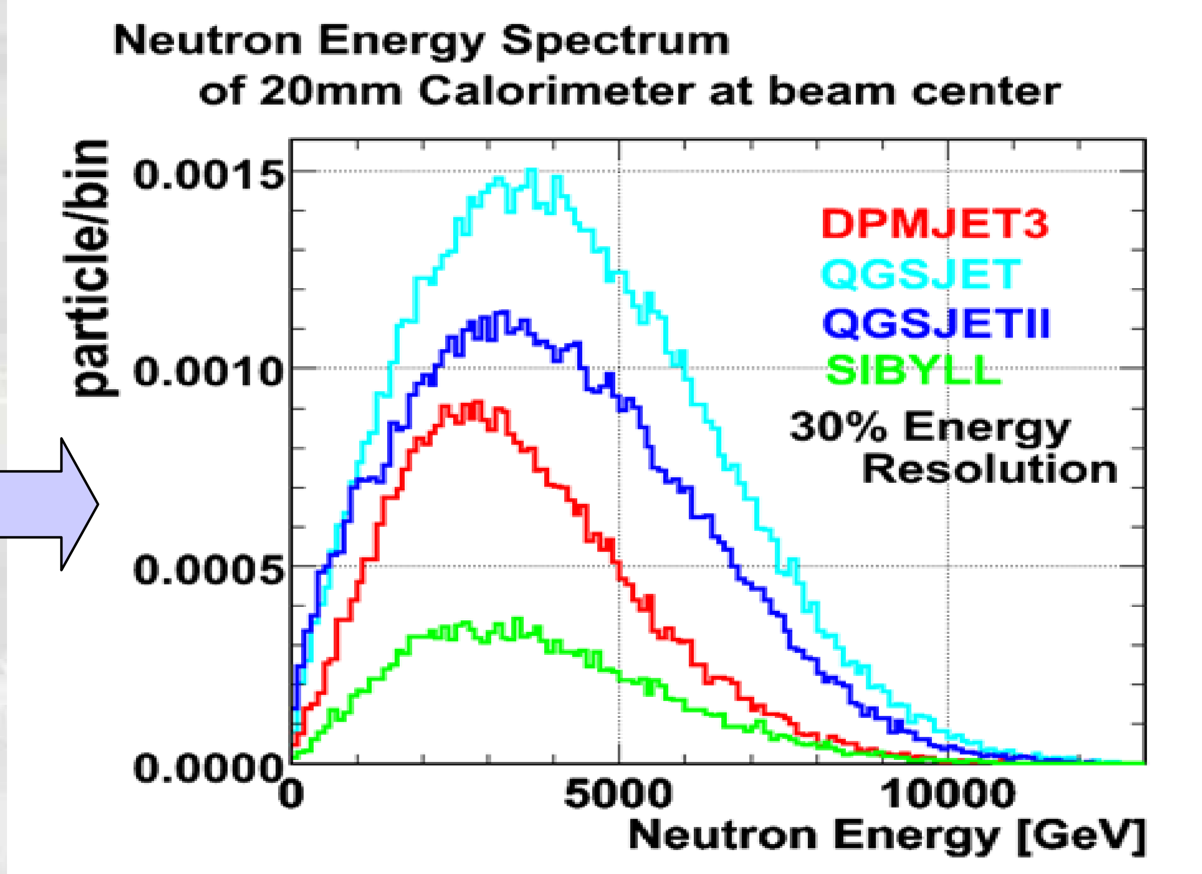
After LHC

Next issue: Inelasticity~ 0 degree neutrons

- E-spectrum, n/γ ratio
- Important for X_{max} and also N_{μ}
- Measurement of inelasticity at LHC energy

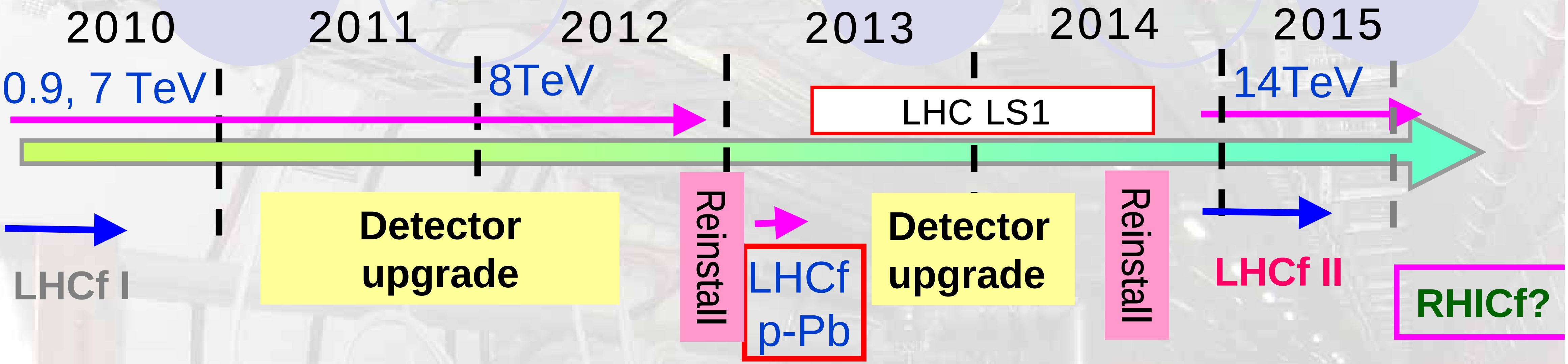


Neutral hadrons at 14 TeV
(LHCf acceptance, no resolution)

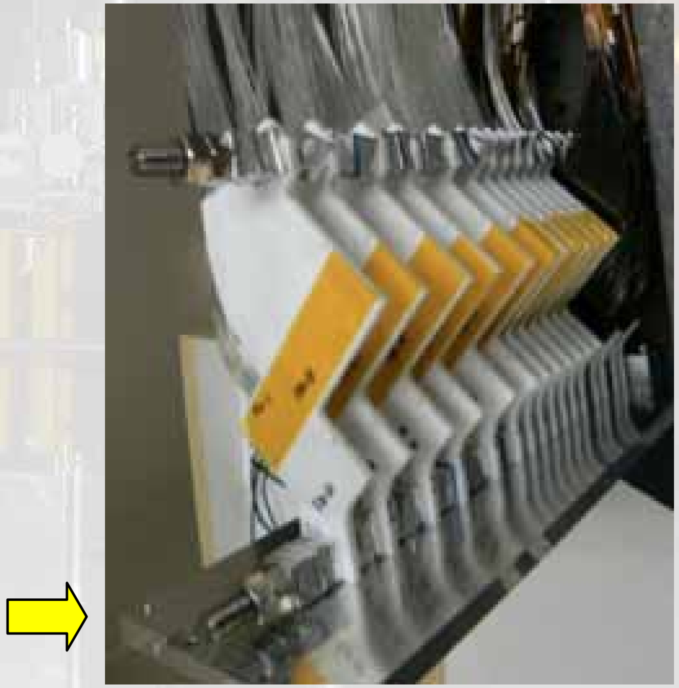


Neutral hadrons at 14 TeV
(LHCf acceptance, 30% resolution)

LHCf future plan



- Analysis ongoing for 2010 data
  - Neutron energy spectra → inelasticity.
- Reinstall Arm2 for p-Pb in early 2013
  - Very important information for nuclear effect.
  - Under discussion of common triggers for combined analysis w/ ATLAS detector.
- Reinstall Arm1+2 for 14TeV in 2014
  - Now upgrading detectors w/ rad-hard GSO.



- **A new measurement at RHIC 0 degree**
  - Under discussions for 500GeV p+p and d + light-A **(or p-A?).**
- Far future (>2020?) p-N and N-N collisions at LHC ?

0-degree measurement for A-A, p-A

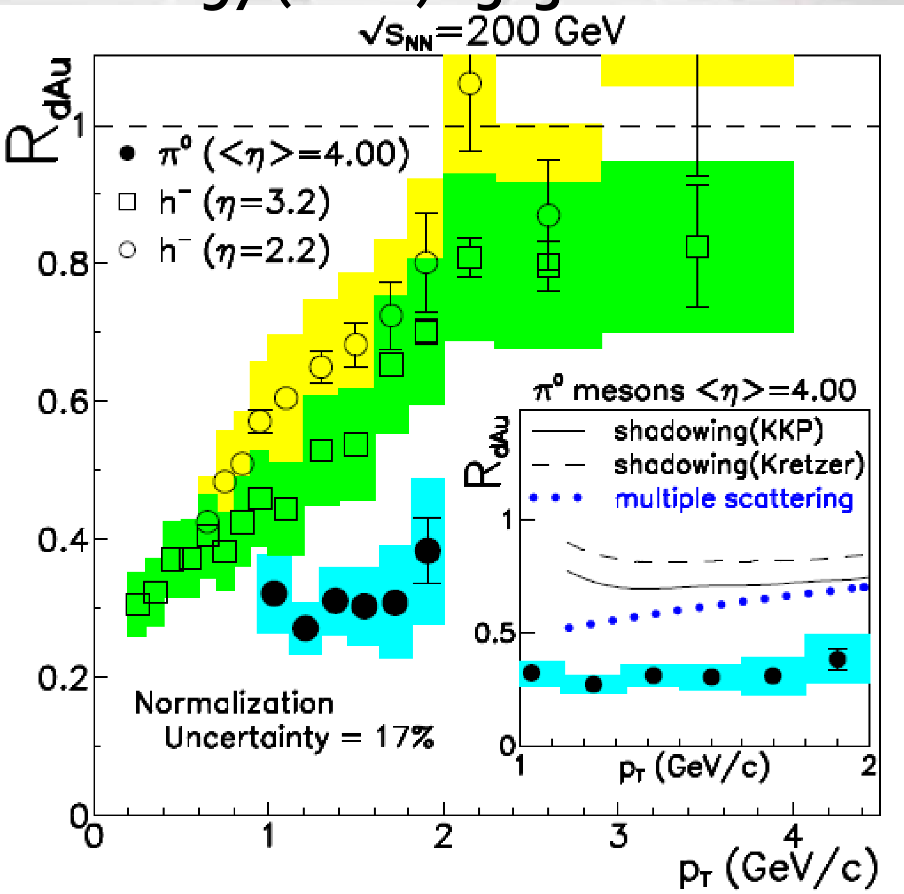
- Air is not actually Hydrogen but mostly Nitrogen !
- CRs are mostly protons but maybe Fe for >10^{19}eV ?
- Can we estimate p-N / Fe-N from p-p data for very forward regions ?
- How we can extrapolate to 10^{20}eV ?
- We need to understand
  - nuclear modification in th very forward region and low p_T
  - its A-dependence and energy dependence

- Forward data for p-p, p-N and p-HI
- Forward data for Fe-N and Fe-HI
- These data at various energies

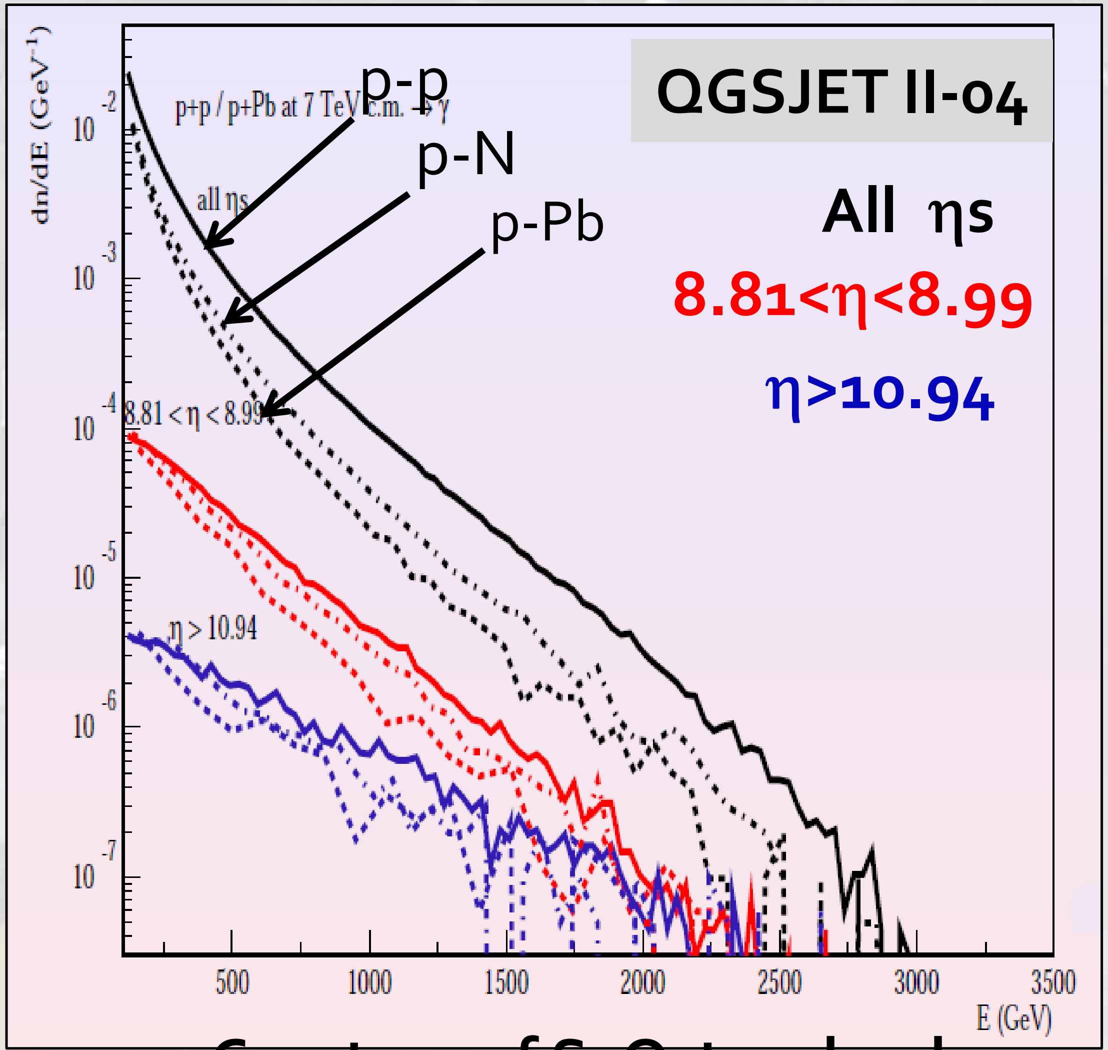
Nuclear effects for very forward region

- Air showers take place via p-N or Fe-N collisions !
  - Nuclear shadowing, final state interaction, gluon saturations
  - Nuclear modification factor at 0 degree may be large.

Phys. Rev. Lett. 97 (2006) 152302

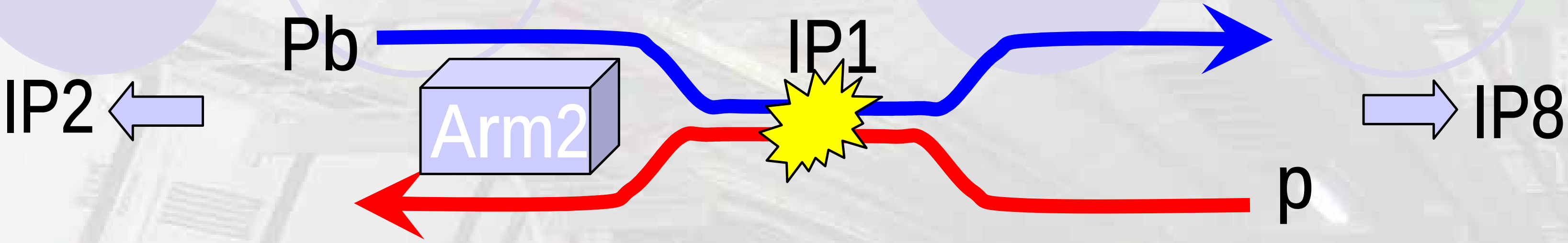


$$R^{Y}_{\rm dAu} = \frac{\sigma^{pp}_{\rm inel}}{\langle N_{\rm bin}\rangle \sigma^{dAu}_{\rm hadr}} \frac{E\, d^3\sigma/dp^3(d + Au \to Y + X)}{E\, d^3\sigma/dp^3(p + p \to Y + X)}$$



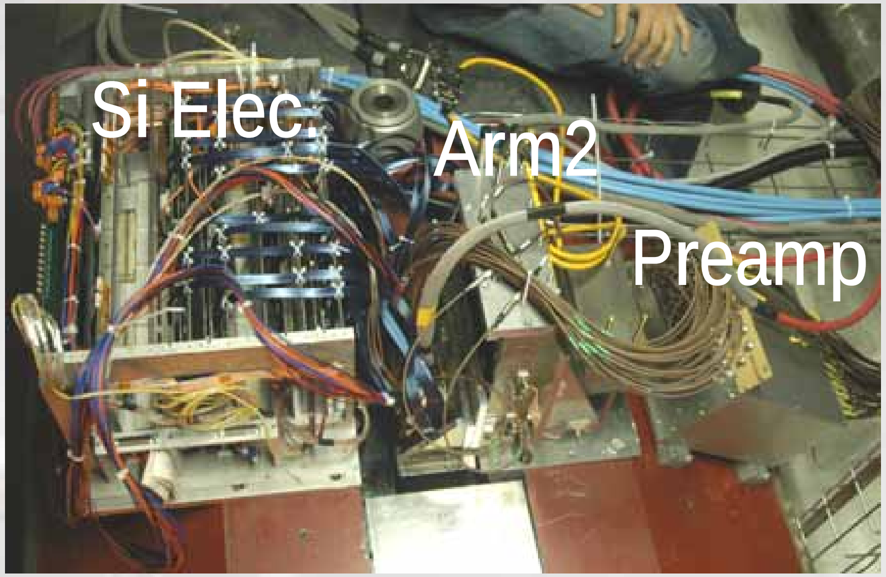
Courtesy of S. Ostapchenko

LHCf p – Pb runs at $\sqrt{s_{NN}}$=4.4TeV (Jan2013)

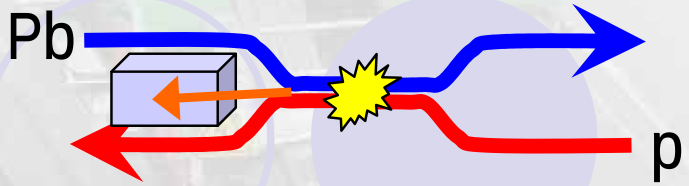


- 2013 Jan / a month of p-Pb opportunity.
  - 3.5TeV p +1.38TeV/n Pb ($\sqrt{s_{NN}}$=4.4TeV)
  - Expected luminosity: $3\times10^{28}cm^{-2}s^{-1}$, σ_{AA}=2b
  - Install only Arm2 at one side (Si tracker good for multiplicity)
  - Trig. exchange w/ ATLAS for centrality tagging

- Requested statistics : Ncoll = 10^8 (Lint = 50 μb^{-1})
  - 2×10^6 single γ
  - 35000 π0
- Assuming L = 10^{26} $cm^{-2}s^{-1}$ (1% of expected lumi)
  - t = 140 h (6 days) !

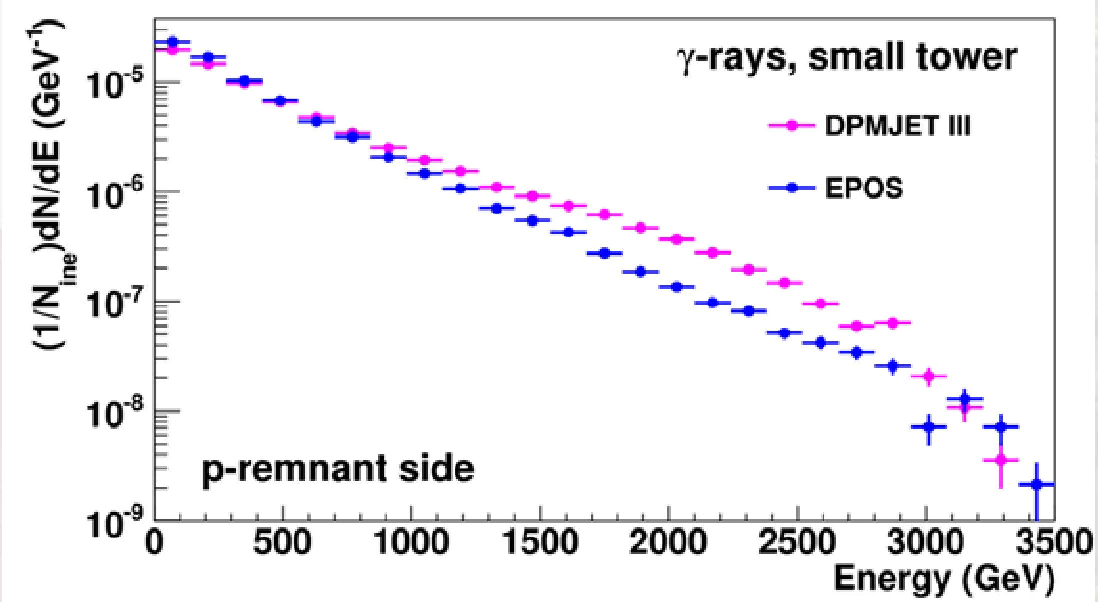


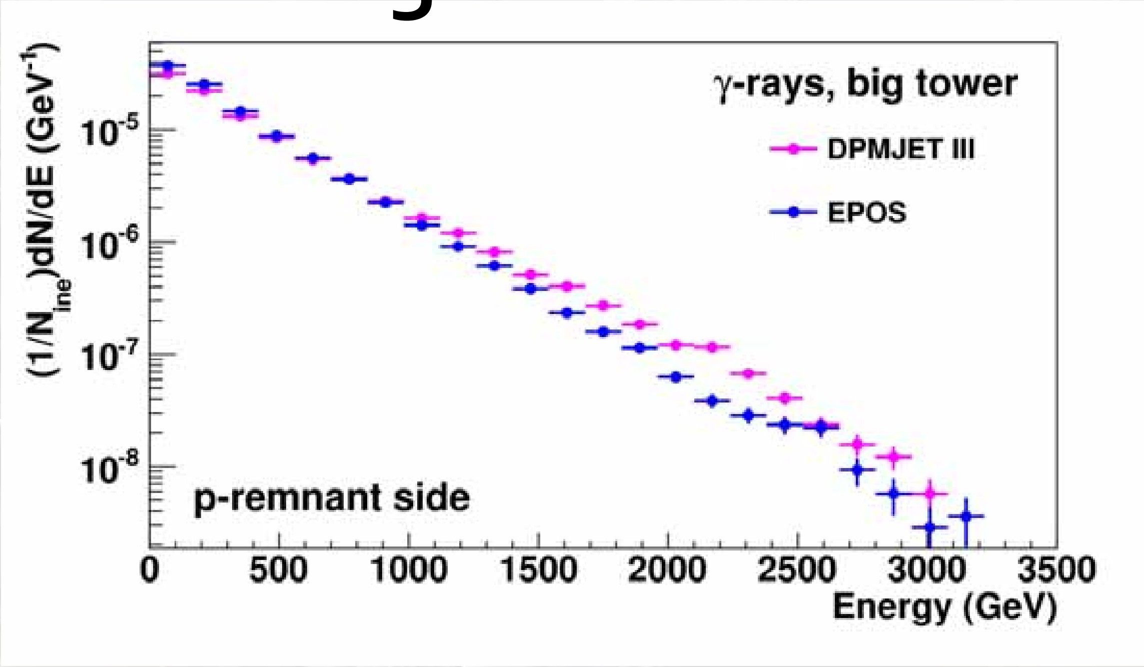
E spectra (proton remnant side)



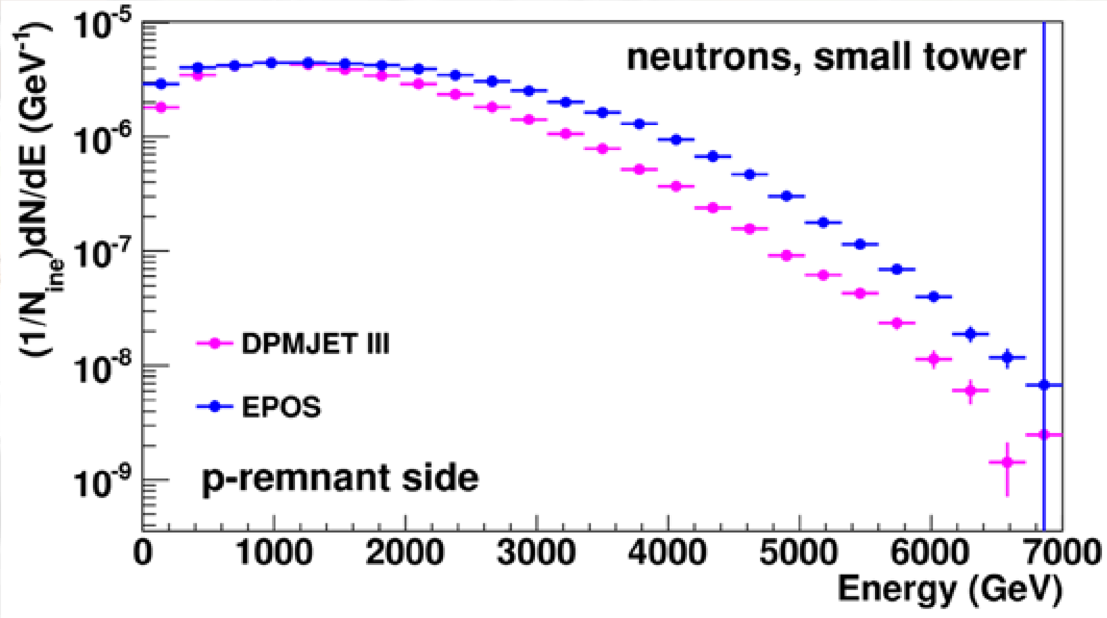
Small tower **Large tower**

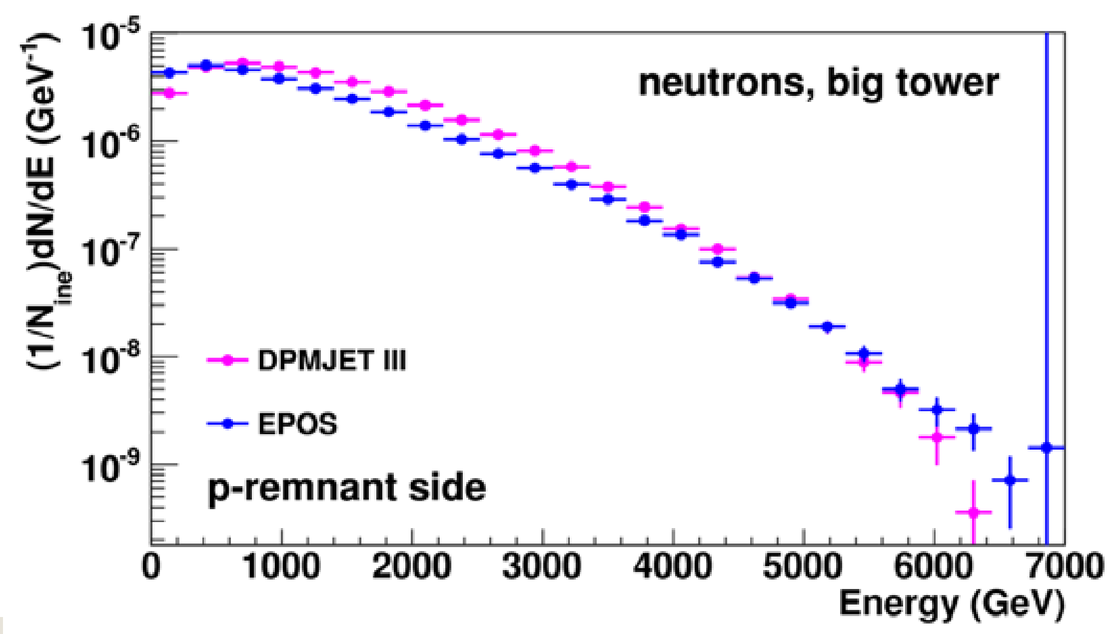
γ





n



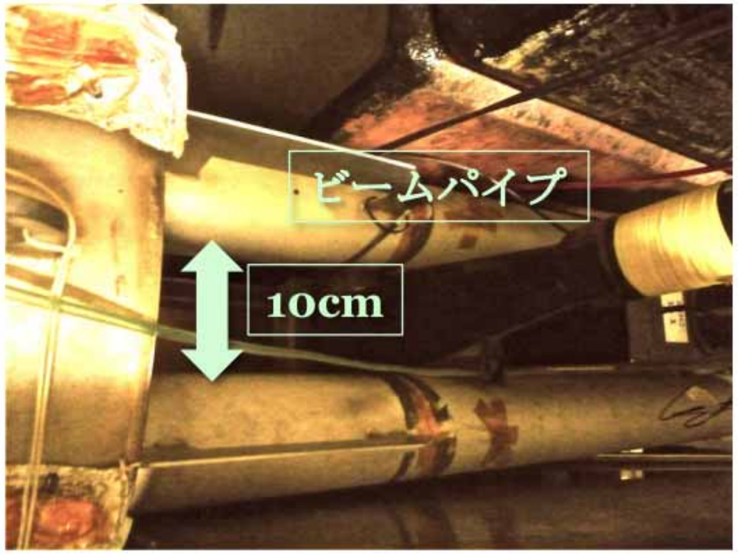


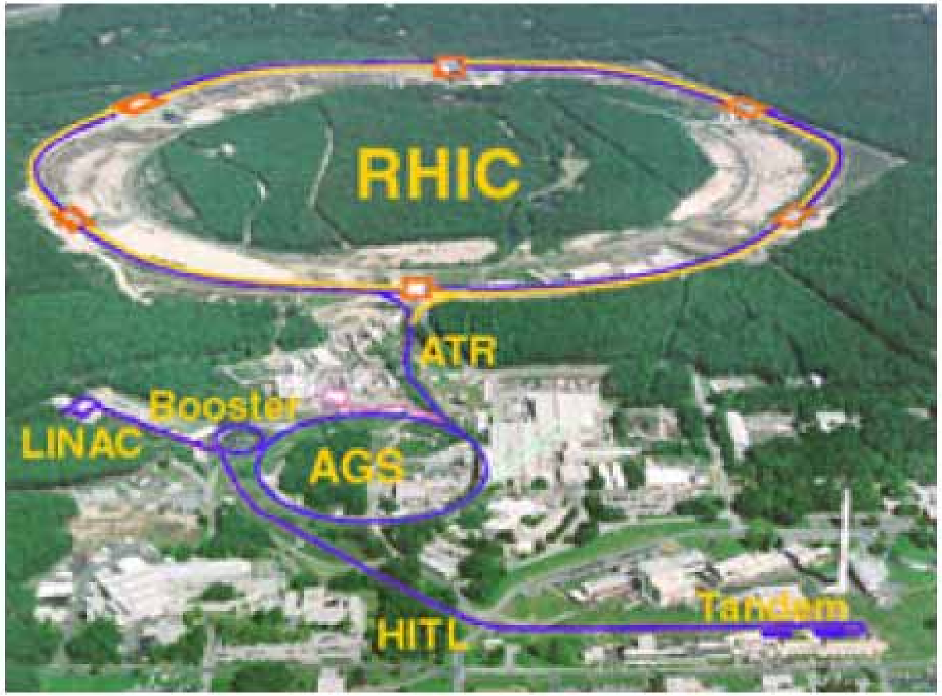
Future p-N and Fe-N in LHC ?

- LHC 7TeV/Z p-N and N-N collisions realize the laboratory energy of 5.2×10^{16}eV and 3.6×10^{17}eV, respectively (N: Nitrogen)
- Suggestions from the CERN ion source experts:
  - LHC can in principle circulate any kind of ions, but switching ion source takes considerable time and manpower
  - Oxygen can be a good candidate because it is used as a 'support gas' for Pb ion production. This reduces the switching time and impact to the main physics program at LHC.
  - According to the current LHC schedule, the realization is not earlier than 2020.
  - New ion source for medical facility in discussion will enable even Fe-N collisions in future

"RHICf" : Possible RHIC 0-degree runs

RHIC also has the zero-degree site





p - p : $\sqrt{s} = 500 GeV$

Just below LHC (E_{CR}~5E13eV)

A - A: $\sqrt{s_{NN}} = 200 GeV$

Au-Au, Cu-Cu or even lighter ?

Advantage of RHIC

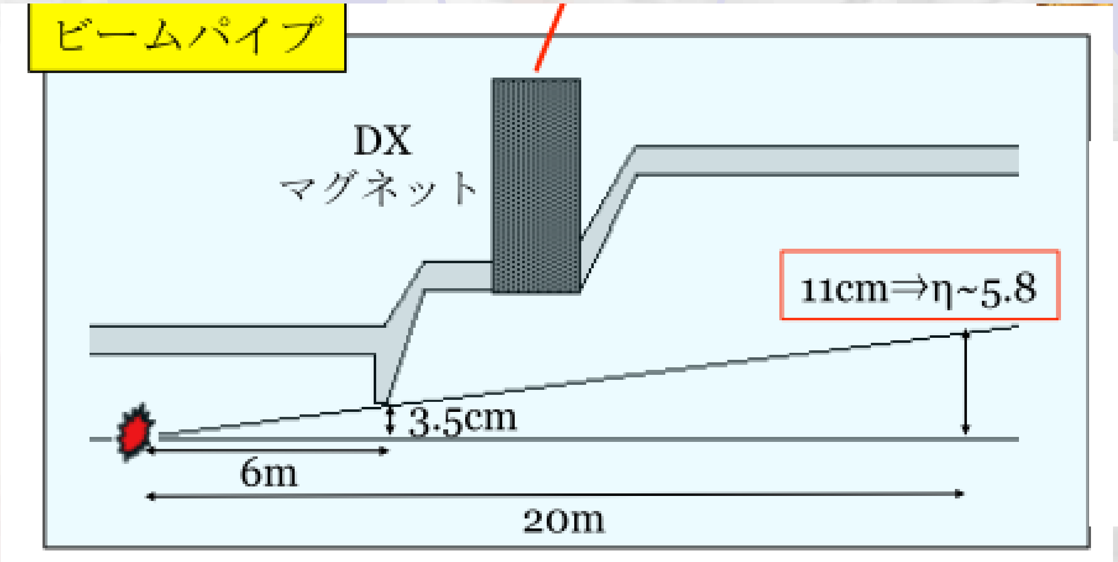
Lower energy data point

Acceptance for π^0

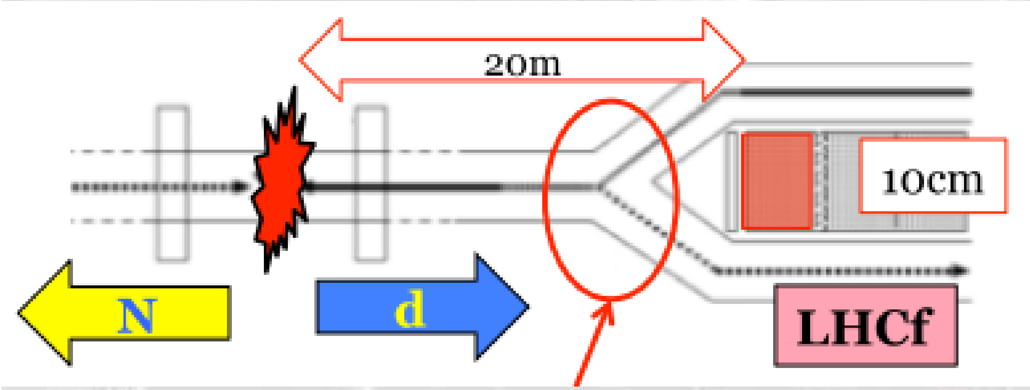
Flexible operation (energy, ion)

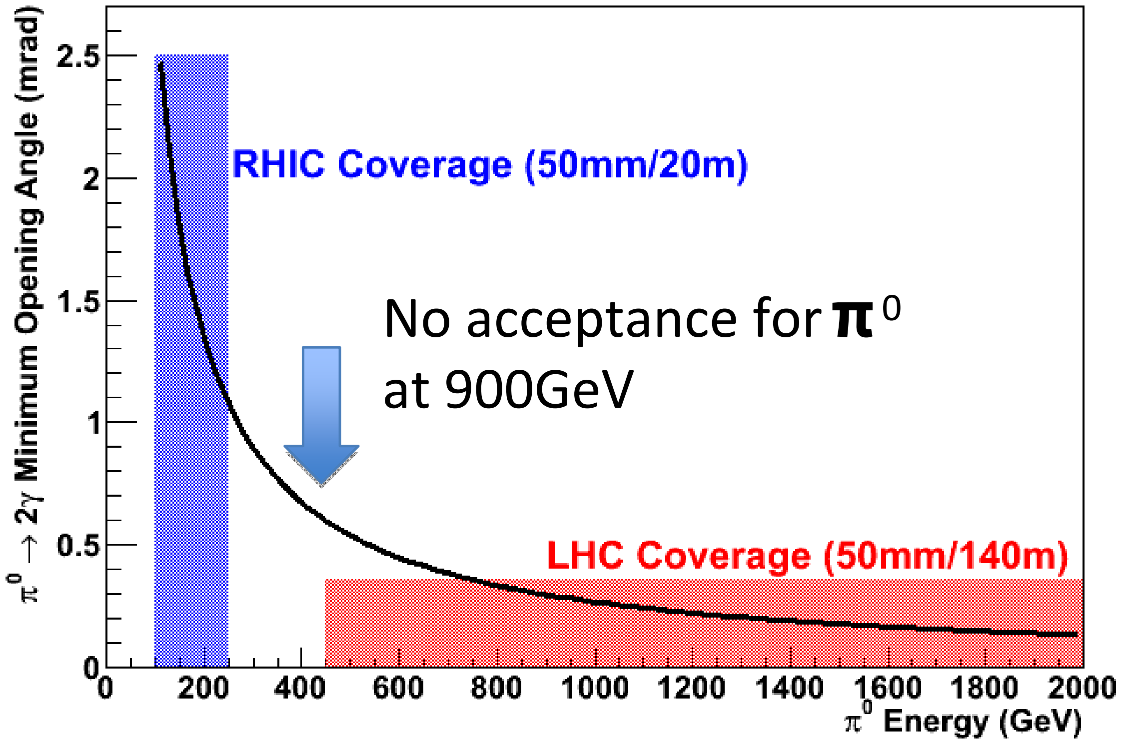
p-N, N-N, Fe-N, etc.....

"RHICf" : η acceptance for 100GeV/n d-N MC

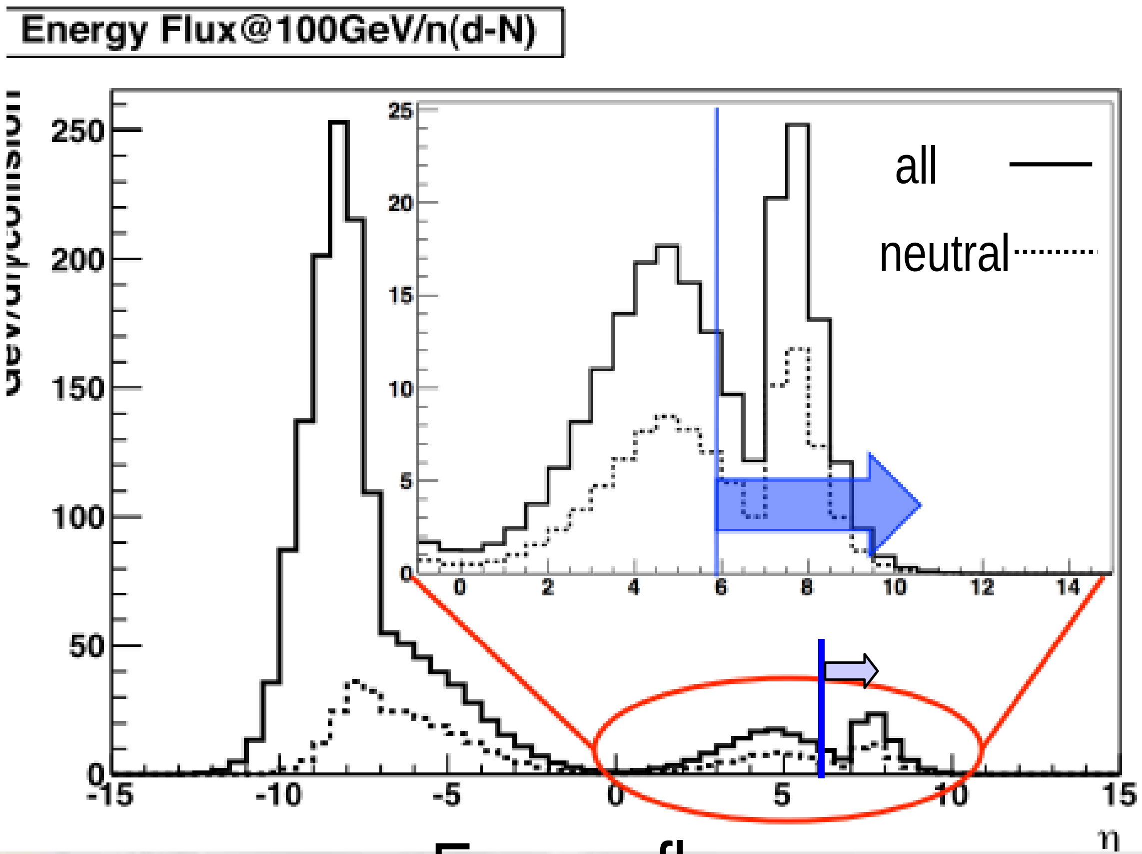


η>5.8 is covered





Acceptance for π0



Energy flow

Summary

- UHECR needs accelerator data to solve the current enigma, and may also hint QCD at beyond-LHC energy.
  - 10^{17}-10^{13}eV is an unique overlap region for colliders and UHECRs
- LHCf provides dedicated measurements of neutral particles at LHC 0 deg to cover most of collision energy flow.
  - E spectra for single gamma at 7TeV and at 900GeV. Agreement is “so-so”, but none of models really agree.
  - PT spectra for 7TeV π^0. EPOS gives nice agreement.
- (Cold) nuclear effect must be tested by p-A at 0degree
  - LHCf p-Pb run in Jan 2012
  - RHIC pp, pA, AA runs are feasible opportunity.
  - LHC light ion runs would be possible but far future.

International Workshop on "High-energy scattering at zero degree"

2nd - 4th March, 2013
KMI, Nagoya University

Organizing committee

Yoshitaka Itow (Nagoya)
Kazunori Itakura (KEK)
Yuji Goto (Riken)
Takashi Sako (Nagoya)
Kenta Shigaki (Hiroshima)
Kiyoshi Tanida (Seoul National)
Yuji Yamazaki (Kobe)

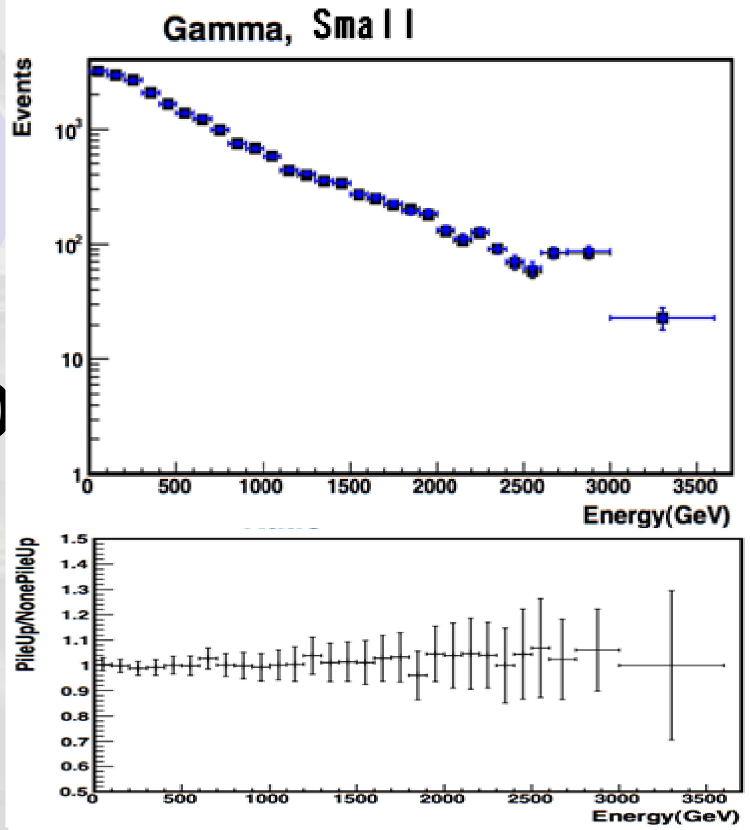
- Diffraction and very forward p-p and p-A scatterings
- Forward and ultra peripheral A-A scatterings
- Spin asymmetry at very forward in polarized p-p scatterings
- High energy cosmic ray interaction models
- QCD aspects in very forward scattering

Workshop site will soon open. Check "topic" in http://www.gcoe.phys.nagoya-u.ac.jp/index_e.html

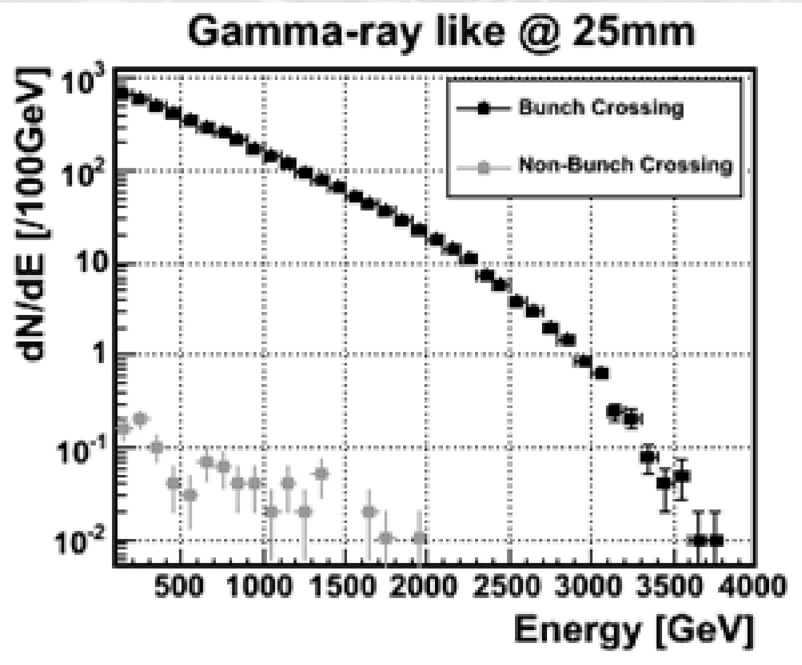
Backup

Beam Related Effects

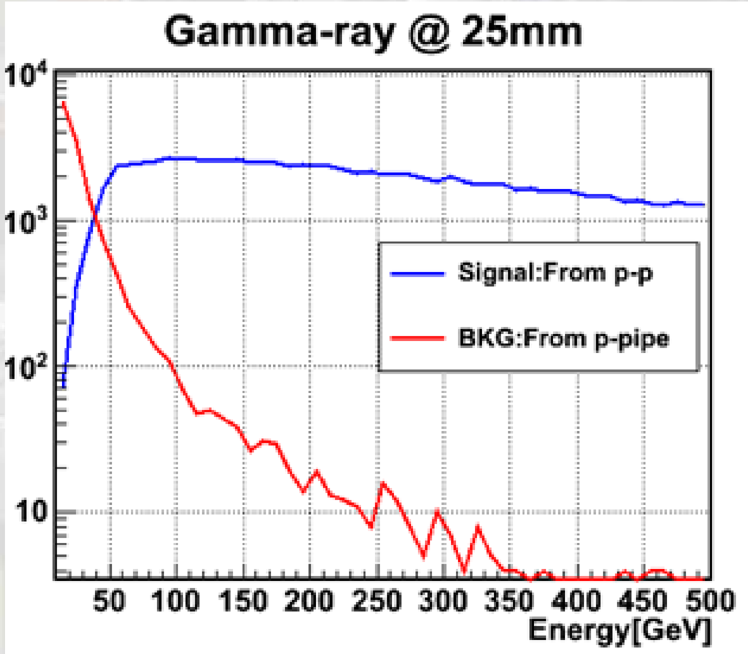
- ✓Pile-up (7% pileup at collisio
- ✓Beam-gas BG
- ✓Beam pipe BG
- ✓Beam position (next slide)



MC w/ pileup vs w/o pileup

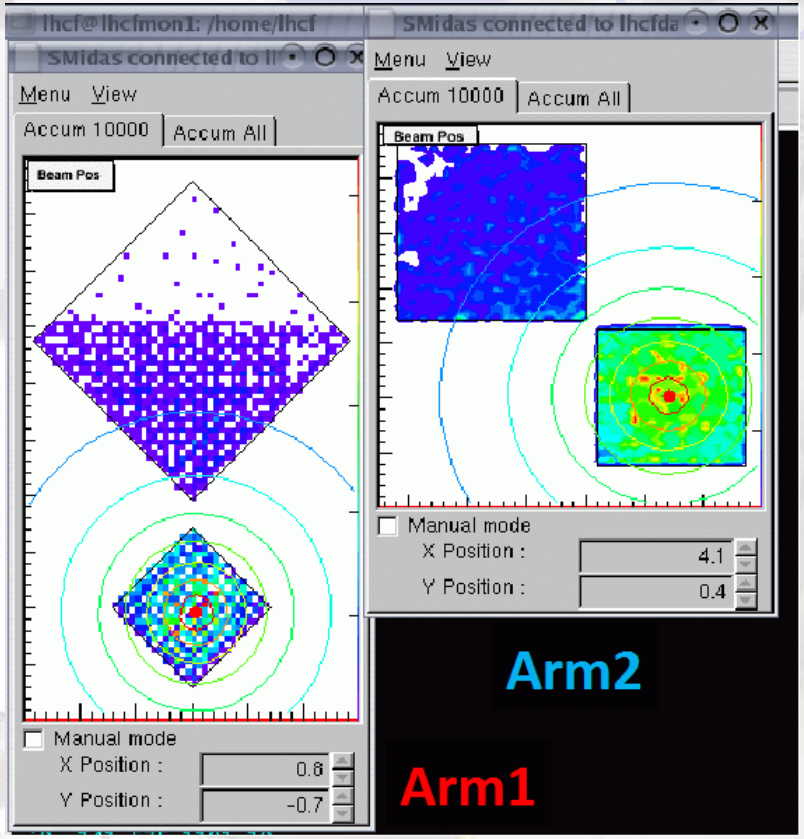


Crossing vs non-crossing bunches

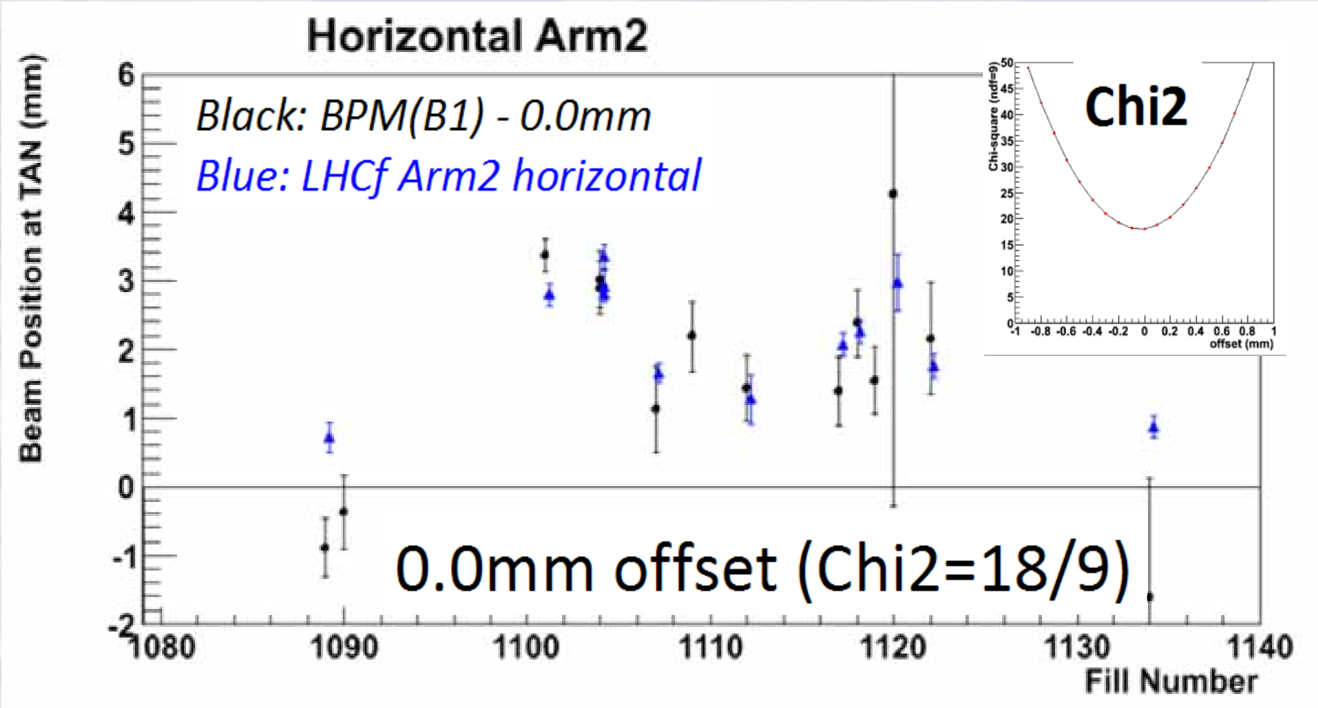


Direct vs beam-pipe photons

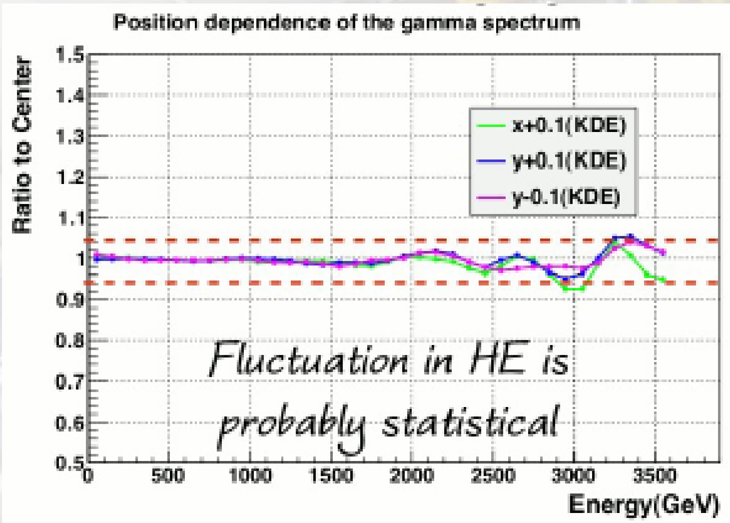
Where is zero degree?

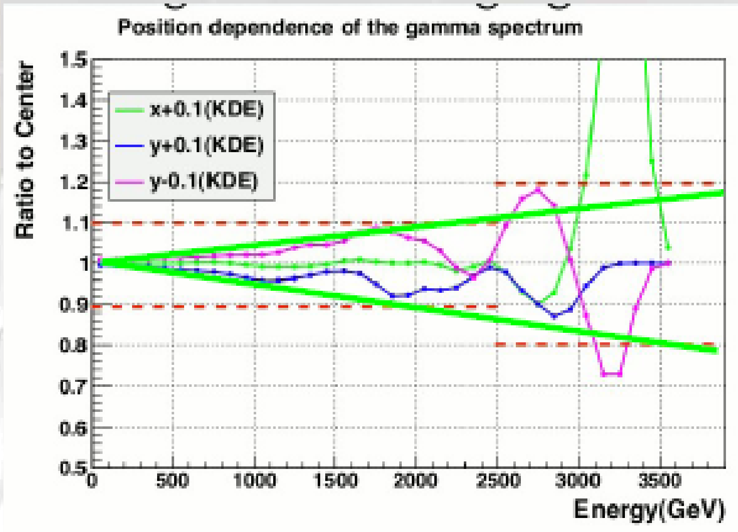


LHCf online hit-map monitor



Beam center LHCf vs BPMSW



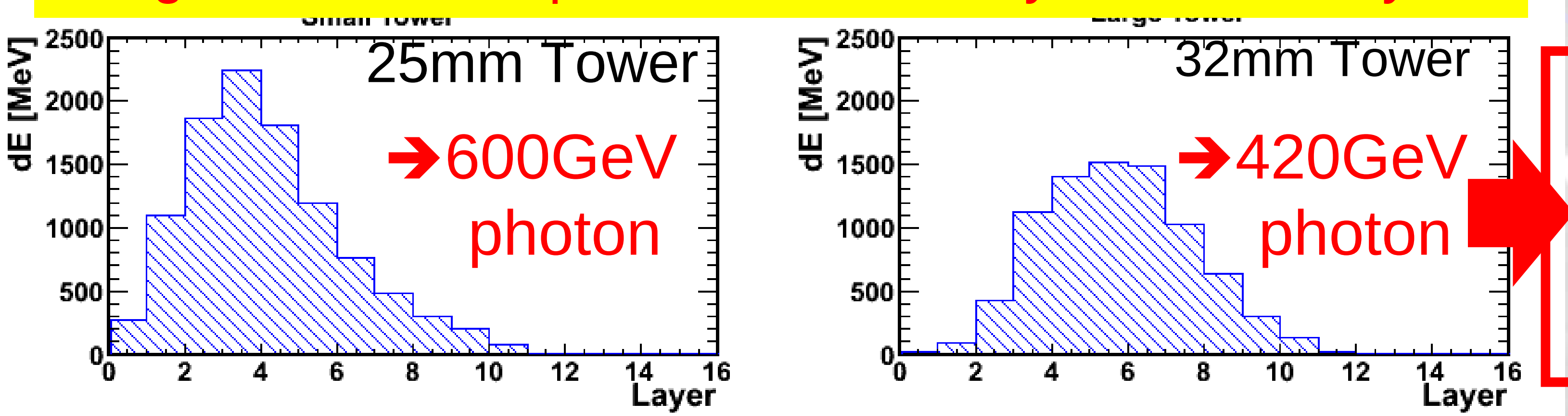


Effect of 1mm shift in the final spectrum

LHCf calorimeters

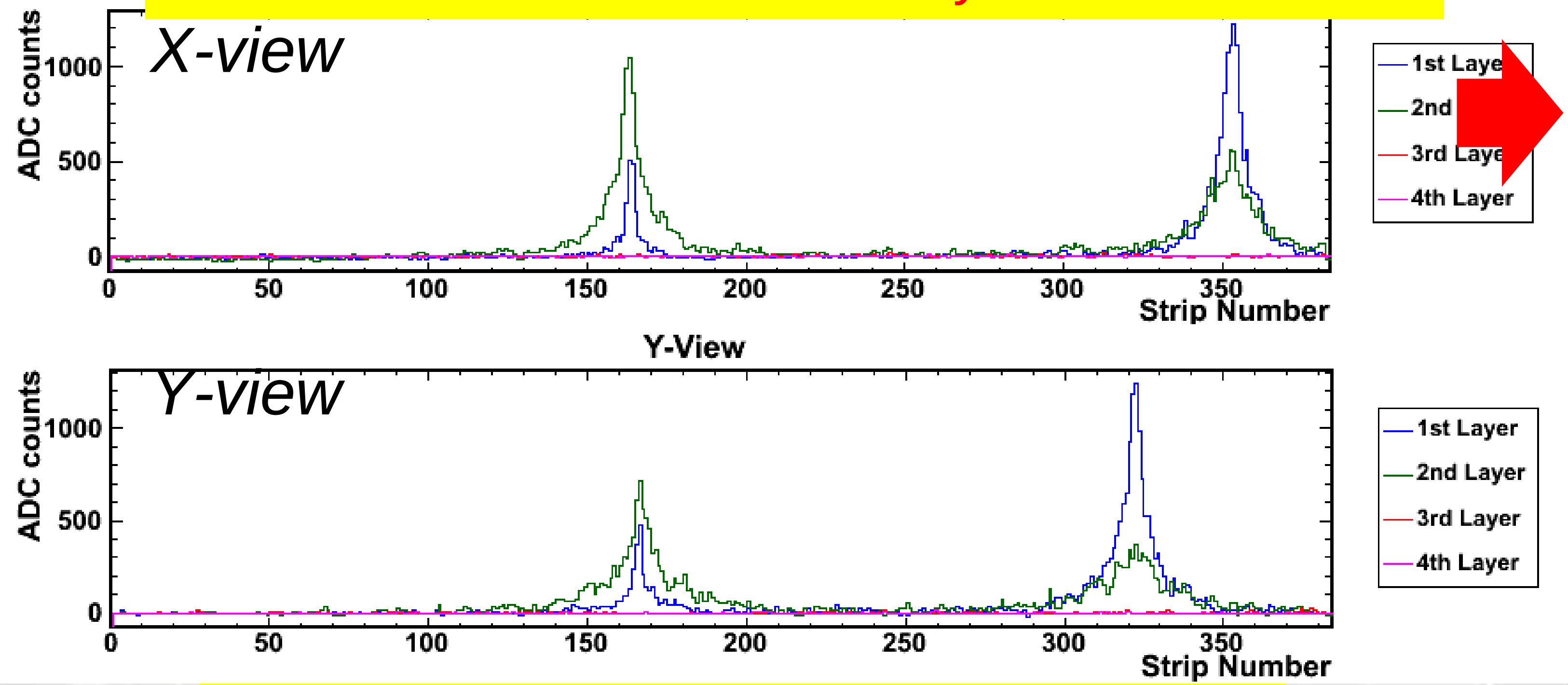
Event sample ($\pi^0 \rightarrow 2\gamma$)

Longitudinal development measured by scintillator layers



Total Energy deposit
➔Energy
Shape
➔PID

Lateral distribution measured by silicon detectors

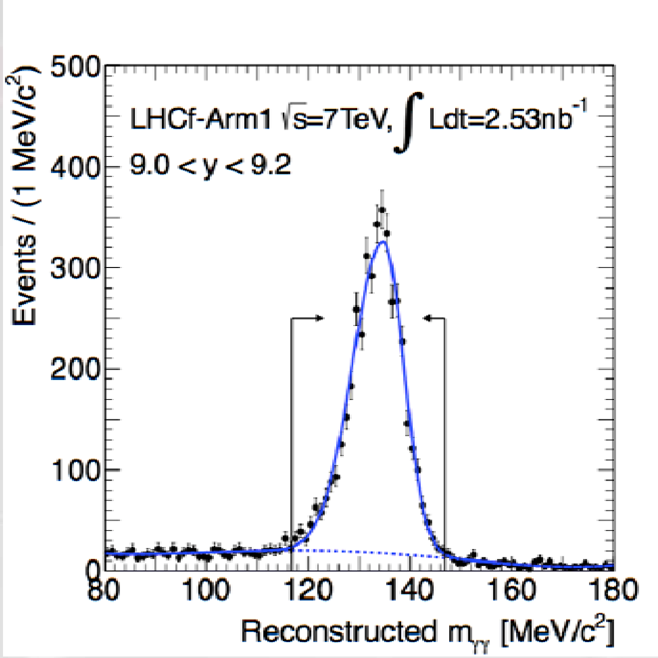


Hit position,
Multi-hit search.

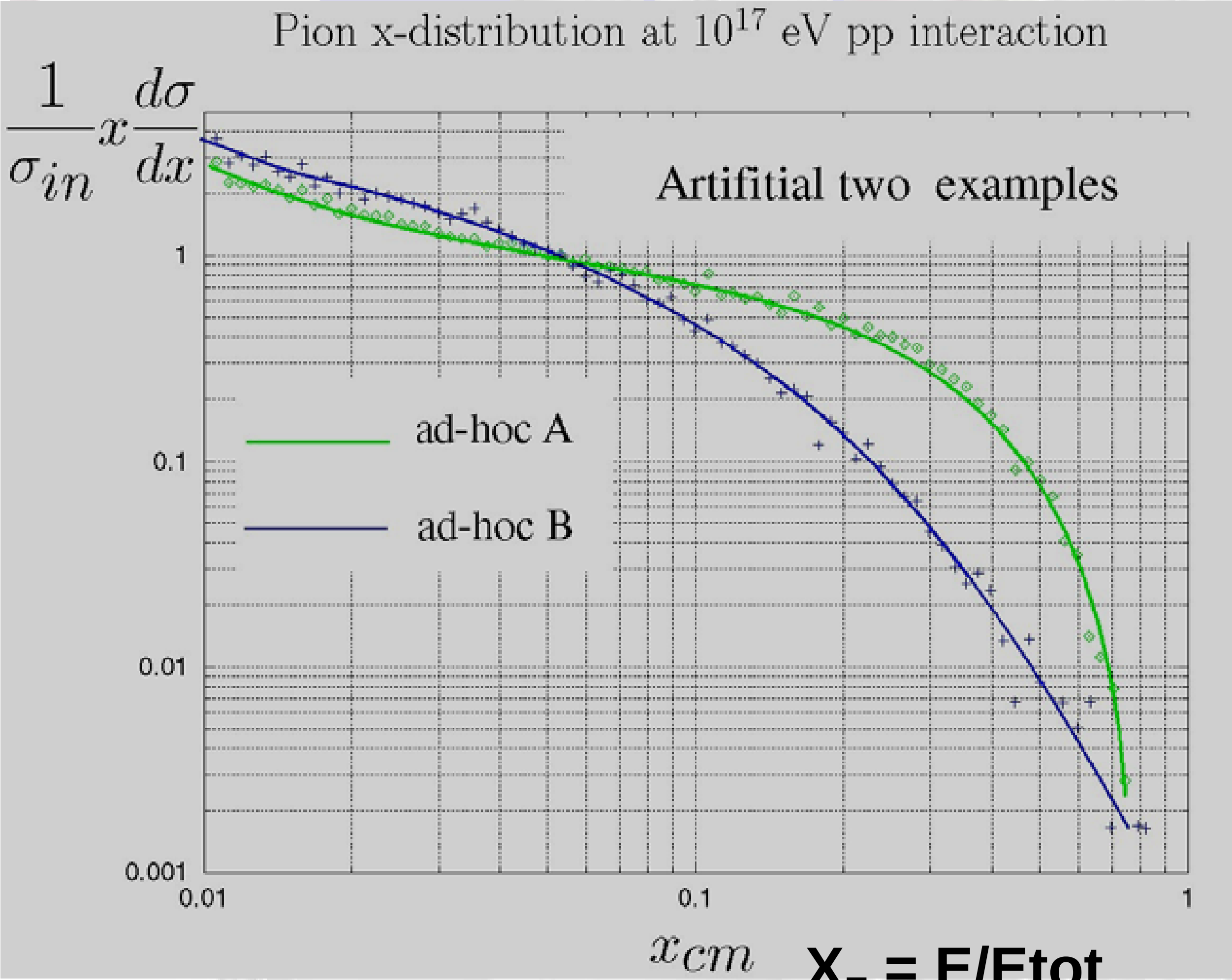
π^0 mass reconstruction from two photon.

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

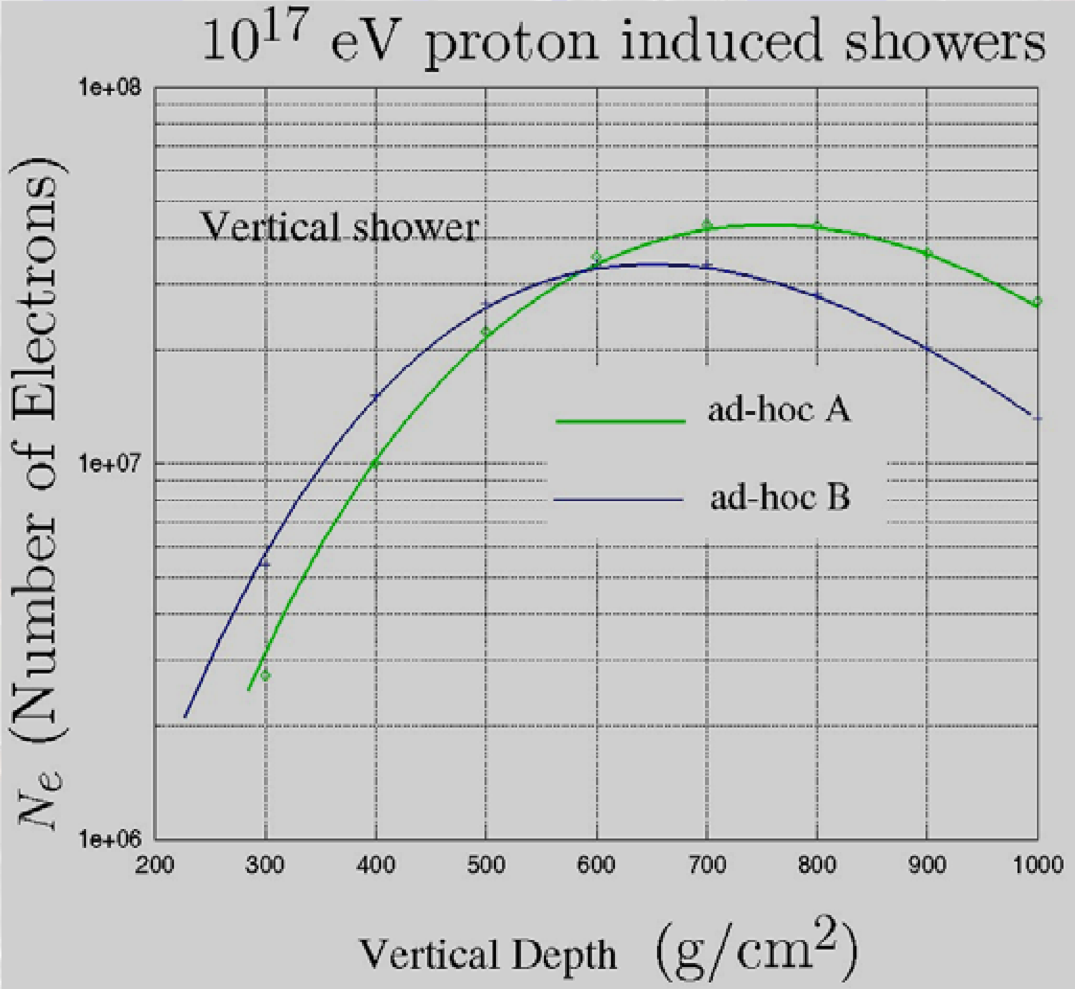
Systematic studies



Forward production spectra vs Shower curve



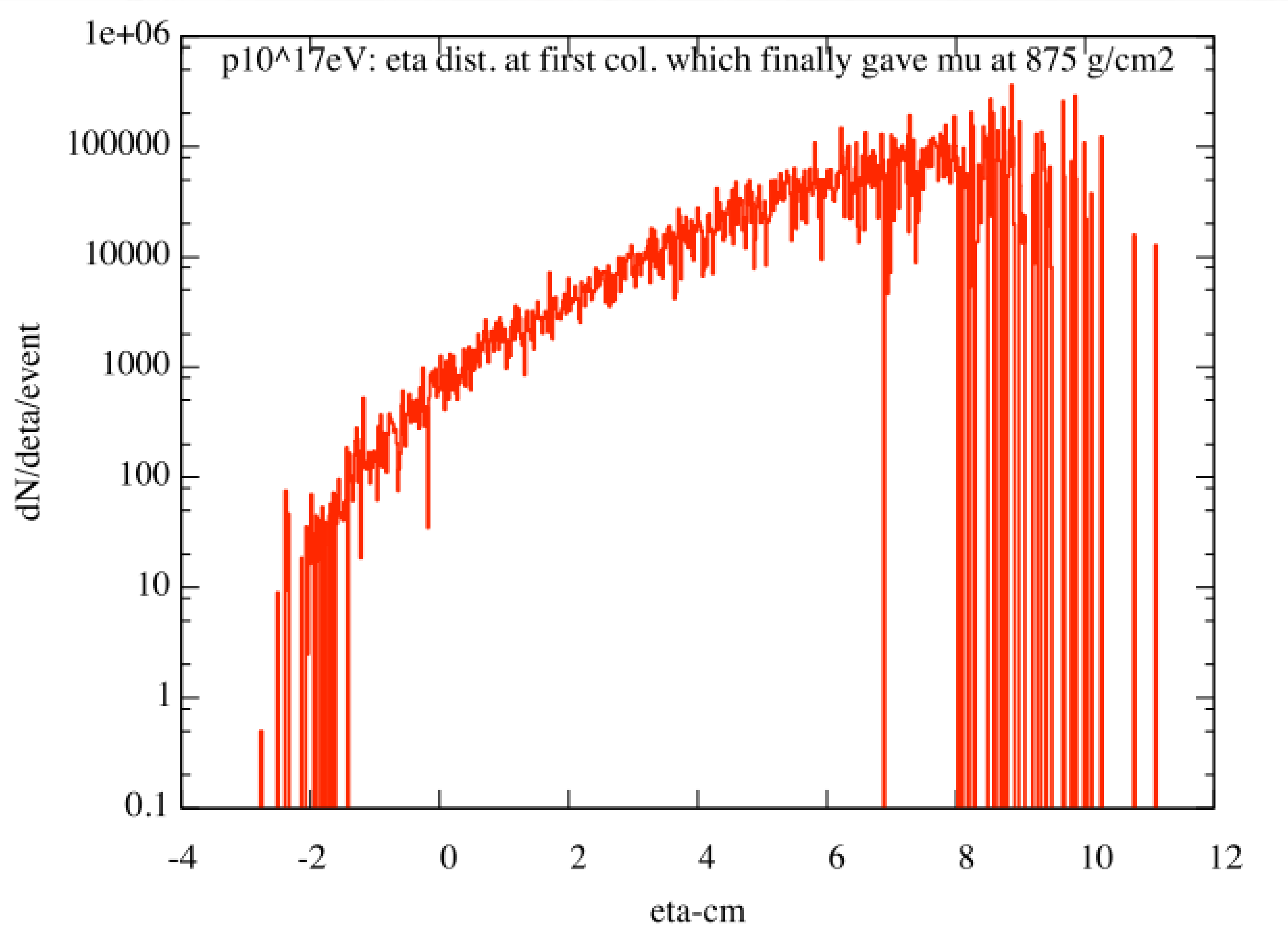
X_F = E/Etot



Half of shower particles comes from large X_F γ

Measurement at very forward region is needed

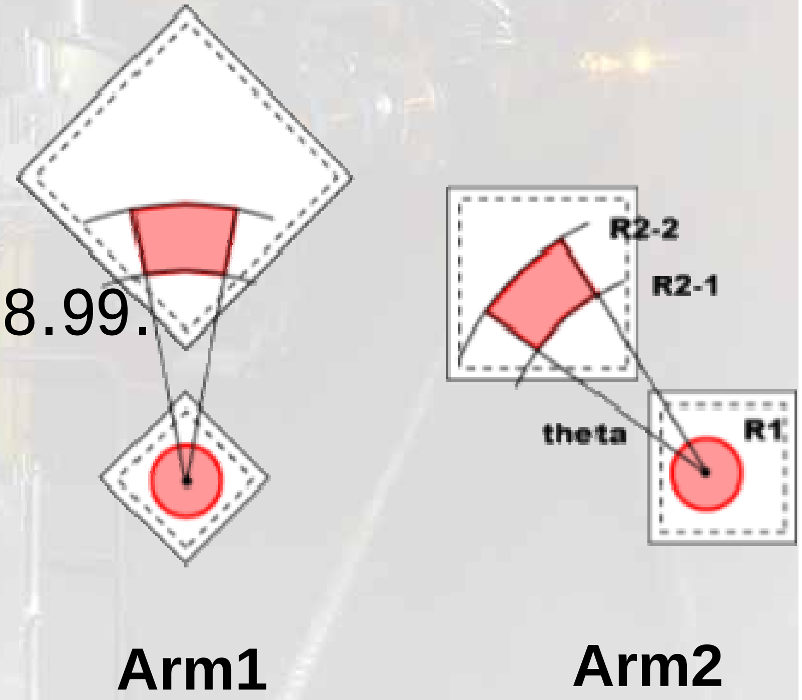
Parent π^0 pseudorapidity producing ground muons



The single photon energy spectra at 0 degree at 7TeV

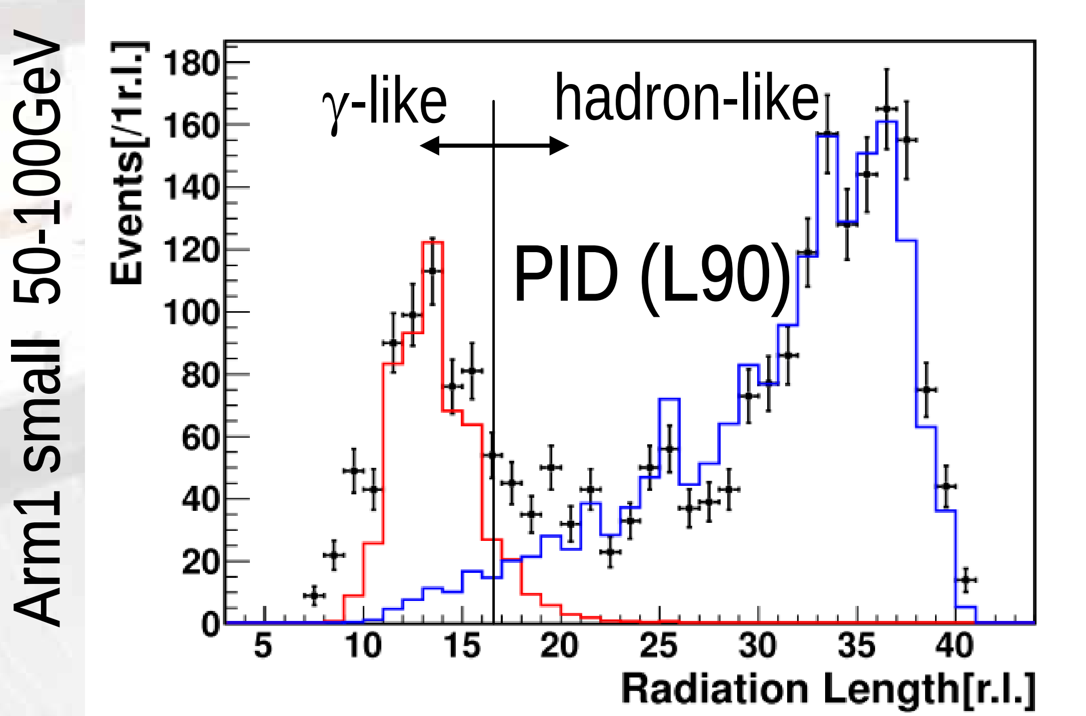
(O.Adriani et al., PLB**703 (2011) 128-134**

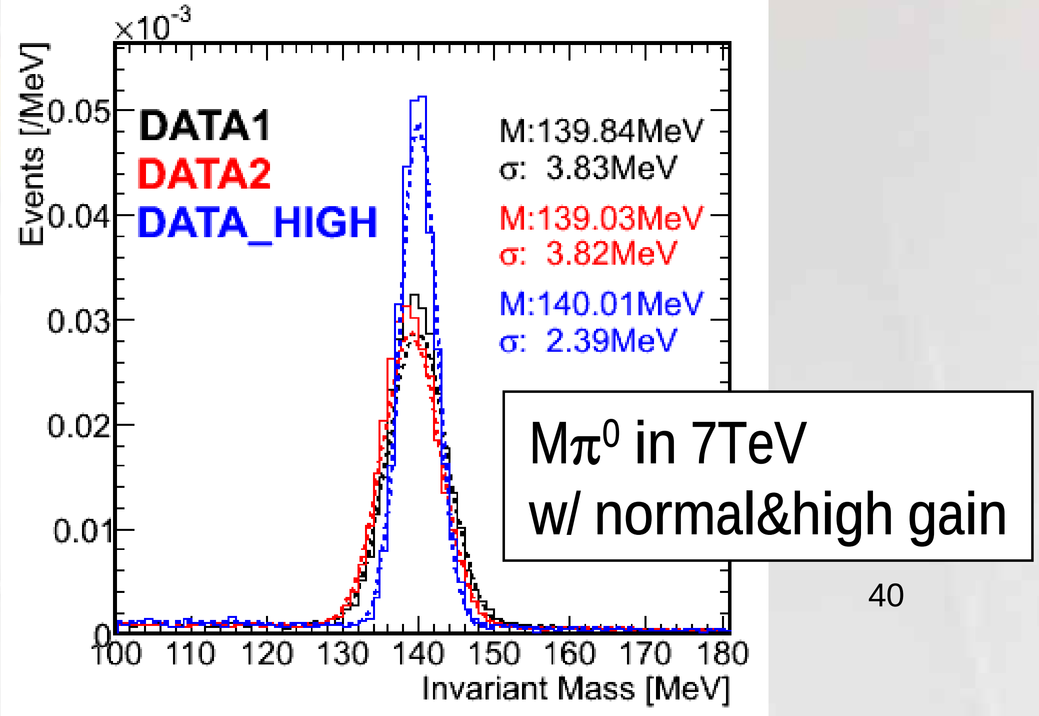
- DATA
  - 15 May 2010 17:45-21:23, at Low Luminosity $6\times10^{28}cm^{-2}s^{-1}$, no beam crossing angle
  - 0.68 nb-1 for Arm1, 0.53nb-1 for Arm2
- MC
  - DPMJET3.04, QGSJETII03, SYBILL2.1, EPOS1.99 PYTHIA 8.145 with the default parameters.
  - 10^7 inelastic p-p collisions by each model.
- Analysis
  - Two pseudo-rapidity, η>10.94 and 8.81<η<8.99.
  - No correction for geometrical acceptance.
  - Luminosity by FrontCounter (VdM scan)
  - **Normalized by number of inelastic collisions** with assumption as σ_{inela} = 71.5mb. (c.f. $73.5\pm0.6^{+1.8}_{-1.3}$ mb by TOTEM)



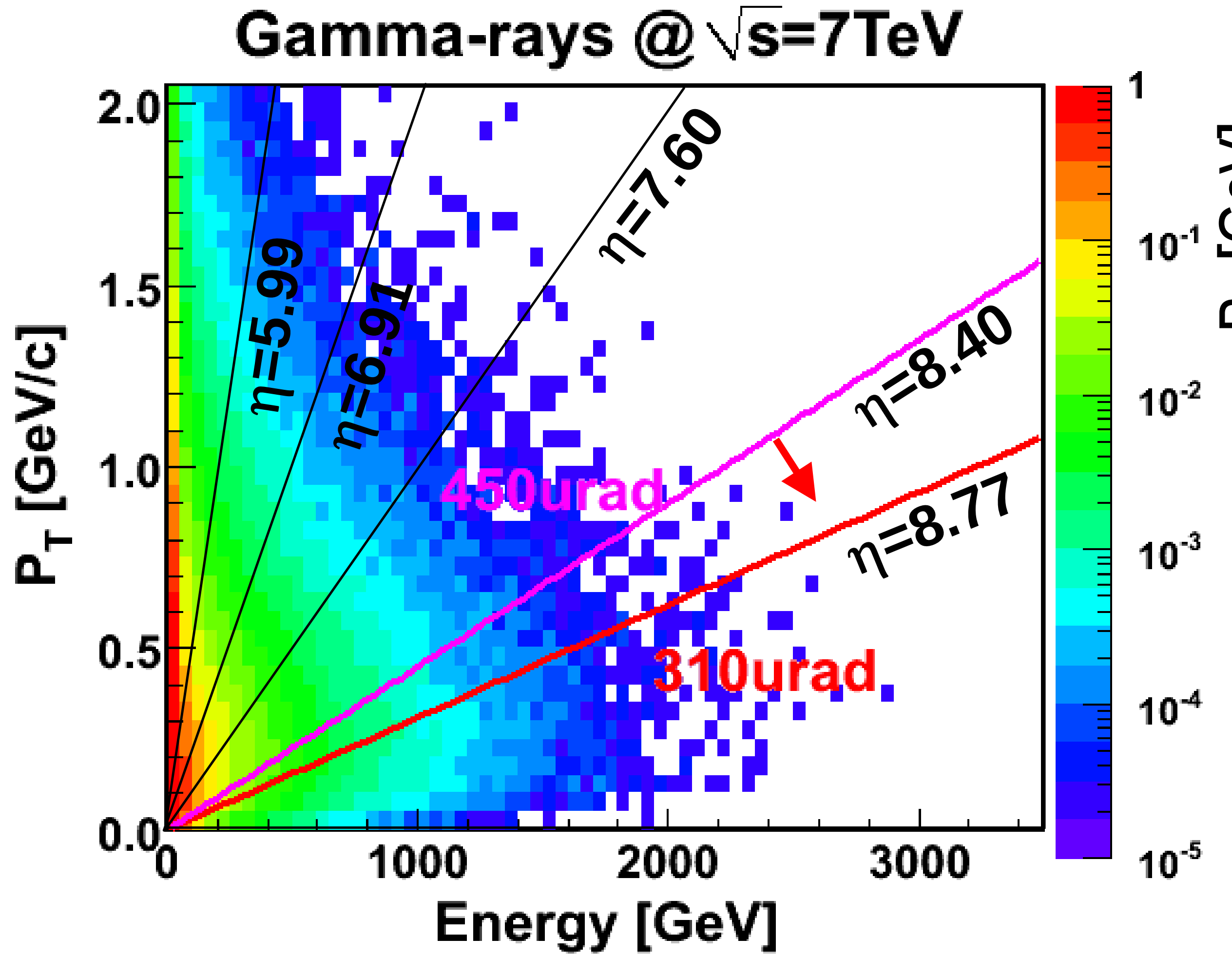
New 900 GeV single γ analysis

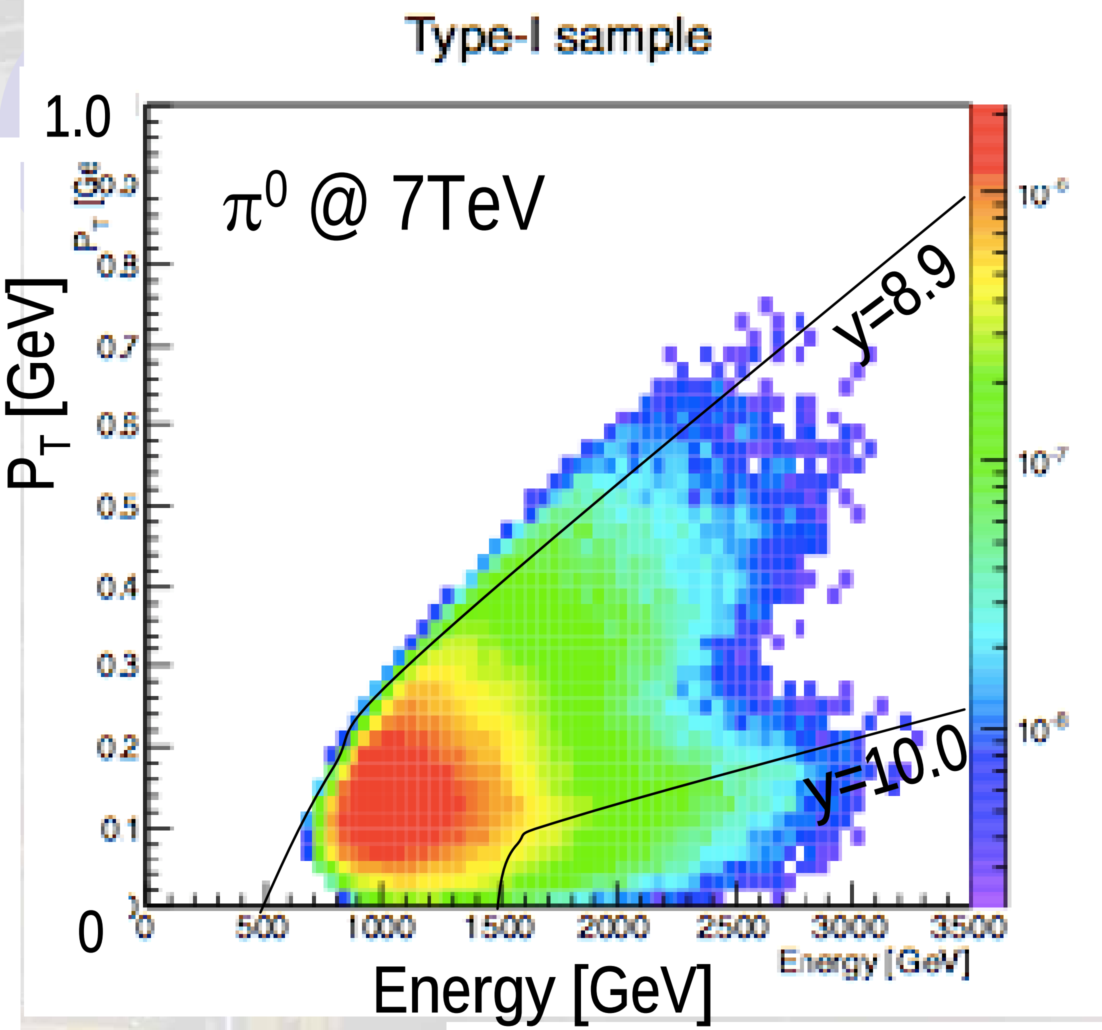
- 0.3nb^{-1} data (44k Arm1 and 63k Arm2 events) taken at 2,3 and 27 May, 2010
- Low luminosity (L~10^{28} typical,1 or 4 xing), negligible pile up (0.05 int./xing).
- Relatively less η-dependence in the acceptance. Negligible multi-incidents at a calorimeter (~ 0.1 γ (>50GeV) /int.)
- Higher gain operation for PMTs. Energy scale calibration by SPS beam, checked with π^0 in 7TeV data.

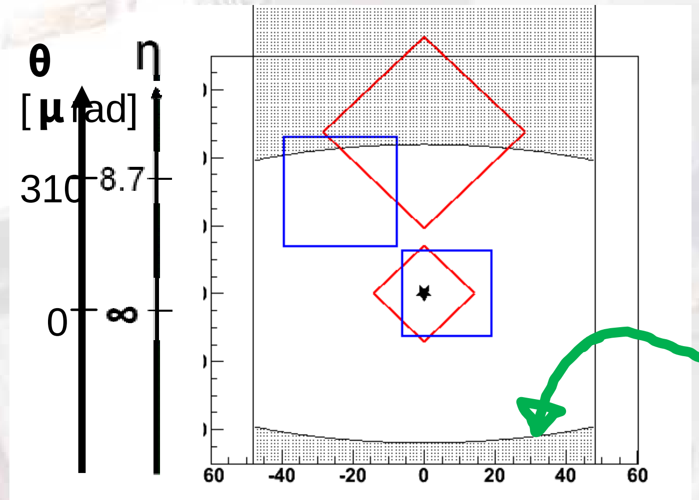




LHCf γ / π^0 measurement



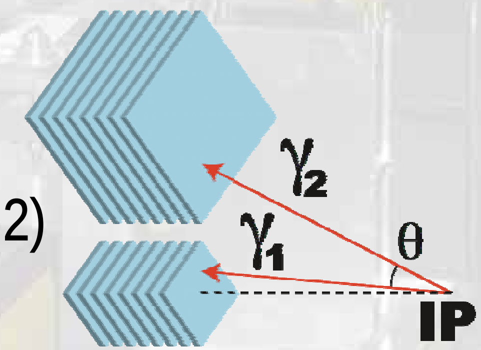


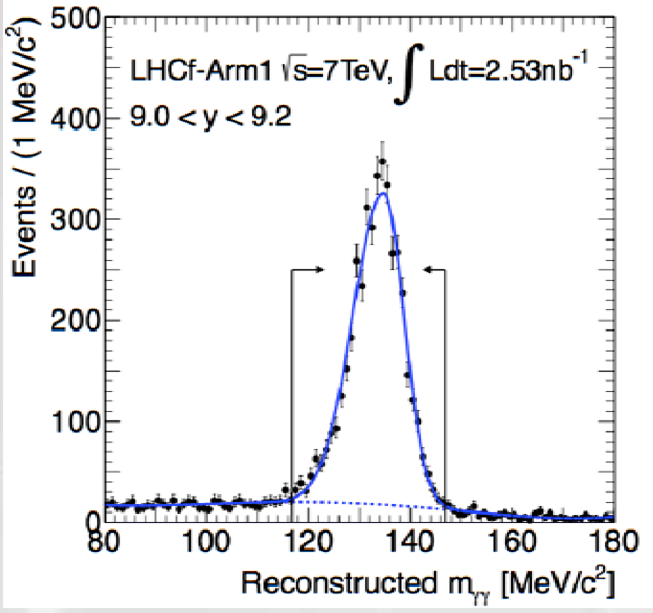


Viewed from IP1
(red:Arm1, blue:Arm2)

Projected edge
of beam pipe

$\pi^0 \rightarrow \gamma\gamma$

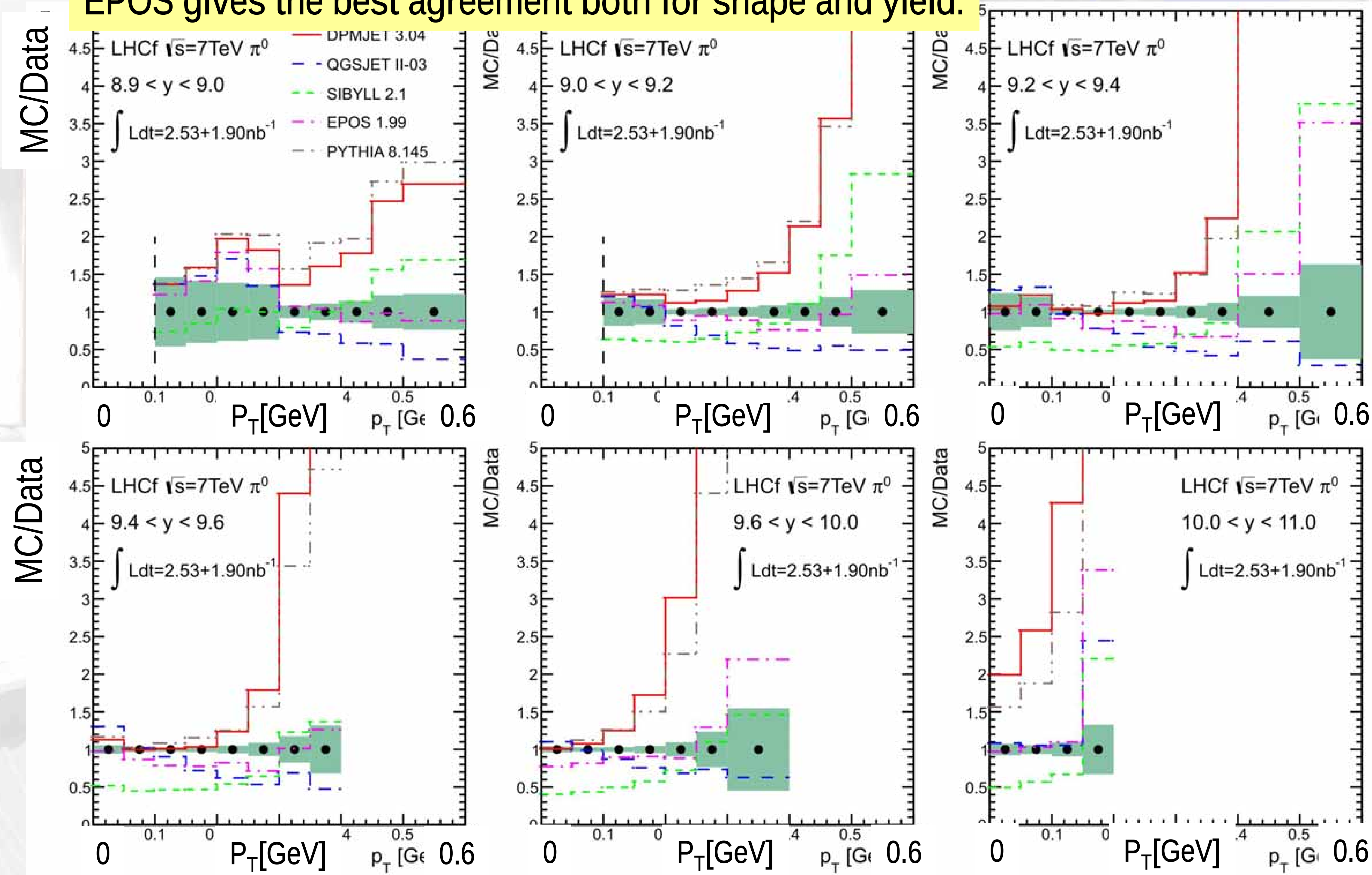




LHCf π^0 P_T spectra at 7TeV (data/MC)

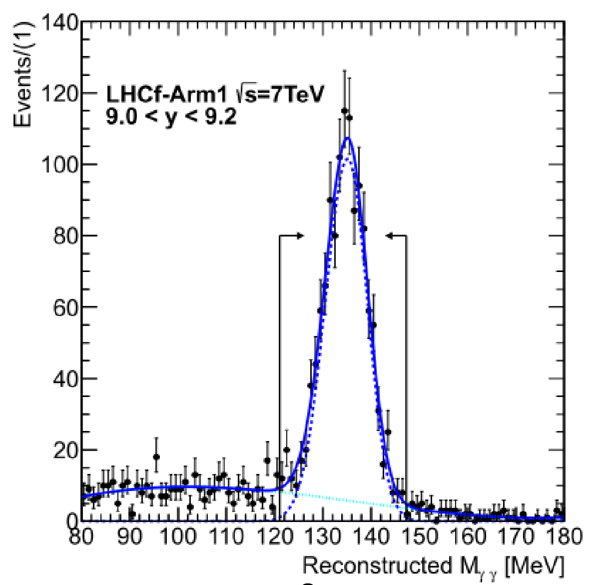
DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

EPOS gives the best agreement both for shape and yield.

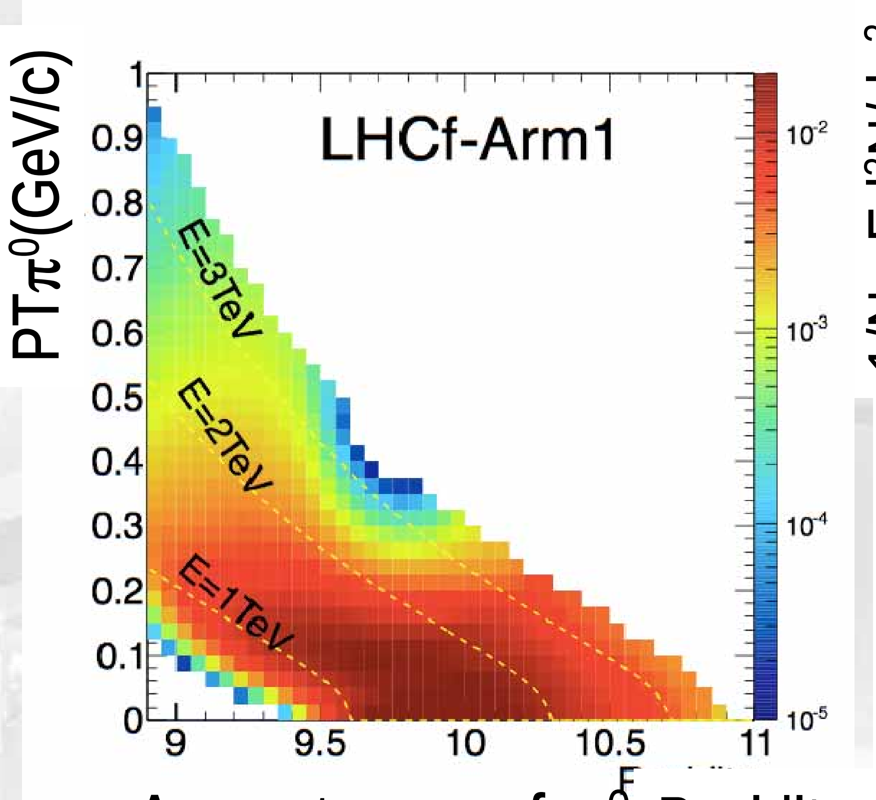


LHCf type-I π^0 analysis

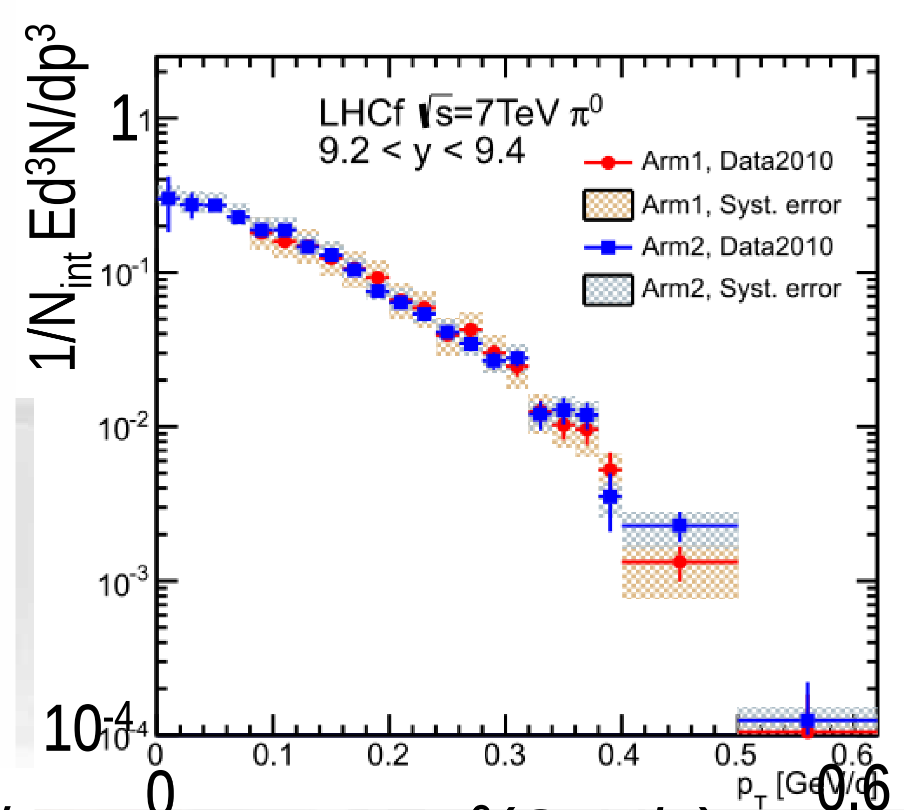
- Low lumi (L~5e28) on 15-16May, 2.53(1.91) nb^{-1} at Arm1 (Arm2). About 22K (39K) π^0 for Arm1(Arm2) w/ 5%BG.
- For Eγ>100GeV, PID (γ selection), shower leakage correction, energy rescaling (-8.1% and -3.8% for Arm1&2).
- (E, P_T) spectra in +-3σ π^0 mass cut w/ side band subtracted.
- Unfolding spectra by toy π^0 MC to correct acceptance and resolution



$M\pi^0$(MeV)



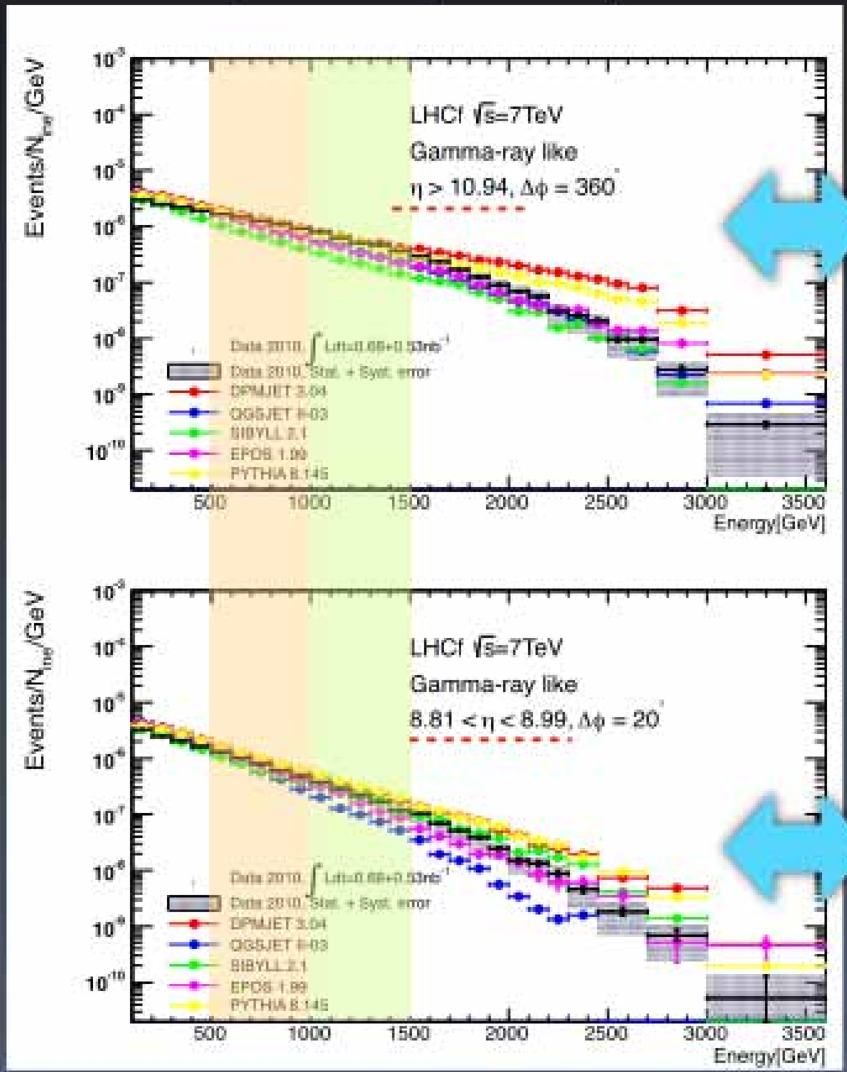
Acceptance of π^0 Rapidity



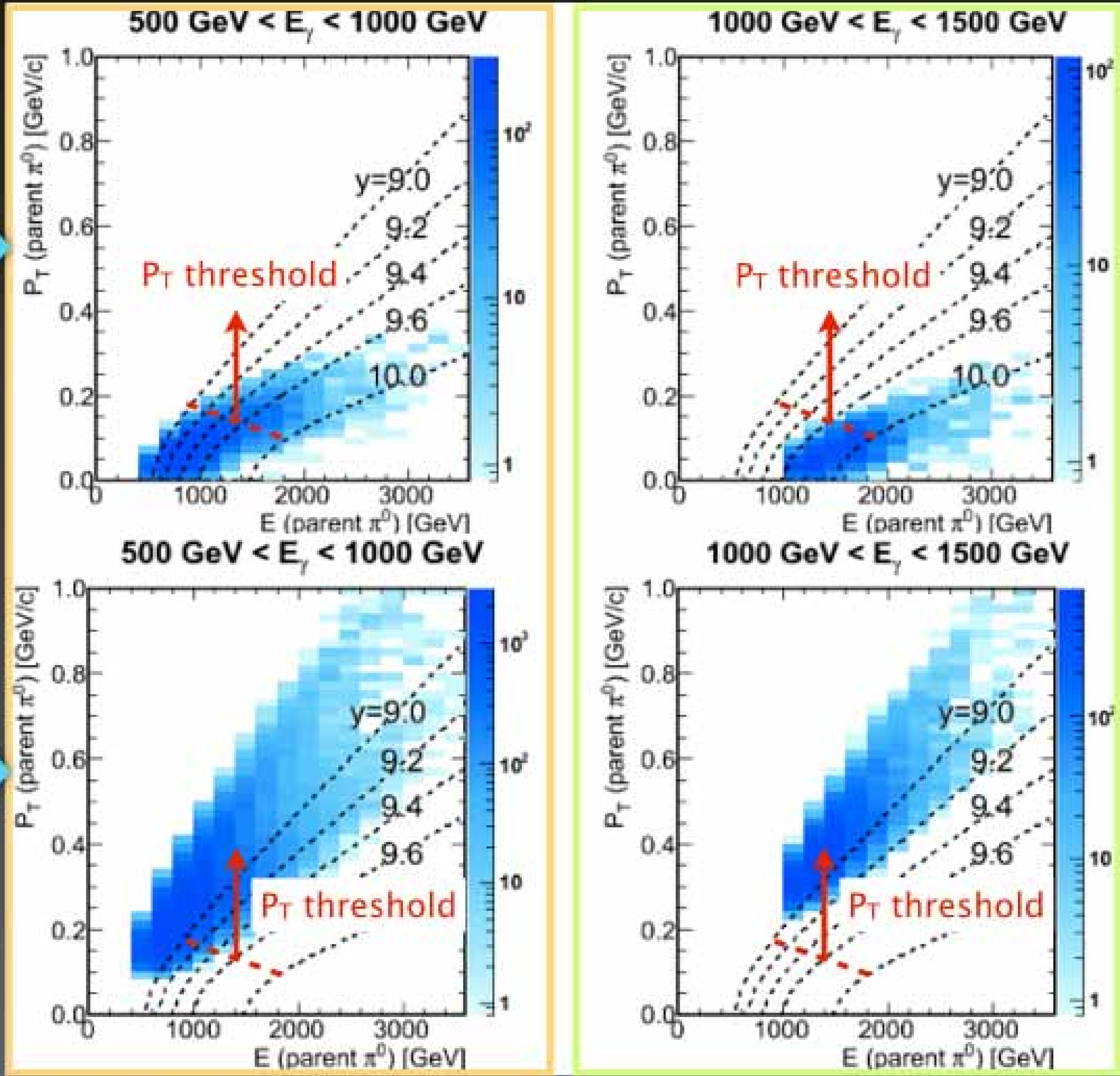
$PT\pi^0$(GeV/c)

7TeV π^0 analysis

7TeV photon spectra by LHCf



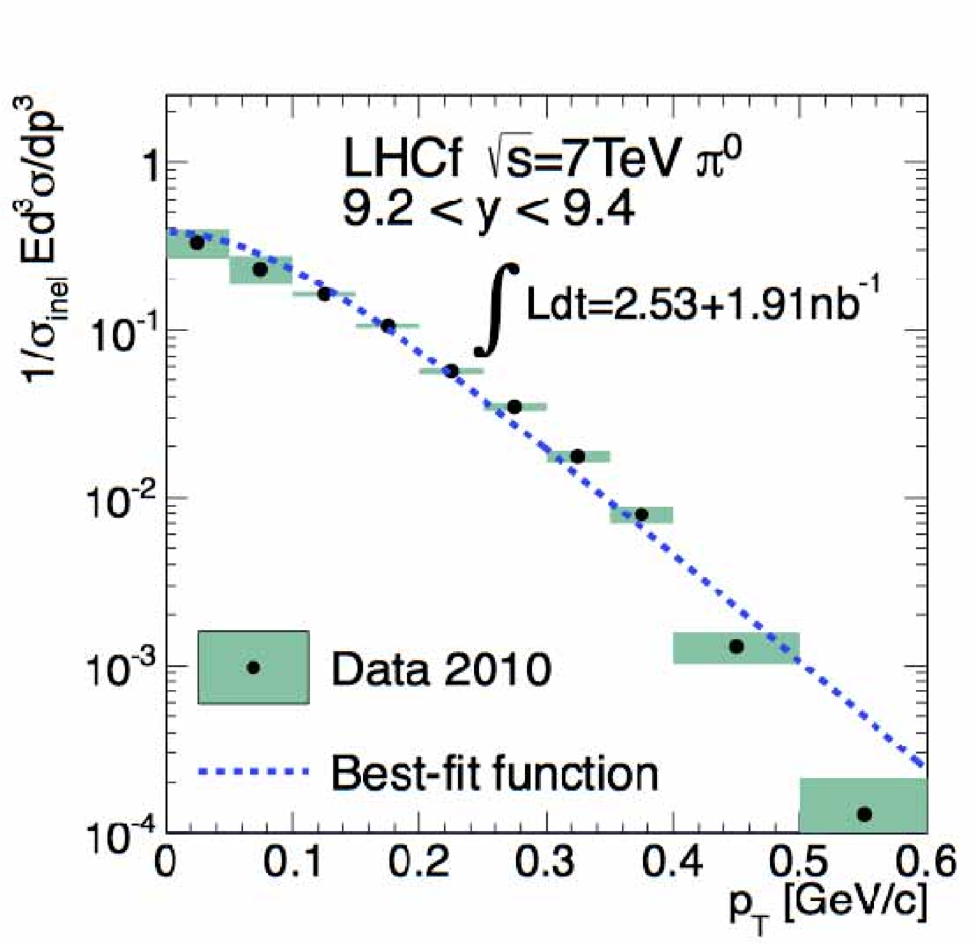
(Phys. Lett. B 703 128-134 (2011))

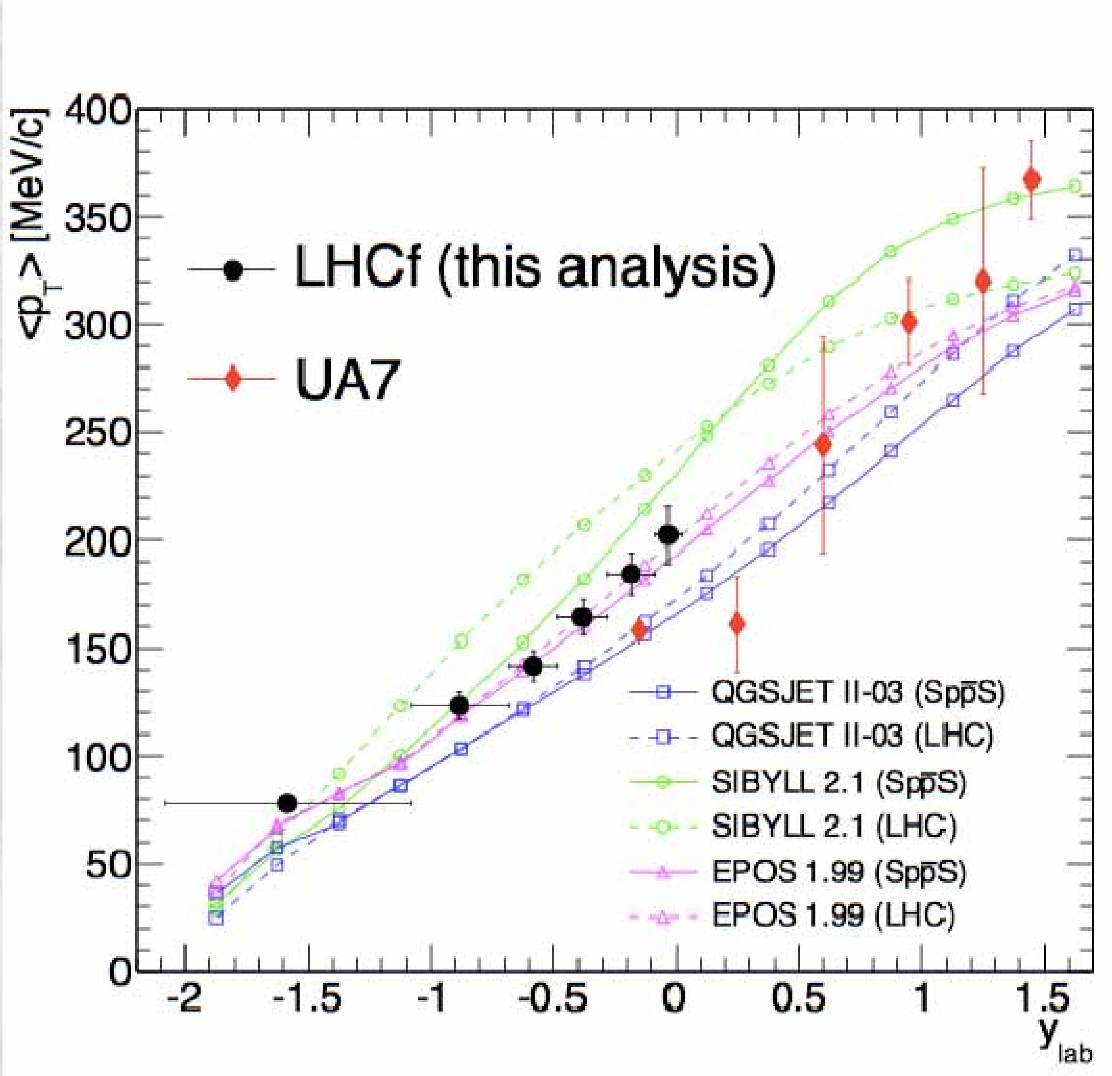


- Photon analysis and π^0 analysis compensate each missing information.
  - High energy photon originates from large P_T π^0 events.
  - Photon spectrum includes a contribution from other hadrons/baryons.

→ Photon P_T analysis can connect each measurement.

Average P_T of π^0





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

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

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

- Comparison w/ UA7@630GeV
- Extend to higher η regions
- Less energy dependence of <PT>?

Comparison of Data/MC ratio at two energies

DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

7TeV

900GeV