The results from LHCf experiment

Yoshitaka Itow
Solar-Terrestrial Environment Laboratory /
Kobayashi-Maskawa Institute
Nagoya University
Apr 23rd, 2013
LANL

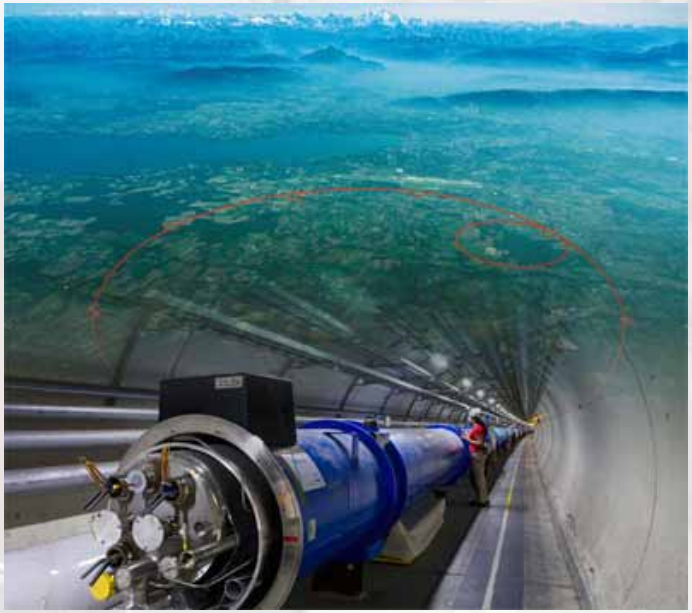
In 2008 same seminar here….

The LHCf experiment

~ Verify hadron interaction models for cosmic rays at 10^{17}eV ~

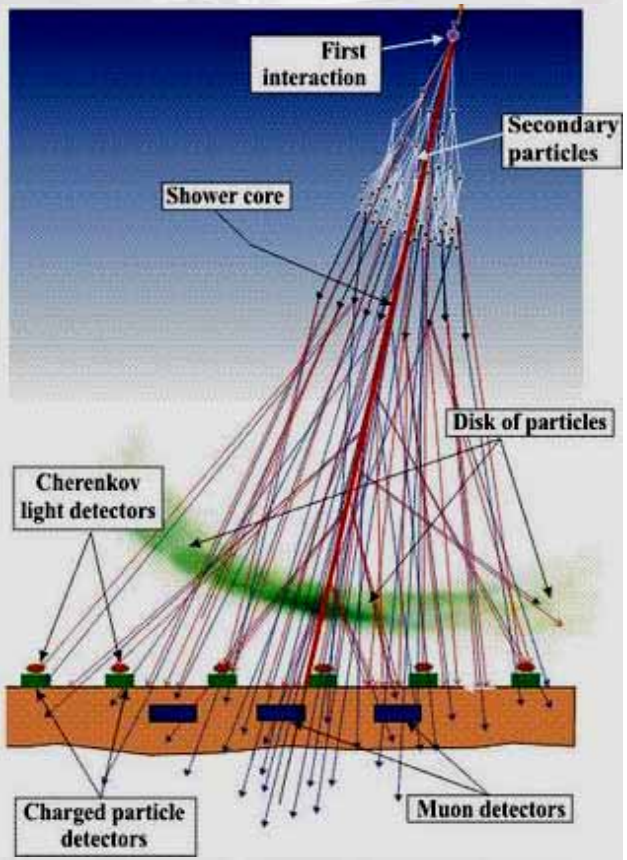
Yoshitaka Itow
Solar-Terrestrial Environment Laboratory
Nagoya University
for the LHCf collaboration

Hadron interactions at ultra high energy
Accelerator ↔ Cosmic rays



Precision improvement

Hint for interactions at ultra-ultra high energy

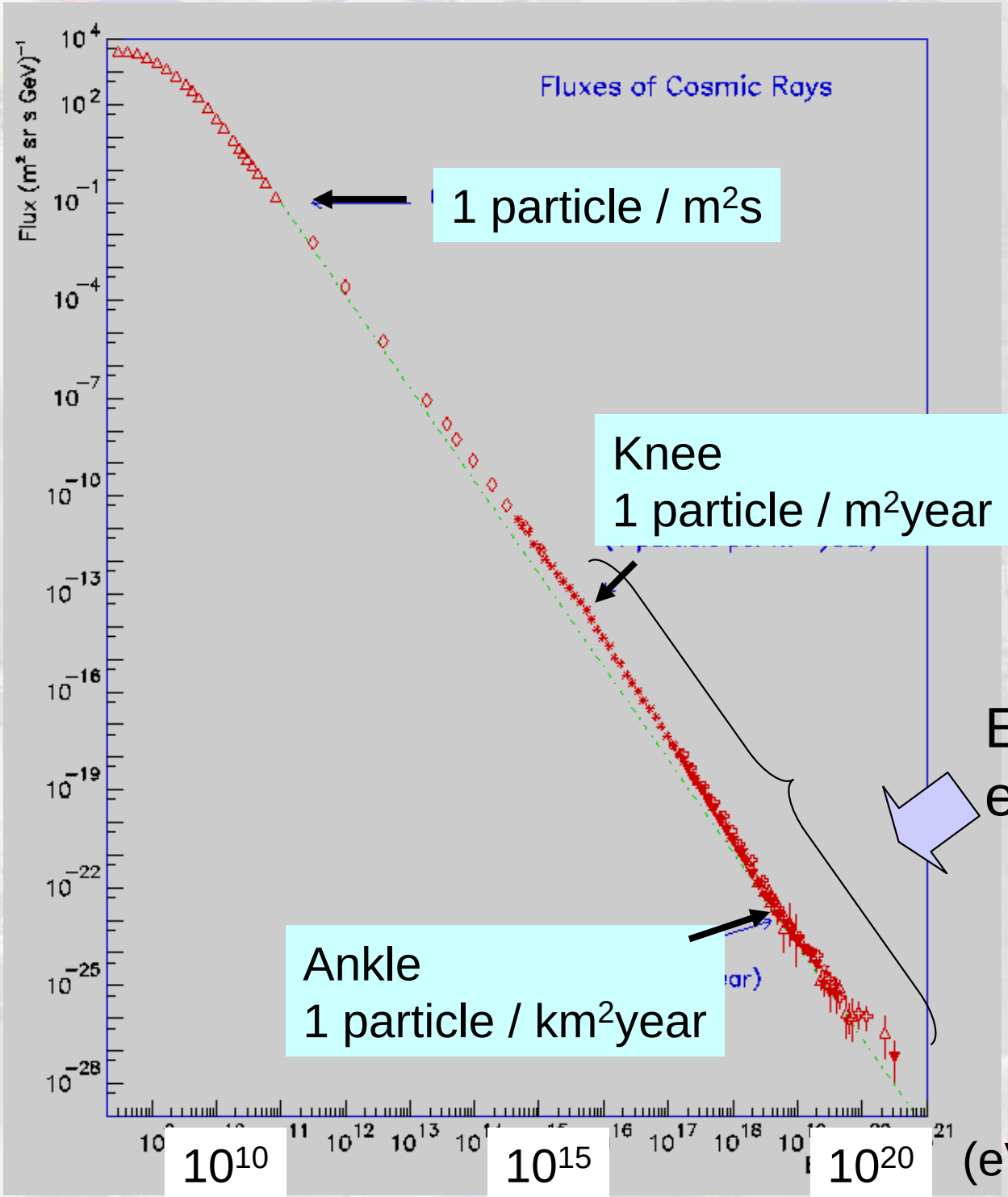


$$E_{CM} \sim (2 \times E_{lab} \times M_p)^{1/2}$$

$\sqrt{s}$=14TeV collision at LHC
→10^{17}eV cosmic rays

Ultra high energy cosmic rays and extensive air showers

High Energy Cosmic Ray Observations



Extensive Air Shower experiments

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

TA

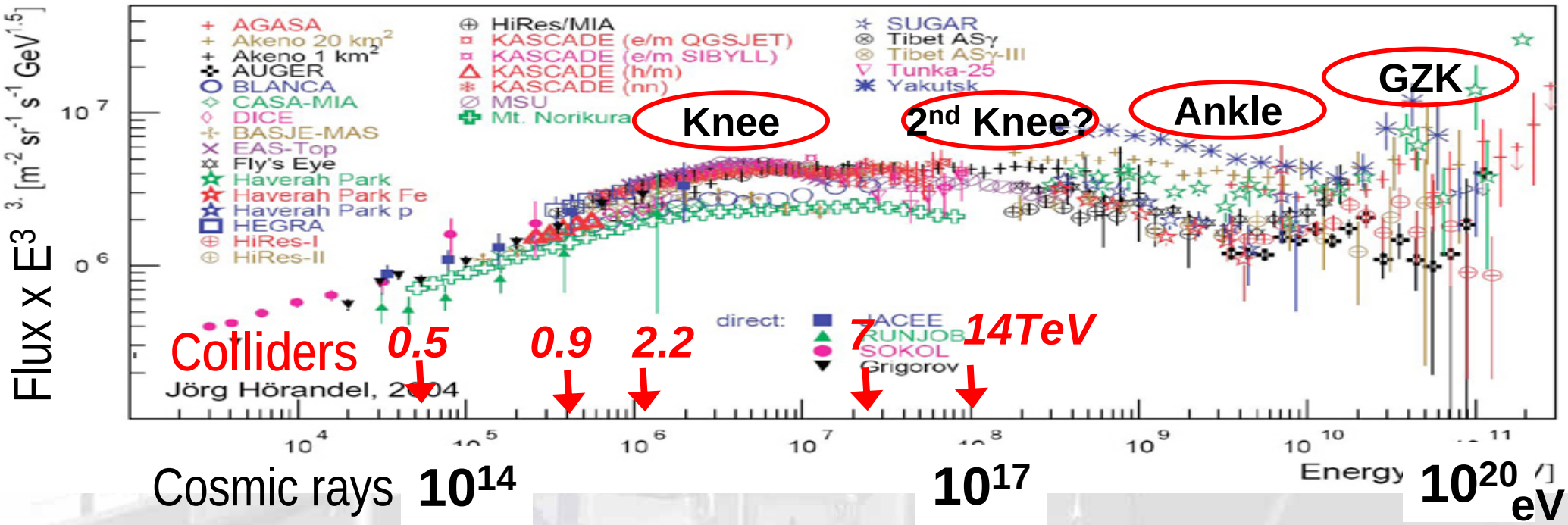
AUGER

Air shower experiments

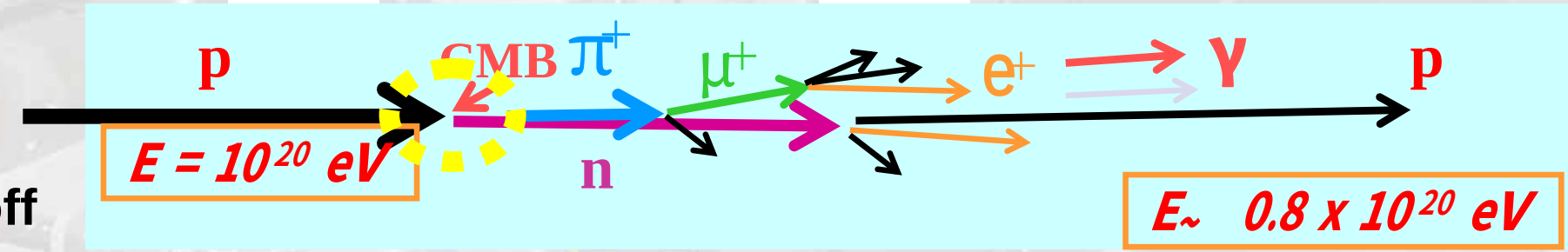
HEAT

TALE

AUGER, TA

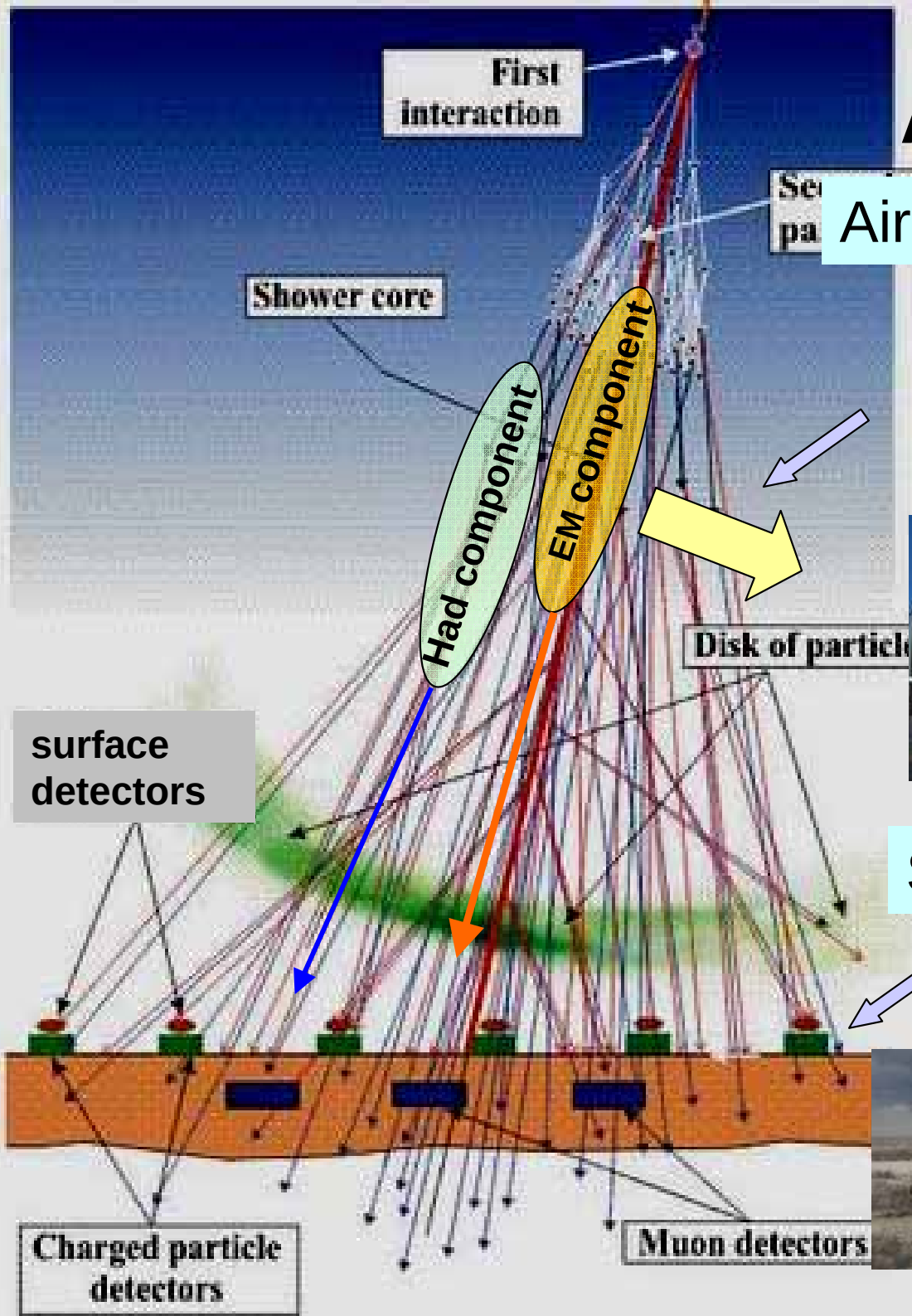


Cosmic rays 10^{14} 10^{17} 10^{20} eV



GZK cut off

Air shower observation



Air Florescence telescope (FD)

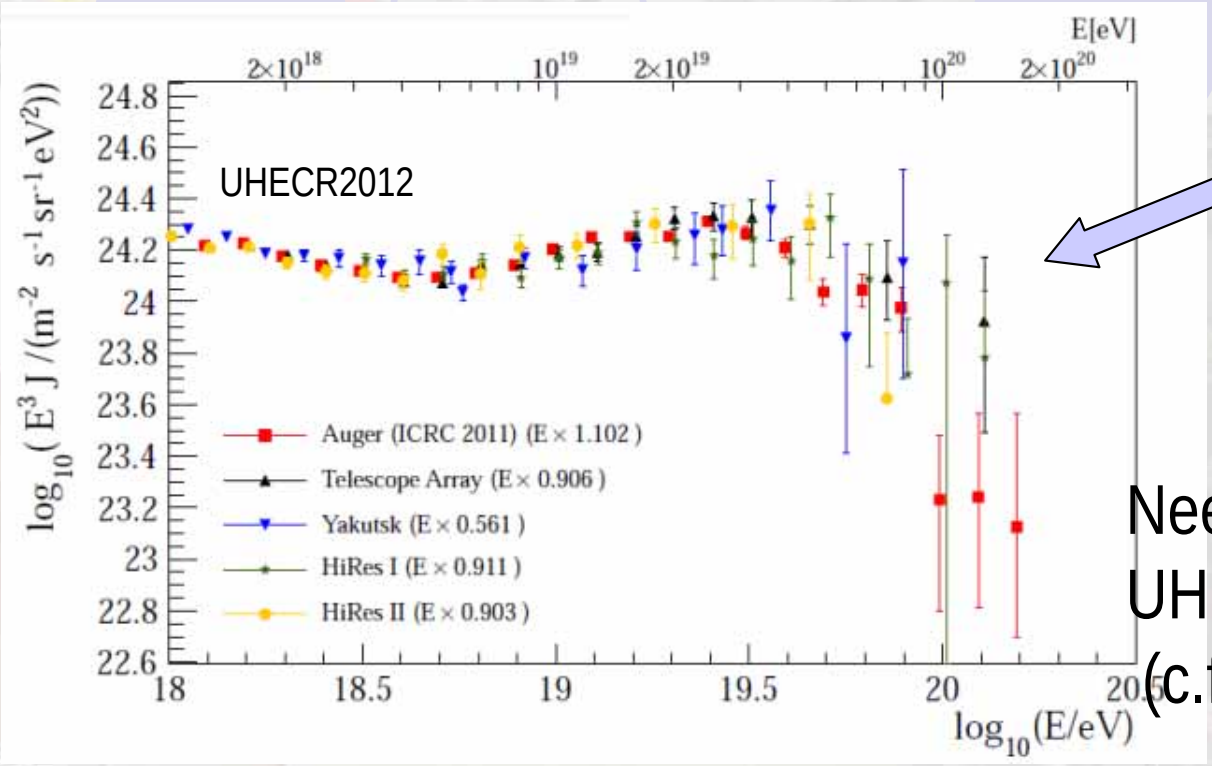
EM component
(>90% of collision energy)

- Total calorimeter
- Shower max altitude

Surface Detectors (SD)

of particles at given altitude
(EM or Muon component)

GZK cut-off confirmed ? But…



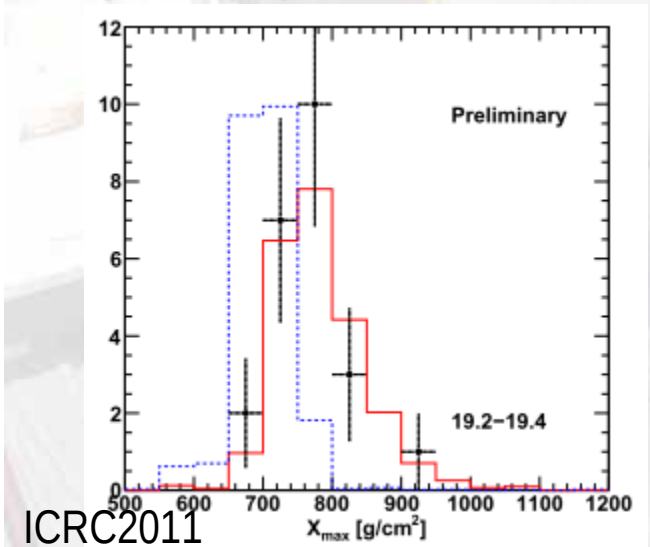
GZK cut off ?

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

Need to confirm
UHECR is "proton"
(c.f. photo-dissociation, A+CMB)

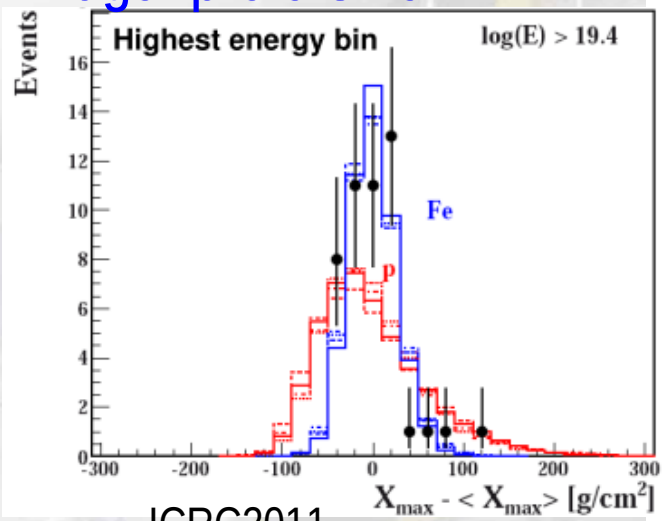
Too many μ @ Auger, if proton

TA prefers proton

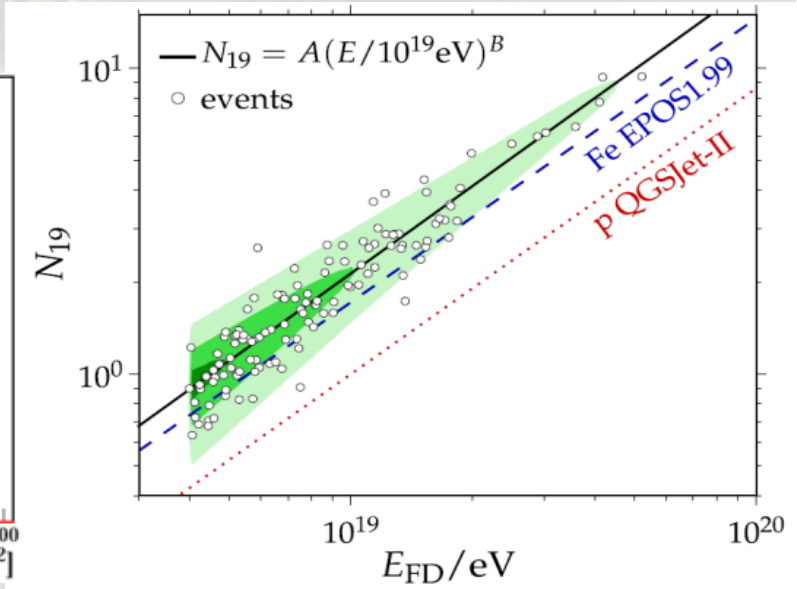


ICRC2011

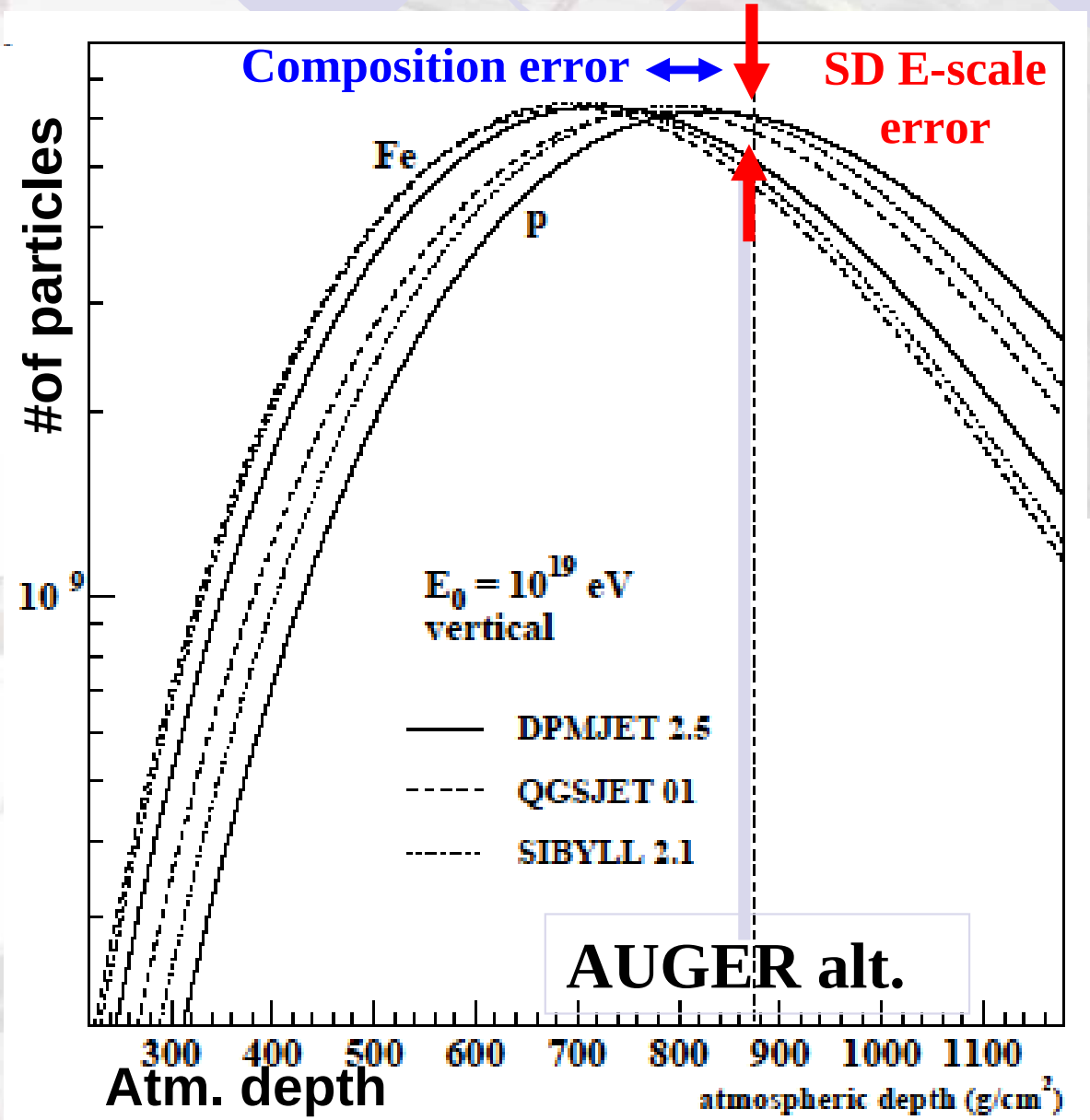
Auger prefers Fe



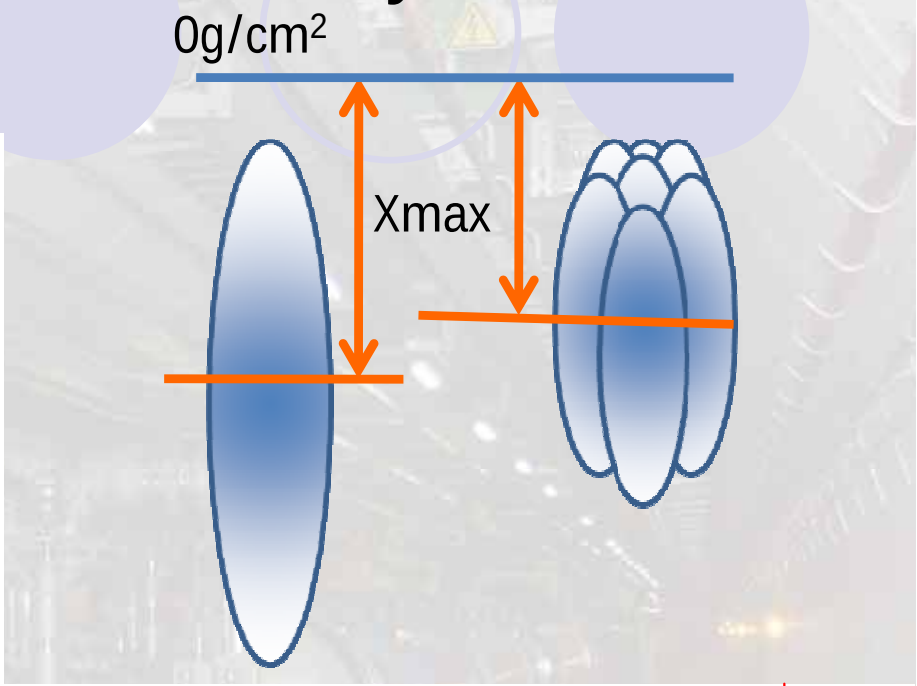
ICRC2011

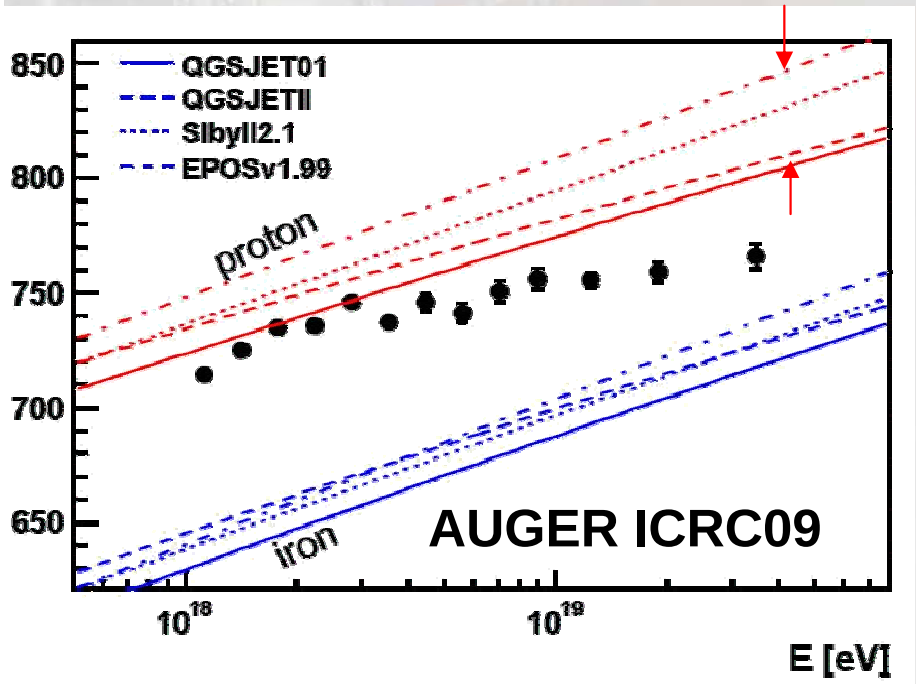


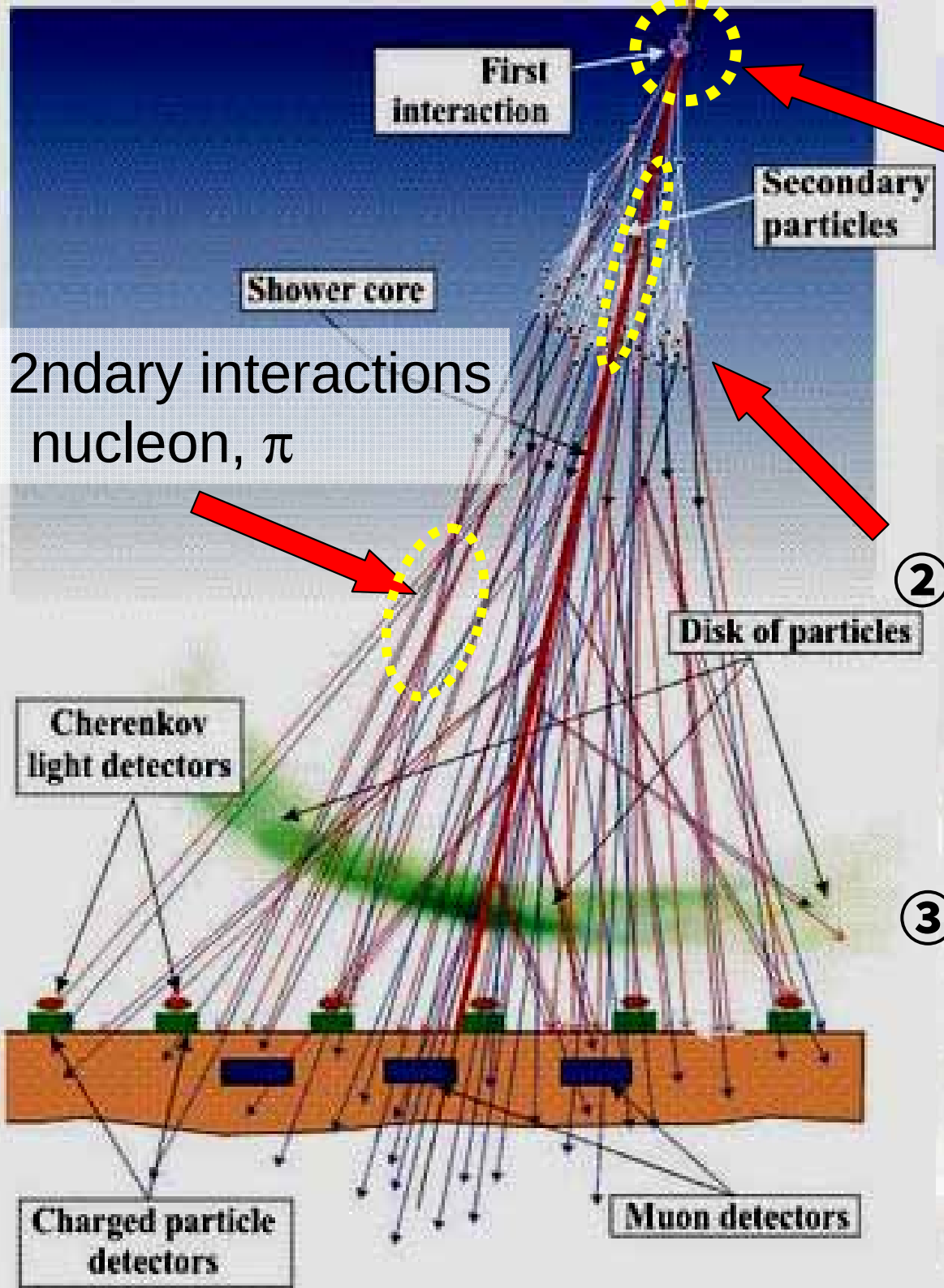
Impact of shower development uncertainty on E-scale/composition



J.Knapp Astropart. Phys.19 (2003) 77







① Inelastic cross section

If large σ
rapid development
If small σ
deep penetrating

② Forward energy spectrum

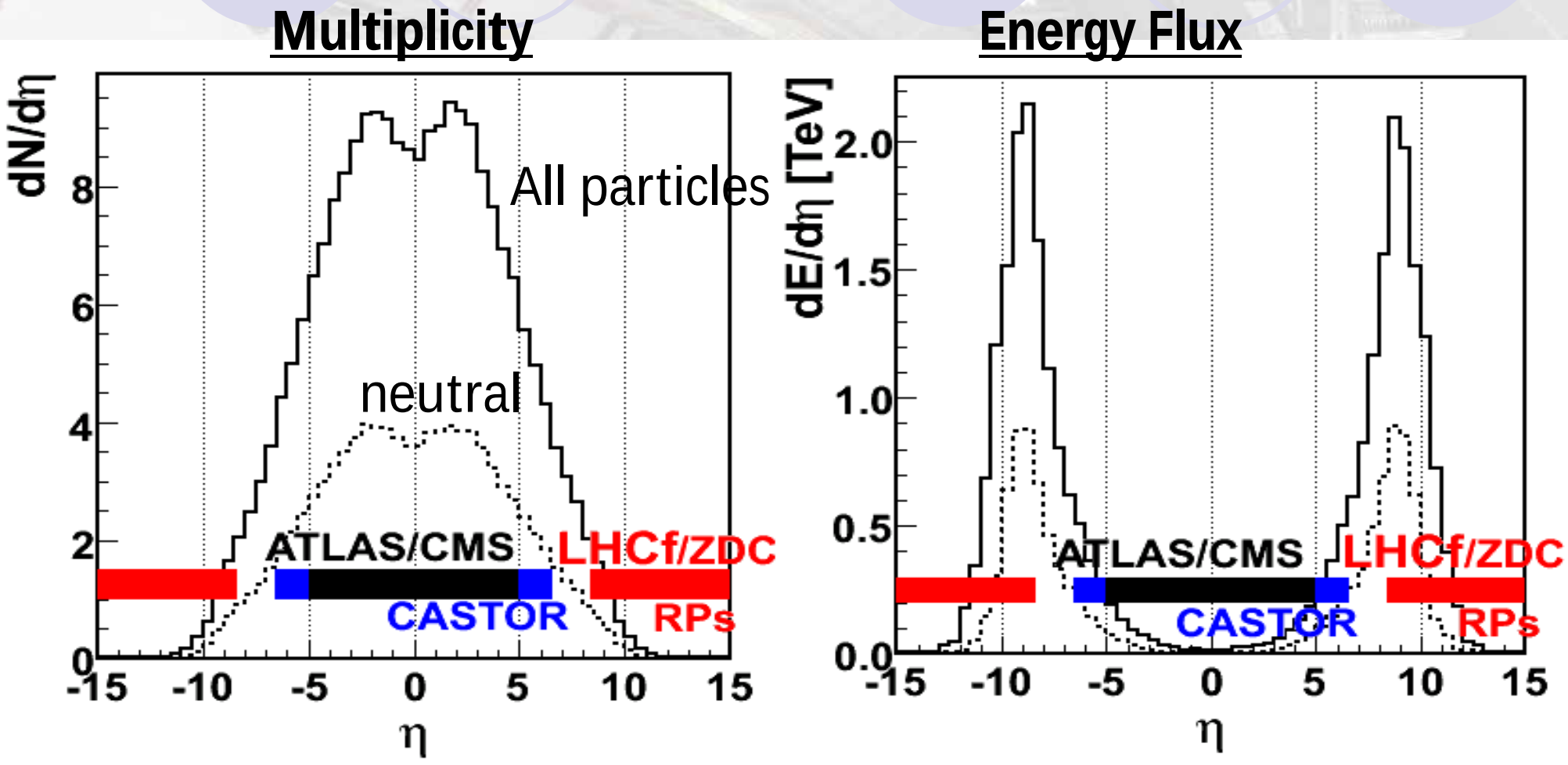
If softer
shallow development
If harder
deep penetrating

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

If large k of baryons
rapid development
If small k of baryons
deep penetrating

④ 2ndary interactions
nucleon, π

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

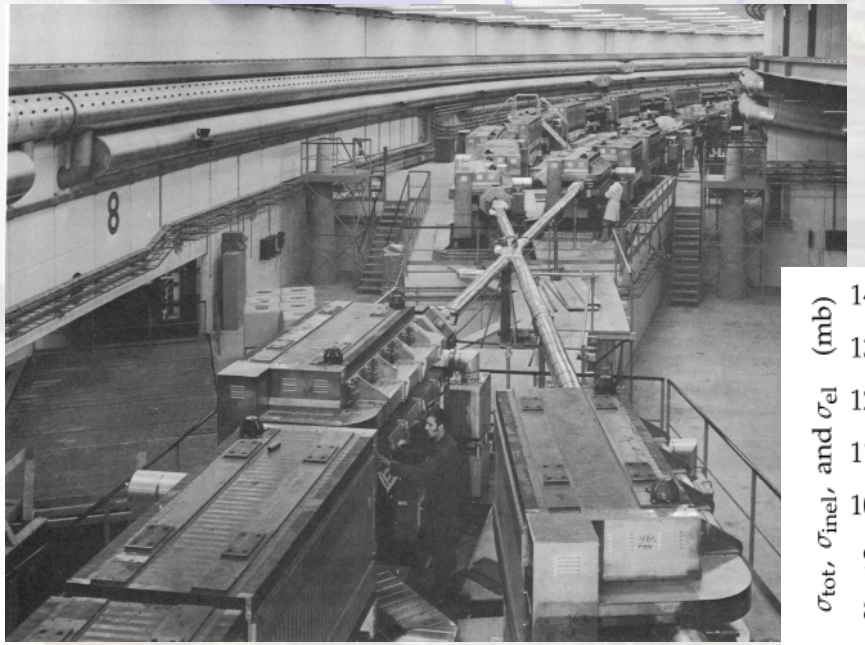


Most of the energy flows into very forward

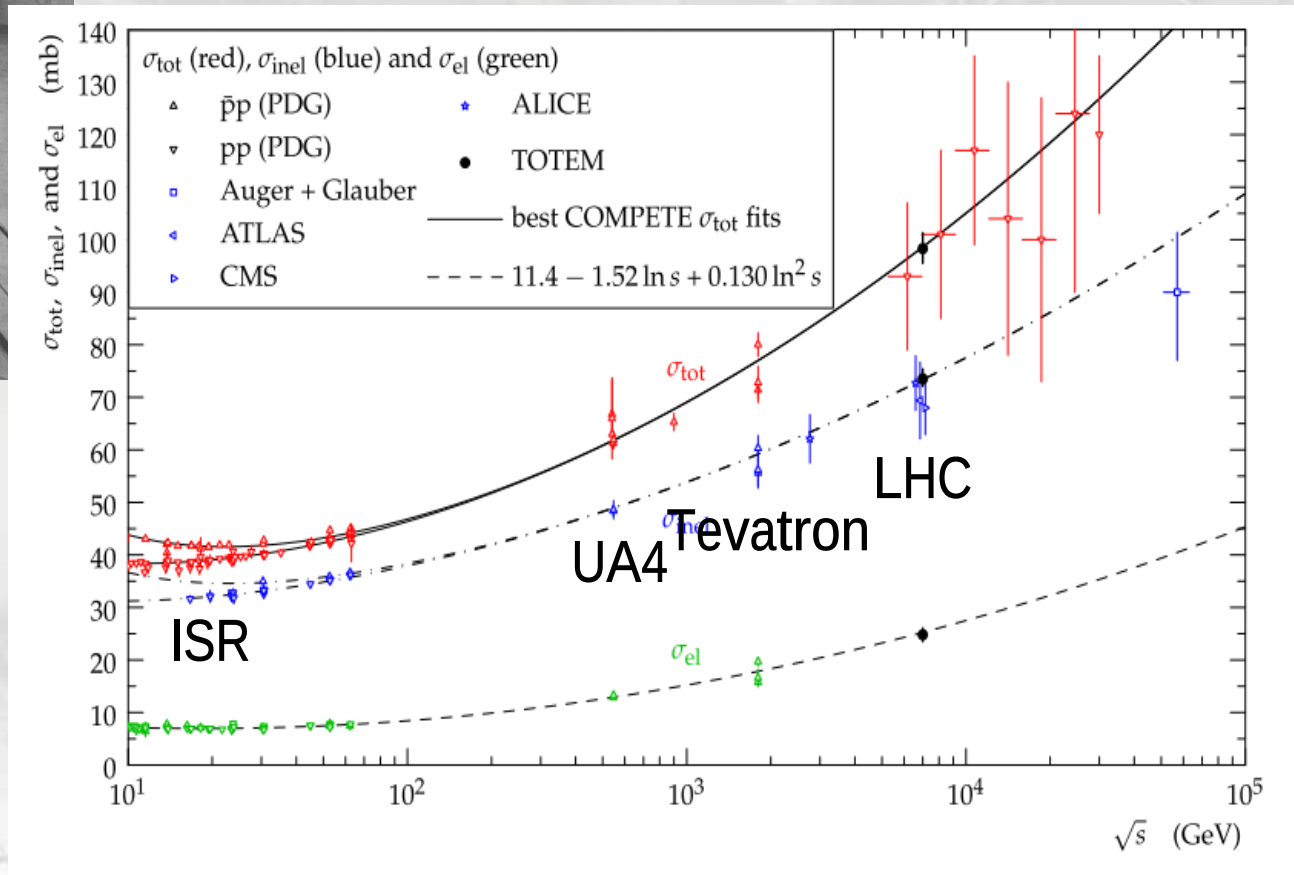
(Particles of X_F > 0.1 contribute 50% of shower particles)

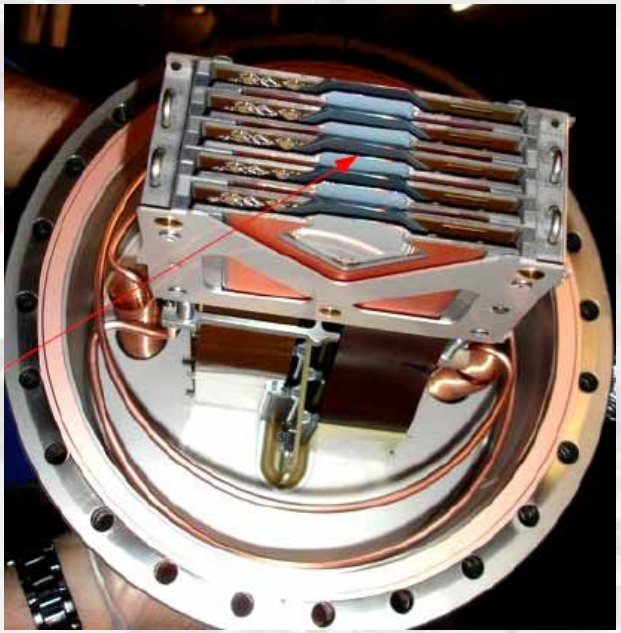
Interactions at very forward region

Cross section rising at high energy collisions



Intersection Storage Ring (ISR)

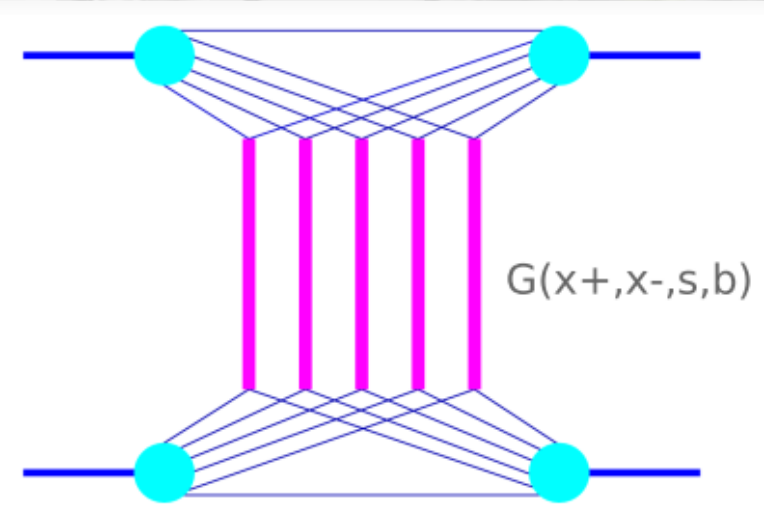


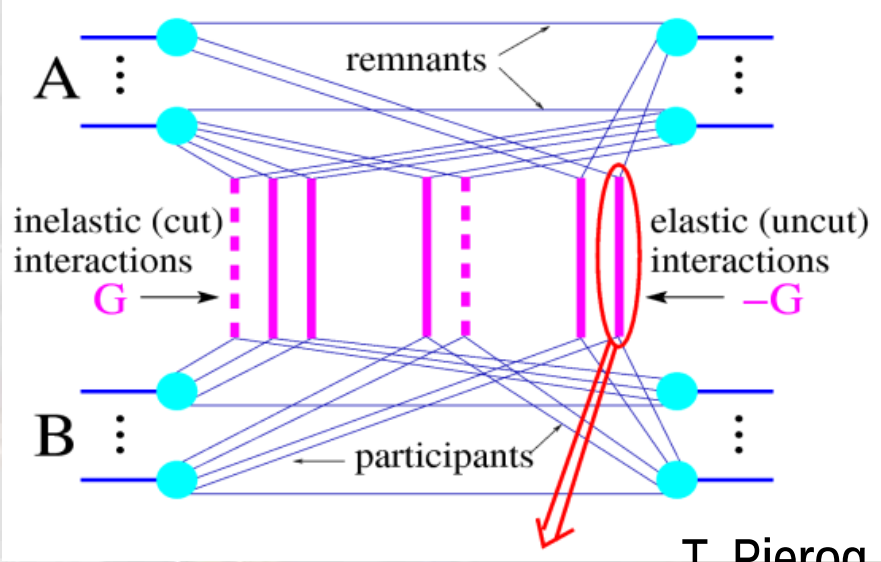


TOTEM Roman Pot (LHC)

Hadron interaction models used for air shower simulations

Based on Gribov-Regge Theory and Optical Theorem

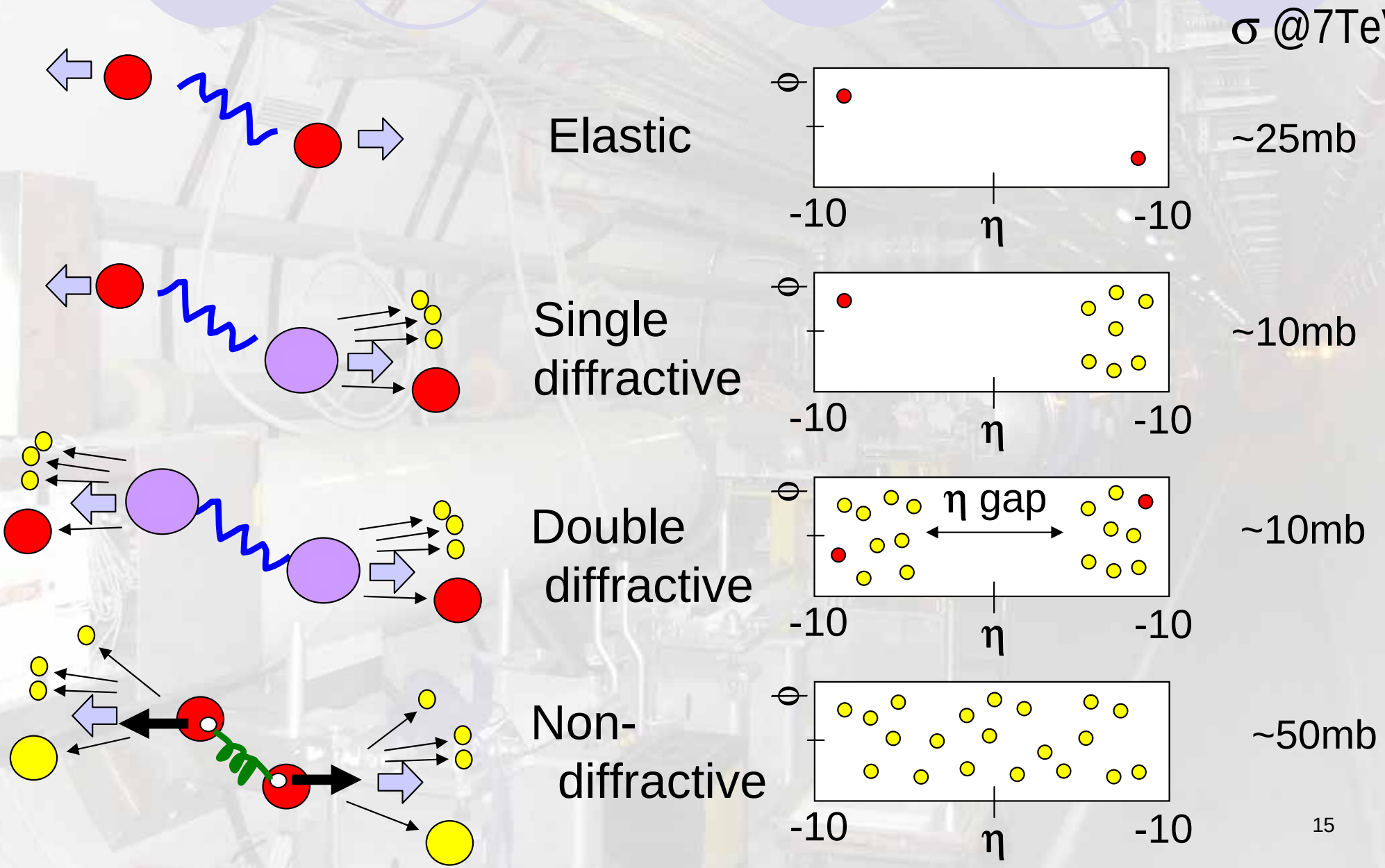




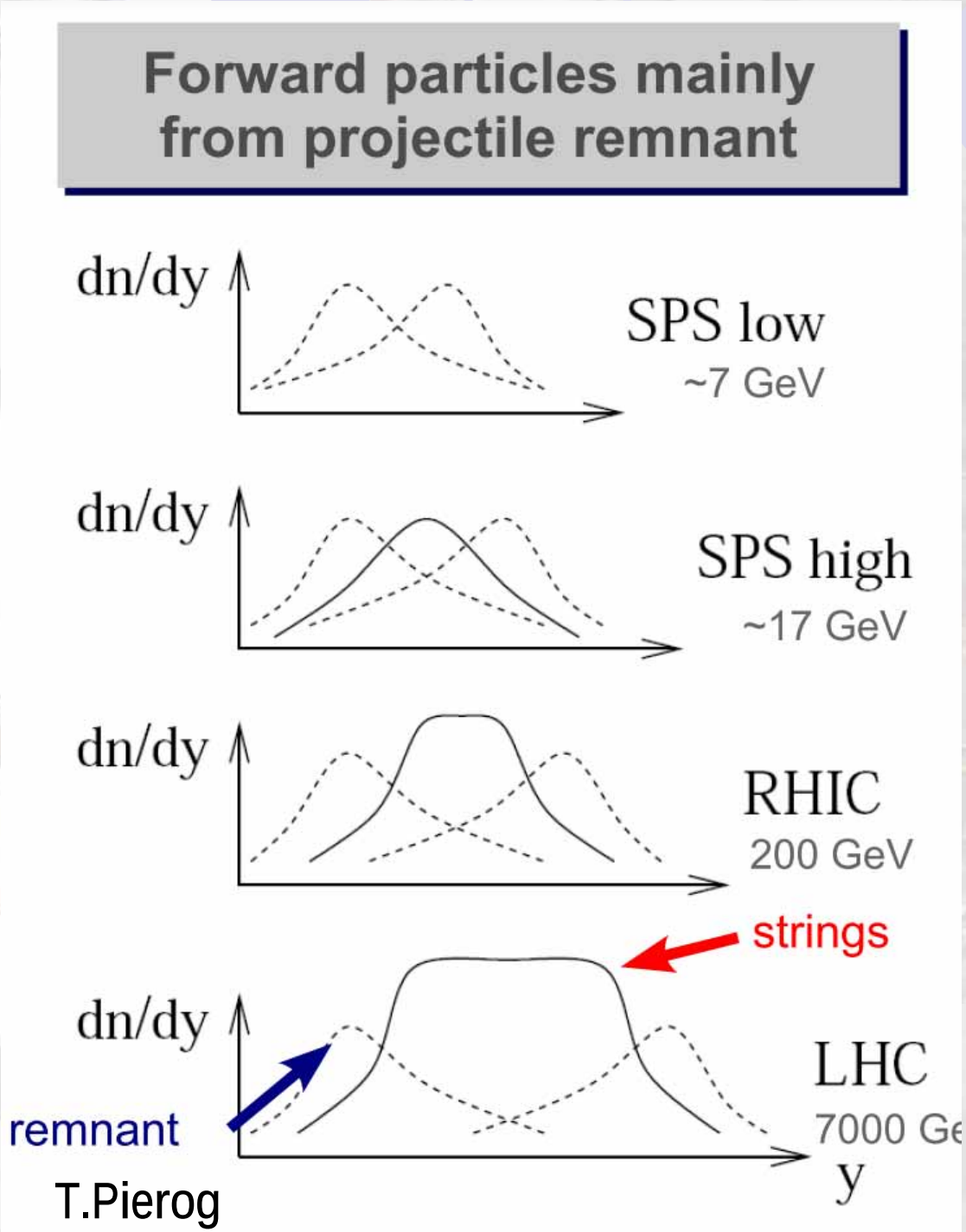
T. Pierog

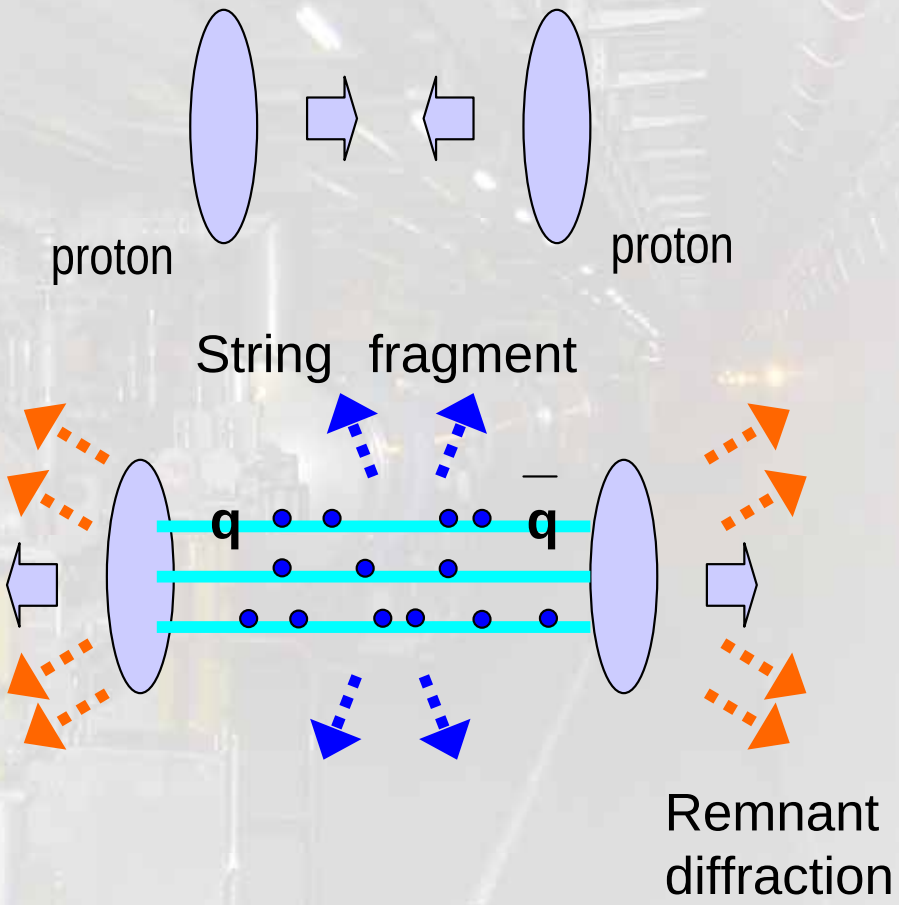
- SYBILL2.1
  - E.J. Ahn et al., Phys. Rev. **D80**, 094003 (2009).
- QGSJET II
  - S. Ostapchenko, Phys. Lett. **636**, 40 (2006).
- DPMJET3
  - S. Roesler, R. Engel and J. Ranft, *Proc. of 27th ICRC.* 2002, 439.
- EPOS1.9
  - T. Pierog and K.Werner, Phys. Rev. Lett. **101**, 171101(2008).

pseudorapidity and interactions



Particle productions in high energy pp collisions





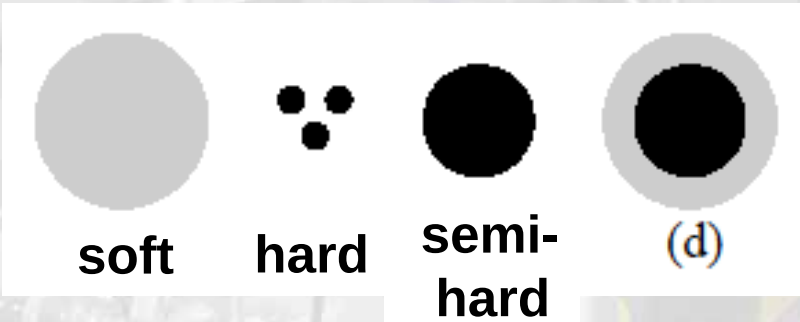
Very forward – connection to low-x physics

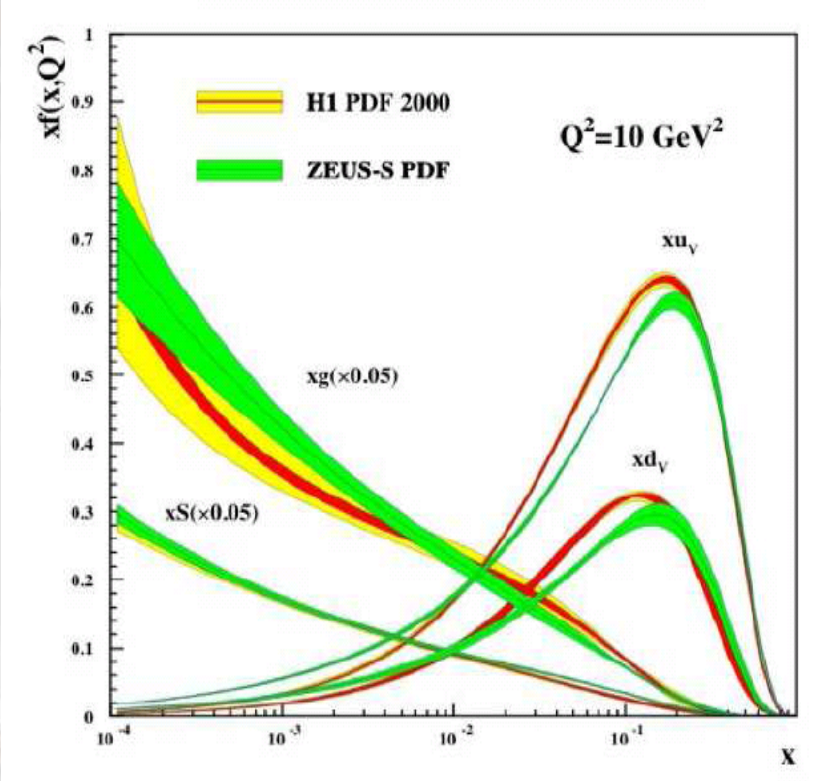
c.f parton-picture

- Very forward region : collision of a low-x parton with a large-x parton
- Small-x gluons dominate in higher energy collisions.
- They may be saturated (Color Glass Condenstation)

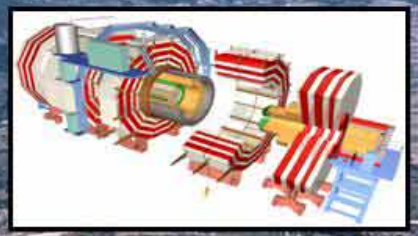
Naively CGC-like suppression may occur in very forward at high energy

→ **However LHCf is looking at non-qQCD (PT<1GeV)**

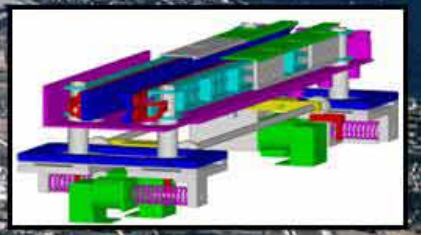




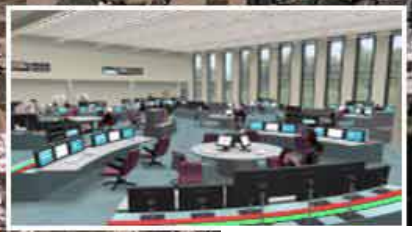
The seven LHC experiments



IP5 :CMS TOTEM

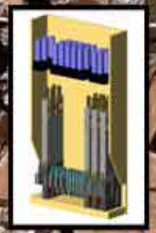


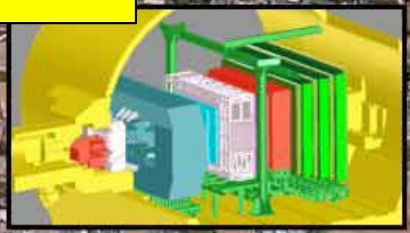
Dedicated to 0-deg EM.
Verify cosmic ray interaction models.



IP1 : ATLAS, LHCf

IP2: ALICE

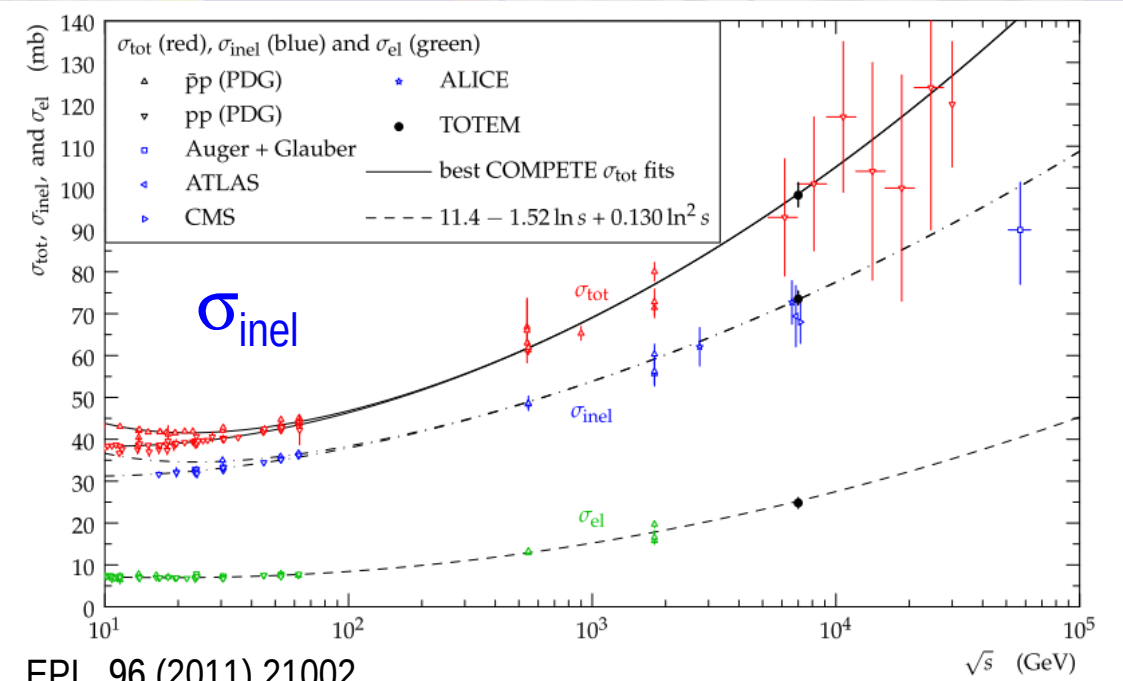




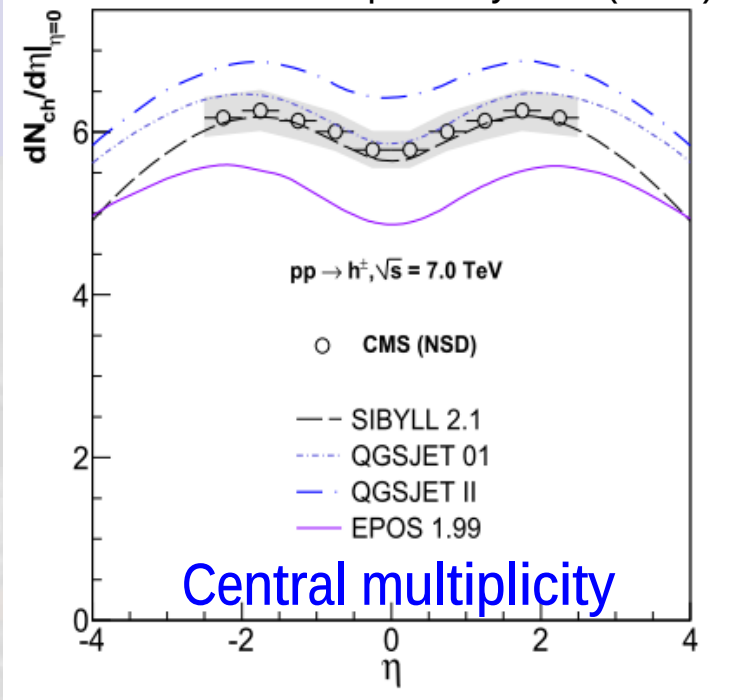
IP8: LHCb, MoEDAL

Feedback from LHC to UHECRs

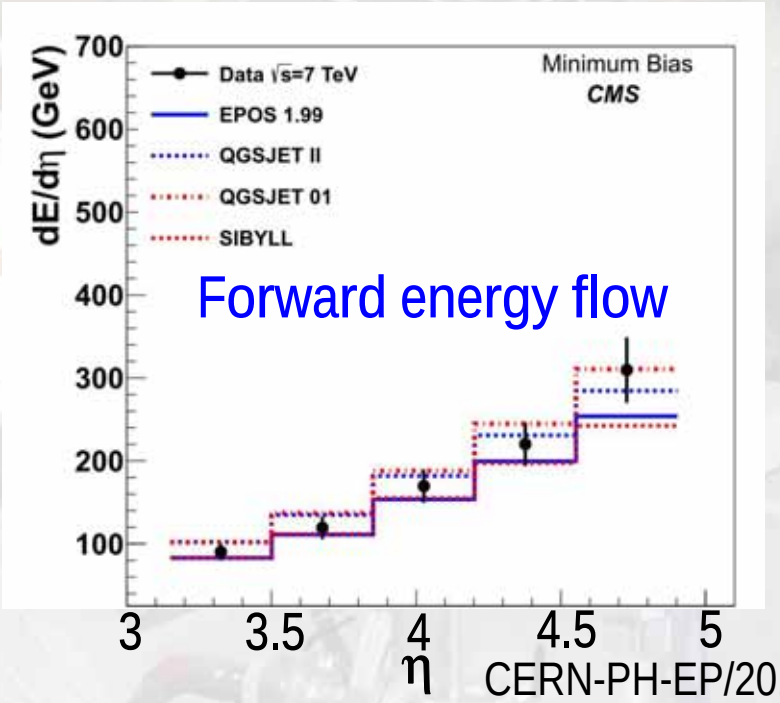
Astropart.Phys. 35 (2011) 98-113



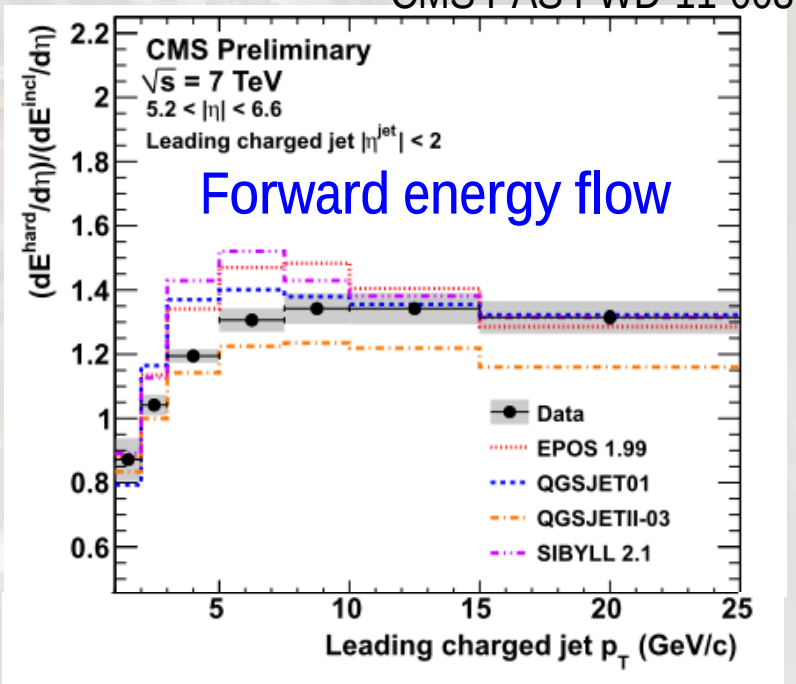
EPL, 96 (2011) 21002



CMS PAS FWD-11-003

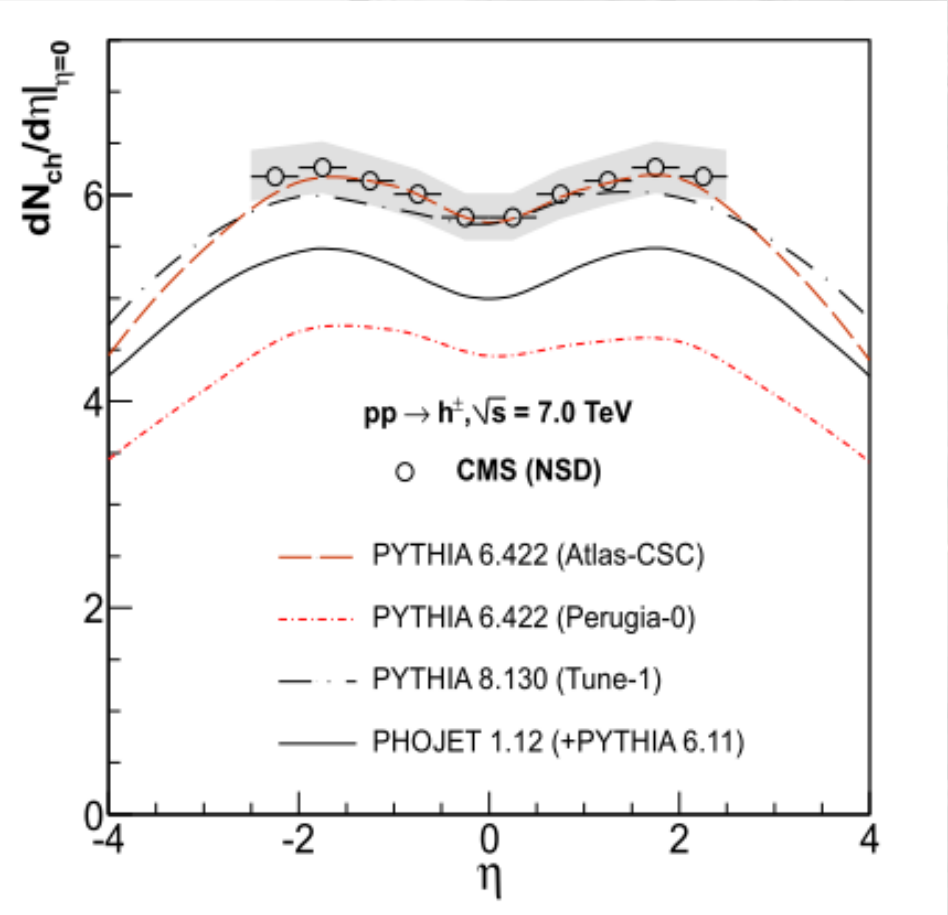


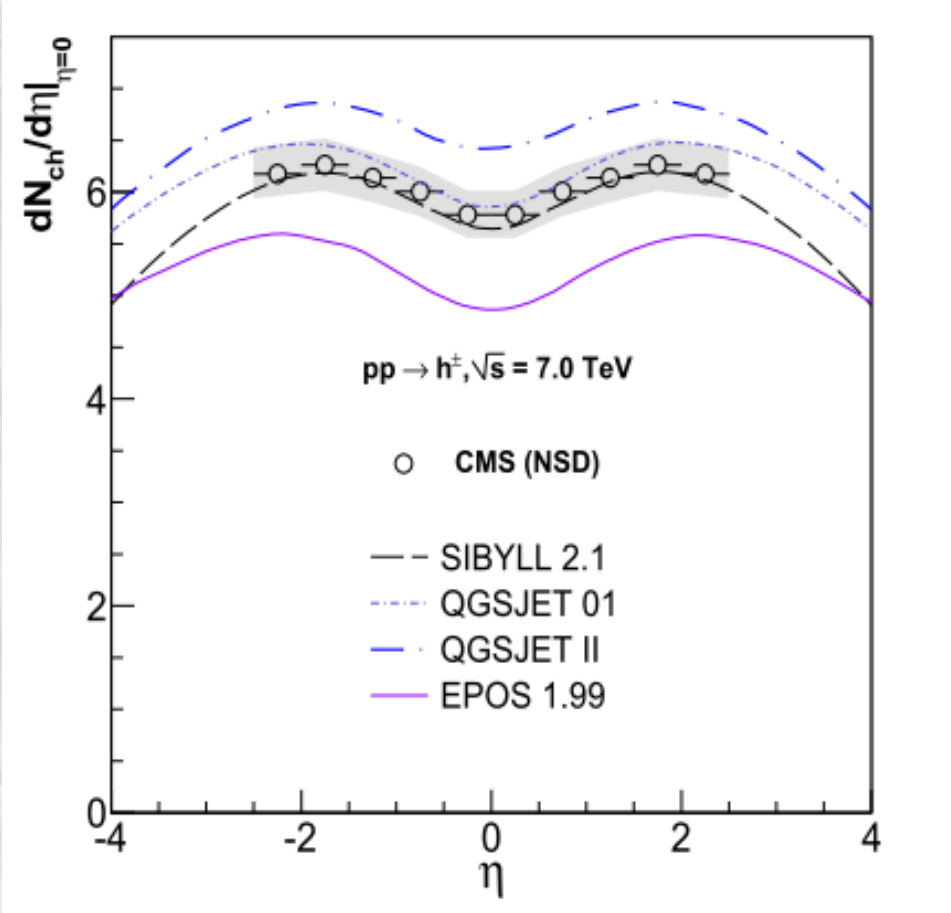
CERN-PH-EP/2011-086



CR int. models work even better

Charged Multiplicity in central η



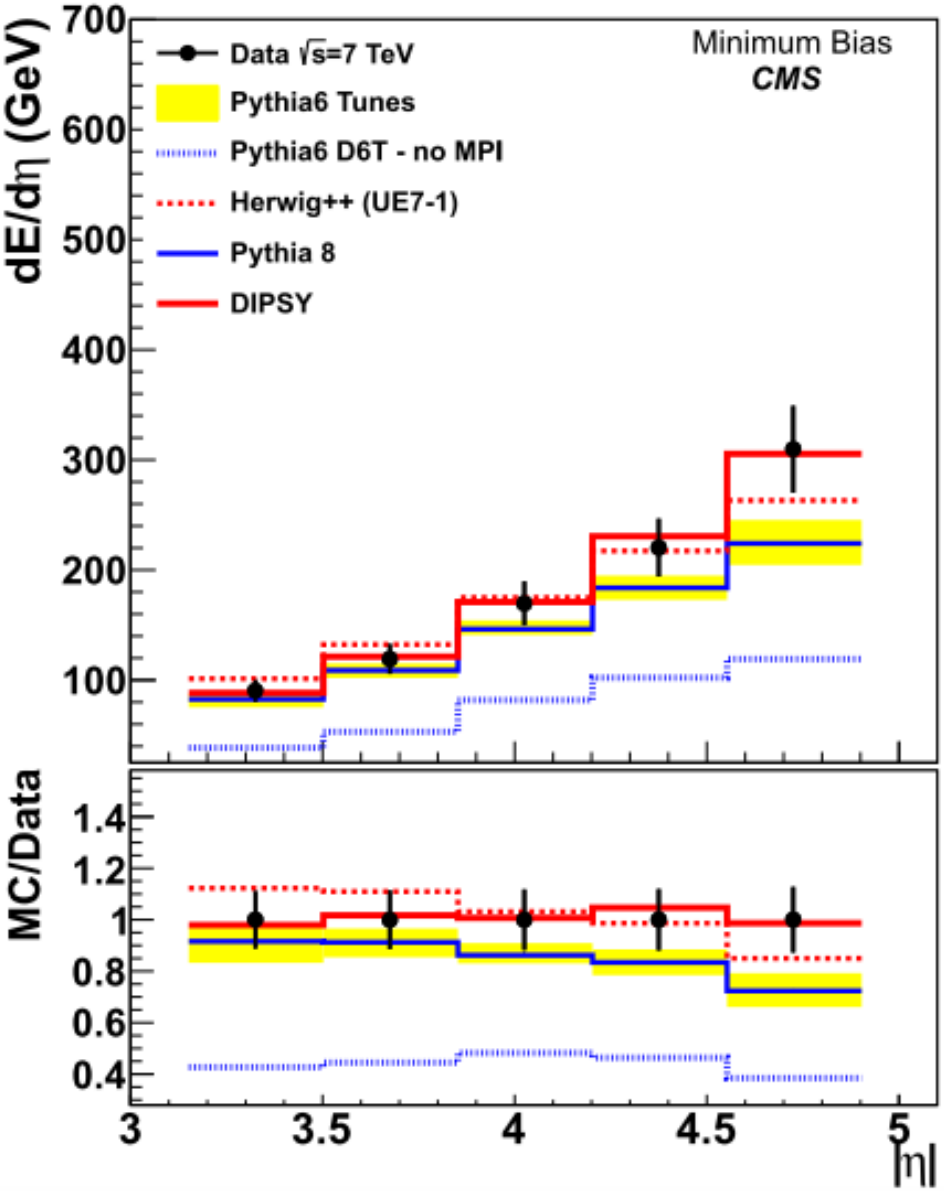


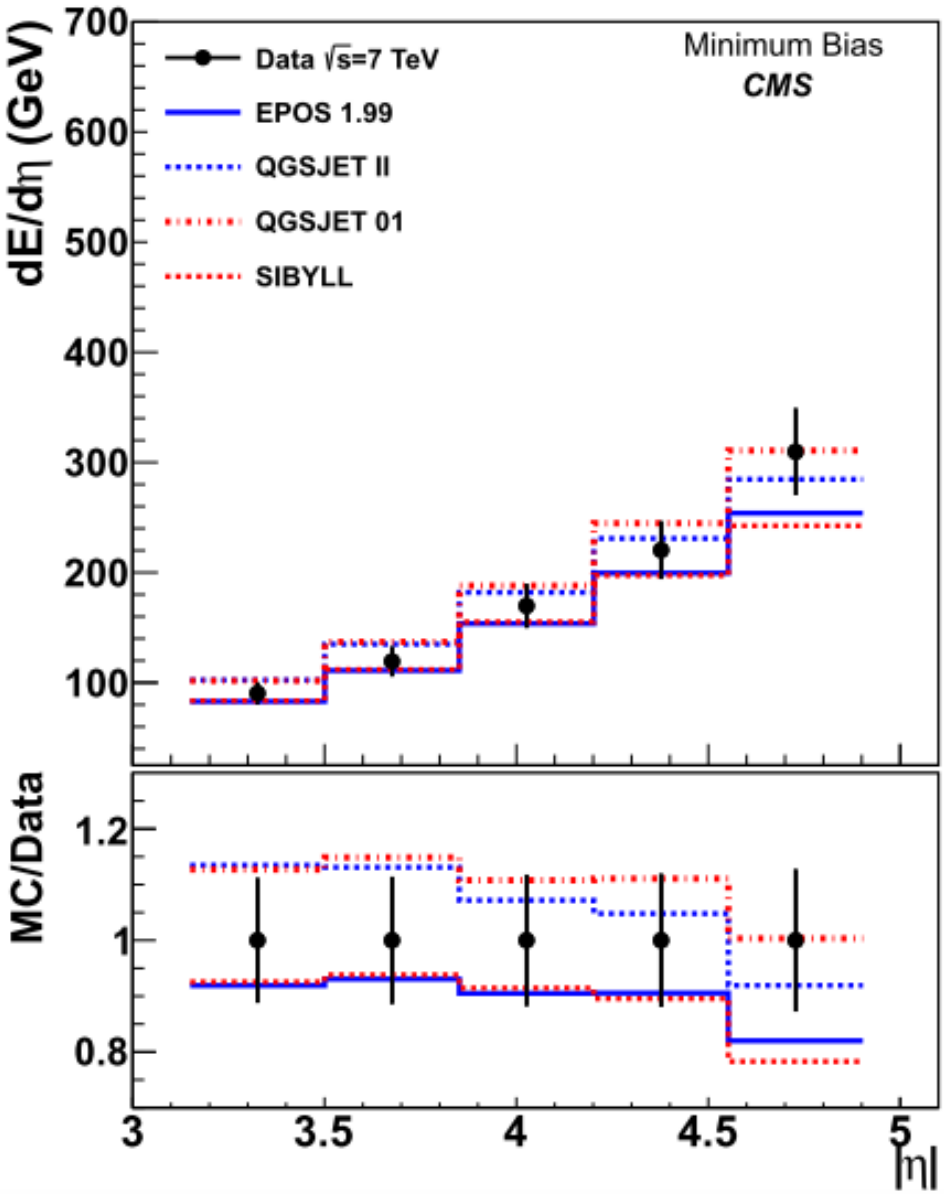
D.d'Enterria et al.,
Astropart. Phys. 35, 98 (2011), arXiv/1101.5596

CR int. models work even better

Forward energy flow

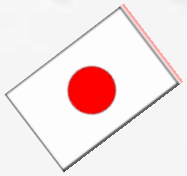
CMS collaboration, arXiv:0329842





How about very forward at LHC (η>8) **?**
The LHCf experiment

The LHCf collaboration



Y.Itow, K.Kawade, Y.Makino, K.Masuda, Y.Matsubara, E.Matsubayashi, G.Mitsuka, Y.Muraki, T.Sako
Solar-Terrestrial Environment Laboratory, Nagoya Univ.

H.Menjo *Kobayashi-Maskawa Institute, Nagoya Univ.*

K.Yoshida *Shibaura Institute of Technology*

K.Kasahara, T.Suzuki, S.Torii
Waseda Univ.

T.Tamura *Kanagawa University*

M.Haguenauer *Ecole Polytechnique, France*

W.C.Turner *LBNL, Berkeley, USA*

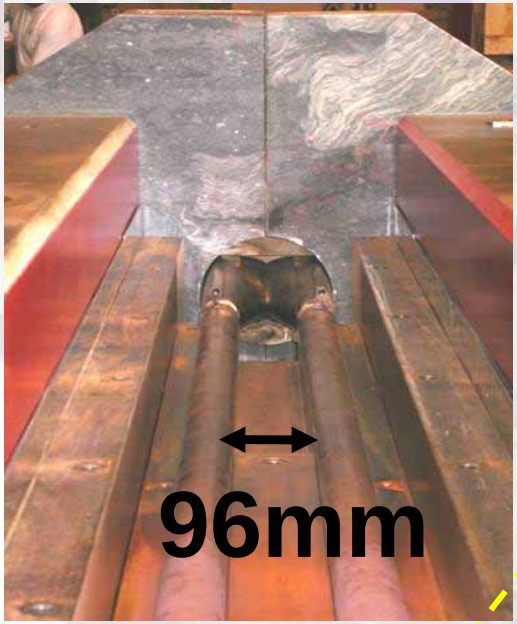
O.Adriani, L.Bonechi, M.Bongi, R.D'Alessandro, M.Grandi, P.Papini, S.Ricciarini, G.Castellini
INFN, Univ. di Firenze, Italy

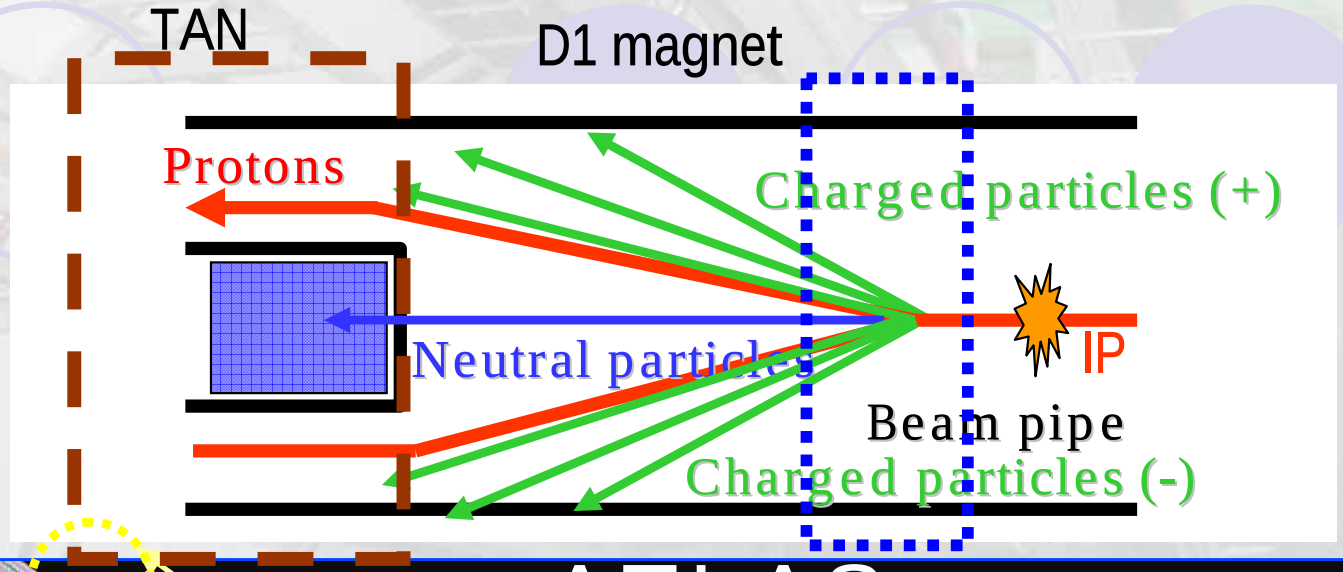
A.Tricomi *INFN, Univ. di Catania, Italy*

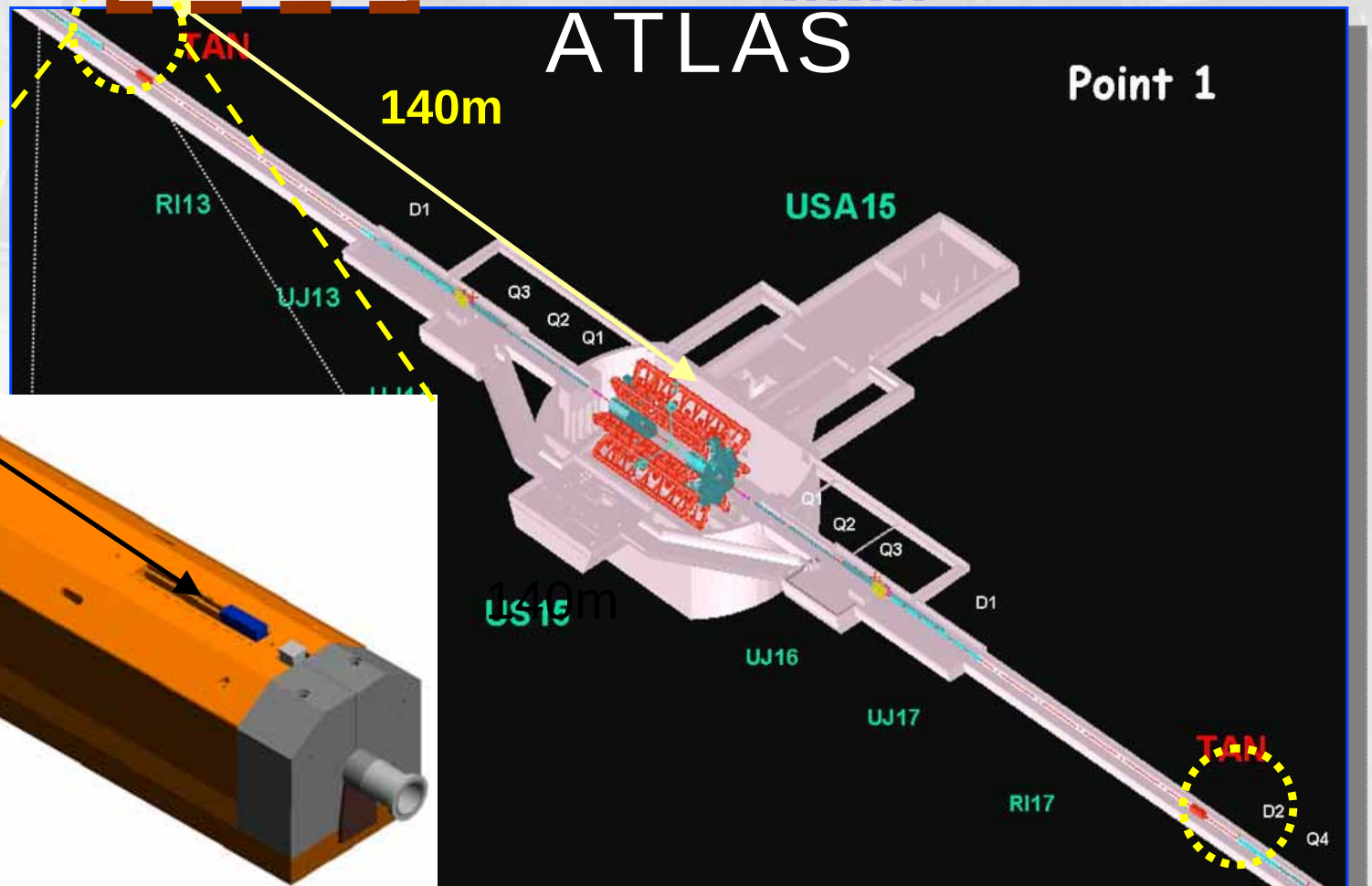
A-L.Perrot, D.Ppeiffer *CERN, Switzerland*

~30 physicists from 5 countries

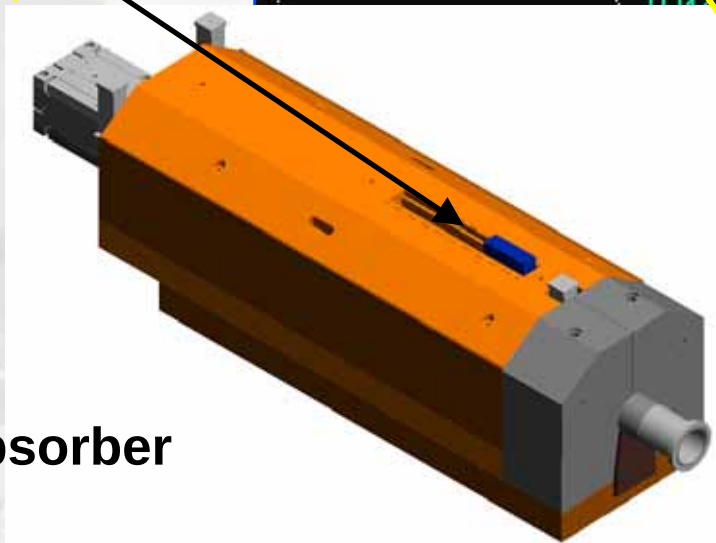
LHCf site





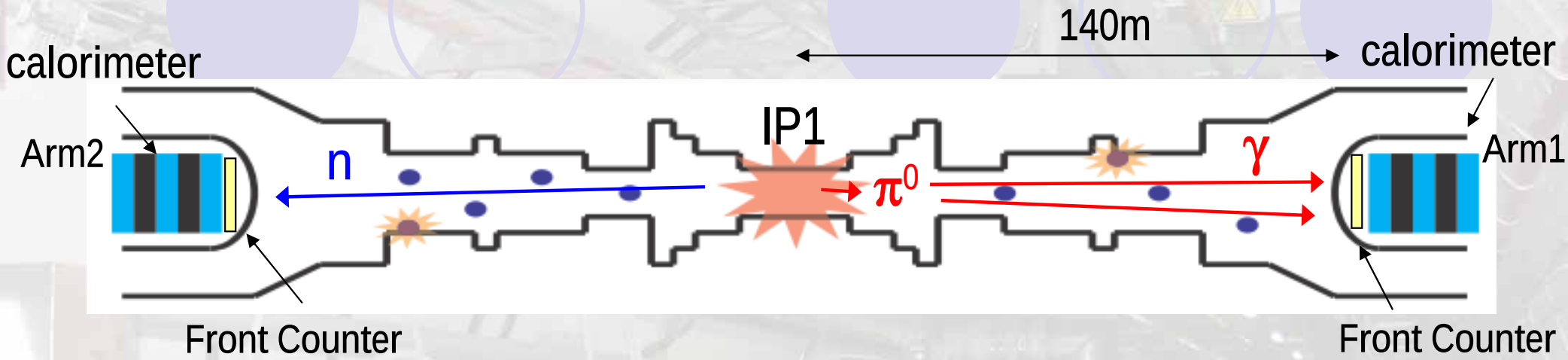


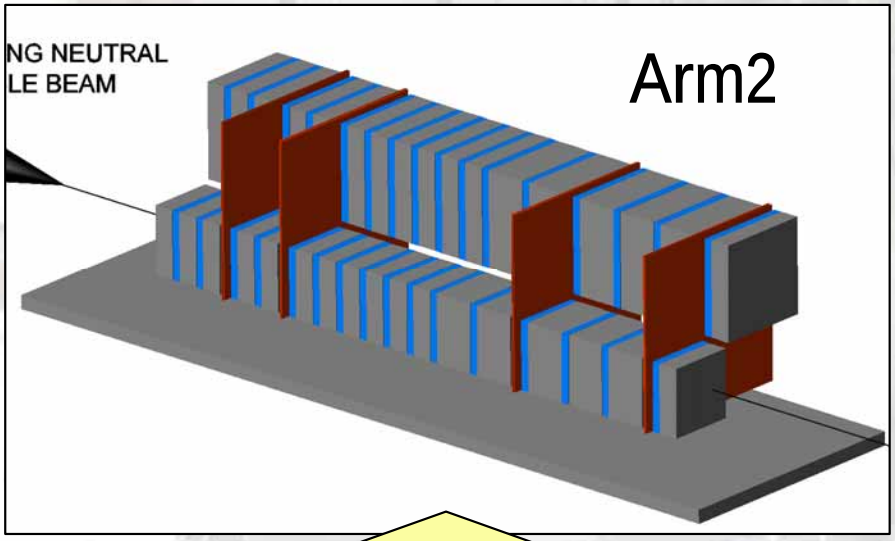
LHCf/ZDC



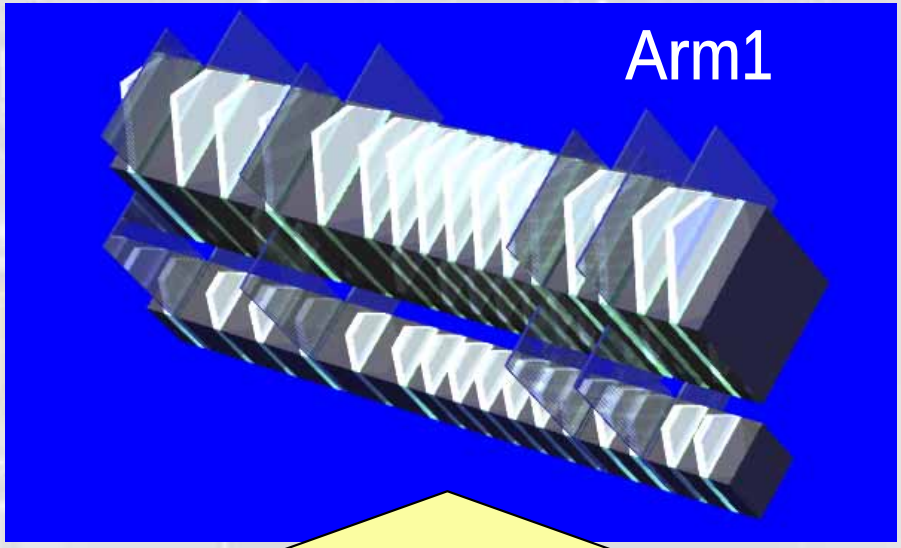
TAN absorber

The LHCf detectors





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

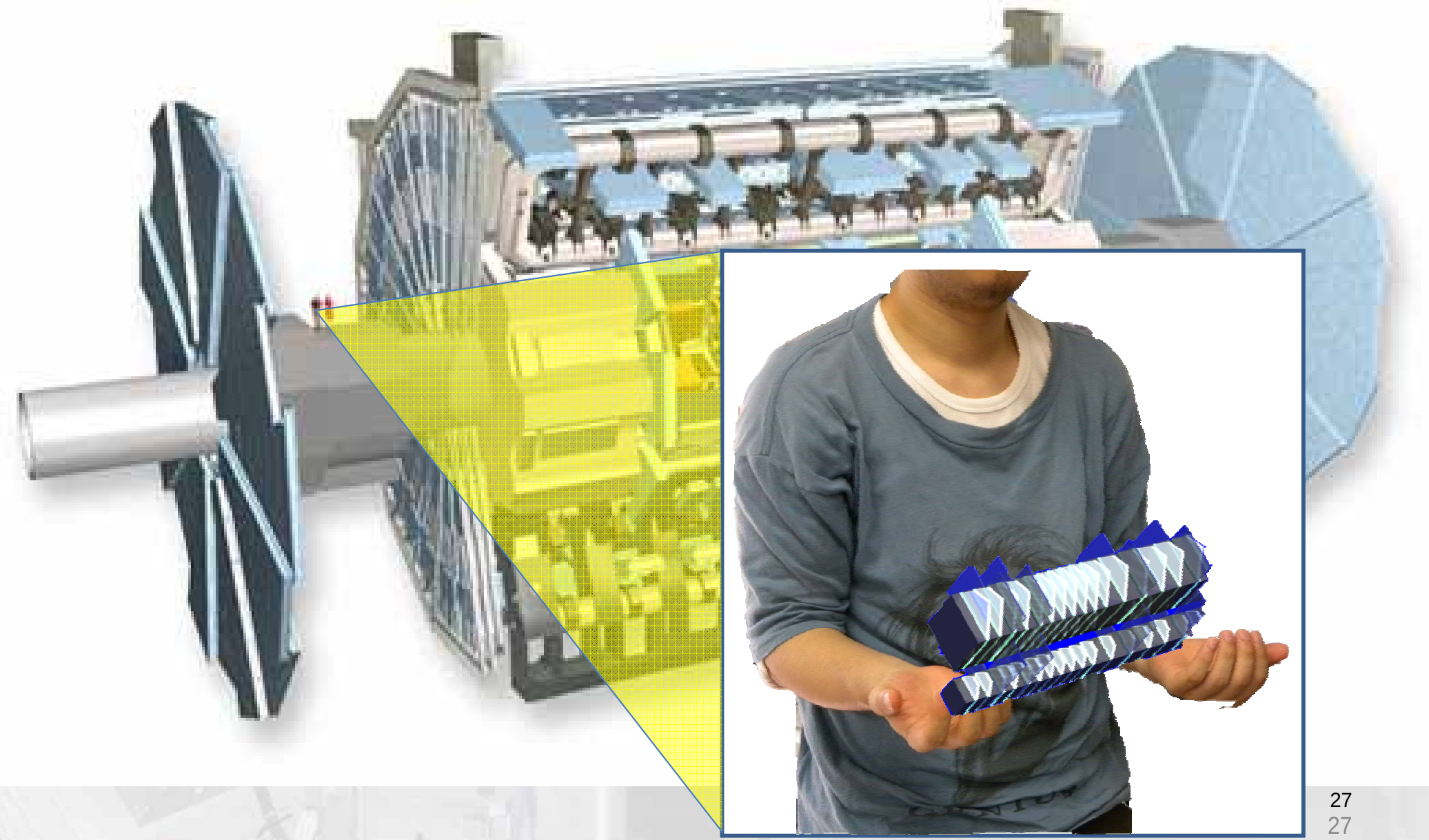


16 tungsten + pl.scinti. layers
25mmx25mm+32mmx32mm
4 Silicon strip tracking layers

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

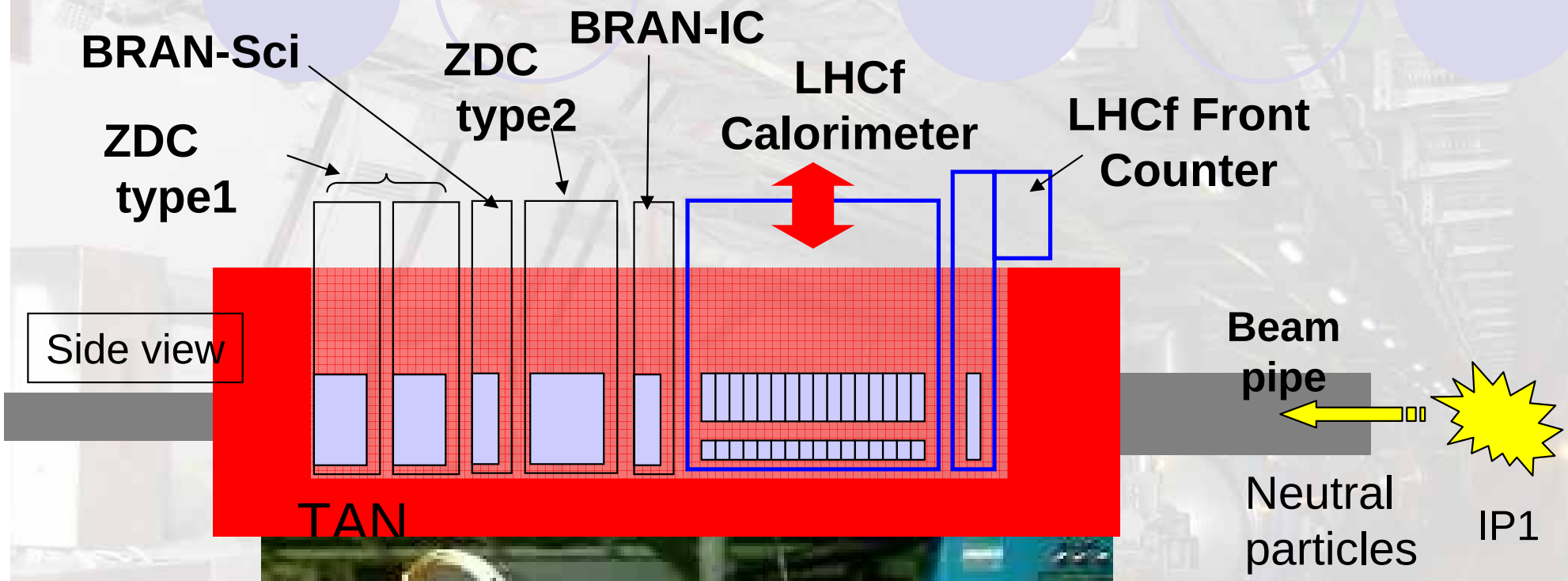
LHCf calorimeters

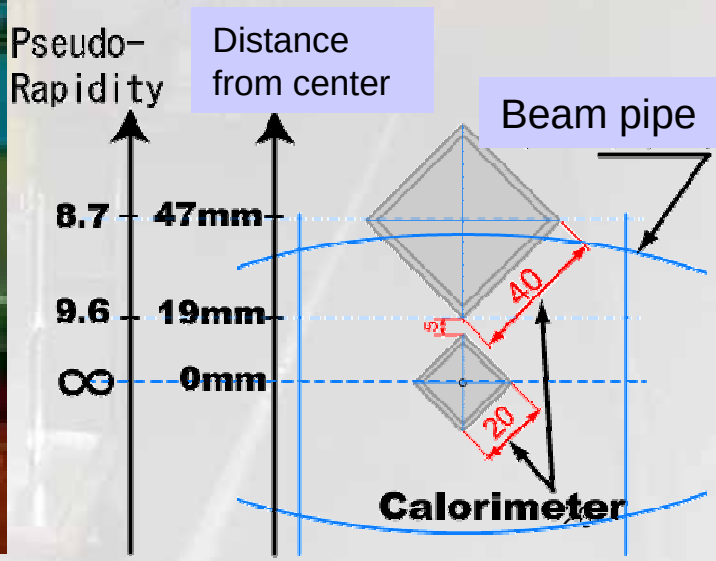
ATLAS & LHCf



27

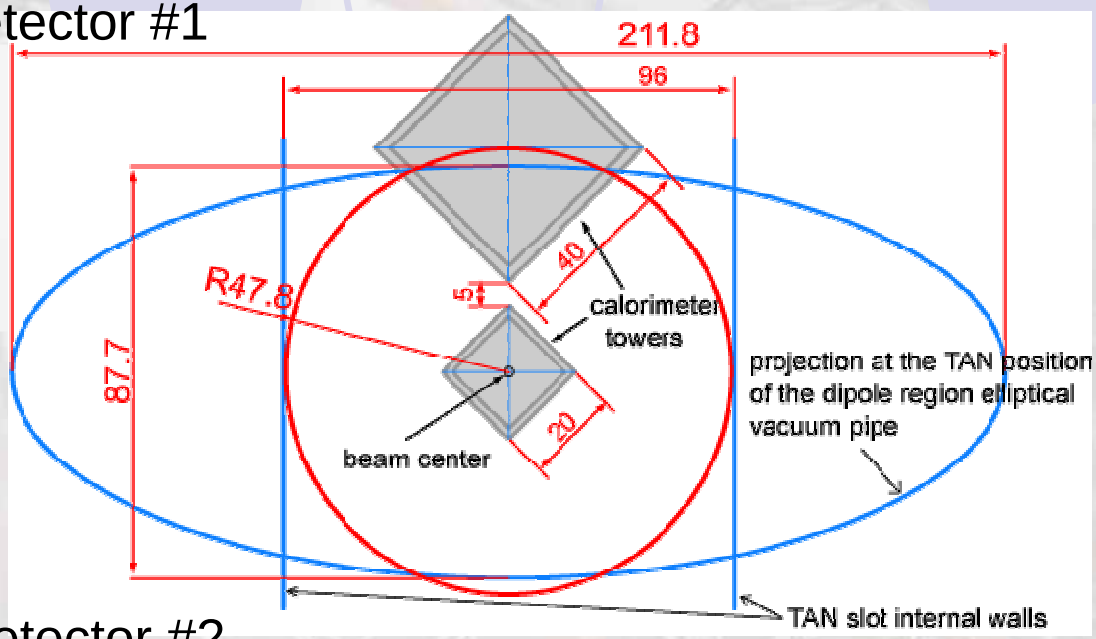
Setup in IP1-TAN (side view)



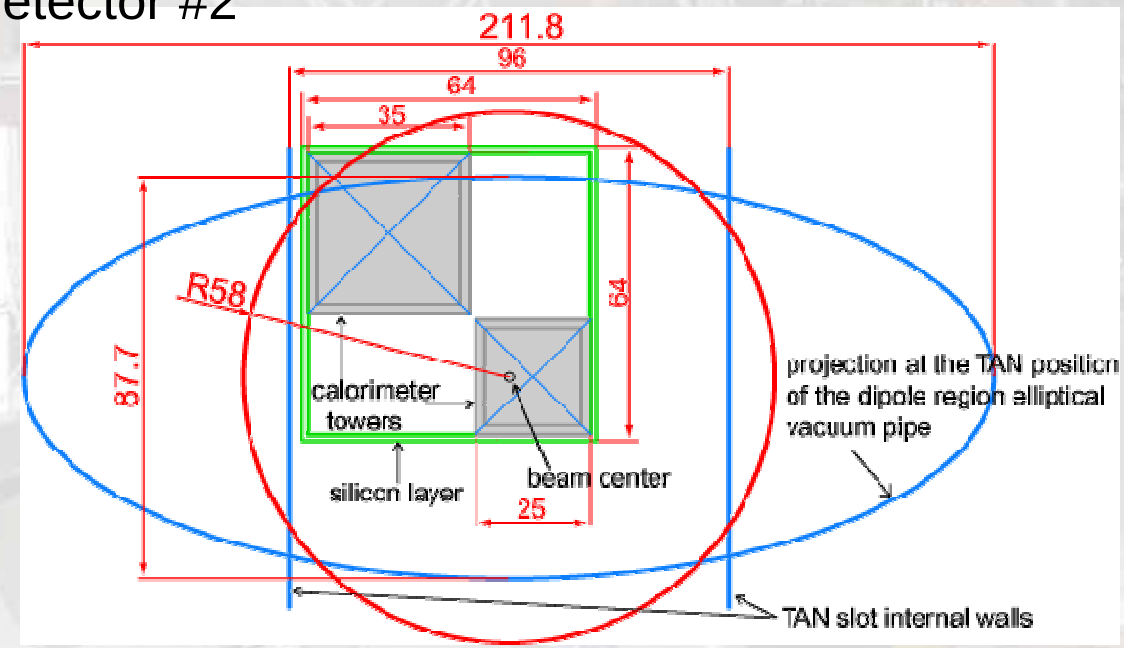


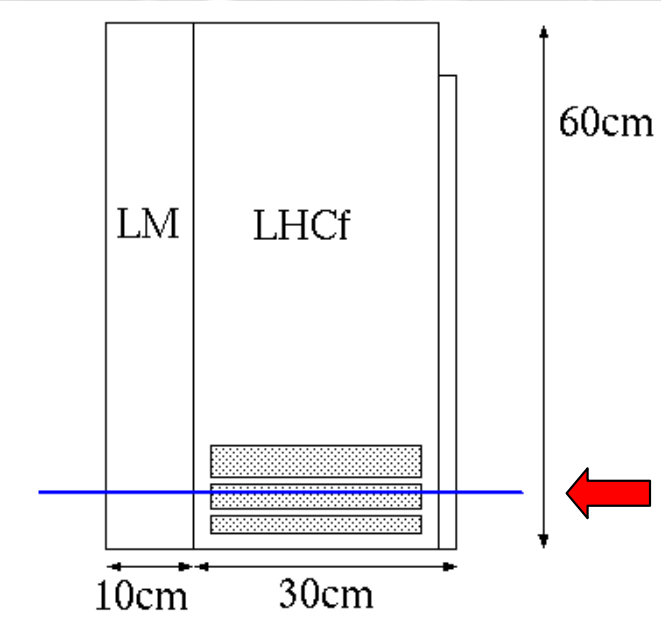
Geometry

The Detector #1



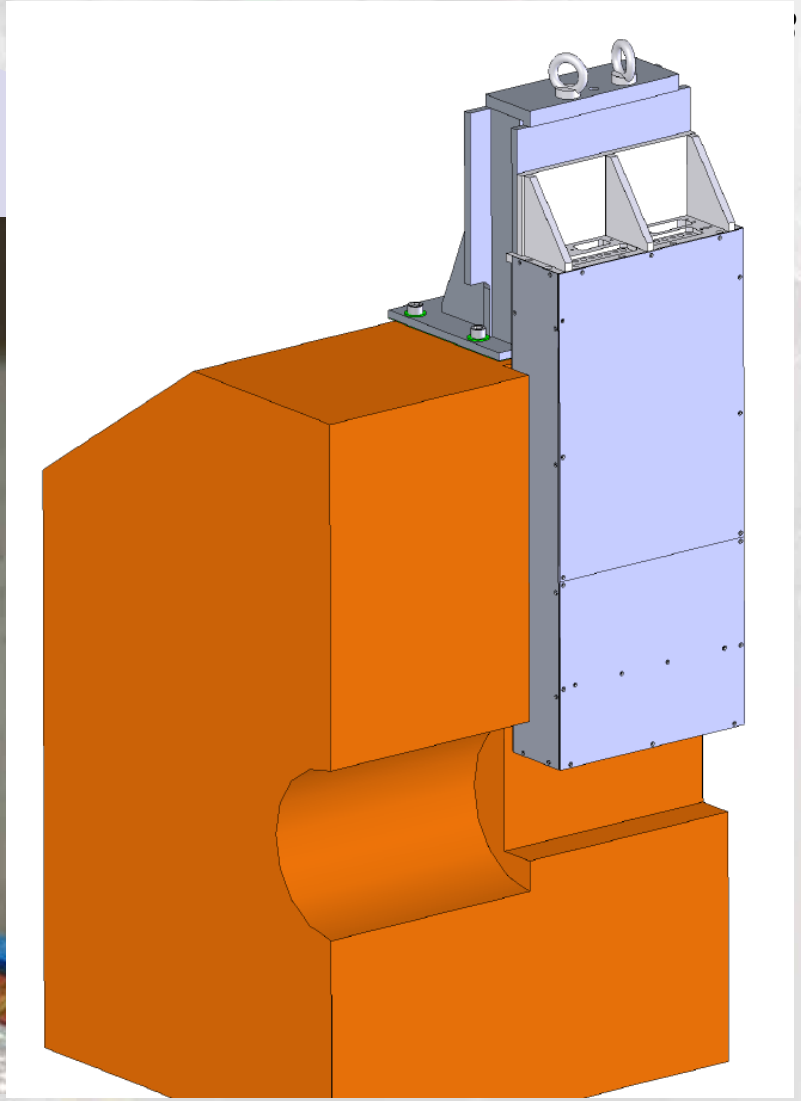
The Detector #2





Side view

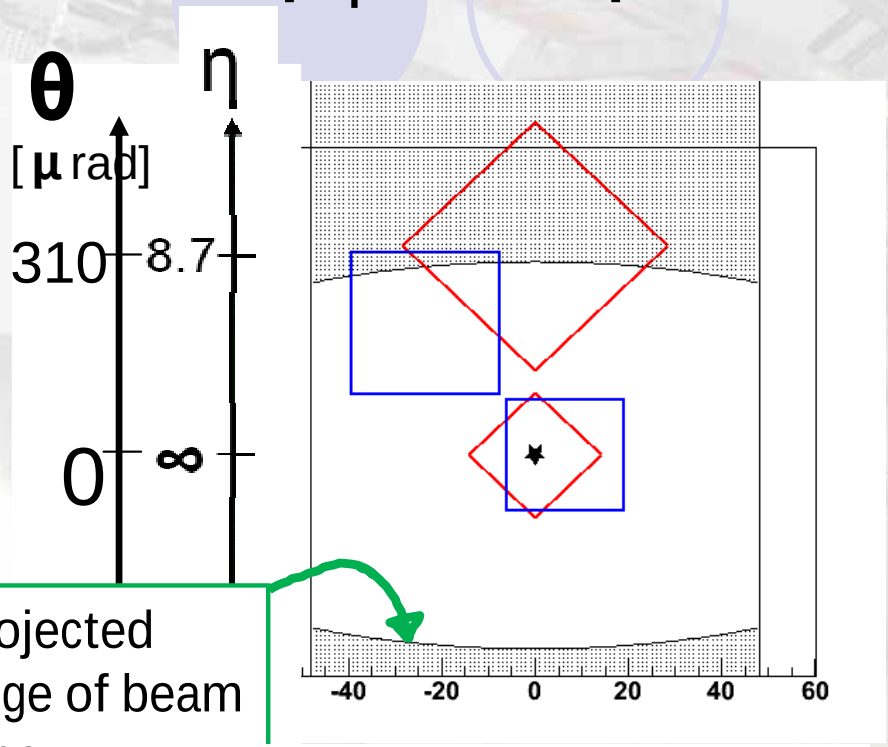
Manipulator



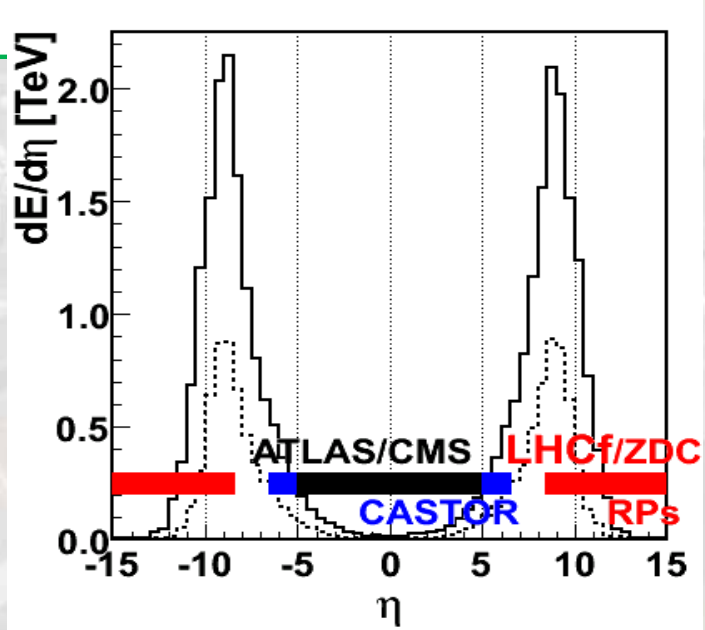
- Retract upward when beam tune to prevent radiation
- Change vertical position to scan covered-p_T region

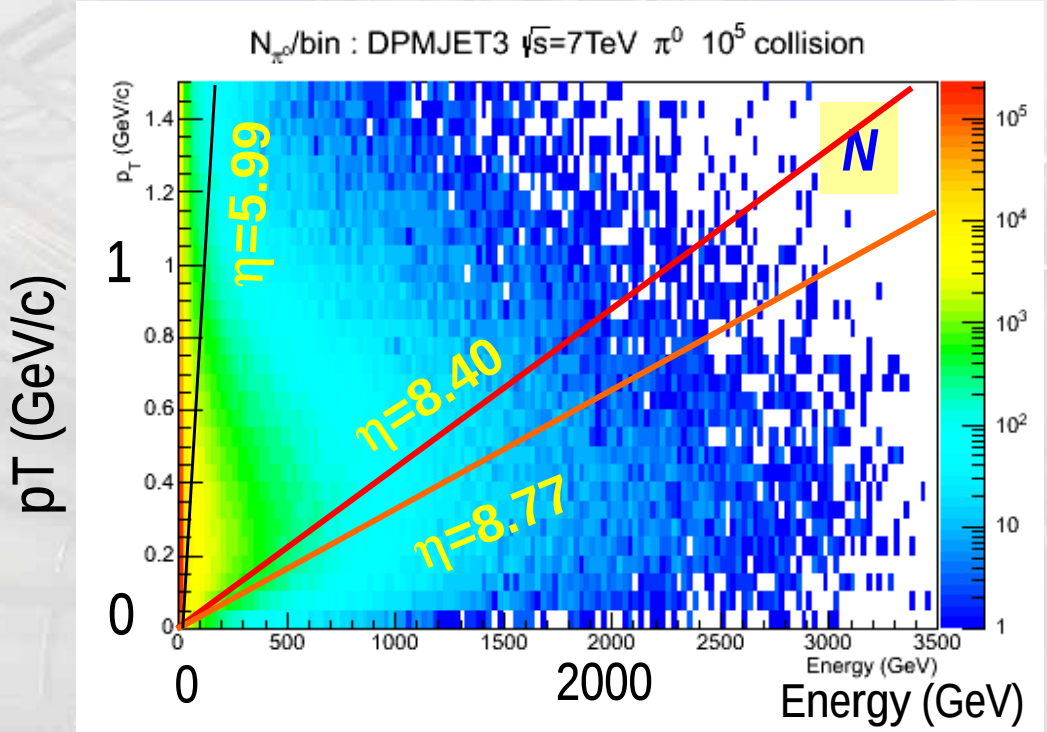
Remote control from USA15
(200m apart)

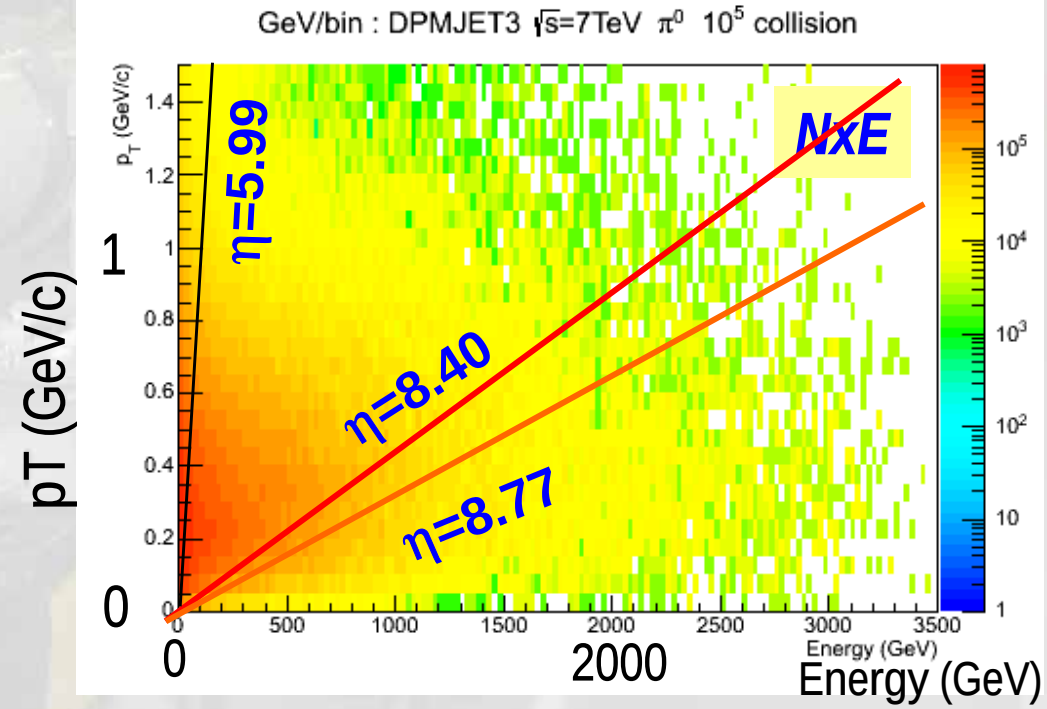
LHCf p_T acceptance



Projected edge of beam pipe

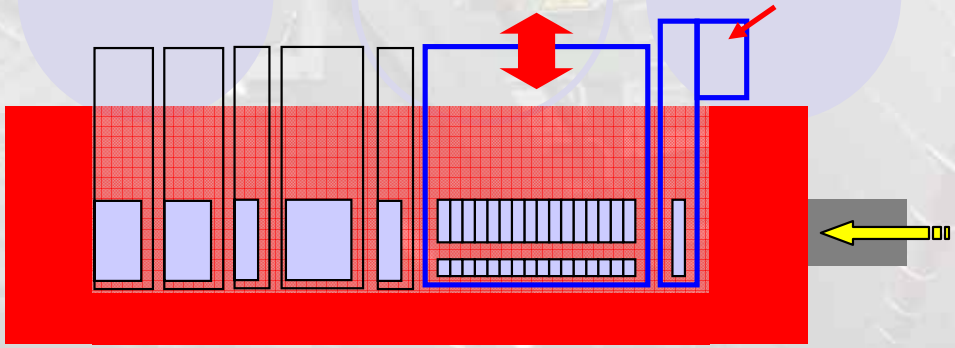


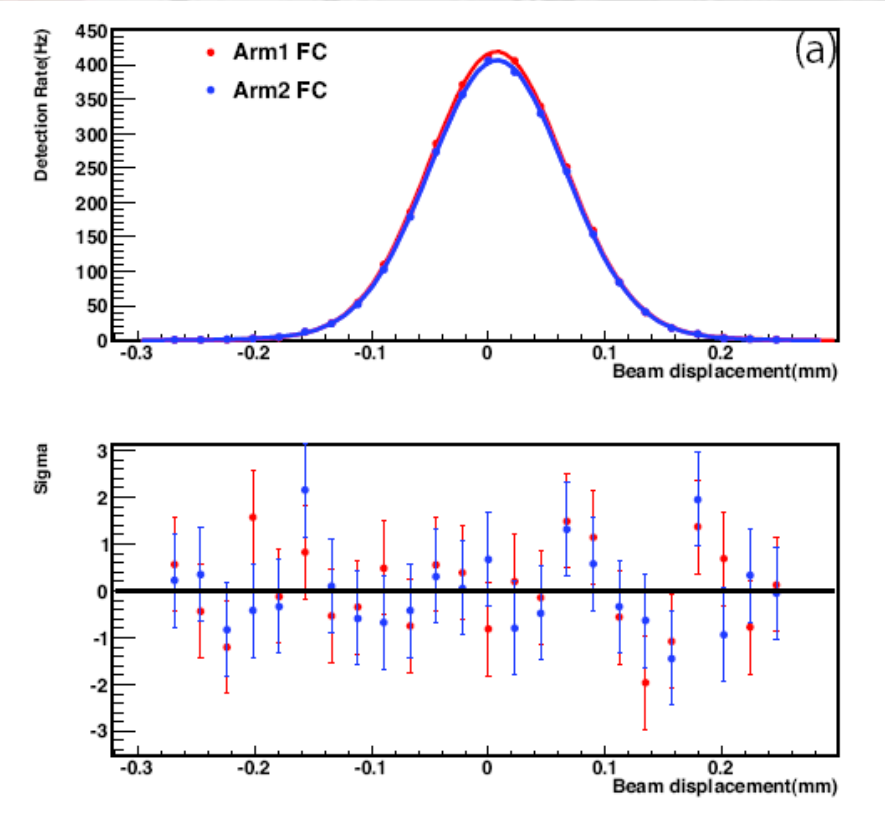


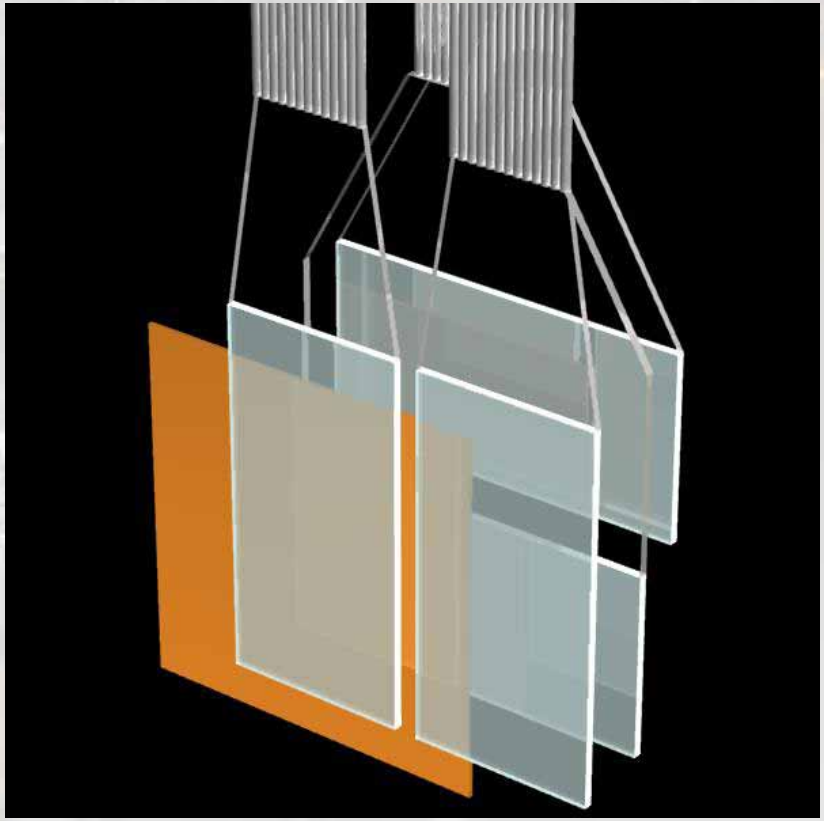


Front Counter

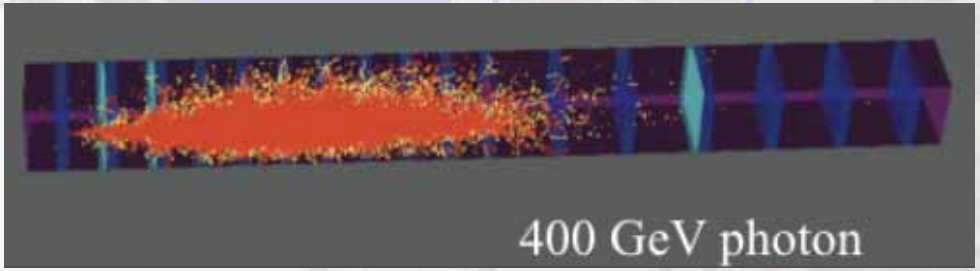
- 2 fixed Front Counters were installed in front of Arm1 and Arm2
- Determine luminosity calibrated by Van der Meer Scan

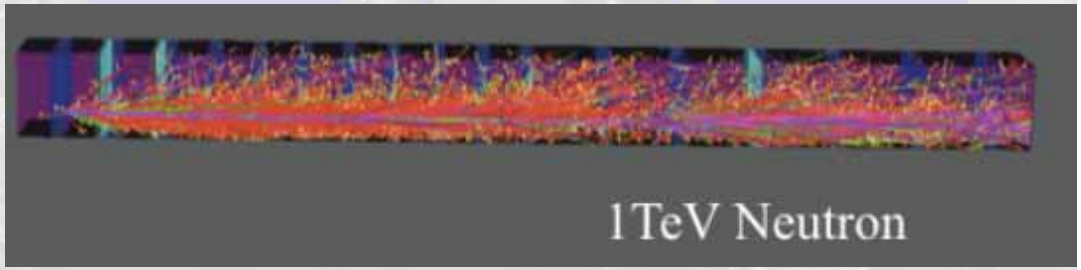




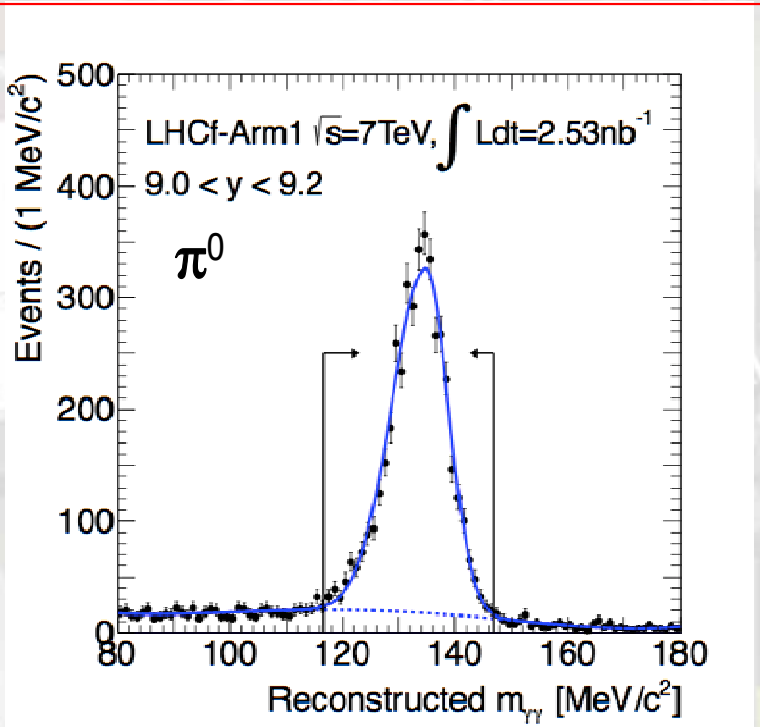


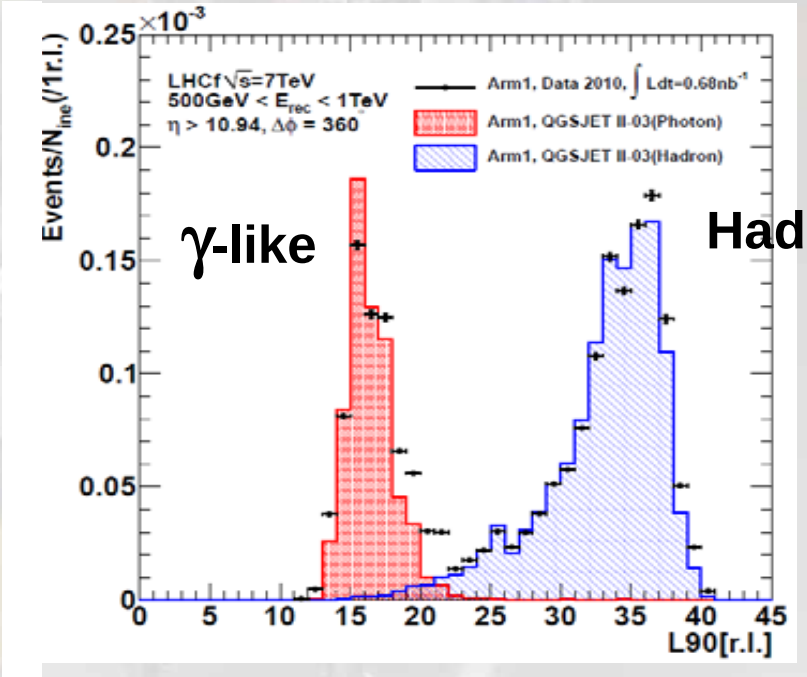
Calorimeter performance





- 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 20-04 LOI
- Feb 2006 TDR
- June 2006 LHCC approved

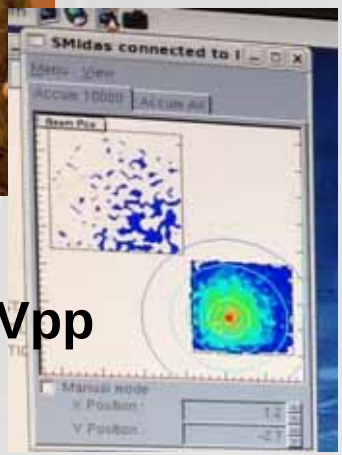
Jul 2006 construction

Aug 2007 SPS beam test

Jan 2008 Installation Sep 1st LHC beam

Dec- Jul 2010 0.9TeV& 7TeV pp

Jul 2010 Detector removal



Dec2012- Feb 2013 5TeV/n pPb, 2.76TeVpp Detector removal

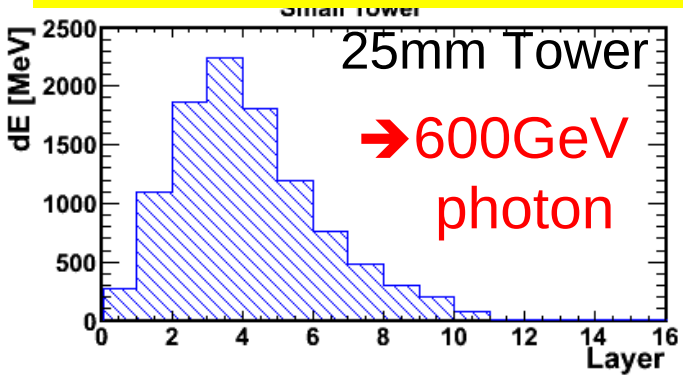
LHCf data

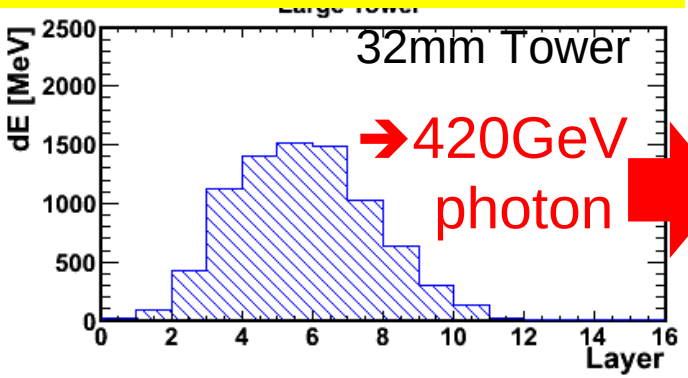
- single γ spectra in two η regions at 7TeV pp and 0.9 TeV pp

- π^0 p_T spectra in various y regions at 7TeV pp

Event display ($\pi^0 \rightarrow 2\gamma$ from 7TeV pp)

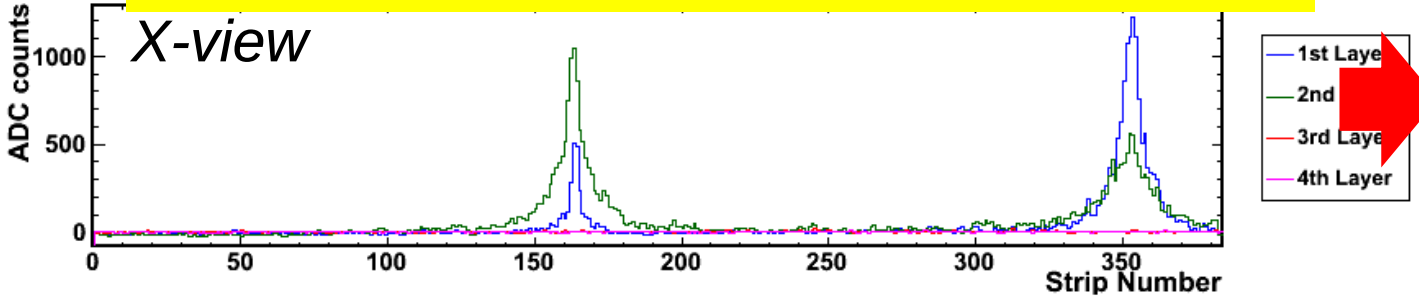
Longitudinal development measured by scintillator layers

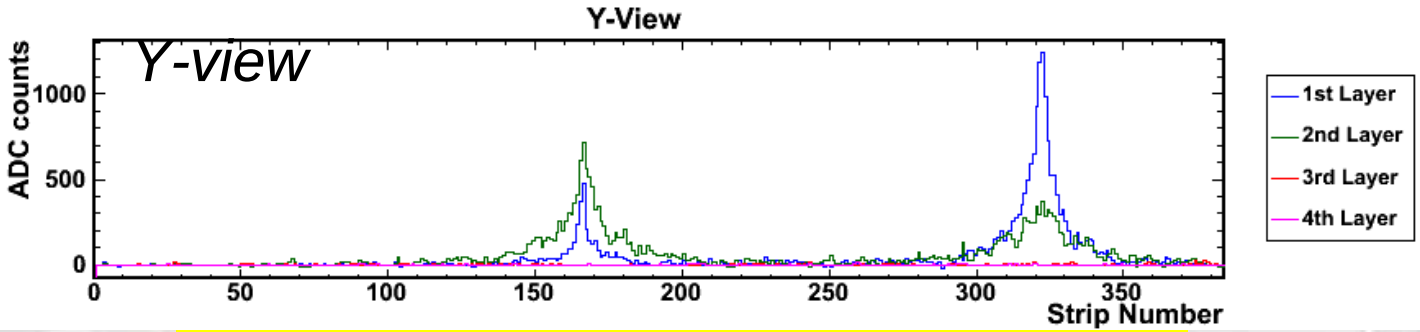




Total Energy deposit
➔Energy
Shape
➔PID

Lateral distribution measured by silicon detectors



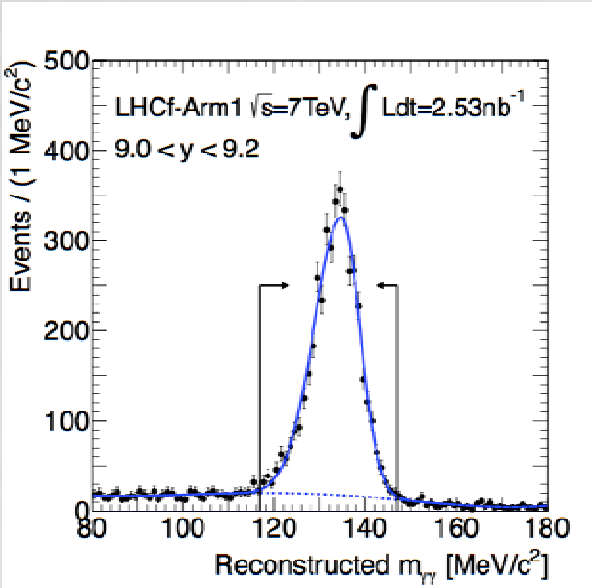


Hit position,
Multi-hit search.

π^0 mass reconstruction from two photon.

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

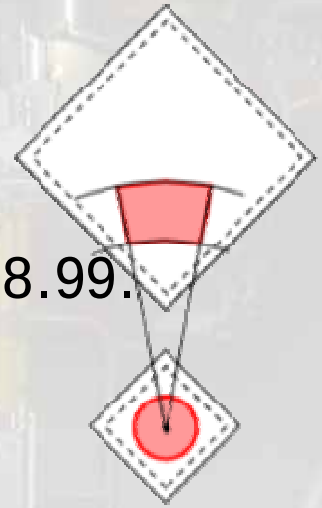
Systematic studies



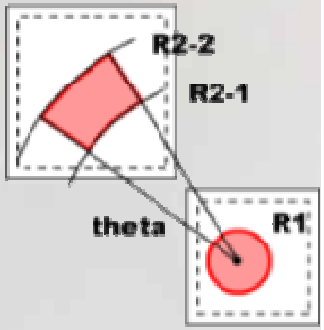
The single photon energy spectra at 0 degree at 7TeV

(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)



Arm1

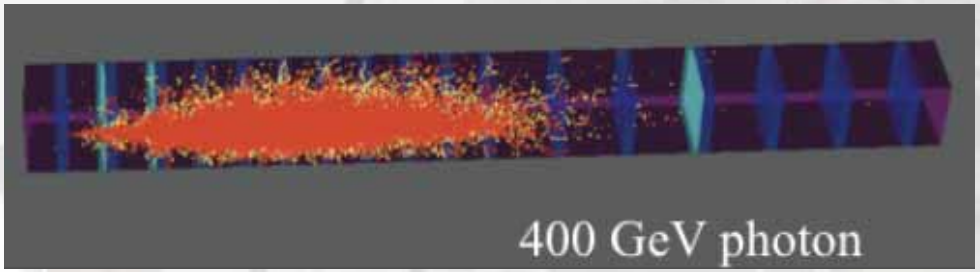


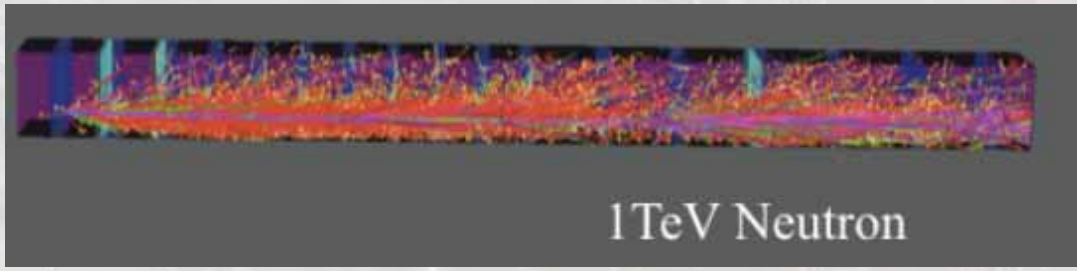
Arm2

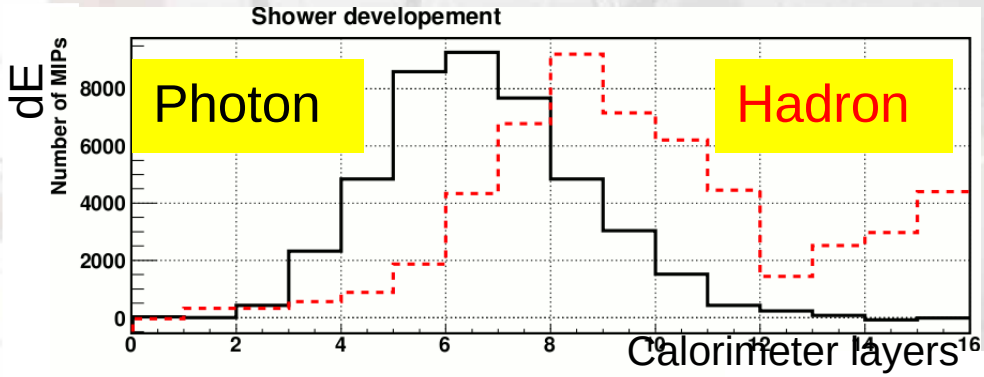
Particle Identification

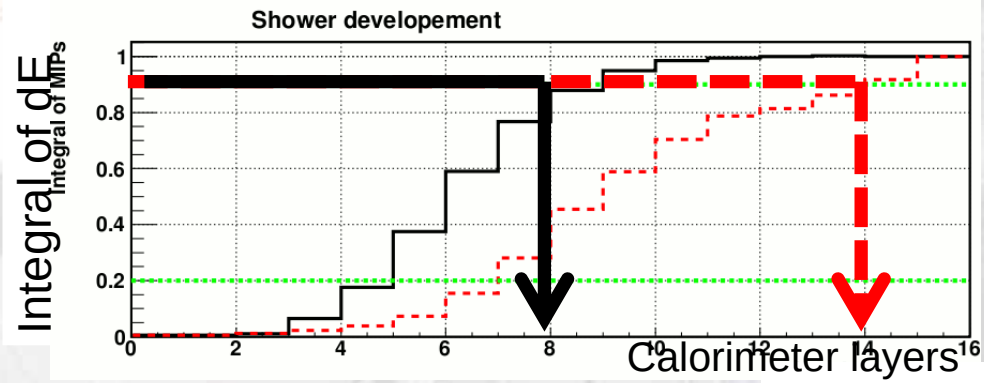
Calorimeter Depth

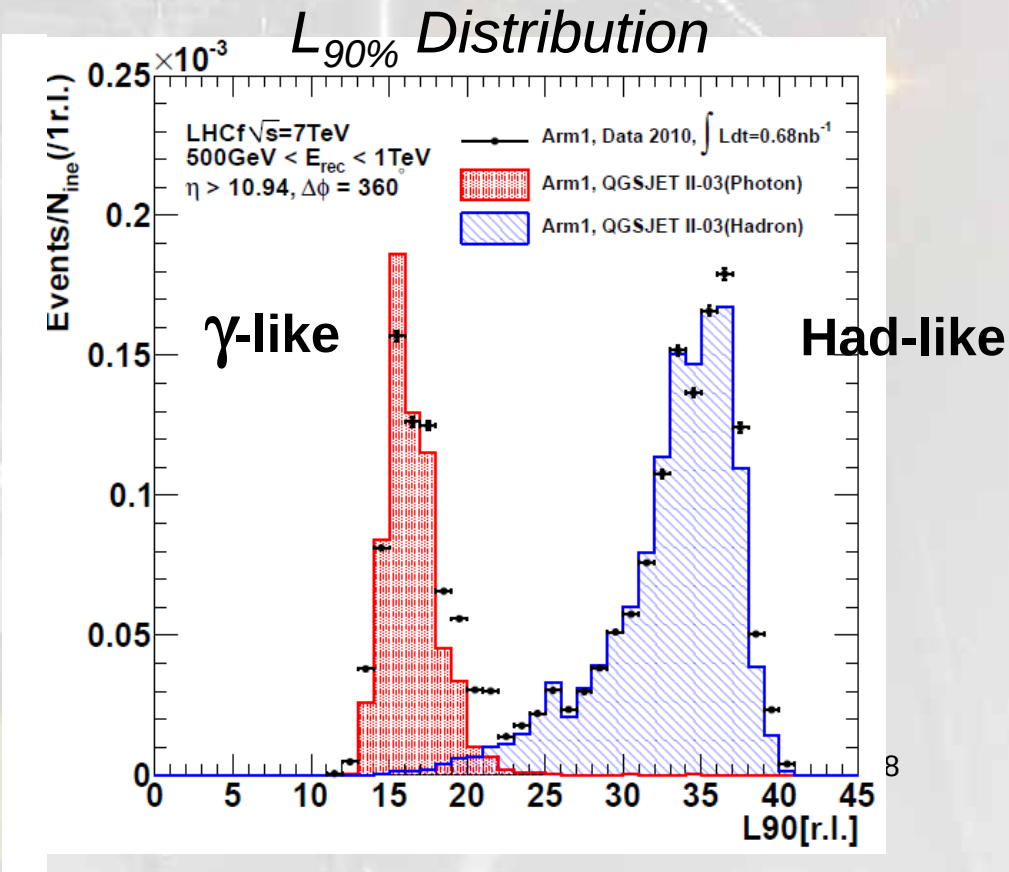
Elemag: 44r.l.
Hadronic: 1.7 λ





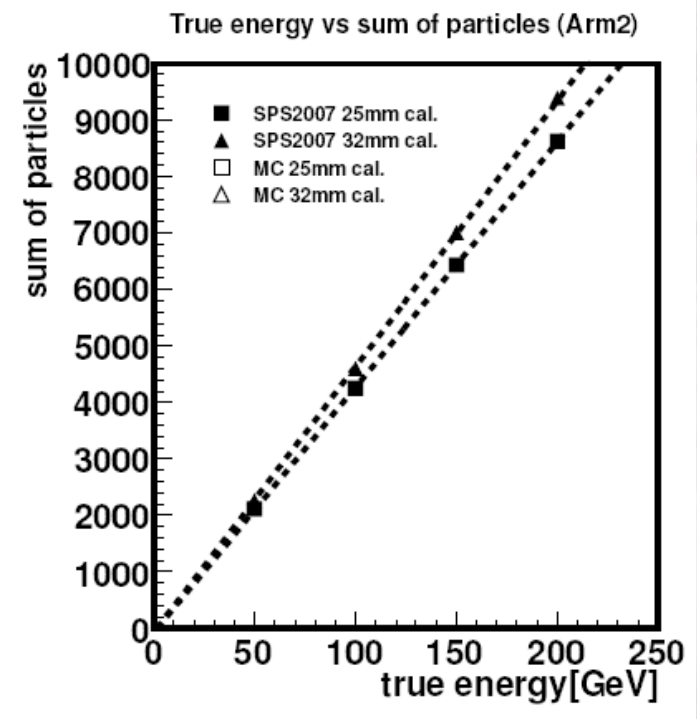


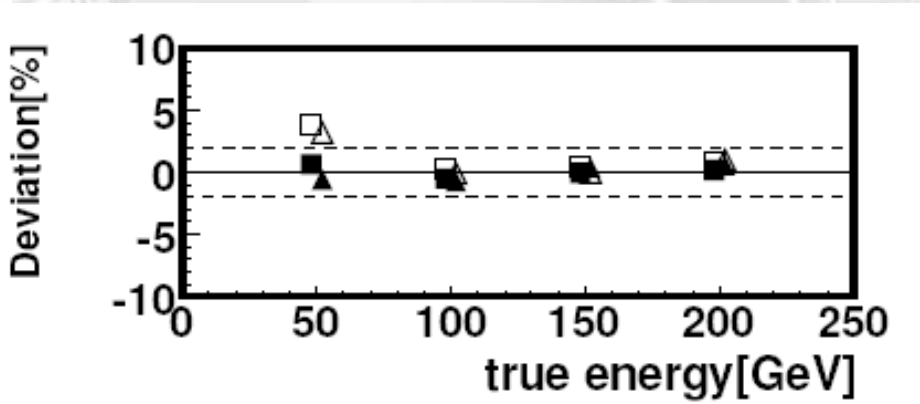




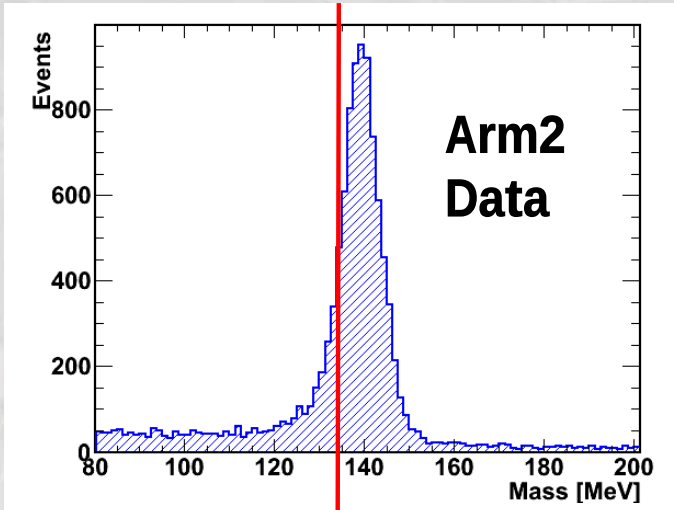
Energy scale

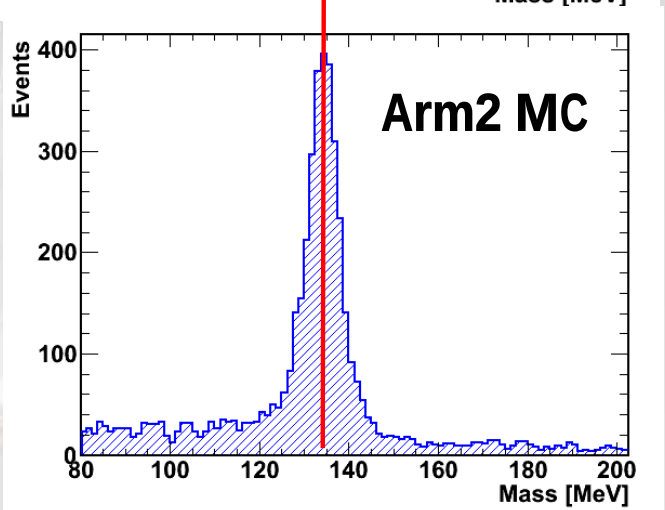
- Determined by SPS H4 beam test
  - 150, 200 GeV electron beam





- Checked by π^0 mass peak at 7TeV in-situ
  - Mass shifts observed both in Arm1 (+7.8%) and Arm2 (+3.7%), not corrected but taken into systematics





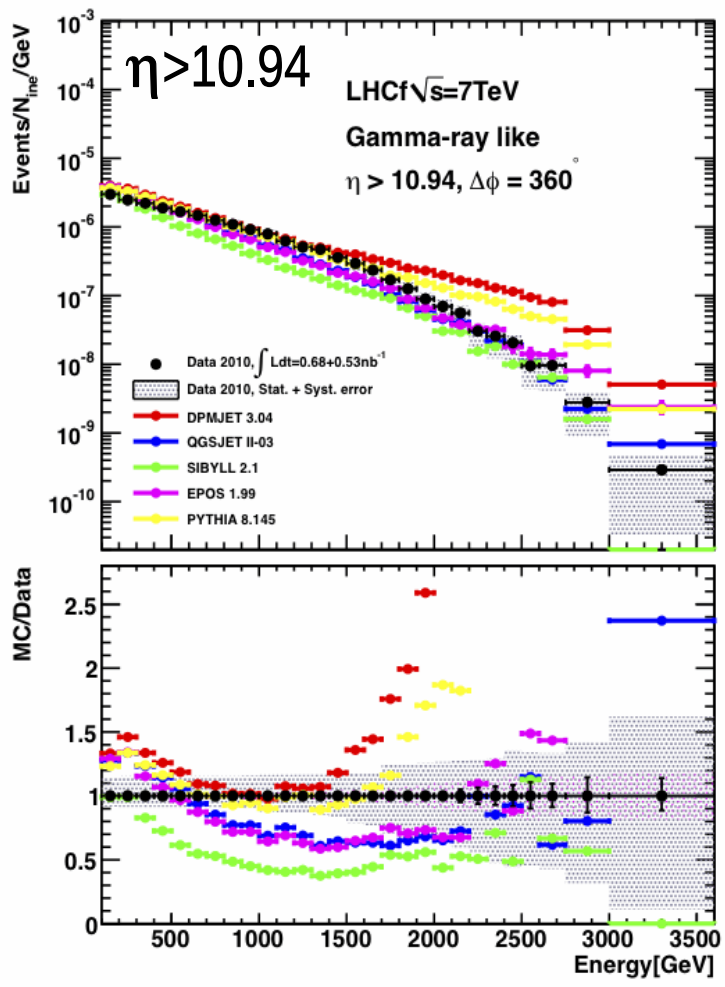
LHCf single γ spectra at 7TeV

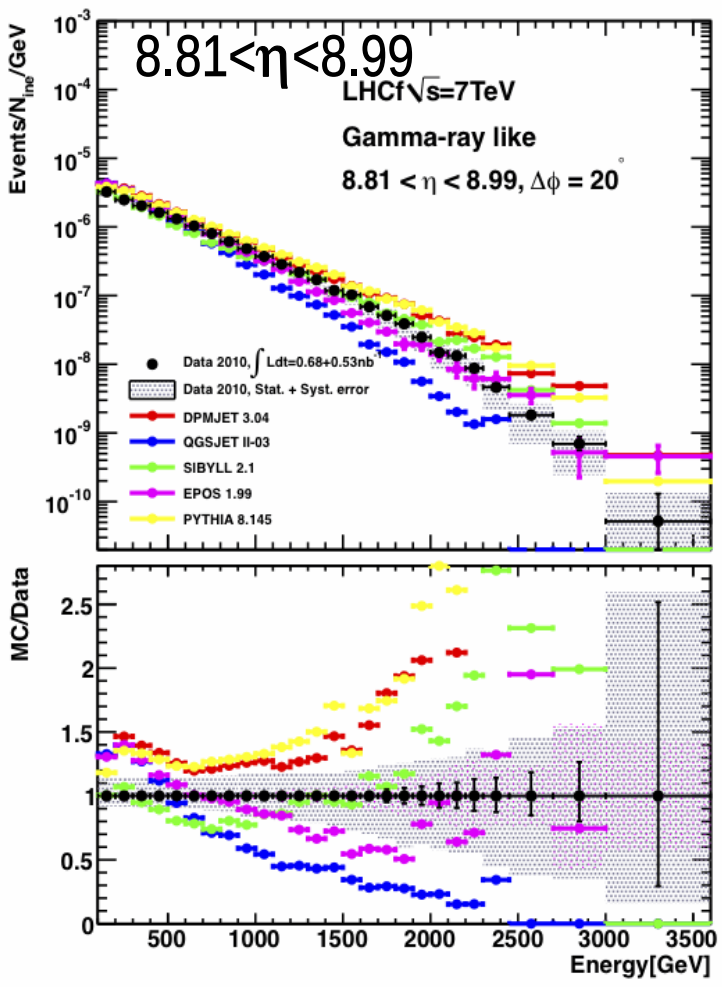
0.68 (0.53)nb^{-1} on 15May2010

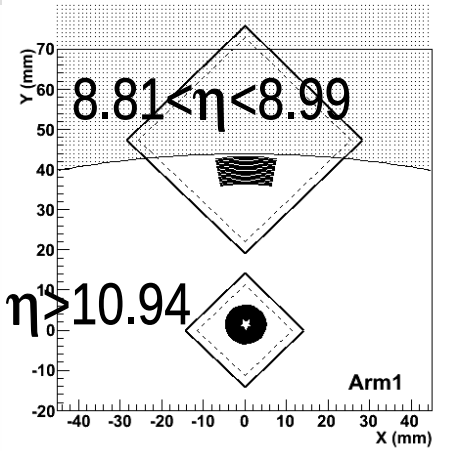
DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

Gray hatch : Sys+stat errors

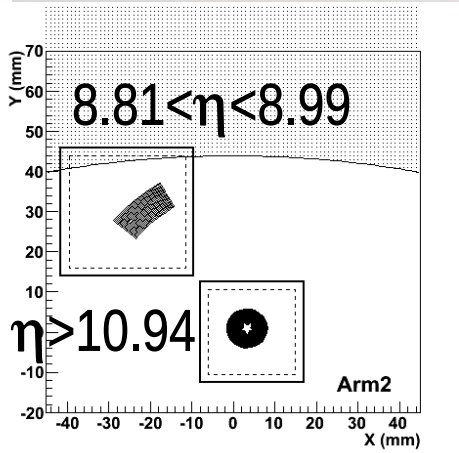
Magenta hatch: Stat errors of MC







Arm1



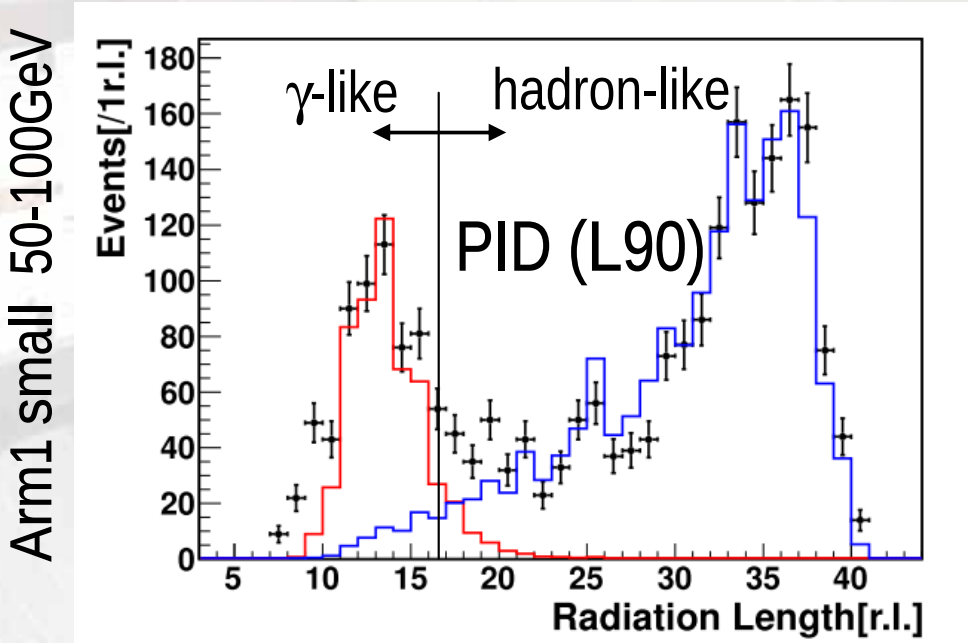
Arm2

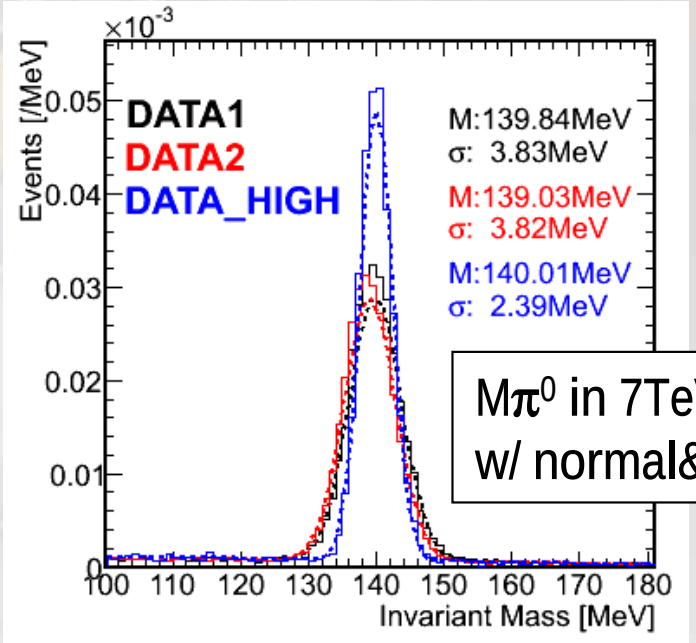
PLB 703 (2011) 128-134

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

single γ analysis from 900 GeV pp

- 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.





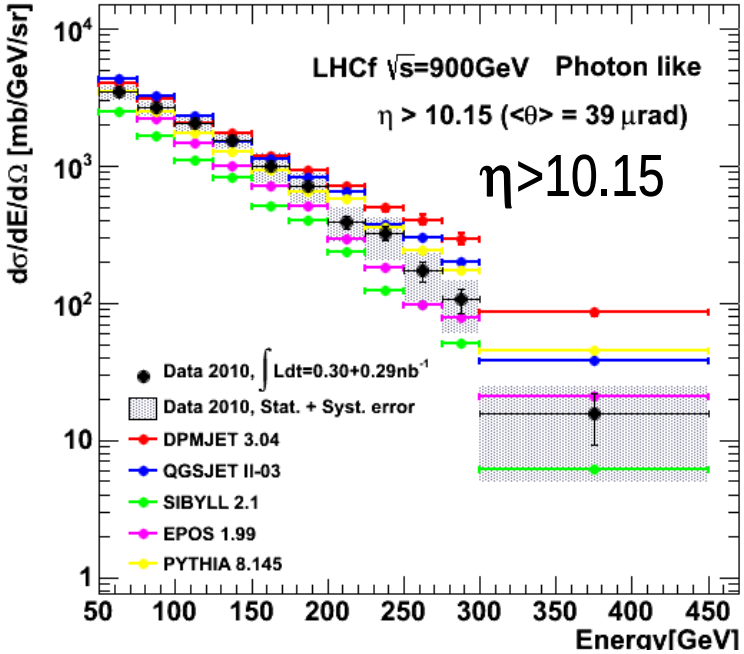
Mπ^0 in 7TeV
w/ normal&high gain

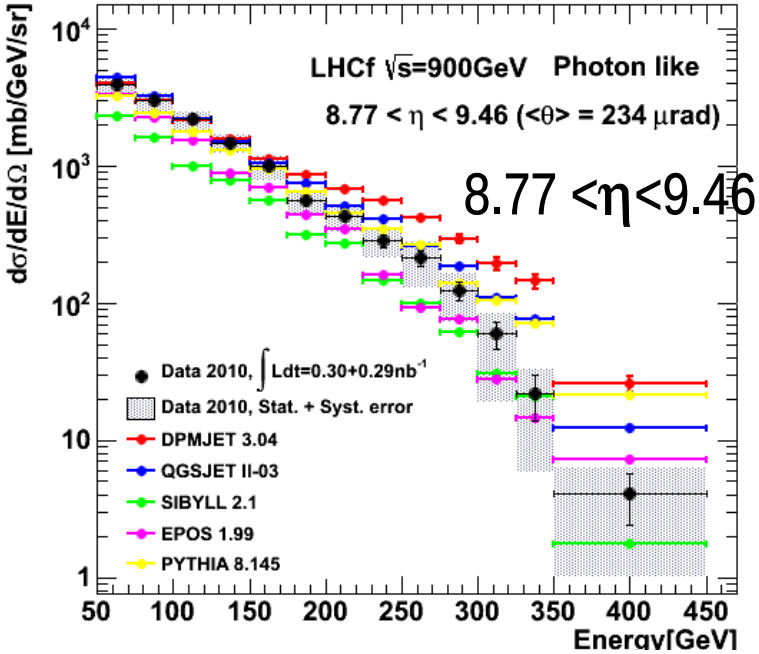
LHCf single γ spectra at 900 GeV

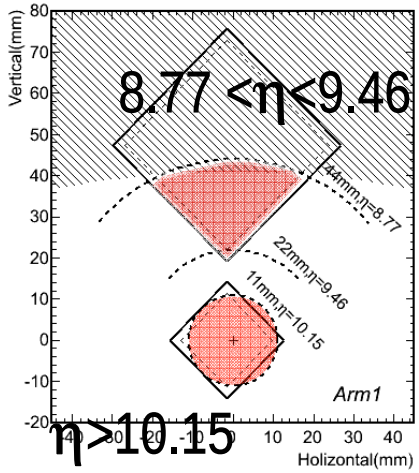
PLB 715 (2012) 298-303

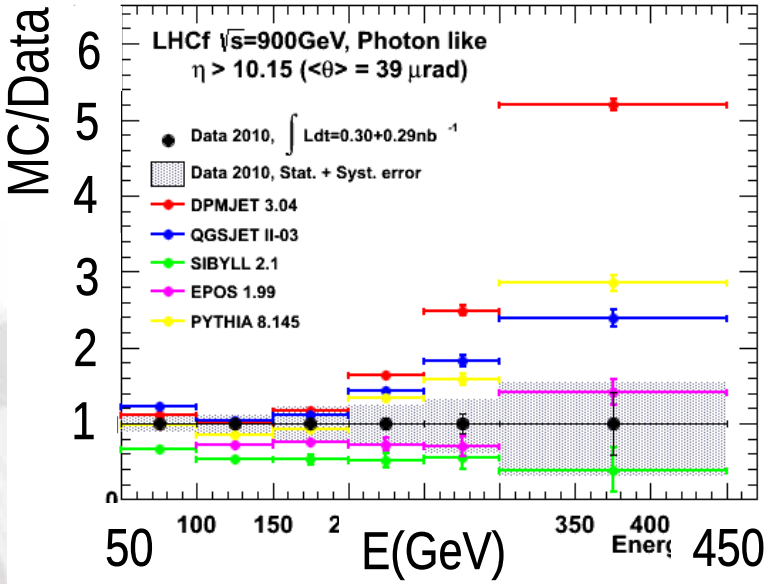
May2010 900GeV data (0.3nb-1 , 21% uncertainty not shown)

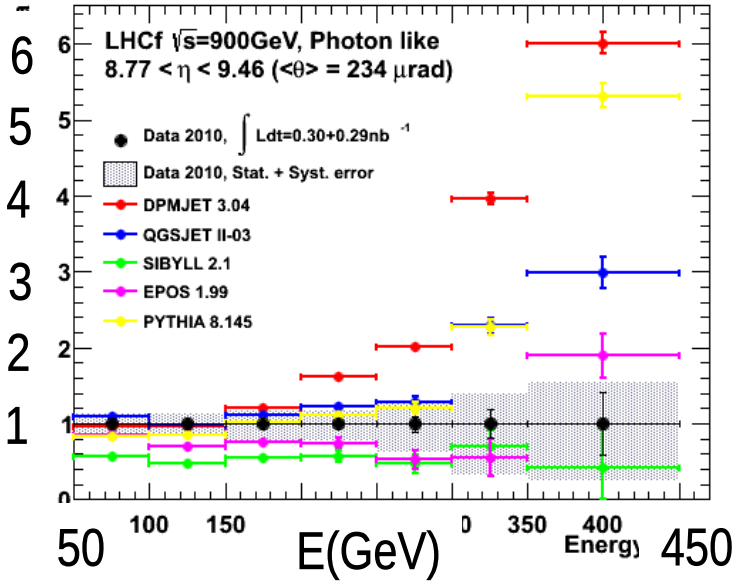
DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

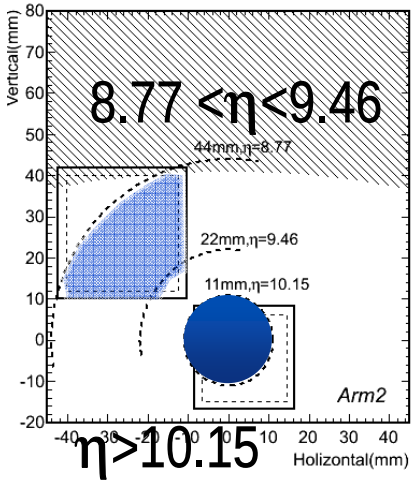








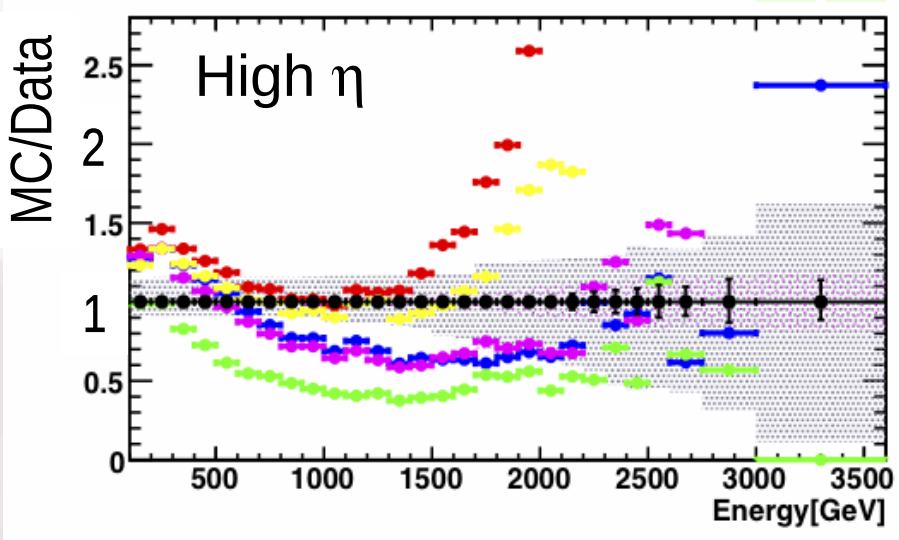


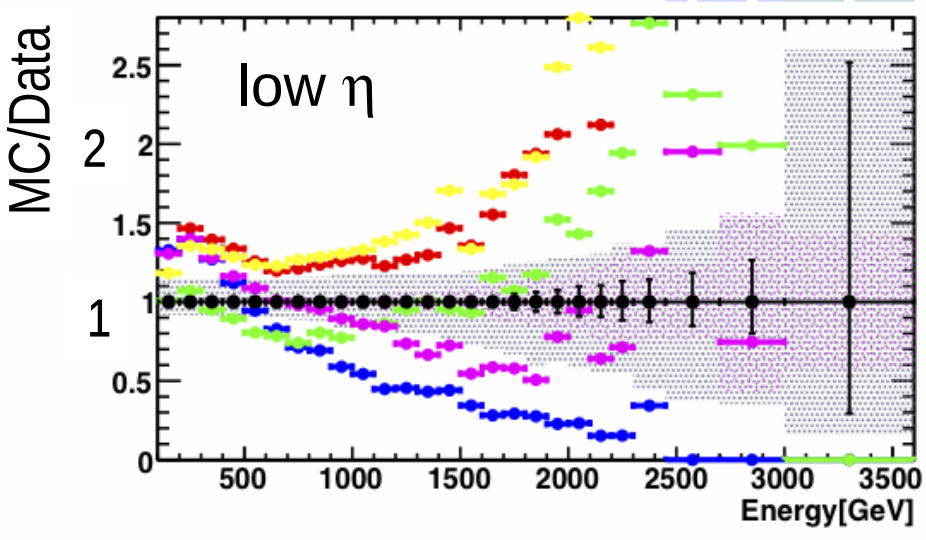


Comparison of Data/MC ratio at two energies

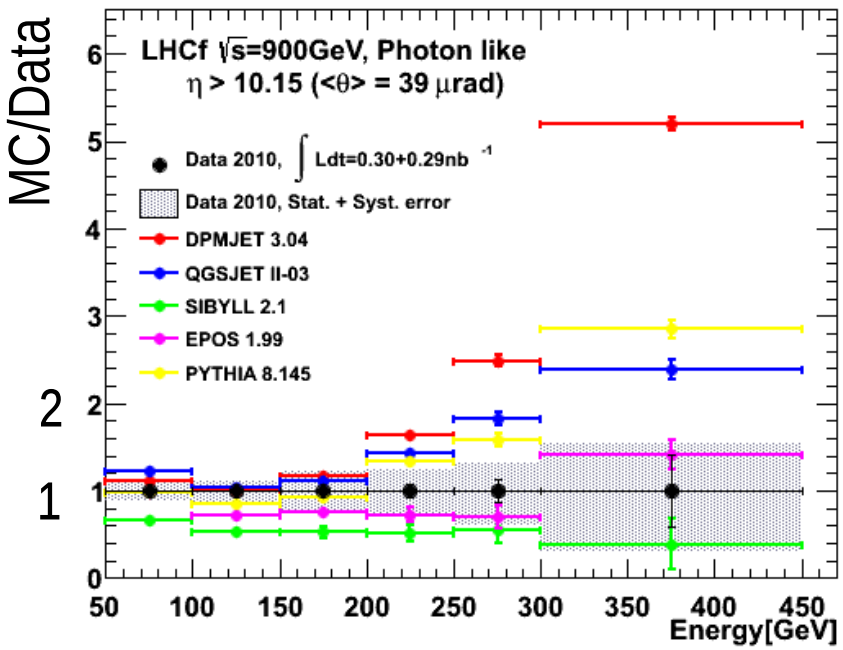
DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

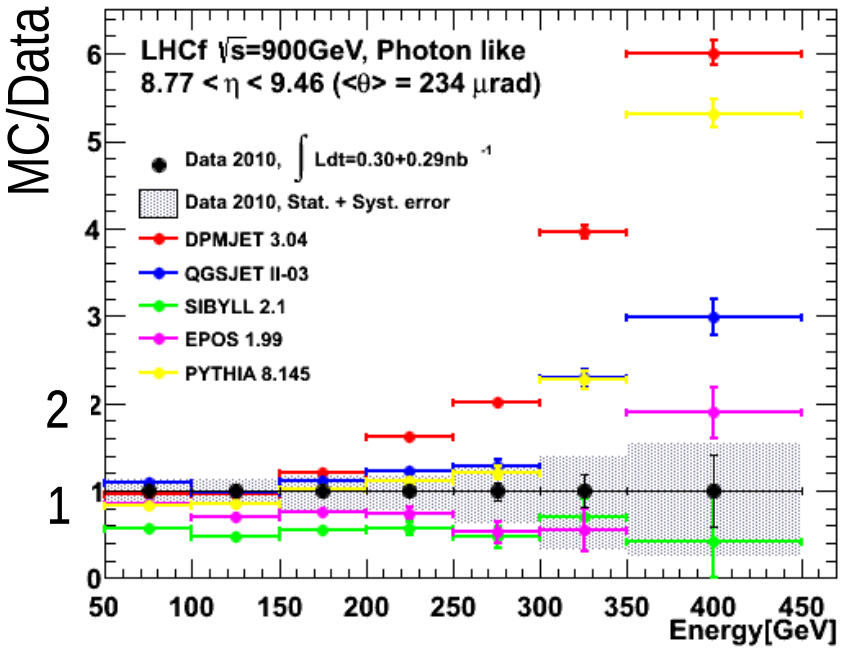
7TeV





900GeV

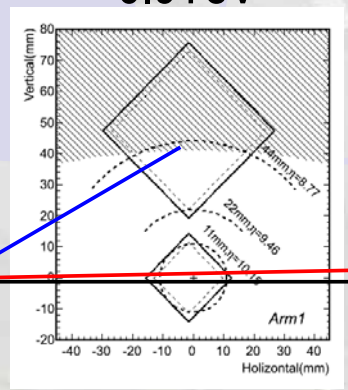




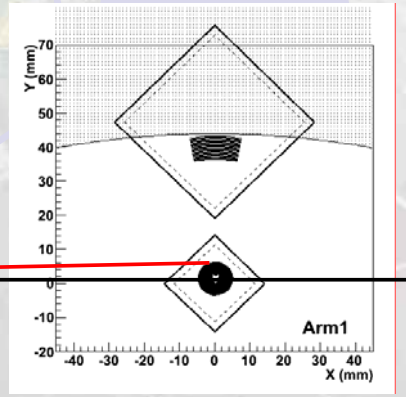
X_F spectra for single γ: 900GeV/ 7TeV comparison

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

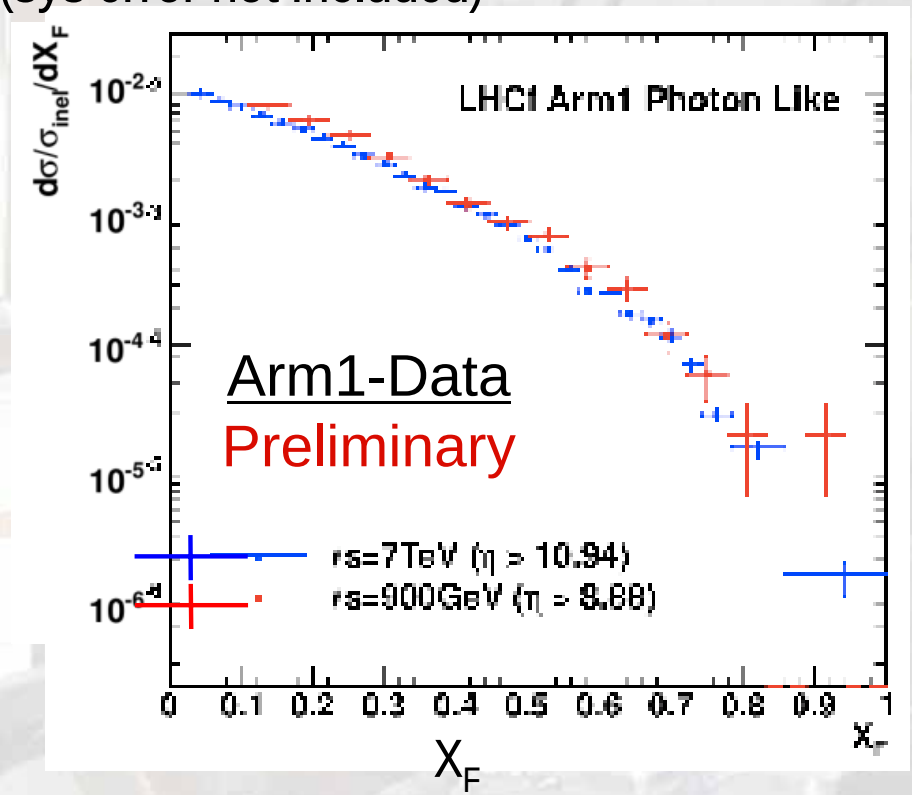
0.9TeV

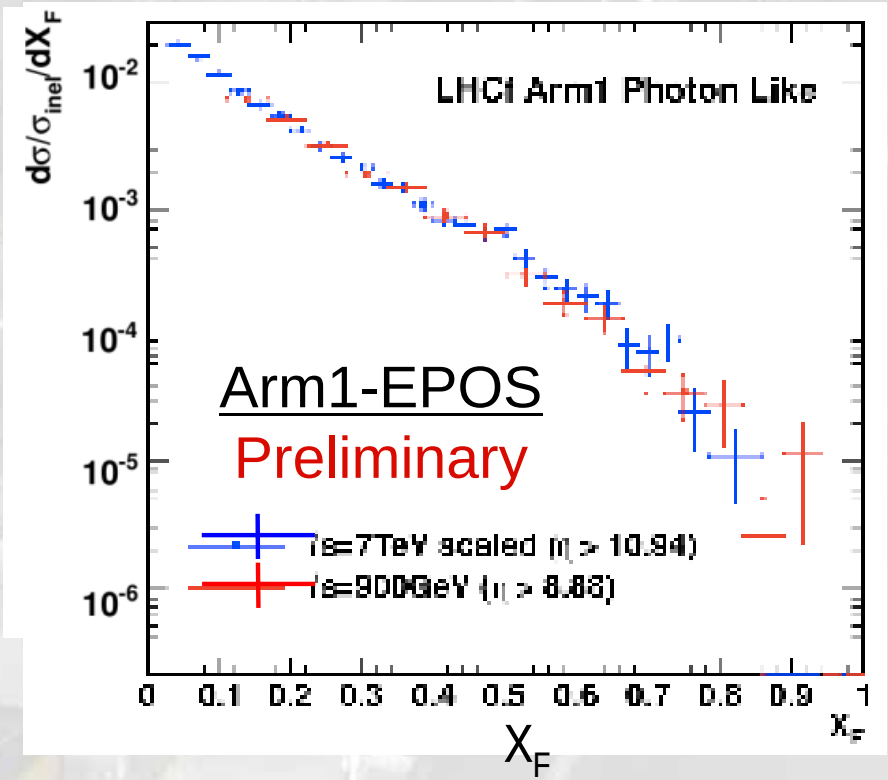


7TeV



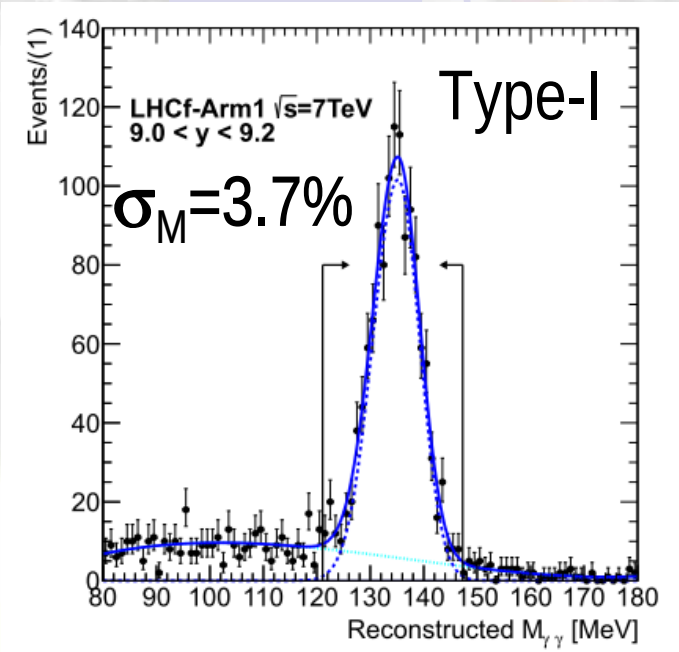
(sys error not included)

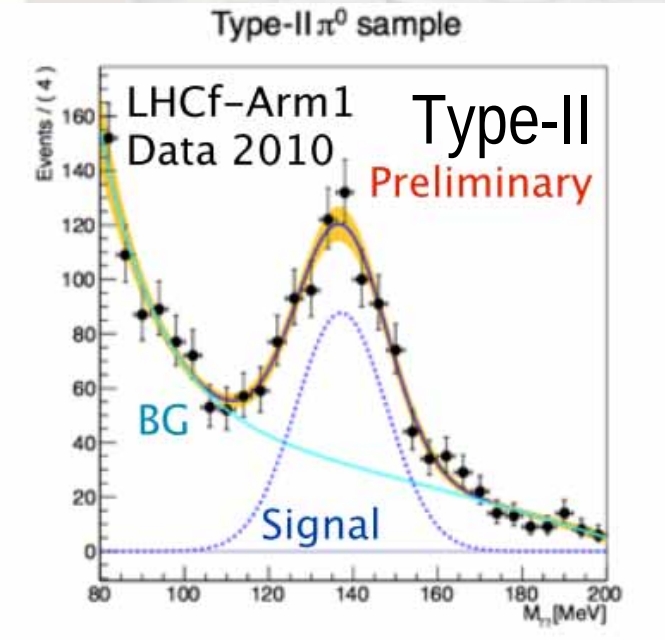




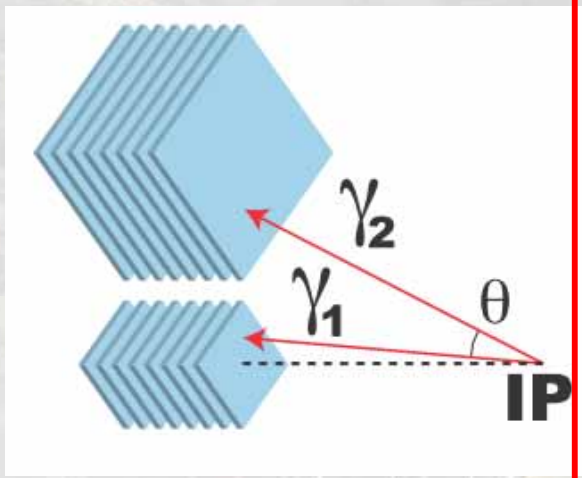
- Comparing X_F for common P_T region at two collision energies.
- Less root-s dependence of P_T for X_F ?

LHCf 7TeV π^0 analysis

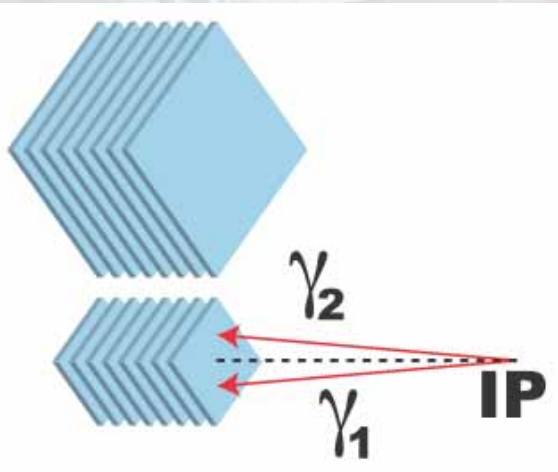


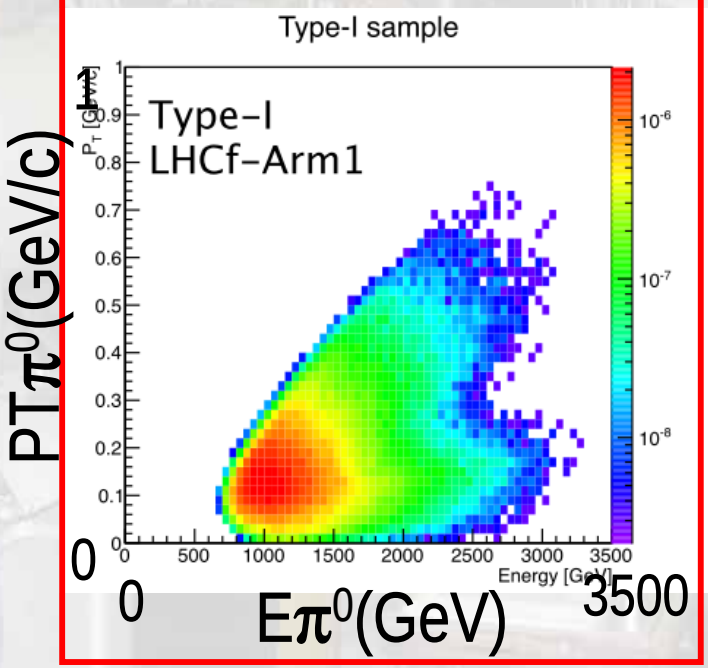


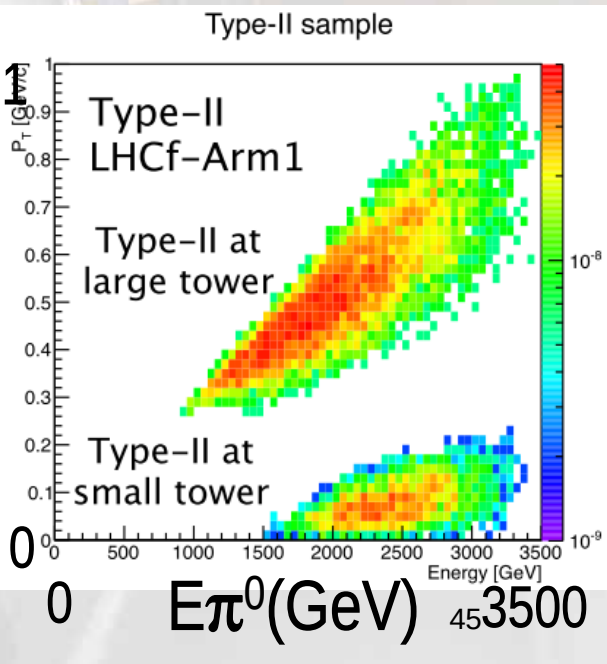
Type-I



Type-II



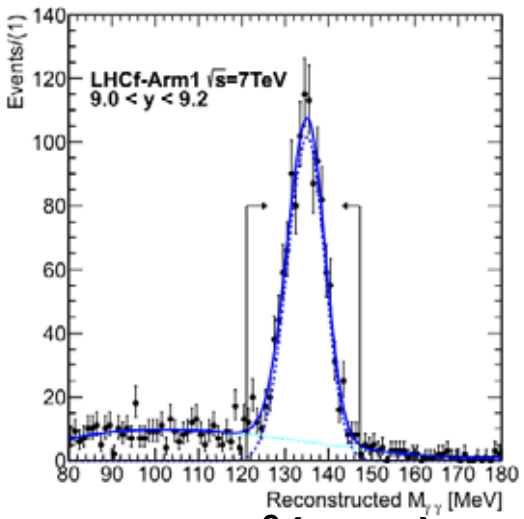




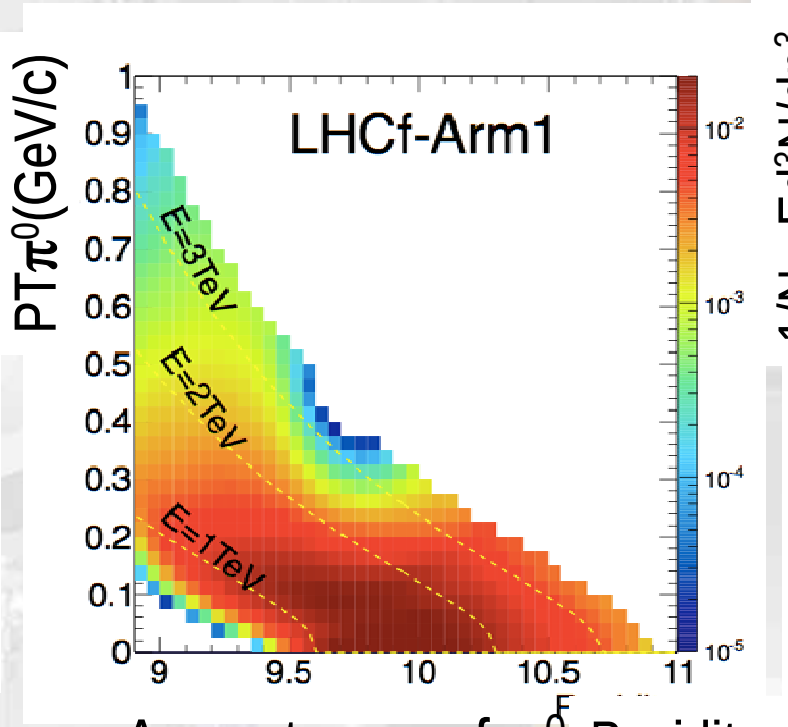
LHCf type-I π^0 results

PRD 86 (2012) 092001

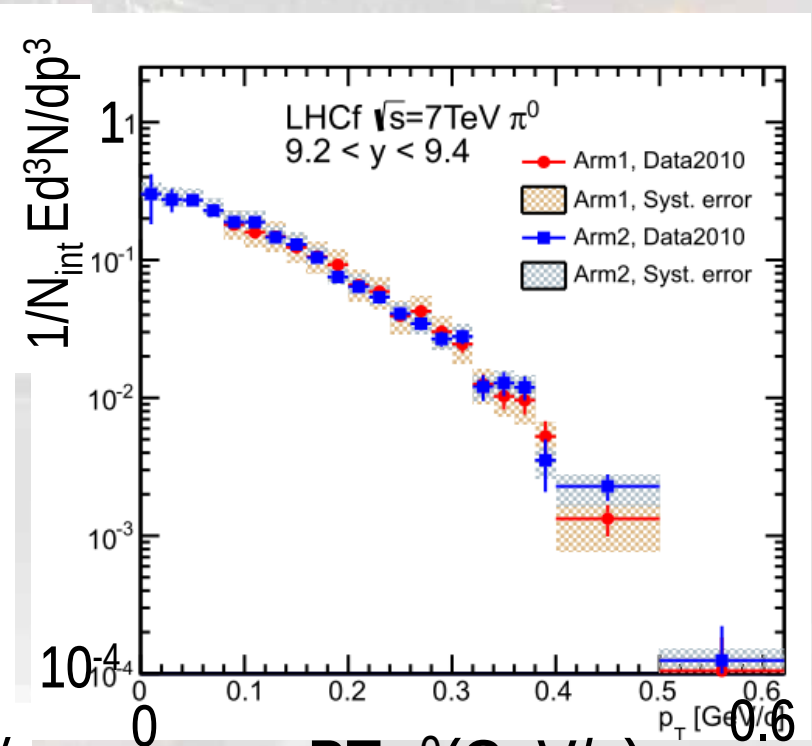
- Low lumi (L~5e28) on 15-16May, 2.53(1.91) nb^{-1} at Arm1 (Arm2). About 22K (39K) π^0 for Arm1(Arm2) w/ 5%BG.
- For $E\gamma$>100GeV, PID (γ selection), shower leakage correction, energy rescaling (-8.1% and -3.8% for Arm1&2).
- (E, P_T) spectra in +-3σ π^0 mass cut w/ side band subtracted.
- Unfolding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



$M\pi^0$(MeV)



Acceptance of π^0

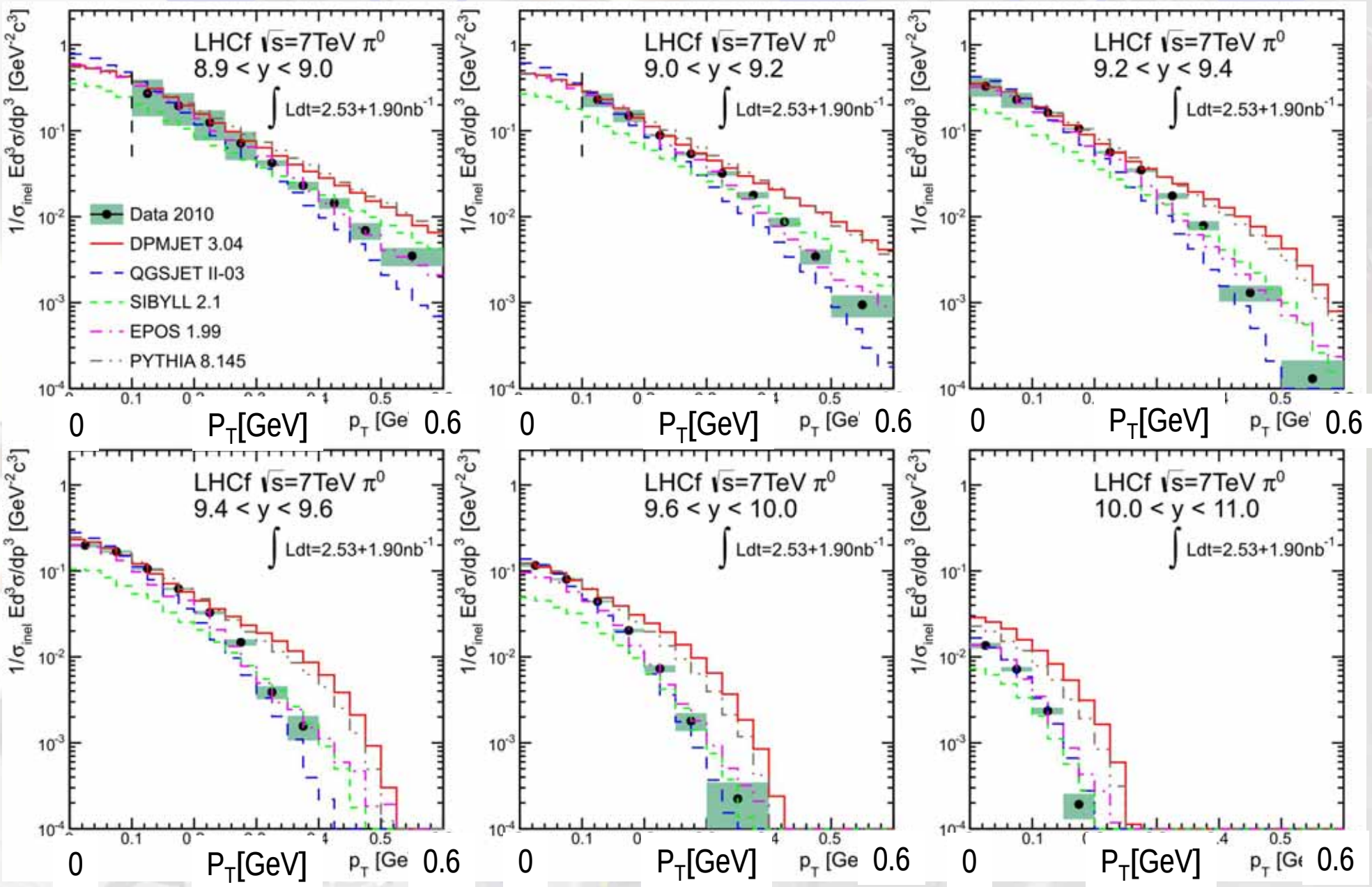


PTπ^0(GeV/c)

LHCf π^0 P_T spectra at 7TeV

PRD 86 (2012) 092001

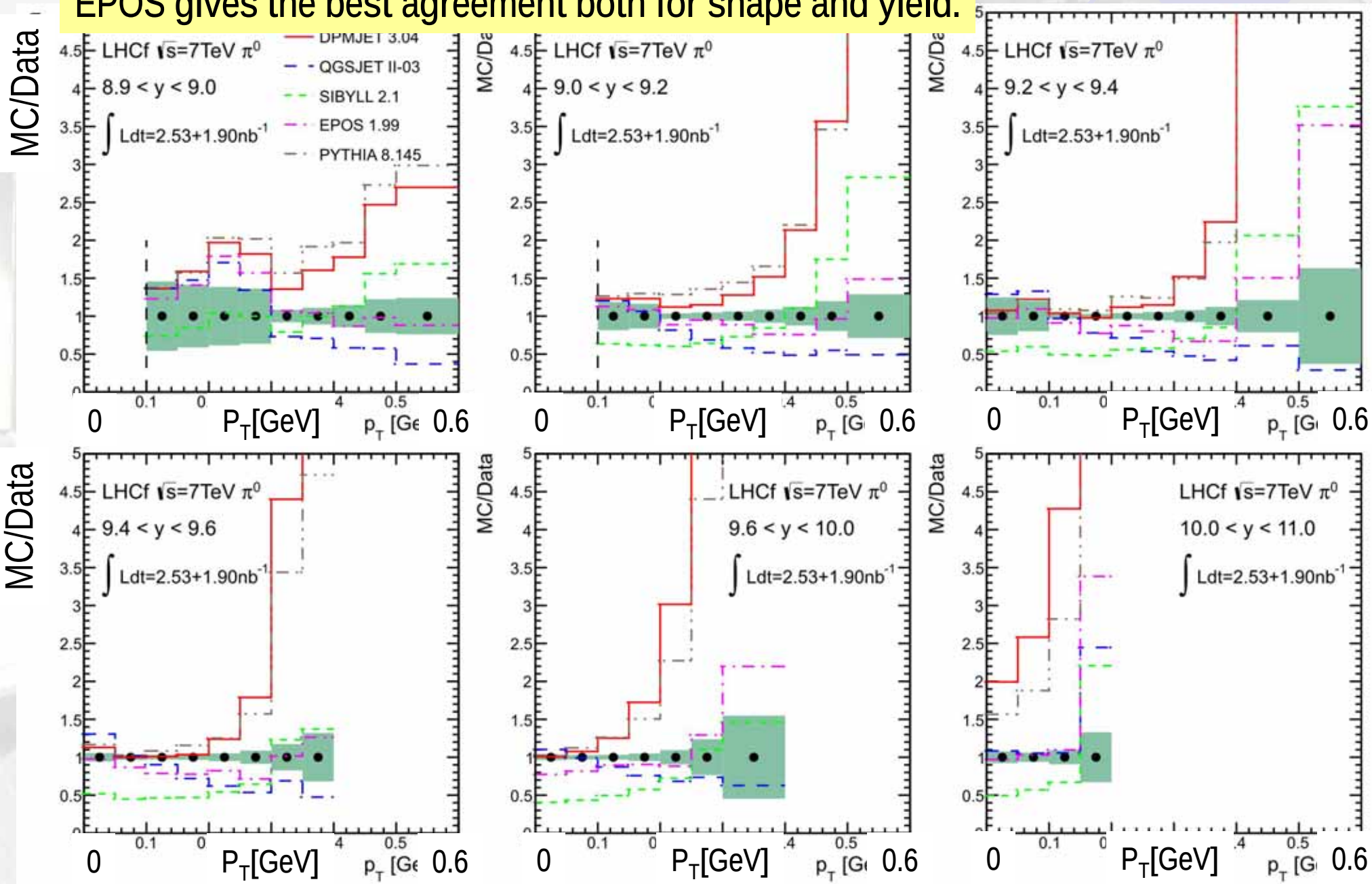
DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145



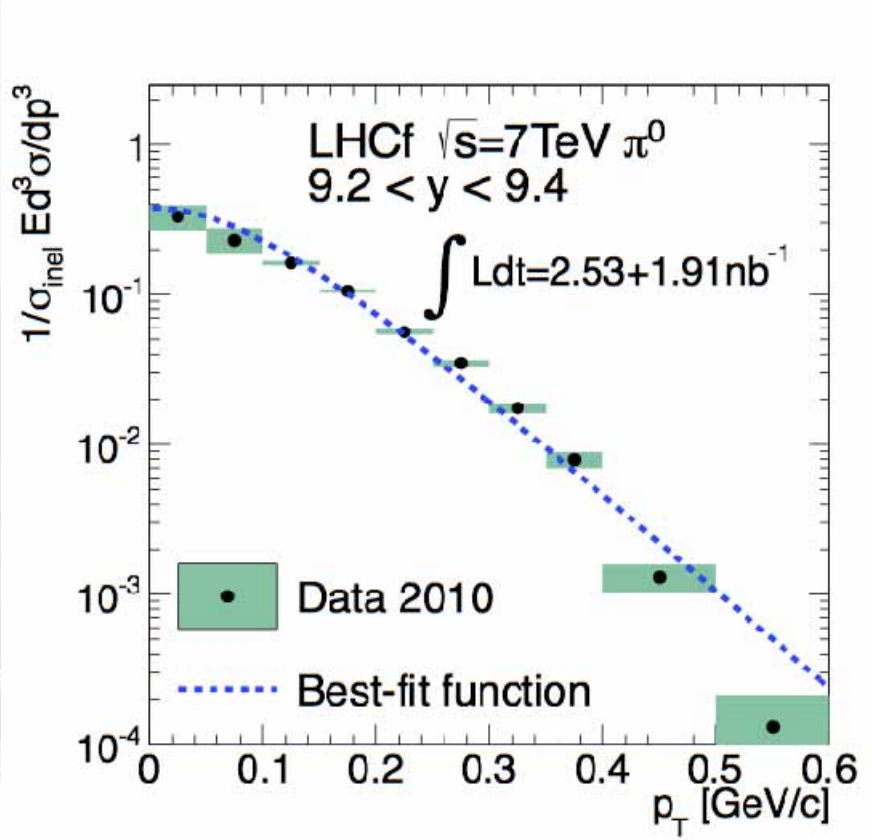
LHCf π^0 P_T spectra at 7TeV (data/MC)

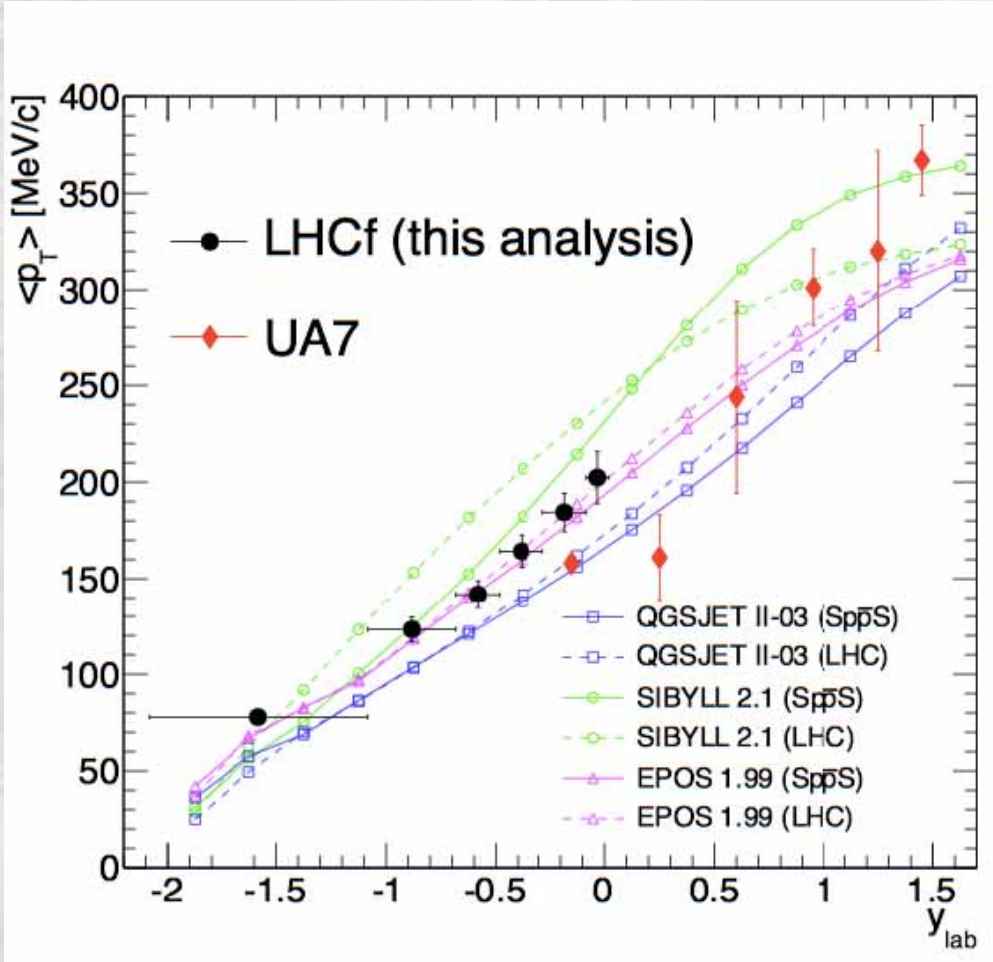
DPMJET 3.04 **QGSJETII-03** **SIBYLL 2.1** **EPOS 1.99** **PYTHIA 8.145**

EPOS gives the best agreement both for shape and yield.



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>?

What we learned from the 1st LHCf resuts

- No cosmic ray interaction model can perfectly reproduce the data.
- However the data points are bracketed by the models.
- Among the models EPOS looks nice (for ex, $\pi 0$ Pt)

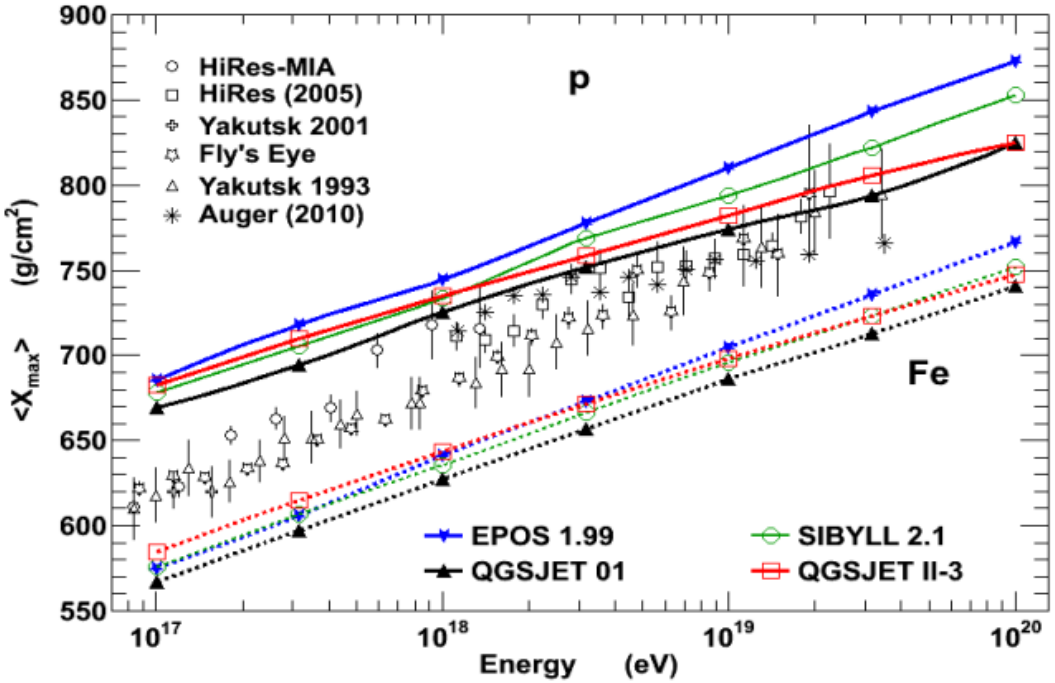
No surprise expected in hadron interactions at ultra high energy forward scatterings
(No disaster **?**)

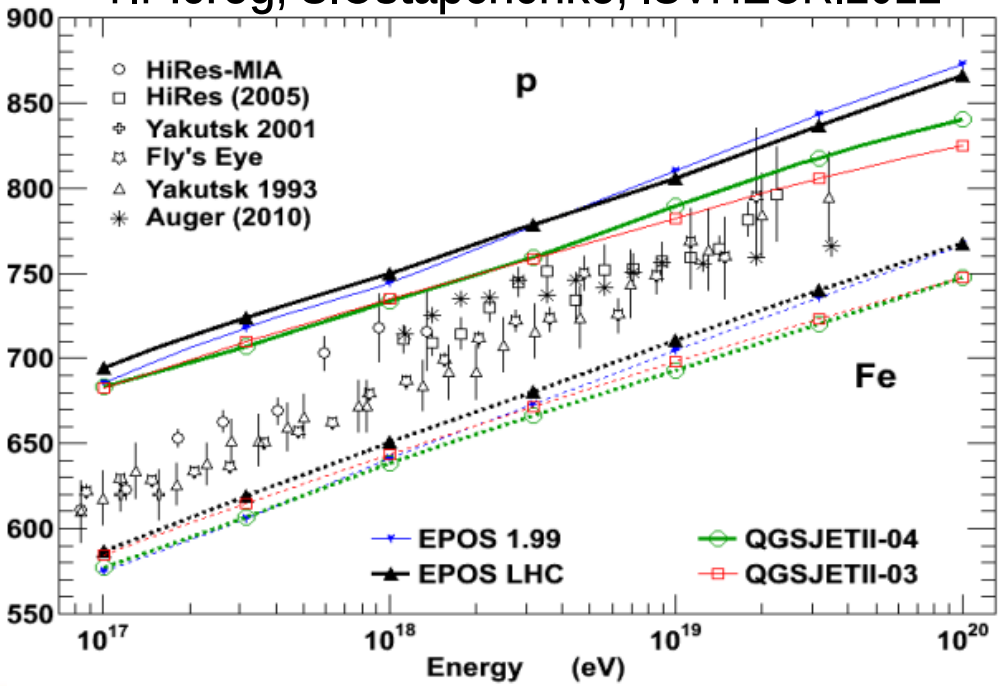
Feed back to UHECR composition

- 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

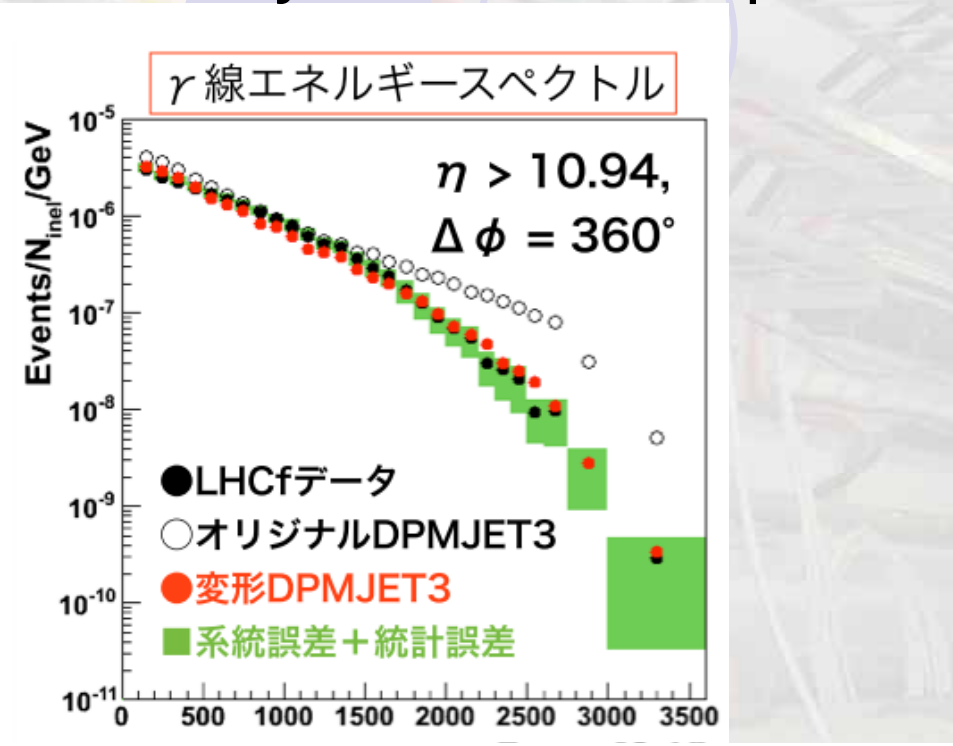


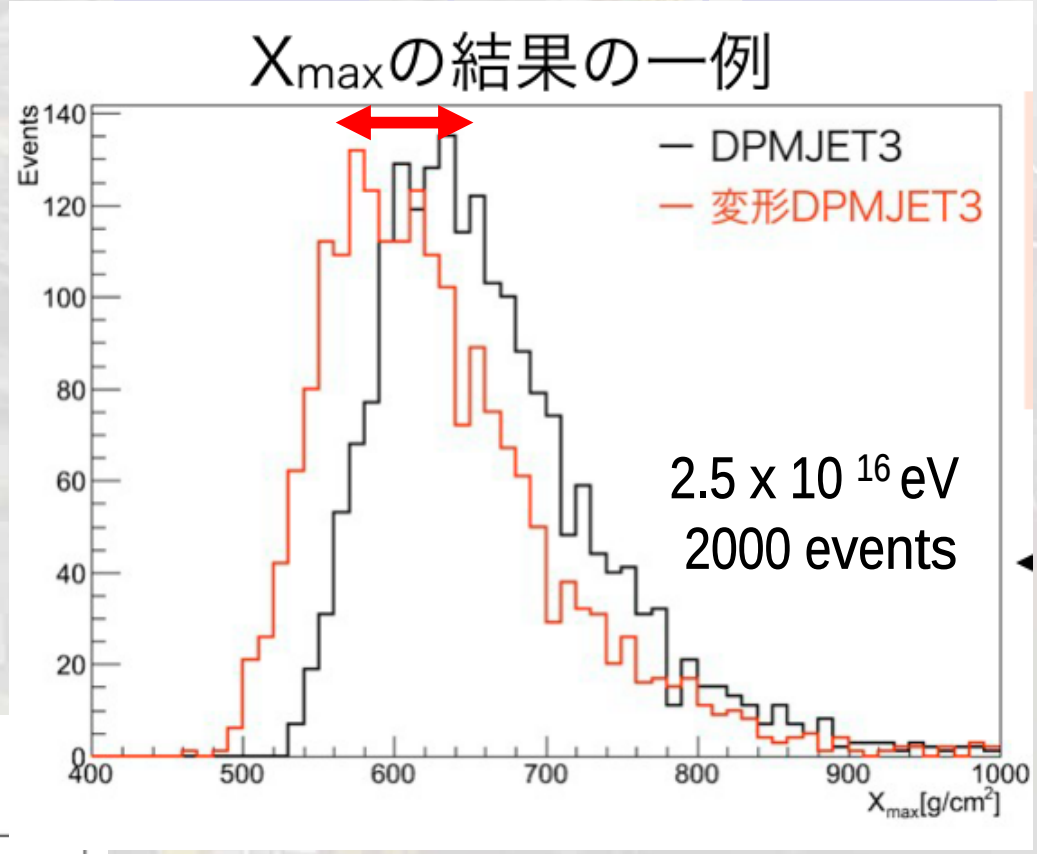


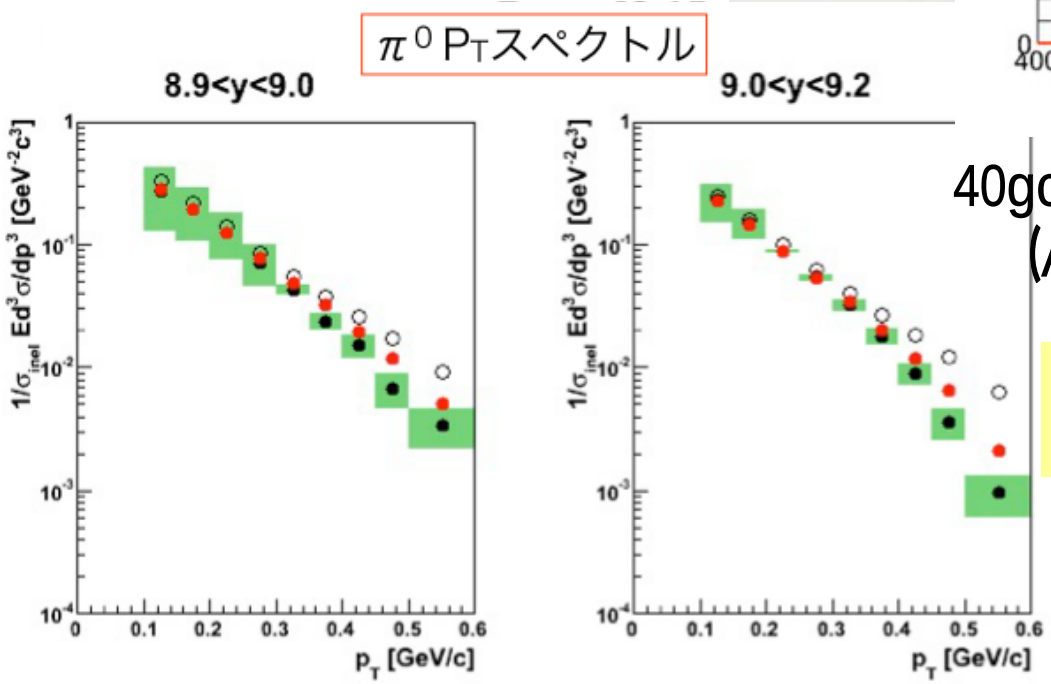
Before LHC

After LHC

How very forward EM spectra effects shower development ?







40gcm^{-2} shift from original DPMJET prediction
(A half of Xmax difference btw p and Fe)

- c.f. does not mean UHECR Xmax shift by 40gcm-1,
- Note DPMJET gives the hardest spectra

Current and future activity

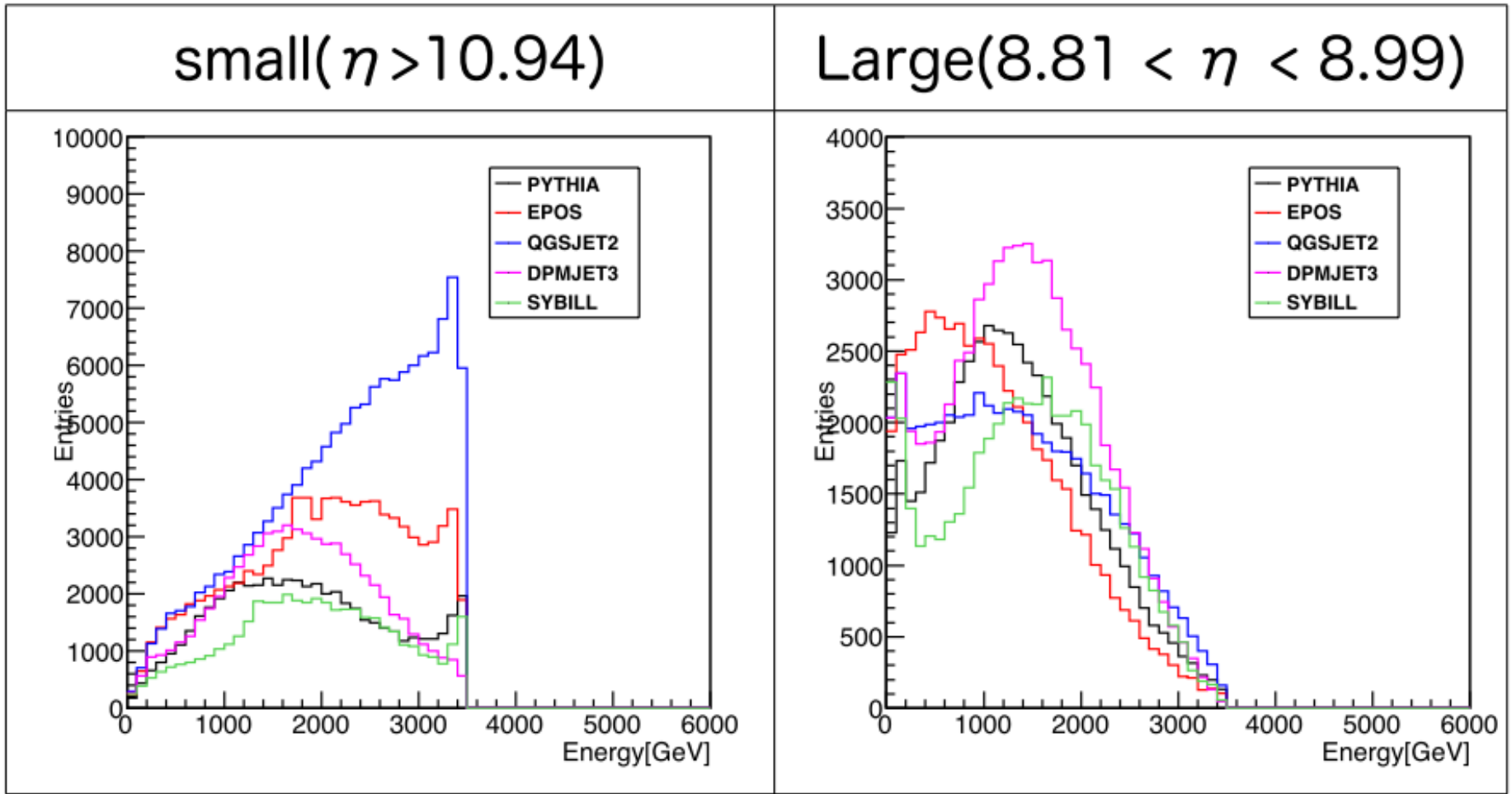
- **Forward neutron spectra**
  - **Inelasticity**
- **Forward strangeness production**
  - **Flux prediction for high energy atmospheric neutrinos**
- **Cold nuclear effect**
  - **LHC p-Pb , modification in particle productions**
- **Energy dependence**
  - **13TeV at LHC, 0.5TeV pp at RHIC**
- **Nuclear dependence**
  - **p-A, A-A at RHIC, and future LHC ?**

Very forward Neutron analysis

- Energy flow carried by leading baryon
  - Bring primary energy deeper atmosphere by No-EM component
  - Slower shower development, **increase ground muons**

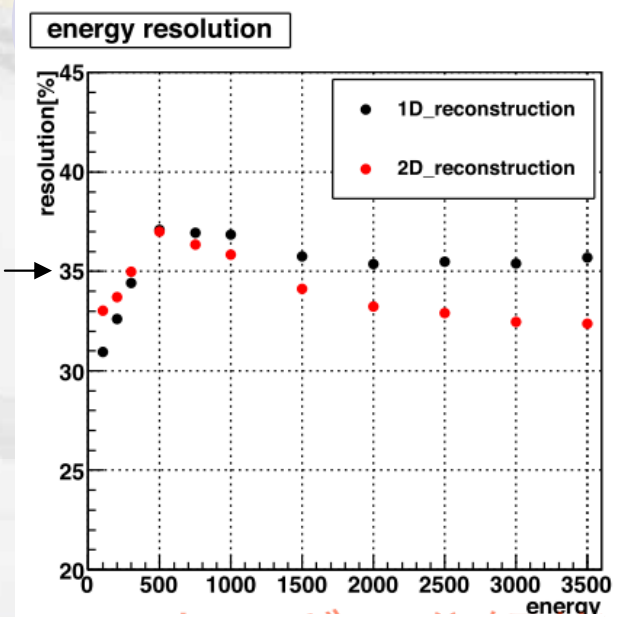
A key to muon anomaly ?

Expected neutron energy spectra at very forward (perfect resolution)

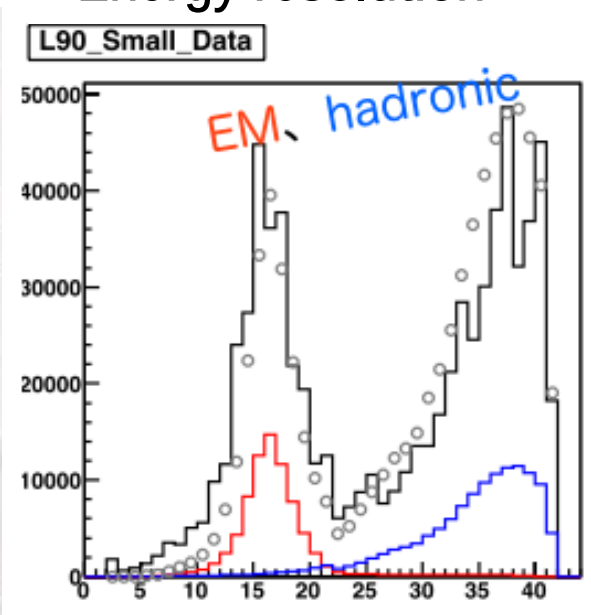


Performance of neutron analysis

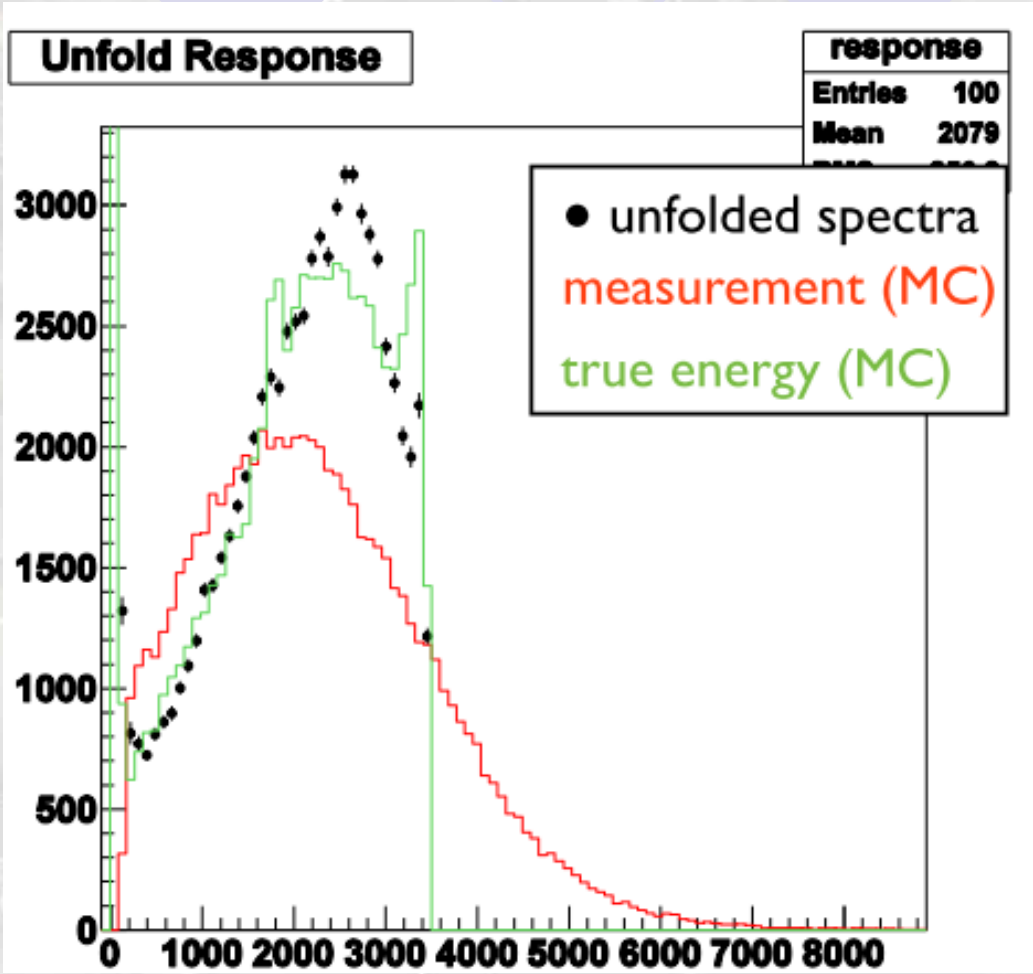
35% →



Energy resolution



EM / hadron PID



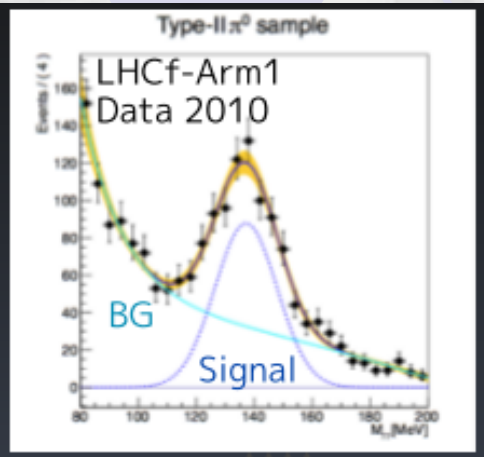
Unfolded energy spectra (R&D by MC)

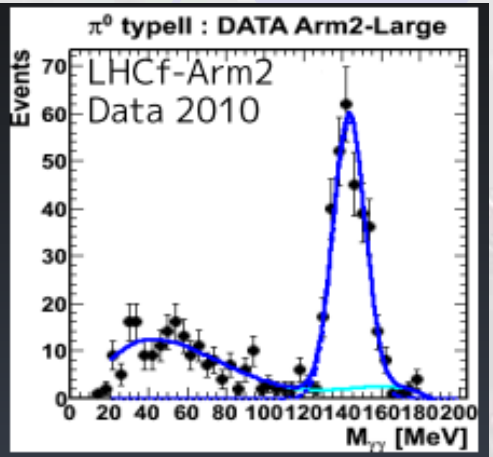
Very forward strangeness

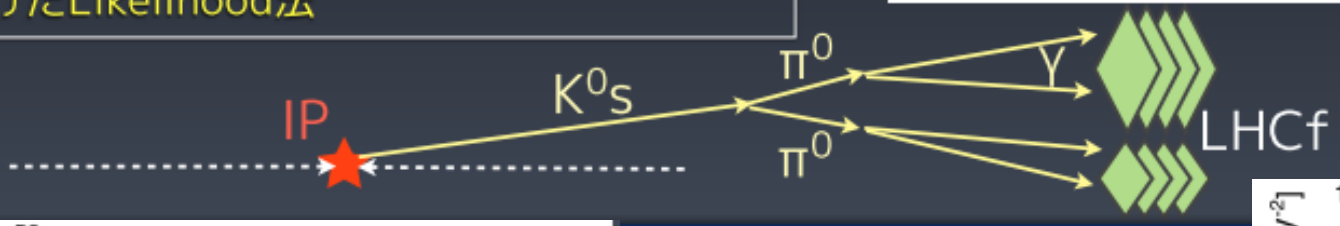
K^0s production at very forward

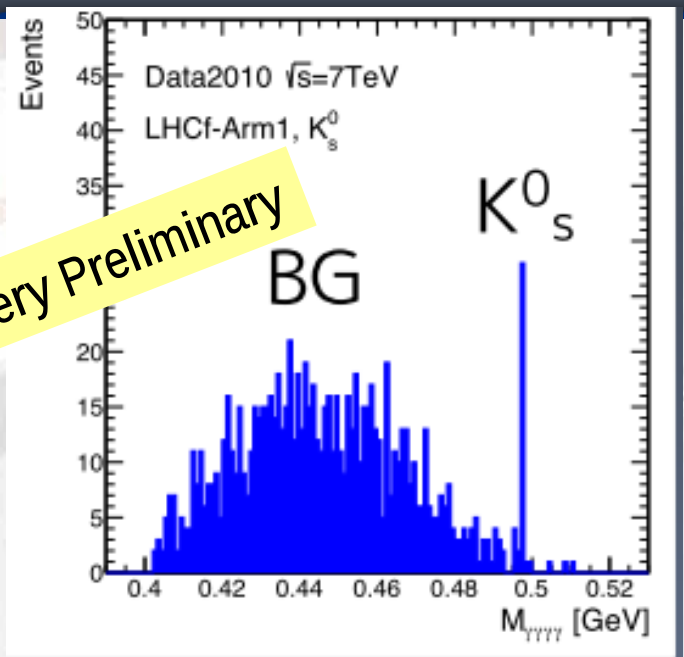
LHCfが観測出来るのはK^0s→4γ崩壊モード(BR=33%)。
当面は一基のタワーに二個のガンマ線が入射した場合を想定して解析を進行する。

K^0_sは比較的飛行するので崩壊vertexをIPと仮定する事は不可能→Kinematicsの制限をつけたLikelihood法



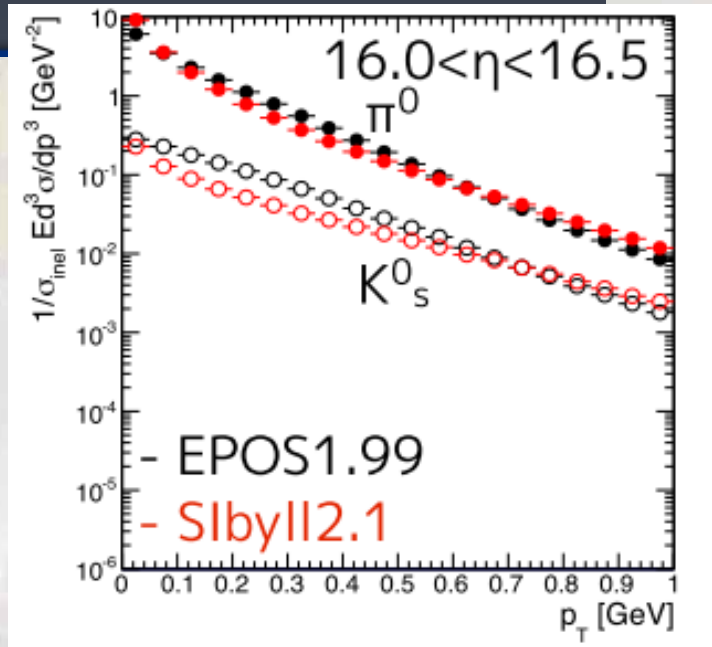






Very Preliminary

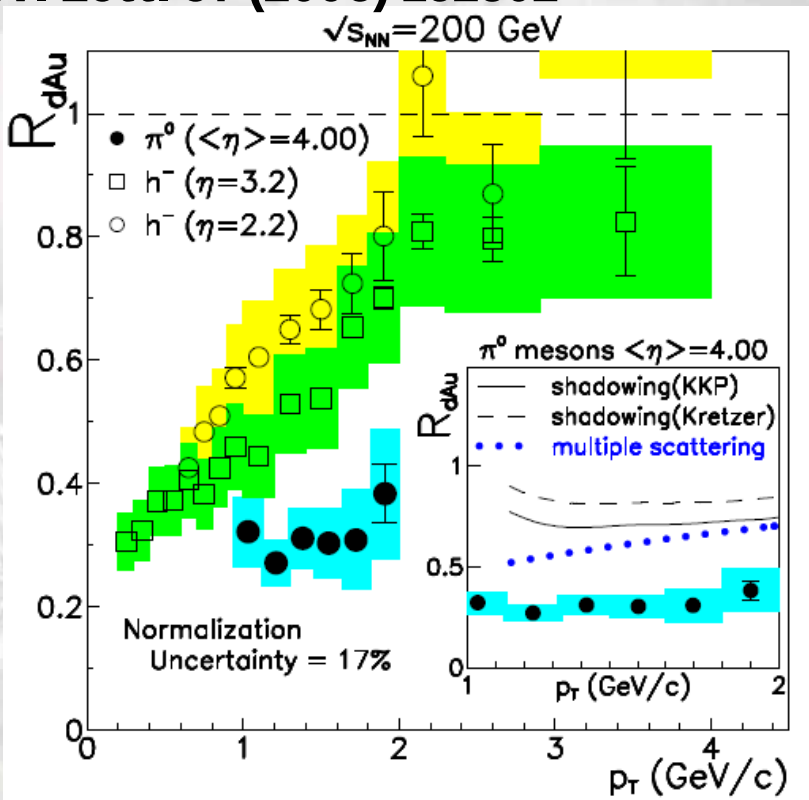
4 γ reconstruction
(7TeV pp data)



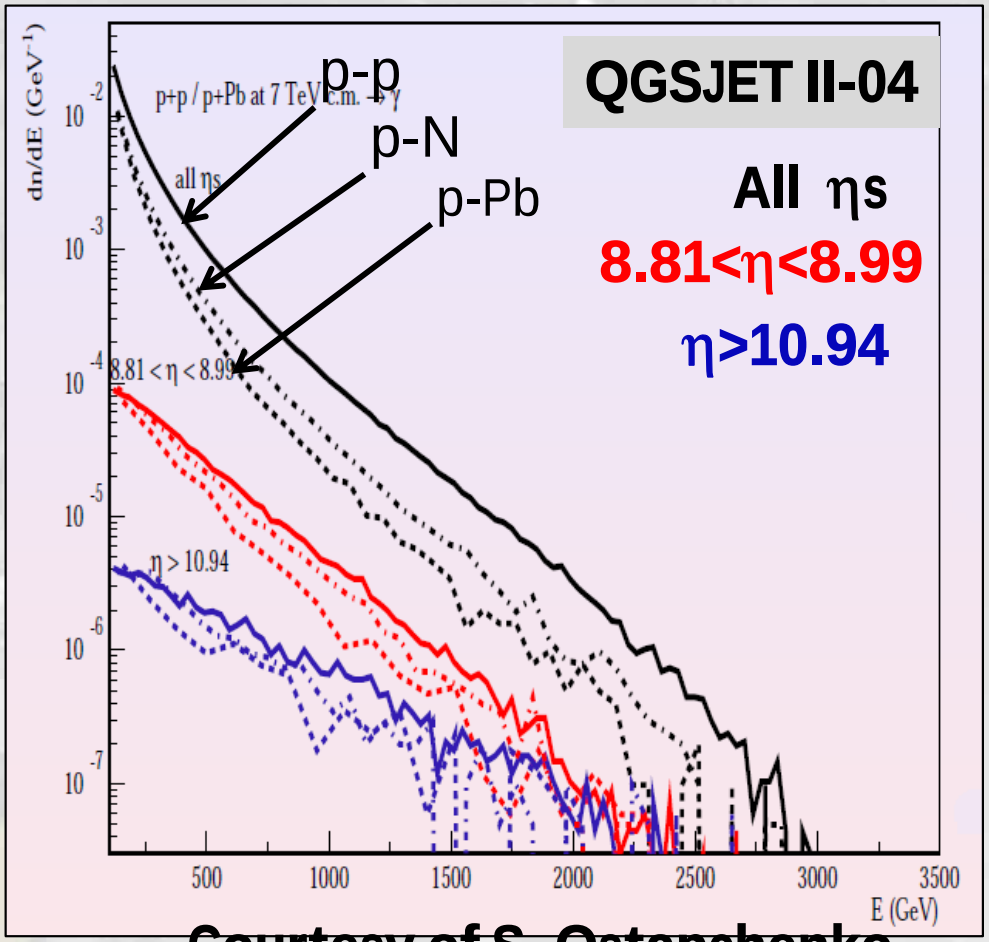
Cold nuclear effects at very forward region

- 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



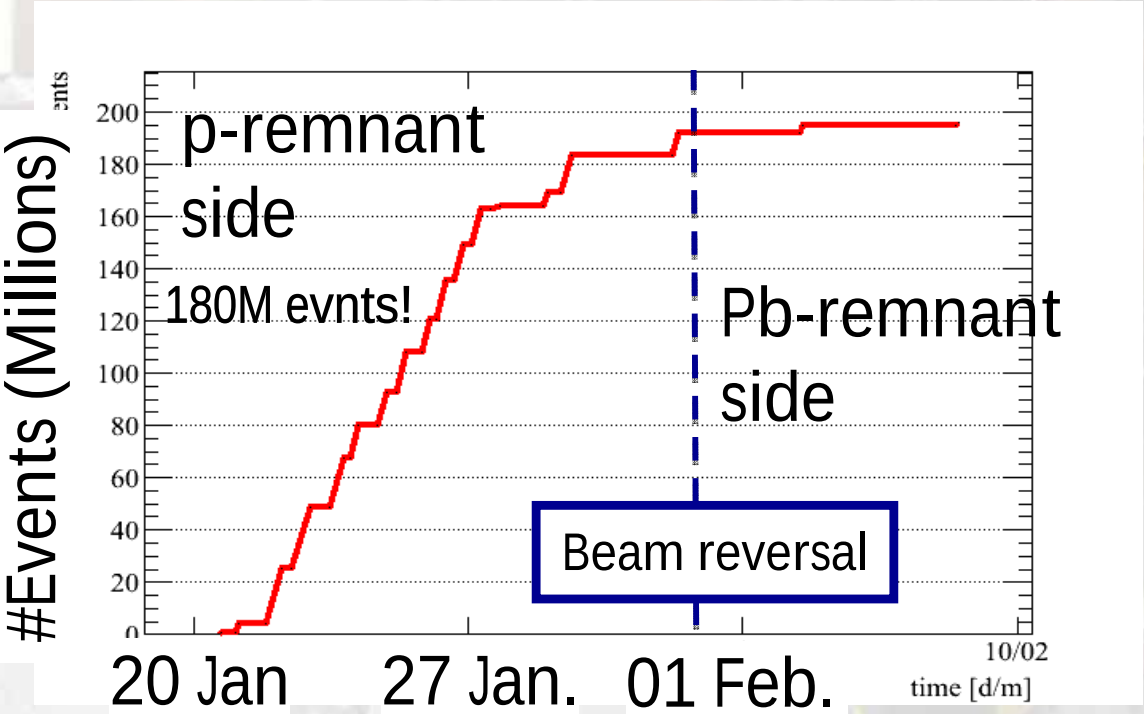
$$R^{Y}_{\mathrm{dAu}} = \frac{\sigma^{pp}_{\mathrm{inel}}}{\langle N_{\mathrm{bin}}\rangle \sigma^{dAu}_{\mathrm{hadr}}} \frac{E\, d^3\sigma/dp^3(d+Au \to Y+X)}{E\, d^3\sigma/dp^3(p+p \to Y+X)}$$



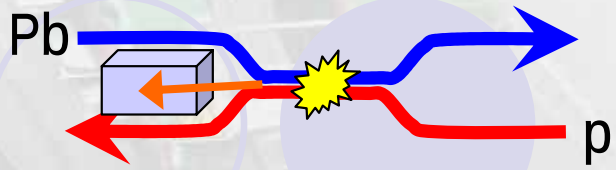
Courtesy of S. Ostapchenko

LHCf p – Pb runs at $\sqrt{s_{NN}}$= 5 TeV (Jan 2013)

- 2013 Jan / a month of p-Pb opportunity.
  - Install only Arm2 at one side (Si good for multiplicity)
  - Data both at p-side (20Jan-1Feb) and Pb-side (1fill, 4Feb)
  - Common pre-scaled trig w/ ATLAS for centrality tag (24Feb-)

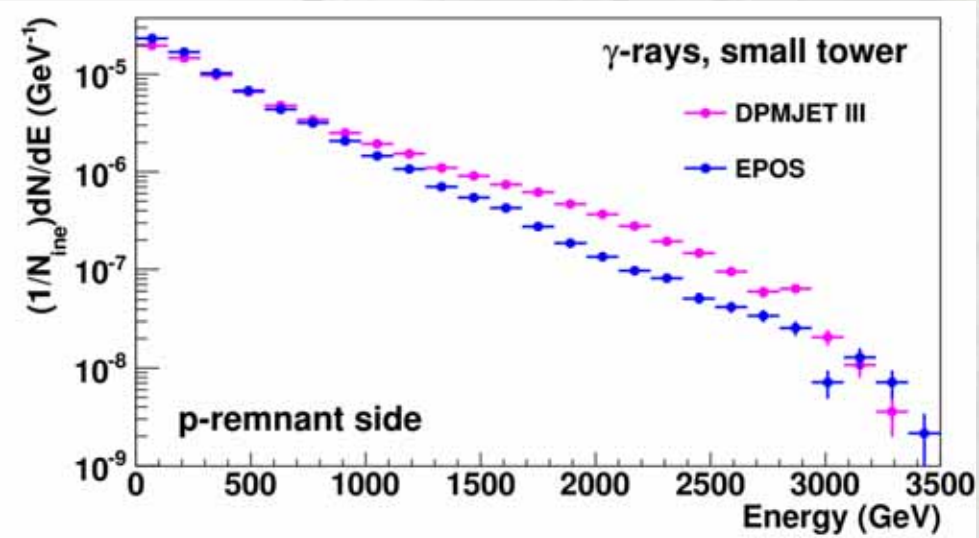


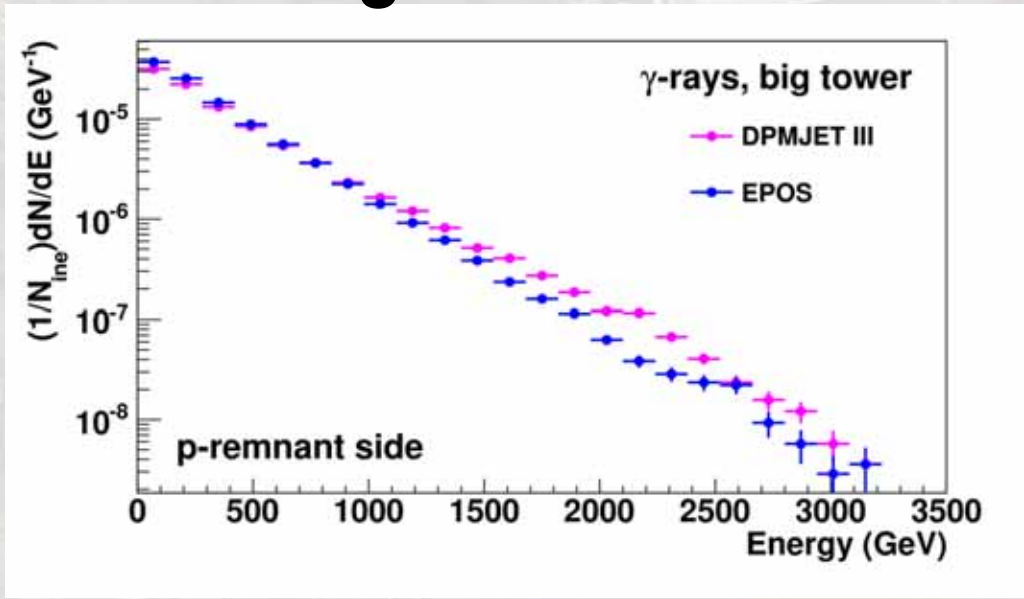
Expected E spectra by MCs (proton remnant side)



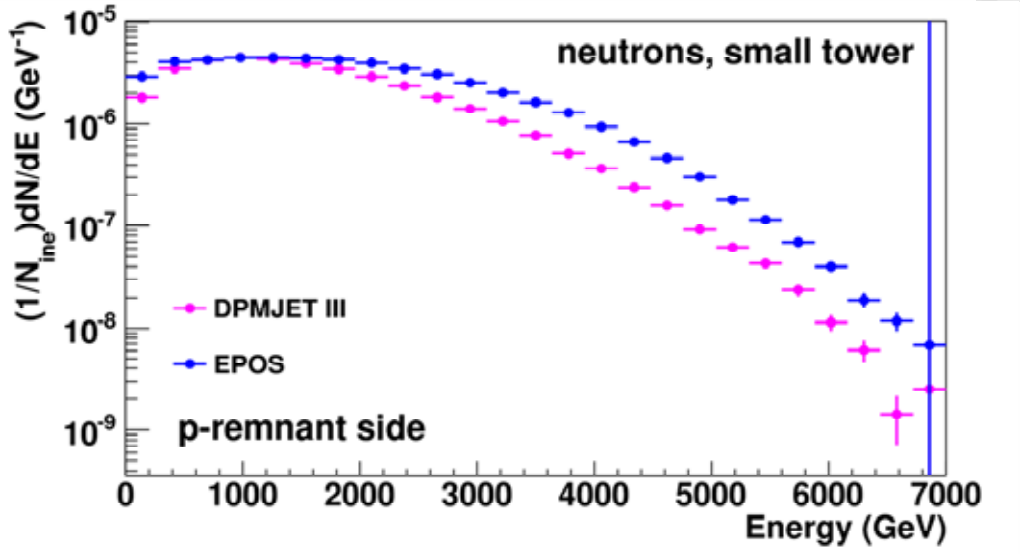
Small tower **Large tower**

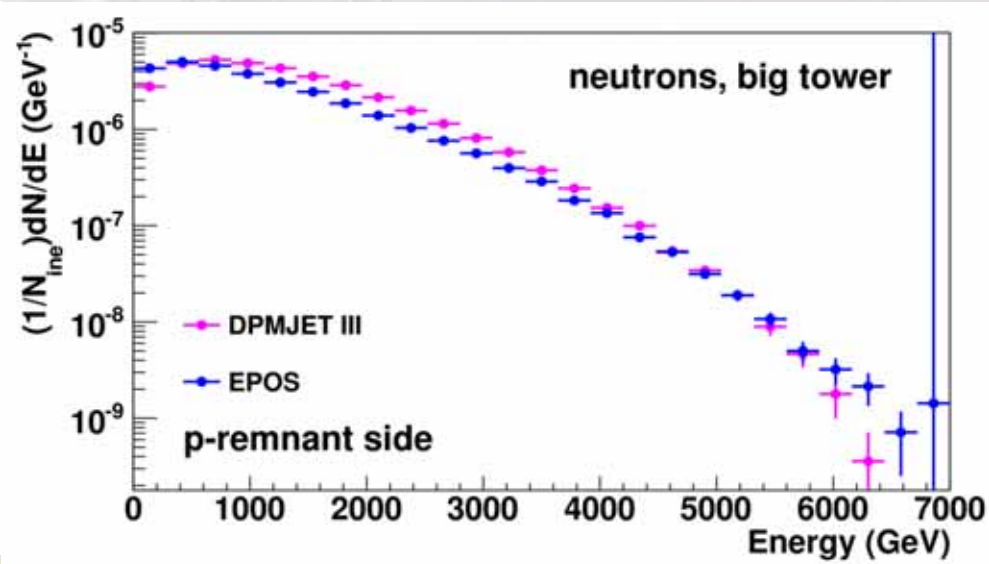
γ





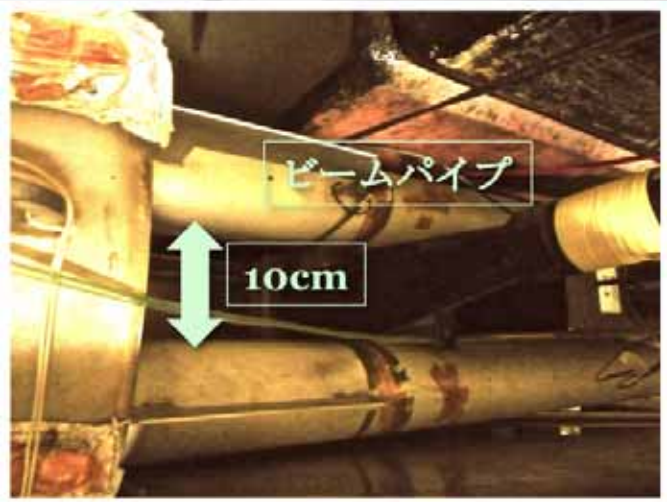
n

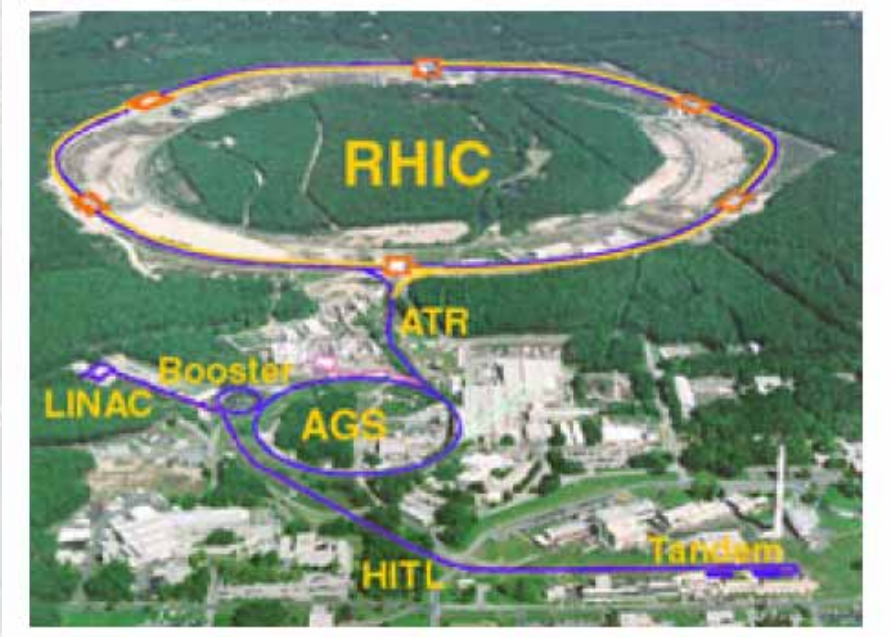




"RHICf" : Possible RHIC 0-degree runs

RHIC also has the zero-degree site





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

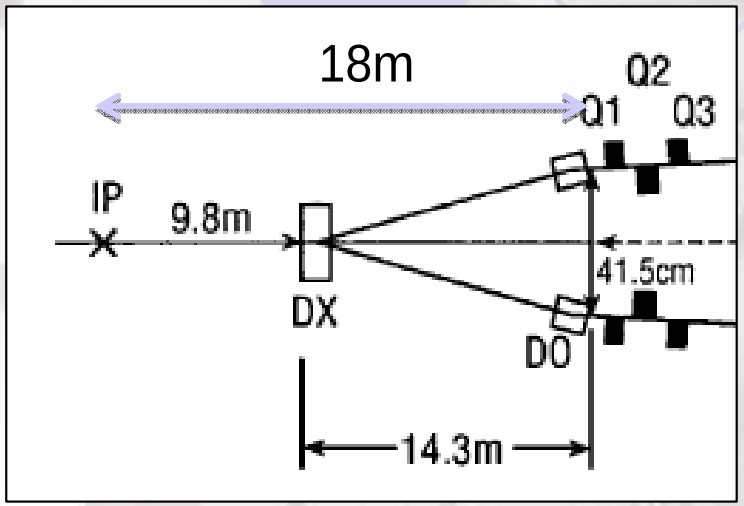
Just below LHC (E_{CR}~5E13eV)

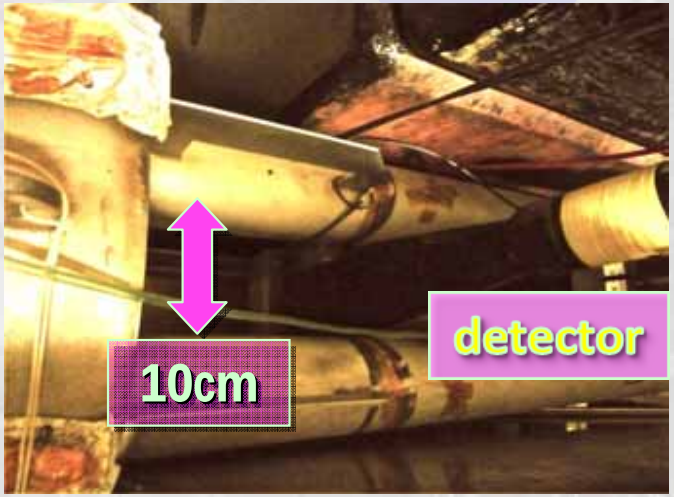
A - A: $\sqrt{s_{NN}} = 200 GeV$

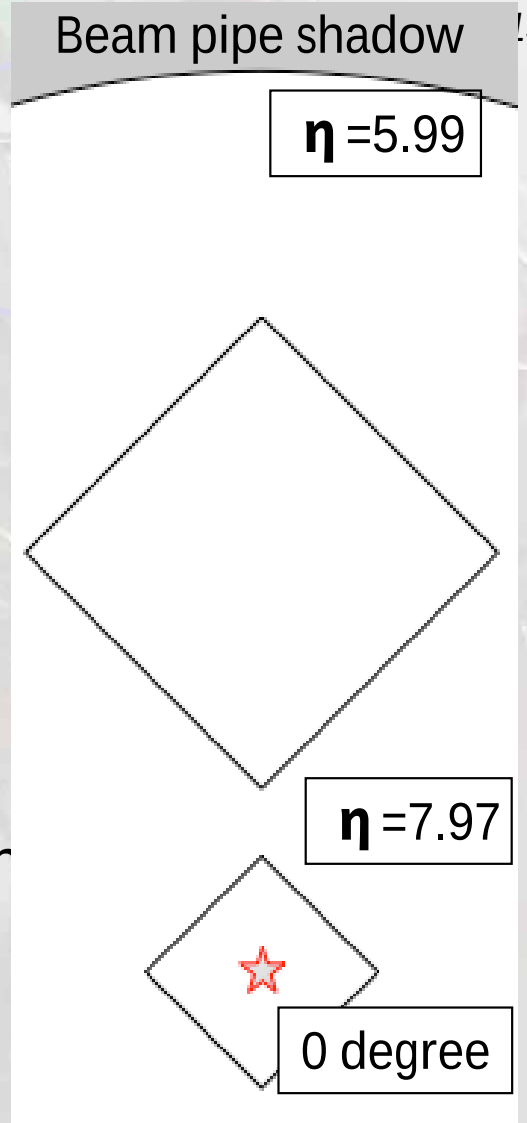
Au-Au, Cu-Cu or even lighter ?

Advantage of RHIC
- Lower energy data point
- Acceptance for π^0
- Flexible operation (energy, ion)
  - p-N, N-N, Fe-N, etc.....

Installation slot







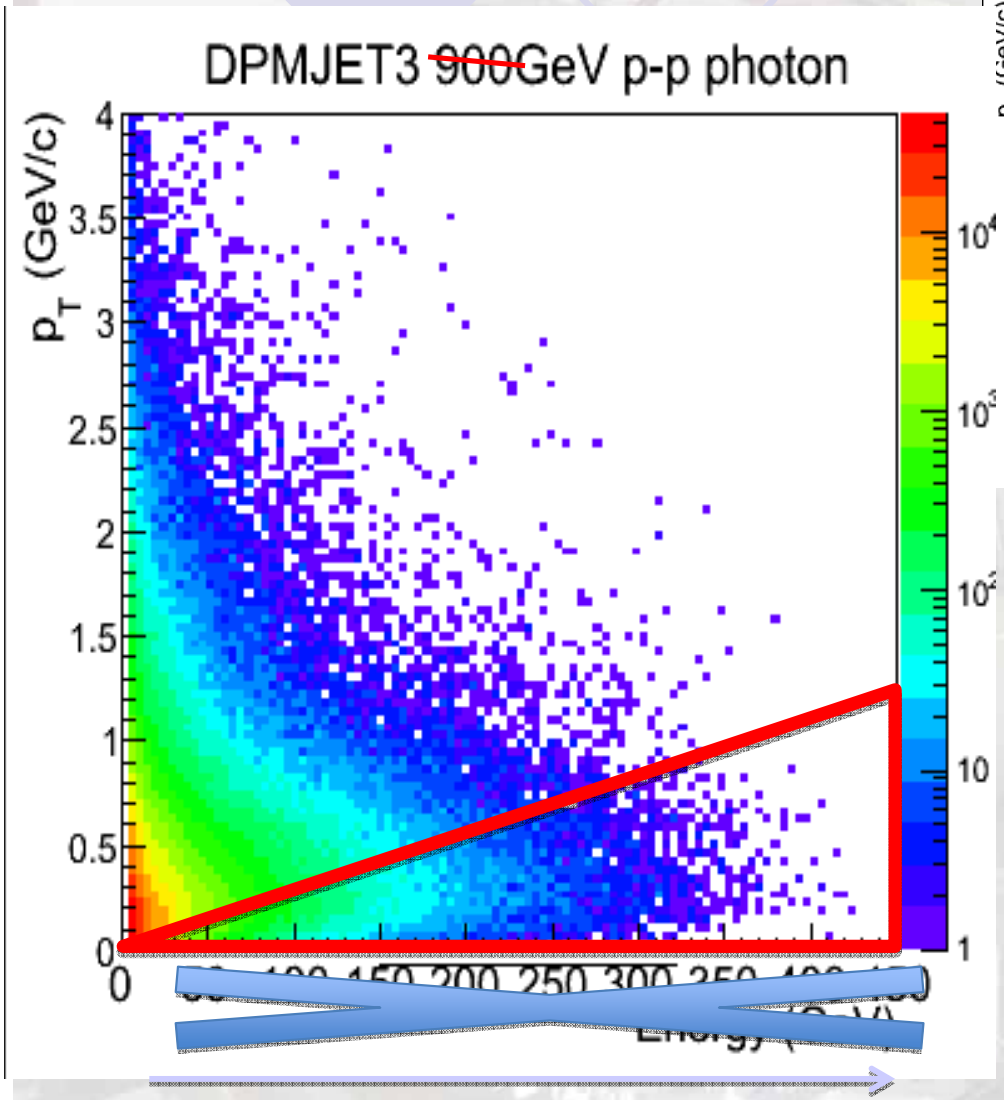
LHCf Arm1 calorimeters viewed from IP

- Perfect for LHCf detector (92mm✕280mm✕620m
- Beam-pipe shadow allows measurement η >6
- η =6 => p_T = 1.25GeV/c at E=250GeV
  close to the LHC 7TeV condition (next slide)
- Wider acceptance for π^0

➢ RHIC 500GeV and LHC 7-14TeV p-p collisions provide uniform dataset for model improvement in a wide energy range

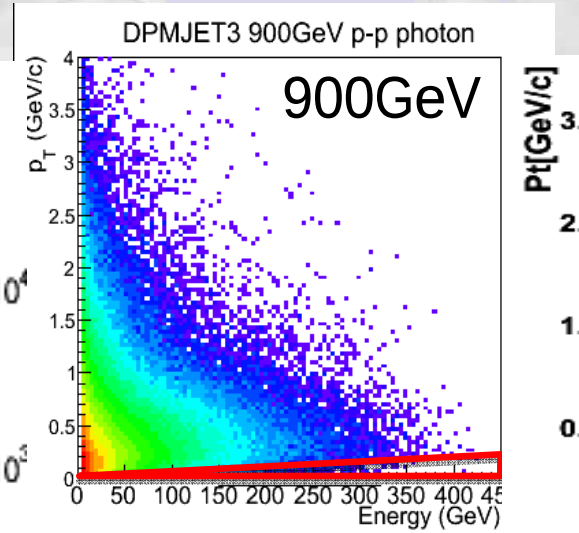
Acceptance at RHIC 500GeV p-p

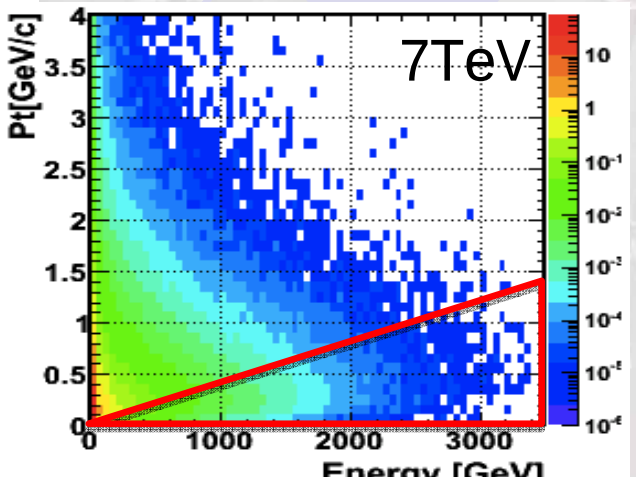
(Assume same as 500GeV p-p …)

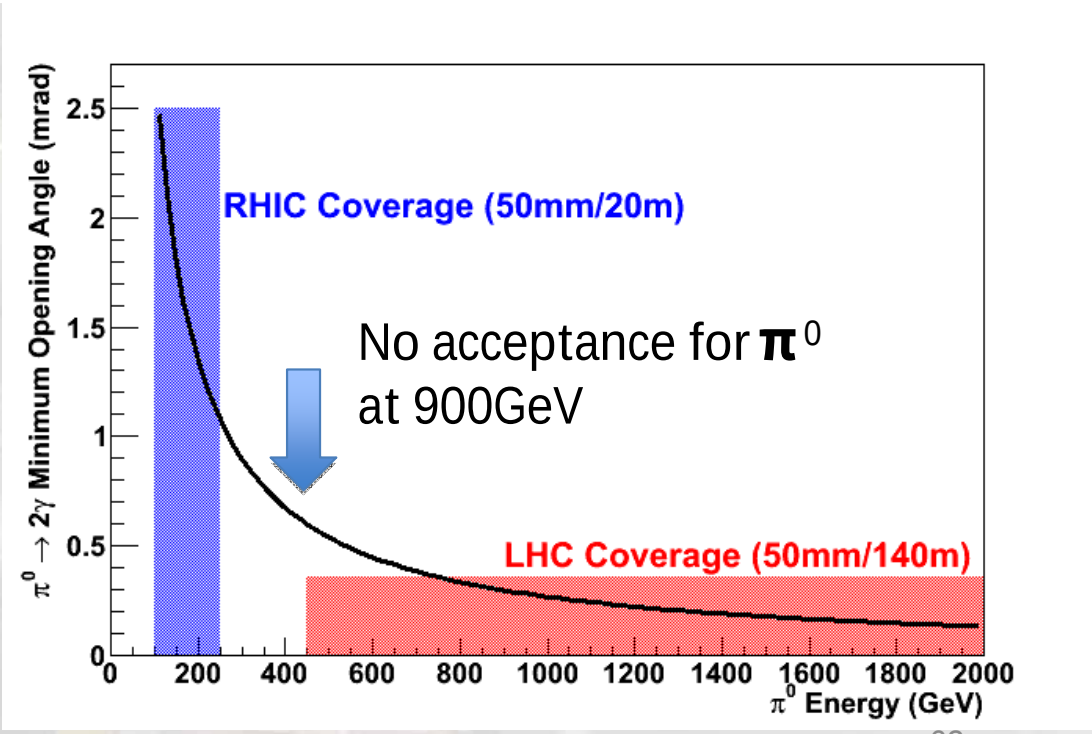


250 GeV

Same phase space coverage as 7TeV

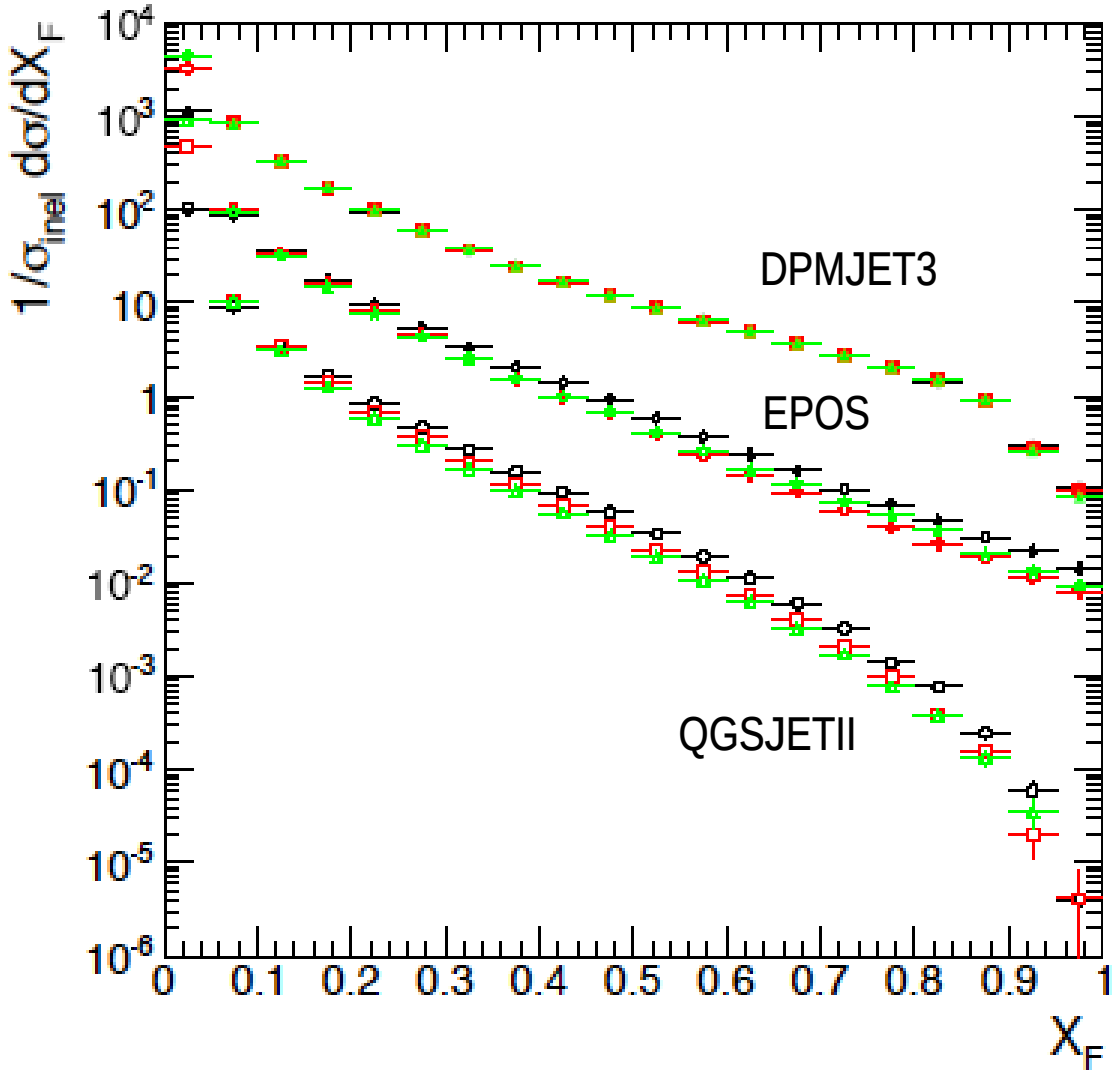






Acceptance for $\pi 0$

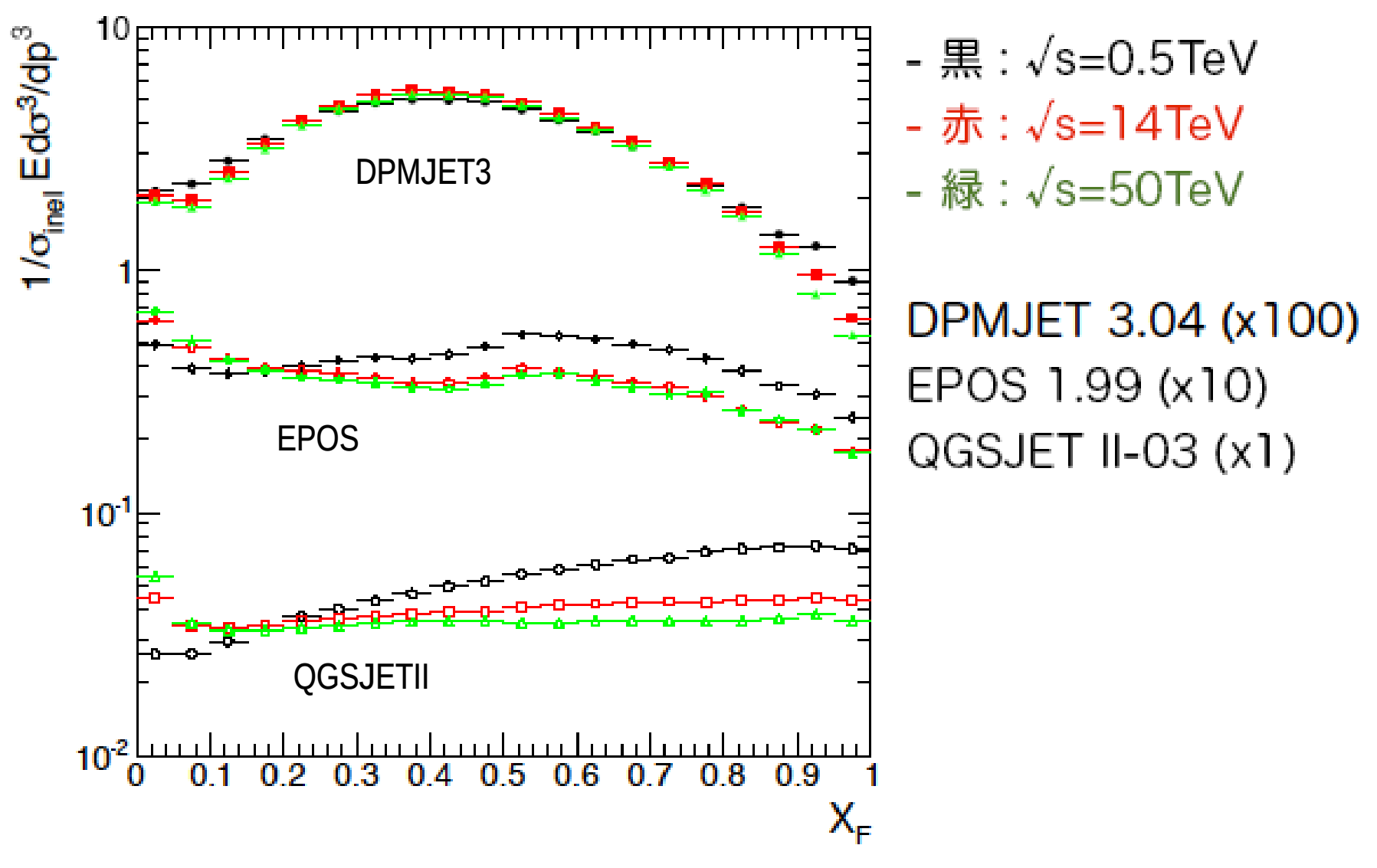
Energy evolution ; X_F π^0 p_T<1.5GeV/c



- 黒 : √s=0.5TeV ⇦ RHIC p-p
- 赤 : √s=14TeV ⇦ LHC p-p
- 緑 : √s=50TeV ⇦ CR

DPMJET 3.04 (x100)
EPOS 1.99 (x10)
QGSJET II-03 (x1)

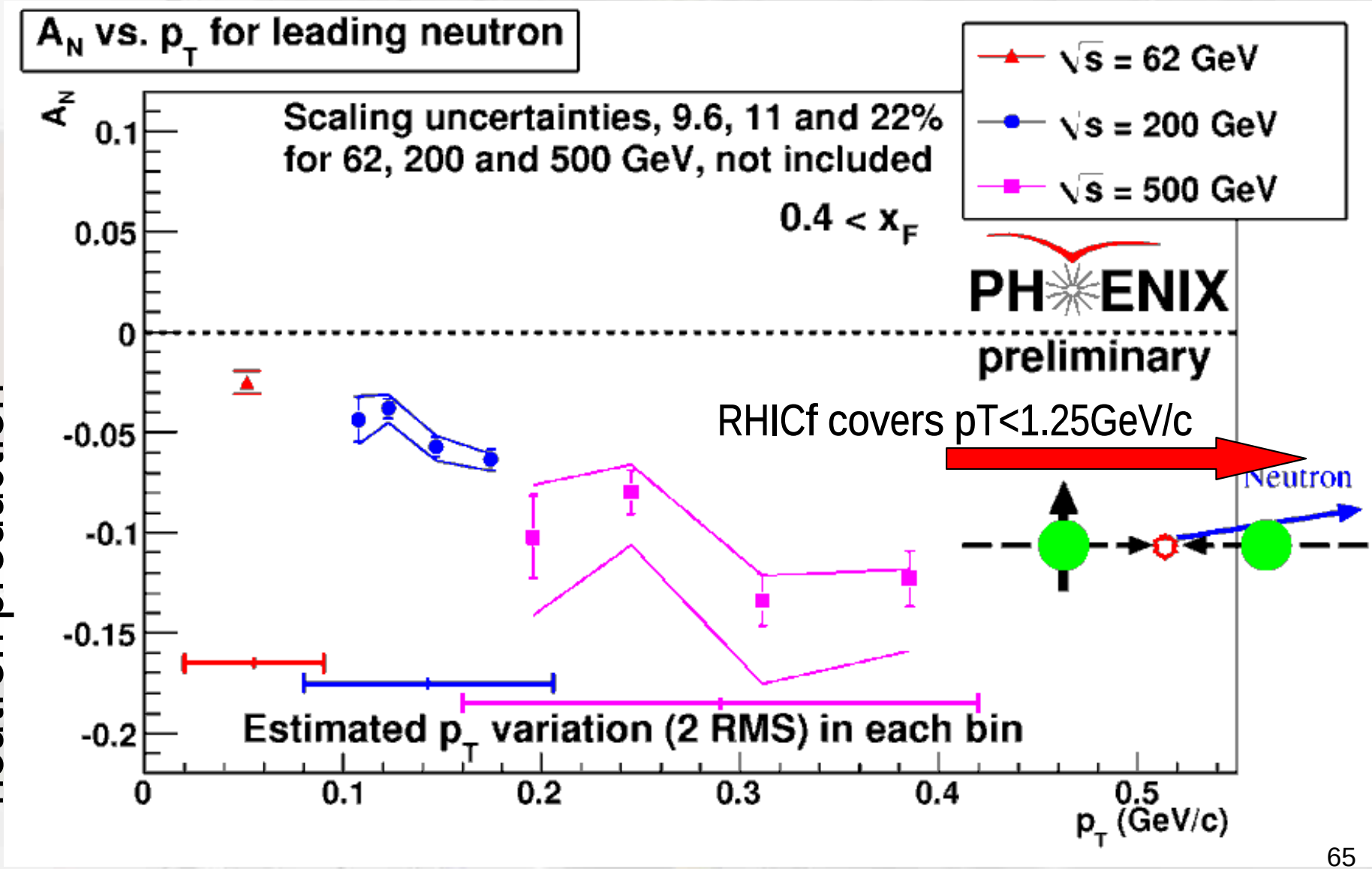
Energy evolution ; X_F neutrons p_T<1.5GeV/c



Spin asymmetry of 0deg neutrons in polarized p-p collisions

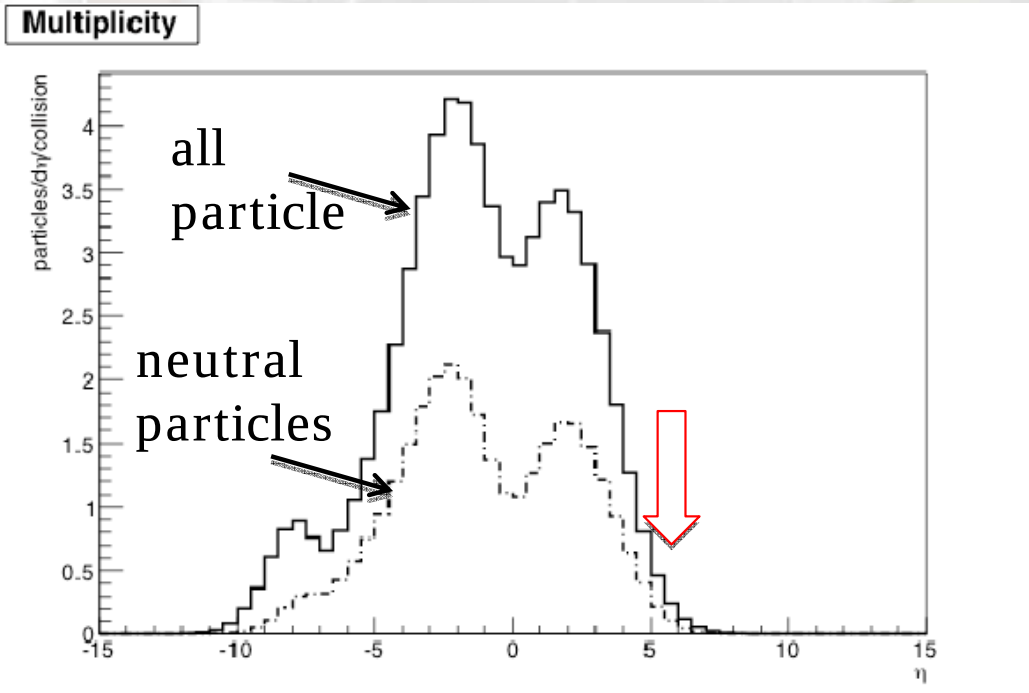
Inclusive neutron

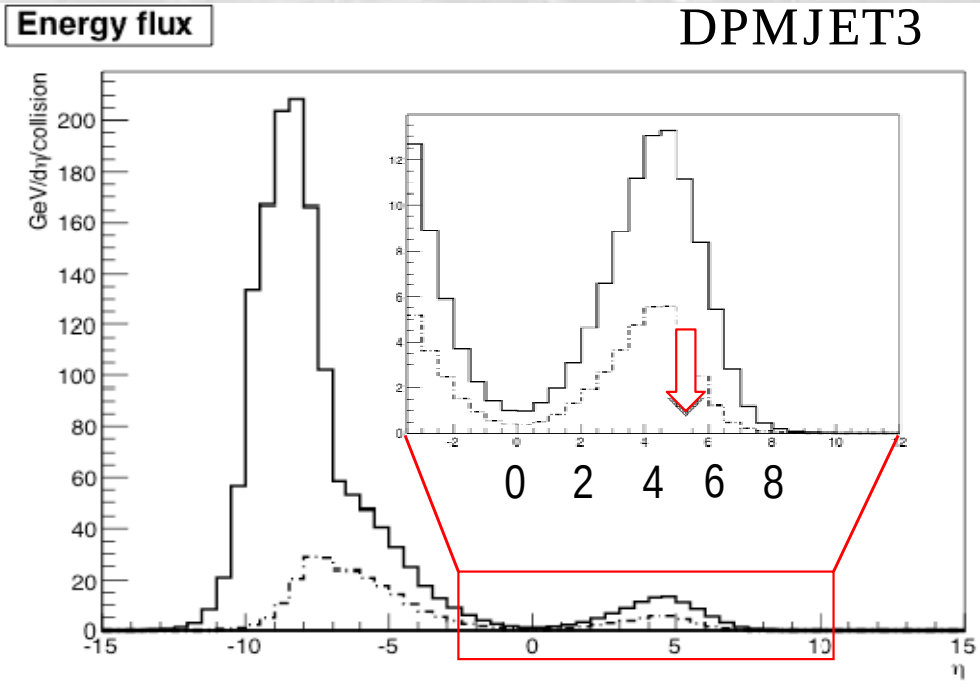
RL asymmetry of near 0 degree neutron production



Very forward region of p-N collisions

Multiplicity and energy flux distribution for p-N collision @ $\sqrt{s_{NN}}$=200GeV.

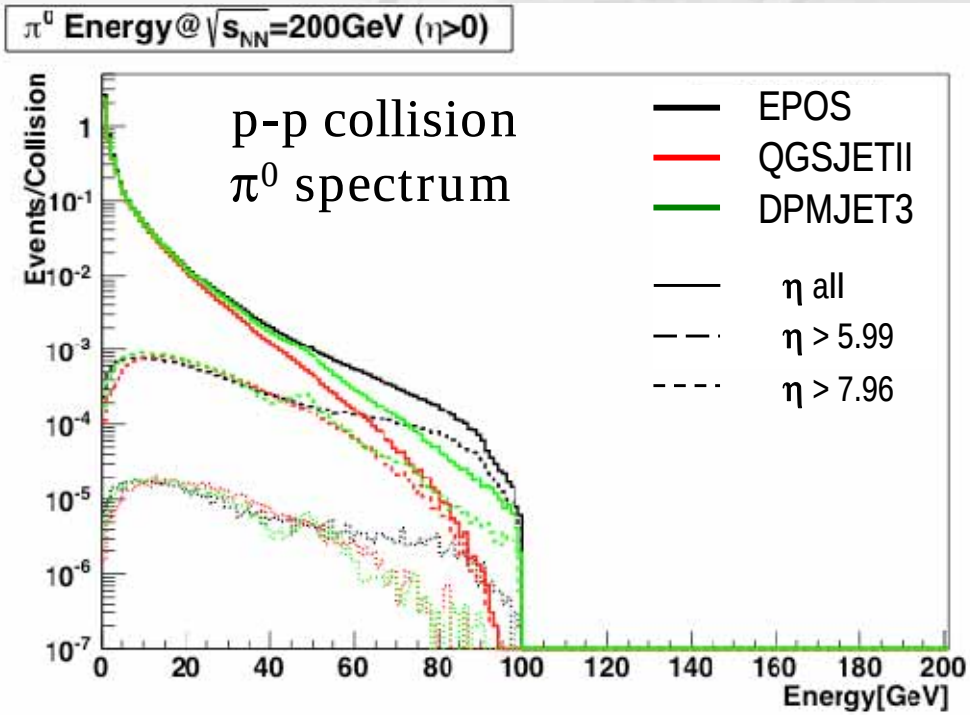


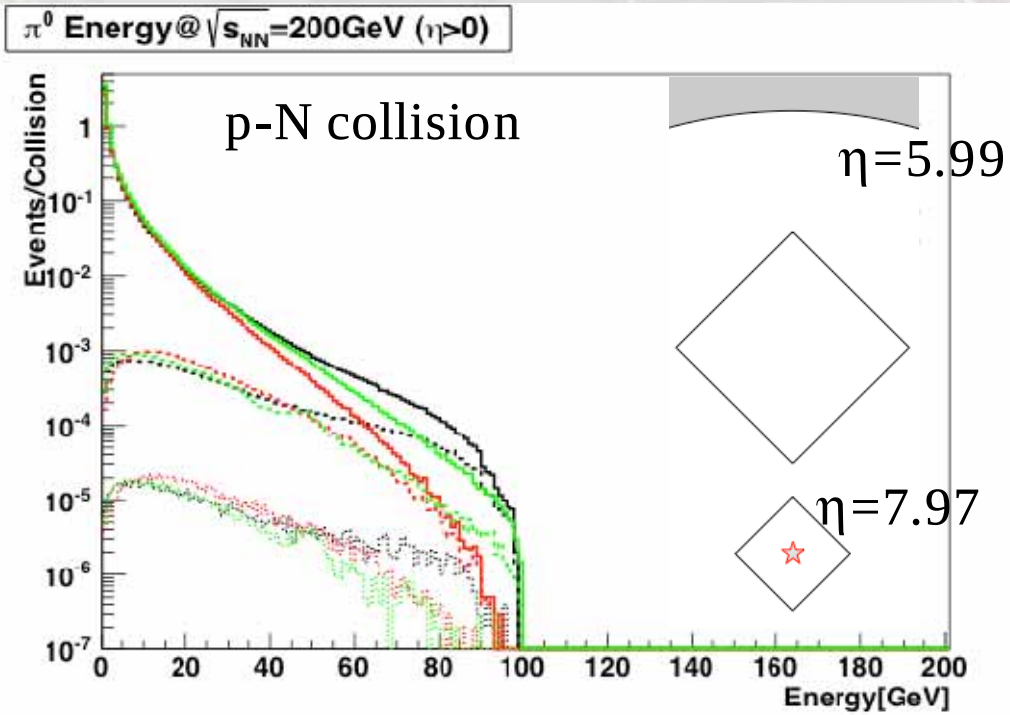


Low multiplicity

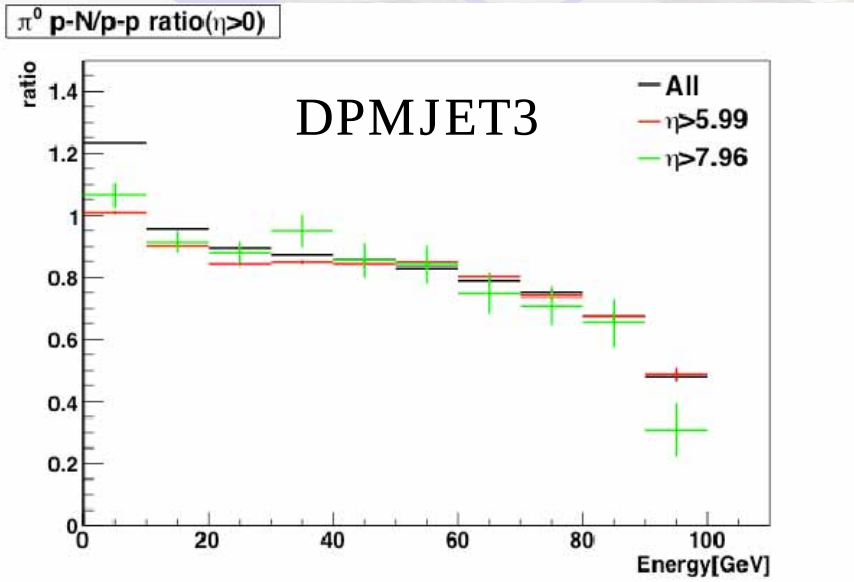
Large amount of energy goes into the forward region

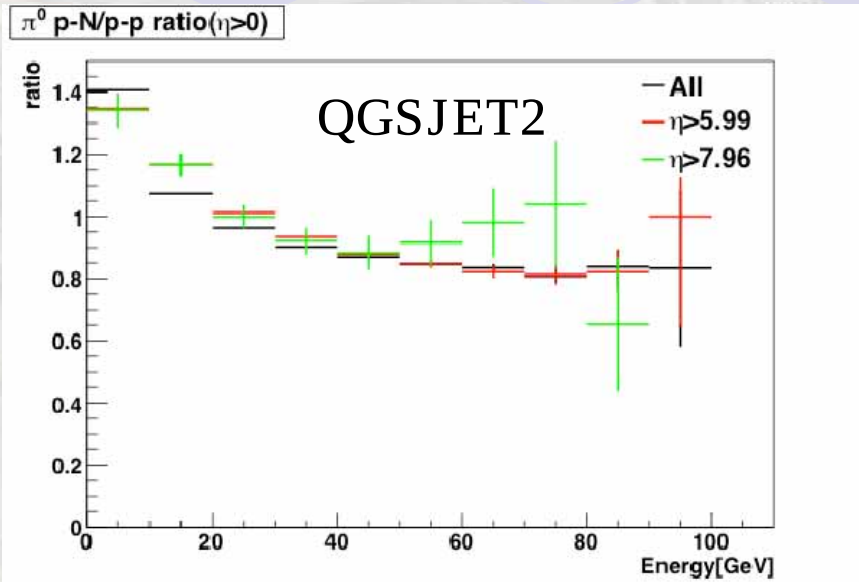
Comparison (p-remnant side)

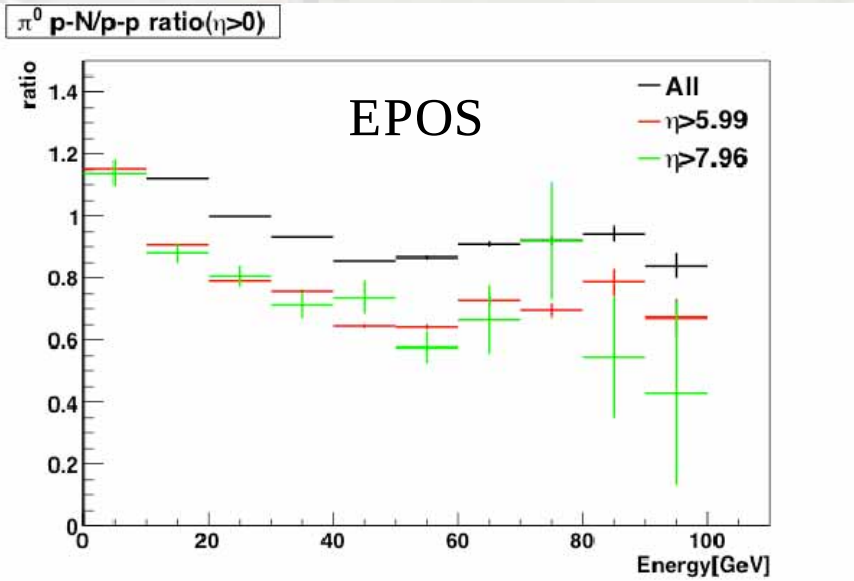




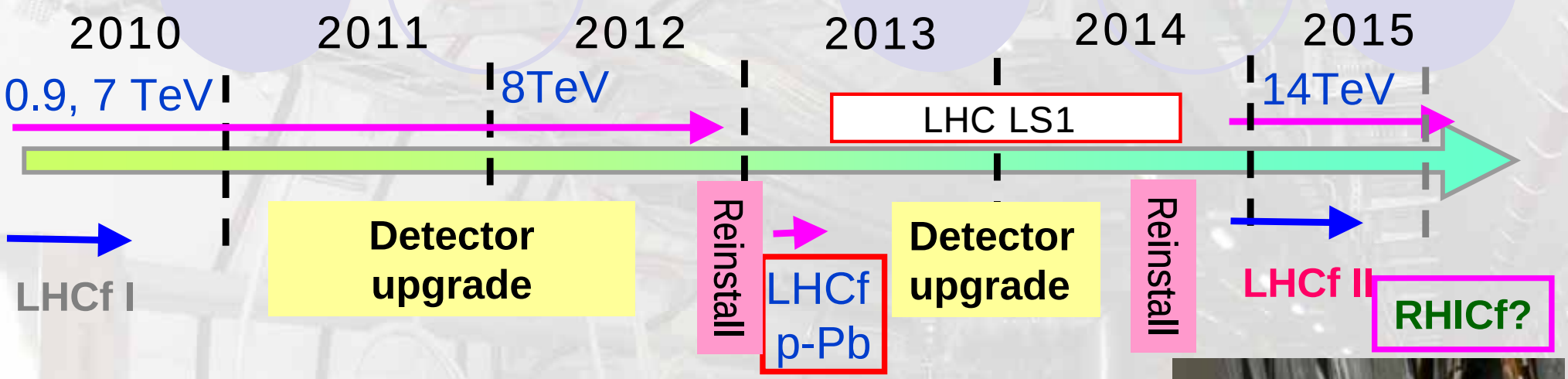
p-N / p-p ratio (π^0)







LHCf future plan



- Analysis ongoing for 2010+2013 data
  - Neutron energy spectra → inelasticity.
  - First p-Pb data → cold nuclear effect.
- 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 ?

Summary

- LHCf： Dedicated to measure neutral particle producitons at very forard at **LHC IP1**
  - Carrying most of collision energies, most relevant to air showers.
  - Useful input for Minimum Bias event study (diffraction)
- EM spectra at 7TeV (0.9TeV) pp （E**γ**, π^0 Pt）
  - No interaction model perfectly reproduce the data
  - Data is well bracketed by spreads of models
  - No surprising in interaction, but need large improvement for UHECR
- Future
  - Very forward neutron, LHC p-Pb data
  - **LHC13TeV** run in early 2015
  - **RHIC**f: possible 0.5TeV p^p, p-N, Fe-N
  - Much more synergy with high energy/nuclear physics
    - With ATLAS central detector. Spin physics in RHIC, etc…

Backup

SPS Beam Test

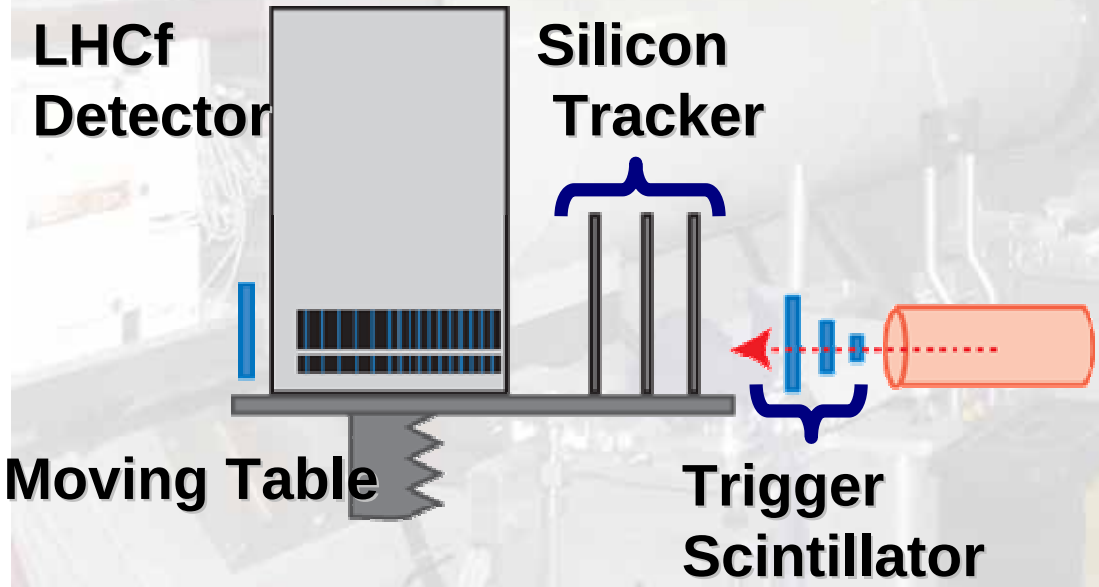
- ✓ CERN : SPS T2 H4
- ✓ Summers 2004, 2006, 2007
- ✓ Incident Particles
  - ✓Proton 150,350 GeV/c
  - ✓Electron 100,200 GeV/c
  - ✓Muon 150 GeV/c

Test was successful

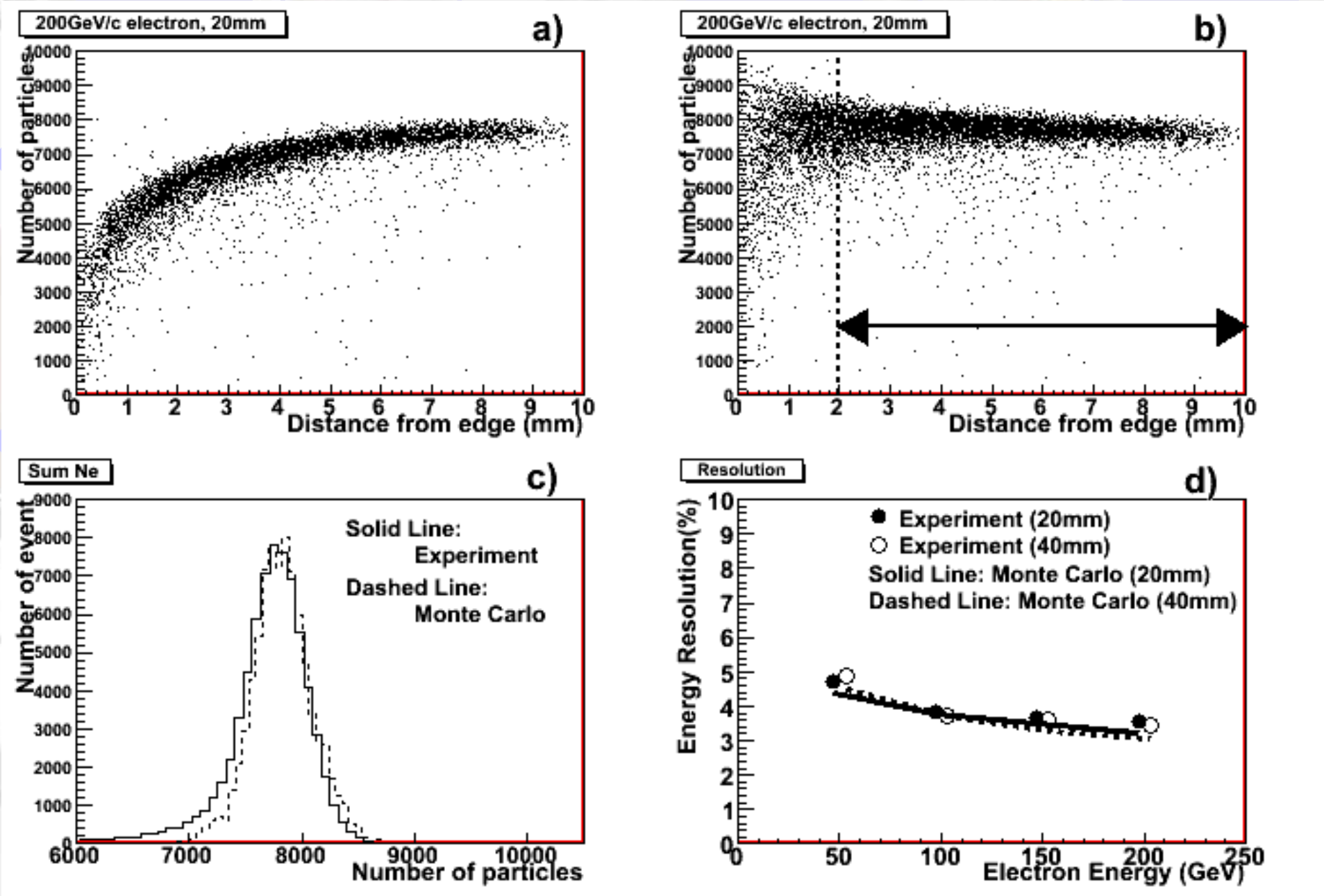
Analysis is under way for

- Energy calibration of the calorimeters
- Spatial resolution of the tracking systems
- PID capability , etc…

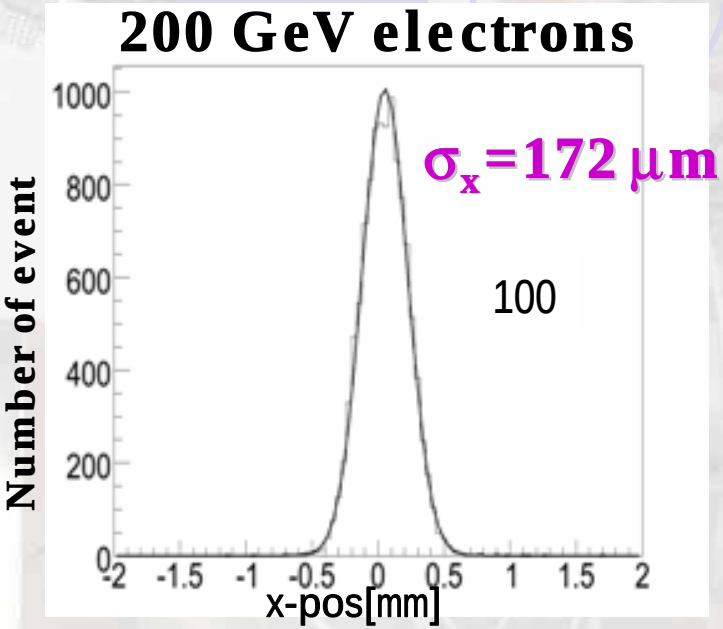
Setup

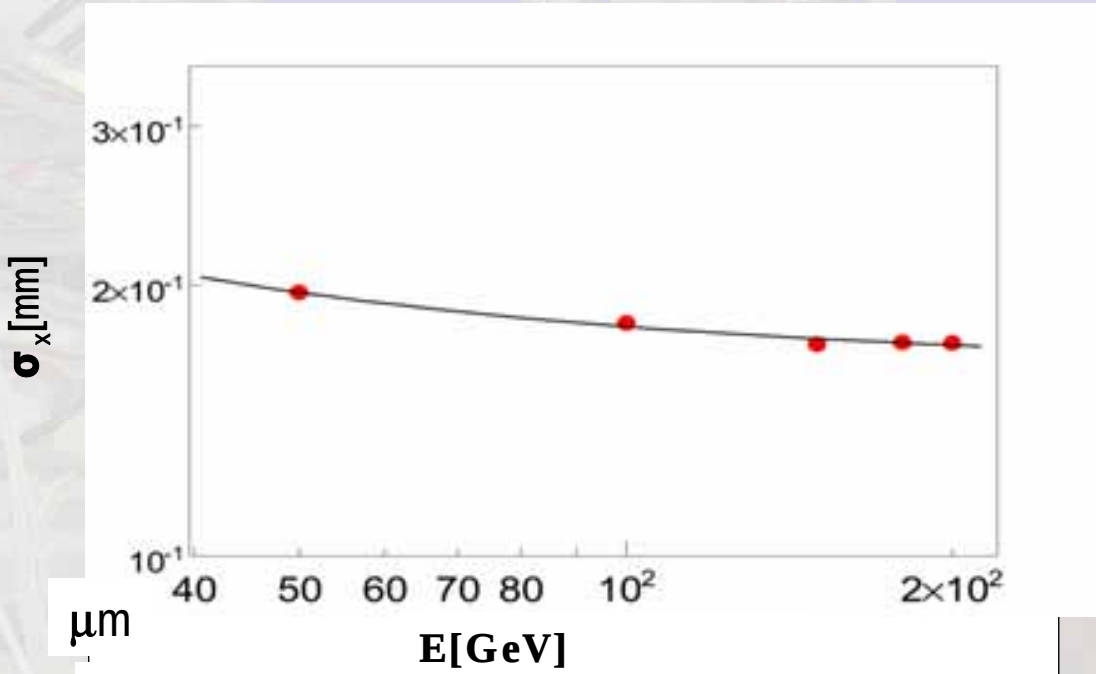


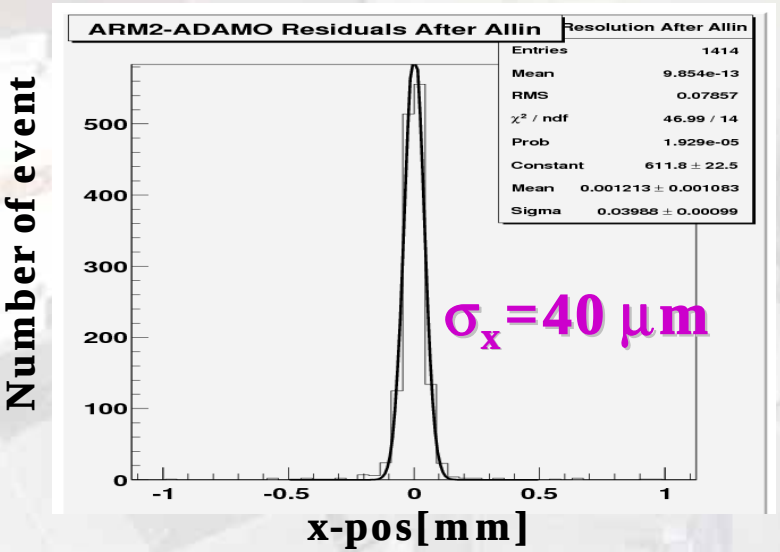
Shower leakage, energy resolution

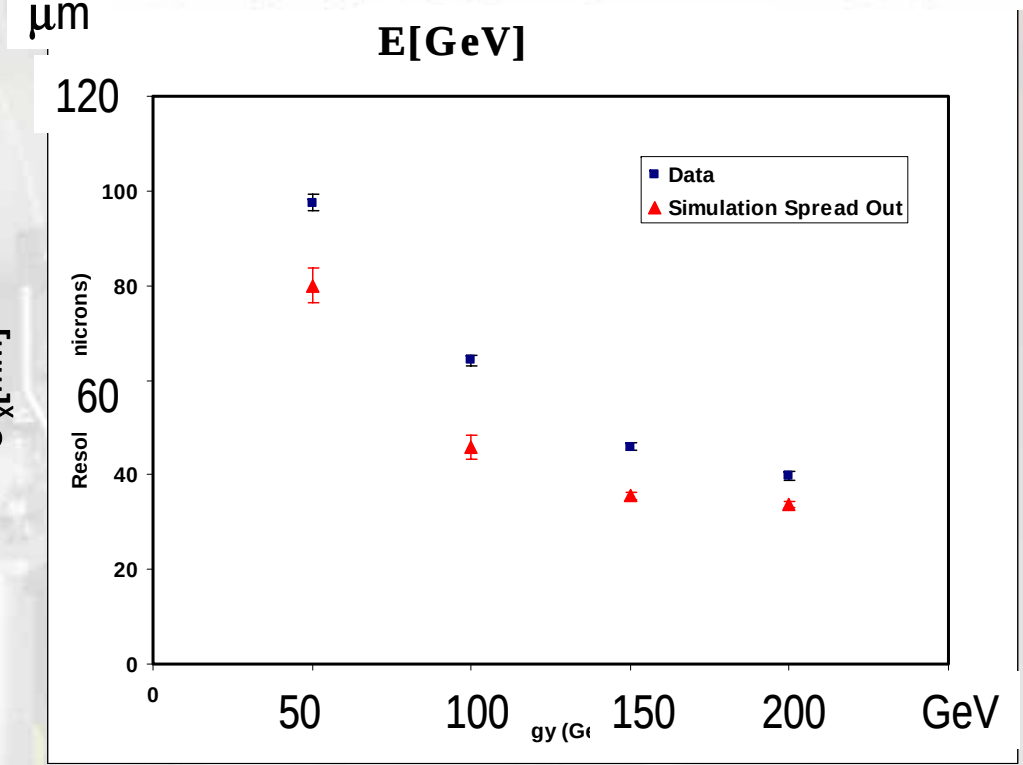


Position resolution for Scfi and Si



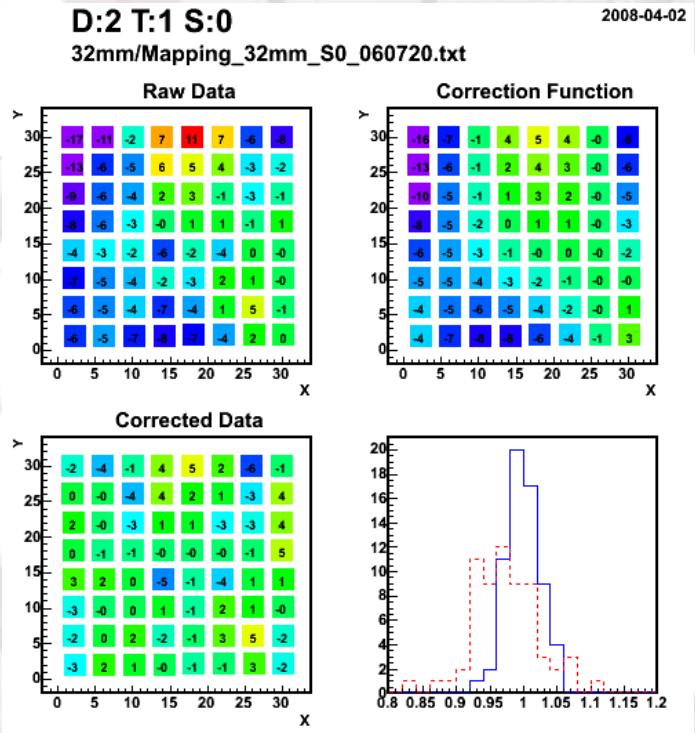


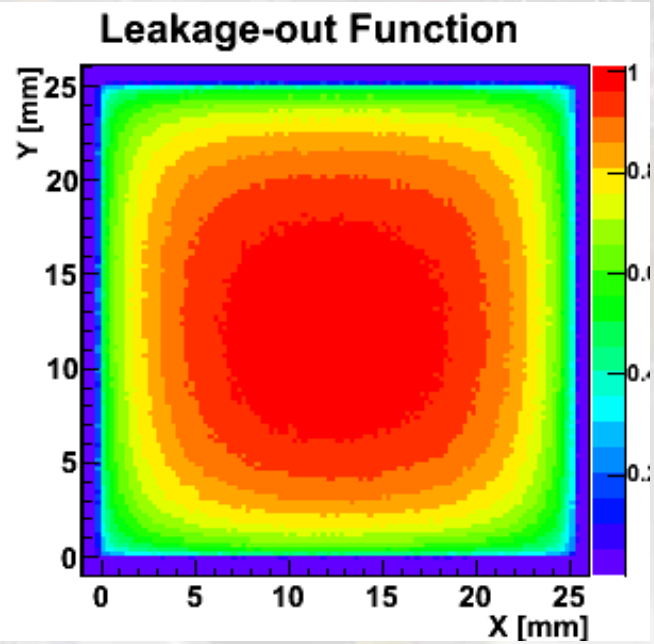


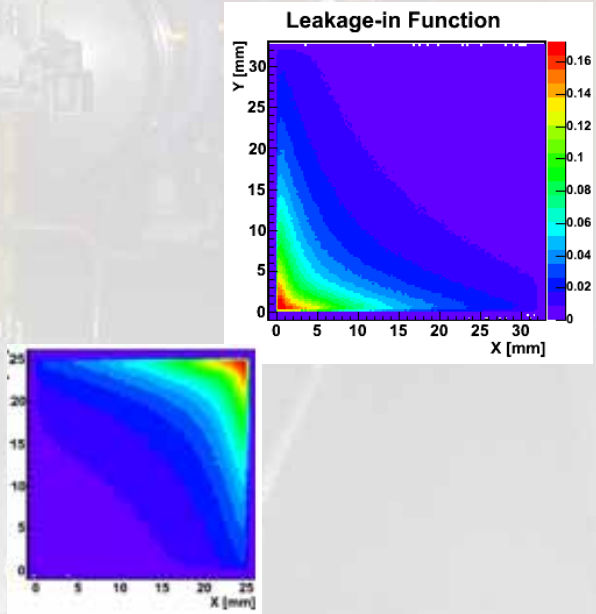


Position dependence of light yield

- Energy reconstruction : $E_{photon} = f(\Sigma(dE_i))$ (i=2,3,…,13)
  ($dE_i = AQ_i$ determined at SPS. f(i) determined by MC. E : EM equivalent energy)
- Impact position from lateral distribution
- Position dependent corrections
  - Light collection non-uniformity
  - Shower leakage-out
  - Shower leakage-in (in case of two calorimeter event)



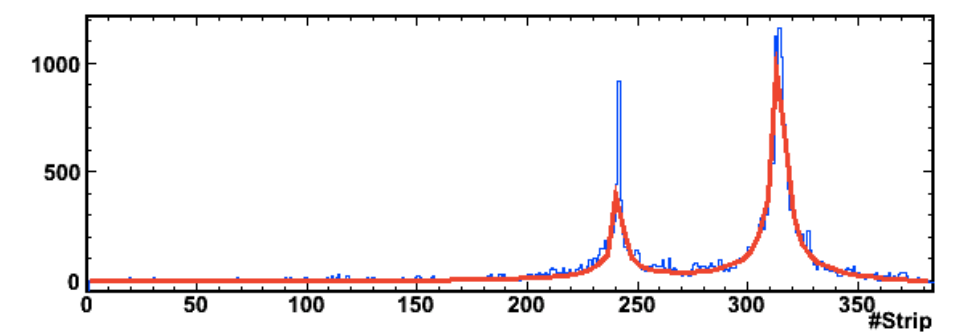




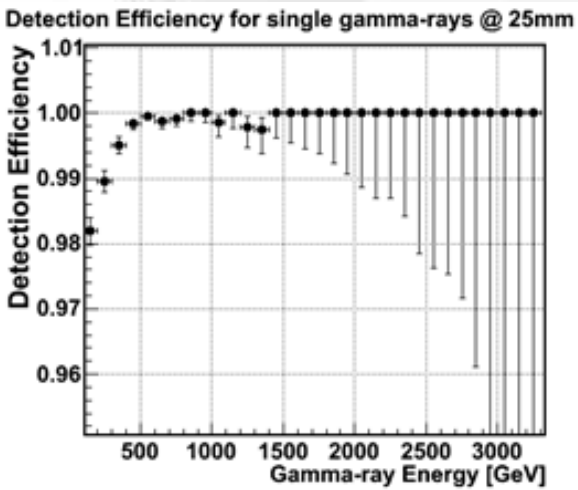
Light collection nonuniformity **Shower leakage-out** **Shower leakage-in**

Multi-incident cut

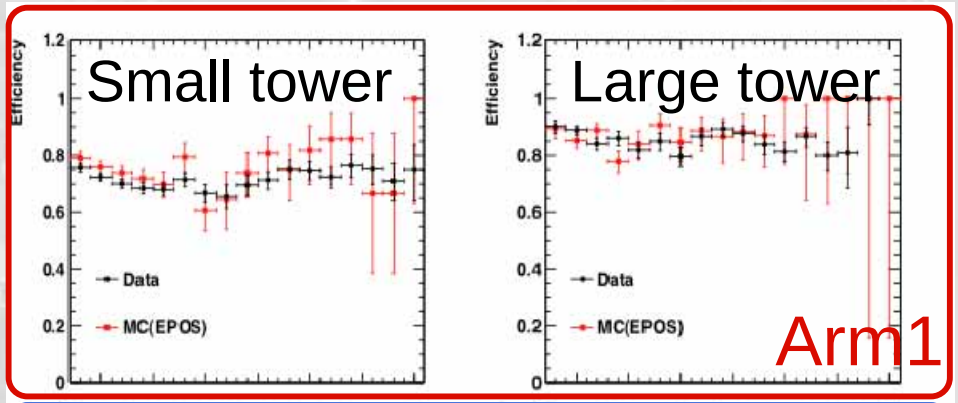
- Single event selection
  - Single-hit detection efficiency
  - Multi-hit identification efficiency (using superimposed single photon-like events)
  - Effect of multi-hit 'cut' (next slide)

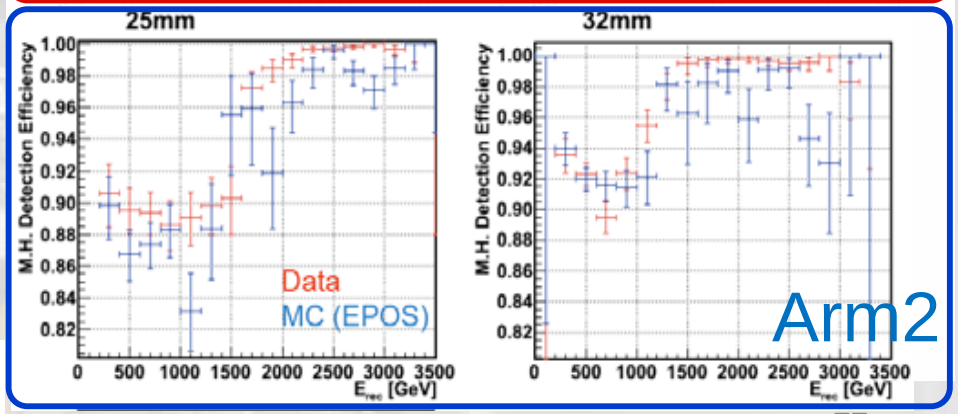


Double hit in a single calorimeter



Single hit detection efficiency

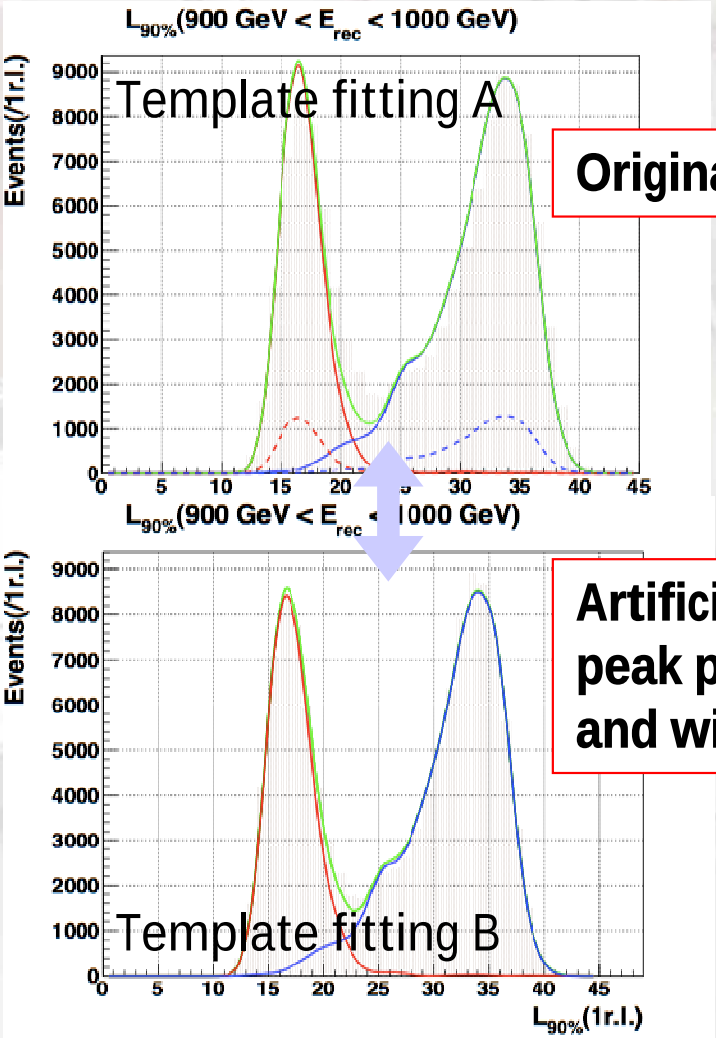




Double hit detection efficiency

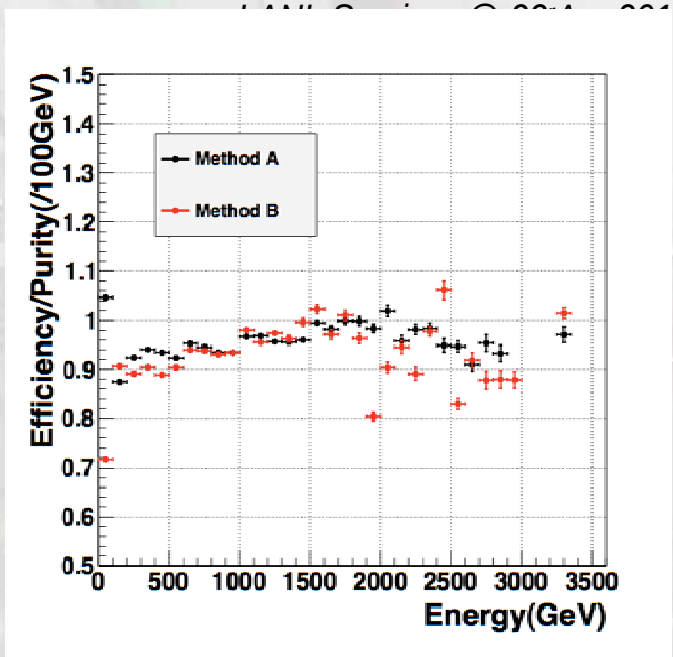
PID systematic error

- $L_{90\%}$ distribution was modified by adjusting peak and width to fit.
- Difference in efficiency/contamination is taken in to systematics.



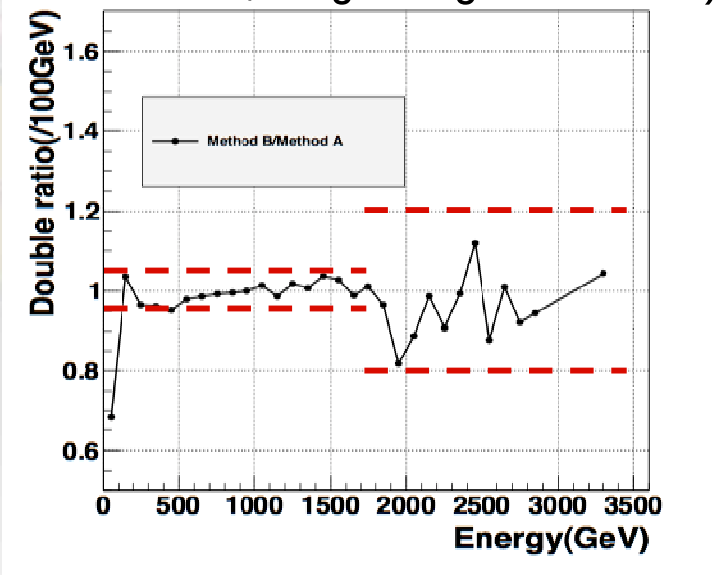
Original method

Artificial modification in peak position (<0.7 r.l.) and width (<20%)



ε /P from two methods

(Small tower, single & gamma-like)

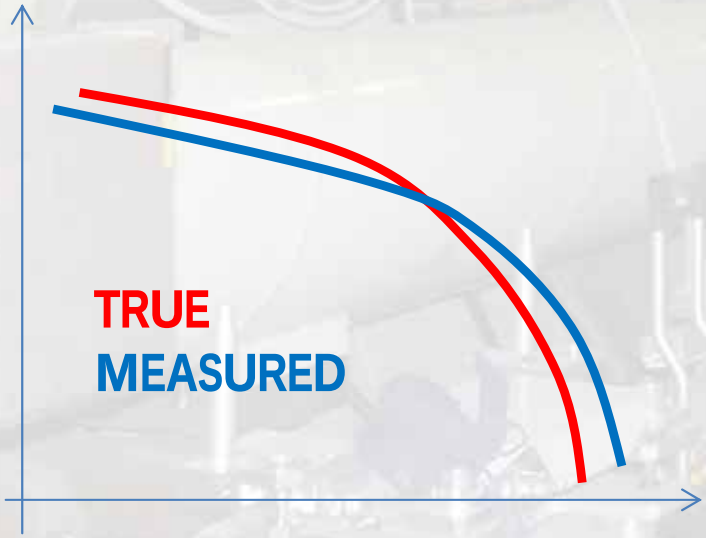


$(\varepsilon/P)_B / (\varepsilon/P)_A$

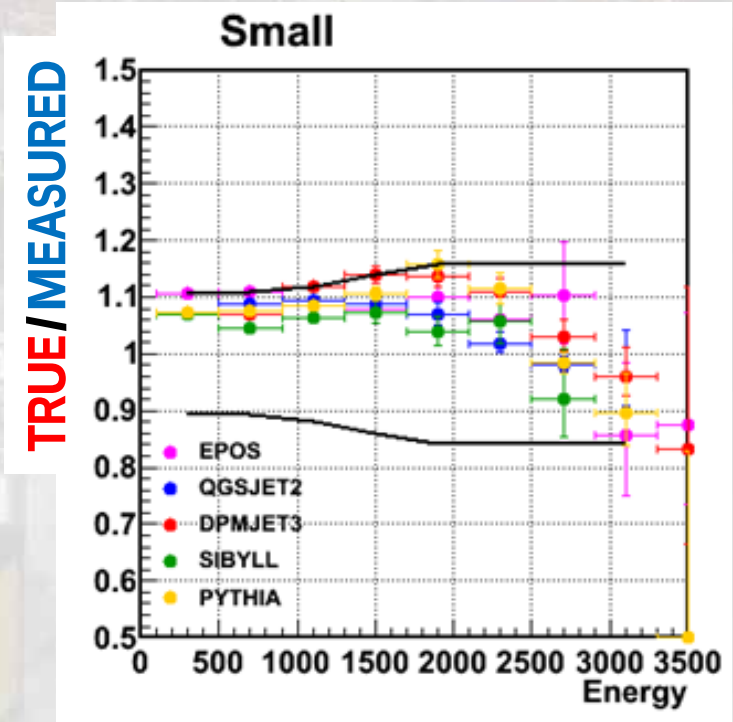
78

Spectral deformation

- Suppression due to multi-hit cut at medium energy
- Overestimate due to multi-hit detection inefficiency at high energy (mis-identify multi photons as single)
- No correction applied, but same bias included in MC to be compared

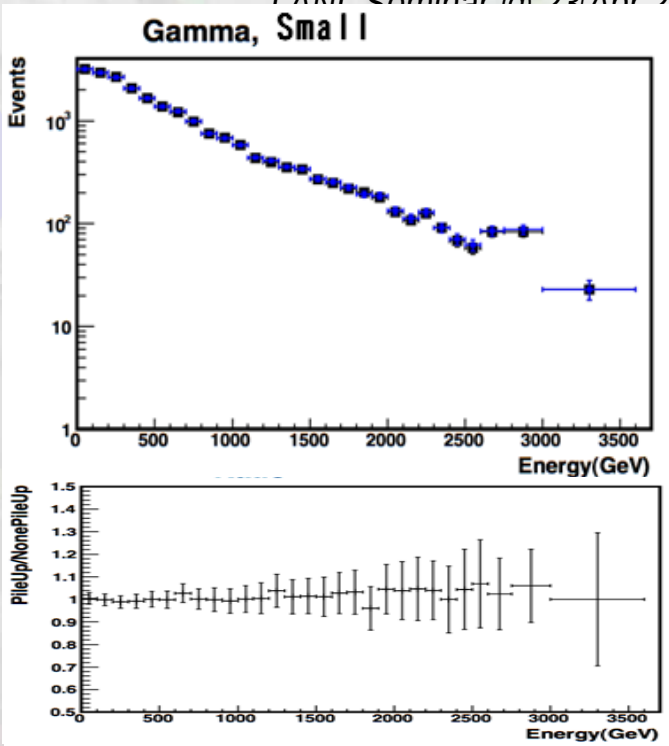


True: photon energy spectrum at the entrance of calorimeter

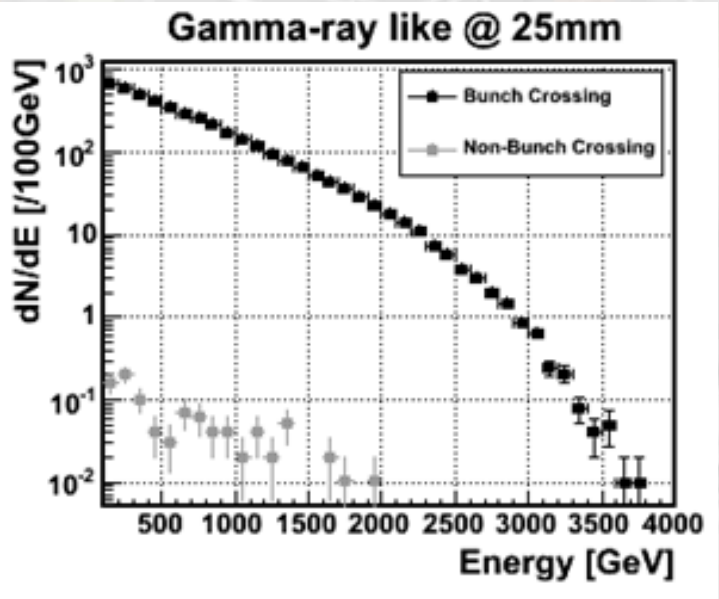


Beam Related Effects

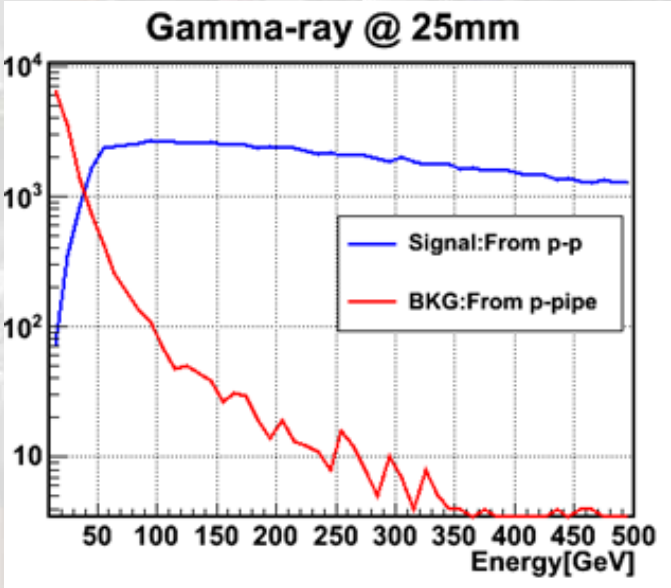
- ✓ Pile-up (7% pileup at collision)
- ✓ Beam-gas BG
- ✓ Beam pipe BG
- ✓ Beam position (next slide)



MC w/ pileup vs w/o pileup

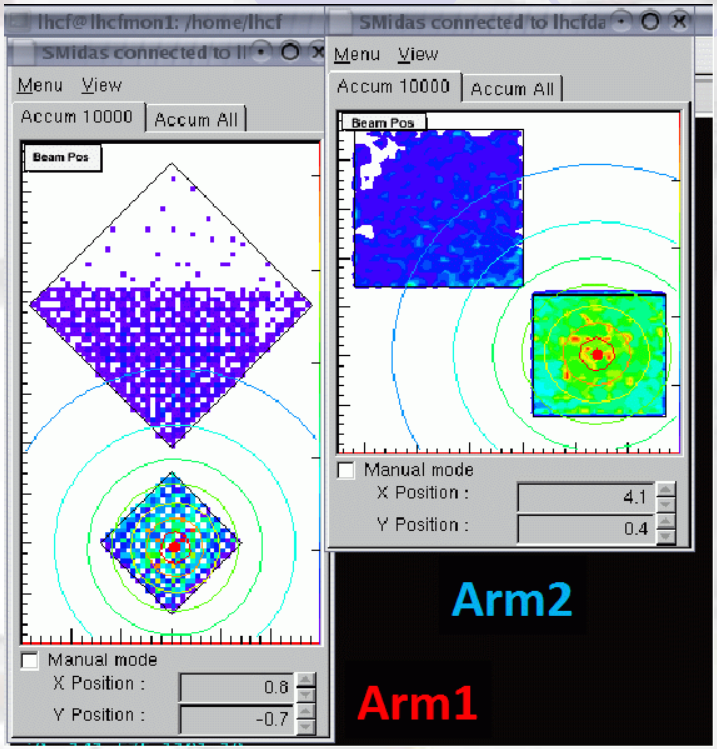


Crossing vs non-crossing bunches

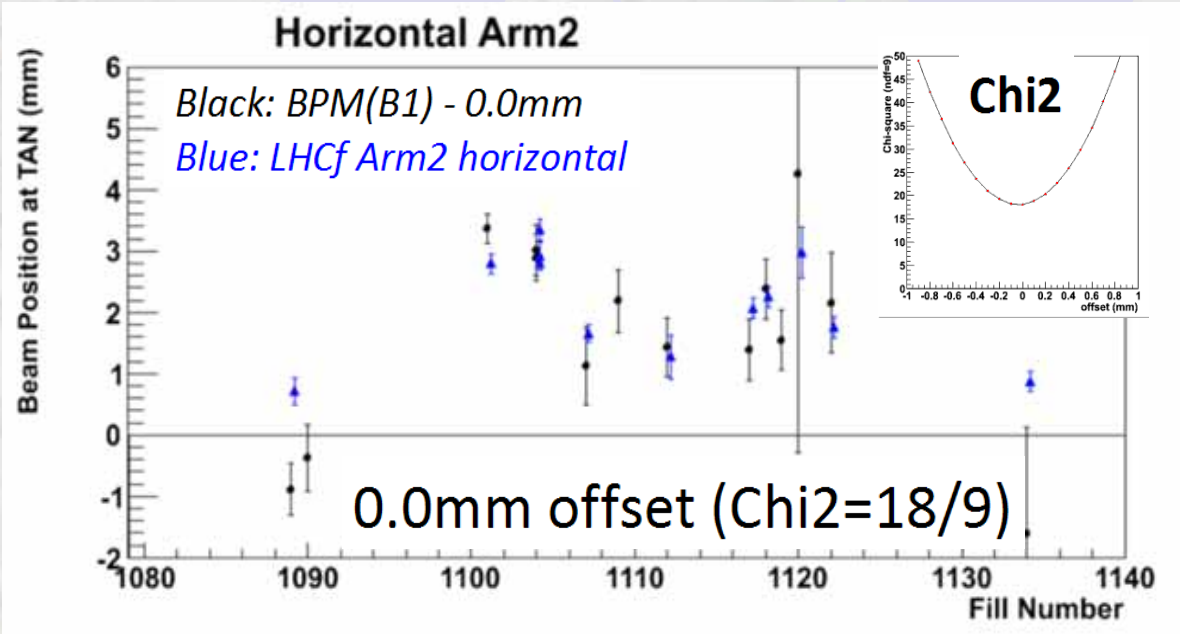


Direct vs beam-pipe photons

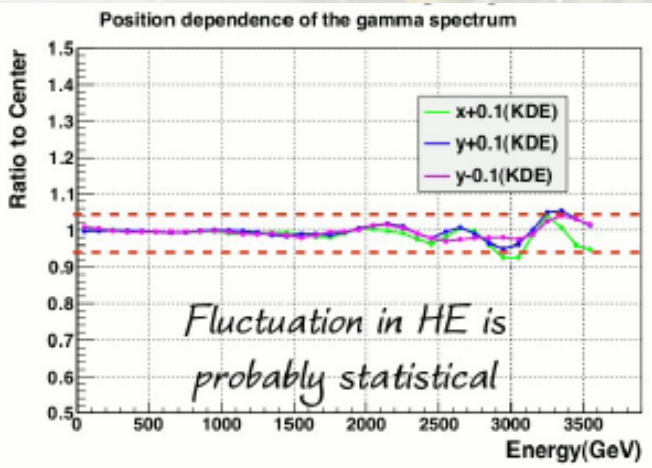
Where is zero degree?

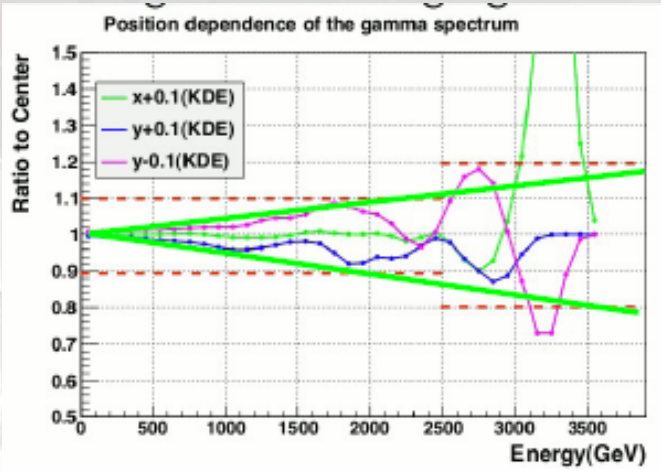


LHCf online hit-map monitor



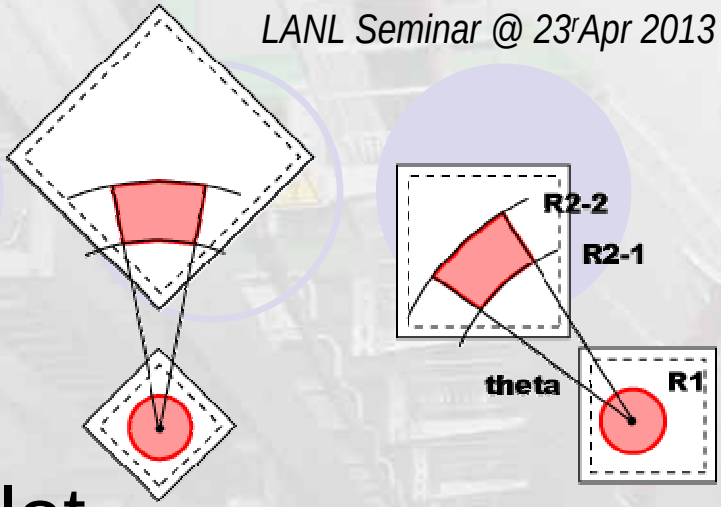
Beam center LHCf vs BPMSW



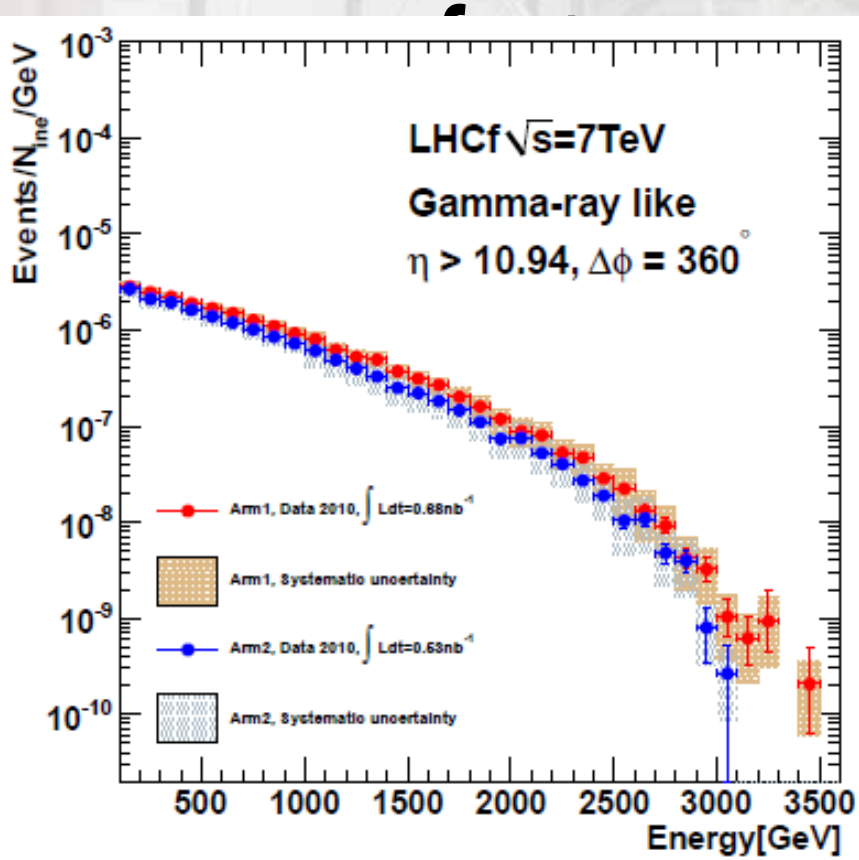


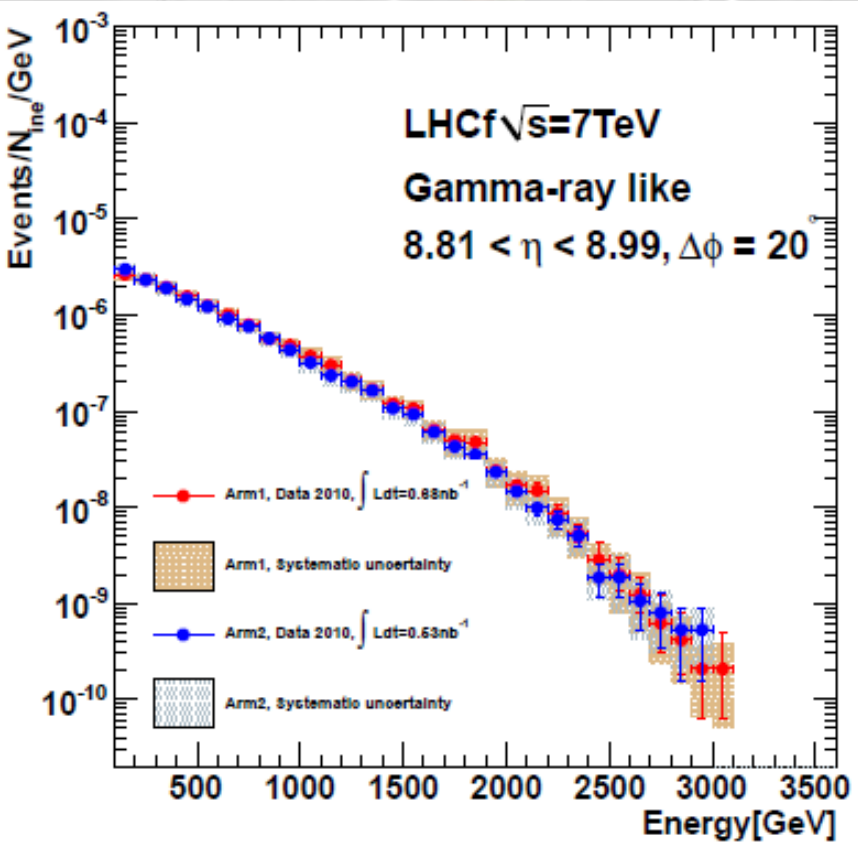
Effect of 1mm shift in the final spectrum

Arm1 vs Arm2 check



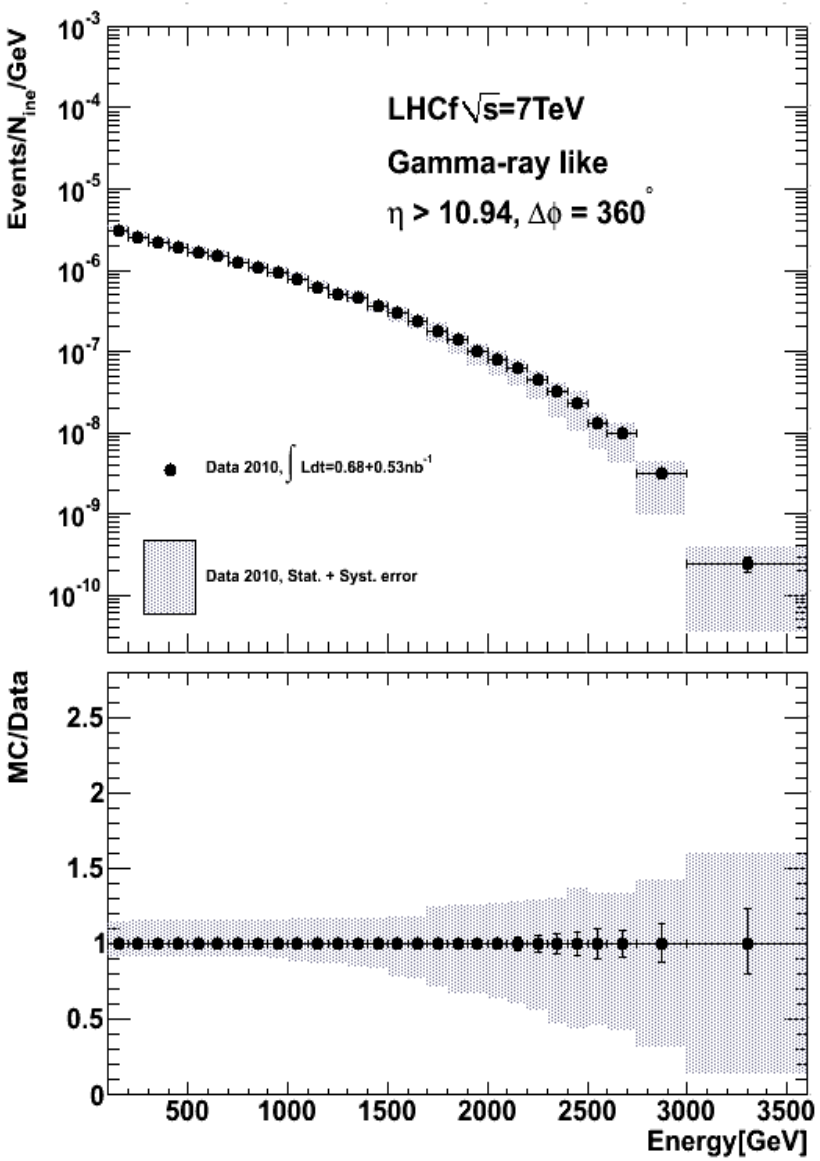
- Spectra in Arm1, Arm2 common rapidity
- Enegy scale error not included in plot (maybe correlated)

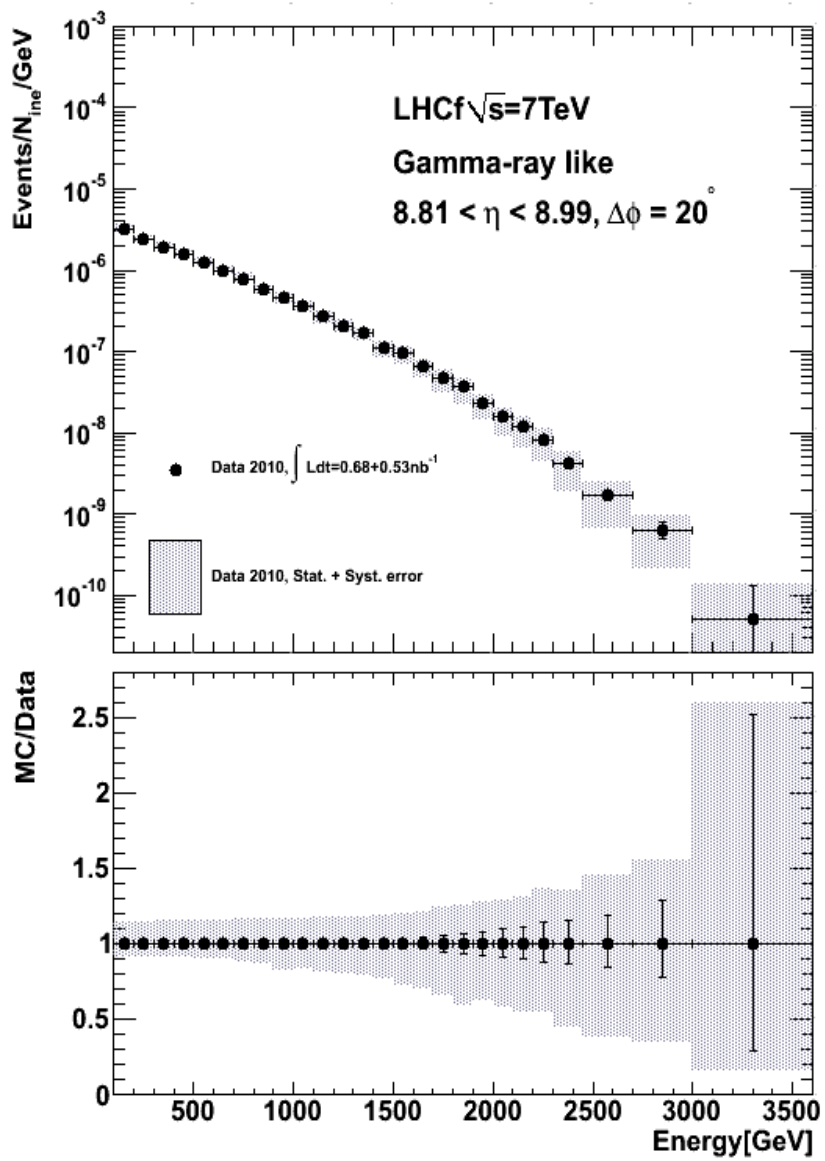




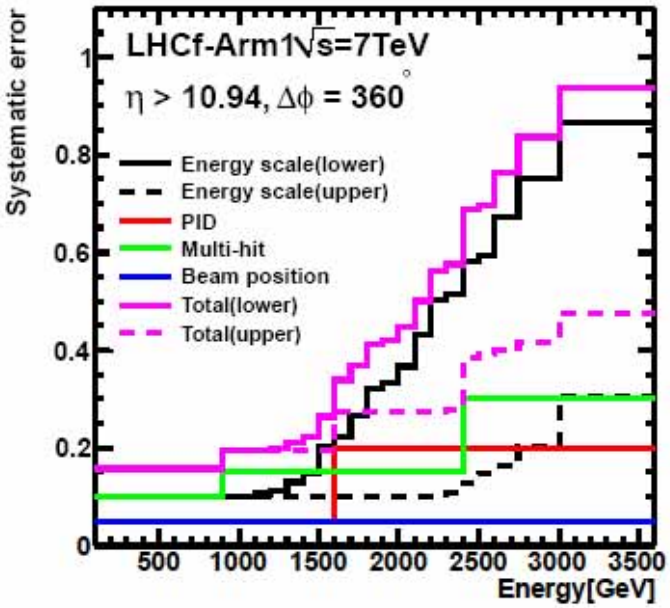
82

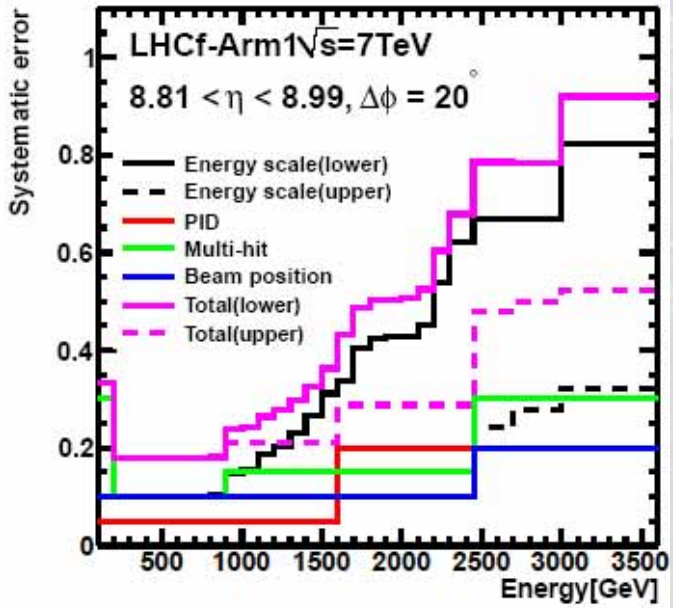
Data with systematic error

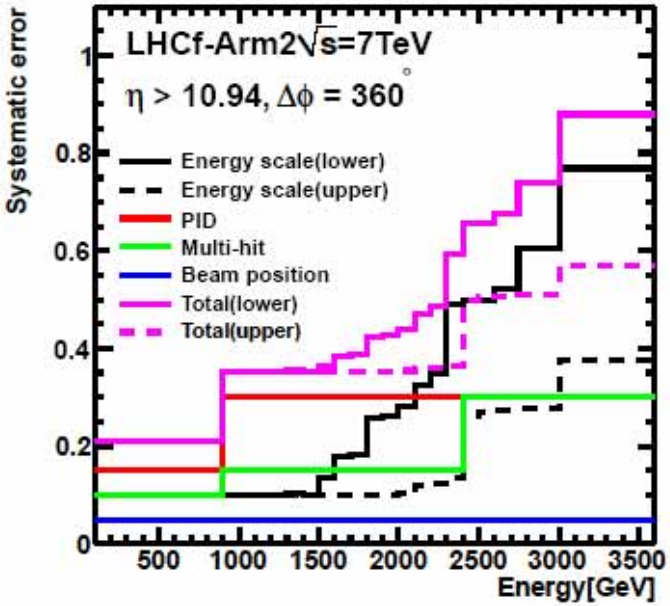


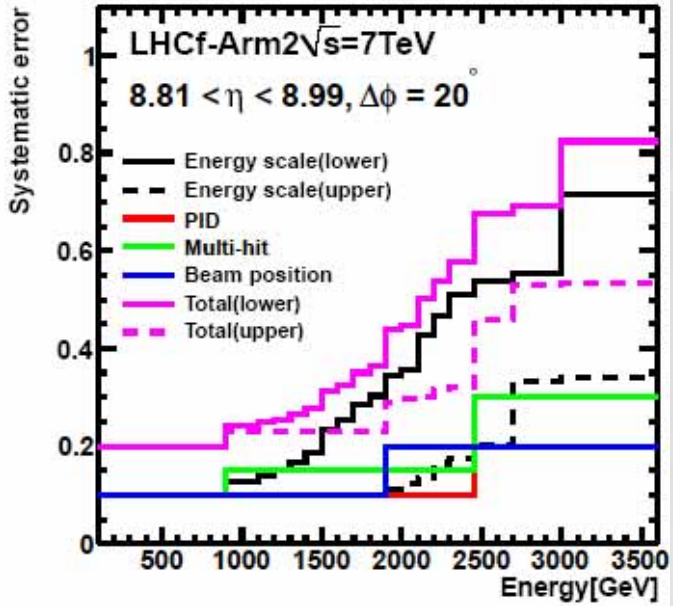


Systematic errors in 7TeV photon analysis



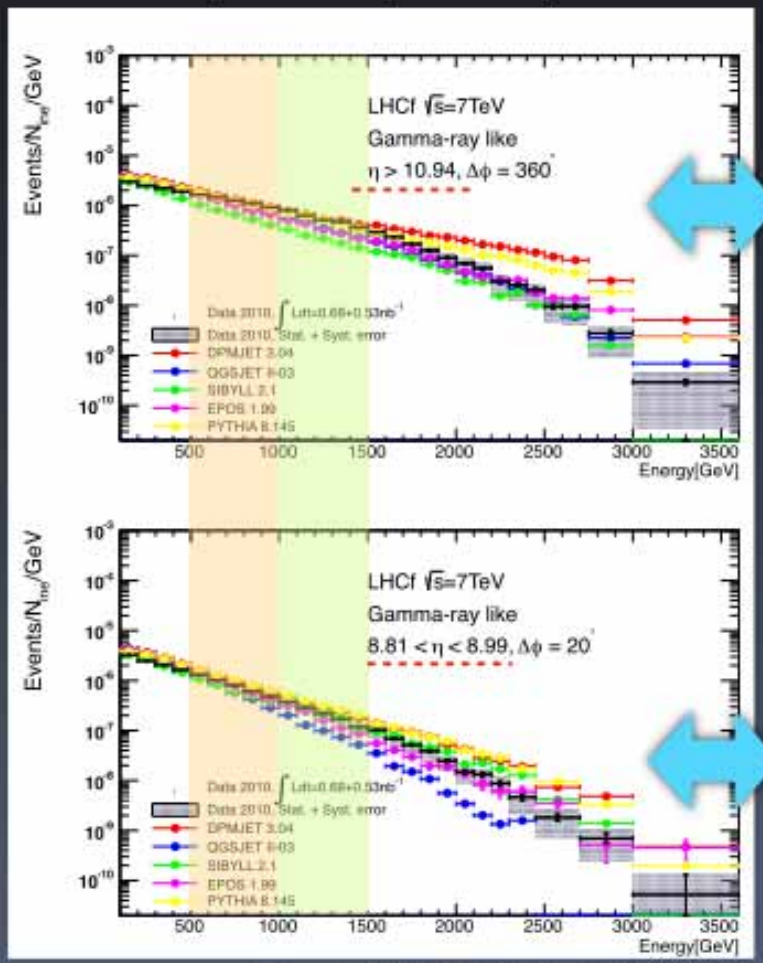




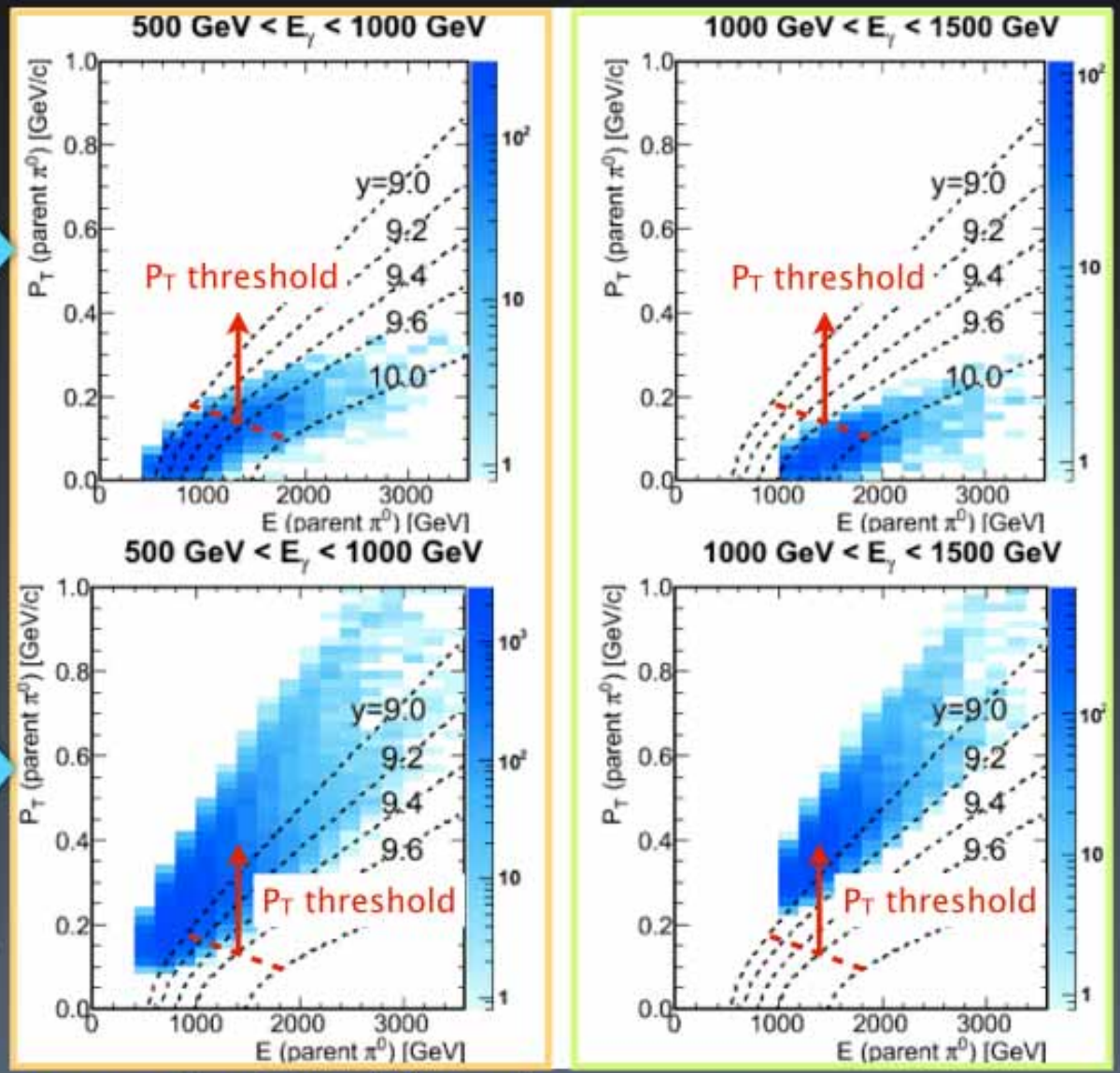


Single γ and Type I π^0 originate in different kinematic regions.

7TeV photon spectra by LHCf



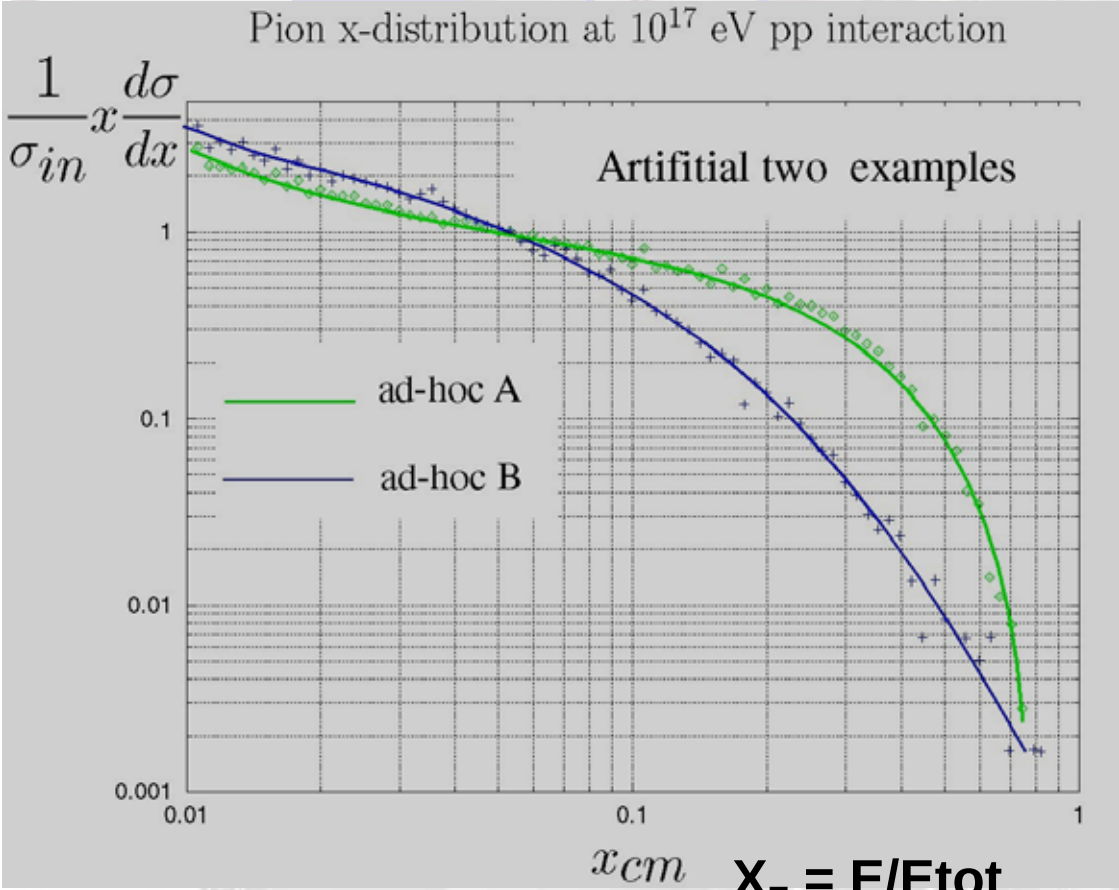
(Phys. Lett. B 703 128–134 (2011))



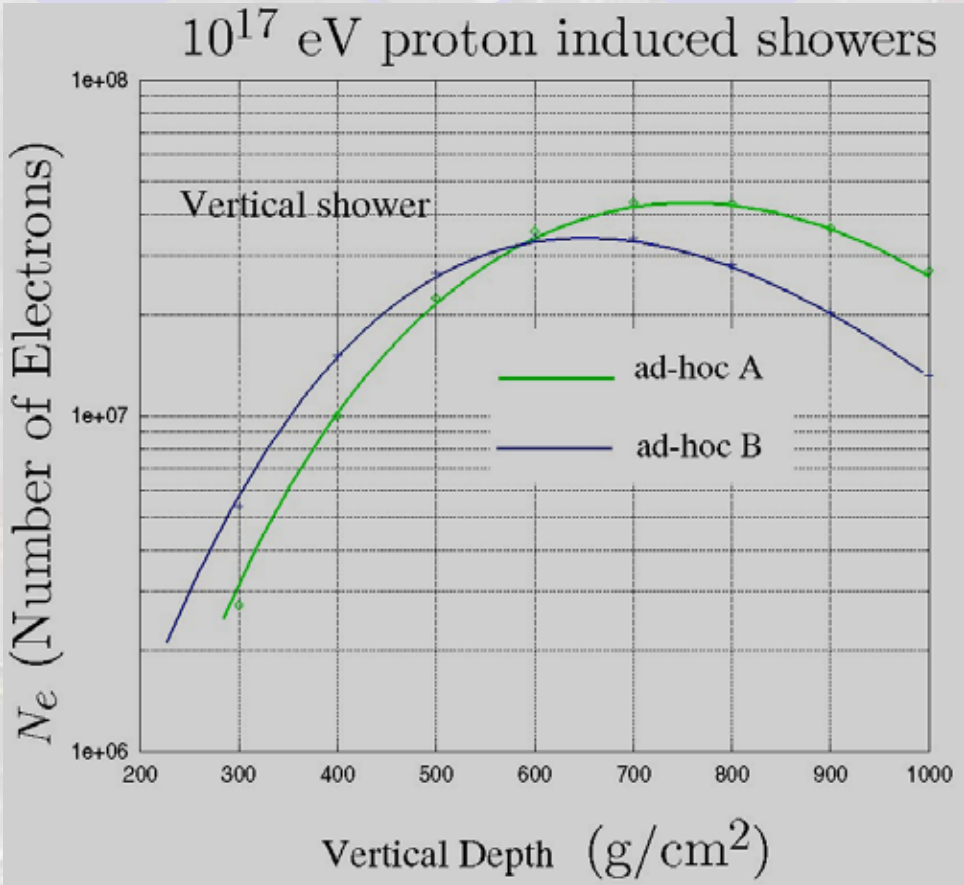
- Photon analysis and π^0 analysis compensate each missing information.
  - High energy photon originates from large P_T π^0 events.
  - Photon spectrum includes a contribution from other hadrons/baryons.

→ Photon P_T analysis can connect each measurement.

Impact of forward EM spectra on shower development



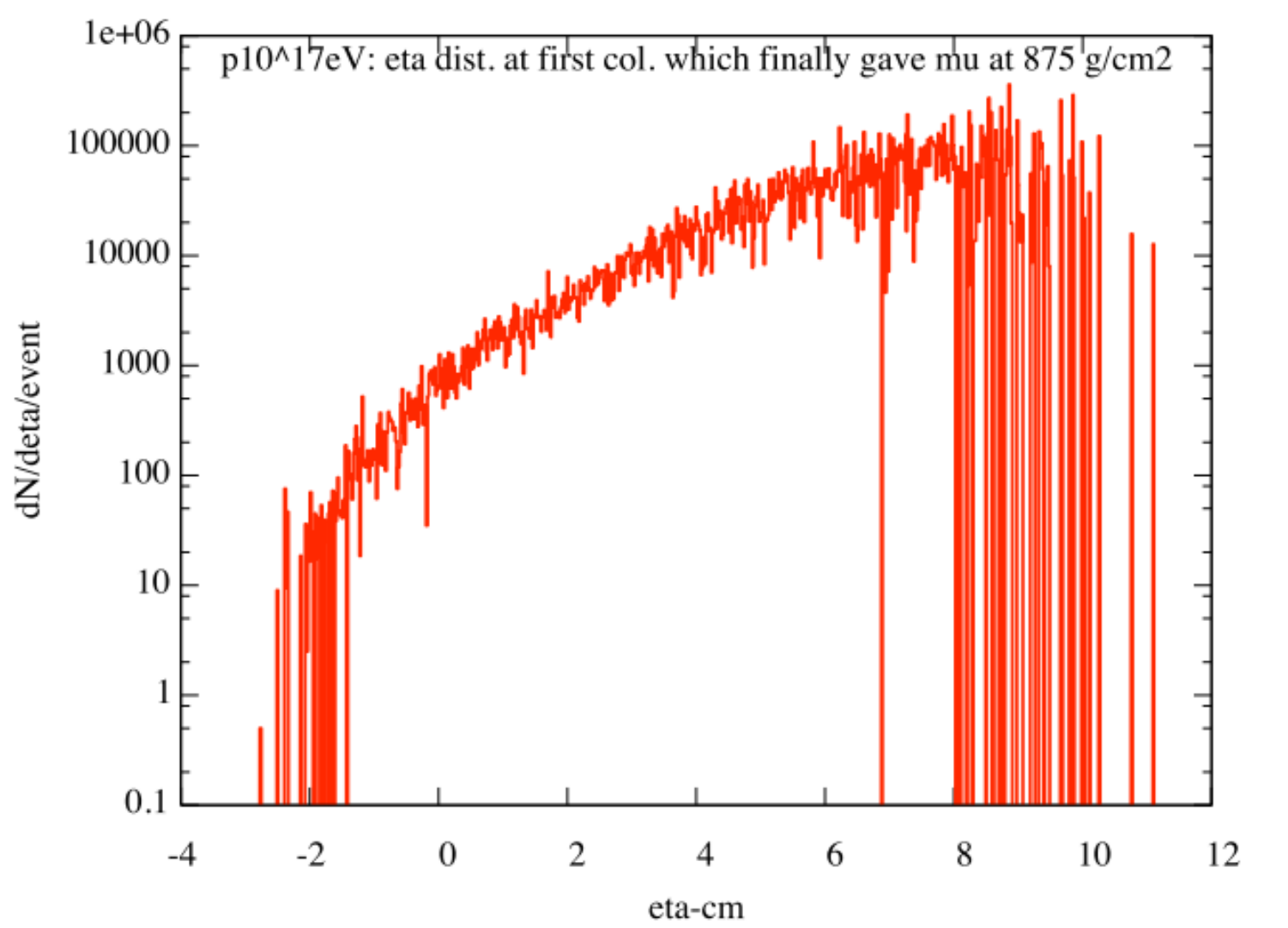
X_F = E/Etot



Half of shower particles comes from large X_F γ

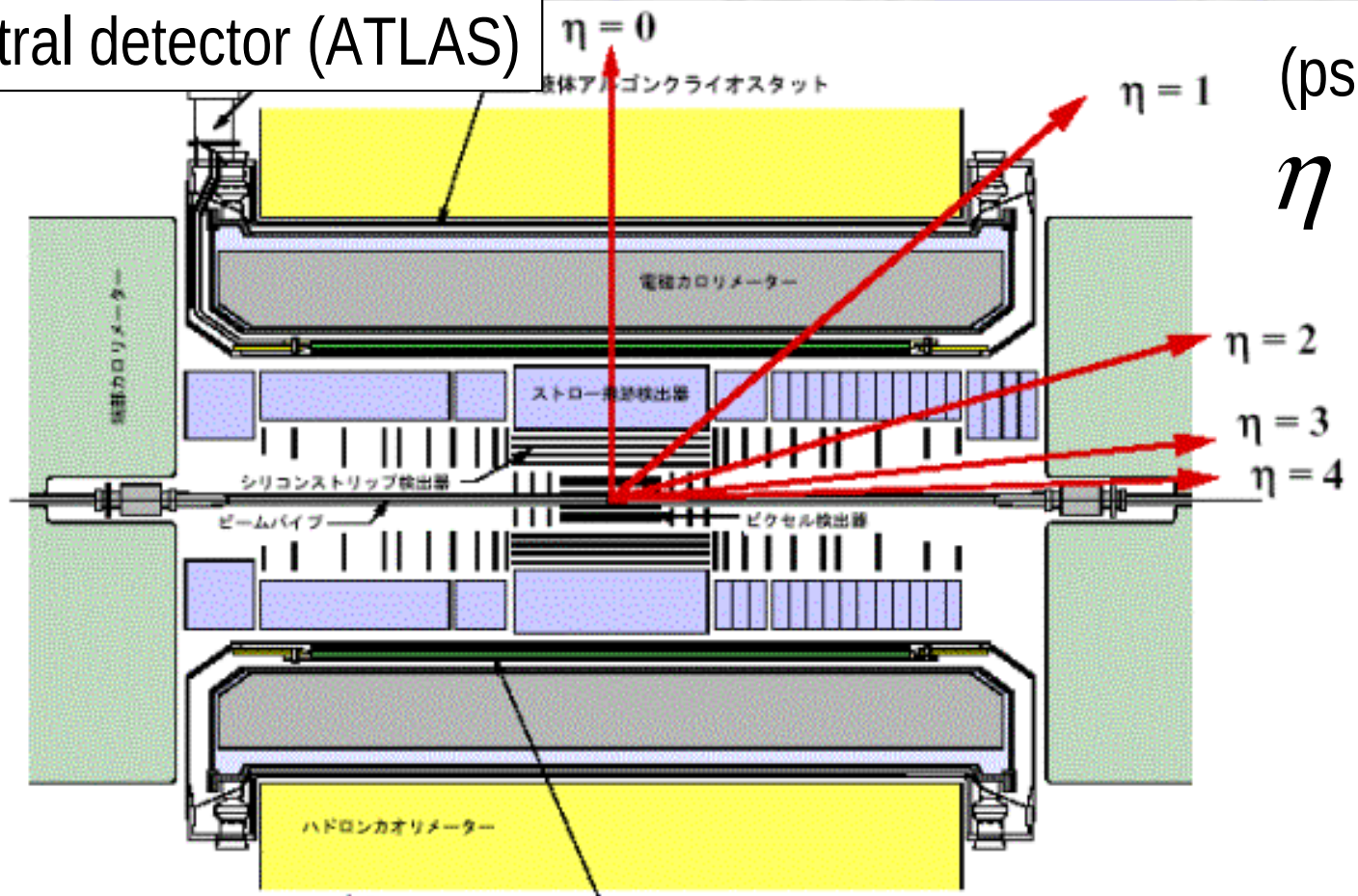
Measurement at very forward region is needed

Parent π^0 pseudorapidity producing ground muons



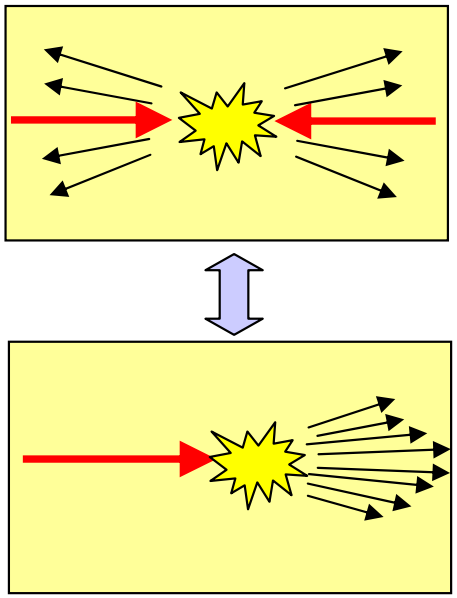
A LHC detector and pseudorapidity

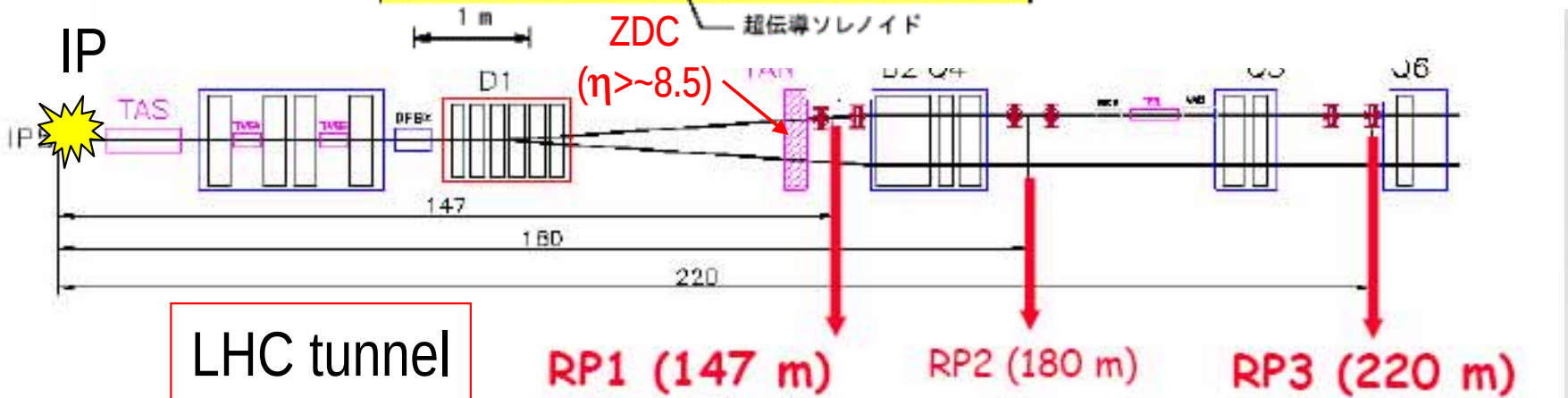
Central detector (ATLAS)



(pseudo)rapidity

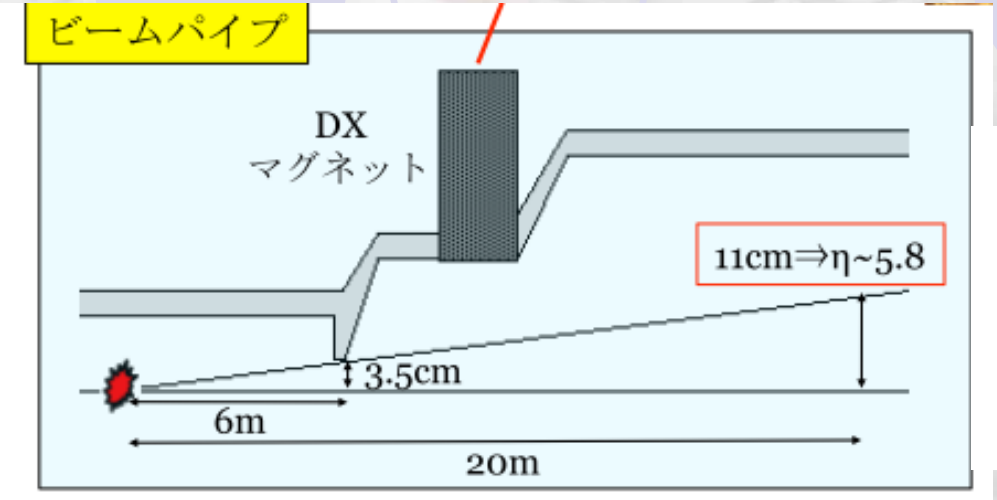
$$\eta = -\ln(\tan\frac{\theta}{2})$$



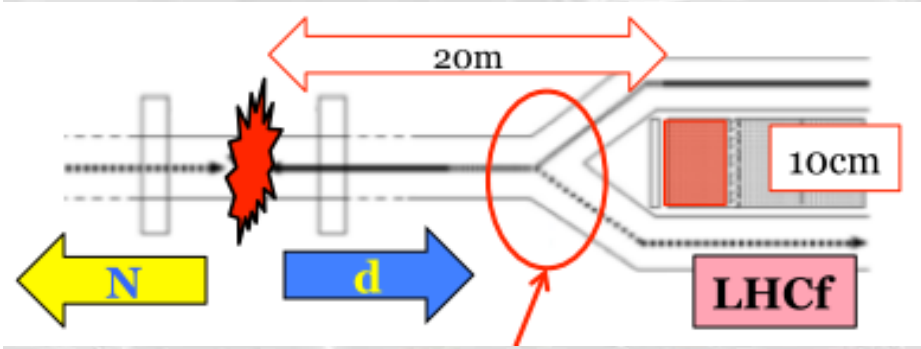


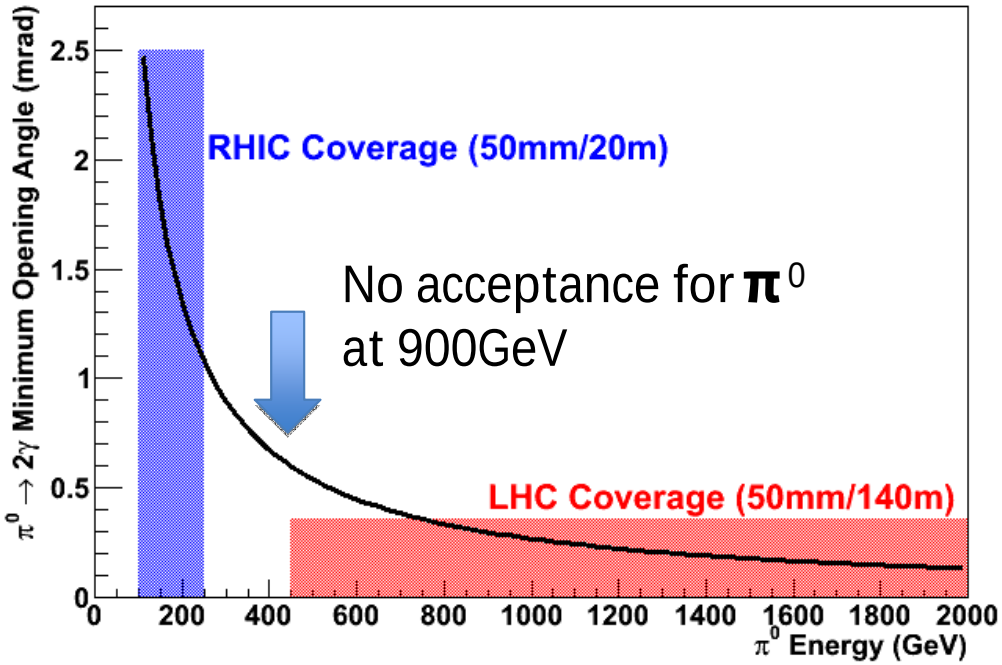
LHC tunnel

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

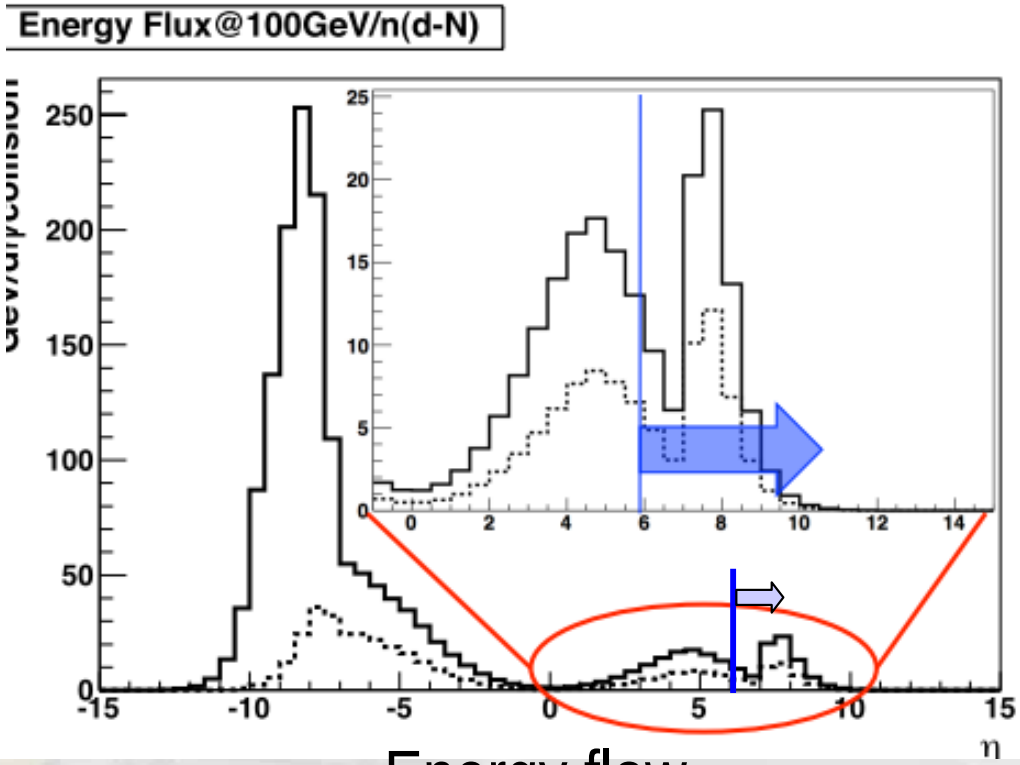


η>5.8 is covered





Acceptance for π0



Energy flow

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

Fe-O or p-O collisions at LHC seems technically feasible, but would not be so realistic in near future (~10yrs)

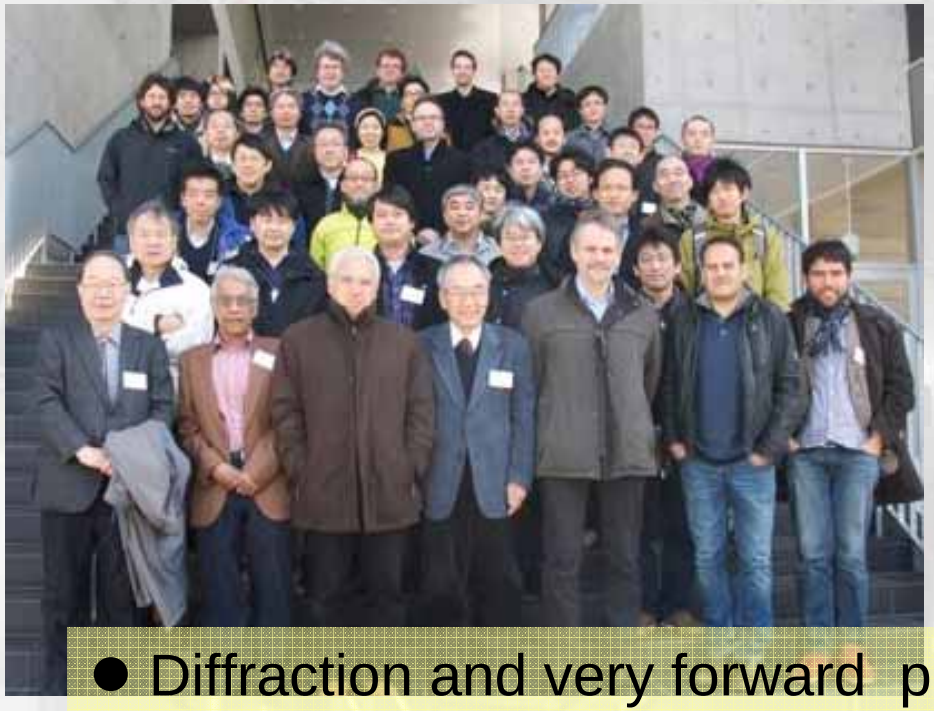
International Workshop on

"High-energy scattering at zero degree"

2nd - 4th March, 2013,

KMI, Nagoya University

http://www.gcoe.phys.nagoya-u.ac.jp/hesz2013



Organizing committee

Yoshitaka Itow (Nagoya)
Kazunori Itakura (KEK)
Yuji Goto (Riken)
Takashi Sako (Nagoya)
Kenta Shigaki (Hiroshima)
Kiyoshi Tanida (SNU)
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