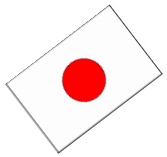
Introduction and results of the LHCf experiment

Takashi SAKO
(KMI/STEL, Nagoya University)
for the LHCf collaboration

The LHCf Collaboration



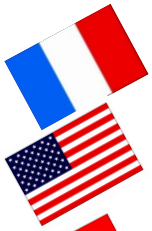
[*,**]Y.Itow, [*]K.Kawade, [*]Y.Makino, [*]K.Masuda, [*]Y.Matsubara, [*]E.Matsubayashi, [**]H.Menjo, [*]Y.Muraki, [*,**]T.Sako, [*]N.Sakurai, [*]Y.Sugiura, [*]Q.D.Zhou

Solar-Terrestrial Environment Laboratory, Nagoya University, Japan
[**]Kobayashi-Maskawa Institute, Nagoya University, Japan
[***]Graduate School of Science, Nagoya University, Japan

K.Yoshida *Shibaura Institute of Technology, Japan*

K.Kasahara, Y.Shimizu, T.Suzuki, S.Torii

Waseda University, Japan



T.Tamura *Kanagawa University, Japan*

M.Haguenauer *Ecole Polytechnique, France*

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

O.Adriani, E.Berti, L.Bonechi, M.Bongi, G.Castellini, R.D'Alessandro, M.Delprete, M.Grandi, G.Mitsuka, P.Papini, S.Ricciarini, A.Tiberio

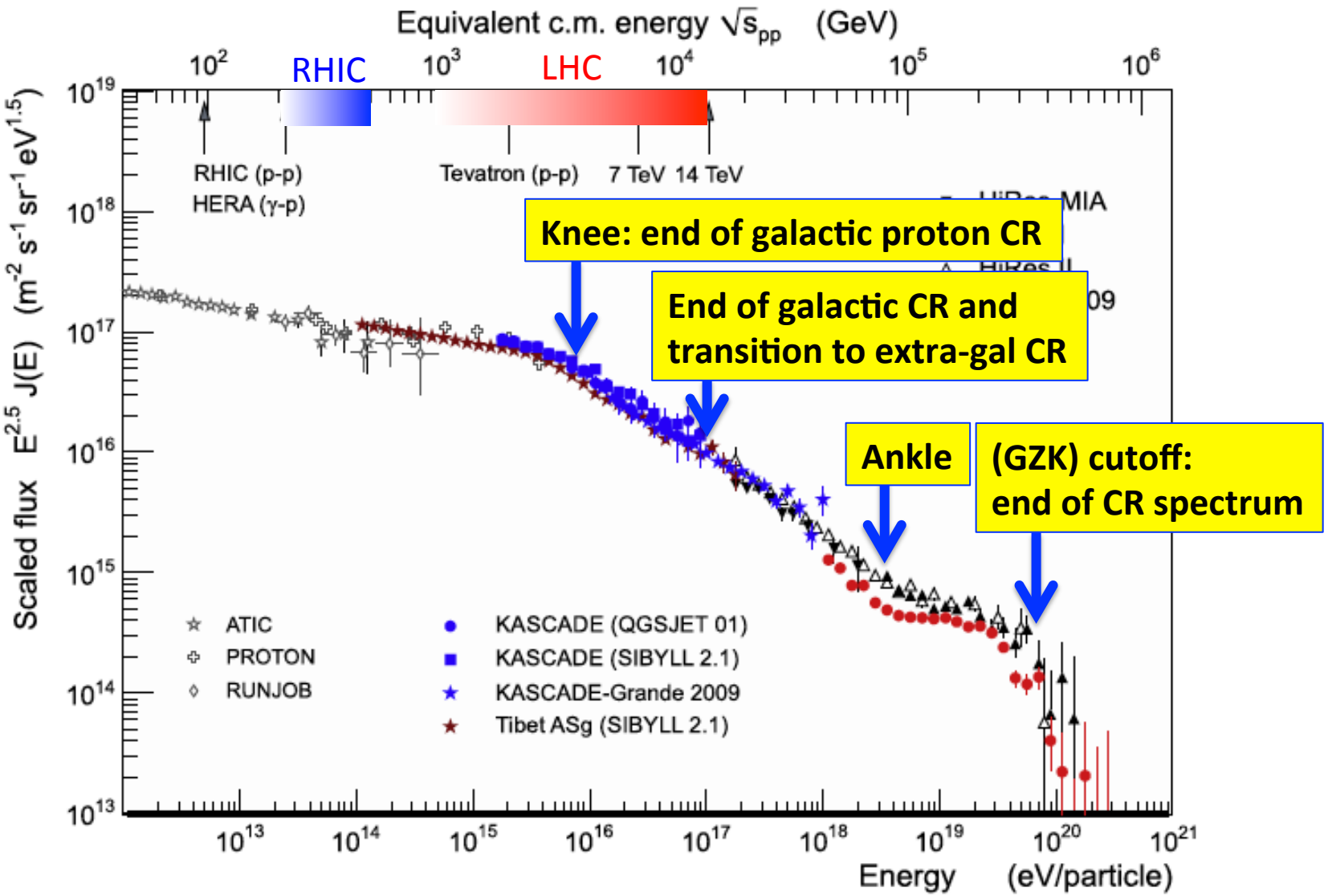
INFN, Univ. di Firenze, Italy

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

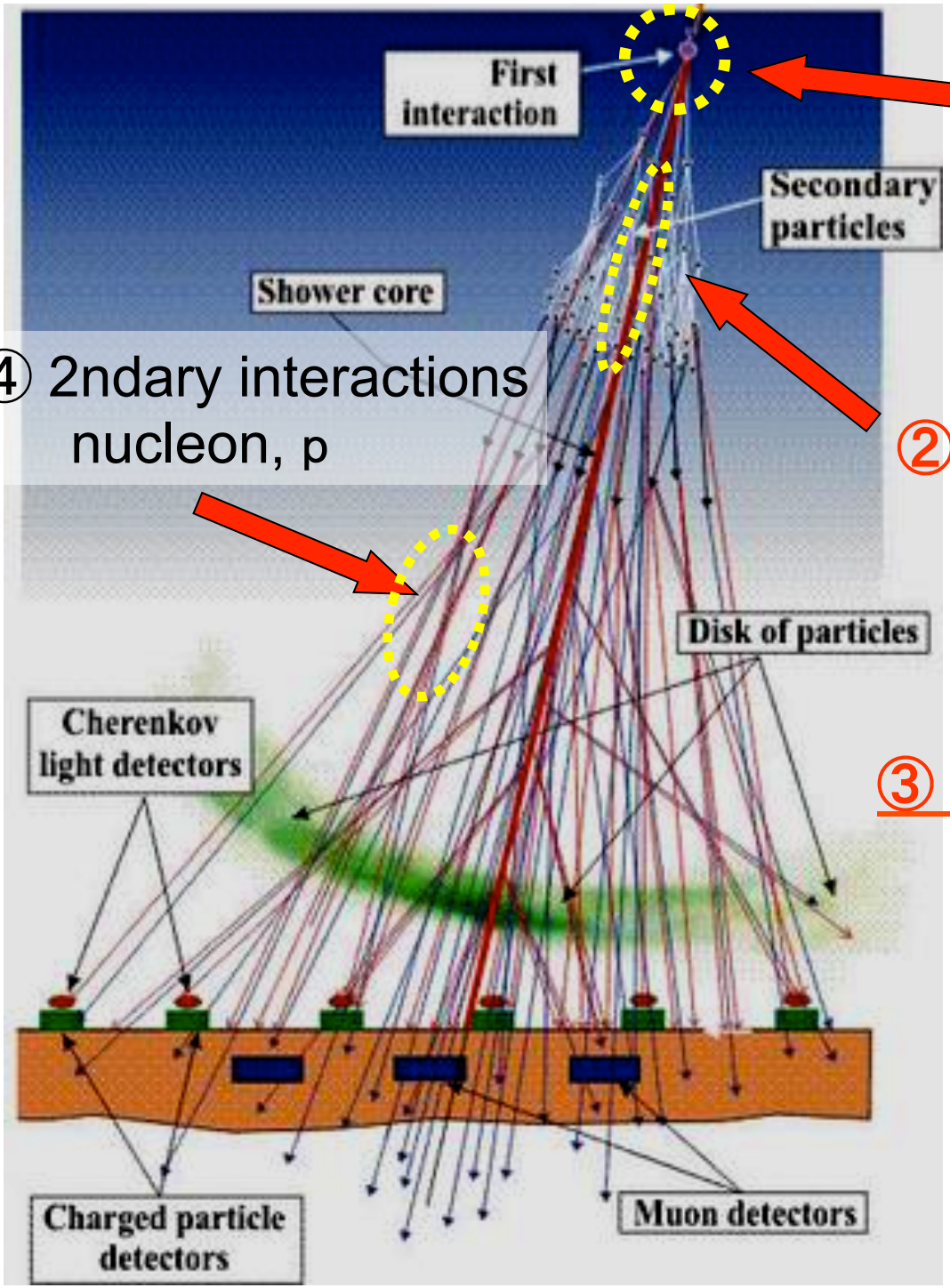
J.Velasco, A.Faus *IFIC, Centro Mixto CSIC-UVEG, Spain*

A-L.Perrot *CERN, Switzerland*

CR physics and Collider energy



D'Enterria et al., APP, 35,98-113, 2011



① Inelastic cross section

If large s
rapid development
If small s
deep penetrating

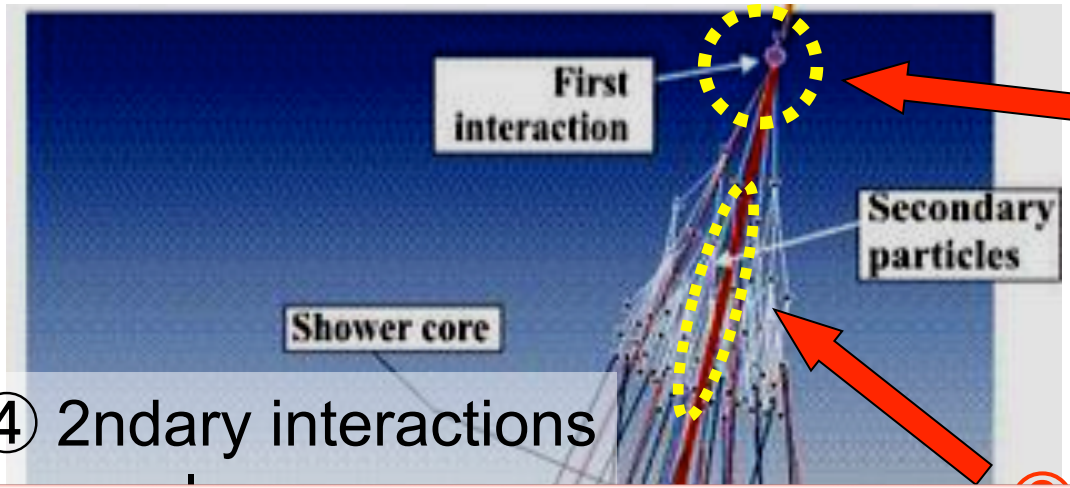
② **Forward energy spectrum**

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

④ 2ndary interactions
nucleon, p



① Inelastic cross section

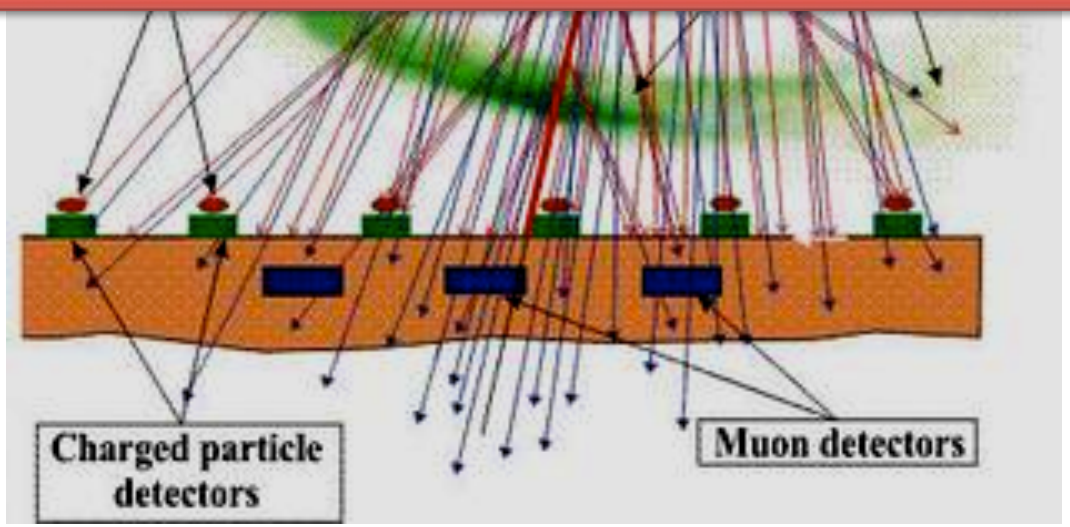
If large s
rapid development
If small s
deep penetrating

④ 2ndary interactions

- Soft interaction (non-perturbative QCD) dominates
- Various phenomenological models are proposed

(keywords: diffraction, Regge theory, multi-Pomeron interaction, Glauber theory,…)

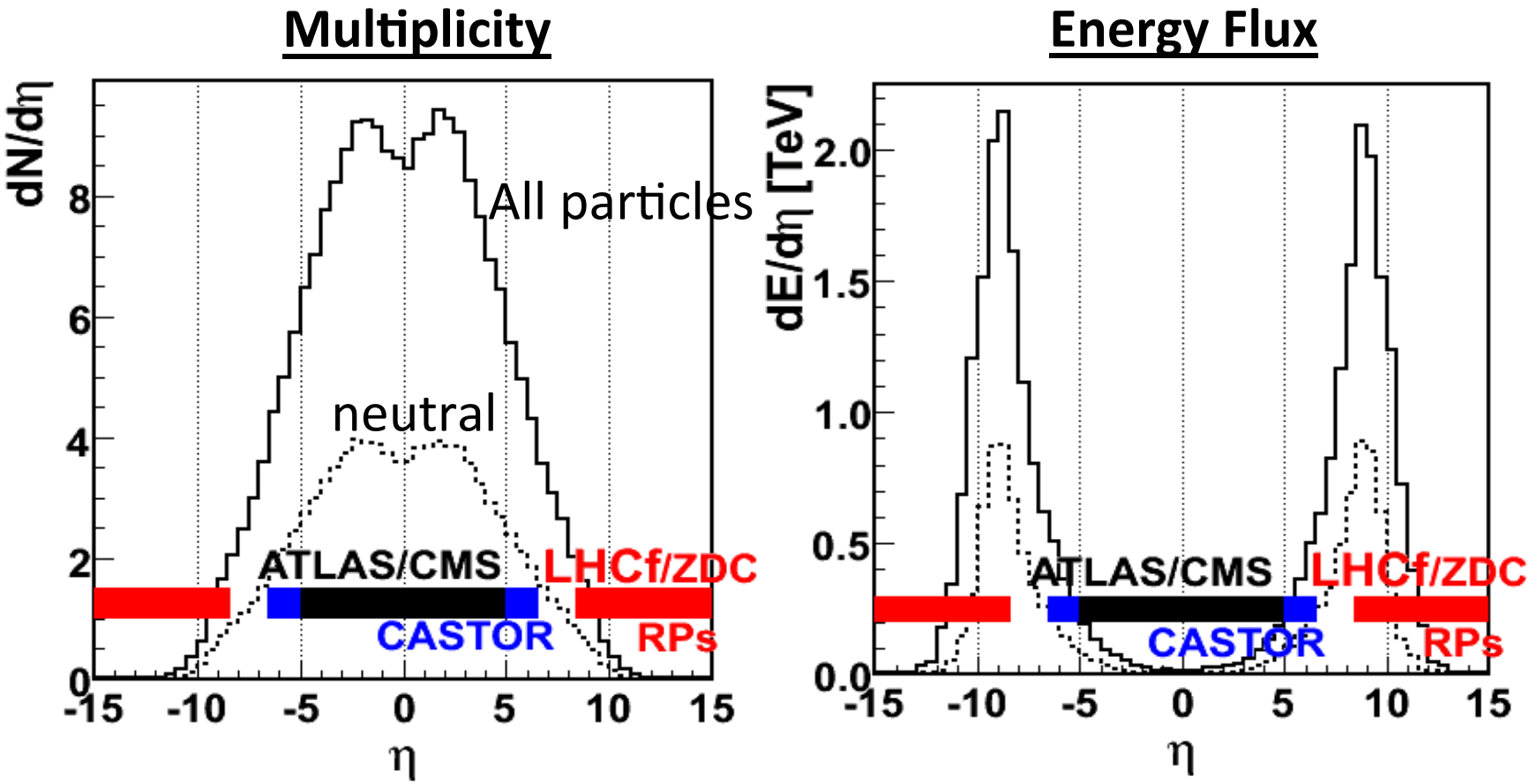
- Experimental inputs are important
- LHC gives the best opportunity



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

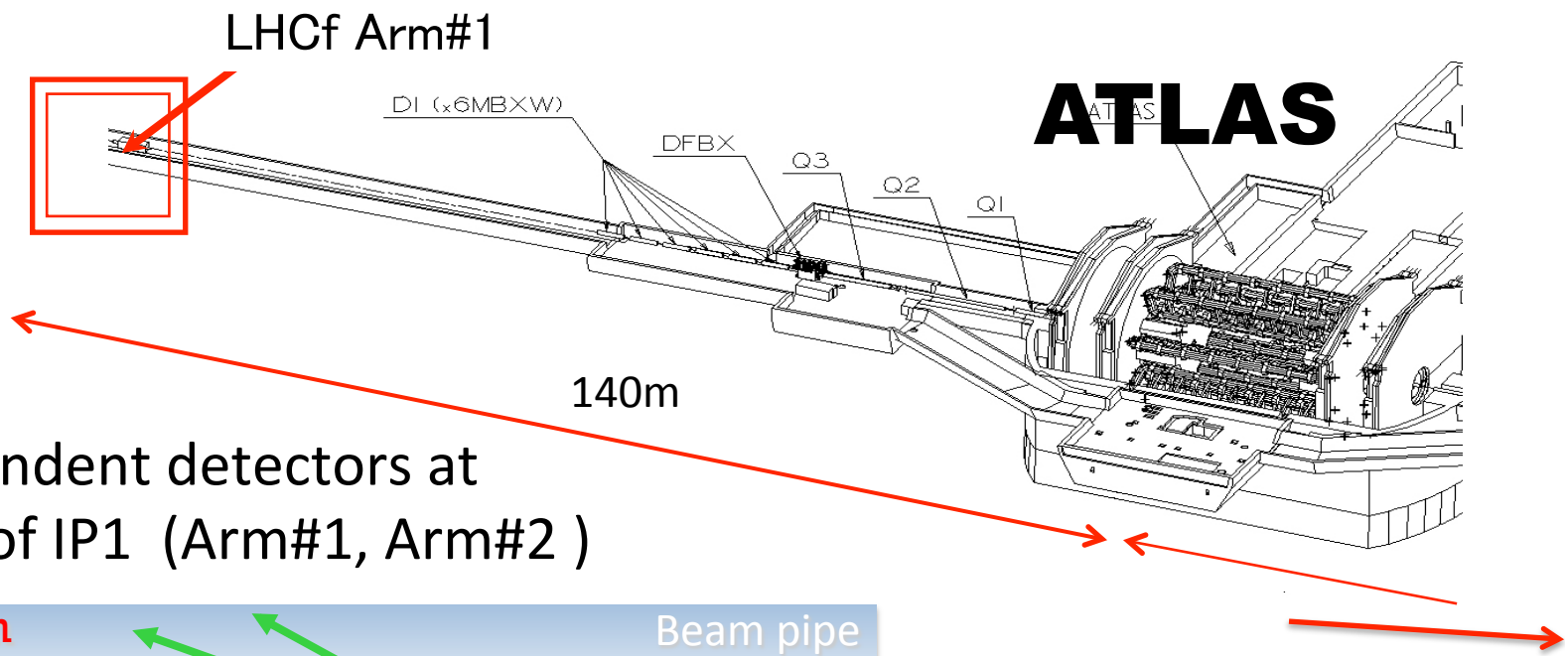
2ry particle flow at colliders

multiplicity and energy flux at LHC 14TeV p-p collisions

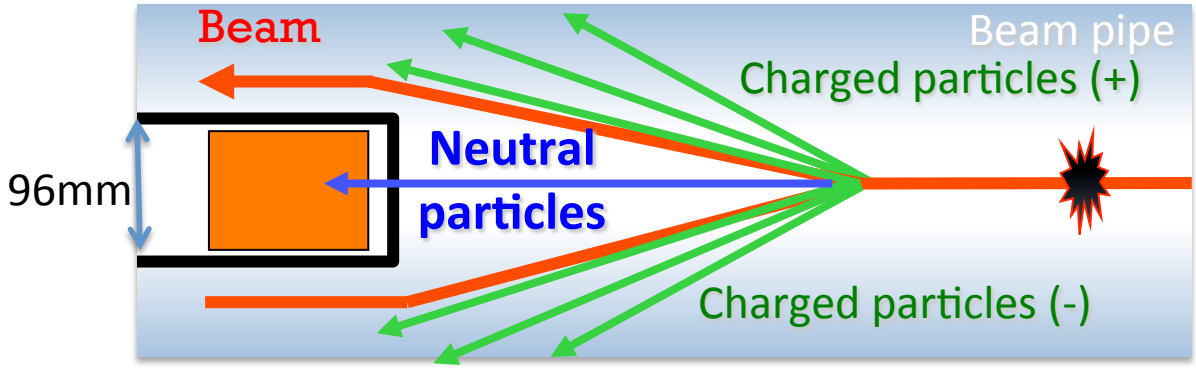


- ✓ LHCf covers the peak of energy flow
- ✓ √s=14 TeV pp collision corresponds to $E_{CR}=10^{17}$eV

The LHC forward experiment



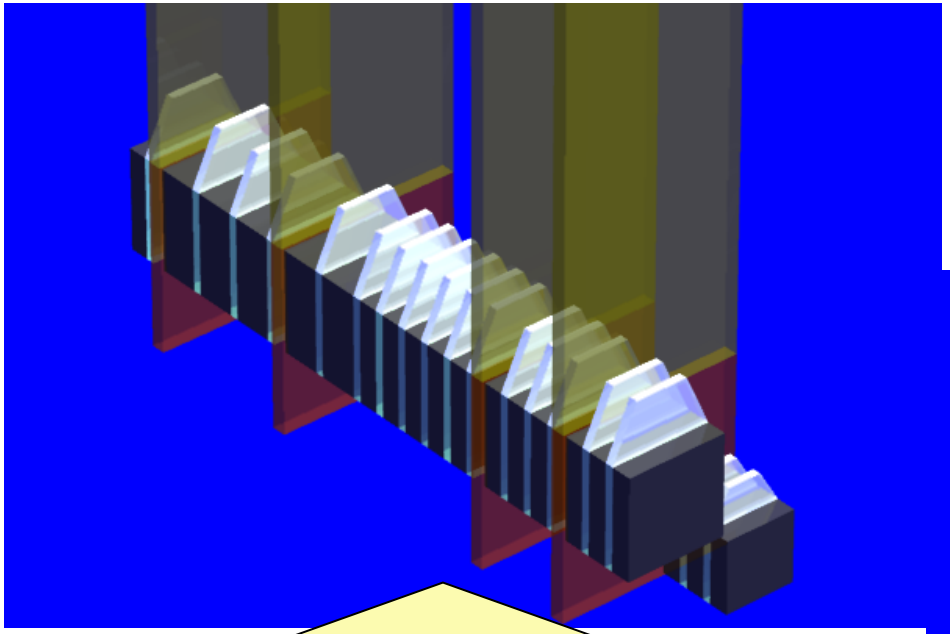
Two independent detectors at either side of IP1 (Arm#1, Arm#2)



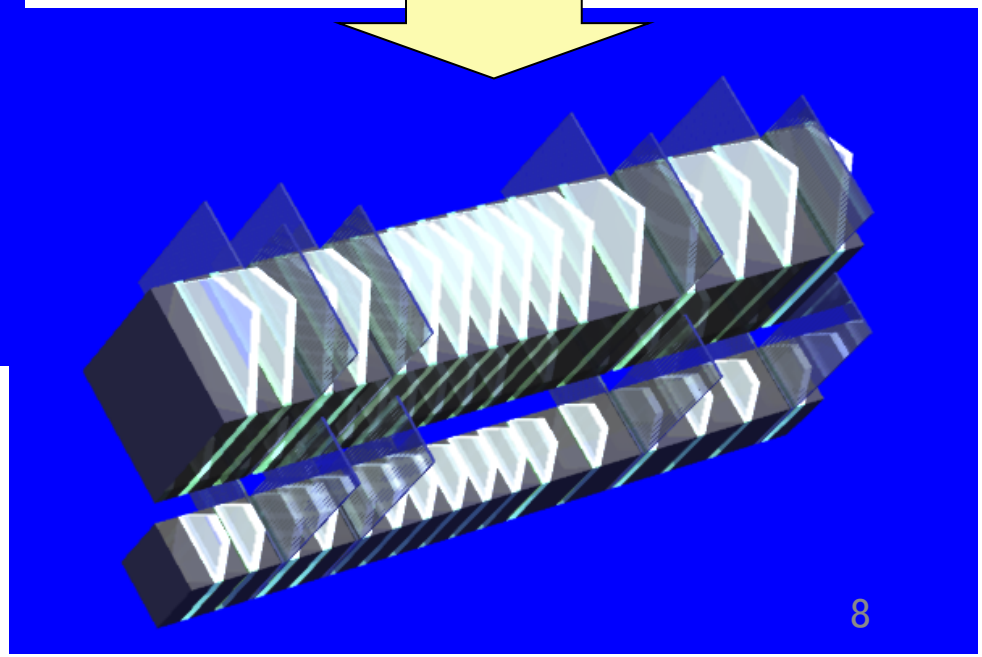
- ✓ All charged particles are swept by dipole magnet
- ✓ Neutral particles (photons and neutrons) arrive at LHCf
- ✓ η>8.4 (to infinity) is covered

LHCf Detectors

- ✓ Imaging sampling shower calorimeters
- ✓ Two calorimeter towers in each of Arm1 and Arm2
- ✓ Each tower has 44 r.l. of Tungsten,16 sampling scintillator and 4 position sensitive layers

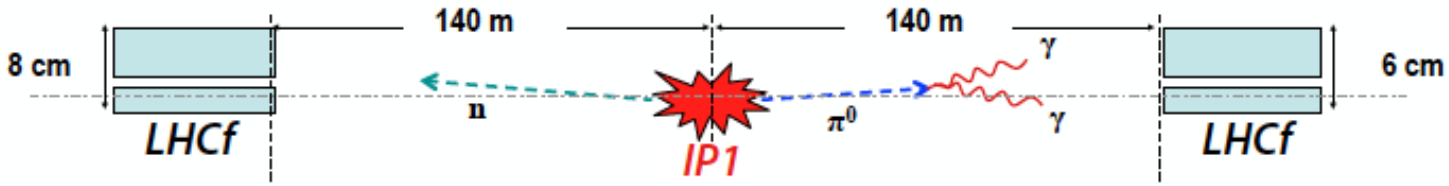


Arm#1 Detector
20mmx20mm+40mmx40mm
4 XY SciFi+MAPMT

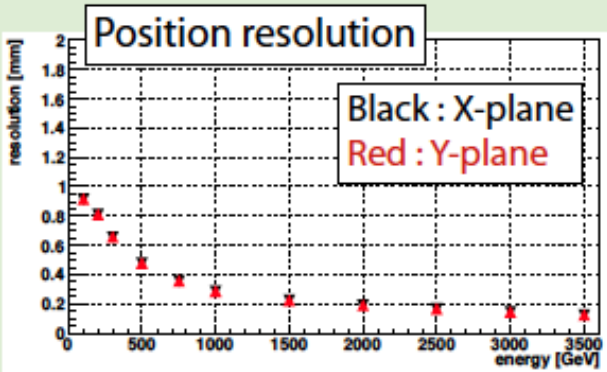


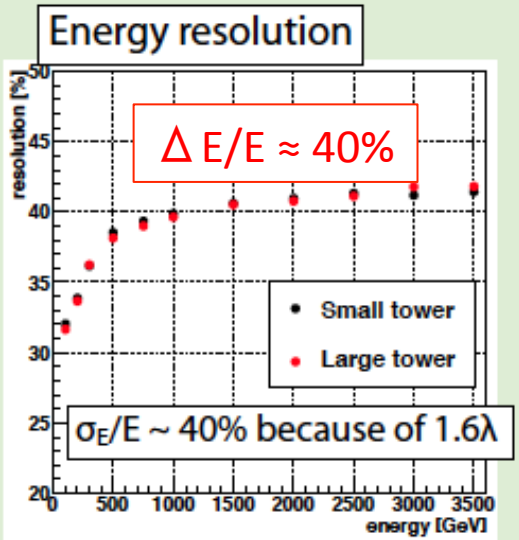
Arm#2 Detector
25mmx25mm+32mmx32mm
4 XY Silicon strip detectors

Detector performance

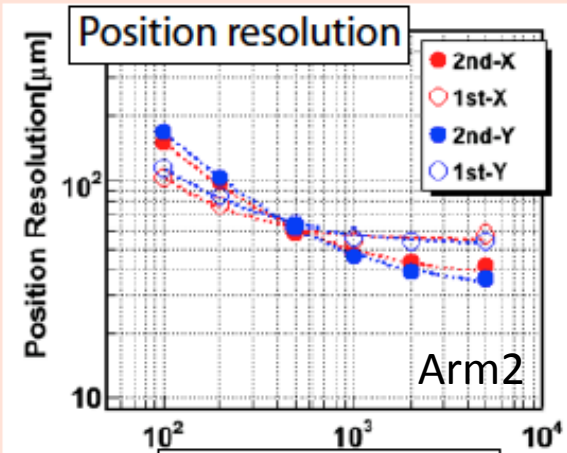


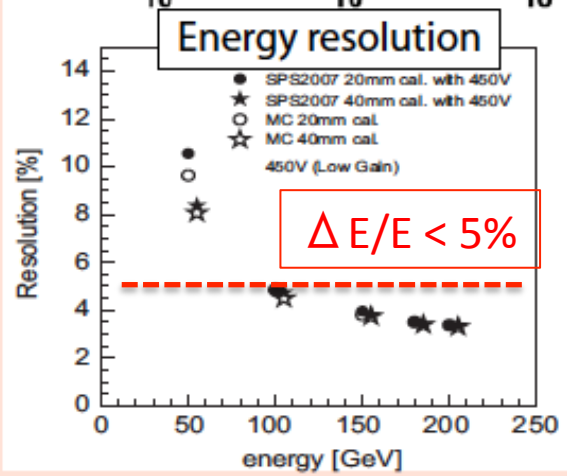
Hadronic shower (MC)





EM shower (MC)





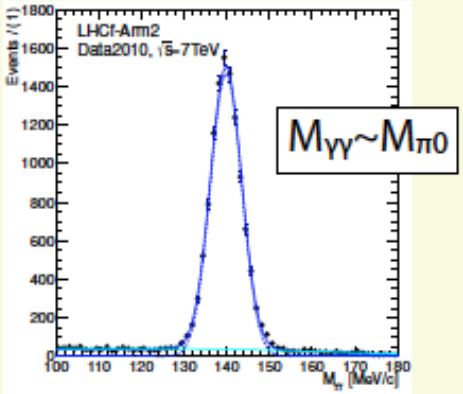
PID technique

400GeV photon

1TeV neutron

Identification of incoming particle by shower shape

π^0 reconstruction



LHCf Status

- ✓ Done
  - 0.9, 2.76, 7 TeV pp collision, 5 TeV pPb collision data taking finished
  - Photon spectra at 0.9 and 7TeV published
  - π^0 spectra at 7 TeV published
  - Performance at 0.9 and 7TeV published
  - π^0 and UPC spectra at 5TeV pPb accepted by PRC (public on arXiv and CDS)
- ✓ On going
  - Neutron spectra at 7TeV (to be published soon)
  - Rad-hard detector upgrade for 13 TeV pp
- ✓ Plan
  - 13TeV pp collision in 2015
  - 0.5TeV pp at RHIC (proposal submitted)
  - Discussions for light ion collision at RHIC and LHC

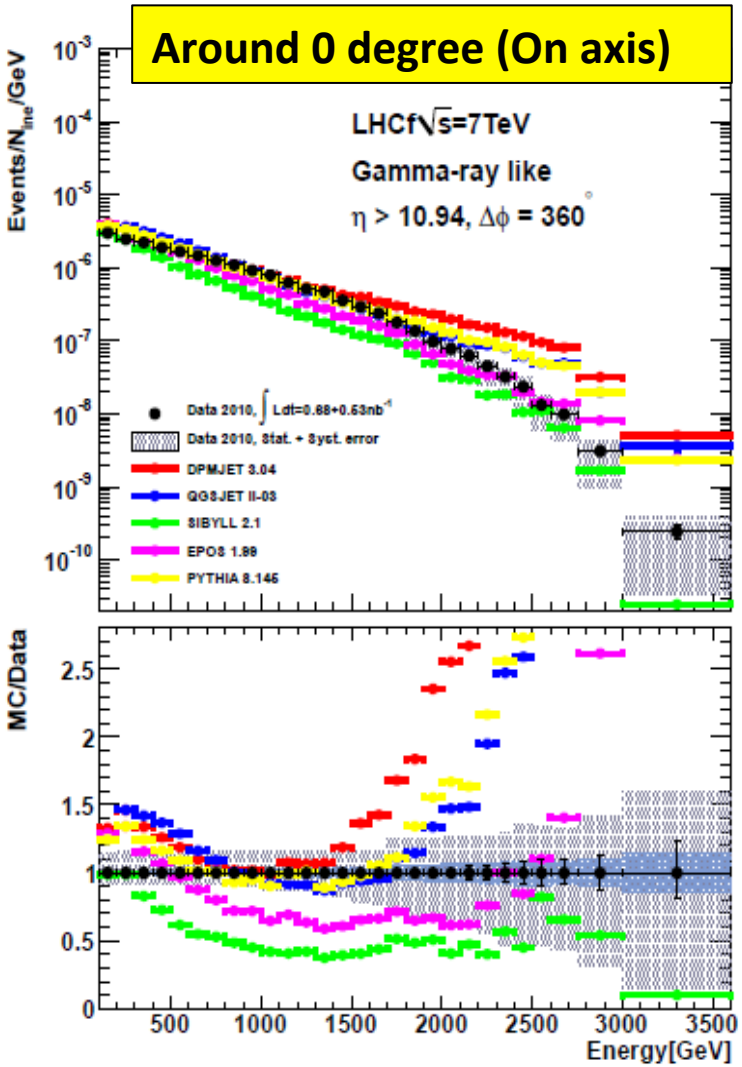
Publication Summary

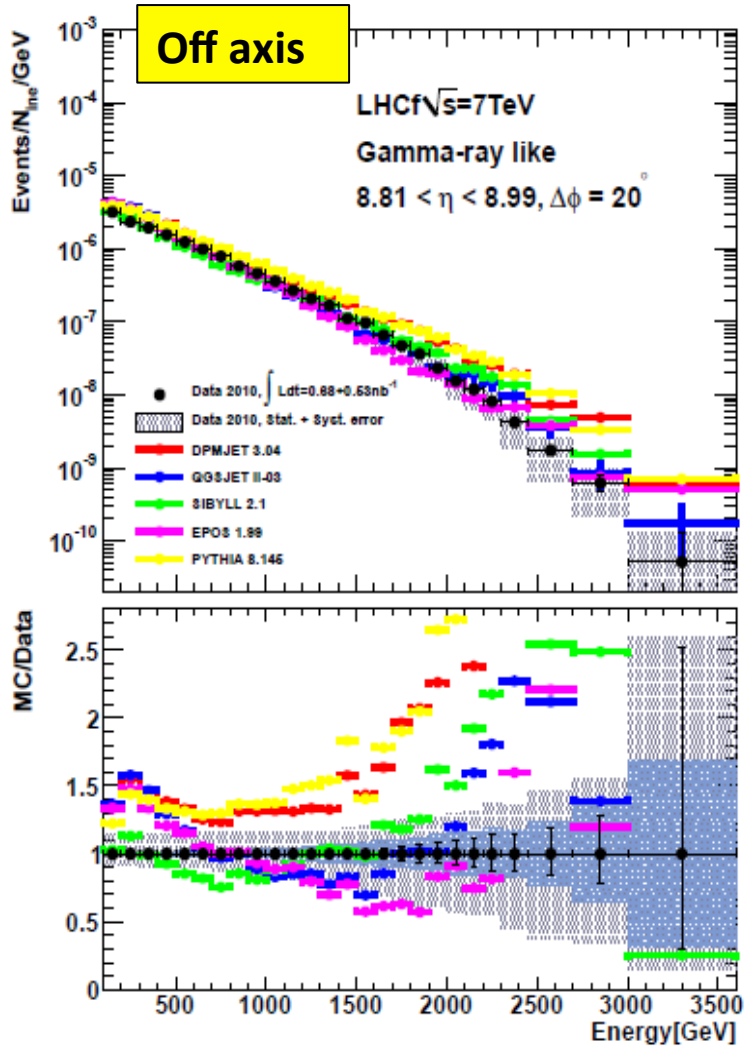
	Photon (EM shower)	Neutron (hadron shower)	π (EM shower)
Test beam at SPS	NIM. A 671, 129–136 (2012)	**JINST, 9, P03016 (2014)**	
p-p at 900GeV	Phys. Lett. B 715, 298-303 (2012)		
p-p at 7TeV	Phys. Lett. B 703, 128–134 (2011)	**to be submitted soon**	Phys. Rev. D 86, 092001 (2012)
p-p at 2.76TeV			**PRC in press arXiv:1403.7845 [nucl-ex](2014)**
p-Pb at 5.02TeV			

LHCf 7TeV pp photon

Photon spectra @ 7TeV (Data vs. Models)

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

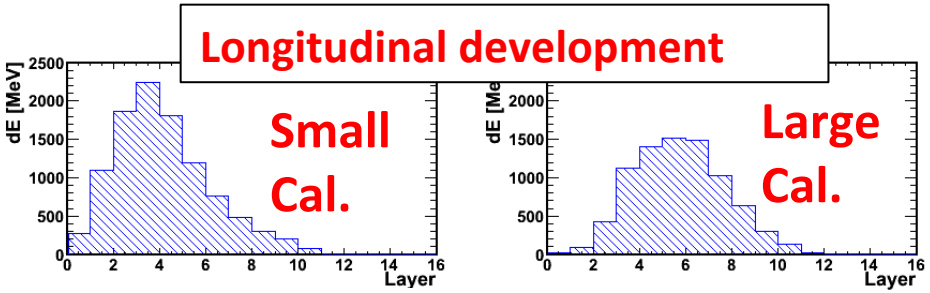


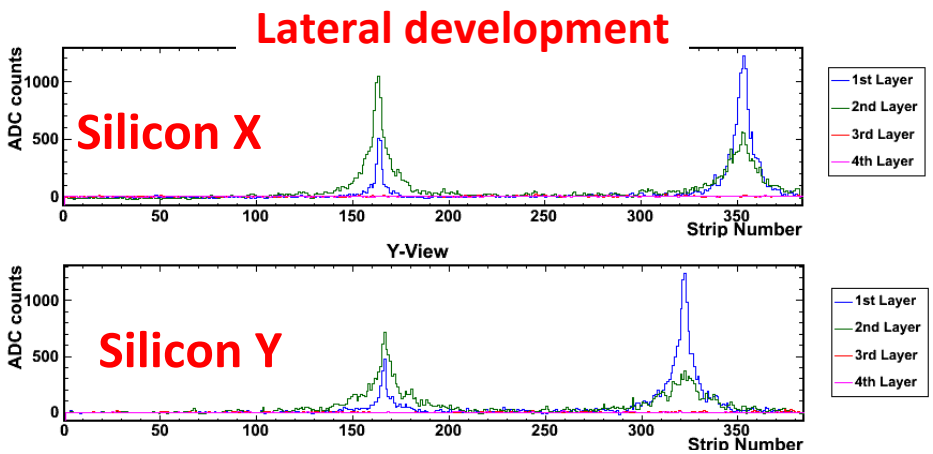


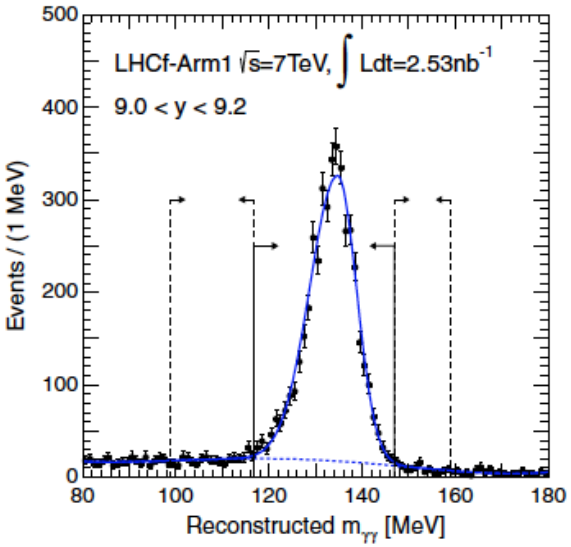
DPMJET 3.04 QGSJET II-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

LHCf 7TeV pp π^0

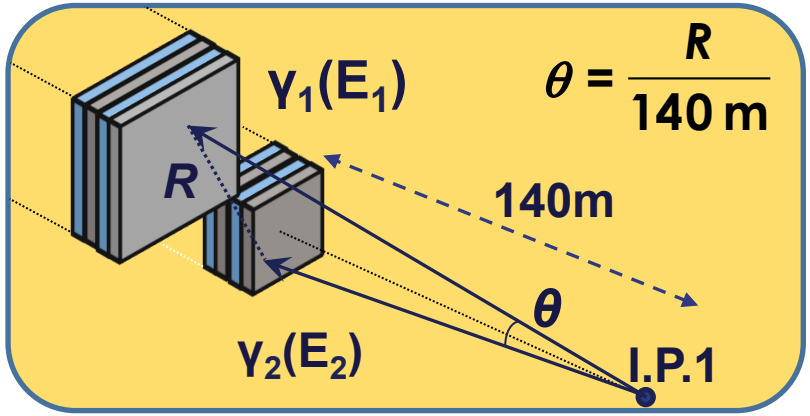
π^0 analysis

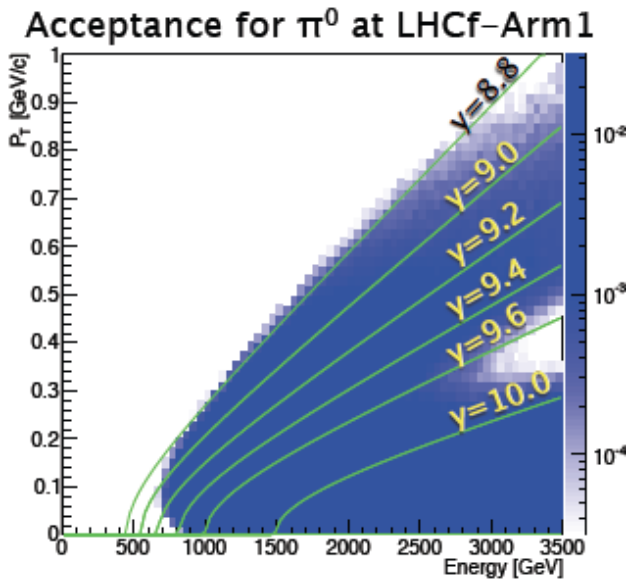






- π^0 candidate
- 599GeV & 419GeV photons in 25mm and 32mm tower, respectively
- $M = \theta\sqrt{(E_1 x E_2)}$

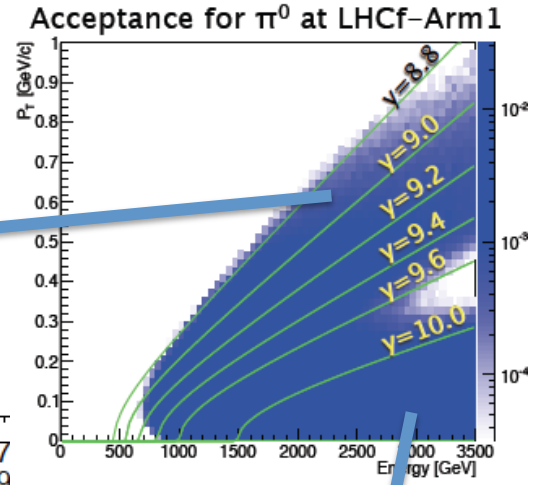


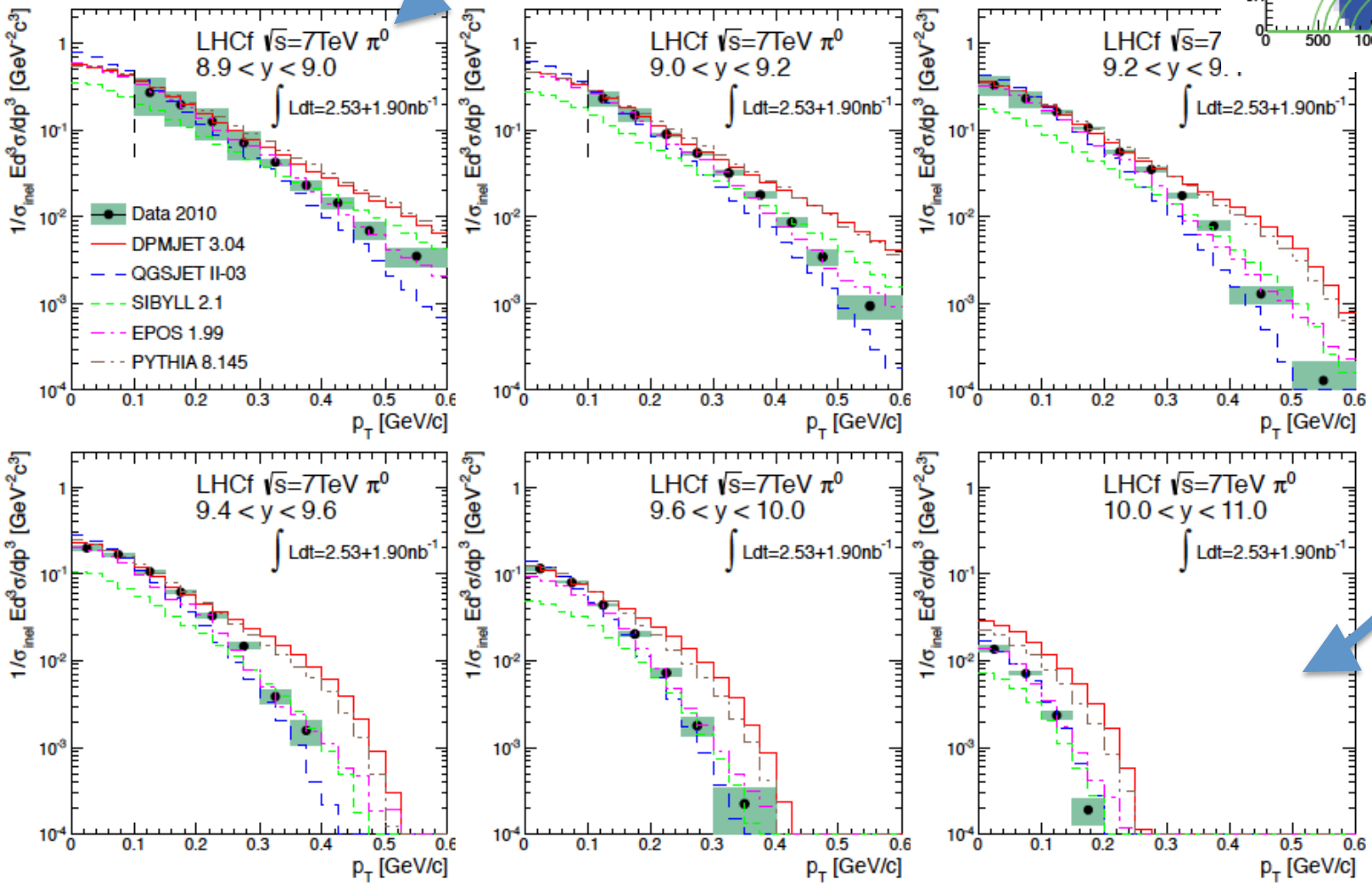


LHCf 7TeV pp π^0

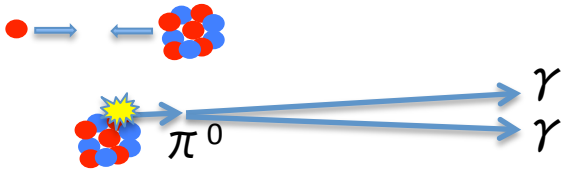
π^0 p_T distribution in different rapidity (y) ranges

Adriani et al., PRD, 86, 092001 (2012)

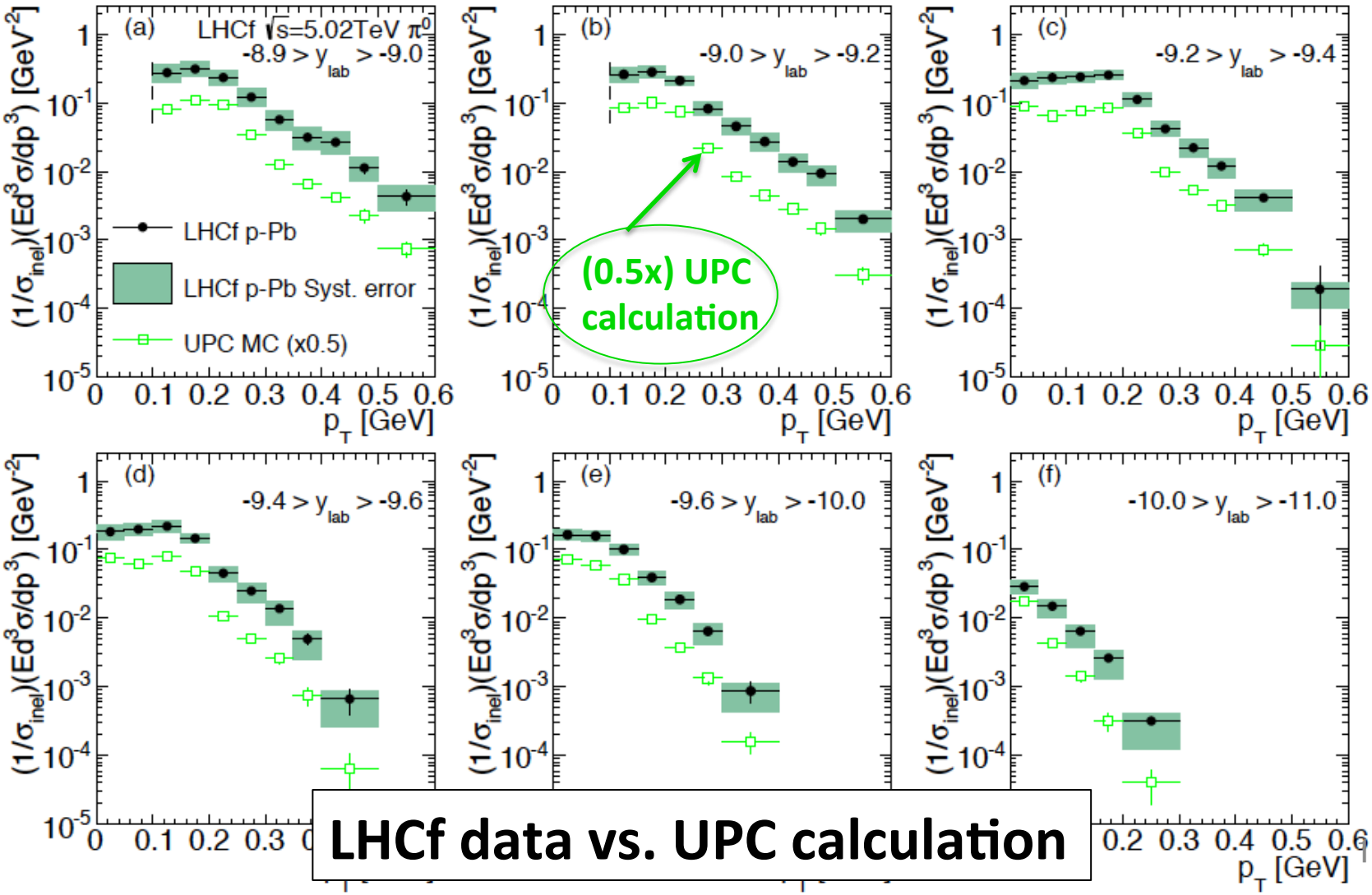




LHCf 5TeV ppb π^0



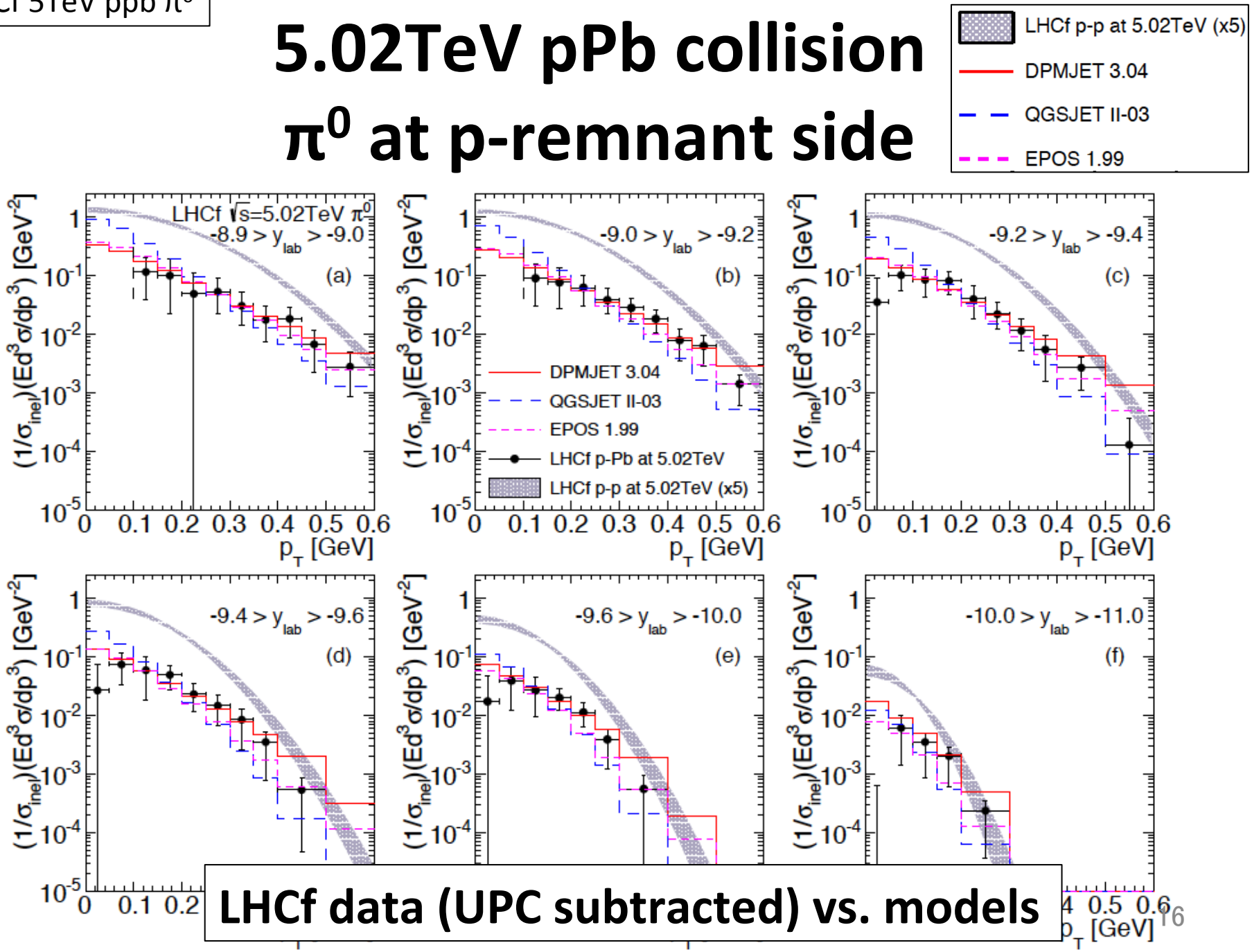
5.02TeV pPb collision π^0 at p-remnant side



LHCf data vs. UPC calculation

LHCf 5TeV ppb π^0

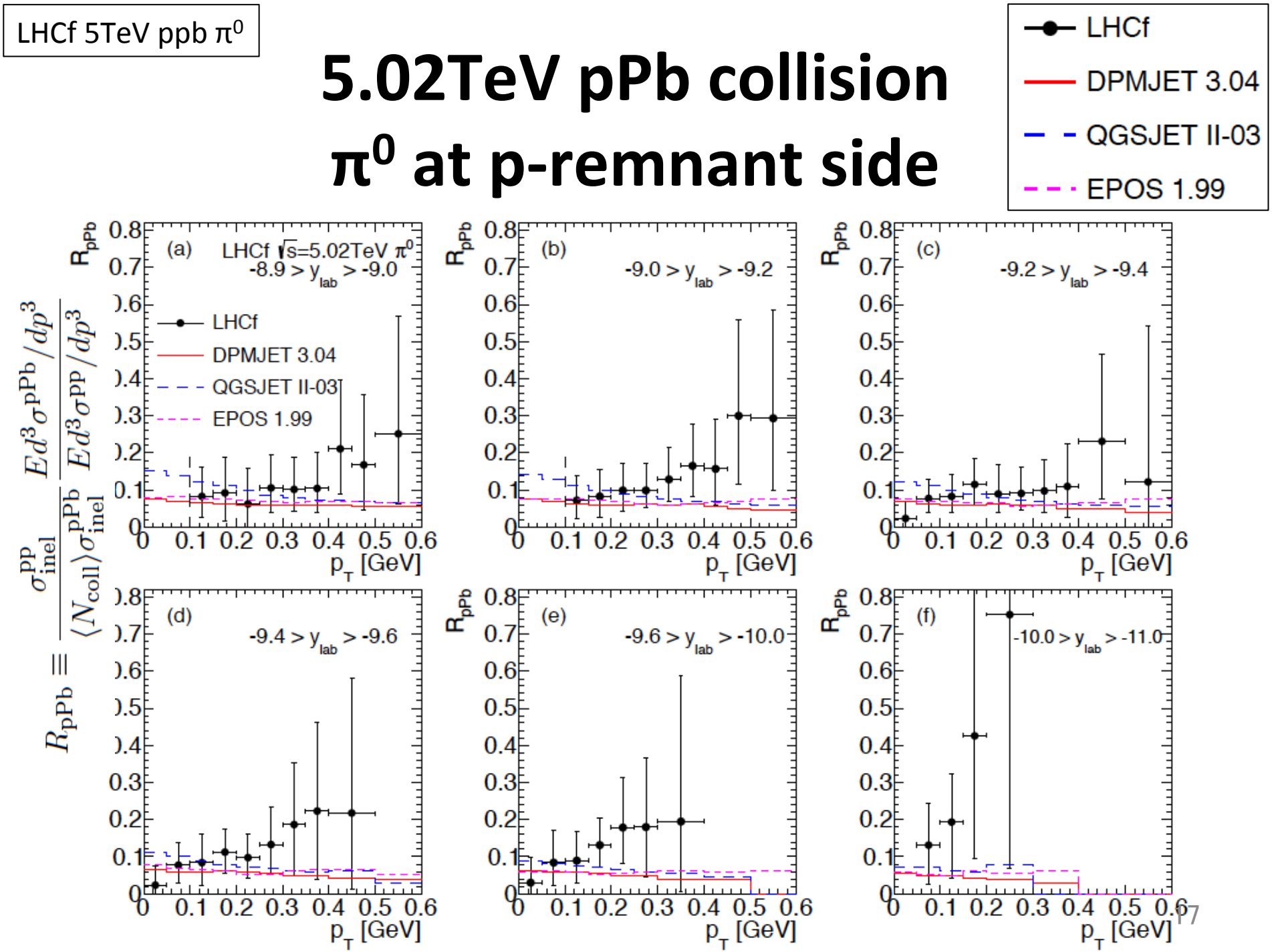
5.02TeV pPb collision π^0 at p-remnant side



LHCf data (UPC subtracted) vs. models

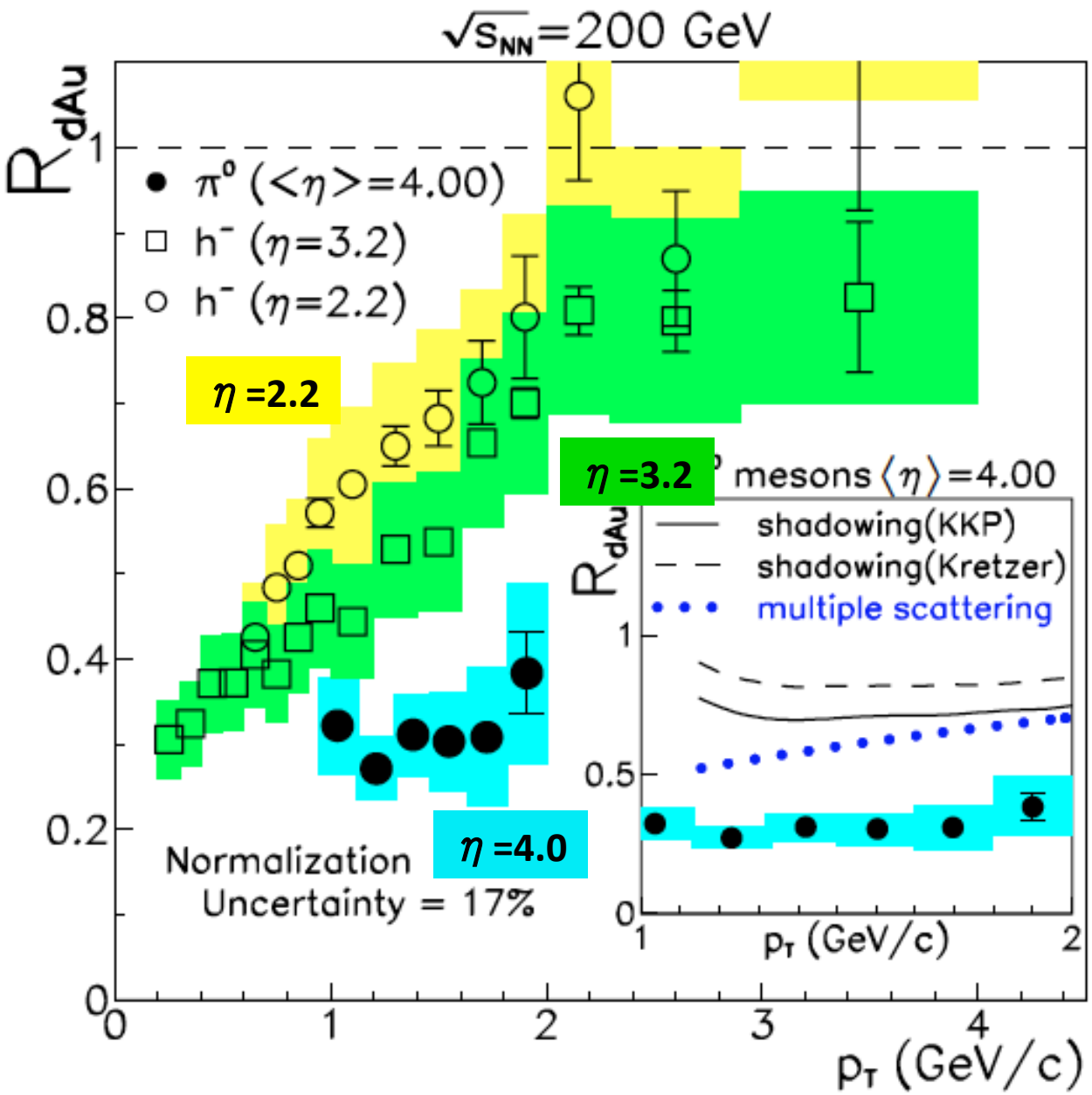
LHCf 5TeV ppb π^0

5.02TeV pPb collision π^0 at p-remnant side



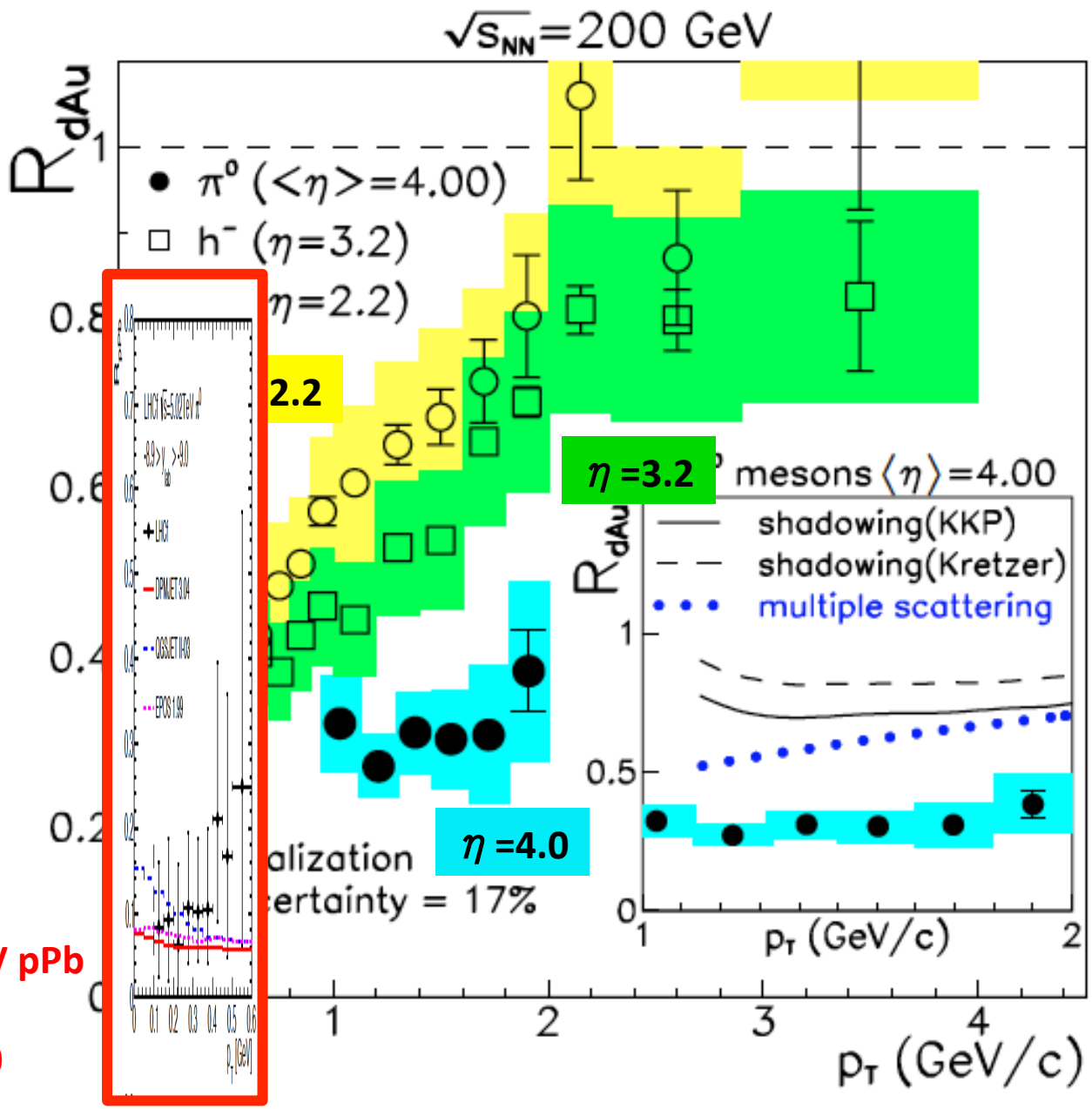
LHCf 5TeV ppb π^0

RHIC 200GeV d-Au, STAR Collaboration
Adams et al., PRL 97 (2006) 152302.



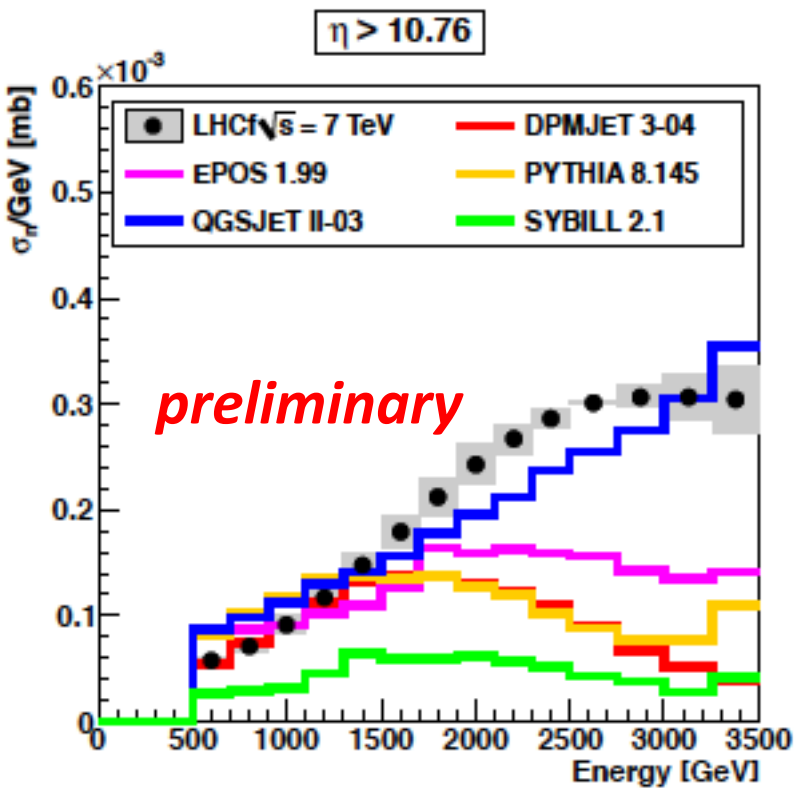
LHCf 5TeV ppb π^0

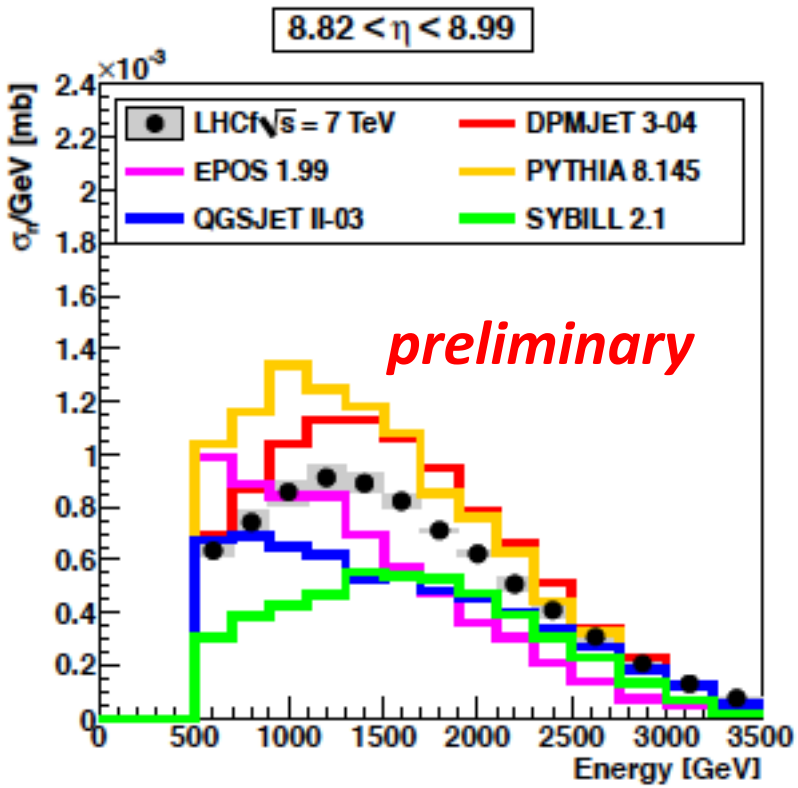
RHIC 200GeV d-Au, STAR Collaboration
Adams et al., PRL 97 (2006) 152302.



LHCf 5TeV pPb
π^0 R_{pPb}
8.9<η<9.0

7TeV pp neutron

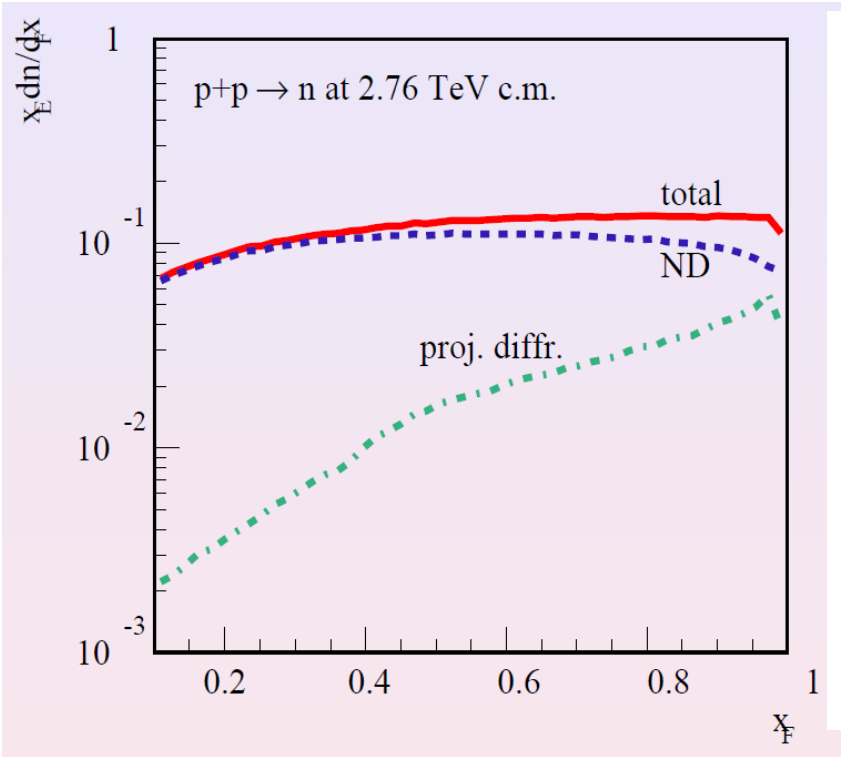


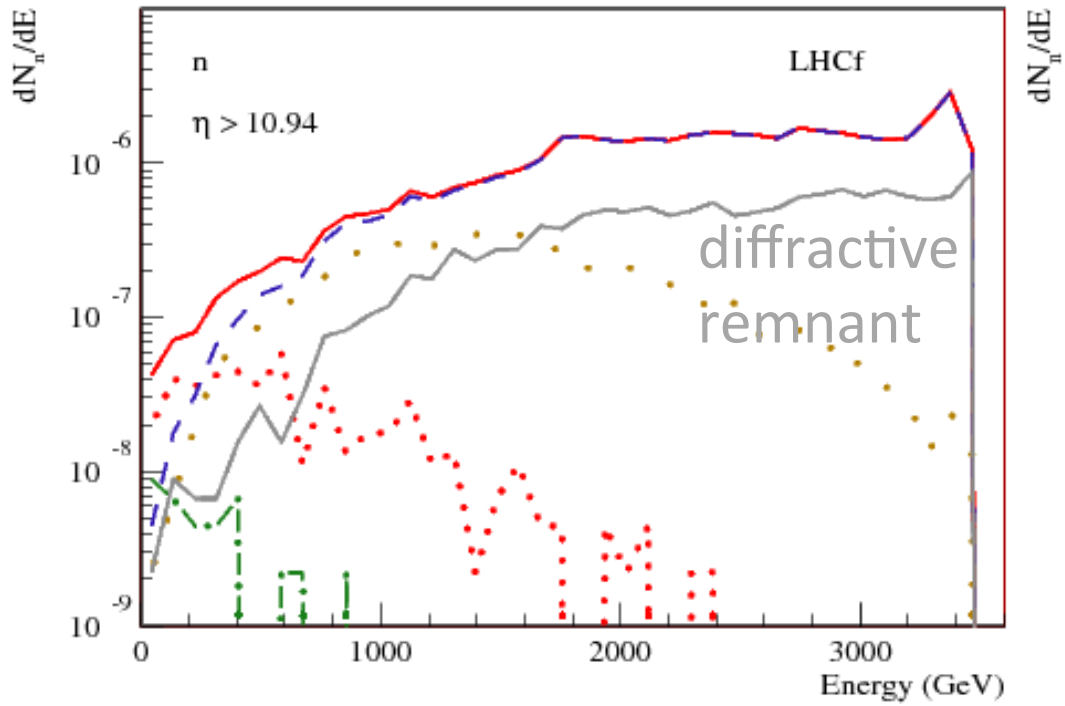


- ✓ Sys-error to be updated
- ✓ Energy resolution 40%, position resolution 0.1-1 mm are unfolded
- ✓ Detection efficiency, PID efficiency, purity are corrected

LHCf 7TeV pp neutron

Origin of 0 degree neutrons





Ostapchenko, QGSJET II

Pierog, EPOS

Next Steps…

- ✓ More analyses
  - analysis of full acceptance
  - correlation with ATLAS (diffractive events)
  - √s dependence
  - reduce systematic errors
  - impact on CR air showers
- ✓ 13TeV p-p run in 2015
  - dedicated run in April-May 2015
  - common trigger with ATLAS (LHCf triggers ATLAS) will help classification of events into MB, diffractive, etc…
- ✓ RHICf for 510GeV p-p run
  - identical x_F-p_T coverage to LHC 7TeV run
  - proposal presented last week at BNL
- ✓ p-O and O-O runs at LHC?
  - direct test of CR-atmosphere interaction
  - technically feasible by LHC

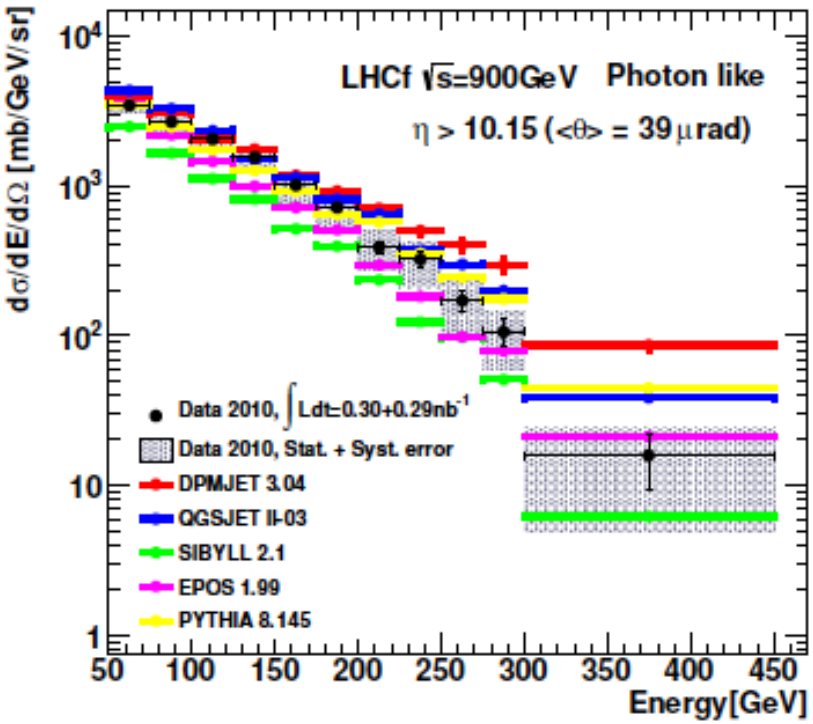
Summary

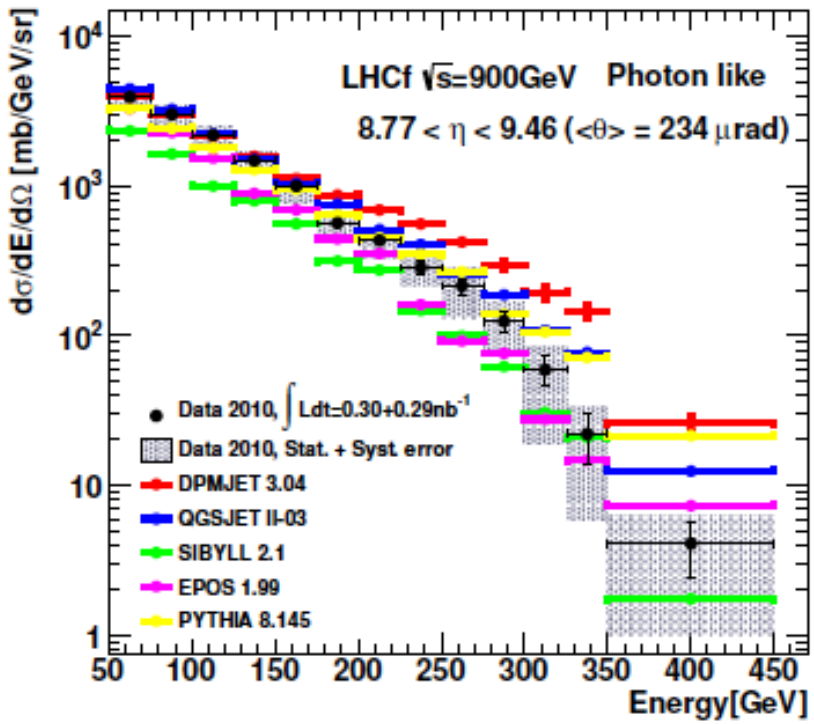
- ✓ LHCf was motivated to understand the fundamental hadronic processes in the CR air shower development, where soft processes relevant to low-X WS dominate
- ✓ LHCf has published spectra of forward neutral particles using LHC 0.9, 2.76, 7TeV p-p and 5.02TeV p-Pb collision data
- ✓ No surprise so far, but LHCf results strongly constrain the models
  - Not only LHCf but many other measurements at LHC give generally same conclusion
  - Note LHC 7TeV p-p measurements are first tests above the knee energy, $E_{CR}=4\times10^{15}$eV
- ✓ LHC 13TeV p-p run is scheduled in early 2015
- ✓ Together with a possible RHIC 510GeV run, a wide coverage in √s can help extrapolation of models beyond the LHC energy, $E_{CR} > 10^{17}$eV

Backup

Photon spectra @ 900GeV

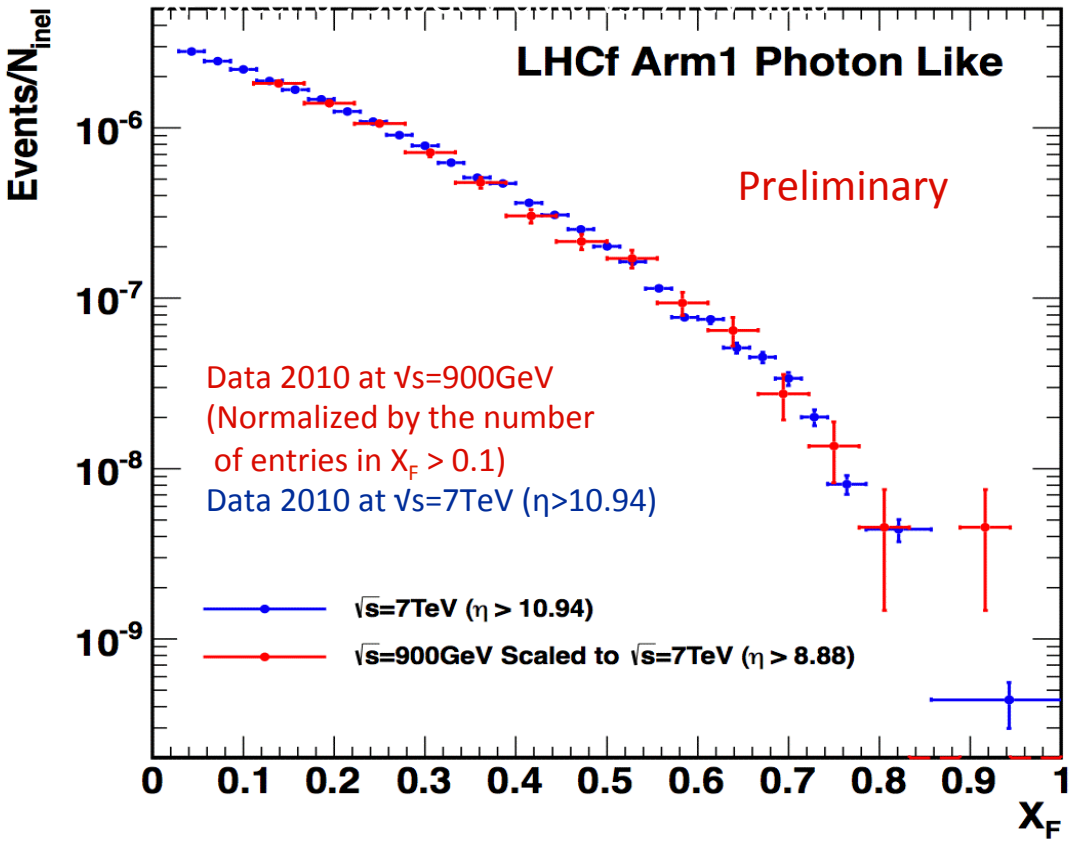
Adriani et al., PLB, 715 (2012) 298-303





LHCf 900GeV and 7TeV pp photon

900GeV vs. 7TeV

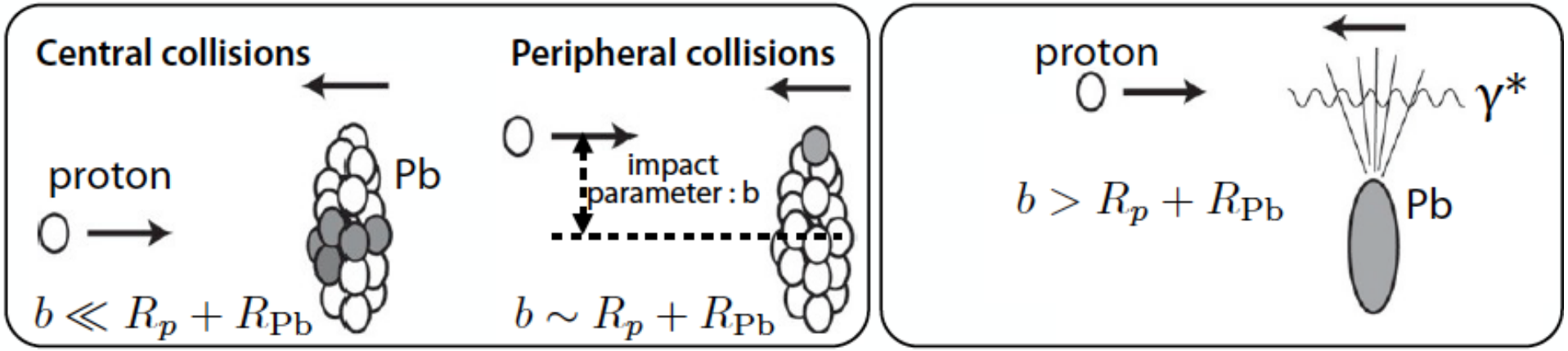


- ✓ Comparison in the same p_T range (pT<0.13x_F GeV/c)
- ✓ Normalized by # of events X_F > 0.1
- ✓ Statistical error only
- ✓ Comparison with 2.76TeV, 13TeV (and RHIC 500GeV) are planned

π^0 event analysis in p-Pb collisions

(Soft) QCD :
central and peripheral collisions

Ultra peripheral collisions :
virtual photon from rel. Pb collides a proton.



Momentum distribution of the UPC induced secondary particles is estimated as

1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation.
2. photon-proton collisions are simulated by the SOHIA model (E_γ > pion threshold).

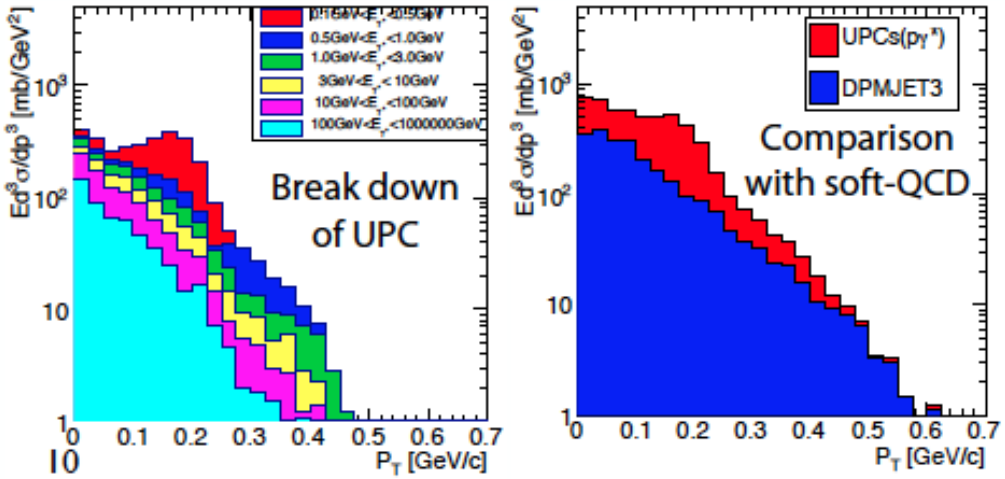
] proton rest frame

3. produced mesons and baryons by γ-p collisions are boosted along the proton beam.

Dominant channel to forward π^0 is

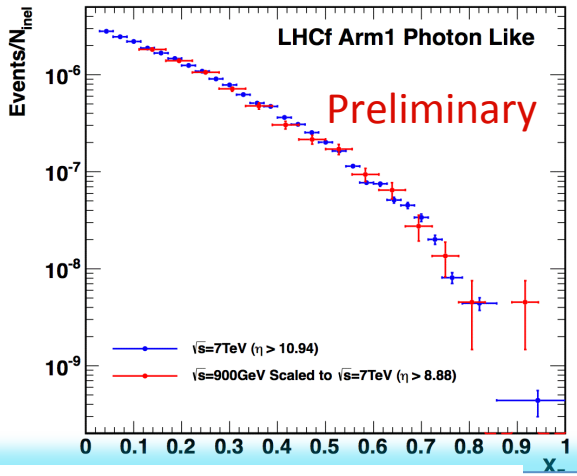
$$\gamma + p \rightarrow \Delta(1232) \rightarrow p + \pi^0$$

About half of the observed π^0 may originate in UPC, another half is from soft-QCD.



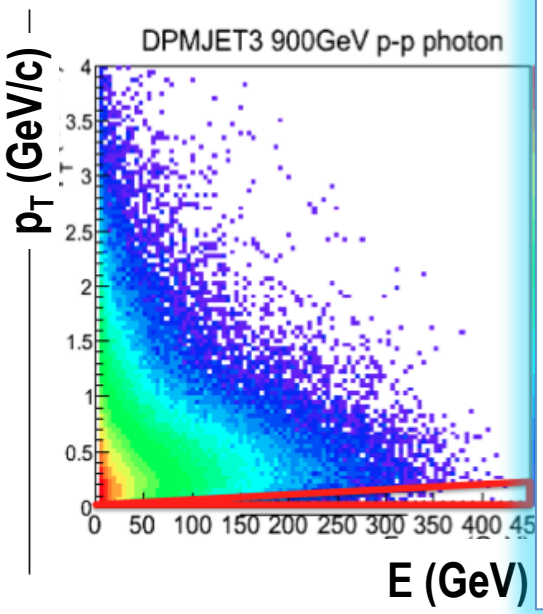
10

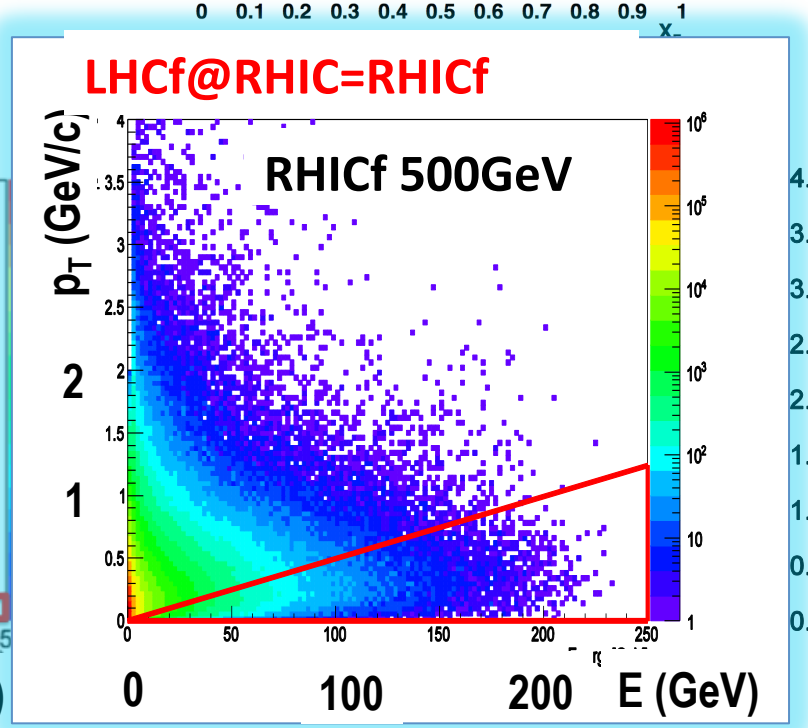
Confirmation of x_F scaling



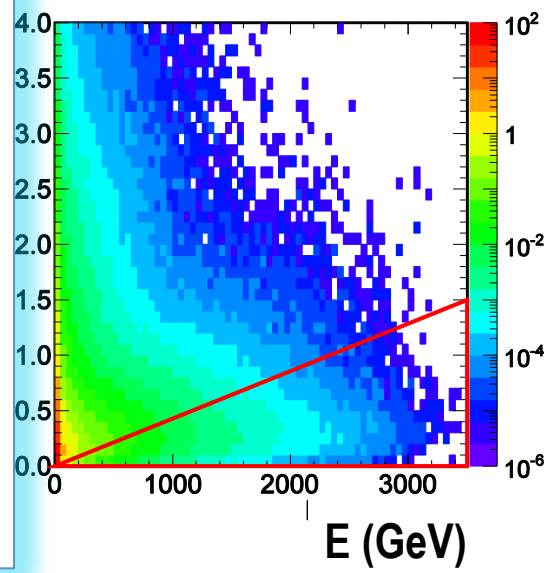
Events selected from very narrow phase space to compare with 900GeV result

Phase space of LHC 900GeV data



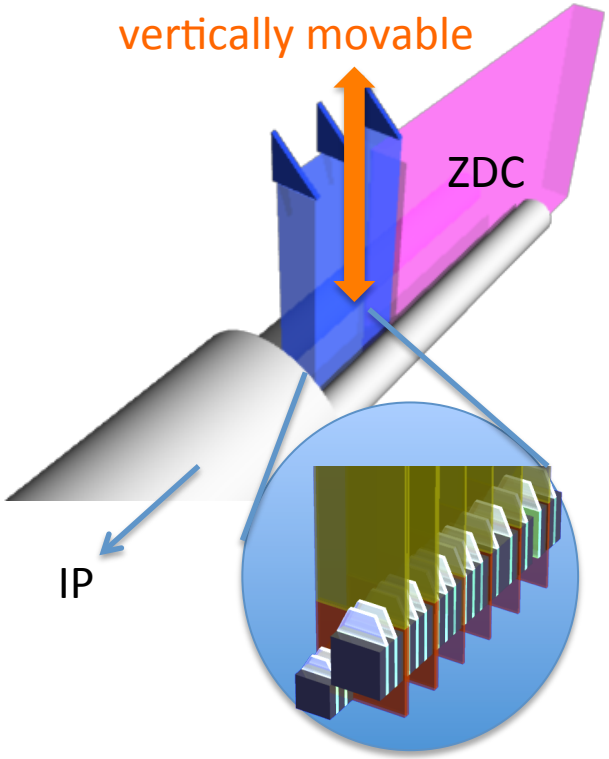


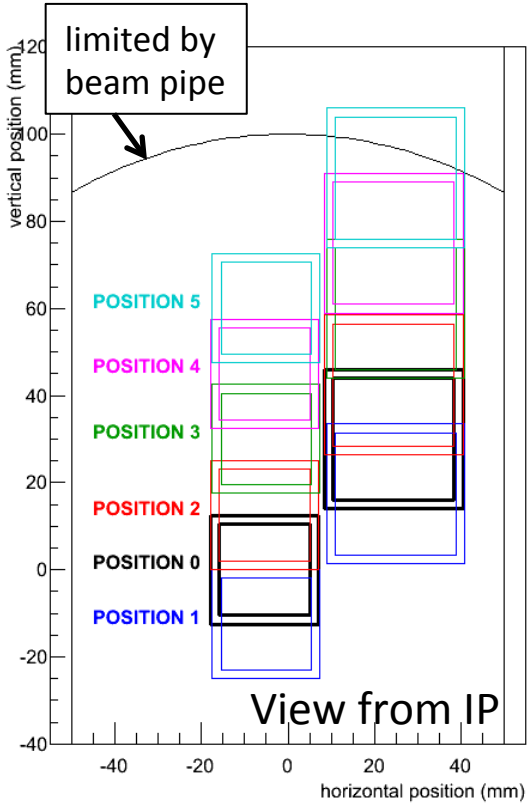
Phase space of LHC 7TeV data

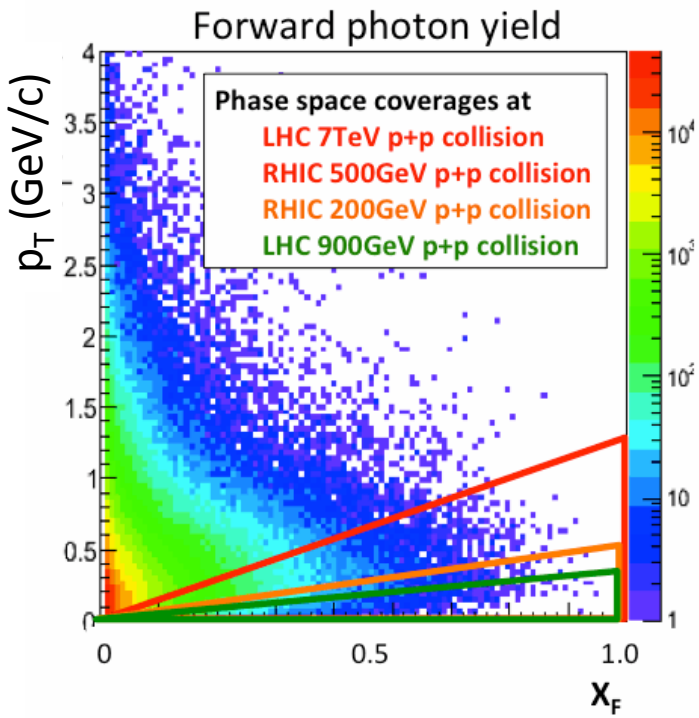


RHICf coverage

Installing the LHCf Arm2 detector at RHIC (PHENIX IP)

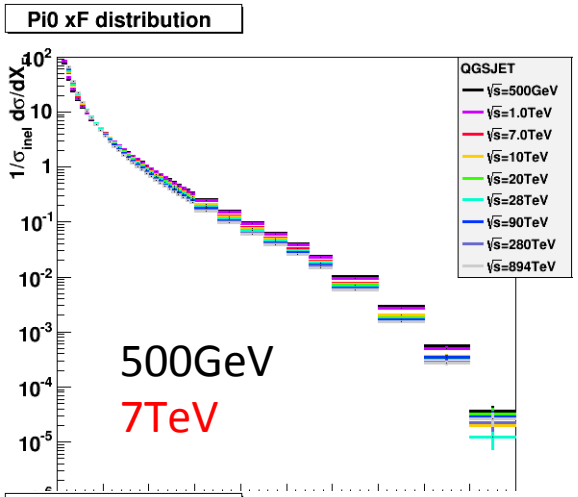


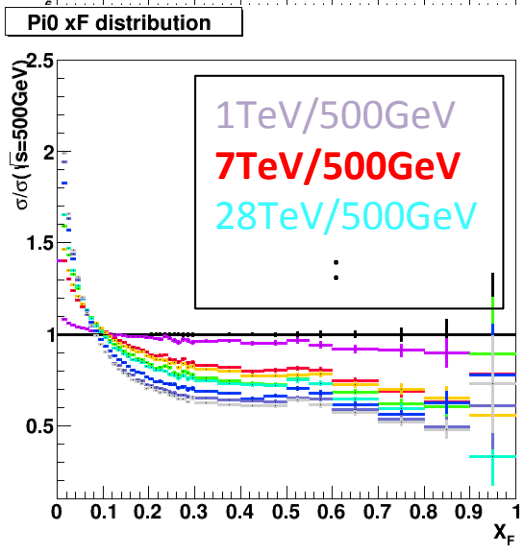




- Detector is moved up-down; wide p_T coverage and to avoid ZDC interference
- x_F-p_T coverage identical to LHC 7TeV collision
- Wider coverage and higher resolution in p_T than PHENIX ZDC+SMD measurements (joint analysis between ZDC and RHICf)

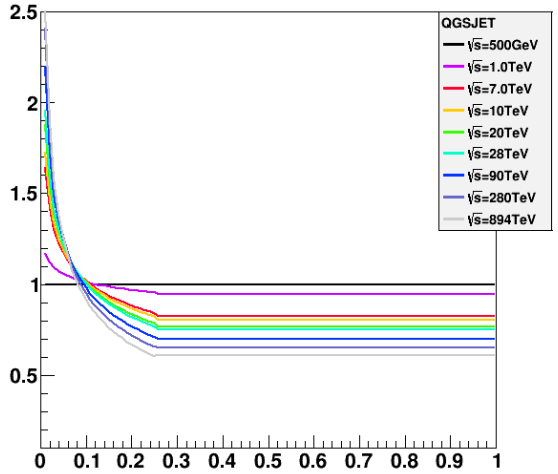
Scaling violation and Air shower
(on going study)

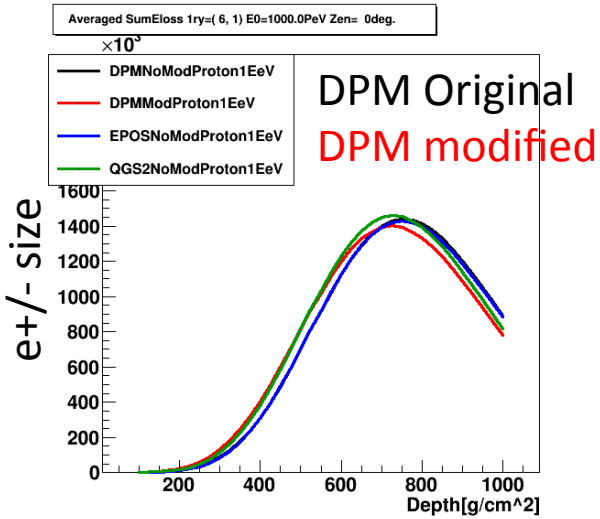


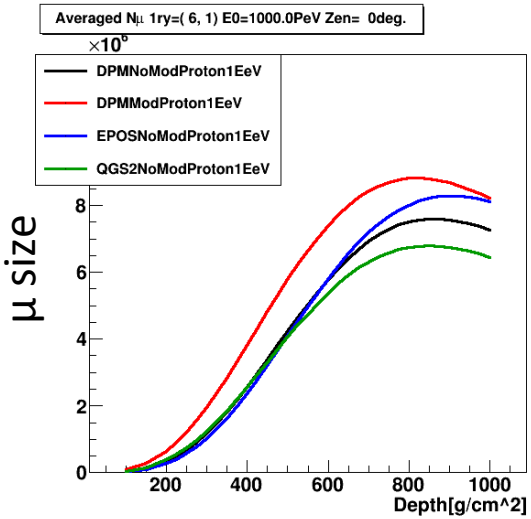


QGSJET II-04 π^0

Artificial scaling-violation function applied to DPMJET3 (perfect scaling model)



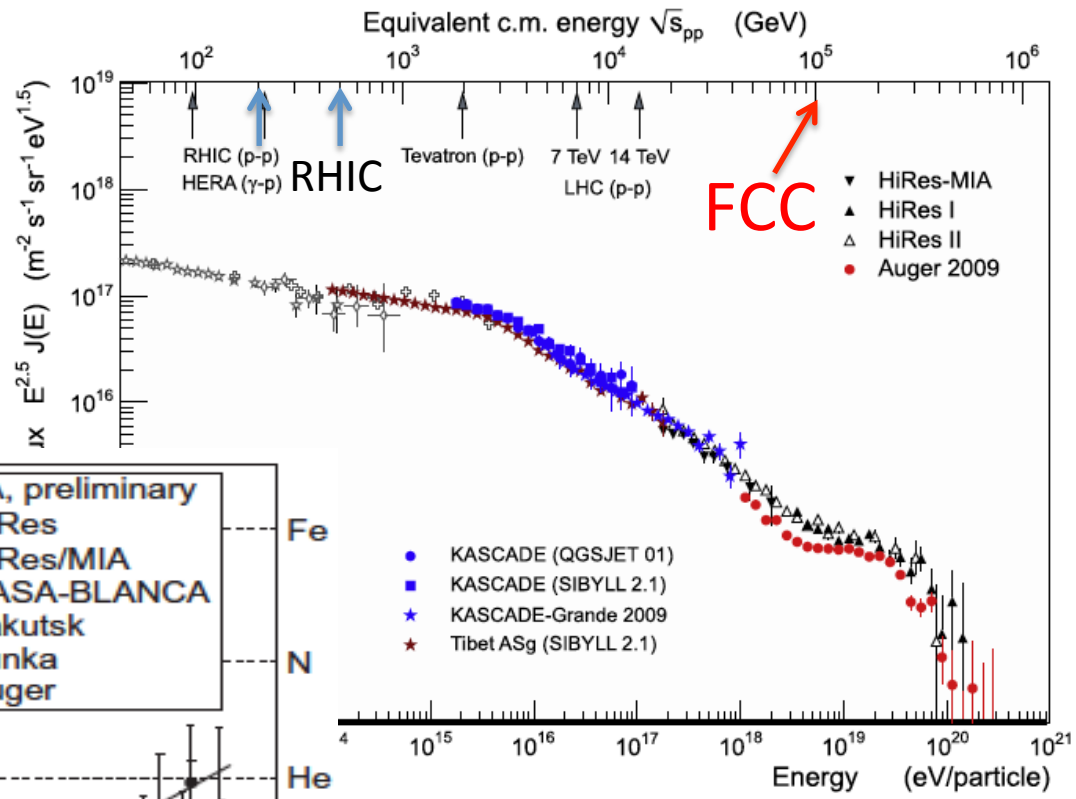


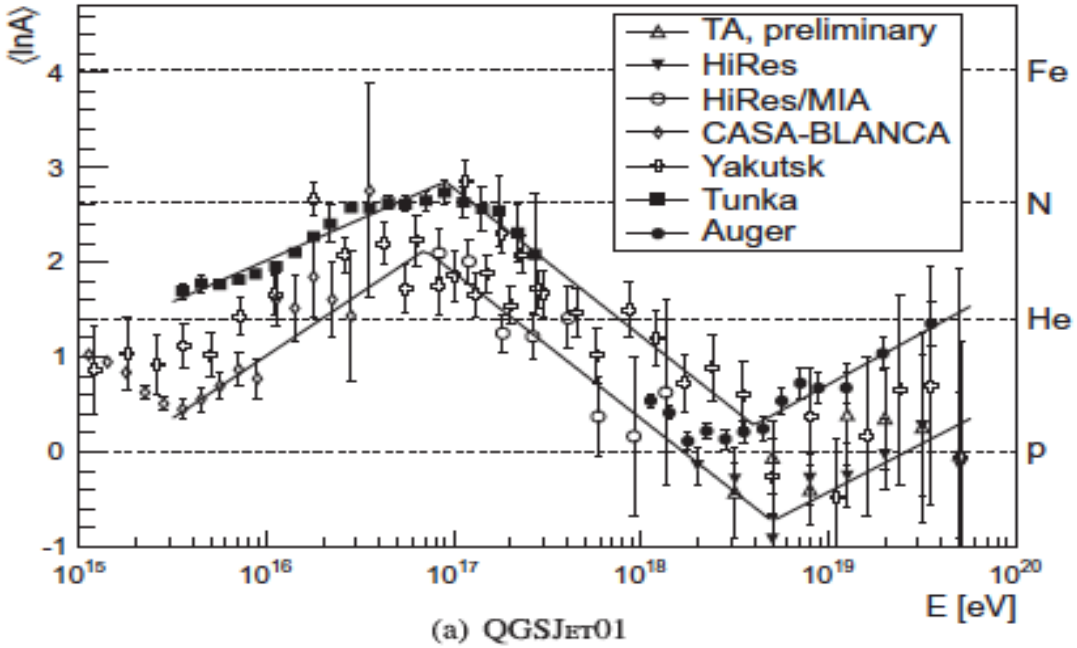


proton shower 10^{18}eV

Recent progress on UHECR observation

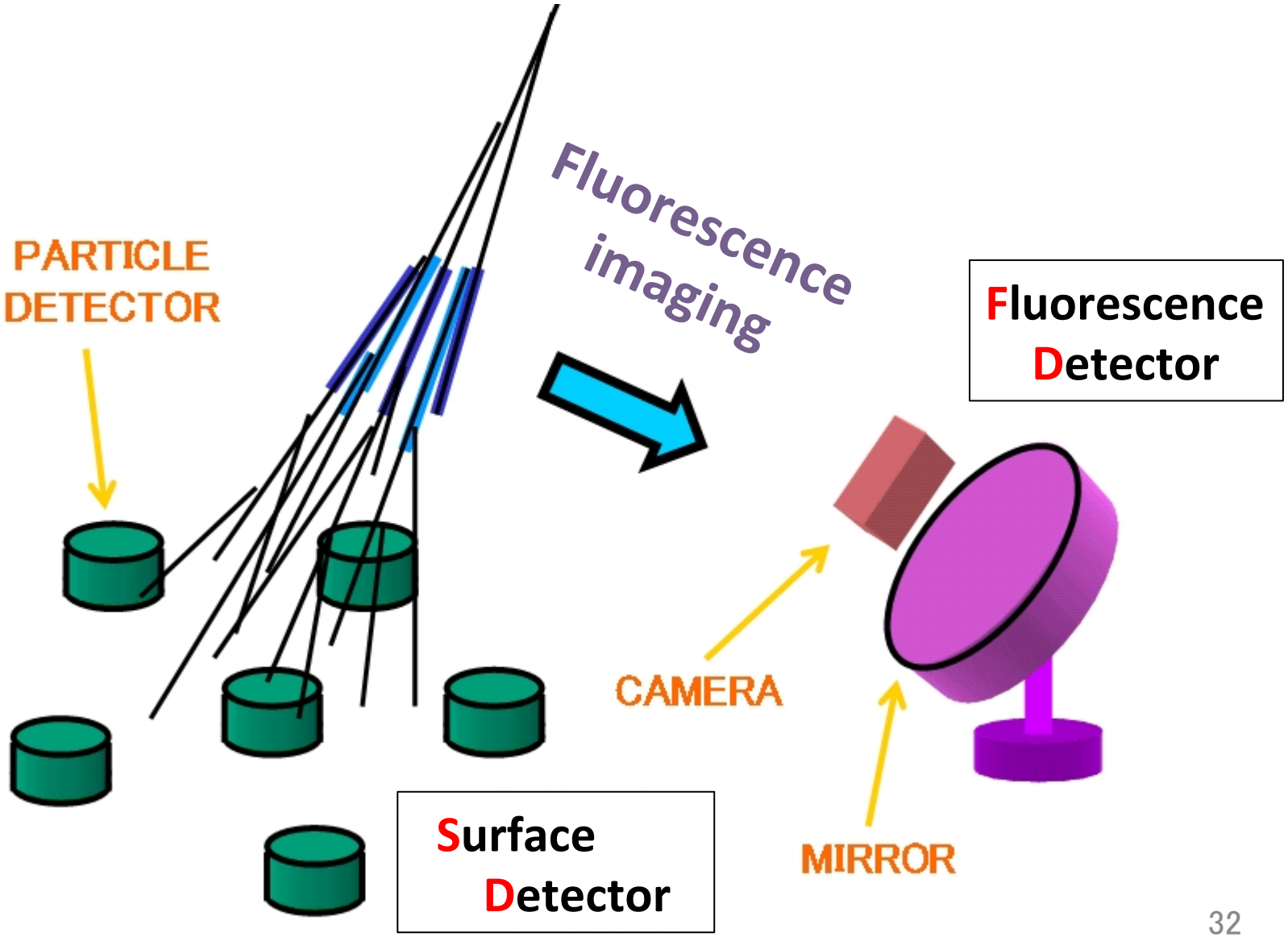
D'Enterria et al., APP, 35,98-113, 2011



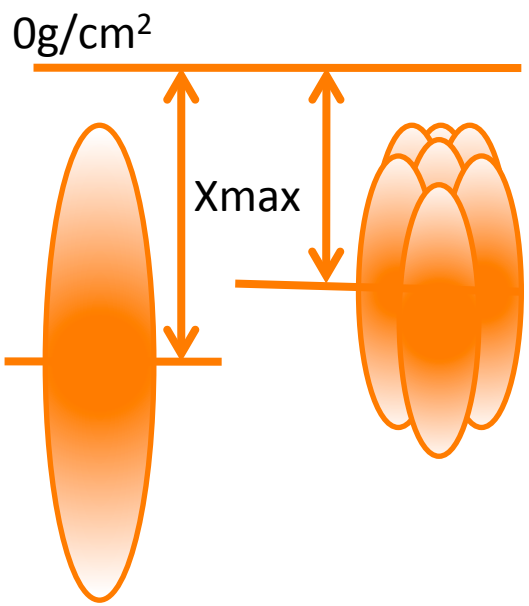


Kampert and Unger, APP., 2012

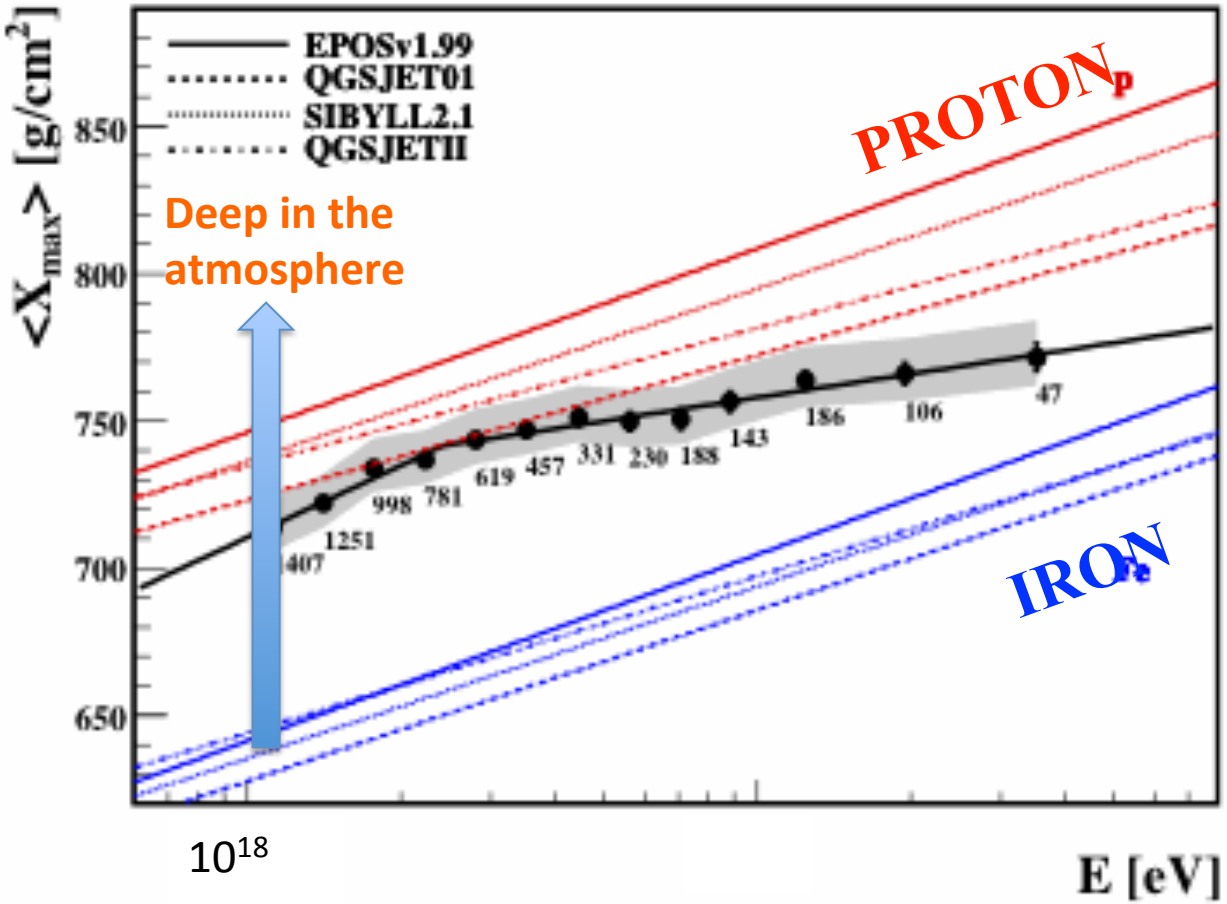
Observation of UHECRs



Uncertainty in hadronic interaction

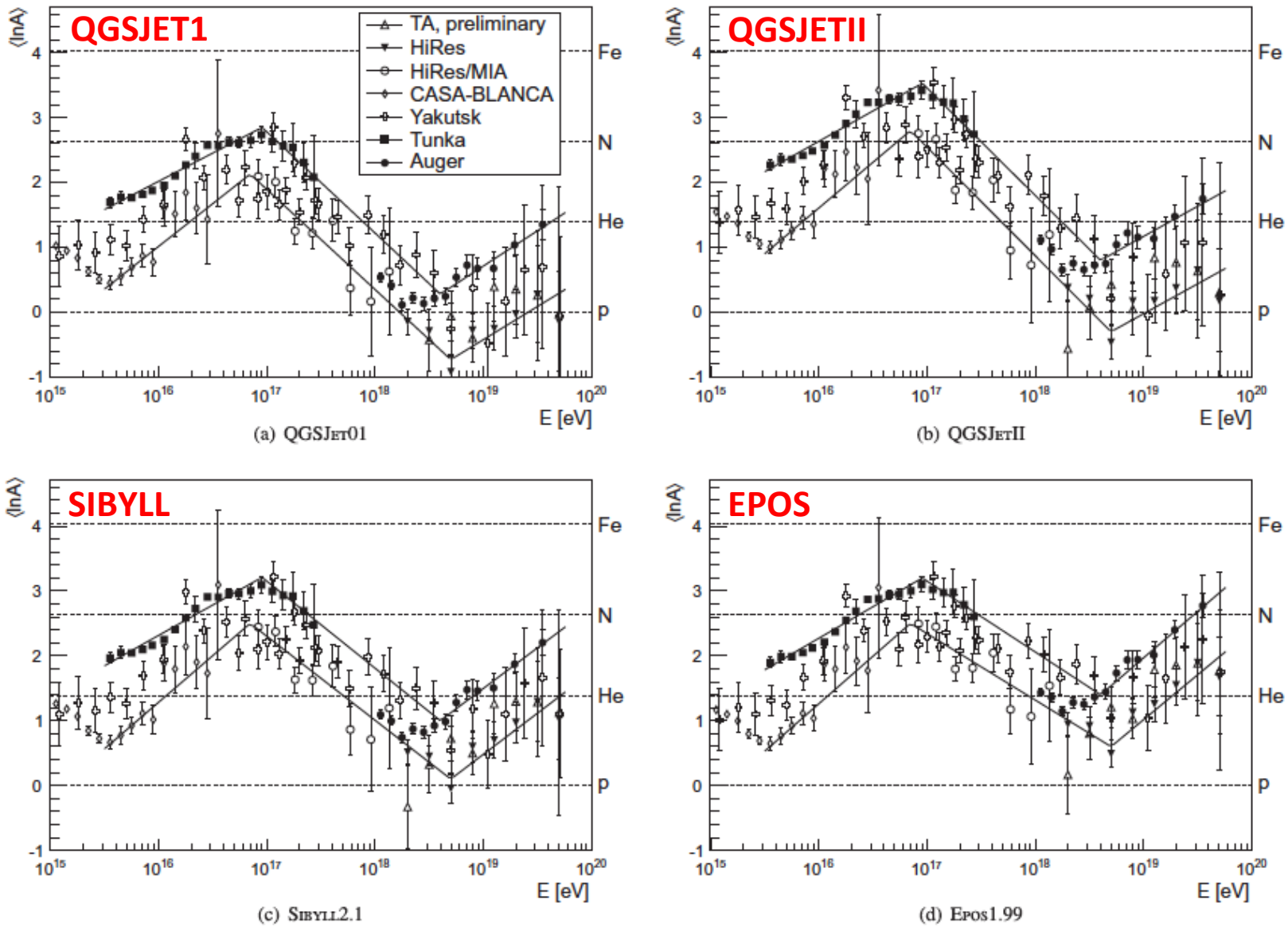


Proton shower and nuclear shower of same total energy



Pierre Auger Observatory (PAO)

AS Interpretation depends on the hadronic interaction model



(a) QGSJET01 (b) QGSJETII (c) SIBYLL2.1 (d) EPOS1.99

(Kampert and Unger, Astropart. Phys., 2012)

AS Interpretation depends on the hadronic interaction model

Problems in the CR data interpretation

Interpretation of AS observations needs help of MC simulation – hadronic interaction model

=> <u>model-originated uncertainty</u> or even <u>discrepancy</u>

✓ Energy

- $E_{SD} > E_{FD}$: discrepancy
- missing energy (μ,ν) in FD : uncertainty

✓ Mass

- Mass vs. X_{max} in FD: uncertainty
- Mass vs. e/μ or μ excess in SD : discrepancy

It is evident that our knowledge of hadronic interaction relevant to CR is missing something