Introduction to the cosmic-ray air shower observations and LHCf

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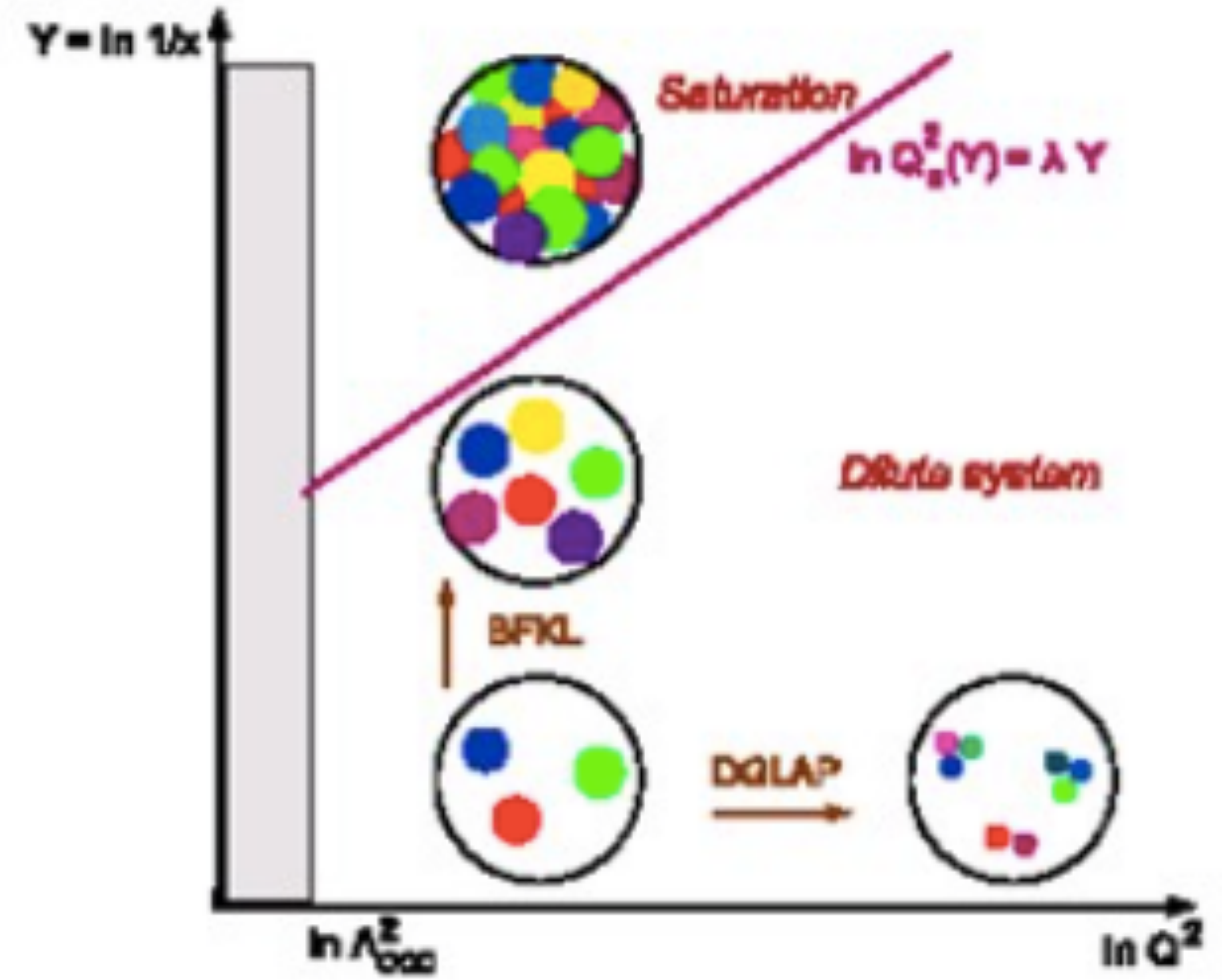
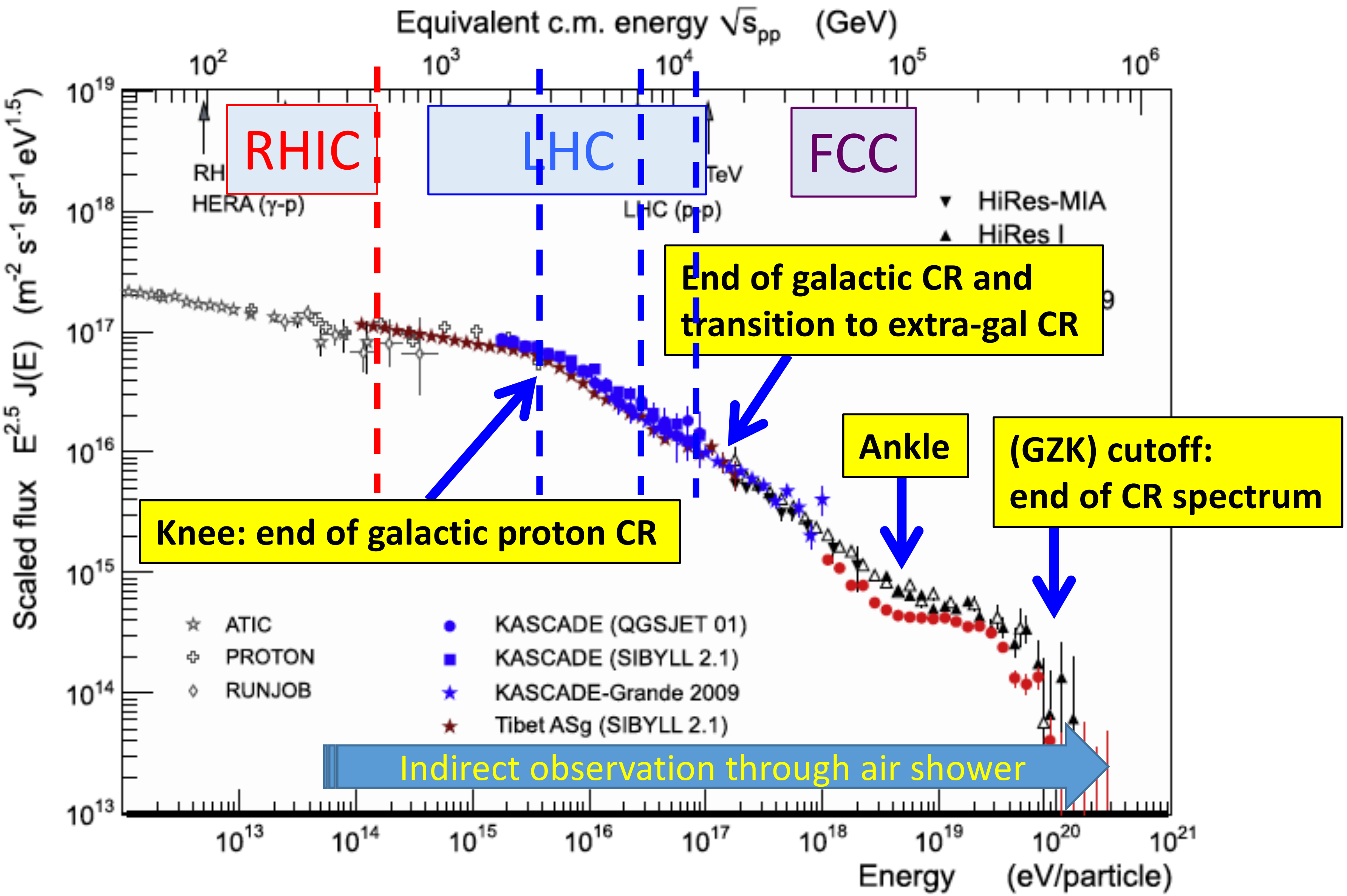

Y = ln 1/x
Saturation
ln Q²s(Y) = λ Y
Dilute system
BFKL
DGLAP
ln Λ²QCD
ln Q²

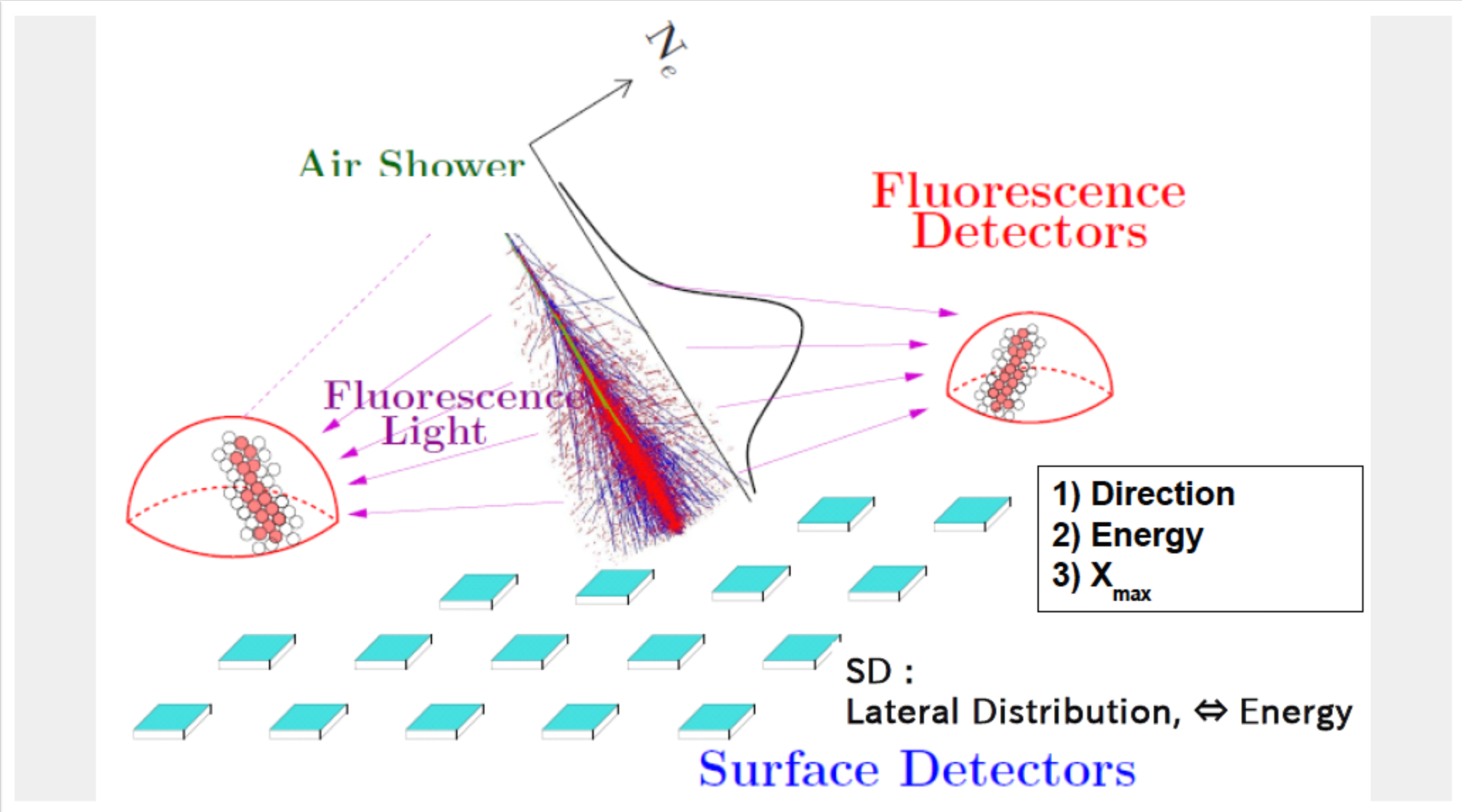
Cosmic-ray spectrum and collider energy

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



Because of low flux, high-energy CRs are observed through atmospheric air showers

Air shower observation technic



Surface detectors = single layer sampling calorimeter
Fluorescence detectors = total absorption calorimeter

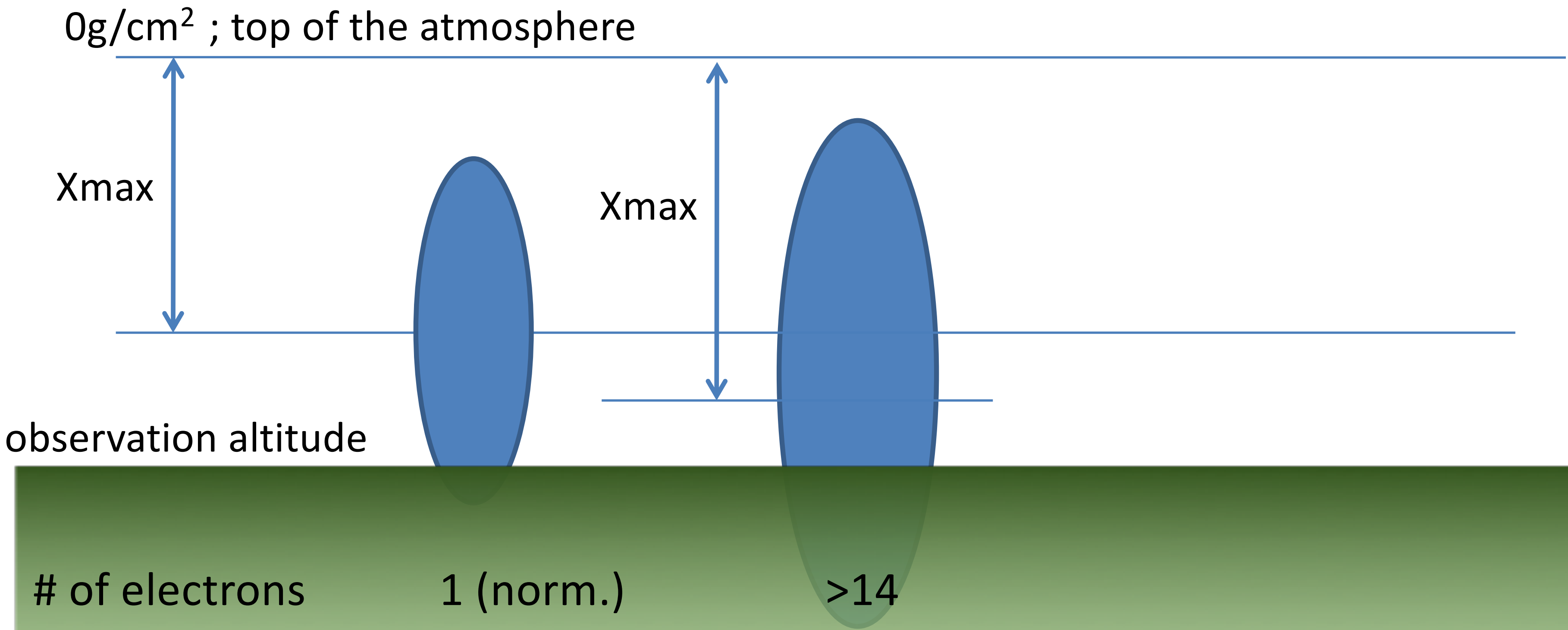
3 key observables in air shower observations

- Energy (spectrum)
  - Acceleration mechanism at source
  - Propagation in the interstellar or intergalactic space (photo-pion production, photo-disintegration)
- Mass (chemical composition)
  - Environment of the source
  - Photo-disintegration in the propagation
- Direction
  - Source direction (astronomy)
  - Bending and diffusion in the magnetic field
  - Rigidity (E/Z) dependence

Not independent each other
=> source and propagation scenario to explain all observations is required

How can we measure energy (E) and mass (A)?

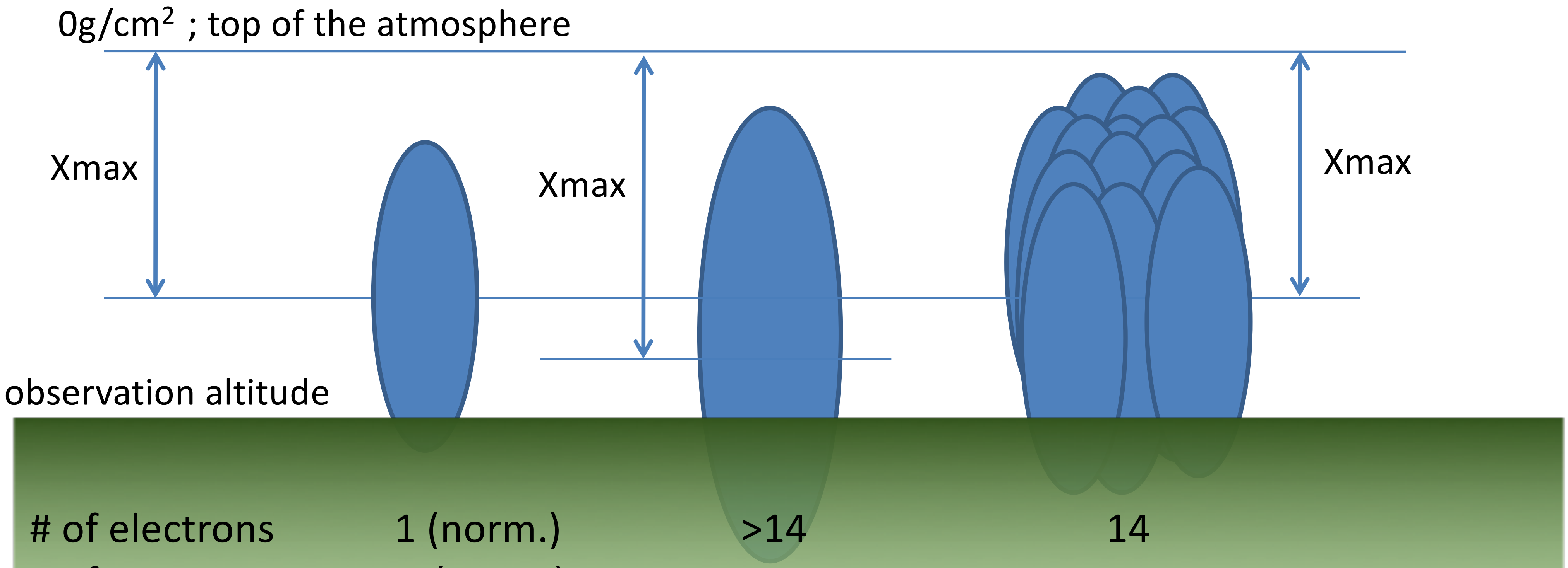
ex) 10^{17} eV proton　　　14×10^{17} eV proton



# of electrons	1 (norm.)	>14
# of muons	1 (norm.)	~14
Xmax	log(1) (norm.)	log(14)
Intensity of Fluor.	1 (norm.)	14

How can we measure energy (E) and mass (A)?

ex) 10^{17} eV proton | 14×10^{17} eV proton | 14×10^{17} eV Nitrogen = 14 superposition of 10^{17}eV proton (nucleon)

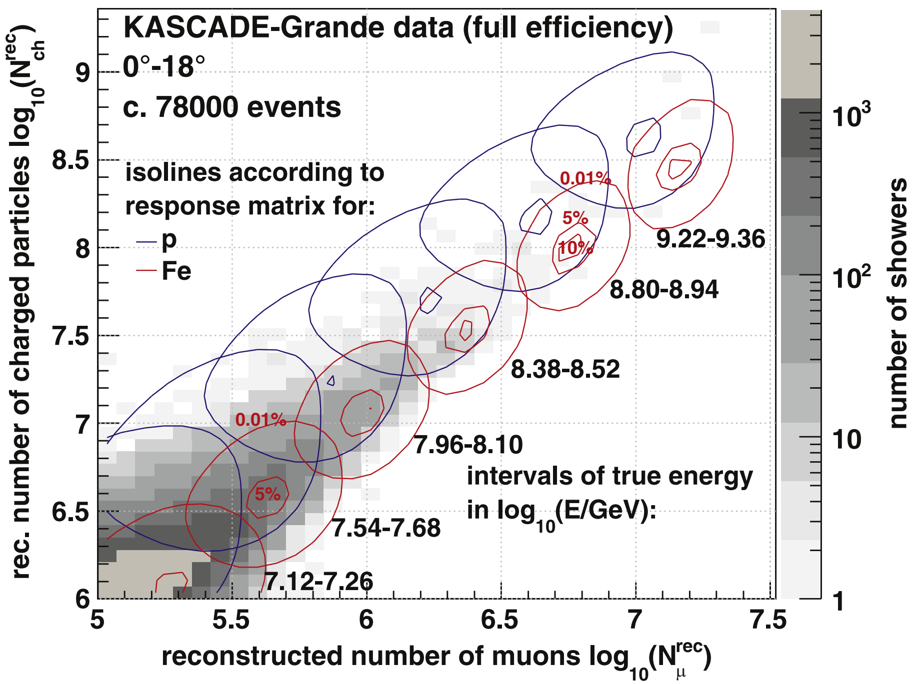


	ex) 10^{17} eV proton	14×10^{17} eV proton	14×10^{17} eV Nitrogen
# of electrons	1 (norm.)	>14	14
# of muons	1 (norm.)	~14	~14
Xmax	log(1) (norm.)	log(14)	log(1)
Intensity of Fluor.	1 (norm.)	14	14

(E,A) degeneracy are usually solved by (I_{fluor}, <Xmax>) or (N_e, N_{mu}) observables

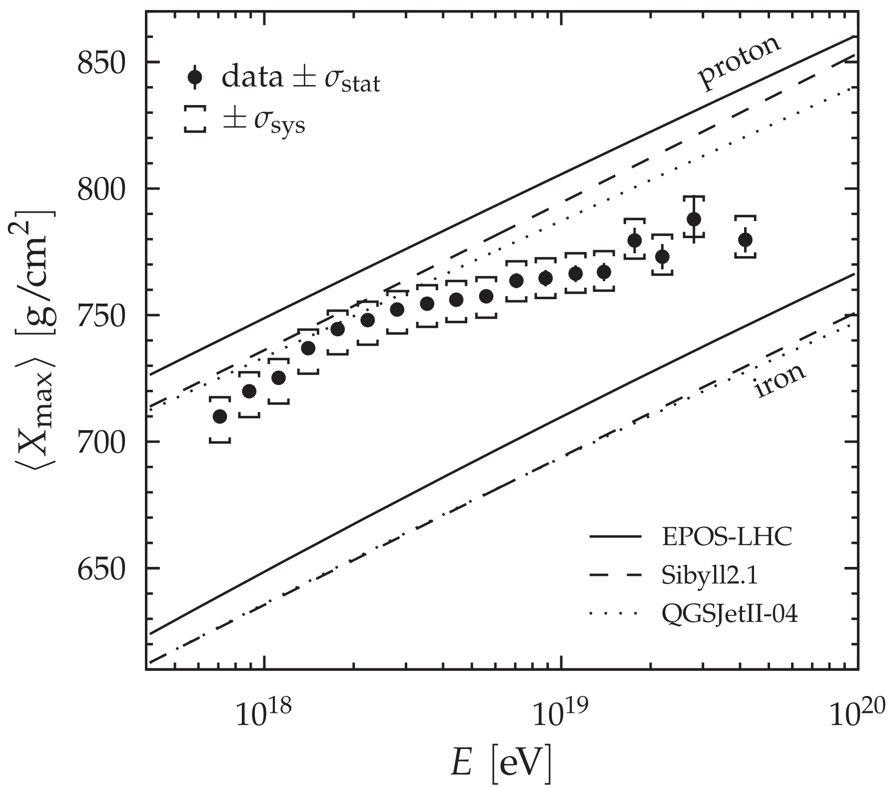
Cosmic-ray measurements and hadronic interaction

KASCADE Grande, Astropart. Phys., 47 (2013) 54-66



Response (color contours) was calculated using QGSJET II-02 + FLUKA 2002.4

PAO, PRD, 90, 122005 (2014)



Interpretations rely on the MC predictions with an assumed hadronic interaction model

Effect to $\langle X_{max} \rangle$

(R.Ulrich et al., PRD, 83 (2011) 054026)

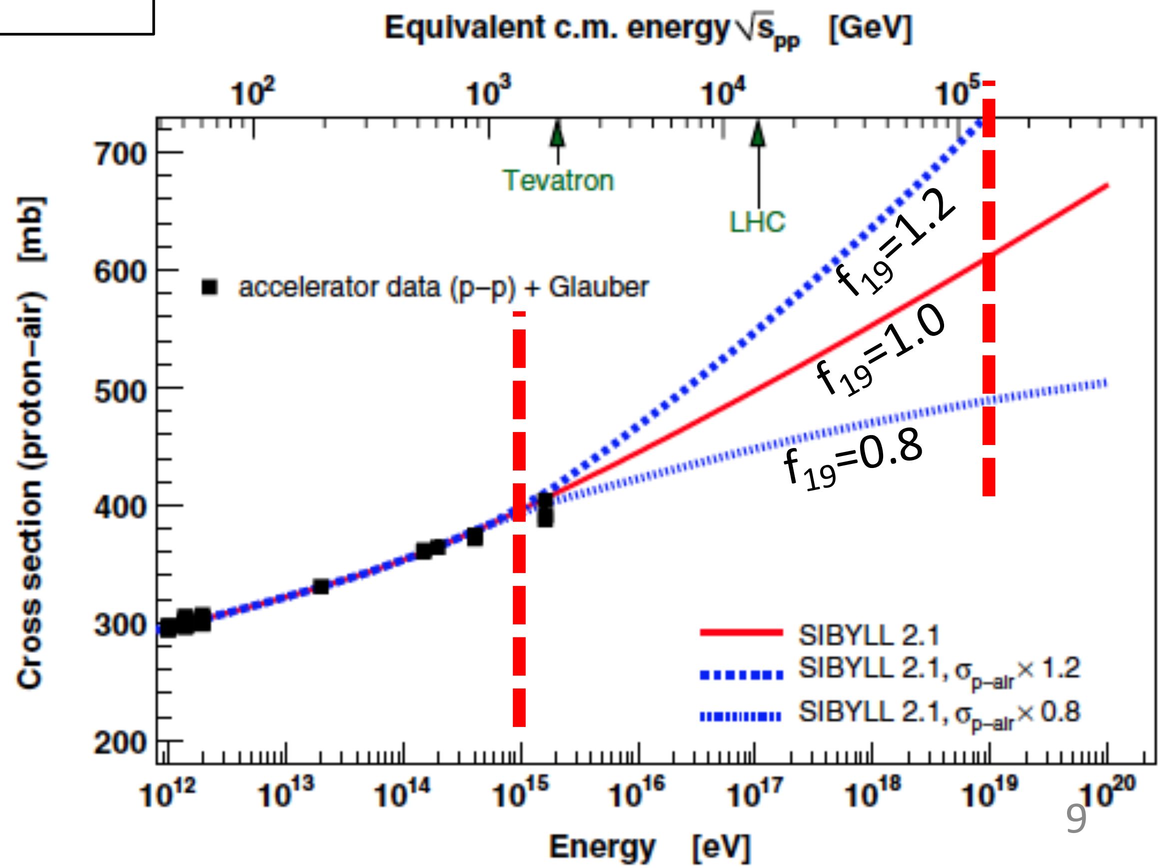
$$f(E, f_{19}) = 1 + (f_{19} - 1)F(E),$$

$$F(E) = \begin{cases} 0 & E \leq 1\ \mathrm{PeV} \\ \frac{\log_{10}(E/1\ \mathrm{PeV})}{\log_{10}(10\ \mathrm{EeV}/1\ \mathrm{PeV})} & E > 1\ \mathrm{PeV} \end{cases}.$$

Artificial modification of parameters

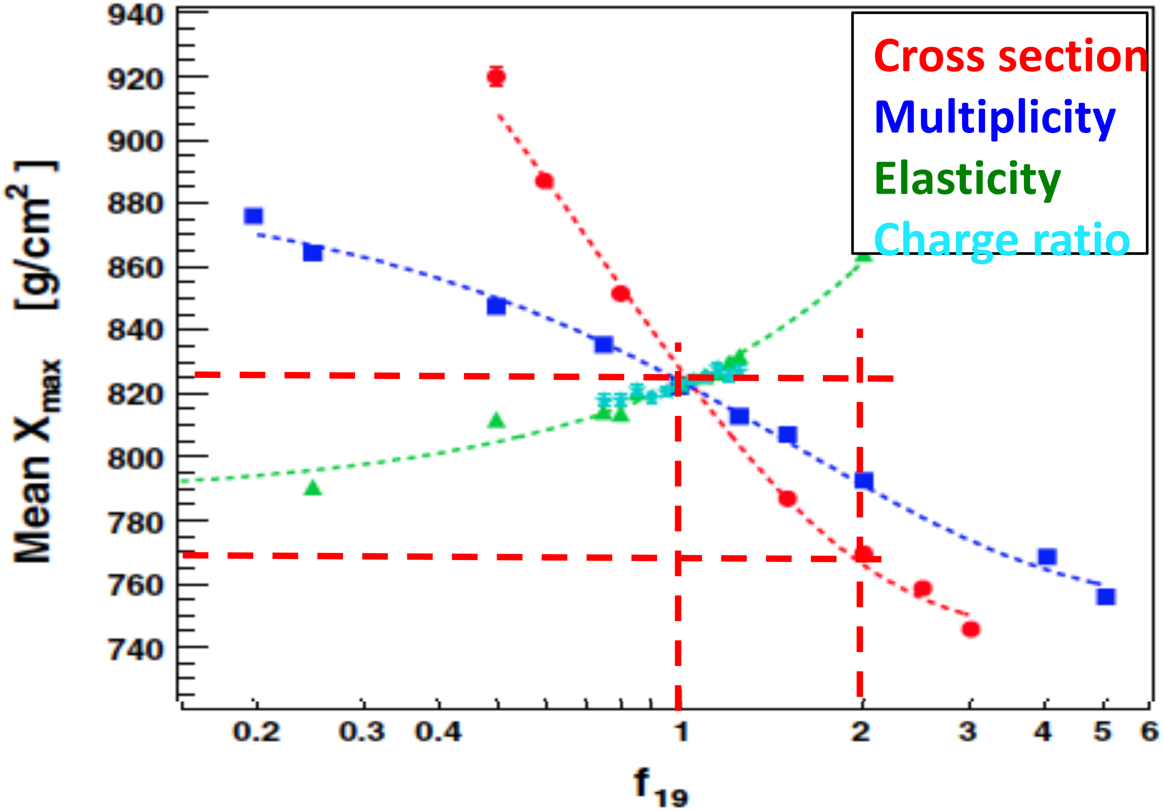
base model : SIBYLL 2.1
no modification $E<10^{15}$eV
f_{19} parameter defines smooth modification $E>10^{15}$eV

ex) f_{19} =0.8, 80% at 10^{19}eV
f_{19}=1.2 120% at 10^{19}eV



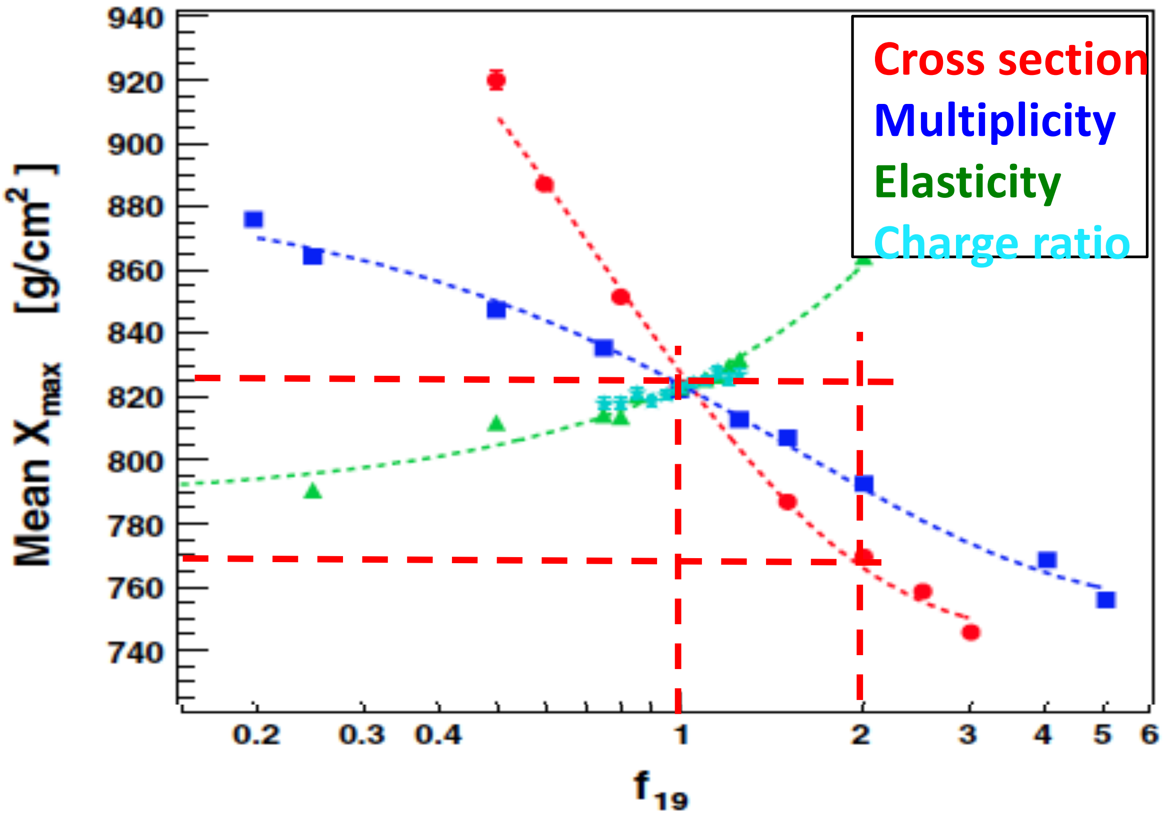
Effect to <X_{max}>

(R.Ulrich et al., PRD, 83 (2011) 054026)



Effect to <X_{max}>

(R.Ulrich et al., PRD, 83 (2011) 054026)



Reasonable range of f_{19} is unknown

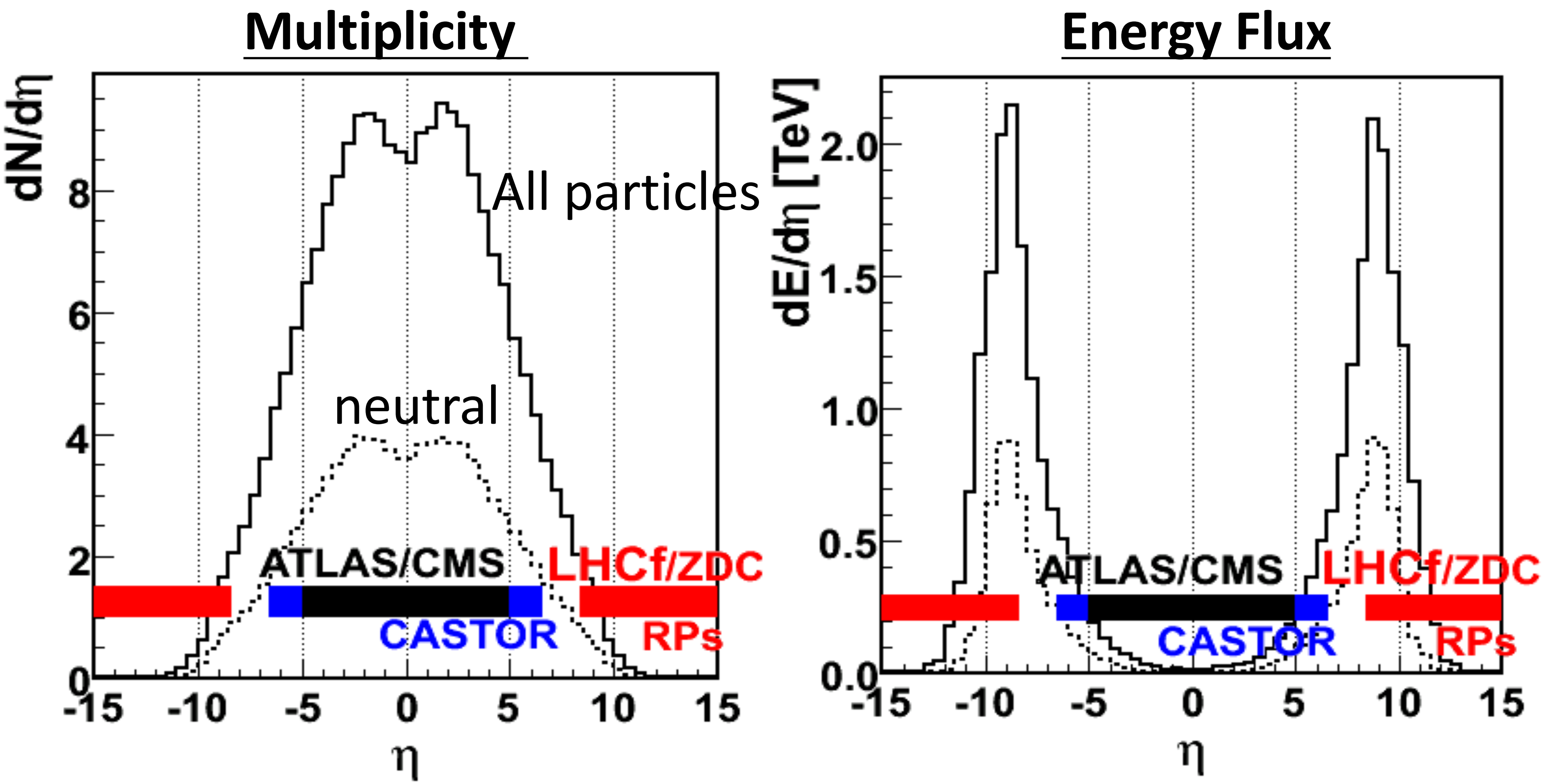
Effects of spectra, nuclear effect are unknown

(difficult to modify a single parameter like f_{19})

Experimental data by accelerators as much as possible are important

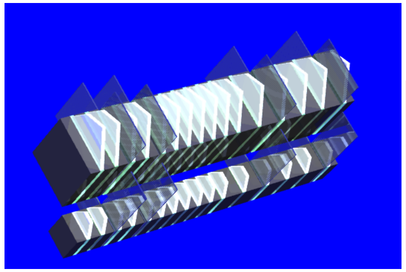
What should be measured at colliders

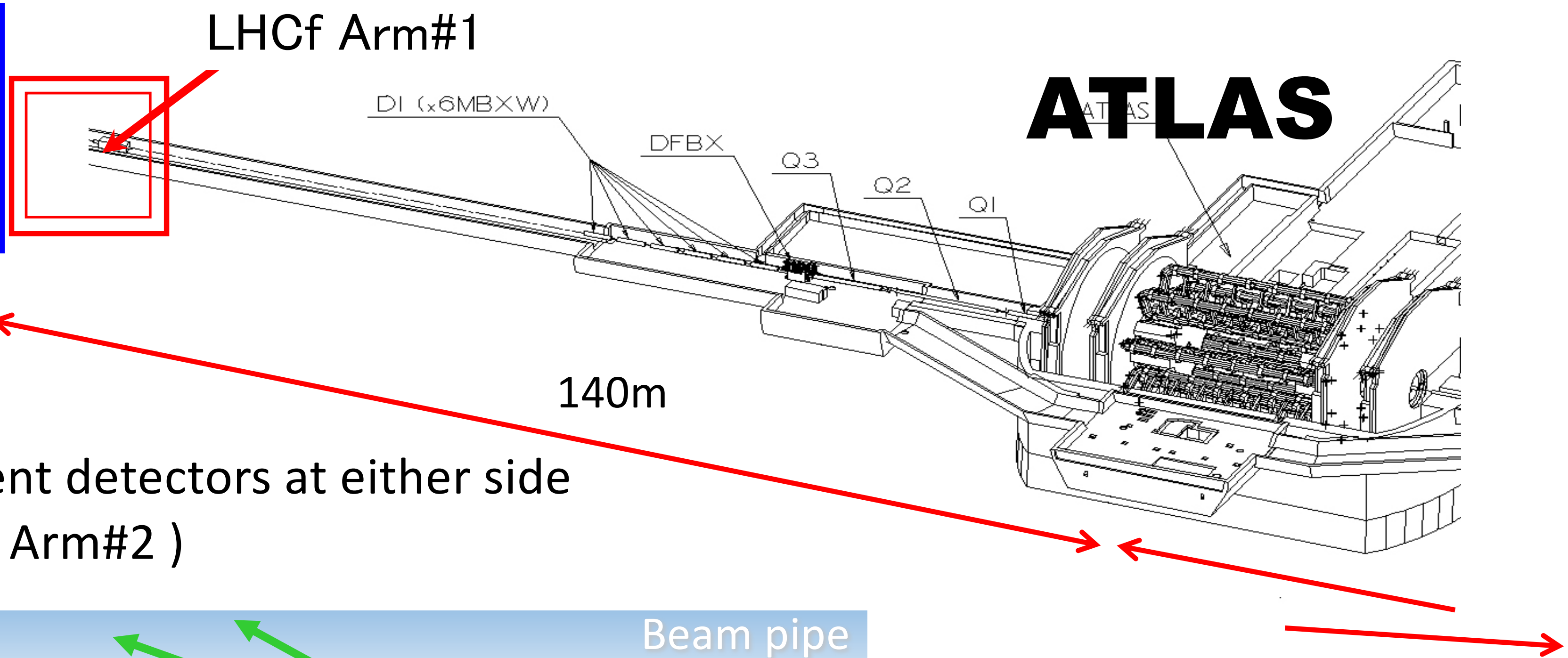
multiplicity and energy flux at LHC 14TeV collisions
pseudo-rapidity; $\eta = -\ln(\tan(\theta/2))$



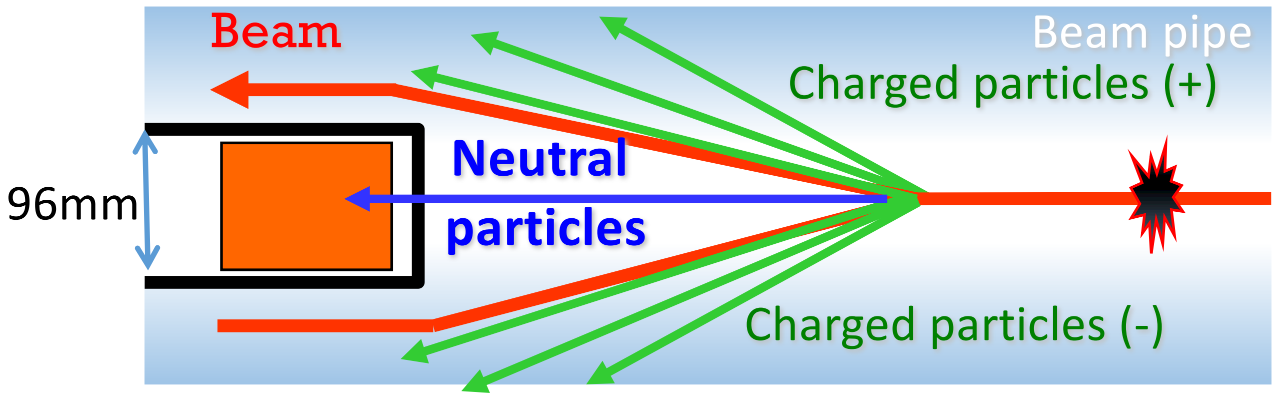
Most of the particles are produced in the central region
Most of the energy flows into very forward = relevant to CR air shower

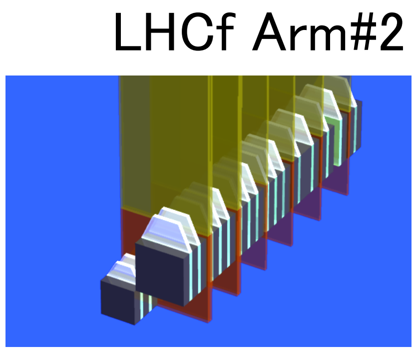
The LHC forward experiment





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

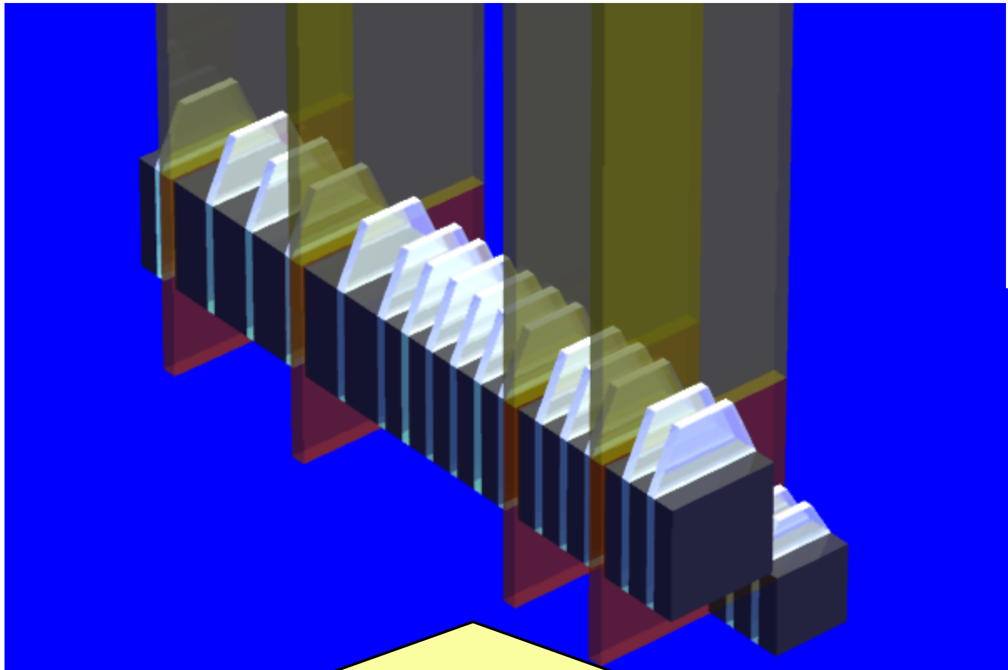




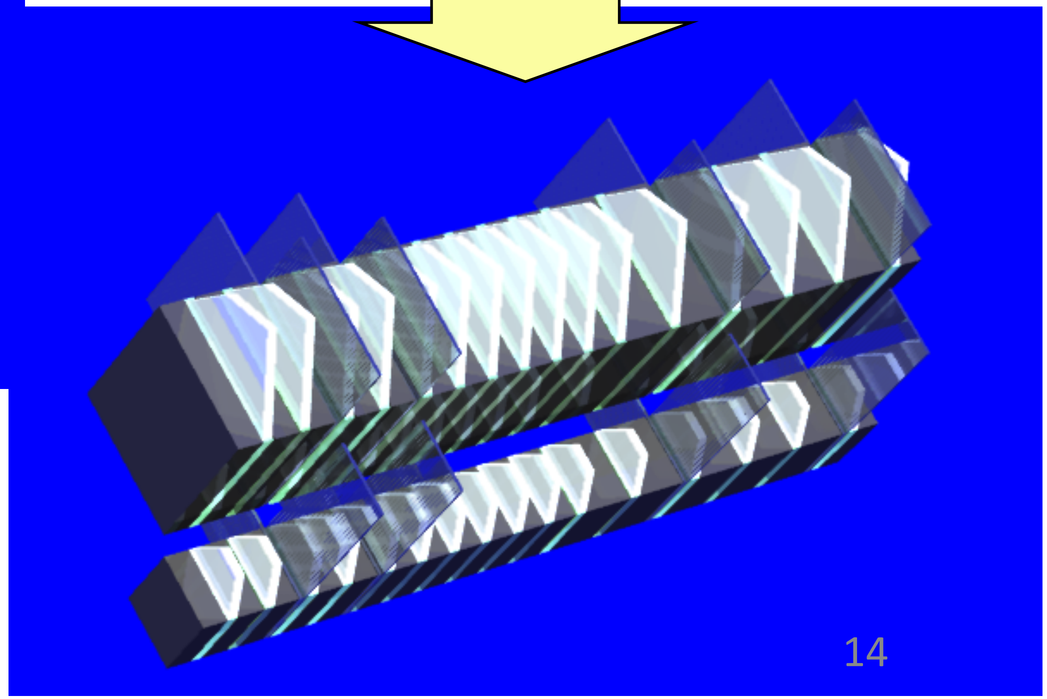
- ✓ All charged particles are swept by dipole magnet
- ✓ Neutral particles (photons and neutrons) arrive at LHCf
- ✓ $\eta>8.4$ (to infinity) is covered

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
- ✓ Plastic scintillators => GSO scintillators, SciFi => GSO bars in Run2

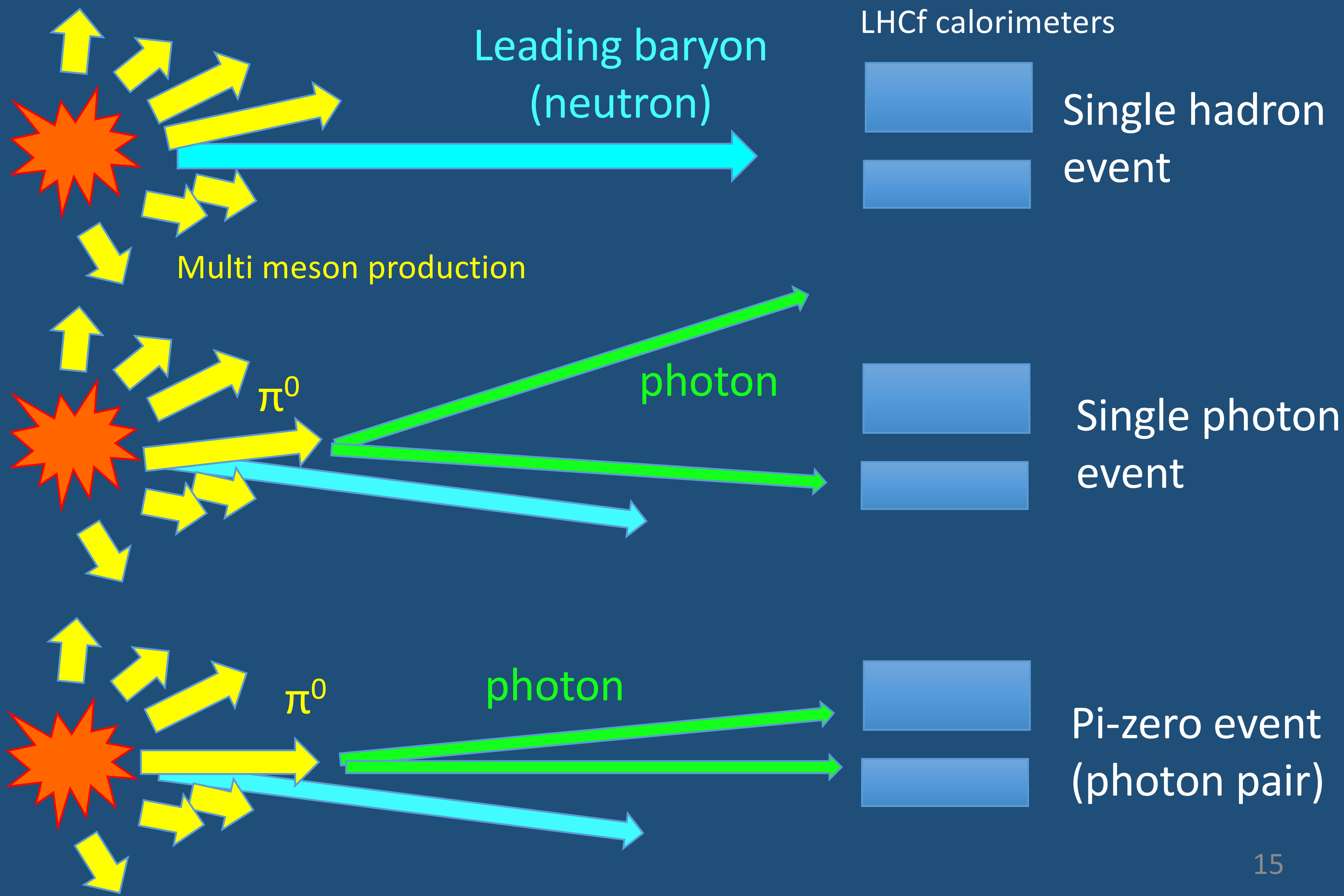


LHCf Arm#1 Detector
20mmx20mm+40mmx40mm
4 XY SciFi+MAPMT

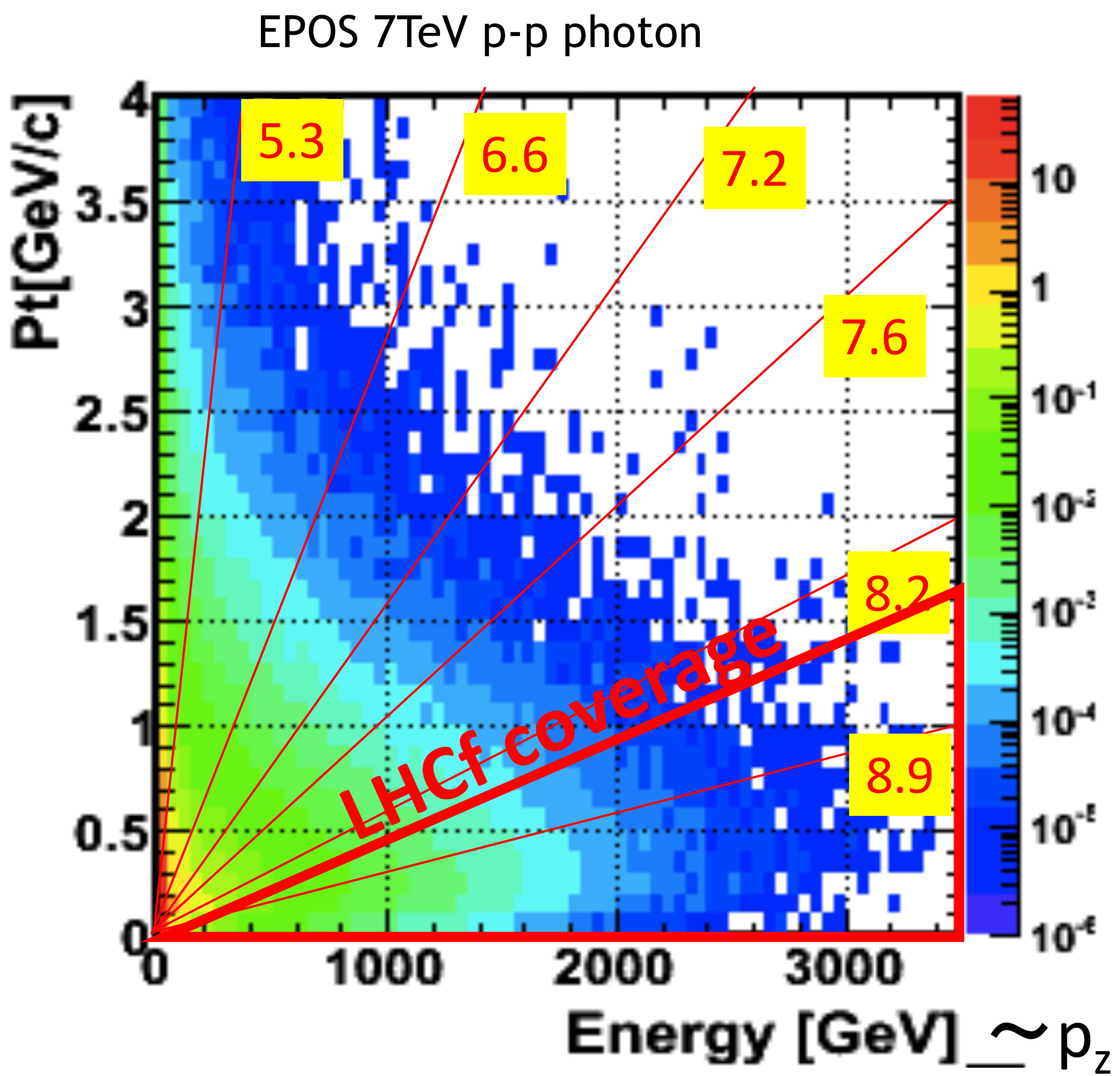


LHCf Arm#2 Detector
25mmx25mm+32mmx32mm
4 XY Silicon strip detectors

Event categories of LHCf



photon (predominantly π^0 decay) cross section at 7TeV p-p collision



LHCf (RHICf) History

- ✓2004 LOI submitted to CERN
- ✓2006 TDR approved by CERN
- ✓2009 First data taking at $\sqrt{s}$=900GeV p-p collision
- ✓2010 $\sqrt{s}$=7TeV p-p collision
- ✓2013 $\sqrt{s}$=2.76TeV p-p & $\sqrt{s_{NN}}$=5TeV p-Pb collisions
- ✓2015 $\sqrt{s}$=13TeV p-p collision
- ✓2016 $\sqrt{s_{NN}}$=8.1TeV p-Pb collision
- ✓2017 $\sqrt{s}$=510GeV p-p collision as RHICf

Publications

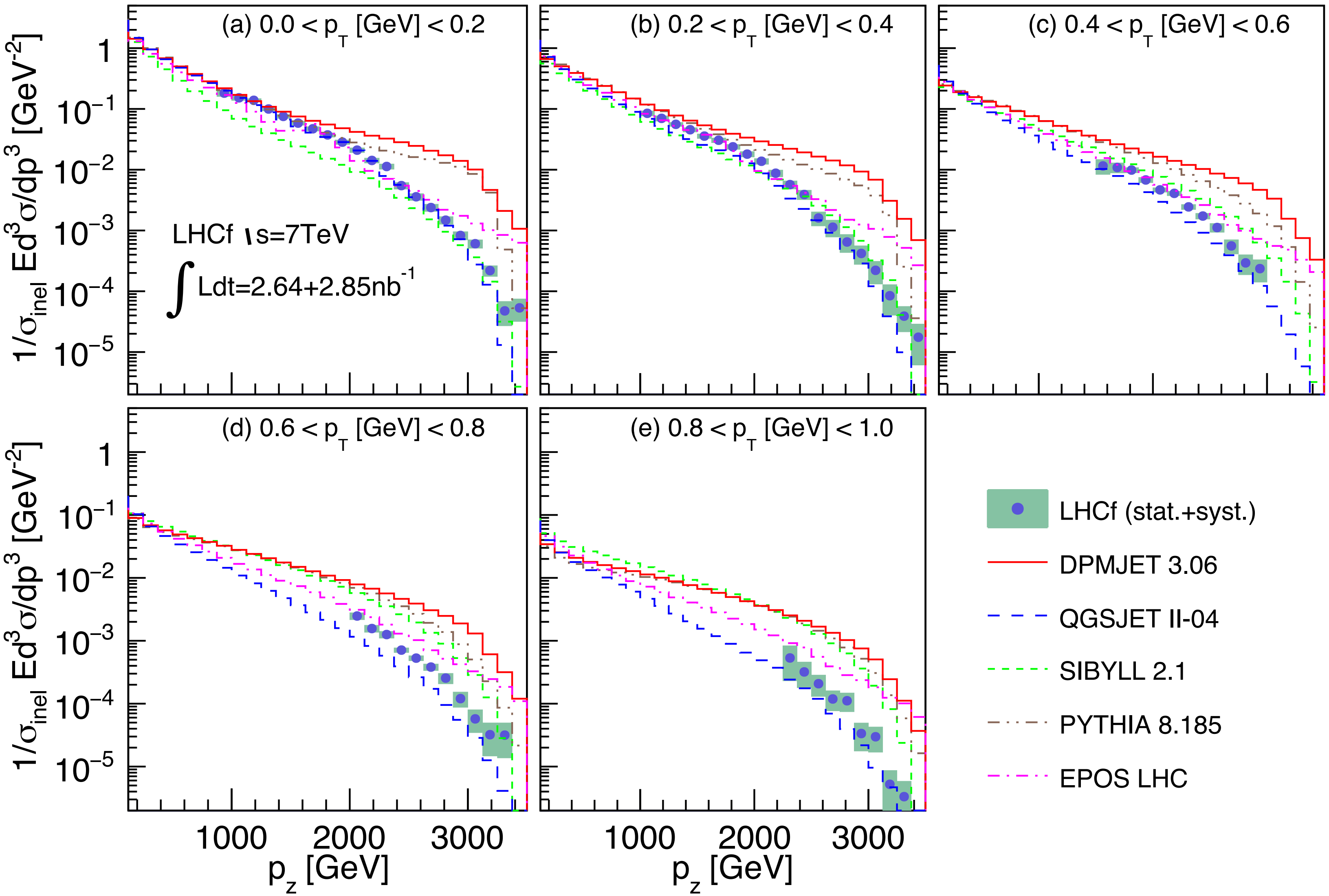
physics results

performance results

<table>
<tr><th></th><th>Photon (EM shower)</th><th>Neutron (hadron shower)</th><th>π^0 (limited acceptance)</th><th>π^0 (full acceptance)</th><th>Performance</th></tr>
<tr><td>Beam test</td><td>NIM, A671 (2012) 129-136</td><td>JINST, 9 (2014) P03016</td><td></td><td></td><td></td></tr>
<tr><td>0.9TeV p-p</td><td>PLB, 715 (2012) 298-303</td><td></td><td></td><td></td><td rowspan="2">IJMPA, 28 (2013) 1330036</td></tr>
<tr><td>7TeV p-p</td><td>PLB, 703 (2011) 128-134</td><td>PLB, 750 (2015) 360-366</td><td>PRD, 86 (2012) 092001</td><td rowspan="3">PRD, 94 (2016) 032007</td></tr>
<tr><td>2.76TeV p-p</td><td></td><td></td><td rowspan="2">PRC, 89 (2014) 065209</td><td></td></tr>
<tr><td>5.02TeV p-Pb</td><td></td><td></td><td></td></tr>
<tr><td>13TeV p-p</td><td>Preliminary</td><td colspan="3">Analysis in progress</td><td></td></tr>
</table>

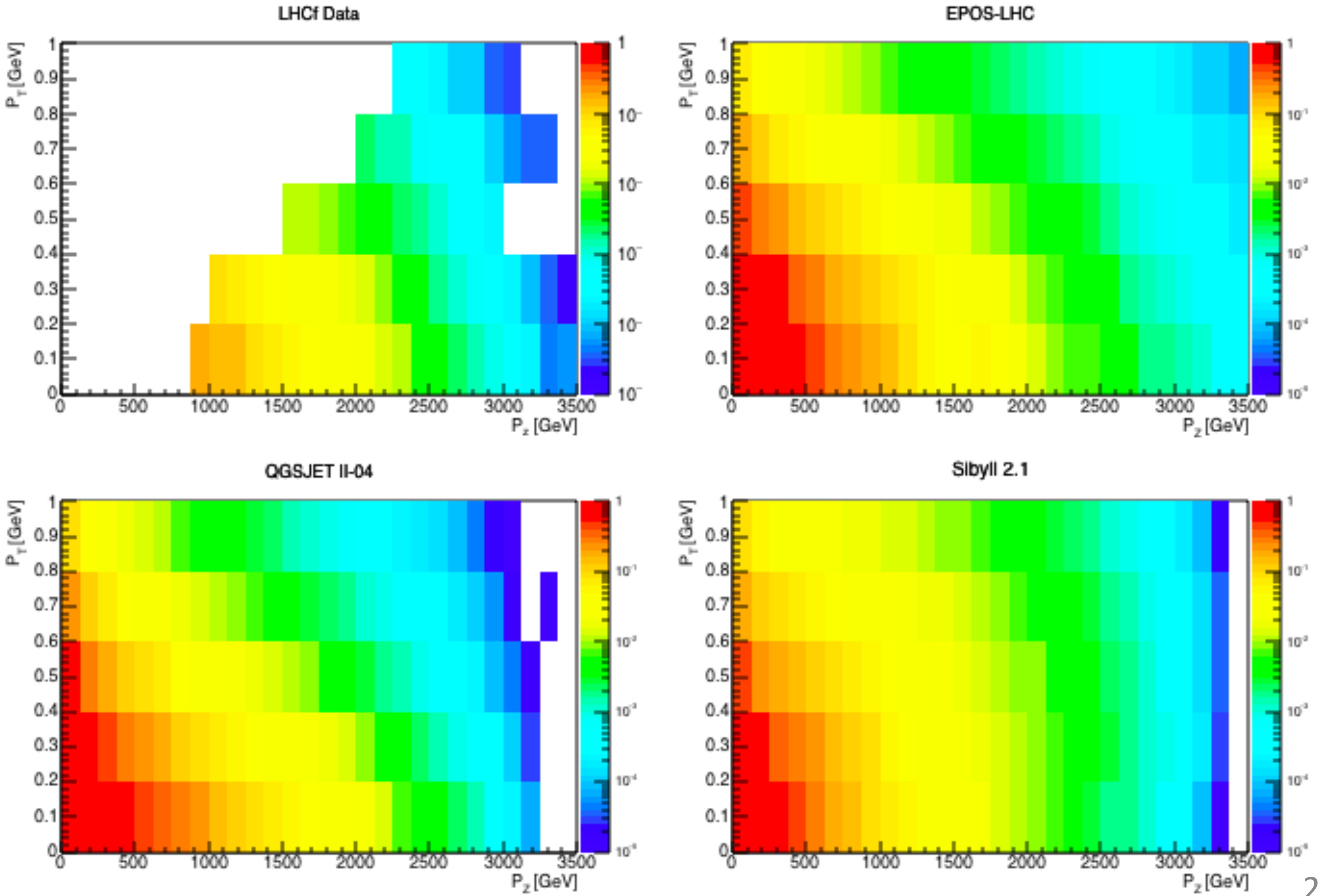
π^0 p_z spectra in 7TeV p-p collisions

(PRD, 94 (2016) 032007)

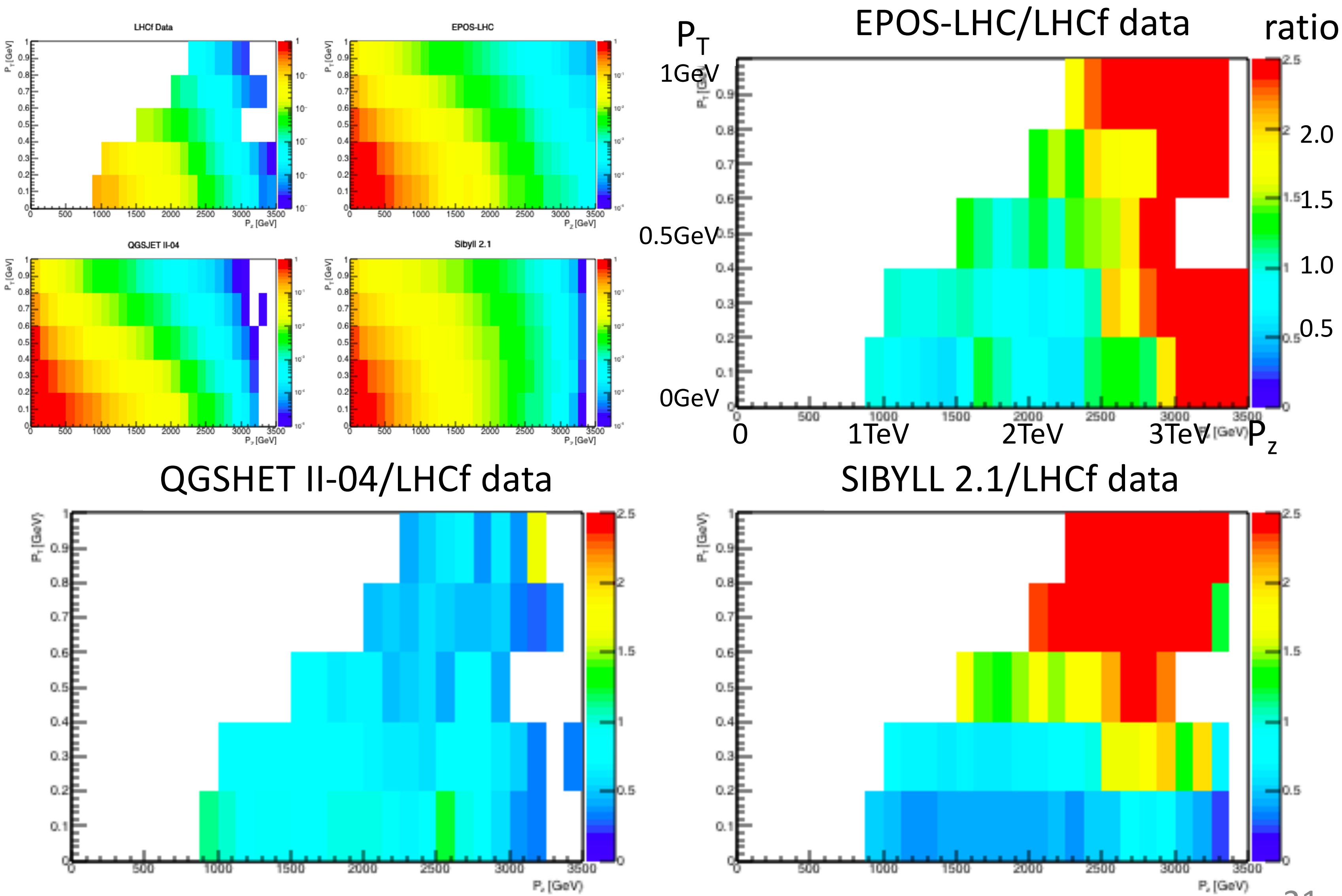


Comparison with models developed for CR physics except PYTHIA

π^0 in 7TeV p-p collision
LHCf and models

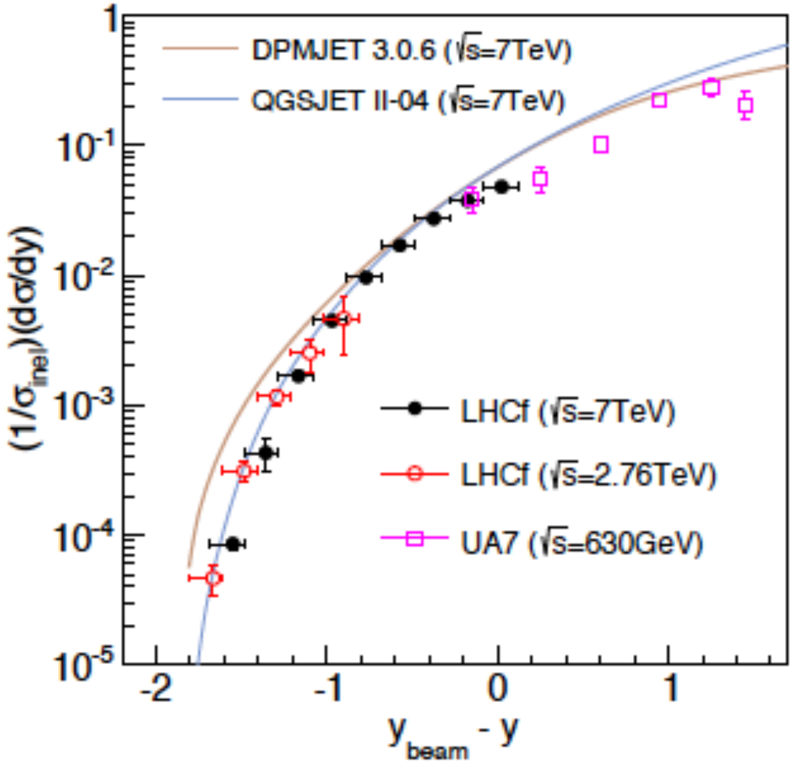


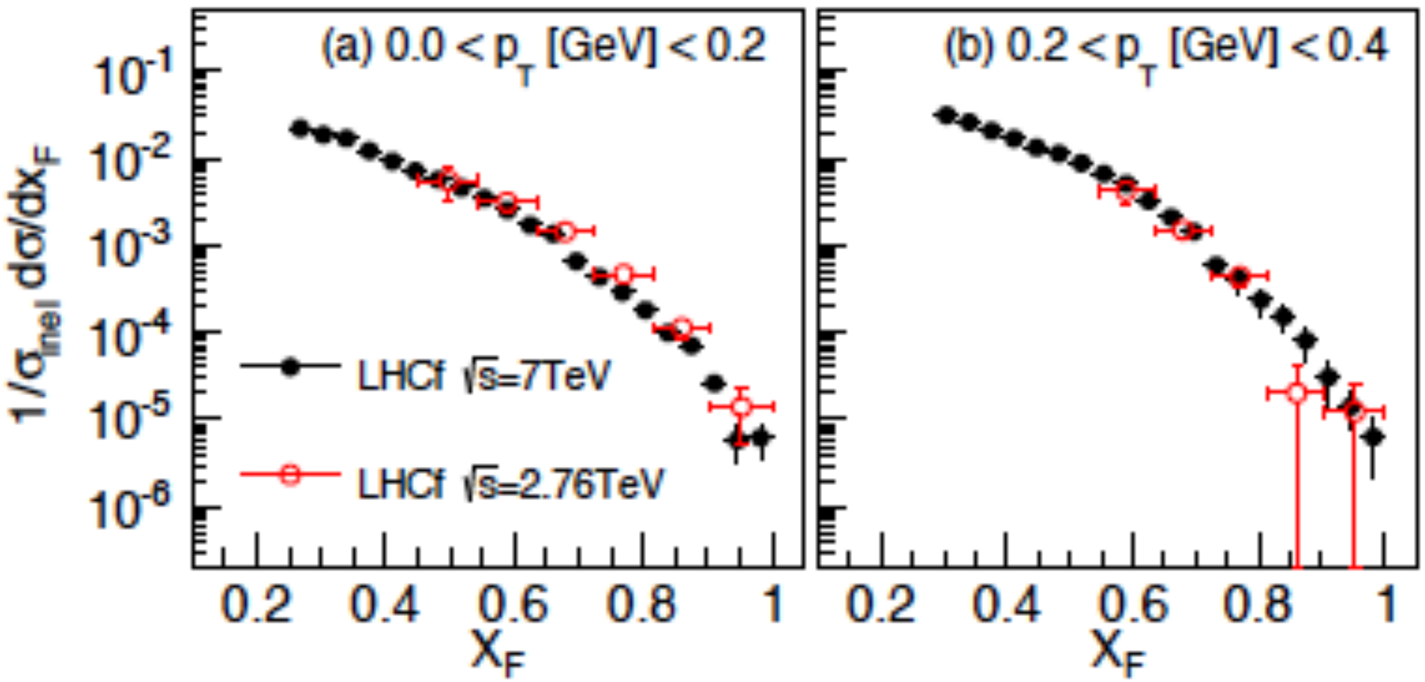
π^0 in 7TeV p-p collision
LHCf and models (ratio to data)



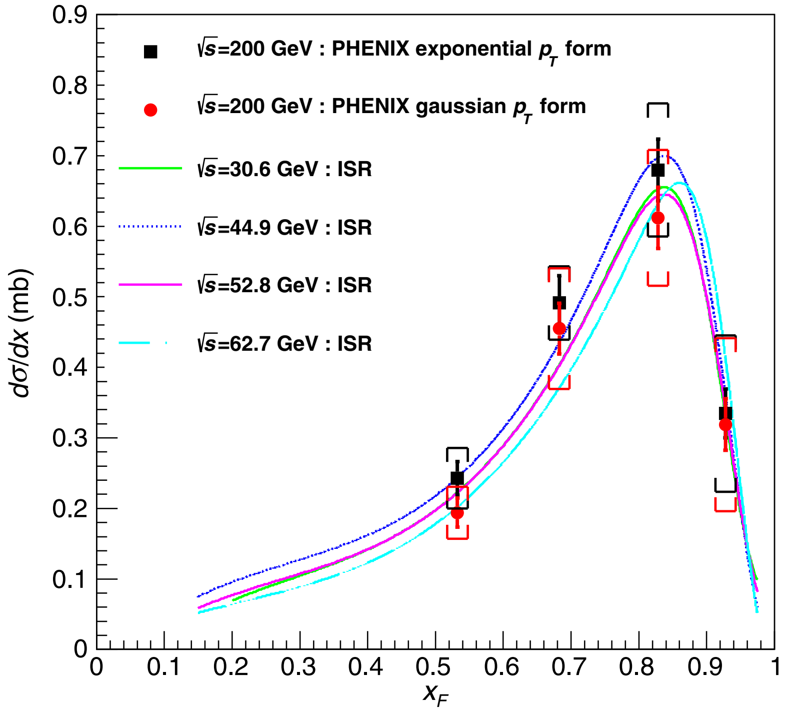
√s scaling ; π^0

- ✓ Scaling is essential to extrapolate beyond LHC
- ✓ (630GeV –) 2.76TeV – 7TeV
  good scaling within uncertainties
- ✓ Wider coverage in y and p_T with 13TeV data
- ✓ Wider √s coverage with RHICf experiment in 2017 at √s=510GeV





√s scaling; Neutron @ zero degree

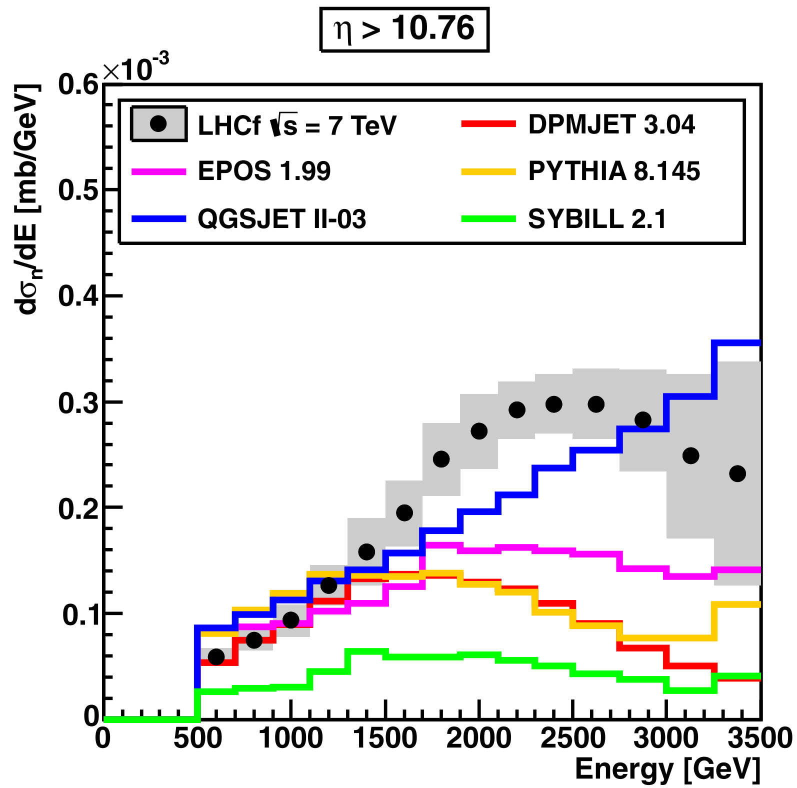


PHENIX, PRD, 88, 032006 (2013)

$p_T < 0.11\ x_F$ GeV/c

√s = 30-60 GeV @ISR

√s = 200 GeV @RHIC



LHCf

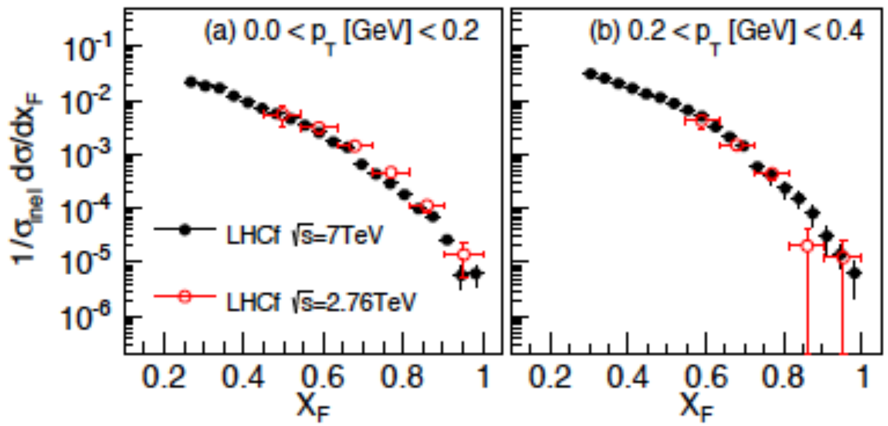
$p_T < 0.15\ x_F$ GeV/c

√s = 7000 GeV @LHC

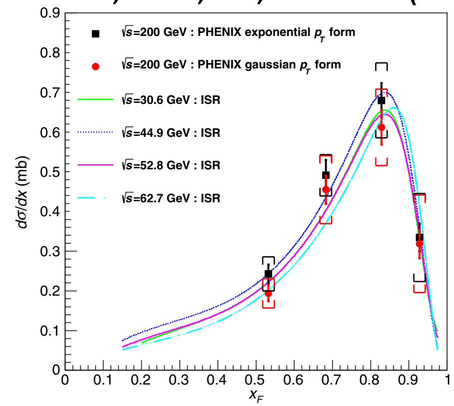
- ✓ PHENIX explains the result by 1 pion exchange
- ✓ More complicated exchanges at >TeV?
- ✓ LHCf data at 900GeV, 2.76TeV and 13TeV to be analyzed
- ✓ RHICf data at 510GeV will be added in 2017

Only highest energy?

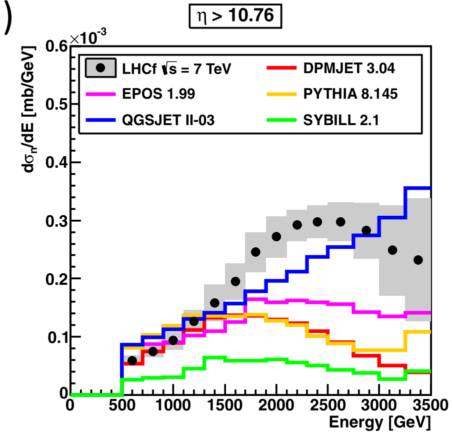
LHCf π^0, PRD (2016)



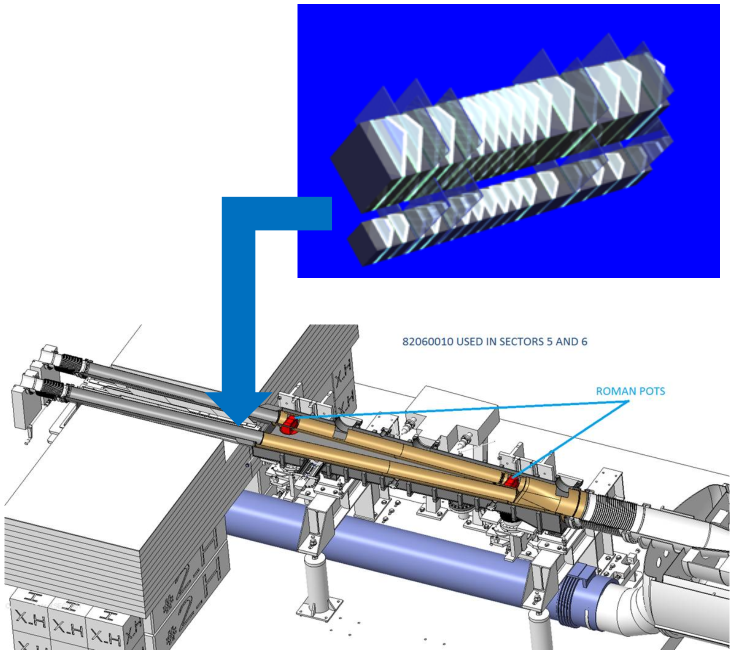
PHENIX and ISR neutrons
PHENIX, PRD, 88, 032006 (2013)



LHCf neutrons
PLB 750 (2015) 360-366



"scaling" is a key to extrapolate beyond the LHC energy



- ✓ RHICf using one of the LHCf detectors is approved for operation in 2017 at 510GeV p+p collisions at RHIC
- ✓ Installation and commissioning are on going

Summary

- Cosmic-ray source and propagation are still key topic of astrophysics
- Air shower observations developed, but uncertainty in the hadronic interaction limits the interpretation
- Forward production (soft interaction) is key
- LHCf and RHICf measure forward particle production
- Hadron physics can make a significant contribution to the astrophysics
- (Air shower observations may contribute hadron physics, or new physics)