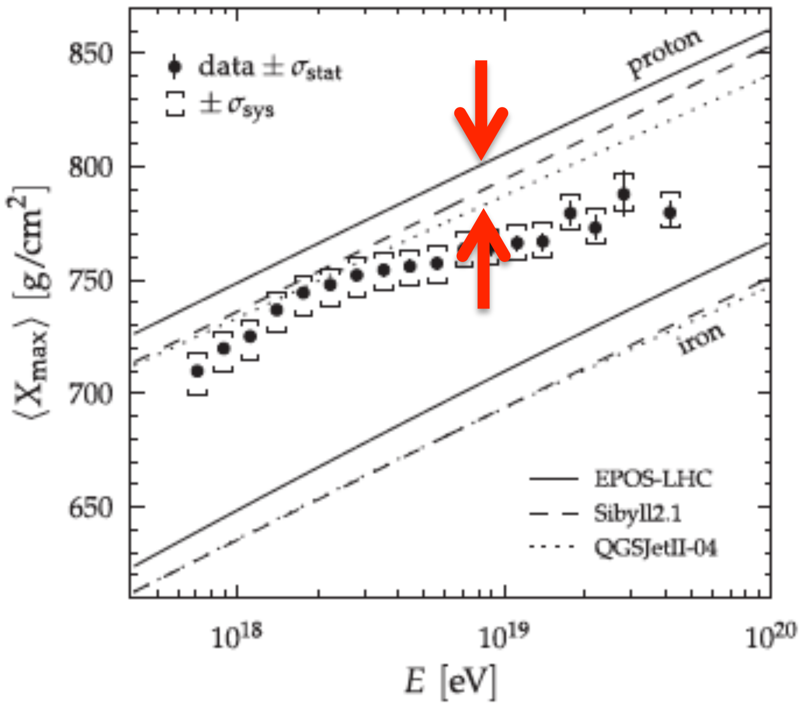
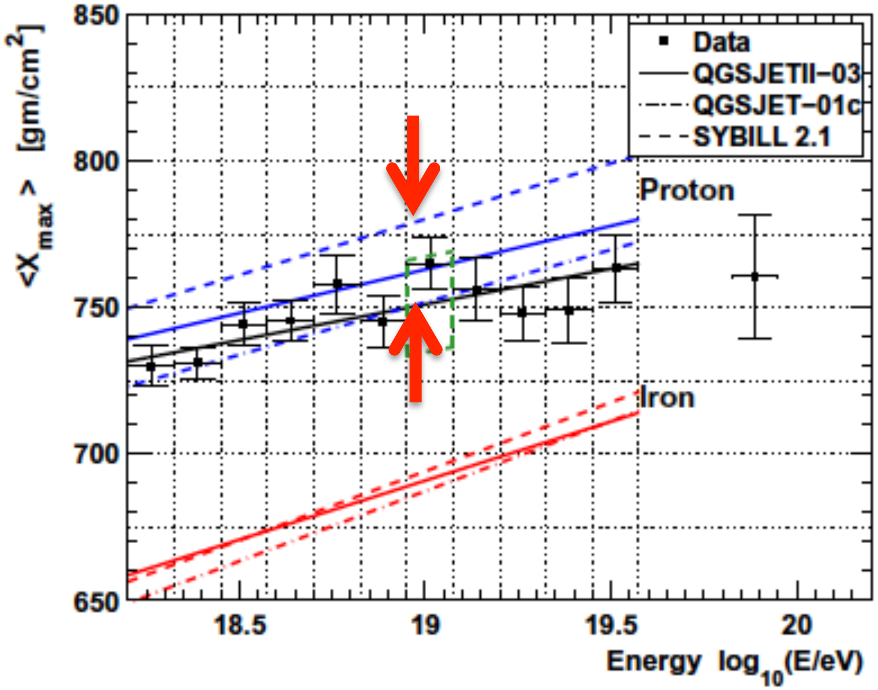
Overview and recent results of LHCf

Takashi SAKO
(KMI/ISEE, Nagoya University)
for the LHCf Collaboration

HECR Composition



PAO, PRD 90, 122005 (2014)

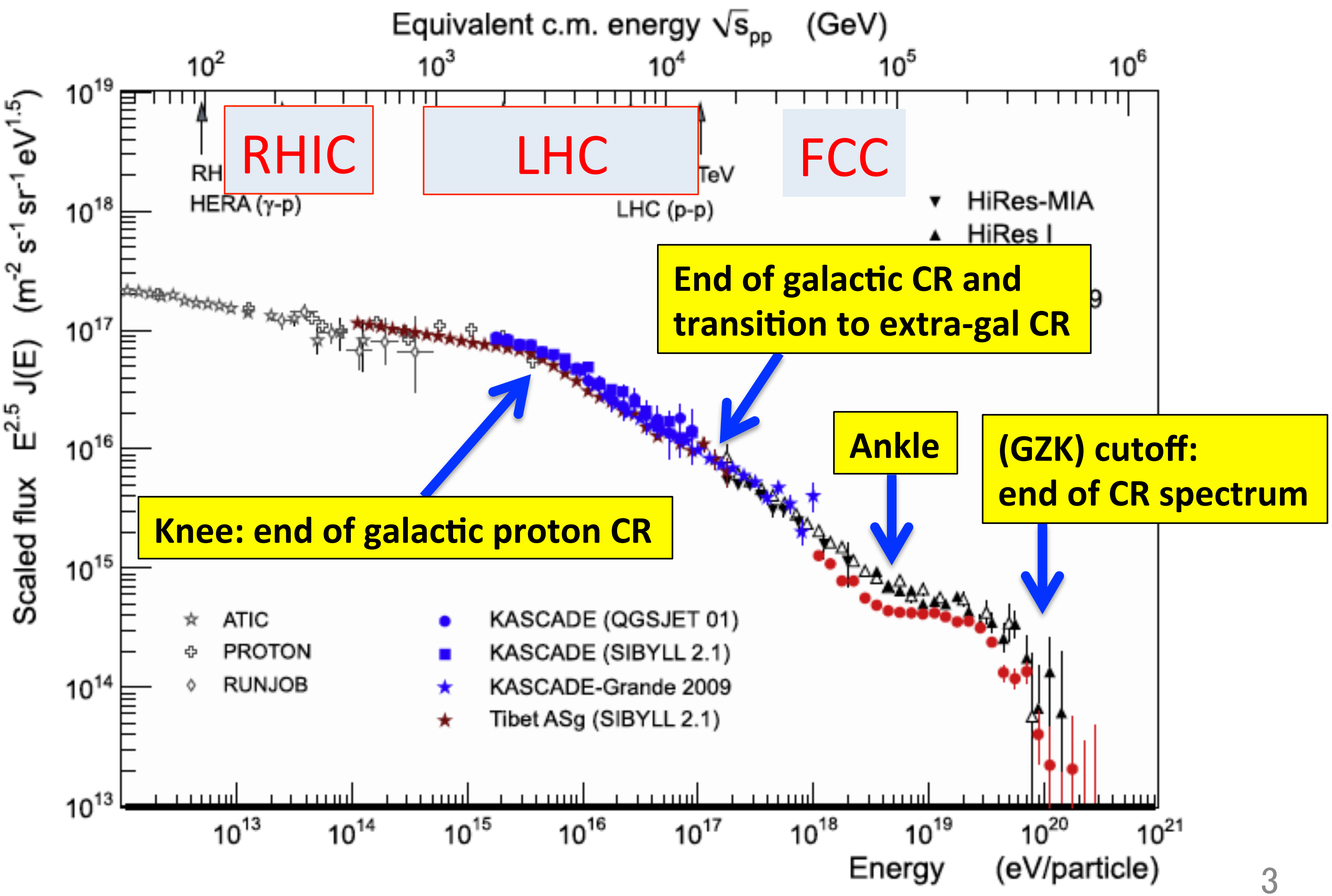


TA, APP 64, 49-62 (2015)

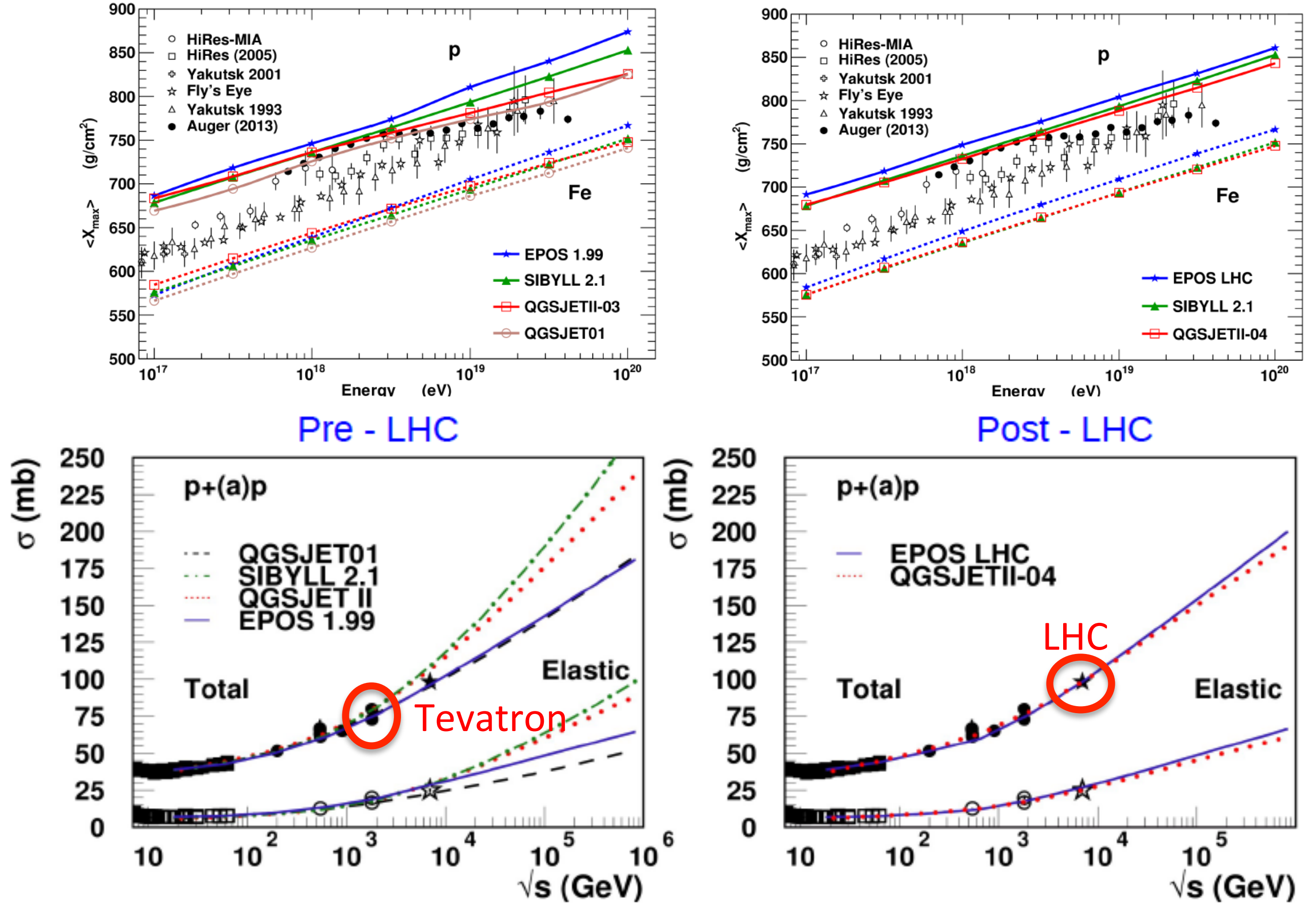
- ✓ Air shower observations determine $<X_{max}>$ vs. energy
- ✓ Model predictions to be compared differ at the level of experimental uncertainties
- ✓ Models must be tested by accelerator experiments

Cosmic-ray spectrum and collider energy

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



LHC Era (T.Pierog, HESZ2015)

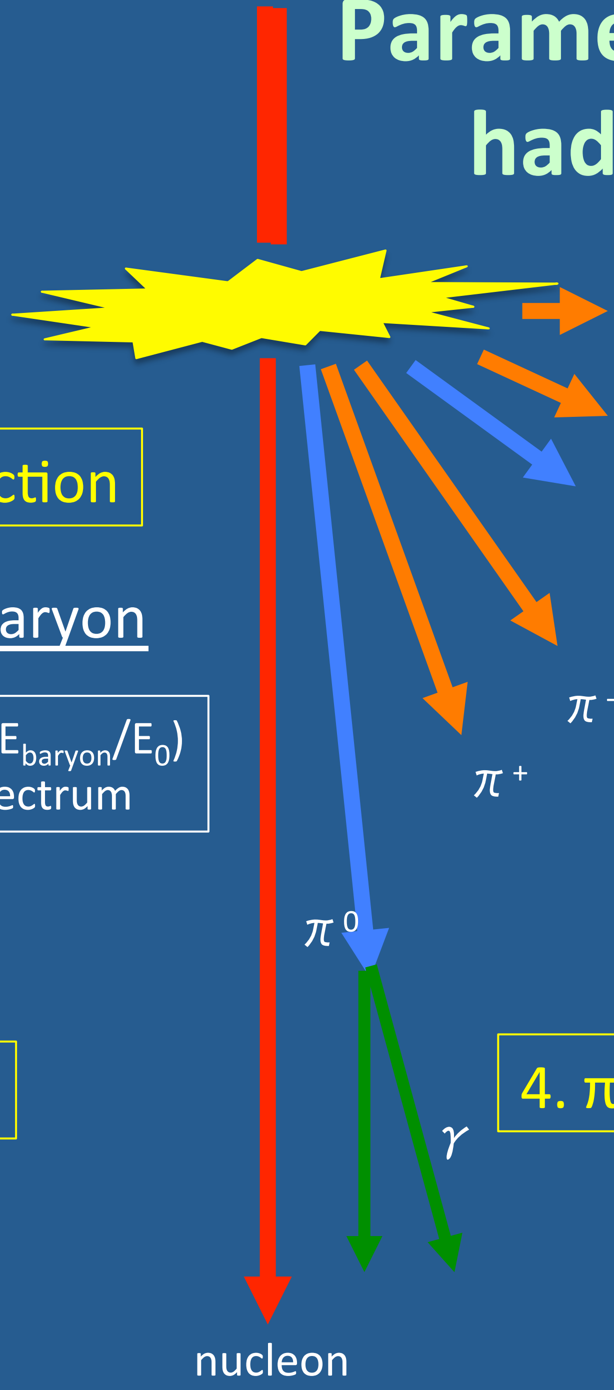


- ✓ Good agreement between post-LHC models, QGS II-04 and EPOS-LHC
- ✓ No update in SIBYLL, but very good agreement with the others. By chance???

Parameters to characterize hadronic interaction

1. σ_{ine} (λ_{int})

2. Particle production



Leading baryon

elasticity (E_{baryon}/E_0)
Baryon spectrum

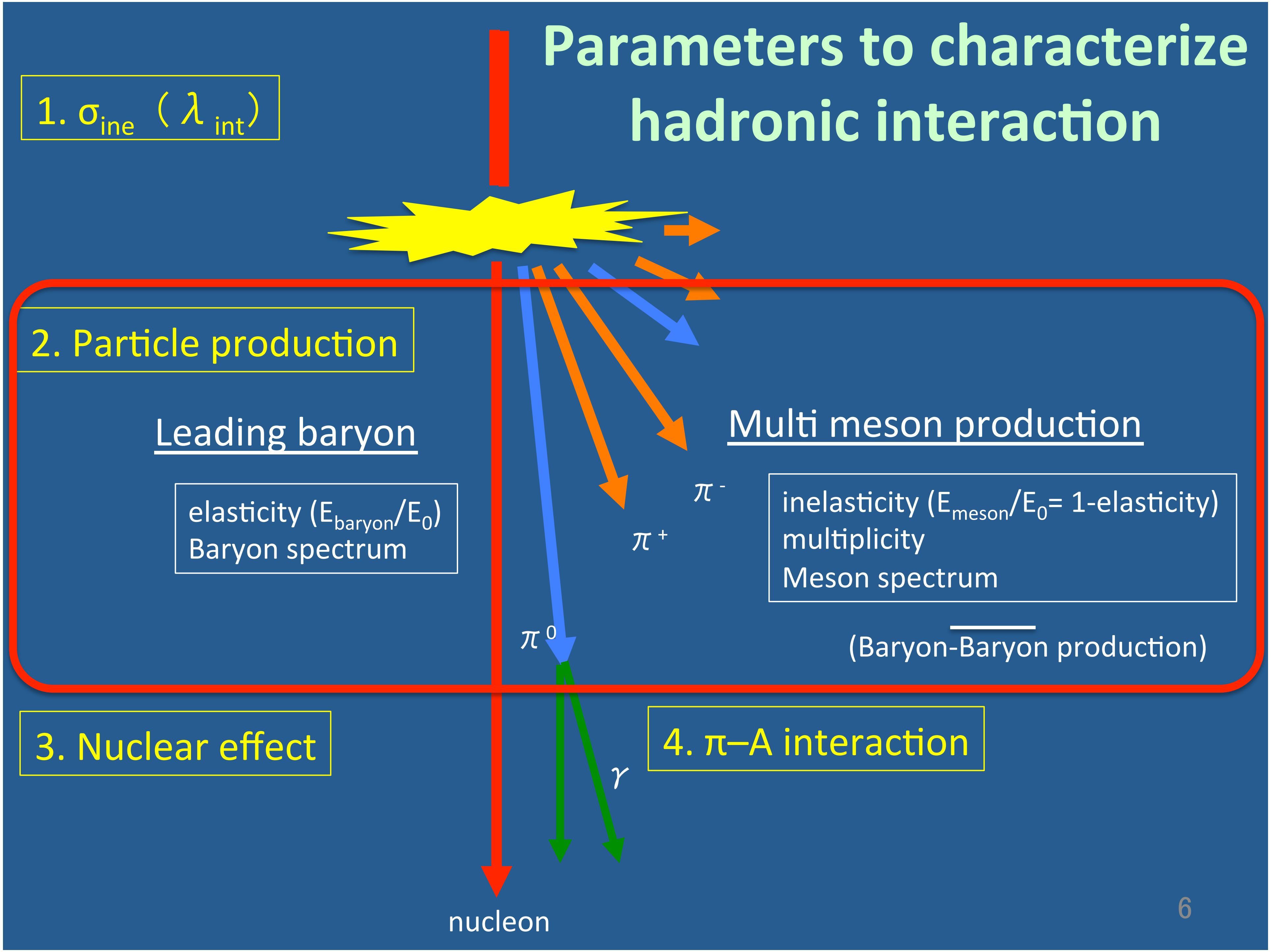
Multi meson production

inelasticity (E_{meson}/E_0= 1-elasticity)
multiplicity
Meson spectrum

(Baryon-$\overline{\text{Baryon}}$ production)

3. Nuclear effect

4. π–A interaction



Parameters to characterize hadronic interaction
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(Baryon-Baryon production)
π -
π +
π 0
γ
3. Nuclear effect
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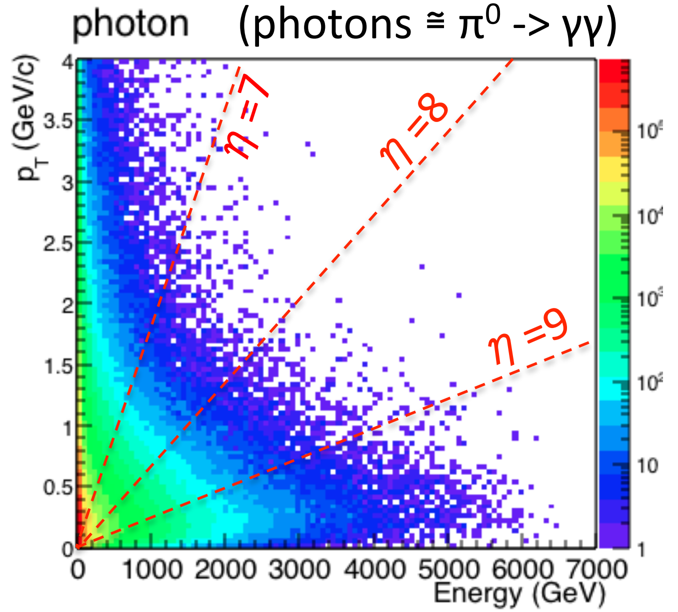
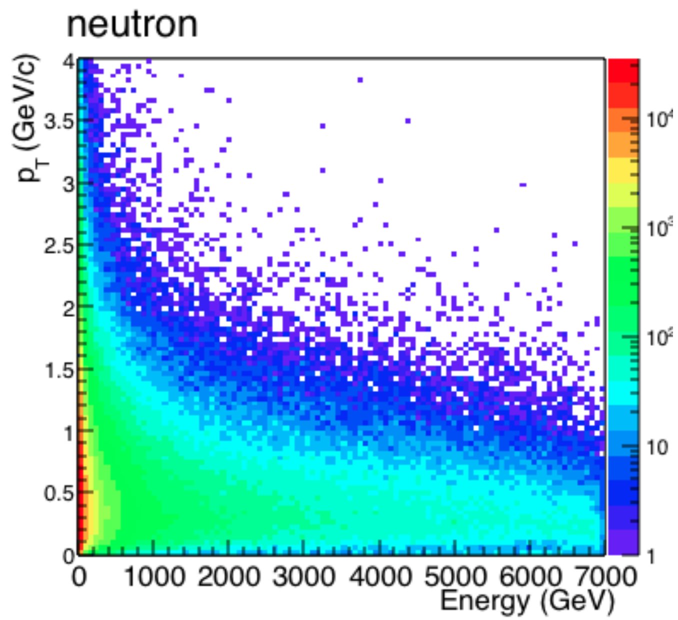
nucleon
6

Forward Particle Production

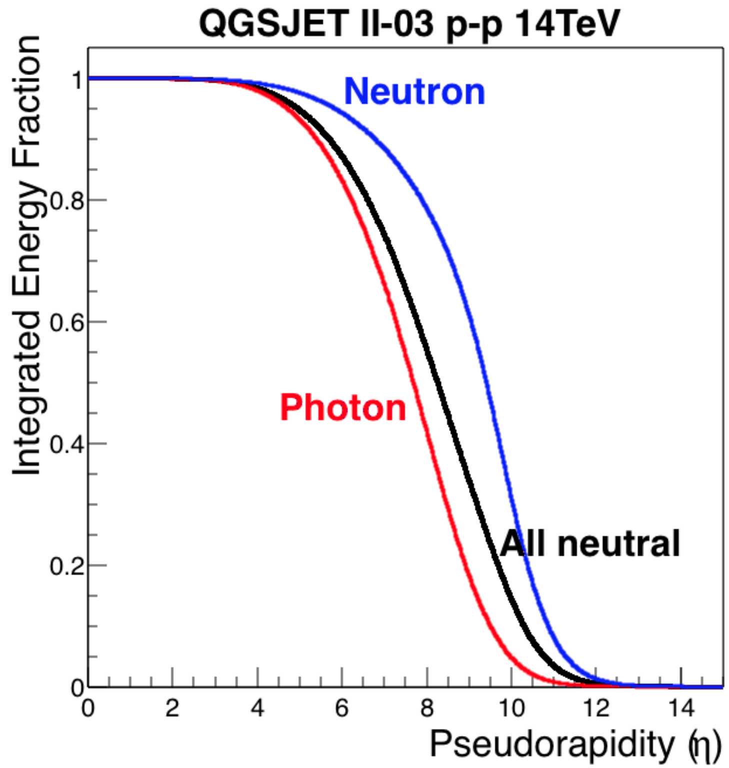
(photons ≅ $\pi^0 \to \gamma\gamma$)





- ✓ $\sqrt{s}$=14 TeV p-p collision (QGSJET II-03)
- ✓ Typical $p_T \approx$1GeV/c

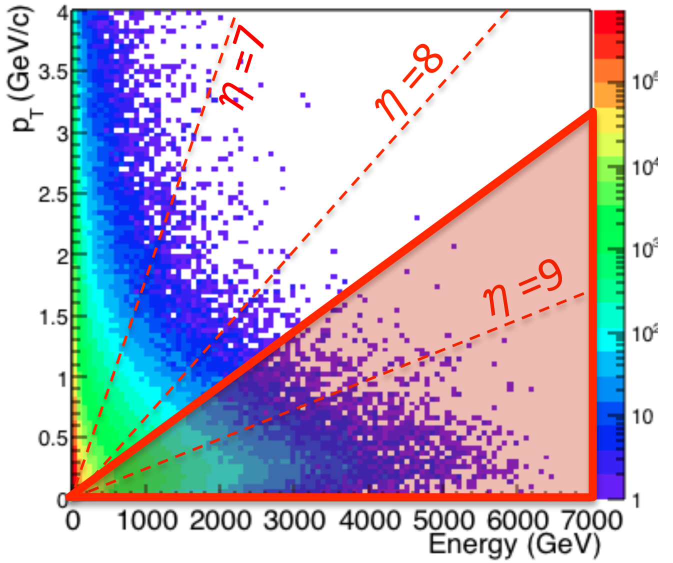
  => high-E particles are emitted forward

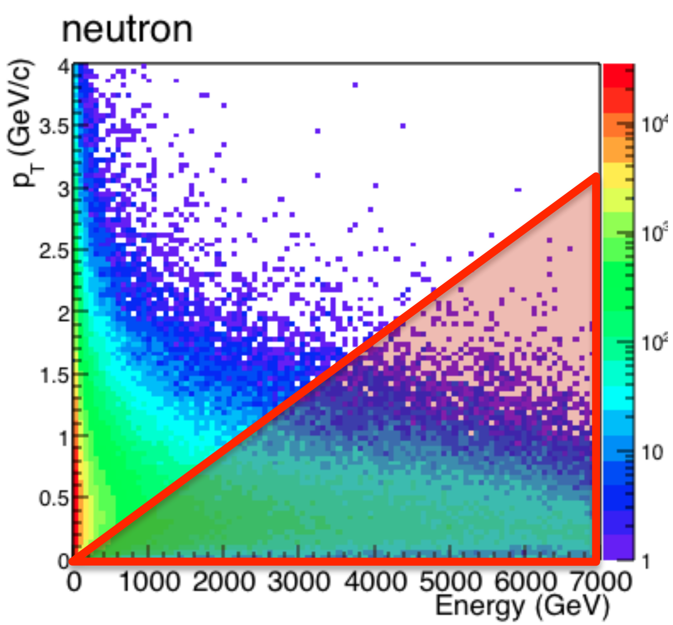


pseudorapidity: $\eta = -\ln(\tan(\theta/2))$

Forward Particle Production

photon (photons ≅ $\pi^0 \rightarrow \gamma\gamma$)





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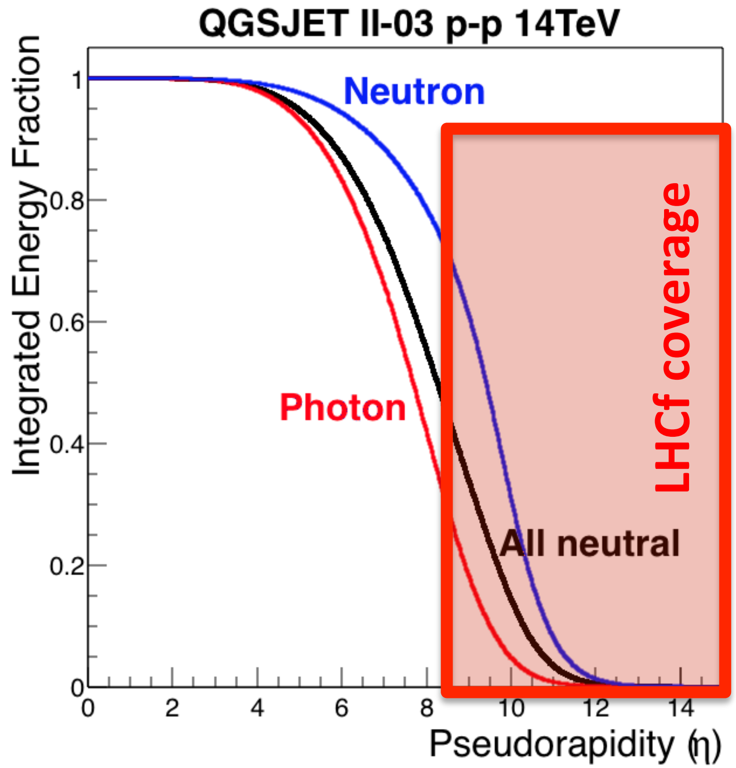

η =8.4 => θ = 440 μrad

The LHCf Collaboration

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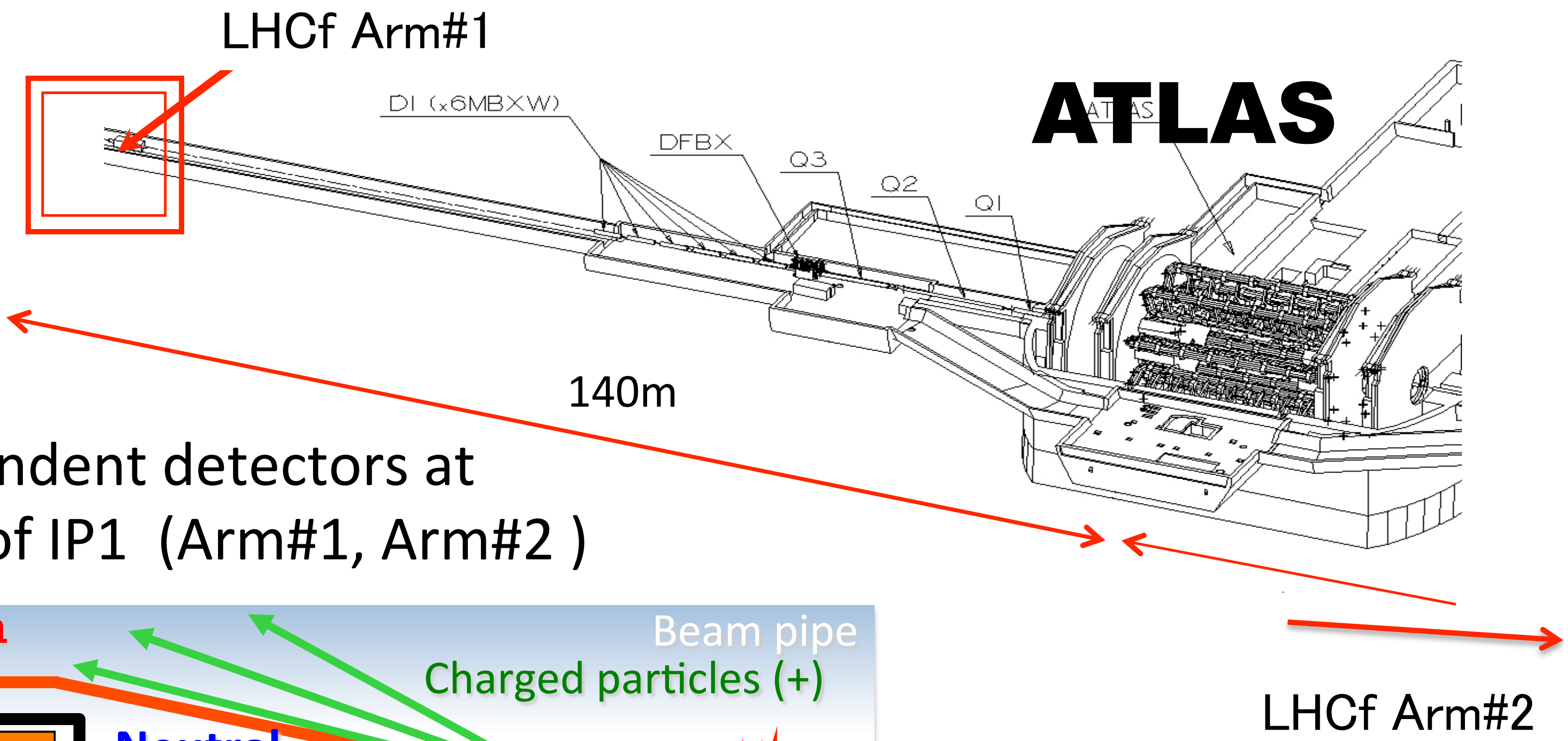
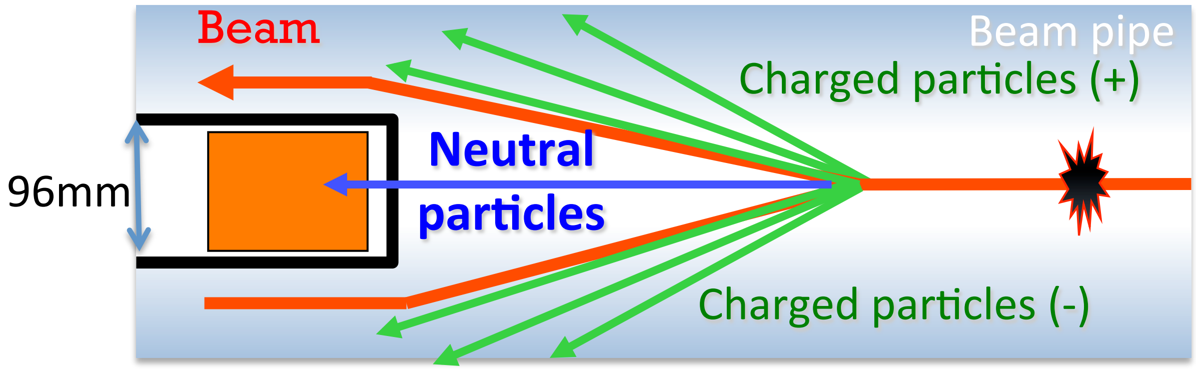
The LHC forward experiment



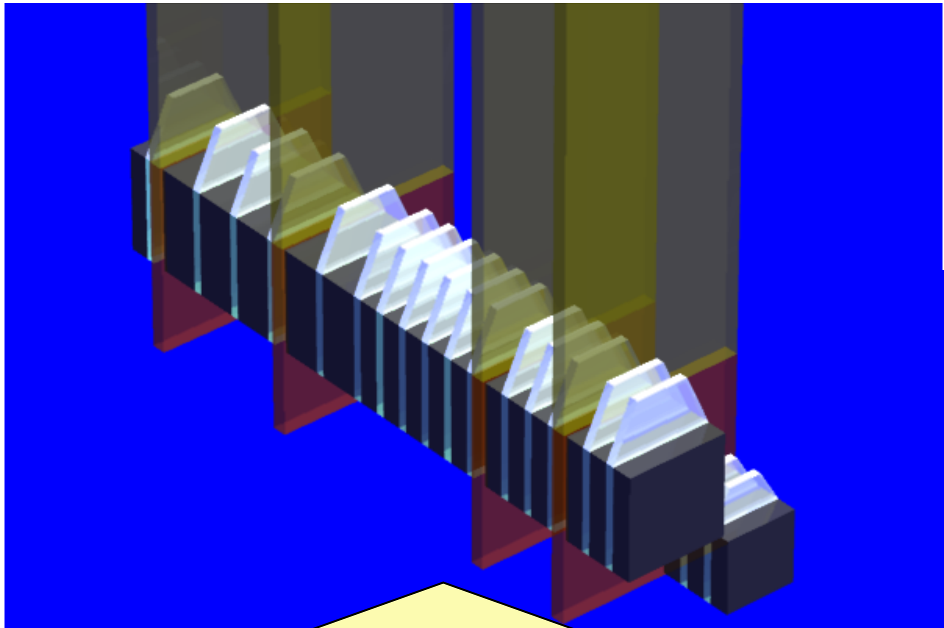
Two independent detectors at
either side of IP1 (Arm#1, Arm#2)



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

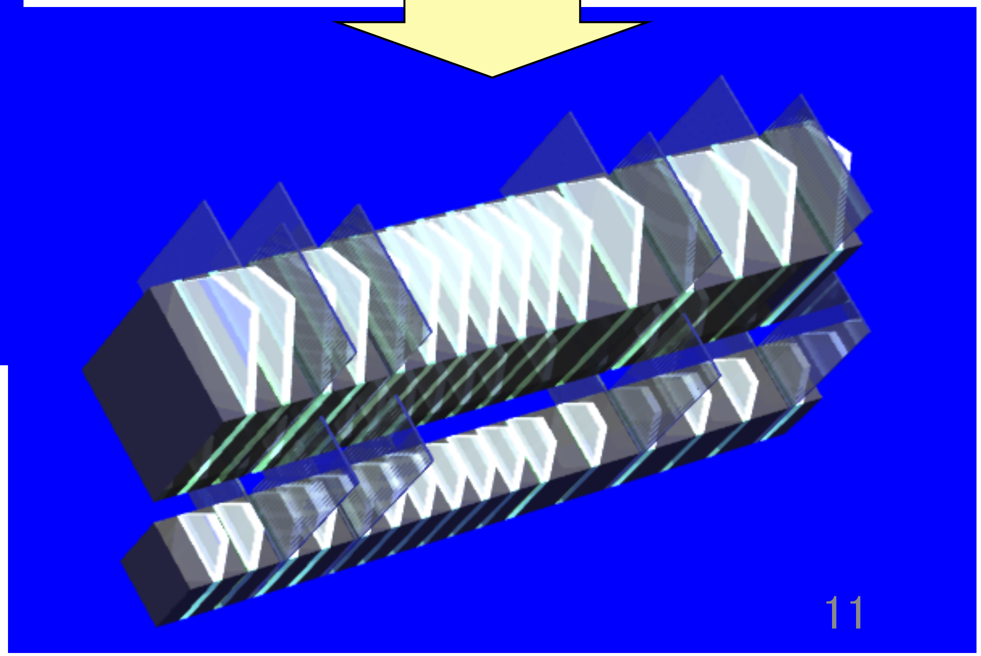
LHCf Detectors

- ✓ 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

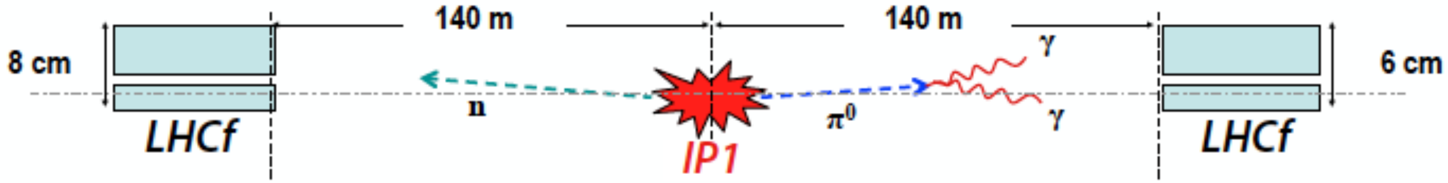


Arm#2 Detector
25mmx25mm+32mmx32mm
4 XY Silicon strip detectors

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

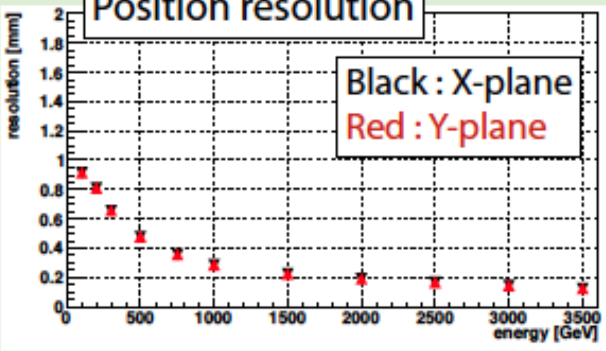


Detector performance

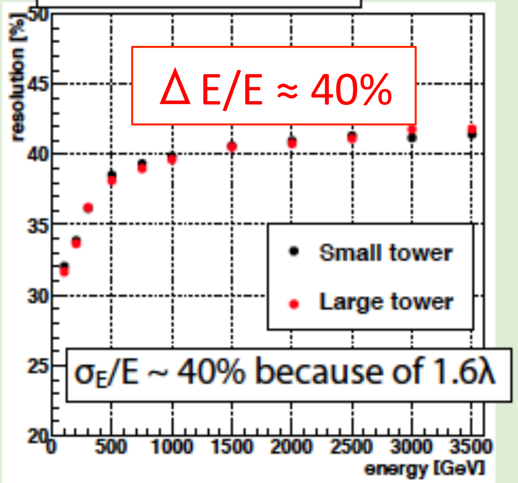


Hadronic shower (MC)

Position resolution

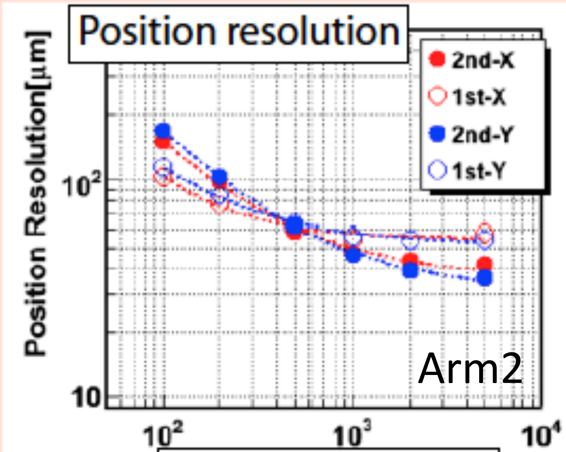


Energy resolution

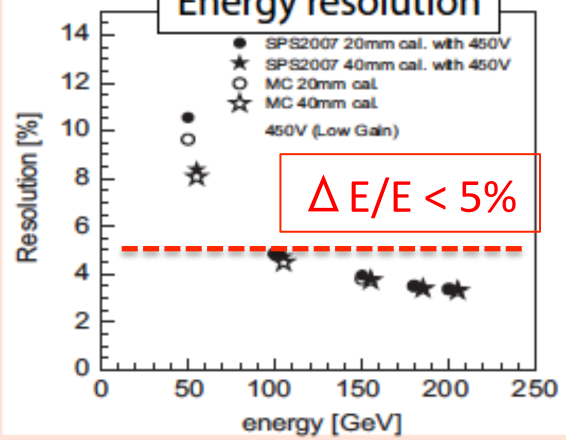


EM shower (MC)

Position resolution



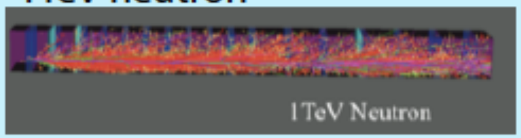
Energy resolution



PID technique

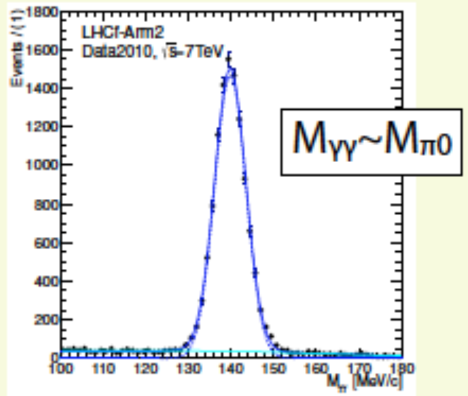
400GeV photon

1TeV neutron



Identification of incoming particle by shower shape

π^0 reconstruction



LHCf Operation History

- 2009-2010
  - Data taking with 900 GeV p-p collisions
  - Data taking with 7 TeV p-p collisions
- 2013 (only Arm2)
  - Data taking with 5.02 TeV p-Pb collisions
  - Data taking with 2.76 TeV p-p collisions
- 2015
  - Data taking with 13 TeV p-p collisions

Publications

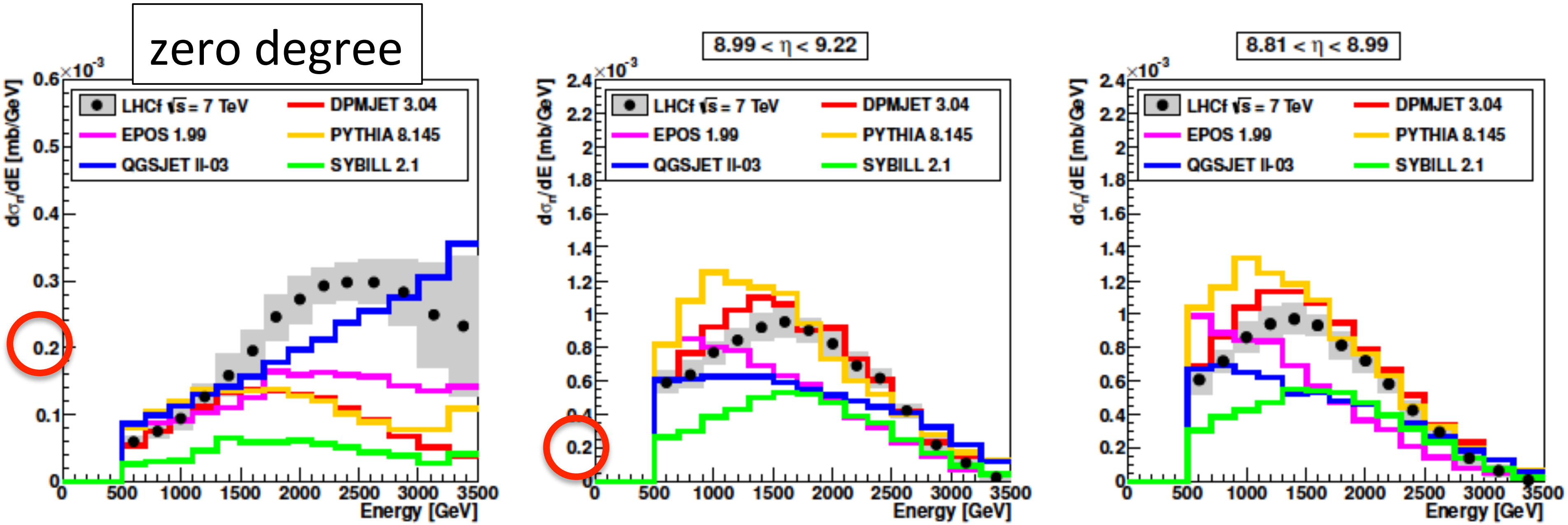
<table>
<tr><th></th><th>Photon (EM shower)</th><th>Neutron (hadron shower)</th><th>π^0 (limited acceptance)</th><th>π^0 (full acceptance)</th><th>Performance</th></tr>
<tr><td>Beam test</td><td>NIM, A671 (2012) 129-136</td><td>JINST, 9 (2014) P03016</td><td></td><td></td><td></td></tr>
<tr><td>0.9TeV 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 submitted</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 colspan="5">Analysis in progress</td></tr>
</table>

physics results

performance results

Forward neutron spectra in 7TeV p-p collisions

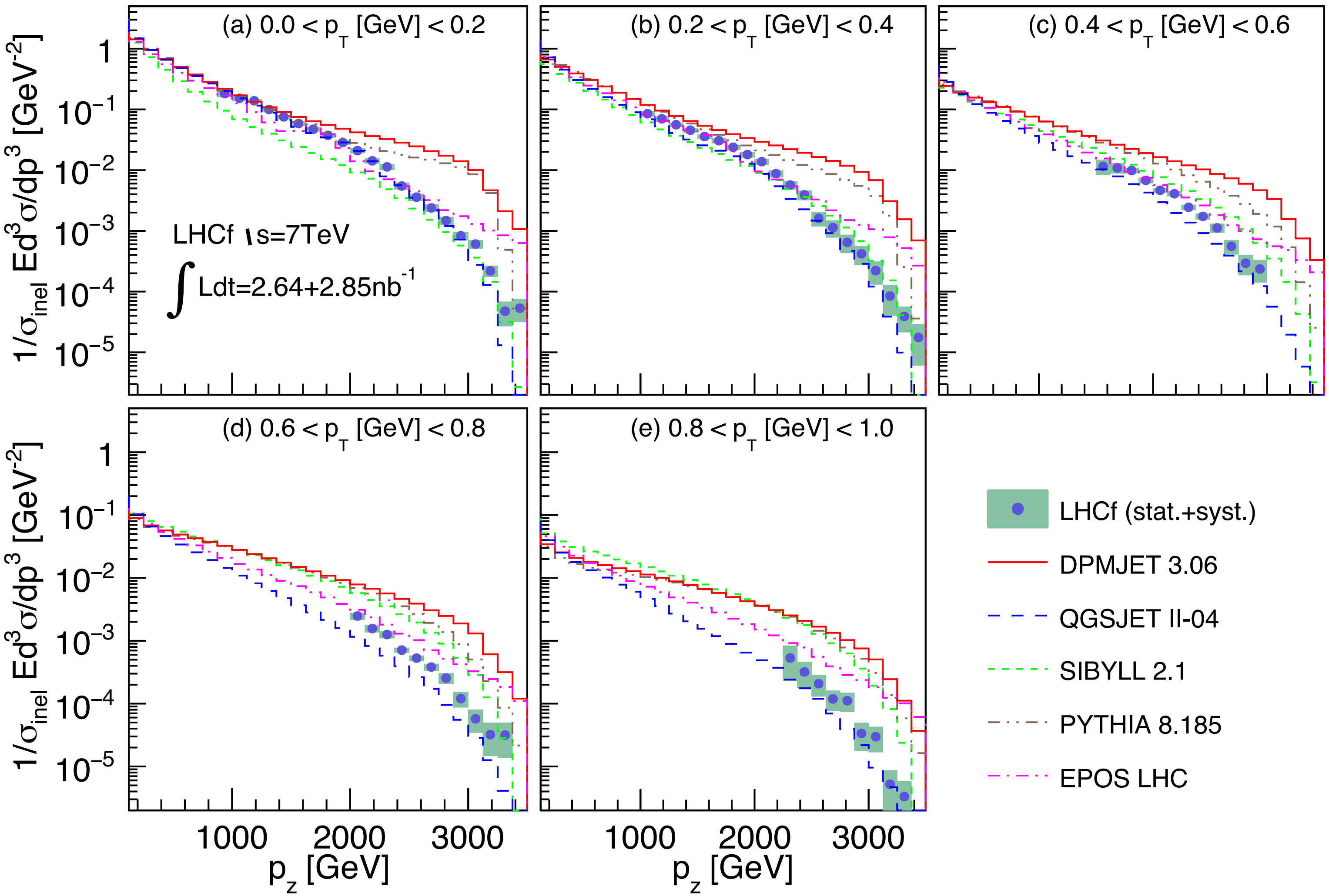
(√s=7TeV p-p ; PLB 750 (2015) 360-366)



- ✓ Zero degree production is qualitatively explained by QGSJET II
- ✓ Non-zero-degree productions (larger cross section) are underestimated by popular QGSJET II and EPOS models

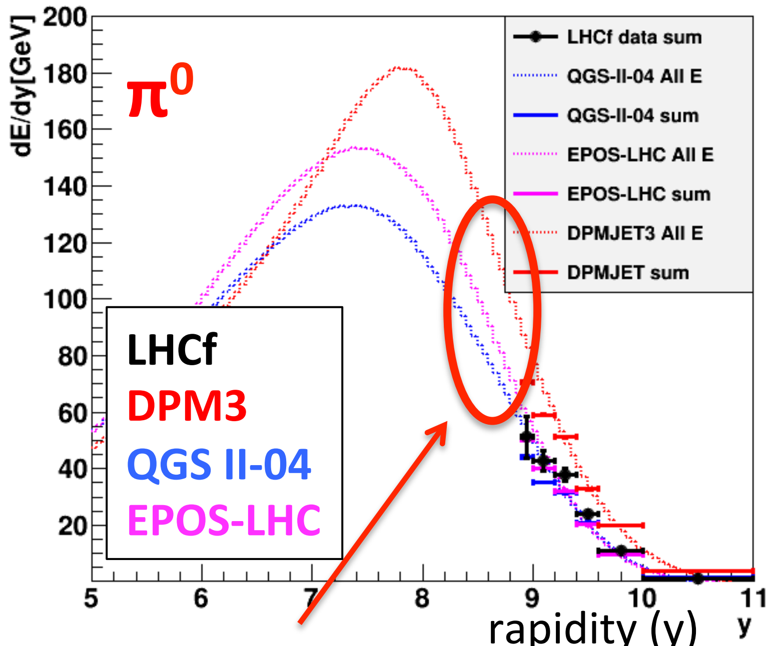
π^0 p_z spectra in 7TeV p-p collisions

(PRD submitted,arXiv:1507.08764 [hep-ex])

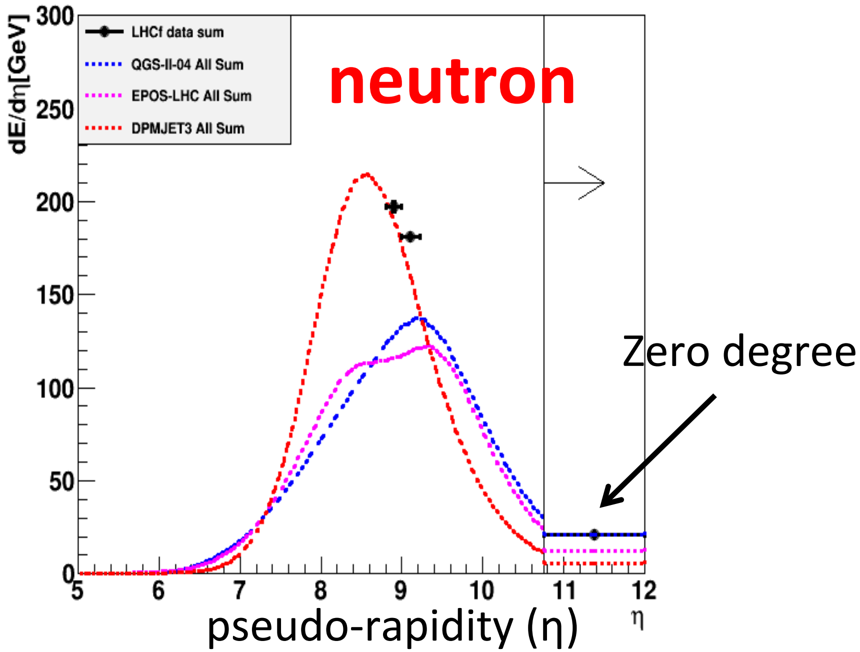


Energy flow in 7TeV p-p collisions

- ✓ Post-LHC models (EPOS-LHC and QGSJET II-04) well explain the π^0 results, but not for neutrons
- ✓ DPMJET3 explains the neutron results, but it is not recently used for CR simulations



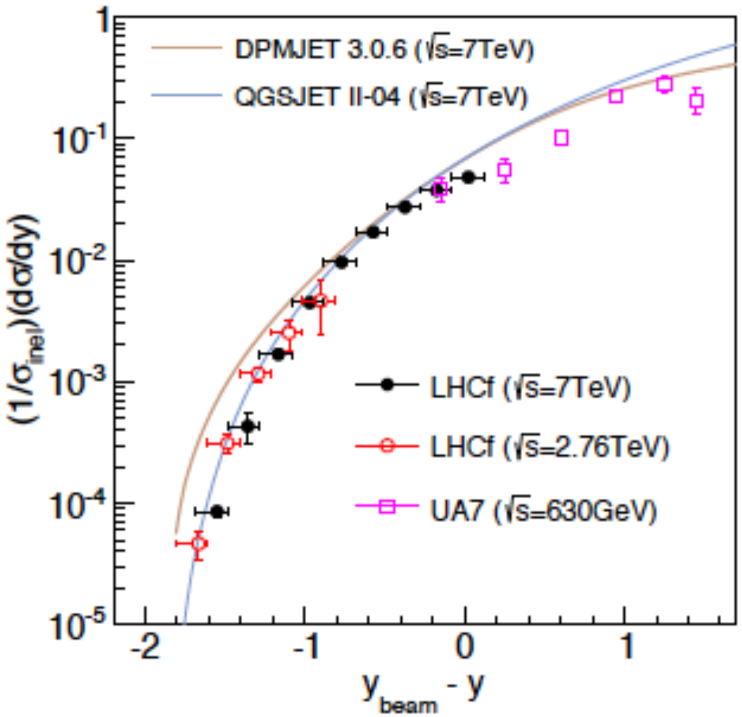
to be covered in 13TeV

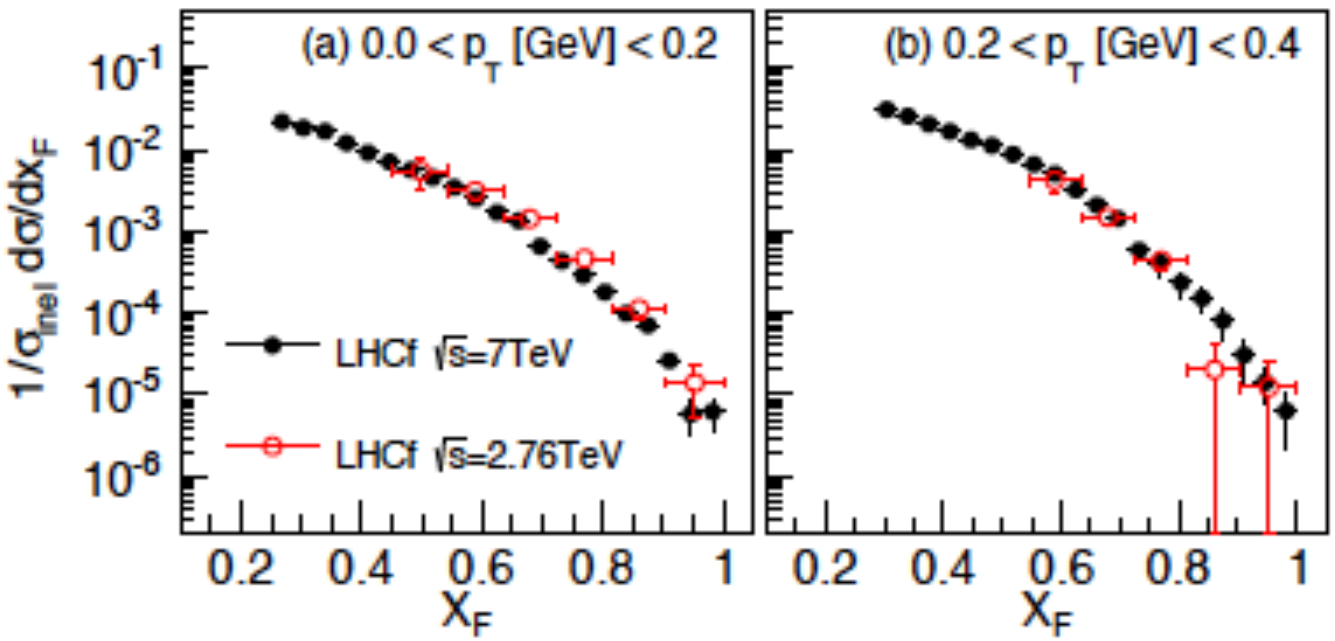


Black solid circle : LHCf data (π^0 , LHCf 2012)
Dotted lines : π^0 energy flow distribution of each model
Thick horizontal line : Energy flow calculation after p_T cut

√s scaling of π^0 production

- ✓ (630GeV –) 2.76TeV – 7TeV
  good scaling within uncertaintes
- ✓ Wider coverage in y and p_T with 13TeV data
- ✓ Wider √s coverage with RHICf experiment in 2017 at √s=510GeV





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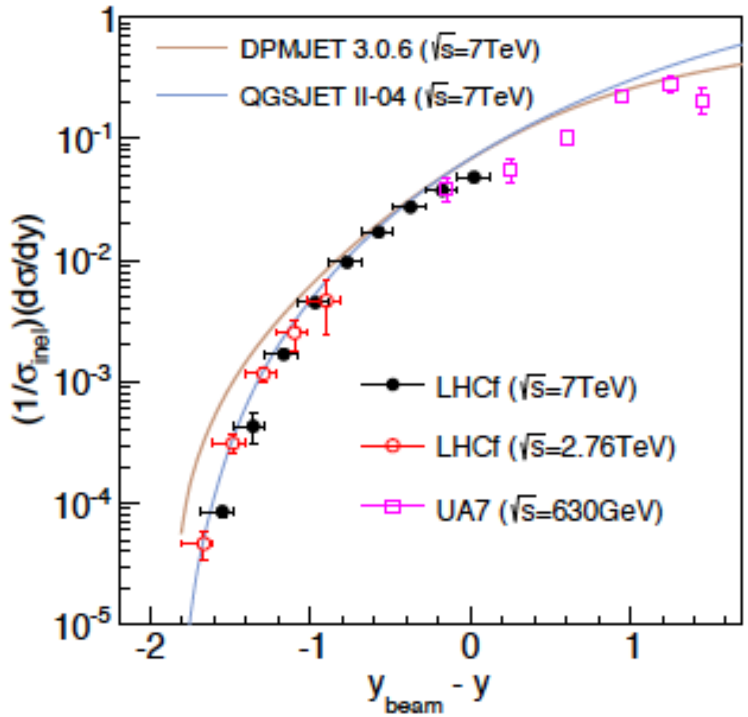
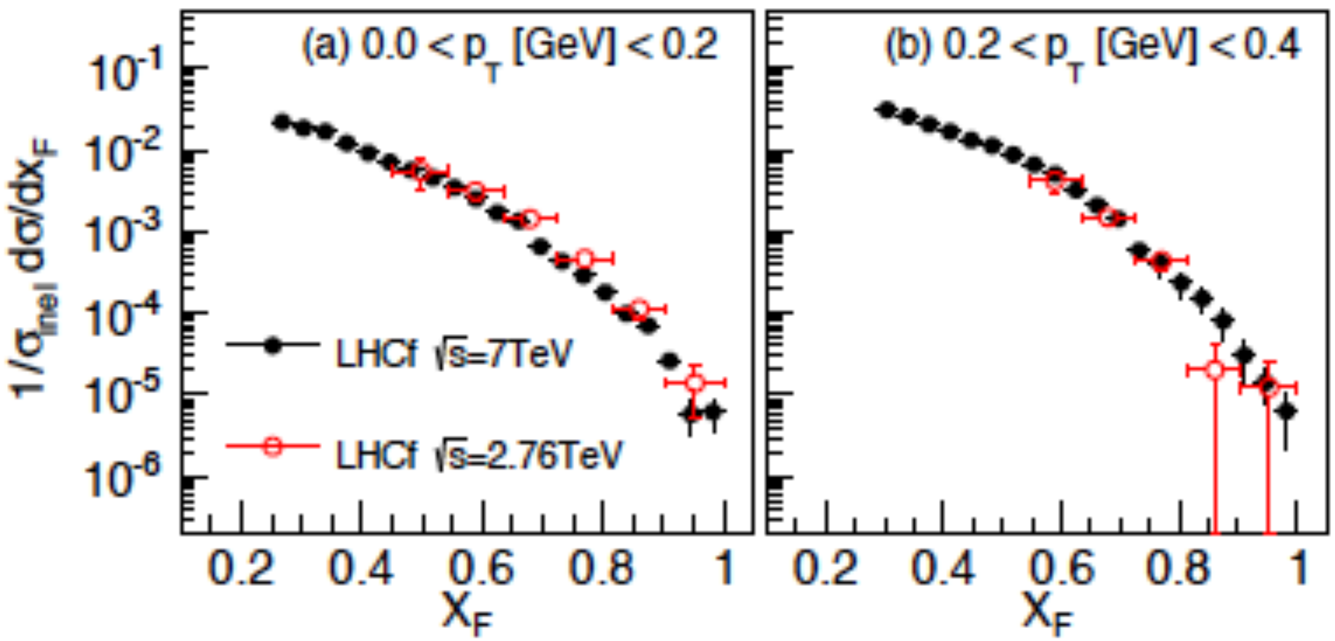
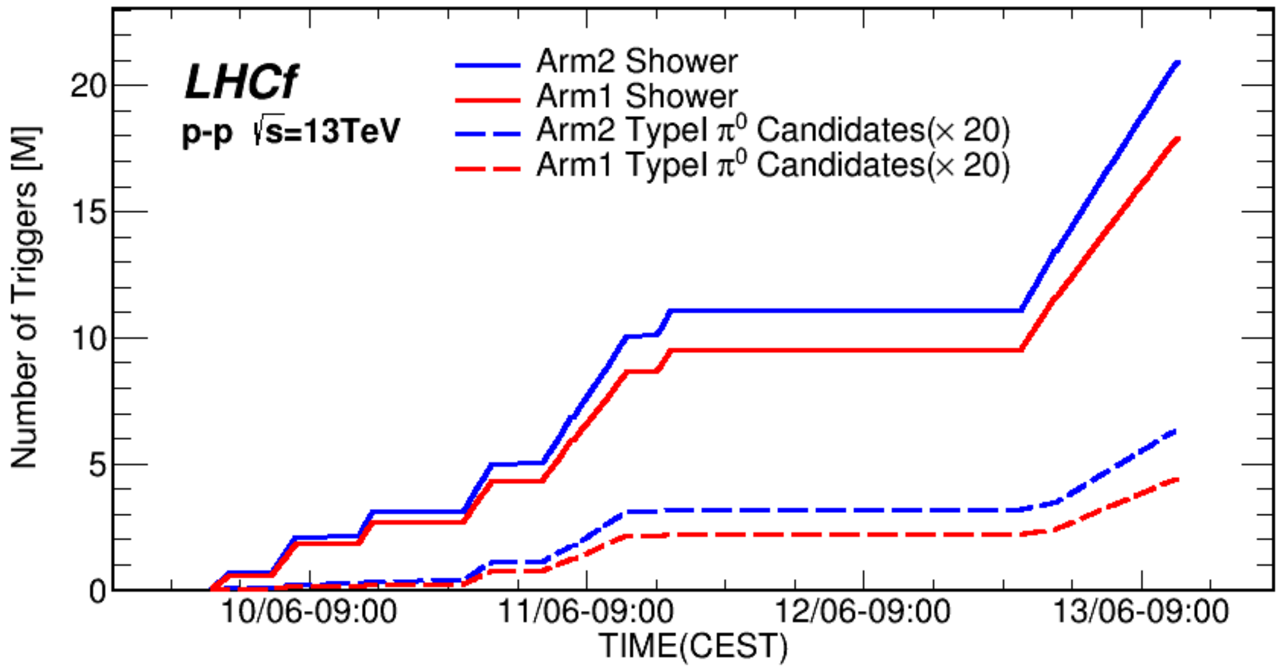


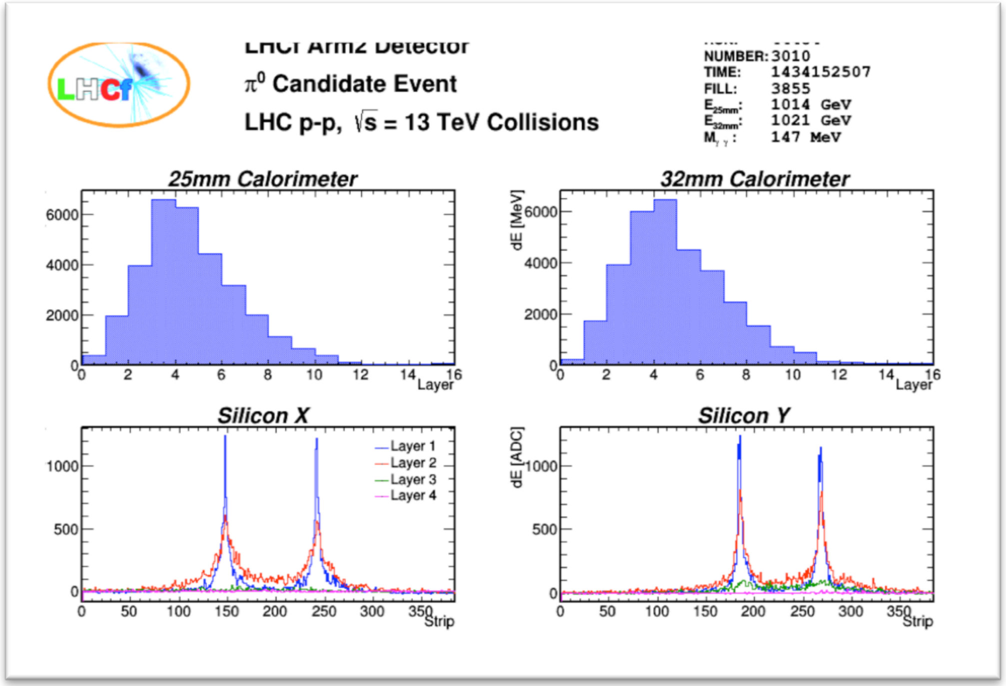


13TeV operation in June 2015



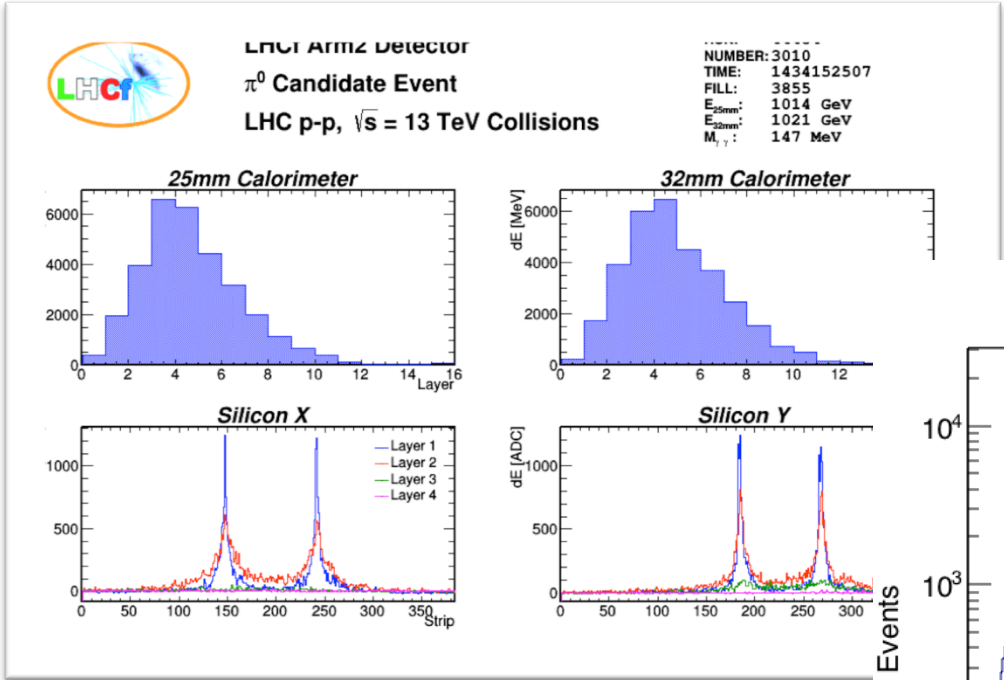
- LHCf physics fills: 10-13 June 2015
- Total physics data taking: **26.6 hours**
- Observed high energy (>100GeV) particles : **39M events**
- π^0 candidates : **0.5 M events**

13TeV operation in June 2015

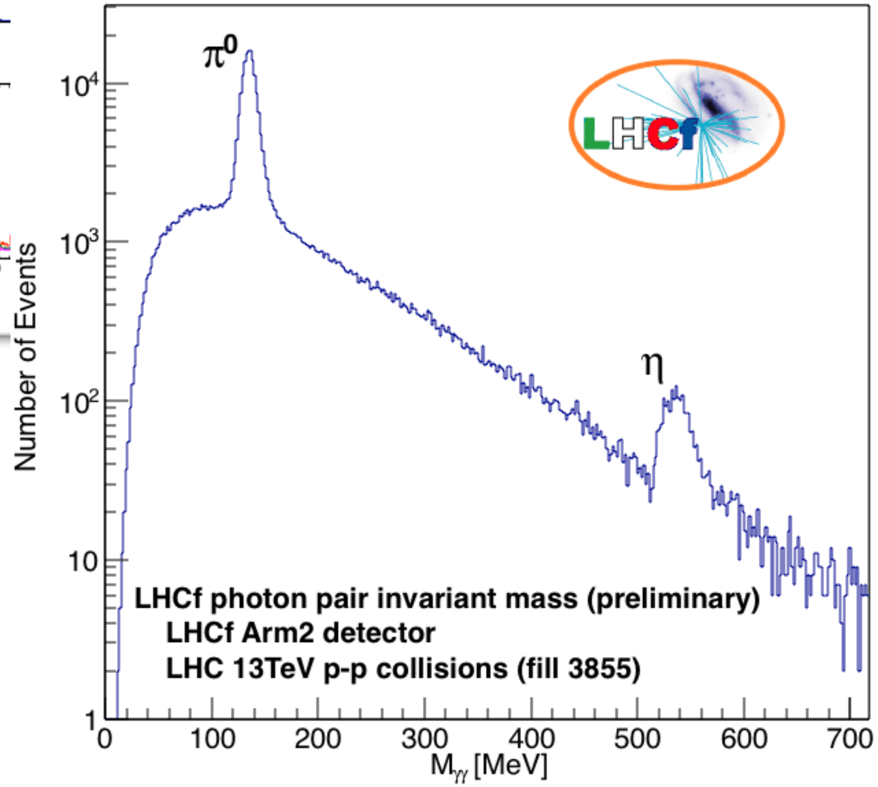


2TeV π^0 by Arm2

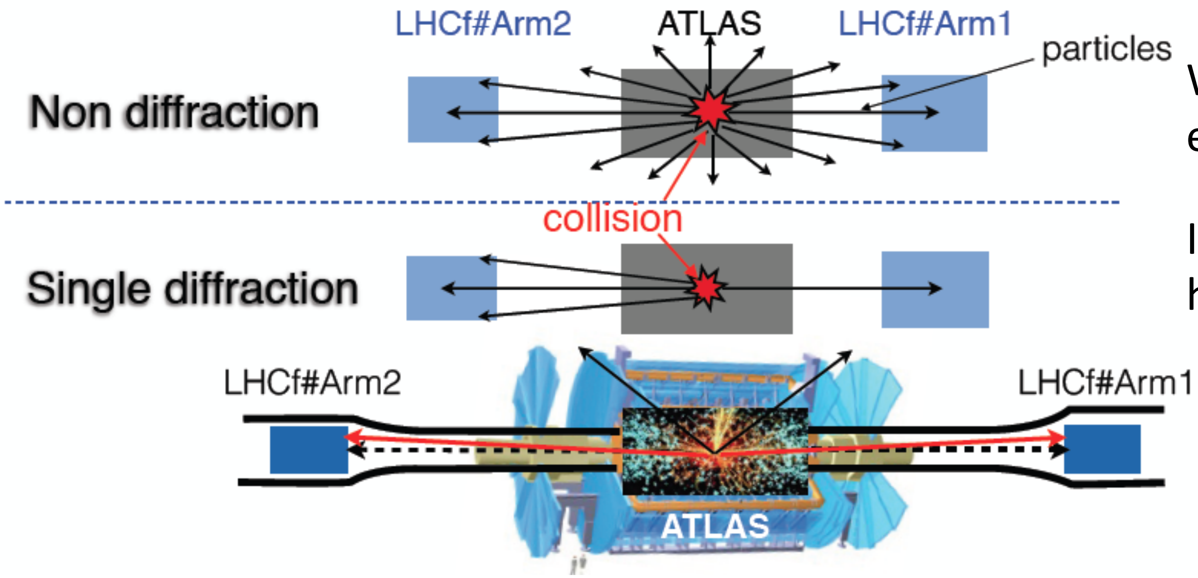
13TeV operation in June 2015



2TeV π^0 by Arm2



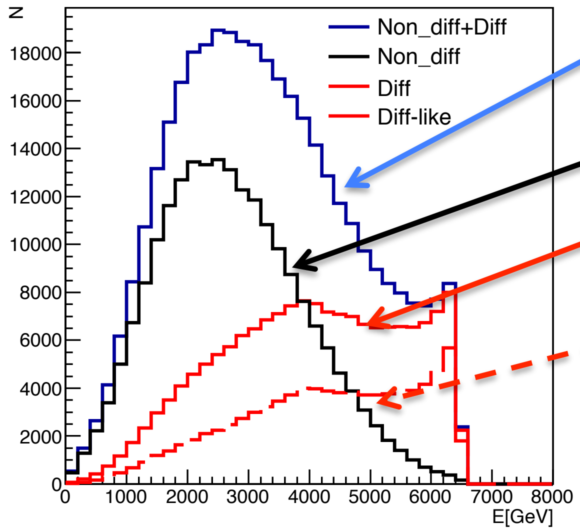
Joint analysis with ATLAS



Well studied by big experiments

Invisible for big experiment but having high energy

PYTHIA8 simulation



All LHCf events (mixture of diffraction and ND)

MC True; non-diffraction (ND)

MC True; diffraction

LHCf events selected using ATLAS information, same shape to the TRUE diffraction events

Summary

- ✓ Collider data improve the hadronic interaction models used in the cosmic-ray studies
- ✓ LHCf measures forward particle spectra, both baryons and mesons, carrying a large fraction of collision energy
  - LHCf π^0 spectra are well explained by the post-LHC models, EPOS-LHC and QGSJET II-04
  - LHCf neutron spectra show excess, 30% in energy flow, than the post-LHC models
  - LHCf confirmed scaling of π^0 production at 2.76 TeV and 7 TeV data, but in a limited phase space
- ✓ 13TeV data taking in 2015 was successful
  - Scaling test with wider phase space at the highest energy
  - More insight to the process by collaborating with ATLAS
- ✓ Low energy extension at RHIC is scheduled in 2017
  - Wider $\sqrt{s}$ coverage for scaling test => important to access $>10^{17}$eV