Cosmic ray physics at accelerators

Gaku Mitsuka
(University of Florence, INFN Firenze, and JSPS fellow)

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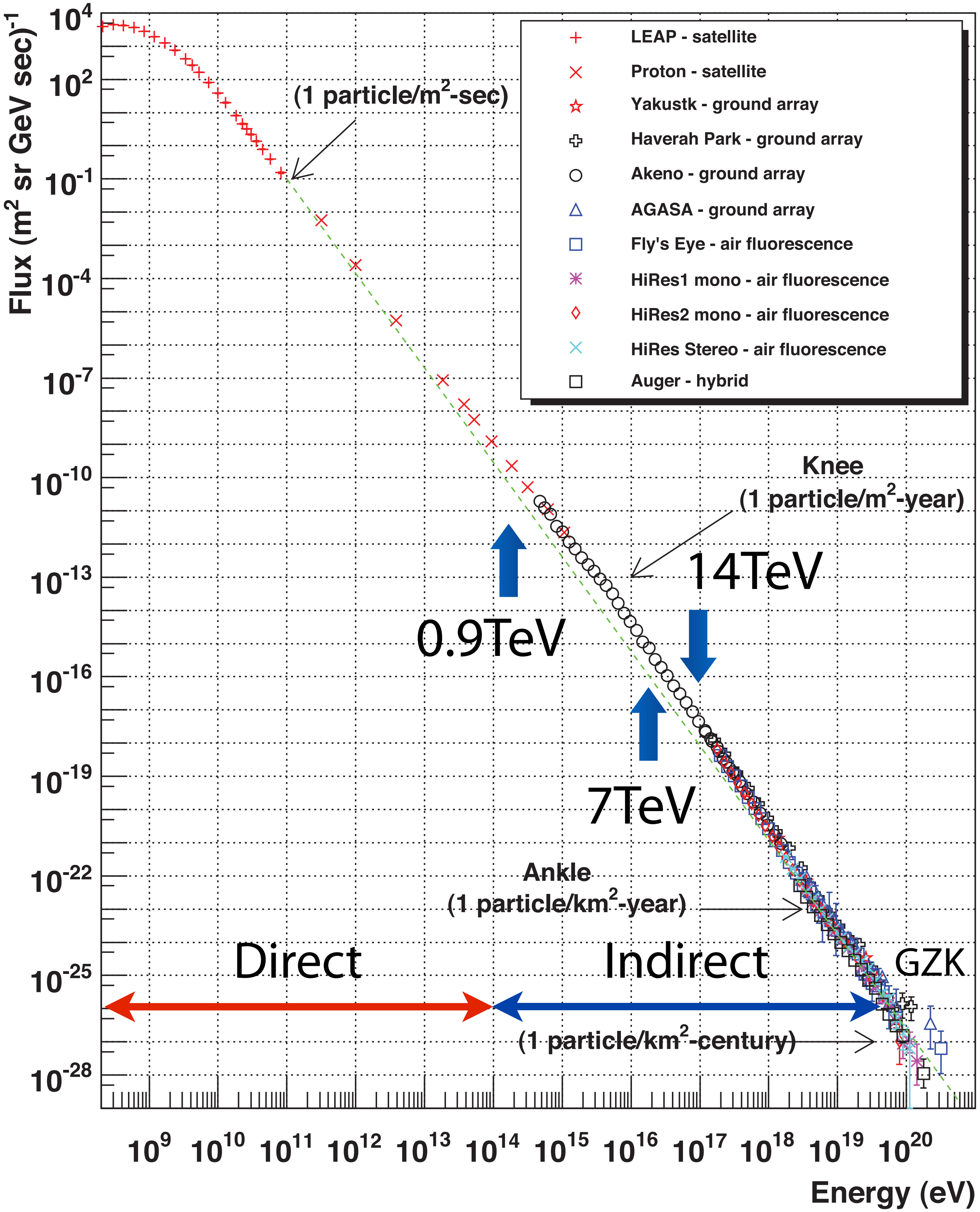
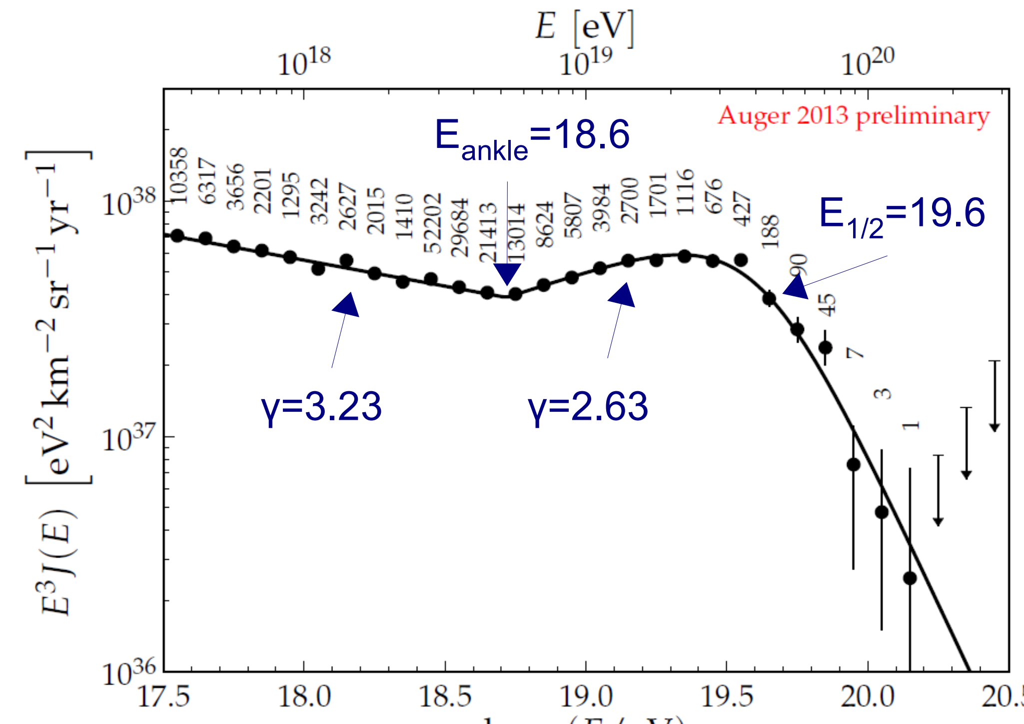
Outline

- Introduction: from cosmic ray to accelerator
- Recent LHC results: LHCf, diffraction, and cross section
- What's next ?
  - Extrapolation and scaling
  - RHICf project
  - Light-ion collision
- Summary

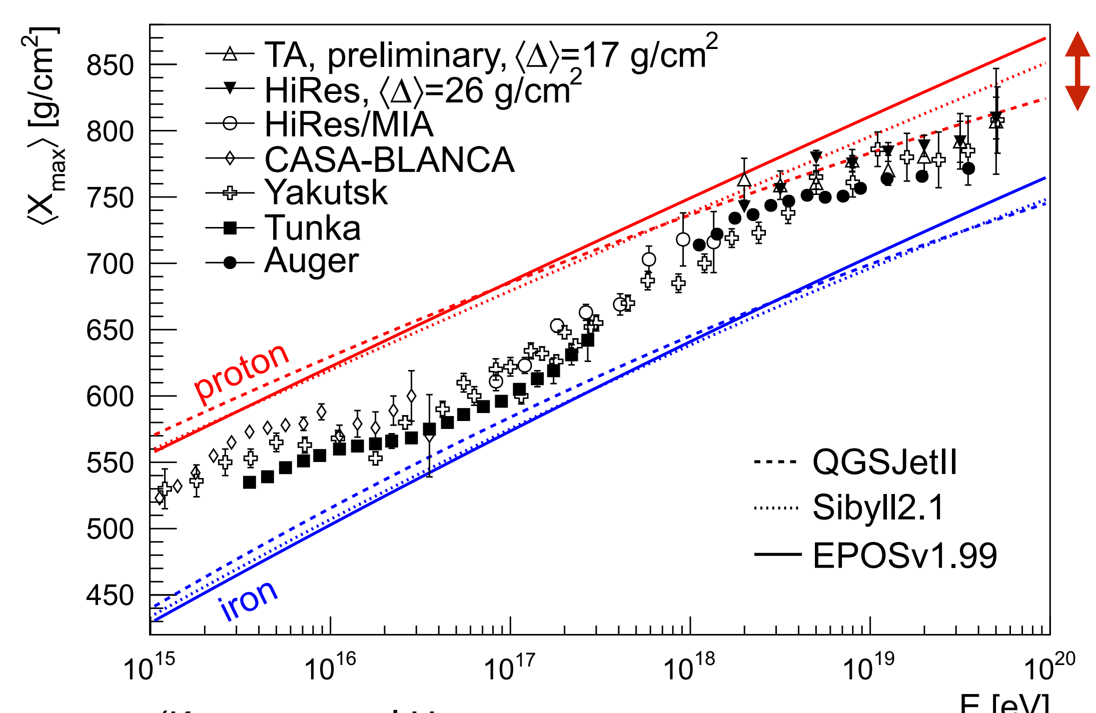
Cosmic ray observation





(ICRC2013, 769)

model error



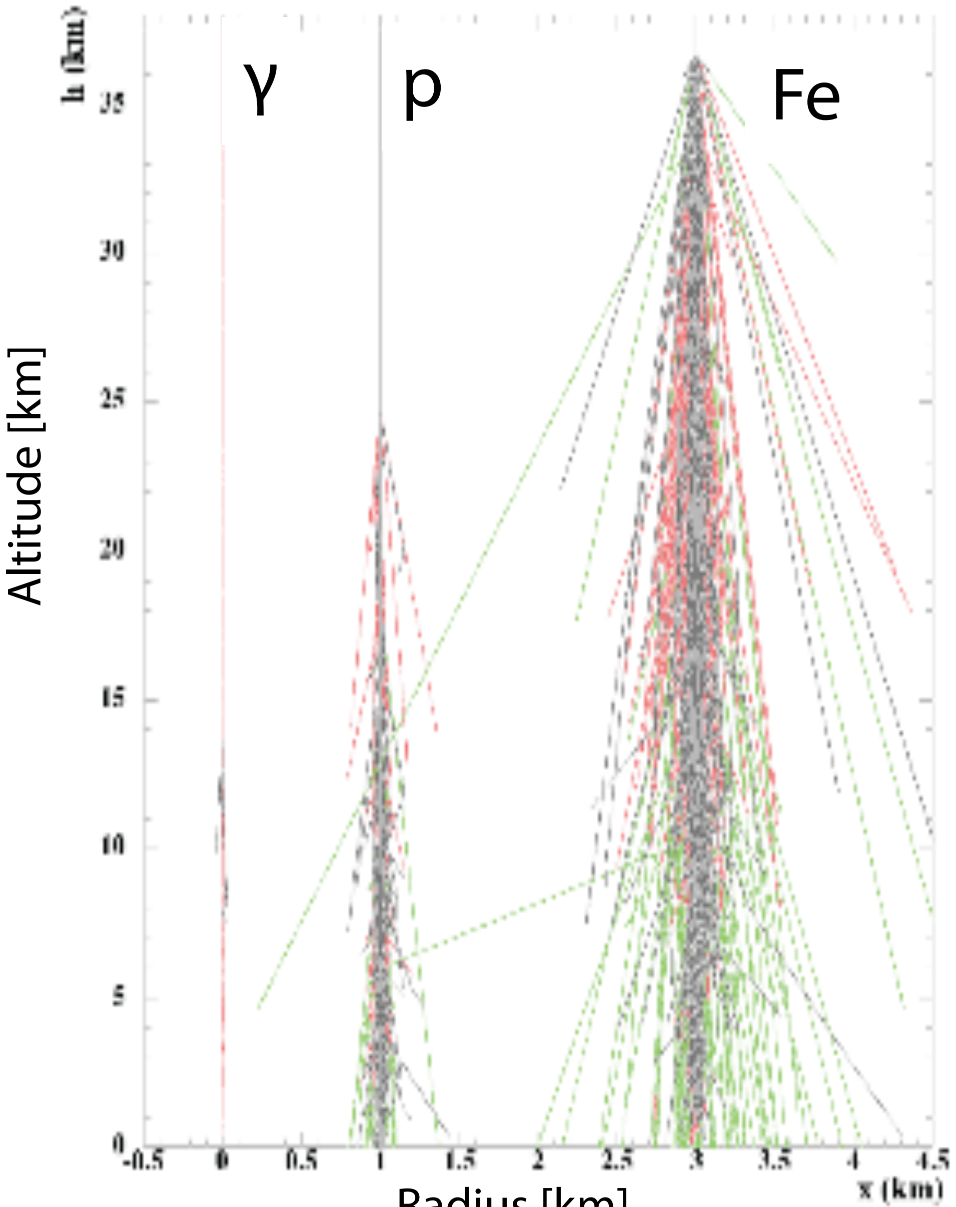
(Kampert and Unger, Astropartphys. 35, 660, (2012))

Energy, mass composition, and direction

→Source of cosmic ray

→Structure of the universe (goal)

Indirect observation of cosmic rays



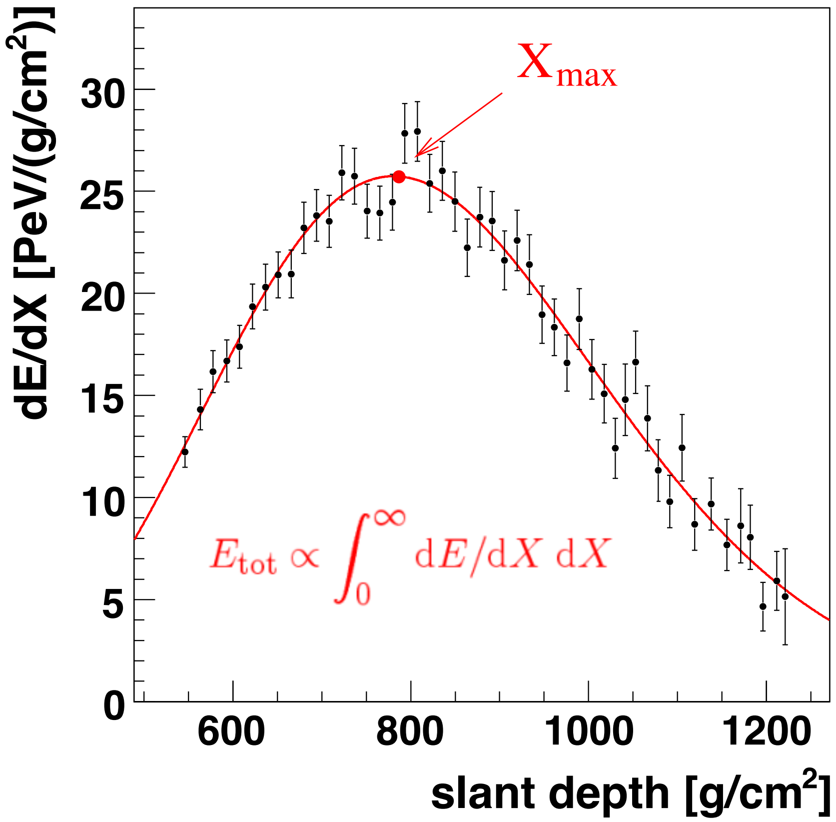
Surface detectors (charged+photon)

- It is impossible to directly* measure cosmic rays properties above 10^{14}eV, but **possible indirectly using the cascade shower of daughter particles, Extensive Air-Shower (EAS).**

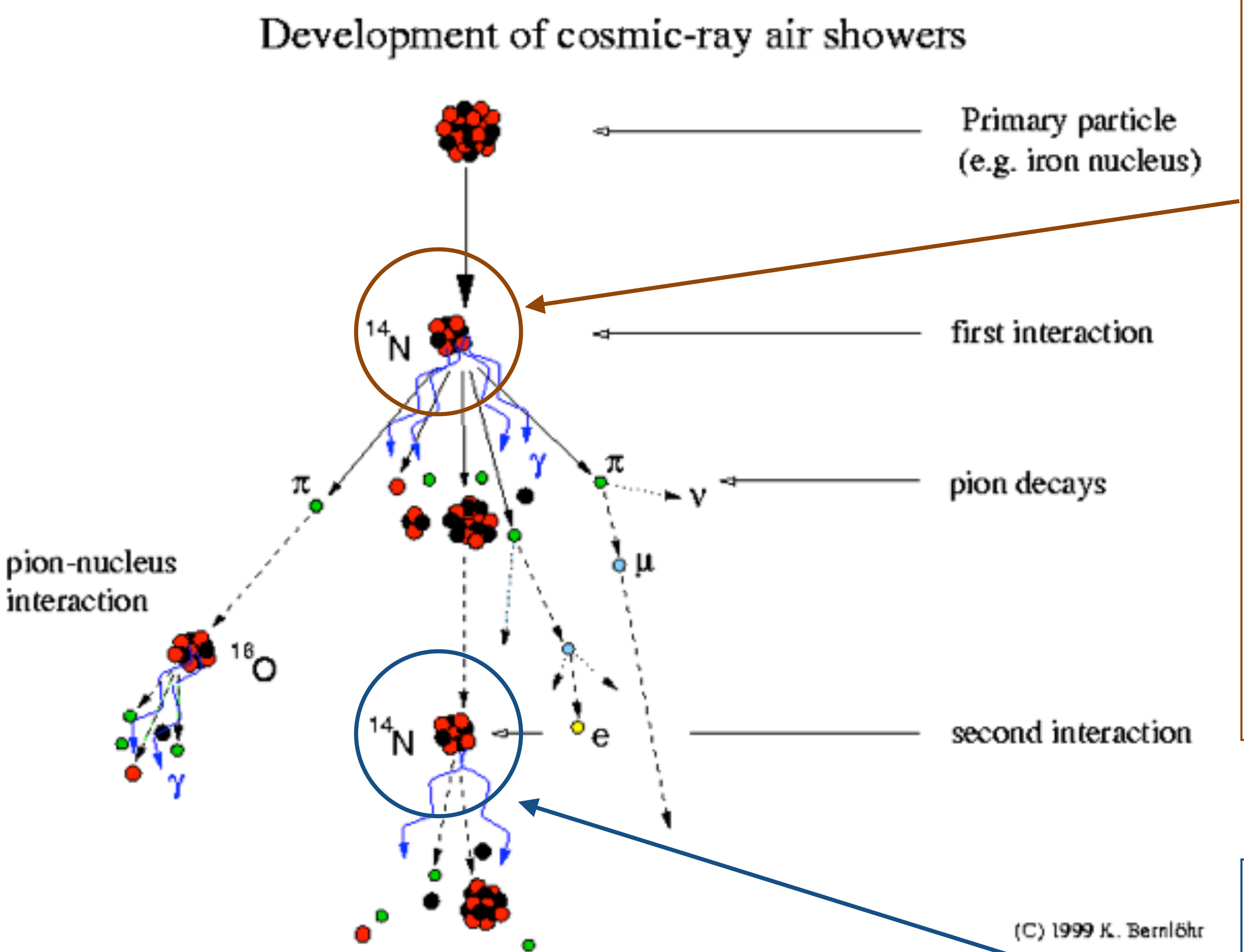
- Dependence of EAS on a mass composition and energy of cosmic rays is used for PID and energy reconstruction.

* direct measurement of cosmic ray <10^{14}eV is done by balloon, satellite, and ISS.

Fluorescence detectors
(UV light from excited N_2)



Hadronic interaction in air shower



Largest systematic uncertainty of indirect measurement is in first interaction.

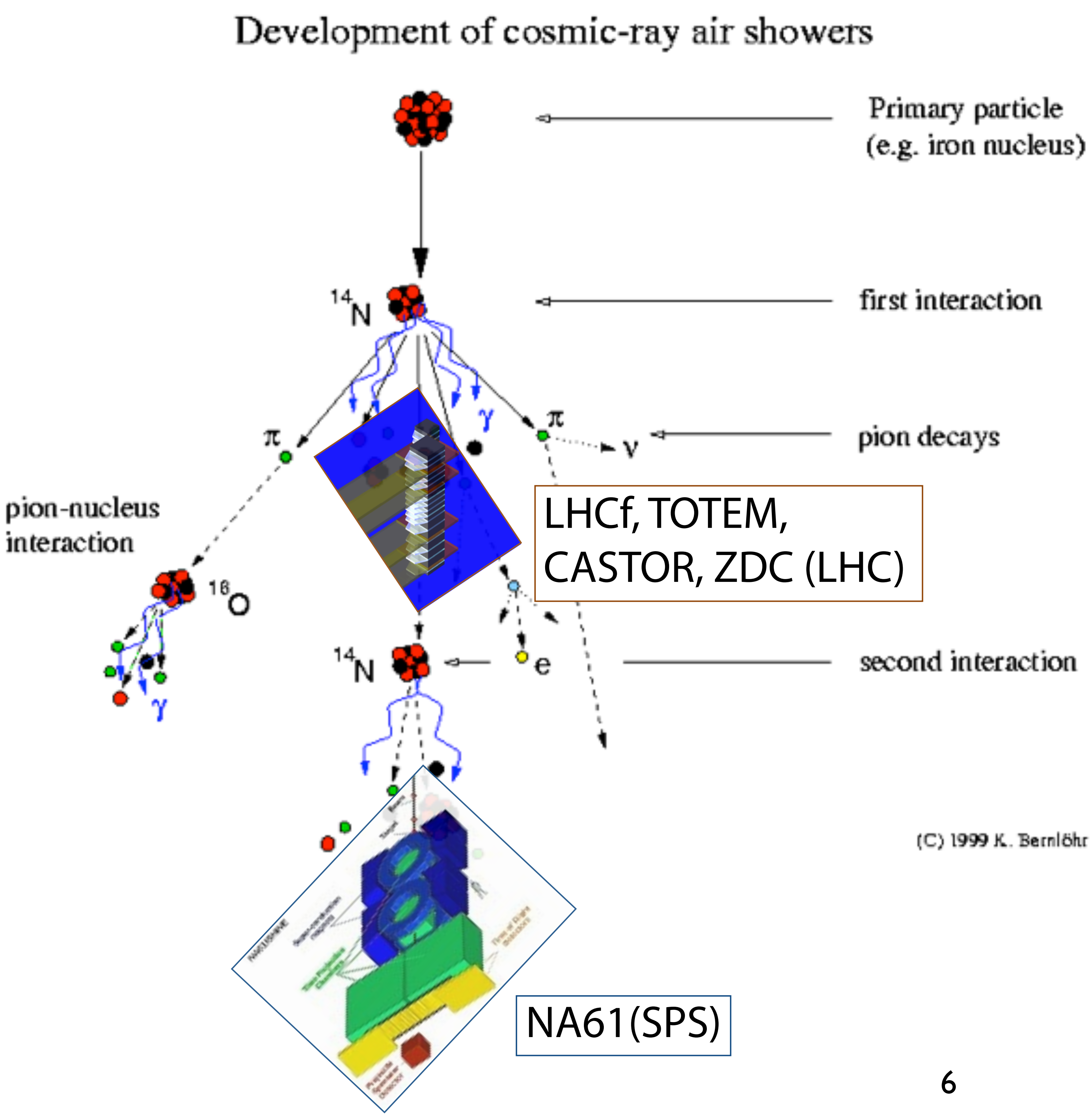
E~TeV

1. **Inelastic cross section**
   large → rapid development
   small → deep penetrating
2. **Inelasticity $k = 1 - p_{lead}/p_{beam}$**
   large → rapid development
   small → deep penetrating
3. **Forward energy spectrum**
   softer → rapid development
   harder → deep penetrating
4. **Nuclear effects**
5. **Extrapolation to high energy**
   precise measurements at available energies are crucial

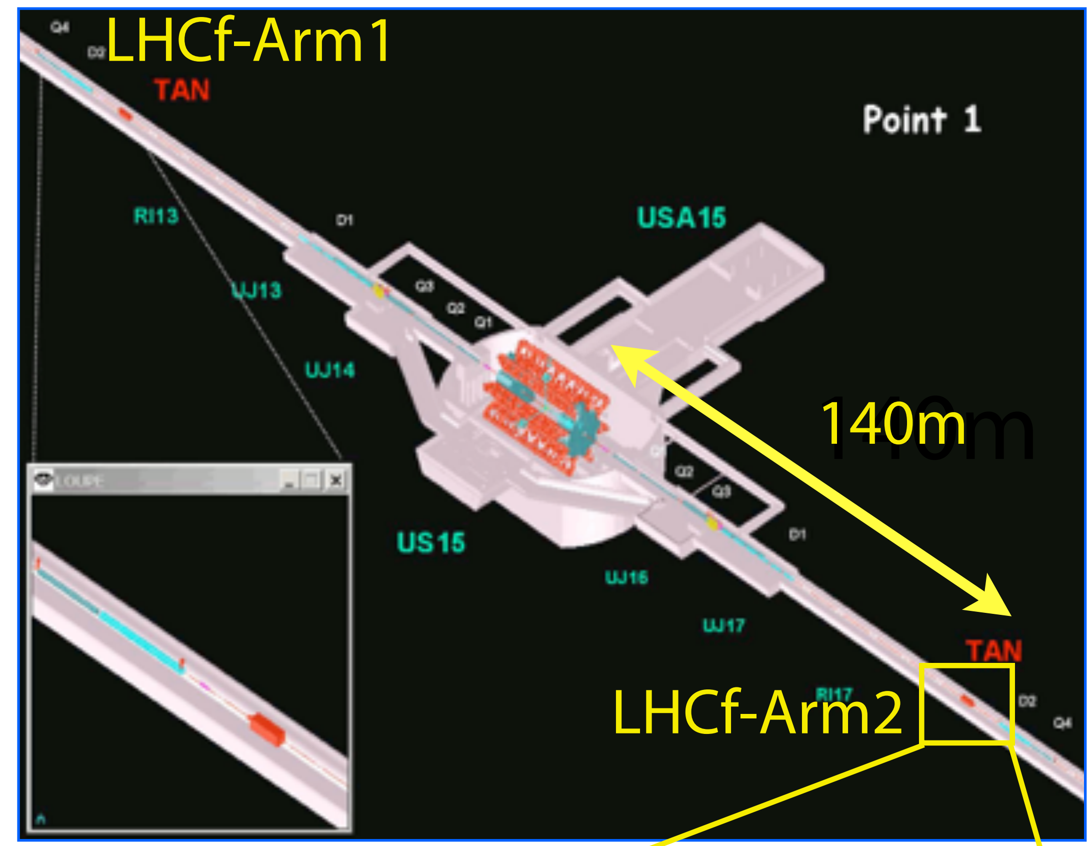
E~GeV

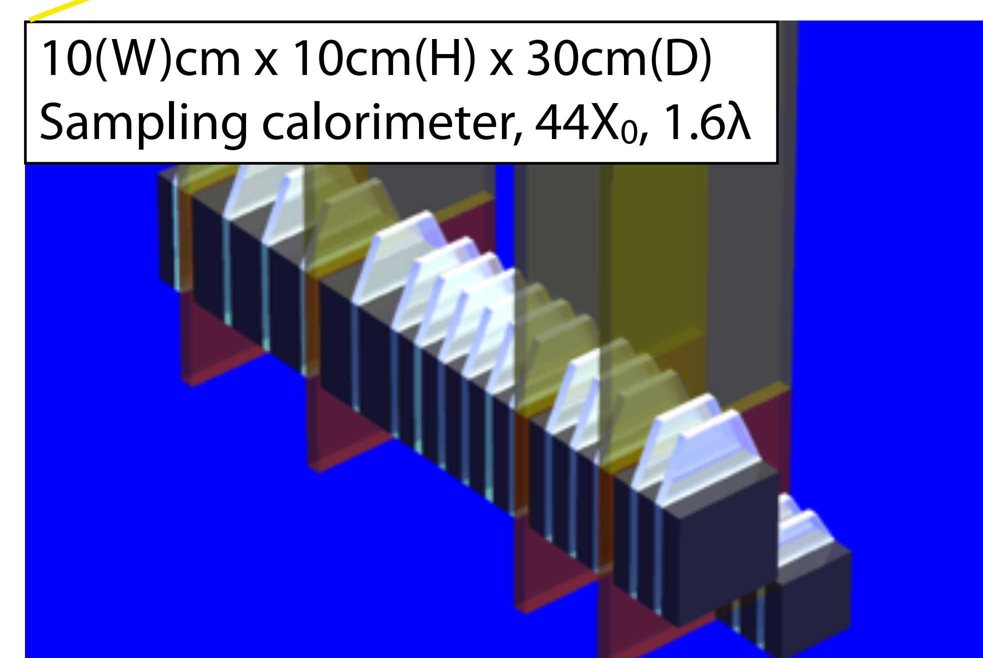
1. **Charge ratio**
2. **Multiplicity**
   number of muons in air shower sensitive to mass composition

Cosmic ray interaction at accelerator



The LHCf experiment





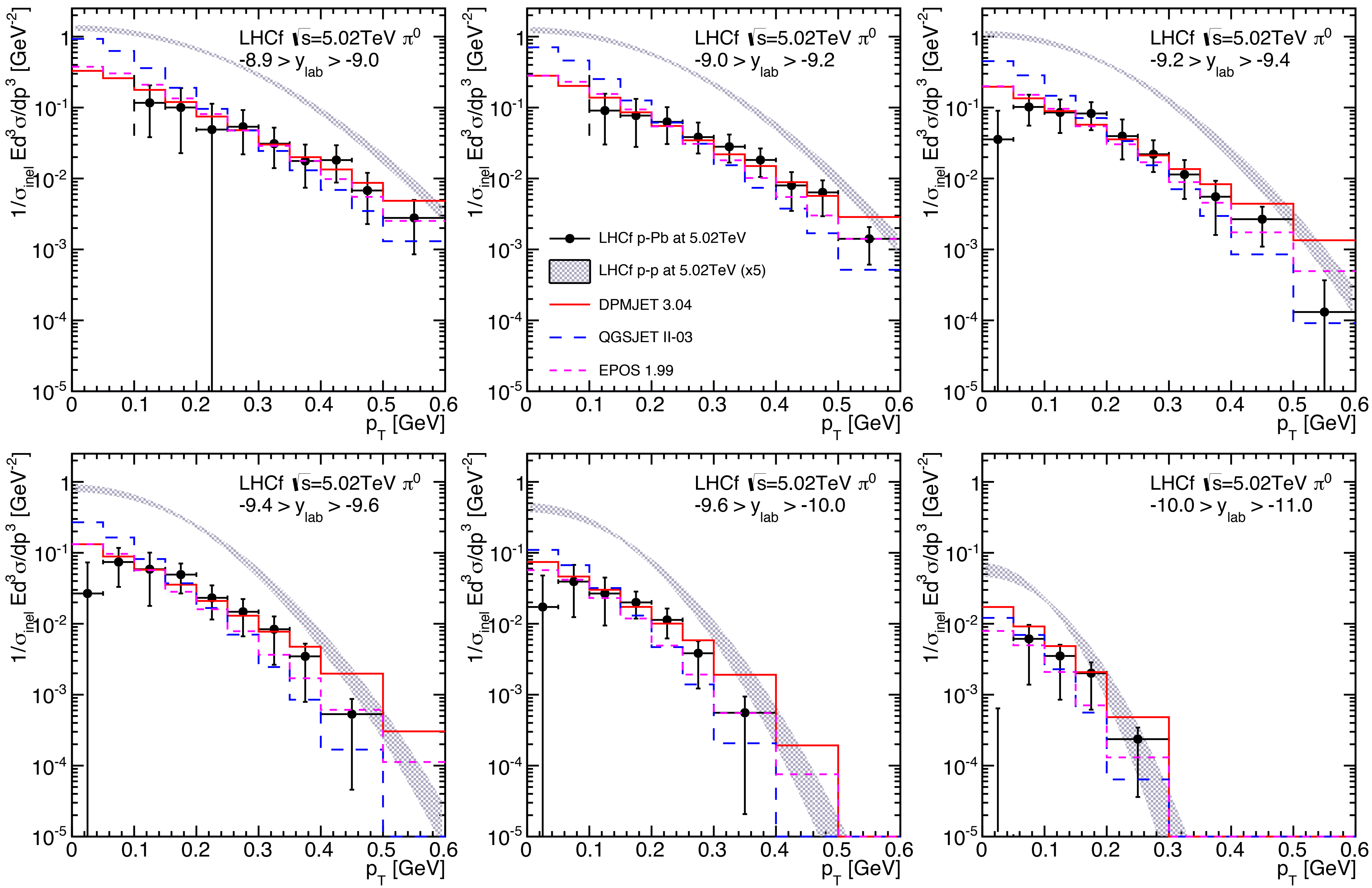
Results at the LHC: LHCf analyses

	Photon (EM shower)	Neutron (hadron shower)	π0 (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	Phys. Rev. D 86, 092001 (2012)
p-p at 2.76TeV			Submitted to Phys Rev. C arXiv:1403.7845, CERN-PH-EP-2014-059
p-Pb at 5.02TeV			

- LHCf analysis activity was so far directed to the EM shower events for its simplicity.
- We have extended the activity to neutron event analysis based on improved tools.
- Also we show the analysis results in p-Pb collisions (submitted to Phys. Rev. C).

Analysis on blank parts are ongoing or planed.

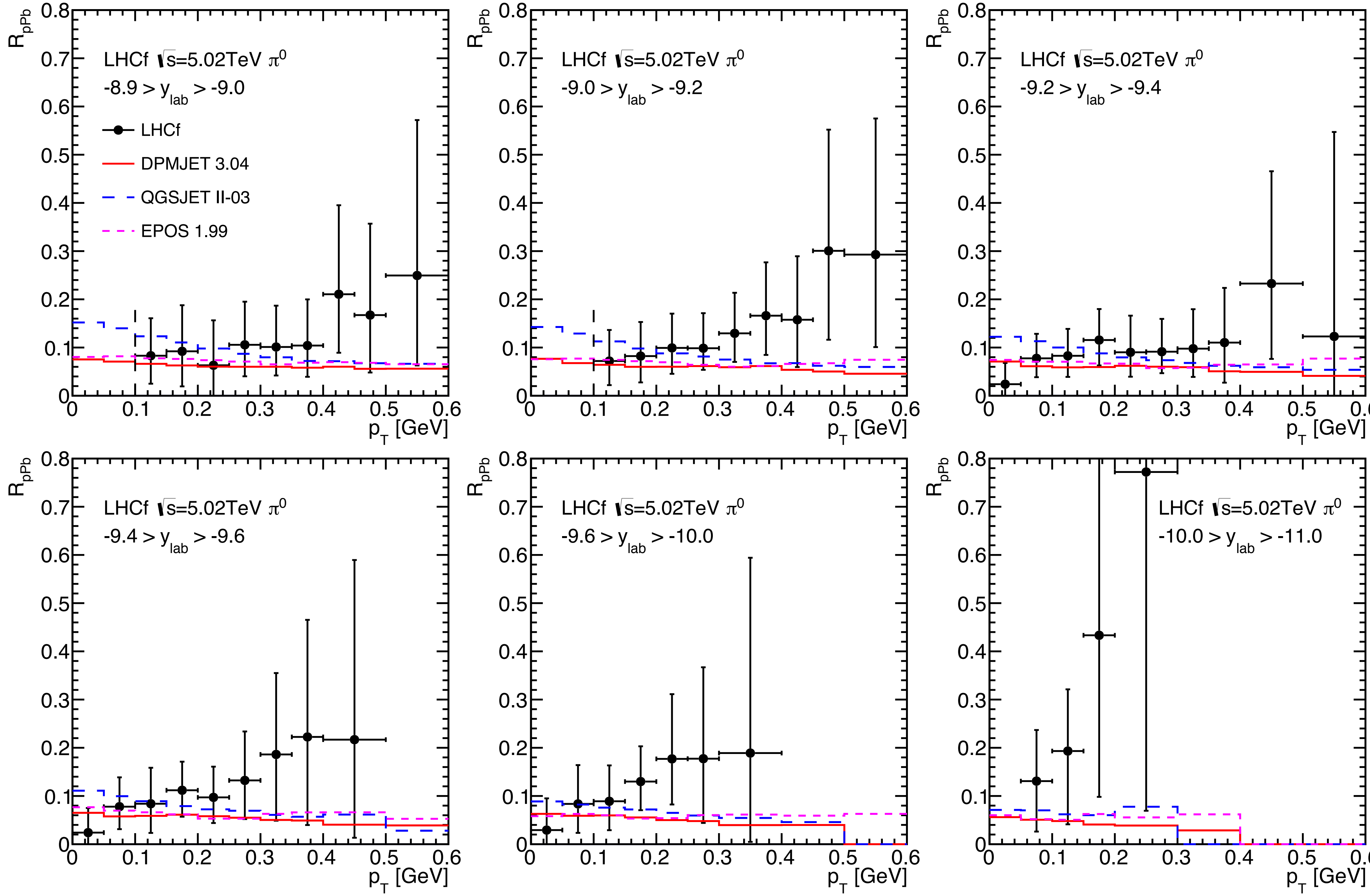
Inclusive π^0 p_T spectra in p-Pb at 5.02TeV



- The LHCf data in p-Pb (filled circles) show good agreement with DPMJET and EPOS.
- The LHCf data in p-Pb are clearly harder than the LHCf data in p-p at 5.02TeV (shaded area). The latter is interpolated from the results at 2.76TeV and 7TeV.

arXiv:1403.7845, CERN-PH-EP-2014-059

Nuclear modification factor in p-Pb at 5.02TeV



$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) \equiv \frac{\sigma^{\mathrm{pp}}_{\mathrm{inel}}}{\langle N_{\mathrm{coll}}\rangle \sigma^{\mathrm{pPb}}_{\mathrm{inel}}} \frac{Ed^3\sigma^{\mathrm{pPb}}/dp^3}{Ed^3\sigma^{\mathrm{pp}}/dp^3}$$

$$\langle N_{\mathrm{coll}}\rangle = 6.9$$

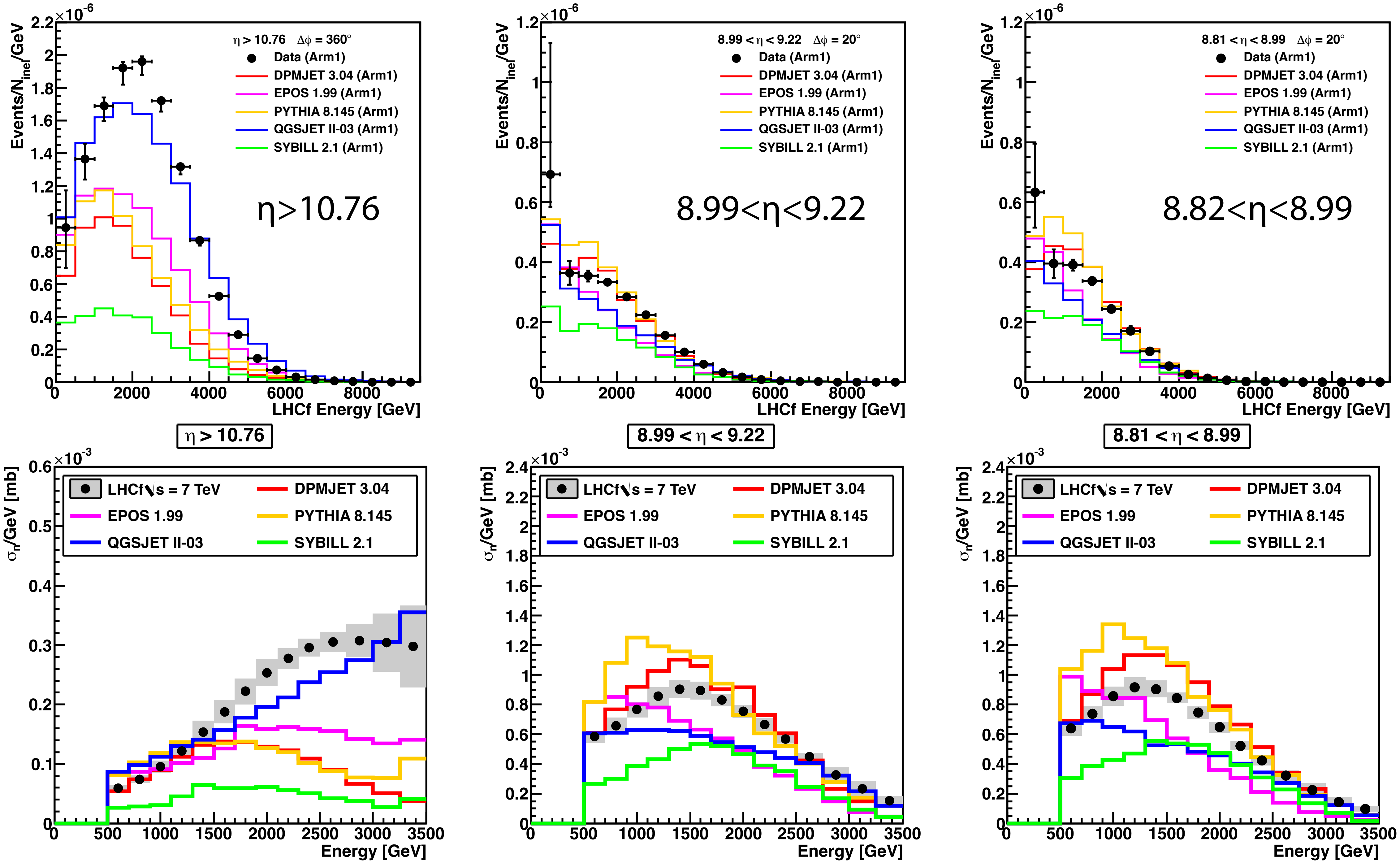
- Both LHCf and MCs show strong suppression.
- But LHCf grows as increasing p_T, understood by the softer p_T spectra in p-p at 5TeV than those in p-Pb.

LHCf Preliminary

Inclusive neutron energy spectra in p-p at 7TeV

before unfolding

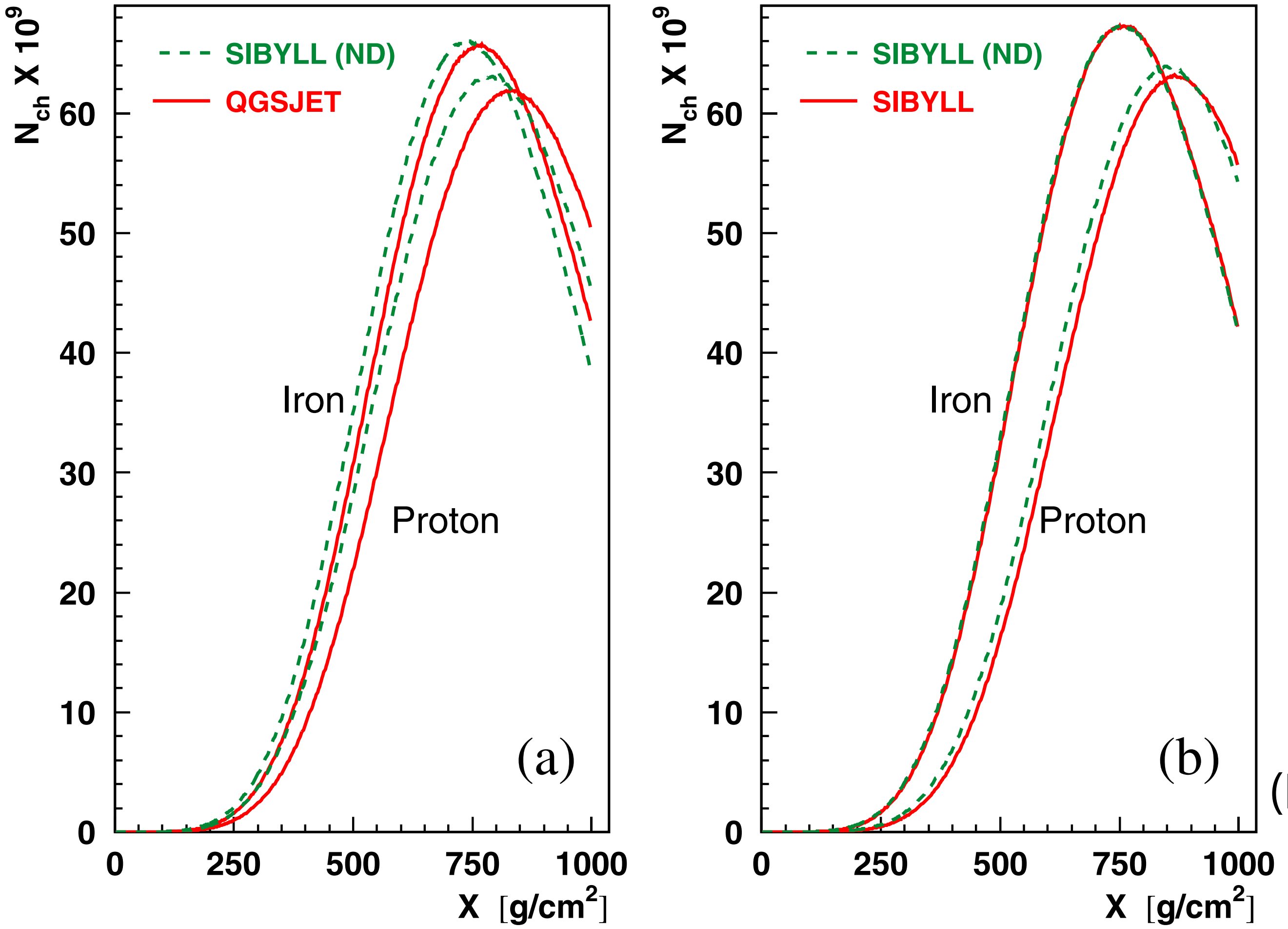
after unfolding



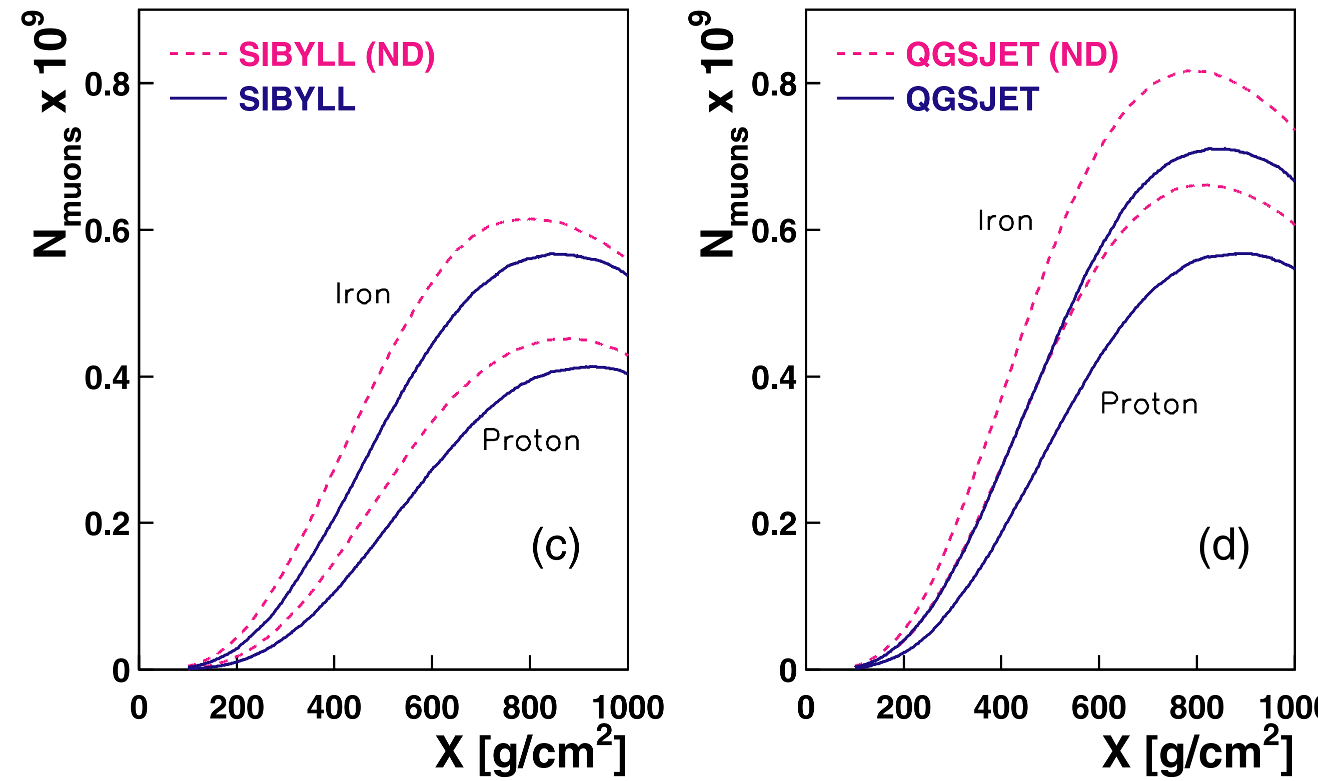
- In η>10.76 huge amount of neutron exists. Only QGSJET roughly reproduces the LHCf result.
- In other rapidity regions, the LHCf results are enclosed by the variation of models.
- These results may indicate small inelasticity in very forward region.

Results at the LHC: diffraction

Number of charged particles



Number of muons



(R. Luna et al. PRD 70, 114034)

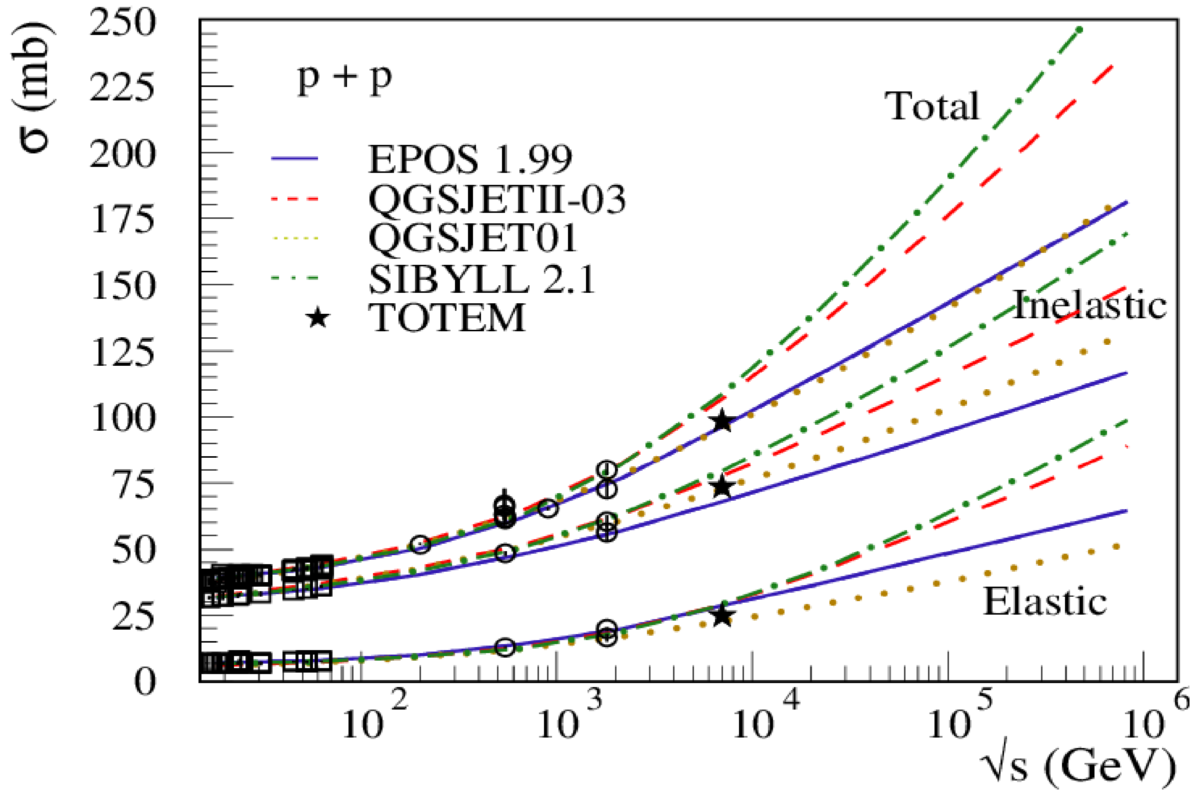
X_{max} of charged particles (dominantly electron) is insensitive to diffraction.

Muons are more sensitive to diffraction (i.e. leading baryon production): small multiplicity leading to less pions and less muons.

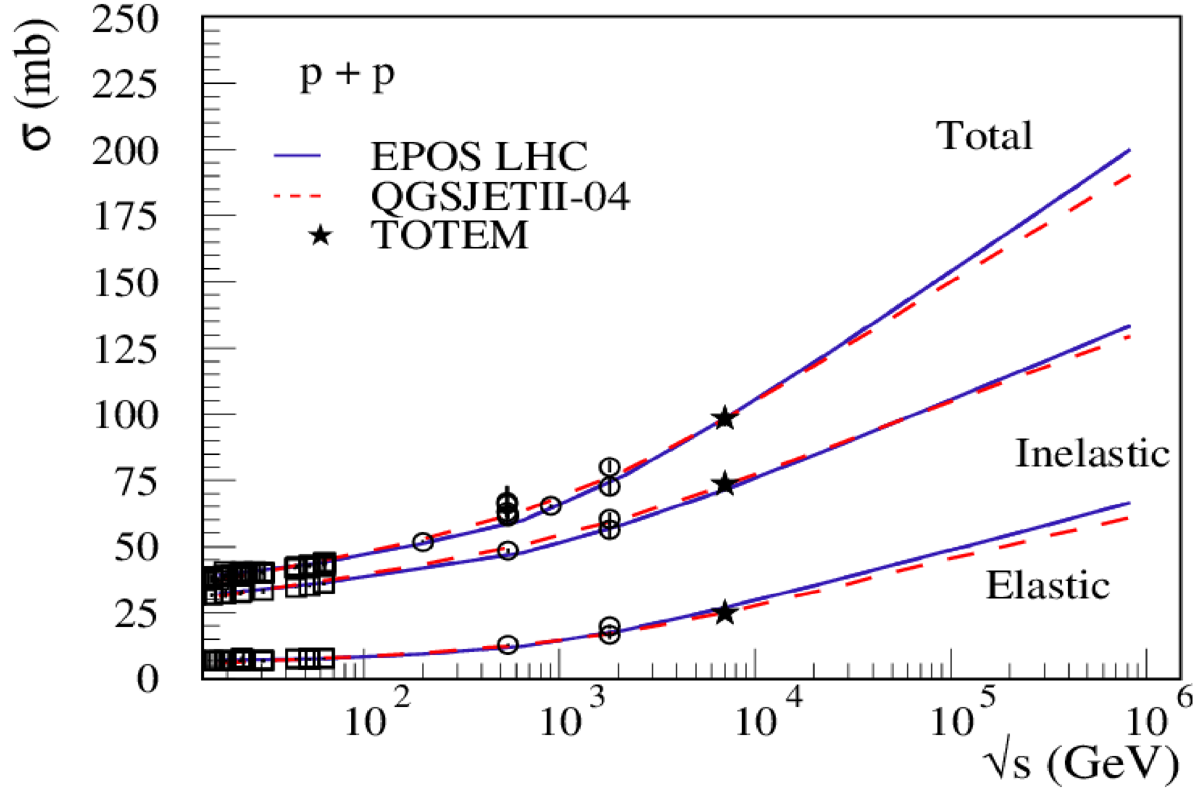
TOTEM Preliminary	$\sigma_{\rm SD} = 6.5 \pm 1.3 mb$
PYTHIA8	$\sigma_{\rm DD(4.7<\lvert\eta_{\rm min}\rvert<6.5)} = 159 \mu b$
PHOJET	$\sigma_{\rm DD(4.7<\lvert\eta_{\rm min}\rvert<6.5)} = 101 \mu b$
TOTEM (PRL101,262001)	$\sigma_{\rm DD(4.7<\lvert\eta_{\rm min}\rvert<6.5)} = 116 \pm 25 \mu b$

Results at the LHC: cross section

Pre LHC



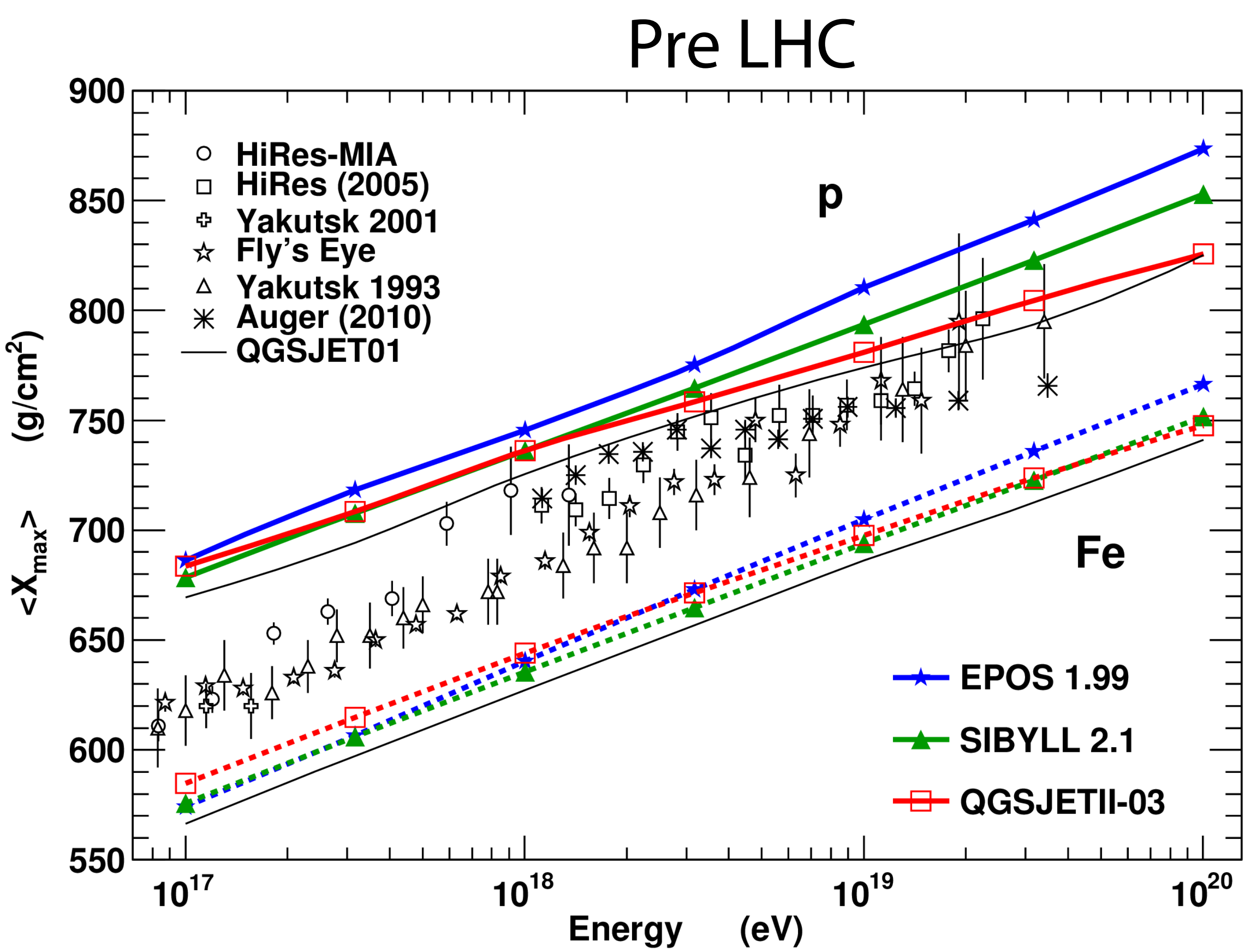
Post LHC

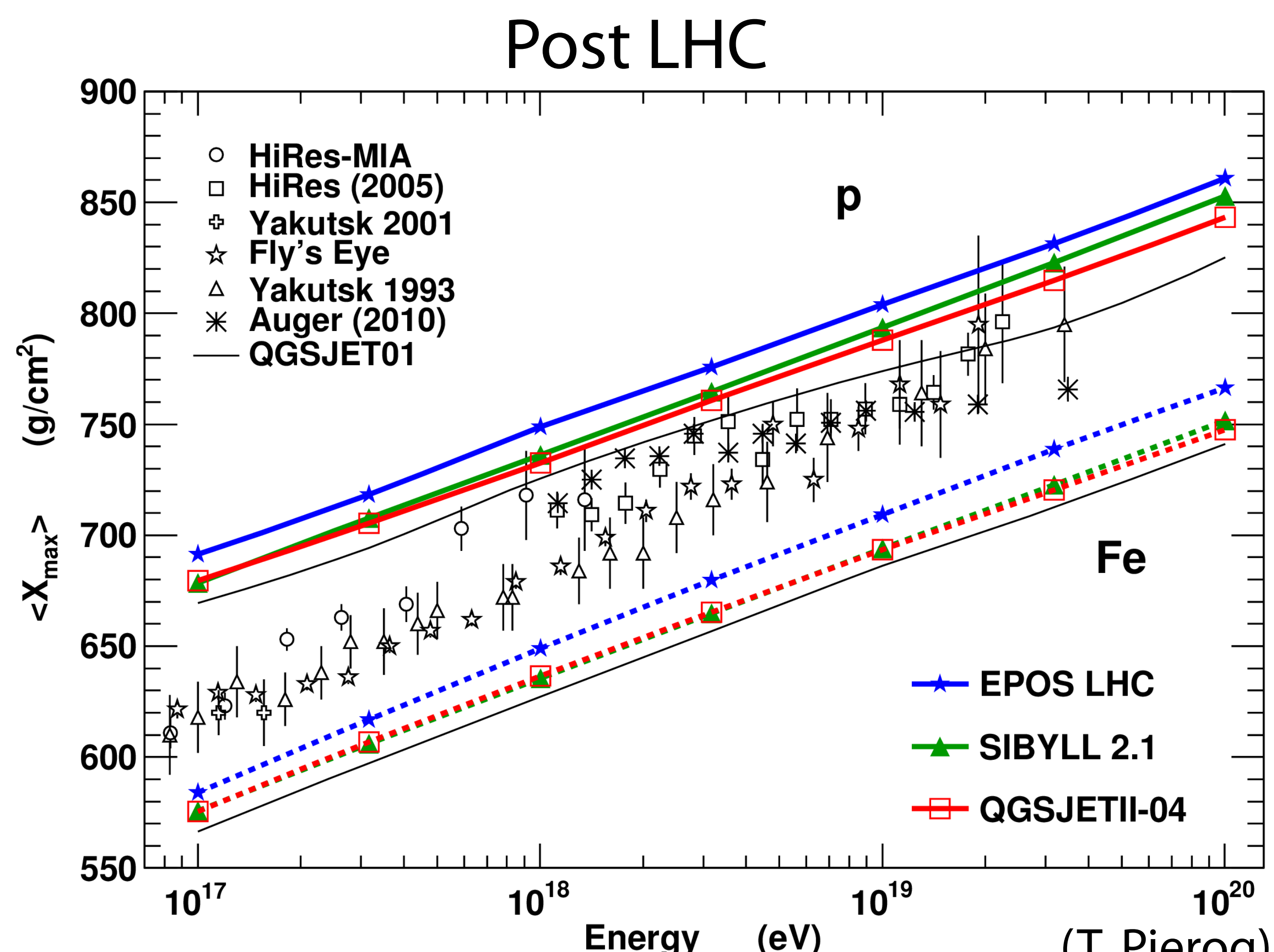


(T. Pierog)

- There is no drastic change from EPOS 1.99 to EPOS LHC.
- Better agreement with TOTEM is found in QGSJET II-04 compared with QGSJET II-03.
- Post LHC models show overall good agreement with data up to the LHC energy.
- They are converged into similar values even at 10^6GeV.

Prediction of X_{max} with retuned models





(T. Pierog)

- Difference of $\langle X_{max} \rangle$ in p-air among pre LHC models is about 50g/cm^2 at 10^{20}eV, although a difference between p-air and Fe-air is about 100g/cm^2.
- Retuned models with the the LHC data are somehow converged into pre-LHC model SIBYLL 2.1.
- Difference between p and Fe is reduced to 20g/cm^2.

What's next ?

- Inelastic p-p cross section
  - It is and will be strongly constrained by the measurements at the LHC.

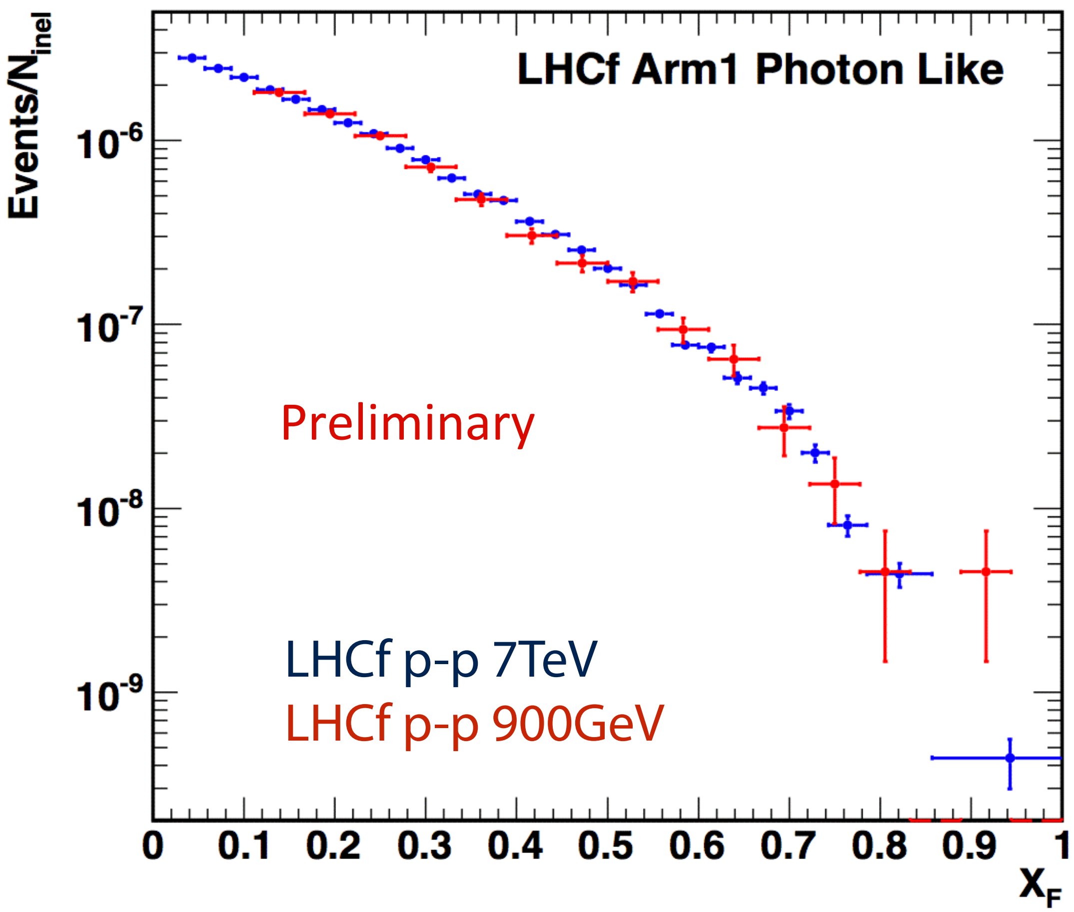
- Inelasticity and forward energy/p_T spectra
  - LHCf analyses at 7TeV were done. Similar analyses will be performed at 13TeV.

- Extrapolation to ultrahigh energy
  - Understanding of scaling raw is of importance to validate an extrapolation.
  - Precise measurements in many collision energies are necessary; 900GeV, 2.76TeV, 7TeV and 8TeV so far, and 13TeV soon.

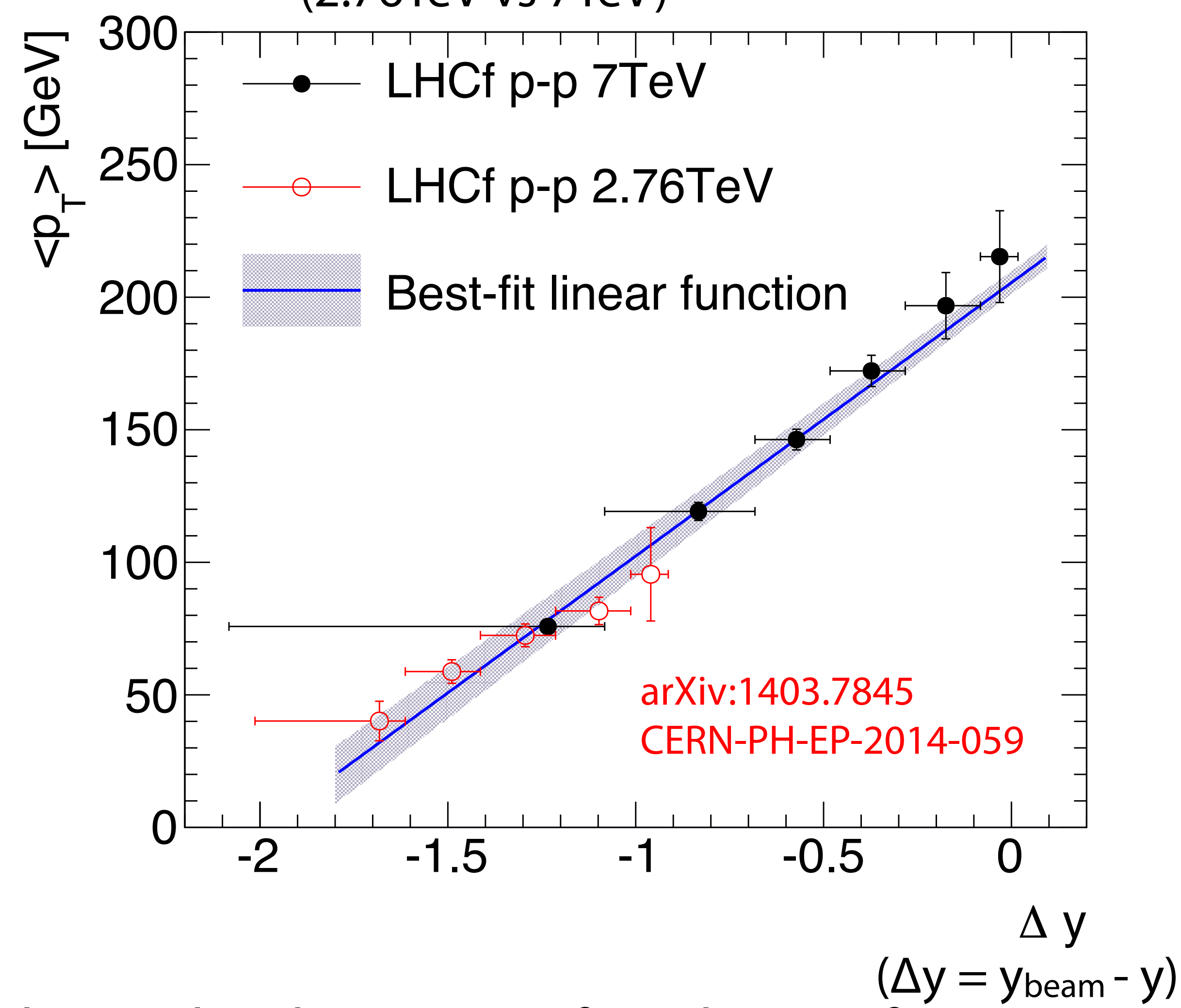
- Nuclear effects
  - p-Pb collision at 5.02TeV is good to imitate a very dense matter which can be realized in p-air collision at E>>TeV.
  - nucleon - light-ion collision (e.g. p-N/O) is needed to test the current implementation of hadronic interaction models at TeV energy region.

Extrapolation and scaling

Scaling of forward photon X_F distribution
(900GeV vs 7TeV)



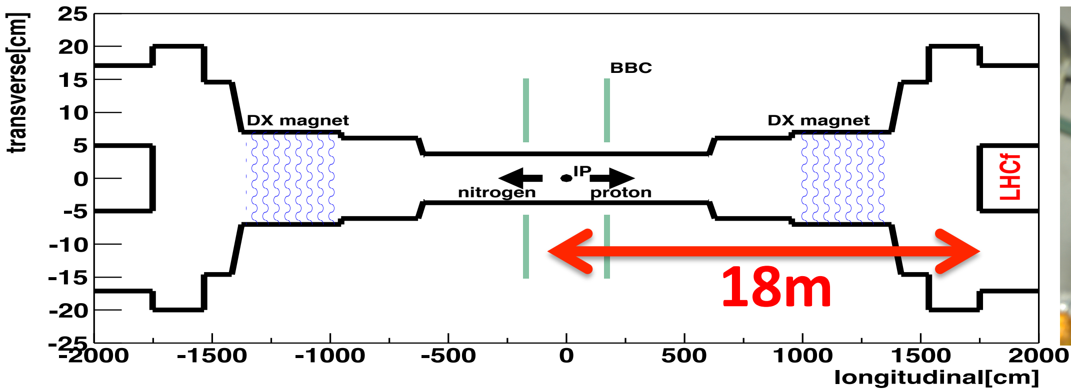
Scaling of forward π^0 average p_T
(2.76TeV vs 7TeV)



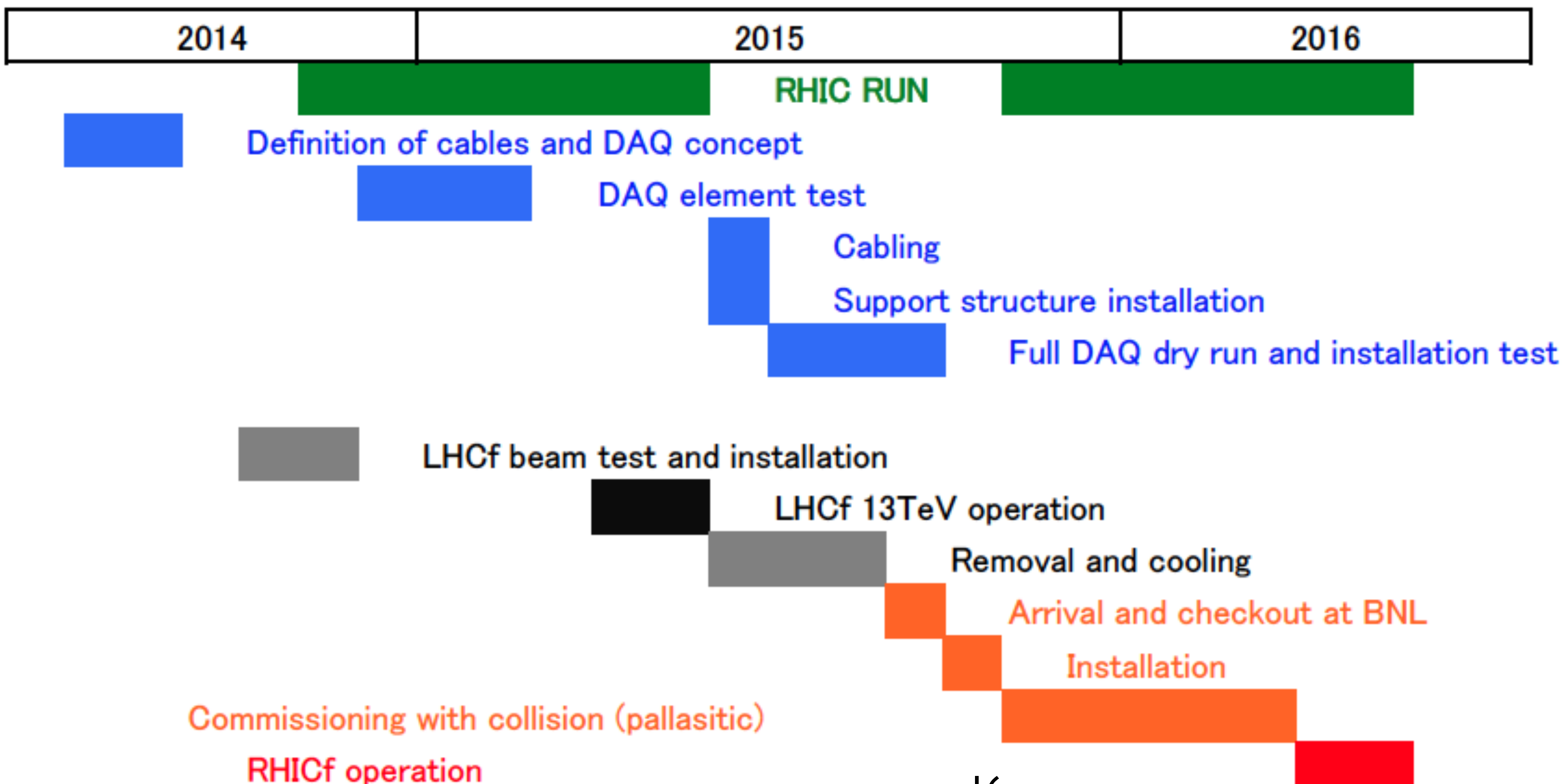
- Feynman scaling of forward photon energy and π^0 p_T distributions are found at LHCf.
- More precise extrapolation to ultrahigh energy.
  - LHC at 13 TeV
  - Extension to lower energy (e.g. RHIC at $\sqrt{s}$=510GeV).

arXiv:1401.1004

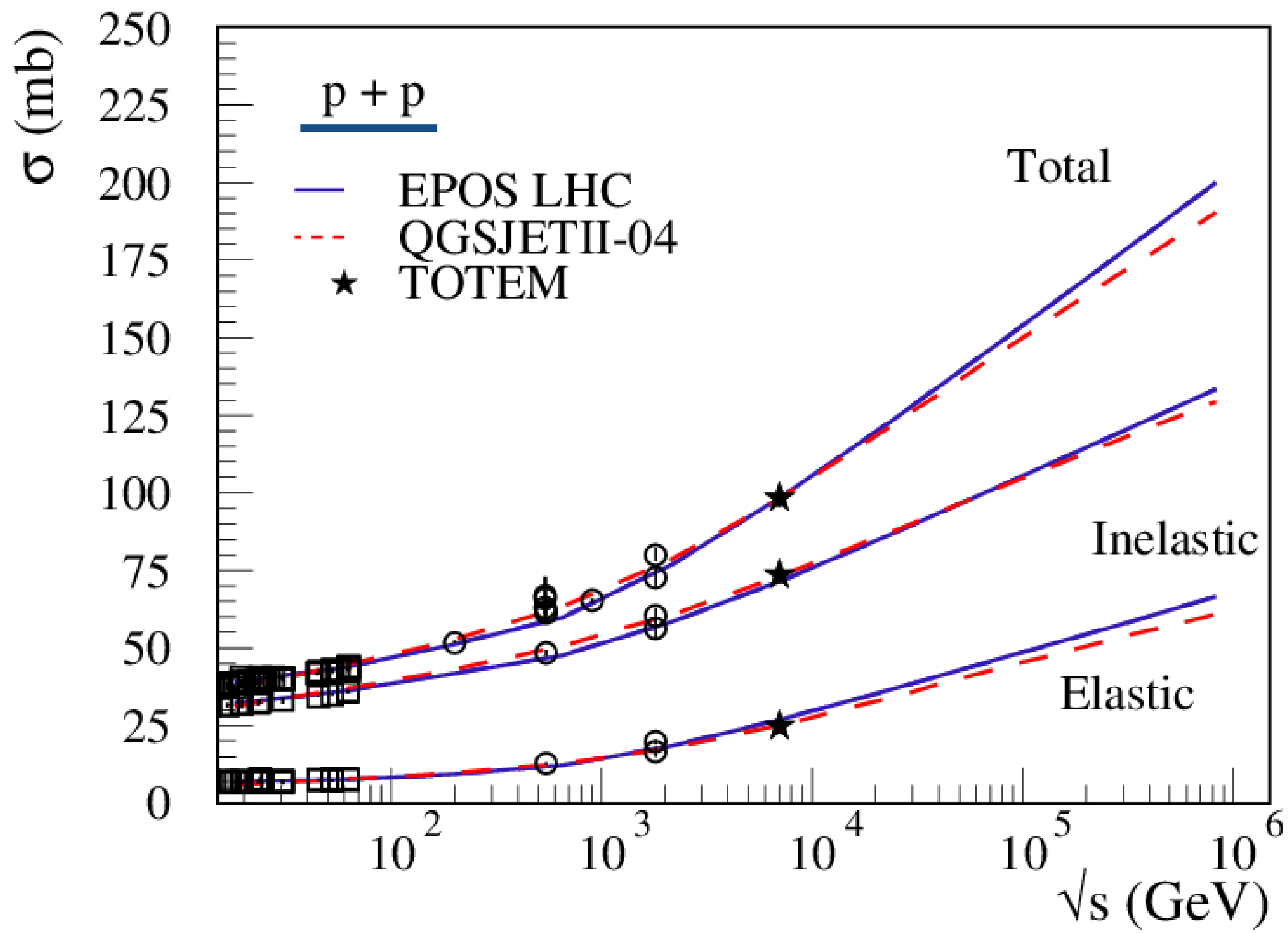
RHICf project (the LHCf detector at RHIC)

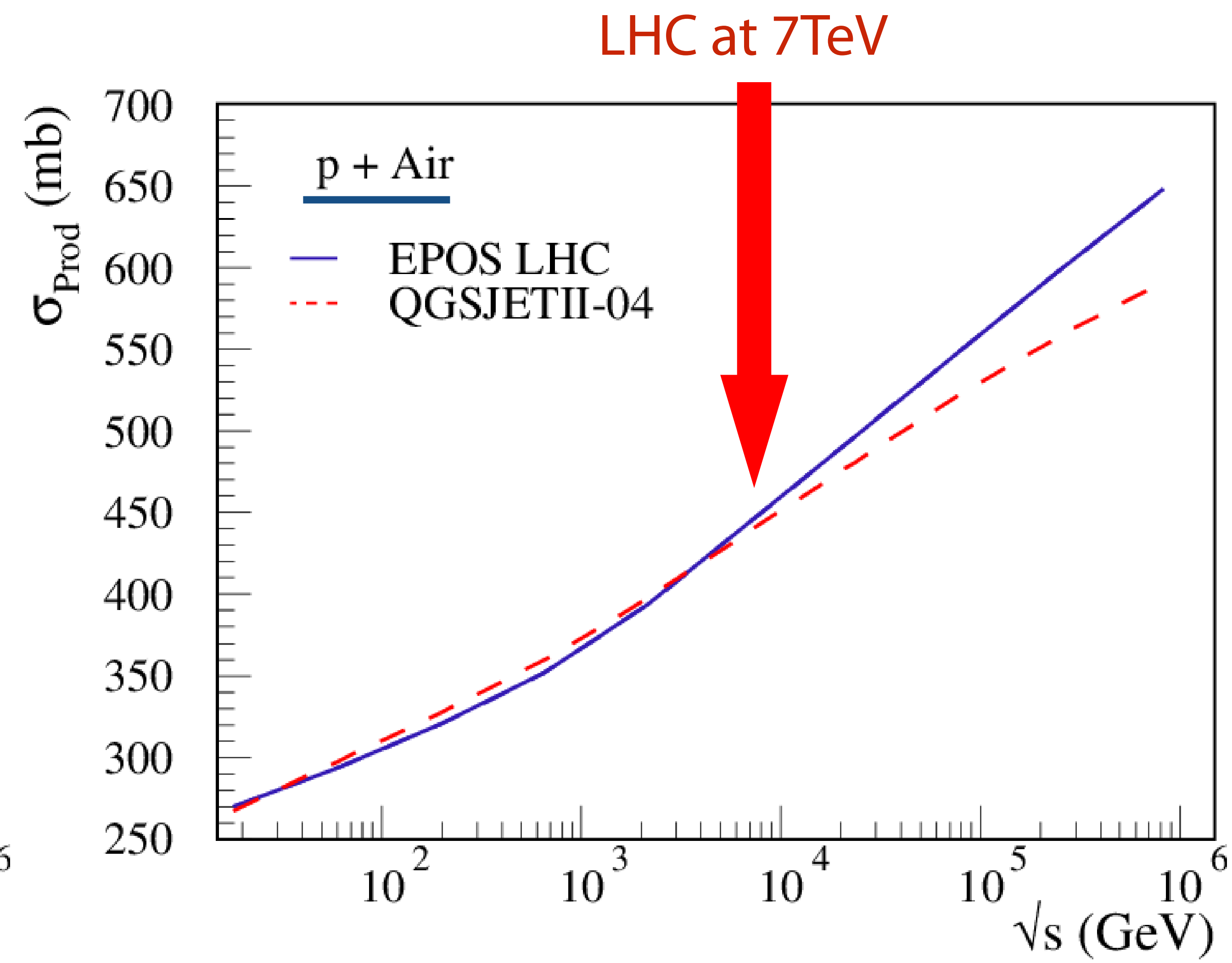


- Testing the Feynman scaling of energy and p_T spectra between SPS and LHC energies.
- Pseudo rapidity can be down to 6 (η>8.4 at LHCf).
- Possibly operation in d(p)-Au collisions.
- Additional contribution to spin asymmetry measurements.



Light-ion collision





(T. Pierog)

- Cross section at ultrahigh energy inevitably involve an uncertainty due to the extrapolation from the LHC energies. A model difference gets bigger above 10^4GeV (> LHC energy).
- Main uncertainty of p-air cross sections is owing to a conversion from p-p to p-air.
- Proton - light-ion collision (N and O) is the best bench to test hadronic interaction models for cosmic ray physics.

Summary

- Understanding of hadronic interaction is crucial to reduce an uncertainty in cosmic ray observation.
- LHC is the best occasion to improve/tune the hadronic interaction models towards an observation of ultrahigh energy cosmic ray.
- Retuned models with LHC data indeed show convergence at the LHC energy.
- Next target is
  - performing a precise extrapolation based on a robust scaling.
  - RHICf; an extension of the LHCf activity to low energy but to wide rapidity range.
  - (hopefully) light ion collision.