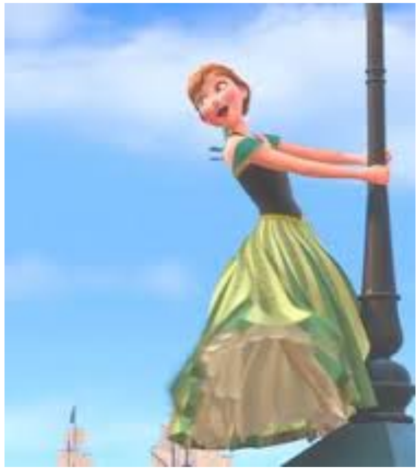
Connection between Astrophysics and Collider physics

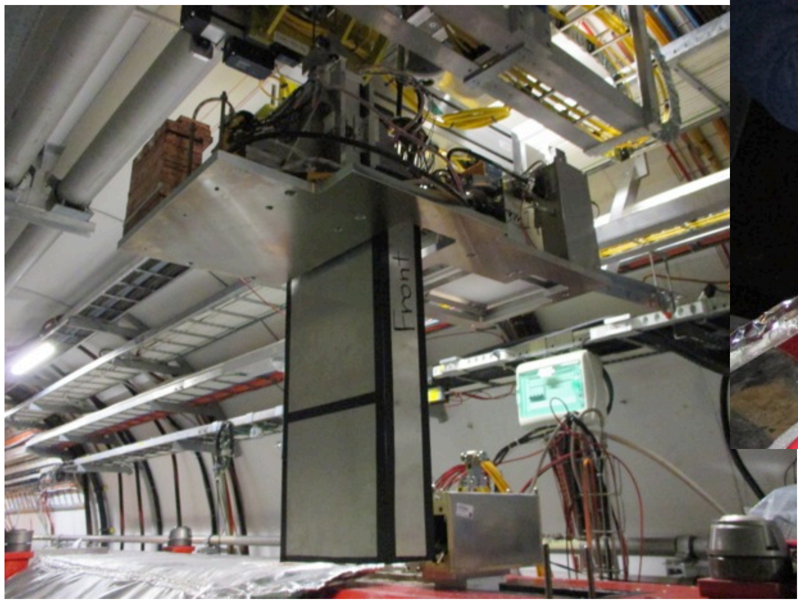
Takashi SAKO

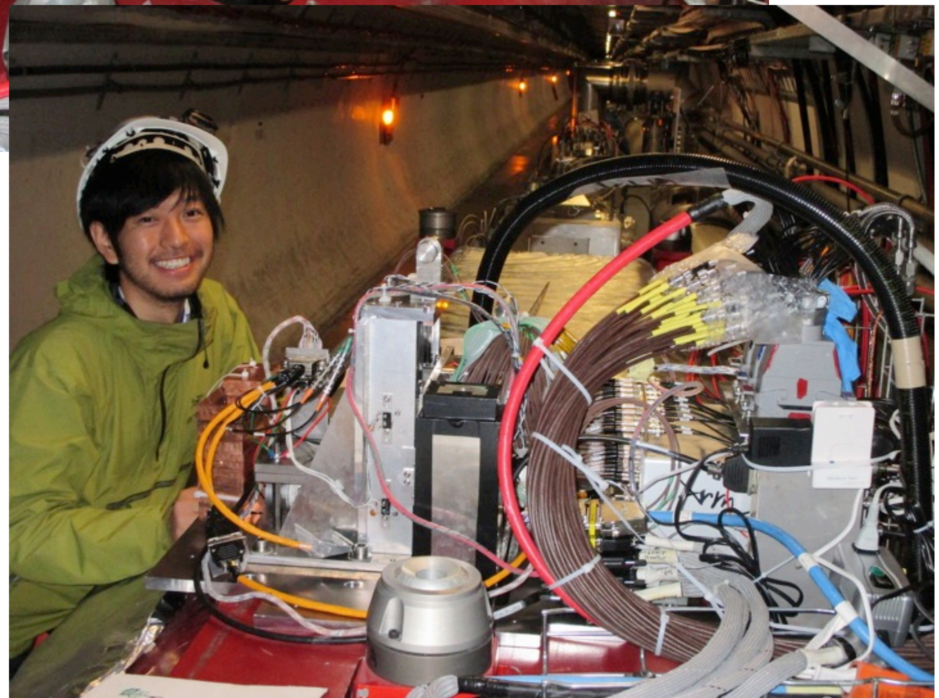
KMI topics…

- My main topics is LHCf
- It is motivated by astrophysics, but technique is fully high-energy physics
- Audience are
  - experts of astrophysics and high-energy physics, but not both
  - how I can satisfy them…
- Let's try to introduce both astrophysical side and high-energy side!!
- reducing about LHCf…
- This style is 'for the first time in forever'



But LHCf



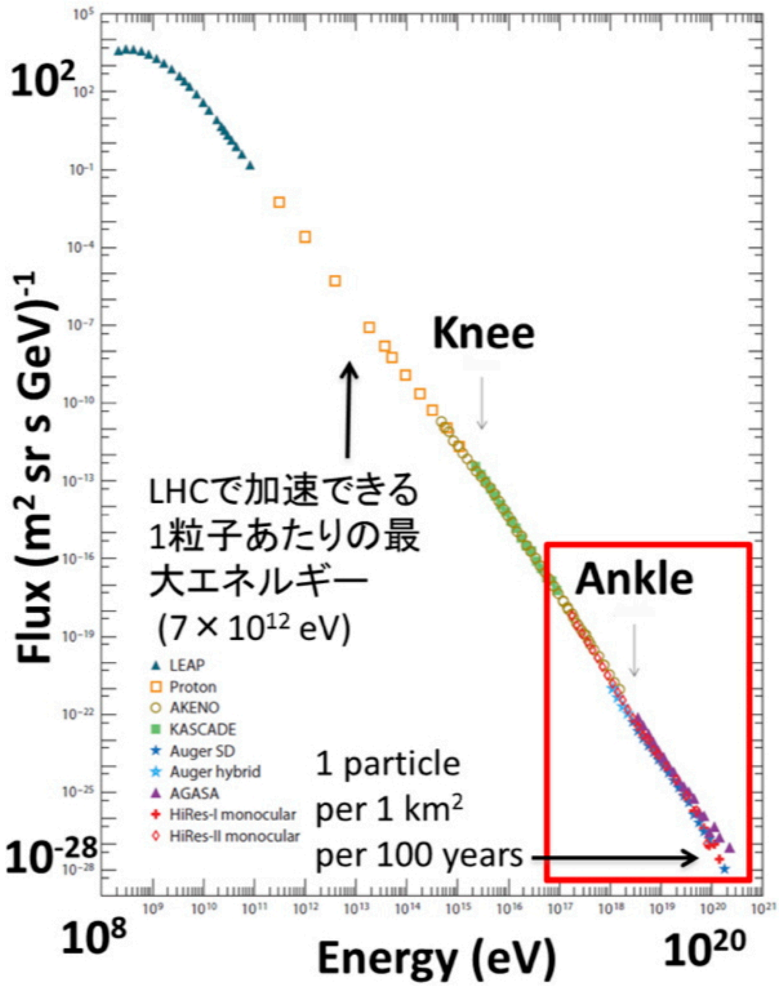


LHCf detectors were successfully installed into the LHC tunnel in November

Commissioning was also successful

Waiting dedicated 13TeV run in May 2015

Cosmic-ray observation



Energy spectrum of CRs
(plot from KMI web page; spot light of Sakurai-san)

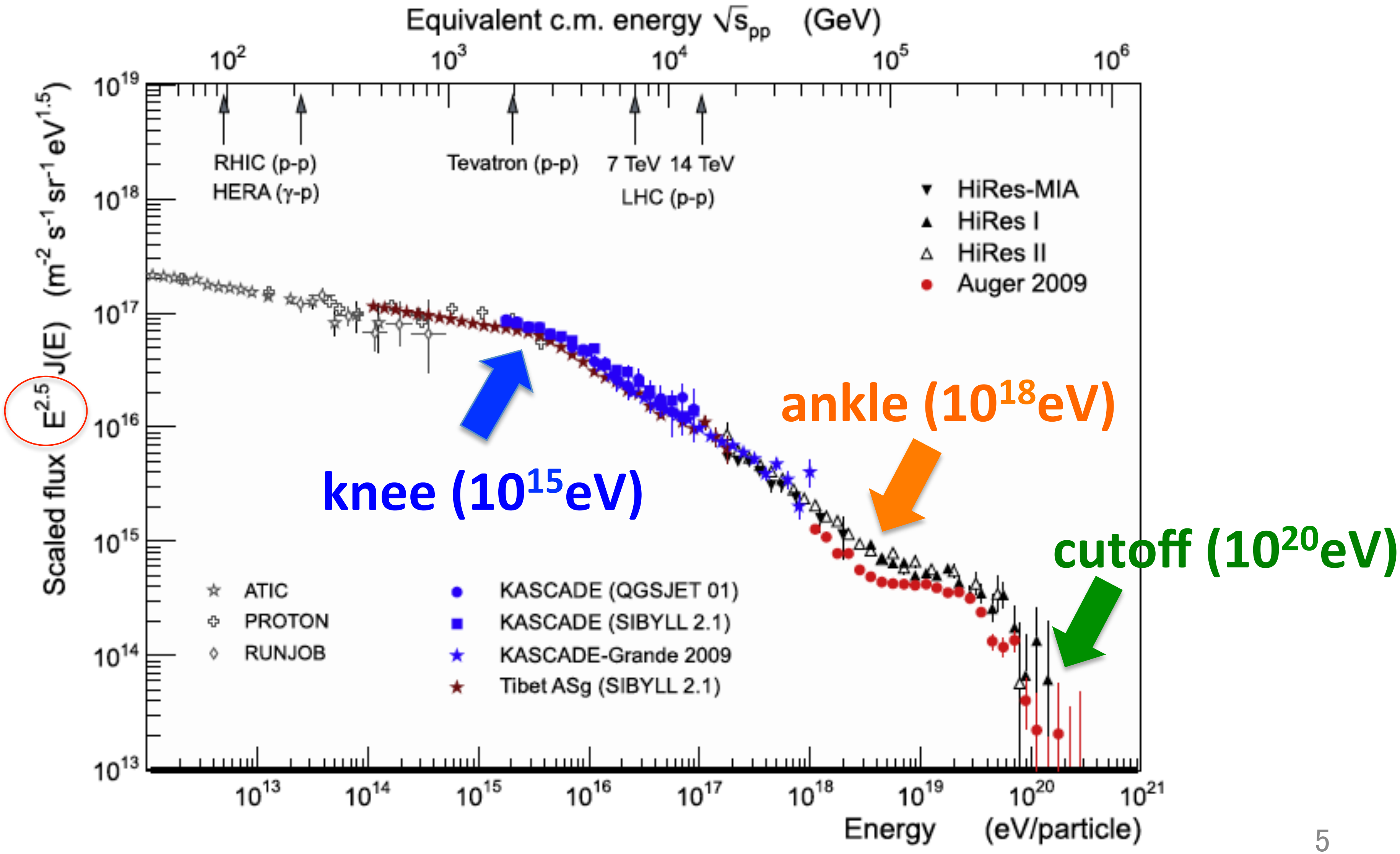
$I(>10^{15}\mathrm{eV}) = 5\times10^{-7}\ \mathrm{m^{-2}\,sr^{-1}\,s^{-1}}$
$= 15\ \mathrm{m^{-2}\,sr^{-1}\,yr^{-1}}$

Limitation in direct (primary) observation in space

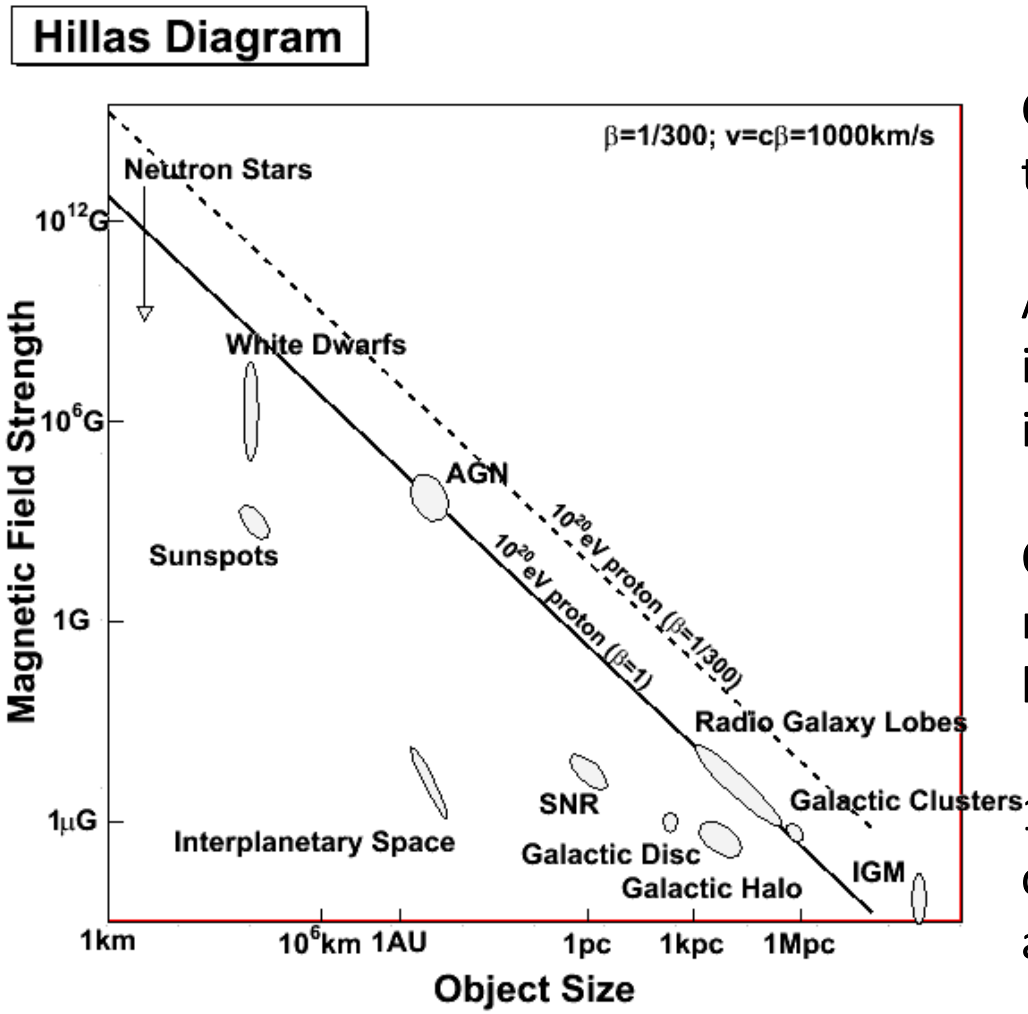
How can we observe higher energy CRs?
=> Come back later

CR spectrum and structures

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



Possible sources (Hillas diagram)



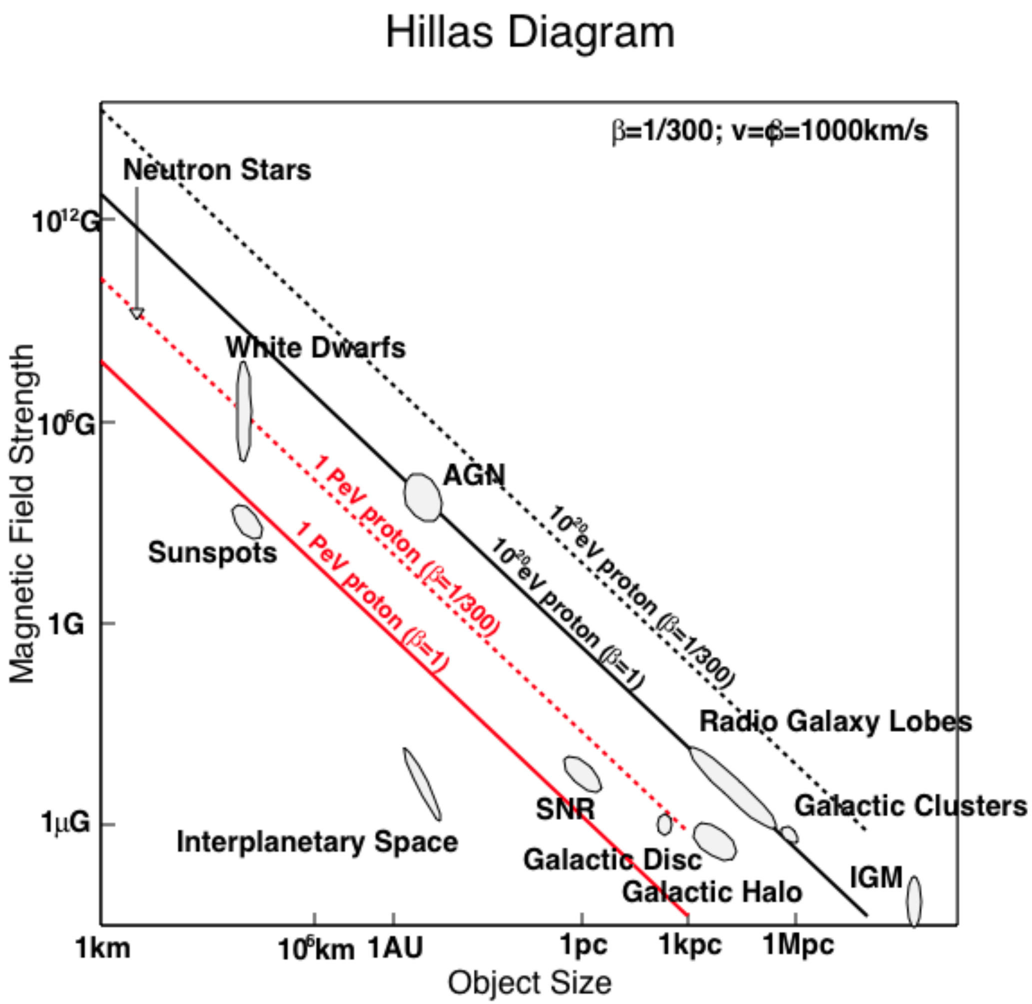
Constraints from the "confinement" in the accelerator

Acceleration by electro-magnetic interaction is assumed, but mechanism is not considered

Other exotic possibilities like decay of relic heavy particles is not considered here

10^{20}eV seems acceleration or confinement limit of known astrophysical objects

Possible sources (Hillas diagram)



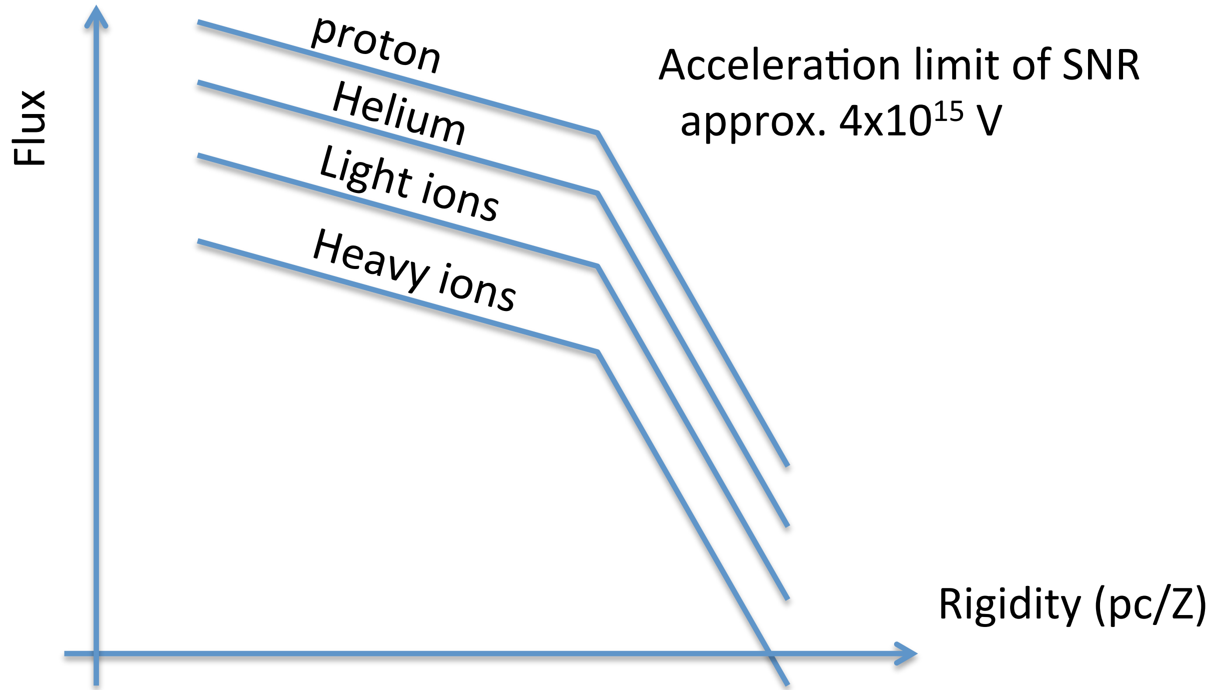
Knee at 1 PeV = 10^{15} eV

Supernova Remnants (SNRs) are good candidates of CR source up to knee

SNRs are classic candidates of galactic cosmic rays since their discovery based on the energy budget

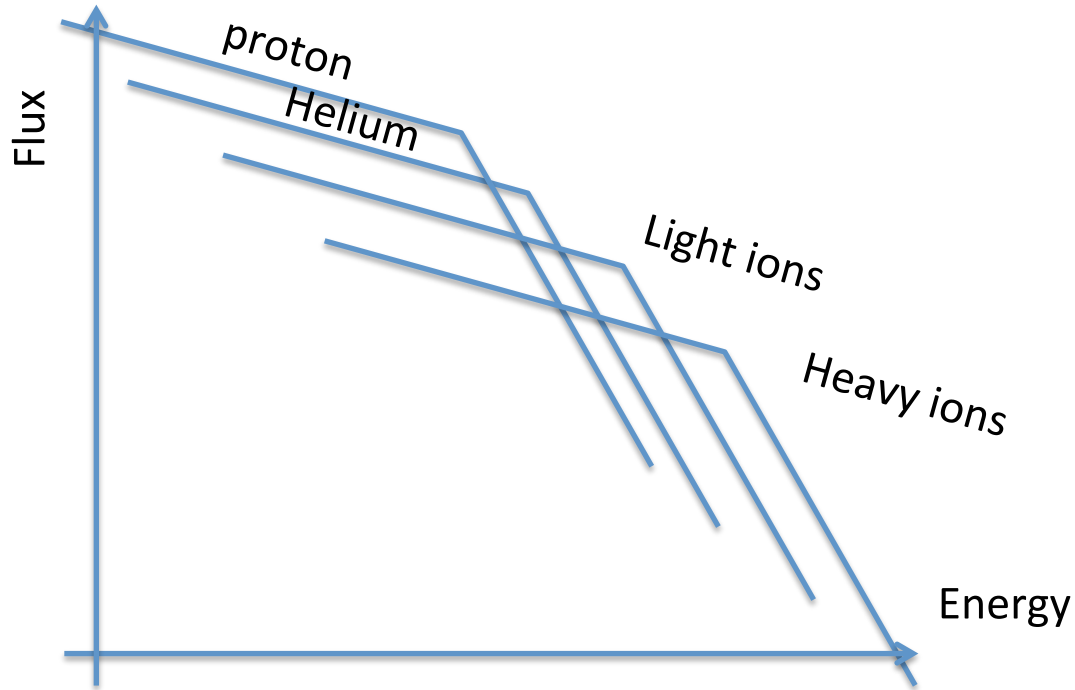
- 1 SN/30ys in a galaxy
- 10% of SN energy

Standard Scenario of the Cosmic-Ray Spectrum



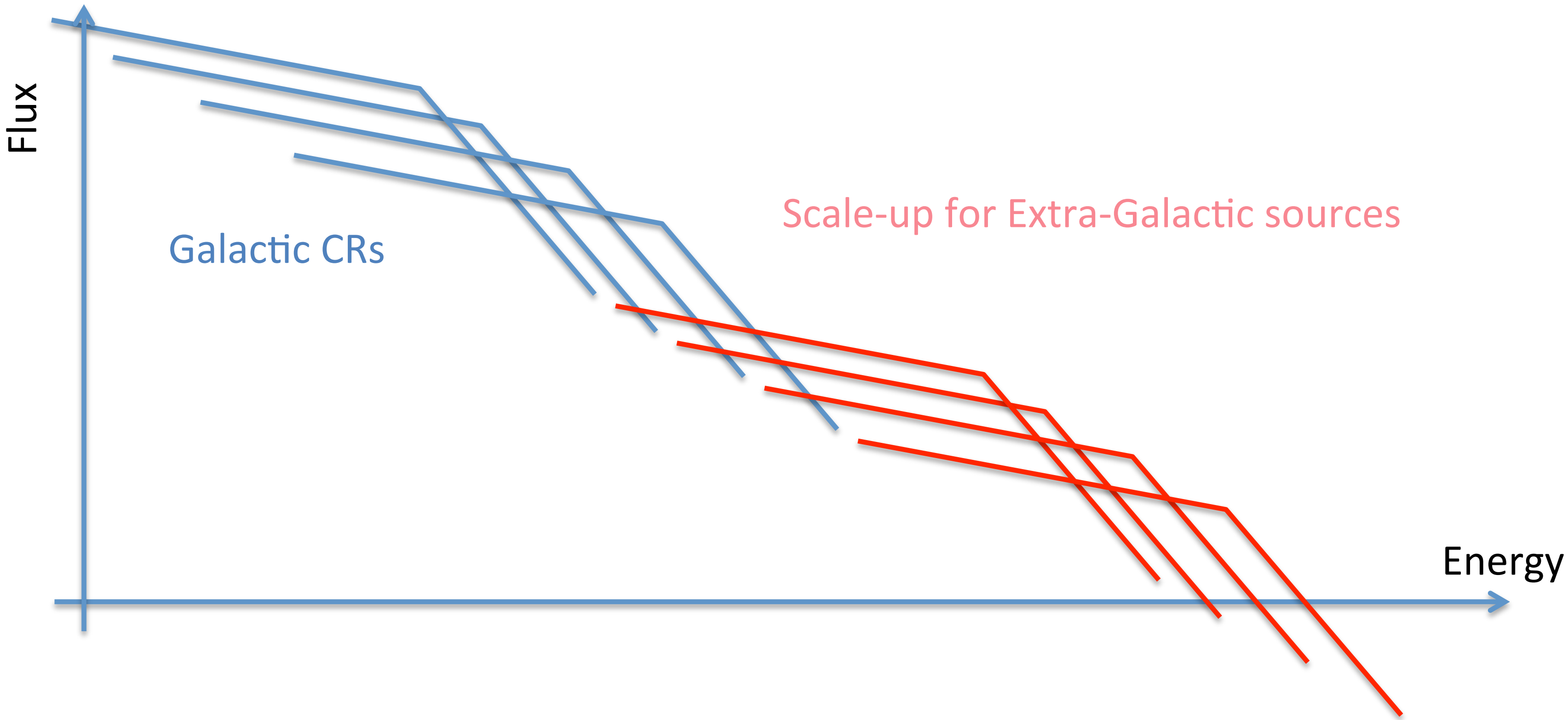
- Cosmic-ray accelerators = PeVatrons have finite size and B field => Acceleration limit same in rigidity for different nuclei

Standard Scenario of the Cosmic-Ray Spectrum



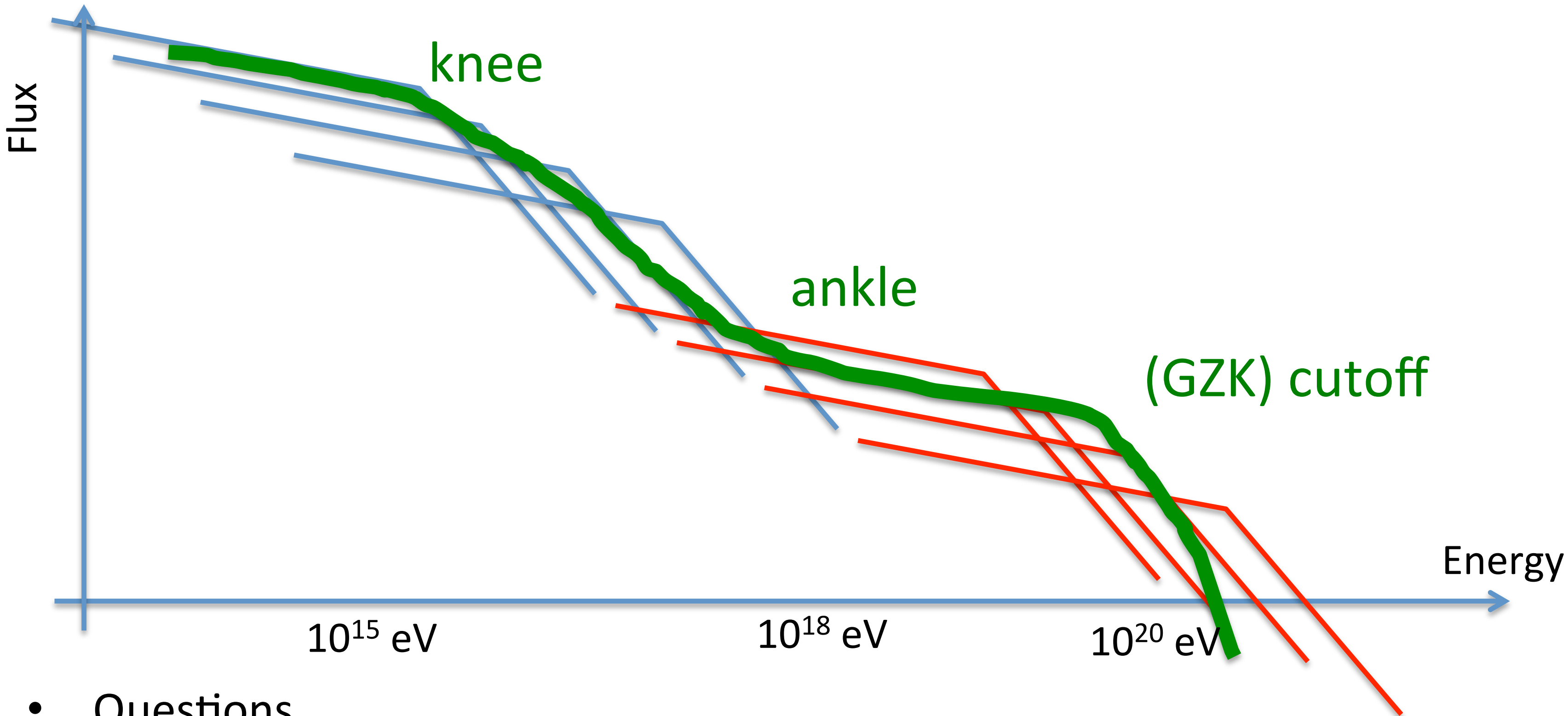
- In term of 'Energy,' heavier particles have Z times higher energy than protons

Standard Scenario of the Cosmic-Ray Spectrum



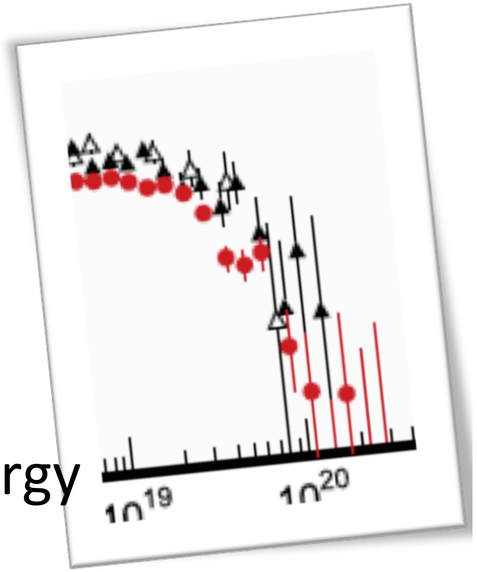
- Over GCR max energy, Extra-galactic CRs appear

Standard Scenario of the Cosmic-Ray Spectrum



- Questions
  - End of GCR
  - Turn over from GCR to EGCR
  - Cutoff (acc. Limit, proton GZK, ion GZK)

Highest energy -complicated…

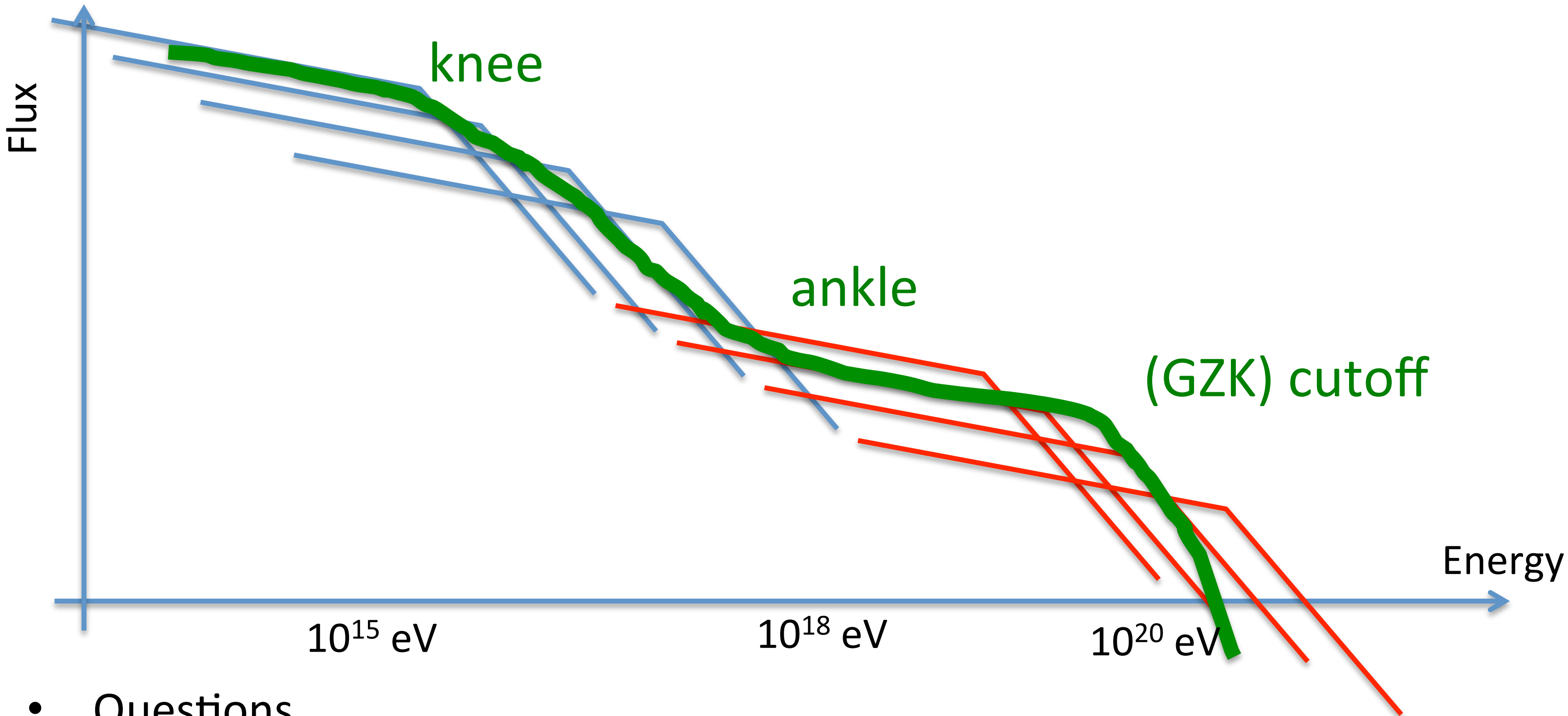


- Without GZK effect,
  - 10^{20}eV can be a limit of acceleration
  - analogous to galactic SNR scenario, highest energy particles can be heavy nuclei
  - can heavy nuclei be accelerated up to such high energy??

- And then, GZK effect
  - high-energy ($>10^{19.5}$eV) protons interact with CMB to lose its energy
  - high-energy nuclei also interact with CMB to dissociate into lighter (lower energy) nuclei

Cutoff at 10^{20}eV is established in the last 10 years
Origin of the cutoff is still under discussion

Standard Scenario of the Cosmic-Ray Spectrum



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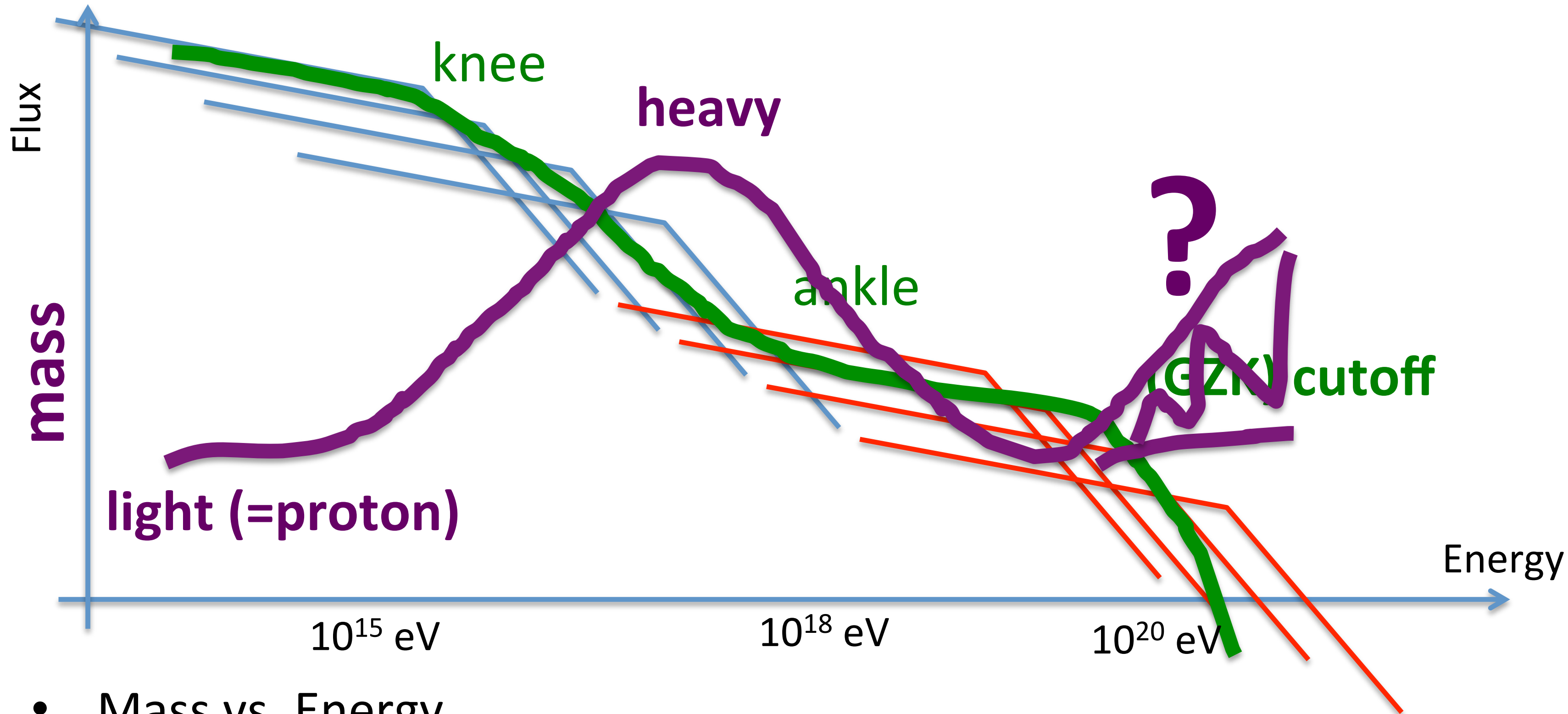
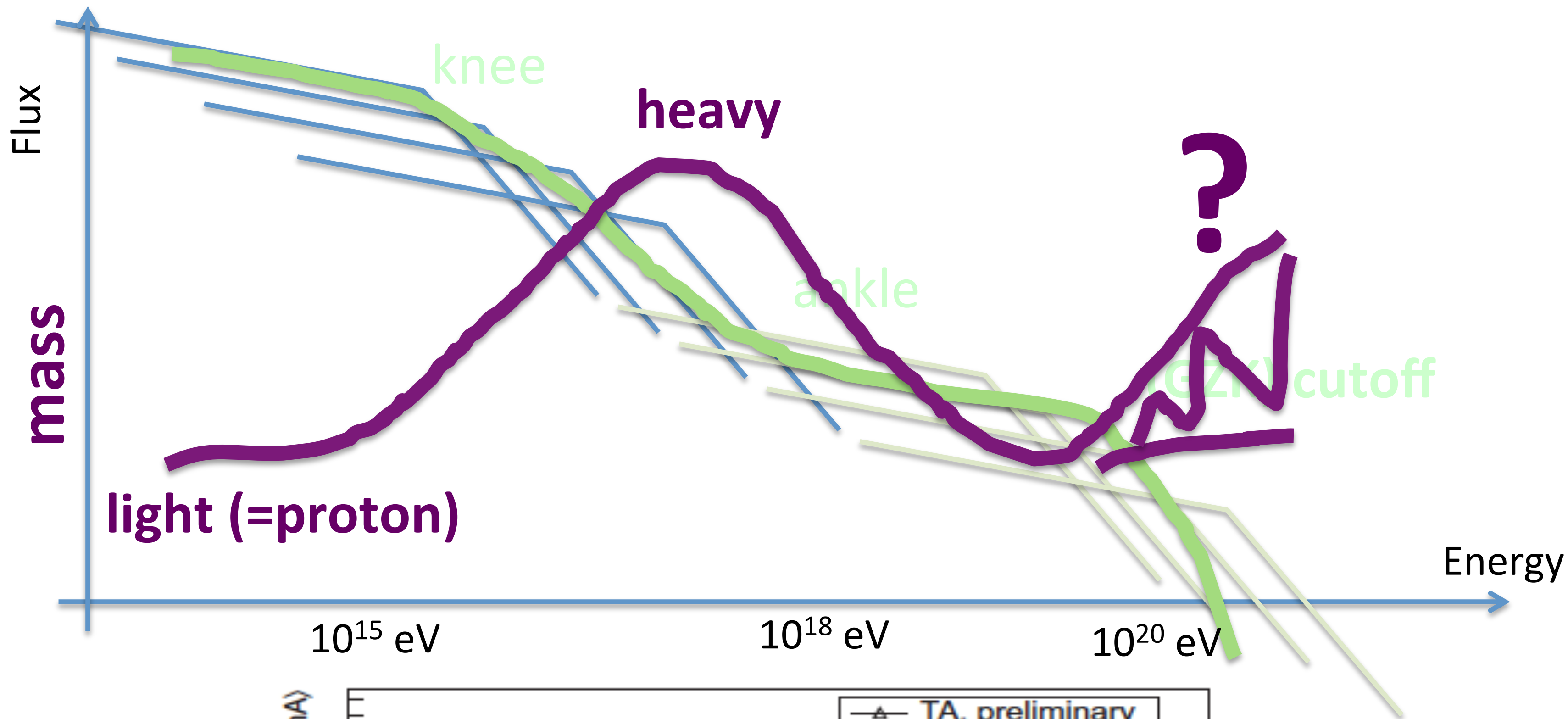
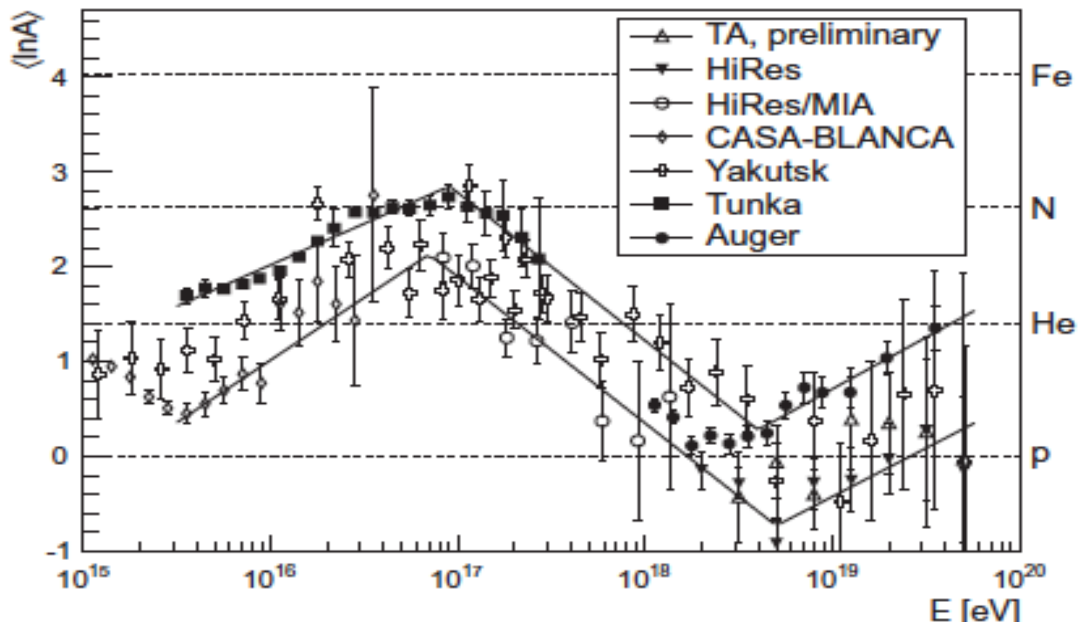
Standard Scenario of the Cosmic-Ray Spectrum



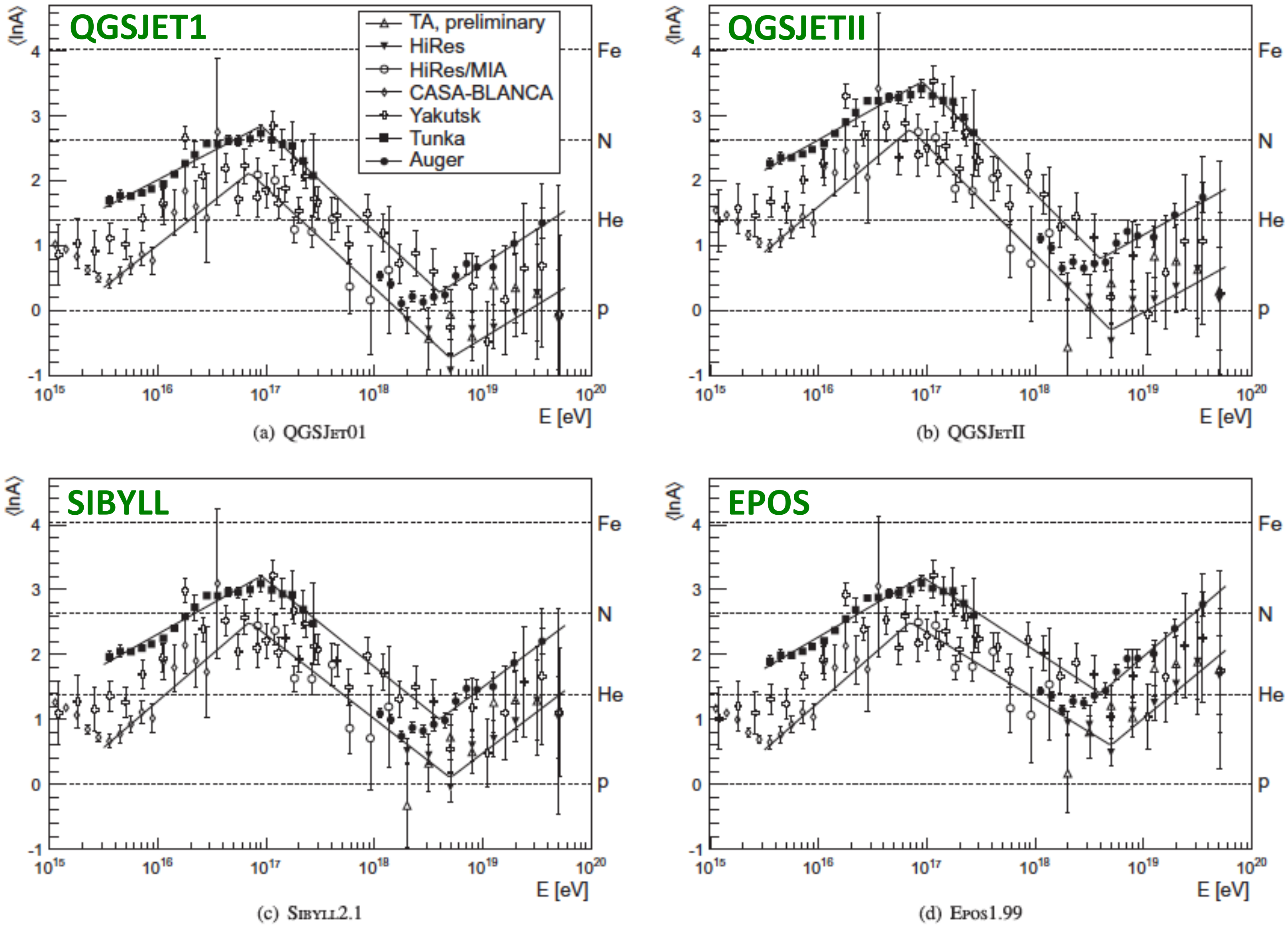
- Mass vs. Energy
  - Light below knee
  - Light to heavy over knee
  - Heavy to light around ankle
  - Light or light to heavy around cutoff





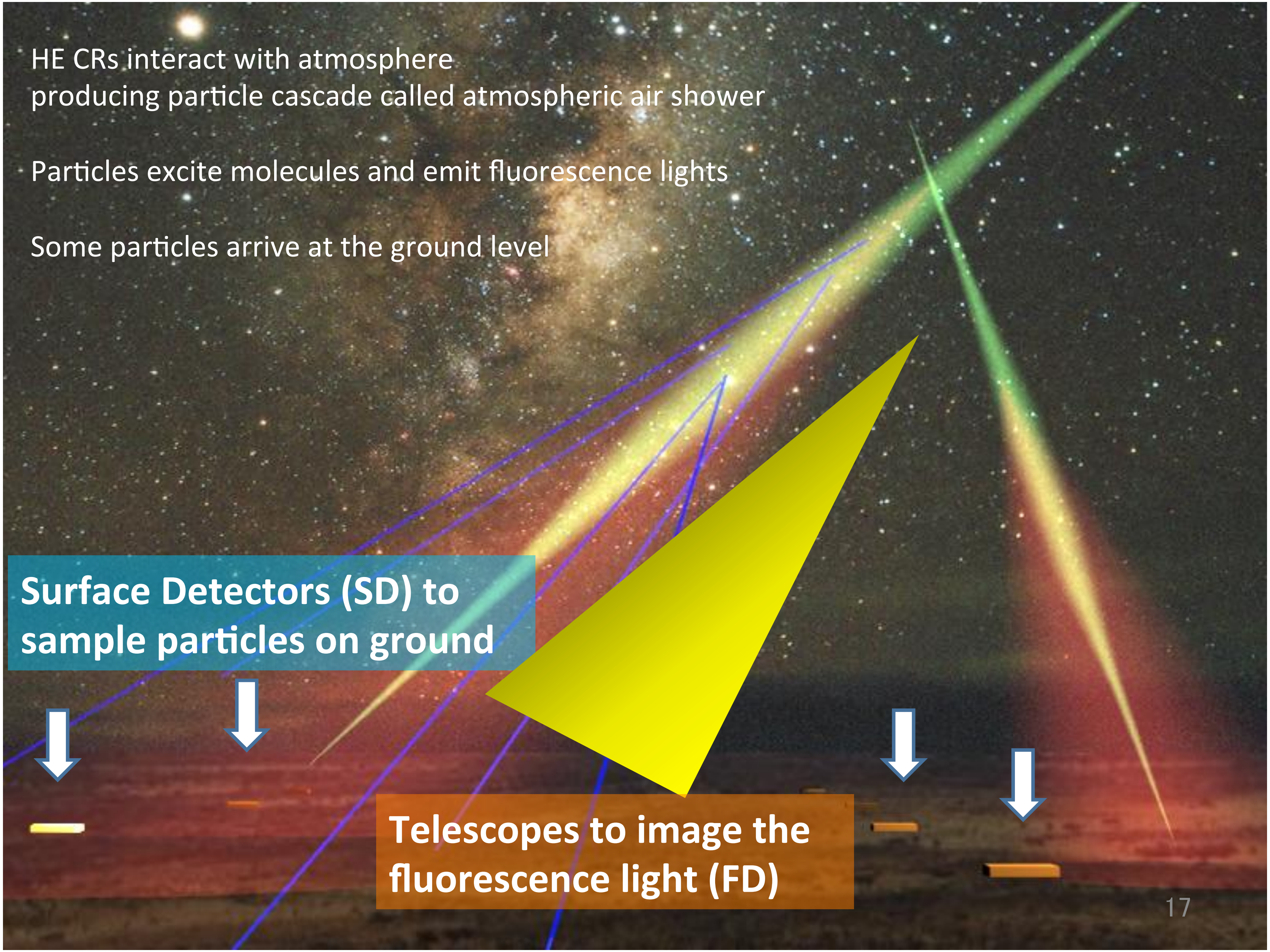
(a) QGSJet01

- Mass vs
  - Light
  - Light
  - Heav
  - Light



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

Interpretation is not unique. WHY??? …Hadronic interaction.


HE CRs interact with atmosphere
producing particle cascade called atmospheric air shower
Particles excite molecules and emit fluorescence lights
Some particles arrive at the ground level
Surface Detectors (SD) to
sample particles on ground
Telescopes to image the
fluorescence light (FD)

Our observables
(Energy, Mass, Direction)

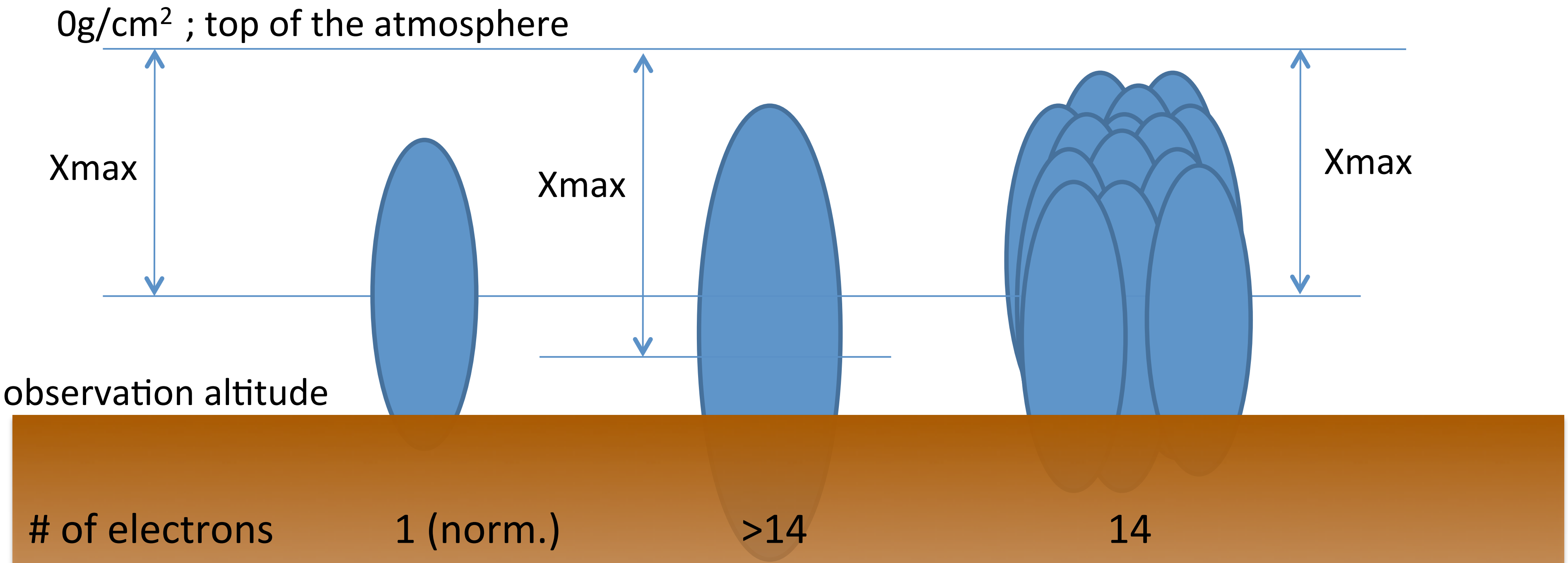
- FD
  - ENERGY: intensity of Fluorescence light
  - MASS: longitudinal shape of showers
  - DIRECTION: image and timing of showers
- SD
  - ENERGY: sampled number density and profile of particles at ground
  - MASS: particle species (but limited)
  - DIRECTION: arrival timing

Our observables
(Energy, Mass, Direction)

Interaction model dependent

- FD
  - ENERGY: intensity of Fluorescence light
  - MASS: longitudinal shape of showers
  - DIRECTION: image and timing of showers
- SD
  - ENERGY: sampled number density and profile of particles at ground
  - MASS: particle species (but limited)
  - DIRECTION: arrival timing

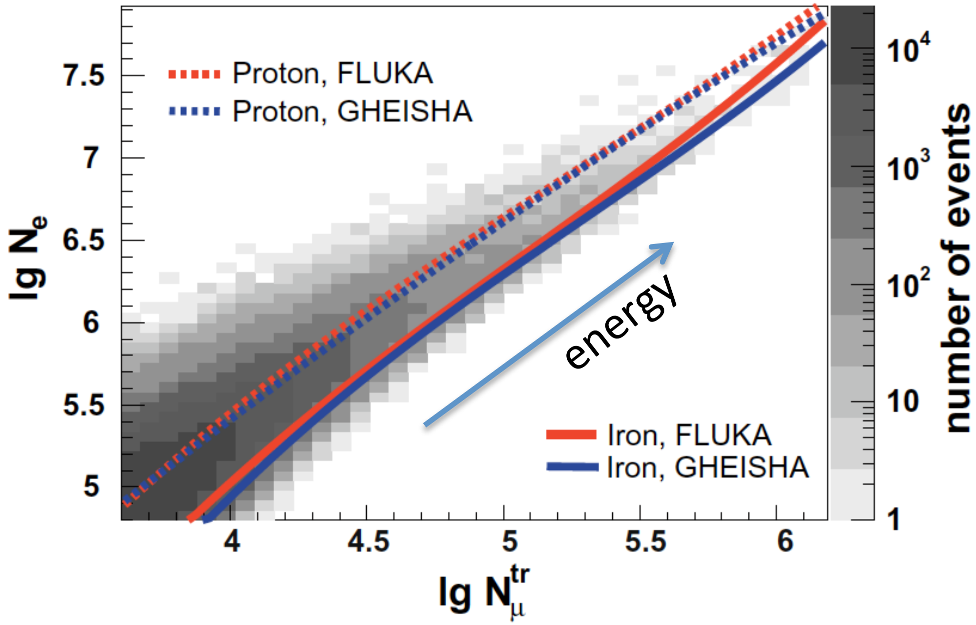
How can we estimate energy and mass?

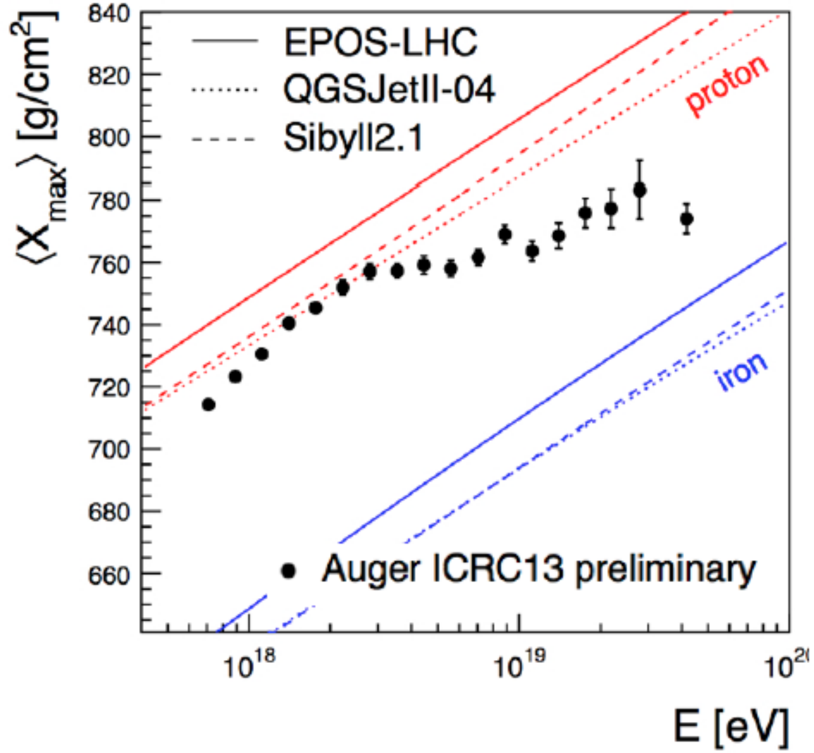


	ex) 10^{17} eV proton	14×10^{17} eV proton	14×10^{17} eV Nitrogen = 14 superposition of 10^{17}eV proton (nucleon)
# of electrons	1 (norm.)	>14	14
# of muons	1 (norm.)	~14	~14
Xmax	log(1) (norm.)	log(14)	log(1)
Intensity of Fluor.	1 (norm.)	14	14

Measurements

KASCADE, Astropart. Phys. 2009

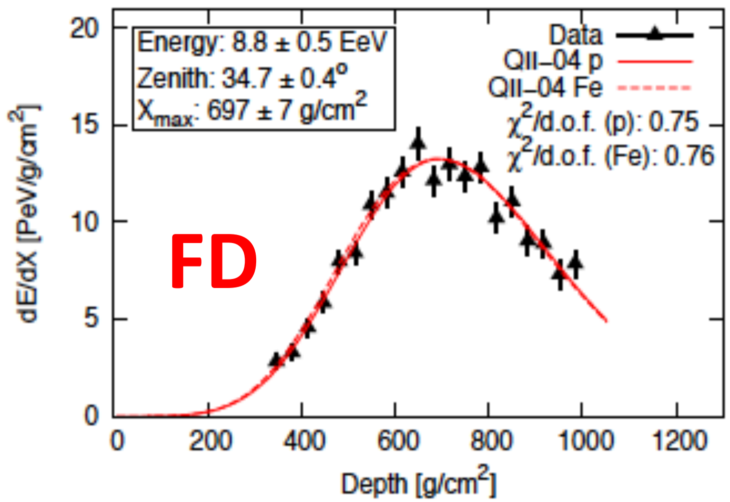


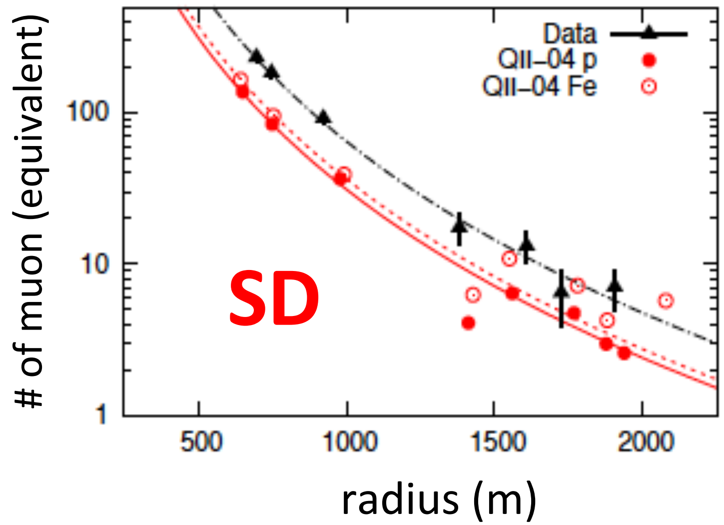


- N_e => E ; helped by air shower simulation
- $I_{fluor.}$ => E ; calorimetric, no air shower simulation, but emissivity calibration
- N_μ-N_e, E-<Xmax> => Mass ; helped by air shower simulation

Air shower MC crisis?

PAO, ICRC2013





Among MC samples of proton and iron primaries, best fit events to an observed FD data were selected [top figure]

Same events were compared between data and MC but for SD results [bottom figure]

Data always show more muon than simulated proton/ Fe showers in SD comparison

FD and SD data are not consistently described

=> Muon excess problem

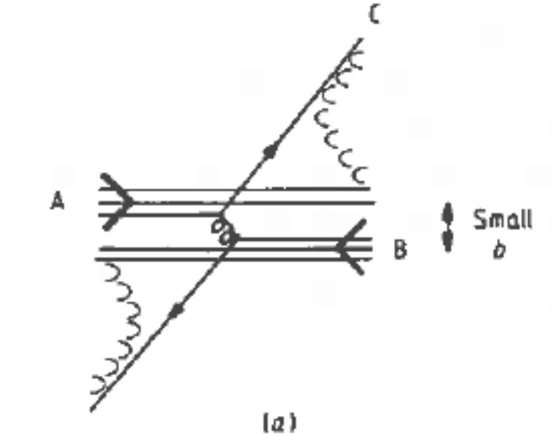
We know that <u>something wrong</u>
So far no hint is found
- more detailed observation of air shower particles
- more comparisons between accelerator data and model predictions

are necessary

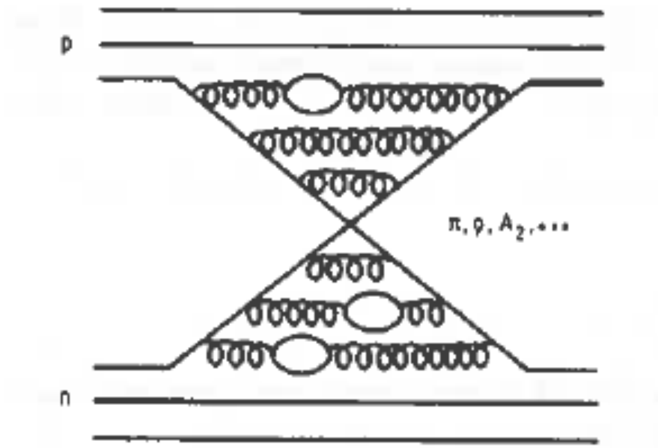
Why MC predictions differ and difficult?

- Higher energy than the accelerator energy
- Essentially soft (small Q^2) interactions dominate
  - particles from soft interaction carry a large fraction of collision energy => important for air shower
  - soft particles are emitted very forward, difficult to measure even at the accelerator energy
  - while cross sections of hard interactions can be calculated by pQCD, it is difficult for soft processes

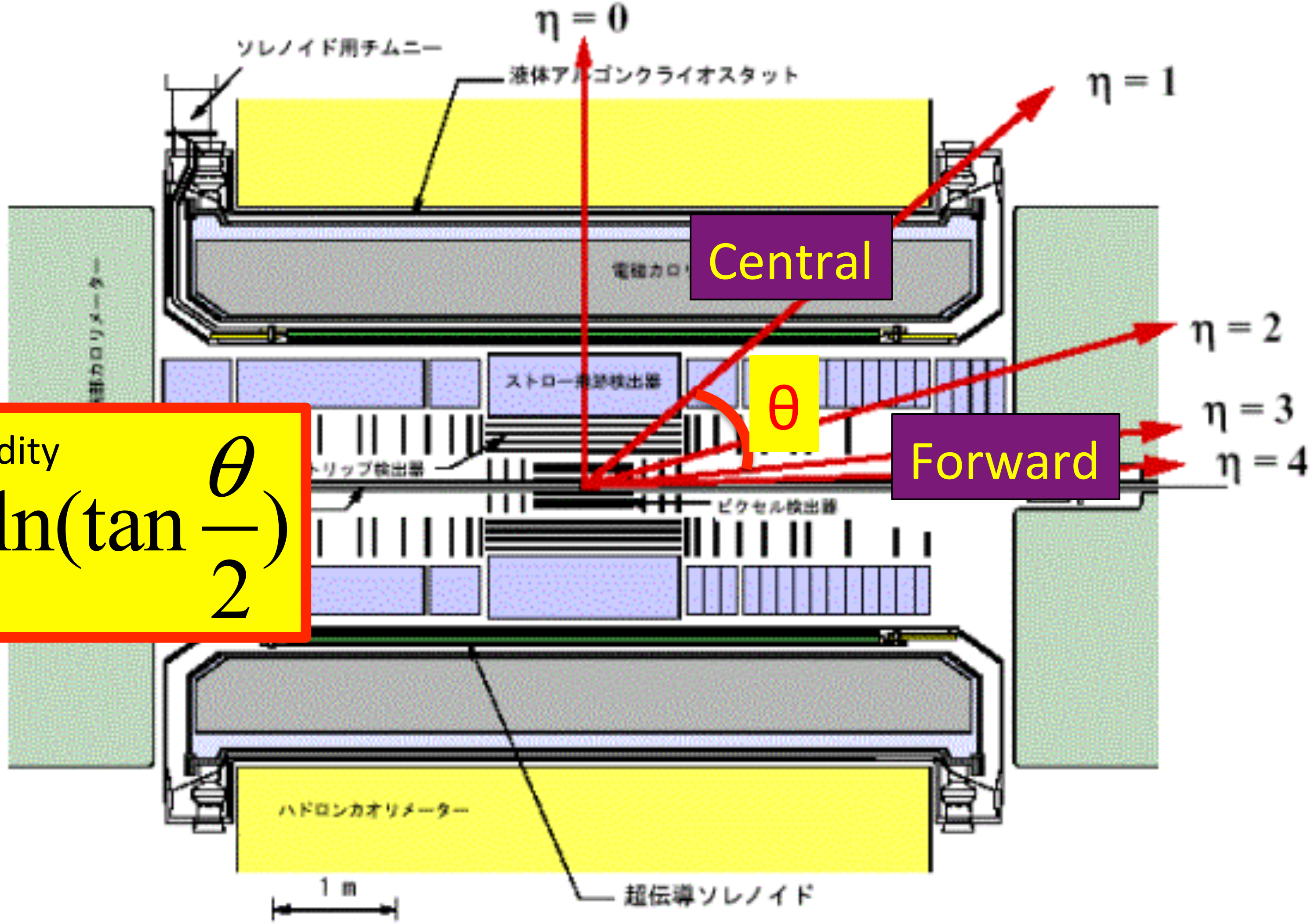
hard interaction : parton-parton interaction as asymptotic free particles



soft interaction : pion exchange, meson exchange, Reggeon exchange, Pomeron exchange, multi-Pomerons exchange



How forward are they emitted?



pseudorapidity

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

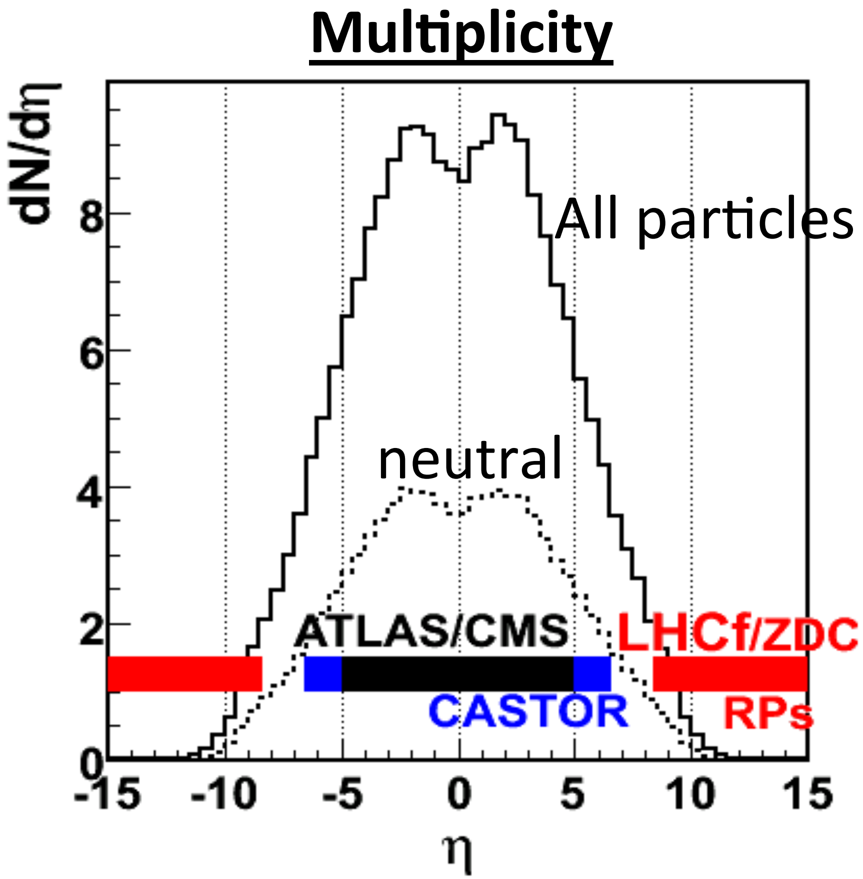
η: pseudorapidity ~ y: rapidity $y = (1/2) \times \ln((E+p_z)/(E-p_z))$

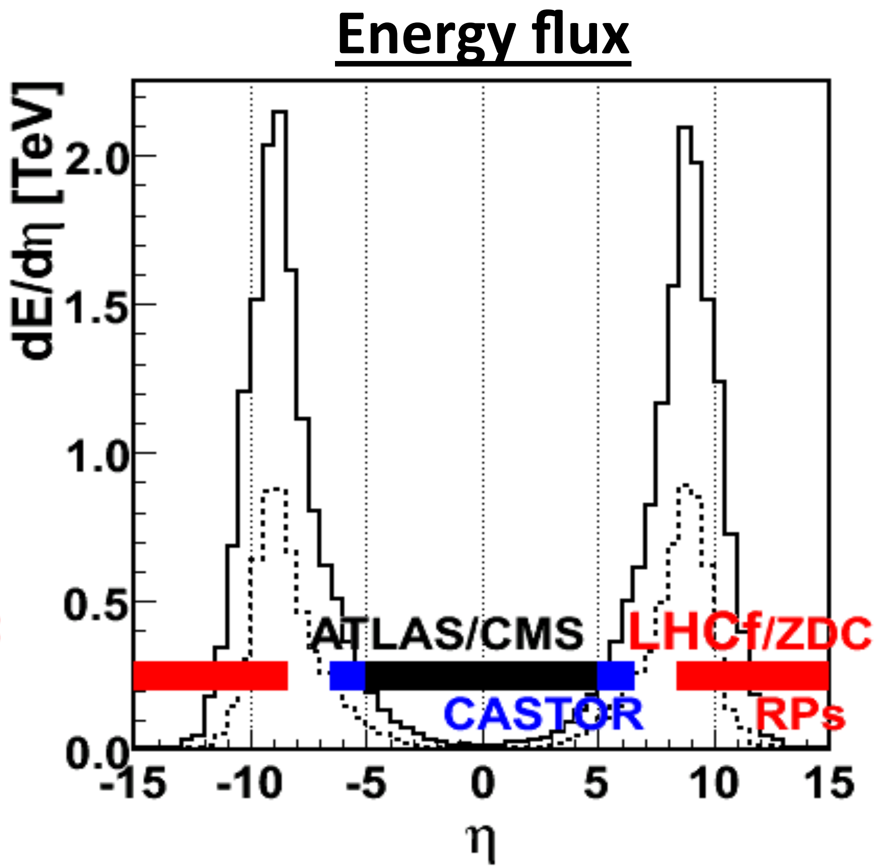
Lorentz変換で、 y => y + const

Secondary particles at LHC energy

multiplicity and energy flux at LHC 14TeV collisions

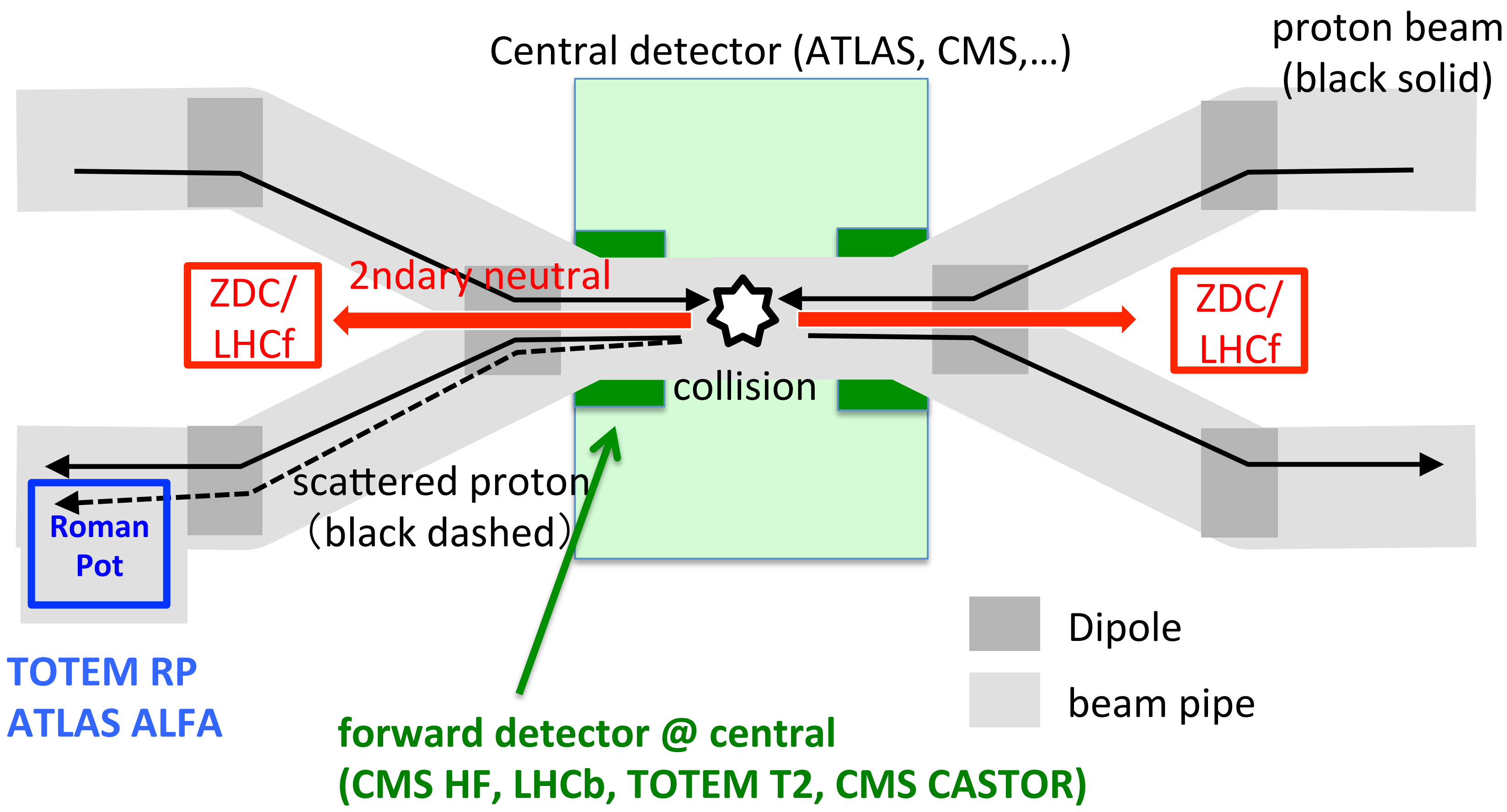
pseudo-rapidity; η= -ln(tan(θ/2))





- Most of the particles are emitted in the center
- Most of the energy is carried forward
  - η =8 => θ = 6.7×10^{-4} rad … almost parallel to the beam pipe!!

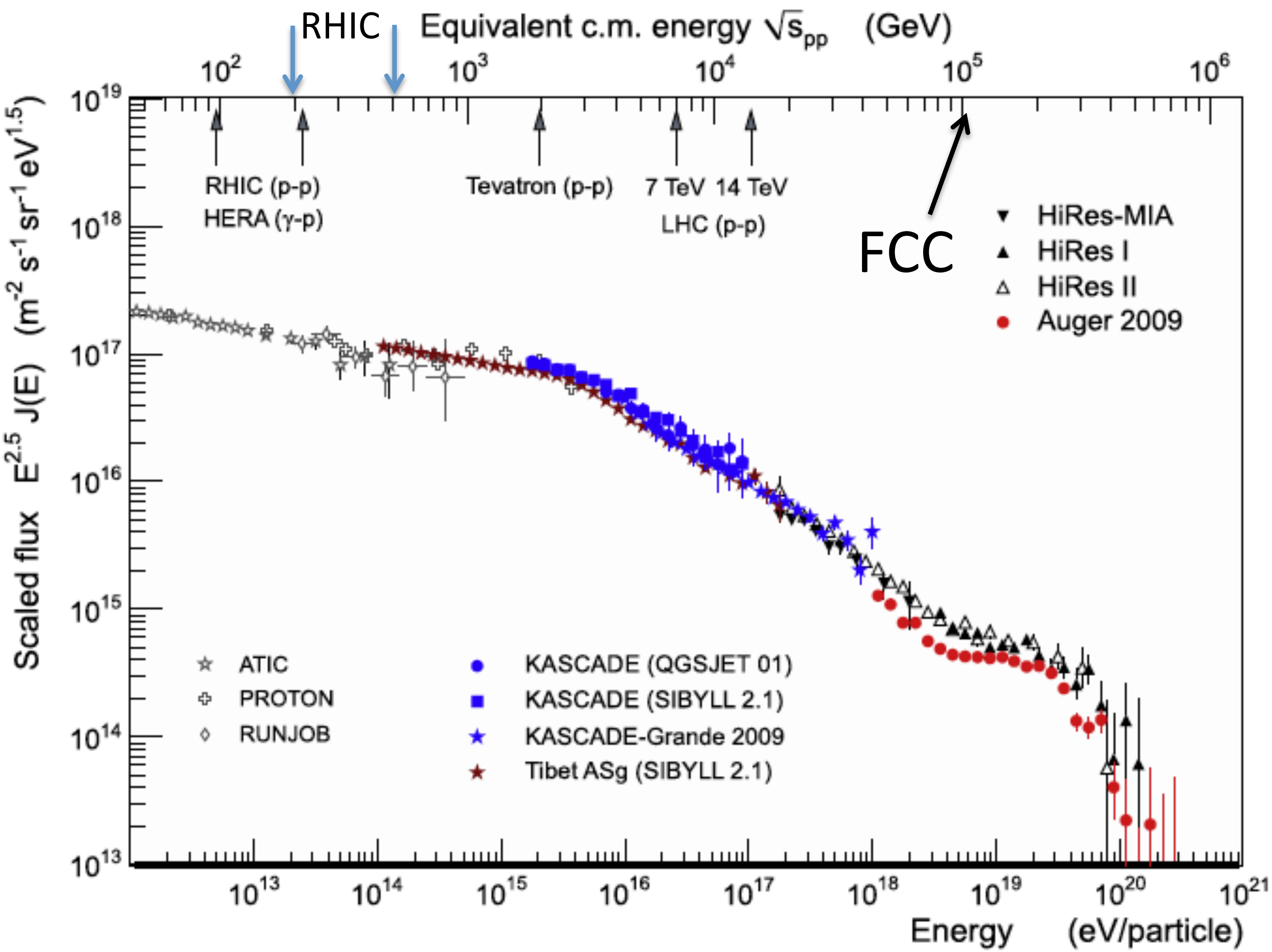
Forward experiments at LHC



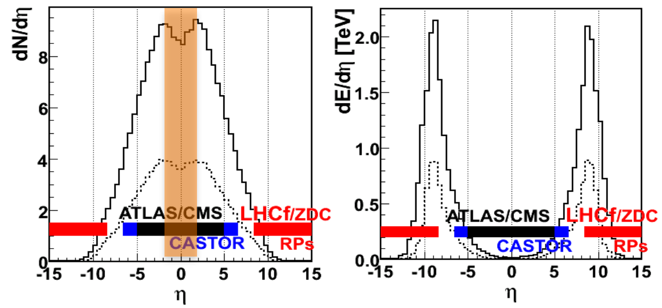
ZDCs were (are) available also at ISR and RHIC

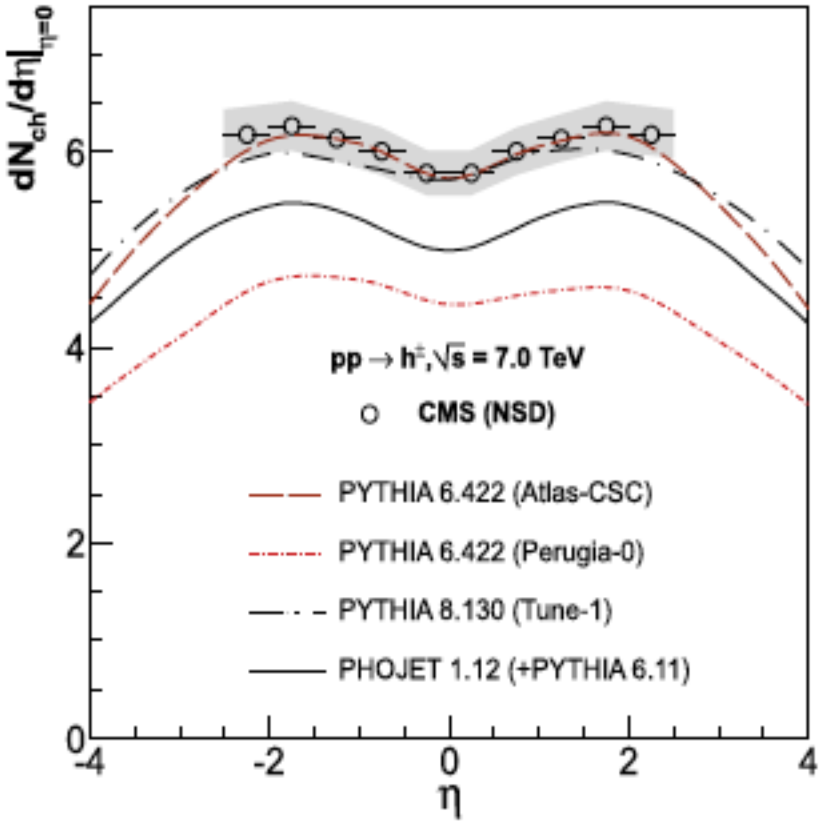
Colliders to test interaction models

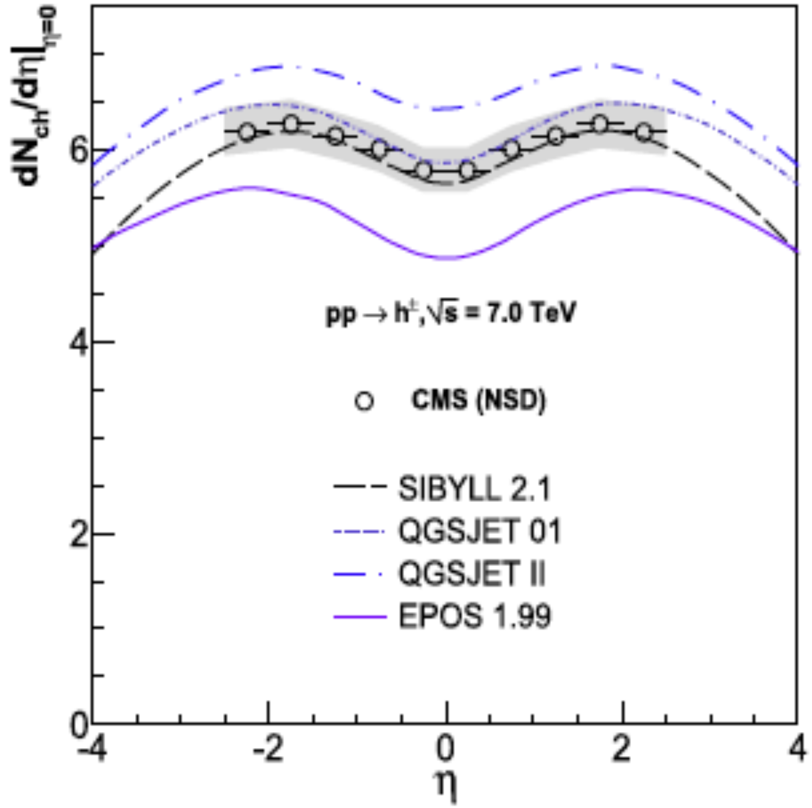
（D'Enterria et al., APP, 35,98-113, 2011 ）



meson multiplicity @central

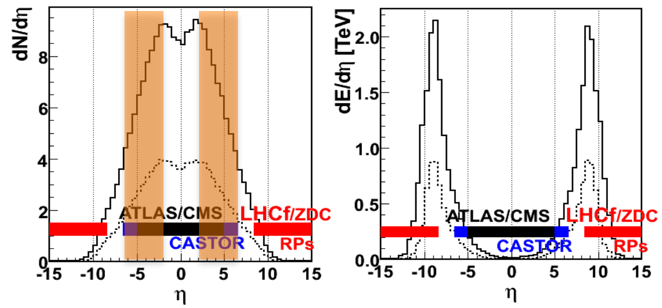


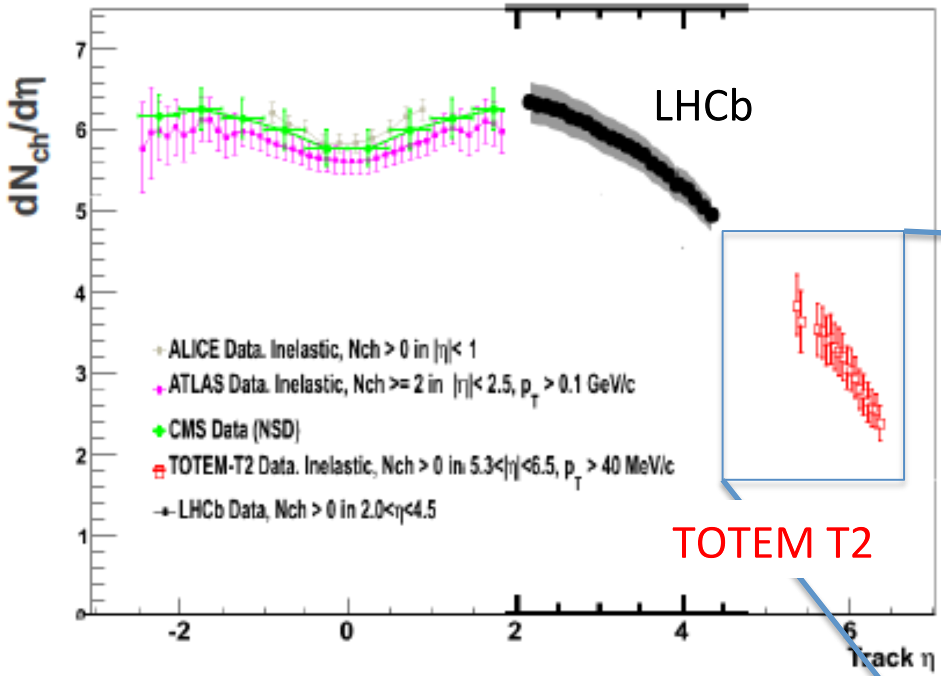


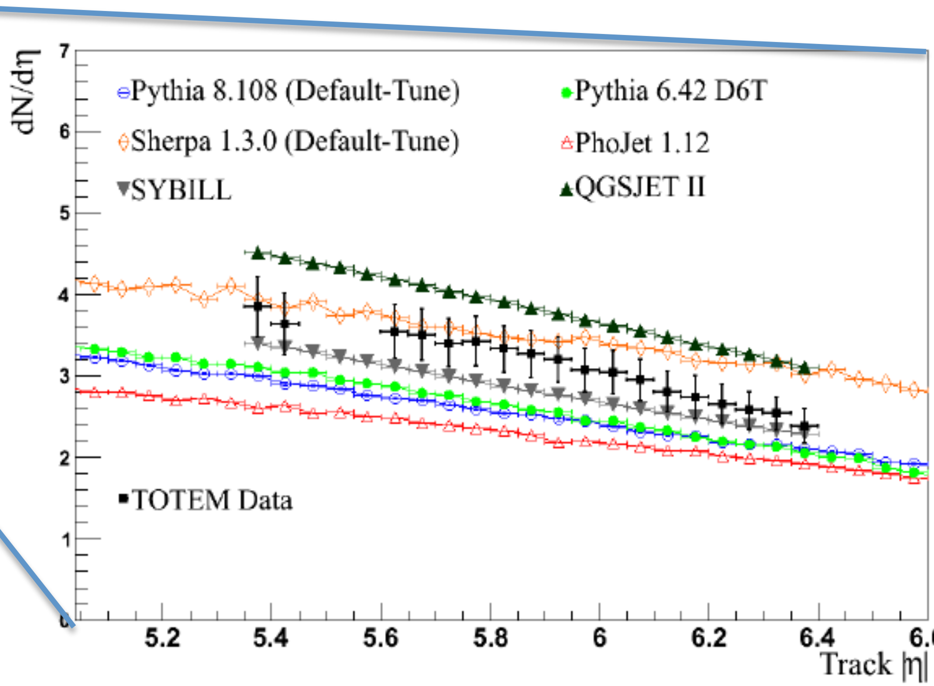


D.D'Enterria et al., Astropart. Phys., 35 (2011) 98-113

TOTEM T2 tracker, LHCb; forward multiplicity

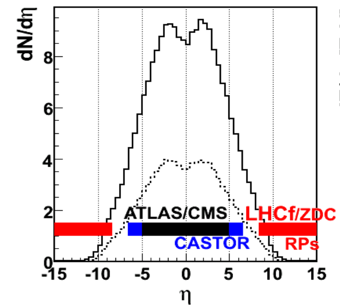


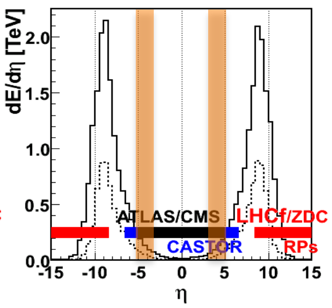


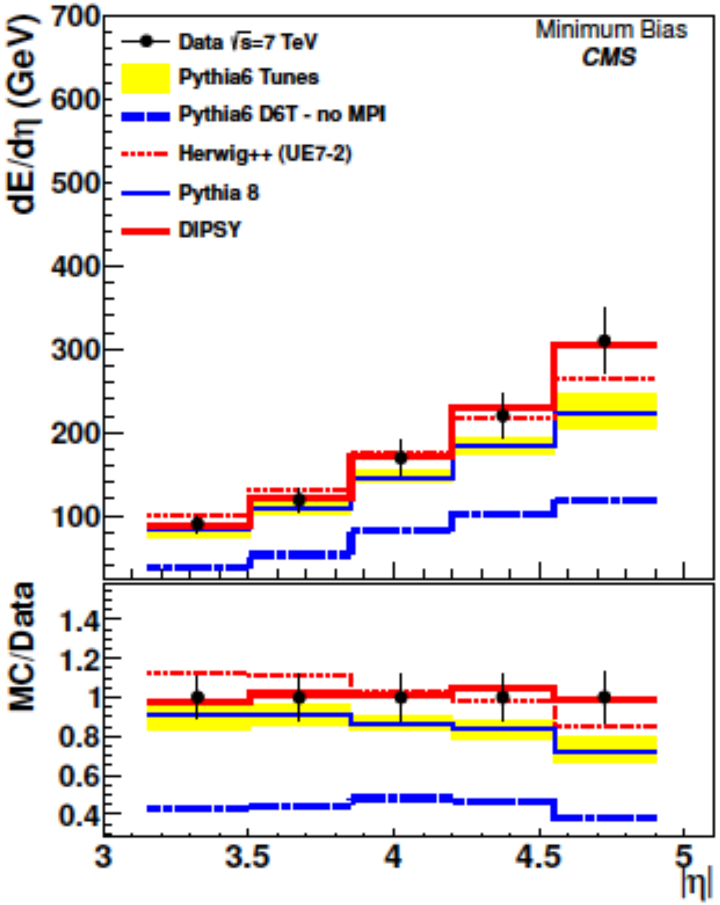


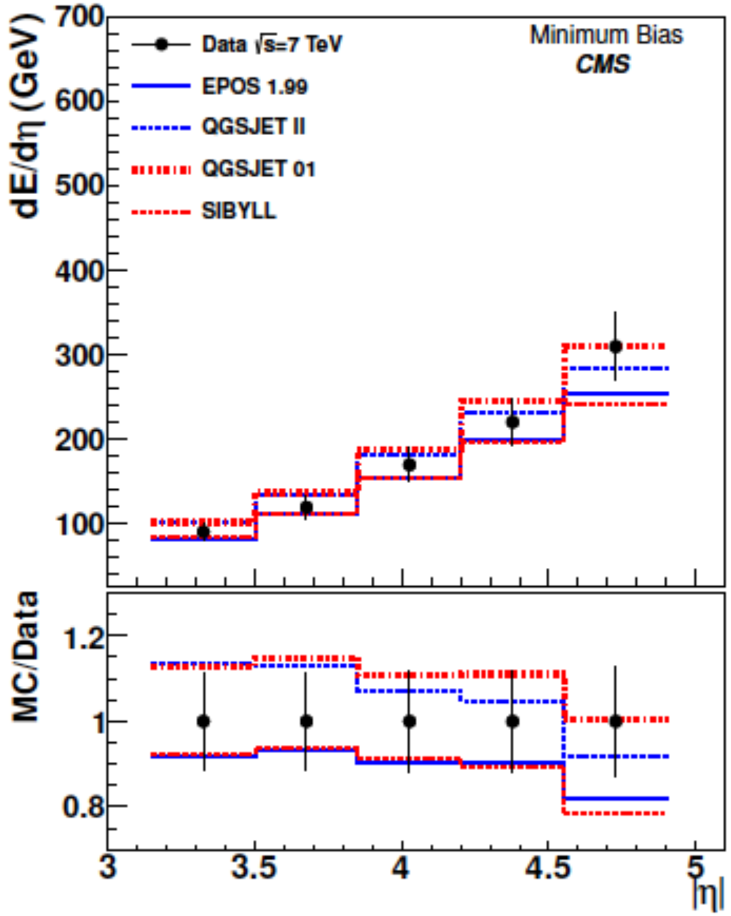
Presentation at QCD at Cosmic Energies - V

CMS HF
(Hadronic Forward Calorimeter)



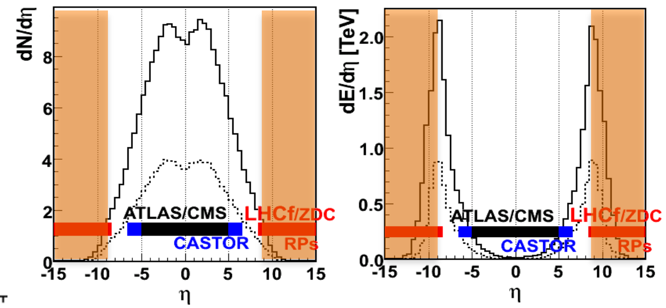


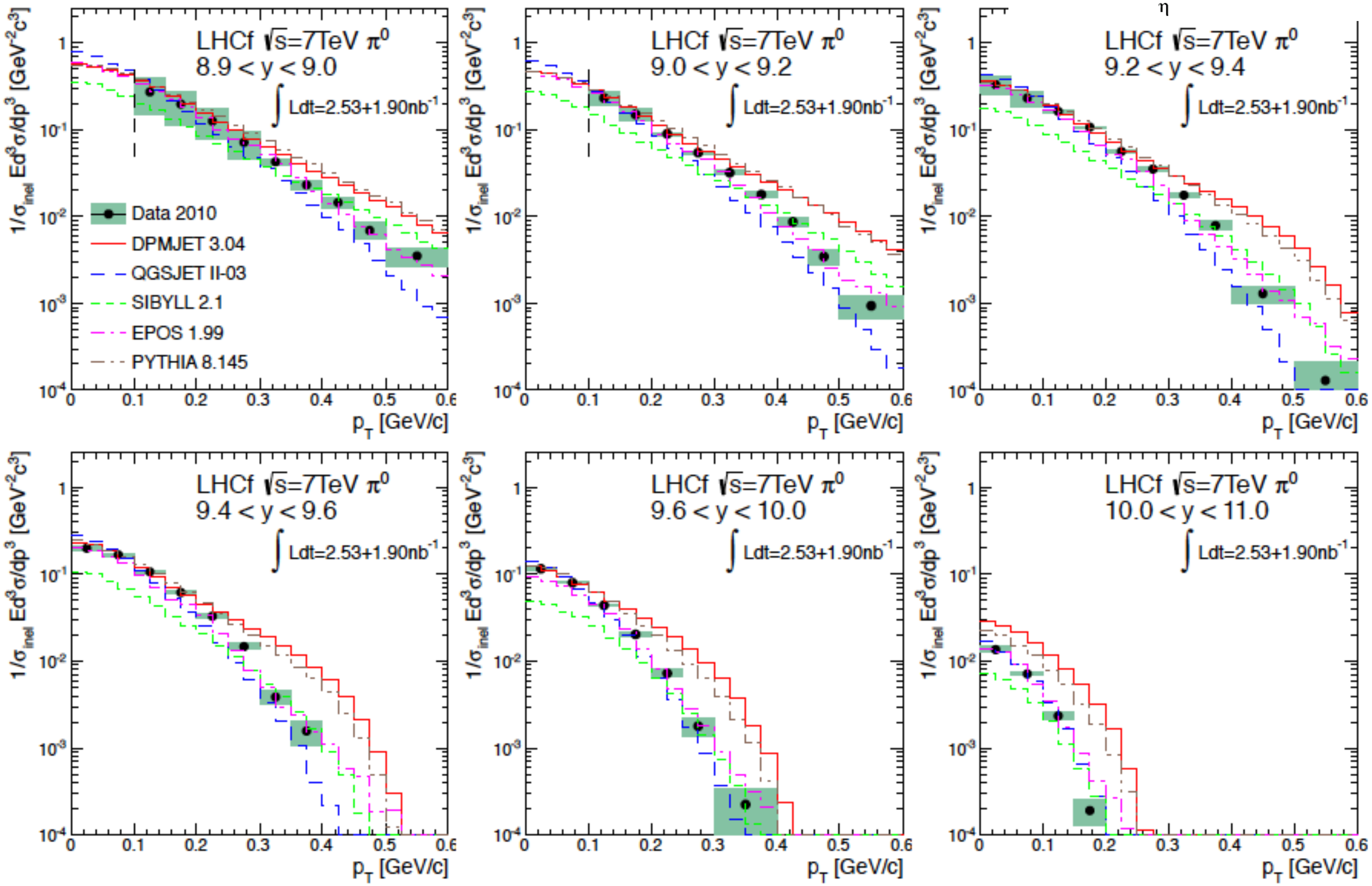




The CMS Collaboration, JHEP, 11 (2011) 148

LHCf; π^0 P_T distribution (6 rapidity bins)



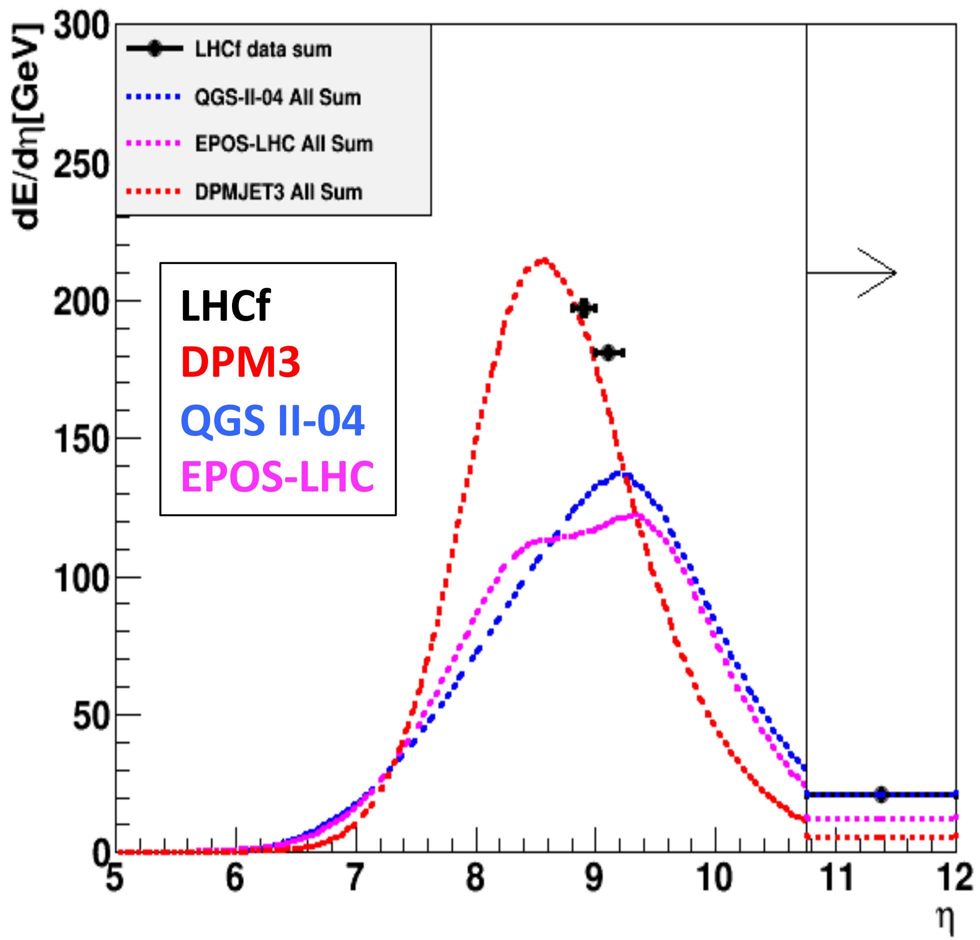


The LHCf Collaboration, PRD, 86, 092001 (2012)

General conclusions from LHC results

- Models, especially QGSJET-II and EPOS, reasonably explain the measurements at LHC
- Are CR physicists happy? Do we just need fine tuning of models?
- No! How can we solve the muon problem?
- Is accelerator data enough?
- Can CR observations constrain more about muon problem?

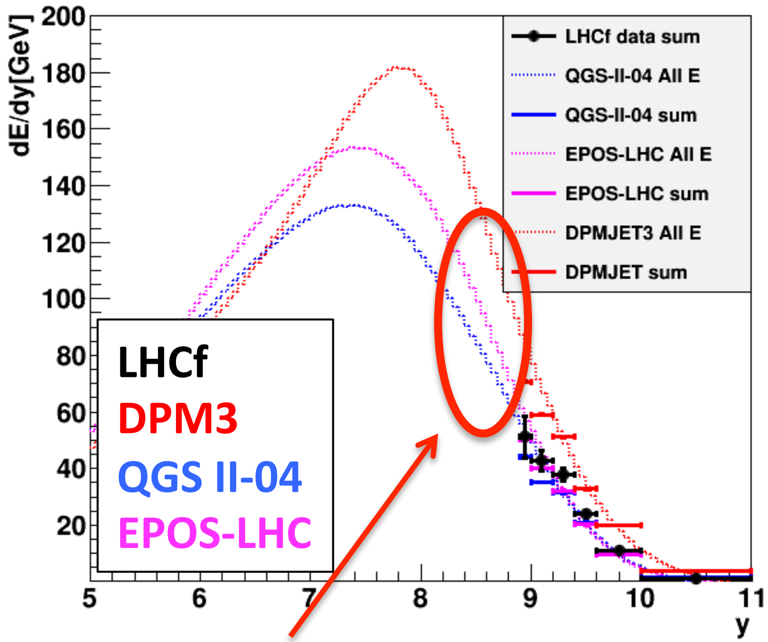
Neutron energy flow by LHCf
(preliminary)



- Black solid circles : LHCf data
- Dotted line : neutron energy flow distribution of each model (E > 500GeV)
- Latest models (EPOS-LHC and QGSJET II-04) included

π^0 energy flow

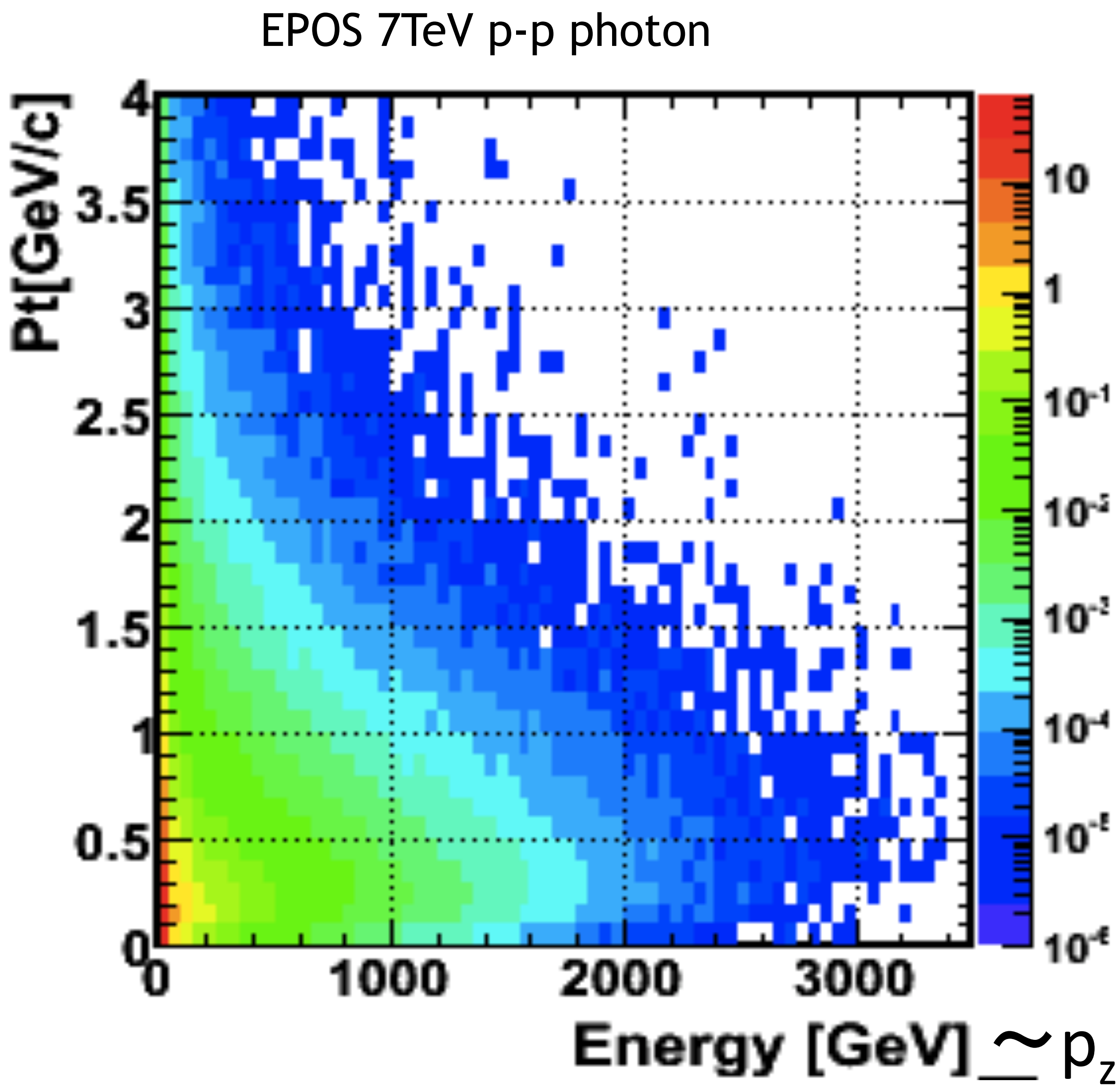
- ✓ Post-LHC models (EPOS-LHC and QGSJET II-04) well explain the LHCf results
- ✓ Difference of models can be tested with 13 TeV p-p data



to be covered in 13TeV

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

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



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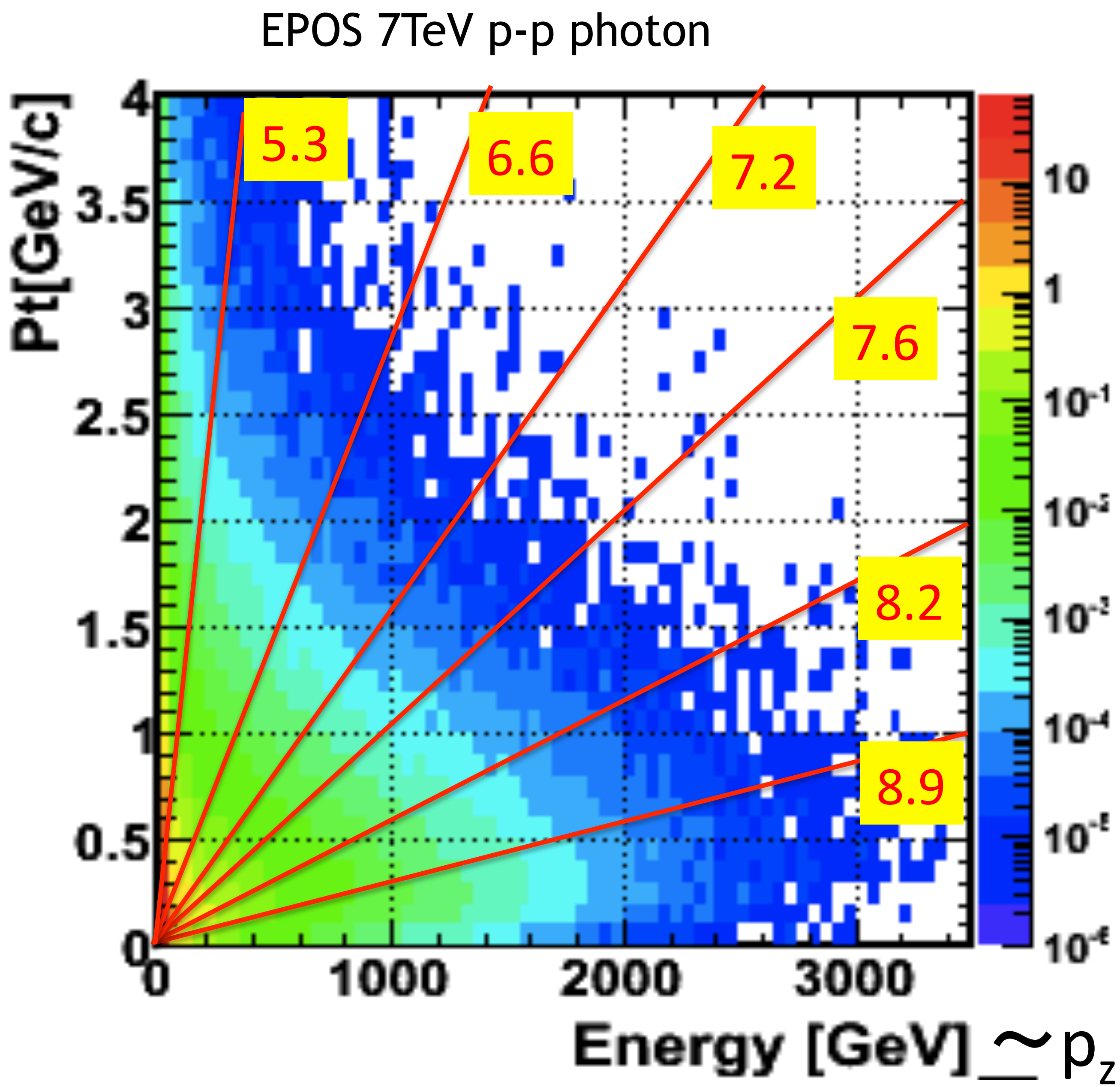

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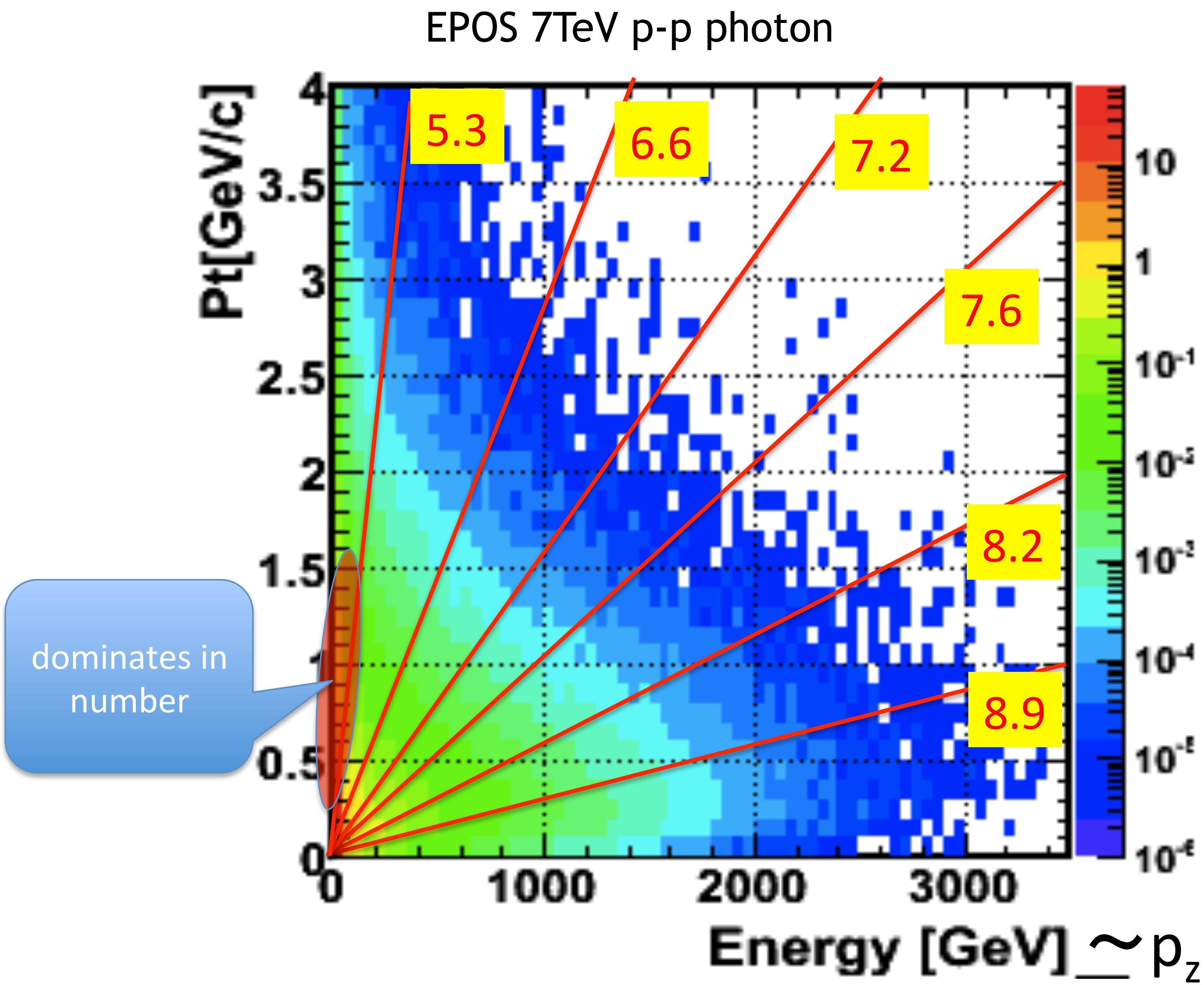
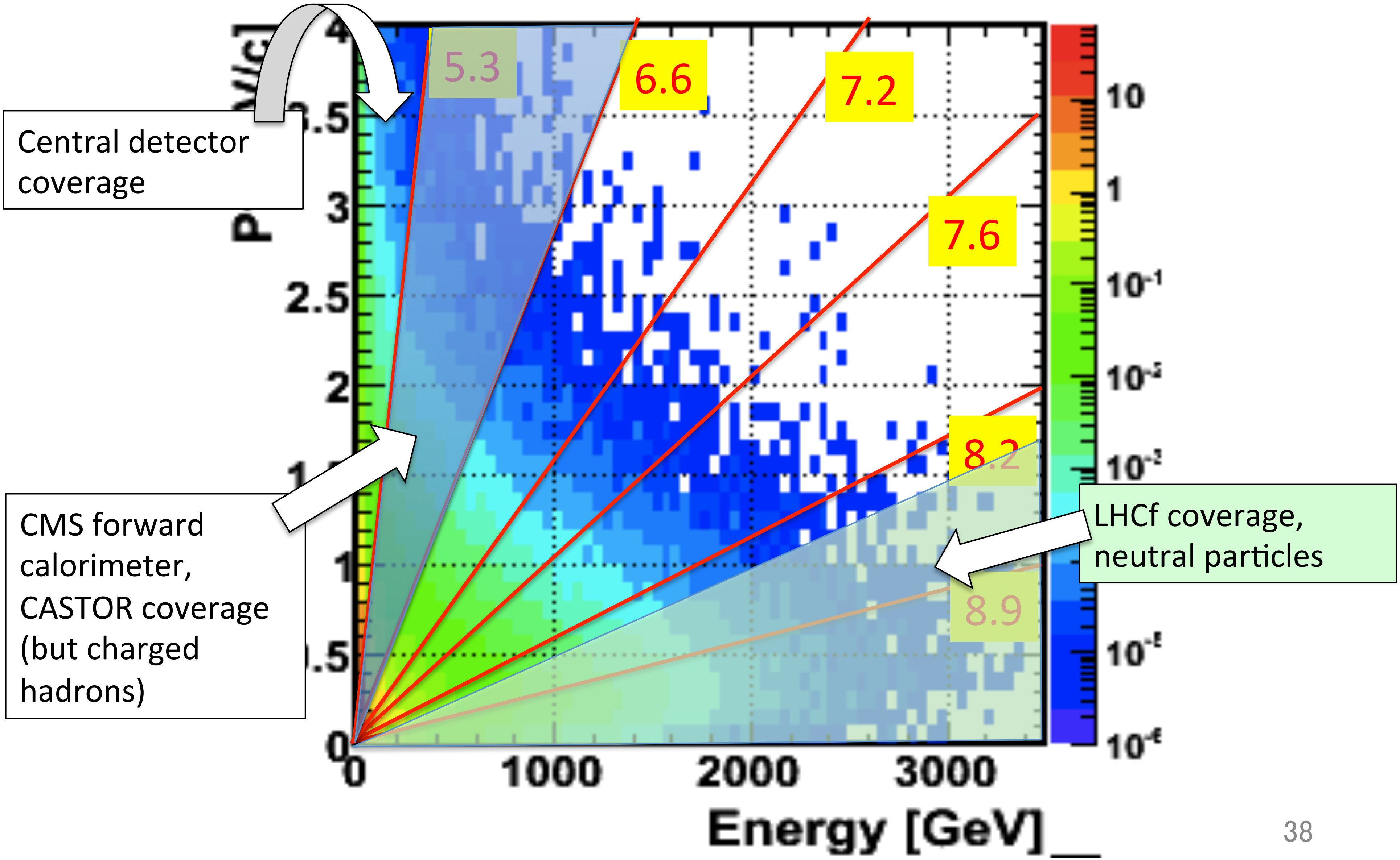


photon (predominantly π^0 decay) cross section at 7TeV p-p collision

EPOS 7TeV p-p photon



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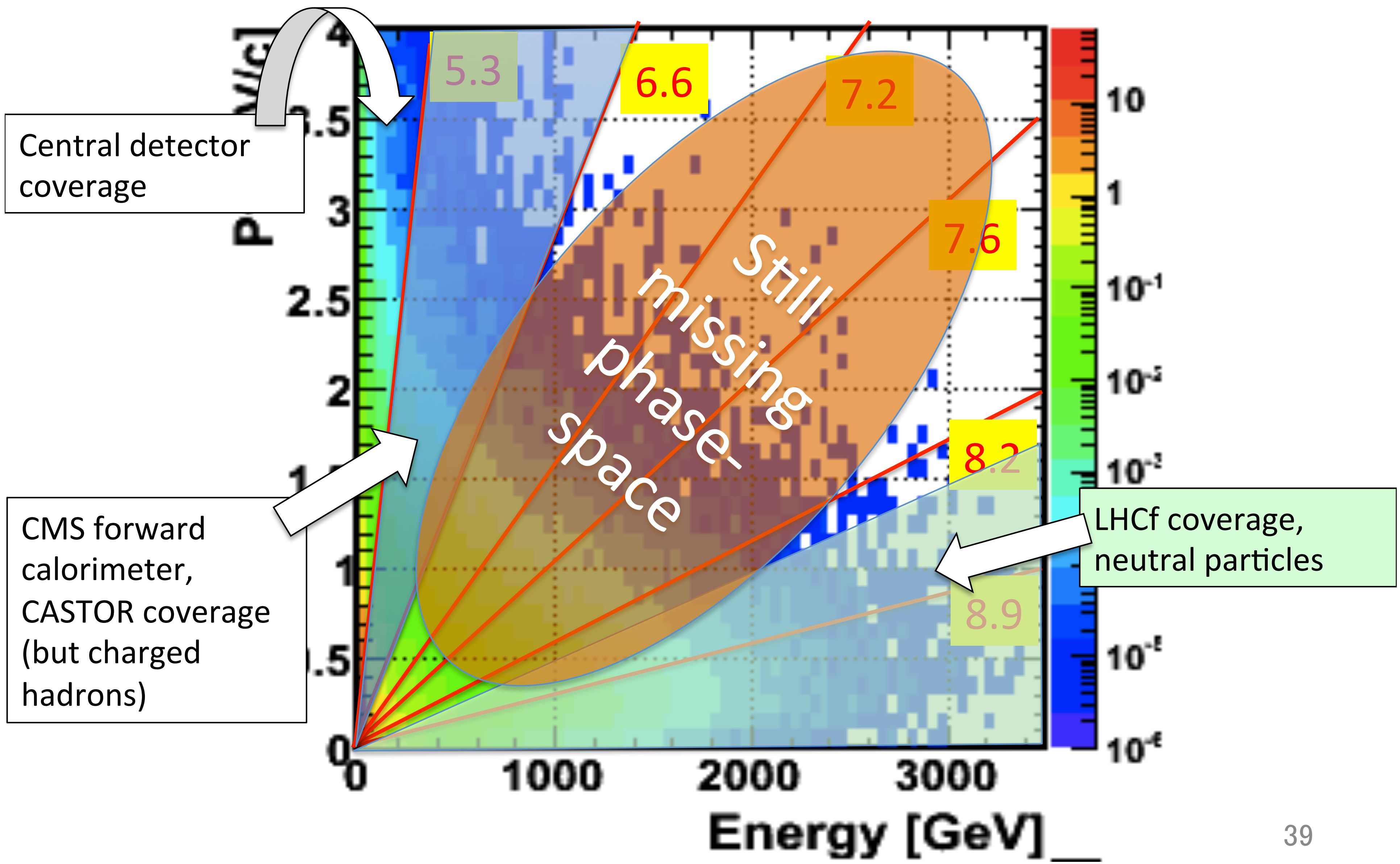


Summary

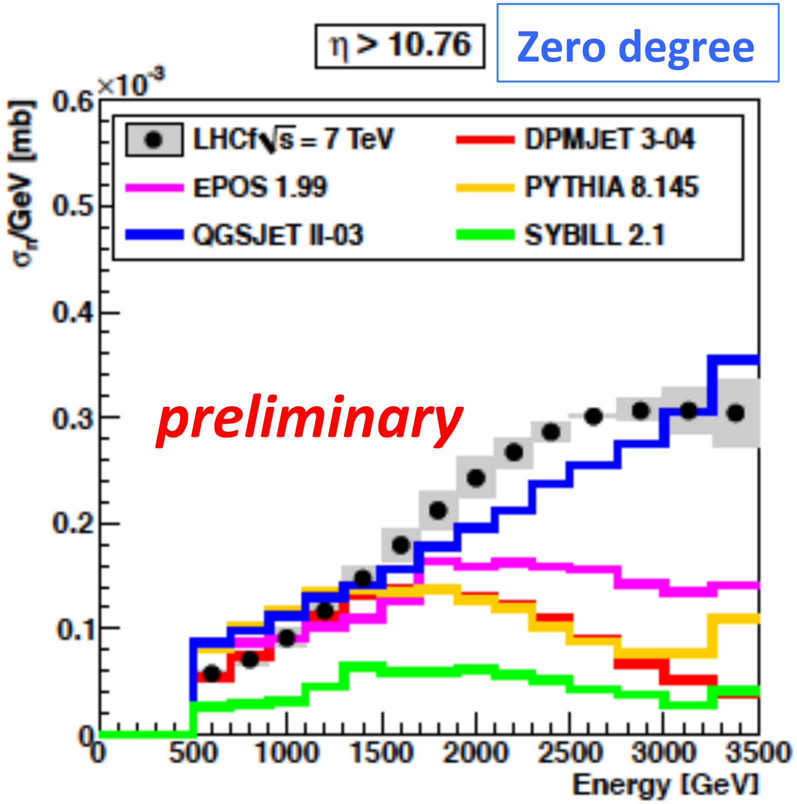
- Cosmic-ray part
  - Cutoff at 10^{20}eV is established
  - Origin is still unknown (GZK is an idea)
  - CR mass of 10^{15}-10^{18} is important to test the CR standard model
  - Uncertainty in hadronic interaction causes uncertainty in interpretation
  - Muon excess indicates we are missing something
- Collider part
  - LHC data show reasonable agreements with CR model predictions => It does not solve the muon problem
  - LHCf neutron data can be a smoking gun?
  - Still large unexplored phase-space at LHC
  - Wider $\sqrt{s}$ coverage is important (LHC 13-14TeV, RHIC, FCC)
  - Light nuclei (atmosphere) collision is completely missing

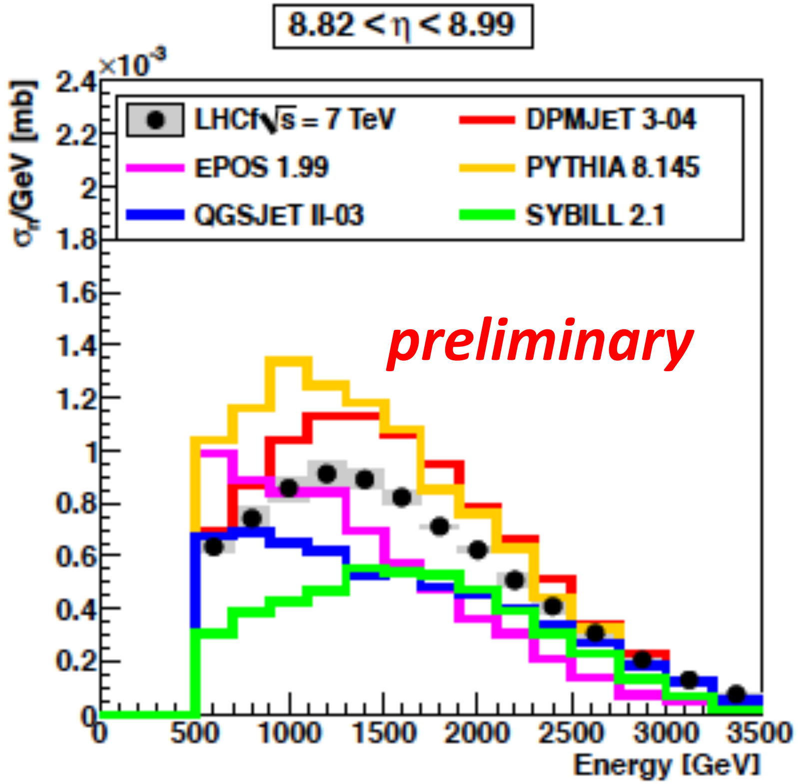
Agitation to KMI members

- Can soft hadronic interaction be described by Latice-QCD technique?
- Good application of latice to astrophysics?

backup

Neutron at 7TeV p-p





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

- ✓ Hard spectrum around zero degree similar to the QGS prediction
- ✓ Still large yield at lower rapidity