UHECR2022: L’Aquila: 3 – 7 October 2022

Evidence for a break in the Elongation Rate of Shower Maximum at ~3 EeV from four independent studies

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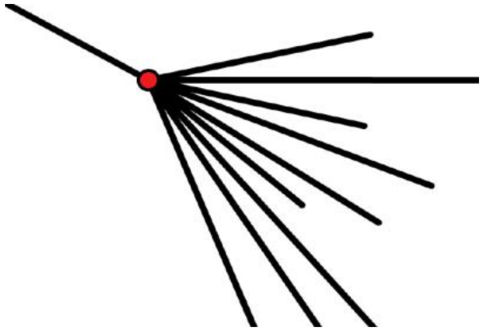

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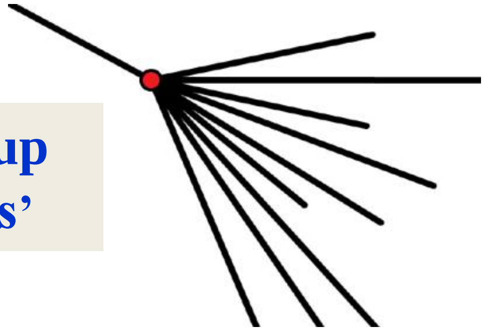
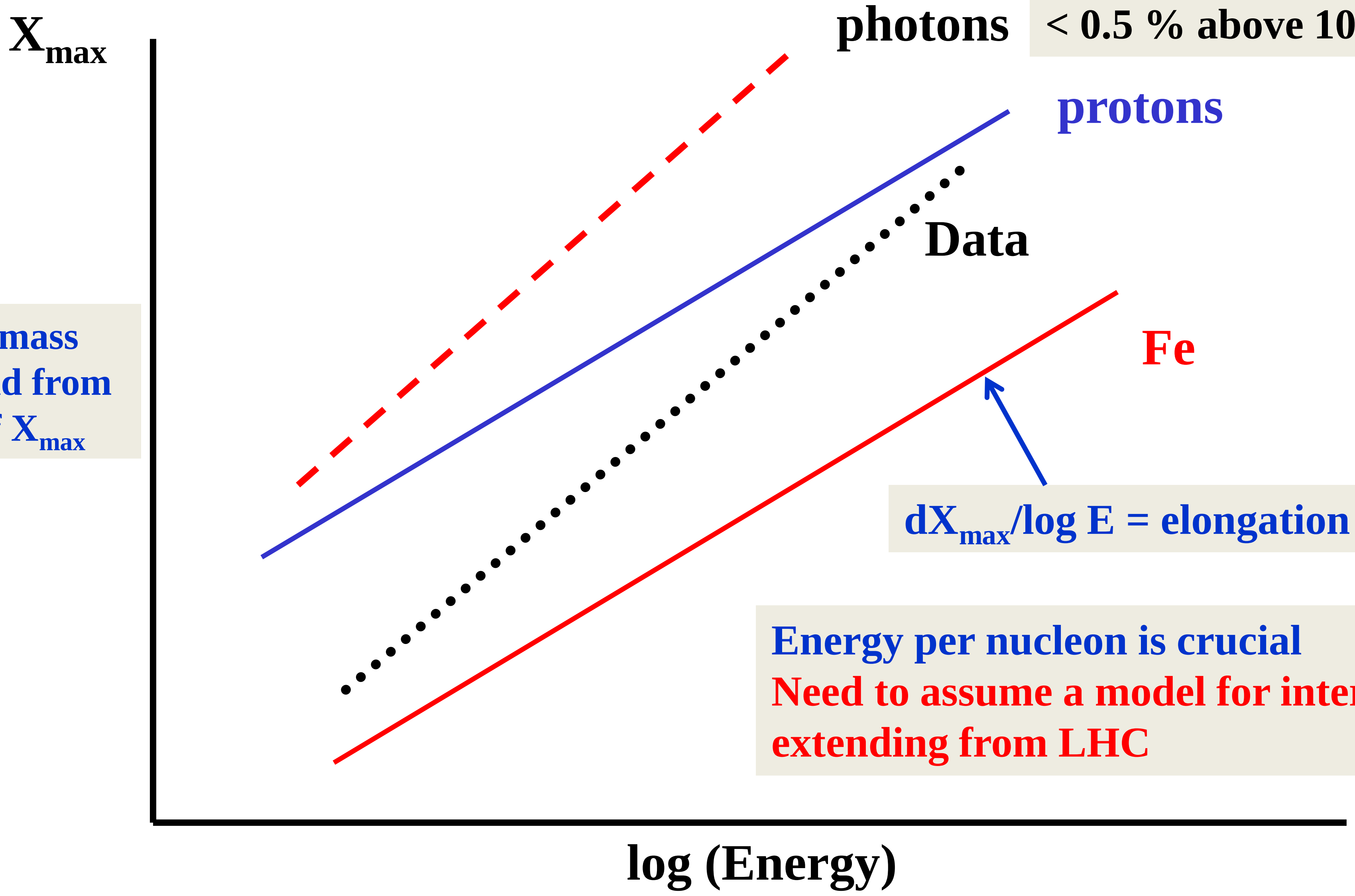
Talk given as, in the view of joint TA/Auger Working group on mass composition, it may help 'spice up the discussions'



The Elongation Rate: Linsley (1977): used extensively to order and understand data

The variation of mass with energy found from measurements of X_{max}



< 0.5 % above 10 EeV

$dX_{max}/\log E$ = elongation rate

Energy per nucleon is crucial

Need to assume a model for interactions extending from LHC

1993: Bird et al. Fly's Eye result: Paper had a big impact – looked as if we were heading for protons – BUT CONCLUSION IS MODEL DEPENDENT

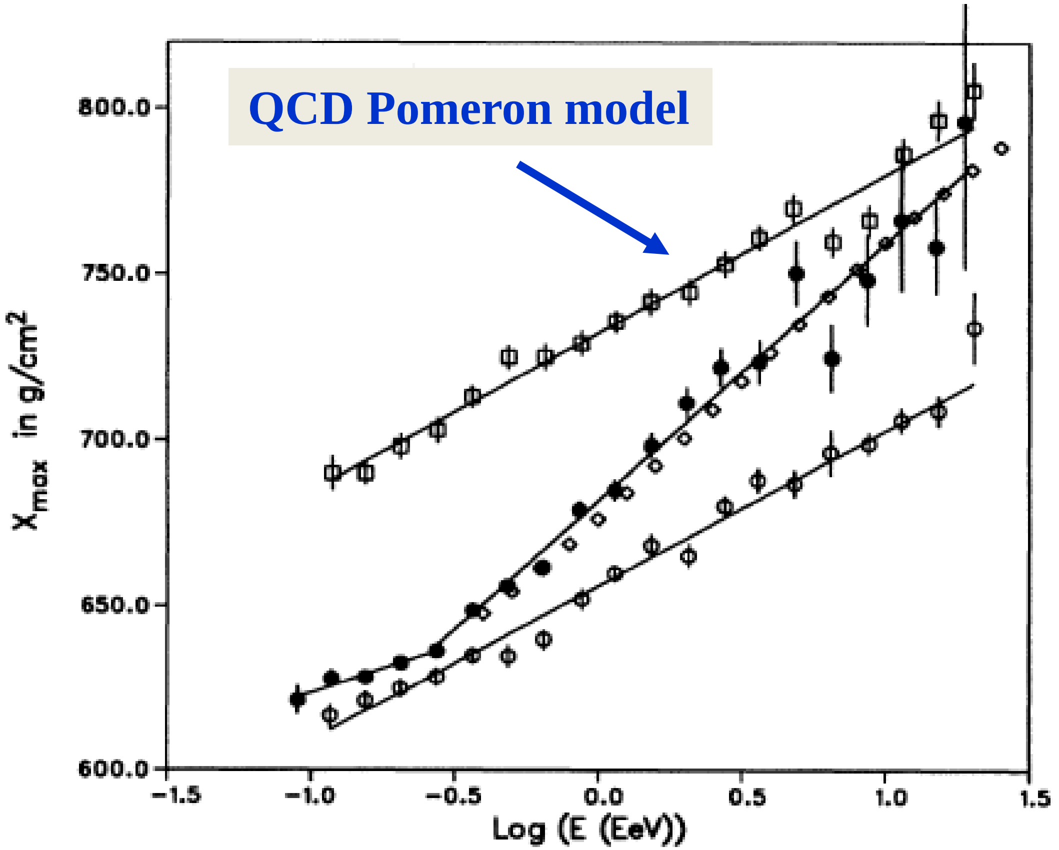
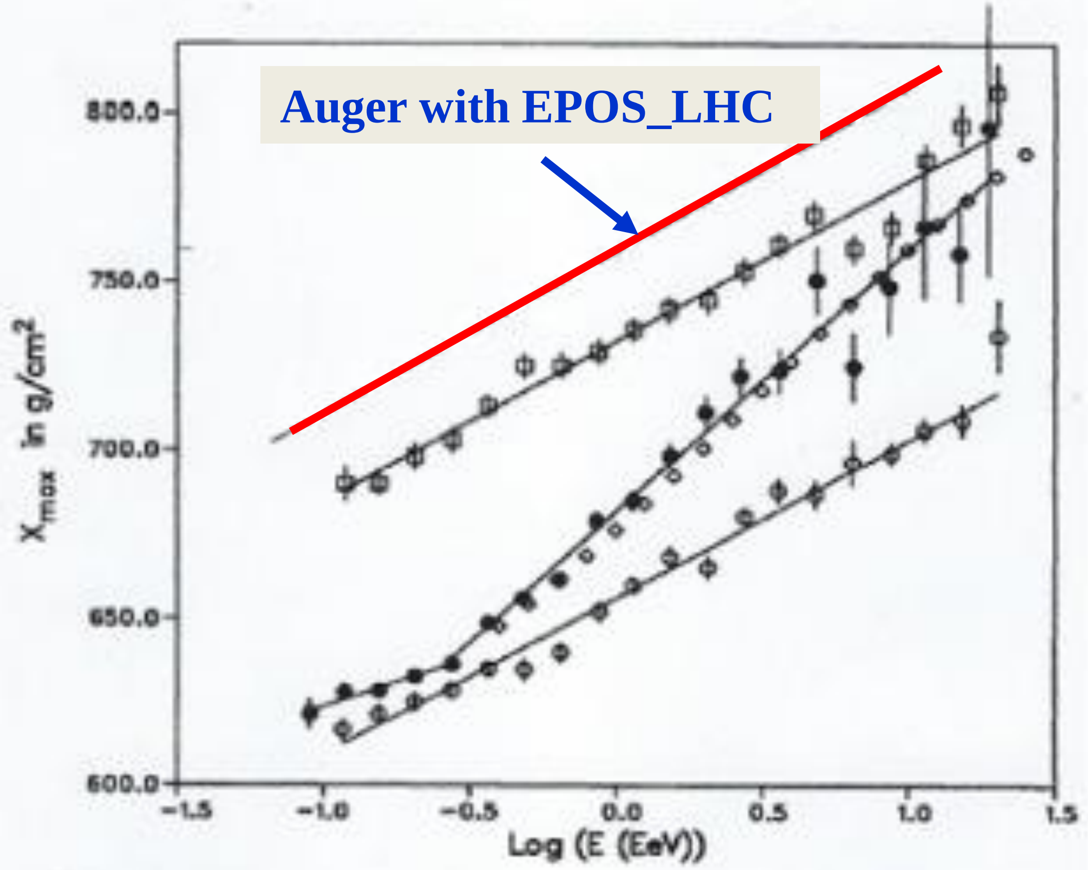


FIG. 3. X_{max} elongation rate are plotted against $\log_{10}E$. Black dots: Fly's Eye data. Open squares: proton X_{max} distribution based on QCD Pomeron model. Open circles: iron X_{max} distribution based on QCD Pomeron model. Diamonds: expected mean X_{max} distribution based on a simple two-component assumption of cosmic rays.



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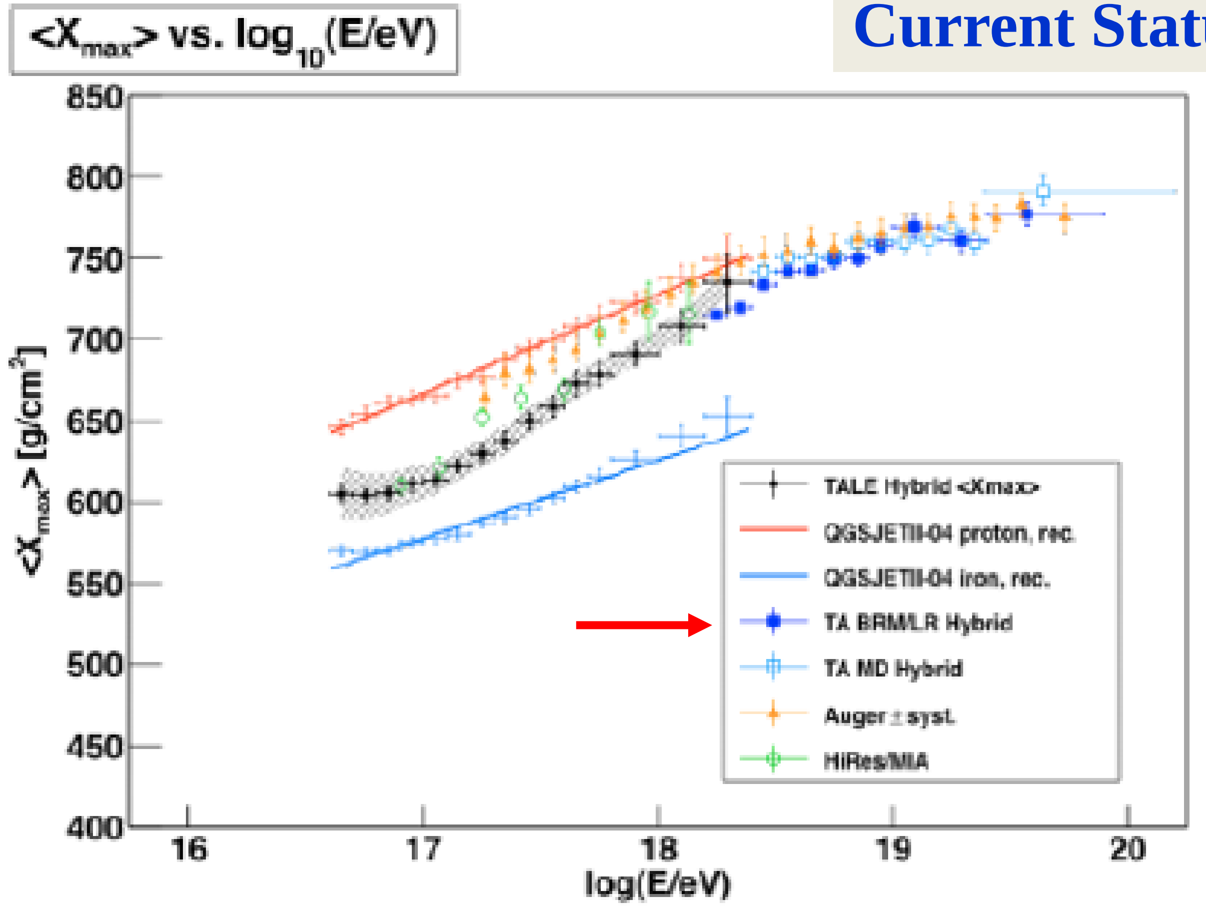
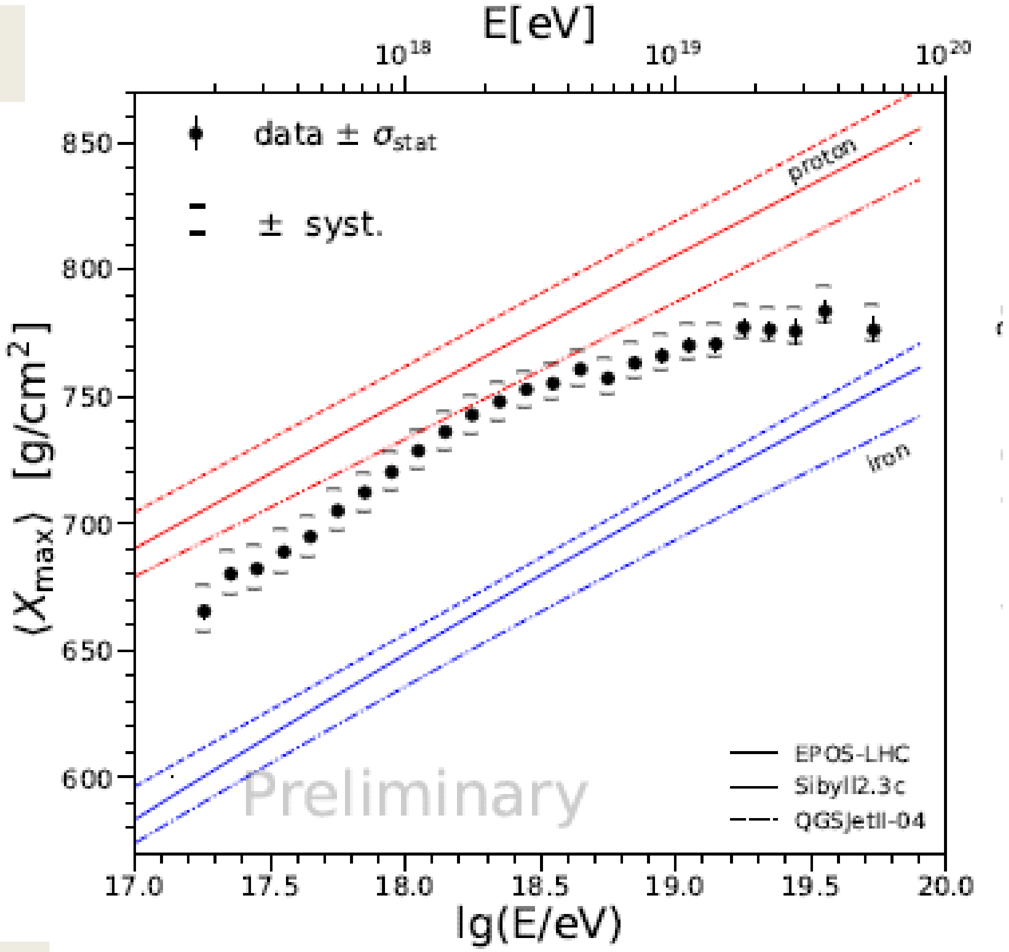
Current Status





H Sagawa for TA Collaboration: ISVHECRI 2022

"We need more statistics to clarify the situation above 10 EeV"

There are 133 events above 10 EeV– and statements can be made

Yushkov for Auger Collaboration: ICRC 2019

Generally agreed that QGSJetII-04 is no longer a viable model (LHC and Auger measurements)

The Unreasonable Effectiveness of the Air-Fluorescence Technique in Determining the EAS Shower Maximum

P. Sokolsky & R. D'Avignon

arXiv 2110.09588 (SDA)

Journal of Experimental and Theoretical Physics **134**, 459–468 (2022) | Cite this article

Major Claims in SDA:

- **Break in Elongation Rate at ~ 3 EeV**
- **Elongation Rates in N and S Hemispheres are different**
- **No comment on mass**

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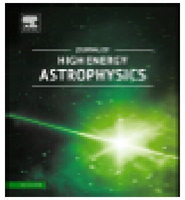


Further evidence for an increase of the mean mass of the highest-energy cosmic-rays with energy

A.A. Watson

School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK

arXiv 2112.06525

P. Sokolsky and R. D'Avignon 2021

Reviewed all existing fluorescence measurement

- **Remarkable agreement for all current and historic experiments over a 30 year period for the energy range from 10^{17} to $3x10^{18}$ eV.**

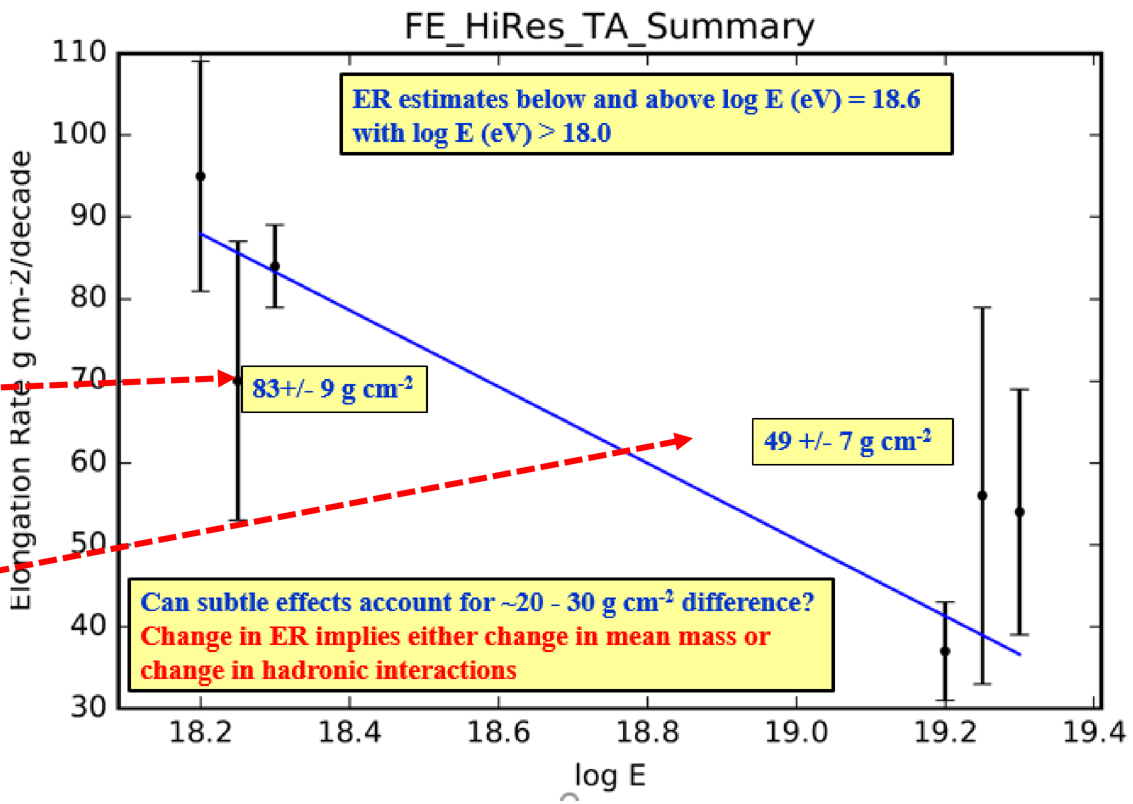
- **The mean elongation rate in this energy interval is near 80 gm/cm^2/decade.**

- **Above 3 EeV:**

Northern hemisphere: ER 48 +/- 10 gm/cm^2/decade

Southern hemisphere: ER 26 +/- 2 gm/cm^2/decade

A A Watson EPJ Web Conf 210 (2019) UHECR2018



Pierre Sokolsky told me that in this paper he was expressing his own views and not necessarily those of the TA Collaboration

The claim for differences in the two hemispheres would have major implications for theories of UHECR origin

Claim merits careful examination

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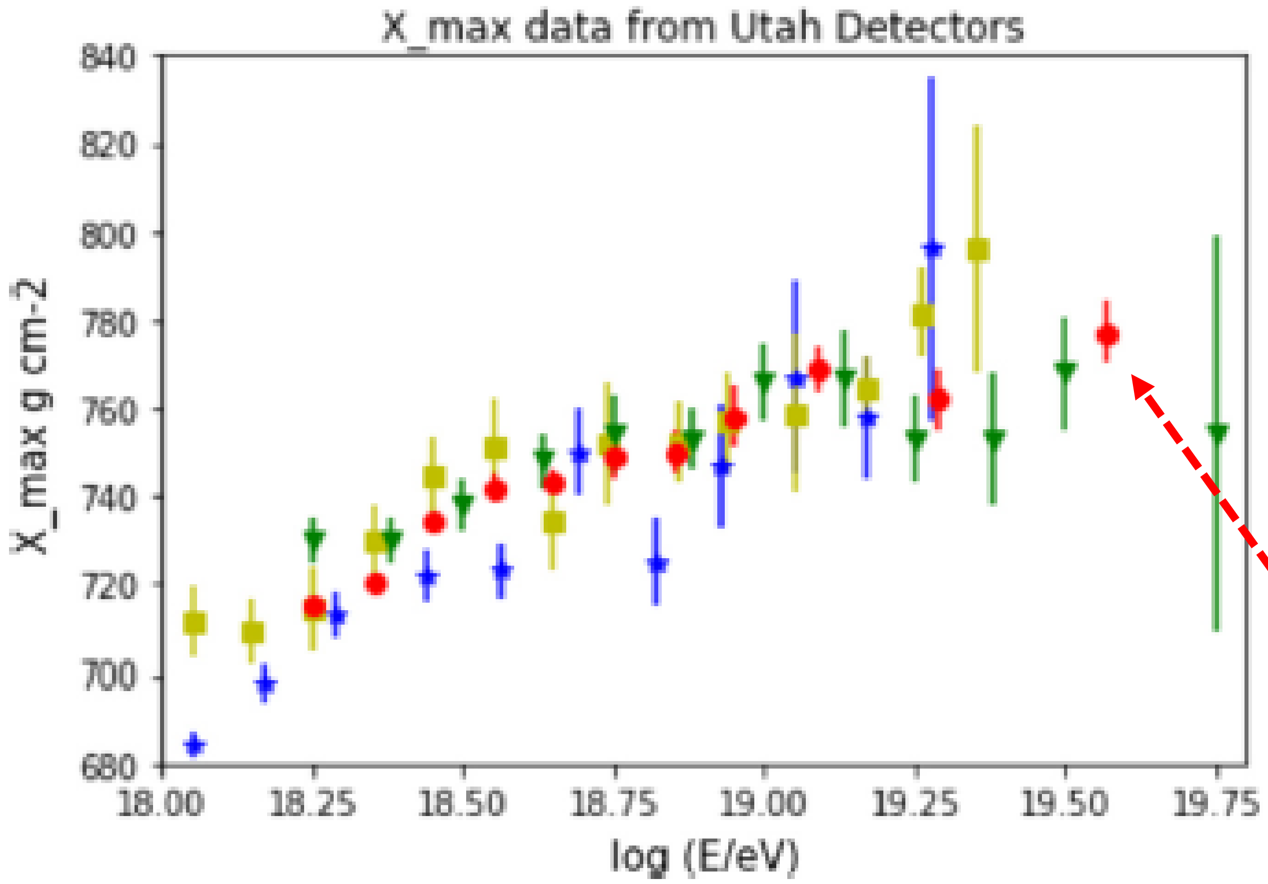


Fig. 2. The data of Fig. 1 are shown together so that the spreads in the measurements, and in particular in the uncertainties, can be readily compared: 'stars': Fly's Eye, Bird et al., 1993; 'squares': HiRes, Abbasi et al., 2010; 'triangles': Middle Drum, Abbasi et al., 2015; 'circles': Black Rock and Long Ridge, Abbasi et al., 2018.

SDA chose to present the data, without any uncertainties

Estimates of the Elongation Rates were obtained from averages of the X_{max} values, in small bins of energy, above and below a break energy of 3EeV

Assigning equal weight to each of these measurement may not be appropriate.

Red circles are the measurements from Black Rock and Long Ridge: 3330 events

3330 > 1.6 EeV
804 > 3 EeV

		Number of events	χ^2/ndf	ER $g\,cm^{-2}$/dec	E_{break} $\log E/eV$	ER1 below $g\,cm^{-2}$/dec	ER2 above $g\,cm^{-2}$/dec
Bird et al., 1993		~1000	$12.2/9=1.4$	74 ± 7	18.6 ± 0.2	86 ± 11	43 ± 32
Abbasi et al., 2010		814	$7.4/12=0.62$	54 ± 6	18.6 ± 0.1	70 ± 18	56 ± 23
Abbasi et al., 2015	?	813	$6.7/10=0.67$	33 ± 6	18.6 ± 0.2	~~29 ± 31~~	~~17 ± 12~~
Abbasi et al., 2018		3330	$27.4/9=3.04$	54 ± 3	18.49 ± 0.06	95 ± 14	37 ± 5

- **A single Elongation Rate is an adequate description of the data in each case, except in the case of data from Abbasi et al., 2018. (Black Rock/Long Ridge FDs)**

- **Apart from for Abbasi et al., 2015, (Middle Drum – formerly a HiRes detector)**

Elongation Rates below the break (ER1) are larger than those above the break (ER2), although the statistical significance is strong only in the Abbasi et al.,2018 work

Conclusion, in agreement with earlier work from Auger Collaboration, and work of SDA - THERE IS BREAK in the Elongation Rate

Unless there is a change in hadronic interactions, mass must be getting heavier

Break Energies:

Auger Collaboration: **log *E*/EeV = 18.27 ±0.04** **(Auger Collaboration, Aab et al., 2014a)**

Telescope Array: **log *E*/EeV = 18.49 ±0.06** **(Telescope Array, Abbasi et al., 2018)**

Difference is apparently significant

Larger than the 10% shifts of energy scale thought to exist between estimates of energy by the two collaborations (Deligny et al., 2019)

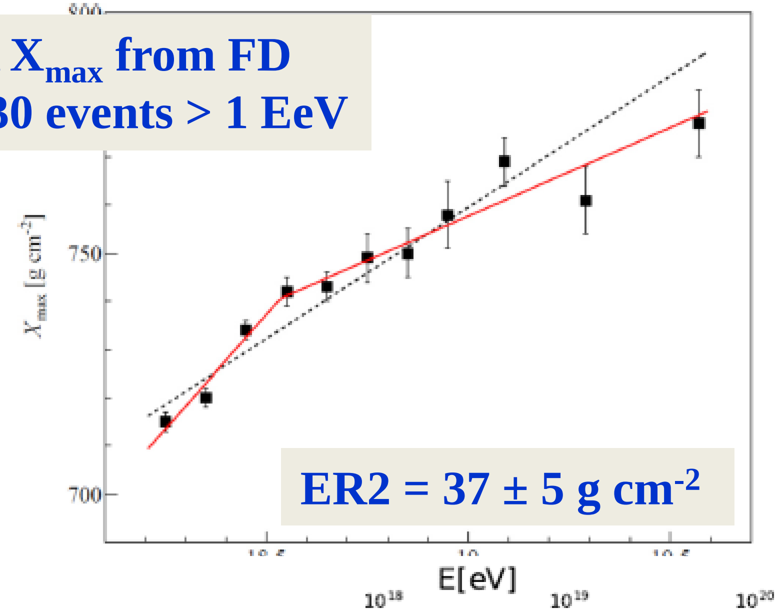
BUT, TA energy scale may need some revision as pure protons are assumed in their model-dependent evaluation of primary energy. Model should be changed as well.

Is there a North/South difference between the values of ER?

TA: 48 ± 10 g cm^{-2} vs Auger: 26 ± 2 g cm^{-2}

Not the 5 sigma result required for a claim of this importance

TA X_{max} from FD
3330 events > 1 EeV



Yakutsk C-light ldf 1156 events

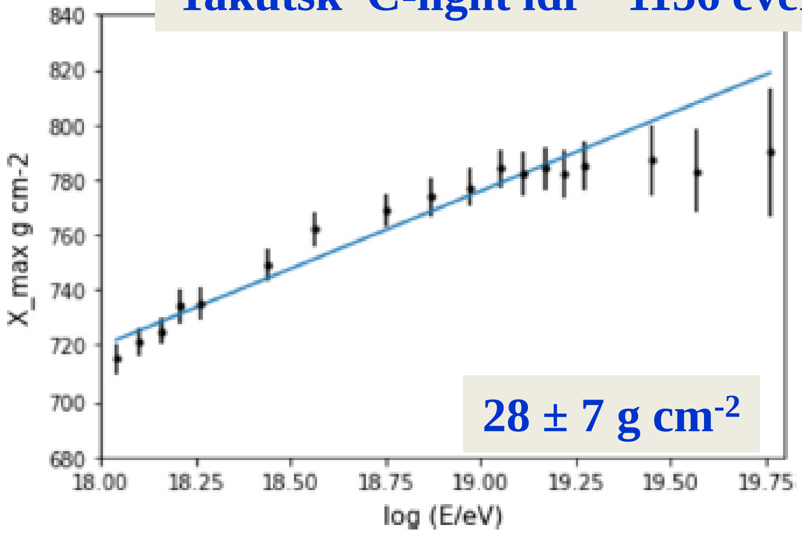
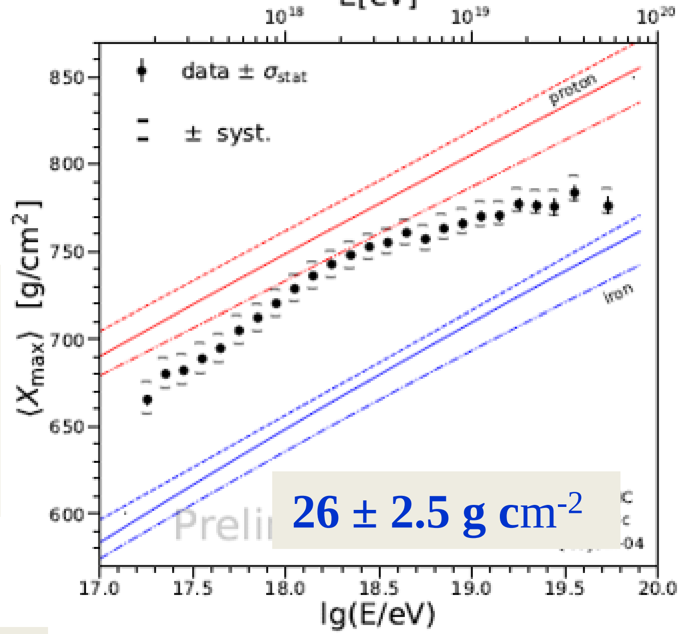
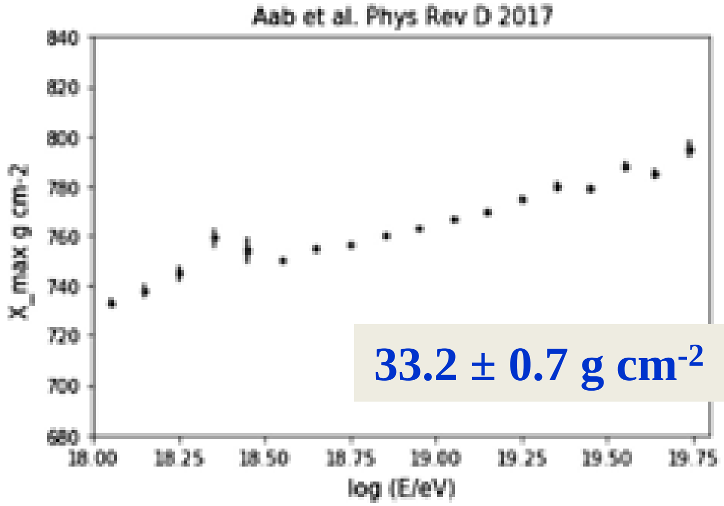


Fig. 4. Data of X_{max} vs $\log E$/eV from Knurenko and Petrov, 2019. The energy scale is derived from measurements of Cherenkov radiation produced by the particles of the air-showers.

Fig. 3. X_{ma}
the points
the full lin
(ER1 = 95

Auger X_{max} from FD
21890 events





Auger X_{max} from Risetime
55501 events

Fig. 6. Estimates of X_{max} as a function of energy made using the risetime technique (Aab et al. 2017). Only data from the 55501 events with energies above 1 EeV are shown.

- **Highest statistics results from TA (2018) are entirely consistent with data from other three measurements**

- **ER2 is smaller than ER1 implying that, above the break energy, the mean mass is increasing with energy.**

- **The weighted averages of ER2:**

  Northern hemisphere: 34 ± 4 g cm^{-2}/decade

  Southern hemisphere: 32.7 ± 0.7 g cm^{-2}/ decade

- **Claim of Sokolsky and D'Avignon for a mass difference between the cosmic rays from the two hemispheres is not substantiated**

- **Unless there is a dramatic change in features of hadronic interactions in collisions above ~3 EeV, one is forced to conclude that the mean mass of high-energy cosmic-rays becomes larger as the energy increases.**

Could there be a change in, for example, the pp cross-section?

Volume 44B, number 1 PHYSICS LETTERS 2 April 1973

THE ENERGY DEPENDENCE OF THE PROTON-PROTON TOTAL CROSS-SECTION FOR CENTRE-OF-MASS ENERGIES BETWEEN 23 AND 53 GeV

U. AMALDI*, R. BIANCASTELLI, C. BOSIO and G. MATTHIAE
Physics Laboratory, Istituto Superiore di Sanità and INFN, Sezione Sanità, Roma, Italy

and

J.V. ALLABY, W. BARTEL, G. COCCONI, A.N. DIDDENS, R.W. DOBINSON and A.M. WETHERELL
CERN, Geneva, Switzerland

Received 23 February 1973

Measurements of proton-proton elastic scattering at angles around 6 mrad have been made at centre-of-mass energies of 23, 31, 45 and 53 GeV using the CERN Intersecting Storage Rings. The absolute scale of the cross-section was established by determination of the effective density of the colliding beams in their overlap region. Proton-proton total cross sections were deduced by extrapolation of the elastic differential cross-section to the forward direction and by application of the optical theorem. The results indicate that over the energy range studied the proton-proton total cross-section increases from about 39 to about 43 mb.

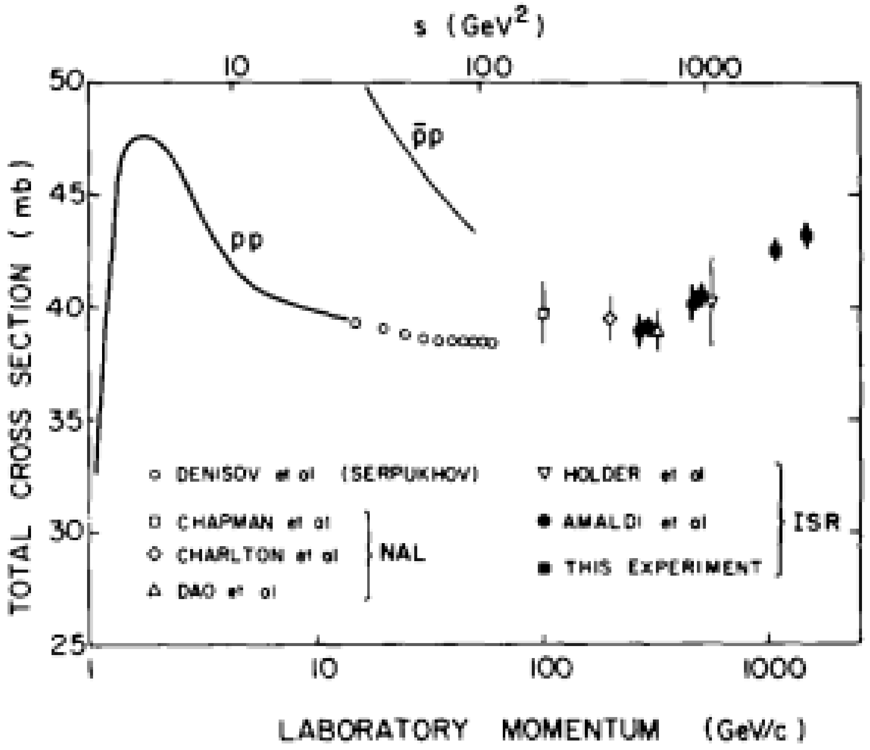


Fig. 3. Total proton-proton cross-sections as a function of the the square of the centre-of-mass energy, s, and of the equivalent laboratory momentum. The general trends of the proton-

386 citations

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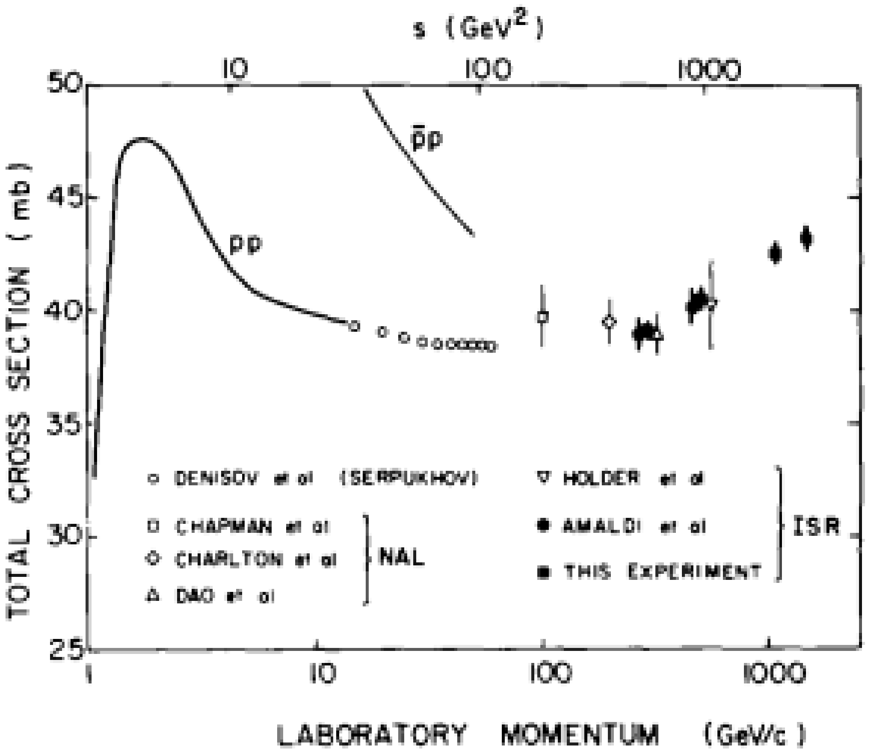

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"Using the Roman pots, the first experiments at the ISR made the startling discovery that the proton-proton total cross section increases at the new energies probed by the ISR". **Matthiae**"Technology Meets Research" a CERN publications ISSN 1793-1339, Section 4.7, pag.112.

The idea that the highest energy particles are protons has dominated thinking since the 1950s

"We remain with the dilemma: protons versus heavy nuclei. A clear cut decision cannot be reached yet. I believe that up to the highest energies the protons are the most abundant in the primary cosmic rays. However, I must confess that a leak proof test of the protonic nature of the primaries at the highest energies does not exist. This is a very important problem. Experimentally it is quite a difficult problem."

G Cocconi: Fifth International Cosmic Ray Conference, Guanajuato, Mexico, 1955

Events with energies above ~ 1 EeV not observed until 1960s

Statements from Volcano Ranch by Linsley, Scarsi and Rossi in early 1960s – but at energies below 1 EeV. Only a few events above 10 EeV had been detected

Linsley (1963 ICRC Jaipur):
Muon distribution above 0.1 EeV implies, that either protons or nuclei in Fe group dominate

- **For reasons that remain unclear, the idea that protons dominated at highest energies became dogma Fly's Eye paper 1882 was important**
- **Theorists promoted it (Berezinsky, Waxman, Lemoine…..)**
- **Ignored fact that it is 26 times easier to accelerate Fe, and that photodisintegration is less of a problem than originally thought**
- **Sociological problem?**
- **Key people have huge influence**

Time to change our views

Take-home messages:

- **There is a break in the Elongation Rate at ~3 EeV**

- **If there is no change in hadronic interactions then mean mass of cosmic rays is increasing above this energy – what the mean mass might be requires model calculations**

- **A change in the pp-cross-section – an 'unknown unknown' – could, of course, change the picture**

(Systematic uncertainties always demanded of experimentalists but rarely discussed by phenomenologists)

- **Anisotropy studies may help to give an answer.**