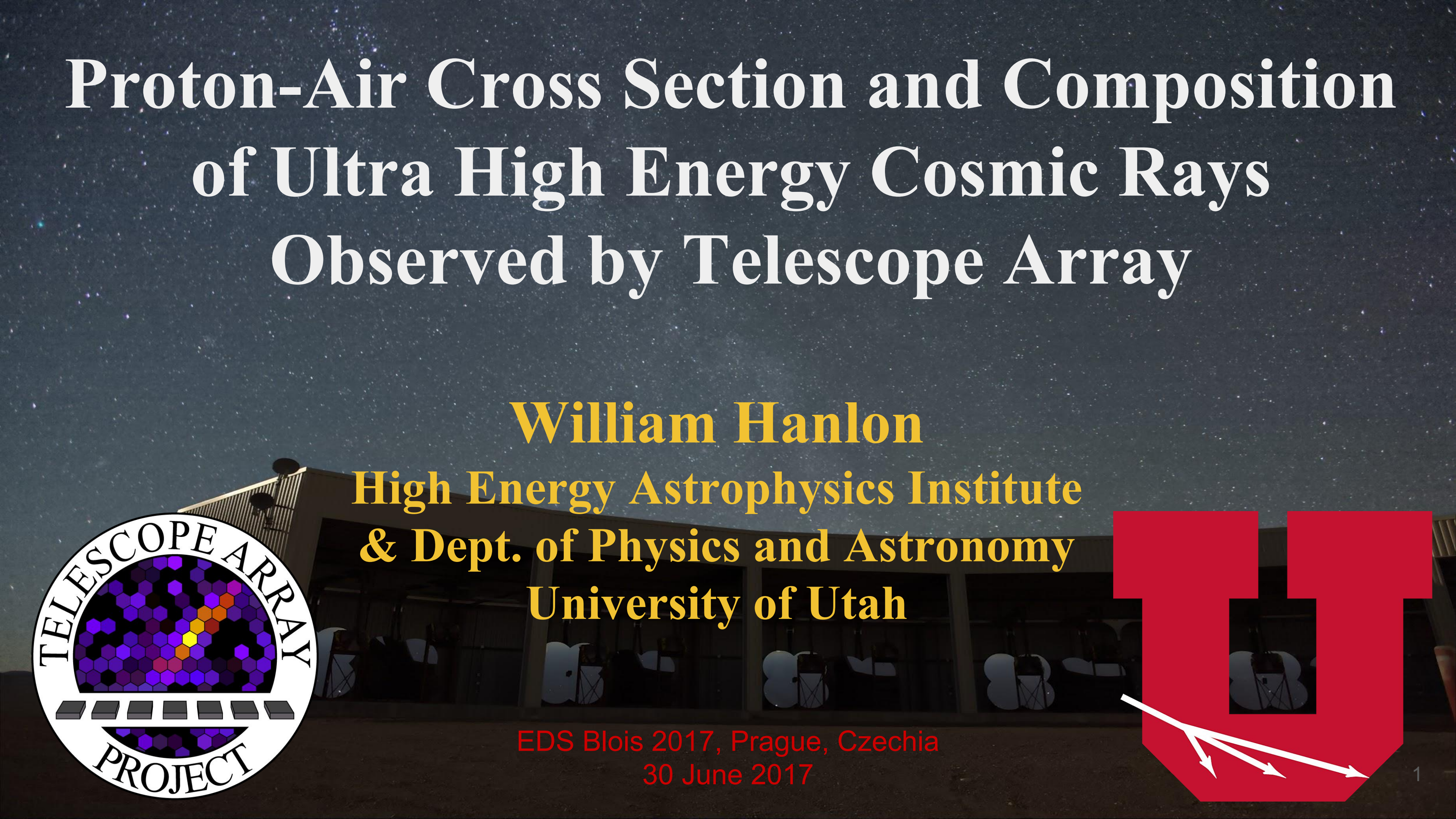
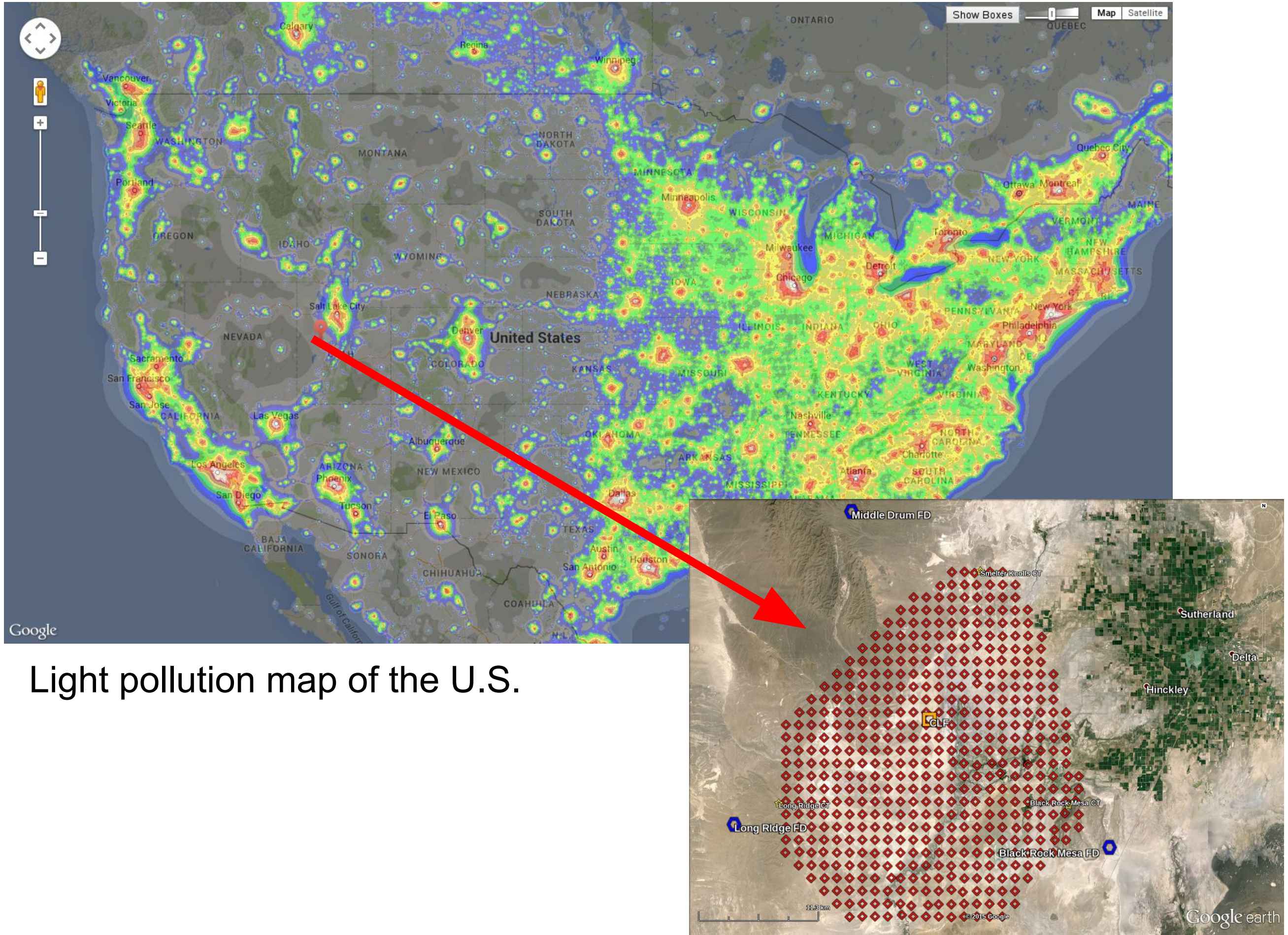


Proton-Air Cross Section and Composition of Ultra High Energy Cosmic Rays Observed by Telescope Array

William Hanlon
High Energy Astrophysics Institute
& Dept. of Physics and Astronomy
University of Utah

EDS Blois 2017, Prague, Czechia
30 June 2017

TA Observatory



Light pollution map of the U.S.

Largest cosmic ray observatory in the Northern hemisphere.

~700 km^2 → ≲ *land* area of New York City.

Millard County, Utah

39° 17’ 48.90457”
112° 54’ 31.43708”
1370 m

~800 g/cm^2 vertical depth

Scintillator surface counters

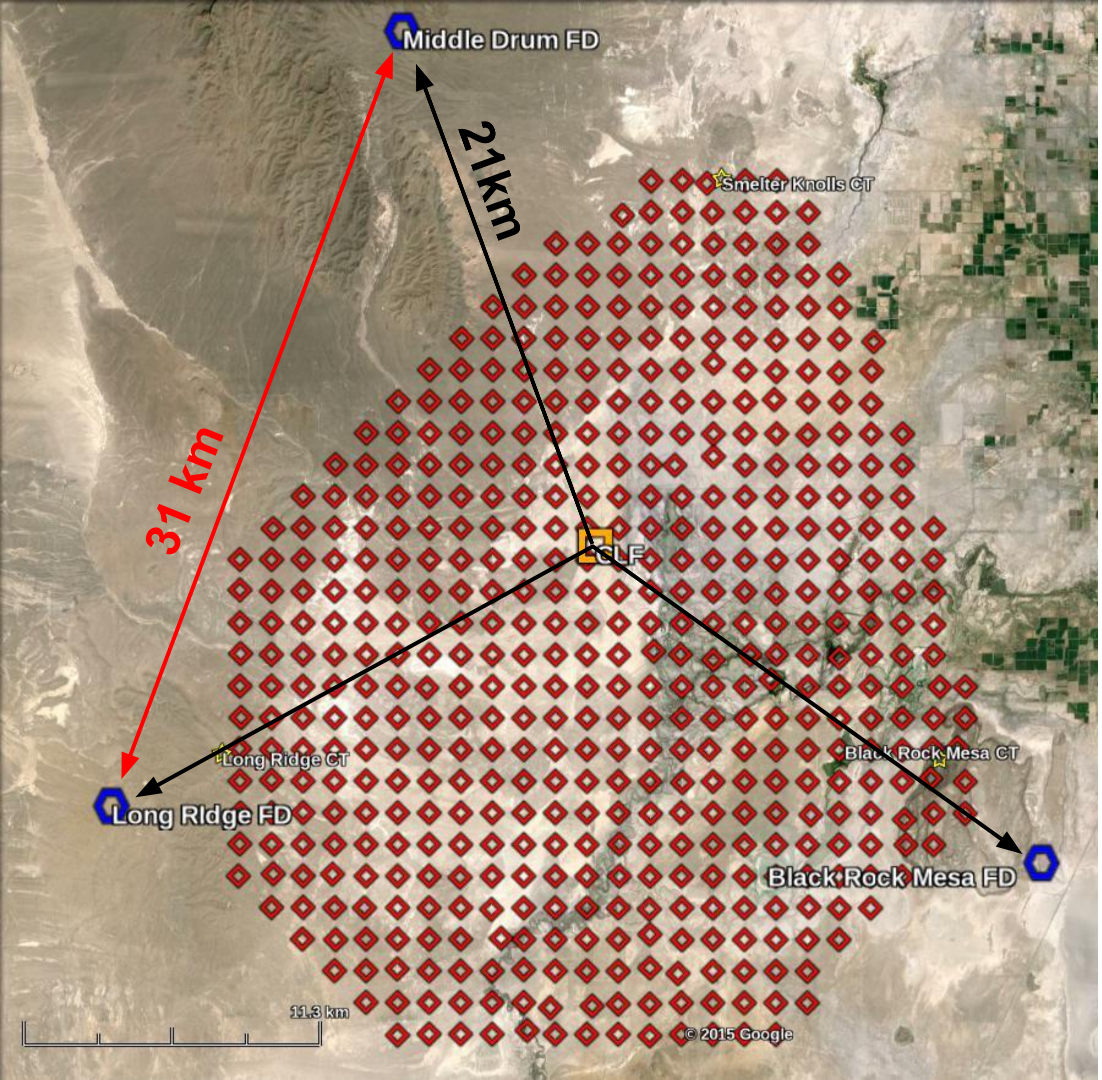
Air fluorescence telescopes

25 kW radar transmitter

Lightning detection array

40 MeV linear accelerator

TA Detectors



507 scintillation counters surface detector

1.2 km grid spacing (3 m^2 area)

Total detection area: ~ 750 km^2

~100% duty cycle

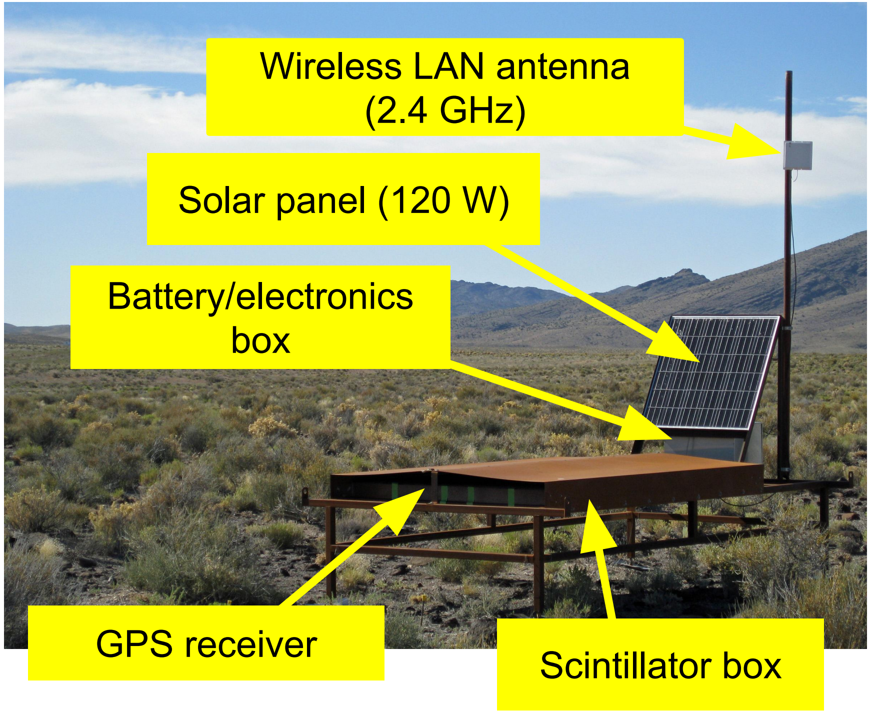
3 fluorescence detector stations

48 FD telescopes

~10% duty cycle

In operation since March 2008

TA Surface Detectors



Solar cell and battery

Wireless LAN (2.4 GHz) communications

12 bit FADC, 50 Msps: 20 nS time resolution, dynamic range of 4096 FADC counts

Event readout/monitoring/calibration via 3 communication towers

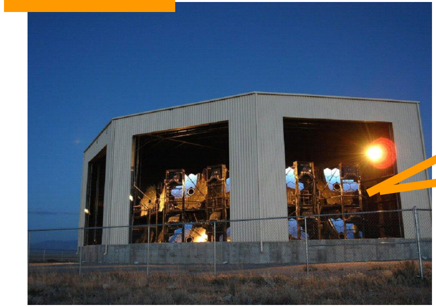
Scintillator:

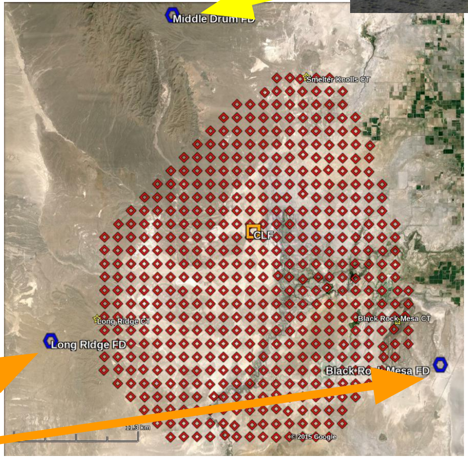
2 layers (upper and lower), each 3 m^2 x 1.25 cm

1 PMT for each layer

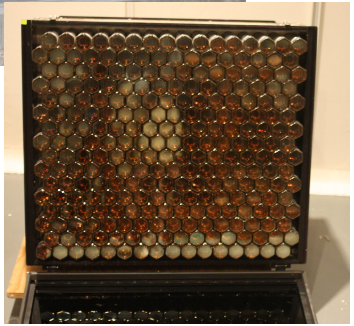
TA Fluorescence Detectors

6.8 m^2





5.2 m^2



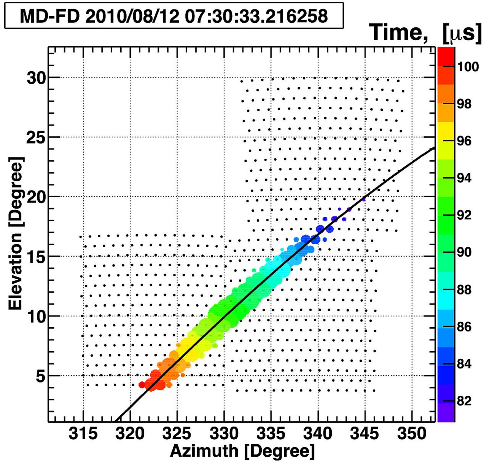
Operation start date
BR: Jun. 2007
LR: Nov. 2007

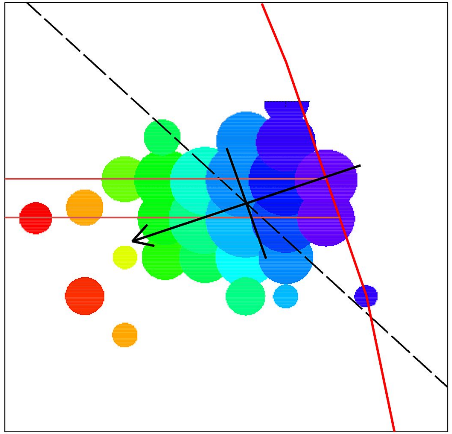
BRM & LR FD stations:
12 telescopes each
256 pixels/telescope @ 1°/pixel
108° azimuth, 3°-33° elevation view
10 MHz FADC readout

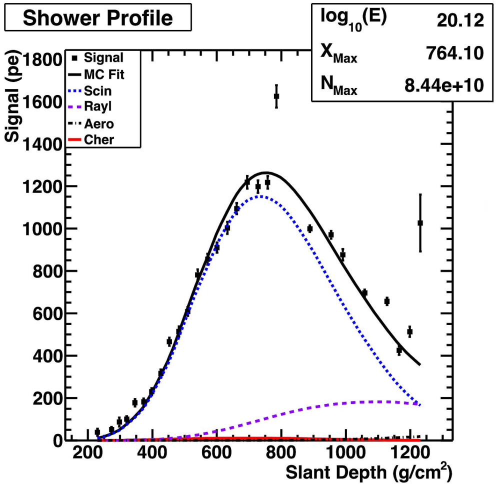
MD FD station:
14 telescopes
256 pixels/telescope @ 1°/pixel
112° azimuth, 3°-31° elevation view
S/H electronics (HiRes1)
Operation start date: Oct. 2007

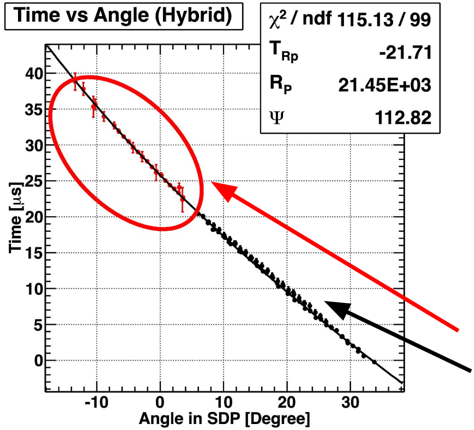
TA Composition Measurement

TA Hybrid High Energy Event









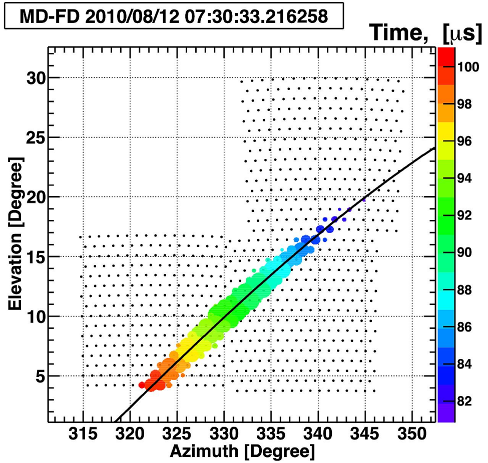
SD counter hits

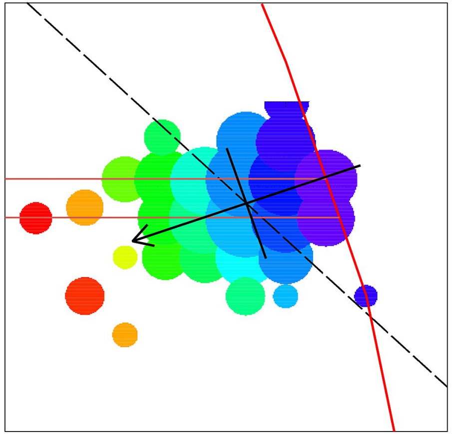
FD tube hits

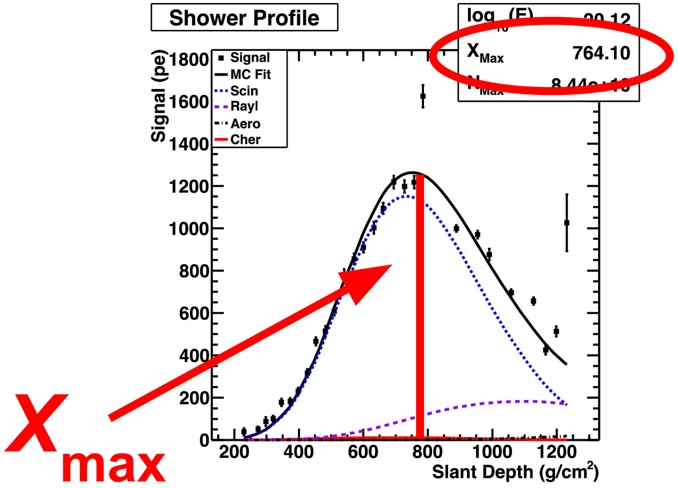
Hybrid combines SD information (core, timing at the ground) with FD information (profile, timing in the atmosphere) to make improved shower measurement.

Energy: 1.3 x 10^{20} eV
R_p: 21 km
zenith: 55.7 deg

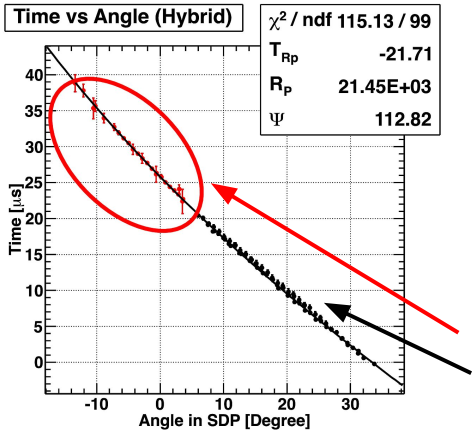
TA Hybrid High Energy Event







X_{max}



SD counter hits

FD tube hits

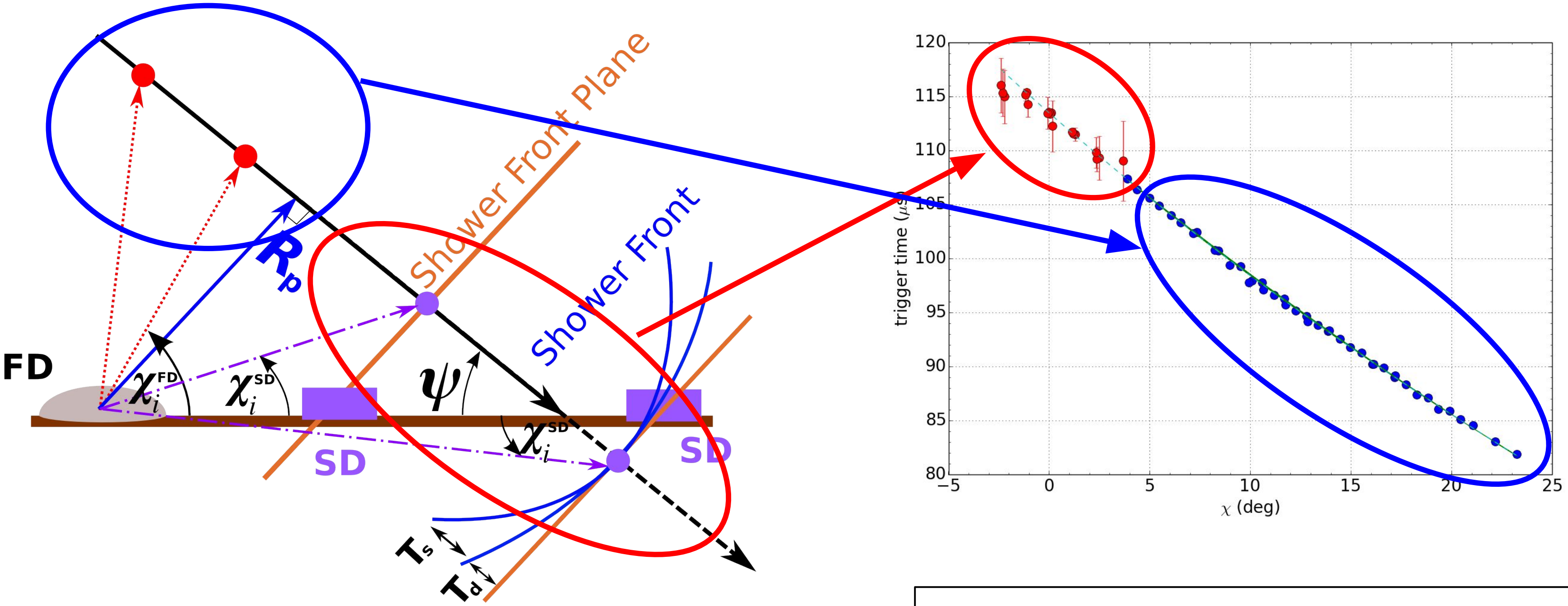
Hybrid combines SD information (core, timing at the ground) with FD information (profile, timing in the atmosphere) to make improved shower measurement.

Energy: 1.3 x 10^{20} eV

R_p: 21 km

zenith: 55.7 deg

Hybrid Reconstruction Method

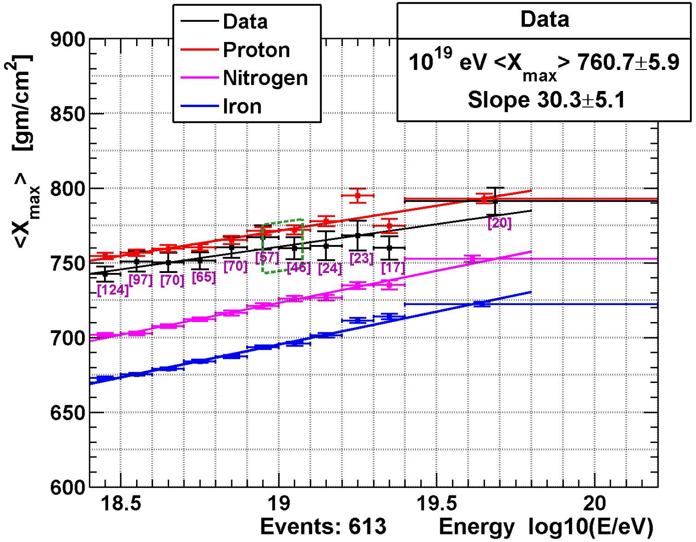


Hybrid combines timing and geometry of FD and SD.
Shower development is observed in the sky → $\Delta\psi$
Core location and time is recorded on the ground.

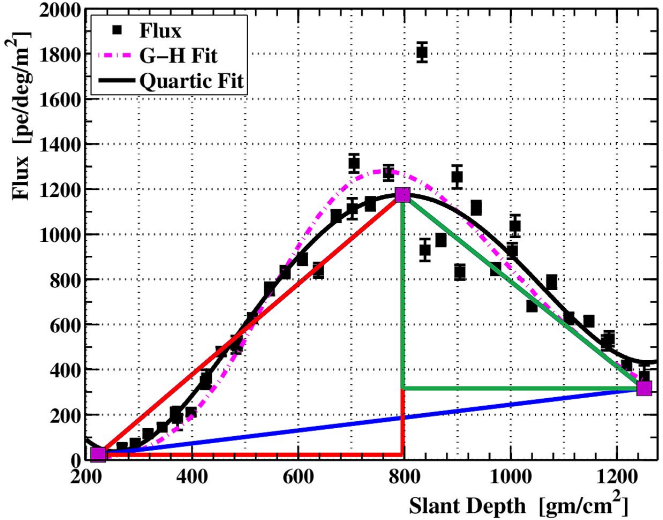
Time vs. Viewing Angle

$$t_i = t_0 + \frac{r_{\rm p}}{c}\tan\left(\frac{\pi - \psi - \chi_i}{2}\right)$$

TA Composition - MD Hybrid



J.P. Lundquist, ICRC2015



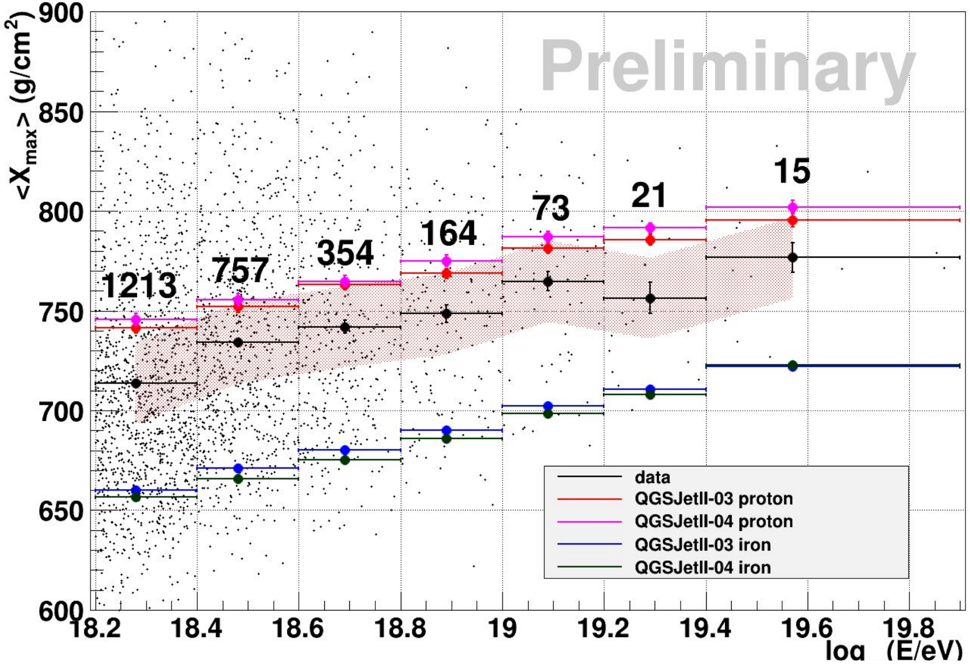
R. Abbasi et al., Astropart.Phys. **64** (2014)

Two composition measurements:

1. Middle Drum hybrid
   (5 year set published 2014)
2. Black Rock/Long Ridge hybrid

7 years of MD FD hybrid data - 613 events [$\log_{10}(E/\mathrm{eV}) > 18.4$]
Improved reconstruction via *pattern recognition* method → ensures curvature of profile is well measured.
X_{max} resolution ~ 22 g/cm^2, reconstruction bias < 2 g/cm^2
Energy resolution ~ 7%

TA Composition - BR/LR Hybrid



W. Hanlon, APS April 2016
UHECR 2016

Red band is systematics on the data (20.3 g/cm^2). Within systematics, <X_{max}> looks more like protons than iron. We say it appears “light”.

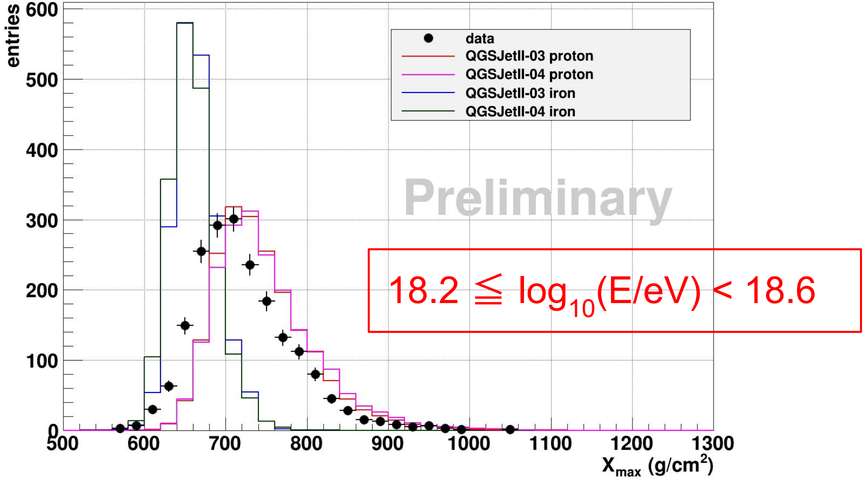
7 year BR/LR hybrid composition

X_{max} resolution ~ 20 g/cm^2 (log$_{10}$(E) > 18.2)
Reconstruction bias ≲ 1 - 2 g/cm^2

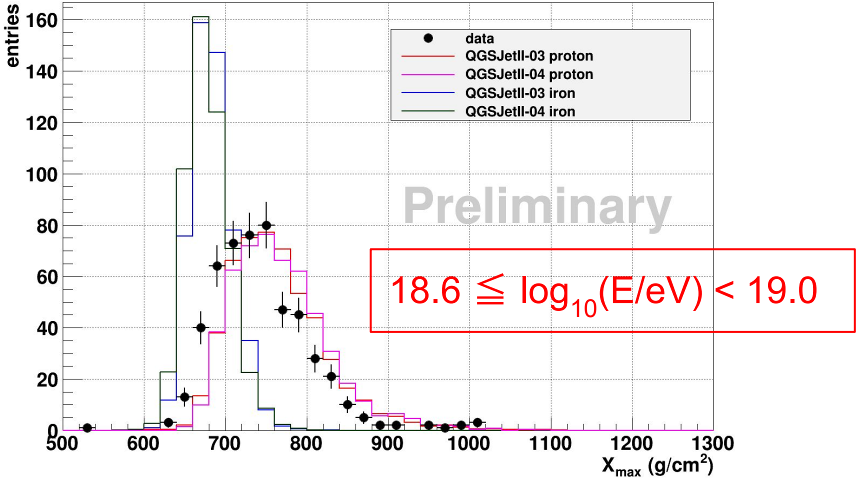
“Standard” quality cuts:
zenith < 55 degrees
Profile & geometry chi^2 cuts
X_{max} bracketing
track length > 10 degrees

Highest statistics composition - 2597 events
vs. 1346 (stereo)
vs. 623 (MD hybrid)

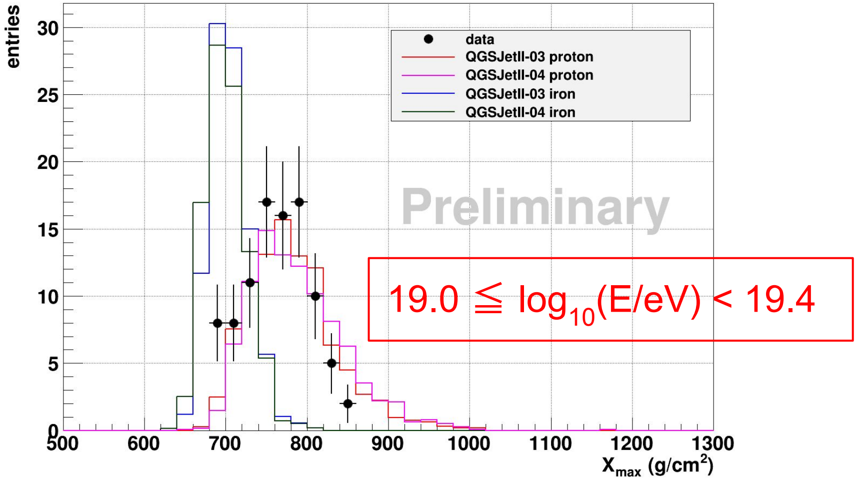
TA Composition - BR/LR Hybrid



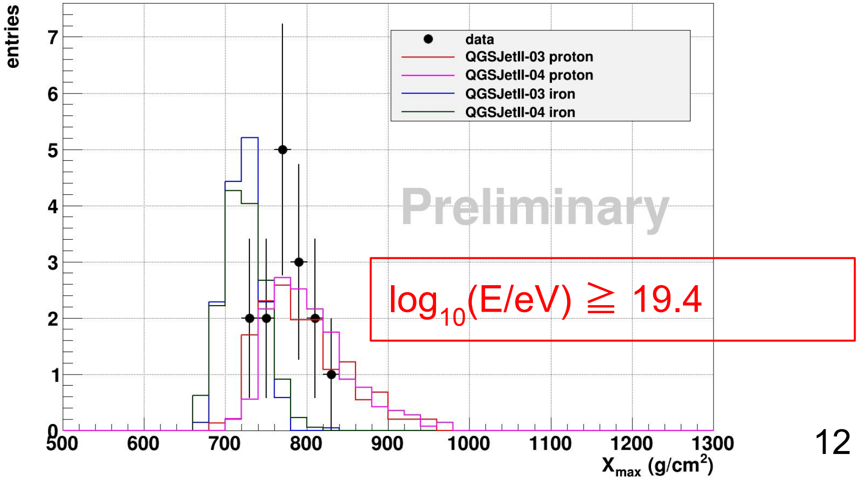
$18.2 \leqq \log_{10}(E/eV) < 18.6$



$18.6 \leqq \log_{10}(E/eV) < 19.0$

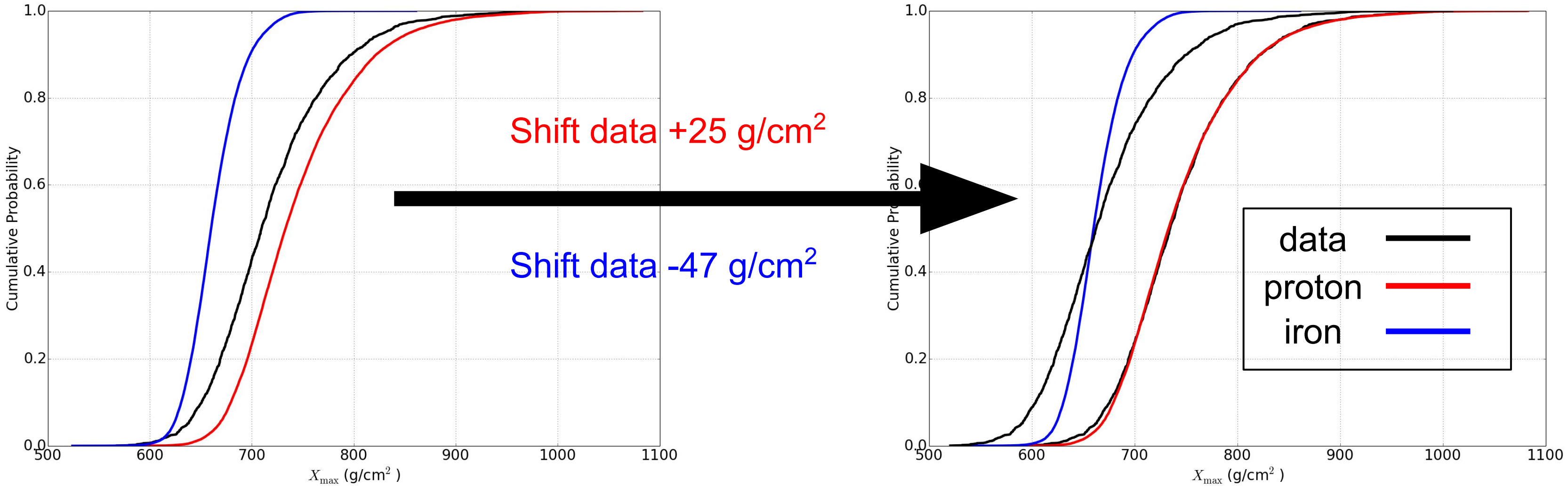


$19.0 \leqq \log_{10}(E/eV) < 19.4$



$\log_{10}(E/eV) \geqq 19.4$

Model Testing: Data vs MC

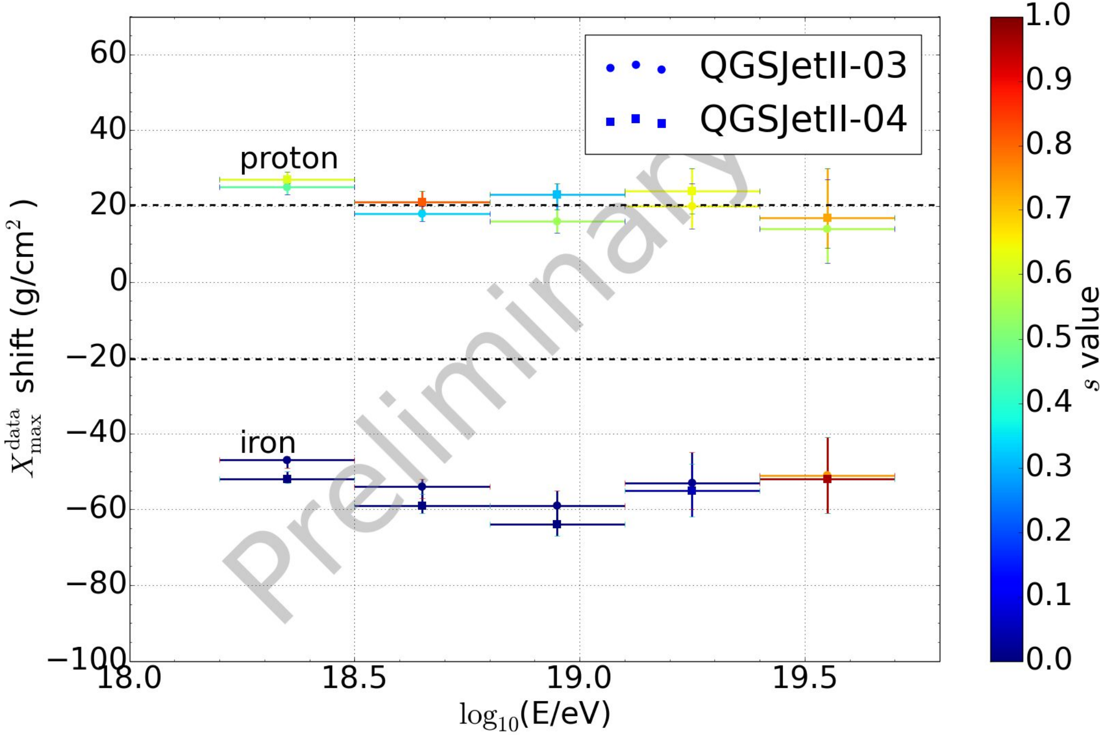


Shift data +25 g/cm^2

Shift data -47 g/cm^2

- Mean and especially RMS may be influenced by what happens in the tails → sampling bias.
- Utilize Cramér-von Mises (CvM) non-parametric goodness of fit test to measure agreement with models.
- Ask the question: how much does data need to be shifted to find agreement with CORSIKA models?
- Apply the CvM test to evaluate the agreement of the entire distribution without relying on the moments of the distribution.

Model Testing: Data vs MC



Amount that data needs to be shifted to match CORSIKA models. Find the best value of the two-sample CvM test statistic.

s-value is the *p*-value under the assumption both samples were drawn from the same parent distribution *after shifting the data.*

To find agreement with heavy elements, large shifts are needed and the *s*-values are too small.

Light composition is favored by systematic shift *and s*-value. In the highest energy bins, tails might be clipped by acceptance, hence *s*-value for proton and iron increases.

$X_{\max}$ systematics: ± 20.3 g/cm^2

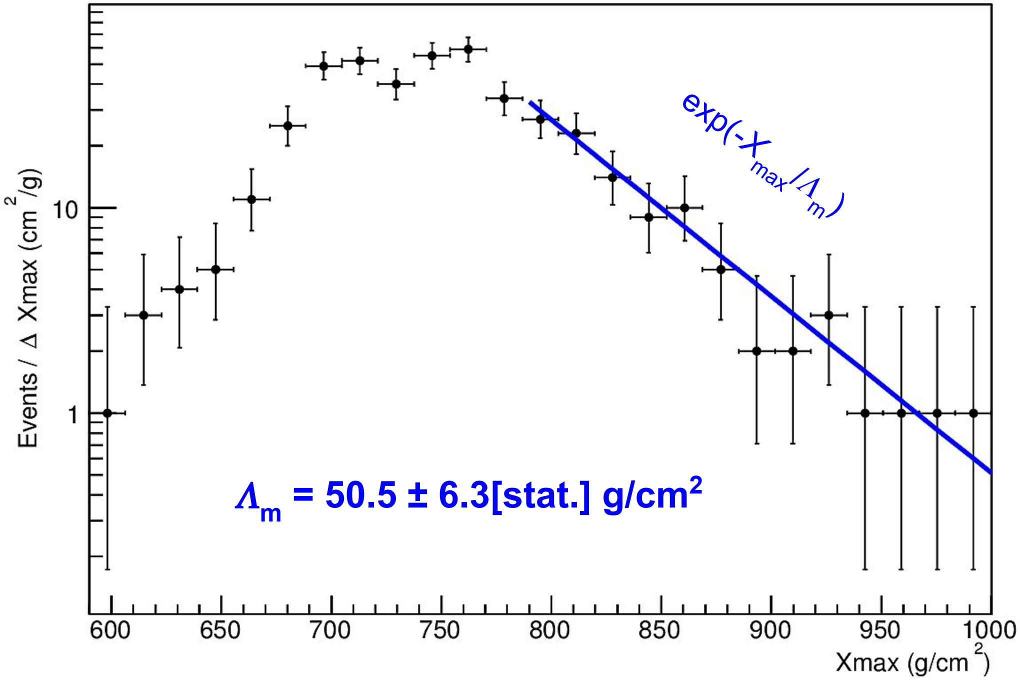
TA Proton Cross Section Measurement

p-air Cross Section from Cosmic Ray X_{max} Distribution

- Interaction length of proton in air

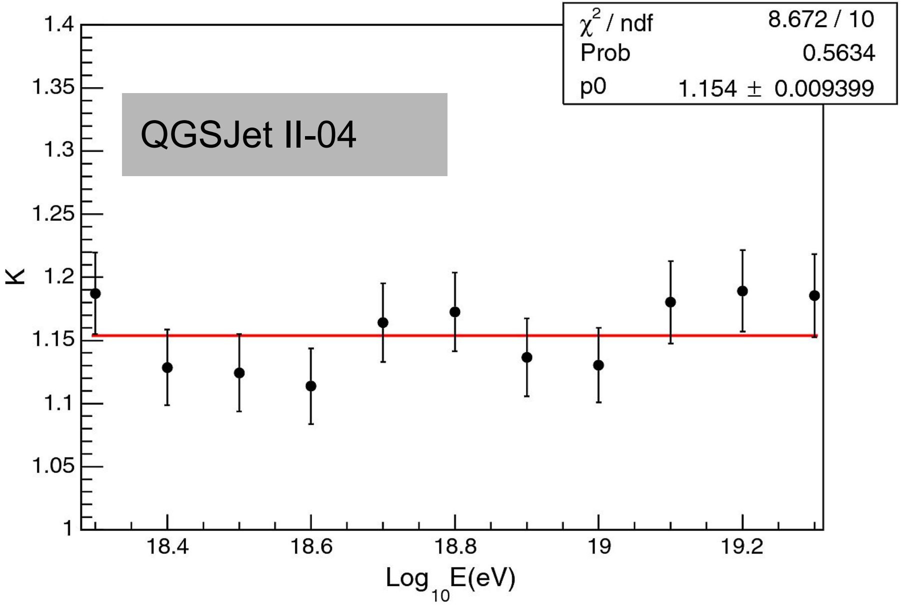
$$\lambda_{p-\mathrm{air}} = \frac{< m_{\mathrm{air}} >}{\sigma_{p-\mathrm{air}}} = \frac{14.45 m_p}{\sigma_{p-\mathrm{air}}}$$

- Depth of first interaction, X_1, follows falling exponential distribution with slope $\lambda_{p\text{-air}}$, but FDs can not observe X_1.
- Air shower development after X_1 is affected by fluctuations in first interaction depth, as well as hadronic cross section, inelasticity, multiplicity ⇒ *model dependence*.
- *K*-factor method fits the tails of X_{max}, because only light particles (protons) penetrate deeply. The slope of the tail is $\Lambda_m = K\lambda_{p\text{-air}}$.
- TA MD data for $10^{18.3} \leqq E \leqq 10^{19.3}$ ($\sqrt{s}$ = 95 TeV): **Λ_m = 50.5 ± 6.3 g/cm²**
- Determine *K* from models to calculate $\sigma_{p\text{-air}}$.



Determining the K factor

- The proportionality constant, *K*, depends upon elasticity, multiplicity, and cross section, therefore it is *model dependent* and a Monte Carlo simulation is used to simulate it.
- For each 0.1 decade energy bin between $10^{18.3}$ and $10^{19.3}$ eV, 10000 CONEX showers were generated for four hadronic models.
- Using the Monte Carlo you know X_1 (mean free length) which is related to $\lambda_{p\text{-air}}$.
- Using $\Lambda_m = K\lambda_{p\text{-air}}$, and the fit to the tail to find Λ_m, you have determined $\lambda_{p\text{-air}}$.
- Fit the *K* values in energy bins to a constant.
- *K* is weakly model dependent ⇒ 3% model uncertainty



Model	*K*
QGSJet II-04	1.15 ± 0.01
QGSJet01	1.22 ± 0.01
SIBYLL	1.18 ± 0.01
EPOS-LHC	1.19 ± 0.01

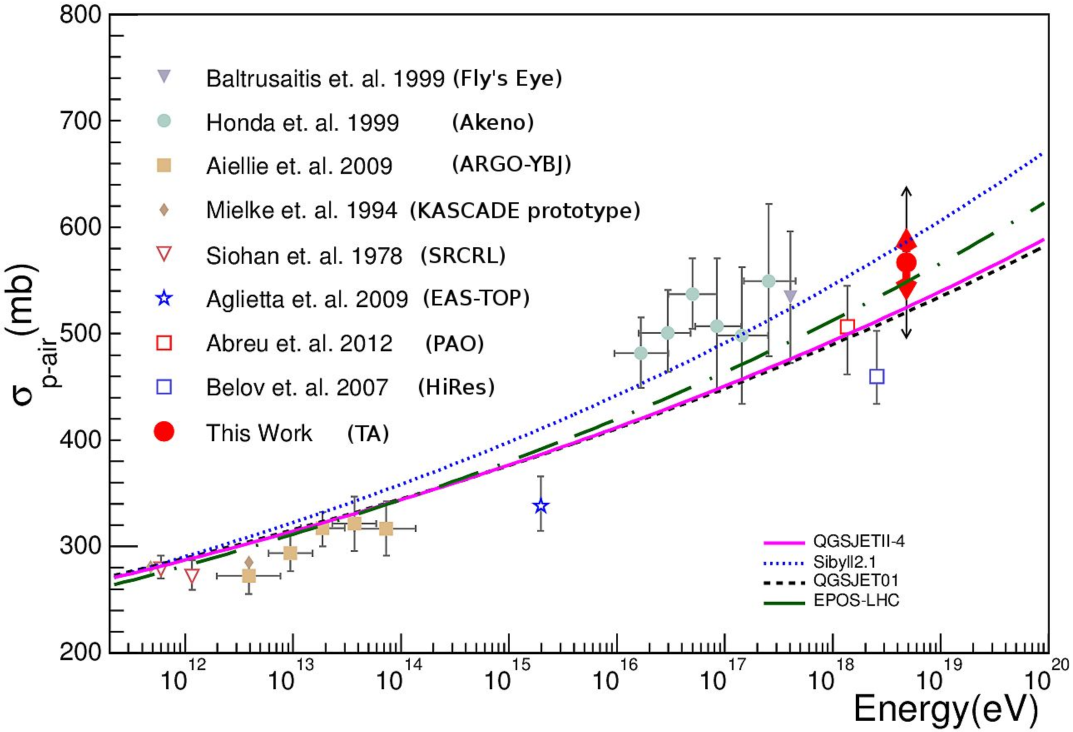
p-air cross section of various models

Model	K	$\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$
QGSJet II-04	1.15 ± 0.01	550.3 ± 68.5 mb
QGSJet01	1.22 ± 0.01	583.7 ± 72.6 mb
SIBYLL	1.18 ± 0.01	564.6 ± 70.2 mb
EPOS-LHC	1.19 ± 0.01	569.4 ± 70.8 mb

$$\sigma_{p-\mathrm{air}}^{\mathrm{inel}} = 567.0 \pm 70.5\ \mathrm{mb}$$

Median of the energy distribution of events: $10^{18.63}$ eV ⇒ $\sqrt{s}$ = 95 TeV

TA $\sigma_{p\text{-}air}$ (inel) measurement & systematics

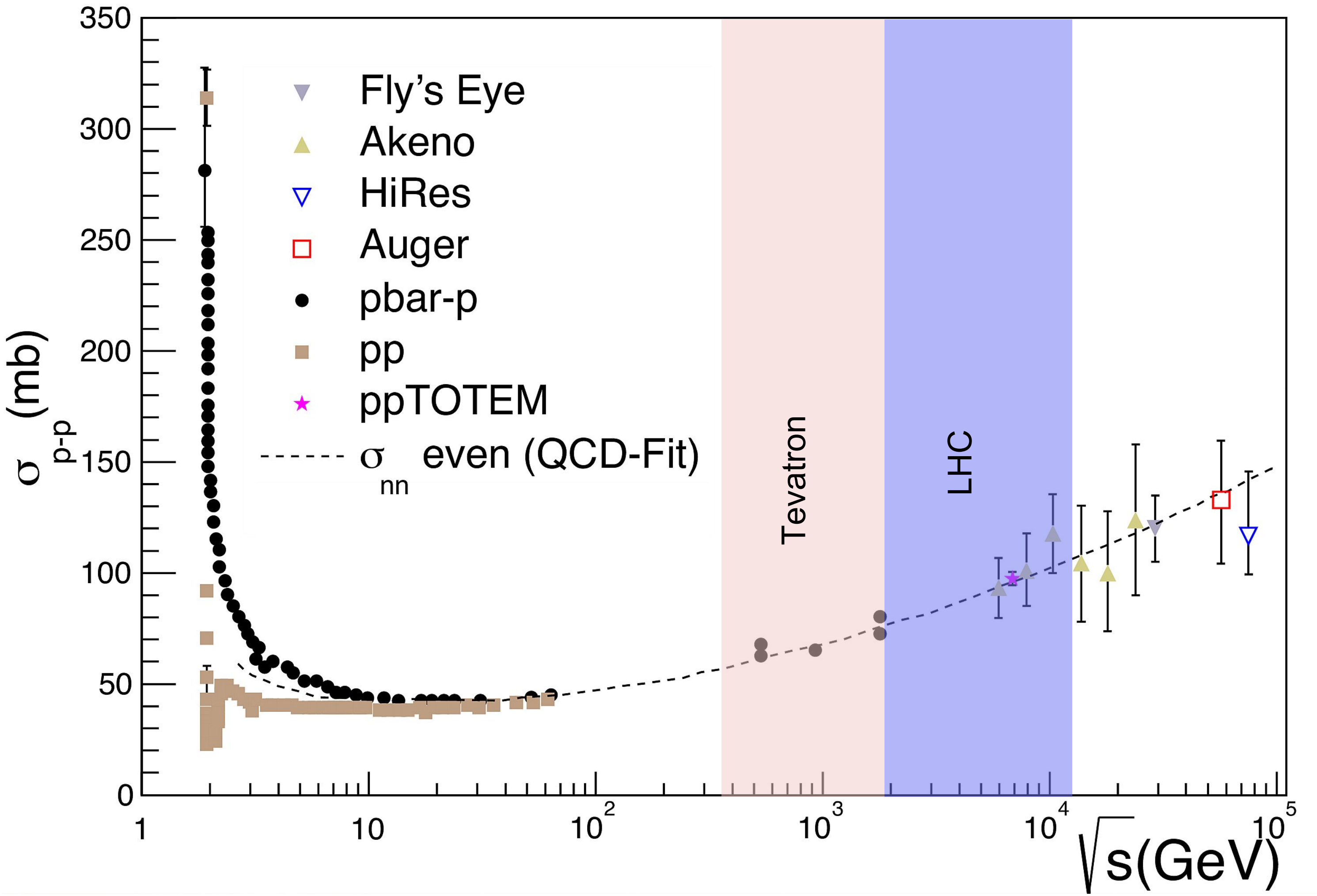


Systematic source	Systematic (mb)
Model dependence	± 17
10% Helium	-9
20% Helium	-18
50% Helium	-42
gamma<1%	+23
Total (20% Helium)	(-25, +29)

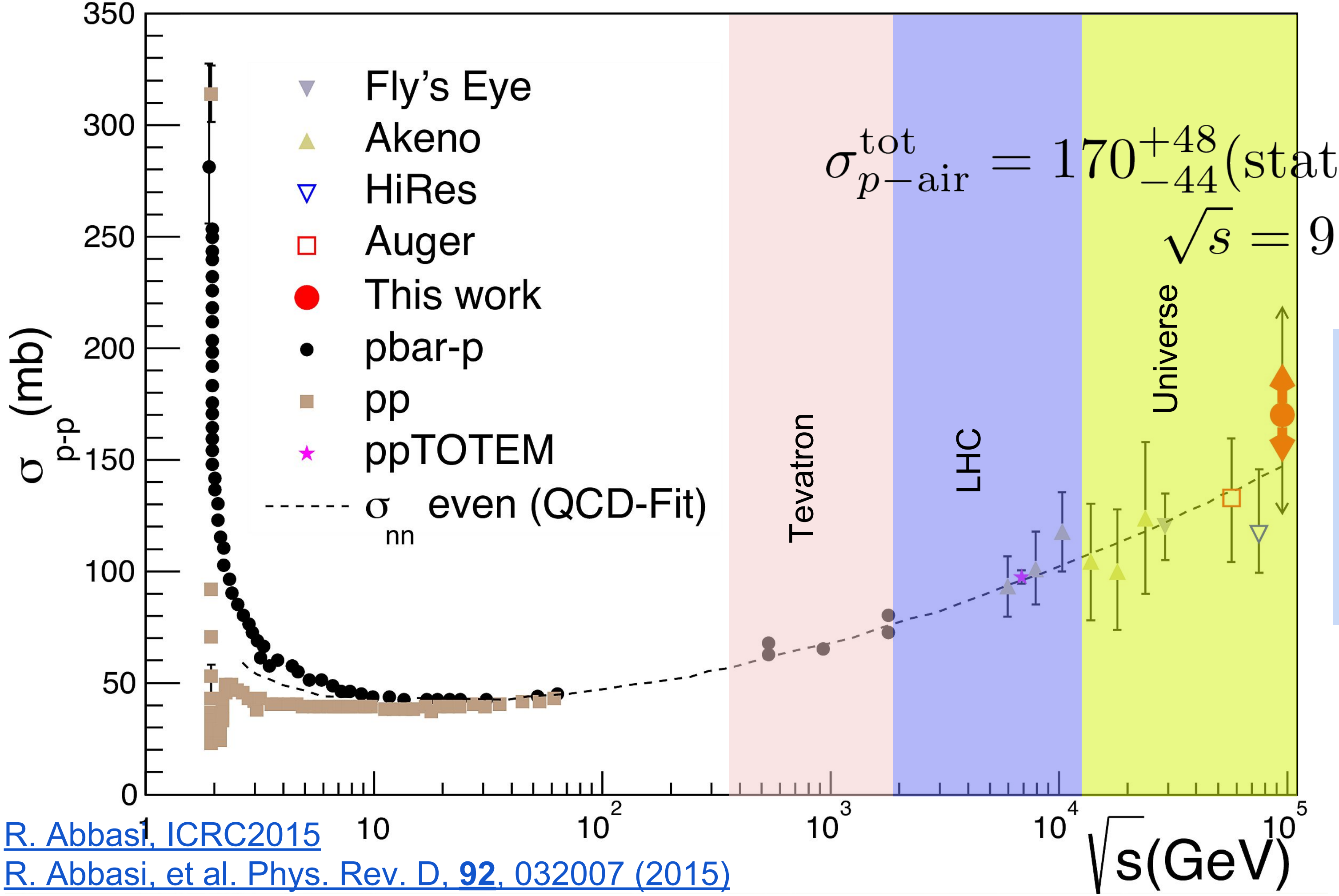
$$\sigma^{\text{inel}}_{p-\text{air}} = 567.0 \pm 70.5(\text{stat})\ ^{+29}_{-25}(\text{sys})\ \text{mb}$$

R. Abbasi, ICRC2015

R. Abbasi, et al. Phys. Rev. D, **92**, 032007 (2015)



350
300
250
200
150
100
50
0
$\sigma_{p\text{-}p}$ (mb)
1
10
10^2
10^3
10^4
10^5
$\sqrt{s}$(GeV)
▼ Fly's Eye
▲ Akeno
▽ HiRes
□ Auger
● pbar-p
■ pp
★ ppTOTEM
σ_{nn} even (QCD-Fit)
Tevatron
LHC



$$\sigma^{\rm tot}_{p-\rm air} = 170^{+48}_{-44}(\rm stat)^{+19}_{-17}(\rm sys)\ \rm mb$$

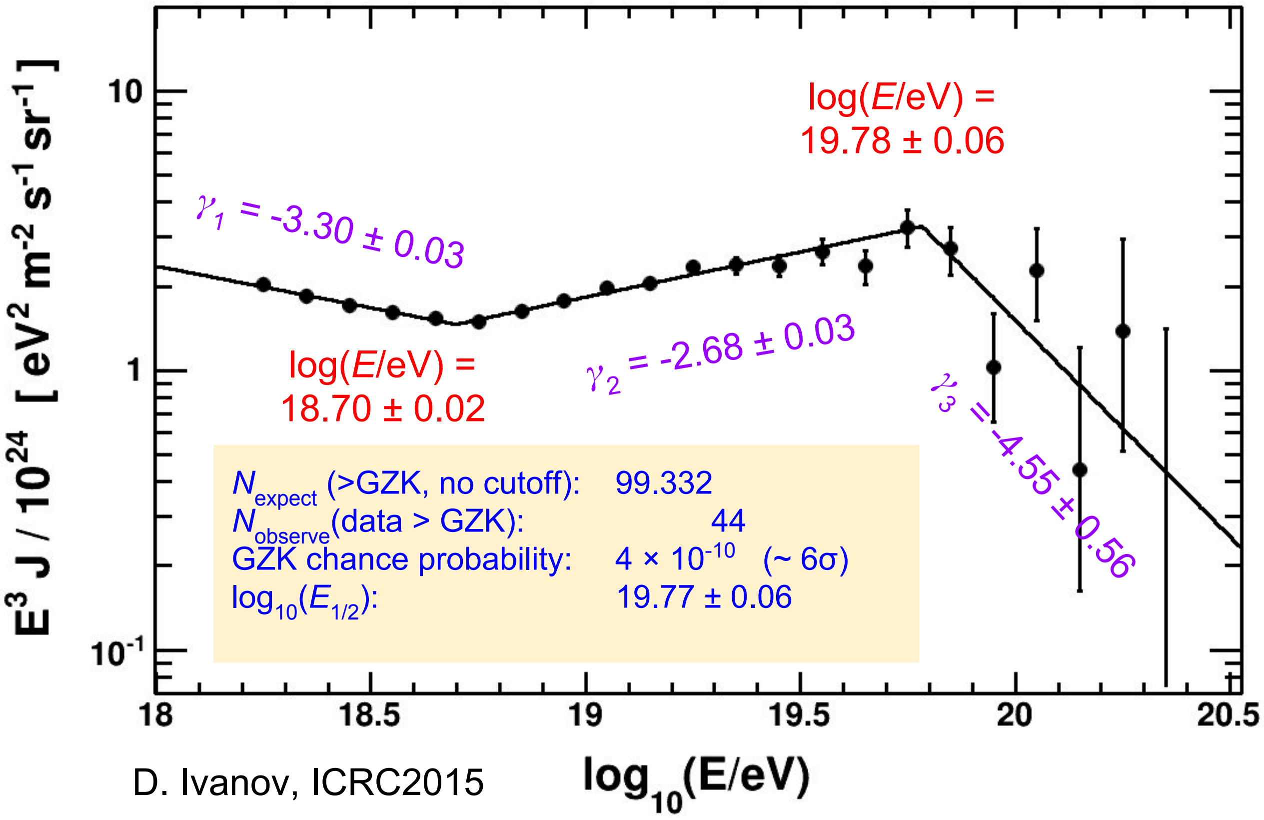
$$\sqrt{s} = 95\ \rm TeV$$

Total *pp* cross section found by applying Glauber theory (B-σ_{pp} plane) and BHS QCD fit (dashed line).

R. Abbasi, ICRC2015

R. Abbasi, et al. Phys. Rev. D, **92**, 032007 (2015)

TA 7 year SD Spectrum



N_{expect} (>GZK, no cutoff):	99.332
$N_{observe}$(data > GZK):	44
GZK chance probability:	4×10^{-10} (~ 6σ)
$\log_{10}(E_{1/2})$:	19.77 ± 0.06

D. Ivanov, ICRC2015

TA SD gives greatest statistical power to measure the UHECR spectrum (~ 100% duty cycle!)

23,854 events over seven years.

Low energy cut: **$10^{18.2}$ eV**.

Two features of UHECR spectrum observed:

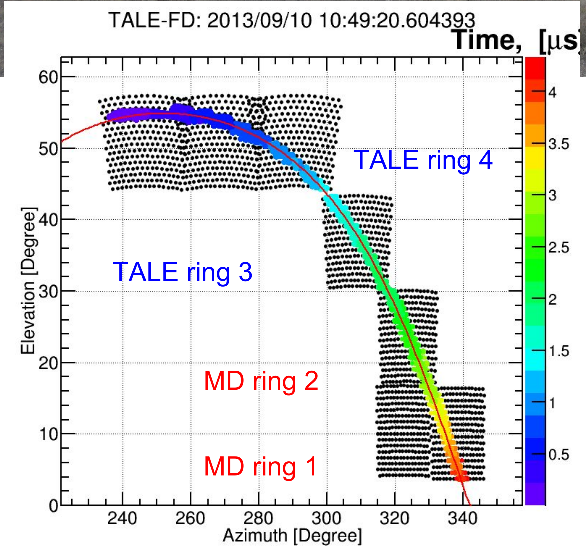
1. Ankle @ $10^{18.7}$ eV
2. GZK break @ $10^{19.78}$ eV
   6 σ significance over expectation without a suppression.

But we can down further...

TA Low Energy Extension (TALE)

Middle Drum FD

TALE FD



7 mirror event!

In operation since May 2013

10 additional telescopes

10 MHz FADC (HiRes2)

100° azimuth, 31°- 57° zenith

Infill array of 105 scintillation counters now operational.

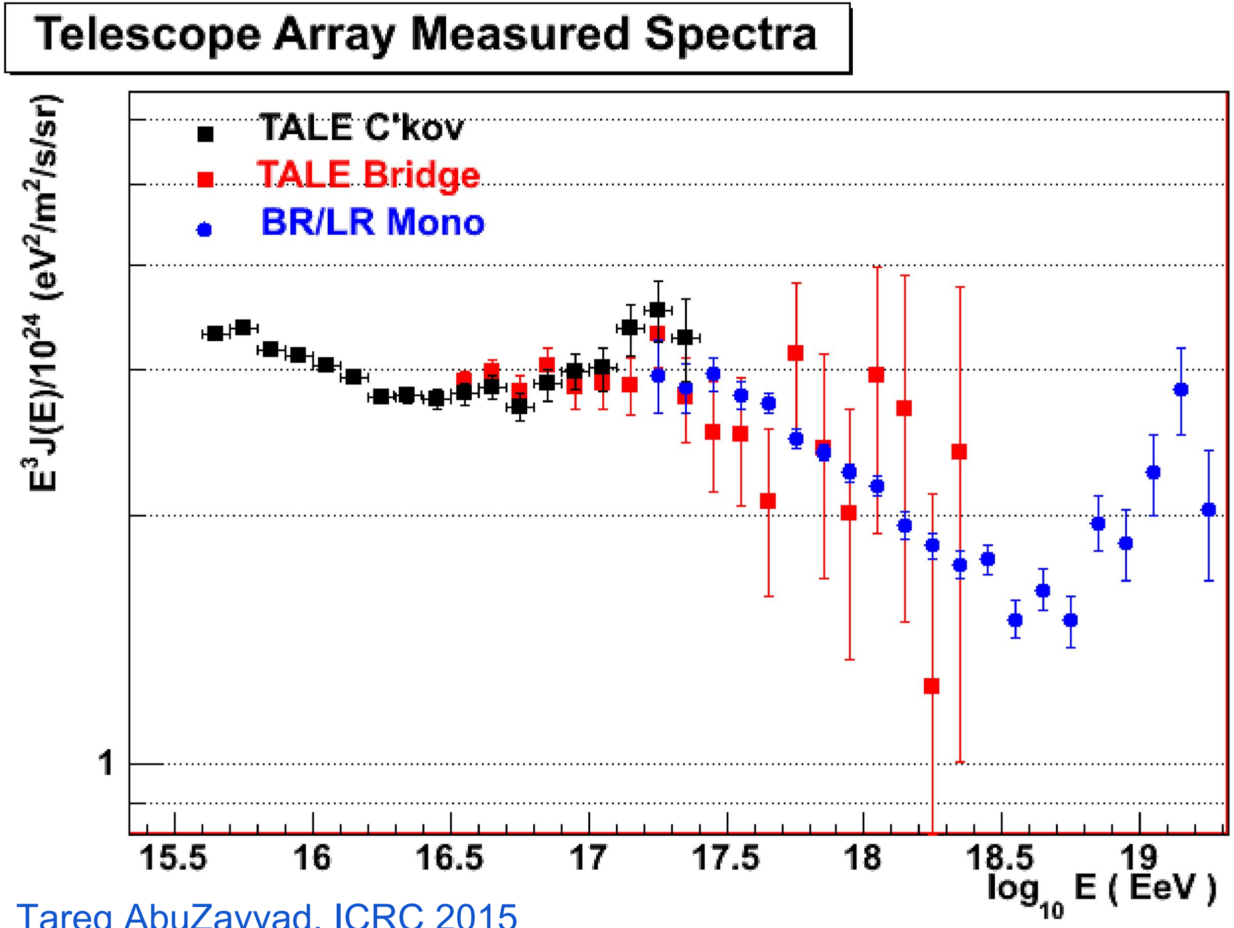
400 m [600 m, 1200 m] spacing

Sensitive $E > 10^{16.5}$ eV

1 detector, 1 energy scale, 1 systematic → galactic to extra-galactic transition in cosmic ray flux → GZK cutoff

But we can down further...

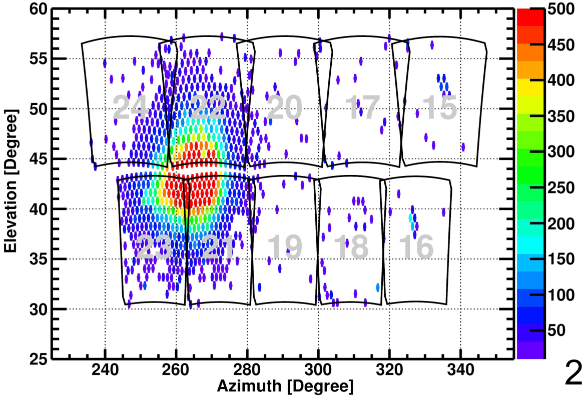
TALE Spectrum via Cherenkov - 1st measurement



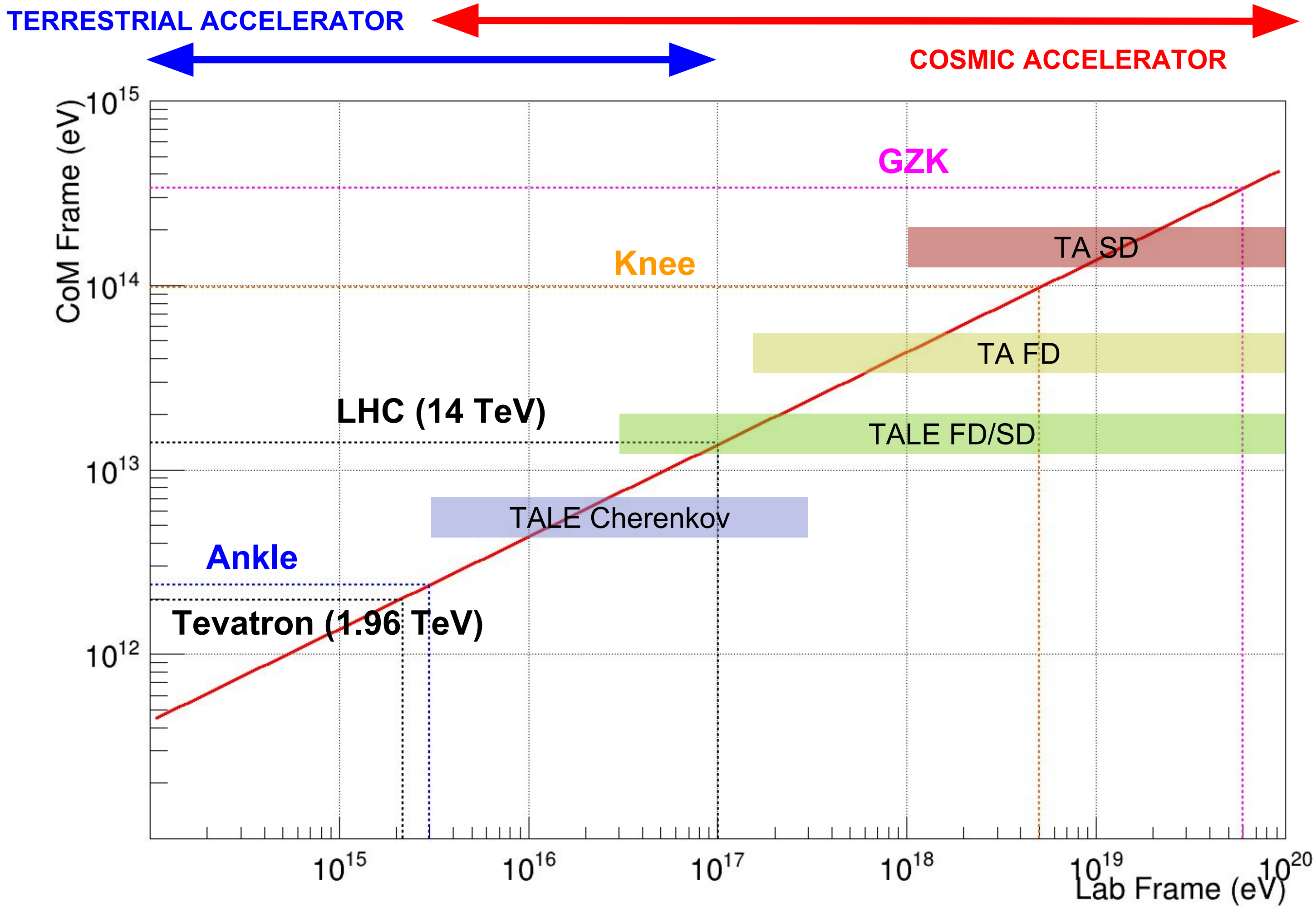
PCGF method - same as used for HiRes1 mono

Simultaneous geom/profile fit. Zenith angle is well constrained.

Extends ~ 2 decades below FD mono, ~ 1 decade below TALE bridge.



Tareq AbuZayyad, ICRC 2015



Measuring the *pp* cross section at UHECR energies, allows us to test for new physics.

Utilizing the different components of TA, we can close the gap between LHC energy scale and the cosmic energy scale, reducing the range of extrapolation from accelerator energies.

$\sqrt{s}$ overlap: 2.4 TeV - 14 TeV

TA Expansion (TA × 4)

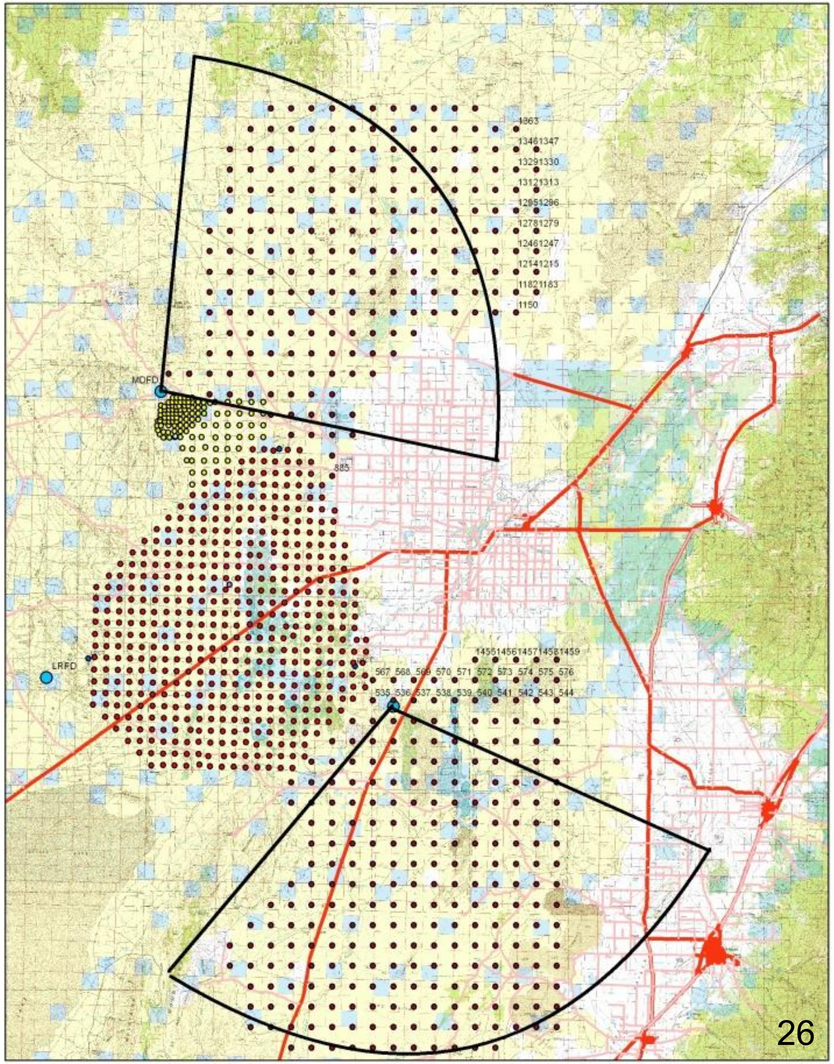
Fourfold increase in the size of the TA SD array.

Add 500 scintillator SDs @ 2.08 km spacing.

Add 2 FD stations, 28 telescopes

Get 20 TA years of data by 2020.

Increased statistics for highest energy range (> 57 EeV) to answer the question of the hotspot.



Summary

- TA has presented seven years of high quality hybrid X_{max} data (important for composition and cross section).
- Within systematic uncertainties, below 10^{19} eV composition appears light (means and shapes of the distributions).
- Above 10^{19} eV, more data is needed to decide about composition.
- An additional 1.5 years of hybrid data has recently been released and will be presented at ICRC 2017, Busan, Korea (in less than two weeks).

- TA has measured the proton-air inelastic cross section at √s = 95 TeV
    - ○ 567.0 ± 70.5[stat.] (+25,-29)[sys.] mb
- Proton-air inelastic cross section can be used to determine the total *pp* cross section using Glauber formalism and BHS fit.
- *pp* total cross section at √s = 95 TeV is measured to be $\sigma_{p\text{-}p}$ (tot) = 170 (+48, -44) [stat] (+19, -17) [sys]
- TA can close the gap even further to produce a direct measurement of *p*-air inelastic to get closer to LHC measurements.
- This measurement can be extended down further in energy using BR/LR hybrid data (0.2 decade lower in lab frame at least)

- TA is expanding by factor of four.
- First new SDs begin operation this year.
- Two new FD stations slated for reconstruction.

MISCELLANEA

Telescope Array Collaboration

THE UNIVERSITY OF UTAH

大阪市立大学 OSAKA CITY UNIVERSITY

愛媛大学 EHIME UNIVERSITY

RUTGERS THE STATE UNIVERSITY OF NEW JERSEY

東京工業大学 Tokyo Institute of Technology

YONSEI UNIVERSITY

UtahState University

이화여자대학교 EWHA WOMANS UNIVERSITY

ICRR Institute for Cosmic Ray Research University of Tokyo

東京大学 THE UNIVERSITY OF TOKYO

千葉大学 Chiba University

WASEDA University

HANYANG UNIVERSITY

東京都市大学 TOKYO CITY UNIVERSITY

CNU 충남대학교 CHUNGNAM NATIONAL UNIVERSITY

KU KANAGAWA UNIVERSITY

University of Yamanashi

VRIJE UNIVERSITEIT BRUSSEL · SCIENTIA VINCERE TENEBRAS ·

TELESCOPE ARRAY PROJECT

KEK - Institute of Particle And Nuclear Studies

広島市立大学 HIROSHIMA CITY UNIVERSITY

ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ РОССИЙСКОЙ АКАДЕМИИ НАУК
INSTITUTE FOR NUCLEAR RESEARCH OF RUSSIAN ACADEMY OF SCIENCES

Tokyo University of Science

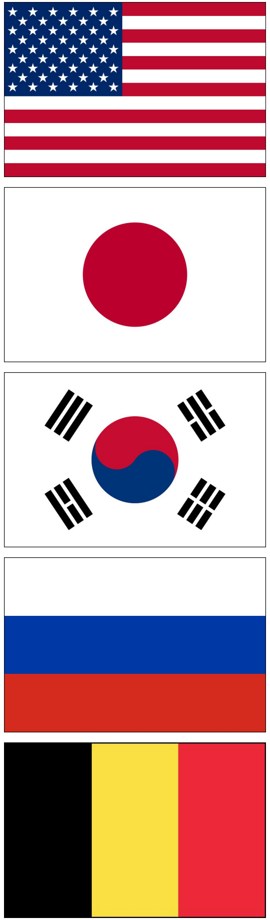
SHIBAURA INSTITUTE OF TECHNOLOGY

KINKI UNIVERSITY

National University Corporation Kochi University

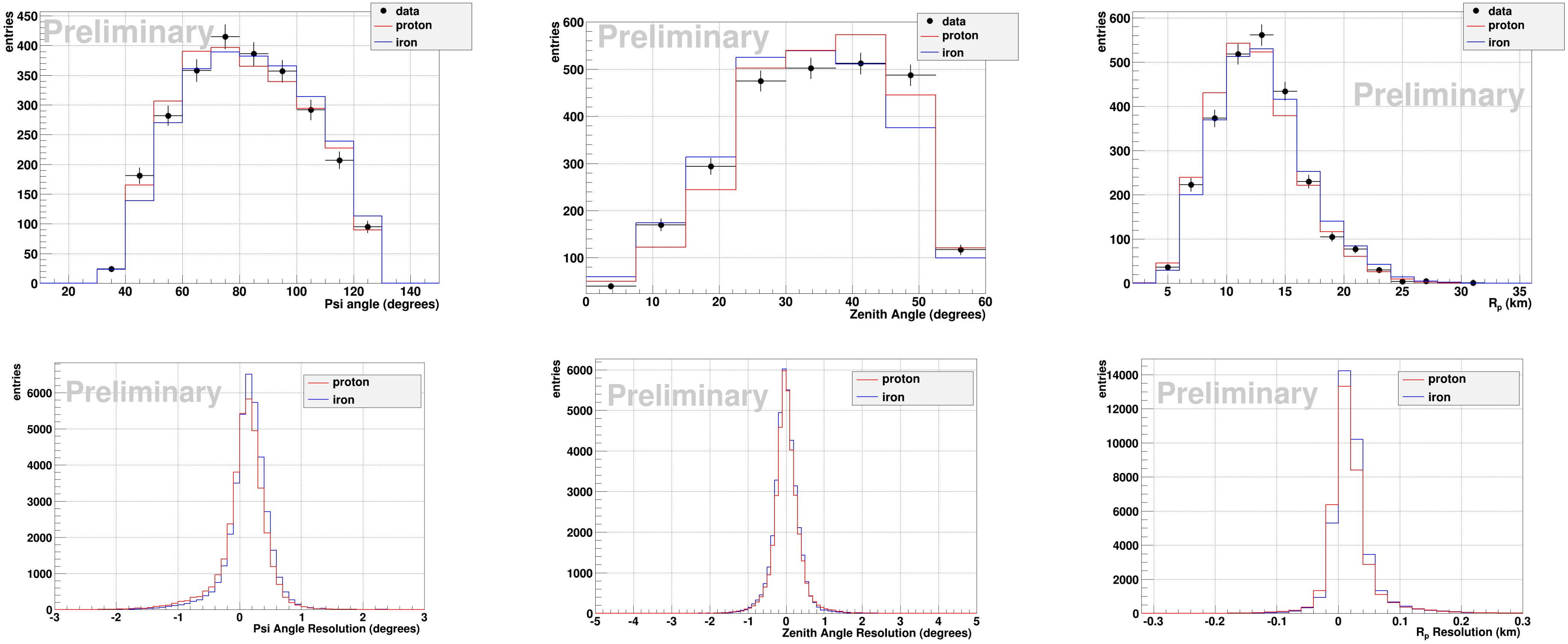
Saitama University

NIRS National Institute of Radiological Sciences 独立行政法人 放射線医学総合研究所



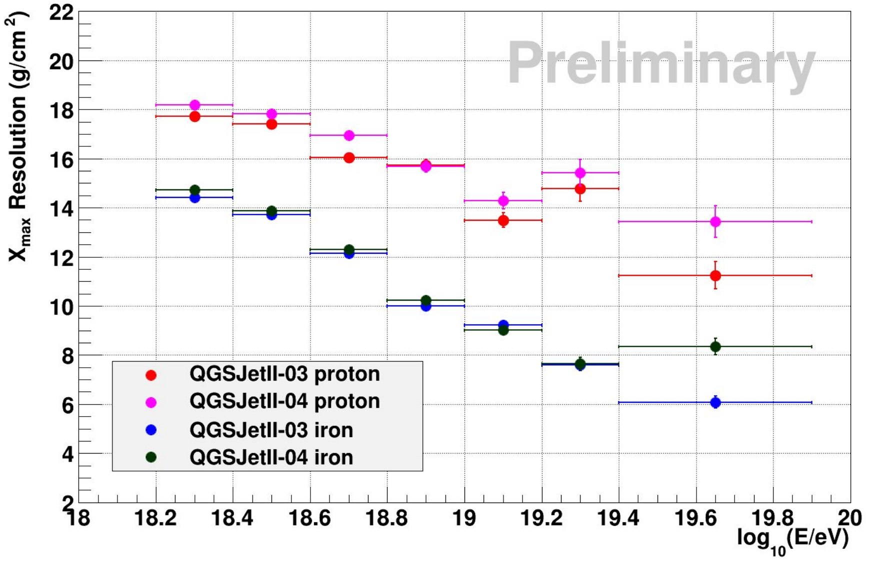
5 nations, 33 institutions, 124 members

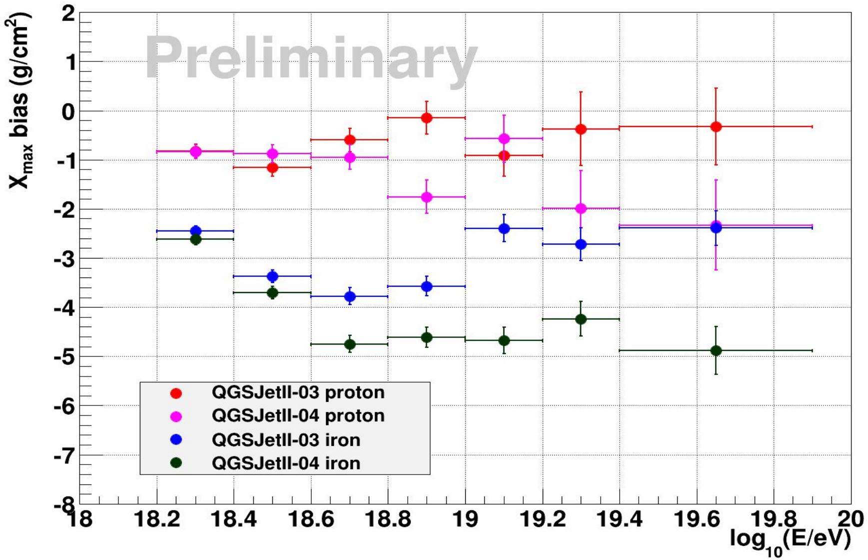
Monte Carlo Reconstruction



QGSJet II-04 resolutions: zenith angle 0.4 degrees, psi angle 0.4 degrees, R_p 40 meters

Hybrid Reconstruction Resolution

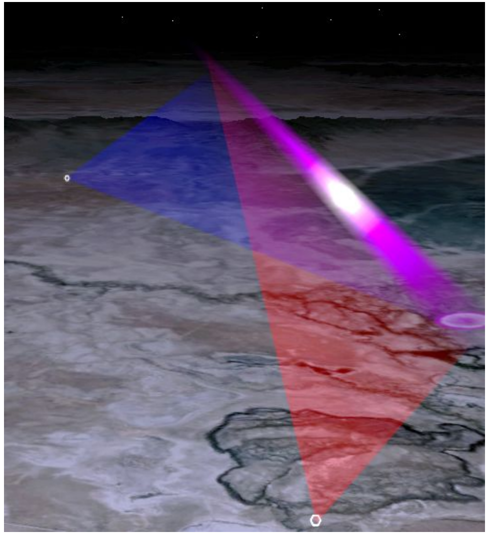


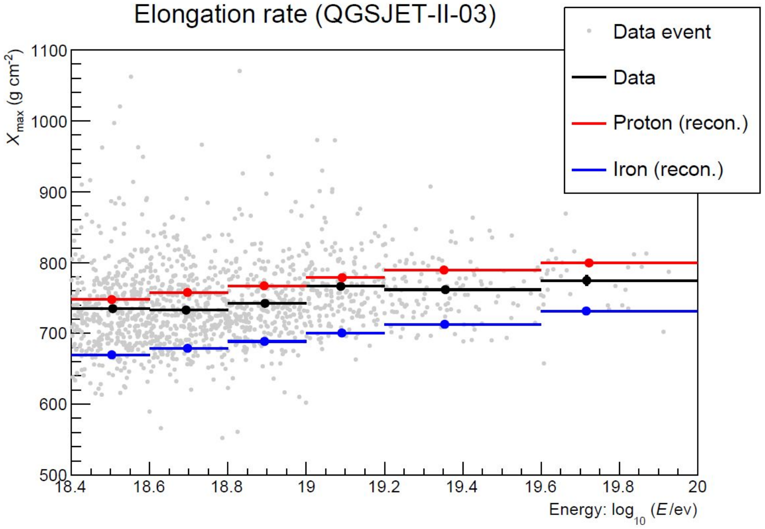


X_{max} resolution is between 12 - 18 g/cm^2 for protons and 6 - 14 g/cm^2 for iron.
For comparison, monocular resolution is 54 g/cm^2 and 46 g/cm^2 for proton and iron

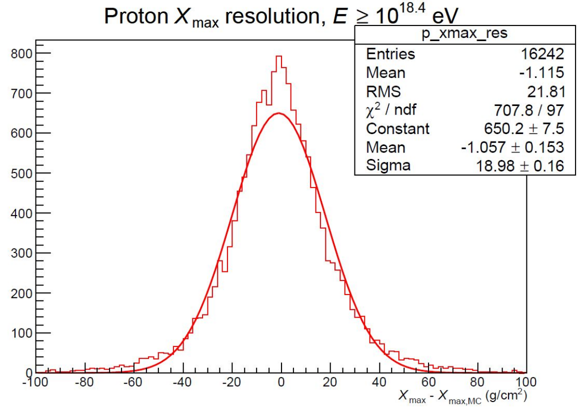
Reconstruction bias is ~ -1 g/cm^2 for proton and ~ -3 g/cm^2 for iron.

TA Composition - Stereo



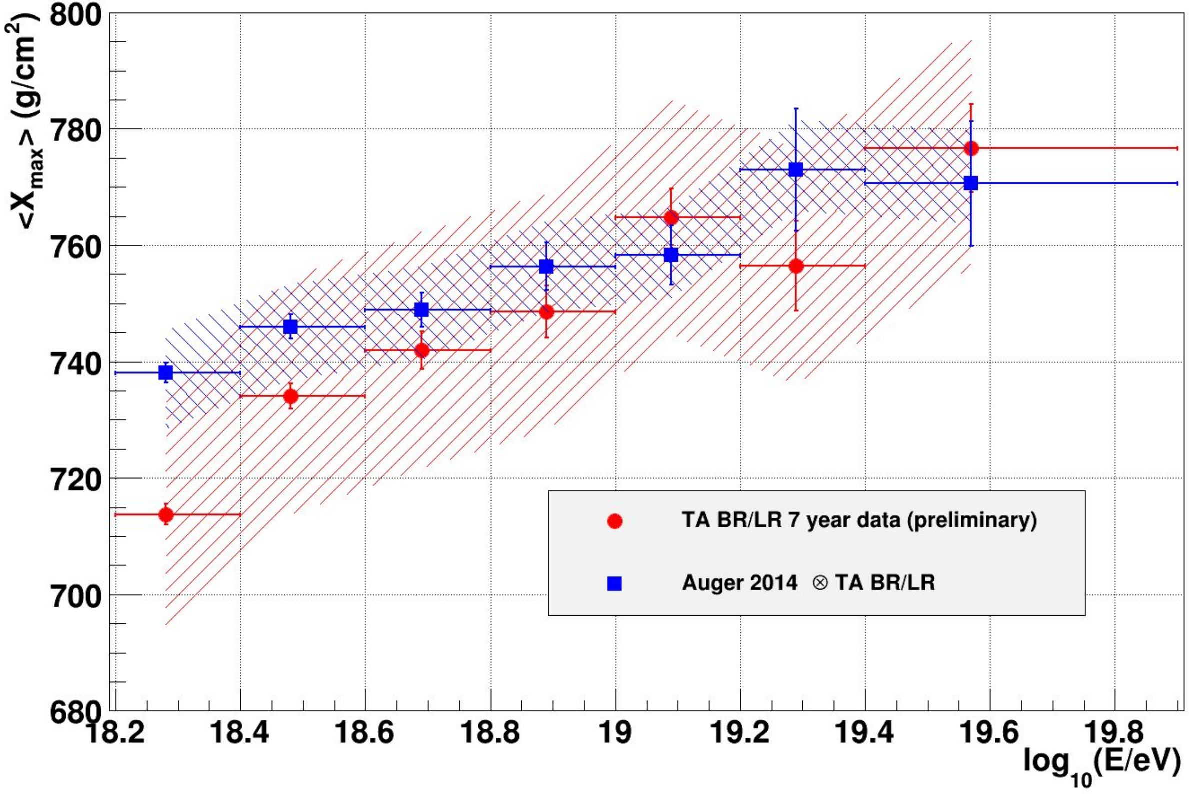


T. Stroman, APS April 2016



8 years data - all FD stations (excluding TALE) - 38 telescopes
Events must be observed by multiple FDs
$\log_{10}(E/\mathrm{eV}) > 18.4$
1346 events
X_{max} resolution ~ 20 g/cm^2, reconstruction bias ~ 1 g/cm^2
Energy resolution ~ 6%

TA/Auger X_{max}



TA and Auger data are in agreement within systematic uncertainties.

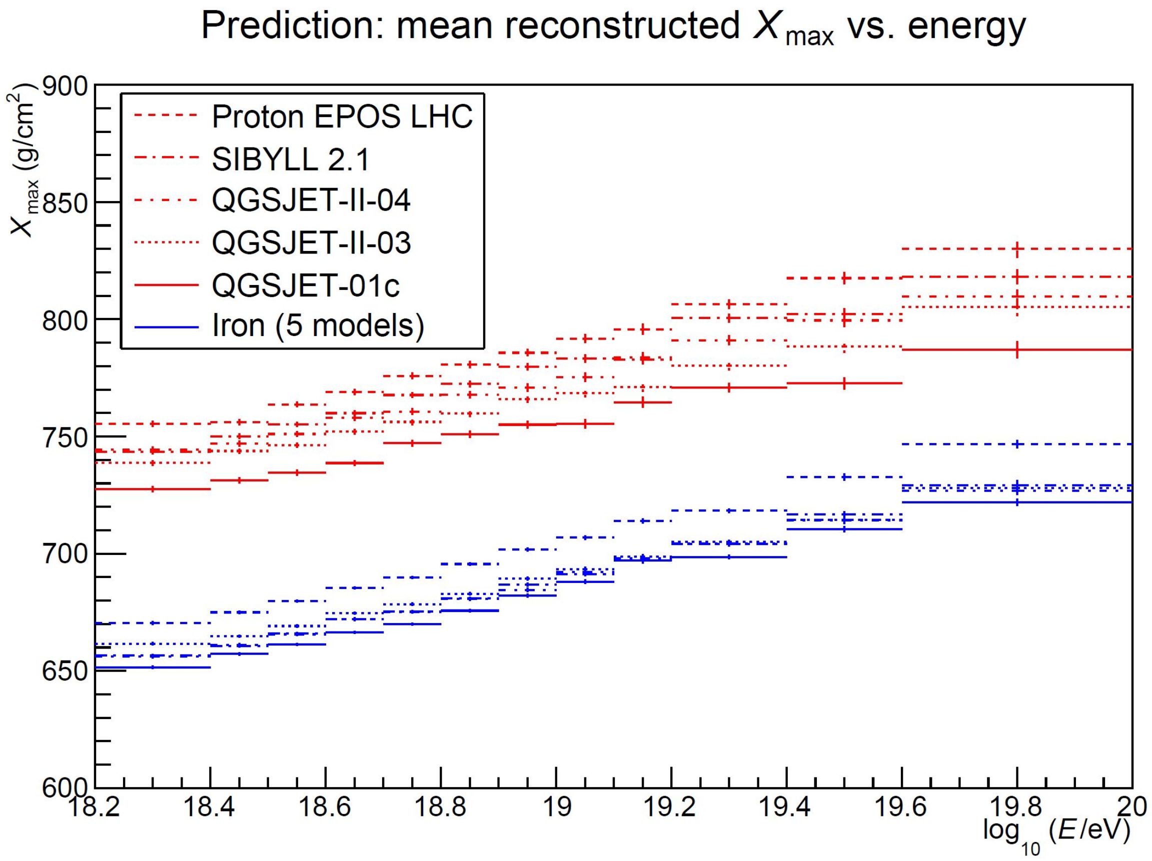
TA and Auger data can not be directly compared because they use different approaches to data analysis.

We can indirectly compare our data by using a composition mixture made up of proton, helium, nitrogen, and iron that is fit to their data. Then TA generates and reconstructs a Monte Carlo data set using the same composition mix. This simulates acceptance and biases of the TA detector and reconstruction algorithms.

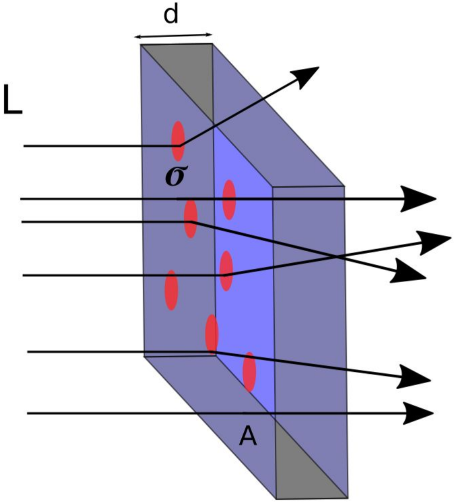
Compare the agreement of this reconstructed mix to TA data.

$(A = B \wedge B = C) \Rightarrow A = C$

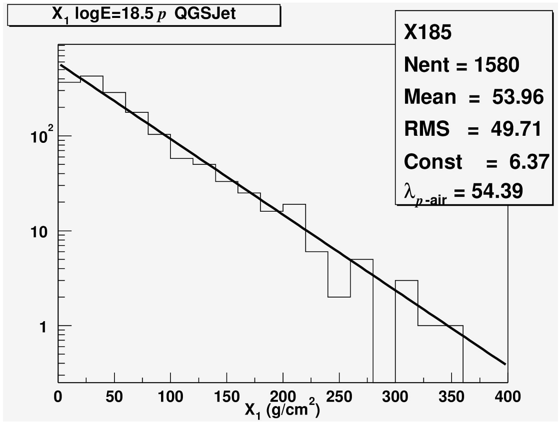
Composition Model Dependence

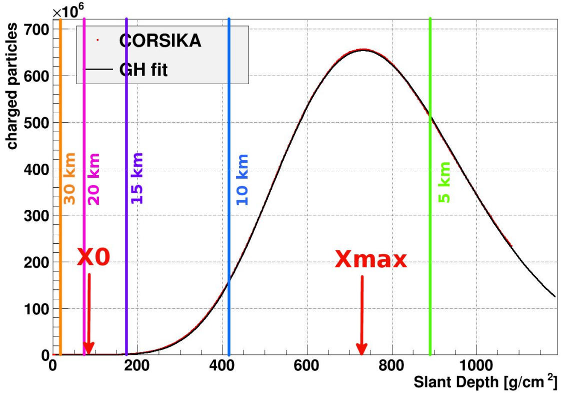


Measuring $\sigma_{p\text{-}air}$



$$dN/dt = L\sigma$$
$$P(x) = \exp(-x/\lambda)$$





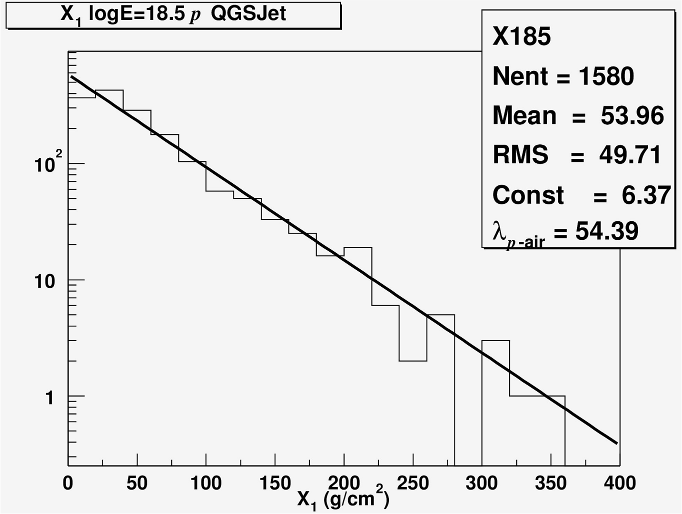
Minimum depth viewed of a shower as a function of core distance

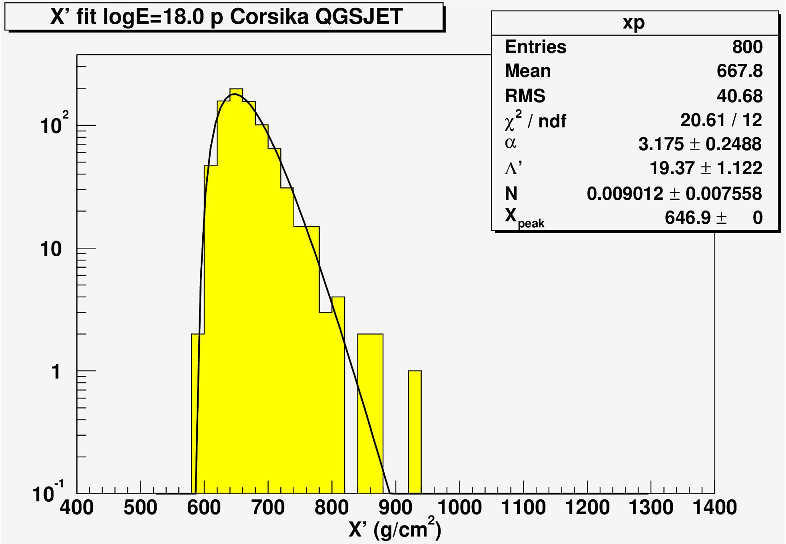
FDs don't observe X_1. Too far, too dim, out of the FOV.

Air showers: X_1 depends only on particle total cross section. Any arbitrary point in shower after depends on model dependent fluctuations (multiplicity, inelasticity, **cross section**).

Choose X_{max} as the observation point, examine models to measure fluctuations between X_1 and X_{max}.

Measuring $\sigma_{p\text{-}air}$



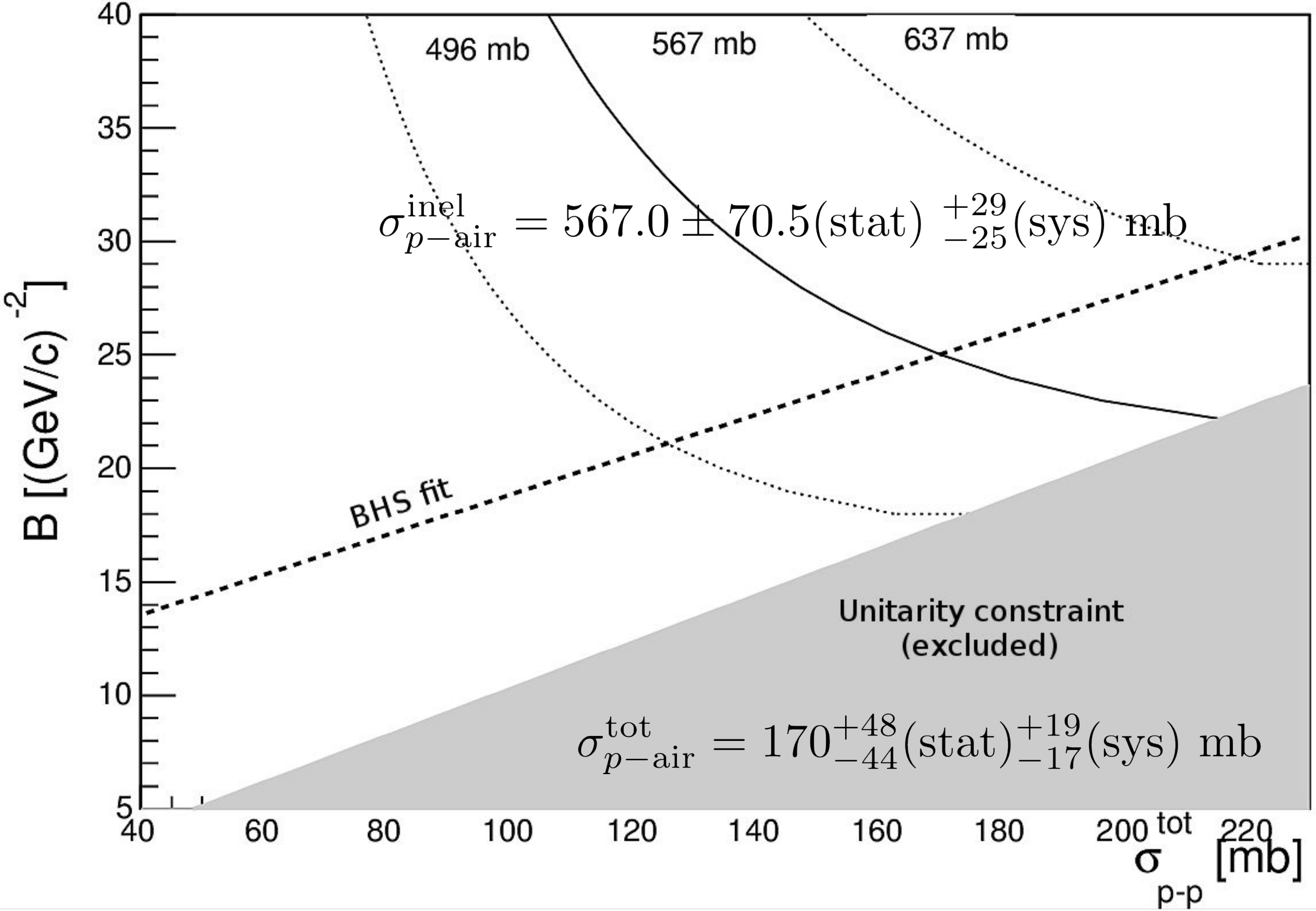


Depth of first interaction X_1. Slope is direct measure of $\lambda_{p\text{-}air}$. X_1 depends only on $\sigma_{p\text{-}air}$.

Not observed by FDs though.

Air shower development after X_1 is affected by fluctuations in first interaction depth, as well as hadronic cross section, inelasticity, multiplicity.

*** Model dependence**

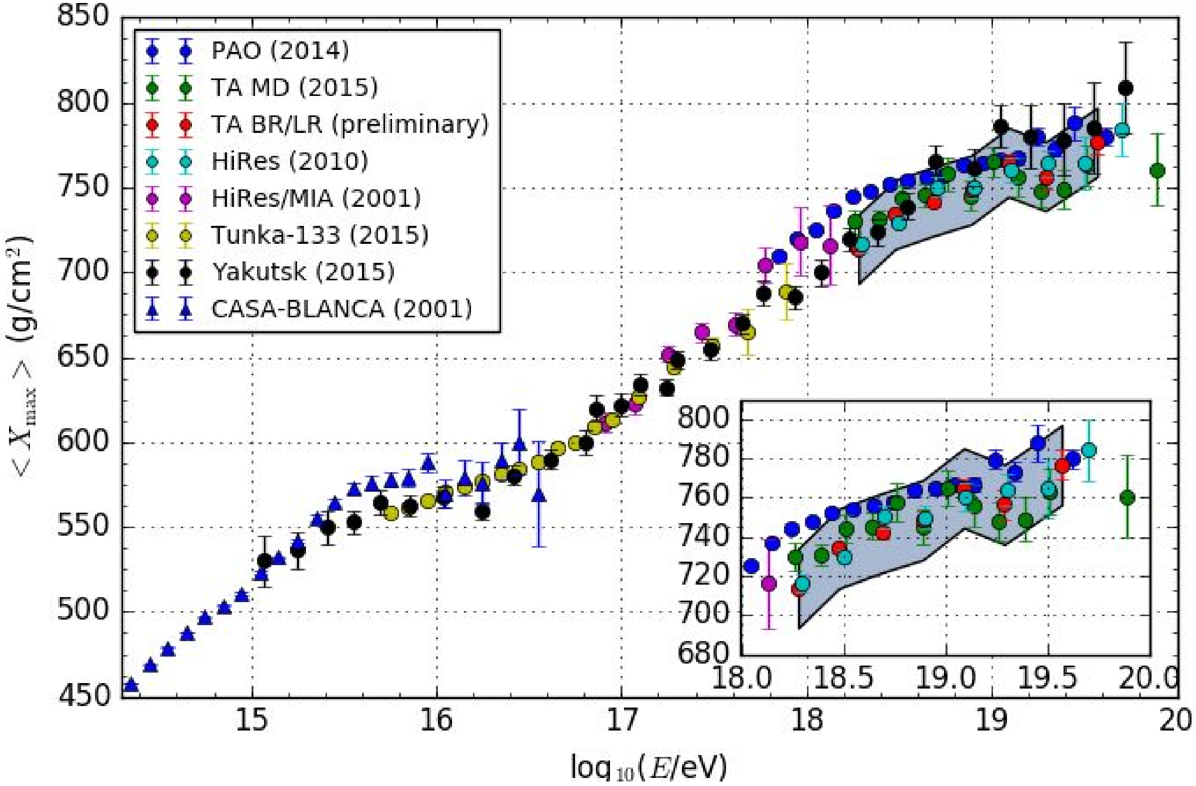


$$\sigma^{\rm inel}_{p-\rm air} = 567.0 \pm 70.5({\rm stat})\ ^{+29}_{-25}({\rm sys})\ {\rm mb}$$

$$\sigma^{\rm tot}_{p-\rm air} = 170^{+48}_{-44}({\rm stat})^{+19}_{-17}({\rm sys})\ {\rm mb}$$

B-σ_{pp} (tot) plane

B is the forward scattering elastic slope and the curves are for constant *p*-air inelastic cross section measured by TA (solid = measured, dotted = statistical uncertainty). The BHS fit is used to determine σ_{pp} in the plane.



History of X_{max} measurements with TA systematics (Auger data is “unbiased”).

Deeper understanding of X_{max} systematics will help close the gap between composition measurements at the highest energies.