

PIERRE  
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OBSERVATORY

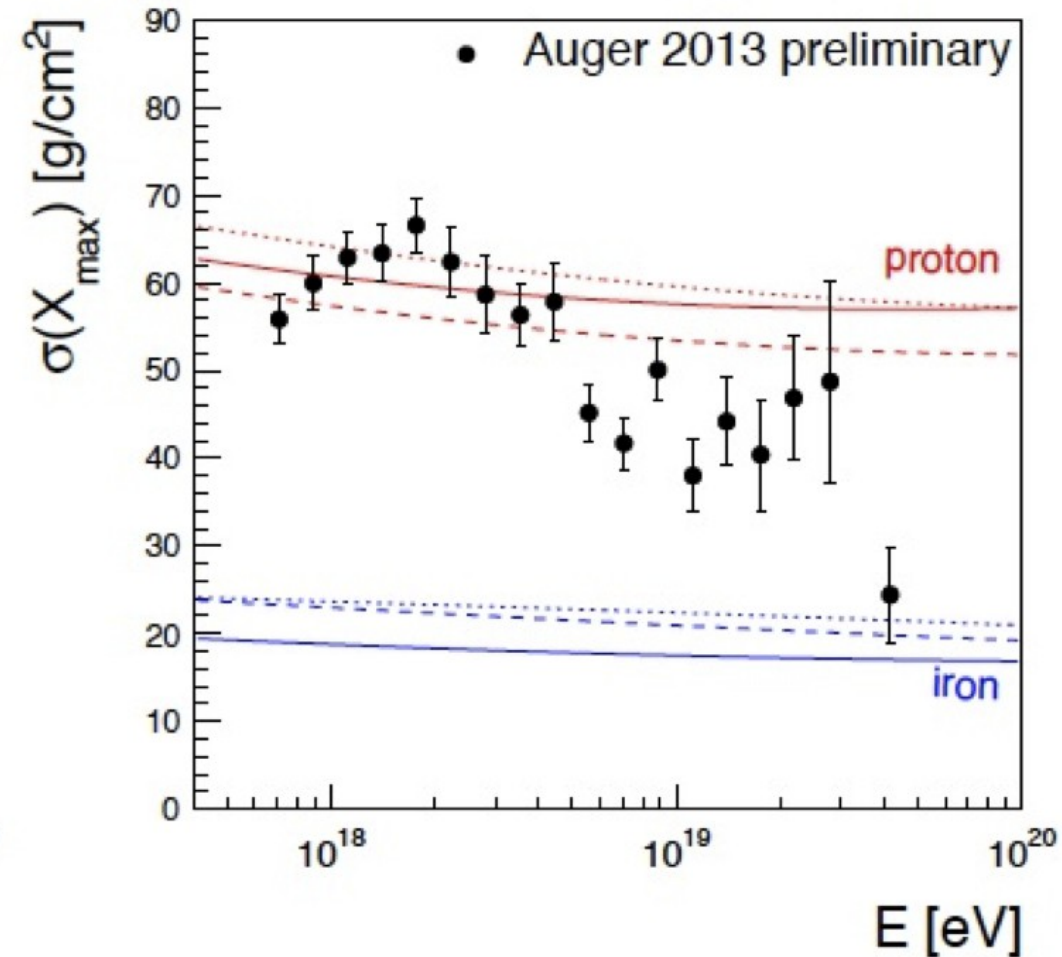
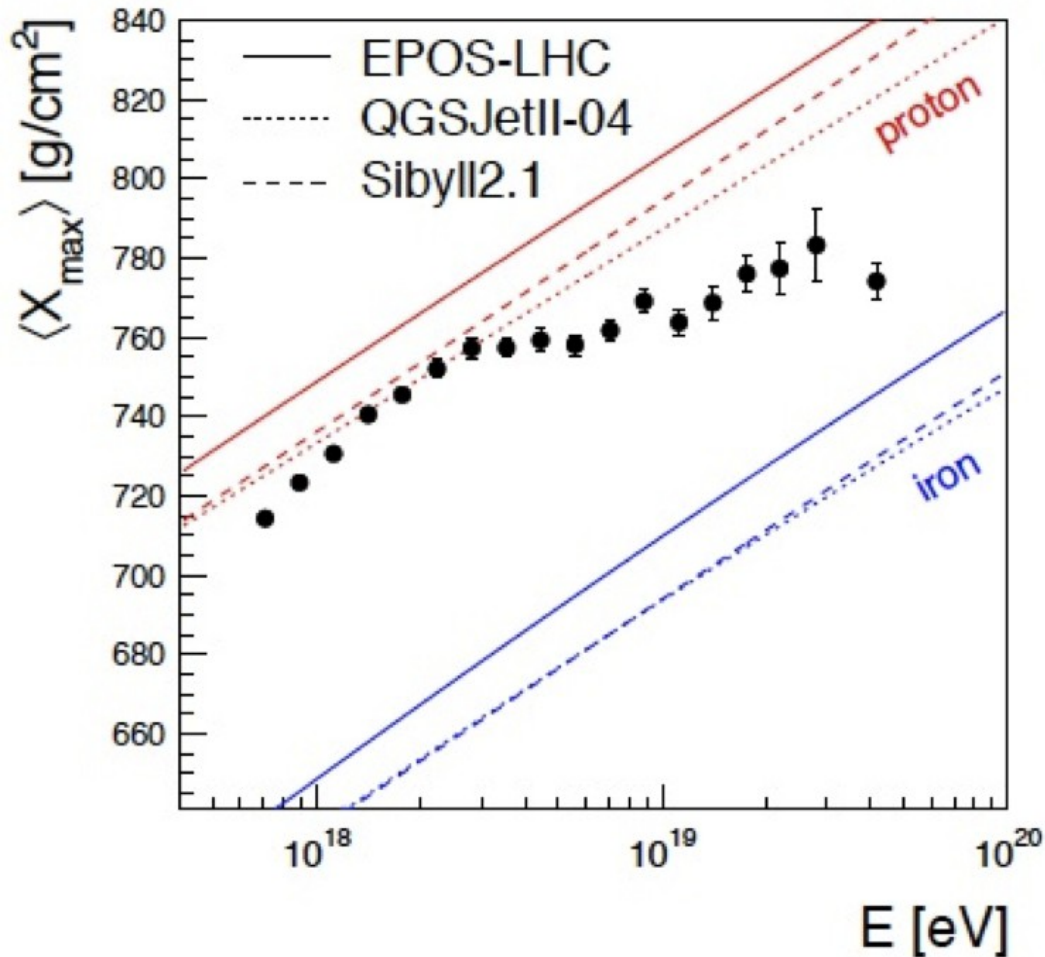
# Another $X_{max}$ analysis

Michael Sutherland  
James Matthews

Auger US analysis meeting  
October 2013

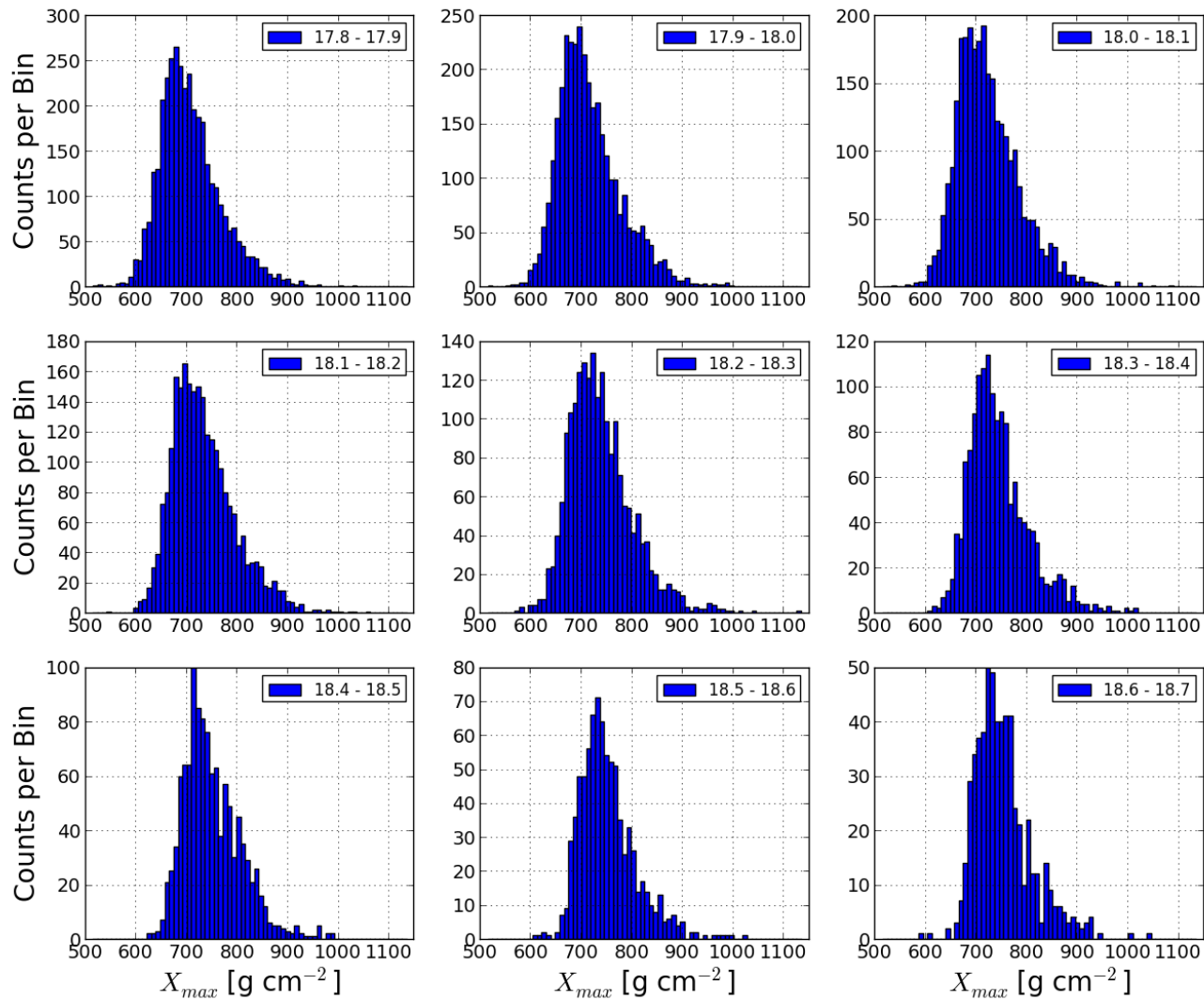
# ICRC 2013 $X_{max}$ Results

- Trend towards heavier composition with energy (according to models)
- These are comparisons of data against simulations; what about data against data?
- Are there complementary nonparametric methods to analyze  $X_{max}$ ?



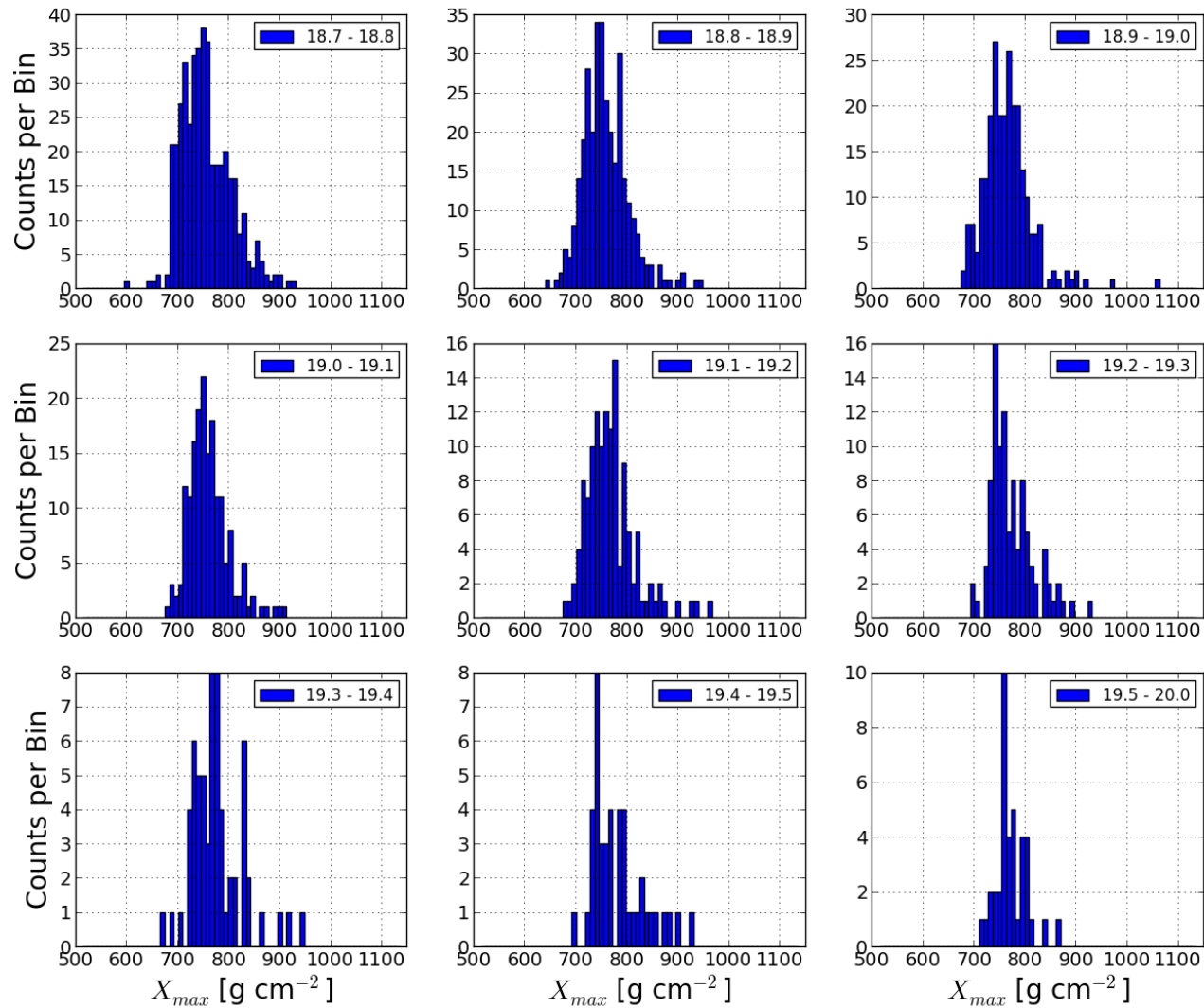
# Is there information in the general shape of the $X_{max}$ distribution?

## $X_{max}$ Distributions



# Is there information in the general shape of the $X_{max}$ distribution?

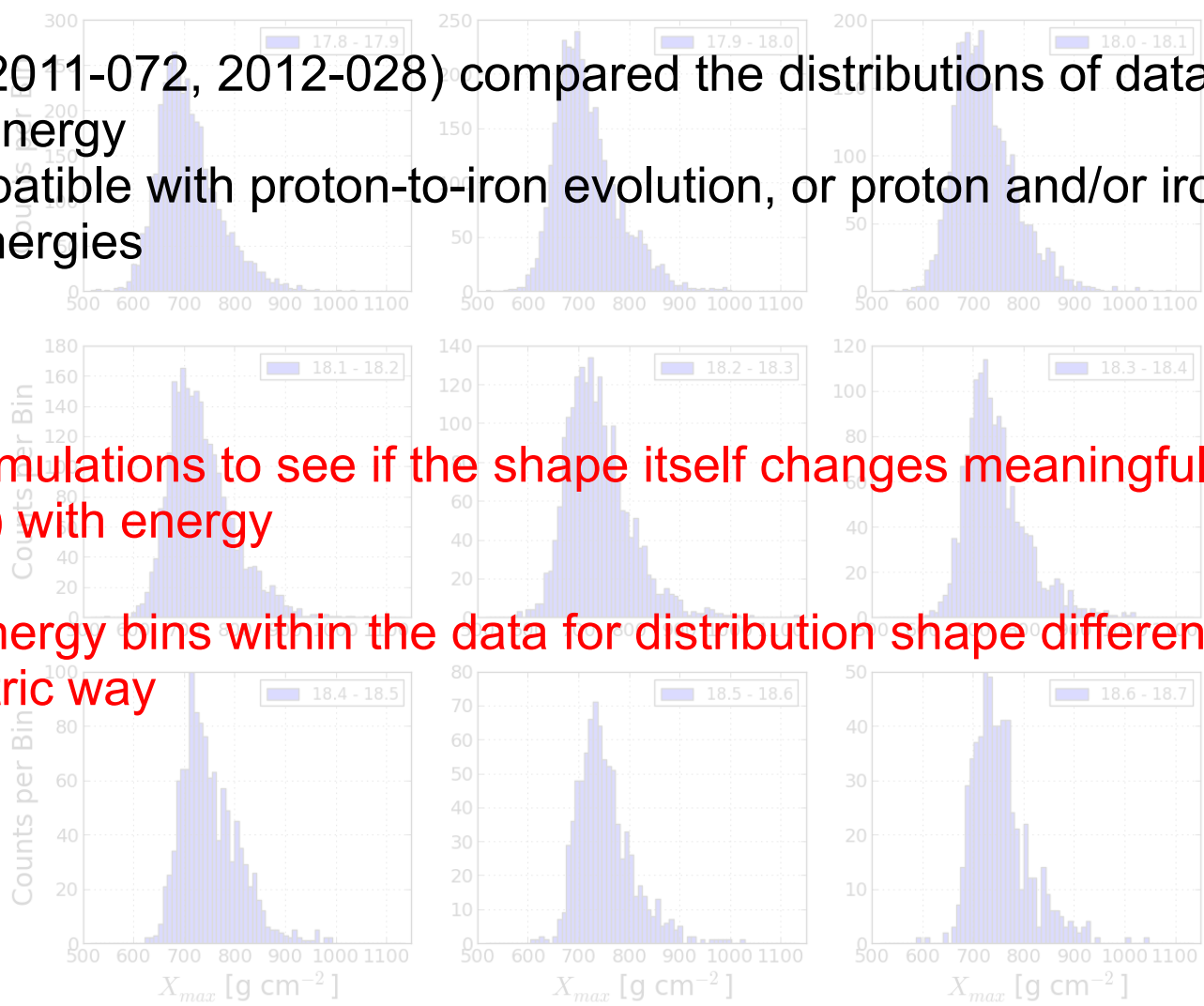
## $X_{max}$ Distributions



# Is there information in the general shape of the $X_{max}$ distribution?

- Many GAP notes discuss analysis of  $X_{max}$  parameterizations (mean, rms, ... )

- EJA & PK (2011-072, 2012-028) compared the distributions of data to simulations energy-by-energy
  - not compatible with proton-to-iron evolution, or proton and/or iron dominance at highest energies

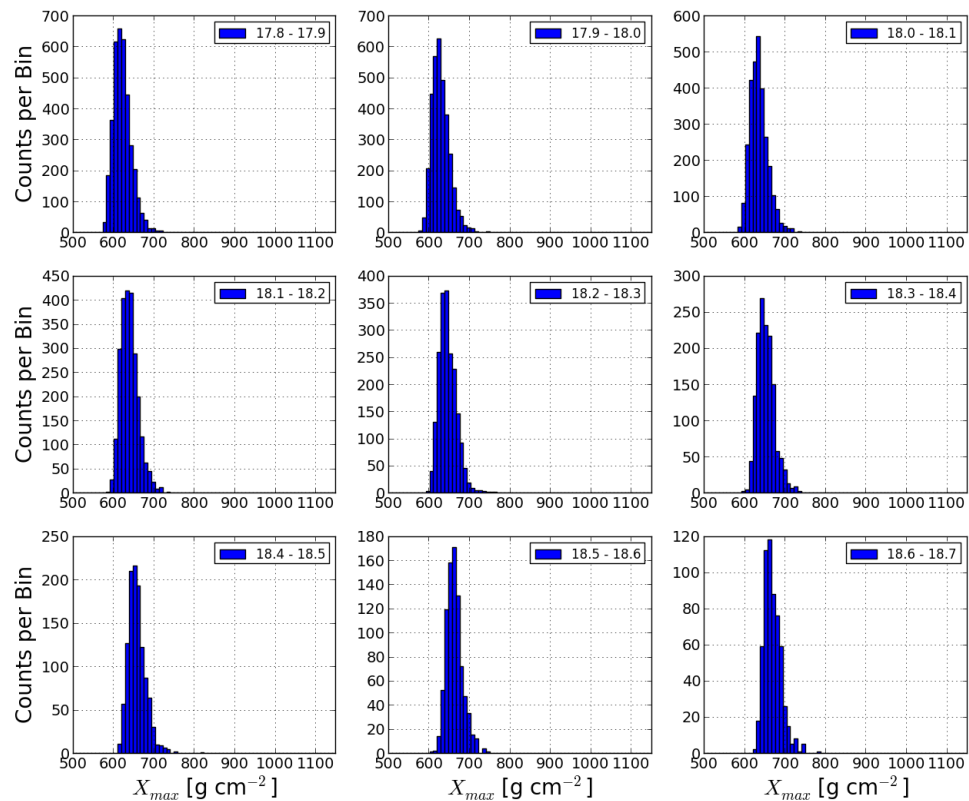


- Generate simulations to see if the shape itself changes meaningfully (within themselves) with energy
- Compare energy bins within the data for distribution shape differences in a nonparametric way

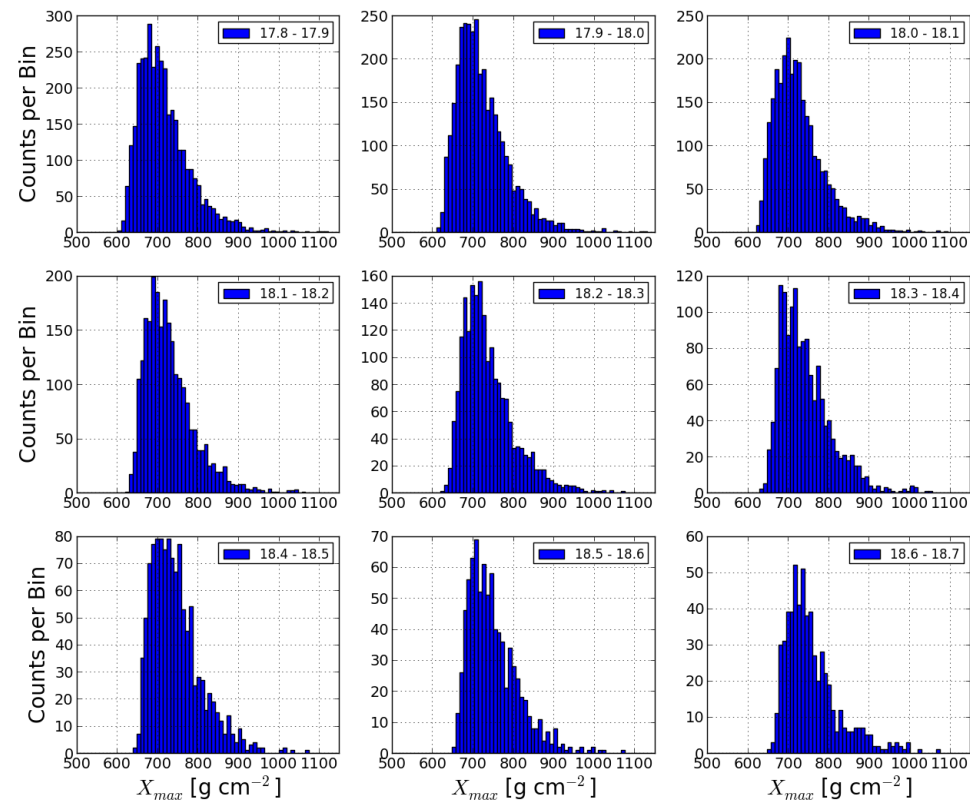
# Simulated $X_{max}$ Distributions

- 10 full proton and iron simulations each (10 showers at each event energy)
- QGSJET using CONEX 2r3.1i out-of-the-box

Iron sim 1

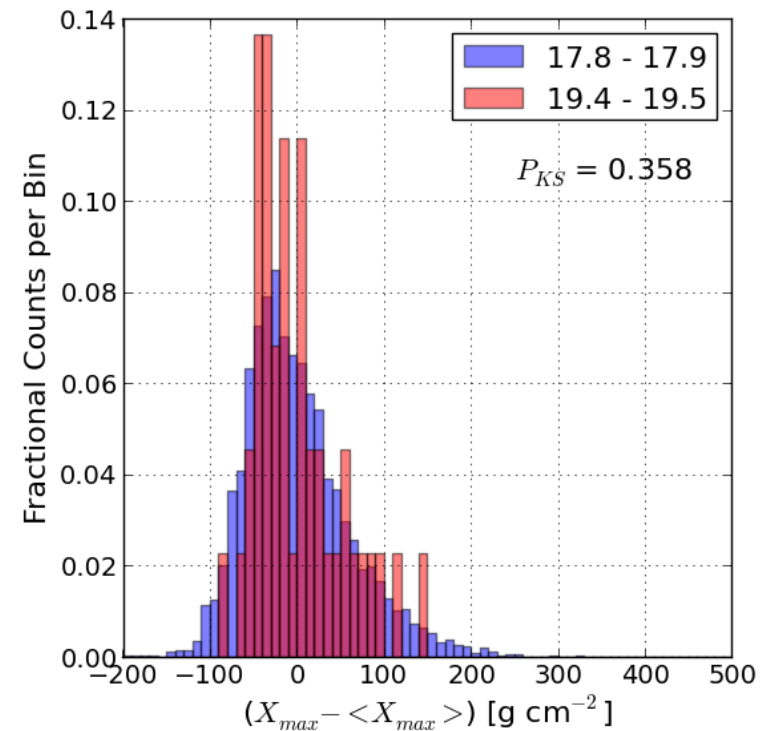
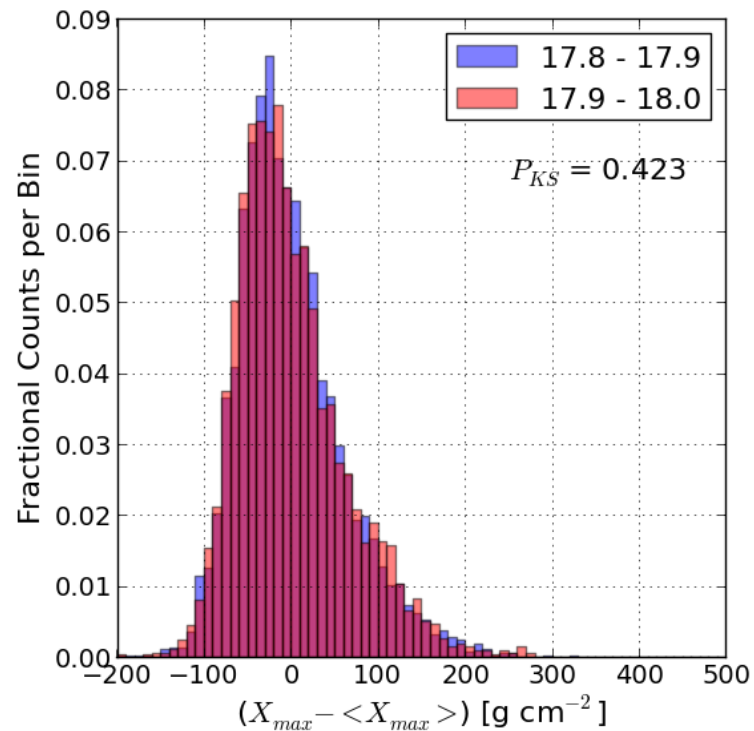


Proton sim 1



# Simulated $X_{max}$ Distributions – Method

- Subtract each distribution by its mean value
- Perform KS test on mean-shifted distributions between different energy bins

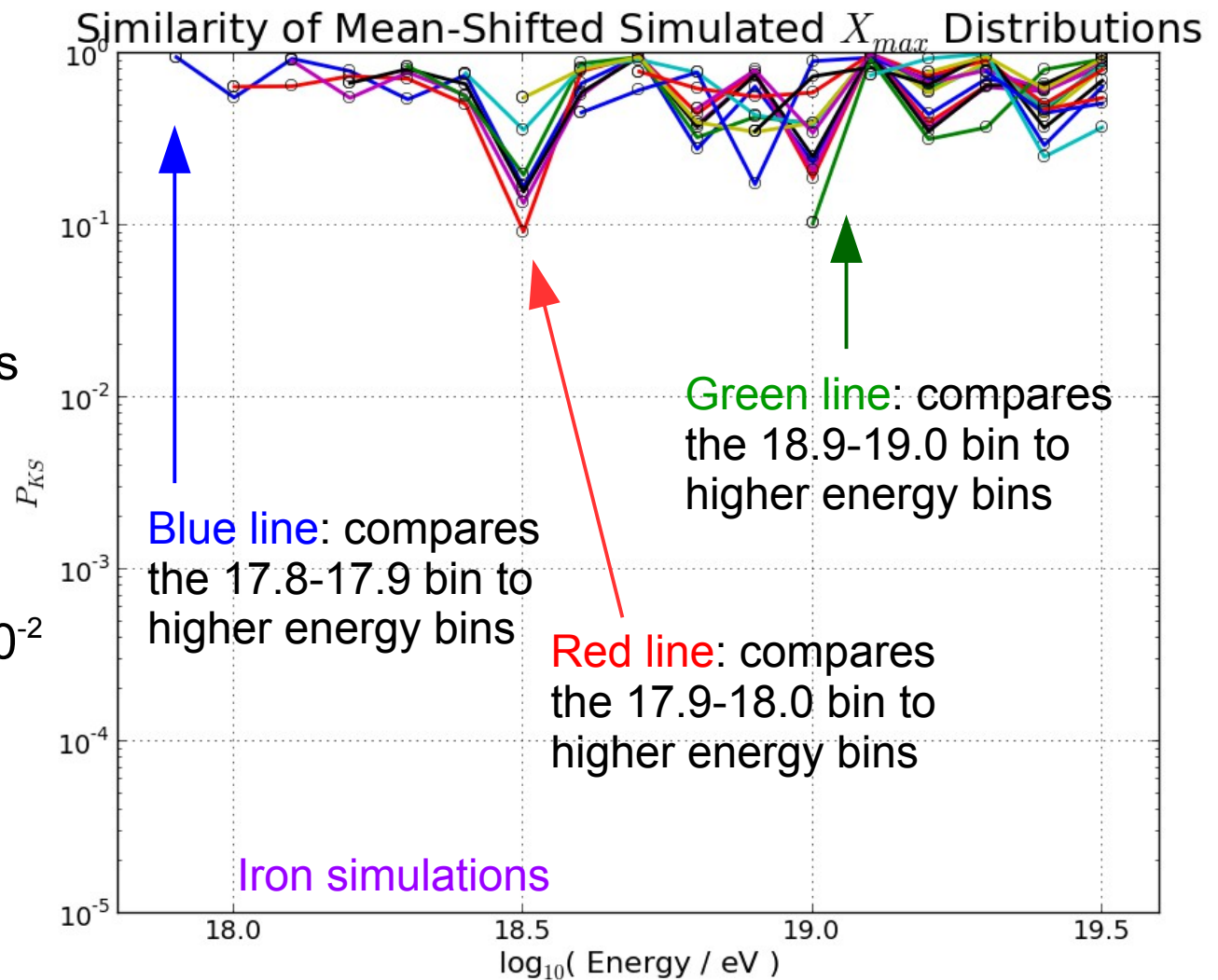


# Simulated $X_{max}$ Distributions – Iron Comparison

- Calculate  $P_{KS}$  for each energy bin compared to every higher energy bin

- For a pure composition  $X_{max}$  distributions appear similar at different energies

- No simulation has  $P_{KS} < 10^{-2}$



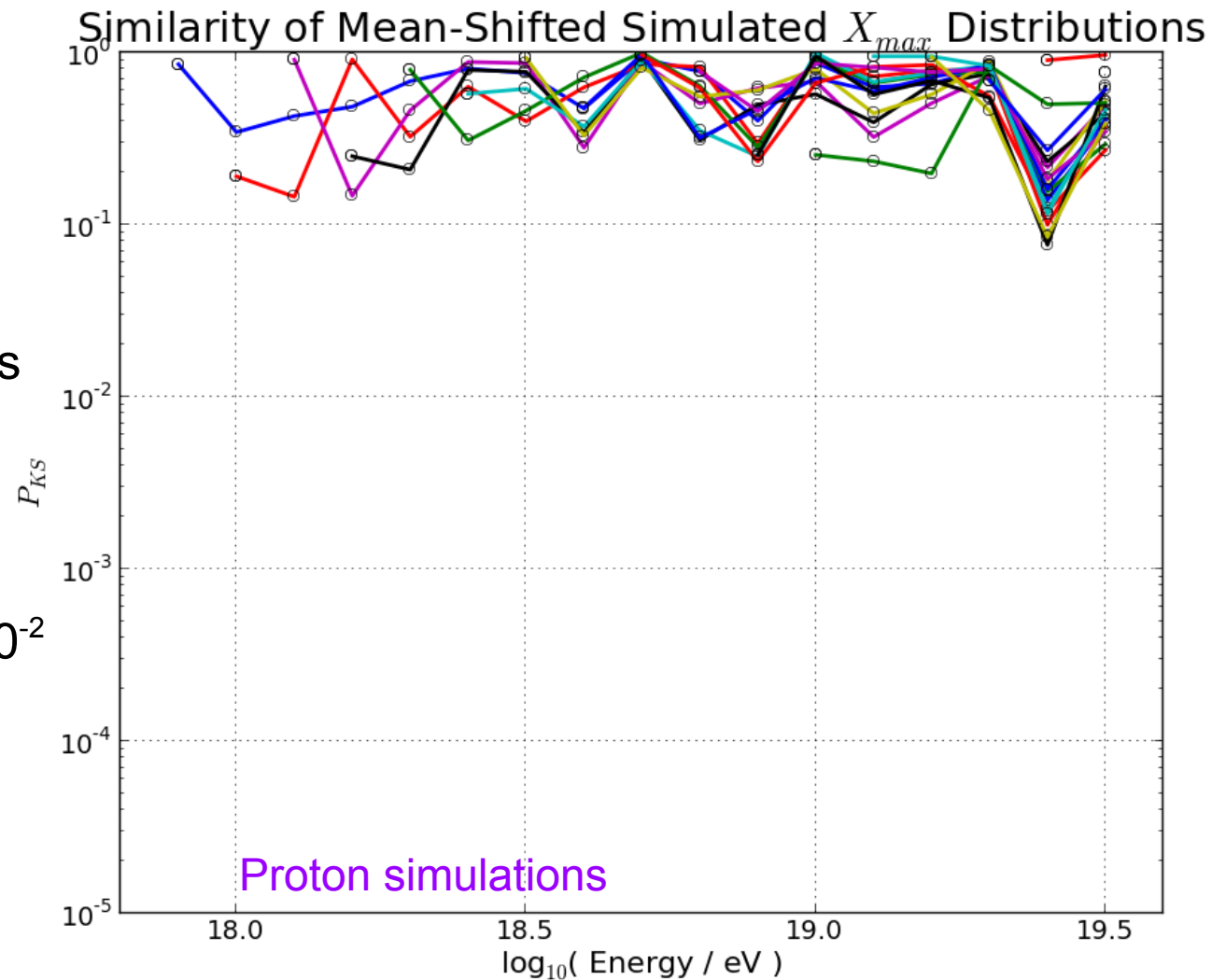


# Simulated $X_{max}$ Distributions – Proton Comparison

- Calculate  $P_{KS}$  for each energy bin compared to every higher energy bin

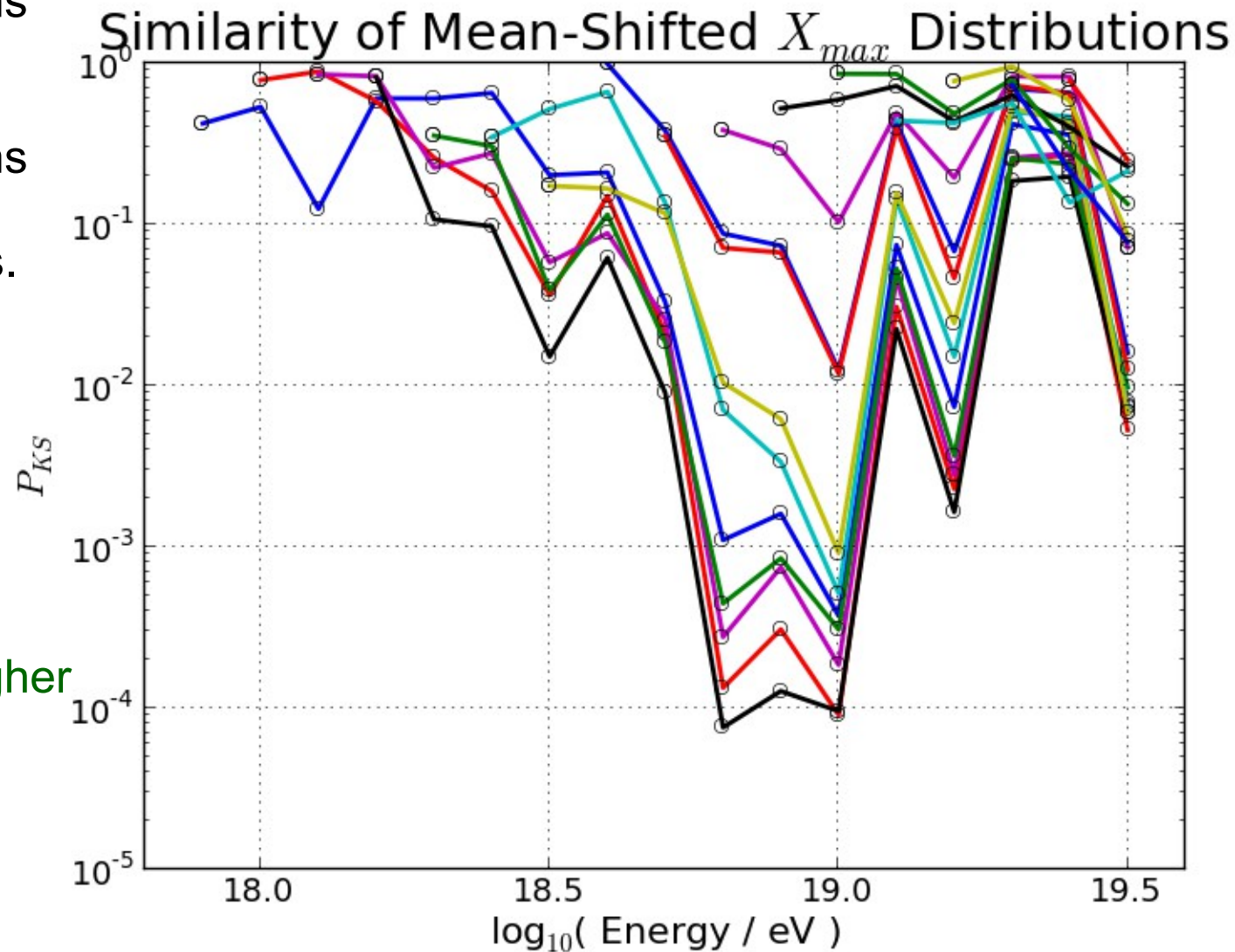
- For a pure composition  $X_{max}$  distributions appear similar at different energies

- No simulation has  $P_{KS} < 10^{-2}$



# Data $X_{max}$ Distributions – Comparison

- Lower energy distributions appear to be similar
- Lower energy distributions appear dissimilar to intermediate energy dists.
- Intermediate and high energy distributions appear similar to themselves
- “Smooth” transition to higher  $P_{KS}$  as lower energy threshold increases



# Data $X_{max}$ Distributions – Comparison

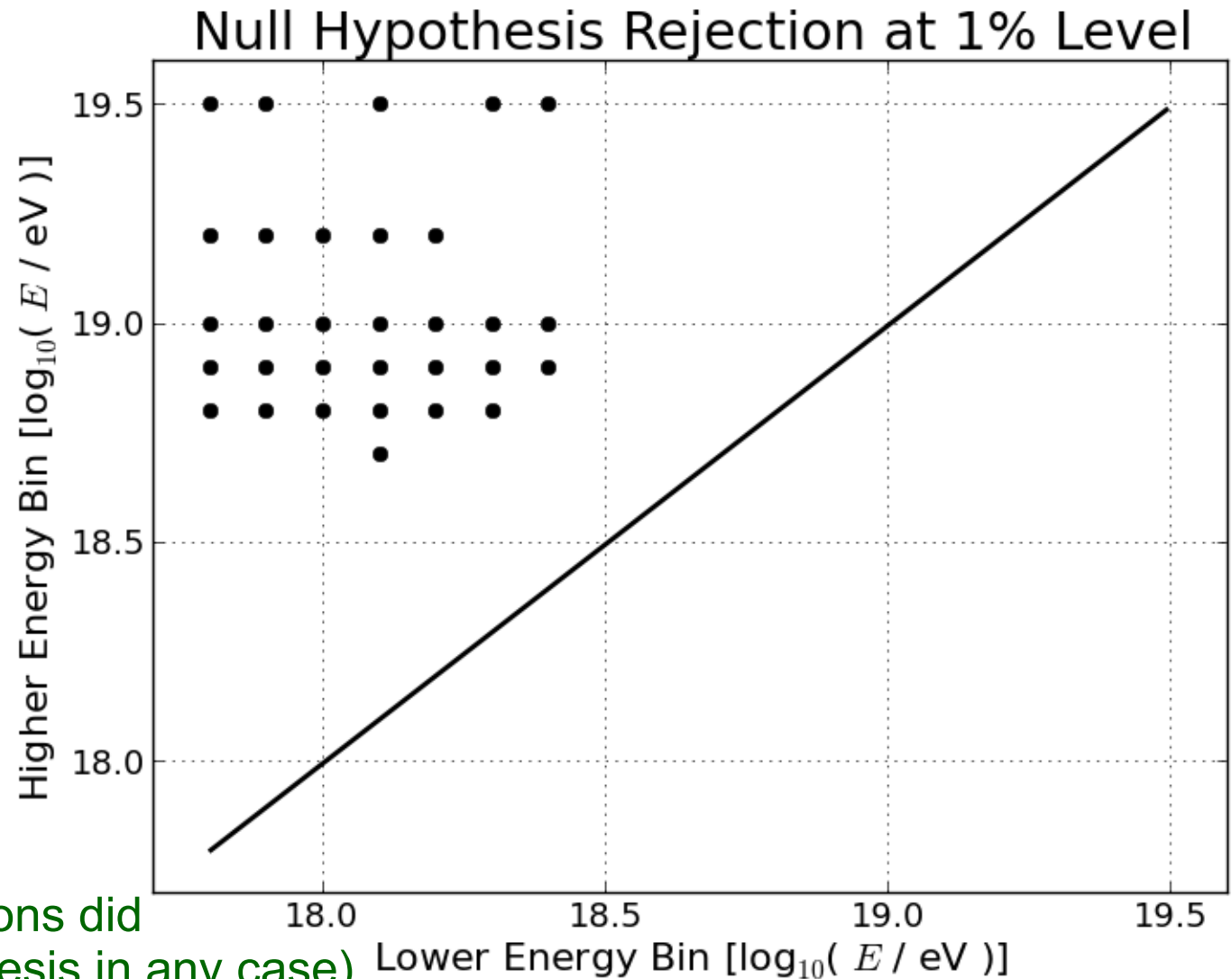
- Reject null hypothesis if

$$D_{n,n'} > c(\alpha) \sqrt{\frac{n+n'}{nn'}}$$

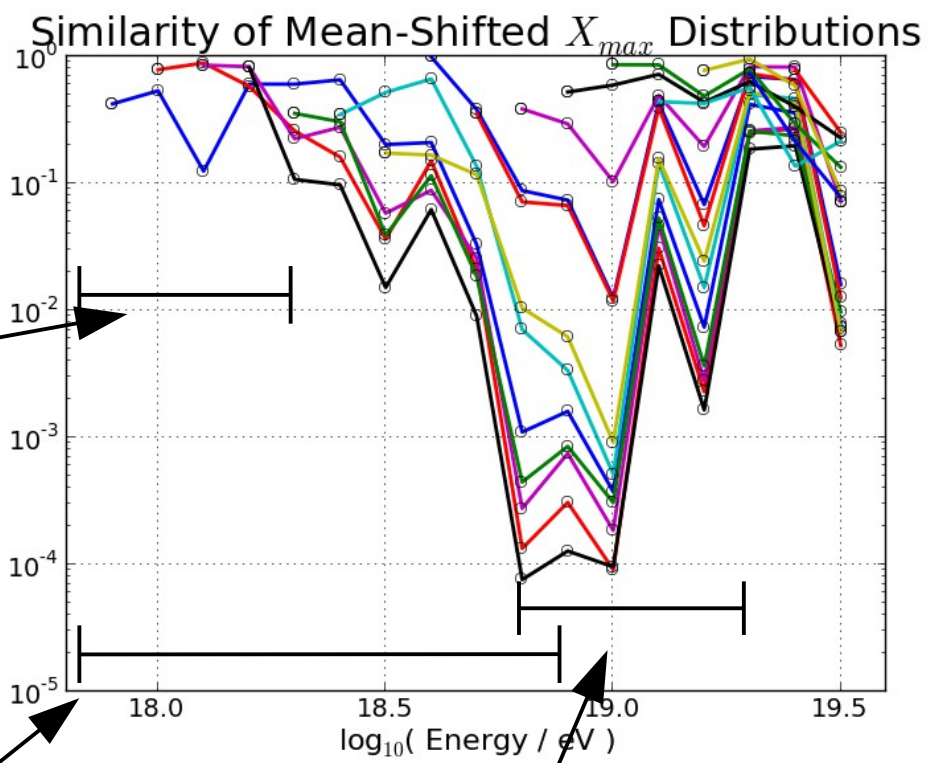
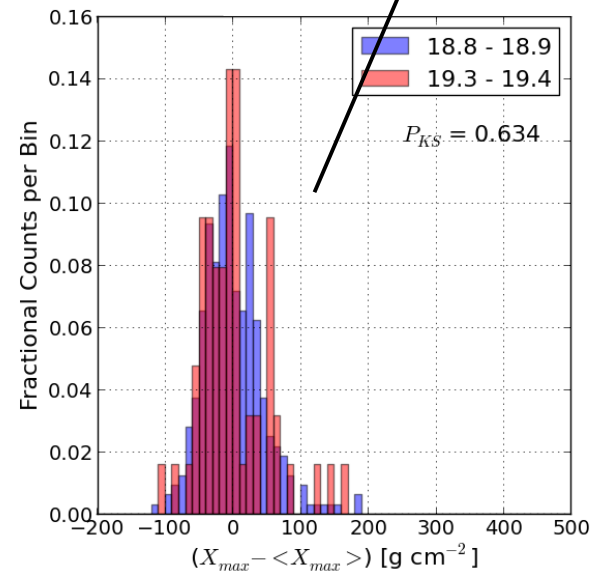
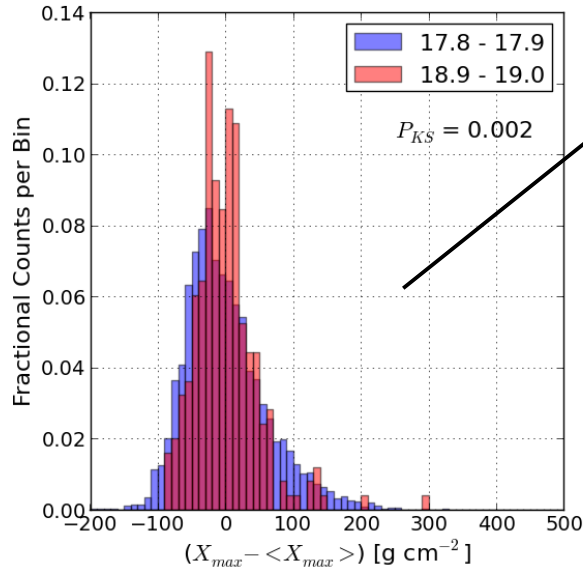
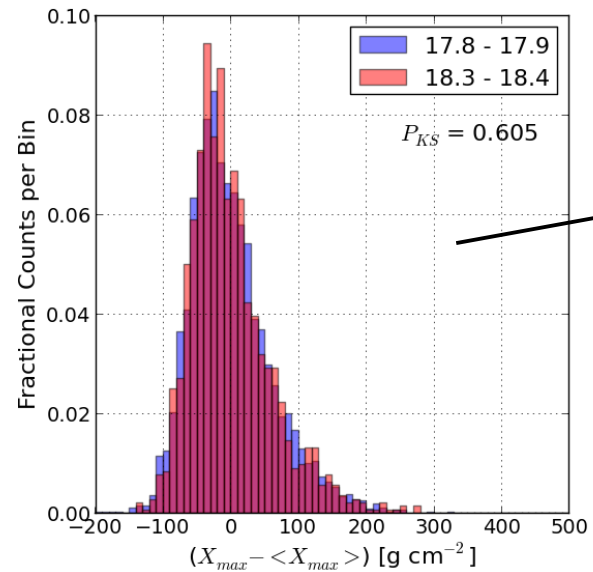
$\alpha$	$c(\alpha)$
.1	1.22
.05	1.36
.025	1.48
<b>.01</b>	<b>1.63</b>
.005	1.73
.001	1.95

(same as reading  $P_{KS}$ )

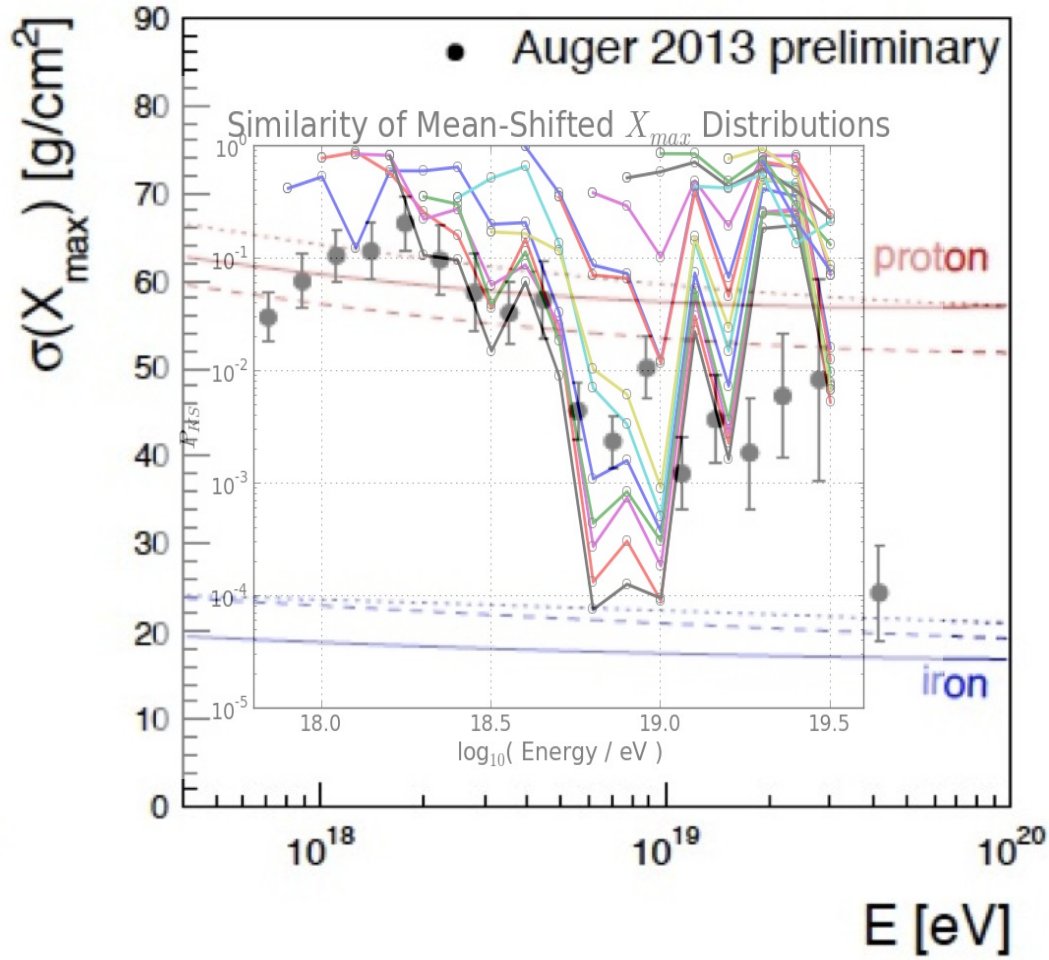
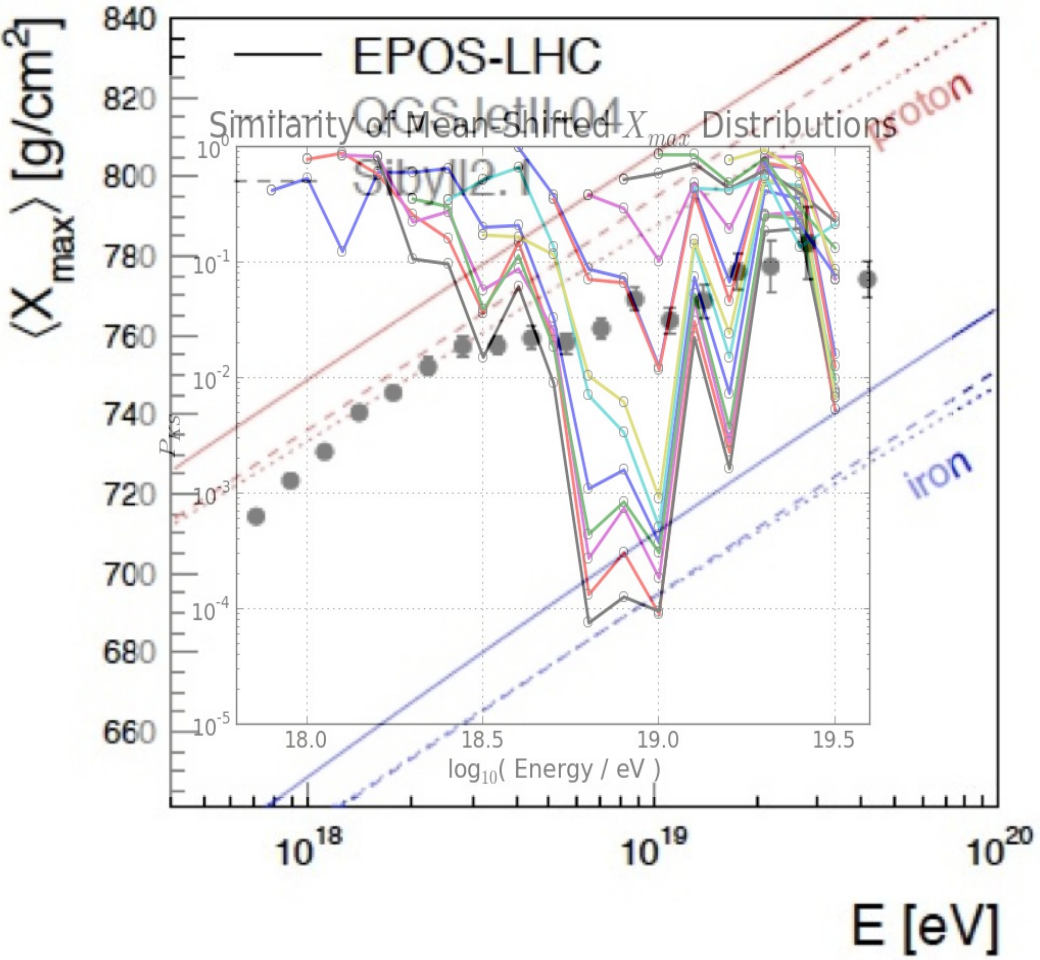
(proton and iron simulations did not reject the null hypothesis in any case)



# Data $X_{max}$ Distributions – Comparison



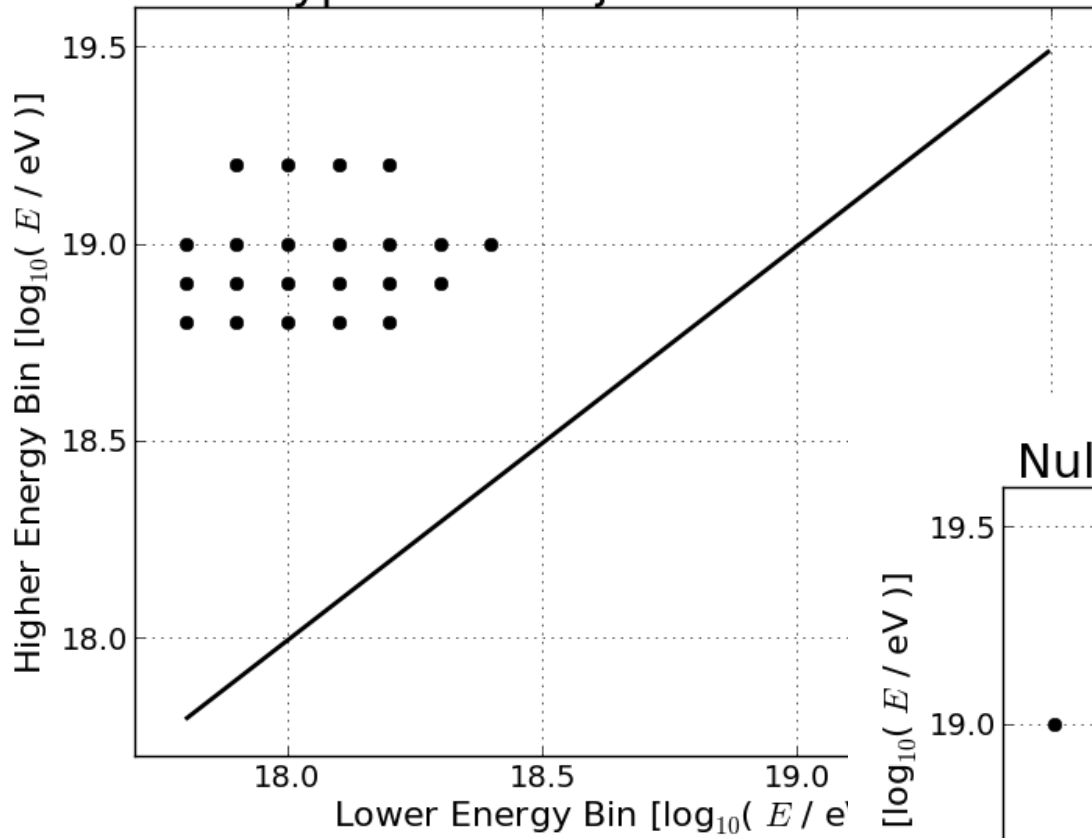
# Data $X_{max}$ Distributions – Comparison



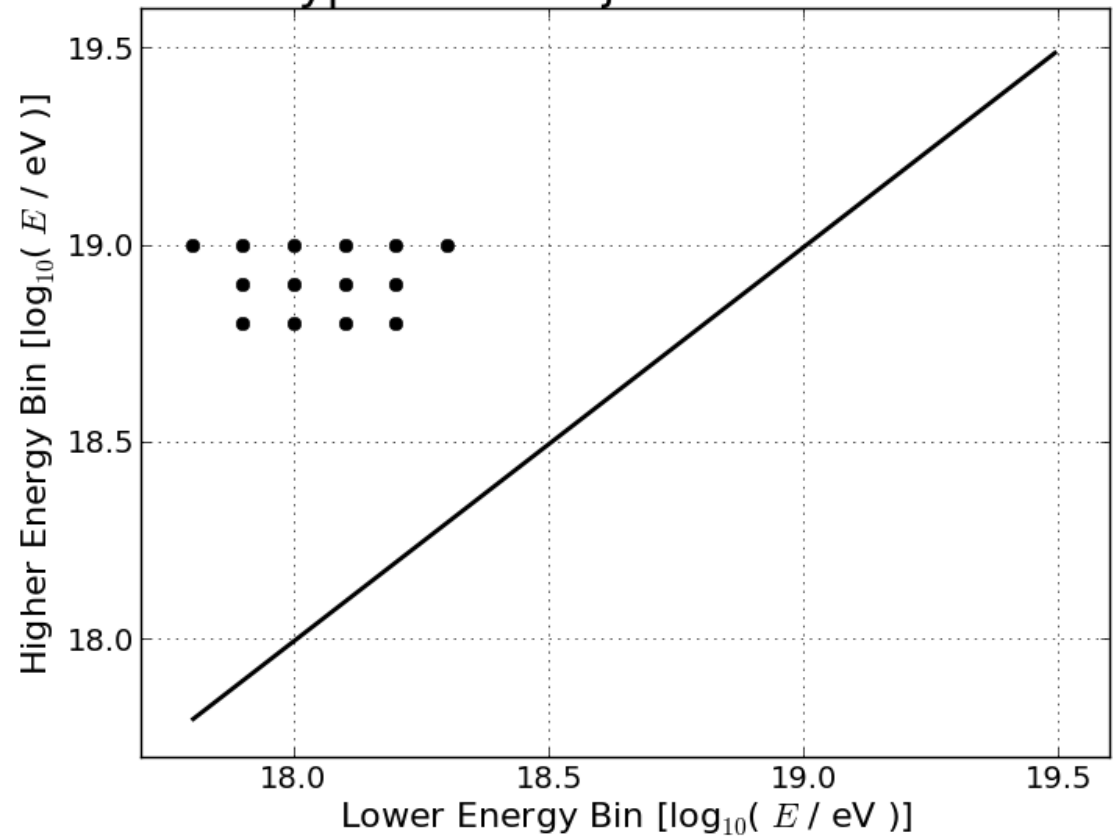
# Conclusions

- $X_{max}$  distribution shape is (statistically significantly) different between lower ( $<10^{18.5}$  eV) and intermediate ( $10^{18.5}$ - $10^{19.0}$  eV) energy bins
- Difference appears to be driven largely by a difference in the distributions' rms
- This is consistent with the energy scale where the  $X_{max}$  mean/rms analysis “observes a transition”, as expected
- Simulations indicate shape differences across energies for pure composition are unlikely

### Null Hypothesis Rejection at 0.5% Level



### Null Hypothesis Rejection at 0.1% Level



# Similarity of Mean-Shifted $X_{max}$ Distributions

