RESULTS FROM TELESCOPE ARRAY AND TALE

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University of Utah
Composition 2015
21 September 2015

TA Experiment

RU Abbasi[1], M Abe[13], T Abu-Zayyad[1], M Allen[1], R Anderson[1], R Azuma[2], E Barcikowski[1], JW Belz[1], DR Bergman[1], SA Blake[1], R Cady[1], MJ Chae[3], BG Cheon[4], J Chiba[5], M Chikawa[6], WR Cho[7], T Fujii[8], M Fukushima[8,9], T Goto[10], W Hanlon[1], Y Hayashi[10], N Hayashida[11], K Hibino[11], K Honda[12], D Ikeda[8], N Inoue[13], T Ishii[12], R Ishimori[2], H Ito[14], D Ivanov[1], CCH Jui[1], K Kadota[16], F Kakimoto[2], O Kalashev[17], K Kasahara[18], H Kawai[19], S Kawakami[10], S Kawana[13], K Kawata[8], E Kido[8], HB Kim[4], JH Kim[1], JH Kim[25], S Kitamura[2], Y Kitamura[2], V Kuzmin[17], YJ Kwon[7], J Lan[1], SI Lim[3], JP Lundquist[1], K Machida[12], K Martens[9], T Matsuda[20], T Matsuyama[10], JN Matthews[1], M Minamino[10], K Mukai[12], I Myers[1], K Nagasawa[13], S Nagataki[14],T Nakamura[21], T Nonaka[8], A Nozato[6], S Ogio[10], J Ogura[2], M Ohnishi[8], H Ohoka[8], K Oki[8], T Okuda[22], M Ono[14], A Oshima[10], S Ozawa[18], IH Park[23], MS Pshirkov[24], DC Rodriguez[1], G Rubtsov[17], D Ryu[25], H Sagawa[8], N Sakurai[10], AL Sampson[1], LM Scott[15], PD Shah[1], F Shibata[12], T Shibata[8], H Shimodaira[8], BK Shin[4], HS Shin[8], JD Smith[1], P Sokolsky[1], RW Springer[1], BT Stokes[1], SR Stratton[1,15], TA Stroman[1], T Suzawa[13], M Takamura[5], M Takeda[8], R Takeishi[8], A Taketa[26], M Takita[8], Y Tameda[11], H Tanaka[10], K Tanaka[27], M Tanaka[20], SB Thomas[1], GB Thomson[1], P Tinyakov[17,24], I Tkachev[17], H Tokuno[2], T Tomida[28], S Troitsky[17], Y Tsunesada[2], K Tsutsumi[2], Y Uchihori[29], S Udo[11], F Urban[24], G Vasiloff[1], T Wong[1], R Yamane[10], H Yamaoka[20], K Yamazaki[10], J Yang[3], K Yashiro[5], Y Yoneda[10], S Yoshida[19], H Yoshii[30], R Zollinger[1], Z Zundel[1]

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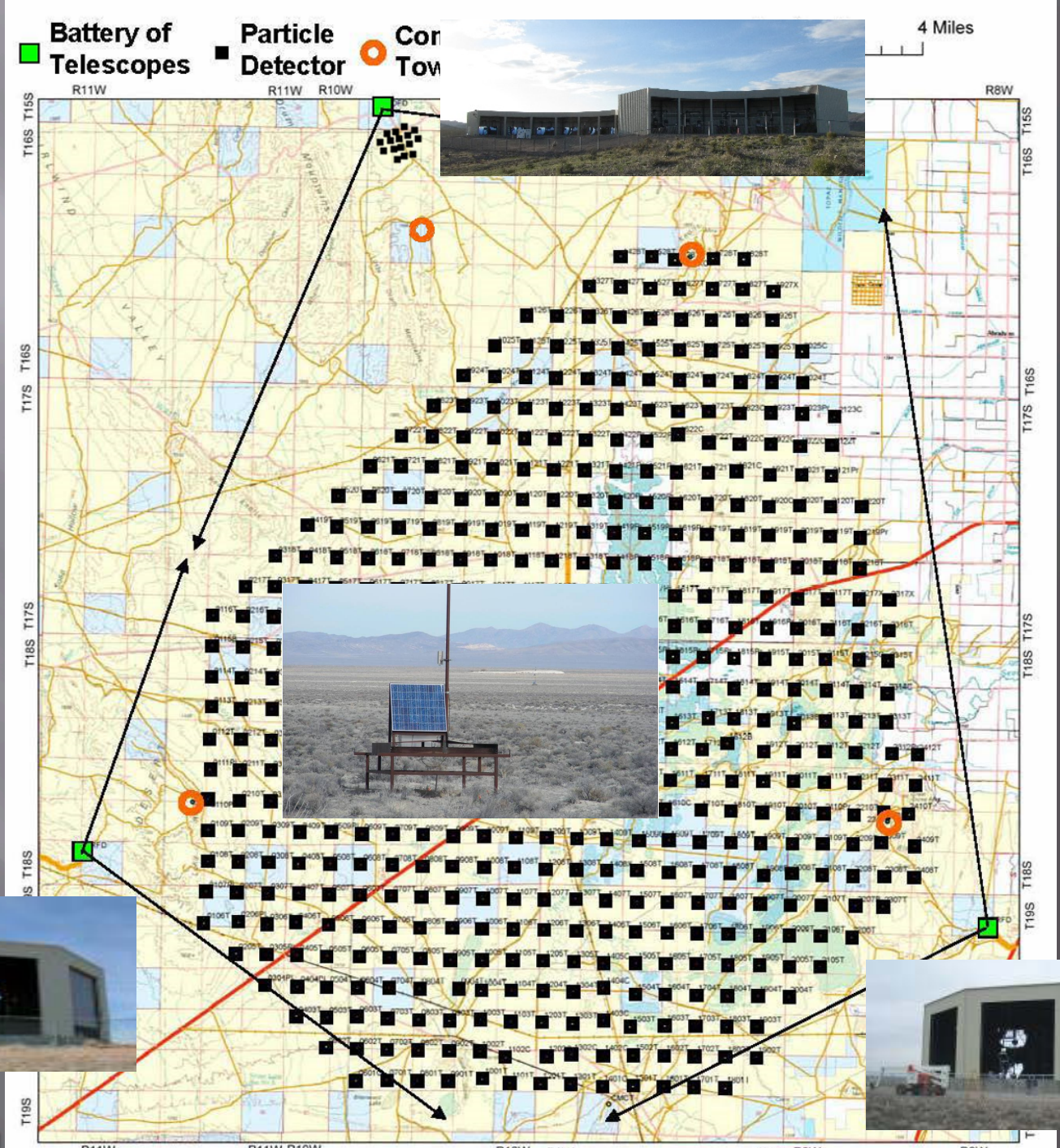
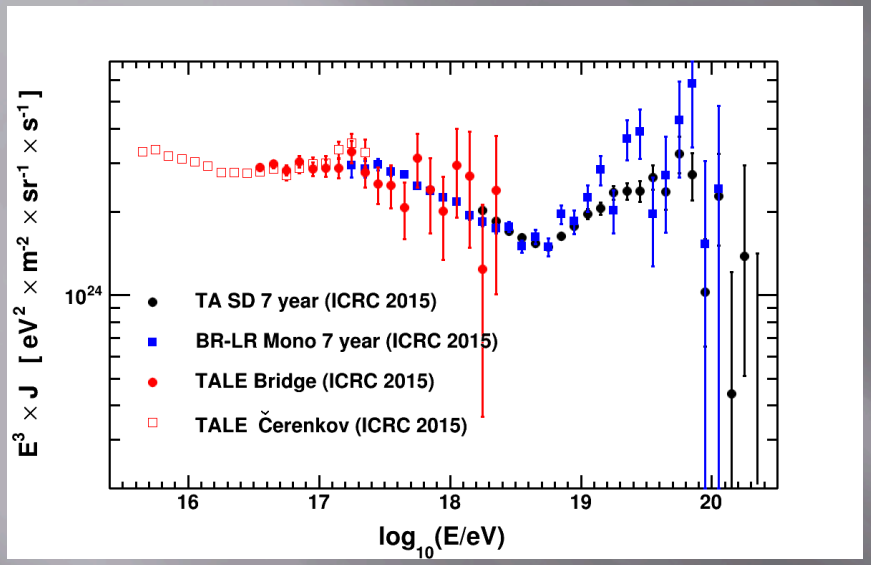
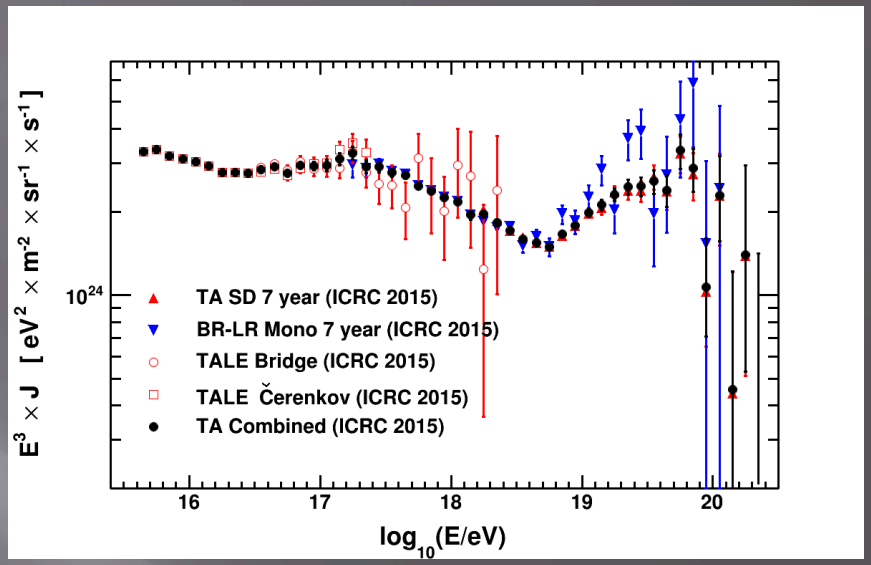
USA, Japan, Korea, Russia, Belgium

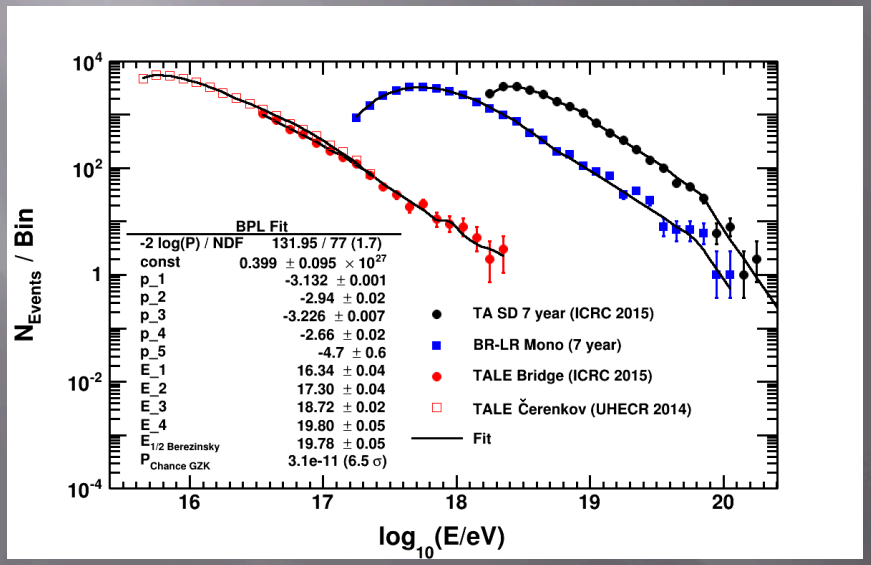
TA & TALE

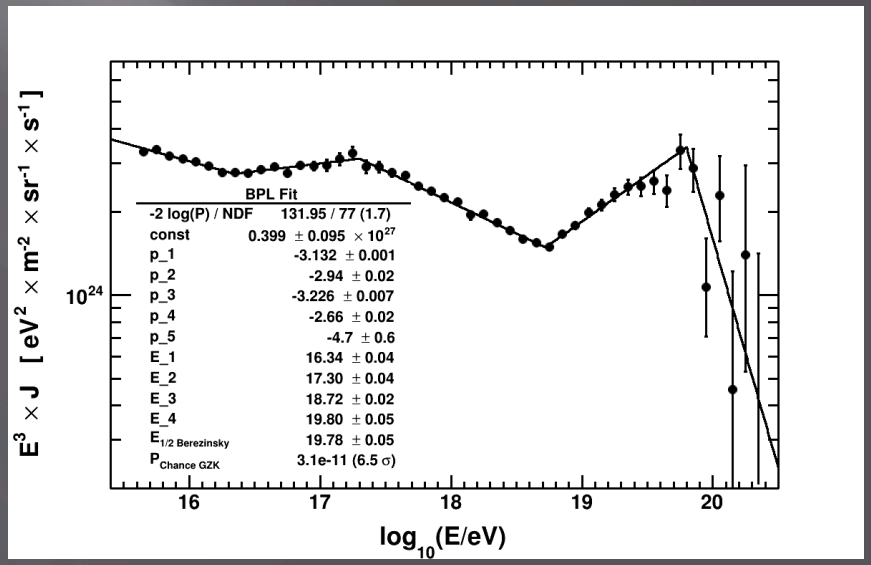

Battery of Telescopes
Particle Detector
4 Miles
R11W
R11W R10W
R8W
T15S
T16S
T17S
T18S
T19S
R11W
R11W R10W
R10W R9W
R9W R8W
R8W

TA/TALE Spectrum

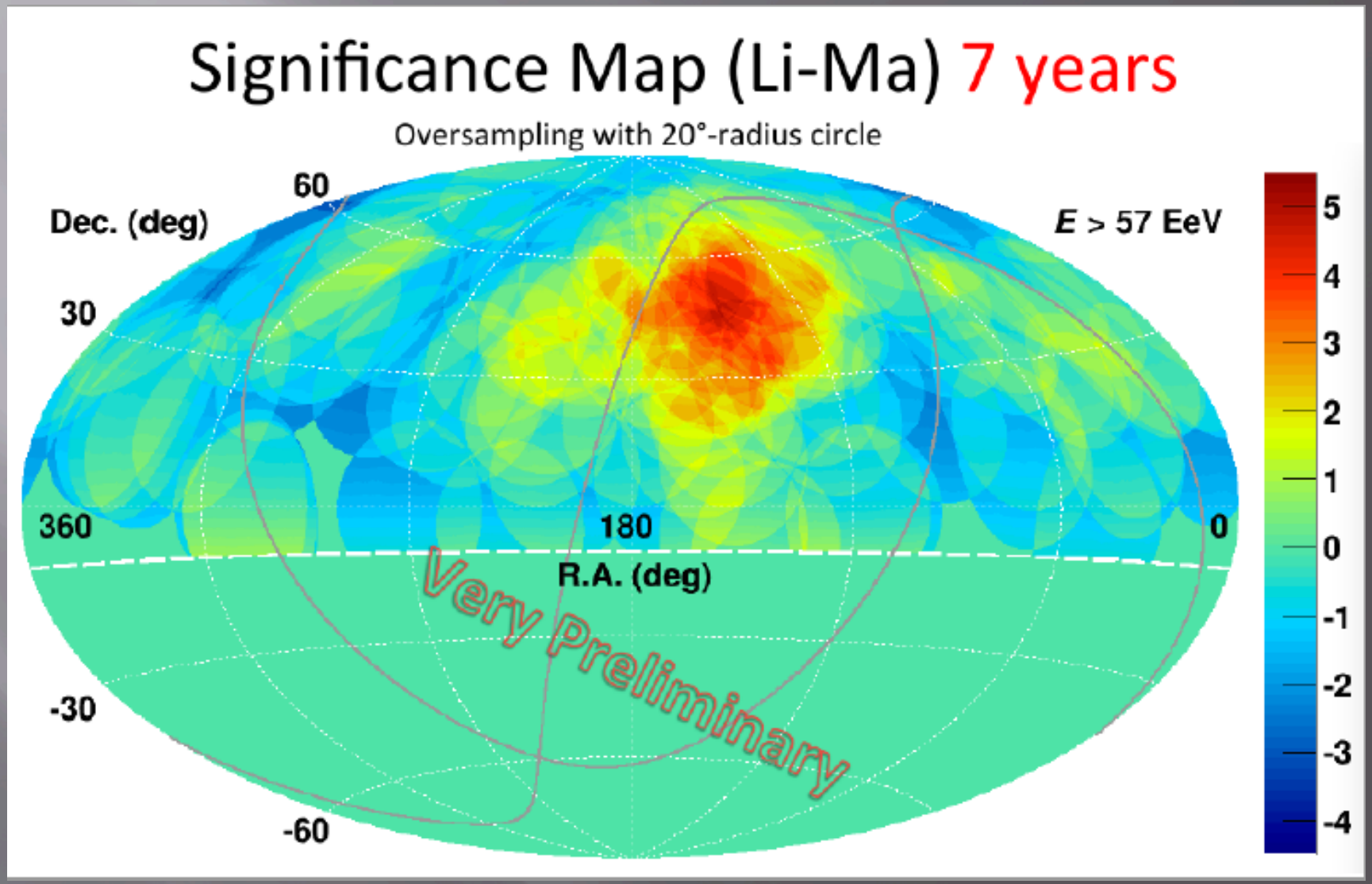






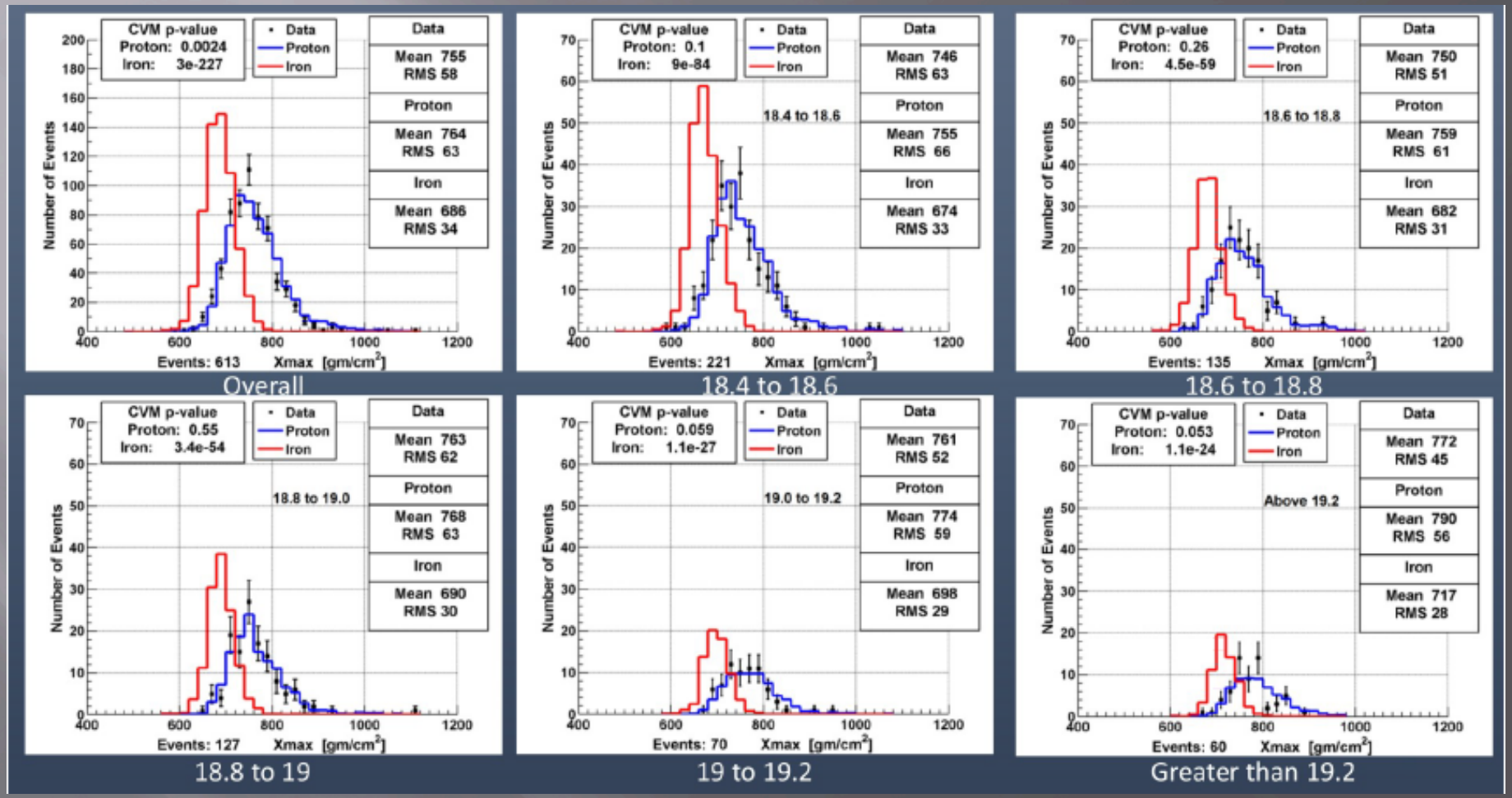


TA Hotspot

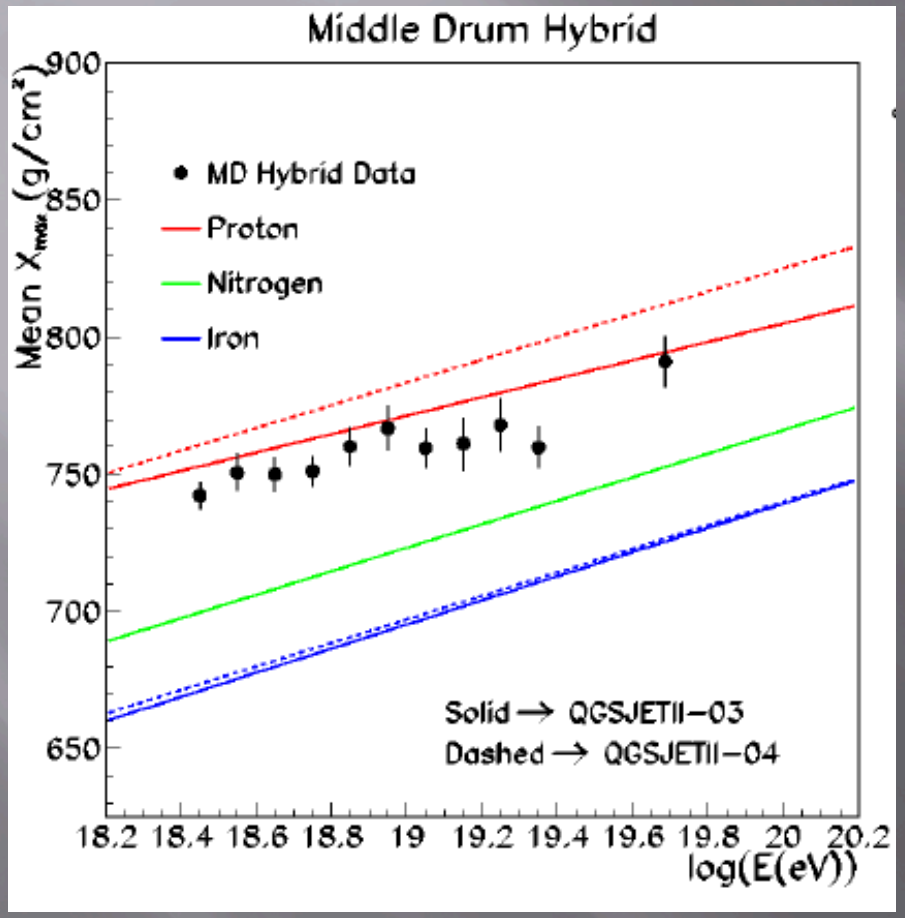

Significance Map (Li-Ma) 7 years
Oversampling with 20°-radius circle
Dec. (deg)
60
30
-30
-60
360
180
0
R.A. (deg)
E > 57 EeV
5
4
3
2
1
0
-1
-2
-3
-4
Very Preliminary

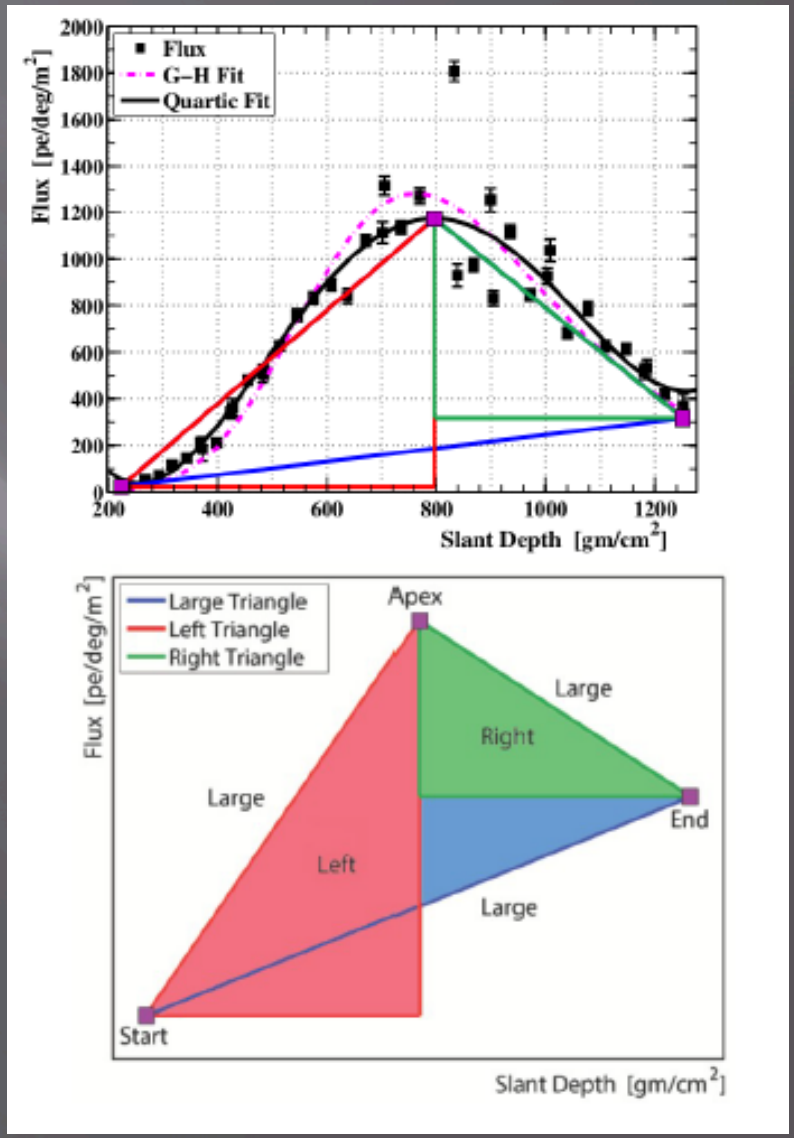
TA/TALE Composition

TA MD Hybrid

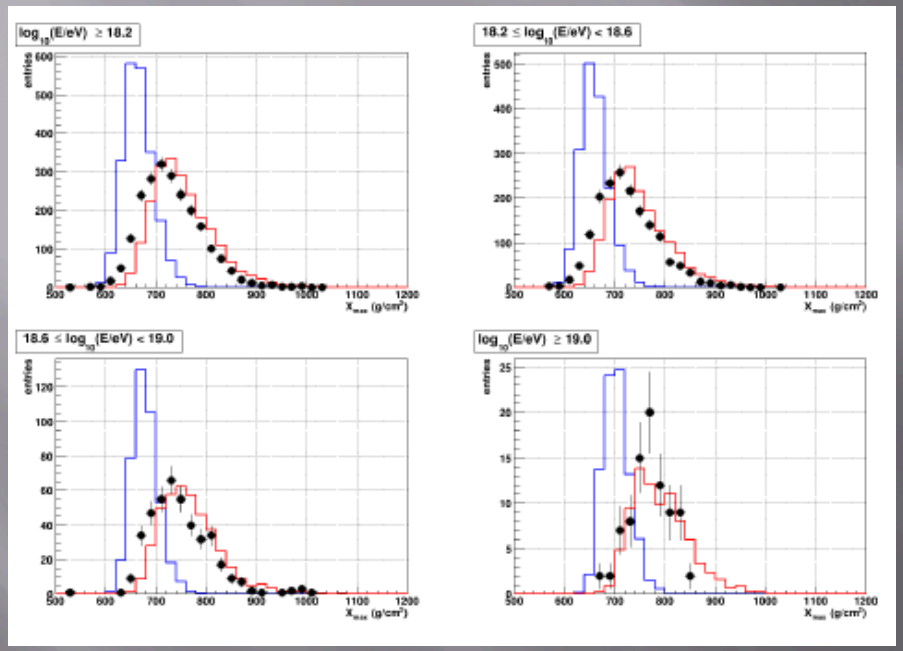

CVM p-value
Proton: 0.0024
Iron: 3e-227
Data
Proton
Iron
Data
Mean 755
RMS 58
Proton
Mean 764
RMS 63
Iron
Mean 686
RMS 34
Number of Events
Events: 613 Xmax [gm/cm²]
Overall
CVM p-value
Proton: 0.1
Iron: 9e-84
18.4 to 18.6
Data
Mean 746
RMS 63
Proton
Mean 755
RMS 66
Iron
Mean 674
RMS 33
Events: 221 Xmax [gm/cm²]
18.4 to 18.6
CVM p-value
Proton: 0.26
Iron: 4.5e-59
18.6 to 18.8
Data
Mean 750
RMS 51
Proton
Mean 759
RMS 61
Iron
Mean 682
RMS 31
Events: 135 Xmax [gm/cm²]
18.6 to 18.8
CVM p-value
Proton: 0.55
Iron: 3.4e-54
18.8 to 19.0
Data
Mean 763
RMS 62
Proton
Mean 768
RMS 63
Iron
Mean 690
RMS 30
Events: 127 Xmax [gm/cm²]
18.8 to 19
CVM p-value
Proton: 0.059
Iron: 1.1e-27
19.0 to 19.2
Data
Mean 761
RMS 52
Proton
Mean 774
RMS 59
Iron
Mean 698
RMS 29
Events: 70 Xmax [gm/cm²]
19 to 19.2
CVM p-value
Proton: 0.053
Iron: 1.1e-24
Above 19.2
Data
Mean 772
RMS 45
Proton
Mean 790
RMS 56
Iron
Mean 717
RMS 28
Events: 60 Xmax [gm/cm²]
Greater than 19.2

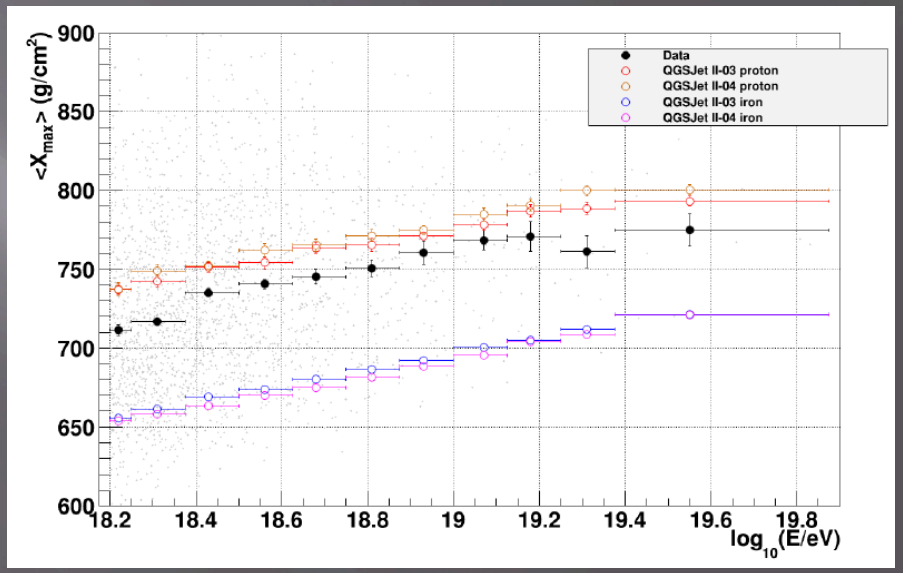
TA MD Hybrid


Middle Drum Hybrid
MD Hybrid Data
Proton
Nitrogen
Iron
Solid → QGSJETII-03
Dashed → QGSJETII-04
Mean X_{max} (g/cm^2)
log(E(eV))

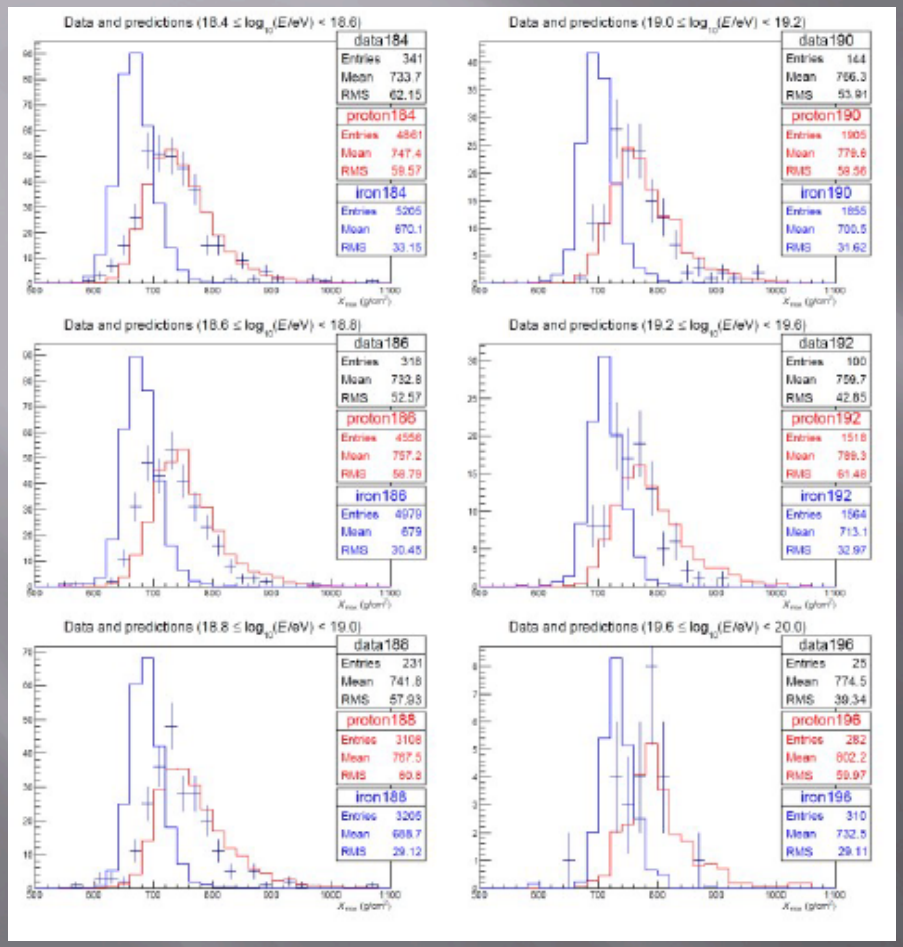

Flux
G-H Fit
Quartic Fit
Flux [pe/deg/m^2]
Slant Depth [gm/cm^2]
Large Triangle
Left Triangle
Right Triangle
Apex
Large
Right
Large
End
Left
Large
Start
Flux [pe/deg/m^2]
Slant Depth [gm/cm^2]

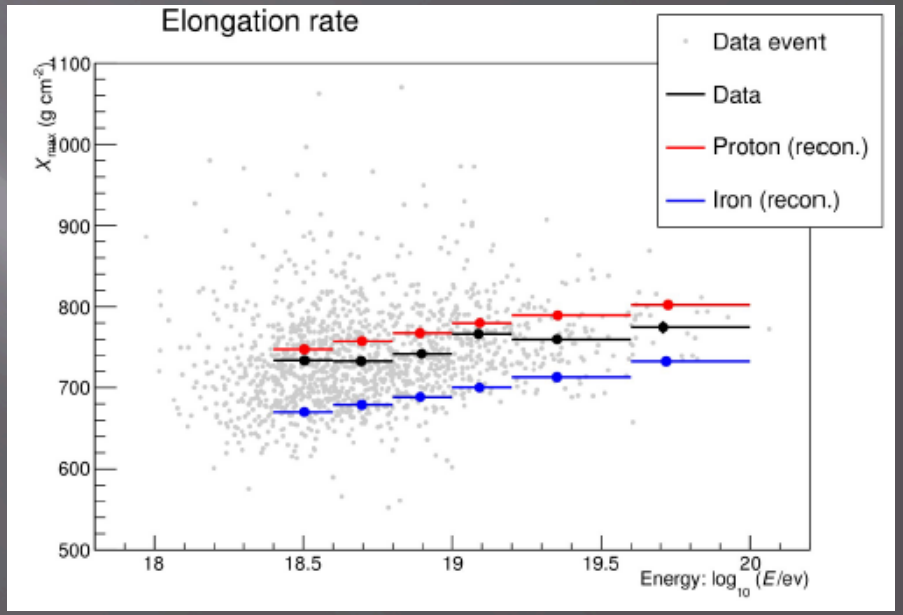
BR/LR Hybrid


log10(E/eV) ≥ 18.2
18.2 ≤ log10(E/eV) < 18.6
18.6 ≤ log10(E/eV) < 19.0
log10(E/eV) ≥ 19.0
entries
Xmax (g/cm2)


Data
QGSJet II-03 proton
QGSJet II-04 proton
QGSJet II-03 iron
QGSJet II-04 iron
<Xmax> (g/cm2)
log10(E/eV)

Stereo


Data and predictions (18.4 ≤ log10(E/eV) < 18.6)
data184
Entries 341
Mean 733.7
RMS 62.15
proton184
Entries 4861
Mean 747.4
RMS 58.57
iron184
Entries 5265
Mean 670.1
RMS 33.15
Data and predictions (19.0 ≤ log10(E/eV) < 19.2)
data190
Entries 144
Mean 756.3
RMS 53.91
proton190
Entries 1905
Mean 779.6
RMS 58.56
iron190
Entries 1855
Mean 700.5
RMS 31.62
Data and predictions (18.6 ≤ log10(E/eV) < 18.8)
data186
Entries 318
Mean 732.8
RMS 52.57
proton186
Entries 4556
Mean 757.2
RMS 58.79
iron186
Entries 4979
Mean 679
RMS 30.45
Data and predictions (19.2 ≤ log10(E/eV) < 19.6)
data192
Entries 100
Mean 759.7
RMS 42.85
proton192
Entries 1518
Mean 789.3
RMS 61.48
iron192
Entries 1564
Mean 713.1
RMS 32.97
Data and predictions (18.8 ≤ log10(E/eV) < 19.0)
data188
Entries 231
Mean 741.8
RMS 57.93
proton188
Entries 3108
Mean 767.5
RMS 60.8
iron188
Entries 3205
Mean 688.7
RMS 29.12
Data and predictions (19.6 ≤ log10(E/eV) < 20.0)
data196
Entries 25
Mean 774.5
RMS 39.34
proton196
Entries 282
Mean 802.2
RMS 59.97
iron196
Entries 310
Mean 732.5
RMS 29.11

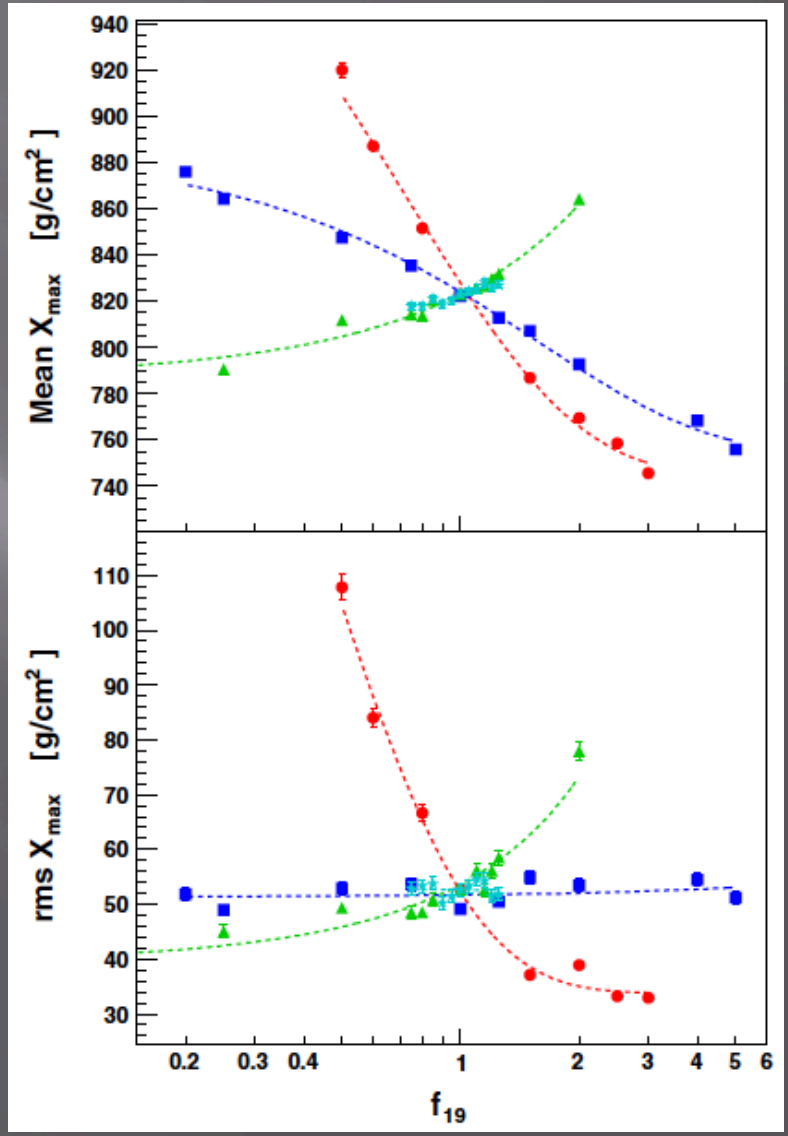

Elongation rate
Data event
Data
Proton (recon.)
Iron (recon.)
X_{max} (g cm^{-2})
Energy: log$_{10}$ (E/ev)

Model Uncertainty

- At UHECR energies, all models are making extrapolations:
  - LHC measurements at 14 TeV constrain primary CR interactions at 100 PeV.
  - Full phase space measurements of p-p collisions only up to 2 TeV (CR @ 2 PeV)
- Even LHC tuned models are extrapolating
- We can estimate how shower distributions depend on p-p interaction distributions

Estimating Uncertainties

- Ulrich, Engel & Unger (PRD 83 054026) measured how EAS distributions in one model (Sybill 2.1) changed when the p-p interaction values were changed.
  - Sybill is just a stand in for all models here
  - I'm just interested in the mean and RMS of the X_{max} distribution



Estimating Uncertainties

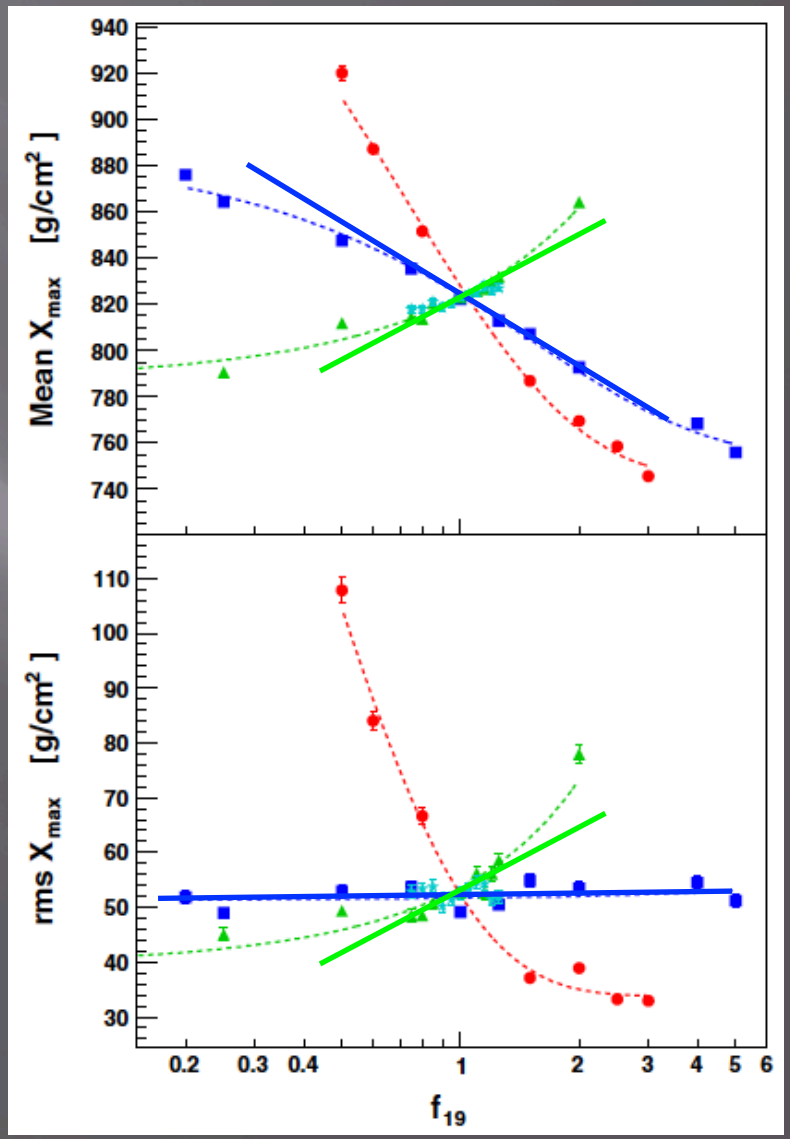
- Measure slopes:

$$\frac{\partial\langle X_{\max}\rangle}{\partial \ln f_{19}(N_{\mathrm{ch}})} = -43\ \mathrm{g/cm^2}$$

$$\frac{\partial\langle X_{\max}\rangle}{\partial \ln f_{19}(K)} = 37\ \mathrm{g/cm^2}$$

$$\frac{\partial \mathrm{RMS}(X_{\max})}{\partial \ln f_{19}(N_{\mathrm{ch}})} = -0.3\ \mathrm{g/cm^2}$$

$$\frac{\partial \mathrm{RMS}(X_{\max})}{\partial \ln f_{19}(K)} = 16\ \mathrm{g/cm^2}$$

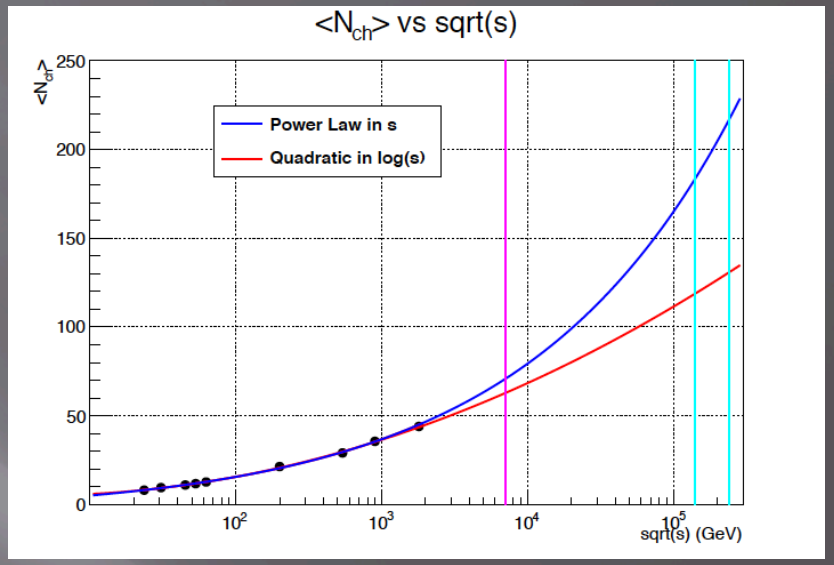


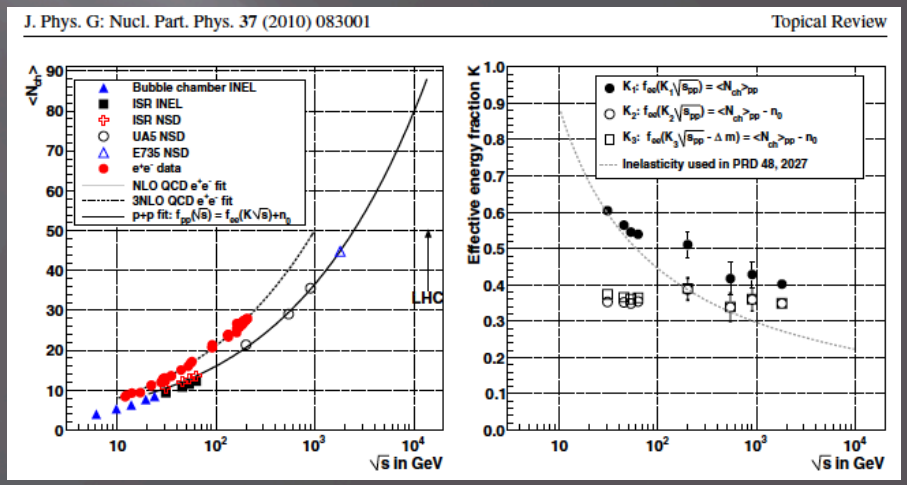
Estimating Uncertainties

- Estimate uncertainty in multiplicity and inelasticity
  - Multiplicity: x2
  - Inelasticity: 10%

$$\delta \ln f_{19}\left(N_{\mathrm{ch}}\right) = \ln 2$$
$$\delta \ln f_{19}\left(K\right) = \ln 1.1$$

- These estimates are probably too *small*





Estimating Uncertainties

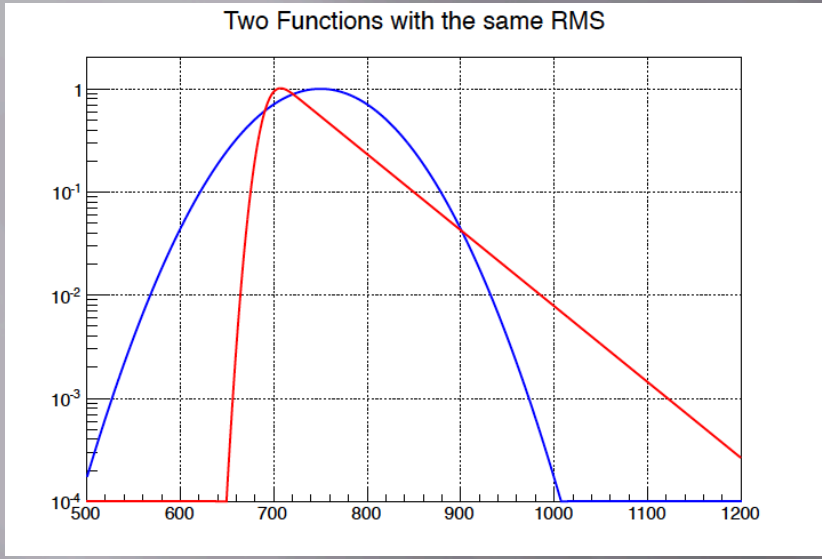
- Propagating errors:

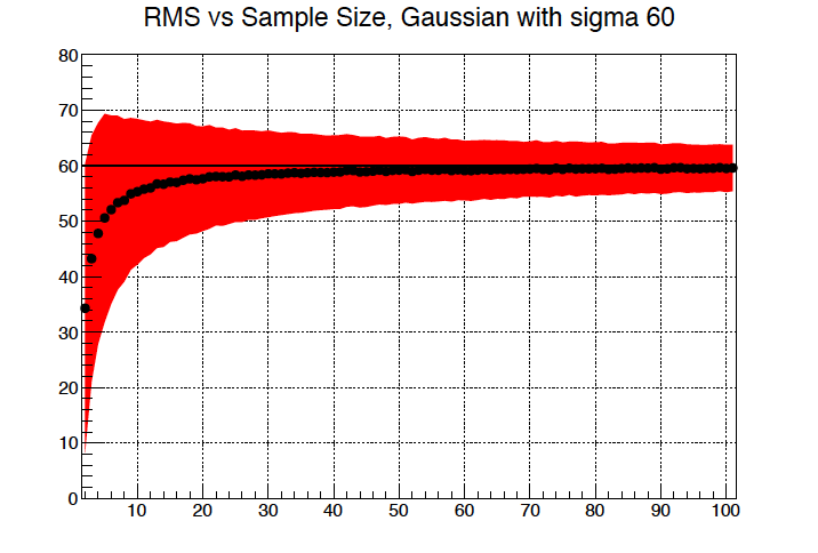
$$\sigma_{<X_{\max}>} = |-43| \times 0.69 + 37 \times 0.10 = 30 + 4 = 34 \text{ g/cm}^2$$

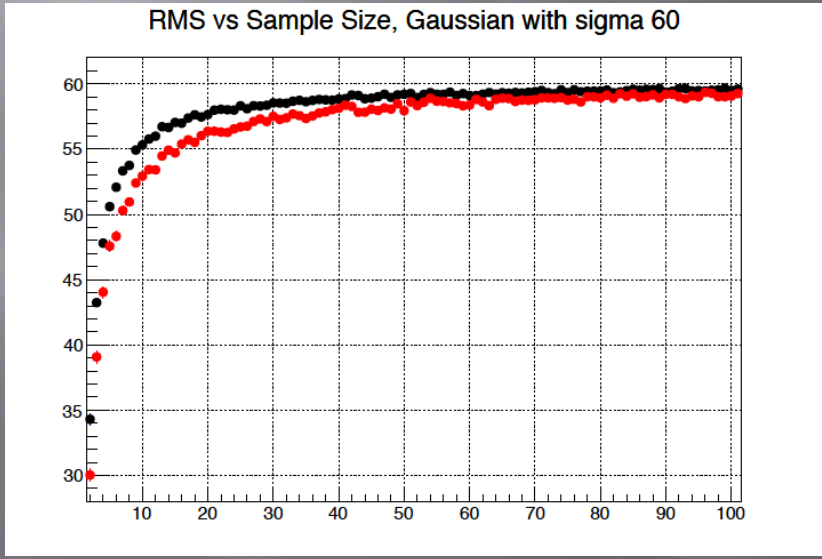
$$\sigma_{\mathrm{RMS}(X_{\max})} = |-0.3| \times 0.69 + 16 \times 0.10 = 0.2 + 1.6 = 1.8 \text{ g/cm}^2$$

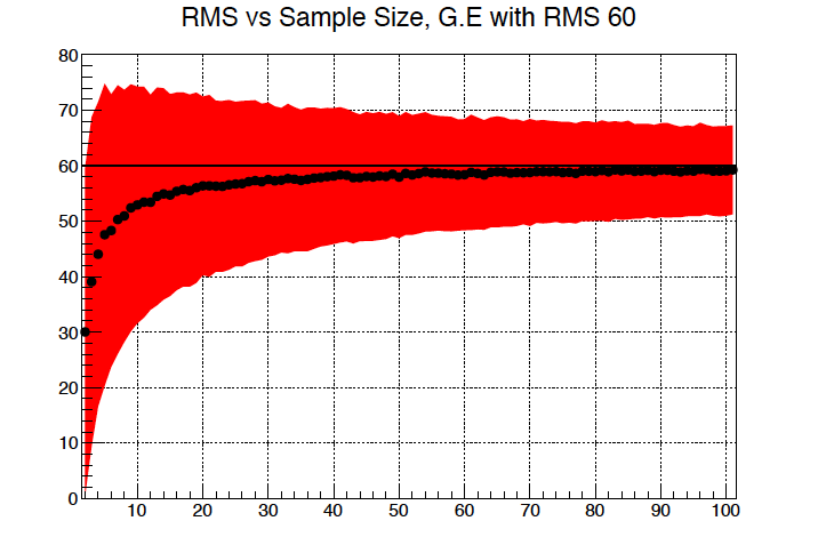
- So the position of the distribution is much more uncertain than the shape.
  - Why not look at the RMS then?
  - The RMS is a bias estimator of width!

RMS: Biased Estimator



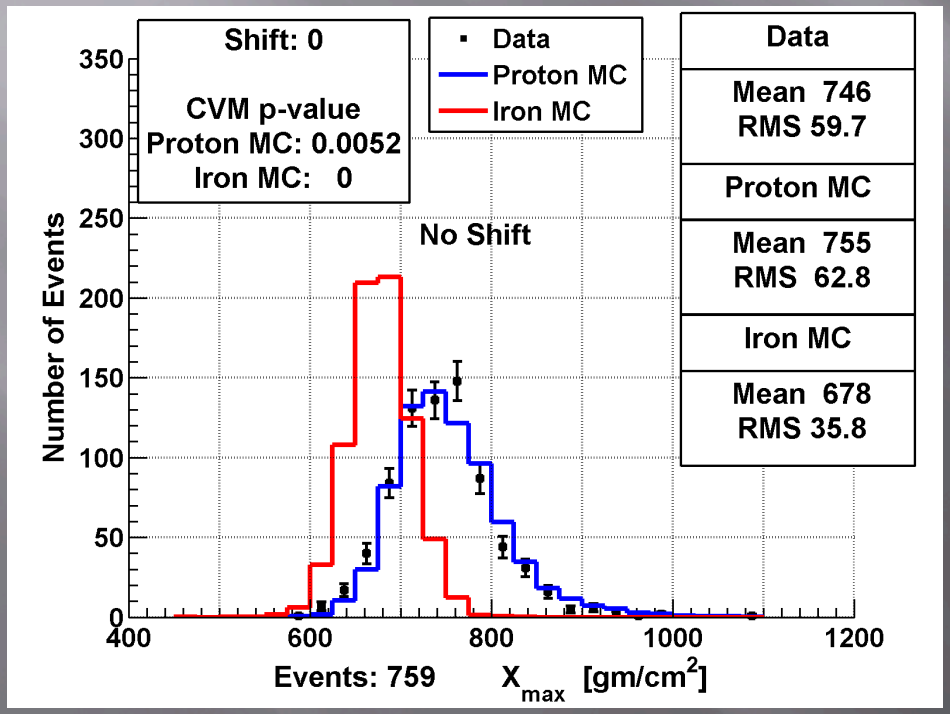


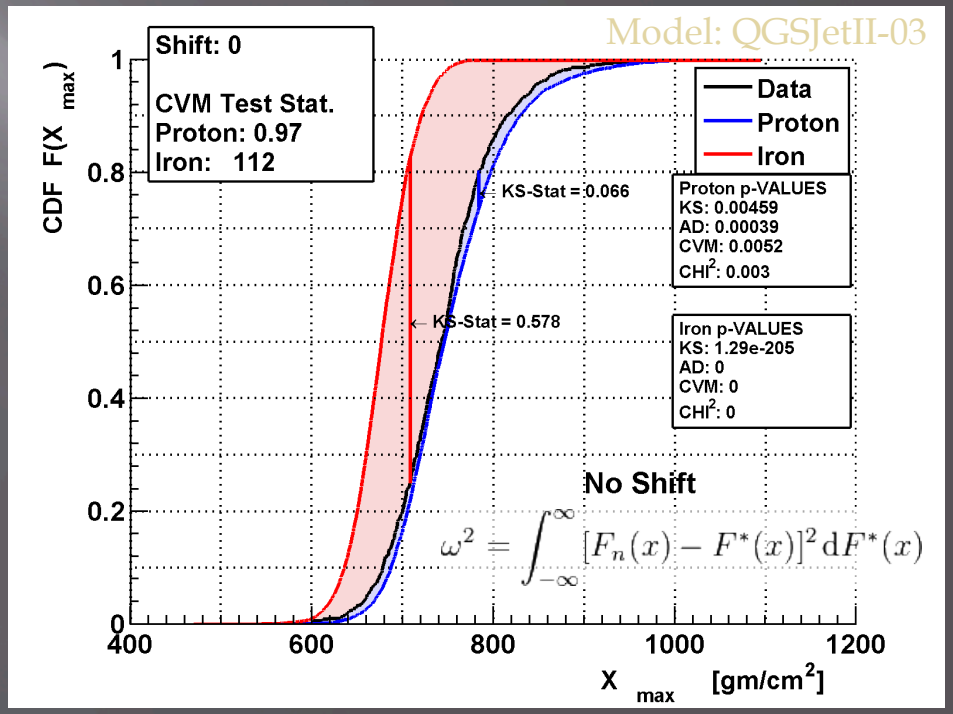




Shift & Quality

- Shift the MC distribution, then see how likely the data and MC come from the same distribution
- KS uses the maximum difference in cumulative distribution
- CvM uses the integral of the difference between the distributions

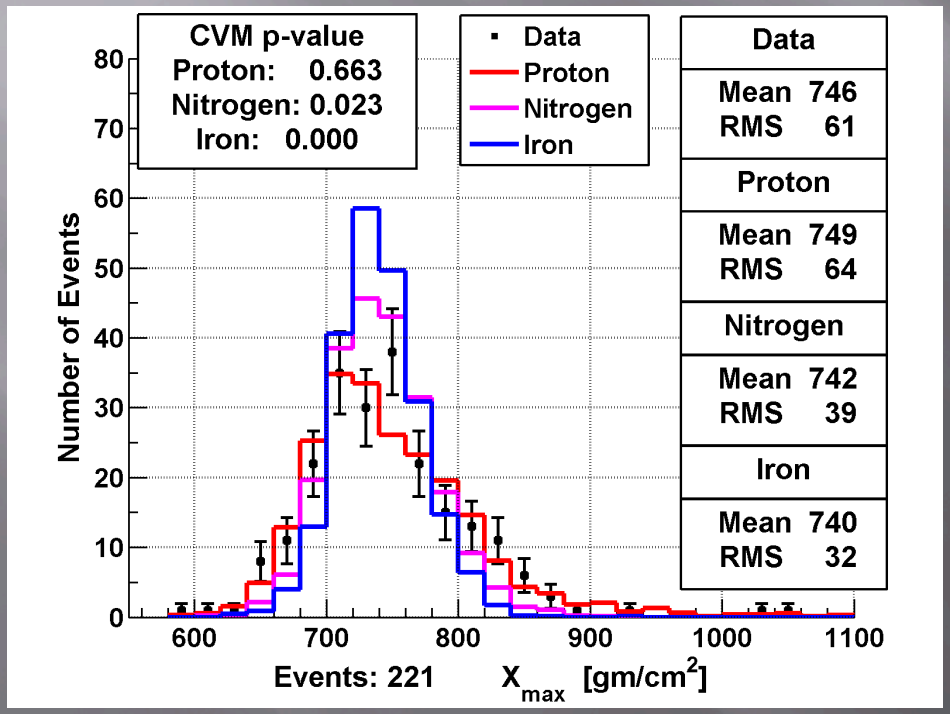




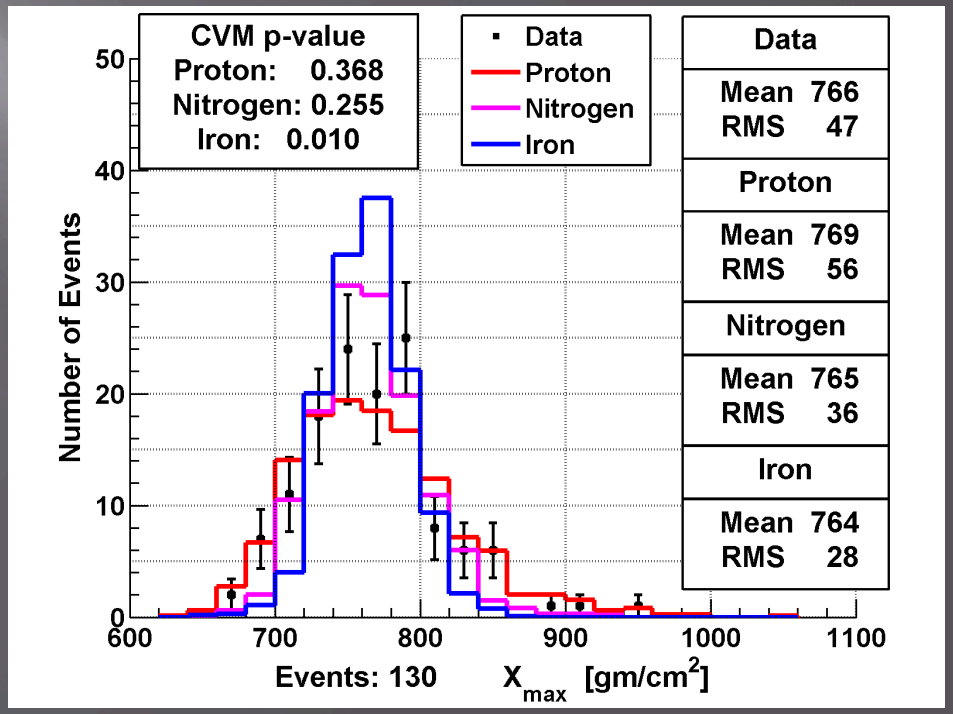
Shift & Quality

- Also have comparisons with Nitrogen
- Compare in energy bins

$18.4 < \log_{10}E < 18.6$



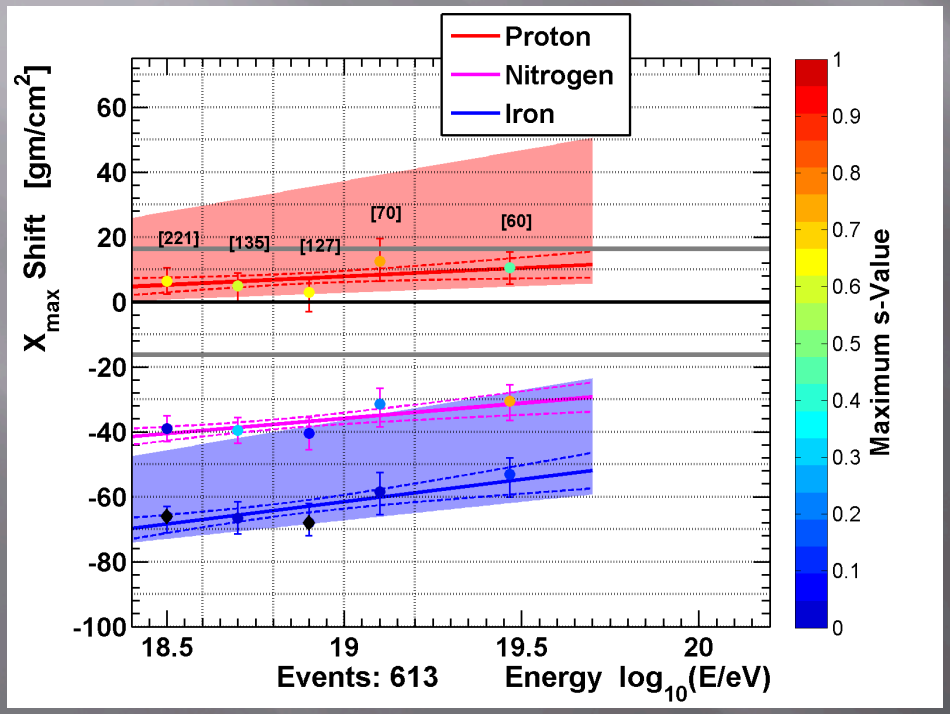
$19.0 < \log_{10}E$

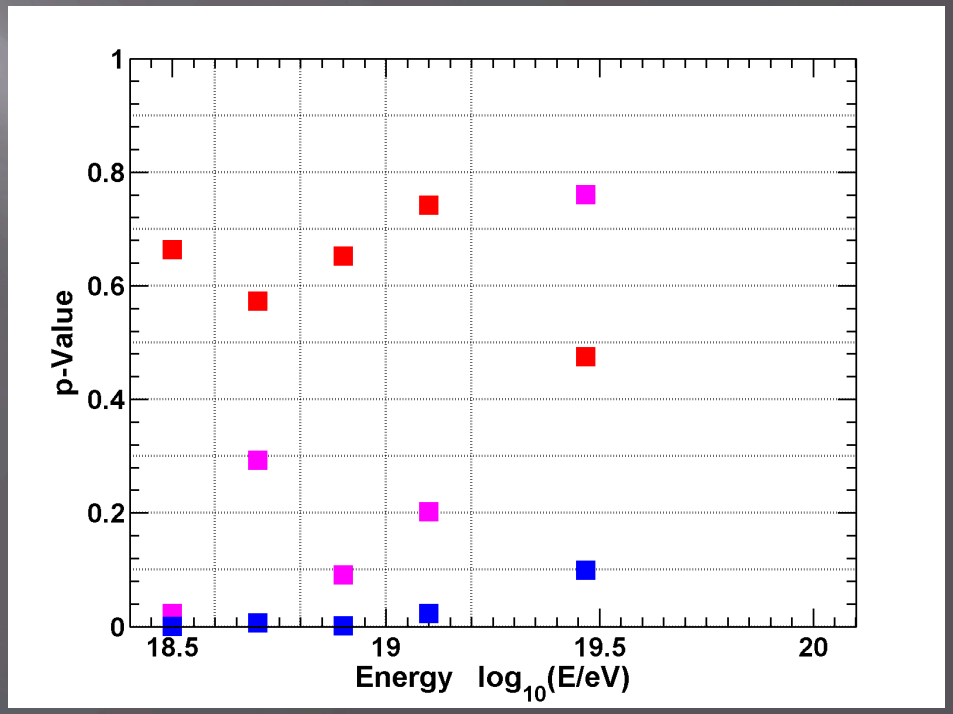


TA MD Composition Result

- The data look like proton
- Nitrogen is disfavored
- Iron is excluded

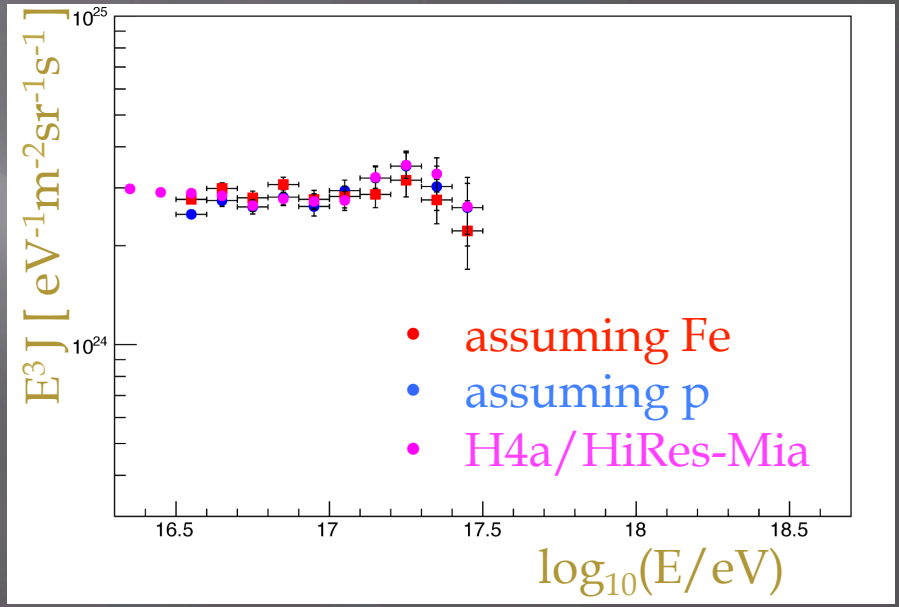
QGSJetII-03





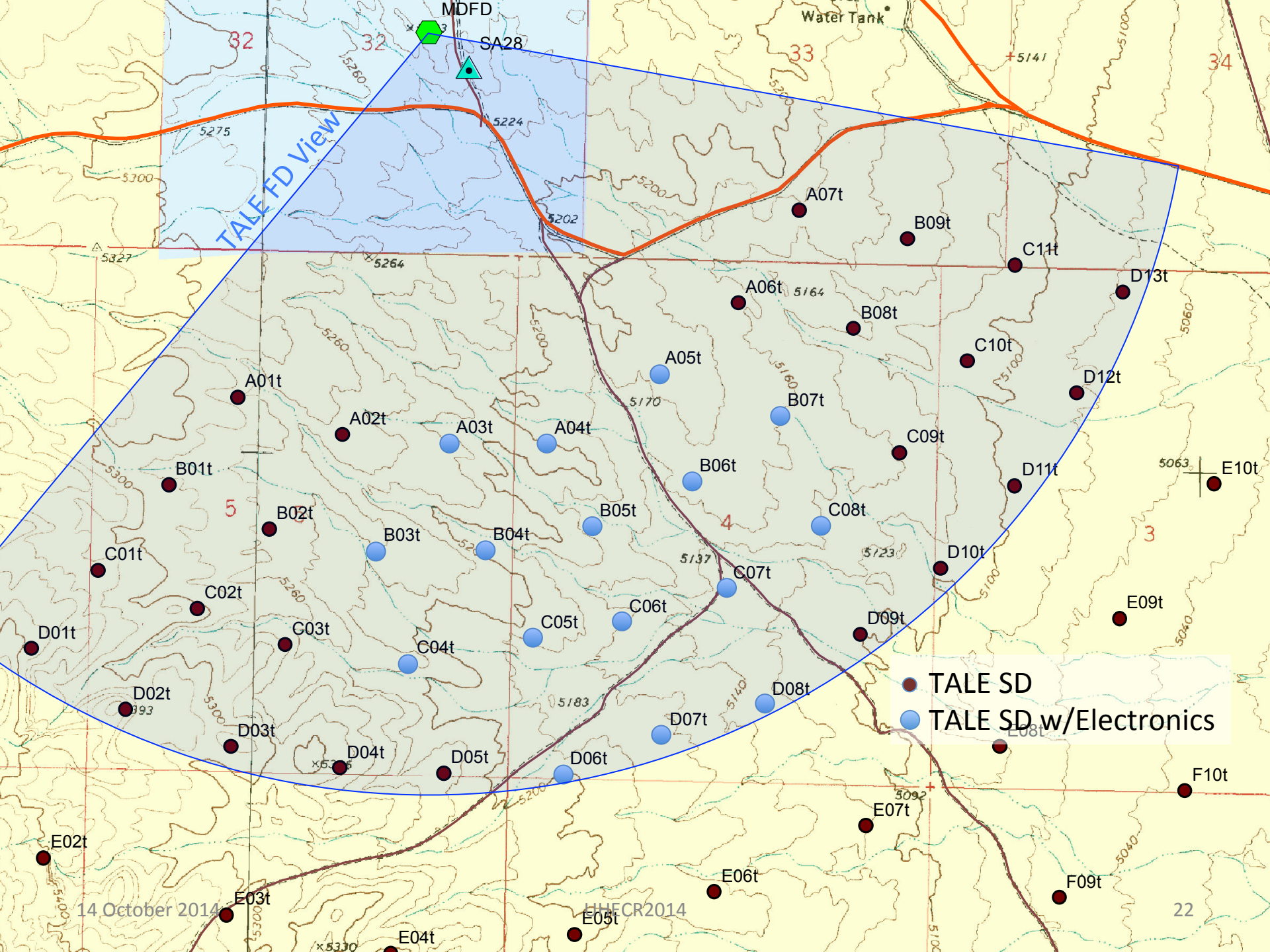
TALE Composition

- Sorry there are no TALE composition measurements yet.
- TALE spectrum measurements are insensitive to composition



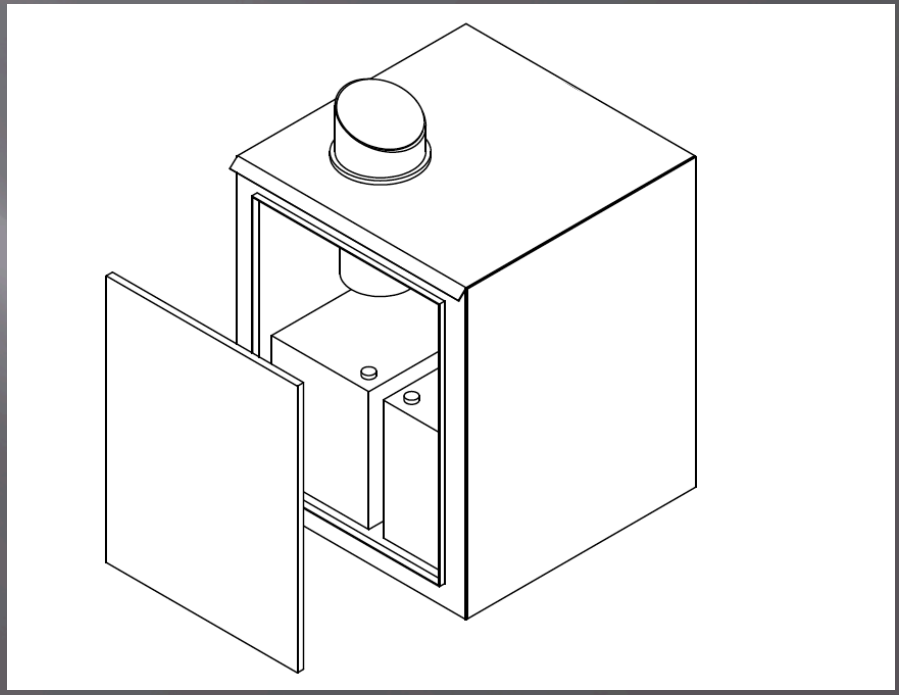
TALE/NICHE Composition

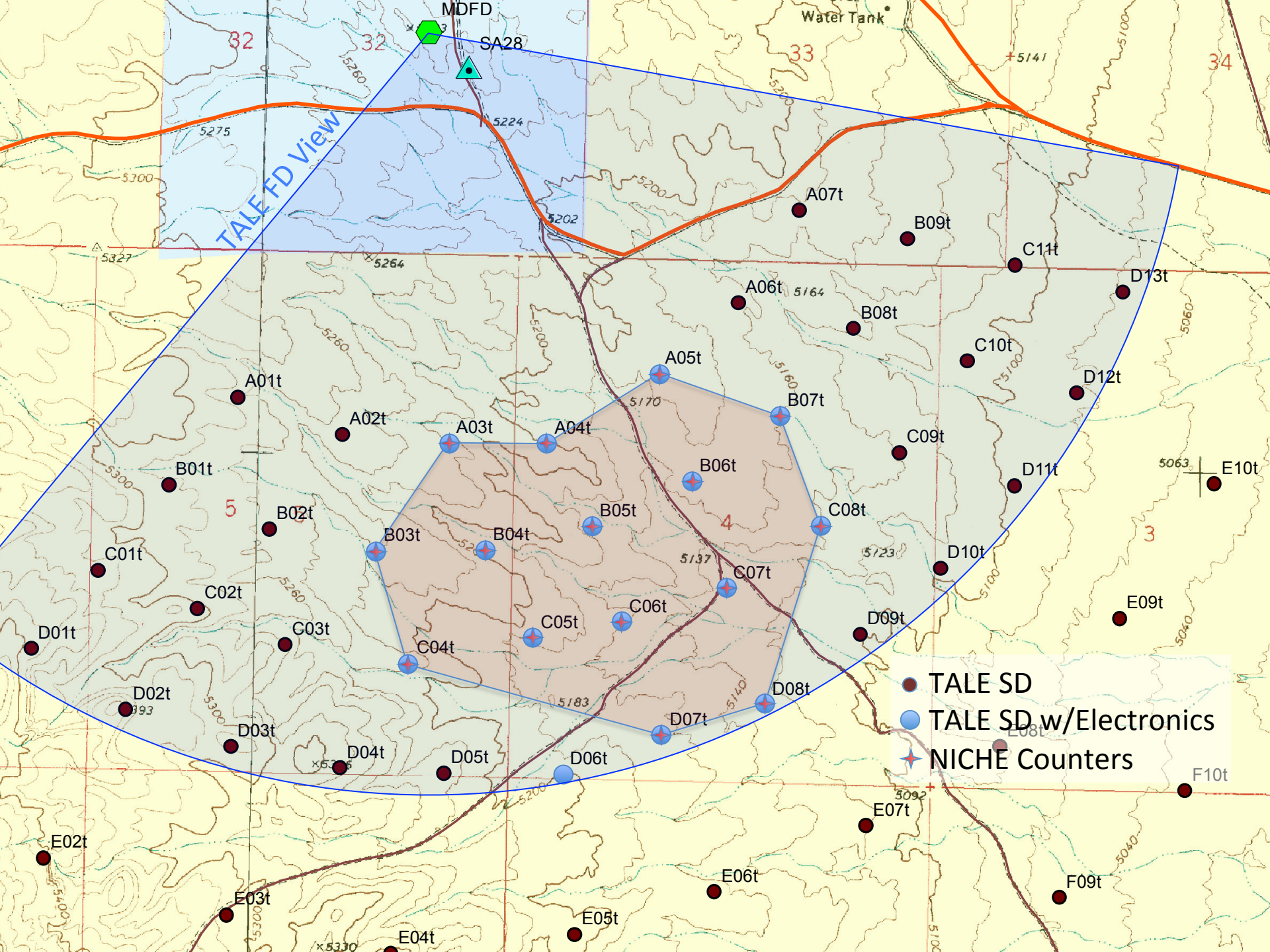
- TALE with in-fill SD array will measure composition down to 30 PeV


MDFD
SA28
TALE FD View
A01t
A02t
A03t
A04t
A05t
A06t
A07t
B01t
B02t
B03t
B04t
B05t
B06t
B07t
B08t
B09t
C01t
C02t
C03t
C04t
C05t
C06t
C07t
C08t
C09t
C10t
C11t
D01t
D02t
D03t
D04t
D05t
D06t
D07t
D08t
D09t
D10t
D11t
D12t
D13t
E02t
E03t
E04t
E05t
E06t
E07t
E08t
E09t
E10t
F09t
F10t
TALE SD
TALE SD w/Electronics

TALE/NICHE Composition

- TALE with in-fill SD array will measure composition down to 30 PeV
- Using Cherenkov light, TALE with NICHE (Non-Imaging CHErenkov array) can go down to 1–2 PeV

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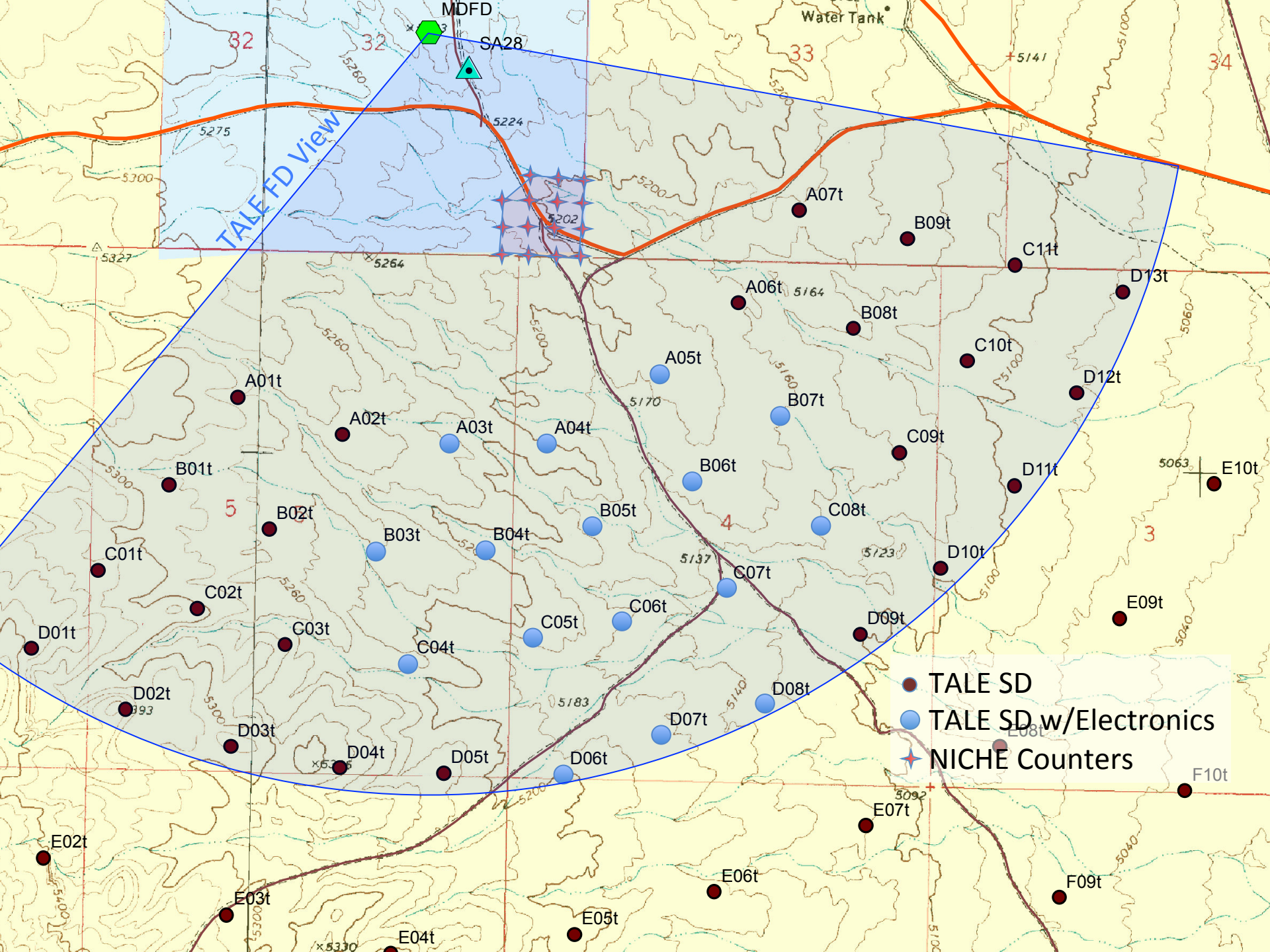
TALE SD
TALE SD w/Electronics
NICHE Counters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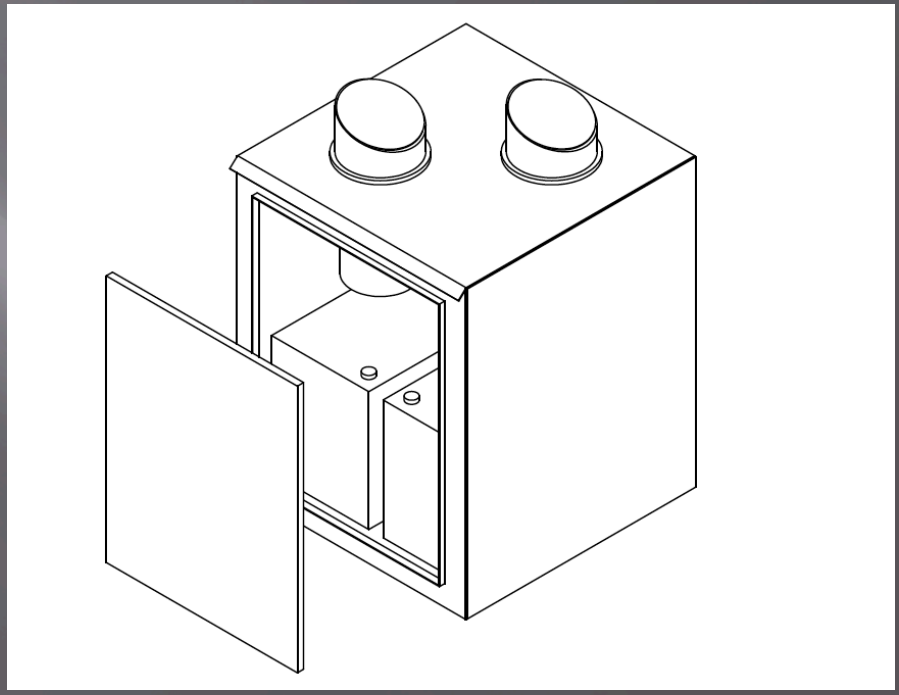
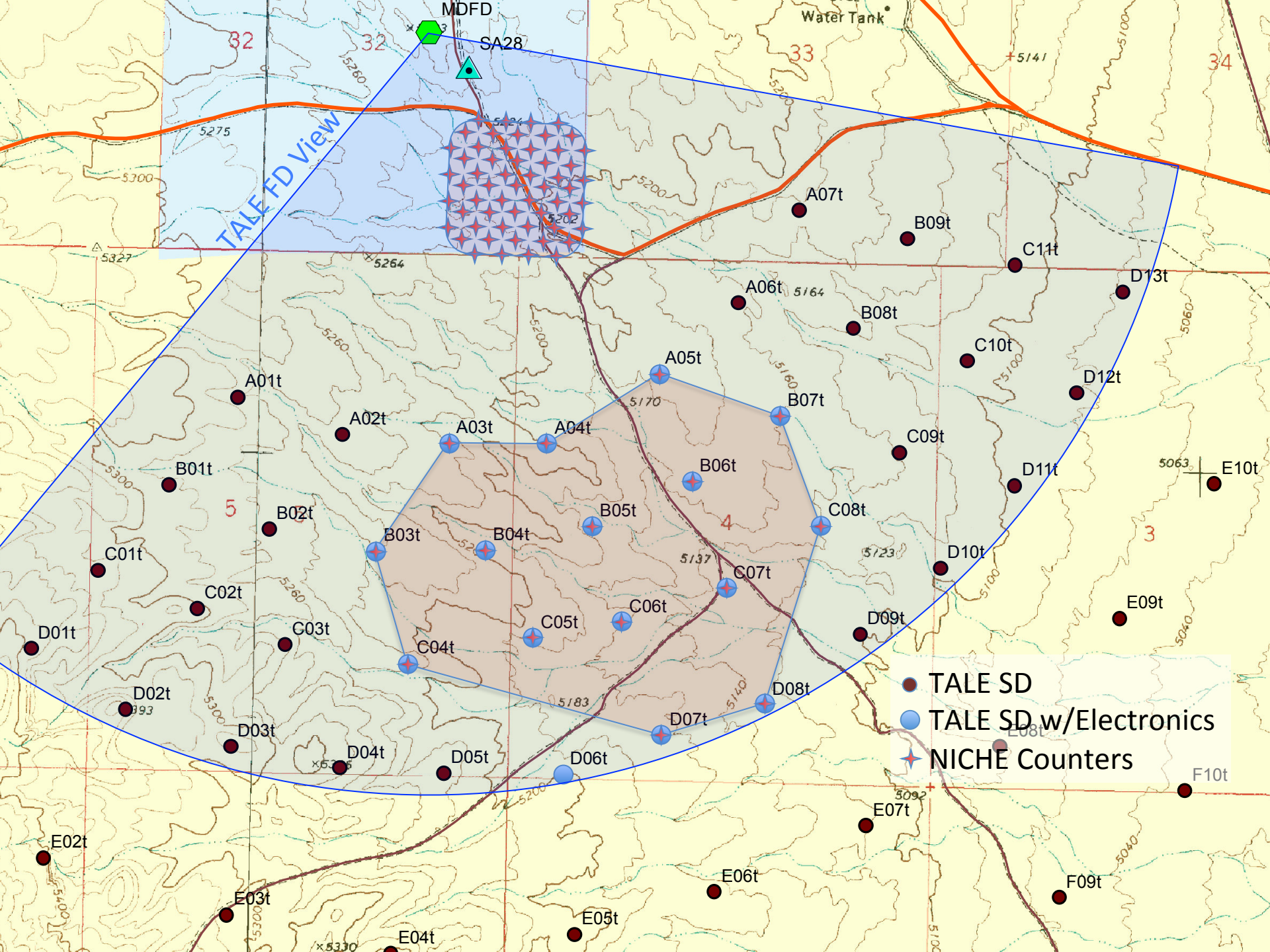
TALE SD
TALE SD w/Electronics
NICHE Counters

TALE/NICHE Composition

- TALE with in-fill SD array will measure composition down to 30 PeV
- Using Cherenkov light, TALE with NICHE (Non-Imaging CHErenkov array) can go down to 1–2 PeV
- Eventually want an array of 60 counters

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E10t
F09t
F10t
TALE SD
TALE SD w/Electronics
NICHE Counters

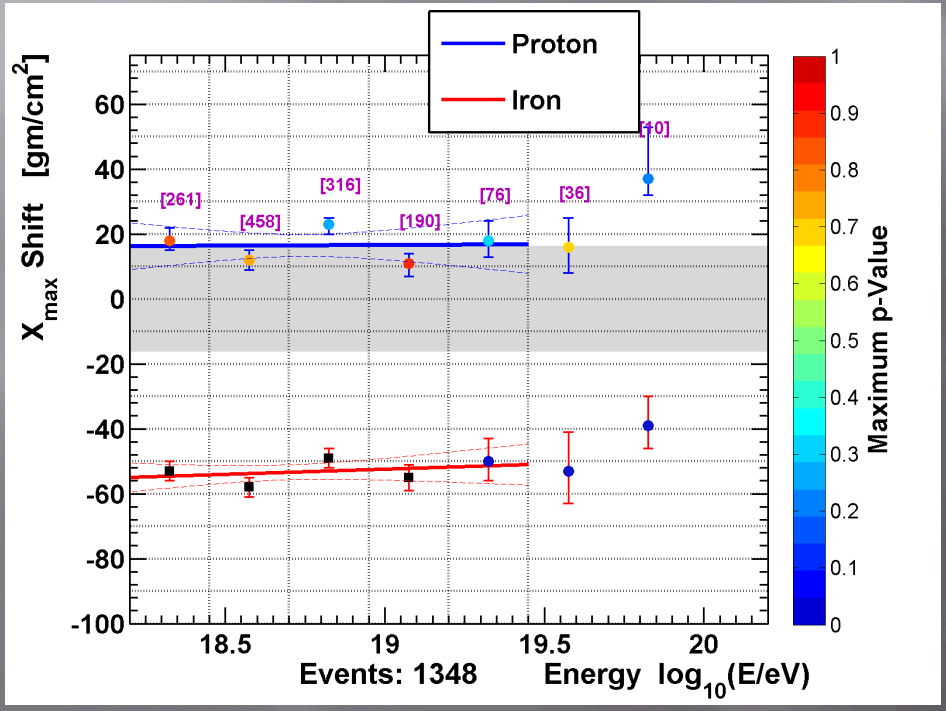
Conclusion

- TA/TALE has measured spectrum of cosmic rays over 4.7 orders-of-magnitude in energy
- TA observes a proton-like composition
  - Using primarily the shape of the X_{max} distribution
- TALE will soon measure the composition in the 30 PeV–1 EeV range
- TALE-Cherenkov and NICHE will push composition measurements down to the PeV range

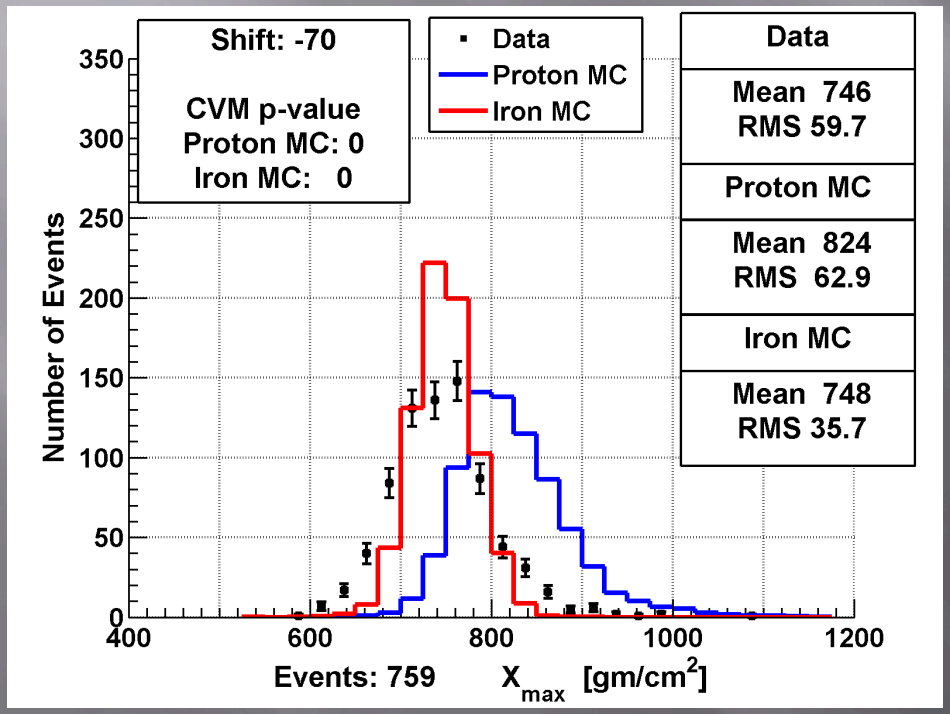
Backup Slides

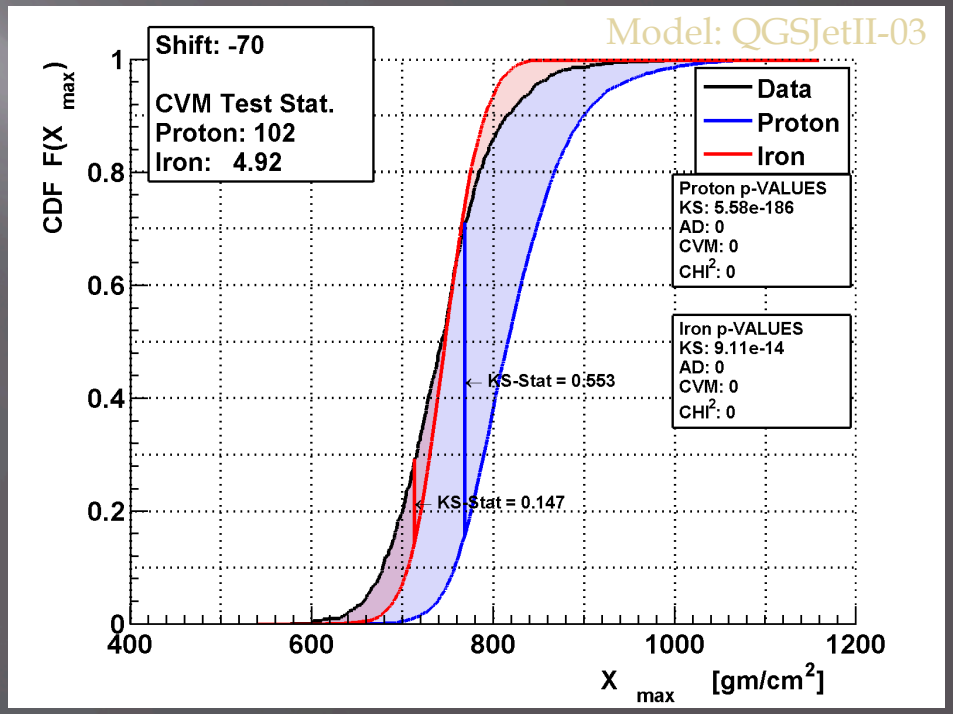
Shift flip-book

TA Stereo Composition Result



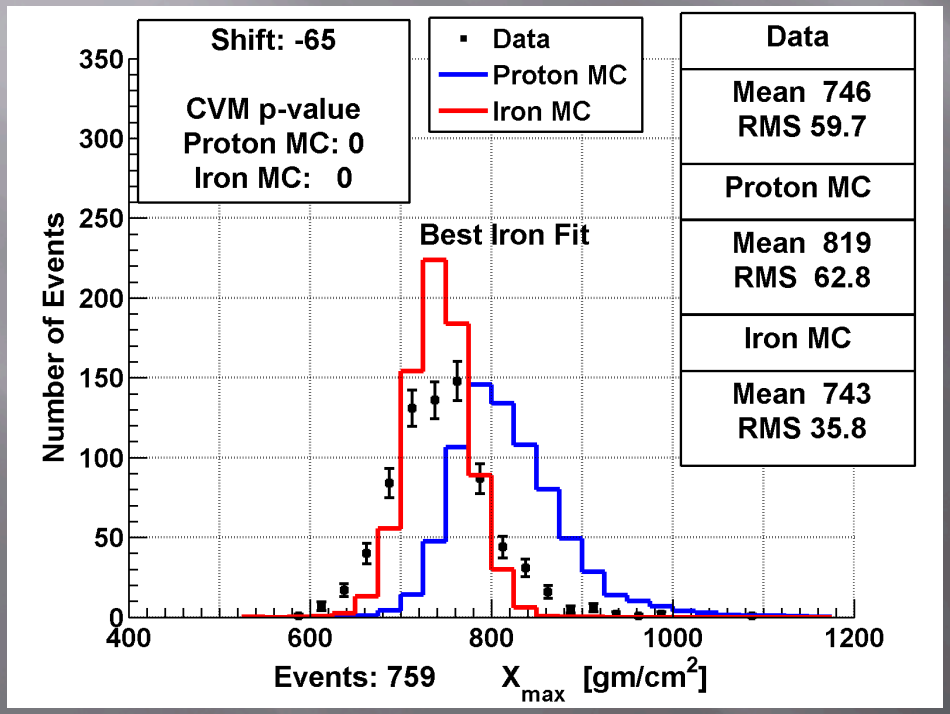
Shift & Quality

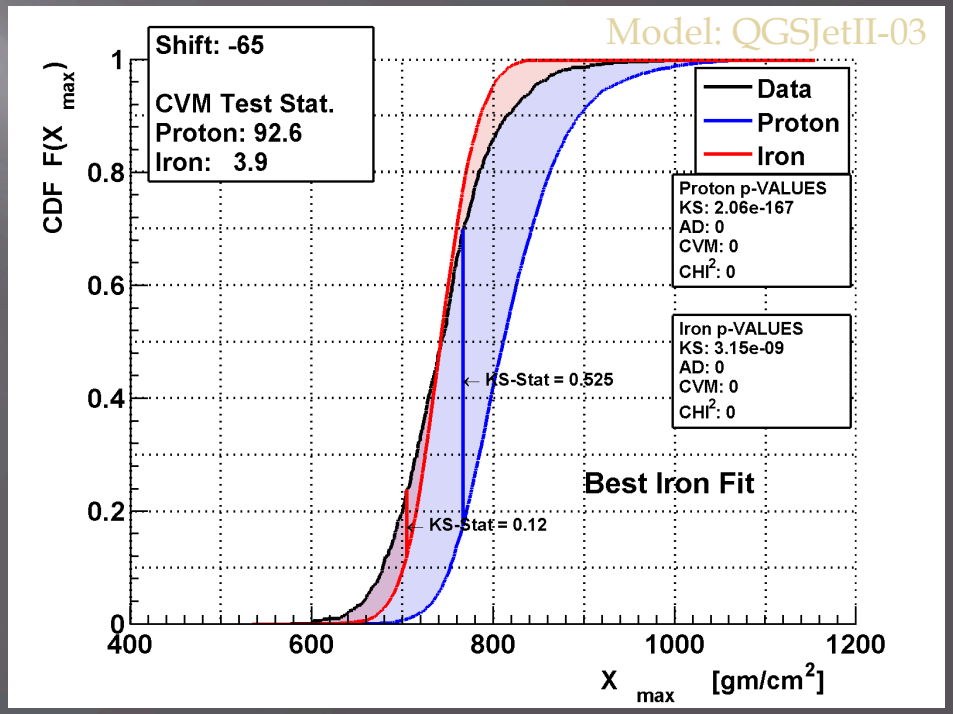




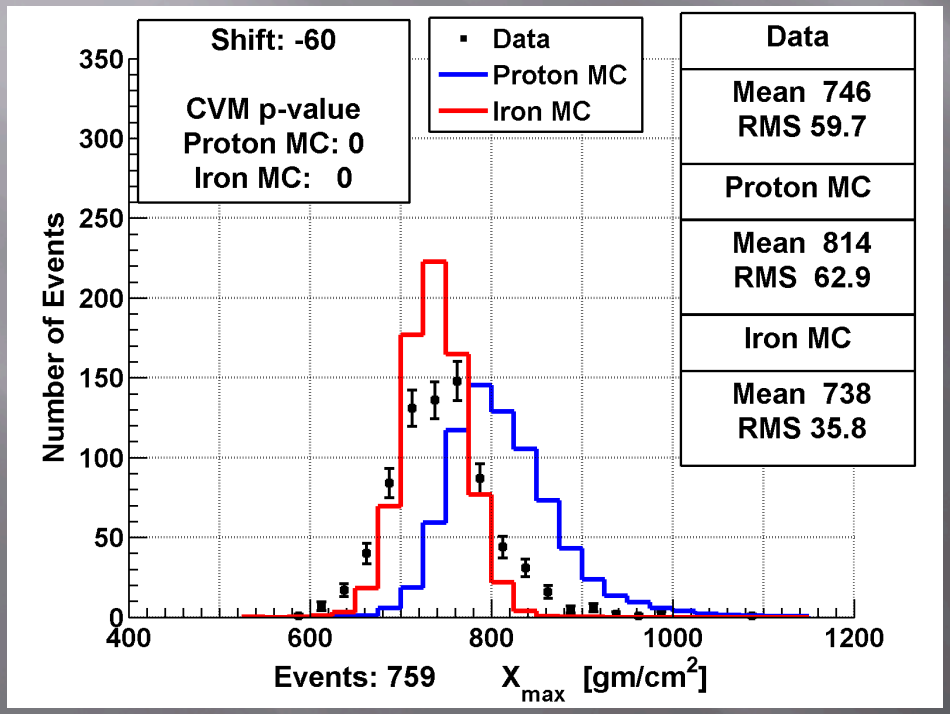
Shift & Quality

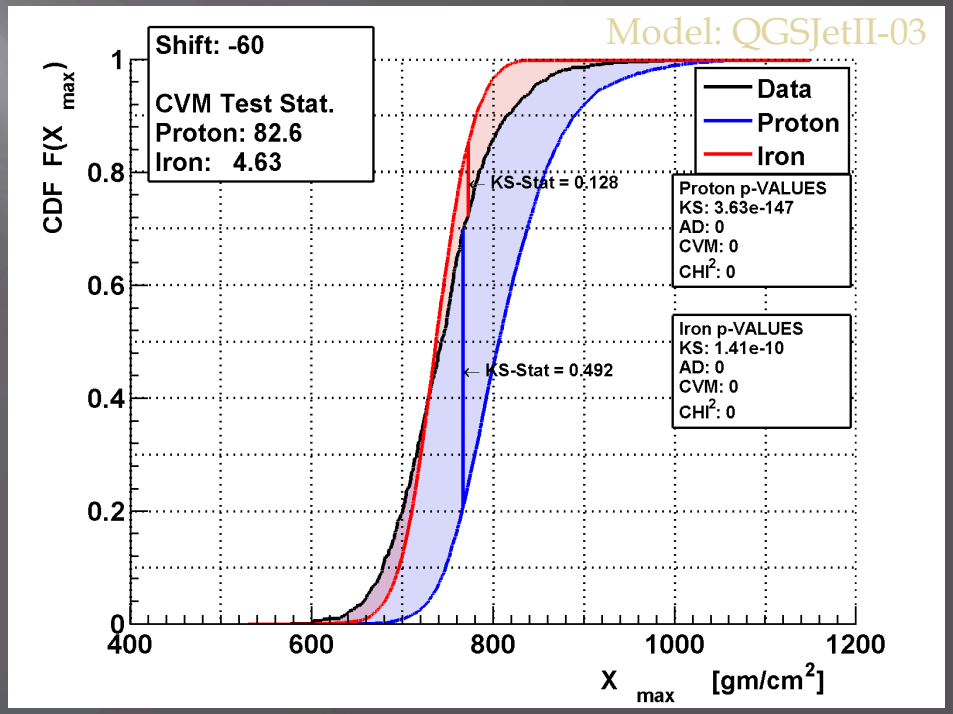
- Best iron: shift data down by 65 g/cm^2



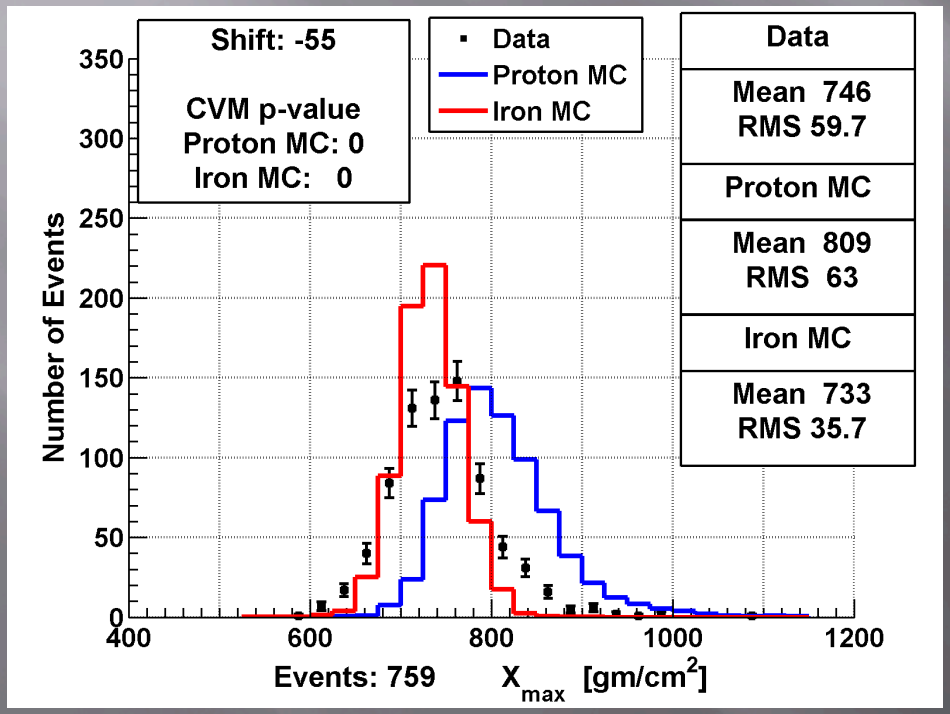


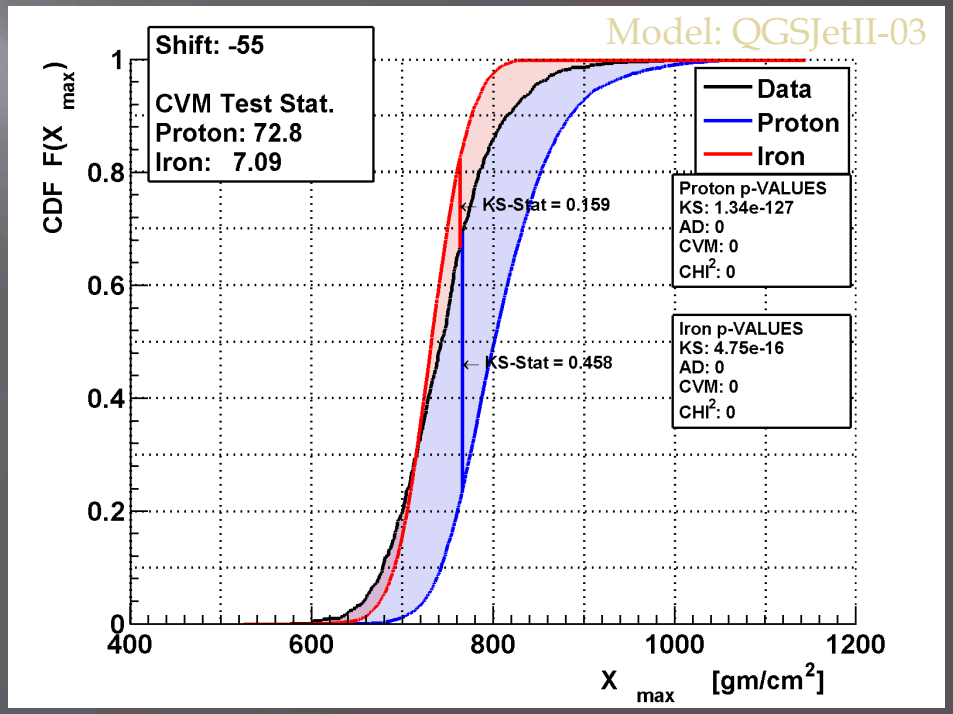
Shift & Quality





Shift & Quality





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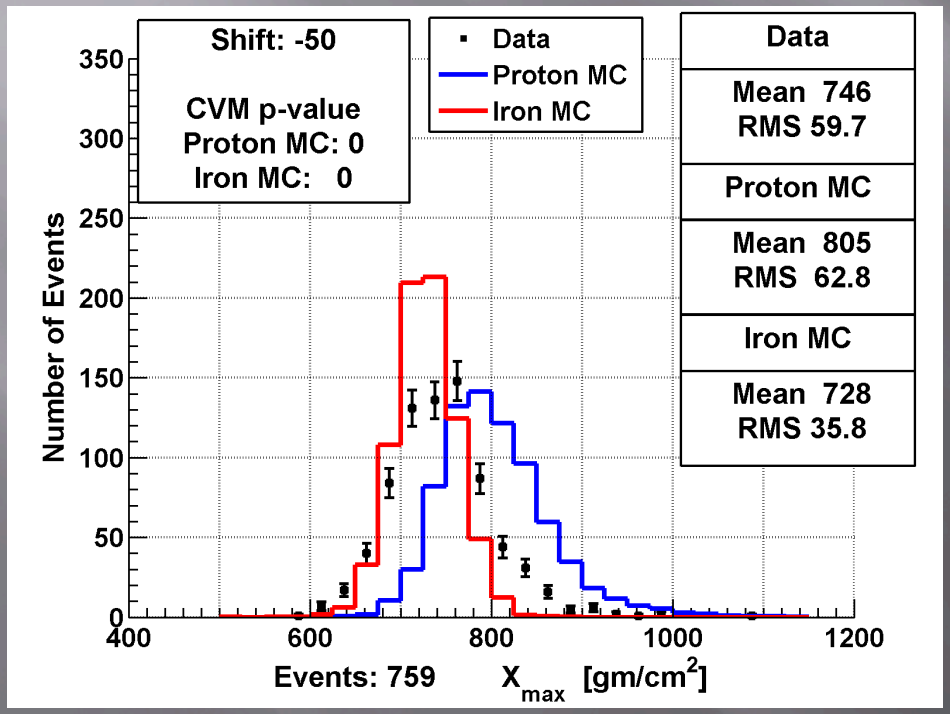
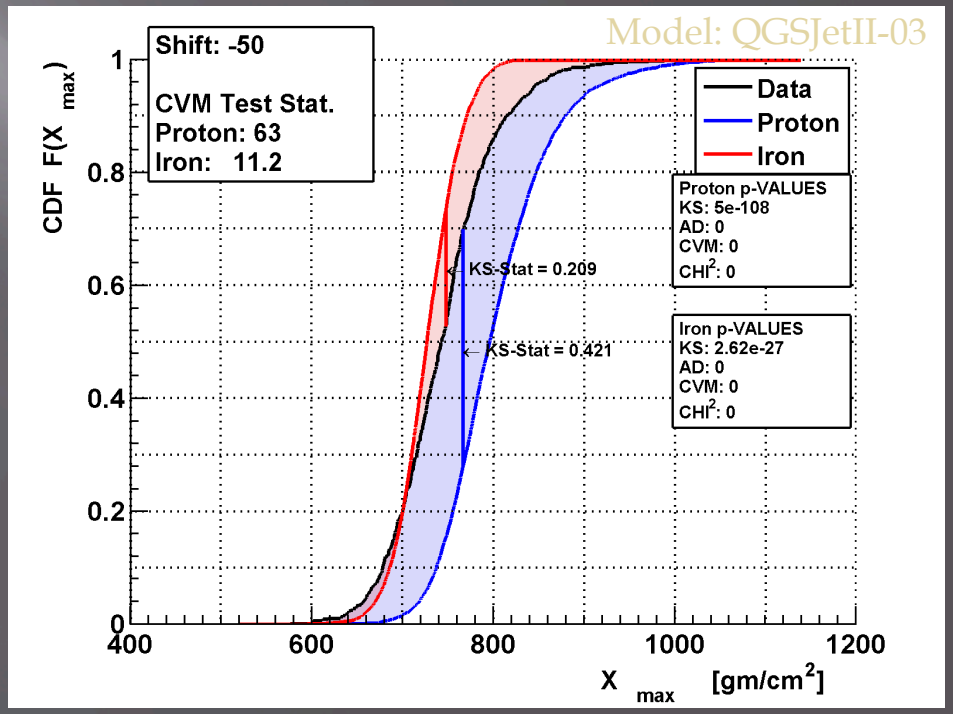
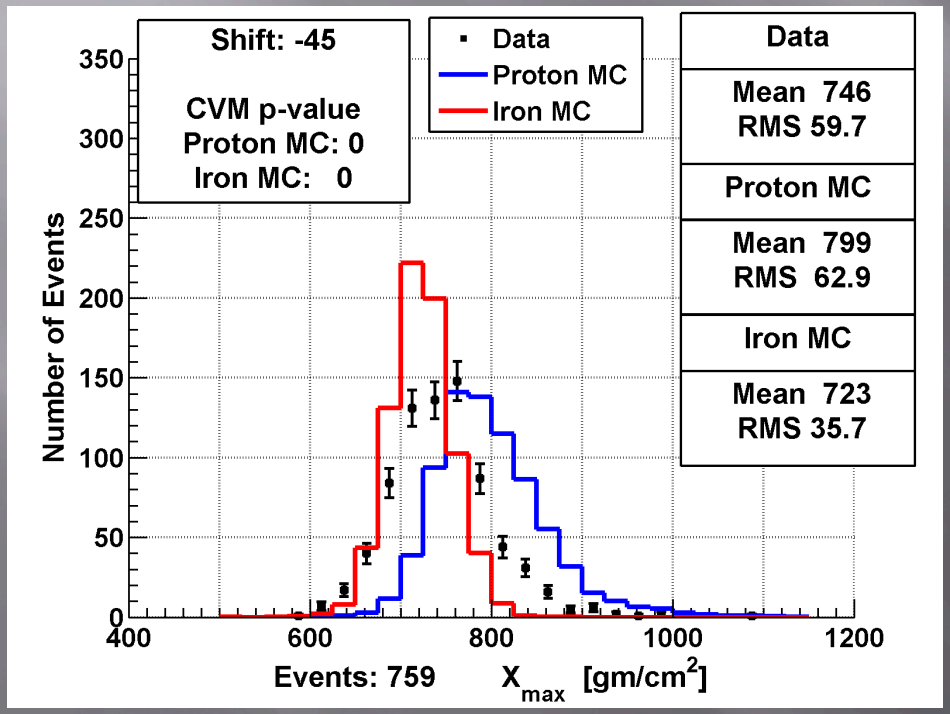
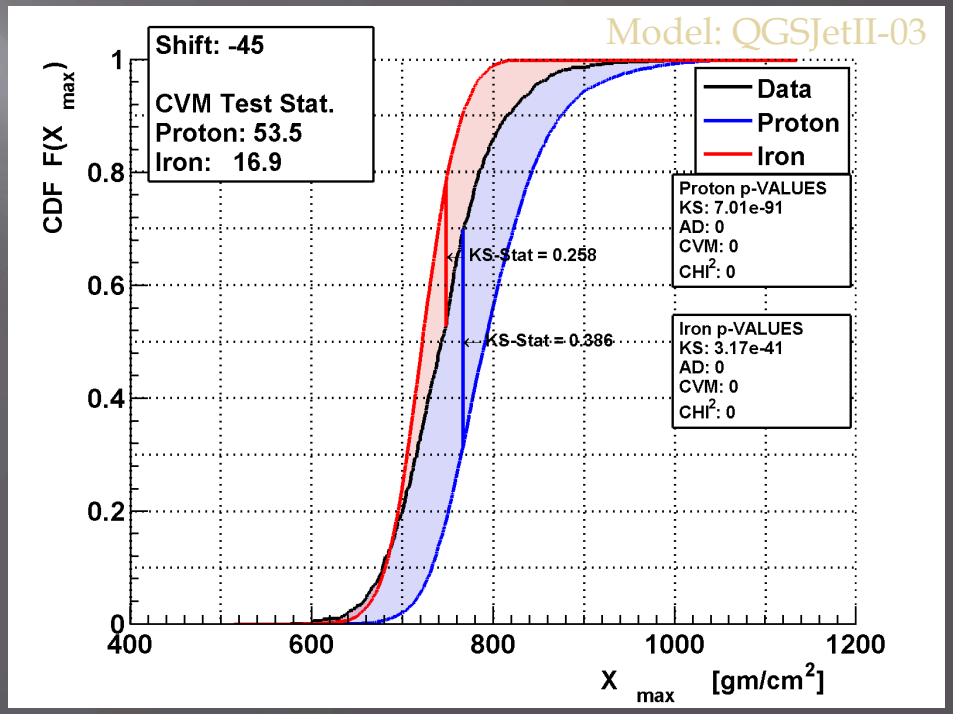




Shift & Quality





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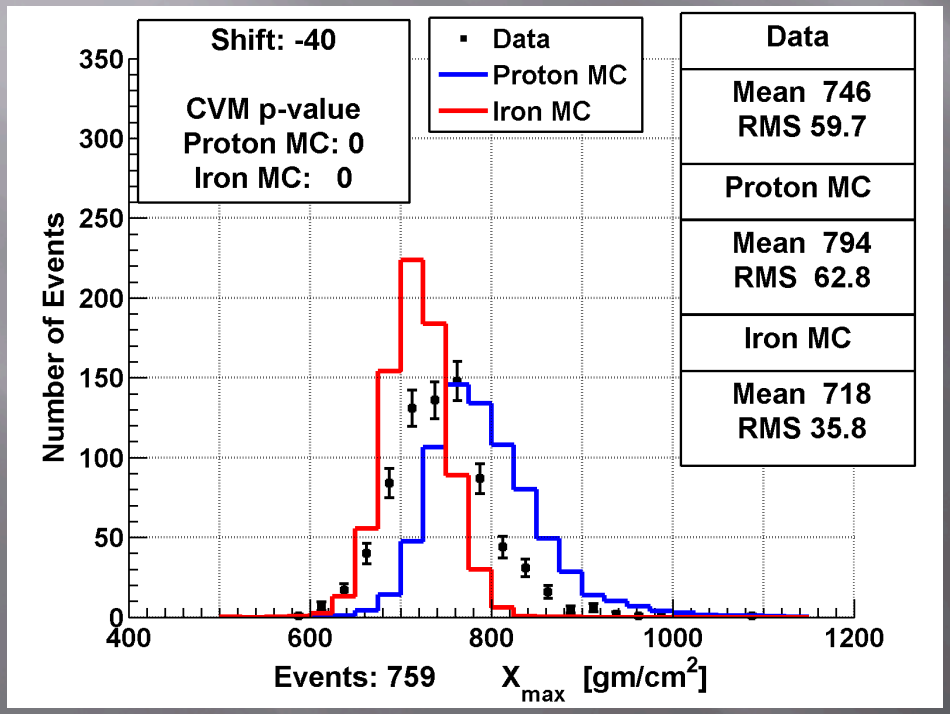

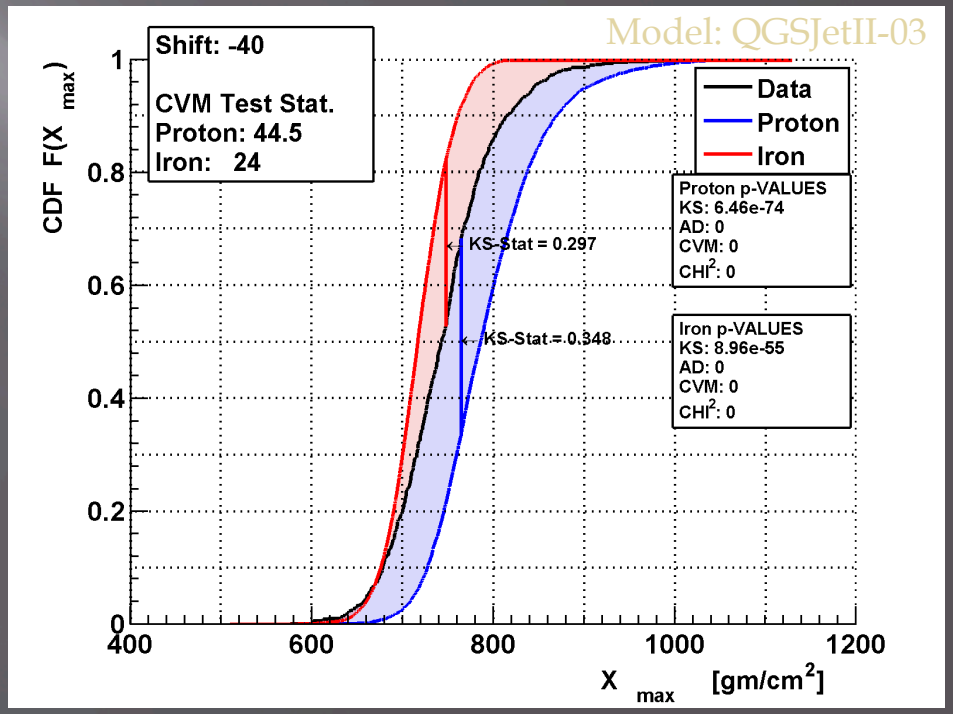

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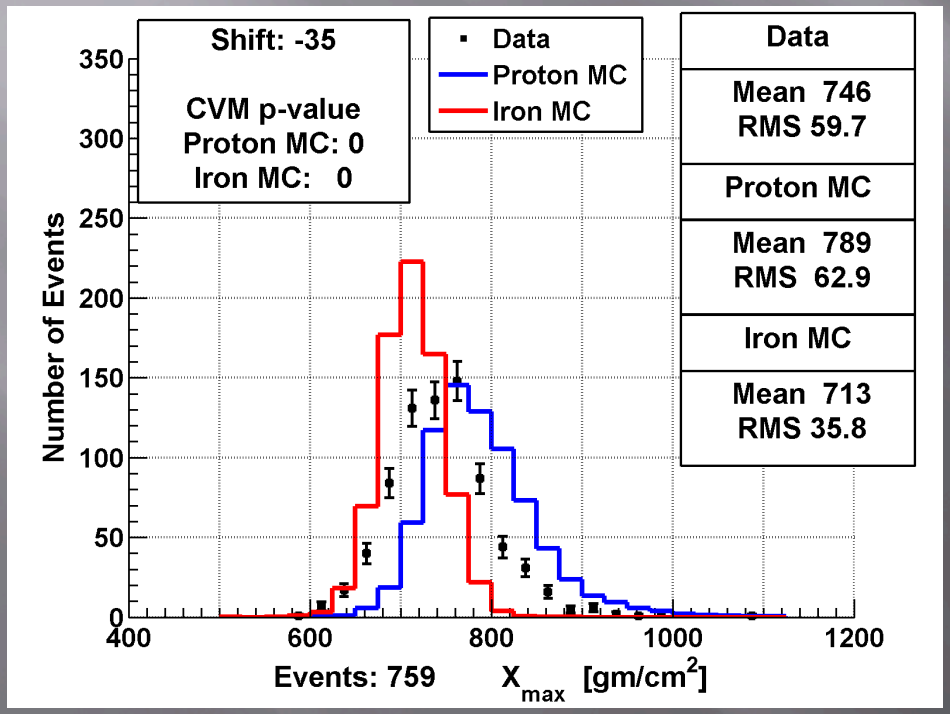

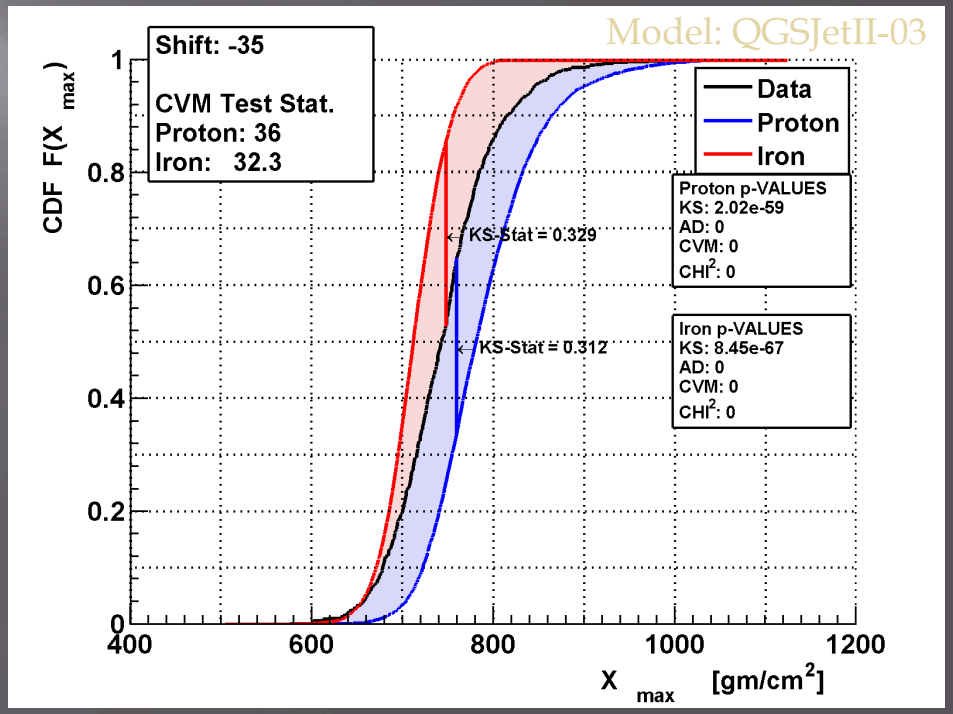

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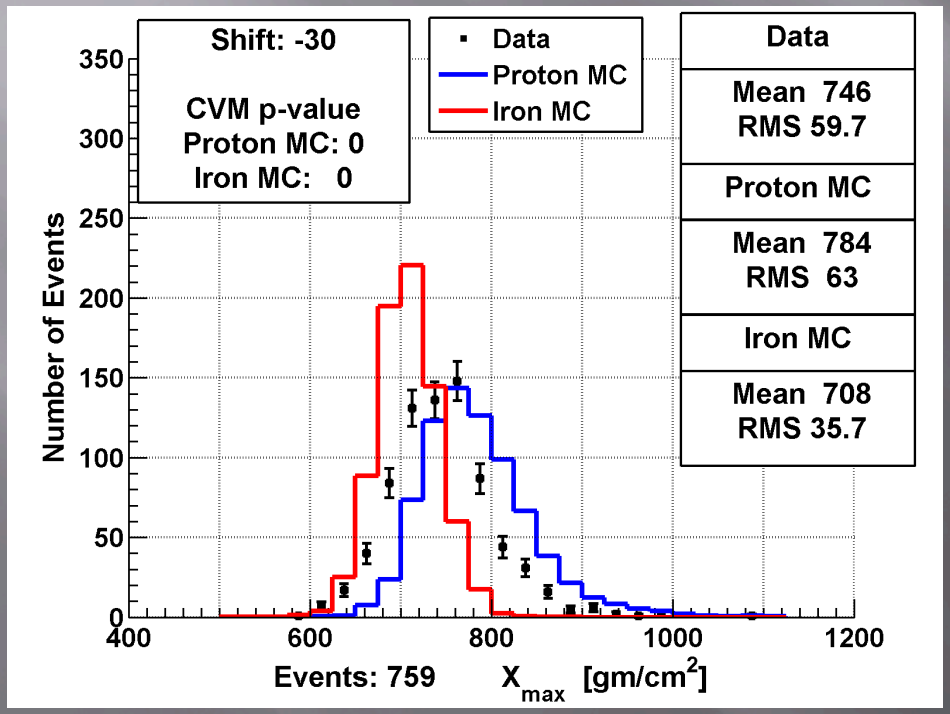

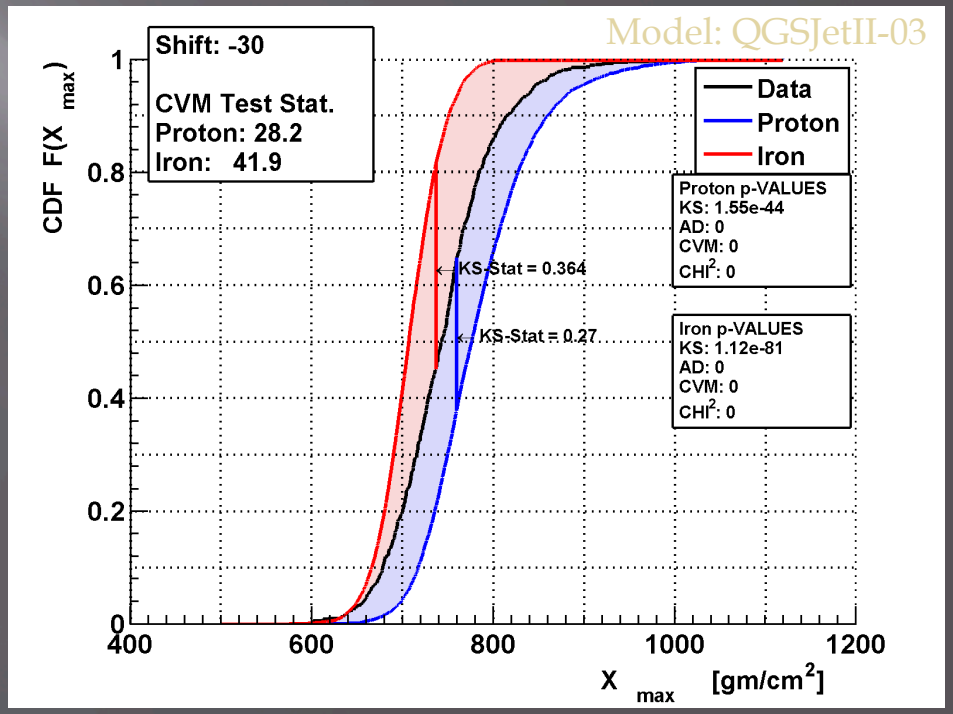

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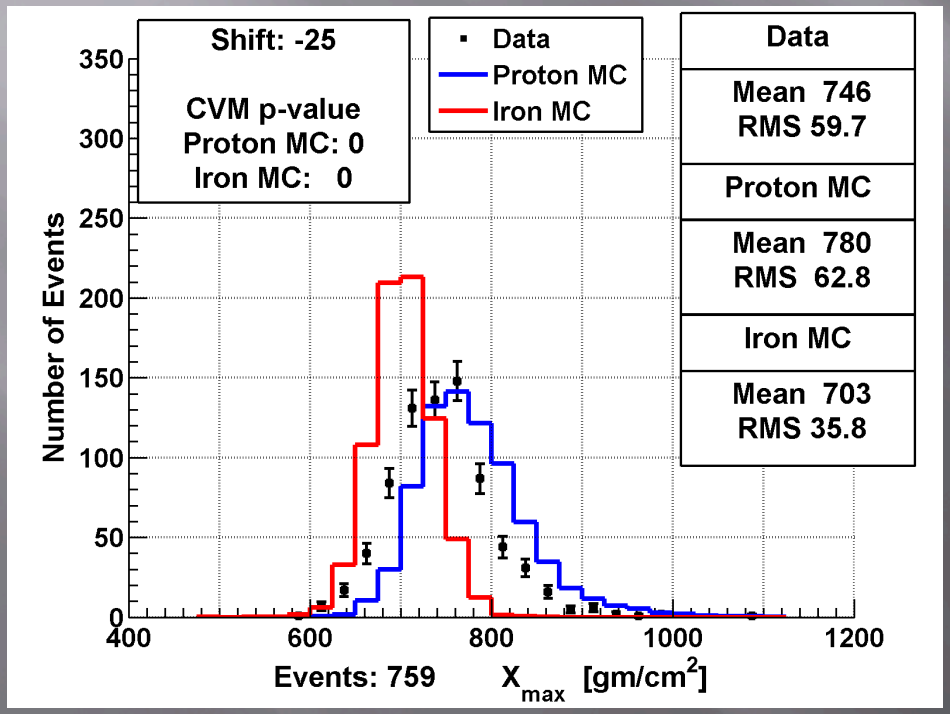
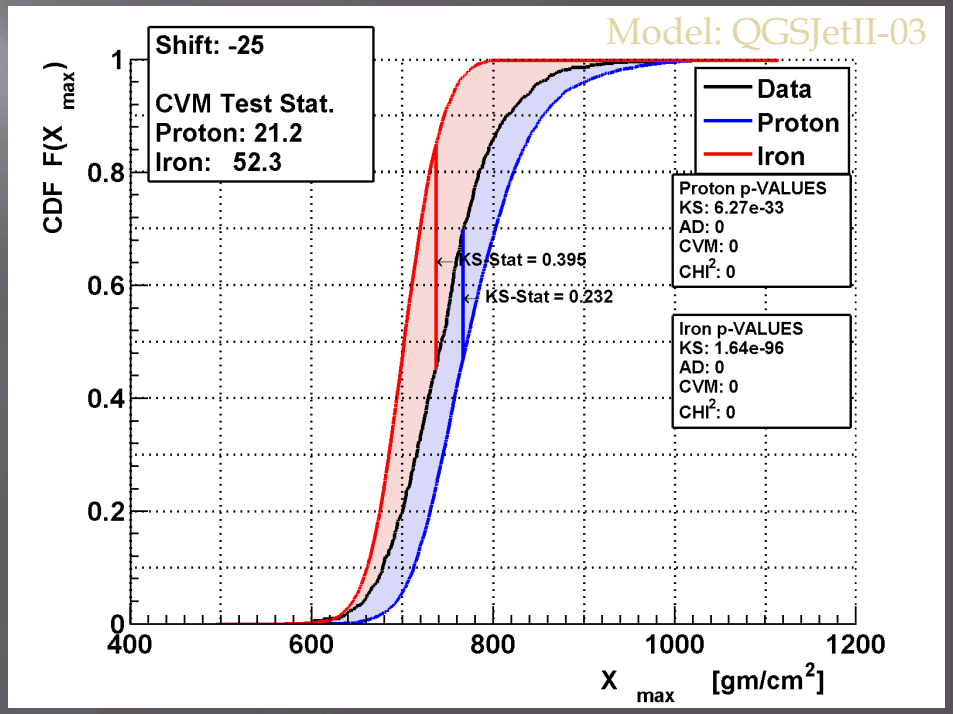
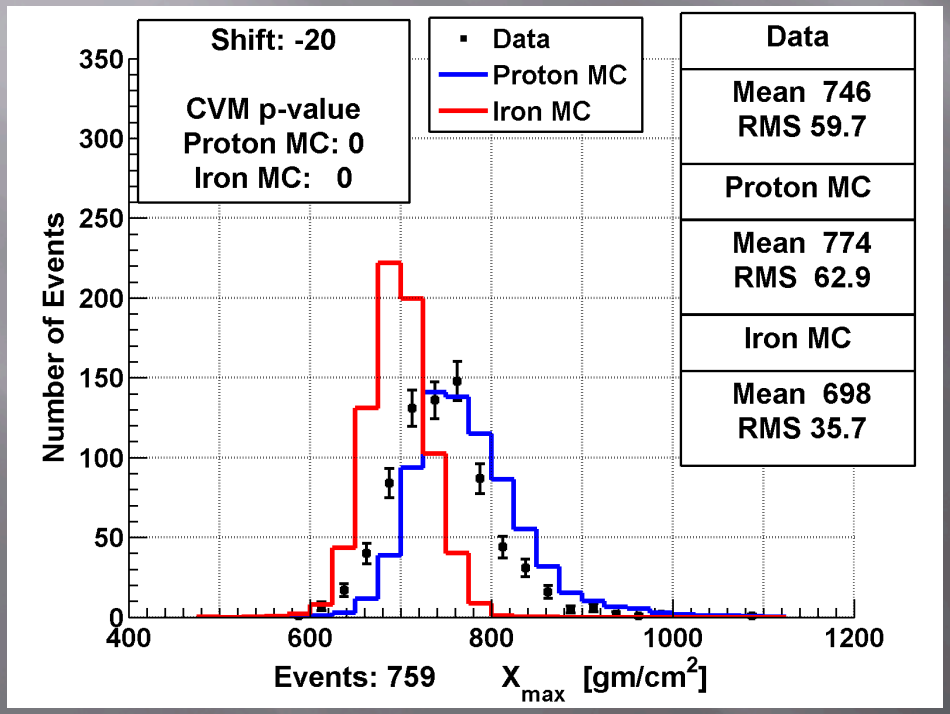
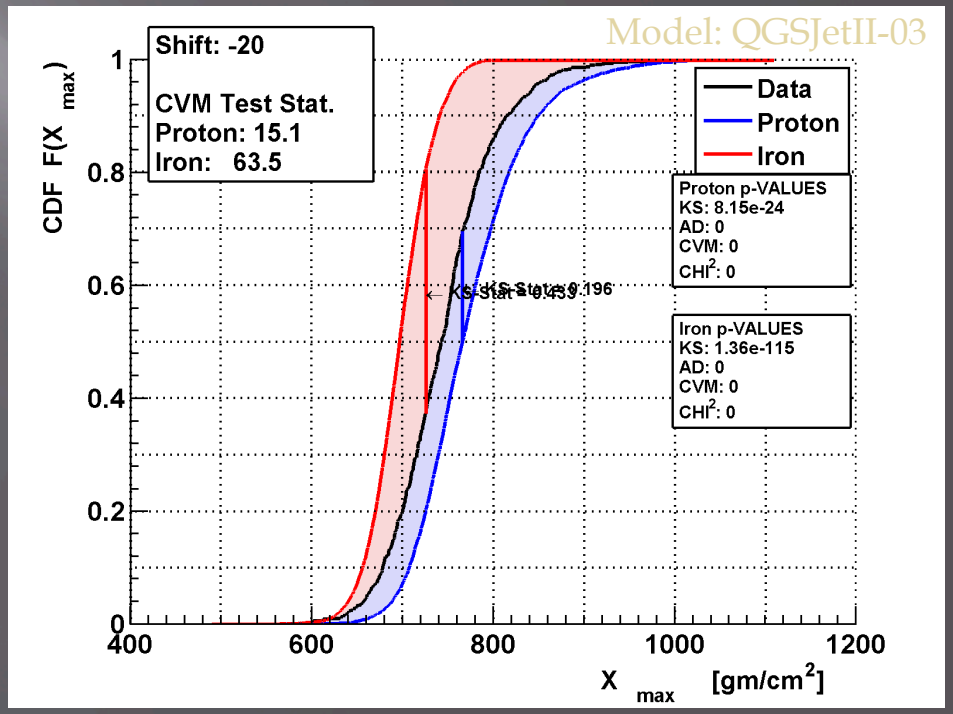


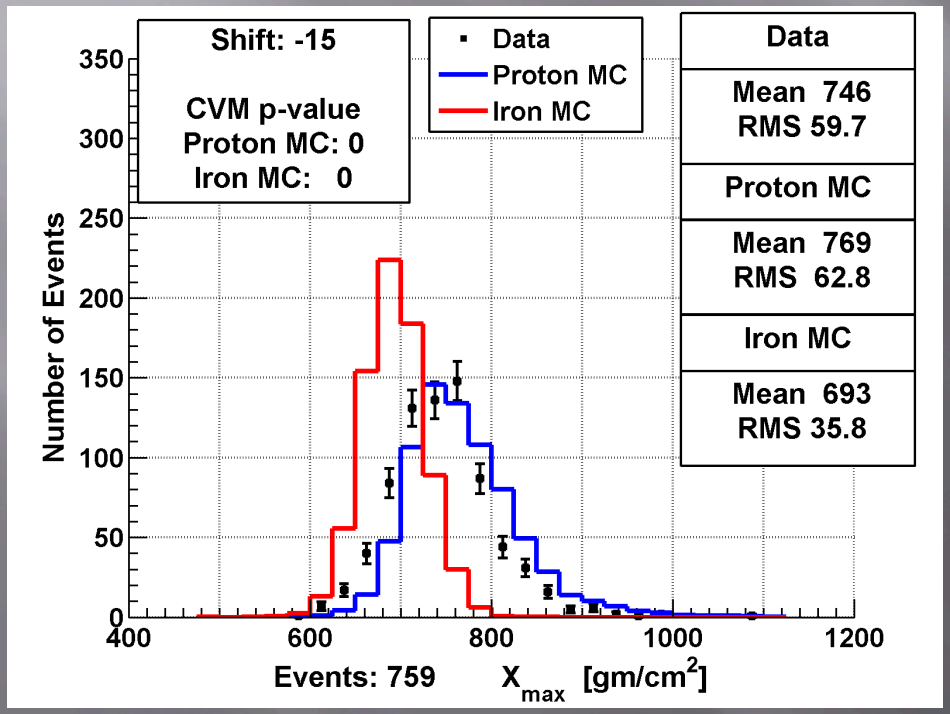


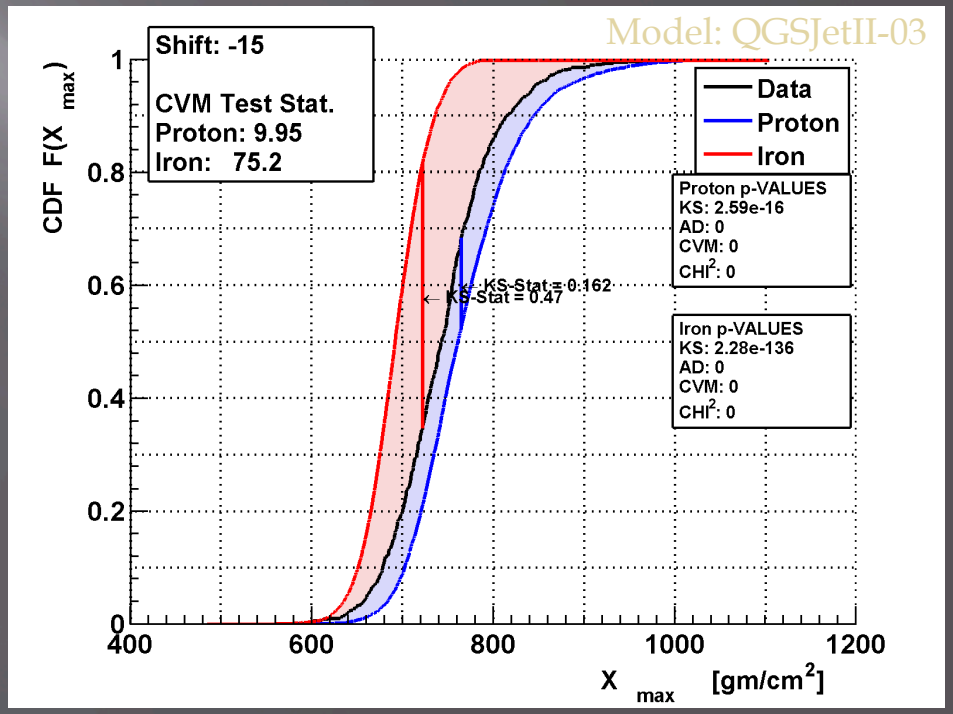
Shift & Quality



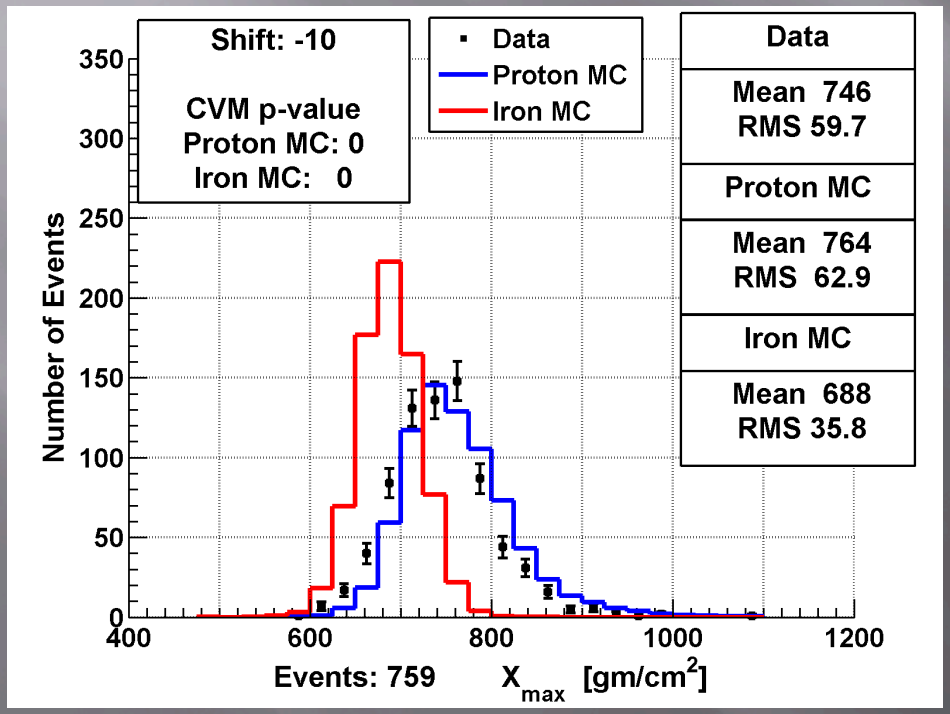


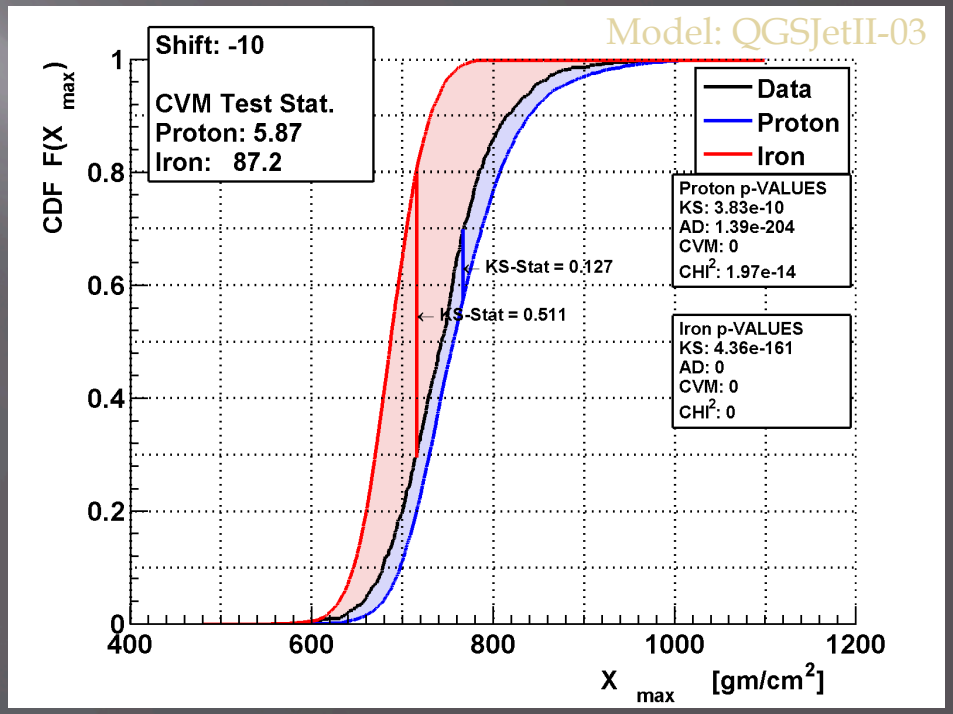
Shift & Quality



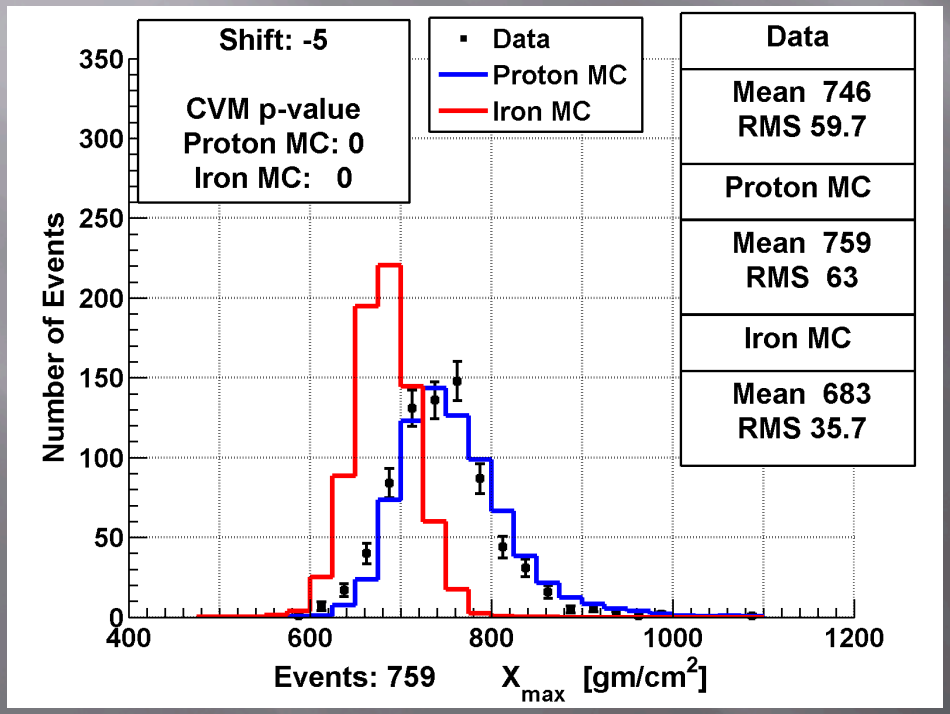


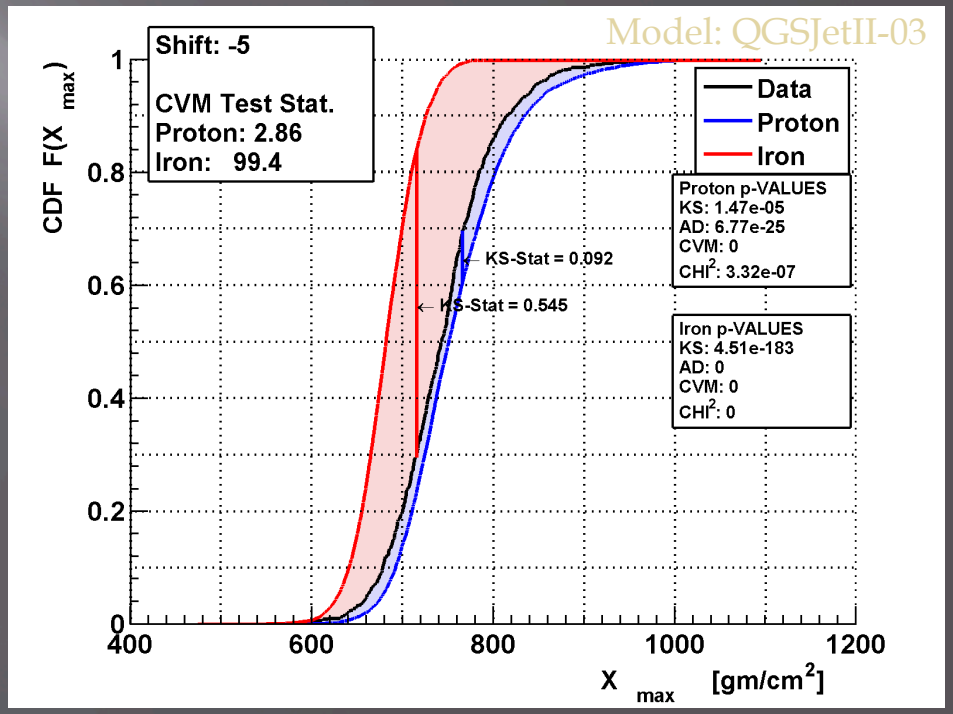
Shift & Quality





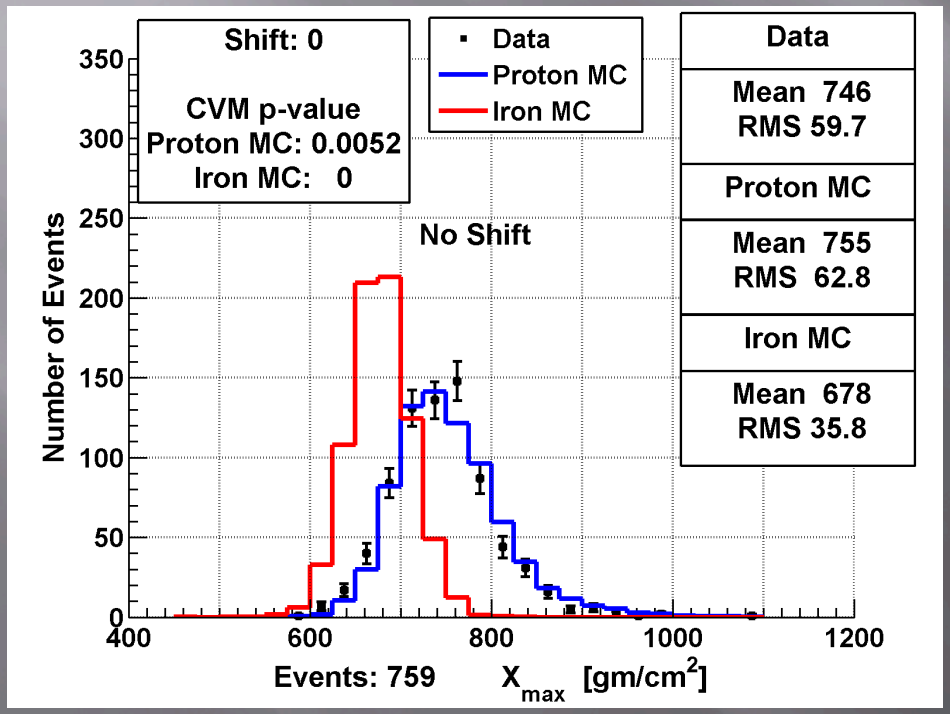
Shift & Quality

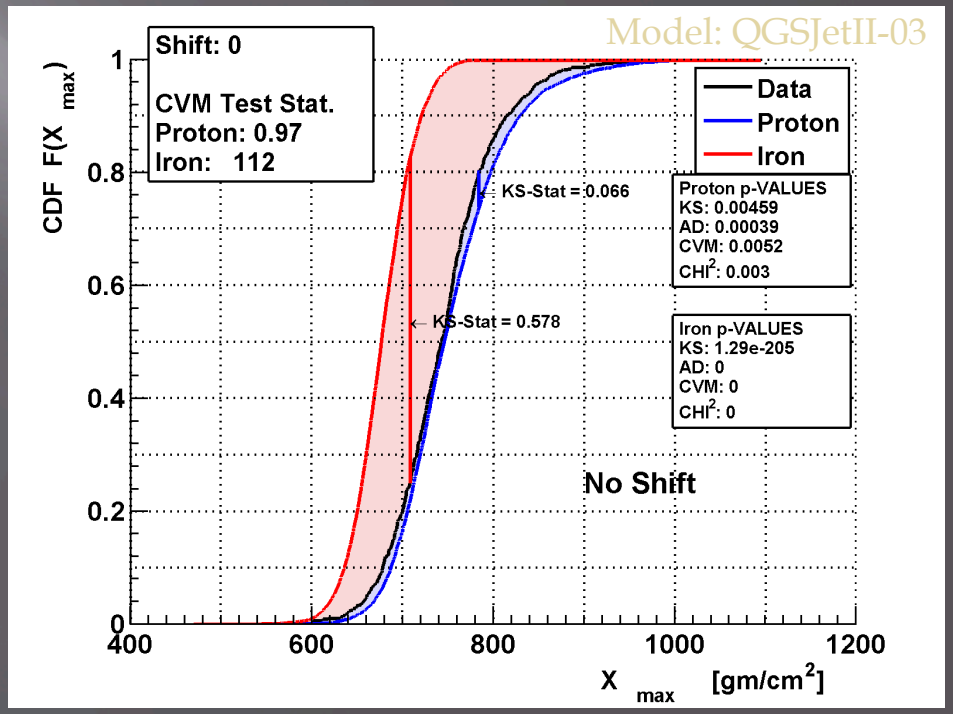




Shift & Quality

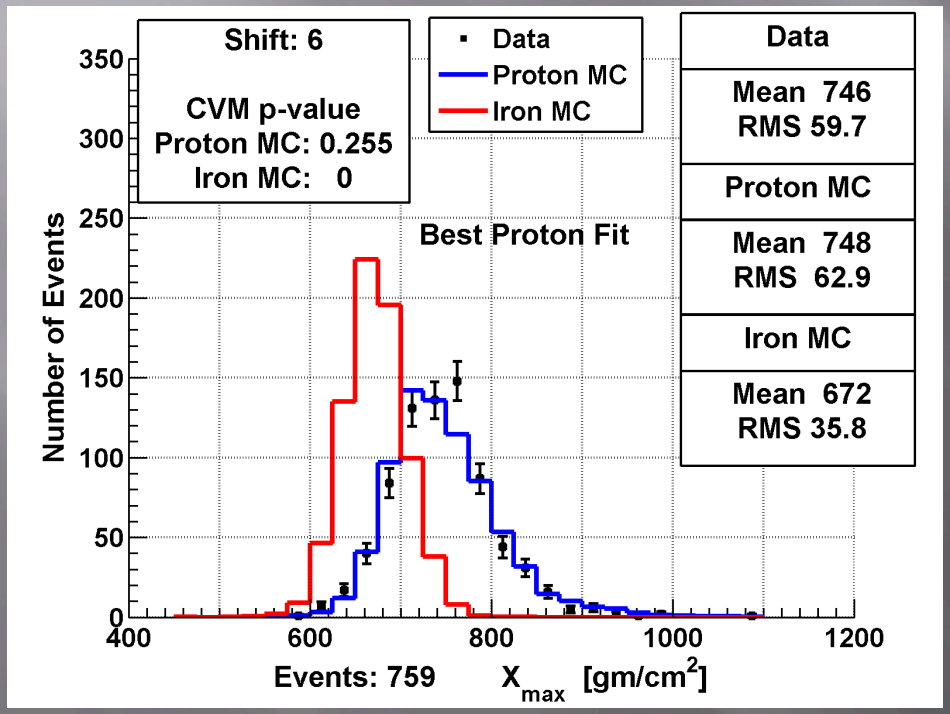
- No shift

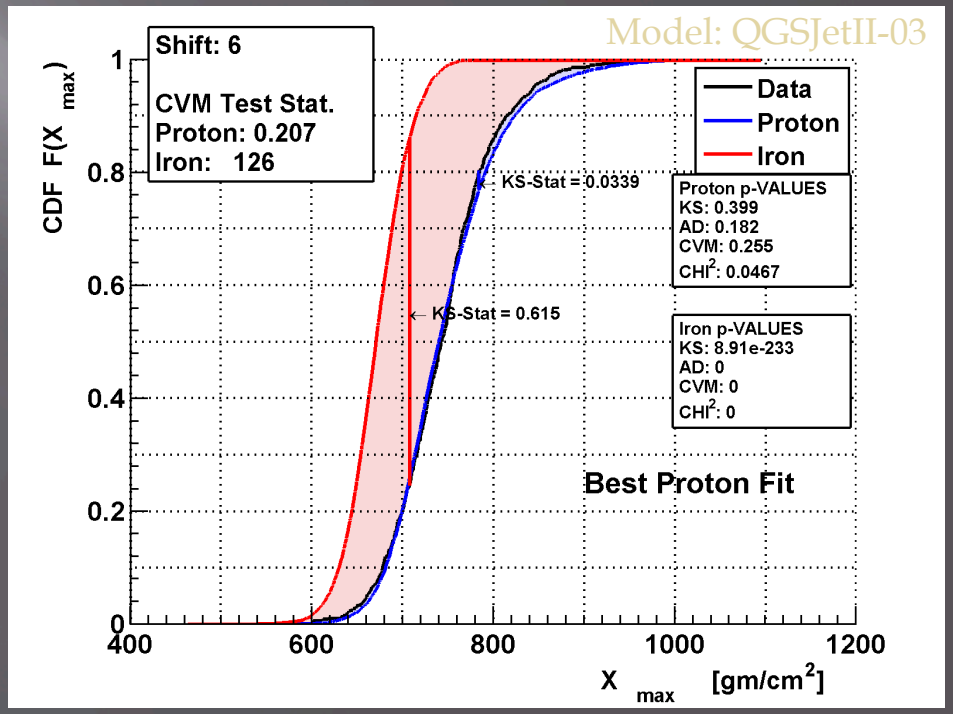




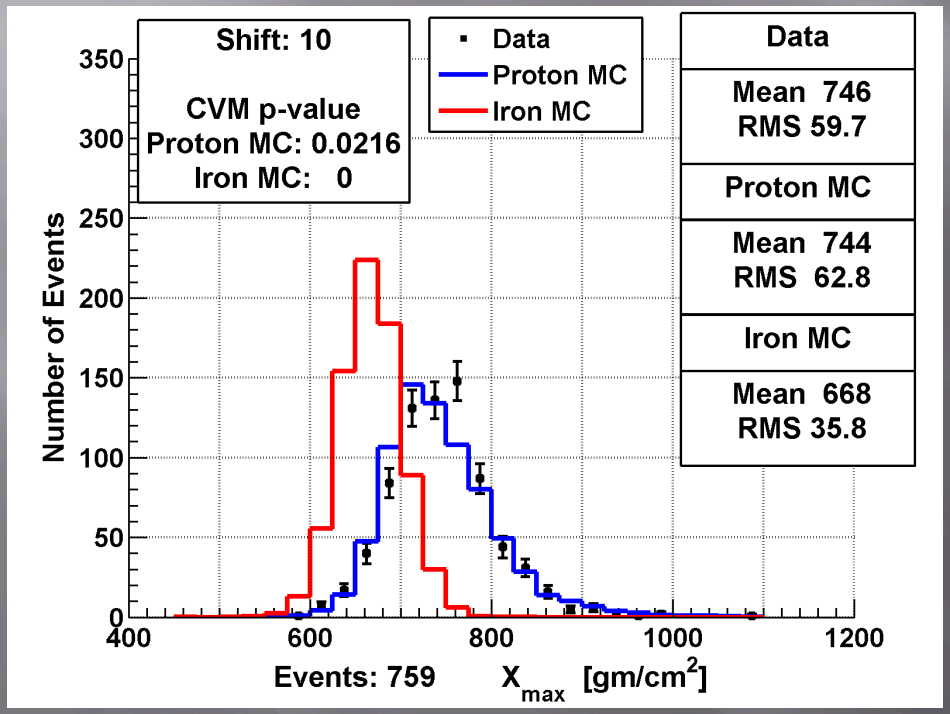
Shift & Quality

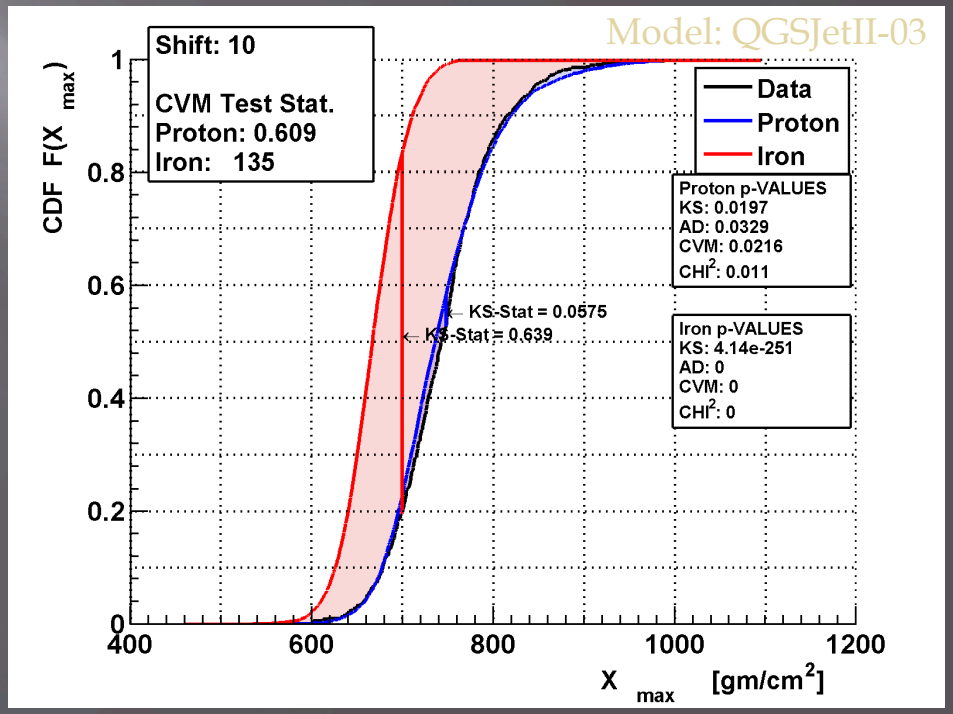
- Best proton: shift data up by 6 g/cm^2





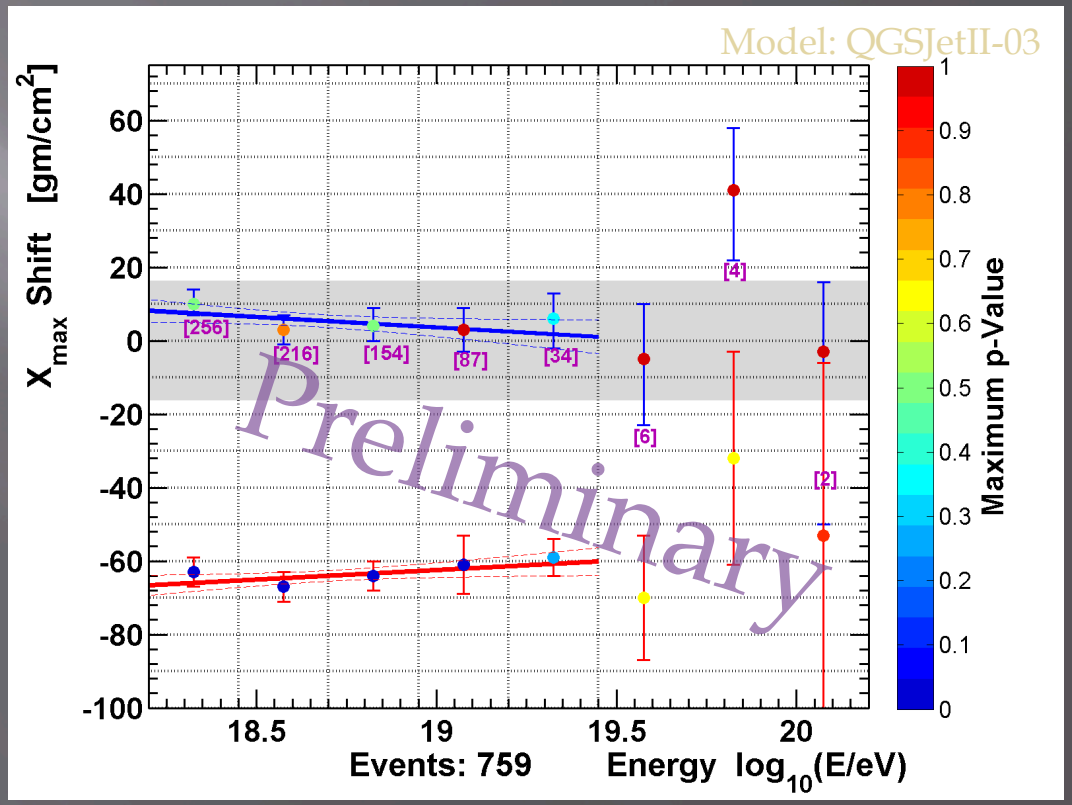
Shift & Quality





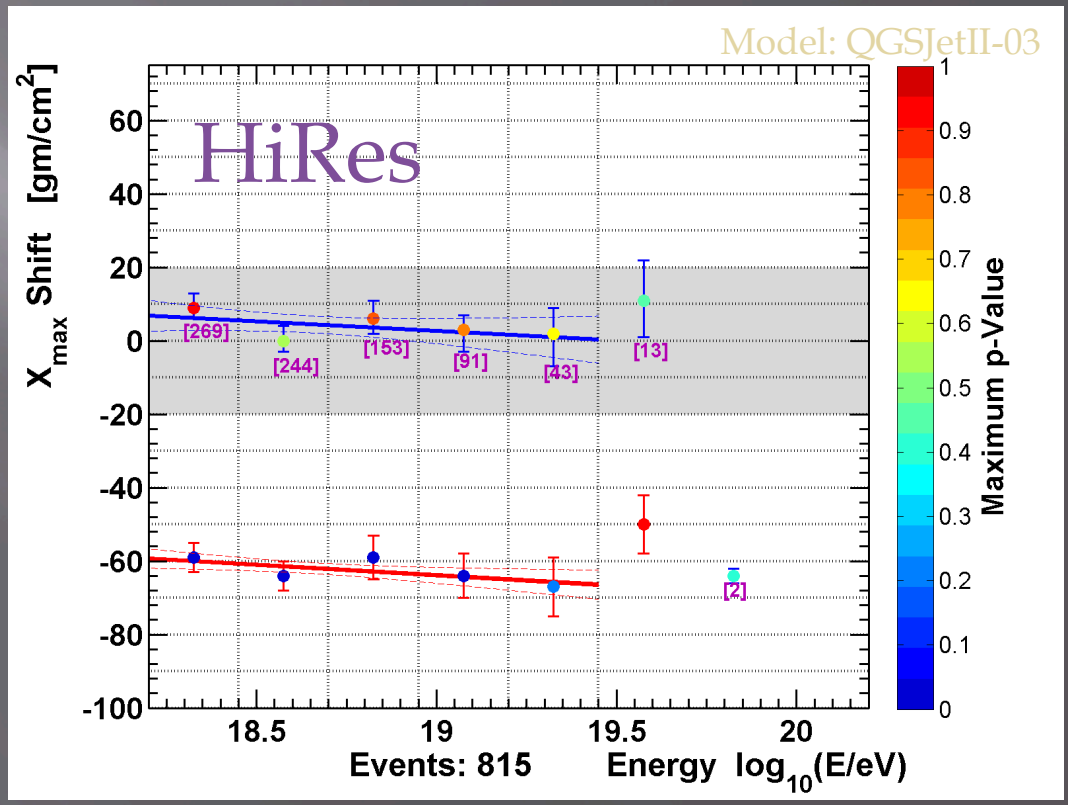
TA MD-Hybrid Composition

- Composition analysis using CvM shifts
  - Using QGSJetII-03 with quarter decade bins
- Protons
  - 5–10 g/cm^2 shifts
  - Matching distributions
- Iron
  - 60 g/cm^2 shifts
  - Distributions don't match
- Consistent with protons



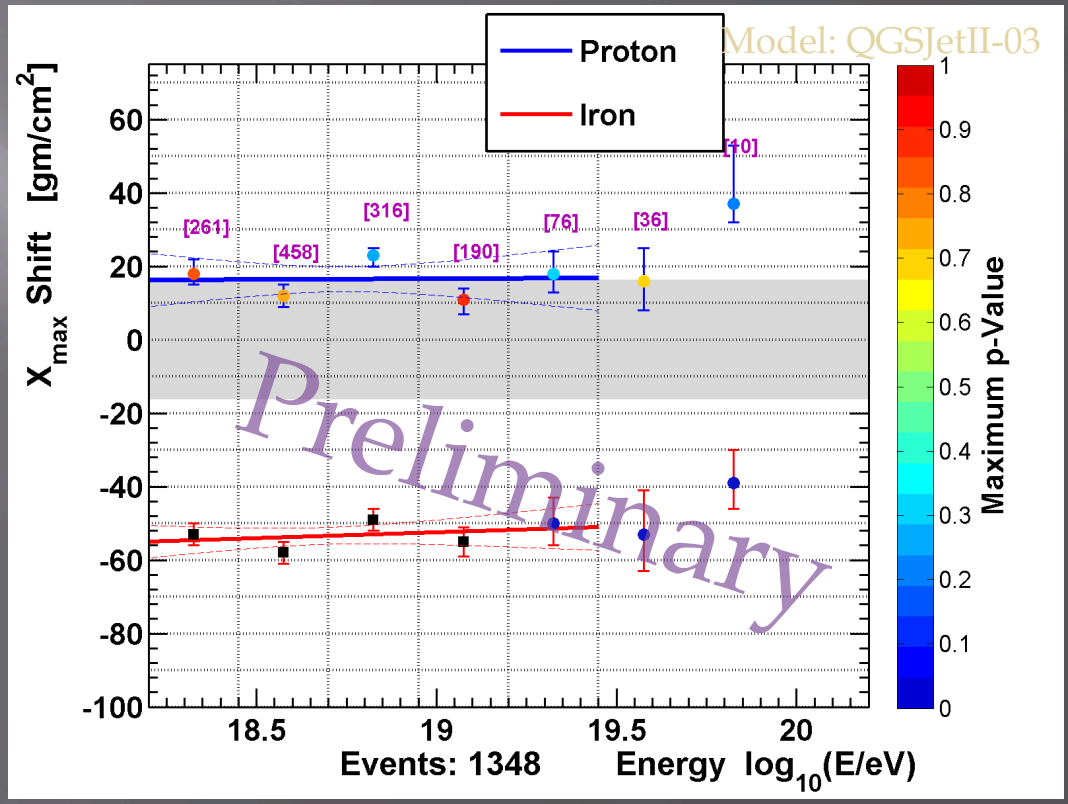
HiRes Composition

- HiRes results for comparison
  - Same conclusions
  - Consistent shifts (not necessarily expected)
  - Consistent p-values



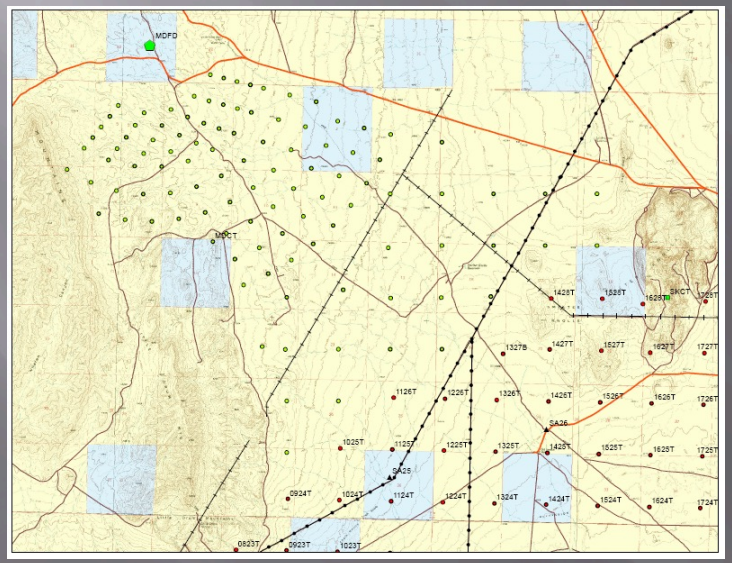
TA Stereo

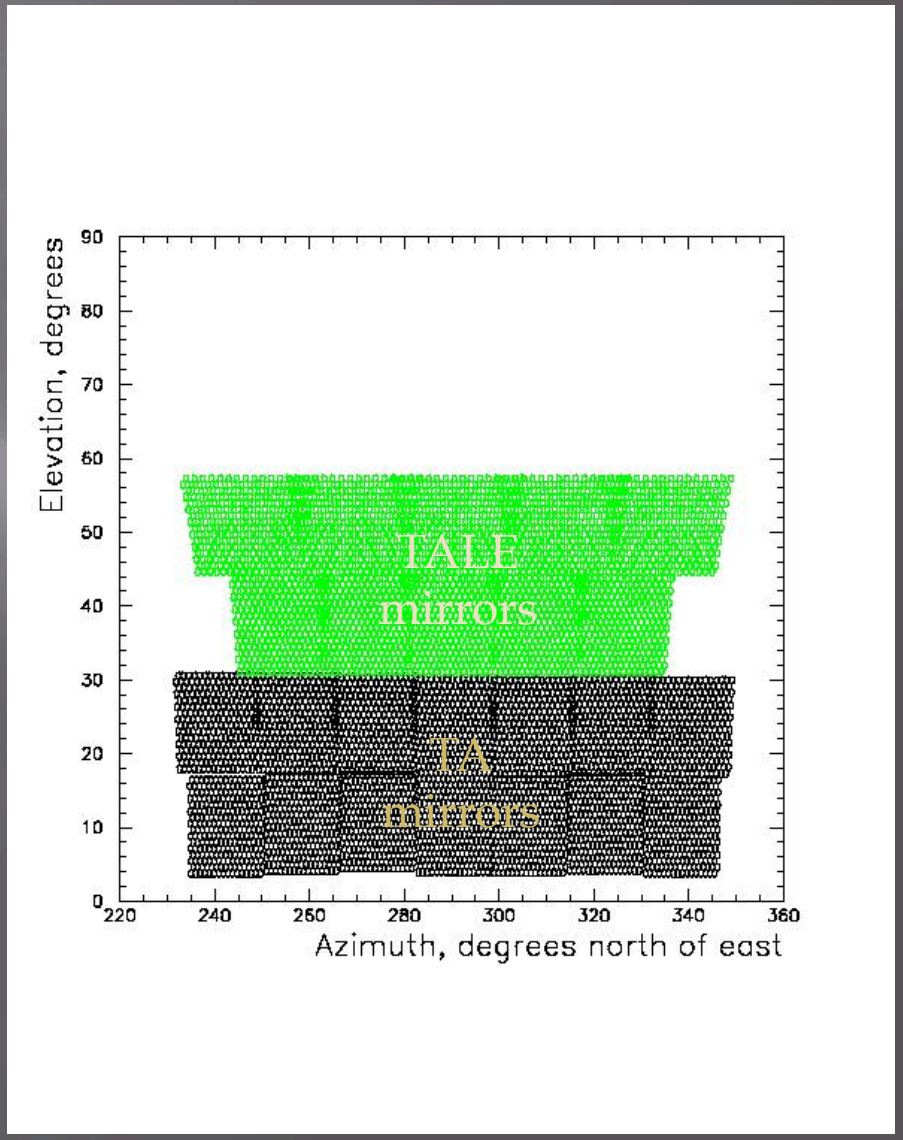
- With stereo we also see very consistent comparison with proton distribution
- Different shift but within the 15 g/cm^2 systematic uncertainty



TALE

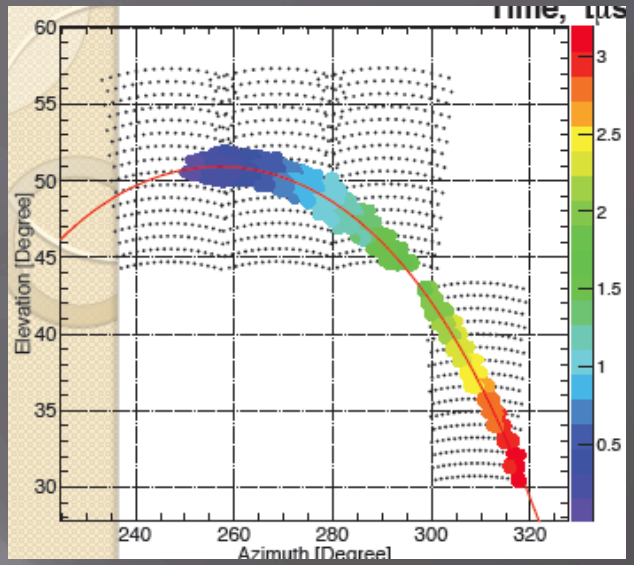
- Add 10 telescopes at the Middle Drum site, looking from 31°-59° in elevation.
  - High elevation angle allows measurement of close-by showers
- Add infill array (400m and 600m spacing) for hybrid observation.

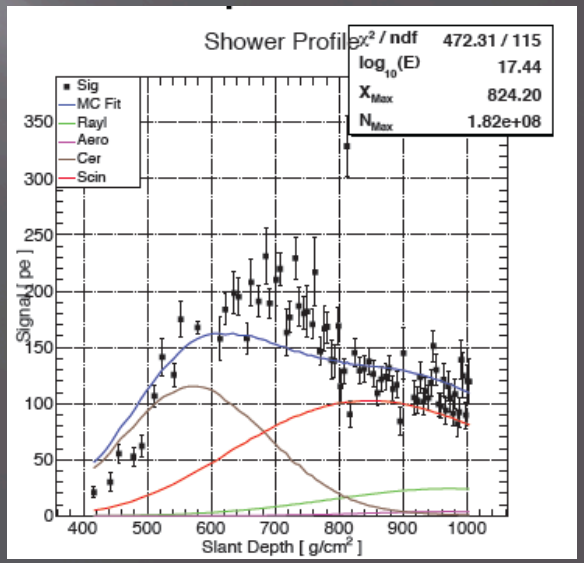




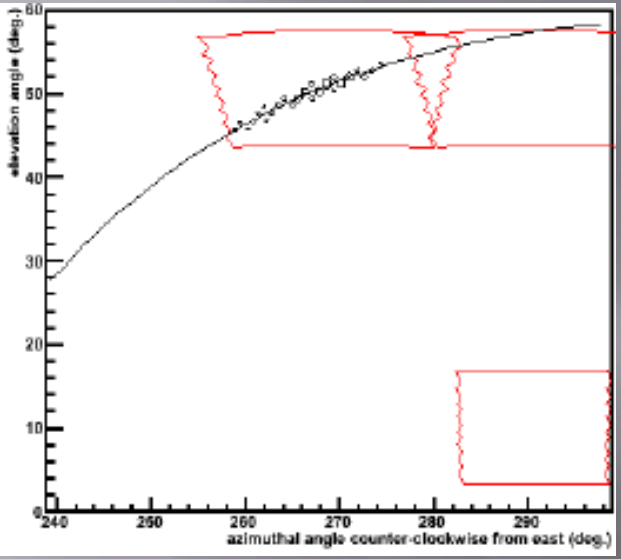
TALE

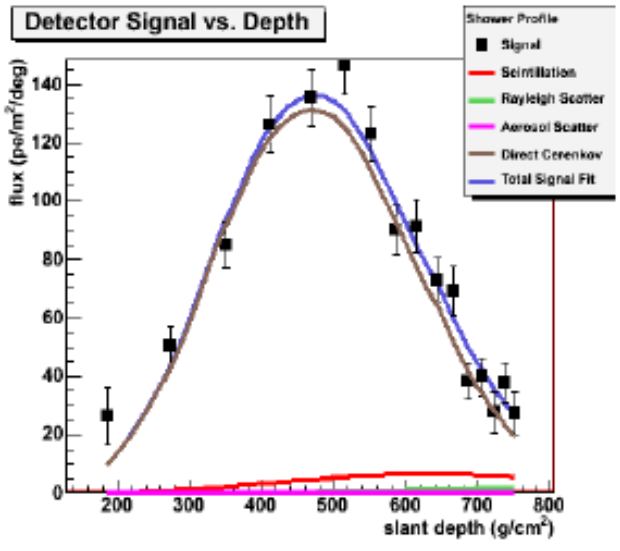
- Can use traditional fluorescence reconstruction allowing for additional direct Cherenkov contribution





TALE Cherenkov

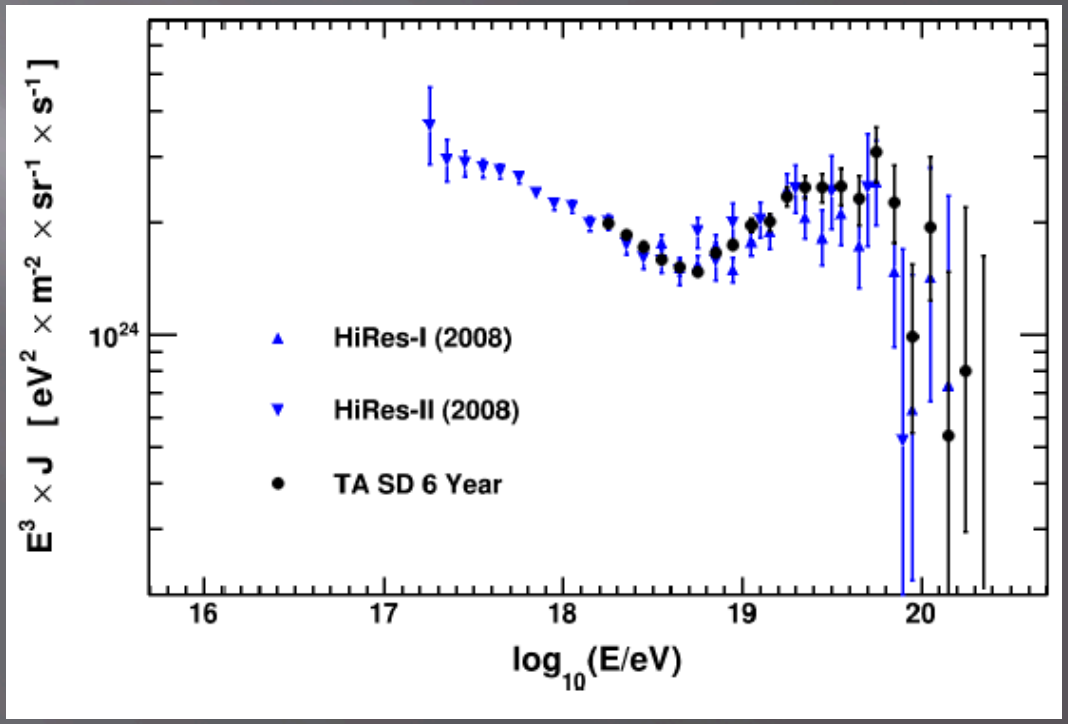




- Can also, surprisingly, look for events **dominated** by Cherenkov radiation
  - This makes TALE the IACT with the largest instantaneous aperture!
  - But not-so-great great resolution
  - Can't do photons, sorry

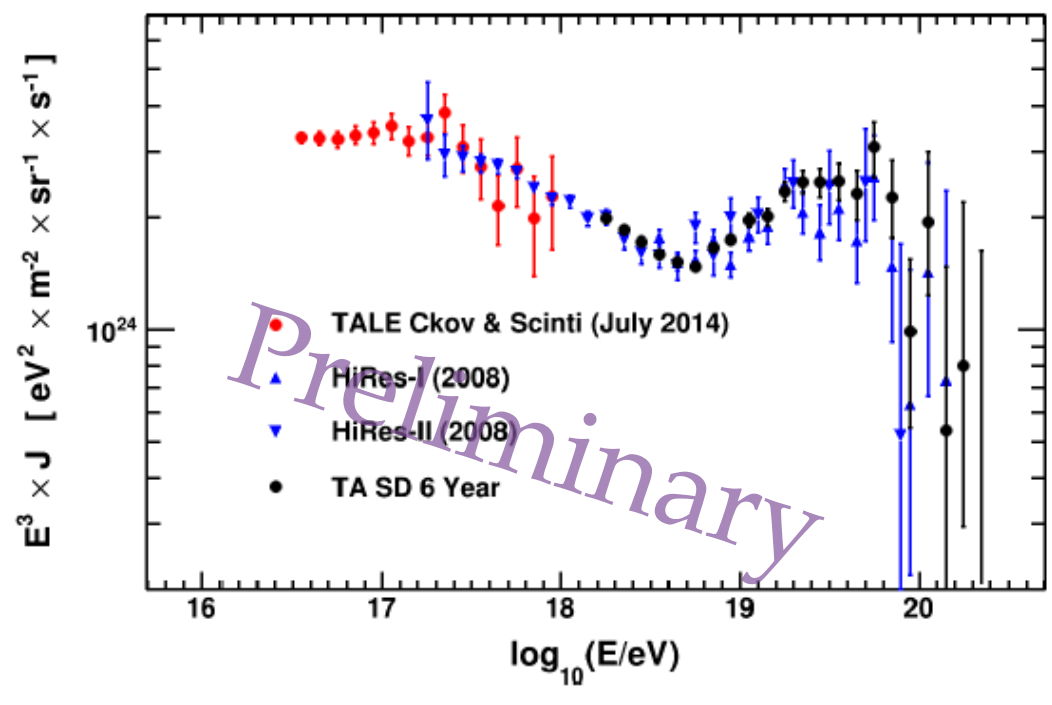
Spectrum

- TA (six-year) spectrum



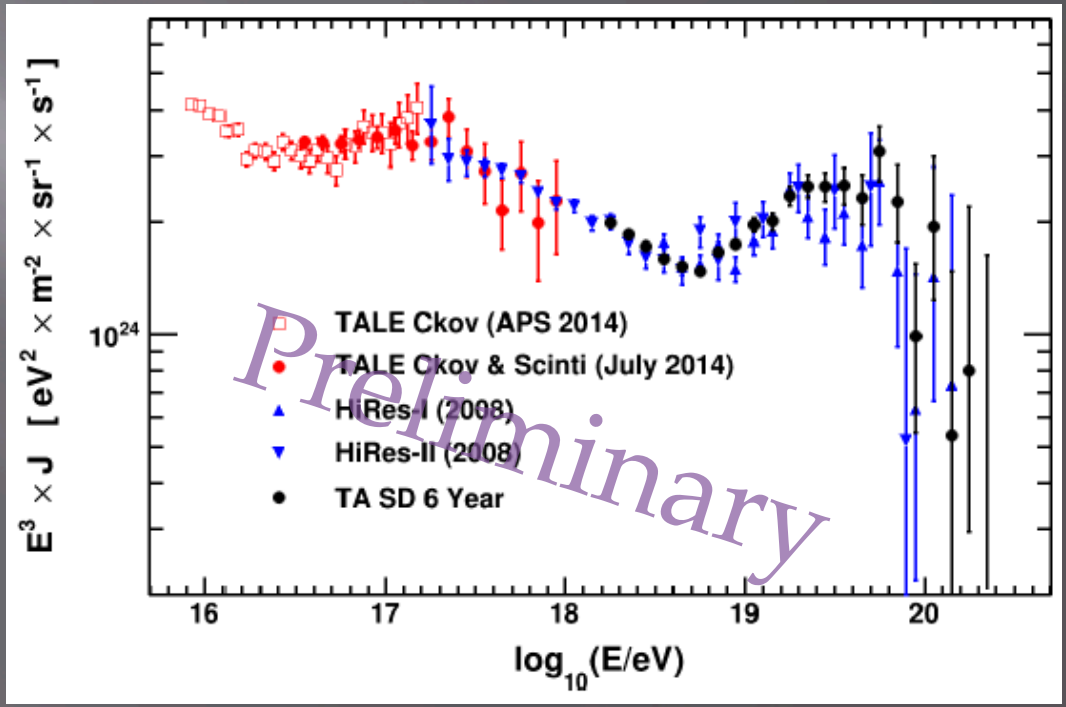
Spectrum

- TA (six-year) spectrum
- Three months of TALE fluorescence



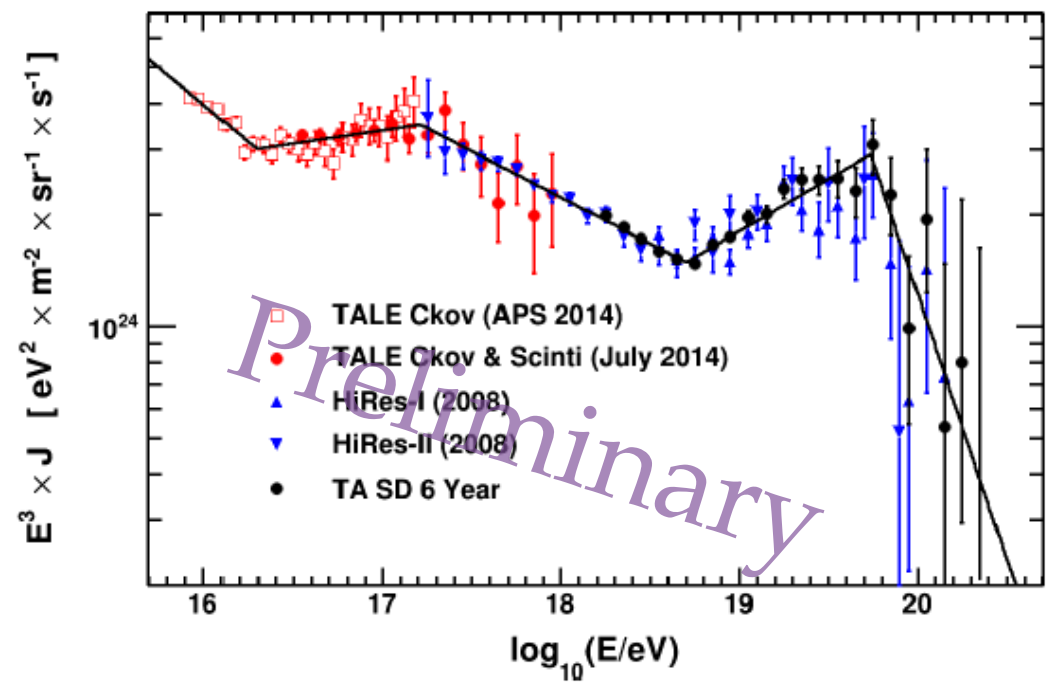
Spectrum

- TA (six-year) spectrum
- Three months of TALE fluorescence
- Three months of TALE Cherenkov



Spectrum

- TA (six-year) spectrum
- Three months of TALE fluorescence
- Three months of TALE Cherenkov
- 4.4 orders of magnitude in energy
  - Four features
- Nota bene: systematic uncertainties from composition (it's not all protons!) become very important



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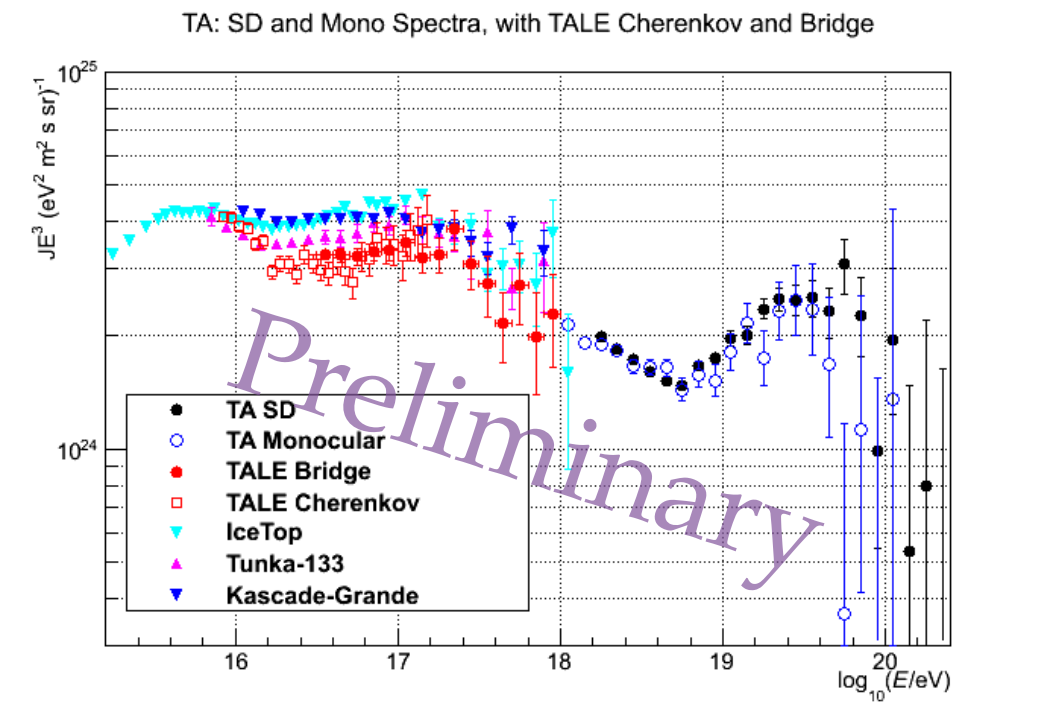
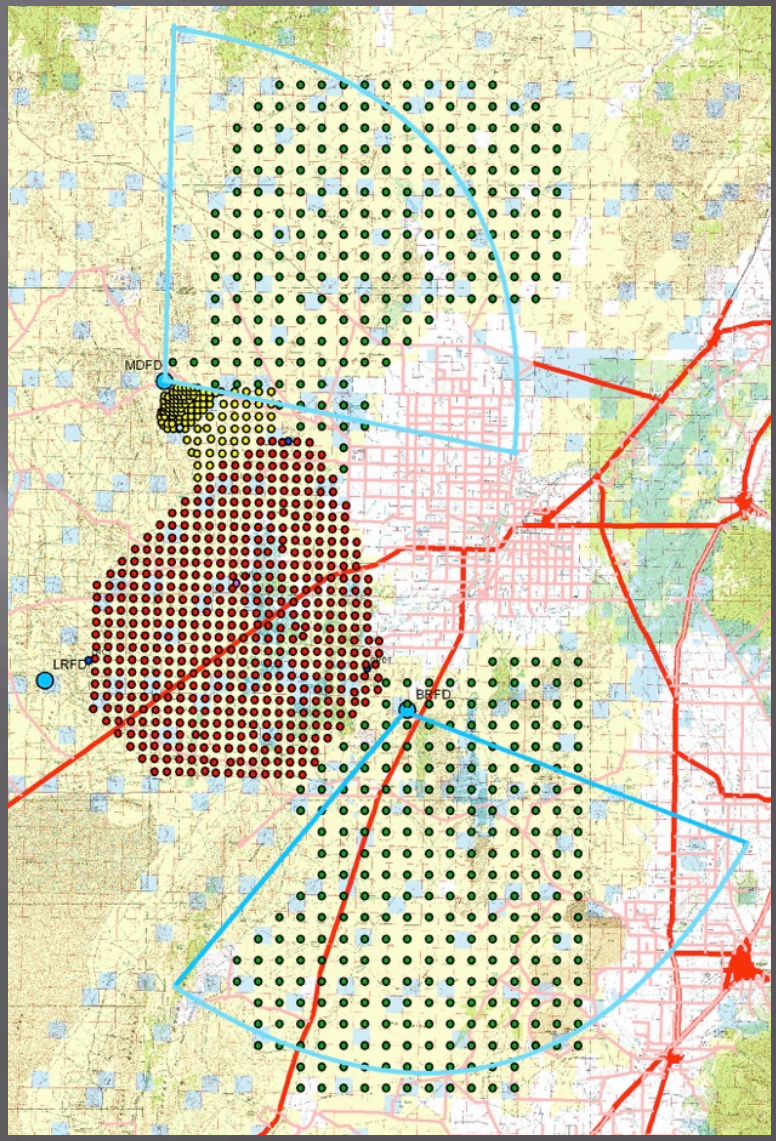


Future Plans

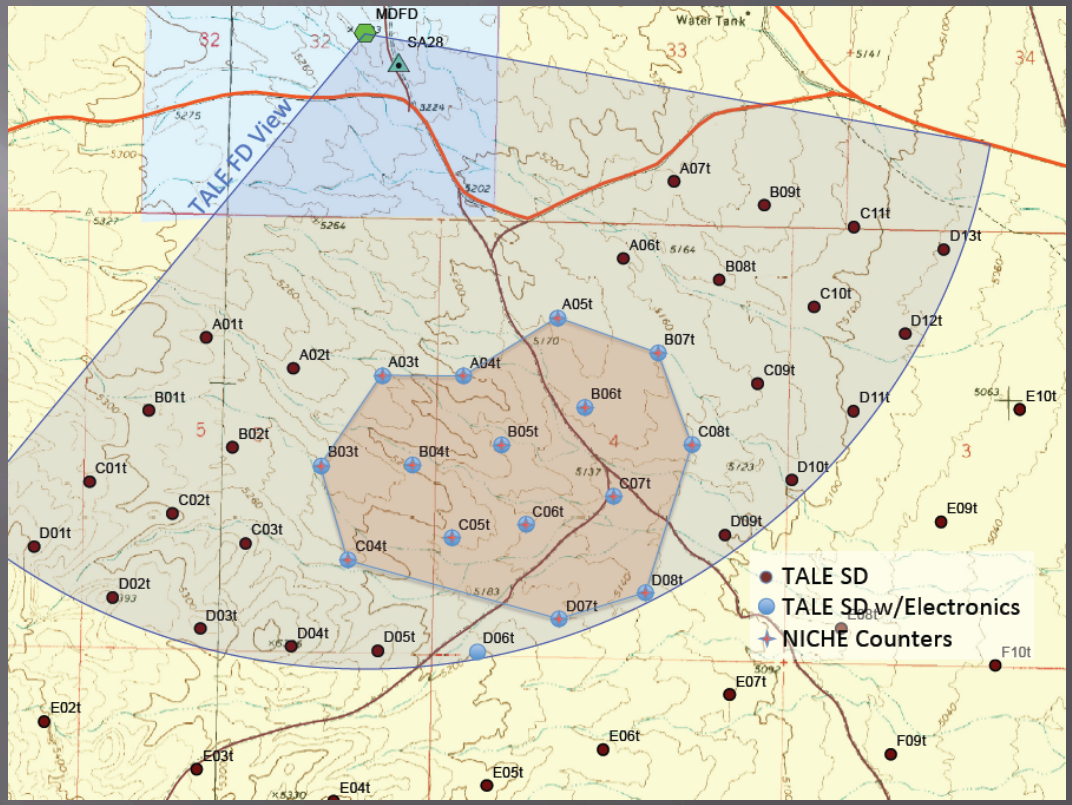
TAx4

- **Fourfold increase in size of TA.**
  - Add 500 SD counters, 2.08 km spacing.
  - Add two FD sites, 28 telescopes
- Get 20 TA-years by 2019: Definitive answer to hotspot question.
- $3.7M from JSPS to build SDs
  - Trying to get NSF funding for FD buildings



NICHE: Cherenkov Hybrid

- To go lower in energy than TALE, need to use Cherenkov light
- Aim to build a Non-Imaging CHErenkov array (NICHE) within the field-of-view of TALE.
- $188k from Kakenhi grant to Yoshiki Tsunesada
  - Build 15 counter prototype array



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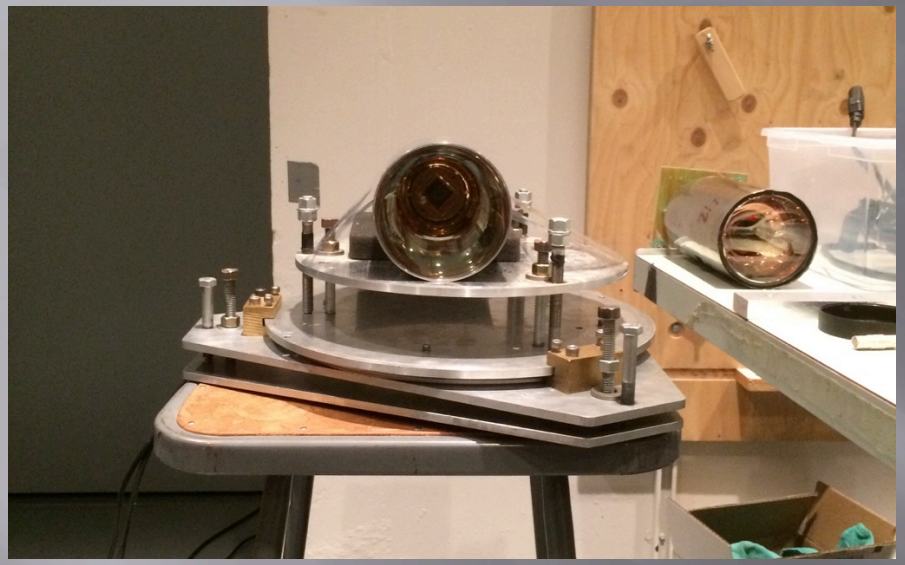
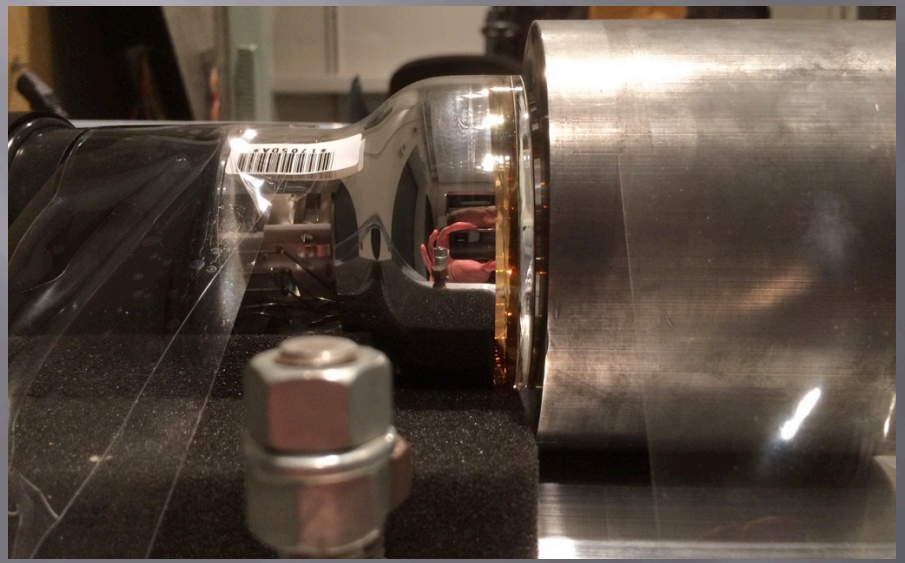
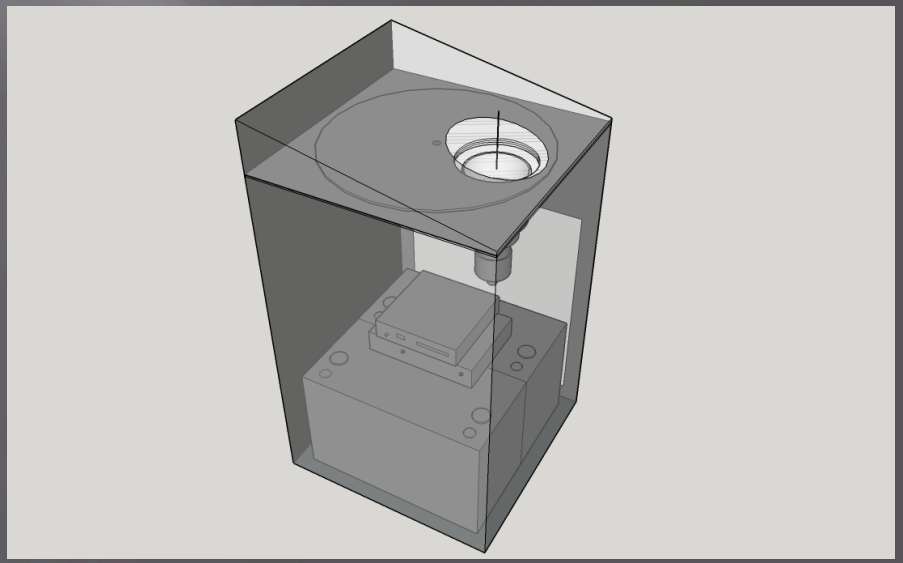
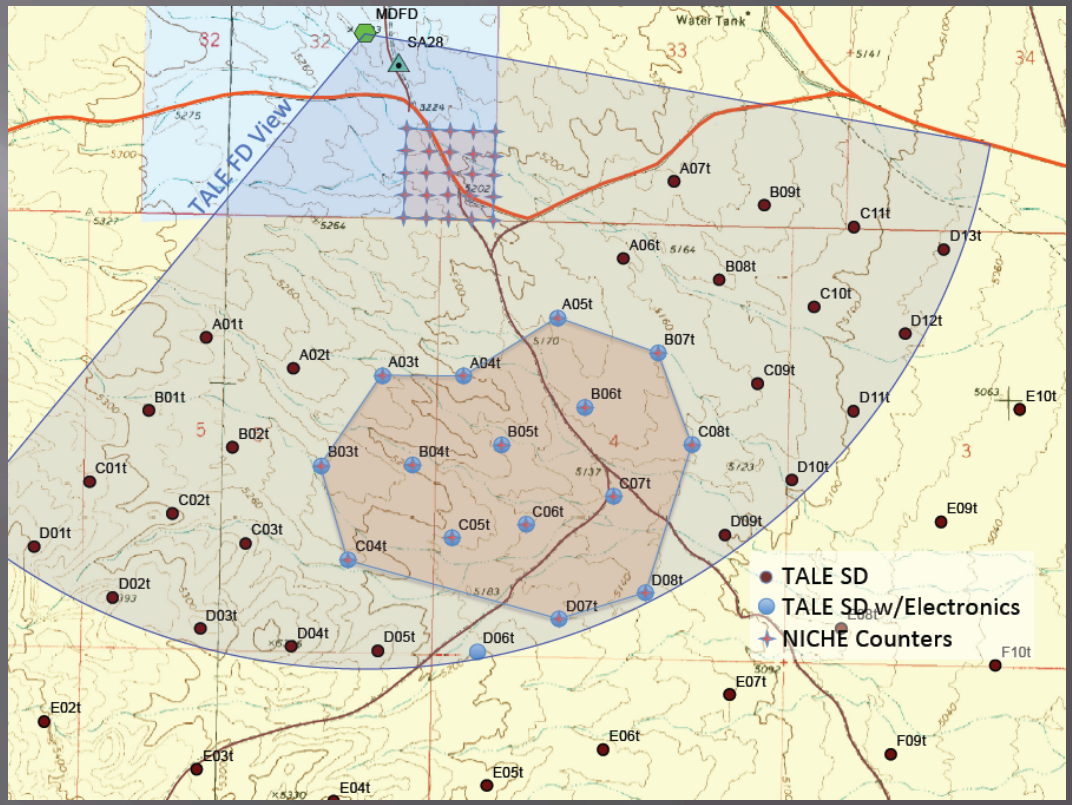






NICHE:

- Advent of TALE Cherenkov allows us to consider doing imaging-non-imaging Cherenkov hybrid
  - Since the goal is overlap at 10^{16} eV instead of 10^{17} eV need only a smaller array
  - Close spacing means better resolution and lower energy threshold
- Measure down to 10^{15} eV in standalone mode



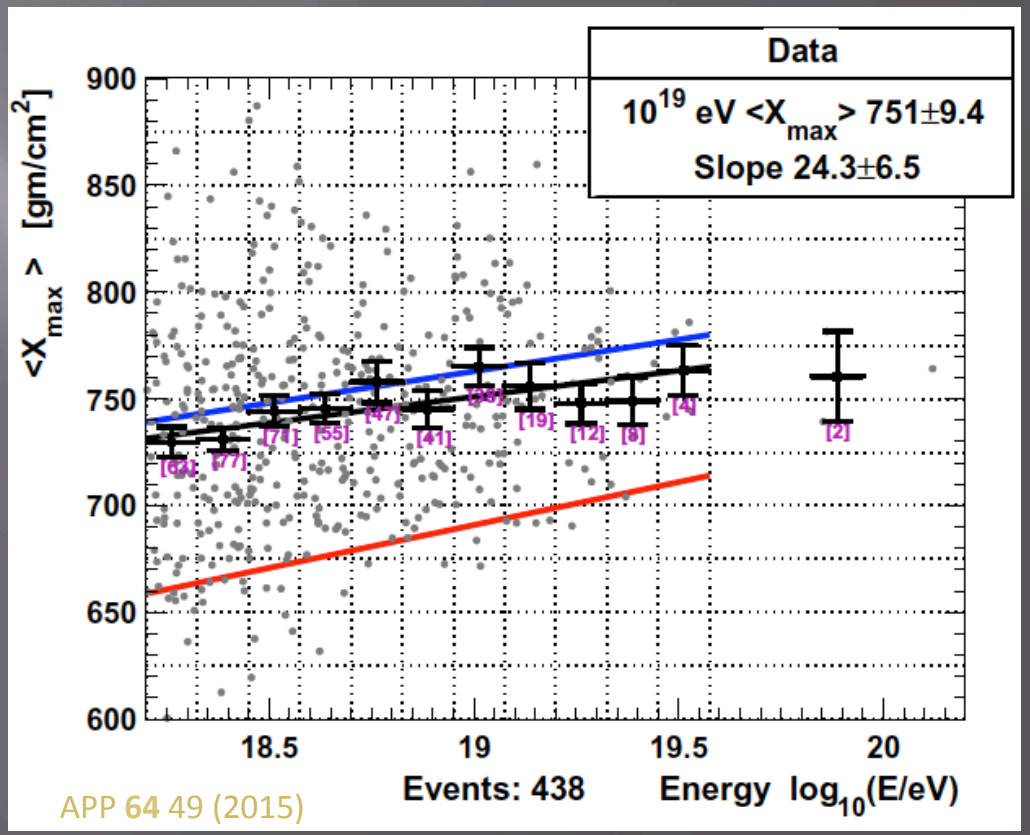
Summary

- Proton-like composition using the full shape of the X_{max} distribution (CvM test)
- Sixth year of anisotropy data increases significance of TA Hotspot to $4\,\sigma$
- Seventh year of TA data will be available in about a week. Expect updates at the ICRC
- With TALE and especially TALE Cherenkov we can measure the spectrum over 4.5 orders of magnitude
- Planned extensions at high energy, TAx4, and low energy, NICHE

Backup Slides

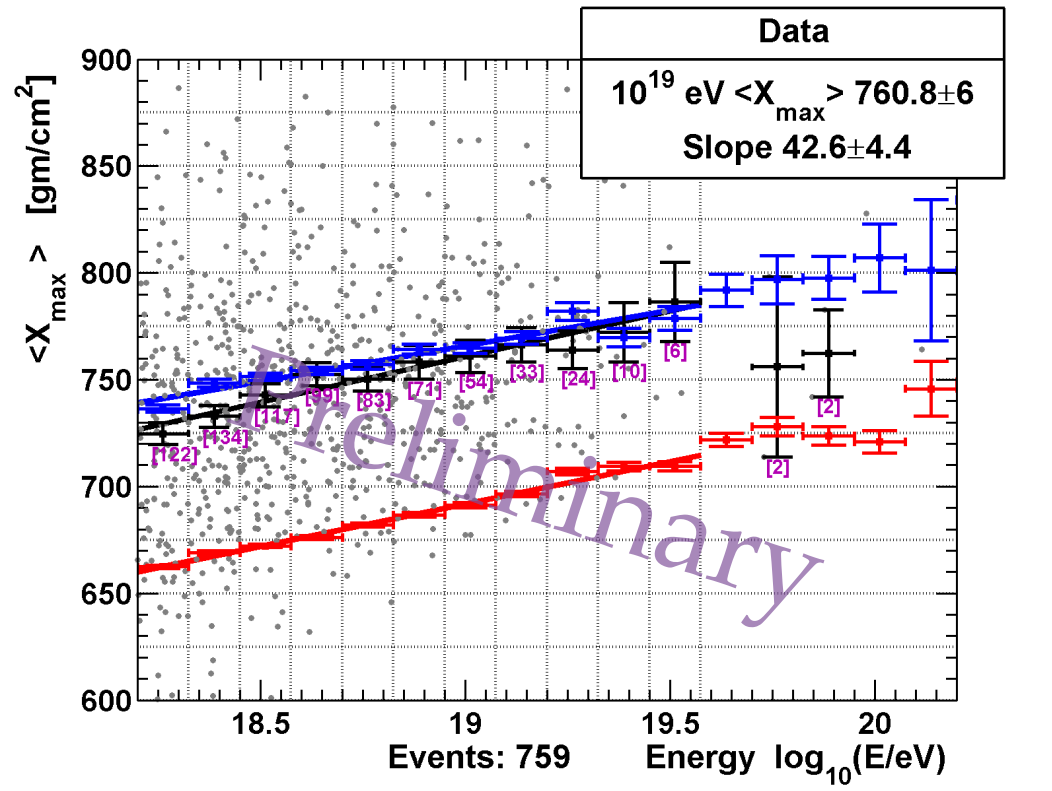
TA MD-Hybrid Composition

- Astroparticle Physics result



TA MD-Hybrid Composition

- New result with 6 years of data, quality factor cut



TA MD-Hybrid Composition

- New result with 6 years of data, quality factor cut
- Median