

Tests of anomalous correlations between UHECRs and BL Lacs with the Telescope Array data

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UHECR-2024, Malargüe, 18.11.2024

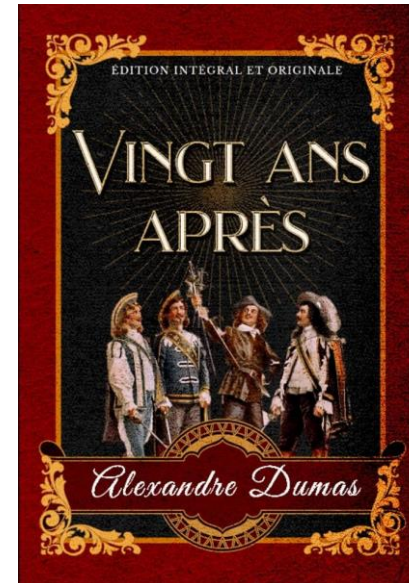


Cosmic rays can test models of fundamental physics (and not only in air showers!)

small-angle correlations
of HiRes stereo UHECRs
with distant BL Lac type
objects* (need new physics)
(2004)

*BL Lacs are a subclass of blazars,
that is of active galactic nuclei
with jets pointing to the observer

tests of the result with the
Telescope Array data
(20 years after)



interpretations and future

This analysis is supported by the Russian Science Foundation,
grant 22-12-00253

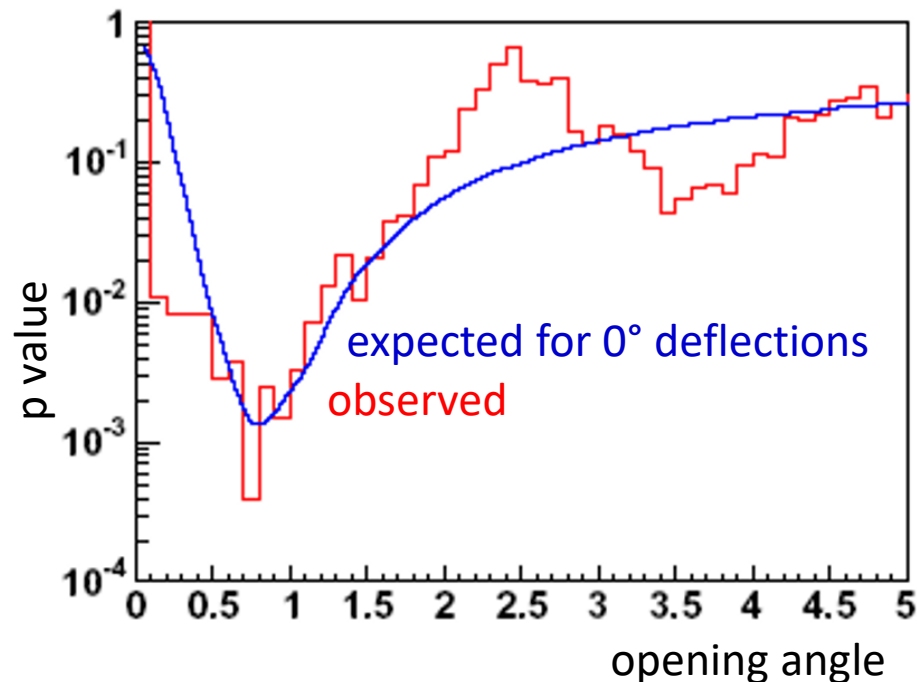


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HiRes stereo & BL Lacs above 10^{19} eV

pair counting



- 271 HiRes stereo events above 10^{19} eV (from a HiRes publication)
- angular resolution of 0.6°
- 156 BL Lac type objects (BLLs) from a pre-defined sample
- observed: **11** pairs “BLL-cosmic ray”
- expected for isotropy: ≈ 3 pairs
- post-trial p value = 10^{-3}

*Gorbunov, Tinyakov,
Tkachev, ST 2004*

deflections of protons in the Galactic magnetic field ~tens of degrees at 10^{19} eV,
much larger than the observed angular scale of associations



~8 of 271 events were caused by neutral particles from BLLs (?)



HiRes stereo & BL Lacs without energy cuts

likelihood ratio

TABLE 4
 HiRES — BL LAC CORRELATION SUMMARY: FRACTION \mathcal{F} OF
 SIMULATED HiRES SETS WITH STRONGER CORRELATION SIGNAL.

Source Sample (# Obj.)	All Energies	$E > 10 \text{ EeV}$
<u>“BL” Objects, $m < 18$ (157)</u>	2×10^{-4}	2×10^{-4}
Confirmed BL Lacs, $m < 18$ (204)	5×10^{-4}	10^{-5}
Confirmed TeV Blazars (6)	10^{-3}	2×10^{-4}

NOTE. — All samples are contained within Table 2 of the Veron 10th Catalog. The samples overlap and are *not* independent: “Confirmed BL Lacs” combines “BL” and “HP” classified BL Lacs; TeV Blazars are a subset of the confirmed BL Lacs.

- full HiRes stereo data set (internal)
- angular resolution event-by-event
- the same pre-defined sample of 156 ± 1 BLLs
- number n_s of events from BLLs as the L ratio parameter
- best-fit $n_s=9$, p-value = 2×10^{-4} for $E > 10^{19}$ eV
- best-fit $n_s=31$, p-value = 2×10^{-4} for all energies

HiRes 2006



~31 of 4495 HiRes stereo showers, of which ~9 of 271 above 10^{19} eV, were caused by neutral particles from BLLs (?)



Why anomalous?

neutral particles from distant sources

deflections of protons in the Galactic magnetic field $>10^\circ$ at 10^{19} eV,
much larger than the observed angular scale of associations (0.6°)



~31 of 4495 events, of which ~9 of 271 events above 10^{19} eV,
came from BLLs without deflections

but

BLLs are 150 Mpc to several Gpc away

Tinyakov&Tkachev 2008

no explanation
within the Standard Model
of particle physics



more tests needed!

- Galactic magnetic field models wrong (holes)?
 - not supported by observations
- neutrons? - decay much faster even at these energies
- photons? – produce pairs on cosmic background light
- neutrinos? – very different air showers
- secondary neutrons? flux ~100 times lower than required



Since then, no conclusive tests so far. Why?

HiRes stereo angular resolution remains unsurpassed

Same HiRes data, various approaches –

Gorbunov, Tinyakov, Tkachev, ST 2004,

HiRes 2006,

Jansson&Farrar 2008,

Kudenko&ST 2024, –

give similar results

with p-values between $\sim 10^{-5}$ and $\sim 10^{-3}$

- background grows as angular resolution squared, while the signal remains constant
- sensitivity depends on the field of view and number of cosmic-ray events
- estimates of future tests (assuming optimistic angular resolutions...)

Gorbunov, Tinyakov, Tkachev, ST 2006

Auger ICRC 2007 –

1672 SD events with $E > 10^{19}$ eV,
no correlation found ($p=0.67$)

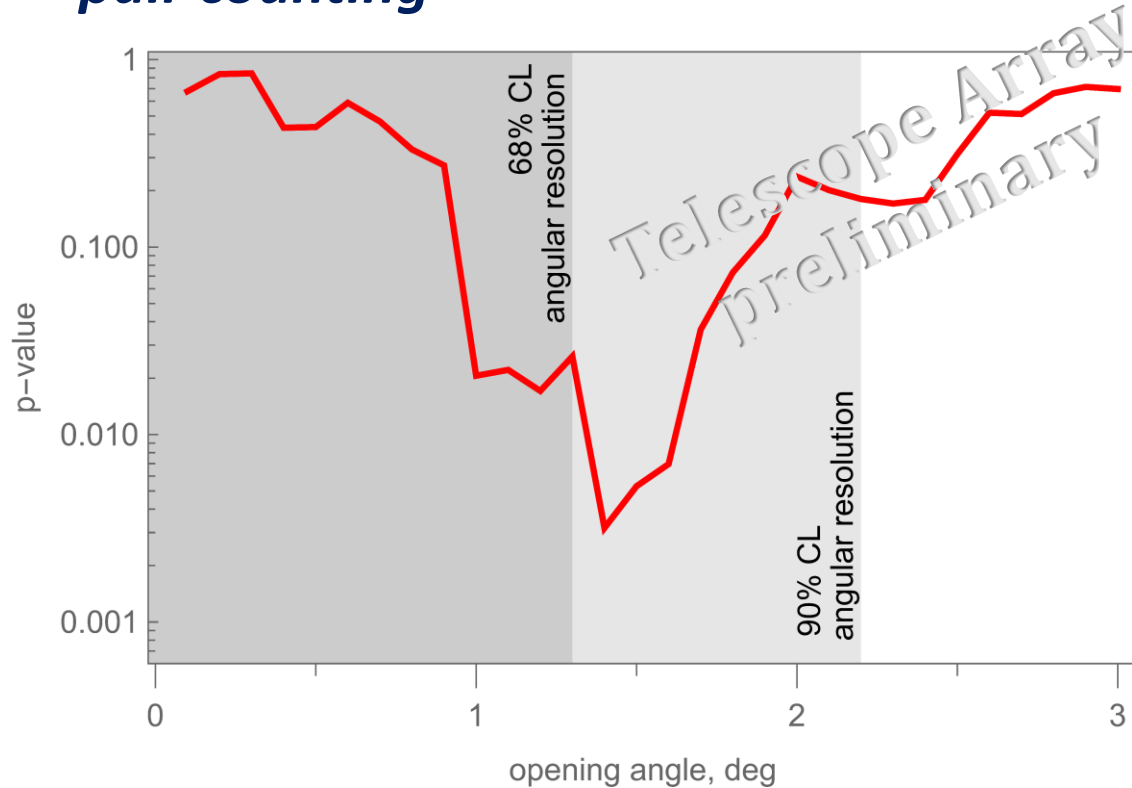
Auger 2007

- 1672 events used, 3500 required for the test
- different baseline energy scale with HiRes
- completely different energy scale for exotic primaries (e.g. photons *Billoir, Roucelle, Hamilton 2007;*
Kalashov, Rubtsov, ST 2009)



Telescope Array SD & BL Lacs above 10^{19} eV

pair counting



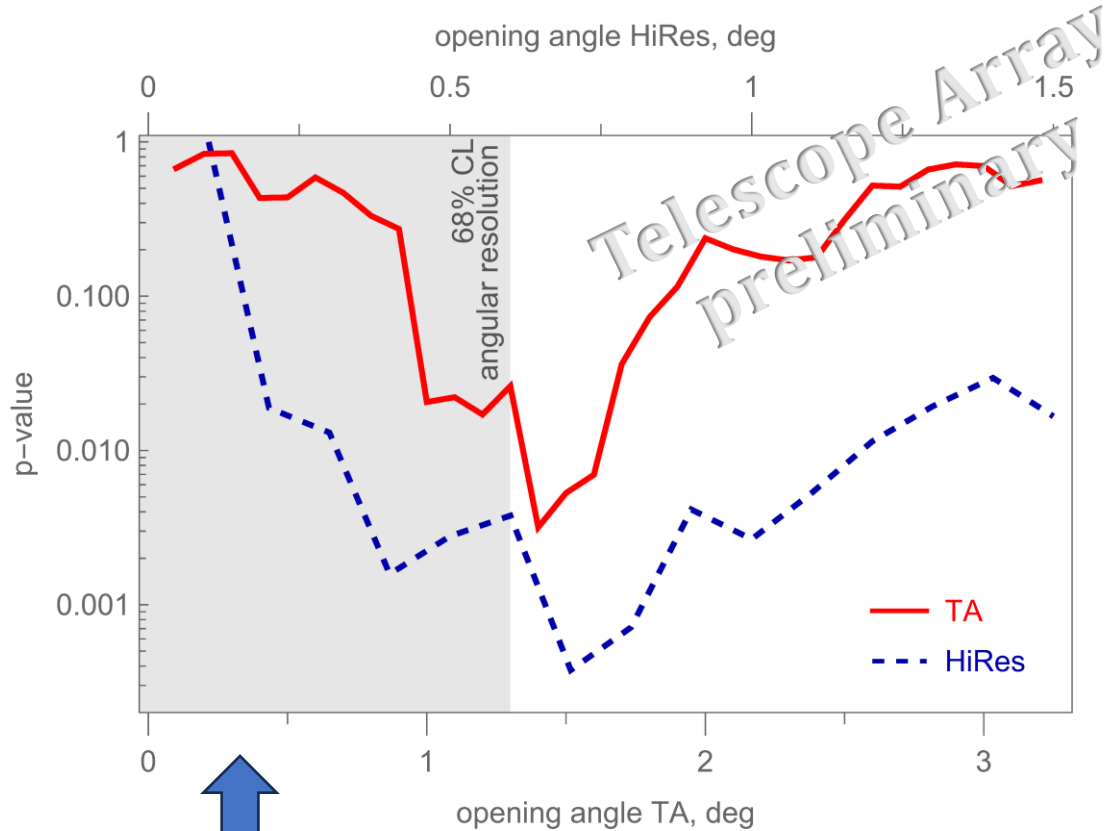
- 6712 TA SD events above 10^{19} eV (16 years, «anisotropy cuts»)
- angular resolution of 1.3°
- 156 BL Lac type objects (BLLs) – the sample studied by HiRes
- min p-value = 3×10^{-3} at opening angle = 1.4°
- observed: **279** pairs, expected for isotropy: ≈ 235 pairs
- at expected angle 1.3° , p-value = 1.7×10^{-2}
- free opening angle as trials, post-trial p-value = 3×10^{-2}

BL Lac / cosmic ray association, observed in HiRes data in 2004, shows up in TA



Telescope Array SD & BL Lacs above 10^{19} eV

is the signal consistent with HiRes?



opening angles **scaled** to 68% CL resolutions

fraction of excess events from BLLs in the data set:

Data set	fraction, %	68% CL	95% CL
HiRes stereo	3.0	± 1.2	$+2.7$ -2.0
TA SD	0.66	± 0.25	$+0.50$ -0.47

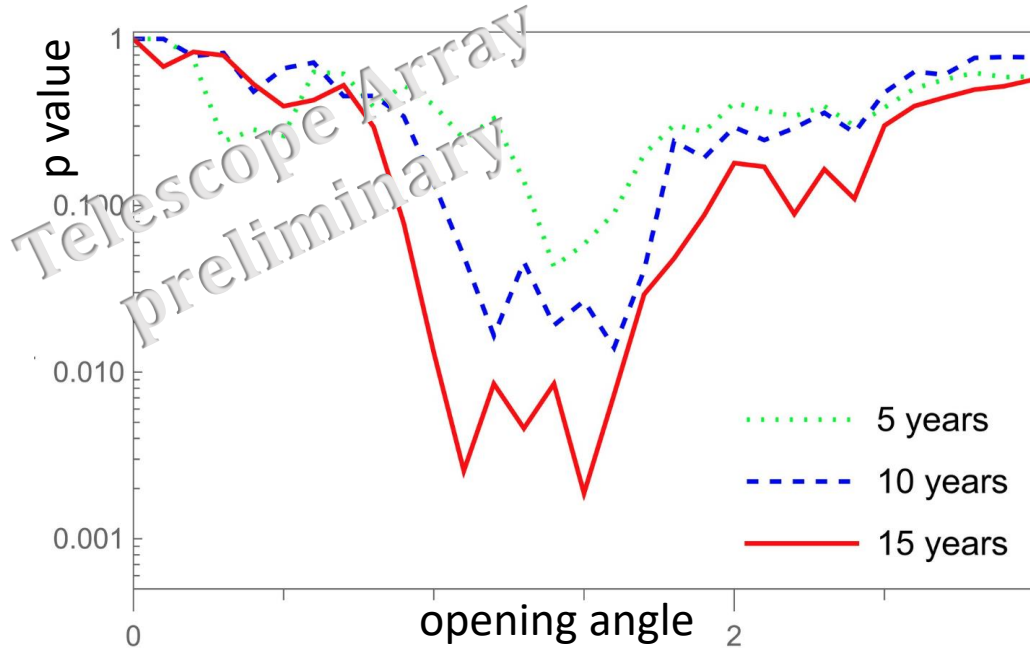


consistent but weaker



Telescope Array SD & BL Lacs above 10^{19} eV

why the signal builds up so slowly = why it is weaker than with HiRes?



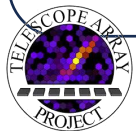
- “usual” primaries cannot explain the effect
- “unusual” primaries should have unusual detector response
- these unusual responses are very different for different detectors
- for a small fraction of unusual events, the primary energy estimate is biased
- if attributed to lower energies, unusual events are lost in energy-limited data sets

well-known example: primary gamma rays (muon-poor showers)

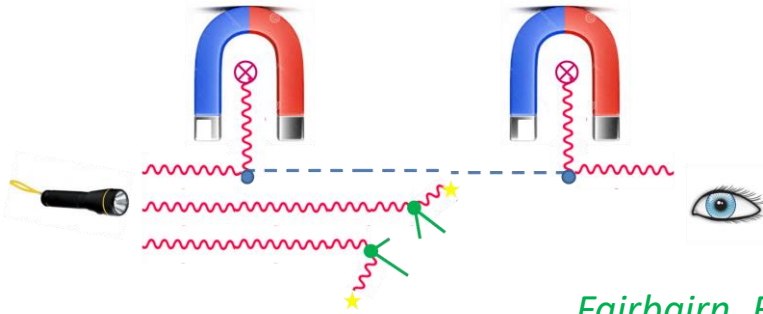
HiRes: FD only

TA SD: scintillators

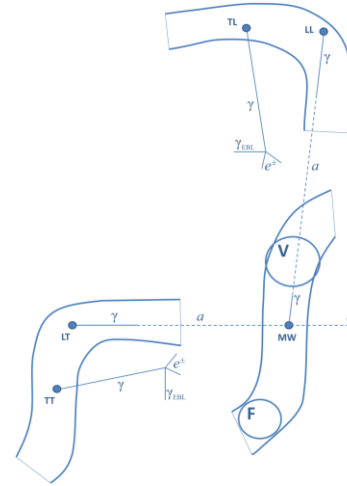
Auger: water tanks



Possible interpretations *new particle physics*



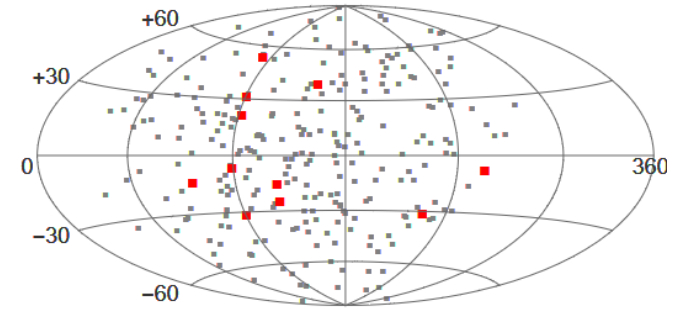
Fairbairn, Rashba, ST 2009



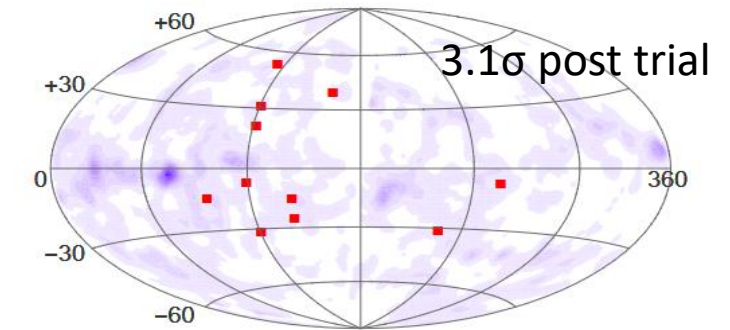
- **axion-like particles (ALP):** “Shining light through the Universe”
- gamma rays convert to inert ALPs and back in cosmic magnetic fields (LSS)
- ALP parameters favored from stellar evolution and GRB 221009A
Ayala et al. 2014; ST 2024 *Galanti et al. 2022; ST 2022, 2023*
- prediction: gamma-ray primaries
- prediction: LSS-related anisotropy of correlations

- **neutral supersymmetric hadrons** *Farrar 1996; Albuquerque, Farrar, Kolb 1999*
- **mirror neutrons** *Berezhiani&Bento 2006*

BLL-associated vs. all HiRes events



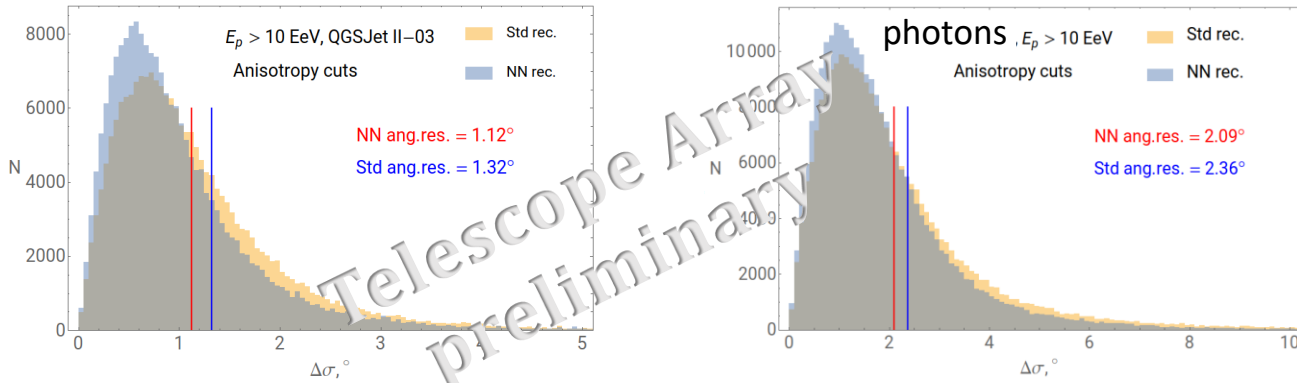
supergalactic coordinates *ST 2020*



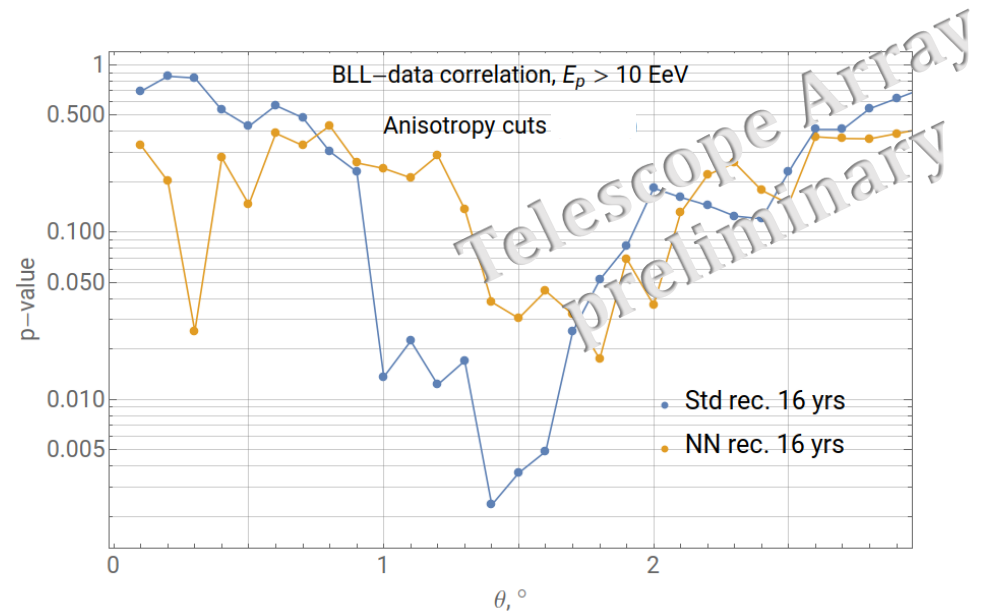
BLL-associated HiRes events and LSS



Future: angular resolution is the key neural networks in TA SD



Ivanov et al. 2021; Telescope Array ICRC 2021



- neural network is being trained with QGSJET II.04 p+Fe mix
- improved angular reconstruction for different MC models and primaries, even photons
- no serious improvement in SD/stereo comparison yet
- weaker BLL correlations in this reconstruction, see plot
- penalty factor for the use of two reconstructions = 1.6, $p=0.048$
- **work in progress**



Future: lots to do in TA

work in progress

- stereo reconstruction: angular resolution worse than in HiRes because of the distance between detectors, started work to improve
- lower energies and event-by-event angular resolution
- sky map and LSS correlations
- primary composition of BLL-associated events (photons?..)

Results are coming soon. Stay tuned!



Conclusions

- ✓ Anomalous directional correlations with BL Lacs are seen in TA data, 20 years after HiRes
- ✓ Imply $(0.66 \pm 0.25)\%$ of the cosmic-ray flux above 10^{19} eV are neutral particles from very distant sources, need new physics
- ✓ Angular resolution and FD-only reconstruction are the key to future tests

