Particle Physics at the Highest Energies

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December 4, 2014

VANDERBILT
UNIVERSITY

Other Projects

Papers collaborated on:

Quantum black holes: detecting low scale gravity using extensive air showers.

Higgs portal $\to \Delta N_{\rm eff}$ and dark matter.

Projects in progress:

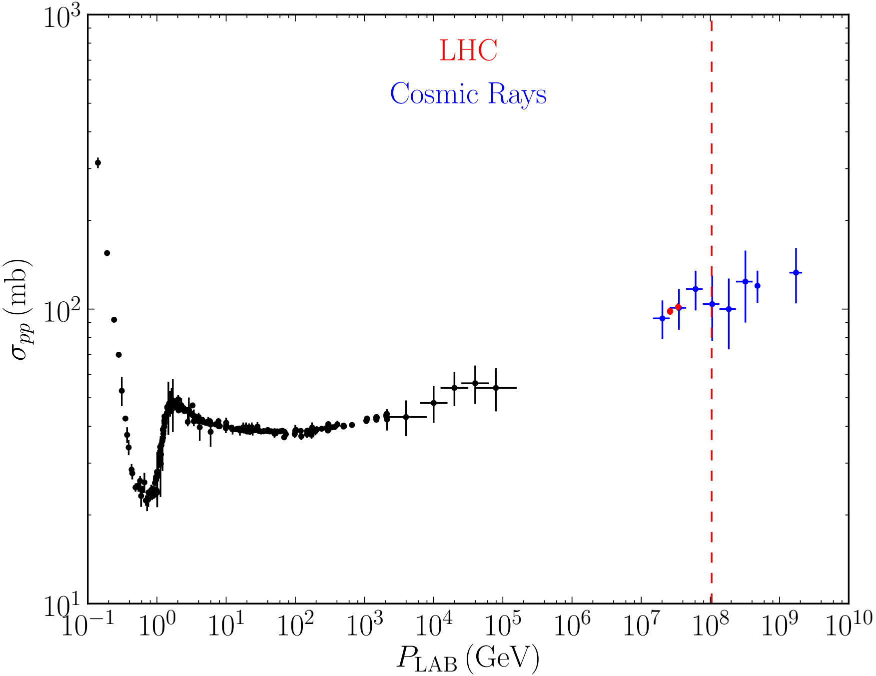
Neutrino energy cutoff $\Rightarrow \pi^\pm$ stability.

Nuetrino anisotropy.

Extending the Reach of the LHC with Integral Dispersion Relations

and

Cosmic Ray Anisotropies


LHC
Cosmic Rays
σ_{pp} (mb)
P_{LAB} (GeV)
10^1
10^2
10^3
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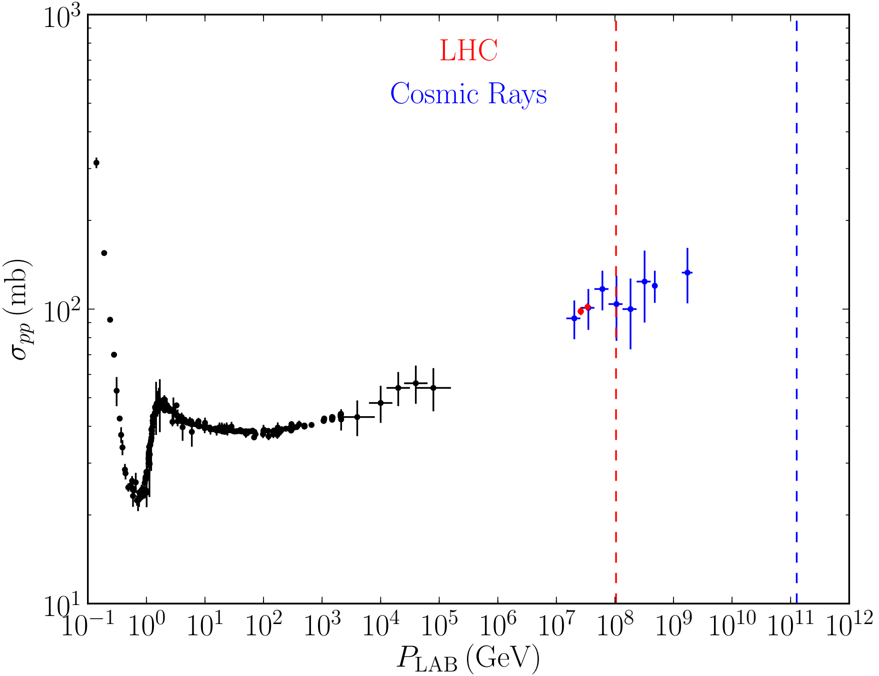
LHC
Cosmic Rays
σ_{pp} (mb)
10^3
10^2
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10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12}
P_{LAB} (GeV)

Extending the Reach of the LHC with Integral Dispersion Relations

and

Cosmic Ray Anisotropies

New Physics at the LHC

Nobel prize for "old" physics found at the LHC.

Nothing "new" (BSM) at the LHC yet.

New physics is constrained to $\mathcal{O}$(few) TeV.

Suppose there is new physics near (above or below) 14 TeV...

About Integral Dispersion Relations: Key Formulas

Cauchy's integral formula:

$$f(z') = \frac{1}{2\pi i} \oint_{\partial A} \frac{f(z)}{z - z'} dz$$

The optical theorem:

$$\sigma_{\text{tot}} = \frac{4\pi}{p} \Im f(\theta = 0)$$

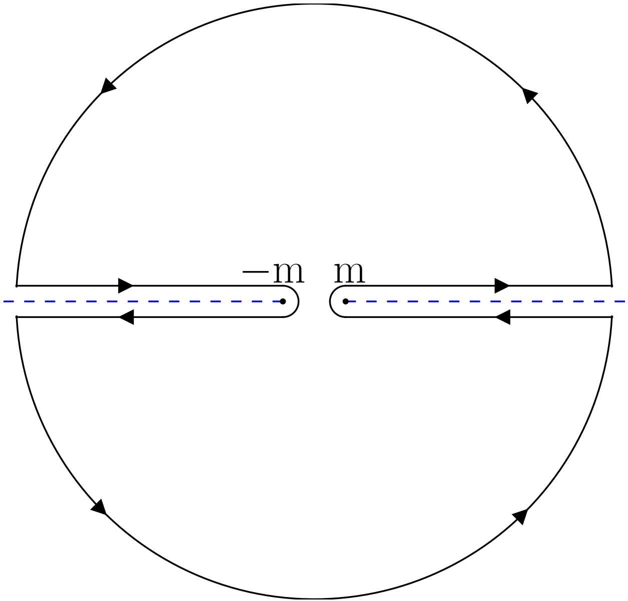
Froissart bound:

$$\sigma_{\text{tot}}(E) \leq C \log^2(E/E_0)$$

Definitions:

$$\rho(E) \equiv \frac{\Re f(E, t = 0)}{\Im f(E, t = 0)} \qquad E \equiv \frac{s - u}{4m} \qquad f_\pm = \frac{1}{2}(f_{p\bar{p}} \pm f_{pp})$$

About Integral Dispersion Relations: Integration Contour



About Integral Dispersion Relations: Subtraction

Cauchy + Integration Contour + Reflection Identities:

$$\Re f_+(E) = \frac{1}{\pi}\mathcal{P}\int_{m_p}^{\infty} dE' \Im f_+(E') \frac{2E'}{E'^2 - E^2}$$

$$\Re f_-(E) = \frac{1}{\pi}\mathcal{P}\int_{m_p}^{\infty} dE' \Im f_-(E') \frac{2E}{E'^2 - E^2}$$

The first integrand scales like $\sigma_{\rm tot}(E')$.

Integral won't converge and the outer circle $\not\to 0$.

Need a subtraction to reduce the power: add a pole.

$$\Re f_+(E) = \Re f_+(0) + \frac{1}{\pi}\mathcal{P}\int_{m_p}^{\infty} dE' \Im f_+(E') \frac{2E^2}{E'(E'^2 - E^2)}$$

New constant $f(0)$ - not physical.

Integral Dispersion Relations

Subtraction + optical theorem:

$$\rho_{pp}(E)\sigma_{pp}(E) = \frac{4\pi}{p}\Re f(0) + \frac{E}{p\pi}\mathcal{P}\int_{m_p}^{\infty} dE' \frac{p'}{E'}\left[\frac{\sigma_{pp}(E')}{E'-E} - \frac{\sigma_{p\bar{p}}(E')}{E'+E}\right]$$

$$\rho_{p\bar{p}}(E)\sigma_{p\bar{p}}(E) = \frac{4\pi}{p}\Re f(0) + \frac{E}{p\pi}\mathcal{P}\int_{m_p}^{\infty} dE' \frac{p'}{E'}\left[\frac{\sigma_{p\bar{p}}(E')}{E'-E} - \frac{\sigma_{pp}(E')}{E'+E}\right]$$

Since $\lim_{E'\to\infty}\sigma(E')/E' \to 0$, outer circle $\to 0$.

For integral to converge need $|\sigma_{pp} - \sigma_{p\bar{p}}| \to 0$.

Experimentally $|\sigma_{pp} - \sigma_{p\bar{p}}| \propto s^{-0.5}$: fast enough (Pomeranchuk).

From data, $f(0)$ is small (contributes < 1 part in 10^5 to ρ).

IDRs allow for the calculation of ρ in a model dependent way.

Integral Dispersion Relations: Simple Cross Section

An analytic calculation requires several simplifications:

$$\sigma_{pp}(E) \to \sigma_0 \leftarrow \sigma_{p\bar{p}}(E)$$

$$m_p \to 0$$

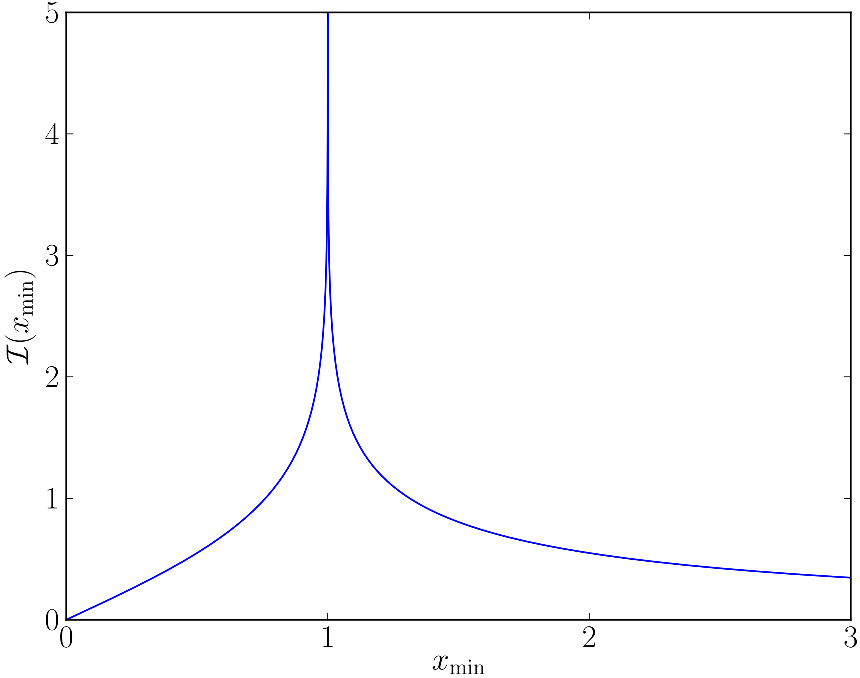
Then,

$$\rho = \frac{2}{\pi}\mathcal{P}\int_0^\infty \frac{dx}{x^2-1} = 0$$

$$x \equiv E'/E.$$

Modifying the cross section with a step increase at $E'_{\min}, x_{\min}$,

$$\mathcal{I}(x_{\min}) \equiv \int_{x_{\min}}^\infty \frac{dx}{x^2-1} > 0$$


5
4
3
2
1
0
0
1
2
3
$\mathcal{I}(x_{\rm min})$
$x_{\rm min}$

Cross Section Modifications

Return $\sigma_{\rm tot} \propto \log^2 E$ and $m_p \neq 0$.

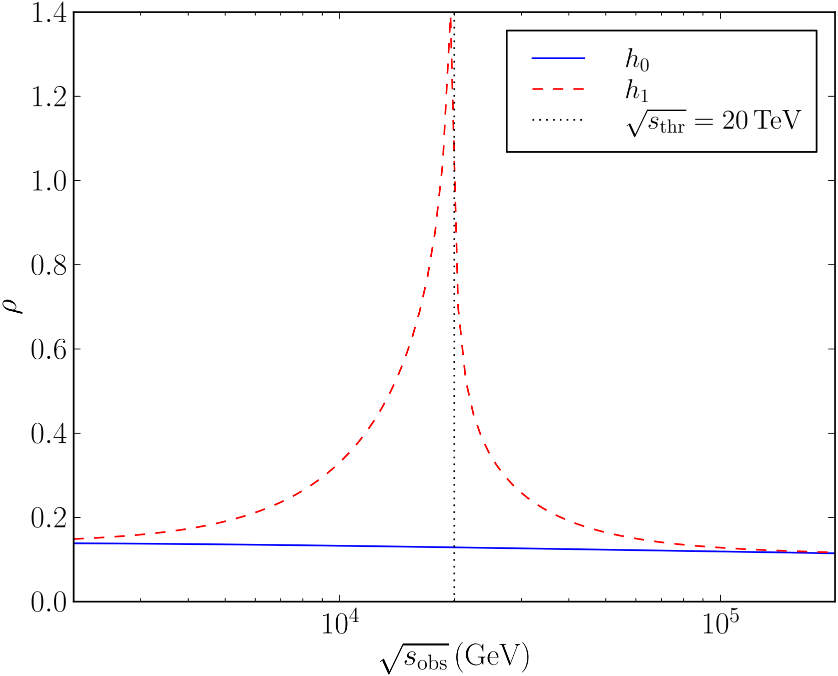
Consider modification of the general form,

$$\sigma(E) = \sigma_{\rm SM}(E)[1 + h(E)]$$

where $h(E) = 0$ for $E < E_{\rm thr}$.

The simplest such modification is $h(E) = D\Theta(E - E_{\rm thr})$.

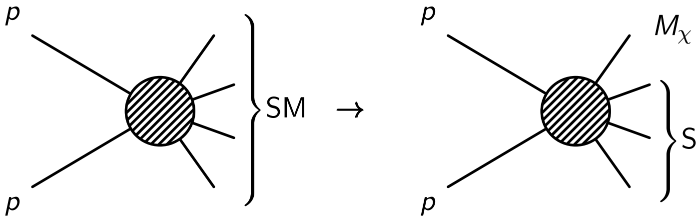
That is, the cross section doubles at $E = E_{\rm thr}$ for $D = 1$.



1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
ρ
10^4
10^5
$\sqrt{s_{\rm obs}}\,(\rm GeV)$
h_0
h_1
$\sqrt{s_{\rm thr}} = 20\,\rm TeV$

More Physical Modifications

RPV SUSY: Replace one final state particle with a heavier partner.



More Physical Modifications: Parton Approach

We reduce the cross section by a phase space ratio given by

$$\sqrt{\frac{\lambda(\hat{s},M_\chi^2,0)}{\lambda(\hat{s},0,0)}}=1-\frac{M_\chi^2}{\hat{s}}$$

We integrate this in terms of the pdfs

$$h_2(s,M_\chi)=z\sum_{i,j}\int_{x_1x_2>M_\chi^2/s}dx_1dx_2$$
$$\times f_i(x_1,M_\chi)f_j(x_2,M_\chi)x_1x_2\left(1-\frac{M_\chi^2}{\hat{s}}\right)$$

where $z=\sigma_{inel}/\sigma_{tot}\sim 0.7$.

More Physical Modifications: Diffractive Approach

Cut final states into two blocks by pseudorapidity and we let M_X be the mass of the more massive one. Let $\xi \equiv M_X^2/s$.

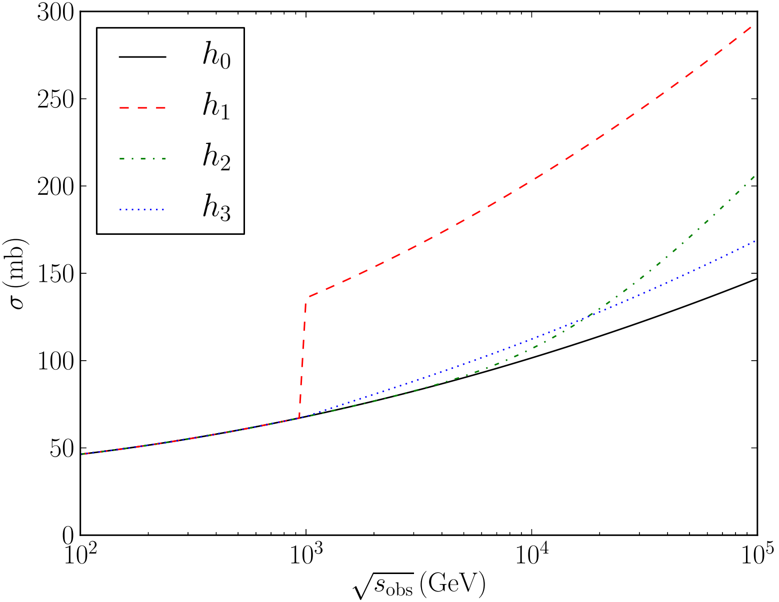
$$\frac{d\sigma}{d\xi} = \frac{1+\xi}{\xi^{1+\epsilon}} \qquad \epsilon \sim 0.08$$

The bounds on the above integral change from SM $\to$ new physics,

$$h_3(s) = z\frac{1-2\epsilon+(\epsilon-1)\xi_\chi^{-\epsilon}+\epsilon\xi_\chi^{1-\epsilon}}{1-2\epsilon+(\epsilon-1)\xi_p^{-\epsilon}+\epsilon\xi_p^{1-\epsilon}}\Theta(1-\xi_\chi)$$

$$\lim_{s\to\infty} h_3(s) = z\left(\frac{m_p}{M_\chi}\right)^{2\epsilon} \approx 0.23\left(\frac{1\,\mathrm{TeV}}{M_\chi}\right)^{2\epsilon}$$

Total Cross Section Modifications



Measuring ρ at the LHC

Most cited values of ρ are calculated from IDRs.

It is possible to measure ρ in a model independent fashion.

$$\frac{d\sigma}{dt} = \frac{\pi}{k^2}|f|^2 \qquad \frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{Bt}$$

B is the measured slope parameter, valid at low $|t|$.

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{\pi}{k^2}\left|(\rho+i)\Im f(t=0)\right|^2 = \frac{\rho^2+1}{16\pi}\sigma_{\rm tot}^2$$

Measuring $\sigma_{\rm tot}$ without ρ is difficult.

Requires an accurate luminosity measurement.

Moreover $\sigma_{\rm tot}$ only weakly depends on ρ.

Experimental Status

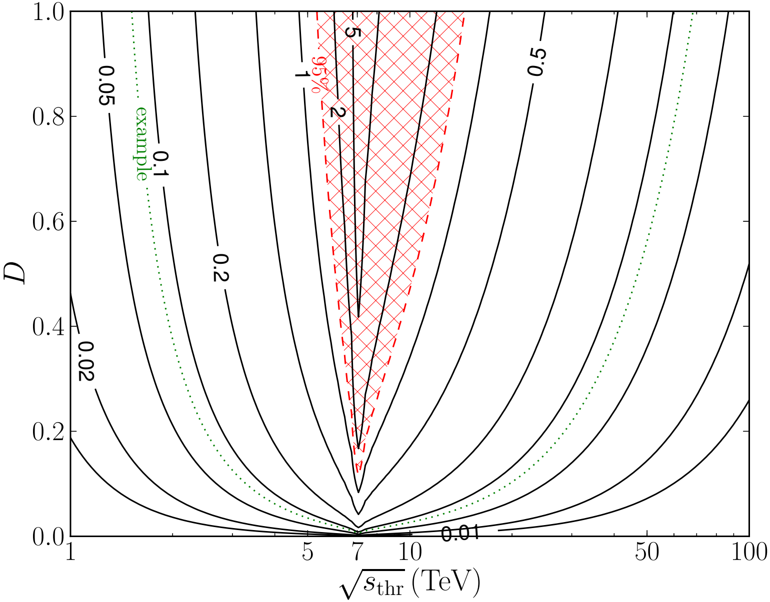
TOTEM: $\rho = 0.145$ at $\sqrt{s} = 7$ TeV (large errors).

SM Prediction: $\rho = 0.1345$ at $\sqrt{s} = 7$ TeV.

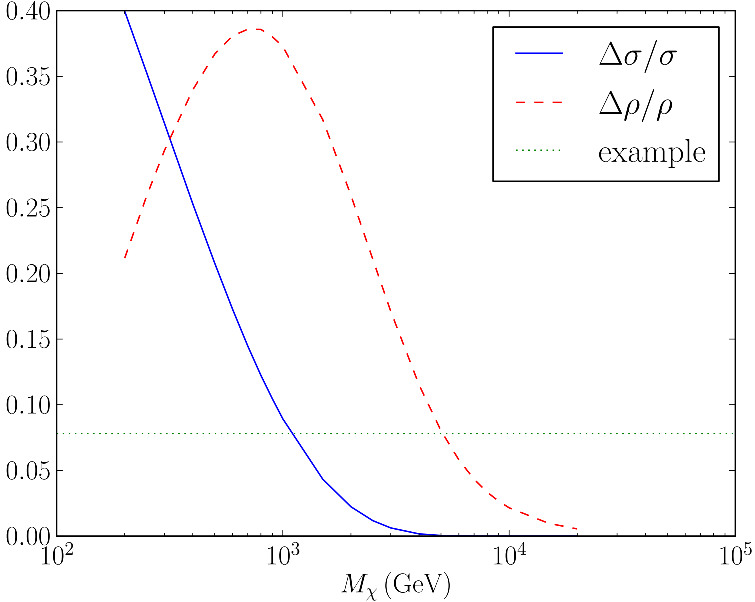
"Signal": $(\rho - \rho_{\rm SM})/\rho_{\rm SM} = 0.0781$ (a 0.1σ "signal").

Excluded: $\rho > 0.32$ at 95%.

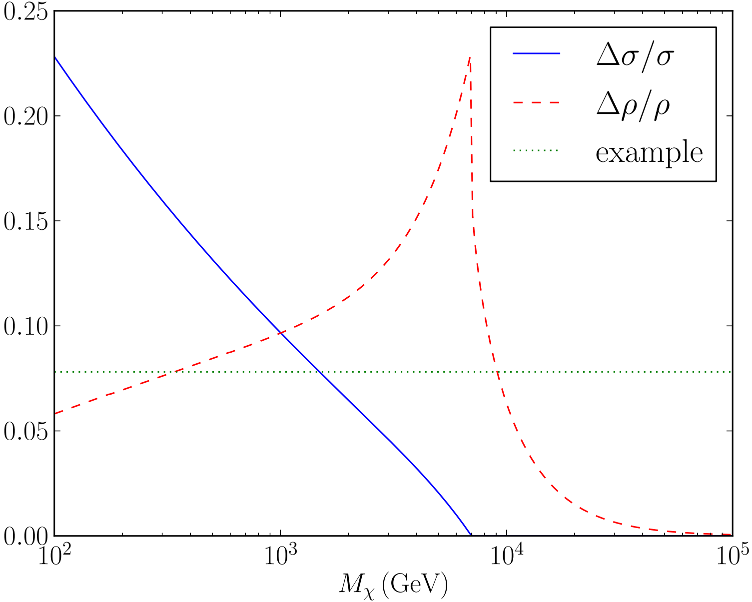
IDR Response at $\sqrt{s} = 7$ TeV for Step Function (h_1)



IDR Response at $\sqrt{s} = 7$ TeV for Parton Approach (h_2)



IDR Response at $\sqrt{s} = 7$ TeV for Diffractive Approach (h_3)



Integral Dispersion Relations: Conclusions

IDRs can probe new physics in a largely model independent fashion.

Most effective for new physics turning on near the machine energy.

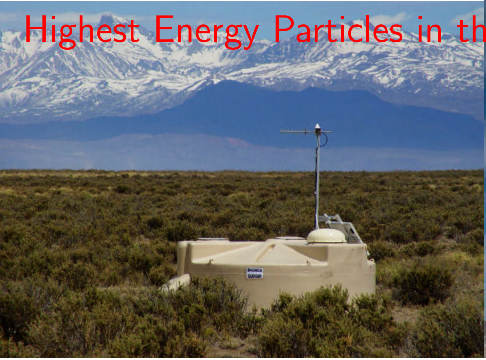
Await new data from the 14 TeV run as TOTEM will be upgraded.

Extending the Reach of the LHC with Integral Dispersion Relations

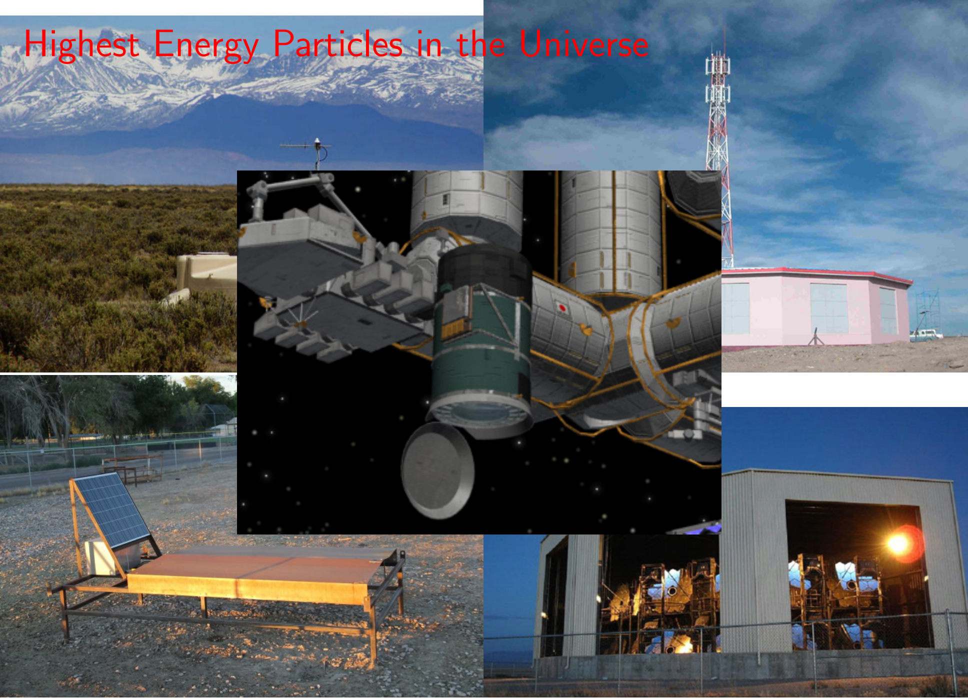
and

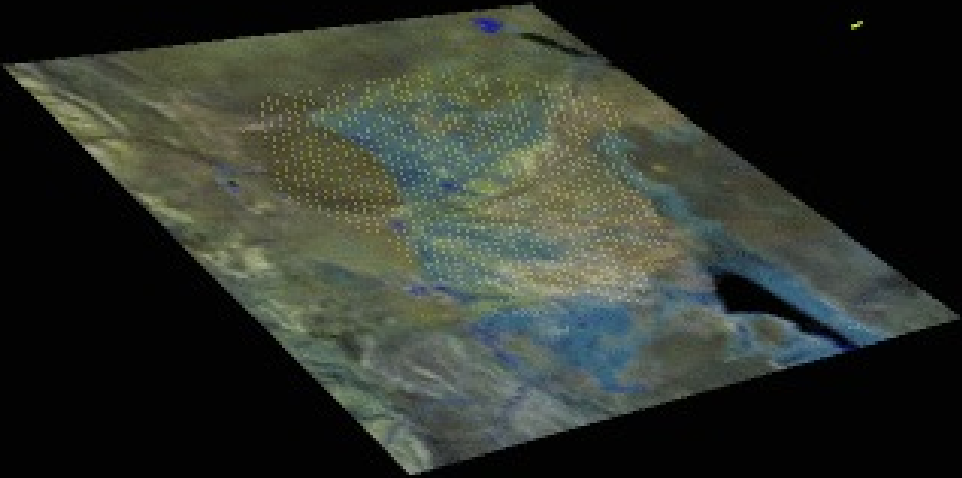
Cosmic Ray Anisotropies

Highest Energy Particles in the Universe



Highest Energy Particles in the Universe





UHECR Anisotropy

The magnetic field in the Milky Way cannot contain ultra high energy cosmic rays.

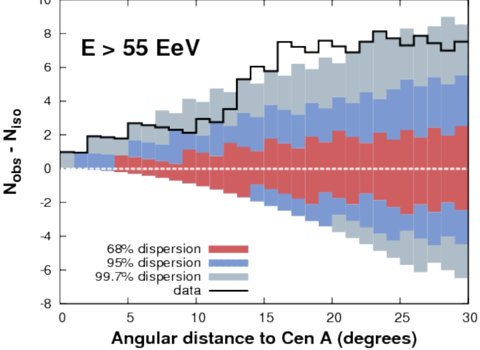
UHECRs with energies above ~ 50 EeV lose energy due to interactions with the CMB.

UHECR sources must be close $\Rightarrow$ anisotropies.

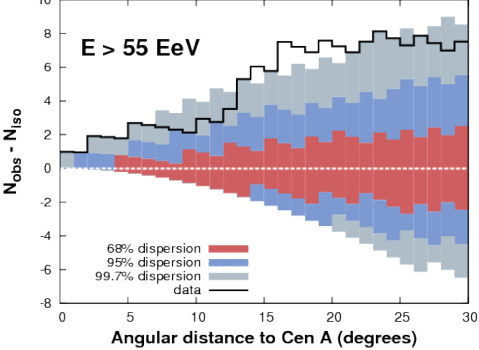
UHECRs bend in galactic and extragalactic magnetic fields.

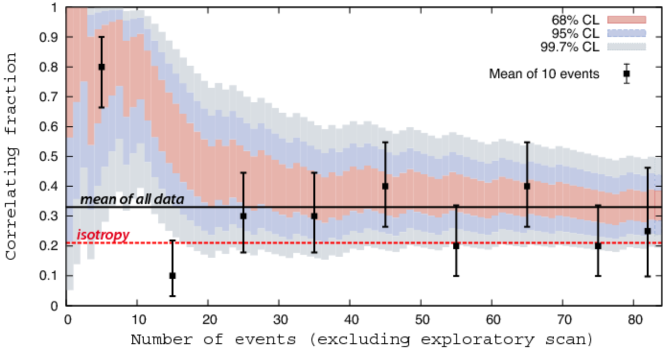
No anisotropies found yet.

UHECR Anisotropy

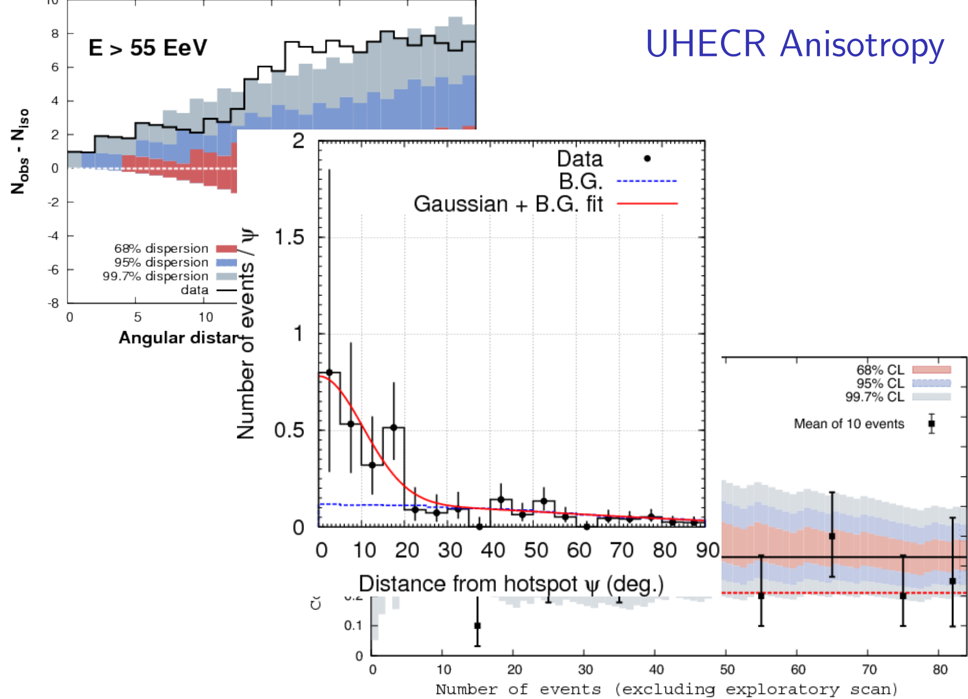


UHECR Anisotropy





UHECR Anisotropy



Spherical Harmonics: Distributions on the Sky

General structure can be quantified in terms of Y_ℓ^m's which provide an orthogonal expansion of the sky.

The true distribution of UHECRs as seen at earth follows

$$I(\Omega) = \sum_{\ell,m} a_\ell^m Y_\ell^m(\Omega)\,.$$

All of the information is encoded in the a_ℓ^m.

On earth we see $I(\Omega) = \frac{1}{N}\sum_i^N \delta(\Omega, \Omega_i)$.

The true distribution may be estimated by $\bar{a}_\ell^m = \frac{1}{N}\sum_i^N Y_\ell^m(\Omega_i)$.

The power spectrum is rotational invariant.

$$C_\ell = \frac{1}{2\ell+1}\sum_m |a_\ell^m|^2$$

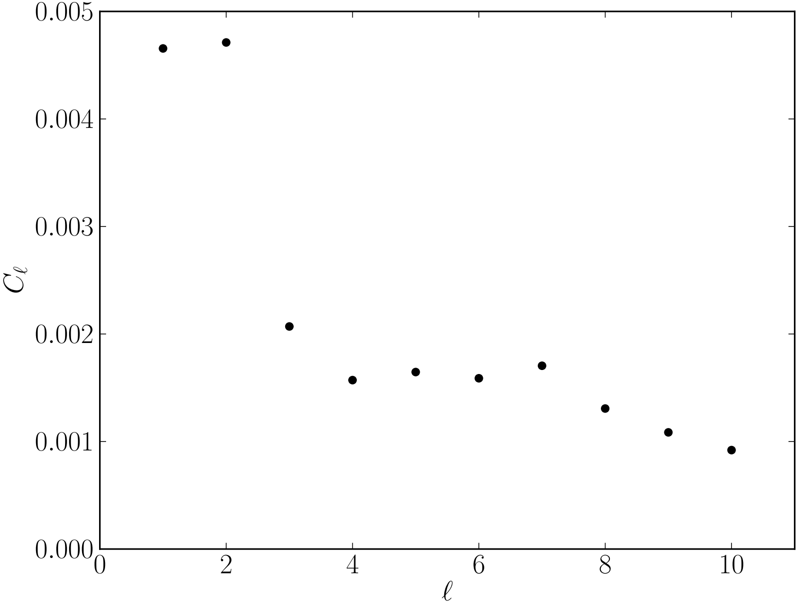
Spherical Harmonics: Possible Sources

Identifiable sources: Cen A, Supergalactic plane, etc. use specific Y_ℓ^m's.

$$\begin{array}{lcll} \text{Point source} & \Rightarrow & \text{dipole:} & I_D \propto a_0^0 Y_0^0 + a_1^0 Y_1^0. \\ \text{Planar source} & \Rightarrow & \text{quadrupole:} & I_Q \propto a_0^0 Y_0^0 + a_2^0 Y_2^0. \end{array}$$

Each Y_ℓ^m partitions the sky into $(\ell+1)^2/2$ so $\ell_{\max} \approx \lfloor\sqrt{2N}-1\rfloor$.

Spherical Harmonics: Possible Sources



Simple Anisotropy Measures

A general anisotropy measure:

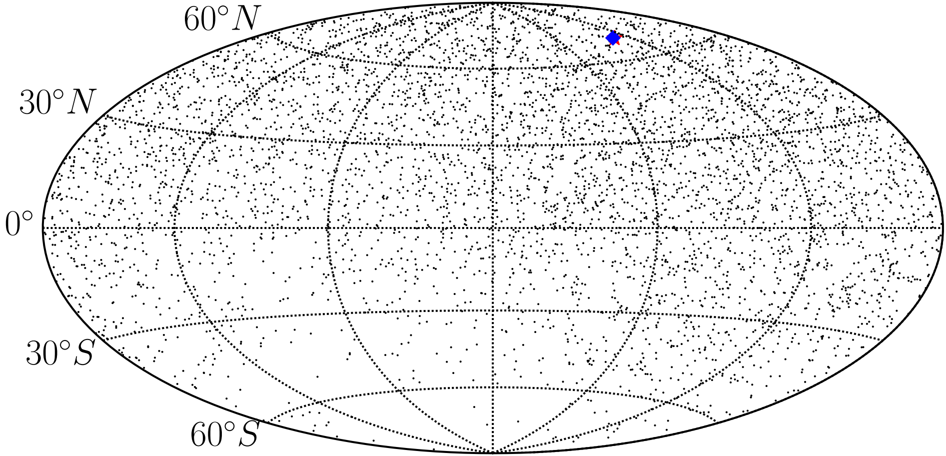
$$\alpha \equiv \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \in [0, 1] \, .$$

Define

$$\alpha_D \equiv \sqrt{3}\frac{|a_1^0|}{a_0^0} \qquad \alpha_Q \equiv \frac{-3\sqrt{\frac{5}{4}}\frac{a_2^0}{a_0^0}}{2 + \sqrt{\frac{5}{4}\frac{a_2^0}{a_0^0}}} \quad (\text{`New' later}) \, ,$$

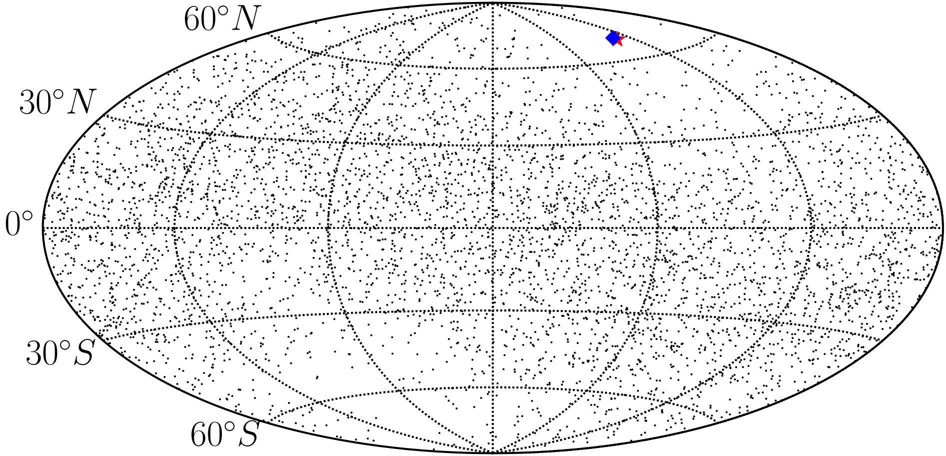
Then $\alpha_D = \alpha$ for a purely dipolar distribution and $\alpha_Q = \alpha$ for a purely quadrupolar distribution.

Sample Dipole



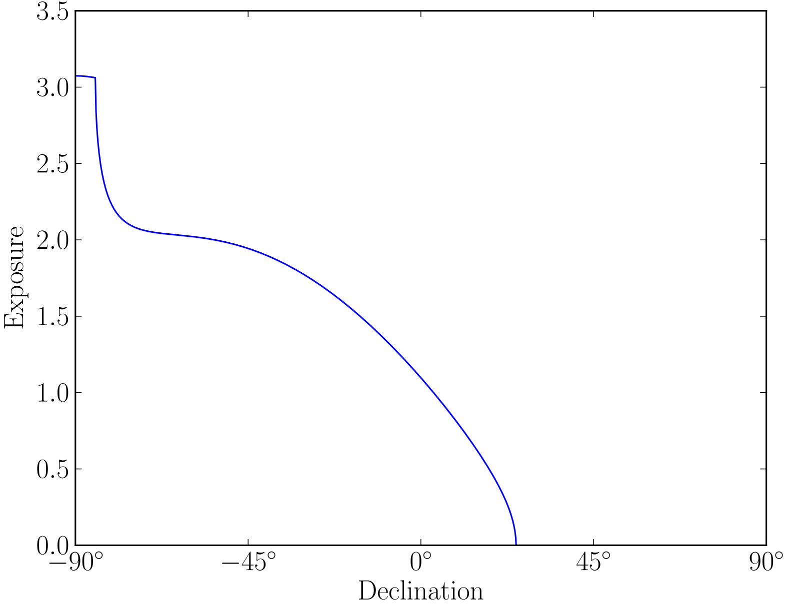
5000 events, $\alpha_D = 1$.
$\theta = 0.3^\circ$, $\Delta\alpha_D = 0.03$.

Sample Quadrupole



5000 events, $\alpha_Q = 1$.
$\theta = 0.8°$, $\Delta\alpha_Q = 0.02$.

Auger's Nonuniform Partial Sky Coverage



Reconstructing a_ℓ^m's for Nonuniform Partial Sky Coverage

Nonuniform exposure is a manageable problem:

$$\bar{a}_\ell^m = \frac{1}{N}\sum_i^N Y_\ell^m(\Omega_i) \to \frac{1}{\mathcal{N}}\sum_i^N \frac{Y_\ell^m(\Omega_i)}{\omega(\Omega_i)}\,,$$

where $\mathcal{N} = \sum_i^N \frac{1}{\omega(\Omega_i)}$,
ω is the exposure function.

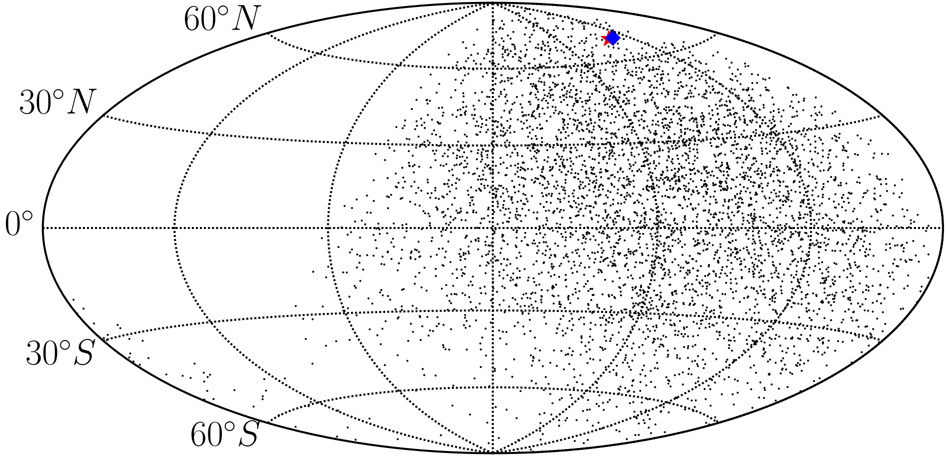
Partial sky is more challenging: no information from part of the sky.

$$[K]_{\ell m}^{\ell' m'} \equiv \int d\Omega\, \omega(\Omega)\, Y_\ell^m(\Omega)\, Y_{\ell'}^{m'}(\Omega)$$

$$b_\ell^m = \sum_{\ell' m'} [K]_{\ell m}^{\ell' m'} a_{\ell'}^{m'} \quad \Rightarrow \quad a_\ell^m = \sum_{\ell' m'}^{\ell_{\max}} [K^{-1}]_{\ell m}^{\ell' m'} b_{\ell'}^{m'}$$

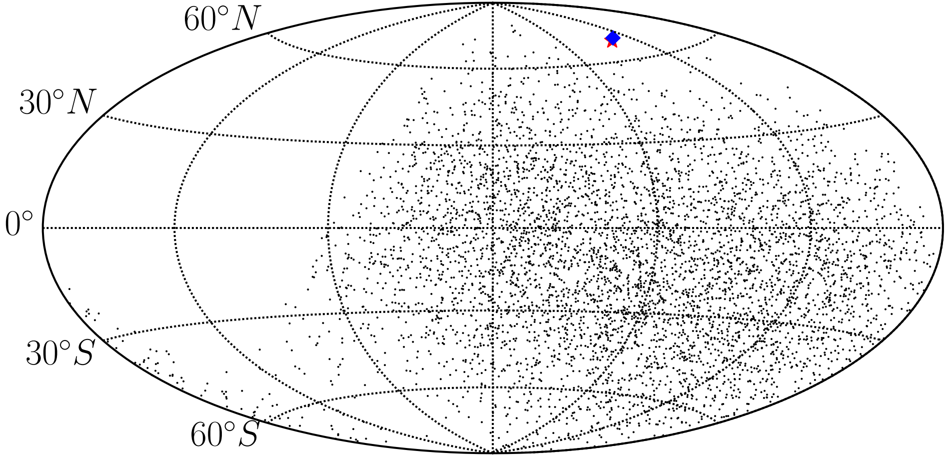
$b_\ell^m \to$ observed on earth,
$a_\ell^m \to$ nature's true anisotropy.

Sample Dipole with Auger's Exposure



5000 events, $\alpha_D = 1.$
$\theta = 2^\circ$, $\Delta\alpha_D = 0.002.$

Sample Quadrupole with Auger's Exposure



5000 events, $\alpha_Q = 1$.
$\theta = 2^\circ$, $\Delta\alpha_Q = 0.02$.

Reconstructing a_ℓ^m's for Nonuniform Partial Sky Coverage

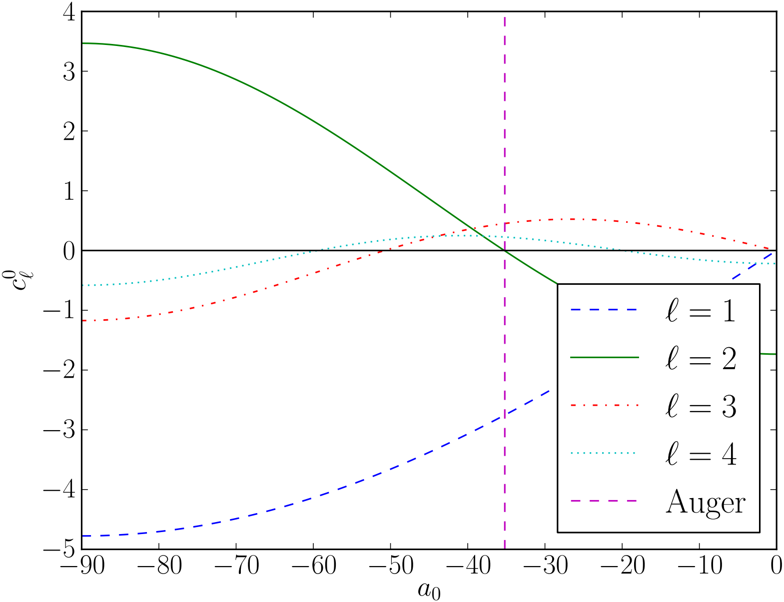
An alternative formalism to the K-matrix approach:

Expand the exposure $\omega(\Omega) = \sum_{\ell,m} c_\ell^m Y_\ell^m(\Omega)$.

ω does not depend on RA $\Rightarrow$ only $m = 0$ coefficients are nonzero.

Fortuitously, $c_2^0 = 0$ for Auger's exposure
(nearly equal to zero for Telescope Array).

Quadrupole Component of Exposure



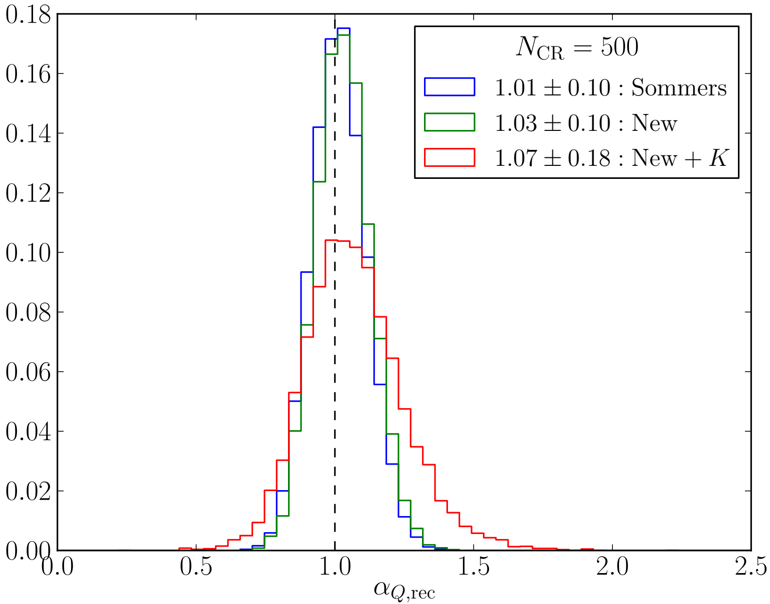
Reconstructing a_ℓ^m's for Nonuniform Partial Sky Coverage

When reconstructing a pure quadrupole, Auger and TA's exposures may be ignored,

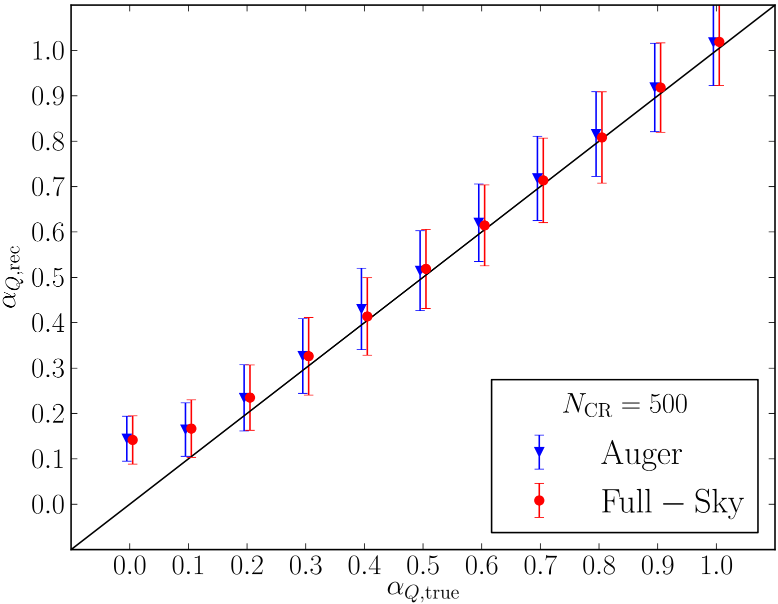
$$b_2^m = a_2^m \left[1 + \frac{(-1)^m c_4^0 f(m)}{7\sqrt{4\pi}}\right]$$

A correction of $0.0546, -0.0364, 0.00909$ for $|m| = 0, 1, 2$.

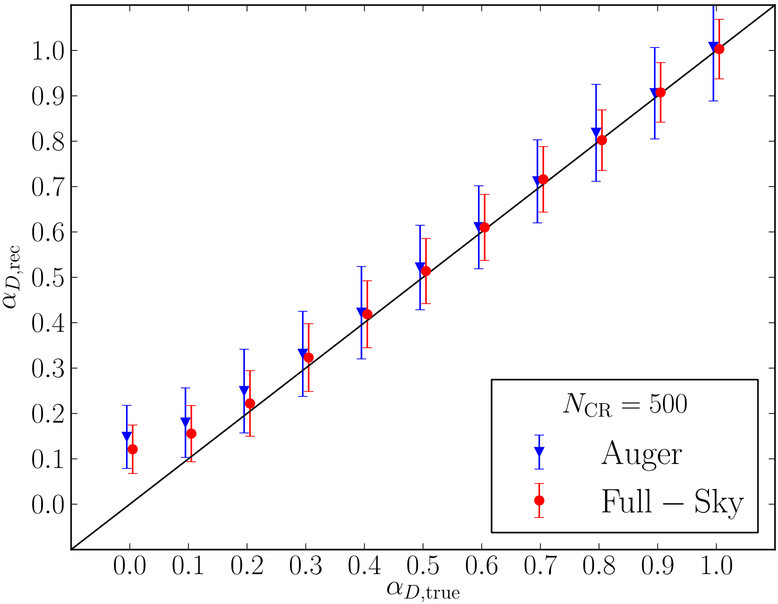
Quadrupole Reconstruction Technique Effectiveness



Quadrupole Reconstruction Effectiveness



Dipole Reconstruction Effectiveness



Catalogs

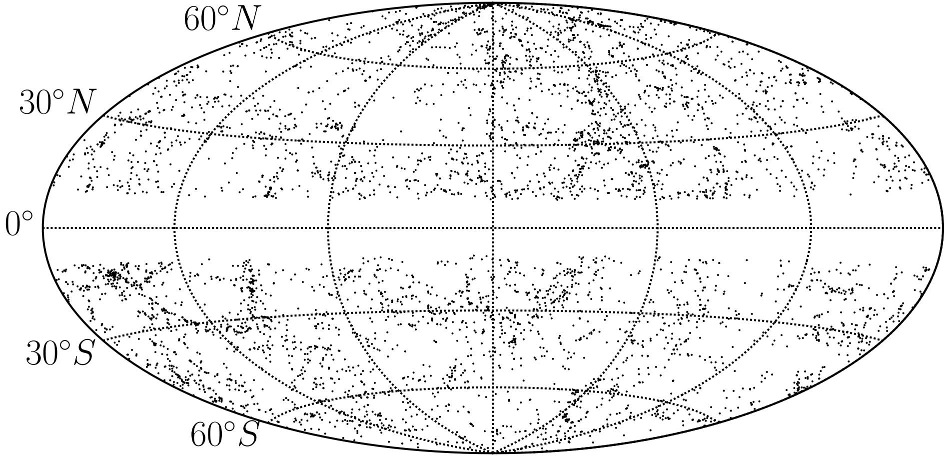
Next step is to consider galactic catalogs.

The catalog used is the 2MRS.

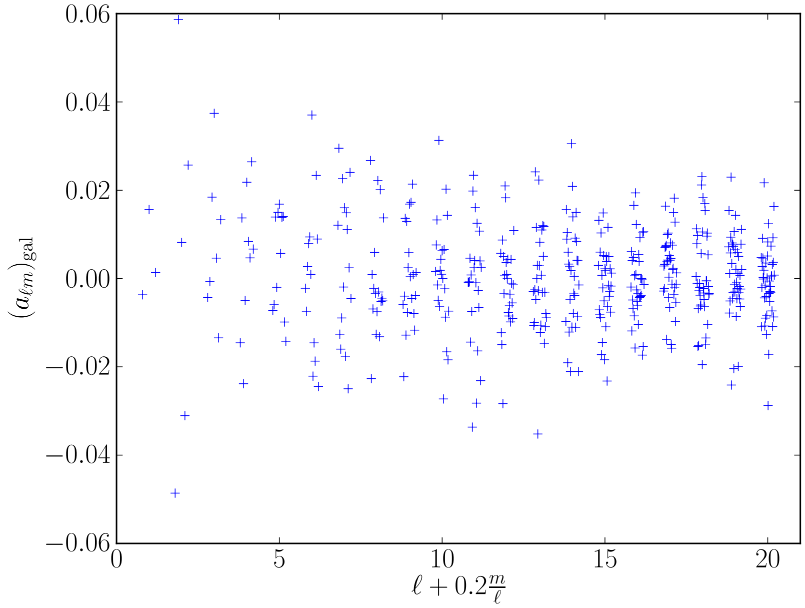
Contains 5310 galaxies out to redshift 0.03: 120 Mpc.

Nearby galaxies need their distances adjusted for peculiar velocities.

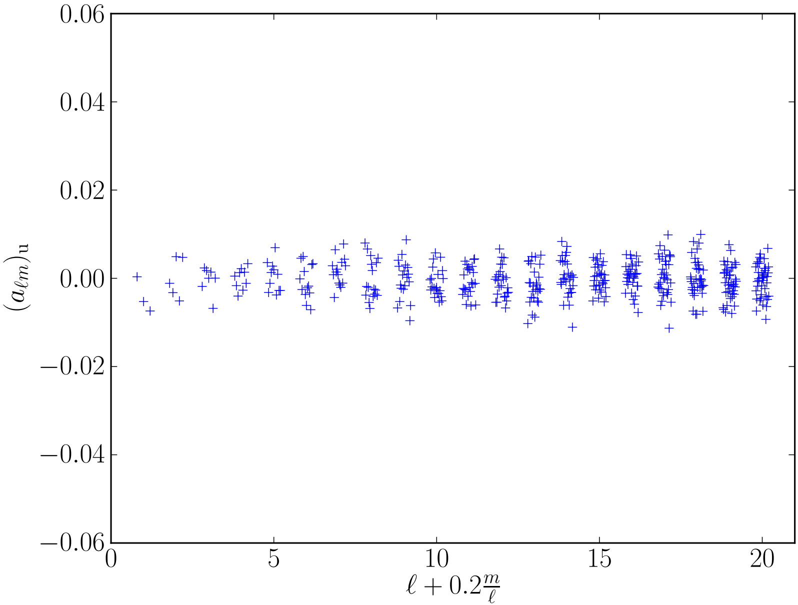
2MRS Sky Map



Spherical Harmonic Coefficients: Galaxies



Spherical Harmonic Coefficients: Uniform



Conclusions

The source(s) of UHECRs is still an open question.

TA has evidence of a warm-spot.

Auger and TA can reconstruct a quadrupole anisotropy without a partial sky penalty.

Auger just (< 2 weeks ago) released a data set tripling their previous release with a hint of anisotropy.

The distribution of galaxies contains more information than just dipole + quadrupole.

Bibliography

References

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Bibliography

Figures

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- TA Collaboration, arXiv:1404.5890.

Images

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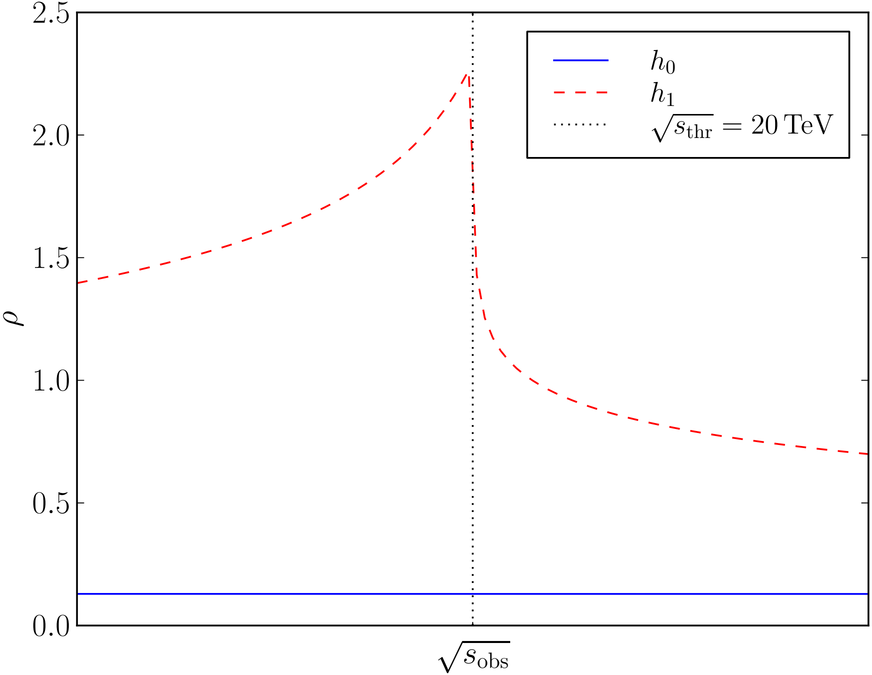
- cerncourier.com/cws/article/cern/50218
- jemeuso.riken.jp/en/about1.html
- auger.org/features/shower_simulations.html


2.5
2.0
1.5
1.0
0.5
0.0
ρ
$\sqrt{s_{\rm obs}}$
h_0
h_1
$\sqrt{s_{\rm thr}} = 20\,{\rm TeV}$

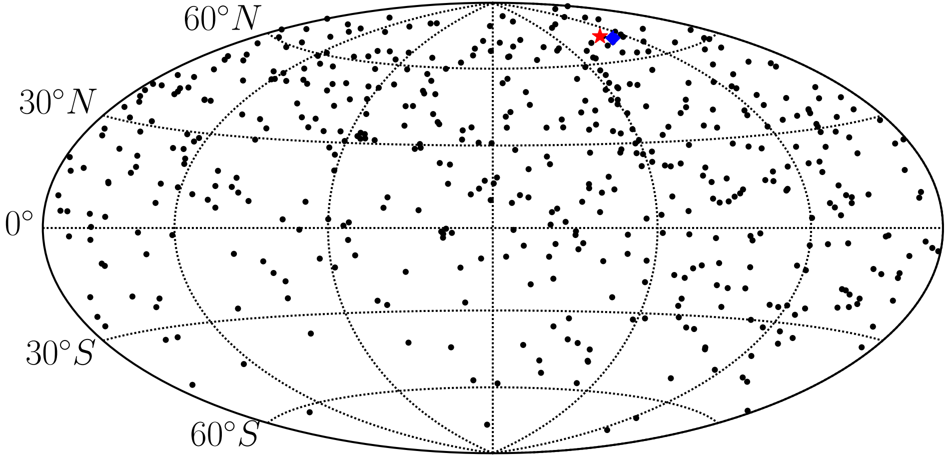
Diffractive Cross Section Reproduces Froissart Bound

The cross section function that goes into the modification h_3 rises like $\log^2 s$ in the appropriate limit:

$$\sigma \propto 1 - \xi_p - \log \xi_p + \left(1 - \xi_p + \xi_p \log \xi_p + \frac{1}{2} \log^2 \xi_p\right) \epsilon + \mathcal{O}(\epsilon^2)$$

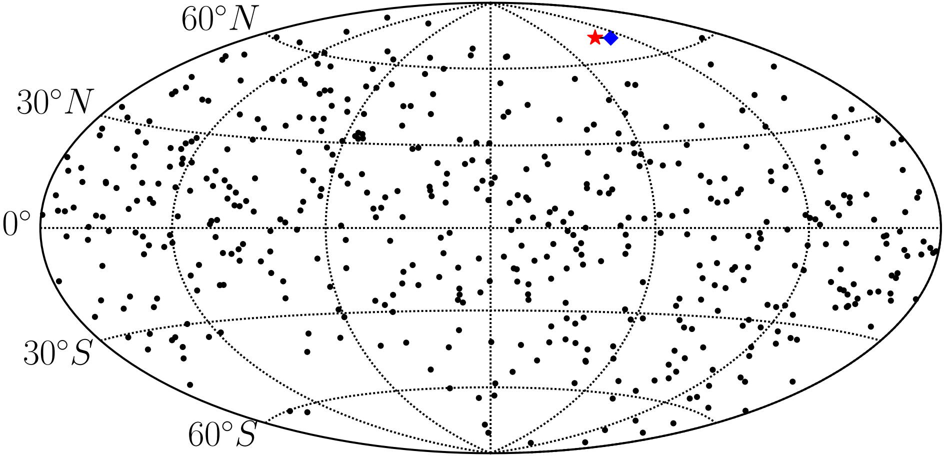
with higher order ϵ terms resulting in higher orders of $\log s$ following the above pattern.

Sample Dipole



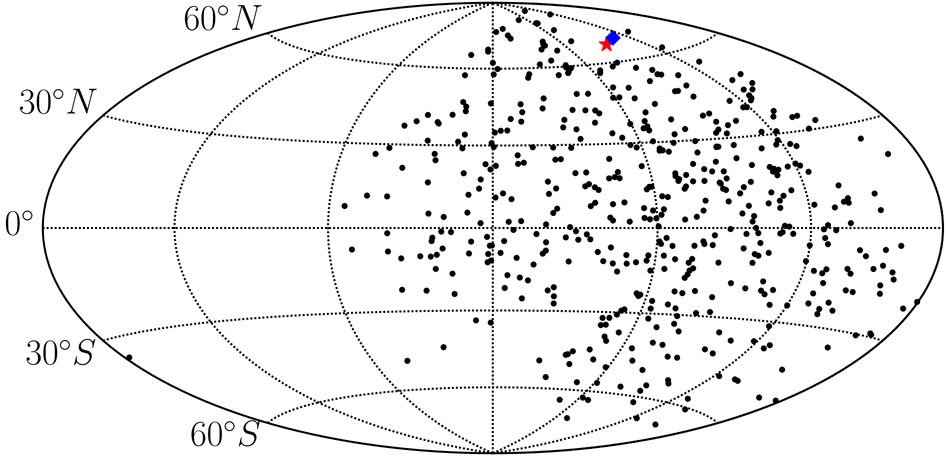
500 events, $\alpha_D = 1$.
$\theta = 3^\circ$, $\Delta\alpha_D = 0.04$.

Sample Quadrupole



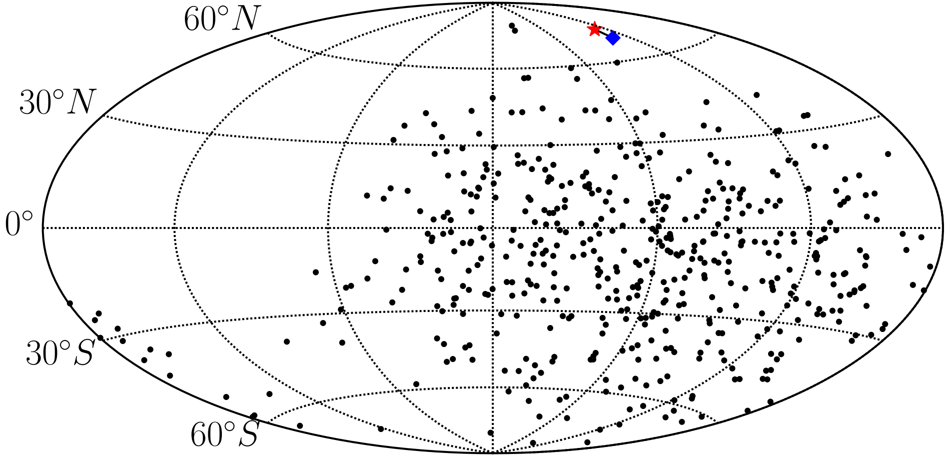
500 events, $\alpha_Q = 1$.
$\theta = 4^\circ$, $\Delta\alpha_Q = 0.06$.

Sample Dipole with Auger's Exposure



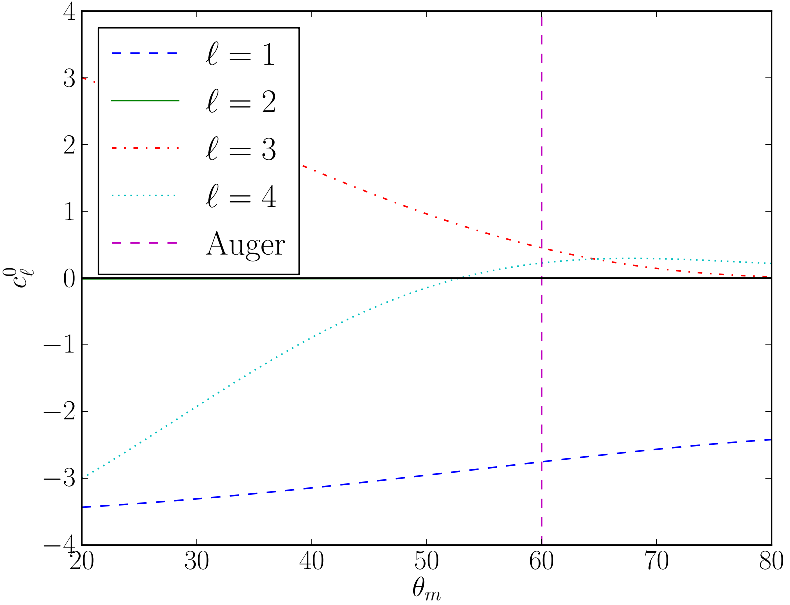
500 events, $\alpha_D = 1.$
$\theta = 6^\circ$, $\Delta\alpha_D = 0.004.$

Sample Quadrupole with Auger's Exposure



500 events, $\alpha_Q = 1$.
$\theta = 4^\circ$, $\Delta\alpha_Q = 0.09$.

Quadrupole Component of Exposure



Quantum Black Holes: Production

See N. Arsene, L. Caramete, PBD, O. Micu, arXiv:1310.2205.

The hoop conjecture says that if two particles collide with impact parameter,

$$b \lesssim \frac{2\ell_{\rm Pl} M}{M_{\rm Pl}}$$

a black hole forms.

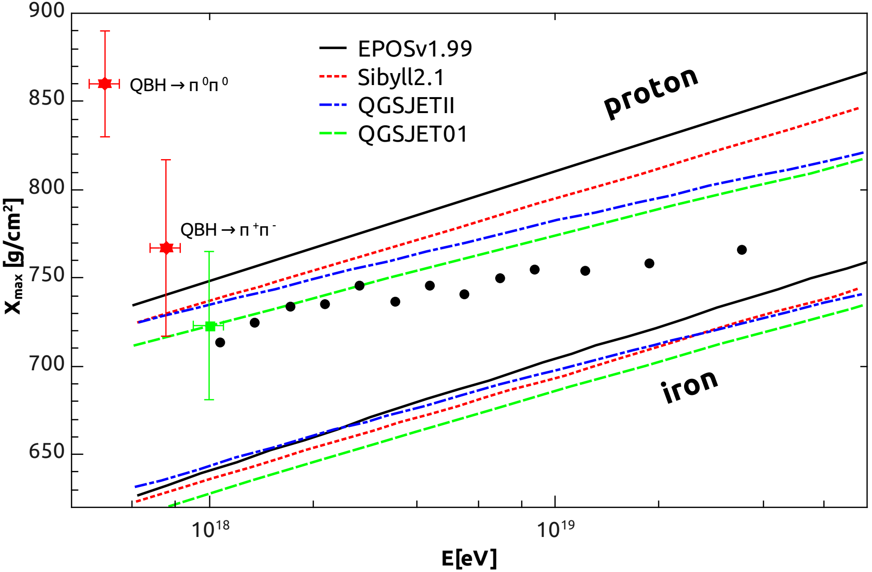
If there is low scale gravity and/or extra dimensions, these could be seen in EASs.

Such events could constitute $1 - 10^3$ events at Auger.

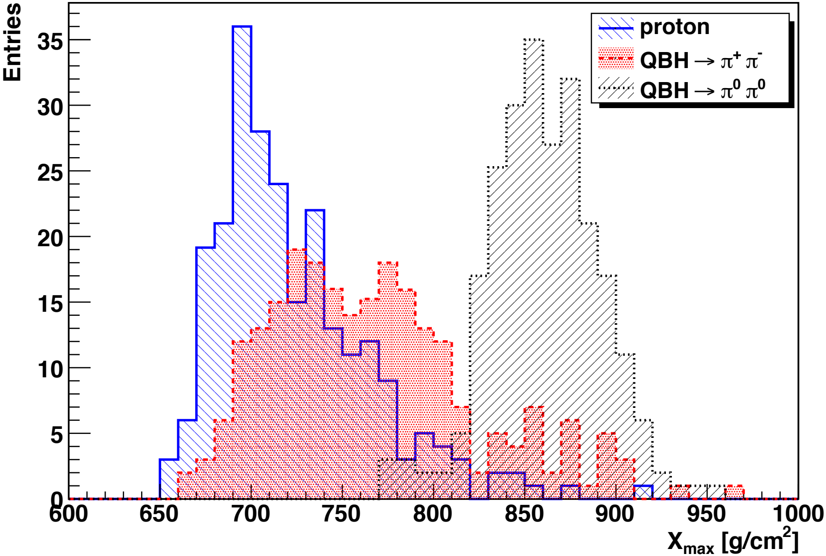
Assume that it decays qBH$\to \pi + \pi$.

Leads to a narrower, deeper shower than p, Fe.

Quantum Black Holes: X_{max} at $E = 1$ EeV



Quantum Black Holes: X_{max} at $E = 1$ EeV



Higgs Portal

See L. Anchordoqui, PBD, H. Goldberg, T. Paul, L. Silva, B. Vlcek, T. Weiler, arXiv:1312.2547.

Add a complex scalar S that couples to the Higgs,

$$\mathscr{L} \supset \partial_\mu S^\dagger \partial^\mu S + \mu^2 S^\dagger S - \lambda (S^\dagger S)^2 - g_\theta (S^\dagger S)(\Phi^\dagger \Phi)$$

S gets a VEV $\langle r \rangle$ and the remaining scalar fields, r, ϕ mix to form h, H.

g_θ small $\Rightarrow$ h is the SM Higgs.

Higgs Portal

Add a Dirac field with a $U(1)$,

$$\mathscr{L} \supset i\bar{\psi}\partial\!\!\!/\psi - m_\psi\bar{\psi}\psi - \frac{f}{\sqrt{2}}\bar{\psi}^c\psi S^\dagger - \frac{f^*}{\sqrt{2}}\bar{\psi}\psi^c S$$

This leads to two massive Majorana fermions including a WIMP DM candidate.

If the additional Goldstone Boson decouples at $T \sim m_\mu$, it will add ~ 0.39 to $N_{\rm eff}$.

Planck $\pm$ HST: $N_{\rm eff} = 3.30, 3.62$.

Higgs Portal: $N_{\rm eff} = 3.39$ Along Yellow Curve