New Physics Searches in Cosmic Ray Showers

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Heavy Ions and New Physics

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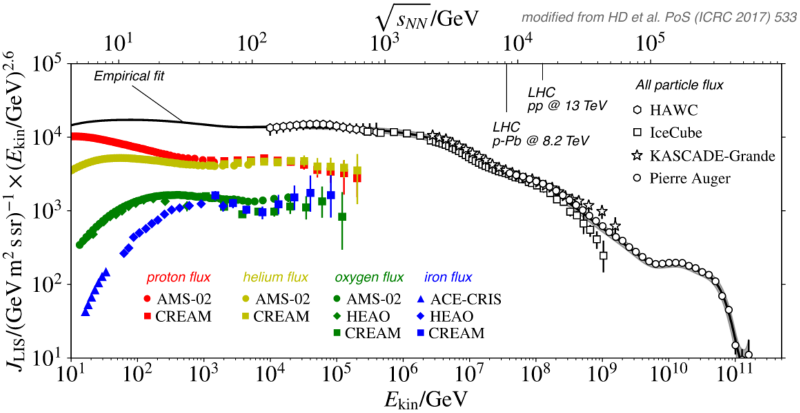
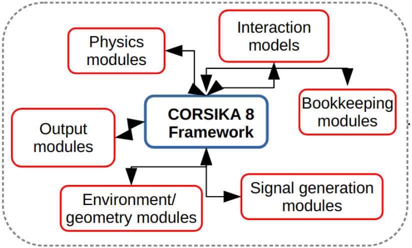
The stage: Cosmic Rays

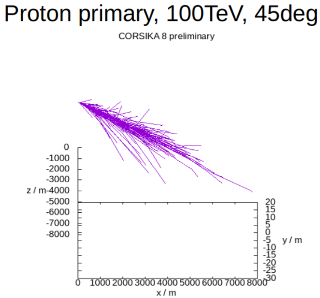


Albrecht *et al.* [2105.06148]

- Interactions above the LHC centre-of-mass energy.
- Cosmic rays provide an untapped source for such interactions.

The tool: CORSIKA8 a few words only





- See talk by R. Ulrich here.
- New framework to investigate particle cascades in astroparticle physics.
- Open source, joint community project. gitlab.ikp.kit.edu
- Highly modular, flexible geometry and physics (PYTHIA8).

On the side: Interactions of mesons from Cosmic Rays

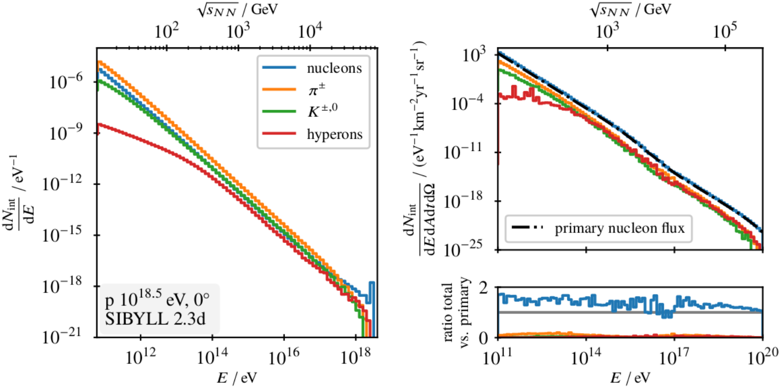
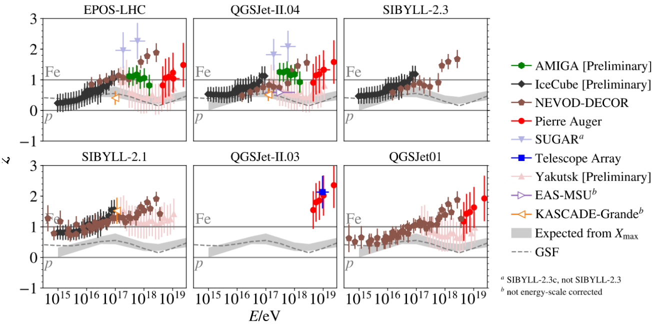


Figure 1: Number of hadronic interactions by species in a single EAS (left) as function of energy, and folded with the CR spectrum (right)

M. Reininghaus, PoS **ICHEP2020** (2021), 602.

Motivation: The muon deficit problem



R. Ulrich *et al.* [2105.06148]

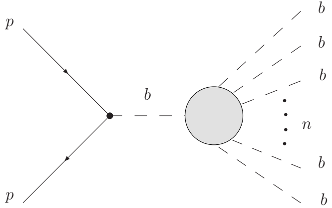
- Simulated/observed muon densities in extensive air showers.
- Visible for showers above ∼10 PeV (10^{16} eV).
- For all hadronic interaction models.
- Physics (beyond) the Standard Model?

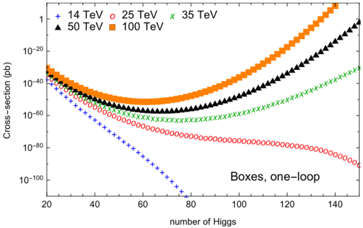
Hypothesis: new process

1. Becomes operative at threshold energy, e.g. ~ 100 PeV.
2. Produce larger number of muons.
   (Muons stem from decaying hadrons.)
3. Cross section $\sim \sigma_{had}$

$\Rightarrow$**Large-multiplicity scattering**

Theory: Large-multiplicity scattering





Spannowsky *et al.*, Phys. Rev. D **94** (2016), 085031

- Creation of $n \gg 1$ of bosons in a single scattering process.
- Large number of diagrams: factorial growth of the amplitude.
  J. M. Cornwall, Phys. Lett. B **243** (1990), 271-278
- Proposed as solution to the hierarchy problem (Higgsplosion).
  V. V. Khoze and M. Spannowsky, Nucl. Phys. B **926** (2018), 95-111
- In principle testable at LHC (and other colliders).
  J. S. Gainer, [arXiv:1705.00737 [hep-ph]]
- $n_{\max}$ limited by $\sqrt{s}$ (σ estimated as $\sim$ ab).

- Large multiplicity cross section σ_{LM} grows exponentially.
- Countered by the growth of the off-shell mediator width.
- Maximum at some threshold energy.
- What is its value?
  1. $\sigma_{LM} \ll \sigma_{had}$: small number of events.
  2. $\sigma_{LM} \gtrsim \sigma_{had}$: dominant process for energy above threshold.
- Agnostic approach: find observables and study data to constrain the cross section

The Model

- Model parameters: f, ϵ, b.
- A fixed fraction f of $\sqrt{s}$ is used to to create bosons b in pairs.
- The kinetic energy ($n_{\mathrm{pairs}}\epsilon$) is distributed among the b pairs.

$$n_{\mathrm{pairs}} = \left\lfloor \frac{f\sqrt{s}}{2m_b(1+\epsilon)} \right\rfloor$$

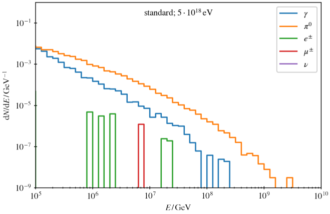
- Isotropic momentum vectors in centre-of-mass system.
- Bosons decay via Pythia8 into long-lived particles.
- Electromagnetic particles are fed into CONEX to generate EM longitudinal profiles by solving the cascade equations.
- Secondary hadronic interactions: QGSJetII-04 above and with UrQMD below 60 GeV.

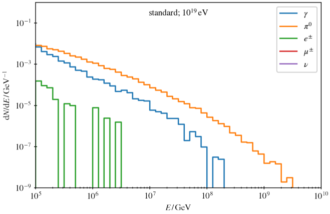
Implemented into CORSIKA8

First we consider only the case: $b = h$.

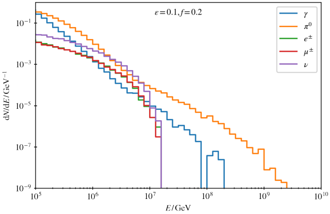
Results

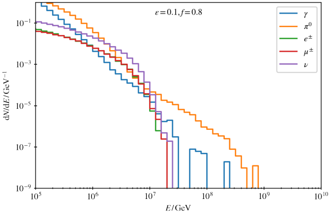
- Standard Model shower:





- Large multiplicity scattering for two values of f:



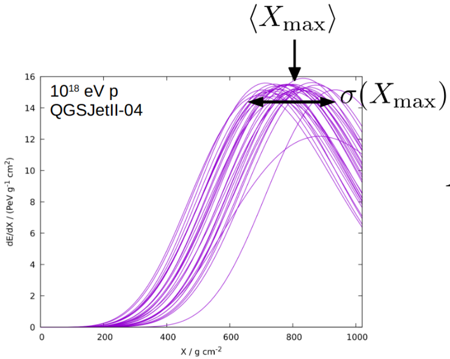


- Kinematics: snapshot a few cm after the scattering.

Observable I - $\langle X_{\max} \rangle$

Slide borrowed from M. Reininghaus, ICHEP 2020

Shower maximum: X_{max}



$$X_{\max} = X_0 + \tilde{X}_{\max}$$

X_0: point of first interaction; $\tilde{X}_{\max}$: shower development

$$\langle X_0 \rangle = \lambda_{\text{int}} = \frac{m_{\text{air}}}{\sigma_{\text{inel.}}}$$

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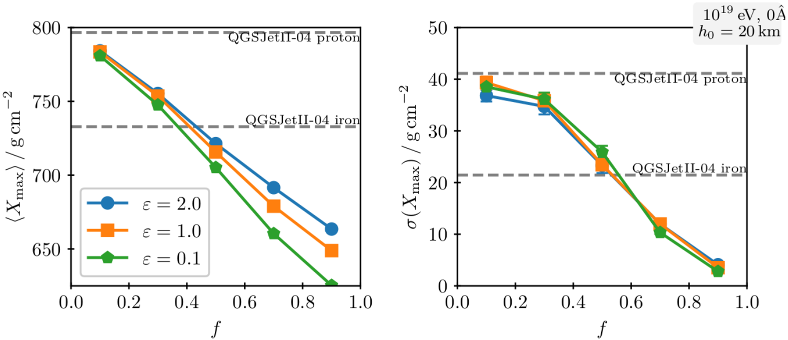
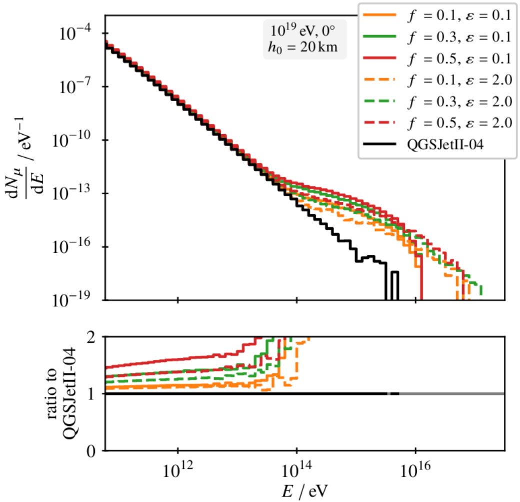
- Depth of the electromagnetic shower maximum.
- Measured in slant depth along the shower axis.

Observable I - $\langle X_{\max} \rangle$ continued



- Remember: f controls n_{pairs}.
- ϵ controls E_{kin} of the bosons, increases the shower depth.
- For $f \to 0$ we get the SM shower back.

Observable II - the muon spectrum



- Overall increase of muon number, esp. at high energy.
- More muons with increasing f and decreasing ϵ.

Outlook

- This was work in progress.
- Next we will also study other bosons $b = Z, W$.
- Other interesting observables: high-energy lepton bundles.
- Other detectors: IceCube, ATLAS/CMS, DECOR.
- Moreover ...

The ANITA excess

20 Nov 2020

Unusual Near-horizon Cosmic-ray-like Events Observed by ANITA-IV

P. W. Gorham,[1] A. Ludwig,[2] C. Deaconu,[2] P. Cao,[3] P. Allison,[4] O. Banerjee,[4] L. Batten,[5] D. Bhattacharya,[6] J. J. Beatty,[4] K. Belov,[7] W. R. Binns,[8] V. Bugaev,[8] C. H. Chen,[9] P. Chen,[9] Y. Chen,[9] J. M. Clem,[3] L. Cremonesi,[5] B. Dailey,[4] P. F. Dowkontt,[8] B. D. Fox,[1] J. W. H. Gordon,[4] C. Hast,[10] B. Hill,[1] S. Y. Hsu,[9] J. J. Huang,[9] K. Hughes,[4] R. Hupe,[4] M. H. Israel,[8] T.C. Liu,[11] L. Macchiarulo,[1] S. Matsuno,[1] K. McBride,[4] C. Miki,[1] J. Nam,[9] C. J. Naudet,[7] R. J. Nichol,[5] A. Novikov,[12,13] E. Oberla,[2] M. Olmedo,[1] R. Prechelt,[1] B. F. Rauch,[8] J. M. Roberts,[1] A. Romero-Wolf,[7] B. Rotter,[1] J. W. Russell,[1] D. Saltzberg,[14] D. Seckel,[3] H. Schoorlemmer,[15] J. Shiao,[9] S. Stafford,[4] J. Stockham,[12] M. Stockham,[12] B. Strutt,[14] M. S. Sutherland,[2] G. S. Varner,[1] A. G. Vieregg,[2] S. H. Wang,[9] and S. A. Wissel[16]

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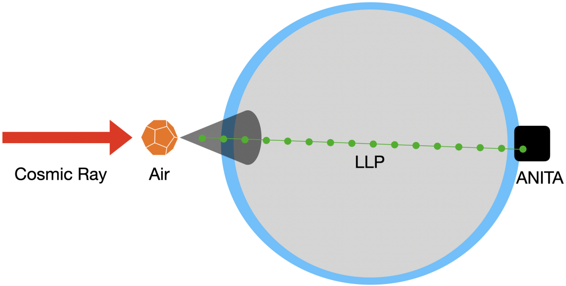
Balloon-borne experiment, [2008.05690]

IceCube: astrophysical explanation assuming SM is disfavoured.

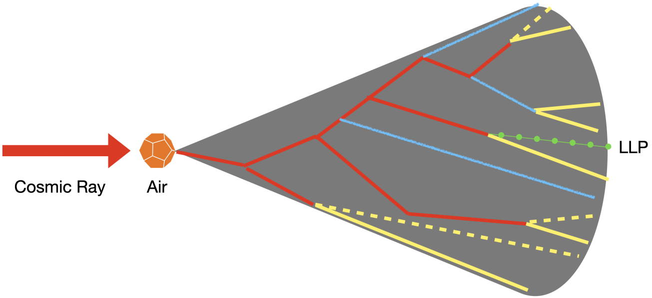
"A search for IceCube events in the direction of ANITA neutrino candidates," [2001.01737]

BSM in super-LHC energy collisions



- Explanations with TeV-scale resonances and Long-Lived Particles (LLP) cf. [1812.00919], [2002.12910], [2004.09464]
- IceCube makes compatible observations. D. B. Fox *et al.* [1809.09615]
- New Physics from resonances with $\sqrt{s} > 14$ TeV, or from rare decays of SM particles.
- Visible signatures in ‘large-scale’ experiments.

LLP in CR showers



- LLP with masses $\sim$ GeV can be produced in hadron decays.
- Possible in a CR shower even without TeV-scale mediator.
- LLP flux that has to be quantified for every model.
- CR at all energies and angles contribute.
- No new detectors necessary:
  Dedicated searches should be sensitive already.

This is an upcoming topic!

- "Unified explanation of flavor anomalies, radiative neutrino masses, and ANITA anomalous events in a vector leptoquark model,"

  P. S. Bhupal Dev *et al.*, [2004.09464]

- "New Constraints on Millicharged Particles from Cosmic-ray Production"

  R. Plestid, V. Takhistov, Y. D. Tsai, T. Bringmann, A. Kusenko and M. Pospelov [2002.11732]

- "Constraining strongly-coupled new physics from cosmic rays with machine learning techniques"

  Spannowsky *et al.* [1906.09064]

- "Searches for Atmospheric Long-Lived Particles"

  Coloma, Argüelles *et al.* [1910.12839]

- "Constraining New Physics with High Multiplicity : I. Ultra-High Energy Cosmic Rays on air-shower detector arrays"

  Jho & Park [1806.03063]

Conclusions

- Cosmic rays constitute a ubiquitous source for BSM:
  - Resonances at super-LHC energies;
  - Long lived particles with masses $\sim$ GeV;
  $\Rightarrow$ Complementarity.
- A link between a CR simulation framework and BSM models is currently missing.
- Signatures in Cosmic Ray showers.
- Useful to study anomalies in IceCube, ANITA, and others.
- New Physics discovery potential!

Thank you.