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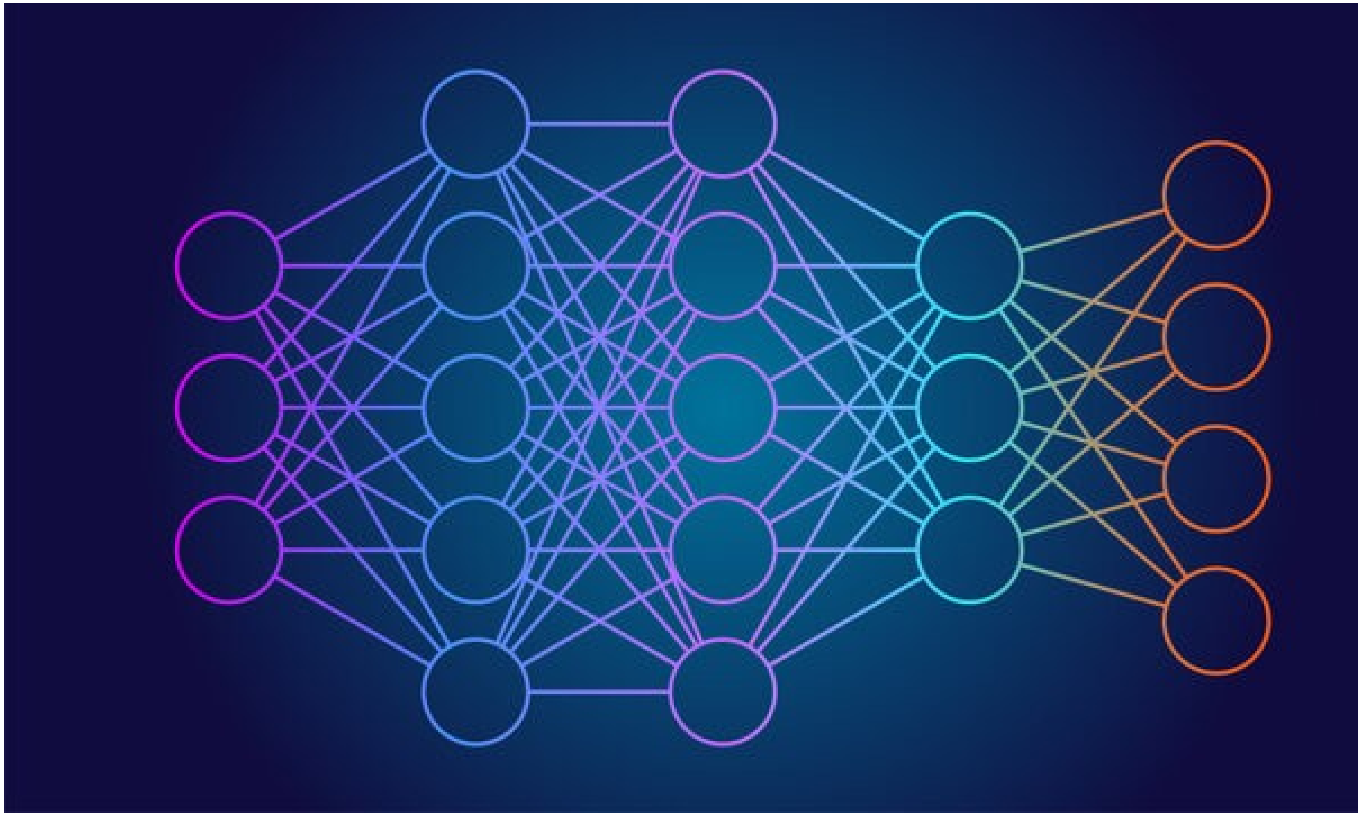
Using machine learning in searches for Lorentz invariance violation

Frascati, 25. 9. 2024

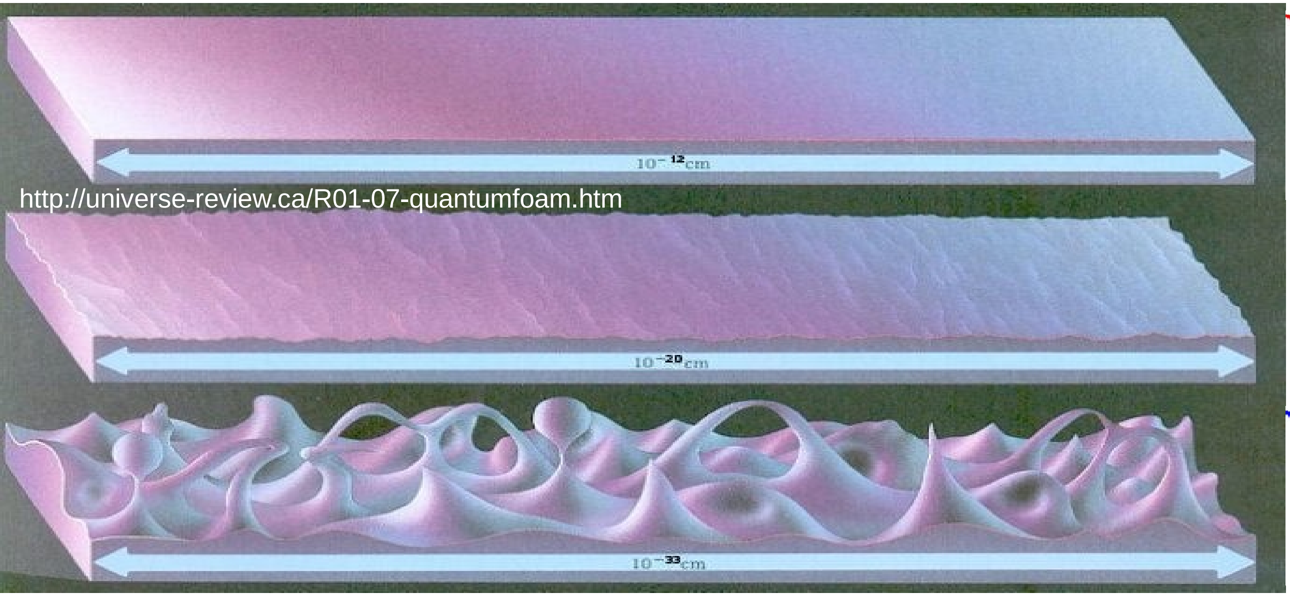
Outline

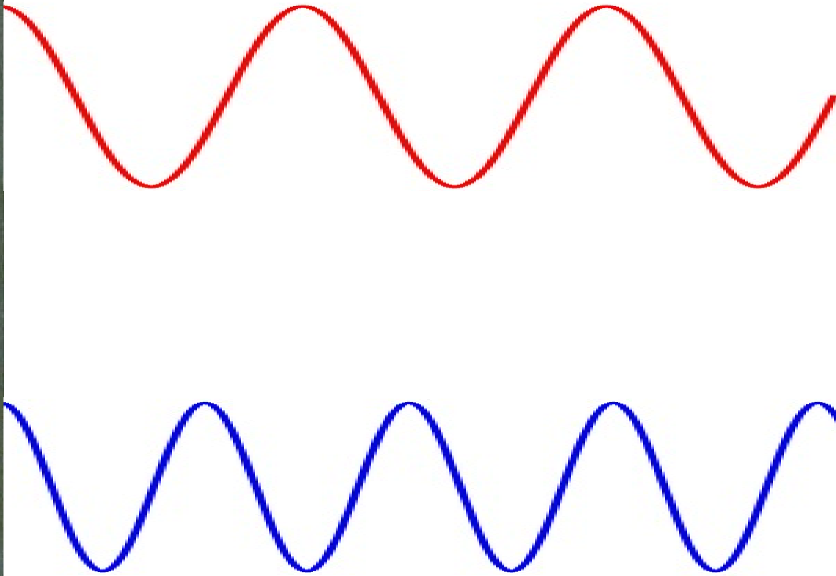
- Lorentz invariance violation (LIV)
- Motivation for employing Artificial neural networks (ANN)
- ANN for LIV
- Training ANN
- Results (work in progress)

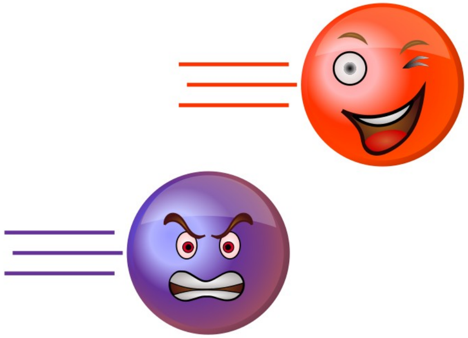


Lorentz invariance violation (LIV)

- Attempt at measuring Quantum Gravity







Lorentz invariance violation (LIV)

- Modified photon dispersion relation
- Usual starting point in searches for effects of QG with gamma rays

photon energy

$$E^2 = p^2c^2 \times \left[1 + \sum_{n=1}^{\infty} S_n \left(\frac{E}{E_{\mathrm{QG},n}}\right)^n\right]$$

QG energy scale

S = ±1

$$\mathrm{E_{QG,n}} = \mathcal{O}(E_{\mathrm{Pl}}) \simeq 1.22 \times 10^{19}\ \mathrm{GeV}$$

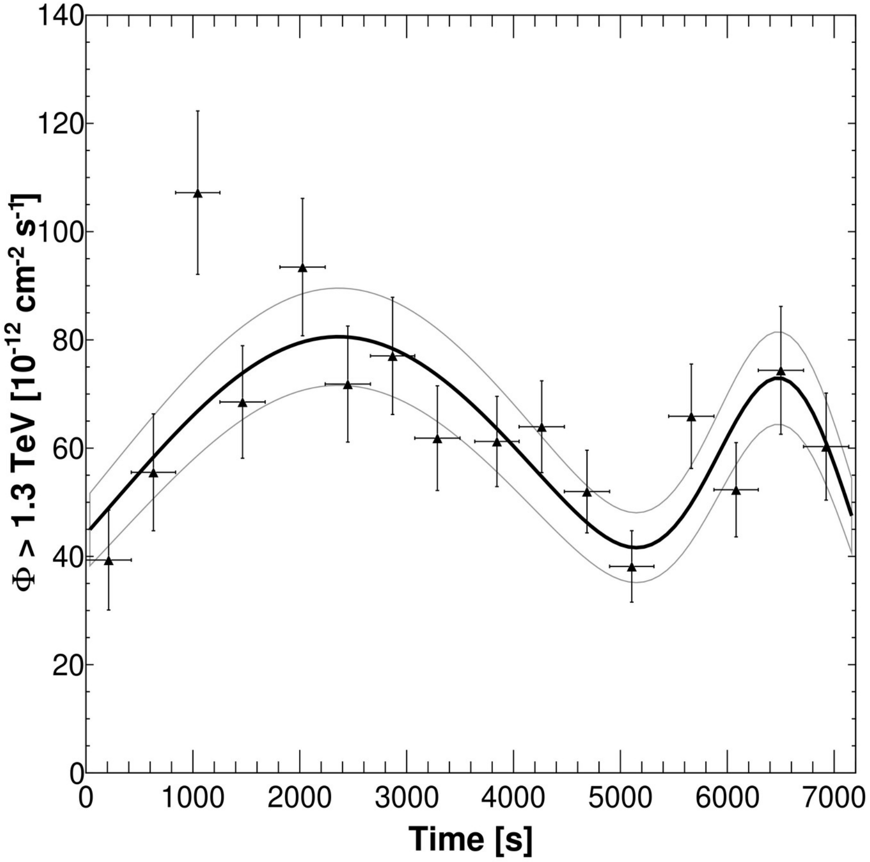
- Not a direct consequence of any particular QG model
- Simple way of parametrizing “out of the ordinary” behaviour

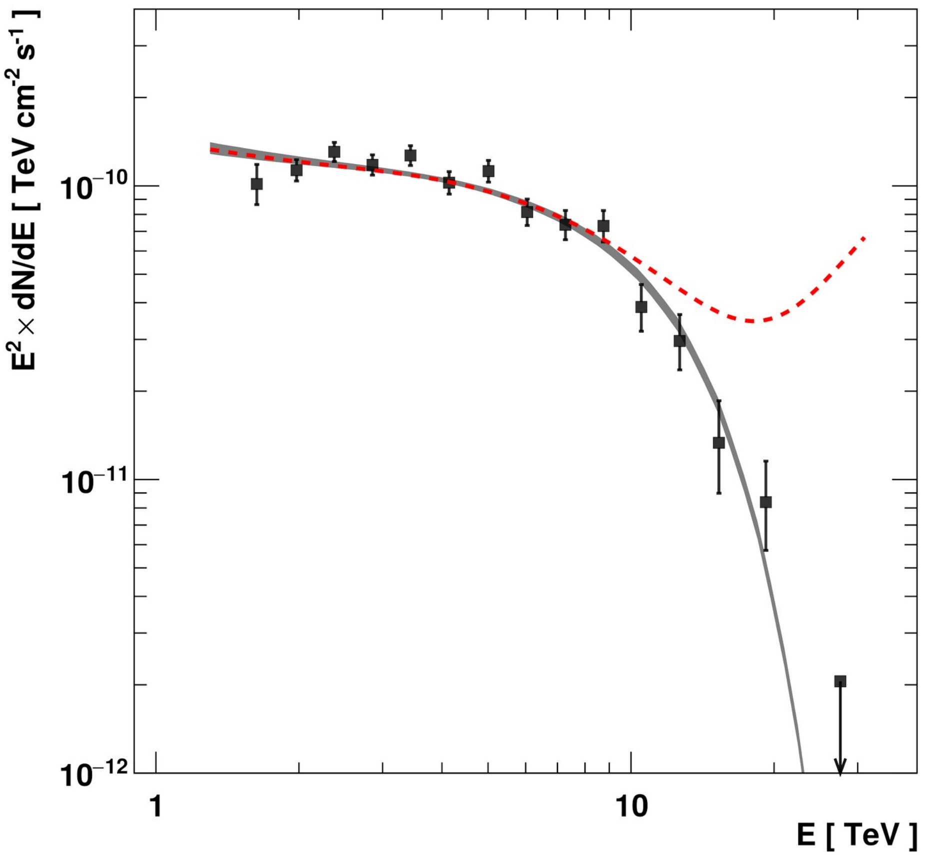
Motivation for using ANN

- Possible consequences of LIV on gamma rays
  - Energy dependent photon group velocity
  - Modified reaction thresholds
  - Modified reaction cross sections
  - Vacuum birefringence
  - …
- So far only one study of more than one LIV effect using the same data set (Abdalla+ 2019)
  - Effects not considered simultaneously!
- **How can multiple effects be tested simultaneously?**
  - NB: Single LIV effect can influence different stages of gamma-ray life
    - e.g. modified reaction threshold or cross section affect gamma-ray absorption on background radiation, but also extensive shower development (gamma-ray detection and reconstruction)

Playground

- Mrk 501 flare from 2014 by H.E.S.S. (Abdalla+ 2019)
  - Simple temporal and spectral distributions
  - ~ 2000 gamma rays 1.3 TeV < E < 30 TeV



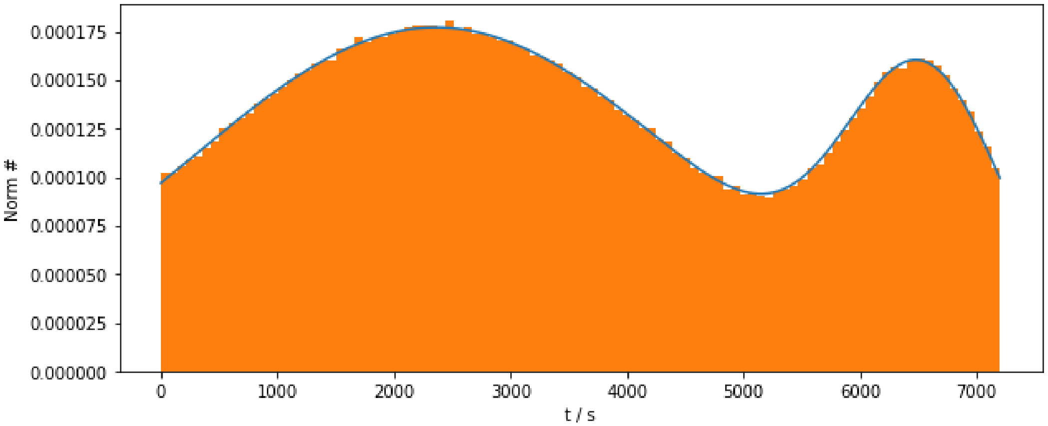


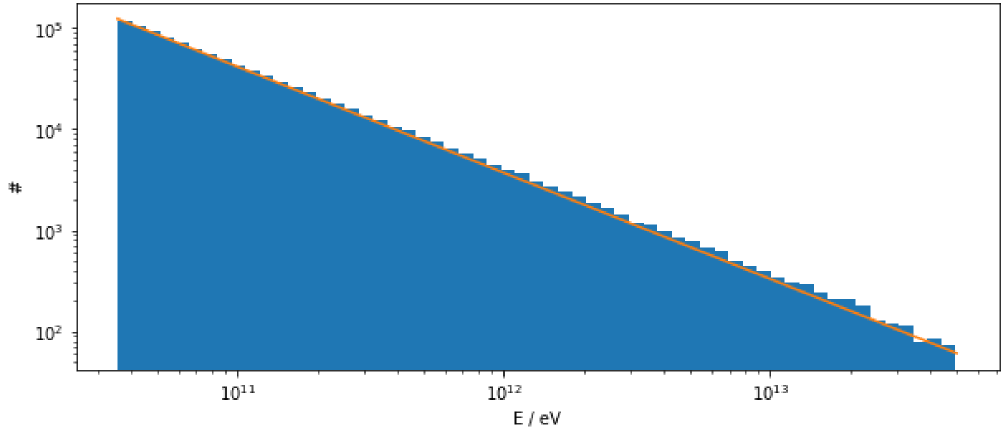
ANN for LIV – First attempt

- Testing simultaneous LIV effect on
  photon group velocity & gamma-ray absorption
- Focussing on 2nd order correction to dispersion relation
- Input data: Light curve parameters (6) + spectral parameters (2)
- Output data: Light curve parameters (6) + spectral parameters (2) + E_{QG}
- Assuming no source-intrinsic correlation
- Assuming perfect instrument

Creating training data sets

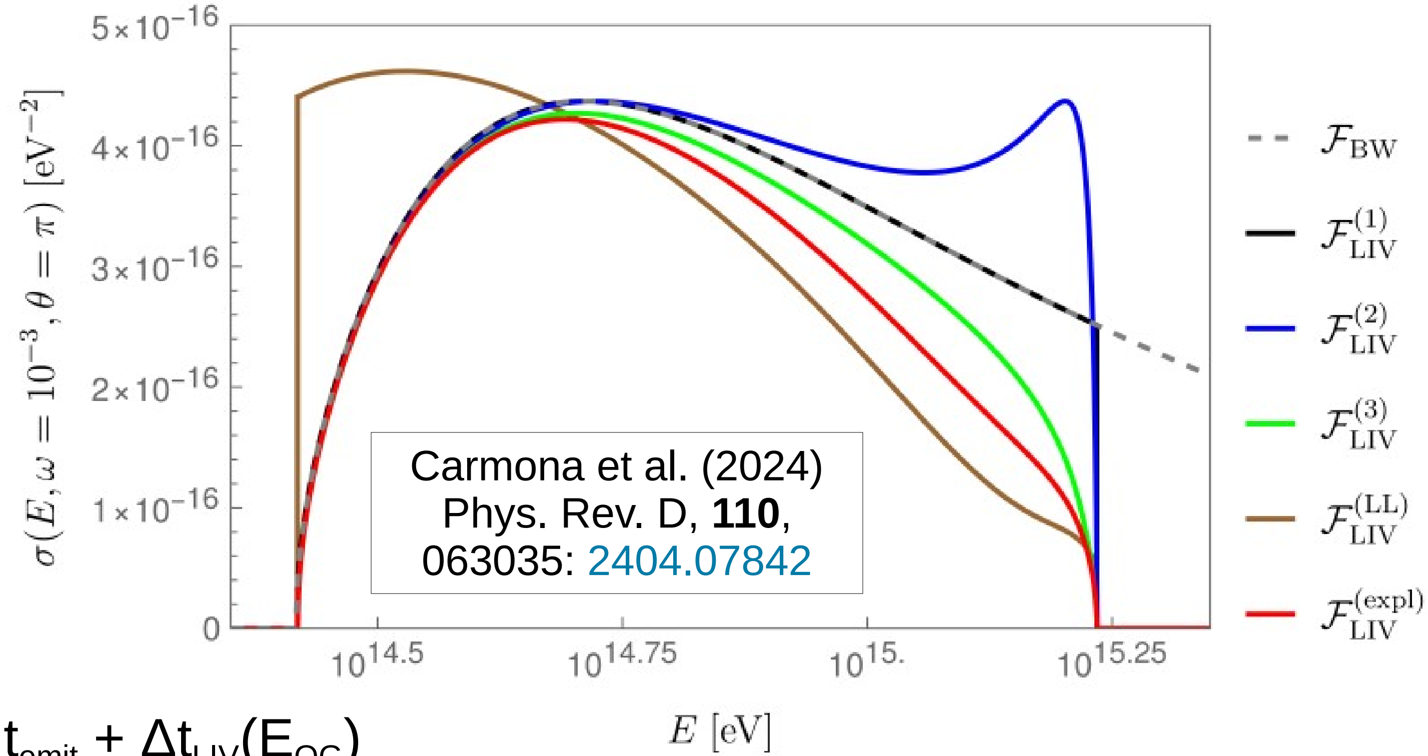
- 10^6 gamma rays simulated with t_{emit}, E_{emit}
  - Light curve: sum of two Gaussians
  - Spectral distribution: power-law
- Performed 210 times for $10^9 < E_{QG} < 10^{30}$
- 210 pools with 10^6 tuples:
  - t_{emit}, E_{emit}, t_{detect}, E_{detect}, $P_{survive}$





Creating training data sets

- $P_{survive}$ – survival probability for photon of energy E_{detect}, and considering E_{QG}



- $t_{detect} = t_{emit} + \Delta t_{LIV}(E_{QG})$
- $E_{detect} = E_{emit} / (1+z)$

Based on Jacob & Piran, 2008: 0712.2170

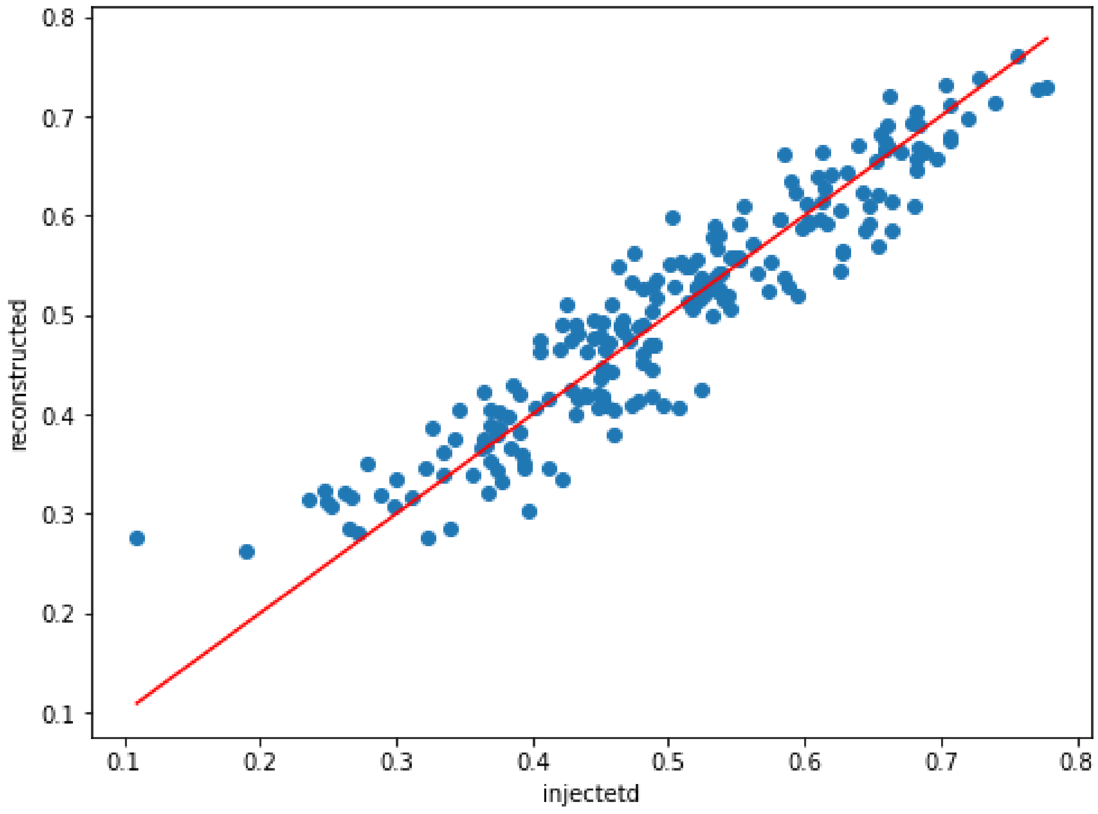
Creating training data sets

- Samples created by randomly picking from pool till N_{detect} = 2000
  - Accounting for survival probability
  - Fit temporal and spectral distributions at detection to get input data: 6 pars for temporal + 2 for spectral distributions
  - Fit temporal and spectral distributions at emission to get output data: 1 par E_{QG} + 6 pars for temporal + 2 for spectral distributions
  - Repeat **100** times for each pool (21’000 samples)

ANN structure

- First attempts for development purposes
- ANN with 3 hidden layers:
  - Input layer: 8 neurons: Detected light curve parameters (6) + detected spectrum parameters (2)
  - Output layer: 9 neurons: Emitted light curve parameters (6) + emitted spectrum parameters (2) + E_{QG}
  - Hidden layers: 1000 neurons
- 2500 iterations
- Manageable on laptop

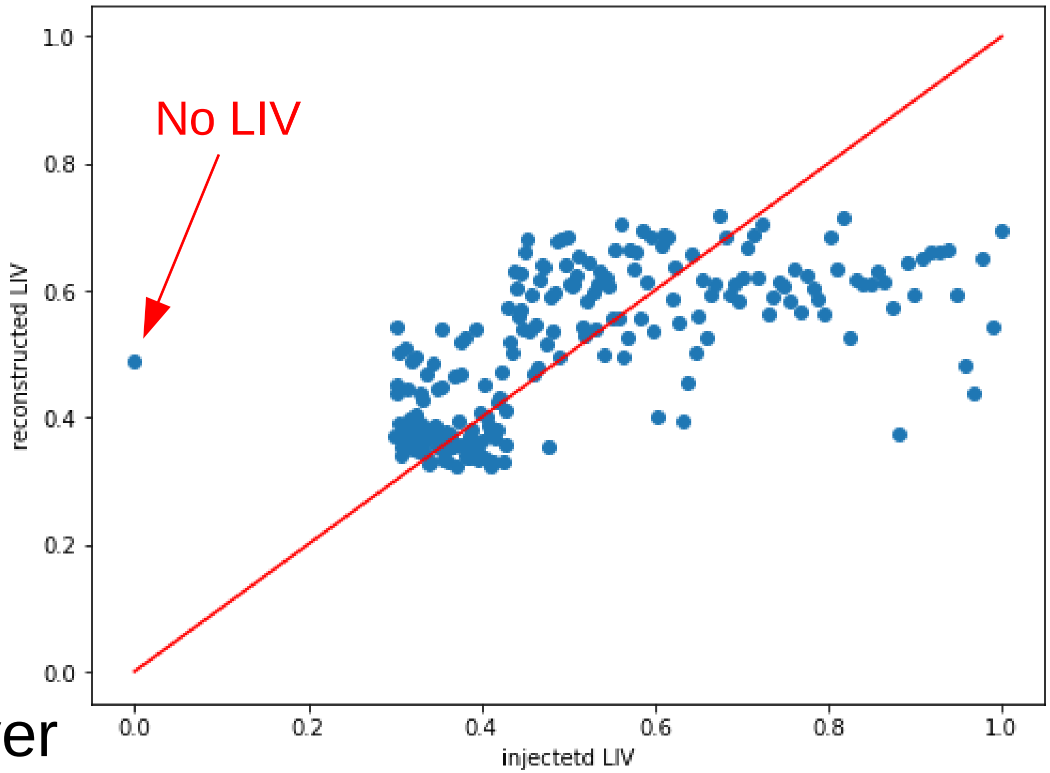
Results 1



- All parameters mapped to [0, 1] interval
- **Clear correlation** between injected and reconstructed parameters describing spectrum and light curve
- Some improvement possible by adjusting the mapping $[par_{min}, par_{max}] \rightarrow [0, 1]$

Results 2

- Some **connection** between injected and reconstructed LIV parameter, but more work needed



- LIV parameter only in input layer
- Room for improvement:
  - Mapping $[par_{min}, par_{max}] \rightarrow [0, 1]$
  - Parameter space coverage
  - ANN hyperparameter optimization

Conclusion & Outlook

- First attempt at simultaneous testing of several LIV effects
- ANN could be a way to go, **however**
- Make it work in the present form
  - Test different ANN settings (hyperparameters): Learning rate, Number of iterations, Number of hidden layers, Number of hidden units (nods), Choice of activation function
  - Test different choices of training sample

Short-term plans (immediate)

- Expand and investigate different approaches:
  - e.g. Individual events or bin contents as input data (instead of parameters)
  - Introduce realistic detectors (acceptance, energy resolution)
- Estimate sensitivity to systematic effects.
- Compare sensitivity to other analysis methods (e.g. likelihood)

Mid-term plans (we’ll get to that)

- Combine multiple observations
- Introduce additional LIV effects (e.g. EAS development)
- Introduce additional free parameters (source intrinsic correlation, cosmology, background models, etc.)

Long-term plans (if I had an army of students)

https://www.cost.eu/actions/CA23130/

CA23130 - Bridging high and low energies in search of quantum gravity (BridgeQG)

Downloads

Home > Browse Actions > Bridging high and low energies in search of quantum gravity (BridgeQG)

www.cost.eu/actions/CA23130/

Description | Management Committee | Main Contacts and Leadership | Working Groups and Membership

Description

Recent advances in both high-energy astrophysics and high-precision table-top experiments are pushing our capability to test nature in regimes where gravity meets quantum physics. Astrophysical observations are now potentially sensitive to tiny residual effects of Planck-scale physics, while table-top experiments are reaching the precision needed to test the interplay between gravity and quantum systems at ultra-low energies. Investigations of these regimes, in particular once they are combined, will provide important clues towards the understanding of the full-fledged theory of quantum gravity.

Action Details

- MoU - 043/24
- CSO Approval date - 17/05/2024
- Start date - 18/09/2024
- End date - 17/09/2028

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Searching for Quantum Gravity in the Sky

Bad Honnef Physics School

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Workshop

Date:	Su, 16.02.2025 18:30 – Fr, 21.02.2025 14:00
Speaker:	Giacomo Rosati (Wrocław), Jelena Strišković (Osijek), Rafael Alves Batista (Sorbonne), Caterina Trimarelli (L'Aquila)
Address:	**Physikzentrum Bad Honnef** Hauptstr. 5, Hauptstr. 5, 53604 Bad Honnef, Germany