ML-Enhanced Discrimination of Gamma-Ray and Hadron Events Using Temporal Features

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- In addition to the morphological properties, gamma and hadronic showers differ also for their time evolution (*refs*)
- Each pixel is then assigned a value between 0 and 255 that represents the time (in ns)
- t_p = time recorded in each pixel (TTP),
- i_p = charge intensity in each pixel,
- n_p = total number of pixels in the cleaned image

suggested parameters

Time RMS *T_RMS*	- measure of the spread of the TTPs - totally independent of the image morphology and position on the camera	$T\_RMS = \sqrt{\sum (t_p - t_{AVG})^2}$ $t_{AVG} = \frac{\sum t_p}{n_p}$.
Time Gradient *T_GRAD*	- image is reduced to 1D by projecting the pixel coordinates onto the major axis (x_p) = first order coefficient ***b*** of the quadratic function = best fits the arrival times versus x_p	$t = ax_p^2 + bx_p + c$
Normalized Time RMS *T_RMSNORM*	Parameter Based on the **Time RMS** $SIZE = \sum i_p$	$T\_RMSNORM = \frac{T\_RMS}{SIZE * n_p}$
Weighted Time RMS *T_RMS_W*	- any effect in the time dispersion related to the pixel charge content - 4th root is used to enhance the separation effect	$T\_RMS\_W = \sqrt[4]{\sum (t_p - t_{AVGW})^2 / n_p^3}$ $t_{AVGW} = \sum (t_p \times i_p) / SIZE$.

suggested parameters (2)

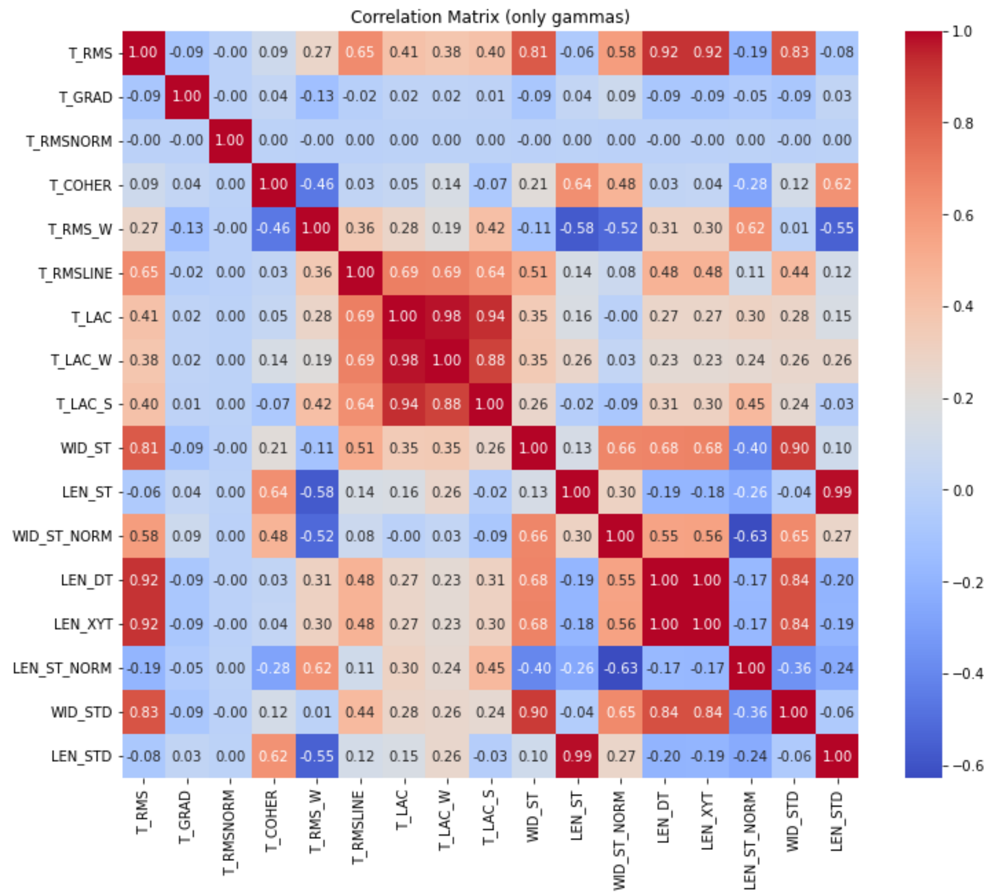
Linearized Time RMS *T_RMS_L*	- measures the time dispersion with respect to the line that describes the shower time evolution along the image ***- b*** and ***c*** are the same coefficients derived for the time gradient	$T\_RMS\_L = \sqrt{\sum(t_p - bx_p - c)^2 / n_p^2}$
Pixel Size-Time (ST space) WID_ST, LEN_ST, WID_ST_NORM, LEN_ST_NORM	tells if **brighter** pixels are **faster** to trigger pixel size = charge content i_p	same algorithm as for the **Hillas parameters**
Pixel Distance-Time (DT space) *LEN_DT*	describes how the shower image evolves in time = = at which **distance** from the image **centroid** the pixels light up first)	same algorithm as for the **Hillas parameters**
3D XYT space LEN_XYT	two spaces defined by X and Y **coordinates** of the pixel plus pixel **time** length in the XYT space	3D genneralization of the **Hillas' algorithm**

suggested parameters (3)

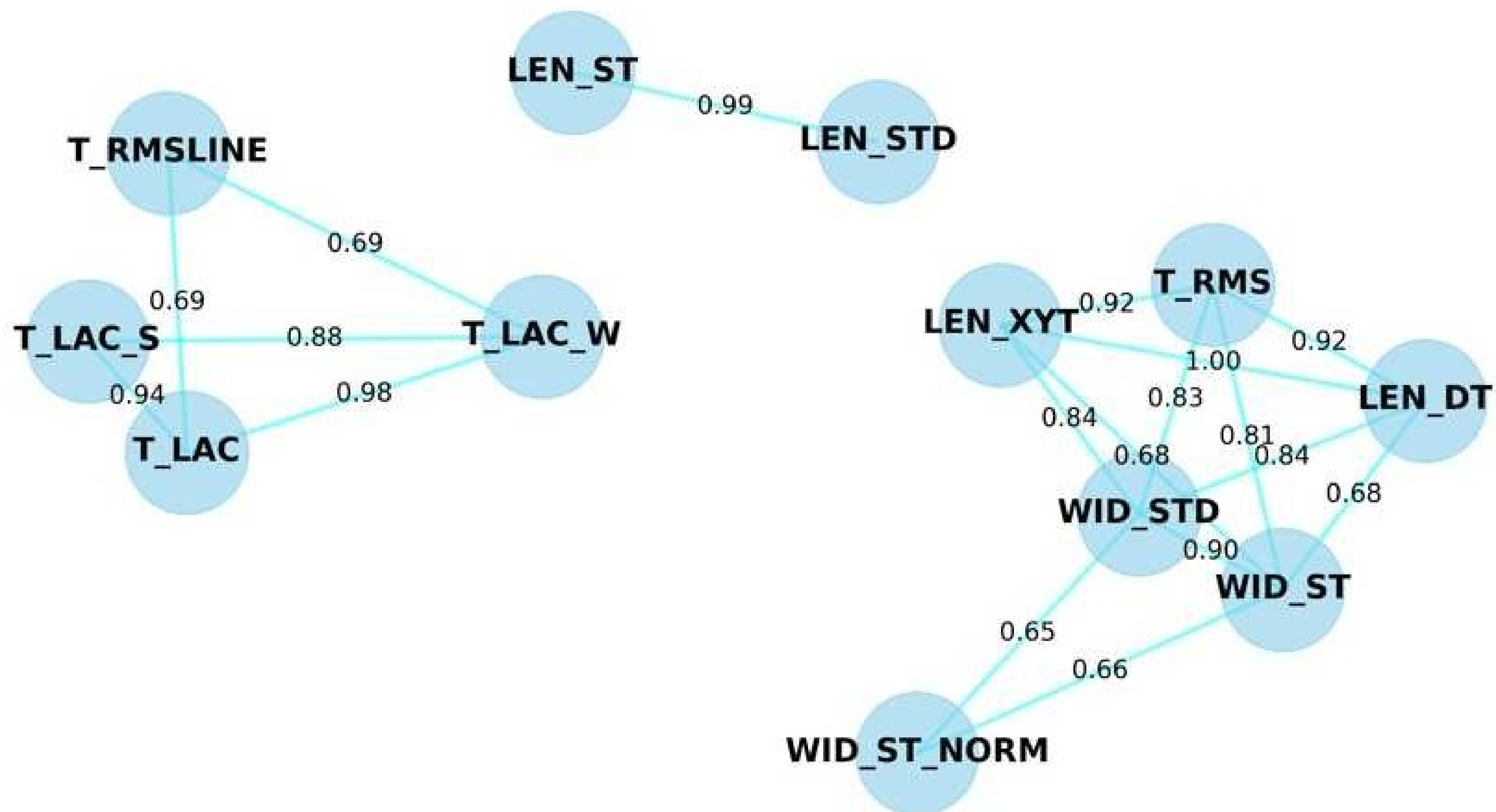
3D STD space *LEN_SDT, WID_SDT*	Pixel Size-Time-Pixel Distance	3D genneralization of the **Hillas' algorithm**
Lacunarity T_LAC T_LAC_S T_LAC_W	- characterize fractals - a gridded timeline, cell = 1 *ns*. If any pixel has time t_p , the cell = 1, otherwise the cell = 0. A sliding box of size n M (>4) is shifted over the timeline grid, and at each step, the mass M of the box (i.e., the number of non-zero cells) → distribution P_M T_LAC_S = stretched lacunarity (???) T_LAC_W = weighted lacunarity, each cell t_p → a value equal to the number of pixel with t_p	$T\_LAC = \frac{\mathrm{Var}(\mathrm{P_M})}{\mathrm{Avg}(\mathrm{P_M})^2} + 1$
Temporal coherence **T_COHER**	time-ordered sequence, d_p = distance to earliest: < 0 if $d_p < d_{p-1}$; > 0 if $d_p > d_{p-1}$	$T\_COHER = \sum d_p.$

Feature selection

- **feature importance scores** generated by the Random Forest model guided our selection of the most relevant parameters
- correlations



Network graph of the temporal parameter correlations



The final set of eight time parameters

- Diversity in Information
- Low Redundancy
- Feature Importance
- Practical Considerations (easier to compute)

Improvement

- quality factor (QF) of 3.32 → 3.68

$$QF = \frac{\epsilon_\gamma}{\sqrt{1-\epsilon_h}}$$

, where ϵ_γ and ϵ_h are, respectively, the number of correctly identified gamma events and the number of correctly identified hadron events.