

## APPENDIX

## A. A2A: Baseline Algorithm (Section V-D of the main paper)

In this section, we provide a detailed description of the baseline algorithm, A2A, including its unbiasedness, variance, and complexity. Its pseudocode is presented in Algorithm 4. Here,  $p(e, e') = \left(\frac{1}{|N_e|} + \frac{1}{|N_{e'}|}\right) \cdot \frac{1}{|E_{\geq 1}|}$  where  $E_{\geq 1} = \{e : N_e \geq 1\}$ . Assume  $E_{\geq 1}$  is given at first. Also, for space efficiency, we assume  $N_e$  is maintained (Line 4).  $HM(A, B)$  on Line 5 denotes the harmonic mean of  $A$  and  $B$ .

**Algorithm 4:** A2A

---

**Input:** (1) a directed hypergraph:  $G = (V, E)$   
 (2) # of samples  $n = q \cdot |E|$  for a given ratio  $q$   
**Output:**  $C[i]$  for every  $i \in [m]$

```

1  $C[i] \leftarrow 0, \forall i \in [m]$ 
2 for  $1 : n$  do
3   Choose  $e \in E_{\geq 1}$  uniformly at random
4    $N_e \leftarrow \{e' \in E \setminus \{e\} : e \cap e' \neq \emptyset\}$ 
5    $C[f(e, e')] \leftarrow C[f(e, e')] + \frac{|E_{\geq 1}|}{2 \cdot n} \cdot HM(|N_e|, |N_{e'}|)$ 
6 return  $C$ 
```

---

**Proposition 10** (Unbiasedness of A2A). *Algorithm 4 is unbiased, i.e.,  $\mathbb{E}[C[i]] = |\Omega_i|$ ,  $\forall i \in [m]$ .*

*Proof.* Follow the flow of the proof of Proposition 2.  $\square$

**Proposition 11** (Variance of A2A). *For each  $i \in [m]$ , the variance of  $C[i]$  obtained by Algorithm 4 is*

$$\begin{aligned} \text{Var}[C[i]] &= \sum_{(e, e') \in \Omega_i} \frac{1}{n} \left( \frac{1}{p(e, e')} - 1 \right) \\ &= \sum_{(e, e') \in \Omega_i} \frac{1}{n} \left( \frac{|E_{\geq 1}|}{2} \cdot HM(|N_e|, |N_{e'}|) - 1 \right). \end{aligned}$$

*Proof.* Follow the flow of the proof of Proposition 3.  $\square$

**Proposition 12** (Time and space complexity of A2A). *The time complexity of Algorithm 4 is  $O(n \cdot (\max_{e \in E} |\bar{e}| \cdot \max_{e \in E} |N_e|))$ . Its space complexity is  $O(\sum_{e \in E} |\bar{e}|)$ .*

*Proof.* The information of a given directed graph is stored in  $O(\sum_{e \in E} |\bar{e}|)$  space at first. For time complexity,  $O(\max_{e \in E} |\bar{e}| \cdot \max_{e \in E} |N_e|)$  time is required assuming  $O(p \cdot q)$  time is taken for set union when there are  $p$  sets, of which size bounded by  $q$ . For space complexity,  $O(|N_e|) \in O(\sum_{e \in E} |\bar{e}|)$  space is needed. Checking  $f(e, e')$  requires  $O(\max_{(e, e') \in \Omega} \min(|\bar{e}|, |\bar{e}'|))$ -time, which is bounded by  $O(\max_{e \in E} |\bar{e}| \cdot \max_{e \in E} |N_e|)$ .  $\square$

## B. Randomization of Directed Hypergraphs (DHs) (Section III-B of the main paper)

To randomize DHs, we extend the configuration model, which is widely-used for (hyper)graphs [52], [38], to DHs. Algorithm 5 outlines the process of obtaining a randomized DH  $G'$  from the input DH  $G$ . It ensures that  $G'$  and  $G$  have the same distributions of hyperarc sizes and node degrees. Hyperarcs are paired and the nodes in the head sets of each pair are shuffled to obtain a shuffled set  $E_{\text{temp}}$  of hyperarcs (Lines 3-13). The same process is applied to the tail sets on  $E_{\text{temp}}$  (Lines 14-24) to obtain the final set  $E'$  of hyperarcs.

**Algorithm 5:** Randomization of Directed Hypergraphs

---

**Input:** a directed hypergraph:  $G = (V, E)$   
**Output:** a randomized directed hypergraph:  $G' = (V', E')$

```

1  $V' \leftarrow V, n_E \leftarrow |E|$ 
2  $E_{\text{temp}}, E' \leftarrow \emptyset, \emptyset$ 
  // Shuffle the two head sets.
3 for  $1 : \lfloor n_E/2 \rfloor$  do
4   Choose  $e_1, e_2 \in \binom{E}{2}$  uniformly at random
5    $E \leftarrow E \setminus \{e_1, e_2\}$ 
6    $H'_1, H'_2 \leftarrow \text{SHUFFLE}(H_1, H_2 | T_1, T_2)$ 
7    $E_{\text{temp}} \leftarrow E_{\text{temp}} \cup \{\langle T_1, H'_1 \rangle, \langle T_2, H'_2 \rangle\}$ 
8 if  $|E| = 1$  then
9    $e_1 \in E$ 
10  Choose  $e_2 \in E_{\text{temp}}$  uniformly at random
11   $E_{\text{temp}} \leftarrow E_{\text{temp}} \setminus \{e_2\}$ 
12   $H'_1, H'_2 \leftarrow \text{SHUFFLE}(H_1, H_2 | T_1, T_2)$ 
13   $E_{\text{temp}} \leftarrow E_{\text{temp}} \cup \{\langle T_1, H'_1 \rangle, \langle T_2, H'_2 \rangle\}$ 
  // Shuffle the two tail sets.
14 for  $1 : \lfloor n_E/2 \rfloor$  do
15  Choose  $e_1, e_2 \in \binom{E_{\text{temp}}}{2}$  uniformly at random
16   $E_{\text{temp}} \leftarrow E_{\text{temp}} \setminus \{e_1, e_2\}$ 
17   $T'_1, T'_2 \leftarrow \text{SHUFFLE}(T_1, T_2 | H_1, H_2)$ 
18   $E' \leftarrow E' \cup \{\langle T'_1, H_1 \rangle, \langle T'_2, H_2 \rangle\}$ 
19 if  $|E_{\text{temp}}| = 1$  then
20   $e_1 \in E_{\text{temp}}$ 
21  Choose  $e_2 \in E'$  uniformly at random
22   $E_{\text{temp}} \leftarrow E_{\text{temp}} \setminus \{e_2\}$ 
23   $T'_1, T'_2 \leftarrow \text{SHUFFLE}(T_1, T_2 | H_1, H_2)$ 
24   $E' \leftarrow E' \cup \{\langle T'_1, H_1 \rangle, \langle T'_2, H_2 \rangle\}$ 
25 return  $G' = (V', E')$ 
  // Shuffle the two sets of nodes
26 Function SHUFFLE( $S_1, S_2 | F_1, F_2$ )
27    $I \leftarrow S_1 \cap S_2$ 
28    $R \leftarrow (S_1 \cup S_2) \setminus I$ 
29    $R' \leftarrow R \setminus F_1 \setminus F_2$ 
30    $S'_1 \leftarrow \text{Choose}(|S_1 \setminus I \setminus F_2|) \text{ elements in } R' \text{ uniformly at random}$ 
31    $S'_2 \leftarrow R' \setminus S'_1$ 
32   return  $I \cup (S_1 \cap F_2) \cup S'_1, I \cup (S_2 \cap F_1) \cup S'_2$ 
```

---

## C. Generation of Directed Hypergraphs (DHs) (Section V-D of the main paper)

Algorithm 6 describes the process of generating a random DH of a desired size. The size of each hyperedge is determined uniformly at random (Line 3), and it consists of randomly selected nodes (Line 4), which are then randomly divided into head and tail sets of almost equal size (Line 5).

**Algorithm 6:** Generation of Directed Hypergraphs

---

**Input:** (1) the number  $n$  of nodes,  
 (2) a ratio  $r$  of hyperedges to nodes,  
 (3) the maximum size  $k$  of a hyperedge  
**Output:** a directed hypergraph:  $G = (V, E)$

```

1  $V \leftarrow [n], E \leftarrow \emptyset$ 
2 for  $1 : r \cdot n$  do
3   Choose the hyperarc size  $d \in \{2, \dots, k\}$  uniformly at random
4   Choose  $U \subseteq V$  such that  $|U| = d$  uniformly at random
5    $T, H \leftarrow \text{Split } U \text{ into two groups of sizes } \lfloor \frac{d}{2} \rfloor \text{ and } \lceil \frac{d}{2} \rceil$ 
6    $E \leftarrow E \cup \{\langle T, H \rangle\}$ 
7 return  $G = (V, E)$ 
```

---

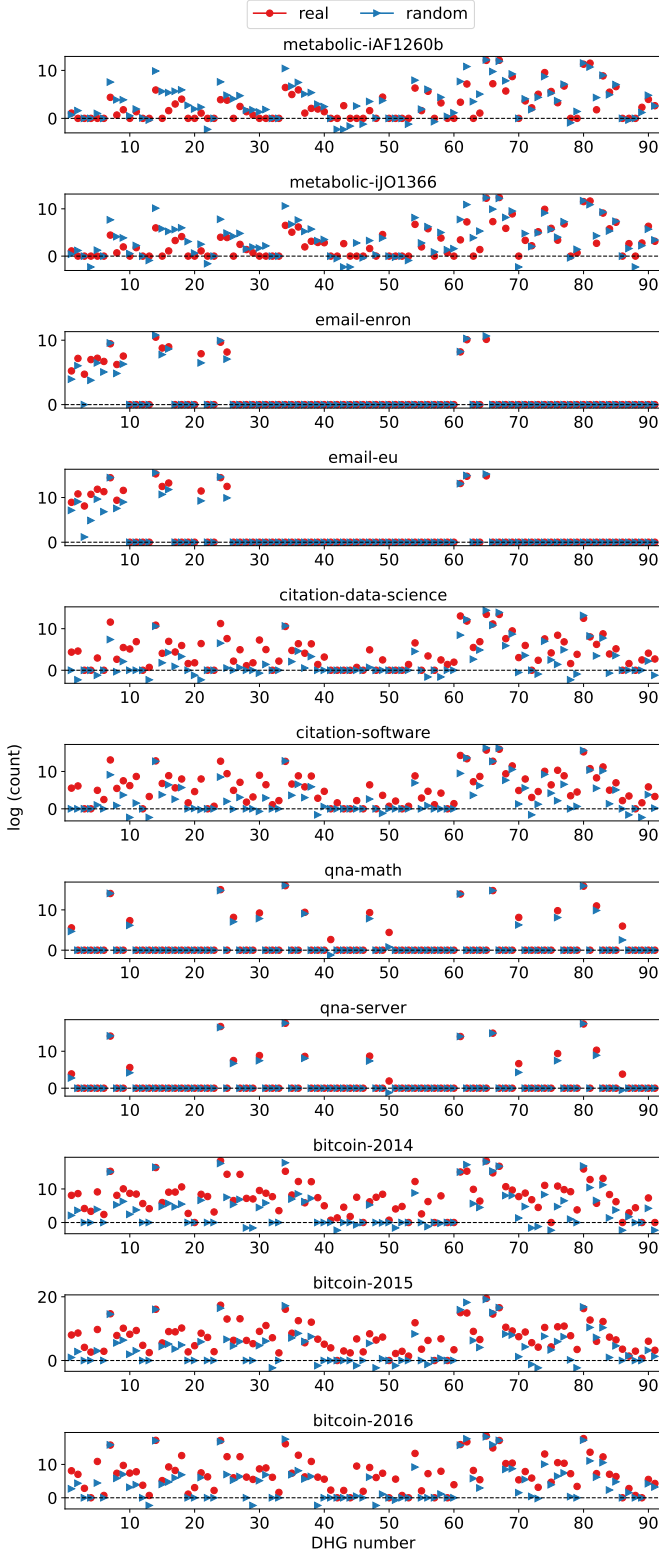


Fig. 13. Log counts of DHGs in real-world and randomized directed hypergraphs (DHs). The counts of DHGs are clearly distinguished in real-world and randomized DHs.

#### D. Count Distributions (Section V-B of the main paper)

We analyze the occurrence distributions of DHGs in real-world and randomized directed hypergraphs (DHs). To ensure statistical significance, we generate ten randomized DHs and report the average counts. As shown in Figure 13, the counts

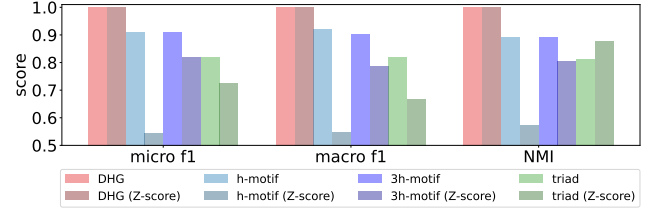


Fig. 14. In most cases, CPs based on the suggested significance measure demonstrate better clustering performance than the CPs based on Z-scores.

of DHGs in real-world directed hypergraphs are distinct from those in randomized directed hypergraphs.

#### E. Characterization of Hypergraphs with Characteristic Profile using Z-Scores (Section V-B of the main paper)

Instead of the suggested significance measure in Eq. (1), Z-scores can be used to compute the characteristic profiles (CPs) as follows:

$$\mu_i^G := \frac{|\Omega_i^G| - |\overline{\Omega_i^{G'}}|}{\text{std}(|\Omega_i^{G'}|) + \epsilon}, \quad (3)$$

where  $|\Omega_i^G|$  represents the count of the instances of DHG- $i$  in  $G$ , and  $|\overline{\Omega_i^{G'}}|$  and  $\text{std}(|\Omega_i^{G'}|)$  are the mean and standard deviation of the counts in ten randomized  $G'$ 's, respectively. We set  $\epsilon$  to 1, preventing from the case where  $\text{std}(|\Omega_i^{G'}|) = 0$ . After computing the significances using Z-scores, we compute the similarity matrix and perform clustering by following the procedures in Section V-B. Note that, regardless of significance measures, using DHGs results in better domain-based differentiation compared to the others, with a 27% clustering performance gain in terms of macro f1-score, as shown in Figure 14. Also note that, in most cases, using the suggested significance measure (i.e., Eq. (1)) leads to better clustering performance than using Z-scores.

#### F. Experimental Settings for Hyperarc Prediction (Section V-C of the main paper)

In this section, we list the hyperparameter settings of the feature vectors and classifiers used for the hyperarc prediction and report the detailed experimental setups.

**Hyperparameter settings of feature vectors:** The embedding dimensions of node2vec, hyper2vec, and deep hyperedges are all fixed to 91. Other hyperparameters of these methods are fixed to their default settings at the following links:

- **node2vec (n2v):** <https://github.com/aditya-grover/node2vec>
- **hyper2vec (h2v):** <https://github.com/jeffhj/NHNE>
- **deep hyperedges (deep-h):** <https://github.com/0xpayne/deep-hyperedges>

Note that h-motif and triad do not have any hyperparameters.

**Details of classifiers:** The hyperparameters of the tree-based classifiers (Decision Tree, Random Forest, XGBoost, and LightGBM), Logistic Regressor, KNN, and MLP are fixed to their default settings at the following links:

- **Decision Tree (DT):** <https://scikit-learn.org/stable/modules/generated/sklearn.tree.DecisionTreeClassifier>
- **Random Forest (RF):** <https://scikit-learn.org/stable/modules/generated/sklearn.ensemble.RandomForestClassifier>
- **XGBoost (XGB):** <https://xgboost.readthedocs.io/en/stable/>

- **LightGBM (LGBM)**: <https://lightgbm.readthedocs.io/en/latest/pythonapi/lightgbm.LGBMClassifier>
- **Logistic Regressor (LR)**: [https://scikit-learn.org/stable/modules/generated/sklearn.linear\\_model.LogisticRegression](https://scikit-learn.org/stable/modules/generated/sklearn.linear_model.LogisticRegression)
- **KNN**: <https://scikit-learn.org/stable/modules/generated/sklearn.neighbors.KNeighborsClassifier>
- **MLP**: [https://scikit-learn.org/stable/modules/generated/sklearn.neural\\_network.MLPClassifier](https://scikit-learn.org/stable/modules/generated/sklearn.neural_network.MLPClassifier)

The hyperparameters of the HNN-based classifiers (HGNN, FastHyperGCN, and UniGCNII) are set as follows: the number of layers and hidden dimension are all fixed to 2 and 128, respectively. We train HGNN and UniGCNII for 500 epochs using Adam with a learning rate of 0.001 and a weight decay of  $10^{-6}$ , and FastHyperGCN for 200 epochs using Adam with a learning rate of 0.01, a weight decay of  $5 \times 10^{-4}$ , and a dropout rate of 0.5.

For these HNN-based classifiers, we employ early stopping, and to this end, we divide the fake hyperarcs into the train, validation, and test sets using a 6:2:2 ratio. In each set, we uniformly sample the same number of real hyperarcs as the number of fake hyperarcs. For every 50 epochs, we measure the validation accuracy and save the model parameters. Then, we use the checkpoint (i.e., saved model parameters) with the highest validation accuracy to measure test performance.

#### *G. Application Results (Section V-C of the main paper)*

In this section, we report the full results of the hyperarc prediction problem. Table IV reports the accuracy and AUROC and results (average over 100 trials). The best performances are highlighted in bold, and the second-best performances are underlined. Notably, in terms of average ranking, using DHG vectors, including the dimension reduced versions, performs best in most settings, achieving up to 33% higher AUROC on the bitcoin-2016 dataset and a 47% higher accuracy on the bitcoin-2014 dataset than the second best features.

TABLE IV

HYPERARC PREDICTION PERFORMANCE. WE COMPARE NINE HYPERARC FEATURE VECTORS USING TEN CLASSIFIERS. THE BEST PERFORMANCES ARE HIGHLIGHTED IN BOLD, AND THE SECOND-BEST PERFORMANCES ARE UNDERLINED. NOTABLY, USING DHG VECTORS LEADS TO THE BEST PERFORMANCE (UP TO 47% AND 33% BETTER IN TERMS OF ACCURACY AND AUROC, RESPECTIVELY) IN MOST SETTINGS, INDICATING THAT DHGS EXTRACT HIGHLY INFORMATIVE HYPERARC FEATURES.

(a) metabolic-iAF1260b

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.664±0.050	0.549±0.061	0.664±0.047	0.649±0.049	0.656±0.057	0.504±0.050	0.511±0.044	0.701±0.055	<b>0.705±0.044</b>
	RF	<b>0.734±0.046</b>	0.650±0.067	0.733±0.048	0.681±0.059	0.690±0.063	0.531±0.054	0.518±0.047	0.714±0.050	0.717±0.060
	DT	<b>0.695±0.055</b>	0.597±0.063	0.683±0.051	0.632±0.065	0.651±0.053	0.512±0.057	0.506±0.056	0.583±0.055	0.615±0.065
	KNN	0.702±0.047	0.625±0.067	0.703±0.044	0.696±0.058	0.696±0.049	0.537±0.050	0.534±0.056	0.704±0.046	<b>0.720±0.050</b>
	MLP	0.709±0.049	0.603±0.062	<b>0.716±0.053</b>	0.646±0.054	0.654±0.063	0.533±0.051	0.537±0.047	0.705±0.054	0.667±0.054
	XGB	0.729±0.048	0.625±0.066	<b>0.741±0.050</b>	0.666±0.059	0.708±0.062	0.514±0.048	0.519±0.045	0.695±0.054	0.717±0.055
	LGBM	0.728±0.047	0.626±0.063	<b>0.740±0.047</b>	0.658±0.053	0.697±0.062	0.527±0.054	0.516±0.052	0.698±0.053	0.713±0.060
	HGNN	0.538±0.047	0.538±0.063	0.546±0.053	0.543±0.040	<b>0.549±0.055</b>	0.483±0.045	0.498±0.067	0.526±0.057	0.540±0.055
	FHGCN	0.562±0.067	0.555±0.055	0.588±0.064	0.535±0.051	<b>0.666±0.067</b>	0.507±0.045	0.491±0.059	0.538±0.050	0.619±0.070
	UGCNI	<b>0.643±0.051</b>	0.596±0.069	0.623±0.057	0.625±0.038	0.618±0.061	0.491±0.050	0.494±0.054	0.597±0.070	0.619±0.066
Max		0.734±0.046	0.650±0.067	<b>0.741±0.050</b>	0.696±0.058	0.708±0.062	0.537±0.050	0.537±0.047	0.714±0.050	0.720±0.050
Avg.		0.670±0.066	0.596±0.036	<b>0.674±0.064</b>	0.633±0.051	0.659±0.045	0.514±0.017	0.512±0.015	0.646±0.072	0.663±0.059
Rank Avg.		2.500±1.360	6.600±0.663	<b>2.200±0.980</b>	5.200±1.536	3.900±1.578	8.500±0.500	8.500±0.500	4.600±1.800	3.000±1.265
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.735±0.059	0.580±0.067	0.727±0.052	0.724±0.049	0.728±0.056	0.506±0.067	0.509±0.052	0.785±0.051	<b>0.791±0.046</b>
	RF	0.815±0.045	0.703±0.087	0.817±0.046	0.784±0.058	0.826±0.046	0.539±0.066	0.533±0.068	0.793±0.051	<b>0.835±0.048</b>
	DT	<b>0.695±0.056</b>	0.599±0.062	0.683±0.051	0.632±0.065	0.651±0.053	0.512±0.057	0.506±0.056	0.583±0.055	0.615±0.065
	KNN	0.770±0.045	0.673±0.076	0.774±0.048	0.755±0.056	0.762±0.051	0.550±0.058	0.552±0.070	0.760±0.047	<b>0.788±0.051</b>
	MLP	0.759±0.053	0.622±0.071	0.778±0.053	0.694±0.074	0.696±0.068	0.543±0.065	0.559±0.059	<b>0.800±0.048</b>	0.710±0.063
	XGB	0.805±0.045	0.684±0.076	0.816±0.046	0.752±0.068	0.812±0.049	0.518±0.063	0.526±0.068	0.775±0.047	<b>0.824±0.047</b>
	LGBM	0.807±0.046	0.680±0.072	0.817±0.046	0.736±0.062	0.799±0.057	0.540±0.059	0.529±0.062	0.785±0.045	<b>0.823±0.049</b>
	HGNN	0.559±0.057	0.541±0.067	0.576±0.048	0.554±0.059	<b>0.594±0.060</b>	0.479±0.058	0.506±0.086	0.522±0.060	0.580±0.055
	FHGCN	0.603±0.080	0.612±0.056	0.637±0.077	0.567±0.072	<b>0.729±0.065</b>	0.506±0.059	0.490±0.067	0.561±0.060	0.693±0.069
	UGCNI	<b>0.702±0.045</b>	0.641±0.097	0.681±0.055	0.674±0.048	0.680±0.060	0.488±0.049	0.489±0.068	0.607±0.092	0.679±0.085
Max		0.815±0.045	0.703±0.087	0.817±0.046	0.784±0.058	0.826±0.046	0.550±0.058	0.559±0.059	0.800±0.048	<b>0.835±0.048</b>
Avg.		0.725±0.083	0.634±0.050	0.731±0.080	0.687±0.076	0.728±0.071	0.518±0.023	0.520±0.023	0.697±0.108	<b>0.734±0.087</b>
Rank Avg.		3.100±1.221	6.400±0.917	2.600±0.917	5.600±0.663	3.000±1.265	8.600±0.490	8.400±0.490	5.100±2.022	<b>2.200±1.470</b>

(b) metabolic-iJ01366

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.662±0.051	0.584±0.055	0.658±0.050	0.648±0.051	0.656±0.048	0.506±0.052	0.505±0.042	<b>0.713±0.057</b>	0.699±0.051
	RF	<b>0.742±0.050</b>	0.666±0.065	0.730±0.045	0.704±0.059	0.698±0.068	0.532±0.045	0.527±0.045	0.723±0.048	0.710±0.066
	DT	<b>0.694±0.051</b>	0.612±0.064	0.680±0.053	0.641±0.057	0.656±0.071	0.509±0.053	0.517±0.049	0.582±0.061	0.612±0.055
	KNN	0.705±0.049	0.628±0.063	0.689±0.045	0.691±0.055	0.682±0.051	0.520±0.053	0.539±0.049	<b>0.725±0.054</b>	0.715±0.061
	MLP	<b>0.718±0.049</b>	0.618±0.064	0.705±0.042	0.653±0.055	0.656±0.059	0.537±0.048	0.539±0.052	0.710±0.055	0.644±0.051
	XGB	<b>0.741±0.050</b>	0.657±0.062	0.732±0.045	0.681±0.054	0.709±0.053	0.519±0.051	0.523±0.048	0.703±0.050	0.719±0.059
	LGBM	<b>0.740±0.052</b>	0.632±0.058	0.734±0.051	0.663±0.056	0.720±0.057	0.509±0.050	0.530±0.047	0.702±0.050	0.713±0.063
	HGNN	0.542±0.052	0.550±0.043	0.564±0.046	0.553±0.036	<b>0.569±0.055</b>	0.499±0.056	0.522±0.037	0.545±0.036	0.558±0.050
	FHGCN	0.591±0.052	0.566±0.059	0.599±0.054	0.532±0.053	<b>0.653±0.071</b>	0.504±0.045	0.498±0.048	0.548±0.060	0.619±0.067
	UGCNI	<b>0.660±0.059</b>	0.610±0.050	0.646±0.055	0.616±0.048	0.621±0.051	0.518±0.047	0.514±0.034	0.633±0.035	0.647±0.052
Max		<b>0.742±0.050</b>	0.666±0.065	0.734±0.051	0.704±0.059	0.720±0.057	0.537±0.048	0.539±0.049	0.725±0.054	0.719±0.059
Avg.		<b>0.680±0.064</b>	0.612±0.035	0.674±0.055	0.638±0.054	0.662±0.042	0.515±0.011	0.521±0.013	0.658±0.070	0.664±0.053
Rank Avg.		<b>2.300±1.900</b>	6.400±0.917	2.800±0.980	5.300±1.005	3.800±1.720	8.600±0.490	8.400±0.490	4.000±2.049	3.400±1.497
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.725±0.064	0.622±0.057	0.724±0.053	0.727±0.058	0.721±0.053	0.501±0.063	0.504±0.058	<b>0.795±0.048</b>	0.782±0.053
	RF	0.824±0.048	0.730±0.076	0.817±0.045	0.794±0.057	<b>0.834±0.048</b>	0.541±0.055	0.546±0.066	0.803±0.043	0.820±0.054
	DT	<b>0.694±0.051</b>	0.611±0.064	0.680±0.053	0.641±0.057	0.656±0.071	0.509±0.053	0.517±0.049	0.582±0.061	0.612±0.055
	KNN	0.774±0.051	0.673±0.077	0.762±0.046	0.752±0.055	0.746±0.054	0.535±0.065	0.560±0.059	0.778±0.051	<b>0.779±0.055</b>
	MLP	0.782±0.050	0.646±0.072	0.761±0.049	0.705±0.075	0.687±0.061	0.548±0.063	0.559±0.069	<b>0.804±0.048</b>	0.682±0.059
	XGB	0.814±0.049	0.710±0.070	0.813±0.047	0.765±0.054	<b>0.819±0.045</b>	0.530±0.063	0.537±0.061	0.792±0.047	0.818±0.049
	LGBM	0.818±0.049	0.687±0.063	0.813±0.049	0.747±0.055	<b>0.822±0.047</b>	0.515±0.057	0.541±0.064	0.794±0.046	0.812±0.047
	HGNN	0.571±0.060	0.552±0.052	0.587±0.048	0.551±0.049	<b>0.601±0.062</b>	0.509±0.051	0.526±0.027	0.534±0.043	0.596±0.053
	FHGCN	0.640±0.062	0.615±0.065	0.647±0.062	0.553±0.070	<b>0.720±0.072</b>	0.506±0.059	0.484±0.059	0.566±0.065	0.692±0.070
	UGCNI	<b>0.713±0.070</b>	0.647±0.056	0.692±0.059	0.663±0.044	0.663±0.058	0.502±0.045	0.503±0.035	0.642±0.043	0.704±0.069
Max		0.824±0.048	0.730±0.076	0.817±0.045	0.794±0.057	<b>0.834±0.048</b>	0.548±0.063	0.560±0.059	0.804±0.048	0.820±0.054
Avg.		<b>0.736±0.079</b>	0.649±0.050	0.730±0.074	0.690±0.082	0.727±0.075	0.520±0.016	0.528±0.024	0.709±0.108	0.730±0.080
Rank Avg.		<b>2.600±1.114</b>	6.400±0.800	3.400±0.800	5.200±1.166	2.900±2.071	8.900±0.300	8.100±0.300	4.600±2.289	2.900±1.513

(c) email-enron

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.772±0.058	0.732±0.058	0.795±0.065	0.752±0.053	<b>0.804±0.054</b>	0.578±0.069	0.492±0.058	0.590±0.062	0.749±0.068
	RF	0.775±0.056	0.712±0.058	0.780±0.071	0.773±0.056	<b>0.796±0.053</b>	0.626±0.069	0.562±0.073	0.592±0.063	0.754±0.066
	DT	0.696±0.064	0.654±0.057	<b>0.705±0.054</b>	0.689±0.071	0.705±0.069	0.551±0.069	0.528±0.073	0.542±0.068	0.650±0.076
	KNN	0.761±0.068	0.694±0.058	0.769±0.064	0.737±0.056	<b>0.777±0.055</b>	0.636±0.058	0.571±0.070	0.567±0.061	0.720±0.066
	MLP	<b>0.810±0.050</b>	0.731±0.054	0.808±0.062	0.751±0.053	0.805±0.055	0.639±0.073	0.551±0.080	0.588±0.064	0.721±0.070
	XGB	0.763±0.059	0.709±0.060	<b>0.780±0.064</b>	0.763±0.064	0.775±0.060	0.614±0.072	0.579±0.074	0.577±0.066	0.750±0.074
	LGBM	0.765±0.057	0.709±0.060	<b>0.775±0.060</b>	0.763±0.056	0.756±0.059	0.609±0.064	0.580±0.077	0.581±0.074	0.750±0.076
	HGNN	0.505±0.047	0.538±0.074	0.512±0.044	<b>0.543±0.063</b>	0.499±0.049	0.513±0.055	0.526±0.048	0.512±0.058	0.510±0.049
	FHGCN	0.587±0.077	<b>0.703±0.101</b>	0.598±0.079	0.651±0.090	<b>0.693±0.117</b>	0.536±0.061	0.566±0.076	0.550±0.069	0.680±0.096
UGCNI	0.668±0.063	<b>0.727±0.046</b>	0.675±0.063	0.708±0.065	0.710±0.050	0.673±0.045	0.689±0.055	0.582±0.051	0.719±0.058	
Max		<b>0.810±0.050</b>	0.732±0.058	0.808±0.062	0.773±0.056	0.805±0.055	0.673±0.045	0.689±0.055	0.592±0.063	0.754±0.066
Avg.		0.710±0.092	0.691±0.055	0.720±0.093	0.713±0.068	<b>0.732±0.087</b>	0.597±0.049	0.564±0.049	0.568±0.025	0.700±0.071
Rank Avg.		4.100±2.300	4.400±2.059	<b>2.800±1.939</b>	3.500±0.922	<u>2.800±2.272</u>	7.000±1.183	7.600±1.960	7.900±1.136	4.900±1.375
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.855±0.052	0.783±0.062	0.870±0.059	0.826±0.058	<b>0.883±0.049</b>	0.627±0.071	0.480±0.076	0.634±0.074	0.820±0.066
	RF	0.839±0.055	0.773±0.059	0.850±0.068	0.856±0.054	<b>0.880±0.047</b>	0.684±0.071	0.624±0.098	0.623±0.074	0.841±0.069
	DT	0.699±0.064	0.652±0.057	<b>0.708±0.056</b>	0.690±0.071	0.707±0.069	0.551±0.069	0.529±0.073	0.542±0.068	0.651±0.075
	KNN	0.827±0.059	0.745±0.060	0.829±0.067	0.810±0.048	<b>0.846±0.051</b>	0.685±0.073	0.597±0.089	0.591±0.073	0.788±0.065
	MLP	0.881±0.039	0.780±0.062	0.881±0.059	0.825±0.061	<b>0.883±0.047</b>	0.697±0.067	0.618±0.096	0.636±0.069	0.786±0.073
	XGB	0.833±0.049	0.765±0.067	0.851±0.065	0.847±0.057	<b>0.863±0.052</b>	0.666±0.082	0.632±0.097	0.610±0.077	0.831±0.074
	LGBM	0.840±0.051	0.769±0.063	<b>0.849±0.063</b>	0.847±0.060	0.842±0.056	0.655±0.081	0.635±0.094	0.612±0.085	0.837±0.070
	HGNN	0.507±0.064	<b>0.554±0.070</b>	0.521±0.053	0.543±0.070	0.505±0.052	0.532±0.070	0.543±0.062	0.532±0.080	0.505±0.060
	FHGCN	0.642±0.078	0.773±0.073	0.663±0.085	0.738±0.099	<b>0.804±0.102</b>	0.548±0.075	0.619±0.084	0.570±0.073	0.763±0.103
UGCNI	0.722±0.066	<b>0.788±0.052</b>	0.724±0.066	0.767±0.065	0.787±0.048	0.706±0.045	0.739±0.056	0.606±0.059	0.784±0.070	
Max		0.881±0.039	0.788±0.052	0.881±0.059	0.856±0.054	<b>0.883±0.049</b>	0.706±0.045	0.739±0.056	0.636±0.069	0.841±0.069
Avg.		0.764±0.114	0.738±0.072	0.775±0.112	0.775±0.093	<b>0.800±0.111</b>	0.635±0.063	0.601±0.067	0.596±0.035	0.761±0.100
Rank Avg.		4.400±1.685	4.500±2.110	3.100±1.814	3.400±0.800	<b>2.100±2.071</b>	7.200±0.980	7.300±2.100	8.000±1.483	5.000±1.612

(d) email-eu

Dimension		13		26		91				431
Measure	Model	DHG-13 triad		DHG-26 h-motif		DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.854±0.009	0.837±0.013	0.855±0.009	0.776±0.019	<b>0.869±0.010</b>	0.618±0.028	0.496±0.012	0.659±0.019	0.799±0.017
	RF	0.883±0.009	0.839±0.011	0.890±0.008	0.838±0.011	<b>0.907±0.010</b>	0.652±0.017	0.515±0.021	0.668±0.020	0.840±0.011
	DT	0.825±0.010	0.787±0.016	0.828±0.010	0.761±0.016	<b>0.849±0.012</b>	0.546±0.015	0.504±0.019	0.564±0.015	0.753±0.018
	KNN	0.867±0.009	0.838±0.011	0.868±0.008	0.780±0.014	<b>0.875±0.010</b>	0.573±0.009	0.556±0.040	0.677±0.013	0.795±0.013
	MLP	0.904±0.008	0.857±0.012	<b>0.911±0.007</b>	0.821±0.023	0.906±0.011	0.660±0.047	0.507±0.018	0.675±0.048	0.808±0.027
	XGB	0.885±0.008	0.854±0.011	0.891±0.008	0.831±0.012	<b>0.903±0.009</b>	0.654±0.018	0.522±0.017	0.656±0.022	0.840±0.011
	LGBM	0.889±0.009	0.856±0.011	0.895±0.008	0.839±0.010	<b>0.906±0.010</b>	0.645±0.027	0.512±0.010	0.645±0.026	0.846±0.011
	HGNN	0.521±0.015	0.520±0.015	0.523±0.016	0.523±0.020	<b>0.529±0.020</b>	0.512±0.018	0.505±0.014	0.513±0.017	0.526±0.021
FHGCN	0.607±0.087	<b>0.790±0.136</b>	0.622±0.095	0.638±0.060	0.742±0.072	0.512±0.020	0.519±0.038	0.547±0.054	0.678±0.072	
UGCNI	0.772±0.014	<b>0.859±0.008</b>	0.788±0.013	0.726±0.009	0.783±0.013	0.724±0.014	0.740±0.020	0.706±0.013	0.762±0.011	
Max		0.904±0.008	0.859±0.008	<b>0.911±0.007</b>	0.839±0.010	0.907±0.010	0.724±0.014	0.740±0.020	0.706±0.013	0.846±0.011
Avg.		0.801±0.125	0.804±0.098	0.807±0.124	0.753±0.097	<b>0.827±0.113</b>	0.610±0.067	0.538±0.069	0.631±0.062	0.765±0.093
Rank Avg.		3.600±1.020	3.700±1.487	2.400±1.114	5.400±1.114	<b>1.400±0.663</b>	8.100±0.300	8.600±0.917	7.200±0.600	4.600±1.200
Measure	Model	DHG-13 triad		DHG-26 h-motif		DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.922±0.009	0.876±0.009	0.926±0.008	0.838±0.015	<b>0.933±0.008</b>	0.691±0.013	0.494±0.018	0.722±0.014	0.868±0.013
	RF	0.941±0.007	0.901±0.009	0.946±0.005	0.921±0.007	<b>0.960±0.005</b>	0.737±0.016	0.529±0.032	0.770±0.015	0.925±0.007
	DT	0.827±0.010	0.785±0.017	0.830±0.010	0.762±0.016	<b>0.852±0.012</b>	0.546±0.015	0.504±0.019	0.564±0.015	0.754±0.018
	KNN	0.915±0.008	0.881±0.010	0.915±0.007	0.854±0.013	<b>0.920±0.008</b>	0.701±0.013	0.586±0.059	0.749±0.014	0.870±0.010
	MLP	0.960±0.005	0.911±0.010	<b>0.963±0.004</b>	0.909±0.013	0.962±0.006	0.790±0.014	0.539±0.052	0.802±0.017	0.887±0.021
	XGB	0.945±0.006	0.905±0.009	0.949±0.005	0.917±0.007	<b>0.961±0.005</b>	0.747±0.014	0.557±0.033	0.777±0.014	0.925±0.008
	LGBM	0.948±0.006	0.908±0.008	0.952±0.005	0.923±0.006	<b>0.963±0.005</b>	0.761±0.014	0.555±0.032	0.796±0.013	0.930±0.007
	HGNN	0.524±0.020	0.516±0.017	0.524±0.020	0.520±0.020	<b>0.529±0.028</b>	0.504±0.018	0.502±0.014	0.500±0.017	0.524±0.024
	FHGCN	0.724±0.082	<b>0.888±0.041</b>	0.745±0.080	0.724±0.051	0.849±0.054	0.520±0.029	0.550±0.057	0.614±0.070	0.768±0.062
	UGCNI	0.864±0.011	<b>0.912±0.007</b>	0.881±0.010	0.805±0.010	0.874±0.010	0.793±0.014	0.812±0.020	0.784±0.012	0.849±0.008
Max		0.960±0.005	0.912±0.007	<b>0.963±0.004</b>	0.923±0.006	0.963±0.005	0.793±0.014	0.812±0.020	0.802±0.017	0.930±0.007
Avg.		0.857±0.131	0.848±0.116	0.863±0.130	0.817±0.119	<b>0.880±0.125</b>	0.679±0.107	0.563±0.087	0.708±0.103	0.830±0.118
Rank Avg.		3.300±0.640	4.200±1.833	2.300±0.900	5.500±0.671	<b>1.400±0.663</b>	8.000±0.447	8.500±0.922	7.400±0.800	4.400±1.200

(e) citation-data-science

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.907±0.008	0.602±0.018	0.918±0.007	0.751±0.039	<b>0.921±0.011</b>	0.527±0.017	0.504±0.008	0.593±0.022	0.837±0.027
	RF	0.952±0.006	0.644±0.022	0.952±0.008	0.855±0.017	<b>0.977±0.004</b>	0.548±0.015	0.500±0.012	0.599±0.023	0.923±0.007
	DT	0.914±0.011	0.583±0.018	0.906±0.015	0.777±0.026	<b>0.963±0.005</b>	0.511±0.016	0.497±0.015	0.539±0.015	0.848±0.015
	KNN	0.922±0.007	0.594±0.016	<b>0.925±0.007</b>	0.787±0.025	0.917±0.010	0.558±0.013	0.514±0.021	0.592±0.014	0.844±0.012
	MLP	0.967±0.005	0.637±0.026	<b>0.971±0.005</b>	0.822±0.035	0.969±0.005	0.545±0.024	0.502±0.010	0.633±0.037	0.888±0.018
	XGB	0.958±0.005	0.639±0.025	0.961±0.006	0.843±0.024	<b>0.975±0.004</b>	0.547±0.018	0.505±0.011	0.618±0.024	0.927±0.011
	LGBM	0.957±0.006	0.652±0.022	0.960±0.006	0.849±0.020	<b>0.977±0.004</b>	0.546±0.020	0.504±0.010	0.601±0.026	0.930±0.009
	HGNN	0.572±0.010	0.534±0.013	0.585±0.012	0.543±0.015	<b>0.595±0.009</b>	0.542±0.012	0.535±0.017	0.519±0.013	0.554±0.017
	FHGCN	0.593±0.093	0.556±0.067	0.621±0.095	0.597±0.087	<b>0.754±0.091</b>	0.505±0.015	0.504±0.013	0.502±0.008	0.622±0.099
	UGCNI	0.923±0.009	0.657±0.012	0.927±0.009	0.798±0.013	<b>0.932±0.005</b>	0.769±0.016	0.630±0.028	0.541±0.011	0.823±0.010
Max		0.967±0.005	0.657±0.012	0.971±0.005	0.855±0.017	<b>0.977±0.004</b>	0.769±0.016	0.630±0.028	0.633±0.037	0.930±0.009
Avg.		0.866±0.143	0.610±0.041	0.873±0.136	0.762±0.102	<b>0.988±0.119</b>	0.560±0.072	0.519±0.038	0.574±0.042	0.820±0.123
Rank Avg.		3.000±0.775	6.300±0.640	2.000±0.632	4.900±0.300	<b>1.300±0.640</b>	7.500±0.806	8.600±0.663	7.600±0.917	3.800±0.600
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.963±0.005	0.644±0.016	0.969±0.006	0.857±0.019	<b>0.969±0.005</b>	0.564±0.015	0.512±0.016	0.653±0.013	0.927±0.012
	RF	0.987±0.003	0.703±0.023	0.987±0.003	0.939±0.008	<b>0.997±0.001</b>	0.573±0.019	0.498±0.017	0.707±0.020	0.975±0.004
	DT	0.914±0.011	0.583±0.018	0.906±0.015	0.777±0.026	<b>0.963±0.005</b>	0.511±0.016	0.497±0.015	0.539±0.015	0.848±0.015
	KNN	0.963±0.005	0.629±0.020	<b>0.965±0.005</b>	0.857±0.023	0.962±0.006	0.595±0.015	0.520±0.030	0.633±0.016	0.908±0.010
	MLP	0.993±0.002	0.693±0.028	<b>0.994±0.002</b>	0.914±0.021	0.990±0.004	0.597±0.021	0.510±0.016	0.776±0.013	0.938±0.012
	XGB	0.991±0.002	0.703±0.025	0.992±0.002	0.937±0.009	<b>0.997±0.001</b>	0.579±0.016	0.507±0.022	0.747±0.012	0.983±0.003
	LGBM	0.990±0.002	0.719±0.021	0.992±0.002	0.941±0.008	<b>0.998±0.001</b>	0.587±0.014	0.511±0.023	0.782±0.011	0.984±0.003
	HGNN	0.595±0.016	0.523±0.013	0.616±0.016	0.528±0.017	<b>0.629±0.008</b>	0.537±0.014	0.540±0.022	0.510±0.013	0.555±0.019
	FHGCN	0.703±0.069	0.637±0.060	0.728±0.069	0.700±0.053	<b>0.861±0.059</b>	0.516±0.028	0.513±0.021	0.505±0.011	0.753±0.059
	UGCNI	0.972±0.005	0.714±0.013	0.974±0.005	0.874±0.010	<b>0.975±0.005</b>	0.851±0.016	0.672±0.042	0.547±0.012	0.899±0.008
Max		0.993±0.002	0.719±0.021	0.994±0.002	0.941±0.008	<b>0.998±0.001</b>	0.851±0.016	0.672±0.042	0.782±0.011	0.984±0.003
Avg.		0.907±0.133	0.655±0.061	0.912±0.125	0.832±0.125	<b>0.934±0.108</b>	0.591±0.092	0.528±0.049	0.640±0.104	0.877±0.126
Rank Avg.		2.800±0.600	6.900±0.539	2.000±0.632	5.200±0.600	<b>1.400±0.800</b>	7.500±0.806	8.400±1.200	7.000±1.342	3.800±0.600

(f) citation-software

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.908±0.005	0.662±0.015	0.912±0.004	0.767±0.007	<b>0.919±0.007</b>	0.541±0.018	0.508±0.013	0.625±0.019	0.829±0.010
	RF	0.966±0.003	0.702±0.019	0.968±0.003	0.866±0.022	<b>0.984±0.002</b>	0.568±0.018	0.501±0.012	0.621±0.022	0.941±0.004
	DT	0.945±0.004	0.623±0.012	0.944±0.004	0.783±0.045	<b>0.974±0.002</b>	0.519±0.010	0.498±0.016	0.548±0.009	0.875±0.012
	KNN	<b>0.947±0.004</b>	0.652±0.013	0.945±0.003	0.834±0.013	0.941±0.005	0.578±0.010	0.521±0.026	0.606±0.006	0.884±0.008
	MLP	0.978±0.002	0.699±0.018	0.979±0.002	0.844±0.029	<b>0.980±0.002</b>	0.575±0.032	0.512±0.022	0.652±0.041	0.919±0.011
	XGB	0.971±0.002	0.704±0.018	0.973±0.002	0.850±0.037	<b>0.984±0.002</b>	0.562±0.023	0.506±0.008	0.636±0.024	0.943±0.007
	LGBM	0.969±0.003	0.713±0.016	0.971±0.002	0.860±0.032	<b>0.984±0.002</b>	0.560±0.028	0.502±0.006	0.622±0.025	0.946±0.006
	HGNN	0.560±0.009	0.529±0.008	0.562±0.009	0.534±0.011	0.555±0.007	0.553±0.009	<b>0.568±0.009</b>	0.521±0.006	0.543±0.007
	FHGCN	0.561±0.074	0.594±0.089	0.572±0.074	0.609±0.086	<b>0.738±0.098</b>	0.503±0.013	0.502±0.009	0.503±0.009	0.630±0.084
	UGCNI	0.917±0.005	0.718±0.010	<b>0.921±0.005</b>	0.739±0.010	0.917±0.006	0.827±0.016	0.823±0.009	0.578±0.012	0.792±0.006
Max		0.978±0.002	0.718±0.010	0.979±0.002	0.866±0.022	<b>0.984±0.002</b>	0.827±0.016	0.823±0.009	0.652±0.041	0.946±0.006
Avg.		0.872±0.157	0.660±0.058	0.875±0.155	0.769±0.108	<b>0.898±0.134</b>	0.579±0.086	0.544±0.095	0.591±0.049	0.830±0.132
Rank Avg.		2.900±1.221	6.200±1.077	2.300±1.005	5.200±1.077	<b>1.700±1.100</b>	7.200±1.400	7.800±2.561	7.500±0.806	4.200±1.077
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.977±0.003	0.722±0.015	0.979±0.002	0.890±0.008	<b>0.980±0.003</b>	0.584±0.010	0.516±0.008	0.688±0.008	0.943±0.005
	RF	0.993±0.001	0.777±0.012	0.994±0.001	0.945±0.012	<b>0.999±0.000</b>	0.611±0.015	0.502±0.017	0.739±0.013	0.986±0.001
	DT	0.945±0.004	0.623±0.012	0.944±0.004	0.783±0.045	<b>0.974±0.002</b>	0.519±0.010	0.498±0.016	0.548±0.009	0.875±0.012
	KNN	<b>0.976±0.002</b>	0.702±0.015	<b>0.976±0.002</b>	0.899±0.010	0.974±0.003	0.632±0.011	0.531±0.034	0.659±0.007	0.940±0.006
	MLP	<b>0.997±0.001</b>	0.775±0.016	<b>0.997±0.001</b>	0.930±0.018	0.996±0.002	0.671±0.019	0.544±0.048	0.806±0.009	0.964±0.008
	XGB	0.995±0.001	0.781±0.014	0.996±0.001	0.939±0.019	<b>0.999±0.000</b>	0.620±0.017	0.522±0.020	0.786±0.009	0.991±0.001
	LGBM	0.995±0.001	0.792±0.012	0.996±0.001	0.946±0.017	<b>0.999±0.000</b>	0.626±0.019	0.525±0.020	0.807±0.008	0.991±0.001
	HGNN	0.584±0.012	0.510±0.012	0.589±0.011	0.509±0.023	0.587±0.006	0.562±0.009	<b>0.590±0.012</b>	0.508±0.007	0.551±0.014
	FHGCN	0.651±0.094	0.714±0.054	0.659±0.085	0.718±0.050	<b>0.852±0.044</b>	0.513±0.025	0.511±0.024	0.505±0.013	0.732±0.045
	UGCNI	0.972±0.002	0.792±0.011	<b>0.973±0.003</b>	0.812±0.010	0.971±0.003	0.899±0.016	0.895±0.007	0.609±0.015	0.868±0.005
Max		0.997±0.001	0.792±0.012	0.997±0.001	0.946±0.017	<b>0.999±0.000</b>	0.899±0.016	0.895±0.007	0.807±0.008	0.991±0.001
Avg.		0.909±0.147	0.719±0.086	0.910±0.145	0.837±0.132	<b>0.933±0.123</b>	0.624±0.103	0.564±0.113	0.666±0.113	0.884±0.134
Rank Avg.		2.900±1.300	6.400±1.020	2.200±1.077	5.300±1.269	<b>1.800±0.980</b>	7.200±1.400	7.700±2.532	7.300±1.187	4.200±1.077

(g) qna-math

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.606±0.010	0.553±0.013	0.607±0.010	0.579±0.011	0.604±0.009	0.500±0.005	0.504±0.006	0.566±0.009	<b>0.615±0.012</b>
	RF	0.640±0.008	0.620±0.012	0.641±0.008	0.613±0.017	<b>0.673±0.010</b>	0.503±0.010	0.502±0.010	0.581±0.024	0.656±0.015
	DT	0.598±0.009	0.572±0.010	0.595±0.009	0.547±0.016	<b>0.617±0.011</b>	0.502±0.008	0.502±0.011	0.547±0.013	0.574±0.017
	KNN	<b>0.607±0.008</b>	0.553±0.011	0.605±0.007	0.576±0.011	0.601±0.010	0.504±0.009	0.506±0.015	0.523±0.008	0.603±0.010
	MLP	0.639±0.017	0.590±0.014	0.640±0.016	0.598±0.015	<b>0.679±0.010</b>	0.505±0.009	0.503±0.005	0.611±0.043	0.626±0.020
	XGB	0.643±0.008	0.629±0.011	0.644±0.009	0.607±0.019	<b>0.681±0.010</b>	0.502±0.010	0.508±0.008	0.601±0.027	0.668±0.016
	LGBM	0.651±0.008	0.641±0.012	0.652±0.009	0.618±0.019	<b>0.690±0.009</b>	0.504±0.009	0.506±0.008	0.577±0.027	0.686±0.015
	HGNN	0.552±0.010	0.529±0.008	<b>0.552±0.009</b>	0.525±0.011	0.549±0.011	0.520±0.011	0.546±0.007	0.545±0.008	0.548±0.008
	FHGCN	0.501±0.006	<b>0.516±0.029</b>	0.501±0.004	0.503±0.007	0.512±0.022	0.500±0.003	0.502±0.008	0.507±0.016	0.508±0.017
UGCNI	0.613±0.005	0.599±0.010	0.614±0.004	0.583±0.009	0.607±0.006	0.615±0.010	0.637±0.008	<b>0.743±0.013</b>	0.609±0.008	
Max		0.651±0.008	0.641±0.012	0.652±0.009	0.618±0.019	0.690±0.009	0.615±0.010	0.637±0.008	<b>0.743±0.013</b>	0.686±0.015
Avg.		0.605±0.044	0.580±0.041	0.605±0.045	0.575±0.037	<b>0.621±0.057</b>	0.515±0.034	0.521±0.040	0.580±0.063	0.609±0.052
Rank Avg.		3.500±1.628	5.600±1.855	3.100±1.814	6.200±1.249	<b>2.500±1.910</b>	8.200±1.778	7.100±2.071	5.700±1.847	3.100±1.375
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.653±0.008	0.580±0.014	0.655±0.010	0.620±0.011	0.652±0.011	0.499±0.009	0.514±0.010	0.600±0.009	<b>0.666±0.013</b>
	RF	0.692±0.009	0.663±0.015	0.695±0.009	0.657±0.020	0.734±0.011	0.505±0.012	0.504±0.014	<b>0.767±0.020</b>	0.716±0.019
	DT	0.602±0.009	0.569±0.010	0.599±0.009	0.547±0.016	<b>0.621±0.011</b>	0.502±0.008	0.502±0.011	0.547±0.013	0.574±0.017
	KNN	<b>0.647±0.009</b>	0.570±0.012	0.644±0.009	0.601±0.013	0.638±0.012	0.506±0.011	0.511±0.019	0.561±0.012	0.638±0.013
	MLP	0.696±0.015	0.634±0.015	0.700±0.016	0.649±0.015	0.737±0.013	0.514±0.013	0.509±0.010	<b>0.834±0.011</b>	0.679±0.022
	XGB	0.700±0.009	0.677±0.014	0.702±0.009	0.660±0.020	0.744±0.011	0.504±0.012	0.513±0.011	<b>0.823±0.010</b>	0.736±0.016
	LGBM	0.708±0.008	0.694±0.015	0.711±0.010	0.679±0.016	0.755±0.010	0.505±0.014	0.513±0.012	<b>0.844±0.009</b>	0.758±0.013
	HGNN	<b>0.576±0.010</b>	0.535±0.012	0.575±0.008	0.520±0.011	0.570±0.013	0.519±0.012	0.566±0.009	0.551±0.010	0.568±0.009
	FHGCN	0.504±0.011	<b>0.545±0.044</b>	0.502±0.008	0.507±0.010	0.538±0.031	0.501±0.005	0.507±0.020	0.521±0.028	0.525±0.028
UGCNI	0.666±0.008	0.642±0.011	0.667±0.007	0.620±0.011	0.658±0.007	0.661±0.012	0.689±0.007	<b>0.817±0.014</b>	0.659±0.009	
Max		0.708±0.008	0.694±0.015	0.711±0.010	0.679±0.016	0.755±0.010	0.661±0.012	0.689±0.007	<b>0.844±0.009</b>	0.758±0.013
Avg.		0.644±0.062	0.611±0.055	0.645±0.064	0.606±0.058	0.665±0.072	0.521±0.047	0.533±0.055	<b>0.687±0.133</b>	0.652±0.073
Rank Avg.		3.700±1.847	5.900±1.814	3.500±1.688	6.600±1.200	<b>2.900±1.578</b>	8.400±1.200	7.000±2.145	3.500±2.617	3.500±1.360

(h) qna-server

Dimension		13		26		91				431
Measure	Model	DHG-13 triad		DHG-26 h-motif		DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.556±0.007	0.530±0.011	0.557±0.007	0.533±0.009	<b>0.561±0.007</b>	0.502±0.004	0.509±0.008	0.556±0.007	0.553±0.007
	RF	0.643±0.005	0.590±0.012	0.640±0.004	0.565±0.012	<b>0.661±0.004</b>	0.500±0.006	0.503±0.005	0.565±0.018	0.631±0.010
	DT	0.615±0.005	0.572±0.012	0.614±0.005	0.528±0.008	<b>0.626±0.006</b>	0.500±0.007	0.501±0.007	0.545±0.009	0.571±0.011
	KNN	<b>0.628±0.005</b>	0.566±0.010	0.626±0.005	0.538±0.007	0.619±0.006	0.504±0.007	0.502±0.009	0.576±0.005	0.562±0.008
	MLP	<b>0.670±0.005</b>	0.603±0.014	<b>0.670±0.005</b>	0.544±0.013	0.668±0.005	0.509±0.006	0.506±0.011	0.598±0.040	0.584±0.014
	XGB	0.658±0.005	0.612±0.016	0.656±0.005	0.575±0.013	<b>0.679±0.005</b>	0.503±0.005	0.503±0.007	0.585±0.019	0.647±0.010
	LGBM	0.666±0.004	0.624±0.013	0.665±0.005	0.585±0.011	<b>0.688±0.004</b>	0.504±0.006	0.503±0.007	0.567±0.018	0.657±0.009
	HGNN	0.588±0.005	0.546±0.005	0.588±0.005	0.539±0.005	0.579±0.006	0.535±0.007	0.572±0.006	0.571±0.005	<b>0.591±0.005</b>
	FHGCN	0.502±0.008	0.515±0.027	0.502±0.007	0.505±0.014	<b>0.530±0.041</b>	0.501±0.003	0.501±0.005	0.502±0.009	0.514±0.030
UGCNI	0.657±0.006	0.605±0.005	0.656±0.006	0.595±0.007	0.713±0.005	0.563±0.005	0.653±0.006	<b>0.752±0.007</b>	0.652±0.005	
Max		0.670±0.005	0.624±0.013	0.670±0.005	0.595±0.007	0.713±0.005	0.563±0.005	0.653±0.006	<b>0.752±0.007</b>	0.657±0.009
Avg.		0.619±0.052	0.576±0.035	0.617±0.051	0.551±0.027	<b>0.632±0.057</b>	0.512±0.020	0.525±0.047	0.582±0.062	0.596±0.046
Rank Avg.		2.500±1.432	5.100±1.513	3.200±1.400	6.700±1.100	<b>1.800±1.077</b>	8.600±0.490	7.800±1.470	4.900±1.700	4.400±1.497

Measure	Model	DHG-13 triad		DHG-26 h-motif		DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.596±0.005	0.558±0.009	0.597±0.006	0.553±0.010	<b>0.598±0.006</b>	0.512±0.006	0.528±0.006	0.586±0.006	0.587±0.009
	RF	0.704±0.005	0.637±0.017	0.701±0.005	0.595±0.016	0.728±0.005	0.501±0.008	0.504±0.009	<b>0.748±0.017</b>	0.692±0.013
	DT	0.619±0.005	0.571±0.010	0.618±0.005	0.524±0.008	<b>0.630±0.006</b>	0.500±0.007	0.501±0.007	0.545±0.009	0.571±0.011
	KNN	<b>0.681±0.005</b>	0.599±0.013	0.678±0.005	0.552±0.009	0.669±0.006	0.505±0.008	0.503±0.013	0.610±0.008	0.586±0.010
	MLP	0.719±0.006	0.630±0.014	0.719±0.006	0.573±0.013	0.717±0.006	0.511±0.006	0.525±0.013	<b>0.815±0.010</b>	0.631±0.015
	XGB	0.713±0.006	0.653±0.021	0.711±0.005	0.612±0.016	0.745±0.005	0.504±0.007	0.507±0.011	<b>0.801±0.007</b>	0.712±0.013
	LGBM	0.719±0.005	0.669±0.018	0.719±0.005	0.628±0.014	0.753±0.005	0.506±0.009	0.513±0.010	<b>0.813±0.007</b>	0.729±0.010
	HGNN	0.629±0.006	0.563±0.006	0.629±0.005	0.543±0.006	0.619±0.008	0.534±0.008	0.599±0.007	0.585±0.009	<b>0.631±0.009</b>
	FHGCN	0.508±0.016	0.546±0.049	0.507±0.016	0.528±0.025	<b>0.593±0.041</b>	0.502±0.007	0.503±0.012	0.511±0.018	0.557±0.045
UGCNI	0.731±0.007	0.649±0.007	0.728±0.006	0.636±0.008	0.645±0.005	0.594±0.010	0.713±0.006	<b>0.824±0.008</b>	0.719±0.007	
Max		0.731±0.007	0.669±0.018	0.728±0.006	0.636±0.008	0.753±0.005	0.594±0.010	0.713±0.006	<b>0.824±0.008</b>	0.729±0.010
Avg.		0.662±0.069	0.607±0.043	0.661±0.068	0.575±0.039	0.670±0.058	0.517±0.027	0.540±0.064	<b>0.684±0.121</b>	0.641±0.063
Rank Avg.		3.000±1.265	5.600±1.020	3.500±1.628	6.900±1.044	<b>2.700±1.792</b>	8.900±0.300	7.500±1.285	3.100±2.166	3.800±1.400

(i) bitcoin-2014

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.552±0.003	0.524±0.002	0.581±0.006	O.O.T.*	<b>0.626±0.022</b>	0.527±0.027	0.527±0.014	0.580±0.027	O.O.T.*
	RF	0.914±0.003	0.731±0.029	0.919±0.003		<b>0.927±0.010</b>	0.540±0.013	0.517±0.005	0.608±0.039	
	DT	0.886±0.003	0.703±0.027	0.891±0.003		<b>0.896±0.017</b>	0.507±0.010	0.503±0.005	0.549±0.011	
	KNN	<b>0.879±0.003</b>	0.699±0.014	0.878±0.003		0.838±0.016	0.577±0.011	0.537±0.010	0.639±0.004	
	MLP	0.763±0.011	0.612±0.049	0.838±0.015		<b>0.922±0.002</b>	0.555±0.031	0.538±0.023	0.629±0.039	
	XGB	0.902±0.004	0.760±0.036	0.912±0.003		<b>0.935±0.003</b>	0.554±0.014	0.520±0.012	0.615±0.032	
	LGBM	0.882±0.005	0.765±0.036	0.896±0.004		<b>0.935±0.002</b>	0.560±0.018	0.526±0.016	0.606±0.034	
	HGNN	0.730±0.003	0.633±0.003	<b>0.731±0.003</b>		0.727±0.003	0.632±0.004	0.628±0.003	0.600±0.003	
	FHGCN	0.517±0.027	0.623±0.090	0.516±0.025		<b>0.705±0.103</b>	0.504±0.009	0.504±0.010	0.505±0.009	
	UGCNI	0.853±0.003	0.771±0.003	<b>0.855±0.002</b>		0.845±0.003	0.773±0.008	0.711±0.005	0.652±0.003	
Max		0.914±0.003	0.771±0.003	0.919±0.003		<b>0.935±0.003</b>	0.773±0.008	0.711±0.005	0.652±0.003	
Avg.		0.788±0.139	0.682±0.077	0.802±0.137		<b>0.836±0.106</b>	0.573±0.075	0.551±0.063	0.598±0.042	
Rank Avg.		2.700±0.781	4.300±1.187	2.000±0.775		<b>1.600±0.917</b>	5.700±0.640	6.600±0.663	5.100±1.136	
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.559±0.013	0.616±0.007	0.674±0.021	O.O.T.*	<b>0.693±0.014</b>	0.569±0.003	0.559±0.002	0.640±0.003	O.O.T.*
	RF	0.971±0.001	0.799±0.034	0.972±0.001		<b>0.976±0.004</b>	0.562±0.015	0.524±0.008	0.729±0.022	
	DT	0.885±0.004	0.704±0.031	0.890±0.003		<b>0.900±0.014</b>	0.507±0.010	0.503±0.005	0.549±0.011	
	KNN	<b>0.941±0.002</b>	0.744±0.016	0.941±0.003		0.905±0.015	0.606±0.013	0.556±0.012	0.694±0.005	
	MLP	0.854±0.013	0.679±0.053	0.917±0.010		<b>0.968±0.002</b>	0.622±0.029	0.577±0.031	0.771±0.009	
	XGB	0.966±0.002	0.841±0.033	0.971±0.002		<b>0.980±0.003</b>	0.575±0.015	0.549±0.009	0.784±0.005	
	LGBM	0.954±0.003	0.847±0.030	0.962±0.002		<b>0.980±0.002</b>	0.583±0.018	0.558±0.011	0.789±0.005	
	HGNN	0.815±0.002	0.663±0.004	<b>0.816±0.003</b>		0.808±0.002	0.664±0.004	0.664±0.003	0.607±0.002	
	FHGCN	0.536±0.044	0.714±0.055	0.540±0.046		<b>0.822±0.028</b>	0.510±0.021	0.506±0.015	0.506±0.012	
	UGCNI	0.932±0.003	0.854±0.003	<b>0.933±0.002</b>		0.926±0.003	0.855±0.008	0.790±0.005	0.713±0.003	
Max		0.971±0.001	0.854±0.003	0.972±0.001		<b>0.980±0.003</b>	0.855±0.008	0.790±0.005	0.789±0.005	
Avg.		0.841±0.155	0.746±0.081	0.862±0.138		<b>0.896±0.090</b>	0.605±0.095	0.579±0.083	0.678±0.094	
Rank Avg.		3.100±1.513	4.200±0.980	1.900±0.539		<b>1.600±0.917</b>	5.500±0.671	6.400±0.917	5.300±1.269	

\* O.O.T: out-of-time (&gt; 1 day).

(j) bitcoin-2015

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.539±0.016	0.539±0.006	0.561±0.003	O.O.T.*	0.566±0.002	0.528±0.029	0.532±0.013	<b>0.569±0.027</b>	O.O.T.*
	RF	0.928±0.003	0.686±0.034	<b>0.929±0.003</b>		0.926±0.012	0.552±0.012	0.520±0.006	0.598±0.037	
	DT	0.904±0.004	0.664±0.036	<b>0.905±0.003</b>		0.889±0.021	0.512±0.009	0.504±0.005	0.543±0.011	
	KNN	<b>0.906±0.002</b>	0.658±0.028	0.895±0.003		0.839±0.025	0.592±0.008	0.539±0.009	0.628±0.004	
	MLP	0.825±0.018	0.635±0.027	0.854±0.014		<b>0.920±0.015</b>	0.571±0.029	0.553±0.023	0.619±0.039	
	XGB	0.918±0.005	0.721±0.042	0.923±0.004		<b>0.939±0.005</b>	0.571±0.012	0.519±0.011	0.606±0.028	
	LGBM	0.901±0.007	0.725±0.038	0.908±0.006		<b>0.941±0.003</b>	0.574±0.019	0.526±0.015	0.596±0.030	
	HGNN	0.748±0.003	0.636±0.003	<b>0.750±0.003</b>		<b>0.750±0.003</b>	0.641±0.006	0.630±0.004	0.603±0.002	
	FHGCN	0.545±0.063	0.599±0.098	0.574±0.067		<b>0.699±0.112</b>	0.506±0.013	0.503±0.008	0.503±0.006	
	UGCNI	0.866±0.003	0.773±0.005	<b>0.867±0.002</b>		0.858±0.002	0.782±0.005	0.717±0.003	0.651±0.003	
Max		0.928±0.003	0.773±0.005	0.929±0.003		<b>0.941±0.003</b>	0.782±0.005	0.717±0.003	0.651±0.003	
Avg.		0.808±0.142	0.664±0.064	0.817±0.134		<b>0.833±0.118</b>	0.583±0.076	0.554±0.064	0.592±0.041	
Rank Avg.		2.800±1.077	4.000±0.775	<b>1.800±0.748</b>		2.000±0.894	5.600±0.917	6.700±0.458	5.100±1.578	
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.552±0.008	0.612±0.010	0.692±0.005	O.O.T.*	<b>0.696±0.012</b>	0.592±0.003	0.563±0.003	0.627±0.003	O.O.T.*
	RF	0.977±0.001	0.755±0.040	<b>0.978±0.001</b>		0.977±0.004	0.578±0.014	0.528±0.008	0.715±0.023	
	DT	0.903±0.004	0.672±0.035	<b>0.904±0.004</b>		0.893±0.019	0.512±0.009	0.504±0.005	0.543±0.011	
	KNN	<b>0.957±0.002</b>	0.705±0.032	0.952±0.002		0.906±0.021	0.627±0.012	0.558±0.011	0.681±0.006	
	MLP	0.917±0.014	0.690±0.020	0.938±0.008		<b>0.967±0.005</b>	0.639±0.032	0.596±0.030	0.761±0.013	
	XGB	0.974±0.002	0.797±0.046	0.977±0.002		<b>0.981±0.004</b>	0.596±0.012	0.553±0.009	0.776±0.007	
	LGBM	0.965±0.003	0.806±0.040	0.969±0.003		<b>0.983±0.002</b>	0.597±0.012	0.561±0.009	0.782±0.007	
	HGNN	0.832±0.003	0.663±0.003	<b>0.834±0.003</b>		0.828±0.002	0.681±0.006	0.666±0.005	0.605±0.002	
	FHGCN	0.592±0.079	0.712±0.070	0.623±0.077		<b>0.823±0.040</b>	0.510±0.018	0.504±0.011	0.503±0.008	
	UGCNI	0.940±0.002	0.857±0.006	<b>0.941±0.002</b>		0.935±0.002	0.863±0.005	0.795±0.004	0.713±0.004	
Max		0.977±0.001	0.857±0.006	0.978±0.001		<b>0.983±0.002</b>	0.863±0.005	0.795±0.004	0.782±0.007	
Avg.		0.861±0.150	0.727±0.072	0.881±0.120		<b>0.899±0.088</b>	0.619±0.095	0.583±0.084	0.671±0.093	
Rank Avg.		2.900±1.578	4.200±0.980	<b>1.700±0.640</b>		2.000±1.000	5.400±0.800	6.500±0.671	5.300±1.269	

\* O.O.T: out-of-time (&gt; 1 day).



(k) bitcoin-2016

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.545±0.002	0.549±0.022	0.551±0.002	O.O.T.*	0.556±0.003	0.527±0.022	0.530±0.015	<b>0.569±0.028</b>	O.O.T.*
	RF	0.915±0.002	0.694±0.030	0.921±0.001		<b>0.934±0.007</b>	0.529±0.010	0.521±0.007	0.609±0.039	
	DT	0.888±0.002	0.671±0.029	0.894±0.002		<b>0.907±0.016</b>	0.509±0.008	0.504±0.005	0.547±0.011	
	KNN	0.888±0.001	0.668±0.028	<b>0.890±0.001</b>		0.866±0.020	0.567±0.010	0.536±0.009	0.626±0.003	
	MLP	0.825±0.010	0.591±0.030	0.830±0.011		<b>0.923±0.003</b>	0.549±0.027	0.545±0.026	0.630±0.040	
	XGB	0.897±0.002	0.722±0.038	0.913±0.002		<b>0.938±0.005</b>	0.544±0.012	0.522±0.013	0.621±0.030	
	LGBM	0.875±0.002	0.733±0.041	0.897±0.002		<b>0.937±0.003</b>	0.551±0.016	0.529±0.016	0.610±0.032	
	HGNN	0.750±0.002	0.633±0.003	<b>0.751±0.002</b>		0.749±0.003	0.627±0.005	0.629±0.003	0.597±0.004	
	FHGCN	0.551±0.064	0.608±0.100	0.553±0.067		<b>0.712±0.110</b>	0.504±0.011	0.504±0.010	0.504±0.011	
	UGCNI	0.862±0.004	0.762±0.005	<b>0.862±0.003</b>		0.854±0.003	0.771±0.010	0.720±0.004	0.646±0.004	
Max		0.915±0.002	0.762±0.005	0.921±0.001		<b>0.938±0.005</b>	0.771±0.010	0.720±0.004	0.646±0.004	
Avg.		0.800±0.133	0.663±0.064	0.806±0.135		<b>0.838±0.121</b>	0.568±0.075	0.554±0.065	0.596±0.041	
Rank Avg.		3.000±0.894	4.000±0.775	1.900±0.700		<b>1.700±0.900</b>	6.000±0.775	6.400±0.800	5.000±1.612	
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.622±0.006	0.612±0.009	0.630±0.011	O.O.T.*	<b>0.654±0.012</b>	0.564±0.003	0.567±0.003	0.635±0.002	O.O.T.*
	RF	0.971±0.001	0.766±0.035	0.974±0.001		<b>0.978±0.003</b>	0.550±0.012	0.529±0.009	0.725±0.021	
	DT	0.885±0.002	0.681±0.032	0.893±0.002		<b>0.909±0.016</b>	0.509±0.008	0.504±0.005	0.547±0.011	
	KNN	<b>0.948±0.001</b>	0.716±0.029	<b>0.948±0.001</b>		0.927±0.014	0.592±0.014	0.553±0.011	0.678±0.006	
	MLP	0.909±0.006	0.655±0.021	0.915±0.008		<b>0.968±0.002</b>	0.600±0.026	0.587±0.033	0.770±0.007	
	XGB	0.964±0.001	0.801±0.041	0.971±0.001		<b>0.982±0.003</b>	0.562±0.012	0.550±0.011	0.783±0.005	
	LGBM	0.951±0.001	0.814±0.044	0.963±0.001		<b>0.982±0.002</b>	0.563±0.011	0.558±0.010	0.788±0.006	
	HGNN	0.833±0.002	0.659±0.003	<b>0.834±0.002</b>		0.827±0.002	0.659±0.006	0.663±0.004	0.596±0.003	
	FHGCN	0.598±0.074	0.712±0.062	0.597±0.078		<b>0.825±0.049</b>	0.508±0.020	0.507±0.017	0.505±0.015	
	UGCNI	0.937±0.003	0.847±0.006	<b>0.937±0.002</b>		0.931±0.002	0.856±0.010	0.801±0.004	0.704±0.005	
Max		0.971±0.001	0.847±0.006	0.974±0.001		<b>0.982±0.003</b>	0.856±0.010	0.801±0.004	0.788±0.006	
Avg.		0.862±0.132	0.726±0.074	0.866±0.133		<b>0.898±0.099</b>	0.596±0.096	0.582±0.085	0.673±0.095	
Rank Avg.		2.700±0.781	4.300±1.005	2.100±0.831		<b>1.600±0.917</b>	5.700±0.781	6.400±0.917	5.200±1.470	

\* O.O.T: out-of-time (&gt; 1 day).