IntNets and DeepSets for Fast Jets

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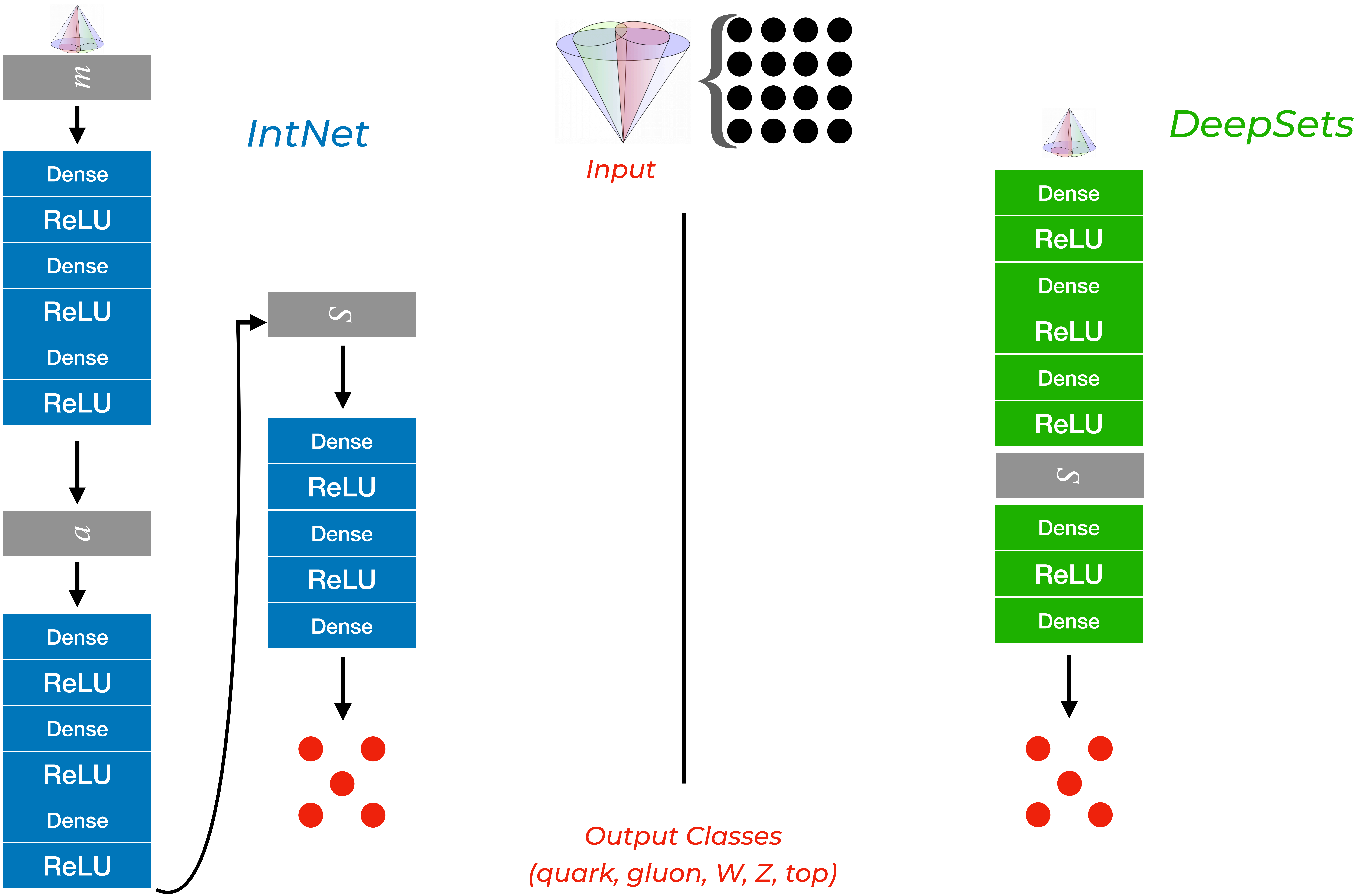
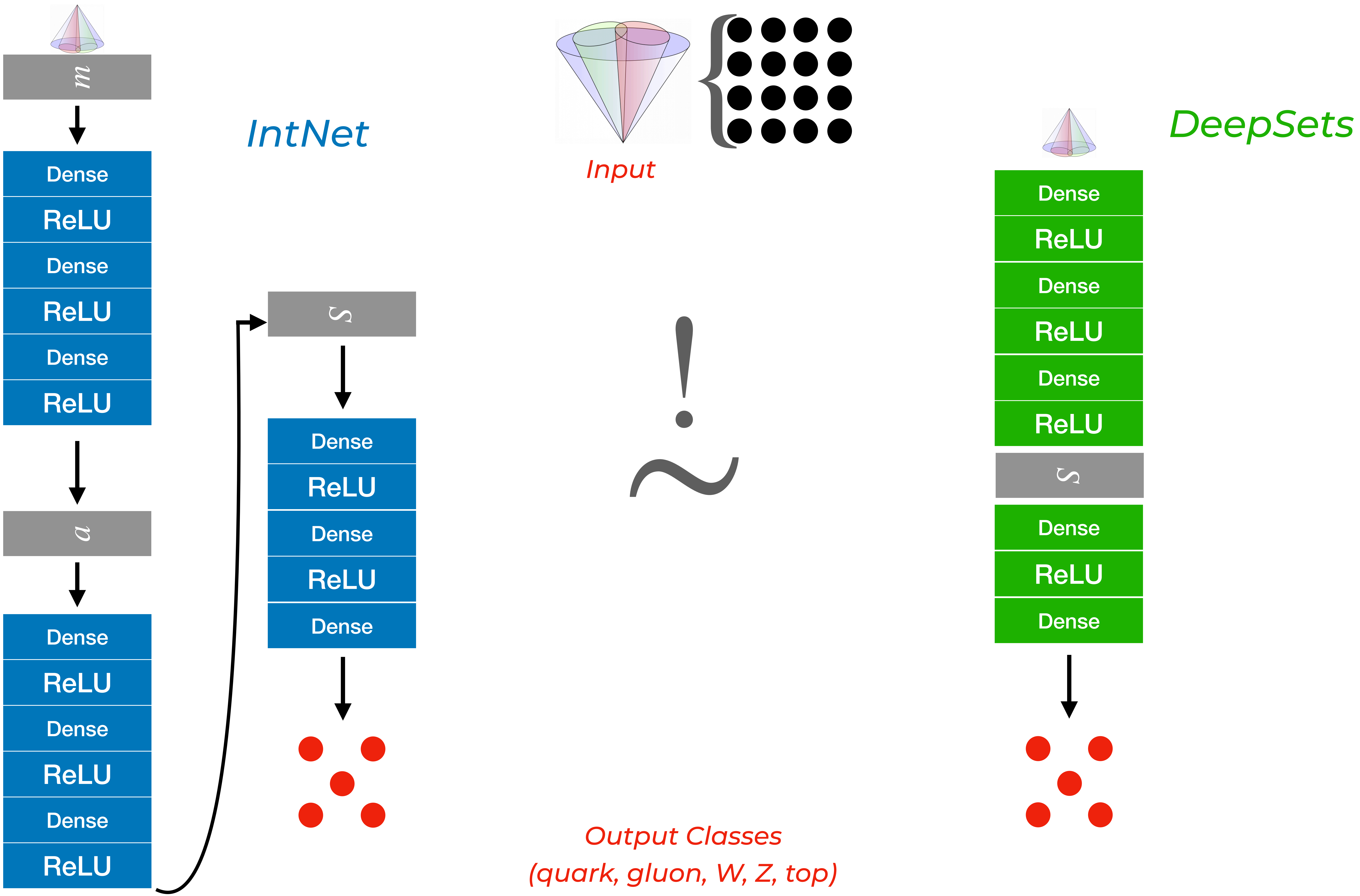

m
IntNet
Dense
ReLU
Dense
ReLU
Dense
ReLU
a
Dense
ReLU
Dense
ReLU
Dense
ReLU
S
Dense
ReLU
Dense
ReLU
Dense
Input
Output Classes
(quark, gluon, W, Z, top)
DeepSets
Dense
ReLU
Dense
ReLU
Dense
ReLU
S
Dense
ReLU
Dense



IntNet
Input
m
Dense
ReLU
Dense
ReLU
Dense
ReLU
a
Dense
ReLU
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Dense
ReLU
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ReLU
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DeepSets
Dense
ReLU
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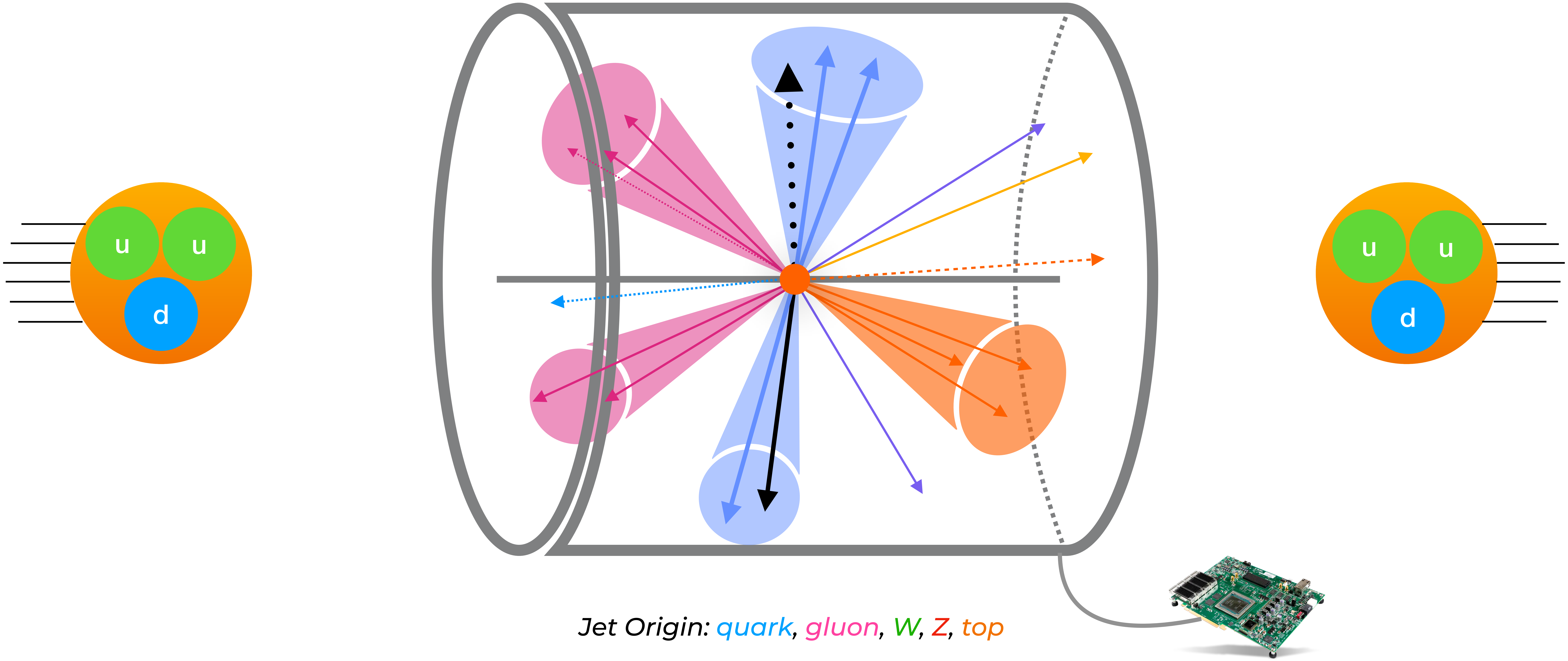
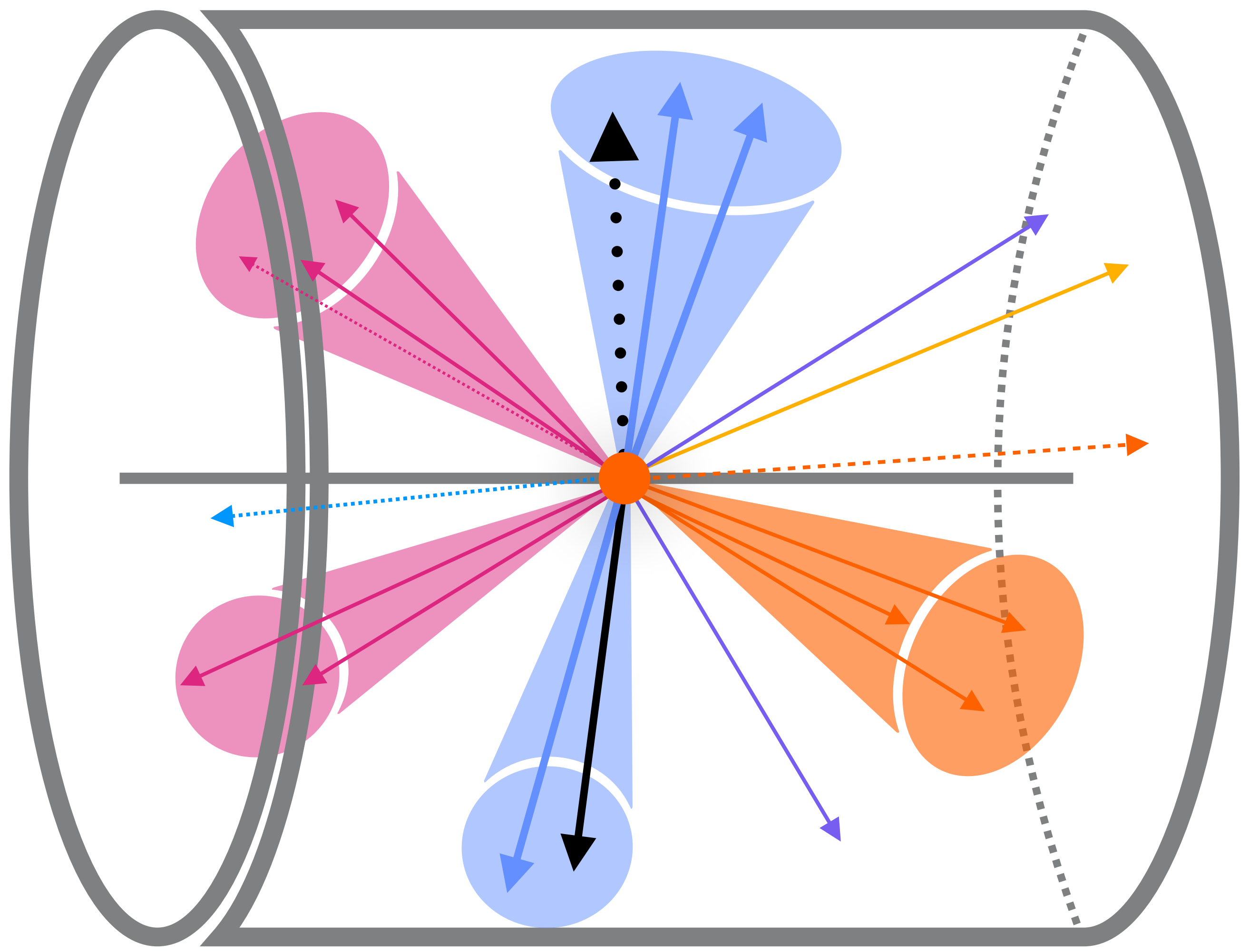
ReLU
Dense
ReLU
Dense
ReLU
Dense
Output Classes
(quark, gluon, W, Z, top)

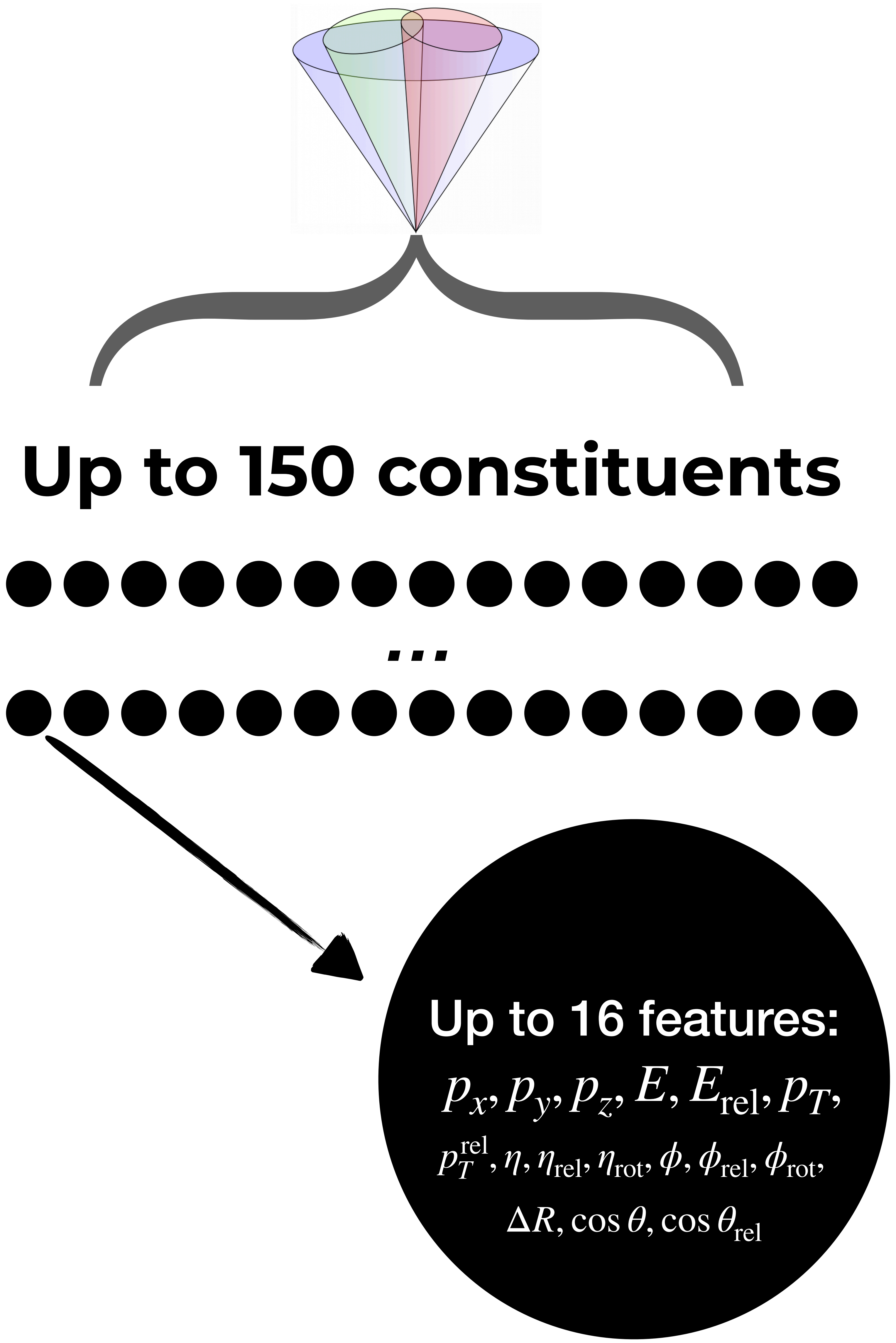
Collision every 25 ns: ~60 Tb/s data influx



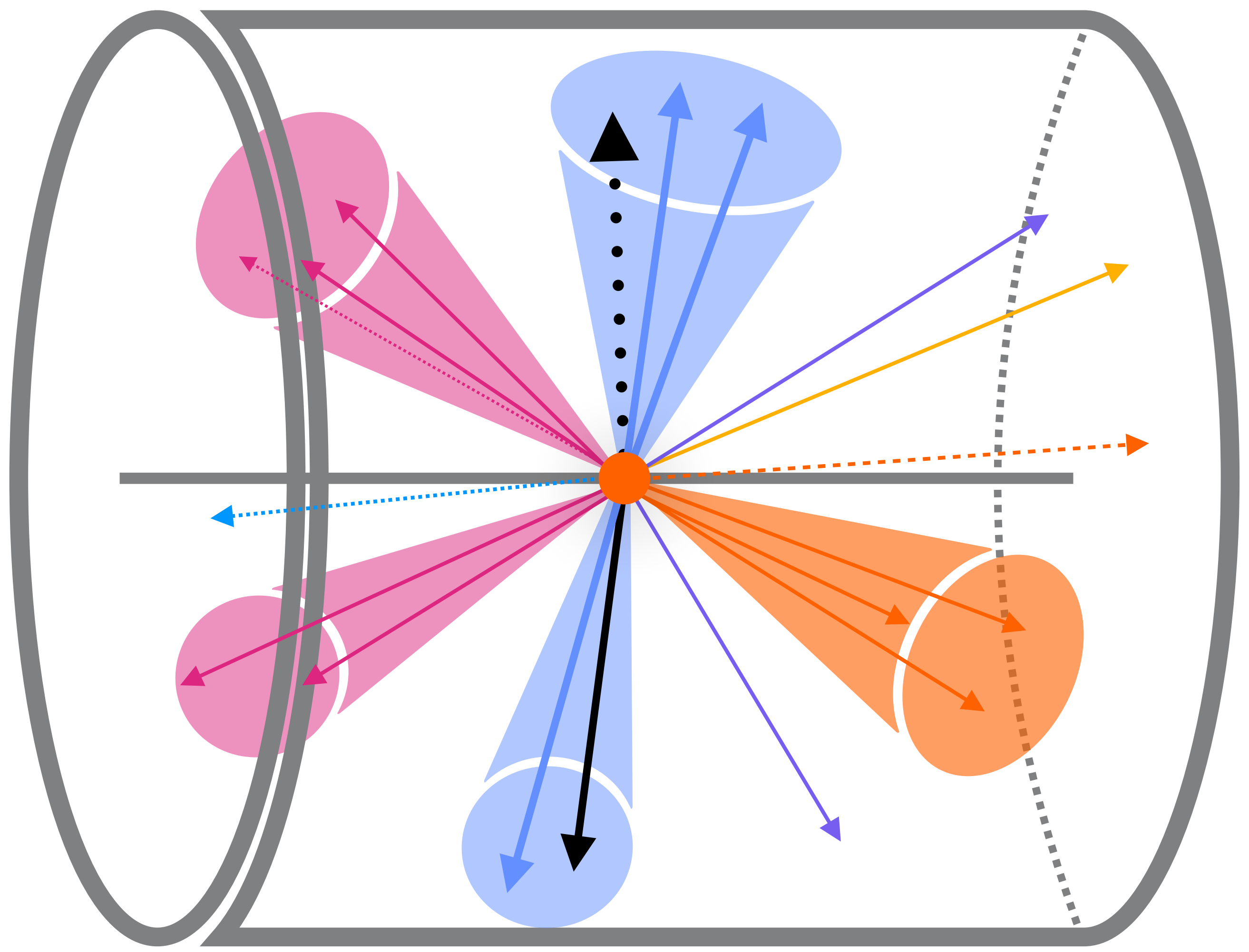
Jet Origin: quark, gluon, W, Z, top



853 390 jets


Up to 150 constituents
...
Up to 16 features:
$p_x, p_y, p_z, E, E_{\mathrm{rel}}, p_T,$
$p_T^{\mathrm{rel}}, \eta, \eta_{\mathrm{rel}}, \eta_{\mathrm{rot}}, \phi, \phi_{\mathrm{rel}}, \phi_{\mathrm{rot}},$
$\Delta R, \cos\theta, \cos\theta_{\mathrm{rel}}$

*speed reasons



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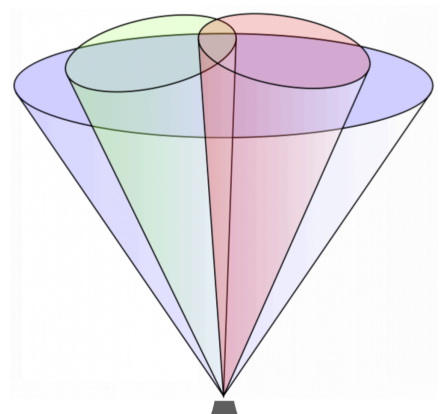
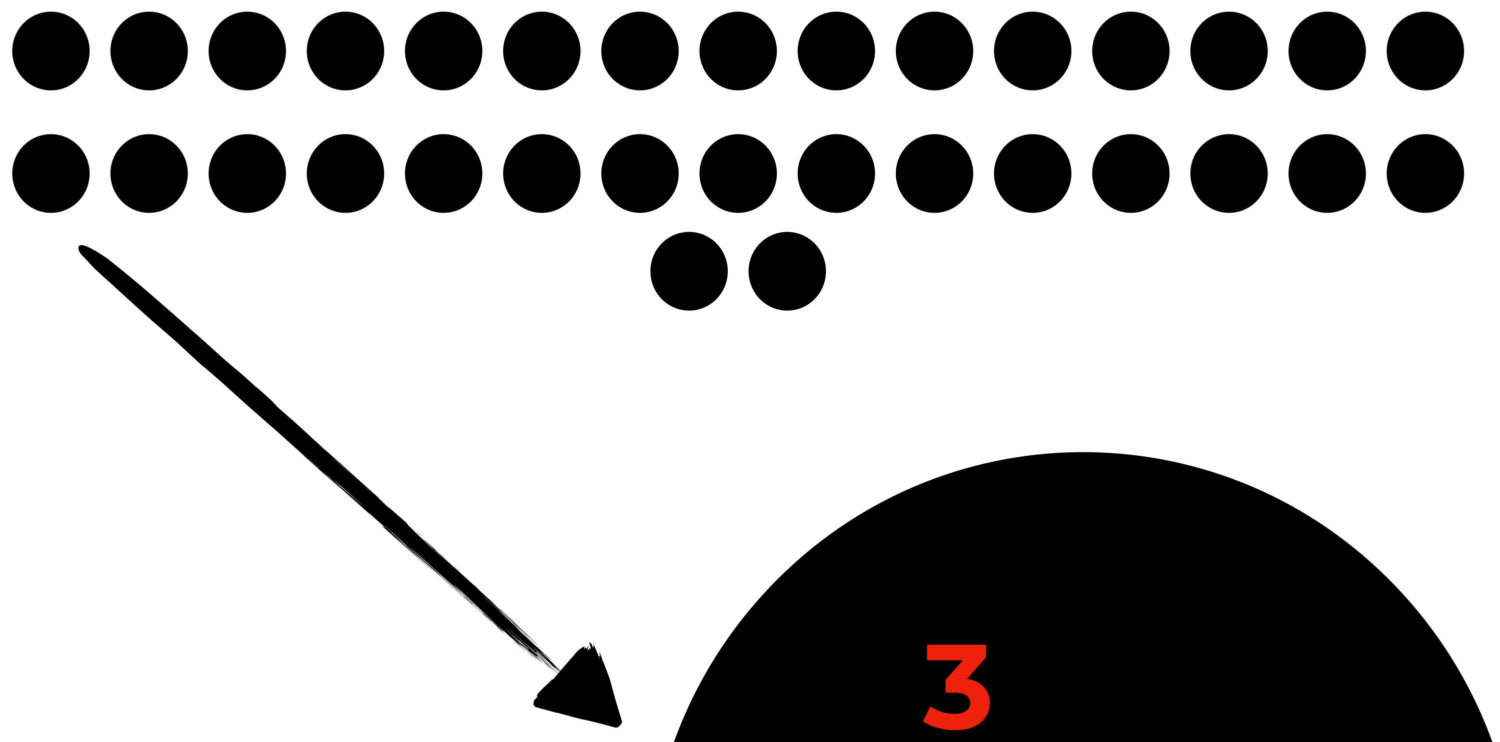


32 most energetic

Up to ~~150~~ constituents



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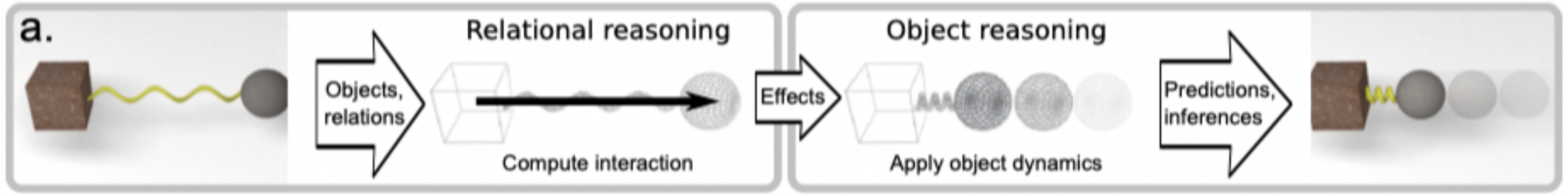
~~Up to 16~~ features:

~~$p_x, p_y, p_z, E, E_{\mathrm{rel}}$~~, p_T,

~~p_T^{rel}, η~~, η_{rel}, ~~$\eta_{\mathrm{rot}}, \phi$~~, ϕ_{rel}, ~~ϕ_{rot}~~

~~$\Delta R, \cos\theta, \cos\theta_{\mathrm{rel}}$~~

An interaction network looks at a complex system in terms of objects and relations, and then in terms of the dynamics and interactions of these elements.



arXiv:1612.00222

$$\text{IN} = \phi_{\text{O}}(a(G, X, \phi_{\text{R}}(m(G))))$$

1. $m(G) \equiv \langle o_i, o_j, r_k \rangle \equiv b_k$

2. $\phi_{\text{R}}(\langle o_i, o_j, r_k \rangle) = e_k$

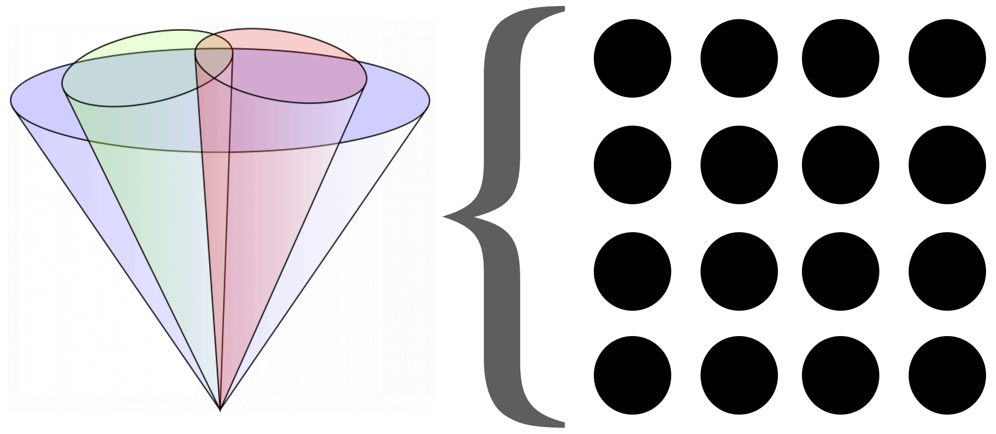
3. $a(G, X, E) \equiv C$

4. $\phi_O(C) = P$

In simulation, can be interpreted as state of the constituents of G at (t+1).

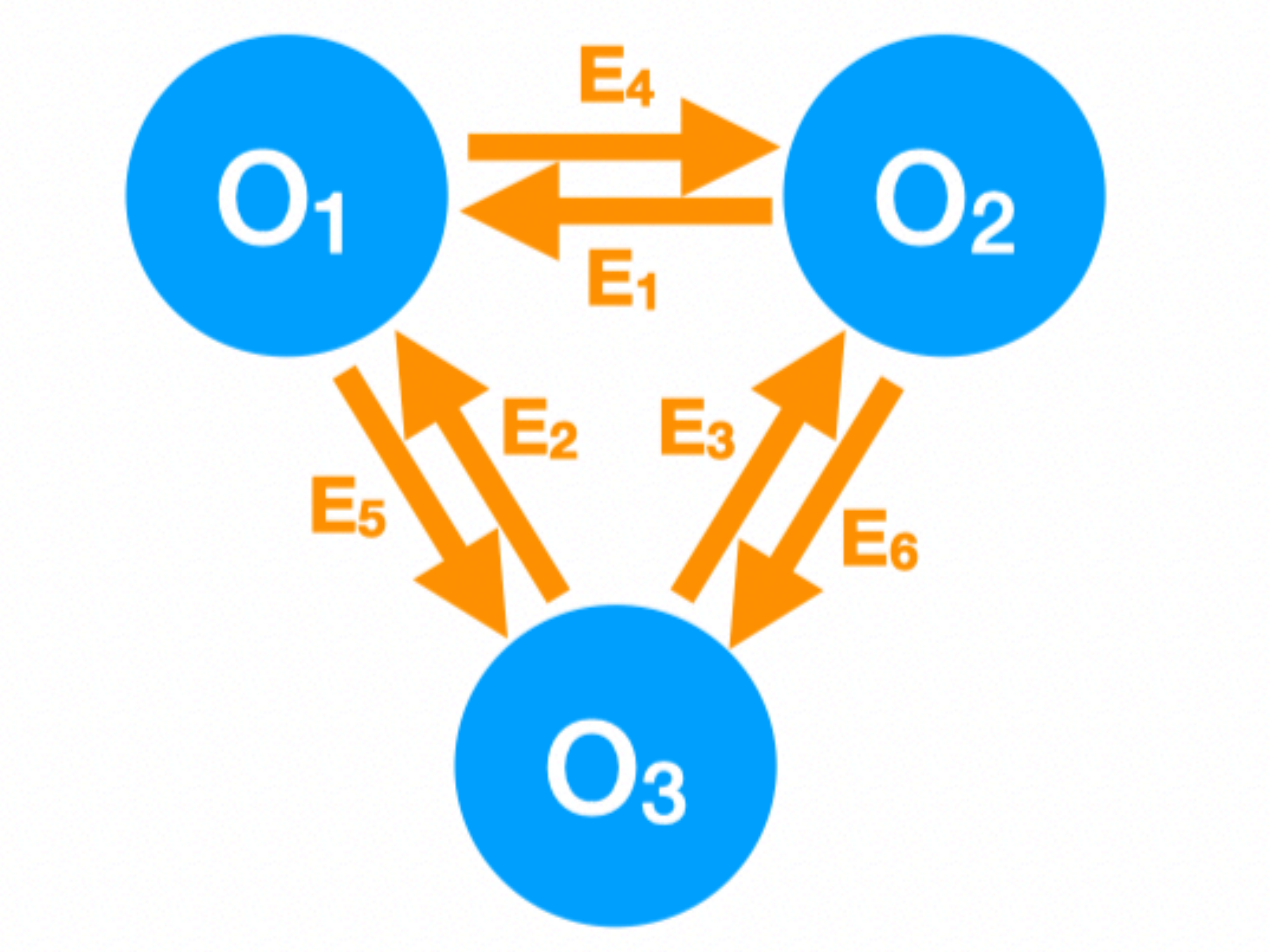
5. $\phi_A(P) = A$

Can learn order of P.



$$I \equiv \begin{pmatrix} p_T^1 & \dots & p_T^{16} \\ \eta^1 & \dots & \eta^{16} \\ \phi^1 & \dots & \phi^{16} \end{pmatrix} \times \left.\begin{matrix} R_S \equiv \begin{pmatrix} 1 & 1 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 1 \end{pmatrix} \\ \dim(R_S) = \dim(R_R) = N_O \times N_E \\ R_R \equiv \begin{pmatrix} 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 1 & 1 & \dots & 0 \end{pmatrix} \end{matrix}\right\} m(G) = B = \begin{pmatrix} I \times R_R \\ I \times R_S \end{pmatrix}$$

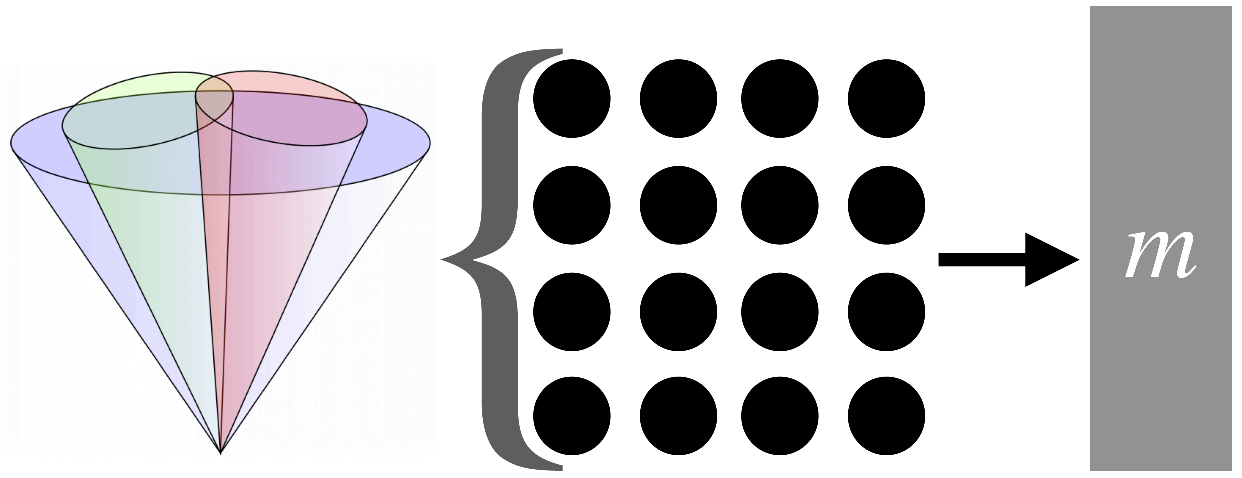
concat.



$$R_S = \begin{array}{c} \\ O_1 \\ O_2 \\ O_3 \end{array} \begin{array}{c} \begin{matrix} E_1 & E_2 & E_3 & E_4 & E_5 & E_6 \end{matrix} \\ \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 \end{pmatrix} \end{array}$$

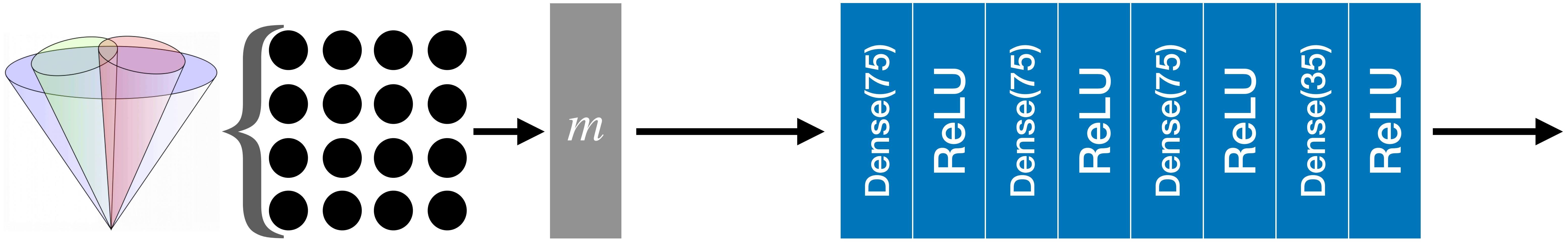
$$R_R = \begin{array}{c} \\ O_1 \\ O_2 \\ O_3 \end{array} \begin{array}{c} \begin{matrix} E_1 & E_2 & E_3 & E_4 & E_5 & E_6 \end{matrix} \\ \begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{pmatrix} \end{array}.$$

arXiv:1908.05318



$$m(G) = B = \begin{pmatrix} I \times R_R \\ I \times R_S \end{pmatrix}$$

$$\dim(B) = (240,\ 6)$$



$$m(G) = B = \begin{pmatrix} I \times R_R \\ I \times R_S \end{pmatrix}$$

$$\dim(B) = (240,\ 6)$$

$$\phi_{\mathrm{R}}(B) = E$$

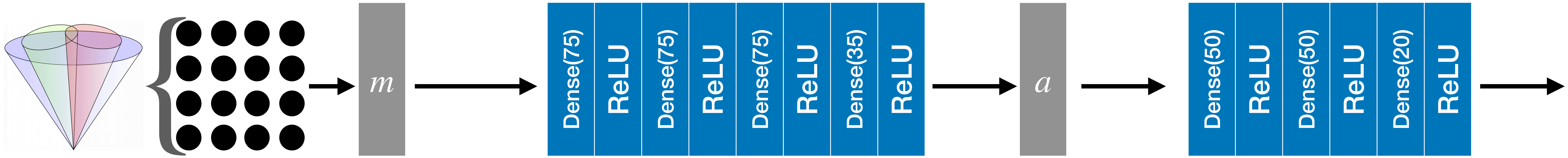
Cumulative effects of interaction received by a given vertex.

$$\bar{E} = ER_R^\top$$

Concatenate to input.

$$C = \begin{pmatrix} I \\ \bar{E} \end{pmatrix}$$

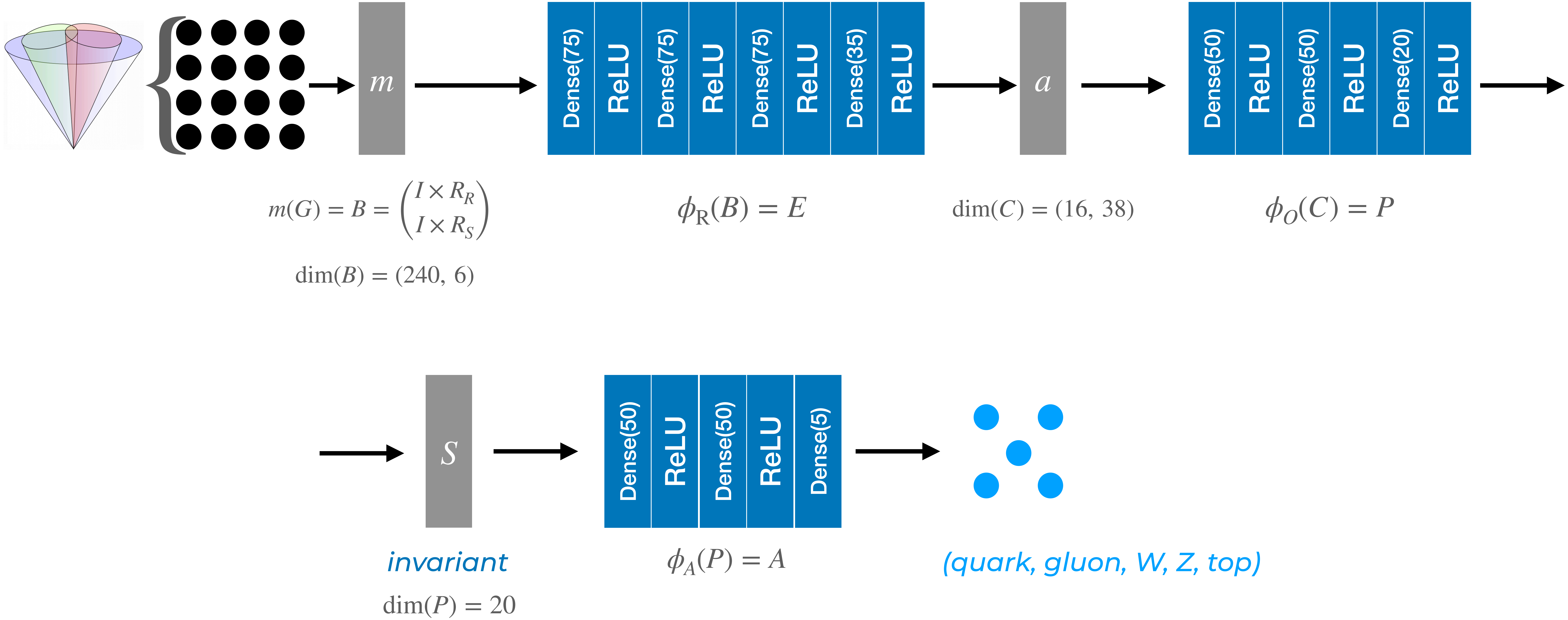
arXiv:1908.05318



$$m(G) = B = \begin{pmatrix} I \times R_R \\ I \times R_S \end{pmatrix} \qquad \phi_{\mathrm{R}}(B) = E \qquad \dim(C) = (16,\ 38) \qquad \phi_O(C) = P$$

$$\dim(B) = (240,\ 6)$$

arXiv:1908.05318



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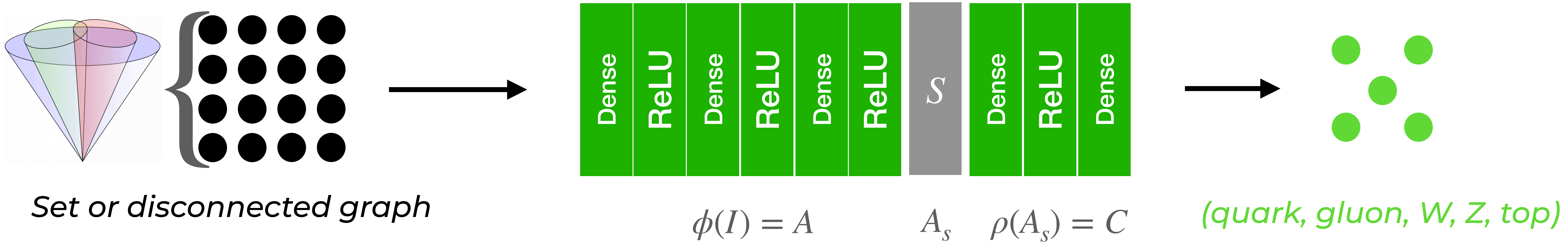
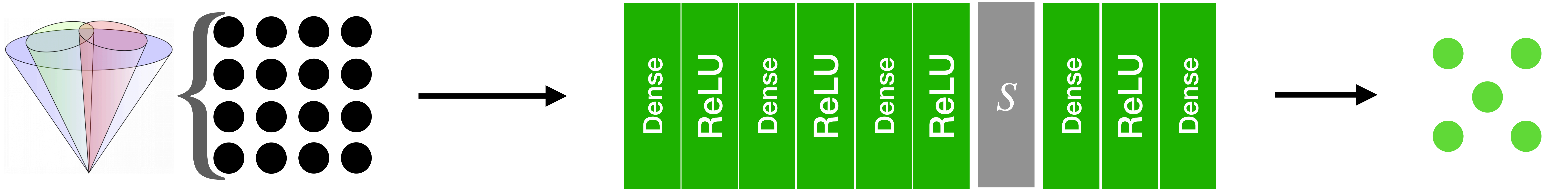


arXiv:1703.06114



Set or disconnected graph

$X = \{x_1, \ldots, x_M\},\ x_m \in \mathfrak{X}$

$\phi(I) = A$ $\quad A_s \quad$ $\rho(A_s) = C$

(quark, gluon, W, Z, top)

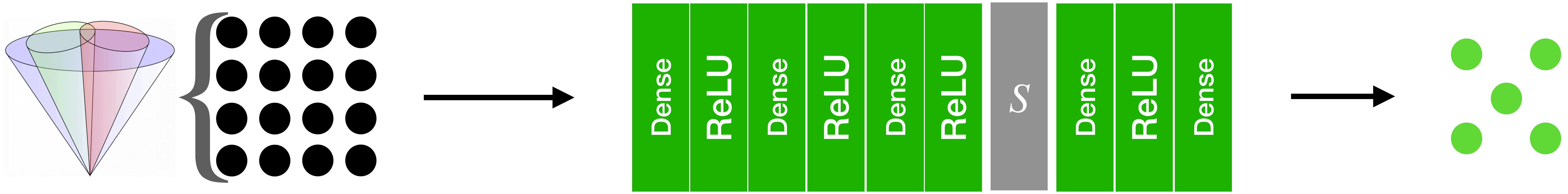
$$f : 2^{\mathfrak{X}} \rightarrow \mathcal{Y}$$

$$f(\{x_1, \ldots, x_M\}) = f(\{x_{\pi(1)}, \ldots, x_{\pi(M)}\})$$

invariant

$$\rho\left(\sum_{x \in X} \phi(x) \right)$$

arXiv:1703.06114



Set or disconnected graph

$X = \{x_1, \ldots, x_M\},\ x_m \in \mathfrak{X}$

$\phi(I) = A$ $\quad A_s \quad$ $\rho(A_s) = C$

(quark, gluon, W, Z, top)

$c : \mathfrak{X} \rightarrow \mathbb{N}$

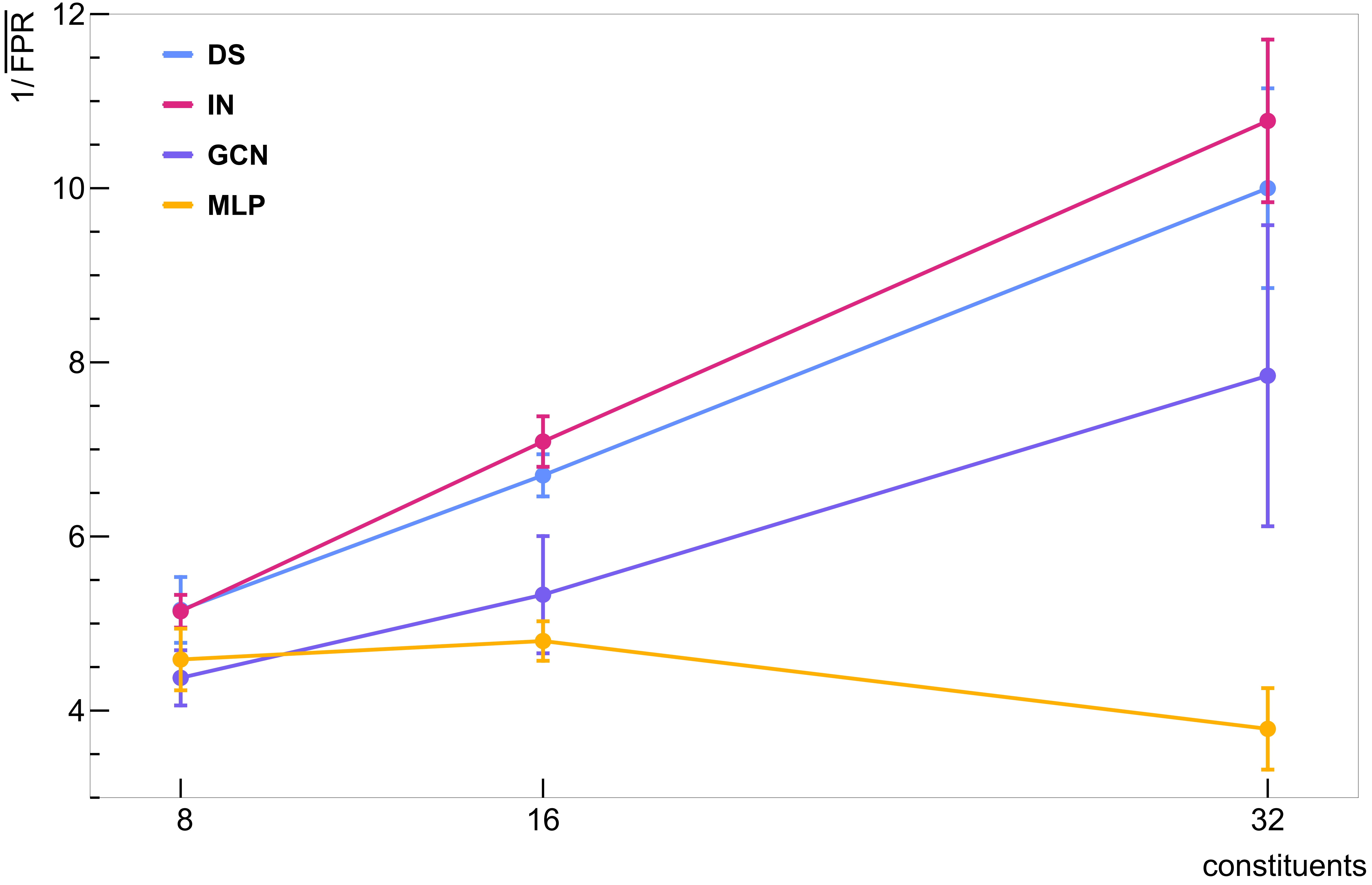
$\phi(x) = 4^{-c(x)}$

then $\sum_{x \in X} \phi(x)$ *is a unique representation for every* $X \in 2^{\mathfrak{X}}$

similarly construct $\rho : \mathbb{R} \rightarrow \mathbb{R}$ s.t. $f(X) = \rho\left(\sum_{x \in X} \phi(x)\right)$

**Countable Sets*

arXiv:1703.06114



$1/\overline{FPR}$
12
10
8
6
4
DS
IN
GCN
MLP
8
16
32
constituents

Xilinx VU9P

Latencies
(ns)

*8 bit quantised

n particles	MLP	DS	IN
8	55	75	175
16	55	95	230
32	55	130	265

Xilinx VU9P

Resources
(LUTs)

**8 bit quantised*

n particles	MLP	DS	IN
8	7.6%	31%	30.8%
16	7.5%	63%	57.6%
32	7.2%	118%	97.2%

- ★ **Set representation ~ fully connected graph (for this data!)**
  - ✴ better representation yet to be found?
  - ✴ other symmetries to be exploited? e.g. rotational invariance
- ★ **Incorporate symmetries bottom-up**
  - ✴ gain intimate understanding of symmetries in data
  - ✴ test each hypothesis separately
- ★ **Geometrical models: smart but more importantly, FAST!**