Autonomous Physics-Inspired Feature Engineering with Lorentz Boost Networks

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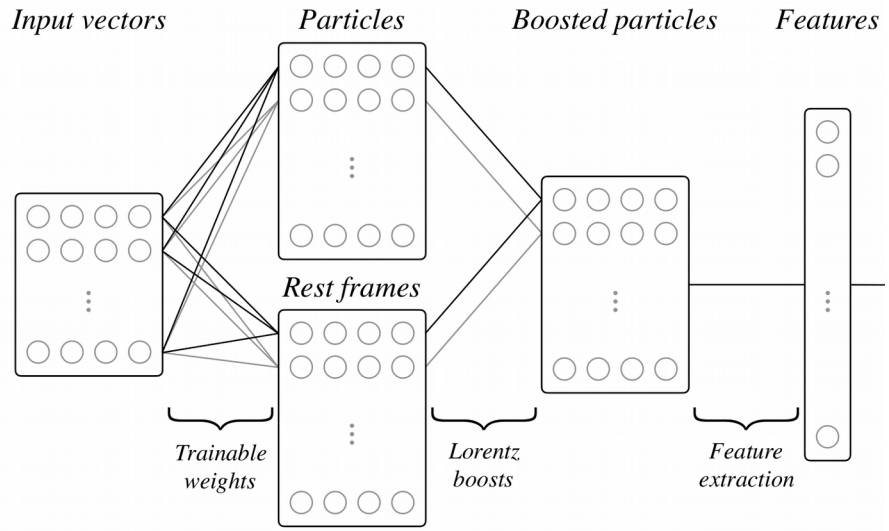
12.03.19



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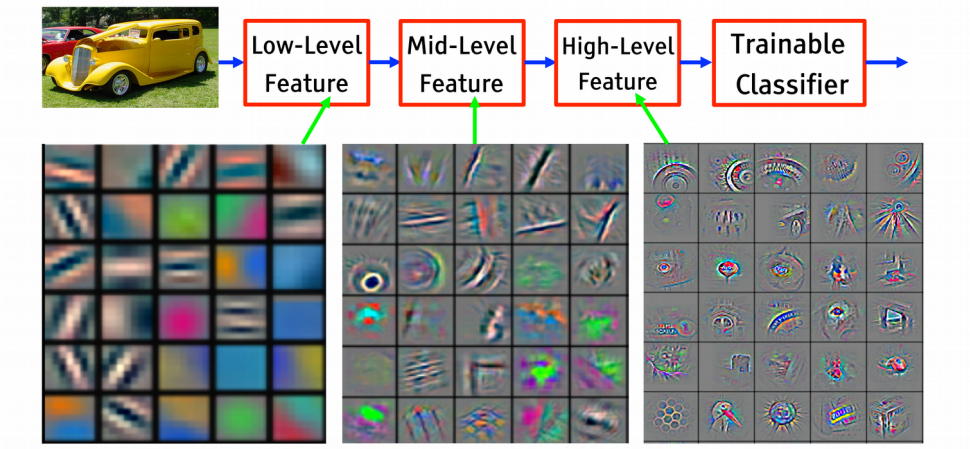
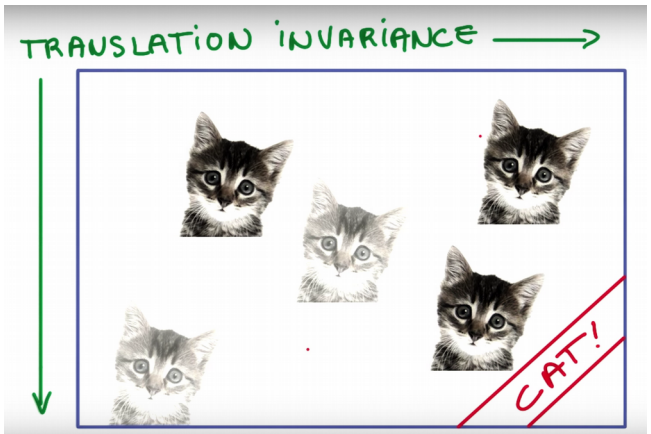
- Wishlist:
  - Model requiring **only low level data** (e.g. particle four momenta)
  - **Interpretable model**
- Computer science: Dedicated architectures exploiting problem structure

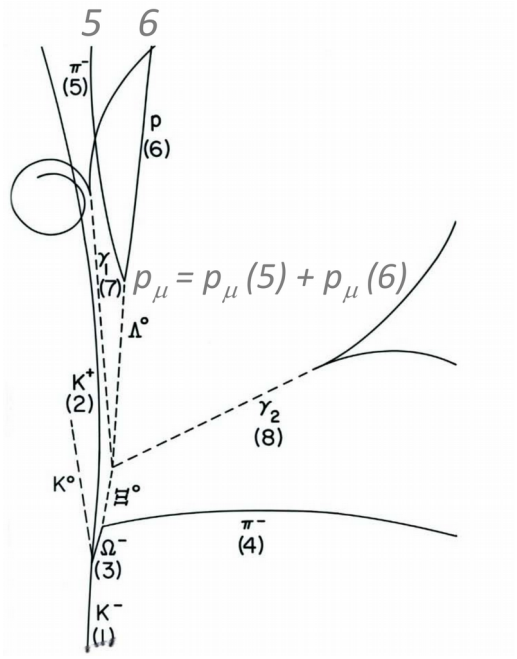


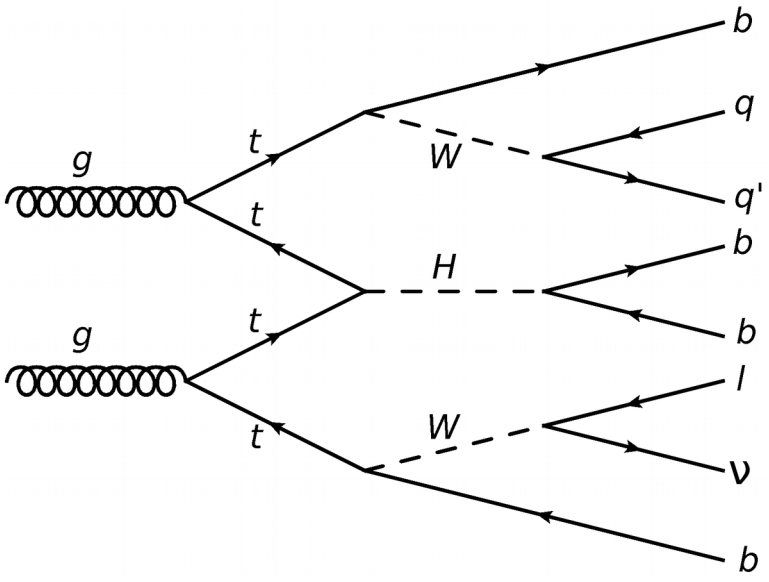
[Zeiler & Fergus 2013], adapted by Yann LeCun



Udacity Course 730, Deep Learning

- Recently many similar developments in physics (e.g. LoLa, Recursive NN)
- Our model: Lorentz Boost Network (LBN)





- Physicist: Combine four momenta of final state particles to build intermediate particles
  - Create characteristic variables
    → Analyse decays in rest frame of parent particle
- **Can we incorporate this into a network architecture?**

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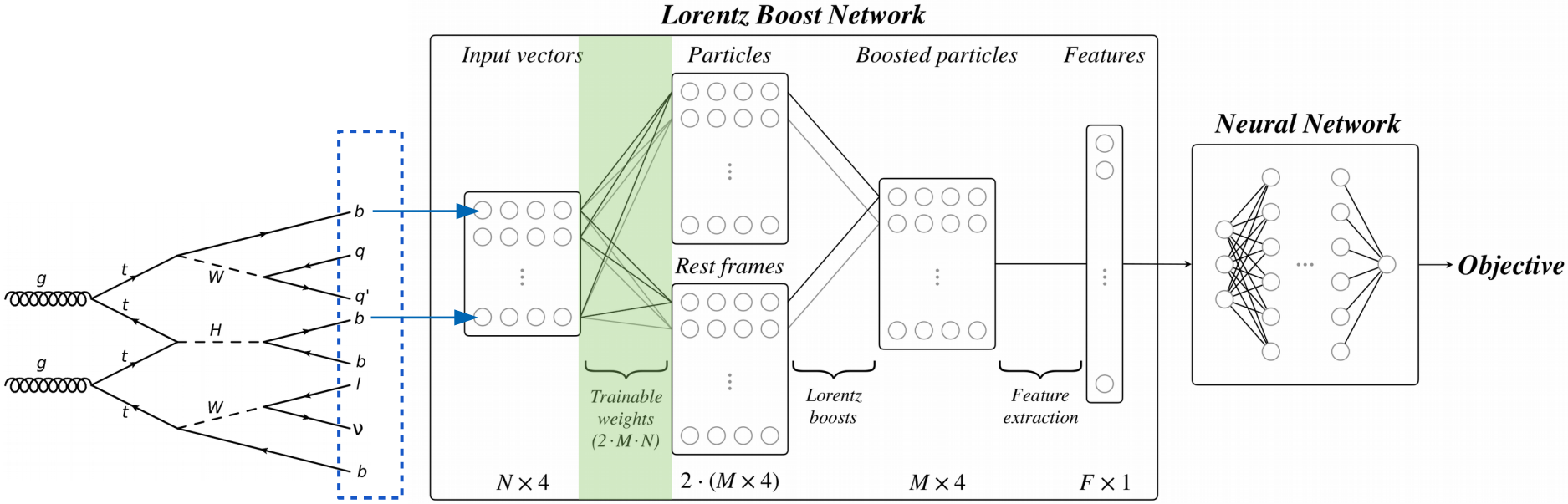

- Create composite particles and rest frames (trainable)

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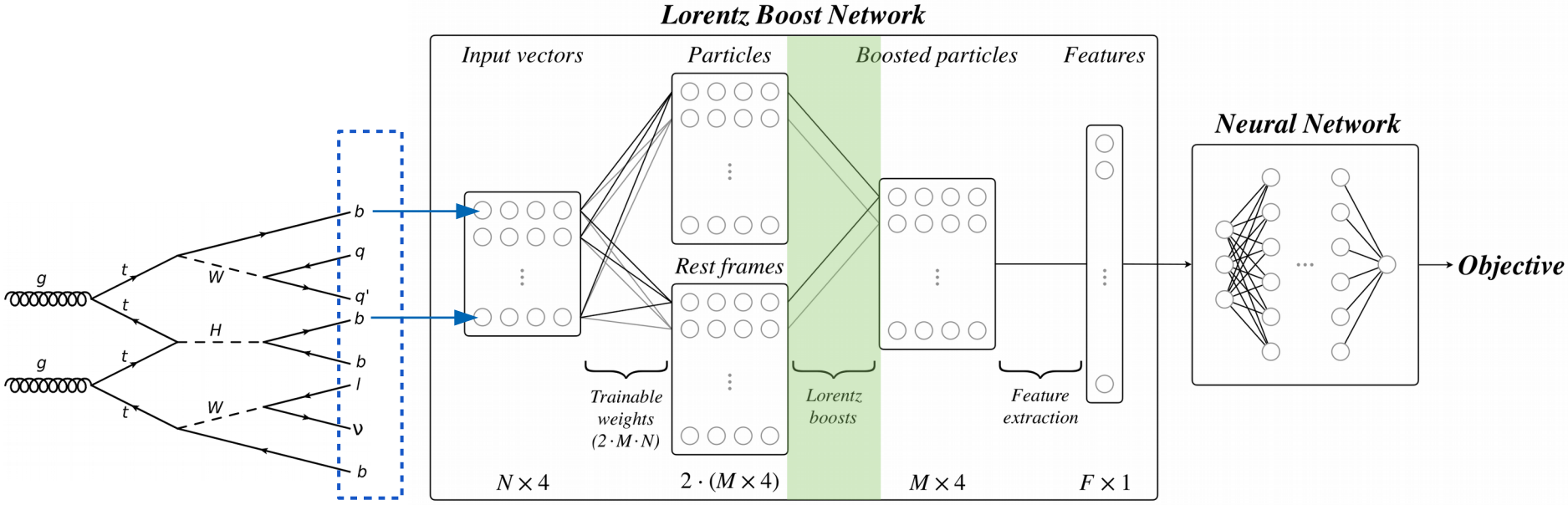

- Create composite particles and rest frames (trainable)
- Perform Lorentz transformation

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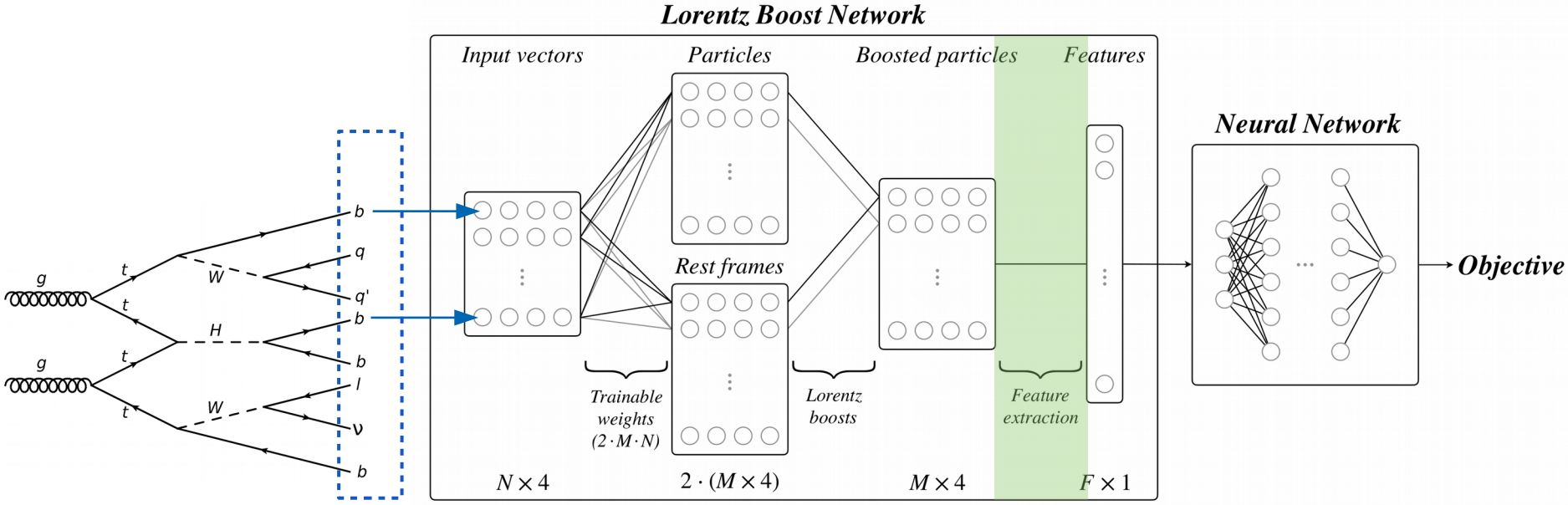

- Create composite particles and rest frames (trainable)
- Perform Lorentz transformation
- Project generic set of features, e.g. energies, pairwise angles

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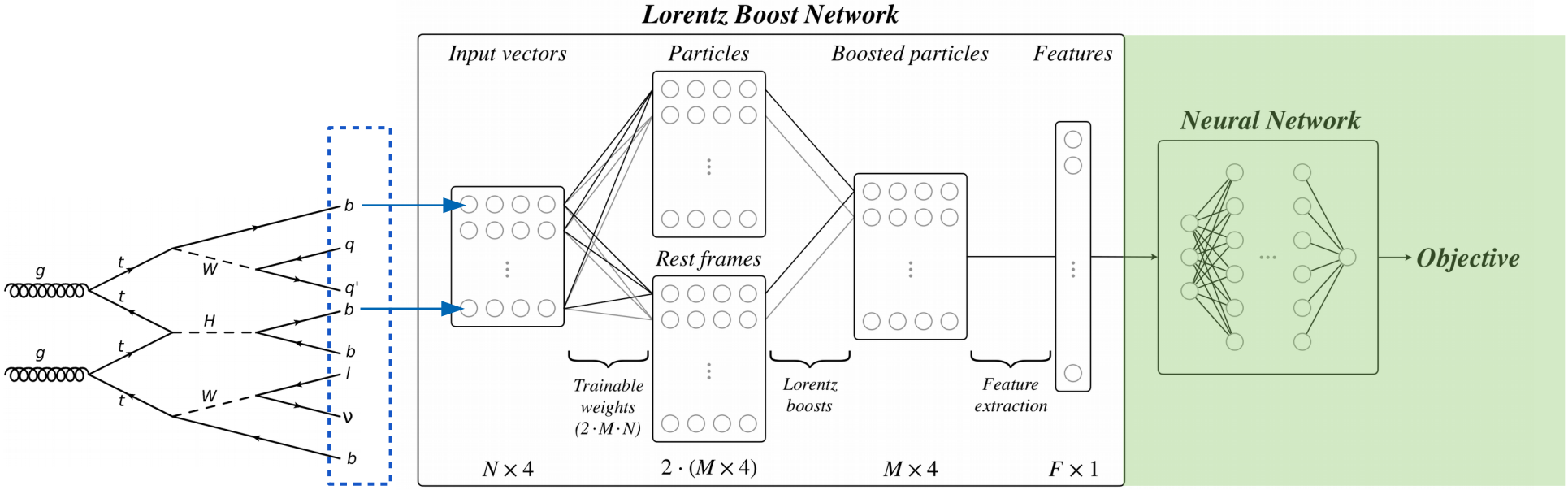
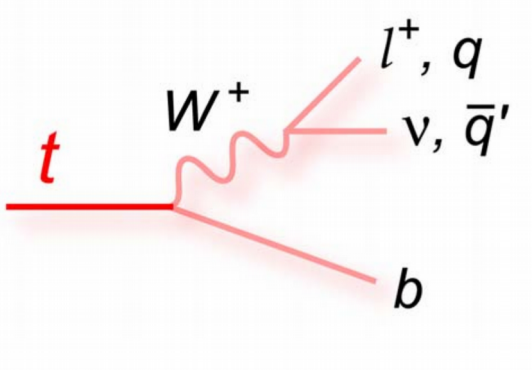
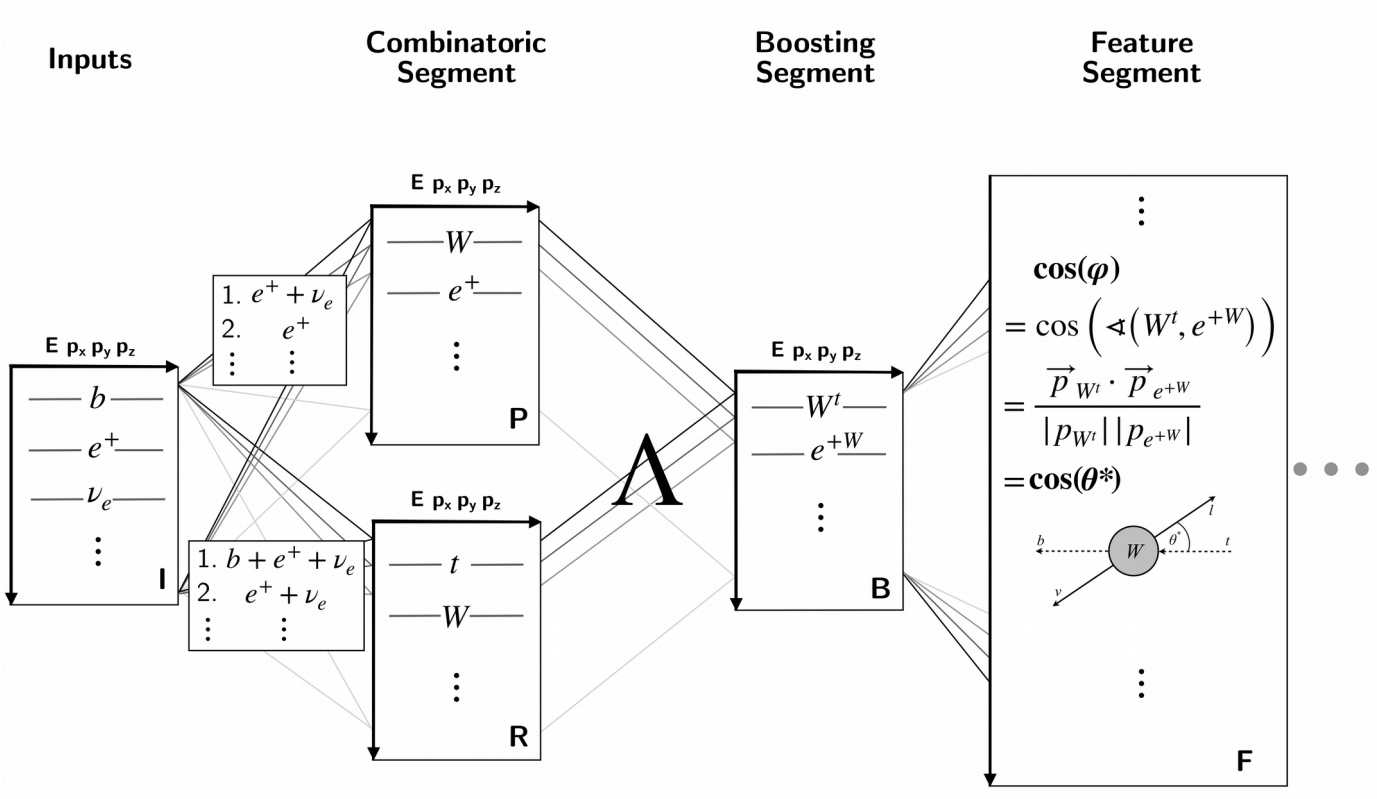


- Create composite particles and rest frames (trainable)
- Perform Lorentz transformation
- Project generic set of features, e.g. energies, pairwise angles
- Use learned features to solve physics problem

- Example of feature construction: helicity angle cos(θ*)



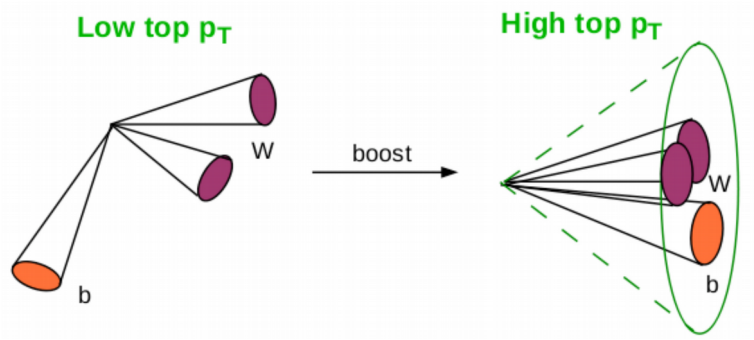


Application

- Currently studying two applications

Top Tagging

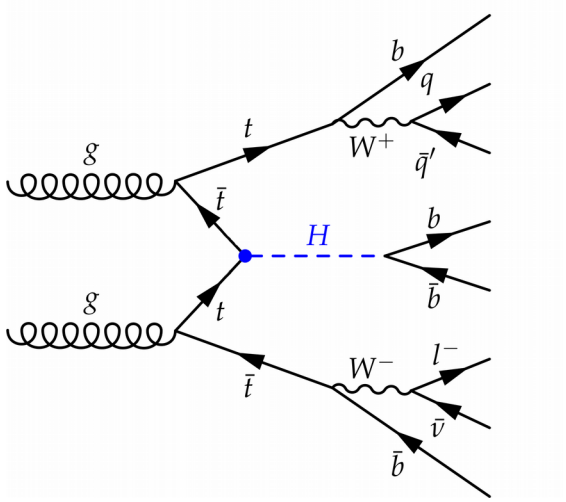
- Distinguish hadronically decaying, highly boosted top quarks from QCD background



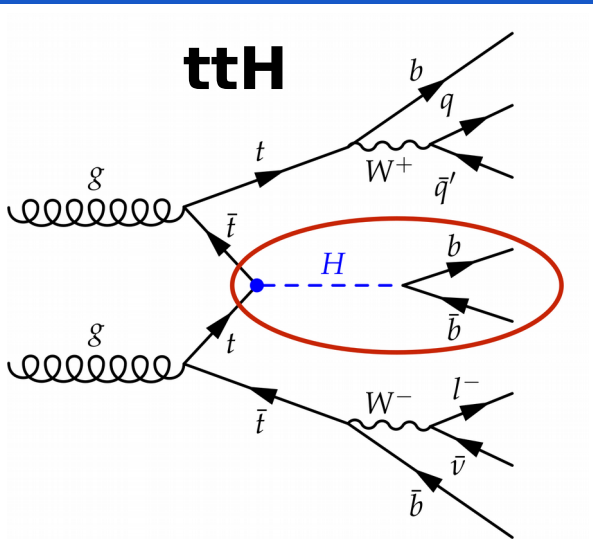
[Method comparison paper: https://arxiv.org/abs/1902.09914]

ttH vs tt+bb

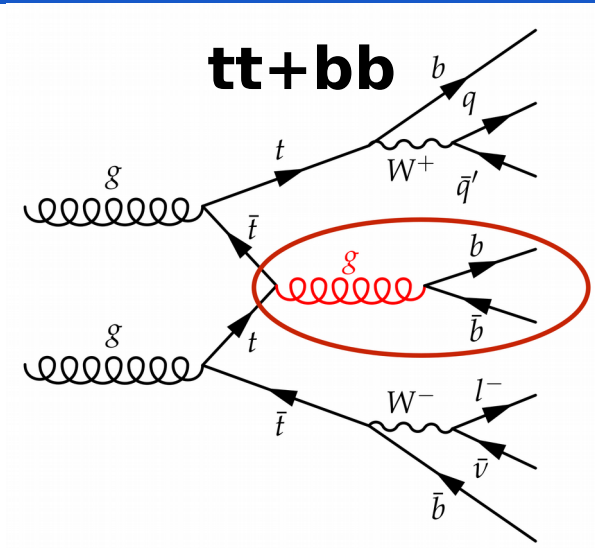
- Separate ttH(H→bb) events from tt+bb background



[https://arxiv.org/abs/1812.09722]



vs.



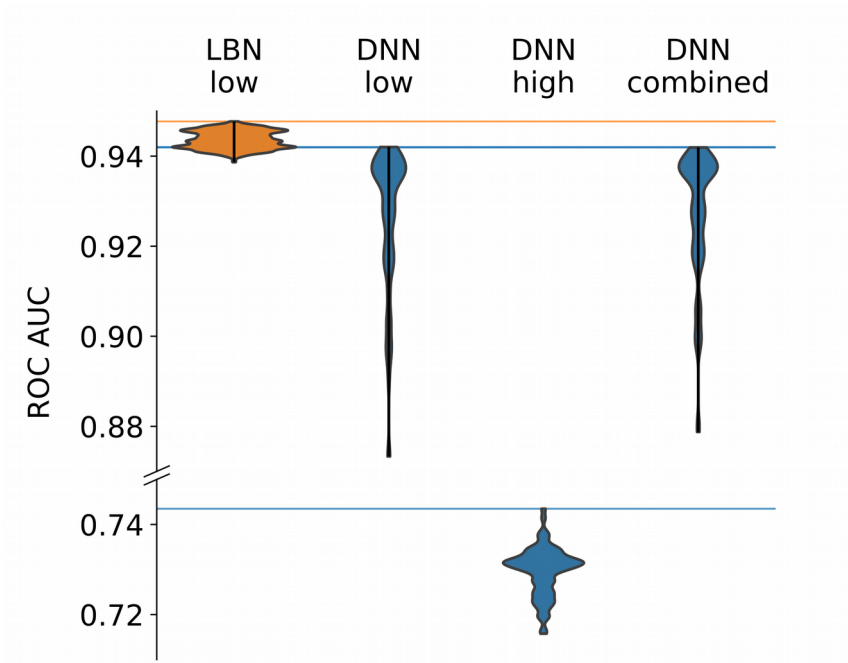
- Final state: 6 jets, 1 charged lepton, 1 neutrino (missing transverse energy)
  → 8 four vectors as input

- Compare LBN against fully connected neural network
  - Trained with same input, with dedicated high-level variables, or both

- Hyperparameter scan with O(100) trainings for each configuration

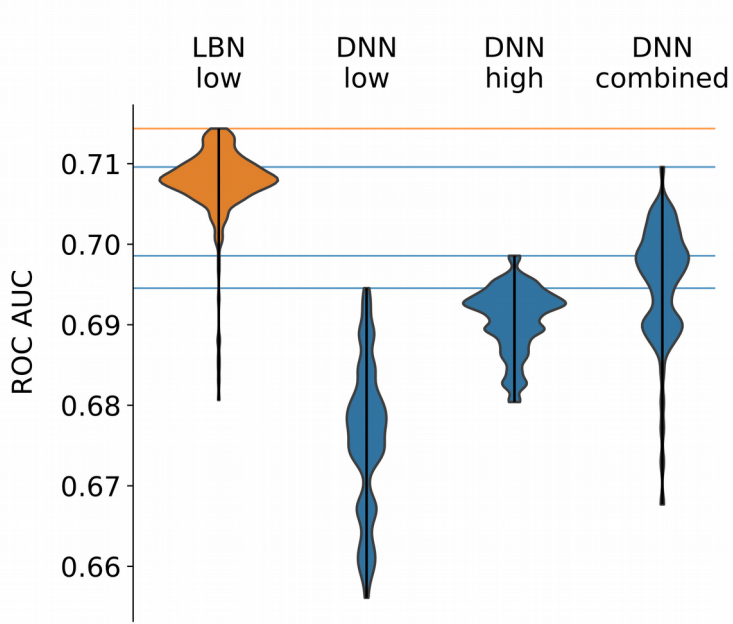
Generator (truth) ordering

→ Isolated LBN performance study



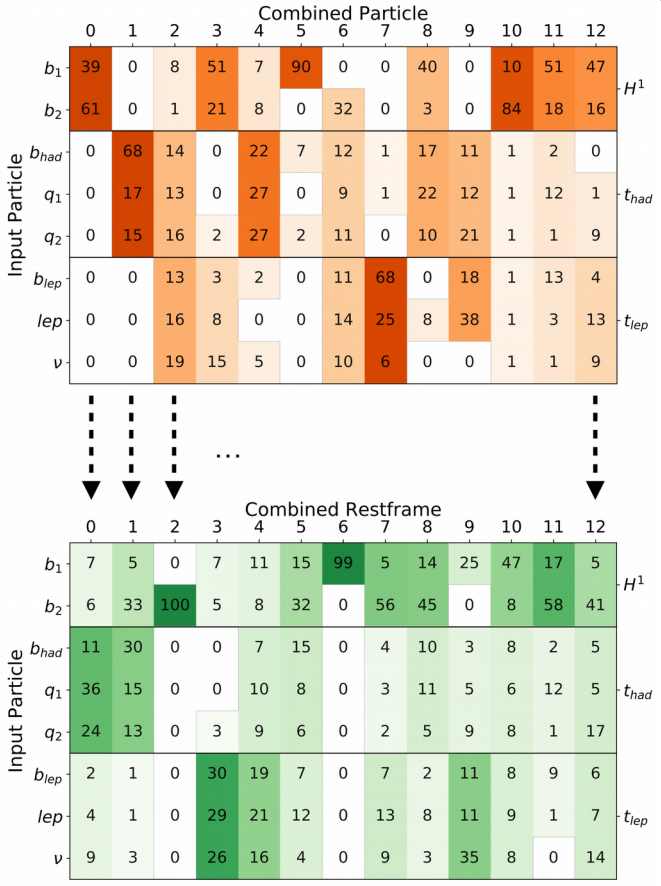
Jet p_T sorting

→ Realistic application



What is learned by the network?

- Study particle combination weights (generator sorting) to gain insights into what the network is learning



- Approximate construction of intermediate particles by LBN
- Focus on Higgs boson (difference between processes)
- **Which features relevant for the separation?**

Feature Example (Mass)

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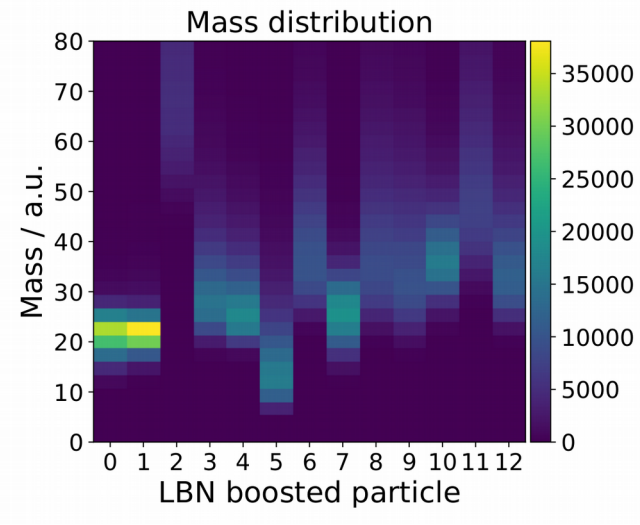
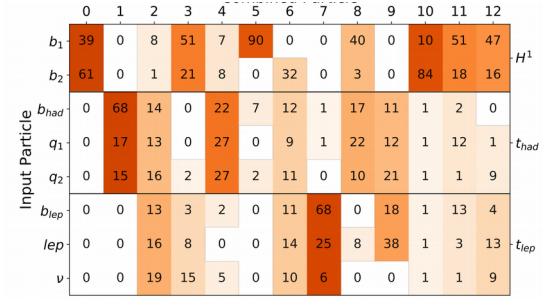
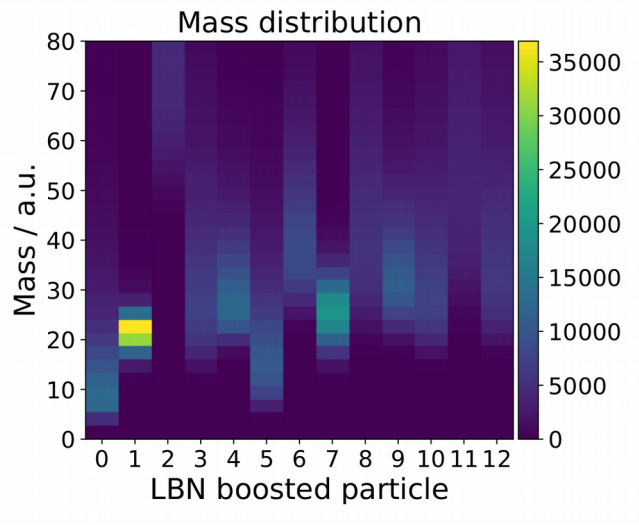
ttH

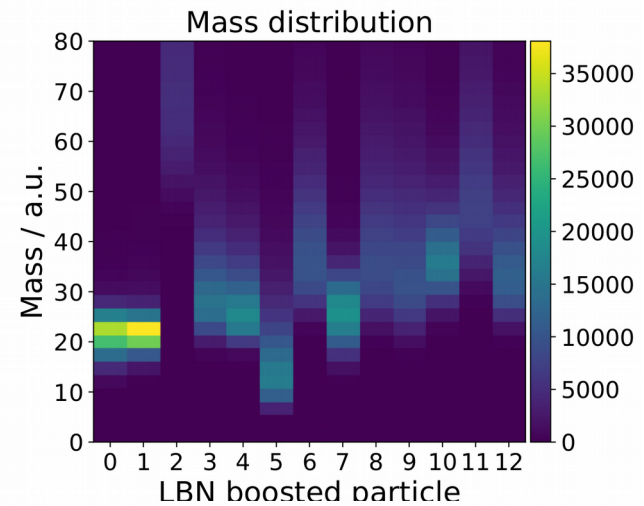


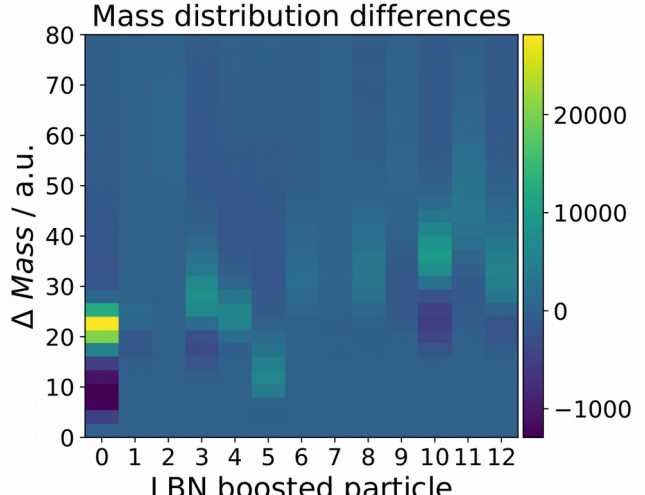


tt+bb

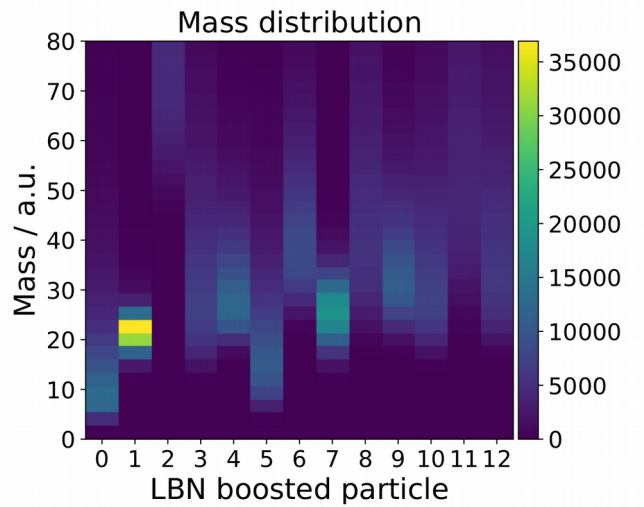


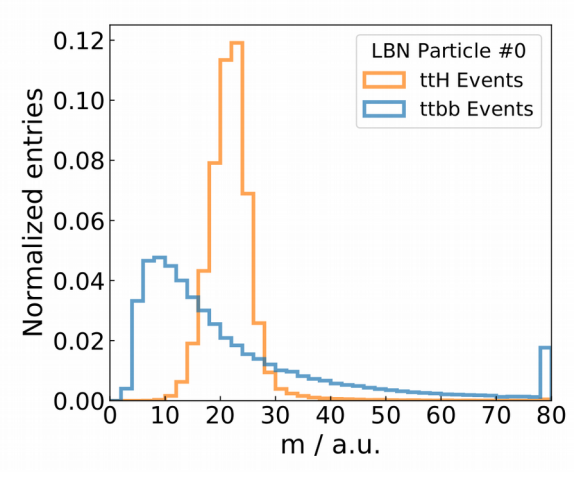
ttH


Mass distribution
Mass / a.u.
LBN boosted particle


Mass distribution differences
Δ Mass / a.u.
LBN boosted particle

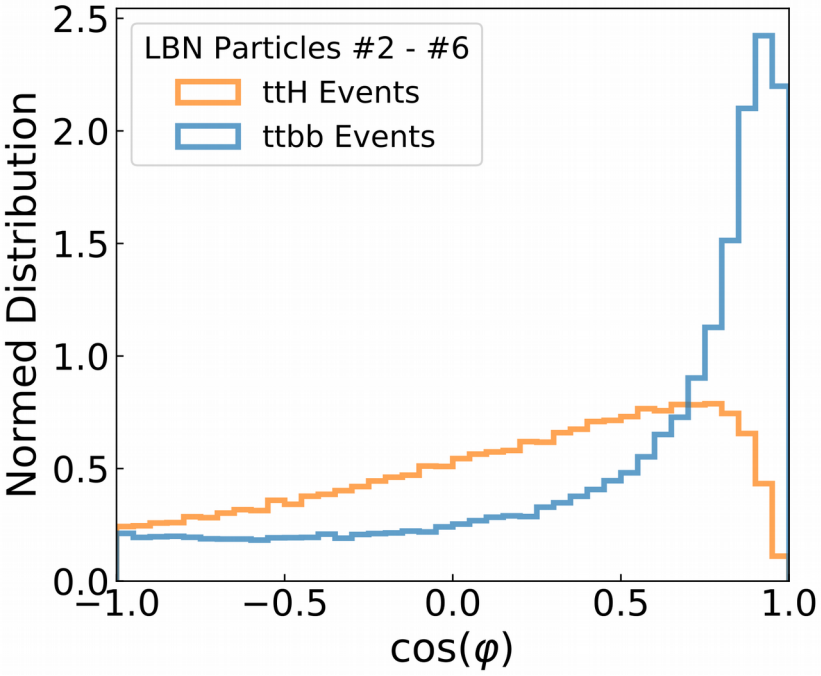
tt+bb

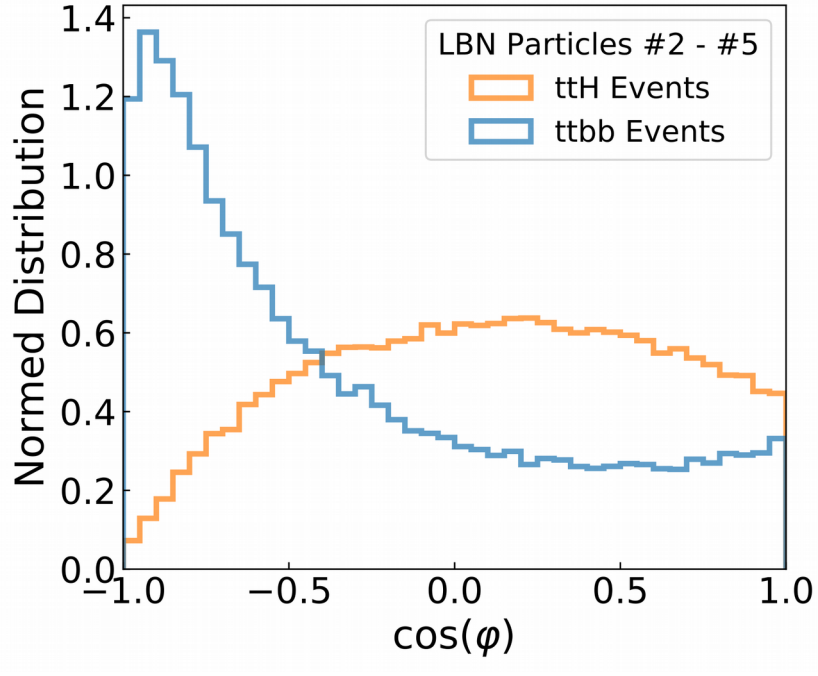

Mass distribution
Mass / a.u.
LBN boosted particle

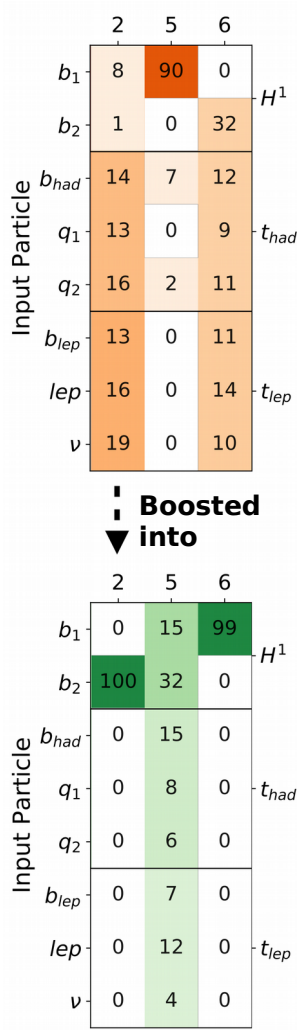

LBN Particle #0
ttH Events
ttbb Events
Normalized entries
m / a.u.

- Mass only dependent on combined particle

  → More complex example: Pairwise angles





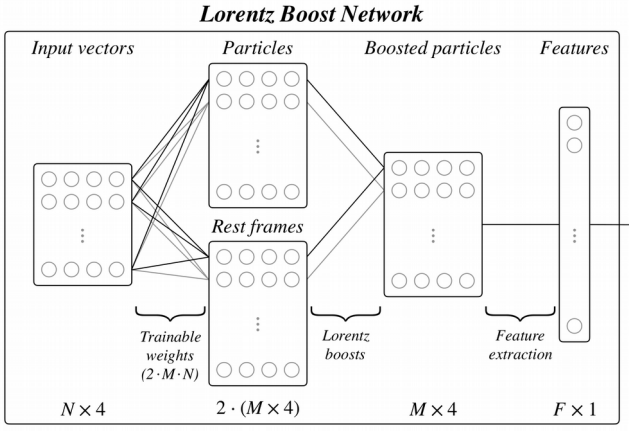


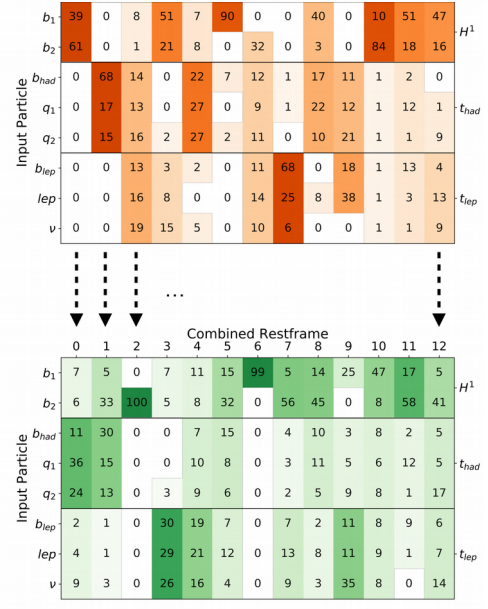
- Lorentz Boost Network: Physics-motivated NN architecture

- Able to autonomously create characteristic features from particle four momenta

- Network components have direct physics interpretation
  - Finds meaningful particle relations, constructs intermediate particles

[https://git.rwth-aachen.de/3pia/lbn]

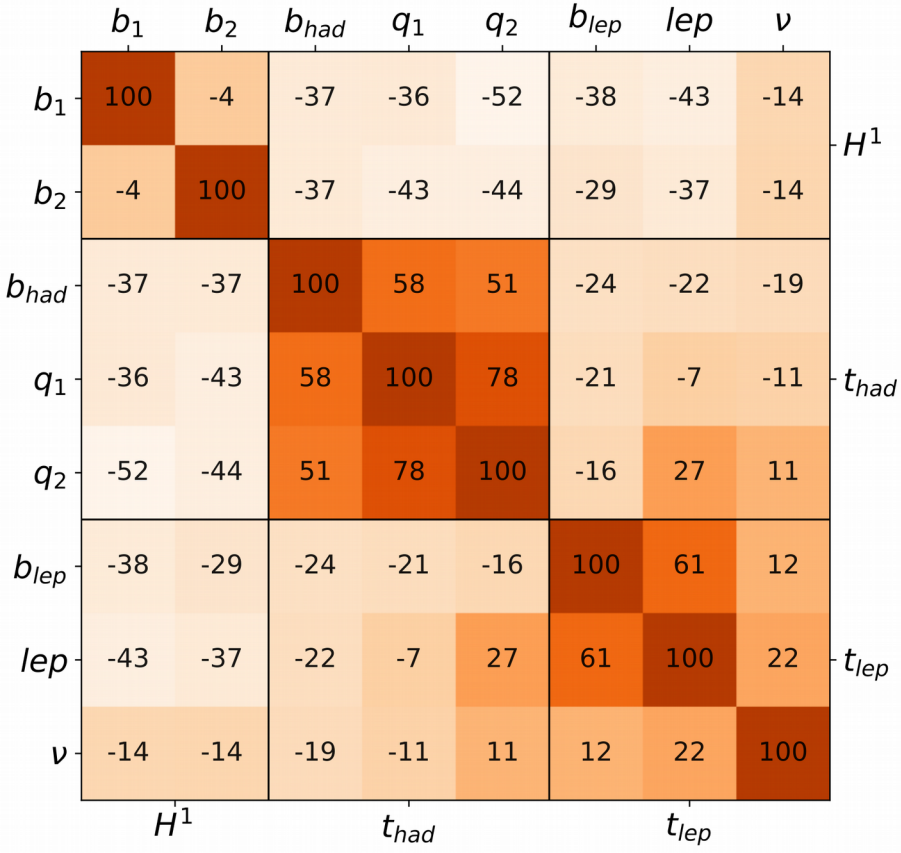




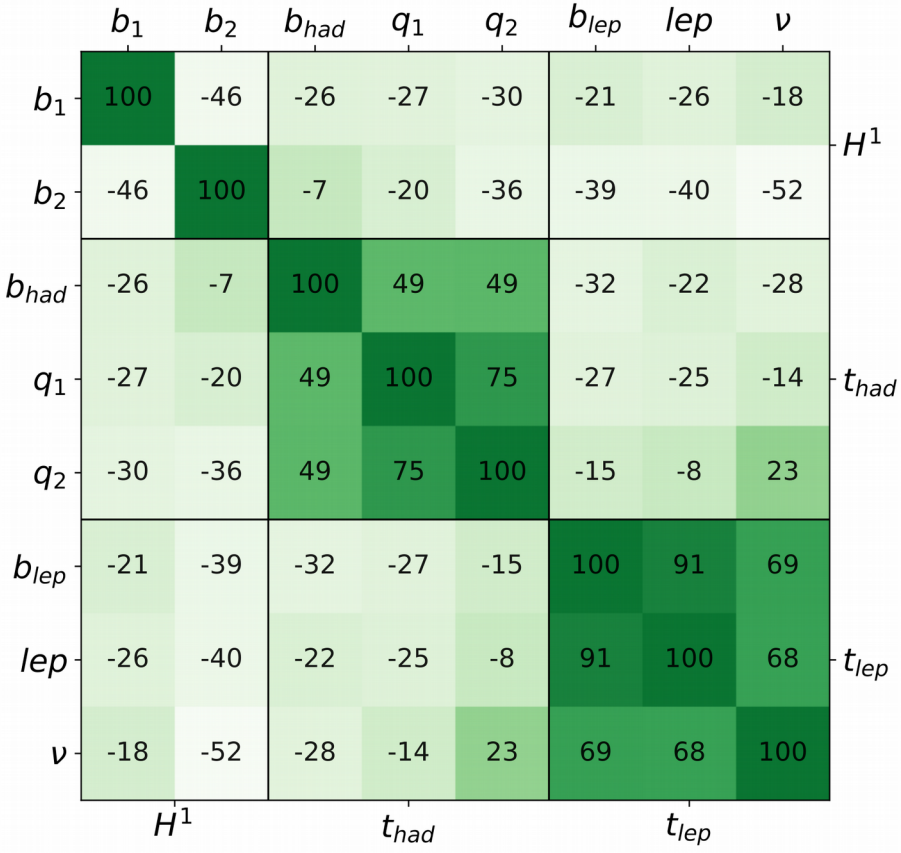
Backup

Correlations

Combined to Particles



Combined to Restframes



Lorentz Boost

$$\Lambda = \begin{bmatrix} \gamma & -\gamma\beta n_x & -\gamma\beta n_y & -\gamma\beta n_z \\ -\gamma\beta n_x & 1+(\gamma-1)n_x^2 & (\gamma-1)n_x n_y & (\gamma-1)n_x n_z \\ -\gamma\beta n_y & (\gamma-1)n_y n_x & 1+(\gamma-1)n_y^2 & (\gamma-1)n_y n_z \\ -\gamma\beta n_z & (\gamma-1)n_z n_x & (\gamma-1)n_z n_y & 1+(\gamma-1)n_z^2 \end{bmatrix}$$

with $\vec{n} = \vec{\beta}/\beta$

- As 4D tensor (batch x particle x 4 x 4):

$$\Lambda = I + (U \oplus \gamma) \odot ((U \oplus 1) \cdot \beta - U) \odot (e \cdot e^T)$$

with $U = \begin{bmatrix} -1^{1\times1} & 0^{1\times3} \\ 0^{3\times1} & -1^{3\times3} \end{bmatrix}$ $e = \begin{bmatrix} 1^{1\times1} \\ -\vec{n}^{3\times1} \end{bmatrix}$

Network Parameters

Network	**LBN+NN**		**DNN**					
Variables	**low-level**		**low-level**		**high-level**		**combined**	
Input Ordering	**gen.**	**p_T**	**gen.**	**p_T**	**gen.**	**p_T**	**gen.**	**p_T**
$M_{\text{part.,rest fr.}}$	13	16	–	–	–	–	–	–
n_{layers}	8	8	8	8	4	4	8	6
n_{nodes}	1024	1024	1024	1024	512	512	1024	1024