Construction and Fitting of a Deep Generative Hadronization Model

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Quantum chromodynamics (QCD)

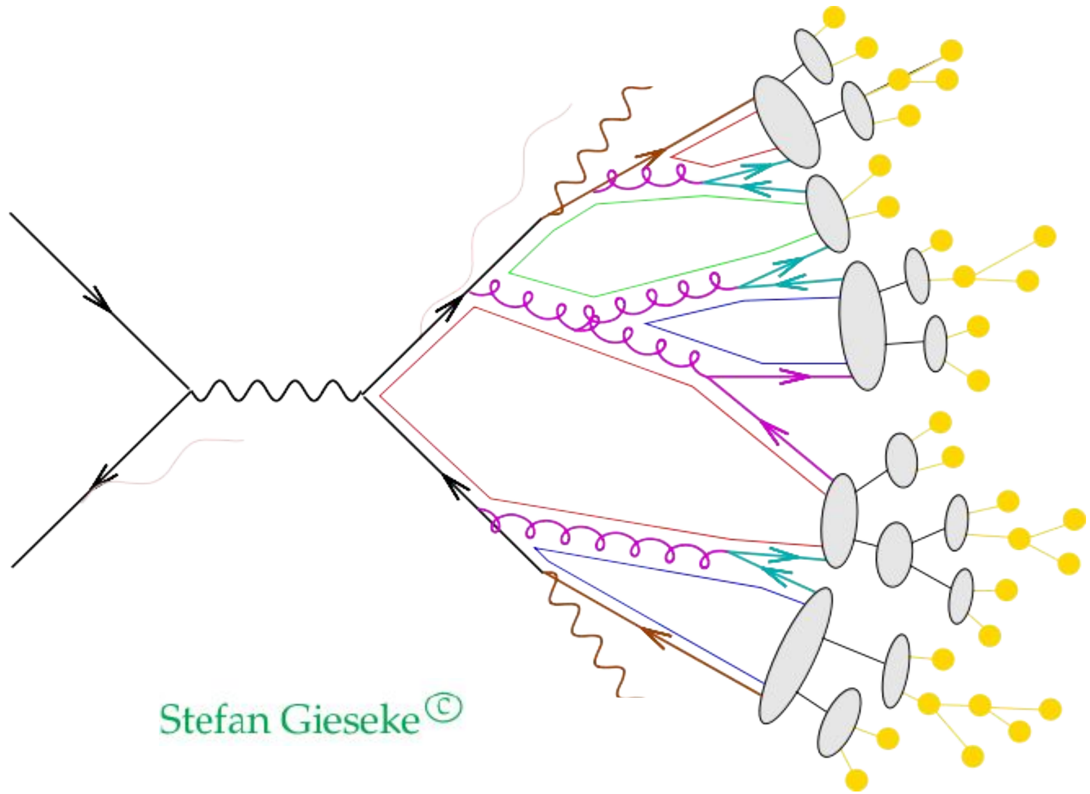
QCD correctly describes strong interactions in each energy range but it is very difficult to obtain precise predictions

High energy

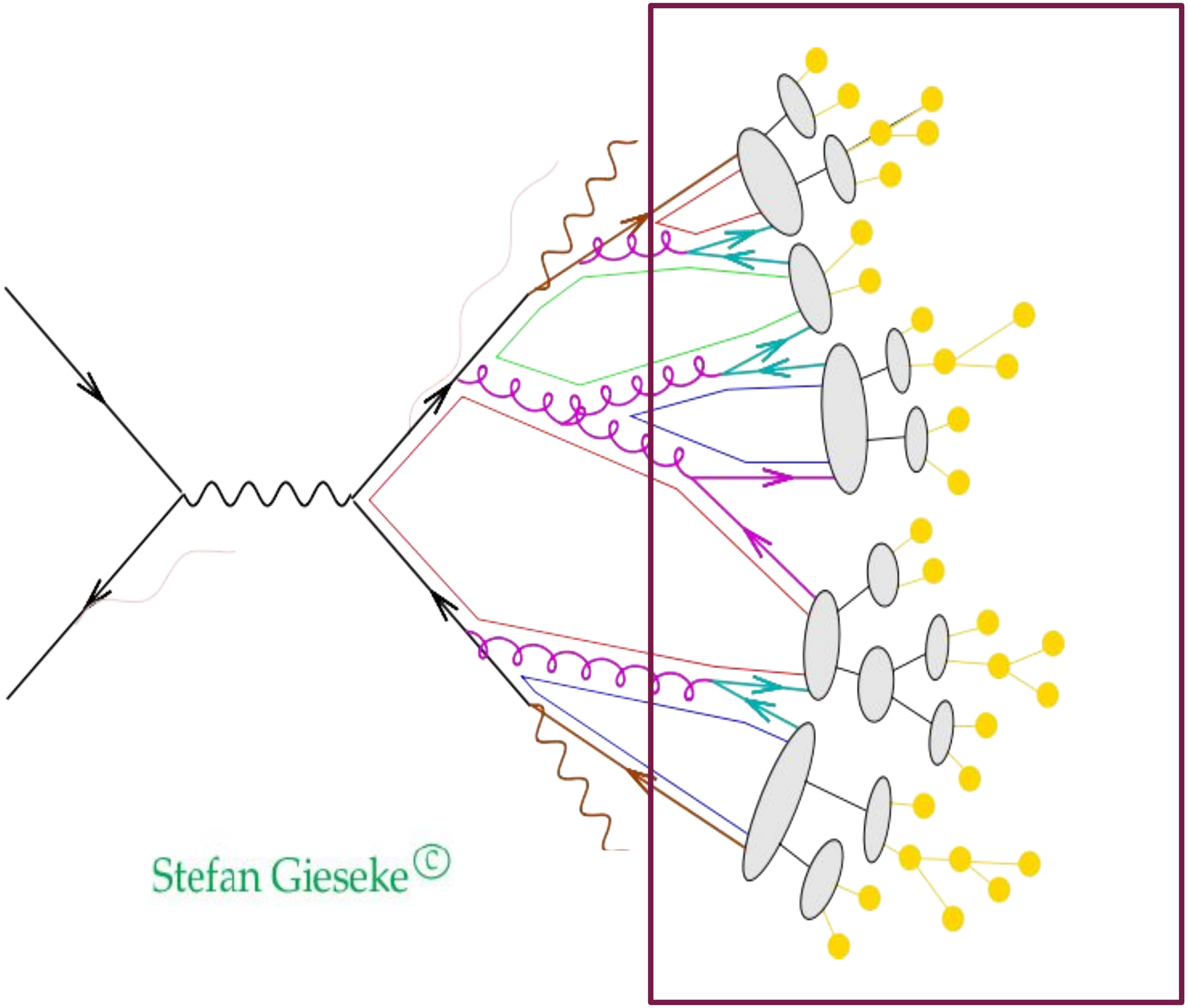
- **perturbative QCD**
- **we have theoretical models**
- **but they are hard to use in practice**

Low energy

- **non-perturbative QCD**
- **we lack solid theoretical models**
- **so we use phenomenological models (with many free parameters)**



Hadronization



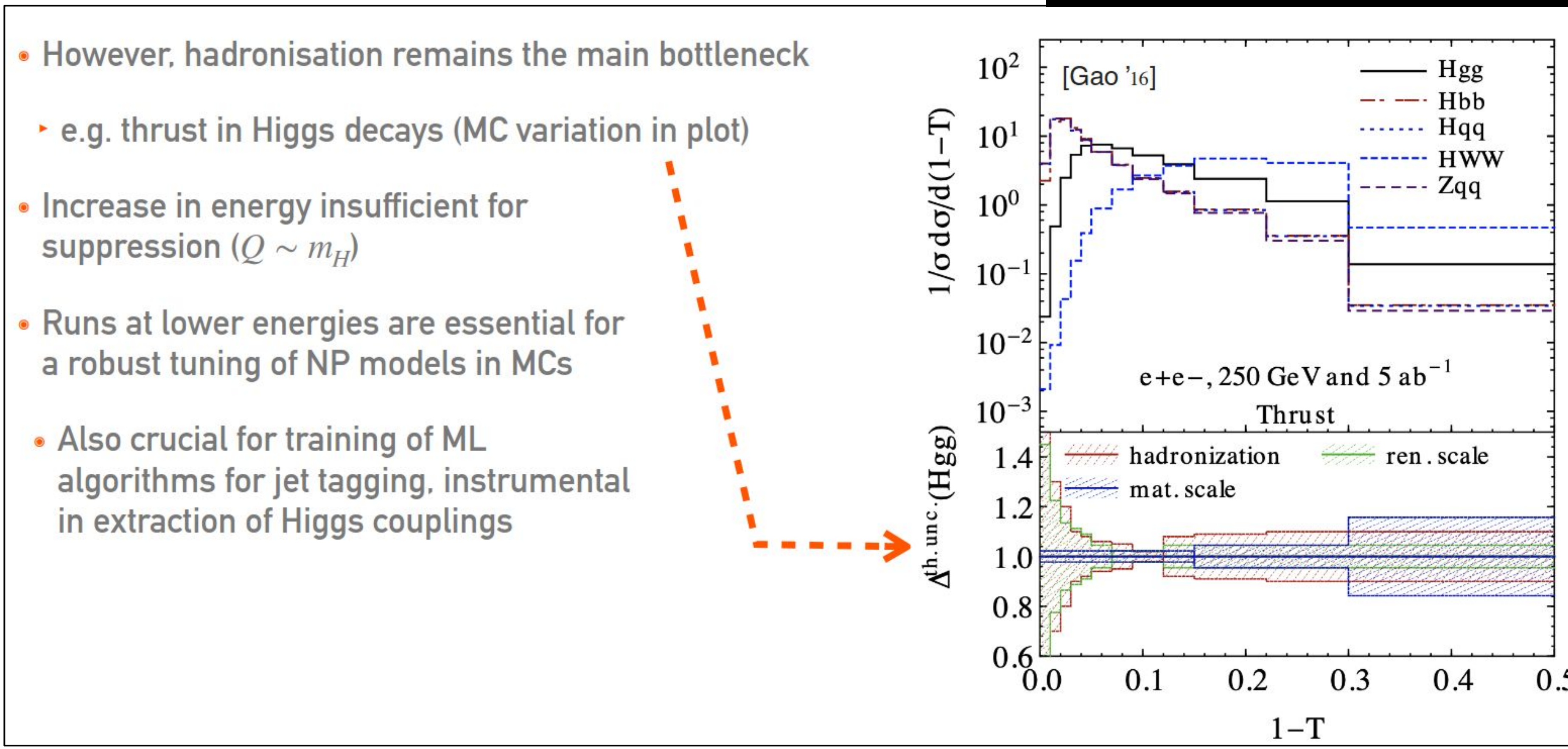
Hadronization:
one of the least understood elements of MCEG

Hadronization:

➔ Good models for perturbative QCD ⇒
LHC measurements are limited by non-perturbative components (e.g. hadronization).

- W mass measurement using a new method [Freytsis at al. JHEP 1902 (2019) 003]
- Extraction of the strong coupling in [M. Johnson, D. Maître, Phys.Rev. D97 (2018) no.5]
- Top mass [S. Argyropoulos, T. Sjöstrand, JHEP 1411 (2014) 043]
- ...

Pier Moni's talk
FCC Physics Workshop 2023



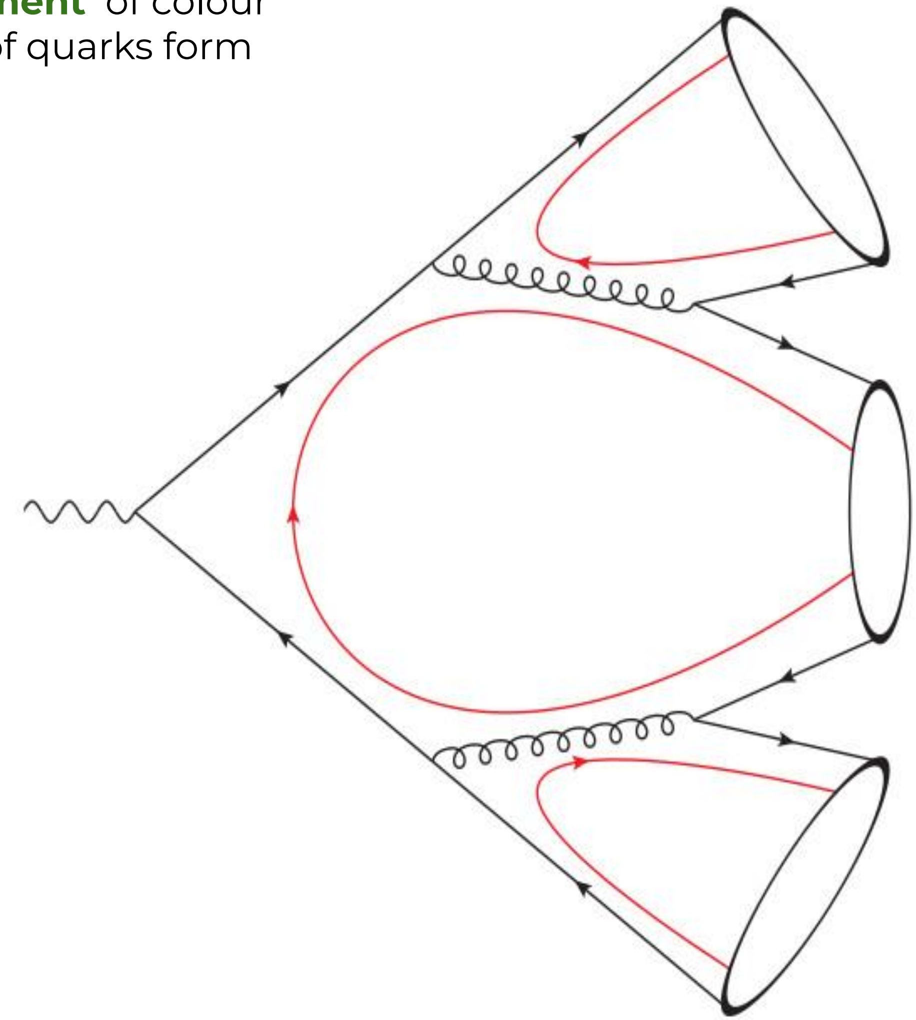
Cluster hadronization model in nutshell

Cluster model in nutshell

[Webber NPB238(1984)492]

The philosophy of the model: use information from perturbative QCD as an input for hadronization.

- QCD provide **pre-confinement** of colour
  - Colour-neutral pairs of quarks form the clusters



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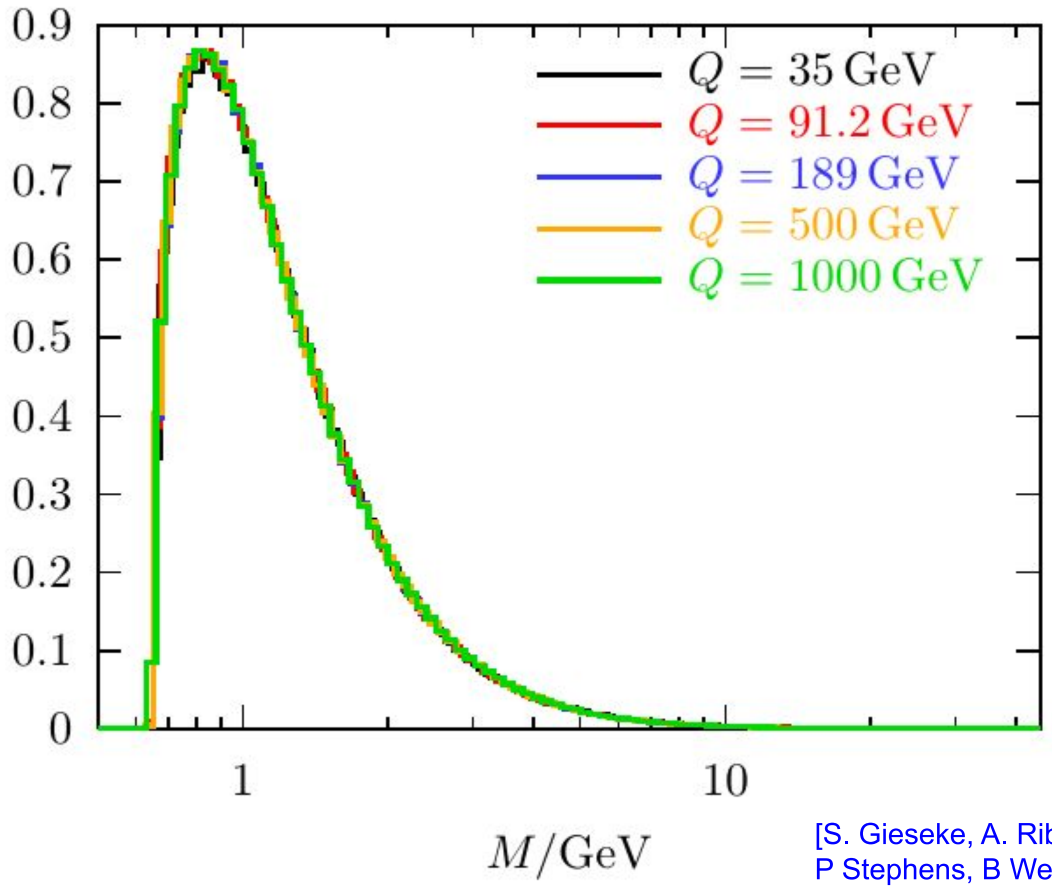
- **Pre-confinement** states that the energy distribution of clusters is independent of the hard process and energy of the collision
  - Peaked at low mass (1-10 GeV) typically decay into 2 hadrons



[S. Gieseke, A. Ribon, MH Seymour, P Stephens, B Webber JHEP 0402 (2004) 005]

Cluster model in nutshell

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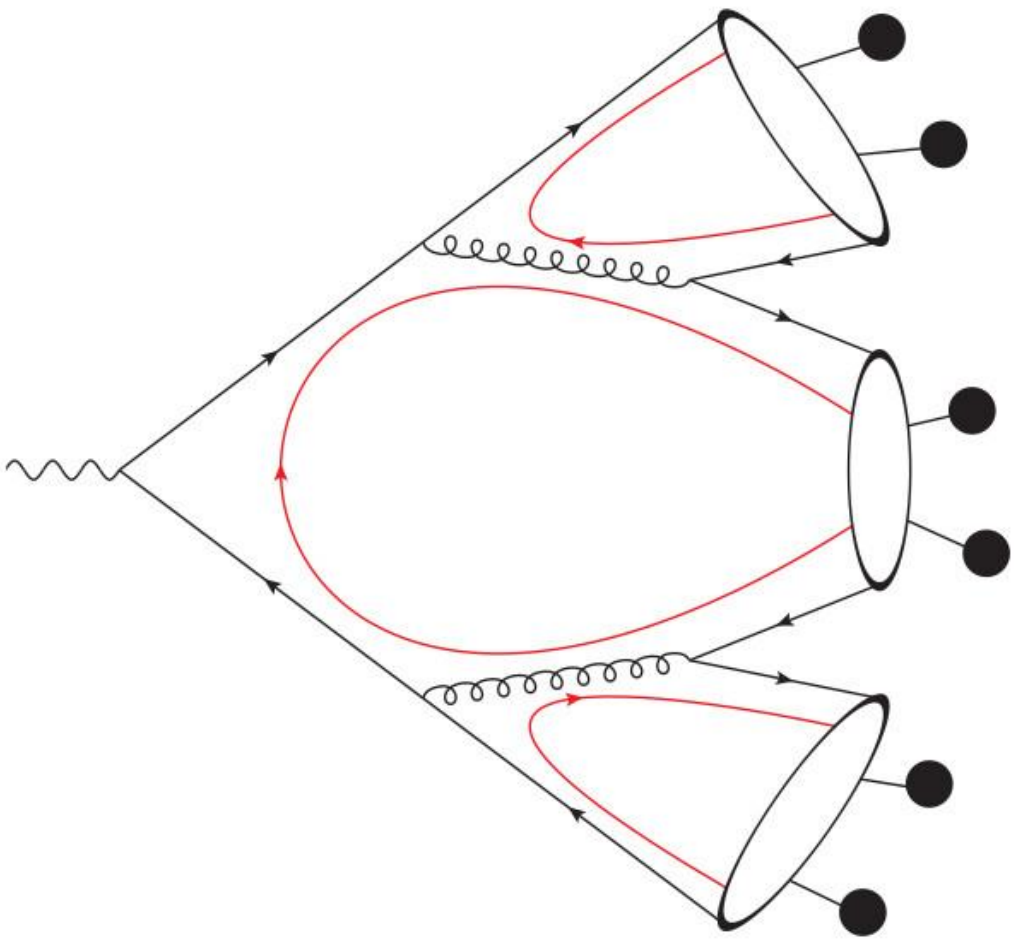

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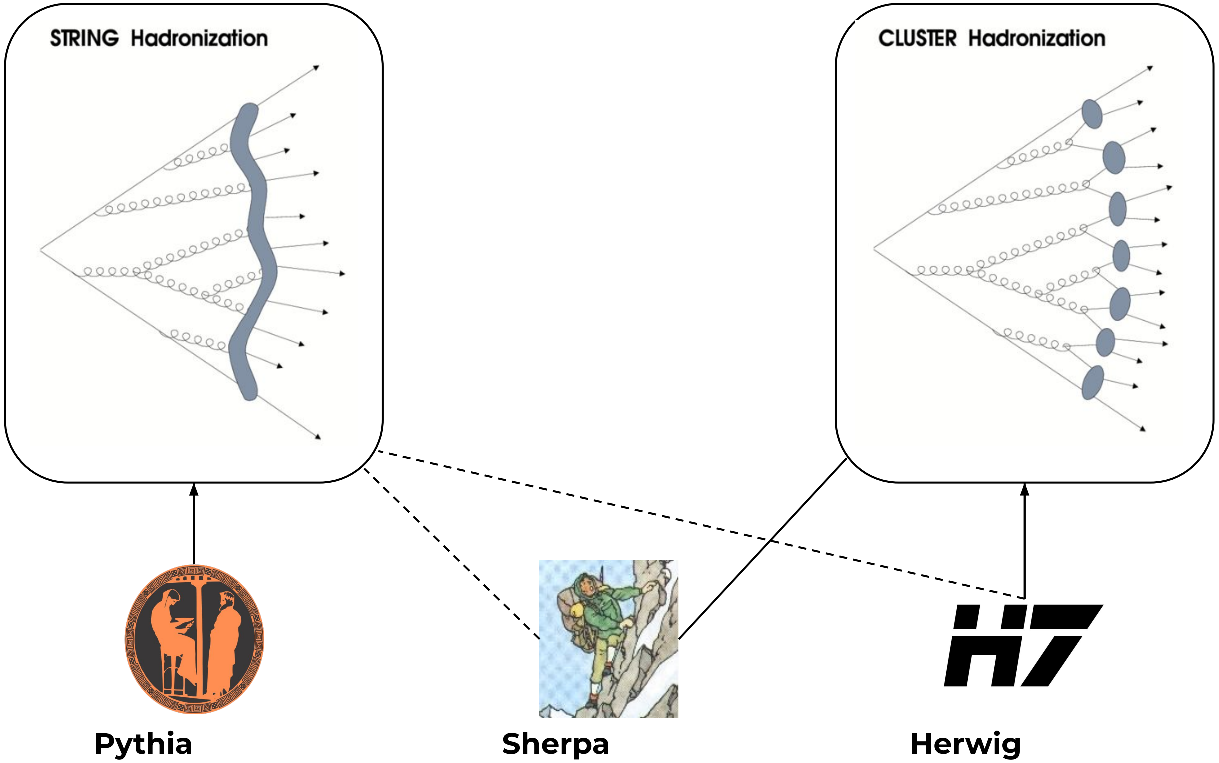
Simulating Hadronization

Hadronization models



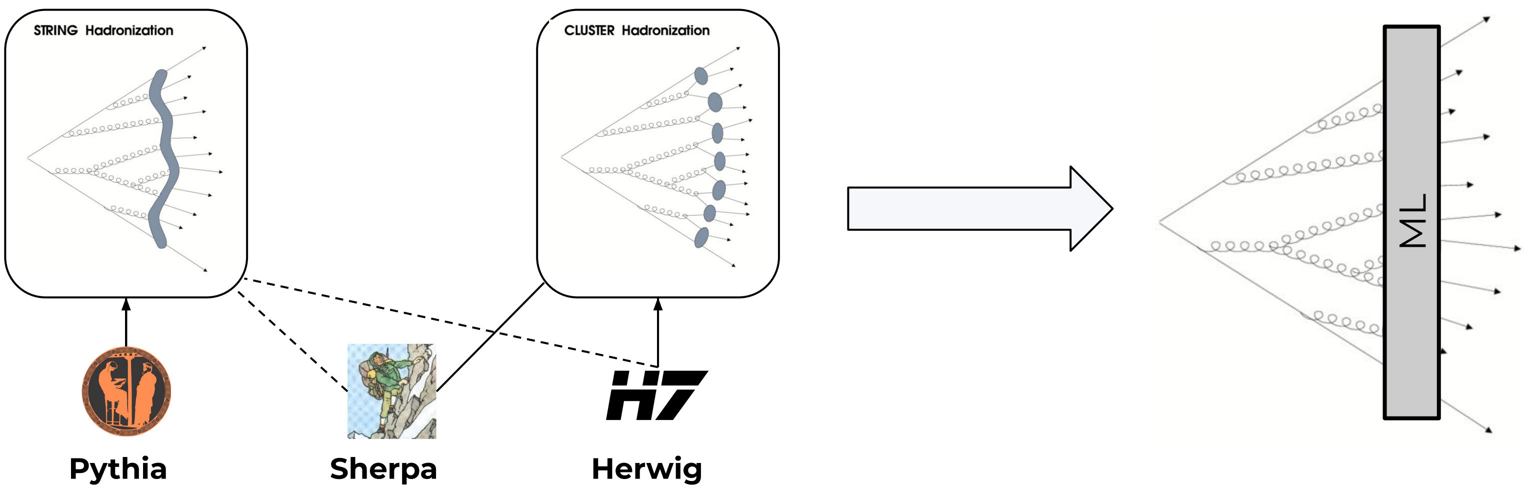
- Hadronization is a fitting problem
    - Existing models are highly parametric.
- Can ML hadronization be more flexible?

  e.g. work on unbinned data

Hadronization models

Early 1980's

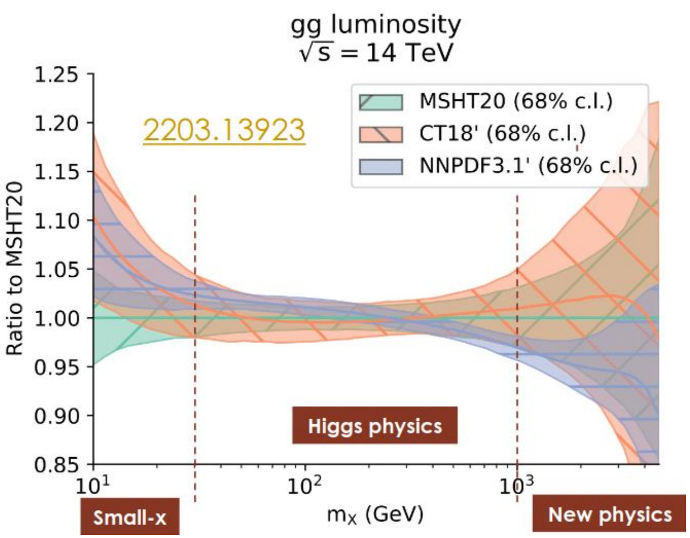
Early 2020's

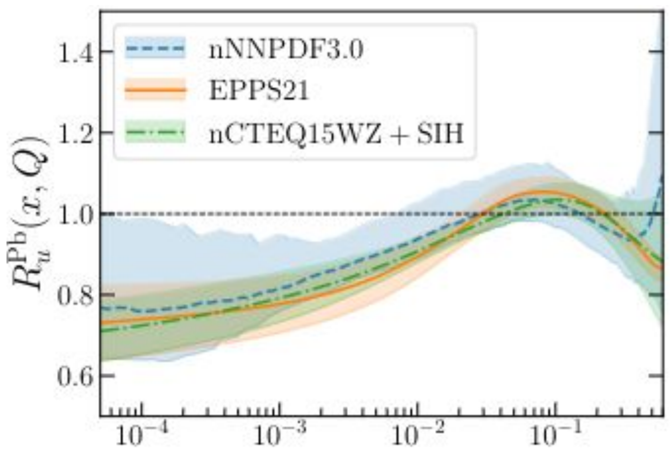


Idea of using Machine Learning (ML) for hadronization.

NNPDF used successfully ML to nonperturbative Parton Density Functions (PDF).

Hadronization is closely related to Fragmentation Functions which were considered the counterpart of PDFs.

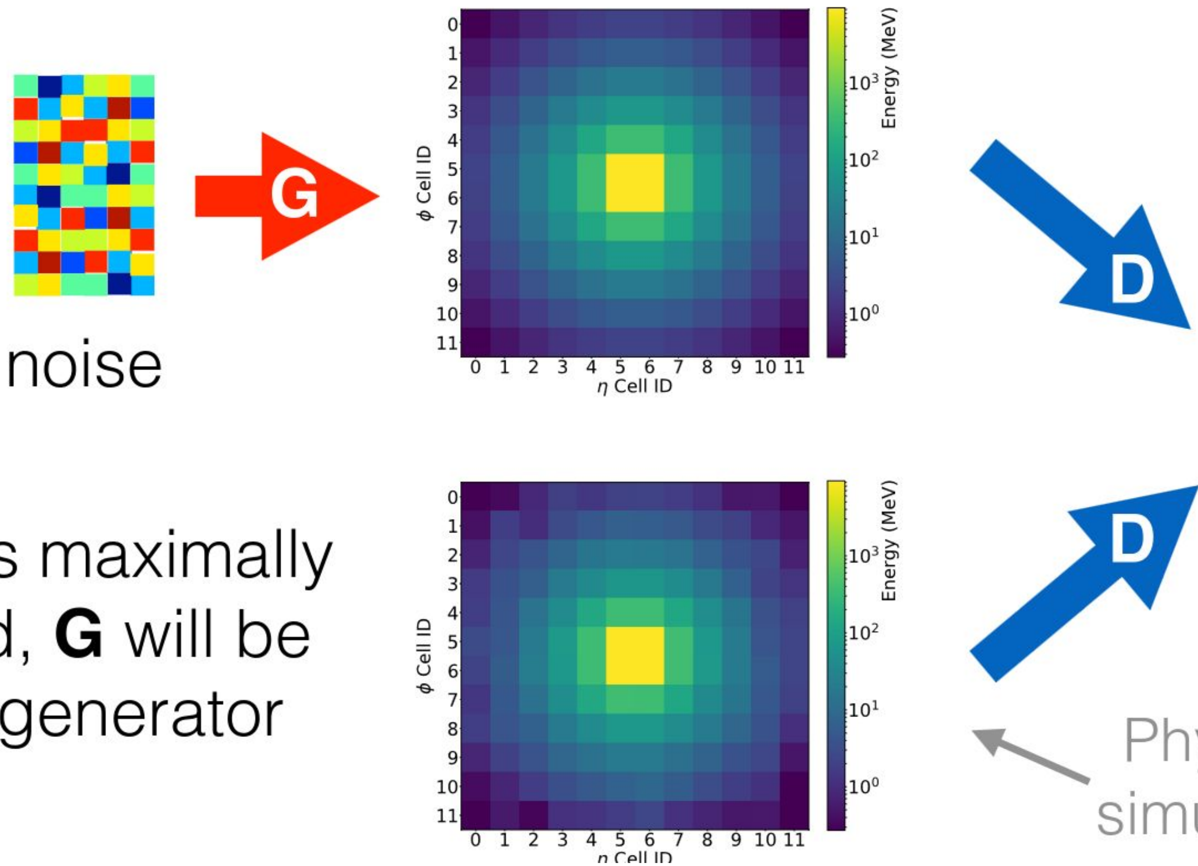




ML Approach

[Goodfellow et al. "Generative adversarial nets". arxiv:1406.2661]

Generative Adversarial Networks (GANs):
A two-network game where one ***maps noise to structure*** *and one* ***classifies images as fake or real.***



{real,fake}

When **D** is maximally confused, **G** will be a good generator

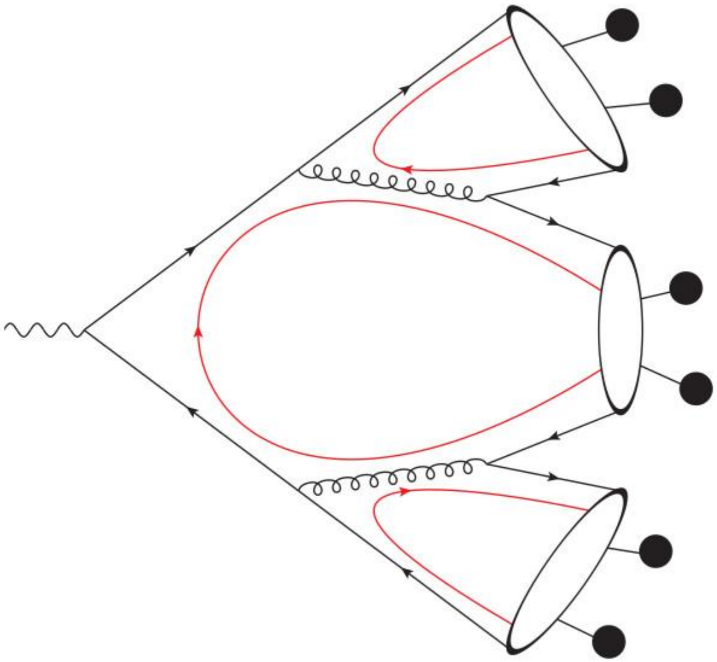
Physics-based simulator or data

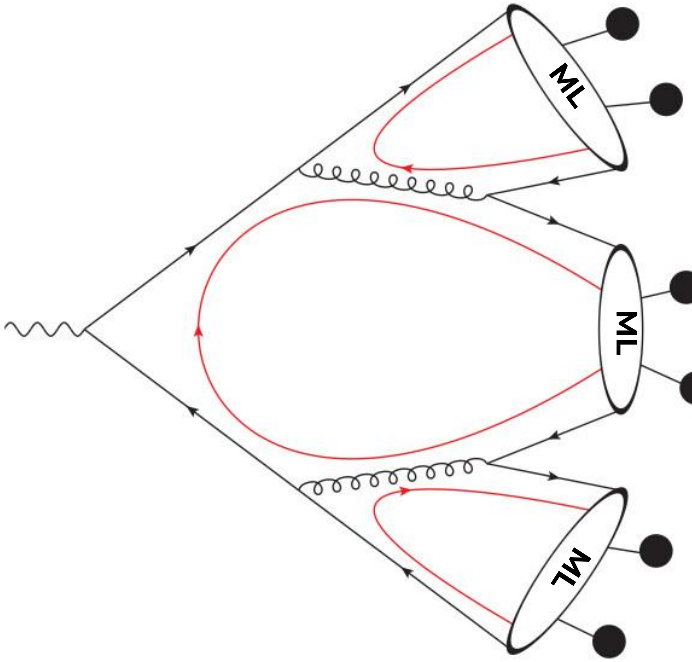
Cluster hadronization model

The philosophy of the model: use information from perturbative QCD as an input for hadronization.

- **ML hadronization**
  1st step: generate kinematics of a cluster decay

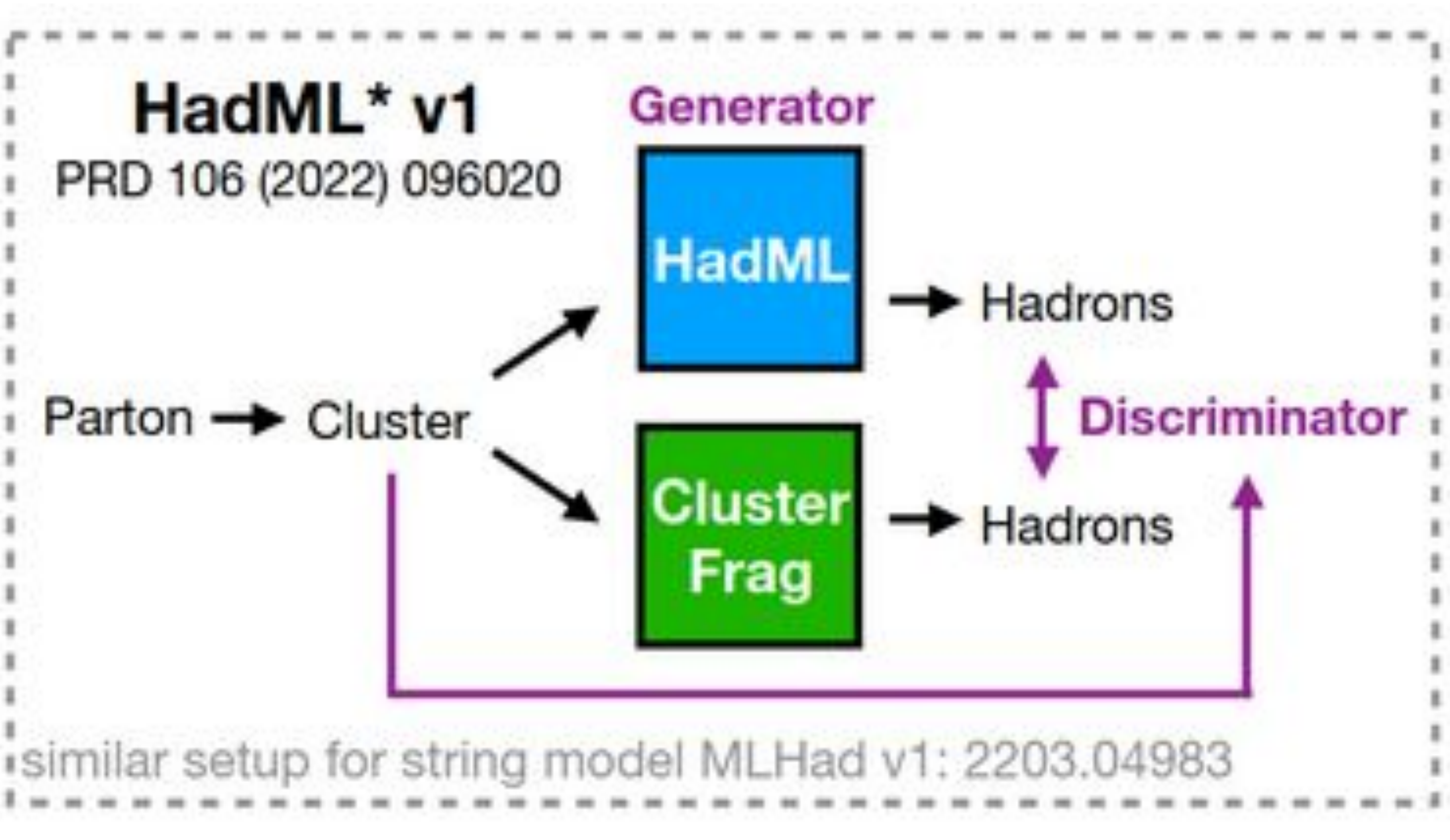
- **How?**
  Use Generative Adversarial Networks (**GAN**)





First Step Towards a ML Model for Hadronization

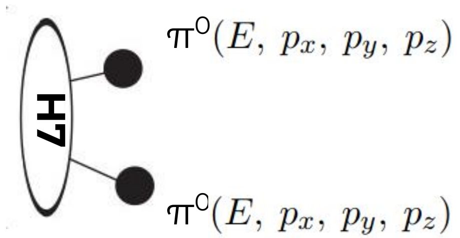
How?



Training data:

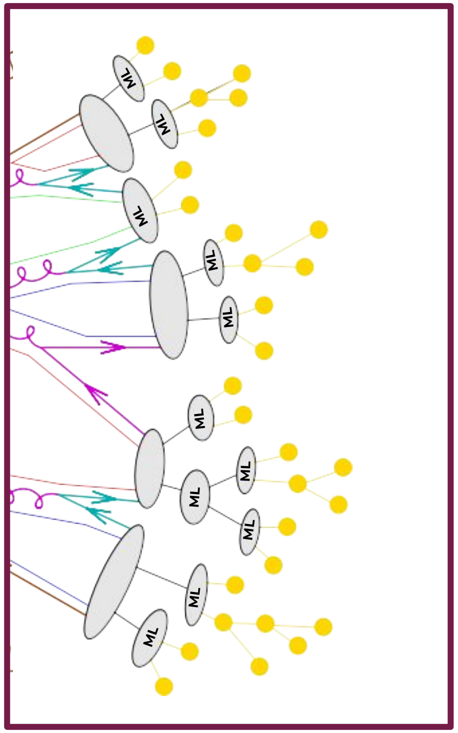
e^+e^- collisions

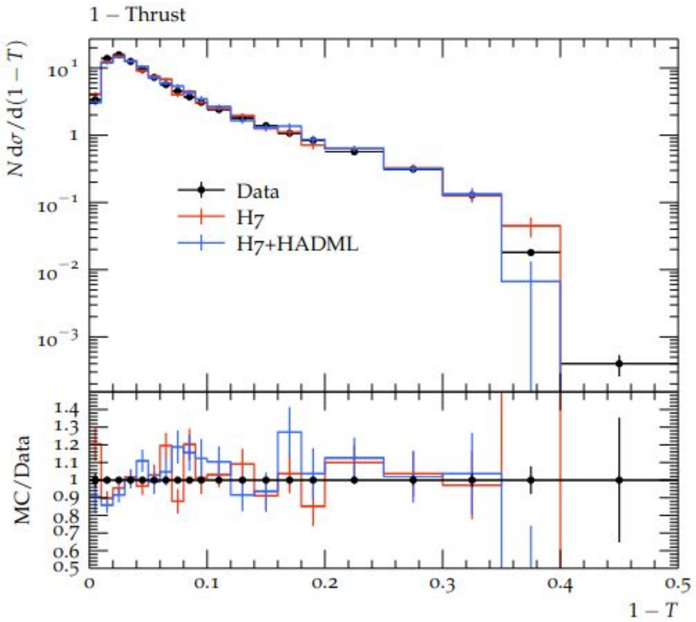
Cluster $(E,\ p_x,\ p_y,\ p_z)$

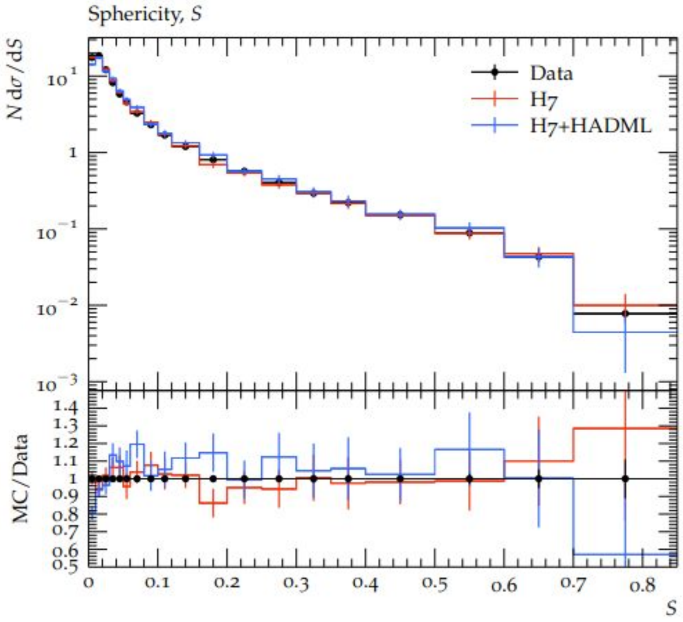


With a "full" model, we can compare directly to data!

LEP DELPHI **Data**

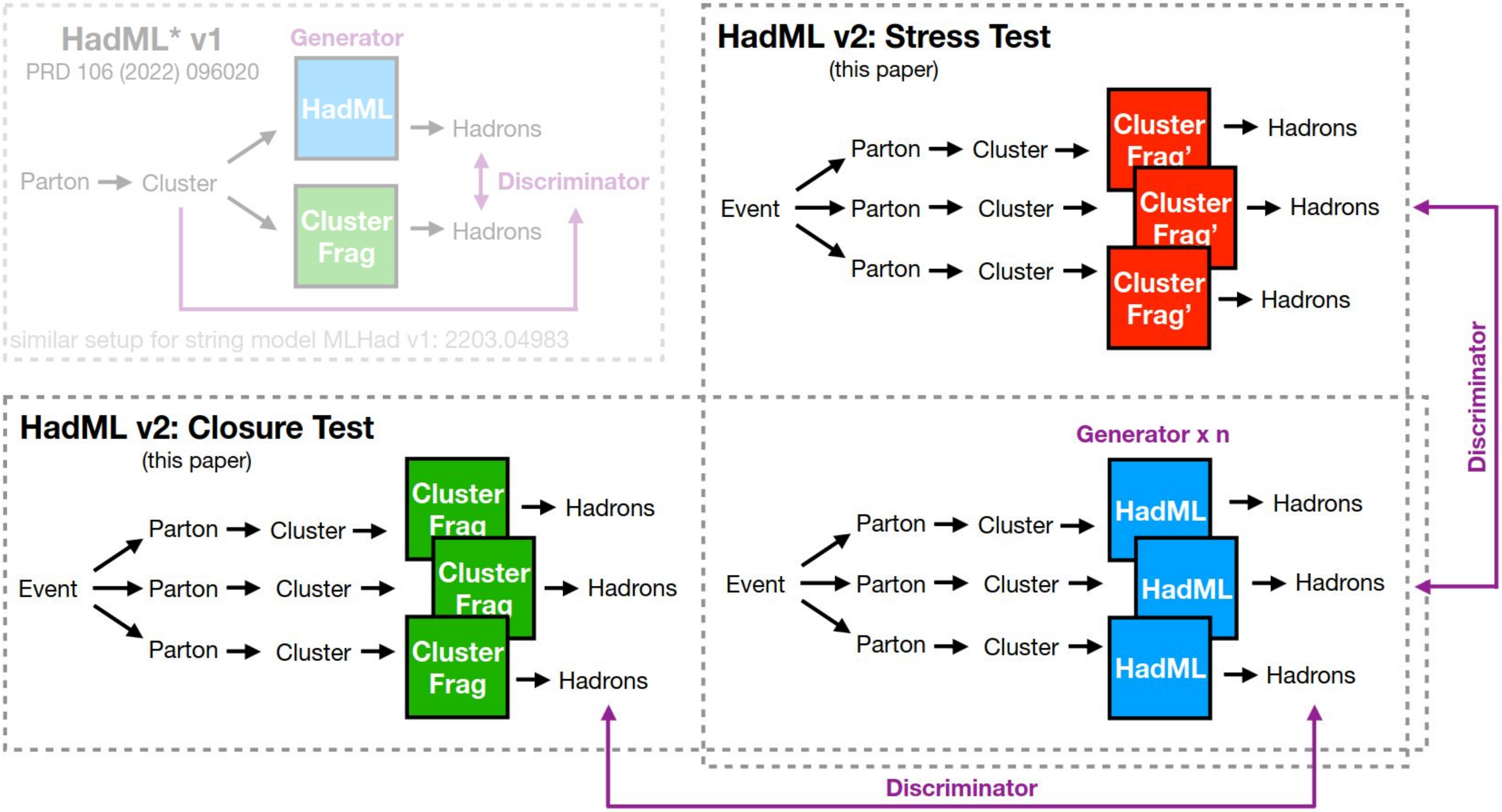




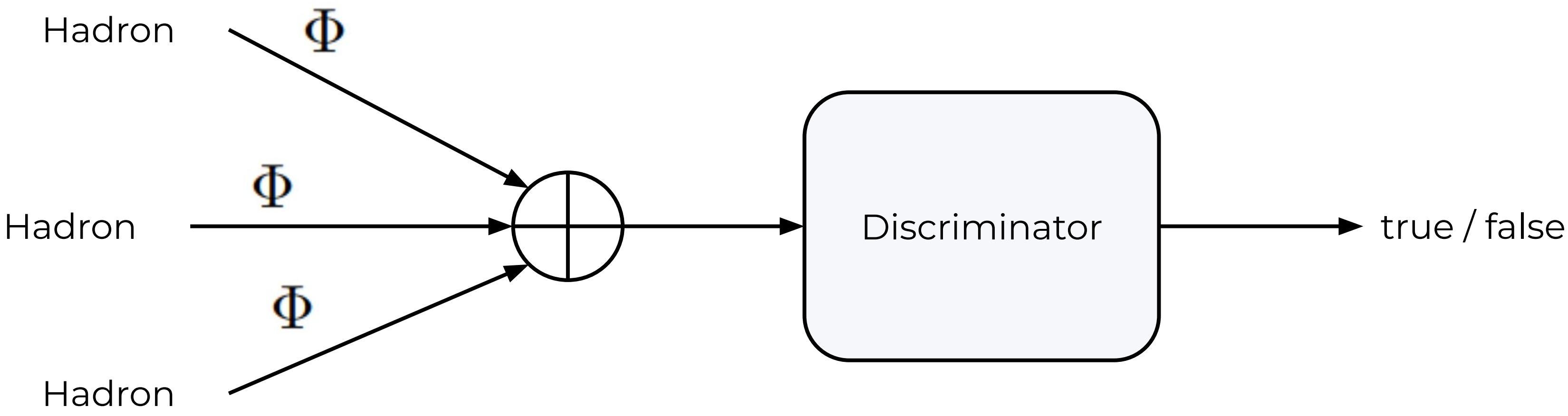


N.B. we have trained on H7, so we don't expect to be any better than it at modeling the data.

HADML v2



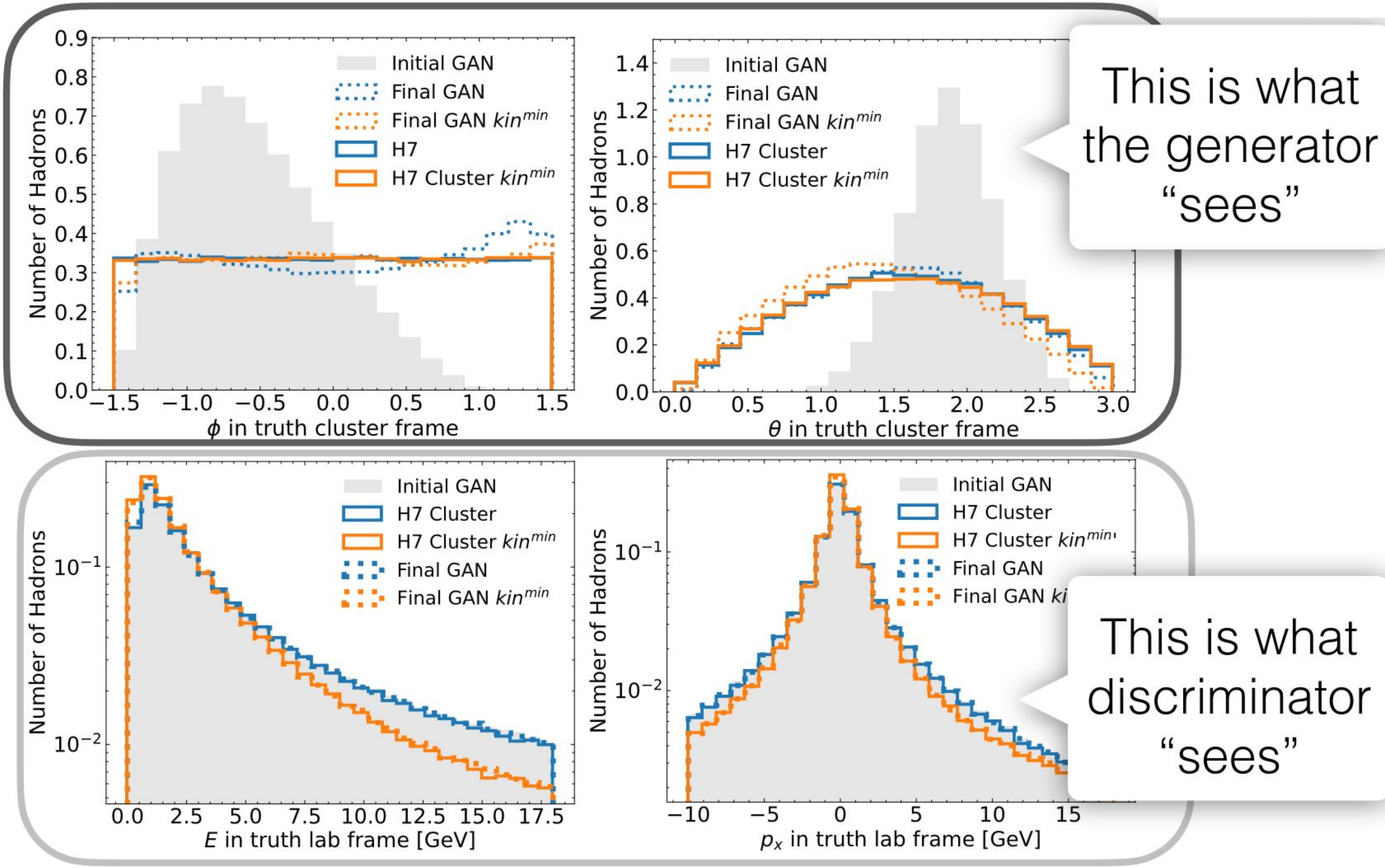
HadML* v1
PRD 106 (2022) 096020
Generator
HadML
Parton
Cluster
Cluster Frag
Hadrons
Discriminator
Hadrons
similar setup for string model MLHad v1: 2203.04983
HadML v2: Stress Test
(this paper)
Event
Parton
Cluster
Cluster Frag'
Hadrons
Discriminator
HadML v2: Closure Test
(this paper)
Event
Parton
Cluster
Cluster Frag
Hadrons
Generator x n
HadML
Hadrons
Discriminator



The discriminator function is modified, we parameterize is as a Deep Sets model

$$D_E(x) = F\left(\frac{1}{n}\sum_{i=1}^{n}\Phi\left(h_i, \omega_{D_\Phi}\right), \omega_F\right)$$

← invariant under permutations of hadrons

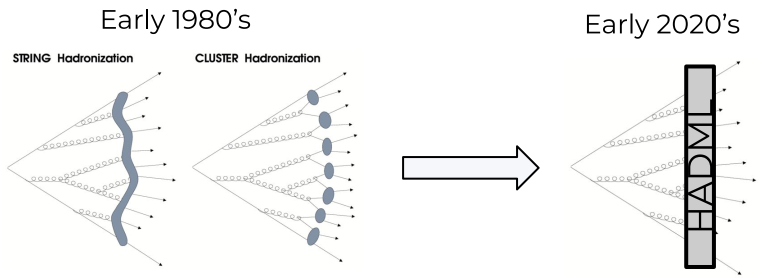


Initial GAN
Final GAN
Final GAN kin^{min}
H7
H7 Cluster kin^{min}
Number of Hadrons
ϕ in truth cluster frame
H7 Cluster
θ in truth cluster frame
This is what the generator "sees"
E in truth lab frame [GeV]
p_x in truth lab frame [GeV]
This is what discriminator "sees"

What is next for HADML?

- Number of technical and methodological step needed:
  - ➔ Directly accommodate multiple hadron species with their relative probabilities
  - ➔ Hyperparameter optimization, including the investigation of alternative generative models
  - ➔ More flexible model with a capacity to mimic the cluster or string models as well as go beyond either model.

There is still a multi-year program ahead of us, but it will be worth it!



So Stay tuned!

A postdoc in ML/HEP position

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If you are interested please contact:
andrzej.siodmok@cern.ch

Thank you