ML-assisted reconstruction of hadron-collider events with mini-jets

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ML4Jets, DESY, Hamburg
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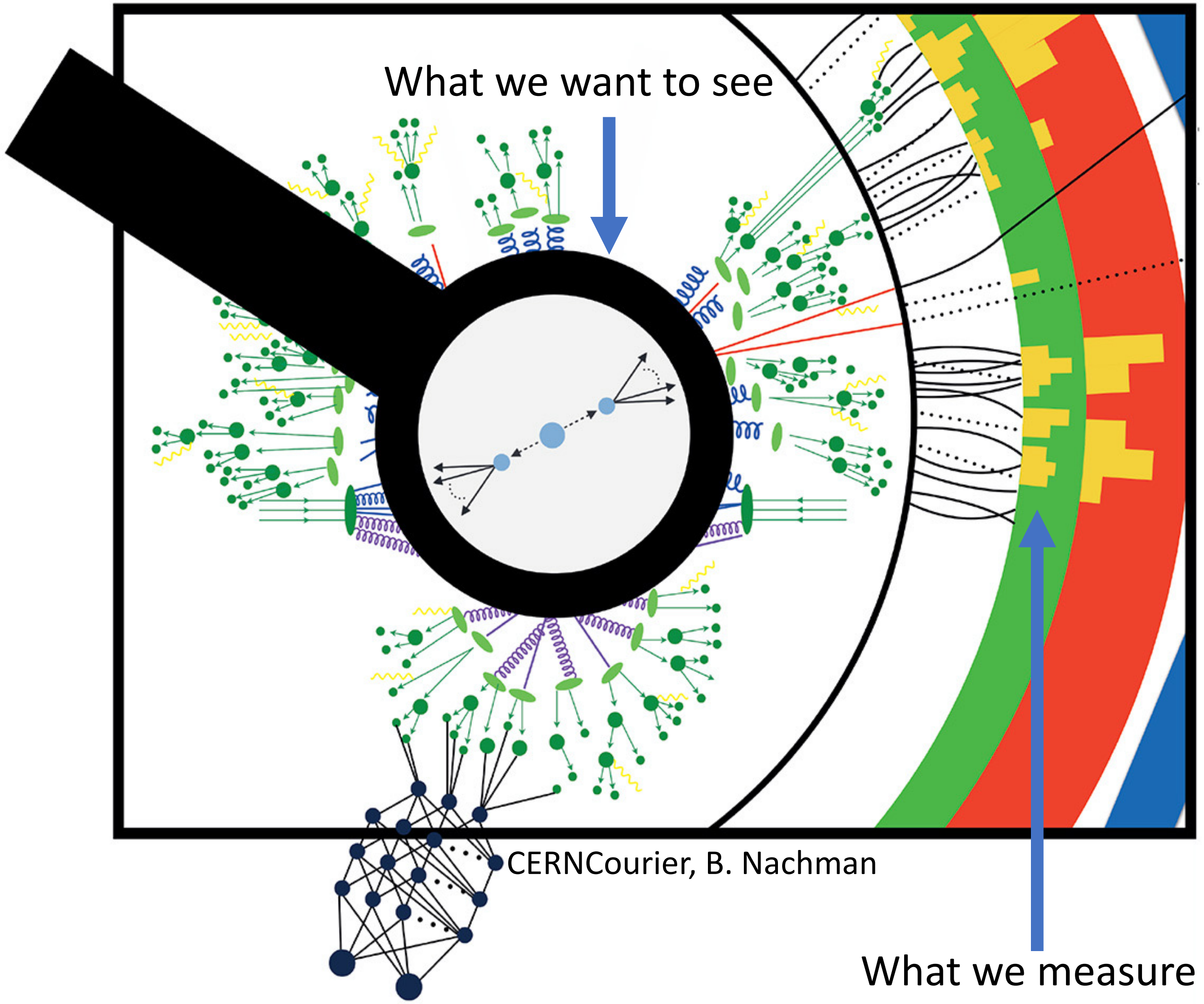
Introduction

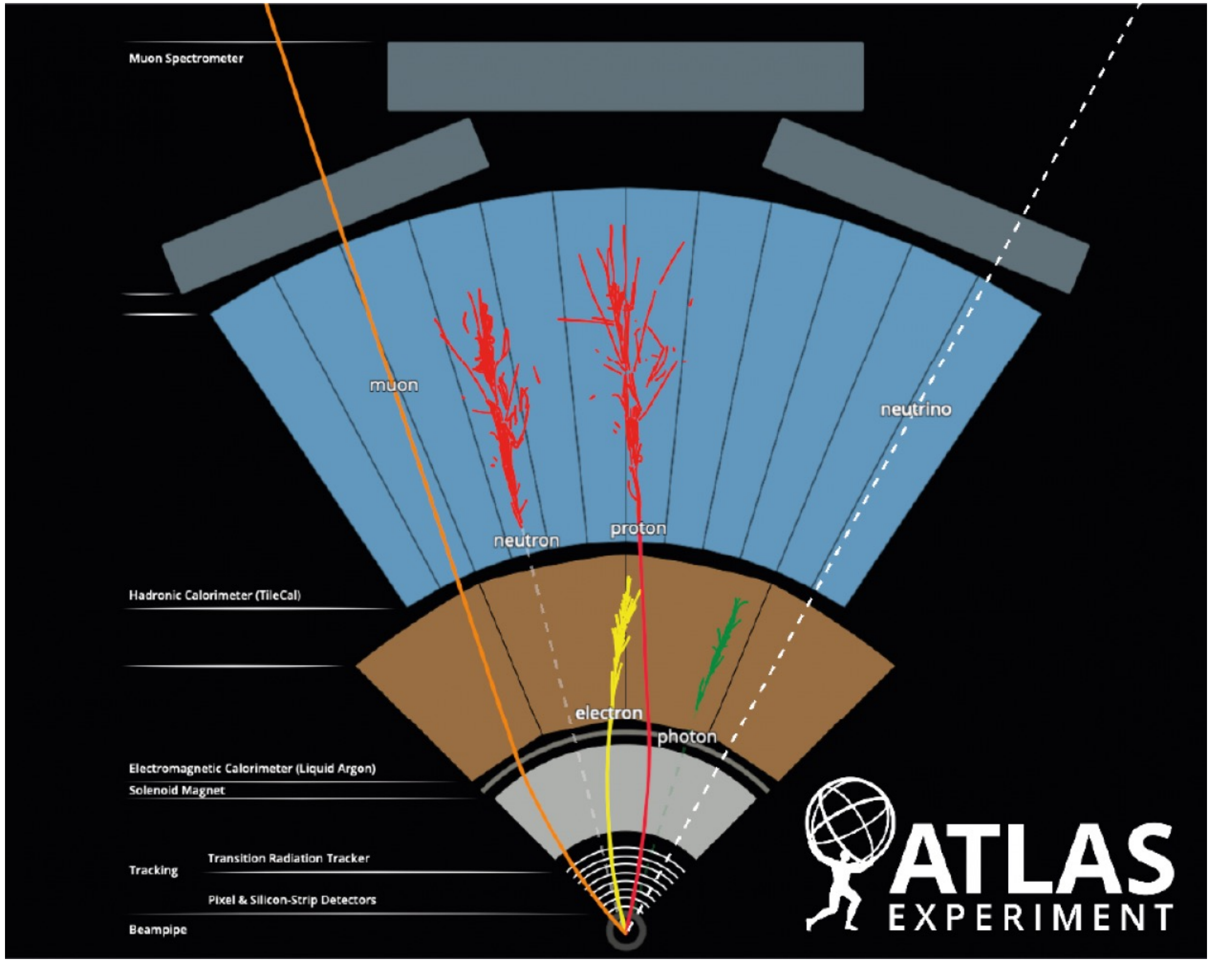
- At hadron colliders, a critical task is the reconstruction of intermediate resonances from Higgs-, W- or Z-bosons or from a top quark decay
- Decays into quarks (hadronic decays) are particularly difficult (but also leptonic decays are challenging when neutrinos are involved)
- Due to colour confinement, quarks cannot be observed directly in experiment
- Instead, they form jets of particles
- Jet algorithms are applied as a proxy for a single quark, or to reconstruct an intermediate resonance directly (H,W,Z,t)



CERNCourier, B. Nachman

Measurement of decay products

- Final state particles:
  - charged leptons, neutrinos, photons, charged and neutral hadrons
- Hadron-Collider:
  - Easy measurement of charged leptons and photons (single tracks, muon hits, isolated clusters)
  - Missing energy is representative for neutrino
  - Hadrons are collected into (jets)
  - H, W, Z-bosons or top-quarks can only be measured indirectly



ATLAS collaboration

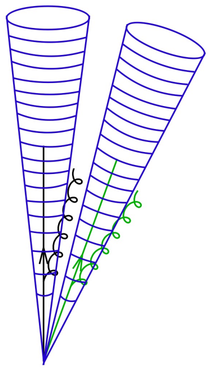
Jet Reconstruction

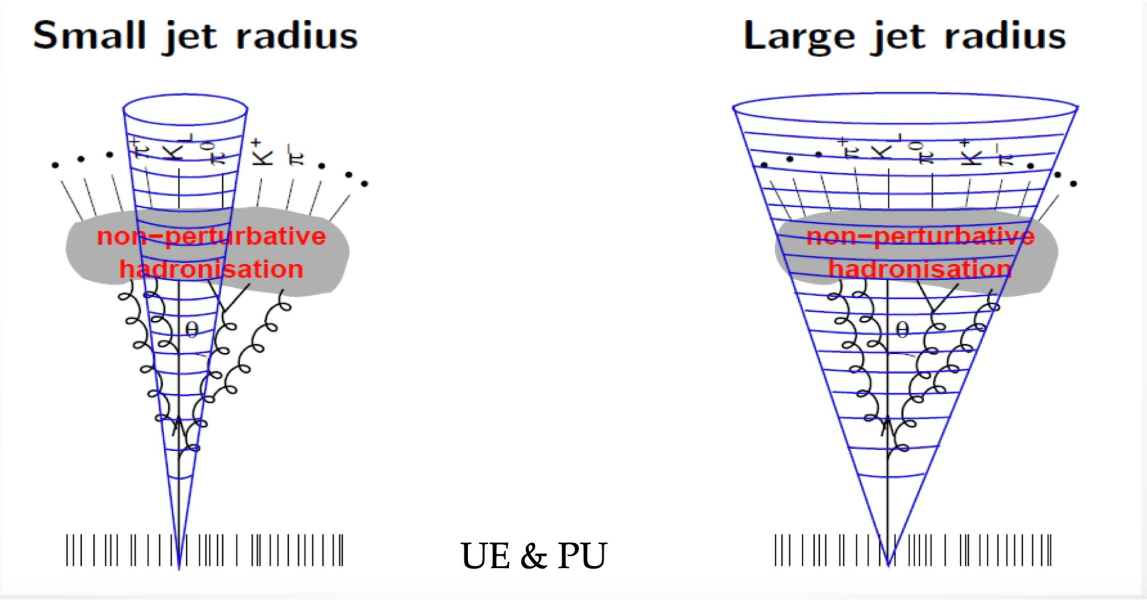
- Many different approaches for jet-analysis
- Most commonly used: Recursive clustering algorithms
- Quantity to describe the size of the jets

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

- Typical values at the LHC:
    - Large-R jets - R =0.8
    - Small-R jets - R=0.4
- New approach:
    - **Mini-jets – R=0.1**
    - Idea: parton-jet duality for sufficiently hard partons from matrix element or hard radiation in parton shower, but insensitive to soft radiation and hadronization effects
    - Challenge: reconstruct H, W, Z-bosons or tops from mini-jets

Mini jet radius

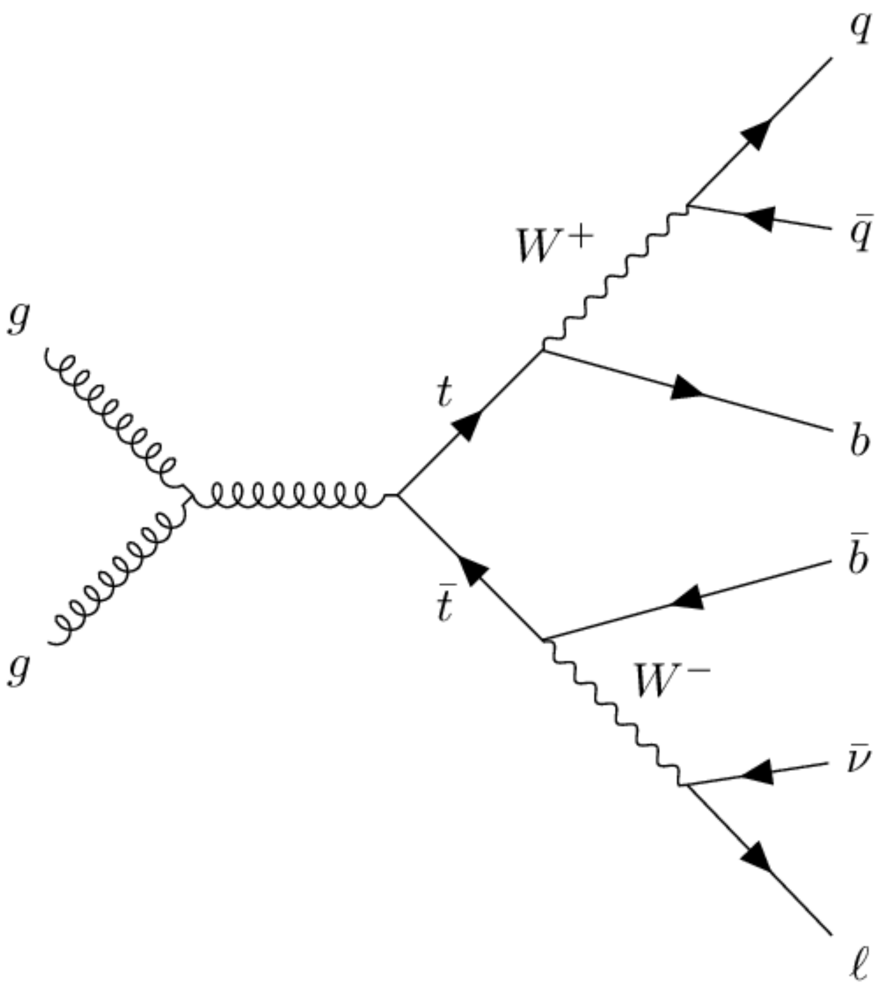




Jets at hadron colliders (2); Gavin Salam

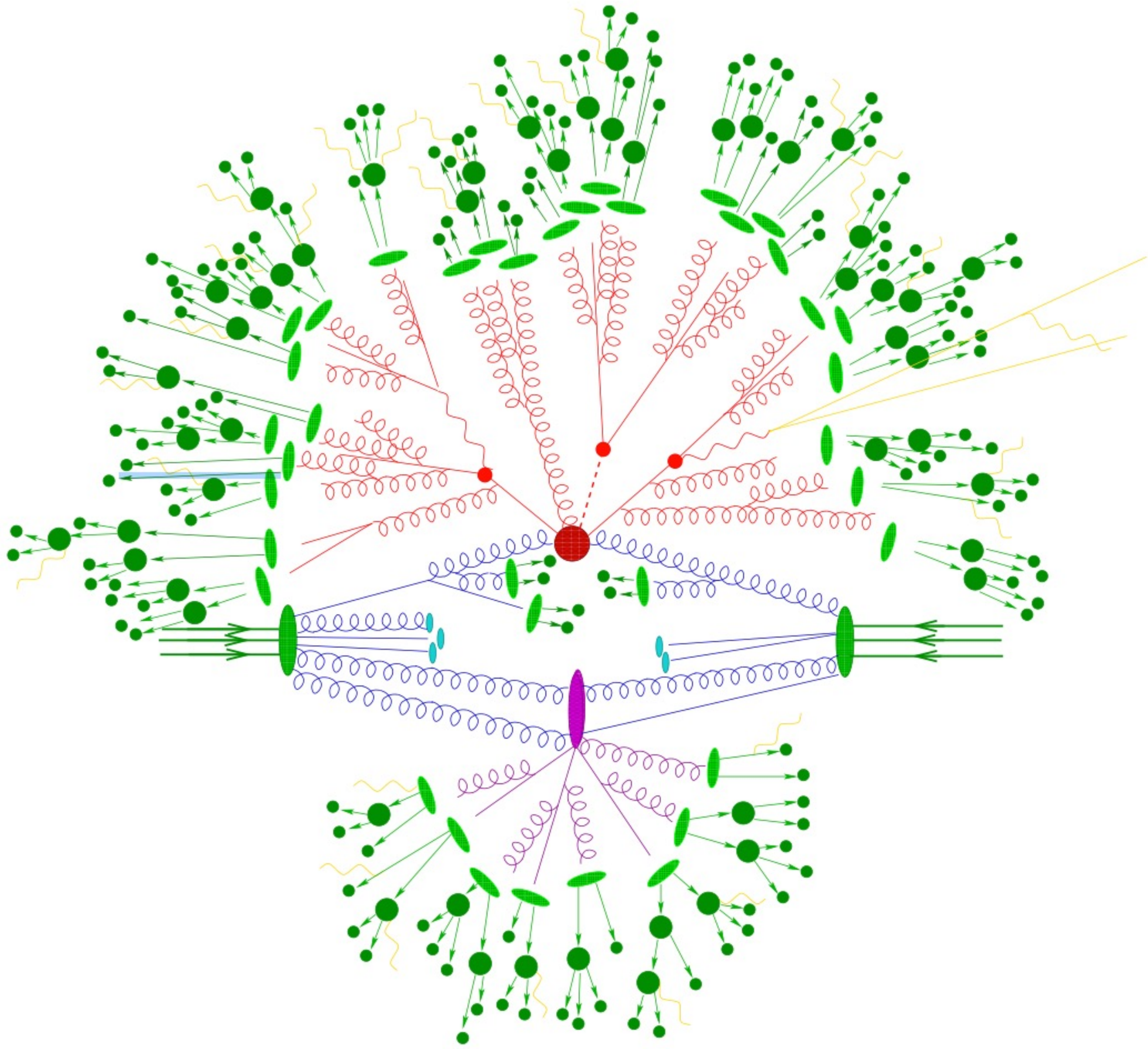
Underlying Physics and Data

- Pair of top quarks decays into two W-bosons and two bottom quarks
- Centre of mass energy: 13 TeV
- W-bosons decay semi leptonically
  - Leptonic W-boson → lepton and neutrino
  - Hadronic W-boson → quark – anti-quark
- Monte Carlo Simulation:
  - Particle-level analysis
  - Anti-kt algorithm (different R-values)
  - ME, parton-shower and hadronization from Pythia 8.3



What We Measure

- Jet clustering is performed at particle level
- All particles, except neutrinos, are input to jet algorithm
    - jets are the only representation of an event
    - also prompt leptons form a jet
    - only MET will be considered separately
- Re-combine multiple mini-jets later to form a H/W/Z/t-jet

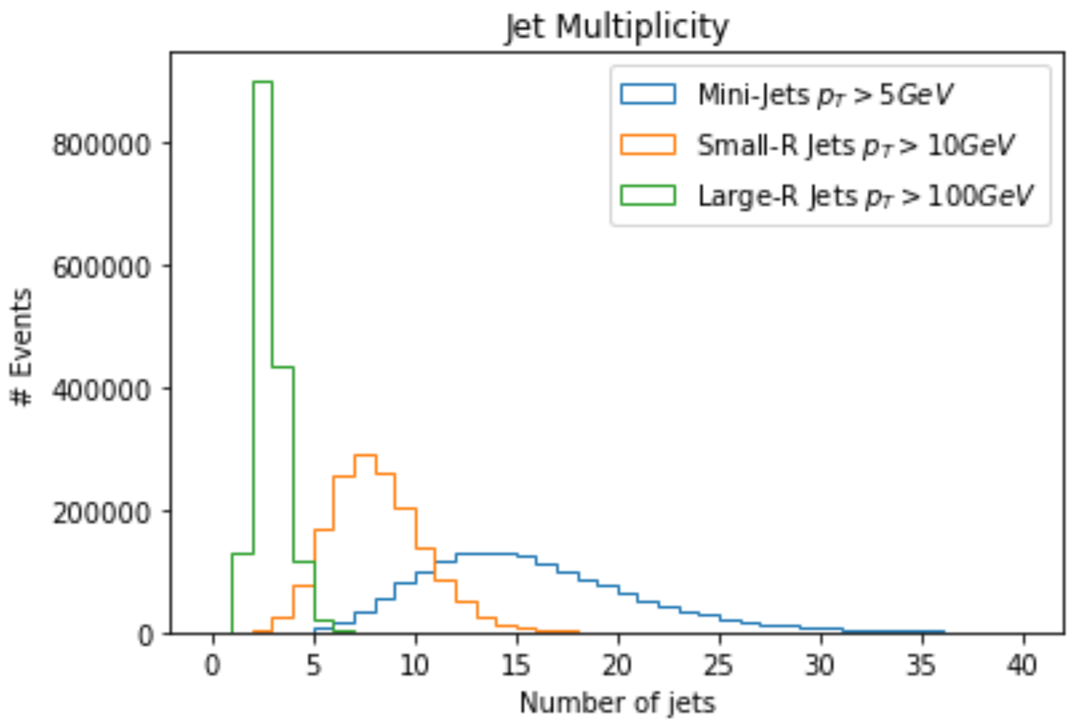


Sketch from arXiv:0811.4622

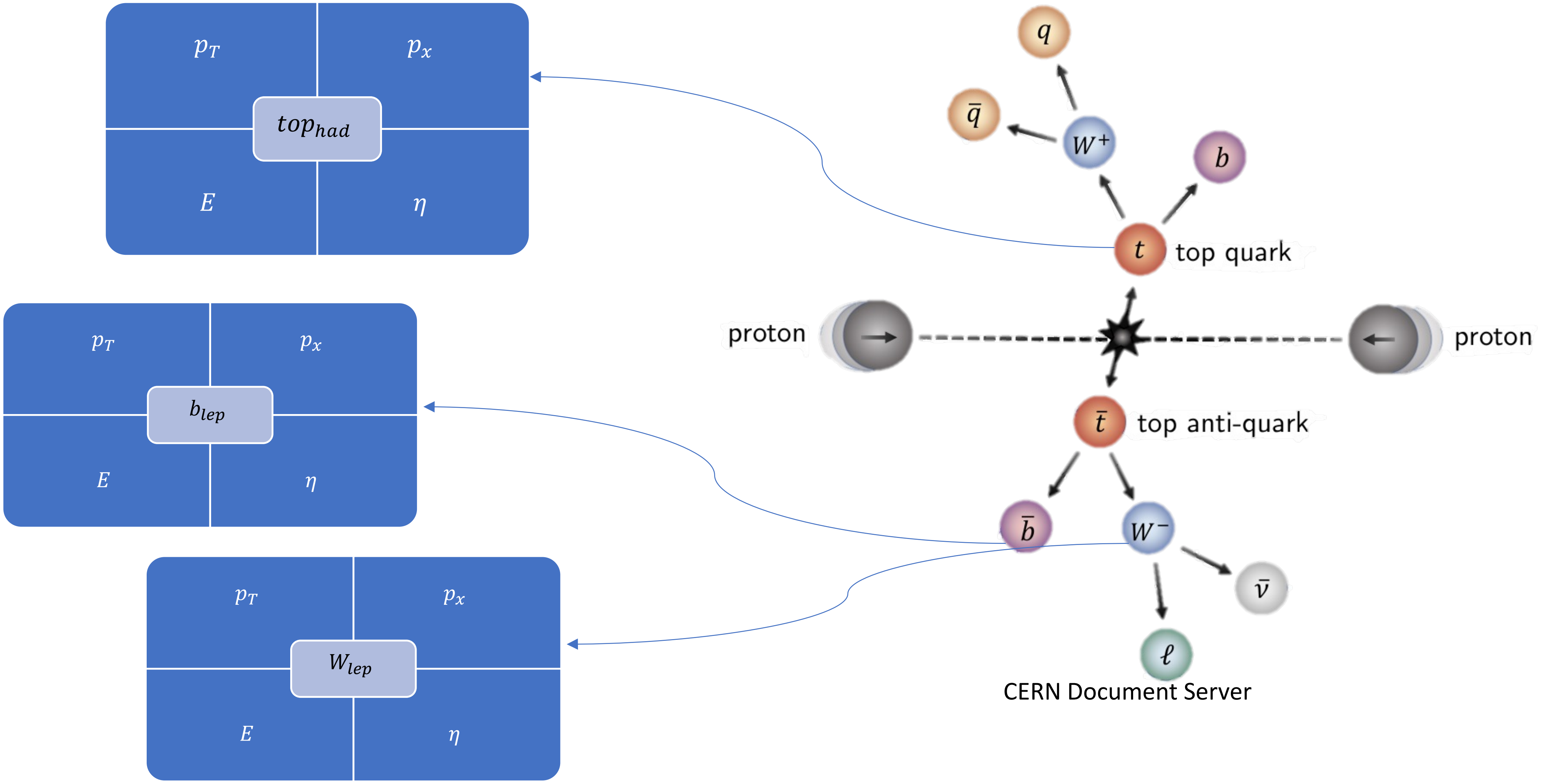
Mini-Jets

- Idea of jet algorithms in common LHC analyses:
  - Define a suitable jet algorithm and size (R=0.4, 0.8, etc.)
  - Assumption: All information of the hard process is contained in the selected jets
- Idea of mini-jets:
  - Use many very small jets and collect all information
  - Sensible jet multiplicity of <n> ~ 15
  - But: Difficult to handle combinatorics to reconstruct underlying hard physics

  → Solution: Let a neural network handle the excessive information

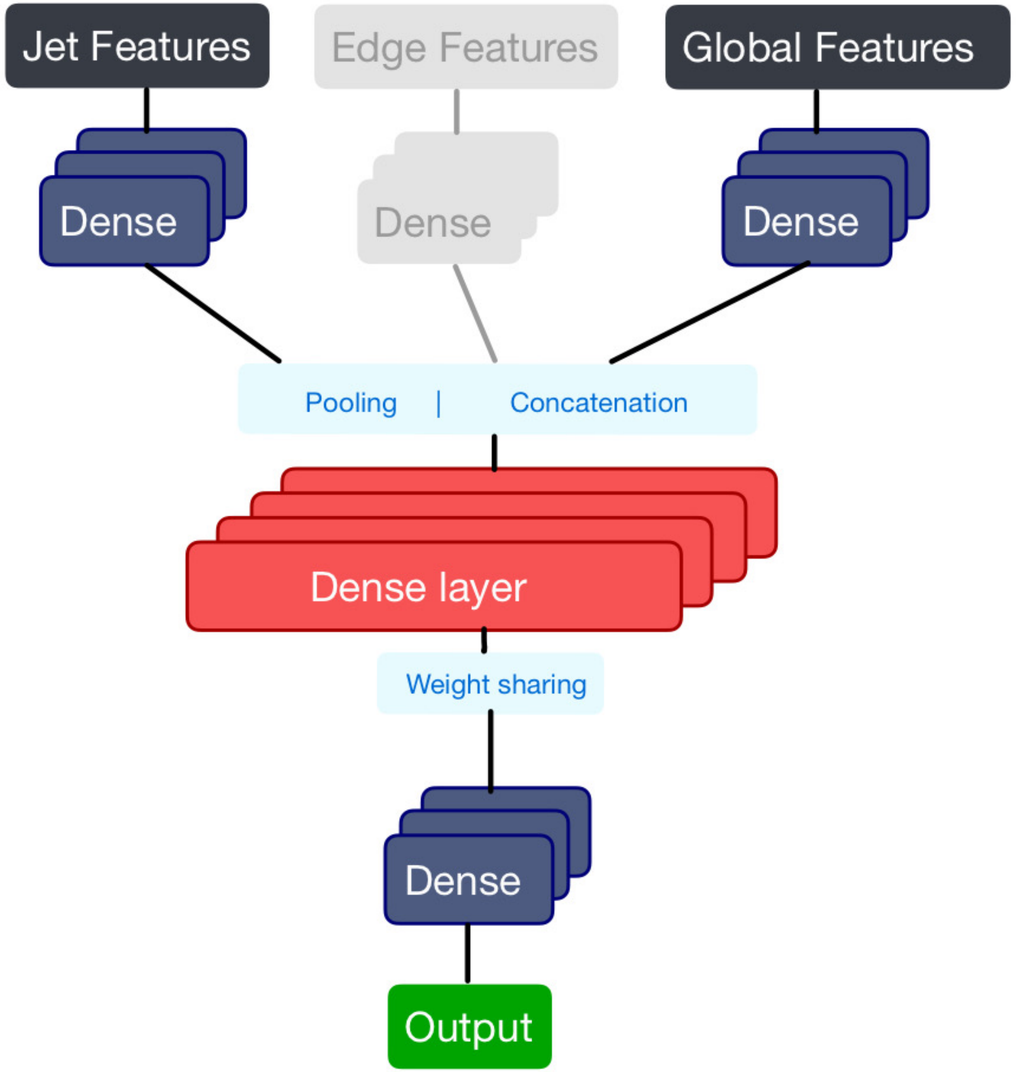


Reconstruction of Particle Properties



Using p_x instead of ϕ to avoid problems with rotational symmetry

Network Architecture



Jet Features:

- 25 mini-jets à 8 features $(p_T, \eta, \phi, p_x, p_y, p_z, E, m)$
- Number of jets vary through different events – zero padding used to make uniform input set

Global Features (Lepton & Neutrino)

- 3 lepton features (p_T, η, ϕ)
- 3 neutrino features (p_T, p_x, p_y)

Global Pooling for jets & concatenation of jets and global features

Core layer:

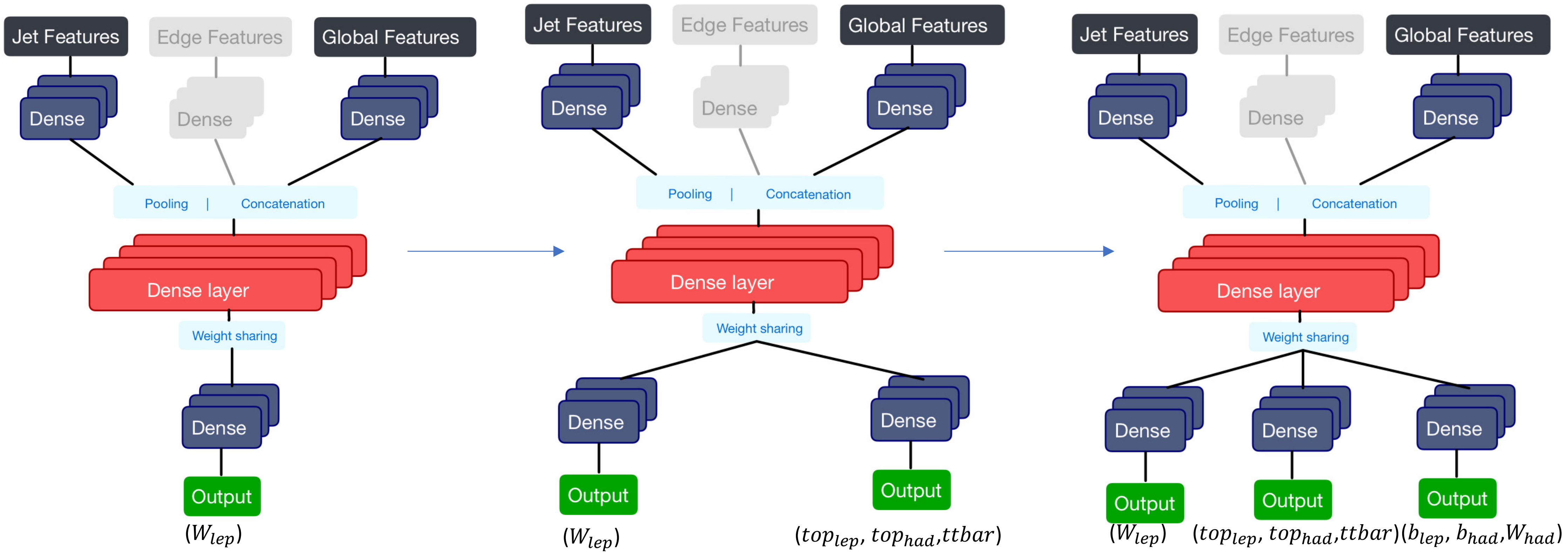
- Multiple dense layers with all relevant information of the event

Output (Regression Branch):

- Extracting information for a specific resonance via dense layer

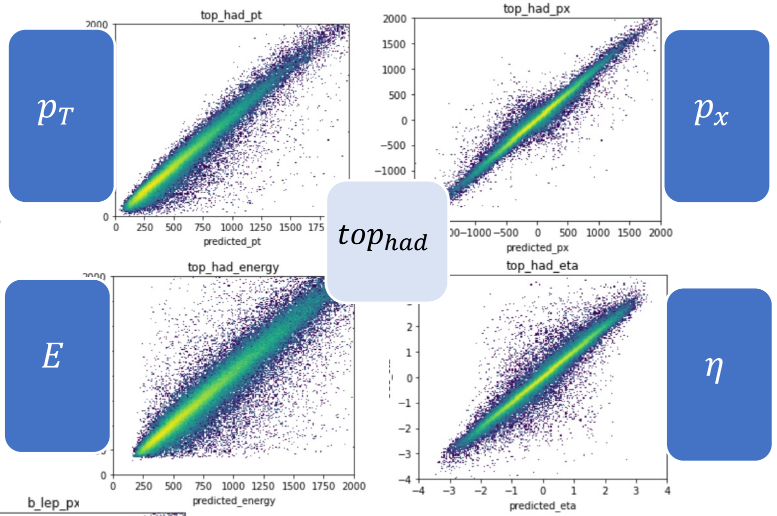
Training the Model

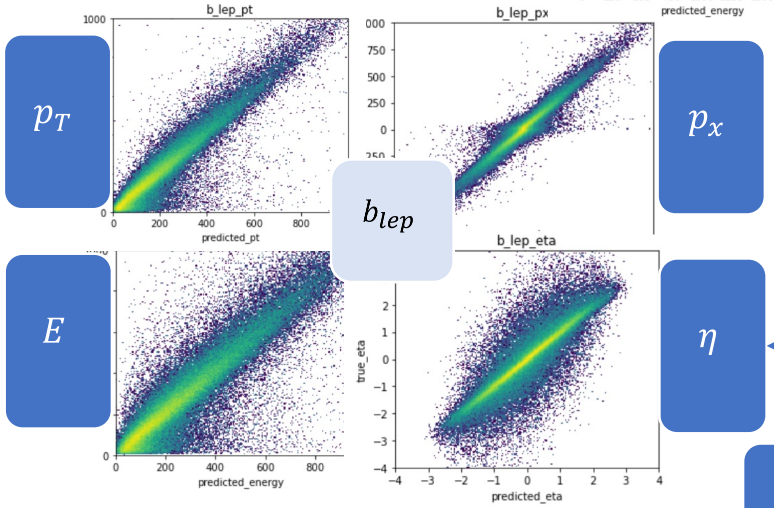
- Start with training one output particle
  - Easiest particle for the model in this case: W-boson decaying leptonically
- Get to more difficult particles step by step
  - Use weights from leptonic W-boson to train top quarks and the invariant mass of top quark pair
  - Use weights from these two models to train bottom quarks and hadronic W-boson



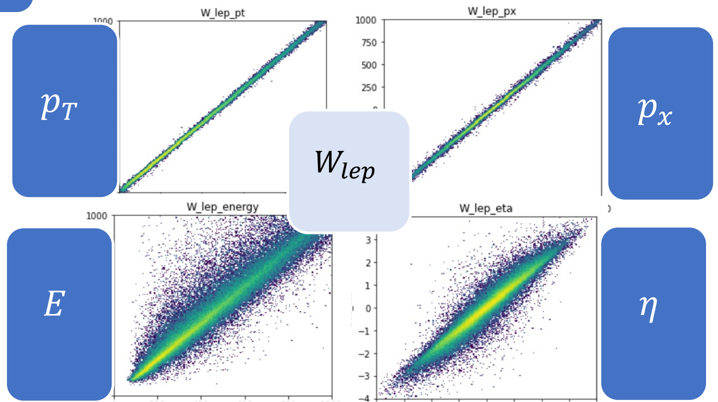
Reconstruction of Particle Properties

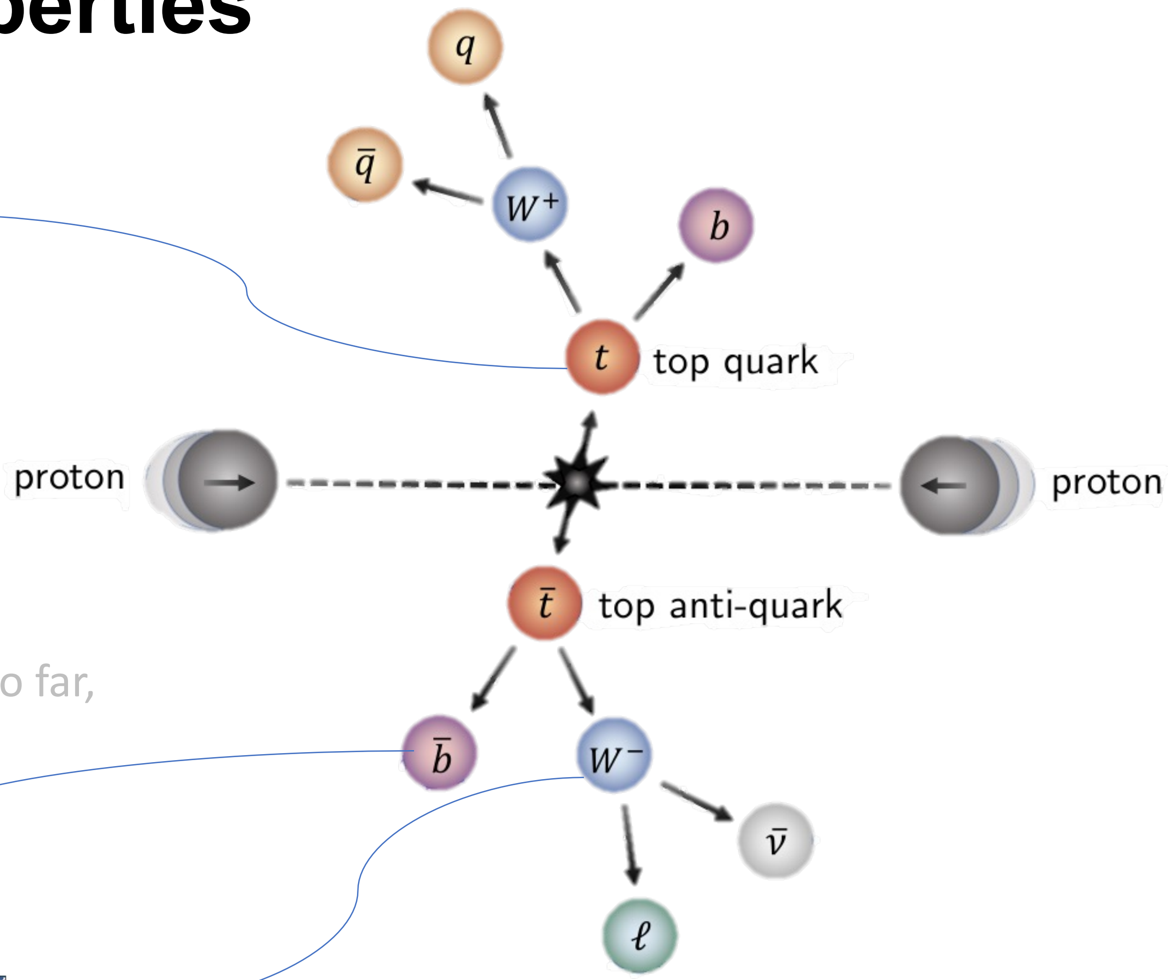
Fully hadronic decay of top quark from low to high p_T





No b-tag used by our DNN so far, reconstruction only from kinematic constraints



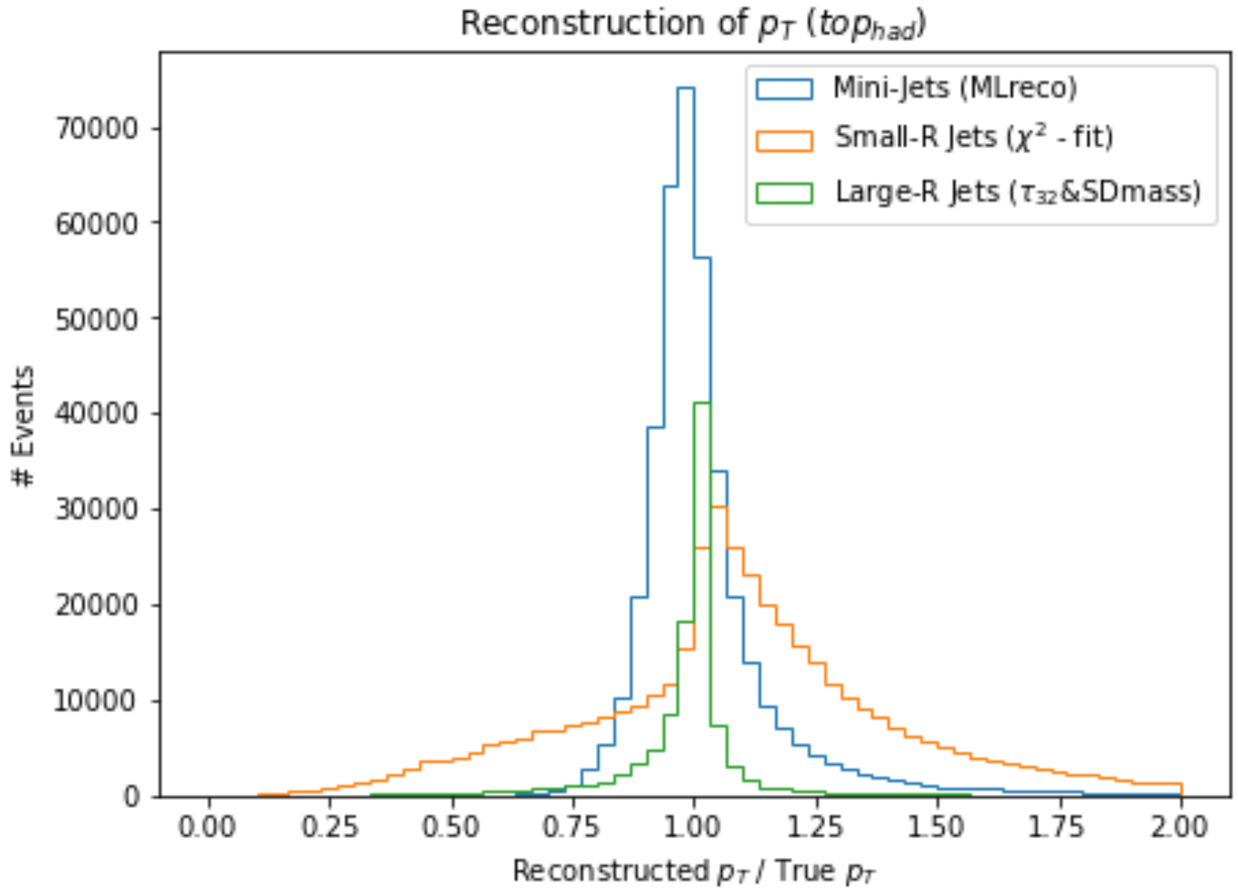


Neutrino p_z unknown → difficult to reconstruct η

Performance of the p_T- Reconstruction

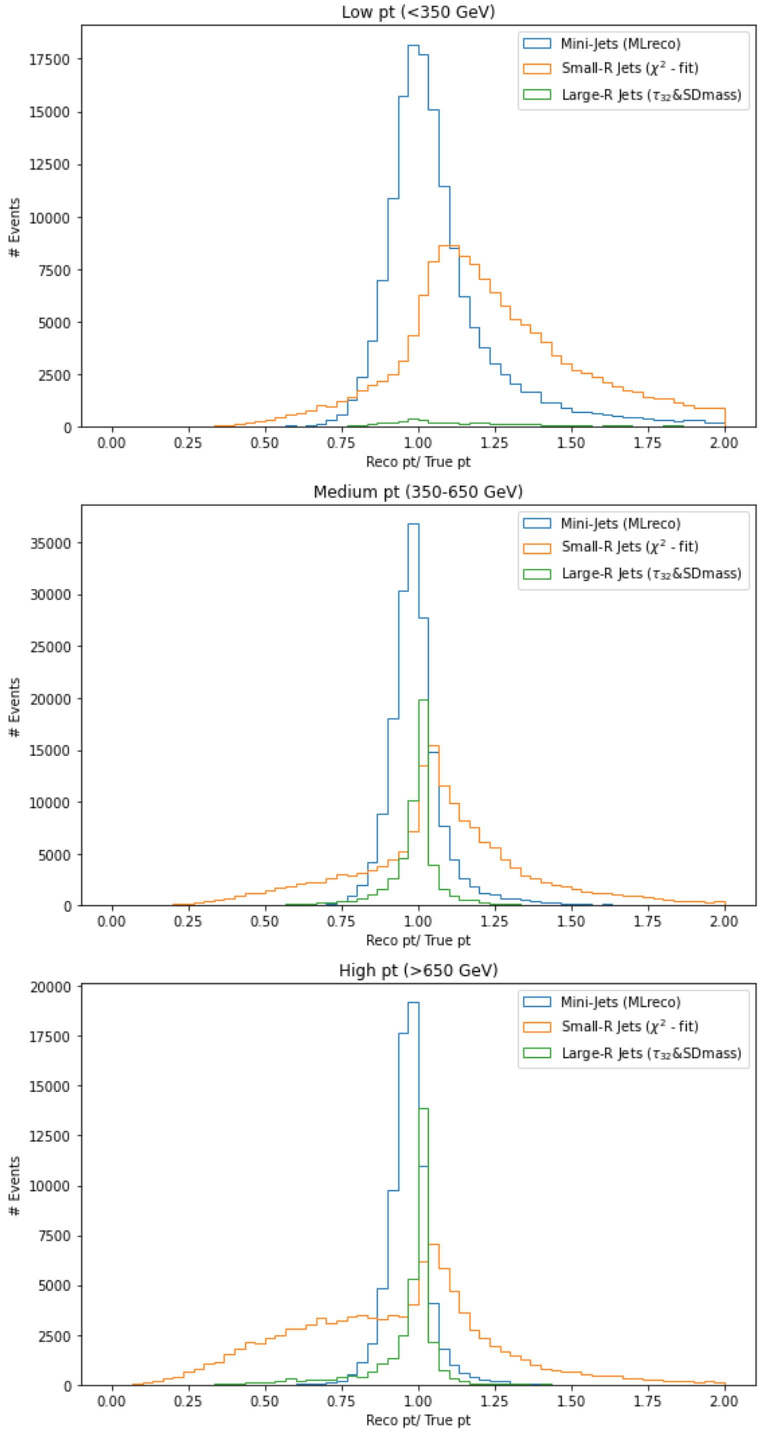
- Ratio of reconstructed and true transverse momentum of hadronically decaying top quark
- Classical Reconstruction for small-R jets:
  - Select 4 leading jets and combine 3 of them. Combination with closest mass to top quark is selected
- Classical Reconstruction for large-R jets:
  - Select events with $\tau_{32} < 0.54$
  - Softdropmass: 110 GeV < SDM < 210 GeV
  - Efficiency ~30%
- Small-R and Large-R reconstruction algorithms suffer from efficiency losses due to additional cuts

- Machine Learning Model outperforms classical reconstruction with small-R and large-R jets



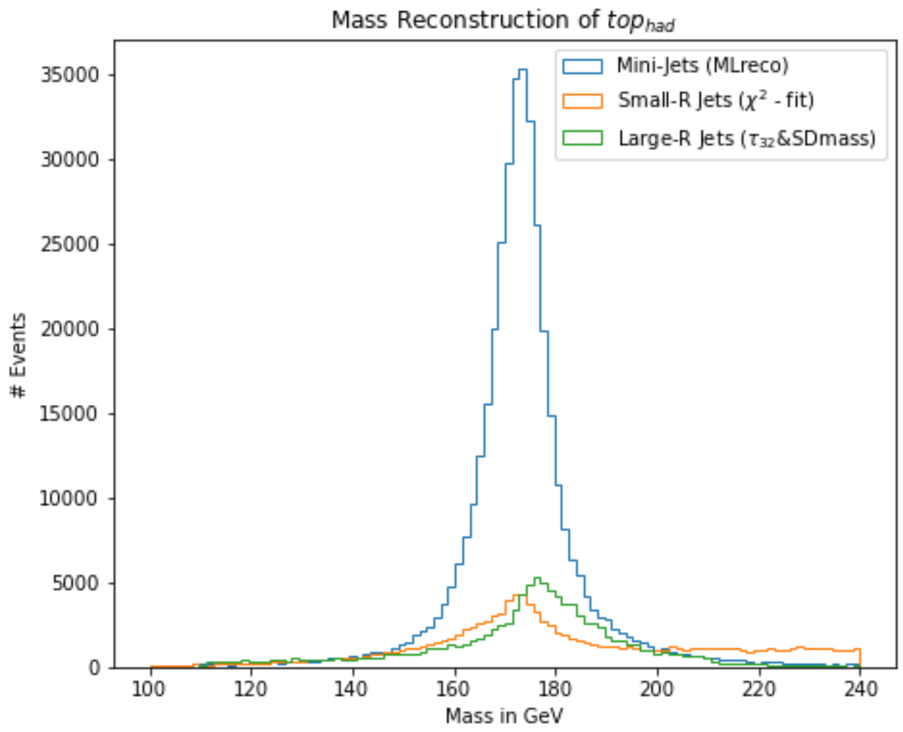
p_T-Reconstruction for different p_T-ranges of the top quark

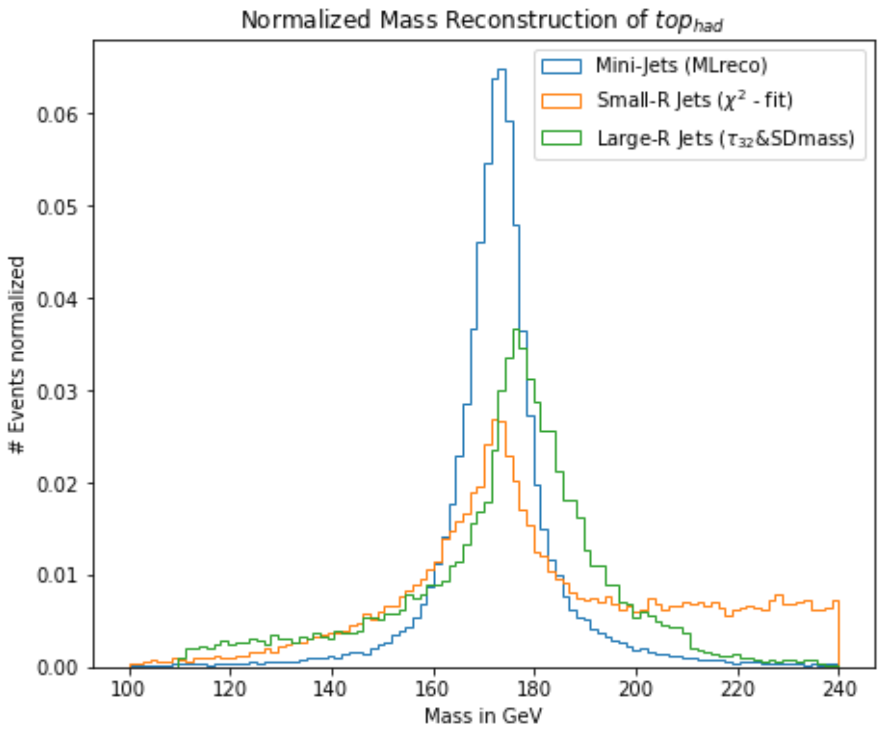
- Low p_T (<350 GeV):
  - Machine Learning model performs best
  - Classical reconstruction methods have problems in low p_T-Regions due to non-boosted decay topology
- Medium p_T(350 GeV – 650 GeV):
  - Better description of physics of classical methods due to more boosted topology
- High p_T (>650 GeV):
  - Large-R reconstruction very good due to highly boosted topology
  - Large-R jets with efficiency of (only) ~40%



Mass-Reconstruction

- A precise measurement of the top quark mass is an important physics goal. However, direct regression of m_{top} not possible in order to avoid a bias towards the MC mass
- Instead, reconstruct m_{top} via energy and total momentum: $M^2 = E^2 - p^2$
- ML reconstruction with mini-jets results in significantly higher efficiency, and furthermore achieves higher resolution than small-R or large-R jets





Summary

- We have studied a new reconstruction methodology for collider events using mini-jets and a deep neural network
- Mini-Jets
  - anti-kt jets with radius of R=0.1
  - Goal: preserve physics of hard interaction, as well as hard emissions in the parton shower
  - Little sensitivity to soft or collinear emissions or hadronization effects
  - reasonable multiplicity of <n>=15 in semi-leptonic ttbar events at $\sqrt{s}$=13TeV
- Mini-jets are input to a ML-based reconstruction of target observables

  → W/Z-boson, top-quark, Higgs-boson quantities
- ML-based reconstruction outperforms classical reconstruction algorithms over a large kinematic range
  - top-quark, W-boson and b-quark properties were studied
  - Algorithm can handle different event topologies at different scales in a single algorithm: e.g. resolved and boosted top-quarks

Backup

Outlook:

- Inclusion of b-tagging information will further improve the performance
- ML based pile-up mitigation will be an inherent part of the algorithm
- Paper in prep. and to be submitted to arXiv soon