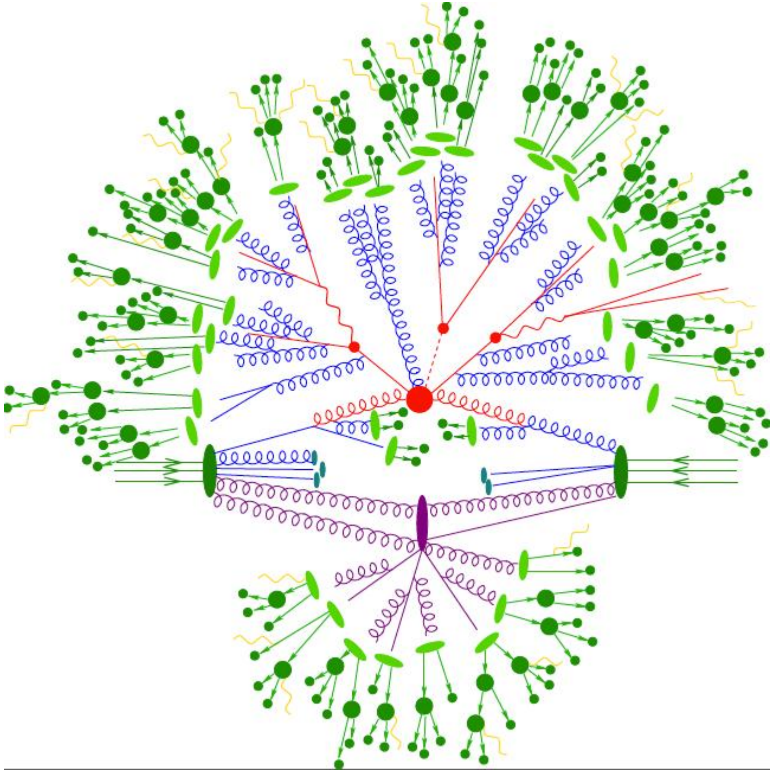
BOOST Camp 2018

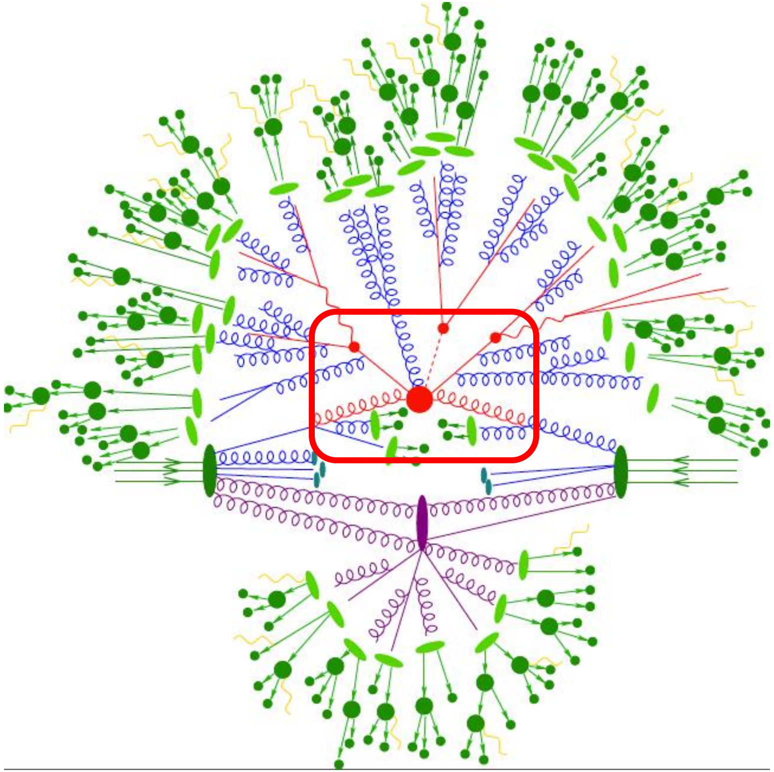
Lais Schunk and Steven Schramm

What is a jet?

Schematics on underlying event, partons, etc

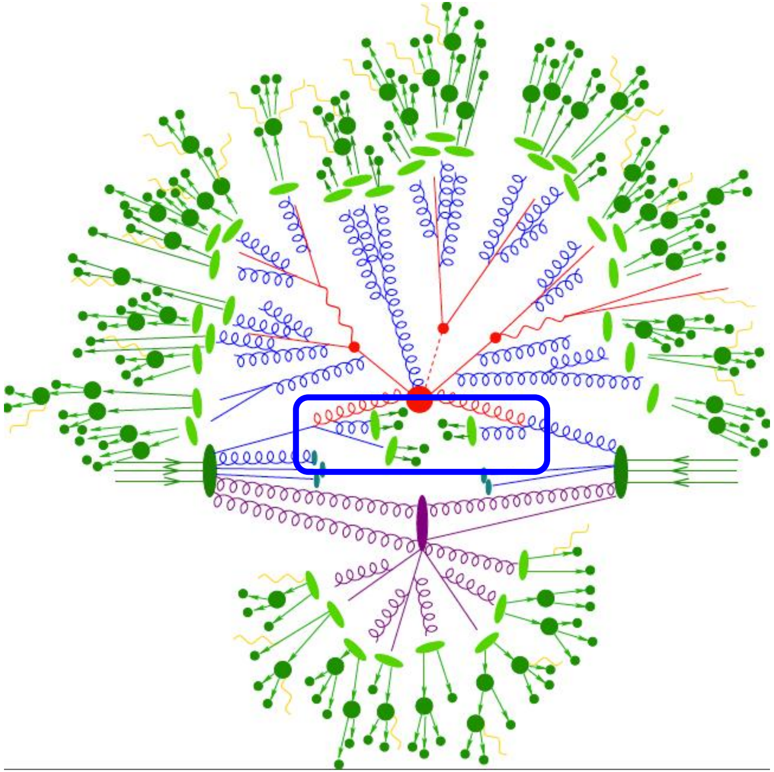


Schematics on underlying event, partons, etc



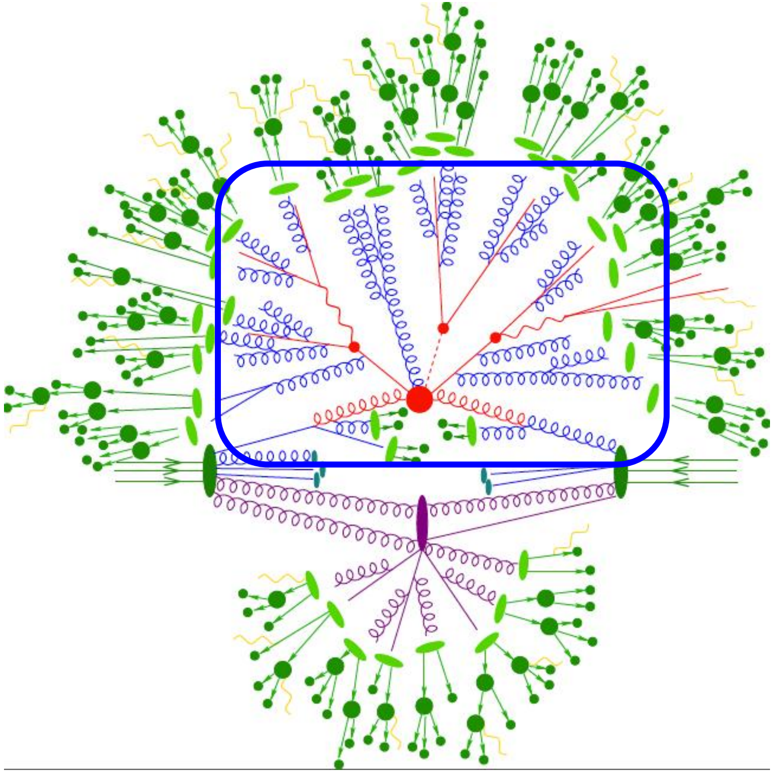
- Hard scattering : g g →W q q

Schematics on underlying event, partons, etc



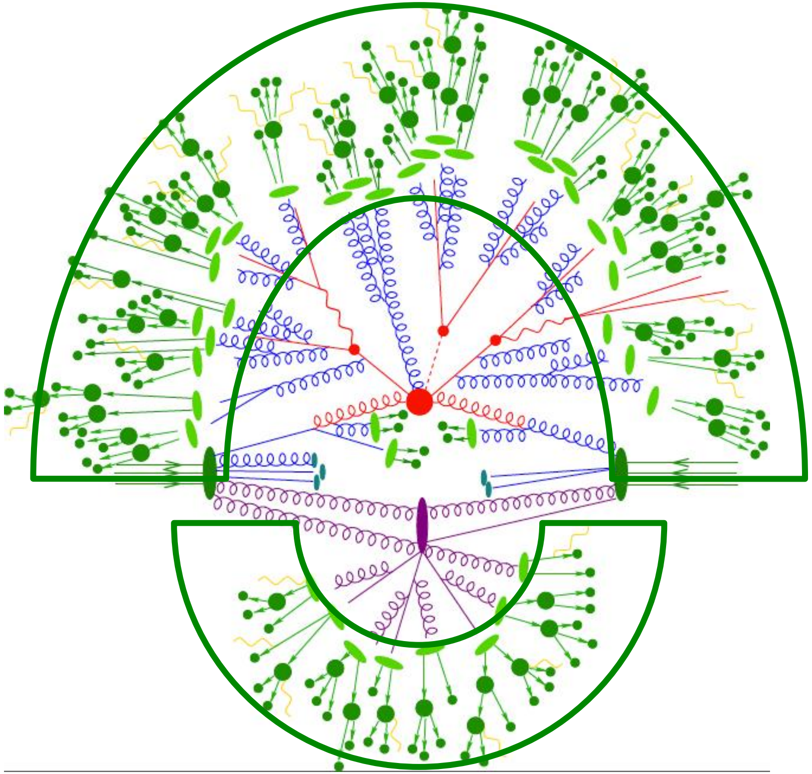
- Hard scattering
- Initial state radiation : emitted by incoming partons before hard scattering

Schematics on underlying event, partons, etc



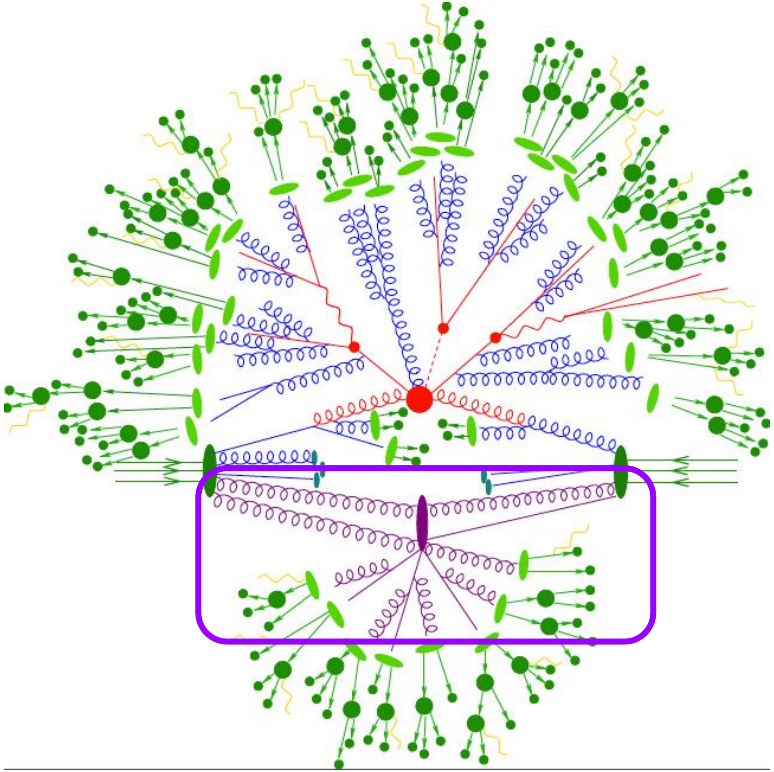
- Hard scattering
- Initial state radiation
- Parton shower : cascades of radiation from QCD decays

Schematics on underlying event, partons, etc



- Hard scattering
- Initial state radiation
- Parton shower
- Hadronization : partons form hadrons

Schematics on underlying event, partons, etc

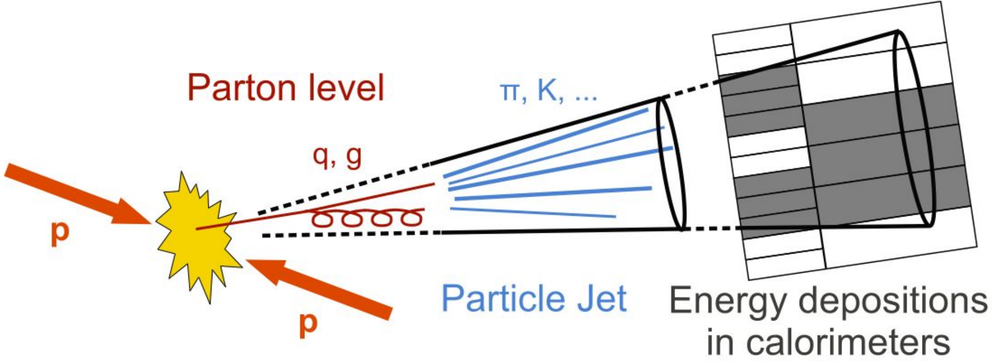


- Hard scattering
- Initial state radiation
- Parton shower
- Hadronization
- Multi-parton interactions (MPI) : additional interactions from the other partons forming the proton

Jets

- A useful tool to interpret such complex hadronic activity
  - Group regions of the detector into a single unified object and four-vector
  - Attempt to group inputs from common sources together
  - Attempt to keep inputs from different sources as separate jets
- The same collision can be interpreted using jets in many different ways
- Example: different “sizes” of jets can be used for different purposes
  - “Small” jets are typically used for quarks and gluons
  - “Large” jets are typically used for hadronic decays of massive particles: W, Z, H, top, etc

What goes into the jet?



- Parton level : before hadronization
    - Generally limited to fixed-order calculations
- Particle level : after hadronization
    - Good proxy for the “truth” definition of a jet (particles generate detector signal)
- Calorimeter / track / particle flow objects
    - Detector-specific views of an event

} Theory / Pheno

} Theory / Pheno / Experiment

} Experiment

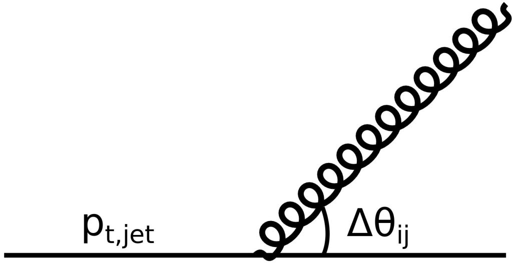
Jet definition

- Jet algorithms are sets of rules on how to cluster particles into a jet.
- Must follow some “rules” : (Snowmass accord)
    - Simple to implement in an experimental analysis;
    - Simple to implement in a theoretical calculation;
    - Defined at any order of perturbation theory;
    - Yields finite cross sections at any order of perturbation theory;
    - Yields a cross section that is relatively insensitive to hadronization.
- Most used today : sequential recombination algorithm
    - Successively combining pair of particles according to a distance measure
    - Advantage of assigning a clustering order

Jet definitions: the kT family of algorithms

- Recursively cluster partons with smallest distance between them

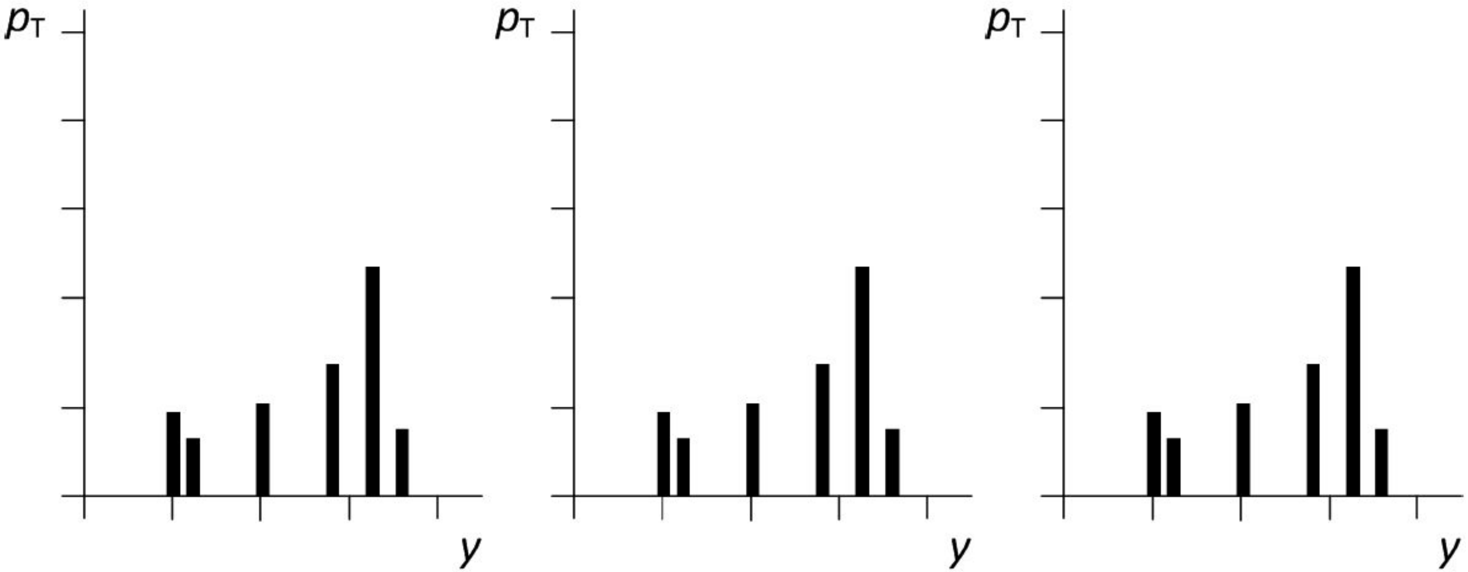
$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta\theta_{ij}^2}{R^2}$$



$$\Delta\theta_{ij}^2 = \Delta y_{ij}^2 + \Delta\phi_{ij}^2$$

- Stops (roughly) when $d_{ij} \gtrsim (p_{t,i})^{2p}$

Jet definitions: the kT family of algorithms

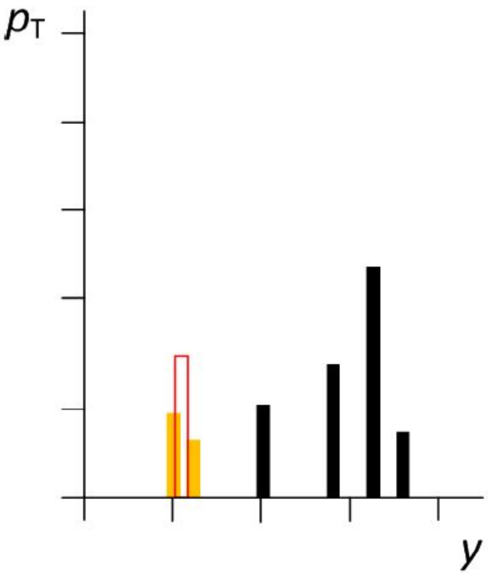


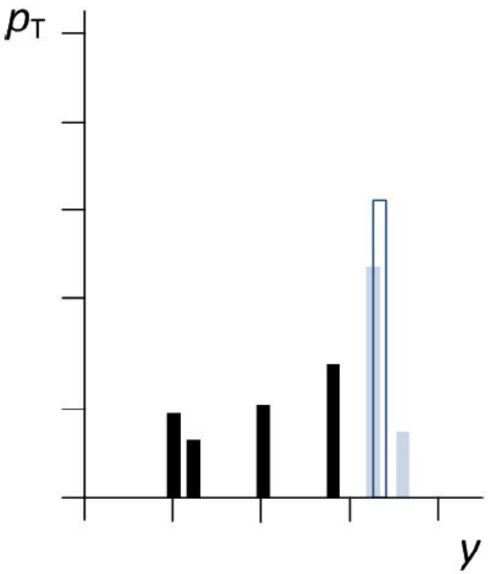
Classic k_T, p = 1

Anti-k_T, p = -1

Cambridge/Aachen, p = 0

Jet definitions: the kT family of algorithms


Classic k_T, $p = 1$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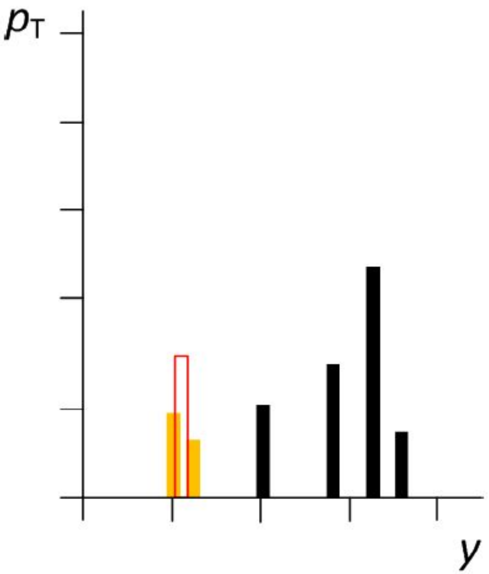
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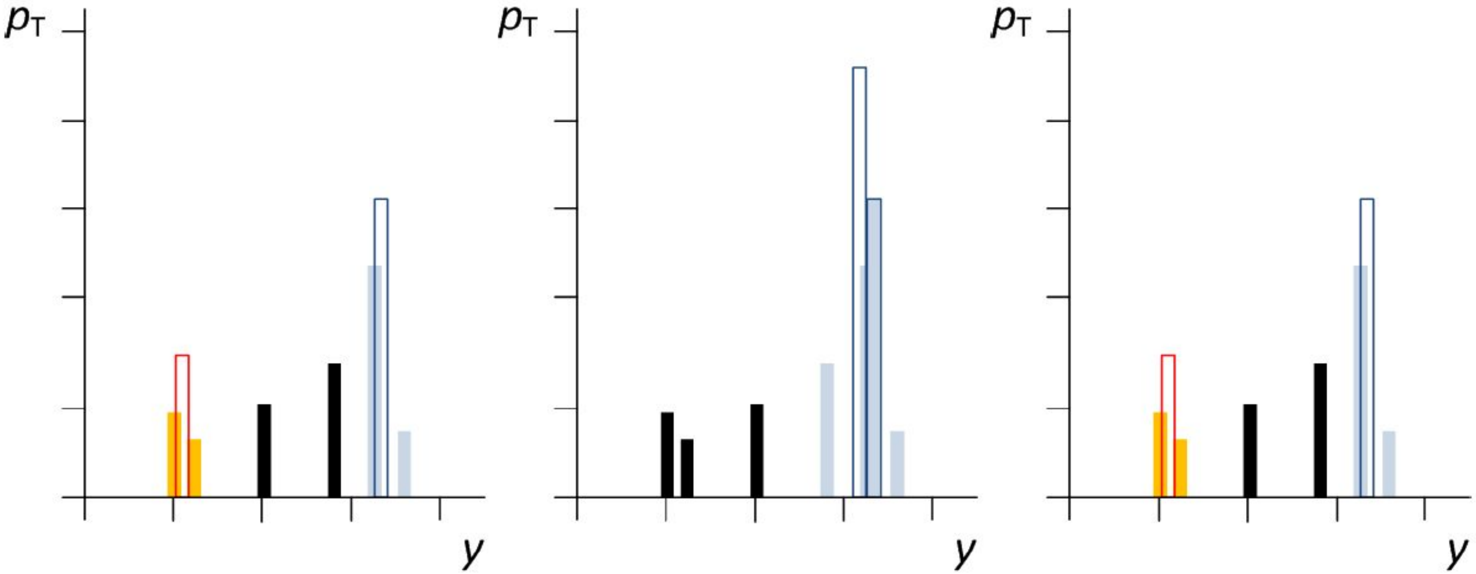
Jet definitions: the kT family of algorithms



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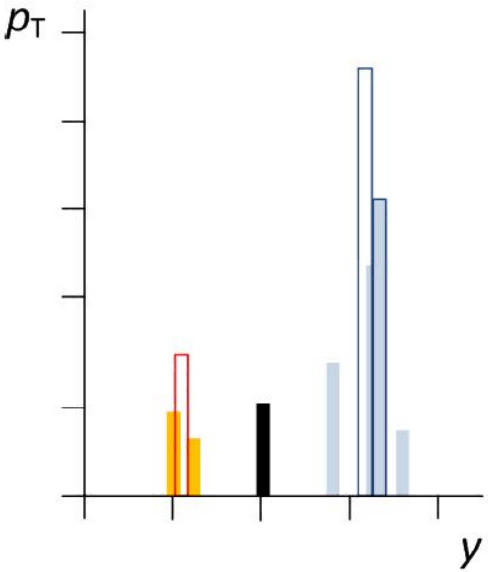
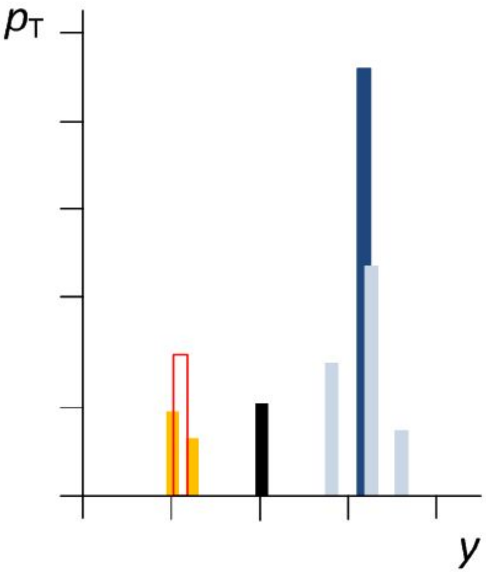
Jet definitions: the kT family of algorithms

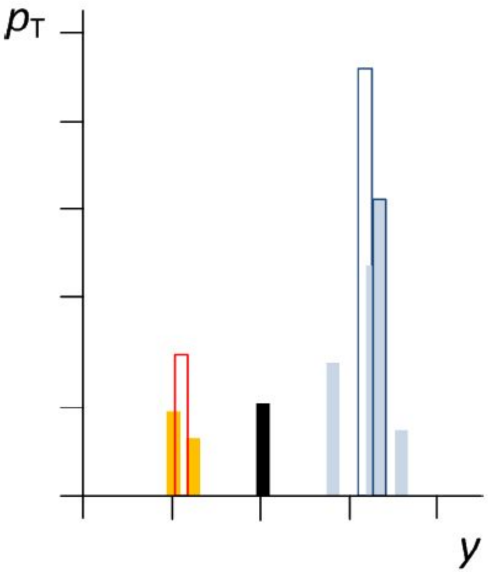
Classic k_T, p = 1



Anti-k_T, p = -1

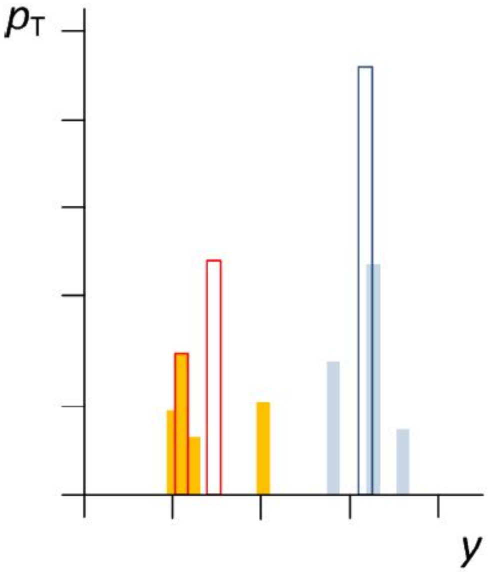


Cambridge/Aachen, p = 0

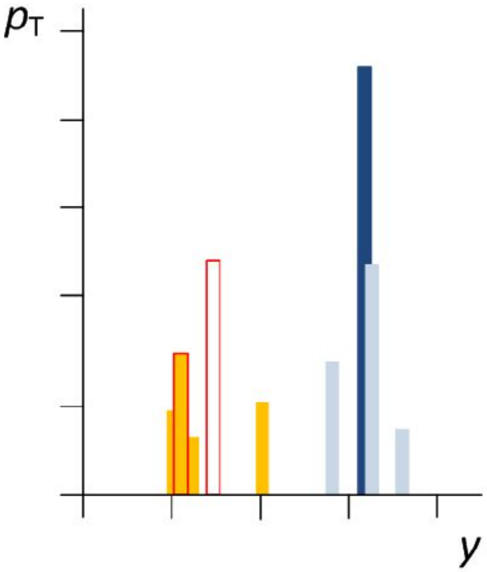


Jet definitions: the kT family of algorithms

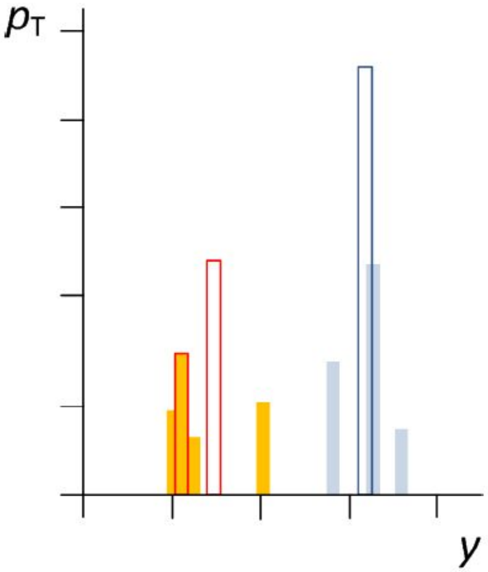
Classic k_T, p = 1



Anti-k_T, p = -1



Cambridge/Aachen, p = 0



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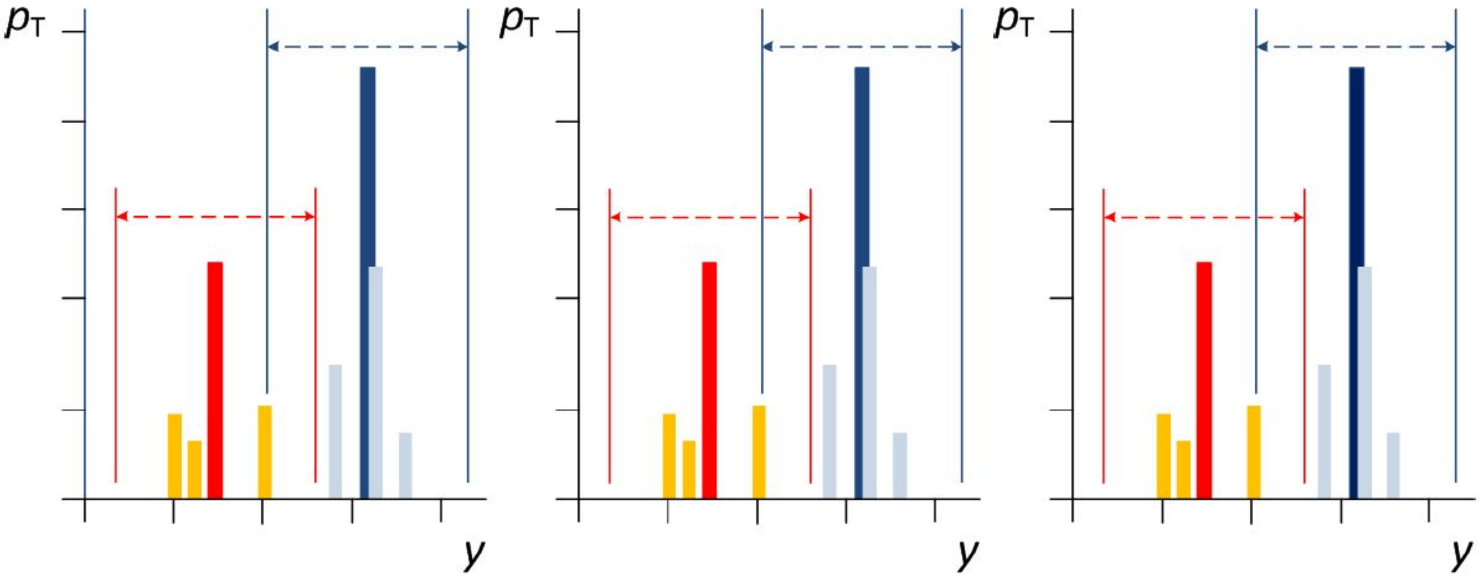

Classic k_T, p = 1

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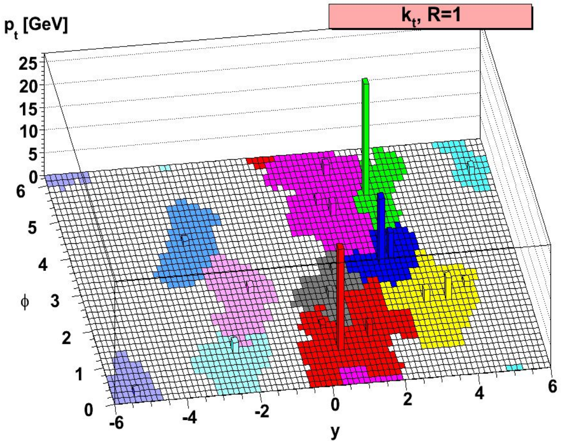
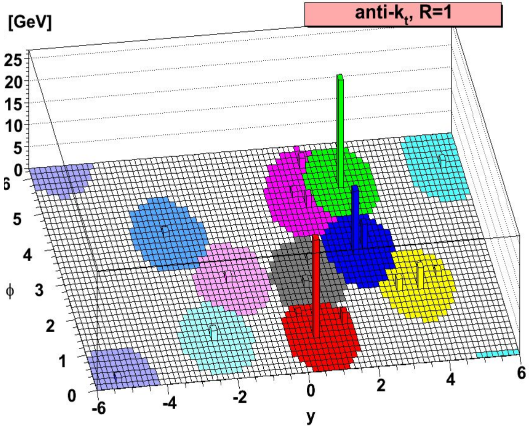
Jet definitions: the kT family of algorithms

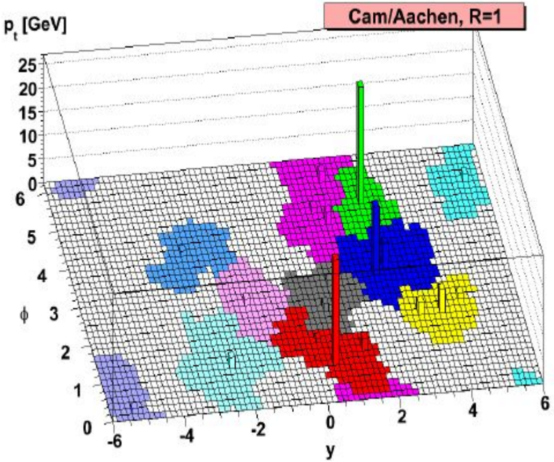
k_t-algorithm p=1



anti-k_t p=-1



Cambridge/ Aachen p=0



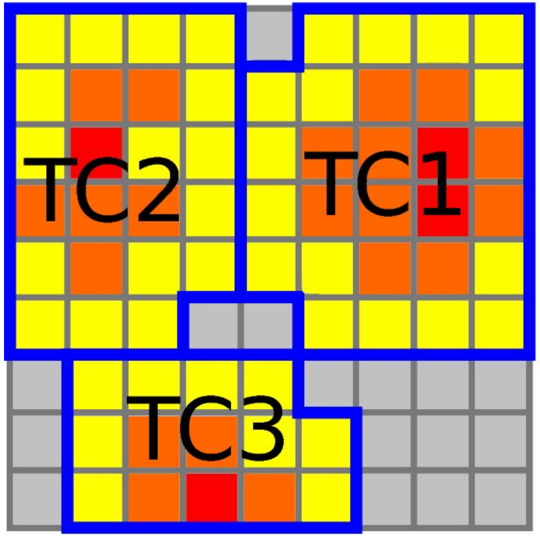
Jet radius

- The radius parameter in the equation roughly controls the size of the jet
  - Complementary information to the algorithm
- Typical choice for small-R jets: R=0.4 (ATLAS and CMS)
  - Used for “standard” QCD jets by most experimental analyses
  - Idea is roughly to contain a light quark or gluon in such a jet
- Typical choice for large-R jets: R=0.8 (CMS) or R=1.0 (ATLAS)
  - Used for “boosted” jets by most experimental analyses
  - Idea is roughly to contain a hadronically decaying particle (W, Z, H, top, etc)
  - We’ll come back to this in much more detail soon
  - BOOSTed jets are the main focus of this conference

Experimental inputs to jet reconstruction

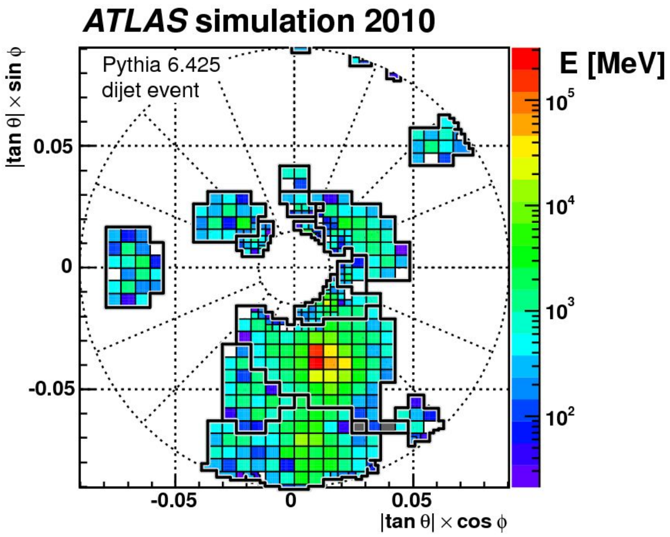
- Calorimeter objects
  - Calorimeters measure the energy of hadronic particles, both charged and neutral
  - **Typical input to ATLAS jet reconstruction**
- Tracks
  - Tracking detectors measure the momentum of charged particles (not neutral)
  - Tracks can typically be traced back to their independent vertex
  - **Typically used to augment jets, not for the jet four-vector**
- Particle flow objects
  - Combinations of calorimeter and tracking information to benefit from both detectors
  - Ideally the best aspects of both tracks and calorimeter objects
  - **Typical input to CMS jet reconstruction, increasingly used in ATLAS**

ATLAS: topological calorimeter-cell clusters



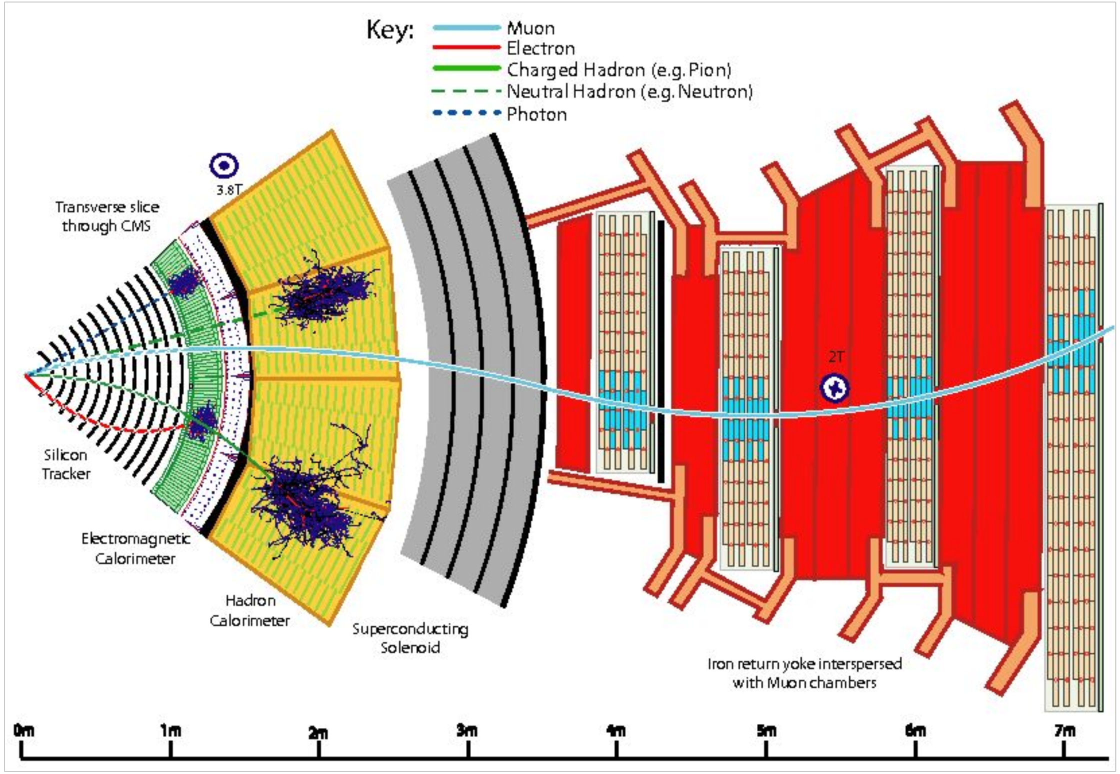
Topoclustering

- 🟥 seed cells $|E| > 4\sigma$
- 🟧 growth cells $|E| > 2\sigma$
- 🟨 boundary cells
- ☐ final topoclusters $\eta \times \phi = \text{dynamic}$



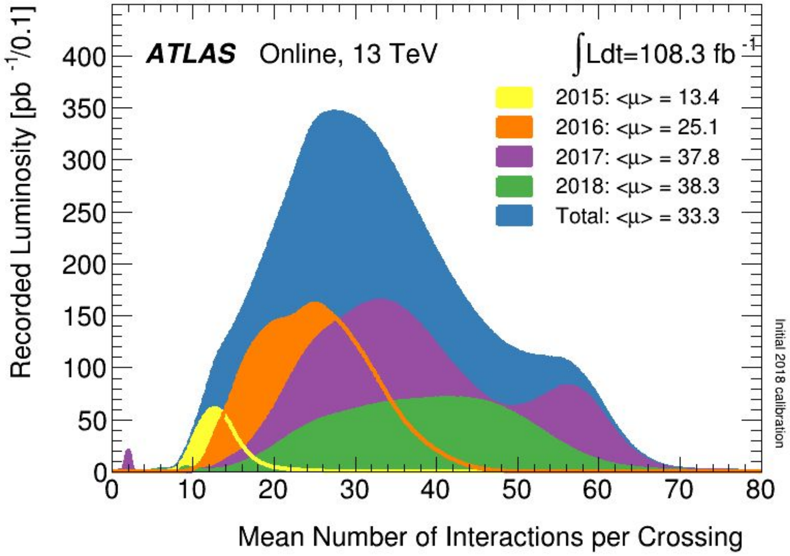
CMS: Particle flow

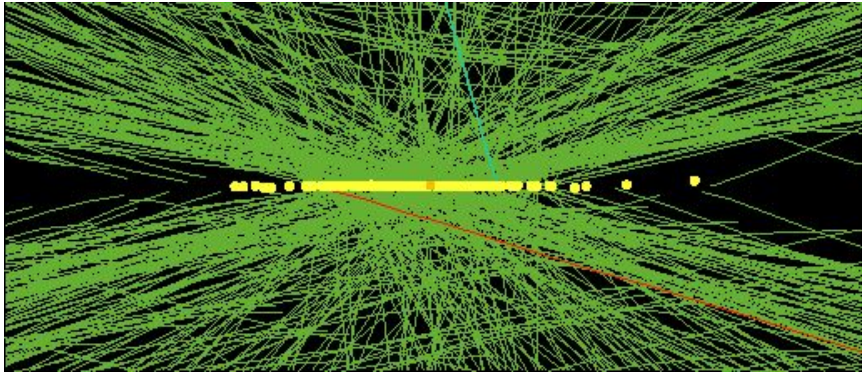
- Match inputs from different detectors and build a coherent single object



Pileup

- At the LHC, we do not (usually) see a single proton-proton collision
    - In Run 2, there are an average of roughly 30 collisions per bunch crossing
    - This produces a lot of “spurious” energy in the detector
    - This is referred to as pileup: a major experimental consideration/challenge





In-time vs out-of-time pileup

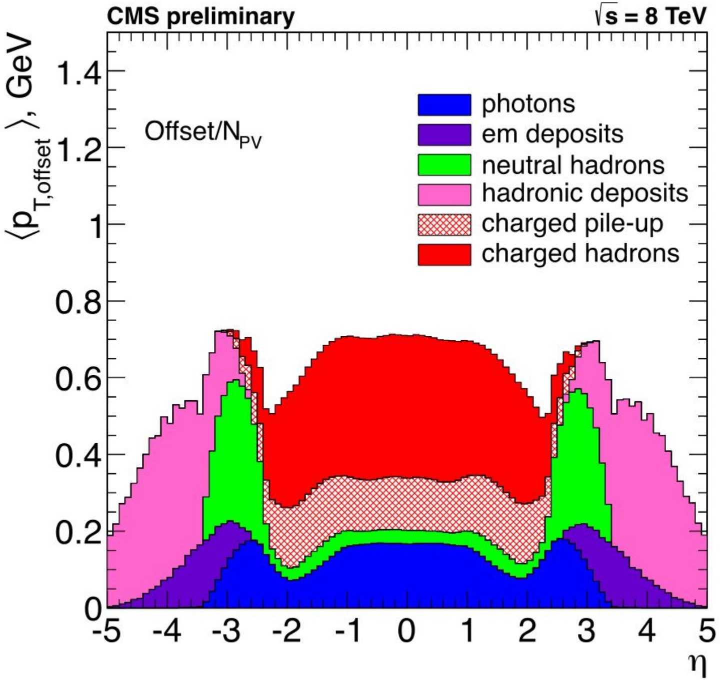
- The last slide was primarily “in-time pileup”
    - The impact of many proton-proton interactions in the same bunch crossing
- Depending on the detector, you may need to consider “out-of-time” pileup
    - The LHC bunch spacing is currently 25 ns
    - What happens if your detector takes longer than 25 ns to read out?
        - Your interpretation of a given event may depend on the previous/next collision
        - Shaping functions are used to minimize such effects, but they are not perfect
    - Different detectors are more or less susceptible to such effects

Impacts of pileup

- This additional spurious energy impacts jets in many ways
- Additional jets in the event, referred to as pileup jets
  - Ideally, we should veto such jets and focus on the hard scatter event
- Additional energy in hard scatter jets
  - Bias the energy of the jet (extra energy, not only the hard scatter)
  - Increase the jet energy resolution (additional noise in the jet)
  - Distort jet substructure (extra energy with random angles within the jet)
- Many other impacts on other observables
  - Missing transverse momentum resolution, lepton isolation, etc

Mitigating pileup

- Tracks are excellent for pileup mitigation
  - Extrapolate to calorimeter with high precision
  - Uniquely identified vertex allows for removing energy from other collisions
  - Labelled “charged hadrons”
- However, there are limitations
  - Tracker does not cover full detector
  - Neutral in-time pileup in calorimeters do not have corresponding tracks
  - Charged or neutral out-of-time pileup in calorimeters has no corresponding tracks
  - Pileup may overlap with hard energy
- Additional means of pileup suppression are required to handle these cases



Pileup-suppressing jets

- There are different approaches to removing pileup beyond tracks
- Traditional: jet-areas based pileup suppression
    - Calculate the average pileup energy density event-by-event
    - Calculate the jet area jet-by-jet
    - Subtract (energy density)x(area) from each jet to correct the energy scale
- More advanced methods are becoming common
    - Defining new jet inputs: particle flow, etc
    - Pileup-suppressing jet inputs: constituent subtraction, SoftKiller, etc
    - Jet-level: jet-areas based correction as explained above
    - Jet modification: grooming is often used for pileup suppression, next slides

Jet grooming

Trimming

- Take jet with radius R
- Reclusters components into smaller subjets with radius $R_{sub} < R$
- Keep subjets that satisfy $p_{t,\,sub} > z_{cut}\, p_{t,\,jet}$

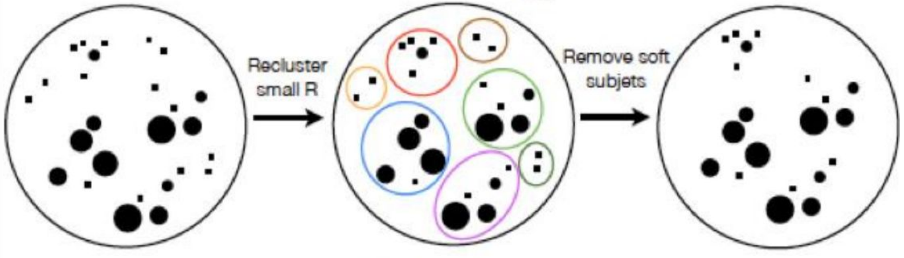
Pruning

- Define pruning radius $R_{prun} = R_{cut} * 2\, m / p_t$
- For every step of clustering $j_1 + j_2 \rightarrow j_{12}$, check:
  - Wide-angle: $\Delta R_{12} > R_{prun}$
  - Soft: $\min(p_{t1}, p_{t2}) < z_{cut}\, p_{t,\,jet}$
- If either condition fails, eliminates softer subjet
- If both pass, continue clustering

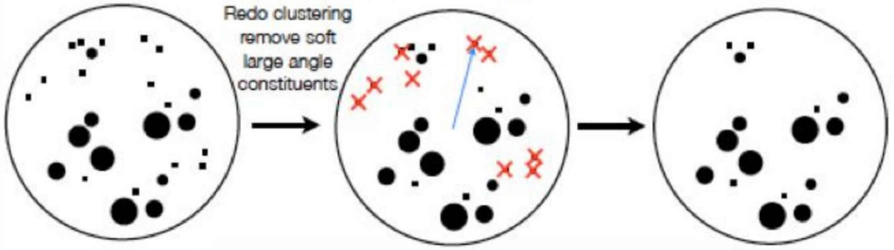
SoftDrop (or mMDT)

- Decluster jet $j_{12} \rightarrow j_1 + j_2$
- Check condition $\min(p_{t1}, p_{t2})/p_{t,jet} > z_{cut}(\Delta R_{12}/R)^{\beta}$
  - z_{cut}, β: tunable values
- If condition fails, the softer subjet is removed
- If passes, stops recursion
- For β=0, it is mMDT

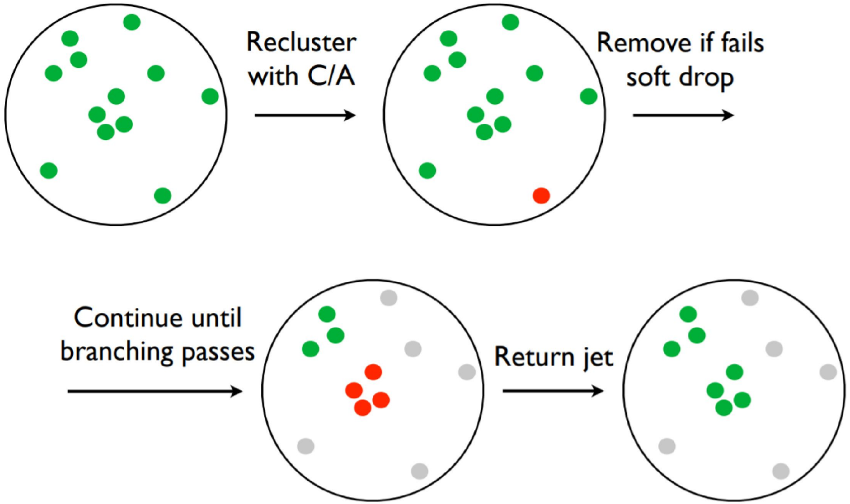
Trimming



Pruning



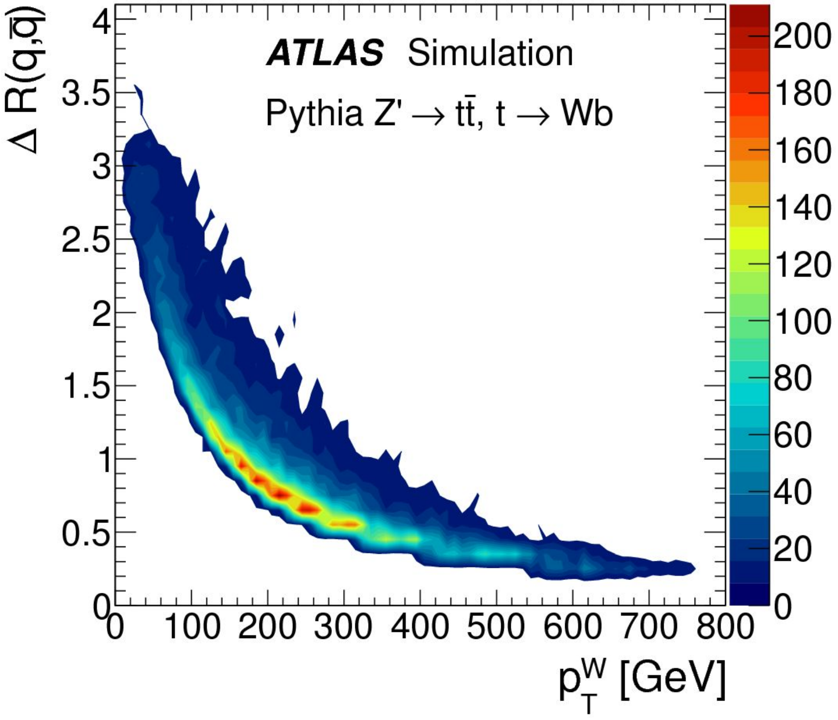
SoftDrop



What is jet substructure?

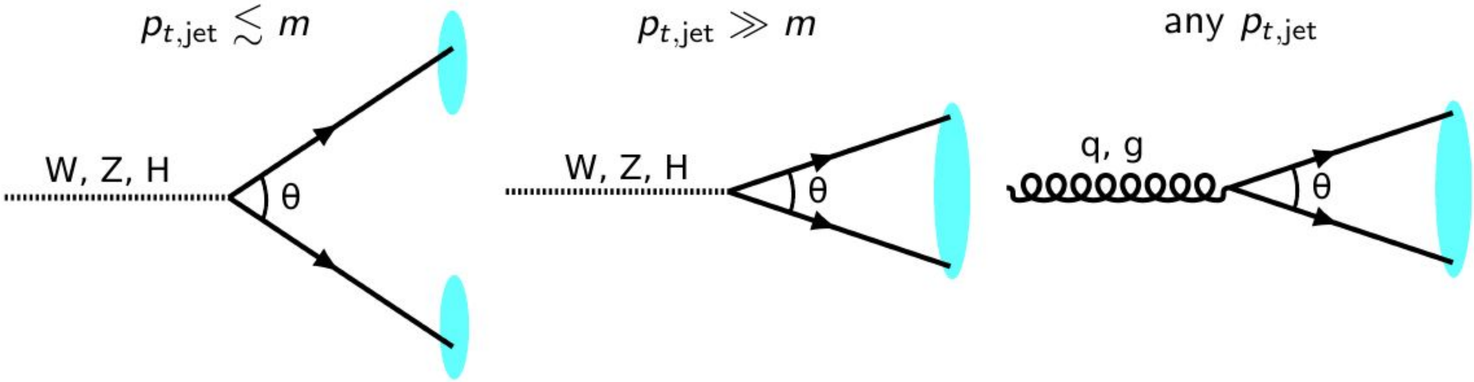
Hadronic decays and collimation

- Hadronic decays back-to-back at rest
  - Boost to experiment frame → collimation
- Two body decay, a → b c
  - $\triangle R_{bc} \approx m_a / \mathbf{x_b}(1-\mathbf{x_b})$
  - $\mathbf{x_b}$ is the fraction of a's momentum attributed to decay product b
    - On average, equal split between b and c, so $\mathbf{x_b} \approx 0.5\, p_{T,a}$
  - Result: $\triangle R_{bc} \approx 2\, m_a / p_{T,a}$
  - Dependence visible in W → qq' decays
- This is for two body decays
  - More complex for many-body decays
  - However, same trend: high $p_{T,a}$ → collimated



Motivation for jet substructure

- QCD jets (background) are collimated at any pt range

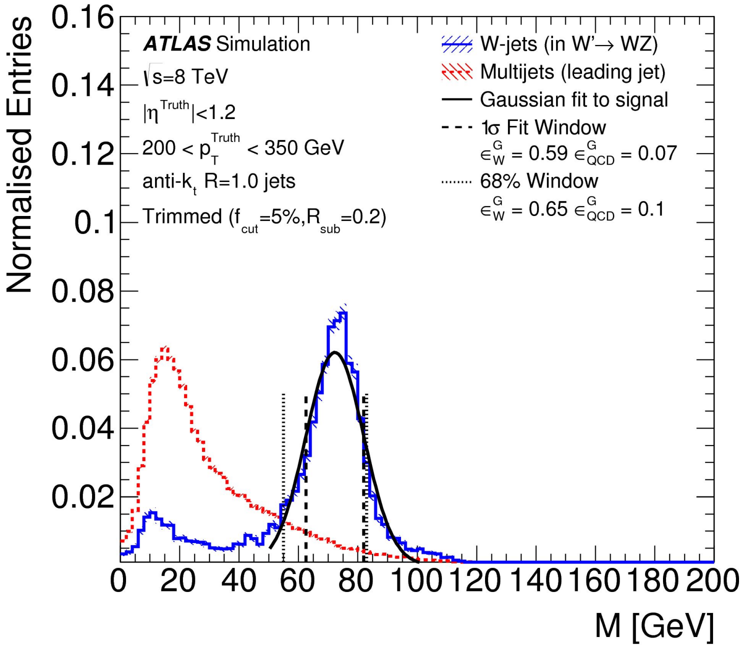


How to discriminate QCD jets and W/Z/H hadronic decay jets?

Use **jet substructure** methods → internal dynamics of the jet

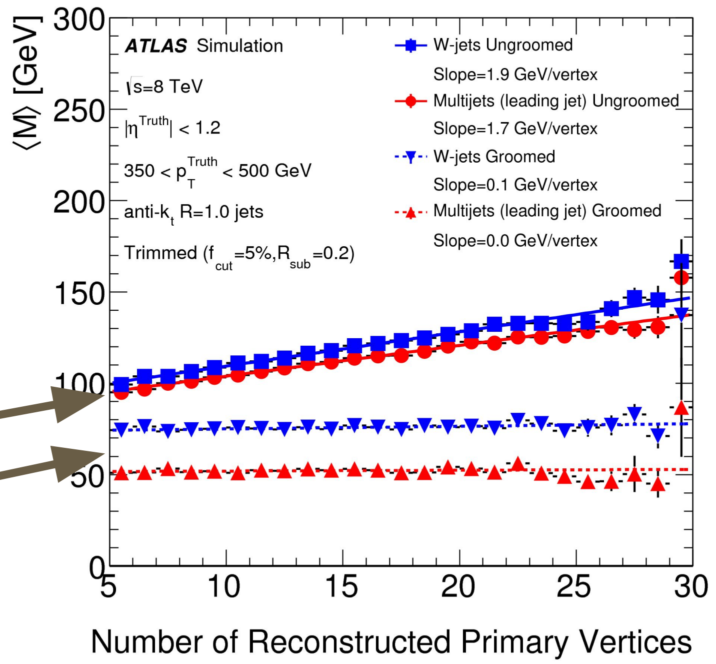
Jet mass

- The most intuitive substructure variable: four-vector invariant mass
- Well-defined expectation for decays
  - Mass of a hadronic decay should correspond to the parent particle (such as the W mass)
  - Assumes full decay contained in the jet
- Ill-defined expectation for QCD jets
  - “Mass” of light quarks and gluons depends on detector granularity, algorithms, etc
  - After grooming, QCD mass peak at low values
- Excellent means of discriminating QCD from hadronic resonance decays



Jet substructure, grooming, and pileup

- Substructure vars are pileup-sensitive
    - Quantify the energy distribution within the jet
    - Pileup overlapping with a hard scatter jet = randomly distributed energy deposits
- Jet grooming originally envisioned to suppress the underlying event
    - However, performs very well against pileup!
- The jet mass is very pileup-unstable
    - After grooming, it becomes pileup robust
    - Also additional QCD vs signal separation
- Similar story for other substructure vars
    - Grooming is important to jet substructure

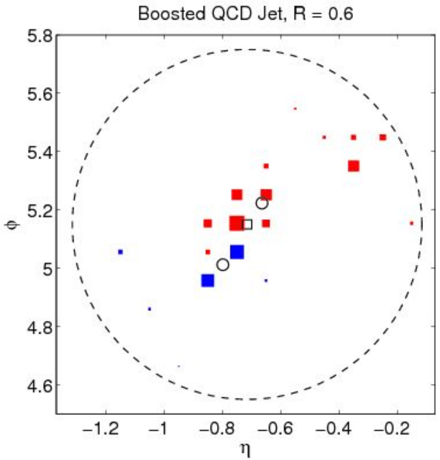


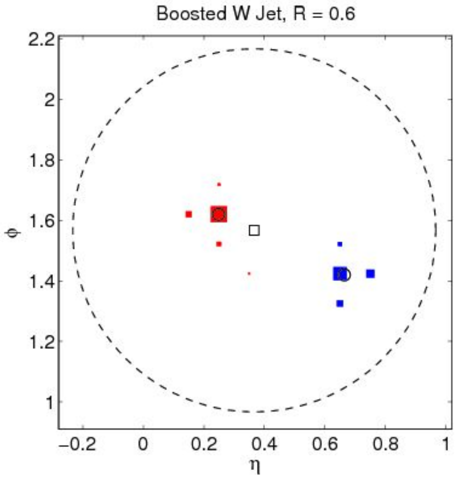
Jet shapes : N-subjettiness

- Measures radiation around N pre-defined axis

$$\tau_N^{(2)} = \frac{1}{p_{t,jet} R^2} \sum_{i \in jet} p_{t,i} \min_{a_i \dots a_N} \left(\theta_{ia_1}^2, \dots, \theta_{ia_N}^2\right).$$

- Use $\tau_{21} = \tau_2/\tau_1$ for 2-pronged jets and $\tau_{32} = \tau_3/\tau_2$ for 3-pronged jets





Jet shapes : Energy correlation functions

- Similar to N-subjettiness (measures “dispersion”)
- Advantage of not needing pre-defined axis ($z_i = p_{t,i} / p_t$, the momentum fraction)

$$e_2^{(\beta)} = \sum_{1\leq i<j\leq n_J} z_i z_j \theta_{ij}^{\beta}$$

$$e_3^{(\beta)} = \sum_{1\leq i<j<k\leq n_J} z_i z_j z_k \theta_{ij}^{\beta} \theta_{ik}^{\beta} \theta_{jk}^{\beta}$$

- For 2-pronged jets
- For 3-pronged jets

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$$

$$C_3^{(\beta)} = \frac{e_4^{(\beta)} e_2^{(\beta)}}{(e_3^{(\beta)})^2}$$

Analytical approach to jet substructure

Why do we need it?

- We can acquire **insight from analytical expressions**
    - Better understand a phenomenon
    - Develop better tools (e.g. boson and top taggers)
- Obtain **more precise results**
    - Parton Shower only provide the lowest logarithm accuracy
    - Resummation can achieve higher accuracies
    - Results are systematically improvable
- Compute robust **uncertainty bands**
    - Correct assessment of the higher orders corrections we are neglecting

Resummation techniques

- Suppose one wants to compute a QCD observable
- We first try a fixed-order expansion in the strong coupling α_s

$$\langle O \rangle = \sum_n \alpha_s^n c_n$$

Fixed-order → truncating this series at a given *n*

- Problem: when c_n is not “well behaved” → **FO expansion does not converge**
- Cases with a strong hierarchy between scales e.g. boosted regimes $p_t \gg m$
- **Need an all-order (in α_s) resummed calculation**

Resummation techniques

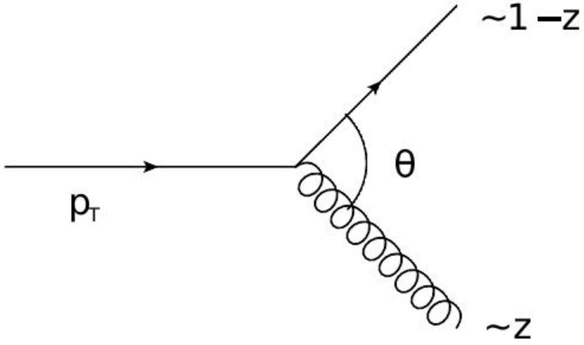
- Resummation rarely describe all phase space
  - needs to be **matched to a fixed-order (FO) calculation**
  - one needs to avoid double-counting of the terms
  - this is a non-trivial process

- Limitation of the analytical approach is the poor understanding of non-perturbative effects (underlying event and hadronization)

- There are different techniques used to so resummation (“perturbative” QCD or SCET -- Soft Collinear Effective Theory), **they are equivalent**

Simple example : jet mass

- Integrated distribution for the jet mass m
- Simplest case: jet with only one emission q → q + g



$$m^2 \simeq p_T^2 z(1-z)\theta^2$$

- Boosted jets $\rightarrow \rho = m^2/(p_t R)^2 \ll 1$

Simple example : jet mass

- For boosted jets :

$$\Sigma(\rho) \simeq \frac{\alpha_s C_F}{\pi}\left[\frac{1}{2}\boxed{\log\left(\frac{1}{\rho}\right)^2} - \frac{3}{4}\log\left(\frac{1}{\rho}\right) + \mathcal{O}(1)\right]$$

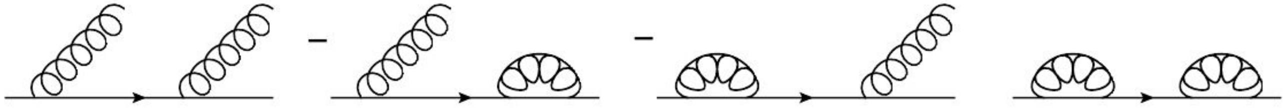
- For higher orders in α_s → terms like $[\alpha_s \log(1/\rho)^2]^n$
- If $\rho \ll 1$ $\rightarrow \alpha_s \log(1/\rho)^2 \sim 1$

→ **fixed-order** expansion **does not converge**

- **Need resummation at all orders**

Simple example : jet mass

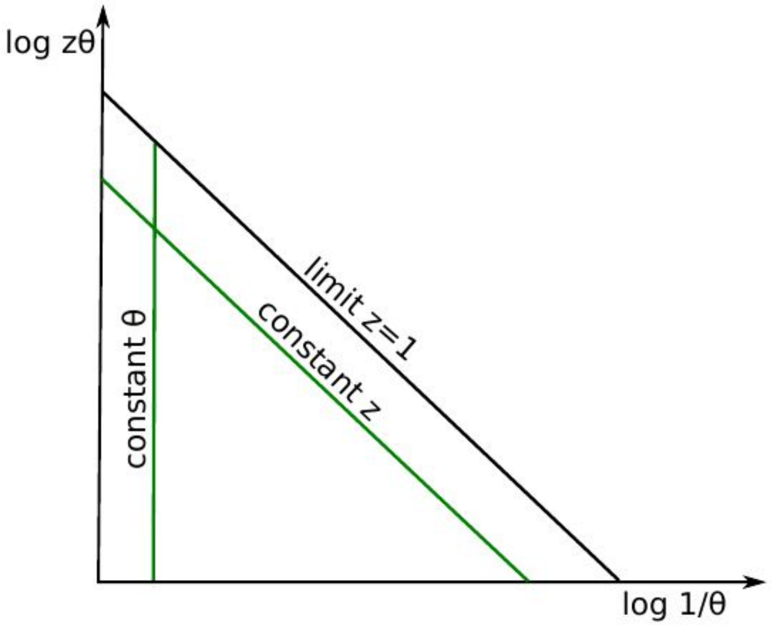
- Only interested at the dominating term ~ $\alpha_s \log(1/\rho)^2$→ **Leading Logarithm (LL)**
- Virtual emissions → cancel out soft and collinear divergences.

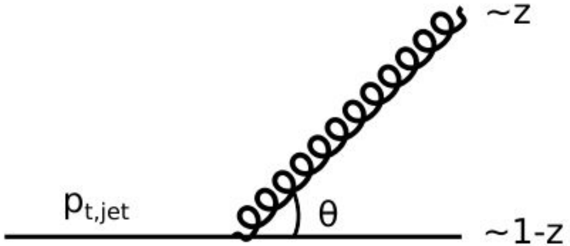


$$\Sigma(\rho) = 1 - \frac{\alpha_s C_F}{\pi} \exp \underbrace{\left[-\frac{\alpha_s C_F}{2\pi} \log\left(\frac{1}{\rho}\right)^2 \right]}_{\text{Sudakov exponent}}$$

Lund diagram

- Graphical representation of emissions in zθ vs. 1/θ coordinates.

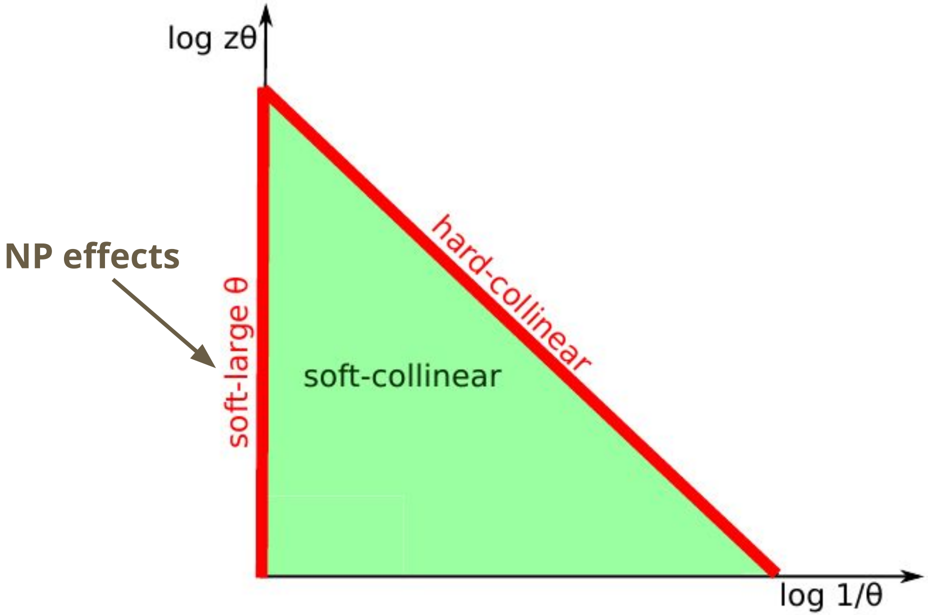


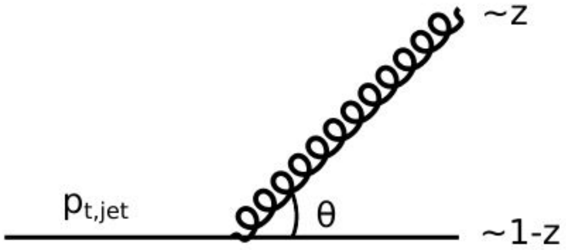


$$dP_{\rm em} \sim \frac{\alpha_s C_R}{\pi}\,\frac{d\theta^2}{\theta^2}\,dz\,p_i(z)$$

Lund diagram

- Graphical representation of emissions in zθ vs. 1/θ coordinates.

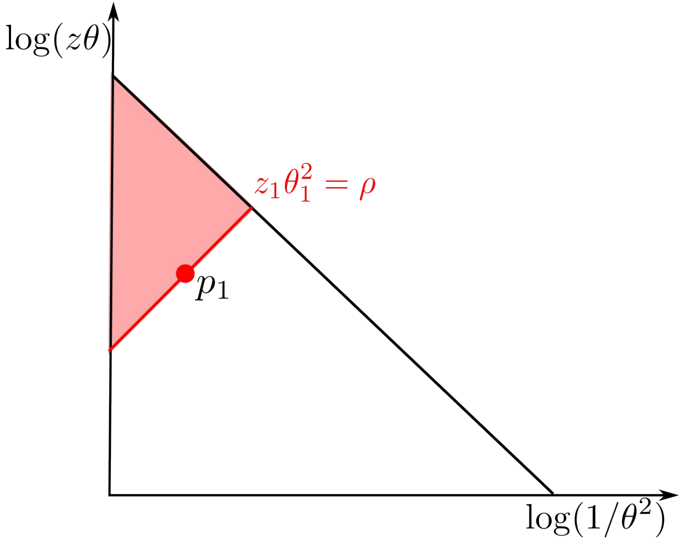




$$dP_{\rm em} \sim \frac{\alpha_s C_R}{\pi} \frac{d\theta^2}{\theta^2} dz\, p_i(z)$$

Back to mass example

- For a jet with mass m, no real emissions allowed with $z\theta^2 > \rho$
- Virtual and real emissions cancel out, except in shaded region
- All-order resummation gives an exponential factor at LL

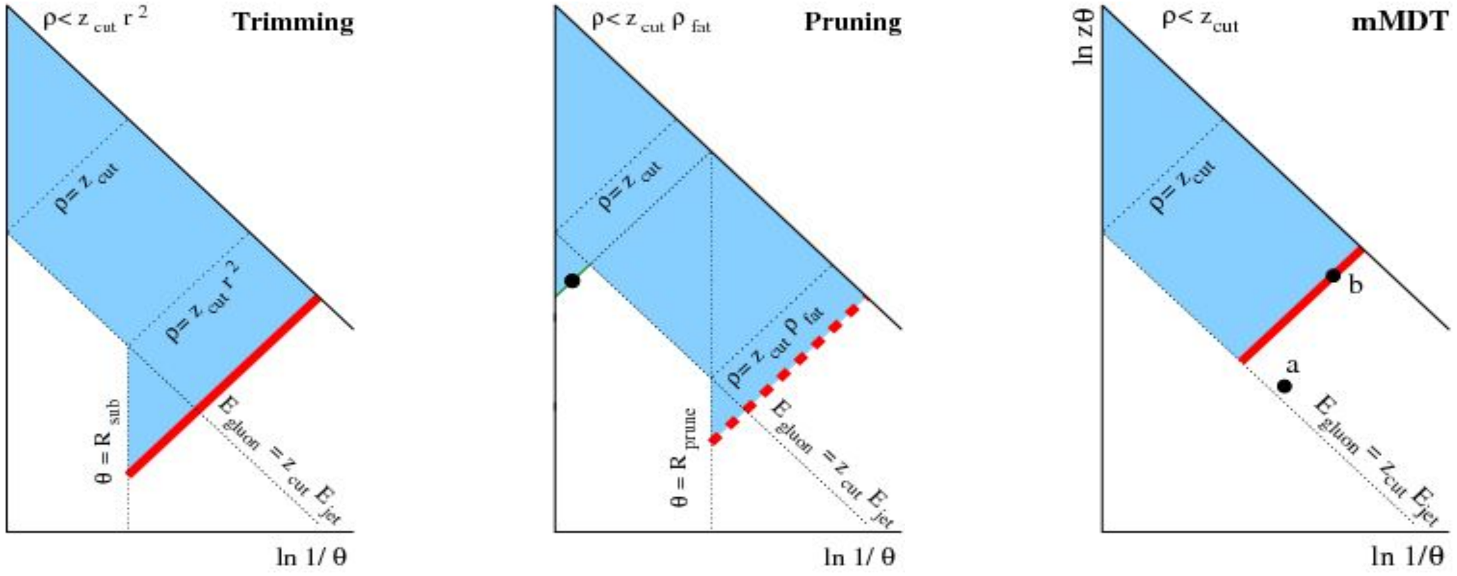


$$\Sigma(\rho) \quad = \quad 1 - e^{-R(\rho)}$$

$$\Sigma(\rho) = 1 - \frac{\alpha_s C_F}{\pi} \exp\left[-\frac{\alpha_s C_F}{2\pi} \log\left(\frac{1}{\rho}\right)^2\right]$$

How grooming works

- Grooming eliminates kinematic region dominated by NP effects



From Dasgupta, Fregoso, Marzani, Salam, (2013) -- first resummed calculations in jet substructure

Groomed jet mass

- Connection between **measurements** and **calculations**
- **Jet mass** is one of the simplest observables
- **Grooming** eliminates part of UE contamination
- Studied modified MassDrop Tagger and SoftDrop
- **Needs to be resummed at all orders, matched to fixed-order**

Groomed jet mass

- Various interesting QCD structures emerging
    - For mMDT it becomes $[\alpha_s f(z_{cut}) \log(1/\rho)]^n$ at leading-log
    - Finite z_{cut} introduce a flavour changing matrix structure
- Compare with experiment → needs a matching procedure:

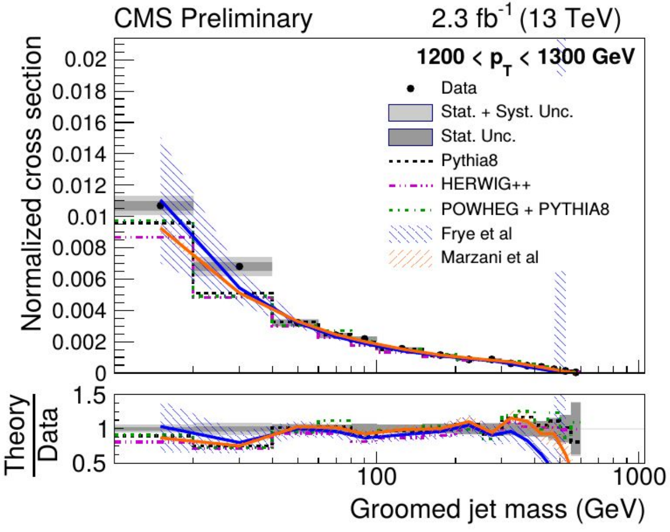
Resummation
of large logs ←

$$\underbrace{N^k LL}_{\text{small } \rho} + \underbrace{N^m LO}_{\text{large } \rho}$$

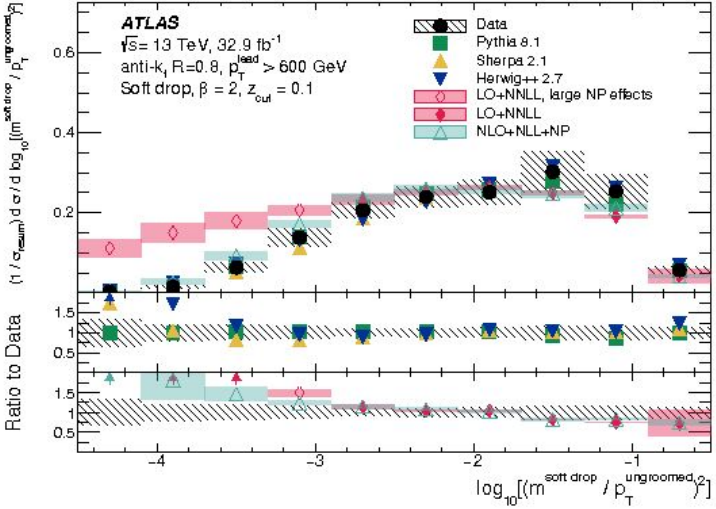
→ **Fixed order**
at ~O(α_s)

- Calculations done with different theoretical approaches
    - NLL + LO for $z_{cut} \ll 1$ Frye, Larkoski, Schwartz, Yan (2016) -- Boost2016
    - LL + NLO for all z_{cut} Marzani, Soyez, LS (2017) -- Boost2017
    - Inclusive jets version Kang, Lee, Liu, Ringer (2018)

Groomed jet mass



CMS measurements with mMDT
CMS-PAS-SMP-16-010



ATLAS measurements with SoftDrop
CERN-EP-2017-231

New angles on energy correlation functions

Moult, Necib,Thaler (2016) -- Boost 2016

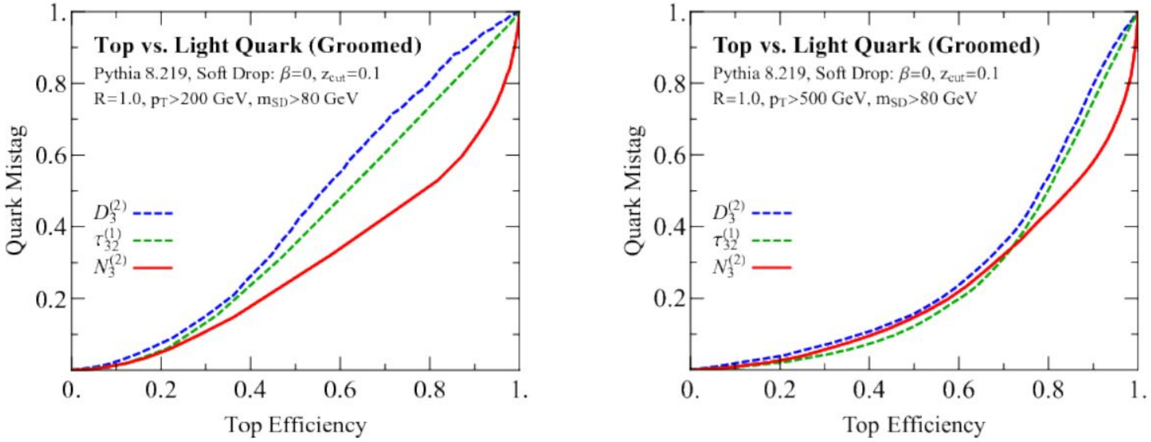
- Generalization of the energy correlation functions

$$ {}_v e_n^{(\beta)} = \sum_{1\leq i_1<\cdots<i_n\leq n_J} z_{i_1}\ldots z_{i_n} \prod_{m=1}^{v} \overset{(m)}{\min_{s<t\in\{i_1\ldots i_n\}}} \{\theta_{st}^{\beta}\} $$

- Defined the series:
  - M_i : identify jets with hard prongs $$M_i^{(\beta)} = \frac{{}_1e_{i+1}^{(\beta)}}{{}_1e_i^{(\beta)}}$$
  - N_i : mimics the behavior of N-subjettiness $$N_i^{(\beta)} = \frac{{}_2e_{i+1}^{(\beta)}}{({}_1e_i^{(\beta)})^2}$$
  - U_i : probe multiple emissions within 1-pronged jets $$U_i^{(\beta)} = {}_1e_{i+1}^{(\beta)}$$

Example : top tagging with N_3

- Observables proposed: $N_3 = {}_2e_4^{(\beta)}/({}_1e^{(\beta)})^2 \sim \tau_3/\tau_2$
- Grooming matters! Affects efficiency of observable.



- These shapes perform slightly better than standard $D_2^{(2)}$

Dichroic Jet Shapes

Salam, LS, Soyez (2016) -- Boost2016

- Explore the interplay between groomers / prong finders and jet shapes;
- Example : N-subjetiness -- the usual τ_{21} measure is

$$\tau_{21} = \frac{\tau_2(\mathrm{mMDT})}{\tau_1(\mathrm{mMDT})} \quad \text{or} \quad \frac{\tau_2(\mathrm{SD})}{\tau_1(\mathrm{SD})} \quad \text{or} \quad \frac{\tau_2(\mathrm{plain})}{\tau_1(\mathrm{plain})}$$

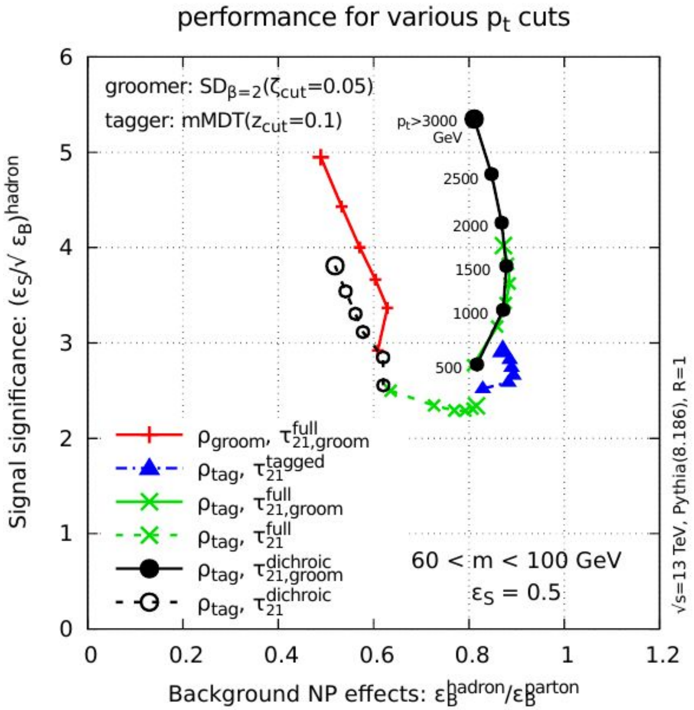
- Dichroic : different subjets for numerator / denominator in τ 21 ratios;

$$\tau_{21}^{\mathrm{dichroic}} \equiv \frac{\tau_2^{\mathrm{full\ /\ SD}}}{\tau_1^{\mathrm{tagged}}}$$

- τ_2 on large jet → sensitivity to different color structures
- τ_1 on small jet → only sensitive to the invariant mass

  → smaller influence of non-perturbative effects.

Dichroic Jet Shapes

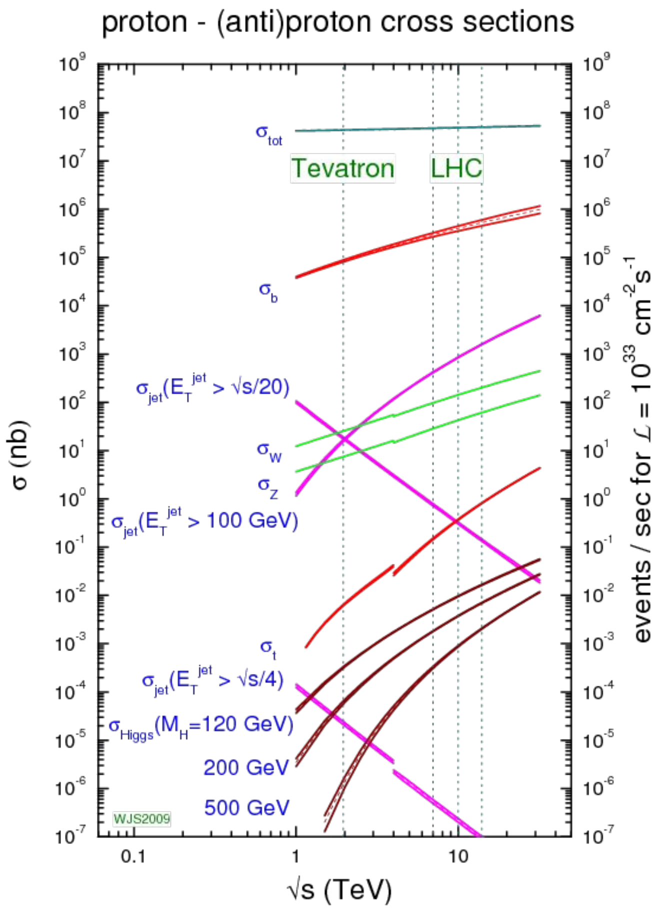


- Dichroic τ_{21} variation→ increases discriminating power
- With **pre-grooming step**→ **reduction of NP effects** and still has a **better performance** (black solid dots)
- Performance gain increases as p_t increases

How can we “tag” (identify) a jet?

Jet identification

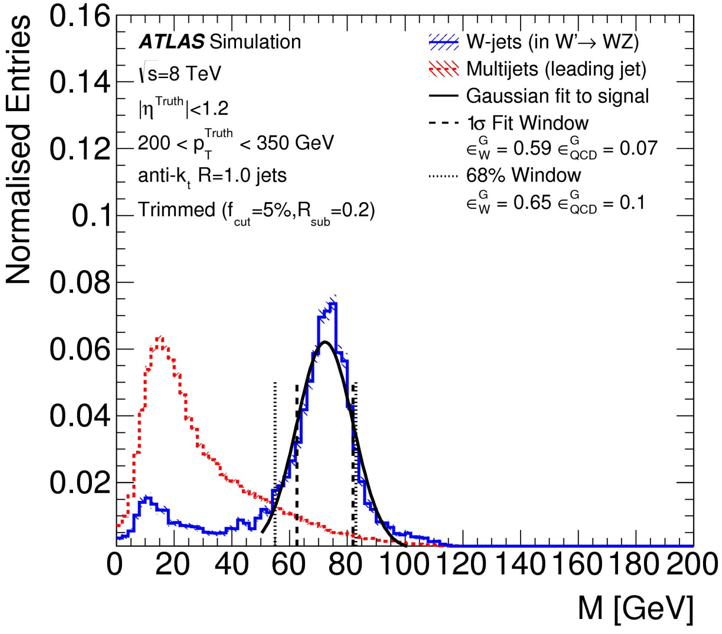
- Common types of jet identification:
  - Massive hadronic particle decays (W/Z/H/top) vs QCD
  - Light-quark vs gluon discrimination
  - Pileup vs hard-scatter jet identification
  - Flavour tagging (b-jets, c-jets, etc)
  - Other types exist, these are just the most common
- We will focus on hadronic decay tagging
  - Fighting the enormous QCD background
  - Need many orders of magnitude QCD rejection

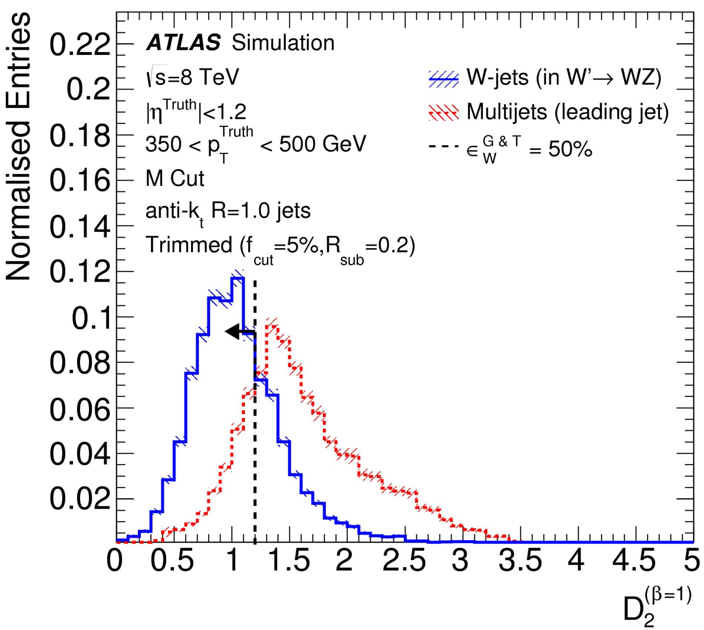


arxiv:1204.0952

Simple cut-based taggers

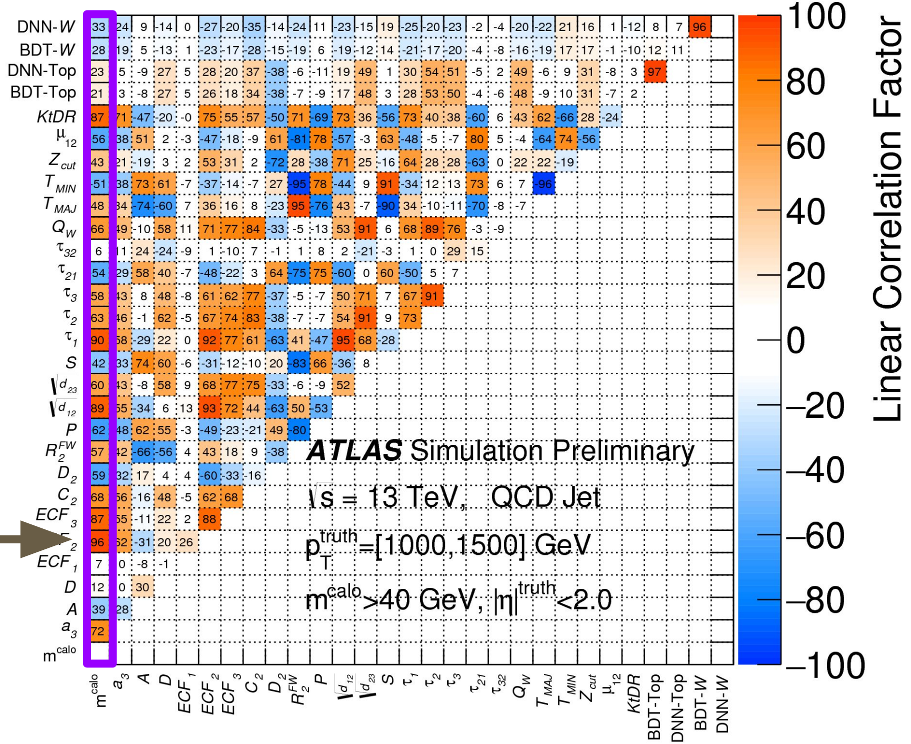
- Cut-based selections are already powerful (e.g. mass+D2 for W/Z-tagging)
    - ~1.5% QCD efficiency for 50% signal efficiency





Substructure variable correlations

- Two-variables are great, why not keep adding more information?
    - There is only so much information to exploit → diminishing returns
- Substructure variables are mostly correlated with each other
    - In particular, most variables are correlated with jet mass
    - Very few light-coloured entries



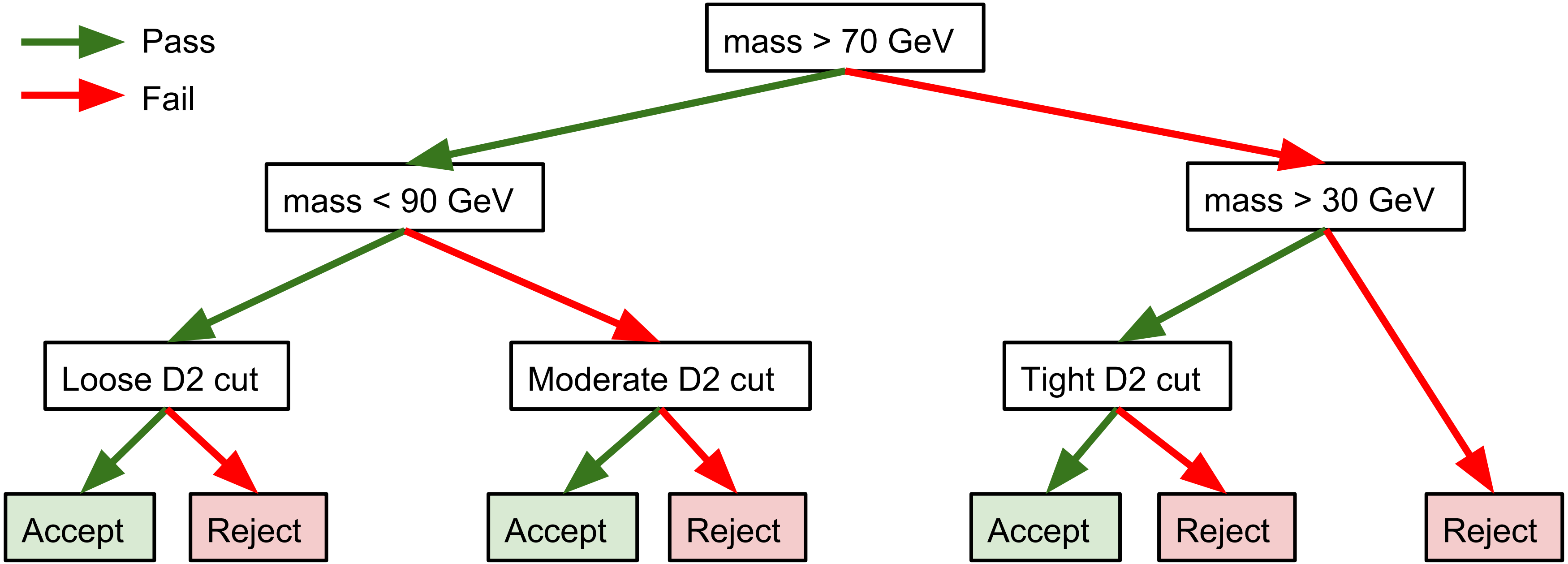
Machine Learning (ML)

- Powerful technique to extract information from a dataset
    - Can leverage non-linear correlations, not just linear correlations (last slide)
- ML has both positives and negatives
    - Usually better jet tagging power than non-ML approaches
        - Gains for using ML can be quite substantial, depending on the task and inputs
    - However, less understanding of what is being done
        - Traditionally a “black-box” approach
        - Need to be careful to ensure the ML is learning real features, not MC artifacts
- There are many, many types of ML techniques
    - We will focus on the two most commonly used techniques in modern HEP

Boosted Decision Trees (BDTs)

- BDTs are excellent for combining variables in taggers
    - Usually fast to train and nearly optimal performance
    - Also easier to “understand” what they are doing
- Idea: build a “decision tree”, or a set of sequential cuts on variables
    - One-dimensional decision tree is just a single variable cut
    - Output is typically a binary decision: “signal” or “background”
- This decision tree will have some rate of misclassifying events
    - Build another decision tree which focuses on these misclassified events
    - This is the “boosting” step in BDT
- Repeat this many times to train your BDT for optimal performance

BDT W-tagging example, inputs = (mass, D2)



Pass

Fail

mass > 70 GeV

mass < 90 GeV

mass > 30 GeV

Loose D2 cut

Moderate D2 cut

Tight D2 cut

Accept

Reject

Accept

Reject

Accept

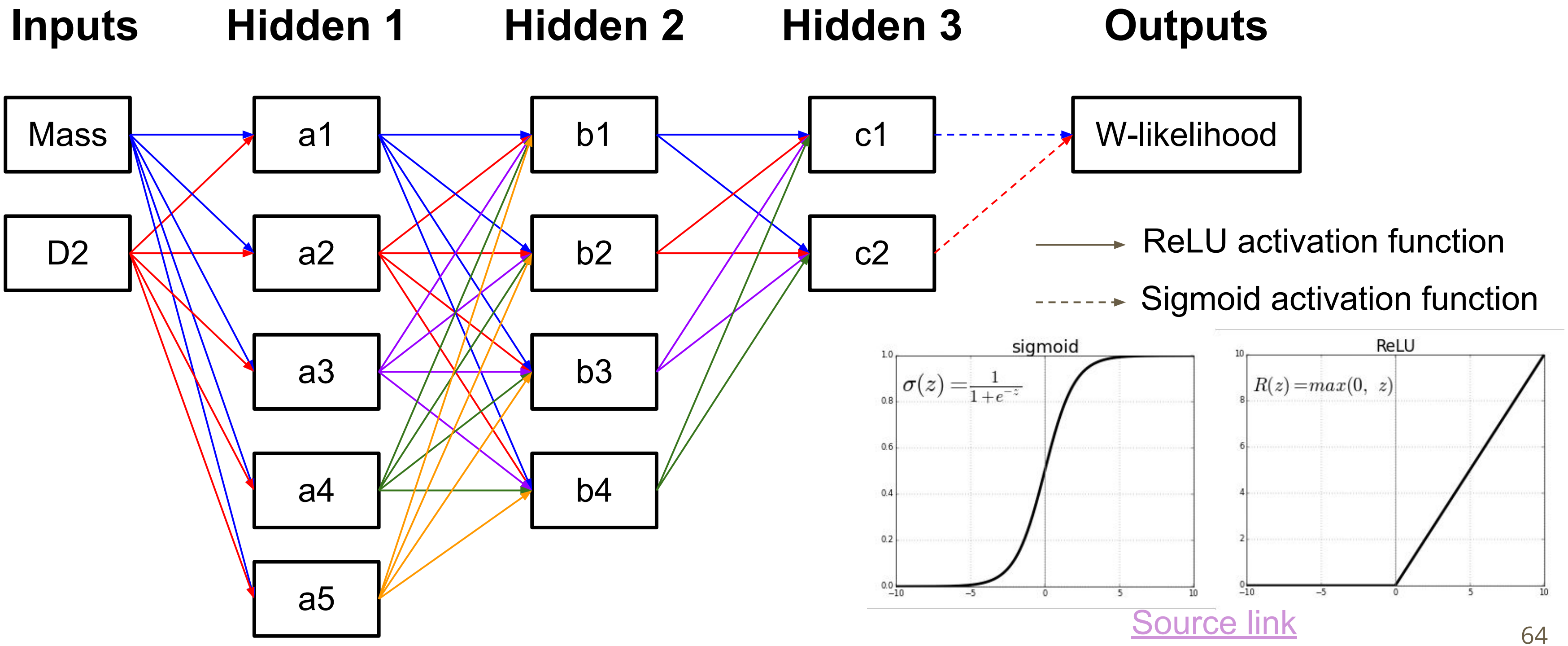
Reject

Reject

Neural Networks (NNs)

- Neural networks were originally inspired by biology and brains
- Comprised of inputs, hidden layer(s), and output(s)
  - Each variable is typically connected with all others in the previous and next layer(s)
    - Weights between nodes control the flow of information
  - If there is more than one hidden layer, it is a “deep network” → “deep learning”
  - One output is a binary discriminant, many outputs is a multi-class discriminant
- There are now many types of neural networks
  - NNs, Deep (DNNs), Convolutional (CNNs), Recurrent+Recursive (RNNs), and more
  - All except for simple NNs are typically “deep”
- Very powerful, but very complex, and difficult to interpret
  - An infinitely deep network can represent any non-linear function

DNN W-tagging example, inputs = (mass, D2)



Inputs **Hidden 1** **Hidden 2** **Hidden 3** **Outputs**

Mass
D2

a1
a2
a3
a4
a5

b1
b2
b3
b4

c1
c2

W-likelihood

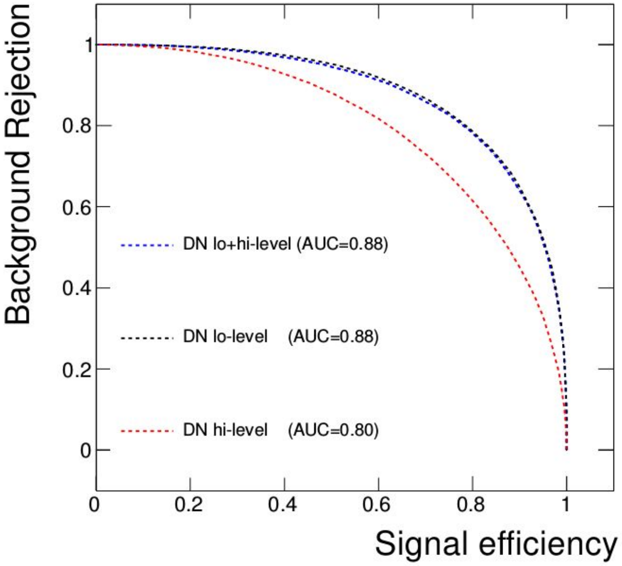
ReLU activation function

Sigmoid activation function

Source link

Machine Learning taggers

- How well do these ML taggers actually work?
  - Short answer: quite well, especially for complex objects
    - Gain is larger for top-tagging than W-tagging, etc
  - No plots to avoid spoiling conference results
- Performance depends on the inputs used for ML
  - “High-level” variables are properties of the jet itself
    - Jet four-vector, substructure variables, etc
  - “Low-level” variables are properties of inputs to jets
    - Constituent four-vectors, constituent properties, etc
- Typically, BDT/DNN perform similarly on high-level inputs
  - However, there is space for DNN improvement with low-level inputs



arxiv:1402.4735

Tagging efficiency scale factors and uncertainties

- With ML taggers, it is very important to evaluate performance in data
    - ML may be learning features of MC which do not represent data
    - Propagating uncertainties on ML inputs is not sufficient
        - ML exploits correlations between variables, which are typically poorly known
- Derive tagging efficiency scale factors and uncertainties *in situ*
    - Use a “standard candle” were we have high purity to measure data/MC differences
    - Example: semi-leptonic ttbar events can be used to evaluate top-tagging efficiencies
- With such a technique, ML becomes a well-defined and useful tool
    - However, we still don’t necessarily know *what it has learned*
    - This remains an open question of great interest for the future

Summary

Summary

- Jet substructure is a rapidly growing and increasingly important field
    - It is increasingly used throughout the experimental physics programs
    - New searches and measurements of jet substructure come out every year
- This introduction should have provided you with the key pieces that you need to understand the majority of this week's talks
    - You won't be able to understand everything, but we won't either!
    - Don't be shy! Ask questions and participate in discussions

- Every year at BOOST, we see lots of interesting new results
    - It will be great to see the new results at this year's BOOST!