Jet Substructure in ATLAS at the LHC - a Tool for Discoveries and Measurements

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Seminar

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Roadmap for this Talk

Jet substructure

- Introduction to jet substructure phenomenology
- Selective review of most popular techniques

Jet reconstruction inputs

- The ATLAS detector
- Jet reconstruction inputs

Substructure reconstruction performance

- Reconstructing observables in the presence of pile-up

Measurements & Searches

- QCD jet structure
- Application of substructure techniques in final states with top quarks

Conclusions and outlook

Jet Substructure

Why Looking Inside Jets at LHC?

Kinematic reach at LHC allows production of (highly) boosted particles

- All decay products of hadronically decaying Standard Model particles can be collected into single jet
  - $W \rightarrow qq$, Higgs bosons $H \rightarrow bb$, top quarks $t \rightarrow Wb \rightarrow qqb$
- Searches for new heavy particles with boosted (SM) decay products
  - Single jet mass indicative observable for new particle production

Experimental challenges – detector granularity & pile-up

- Limited granularity introduces limits in resolving sub-structure in a jet
  - E.g., signals from near-by particles can easily overlap in calorimeters
- Presence of pile-up can disturb single jet mass reconstruction from internal flow measurements
  - Needs to extract relevant internal jet energy flow structures for mass reconstruction etc. from diffuse pile-up contributions

Jet substructure analysis

- Collection of techniques aiming at enhancing two- or three-particle ("prongs") decay patterns in single jets
  - Typically leads to suppression of QCD-like backgrounds from quark- and gluon jets with their typical parton shower and fragmentation driven internal flow structure

Separation of Flow Patterns

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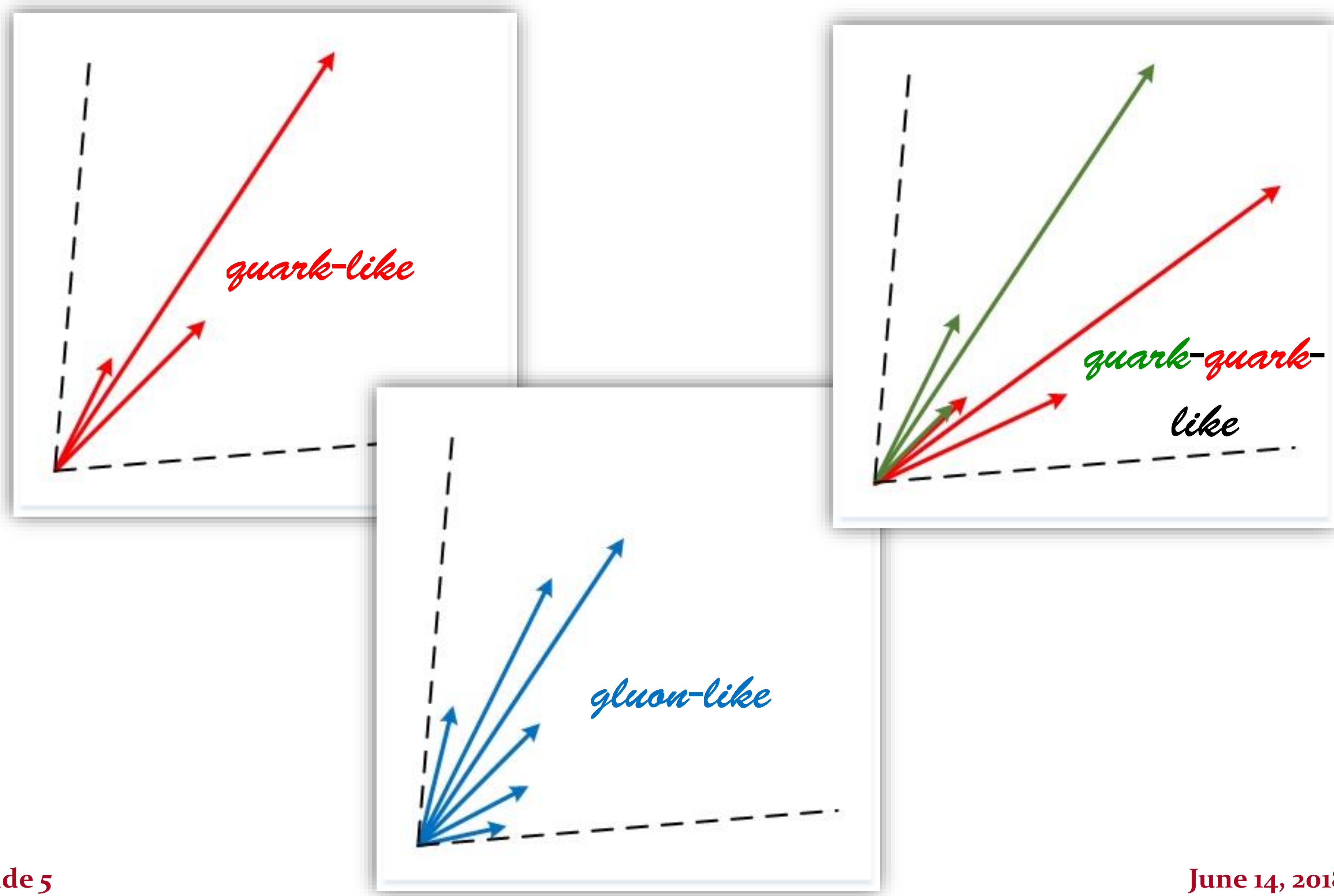

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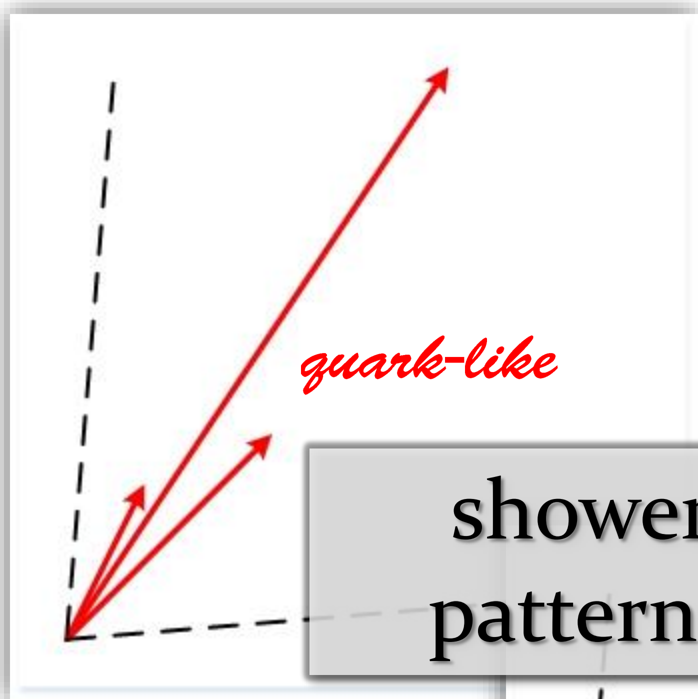
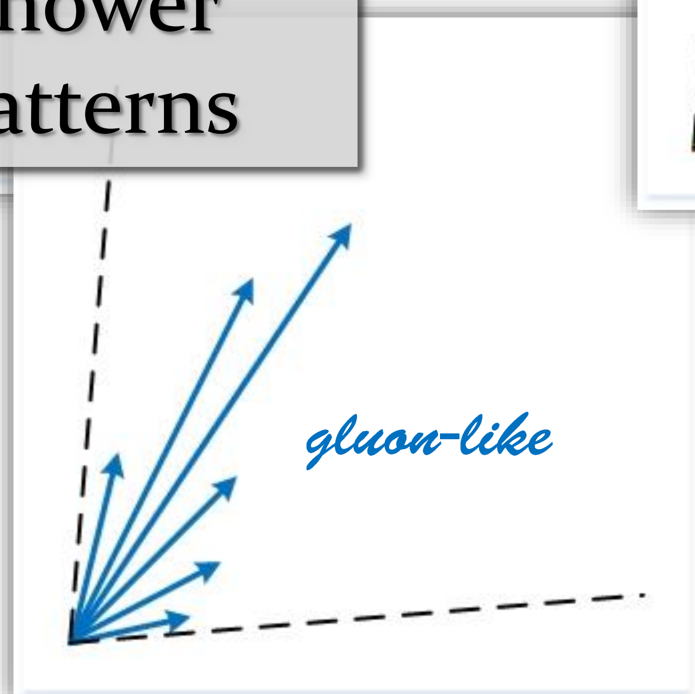
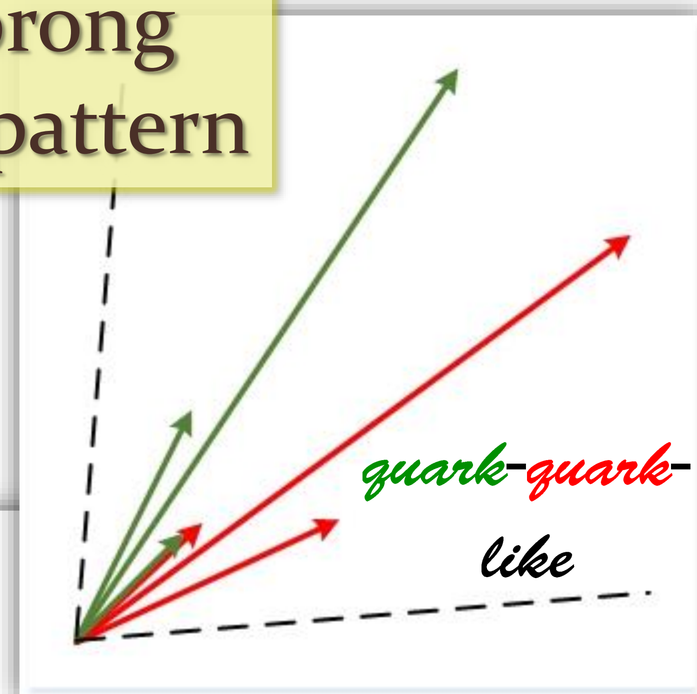
Separation of Flow Patterns

shower patterns



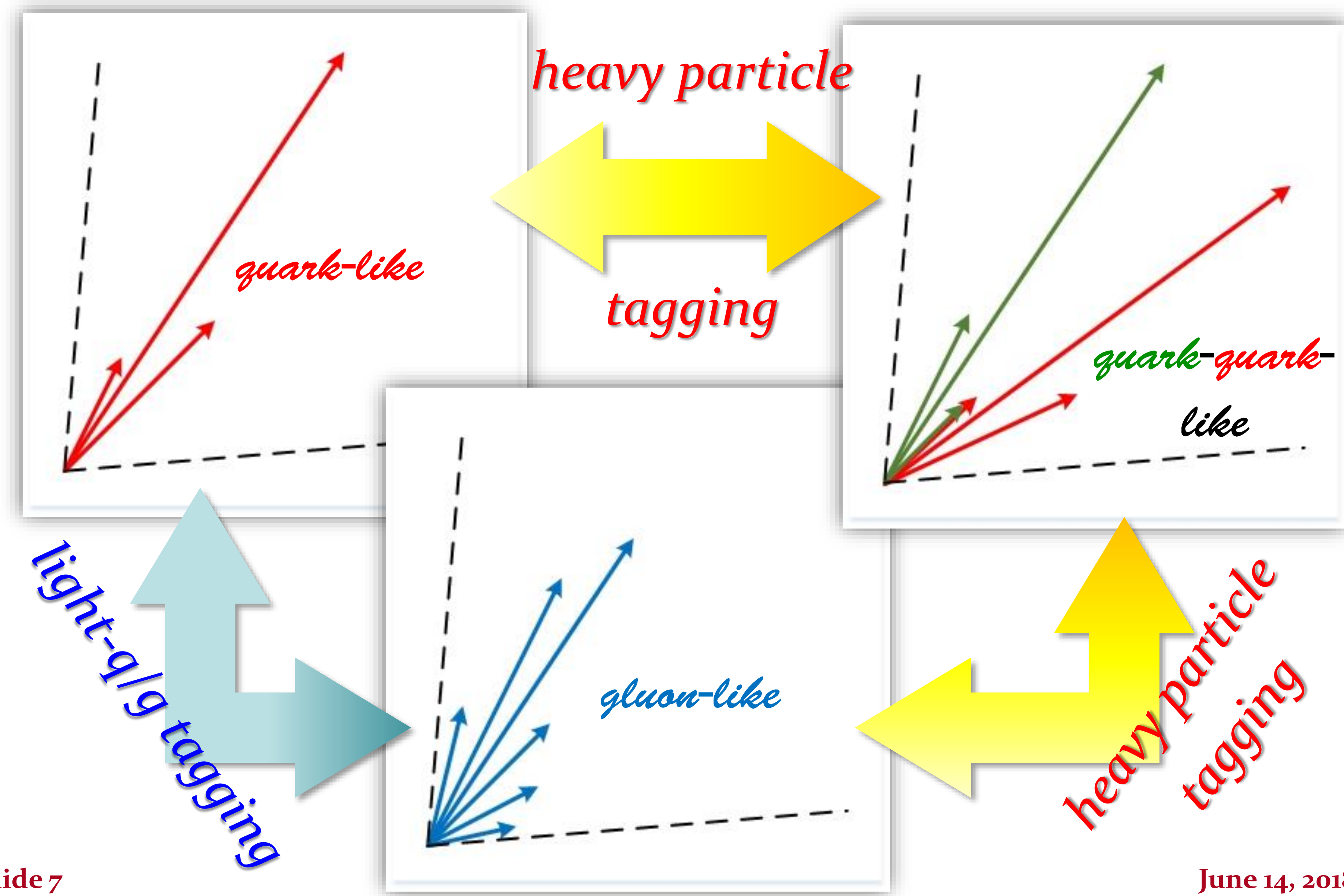


N^*-prong decay pattern



*staged fast decays like $t \to Wb \to qqb$, boosted system of > 1 decaying particle, like in $HH \to bbbb$ etc.

Separation of Flow Patterns



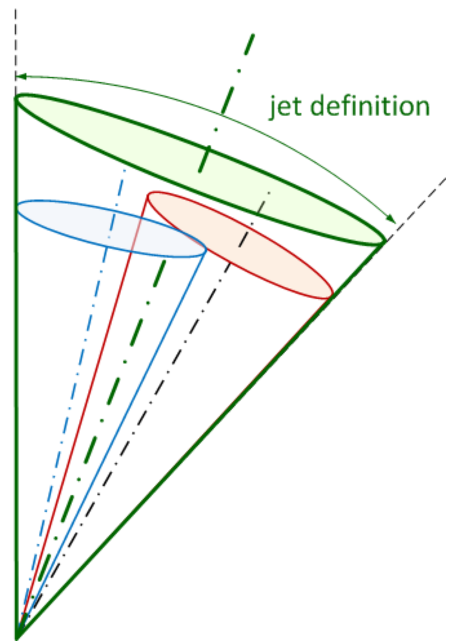
Jet Substructure

Particle flow inside a jet hints to source

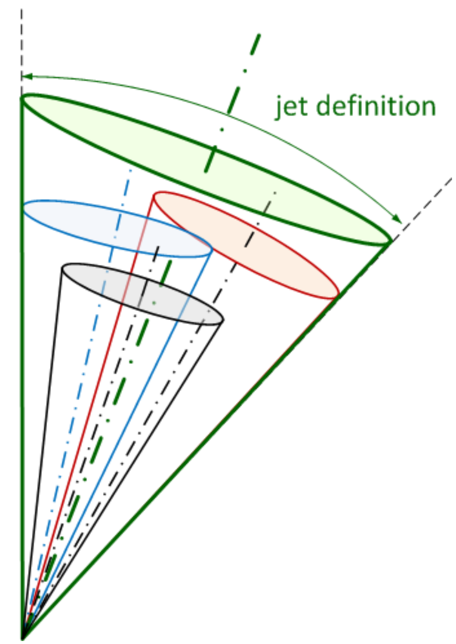
- Boosted (heavy) particle decay emits particles in typical jet cones
  - Standard Model as well as new particles
- Usefulness depends on the ability to resolve decay structure
  - E.g., 2-prong (like W) or 3-prong (top) decays
  - Resolution scale given by (hypothetic) mass of particle – limited by detector capabilities

Jet size

- "Rule of thumb" $\boldsymbol{R = 2m/p_{\mathrm{T}}}$
  - Cone of size R contains decay products of particle with mass m and transverse momentum p_{T}



2 – prong decay inside reconstructed jet, e.g. from $W \rightarrow q\bar{q}$ (SM) or heavy new object like $\phi \rightarrow gg$ or $Z' \rightarrow q\bar{q}$ (BSM)



3 – prong decay inside reconstructed jet, e.g. from $t \rightarrow q\bar{q}b$ (SM) or heavy new object like $\phi_{\mathrm{KK}} \rightarrow Q\bar{Q}b + X$ or $t' \rightarrow q\bar{q}b$ (BSM)

Example for Boosted Particle Decays

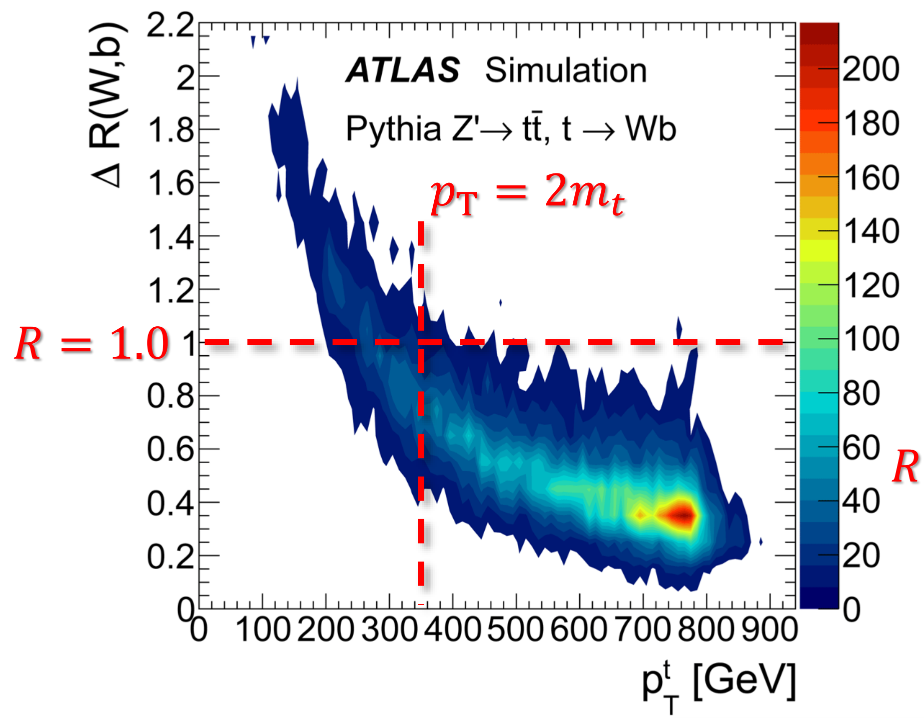
High p_T top quark hadronic decay

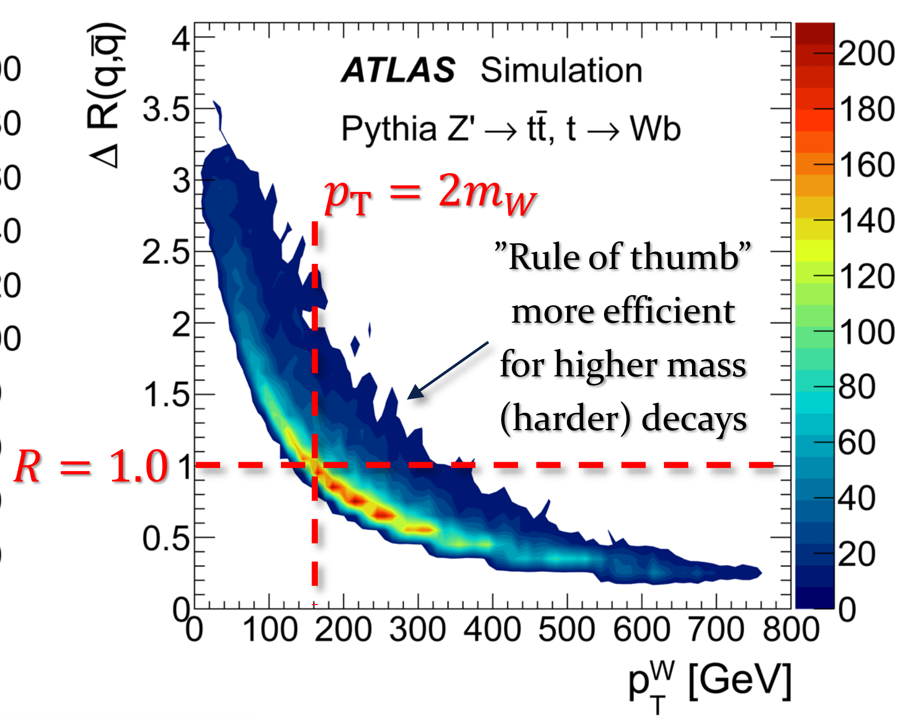
Simulated decay of new heavy particle $Z' \to t\bar{t}$

Topology is two sequential 2-prong decays with high p_{T}

Top quarks have high p_{T} – decay into $t \to Wb$ with high-p_{T} W boson

$$\Delta R(W,b) = \sqrt{\Delta y^2_{W\leftrightarrow b} - \Delta\varphi^2_{W\leftrightarrow b}} \text{ and } \Delta R(q,\bar{q}) = \sqrt{\Delta y^2_{q\leftrightarrow \bar{q}} - \Delta\varphi^2_{q\leftrightarrow \bar{q}}}$$





JHEP 1309 (2013) 76

Jet Substructure Language

Jet grooming – groomed jet

- Means **any** substructure technique has been applied to a jet
  - Including combinations of several techniques

Fat jet

- Reconstructed large-R jet
  - Often configured as a search tool
  - Popular are anti-k_t and C/A jets in filter-type applications
  - Typically $R \geq 1$

Sub-jet

- Narrow jet inside a fat jet
  - Result of filter-type applications
  - Selected sub-jets are recombined to reconstruct observables of interest

Taggers

- Characterization of a specific jet source
  - Implemented by (optimized) combinations of substructure techniques
  - E.g., HEPTopTagger[1], W boson tagging[2] etc.

(1) T. Plehn, M.Spannowsky, M.Takeuchi, & D.Zerwas, JHEP 1010, 078 (2010)
(2) Y.Cui, Z.Han, & M.D.Schwartz, Phys.Rev. D83 (2011) 074023

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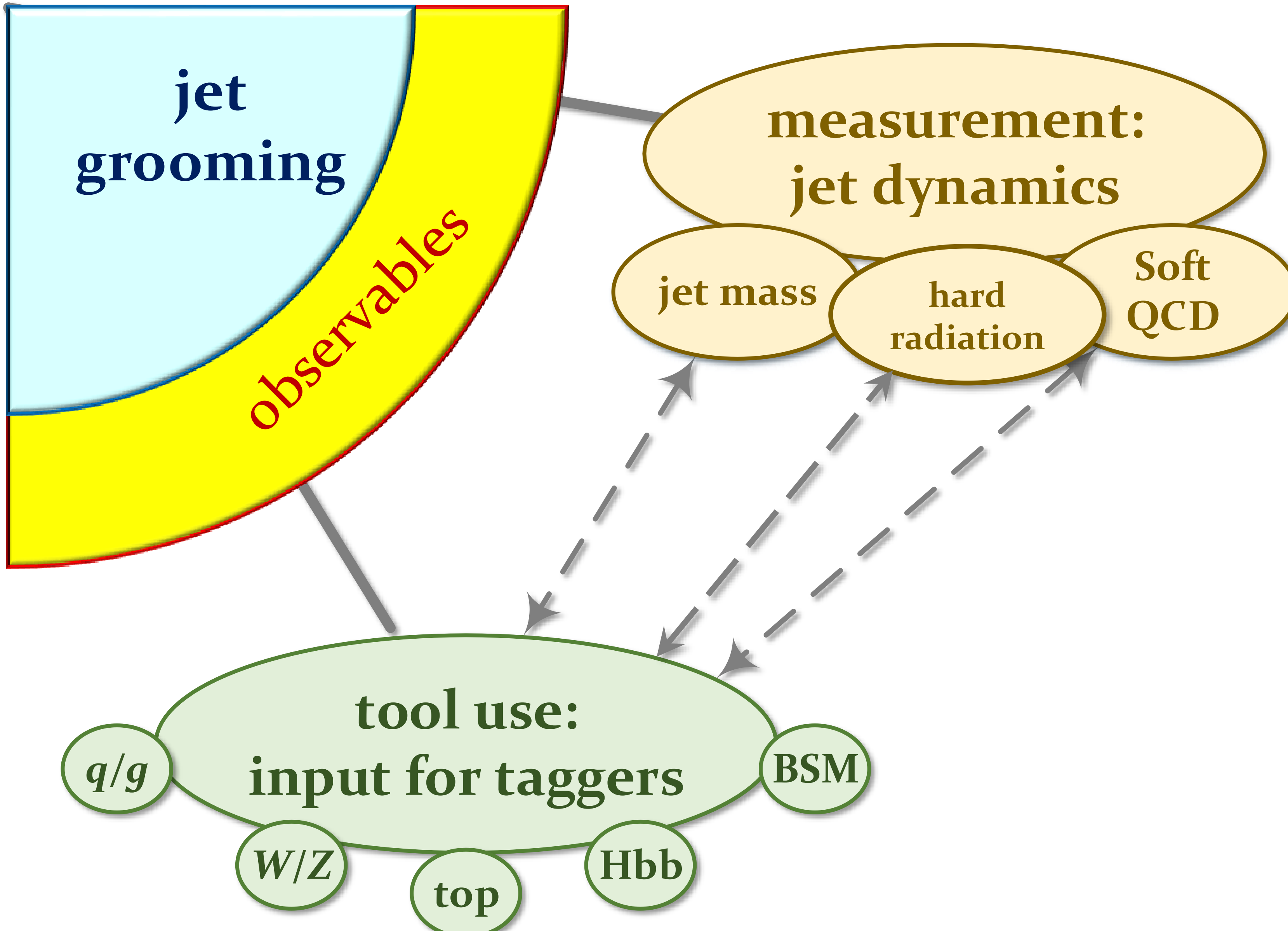
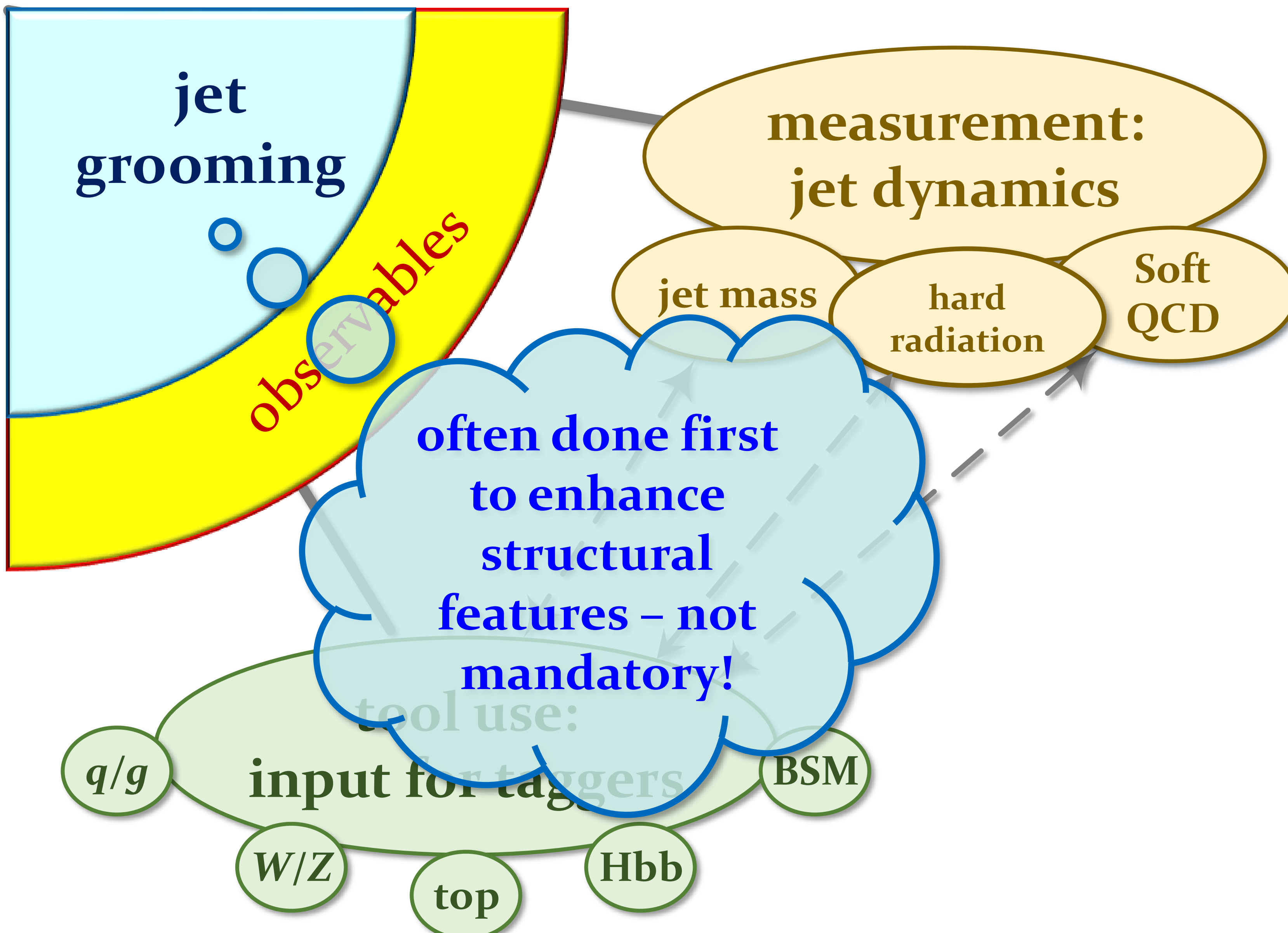
Jet Substructure in Physics Analysis



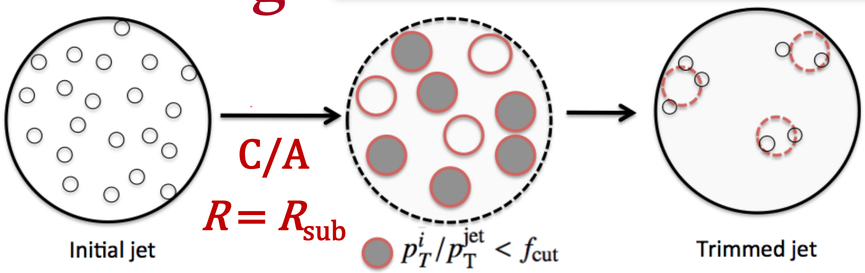
Jet Substructure in Physics Analysis



Jet Grooming Techniques (1)

Trimming

D.Krohn, J.Thaler, L.Wang, JHEP 02 (2010) 84



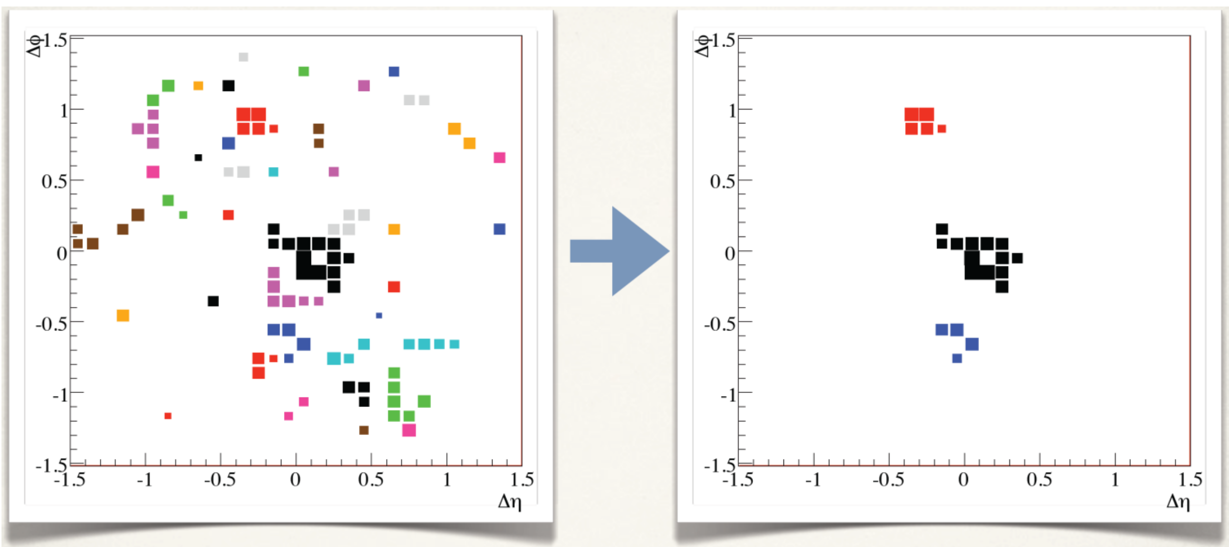
$$R_{sub} = \{0.2, 0.3\}$$

$$f_{sub} = \{0.01, 0.03, 0.05\}$$

$$p_T^{sub} > f_{sub} \times p_T^{jet} \text{ (accepted sub-jets)}$$

Recombine surviving sub-jets to form groomed jet

Works with any meaning full initial jet definition

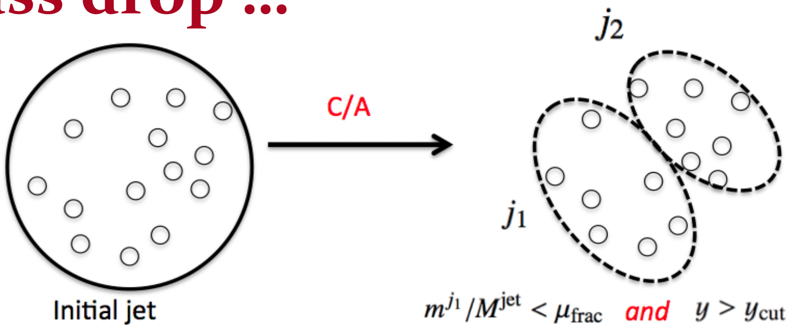


Jet Grooming Techniques (2)

Mass drop …

Butterworth, Davison, Rubin, Salam, Phys.Rev.Lett. 100 (2008) 242001

REQUIRES MEANINGFUL RECURSIVE RECOMBINATION JET CLUSTER SEQUENCE



Split jet into two sub-jets by undoing last recombination

Accept if masses of sub-jets considerably smaller than initial jet mass …

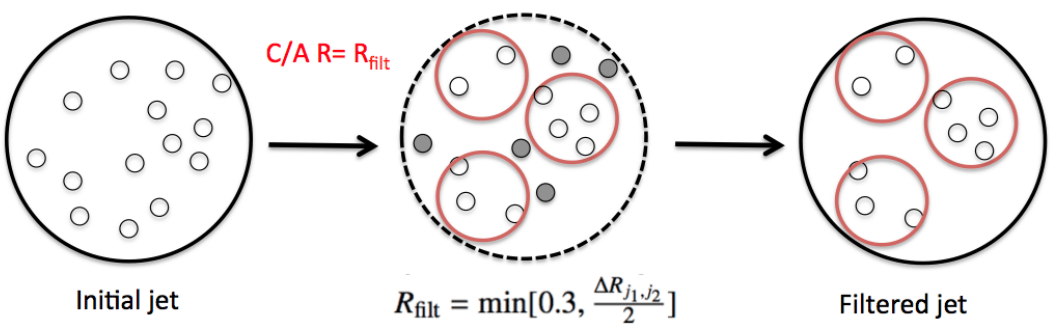
$\min(m_1, m_2)/m < \mu_{\text{frac}}$ with $\mu_{\text{frac}} = \left\{\frac{1}{5}, \frac{1}{3}, \frac{2}{3}\right\}$

… and p_{T} sharing fairly symmetric

$y = \min(p_{\text{T},1}^2, p_{\text{T},2}^2)/m^2 \times \Delta R_{12} < y_{\text{cut}}$ with $y_{\text{cut}} = 0.09$

BDRS

… and filter



$R_{filt} = \min(0.3, \Delta R_{12}/2)$

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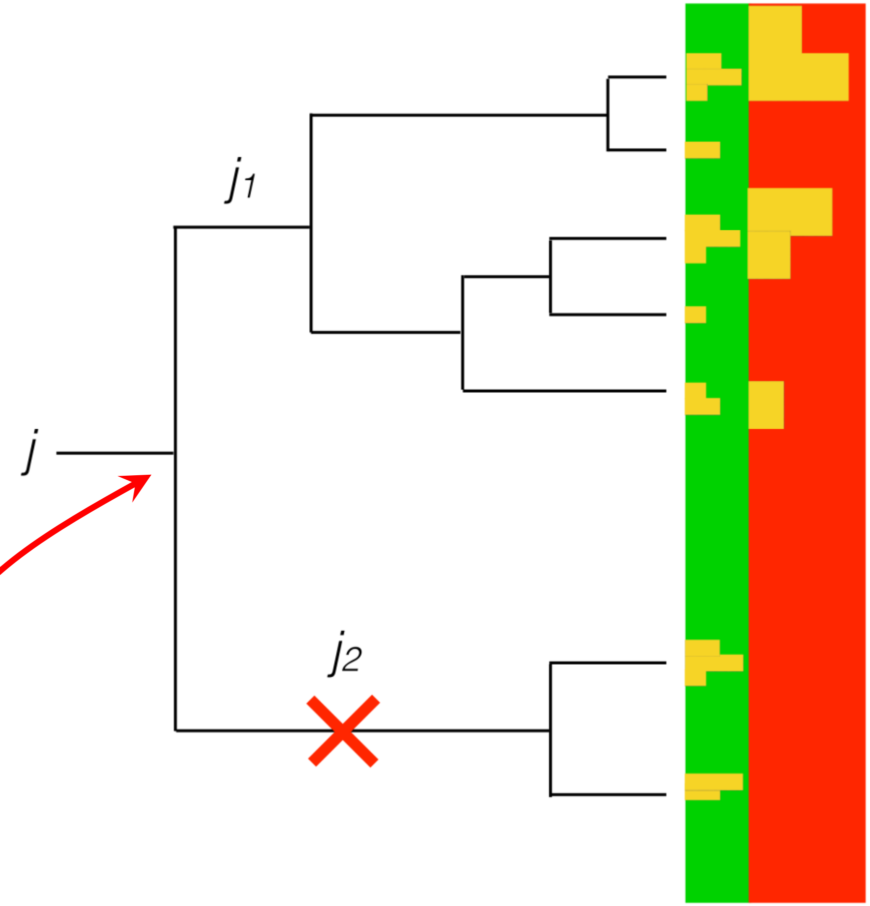
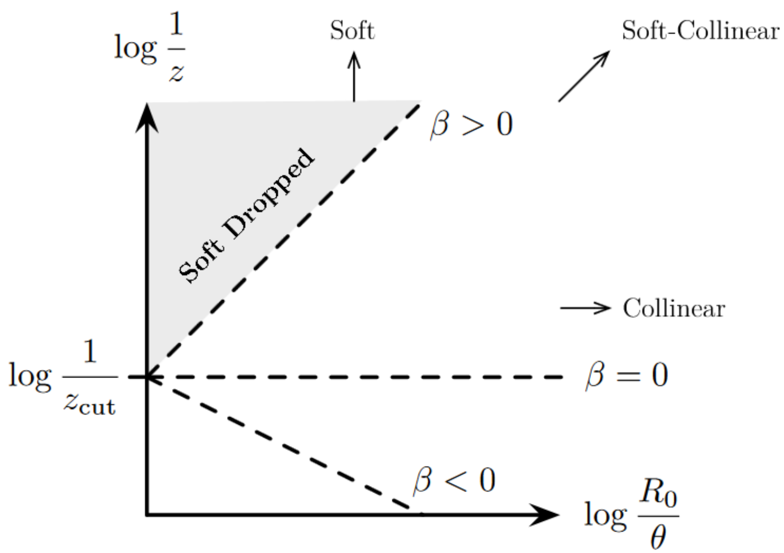
Soft Drop

Larkoski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146

De-clustering algorithm removes wide angle soft emissions inside any IRC safe clustered jet





Controlling soft drop phase space

- $\beta \to \infty$ yields ungroomed jet
- $\beta = 0$ corresponds to modified mass drop
- $\beta > 0$ removes soft radiation
- $\beta < 0$ removes soft-collinear radiation

fails **soft drop condition** $\min(p_{\mathrm{T},1}, p_{T,2})/(p_{\mathrm{T},1} + p_{\mathrm{T},2}) > z_{\mathrm{cut}}\,(\Delta R_{12}/R_0)^{\beta}$

Jet Grooming Techniques (3)

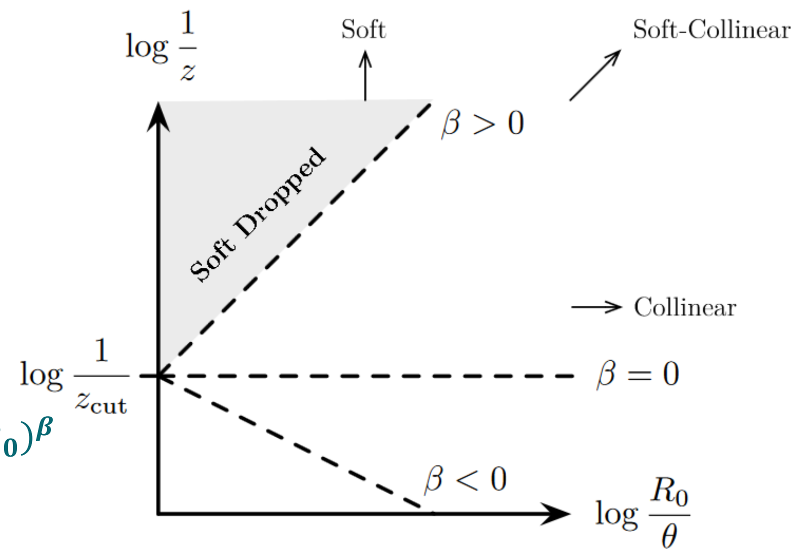
Soft Drop

Larkoski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146

De-clustering algorithm removes wide angle soft emissions inside any IRC safe clustered jet

1. Needs physically meaningful cluster sequence – recluster jet with C/A recursive recombination algorithm
2. Undo the last stage of C/A clustering (largest angular distances!) → check if sub-jets j_1, j_2 pass the soft drop condition

   $\min(p_{T,1}, p_{T,2})/(p_{T,1} + p_{T,2}) > z_{cut}\,(\Delta R_{12}/R_0)^{\beta}$
   with parameters $z_{cut}\sim 0.1$, β – R_0 is nominal jet size
3. If condition passed → original jet is soft dropped jet
4. If softer sub-jet fails, harder sub-jet is redefined as the new jet → procedure is iterated until no more sub-jets are dropped
5. If jet is a singleton and cannot be de-clustered anymore → **removed** from considerations (**tagging** mode) or considered as the **final soft-dropped jet** (**grooming** mode)



Controlling soft drop phase space
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Jet Substructure Observables

Relatively long list …

- Volatility, jet width/angularities, jet planarity, …
- Application depends on signal extraction efficiency and background rejection for a given search
- Some are very sensitive to e.g. pile-up – performance can be largely degraded in the experiment
- Some are hard to control experimentally – systematic uncertainties can be large

… recently most popular with experiments:

- Single jet mass
- Generalized angularities
- Splitting scale
- *N*-subjettiness
- Energy-energy correlations
- Soft drop mass

Jet Substructure Observables

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… recently most popular with experiments:

Single jet mass

CAN BE USED WITH ANY MEANINGFUL JET ALGORITHM

$$m^{\rm jet} = \sqrt{(E^{\rm jet})^2 - |\vec{p}^{\rm jet}|^2}$$

Powerful and indicative observable in (resonant) searches

Useful in tag direct or subsequent decays of (boosted) SM particles

Rule of thumb for light quark/gluon jets (from NLO)

$$\sqrt{\langle (m^{\rm jet})^2 \rangle_{\rm NLO}} \approx (0.1 - 0.2) \cdot p^{\rm jet} R$$

Ellis, Huston, Loch, Tönnesmann, Prog.Part.Nucl.Phys. 60 (2008) 484-551

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… recently most popular with experiments:

Single jet mass

Generalized angularities

CAN BE USED WITH ANY MEANINGFUL JET ALGORITHM

$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \times (R_i/R_0)^\beta$, with $z_i^\kappa = \left(p_{\mathrm{T},i}/\sum_{k \in \text{jet}} p_{\mathrm{T},k}\right)^\kappa$

E.g., **jet width** ($\kappa = 1, \beta = 1$) useful for quark-gluon tagging

Larkoski, Thaler, Waalewijn, JHEP 11 (2014) 129

Jet Substructure Observables

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… recently most popular with experiments:

- Single jet mass
- Generalized angularities
- Splitting scale

REQUIRES MEANINGFUL RECURSIVE RECOMBINATION JET CLUSTER SEQUENCE

$$d_{ij} = \min(p_{\mathrm{T},i}^2, p_{\mathrm{T},j}^2) \times \Delta R_{ij}^2 \Rightarrow y_{\mathrm{scale}}^{i \to j} = \sqrt{d_{ij}}/\Delta R_{ij}$$

Has expectation value for pronged decays, e.g. $d_{12} \approx (m/2)^2$

d_{12} $(t \to Wb)$ and d_{23} $(W \to qq')$ used in hadronic top decay tagging

Butterworth, Cox, Forshaw, Phys.Rev. D65(2002) 096014

Jet Substructure Observables

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… recently most popular with experiments:

- Single jet mass
- Generalized angularities
- Splitting scale
- N-subjettiness
  - $\tau_N = \sum_k p_{\mathrm{T},k} \times \min\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\} / \left(R_0 \sum_k p_{\mathrm{T},k}\right)$
  - Likelihood measure for jet to have 1 … N subjets
  - Ratios like $\tau_{21} = \tau_2/\tau_1$ and $\tau_{32} = \tau_3/\tau_2$ highly indicative of 2- or 3-prong decay structure – used in hadronic top decay tagging

CAN BE USED WITH ANY MEANINGFUL JET ALGORITHM

Thaler, Van Tilburg, JHEP 1103(2011) 015

Jet Substructure Observables

Relatively long list …

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… recently most popular with experiments:

- Single jet mass
- Generalized angularities
- Splitting scale
- N-subjettiness
- Energy-energy correlations
  - Employs N-point energy correlation functions between jet constituents

CAN BE USED WITH ANY MEANINGFUL JET ALGORITHM

$$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\cdots<i_N\in\mathrm{Jet}}\left(\prod_{a=1}^{N} p_{\mathrm{T}i_a}\right)\left(\prod_{b=1}^{N-1}\prod_{c=b+1}^{N} R_{i_b i_c}\right)^{\beta}$$

Larkoski, Salam, Thaler, JHEP 1306(2013) 108

Jet Substructure Observables

Relatively long list …

Volatility, jet width/angularities, jet planarity, …

Application depends on signal extraction efficiency and background

0-point corr. $\mathrm{ECF}(0,\beta) = 1$

1-point corr. $\mathrm{ECF}(1,\beta) = \sum_{i\in\mathrm{jet}} p_{\mathrm{T}i}$

2-point corr. $\mathrm{ECF}(2,\beta) = \sum_{i<j\in\mathrm{jet}} p_{\mathrm{T}i}\, p_{\mathrm{T}j} \left(R_{ij}\right)^{\beta}$

3-point corr. $\mathrm{ECF}(3,\beta) = \sum_{i<j<k\in\mathrm{jet}} p_{\mathrm{T}i}\, p_{\mathrm{T}j} p_{\mathrm{T}k} \left(R_{ij}R_{ik}R_{jk}\right)^{\beta}$

4-point corr. $\mathrm{ECF}(4,\beta) = \sum_{i<j<k<l\in\mathrm{jet}} p_{\mathrm{T}i}\, p_{\mathrm{T}j} p_{\mathrm{T}k} p_{\mathrm{T}l} \left(R_{ij}R_{ik}R_{il}R_{jk}R_{jl}R_{kl}\right)^{\beta}$

Energy-energy correlations

Employs N-point energy correlation functions between jet constituents

$$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\cdots<i_N\in\mathrm{Jet}} \left(\prod_{a=1}^{N} p_{\mathrm{T}i_a}\right) \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^{N} R_{i_b i_c}\right)^{\beta}$$

Larkoski, Salam, Thaler, JHEP 1306(2013) 108

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Relatively long list …

Volatility, jet width/angularities, jet planarity, …

Application depends on signal extraction efficiency and background

Double-ratios indicate jet source

Generally $C_N^{(\beta)} = (\mathrm{ECF}(N+1,\beta)\mathrm{ECF}(N-1,\beta))/ECF(N,\beta)^2$

$C_1^{(\beta)}$ is useful for quark/gluon separation for small $\beta \simeq 0.2$ – exploits different soft radiation patterns (uses 2-point correlations)

$C_2^{(\beta)}$ helps with boosted $\mathrm{W}/Z/H$ identification with $\beta \simeq 0.5$ better for high mass and $\beta \simeq 2$ better for lower mass resonances – at a fixed p_{T} (uses 3-point correlations)

$C_3^{(\beta)}$ distinguishes QCD jets from boosted top quarks best for $\beta \approx 1-2$ (uses 4-point correlations)

Energy-energy correlations

Employs N-point energy correlation functions between jet constituents

$$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\cdots<i_N\in\mathrm{Jet}}\left(\prod_{a=1}^{N} p_{\mathrm{T}i_a}\right)\left(\prod_{b=1}^{N-1}\prod_{c=b+1}^{N} R_{i_b i_c}\right)^{\beta}$$

Larkoski, Salam, Thaler, JHEP 1306(2013) 108

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`Eur.Phys.J. C76 (2016), no.3, 154`

Boosted boson tagging in ATLAS

$$C_2^{(\beta)} = \left(\mathrm{ECF}(3,\beta)\mathrm{ECF}(1,\beta)\right)/\left(\mathrm{ECF}(3,\beta)\right)^2$$

and optimized for 2-prong decays

$$D_2^{(\beta)} = \left(\mathrm{ECF}(3,\beta)\mathrm{ECF}(1,\beta)\right)/\left(\mathrm{ECF}(3,\beta)\right)^3$$

with $\beta = 1{,}2$ studied

`Larkoski, Moult, Neill, JHEP 1409 (2014)`

Energy-energy correlations

Employs N-point energy correlation functions between jet constituents

$$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\cdots<i_N\in\mathrm{Jet}}\left(\prod_{a=1}^{N} p_{\mathrm{T}i_a}\right)\left(\prod_{b=1}^{N-1}\prod_{c=b+1}^{N} R_{i_b i_c}\right)^{\beta}$$

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… recently most popular with experiments:

- Single jet mass
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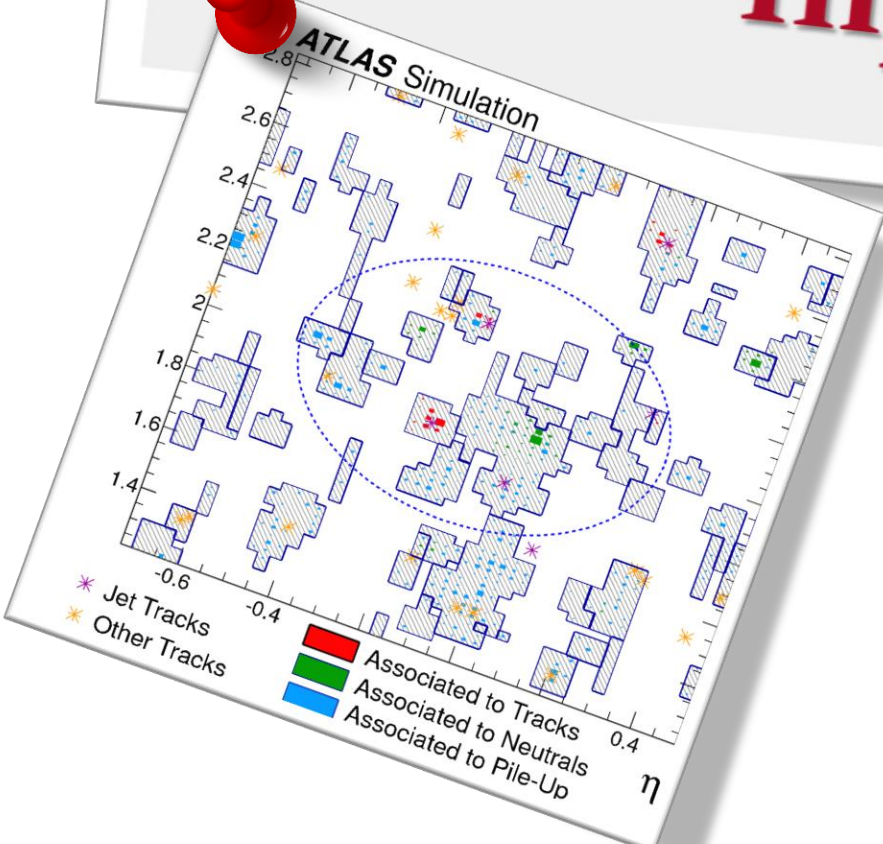
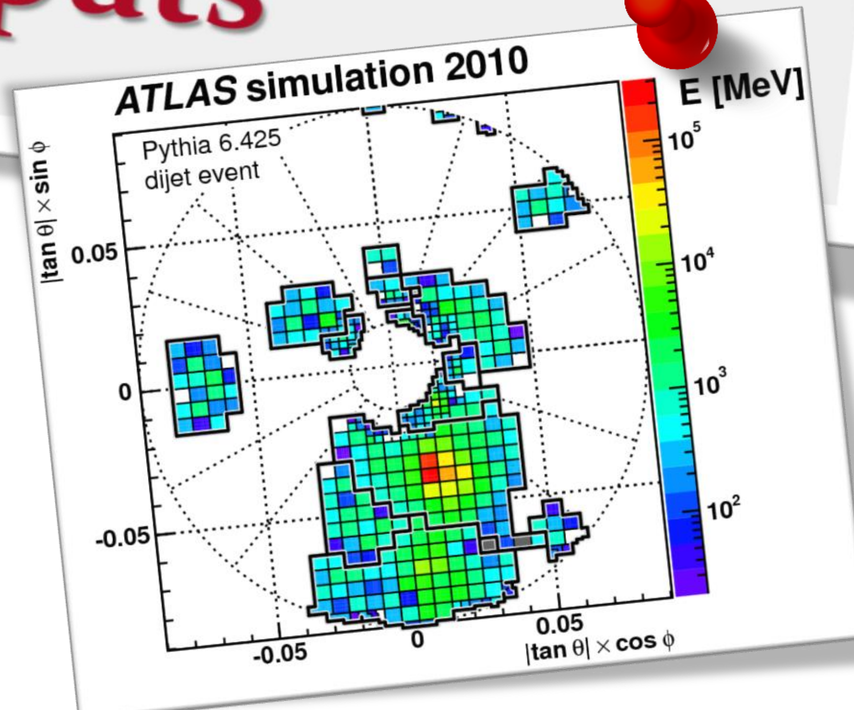
- Splitting scale
- N-subjettiness
- Energy-energy correlations
- Soft drop mass
  - Recalculate mass of soft dropped jet – e.g. gives experimental access to evaluation of calculated internal dynamics of QCD jets

Jet Reconstruction Inputs





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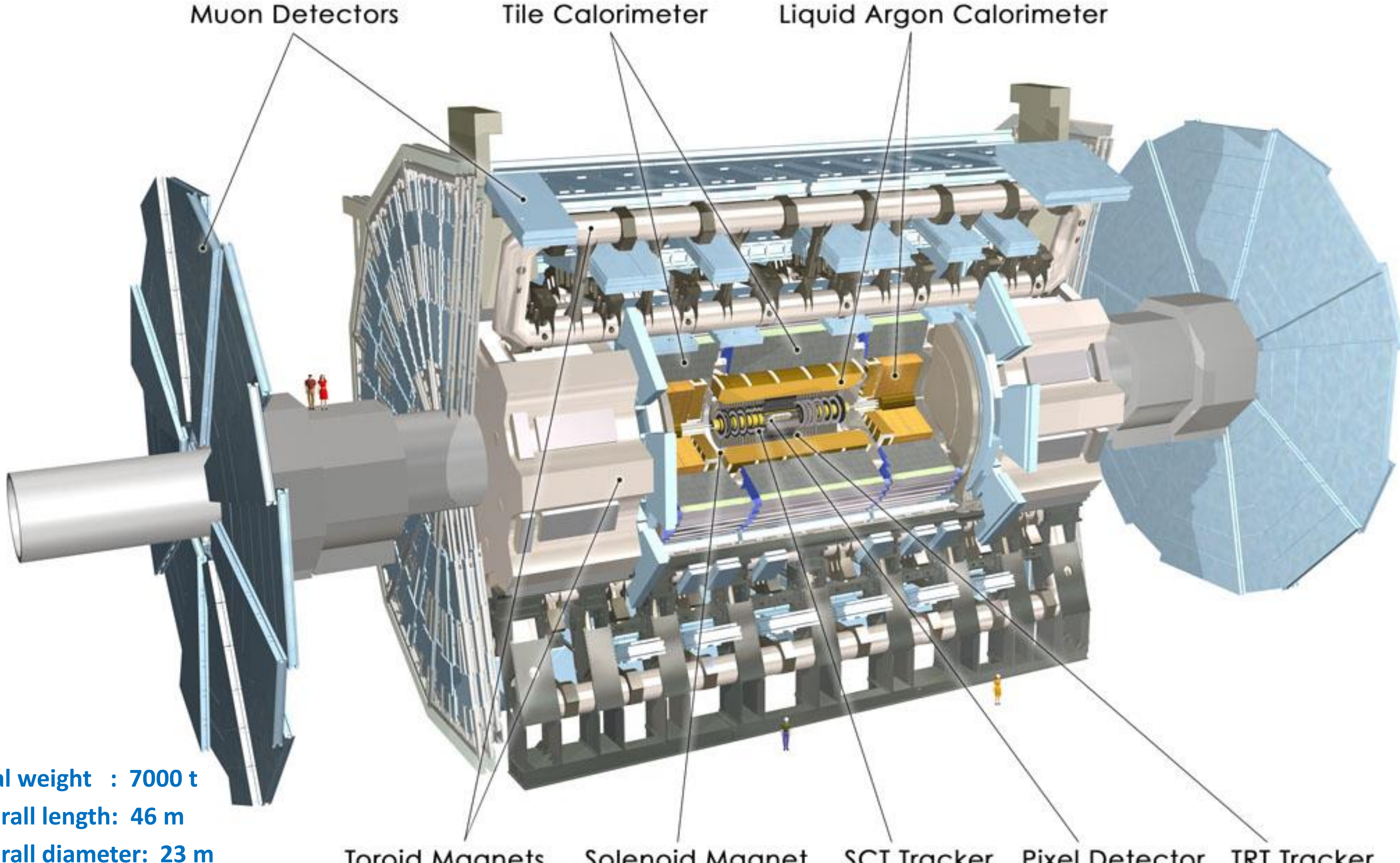
A multi-purpose detector system



Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid + (varying) toroid field

Detectors for Jet Substructure Reconstruction

Calorimeters (Calo)

- Provides principal signals for jet kinematics and substructure measurement
  - Full coverage within $|\eta| < 4.9$ with depth $\gtrsim 10\ \lambda_{\mathrm{int}}$
- Highly segmented for energy flow measurements (~188,000 channels)
  - Granularity in $\Delta\eta \times \Delta\varphi = 0.025 \times \pi/128$ (central EM, $|\eta| \lesssim 2.5$)
  - Up to seven depth layers (*samplings*)

Inner detector (ID)

- Provides charged particle tracks and vertices
  - Coverage $|\eta| < 2.5$, $p_{\mathrm{T}} > 500$ MeV
  - Pile-up mitigation and overall jet calibration refinement by associating vertex with jets and/or sub-jets
  - Track-assisted measurement of flow structures – improved angular component in substructure and mass reconstruction
- Particle flow
  - Replace charged response in calorimeter with kinematics from well-measured tracks

Calorimeter Signals: Topo-cluster

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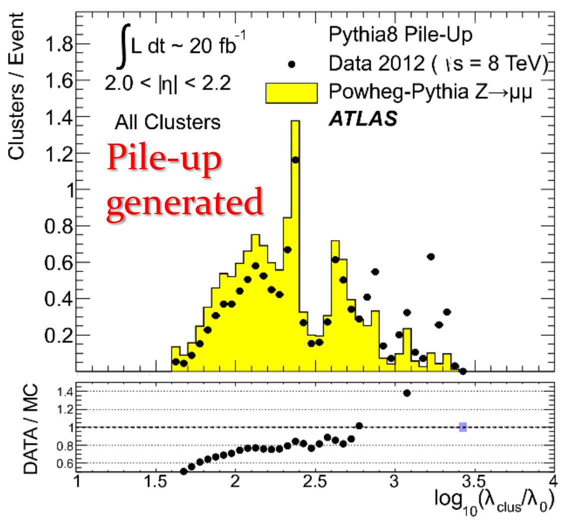
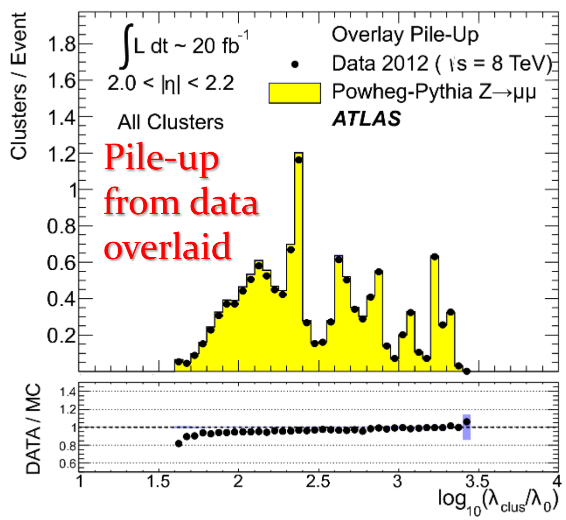
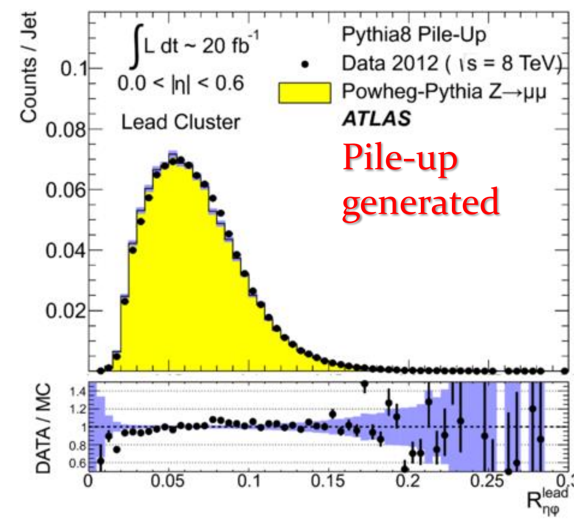
Topological clustering

- Collects signals from individual or close-by particles into 3-dimensional *energy blobs*
  - Connect cells by following spatial signal significance patterns with seed and growth control
- Massless pseudo-particle representation
  - Recombines (weighted) cell energies to four-momentum $P_{\mathrm{clus}} = (E_{\mathrm{clus}}, \eta_{\mathrm{clus}}, \varphi_{\mathrm{clus}}, m_{\mathrm{clus}} = 0)$
  - Cluster direction with respect to nominal collision vertex
- Cluster signal on basic (EM) or locally calibrated (LCW) scale
  - $P_{\mathrm{clus}} = P_{\mathrm{clus}}^{\mathrm{EM}} = \left(E_{\mathrm{clus}}^{\mathrm{EM}}, \eta_{\mathrm{clus}}^{\mathrm{EM}}, \varphi_{\mathrm{clus}}^{\mathrm{EM}}, 0\right)$ or $\boldsymbol{P_{clus} = P_{clus}^{\mathrm{LCW}} = \left(E_{clus}^{\mathrm{LCW}}, \eta_{clus}^{\mathrm{LCW}}, \varphi_{clus}^{\mathrm{LCW}}, 0\right)}$
  - **LCW** uses cluster shapes – **preferred for substructure** but some sensitivity to pile-up





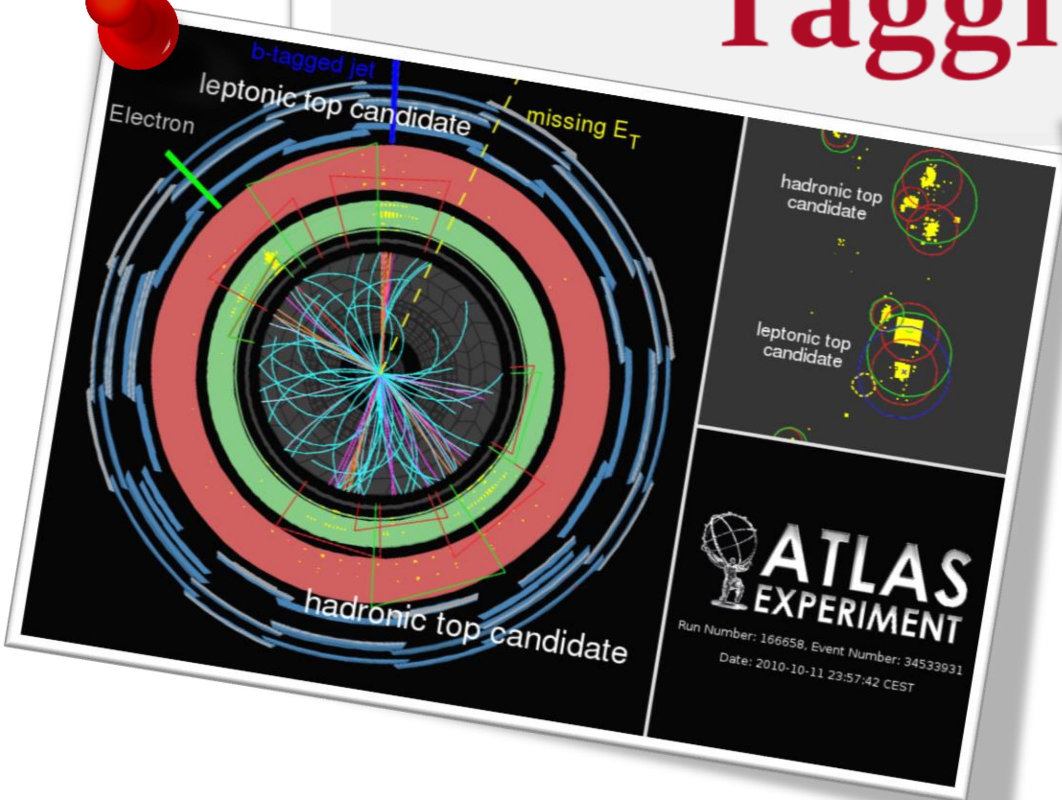
Topo-cluster depth location measure $\log_{10}(\lambda_{\mathrm{clus}}/1\ \mathrm{mm})$

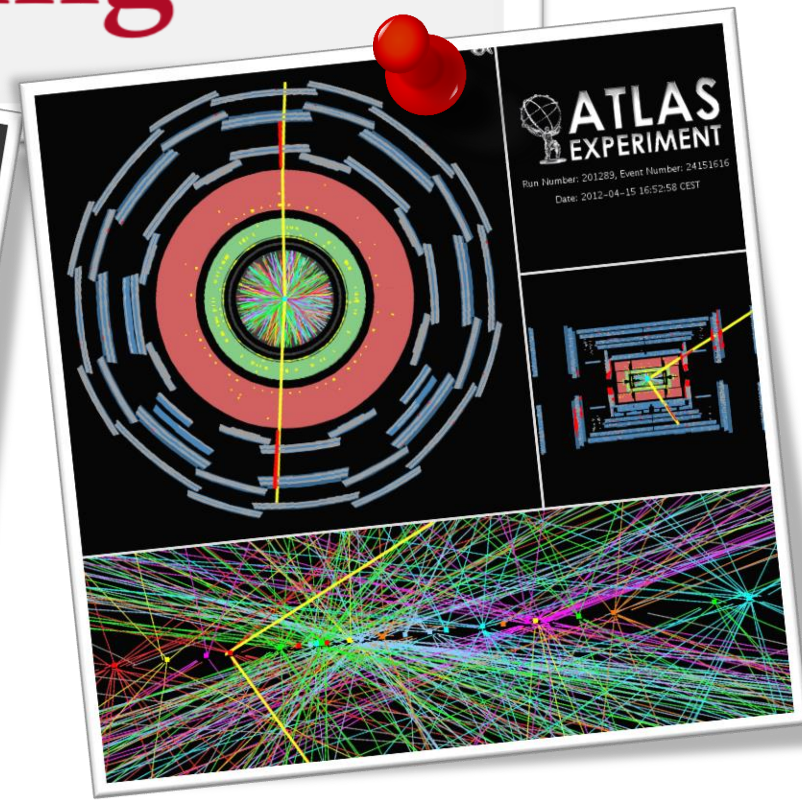


Leading topo-cluster size $R_{\eta\varphi}^{\mathrm{lead}}$

Eur.Phys.J. C77 (2017)

Substructure Performance & Tagging

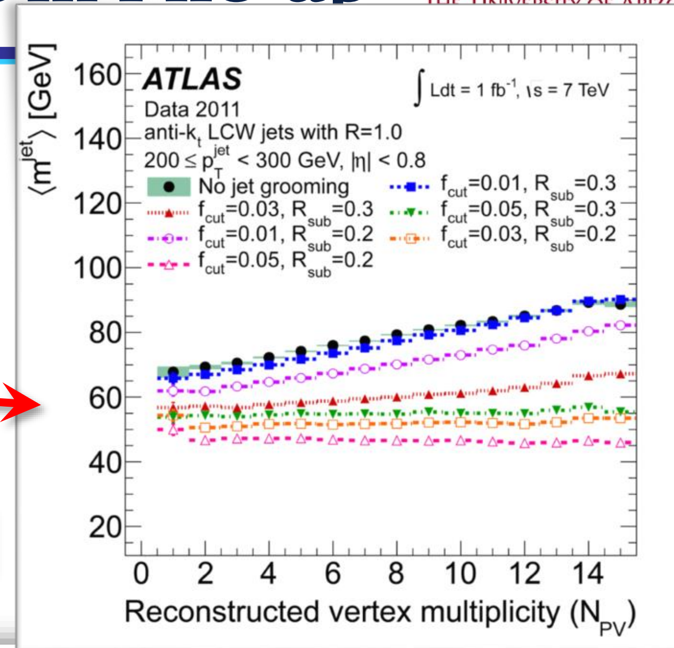


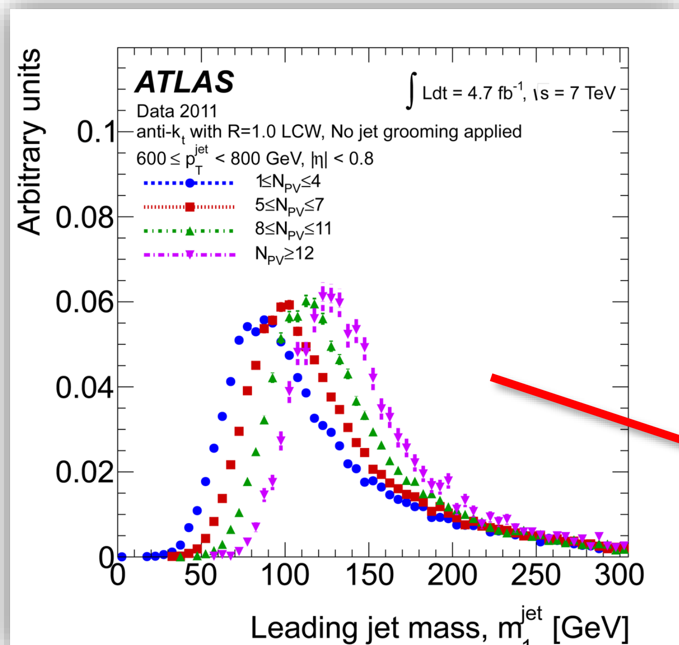


Single Jet Mass Measurement in Pile-up

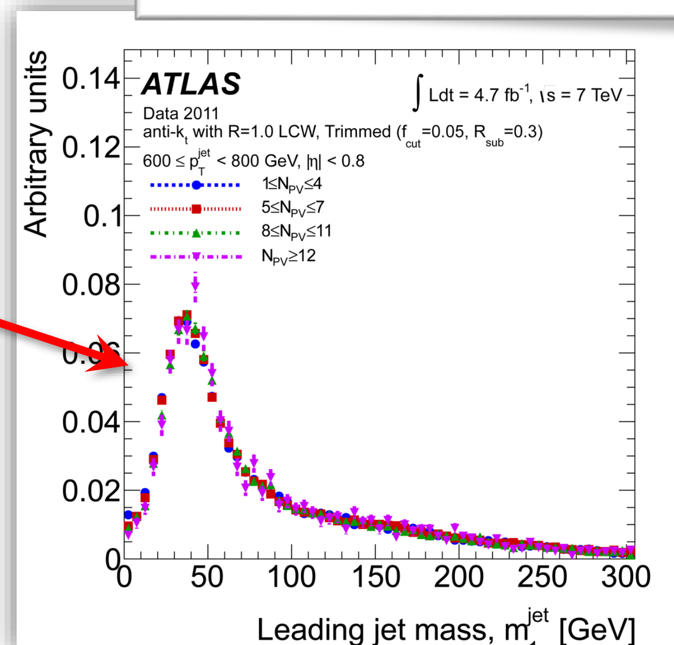
Apply grooming techniques to mitigate pile-up effects

Pile-up affects average reconstructed mass for jets





JHEP 1309 (2013) 76



Anti-k_t, $R = 1.0$

$600 \leq p_T^{\rm jet} < 800$ GeV

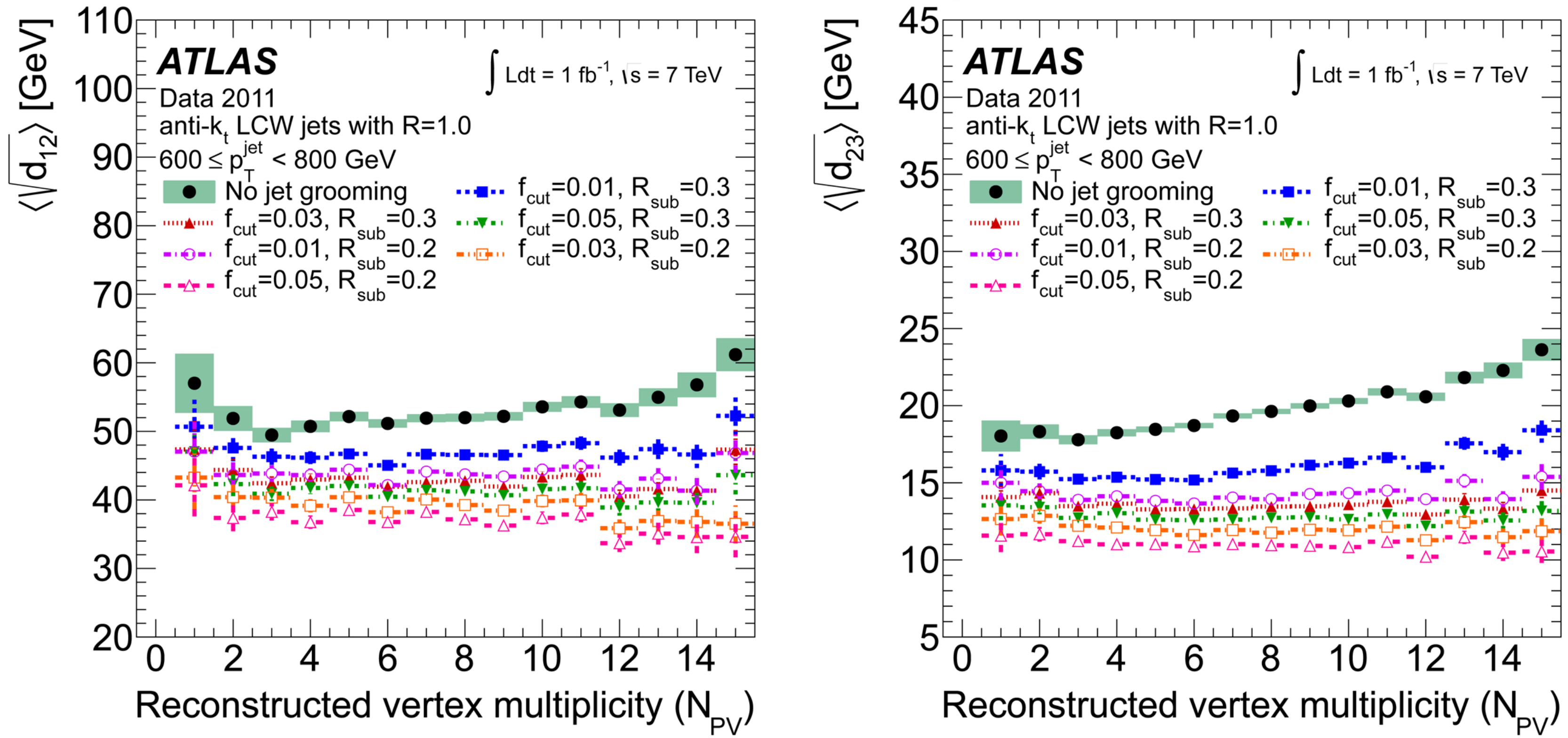
Substructure in Pile-up (1)

Pile-up mitigation by trimming

Splitting scales

Anti-k_t, $R = 1.0$

$600 \leq p_{\mathrm{T}}^{\mathrm{jet}} < 800$ GeV



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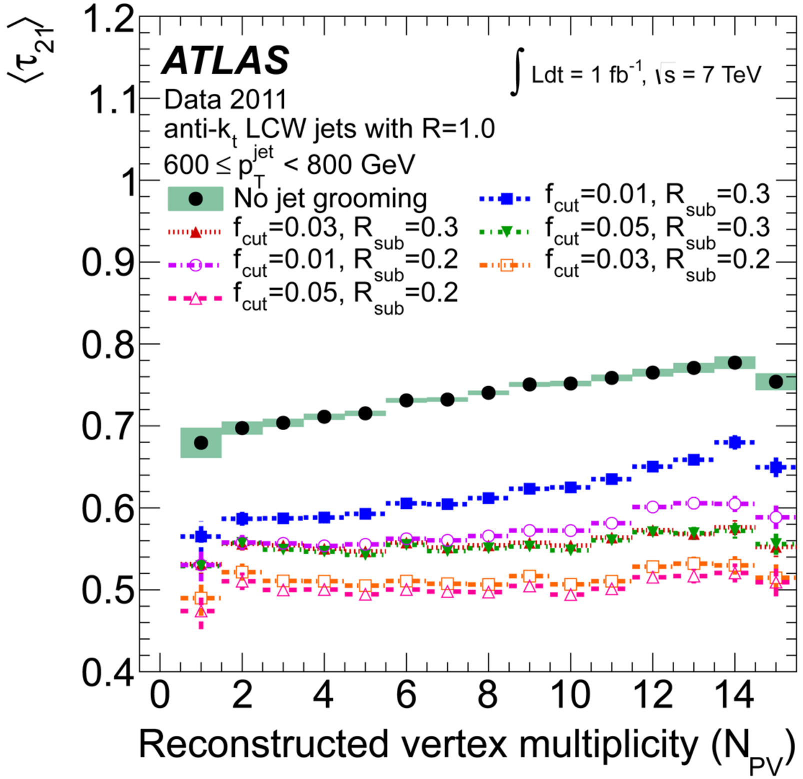
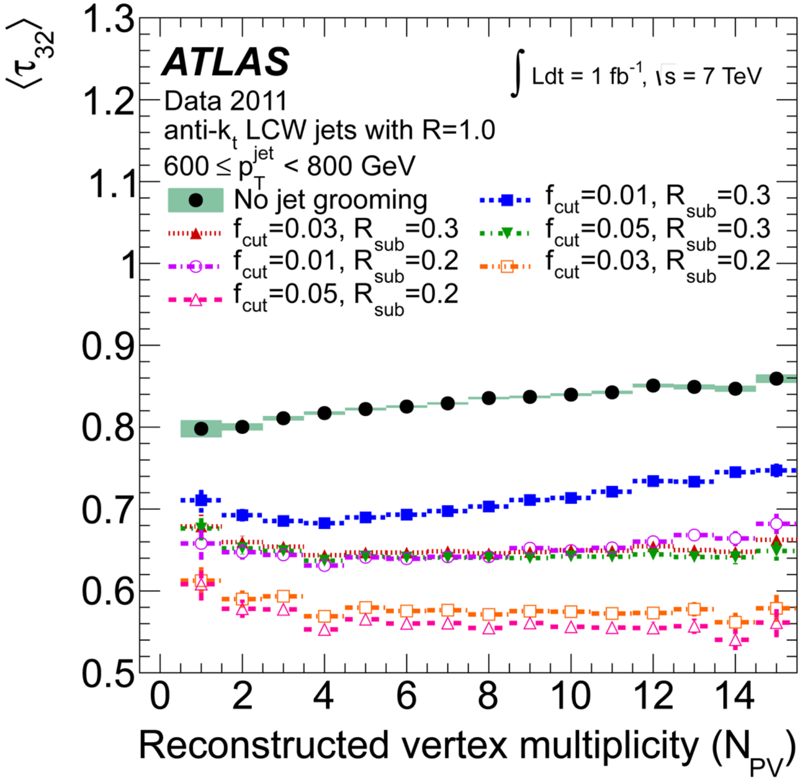
Pile-up mitigation by trimming

***N*-subjettiness**

Anti-k_t, $R = 1.0$

$600 \leq p_{\mathrm{T}}^{\mathrm{jet}} < 800$ GeV





JHEP 1309 (2013) 76

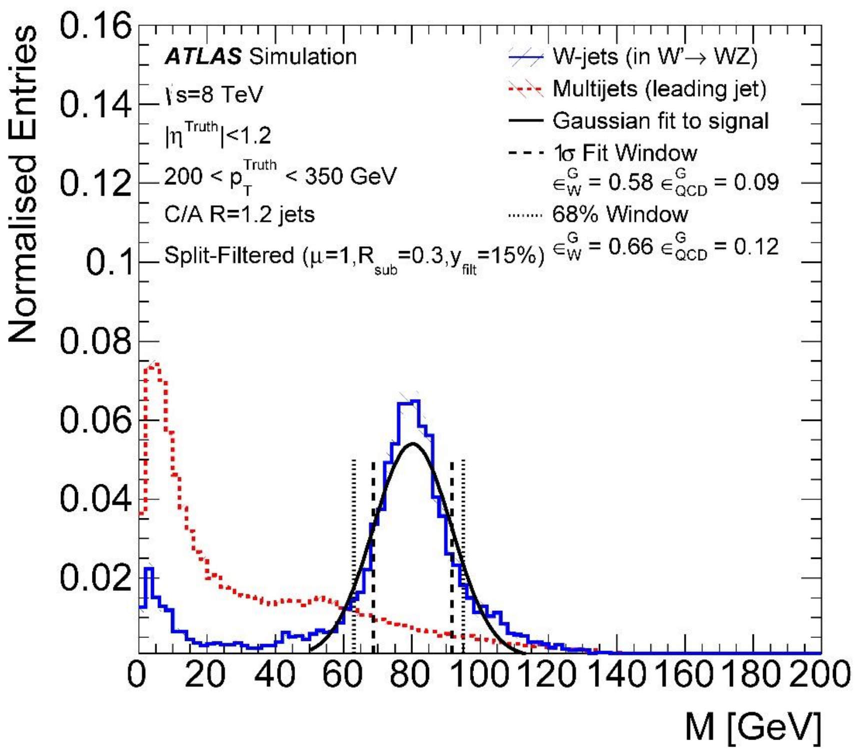
Effectiveness of Grooming Techniques

Grooming techniques/configurations need optimization

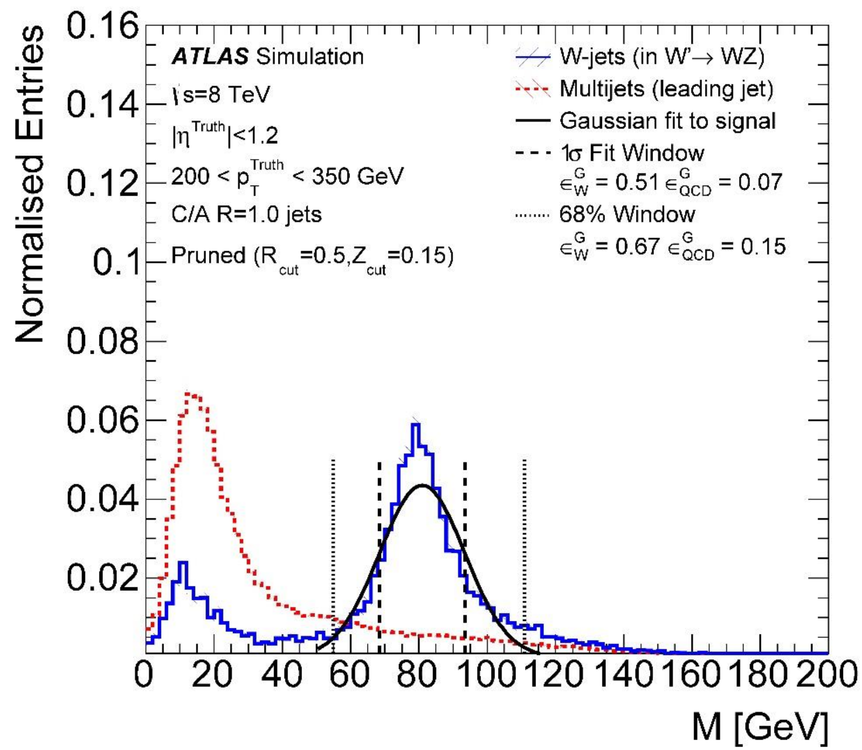
Adapt to search goal – signal efficiency and background rejection

Example: grooming in simulated $W' \to WZ$ with $W \to qq$

EPJC 76 (2016) No 3. 154



split-filtered C/A $R = 1.2$ jets



pruned C/A $R = 1.0$ jets

Configuring Tagging

SM $t\bar{t}$ final state with one full hadronic top decay

- Efficient event selection from semi-leptonic decay
  - Lepton and missing transverse momentum triggers
  - Offline event selection based on leptons, missing transverse momentum and number of (small radius) jets (e.g., $N_{\mathrm{jet}} \geq 4$)
- Three-prong decay $t \rightarrow Wb \rightarrow qq'b$
  - Measure performance of substructure observables in top decay dynamics – useful for searches for new particles decaying into top quarks
- Enhanced sample for two-prong decay $W \rightarrow qq'$
  - Most efficient source for hadronic W decays

Allows evaluation of W or top tagging configurations

- Momentum and topology selection of large radius jet ($R_{\mathrm{jet}} = 1$)
  - E.g., $p_{\mathrm{T}}^{\mathrm{jet}} > 200$ GeV, large angular distance $\Delta R(W,b) > R_{\mathrm{jet}}$, two-prong decay indication (τ_{21} small, $\sqrt{d_{12}} \approx m_W$, ...) → contains (only) hadronic W decay
  - E.g., $p_{\mathrm{T}}^{\mathrm{jet}} > 350$ GeV, small angular distance $\Delta R(W,b) < R_{\mathrm{jet}}$, three-prong decay indication ($\sqrt{d_{12}} \approx m_{\mathrm{top}}/2$, $\sqrt{d_{23}} \approx m_W/2$, ...) → contains hadronic top decay
- W can be reconstructed in large radius jets in enhanced top sample!

N-subjettiness & Splitting Scale

Modeling in $t\bar{t}$ decays

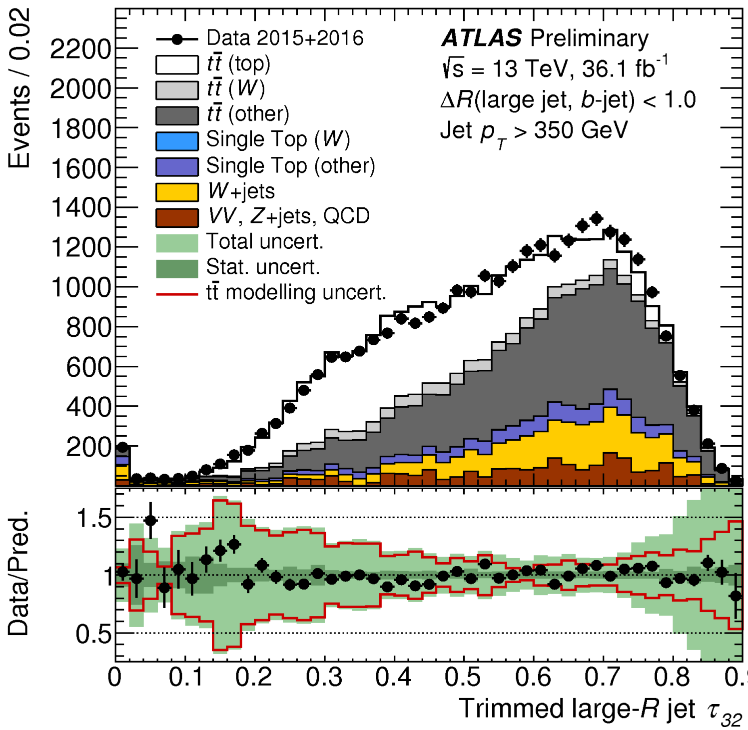
Complex measures in a physics analysis application

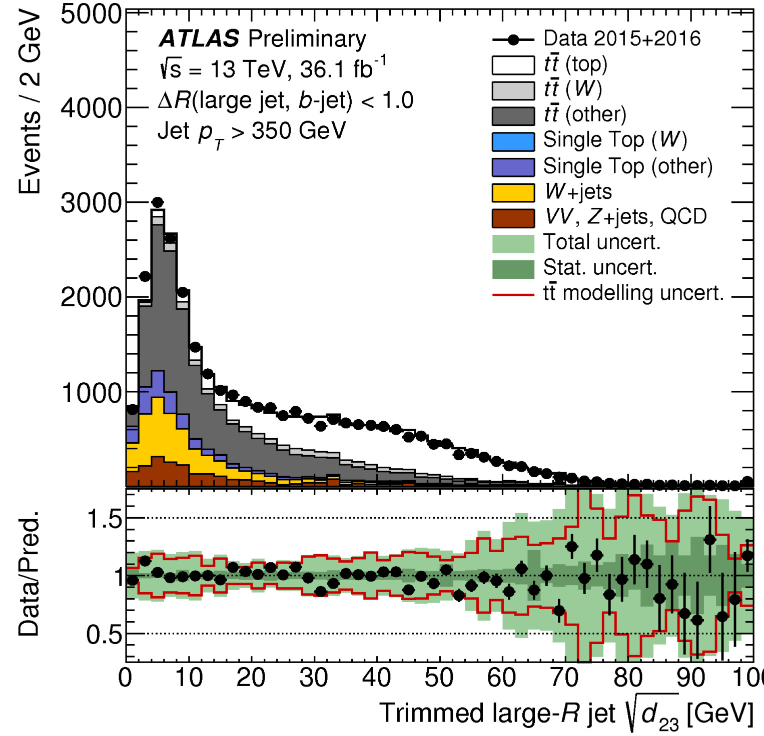
Understanding non-trivial distributions in data → input to BDTs, (deep) neural networks (DNN), machine learning (ML), …

Anti-k_t, $R = 1.0$

$p_T^{\text{jet}} > 350$ GeV

(**top** enhanced)





ATLAS-CONF-2017-064 (2018)

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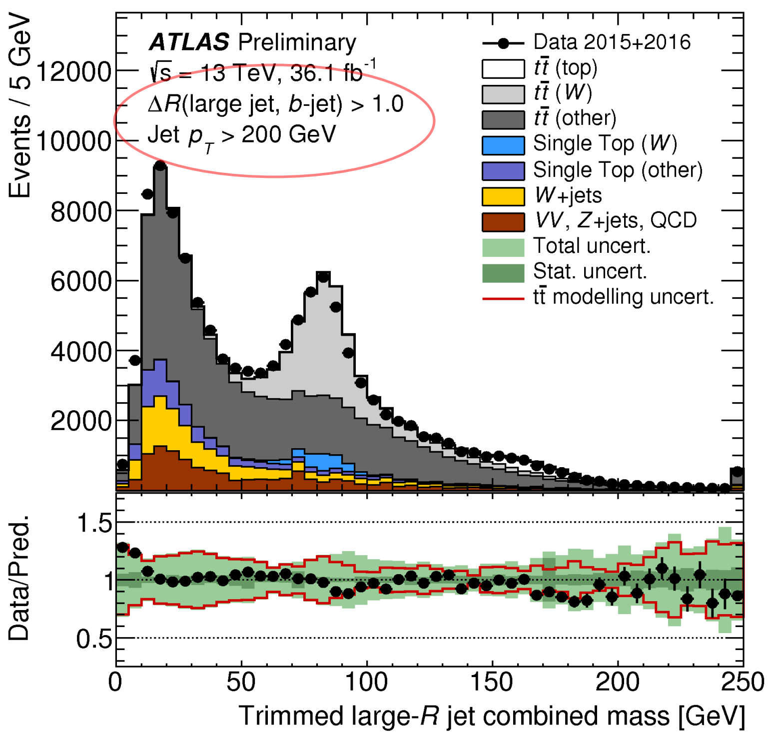
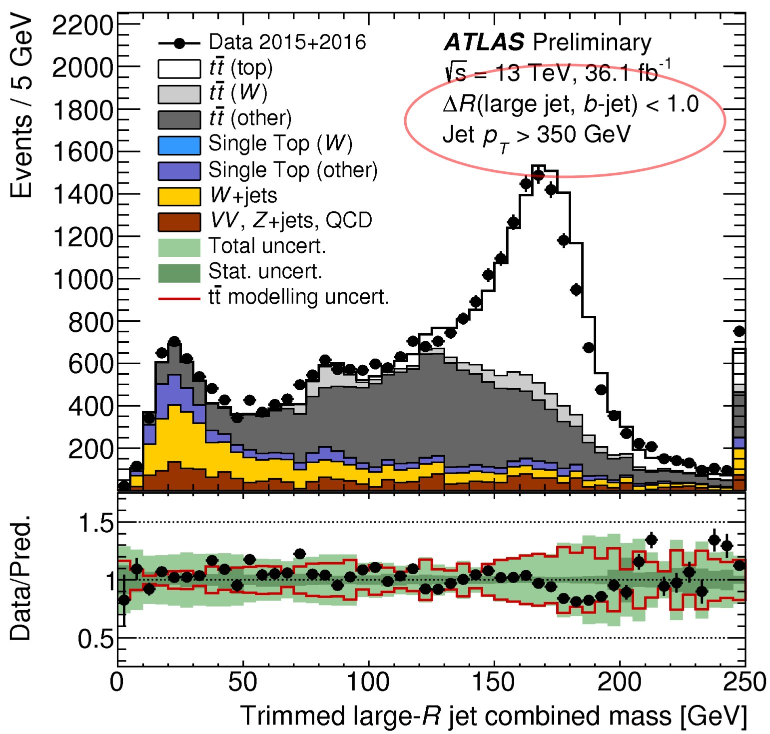
Decay Tagging in $t\bar{t}$ Final State

Anti-k_t, $R = 1.0$
$p_T^{\text{jet}} > 200$ GeV
(***W*** enhanced)

Anti-k_t, $R = 1.0$
$p_T^{\text{jet}} > 350$ GeV
(**top** enhanced)





`ATLAS-CONF-2017-064 (2018)`

Boosted Top Decay in ATLAS

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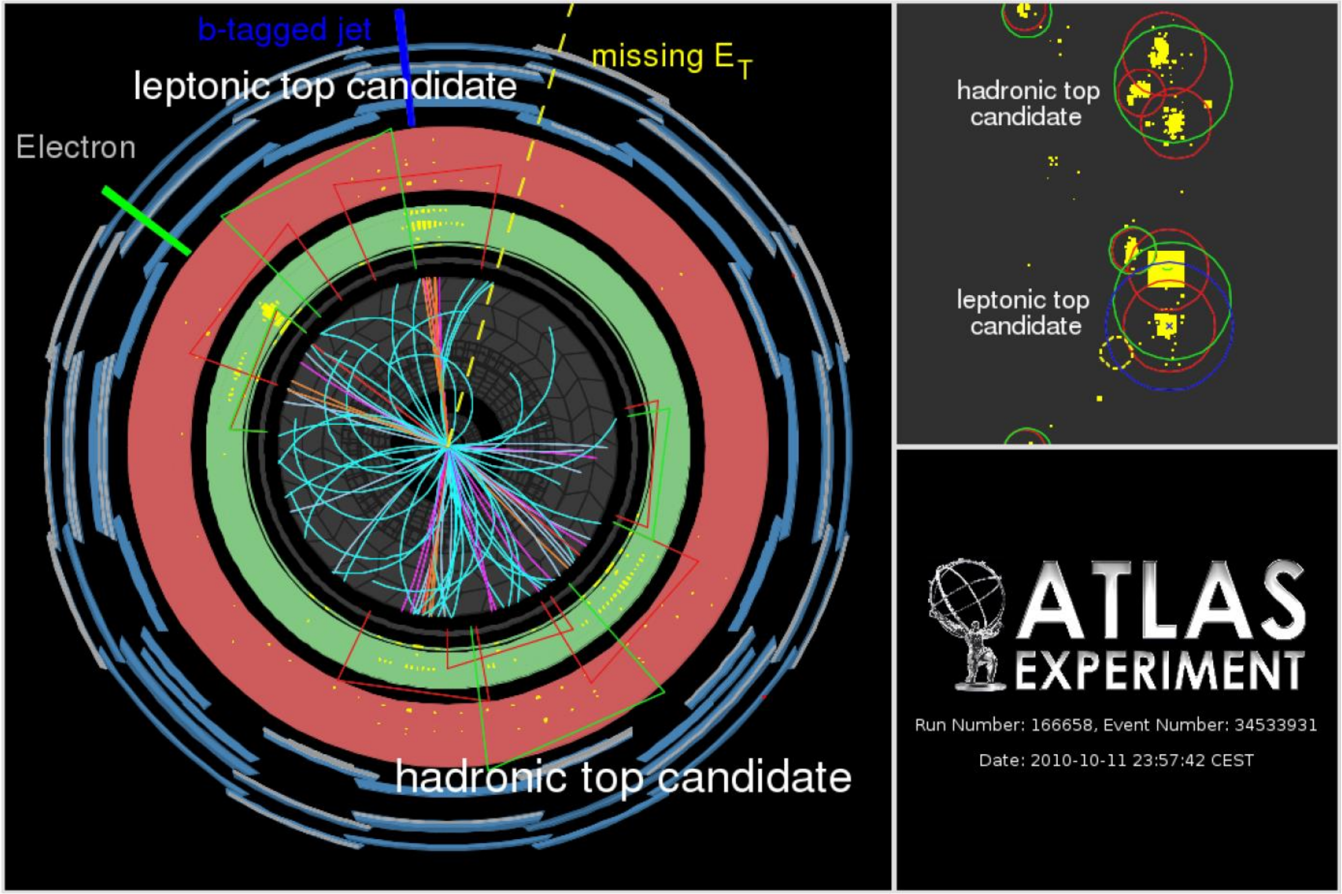


Leptonic top	E_T^{miss}: E_T = 36 GeV, ϕ = -1.5 electron: p_T = 145 GeV, η = 1.1, ϕ = 2.5 jet: index = 1, E_T = 194 GeV, η = 1.2, ϕ = 1.7, m_j = 17 GeV
Hadronic top (R =0.4 clustering)	jet 2, E_T = 155 GeV, η = 1.1, ϕ = -0.7 rad, m_j = 22.7 GeV + jet 3, E_T = 113 GeV, η = 1.3, ϕ = -1.7 rad, m_j = 14 GeV + jet 4, E_T = 54 GeV, η = 0.6, ϕ = -1.7 rad, m_j = 8 GeV
Hadronic top (R =1.0 clustering)	jet 1, E_T = 356 GeV, η = 1.3, ϕ = -1.1 rad, m_j = 197 GeV $\sqrt{d_{12}}$ = 110, $\sqrt{d_{23}}$ = 40

Much more to say …

Improving jet substructure

Mass measurement improvement

Track-assisted mass $m_{\mathrm{TA}} = p_{\mathrm{T}}^{\mathrm{calo}} / p_{\mathrm{T}}^{\mathrm{track}} \times m_{\mathrm{track}}$

Combining m_{calo} and m_{TA}

Track-Calo-Cluster (TCC)

Using calorimeter response and track direction – efficient at high jet p_{T}

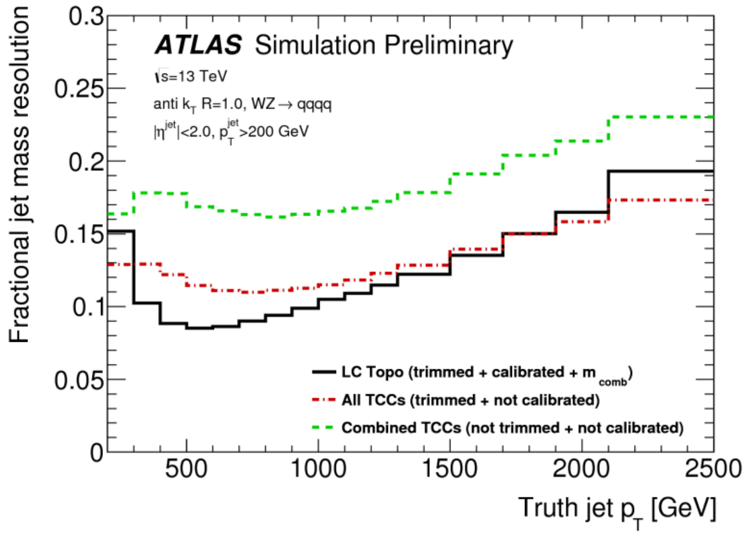
Track-assisted & TCC substructure

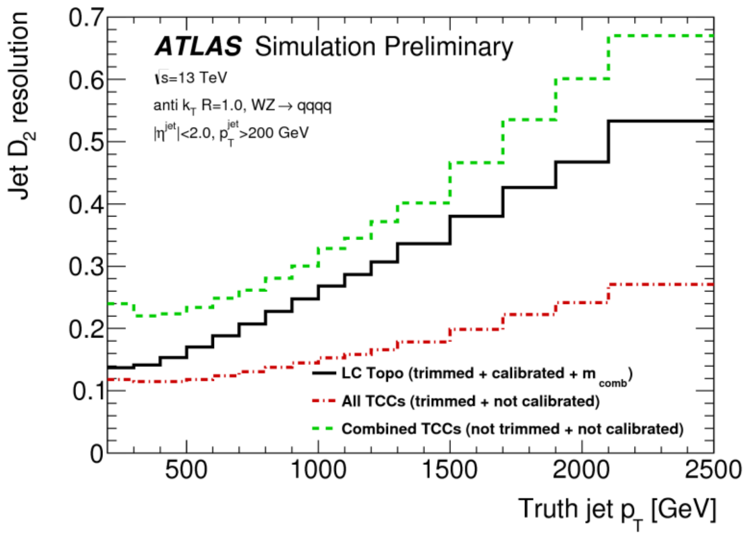
E.g., energy-energy correlation D_2

Reclustering

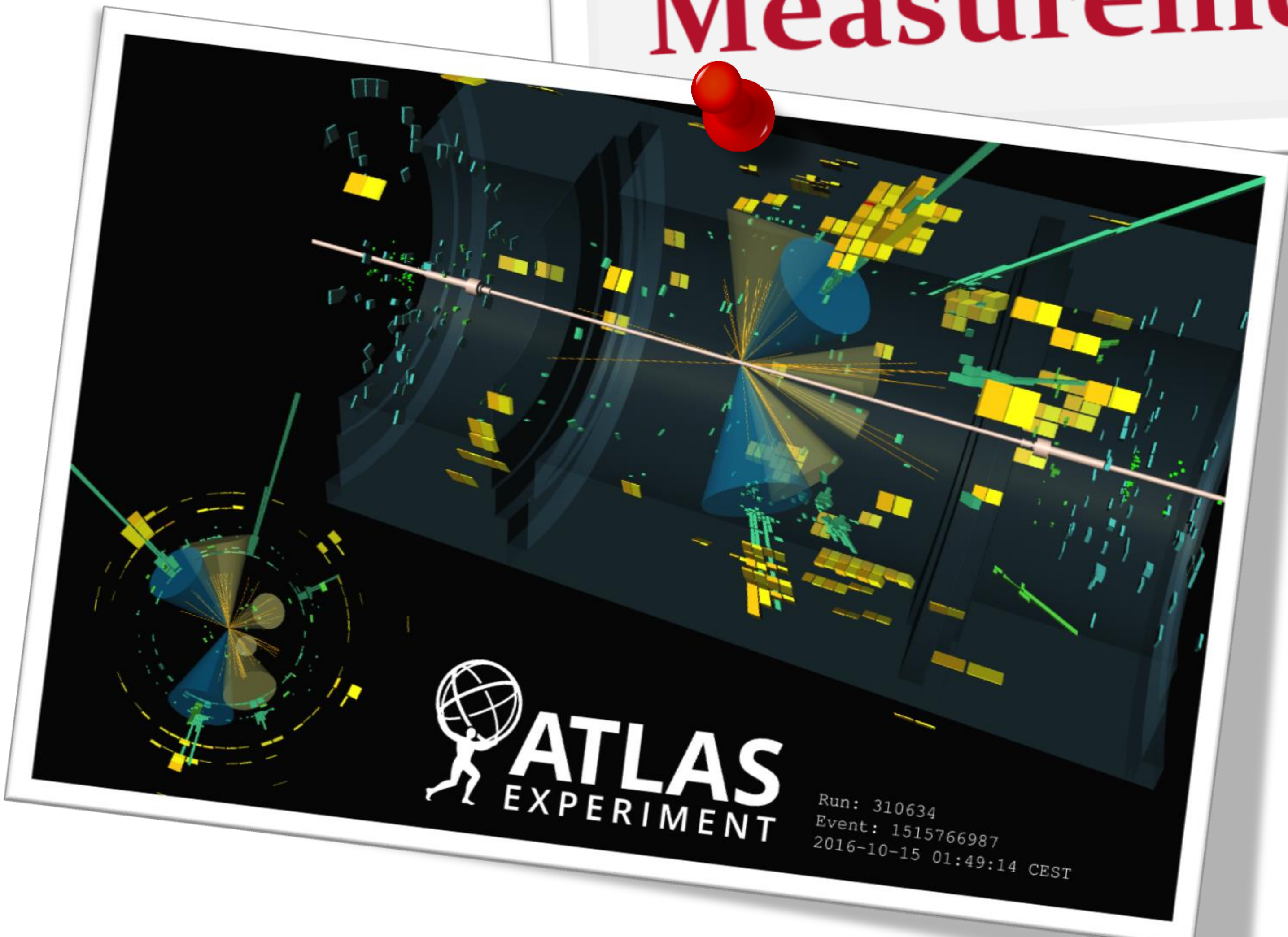
Cluster fat jets from narrow jets

Fully calibrated and pile-up corrected





Measurements



Soft Drop Mass Measurement

Predictions for $\rho = m^{\text{soft-drop}} / p_{\text{T}}^{\text{ungroomed}}$

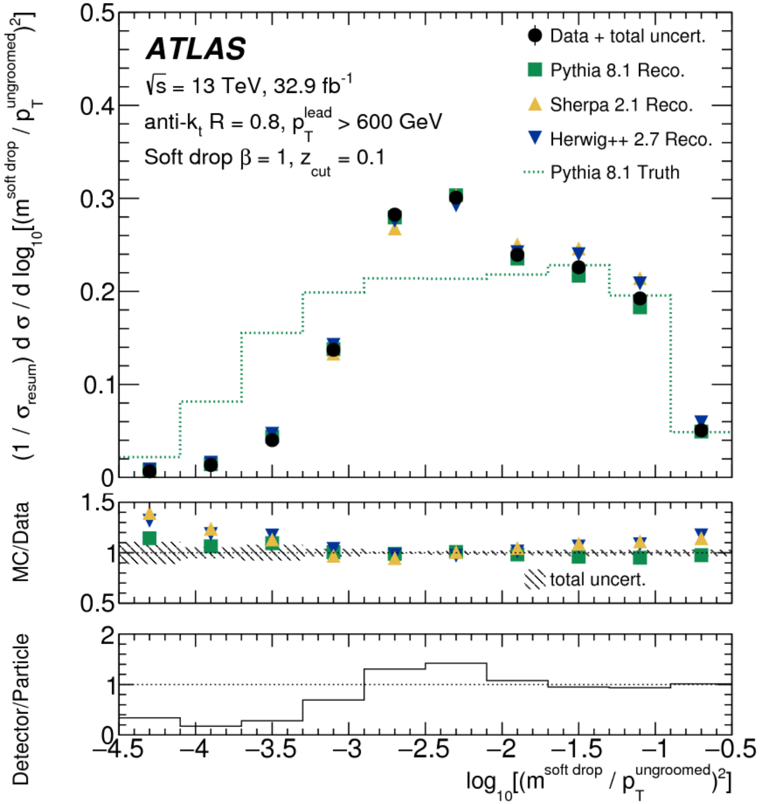
- Available (recently) NLO (order α_s) + NLL (resummation), LO + NNLL

Measurements

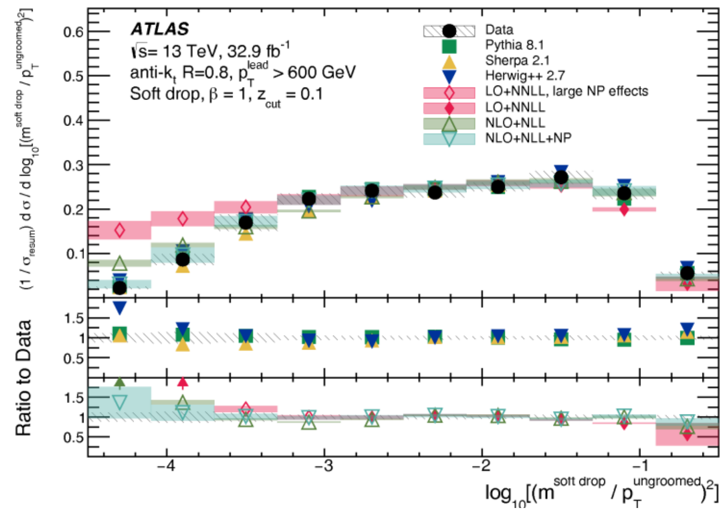
- Evaluate calculations of ρ using data
  - $\log_{10}(\rho^2)$ distributions reflect internal jet dynamics
- Algorithm and selections
  - Anti-k_t, $R = 0.8$ jets
  - Di-jet topology with $p_{\text{T},1} > 600$ GeV and $p_{\text{T},1}/p_{\text{T},2} < 1.5$
  - Soft drop configuration $z_{\text{cut}} = 0.1$, $\beta = \{0,1,2\}$
- Dominating systematic uncertainties
  - Calorimeter (topo-cluster) energy scale (*bottom-up* approach)
  - Modeling – limitations in fixed-order (particle) generators (PYTHIA and SHERPA)

Soft Drop Mass Measurement - Results

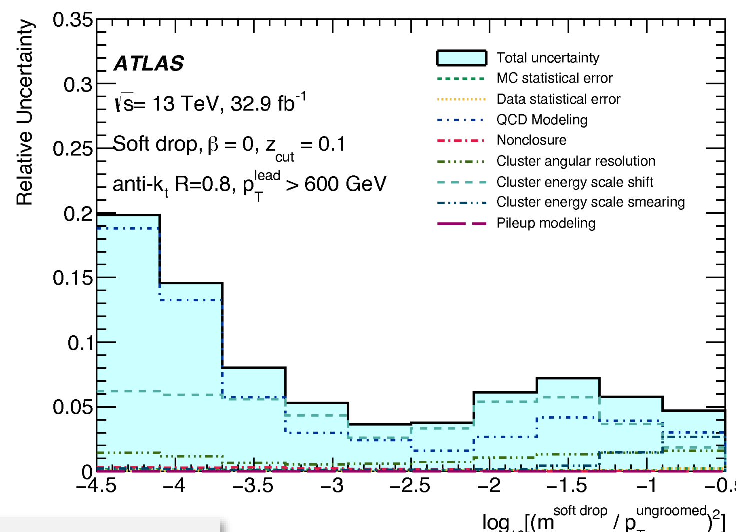
Detector-level …



… unfolded measurements



Systematic uncertainties ⟶



arXiv:1711.08341 (2017)

Soft Drop Mass – Interpretation

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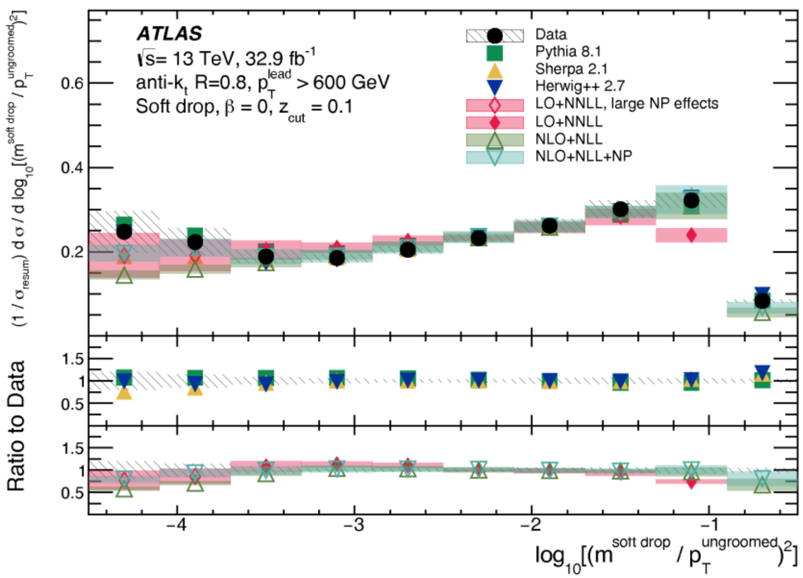
$\beta = 0$

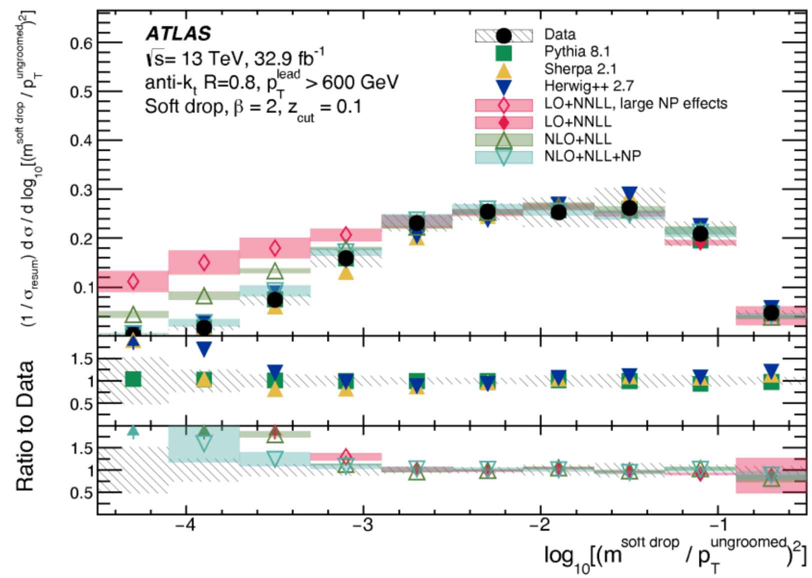
Removes soft→collinear radiation



arXiv:1711.08341 (2017)

$\beta = 2$

Removes soft radiation



arXiv:1711.08341 (2017)

Soft Drop Mass – Interpretation

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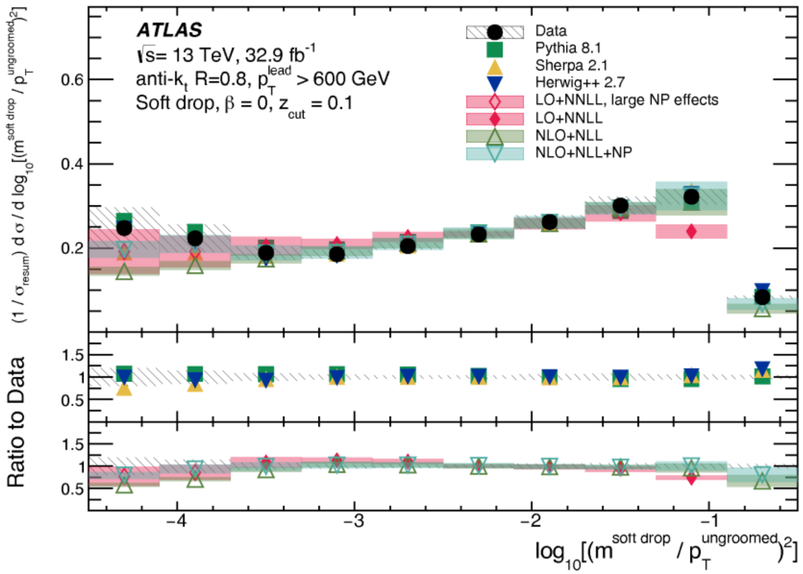
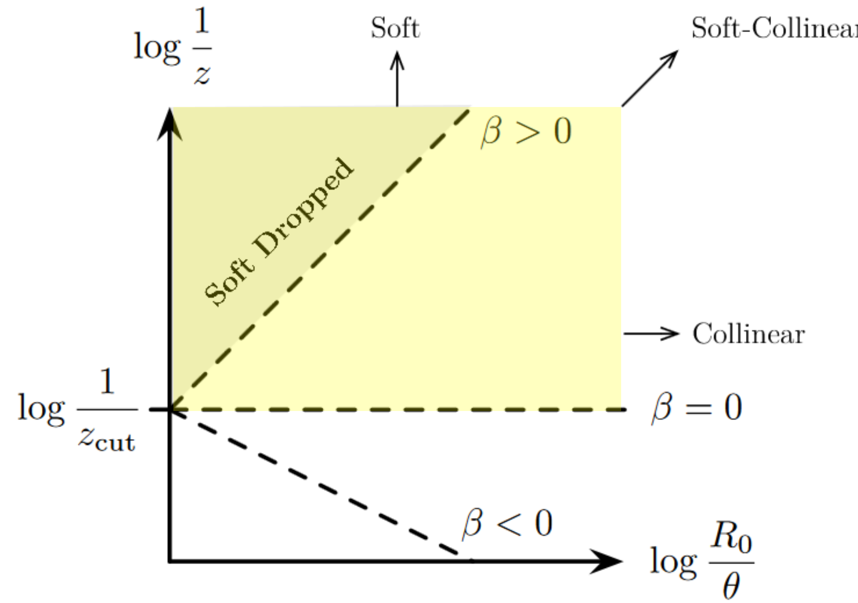
Removes soft→collinear radiation



$\beta = 2$

Removes soft radiation



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$\beta = 0$

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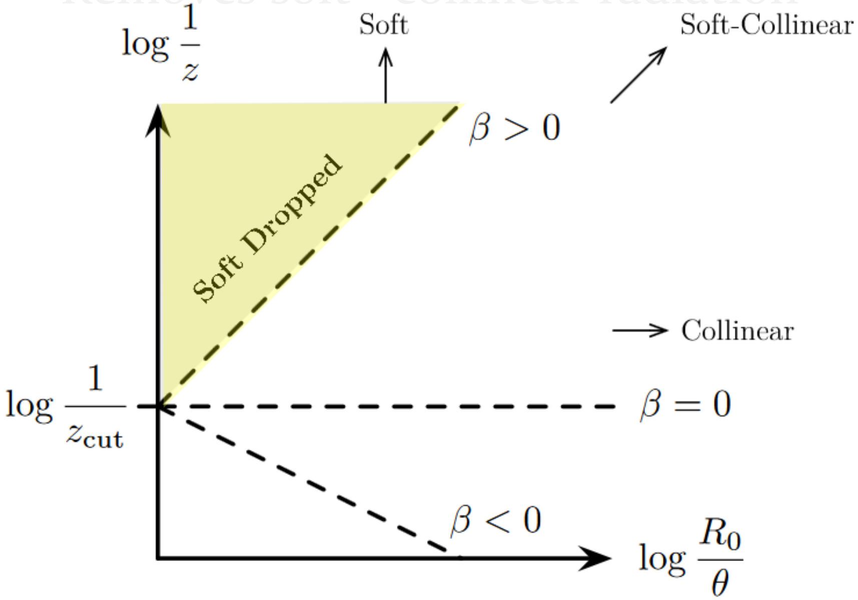
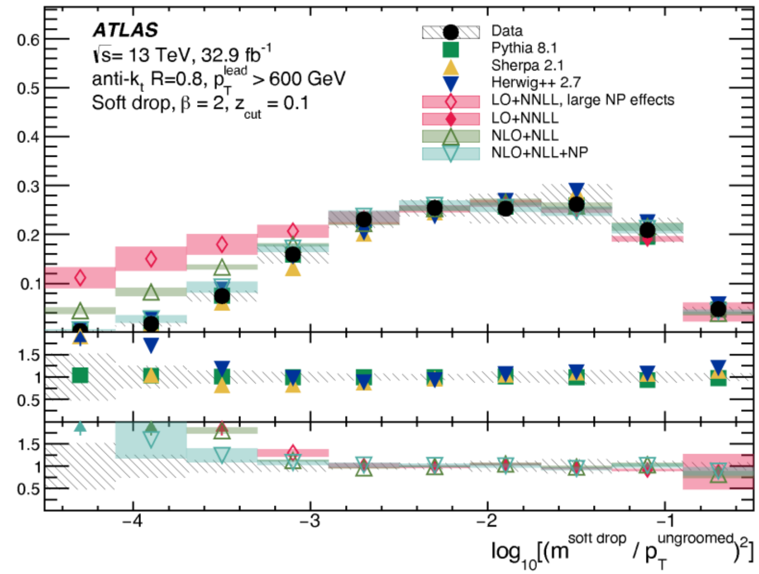


$\boldsymbol{\beta = 2}$

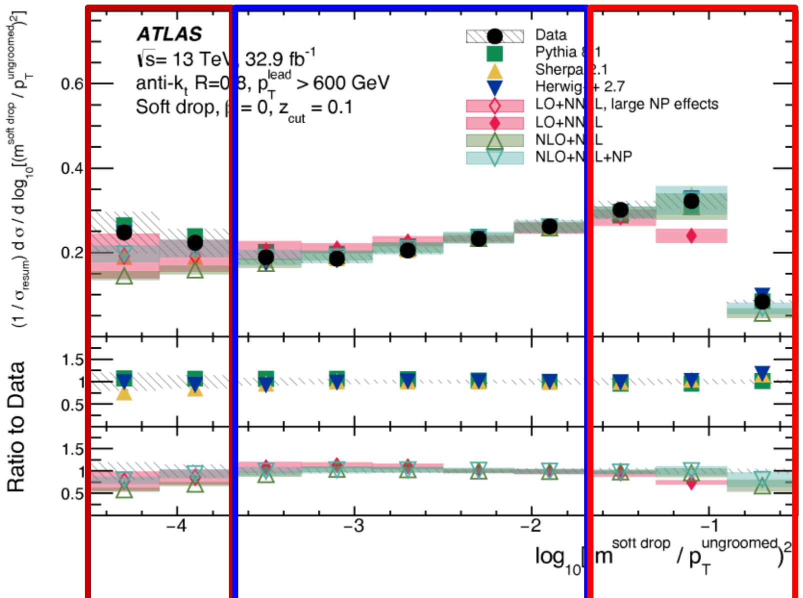
Removes soft radiation



Soft Drop Mass – Interpretation

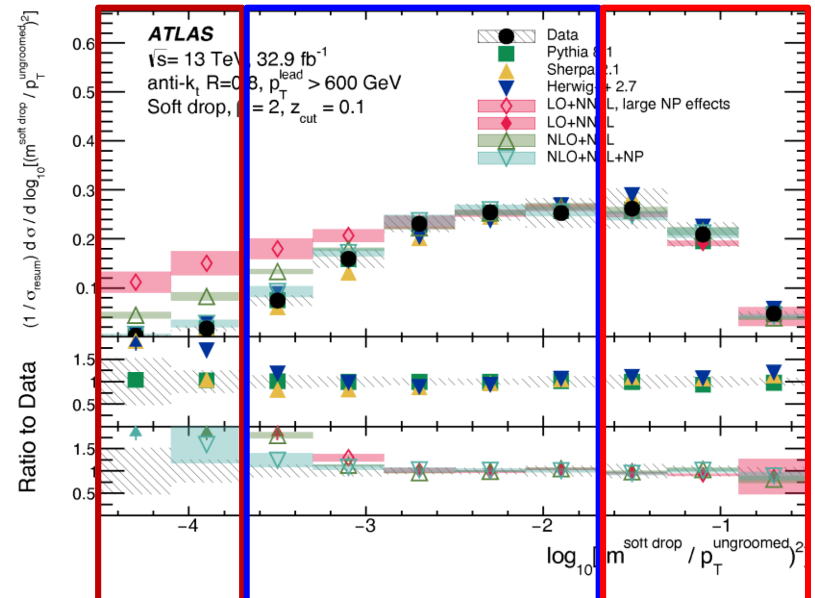
$\beta = 0$

Removes soft→collinear radiation



$\beta = 2$

Removes soft radiation



< -3.7 non-perturbative regime

$-3.7 \rightarrow -1.7$ resummation region

> -1.7 fixed order regime
(large angle gluon emission)

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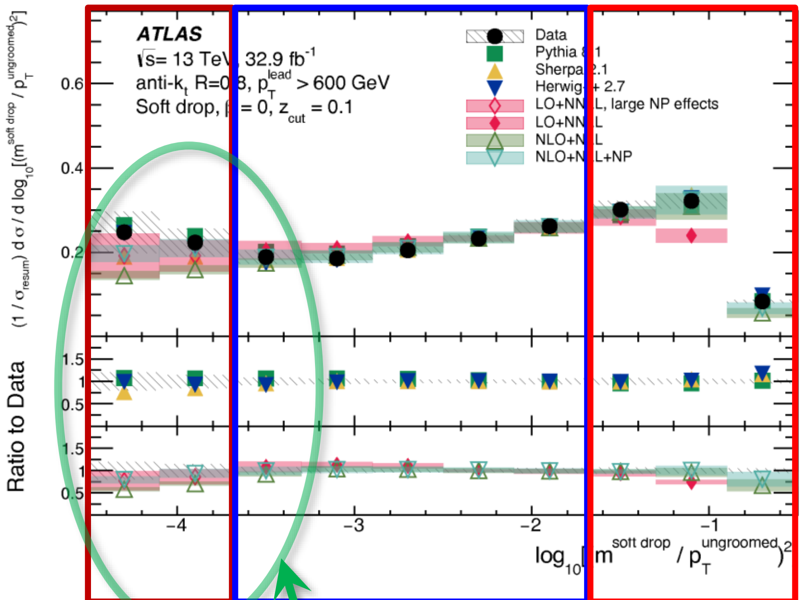
Soft Drop Mass – Interpretation

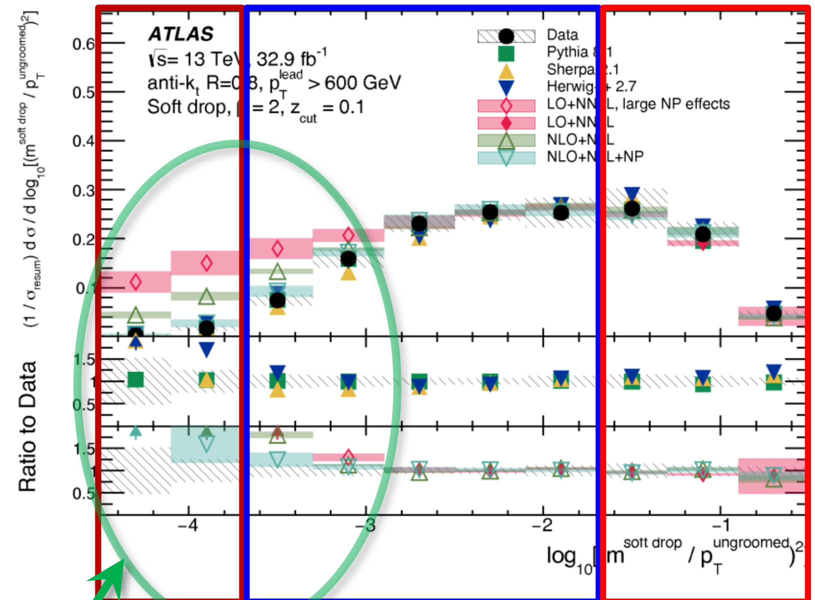
$\beta = 0$

Removes soft→collinear radiation



$\beta = 2$

Removes soft radiation



Larger disagreements for less inclusive ($\beta = 2$) soft contribution removal

(large angle gluon emission)

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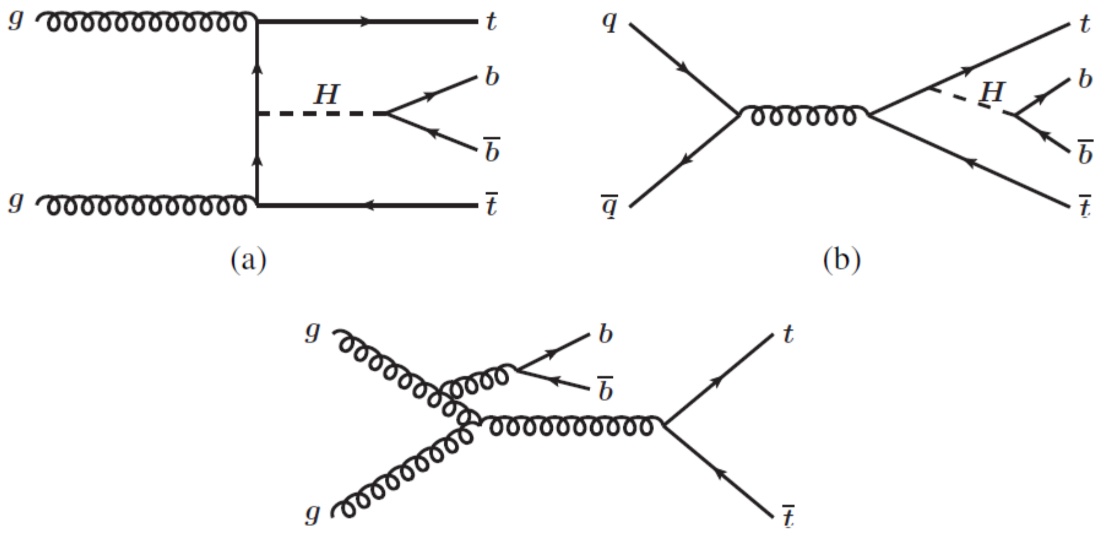
Boosted $t\bar{t}H$ Production

Motivation

Phys.Rev. D97 (2018) 072016

Direct experimental access to top-quark Yukawa coupling

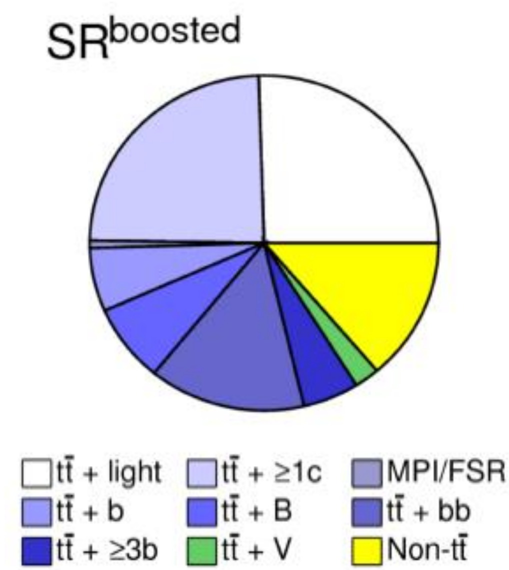


(a) (b) (c)

Final state of interest for boosted analysis

$H \to b\bar{b}$ reconstructed as anti-k_t jet ($R = 1.0$) with two b-tagged sub-jets

$t \to Wb$ reconstructed as anti-k_t jet ($R = 1.0$) with one b-tagged sub-jets and ≥ 1 sub-jet not b-tagged

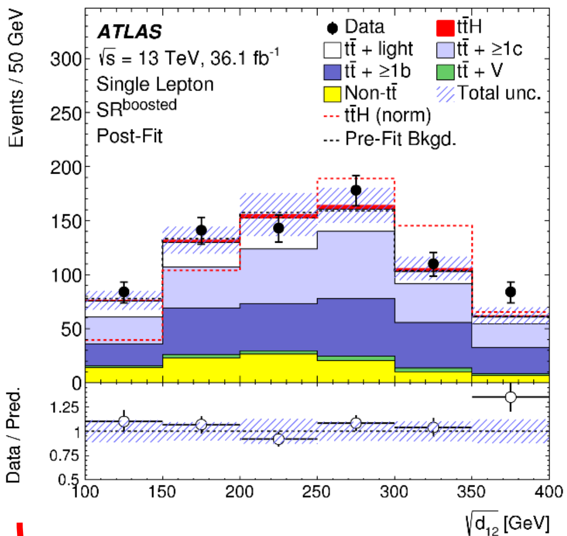


Boosted $t\bar{t}H$ Production

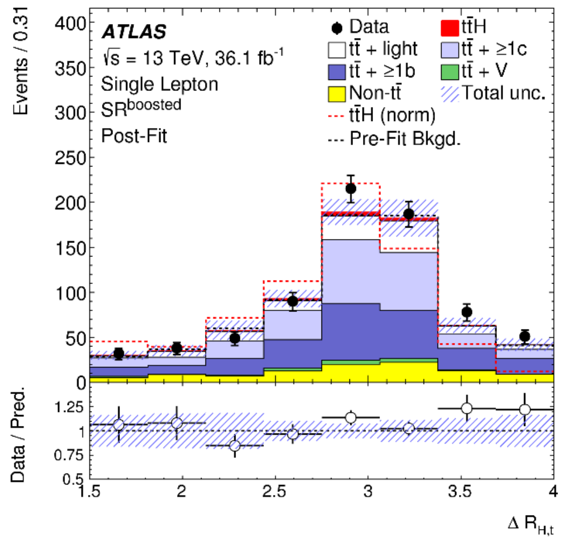
Highest discrimination in BDT

Phys.Rev. D97 (2018) 072016

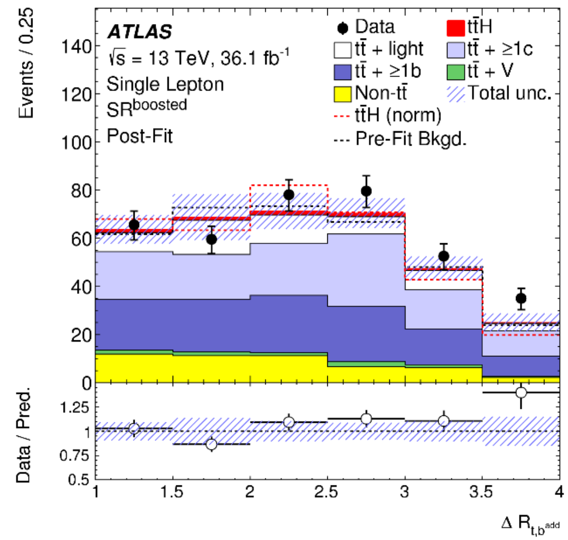
Splitting scale $\sqrt{d_{12}}$

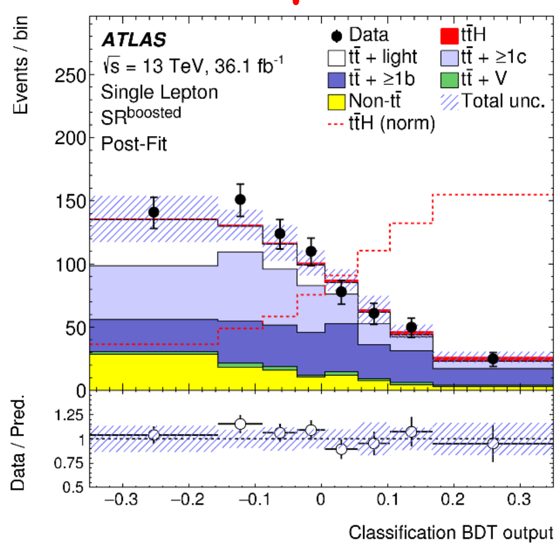


angular distance $H \leftrightarrow t$



angular distance $t \leftrightarrow b$





Conclusions

Jet substructure is mainstream analysis tool

- Many relevant observables well understood
  - Powerful observables to extract hard internal jet structure often little dependent on pile-up
  - Residual or fundamental dependences on pile-up can be mitigated by appropriate grooming techniques
- Well applicable both in searches and measurements
  - Measurement of mass of light quark/gluon jets provides guidance for theory for calculations in soft and soft-collinear regimes
  - Contribution to important measurements of Higgs production mechanisms
  - Direct searches for new heavy particles decaying into gluons or light quarks
  - Indirect searches for new heavy particles decaying into heavy quarks and/or gauge bosons

Exiting field poses significant experimental challenges

- Limited detector capabilities
  - Resolution of energy flow in highly boosted regimes in calorimeters
  - Effects of pile-up at high-luminosity LHC operations – calorimeters and tracking (e.g. vertex resolution)
- Combining reconstructed objects
  - Track-assisted reconstruction – combing direction of charged flow from tracking with complete energy measurement in calorimeters

Conclusions

Jet substructure is mainstream analysis tool

Many relevant observables well understood

Powerful observables to extract hard internal jet structure often little dependent on pile-up

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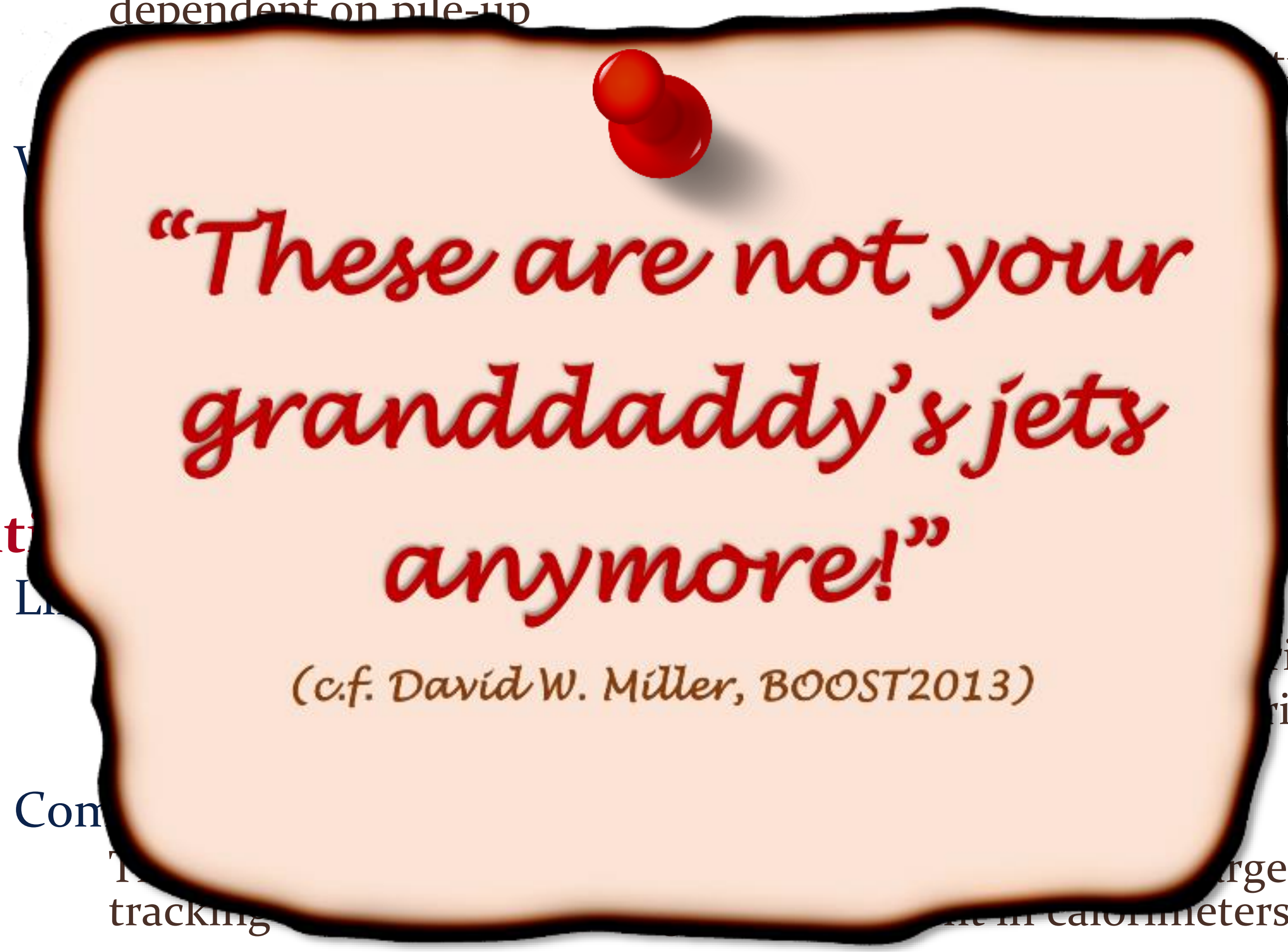
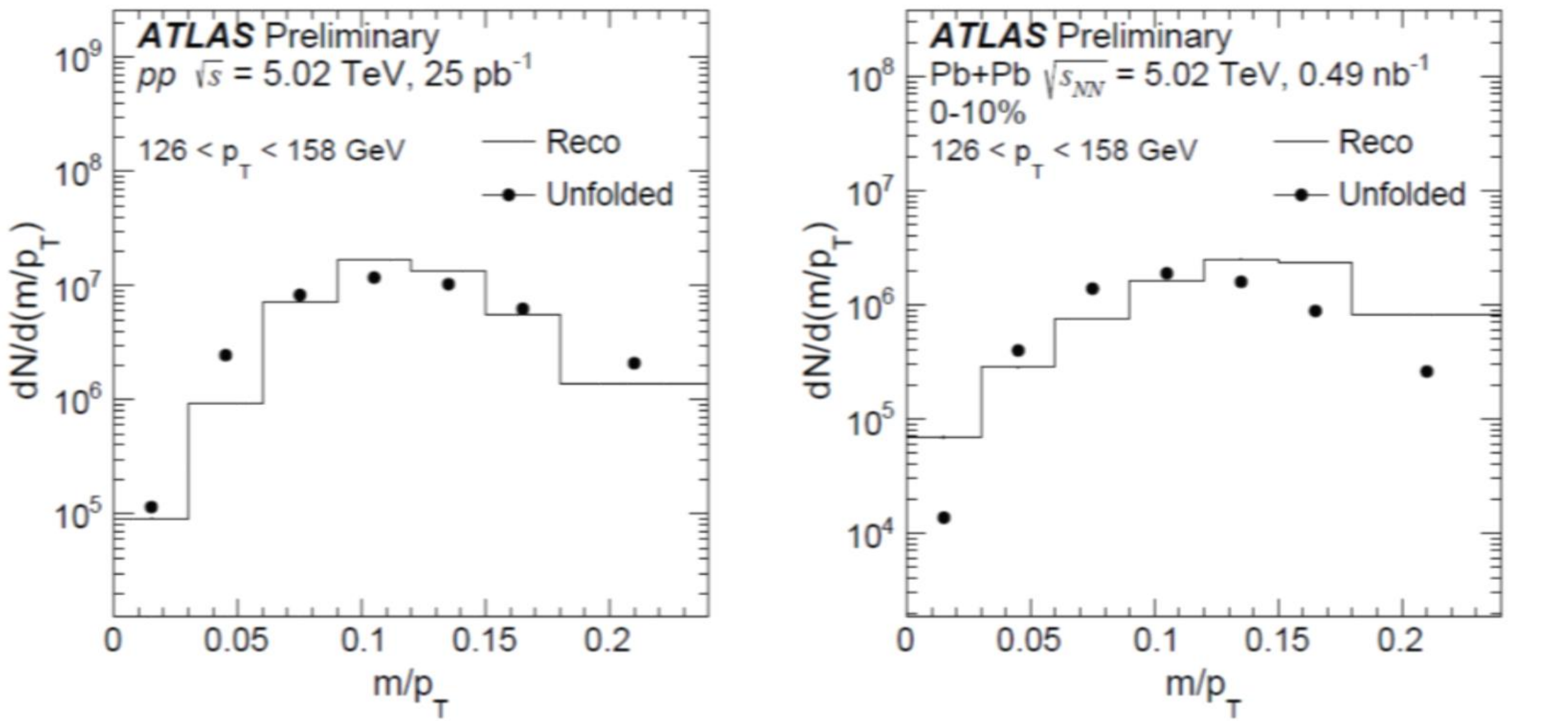


Additional Material

Jet Substructure In Heavy Ion Collisions

C. Delitzsch, LHCP 2018

- Measurement of m/p_T in pp and PbPb collisions at $\sqrt{s} = 5.02$ TeV
  ATLAS-CONF-2018-014
- Jet mass measurement in PbPb gives insights in the modification of the jet while passing through quark-gluon plasma
- Jets are reconstructed with anti-k_t $R = 0.4$ algorithm from 0.1×0.1 towers
  - Underlying event is subtracted from towers before calibrations are applied



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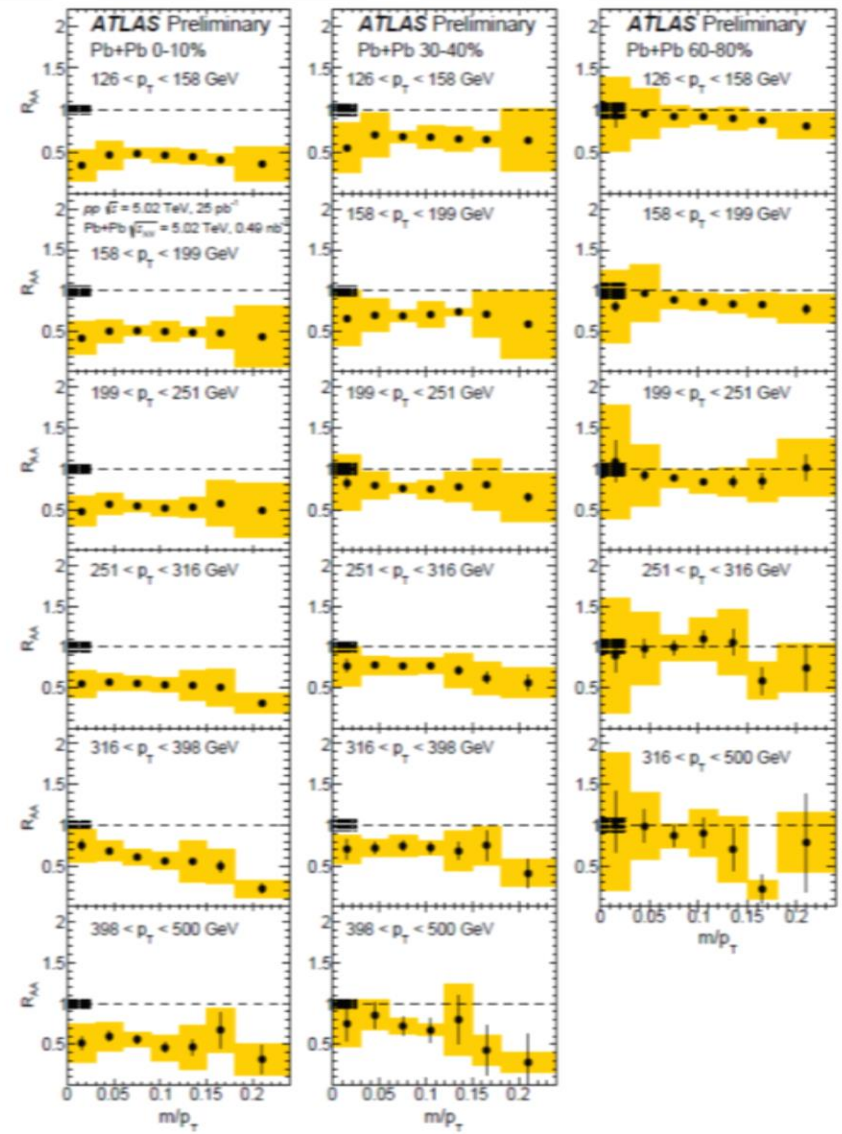
- **Nuclear modification factor R_{AA}:**
  - Quantifies modification of jet yields PbPb collisions with respect to *pp*

$$R_{AA}(m/p_T, p_T) = \frac{\left.\frac{1}{N_{evt}} \frac{dN_{jet}^{Pb+Pb}}{d(m/p_T)}(p_T)\right|_{cent}}{\langle T_{AA}\rangle \frac{d\sigma_{jet}^{pp}}{d(m/p_T)}(p_T)}$$

- $\langle T_{AA}\rangle$: nuclear thickness function
- R_{AA} measured for various p_T and centralities (based on E_T in FCal)
- Modification factor is relatively flat in m/p_T but shows suppression of jets in PbPb collisions



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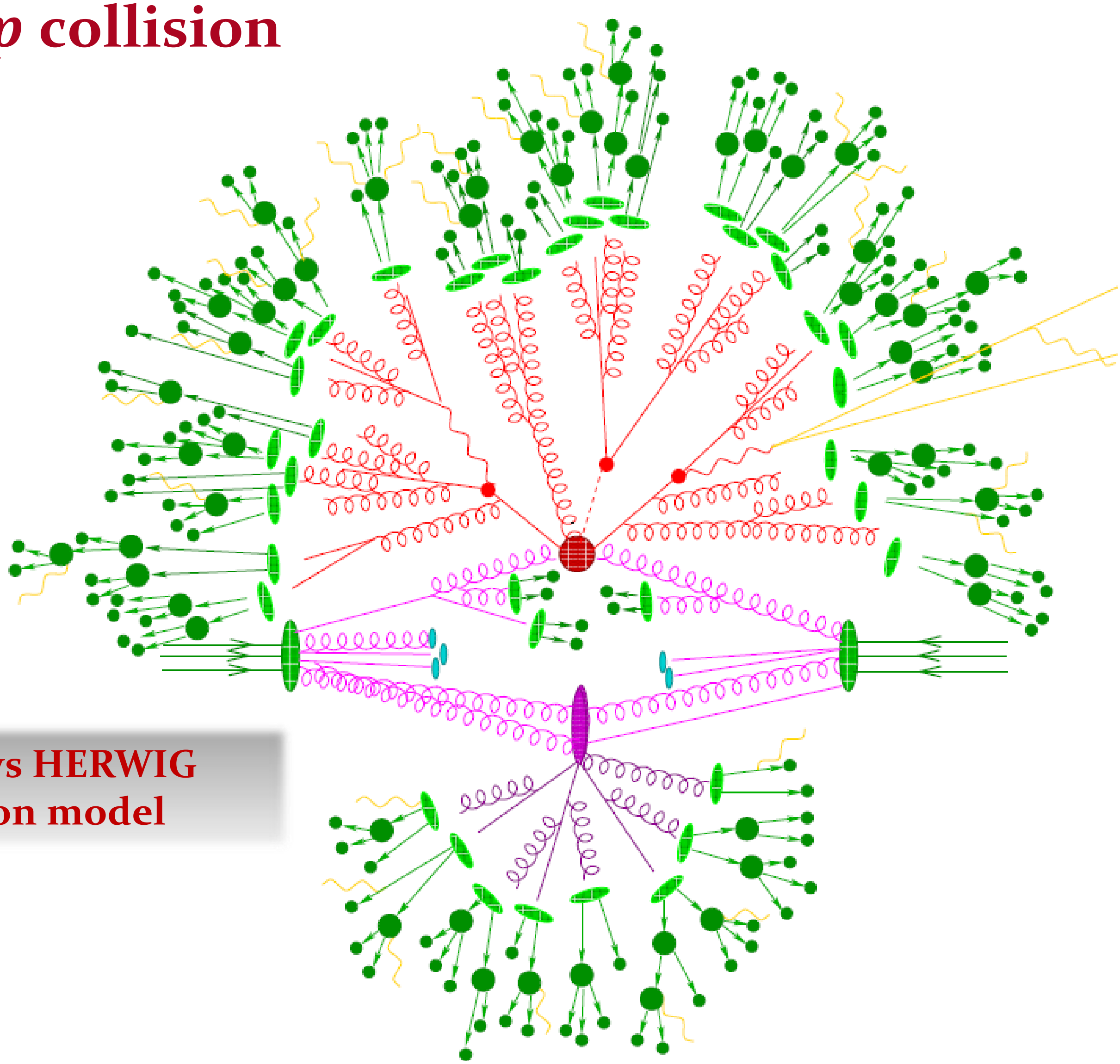
Schematic *pp* collision



Graphics shows HERWIG fragmentation model

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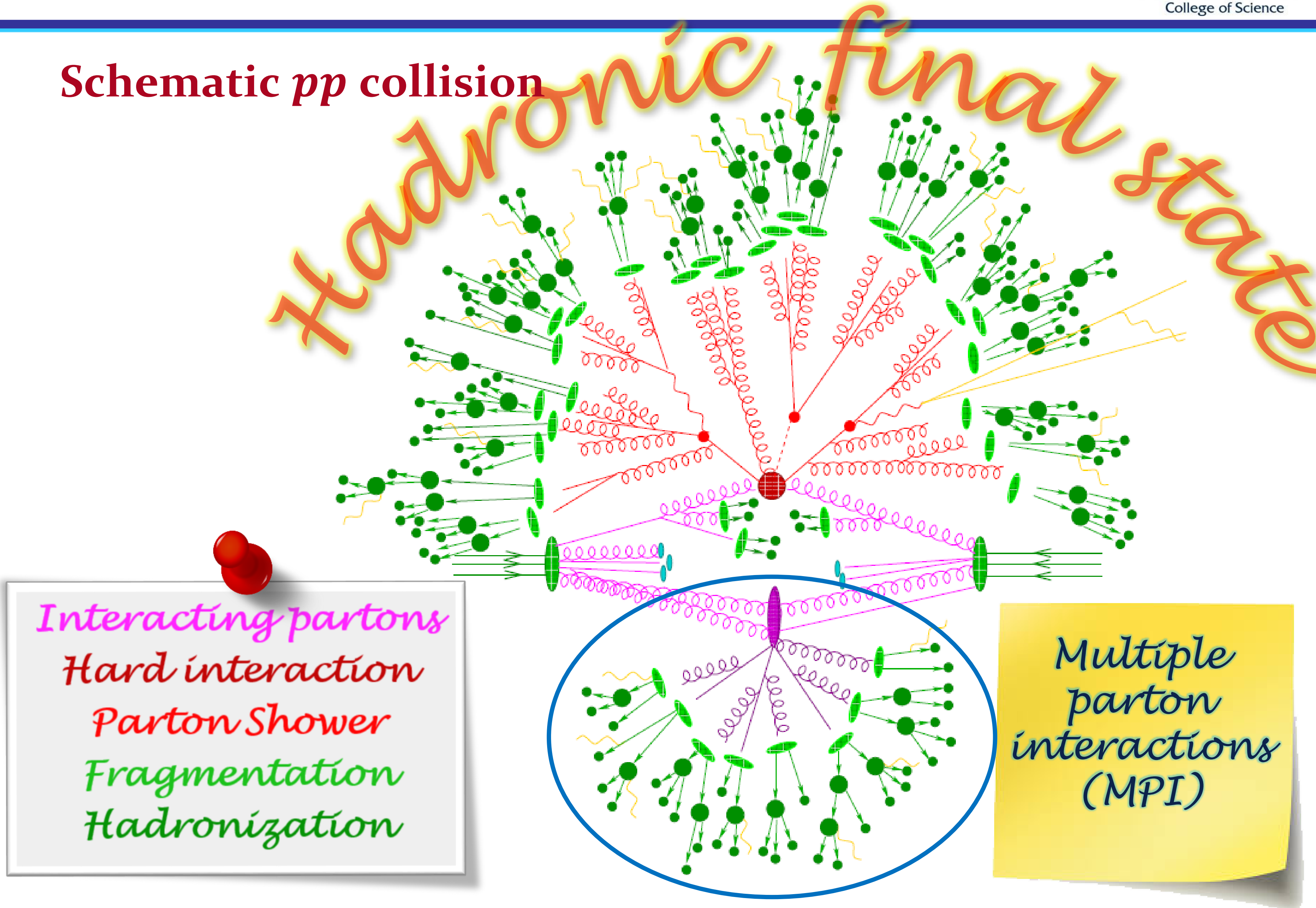
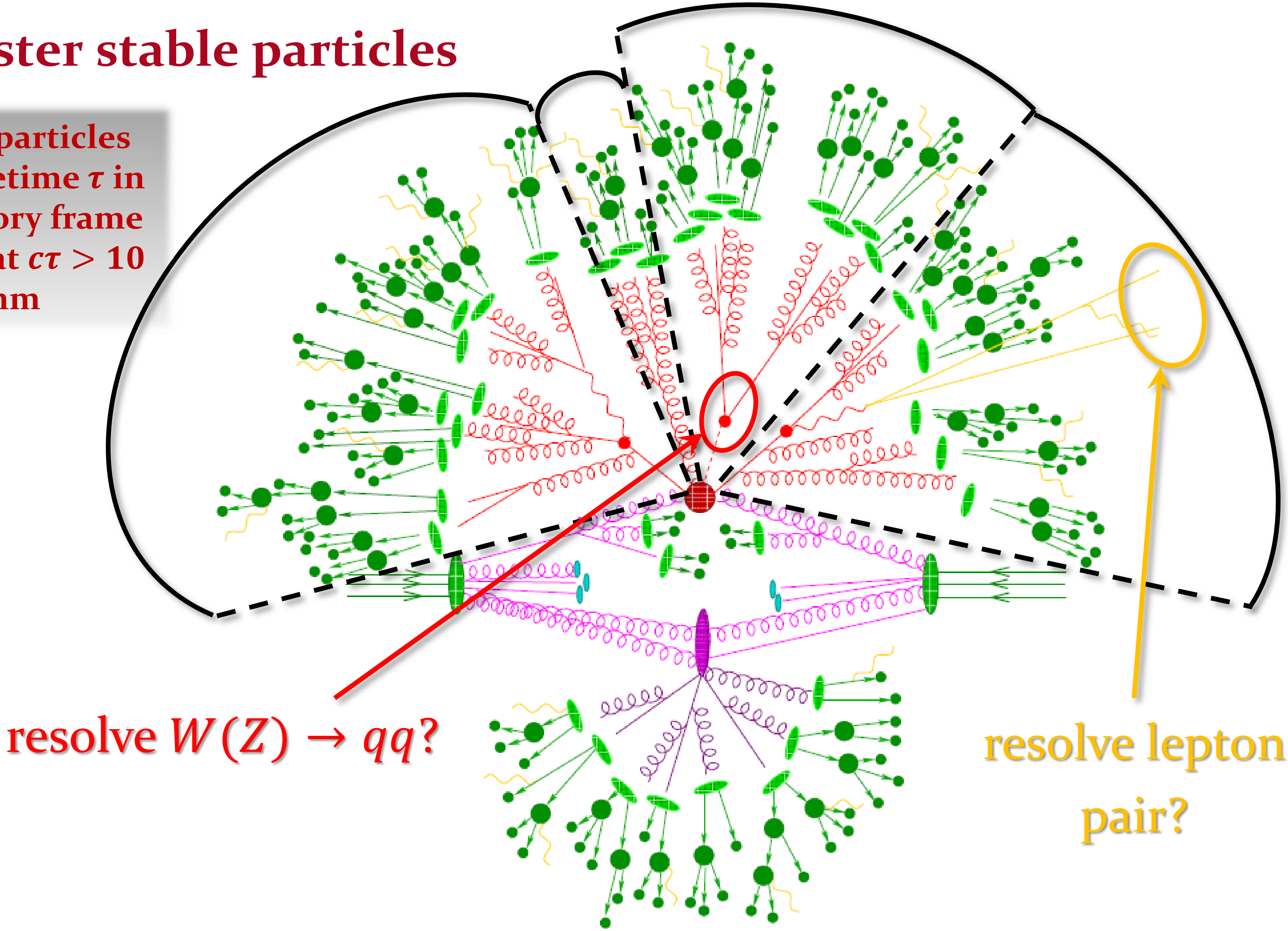
Schematic *pp* collision



Particle Jet Reconstruction (MC only)

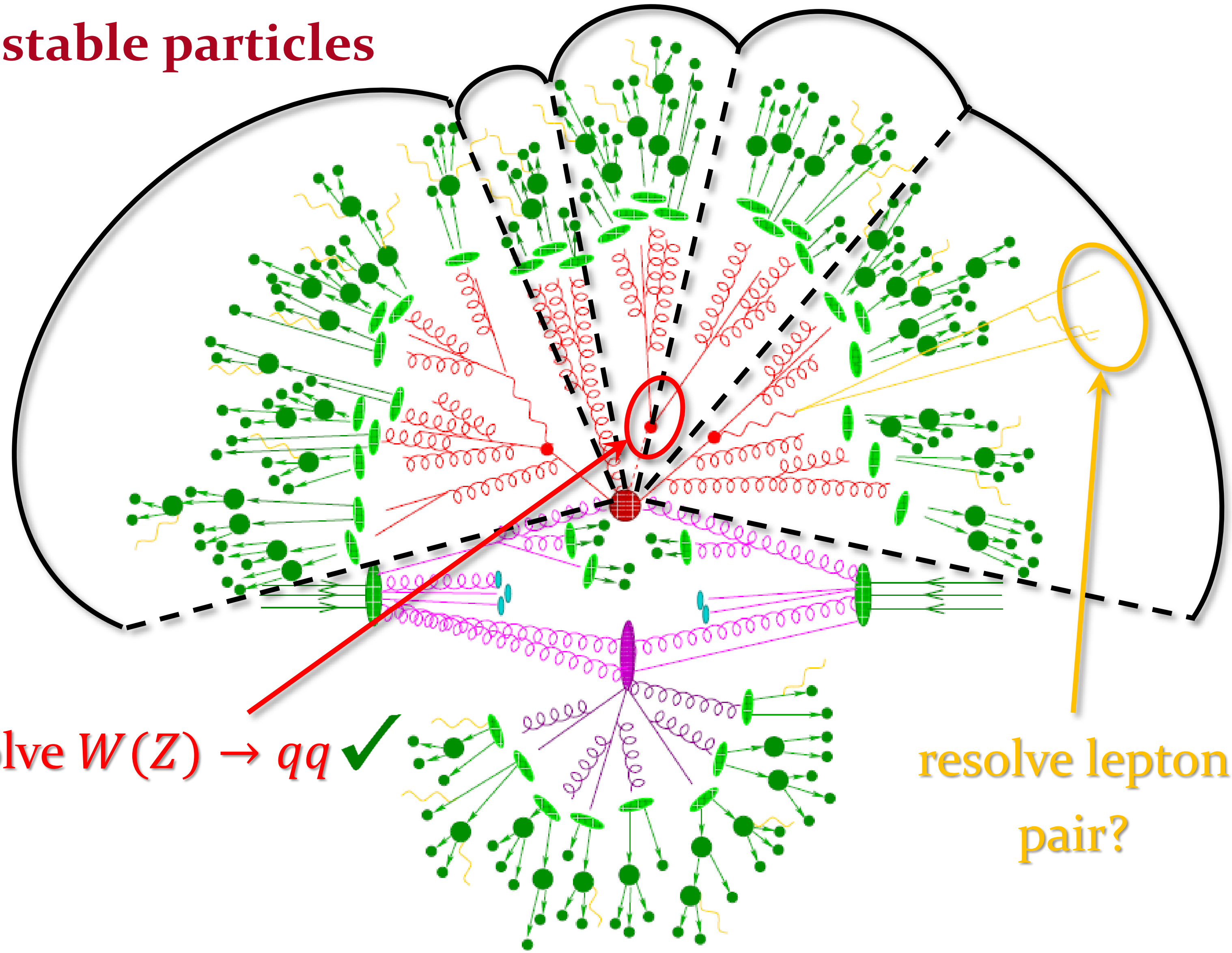
Cluster stable particles

Stable particles have lifetime τ in laboratory frame such that $c\tau > 10$ mm



… or is this better?

Cluster stable particles



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Final state component

- Proxy for parton-level direction and energy
  - Partonic energy/momentum flow → indicative of process
  - Final states needs to be calculable in perturbation theory (pQCD)
  - Safe against soft emissions (**infrared safety**)
  - Stable against collinear splitting (**collinear safety**) – total energy carried by one or more particles in the same direction should have no effect

Algorithm choices

- LHC uses recursive recombination algorithms (nearly) exclusively
  - Infrared safe – soft emissions may only affect jet shapes but not global kinematics
  - Collinear safe – no seeds used
- Improvement from Tevatron
  - Computationally affordable implementations available – avoid seeded cone algorithms and workarounds to fix infrared and collinear issues

Jet Definition

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Allow comparisons experiment ↔ models (calculations)

- Jet inputs
  - LHC – experiments correct jets to **particle level**
- Jet algorithm type
  - **Recursive recombination**, seedless cones, …
- Recombination scheme
  - Two *proto-jets* recombined exclusively by **energy scheme** (adding four-momenta) – massive proto-jets after first recombination
- Distance parameter (“radius”)
  - Defines maximum angular distance $\sqrt{\Delta y^2 + \Delta \varphi^2}$ considered in clustering
  - Controls catchment area and jet shape – **spatial resolution** in energy flow
  - Angular scale for jets from gluon radiation – collinear limit in calculations
- Minimum transverse momentum requirement
  - Sets acceptance/sensitivity in energy flow reconstruction

Agreed-upon concept at LHC …

… since it’s early days!

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Favorite Jet Algorithms

k_T algorithm

Use intrinsic transverse momentum (k_T) between particles to decide on combination

- Originally motivated by inversion of gluon splitting kernel $g \to gg$ Implements physically meaningful clustering sequence ("undoing" fragmentation)

Combination starts with the smallest available four-momentum

- Large and irregularly shaped (y, φ) catchment area – jet four-momentum "walks" around a lot before final jet is formed

Cambridge/Aachen (C/A) flavor of k_T

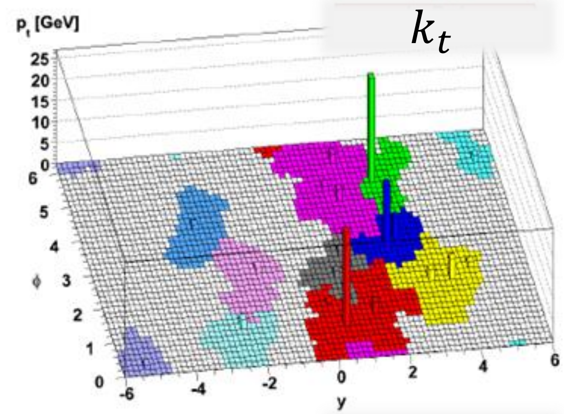
Uses angular distance scale

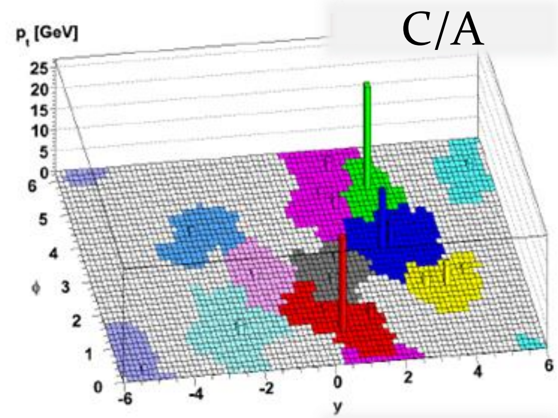
- Similar jets than k_T

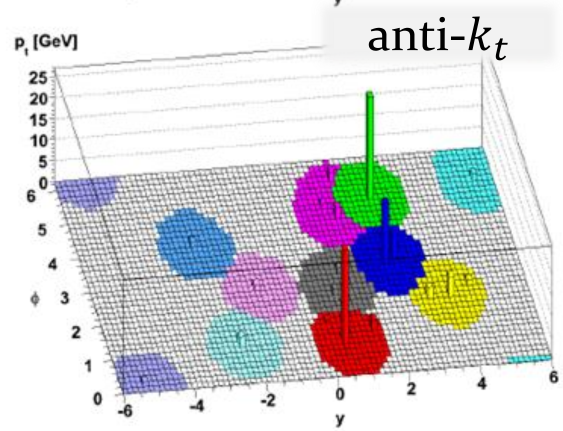
Anti-k_T algorithm

Inversion of k_T algorithm – start with largest four-momentum

- Smaller and regular (circular) (y, φ) catchment area
- Final jet physically meaningful but clustering sequence not physically meaningful (!)







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Underlying event (experimental view)

- Stochastic component
  - MPI generated independently from hard scatter interaction – but maybe reconnected by color flow
  - Total phase space limited by hard scatter
- Correlated component
  - Initial (ISR) and final (FSR) state radiation off quarks and gluons involved in the hard scatter interaction
- But we cannot disentangle them in the experiment
  - Suggestions for FSR jet tagging have been tested – low efficiency…

Pile-up

- Diffuse emission of low-energy particles into a jet
  - Purely stochastic – no correlation to hard scatter interaction
  - Generated by additional (soft) proton-proton interactions occurring in the same bunch-crossing as the hard scatter
  - Scales with instantaneous luminosity – average number of additional interactions $\langle\mu\rangle$

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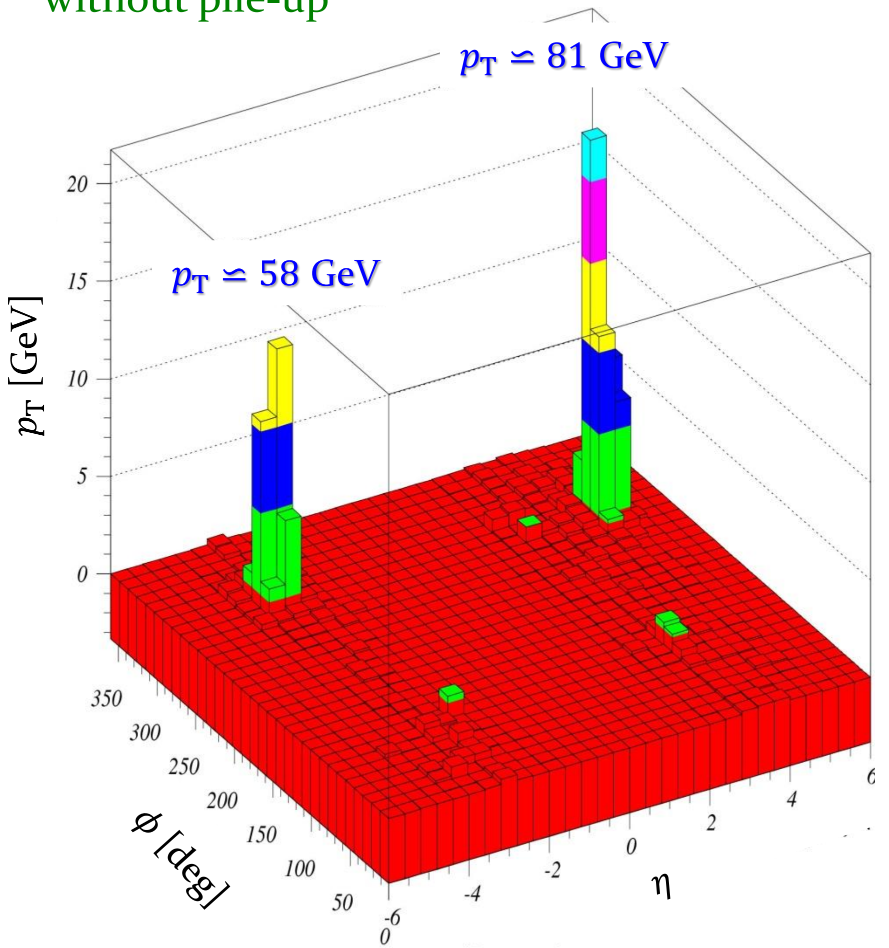
Pile-up

- Affects jet kinematics and shapes
  - Introduces additional energy/transverse momentum in jets
  - Deteriorates reconstruction of jet mass & internal particle flow features
- Number of pile-up collisions μ
  - $\mu = (\mathcal{L}_{\mathrm{inst}} \times \sigma_{\mathrm{inel}}^{pp})/(N_{\mathrm{b}} \times f_{\mathrm{LHC}})$
  - $\mathcal{L}_{\mathrm{inst}}$ – instantaneous luminosity
  - $\sigma_{\mathrm{inel}}^{pp}$ – inelastic pp cross section
  - N_{b} – number of colliding bunches in LHC
  - f_{LHC} – LHC revolution frequency

without pile-up



$qq \rightarrow qqWW \rightarrow qqH \rightarrow qq\nu\nu\nu\nu$

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Pile-up

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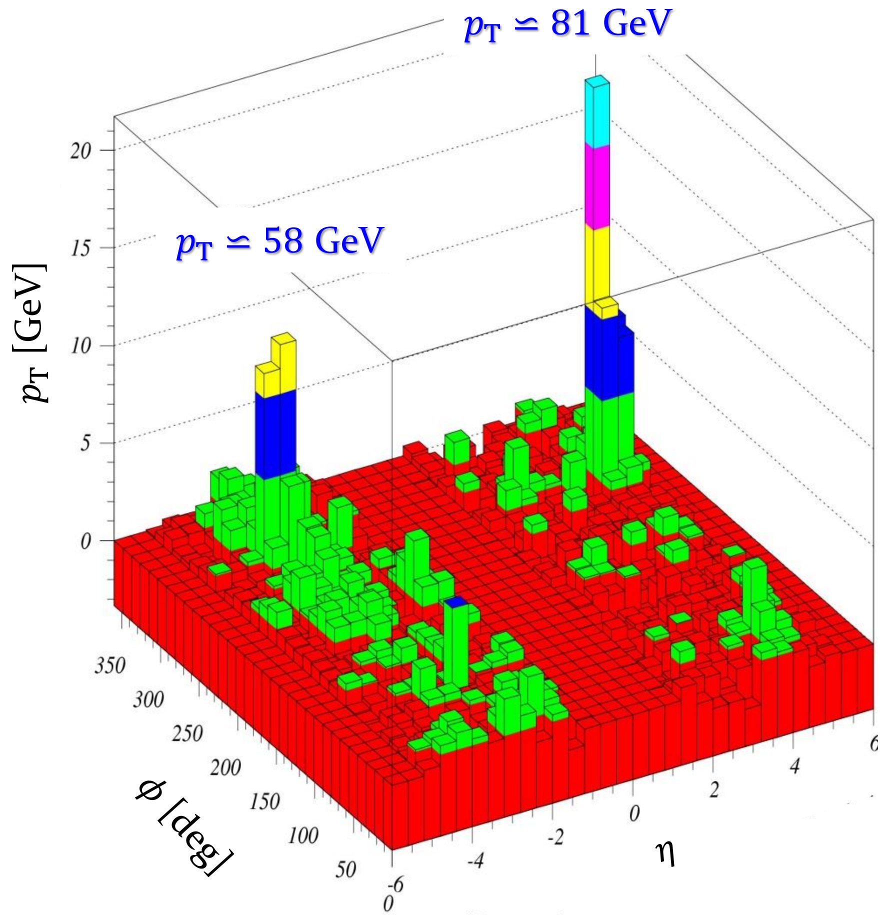
  - $\mathcal{L}_{\rm inst}$ – instantaneous luminosity
  - $\sigma^{pp}_{\rm inel}$ – inelastic pp cross section
  - $N_{\rm b}$ – number of colliding bunches in LHC
  - $f_{\rm LHC}$ – LHC revolution frequency

with pile-up @ $\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



$qq \to qqWW \to qqH \to qq\nu\nu\nu\nu$

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