New techniques for LHC BSM searches in Run II

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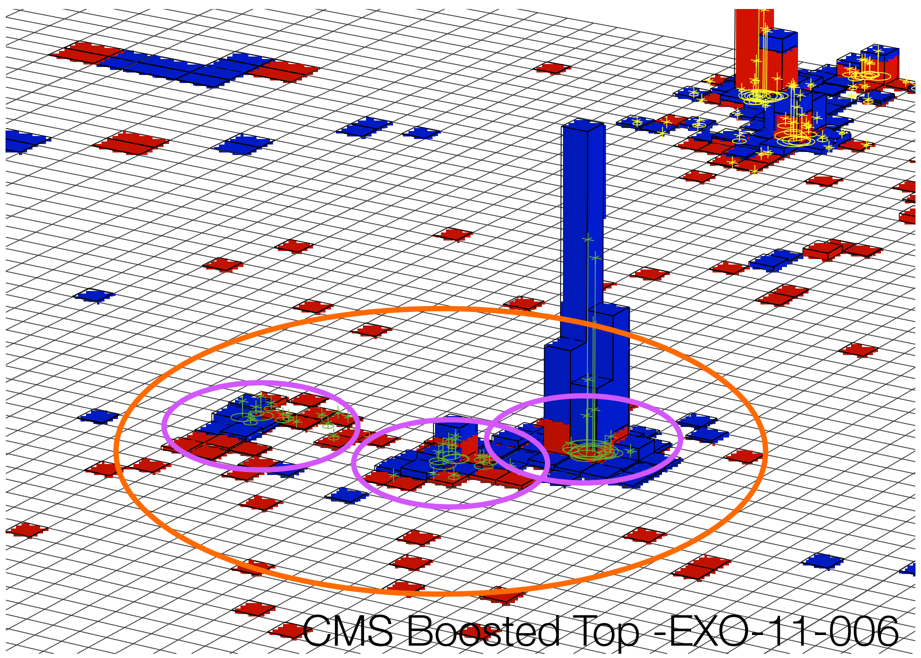
Aspen Center for Particle Physics - January 15, 2016

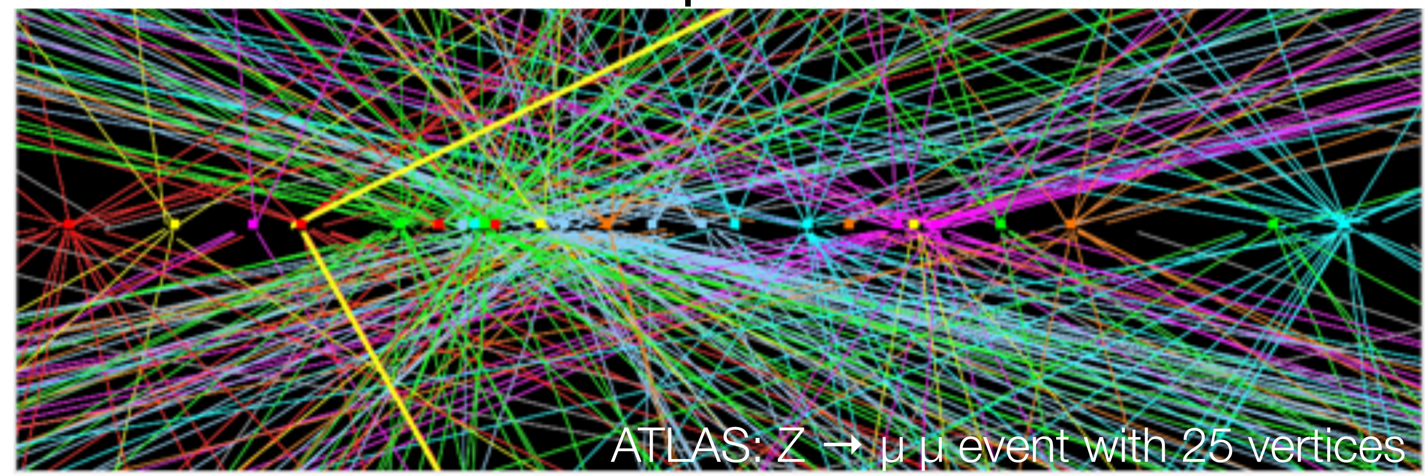
Outline: new techniques at the LHC

Jet tools



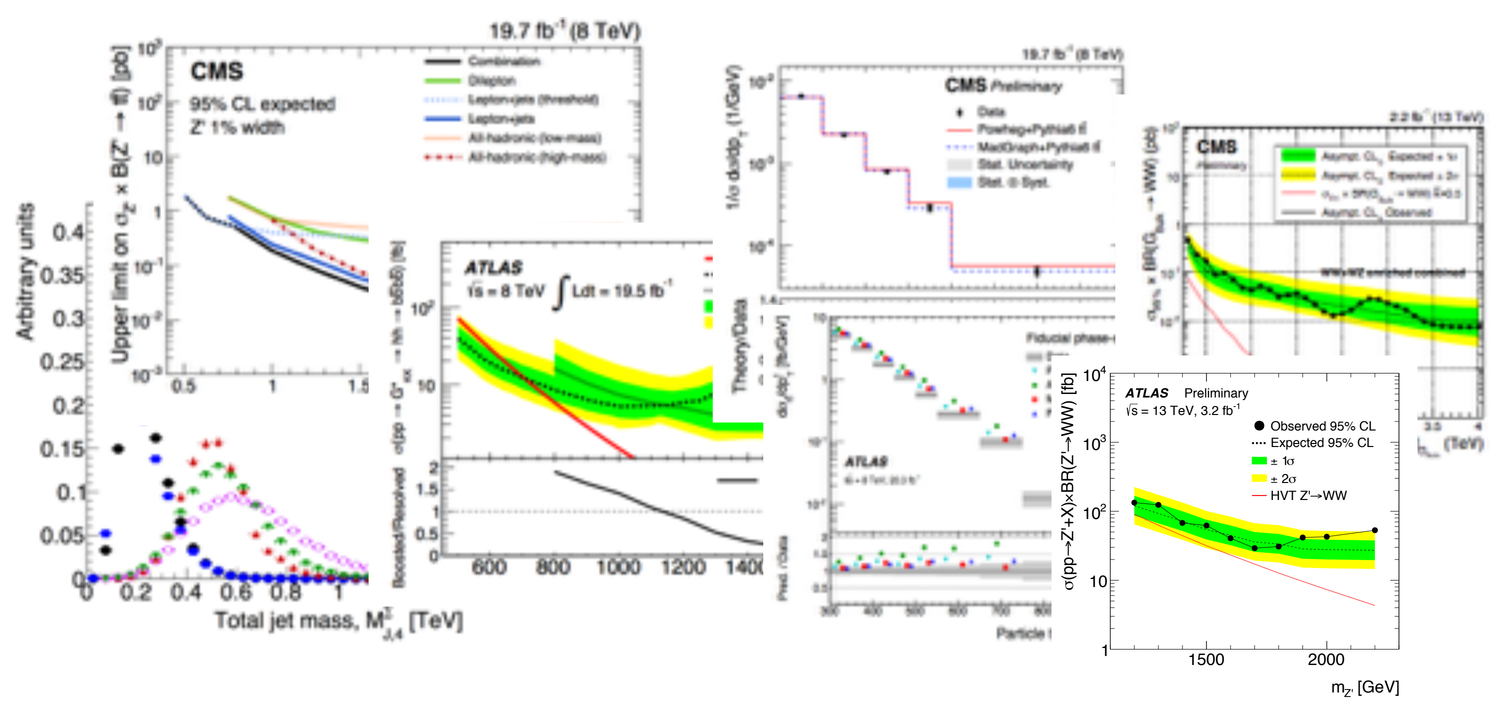
- Boosted top/W/Z/H tagging
  - Grooming
  - Jet shape variables
- Subjet b-tagging
- Double b-tagging
- Quark/gluon tagging

Pileup tools



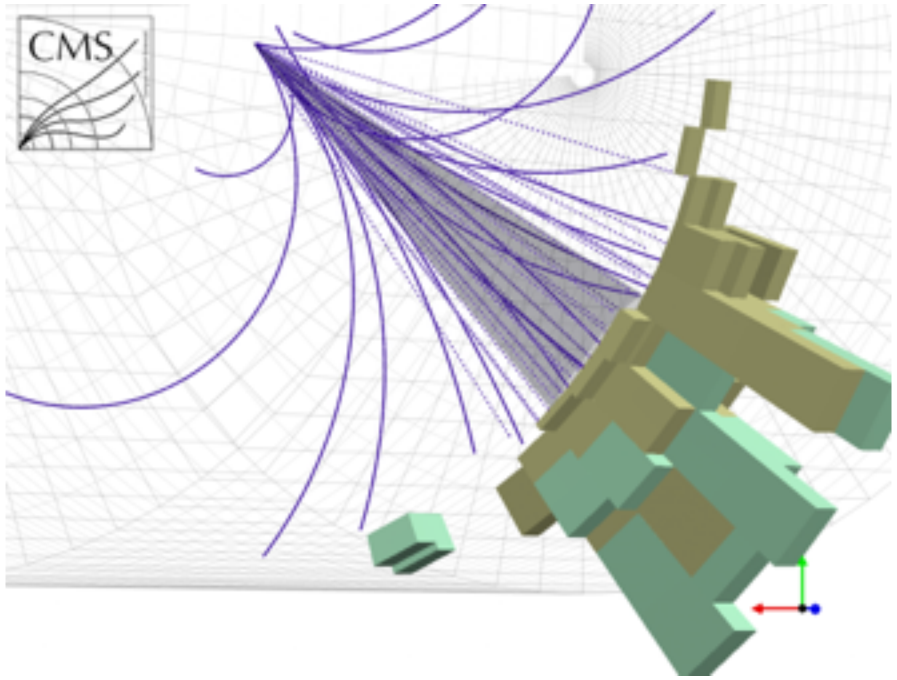
- Pileup Jet ID
- Pileup subtraction
- CHS/SK/PUPPI
- Isolation
- MET

Analysis examples

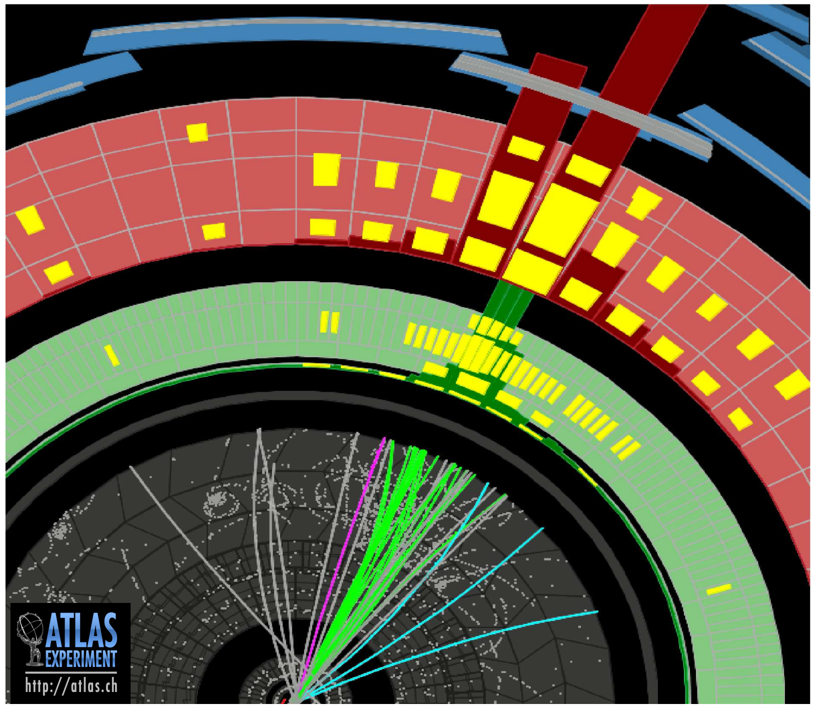


Jets and jet tools

- Jets (a collimated spray of hadrons resulting from an initial state quark or gluon) are ubiquitous at hadron colliders



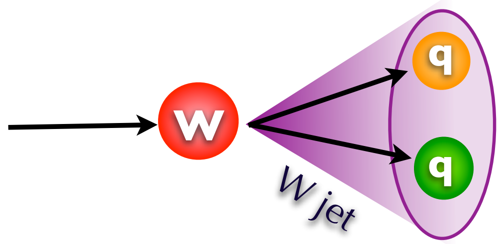
- LHC jet revolution
  - Particle flow (CMS), topo-clusters (ATLAS)
    - Improved jet resolution
    - Pileup removal before clustering
  - Sequential recombination jet algorithms
  - Boosted heavy object jet tagging
    - all decay products of heavy particle (ex. top, W, Z, Higgs) reconstructed within one jet
    - jet grooming, subjets
  - Subjet b-tagging, double b-tagging
  - Pileup jet ID, Quark/gluon discrimination



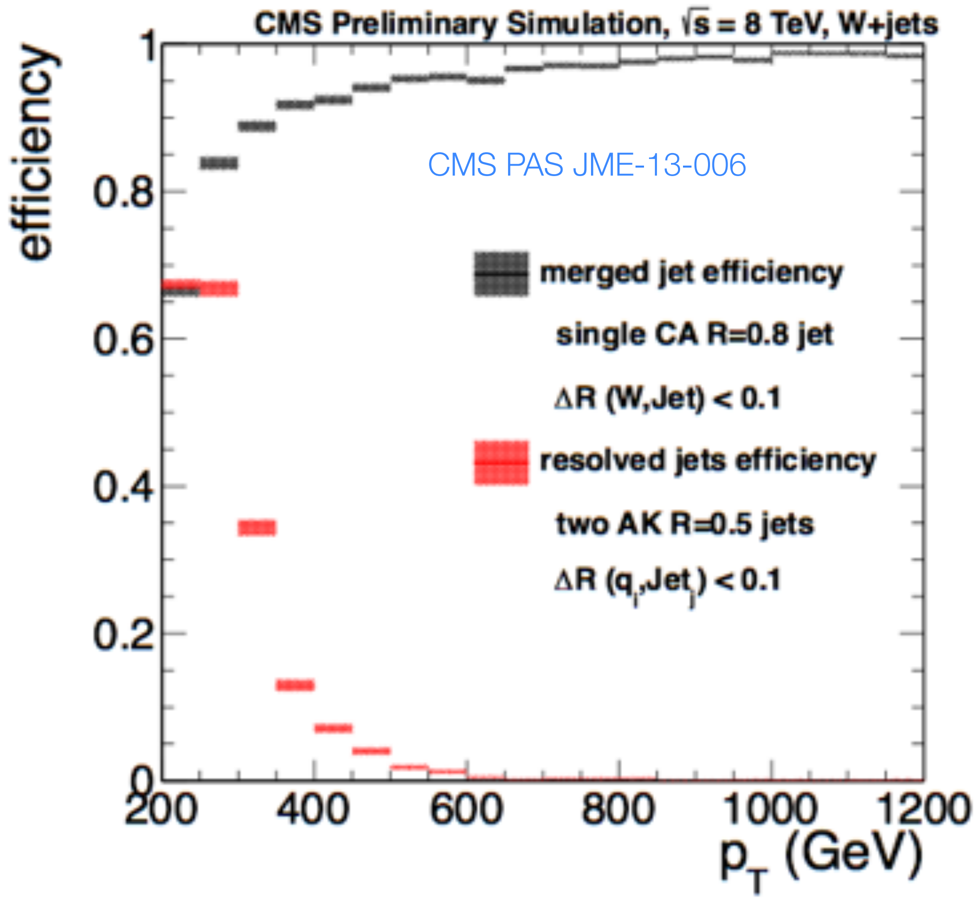
LHC jet tagging

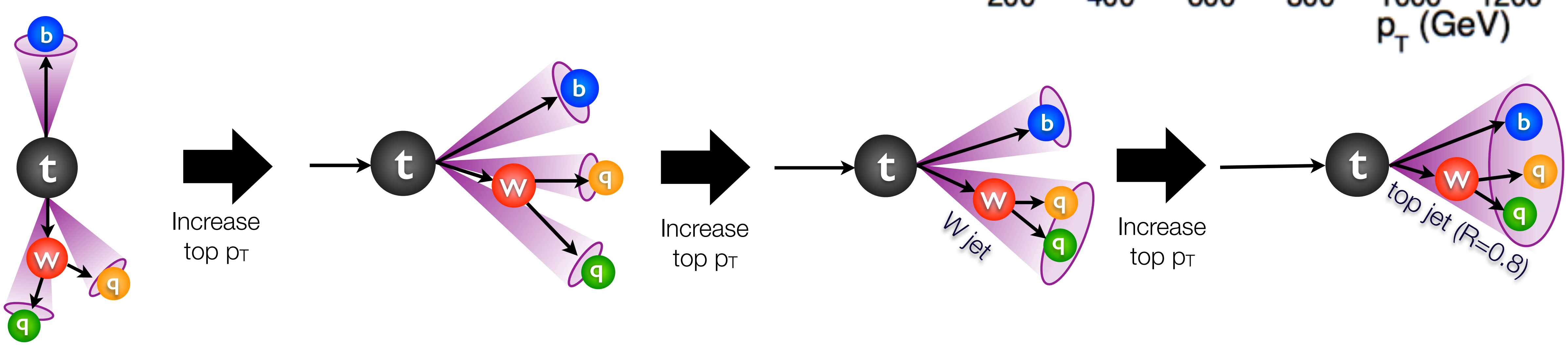
Boosted heavy object tagging

- example: 2 body decay
  - decay product angular separation $\Delta R \sim 2M/p_T$



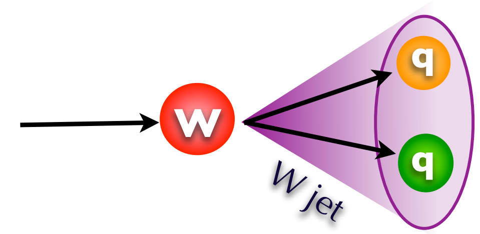
- Boosted heavy object jets are identifiable based on their mass and via jet substructure
  - The jet, it's constituents, and it's clustering history, contain useful information which can be used to identify these objects
    - examples: jet mass, "subjettiness", W mass within a top jet

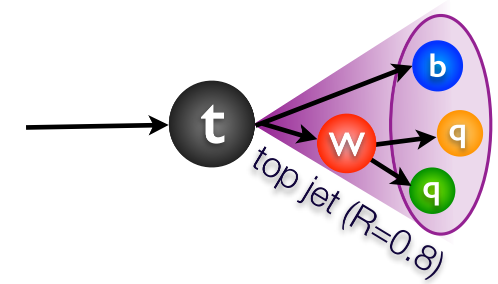




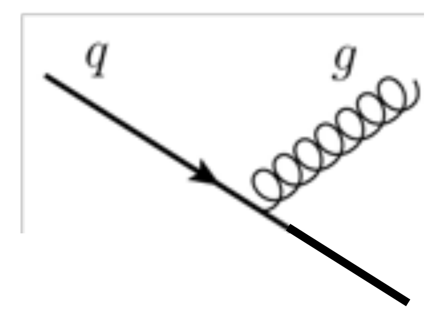
Jet mass as a tagging variable

- For a merged top/W/Z/H jet, the LO jet mass is the heavy object mass





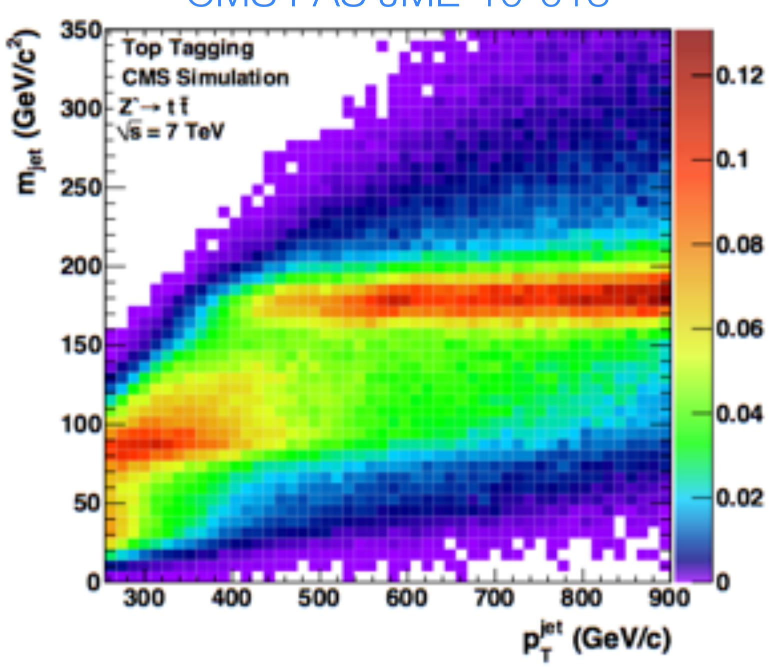
- For background jets (quark/gluon) the LO jet mass is ~ 0, but perturbative effects lead to measured mass

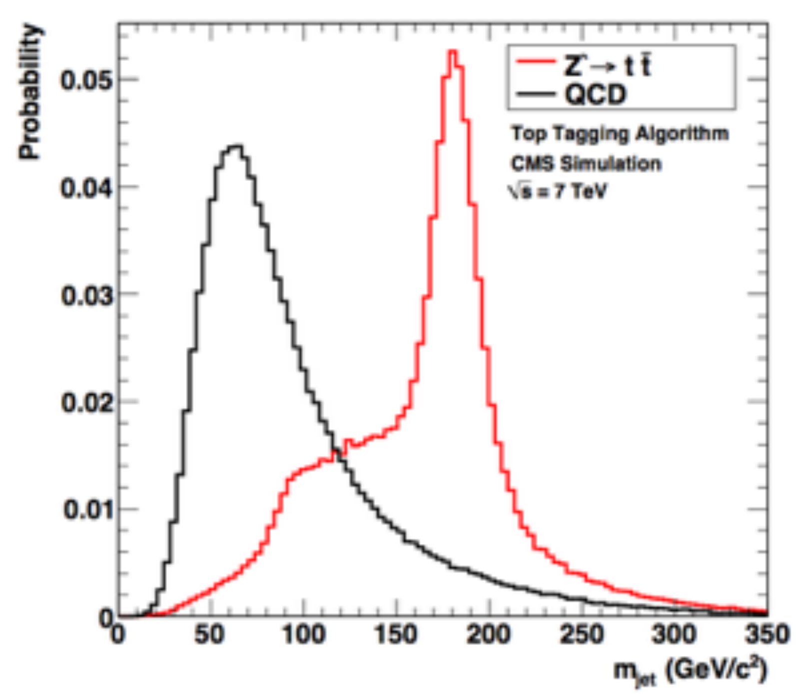


$$\langle M^2 \rangle \simeq C \cdot \frac{\alpha_s}{\pi} p_t^2 R^2$$

Ellis et al. Prog. Part. Nucl. Phys. 60 (2008)

CMS PAS JME-10-013



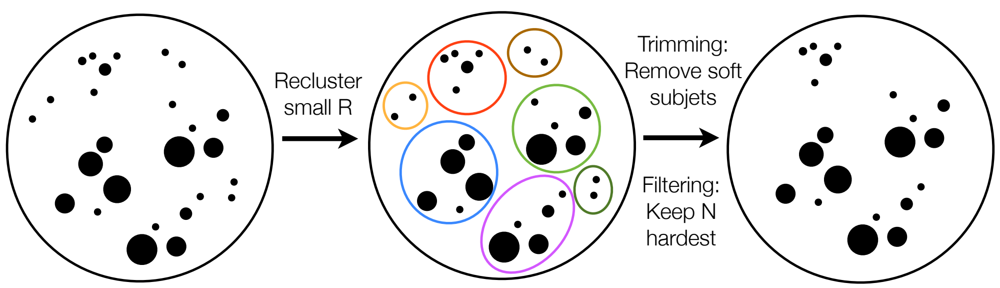


Jet grooming

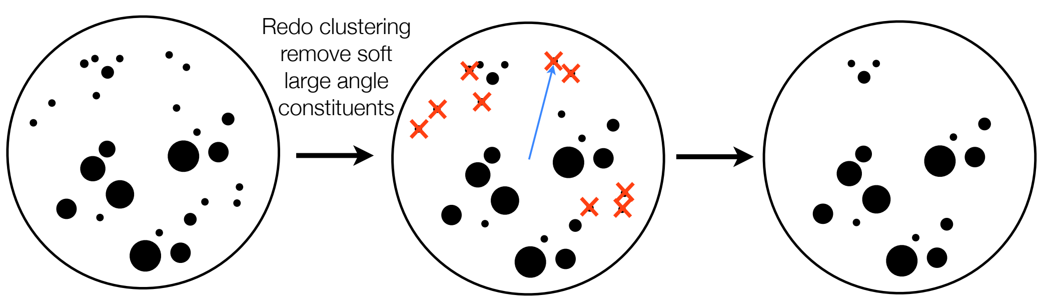
Algorithmic jet substructure techniques designed to remove isolated soft radiation in jets (contamination from ISR, UE, pileup)

J. Dolen

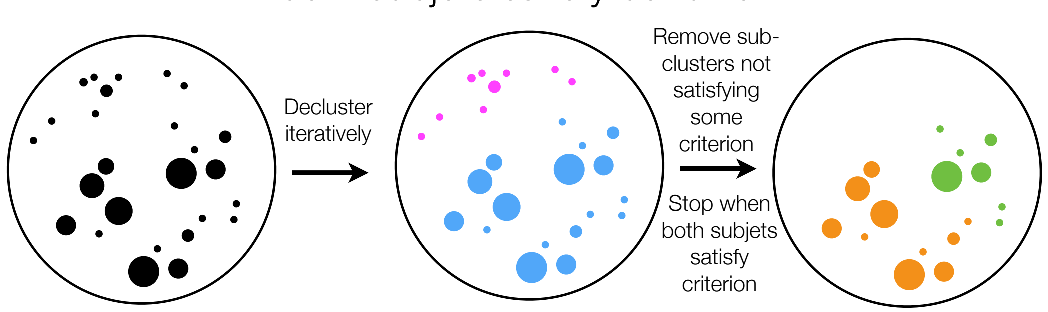
Trimming, Filtering - Recluster jet with smaller distance parameter. Condition based subjet removal.

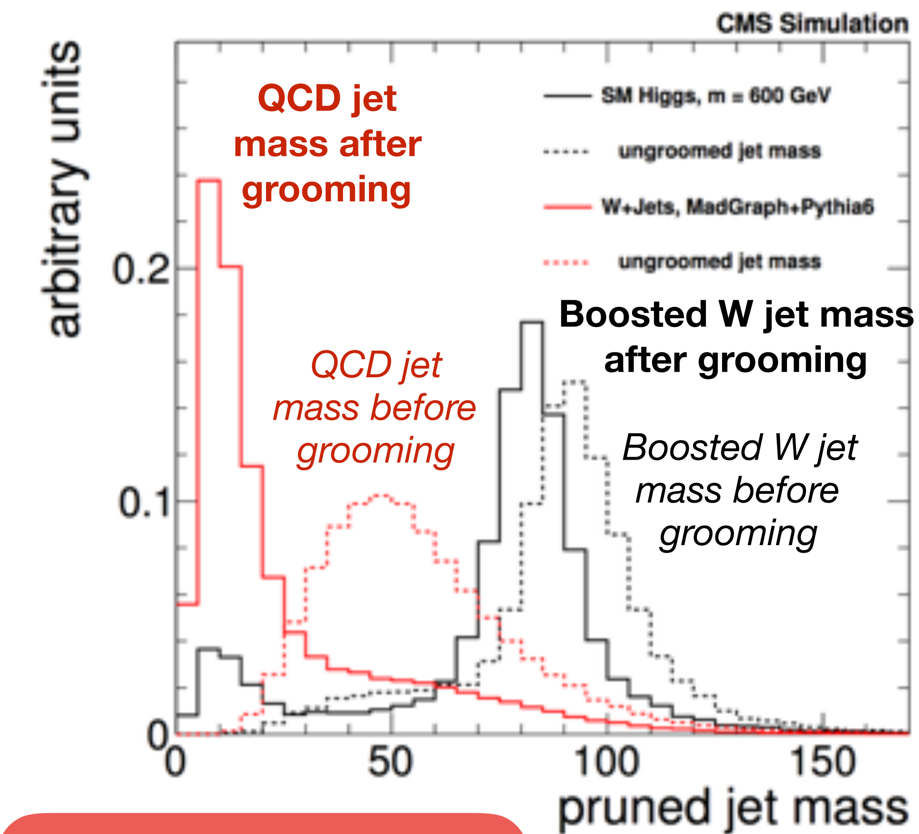


Pruning - Recluster jet. Remove soft large angle particles.



BDRS, MMDT, Soft Drop, JHU top tagger, CMSTT - Recursively decluster jet. Remove sub-clusters not satisfying algorithm condition. Stop declustering when both subjets satisfy condition.





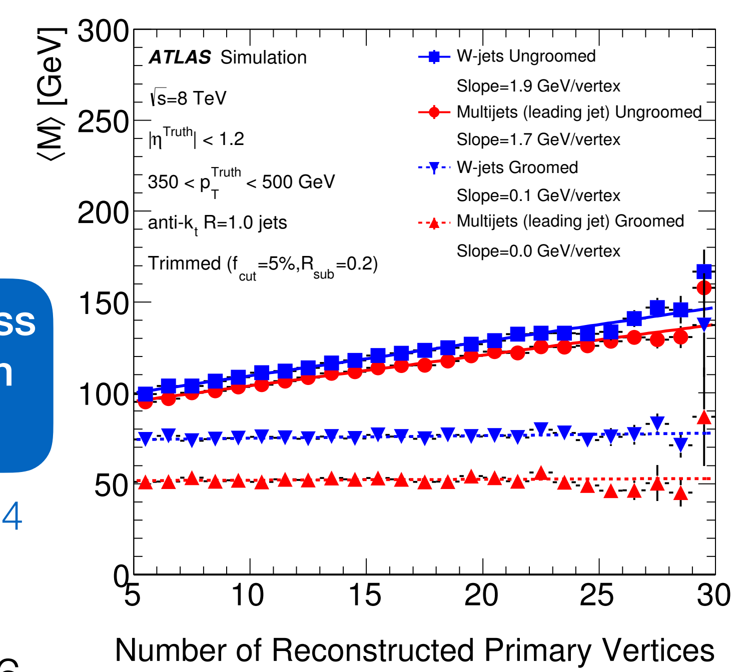
CMS HIG-13-008
H → WW → lνqq

Improved jet mass resolution for boosted heavy object

Reduces measured QCD jet mass (improves discrimination)

Reduces jet mass dependence on pileup

ATLAS CERN-PH-EP-2015-204
arxiv:1510.05821



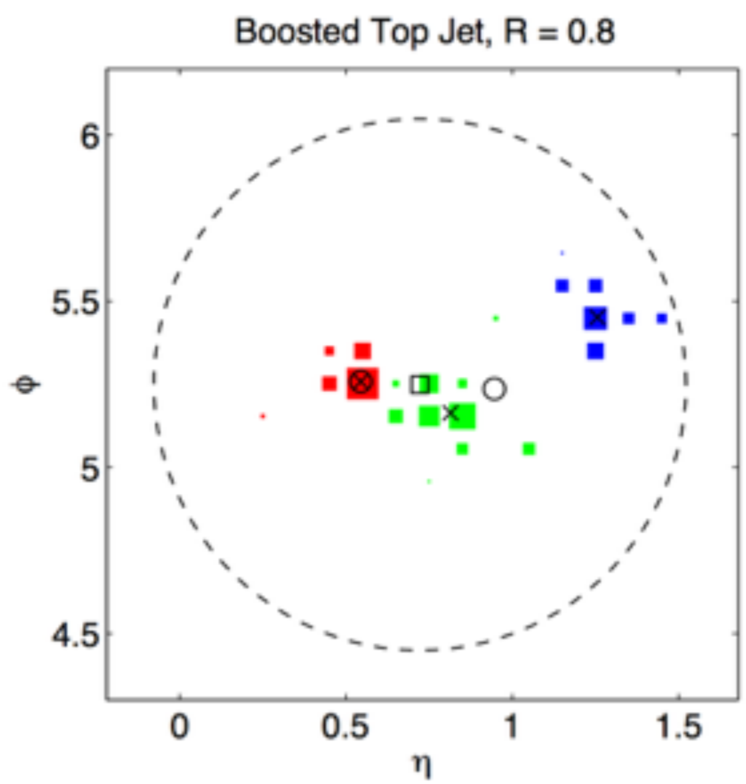
Jet shape tagging variables

Particle energy pattern within a jet used to identify "multi-prong" jets

N-subjettiness

$$\tau_N = \frac{\sum_{i=1}^{n_{\text{constituents}}} p_{T,i} \min\{\Delta R_{1,i}, \Delta R_{2,i}, ..., \Delta R_{N,i}\}}{\sum_{i=1}^{n_{\text{constituents}}} p_{T,i} R}$$

Determines how consistent a jet is with having N or fewer subjets



$\tau_N \to 0 \Longrightarrow$ energy spread is close to the subjet axes

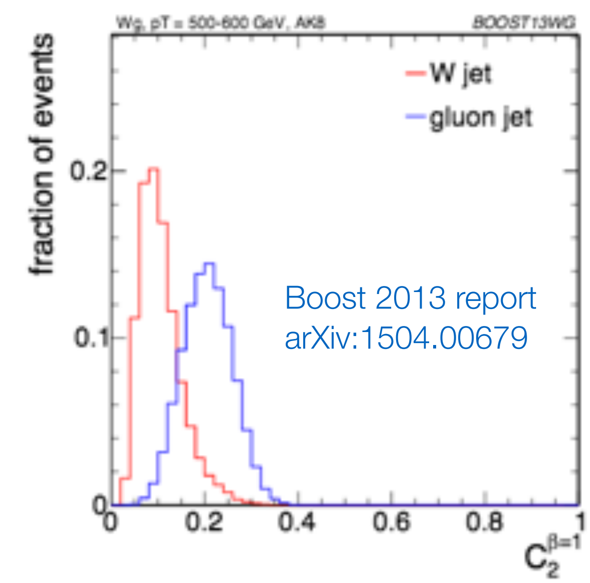
Better discrimination by using ratios (ex. τ_3/τ_2)

J. Thaler, K. Van Tilburg, JHEP 2011:15

Energy Correlation Functions (ECF)

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

Jet constituent based observables sensitive to N subjet substructure



$$C_N^{(\beta)} = \frac{\text{ECF}(N+1,\beta)\,\text{ECF}(N-1,\beta)}{\text{ECF}(N,\beta)^2} \qquad D_2(\beta) = \frac{\text{ECF}(3,\beta)\text{ECF}(1,\beta)^3}{\text{ECF}(2,\beta)^3}$$

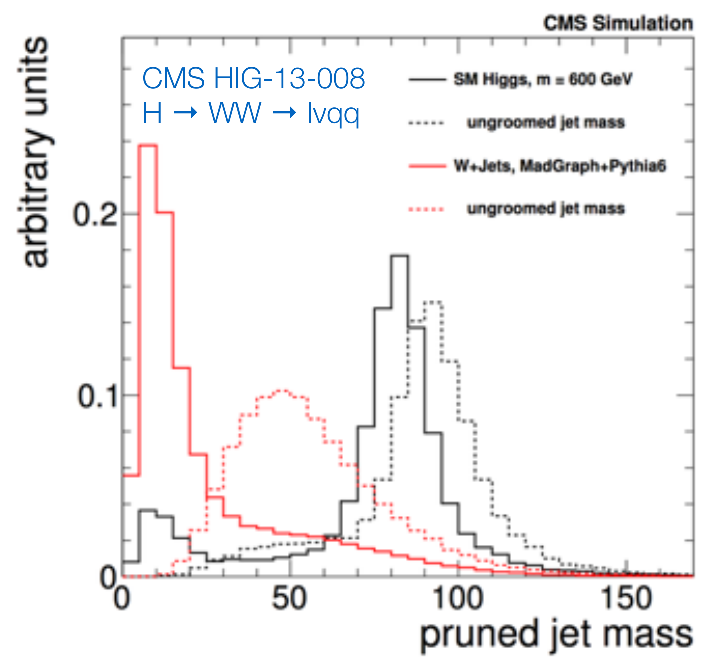
ECF ratios (C2,D2, etc.) for boosted object discrimination (Small C2 $\Longrightarrow$ 2 subjets)

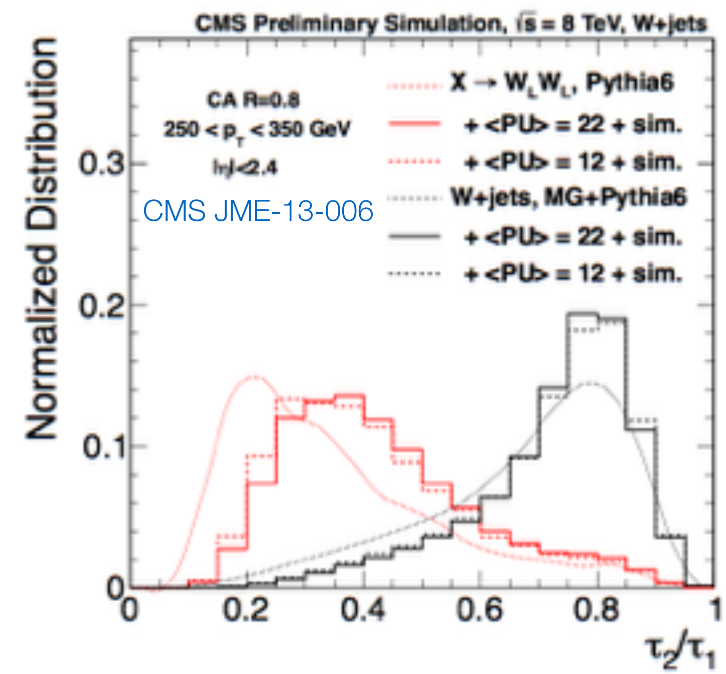
β parameter allows access to different angular scales

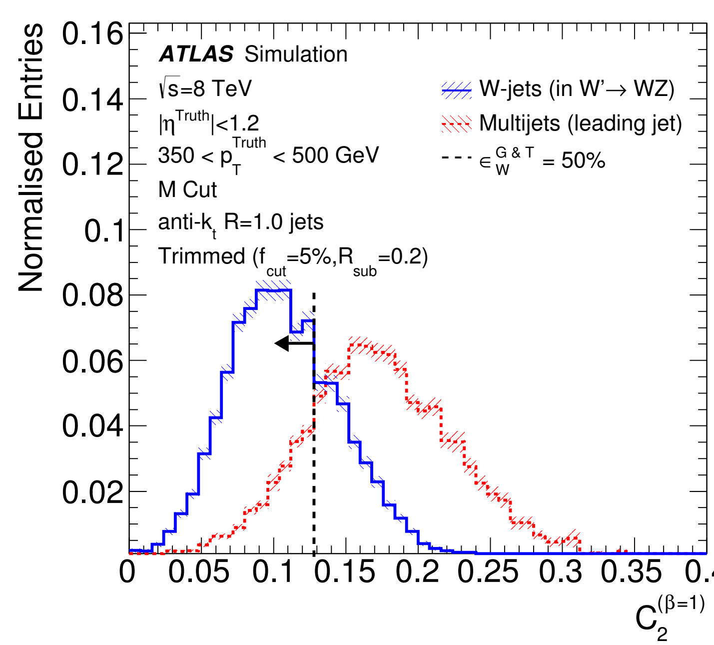
A. Banfi, G. P. Salam, and G. Zanderighi, JHEP 0503 (2005) 073
M. Jankowiak and A. J. Larkoski JHEP 1106 (2011) 057
A. Larkoski, G. Salam, J. Thaler JHEP 2013:108

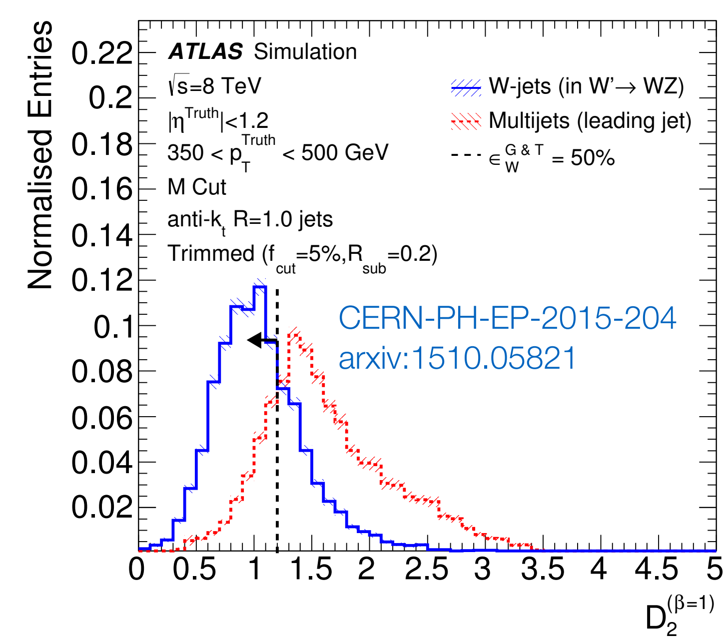
2-prong tagging “V-tagging”

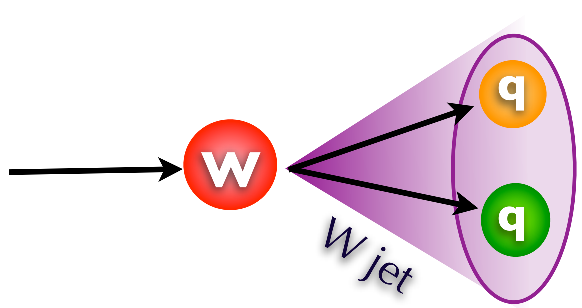
- Boosted W, Z, H tagging
- General technique: select V jets based on groomed jet mass and “2-subjettiness”
- CMS default:
  - pruned jet mass + N-subjettiness
- ATLAS:
  - Run 1 : split filtering + subjet momentum balance
  - Run 2 : trimmed jet mass + D2



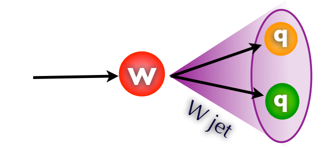






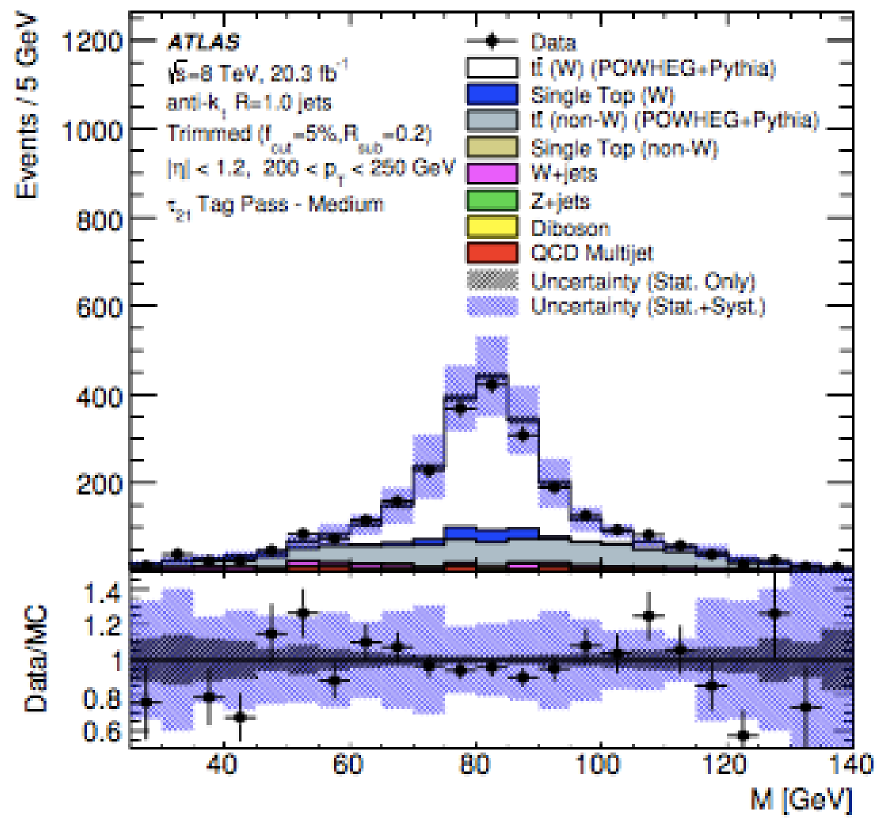


W-tagging data-MC

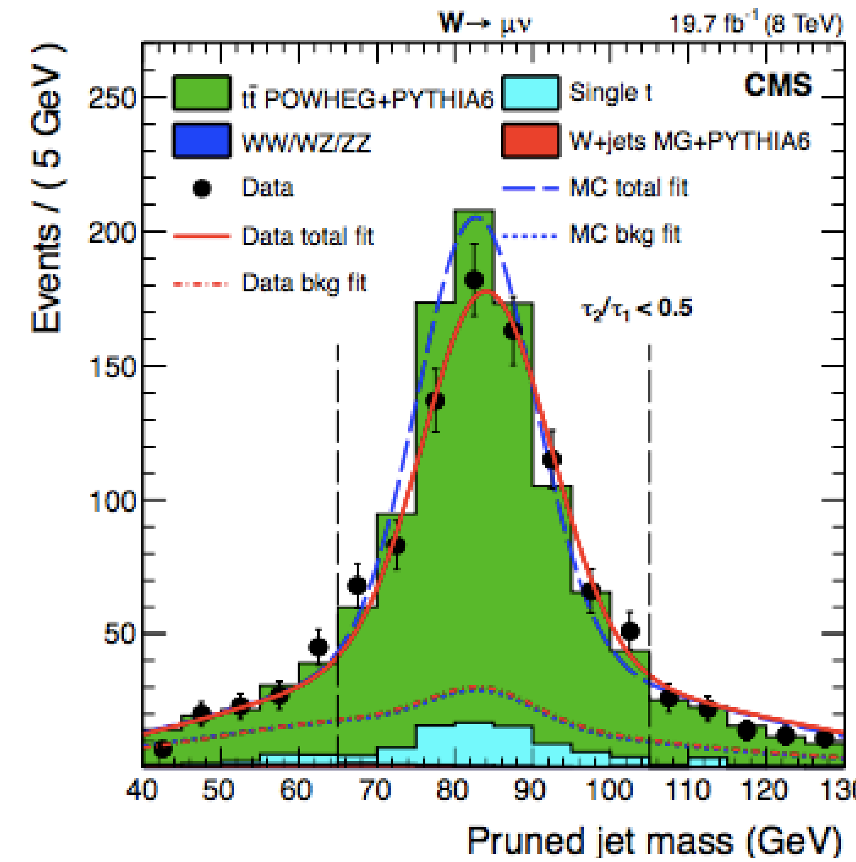


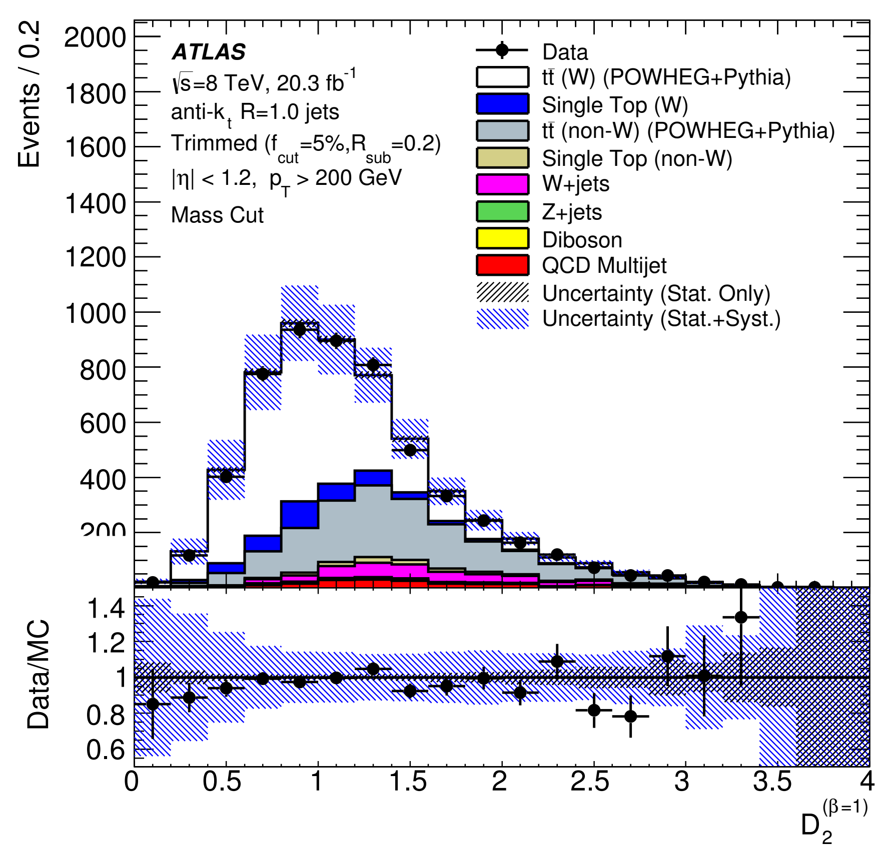
- Semileptonic ttbar selection → very pure sample of boosted Ws
- Data-MC scale factors measured

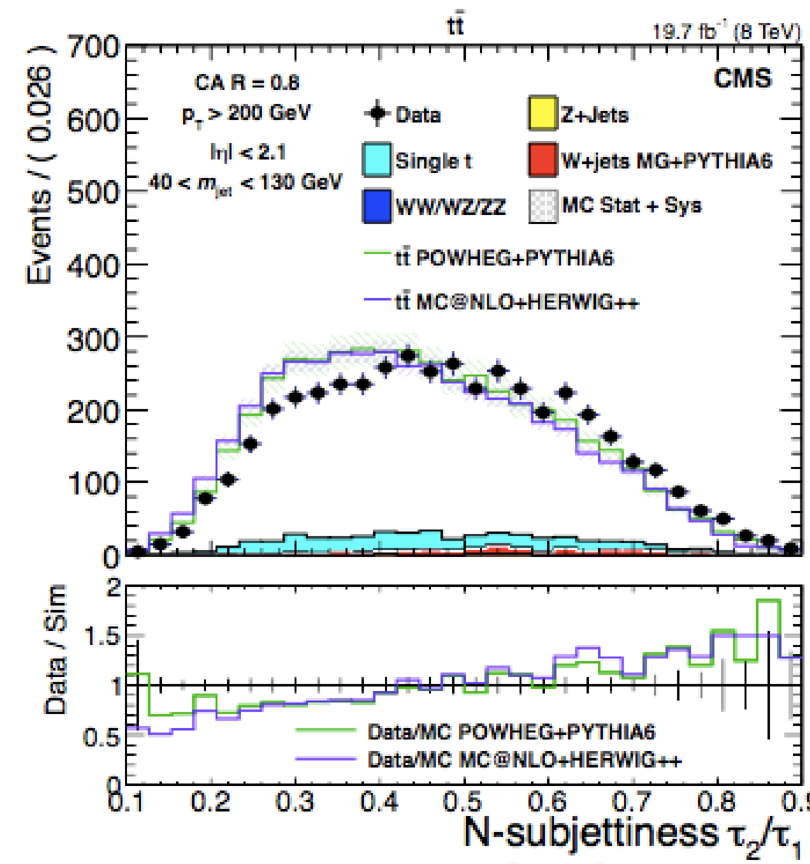
CERN-PH-EP-2015-204



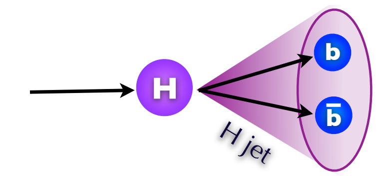
CMS JME-14-002



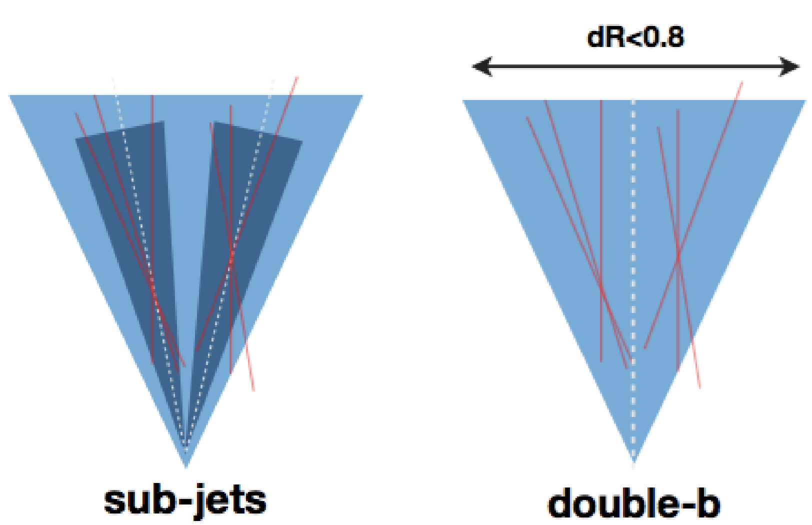


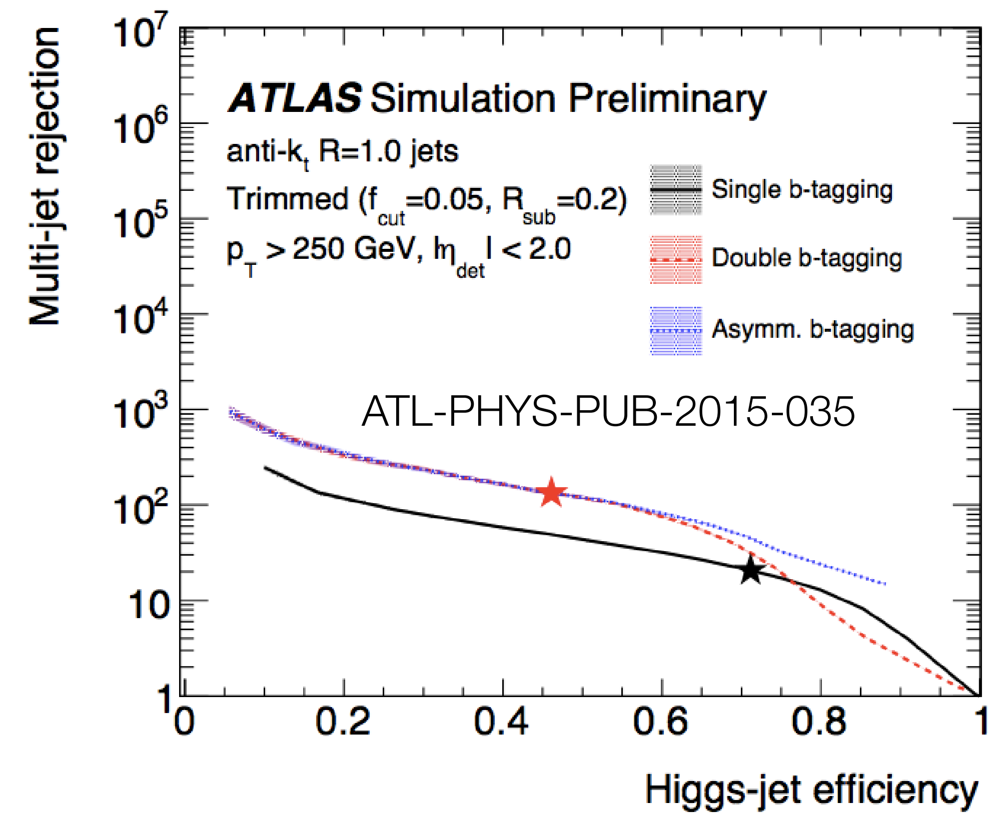


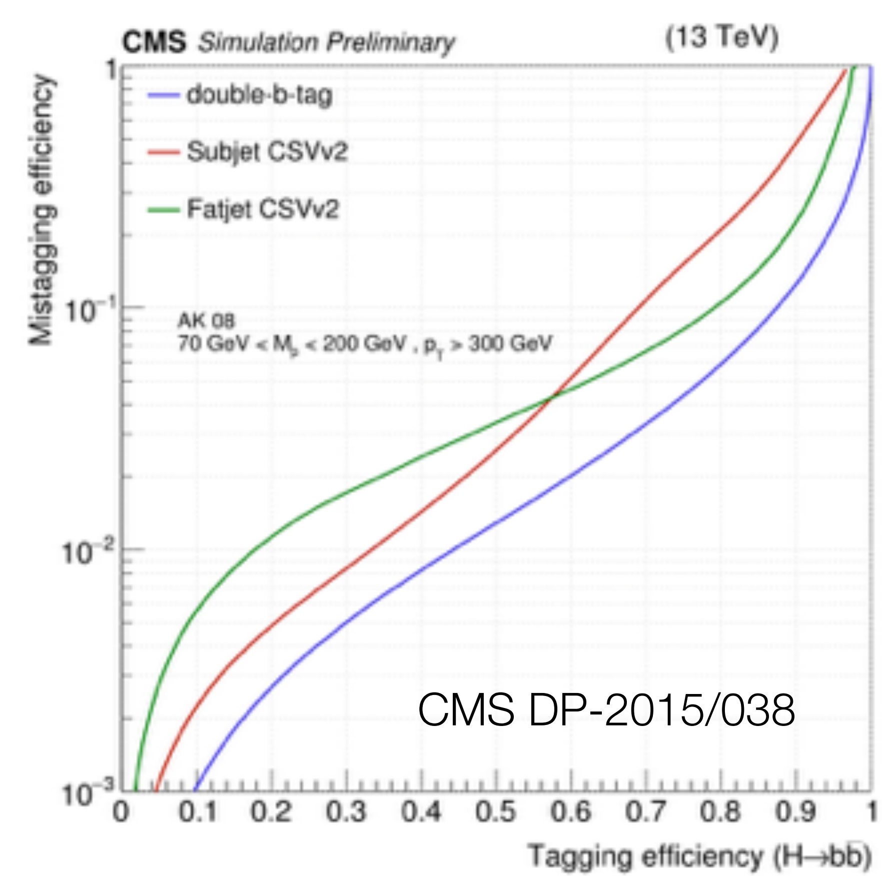
H-tagging



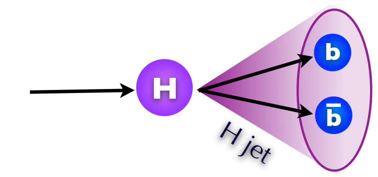
- Boosted Higgs → bb
- Use the same tools as with W/Z tagging (groomed jet mass, N-subjettiness, ECF) + additional information from b-jets
- B-tagging H-jets
  - ATLAS:
    - Double subjet b-tagging with matched small R (R=0.2) track jets
  - CMS:
    - Double subjet b-tagging (example: pruned subjets)
    - Dedicated wide jet double b-tagger

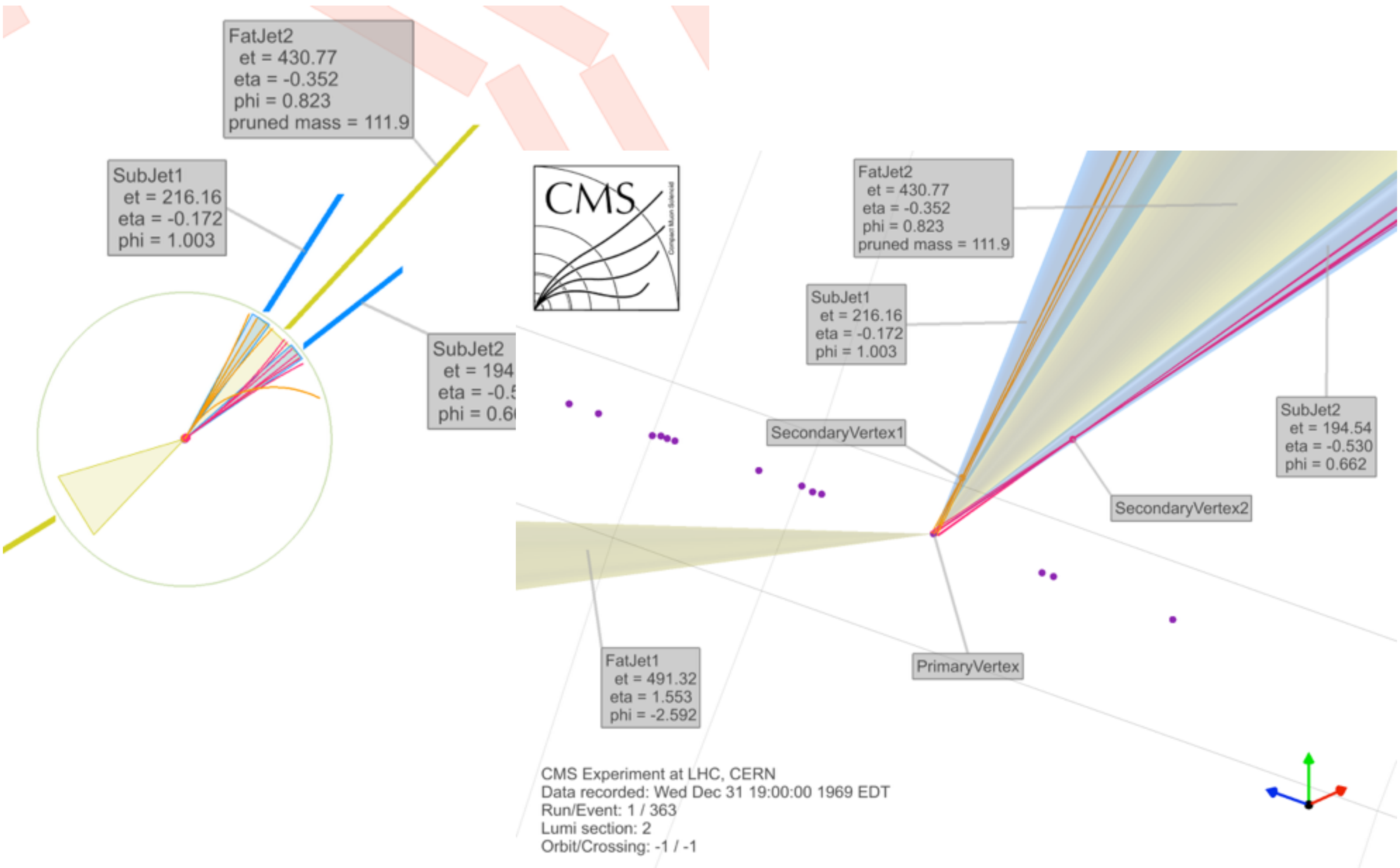




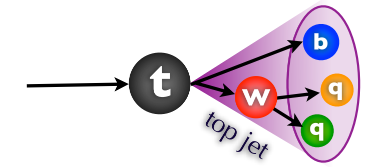


Double b-tagged H-jet

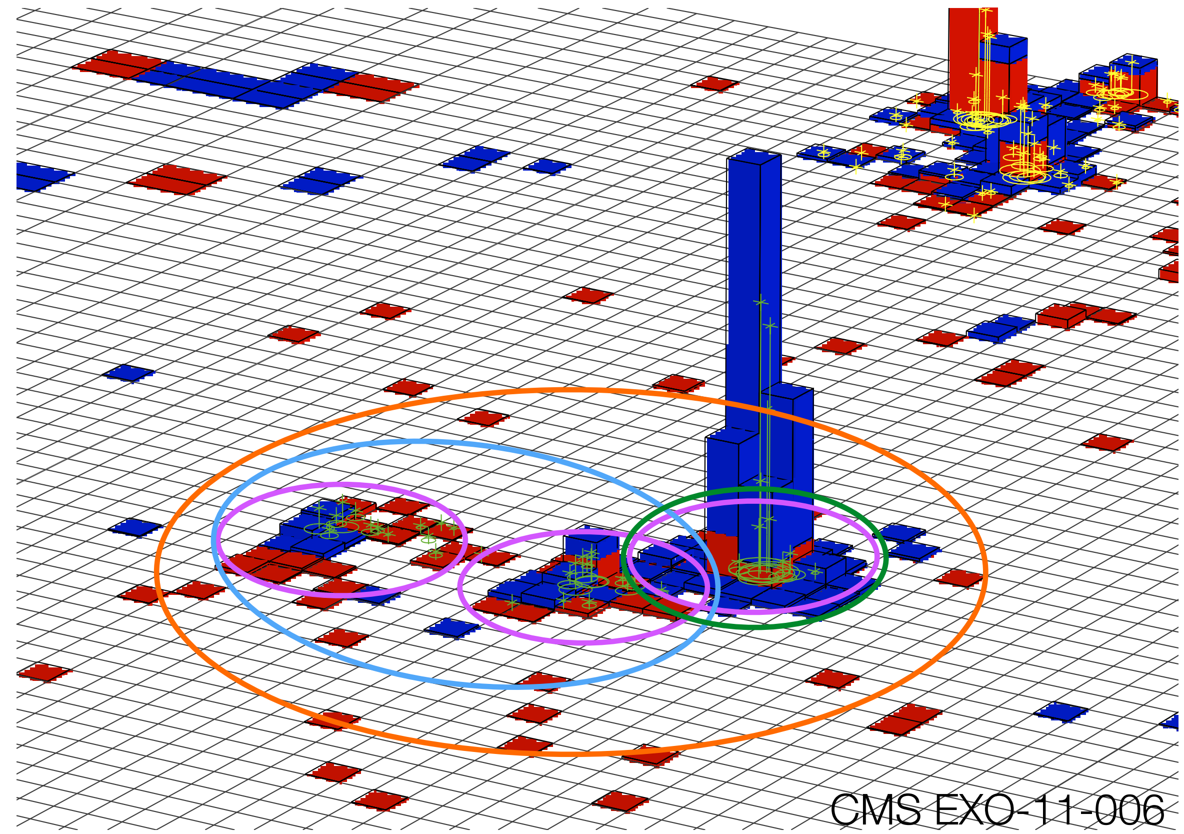


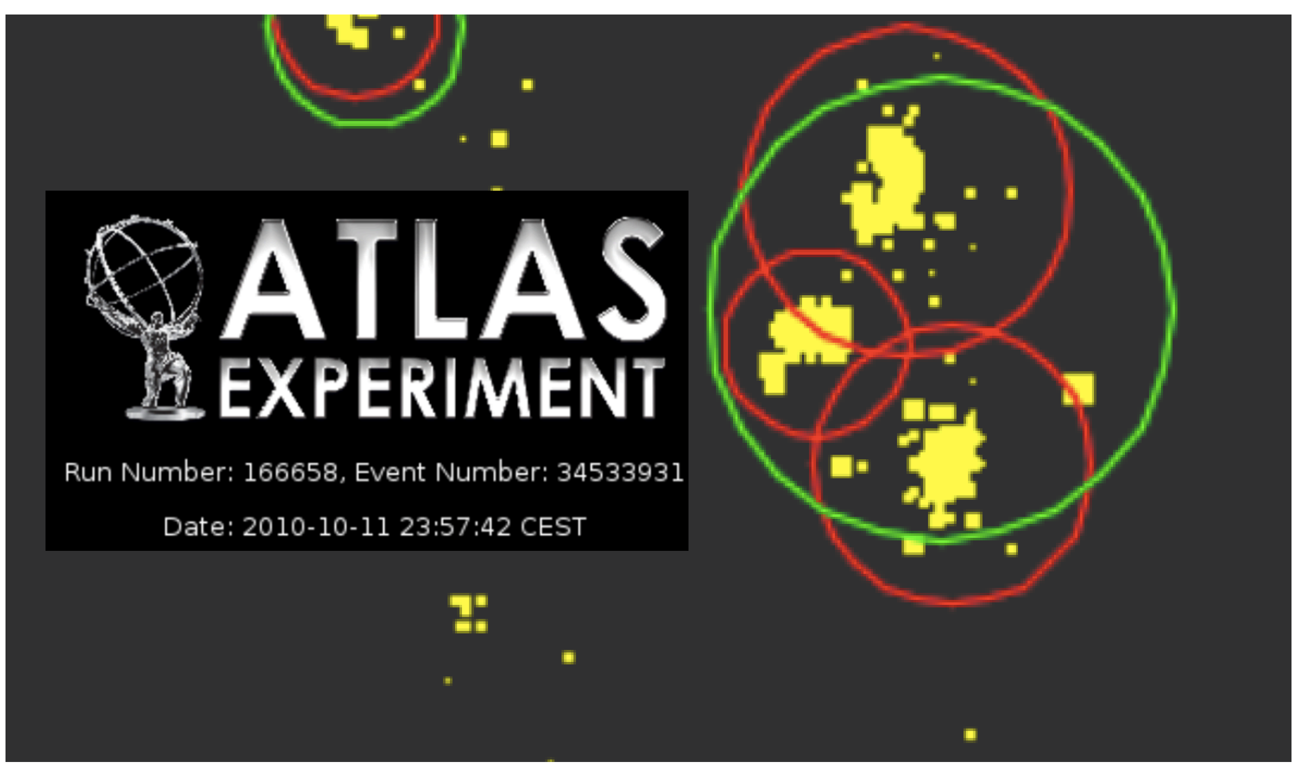


Top tagging



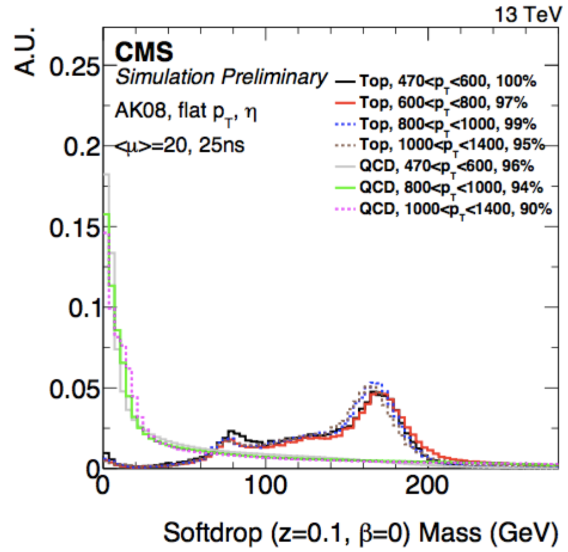
- Top jet properties used for discrimination:
  - jet mass = top mass
  - substructure (3 subjets)
  - two subjets with pairwise mass = W mass
  - one subjet b-tagged

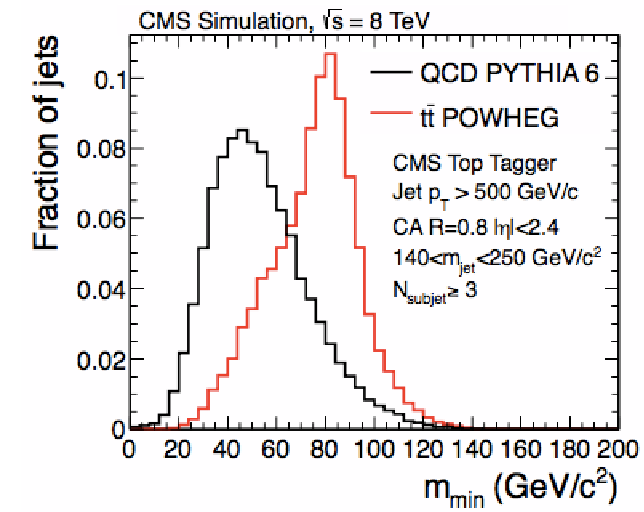


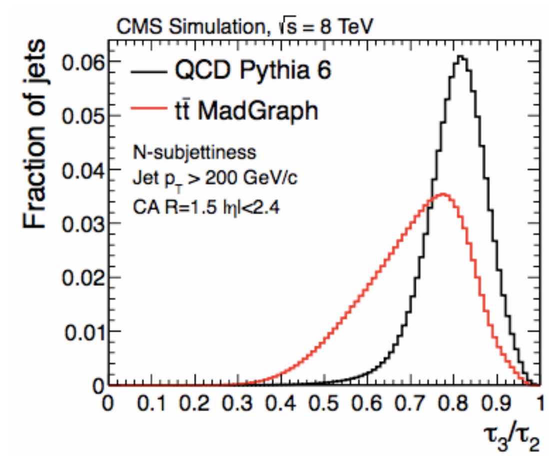


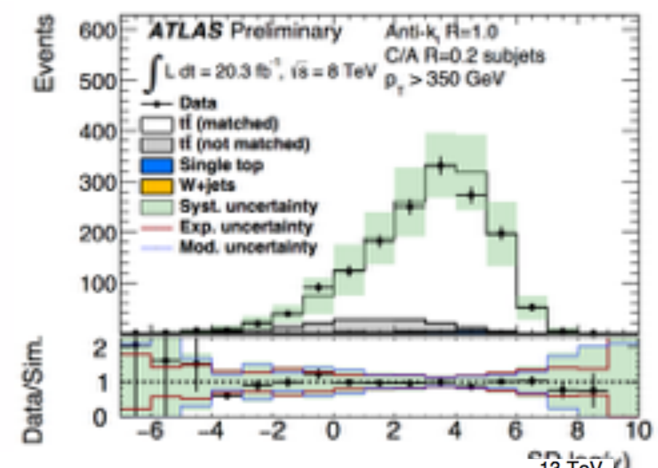
Top tagging algorithms

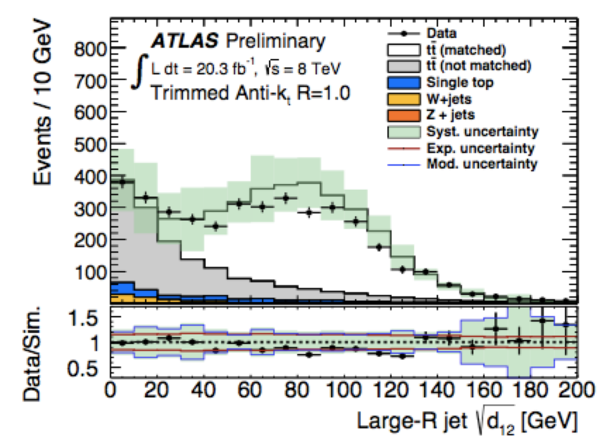
- Taggers utilizing general algorithms
  - Groomed mass + N-subjettiness (τ_3/τ_2)
  - Shower deconstruction [1]
  - Splitting scale
  - Subjet b-tagging
- Dedicated algorithms
  - CMS Top Tagger (JHU Top Tagger) [2]
    - Decluster jet twice to find 1-4 subjets
    - Select tops based on top mass, W mass, Nsubjets
  - HEP Top Tagger v1 [3]
    - Very large jets (R=1.2-1.5)
    - Multistep decluster + filter procedure
    - Select tops based on top mass, W mass
  - HEP Top Tagger v2 [4]
    - Multiple algorithm improvements + multi R approach
    - Select tops based on top mass, W mass, optimal jet size

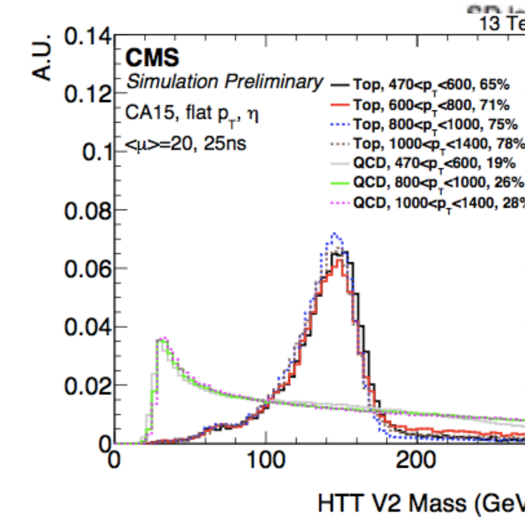






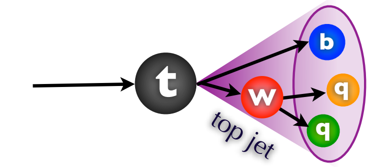


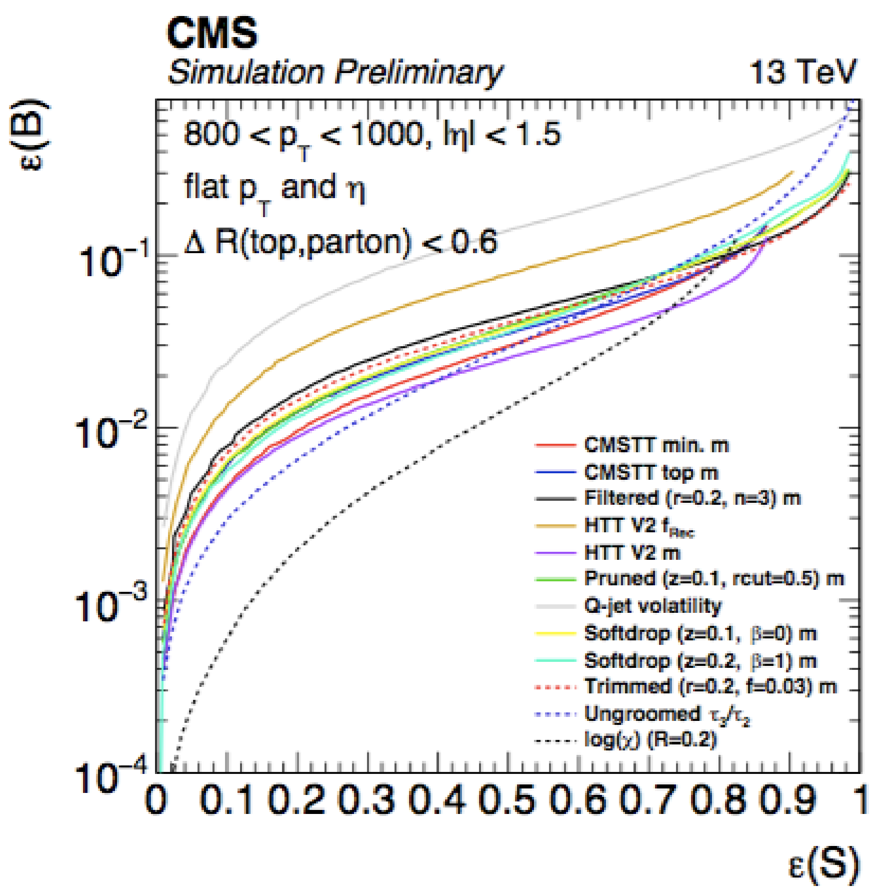


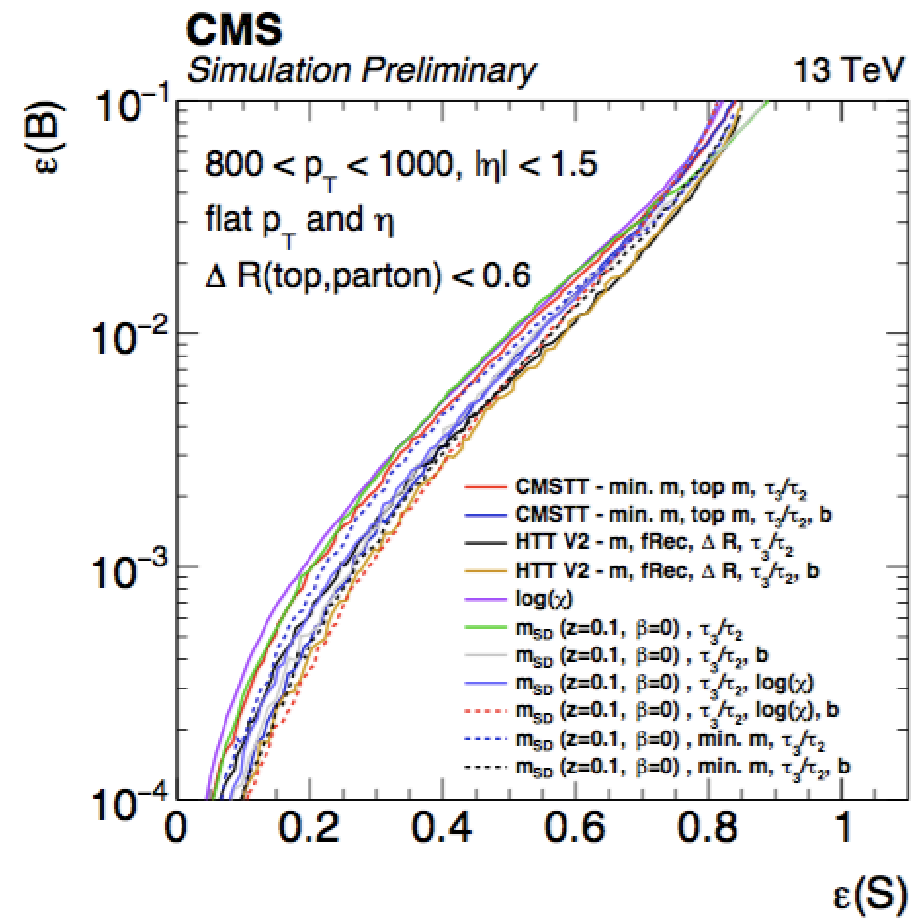


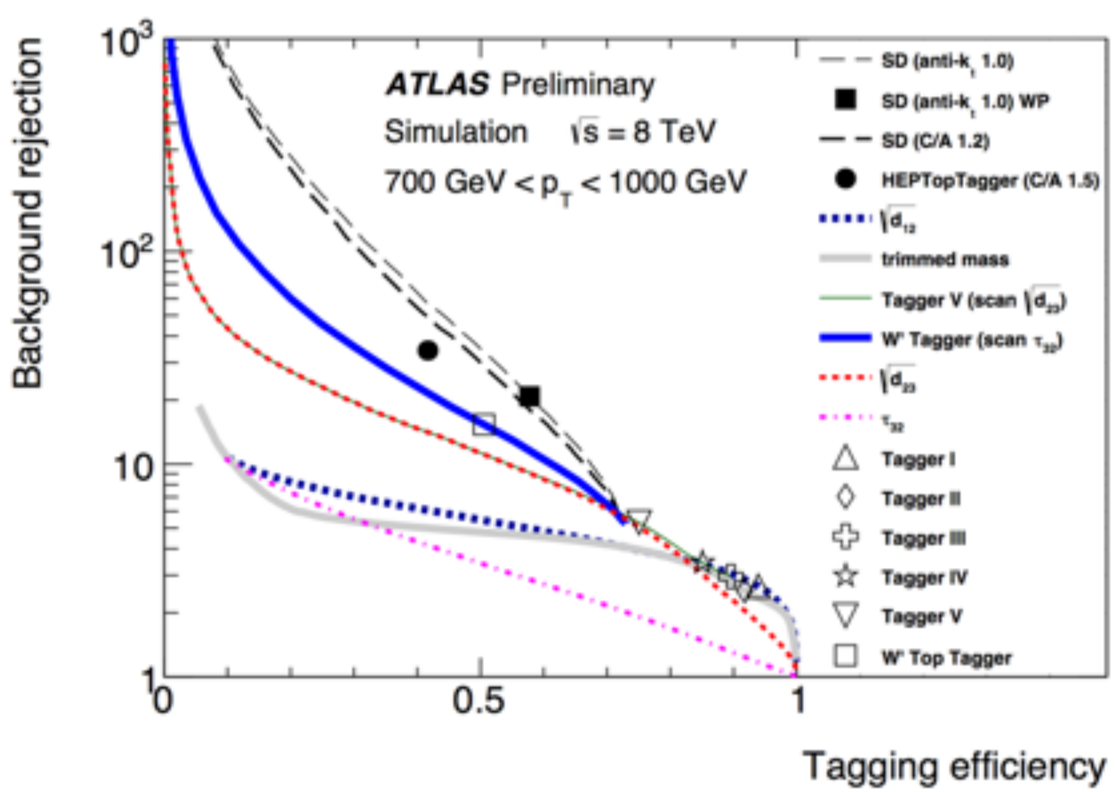
[1] D. Soper, M. Spannowsky arXiv:1211.3140
[2] D. E. Kaplan, K. Rehermann, M. D. Schwartz, and B. Tweedie, arXiv:0806.0848
[3] T. Plehn, M. Spannowsky, M. Takeuchi, D. Zerwas, arXiv:1006.2833
[4] G. Kasieczka, T. Plehn, T. Schell, T. Strebler, G. Salam arXiv:1503.05921

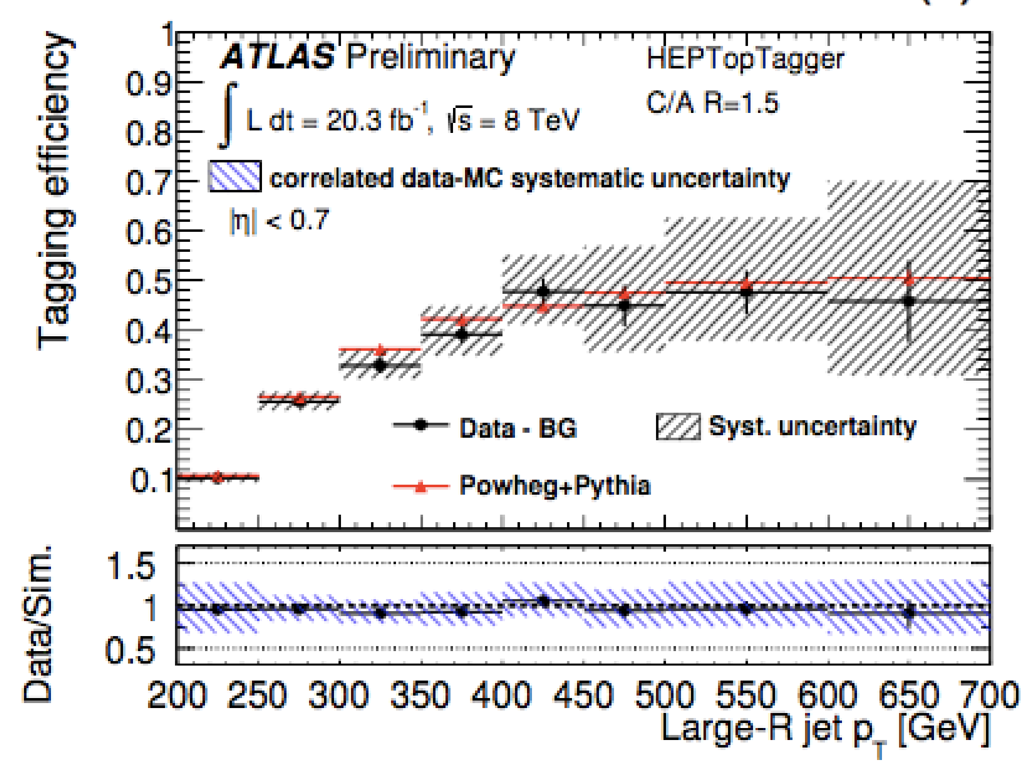
Top tagging performance







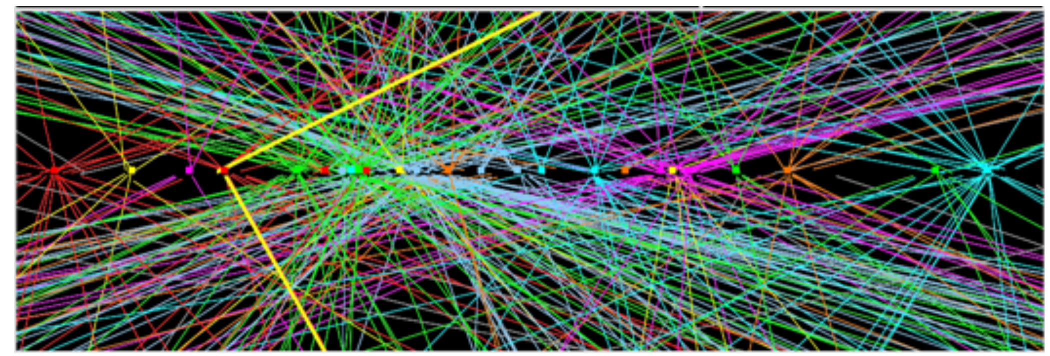




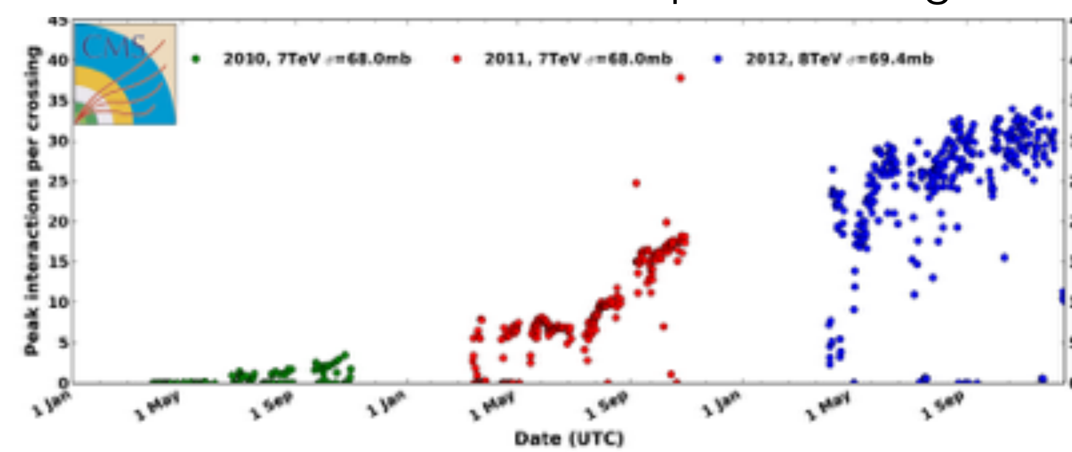
Pileup

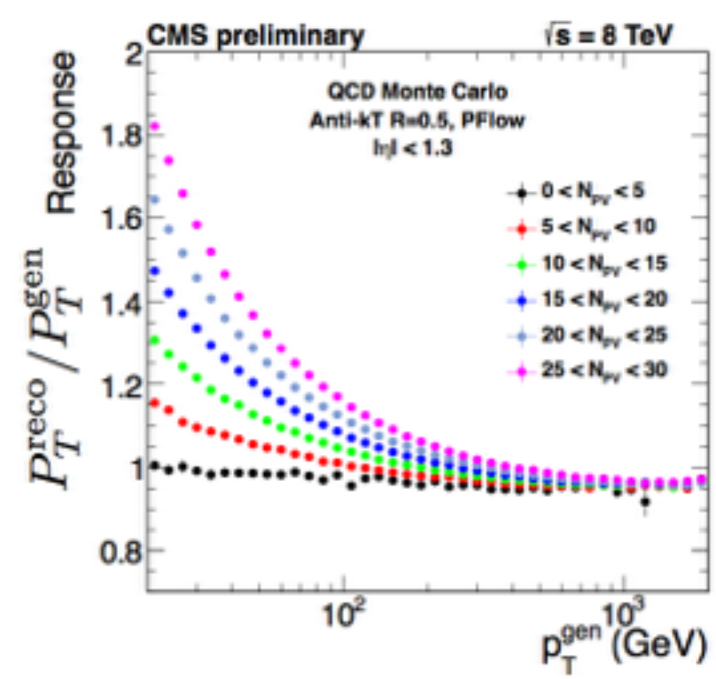
- LHC: high intensity machine
    - Multiple collisions per bunch crossing (*in-time pileup*)
        - Run 1: 21 interactions per crossing
        - Run 2: 40 interactions per crossing
        - High Luminosity LHC: 100 interactions
    - High collision rates → particles/signals from previous and future collisions affect the current event (*out-of-time pileup*)
- Presents numerous challenges:
    - Trigger/computing
        - More hits, more energy
    - Contributes extra energy to event
        - Needs to be subtracted to correctly measure jets, MET, photons, taus, electrons etc.
        - jet/MET resolution degrades
        - Pileup jets

Z → μ μ event with 25 vertices at ATLAS



Peak number of interactions per crossing vs. time

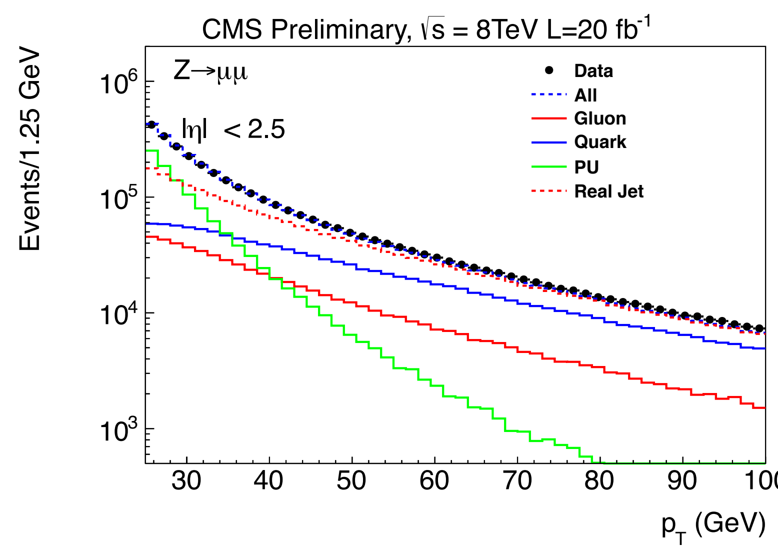


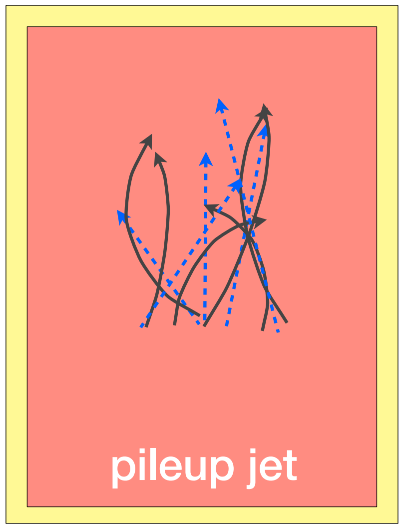


Pileup jet tagging

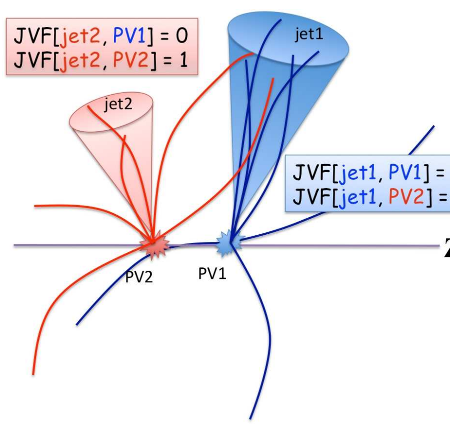
CMS JME-13-005
ATLAS-CONF-2014-018

- Each pileup vertex contributes ~0.7 GeV of energy per unit area (η,Φ) of the detector
  - High pT pileup jets are formed from overlapping low pT energy from pileup



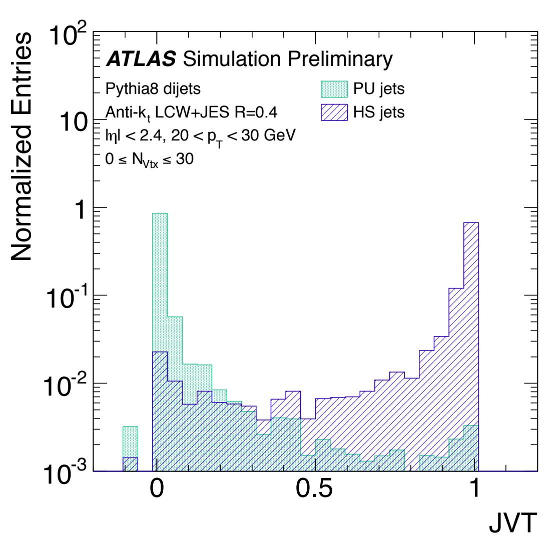


- Pileup jets can be rejected using tracking and jet shape information
  - Charged particles inside pileup jets are not associated with the primary vertex
  - Pileup jet more defuse (overlapping soft particles from multiple vertices)
- Pileup jet ID essential for MET resolution and jet counting



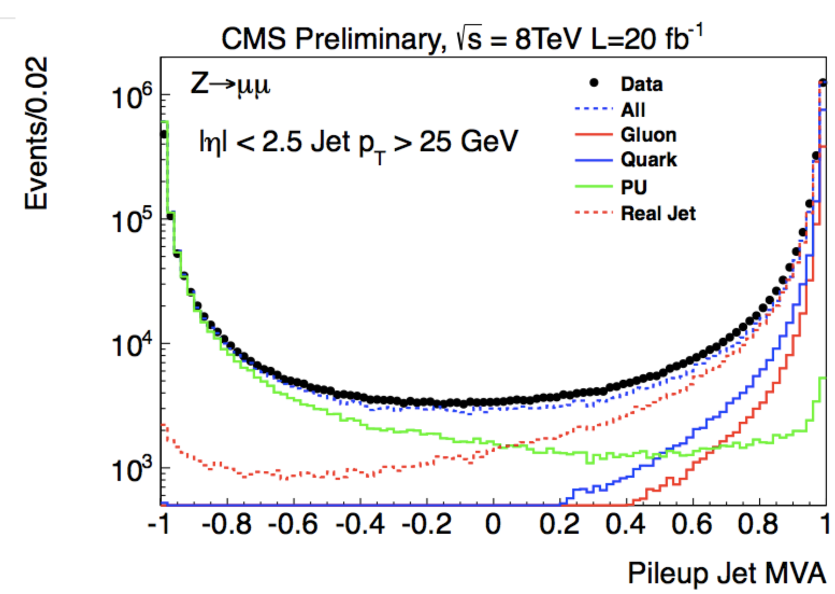
ATLAS: Jet Vertex Tagger (JVT)

2-dimensional likelihood of track/vertex variables



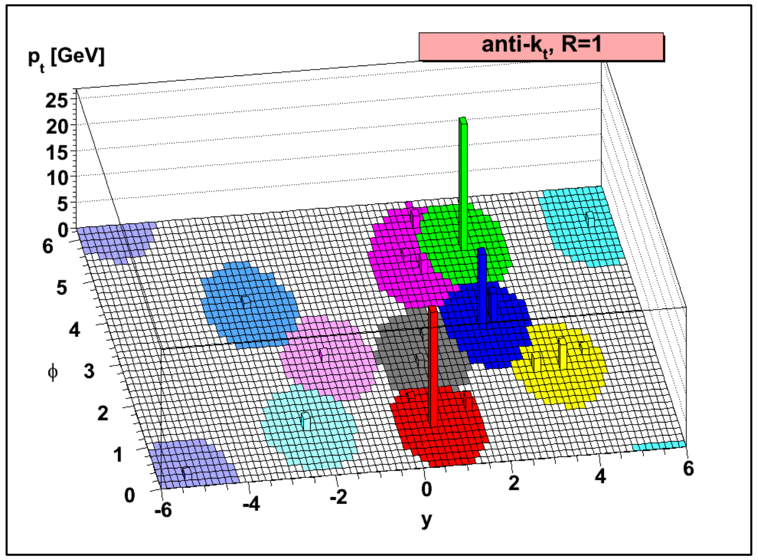
CMS: Pileup ID MVA

BDT with 4 track/vertex variables and 5 jet shape variables



Pileup Subtraction

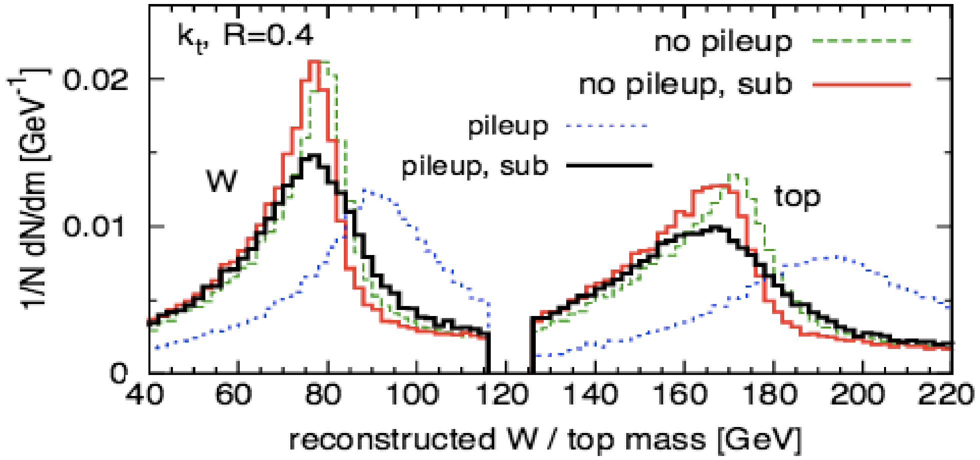
- Jet area - the region around a jet in which energy will be clustered within the jet
- Jet area pileup subtraction method
  - Measure the pileup energy density (per event)
  - Subtract energy density × jet area from each jet



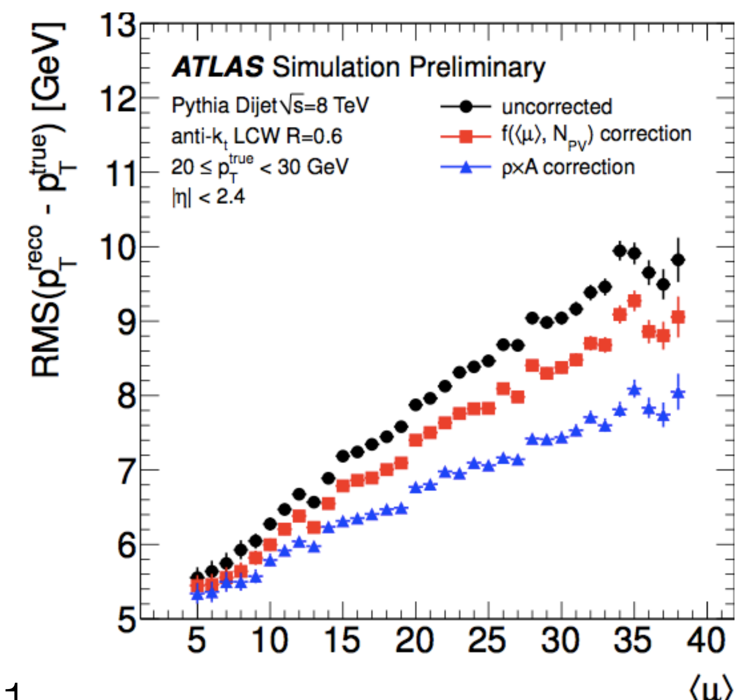
Jet area method

G. Salam, M. Cacciari arXiv:0707.1378

$$p_{\rm T}^{\rm sub} = p_{\rm T} - \rho A$$
$$\rho = {\rm median}[p_{{\rm T}j}/A_j]$$

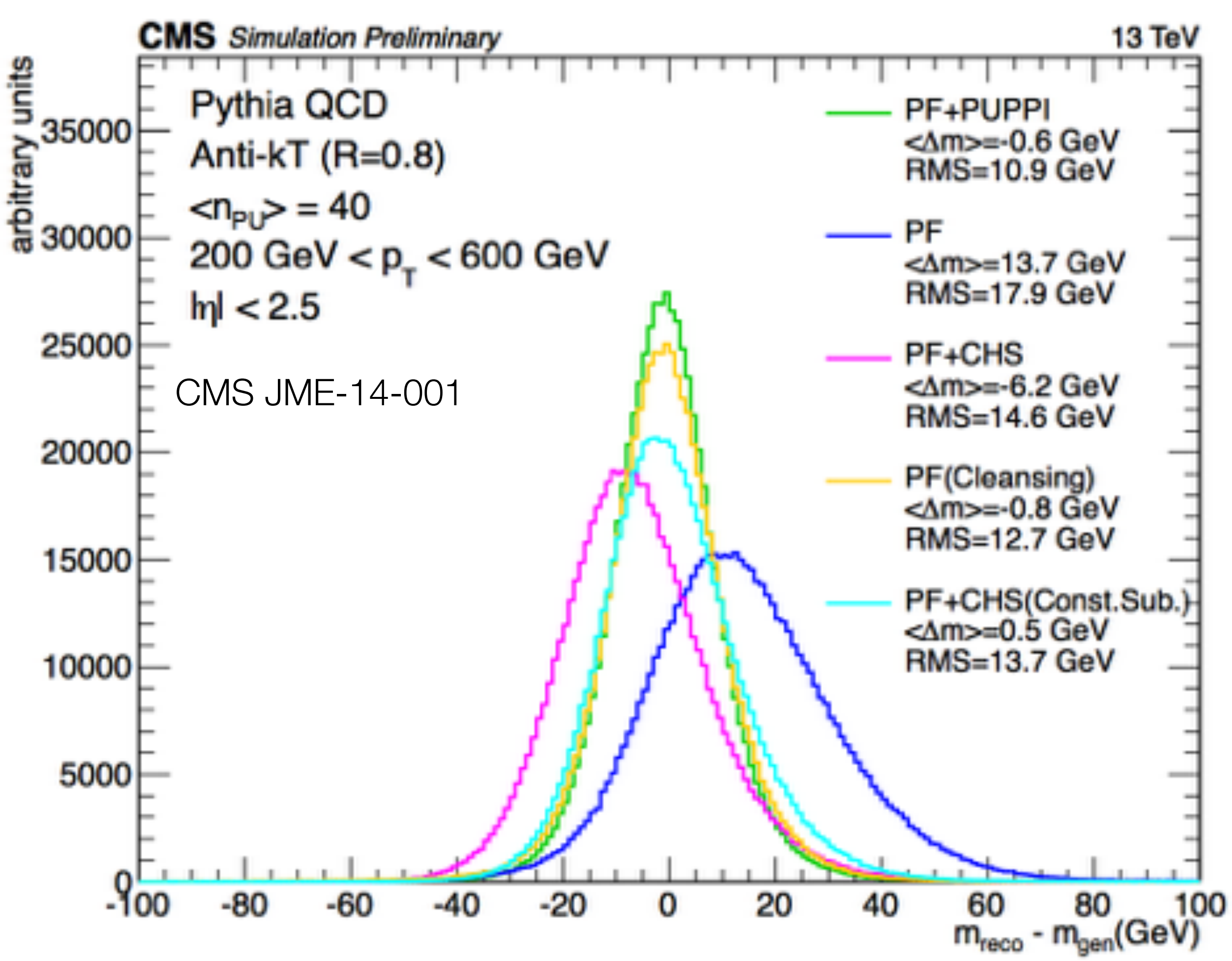


- The problem: subtracting only the *average* pileup energy within a jet
  - Result: jet momentum smeared by the jet to jet pileup fluctuations → reduced jet energy resolution
  - *Example: High Luminosity LHC (2022) - 100 pp collision per crossing*
    - *a typical anti-kt R=0.4 jet has on average 35 GeV of excess energy from pileup which needs to be subtracted → fluctuations ~ √35 GeV*
    - *large R top jet (ex. R=1.0) has 200 GeV of excess energy from pileup*



Pileup removal before jet clustering

- Charged Hadron Subtraction (CHS)
  - enabled by particle flow
  - remove charged particles originating from pileup vertices before clustering jets
  - does not remove neutral pileup



- New tools which utilize additional information for pileup removal
  - ***Constituent subtraction [1]*** - per particle area subtraction
  - ***Jet cleansing [2]*** - charged particle vertex information used to correct jets at the subjet level
  - ***Soft killer [3]*** - progressively remove soft particles until the average pileup density in the event is 0
  - ***Pileup Per Particle Identification (PUPPI) [4]*** - jet shape and charged particle vertex information used to suppress pileup

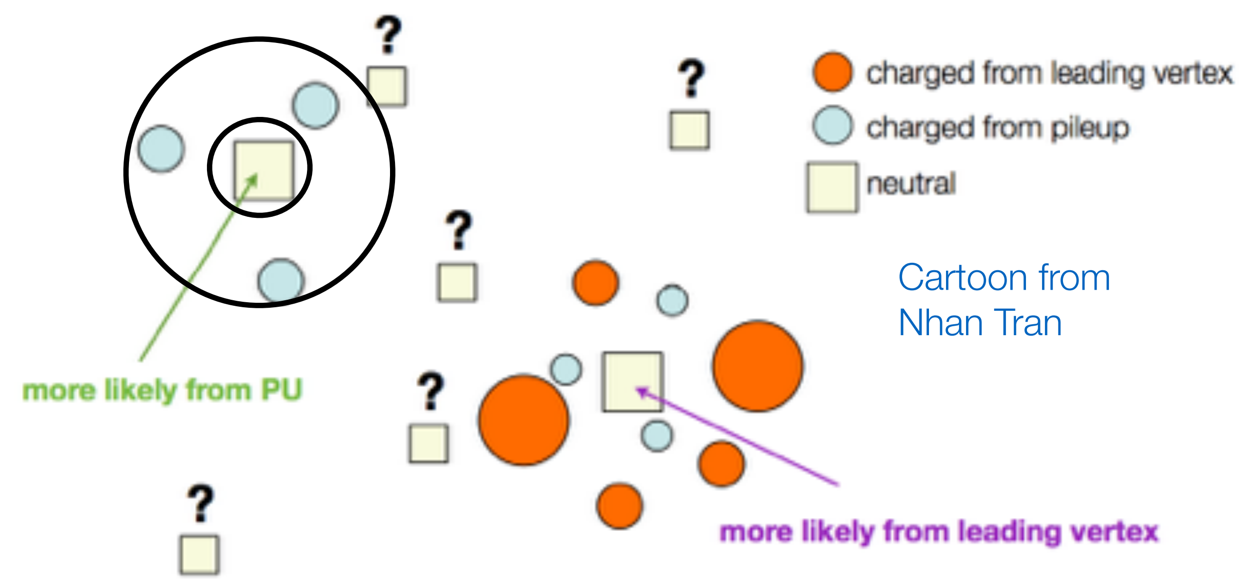
Jet mass resolution improved by Charged Hadron Subtraction (CHS)

Jet mass resolution is further improved by new techniques which also remove neutral pileup

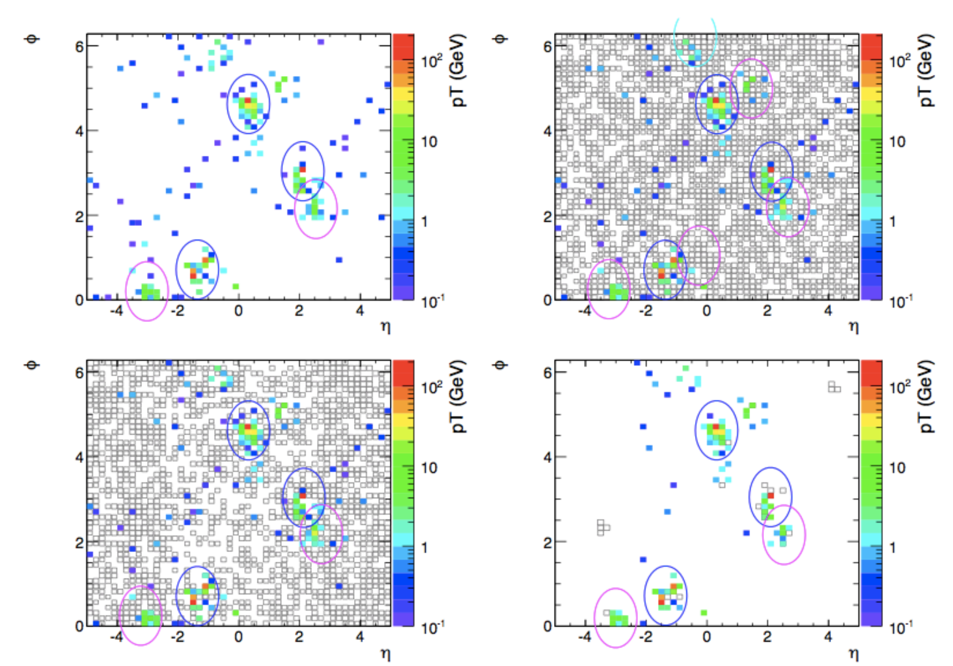
[1] P. Berta, M. Spousta, D. Miller, R. Leitner arXiv:1403.3108
[2] D. Krohn, M. Low, M. Schwartz, L. Wang, arXiv:1309.4777
[3] M. Cacciari, G. Salam, G. Soyez, arXiv:1407.0408
[4] D. Bertolini, P. Harris, M. Low, N. Tran, arXiv:1407.6013

PileUp Per Particle Identification (PUPPI)

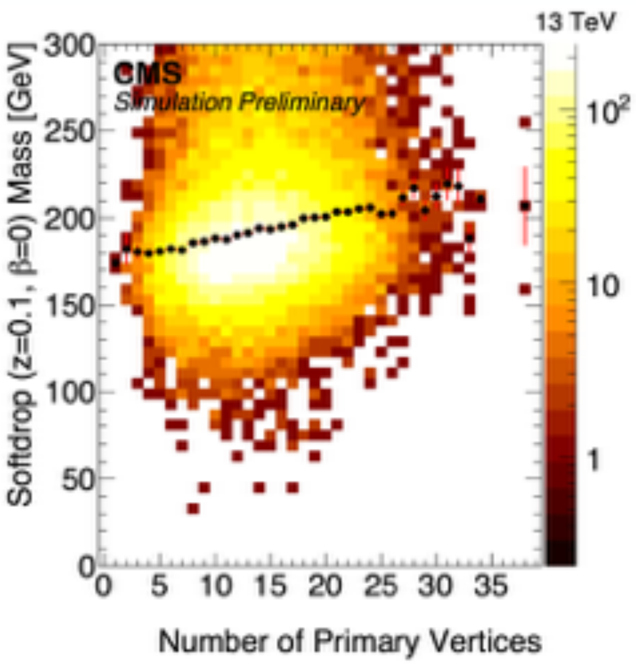
- Pileup handles:
  - Tracking/vertexing→ we know which charged particles come from pileup and which ones come from the hard scatter
  - Pileup is randomly distributed, while collinear radiation from a particle from the hard scatter is preferentially radiated at small angles
  - p_T spectrum of pileup falls quickly

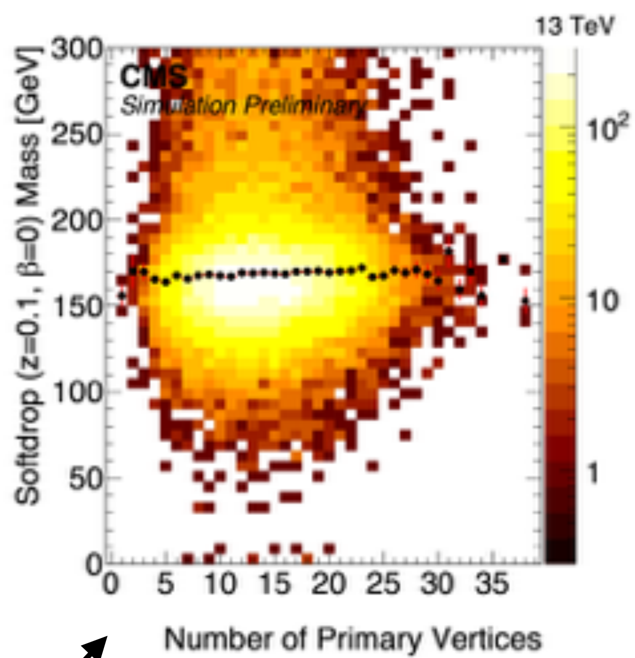


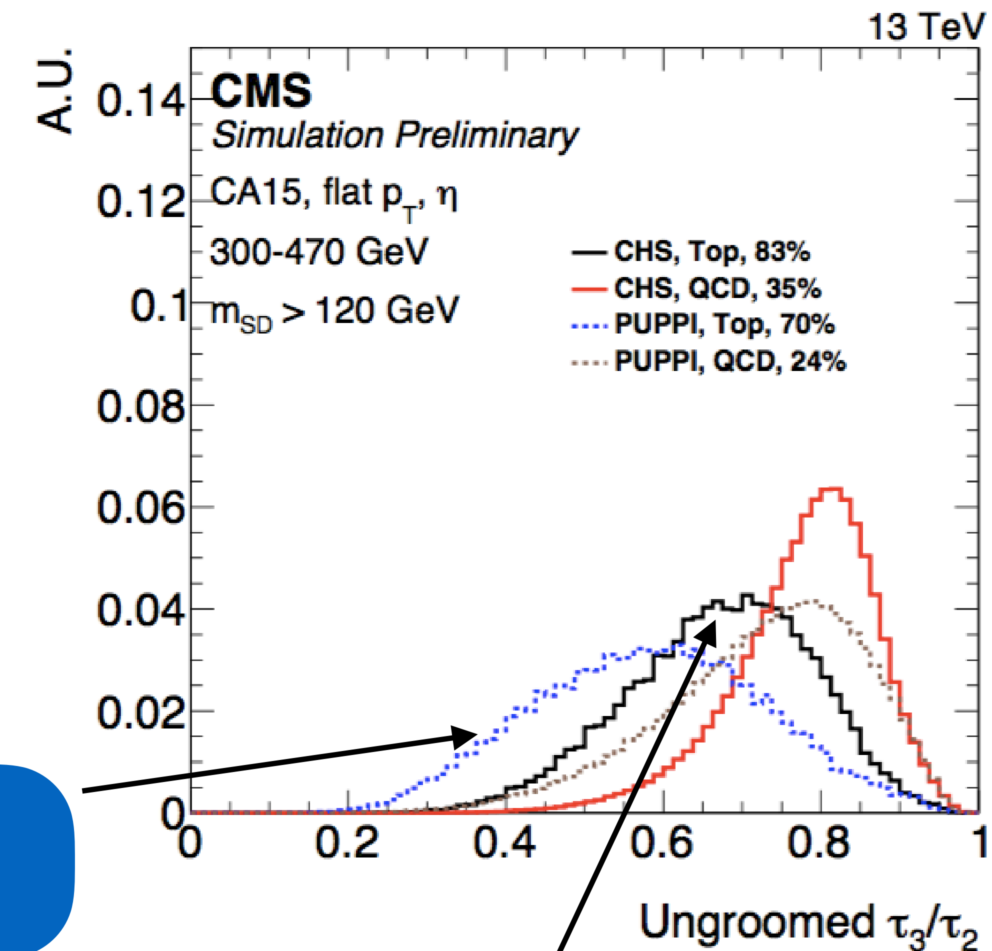
- PUPPI assigns each particle a weight based on the likelihood it originated from pileup
  - Handle: Calculate $\alpha = \sum p_{Tj}/\Delta R_{ij}$ for each particle j within an annulus around particle i
    - α small for particles from pileup (nearby particles are soft and at large angle)
    - α large for particles from the LV (radiation around the particle harder and at small angle)



PUPPI performance







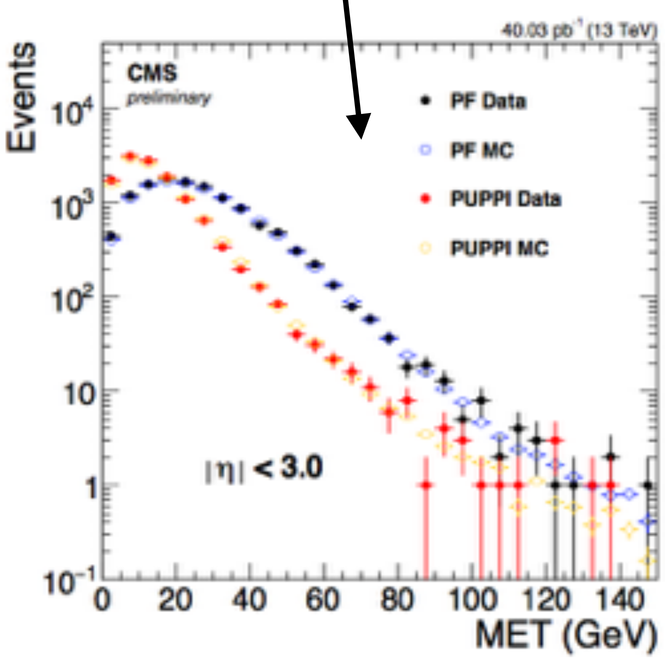
PUPPI jet mass stable with pileup

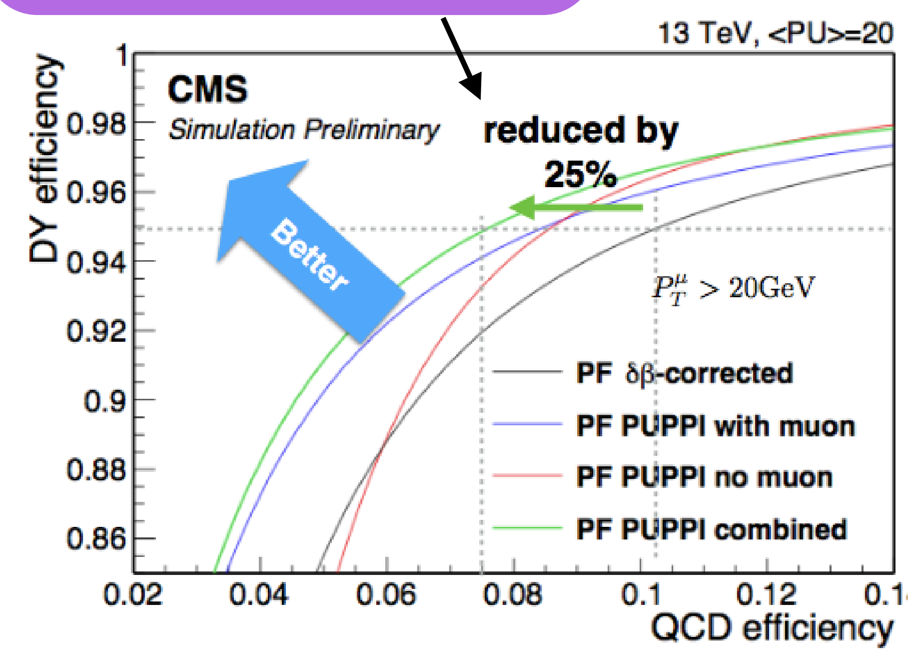
PUPPI corrects jet shapes for pileup → improves tagging discrimination

With pileup the top jet N-subjettiness value is shifted to be more QCD like

Improved MET resolution

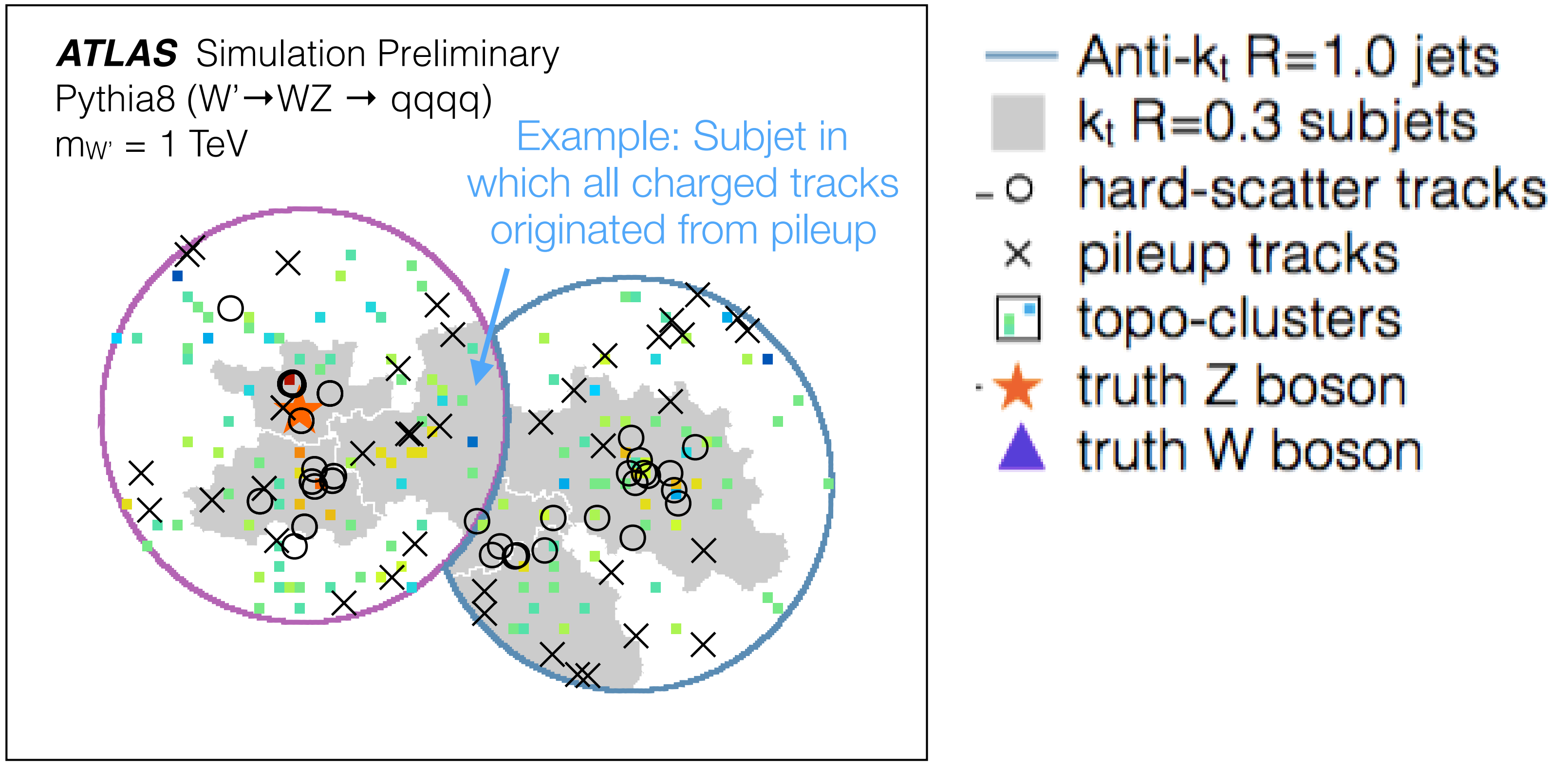
Improved lepton isolation



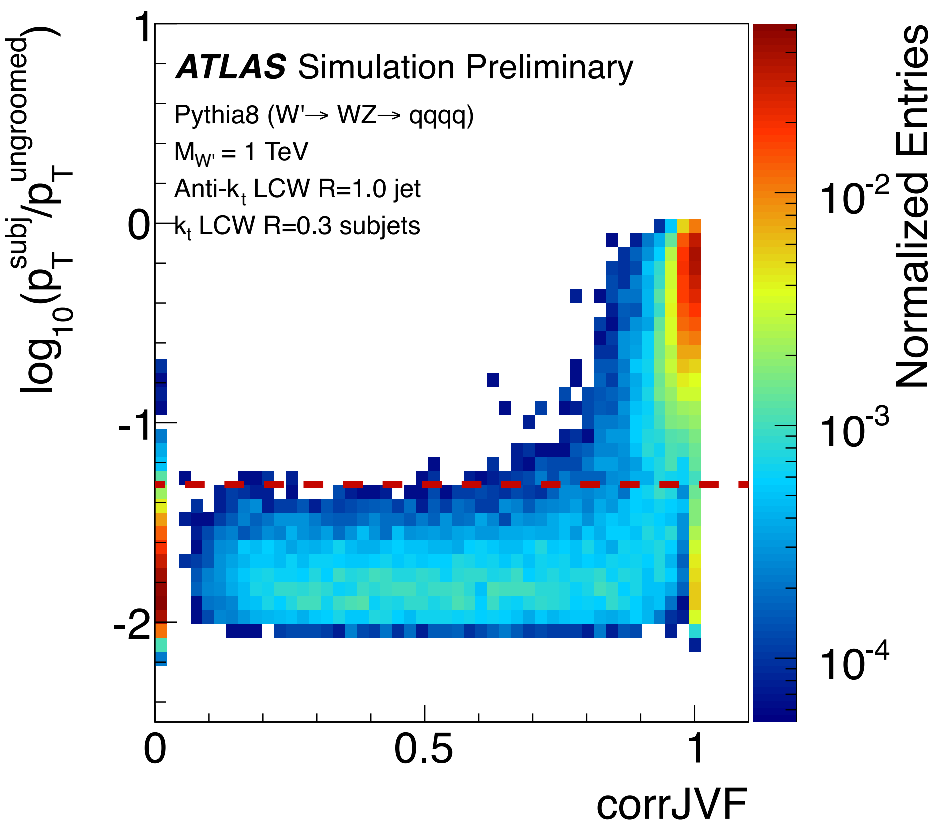


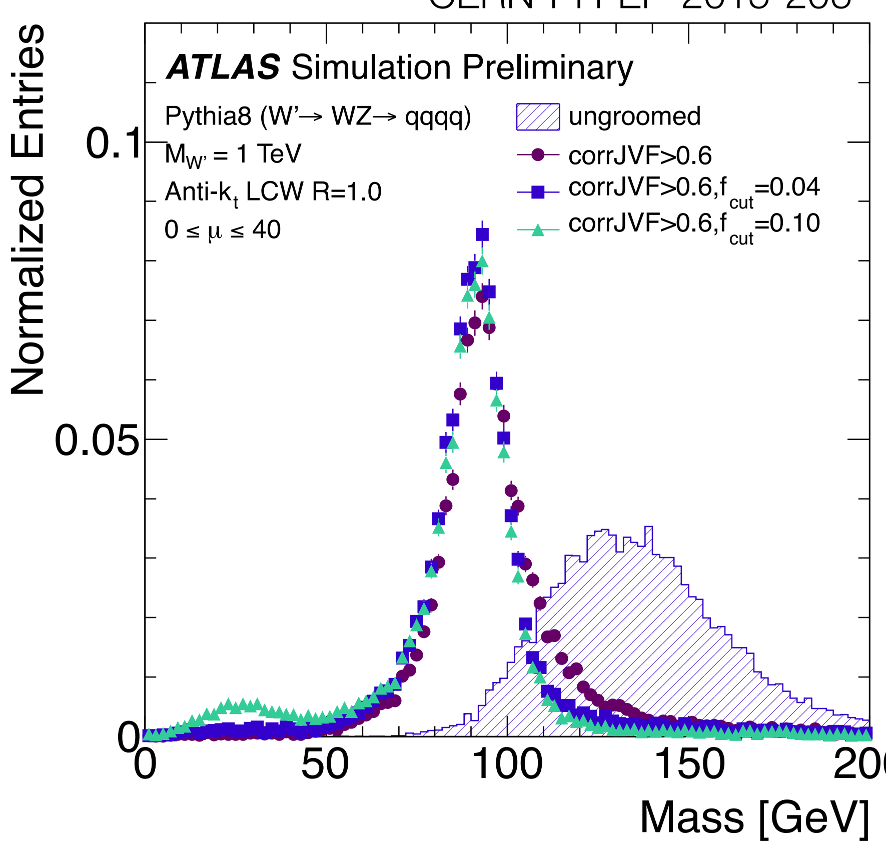
Track based grooming

- Apply track based pileup ID to subjets
    - Example: jet subjets satisfy trimming momentum fraction cut, but one has a large number of pileup tracks



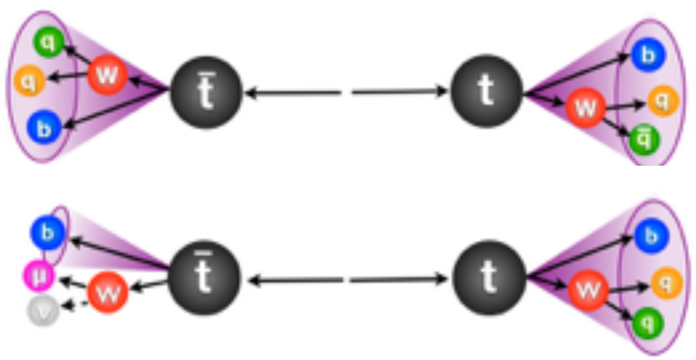
CERN-PH-EP-2015-206





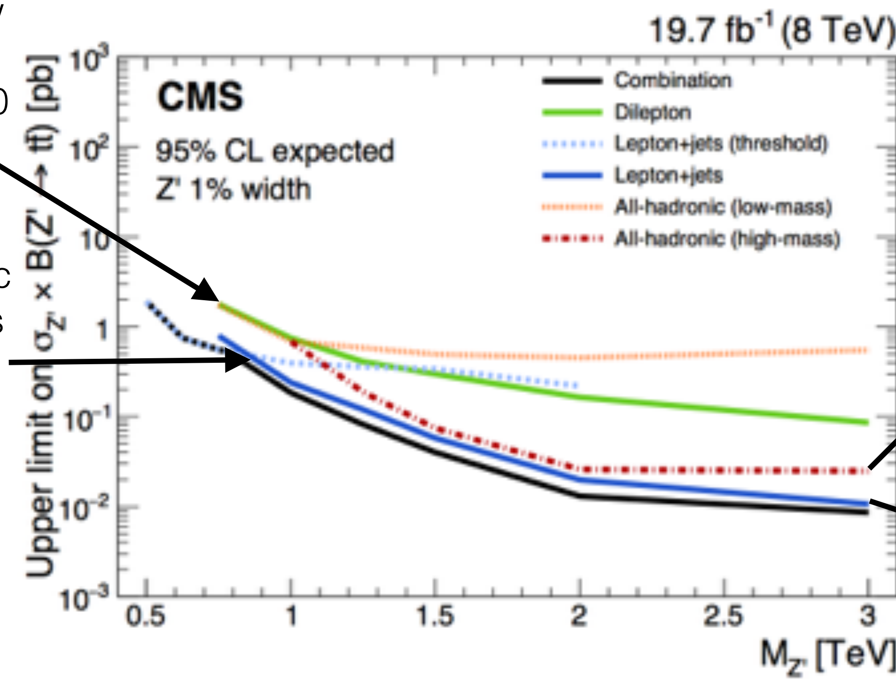
Examples of new tools in LHC analyses

Top resonance search
CMS B2G-13-008



Very fat jets (R=1.5) allow all-hadronic analysis to extend down to $M_{Z'}$ = 750 GeV

Unboosted semileptonic channel underperforms for $M_{Z'}$ > 850 GeV

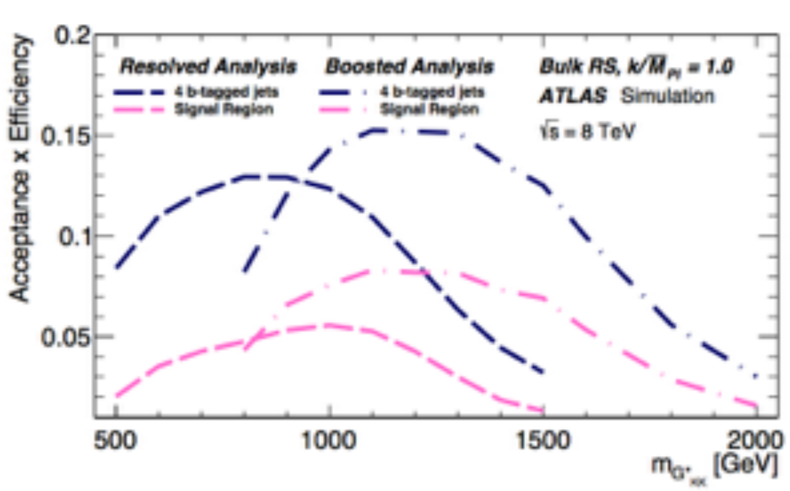


Boosted top-tag:
CMS Top Tagger +
N-subjettiness +
subjet b-tag

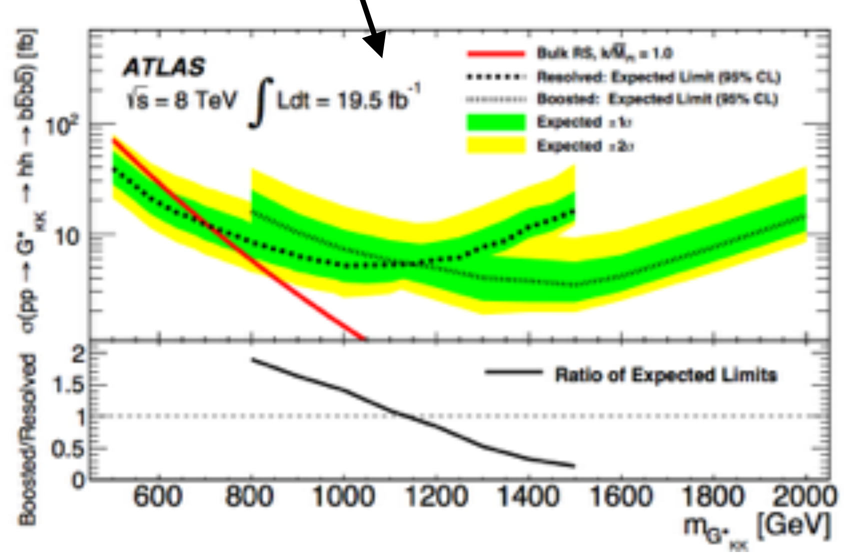
All-hadronic ttbar channel competitive with semi-leptonic channel

Semi-leptonic channel with boosted top jets and non-standard lepton isolation

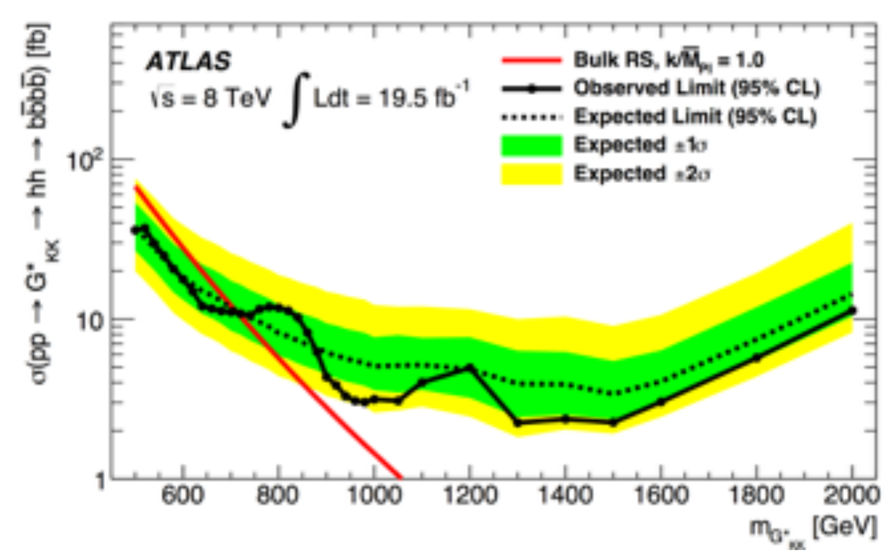
HH resonance search
ATLAS CERN-PH-EP-2015-099



Boosted analysis necessary for m_{HH} > 1150 GeV



Boosted H-tag:
Trimmed AK R=1.0 jets
Matched R=0.3 b-tagged track jets



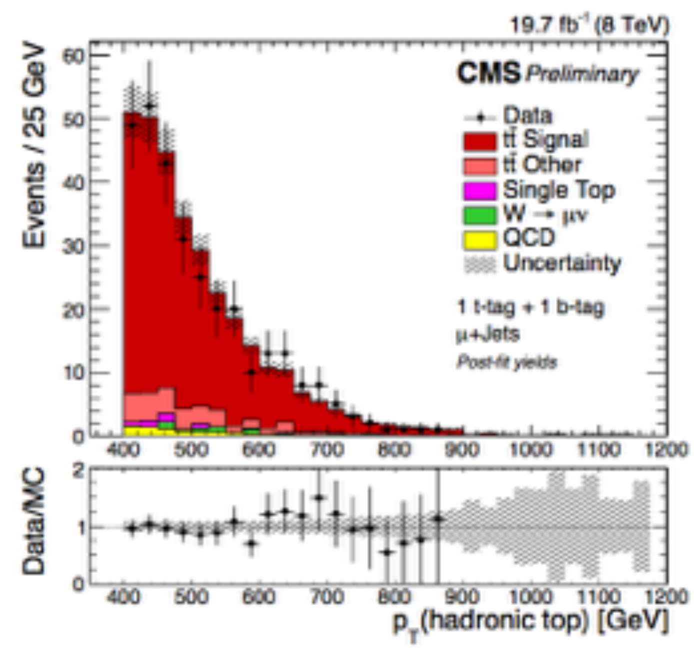
Examples of new tools in LHC analyses

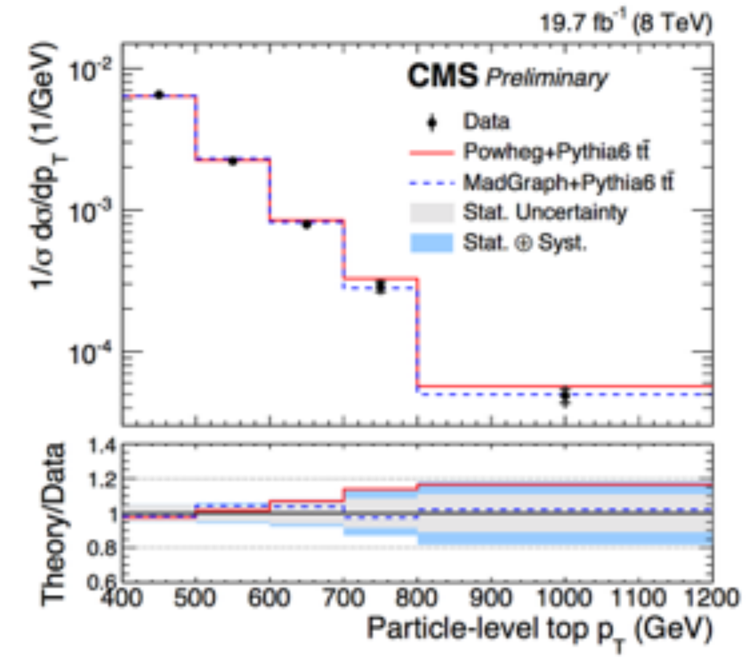
See talk by Mayda on Monday

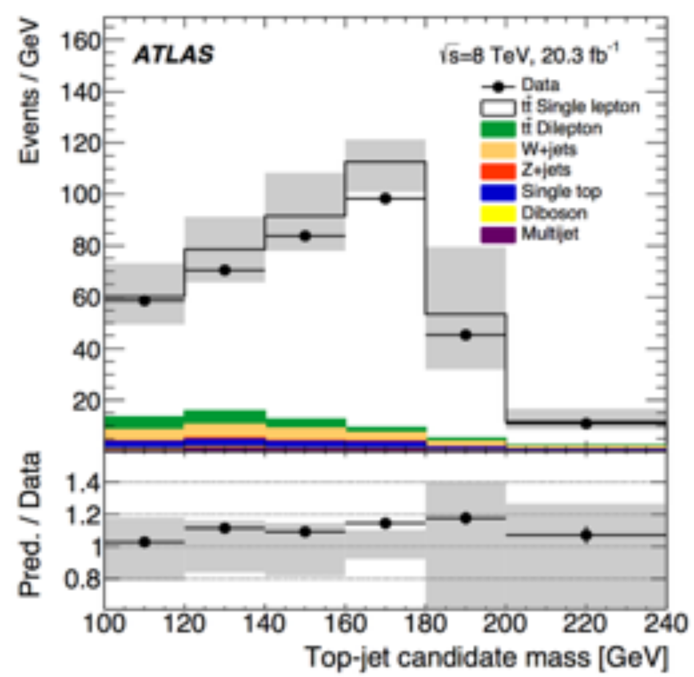
Top cross section measurement (boosted)
CMS TOP-14-012
ATLAS TOPQ-2014-15

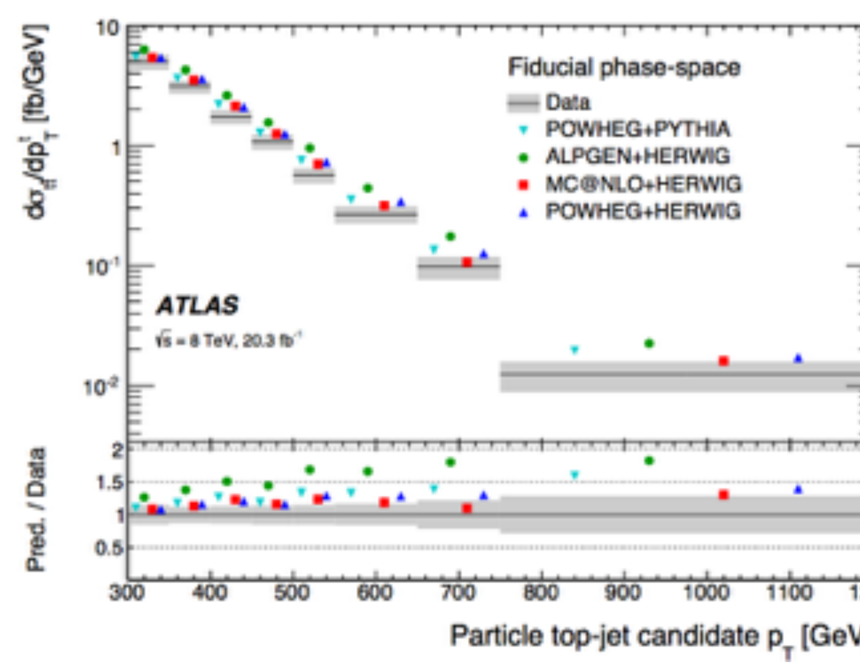
ATLAS top tag :
- R=1.0 jet
- Trimmed jet mass > 100 GeV
- Splitting scale $\sqrt{d_{12}}$ > 40 GeV
- Matched small-R jet b-tagged

CMS top tag :
- R=0.8 jet
- CMS Top Tagger
- (140< jet mass < 250,
- minMass>50
- $N_{subjets} \geq 3$)







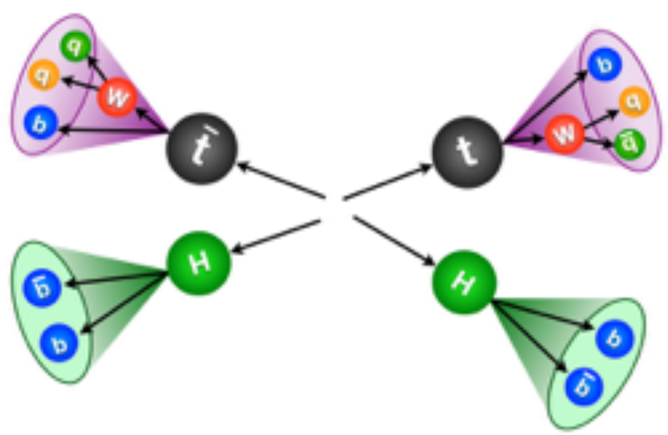


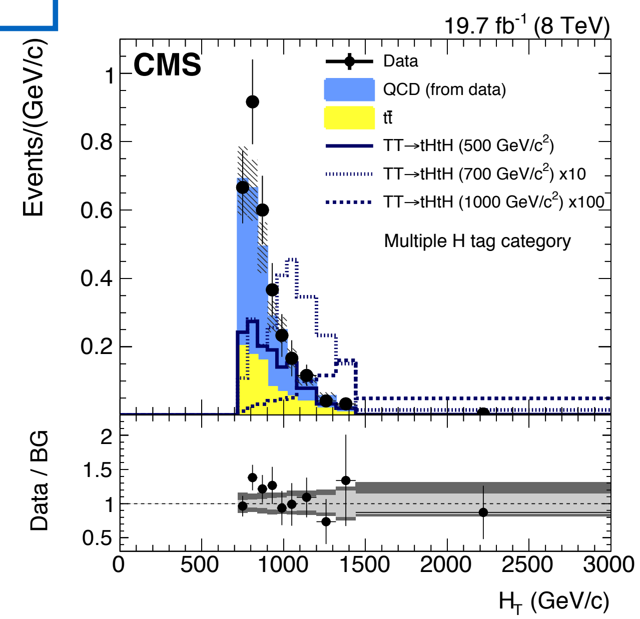
Examples of new tools in LHC analyses

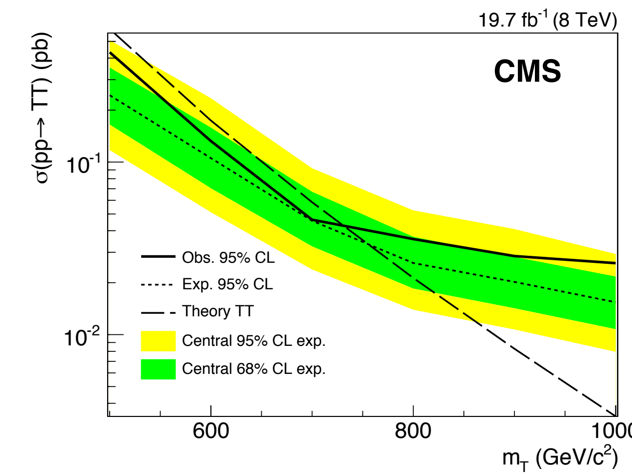
VLQ Top partners decaying to tH
CMS B2G-14-002

Boosted top-tag
R=1.5 jet - HEP Top Tagger + filtered subjet b-tag

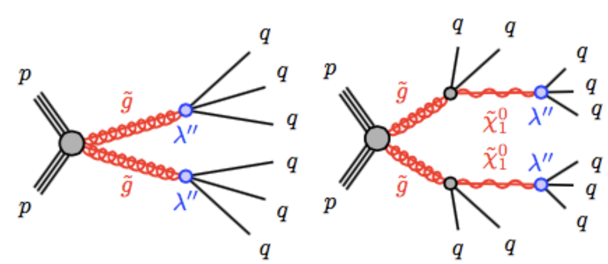
Boosted H-tag
R=1.5 jet - 2 filtered subjet b-tags and pairwise b-tagged subjet mass > 60 GeV

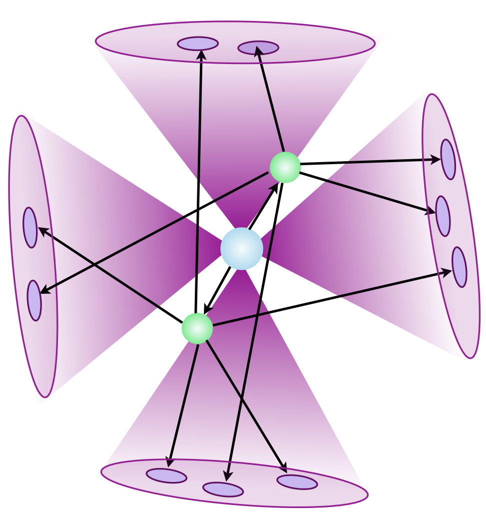






SUSY multijet (accidental substructure)
CERN-PH-EP-2015-020

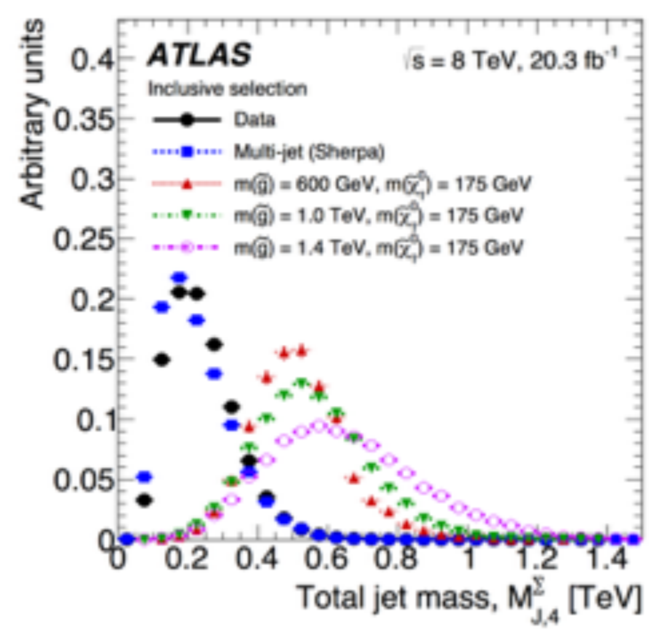


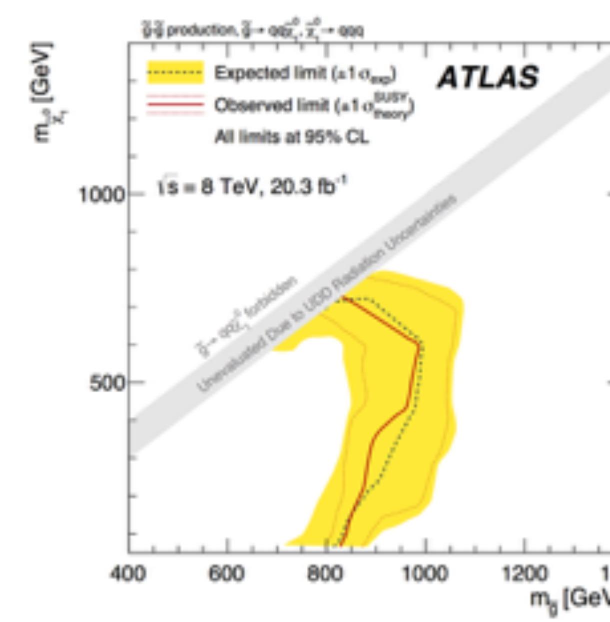


$$M_J^\Sigma = \sum_{\substack{p_T > 100\ \mathrm{GeV} \\ |\eta| \le 2.5}}^{4} m^{\mathrm{jet}}$$

Large M_J ⇒

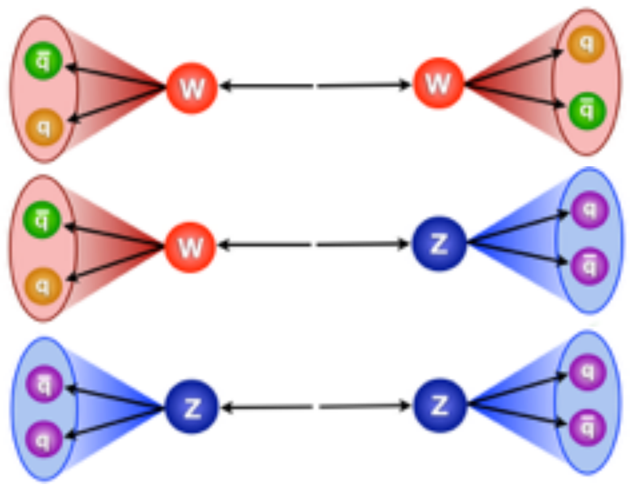
- Angular structure
- Many energetic hadrons





Examples of new tools in LHC analyses

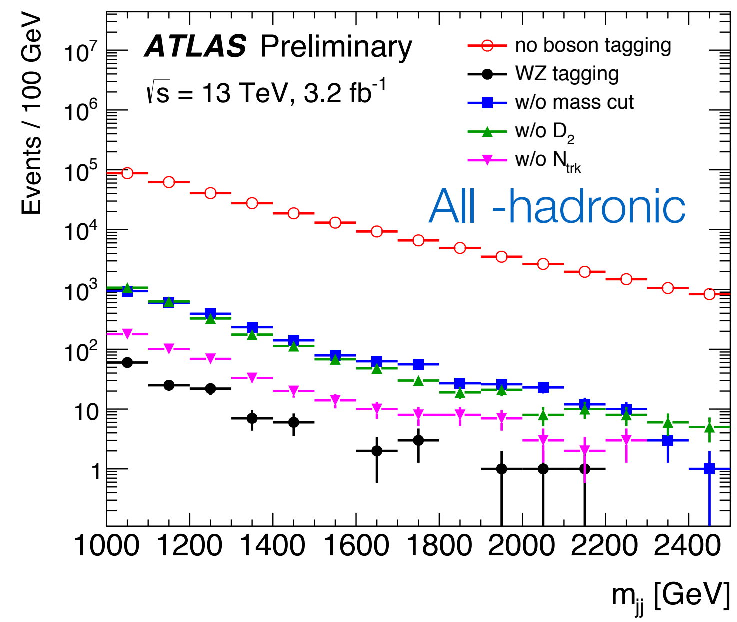
VV resonance
ATLAS-CONF-2015-073
CMS EXO-15-002

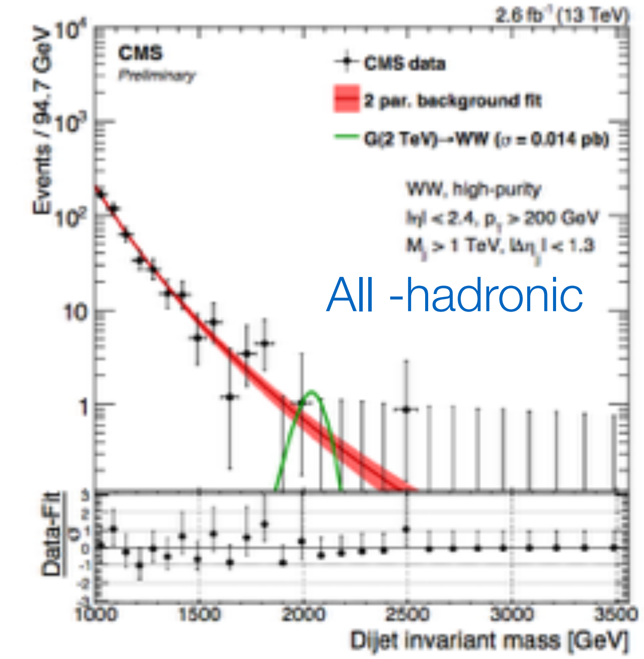


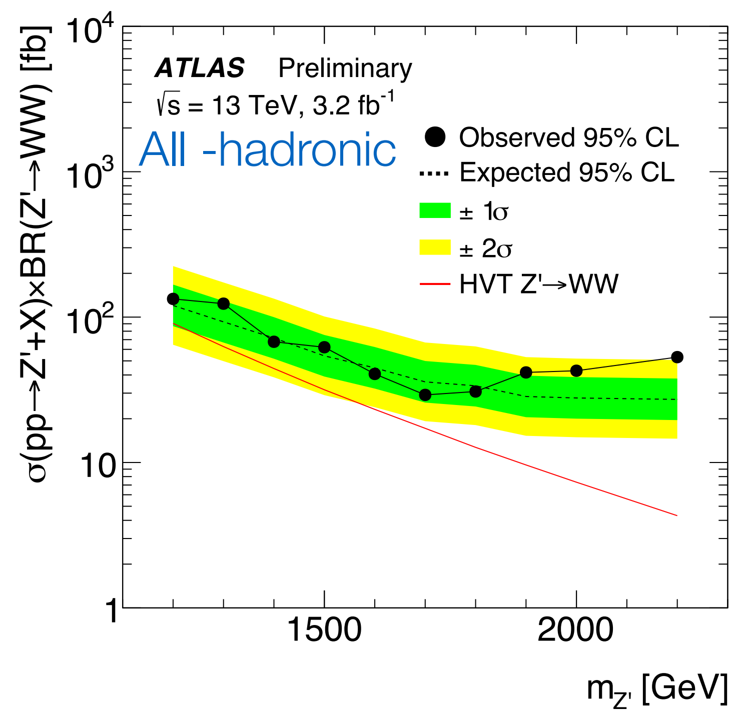
ATLAS Run I V-tag :
R=1.2
Split filtered jet mass window
y < 1.2
N_{track} < 30

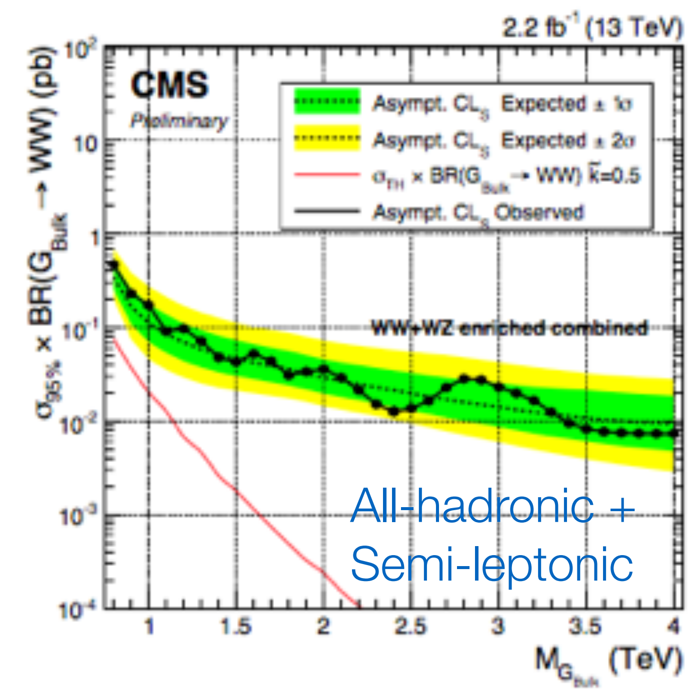
ATLAS Run II V-tag :
R=1.0
Trimmed jet mass window
D2 (β=1) < 1.2 (p_T dependent)
N_{track} < 30

CMS V-tag :
R=0.8
Pruned jet mass window
$\tau_2/\tau_1 < 0.45$, $0.45 < \tau_2/\tau_1 < 0.75$



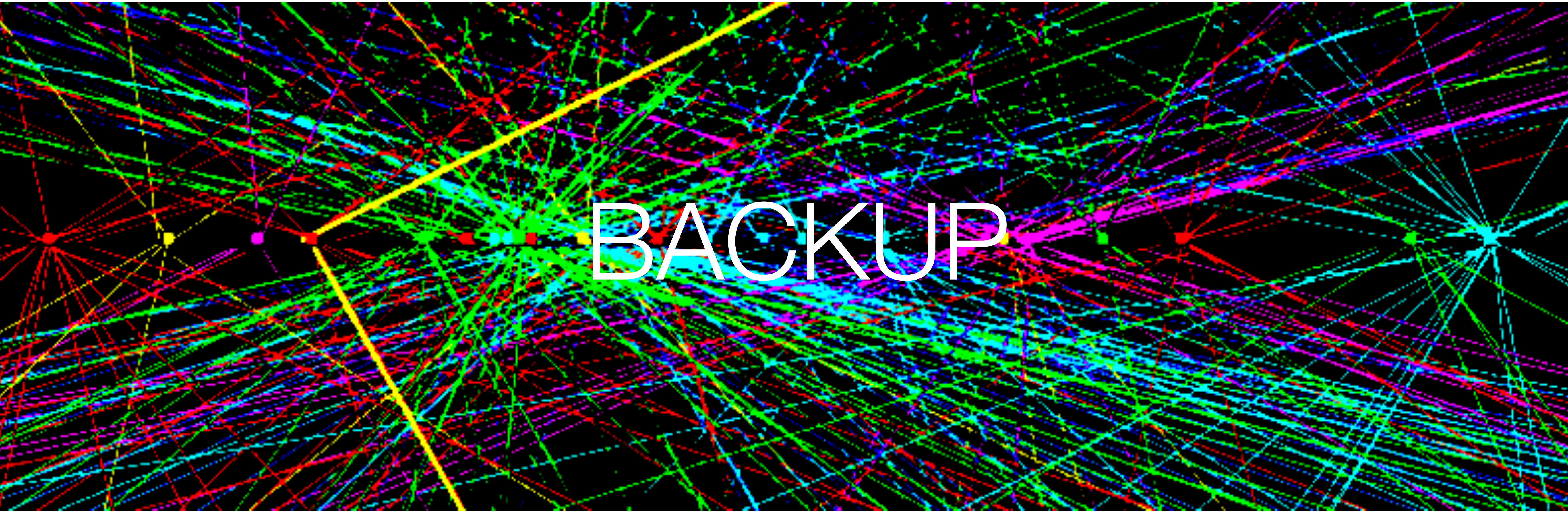






Conclusions

- New jet tools have proven to be indispensable to LHC analyses
  - Impressive progress in the last 5 years developing and commissioning jet tools
    - Boosted objects are now mainstream
      - Thoroughly calibrated and commonly used
      - example: groomed jet mass is now in the CMS trigger
    - Strong community of theorists and experimenters
      - Short turnaround time between new ideas and results
- Pileup poses a significant challenge for run II and beyond
  - New pileup subtraction techniques - improve jet energy measurement and resolution for all jets
  - Jet grooming - essential for boosted object tagging
  - Per particle pileup removal - correct both jet p4 and jet shape
  - Removing pileup essential for jets, MET, isolation

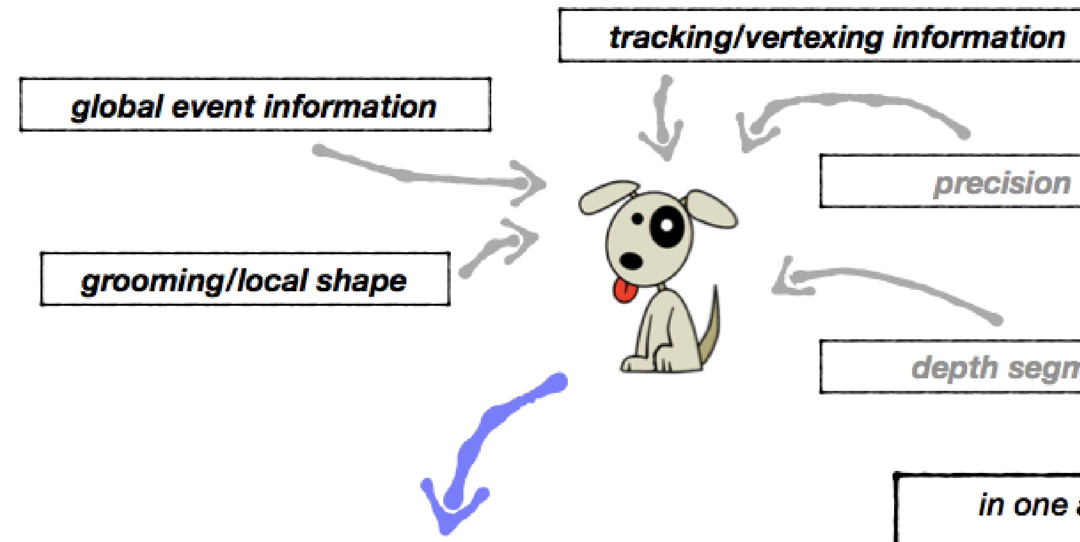


BACKUP

Pileup Per Particle Identification (PUPPI)

arXiv:1407.6013v1

- PUPPI framework designed to utilize all handles to mitigate pileup
  - ρ (pileup energy density measured per event)
  - charged tracks from the hard scatter
  - charged tracks from pileup vertices
  - the local distribution of pileup with respect to particles from the leading vertex
    - LV particle radiates preferentially at small angle. Pileup from many vertices is randomly distributed in angle and its pT spectrum falls more rapidly

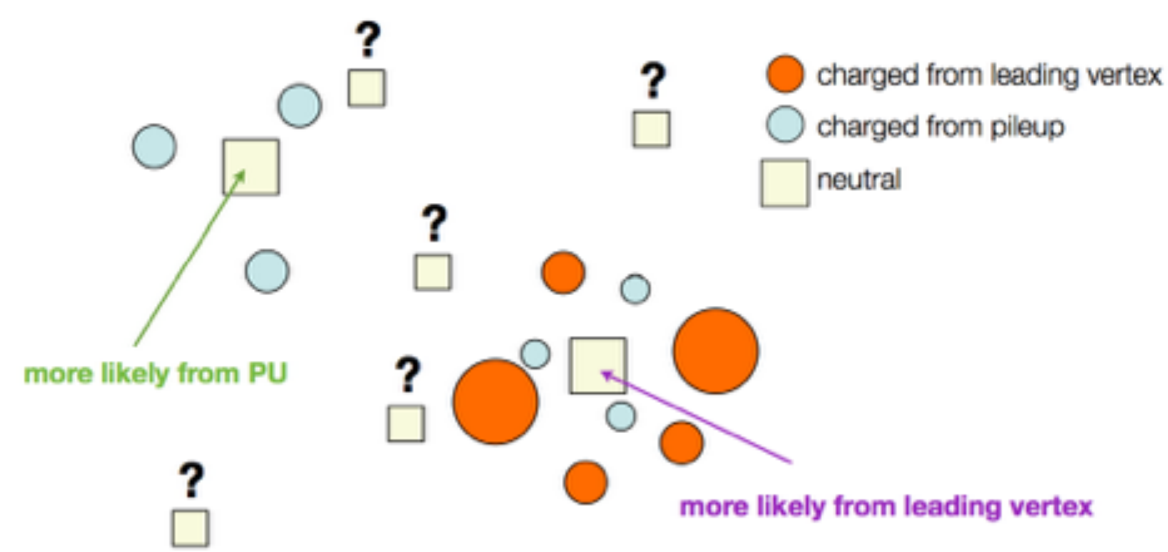


Cartoon from Nhan Tran

following the "jets without jets" paradigm...
Define on a ***per particle*** basis, ***before jet clustering***, a weight for ***how likely*** a particle (or jet constituent) is to be from pileup or the leading vertex, then rescale each particle four momentum by that likelihood

in one algorithm:
correct the jet pT
correct the jet mass/ shapes
perform pileup jet ID
classify particles for MET determination

- Assign a weight to each particle equal to the probability that the particle originates from pileup
  - 0 very likely pileup → 1 very likely hard scatter
  - Multiply weight by particle 4-vector
  - Remove particles with small weight
  - Cluster jets with weighted particles
    - Also corrects the jet shape

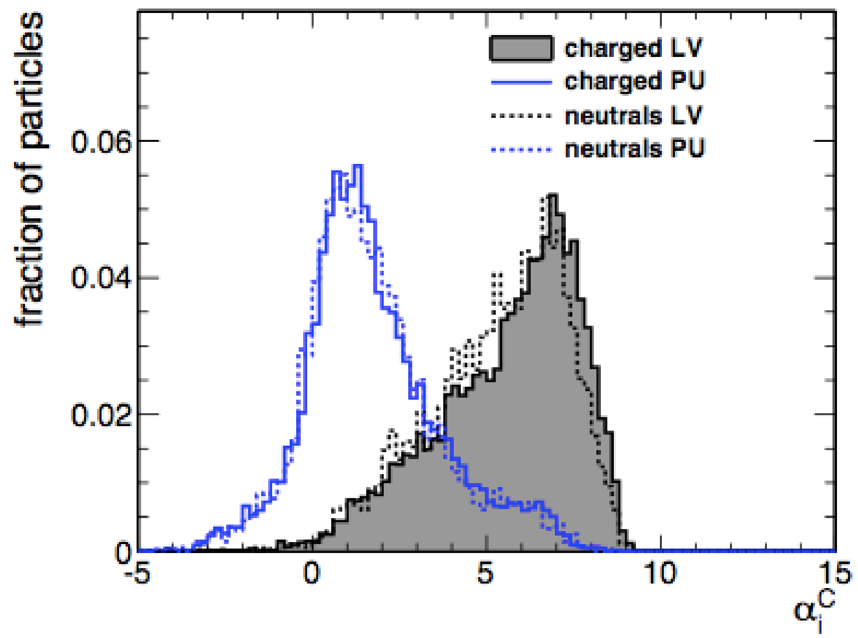


PUPPI Algorithm

1. Calculate α_i for each particle i
   - Sum of $p_{Tj}/\Delta R_{ij}$ for each particle j within an annulus around particle i
     - R_0 determines the outer cone size
     - R_{min} chosen based on detector resolution
   - Choice of ξ_{ij}
     - $\sim 1/\Delta R$: Collinear radiation from a particle from the hard scatter is mostly radiated at small angles while pileup has no angular preference (bigger ΔR → smaller α → less likely to be pileup)
     - $\sim p_{Tj}$: pT spectrum of pileup pileup falls off faster than pT of particles from the hard scatter (smaller pT → smaller α → less likely to be pileup)
   - In tracking region sum over charged particles from the LV, in forward region sum over all particles

$$\alpha_i = \log \sum_{j \in \text{event}} \xi_{ij} \times \Theta(R_{\min} \leq \Delta R_{ij} \leq R_0),$$

$$\text{where } \xi_{ij} = \frac{p_{Tj}}{\Delta R_{ij}}.$$

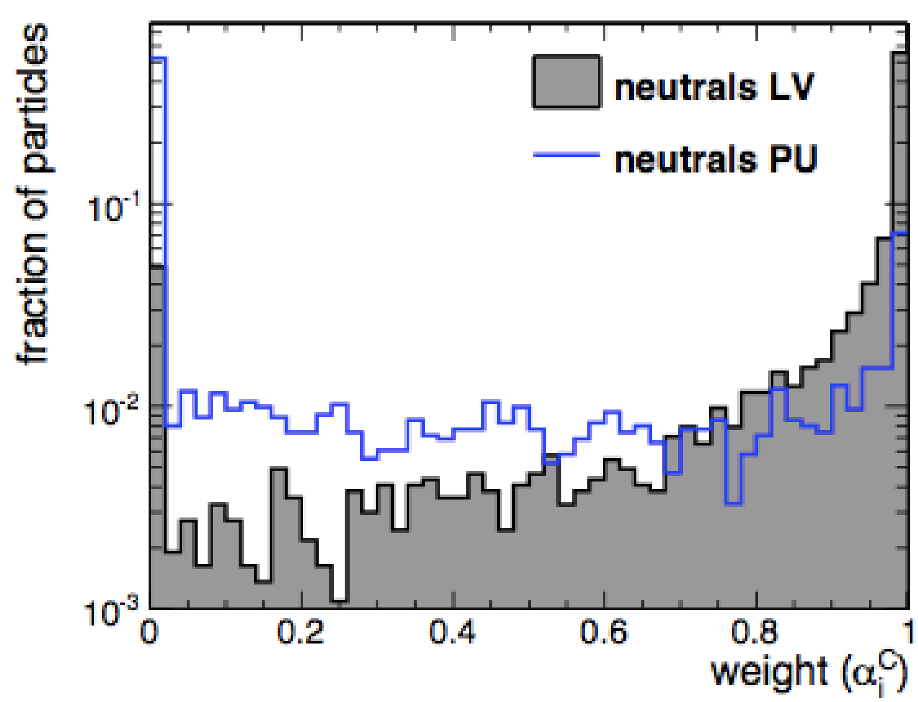


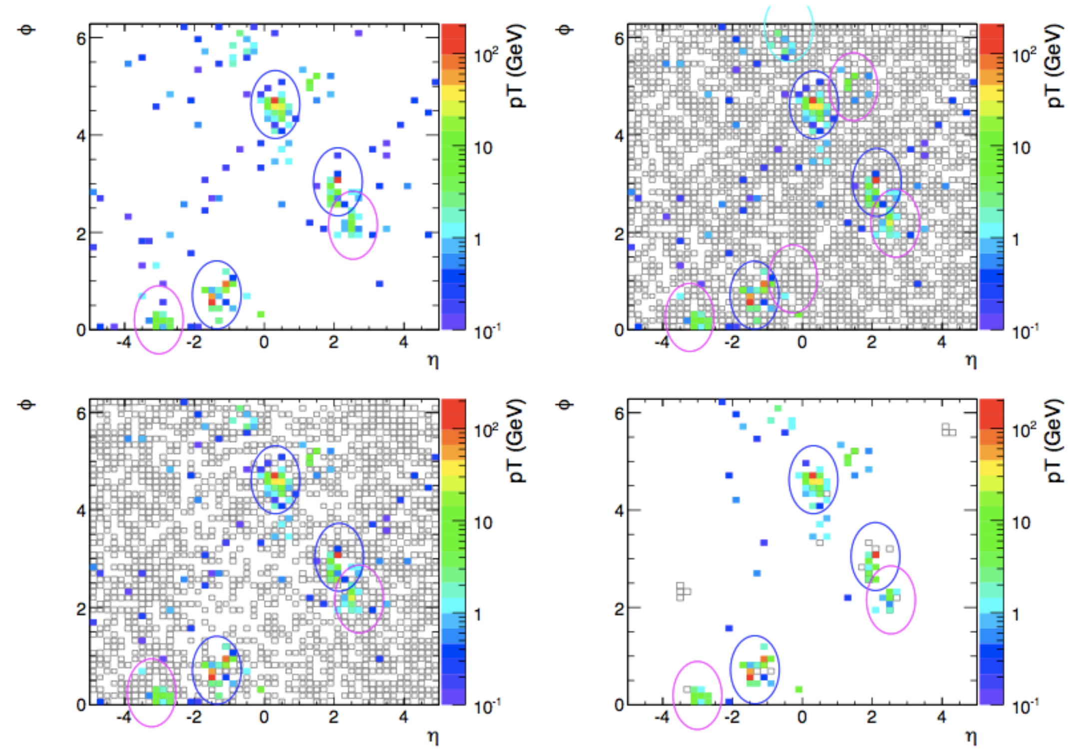
PUPPI Algorithm

2. All charged pileup particles are assigned a weight $w_i = 0$ and all charged leading vertex particles are assigned a weight $w_i = 1$
3. The weights of all other particles are calculated using:

$$\chi_i^2 = \Theta(\alpha_i - \bar{\alpha}_{\mathrm{PU}}) \times \frac{(\alpha_i - \bar{\alpha}_{\mathrm{PU}})^2}{\sigma_{\mathrm{PU}}^2}$$

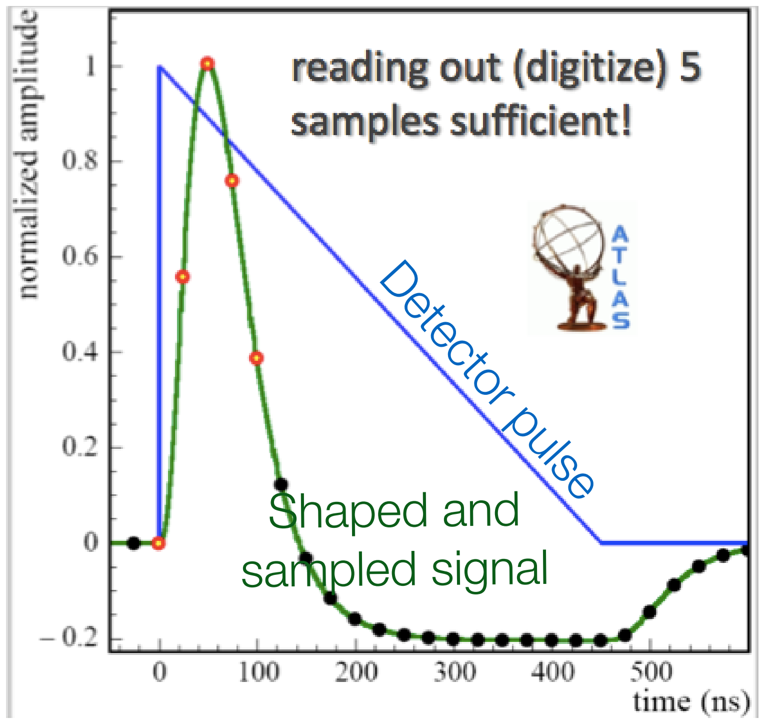
4. The four-momentum of each particle is rescaled by its weight $p_i^\mu \rightarrow w_i \times p_i^\mu$
5. Particles with small weights $w_i < w_{cut}$ or with low (rescaled) transverse momentum $p_{Ti} < p_{T,cut}$ are discarded.



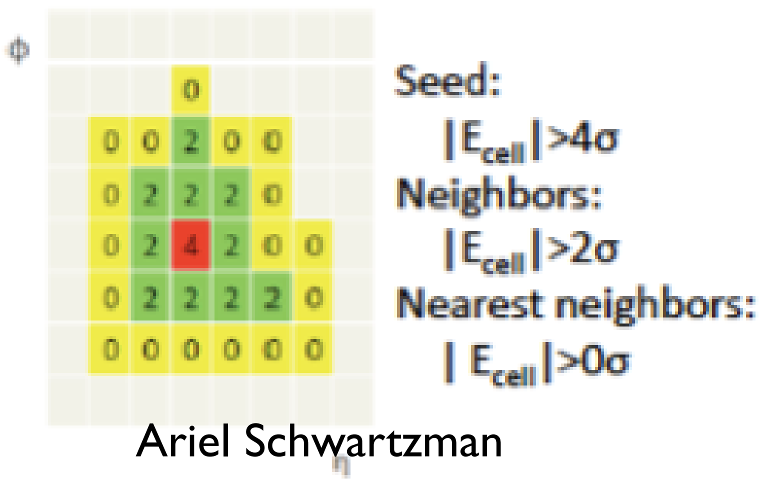


Reconstruction level pileup suppression

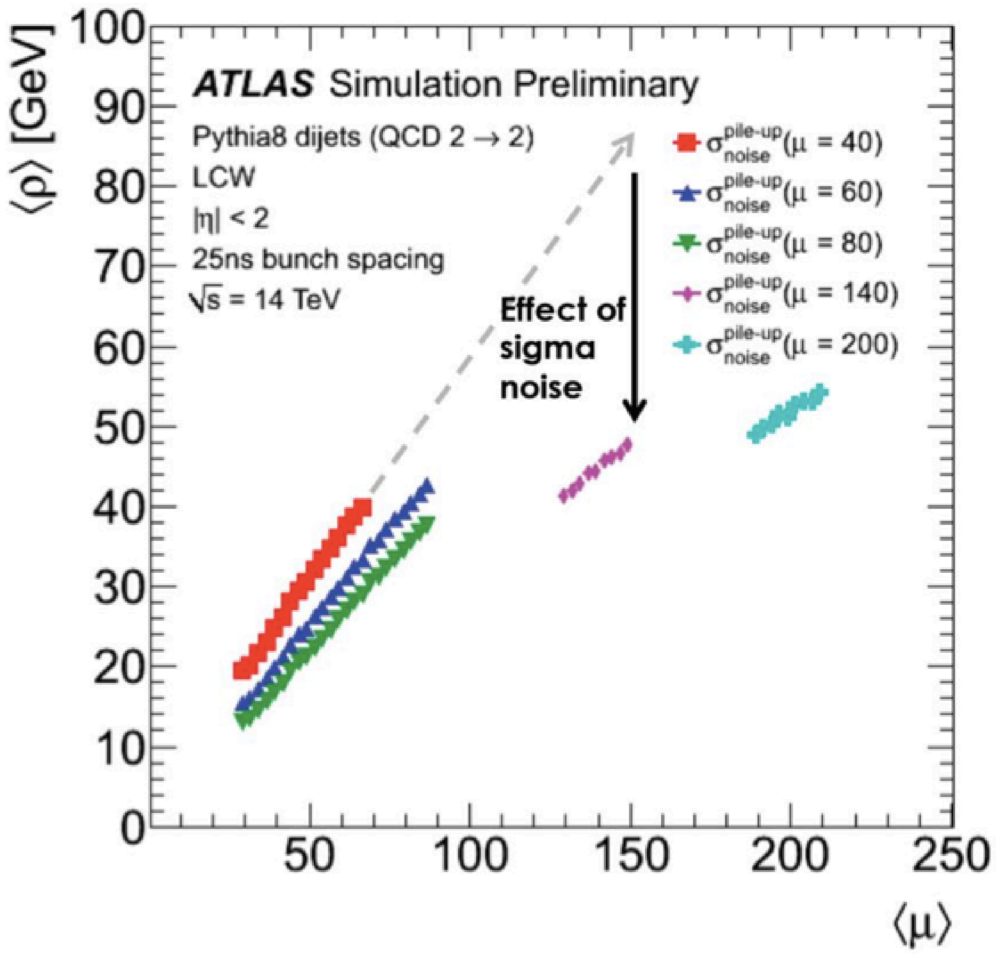
Peter Loch



- Pulse Integration (ATLAS)
  - Fast signal shaping such that pulse integral = 0 and amplitude proportional to energy→ Net average signal contribution from pileup = 0
  - Works best for small bx (25ns)
  - Can not reduce out-of-time pileup event by event fluctuations
- Jets clustered from topoclusters (ATLAS)
  - Pileup energy and electronic noise suppression included in topocluster reconstruction
  - “4/2/0” clustering tuned based on expected max ⟨μ⟩

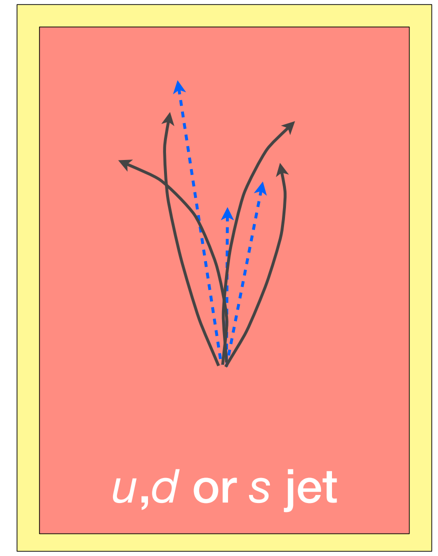


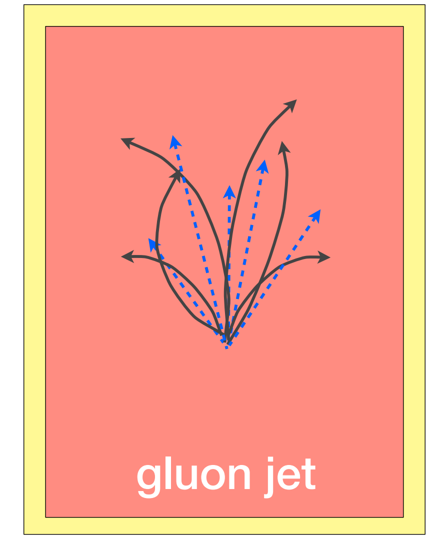
Ariel Schwartzman

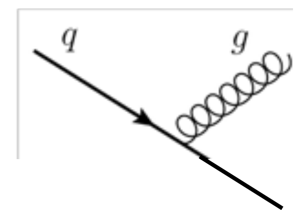


Quark/gluon discrimination

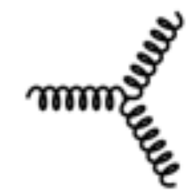
- Quarks and gluons have different QCD color factors
  - Gluon more likely to radiate a gluon
  - Gluon jets tend to be wider with larger multiplicities and correspondingly fewer hard particles
  - Quark jets tend to be narrow with smaller multiplicities and asymmetrical energy shared between constituents







$C_F = 4/3$



$C_A = 3$

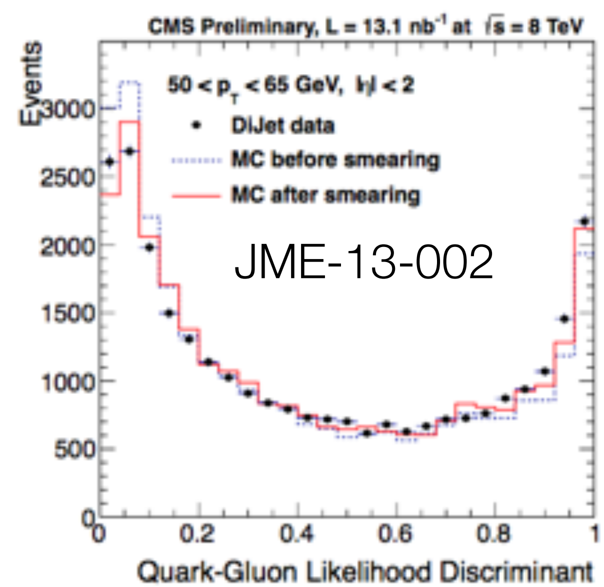
- Quark/gluon jet discriminator variables:
  - ATLAS
    - Number of tracks
    - Track/Calorimeter width $w = \frac{\sum_i p_{T,i} \times \Delta R(i, \text{jet})}{\sum_i p_{T,i}}$
    - Energy correlation angularity (track based)

$$\text{ang}_{\text{EEC}} = \frac{\sum_i \sum_j p_{T,i} \times p_{T,j} \times (\Delta R(i,j))^\beta}{(\sum_i p_{T,i})^2}$$

  - CMS
    - jet multiplicity
    - jet shape (minor axis width)
    - pTD (energy sharing)

$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

→ 1 if all momentum carried by one particle
→ 0 if jet has infinite number of particles



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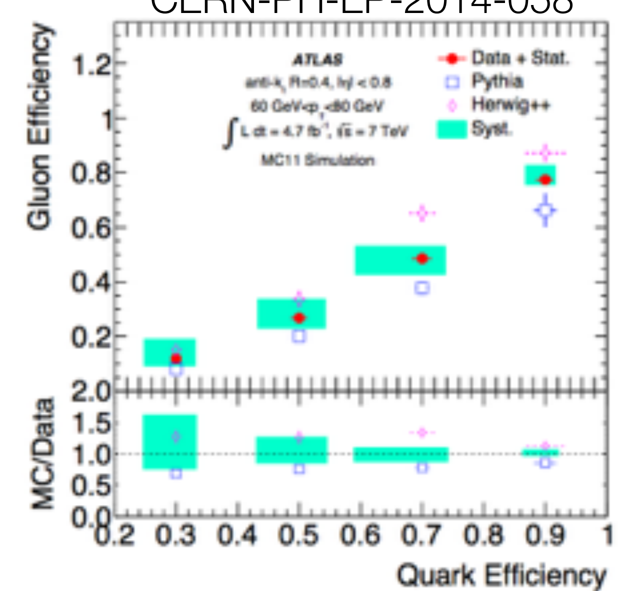
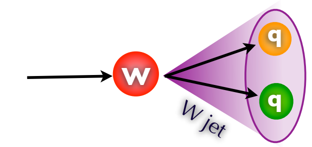
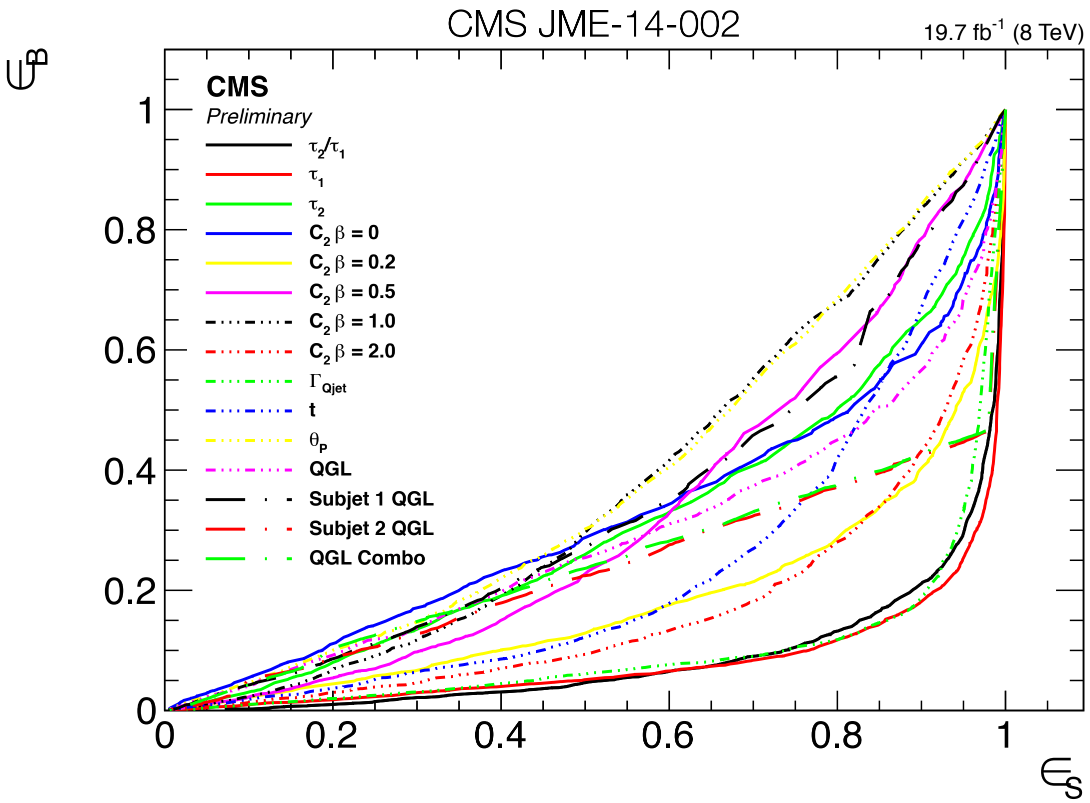
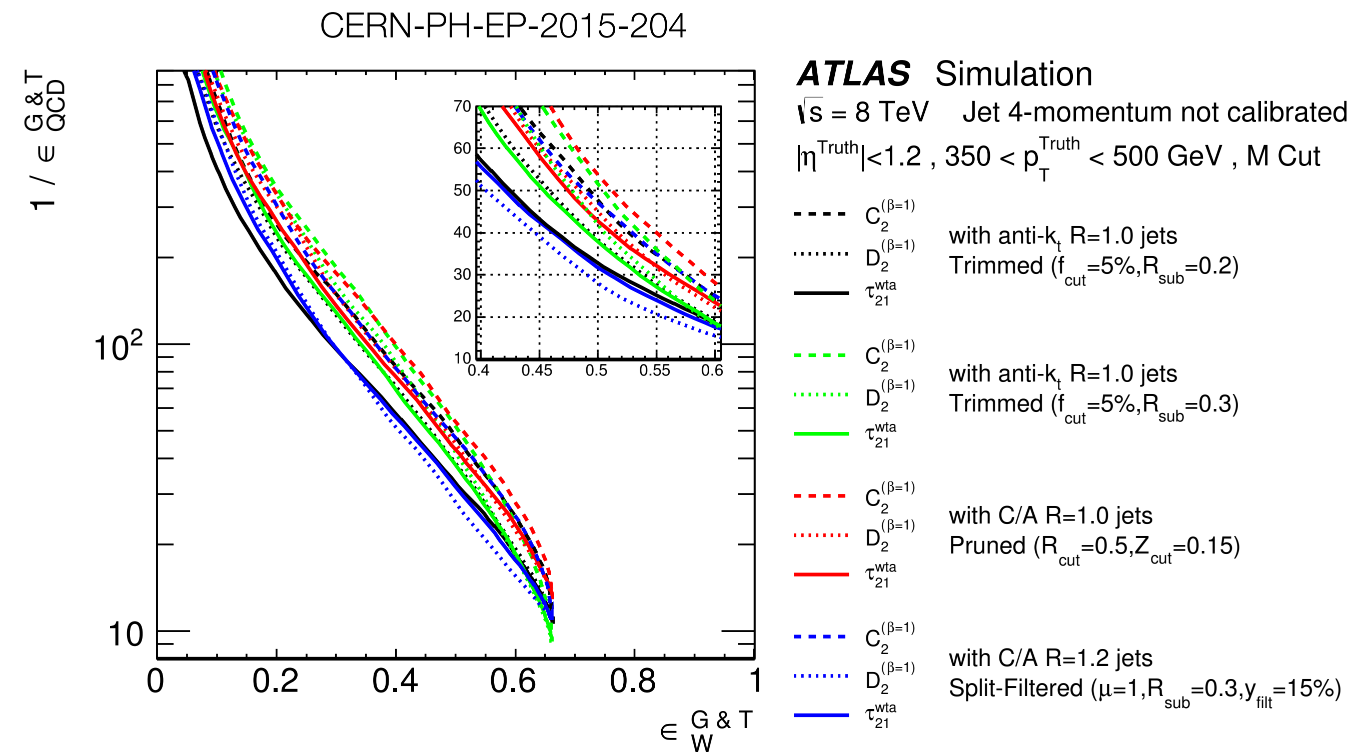


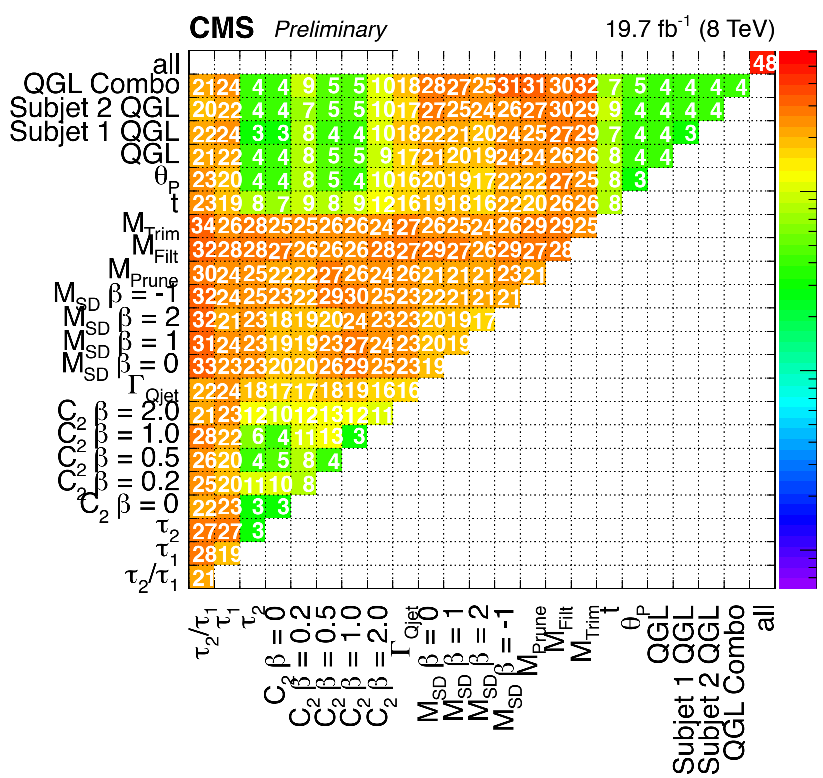
V-tagging optimization

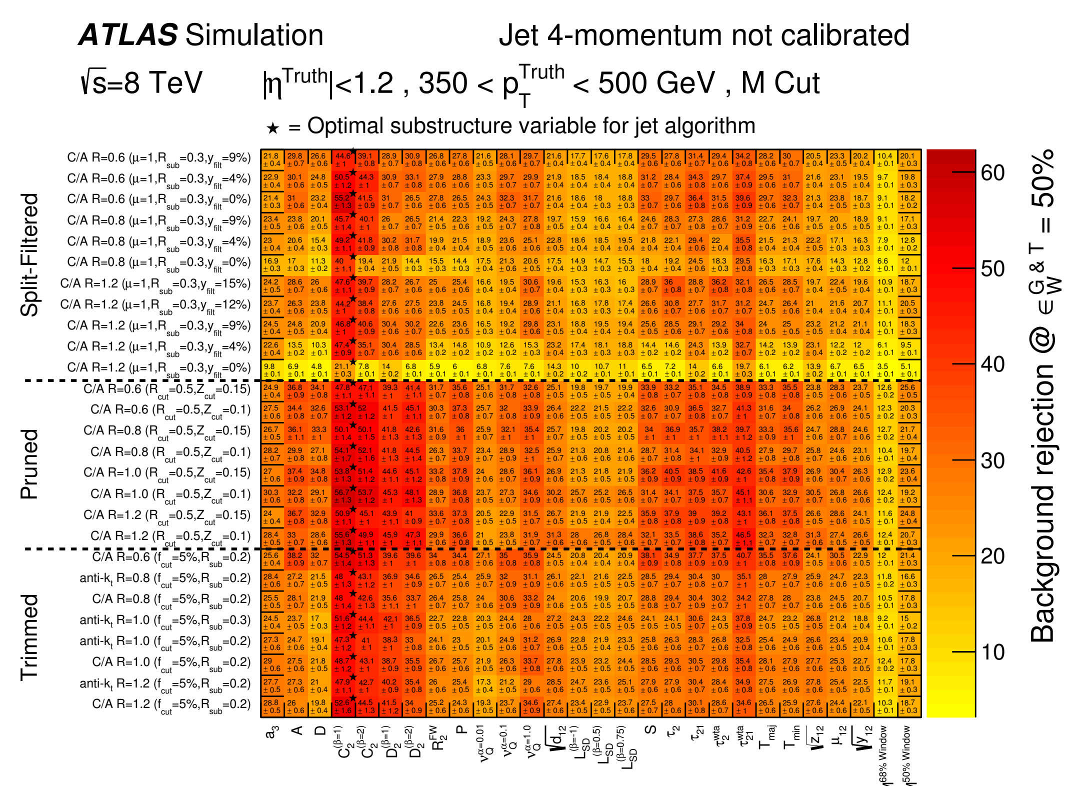




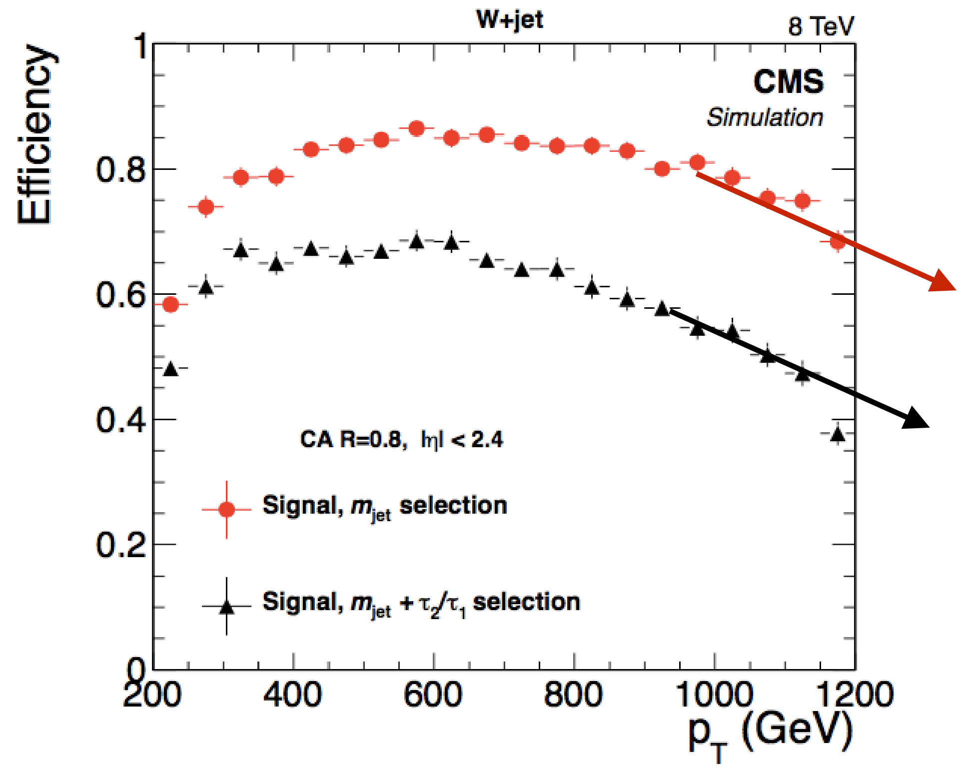


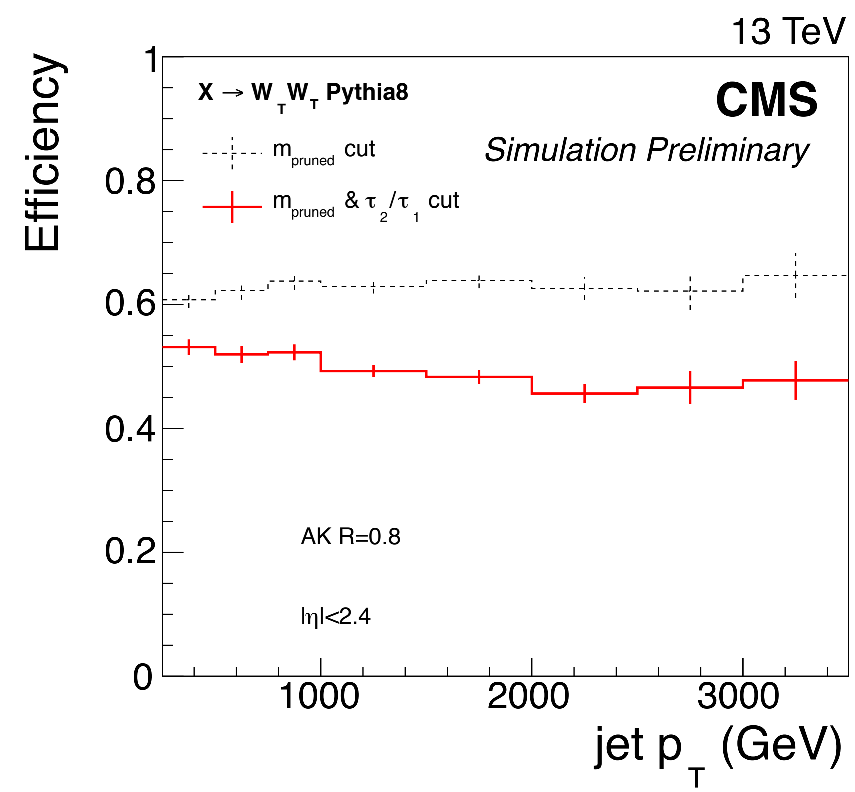
W-tagging variables, parameters, and correlations extensively studied





Very high pT tagging





- Run 1 - tagging efficiency for boosted objects decreased at high pT
- Run 2 - Improvements to particle reconstruction
  - make better use of detecter granularity
  - tagging efficiency now stable at high pT