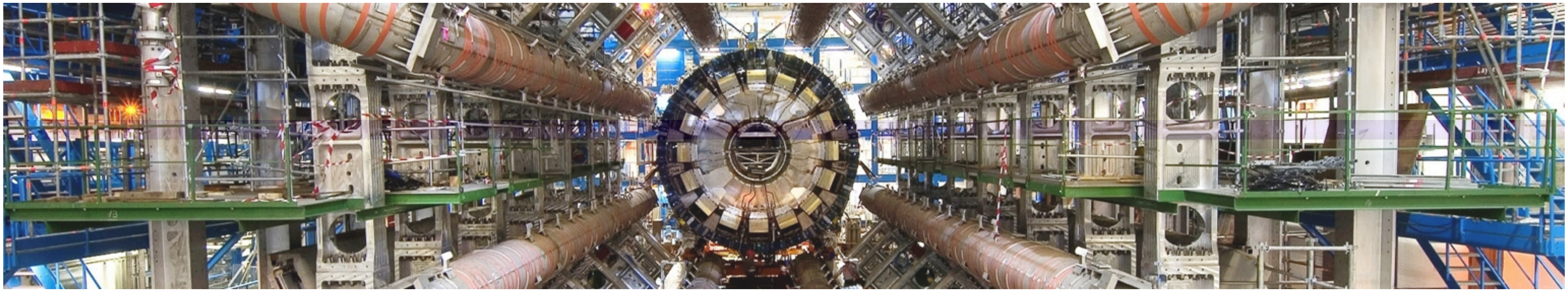

Event Reconstruction and Particle Identification

Part Three

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Hadron Collider Physics Summer School

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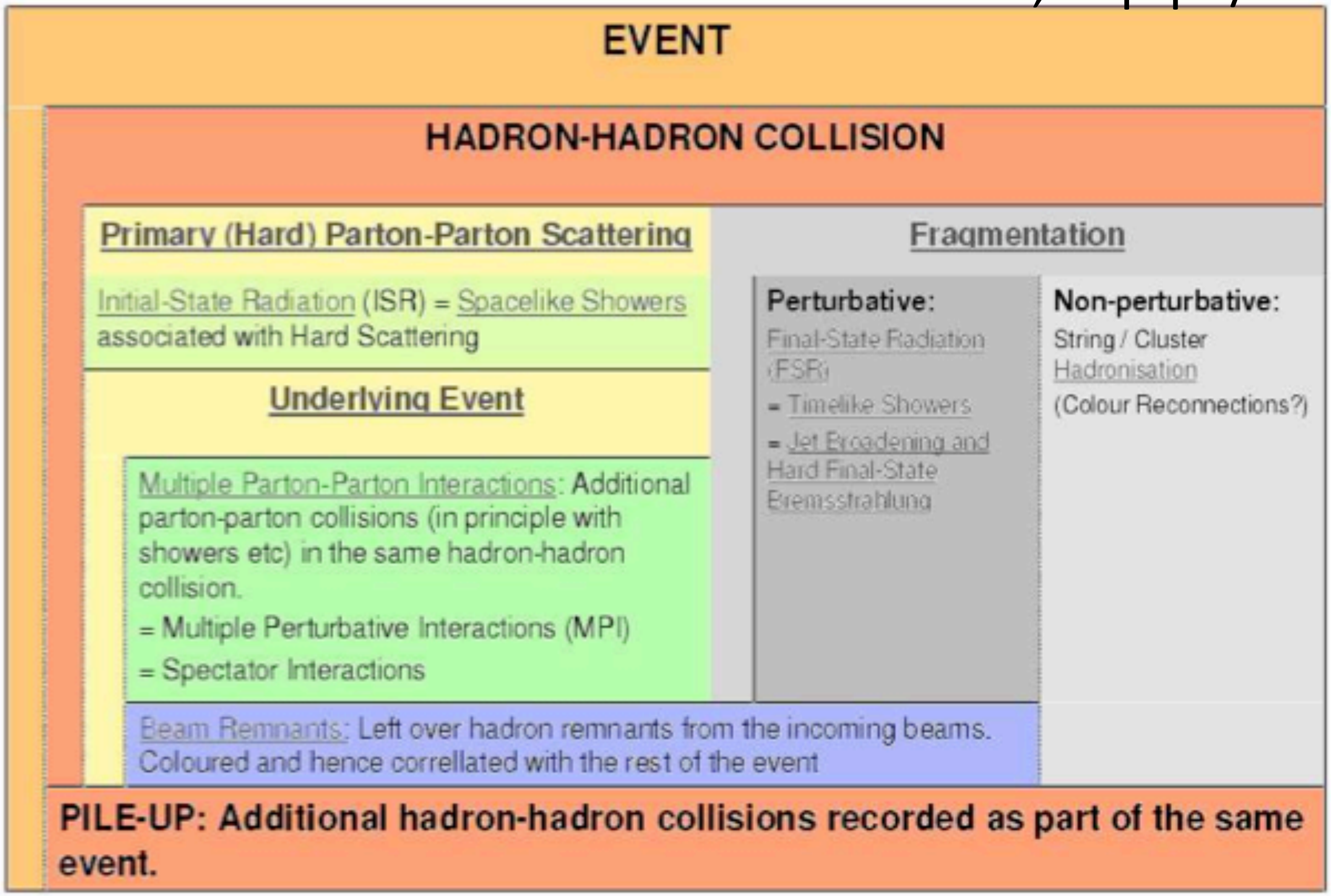
Outline for Today

- Jet reconstruction
  - Jet clustering algorithms, calculations, calibrations
  - Jet cleaning (calorimeter effects)
  - Pileup subtraction and assignment techniques
- Tau lepton reconstruction
  - Tau lepton decay signatures
  - Tau lepton identification algorithms
- Heavy-flavor tagging
  - Geometry of heavy-flavor hadron decays
  - Multivariate techniques and calibration
- W boson and top quark tagging
  - Jet grooming techniques, boosted jet shape calculations
  - Top-tagging algorithms
- Missing E_T

Definition of Proton-Proton Interactions

Dictionary of Hadron Collider Terminology

P. Skands et al., hep-ph/0610012



EVENT

HADRON-HADRON COLLISION

Primary (Hard) Parton-Parton Scattering

Initial-State Radiation (ISR) = Spacelike Showers associated with Hard Scattering

Underlying Event

Multiple Parton-Parton Interactions: Additional parton-parton collisions (in principle with showers etc) in the same hadron-hadron collision.

= Multiple Perturbative Interactions (MPI)

= Spectator Interactions

Beam Remnants: Left over hadron remnants from the incoming beams. Coloured and hence correllated with the rest of the event

Fragmentation

Perturbative:

Final-State Radiation (FSR)

= Timelike Showers

= Jet Broadening and Hard Final-State Bremsstrahlung

Non-perturbative:

String / Cluster Hadronisation

(Colour Reconnections?)

PILE-UP: Additional hadron-hadron collisions recorded as part of the same event.

Tagging Multiple-Particle Signatures

- Today: particle ID for particles with complicated decay signatures
  - Tau leptons, b hadrons (b quarks), W bosons, top quarks, neutrinos
- High-mass particles with short lifetimes
  - Particles do not interact in detector
  - Multiple particles in final state can be reconstructed to mother particle

- These complicated reconstruction/particle ID challenges are still under heavy development by experiment (and theory)
  - Only recent hadron colliders have made it possible to study these particles
  - High LHC energies imply high-pT production, leading to boosted signatures

Jets: As Observed

- Partons may be real, too, but jets are what we see in experiment
  - Result of boosted partons radiating, then hadronizing
  - Clustering is, in some way, an attempt to "undo" these processes
- We do not expect a perfect one-to-one correspondence, except possibly for high-p_T well-separated partons
  - Relation between the two should be calculable on average to be useful
  - Notions of jet-parton duality are good rules of thumb
- Experimentalists are becoming more savvy about jet algorithms and how to compare measurements and calculations
  - Cutting-edge calculations are often parton-only, so seek a middle ground in which to compare results
  - Particle-level results should be independent of all detector effects
  - But what is clustered? Particles or calorimeter energy deposits?

Experimental Requirements

- *Detector Independence* — There should be little or no dependence on detector segmentation, energy response, or resolution.
- *Minimization of Resolution Smearing* — The algorithm should not amplify the inevitable effects of resolution smearing and angle biases.
- *Stability with Luminosity* — Jet-finding should not be strongly affected by multiple hard scatterings at high beam luminosities (*i.e.*, jets should not grow to excessively large sizes because of additional pp interactions).
- *Resource Efficiency* — The jet algorithm should identify jets using a minimum of computer time.
- *Reconstruction Efficiency* — The jet algorithm should identify all physically interesting jets (*i.e.* jets associated with partons).

Components of Jet Algorithms

- Physical process from parton to hadrons is hadronization; in jet clustering, we seek to reverse the physical process
  - Both of these depend on the art of non-perturbstive QCD

- Three parts of any jet reconstruction algorithm:
  - Which input particles to cluster? Truth, cells, clusters, tracks?
  - In what order should particles combined into a jet?
  - How should the particle 4-momenta be combined?
    - This one is simple: everyone agrees we should add 4-momenta vectorially.

- Look for jet algorithms that are fast, robust under particle boosts (along z), collinear and infrared safe (see Fernando's lectures)

Jet Clustering: Algorithms

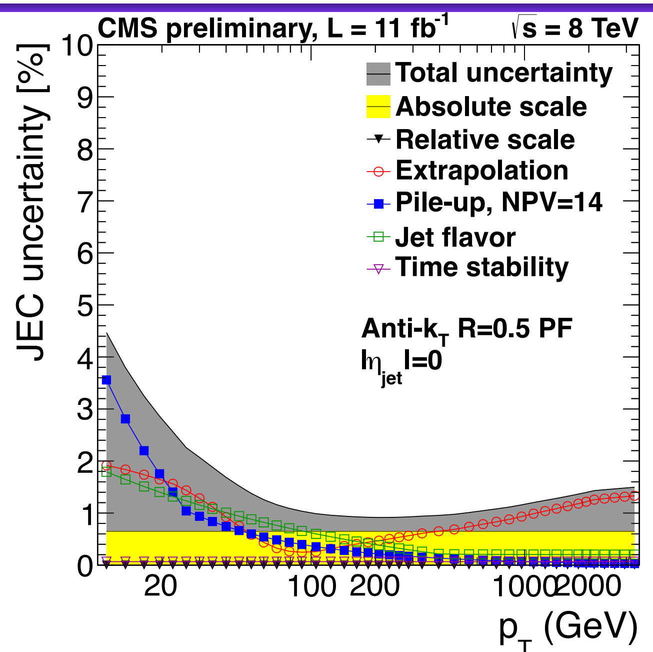
- Class of algorithms that combine nearest particles first, instead of fixing seed and cone (mimic parton shower)
  - Cambridge/Aachen algorithm: combine particles nearest each other in (η,ϕ) space (minimum d_{ij})
  - "kT" algorithm: preference for combining lower-momentum particle pairs first, then moving on to higher-momentum pairs until only beams are left
- These algorithms correspond to p=0 and p=1 in

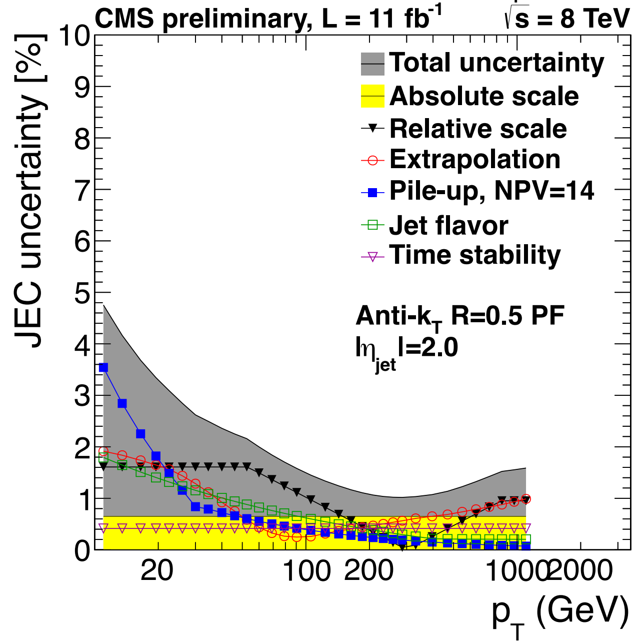
$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

  - What about p=-1? Is this a physical choice of p?
- Anti-kt algorithm collects particles around the hardest particle first
  - Guarantees "cone-like geometry" with well-defined borders around the highest-kT particles.
  - Maintains the infrared safety and collinear safety of sequential recombination family

Jet Energy Calibration

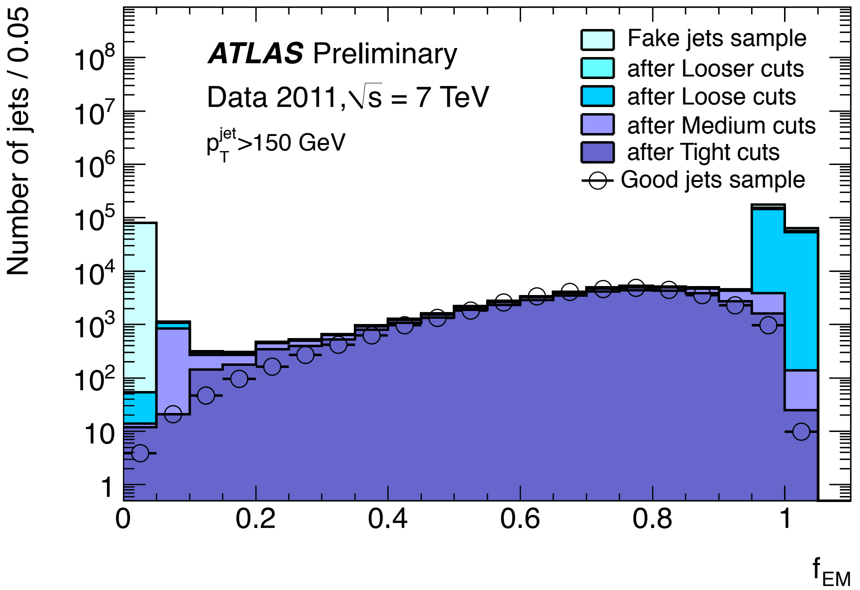
- Correct detector-level jet energy to the particle level
  - Correct for varying detector response (dijet balance) due to non-linearity, uninstrumented regions (cracks)
  - Average correction for EM+HAD contributions (γ+jet balance assumes known EM scale energy of photon)
  - Overall absolute scale calibration using γ+jet events
  - Correct for average loss of particles due to B field, average gain from contributions of underlying event
- Corrections add uncertainties to "Jet Energy Scale / Calibration"

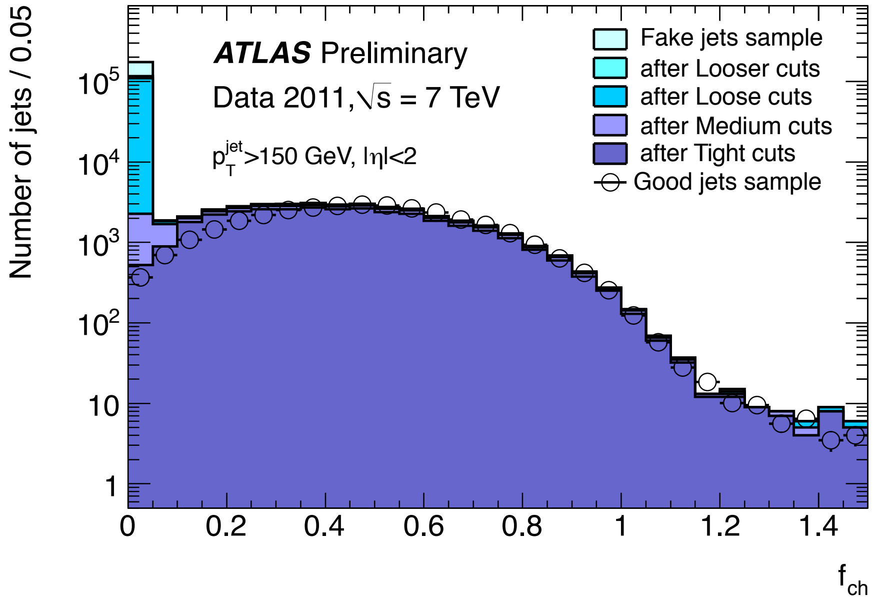


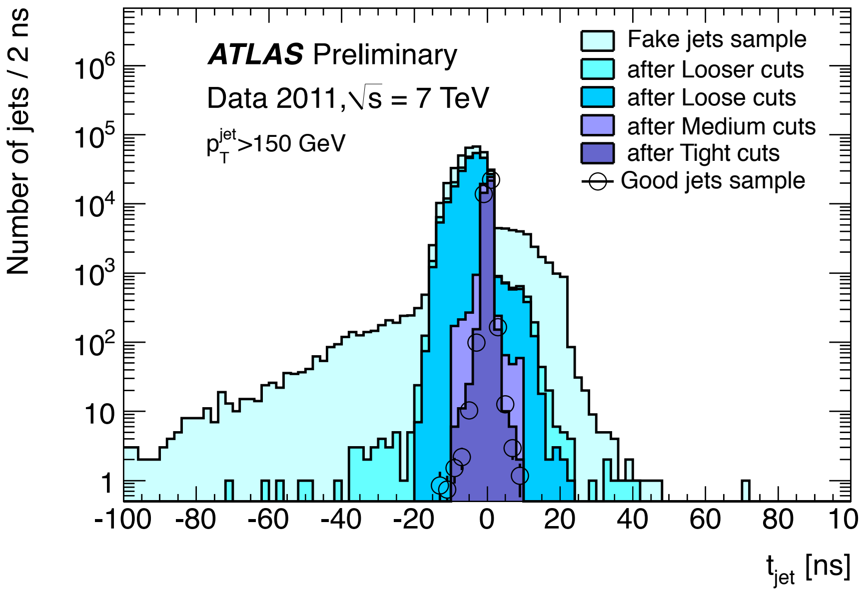


Jet Cleaning

- Require charged tracks, ECAL+HCAL contributions, all in time with beam crossing
  - Rejects cosmic background, calorimeter noise, and beam backgrounds, respectively
- This still leaves pileup contribs.

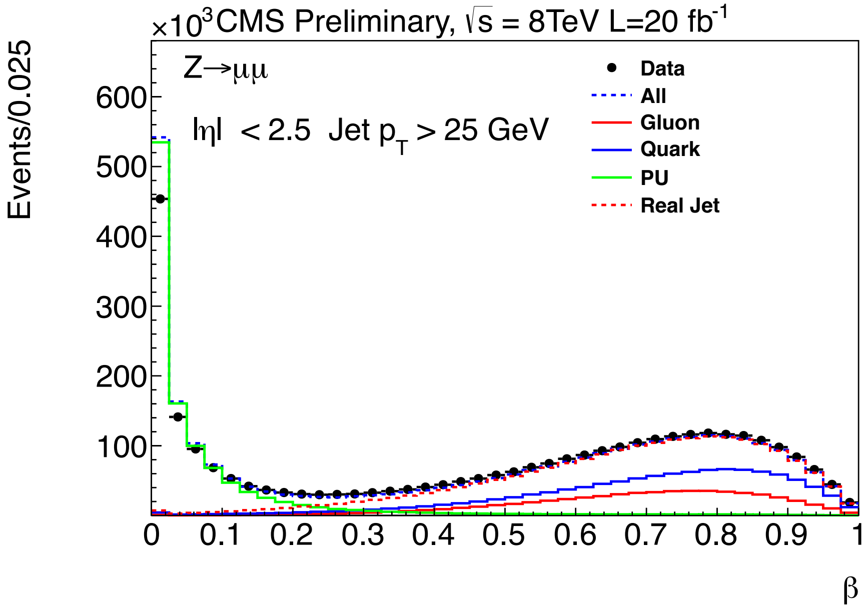


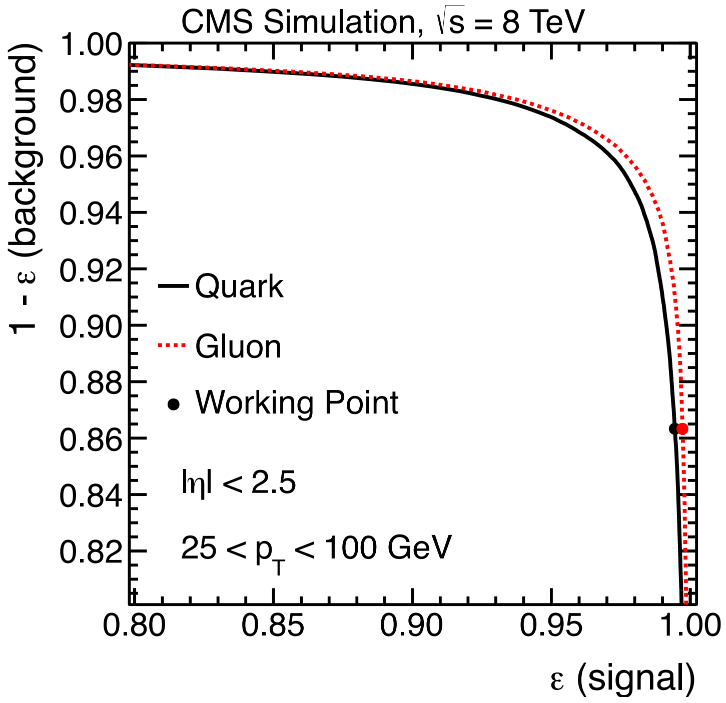




Pileup Jets

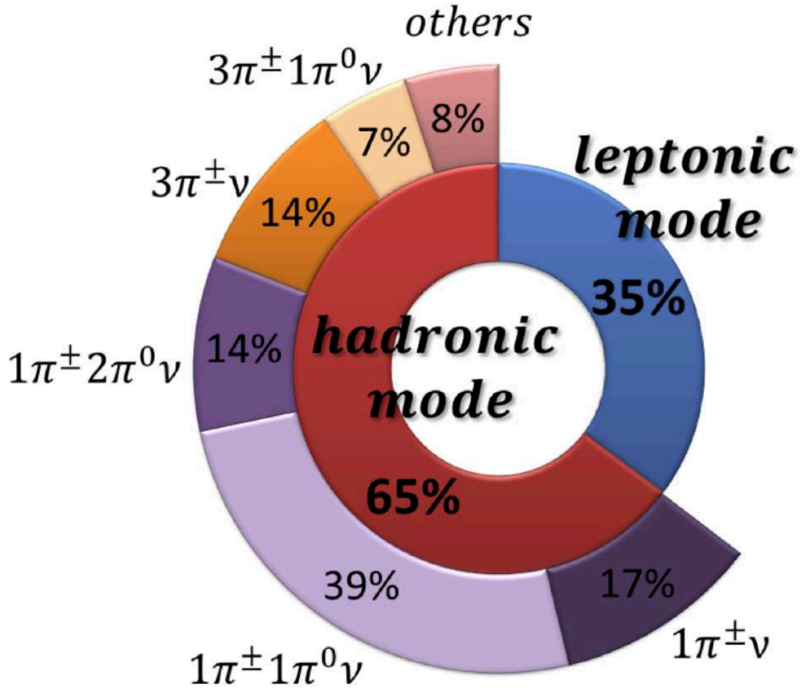
- Use to mitigate jet counting migration: 1->2, etc.
- For p_T<25 GeV, pileup jets are the largest single source of jets!
  - Low p_T jets overlap to form high p_T
- Use jet shape and vertex properties to flag pileup PF jets
  - Number of primary vertices
  - Δz: distance from highest-pT charged PF to the primary vertex (PV)
  - β: fraction of charged PF from PV
  - Radial width: flat for pileup jets

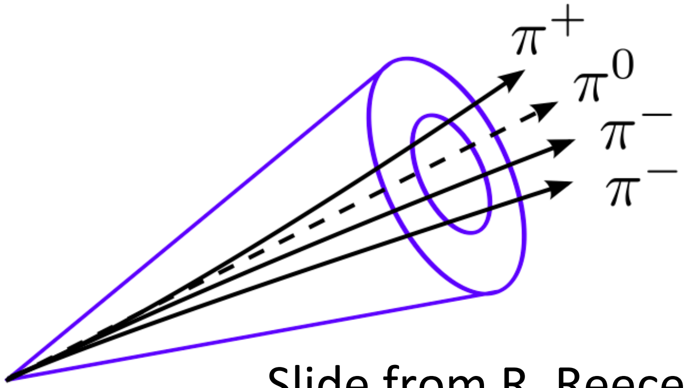




Tau Lepton Signatures

- Only lepton massive enough to decay hadronically (1.8 GeV)
- 65% hadronic decays
  - 50% 1-prong, 15% 3-prong
- Decay in beam pipe cτ=87 μm
- Signature: narrow jets with 1 or 3 tracks, possibly with neutrals
- Important particle for neutral and charged Higgs decays
- How to address the large multijet background, which also has many narrow jets?

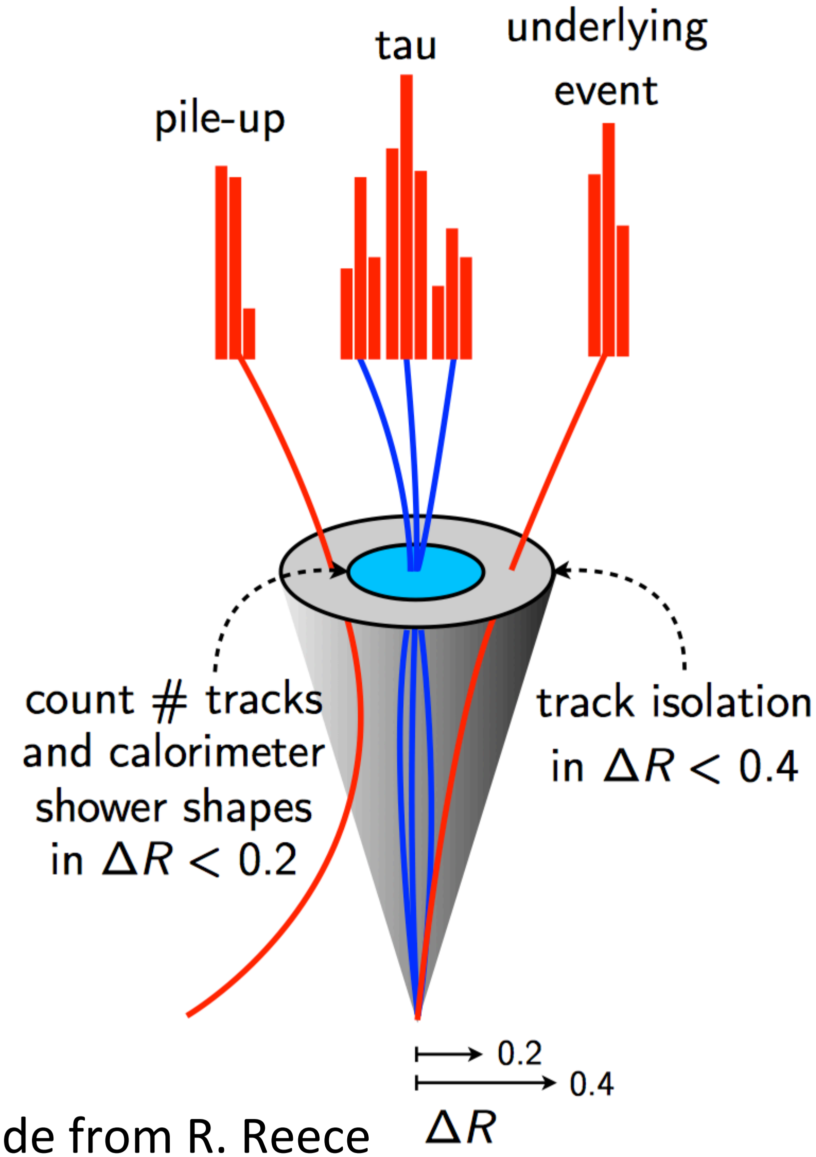




Slide from R. Reece

Tau Lepton Reconstruction

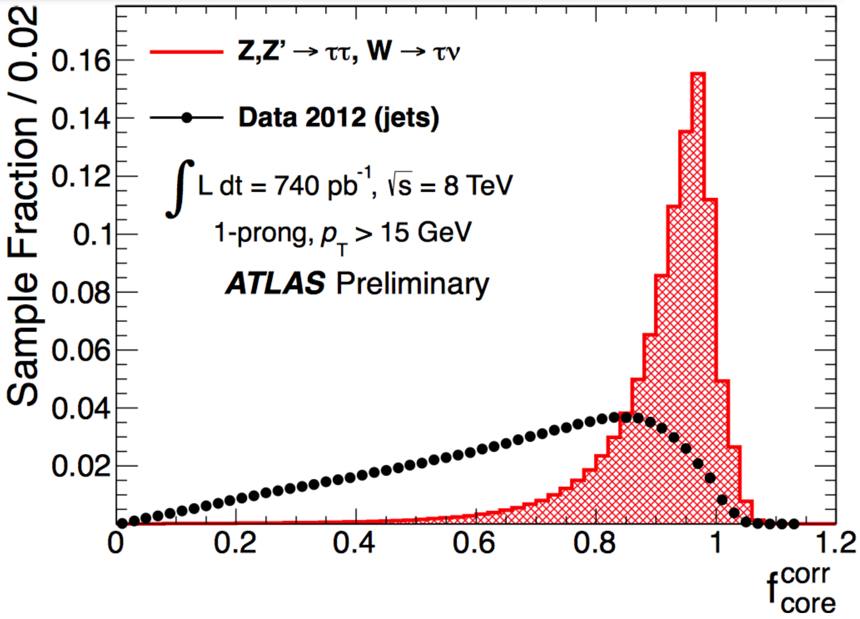
1. Seeded by anti-kt jets (R=0.4) of 3-D topological calorimeter clusters
2. Define the four-momentum as the jet axis with a tau-specific calibration
3. Associate tracks with the jet that are consistent with the chosen vertex
4. Calculate characteristic variables from combined calorimeter and tracking information
5. Put in multivariate estimator ;-)

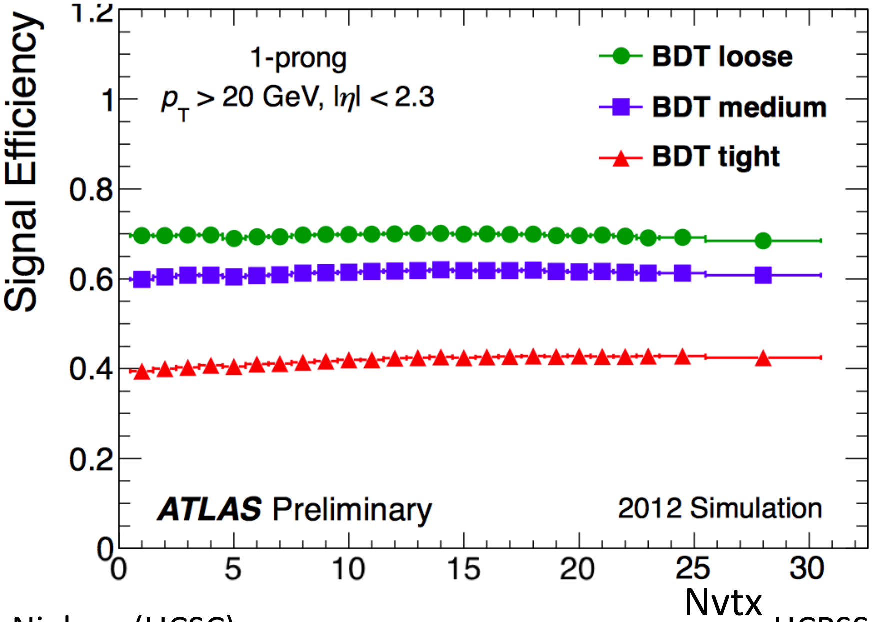


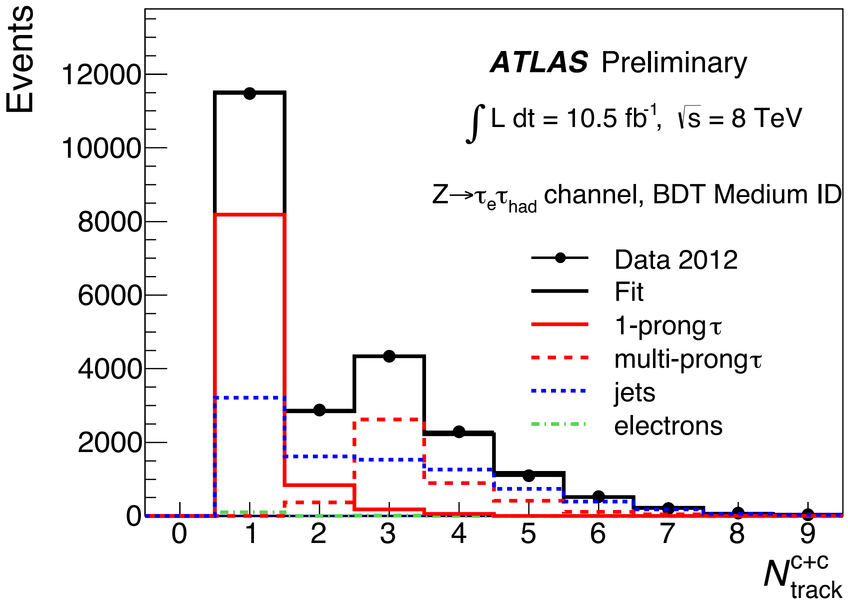
Slide from R. Reece

Multivariate Tau ID

- Combine key variables like core energy fraction, decay length significance, and jet track width
- Fit to Ntrack distribution gives background and signal contributions for efficiency measurements



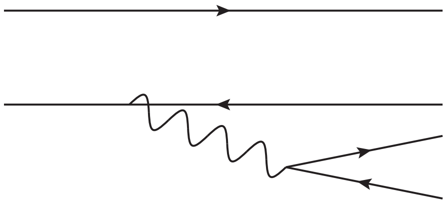




Heavy Flavor Tagging

- Important particle ID for Higgs decays and stop decays
  - Tag of jet flavor possible for b (and sometimes c) unlike for uds

- b quarks (& B/Λ_b hadrons) have following special properties:
  - Long-lived (due to CKM suppression)
  - Massive with respect to decay products
  - Semileptonic decays through spectator
  - High multiplicity decays



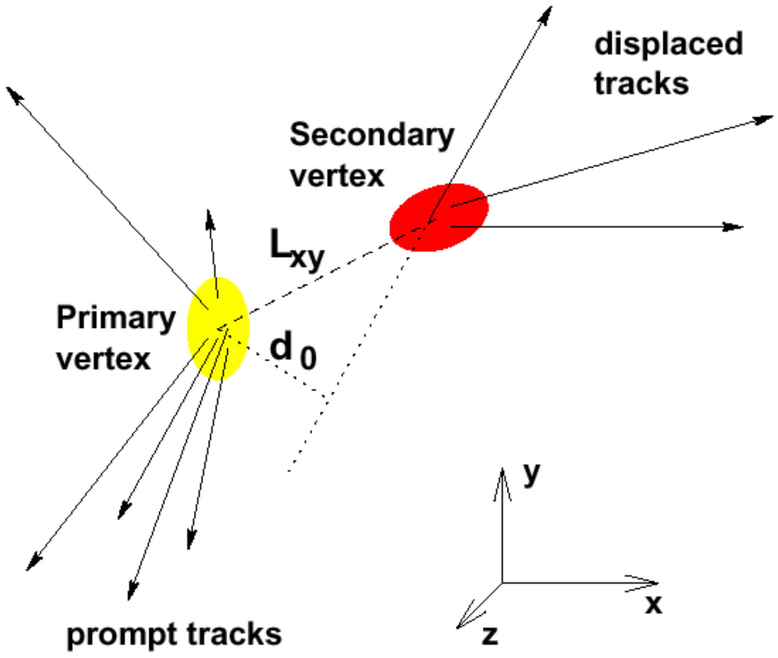
- Compare $c\tau_b$=500μm with $c\tau_c$=310μm and $c\tau_\tau$=90μm
  - Major difference in number of particles in jet
  - Difference in masses – is it important? Think about γ boost factors

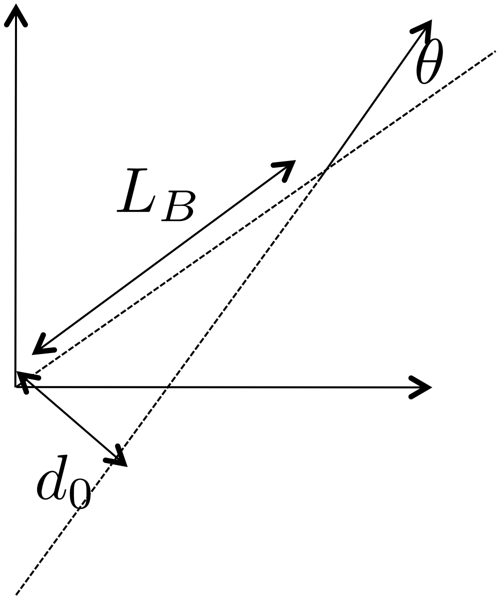
Geometry of b/c Hadron Decays

- Decay products point back to Secondary Vertex, not PV
  - Measure the decay length L_{xy} or impact parameter d_0

$$d_0 \sim \theta L_B \sim \left(\frac{p_\perp}{p_{||}}\right) L_B \sim \left(\frac{p_\perp}{p_{||}}\right)(c\tau_B)\gamma_B \sim \left(\frac{m_B}{p_B}\right)(c\tau_B)\gamma_B \sim (c\tau_B)$$

- Need measurements with precision 10% x O(300μm)
  - Note that charm d_0, L_{xy} are essentially the same as for B



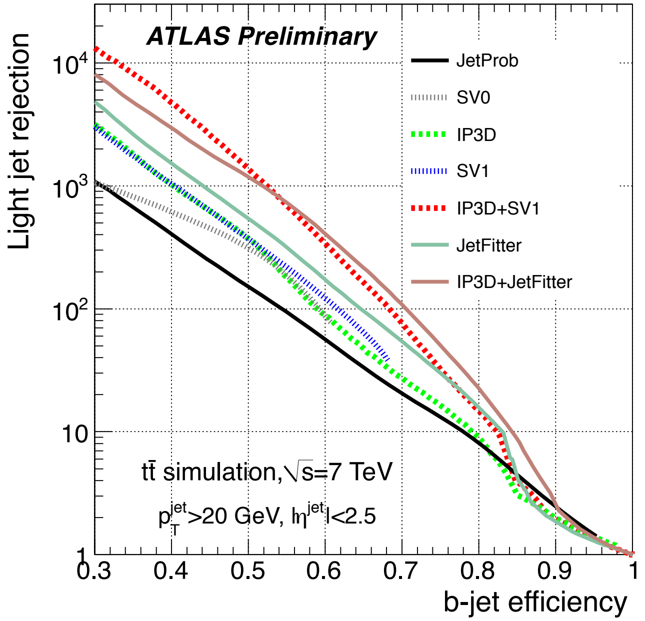


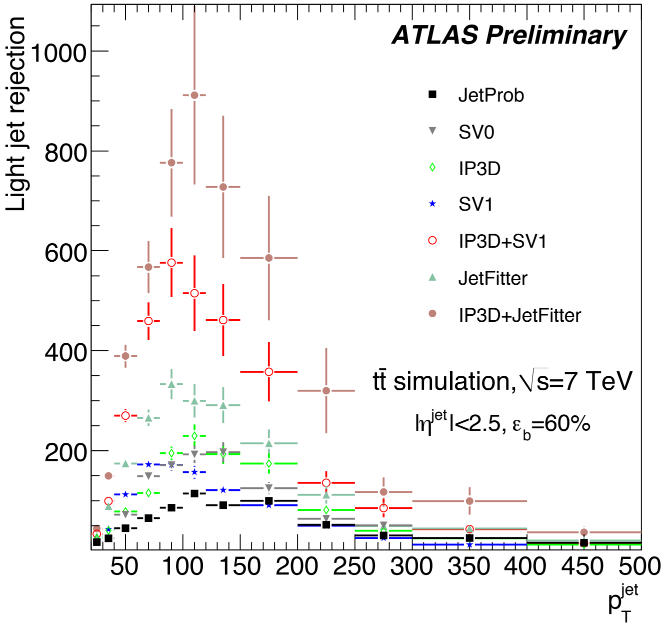
Discriminating b jets from uds jets

- Impact parameter likelihood
  - Product of each track's incompatibility with originating at primary vertex
- Secondary vertex decay length significance
  - Measures separation between SV and PV: L/σ_L
  - Geometry of b and c decay vertices: constrained to lie along line of flight
- Soft lepton identification from semileptonic HF decay
  - Typically muons @ few GeV
- Vertex mass calculation
  - Direct comparison of quark masses m_b, m_c, m_{uds}
- Number of tracks associated with vertex
  - Favors higher-multiplicity B decays
- Multivariate techniques
  - Include all of the above, plus total track multiplicity in jet and jet width

Multivariate Techniques

- Each b-tagging algorithm has its own complicated output
  - Decay length significance (2-D or 3-D)
  - Impact parameter-based probability
  - Internal neural network output
- Several taggers can be combined if their power is complementary
  - IP3D gives impact parameter probability
  - JetFitter classifies jets by number of vertices and number of tracks in each vertex
- Training combined neural network on b-jet signal vs. light (udsg) background
  - Reduced performance at high p_T is due to merged pixel clusters and pattern recognition

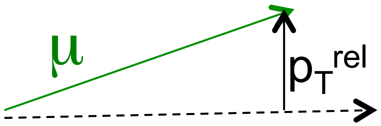


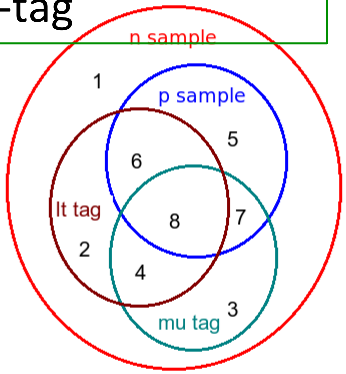


Measuring b-tag Efficiency and Fake Rates

- Challenge: produce pure b-jet sample for efficiency measurement, or play samples of different composition against each other

"System 8": 3 uncorrelated criteria: Lifetime tag, muon p_T relative to axis, opposite-side b-tag

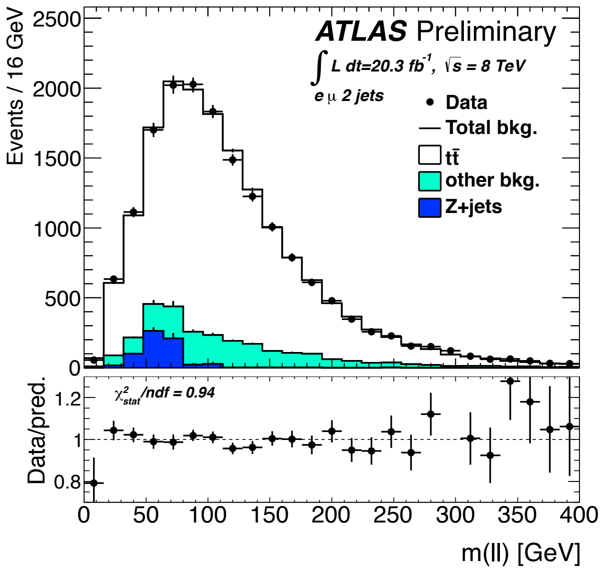




$$
\begin{aligned}
n &= n_b + n_{cl} \\
p &= p_b + p_{cl} \\
n^{LT} &= \epsilon_b^{LT} n_b + \epsilon_{cl}^{LT} n_{cl} \\
p^{LT} &= \alpha_6 \epsilon_b^{LT} p_b + \alpha_4 \epsilon_{cl}^{LT} p_{cl} \\
n^{MT} &= \epsilon_b^{MT} n_b + \epsilon_{cl}^{MT} n_{cl} \\
p^{MT} &= \alpha_5 \epsilon_b^{MT} p_b + \alpha_3 \epsilon_{cl}^{MT} p_{cl} \\
n^{LT,MT} &= \alpha_1 \epsilon_b^{LT} \epsilon_b^{MT} n_b + \alpha_2 \epsilon_{cl}^{LT} \epsilon_{cl}^{MT} n_{cl} \\
p^{LT,MT} &= \alpha_7 \alpha_6 \alpha_5 \epsilon_b^{LT} \epsilon_b^{MT} p_b + \alpha_8 \alpha_4 \alpha_3 \epsilon_{cl}^{LT} \epsilon_{cl}^{MT} p_{cl}
\end{aligned}
$$

Select for top pair dilepton events, in which the only high-p_T jets are b-jets

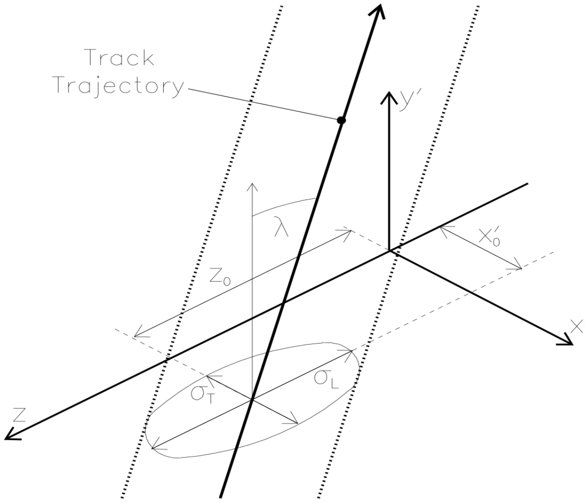
ATLAS-CONF-2014-004



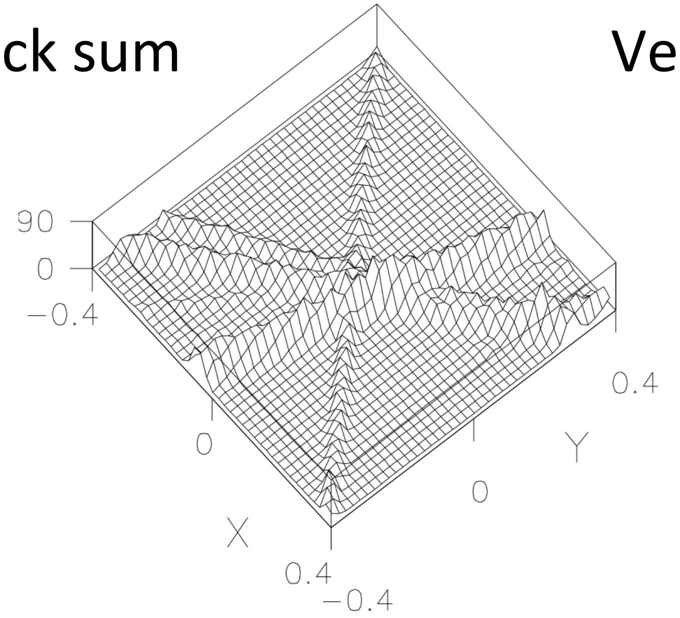
$$
f_{2\ \mathrm{tags}} = f_{bb}\epsilon_b^2 + f_{bj}\epsilon_j\epsilon_b + \left(1 - f_{bb} - f_{bj}\right)\epsilon_j^2
$$

Probability Flux Tube Calculations

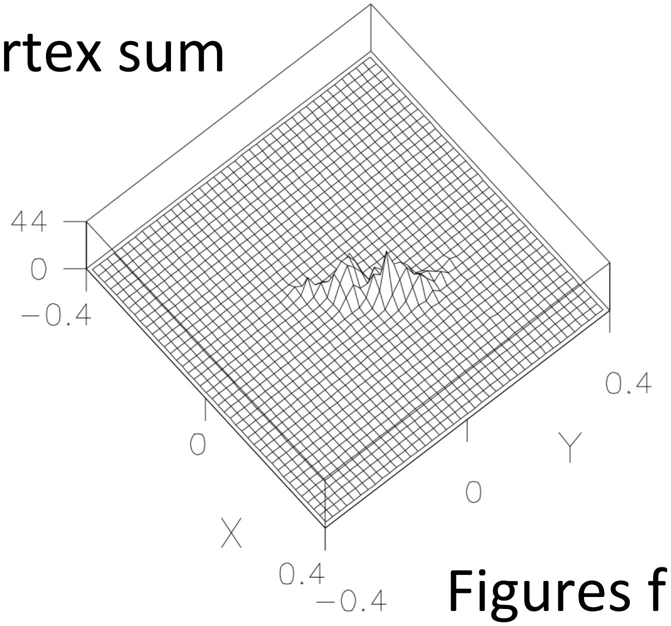
- Create a Gaussian probability tube around each track in the jet
  - Depends on estimate of resolution at each point along the track: full error matrix
- Sum probabilities for each point on a 2- or 3-D spatial grid to find vertex
  - May be slow in large volume, but O(Ntrks)



Track sum



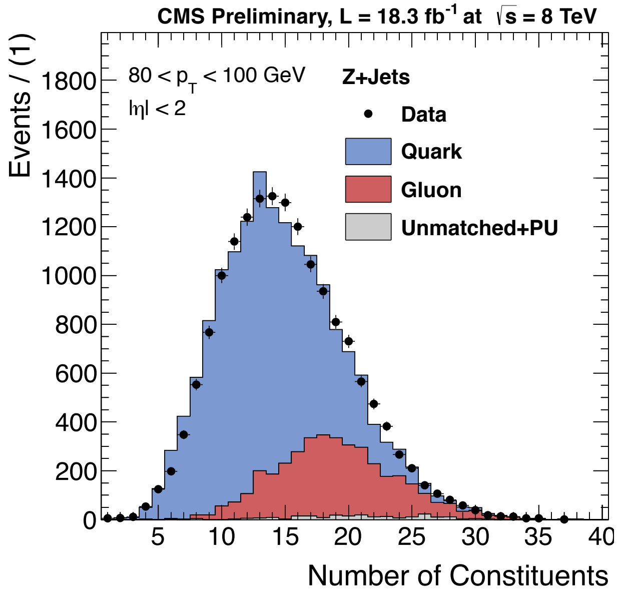
Vertex sum

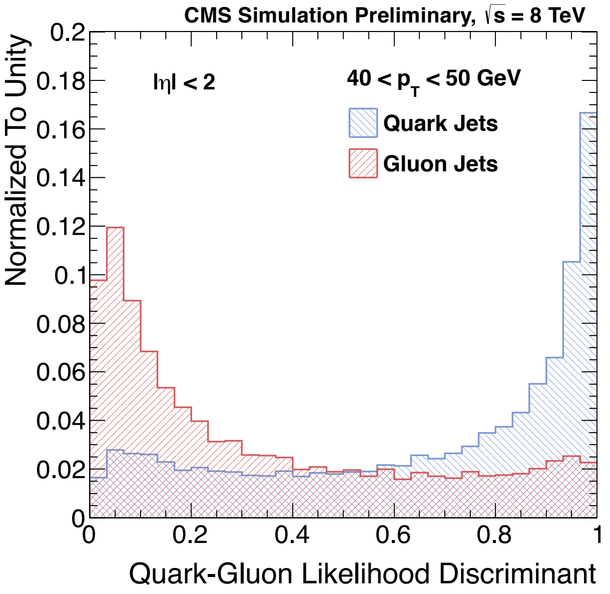


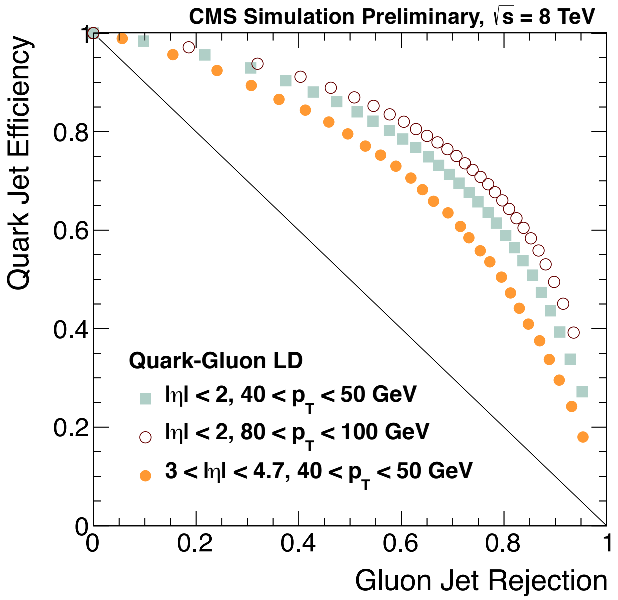
Figures from SLD

Quark-Gluon Tagging

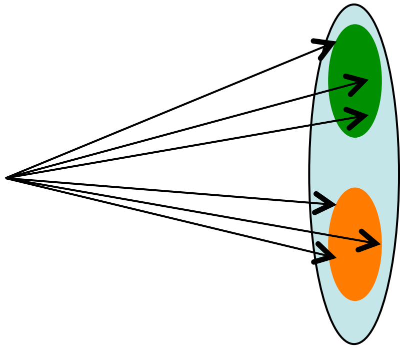
- Many measurements and searches can benefit from identifying jets from initial-state quarks from gluon jets
- Main differences have to do with jet shape and track multiplicity
  - Light (uds) jets fragment to small number of hadrons
  - Gluon jets, especially at high p_T, tend to have high multiplicity
- Continuous variables: “girth” (p_T-weighted summed radius)
- Discrete variables: number of tracks, number of Akt 0.1 subjets







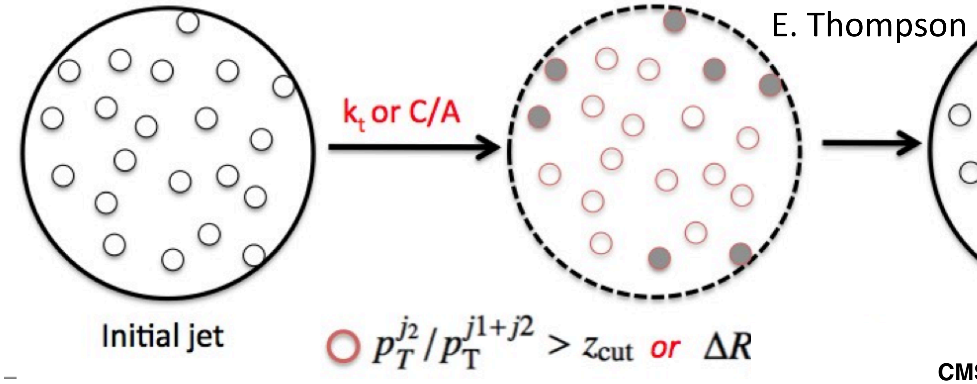
W Boson Tagging



- For 13 TeV, many analyses with W bosons move to boosted regimes, where SM backgrounds are reduced
  - WH measurements
  - WW measurements and high-mass searches
  - Boosted top quark decays
- Hadronic decays of W bosons may be boosted into a single (fat) jet
  - Typical size of this jet is $\Delta R > 2/\gamma$, where γ is boost factor of W
  - How can we separate these "W-jets" from light uds jets and b-jets?
- Several well-motivated handles to quantify substructure
  - Main observable is the mass of the boosted (fat) jet
  - Jet pruning techniques serve to reduce the mass of QCD light jets while maintaining the high mass of the W-jet
  - Mass drop observable contrasts fat jet mass with subjet masses
  - Jet variables are intended to be robust against pileup contributions

Jet Pruning Techniques

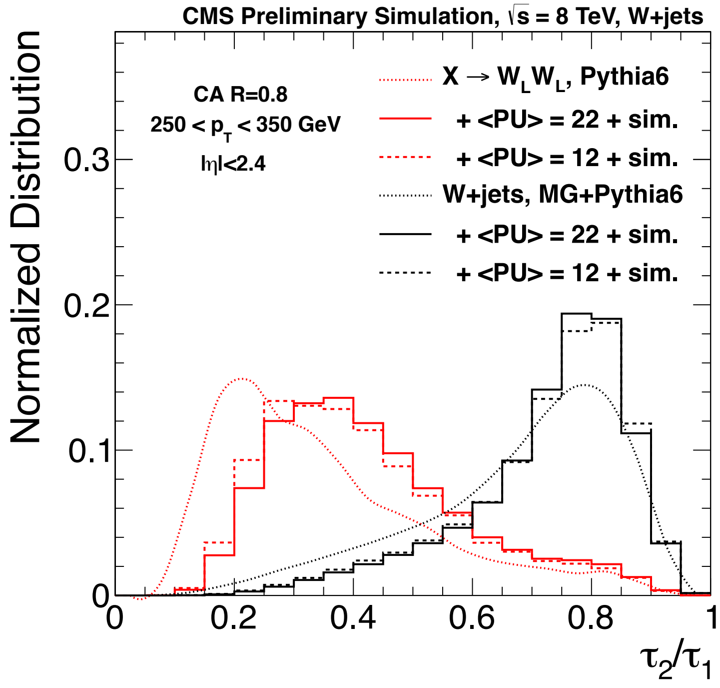
- Selective removal of jet constituents from initially clustered jet
  - Reclustering with C/A but vetoing soft or wide-angle combinations



- "Subjettiness": undo the last prune/clustering to get two subjets

$$\tau_N \sim \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k})$$

- Ratio τ_2/τ_1 is small when consistent with 2 subjets



Jet Mass Measurements

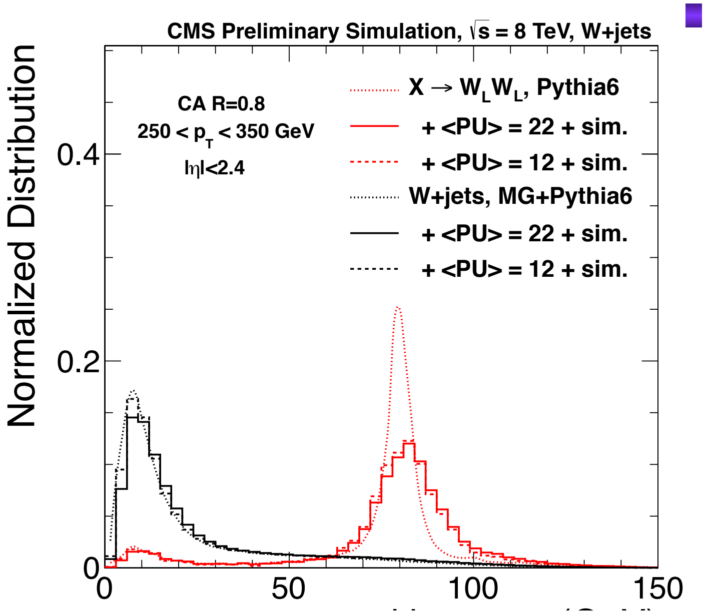
- Mass of original fat jet is very different for W jets and light jets (even w/ pileup)
- Pruning only serves to enhance this effect by removing wide angle particles

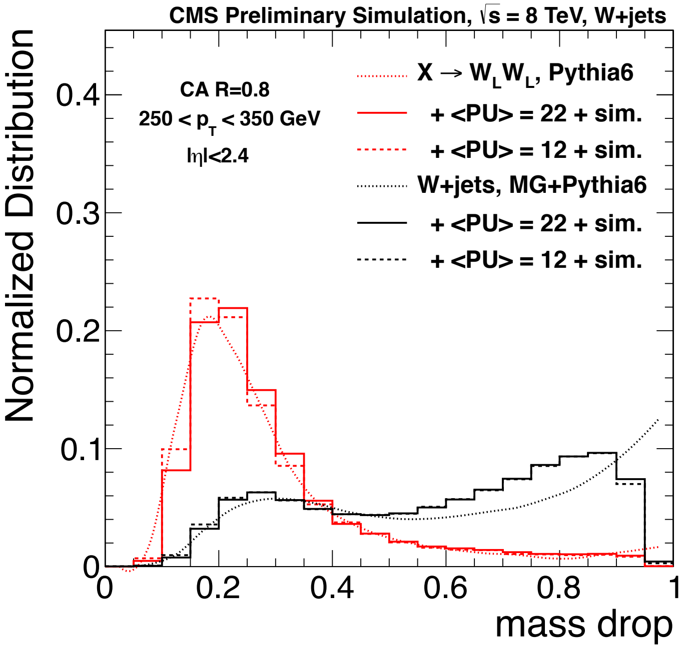
- For mass drop measurement, go back one step to the final 2-subjet stage
- Mass drop focuses on main subjet mass

$$\mu = m_{\mathrm{sub1}}/m_{\mathrm{jet}}$$

  - Small μ when W decays to ud or cs

- Combine these techniques
  - Prune first, then make mass drop cut, then calculate subjettiness with pruned particles

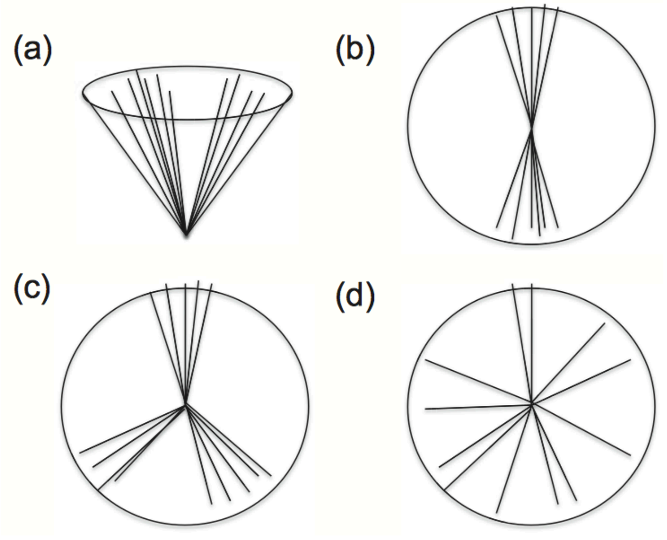




Boosted Jet Shape Techniques

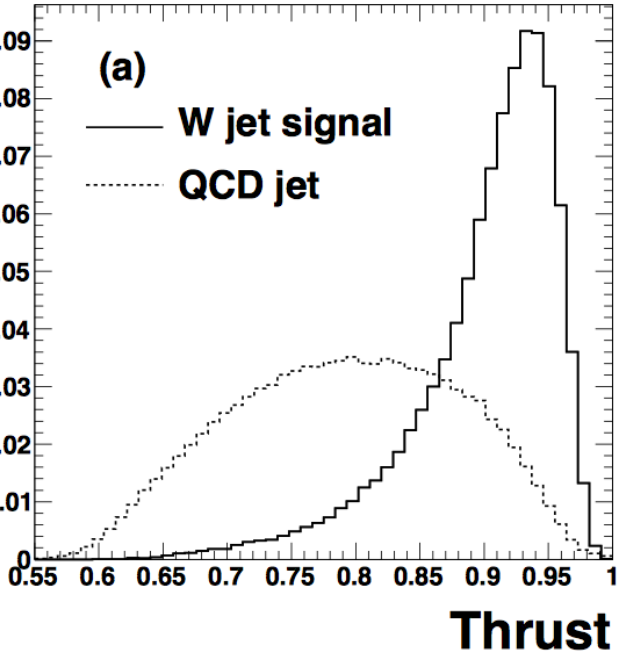
- Completely different approach: look at jet in its own rest frame
  - Is it a dijet-like geometry? No jet clustering
- If we treat this boosted jet like a mini-event, is it linear (W-jet, a&b) or spherical (QCD jet, c&d)?

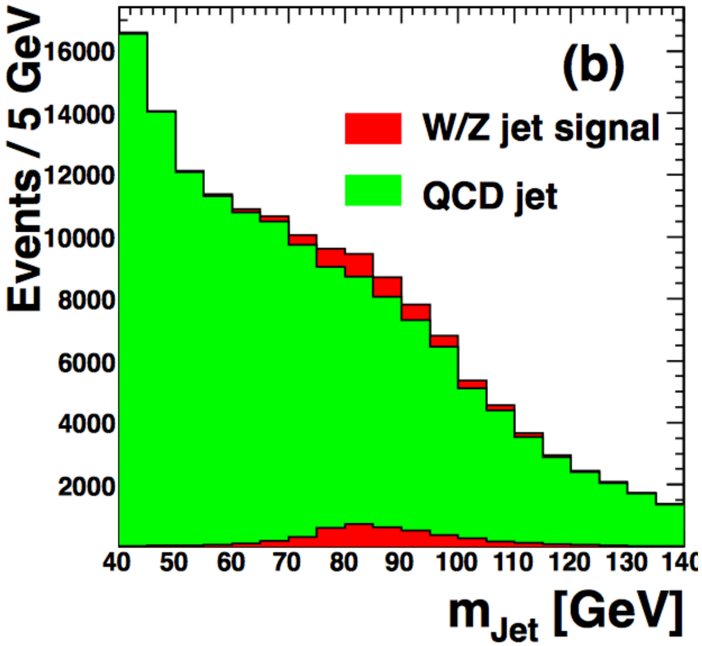
Chen, PRL 85, 034007 (2012)



Find thrust axis to maximize T

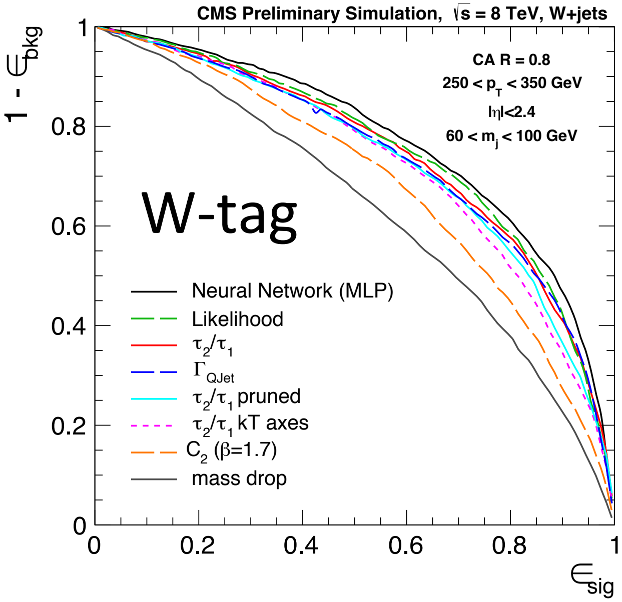
$$T = \frac{\sum_i \left|\hat{T}\cdot\vec{p_i}\right|}{\sum_i |\vec{p_i}|}$$

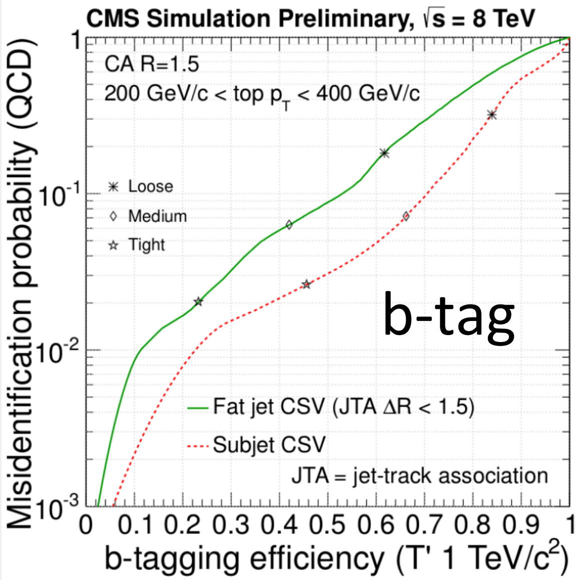




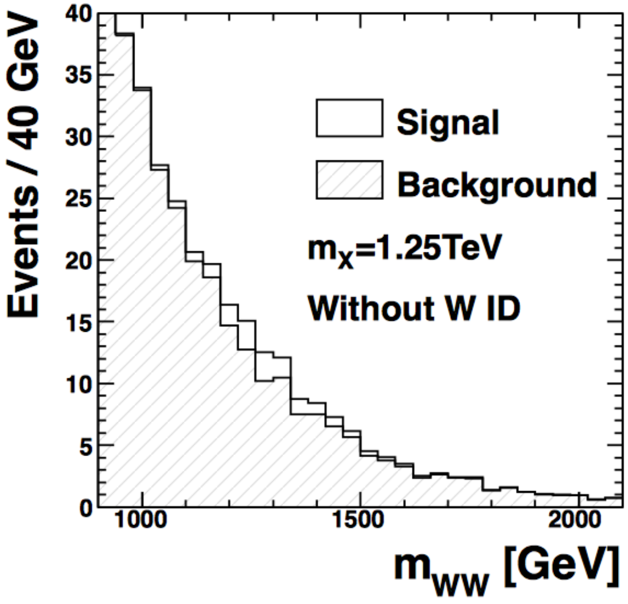
Results for Boosted W Bosons

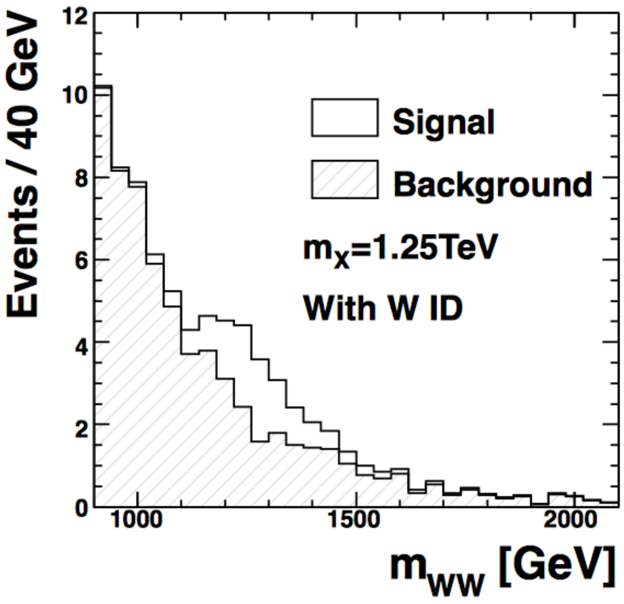
- W-tagged sample is not as pure as the b-tagged sample, but impressive!





- Use the W-tagger to pick out a resonant WW signal at high mass (boosted W jets)





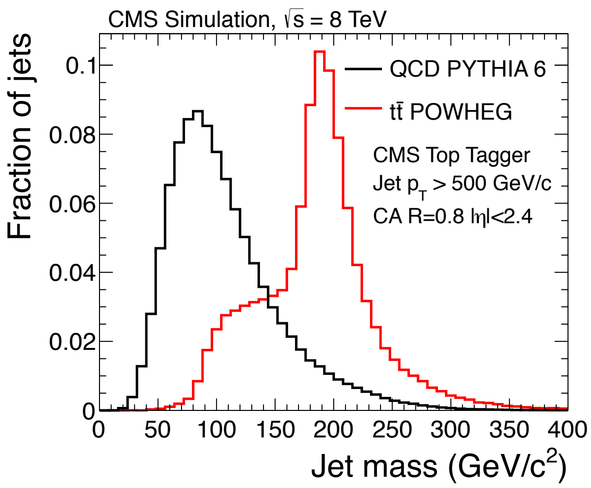
Top Quark Tagging

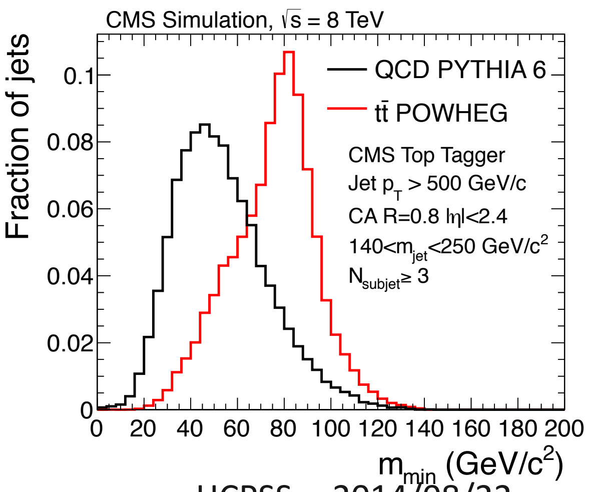
CMS PAS JME-13-007

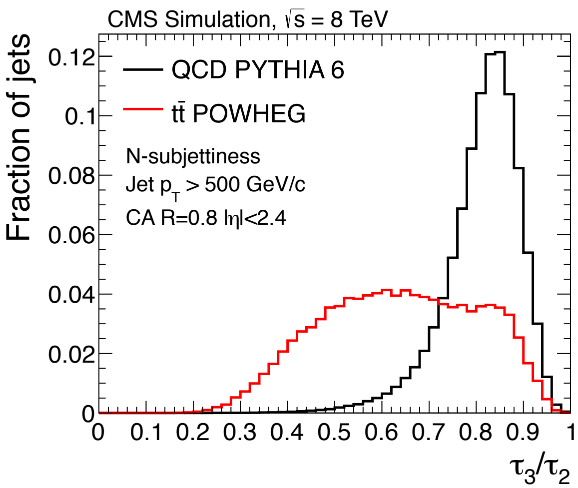
- If boosted W boson can be identified in a single jet, why not top?
- Boosted top quarks could be produced in decays of ultra-high-mass exotic resonances (Z') or high mass stops
- Why top? Striking hadronic decay signature, even more distinct that b-quark decays
  - Boosted W boson jet and high-p_T b jet
- High mass of top quark means jet width is increased relative to W
  - Typical C/A jet radius is 0.8 or even 1.5 (HEP Top Tagger)
- Several algorithms have been developed, tested, combined
  - All depend on the jet substructure and mass drop from top to W to udcs
  - B-tagging the subjets is not trivial; ongoing improvement to define subjets based on tracking alone
- Look at two examples: CMS Top Tagger and HEP Top Tagger

Top Quark Tagging Methods

- CMS Top Tagger (JHU Top Tagger) [Kaplan et al., PRL 101 (2008) 142001]
  - Declusters the C/A R=0.8 jet until it finds two subclusters which are
    - well separated: $\Delta R > 0.4 - 0.0004 \times p_T^{\mathrm{hardjet}}$
    - contain a significant fraction of the hard jet: $p_T^{\mathrm{cluster}} > 0.05 \times p_T^{\mathrm{hardjet}}$
- Calculate variables using subclusters (subjets) as components
  - Jet mass, with subclusters combined
  - Minimum pairwise mass of three leading subclusters
  - "N-jettiness" measures the N-jet hypothesis inside boosted jet: note τ_3/τ_2





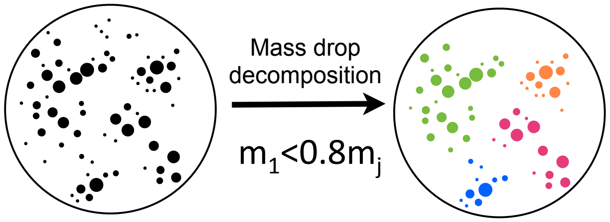


Top Quark Tagging Methods

- HEP Top Tagger [Plehn et al., *JHEP* 1010 (2010) 078]
  - Complex combination of mass drop and filtering

Slide from CMS

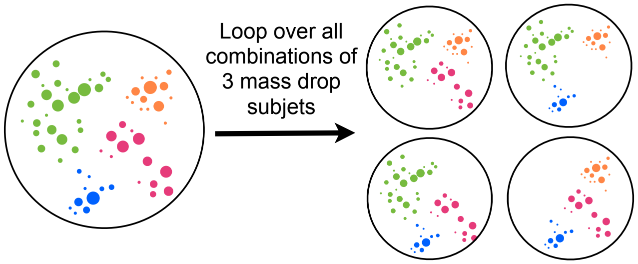
Step 1:



Mass drop decomposition

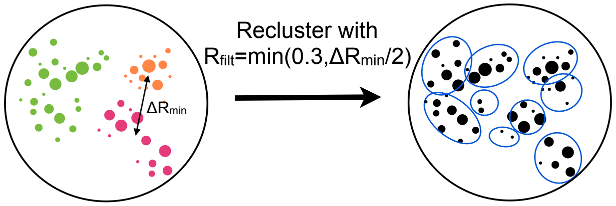
$m_1 < 0.8 m_j$

Step 2:



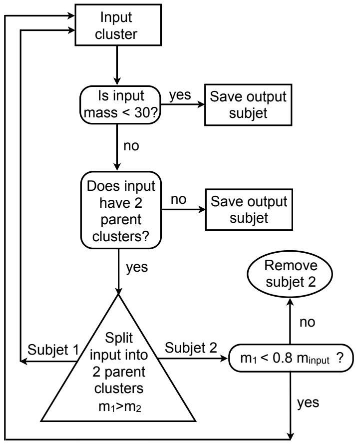
Loop over all combinations of 3 mass drop subjets

Step 3:

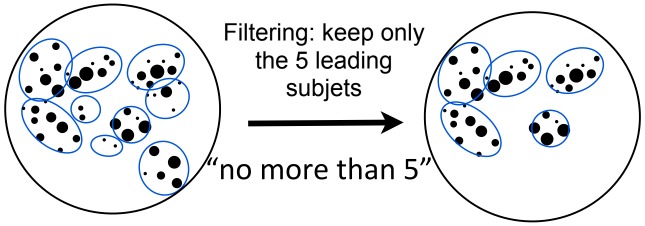


Recluster with $R_{filt} = \min(0.3, \Delta R_{min}/2)$

HEP Top Tagger
Mass drop decomposition



Step 4:

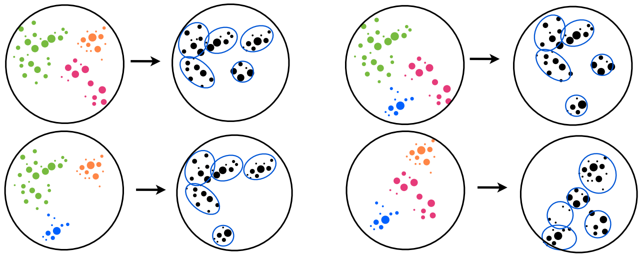


Filtering: keep only the 5 leading subjets

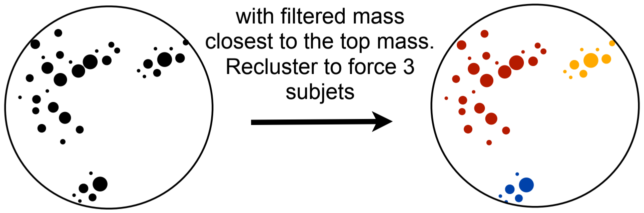
"no more than 5"

Step 5:

Repeat reclustering and filtering procedure for all combinations of 3 mass drop subjets



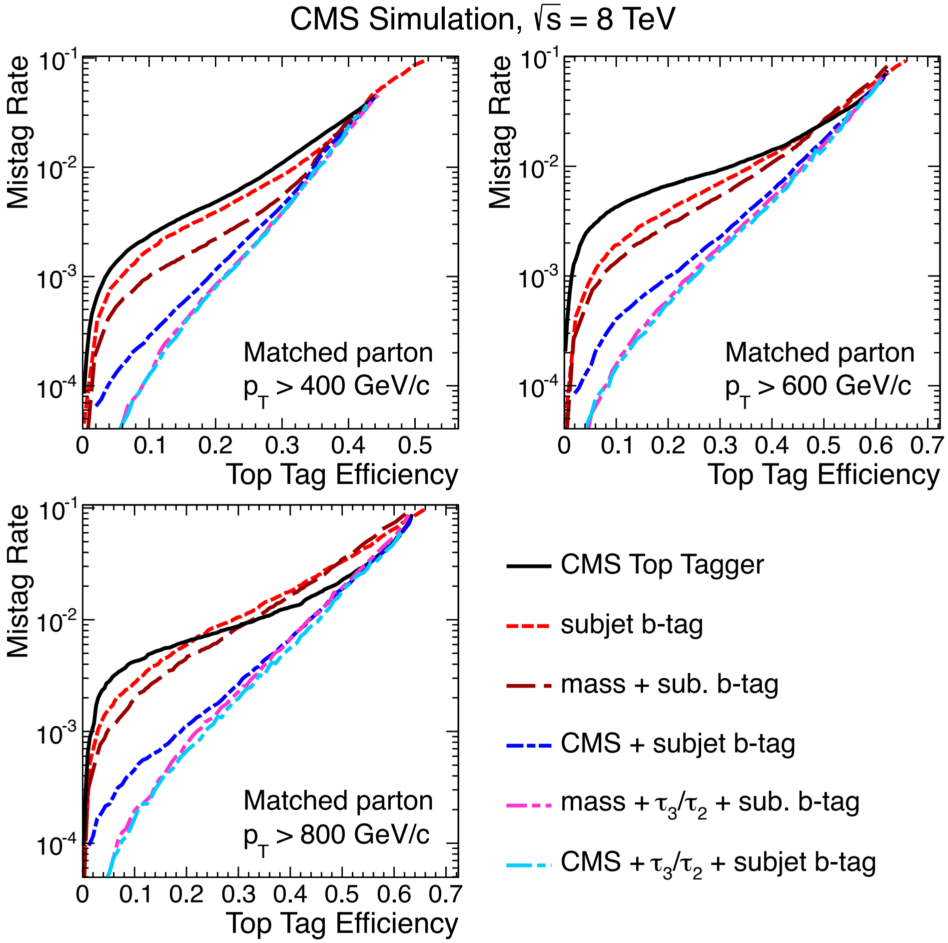
Step 6:

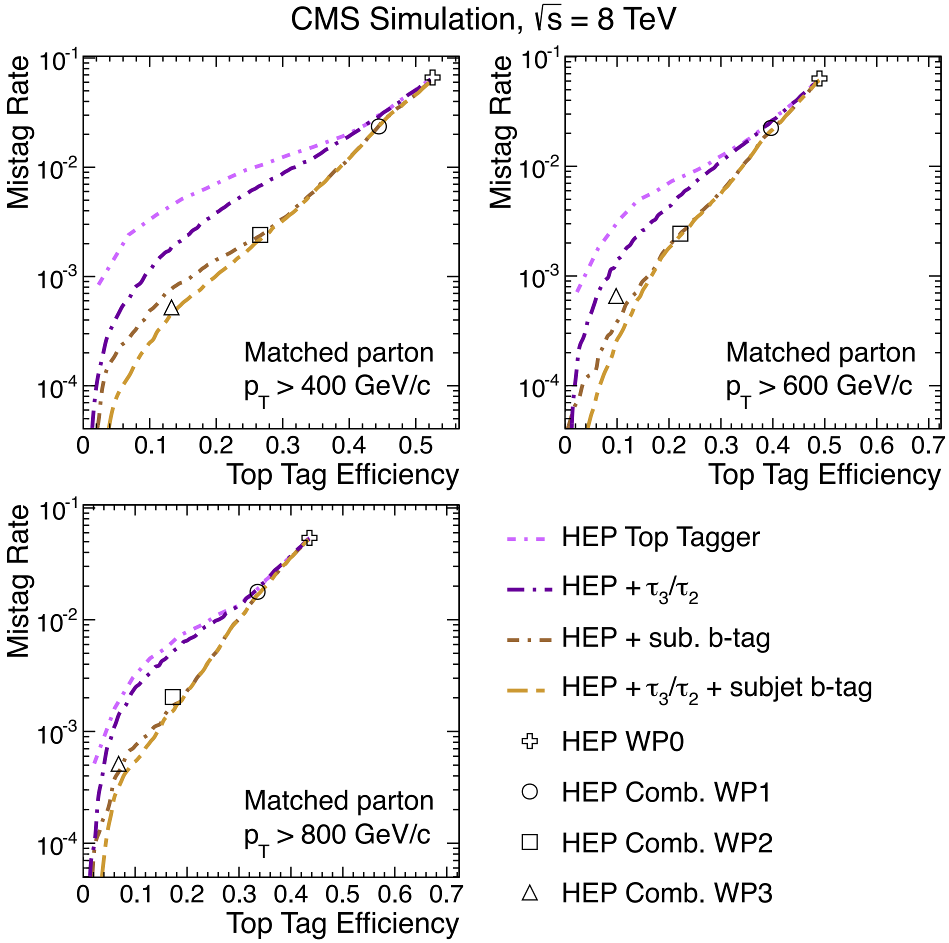


Pick the combination with filtered mass closest to the top mass. Recluster to force 3 subjets

Top Quark Tagging Performance

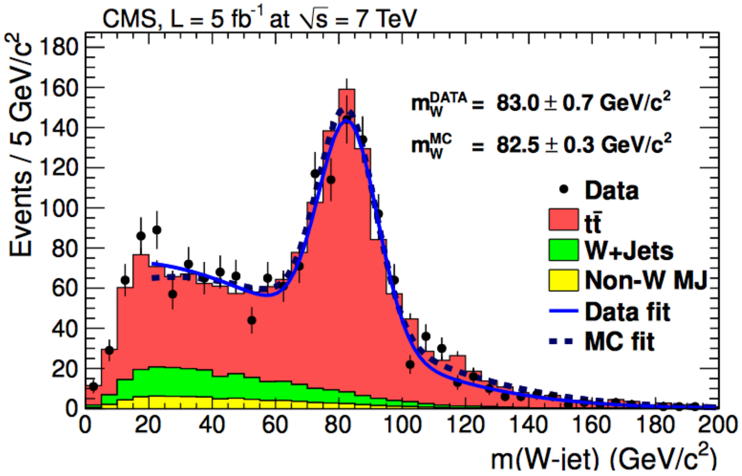
- Combined taggers include other variables and subjet b-tagging
- Best-performing algorithm depends on kinematic (top p_T) regime

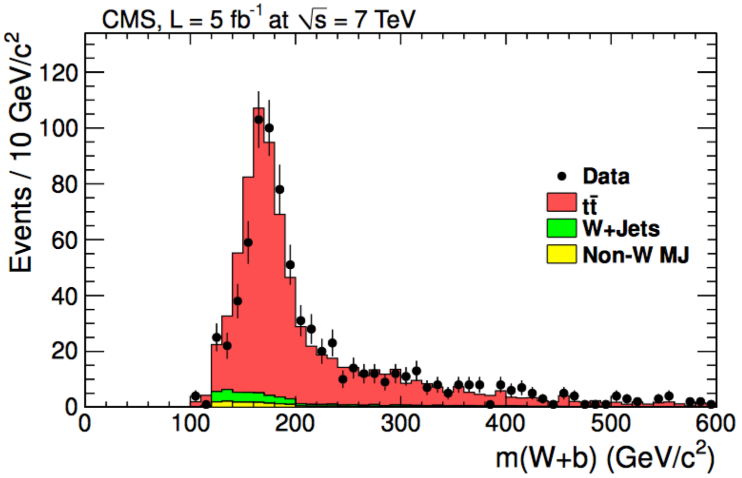




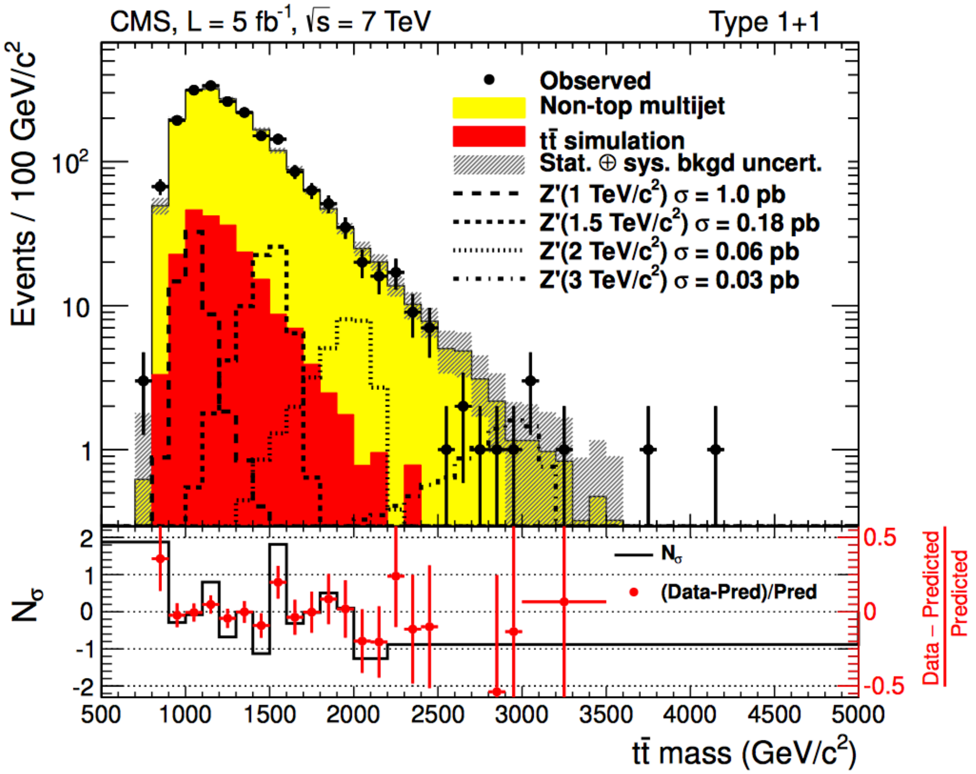
Results Using Top Quark Tagging

- “Search for anomalous tt production in the highly-boosted all-hadronic final state” [JHEP 09 (2012) 029]
  - Optimized for Z’ masses greater than 1 TeV
  - Simplified version of the HEP Top Tagger w/ mass drop and pruning



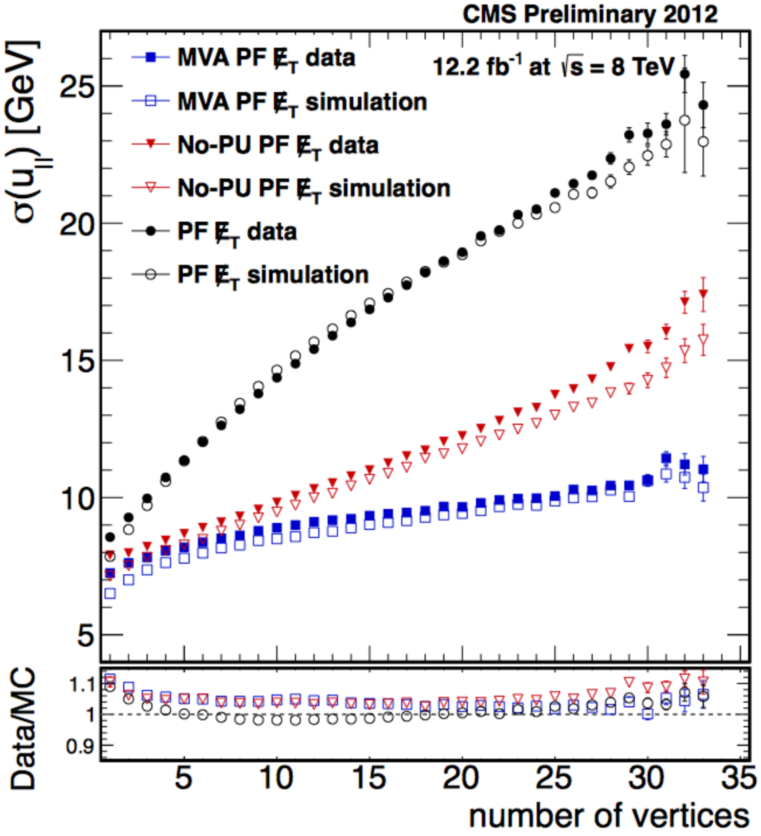


Fully-merged jets channel



Missing E_T

- I’ve left this for last because it is the opposite of everything we’ve discussed: “non-particle-ID” and “non-reconstruction”
- Nevertheless, it is particle ID for neutrinos and dark matter particles
  - These neutral particles do not decay and do not shower hadronically



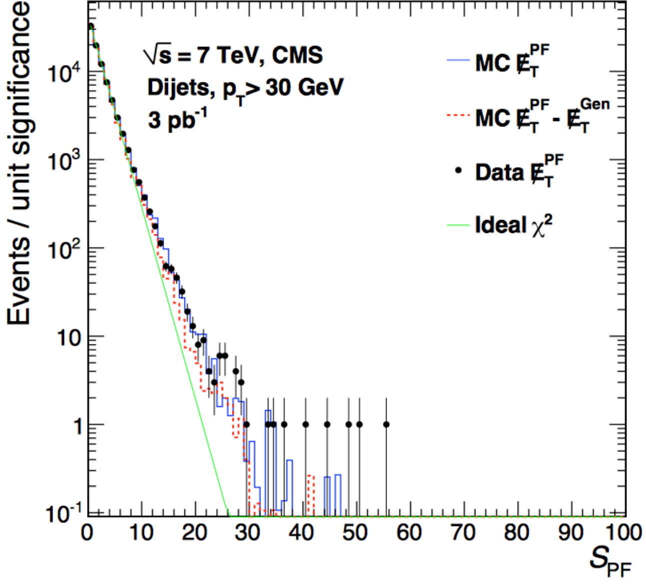
- Particle Flow helps MET reco by removing/calibrating soft particles
- Each pileup adds 3.5 GeV in quadrature to MET resolution
- CMS No-Pileup algorithm deweights particles that are likely to have come from a pileup vertex
  - Big reduction in MET in Z($\mu\mu$) events

Missing ET Significance

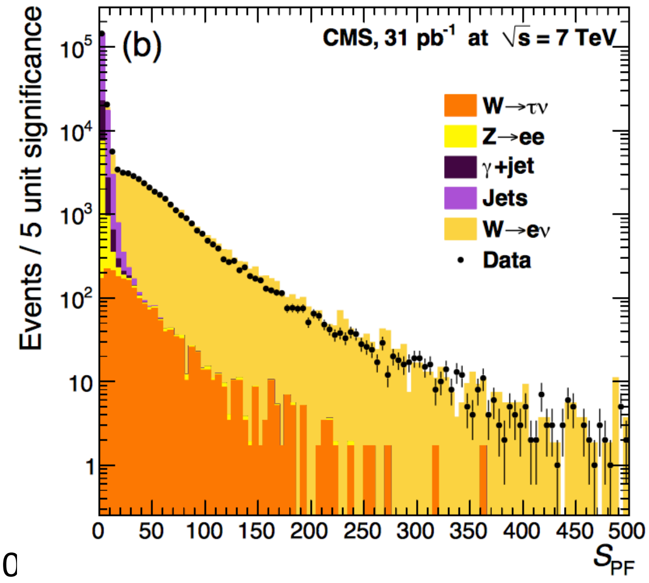
- Developed at Tevatron to quantify: how consistent is a single event with the MET=0 hypothesis?
  - Include somehow the resolution effects in the missing E_T variable
  - This requires a resolution calculation for each individual contribution: jets, single charged particles, neutral calorimeter clusters (even PF particles)
- Build a product of many Gaussian resolution functions into a likelihood, and calculate the ratio

$$\mathcal{S} \equiv 2\ln\left(\frac{\mathcal{L}(\vec{\varepsilon}=\sum\vec{\varepsilon}_i)}{\mathcal{L}(\vec{\varepsilon}=0)}\right)$$

Dijet events



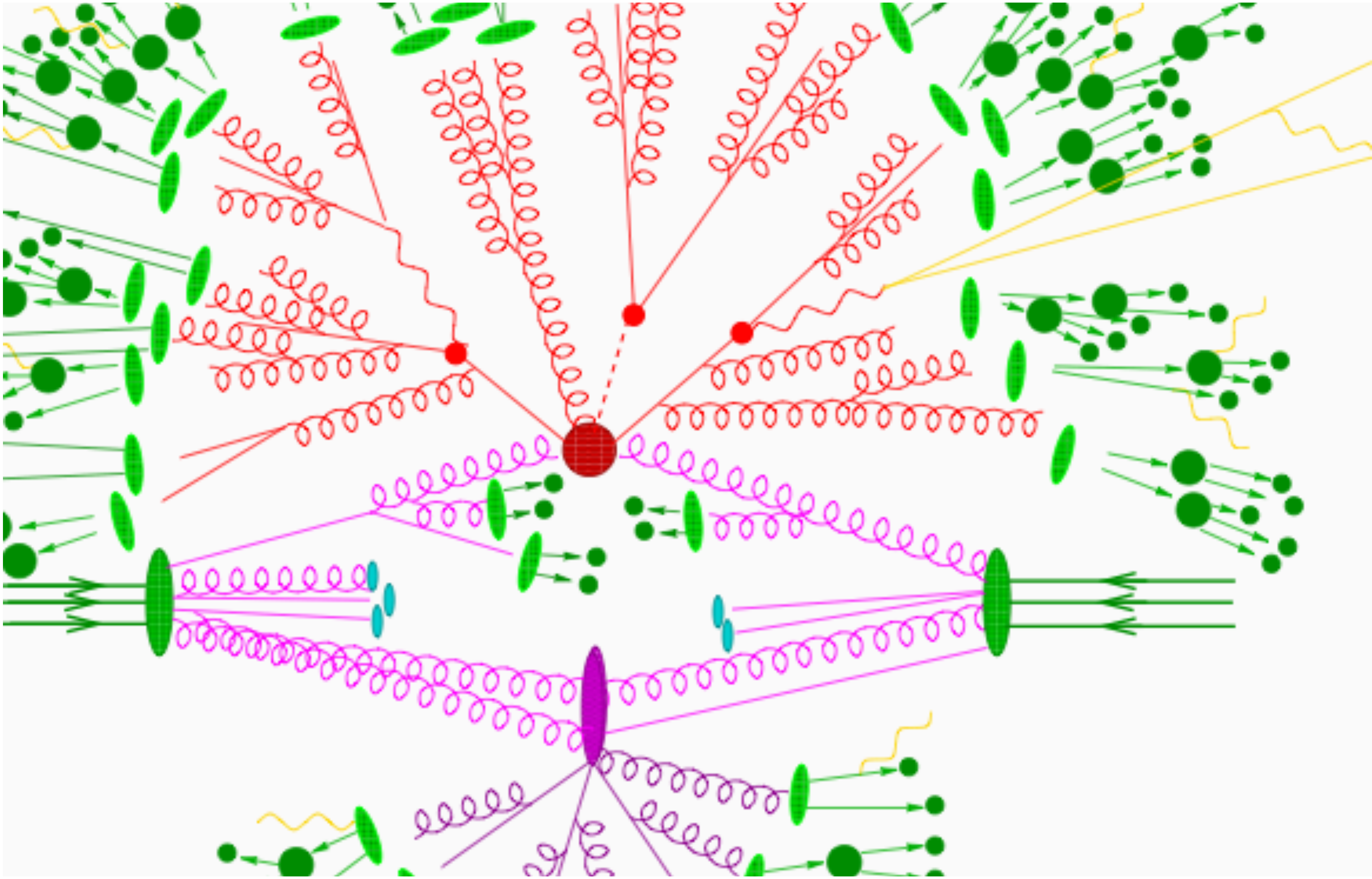
W events



Summary of Today's Topics

- Reconstructed jets associated with partons from hard scatter
  - Key point: well-behaved algorithm to unravel non-perturb. QCD step
  - Jet cleaning, calibration, and pileup subtraction improve this connection
- Tau lepton reconstruction
  - Leptonic or hadronic decays require different algorithms and techniques
  - Hadronic decay signatures are skinny (mini-) jets
- Heavy-flavor tagging has applications in searches and Higgs
  - Discriminating variables take advantage of long lifetime and large mass.
  - Multivariate techniques can even distinguish b quark from gluon jets
- W boson and top quark tagging for highly-boosted states
  - Groomed or boosted jets show W bosons decaying inside a single jet
  - Top-tagging algorithms are based on jet substructure and kinematics
- Missing E_T
  - Improving resolution allows us to associate missing E_T with neutrinos or LSPs

Good Luck



Guide to Further Reading

- Jets:
  - Lectures in this school by Fernando Febres Cordero
  - G. Salam, “Toward Jetography,” arXiv:0906.1833
- Tau identification:
- Heavy-flavor / gluon jet tagging:
  - Gallichio and Schwartz, “Quark and Gluon Tagging at the LHC ,” arXiv: 1106.3076
  - G. Piacquadio’s thesis: CERN-THESIS-2010-027
- W/top tagging:
  - Ellis, Vermilion, and Walsh, “Pruning as a Tool for Heavy Particle Searches,” hep-ph/0912.0033