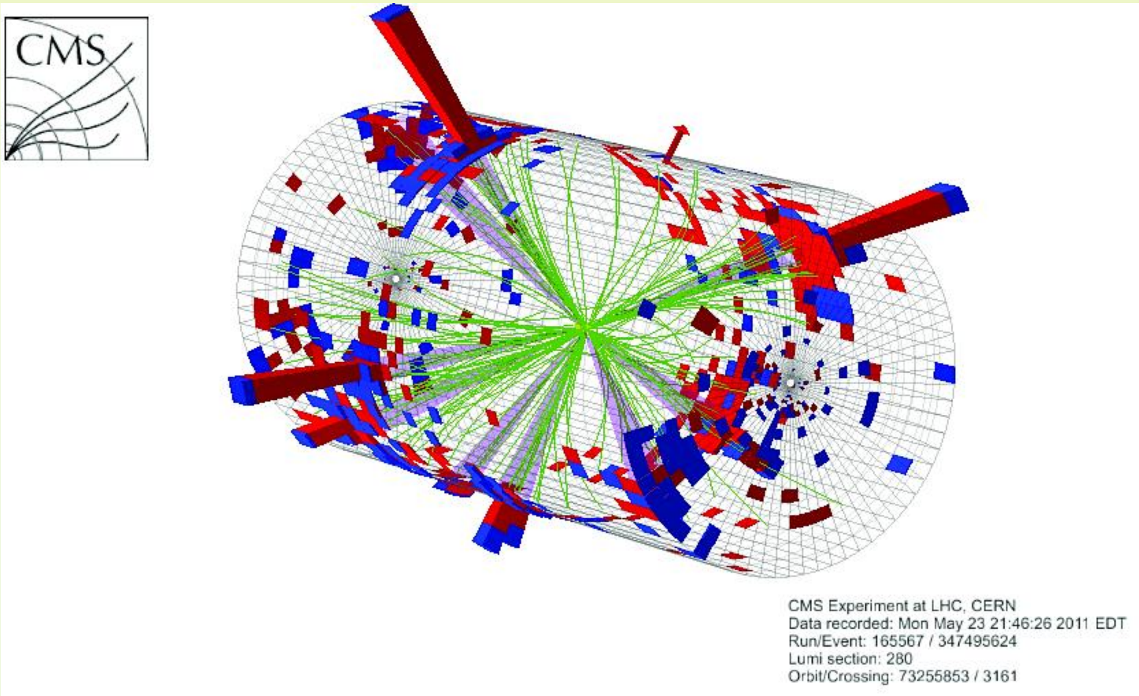
Jet Substructure by Accident

by Hou Keong (Tim) Lou
Princeton University

In collaboration with
Timothy Cohen, Eder Izaguirre and Mariangela Lisanti
(arXiv: 1212.1456)

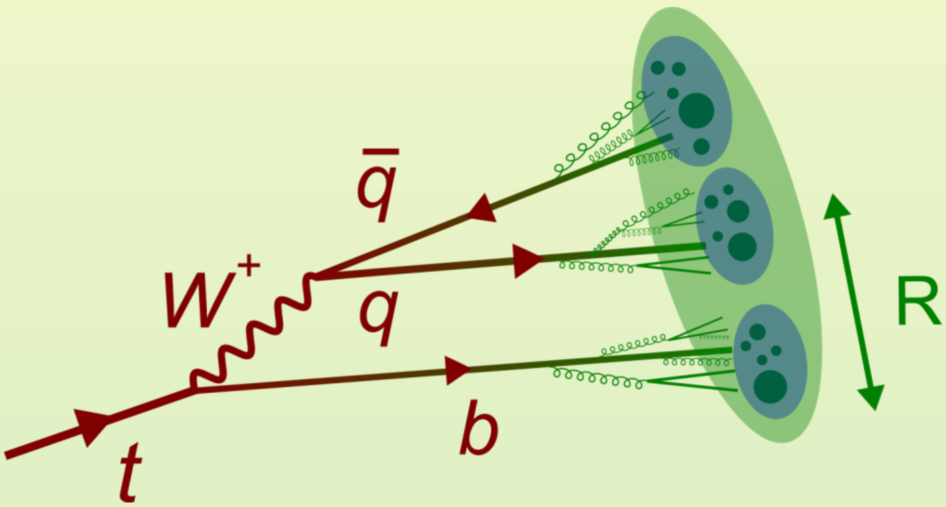
New Physics in Multijets

- Natural SUSY → light stops → multitops/multijets
- New physics could be hiding in multi-jets
- Need robust multijet search techniques



Jet Substructure

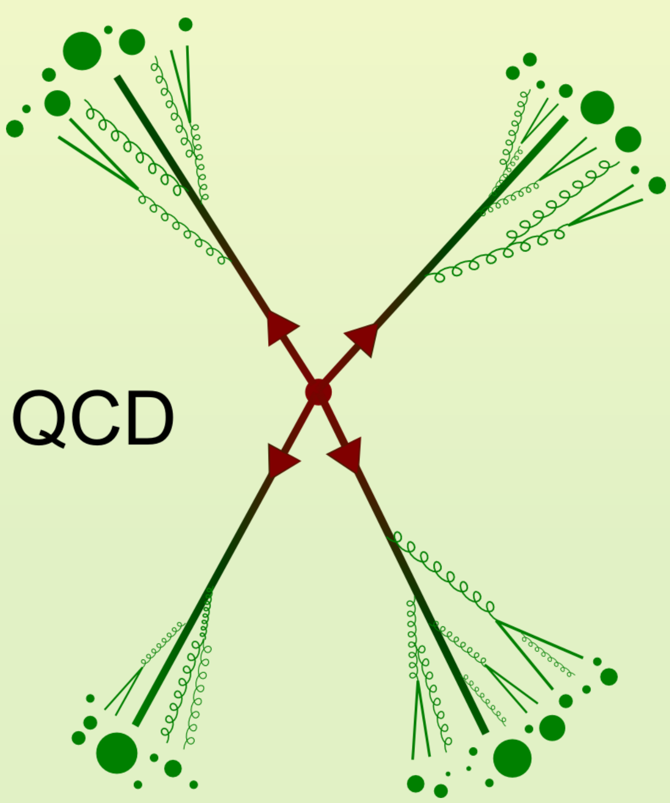
- Boosted particle can decay into collimated final states
  - Size $R \sim m/|\vec{p}|$
  - Cluster into a single fat-jet
- Boosted particles decay → jet substructure

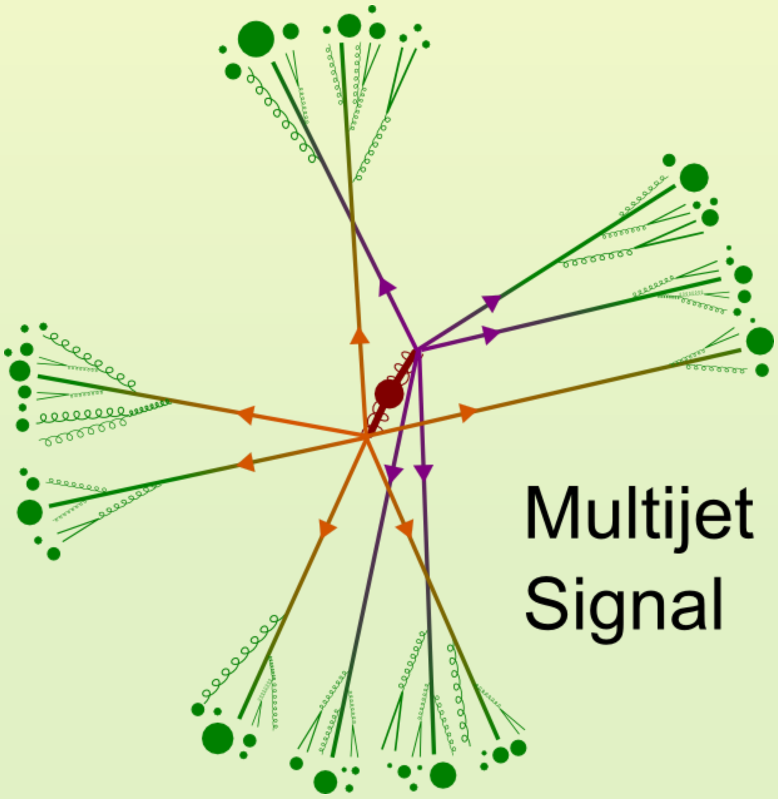


- Can we use substructure for non-boosted particles?

Accidental Substructure

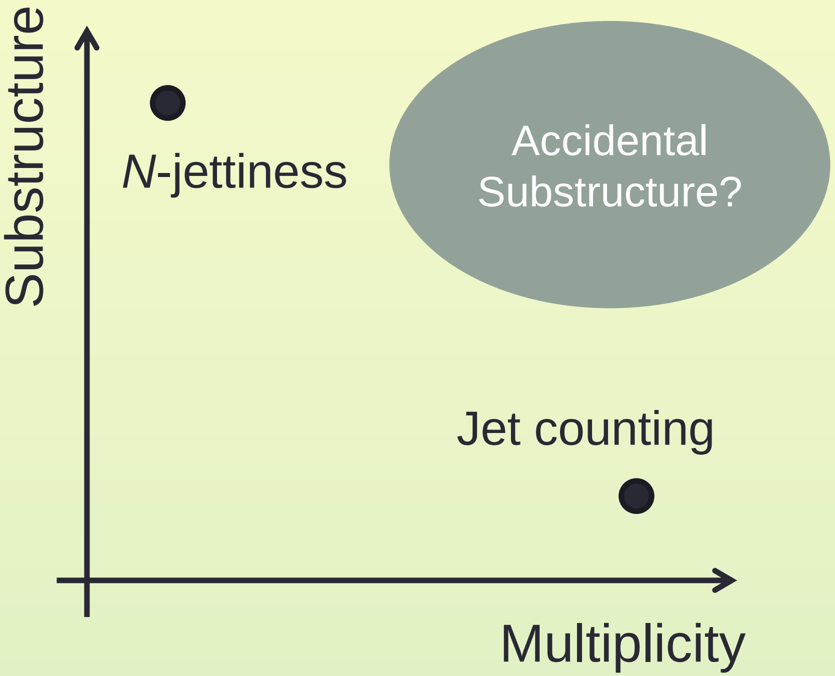
- Substructure without "boost"?
- Multiple quarks get clustered together by accident





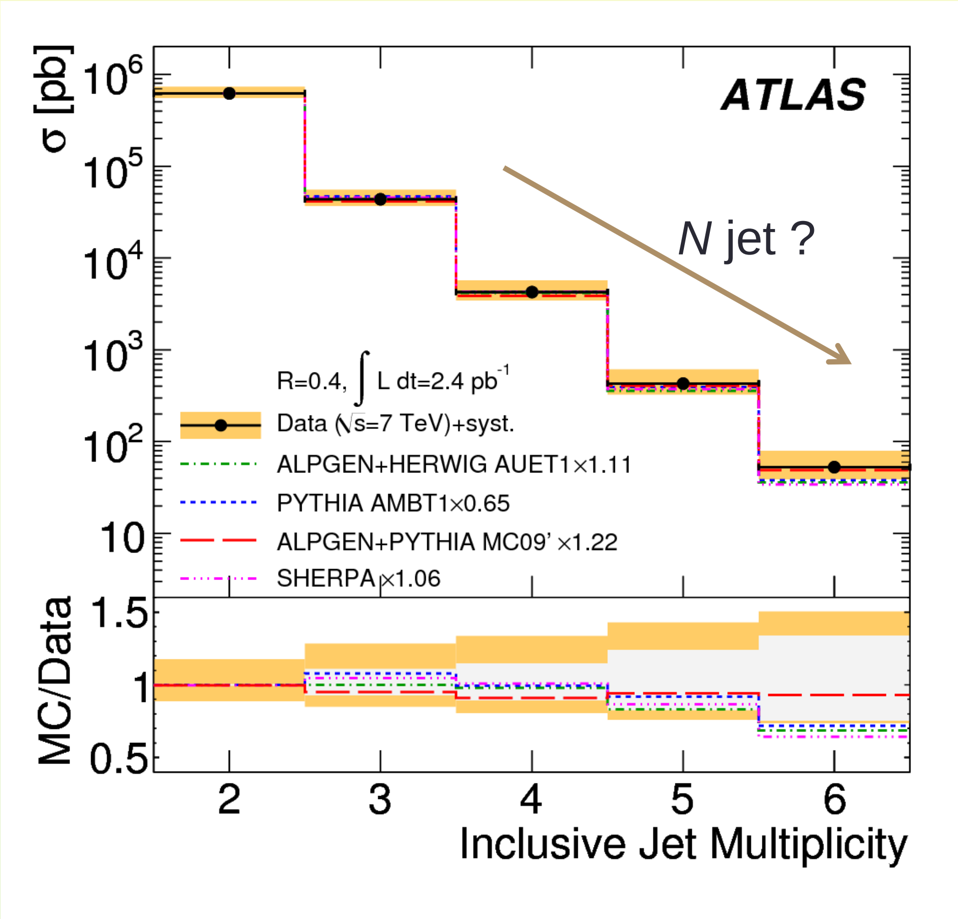
Accidental Substructure

- Idea not new:
  - Event Shapes
    - *N*-jettiness (Stewart et. al.)
- Multi-jet = multiple interpretations
- Optimization:
  - Background control
  - Signal discrimination



Multijet challenges

- Modeling ≳ 8 jets challenging:
  - matrix elements
  - matching
- Need data-driven method
- $Jet_{N+1} / Jet_{N} = ?$
  (E. Gerwick et. al. arXiv:1208.3676)
- Alternatives?

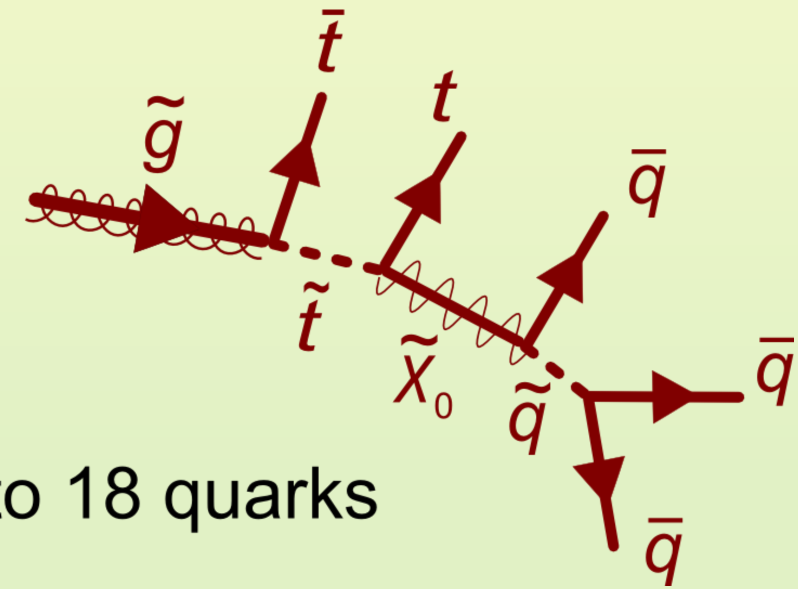


Fat-Jets

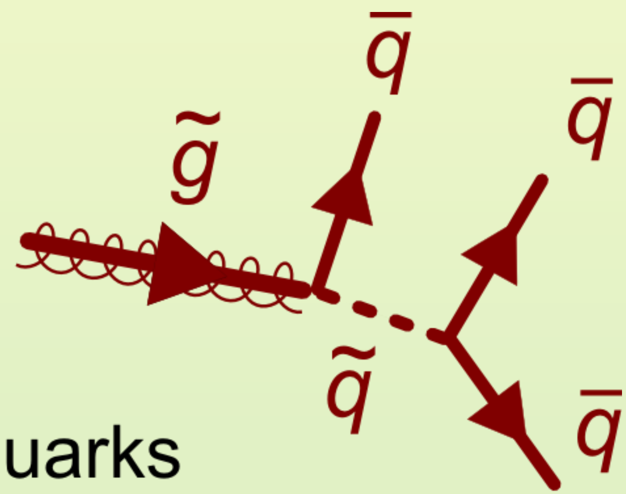
- Factorize phase space
- Fix 4 Fat-jets
- Anomalies in substructures
- Data-Driven background
- QCD = MC ⊗ Data Driven
  - Kinematics: MC
  - Substructure: Data Driven
  - $P_{\text{4-jets}} = P_{\text{jet1}} \bullet P_{\text{jet2}} \bullet P_{\text{jet3}} \bullet P_{\text{jet3}}$

Case Study

- SUSY $\tilde{g}$ pair production
- $\tilde{g}$ or $\tilde{\chi}_0$ decay through RPV $U^c D^c D^c$ term
- No (suppressed) Missing E_T



up to 18 quarks



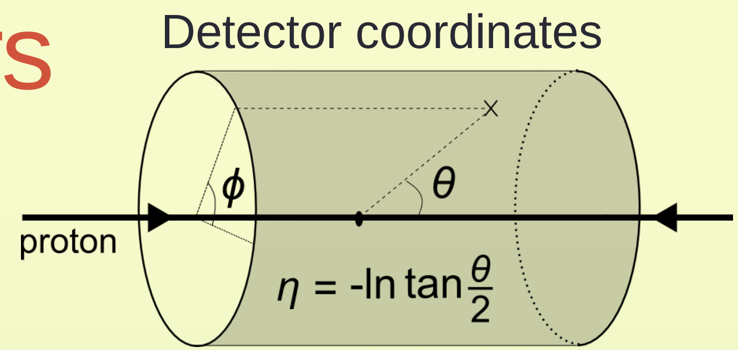
6 quarks

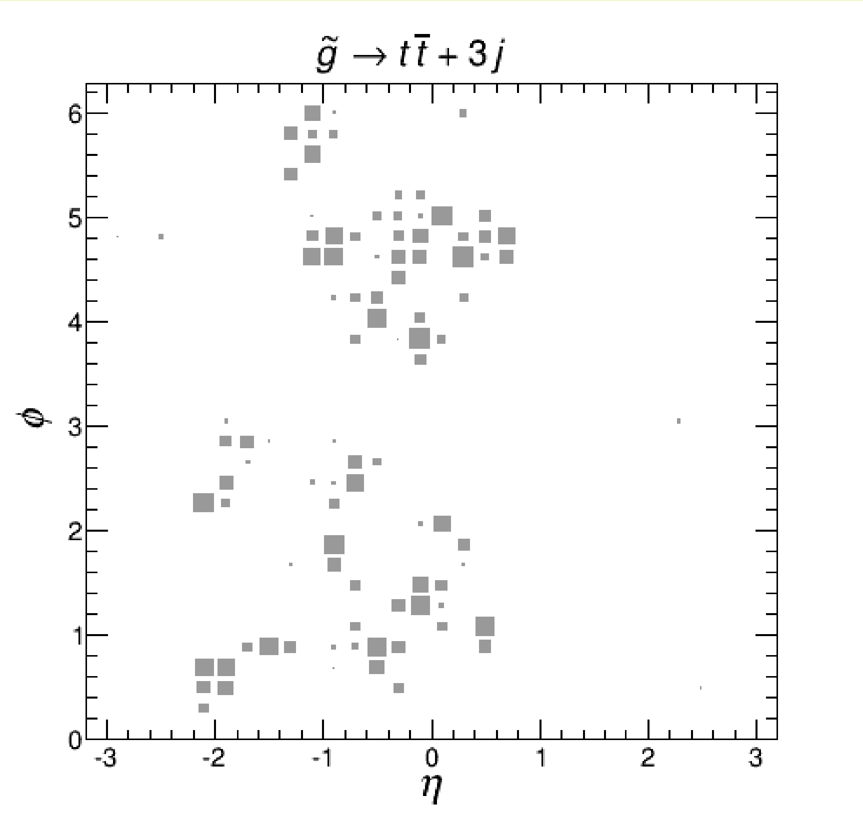
Monte Carlo Modeling

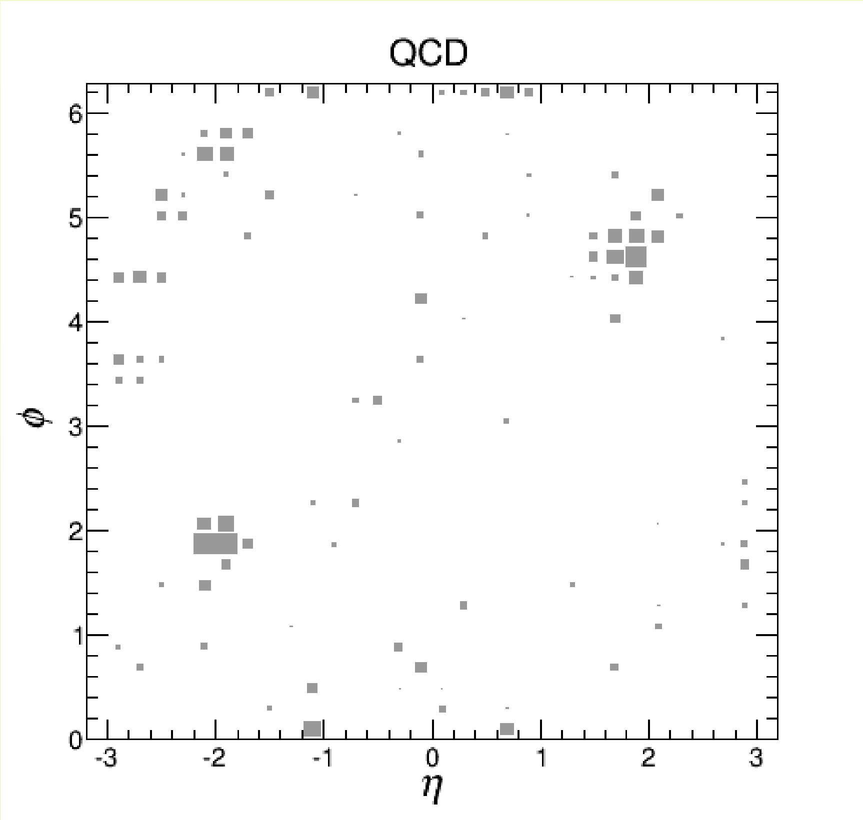
- QCD
  - Sherpa event generation and showering
  - $p\,p \rightarrow$ up to 6 partons
  - tree-level matrix elements, matched
  - 400 million events
- Signal
  - Madgraph/Pythia for event generation
  - Pythia for parton showering
  - 50 thousand events/mass point
- Analysis
  - Fastjet-3 for jet clustering
  - Simplified detector mockup

Skinny-Jets at colliders

- Jet clustering: anti-k_T algorithm
- Small radius (R=0.4)



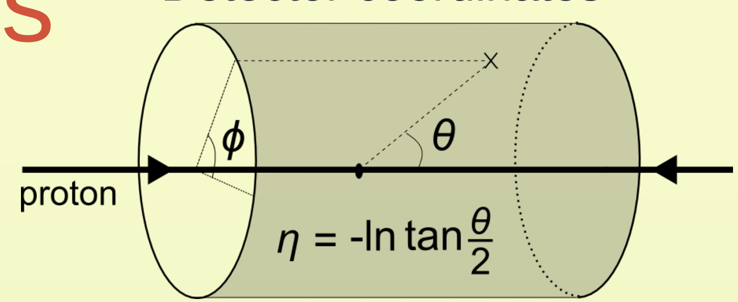


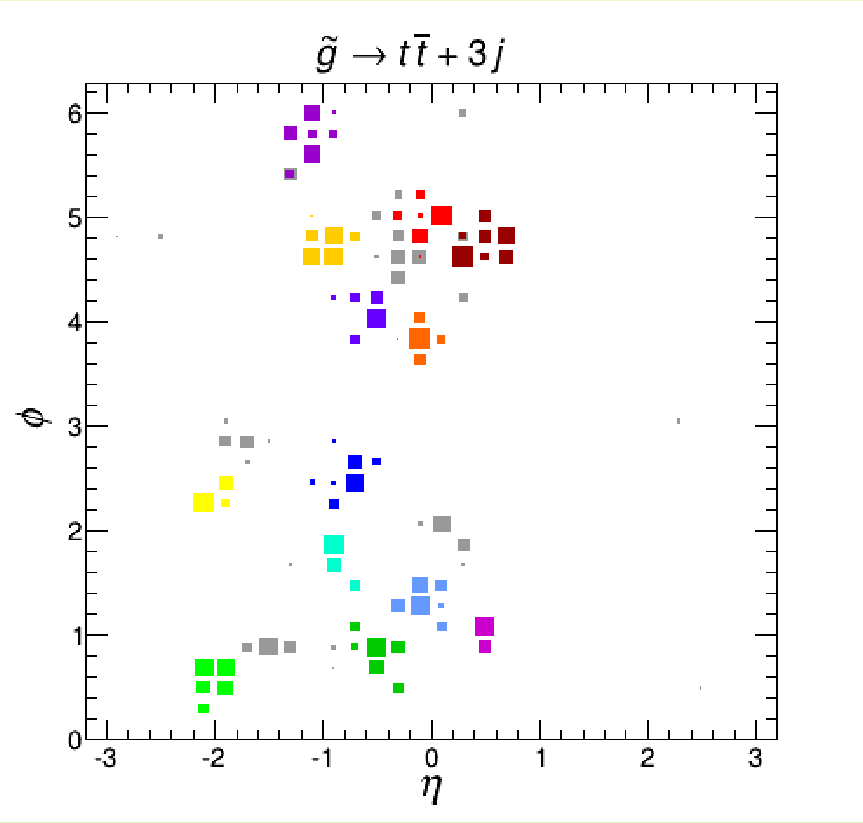


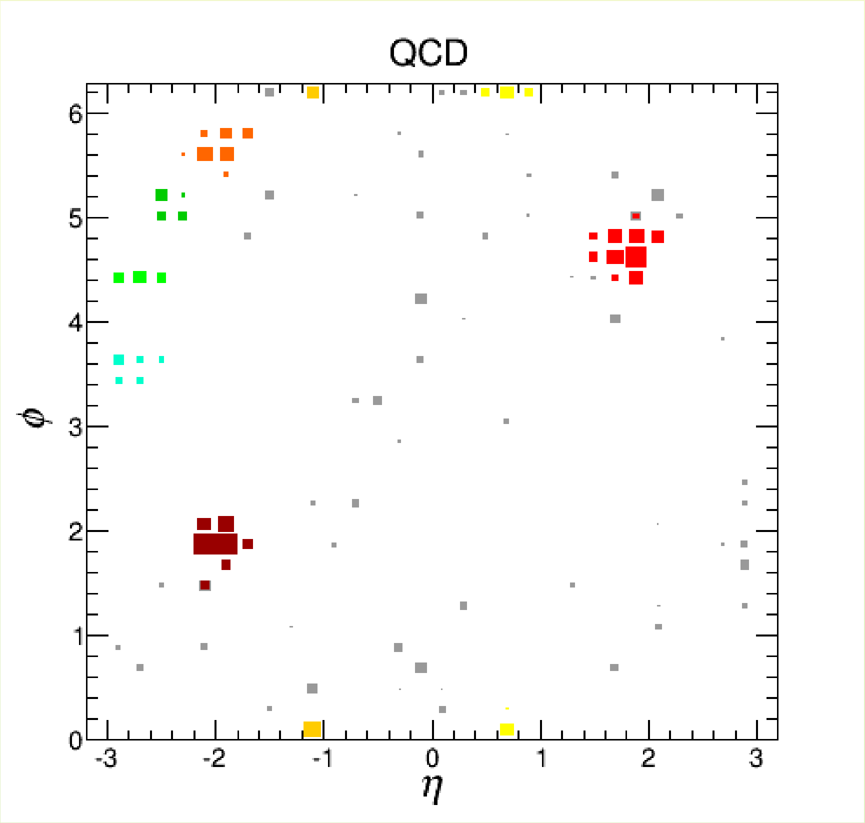
Skinny-Jets at colliders

- Jet clustering: anti-k_T algorithm
- Small radius (R=0.4)

Detector coordinates

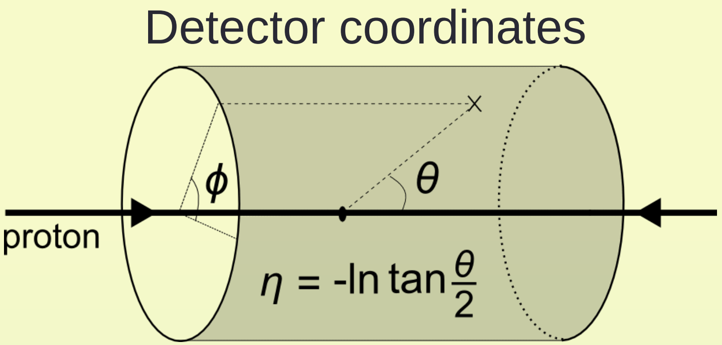


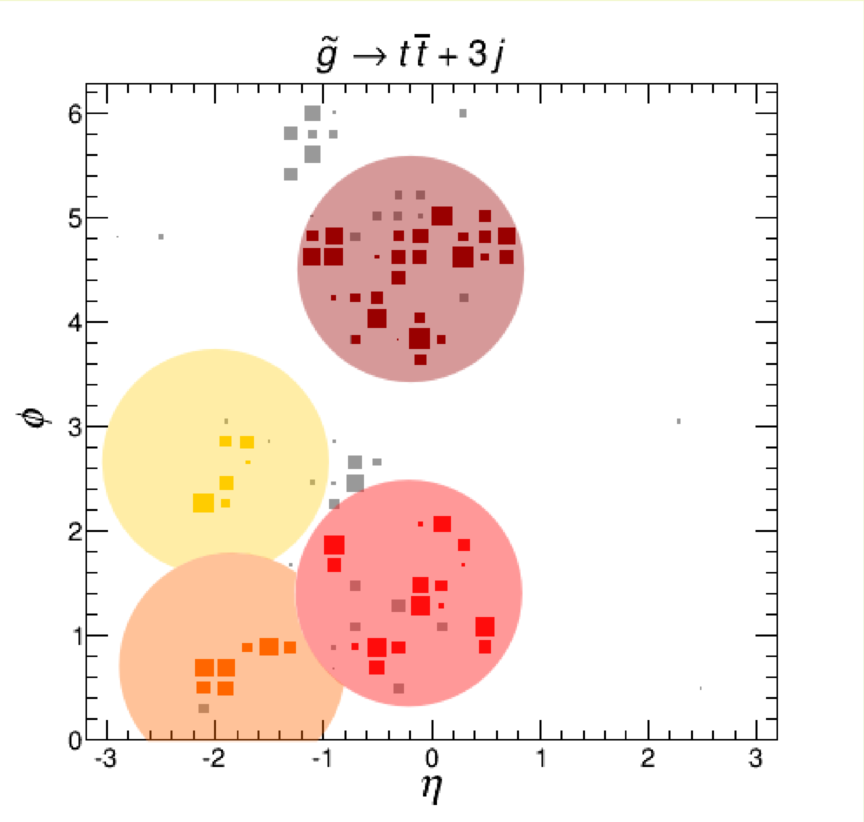


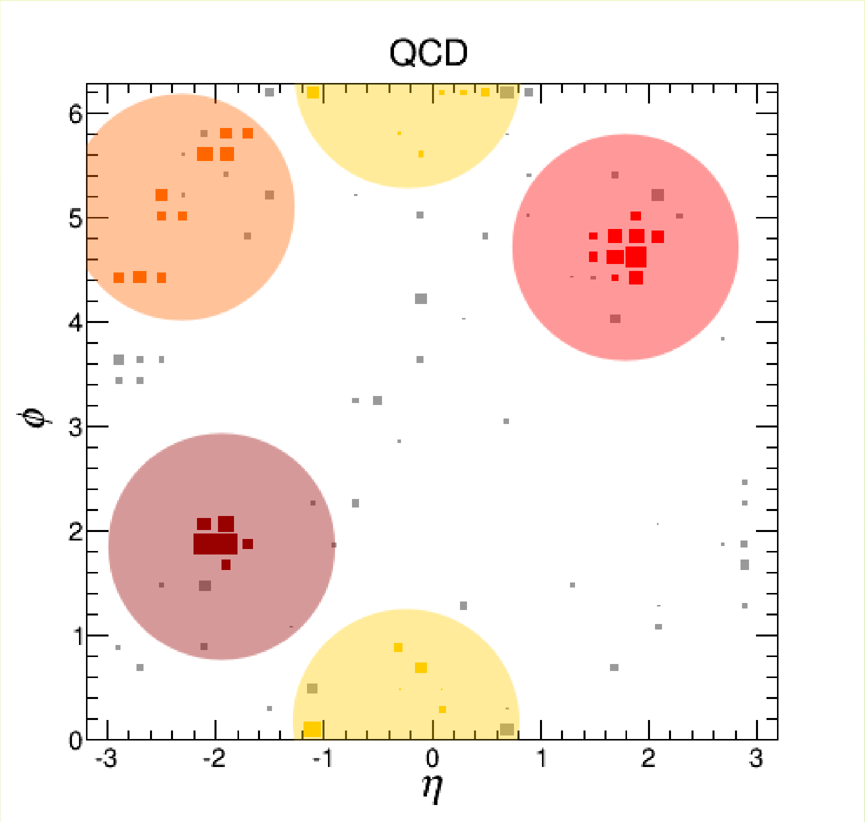


Fat-Jets at colliders

- Jet clustering: anti-k_T algorithm
- Big radius (R=1.2)







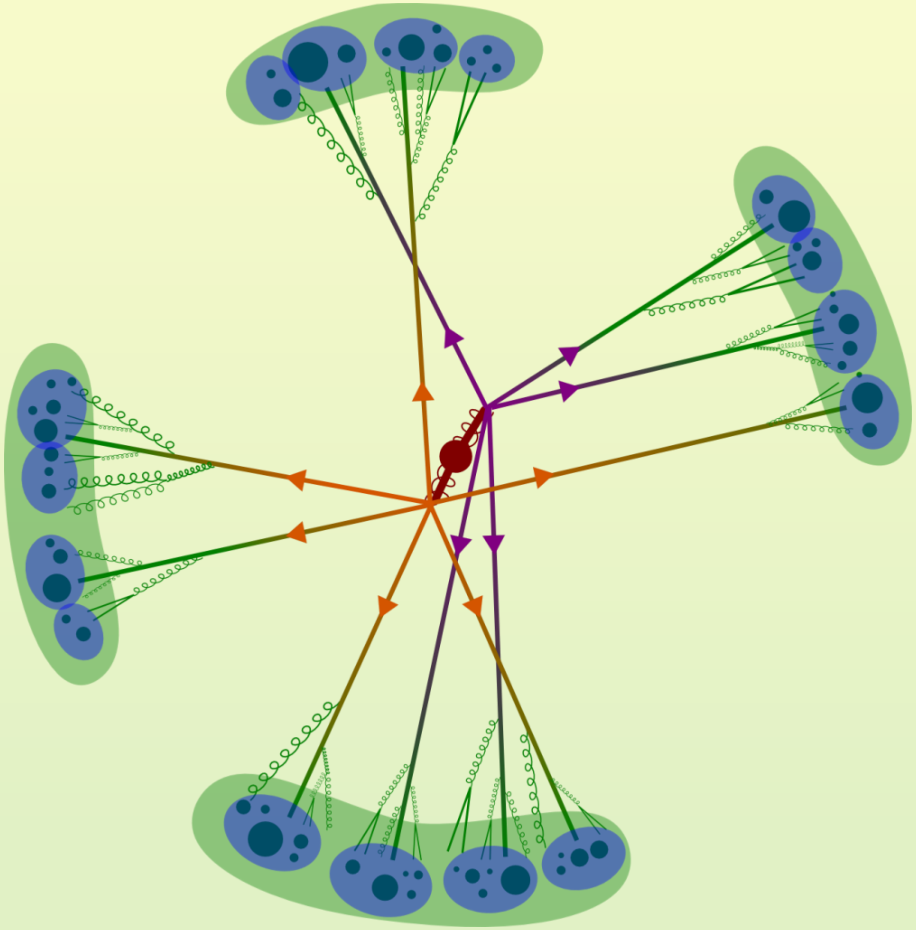
Accidental Substructure

- *N*-subjettiness, τ_{mn}
  (J. Thaler et al.)

- Event-subjettiness

$$T_{mn} = \left(\prod_{j=1}^{4} \tau_{mn,j} \right)^{\frac{1}{4}}$$

  - $T_{43} \ll 1$ for signal



Event with small T_{43}

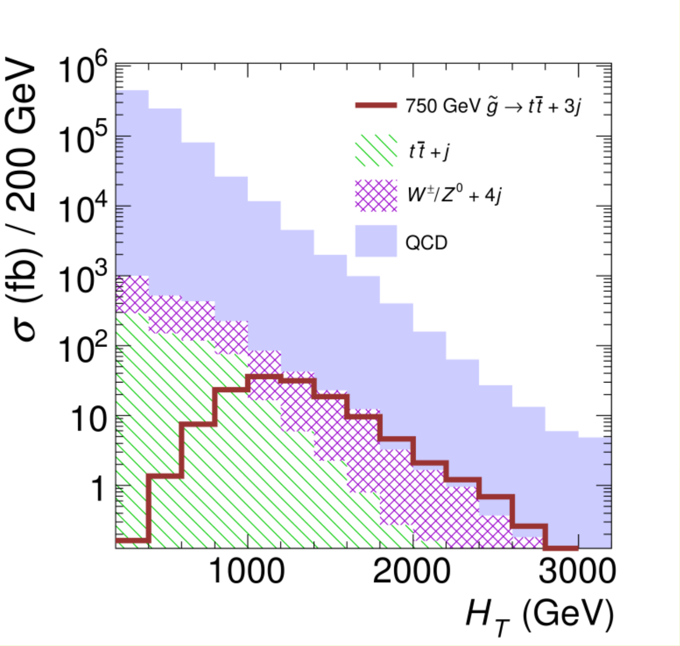
$\tilde{g} \to t\bar{t} + 3j$

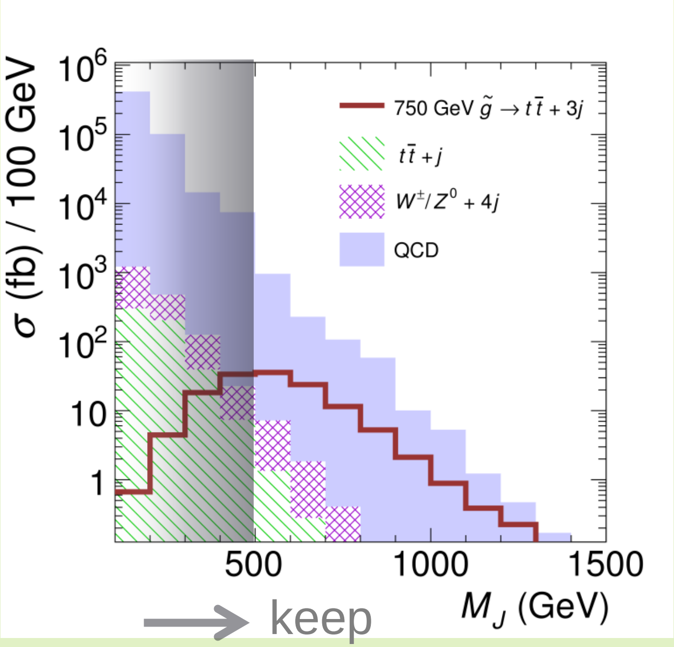
- Demand 4 jets > 50 GeV:
  - 1st jet > 100 GeV
  - trimmed with R_{sub} =0.3, $f_{cut} = 0.05$
- Jet mass:
  - QCD $m_j^2 \approx \alpha_s p_T^2 R^2$
  - Multijet new physics
    - $m_j^2 \approx p_T^2 R^2$
- Define Total Jet Mass

  (Hook et. al.)

$$M_J = \sum_{j=1}^{4} m_j$$

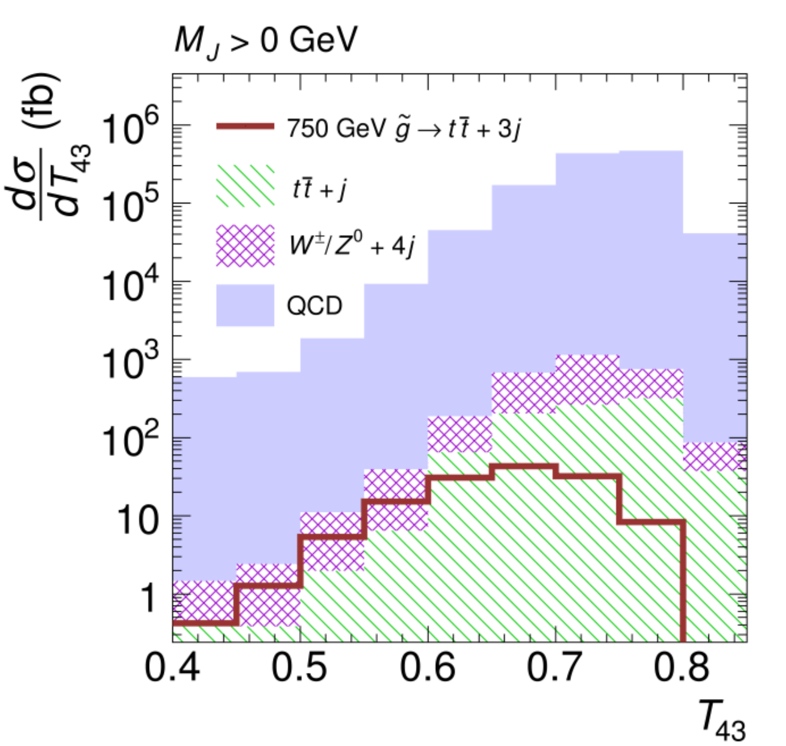
  - M_J > 500

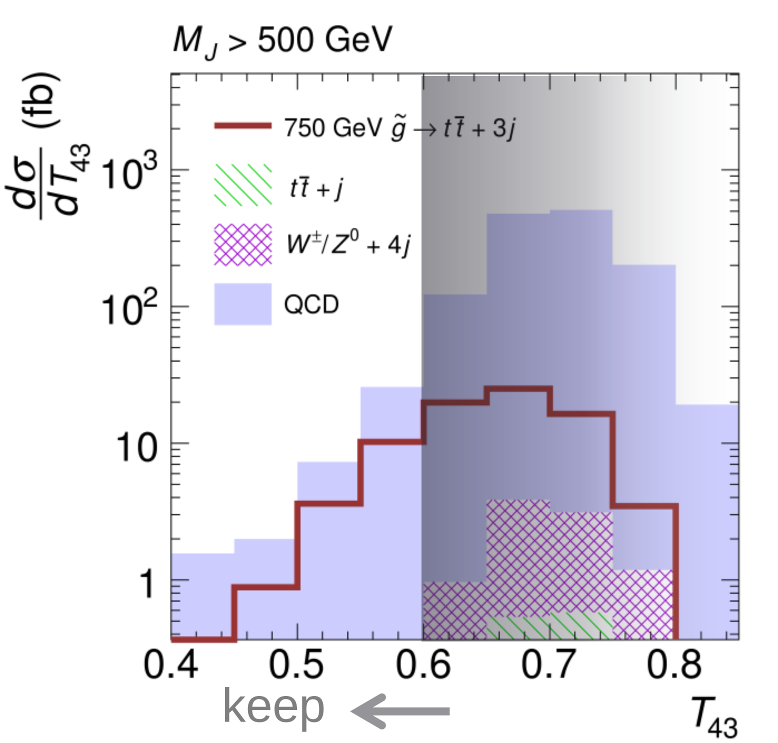




$\tilde{g} \to t\,\bar{t} + 3\,j$

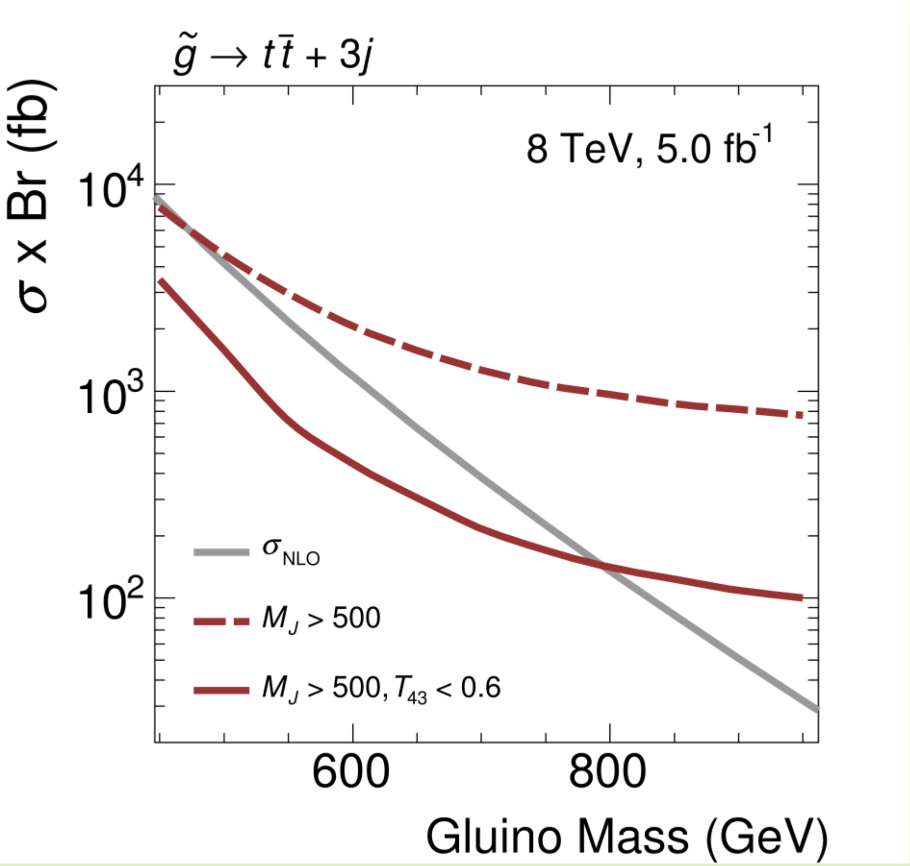
- Event-subjettiness: $T_{43} < 0.6$





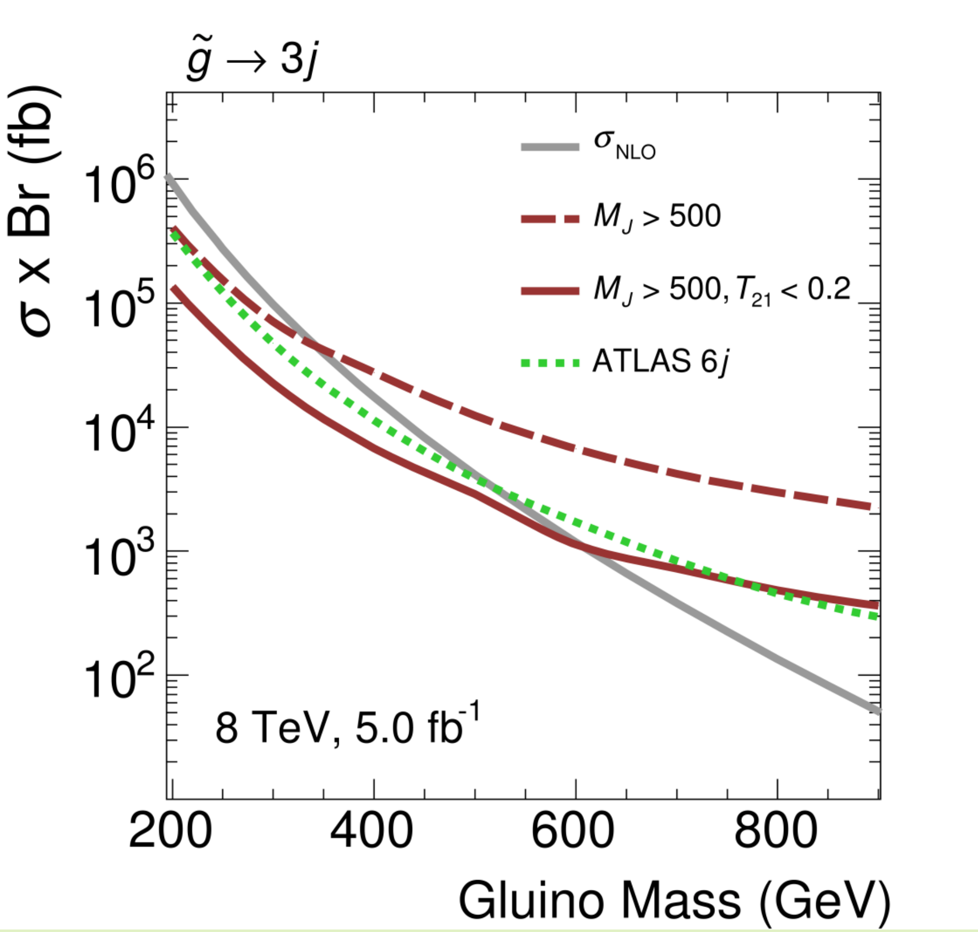
$\tilde{g} \to t\,\bar{t} + 3\,j$

- Event-subjettiness ($T_{43} < 0.6$) improves limits by 350 GeV



$\tilde{g} \to 3j$

- Same cut as before except $T_{21} < 0.2$
- Competitive with ATLAS's skinny-jet result (in green)
- Our method is viable and competitive



Conclusion

- New Physics could be hiding in Multijets
- Need for robust data-driven technique
- Accidental Substructure in Multijet
- Accidental Substructure is competitive with simple jet counting

Future directions

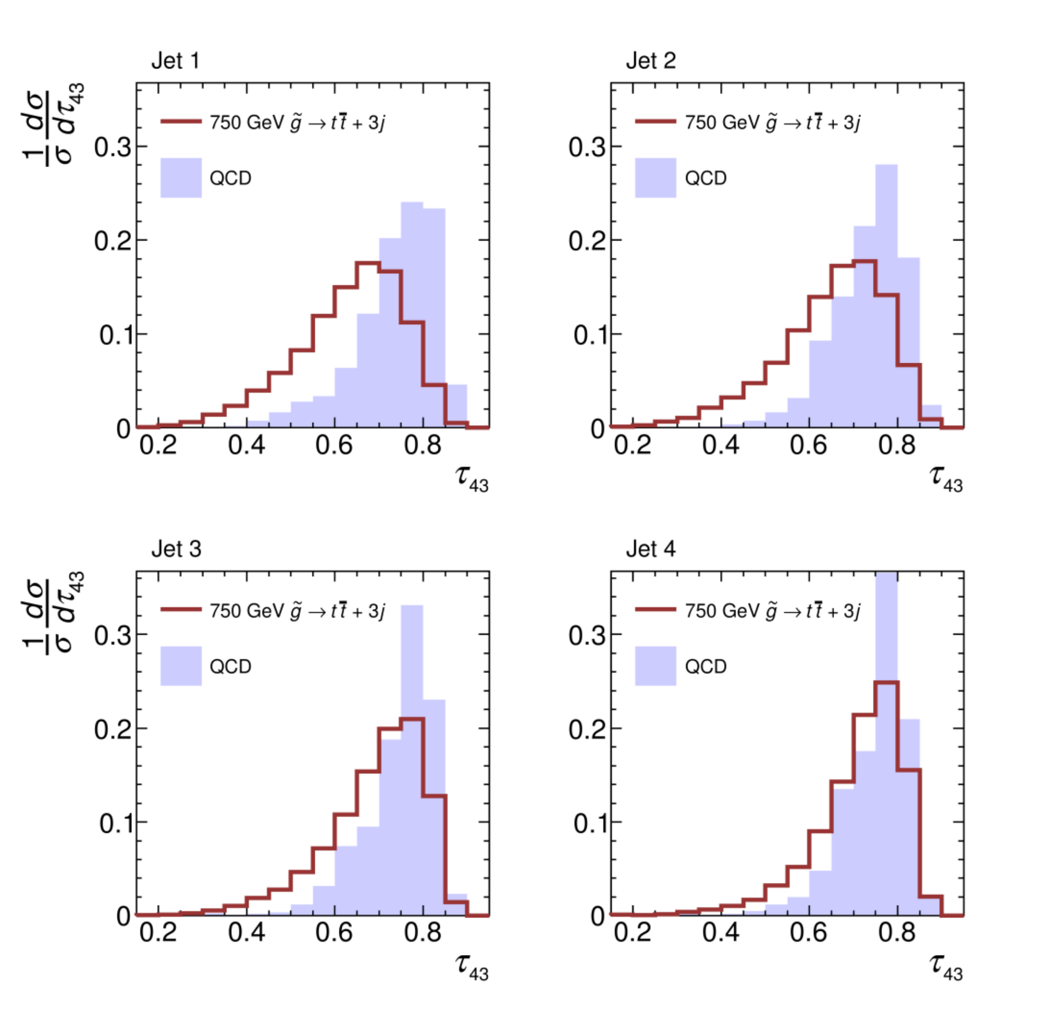
- Data-driven background
- Other substructure variables
  - Energy correlation? (Larkoski et. al.)
- Multivariate optimization
- Detector effects, underlying events and pileup

Thank You!

Questions?

Back up Slides

τ_{43} Plots



Jet 1
Jet 2
Jet 3
Jet 4
$\frac{1}{\sigma}\frac{d\sigma}{d\tau_{43}}$
750 GeV $\tilde{g} \to t\bar{t} + 3j$
QCD
τ_{43}
0
0.1
0.2
0.3
0.2
0.4
0.6
0.8

Data-Driven Substructure

- Build template densities $\rho(\tau_{21}, p_T)$ from dijet sample
- Obtain $p_{T,j}$ from MC, and τ_{21} from template densities assuming:
  - $\rho\left(\tau_{21,1},\ \tau_{21,2},\ \tau_{21,3},\ \tau_{21,4}\right) = \rho(\tau_{21,1}) \cdot \rho(\tau_{21,2}) \cdot \rho(\tau_{21,3}) \cdot \rho(\tau_{21,4})$

- If correlation between jets are small, we may be able to apply a perturbative expansion

- Potential problems:
  - Correlations may be large
  - How to parameterize quark vs. gluon mixture?
  - How to quantify systematics?

Exclusion statistics

- To compute the excluded cross-section:
  1. For a given set of cuts, and a given luminosity $\int L dt$ we obtain *B* and the sign cut efficiency $\epsilon_{\rm cut}$ from MC
  2. We compute the probability of observing at most *B* events given a background distribution around μ events

$$\text{Prob}(N \le B|\mu) = e^{\mu} \sum_{N=0}^{B} \frac{\mu^N}{N!}$$

  3. To take systematic uncertainty ($\epsilon_{\rm sys} = 20\%$) into account, we take the test statistics to be

$$\text{p-value} = \int_0^\infty dy \; \text{Prob}(N \le B|S_{\rm exc} + y) \frac{1}{y\sqrt{2\pi\epsilon_{\rm sys}}} \exp\left[-\frac{(\ln y - \ln B)^2}{2\epsilon_{\rm sys}}\right]$$

  4. For a given *B*, we solve for $S_{\rm exc}$ for p-value=0.05 (95% exclusion)

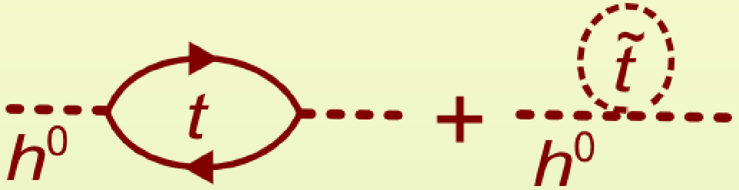
$$\sigma_{\rm exc} = \frac{S_{\rm exc}}{\epsilon_{\rm cut} \times \int L dt}$$

Jet clustering

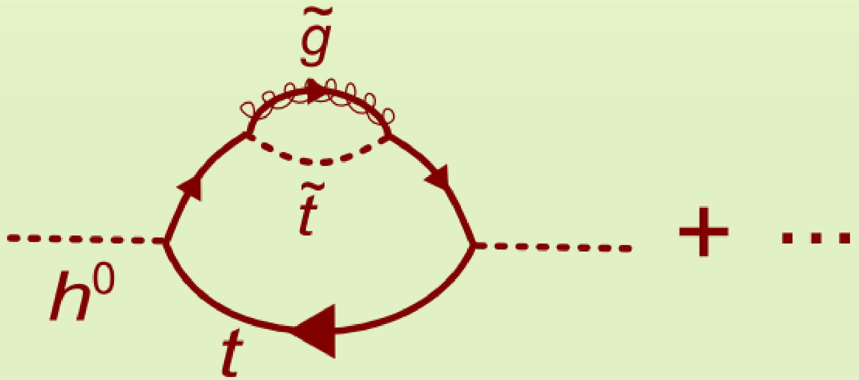
- Sequential clustering:
  - mesons and baryons are clustered into “pseudojet” sequentially
  - Algoirthm terminates and pseudojets are turned into jets
  - Controlled by two functions
    - d_{ij} the pseudojet-pseudojet distance for each pair of pseudojet
    - d_{iB} the pseudojet-beam distance for each pseudojet
- Algorithm
  1. Compute $\min\{d_{ij}, d_{iB}\}$
     a) If minimum is d_{ij}, cluster pseudojet ij, replace them by their sum
     b) If minimum is d_{iB}, promote pseuojet j to jet and remove it from clustering
  2. Repeat until no more pseudojets are jet
- anti-k_T algorithm: $d_{ij} = \min\{p_{T,i}^{-2}\ ,\ p_{T,j}^{-2}\}\frac{\Delta R_{ij}^2}{R^2}$ and $d_{iB} = p_{T,i}^{-2}$

Natural SUSY

- Higgs mass fine-tuning comes from quadratic divergences from stop (Papucci et al.)



- Fine tuning $\Delta \sim |\delta m_h^2|/m_h^2$
- Constrains stop mass
- Gluino correction comes in two loop level



N-subjettiness

- First we define (first considered by Thaler et. al.)

$$\tau_n = \frac{1}{d} \sum_{i \in \text{jet}} p_{T,i}^2 \min_{n\text{-axes}} \{\Delta R_{i1}^2, \cdots, \Delta R_{in}^2\} \quad d = \sum_{i \in \text{jet}} p_{T,i}^2$$

  - Summation is over the constituents of a jet
  - Minimization done over all choices of *n*-axes, τ_n computes a jet's deviation from having exactly *n*-constituents

- Then define $\tau_{mn} := \tau_m / \tau_n$
  - a jet with *m*-subjet will have small τ_m
  - a jet with more than *n*-subjet will have $\tau_n \approx 1$
  - for example a small τ_{43} indicates that a jet likely has 4 subjets