

# The Case for Jet Substructure

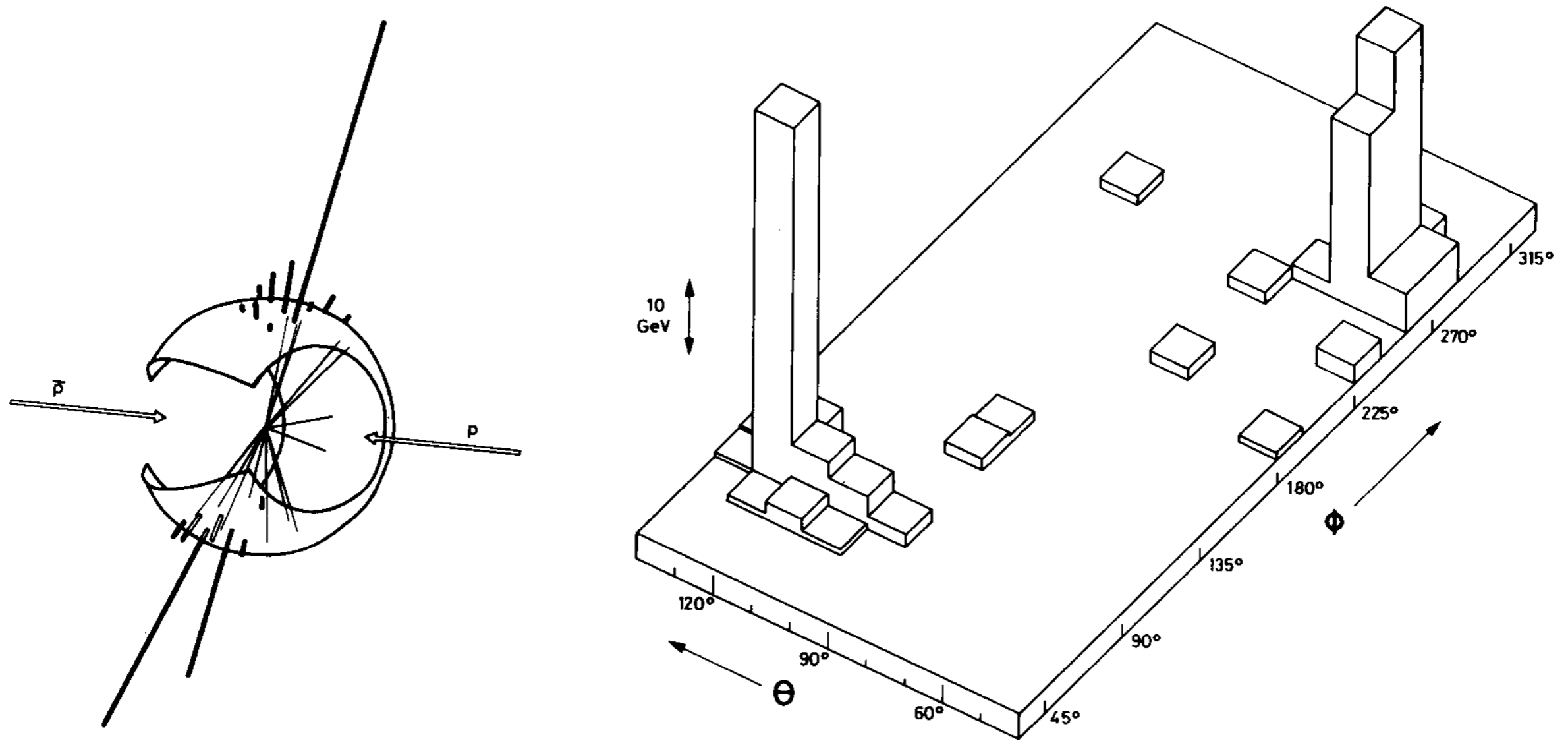
Jesse Thaler



LCWS 2014, Belgrade — October 6-10, 2014

# UA2 Jet Production

1982

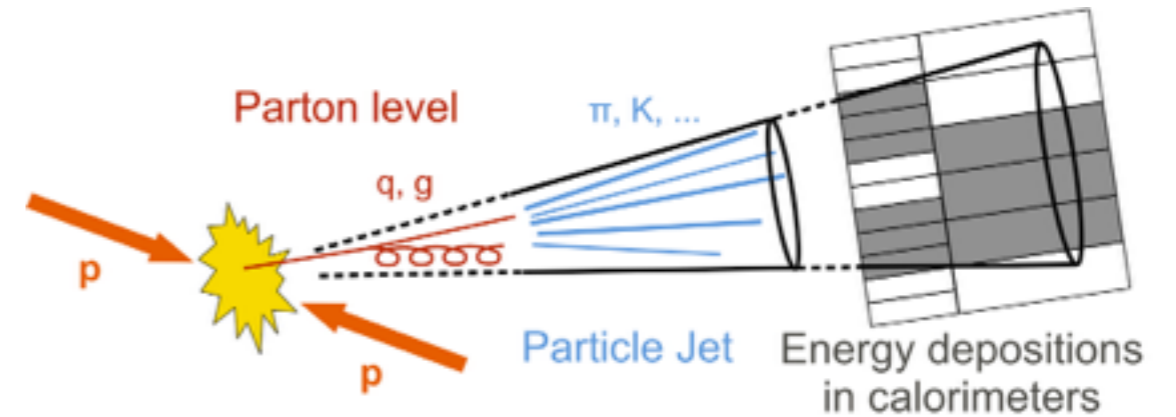


*Almost 40 years of jet physics!*

[see also SPEAR, 1975; PETRA, 1979]

# A QCD Renaissance!

c. 2008–present

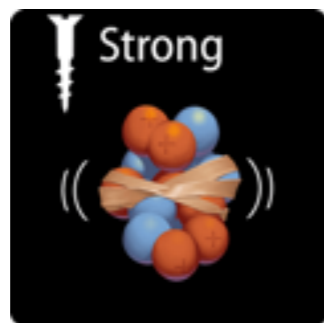


**LHC** (vs. *Tevatron*)

Higher Energy ( $\approx \times 3.5-7$ )

Higher Luminosity ( $\approx \times 10-20$ )

**Finer Segmentation** ( $\approx \times 5$ )



## Theoretical Progress

New Jet Algorithms (esp. anti- $k_T$ )

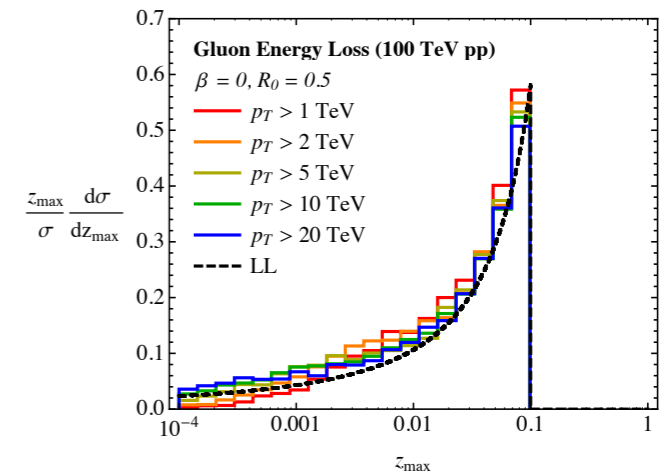
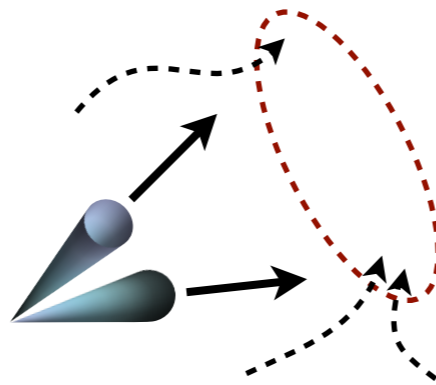
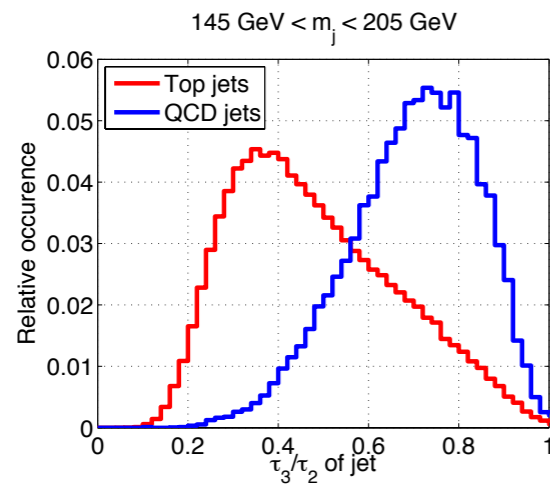
Loop/Leg/Log Explosion

**Jet Substructure**

[Anti- $k_T$ : Cacciari, Salam, Soyez, 2008]

[BDRS: Butterworth, Davison, Rubin, Salam, 2008; see also Seymour, 1991, 1994]

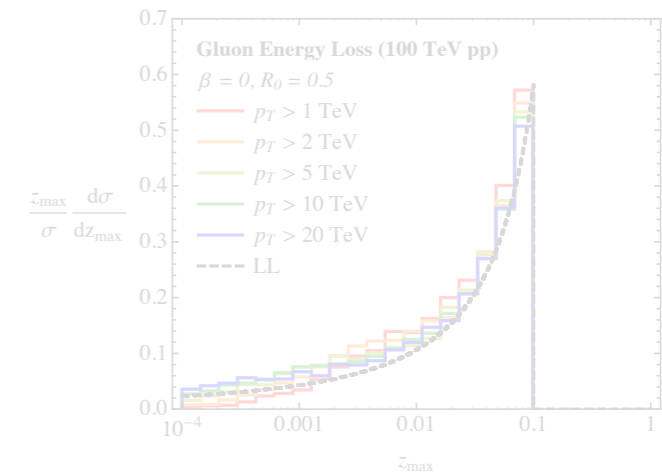
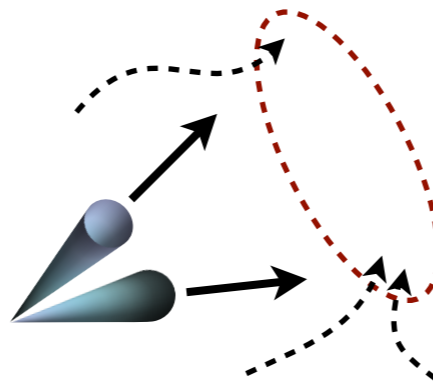
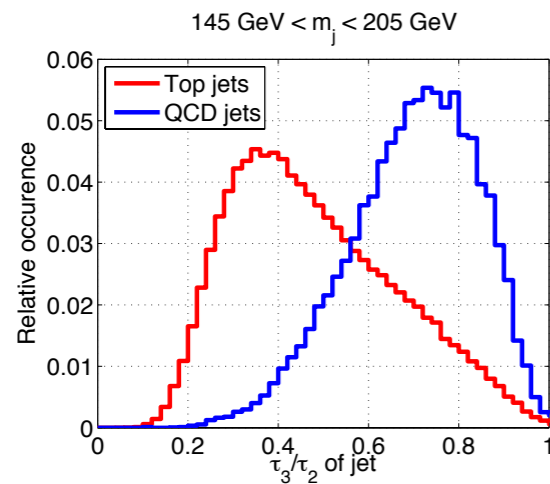
# The Case for Jet Substructure



Maximize discovery potential of LHC

Enhance understanding of QCD

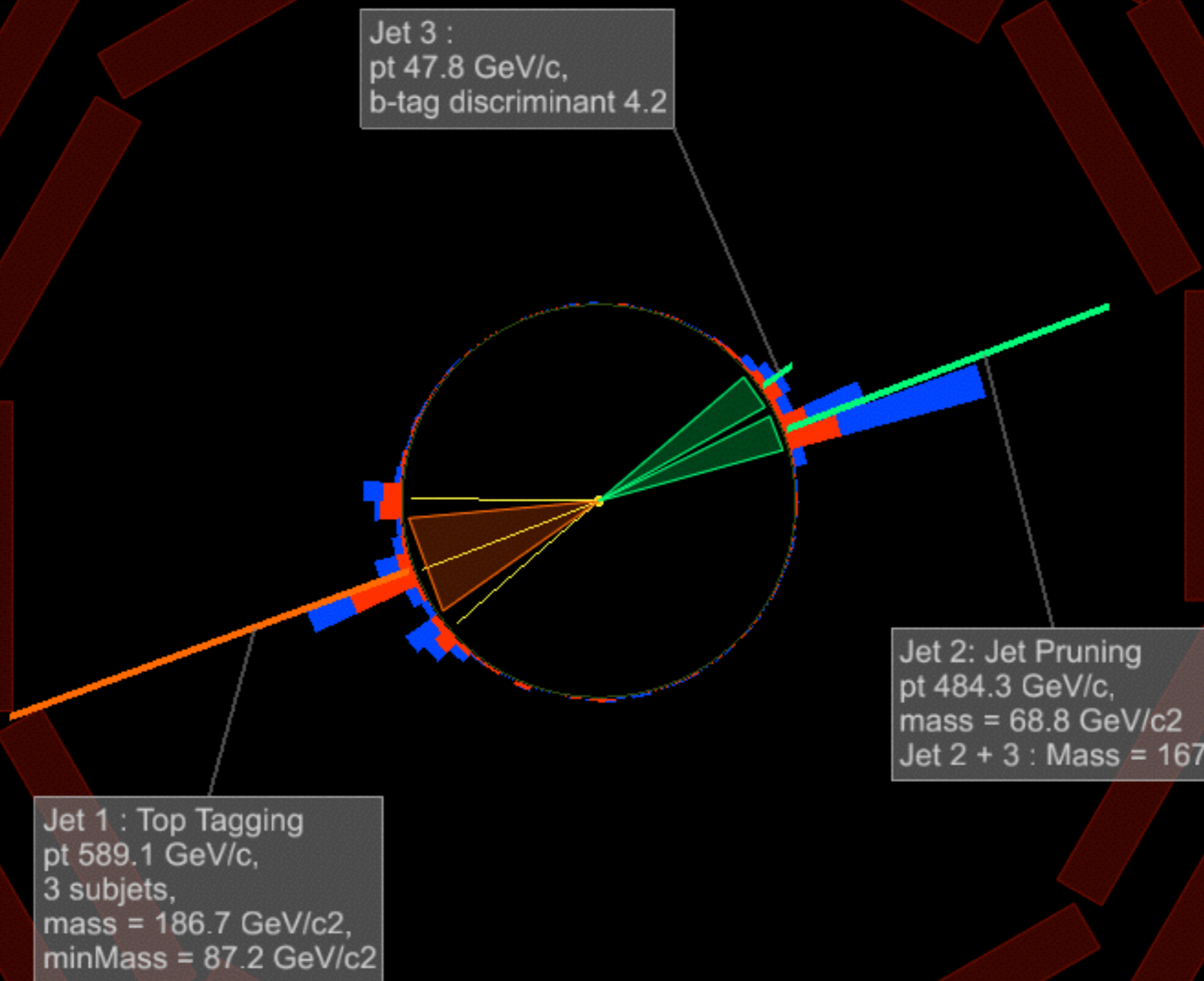
*What does this have to do  
with future lepton colliders?*



# Maximize discovery potential of LHC

## Enhance understanding of QCD

# Jets or Jet Substructure?



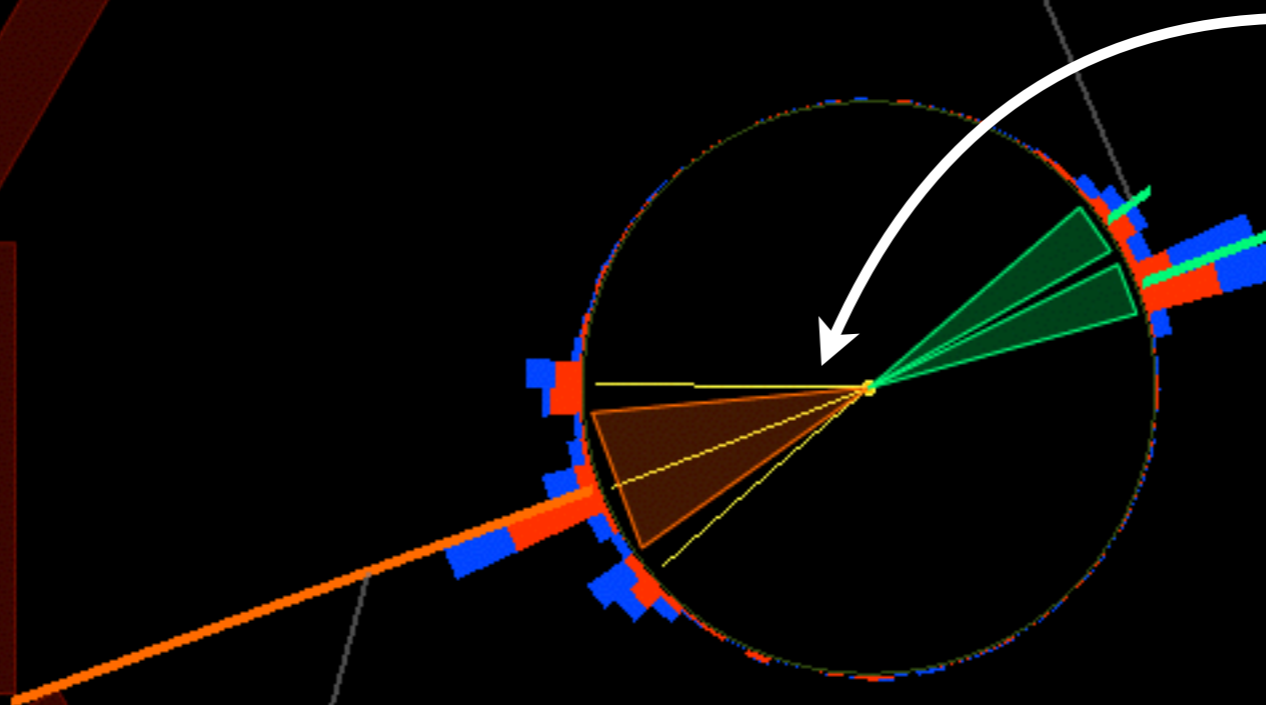
[CMS EXO-11-006, CMS JME-13-007]

[Using JHU/CMSTopTagger: Kaplan, Rehermann, Schwartz, Tweedie, 0806.0848]

[Using Pruning: Ellis, Vermilion, Walsh, 0903.5081]

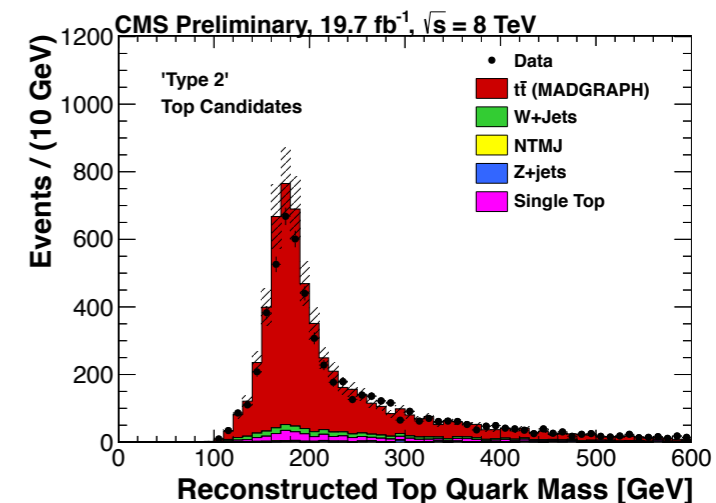
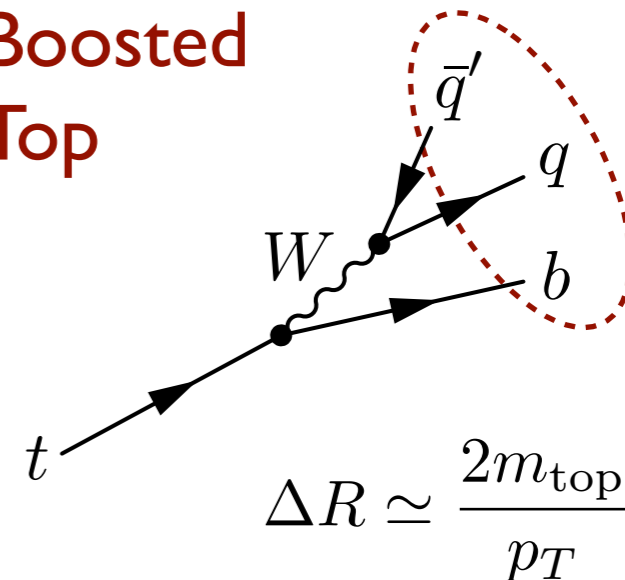
# Jets or Jet Substructure?

Jet 3 :  
pt 47.8 GeV/c,  
b-tag discriminant 4.2



Jet 1 : Top Tagging  
pt 589.1 GeV/c,  
3 subjets,  
mass = 186.7 GeV/c<sup>2</sup>,  
minMass = 87.2 GeV/c<sup>2</sup>

Boosted  
Top

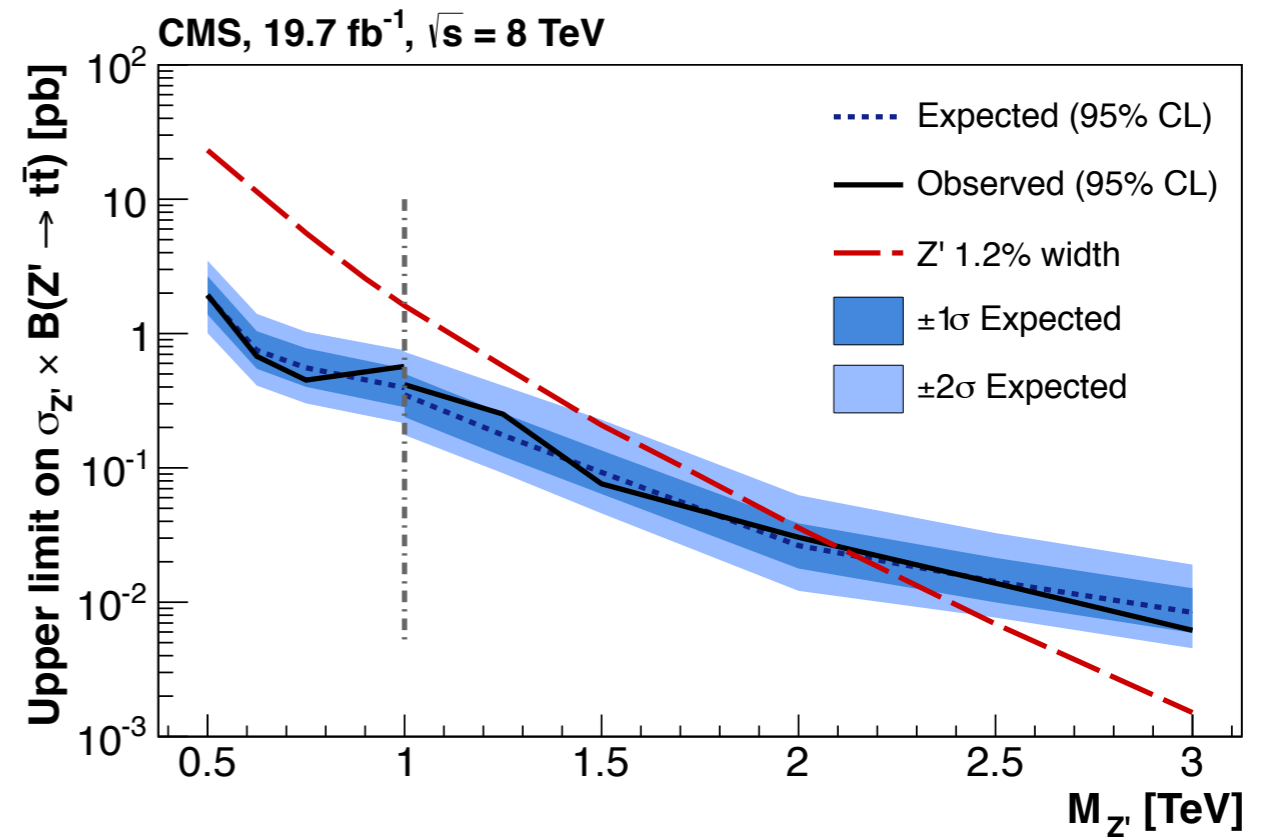
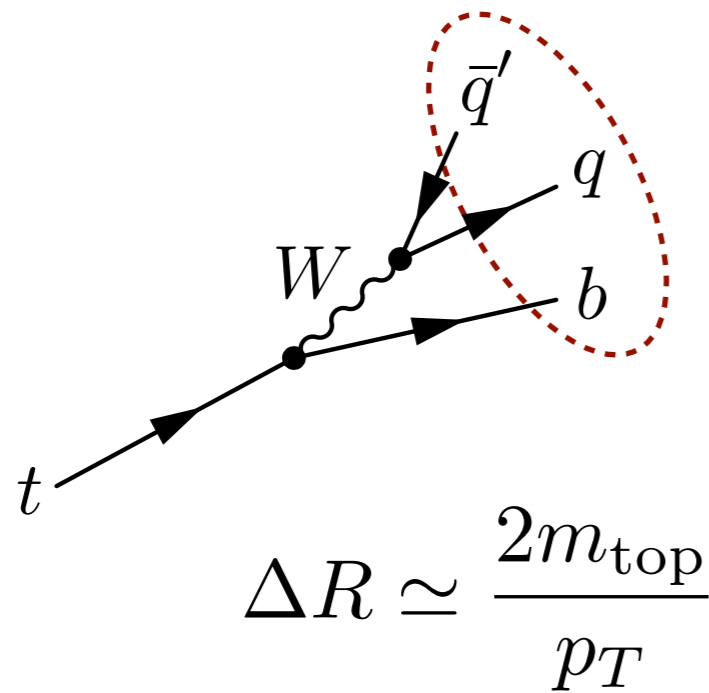
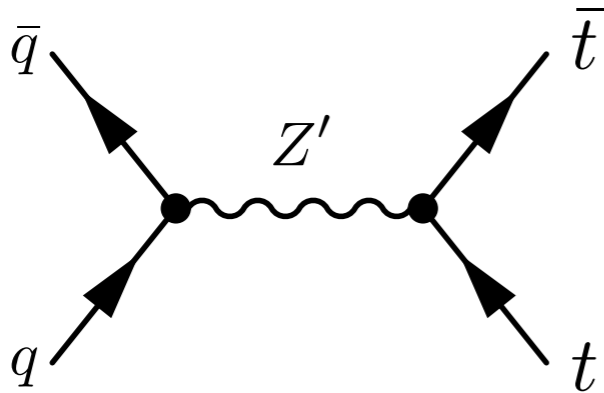


[CMS EXO-11-006, CMS JME-13-007]

[Using JHU/CMSTopTagger: Kaplan, Rehermann, Schwartz, Tweedie, 0806.0848]

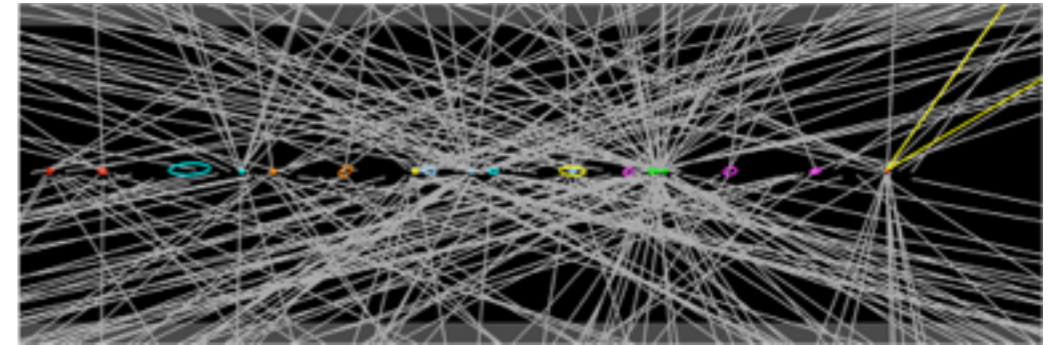
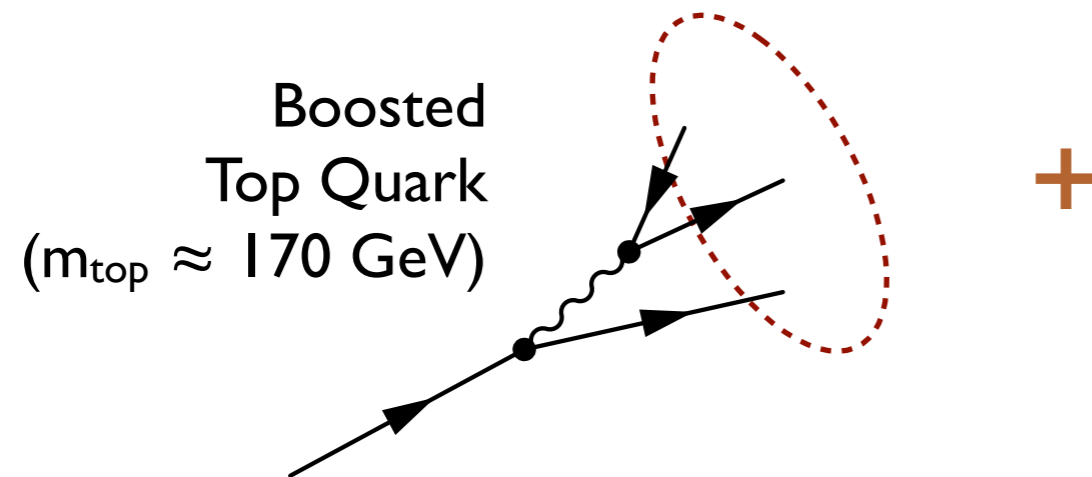
[Using Pruning: Ellis, Vermilion, Walsh, 0903.5081]

# High Energy: Boosted Regime is Inevitable

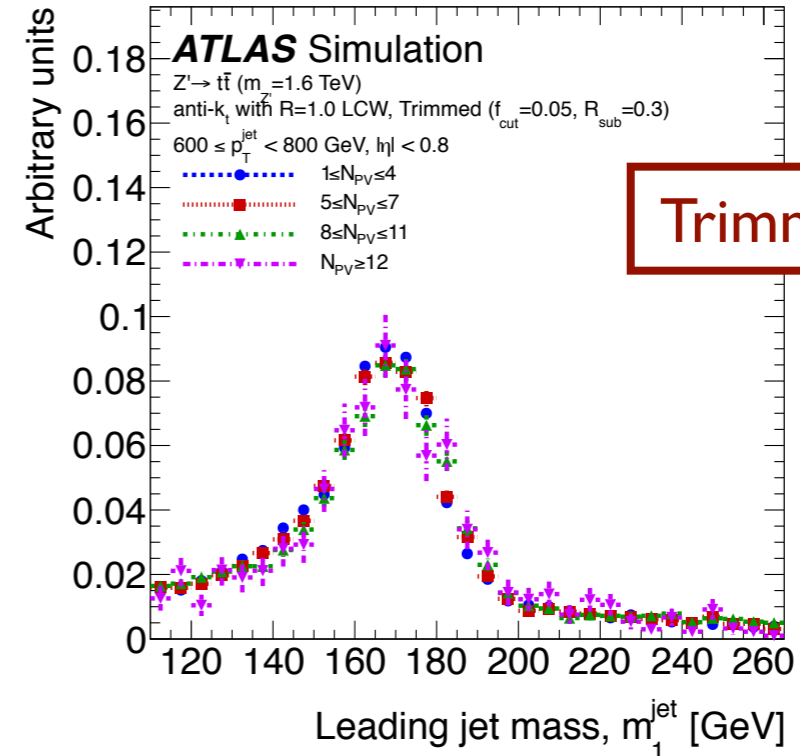
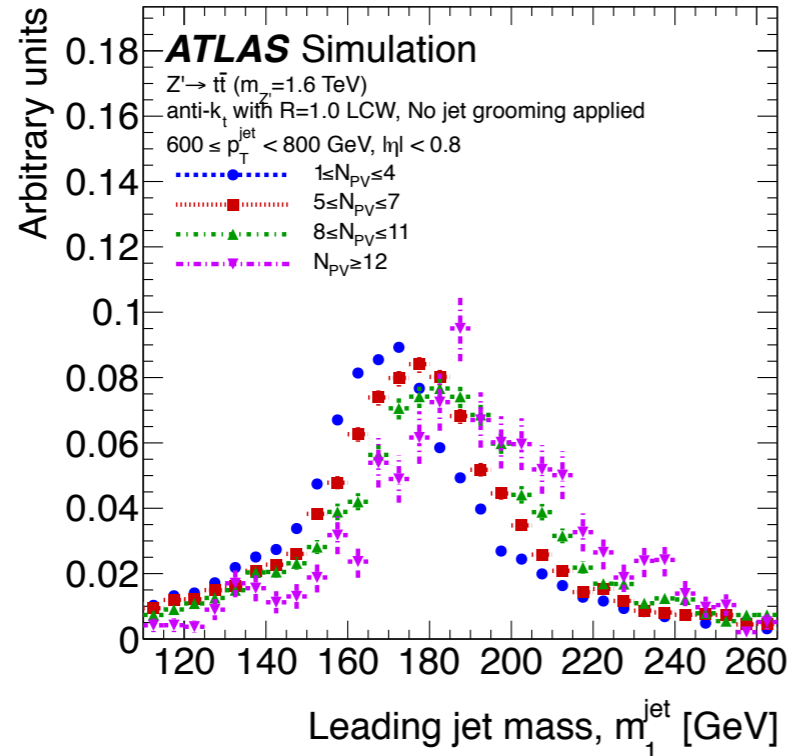


[CMS B2G-13-001]

# High Luminosity: Pileup is Inevitable



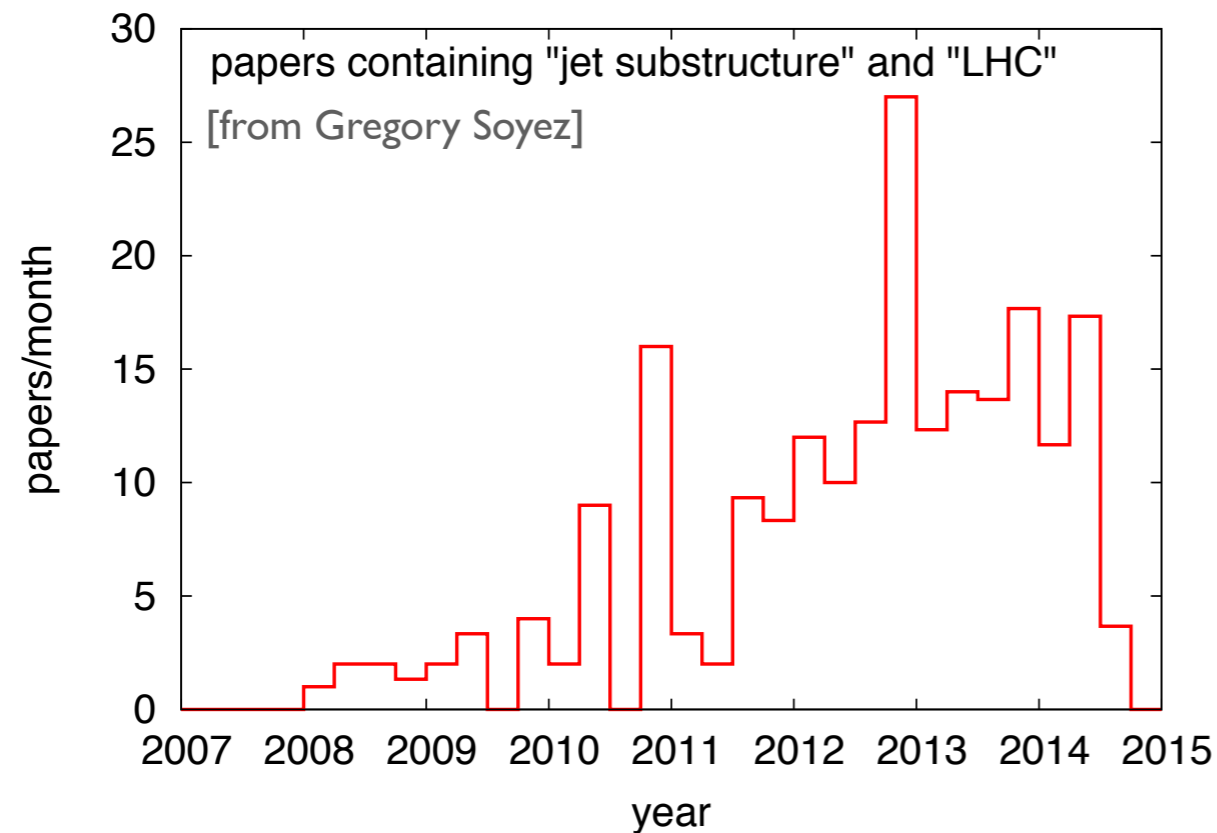
Secondary Collision Debris



Trimming

[ATLAS PERF-2012-02]  
 [Krohn, JDT, Wang, 0912.1342]

# High Stakes: Cleverness is Inevitable



Mass Drop,  $p_T$  Balance, Y-splitter, Filtering, Trimming, Pruning, Soft Drop, **Angularities**, Planar Flow, **N-subjettiness**, Angular Structure Functions, Jet Charge, Jet Pull, Energy Correlation Functions, Dipolarity,  $p_T^D$ , Zernike Coefficients, Fox-Wolfram Moments, JHU/CMSTopTagger, HEPTopTagger, Template Method, Shower Deconstruction, Jets Without Jets, Subjet Counting, Wavelets, Q-Jets, Telescoping Jets, Jet Reclustering, etc.

## Core Principles of Jet Substructure:

**Prong-like Behavior**  
**Radiation Patterns**  
**Flavor Tagging**  
(& Pileup Mitigation)

$$t \rightarrow bW$$

$$H \rightarrow b\bar{b}$$

$$Z \rightarrow q\bar{q}$$

$$W \rightarrow q\bar{q}'$$

$b$

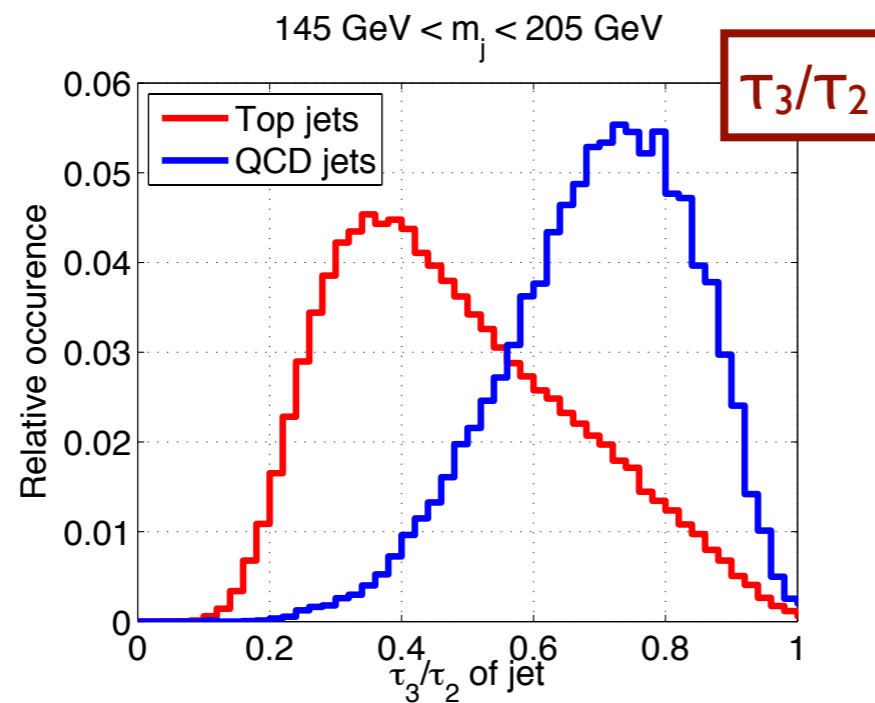
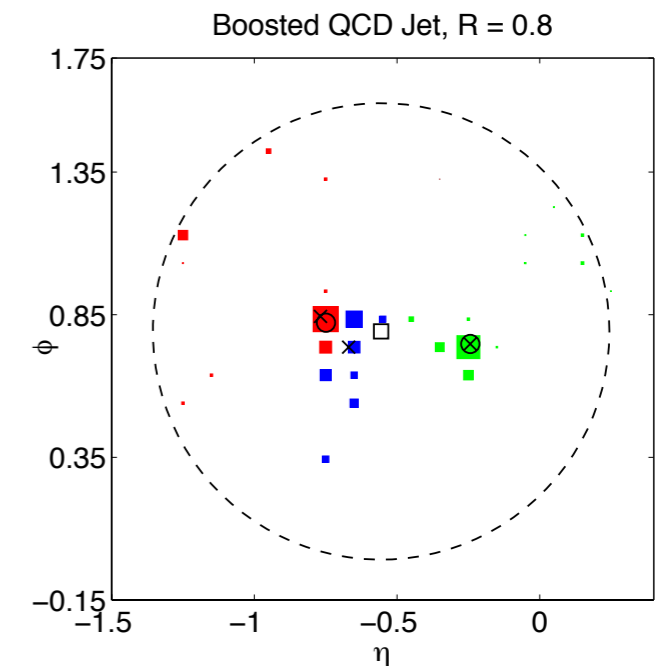
$c$

$s$

$d$

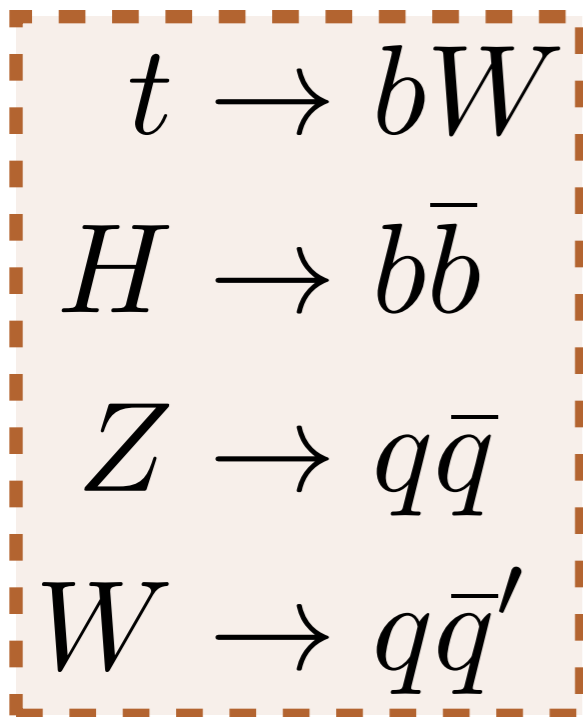
$u$

$g$

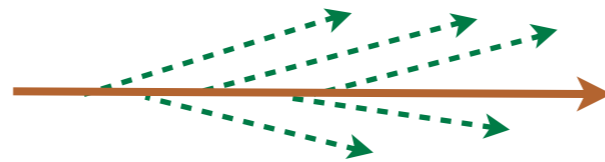
$$\left. \begin{array}{l} t \rightarrow bW \\ H \rightarrow b\bar{b} \\ Z \rightarrow q\bar{q} \\ W \rightarrow q\bar{q}' \end{array} \right\} \tau_3/\tau_2$$

$$\tau_N = \sum_k p_{T,k} \min \{ \Delta R_{k,1}, \dots, \Delta R_{k,N} \}^\beta$$

(transverse)  
momentum
distance to subjet core

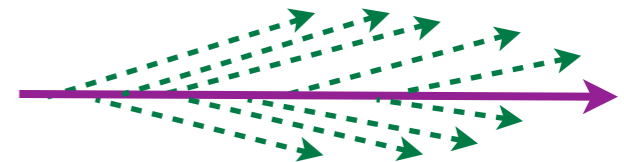
[See also N-jettiness: Stewart, Tackmann, Waalewijn, 1004.2489]



# Quark-like vs. Gluon-like

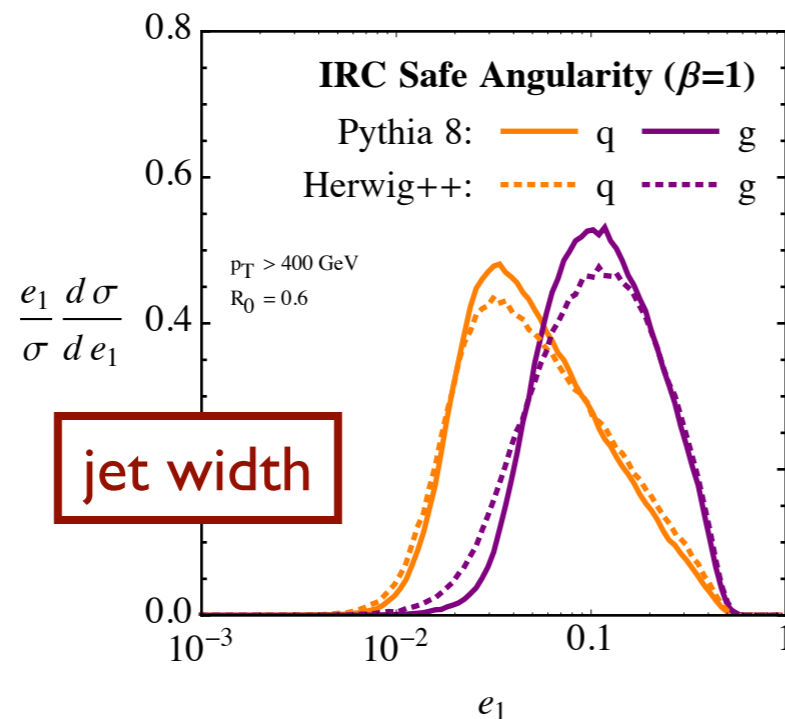


$$C_F = 4/3$$



$$C_A = 3$$

- $b$
- $c$
- $s$
- $d$
- $u$
- $g$



## e.g. Angularities:

(a.k.a. l-subjettiness)

$$e_\beta \simeq \sum_{i \in \text{jet}} z_i (\theta_i)^\beta$$

energy fraction      angle to axis

[Berger, Kucs, Sterman, 2003; Ellis, Vermilion, Walsh, Hornig, Lee, 2010]  
[Recoil-free Versions: Larkoski, Salam, JDT, 1305.0007; Larkoski, Neill, JDT, 2014]

# (Sub)jet B-tagging

$$t \rightarrow bW$$

$$H \rightarrow b\bar{b}$$

$$Z \rightarrow q\bar{q}$$

$$W \rightarrow q\bar{q}'$$

$b$

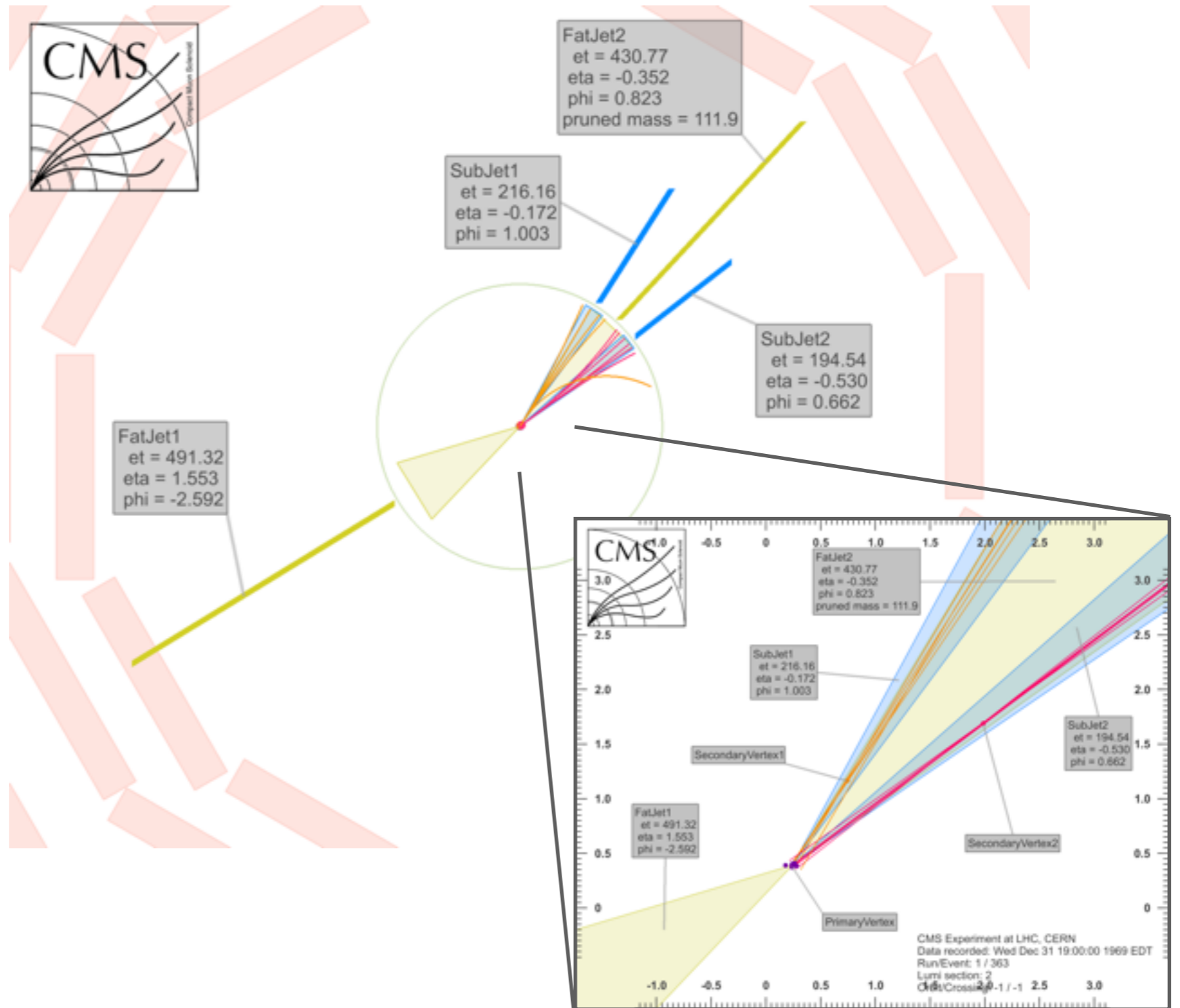
$c$

$s$

$d$

$u$

$g$

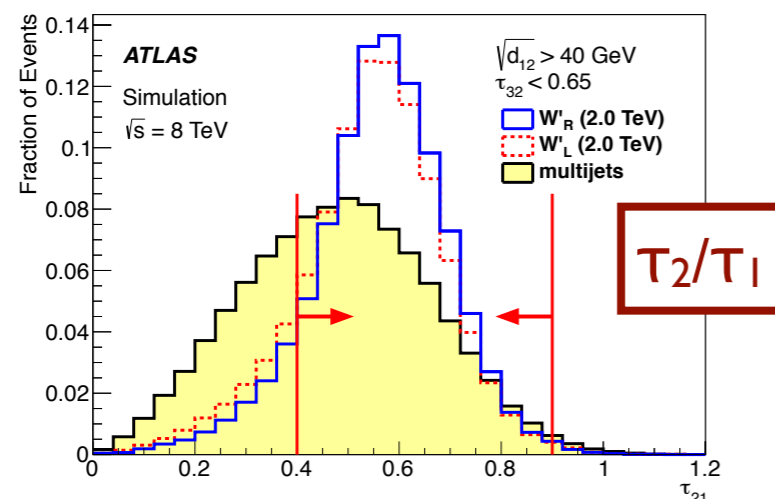
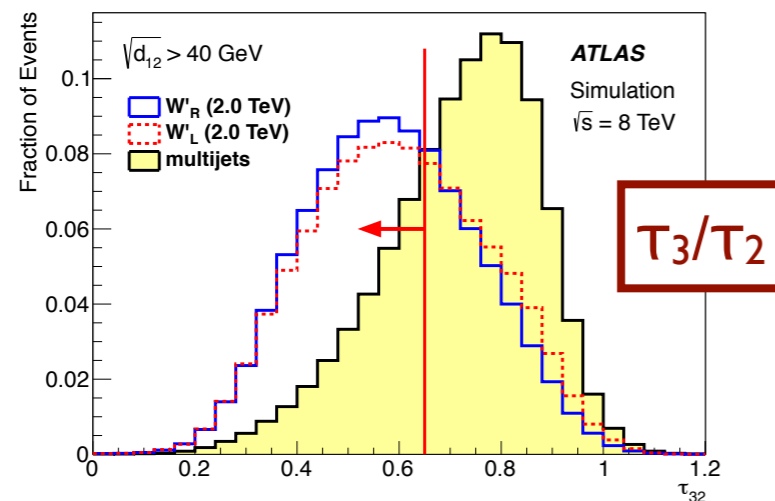
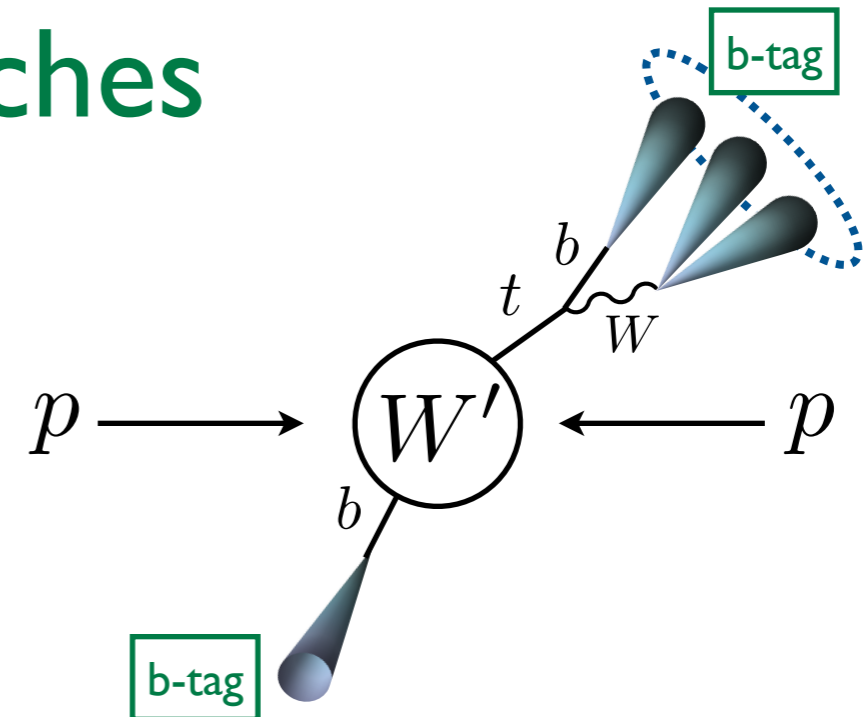


[CMS BTv-13-001]

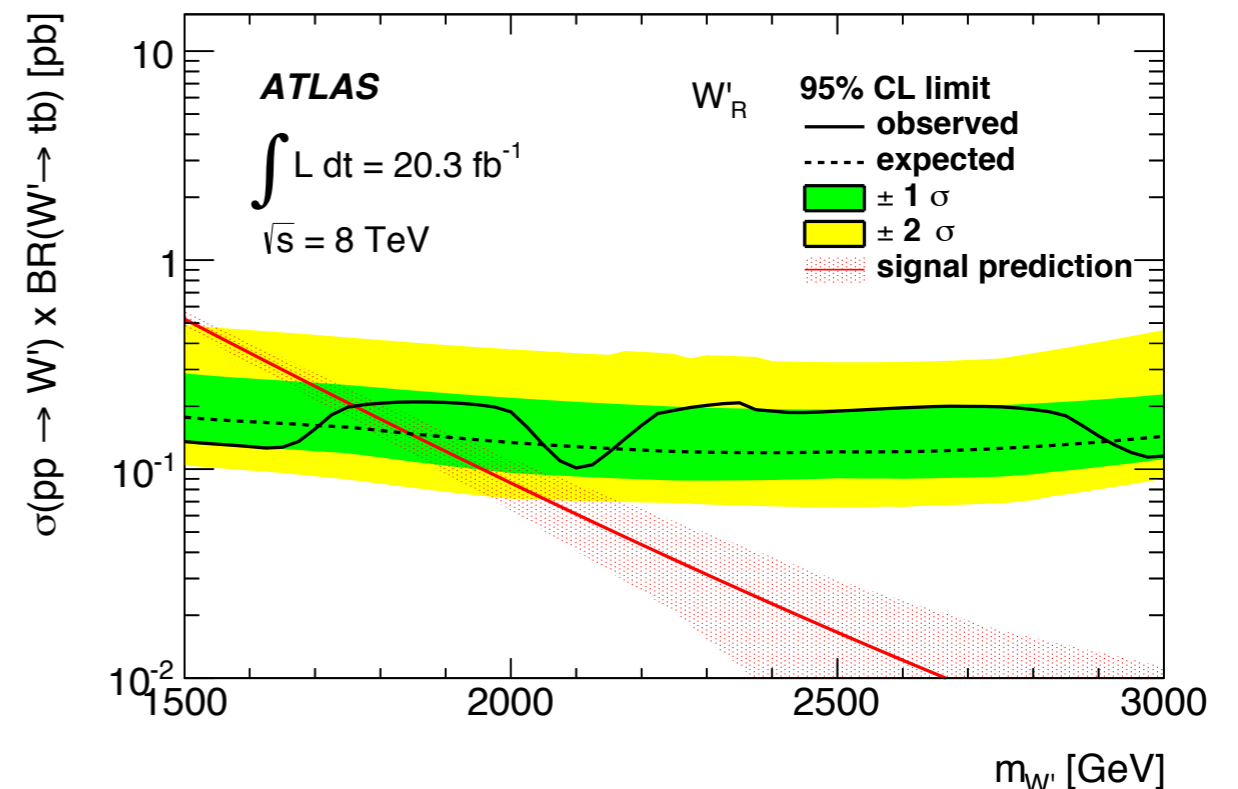
# Boon for New Physics Searches

e.g. Heavy  $W'$  Search

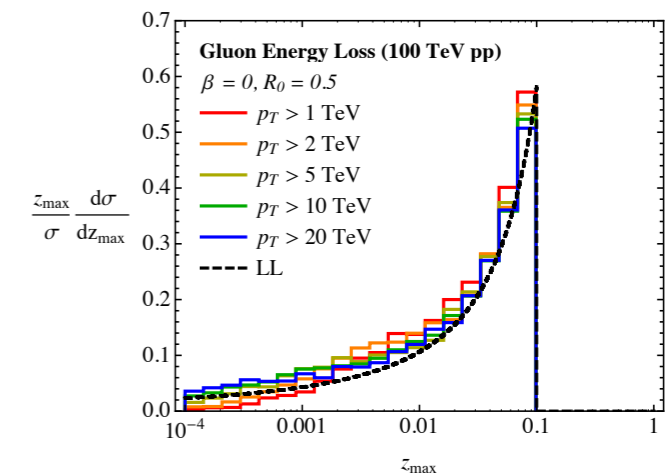
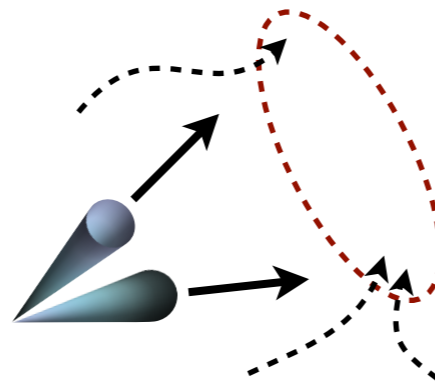
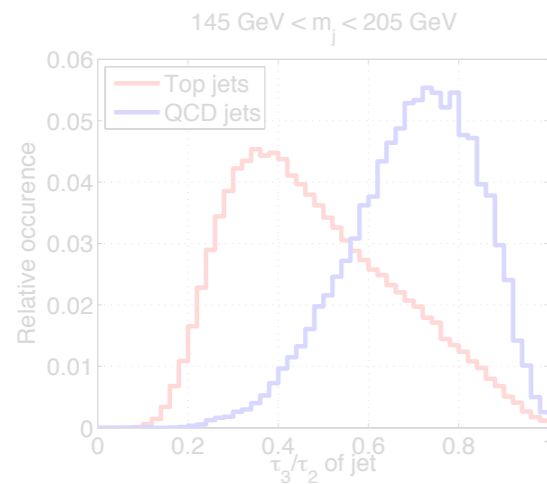
Trimming + B-tagging +  
 $k_T$  Splitting + N-subjettiness



$$W' \rightarrow t\bar{b} \rightarrow Wb\bar{b} \rightarrow q\bar{q}'b\bar{b}$$



[ATLAS, 1408.0886]

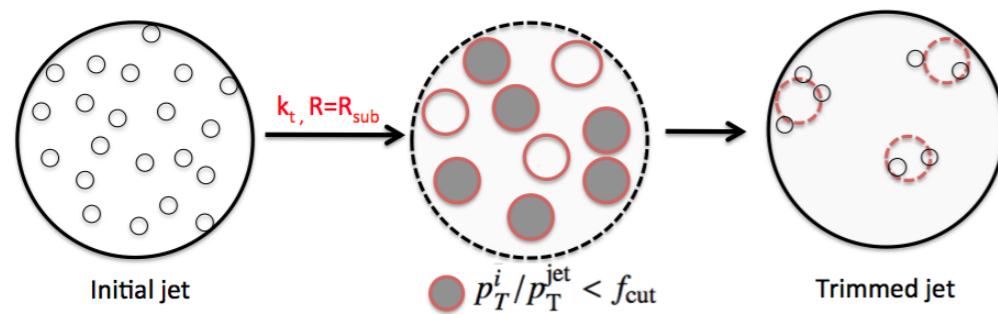


Maximize discovery potential of LHC

Enhance understanding of QCD

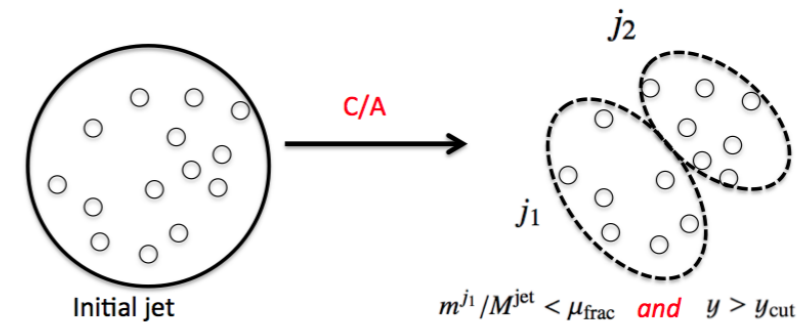
# Techniques Inspire Analytics...

## Jet Trimming



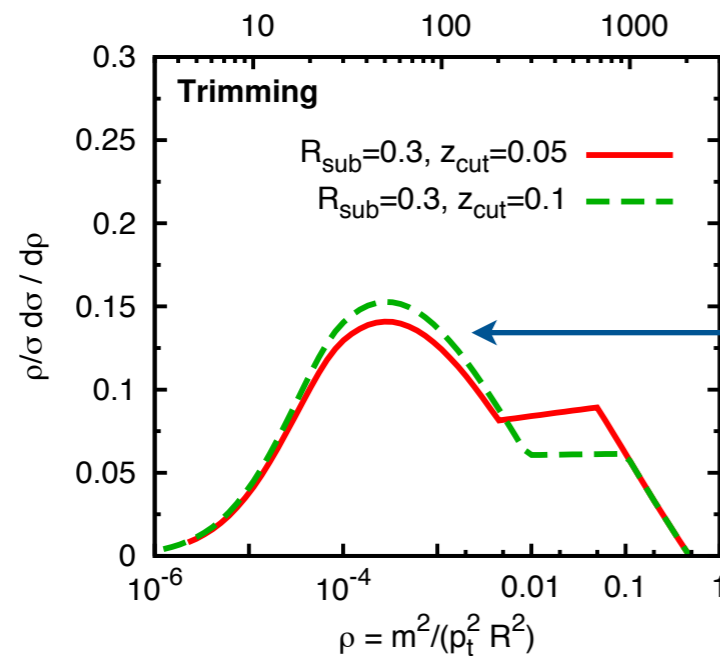
[Krohn, JDT, Wang, 0912.1342]

## (Modified) Mass Drop



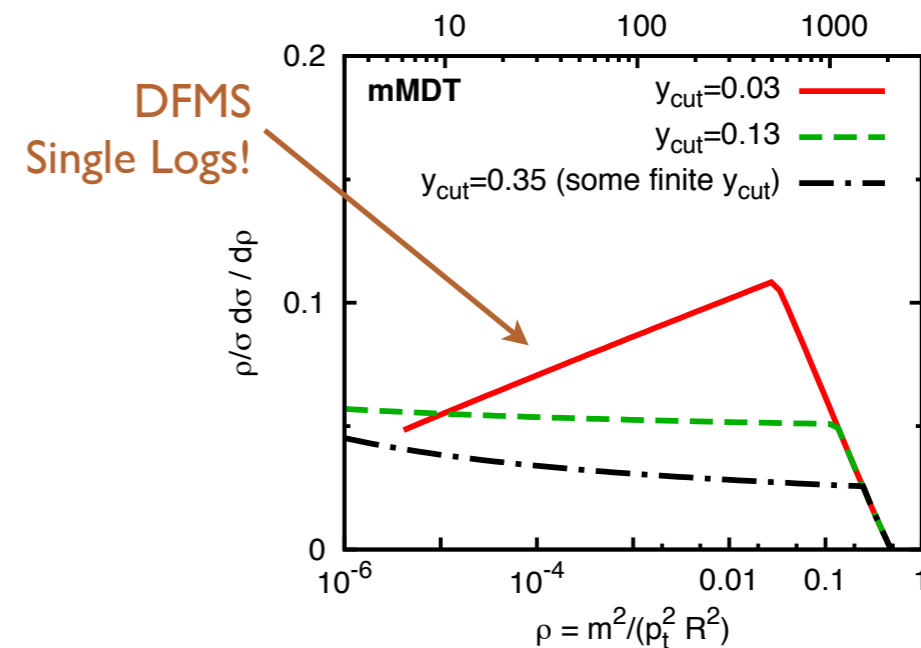
[Butterworth, Davison, Rubin, Salam, 0802.2470]

## Trimmed Jet Mass



Sudakov  
Double Logs

## Mass-Dropped Jet Mass



[Diagrams from ATLAS, 1306.4945]  
[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

# ...Inspire Techniques (and Analytics)...

## Soft Drop

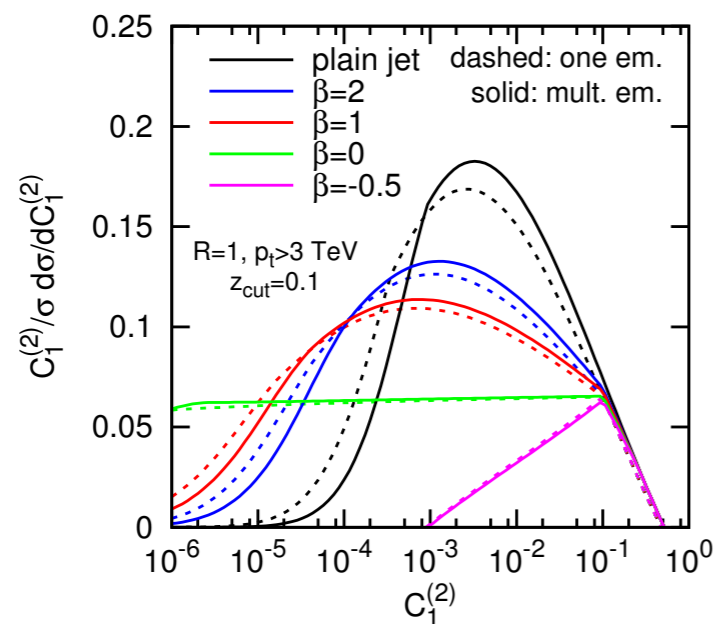
$$\beta = 0 \quad \beta > 0 \quad \beta \rightarrow \infty$$

Adjustable

Jet Unchanged

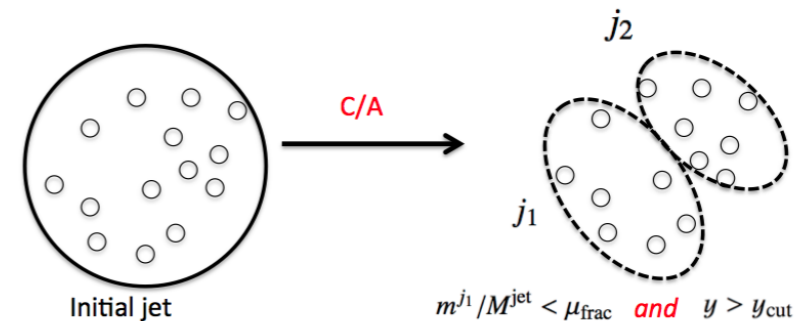
Mass Drop

## Soft-Dropped Jet Mass



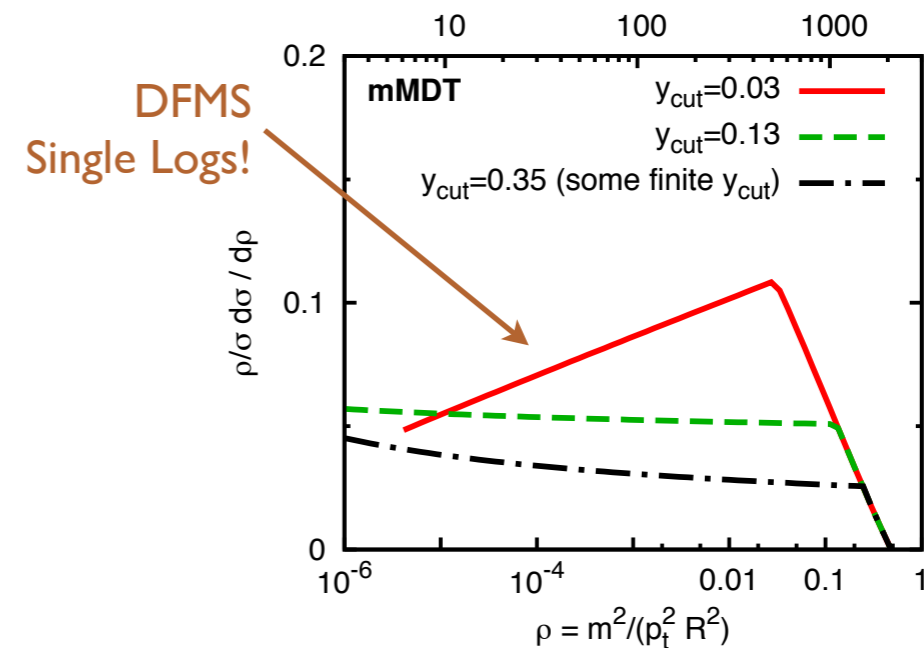
[Larkoski, Marzani, Soyez, JDT, 1402.2657]

## (Modified) Mass Drop



[Butterworth, Davison, Rubin, Salam, 0802.2470]

## Mass-Dropped Jet Mass



[Diagrams from ATLAS, 1306.4945]

[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

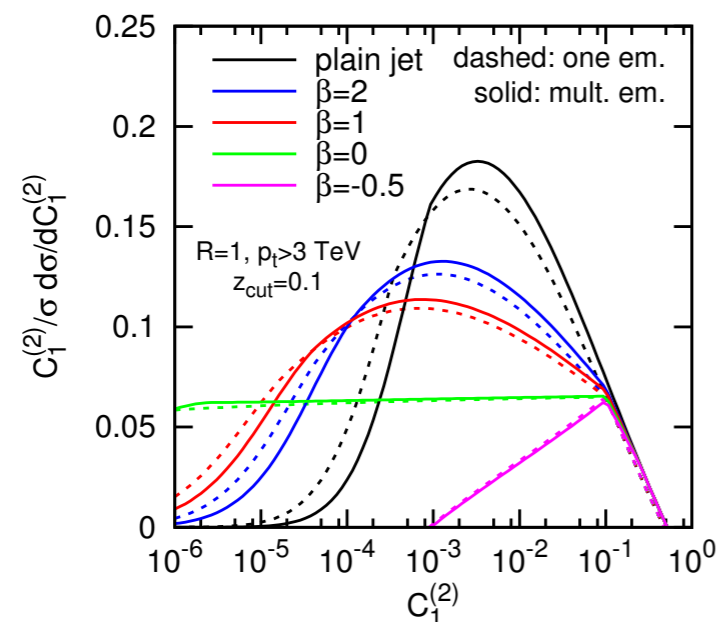
# ...Inspire Measurements!

## Soft Drop

$$\beta = 0 \quad \beta > 0 \quad \beta \rightarrow \infty$$

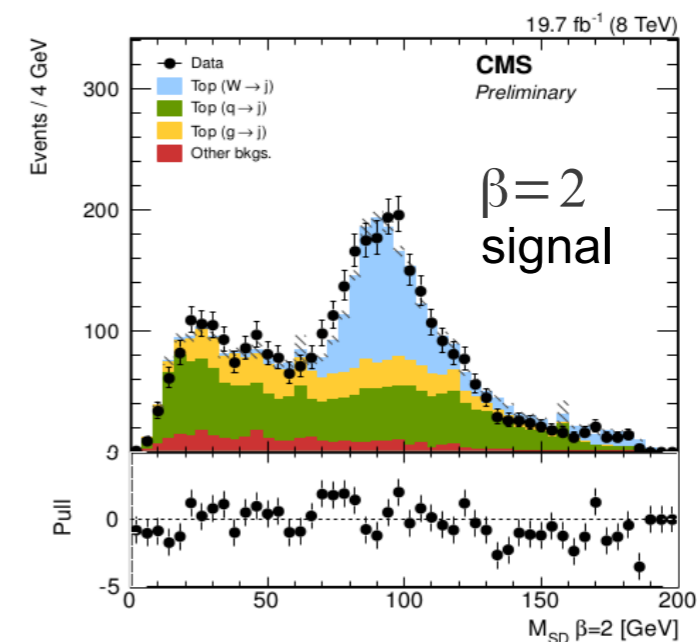
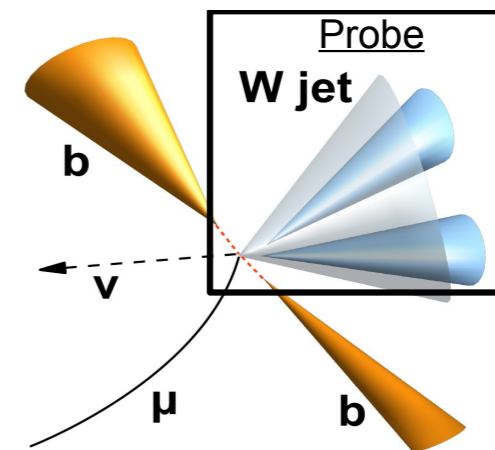


## Soft-Dropped Jet Mass



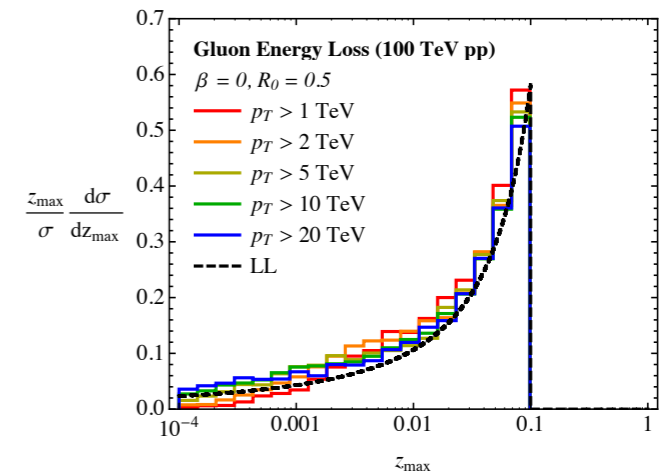
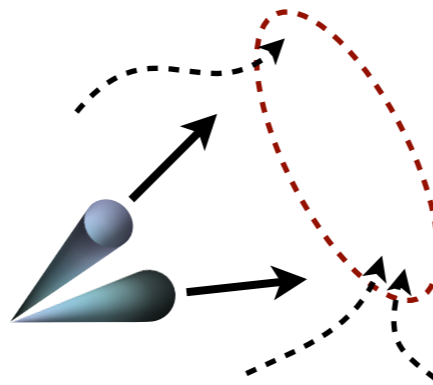
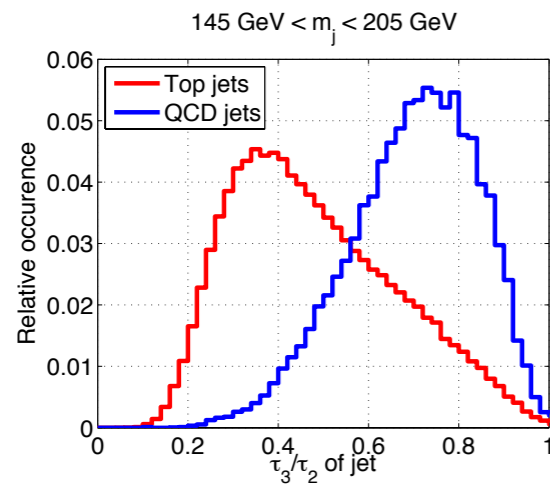
[Larkoski, Marzani, Soyez, JDT, 1402.2657]

## CMS W-Tagging Study



[CMS PAS JME-14-002]

# The Case for Jet Substructure



*Exceptional LHC performance + Extreme kinematics + Jet contamination + (B)SM physics*

## Maximize discovery potential of LHC

*Creative analysis strategies for hadronic final states*

## Enhance understanding of QCD

*New analytic results in (non)perturbative field theory*

# The Case for Jet Substructure

Jesse Thaler



LCWS 2014, Belgrade — October 6-10, 2014

# *Backup Slides*

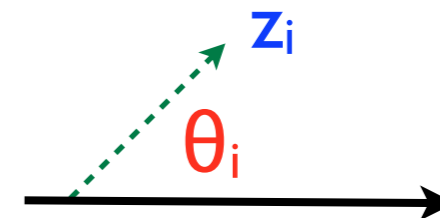
# Reconsidering Old Assumptions

## *Recoil-Sensitive vs. Recoil-Free Angularities*

$$e_\beta \simeq \sum_{i \in \text{jet}} z_i (\theta_i)^\beta$$

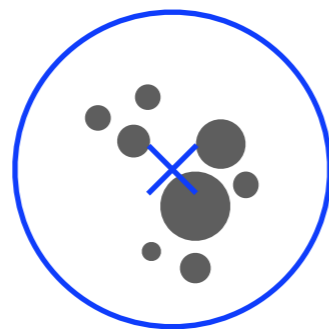
↑                      ↑  
energy fraction      angle to axis

Measure of gluon radiation  
about hard jet core

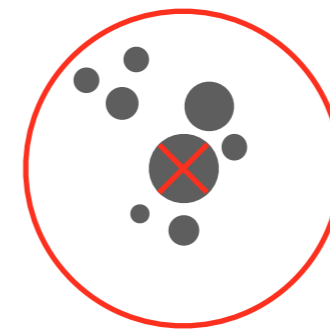


## Which Axis?

Recoil-Free: Measurement Axis  $\approx$  Hard Parton



Jet Momentum Axis  
(Mean)



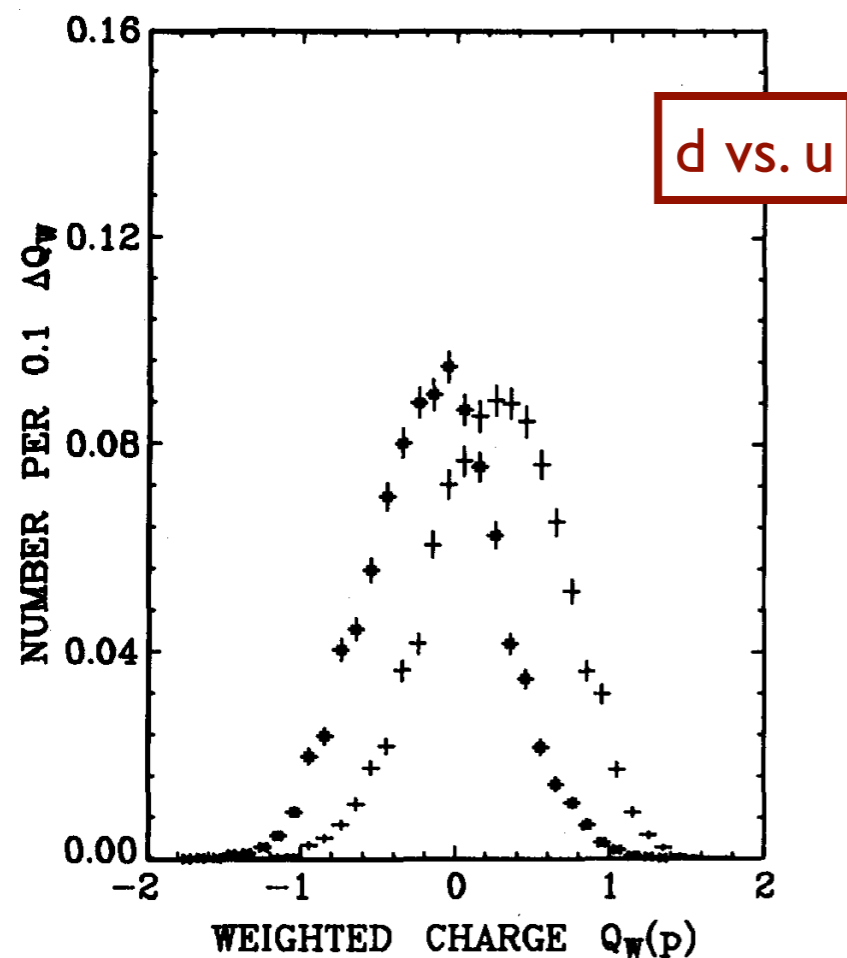
Winner-Take-All Axis  
(Median)

[Bertolini, Chan, JDT, 1310.7584; Larkoski, Neill, JDT, 1401.2158; Salam, unpublished]

# Old Ideas Revisited

## Weighted Jet Charge...

$$Q_W(p) = \sum_i z_i^p q_i$$

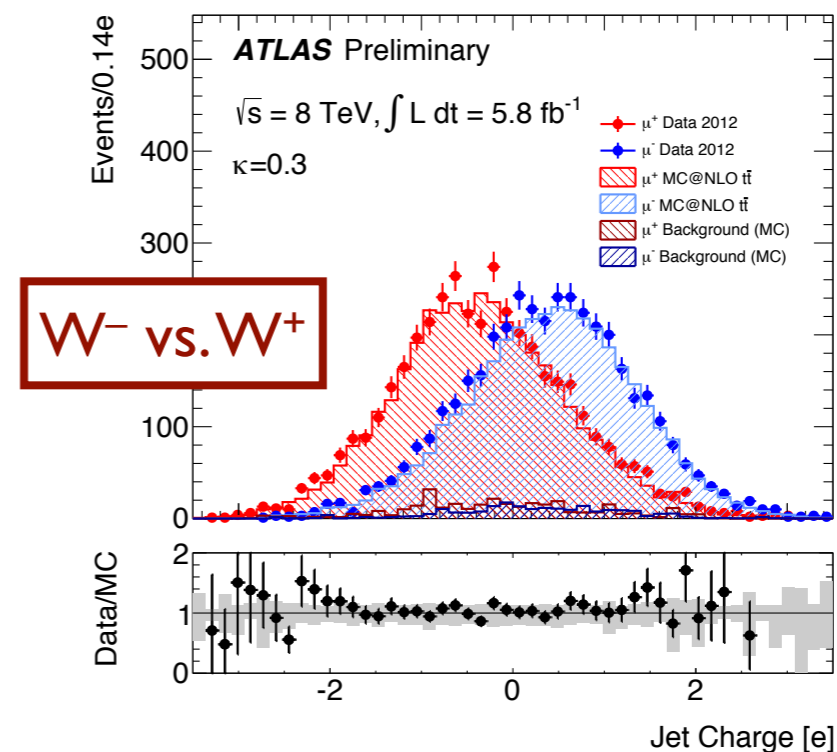


[Feynman, Field, 1978]

## ...on Firm Theoretical Ground

### Generalized Fragmentation Function

$$\begin{aligned} \mu \frac{d}{d\mu} D_i(Q, \kappa, \mu) &= \frac{1}{2} \sum_j \int dQ_1 dQ_2 dz \gamma_{ij}^D(z, \mu) \\ &\times D_j(Q_1, \kappa, \mu) D_{a(ij)}(Q_2, \kappa, \mu) \\ &\times \delta[Q - z^\kappa Q_1 - (1-z)^\kappa Q_2] \end{aligned}$$

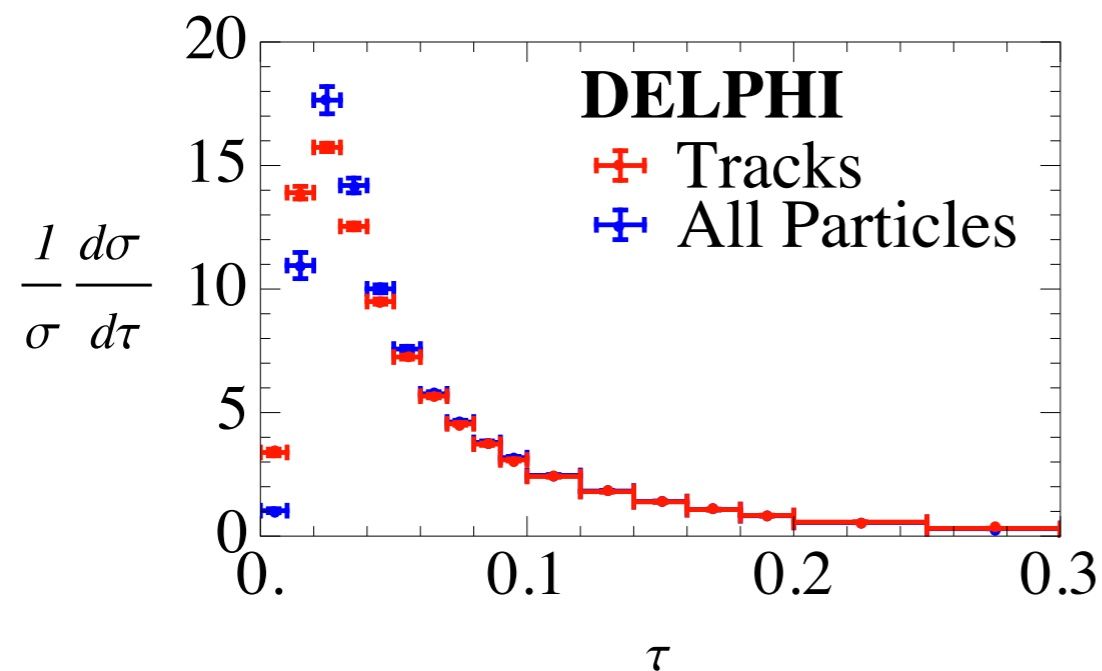


[Krohn, Schwartz, Lin, Waalewijn, 1209.2421; Waalewijn, 1209.3019]  
[ATLAS-CONF-2013-086]

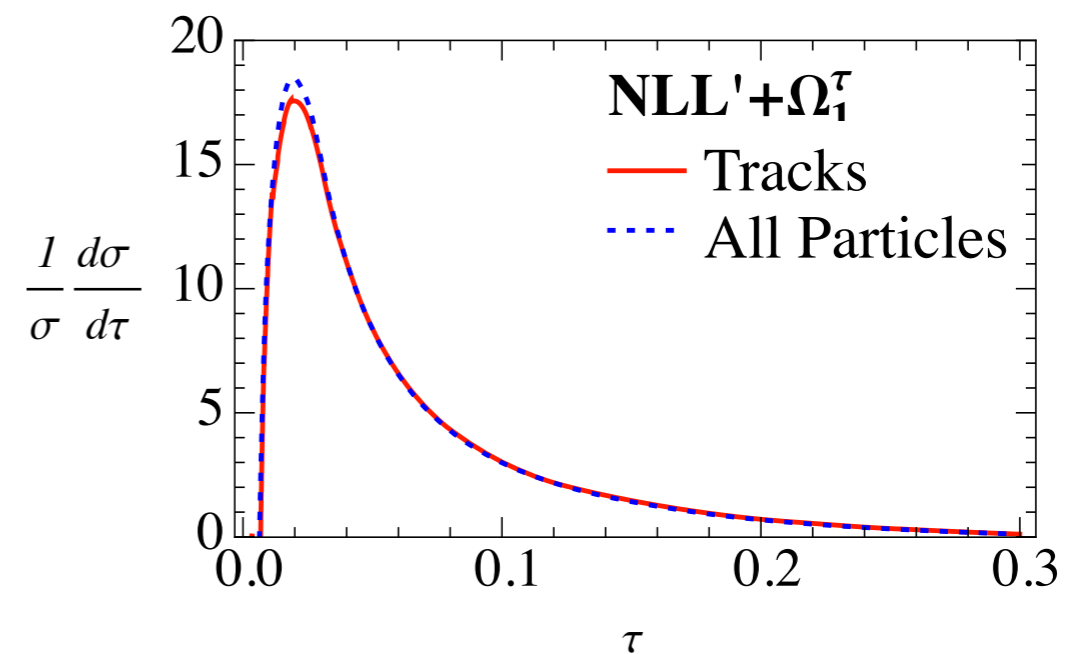
# Old Measurements Revisited

## Track-Based Observables

### Thrust @ LEP



### SCET + “Track Functions”



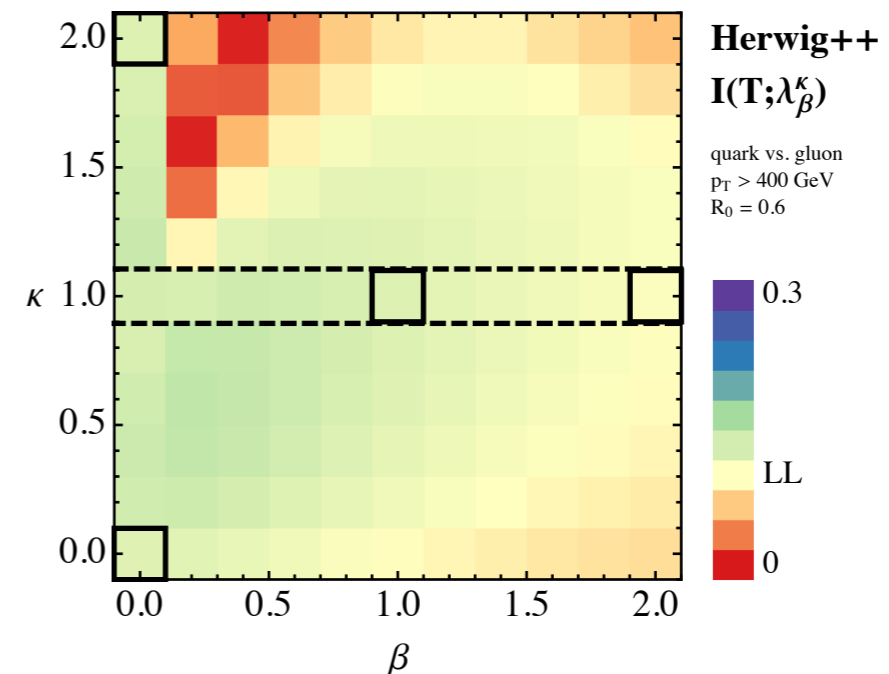
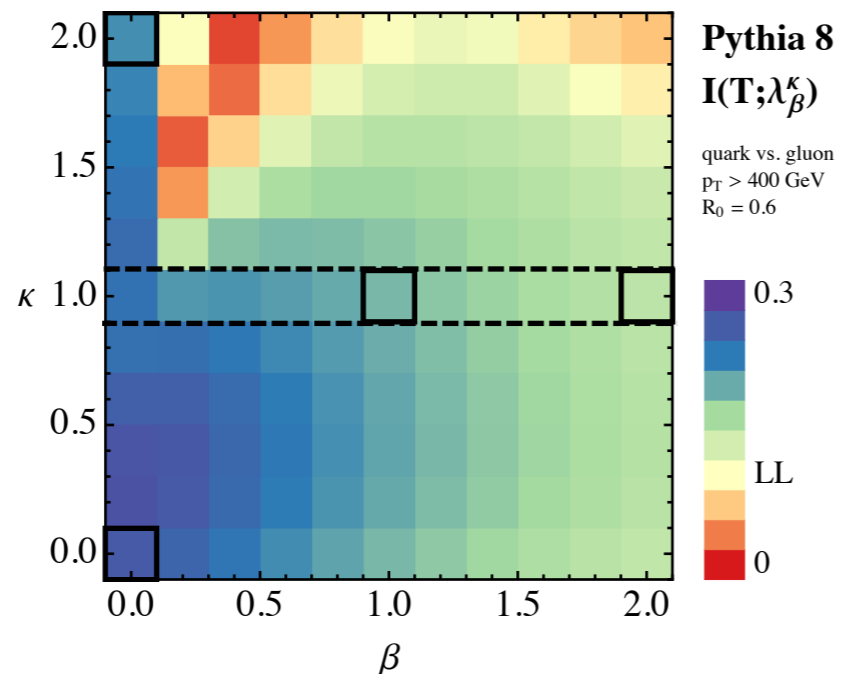
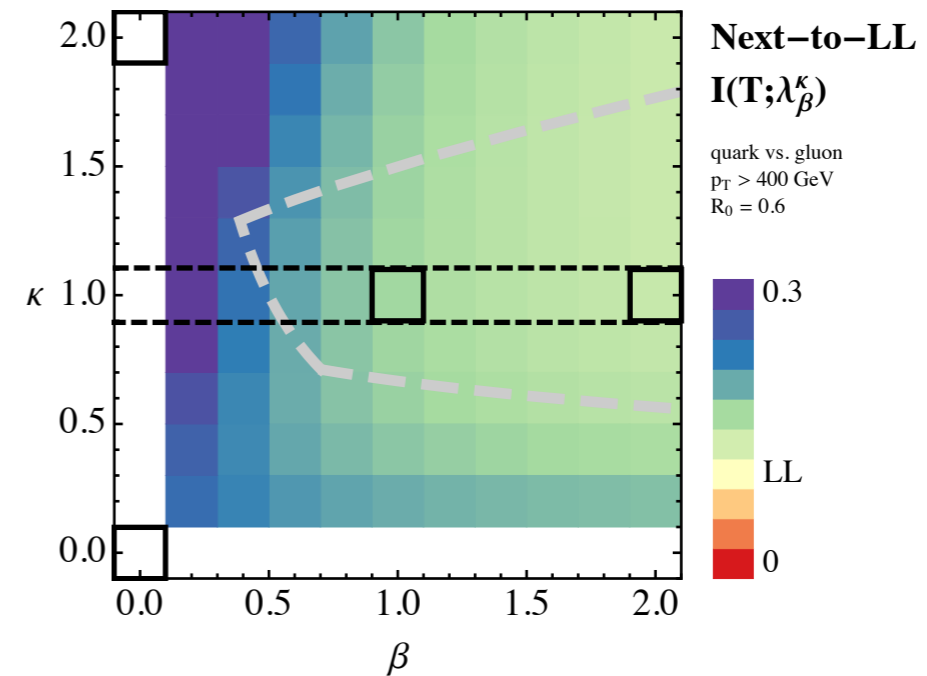
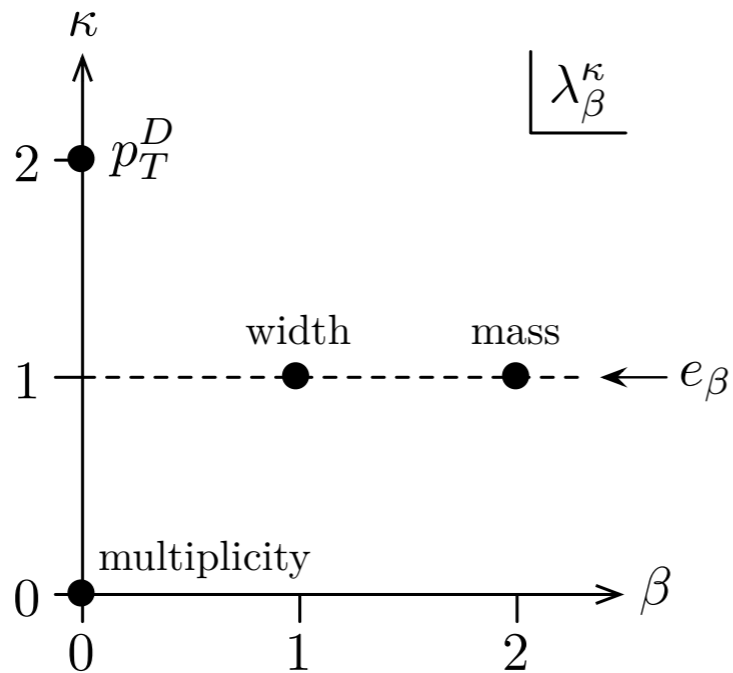
*Theme: Non-perturbative Objects  
with Perturbative Evolution*

[Chang, Procura, JDT, Waalewijn, 1303.6637, 1306.6630]

# New Measurements Required

## Quark/Gluon Truth Overlap

$$\lambda_{\beta}^{\kappa} = \sum_{i \in \text{jet}} z_i^{\kappa} \theta_i^{\beta}$$

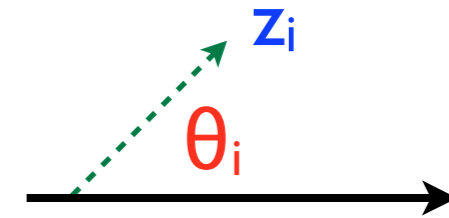


[Larkoski, JDT, Waalewijn, 1408.3122]

# New Computational Paradigms

*Angularities:*

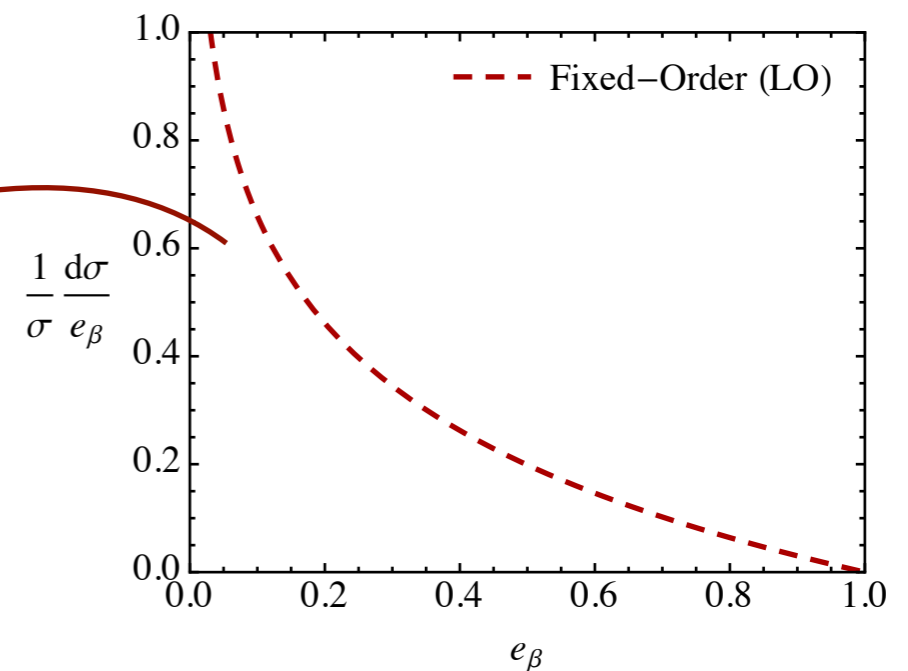
$$e_\beta \simeq \sum_{i \in \text{jet}} \underset{\substack{\uparrow \\ \text{energy fraction}}}{z_i} (\underset{\substack{\uparrow \\ \text{angle to axis}}}{\theta_i})^\beta$$



*Ratio Observables:*  
(Ubiquitous in Jet Substructure)

$$r = \frac{e_\alpha}{e_\beta}$$

*Divide by Zero*  
 $\Rightarrow$  Infrared Unsafe



# New Computational Paradigms

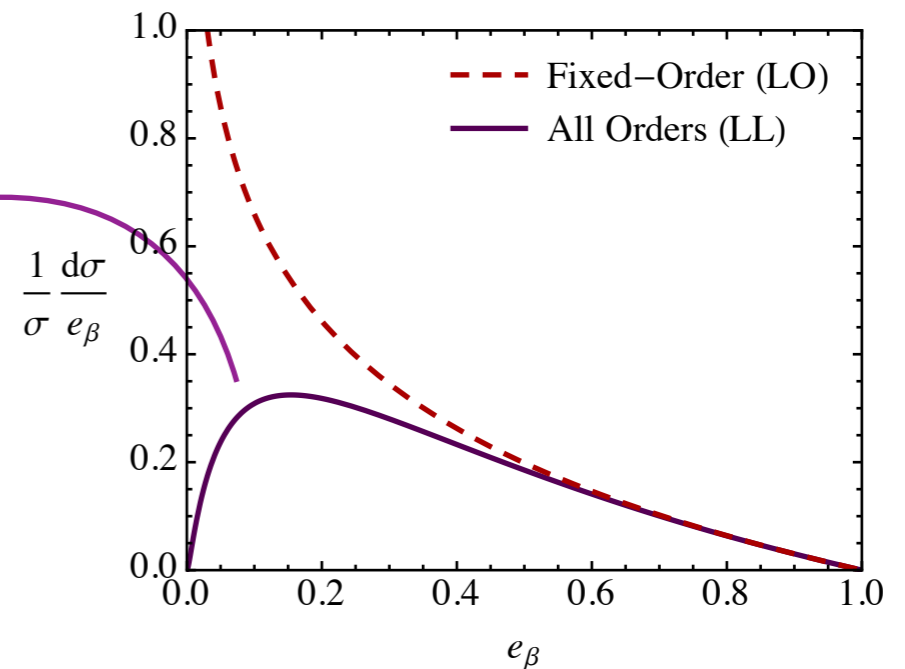
**Angularities:**  $e_\beta \simeq \sum_{i \in \text{jet}} z_i (\theta_i)^\beta$

energy fraction      angle to axis

**Ratio Observables:**  
(Ubiquitous in Jet Substructure)

$$r = \frac{e_\alpha}{e_\beta}$$

*Sudakov Form Factor*  
 $\Rightarrow$  “Sudakov Safe”



$$\frac{d\sigma^{\text{LL}}}{dr} = \sqrt{\alpha_s} \frac{\sqrt{C_F \beta}}{\alpha - \beta} \frac{1}{r} + \mathcal{O}(\alpha_s)$$

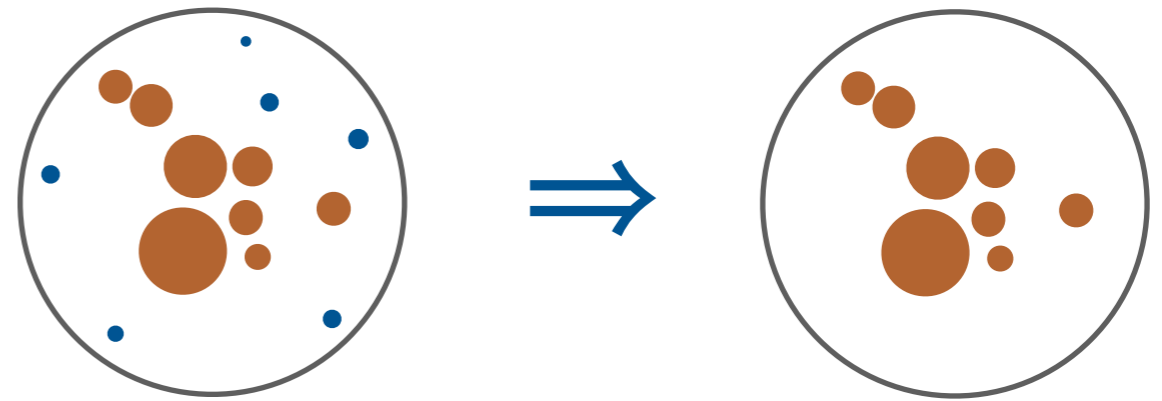
Unsafe...but Calculable

[Larkoski, JDT, 1307.1699]

# A Standard Candle for Jets?

## Soft Drop ( $\beta \rightarrow 0$ )

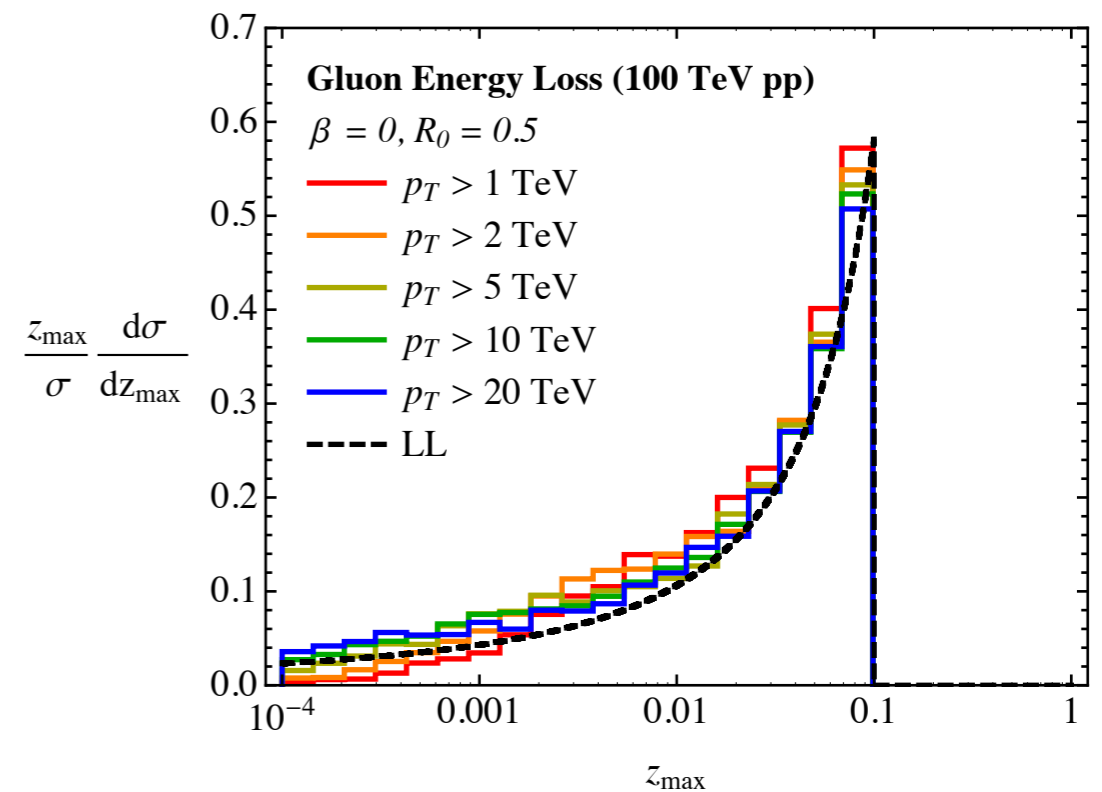
(a.k.a Modified Mass Drop)



## Fractional Energy Loss

$$\left. \frac{d\sigma}{d \log \Delta_E} \right|_{\beta=0} \propto \frac{1}{\log^2 \Delta_E}$$

↑  
no  $\alpha_s$  at fixed coupling (!)  
 $\approx$  independent of quark vs. gluon  
 $\approx$  independent of jet  $p_T$ , jet radius



[Larkoski, Marzani, Soyez, JDT, 1402.2657; Larkoski, JDT, 1406.7011]