New Observables for Jet Substructure

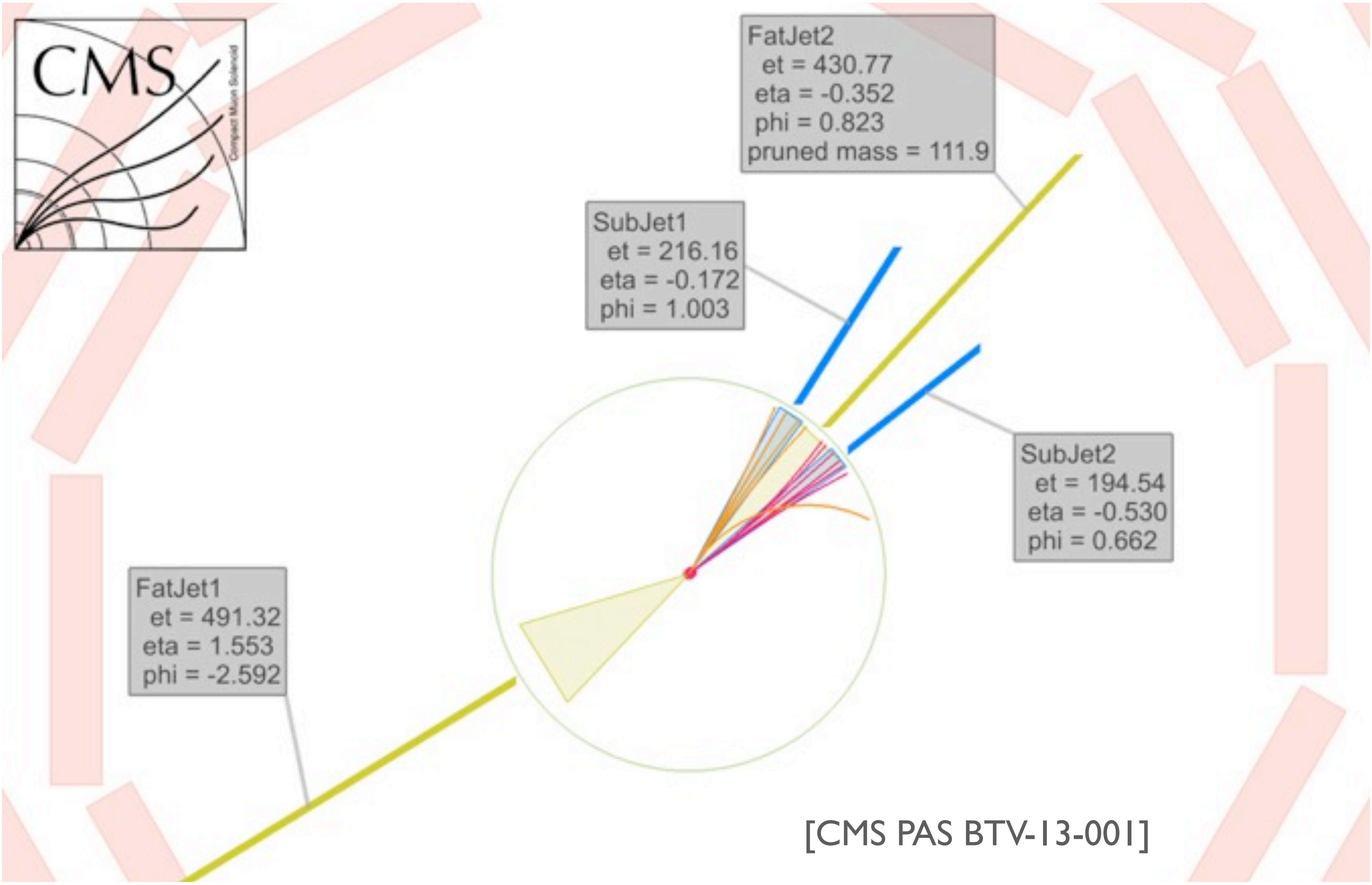
Multi-particle Dynamics at High-p_T

Jesse Thaler

ISMD 2013, Chicago — September 16, 2013

What is Jet Substructure?

Maximizing the Physics Potential of Hadronic Final States



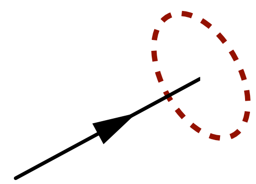
Upcoming Talks: Amazing Experimental Progress

[see talks by Bose, Wardrope, Loch, Marchesini, Stoebe, Matera, De Lorenzi, ...]

↳ Boost 2013

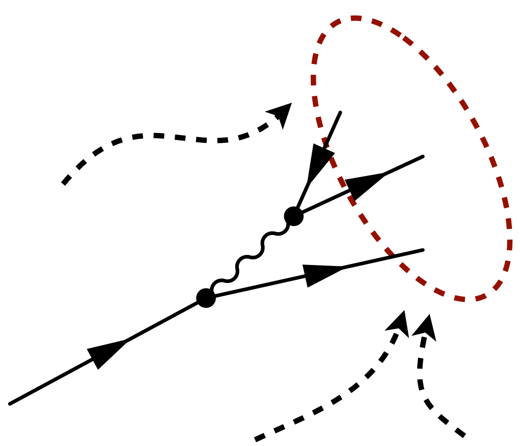
Multi-particle Dynamics at High-p_T?

Traditionally: Jet → proxy for short-distance parton



Ordinary Jet → u/d/s/g
Tagged Jet → b, maybe c

Jet Substructure: Use multi-hadron observables for clues about underlying physics



Angularities, Jet charge → quark vs. gluon
N-prong substructure → boosted W/Z/Top/Higgs

(and accept that jets are fundamentally ambiguous, messy)

Dependence on Jet Definition
Perturbative Fractal Structure (i.e. Parton Shower [see talk by Nagy])
Non-perturbative Hadronization Effects
Jet Contamination from UE/ISR, Pileup [see talk by Sullivan]

New Observables for Jet Substructure

N-subjettiness

with Ken Van Tilburg: 1011.2268 & 1108.2701

Energy Correlation Functions

with Andrew Larkoski & Gavin Salam: 1305.0007

(Jets Without Jets)

with Daniele Bertolini & Tucker Chan: forthcoming

Only small sampling of jet substructure tools/techniques

[see also talks by Roy, Krohn]

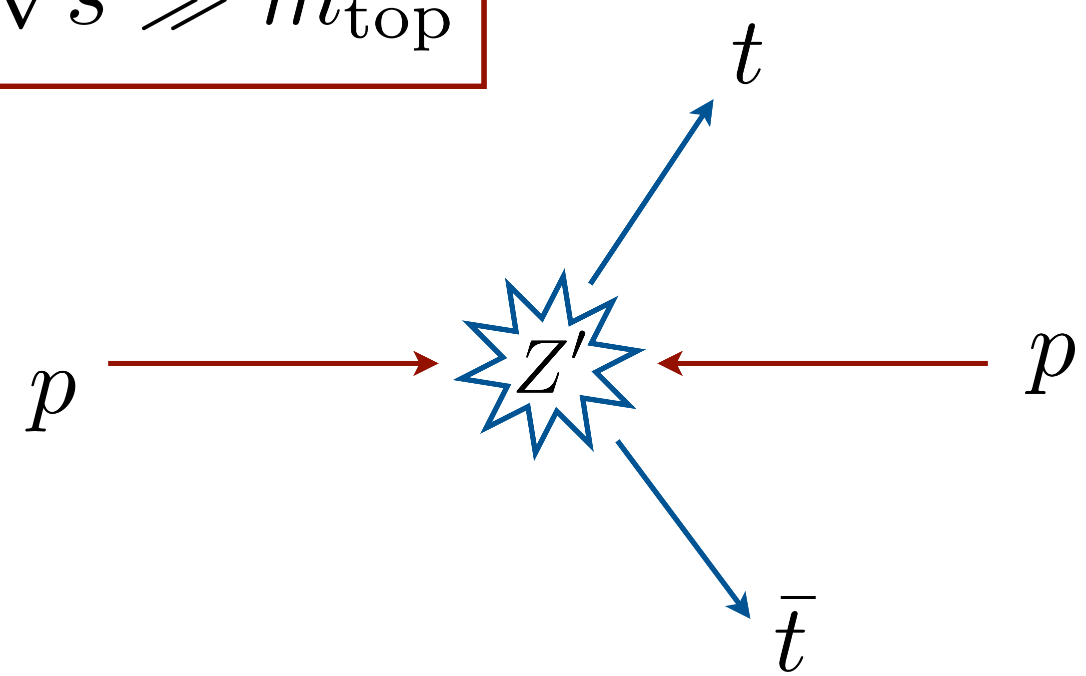
N-subjettiness

[JDT, Van Tilburg: 1011.2268 & 1108.2701]

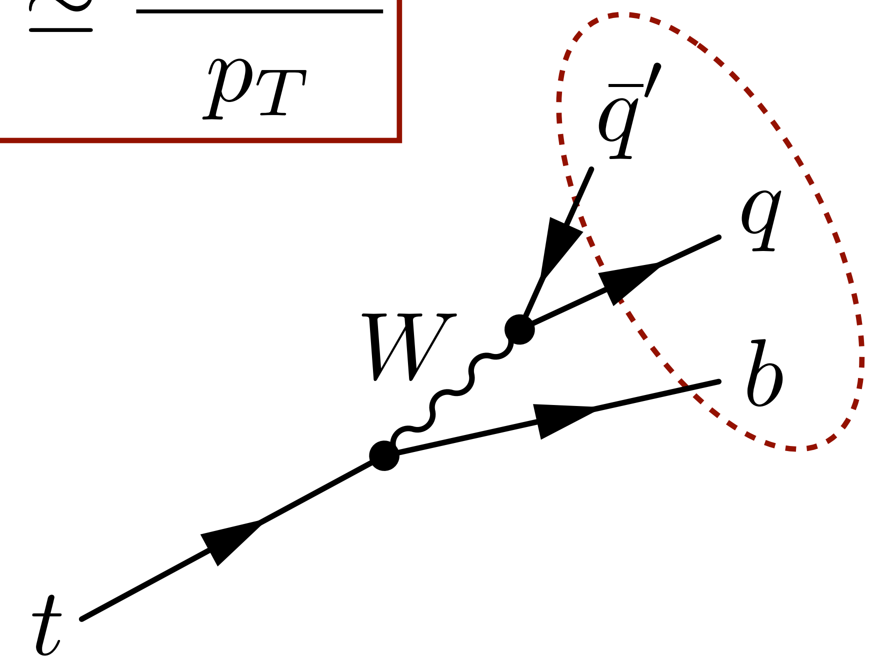
Classic Jet Substructure

High mass di-top resonances

$$\sqrt{\hat{s}} \gg m_{\text{top}}$$



$$\Delta R \simeq \frac{2m_{\text{top}}}{p_T}$$



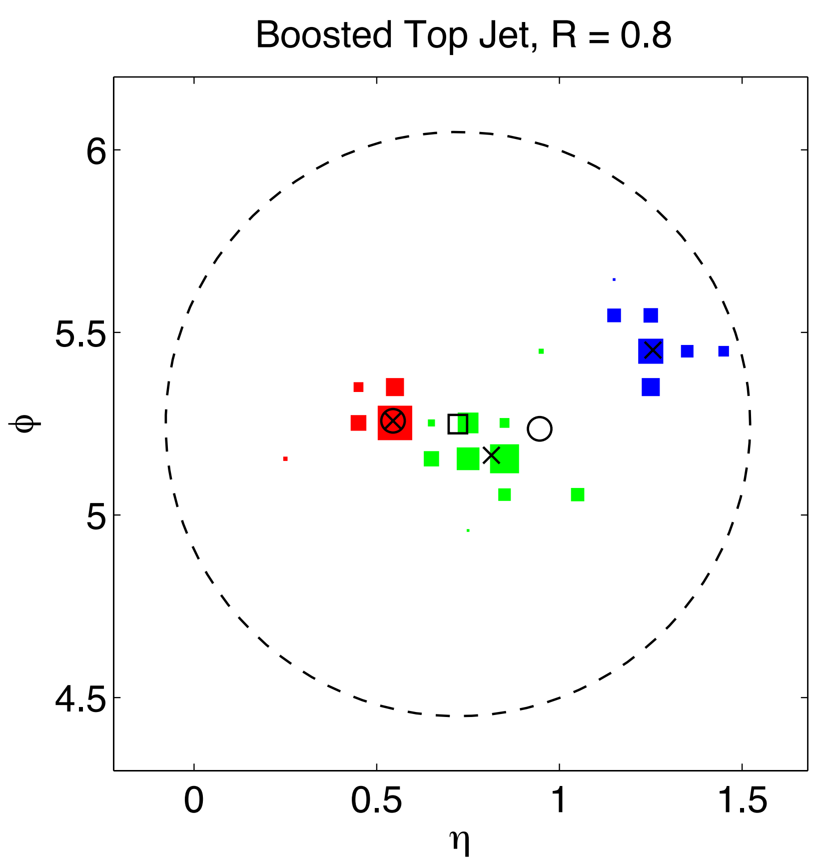
Heavy resonance to boosted tops...looks like QCD dijets

Robust/Growing Set of Tagging Tools:

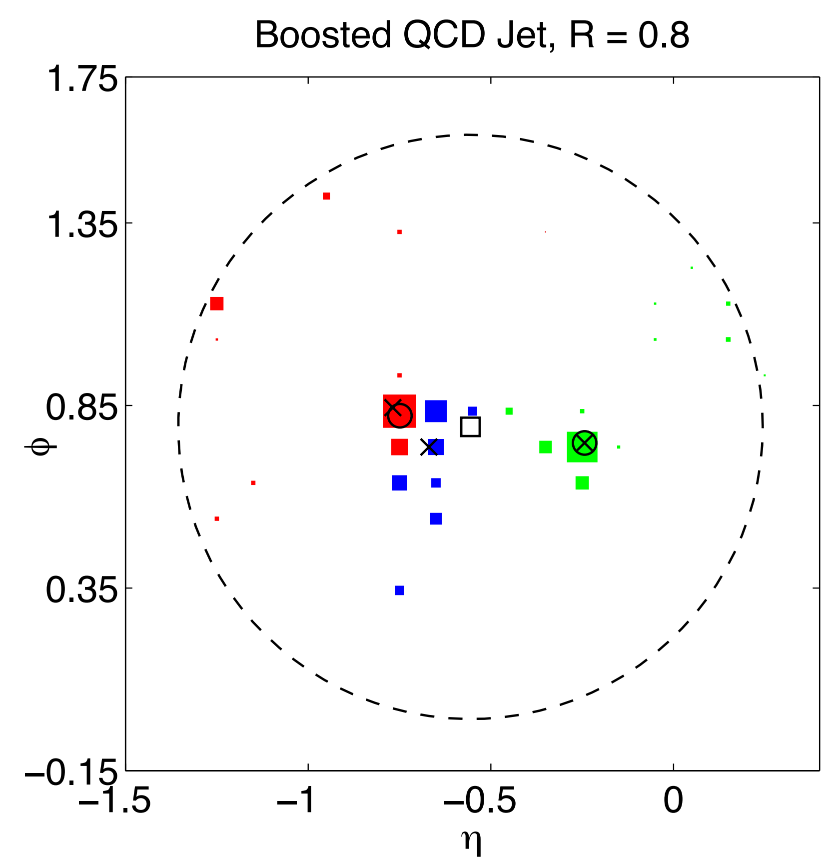
Mass Drop, Trim/Filter/Prune, Y-splitter, Planar Flow, JHU/CMS Top Tagger, HEPTopTagger, Top Template Method, N-subjettiness, Q-Jets, Telescoping Jets, Shower Deconstruction, ...

Jet Substructure by Eye

Coloring by exclusive k_T



vs.



Boosted Top Quark

QCD Jet ($m_{jet} \approx m_{top}$)

$$\langle m_{\rm jet}^2 \rangle \simeq \alpha_s \, p_{T\rm jet}^2 R^2$$

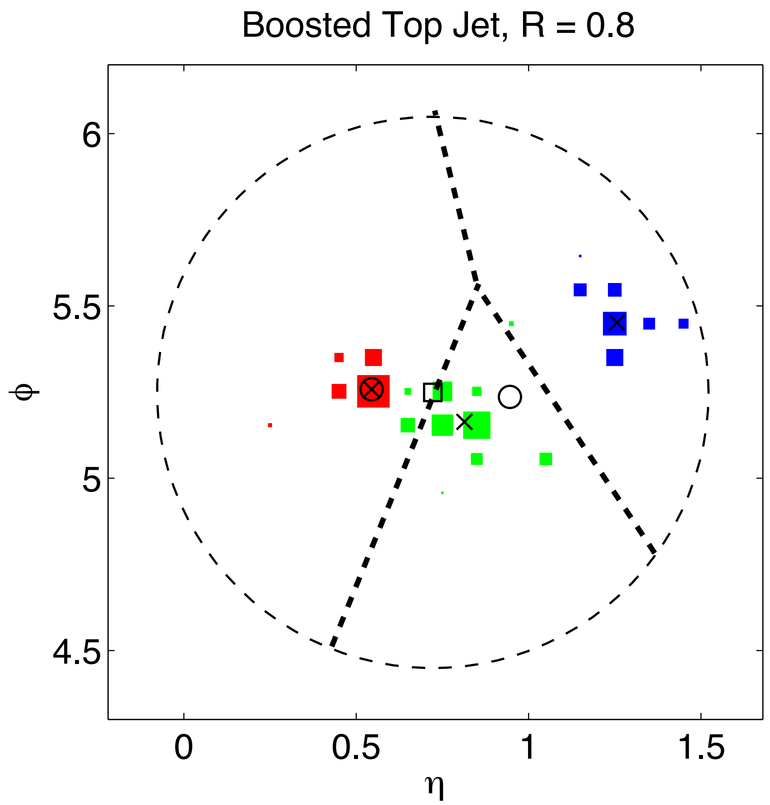
Additional discrimination possible beyond just jet mass

N-subjettiness

Testing N-prong substructure

Freedom to Exploit ↓ β

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\left\{\Delta R_{k,1}, \Delta R_{k,2}, \ldots, \Delta R_{k,N}\right\}^{\beta}$$



Find axes by minimizing τ_N

# subjets:	$\leq$ N	> N
τ_N:	0	1

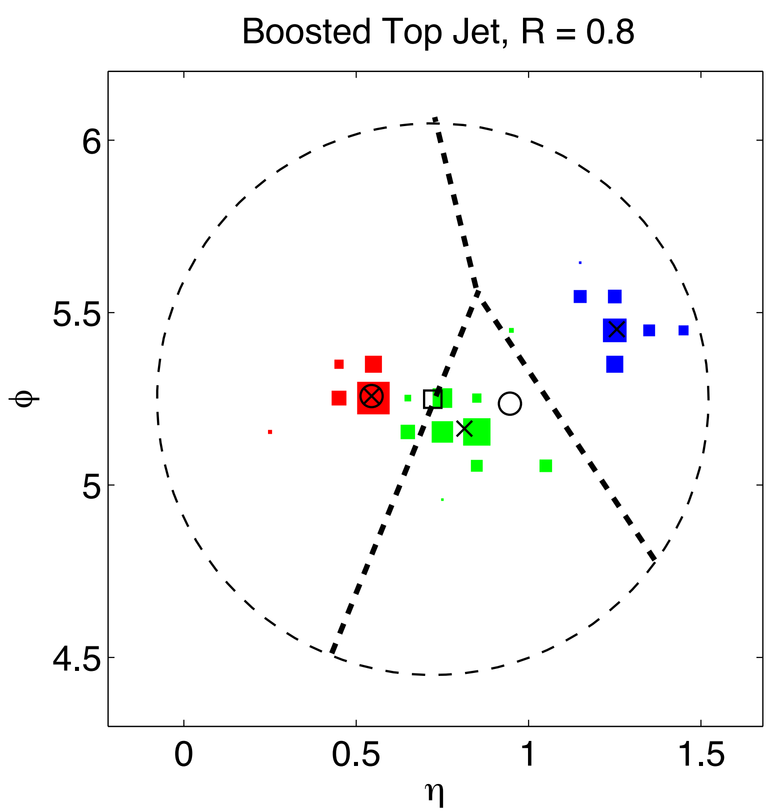
N-jettiness: [Stewart, Tackmann, Waalewijn]
N-subjettiness: [JDT, Van Tilburg]

N-subjettiness

Testing N-prong substructure

Freedom to Exploit

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{k,1}, \Delta R_{k,2}, \ldots, \Delta R_{k,N}\}^{\beta}$$



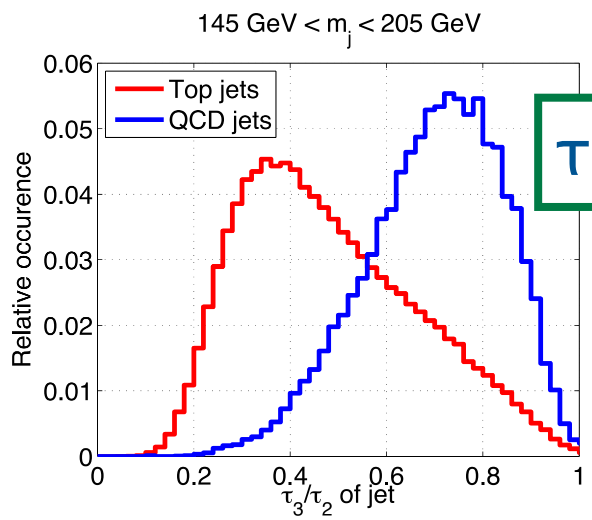
Find axes by minimizing τ_N

subjets: ≤ N > N

τ_N: 0 1

τ_3/τ_2: Tops

τ_2/τ_1: W/Z/H



τ_3/τ_2

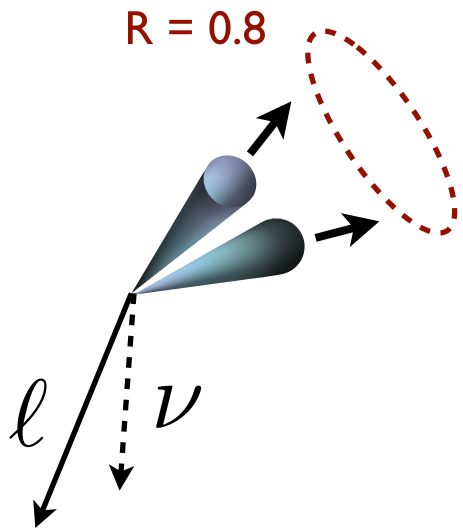
N-jettiness: [Stewart, Tackmann, Waalewijn]
N-subjettiness: [JDT, Van Tilburg]

Applications in Higgs Physics

High Mass $h \to WW$

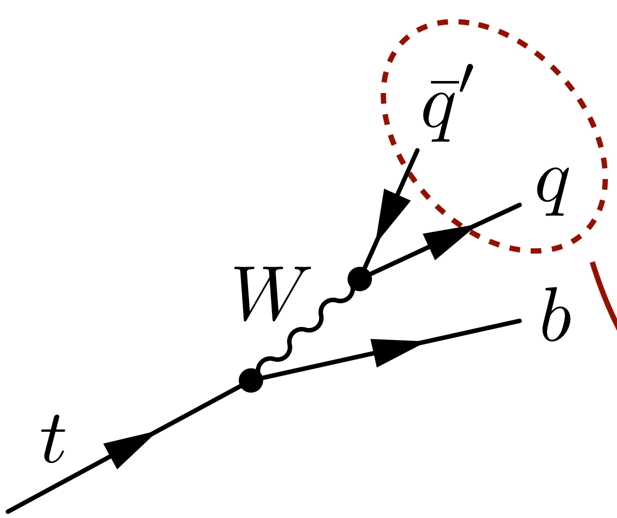
$$h \to \begin{cases} W \to q\bar{q}' \\ W \to \ell\nu \end{cases}$$

(boosted)

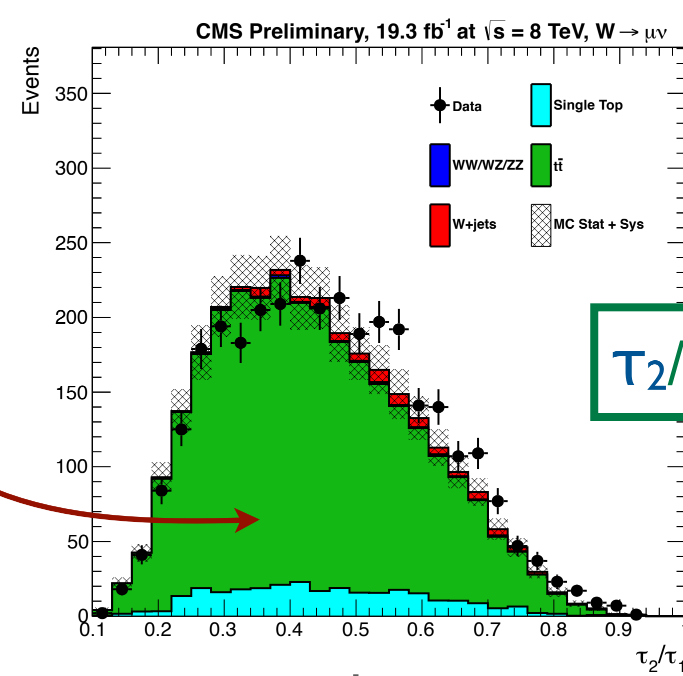


[Uses pruned jet mass: Ellis, Vermilion, Walsh]

[CMS PAS HIG-13-008]

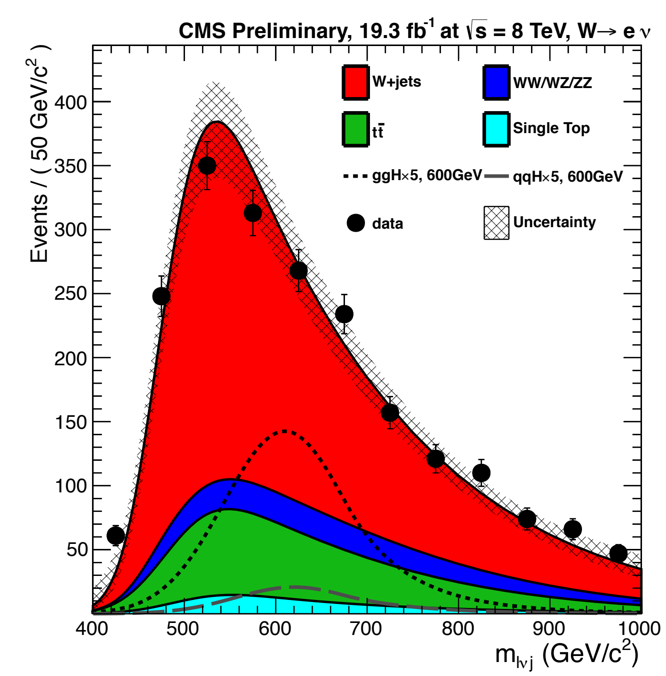


Validated on quasi-boosted semi-leptonic top sample



τ_2/τ_1

W-like ⟷ QCD-like



$m_{\ell\nu W_{\rm jet}}$

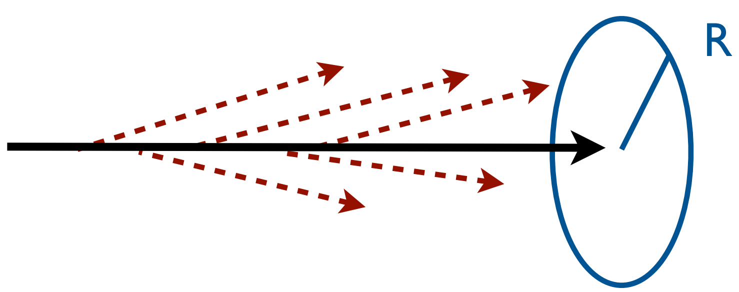
Energy Correlation Functions

[Larkoski, Salam, JDT: 1305.0007]

Quark/Gluon Discrimination

The White Whale of Jet Substructure [see e.g. Gallicchio, Schwartz]

Jets, simplified:



In soft & collinear limit:

$$\mathcal{P} = \frac{2\alpha_s C}{\pi} \frac{dz}{z} \frac{d\theta}{\theta}$$

z = Energy Fraction
θ = Splitting Angle

Color Factor:
C_F = 4/3 (quarks) vs. C_A = 3 (gluons)

In this limit, for most any* observable:

Quark Efficiency = x

Gluon Mistag = $x^{9/4}$

Improves S/B but marginal change in significance ($S/\sqrt{B}$)

White Whale: Exploit subleading structure, evade Casimir scaling

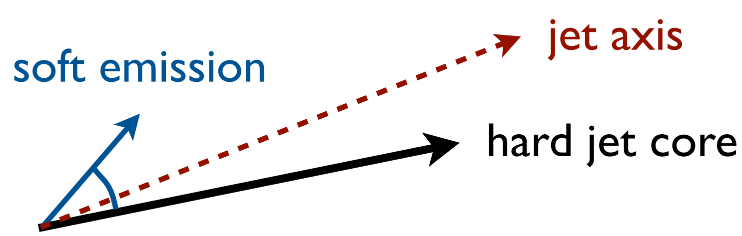
1-subjettiness for Quark vs. Gluon?

a.k.a. angularities [Berger, Kucs, Sterman]

Freedom to Exploit ↓

$$\tau_1 = \frac{1}{p_{T\mathrm{jet}}} \sum_k p_{T,k}\, \Delta R_{k,1}^{\beta}$$

↑ Jet Axis



z = energy fraction
θ = splitting angle

$$\tau_1 \simeq \boxed{z\,\theta^\beta} + \boxed{z^\beta \theta^\beta}$$

"Direct" contribution

Sensitive to pattern of soft radiation
Dominates for $\beta > 1$
Effective for q vs. g

"Recoil" contribution

Sensitive to displacement of jet axis
Dominates for $\beta < 1$
Less effective for q vs. g

Alternative: use recoil-free axis, e.g. "broadening axis" [Larkoski, Neill, JDT, forthcoming]

Energy Correlation Functions

Axis-free (and recoil-free) probe for substructure [Larkoski, Salam, JDT]

$$\mathrm{ECF}(1,\beta) = \sum_i p_{Ti}$$

$$\mathrm{ECF}(2,\beta) = \sum_{i<j} p_{Ti}\, p_{Tj}\, (R_{ij})^\beta \quad \longleftarrow$$ [see Banfi, Salam, Zanderighi; Jankowiak, Larkoski]

$$\mathrm{ECF}(3,\beta) = \sum_{i<j<k} p_{Ti}\, p_{Tj}\, p_{Tk}\, (R_{ij} R_{jk} R_{ki})^\beta$$

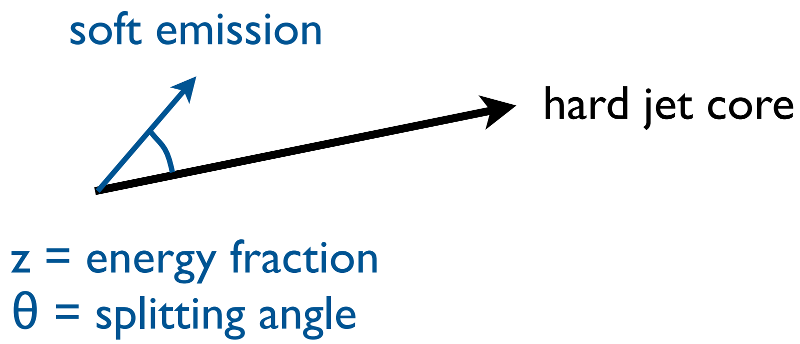
$$\mathrm{ECF}(N,\beta) = \sum_{\text{sets of } N} (N \text{ energies}) \times \left(\binom{N}{2} \text{ angles}\right)^\beta$$

Convenient Dimensionless Ratio:

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

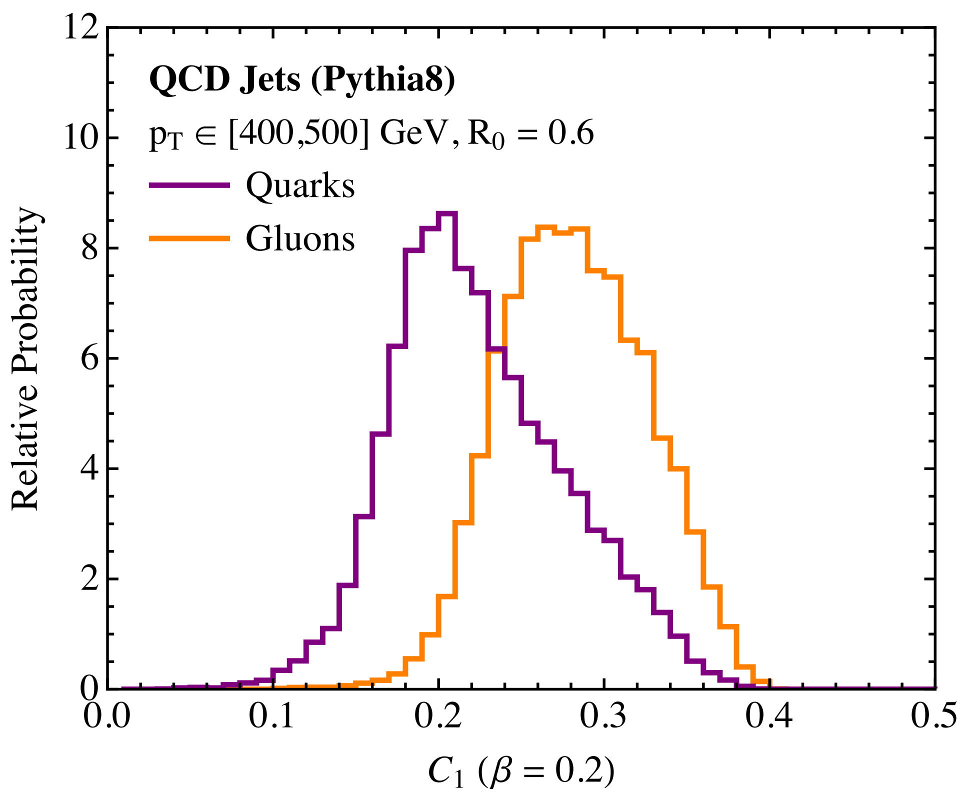
N narrow prongs: $C_N \to 0$

C_1 for Quarks vs. Gluons



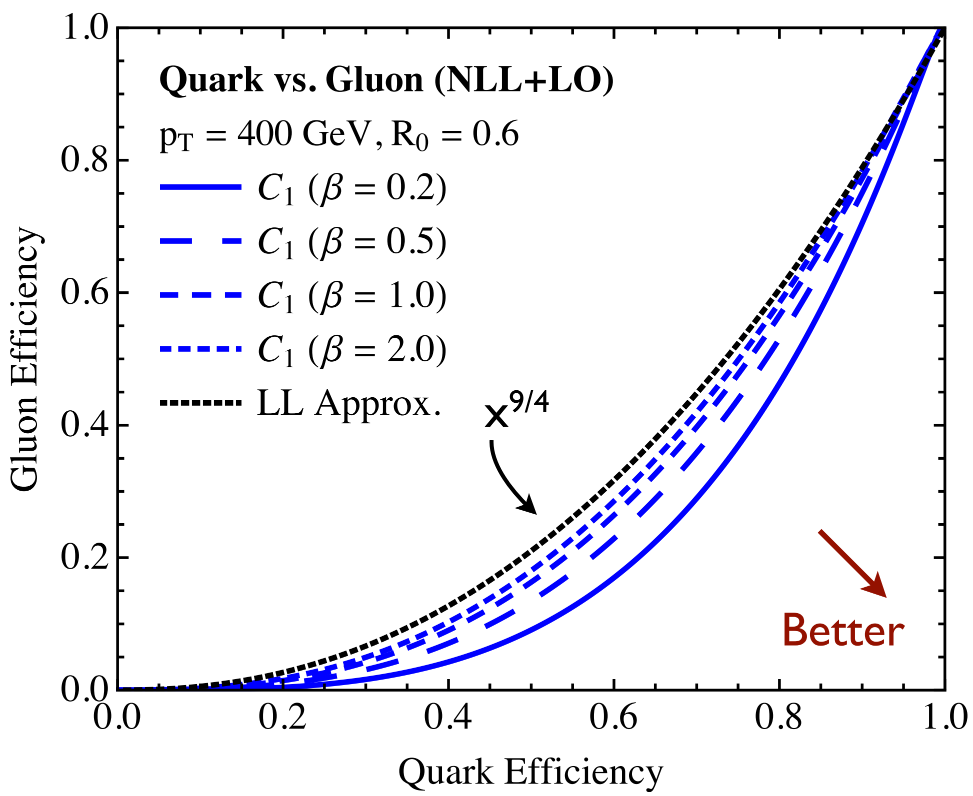
$$C_1^{(\beta)} = \frac{1}{(p_{T\text{jet}})^2} \sum_{i<j} p_{Ti}\, p_{Tj}\, (R_{ij})^\beta \Rightarrow \boxed{z\,\theta^\beta}$$

No recoil!



quark-like ↔ gluon-like

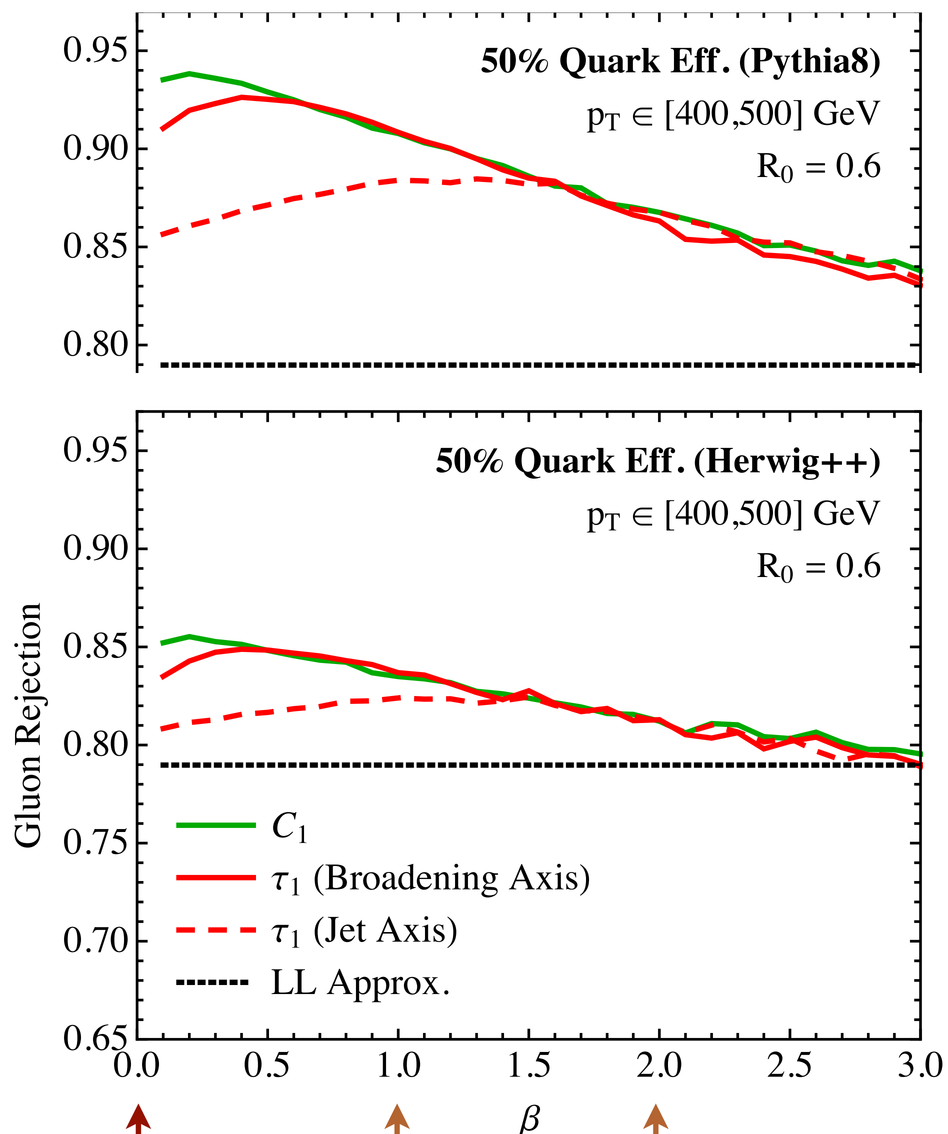
NLL Resummation



Small β emphasizes higher-order quark/gluon differences

Opportunity for Monte Carlo Calibration?

Pythia 8 vs. Herwig++



p_T^D

≈ Broadening/ Girth/Width

≈ Thrust/ Jet Mass

[CMS PAS JME-13-005]

Parton shower:
Formally accurate to LL

β-dependence:
Starts at NLL

Determine correct behavior from data?

$$C_1^{(\beta)} = \frac{1}{(p_{T\text{jet}})^2} \sum_{i<j} p_{Ti}\, p_{Tj}\, (R_{ij})^\beta$$

Looking to the Future

This Talk: Observables calculable in perturbative QCD

e.g. Infrared/Collinear Safe or "Sudakov Safe"

[see Larkoski, JDT]

⇒ Essentially multi-parton dynamics

ISMD 2014: Fundamentally non-perturbative observables?

e.g. p_T^D from CMS
Jet Charge
Track-based Observables

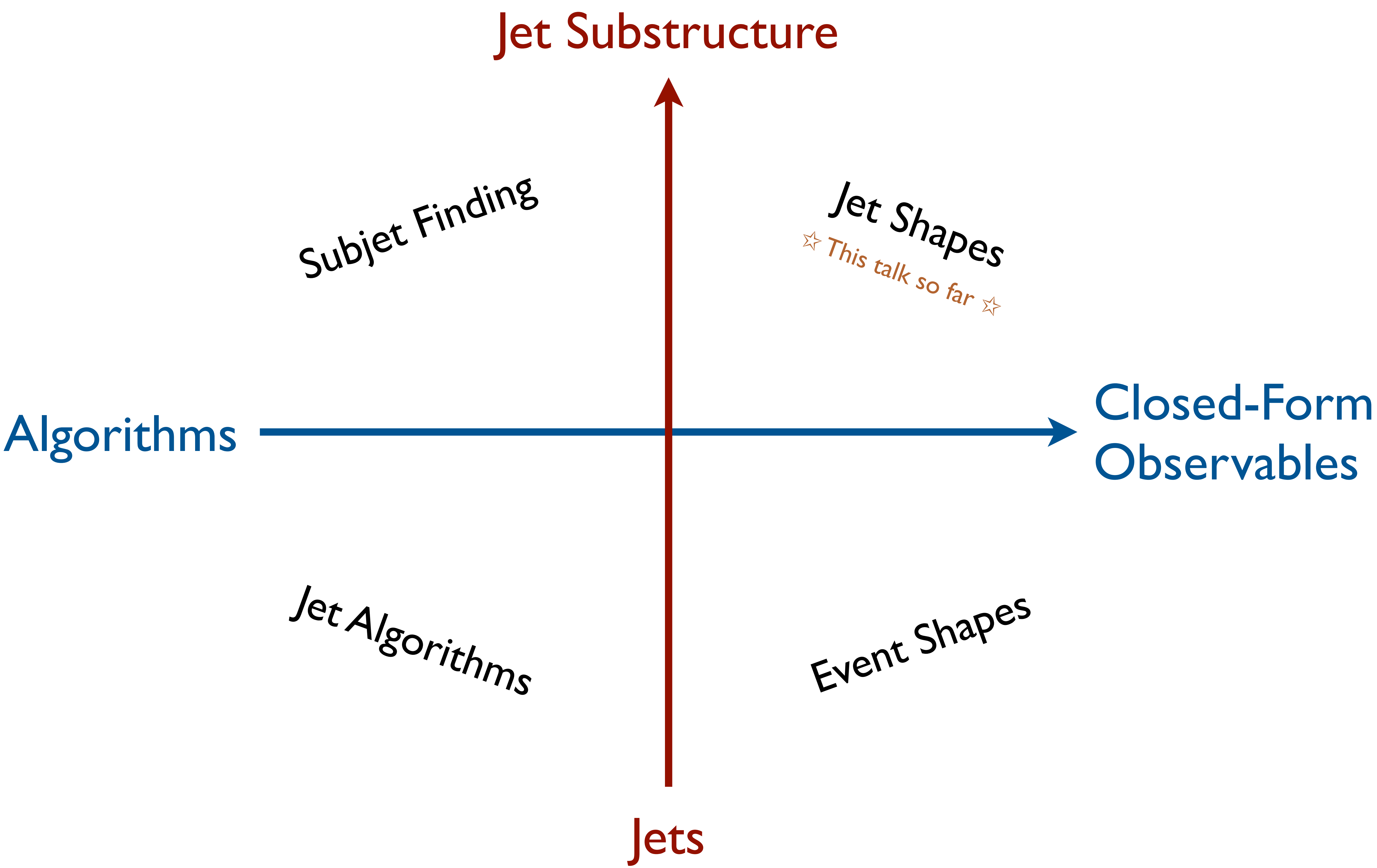
} Still (some) perturbative control!

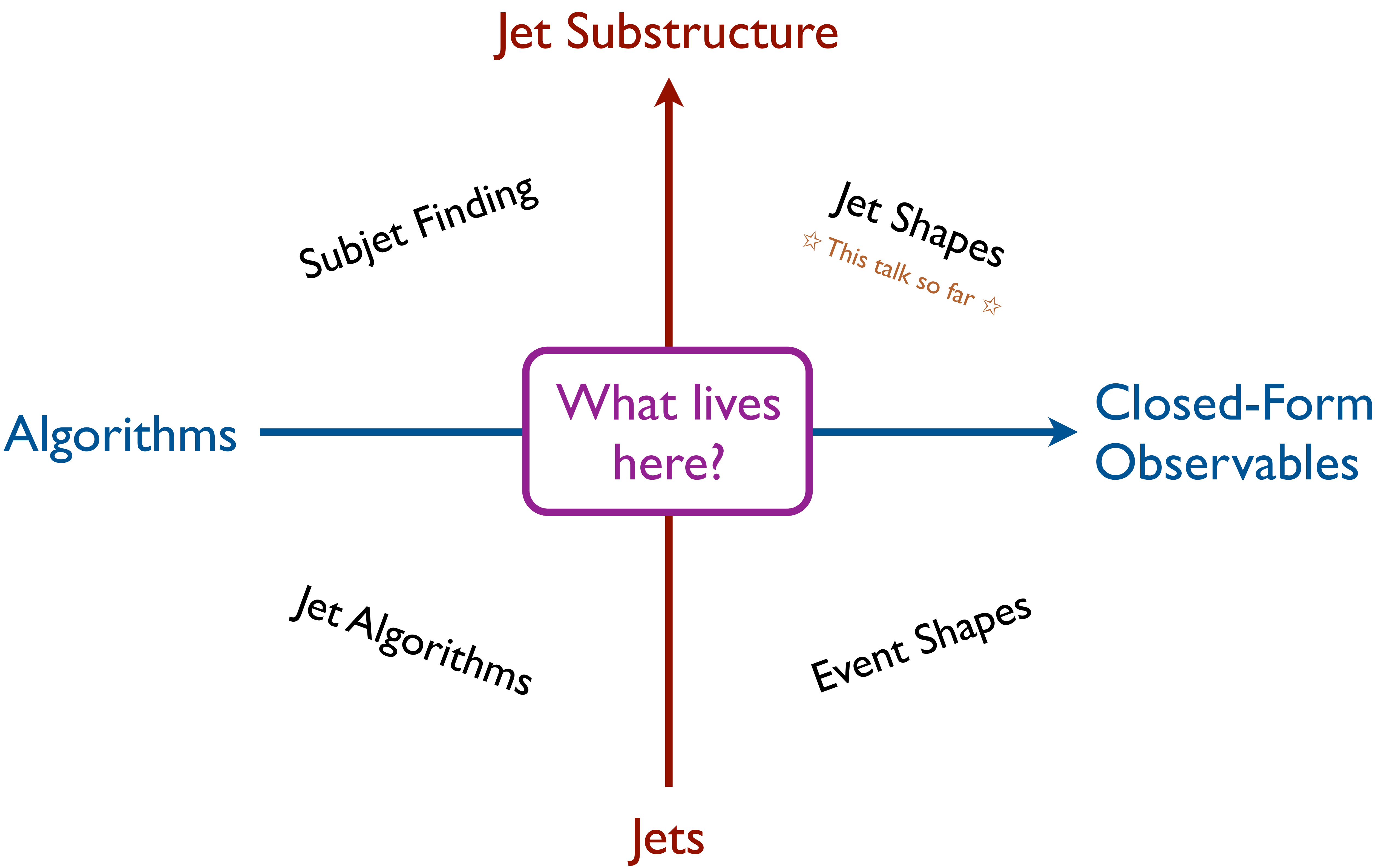
[see Krohn, Lin, Schwartz, Waalewijn; Chang, Procura, JDT, Waalewijn]

⇒ Interplay of multi-hadron/parton dynamics

(Jets Without Jets)

[Bertolini, Chan, JDT: forthcoming]


Jet Substructure
Subjet Finding
Jet Shapes
✫ This talk so far ✫
Algorithms
Closed-Form Observables
Jet Algorithms
Event Shapes
Jets


Jet Substructure
Subjet Finding
Jet Shapes
☆ This talk so far ☆
Algorithms
What lives here?
Closed-Form Observables
Jet Algorithms
Event Shapes
Jets

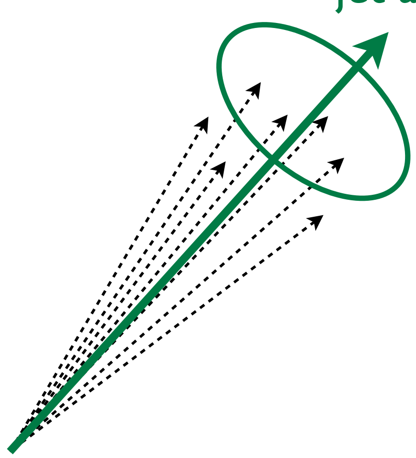
Jet-like Event Shapes

or subjet-like jet shapes

$$\widetilde{N}_{\text{jet}} = \sum_{i \in \text{event}} \frac{p_{Ti}}{p_{Ti,R}} \Theta(p_{Ti,R} > p_{T\text{cut}})$$

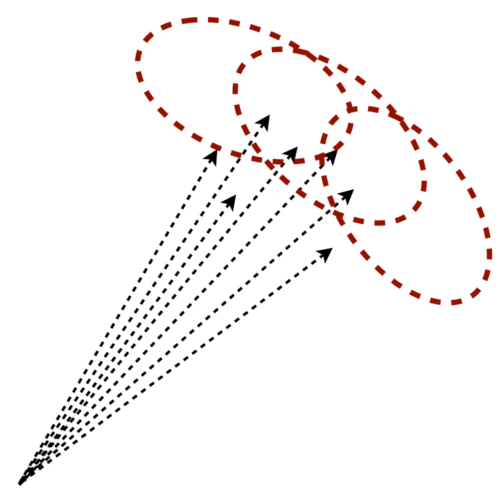
"Local"

$$p_{Ti,R} = \sum_{j \in \text{event}} p_{Tj}\, \Theta(R_{ij} < R)$$

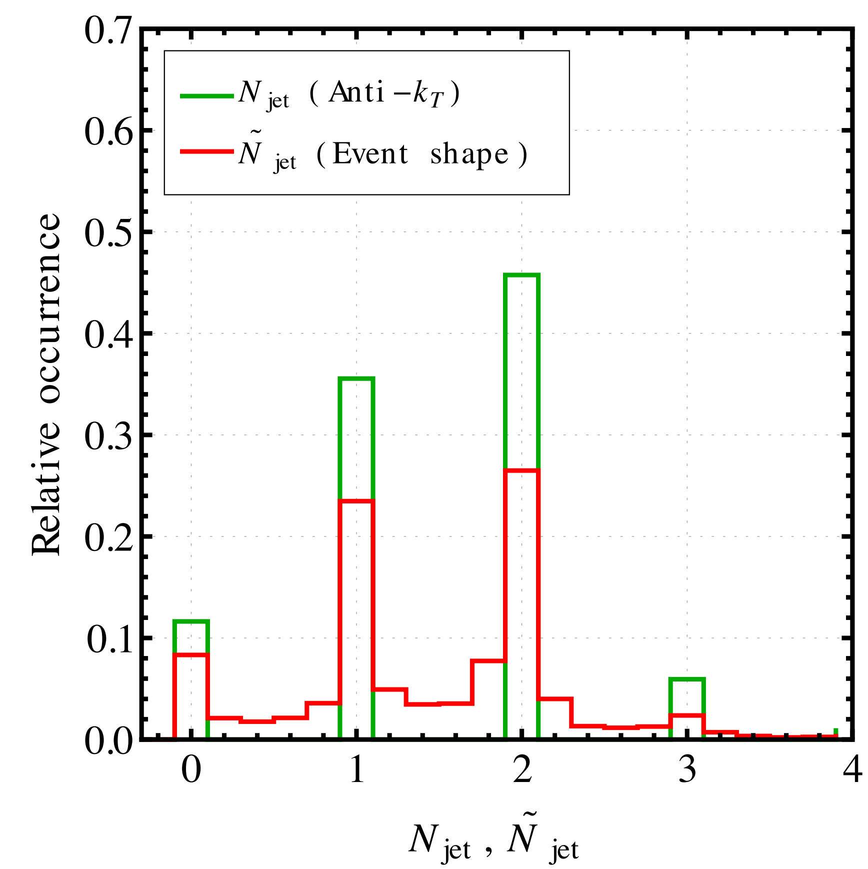


Jet Algorithm

vs.



Jet-like Event Shape

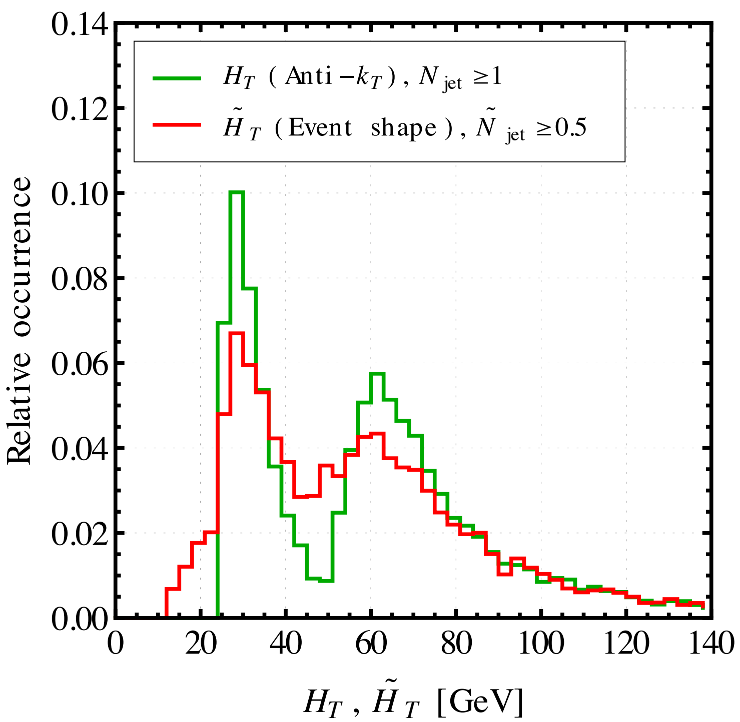


Dijets @ LHC8, R = 0.6, $p_{T\text{cut}}$ = 25 GeV

A Hammer in Search of a Nail

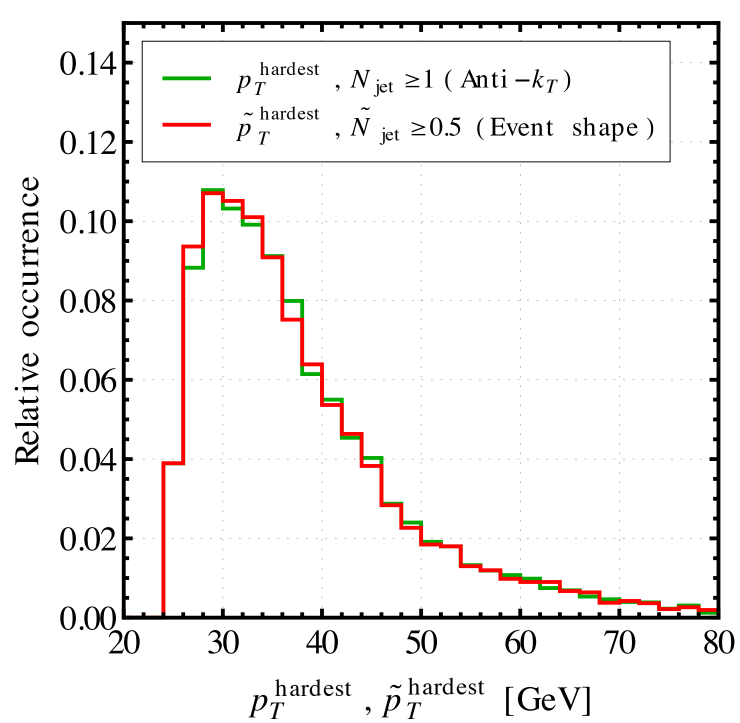
Reproducing standard jet observables

$H_T = \sum p_T$



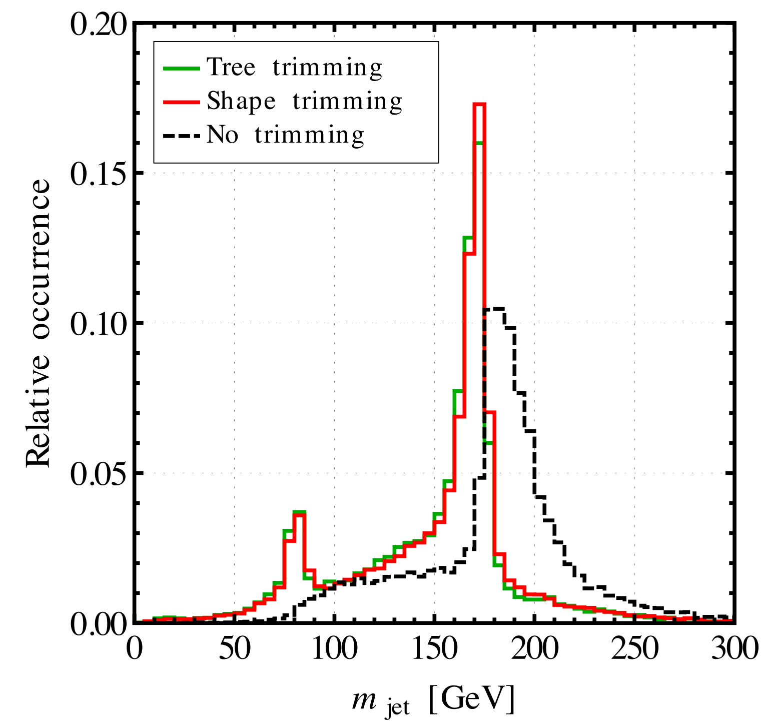
p_T of hardest jet

(without identifying that jet)



Jet Trimming

[Krohn, JDT, Wang]



Dijets @ LHC8, R = 0.6, p_{Tcut} = 25 GeV

Boost2010 Top Sample

R = 1, p_T > 200 GeV, R_{sub} = 0.2, f_{cut} = 0.05

Improved triggering? Pileup mitigation? Overlapping jets?
Smoother interpolation of jet (sub)structure? Calculational tractability?

New Observables for Jet Substructure

N-subjettiness

Effective test for N-prong substructure

Energy Correlation Functions

Importance of recoil-free observables for quarks vs. gluons

(Jets Without Jets)

Characterize (sub)jet-like structure without jet finding

Bottom Line: Can define observables sensitive to desired physics

Interplay: Measurable ↔ Useful ↔ Calculable

Backup Slides

Boosted Regime is Inevitable

Di-tops in the standard model

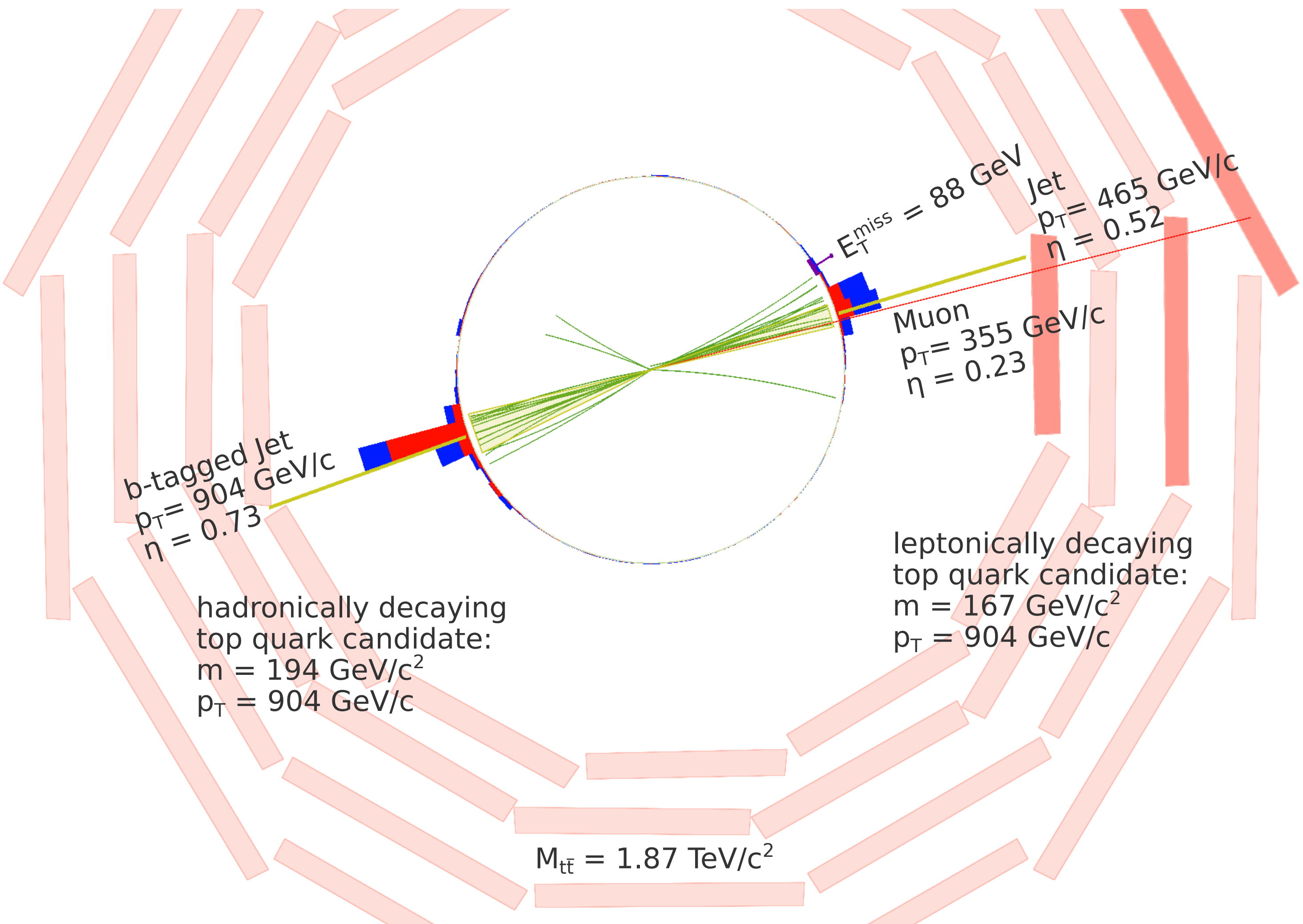
Merged Jet Radius

R ≈ 0.8 → Boosted production

R ≈ 0.4 → Highly boosted

Expected number of events	Tevatron run II 10 at 1.96 TeV	LHC 2012 20 at 8 TeV	LHC design 300 at 13 TeV
Inclusive $t\bar{t}$ production	6×10^4	4×10^6	2×10^8
Boosted production	23	6×10^4	5.2×10^6
Highly boosted	0	500	1.1×10^5

[h/t Marcel Vos; Boost 2012 Report (forthcoming)]

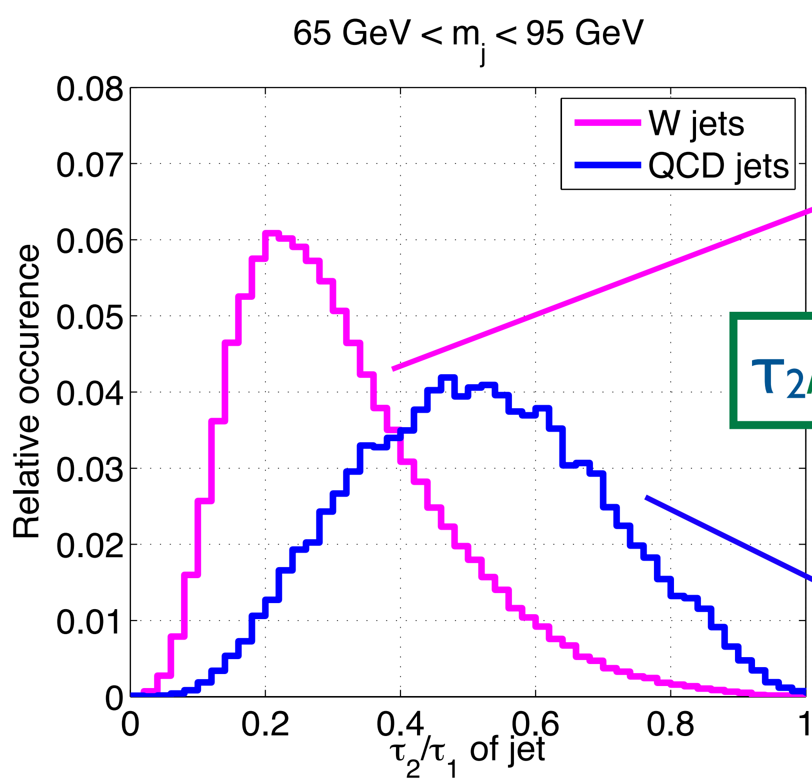


Semi-leptonic t-tbar: Not so extreme at 13/14 TeV

[CMS PAS B2G-12-006]

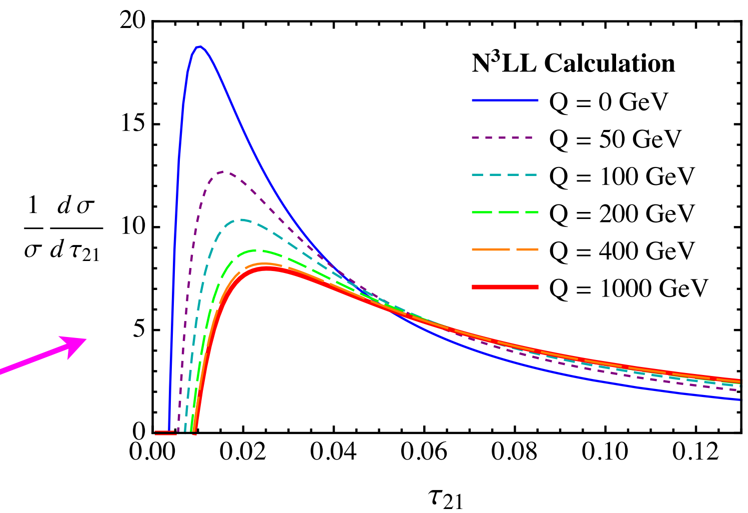
Validating 2-subjettiness

Calculations & Measurements



τ_2/τ_1

W-like

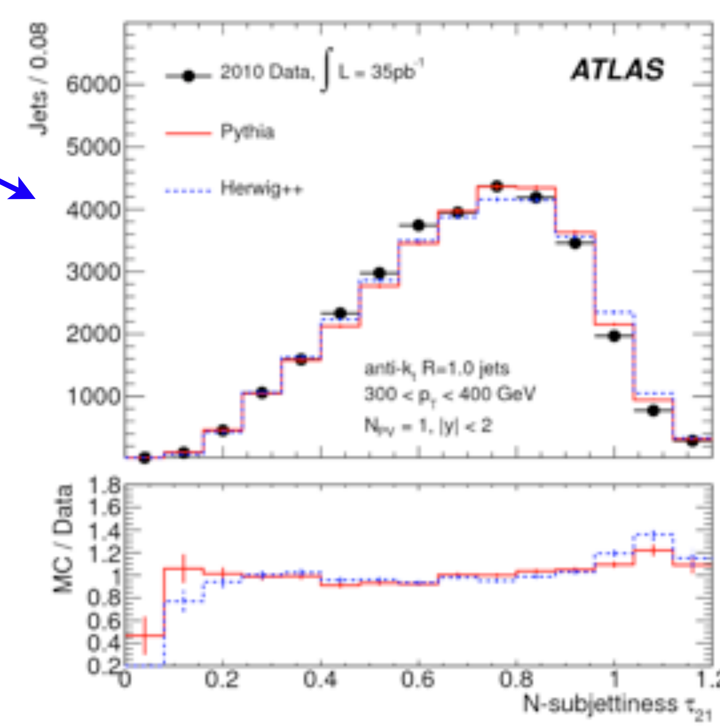


$$W \;\rightarrow\; q\bar{q}'$$

Color singlet resonance at N^{3}LL for β = 2

[Fiege, Schwartz, Stewart, JDT]

QCD-like



Measure in dijets at low pileup

Good agreement with parton showers

[ATLAS: CERN-PH-EP-2012-031]