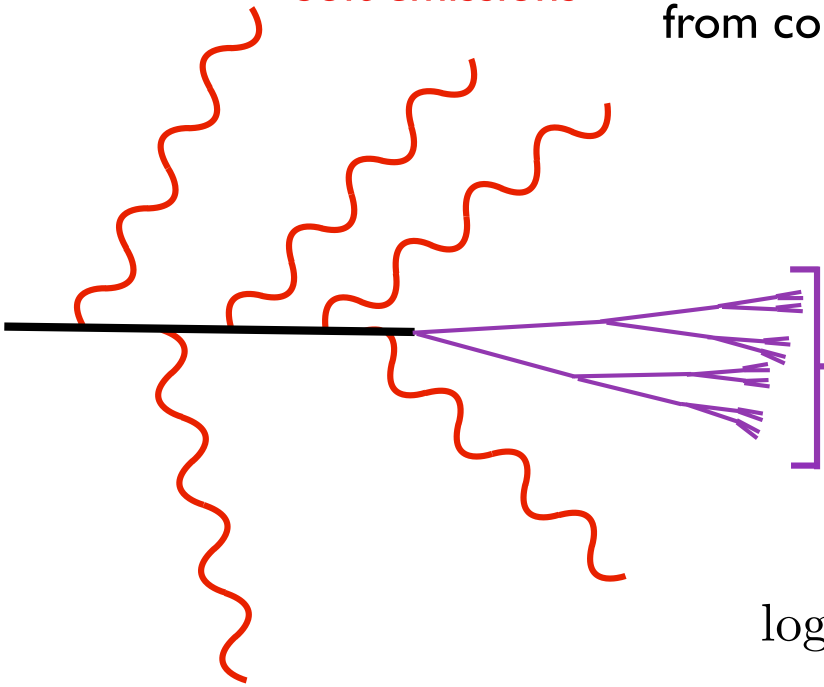
Theoretical Status of Jet Substructure

Andrew Larkoski
MIT

LPC Workshop: JetMET at High Pile-up, Preparation for LHC Run II, January 27, 2014

Introduction

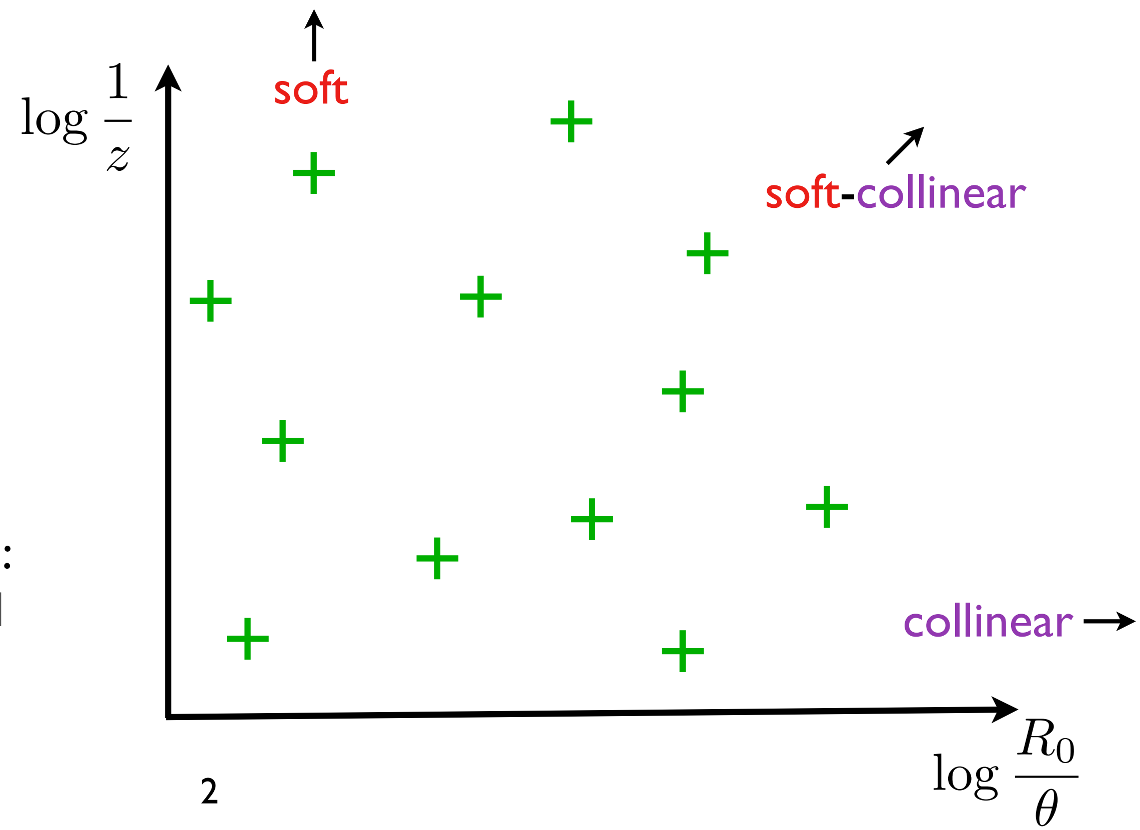


Soft emissions described by coherent emission from color-singlet antennae

Collinear emissions described by Altarelli-Parisi parton evolution

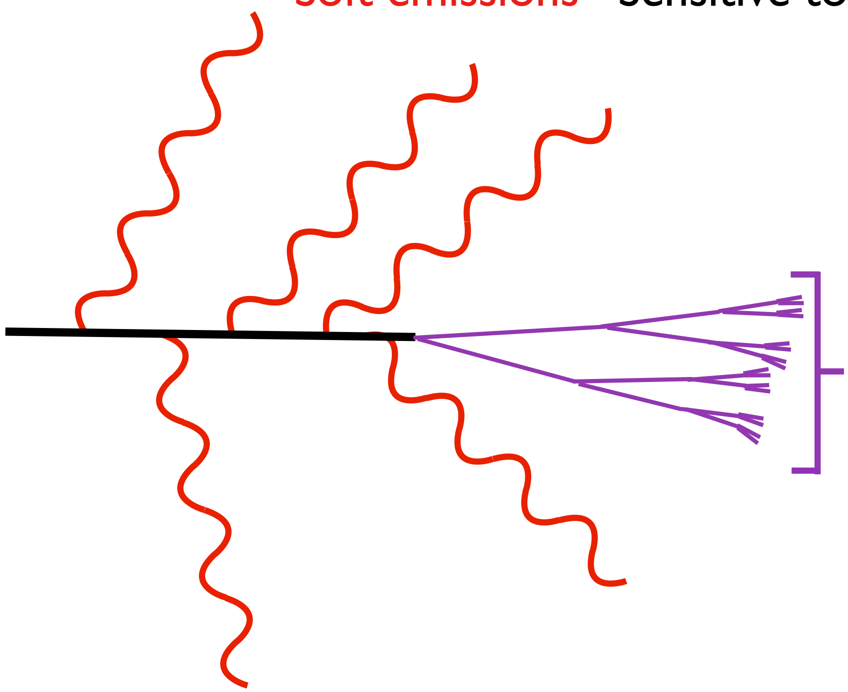
Parton Shower/Resummation:
Jet emitting soft or collinear particles in a Poisson-like process or Markov chain

Leading Logarithmic Approximation:
Emissions are uniformly distributed in ($\log 1/\theta$, $\log 1/z$) plane



Introduction

Soft emissions Sensitive to total color of jet



Collinear emissions

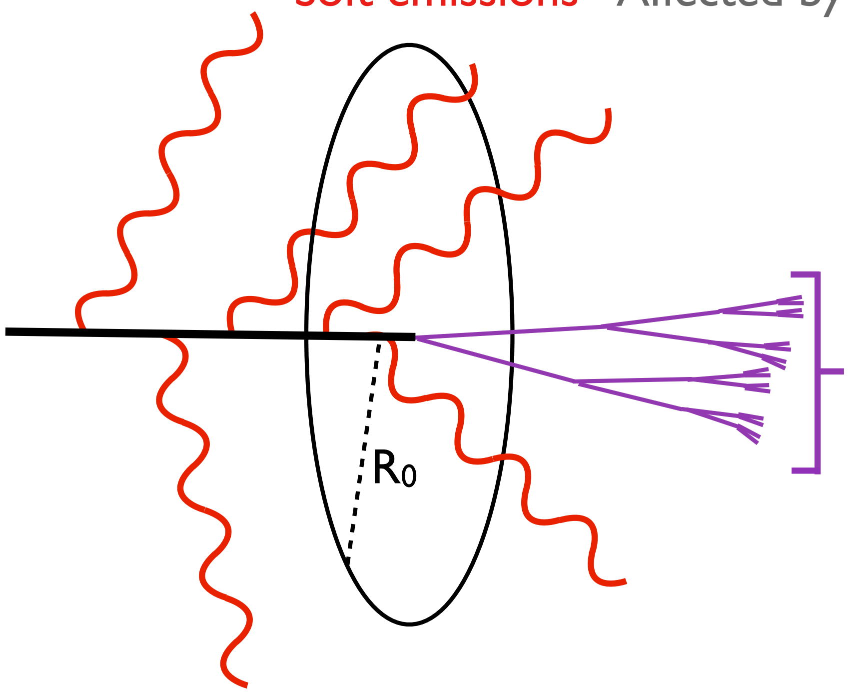
Sensitive to color, spin of jet

Exploited in, e.g. pTD and C_1 for quark vs. gluon discrimination

Introduction

Sensitive to total color of jet

Soft emissions Affected by finite jet radius



Collinear emissions

Sensitive to color, spin of jet

Exploited in, e.g. pTD and C_1 for quark vs. gluon discrimination

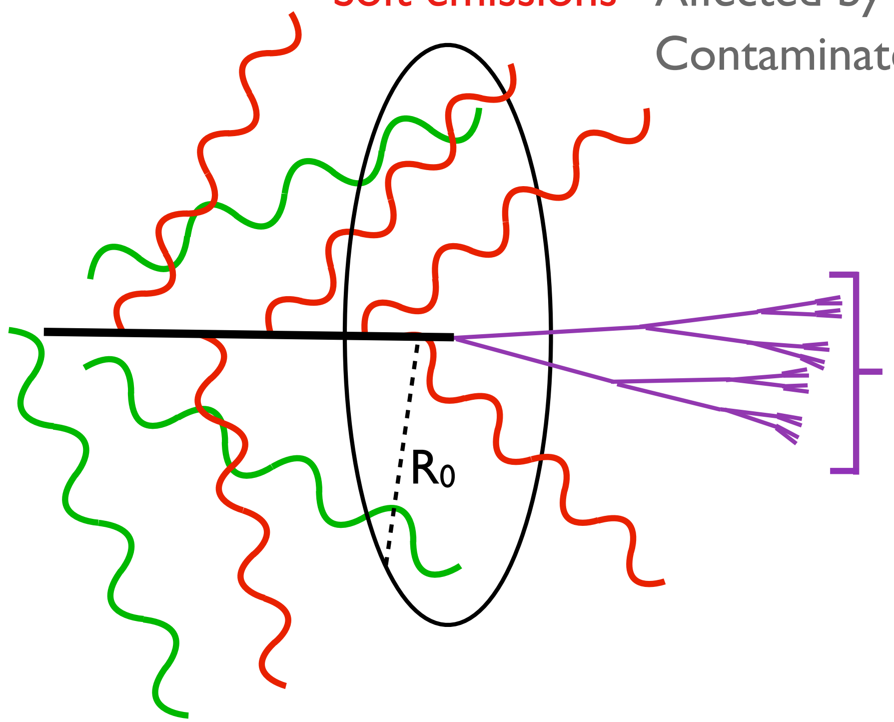
Introduction

Soft emissions

Sensitive to total color of jet

Affected by finite jet radius

Contaminated by uncorrelated radiation



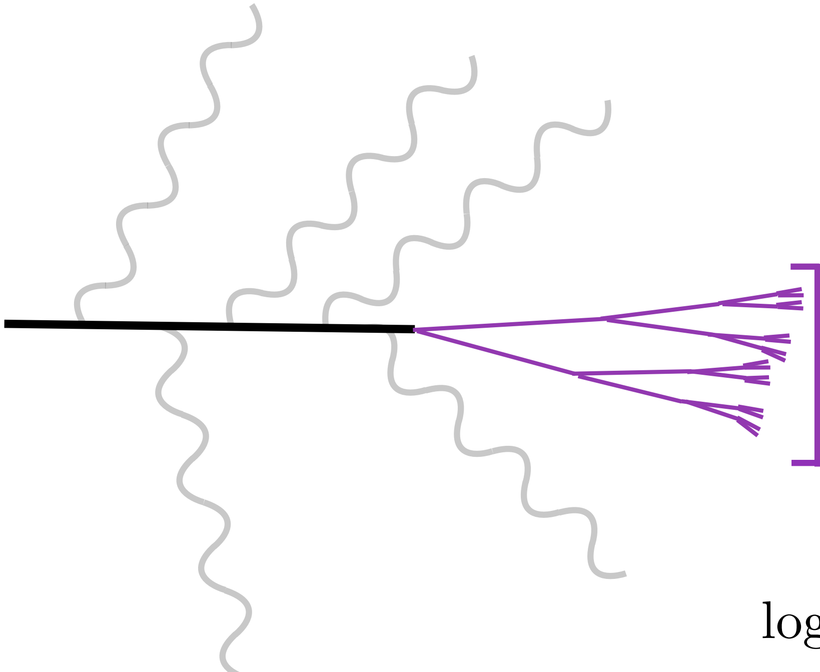
Collinear emissions

Sensitive to color, spin of jet

Exploited in, e.g. pTD and C_1 for quark vs. gluon discrimination

Underlying Event
Initial State Radiation
Pile-Up

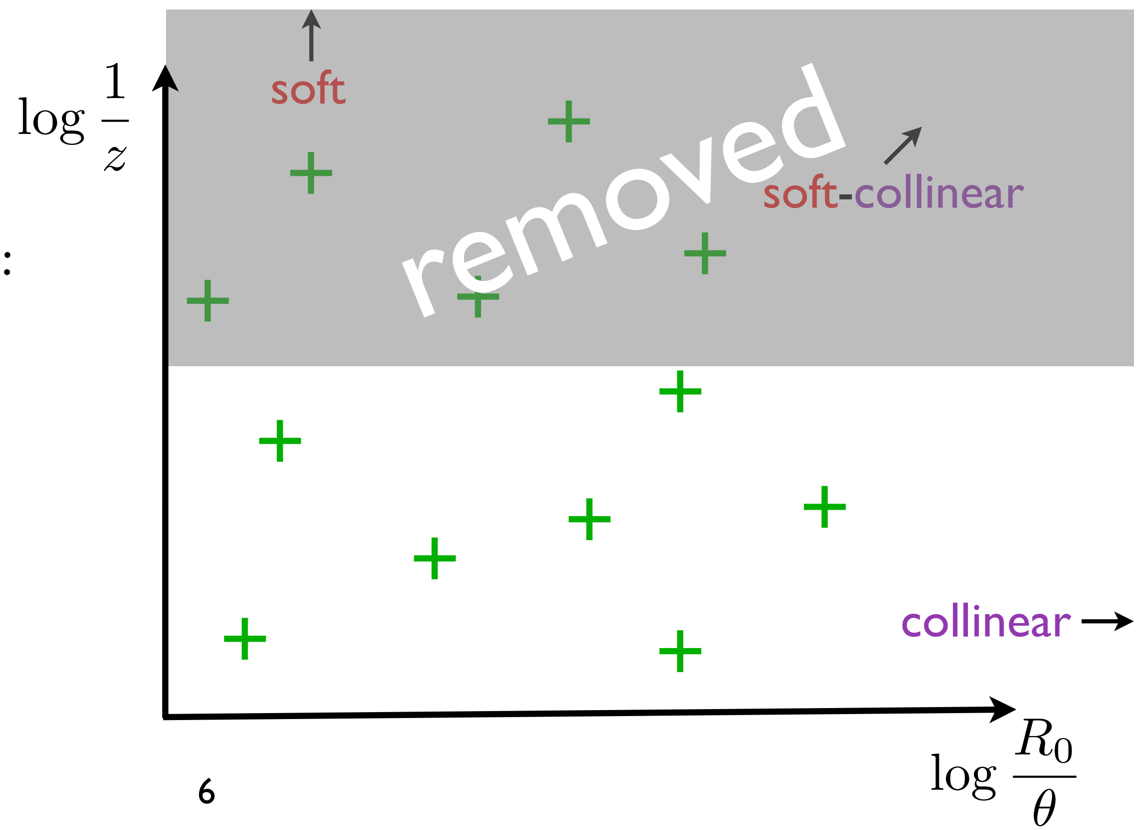
Introduction



Collinear emissions
Accurately described by
Monte Carlo, analytics

Removing sensitivity to soft radiation:
Contamination is reduced
Jet radius dependence is eliminated

Removing sensitivity to soft-collinear radiation:
Many observables become scale invariant; controlled behavior over a wide dynamic range



Outline

Recoil-free axes, observables and jet algorithms

Energy Correlation Functions (ECF)
Broadening Axis Angularities
"Winner-Take-All" Jet Recombination

Observables with no/reduced soft divergences

modified Mass Drop Tagger (mMDT)
Soft Drop Grooming

Observables for tagging Pile-Up Jets

Angles between jet axes

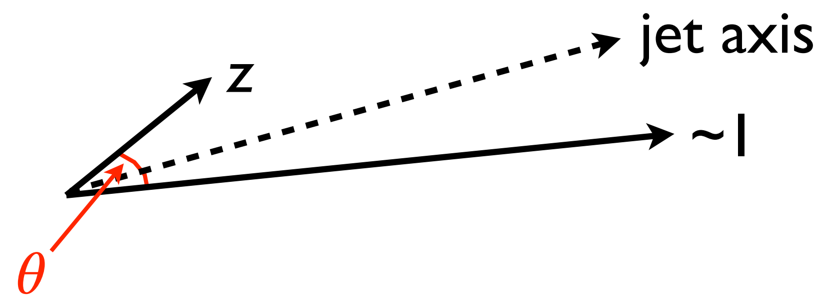
Recoil Sensitivity

AJL, G. Salam, J. Thaler 1305.0007
AJL, D. Neill, J. Thaler 1401.2158

Effect of Recoil

$$\tau^{(\beta)} = \frac{1}{p_{TJ}} \sum_{i \in J} p_{Ti} R_i^\beta \simeq \sum_{i \in J} z_i \theta_i^\beta$$

angle from particle *i* to jet axis



$$\tau^{(\beta)} \simeq z^\beta \theta^\beta + z\theta^\beta$$

"recoil" contribution

"direct" contribution

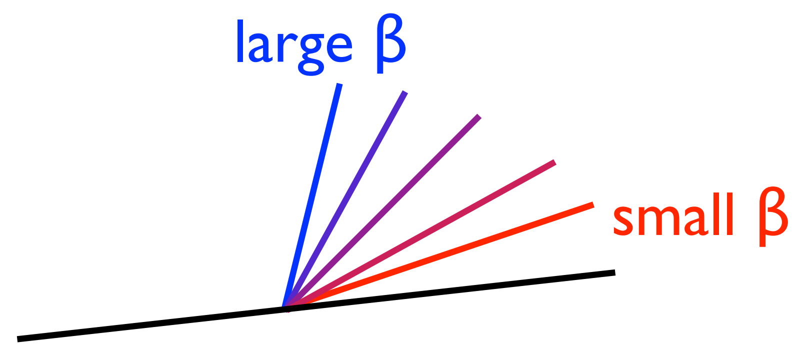
$\beta > 1: \quad \tau^{(\beta)} \to z\theta^\beta$ — includes thrust/mass (β = 2)

$\beta = 1: \quad \tau^{(\beta)} \to 2z\theta$ — broadening/width/girth

$\beta < 1: \quad \tau^{(\beta)} \to (z\theta)^\beta$ — recoil-dominated angularities

Quark vs. Gluon Discrimination

$$\tau^{(\beta)} = \frac{1}{p_{T\text{jet}}} \sum_{i \in J} p_{Ti} R_{iJ}^{\beta}$$



β = 2:
thrust, jet mass

β = 1:
broadening/width/girth

Large β: Dominated by soft radiation
Sensitive to total color of jet

Small β: Dominated by collinear radiation
Sensitive to color and spin of jet

Expect better quark/gluon discrimination at small β

*For $n_F = C_A$, no improvement over LL discrimination

Issue of Recoil

Two resolutions:

Observable does not reference an axis at all

Observable is measured with respect to a recoil-free axis

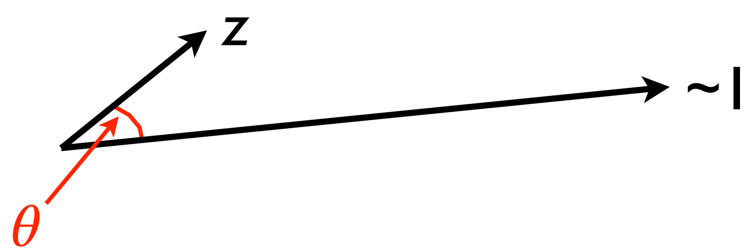
Issue of Recoil

Two resolutions:

Observable does not reference an axis at all

Observable is measured with respect to a recoil-free axis

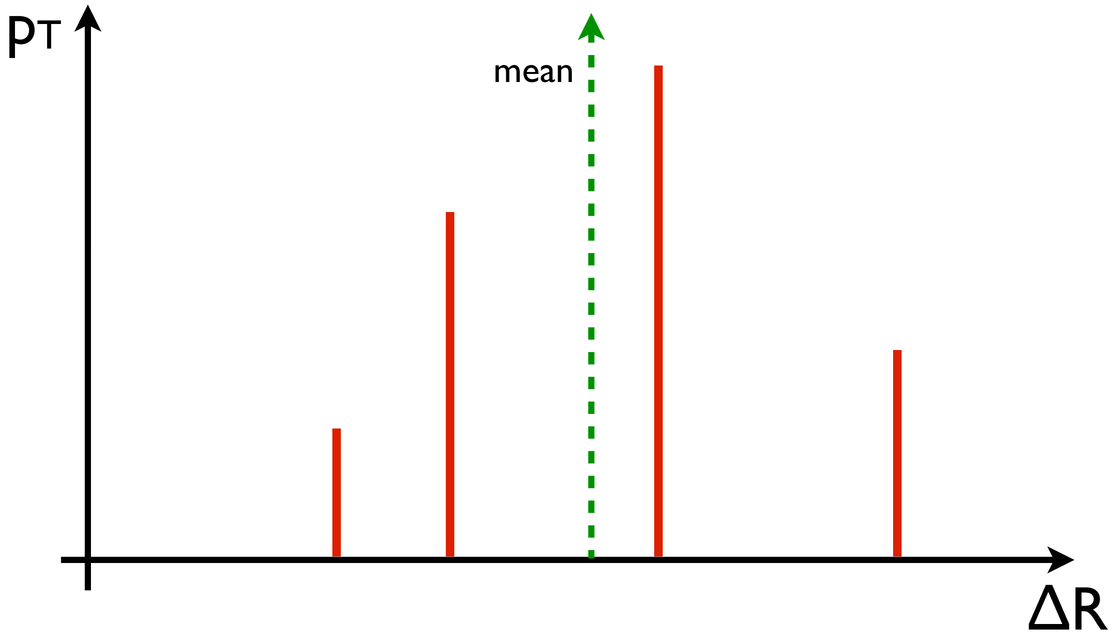
$$C_1^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{i,j \in J} p_{Ti} p_{Tj} R_{ij}^\beta$$



$$C_1^{(\beta)} \simeq z\theta^\beta$$

Issue of Recoil

Interlude: Recoil-Free Axes



"Mean Axis"

Affected by outliers

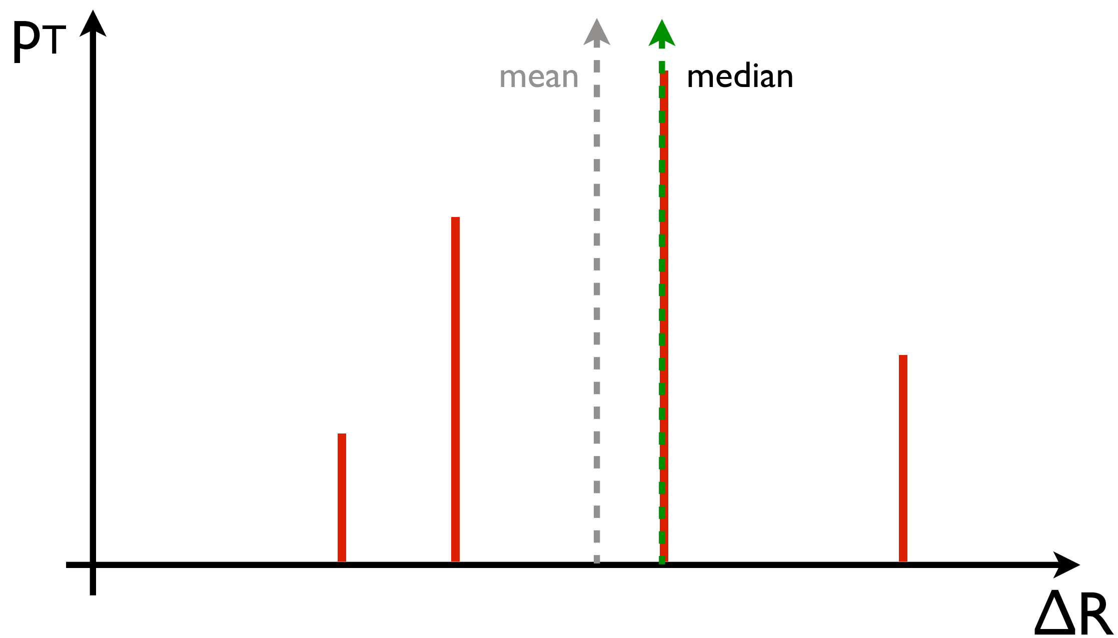
Defined by summing particles' momenta

$$\min_{\hat{t}} \sum_{i \in J} p_{Ti} R_{i\hat{t}}^2$$

Equivalent to thrust axis

Issue of Recoil

Interlude: Recoil-Free Axes



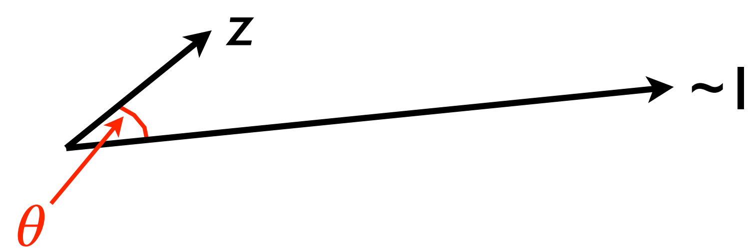
"Mean Axis"		"Median Axis"	
Affected by outliers		Unaffected by outliers	
Defined by summing particles' momenta	$\min_{\hat{t}} \sum_{i \in J} p_{Ti} R_{i\hat{t}}^2$	No closed-form expression	$\min_{\hat{b}} \sum_{i \in J} p_{Ti} R_{i\hat{b}}$
Equivalent to thrust axis		Defined as "broadening axis"	

Issue of Recoil

Two resolutions:

Observable does not reference an axis at all

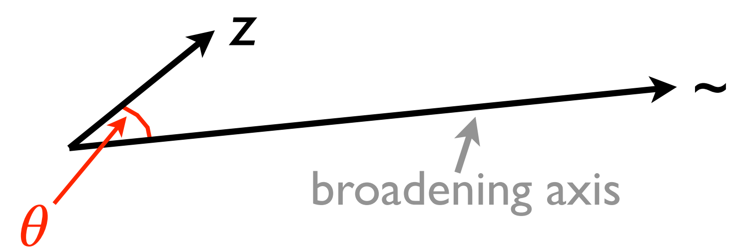
$$C_1^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{i,j \in J} p_{Ti} p_{Tj} R_{ij}^{\beta}$$



$$C_1^{(\beta)} \simeq z\theta^{\beta}$$

Observable is measured with respect to a recoil-free axis

$$\tau_{\hat{b}}^{(\beta)} = \frac{1}{p_{TJ}} \sum_{i \in J} p_{Ti} R_{i\hat{b}}^{\beta}$$



$$\tau_{\hat{b}}^{(\beta)} \simeq z\theta^{\beta}$$

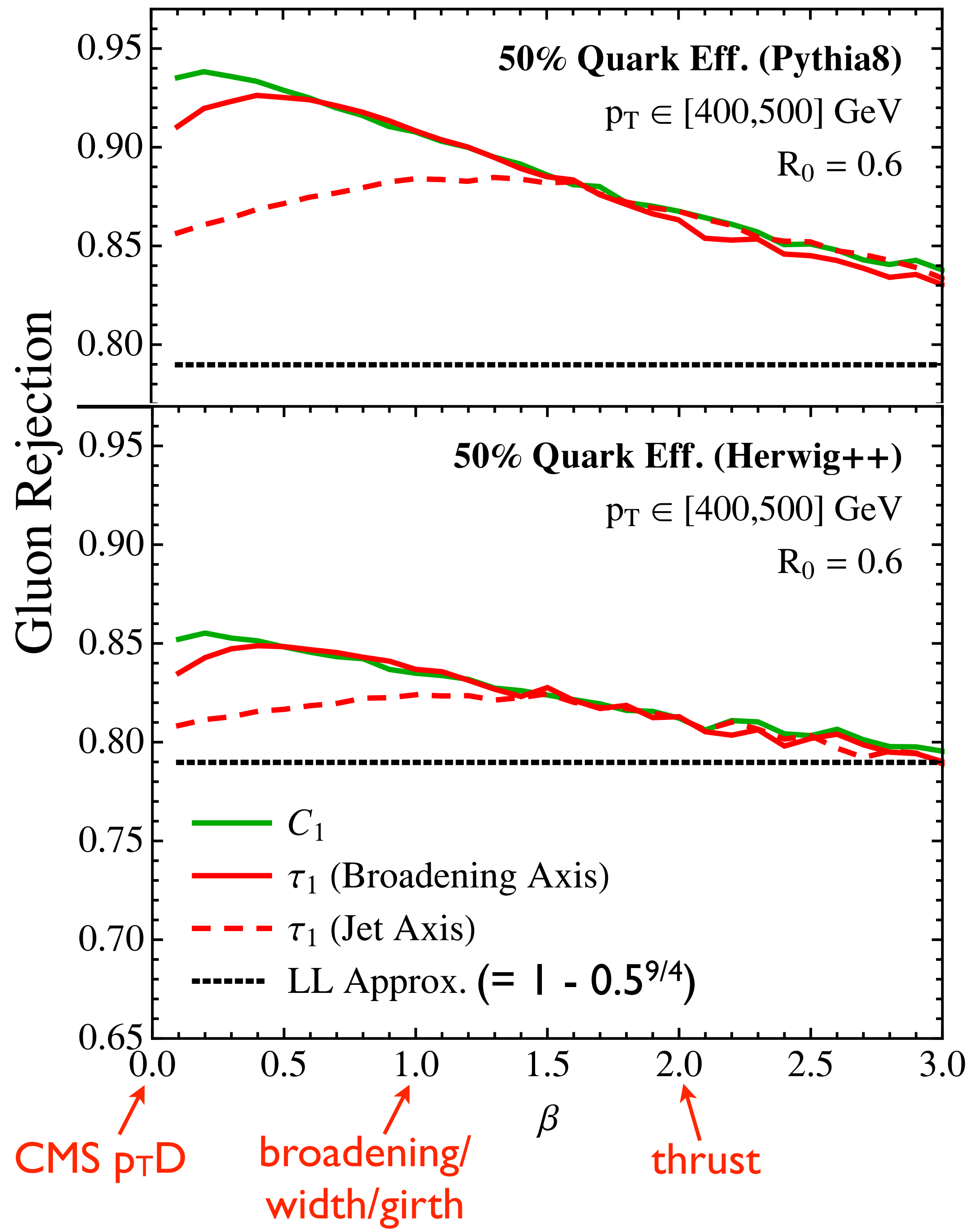
Monte Carlo

Improved discrimination with recoil-free observables

Significant difference between Pythia and Herwig (and data?)

Tune Monte Carlo to rejection curve?

Deviation from dashed line is formally beyond MC accuracy



Recoil-Free Jet Algorithms

Reminder: Components of jet algorithms

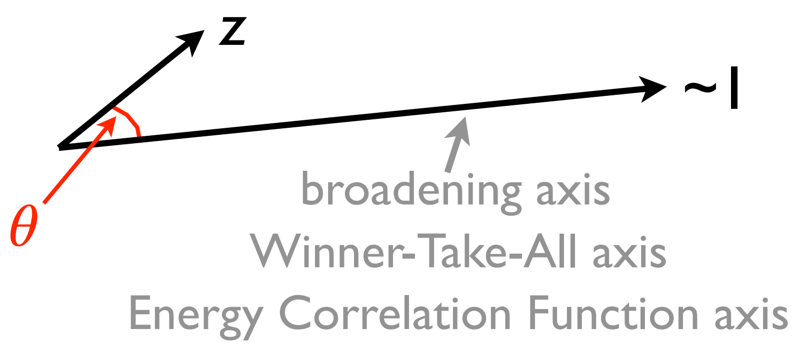
k_T metric: $d_{ij} = \min\left[p_{Ti}^n, p_{Tj}^n\right] R_{ij}^2$ $\quad d_i = p_{Ti}^n R_0^2$

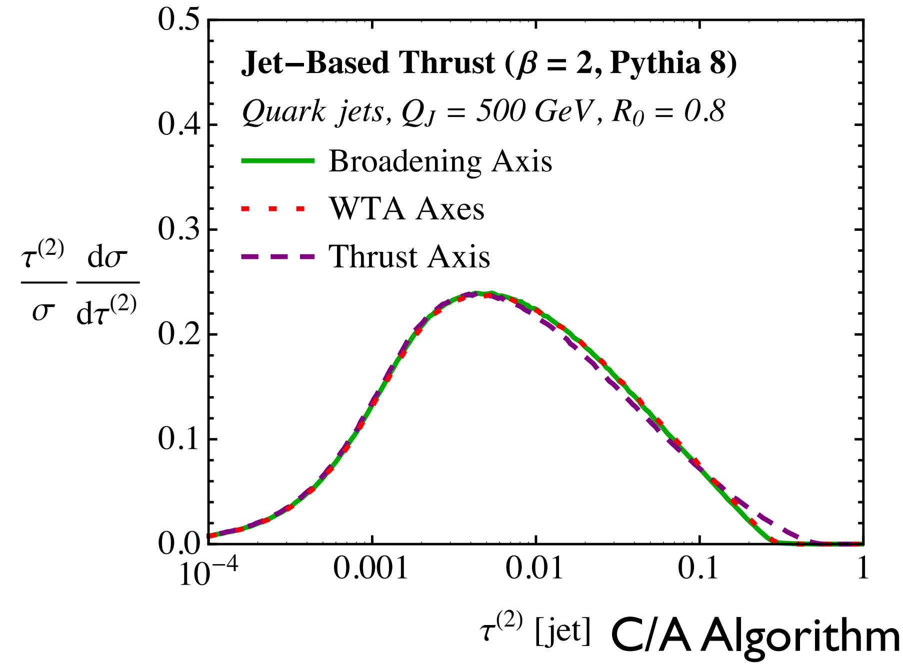
recombination scheme:

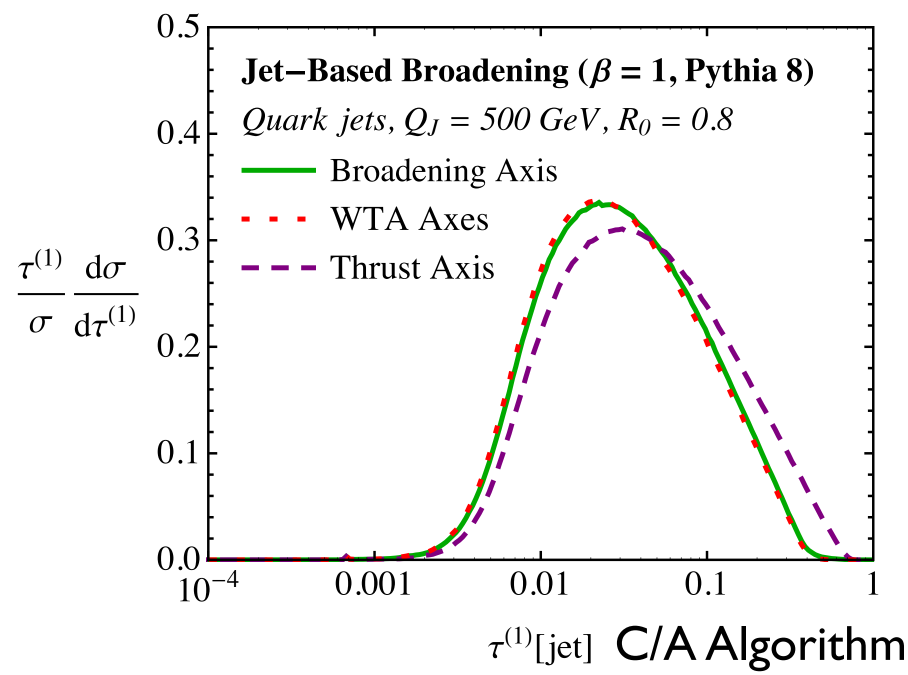
E/p_T-Scheme	p_T^2-Scheme	Winner-Take-All Scheme
$p_{TJ} = p_{Ti} + p_{Tj}$	$p_{TJ} = p_{Ti} + p_{Tj}$	$p_{TJ} = p_{Ti} + p_{Tj}$
$\phi_J = \frac{p_{Ti}\phi_i + p_{Tj}\phi_j}{p_{Ti} + p_{Tj}}$	$\phi_J = \frac{p_{Ti}^2\phi_i + p_{Tj}^2\phi_j}{p_{Ti}^2 + p_{Tj}^2}$	$\phi_J = \begin{cases} \phi_i, & p_{Ti} > p_{Tj} \\ \phi_j, & p_{Tj} > p_{Ti} \end{cases}$
$\eta_J = \frac{p_{Ti}\eta_i + p_{Tj}\eta_j}{p_{Ti} + p_{Tj}}$	$\eta_J = \frac{p_{Ti}^2\eta_i + p_{Tj}^2\eta_j}{p_{Ti}^2 + p_{Tj}^2}$	$\eta_J = \begin{cases} \eta_i, & p_{Ti} > p_{Tj} \\ \eta_j, & p_{Tj} > p_{Ti} \end{cases}$
Ubiquitous	Option in FastJet	New, simple to implement
Sensitive to recoil from soft, wide angle emissions	Less sensitive to recoil	Insensitive to recoil

Recoil-Free Jet Algorithms

Jet Axis with
WTA Recombination
=
Broadening Axis





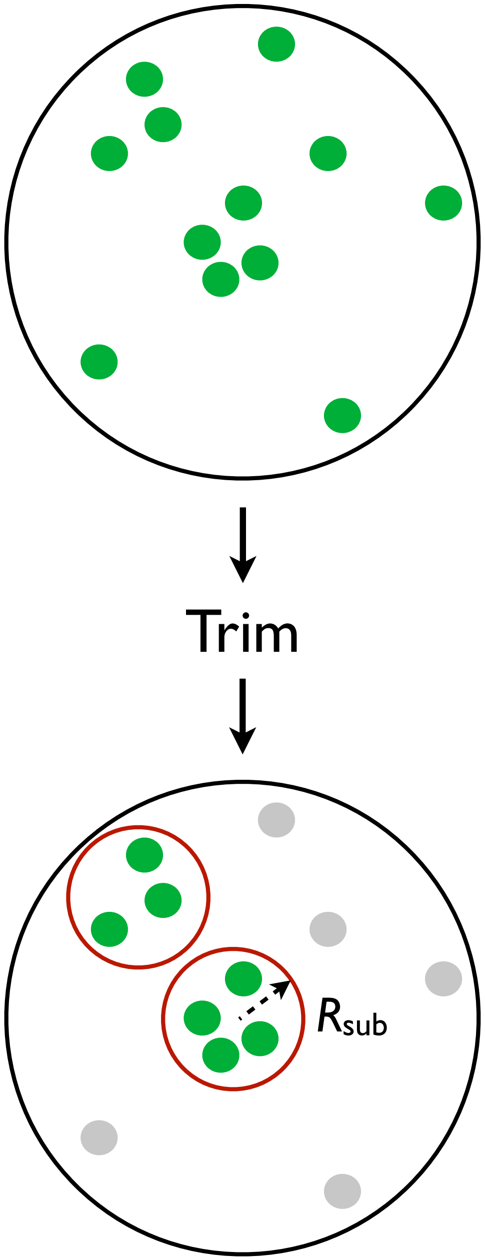


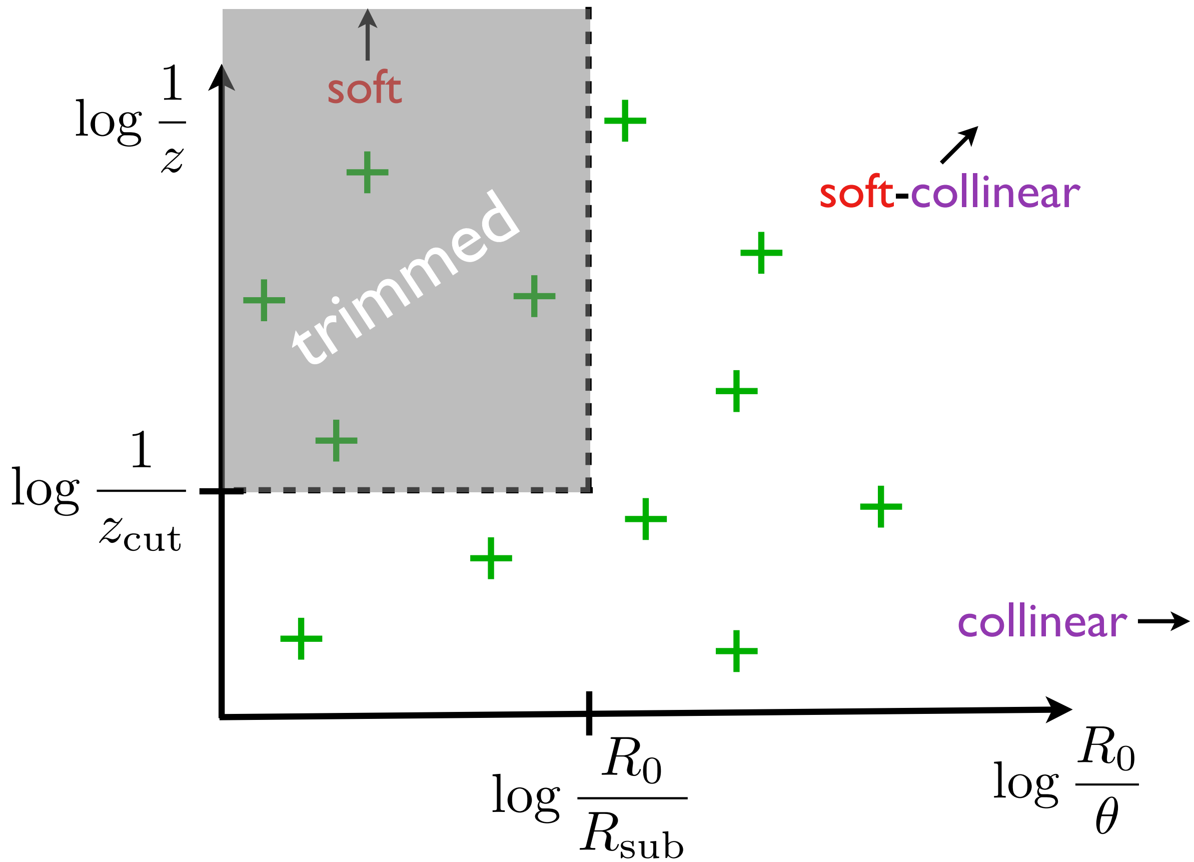
Moral:
To remove recoil contamination, define axis that only depends on hard, collinear particles in jet

Soft Divergence-Free Observables

J. Tseng, H. Evans 1304.1025
M. Dasgupta, A. Fregoso, S. Marzani, G. Salam 1307.0007
AJL, S. Marzani, G. Soyez, J. Thaler 140X.xxxx

Removing Soft Divergences





Removing Soft Divergences

Soft Drop Grooming

For a jet with two particles:

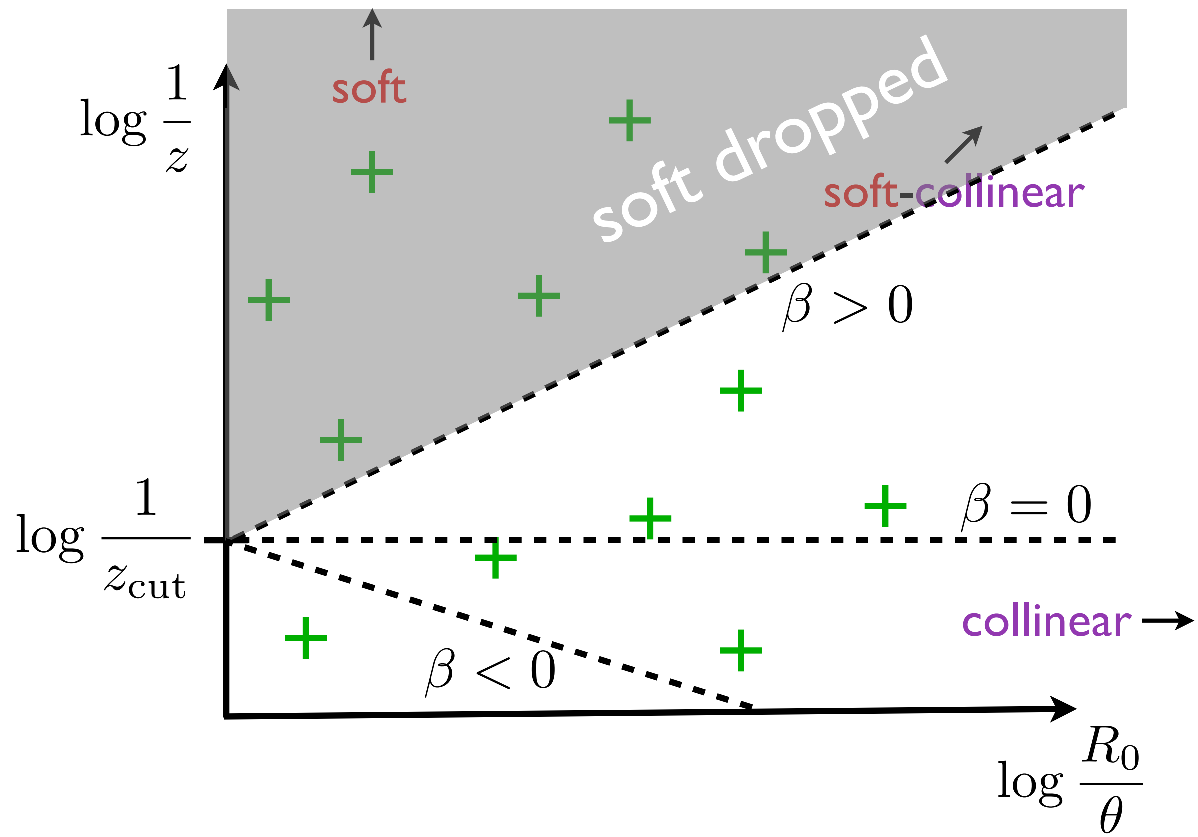
$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

β = ∞
no grooming

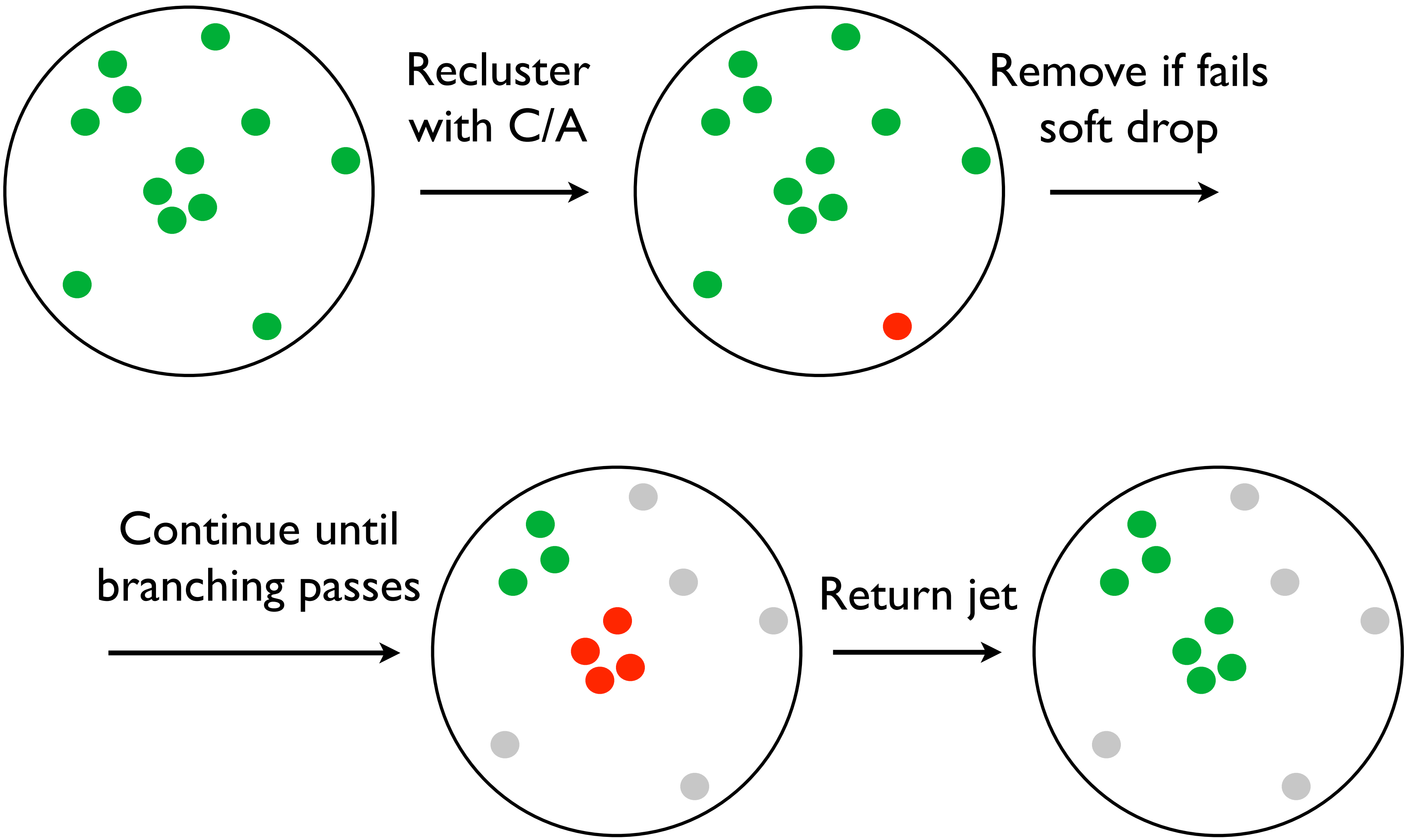
β > 0
soft, wide angle removed
some soft-collinear removed

β = 0
all soft emissions removed
modified Mass Drop limit

β < 0
all soft and collinear
emissions removed

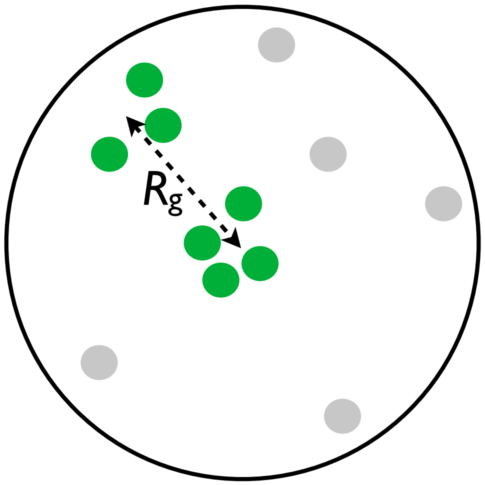


Removing Soft Divergences



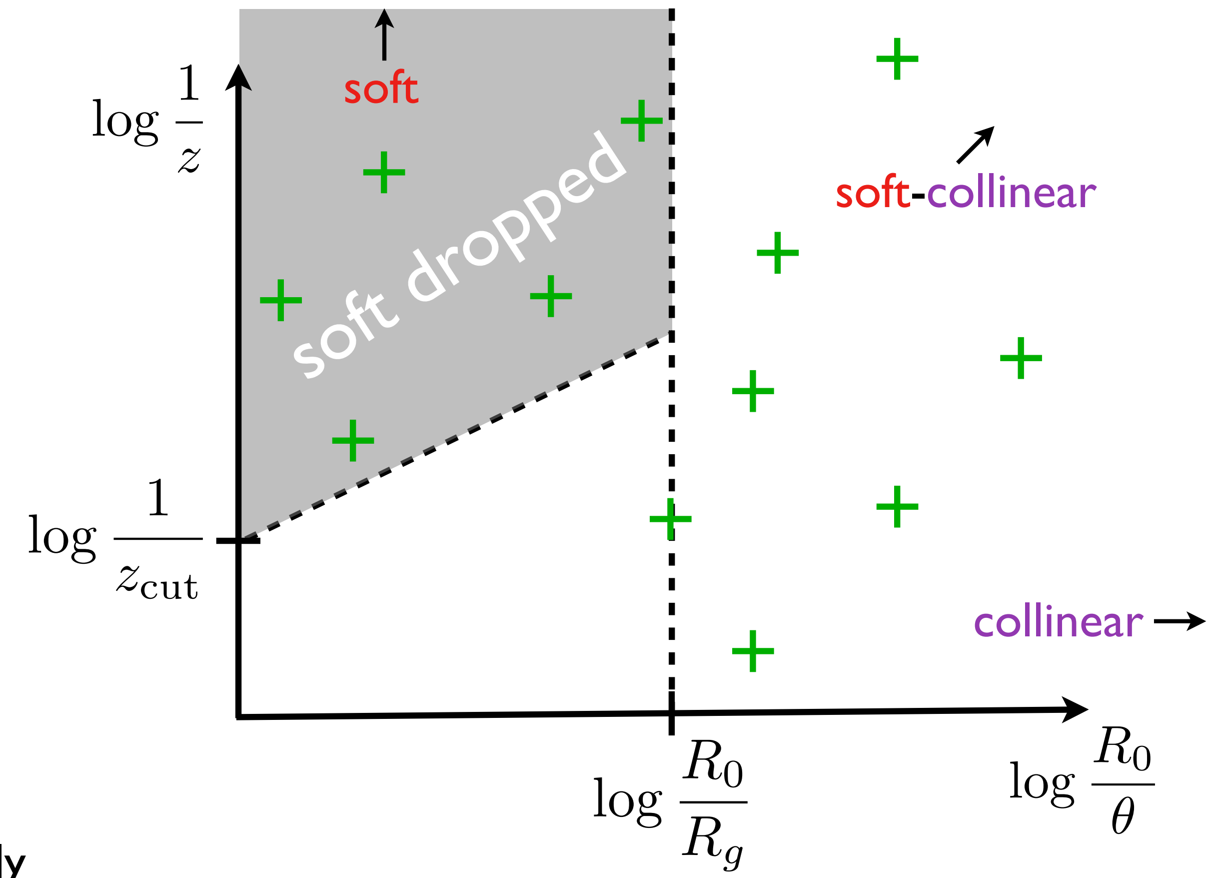
Removing Soft Divergences

Soft-Drop Groomed Jet

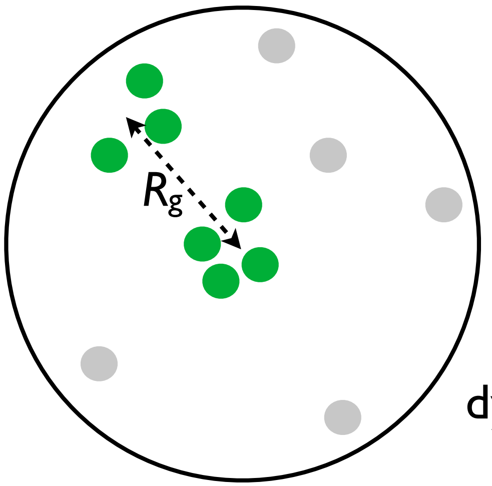


Removes soft, wide angle radiation

Groomed jet radius is set by the dynamics of the jet, and not externally



Groomed Jet Radius

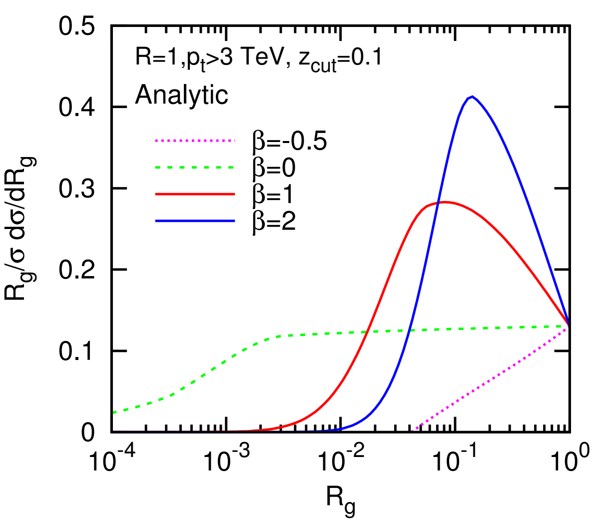


Groomed jet radius is set by the dynamics of the jet, and not externally

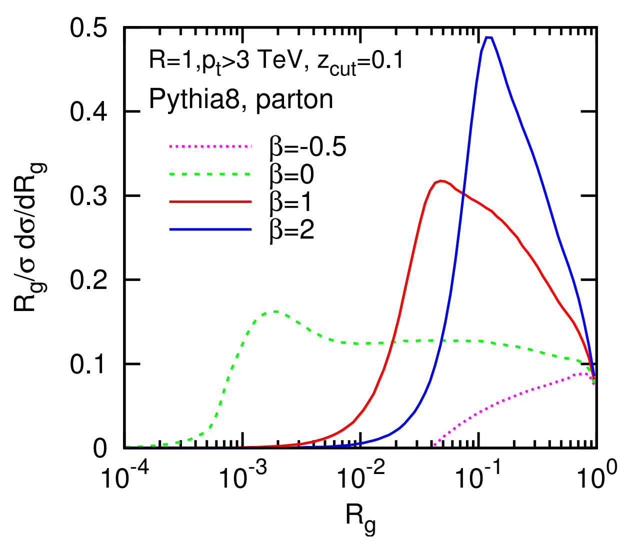
Effective measure of sensitivity to pile-up

$$R_{\rm eff} = \left(\frac{A_{\rm active}}{\pi}\right)^{1/2}$$

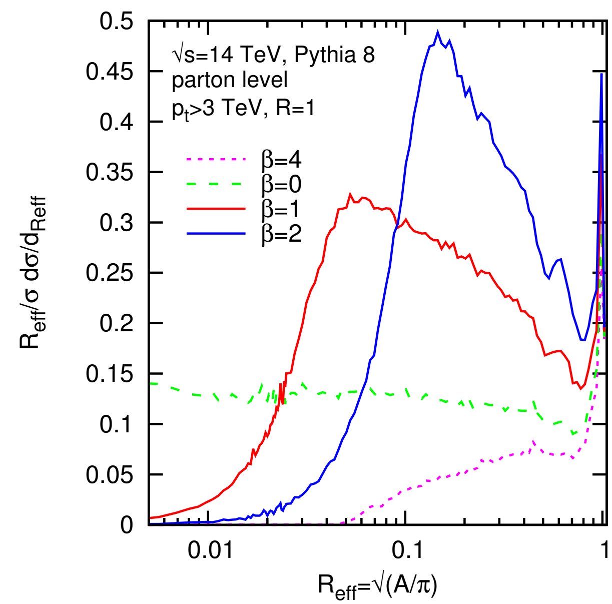
Well-understood analytically and well-modeled in Monte Carlo



analytic



monte carlo

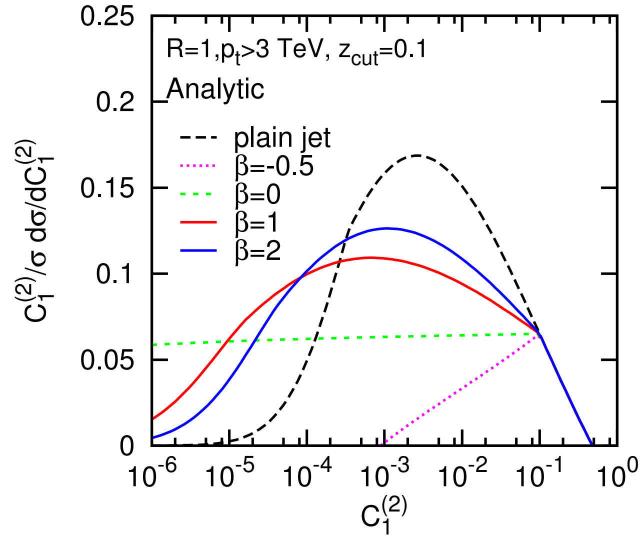


active jet radius

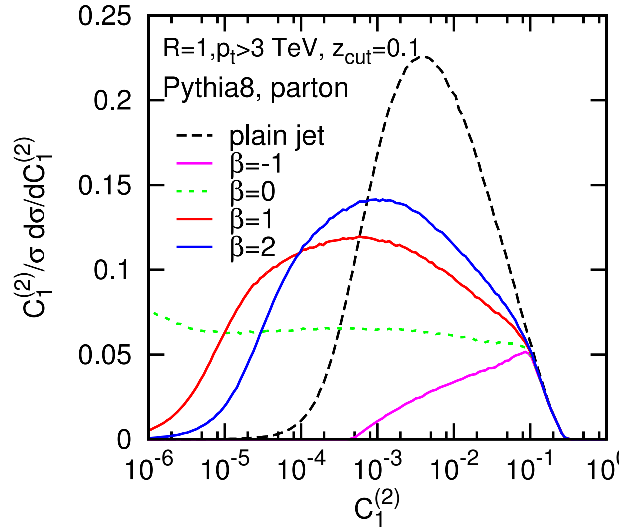
Observables with no/reduced softs

mass/thrust

Soft-collinear logarithms manifest themselves as concave down parabola



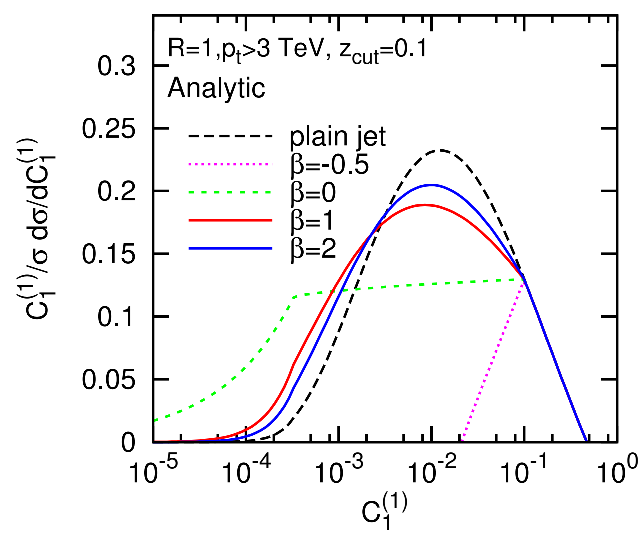
analytic



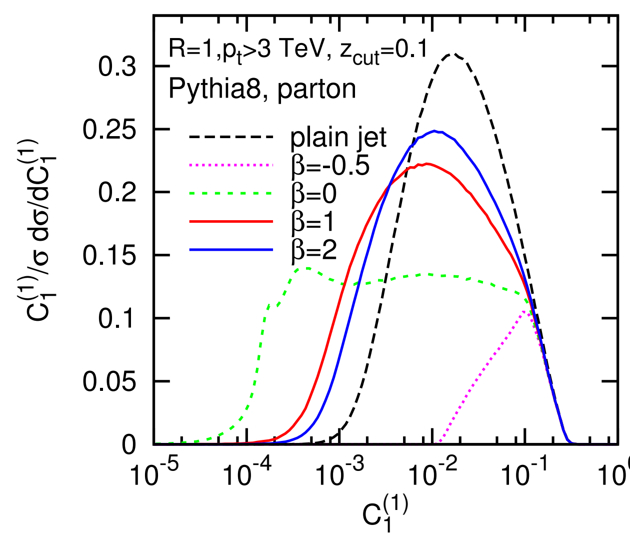
monte carlo

As β → 0, the parabola disappears indicating that soft radiation is removed

broadening



analytic



monte carlo

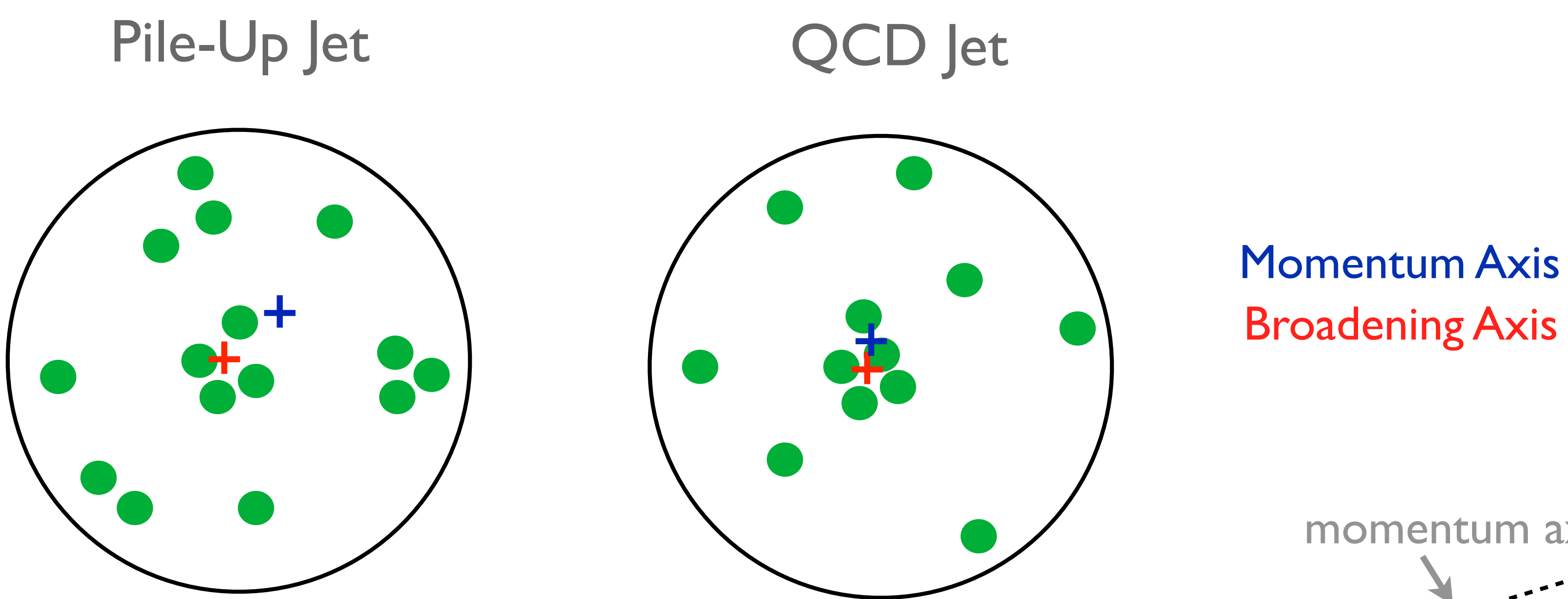
Sideband analysis could simplify in this limit

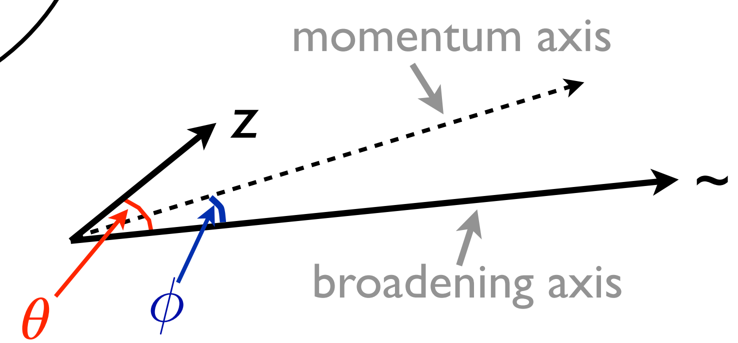
Pile-Up Jet Observables

M. Freytsis, BOOST 2012 talk
D. Curtin, R. Essig, B. Shuve 1210.5523

Ex: Pile-Up tagging observable

Pile-Up jet versus QCD





Angle between momentum and broadening axes ~ |mean - median|

Measure of non-zero skewness of distribution of energy in jet

$$\phi \simeq z\theta \simeq C_1^{(1)} \simeq \tau_{\hat{b}}^{(1)}$$

Recoil-free broadening

Conclusions

Recoil-free observables and jet algorithms should have wide-spread use in experiment

Soft-drop grooming techniques generalize mMDT and have nicer properties than, e.g., trimming

The angle between the momentum and broadening axes in a jet should provide a pile-up jet discriminant