Aspects of Jets at 100 TeV

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AJL, J. Thaler arXiv:1406.7011

Exploring the Physics Frontier with Circular Colliders, January 30, 2015

Fun with QCD at 100 TeV

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Outline

Pileup Sensitivity at 100 TeV

Recoil-free jet axes
Robustness to non-uniform pileup

Jet Grooming at 100 TeV

Soft-Drop Groomer
Improved mass resolution

New Standard Candles at 100 TeV

Sudakov Safe observables
α_s-independence

Event Samples

Event Generation and Showering:
Pythia 8.183
Born-level only; no fixed-order corrections

Sjöstrand, Mrenna, Skands 0710.3820

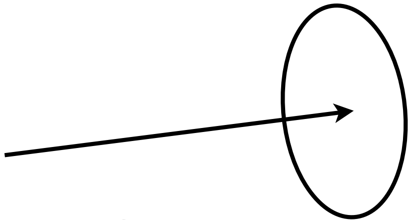
Jet Analysis:
FastJet 3.0.3
Particle level; no detector simulation

Cacciari, Salam, Soyez 1111.6097

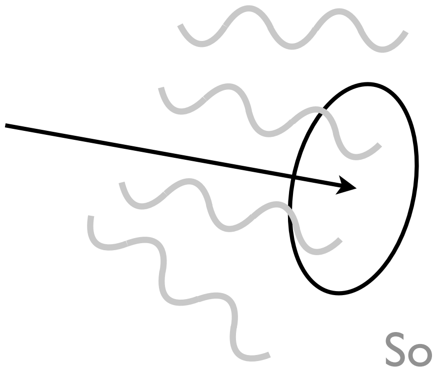
All algorithms and groomers are available in the NSubjettiness and RecursiveTools FastJet contribs

Pileup Sensitivity at 100 TeV

Pileup Sensitivity



Hard radiation/Fixed Order



Soft radiation:
Perturbative, ISR, UE, PU

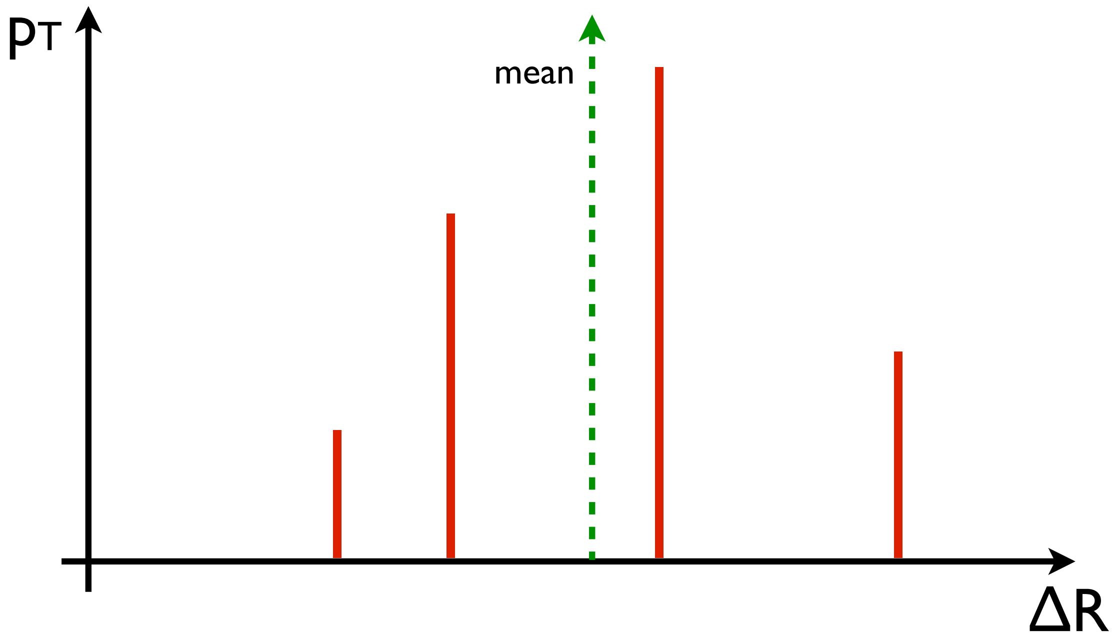
Want to define jet axes robust to soft radiation in a jet:

Experiment	Theory
Validation of pileup removal techniques	Simplifies calculations of observables AJL, Neill, Thaler 1401.2158; see: CTW 1992 vs. DLMS 1997
Robust to detector noise/resolution	Important for quark vs. gluon jet discrimination Banfi, Salam, Zanderighi 2004; AJL, Salam, Thaler 1305.0007

Traditional jet axis definition: sum of constituent momenta

"Recoil-sensitive"

Recoil-Free Axes



“Mean Axis”

Affected by outliers

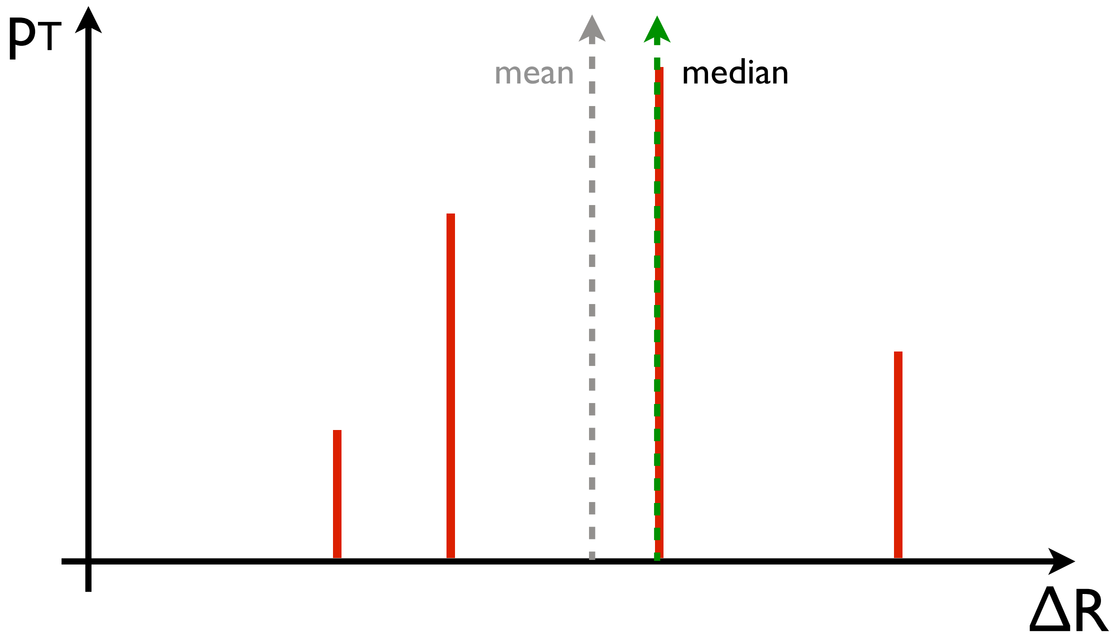
Defined by summing particles’ momenta

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

Farhi 1977

Equivalent to thrust axis

Recoil-Free Axes



"Mean Axis"		"Median Axis"	
Affected by outliers		Unaffected by outliers	
Defined by summing particles' momenta	$\min_{\hat{t}} \sum_{i\in J} p_{Ti} R^2_{i\hat{t}}$	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"	Georgi, Machacek 1977 Thaler, van Tilburg 1108.2701 AJL, Neill, Thaler 1401.2158

Reminder: Components of jet algorithms

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

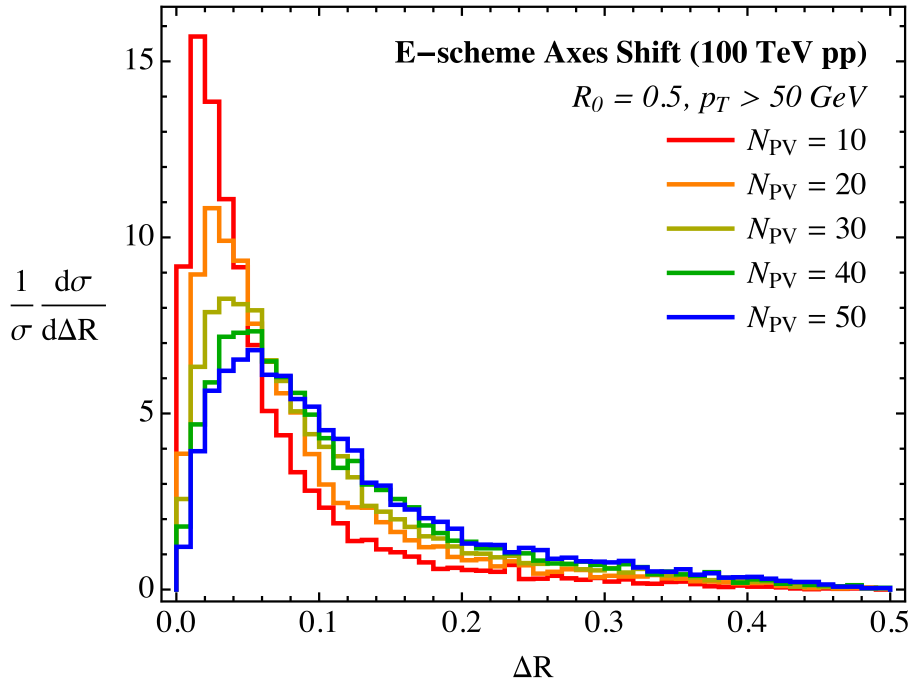
recombination scheme:

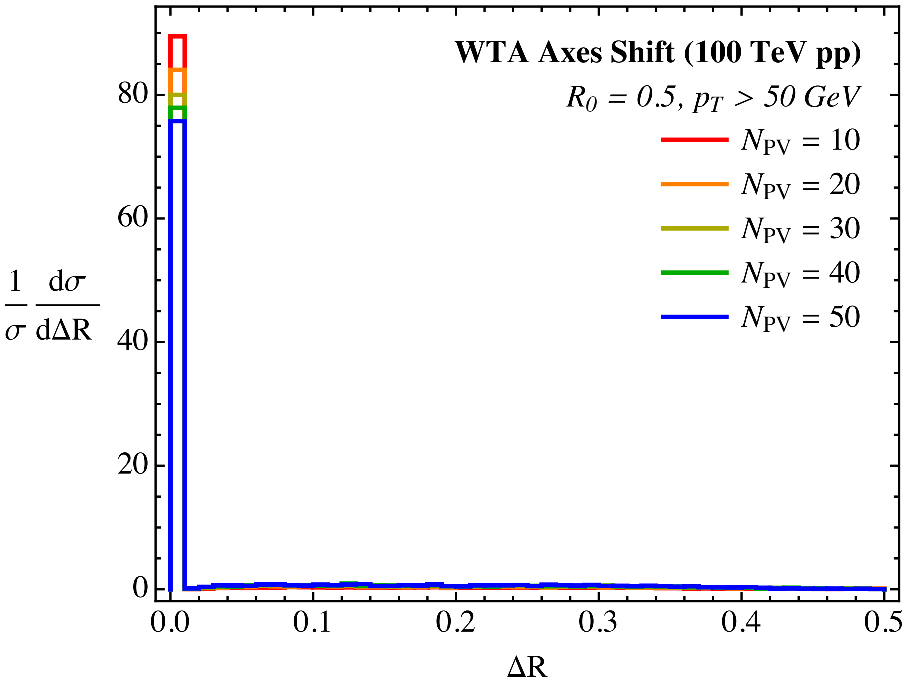
Catani, Dokshitzer, Seymour, Webber 1993
Butterworth, Couchman, Cox, Waugh 2002

Salam, unpublished
AJL, Neill, Thaler 1401.2158

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

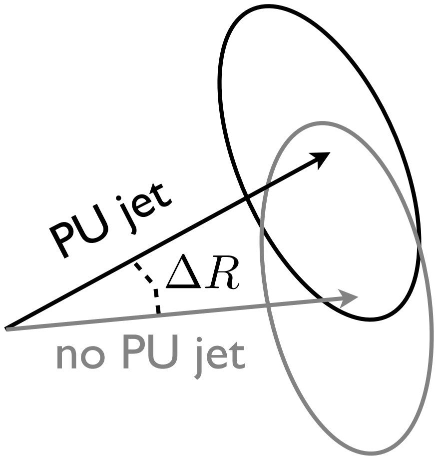
Jet Axis Sensitivity to Pileup





ΔR = 0

N_{PV}	E-scheme	WTA
10	0%	89%
50	0%	76%



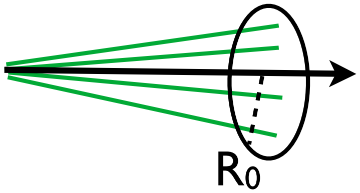
ΔR < 0.1

N_{PV}	E-scheme	WTA
10	82%	92%
50	53%	81%

larger = more robust to pileup

Non-Uniform Pileup Sensitivity

Berger, Kucs, Sterman 0303051



Jet Axis
(WTA or AKT)

$$e_\beta = \sum_{i \in J} p_{Ti} \left(\frac{R_i}{R_0} \right)^\beta$$

$e_2 = \tau$: jet thrust/mass

$e_1 = b$: jet broadening/width/girth

$e_\alpha < e_\beta$ for $\alpha > \beta$

$$\Delta \equiv e_\beta - \frac{\alpha + 2}{\beta + 2} e_\alpha$$

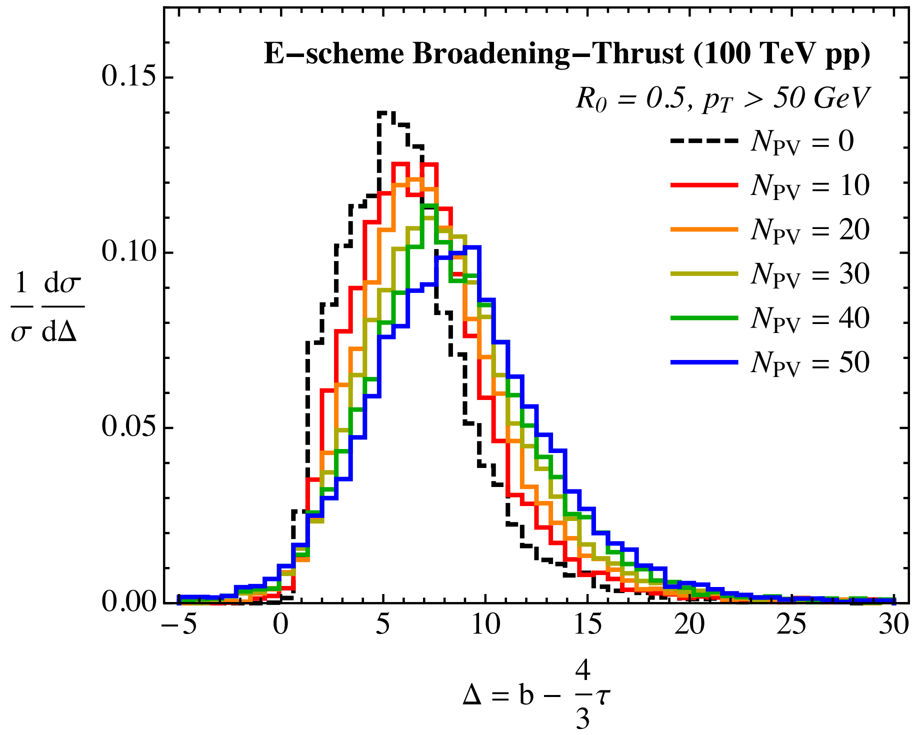
E.g.,

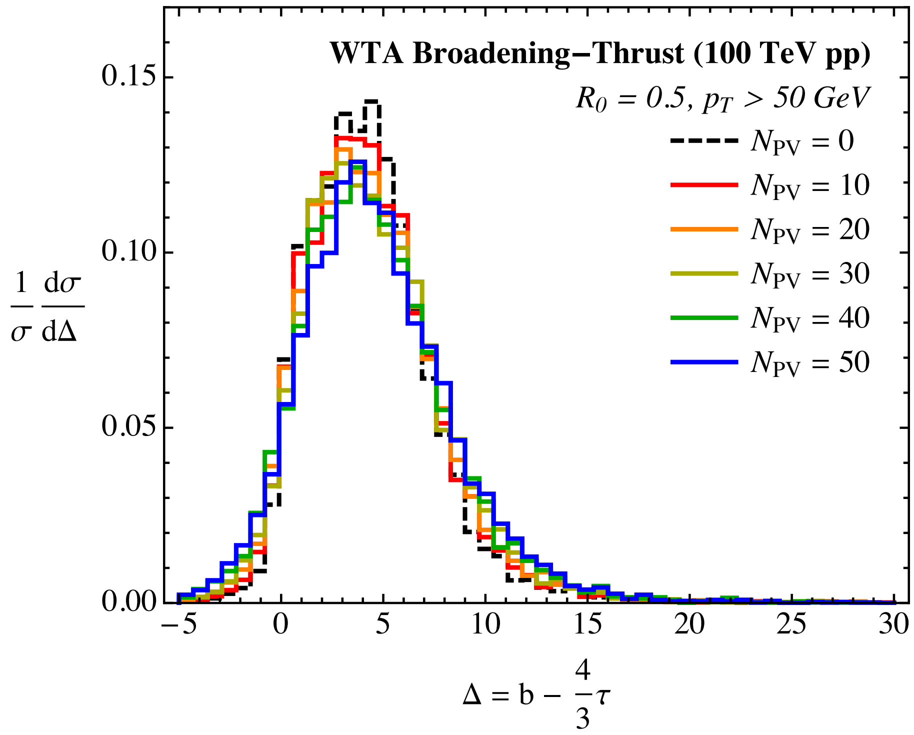
$$\Delta = b - \frac{4}{3} \tau$$

Insensitive to uniform pileup

b gets contributions from pileup over an area of the jet that is 4/3 larger than τ

Soyez, Salam, Kim, Dutta, Cacciari 2012





Pileup Sensitivity

$\langle\Delta\rangle$

N_{PV}	E-scheme	WTA
0	6.3	4.2
30	8.1	4.5
50	8.8	4.7

40% drift

$\langle\Delta^2\rangle - \langle\Delta\rangle^2$

N_{PV}	E-scheme	WTA
0	14.5	11.3
30	19.2	13.5
50	23.7	15.8

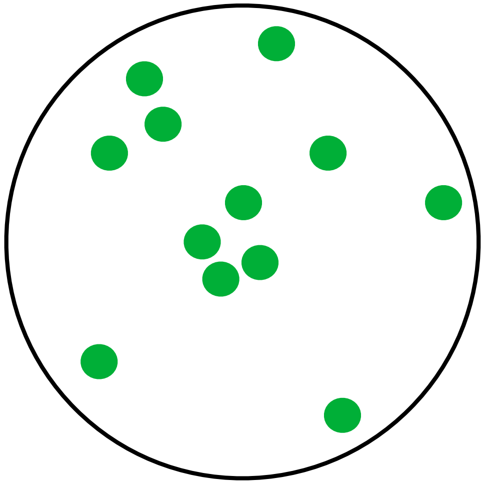
Jet Grooming at 100 TeV

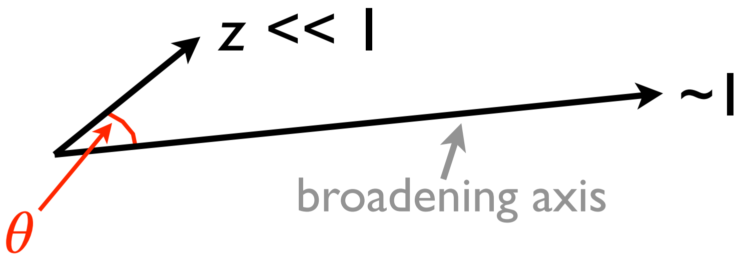
Jet Grooming

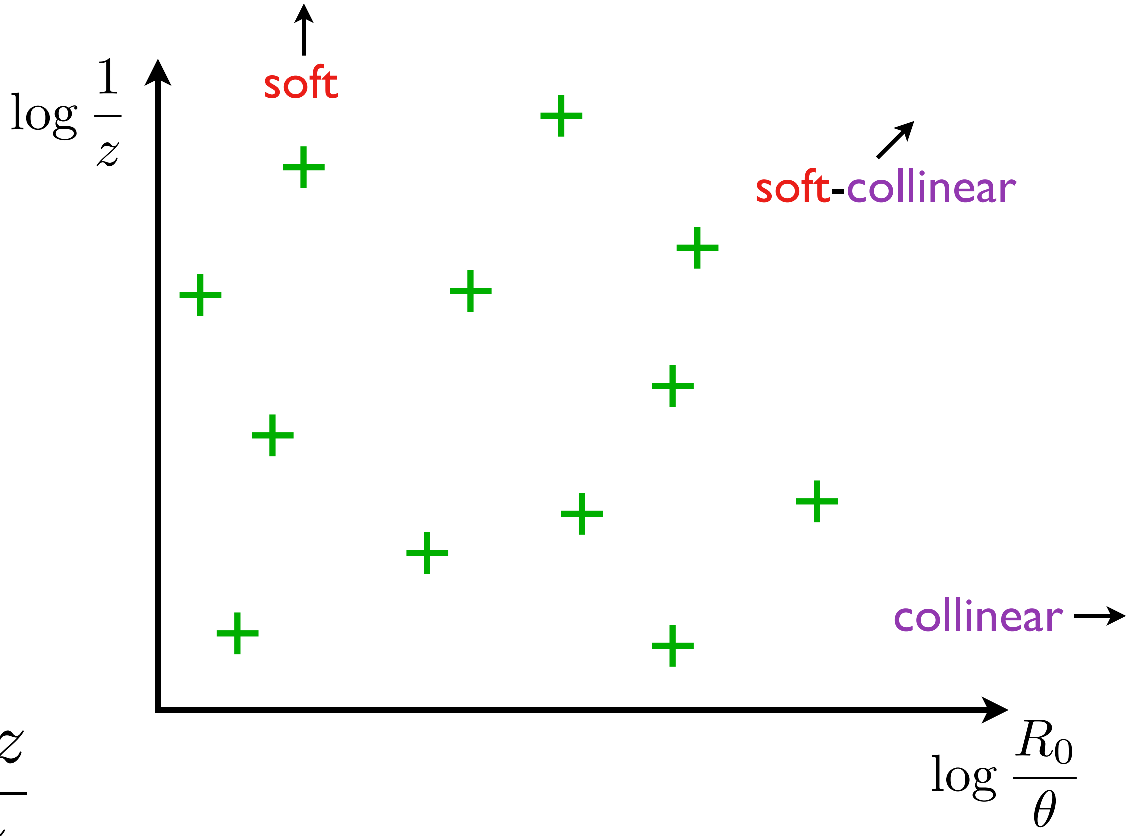
Filtering: Butterworth, Davison, Rubin, Salam 0802.2470

Pruning: Ellis, Vermilion, Walsh 0912.0033

Trimming: Krohn, Thaler, Wang 0912.1342







$$S(z,\theta)dz\,d\theta = 2\frac{\alpha_s}{\pi}C_F\frac{d\theta}{\theta}\frac{dz}{z}$$

Jet Grooming

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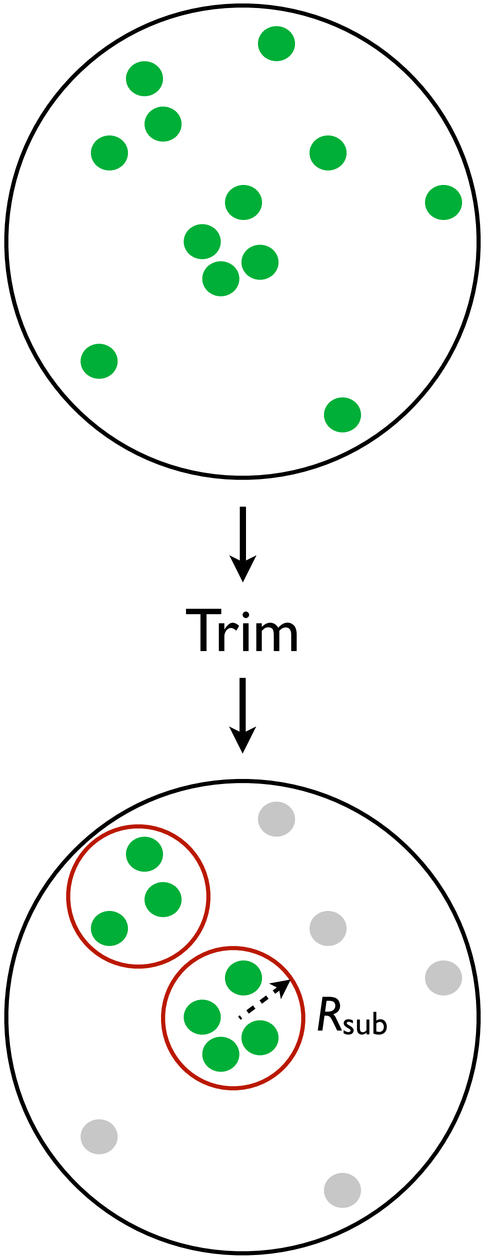
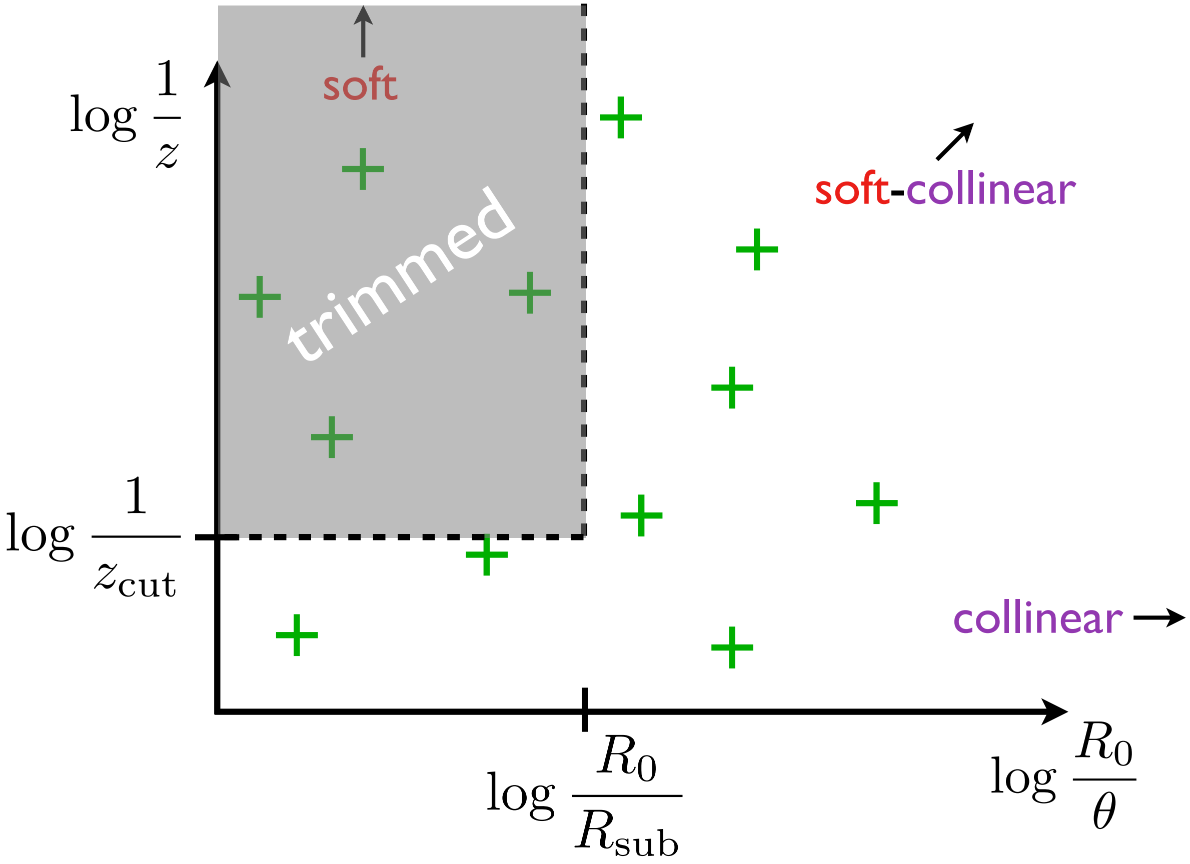




Jet Grooming: Soft Drop

AJL, Marzani, Soyez, Thaler 1402.2657

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

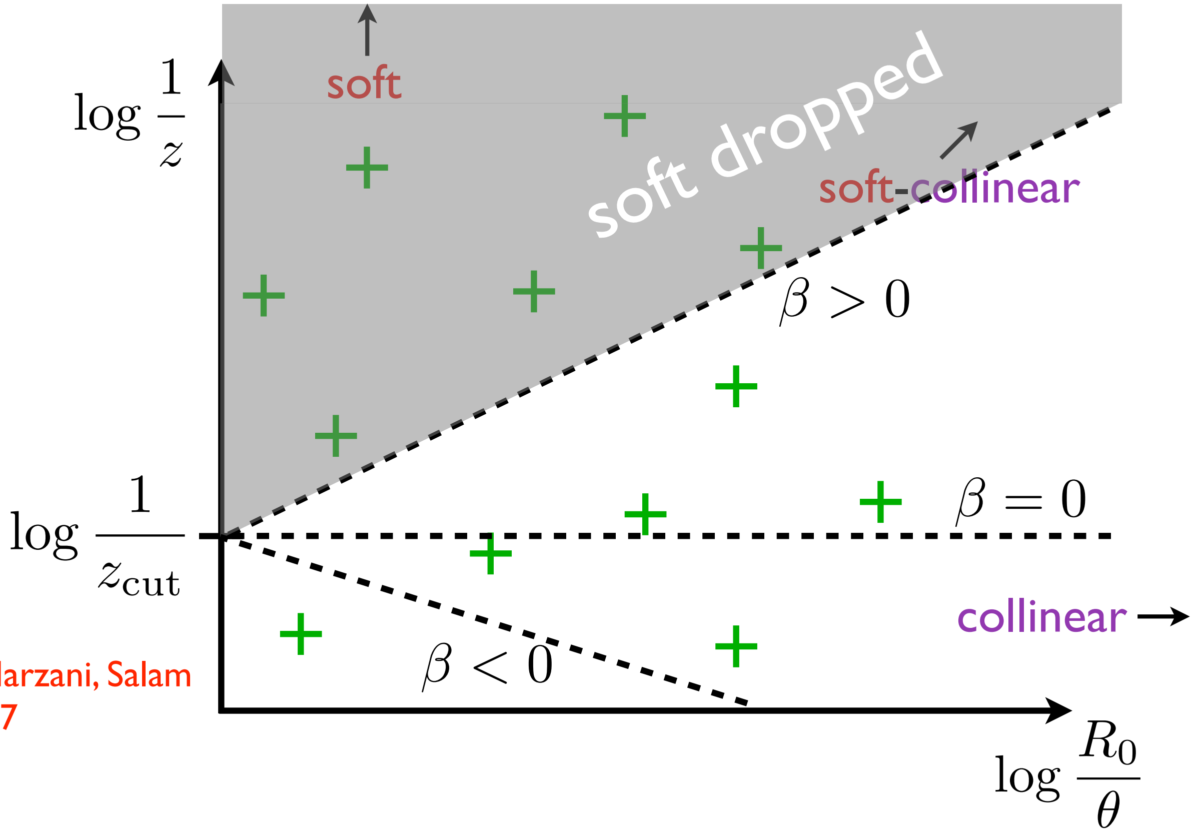
all soft emissions removed

modified Mass Drop limit

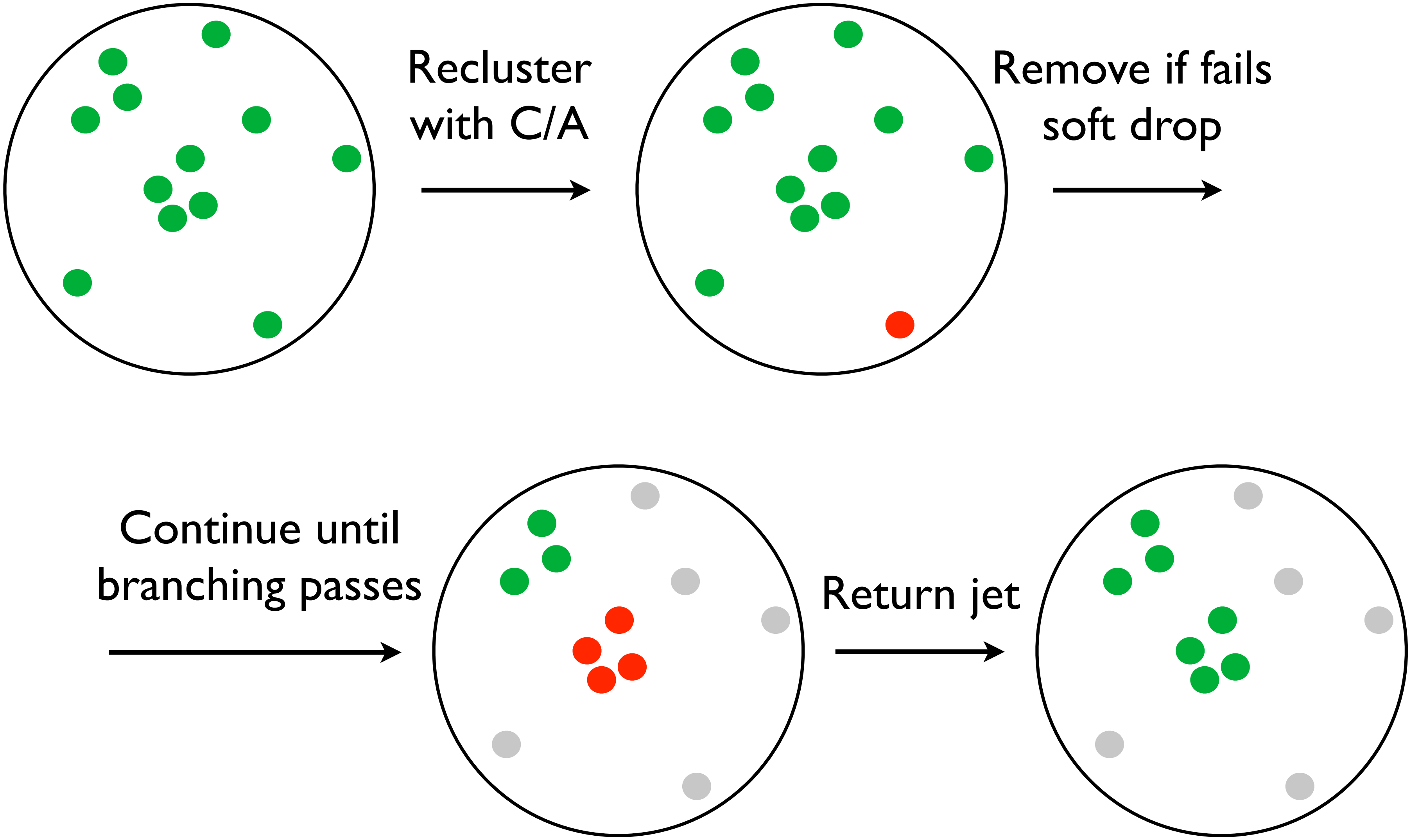
Dasgupta, Fregoso, Marzani, Salam 1307.0007

β < 0

all soft and collinear emissions removed



Jet Grooming: Soft Drop



Recluster with C/A

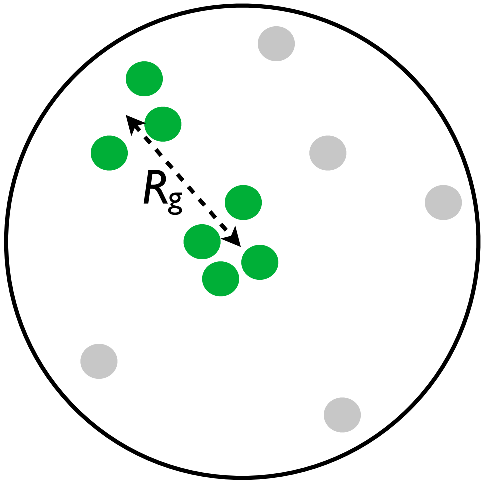
Remove if fails soft drop

Continue until branching passes

Return jet

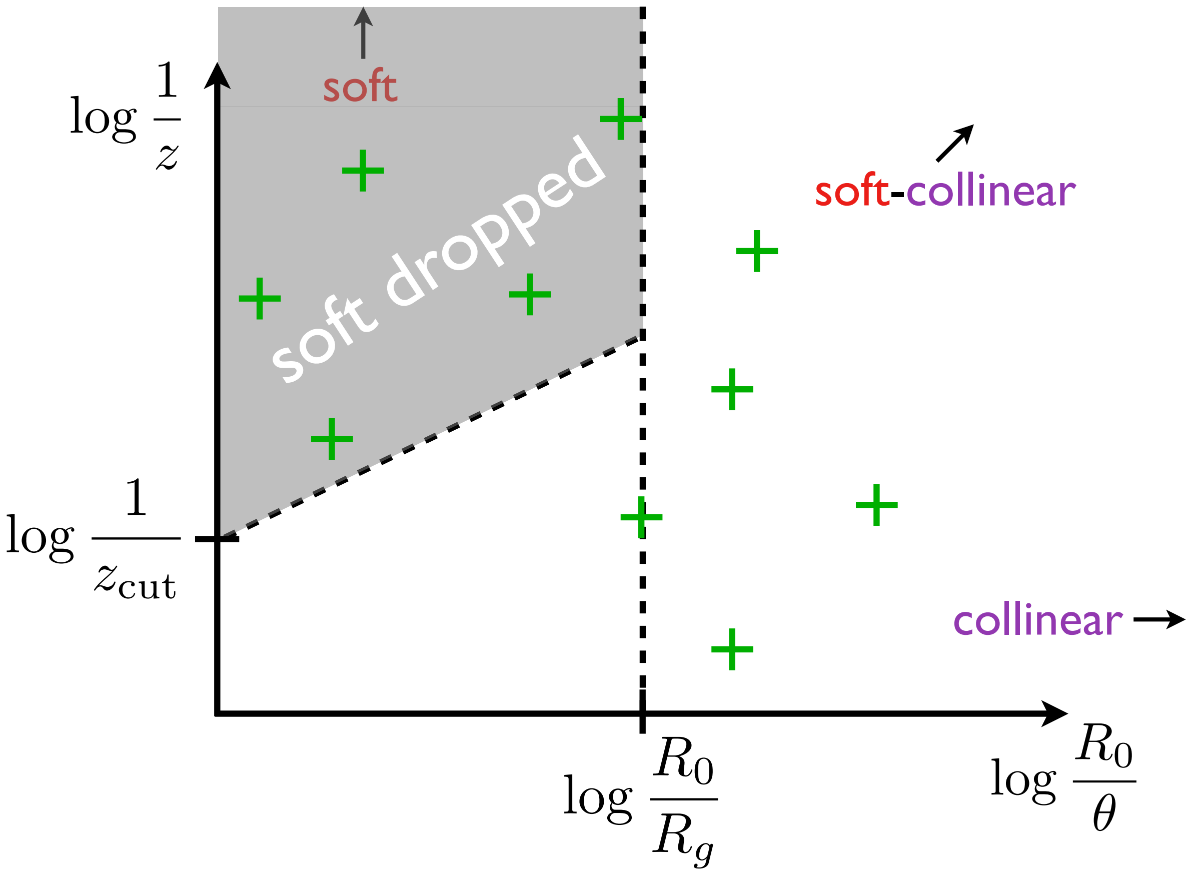
Jet Grooming: Soft Drop

Soft-Drop Groomed Jet

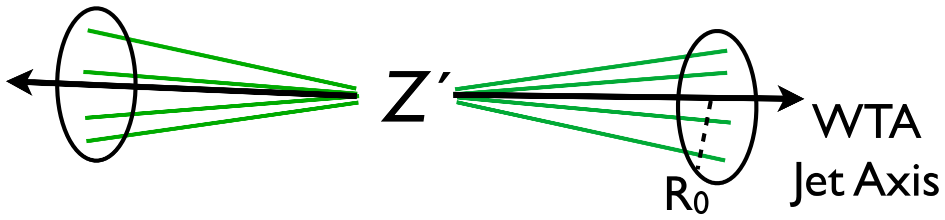


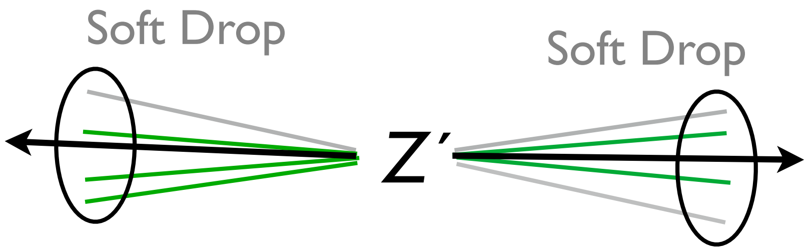
Removes soft, wide angle radiation

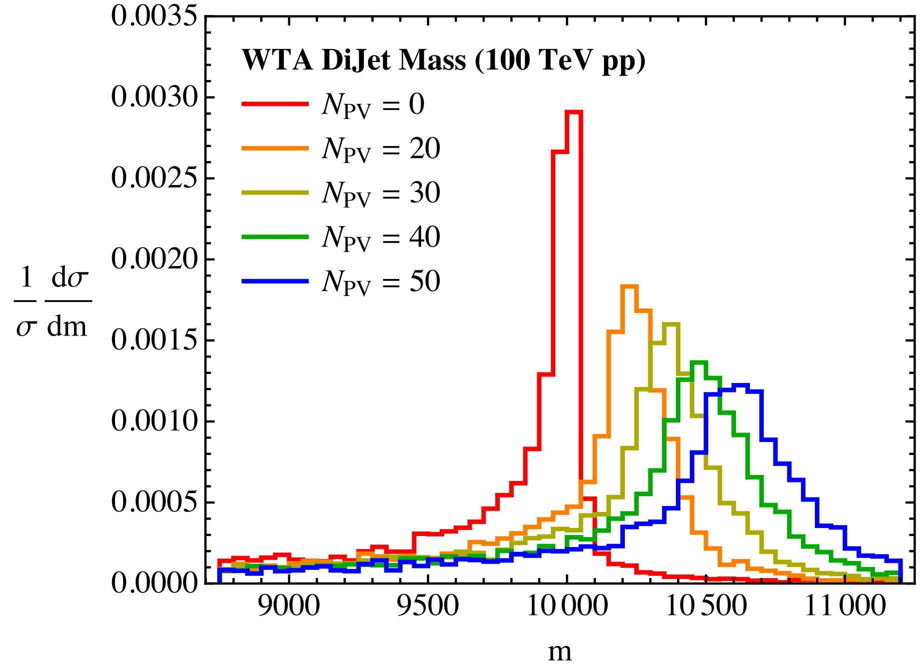
Groomed jet radius is set by the dynamics of the jet, not externally

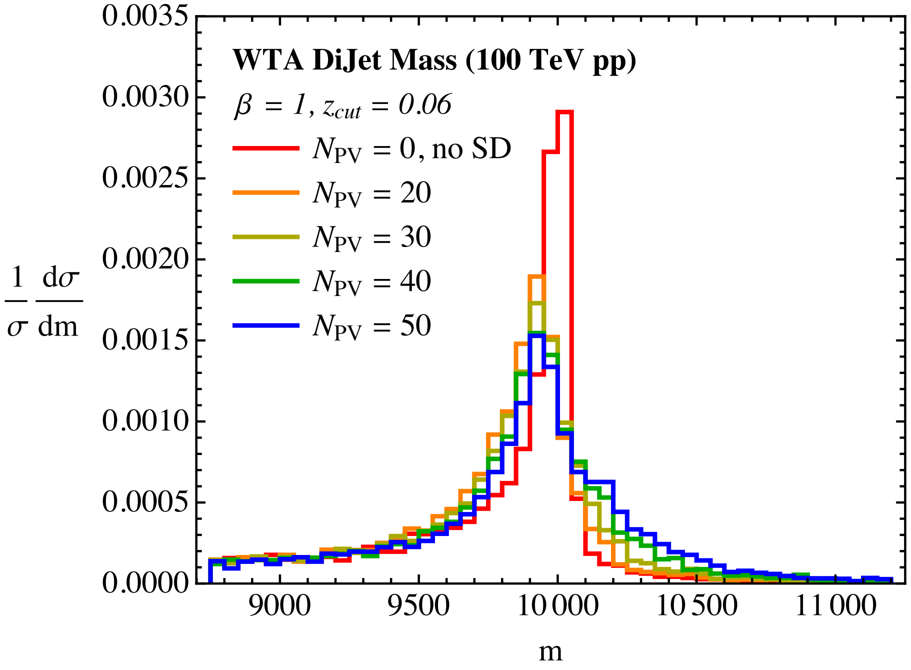


Resonance Resolution



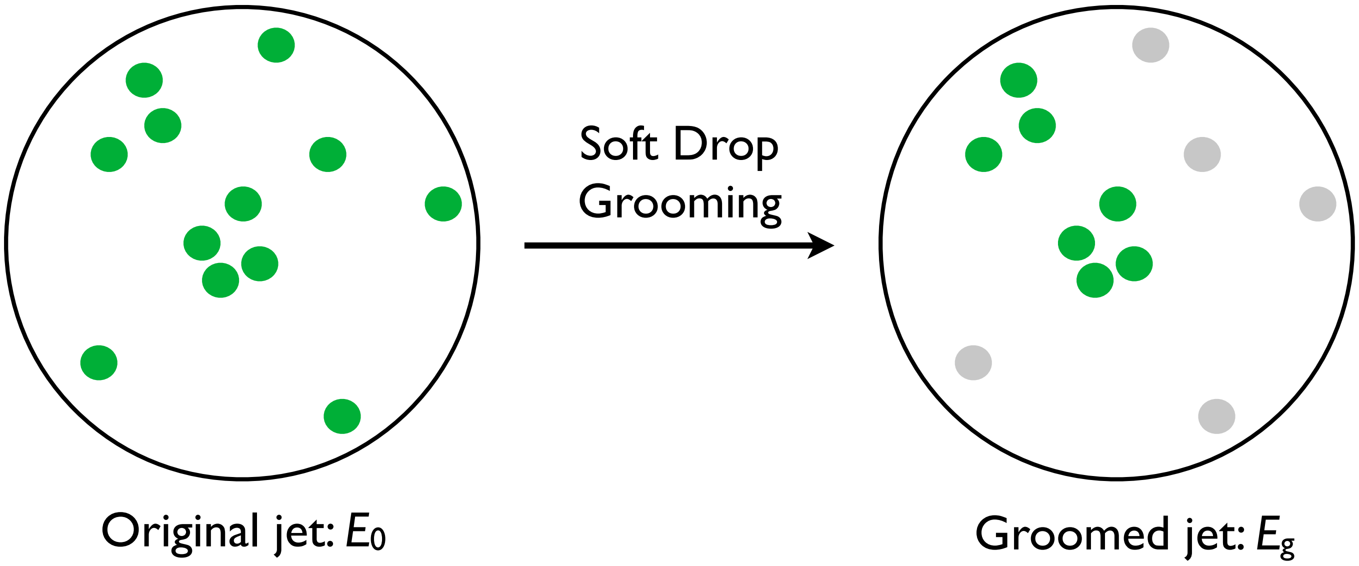






New Standard Candles at 100 TeV

New Standard Candles



$$z_{\max} = \frac{E_0 - E_g}{E_0}$$

Measures the fraction of radiation removed
by the soft drop groomer

Could be measured to calibrate response
of calorimeter to soft radiation

Simple enough to be perturbatively calculable

Actually, defined as only depending on the energy
of the first emission in the jet passing soft drop

Energy loss distribution

AJL, Marzani, Soyez, Thaler 1402.2657
AJL, Thaler 1406.7011

$$\boxed{\Sigma(z_{\max}) = \frac{\log z_{\rm cut} - B_i}{\log z_{\max} - B_i} + \frac{\pi\beta}{2C_i\alpha_s(\log z_{\max} - B_i)^2}\left(1 - e^{-2\frac{\alpha_s}{\pi}\frac{C_i}{\beta}\log\frac{z_{\rm cut}}{z_{\max}}\left(\log\frac{1}{z_{\max}}+B_i\right)}\right)}$$

α_s expansion: $\Sigma(z_{\max}) = 1 - \frac{\alpha_s}{\pi}\frac{C_i}{\beta}\log^2\frac{z_{\rm cut}}{z_{\max}} + \mathcal{O}\left(\left(\frac{\alpha_s}{\beta}\right)^2\right)$

Taylor series about $\alpha_s = 0$
Infrared and collinear safe for $\beta > 0$
Calculable order-by-order in perturbation theory

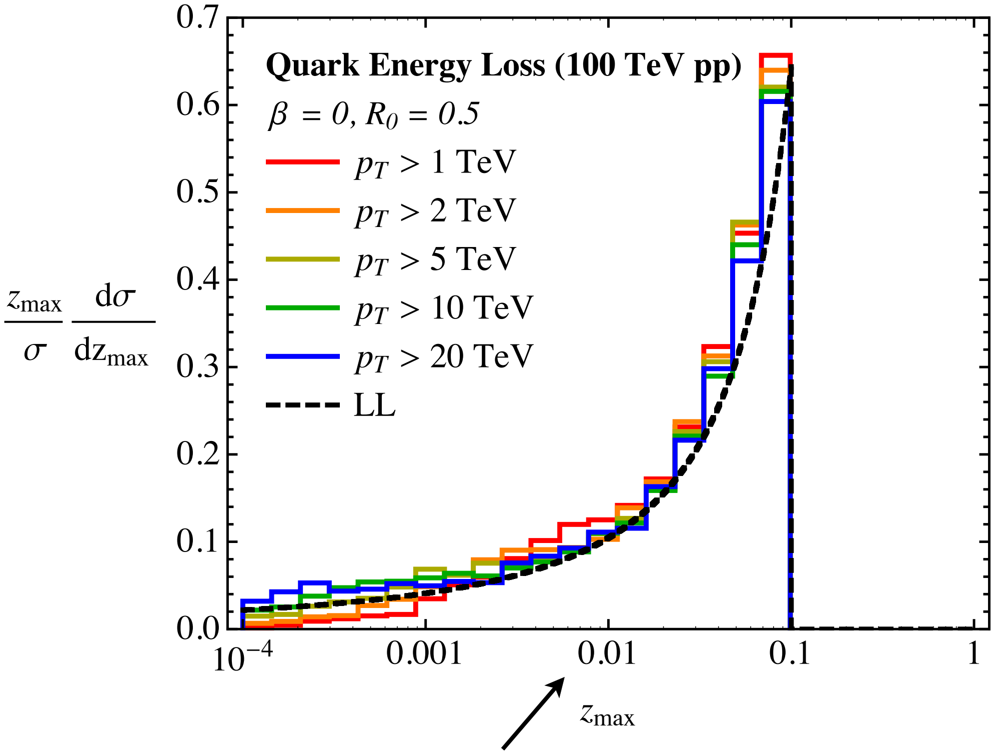
$\beta = 0$: $\Sigma(z_{\max})_{\beta=0} = \frac{\log z_{\rm cut} - B_i}{\log z_{\max} - B_i}$ independent of α_s!?

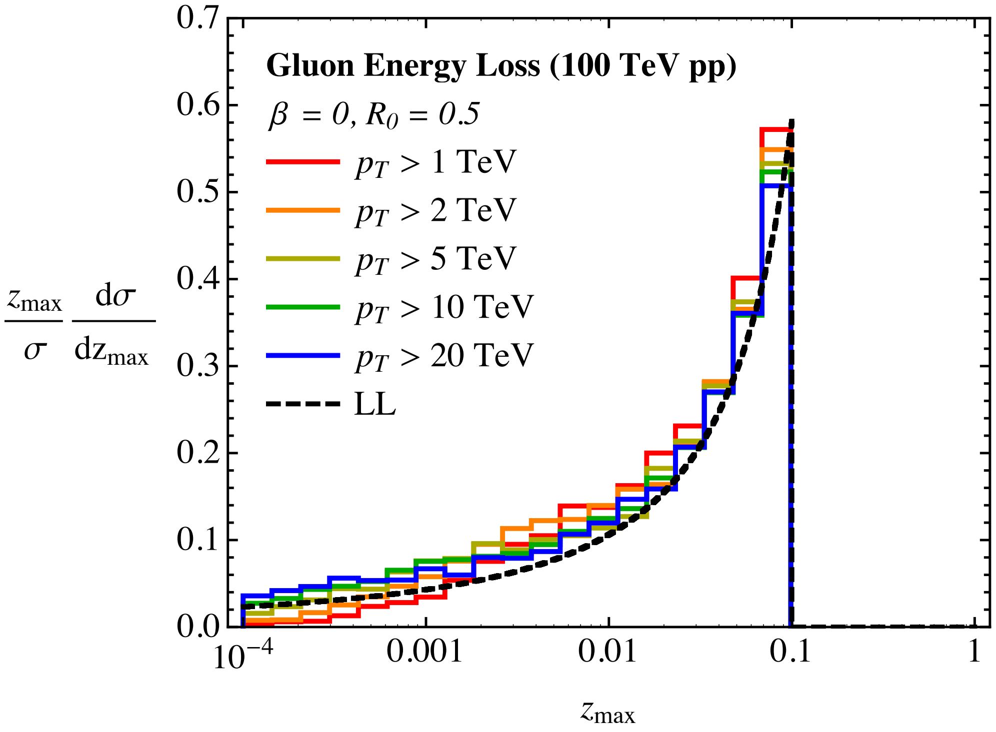
Independent of α_s and total jet color
Very weak scale dependence controlled by the (small) QCD β-function
IRC unsafe yet calculable when all-orders effects are included

Sudakov Safe Observable

AJL, Thaler 1307.1699

New Standard Candles





1 TeV Jet: 10 GeV emission

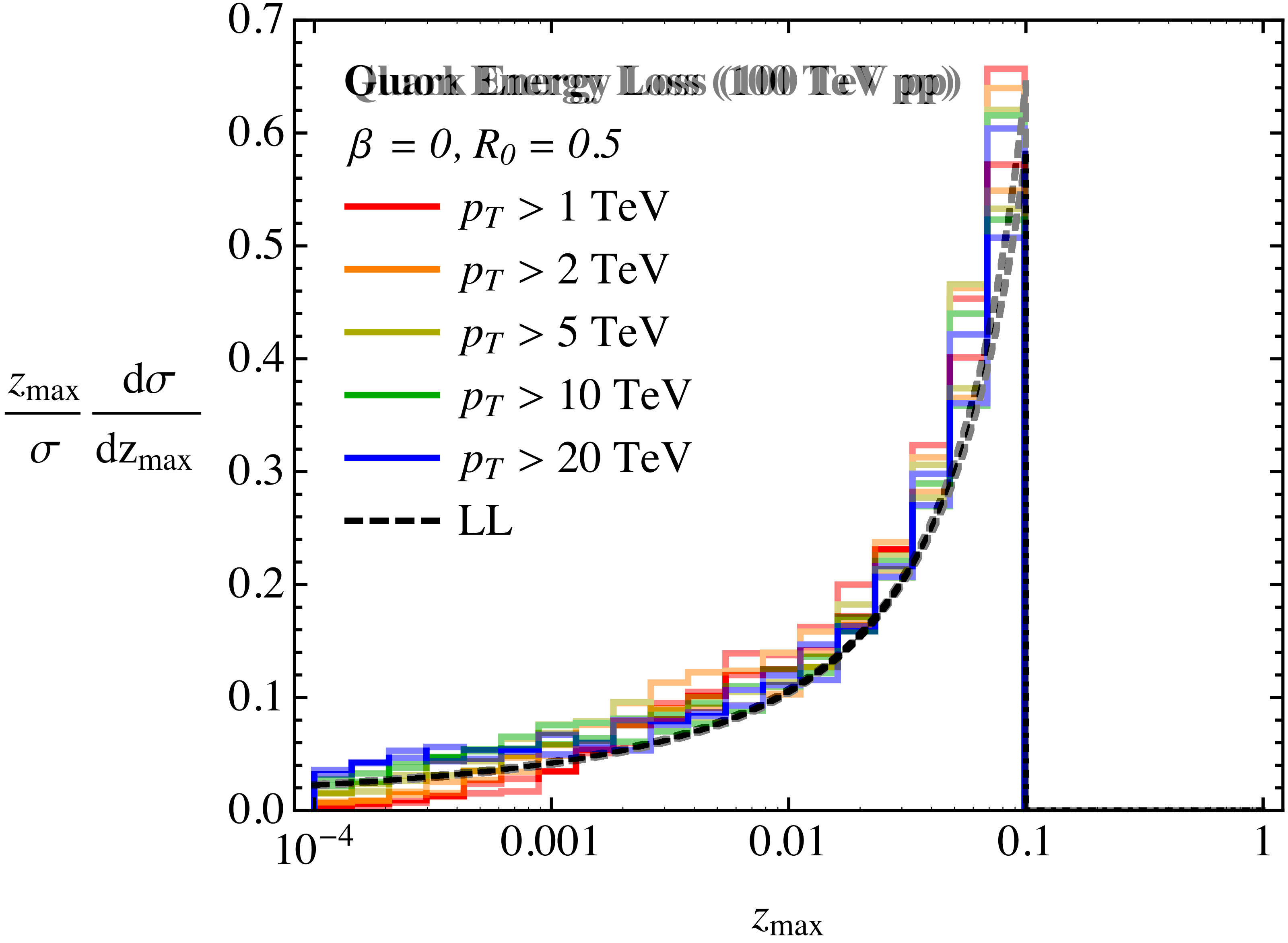
20 TeV Jet: 200 GeV emission

Weak jet energy dependence

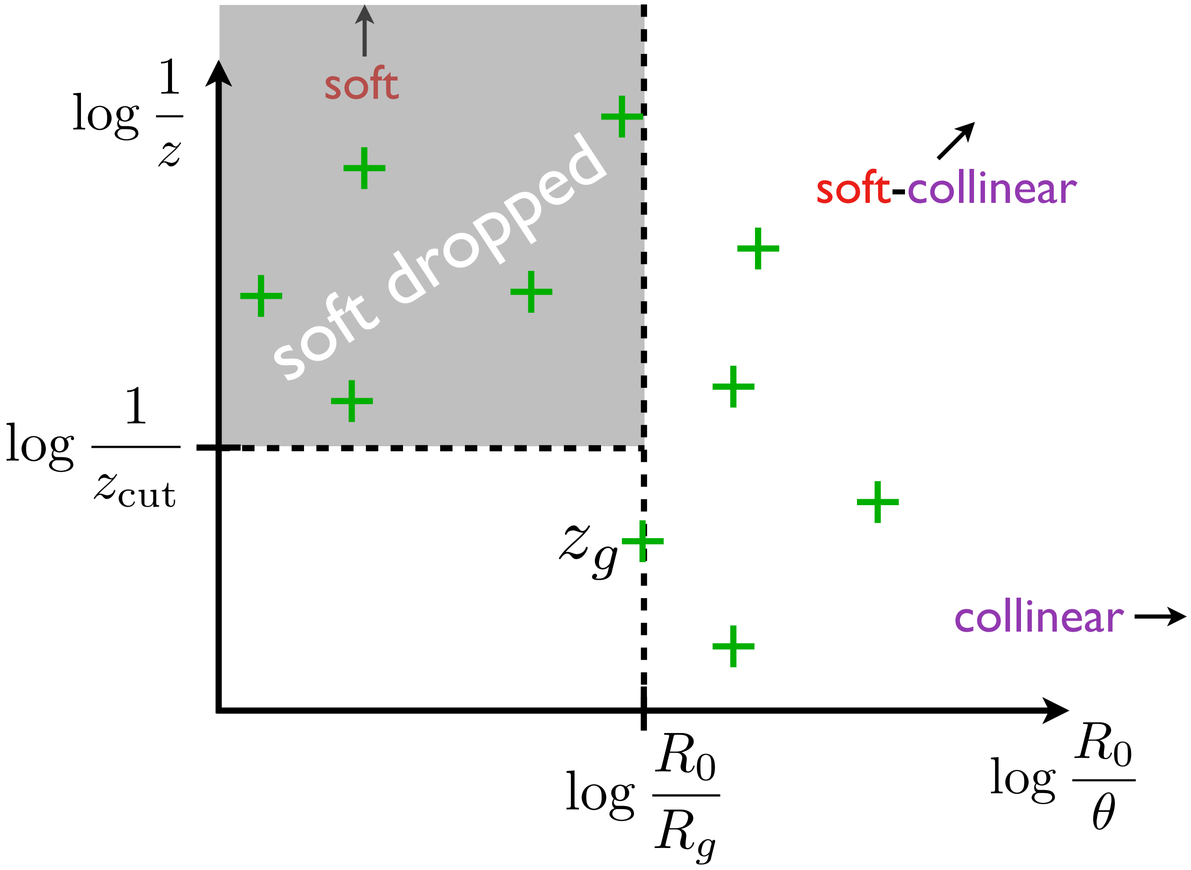
Weak jet flavor dependence

Distribution of $z_{\max}$ should be ~independent of jet sample energy and composition!

New Standard Candles



New Standard Candles



Measures the energy fraction of the emission
that passes soft drop groomer

Easy to measure and not very sensitive to contamination

Simple enough to be perturbatively calculable

β = 0:

$$\boxed{\frac{1}{\sigma}\frac{d\sigma}{dz_g} = \frac{\overline{P}_i(z_g)}{\int_{z_{\rm cut}}^{1/2} dz\, \overline{P}_i(z)}}$$

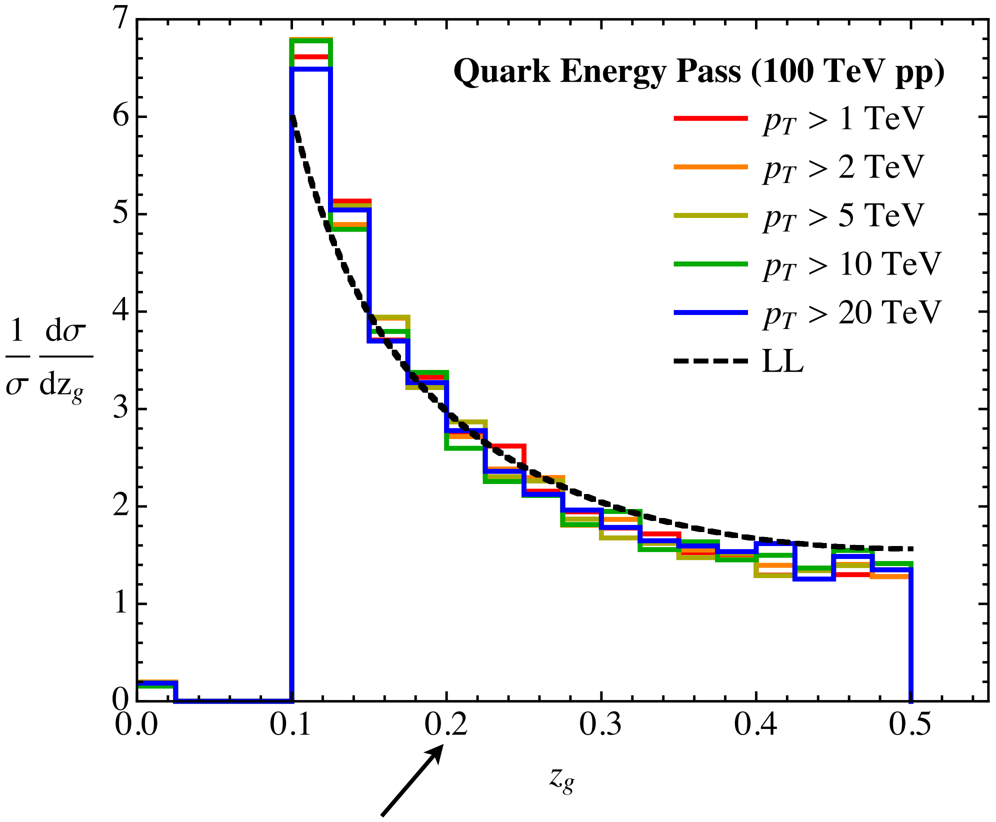
AJL, Marzani, Thaler 1502.xsoon

Independent of α_s
and total jet color

Distribution is literally the appropriate
QCD splitting function

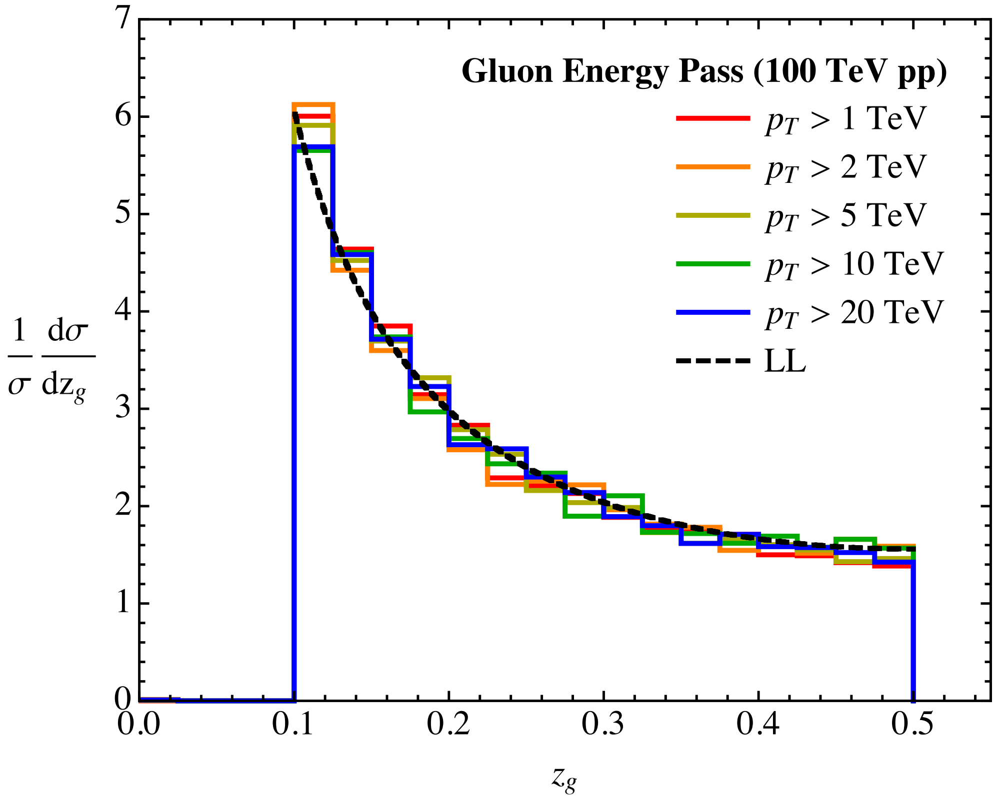
IRC unsafe yet calculable when
all-orders effects are included

New Standard Candles



1 TeV Jet: 200 GeV emission

20 TeV Jet: 4 TeV emission



Weak jet energy dependence

Weak jet flavor dependence

Conclusions

Jets at 100 TeV will teach us an enormous amount about the Standard Model

Winner-take-all jet axis definition robust to ISR/UE/PU

Can study the evolution of a weakly-coupled,
near-CFT (QCD) over 3+ decades in energy

Sudakov safe observables provide a unique probe into QCD dynamics

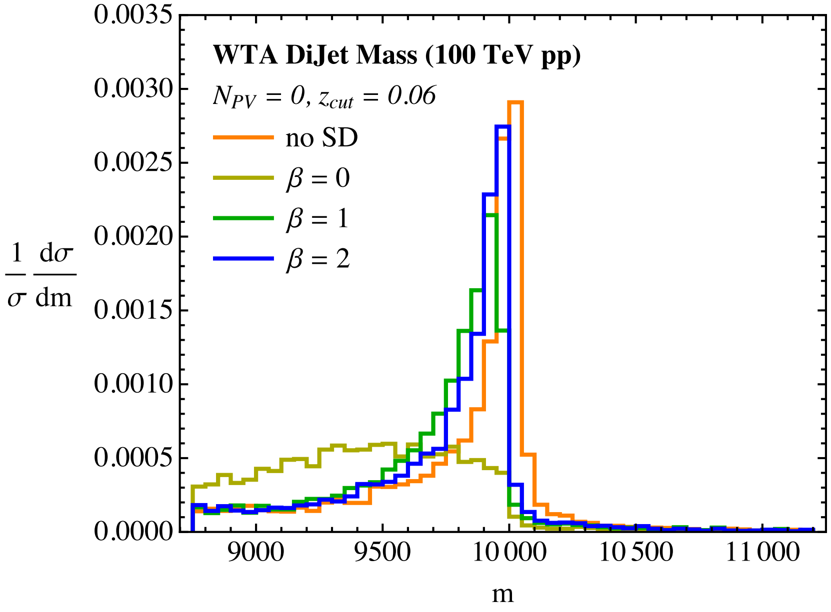
Understanding

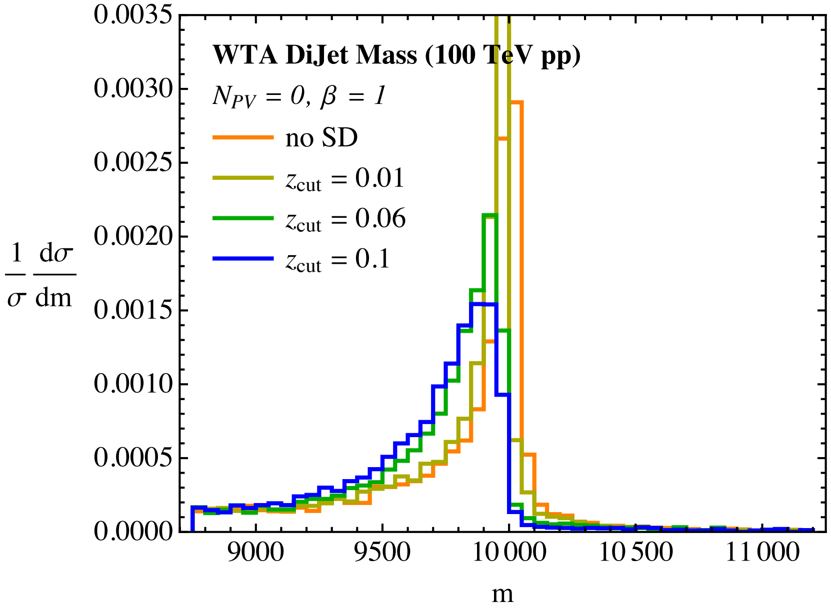
is just as interesting and important as

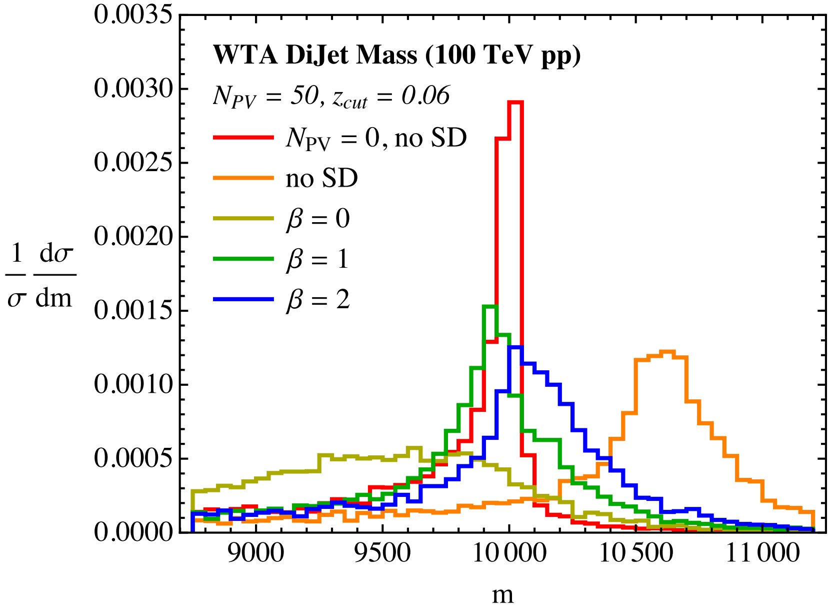
Discovery

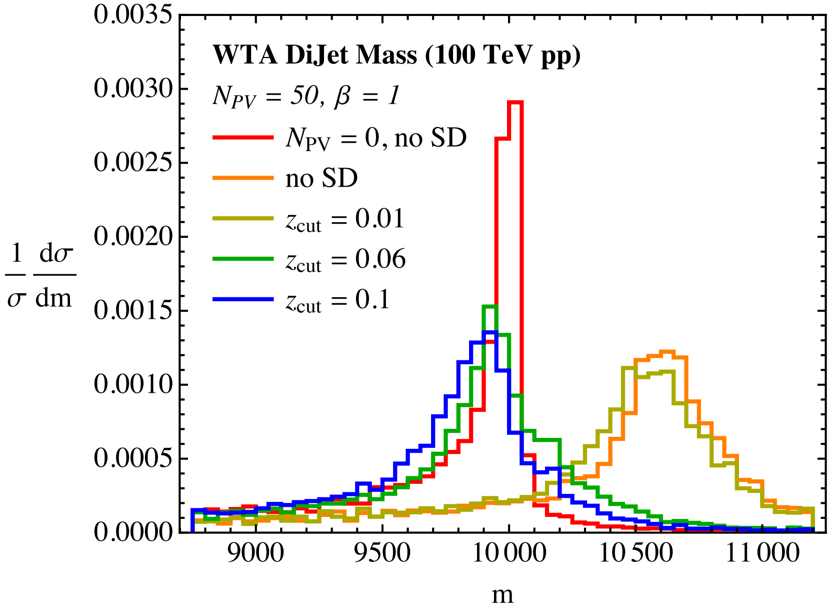
Back-Up Slides

Jet Grooming

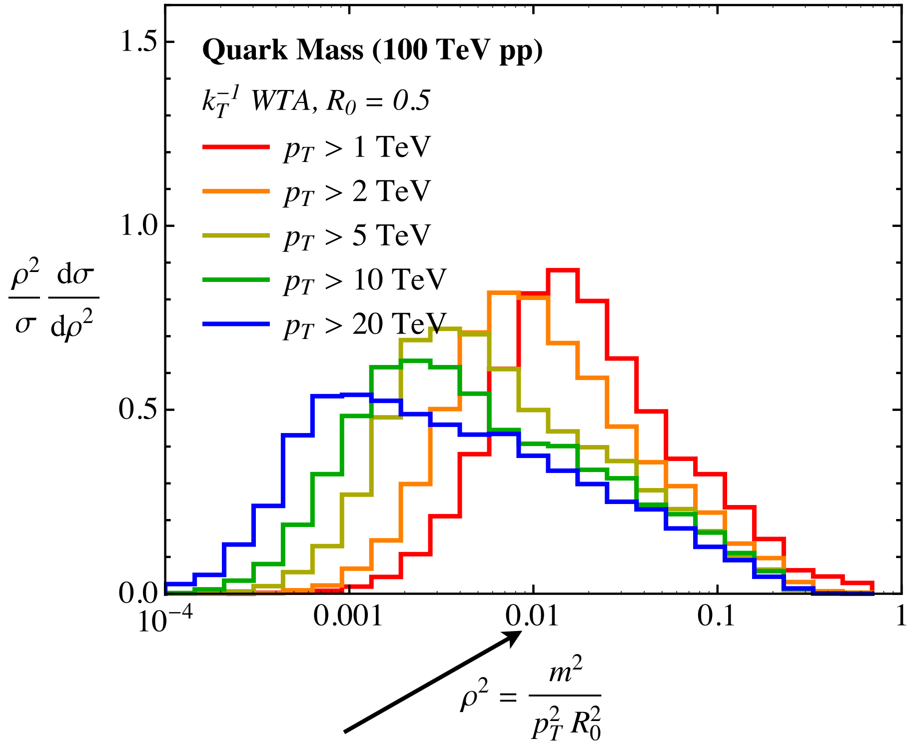


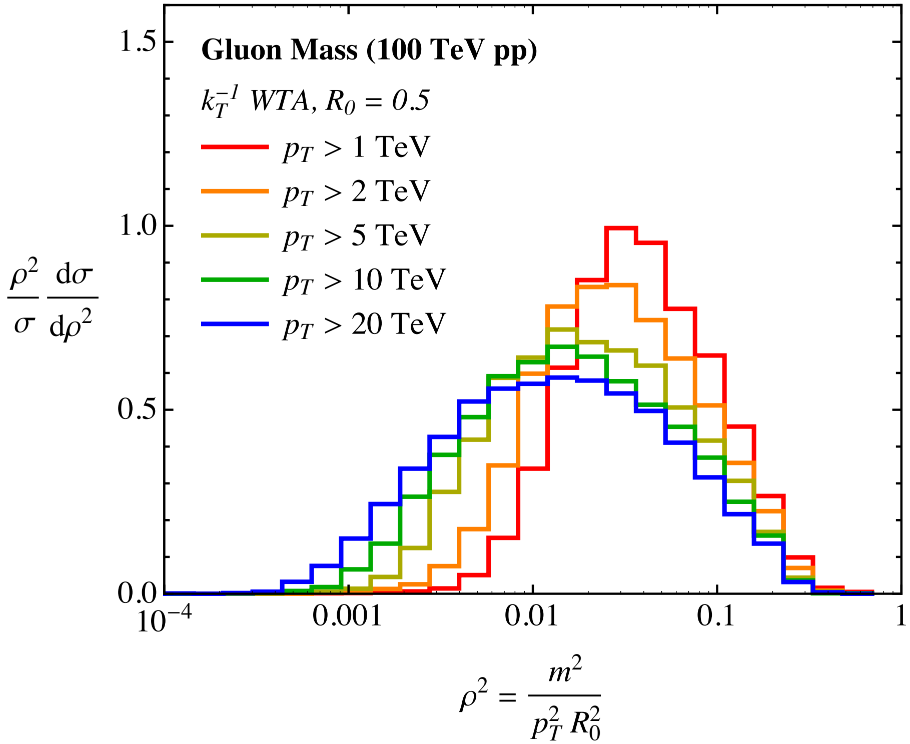






New Standard Candles





1 TeV Jet: 10 GeV emission

20 TeV Jet: 200 GeV emission

Strong jet energy dependence:
$\langle \rho^2 \rangle \sim \alpha_s(p_T R_0)$

Strong jet flavor dependence:
$C_A \langle \rho_q^2 \rangle \sim C_F \langle \rho_g^2 \rangle$

New Standard Candles