Jet Substructure at the Precision Frontier

Andrew Larkoski
Harvard University

Stress-testing the Standard Model at the LHC, May 24, 2016

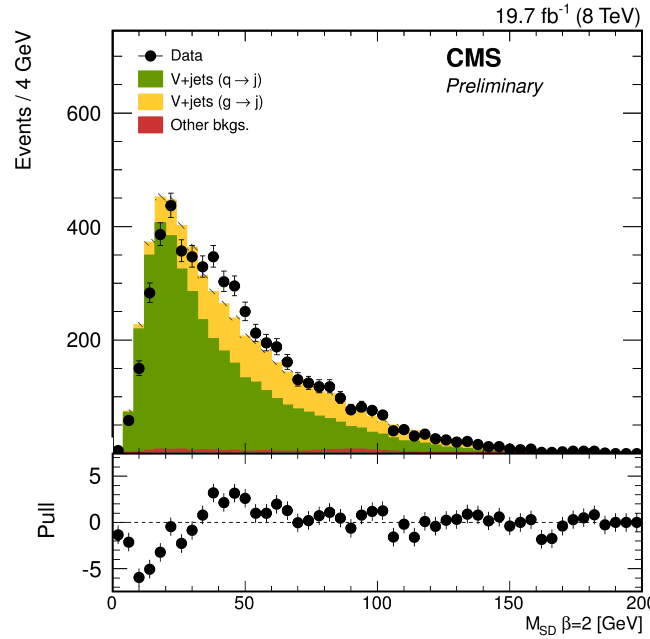
Motivation for Precision Jet Substructure

Ever increasing set of experimental measurements

Probing orthogonal regime of QCD

New α_s extractions using resummation-sensitive observables

Quark and gluon jet definitions important for new physics and pdf constraints



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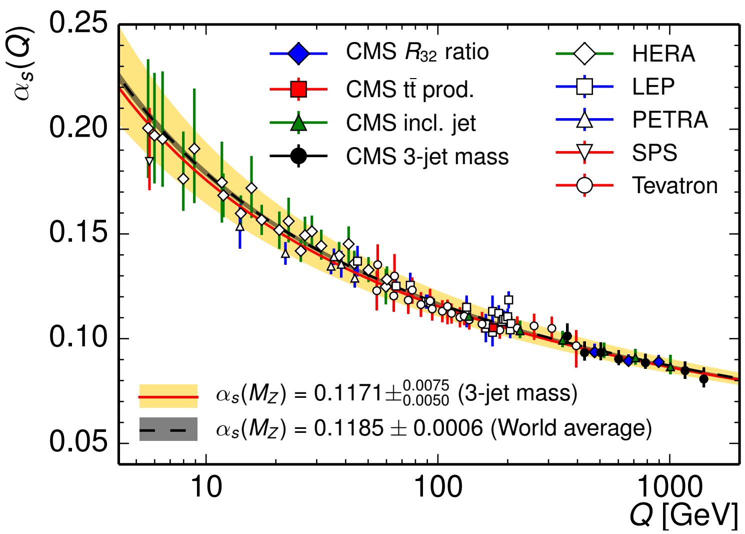


Eur. Phys. J. C 75 (2015) 186

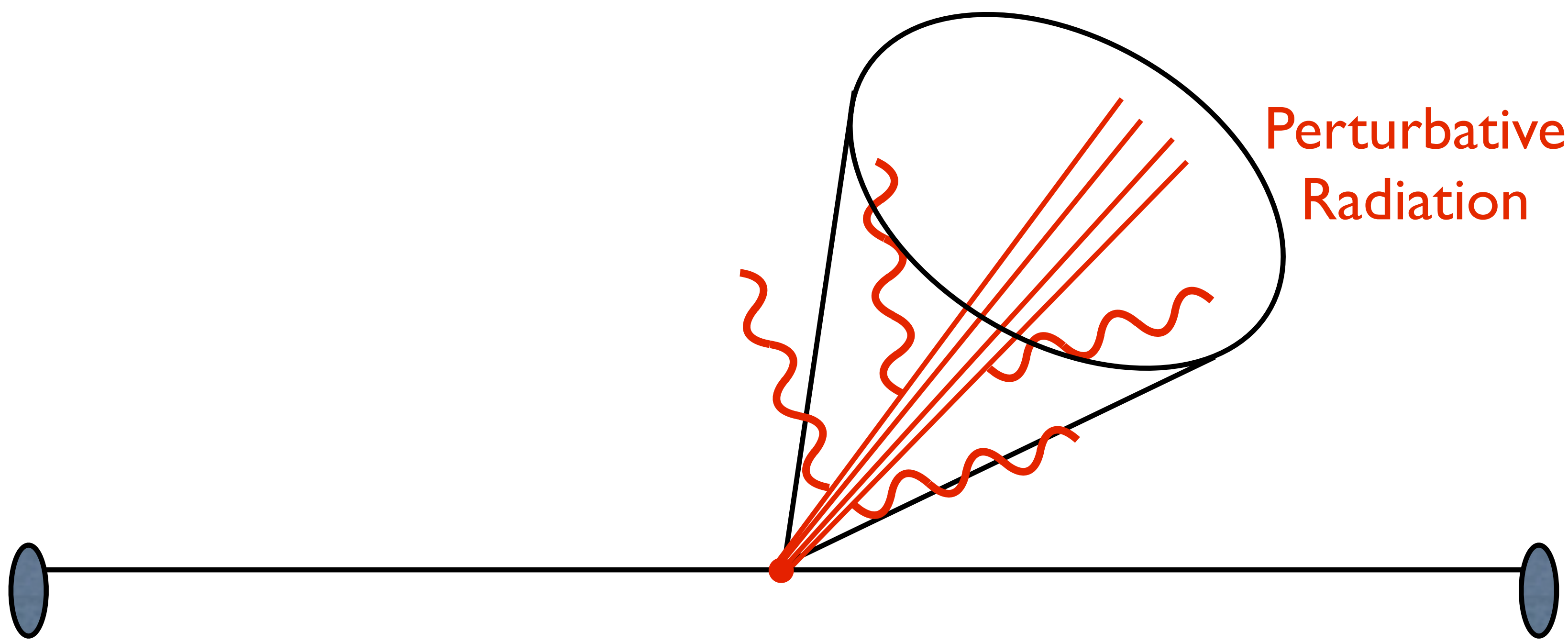
How to get to Precision Jet Substructure

Measure m_J^2 on the jet in pp → Z + j events

How to get to Precision Jet Substructure

Measure m_J^2 on the jet in pp → Z + j events

Experimental Challenge:
Contamination captured in the jet



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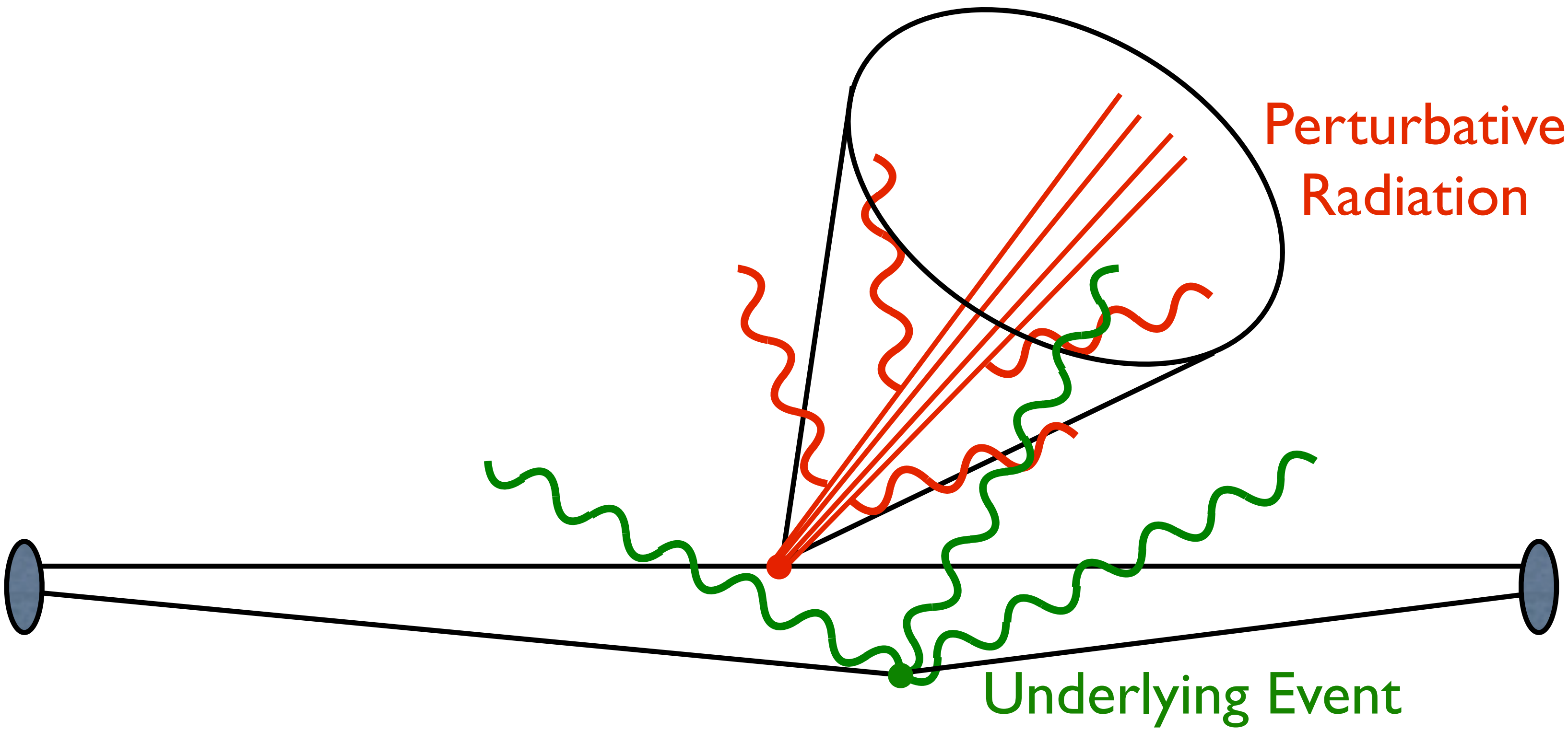

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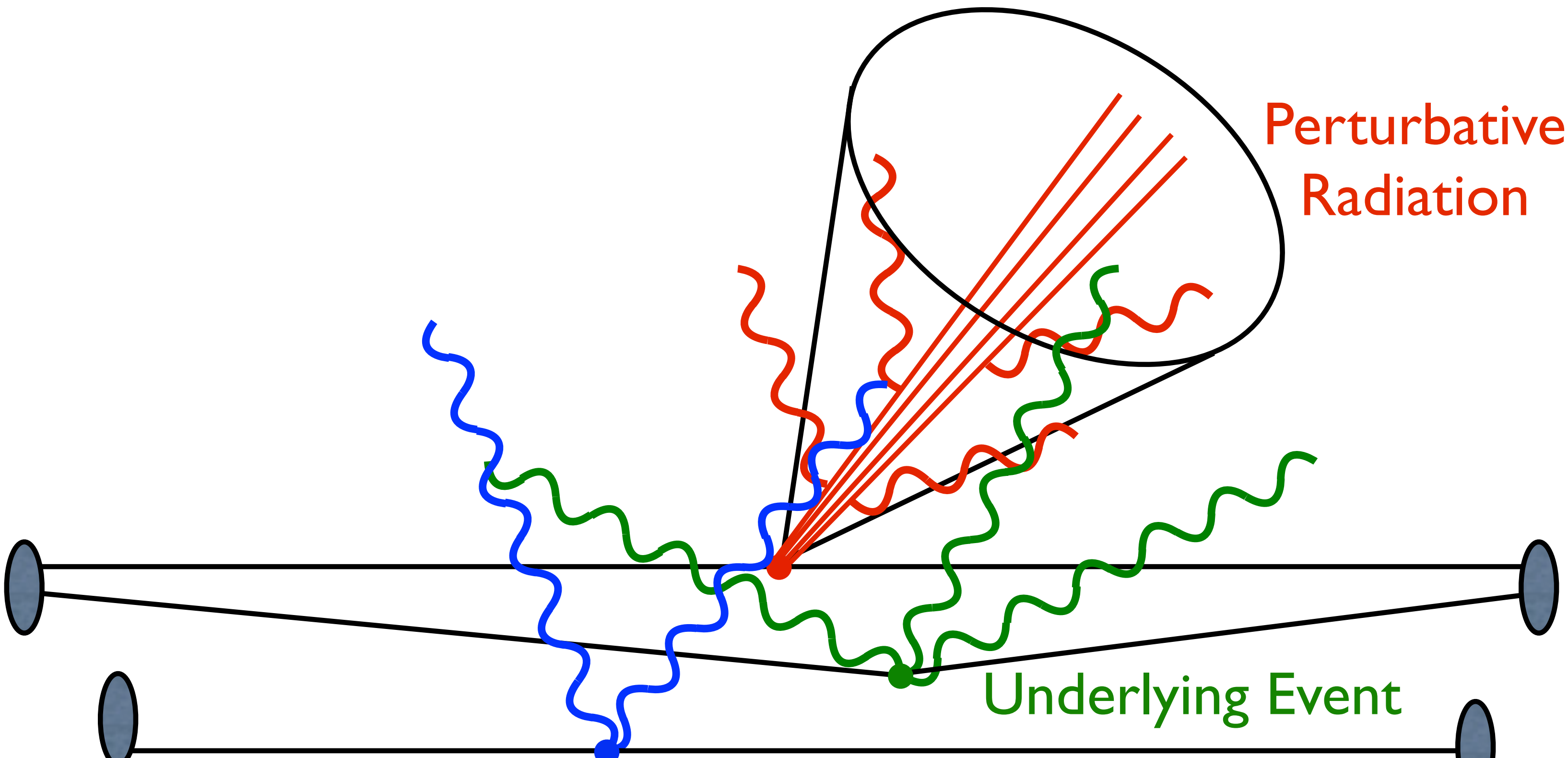
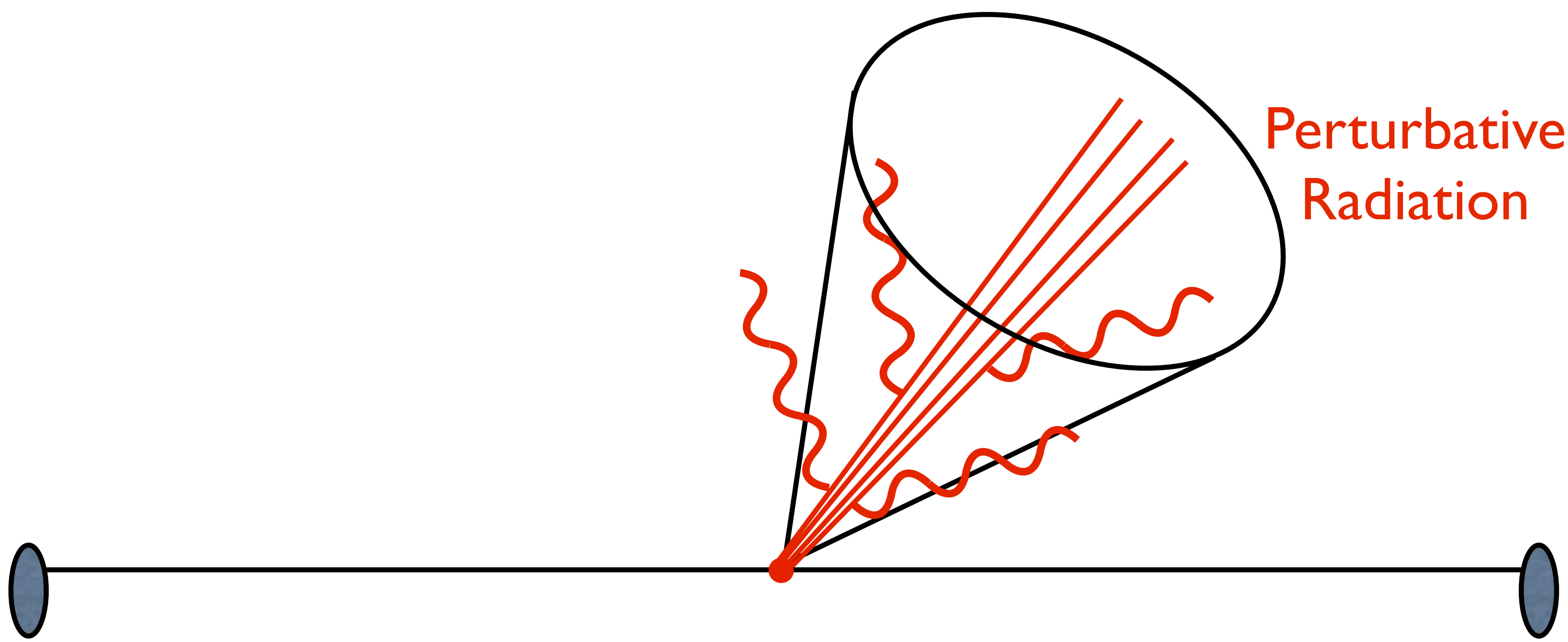


How to get to Precision Jet Substructure

Measure m_J^2 on the jet in pp → Z + j events

Theoretical Challenge:
Non-Global Logarithms

Dasgupta, Salam 2001



How to get to Precision Jet Substructure

Measure m_J^2 on the jet in pp → Z + j events

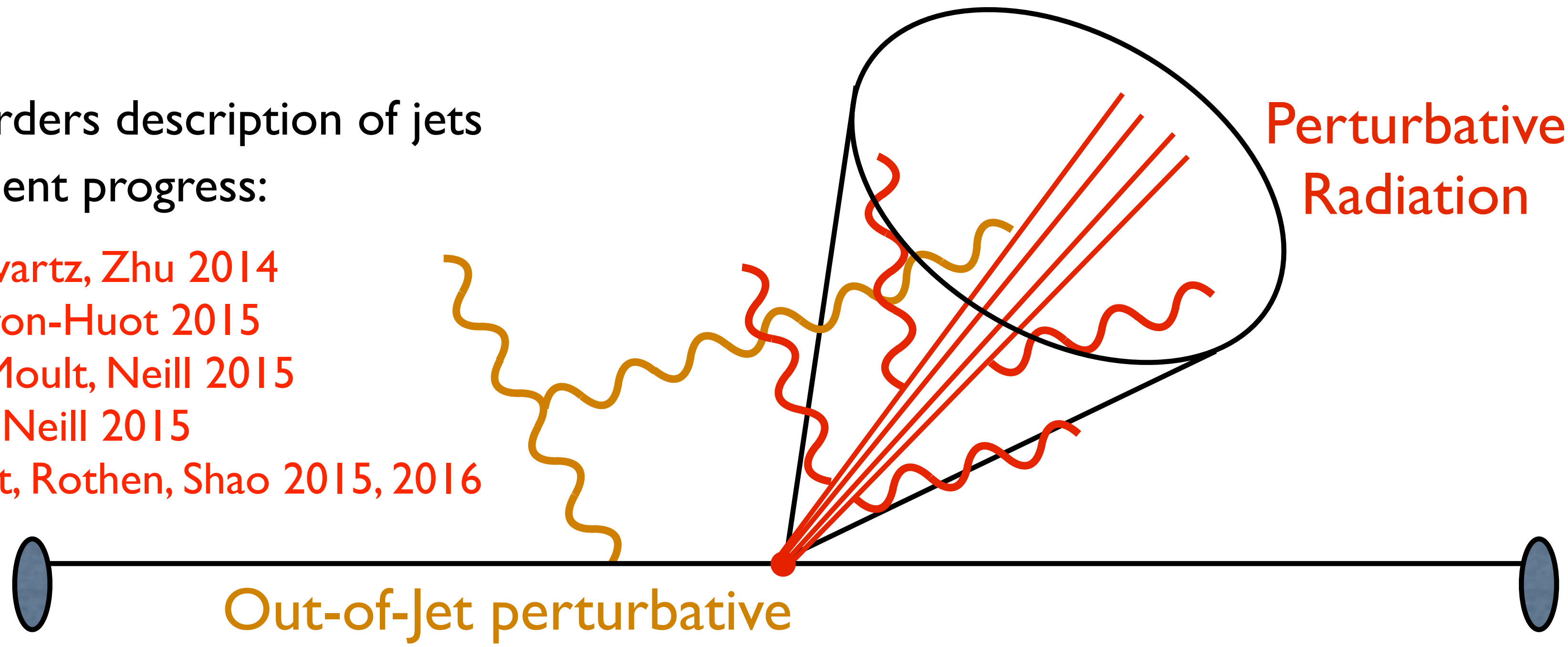
Theoretical Challenge:
Non-Global Logarithms

Dasgupta, Salam 2001

Prohibits all-orders description of jets

Recent progress:

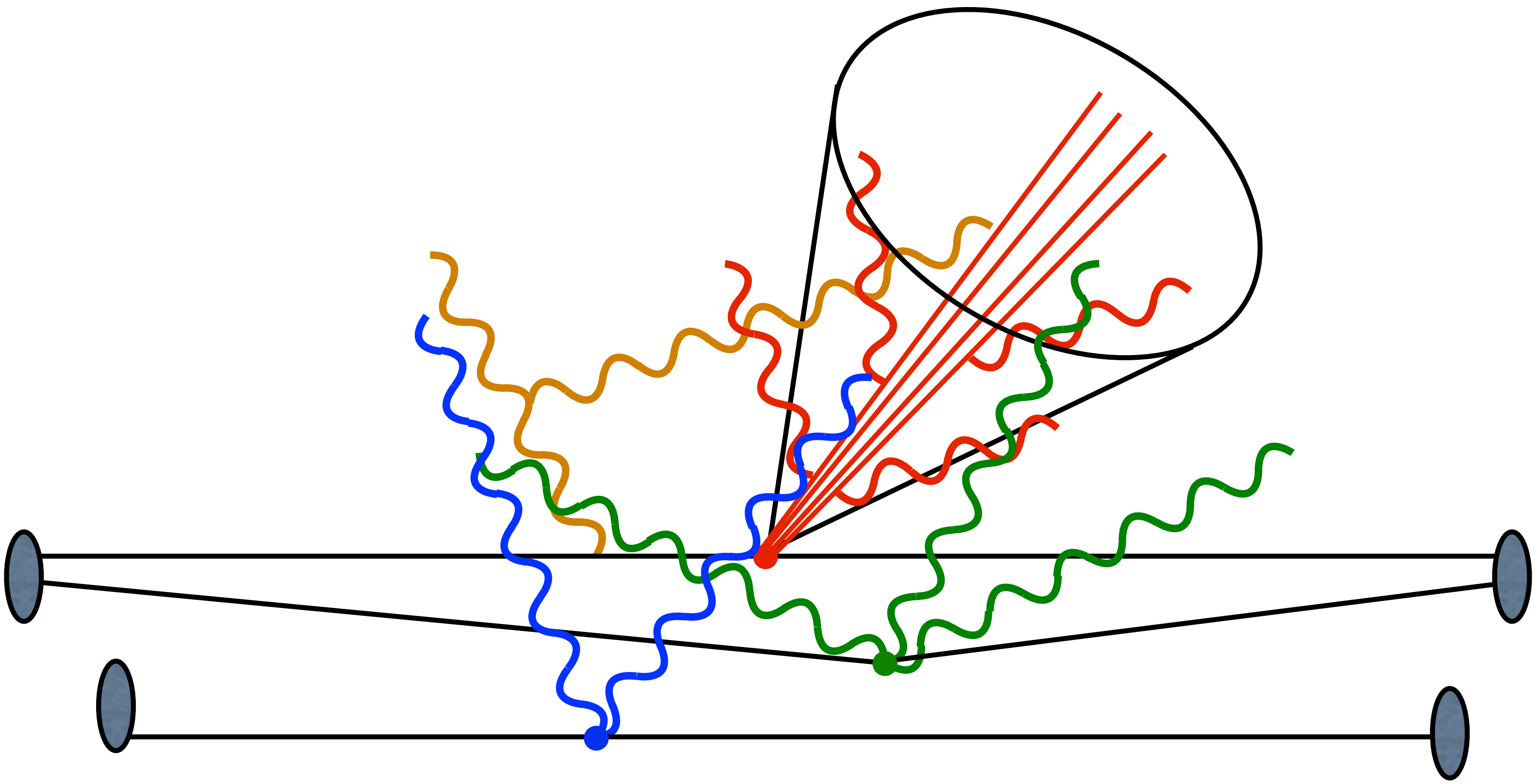
Schwartz, Zhu 2014
Caron-Huot 2015
AJL, Moult, Neill 2015
Neill 2015
Becher, Neubert, Rothen, Shao 2015, 2016



How to get to Precision Jet Substructure

Measure m_J^2 on the jet in pp → Z + j events

Can eliminate these problems by grooming the jet!

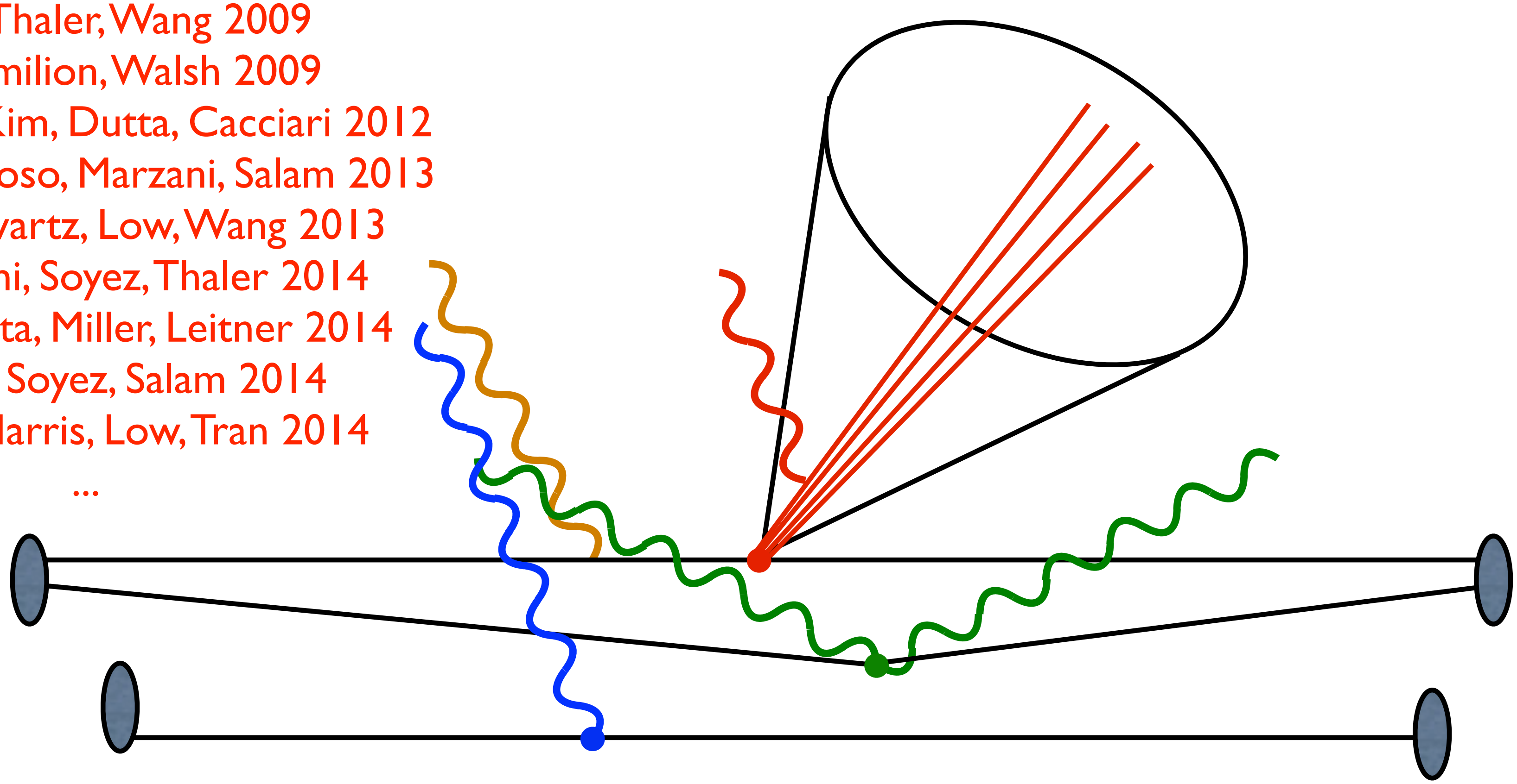


How to get to Precision Jet Substructure

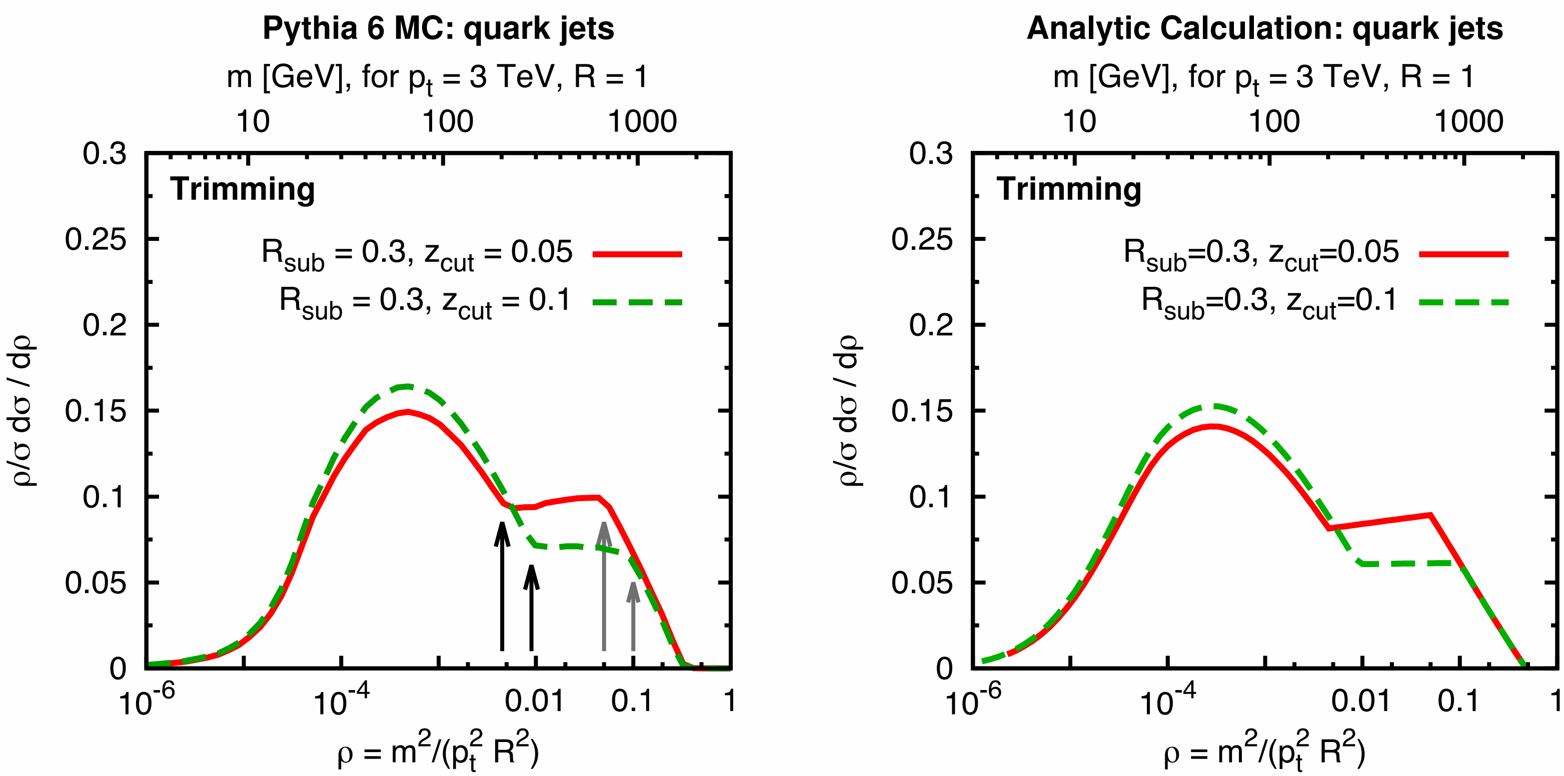
Measure m_J^2 on the jet in pp → Z + j events

Can eliminate these problems by grooming the jet!

Butterworth, Davison, Rubin, Salam 2008
Cacciari, Salam, Soyez 2008
Krohn, Thaler, Wang 2009
Ellis, Vermilion, Walsh 2009
Soyez, Salam, Kim, Dutta, Cacciari 2012
Dasgupta, Fregoso, Marzani, Salam 2013
Krohn, Schwartz, Low, Wang 2013
AJL, Marzani, Soyez, Thaler 2014
Berta, Spousta, Miller, Leitner 2014
Cacciari, Soyez, Salam 2014
Bertolini, Harris, Low, Tran 2014
...



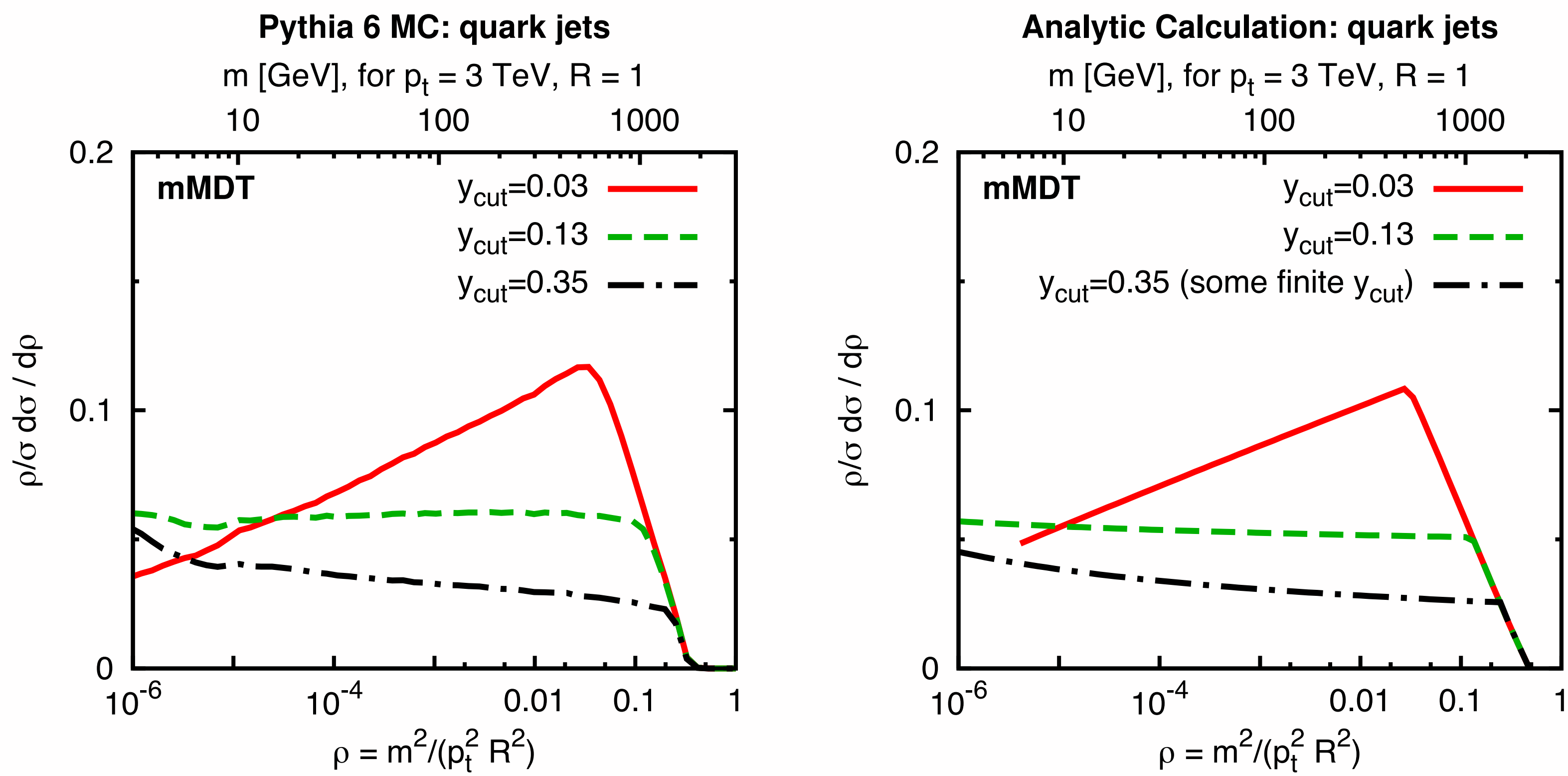
What has been done: NLL resummation



Dasgupta, Fregoso, Marzani, Salam 2013

Trimming:
Krohn, Thaler, Wang 2009

What has been done: NLL resummation

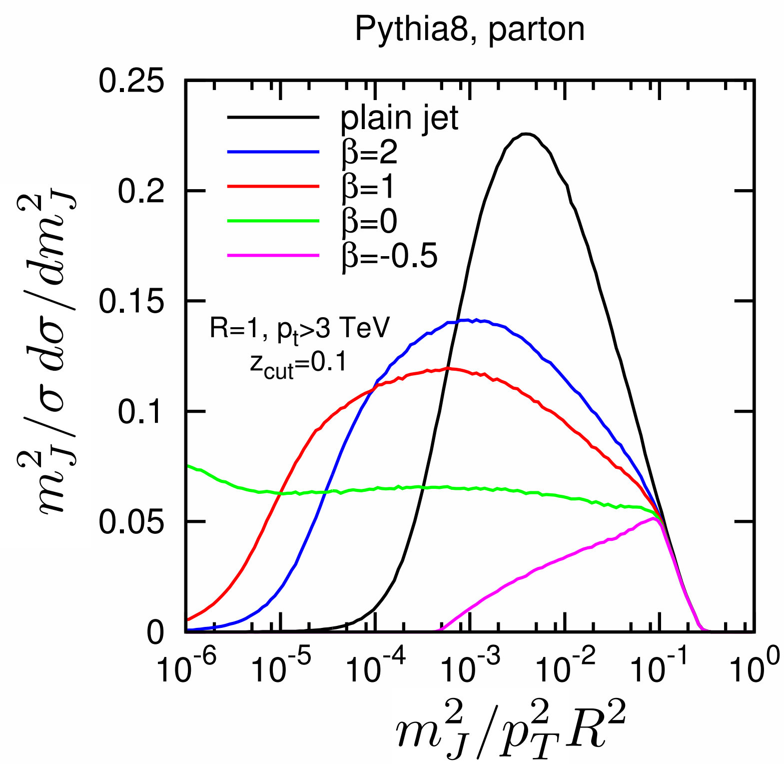


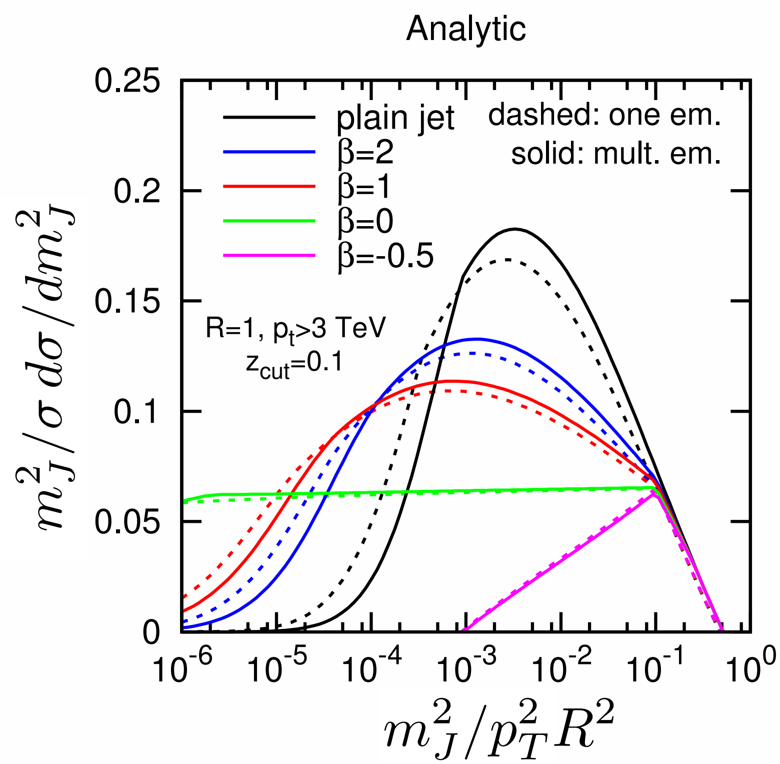
Dasgupta, Fregoso, Marzani, Salam 2013

	highest logs	transition(s)	Sudakov peak	NGLs	NP: $m^2 \lesssim$
plain mass	$\alpha_s^n L^{2n}$	—	$L \simeq 1/\sqrt{\bar{\alpha}_s}$	yes	$\mu_{\rm NP}\, p_t\, R$
trimming	$\alpha_s^n L^{2n}$	$z_{\rm cut},\ r^2 z_{\rm cut}$	$L \simeq 1/\sqrt{\bar{\alpha}_s} - 2\ln r$	yes	$\mu_{\rm NP}\, p_t\, R_{\rm sub}$
pruning	$\alpha_s^n L^{2n}$	$z_{\rm cut},\ z_{\rm cut}^2$	$L \simeq 2.3/\sqrt{\bar{\alpha}_s}$	yes	$\mu_{\rm NP}\, p_t\, R$
MDT	$\alpha_s^n L^{2n-1}$	$y_{\rm cut},\ \frac{1}{4} y_{\rm cut}^2,\ y_{\rm cut}^3$	—	yes	$\mu_{\rm NP}\, p_t\, R$
Y-pruning	$\alpha_s^n L^{2n-1}$	$z_{\rm cut}$	(Sudakov tail)	yes	$\mu_{\rm NP}\, p_t\, R$
mMDT	$\alpha_s^n L^n$	$y_{\rm cut}$	—	no	$\mu_{\rm NP}^2 / y_{\rm cut}$

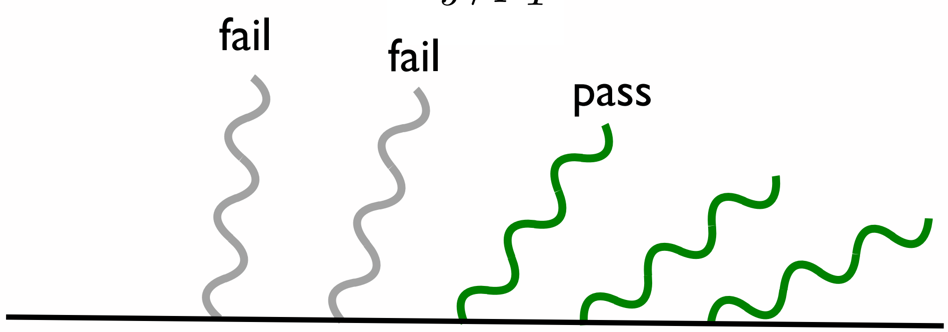
Explicit calculations suggest better techniques!

What has been done: NLL resummation





AJL, Marzani, Soyez, Thaler 2014



Only mMDT/Soft Drop groomers eliminate NGLs!

Soft Drop: $$\frac{\min[p_{Ti}, p_{Tj}]}{p_{Ti}+p_{Tj}} > z_{\text{cut}}\left(\frac{R_{ij}}{R}\right)^{\beta}$$

β = 0: mMDT

Procedure to get NNLL Resummation

Soft Drop the hardest jet
in pp → Z + j events

$$\frac{\min[p_{Ti}, p_{Tj}]}{p_{Ti} + p_{Tj}} > z_{\mathrm{cut}} \left(\frac{R_{ij}}{R}\right)^{\beta}$$

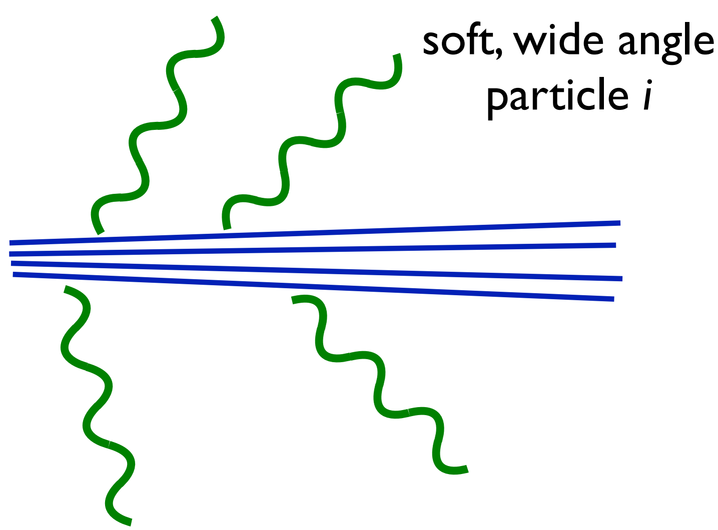
Measure m_J^2 of the
soft dropped jet:

$$m_J^2 \simeq \sum_{i<j\in J} p_{Ti} p_{Tj} R_{ij}^2$$

Focus on the regime where:

$$m_J^2 \ll z_{\mathrm{cut}} p_{TJ}^2 \ll p_{TJ}^2$$

All remaining particles in the jet must be collinear!



1) $\frac{p_{Ti}}{p_{TJ}} \sim z_{\mathrm{cut}} \longrightarrow m_J^2 \sim z_{\mathrm{cut}} p_{TJ}^2$

2) $\frac{p_{Ti}}{p_{TJ}} \sim \frac{m_J^2}{p_{TJ}^2} \longrightarrow$ groomed away

Factorization for NNLL Resummation

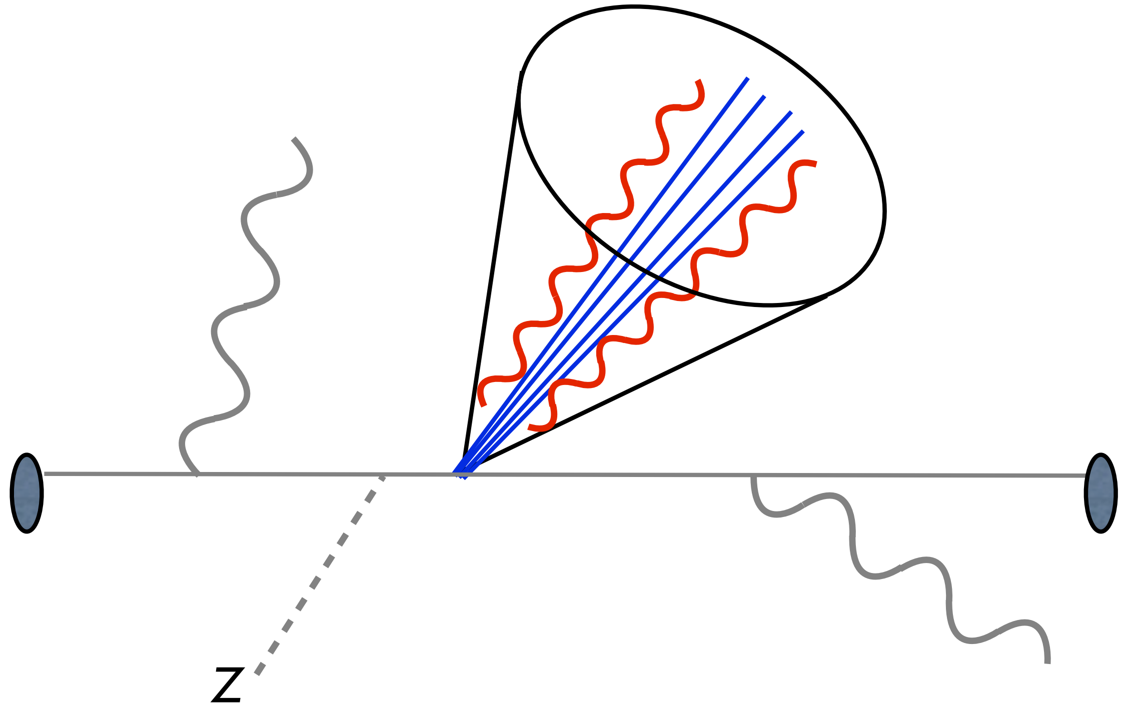
Effective theory for soft drop groomed jets

Frye, AJL, Schwartz, Yan 2016

Coefficient D_k can be extracted from fixed-order

Only assumes collinear factorization of high p_T jets in pp collisions

See Ira's talk



$$m_J^2 \ll z_{\text{cut}} p_{TJ}^2 \ll p_{TJ}^2$$

$$\frac{d\sigma^{\text{resum}}}{dm_J^2} = \sum_{k=q,\bar{q},g} D_k(p_T, z_{\text{cut}}, R) S_{C,k}(z_{\text{cut}} m_J^2) \otimes J_k(m_J^2)$$

sum over jet flavor

includes pdfs, emissions that were groomed away, out-of-jet radiation,...

collinear-soft radiation

hard collinear radiation

Matching NNLL to α_s^2

$$\frac{d\sigma^{\mathrm{NNLL}+\alpha_s^2}}{dm_J^2} \equiv \frac{d\sigma^{\mathrm{NNLL}}}{dm_J^2} + \frac{d\sigma^{\alpha_s^2}}{dm_J^2} - \frac{d\sigma^{\mathrm{NNLL},\alpha_s^2}}{dm_J^2}$$

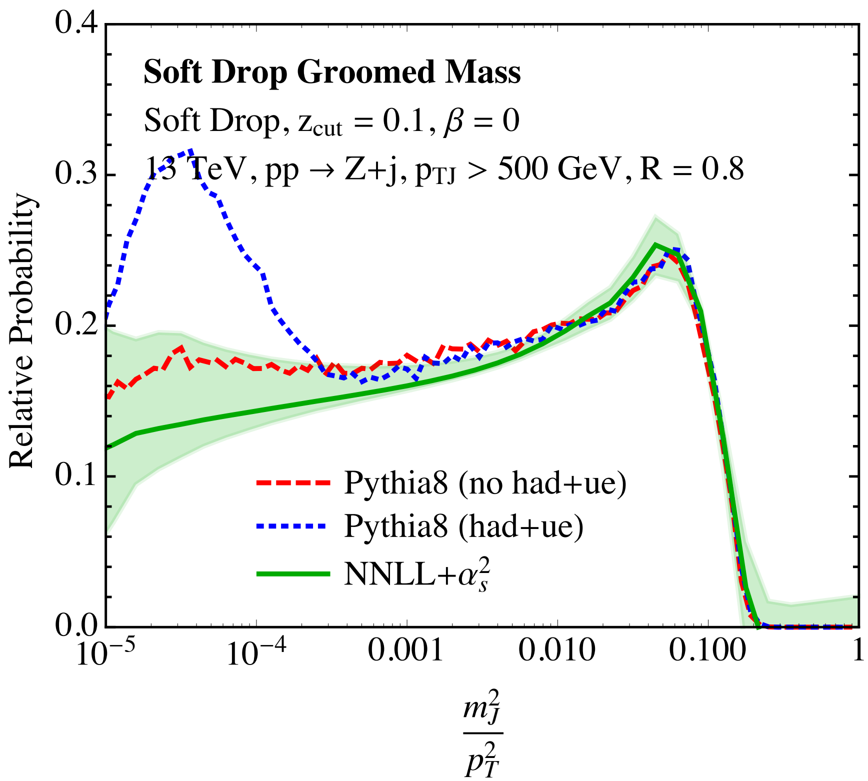
Use MCFM to generate relative α_s^2 cross section

pp → Z + j at NNLO with $m_J^2 > 0$ = pp → Z + 2j at NLO

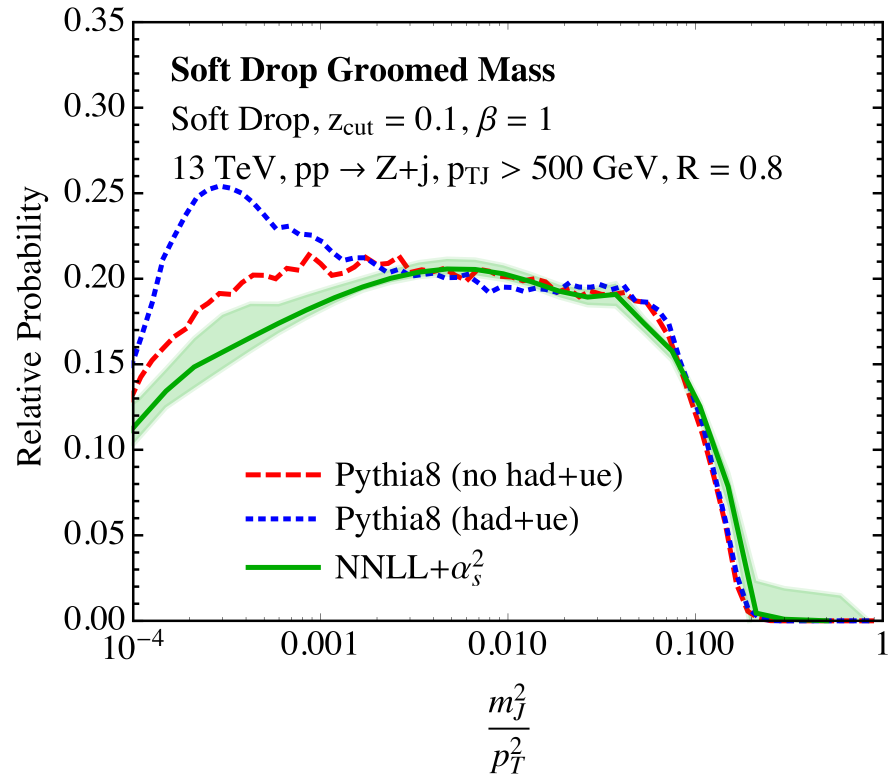
Required extreme computing power:
To make the following plots required centuries of CPU time

The very first jet substructure calculation at high precision!

Results: NNLL+α_s^2 Jet Substructure



NNLL+α_s^2, β = 0



NNLL+α_s^2, β = 1

Comparison with Pythia8 Monte Carlo

Hadronization and underlying event only dominate for $m_J^2/p_T^2 \lesssim 10^{-3}$

Almost three decades of perturbative control in a single jet distribution!

Frye, AJL, Schwartz, Yan 2016

Summary

Precision calculations for jet substructure requires jet grooming

Only mMDT/soft drop remove contamination and eliminate NGLs

All radiation that remains in the jet is collinear

NNLL resummation of groomed jet mass is accomplished

Looking Ahead

mMDT/soft drop also makes quark/gluon jet flavor IRC safe

Improved input into pdfs?
Monte Carlo tuning to gluon jets?
Tuning Monte Carlos to precision calculations?

Precision jet substructure measurements?

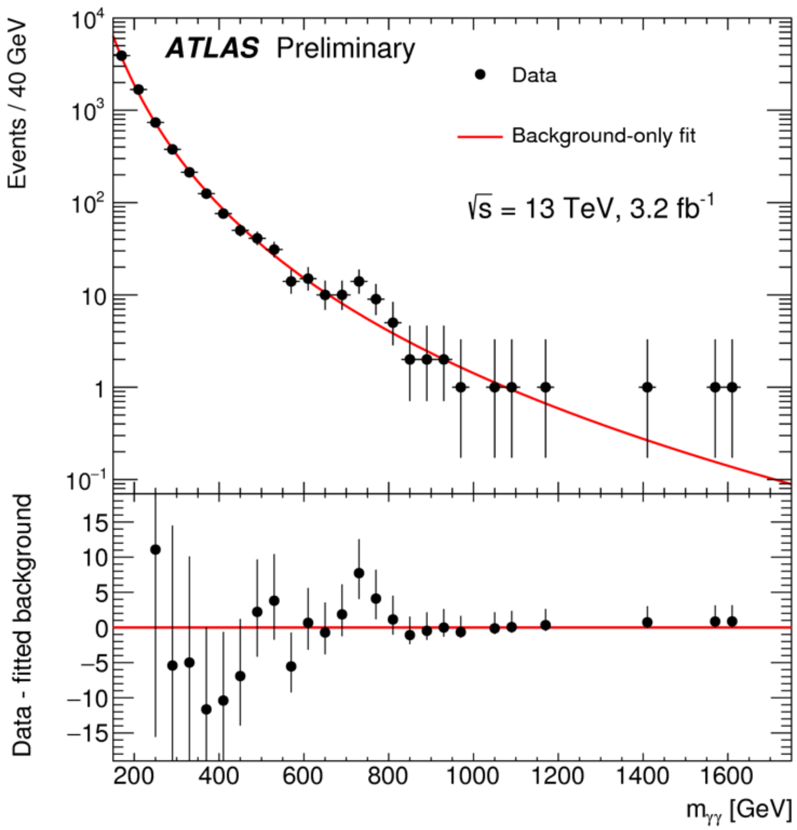
Motivation for ATLAS and CMS to make identical jet measurements?
Possible for systematics at %-level?

Feedback to Fixed-Order Community

Jet substructure observables are sensitive to infrared phase space region
Need very efficient methods to sample deep infrared
Generic phase space reweighting à la EVENT2?

Bonus Slides

Jet Substructure



ATLAS-CONF-2015-081

Should also see evidence in W/Z/H channels

Requires identification from decays

$$\frac{\Gamma_{Z\to l^+l^-}}{\Gamma_Z} \simeq 10\%$$

$$\frac{\Gamma_{Z\to \mathrm{had}}}{\Gamma_Z} \simeq 70\%$$

Understanding hadronic decays is essential!

Background to boosted hadronically-decaying EW bosons are massive QCD jets!

Need precise understanding, definition, theory predictions of QCD jets at the LHC

See Jesse's Talk

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Experimental Challenge:
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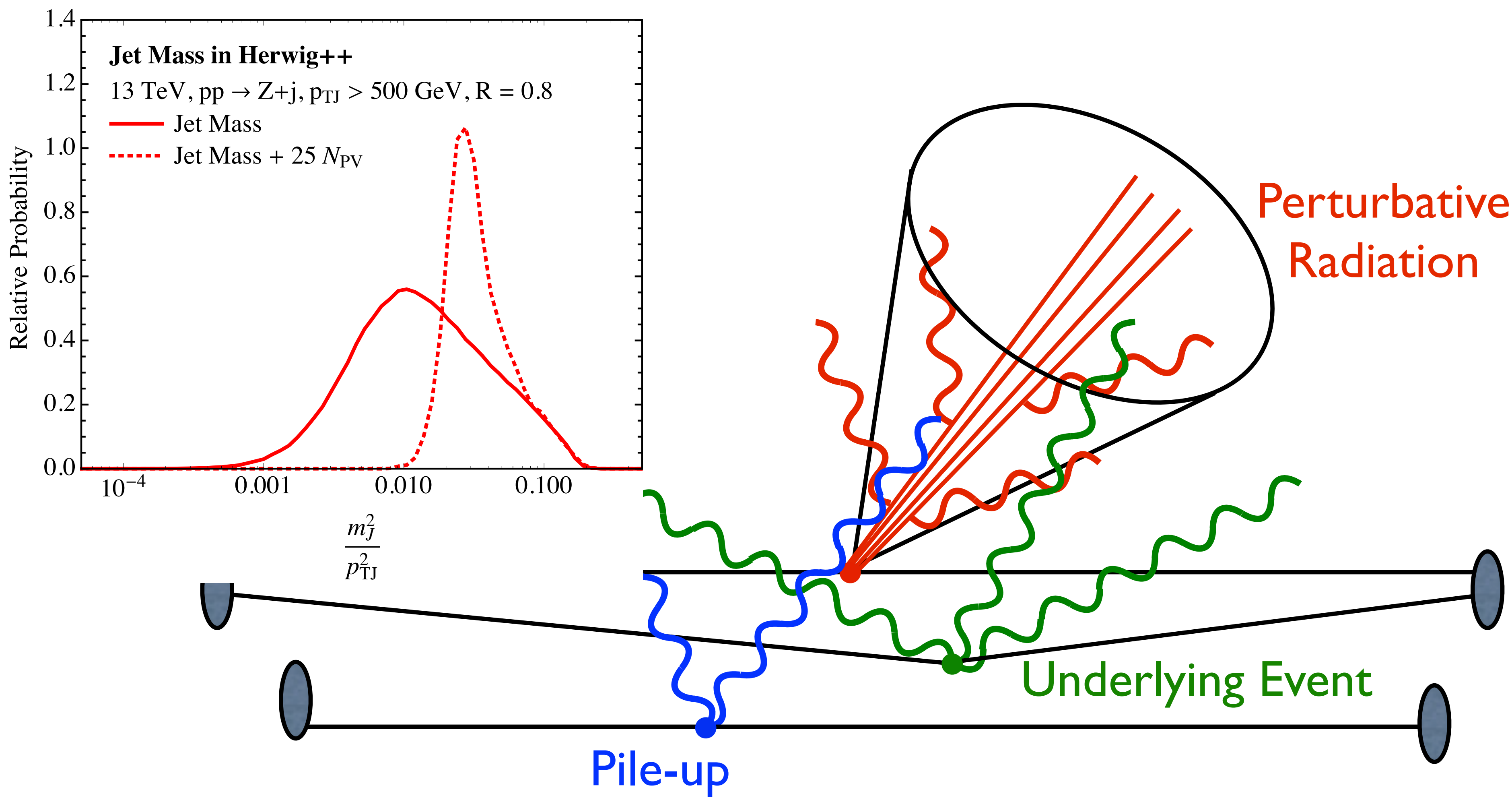
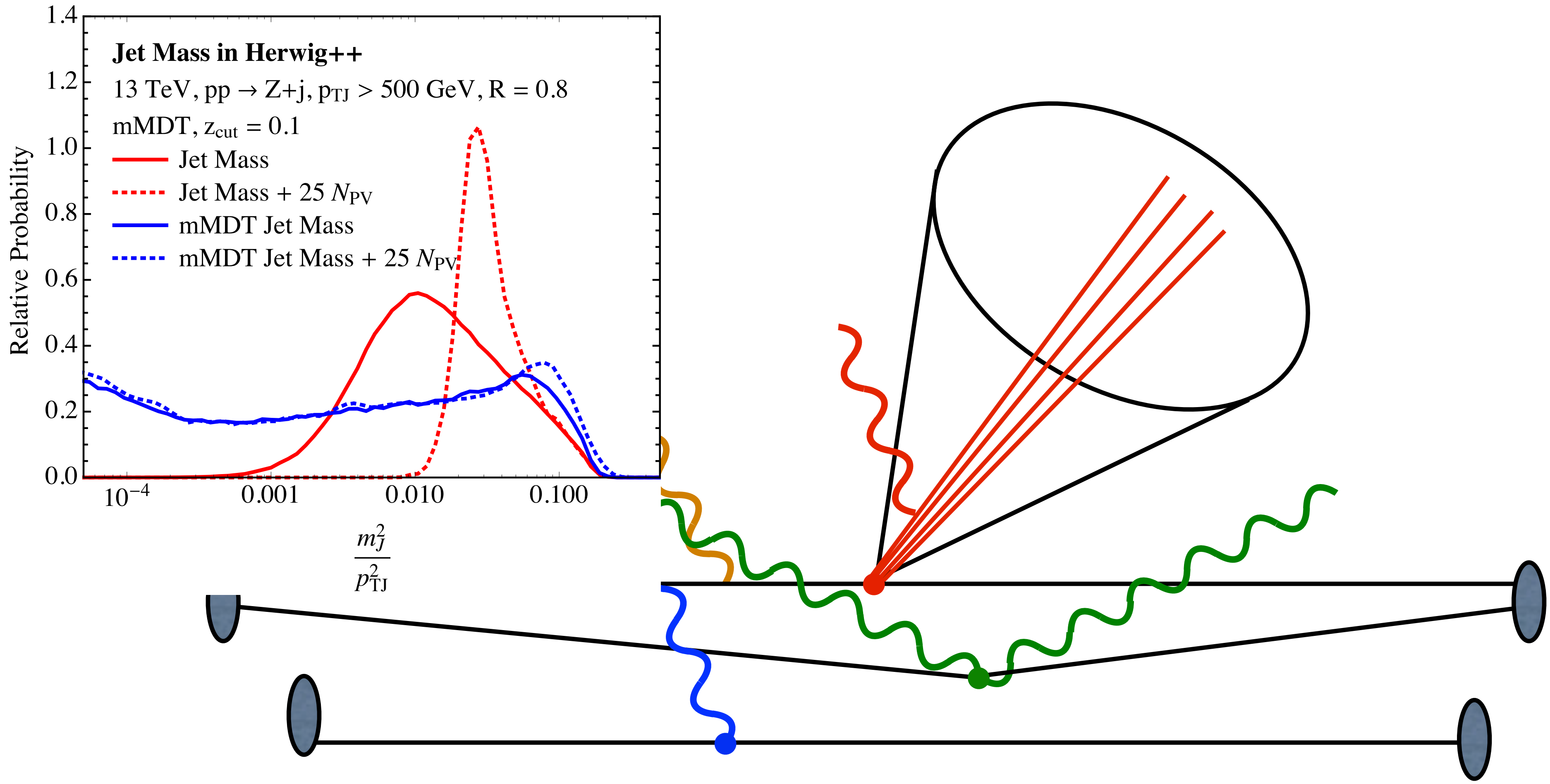


How to get to Precision Jet Substructure

Measure mMDT/soft drop m_J^2 on the jet in pp → Z + j events

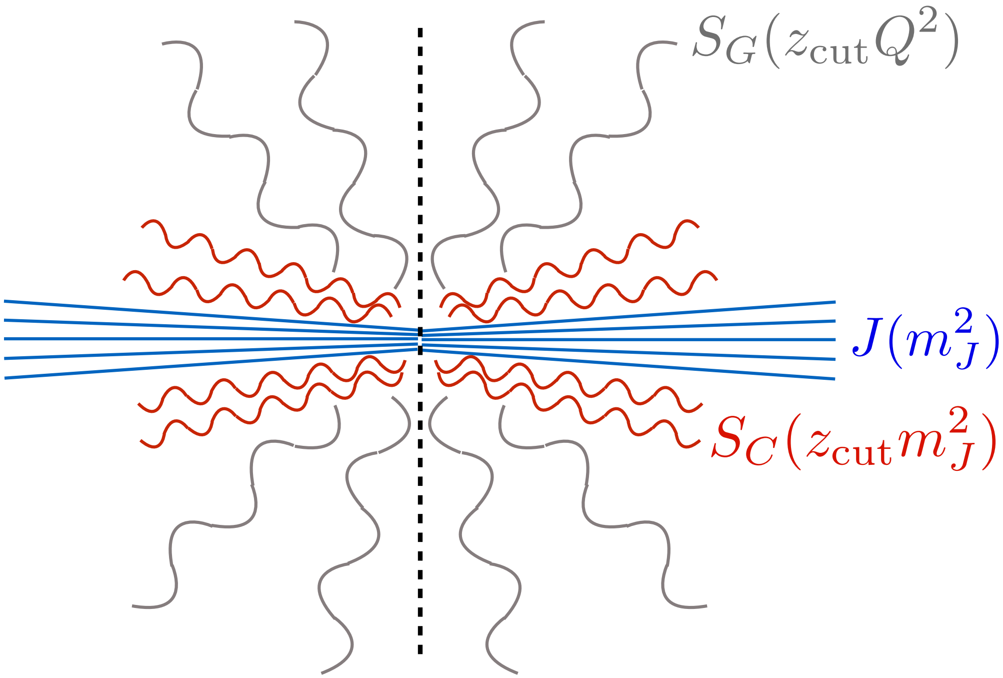
Removes contamination radiation from the jet

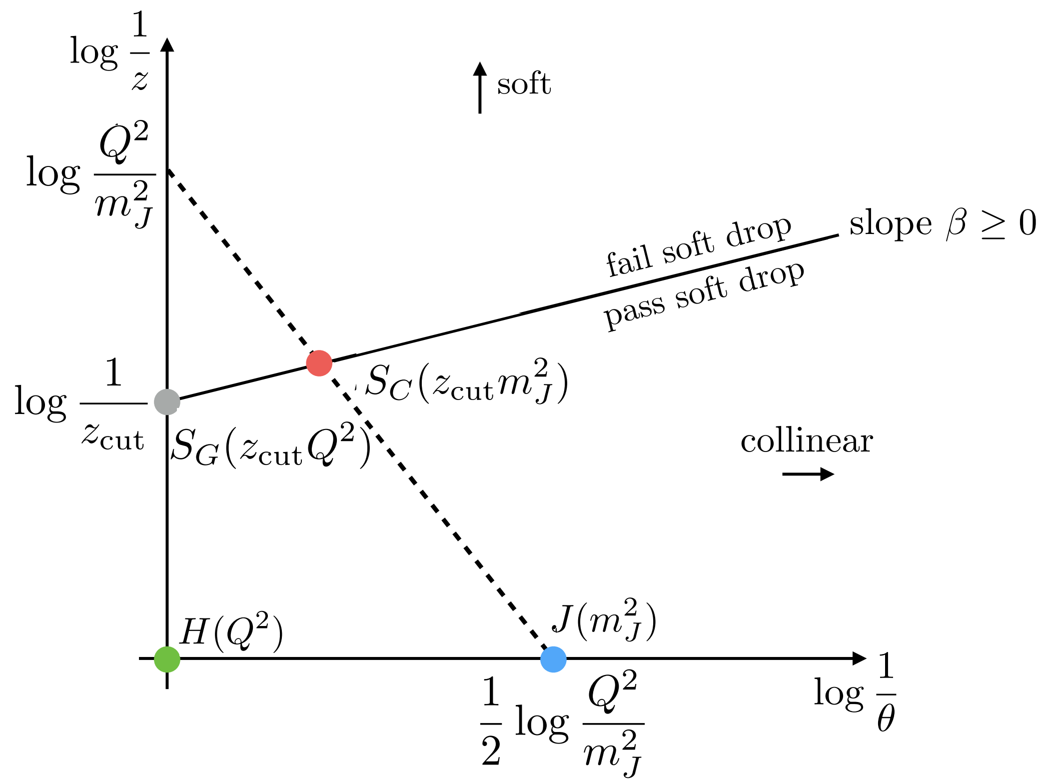
Eliminates non-global logarithms



Aside: Getting Collinear-Soft Function to NNLL

Factorization theorem in e+e- collisions:





$$m_J^2 \ll z_{\rm cut}Q^2 \ll Q^2$$

$$\frac{d^2\sigma}{dm_{J,L}^2\,dm_{J,R}^2} = H(Q^2)S_G(z_{\rm cut}Q^2)\left[S_C(z_{\rm cut}m_{J,L}^2)J(m_{J,L}^2)\right]\left[S_C(z_{\rm cut}m_{J,R}^2)J(m_{J,R}^2)\right]$$

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$H(Q^2)$: Hard function for $e^+e^- \to qq$. Known beyond two-loops.

van Neerven 1986

Matsuura, van der Marck, van Neerven 1989

$J(m_J^2)$: Jet function. Known at two-loops for quarks and gluons.

Bauer, Manohar 2003

Becher, Neubert 2006

$S_G(z_{\rm cut} Q^2)$: Global soft function. Related to two-loop soft function with energy veto (up to calculable clustering effects).

von Manteuffel, Schabinger, Zhu 2013

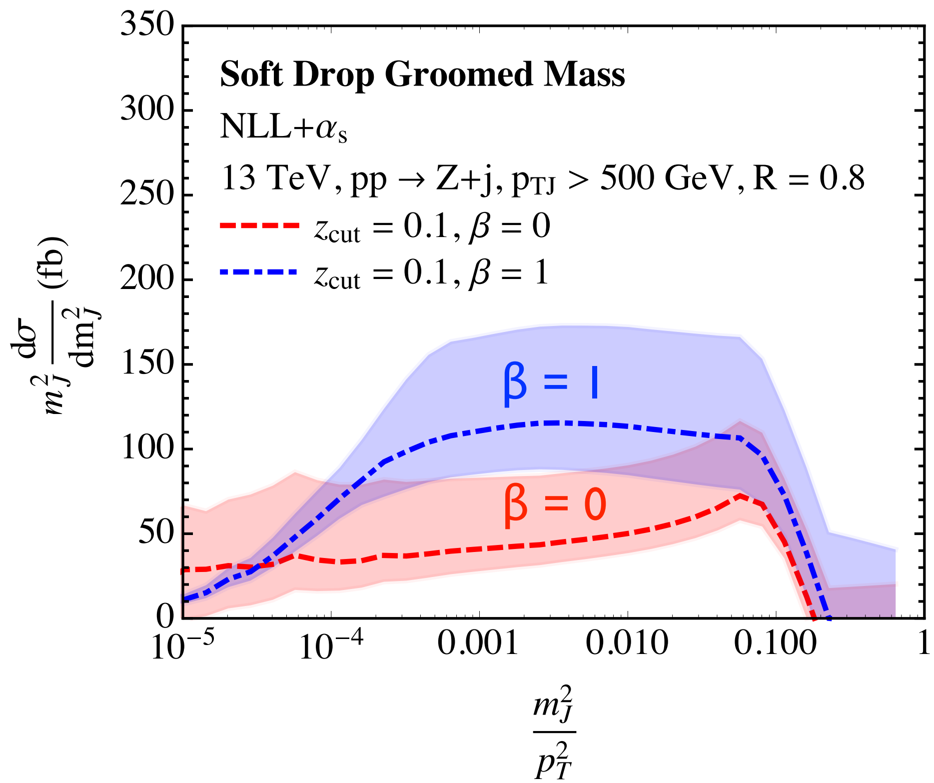
Chien, Hornig, Lee 2015

$S_C(z_{\rm cut} m_J^2)$: Collinear-soft function. New, no two-loop calculation exists.

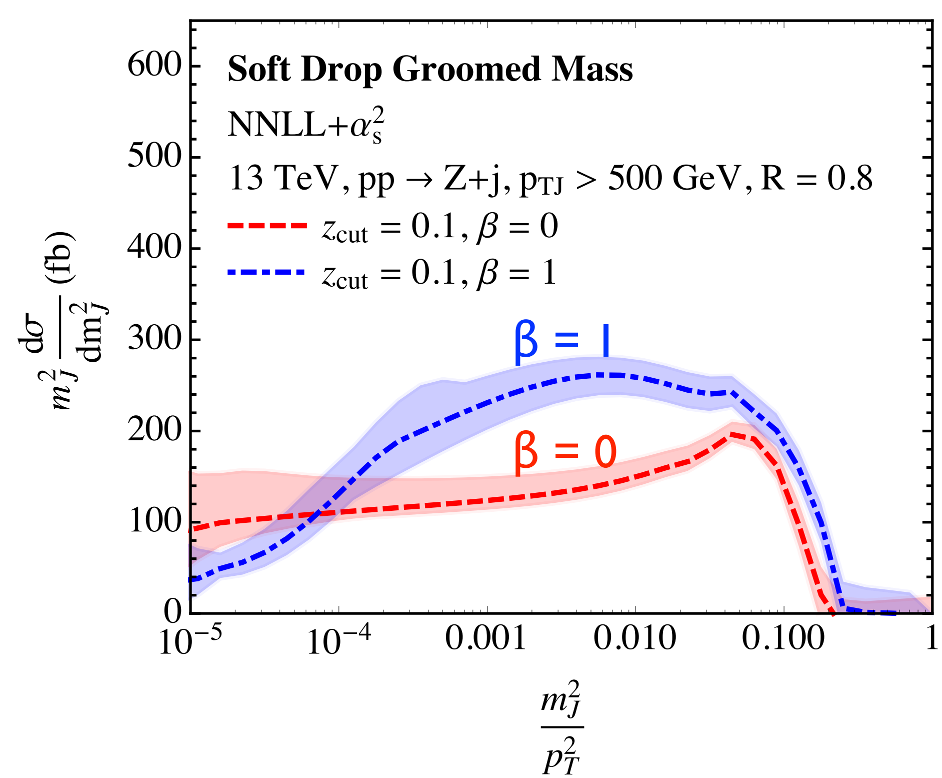
Can get everything from literature and by exploiting RG invariance!

$$0 = \gamma_H + \gamma_{S_G} + 2\gamma_J + 2\gamma_{S_C}$$

Results: NNLL+α_s^2 Jet Substructure



NLL+α_s



NNLL+α_s^2

Soft Drop: $$\frac{\min[p_{Ti}, p_{Tj}]}{p_{Ti} + p_{Tj}} > z_{\text{cut}} \left(\frac{R_{ij}}{R}\right)^{\beta}$$

Significant decrease in residual scale uncertainty at NNLL+α_s^2!

Frye, AJL, Schwartz, Yan 2016

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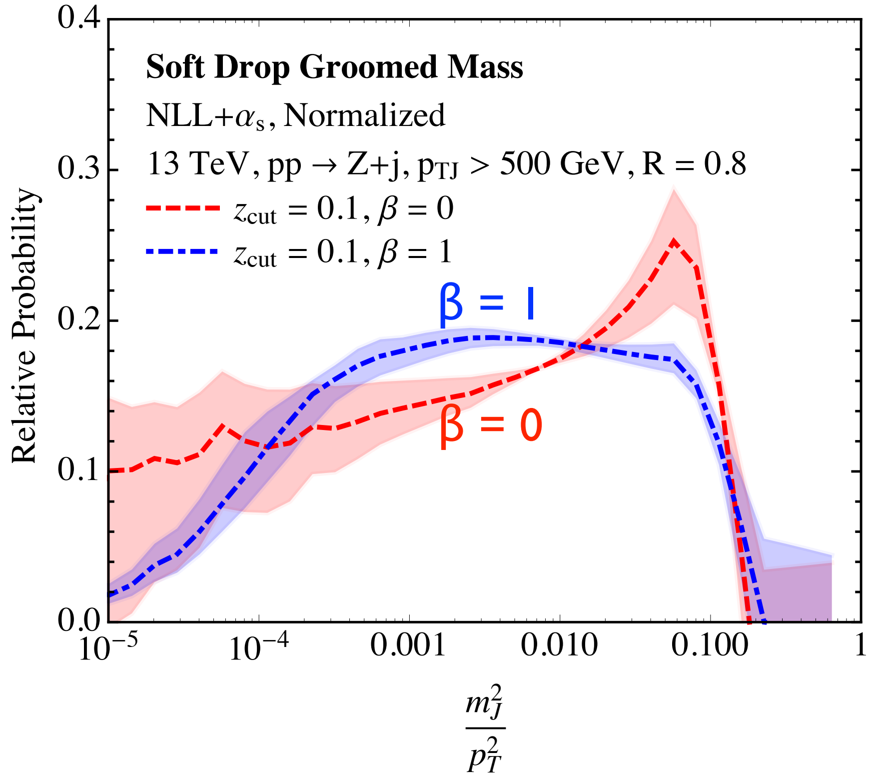
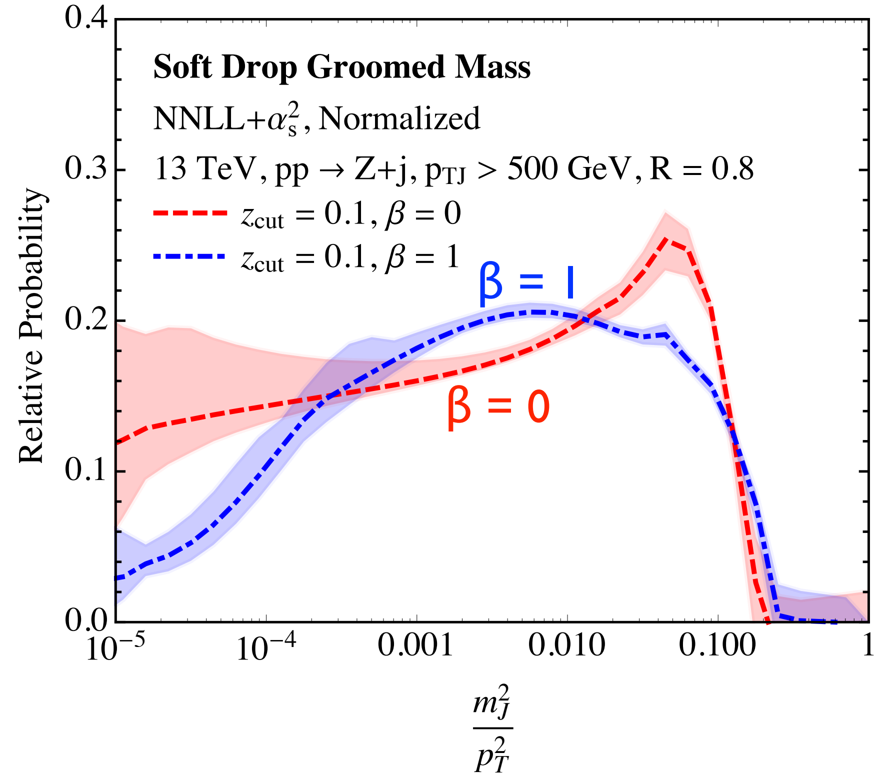


NLL+α_s



NNLL+α_s^2

Shape of distribution only depends on collinear physics

$$\frac{d\sigma^{\text{resum}}}{dm_J^2} = \sum_{k=q,\bar{q},g} D_k(p_T, z_{\text{cut}}, R) S_{C,k}(z_{\text{cut}} m_J^2) \otimes J_k(m_J^2)$$

<10%-level residual scale uncertainties in normalized distributions!

Frye, AJL, Schwartz, Yan 2016