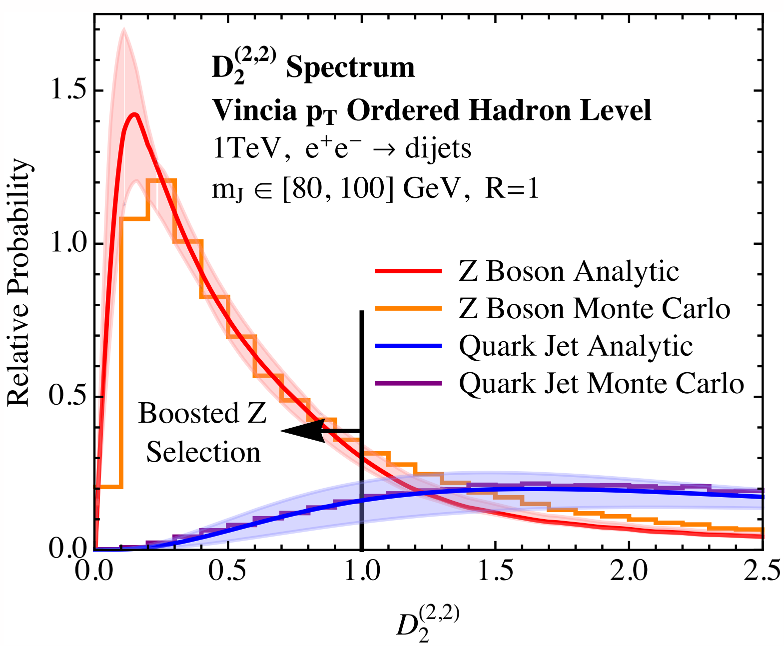
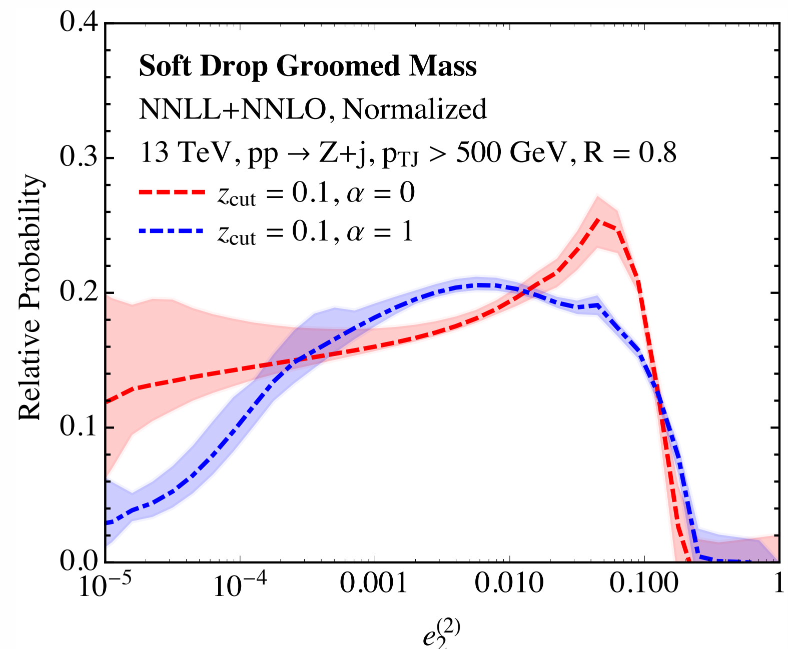
Precision Jet Substructure
at the
Large Hadron Collider

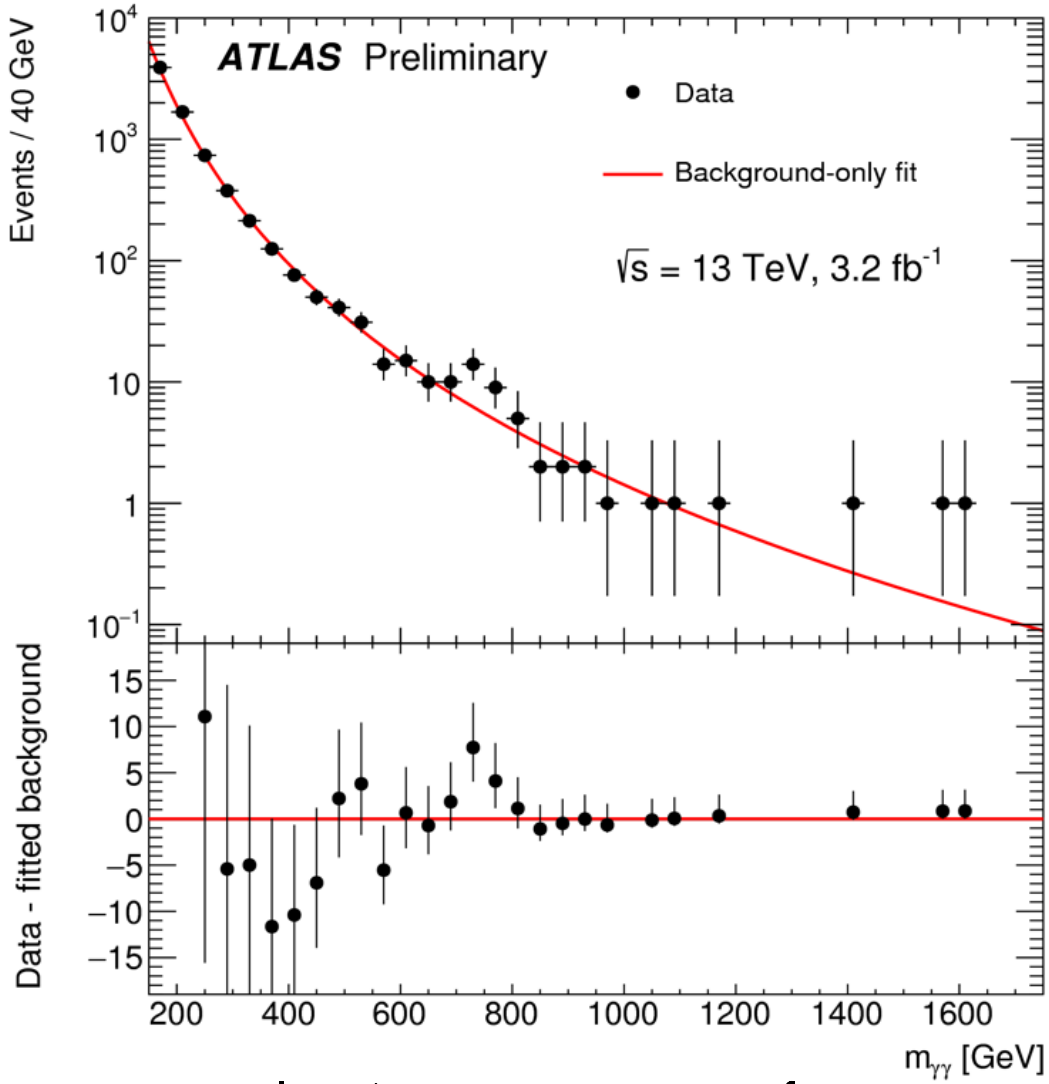




Andrew Larkoski
Harvard University

Fermilab, Ides of March - 1, 2016

December 15, 2015
LHC Jamboree



Invariant mass spectrum of
pp > γ γ

Excess around 750 GeV

Evidence for pp > X_{750} > γ γ?

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!

ATLAS-CONF-2015-081

Searches in Diboson Final States using **Jet Substructure**

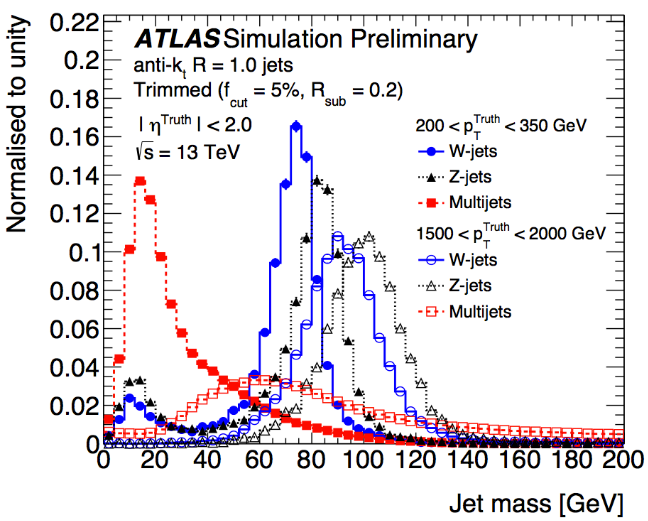
Searches for VV or VH resonances in several topologies involving boson (W, Z and H) tagging

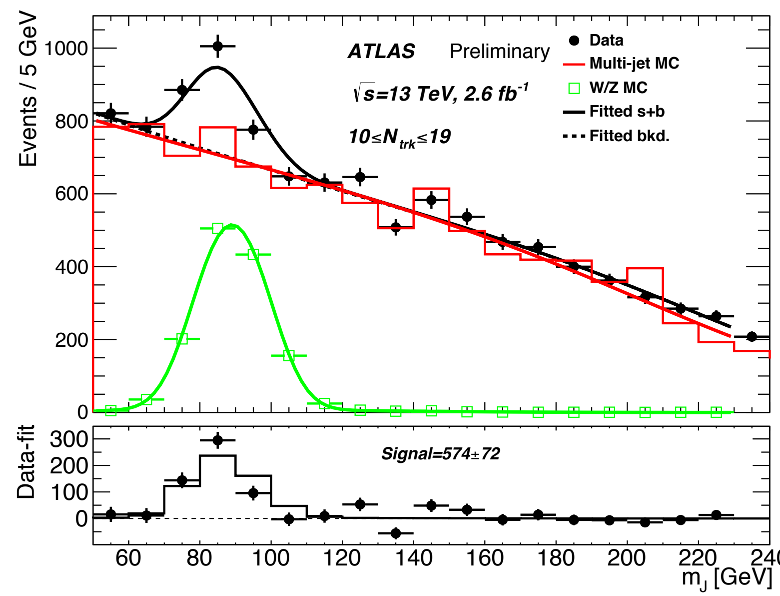
Nominal boson tagging algorithm

- Anti-kT R=1.0
- Trimming: fcut = 5% and Rsub = 0.2
- pT dependent (energy correlation ratio) D2 selections for W and Z separately (Multijet reduction by 40 – 70)

Boson tagging at work

W and Z peak in the data from dijet events applying the nominal boson tagging algorithm





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*from Marumi Kado's talk for ATLAS
12/15/2015

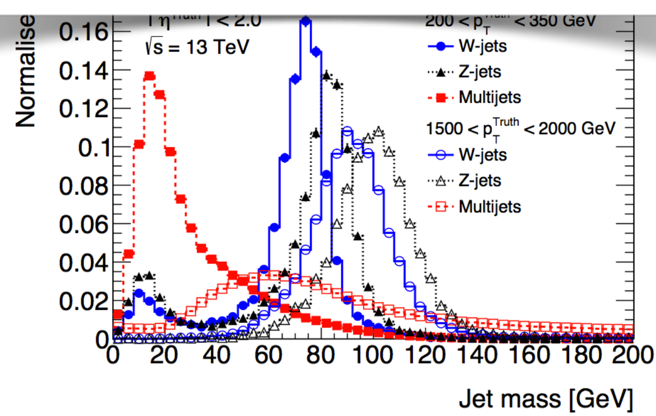
Searches in Diboson Final Sta

Searches for VV or VH resonances in several

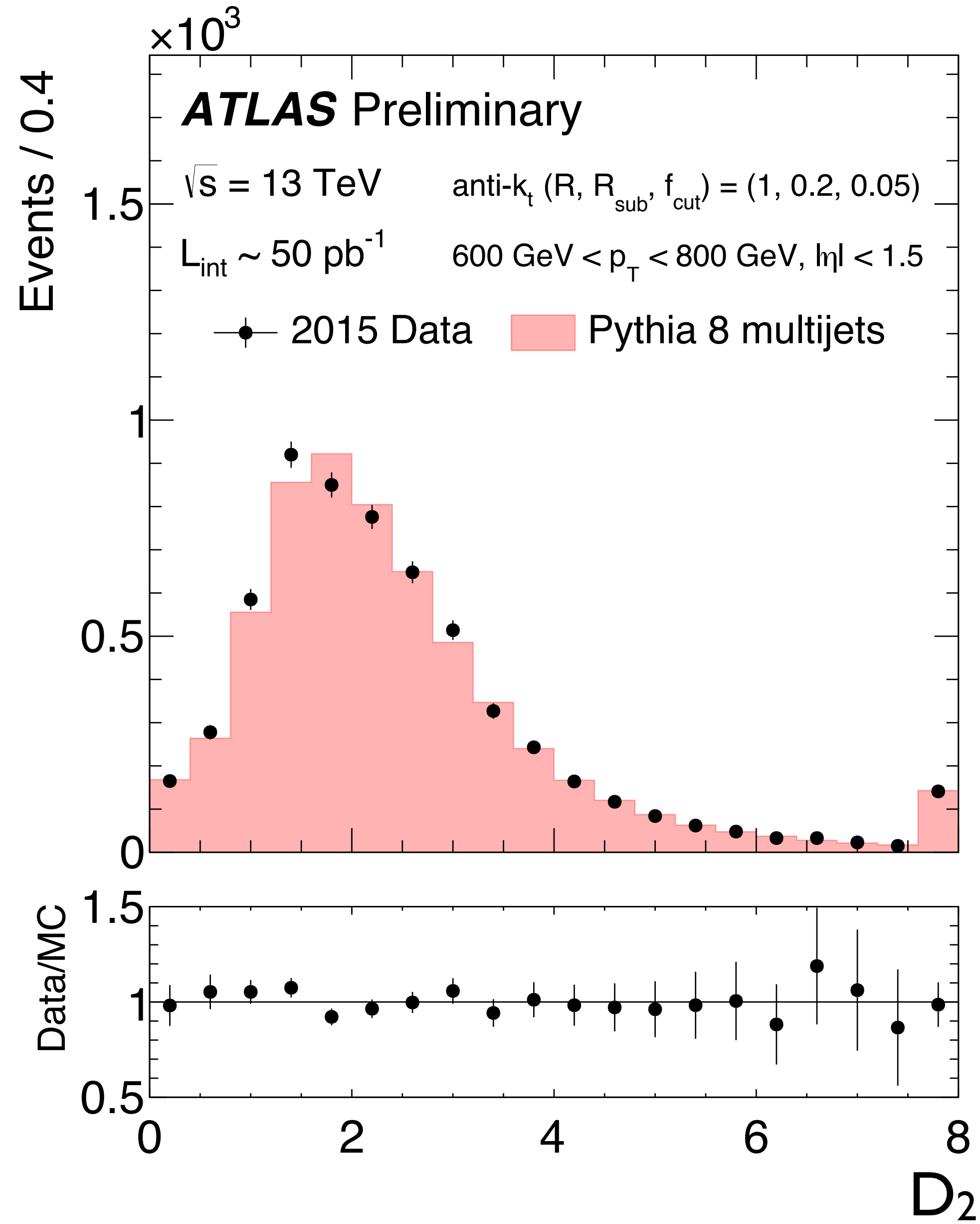
Nominal boson tagging algorithm

- Anti-kT R=1.0
- Trimming: fcut = 5% and Rsub = 0.2
- pT dependent (energy correlation ratio) D2

AJL, et al.
2013: Energy Correlation Functions
2014: Definition of D_2
2015: Explicit Prediction in QCD



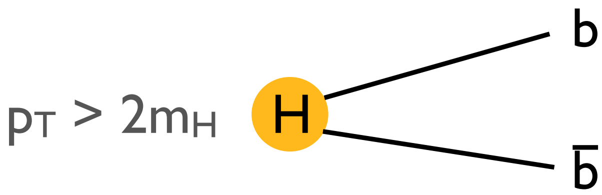
*from Marumi Kado's talk for ATLAS
12/15/2015



One of the first measurements of Run 2!

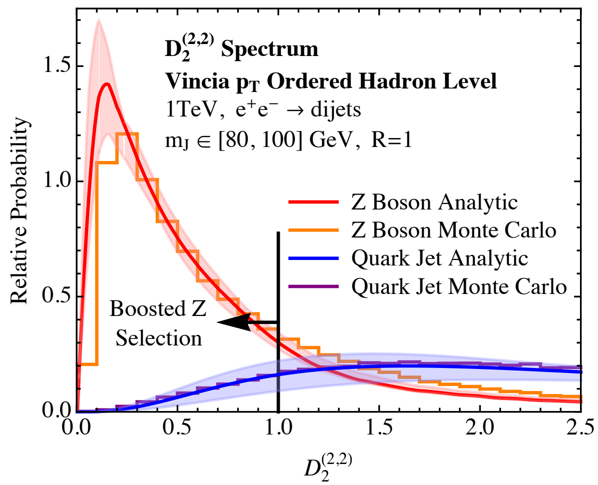
ATLAS-CONF-2015-035

Outline



Introduction to Jet Substructure

Opening the door to a new regime of Standard Model physics

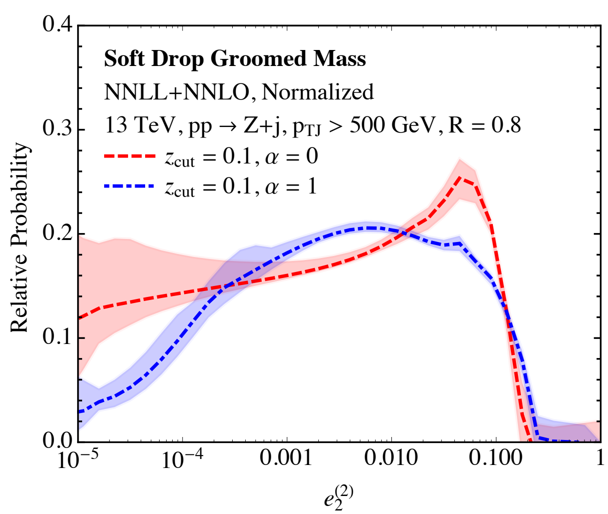


Motivate and define D_2

Building the optimal observable from simple building blocks

Analytic predictions from pQCD

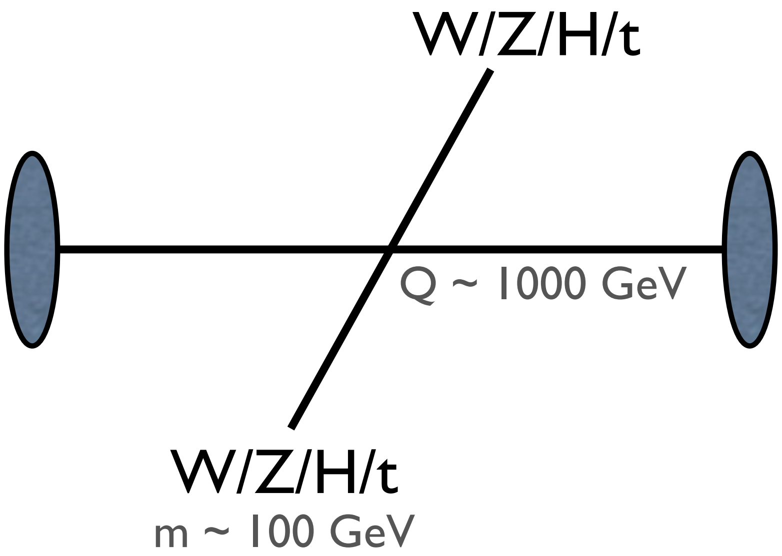
Unprecedented multi-differential jet observable calculations



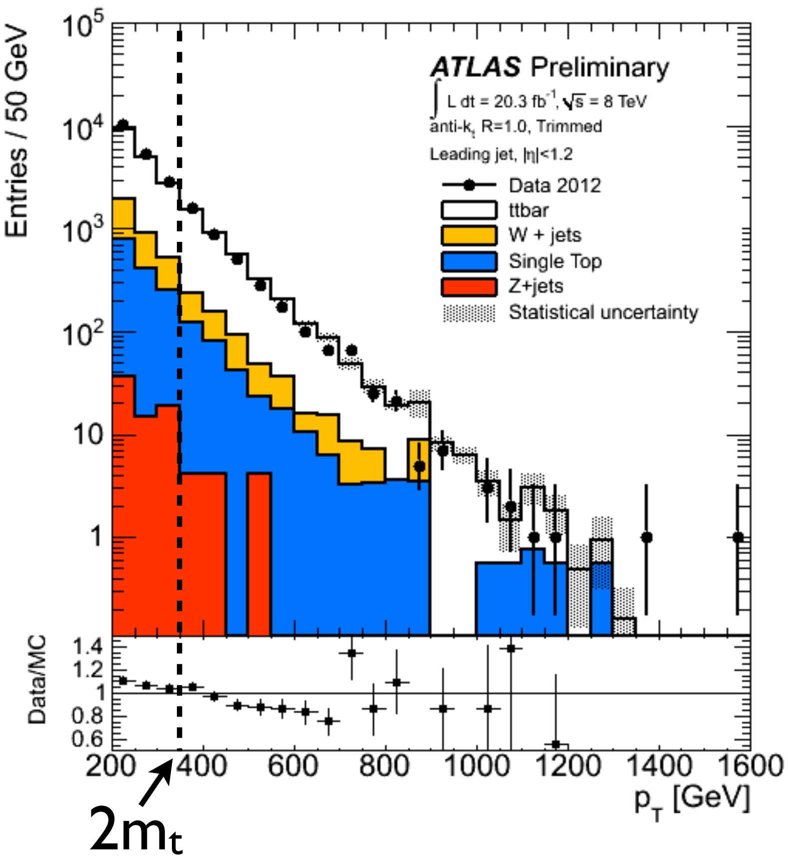
Pushing the Precision Frontier

First jet physics predictions at NNLL matched to NNLO accuracy

Why jet substructure?



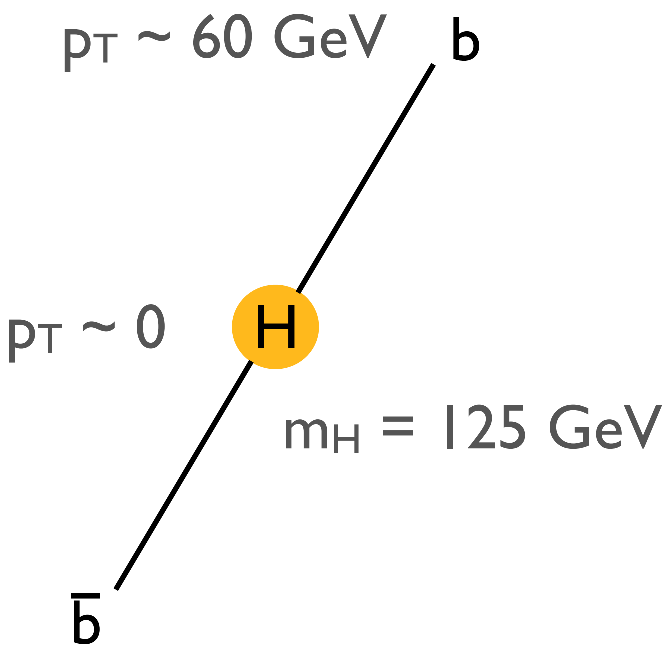
LHC can produce heavy Standard Model particles with large Lorentz boosts



Case study 1: Boosted top quarks in ATLAS

Thousands of top quarks with $p_T > 2m_t$

Powerful probe into TeV scale physics!



Case study 2: $H \to b\bar{b}$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{\rm tot}} \sim 60\%$$

Rates at 14 TeV LHC

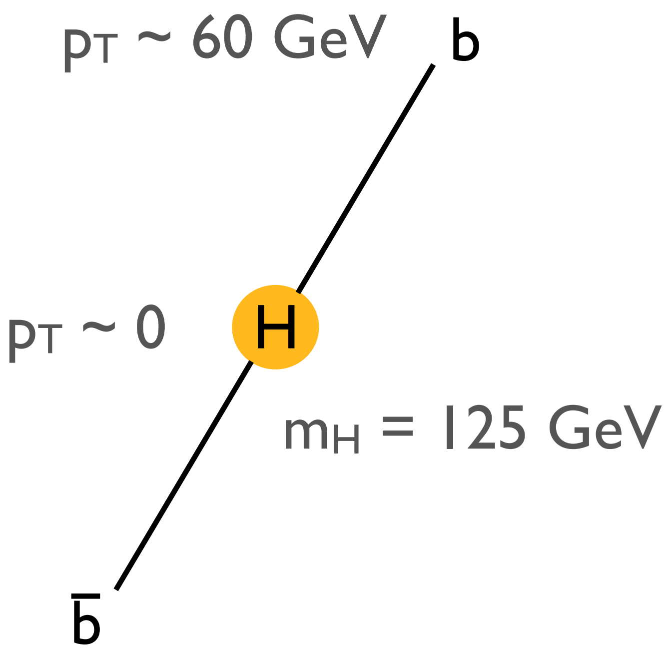
$$\sigma(pp \to H \to b\bar{b}) \sim 0.5 \text{ pb}$$

$p_T > 60$ GeV

$$\sigma(pp \to b\bar{b}) \sim 5 \times 10^4 \text{ pb}$$

$$\mathcal{L} = 30 \text{ fb}^{-1} \qquad \frac{S}{\sqrt{B}} \sim 0.4$$

Case study 2: $H \rightarrow b\bar{b}$



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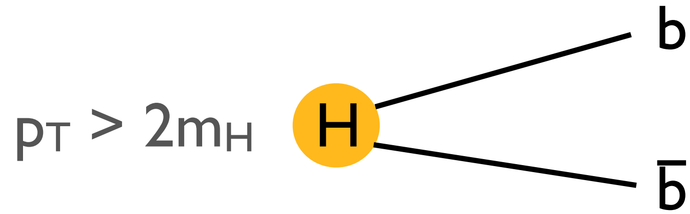


Looks like a QCD jet!

Rates at 14 TeV LHC

$$\sigma(pp \rightarrow H \rightarrow b\bar{b}) \sim 0.5 \text{ pb}$$

p_T > 60 GeV

$$\sigma(pp \rightarrow b\bar{b}) \sim 5 \times 10^4 \text{ pb}$$

$$\mathcal{L} = 30 \text{ fb}^{-1} \qquad \frac{S}{\sqrt{B}} \sim 0.4$$

Rates at 14 TeV LHC
pT > 250 GeV

$$\sigma(pp \rightarrow ZH \rightarrow Zb\bar{b}) \sim 0.01 \text{ pb}$$

$$\sigma(pp \rightarrow Zb\bar{b}) \sim 1 \text{ pb}$$

$$\mathcal{L} = 30 \text{ fb}^{-1} \qquad \frac{S}{\sqrt{B}} \sim 1.7$$

Jet Substructure is an extremely active field!

Filtering, Trimming, Pruning, HEPTopTagger, JH Top Tagger, N-subjettiness, Dipolarity, Shower Deconstruction, Accidental Substructure, PUPPI, CMS Top Tagger, Planar Flow, Jet Cleansing, Jet Templates, QJets, Angular Correlation Functions, Soft Drop, modified Mass Drop Tagger, Soft Killer, Energy Correlation Functions, Pull, Jet Charge, Jets-without-Jets, Telescoping Jets, X-Cone algorithm, Recoil-free axes, Jet Reclustering, Area Subtraction, Constituent Subtraction, Y-Splitter, Angularities, Zernike Coefficients, Subjet Counting, Wavelets, Sudakov Safety, Associated Subjets,...

BOOST meeting reports

BOOST 2010: Eur. Phys. J. C 71, 1661 (2011)
BOOST 2011: J. Phys. G 39, 063001 (2012)
BOOST 2012: Eur. Phys. J. C 74, no. 3, 2792 (2014)

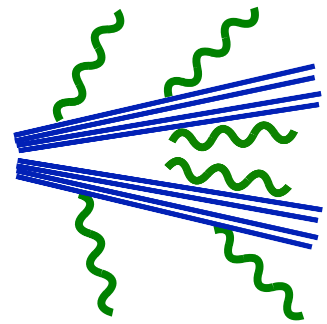
Towards an Understanding of the Correlations in Jet Substructure

Report of BOOST2013, hosted by the University of Arizona, 12^{th}-16^{th} of August 2013.

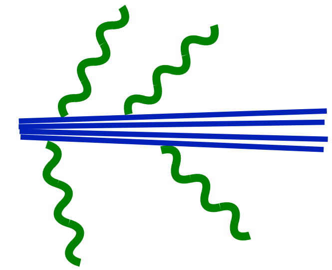
Eur. Phys. J. C75, no.9, 409 (2015)
Editors: AJL, et al.

Goals of jet substructure:

W/Z/H



QCD

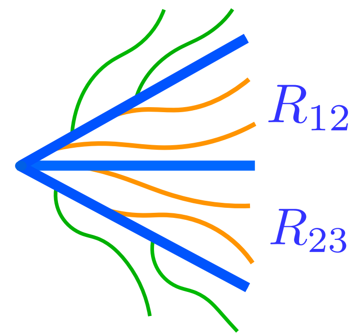


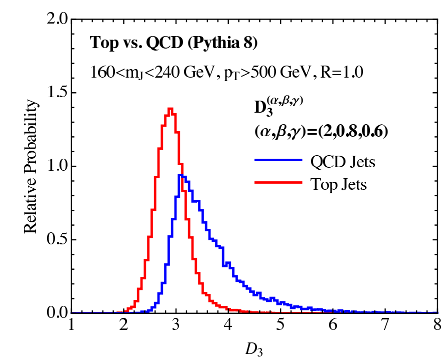
Boosted W/Z/H vs. QCD

AJL, Salam, Thaler
JHEP 1306, 108 (2013)

AJL, Moult, Neill
JHEP 1412, 009 (2014)

AJL, Moult, Neill
arXiv:1507.03018



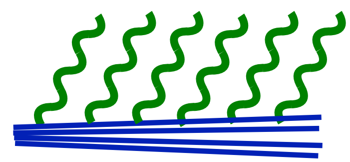


Boosted Top Quarks vs. QCD

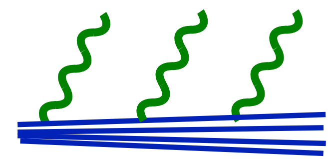
Jankowiak, AJL
JHEP 1106 (2011) 057

AJL, Moult, Neill
Phys. Rev. D 91, no. 3, (2015)

AJL, Maltoni, Selvaggi
JHEP 1506 (2015) 032



gluon



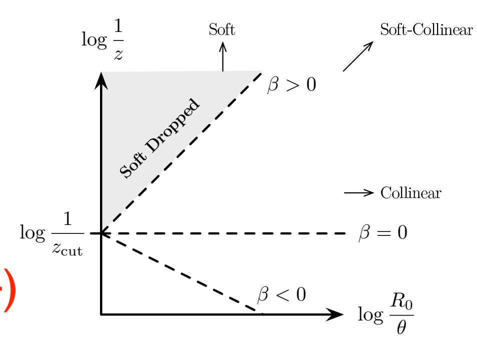
quark

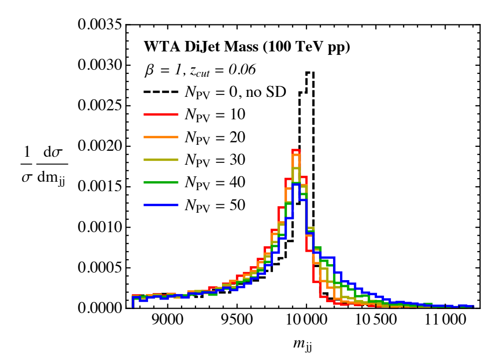
Quark vs. Gluon Jet Discrimination

AJL, Salam, Thaler
JHEP 1306, 108 (2013)

AJL, Neill, Thaler,
JHEP 1404 (2014) 017

AJL, Thaler, Waalewijn
JHEP 1411 (2014) 129





Contamination Removal

AJL, Marzani, Soyez, Thaler
JHEP 1405, 146 (2014)

AJL, Thaler
Phys. Rev. D 90, no. 3, (2014)

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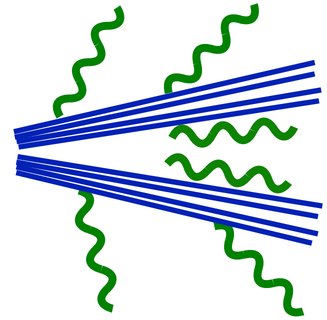
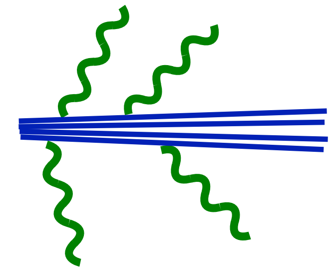
AJL, Moult, Neill
JHEP 1412, 009 (2014)

AJL, Moult, Neill
arXiv:1507.03018

W/Z/H



QCD



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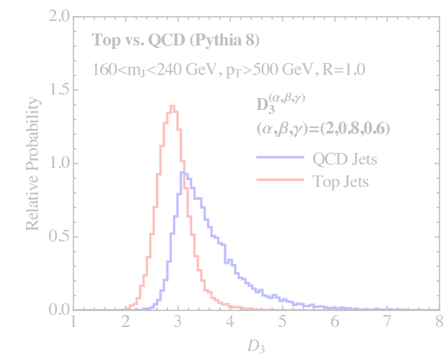

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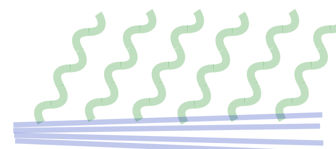
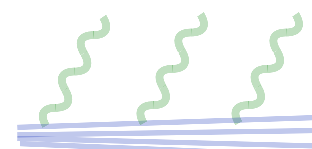


gluon



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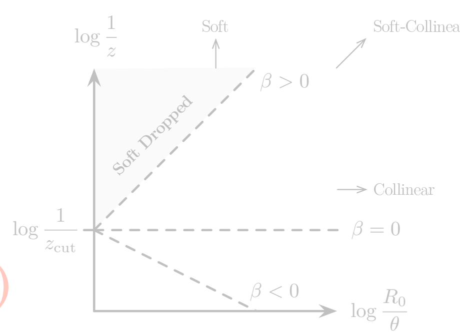
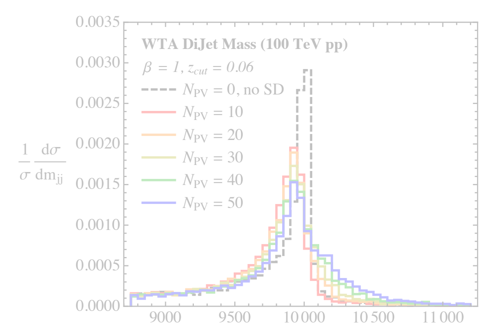




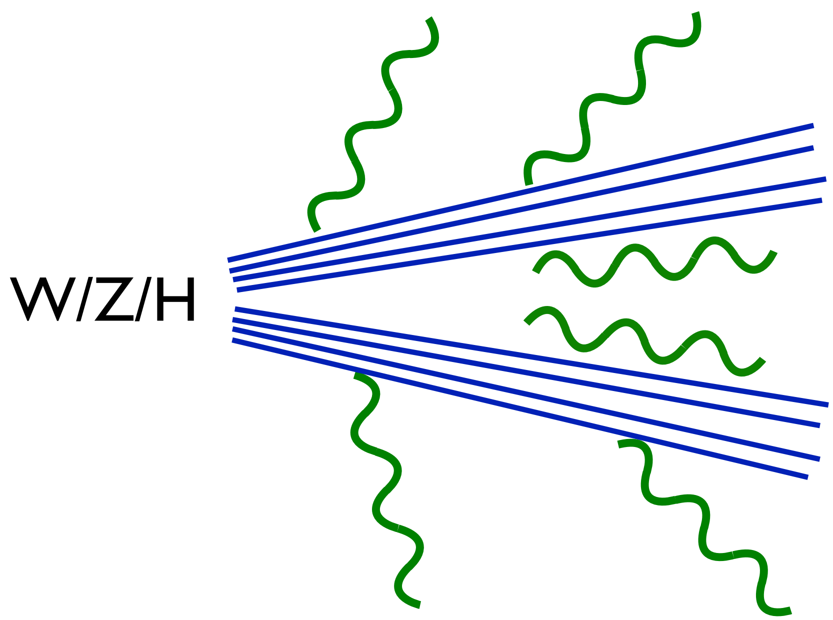
Constructing the optimal discriminant: D_2

AJL, Salam, Thaler
JHEP 1306, 108 (2013)

AJL, Moult, Neill
JHEP 1412, 009 (2014)

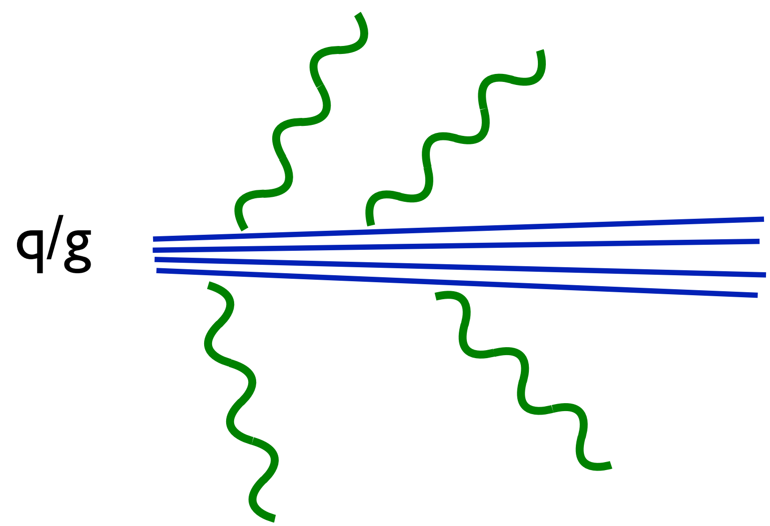
AJL, Moult, Neill
arXiv:1507.03018

Goal:
Discriminate between QCD jets and boosted hadronic decays of W/Z/H bosons



Signal: Two-prong jet

Characteristic angular size
determined by mass



Background: One-prong jet

No intrinsic angular size

Energy correlation functions:

AJL, Salam, Thaler
JHEP 1306, 108 (2013)

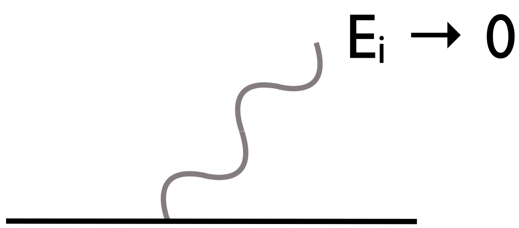
$$e_2^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{i<j\in J} p_{Ti} p_{Tj} R_{ij}^{\beta}$$

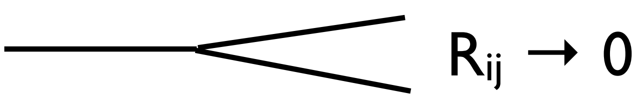
jet p_T

sum over distinct pairs of particles in the jet

angle between *i* and *j*

$$e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{i<j<k\in J} p_{Ti} p_{Tj} p_{Tk} R_{ij}^{\beta} R_{ik}^{\beta} R_{jk}^{\beta}$$





$e_2^{(\beta)}$, $e_3^{(\beta)}$ are infrared and collinear safe

Requirement for predictivity in QCD

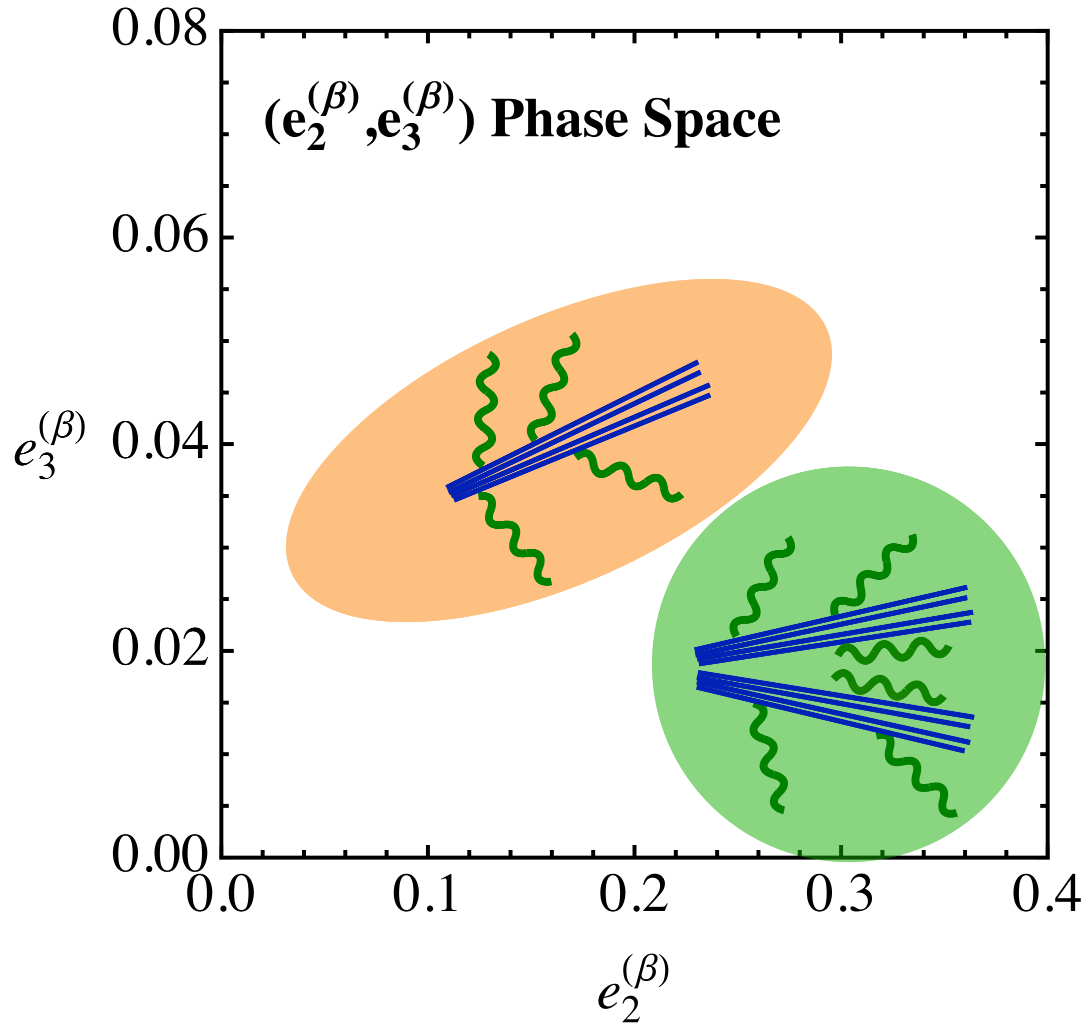
Must sum over degenerate states in 0 energy and collinear limit

Divergences then cancel

$$e_2^{(\beta)} = 0$$
$$e_3^{(\beta)} = 0$$

$$e_2^{(\beta)} \neq 0$$
$$e_3^{(\beta)} = 0$$

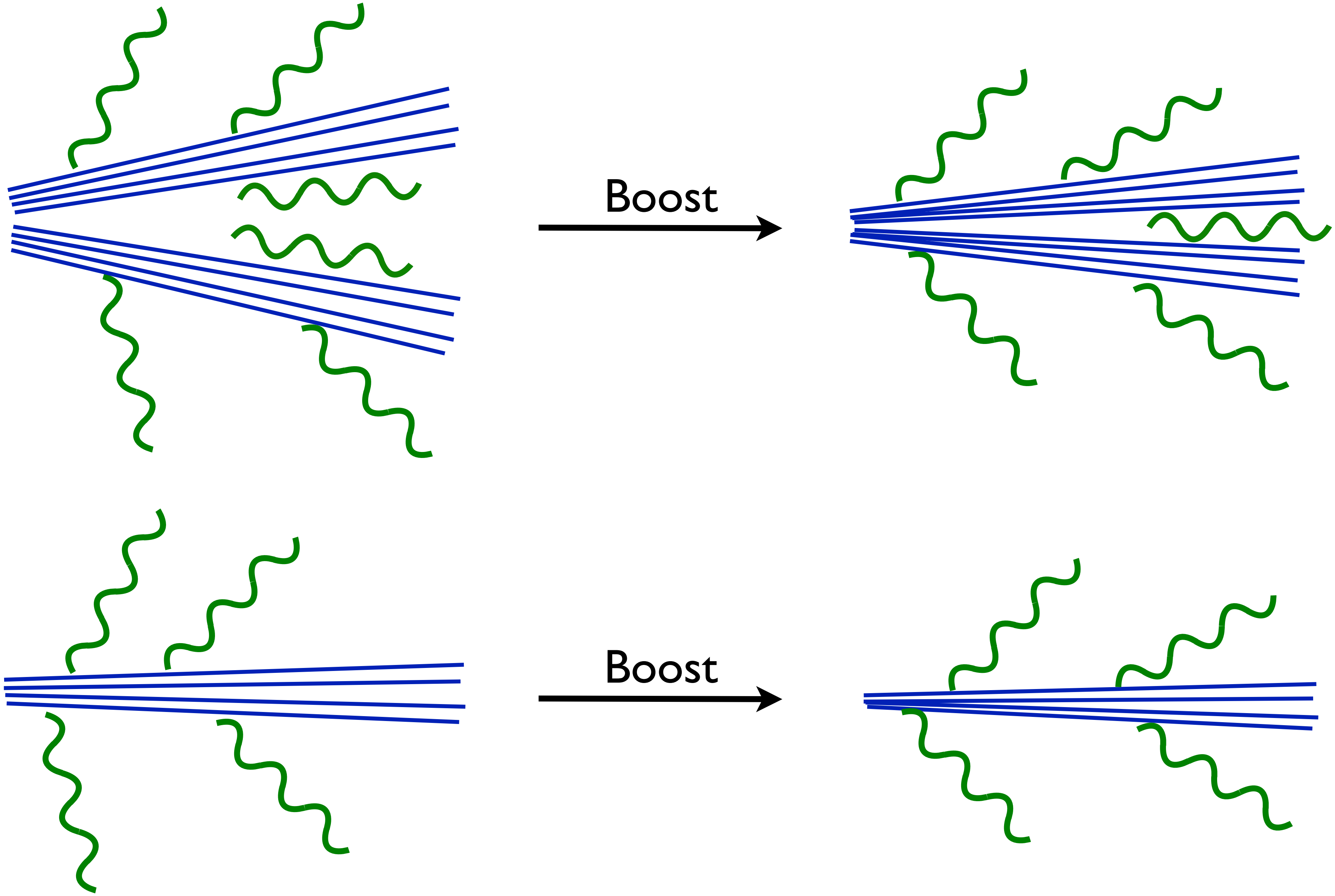
$$e_2^{(\beta)} \neq 0$$
$$e_3^{(\beta)} \neq 0$$



$e_2^{(\beta)}$ sensitive to radiation off of a single hard core

$e_3^{(\beta)}$ sensitive to radiation off of two hard cores

Exploiting boost invariance:



Boundary between one- and two-prong regions is boost invariant!

Exploiting boost invariance:

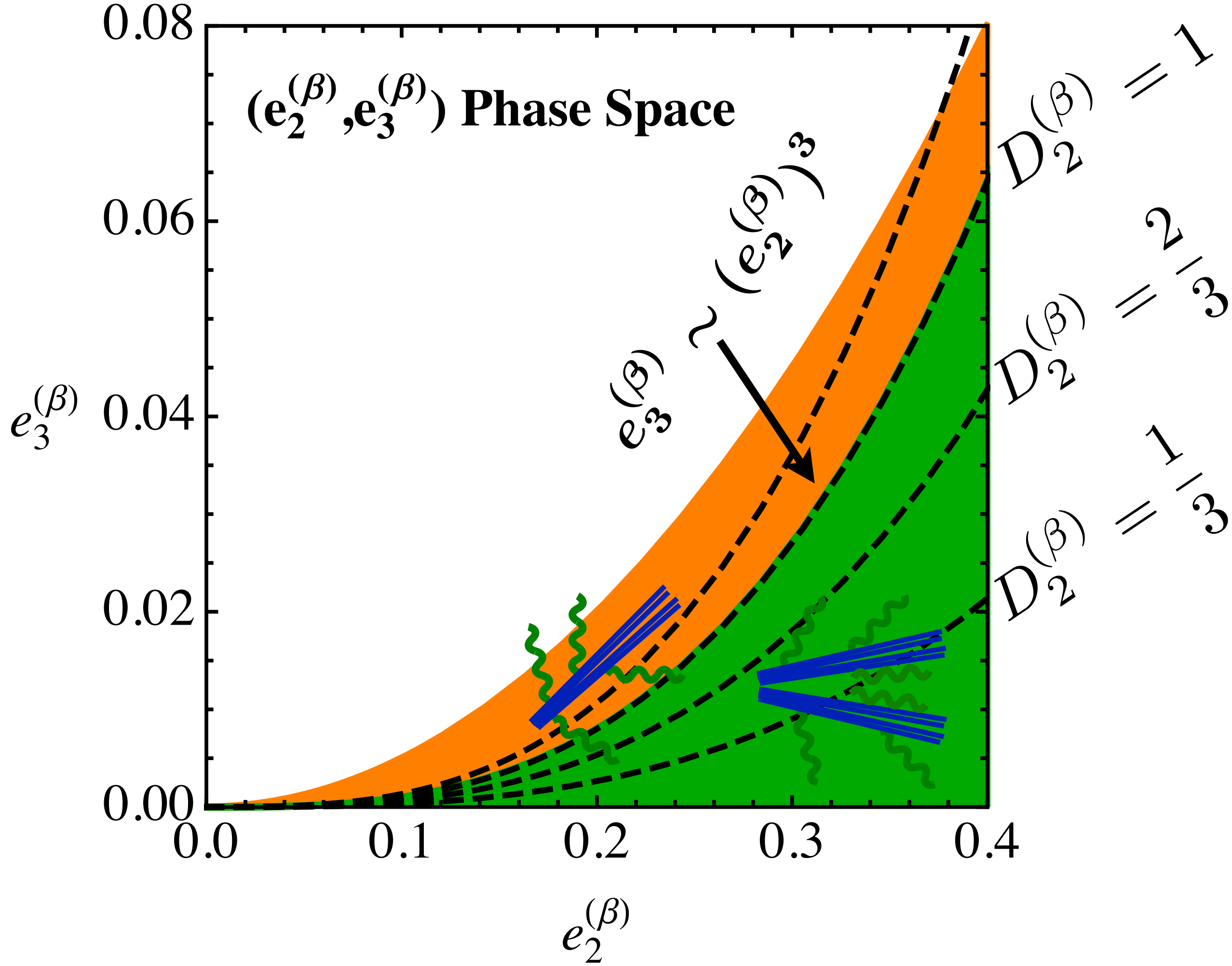
$$p_T \to \gamma p_T \qquad e_2^{(\beta)} \to \gamma^{-\beta} e_2^{(\beta)}$$

$$R_{ij} \to \gamma^{-1} R_{ij} \qquad e_3^{(\beta)} \to \gamma^{-3\beta} e_3^{(\beta)}$$

Optimal Observable:

$$D_2^{(\beta)} \equiv \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$$

AJL, Moult, Neill
JHEP 1412, 009 (2014)



Experiment

Measure a set of IRC safe observables

Make cuts to classify different jet structures

Events in each cut region separately treated

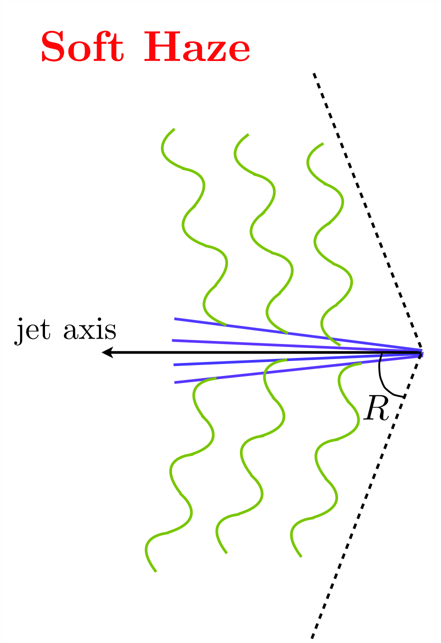
Calculation

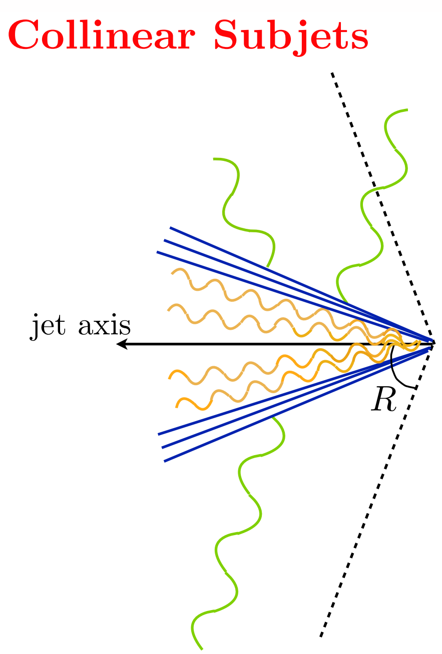
Calculate a set of IRC safe observables

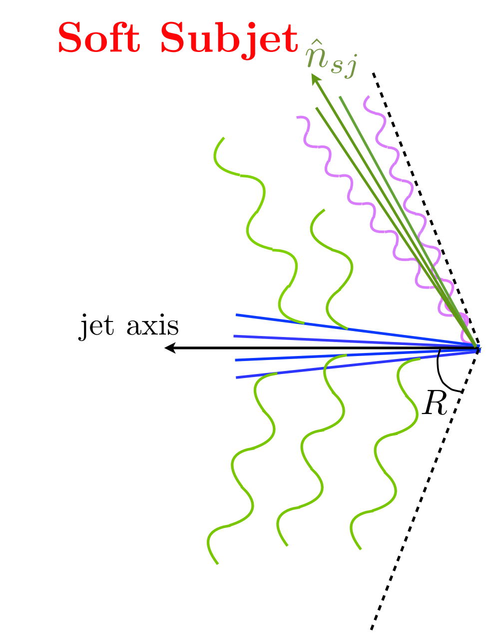
Parametric relations between observables define classification

Effective theory description is used to calculate each classification

Effective Theories for 2-prong substructure:







AJL, Moult, Neill
arXiv:1507.03018

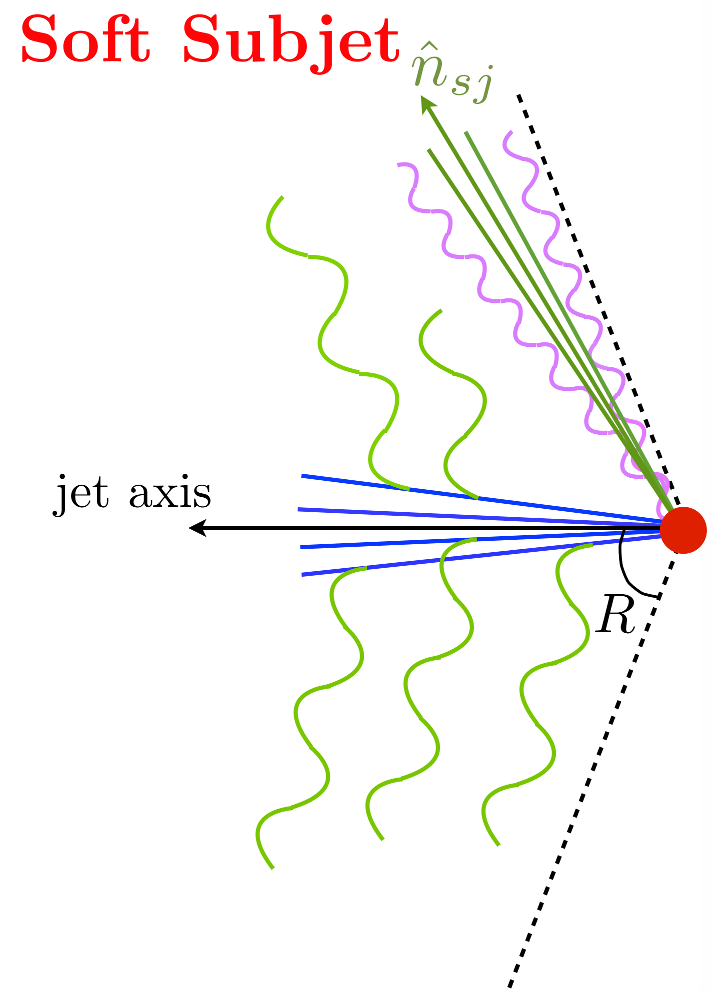
Effective theory for soft subjet

AJL, Moult, Neill
JHEP 1509, 143 (2015)

Vital for understanding wide range of processes with large kinematic hierarchies

$e_2^{(\beta)}$ set by wide angle soft subjet

Contributions to $e_3^{(\beta)}$ factorize into collinear, soft, soft subjet, and collinear-soft

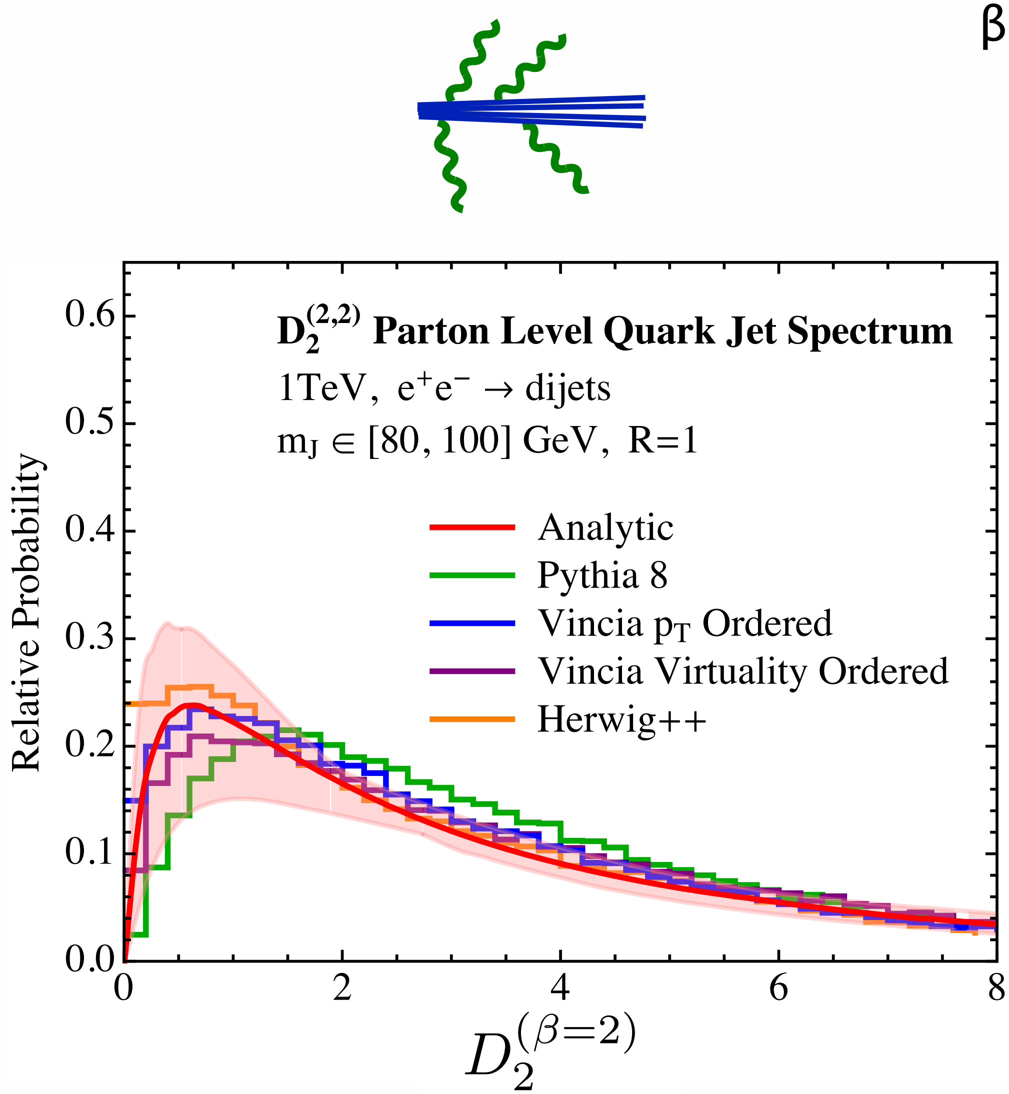


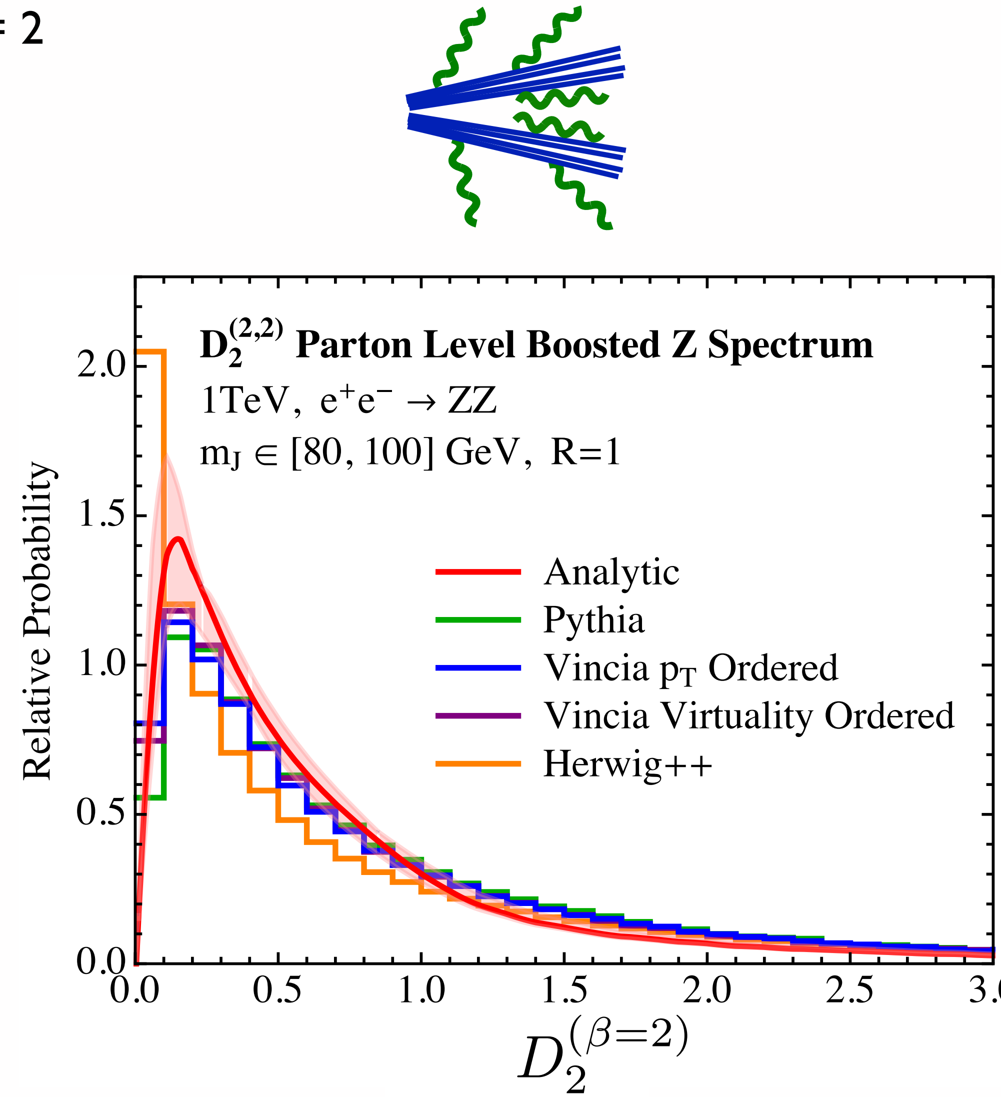
$$\frac{d\sigma}{dz\, de_2^{(\beta)}\, de_3^{(\beta)}} = \int de_3^{J_n}\, de_3^{J_{sj}}\, de_3^{S}\, de_3^{S_{sj}}\, \delta(e_3^{(\beta)} - e_3^{J_n} - e_3^{J_{sj}} - e_3^{S} - e_3^{S_{sj}})$$

$$\times H_{n\bar{n}} J_{\bar{n}} H_{n\bar{n}}^{sj} \left(z, e_2^{(\beta)}\right) J_n \left(e_3^{J_n}\right) S_{n\bar{n}n_{sj}} \left(e_3^{S}\right) J_{n_{sj}} \left(e_3^{J_{sj}}\right) S_{n_{sj}\bar{n}_{sj}} \left(e_3^{S_{sj}}\right)$$

Parton-level plots:

β = 2



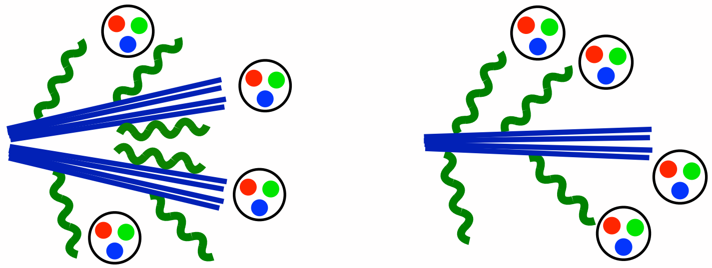


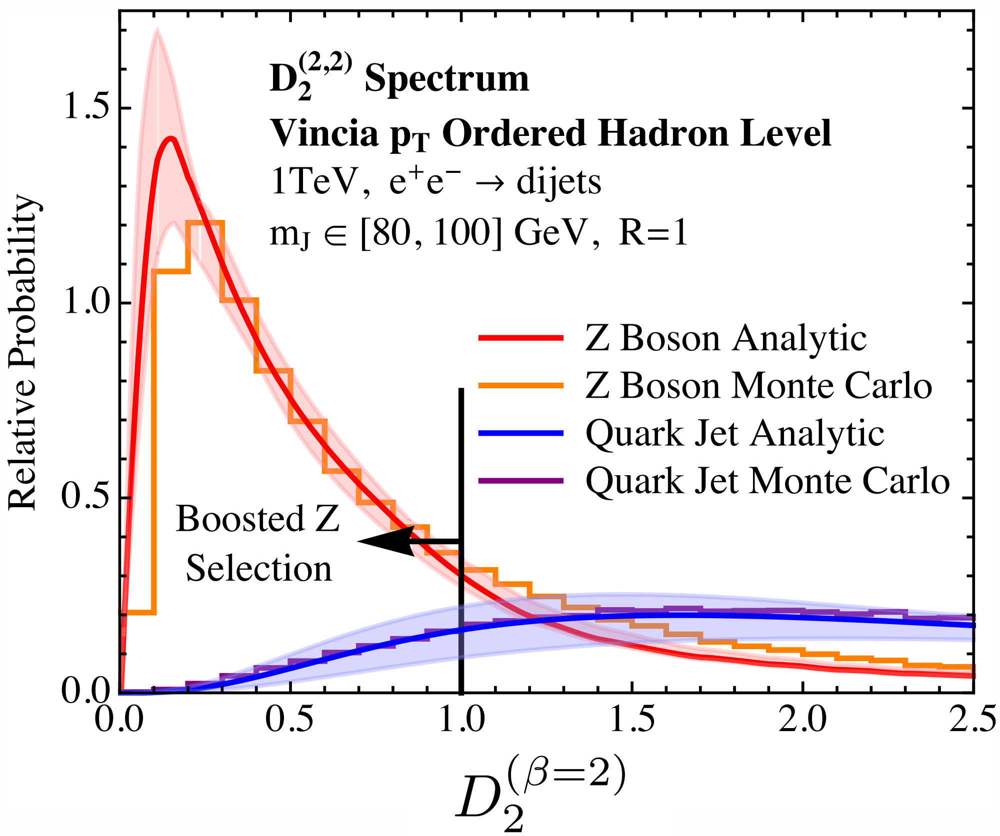
First analytic jet calculation at NLL for two-prong observables!

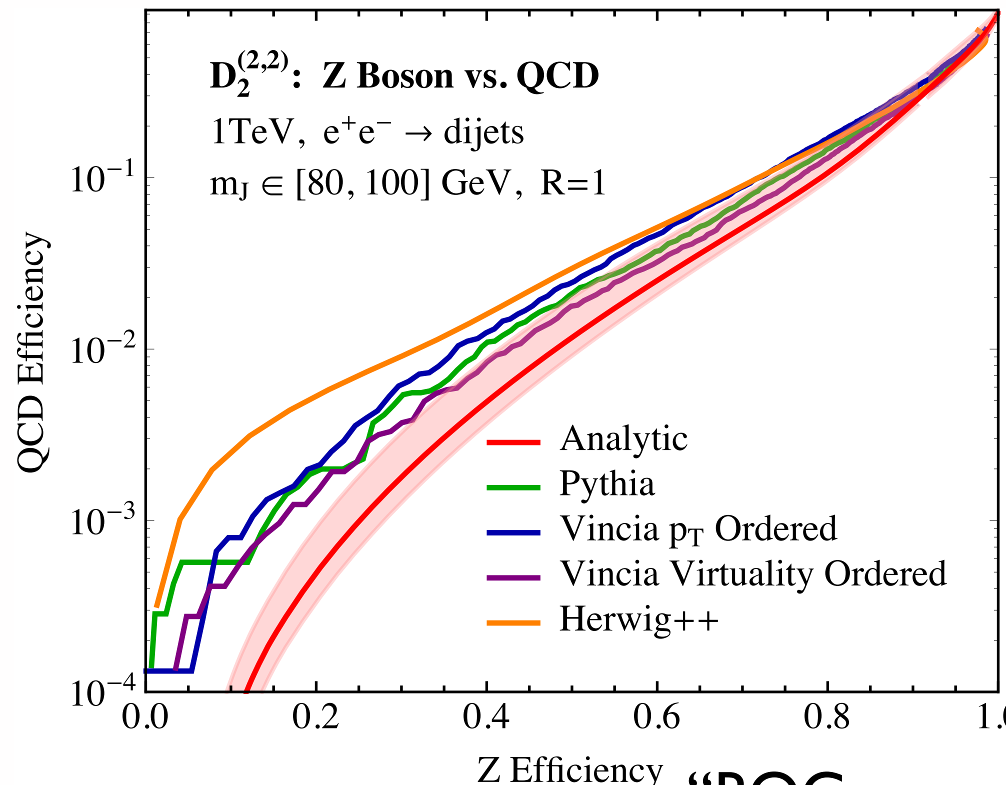
AJL, Moult, Neill
arXiv:1507.03018

Hadron-level plots:

$\beta = 2$







"ROC curve"

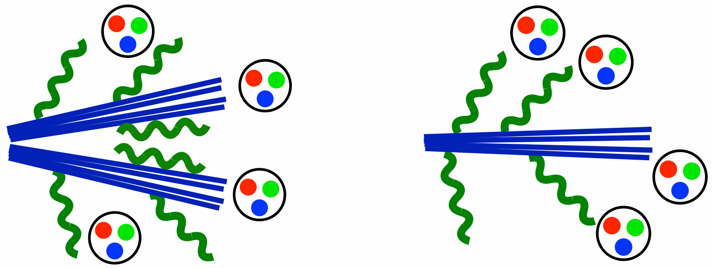
First analytic prediction for discrimination power of two-prong observables!

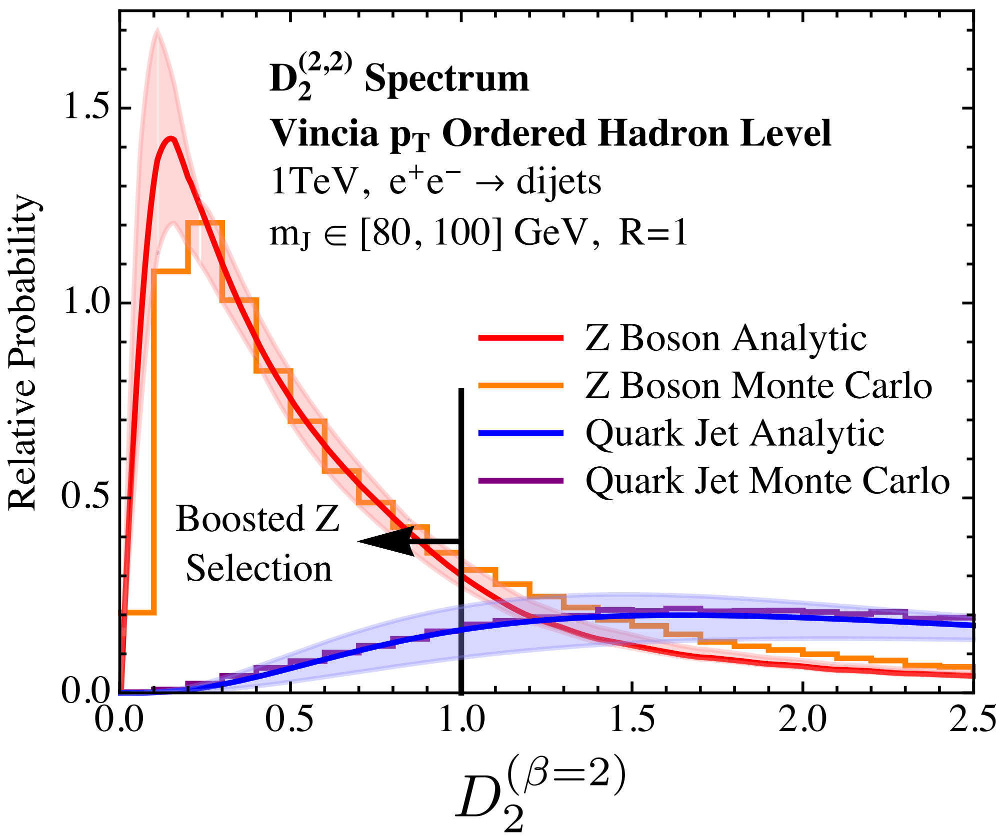
AJL, Moult, Neill
arXiv:1507.03018

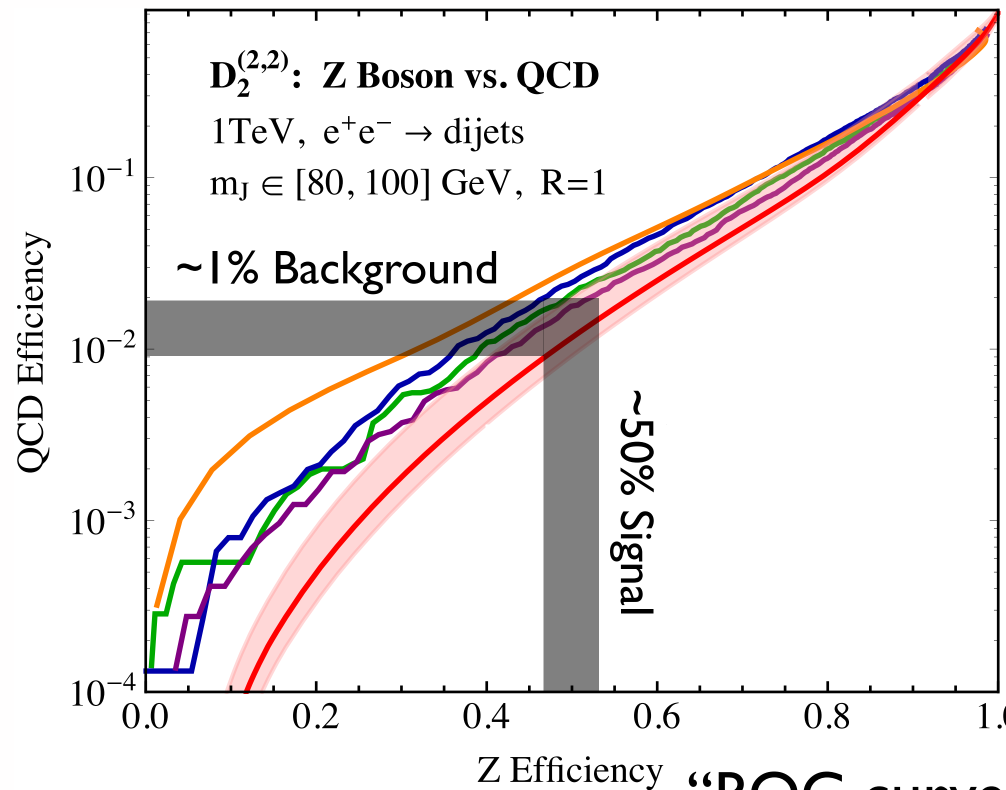
*For one-parameter hadronization model in analytics, see back-ups

Hadron-level plots:

β = 2







"ROC curve"

First analytic prediction for discrimination power of two-prong observables!

AJL, Moult, Neill
arXiv:1507.03018

*For one-parameter hadronization model in analytics, see back-ups

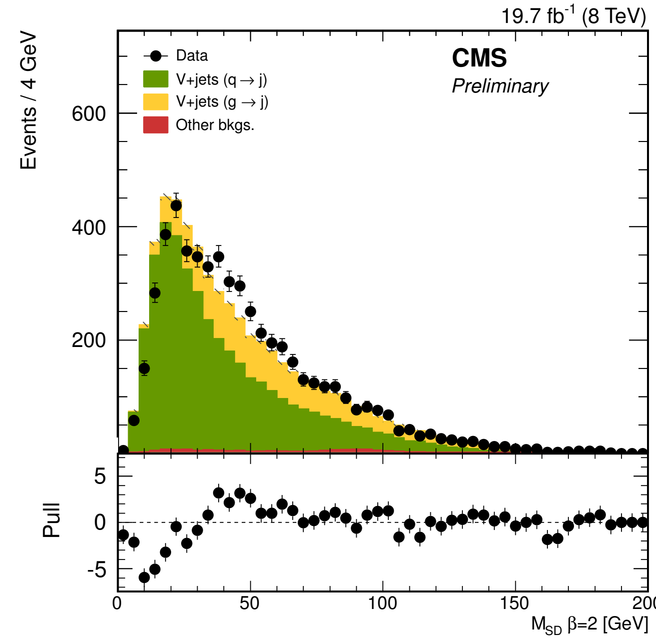
Defining the Precision Frontier: NNLL+NNLO Jet Substructure

AJL, Marzani, Soyez, Thaler
JHEP 1405, 146 (2014)

Frye, AJL, Schwartz, Yan
2016

Motivation for going to NNLL+NNLO

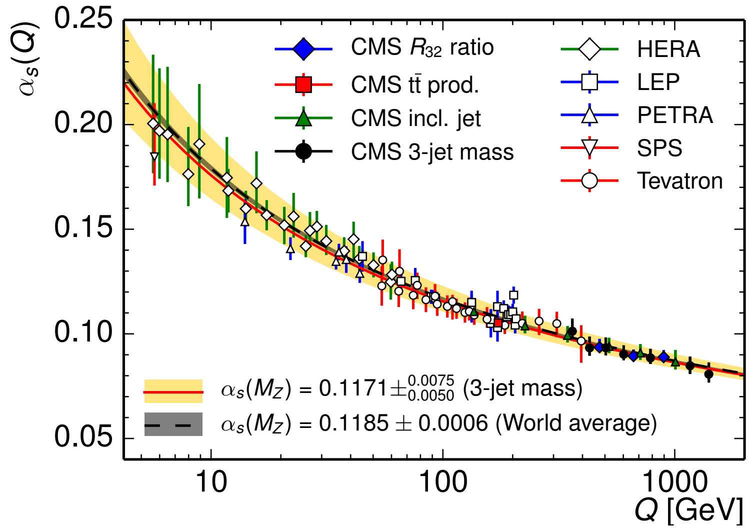
Ever increasing set of experimental measurements



CMS-PAS-JME-14-002

Probing orthogonal regime of QCD

New α_s extractions using resummation-sensitive observables



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

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

How to get to NNLL+NNLO

Measure $e_2^{(2)}$ on the jet in pp → Z + j events

$$e_2^{(2)} \sim \frac{m_J^2}{p_T^2}$$

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Experimental Challenge:
Contamination captured in the jet

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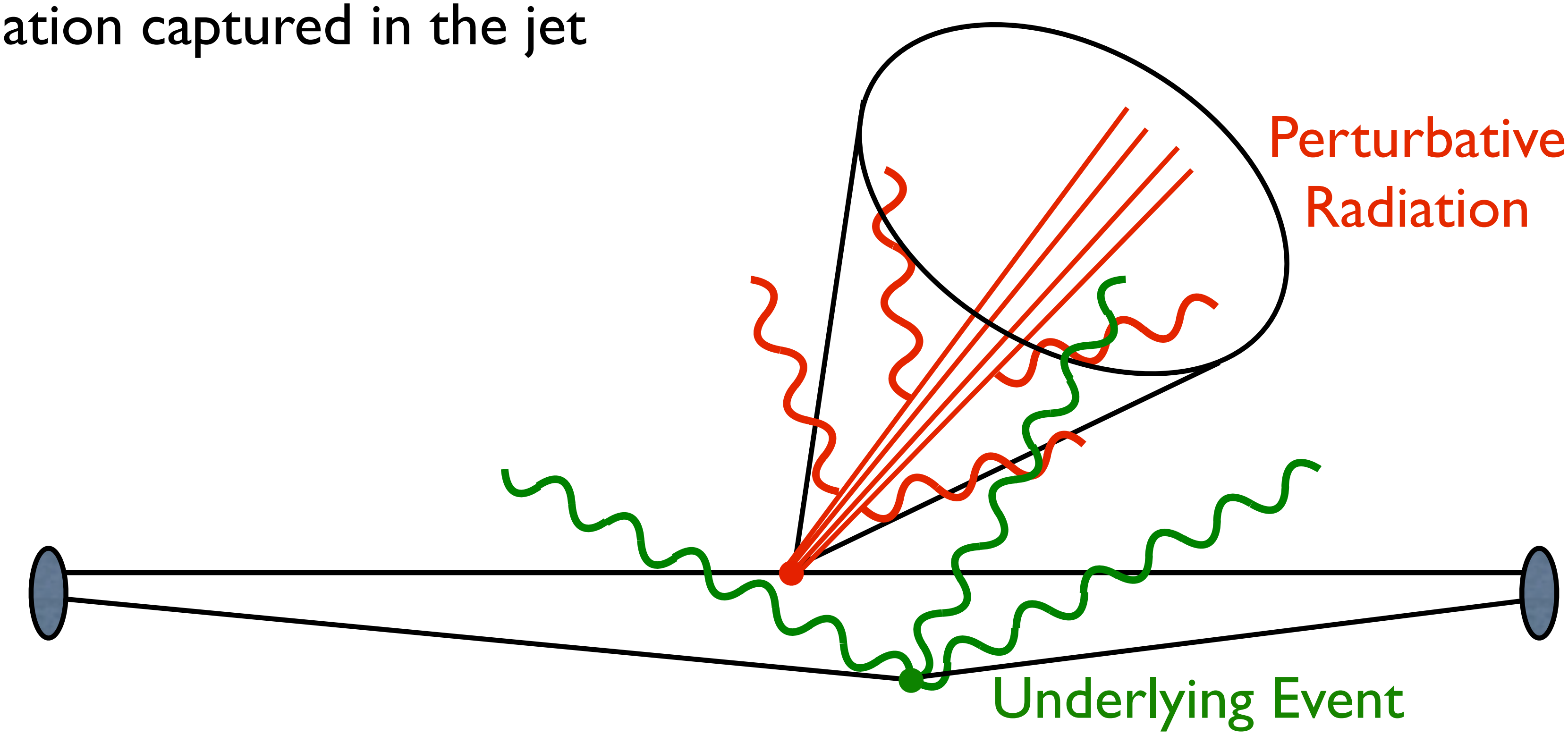

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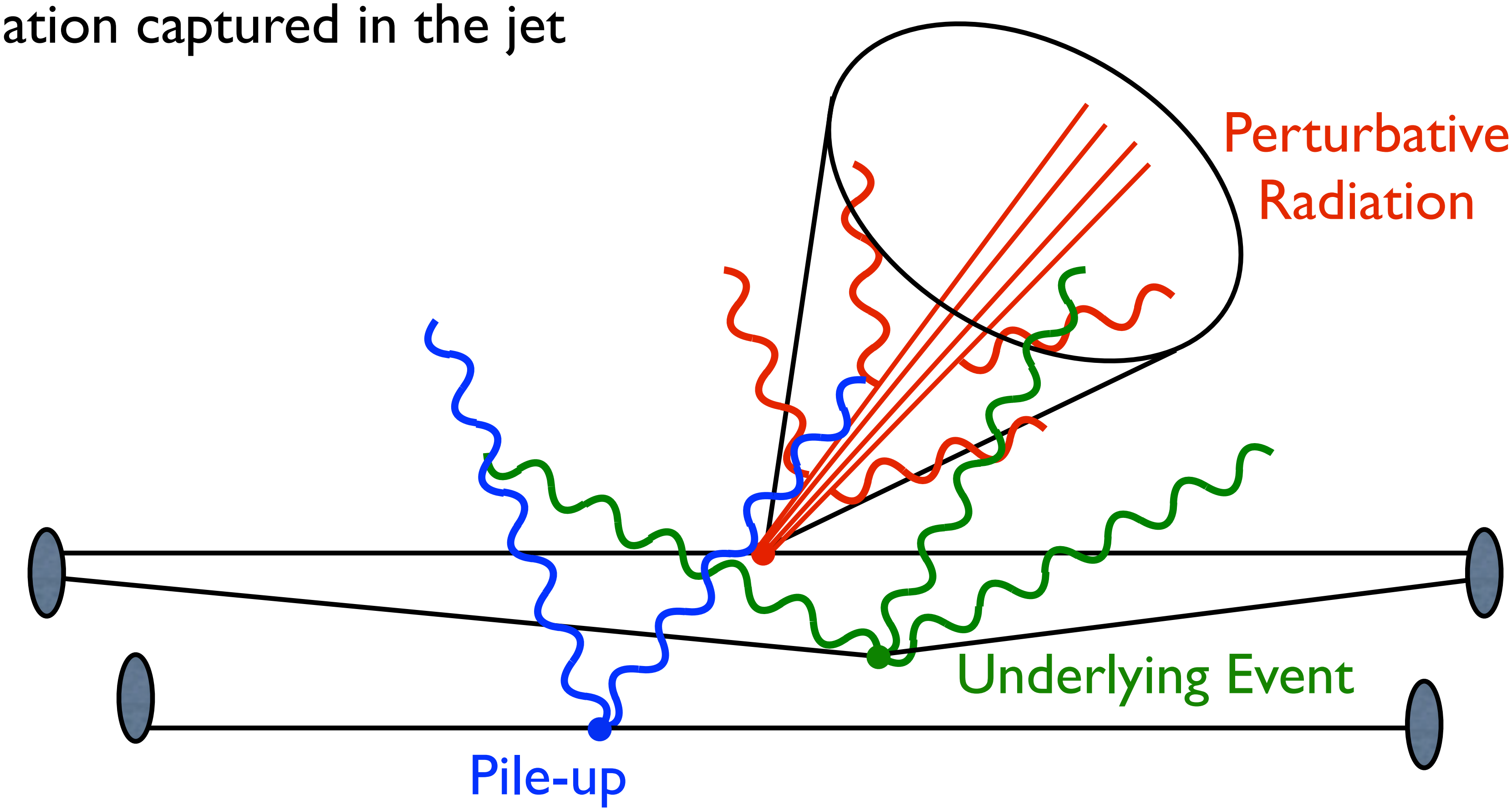

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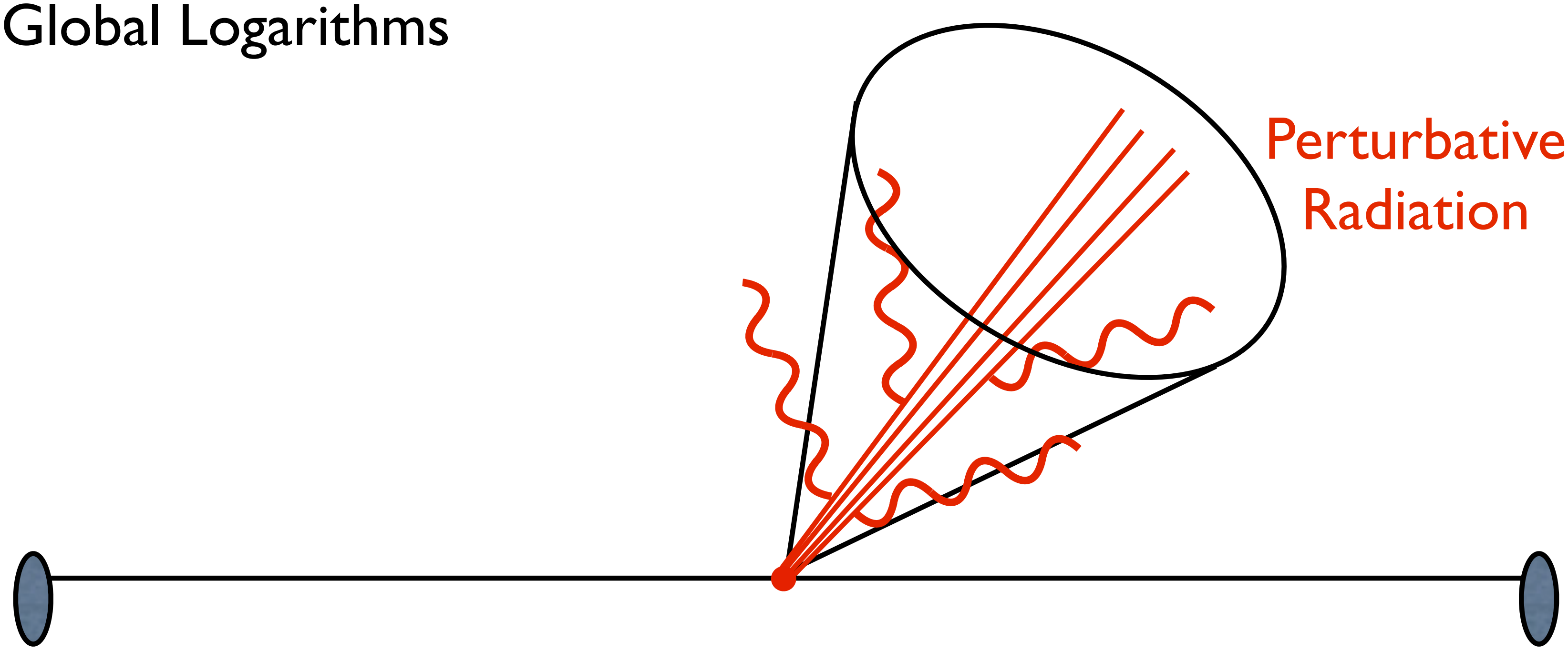
Theoretical Challenge:
Non-Global Logarithms



How to get to NNLL+NNLO

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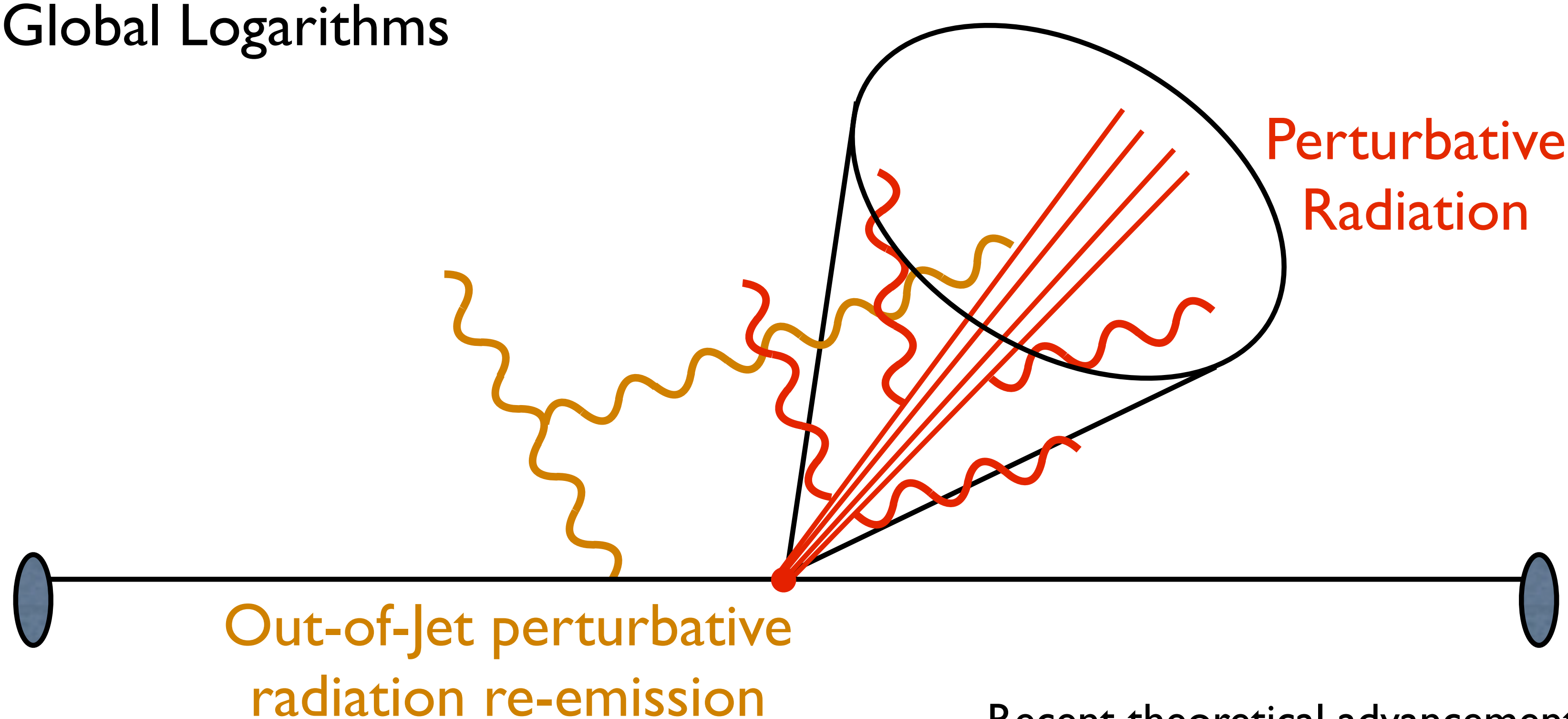


Recent theoretical advancements:

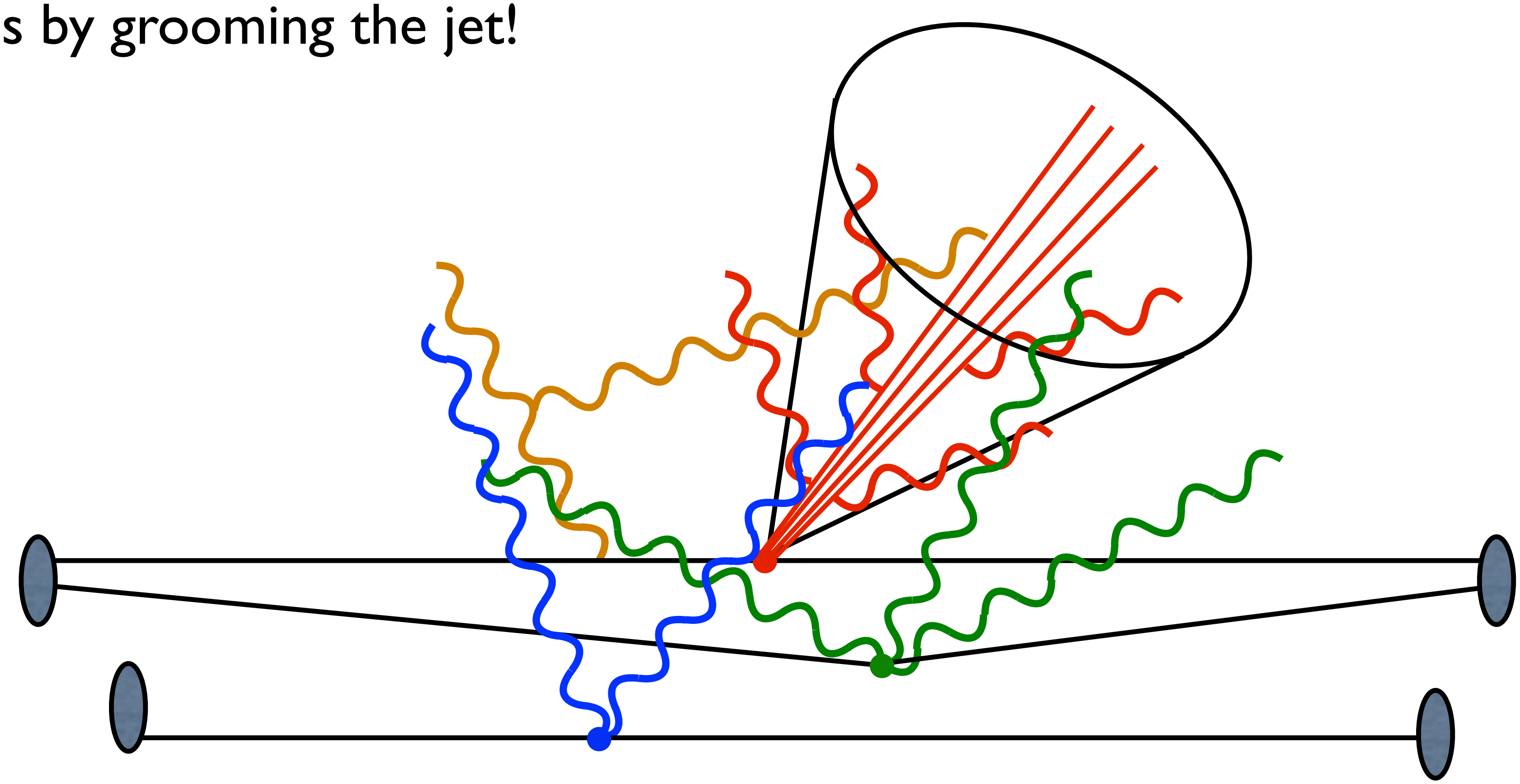
AJL, Moult, Neill
JHEP 1509, 143 (2015)

How to get to NNLL+NNLO

Measure $e_2^{(2)}$ on the jet in pp → Z + j events

$$e_2^{(2)} \sim \frac{m_J^2}{p_T^2}$$

Can eliminate all of these problems by grooming the jet!



How to get to NNLL+NNLO

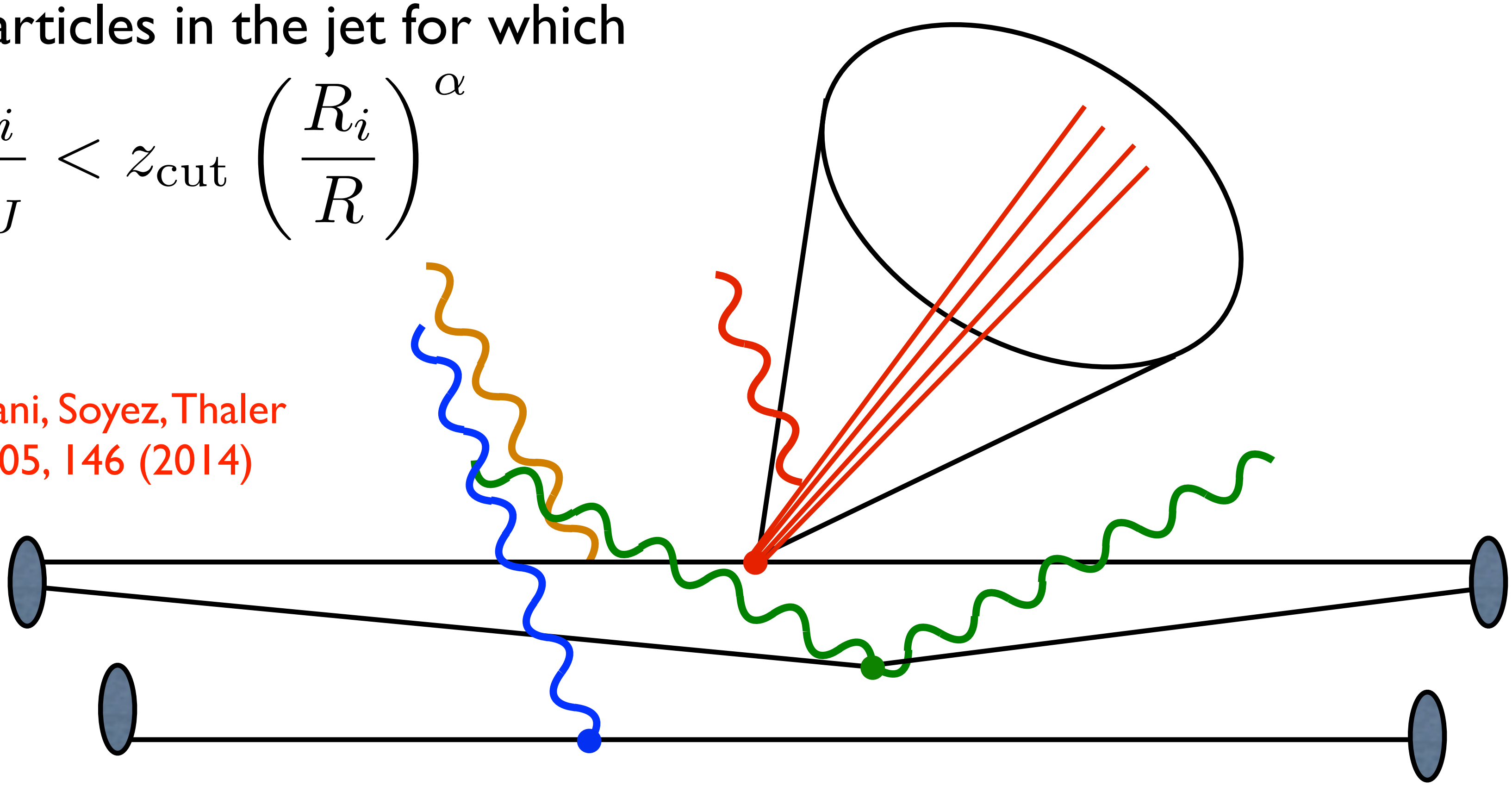
Measure $e_2^{(2)}$ on the jet in pp → Z + j events

$$e_2^{(2)} \sim \frac{m_J^2}{p_T^2}$$

Soft Drop:

Remove particles in the jet for which

$$\frac{p_{Ti}}{p_{TJ}} < z_{\text{cut}} \left(\frac{R_i}{R}\right)^{\alpha}$$



AJL, Marzani, Soyez, Thaler
JHEP 1405, 146 (2014)

Procedure to get NNLL Resummation

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

$$\frac{p_{Ti}}{p_{TJ}} < z_{\text{cut}} \left(\frac{R_i}{R}\right)^{\alpha}$$

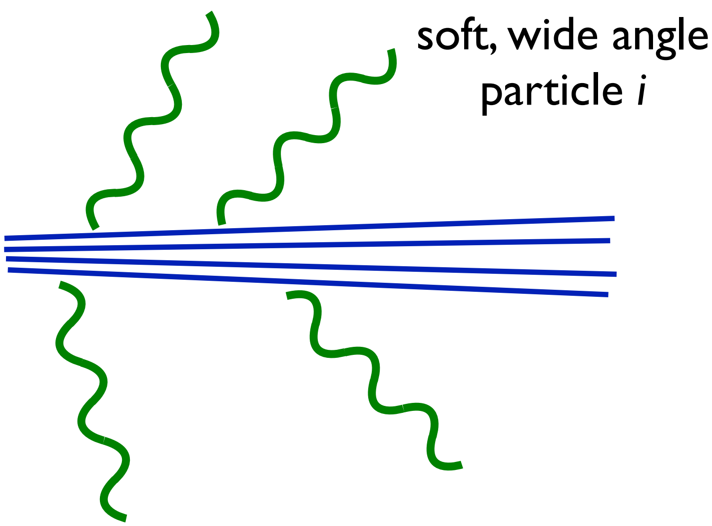
Measure $e_2^{(2)}$ on the soft dropped jet:

$$e_2^{(2)} \sim \frac{m_{\text{SD}}^2}{p_T^2}$$

Focus on the regime where:

$$e_2^{(2)} \ll z_{\text{cut}} \ll 1$$

All remaining particles in the jet must be collinear!



1) $\frac{p_{Ti}}{p_{TJ}} \sim z_{\text{cut}} \longrightarrow e_2^{(2)} \sim z_{\text{cut}}$

2) $\frac{p_{Ti}}{p_{TJ}} \sim e_2^{(2)} \longrightarrow$ groomed away

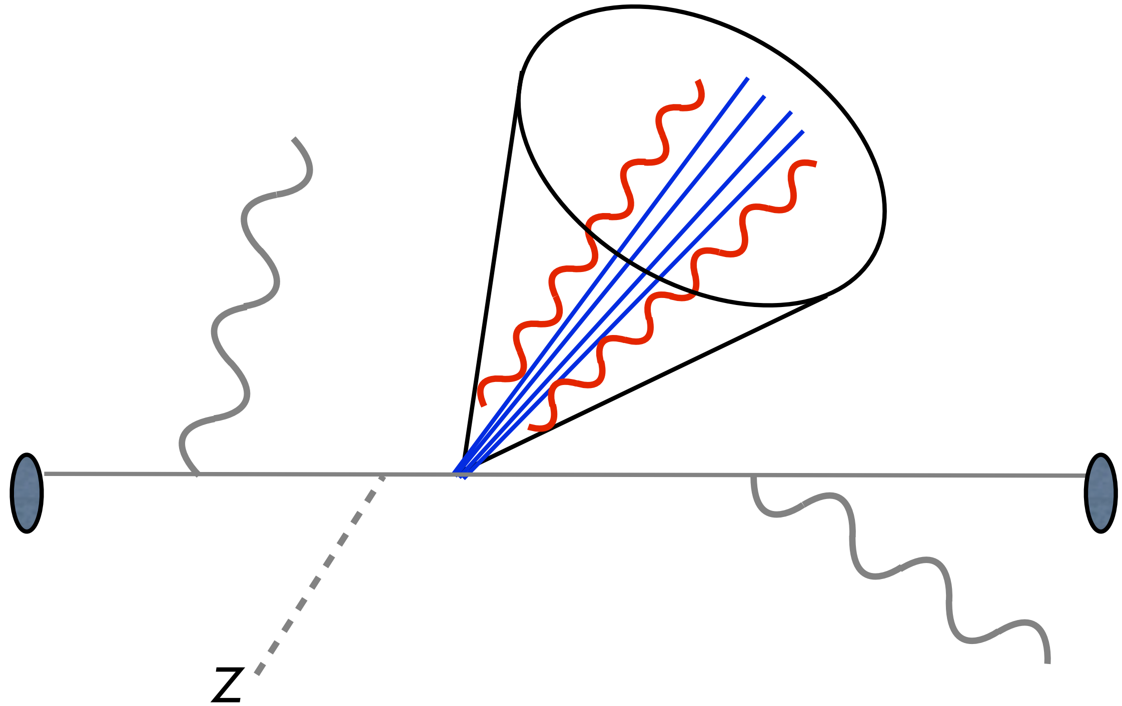
Factorization for NNLL Resummation

Effective theory for soft drop groomed jets

Frye, AJL, Schwartz, Yan 2016

Coefficient D_k can be extracted from fixed-order

Jet function can be recycled from e^+e^- collisions



$$e_2^{(2)} \ll z_{\text{cut}} \ll 1$$

$$\frac{d\sigma^{\text{resum}}}{de_2^{(2)}} = \sum_{k=q,\bar{q},g} D_k(p_T, z_{\text{cut}}, R) S_{C,k}(z_{\text{cut}}, e_2^{(2)}) \otimes J_k(e_2^{(2)})$$

sum over jet flavor

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

collinear-soft radiation

hard collinear radiation

Matching NNLL to NNLO

$$\frac{d\sigma^{\mathrm{NNLL+NNLO}}}{de_2^{(2)}} \equiv \frac{d\sigma^{\mathrm{NNLL}}}{de_2^{(2)}} + \frac{d\sigma^{\mathrm{NNLO}}}{de_2^{(2)}} - \frac{d\sigma^{\mathrm{NNLL},\alpha_s^2}}{de_2^{(2)}}$$

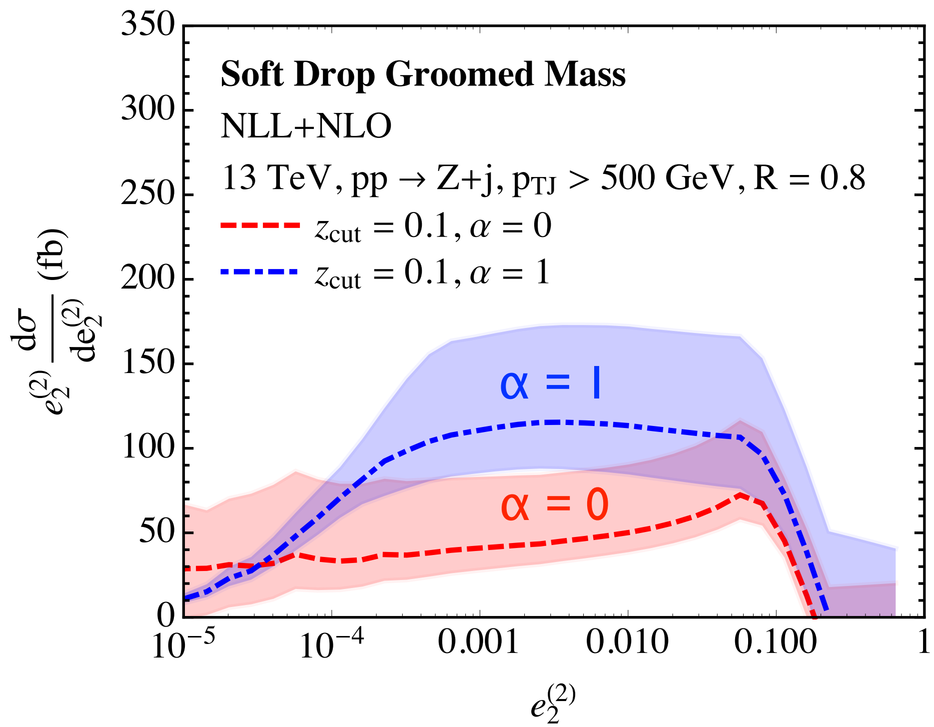
Use MCFM to generate NNLO cross section

pp → Z + j at NNLO with $e_2^{(2)} > 0$ = pp → Z + 2j at NLO

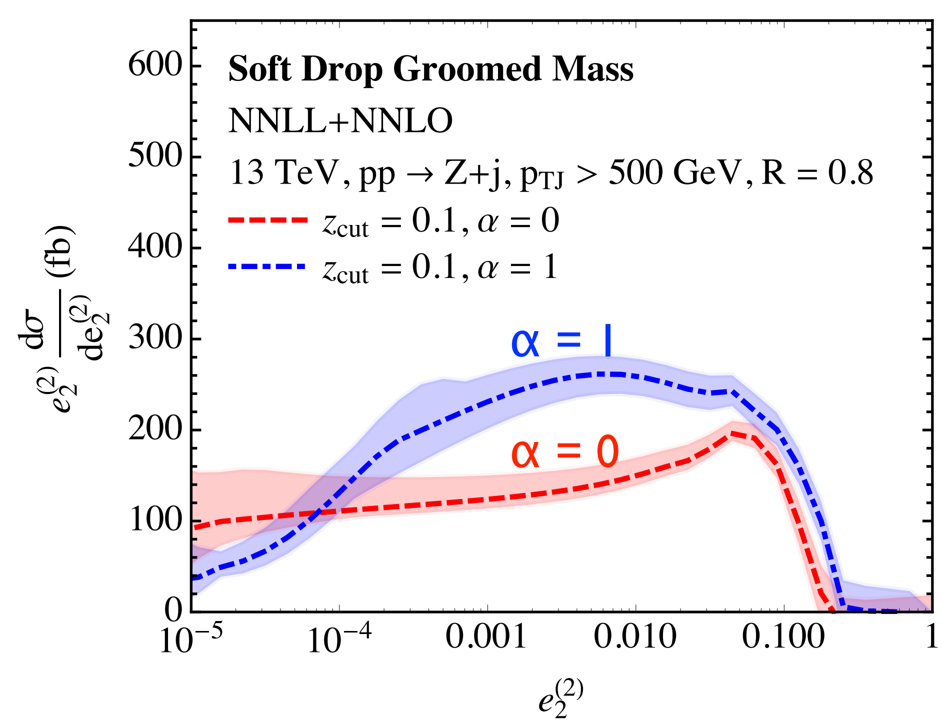
Required extreme computing power:
To make the following plots required centuries of CPU time

The very first jet substructure calculation at high precision!

Results: NNLL+NNLO Jet Substructure



NLL+NLO



NNLL+NNLO

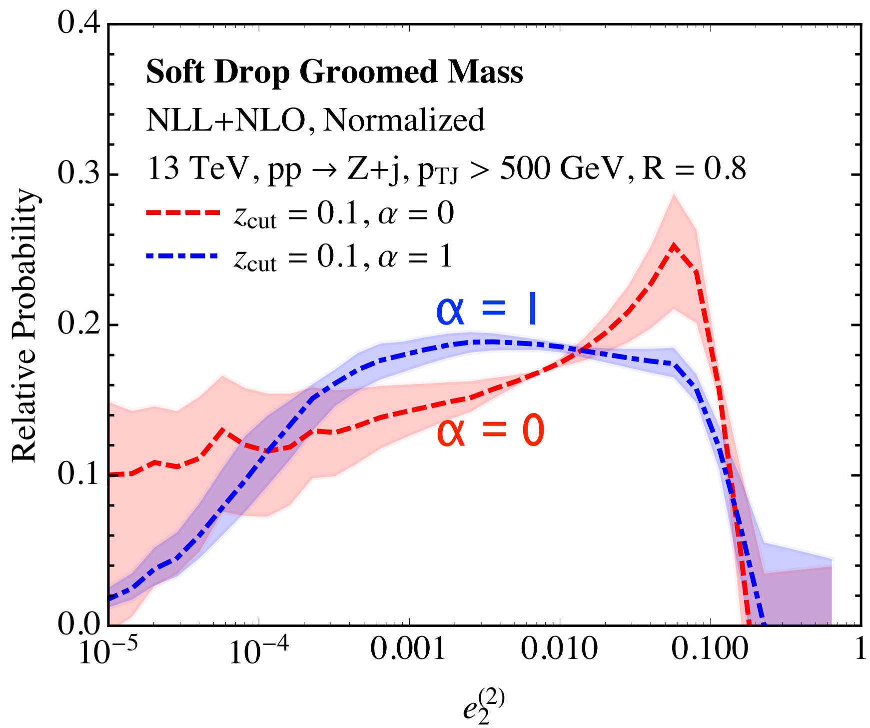
Soft Drop: $\frac{p_{Ti}}{p_{TJ}} < z_{\text{cut}} \left(\frac{R_i}{R}\right)^\alpha$

$$e_2^{(2)} \sim \frac{m_{\text{SD}}^2}{p_T^2}$$

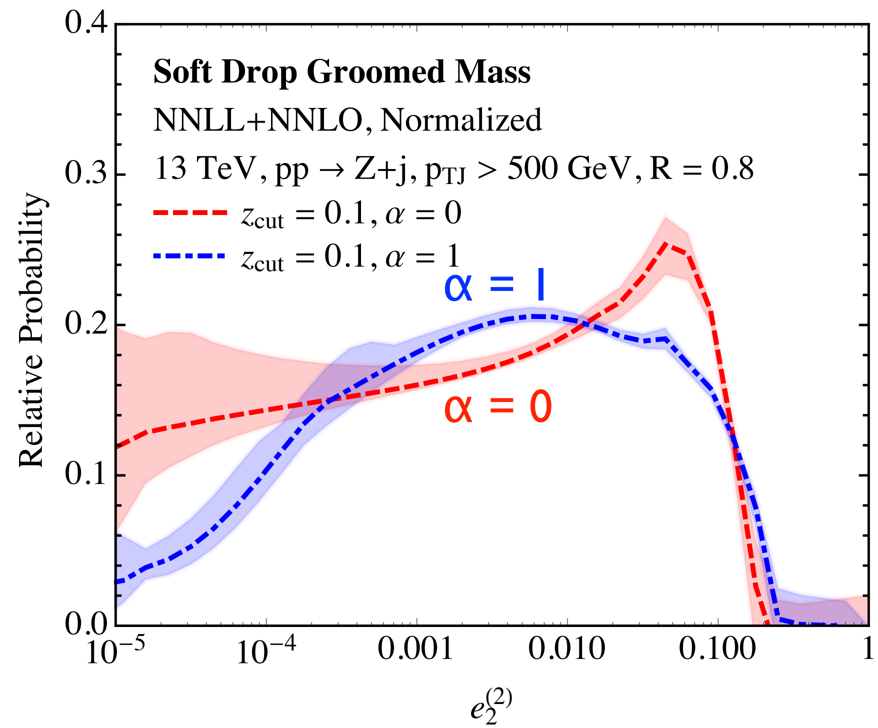
Significant decrease in residual scale uncertainty at NNLL+NNLO!

Frye, AJL, Schwartz, Yan 2016

Results: NNLL+NNLO Jet Substructure



NLL+NLO



NNLL+NNLO

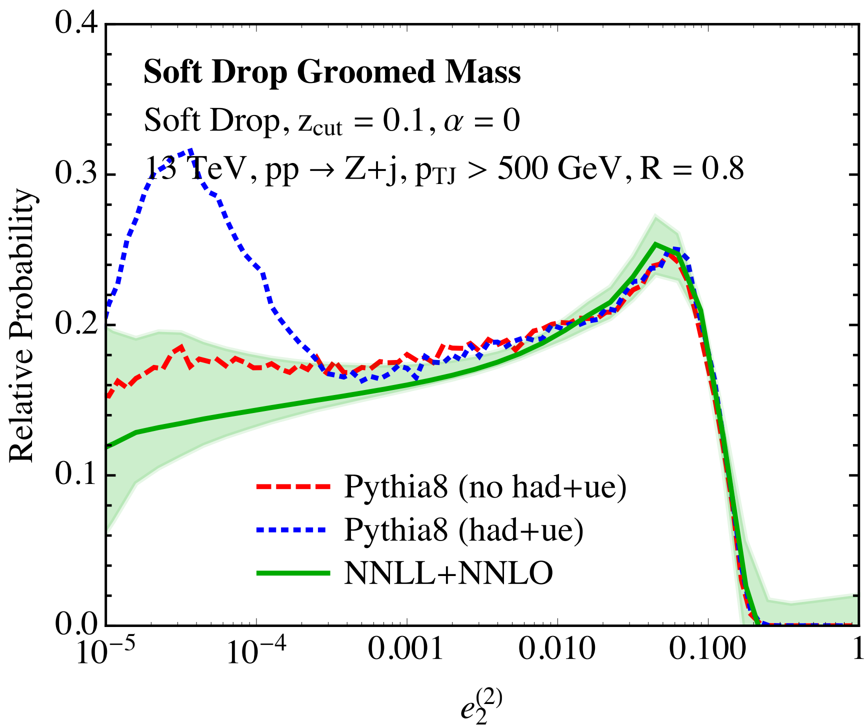
Shape of distribution only depends on collinear physics

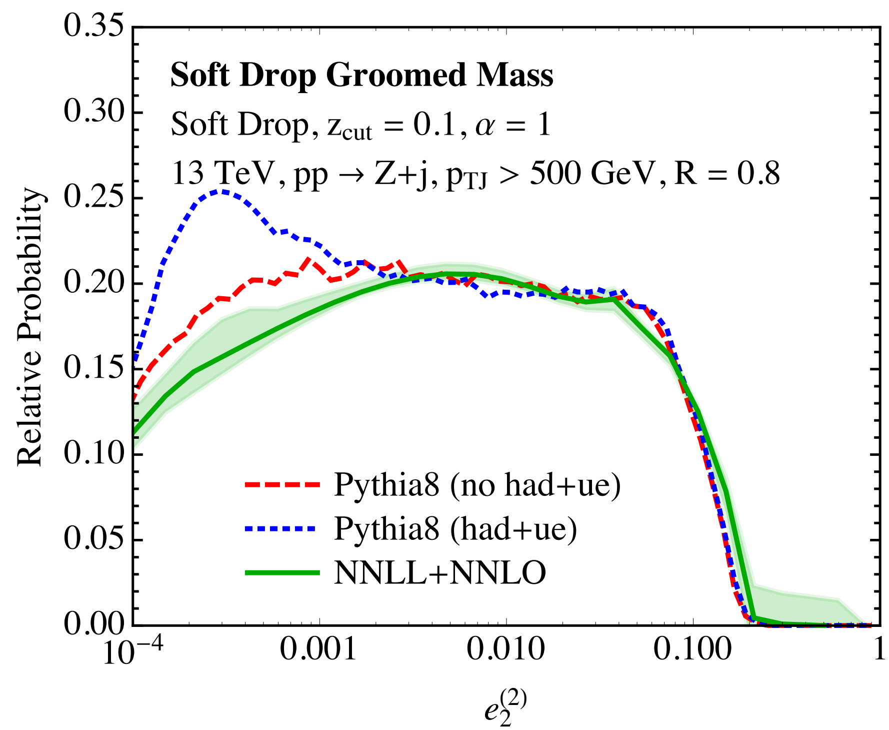
$$\frac{d\sigma^{\text{resum}}}{de_2^{(2)}} = \sum_{k=q,\bar{q},g} D_k(p_T, z_{\text{cut}}, R) S_{C,k}(z_{\text{cut}}, e_2^{(2)}) \otimes J_k(e_2^{(2)})$$

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

Frye, AJL, Schwartz, Yan 2016

Results: NNLL+NNLO Jet Substructure





NNLL+NNLO, α = 0

NNLL+NNLO, α = 1

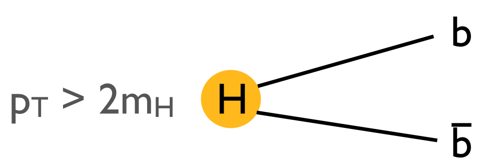
Comparison with Pythia8 Monte Carlo

Hadronization and underlying event only dominate for $e_2^{(2)} \lesssim 10^{-3}$

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

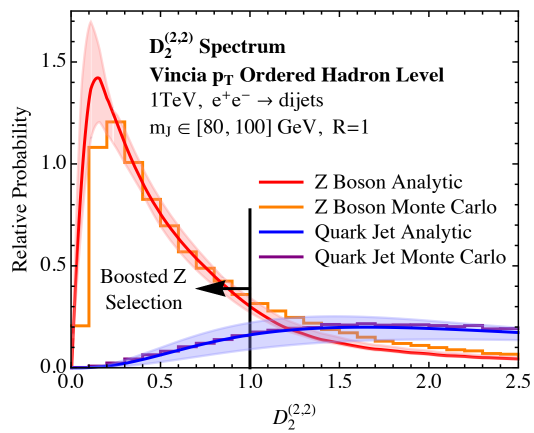
Frye, AJL, Schwartz, Yan 2016

Summary



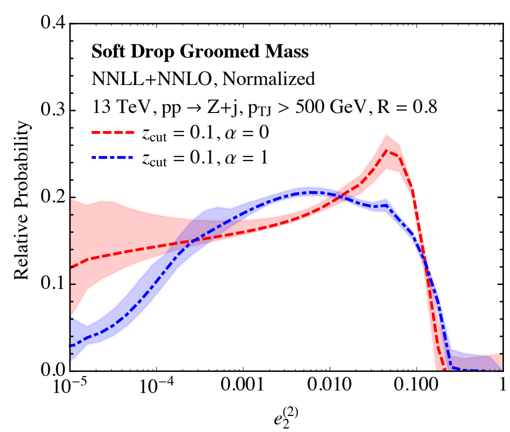
Jet Substructure is ubiquitous at the LHC

Powerful handle on backgrounds at high p_T



D_2: The Optimal 1- versus 2-prong Discriminant

Standard analysis tool at ATLAS



Unprecedented NNLL+NNLO Predictions

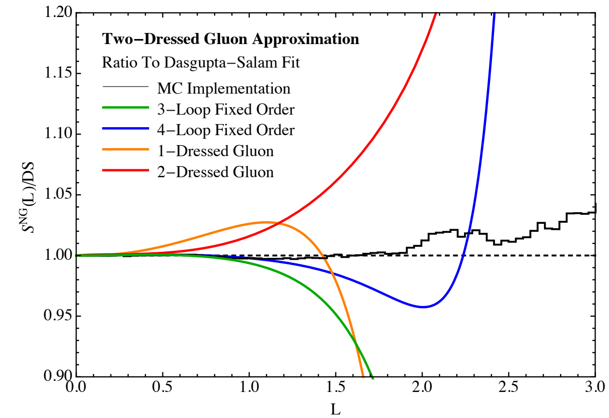
Jet substructure has now entered the precision regime

Conclusions

Only scratched the surface of
jet substructure and its applications

Systematic organization of non-global logarithms

AJL, Moult, Neill
JHEP 1509, 143 (2015)

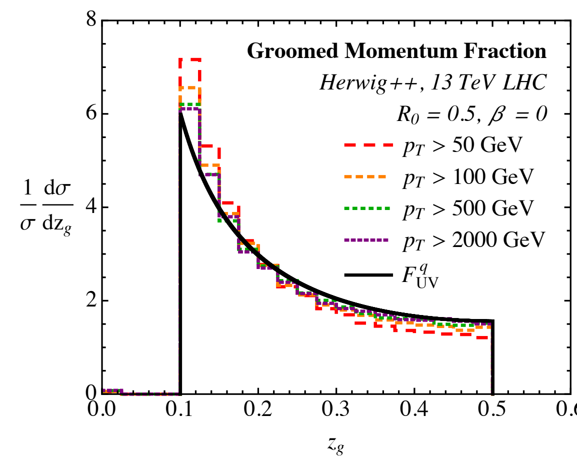


Sudakov Safety: infrared and collinear unsafe but calculable observables

Independent of the coupling as Q → ∞!

AJL, Thaler
JHEP 1309, 137 (2013)

AJL, Marzani, Thaler
Phys. Rev. D 91, no. 11, 111501 (2015)



Jet substructure is a vital component of physics in the Standard Model and beyond for Run 2 and the future of the LHC!

Bonus Slides

Hadronization

Hadronization corrections can be included analytically in calculation

Non-perturbative effects included by universal shape function convolved with soft function

$$S(\mathcal{O}) = \int d\epsilon \, F(\epsilon) \, S_{\text{pert}} \left(\mathcal{O} - \epsilon\right)$$

One parameter shape function:

$$F(\epsilon) = \frac{4\epsilon}{\Omega_D^2} e^{-2\epsilon/\Omega_D}$$

Precision calculations required for hadron-level comparisons!