Factorization for Jet Substructure

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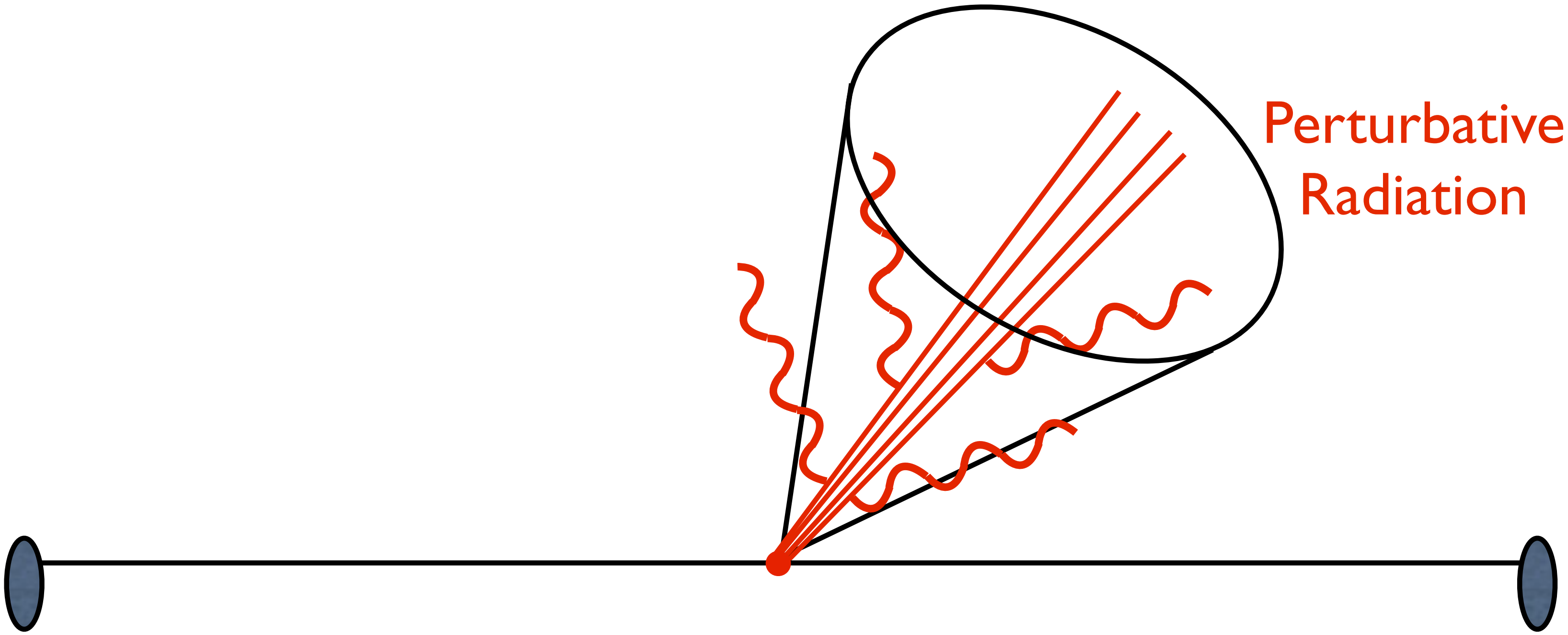
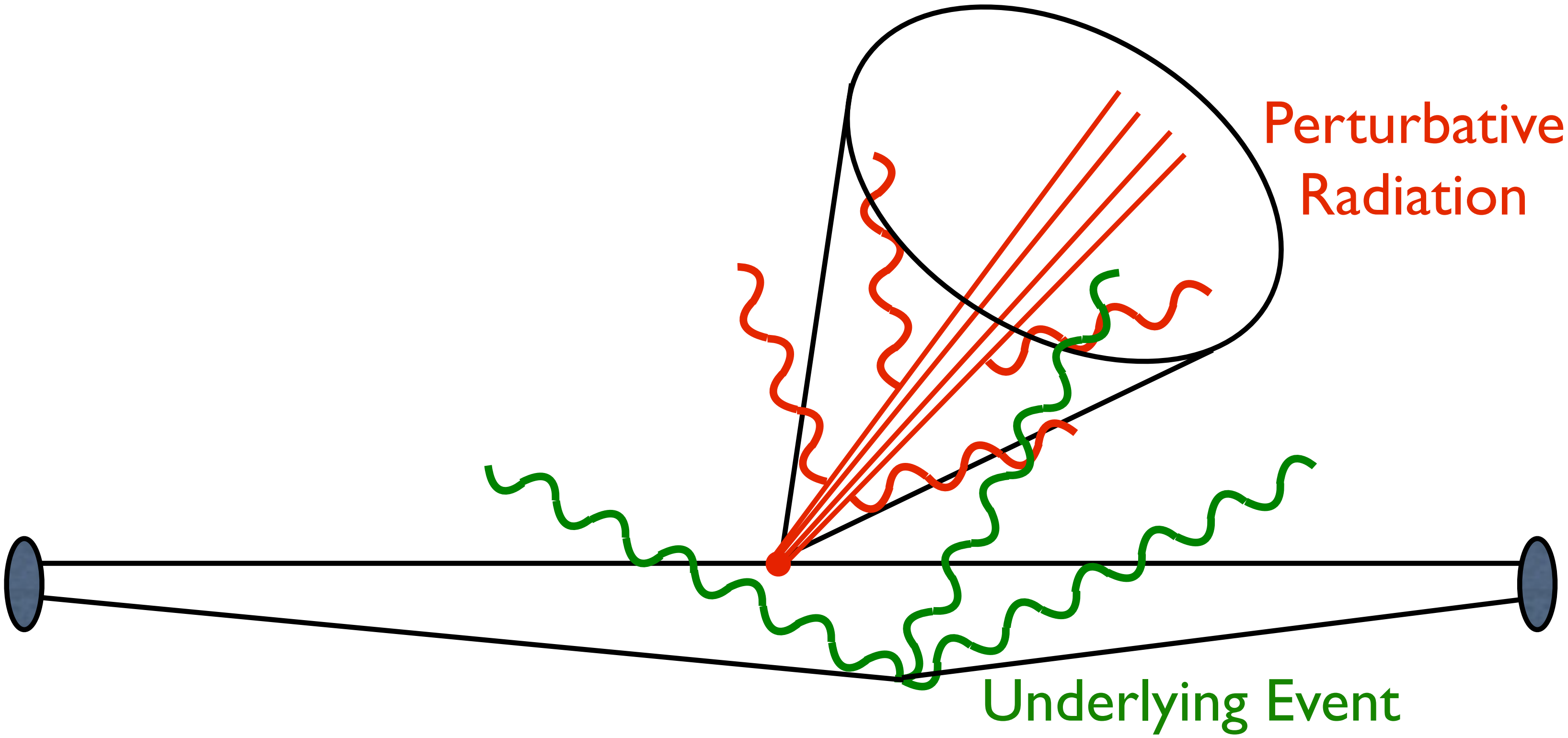
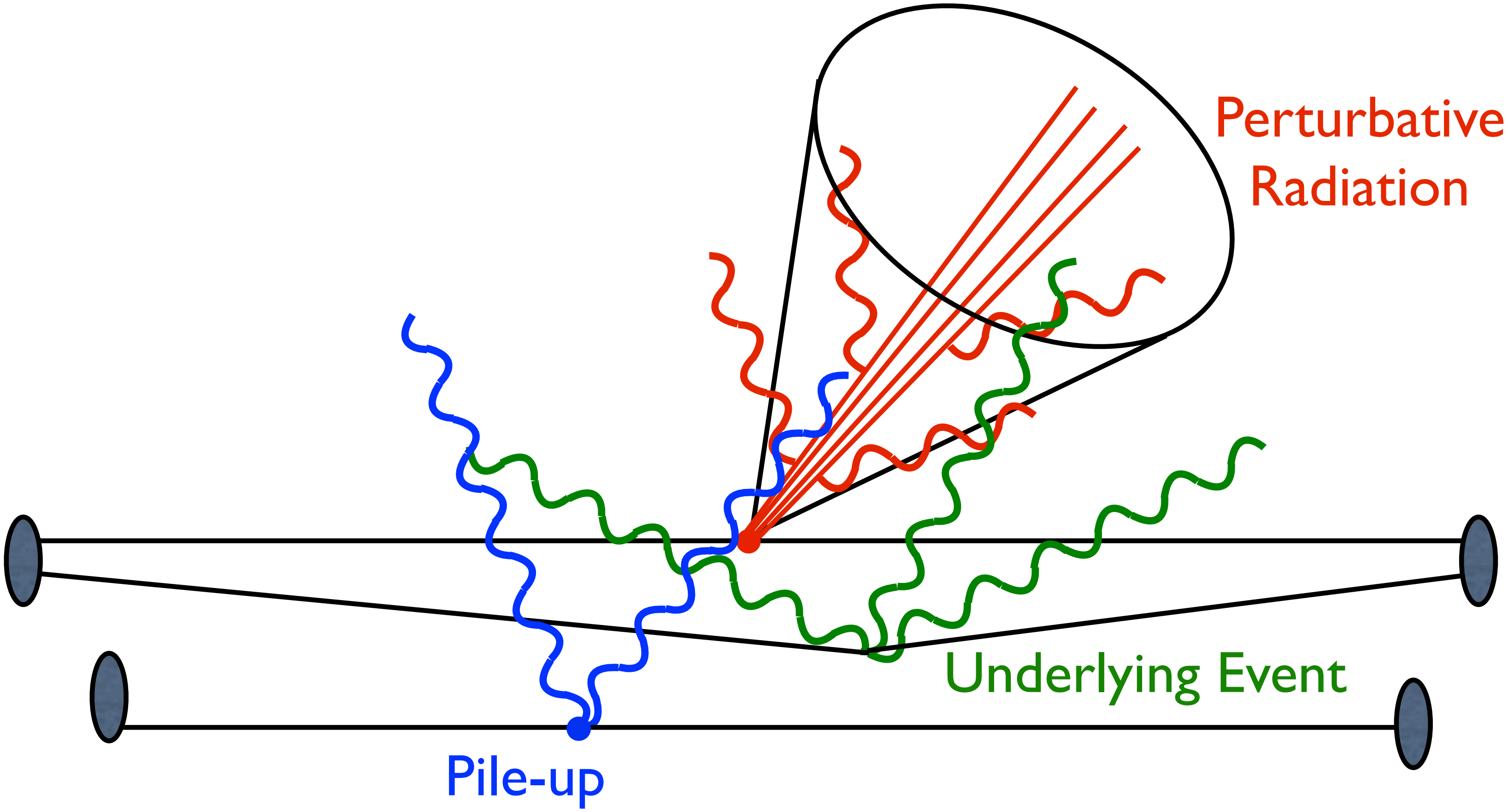
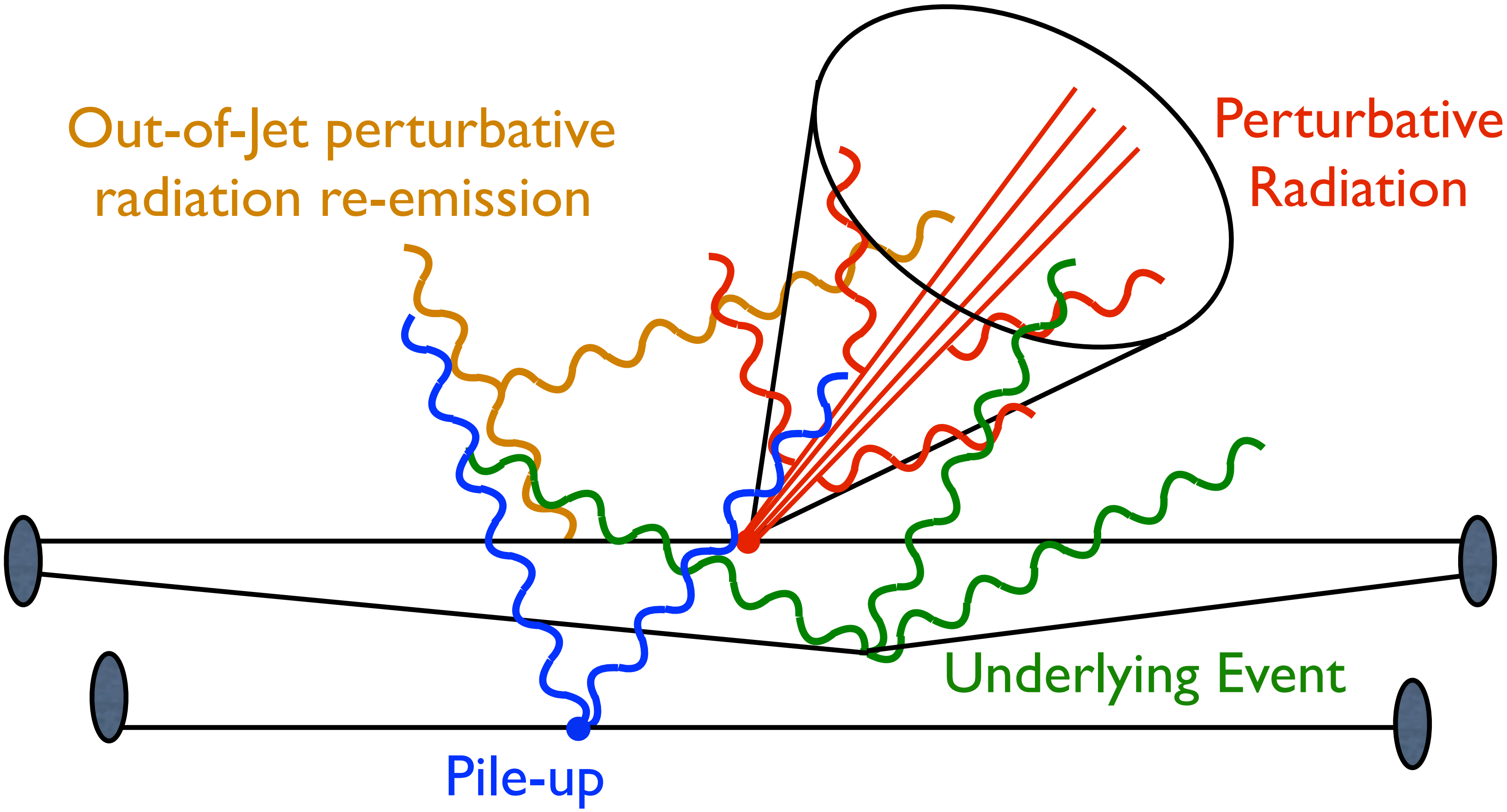
Goal:
Precision Calculations on Isolated Jets at the LHC

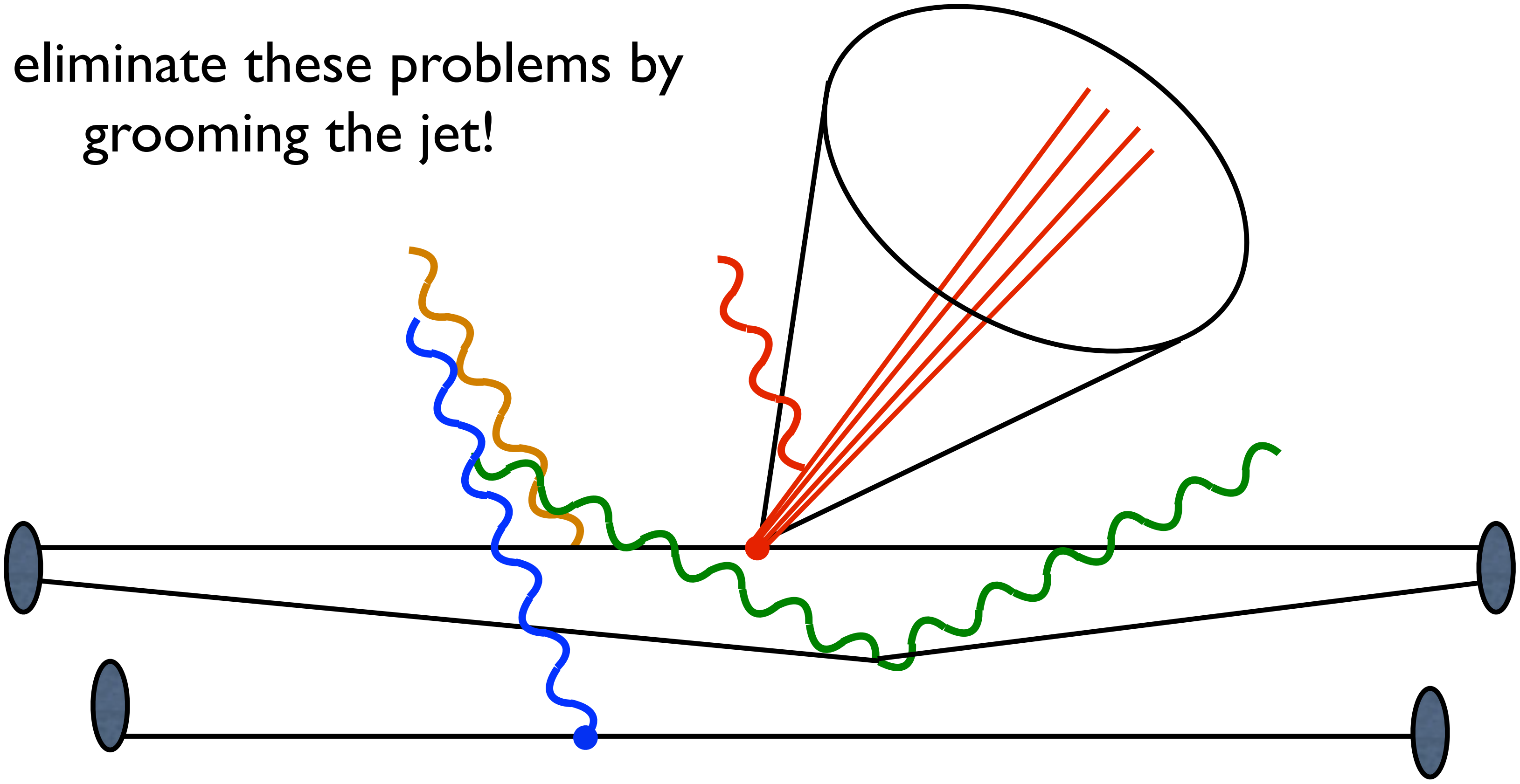

Perturbative
Radiation


Perturbative
Radiation
Underlying Event


Perturbative
Radiation
Underlying Event
Pile-up


Out-of-Jet perturbative radiation re-emission
Perturbative Radiation
Underlying Event
Pile-up

Can eliminate these problems by grooming the jet!

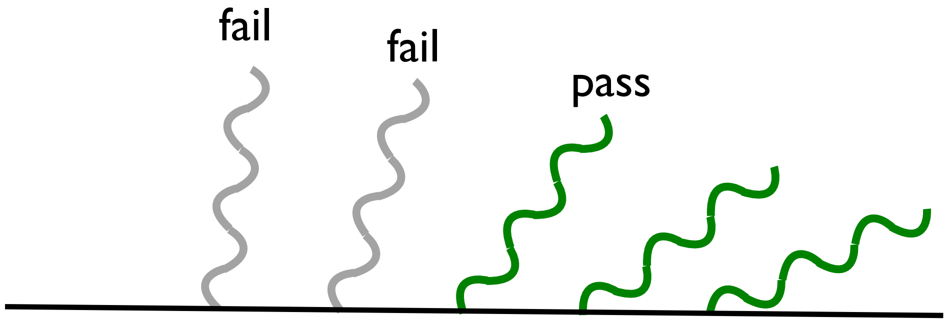


Butterworth, Davison, Rubin, Salam 2008
Krohn, Thaler, Wang 2009
Soyez, Salam, Kim, Dutta, Cacciari 2012
Krohn, Schwartz, Low, Wang 2013
Berta, Spousta, Miller, Leitner 2014
Bertolini, Harris, Low, Tran 2014...

Cacciari, Salam, Soyez 2008
Ellis, Vermilion, Walsh 2009
Dasgupta, Fregoso, Marzani, Salam 2013
AJL, Marzani, Soyez, Thaler 2014
Cacciari, Soyez, Salam 2014

Soft Drop Grooming

Only one jet groomer removes contamination and eliminates NGLs



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

Dasgupta, Fregoso, Marzani, Salam 2013
AJL, Marzani, Soyez, Thaler 2014

Soft Drop Grooming

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

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

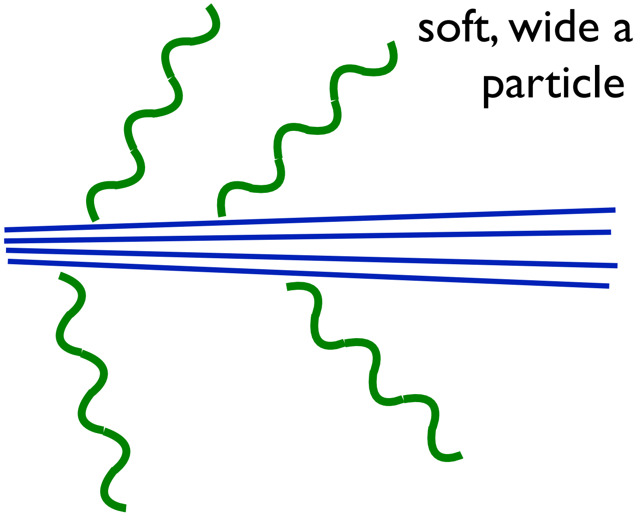
Measure m_J^2 of the
soft dropped jet:

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

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!

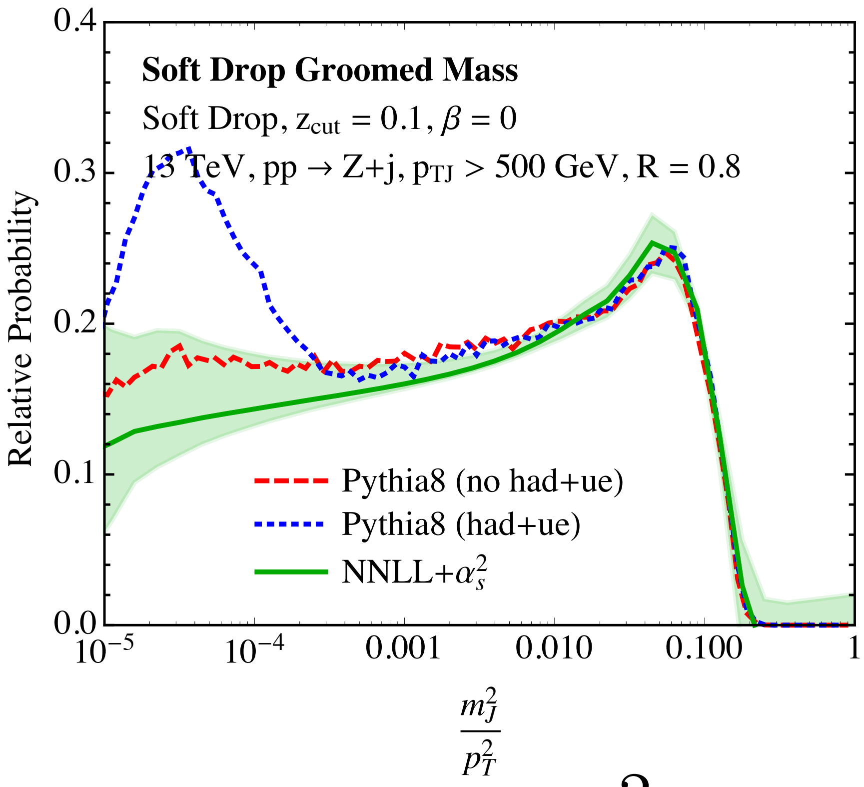


soft, wide angle
particle *i*

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

SCET 2016:



Enables all-orders factorization of jet observables with no NGLs

Presented NNLL+NLO predictions

Frye, AJL, Schwartz, Yan 2016
See talks by: C Frye, K. Yan

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

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

sum over jet flavor

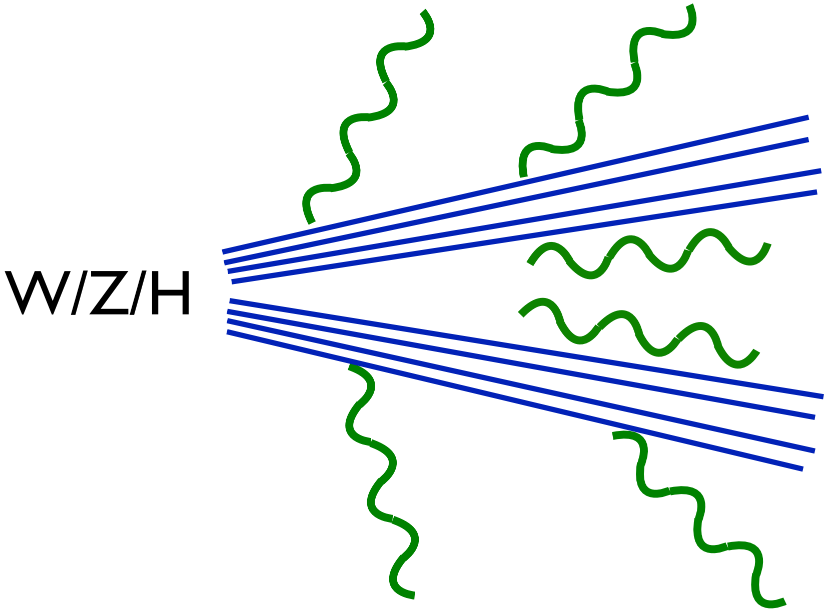
includes pdfs, emissions that were groomed away, out-of-jet radiation,...

collinear-soft radiation

hard collinear radiation

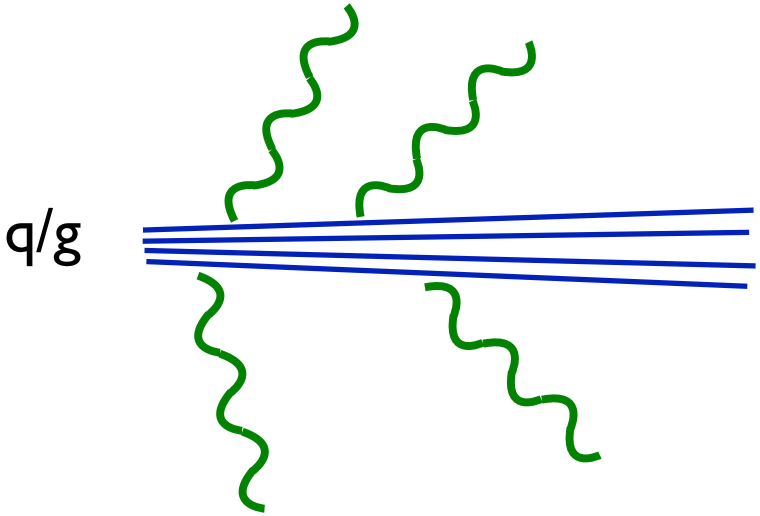
Goal:

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



Signal: Two-prong jet

Characteristic angular size
determined by mass

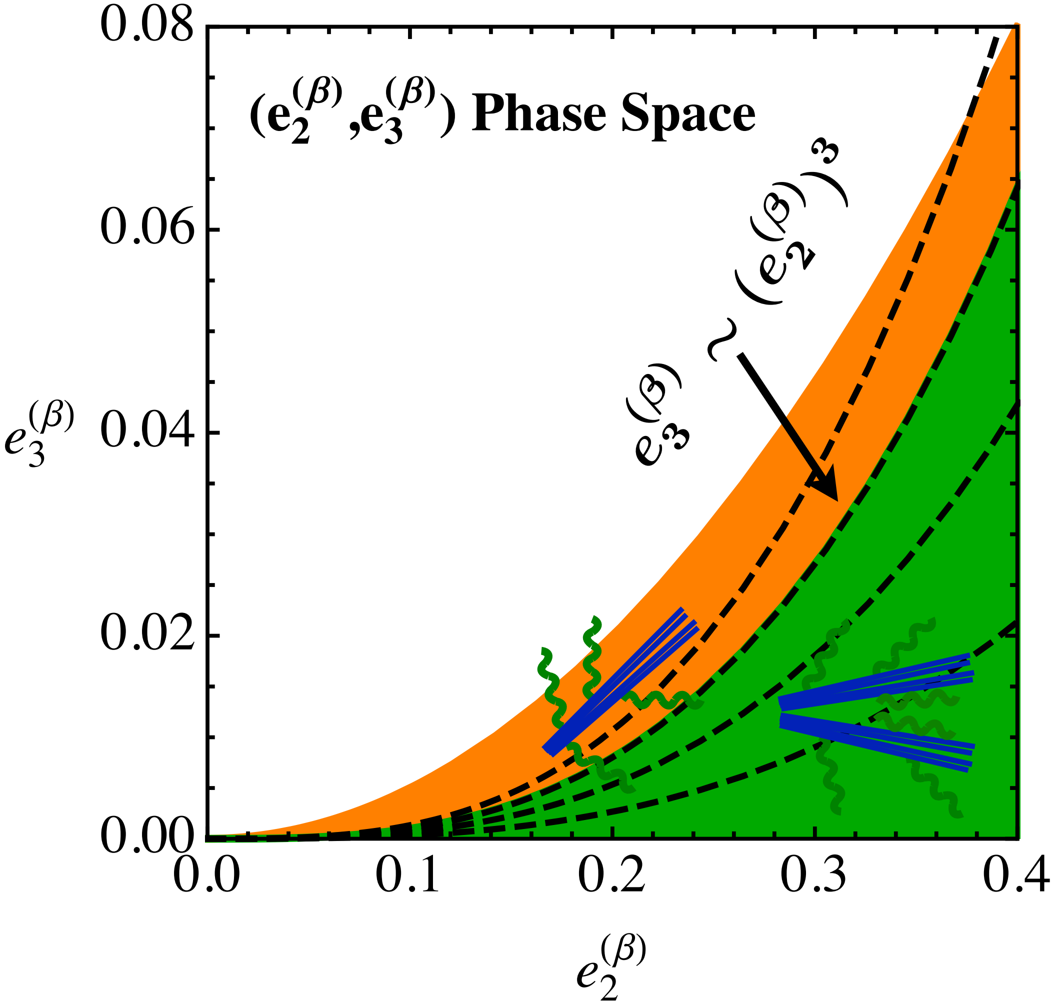


Background: One-prong jet

No intrinsic angular size

Optimal Observable:

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



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

jet p_T

sum over distinct pairs of particles in the jet

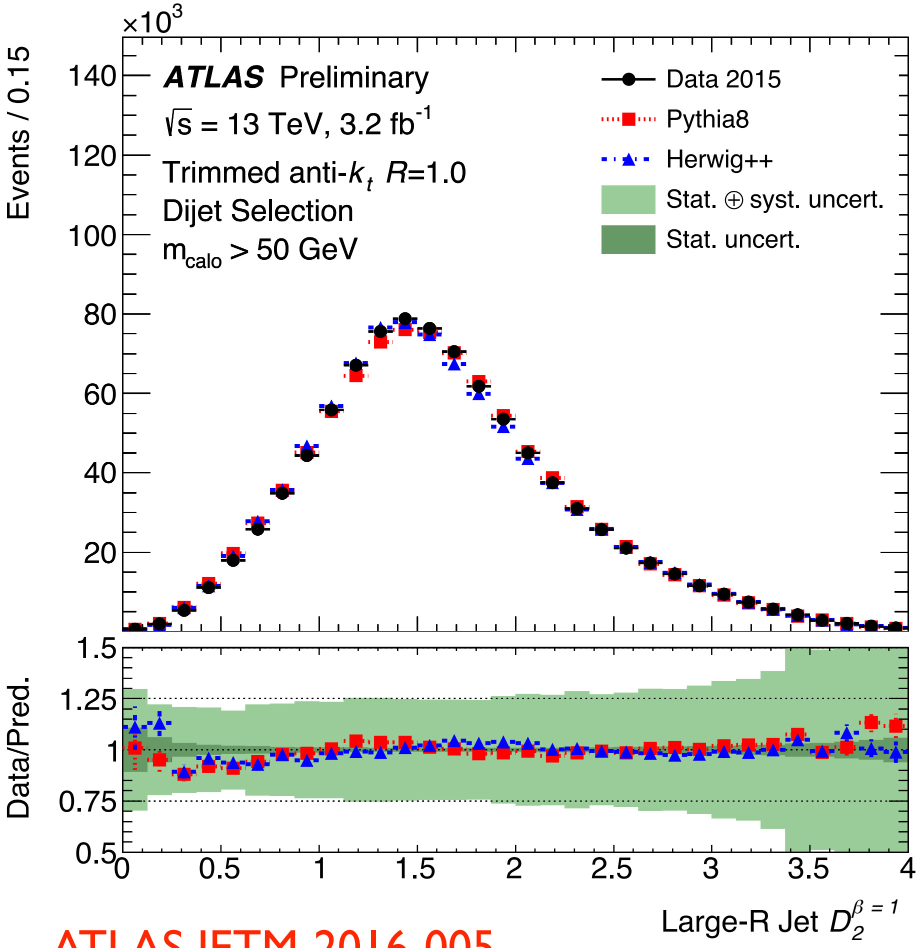
angle between *i* and *j*

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

Note:

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

AJL, Moult, Neill 2014



ATLAS JETM-2016-005

Measurements in LHC Data

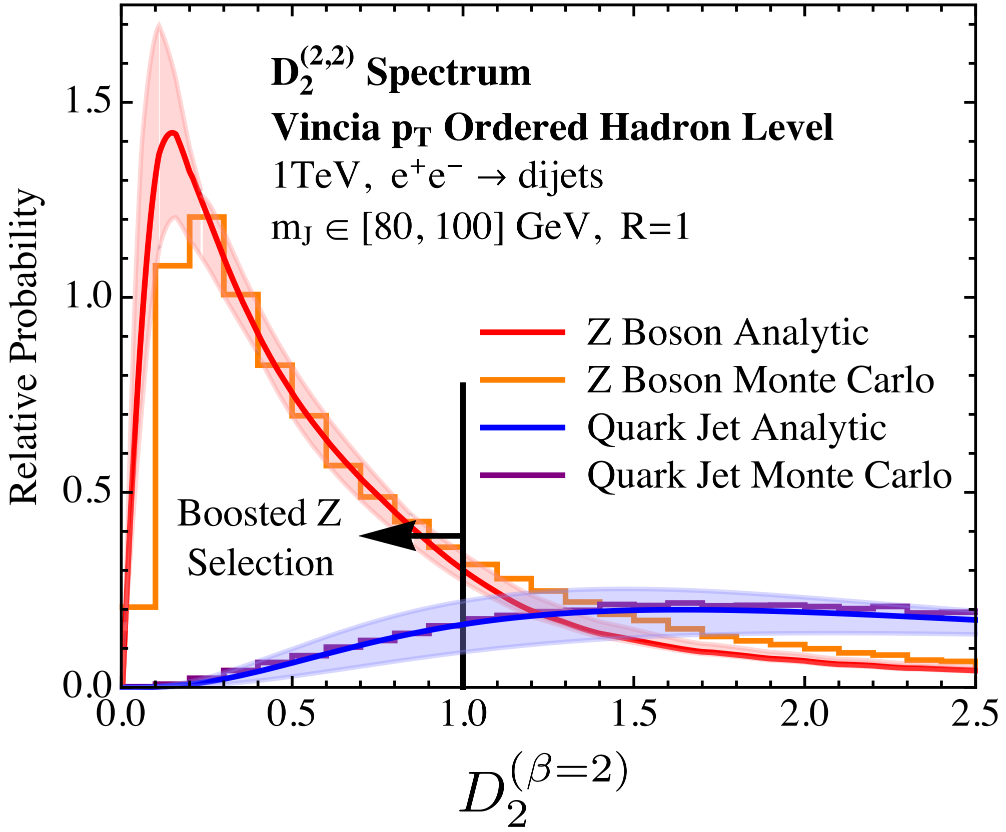
Groomed (with Trimming)

← Angular exponent: beta = 1

Calculations in e^+e^- at NLL

No grooming; ignoring NGLs

Angular exponent: beta = 2 →



AJL, Moult, Neill 2015

Goal:
Precision Soft Dropped D_2 Predictions

AJL, Moult, Neill 17xx.sooon

Three Observations of Soft Dropped D_2:

Kinematic Endpoint Fixed; Independent of Jet Properties

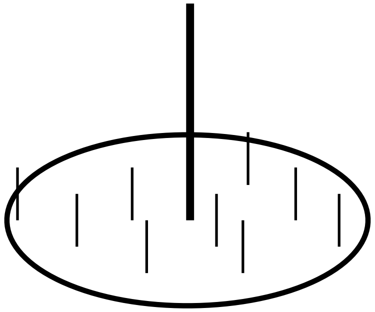
Suppressed Non-Perturbative Corrections

Process Universality

Kinematic Endpoint Fixed; Independent of Jet Properties:

Ungroomed Case

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



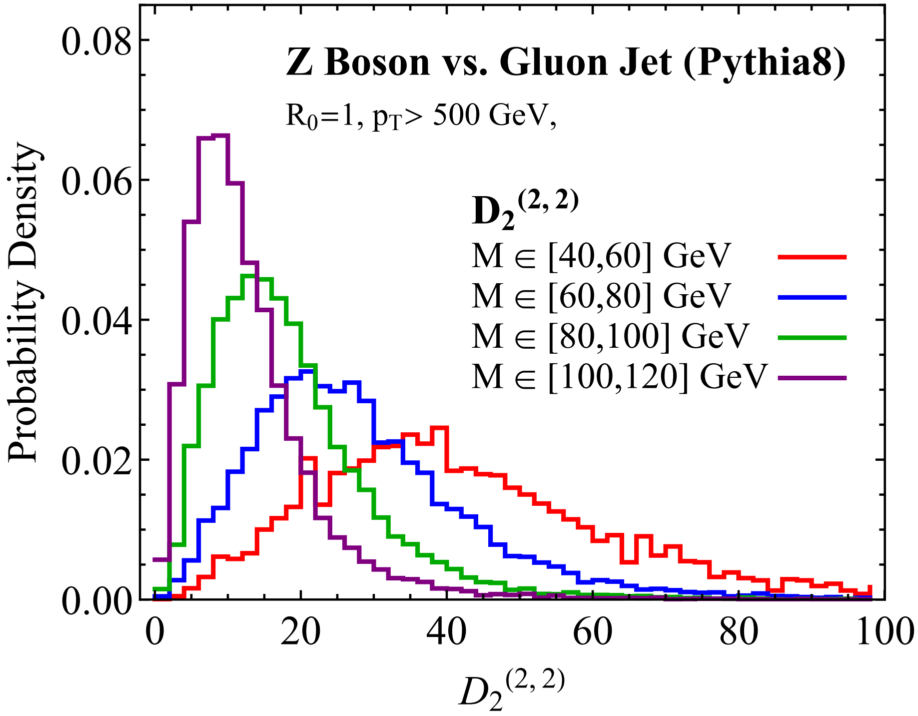
Maximum e₃ for one hard prong and uniform soft radiation

$$e_3^{(\beta)}\Big|_{\max} = \frac{(e_2^{(\beta)})^2}{2}$$

$$D_2^{(\beta)}\Big|_{\max} = \frac{1}{2e_2^{(\beta)}}$$

$$D_2^{(2)}\Big|_{\max} \simeq \frac{p_T^2}{2m_J^2}$$

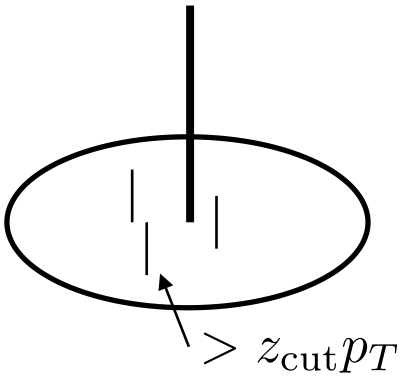
Endpoint drifts as mass cut is changed!



Kinematic Endpoint Fixed; Independent of Jet Properties:

Soft Drop Groomed Case

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



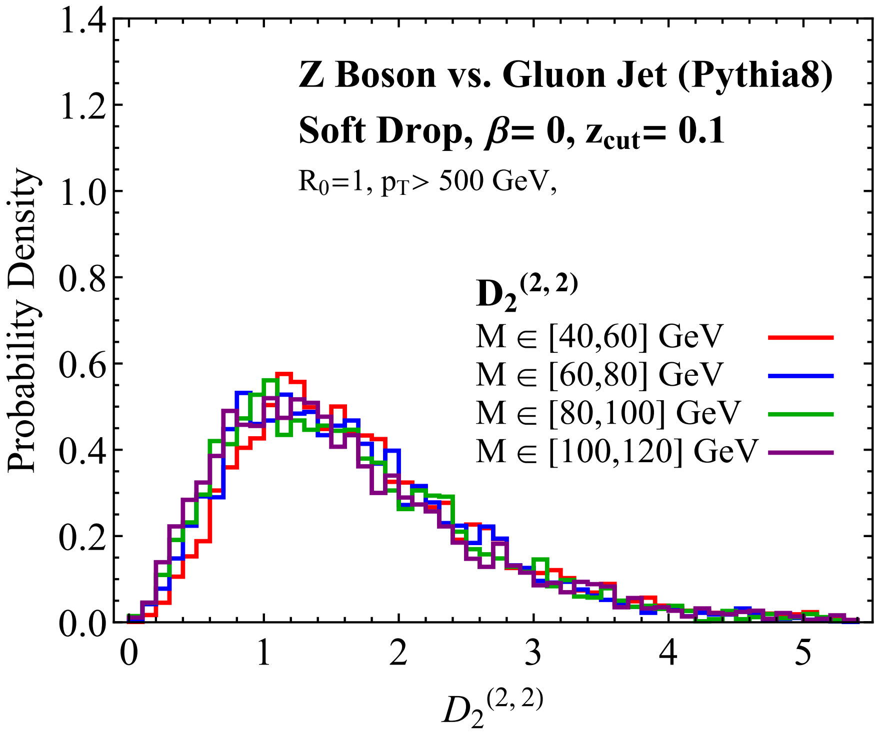
Maximum e₃ for one hard prong and uniform soft radiation

$$e_3^{(\beta)}\Big|_{\max} = \frac{(e_2^{(\beta)})^3}{2z_{\mathrm{cut}}}$$

$$D_2^{(\beta)}\Big|_{\max} = \frac{1}{2z_{\mathrm{cut}}}$$

Endpoint independent of mass cut!

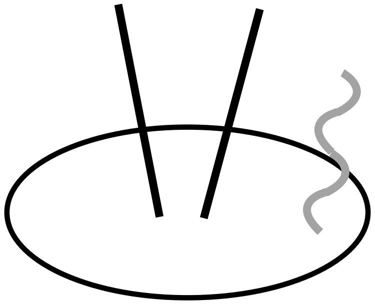
Robust distribution



Suppressed Non-Perturbative Corrections

Ungroomed Case

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



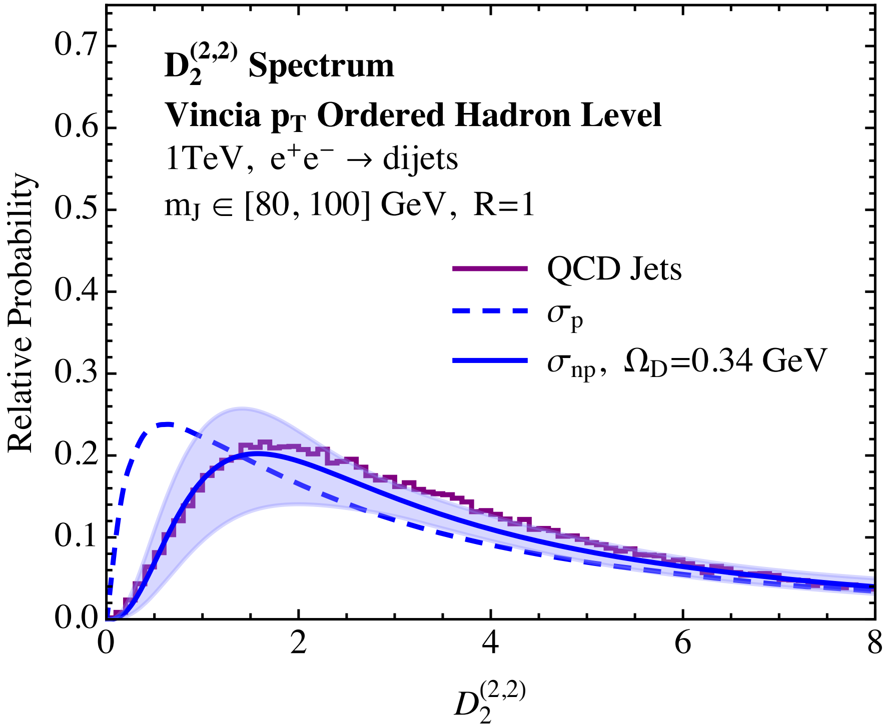
Value of e₃ dominated by a wide angle non-perturbative gluon:

$$e_3^{(\beta)}\Big|_{\mathrm{NP}} \lesssim \frac{\Lambda_{\mathrm{QCD}}}{p_T} e_2^{(\beta)}$$

$$D_2^{(\beta)}\Big|_{\mathrm{NP}} \lesssim \frac{\Lambda_{\mathrm{QCD}}}{p_T} \frac{1}{(e_2^{(\beta)})^2}$$

$$D_2^{(2)}\Big|_{\mathrm{NP}} \lesssim \frac{\Lambda_{\mathrm{QCD}} p_T^3}{m_J^4}$$

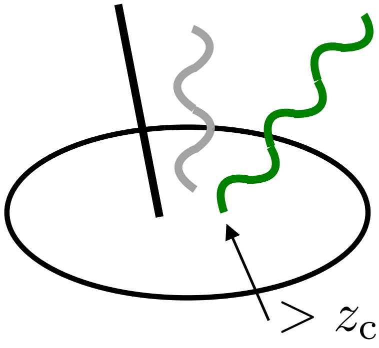
Severe sensitivity to non-perturbative effects as cuts are varied



Suppressed Non-Perturbative Corrections

Soft Drop Groomed Case

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



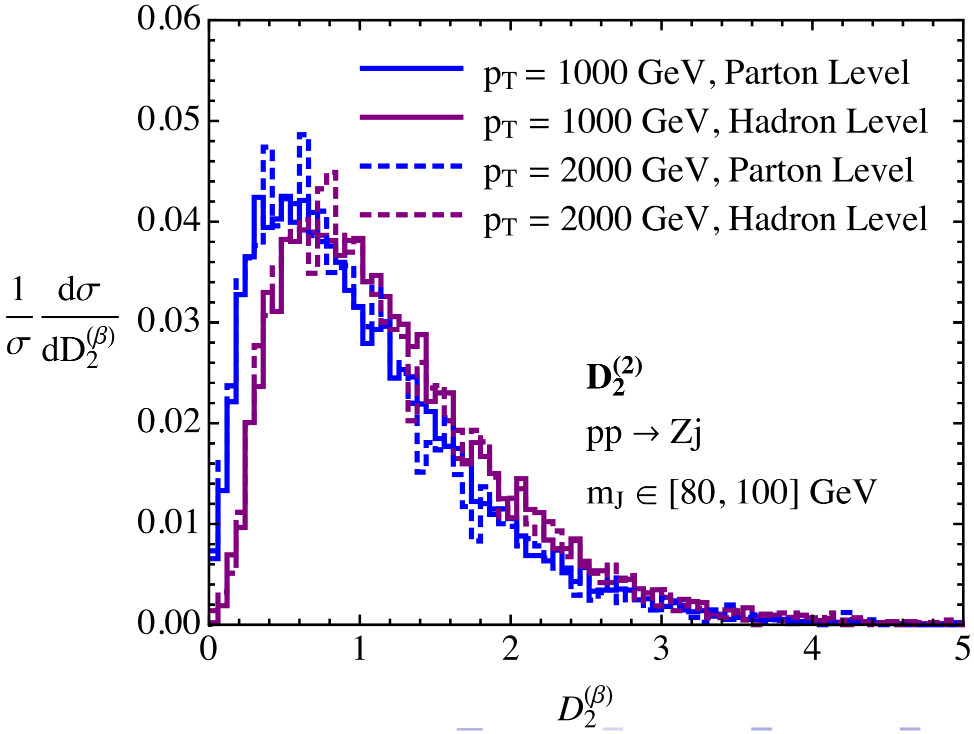
Value of e_3 dominated by a soft-collinear non-perturbative gluon:

$$e_3^{(\beta)}\Big|_{\text{NP}} \lesssim \frac{\Lambda_{\text{QCD}}}{p_T} \frac{\left(e_2^{(\beta)}\right)^{3-\frac{1}{\beta}}}{z_{\text{cut}}^{2-\frac{1}{\beta}}}$$

$$D_2^{(\beta)}\Big|_{\text{NP}} \lesssim \frac{\Lambda_{\text{QCD}}}{p_T} \frac{1}{\left(e_2^{(\beta)}\right)^{\frac{1}{\beta}} z_{\text{cut}}^{2-\frac{1}{\beta}}}$$

$$D_2^{(2)}\Big|_{\text{NP}} \lesssim \frac{\Lambda_{\text{QCD}}}{m_J z_{\text{cut}}^{3/2}}$$

No non-perturbative sensitivity to the jet p_T!



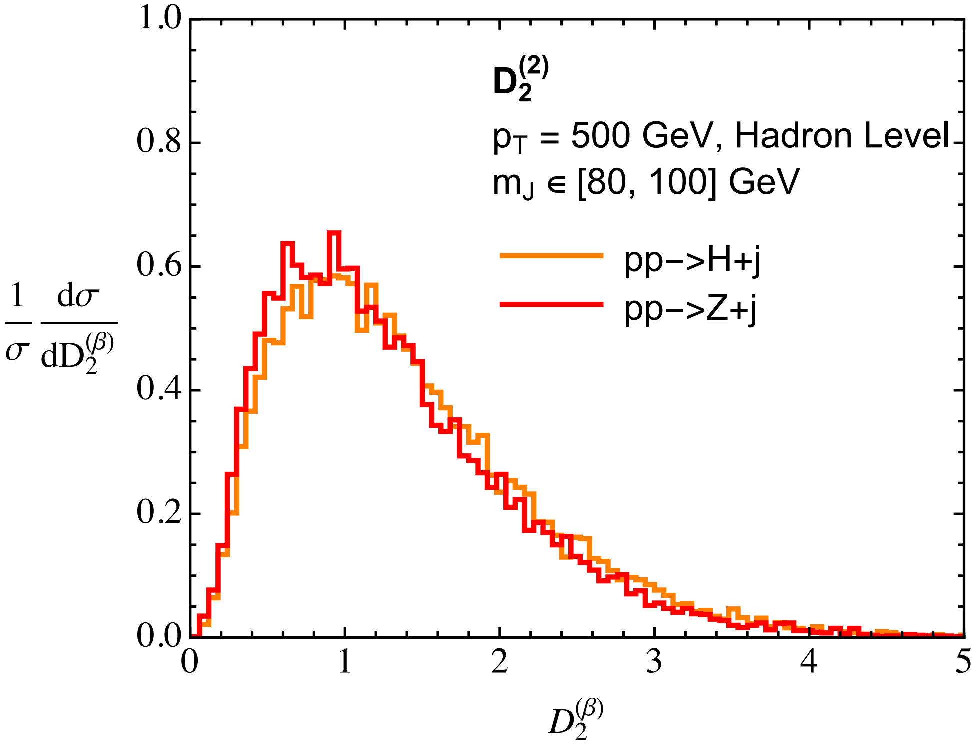
Process Universality
Soft Drop Groomed Case

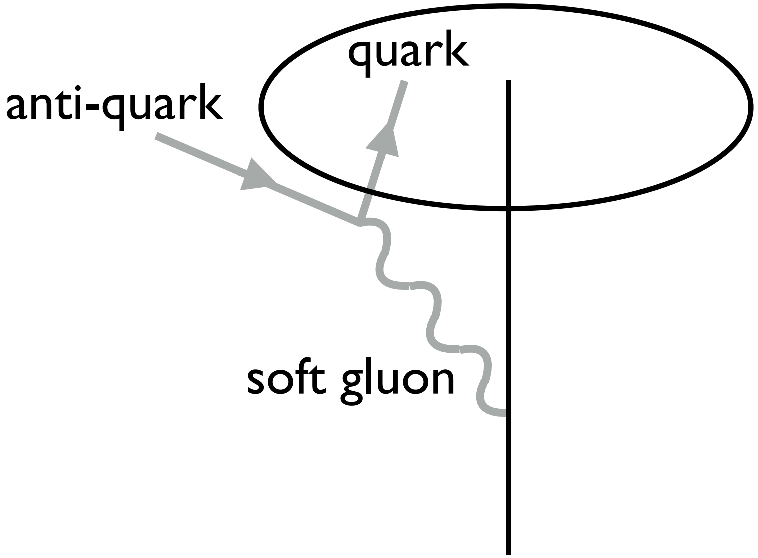
p p > Z + j: ~80% quark
~20% gluon

p p > H + j: ~50% quark
~50% gluon

Soft Drop renders quark and gluon jet flavor IRC safe!

Possible flavor ambiguities are groomed away





Process Universality

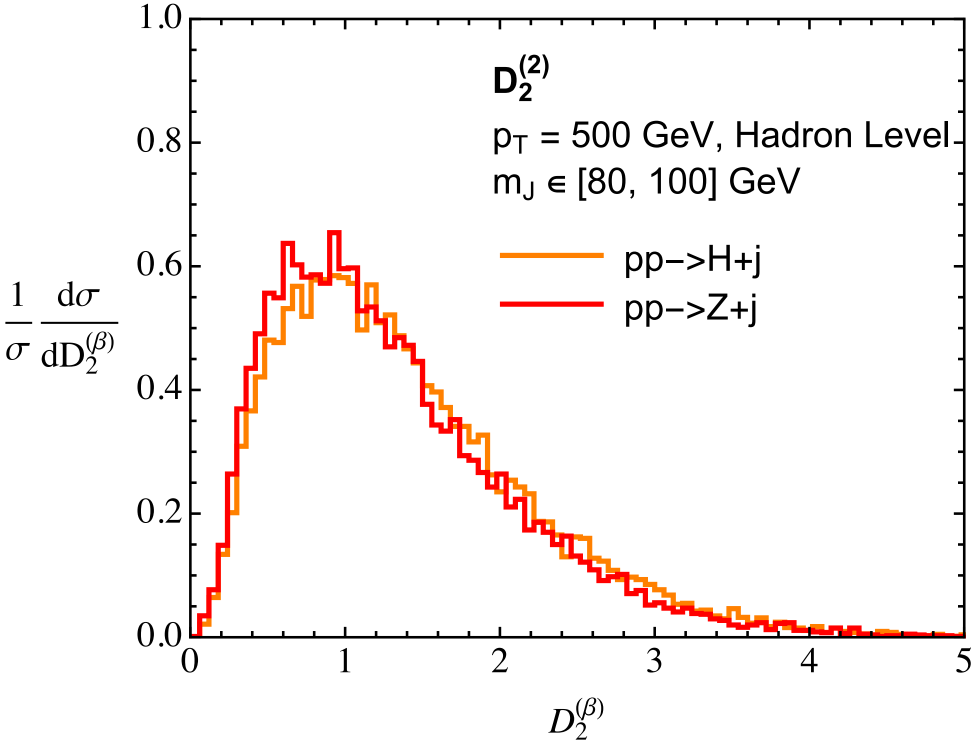
Soft Drop Groomed Case

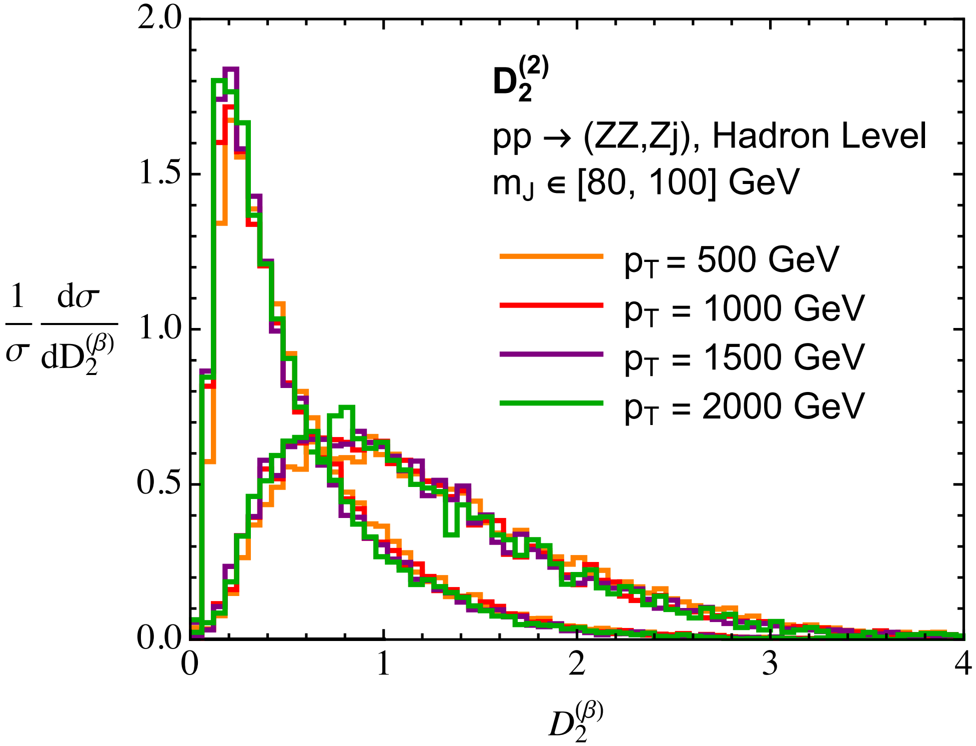
p p > Z + j: ~80% quark
~20% gluon

p p > H + j: ~50% quark
~50% gluon

Differences between quarks and gluons largely eliminated

Robust, stable discrimination over huge range of p_T!





Summary

Soft Drop jet grooming can be used to eliminate NGLs in jet distributions

Powerful techniques necessary to identify hadronic decays of W/Z/H

Grooming improves robustness to process, cuts, and hadronization

Predictions at NLL (and beyond!) soon

AJL, Moult, Neill 17xx.sooon