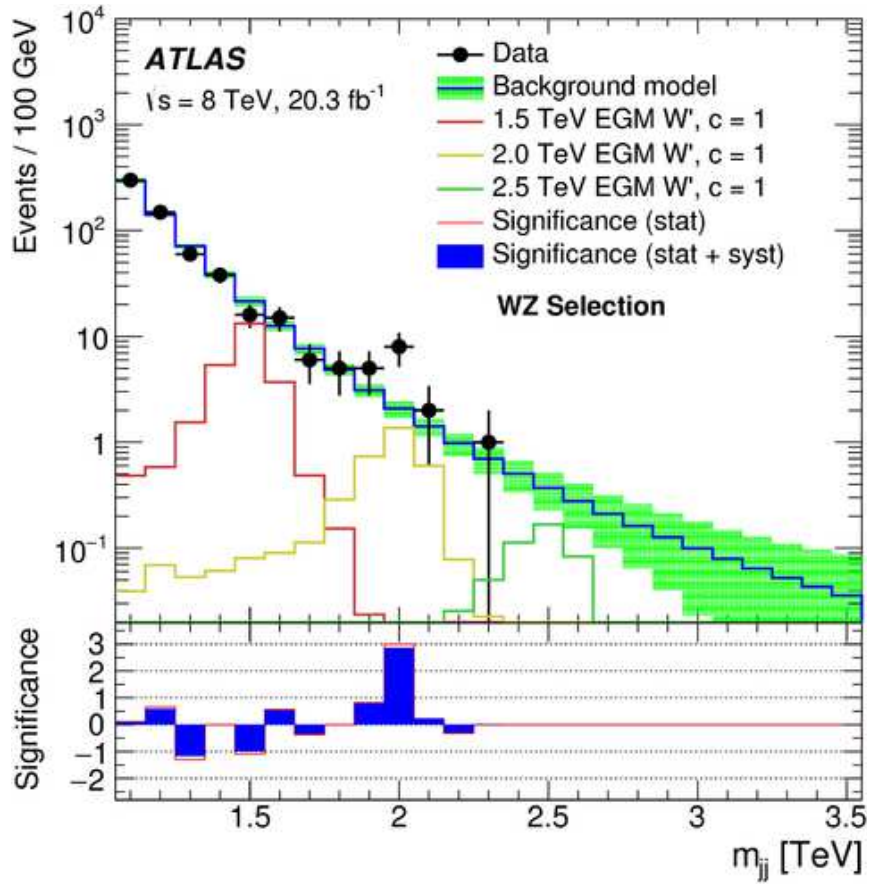
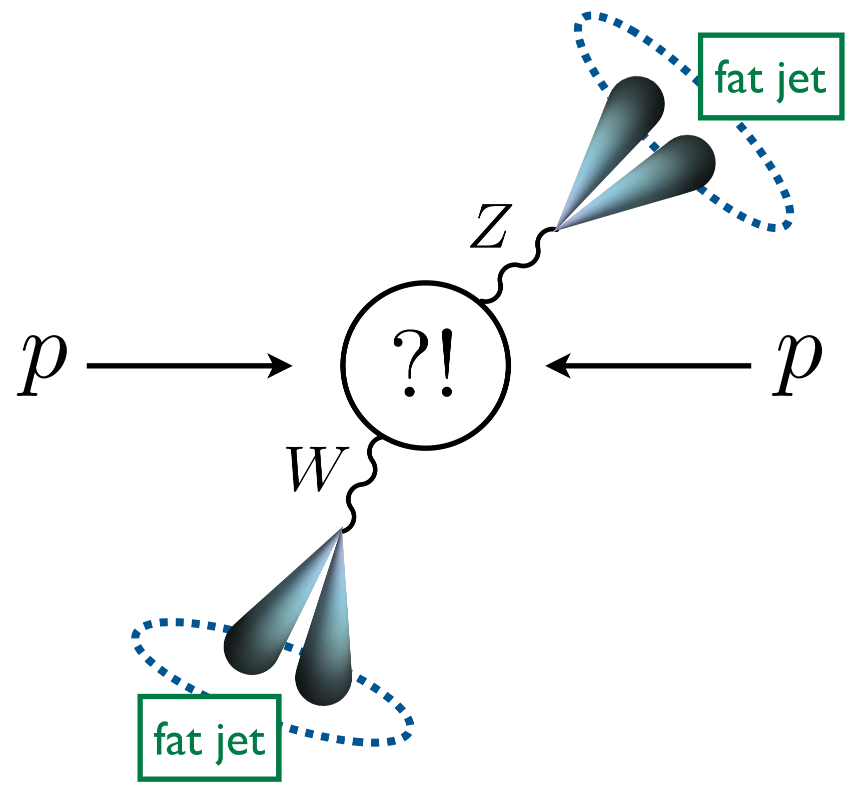
Theoretical Advances in Jet Substructure

Jesse Thaler

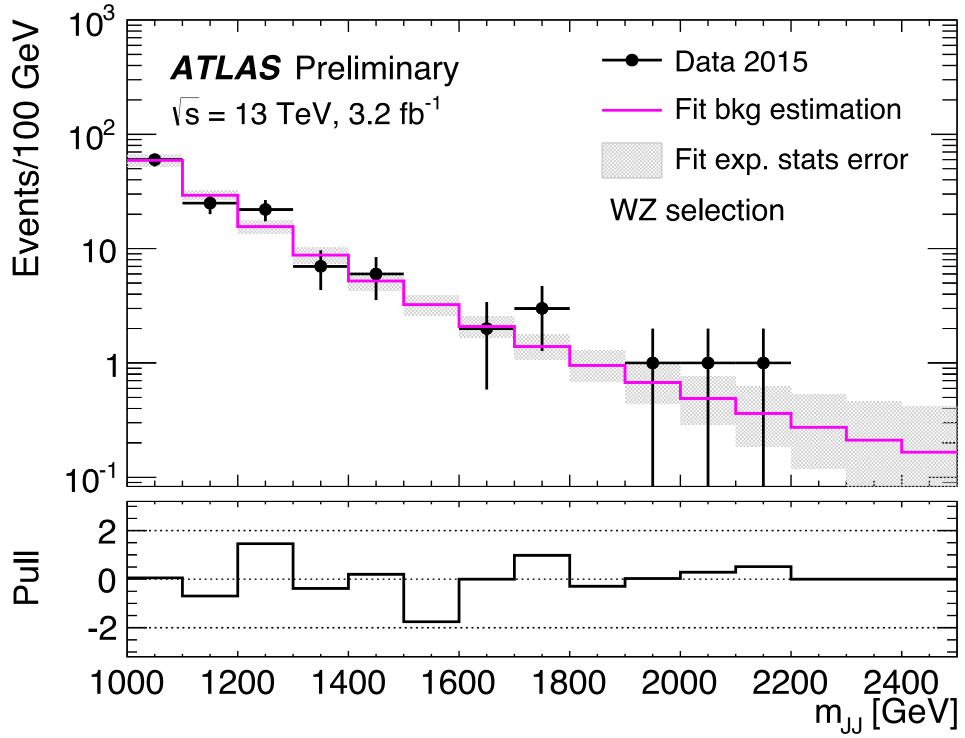
Aspen Winter Conference — January 15, 2016

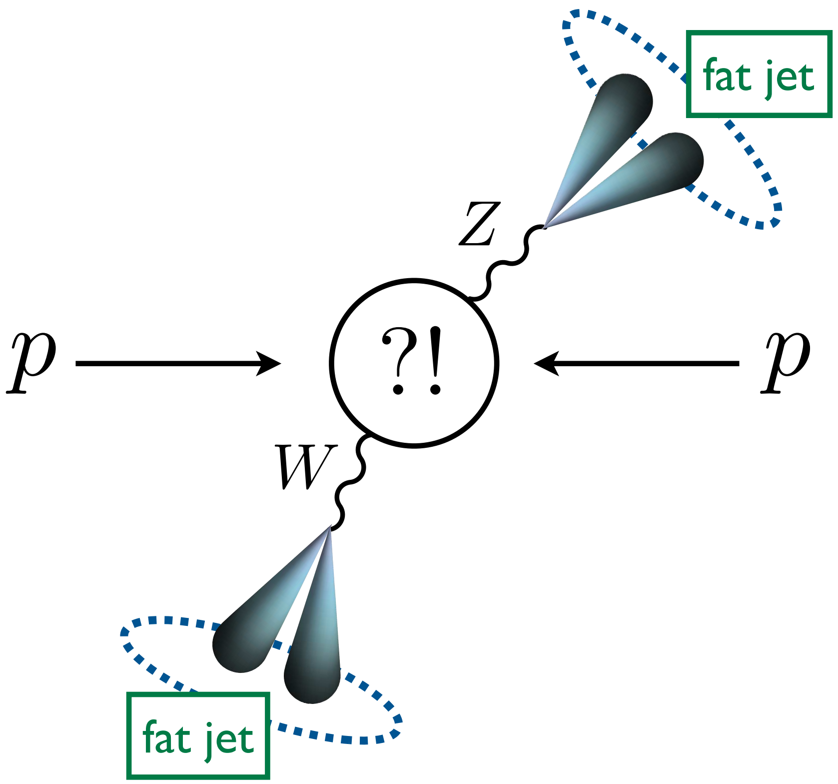
Diboson Excitement in 2015





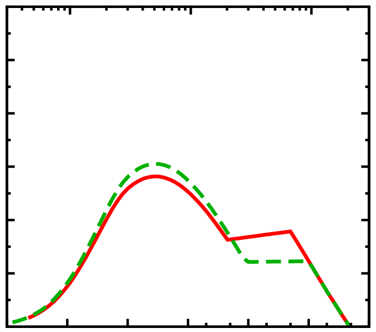
More Excitement in 2016?



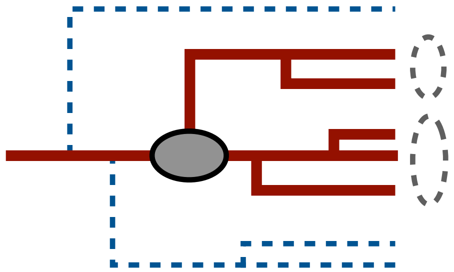


Bumps may come and go, but jet substructure techniques are here to stay

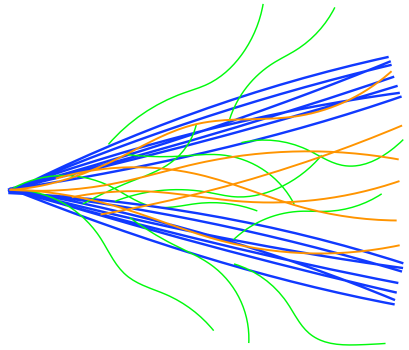
Outline



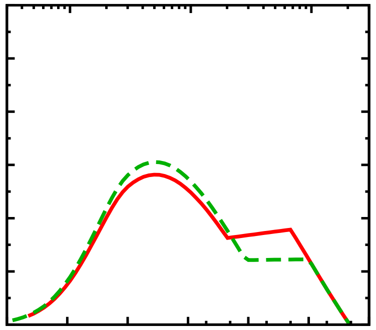
Substructure from First Principles



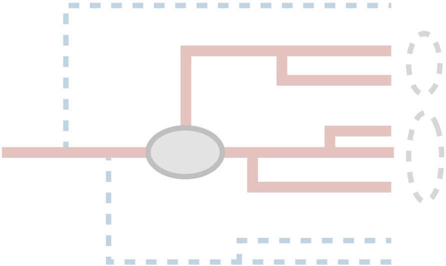
z_g: Testing the Foundations of QCD



D_2: The Power of Power Counting



Substructure from First Principles



z_g: Testing the Foundations of QCD

D_2: The Power of Power Counting

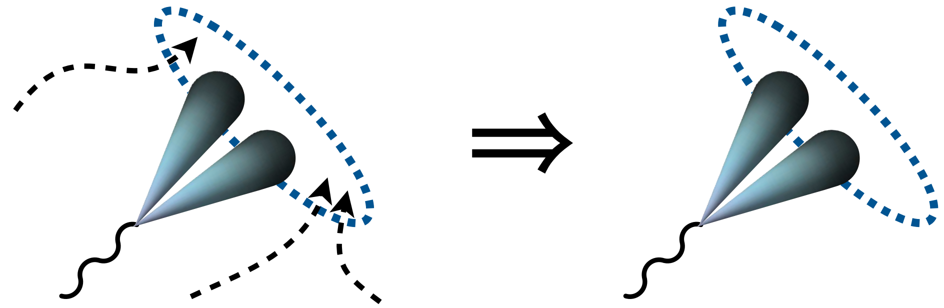
Key Substructure Techniques

Baseline W/Z-Tagging @ CMS 13 TeV

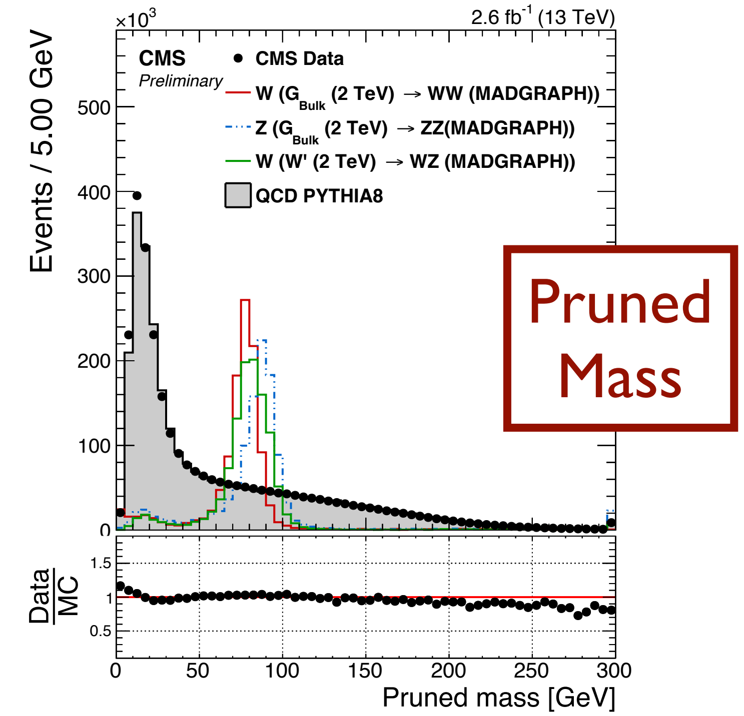
[CMS-PAS-EXO-15-002]

Jet Cleaning:

e.g. ISR/UE/pileup



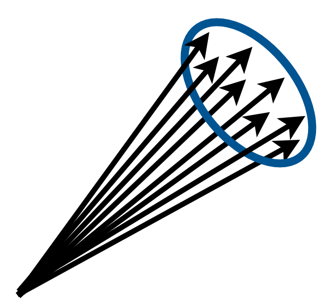
[Mass Drop/Filtering, Trimming, Pruning, Soft Drop, Jet Reclustering…;
for pileup: Area Subtraction, Jet Cleansing, SoftKiller, PUPPI, Constituent Subtraction…]



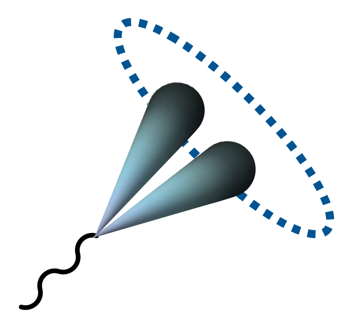
[using Ellis, Vermilion, Walsh, 0903.5081, 0912.0033]

Discrimination:

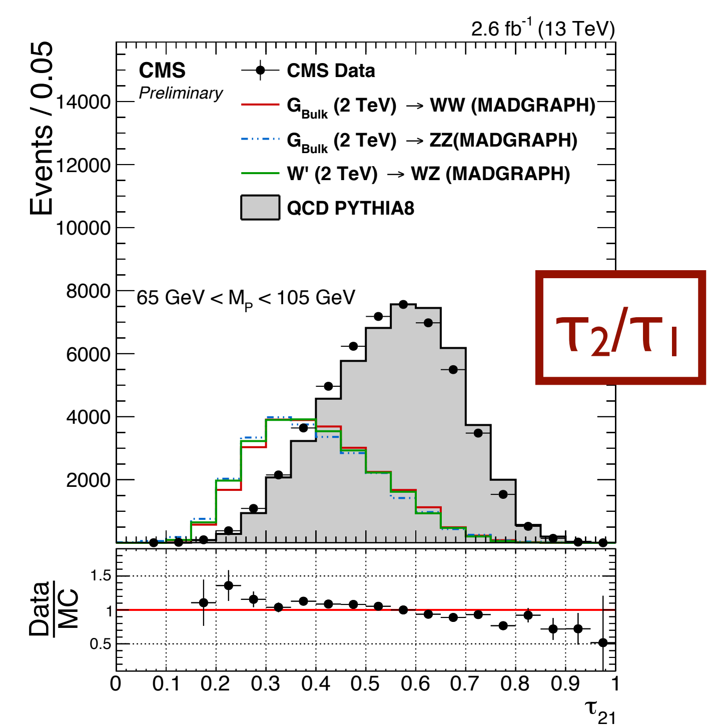
e.g. 1-prong vs. N-prong



vs.



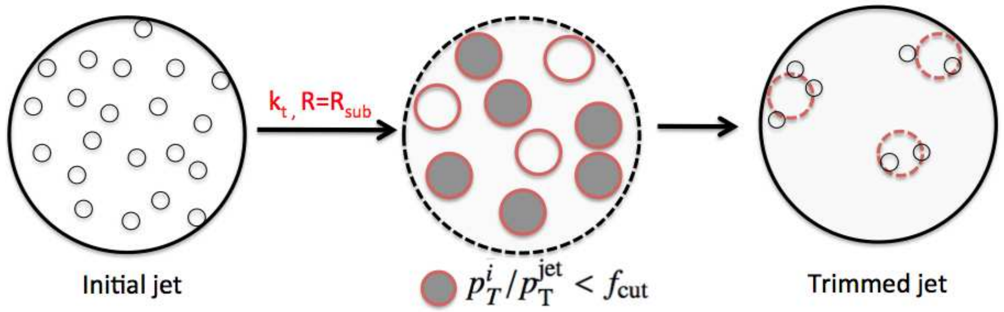
[p_T Balance, Y-splitter, Angularities, Planar Flow, N-subjettiness, Angular Structure Functions, Jet Charge, Jet Pull, Energy Correlation Functions, Dipolarity, p_T^D, Zernike Coefficients, Fox-Wolfram Moments, JHU/CMSTopTagger, HEPTopTagger, Template Method, Shower Deconstruction, Subjet Counting, Wavelets, Q-Jets, Telescoping Jets…]



[using JDT, Van Tilburg, 1011.2268, 1108.2701]

Substructure from First Principles?

e.g. Jet Trimming

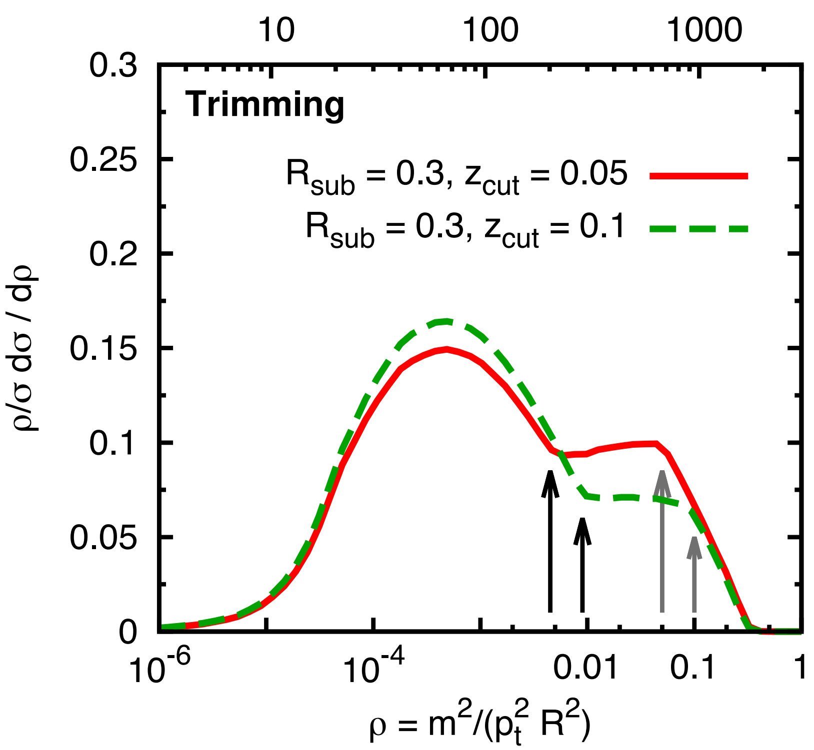


[Krohn, JDT, Wang, 0912.1342; diagram from ATLAS, 1306.4945]

Trimmed Jet Mass:

3 TeV quark jets

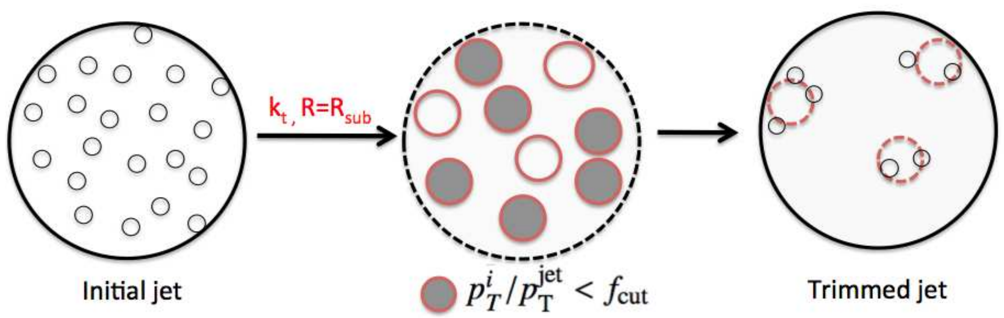
Pythia 6 Simulation



[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Substructure from First Principles?

e.g. Jet Trimming

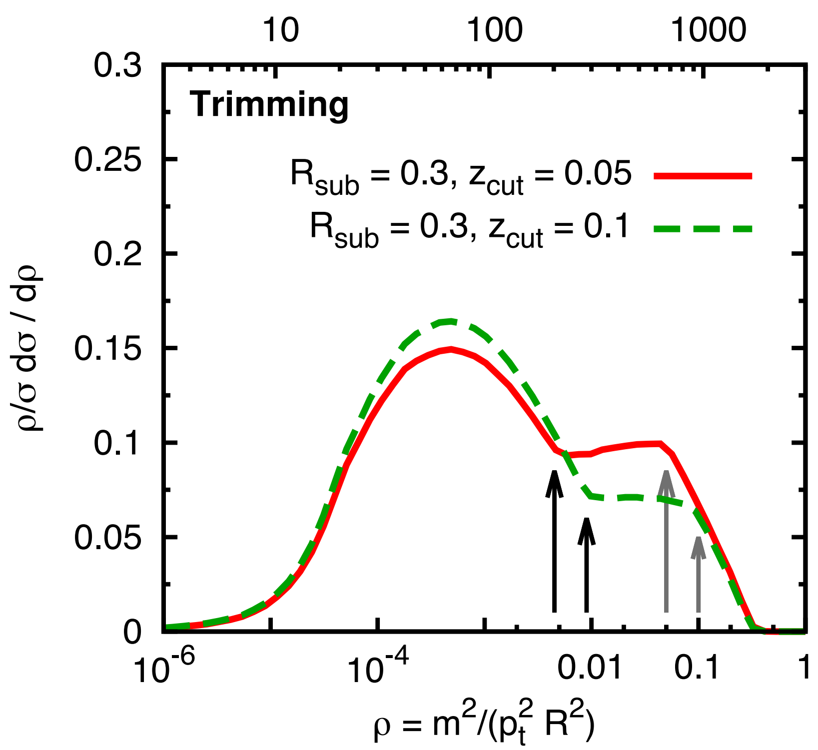


[Krohn, JDT, Wang, 0912.1342; diagram from ATLAS, 1306.4945]

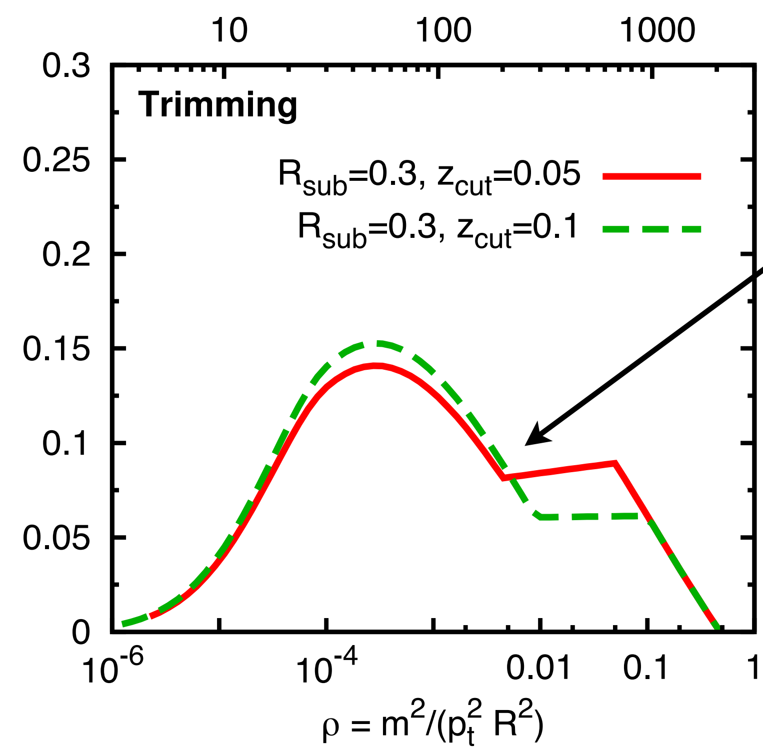
Trimmed Jet Mass:

3 TeV quark jets

Pythia 6 Simulation



First-principles QCD (MLL)



Analytically understand Sudakov peak, kink, and plateau

[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Recent Analytic Progress

1-prong substructure:

Jet mass: Dasgupta, Khelifa-Kerfa, Marzani, Spannowsky, 1207.1640; Chien, Kelley, Schwartz, Zhu, 1208.0010; Jouttenus, Stewart, Tackmann, Waalewijn, 1302.0846
Jet shapes: Ellis, Vermilion, Walsh, Hornig, Lee, 1001.0014; Banfi, Dasgupta, Khelifa-Kerfa, Marzani, 1004.3483; Li, Li, Yuan, 1107.4535;
Larkoski, Neill, JDT, 1401.2158; Hornig, Makris, Mehen, 1601.01319
Angular scaling: Jankowiak, Larkoski, 1201.2688; Larkoski, 1207.1437
Quarks vs. gluons: Larkoski, Salam, JDT, 1305.0007; Larkoski, JDT, Waalewijn, 1408.3122; Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, Webber, 1501.04794
QCD grooming: Dasgupta, Fregoso, Marzani, Salam, 1307.0007; Dasgupta, Fregoso, Marzani, Powling, 1307.0013; Larkoski, Marzani, Soyez, JDT, 1402.2657
Double differential: Larkoski, JDT, 1307.1699; Larkoski, Moult, Neill, 1401.4458; Procura, Waalewijn, Zeune, 1410.6483
In heavy ions: Chien, Vitev, 1405.4293; Chien, 1411.0741
p_T balance: Larkoski, Marzani, JDT, 1502.01719

2-prong substructure:

Signal grooming: Rubin, 1002.4557; Dasgupta, Powling, Siodmok, 1503.01088
2-prong jet shapes: Feige, Schwartz, Stewart, JDT, 1204.3898; Isaacson, Li, Li, Yuan, 1505.06368
Separation power: Larkoski, Moult, Neill, 1409.6298, 1507.03018; Dasgupta, Schunk, Soyez, 1512.00516

3-prong substructure:

Planar flow: Field, Gur-Ari, Kosower, Mannelli, Perez, 1212.2106
Fractional jets: Bertolini, JDT, Walsh, 1501.01965
Power counting: Larkoski, Moult, Neill, 1411.0665

Non-perturbative substructure:

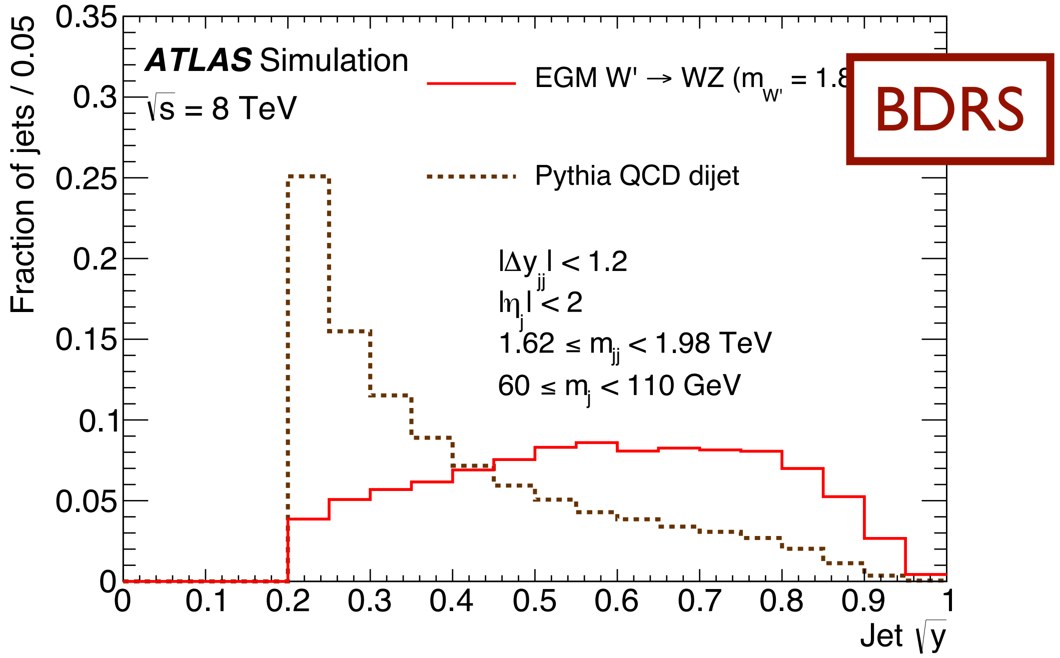
Jet charge: Krohn, Schwartz, Lin, Waalewijn, 1209.2421; Waalewijn, 1209.3019
Track-only shapes: Chang, Procura, JDT, Waalewijn, 1303.6637, 1306.6630

Combination of fixed-order, direct resummation, SCET, RG evolution, and new techniques (e.g. Sudakov safety, multi-differential projections)

Two 2-Prong Case Studies

ATLAS 8 TeV Excess

[ATLAS, 1506.00962]

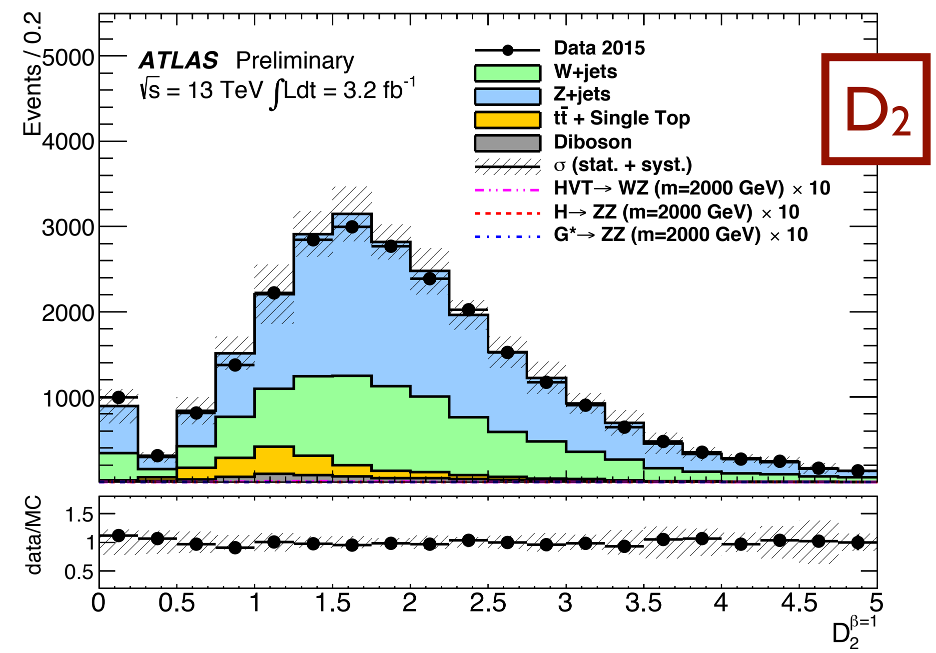


[using Butterworth, Davison, Rubin, Salam, 0802.2470]

Simple observable requires new calculational techniques

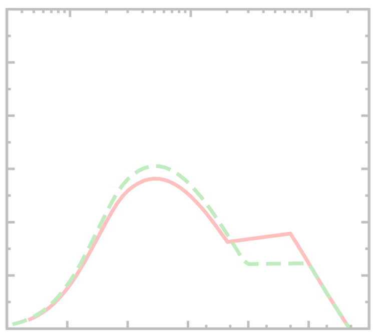
ATLAS 13 TeV Baseline

[ATLAS-CONF-2015-068, -071, -075, -080, see also 1510.05821]

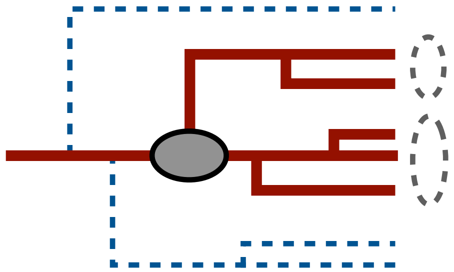


[using Larkoski, Moult, Neill, 1409.6298, 1507.03018]

Theoretical insights yield powerful new discriminant



Substructure from First Principles



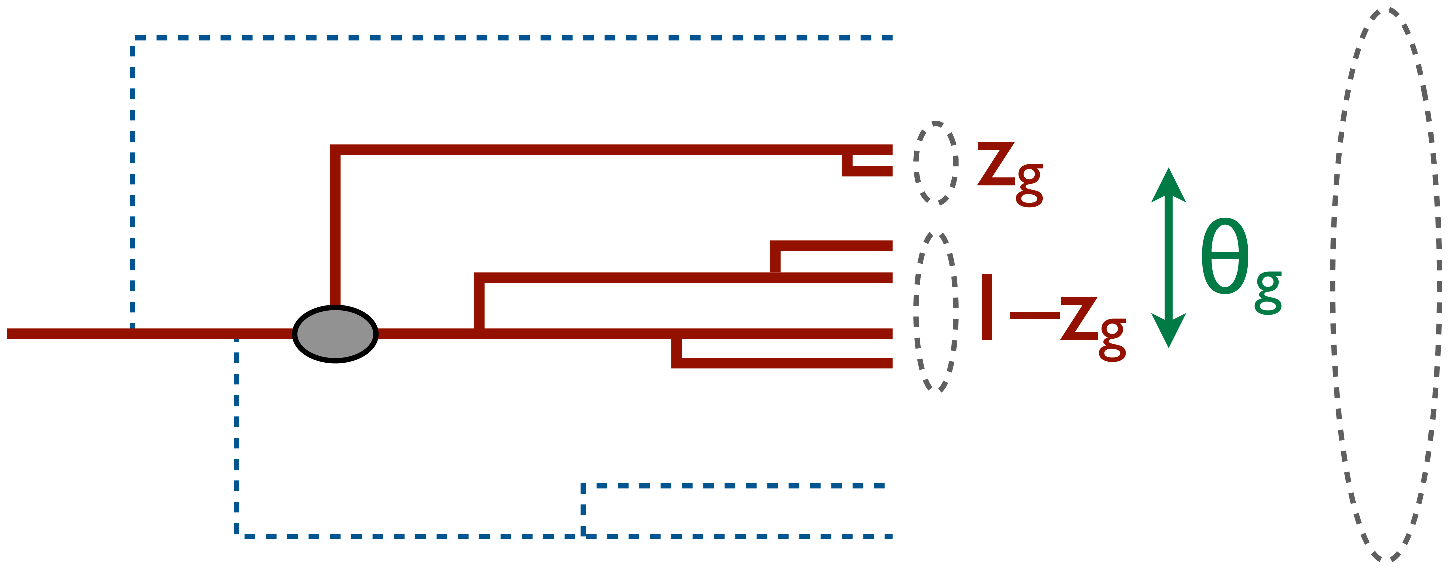
z_g: Testing the Foundations of QCD

D_2: The Power of Power Counting

ATLAS 8 TeV: Boson Tagging with BDRS

Groomed
angular-ordered
clustering tree:

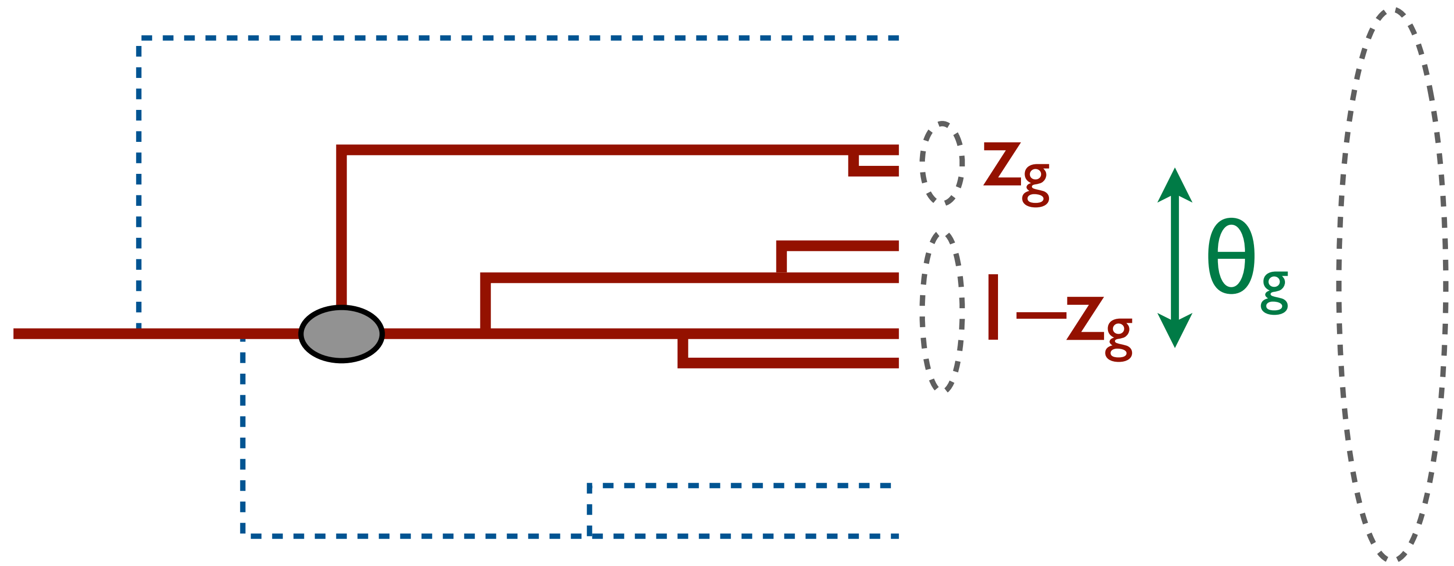
[Butterworth, Davison, Rubin, Salam, 0802.2470]



ATLAS 8 TeV: Boson Tagging with BDRS

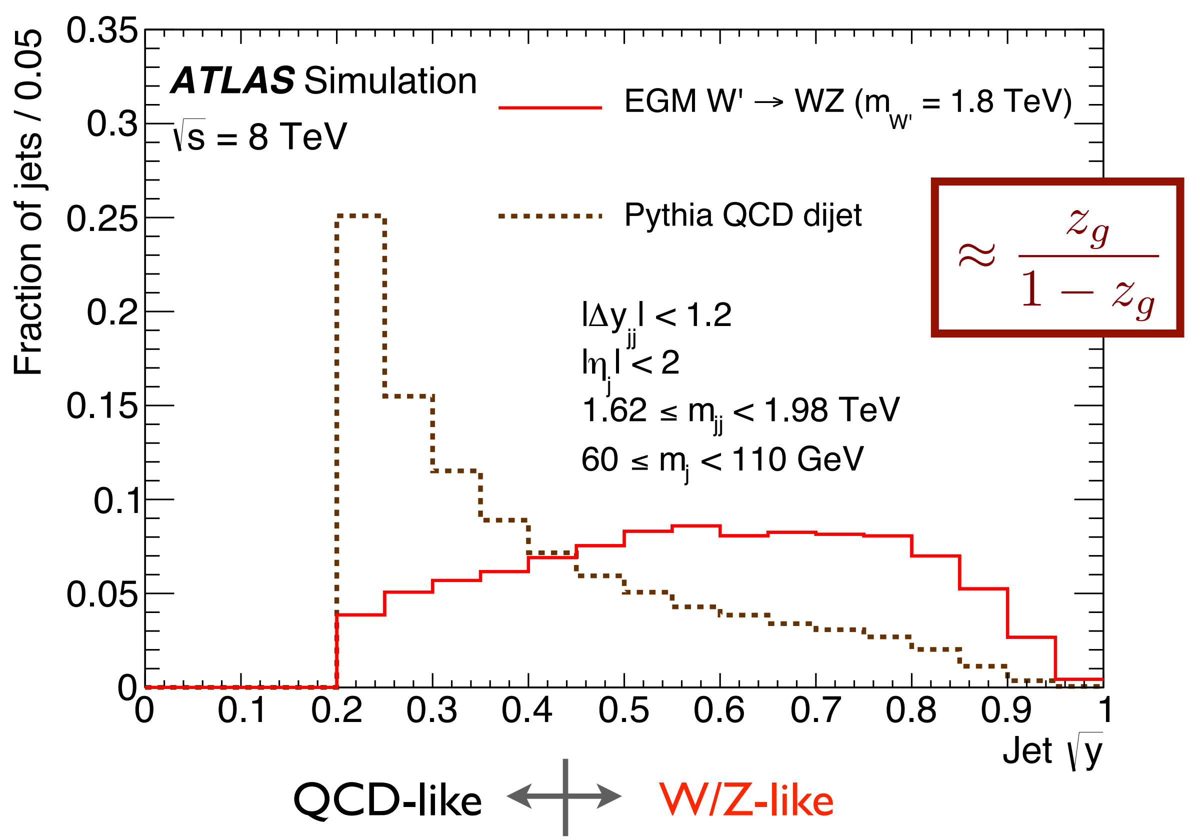
Groomed angular-ordered clustering tree:

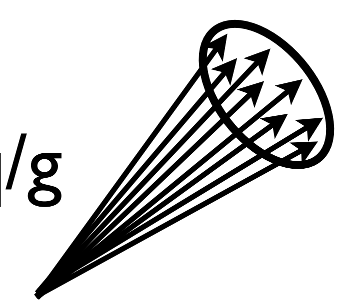
[Butterworth, Davison, Rubin, Salam, 0802.2470]



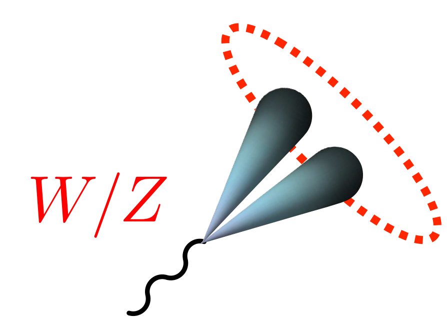
2-prong discriminant from first principles?

[ATLAS, 1506.00962]

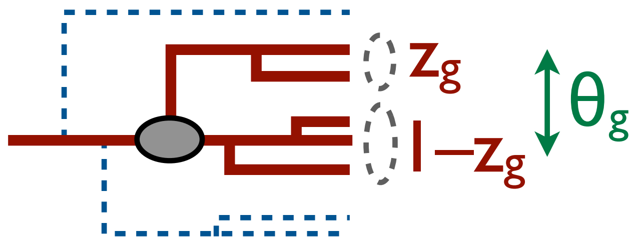




vs.



Calculating Momentum Balance?



Collinear Unsafe*

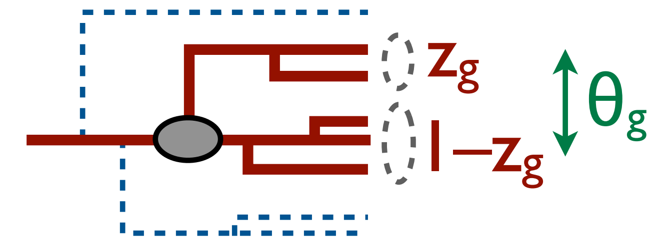
Want: $p(z_g) = \frac{1}{\sigma}\frac{d\sigma}{dz_g}$

*unless you simultaneously restrict jet mass

z_g ??

[Larkoski, JDT, 1307.1699; Larkoski, Marzani, JDT, 1502.01719]

Calculating Momentum Balance?



Collinear Unsafe*

Want: $p(z_g) = \frac{1}{\sigma}\frac{d\sigma}{dz_g}$

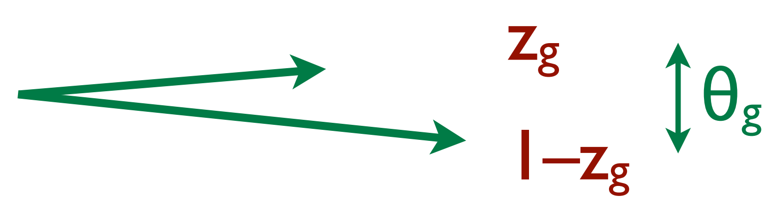
*unless you simultaneously restrict jet mass

Calculable…

Need: $p(z_g|\theta_g) = \frac{p(z_g, \theta_g)}{p(\theta_g)}$

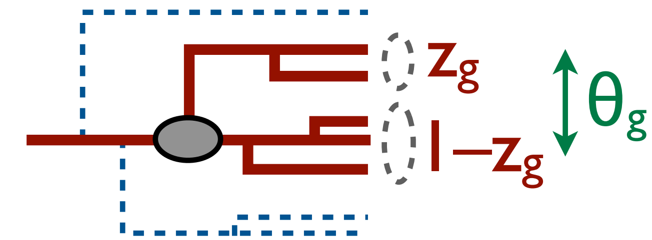
…with Safe companion

vs.



[Larkoski, JDT, 1307.1699; Larkoski, Marzani, JDT, 1502.01719]

Calculating Momentum Balance?



Collinear Unsafe*

Want: $p(z_g) = \frac{1}{\sigma}\frac{d\sigma}{dz_g}$

*unless you simultaneously restrict jet mass

Calculable…

Need: $p(z_g|\theta_g) = \frac{p(z_g, \theta_g)}{p(\theta_g)}$

…with Safe companion

"Sudakov Safe"

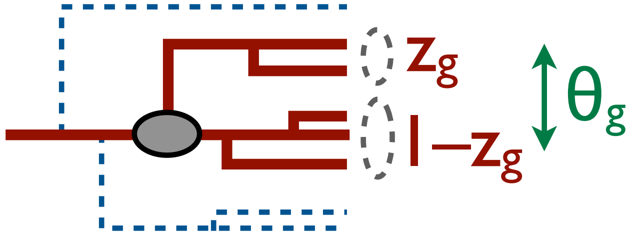
Insight: $p(z_g) = \int d\theta_g \, p(\theta_g) \, p(z_g|\theta_g)$

Sudakov form factor (all orders in α_s)

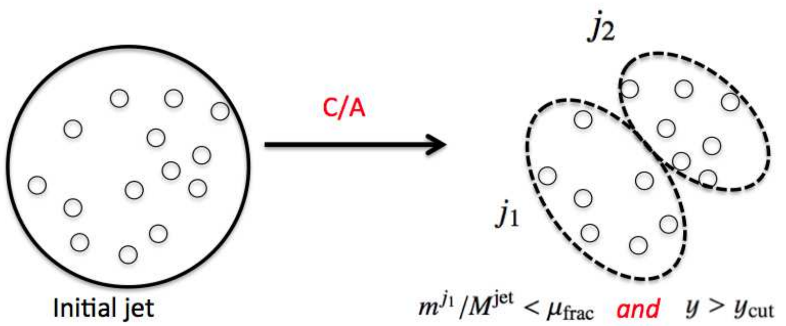
Perturbative (fixed order in α_s)

[Larkoski, JDT, 1307.1699; Larkoski, Marzani, JDT, 1502.01719]

Introducing β



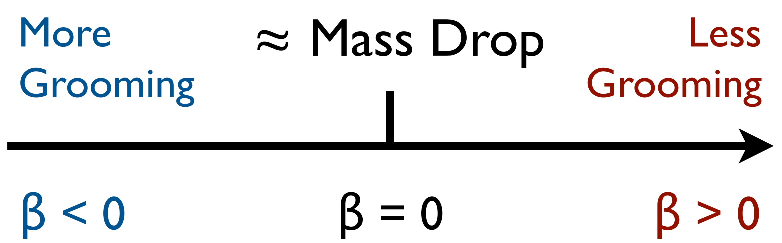
Mass Drop



[Butterworth, Davison, Rubin, Salam, 0802.2470;
Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

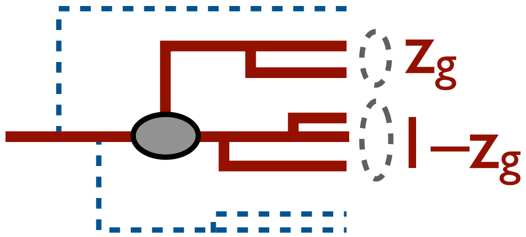
Soft Drop

$$z > z_{\rm cut}\, \theta^\beta$$

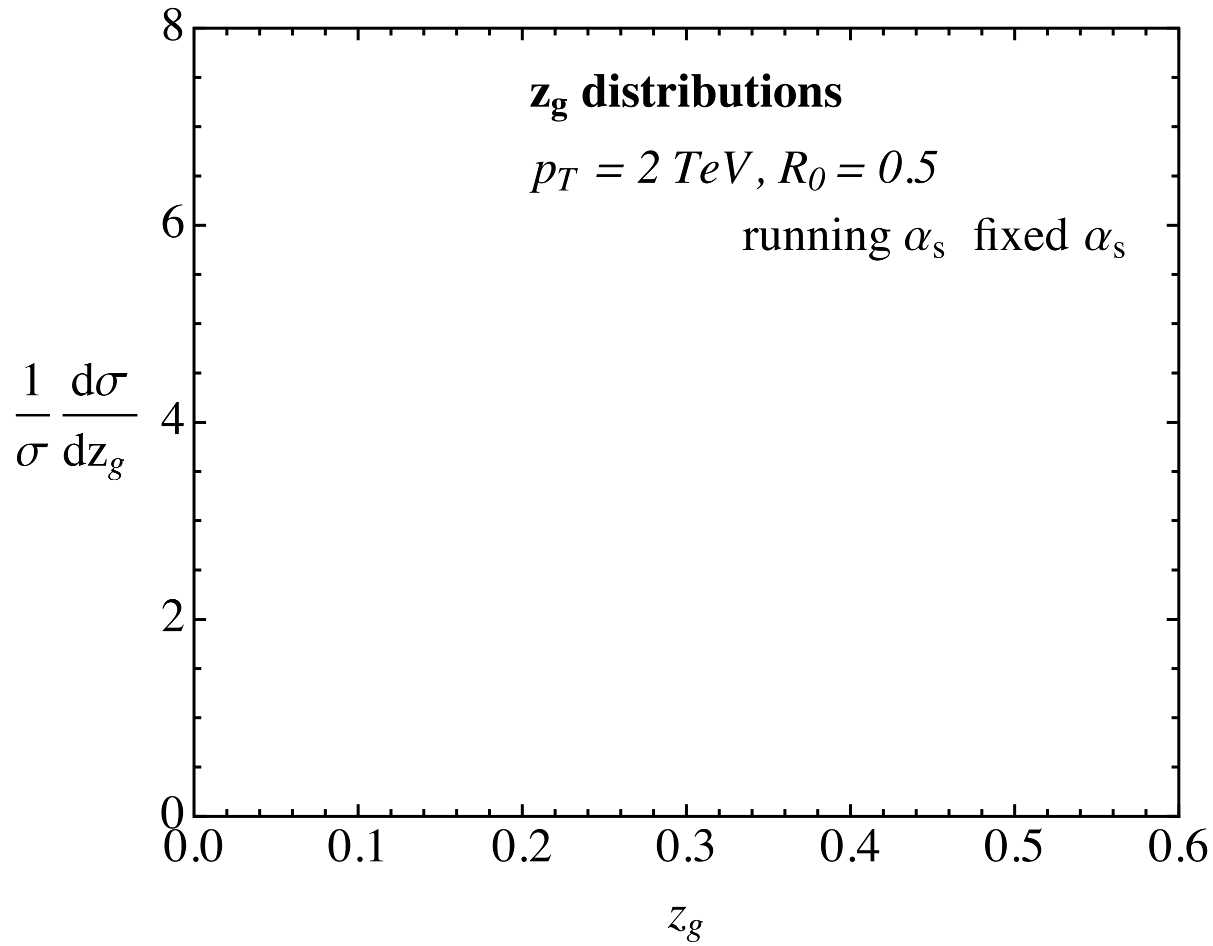


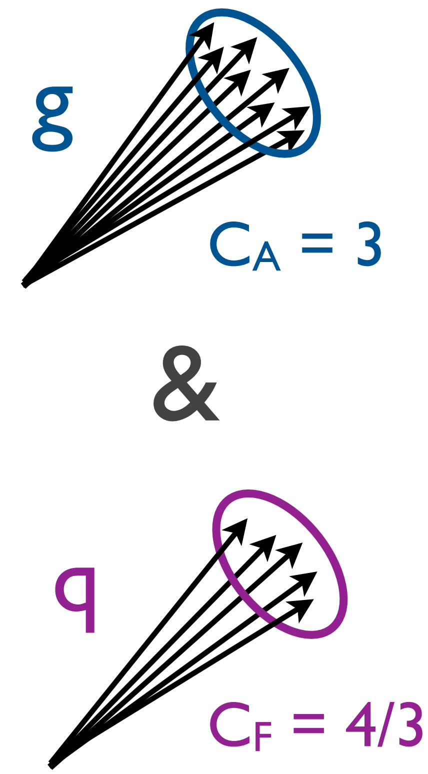
[Larkoski, Marzani, Soyez, JDT, 1402.2657]

First-Principles QCD

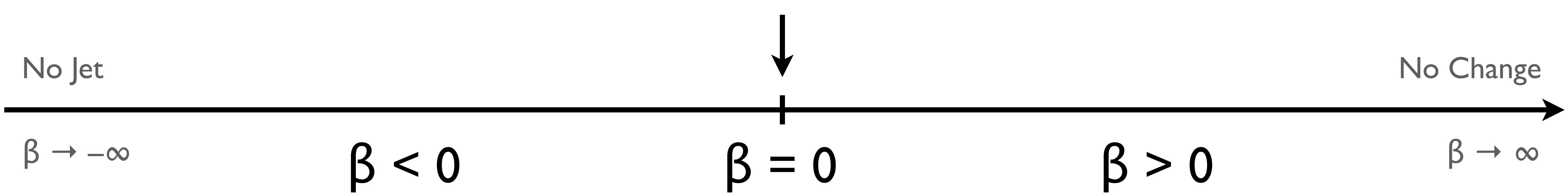


$$z > z_{\text{cut}}\,\theta^{\beta}$$



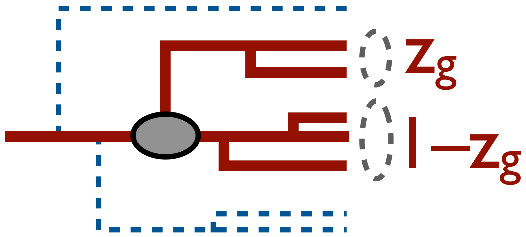


ATLAS 8 TeV
Diboson Study

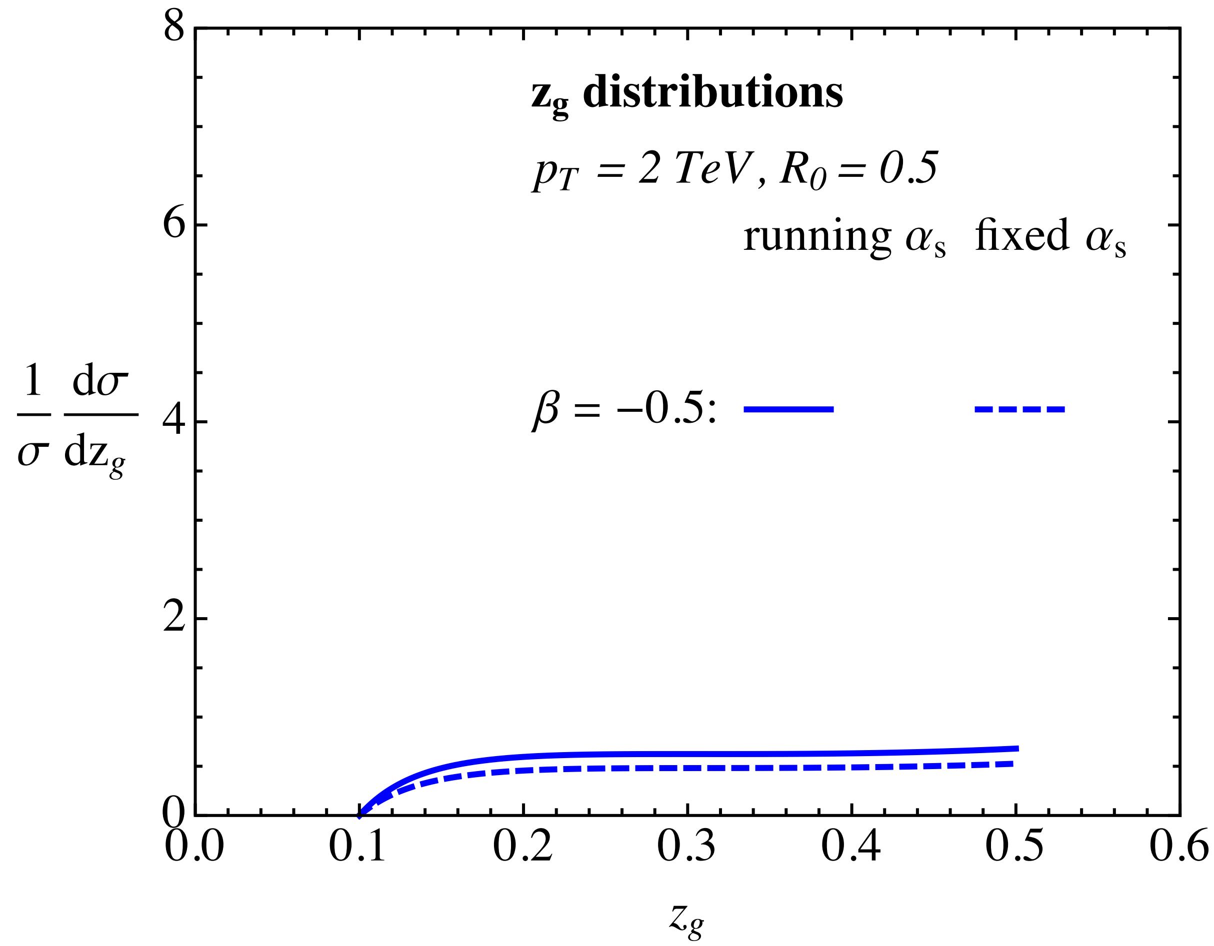


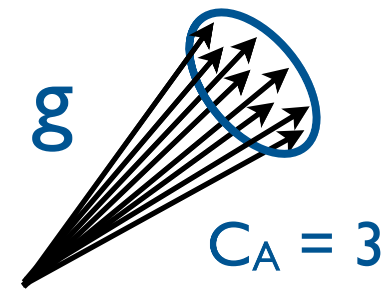
[Larkoski, Marzani, JDT, 1502.01719; using calculational techniques in Dasgupta, Fregoso, Marzani, Salam, 1307.0007; Larkoski, JDT, 1307.1699]

First-Principles QCD

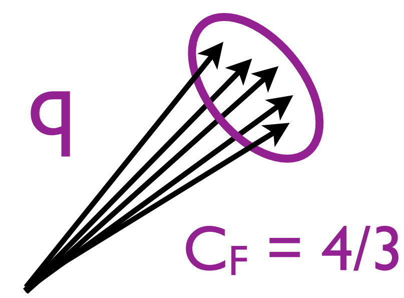


$$z > z_{\text{cut}}\,\theta^\beta$$

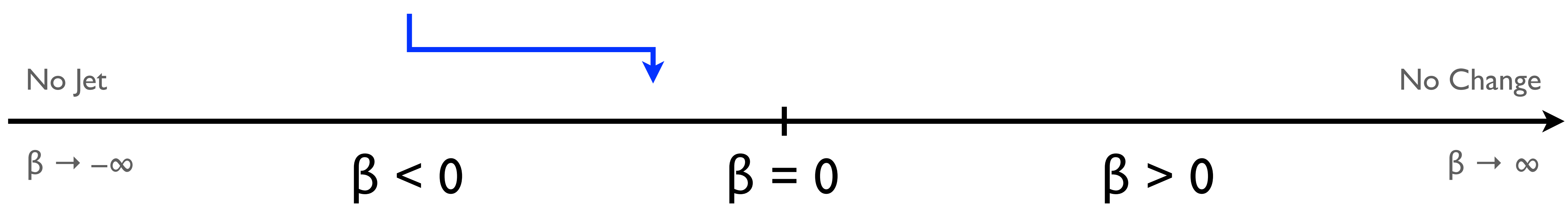




&

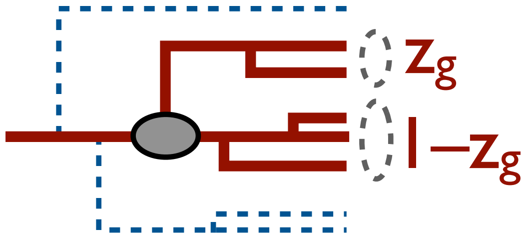


$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\,\frac{1}{z_g}\log\frac{z_g}{z_{\text{cut}}}$$

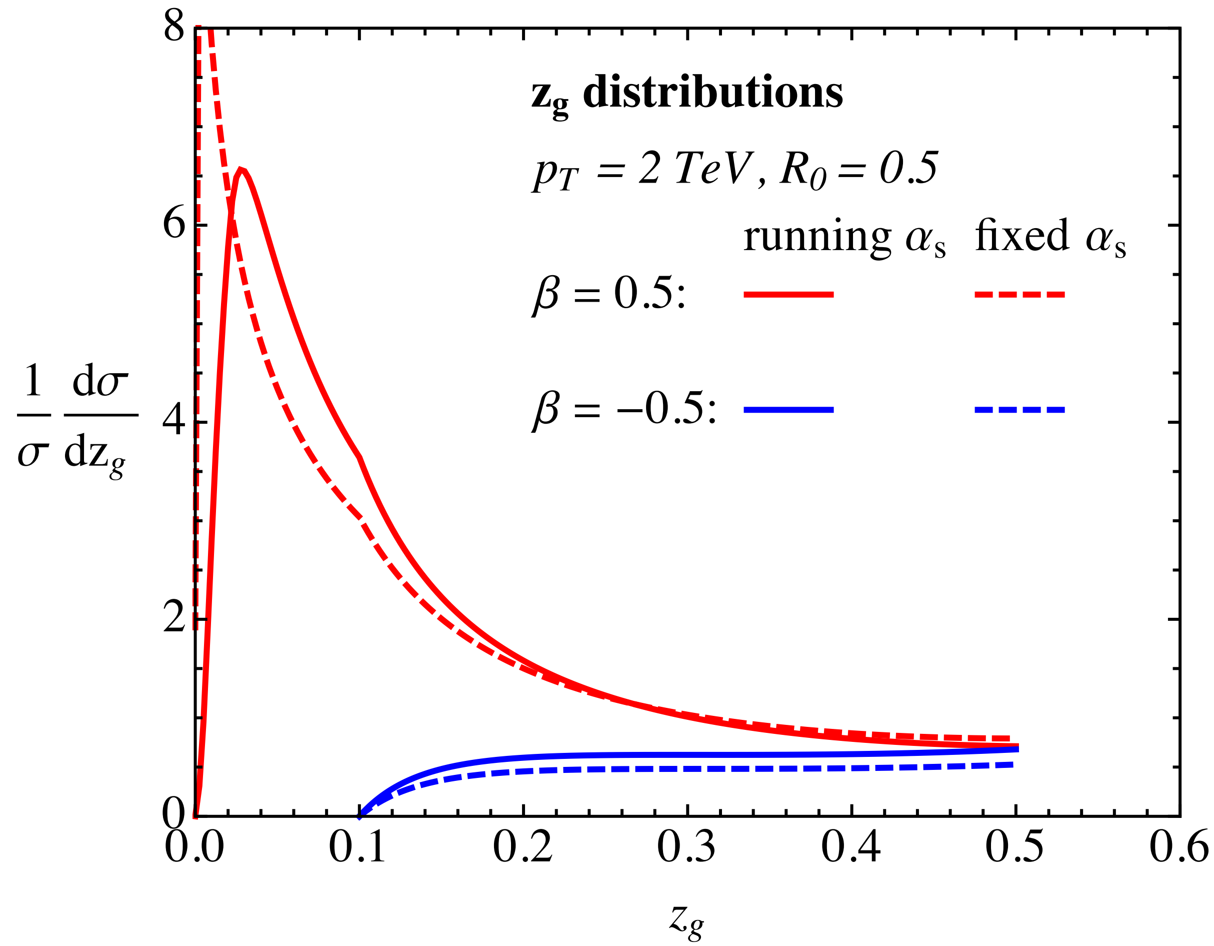


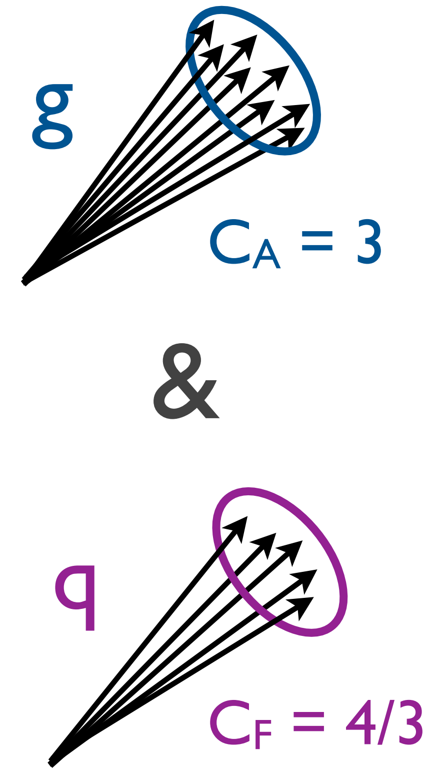
[Larkoski, Marzani, JDT, 1502.01719; using calculational techniques in Dasgupta, Fregoso, Marzani, Salam, 1307.0007; Larkoski, JDT, 1307.1699]

First-Principles QCD



$$z > z_{\text{cut}}\,\theta^{\beta}$$

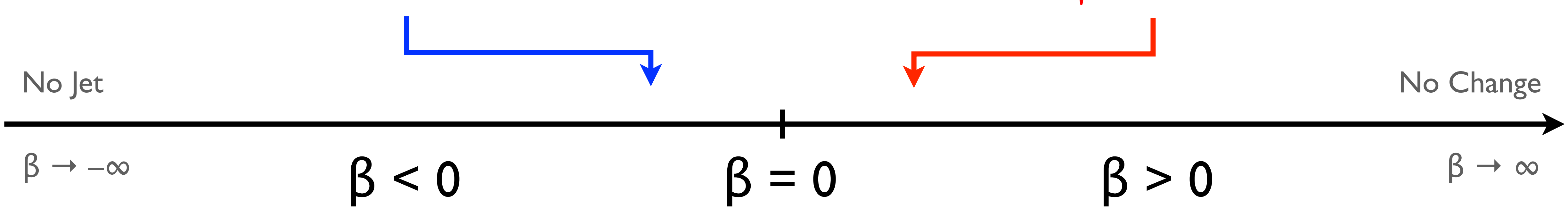




$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\,\frac{1}{z_g}\log\frac{z_g}{z_{\text{cut}}}$$

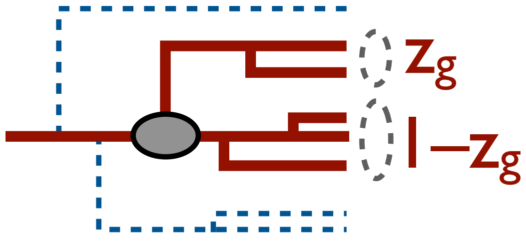
$$\simeq \sqrt{\frac{\alpha_s C_i}{\beta}}\,\frac{1}{z_g}$$

Beyond traditional perturbation theory (Sudakov safe)

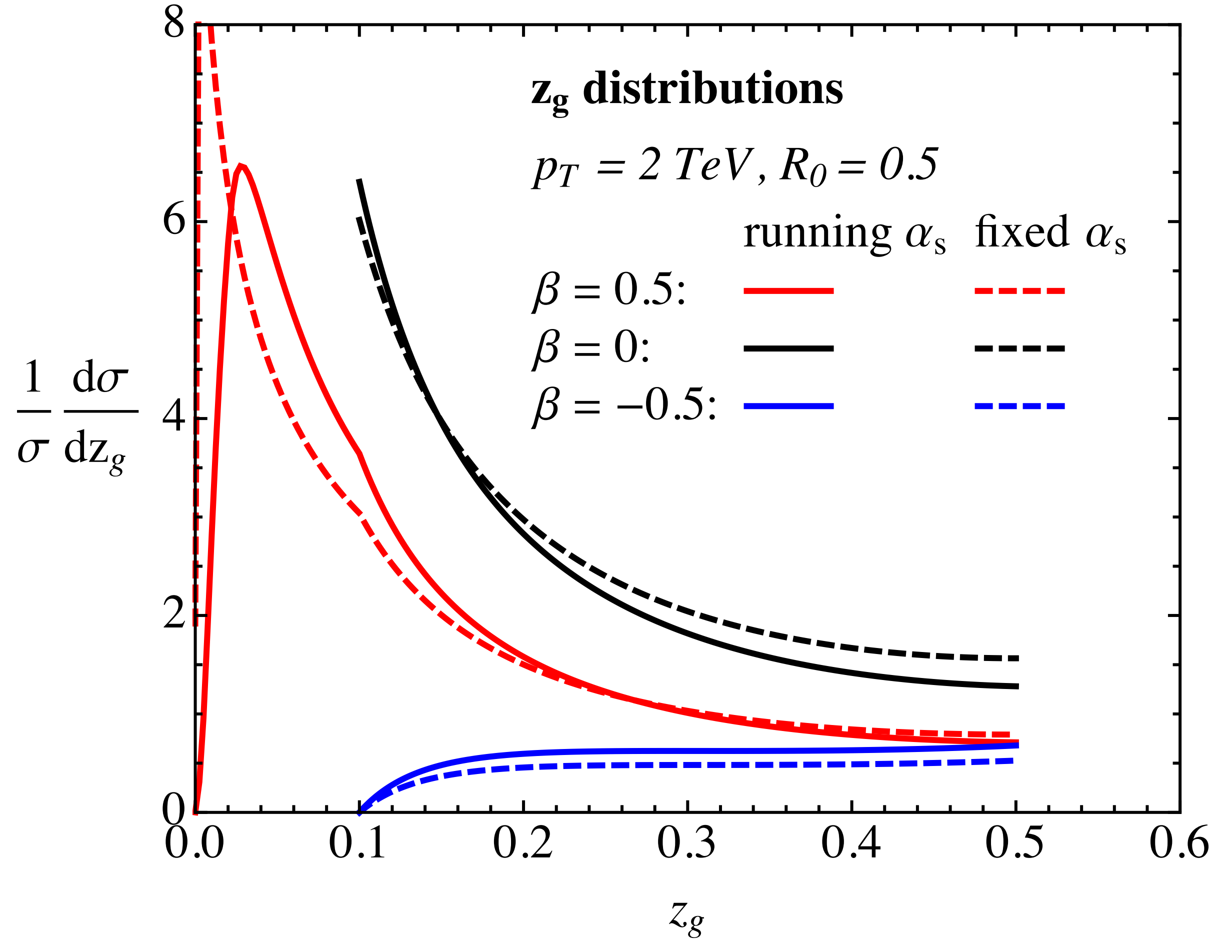


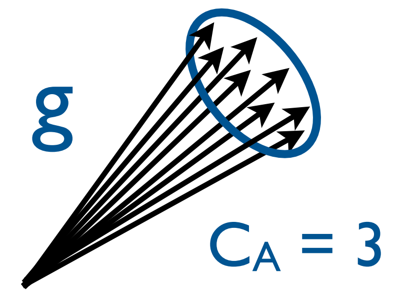
[Larkoski, Marzani, JDT, 1502.01719; using calculational techniques in Dasgupta, Fregoso, Marzani, Salam, 1307.0007; Larkoski, JDT, 1307.1699]

First-Principles QCD

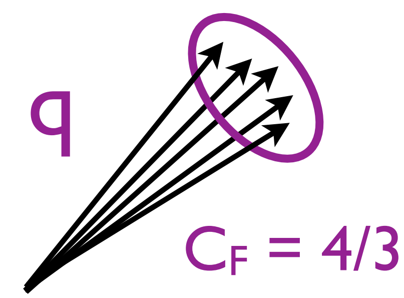


$$z > z_{\rm cut}\,\theta^{\beta}$$





&



$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\,\frac{1}{z_g}\log\frac{z_g}{z_{\rm cut}} \qquad \simeq \frac{1}{z_g}\ (!) \qquad \simeq \sqrt{\frac{\alpha_s C_i}{\beta}}\,\frac{1}{z_g}$$

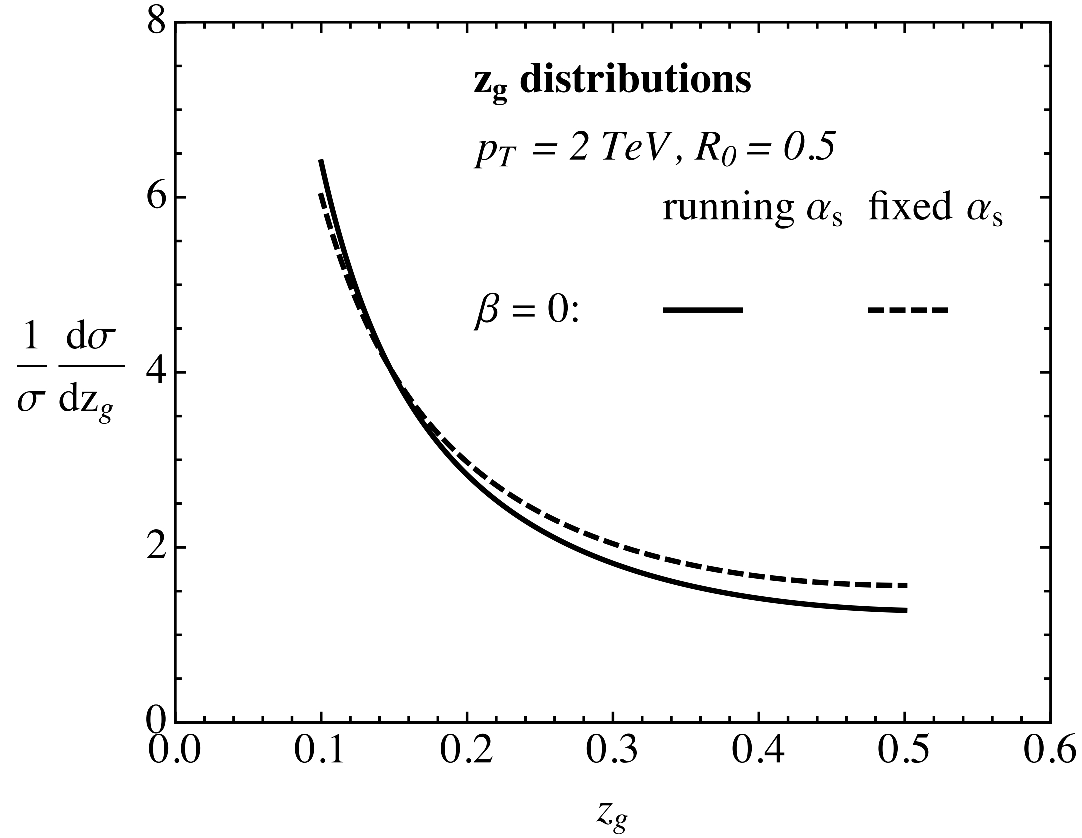
Beyond traditional perturbation theory (Sudakov safe)

No Jet — No Change

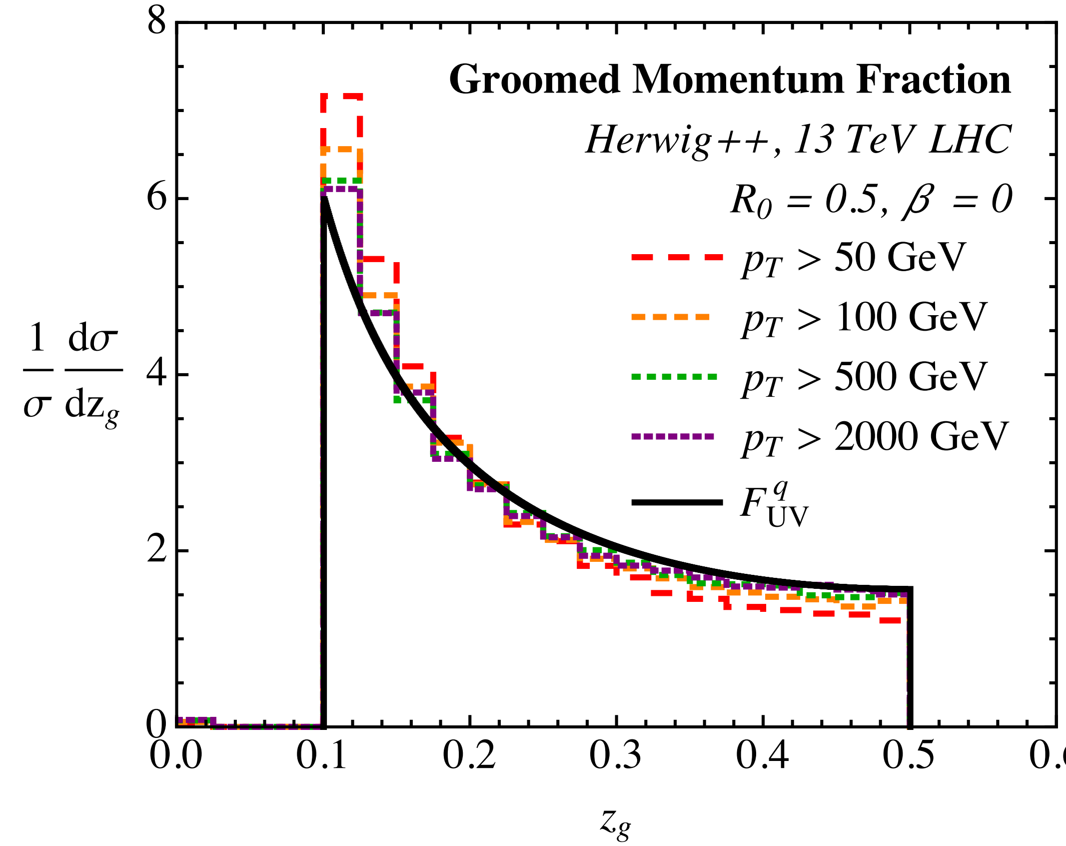
$\beta \to -\infty$ — $\beta < 0$ — $\beta = 0$ — $\beta > 0$ — $\beta \to \infty$

[Larkoski, Marzani, JDT, 1502.01719; using calculational techniques in Dasgupta, Fregoso, Marzani, Salam, 1307.0007; Larkoski, JDT, 1307.1699]

First-Principles QCD



Simulated LHC Data

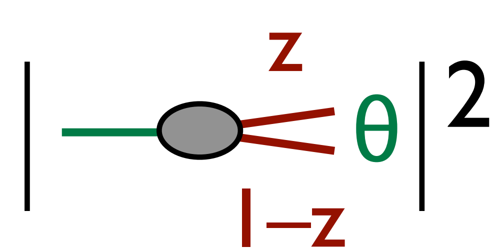


Core Feature of QCD: $\simeq \dfrac{1}{z_g}$

≈ independent of α_s (!)
≈ independent of jet energy/radius
≈ same for quarks/gluons

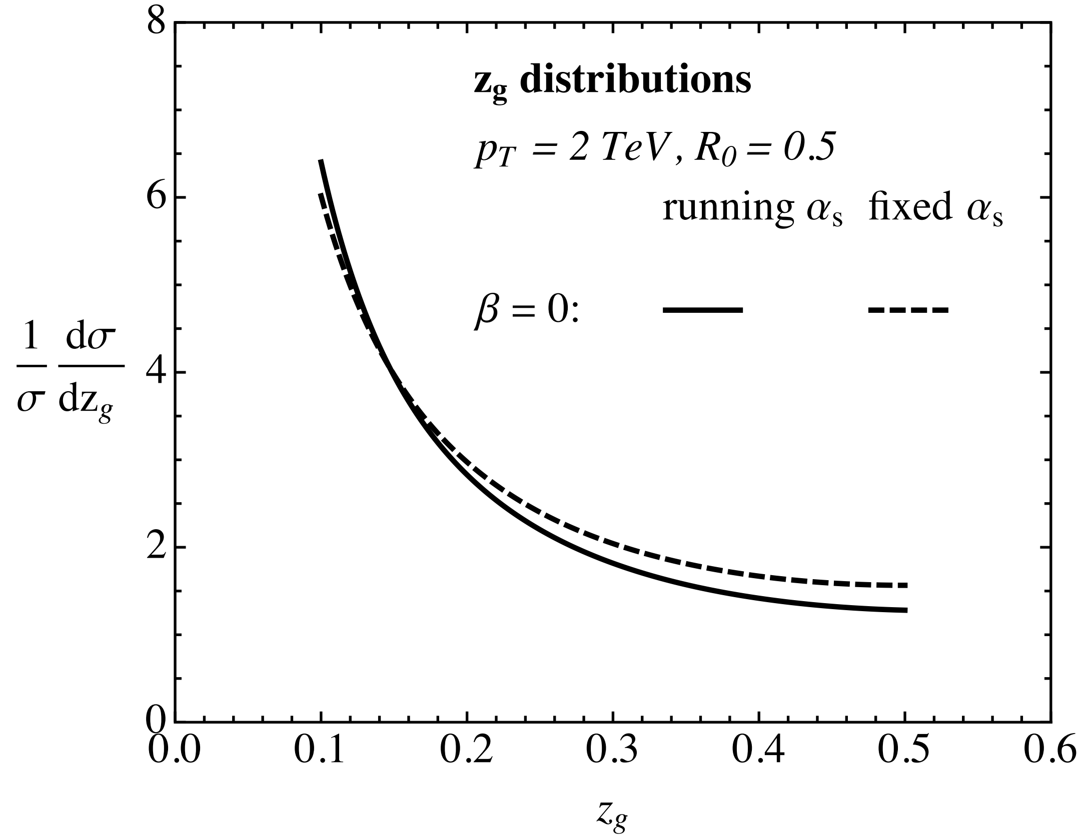
↕

$$\mathrm{d}P_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}$$

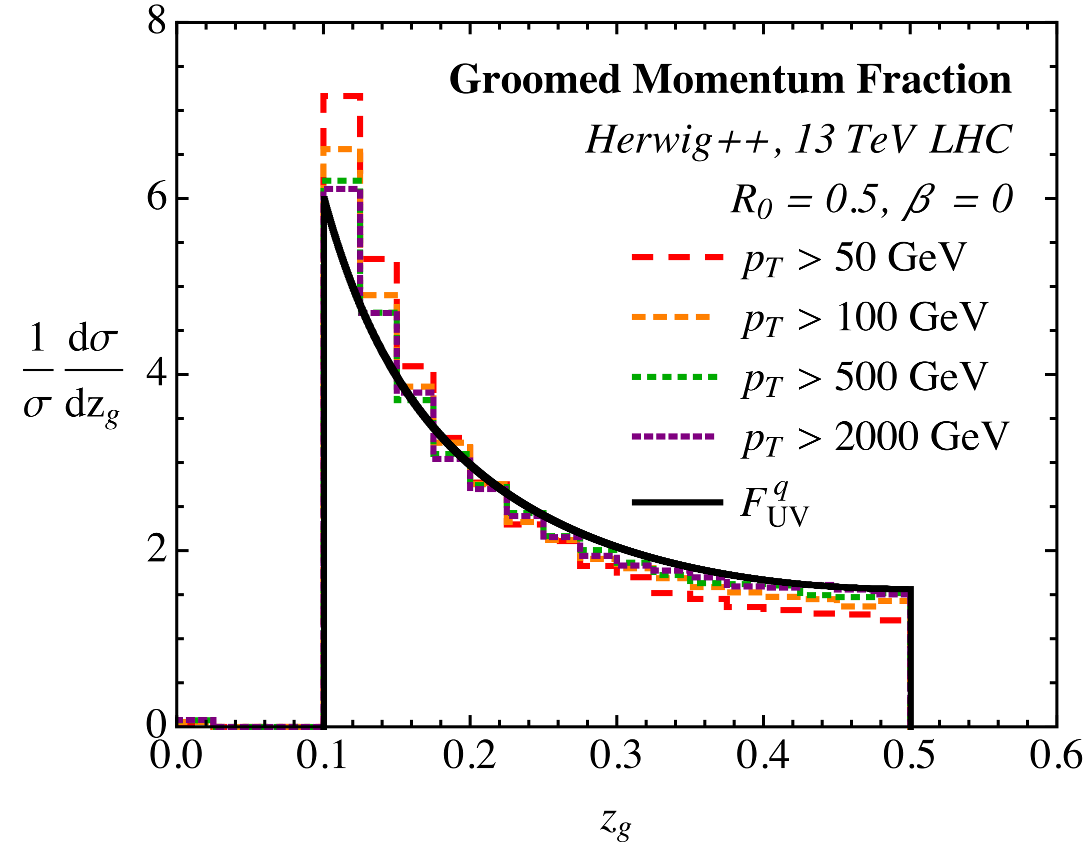
cf. 

[Larkoski, Marzani, JDT, 1502.01719; using Larkoski, JDT, 1307.1699]

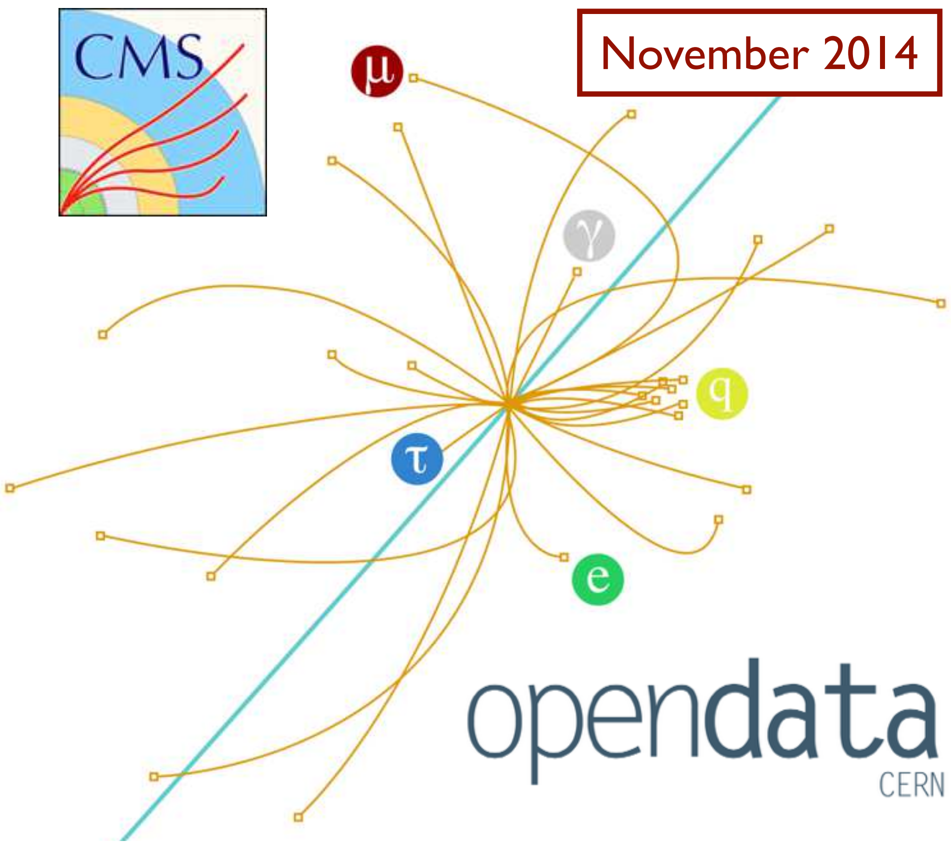
First-Principles QCD



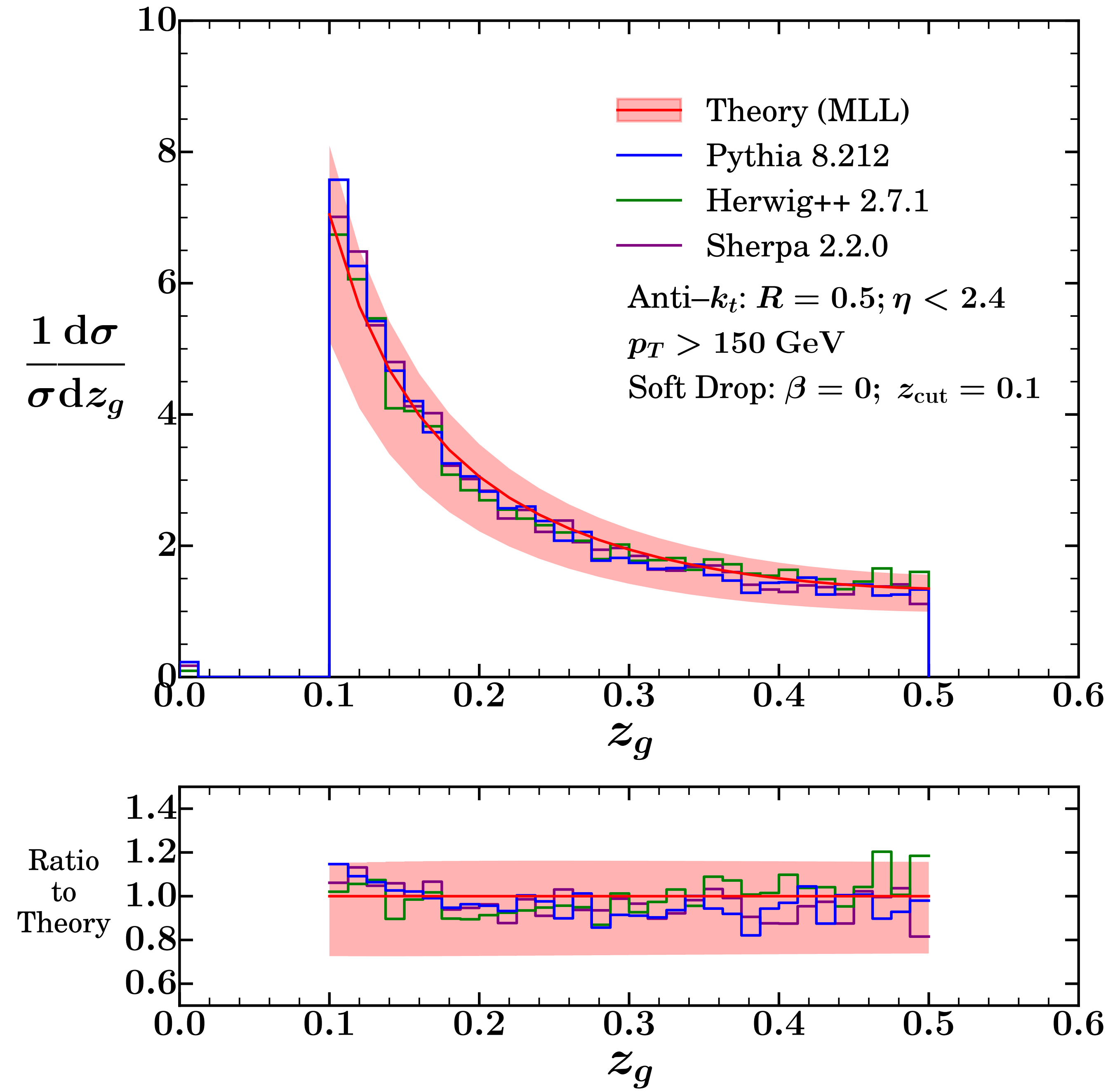
Simulated LHC Data



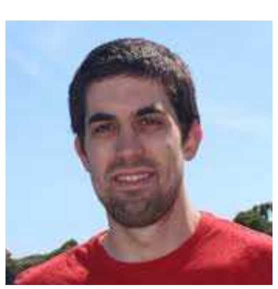
Actual
LHC Data?



CMS 2010:
Unique, low pileup data set



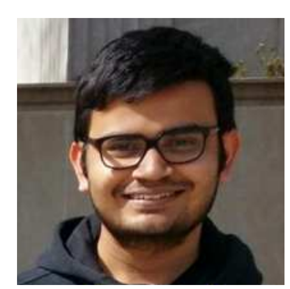
Andrew Larkoski



Simone Marzani

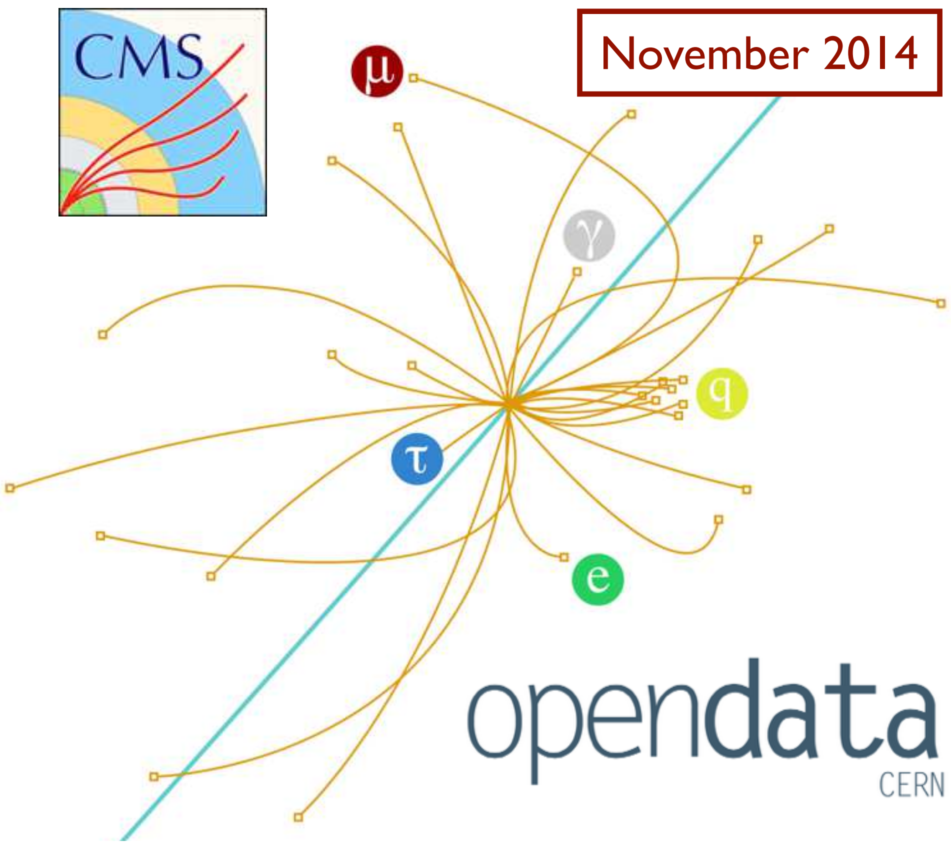
Alexis Romero

Aashish Tripathee

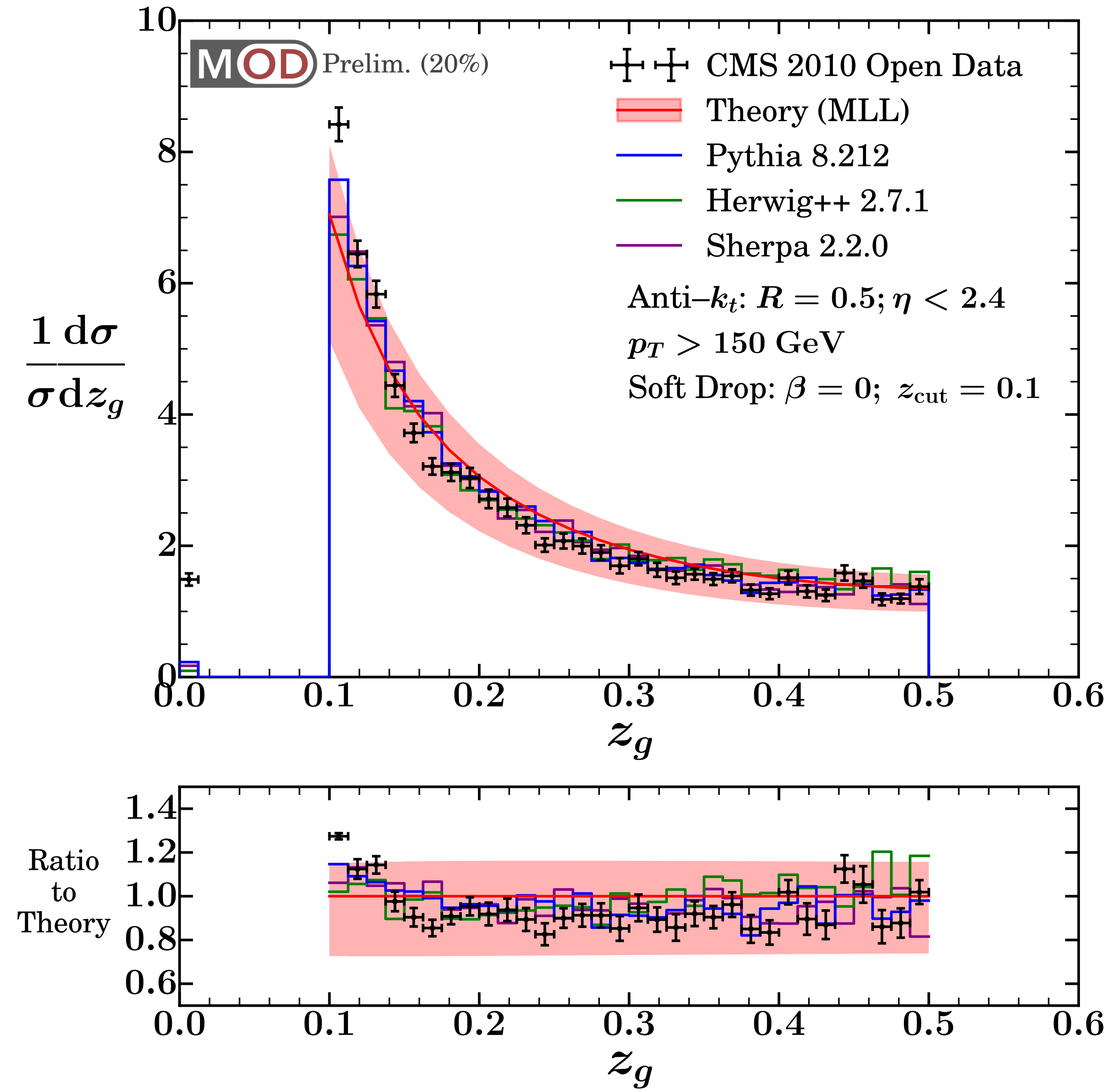


Wei Xue

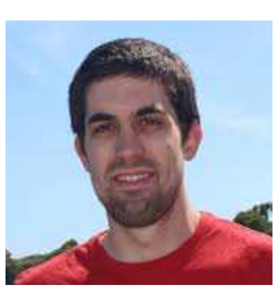
CMS advice from Sal Rappoccio



CMS 2010:
Unique, low pileup data set



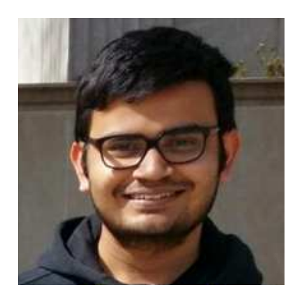
Andrew Larkoski



Simone Marzani

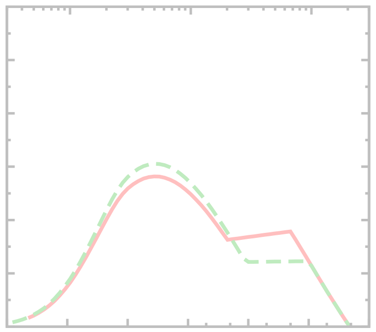
Alexis Romero

Aashish Tripathee

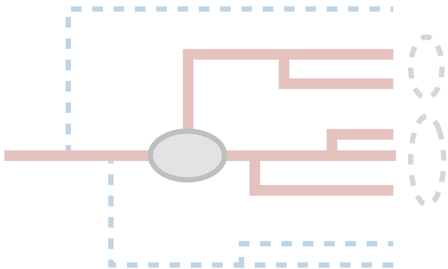


Wei Xue

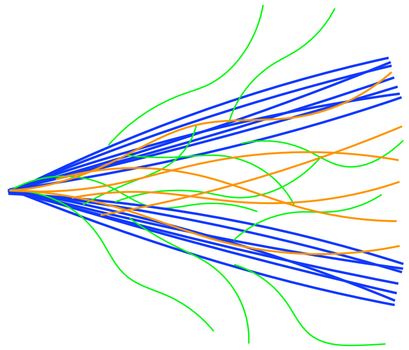
CMS advice from Sal Rappoccio



Substructure from First Principles

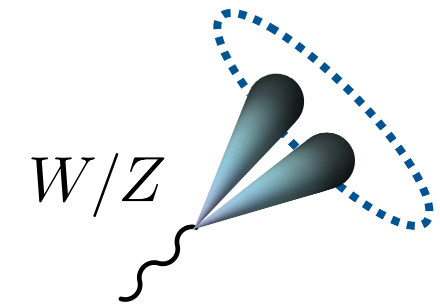


z_g: Testing the Foundations of QCD



D_2: The Power of Power Counting

D_2: Test for 2-Prong Substructure



Energy correlation functions:

$$e_2^{(\beta)} = \sum_{i<j} z_i \, z_j \, (R_{ij})^\beta$$

$$e_3^{(\beta)} = \sum_{i<j<k} z_i \, z_j \, z_k \, (R_{ij} R_{jk} R_{ki})^\beta$$

[Larkoski, Salam, JDT, 1305.0007; see also Banfi, Salam, Zanderighi, hep-ph/0407286; Jankowiak, Larkoski, 1104.1646]

momentum fraction $z = p_T / p_{T\text{jet}}$

pair-wise angles

adjustable exponent ATLAS: β=1

Discriminants:

$X_2 \to 0$ for exactly 2-prong

$$C_2 = \frac{e_3}{(e_2)^2}$$

Natural choice?

(same number of z's in numerator/denominator)

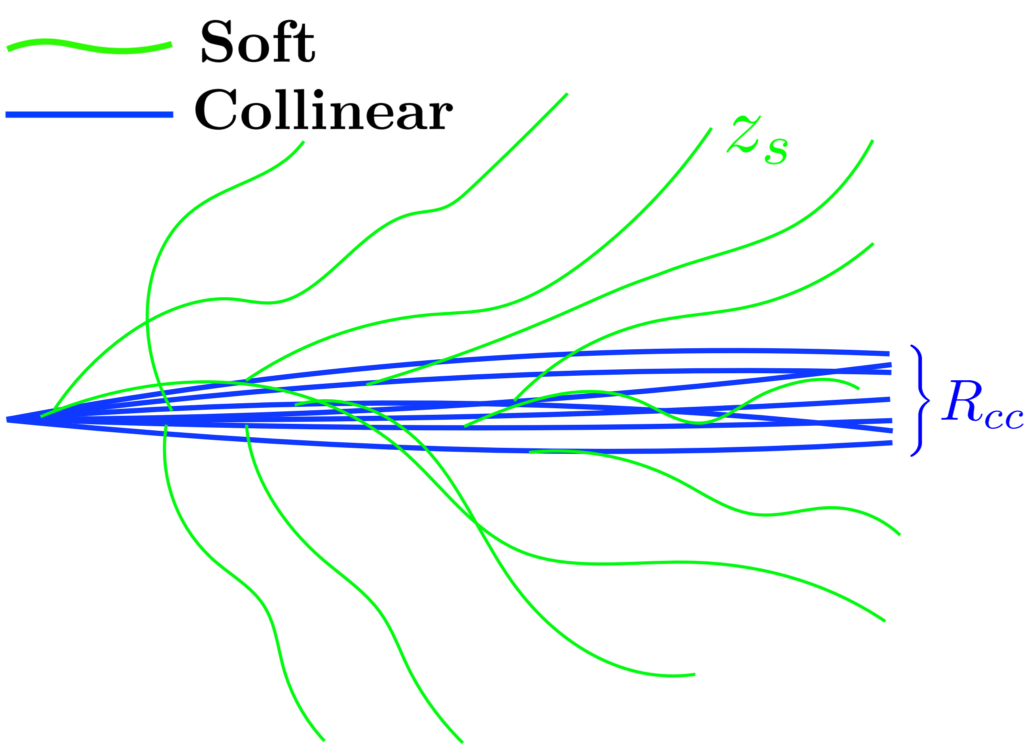
$$D_2 = \frac{e_3}{(e_2)^3}$$

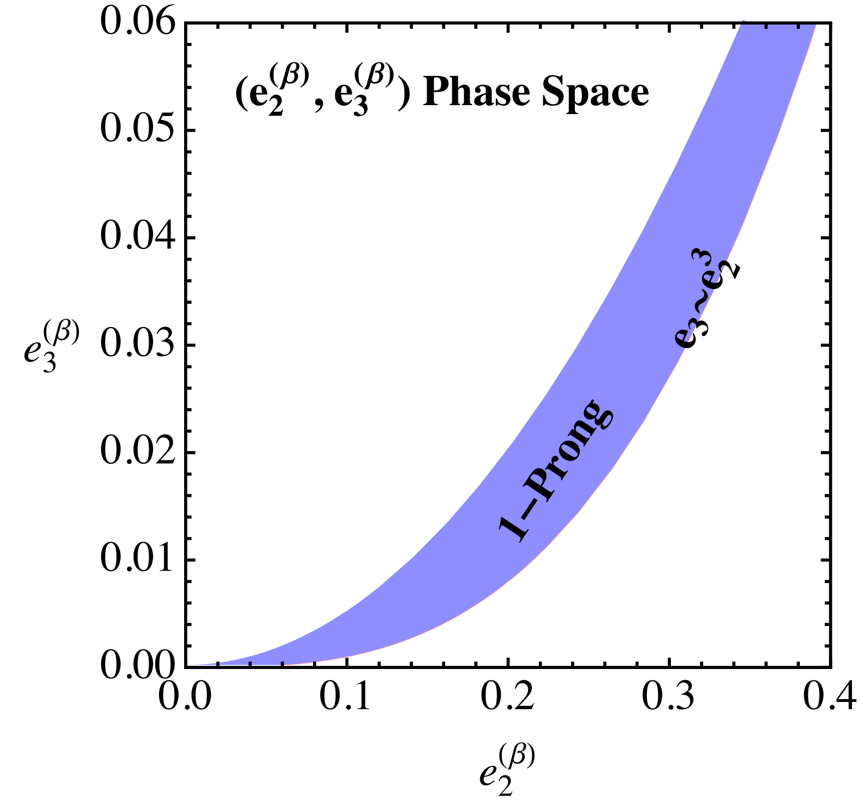
key!

Provably best choice!

[Larkoski, Moult, Neill, 1409.6298]

Power Counting: 1-prong Background



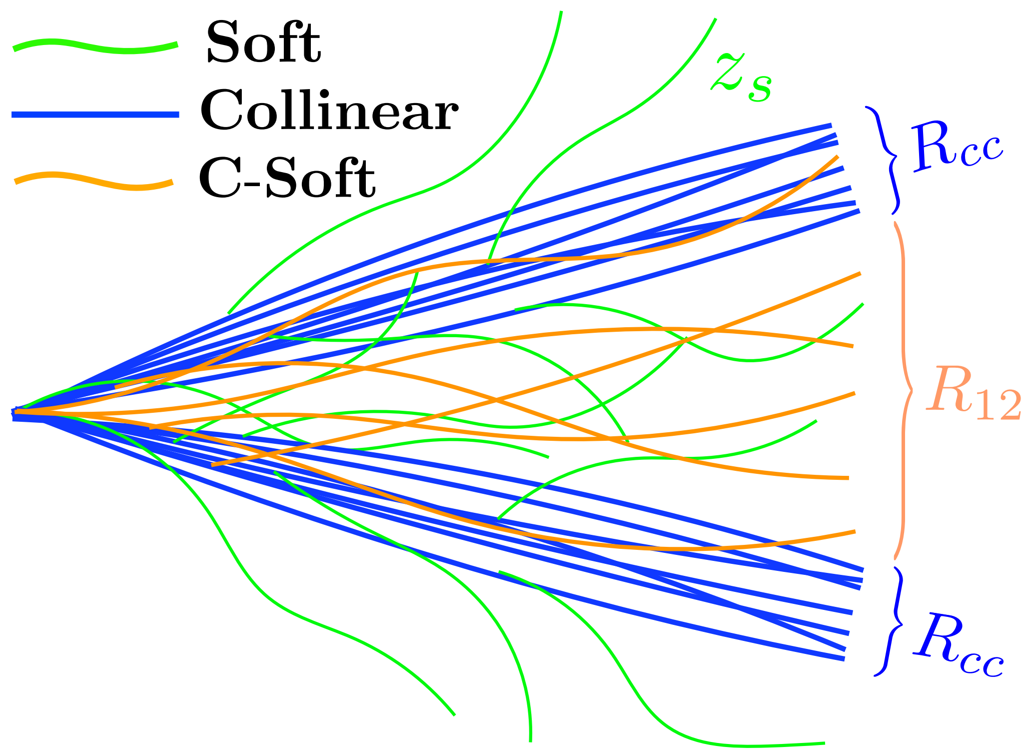


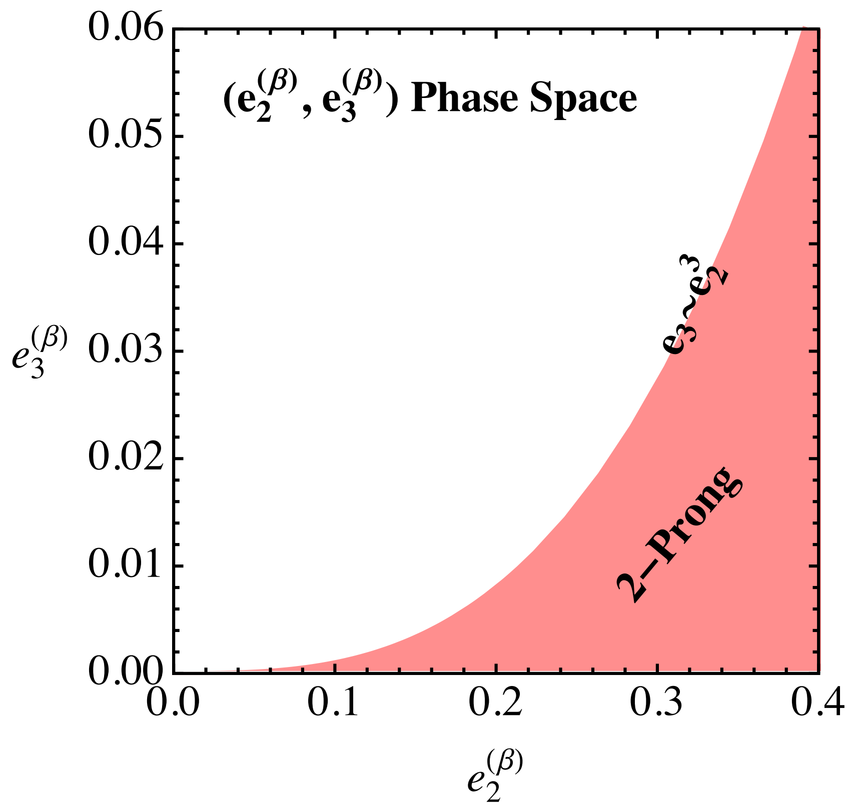
	C	S
$z_i \simeq$	1	z_s
	CC	SX
$R_{ij} \simeq$	R_{cc}	1

	CC		CS		
$e_2 \simeq$	R_{cc}	$+$	z_s		
	CCC		CCS		CSS
$e_3 \simeq$	R_{cc}^3	$+$	$R_{cc} z_s$	$+$	z_s^2

[Larkoski, Moult, Neill, 1409.6298, 1507.03018]

Power Counting: 2-prong Signal





	C	Cs	S
$z_i \simeq$	1	z_{cs}	z_s
	CC	C₁C₂ or CCs	SX
$R_{ij} \simeq$	R_{cc}	R_{12}	1

C₁C₂

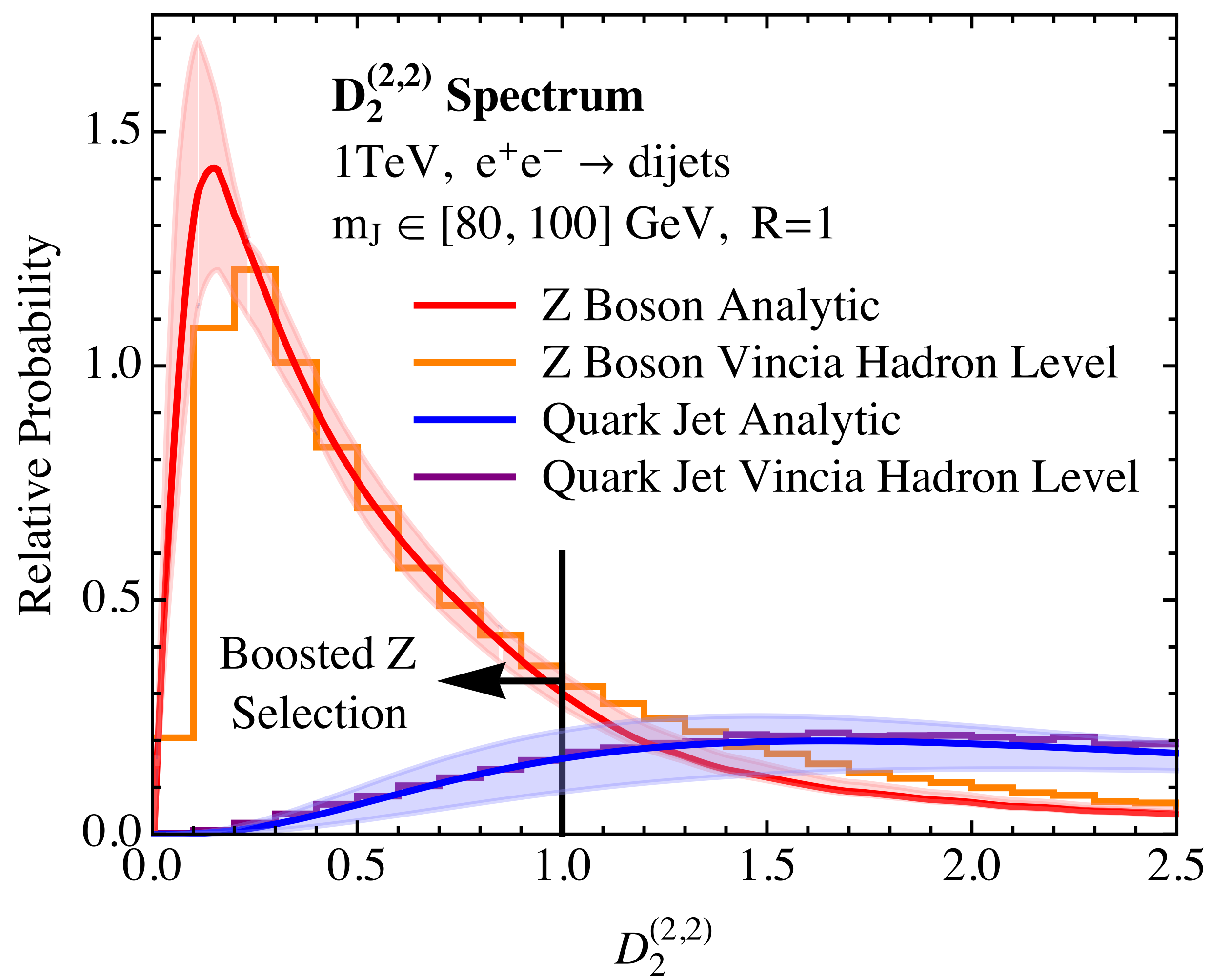
$$e_2 \simeq R_{12}$$

C₁C₂S, C₁C₂C, C₁C₂Cs

$$e_3 \simeq R_{12} z_s + R_{12}^2 R_{cc} + R_{12}^3 z_{cs}$$

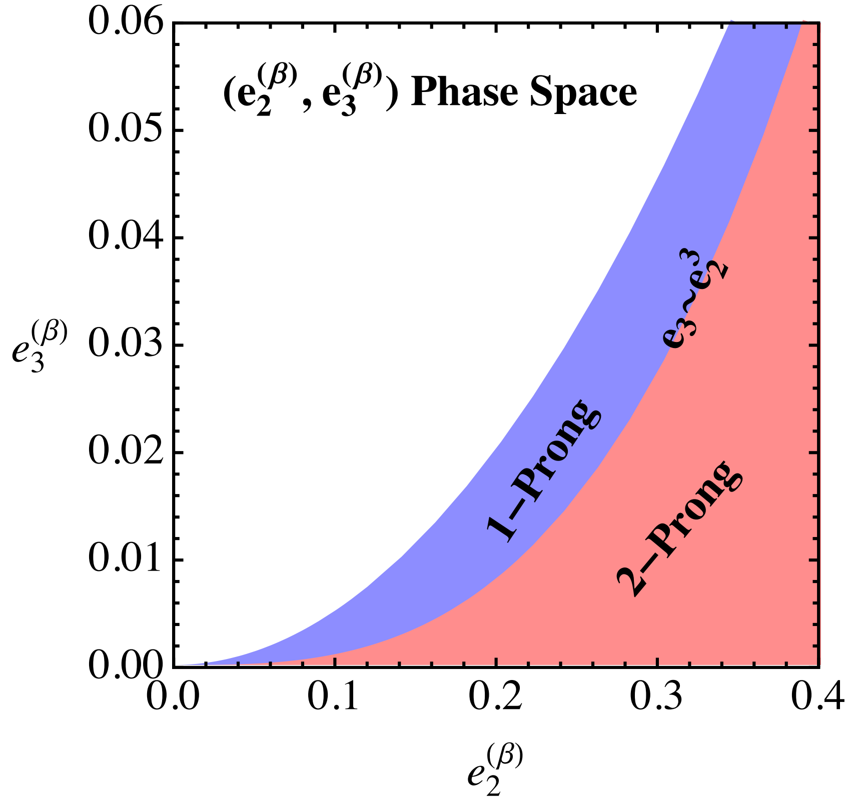
[Larkoski, Moult, Neill, 1409.6298, 1507.03018; collinear-soft modes also appear in Bauer, Tackmann, Walsh, Zuberi, 1106.6047; Procura, Waalewijn, Zeune, 1410.6483; Larkoski, Moult, Neill, 1501.04596; Becher, Neubert, Rothen, Shao, 1508.06645; Chien, Hornig, Lee, 1509.04287]

Optimal 2-prong Discriminant: $D_2 = \frac{e_3}{(e_2)^3}$



Novel QCD calculation based on
merging two SCET factorization theorems (!)
and projecting triple-differential cross section (!)

(n.b. e^+e^- calculation with $\beta = 2$)

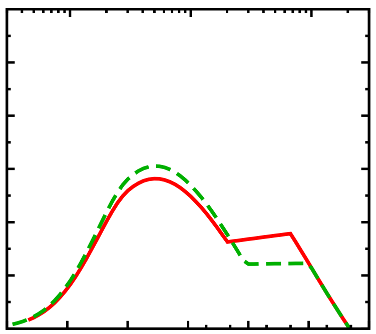


Unlike C_2, clean separation of 1-prong from 2-prong

Basis for ATLAS "R2 D_2" tagger

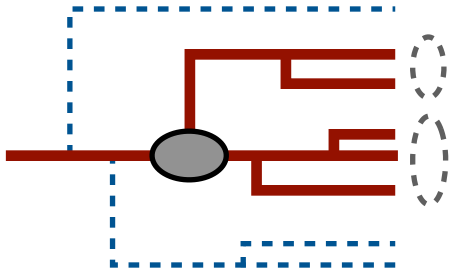
[Larkoski, Moult, Neill, 1409.6298,1507.03018]

Summary



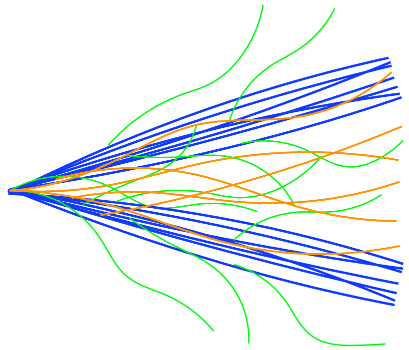
Substructure from First Principles

From tests in simulated data to calculations in QCD
Growing catalog of observables, growing toolbox of approaches



z_g: Testing the Foundations of QCD

Simple observable requires new calculational technique (Sudakov safety)
The future? Idea → simulation → calculation → open data analysis

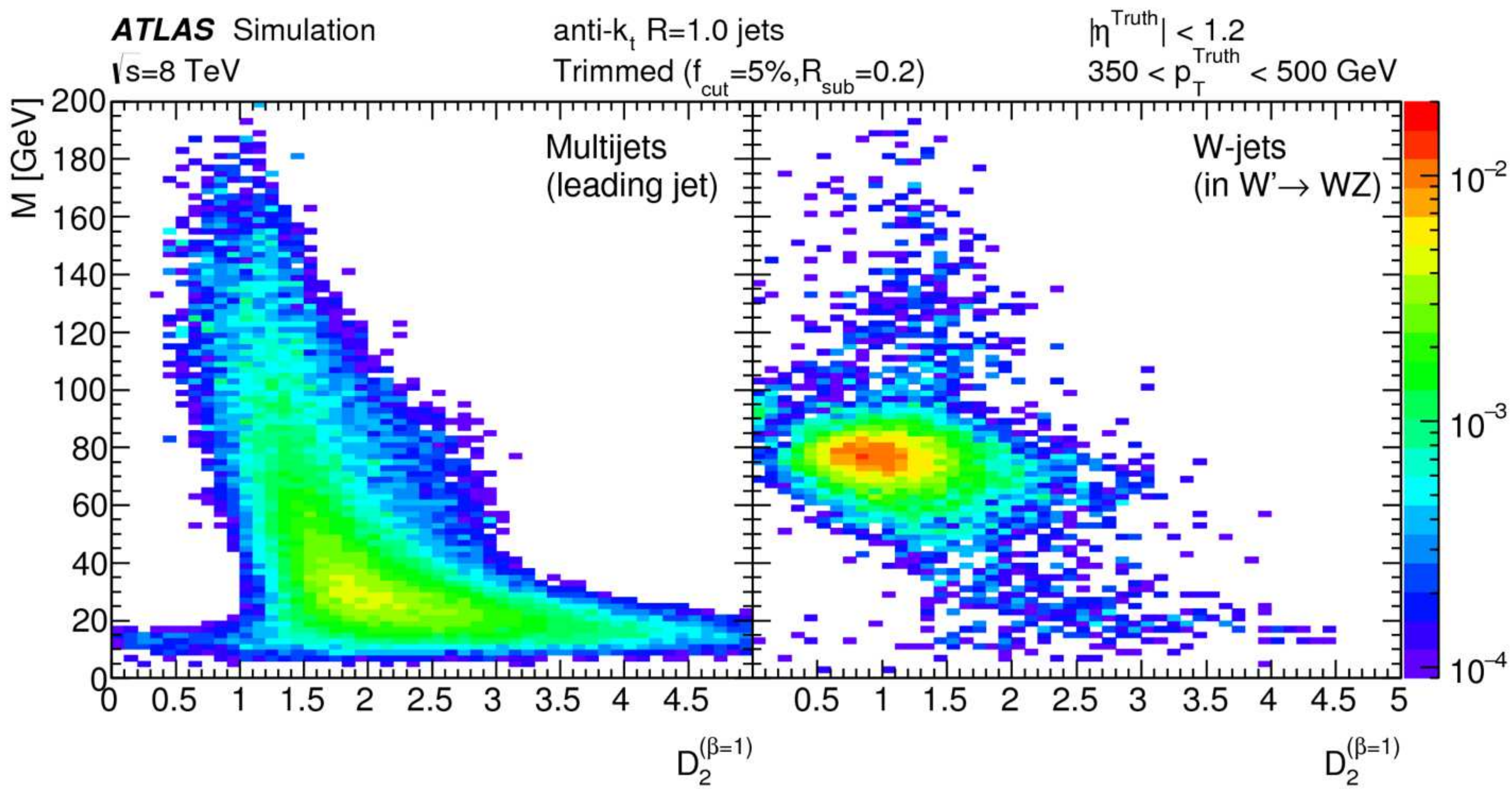


D_2: The Power of Power Counting

Theoretical insights yield powerful new 2-prong discriminant

More About R2 D_2

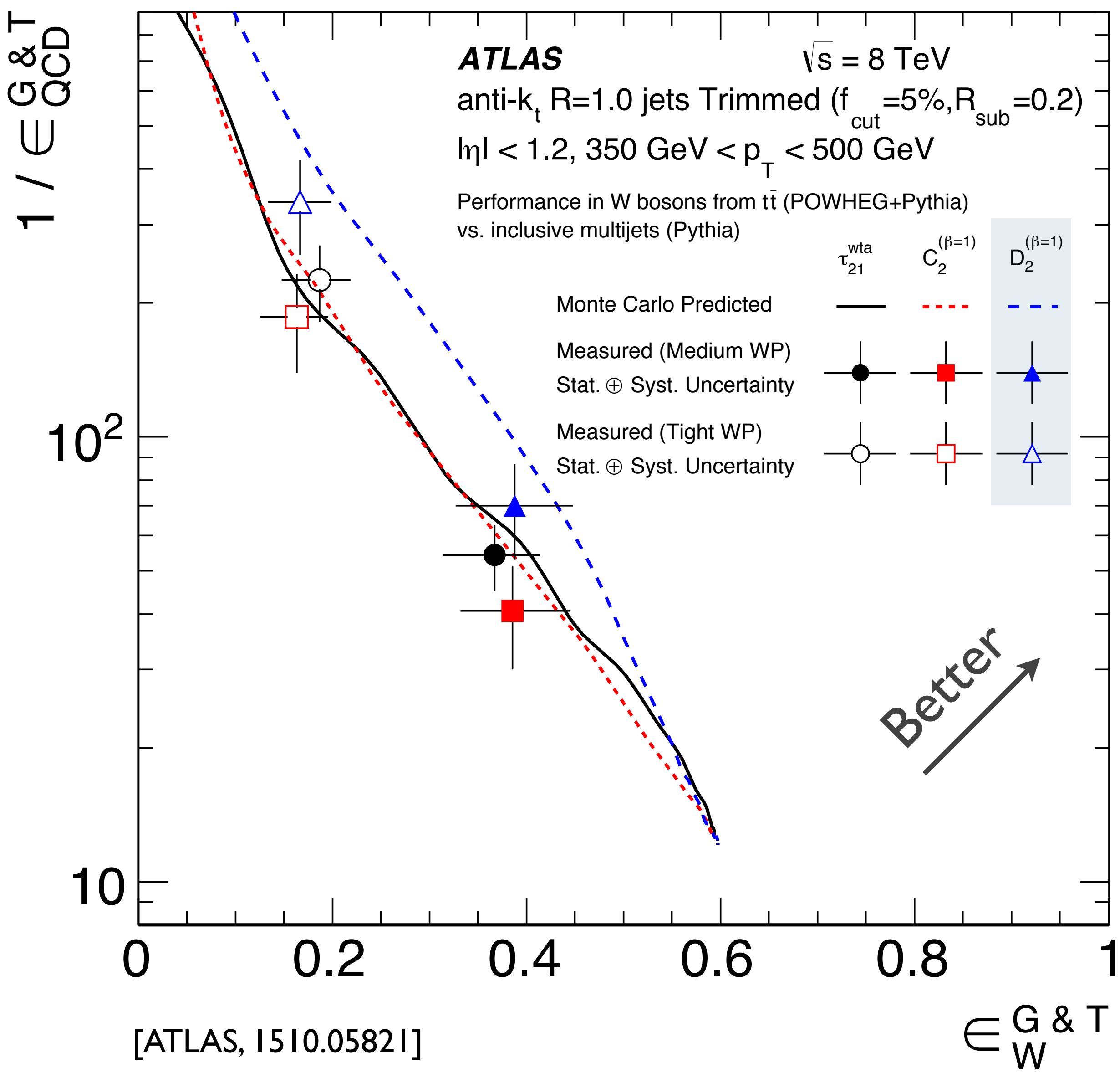
ATLAS 13 TeV Baseline: "R2 D_2"



R_{sub} = 0.2 trimming with D_2 tagging

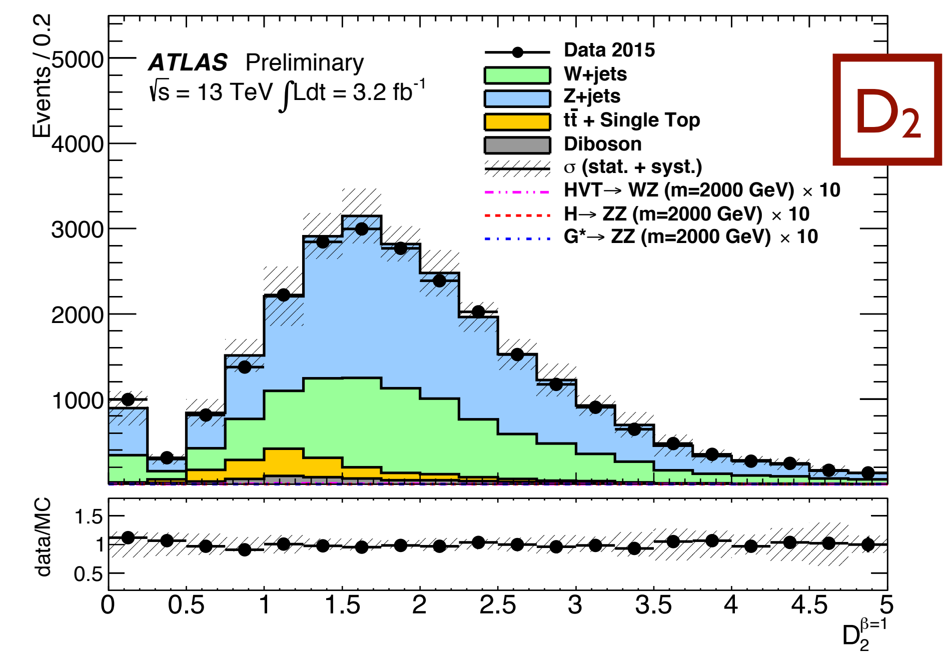
[ATLAS, 1510.05821]

ATLAS 13 TeV Baseline: “R2 D_2”



[ATLAS, 1510.05821]

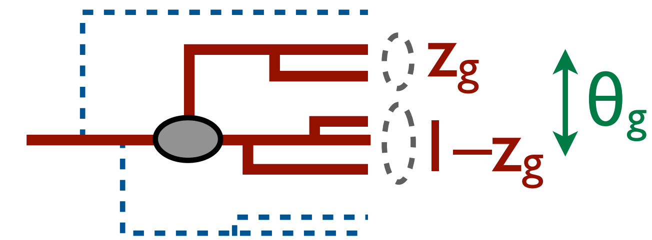
First 13 TeV results



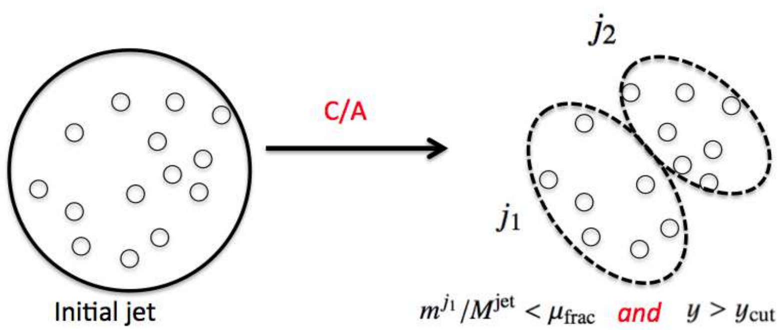
[ATLAS-CONF-2015-068, -071, -075, -080]

More About Sudakov Safety

Calculating Groomed Jet Mass



Mass Drop



[Butterworth, Davison, Rubin, Salam, 0802.2470]

Soft Drop

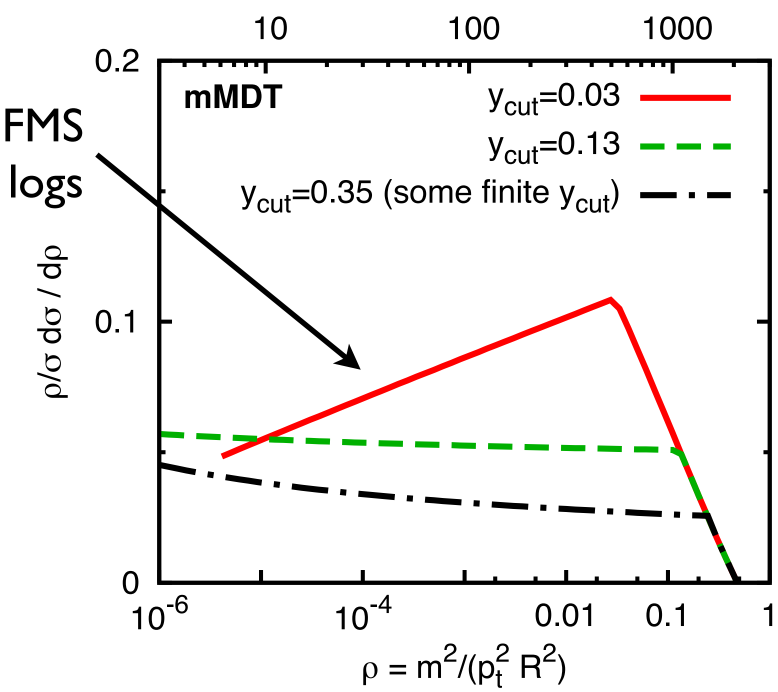
$$z > z_{\text{cut}}\, \theta^{\beta}$$

More Grooming — ≈ Mass Drop — Less Grooming

$\beta < 0$ — $\beta = 0$ — $\beta > 0$

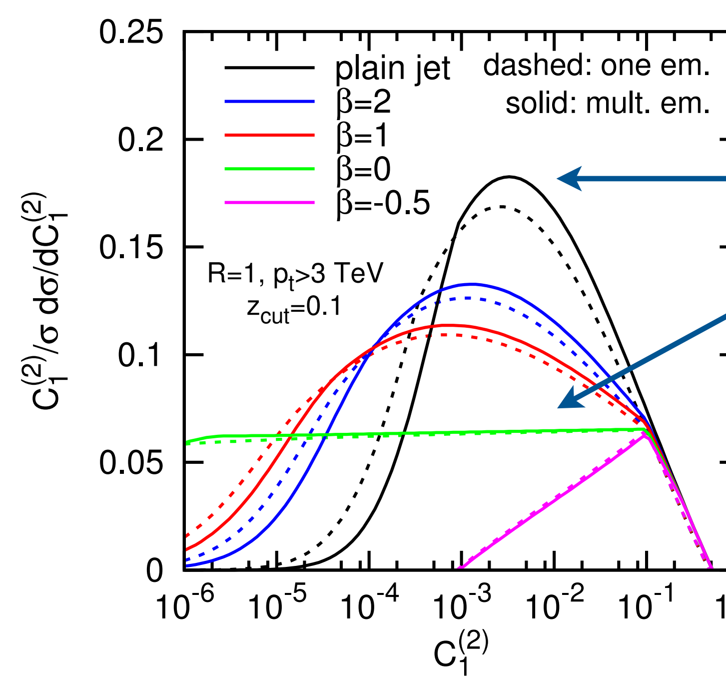
Mass-Dropped Jet Mass

DFMS single logs



[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Soft-Dropped Jet Mass



From double logs to single logs

[Larkoski, Marzani, Soyez, JDT, 1402.2657]

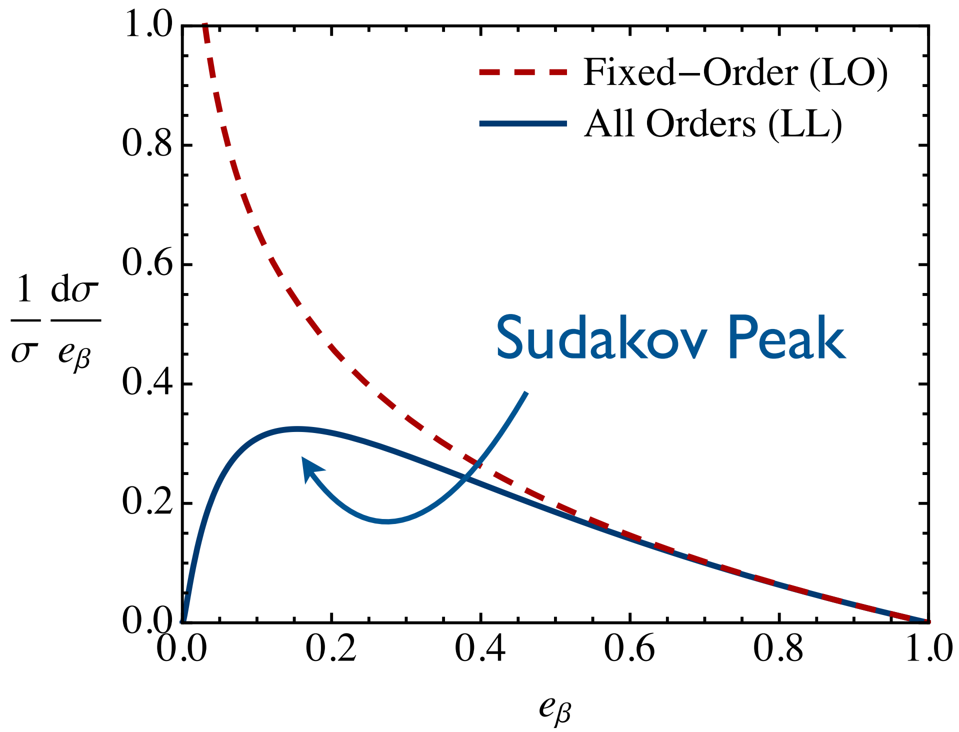
1. Use Sudakov Form Factors

Measure jet mass? | Jet mass never zero!

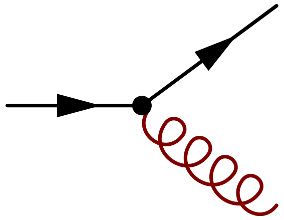
z_g — IR Safe, C Unsafe

$z_g^{\,m>0}$ — IRC Safe $\Rightarrow$ z_g — Sudakov Safe

Jet mass distribution



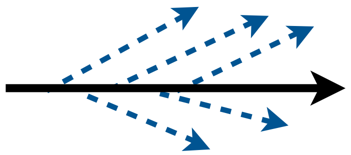
Fixed $O(\alpha_s)$



m=0 singular

vs.

All α_s Orders (resummed logs)



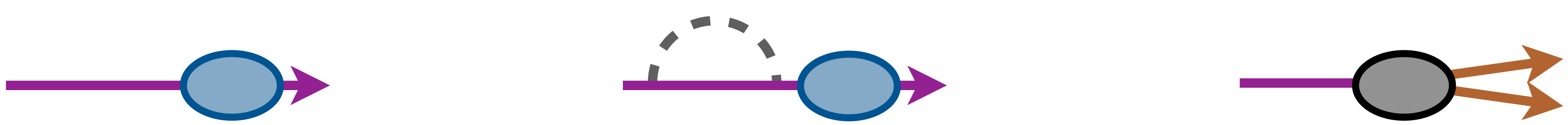
m=0 suppressed

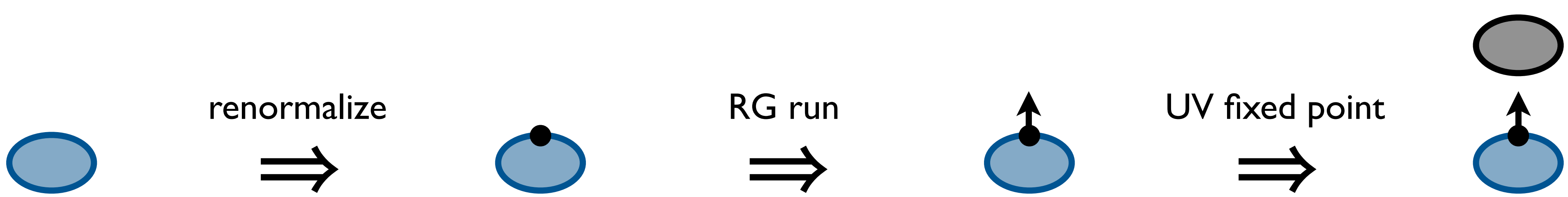
[Larkoski, JDT, 1307.1699; Larkoski, Marzani, JDT, 1502.01719]

2. Use Fragmentation Functions

$\mathbf{z_g}$ — IR Safe, C Unsafe ← Absorb singularities into universal function (just like PDFs!)

$$\frac{d\sigma}{dz_g} \simeq F(z_g) - \frac{1}{2\epsilon}\frac{\alpha_s C}{\pi}F(z_g) + \frac{\alpha_s C}{\pi}\int \frac{d\theta}{\theta}P(z_g)$$

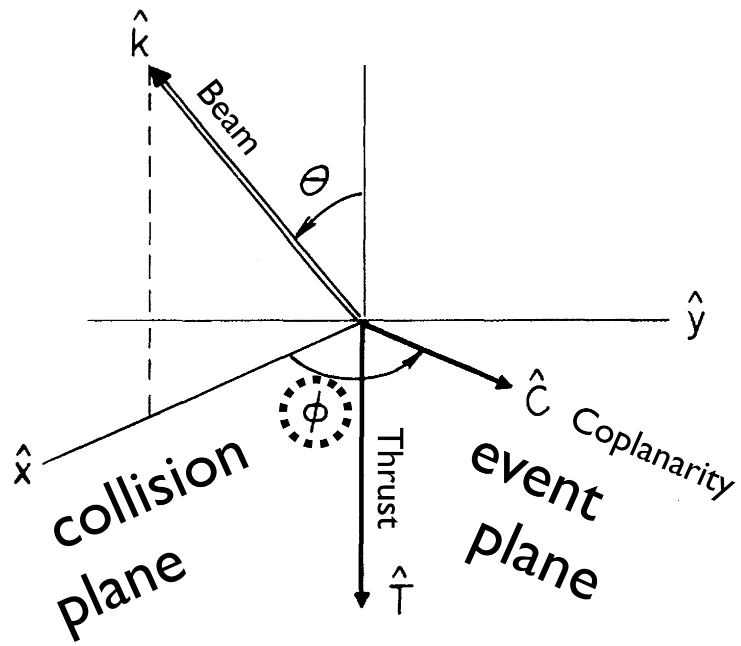


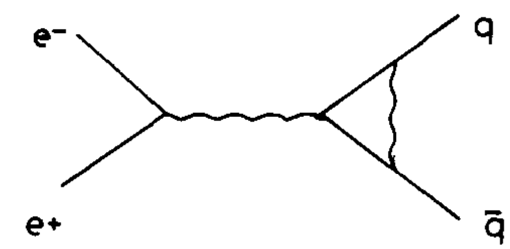


$F(z_g) \Rightarrow F(z_g;\mu) \Rightarrow d/d\mu \Rightarrow P(z_g)$

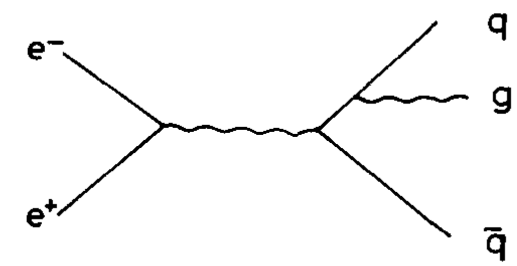
[Larkoski, Marzani, JDT, 1502.01719]

3. Learn from Our Elders





φ ambiguous



φ well-defined

Me: “φ is IRC unsafe”

My Elder: “We explicitly calculated dσ/dφ in 1978”

$$\frac{2\pi}{\sigma_0}\frac{d\sigma}{d\varphi} = 1 + O(\alpha_s(Q^2)) + \frac{\alpha_s(Q^2)}{\pi}\left(\frac{16}{3}\ln\frac{3}{2} - 2\right)\cos 2\varphi$$

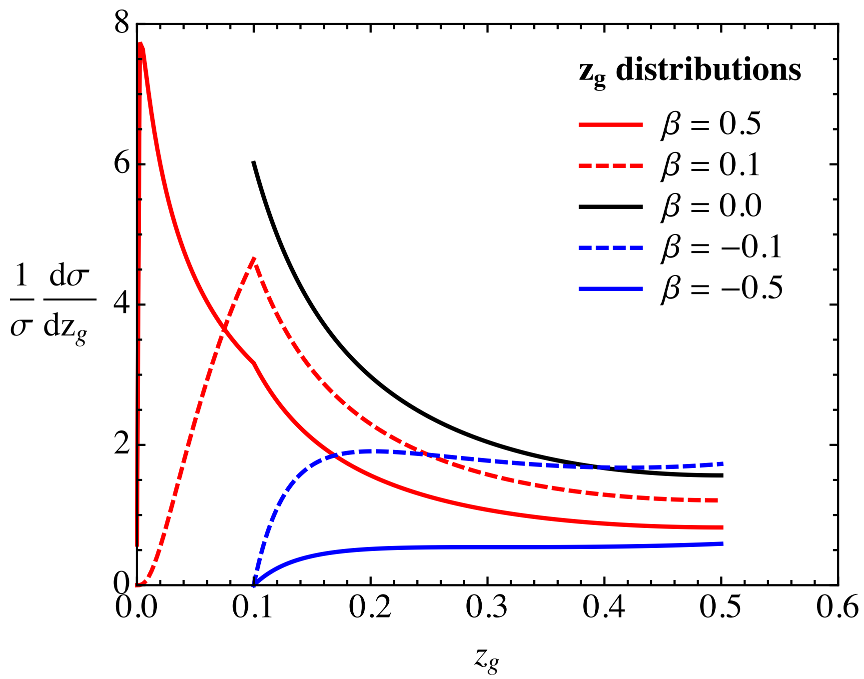
Born cross section despite ambiguity (!)

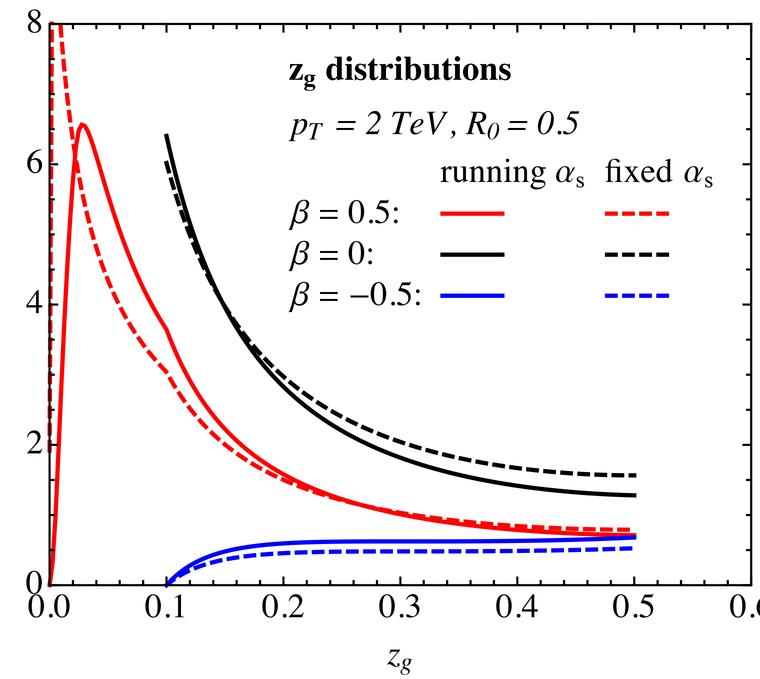
Lesson: Use IRC limit to resolve ambiguities

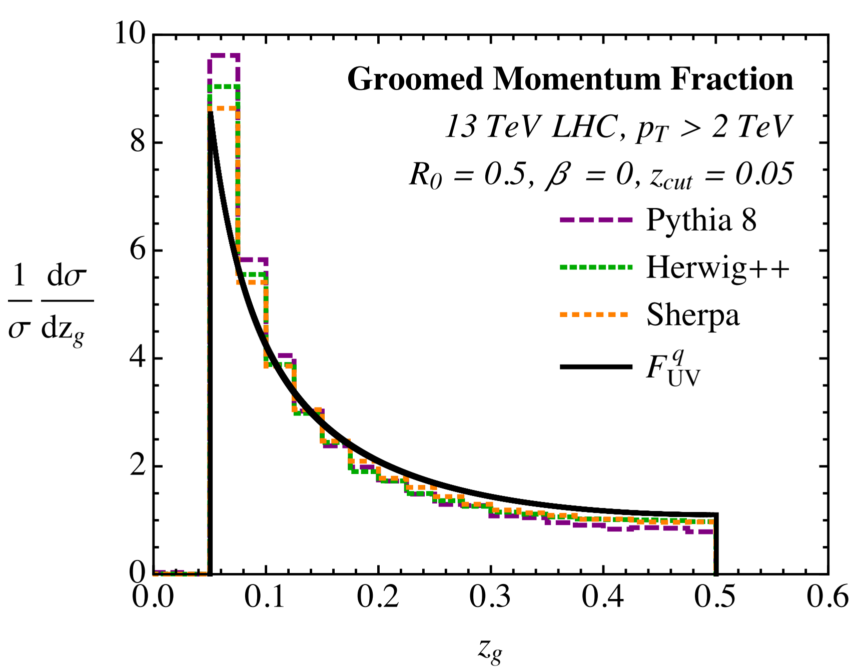
[Pi, Jaffe, Low, 1978; Kramer, Schierholz, Willrodt, 1978]

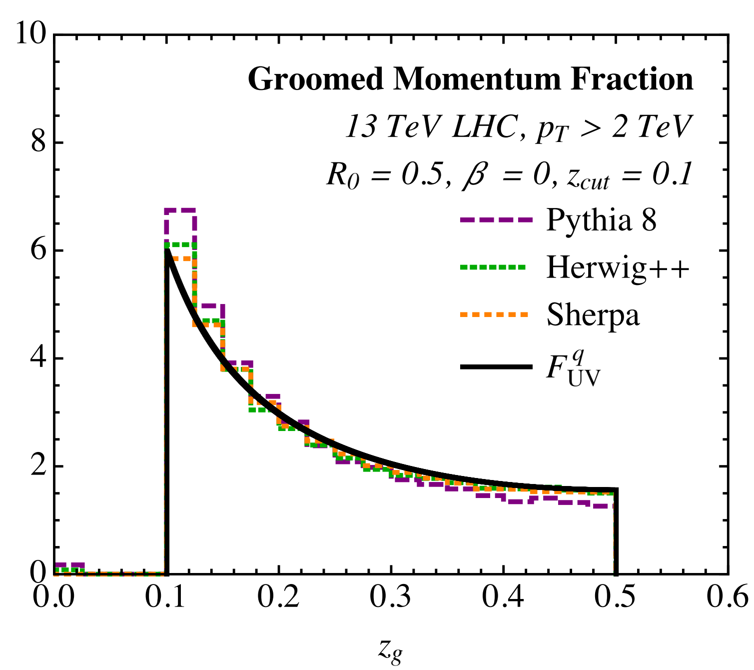
More About Open Data

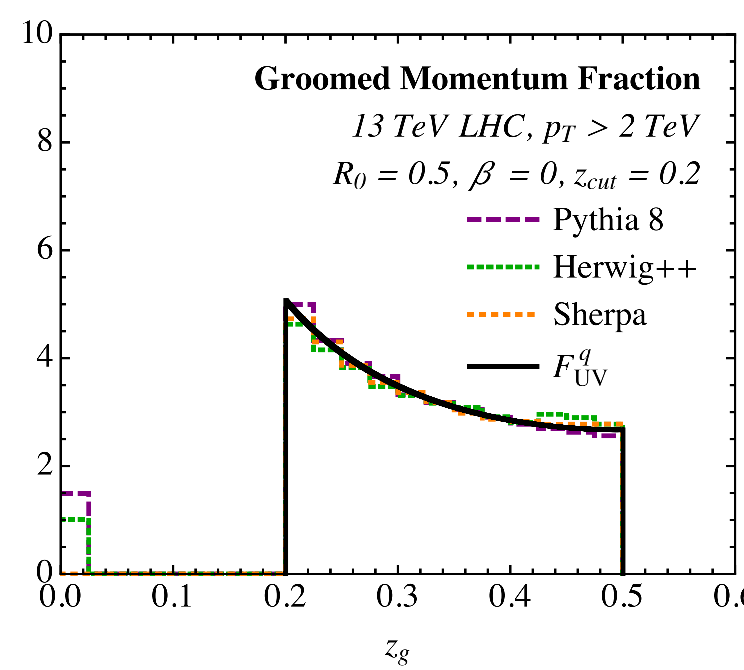
Additional z_g Theory Plots





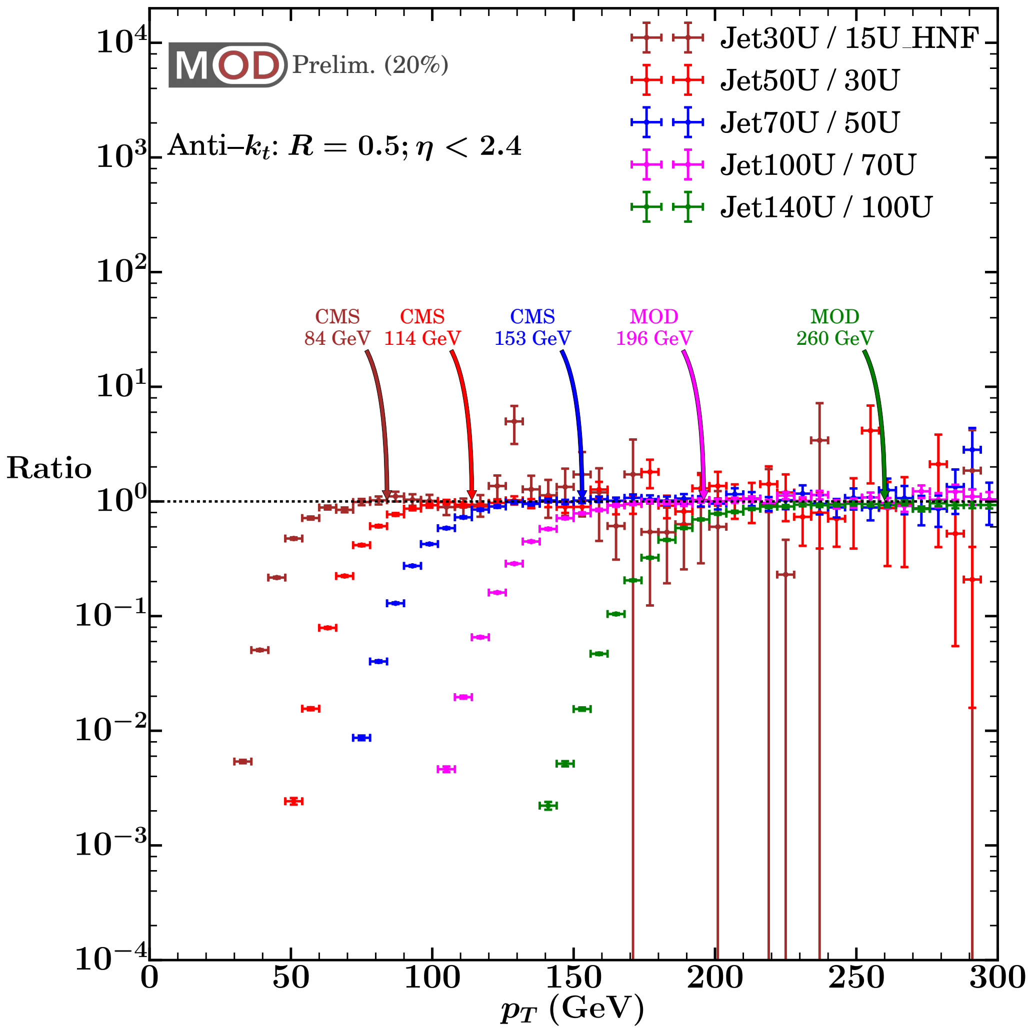


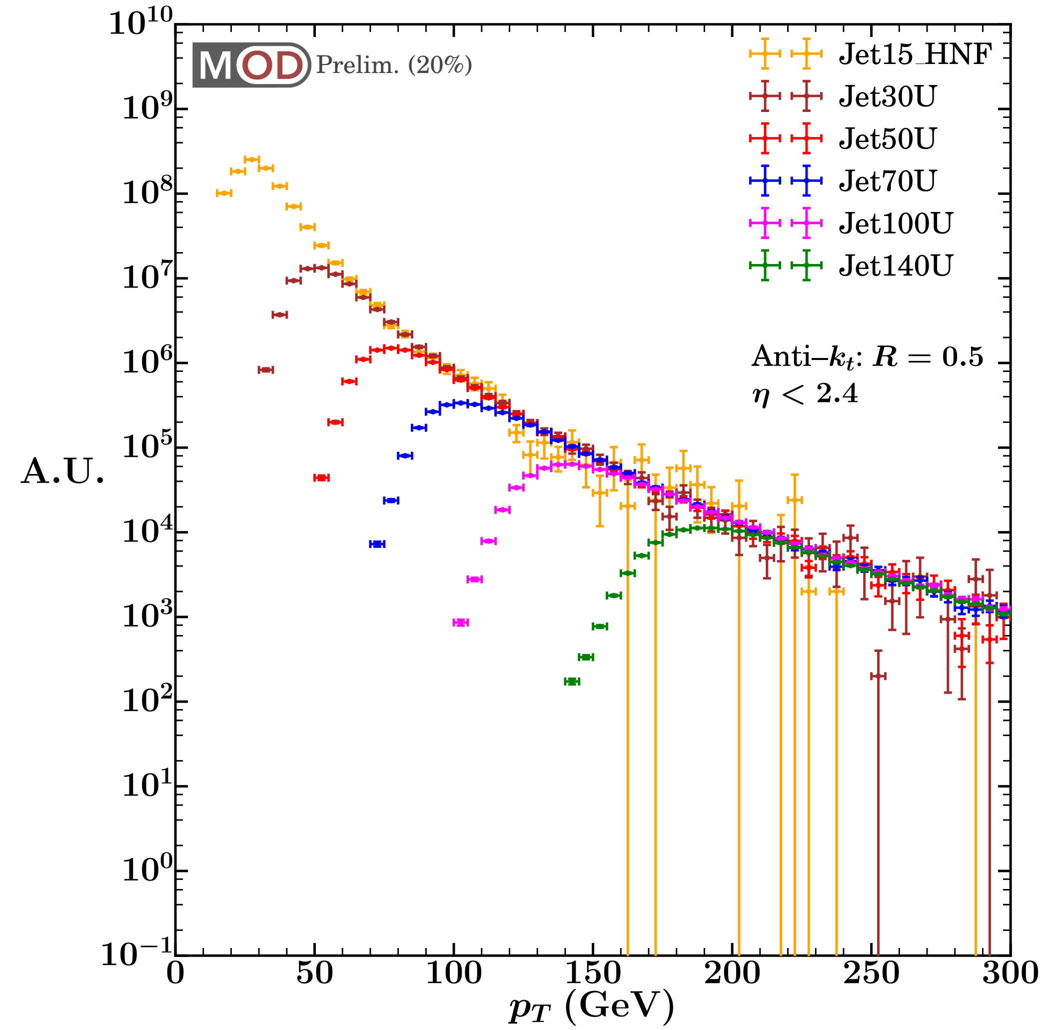




[Larkoski, Marzani, JDT, 1502.01719]

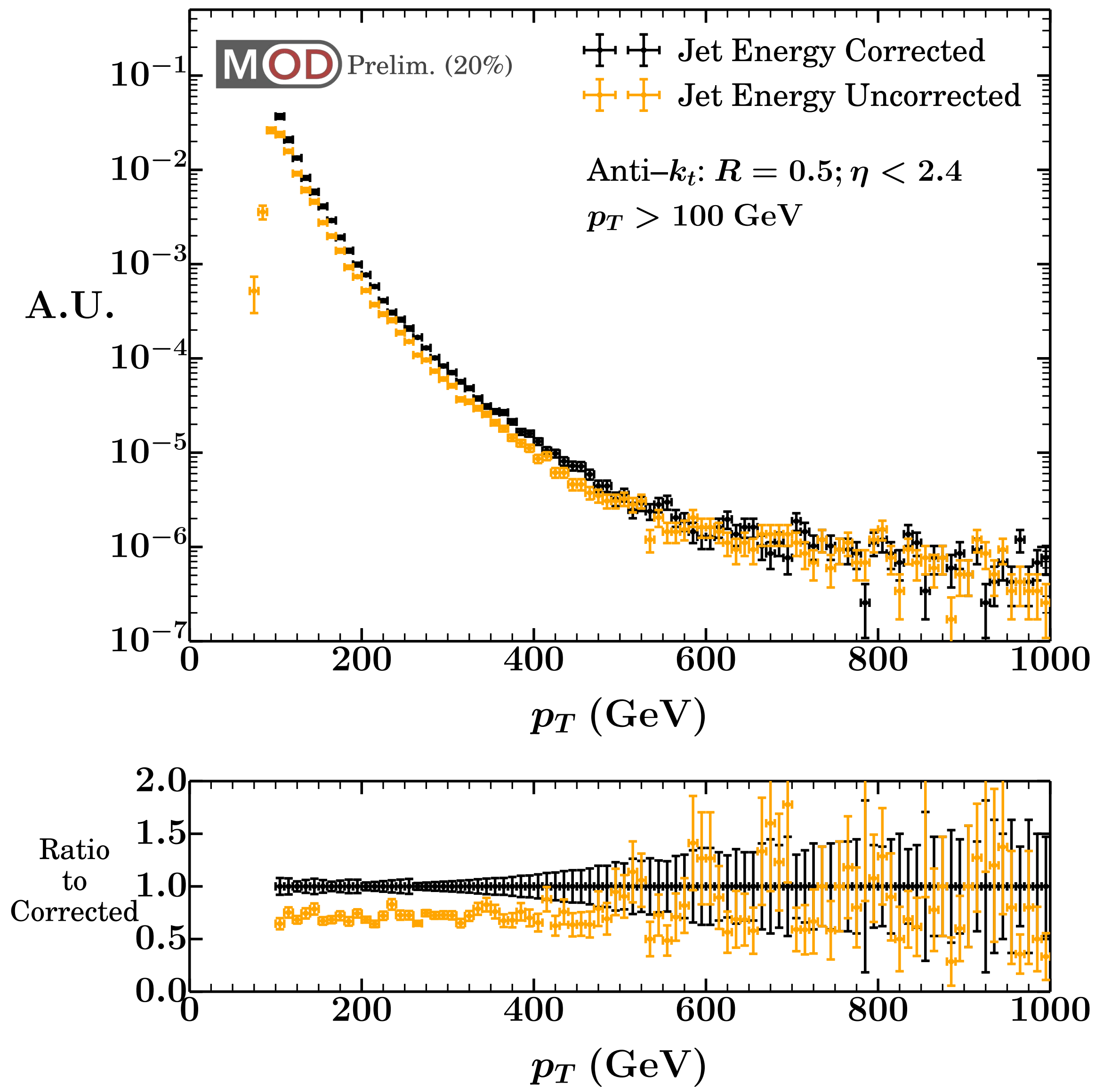
CMS Jet Primary Data Set Triggers

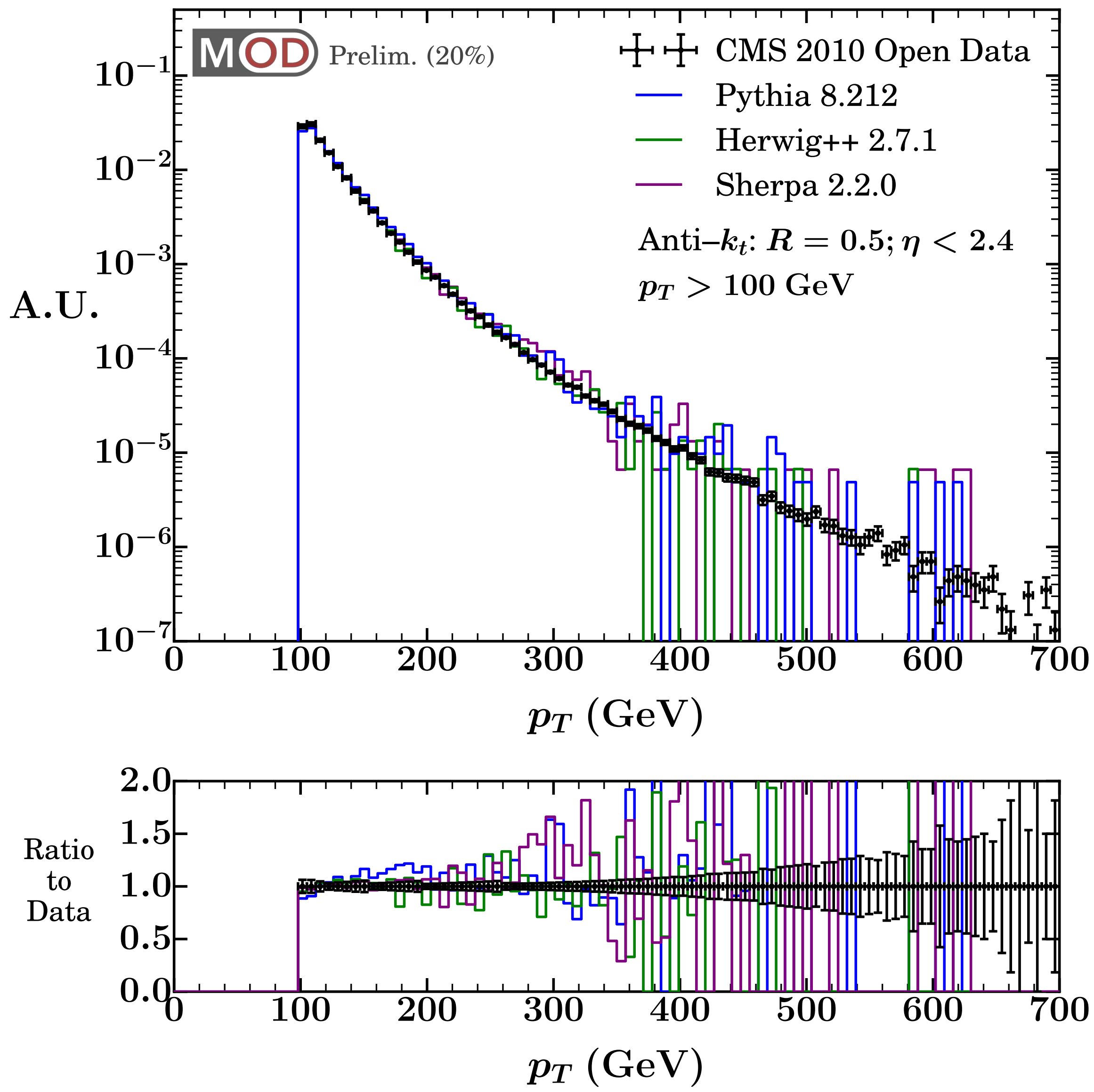




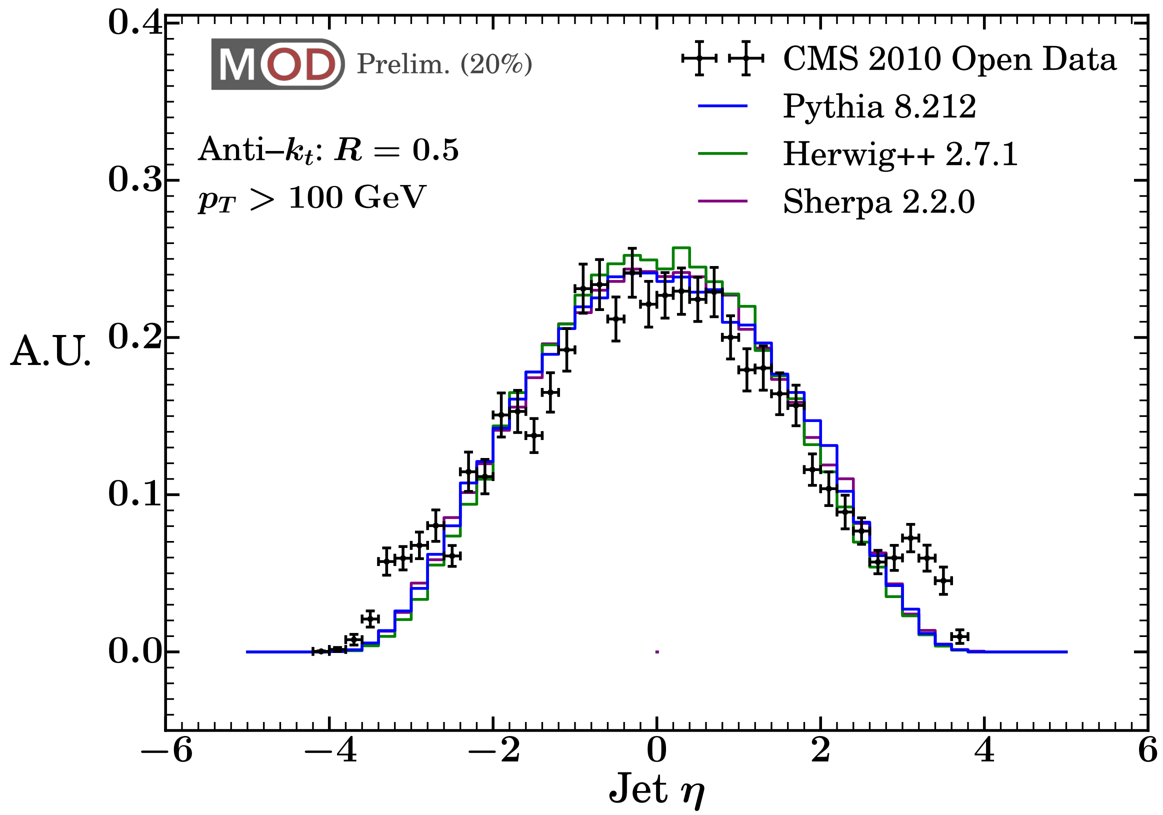

```
HLT_Jet15U + _v3
HLT_Jet15U_HcalNoiseFiltered + _v3
```
HLT_Jet30U + _v3
HLT_Jet50U + _v3
HLT_Jet70U + _v2 + _v3
HLT_Jet100U + _v2 + _v3
```
HLT_Jet140U_v1 + _v3
HLT_Jet180U_v3

HLT_DiJetAve15U + _v3
HLT_DiJetAve30U + _v3
HLT_DiJetAve50U + _v3
HLT_DiJetAve70U + _v2 + _v3
HLT_DiJetAve100U_v1 + _v3
HLT_DiJetAve140U_v3

HLT_QuadJet20U
HLT_QuadJet25U

HLT_HT100U
HLT_HT120U
HLT_HT140U

HLT_EcalOnly_SumEt160
```

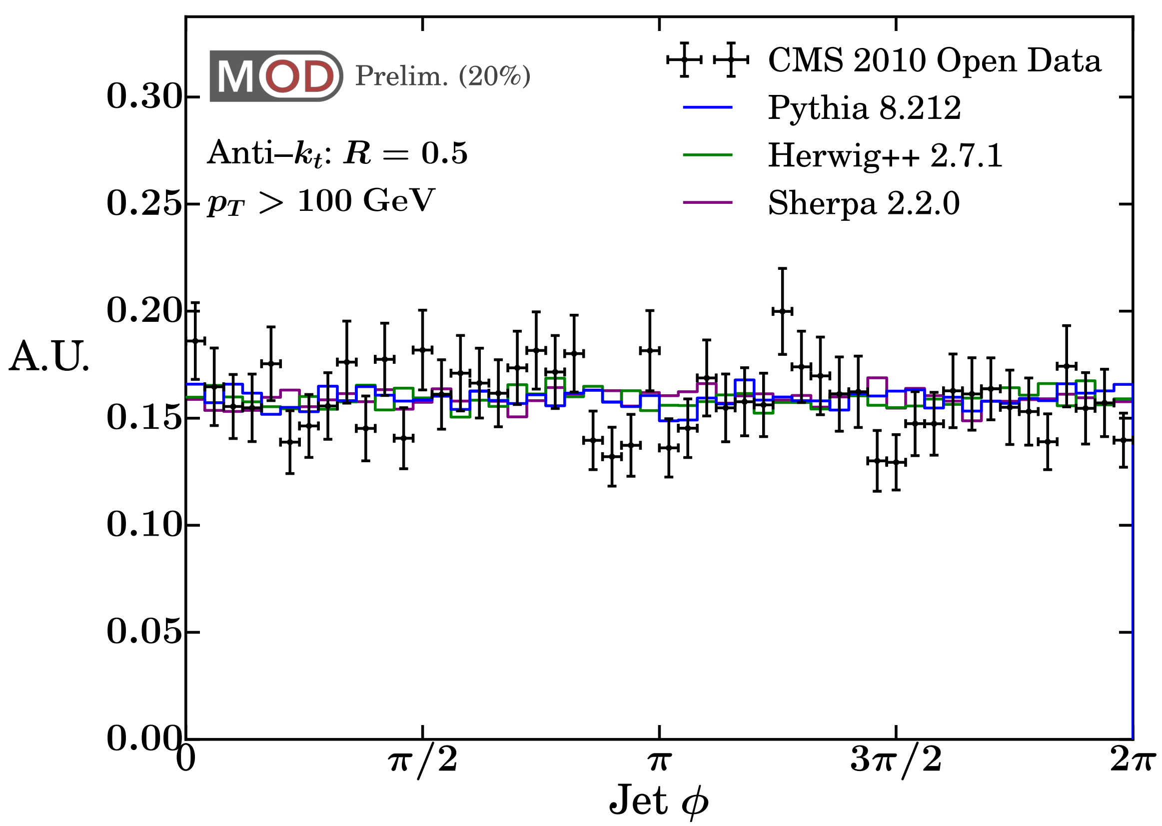
Corrected Jet p_T Spectrum



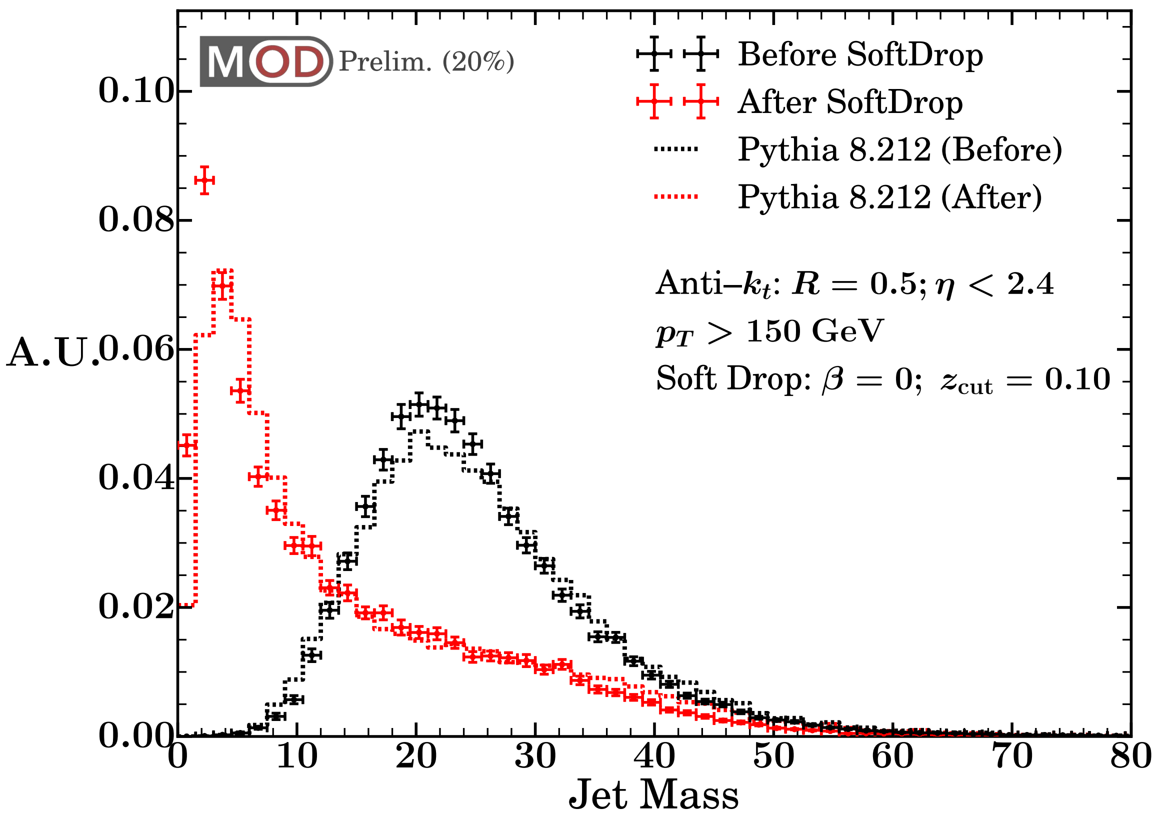


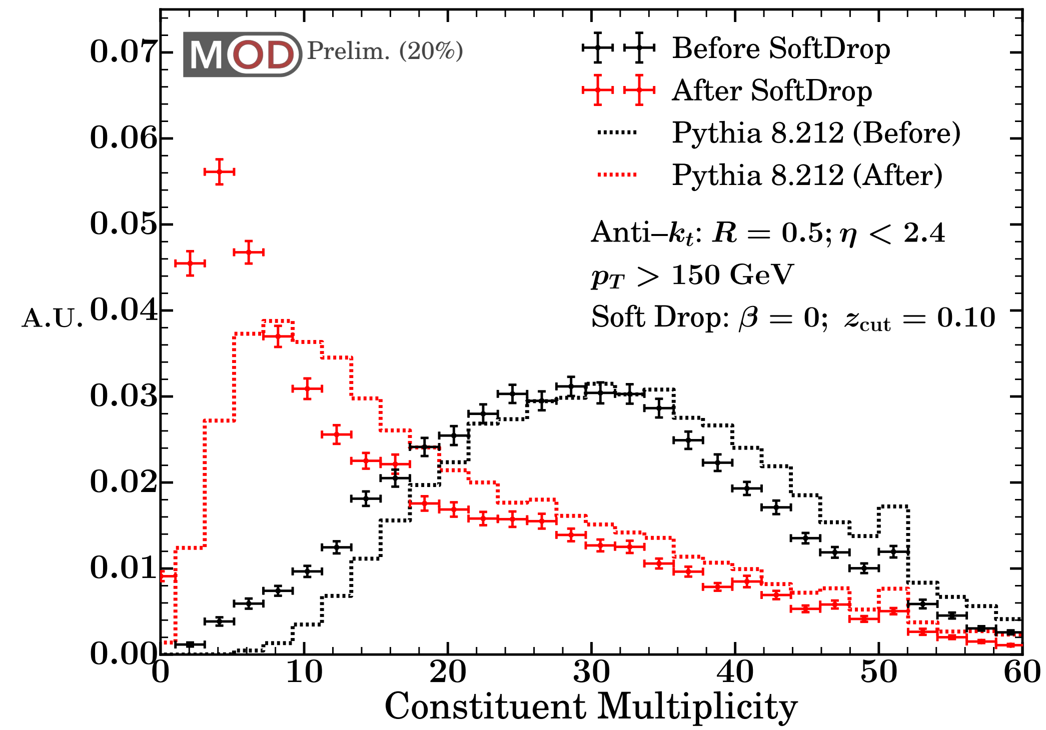
Jet Kinematics

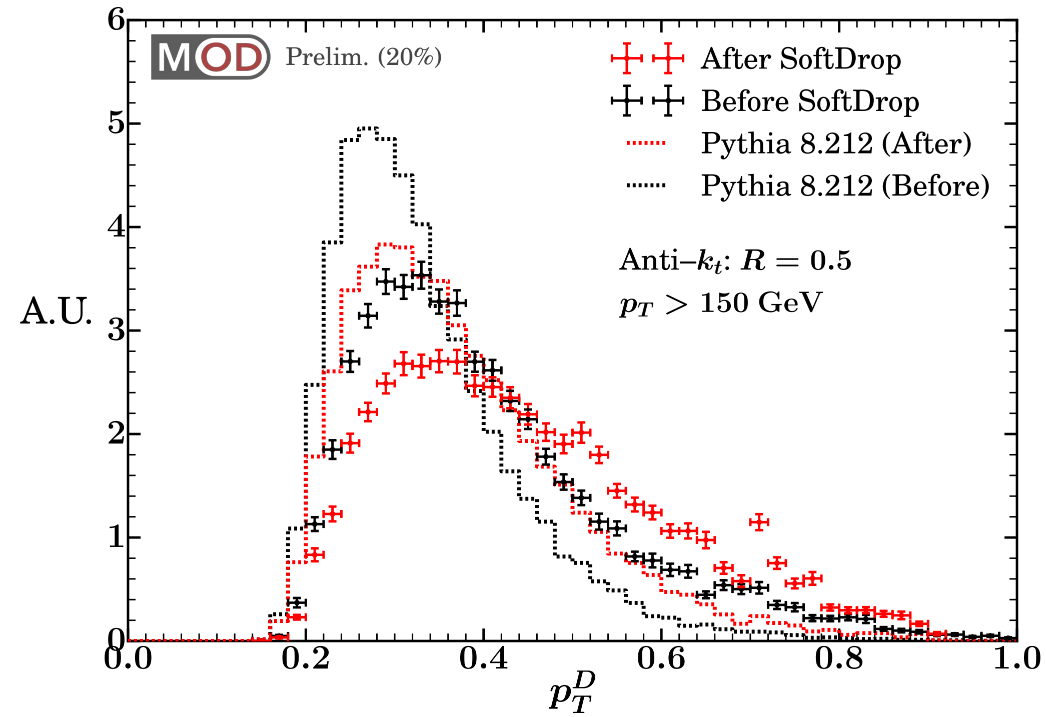




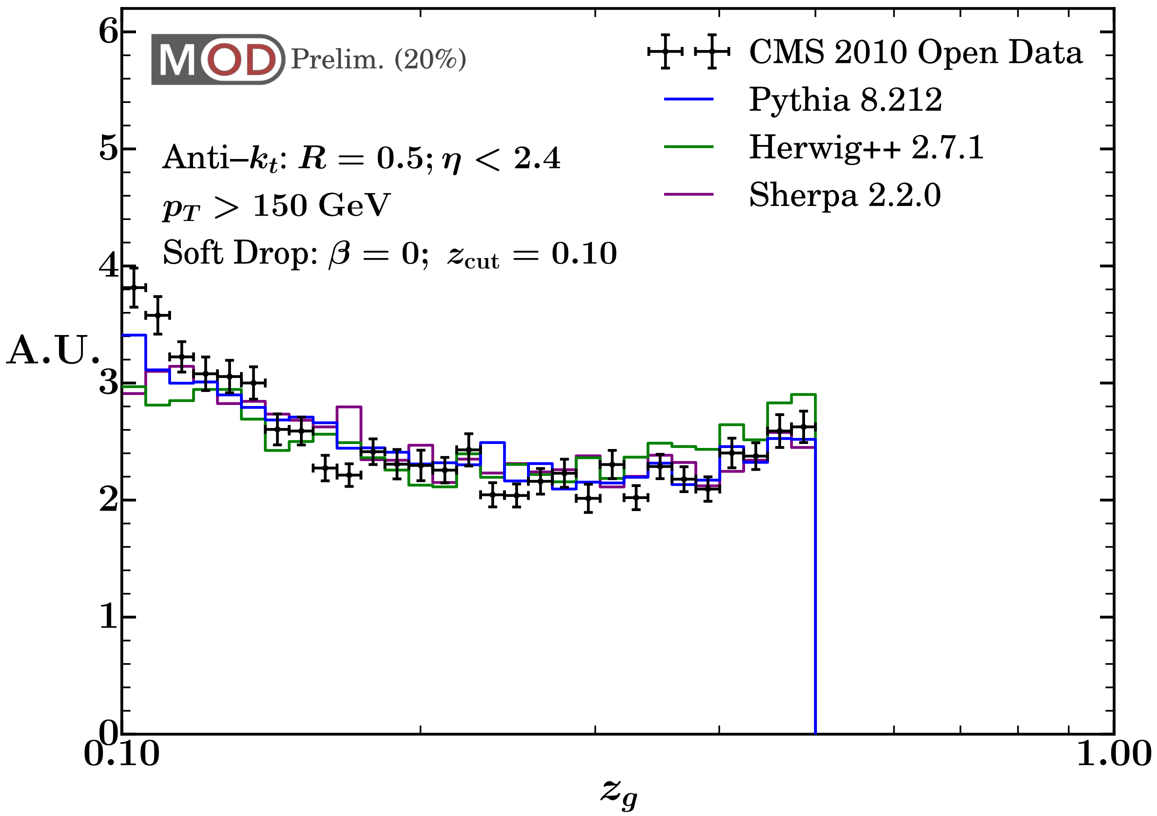
Simple Substructure

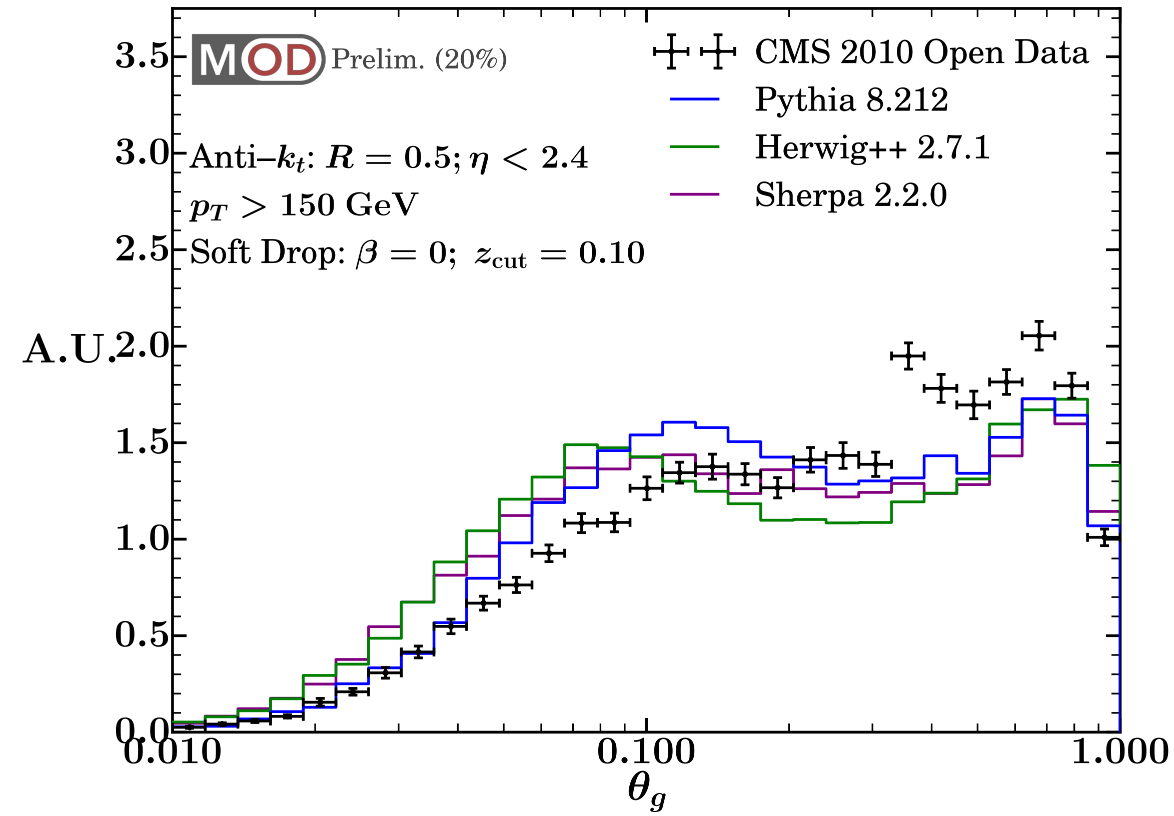


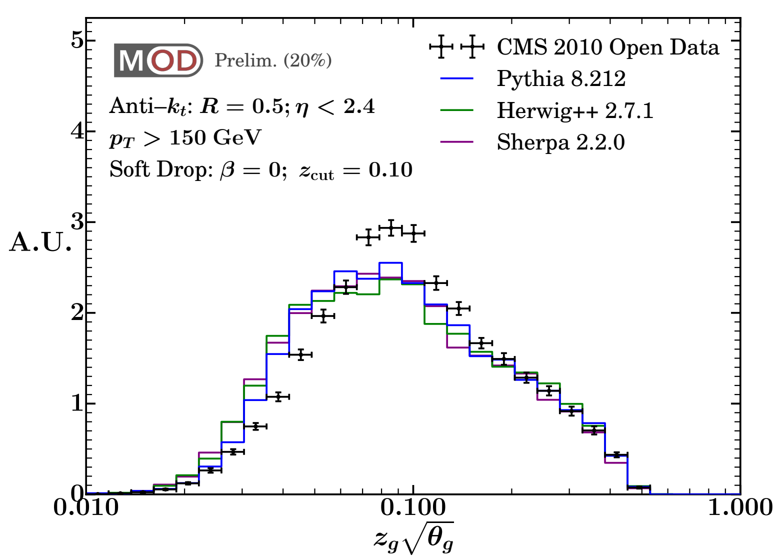


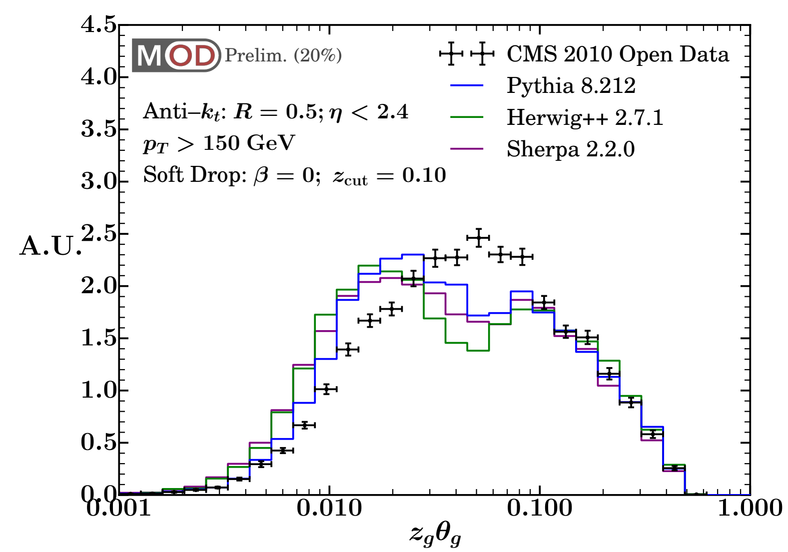


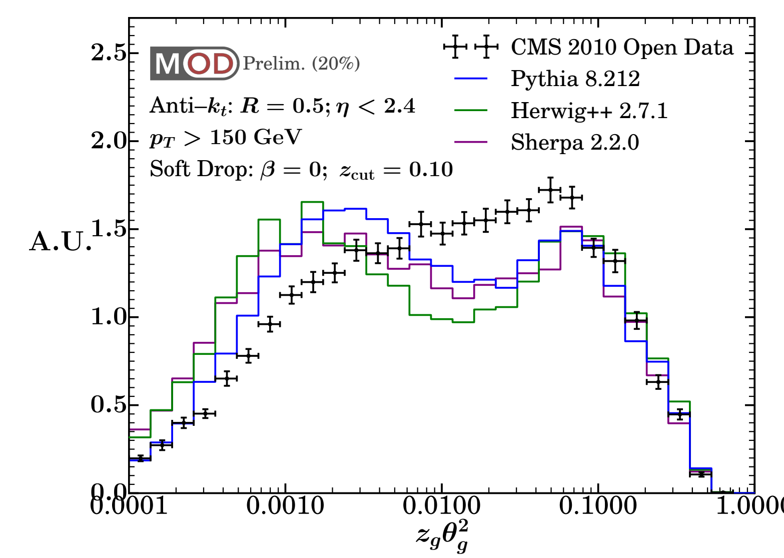
2-prong Substructure



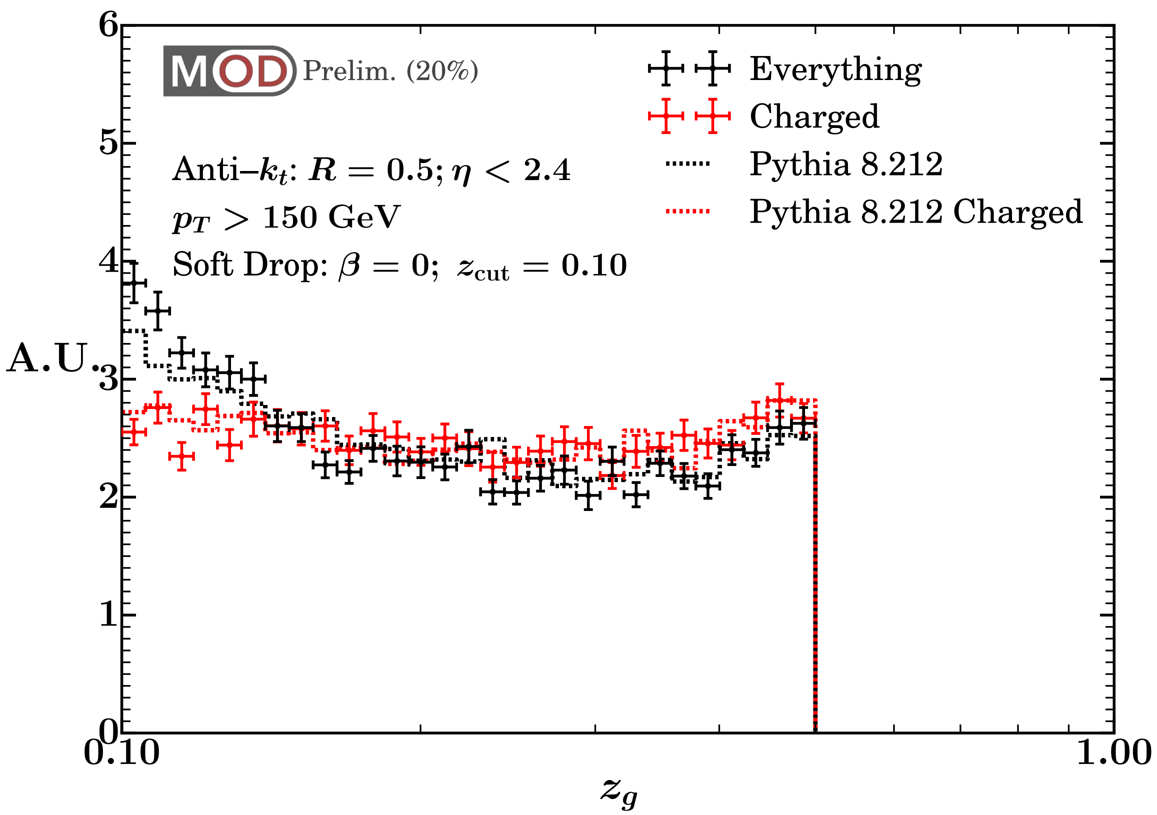


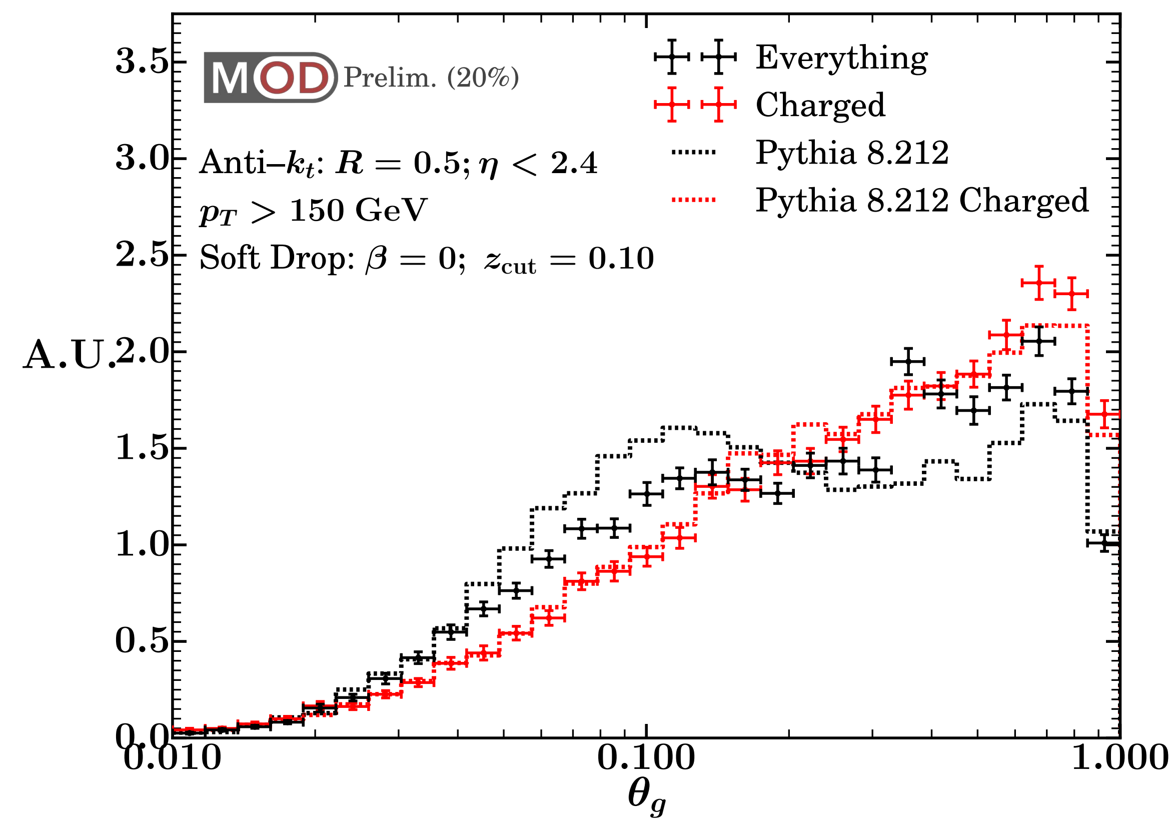


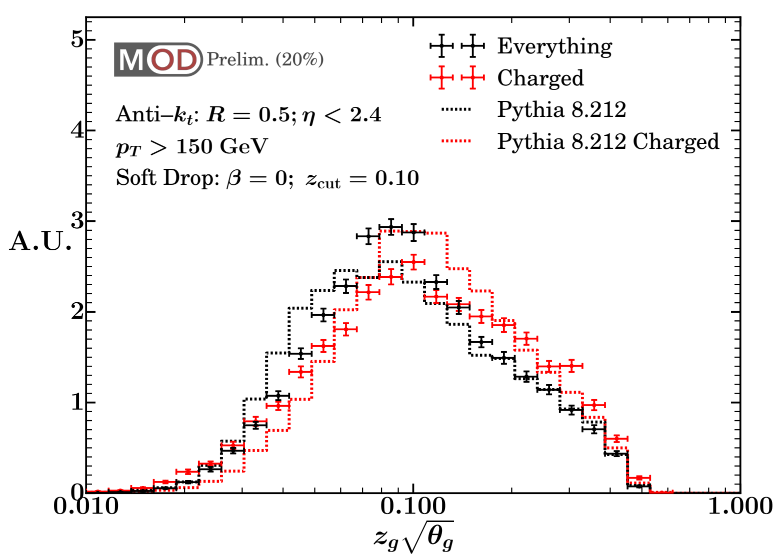


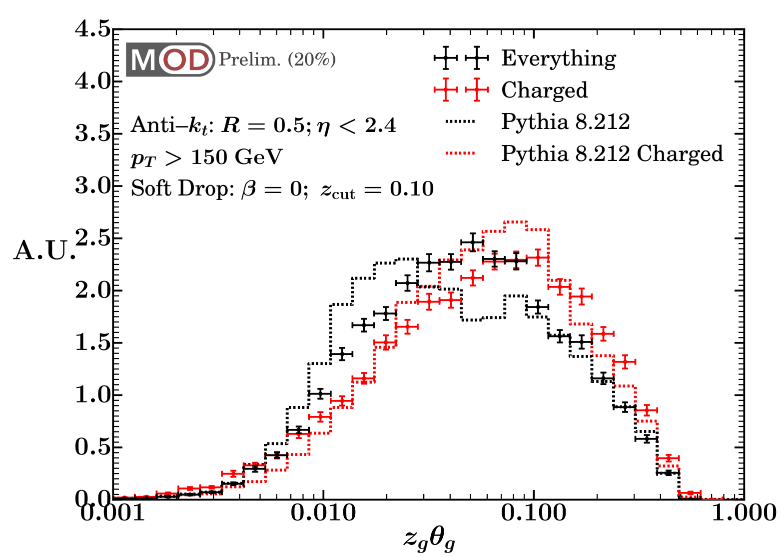


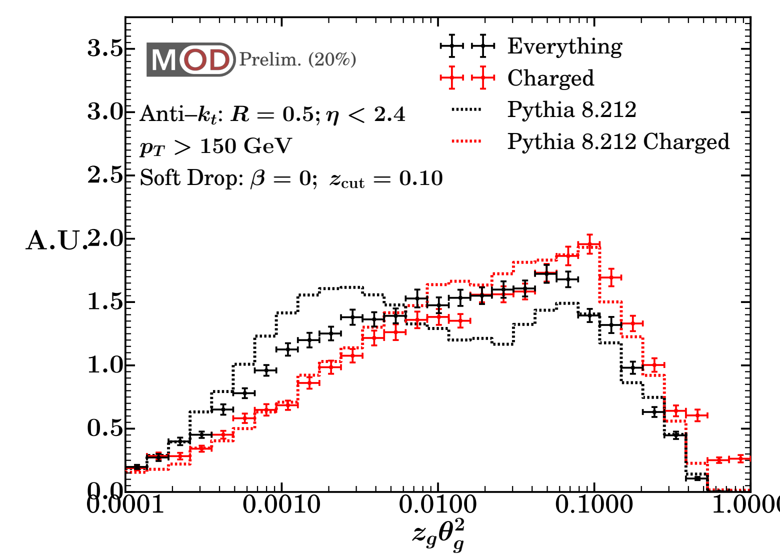
Track-Only Substructure



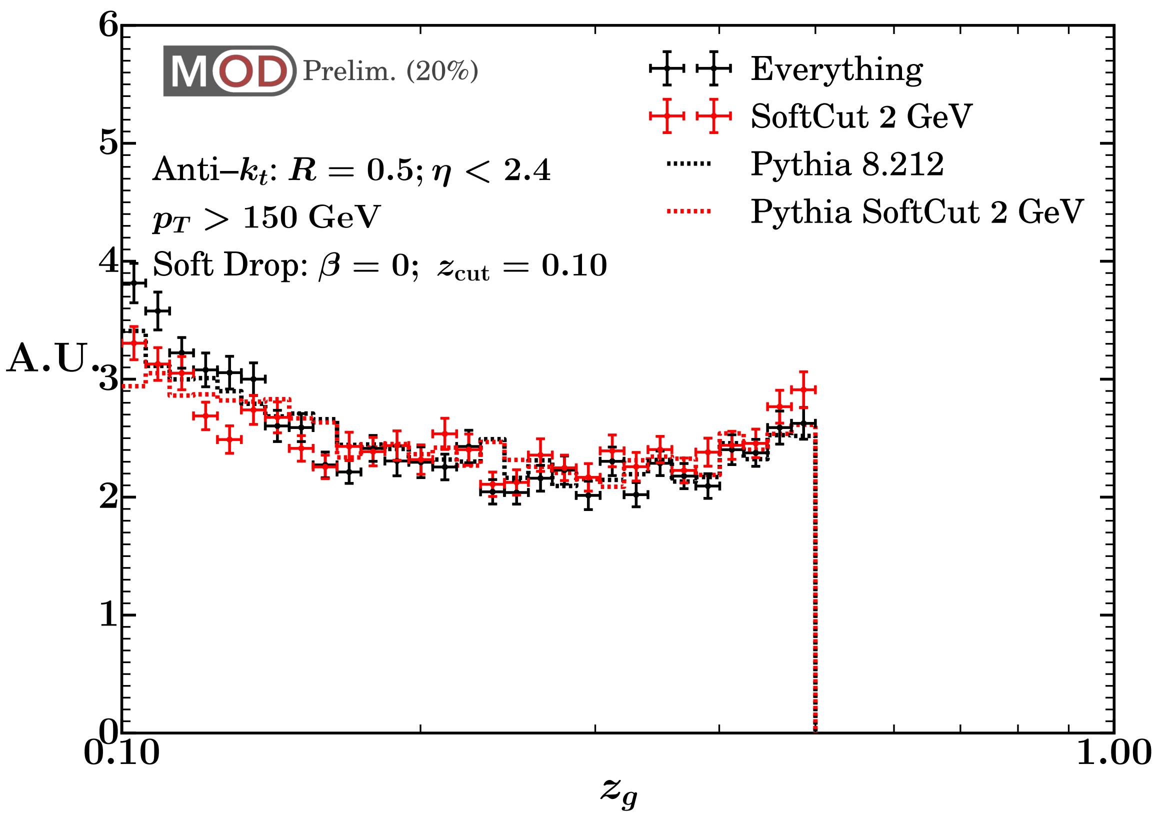


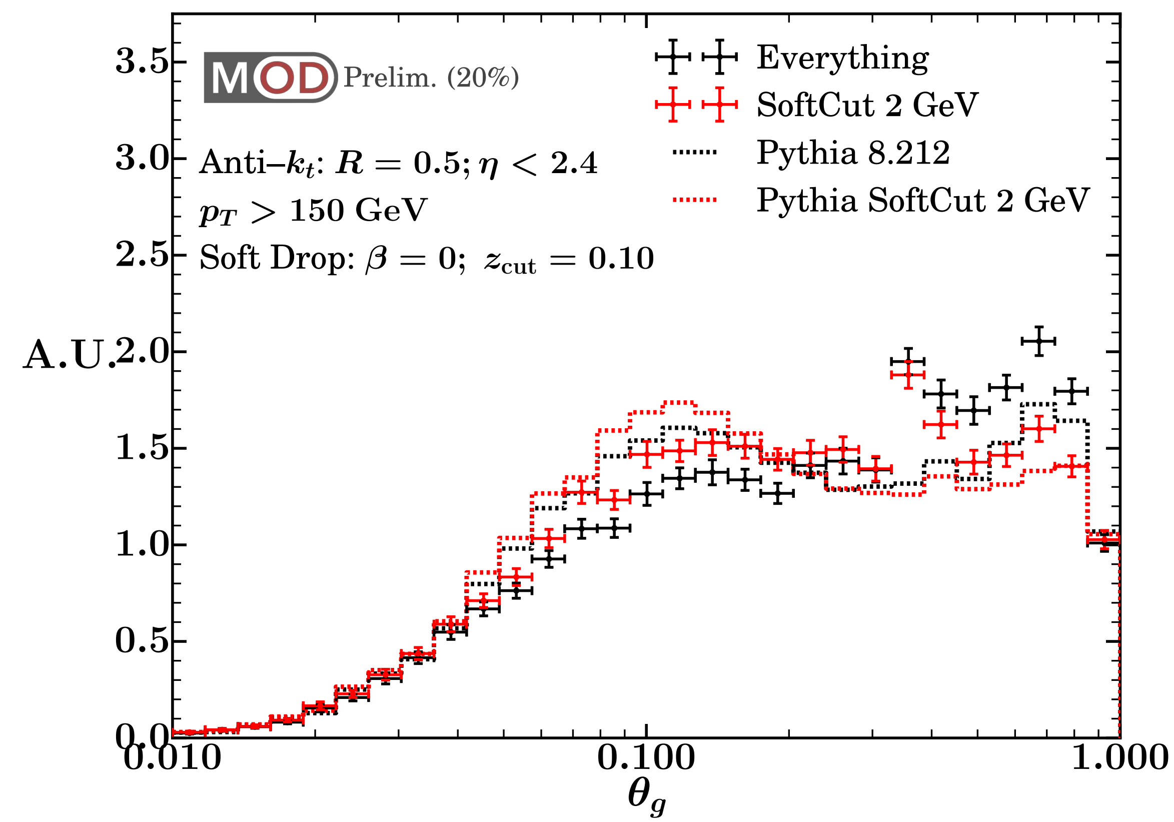


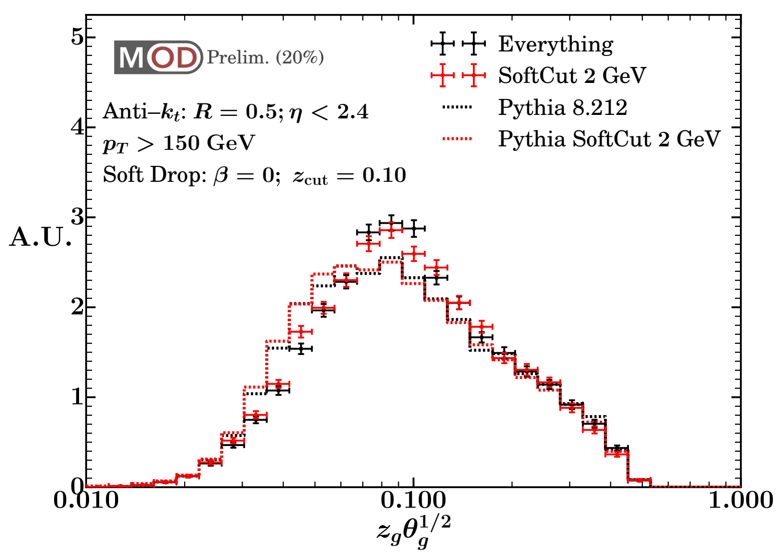


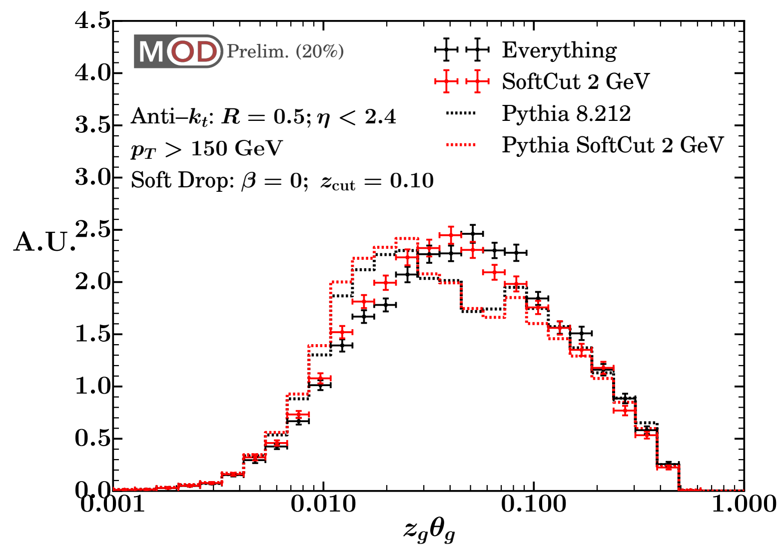


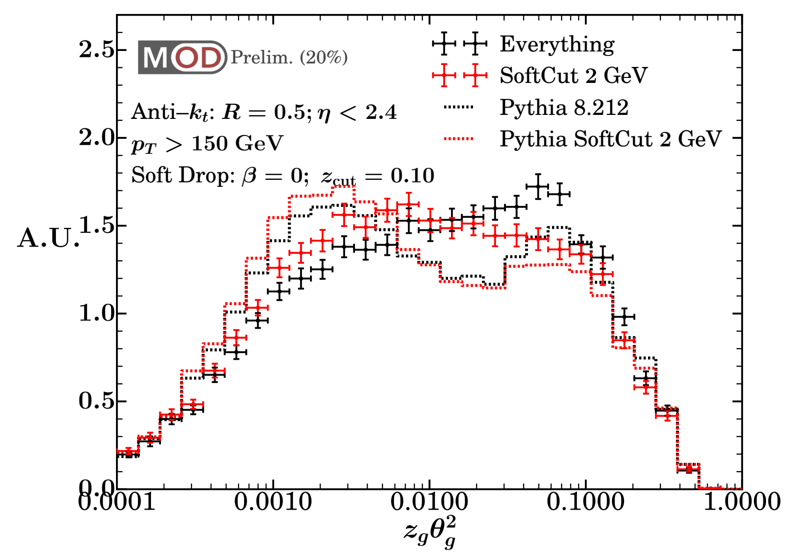
Soft-Killed Substructure











Changing z_{cut}