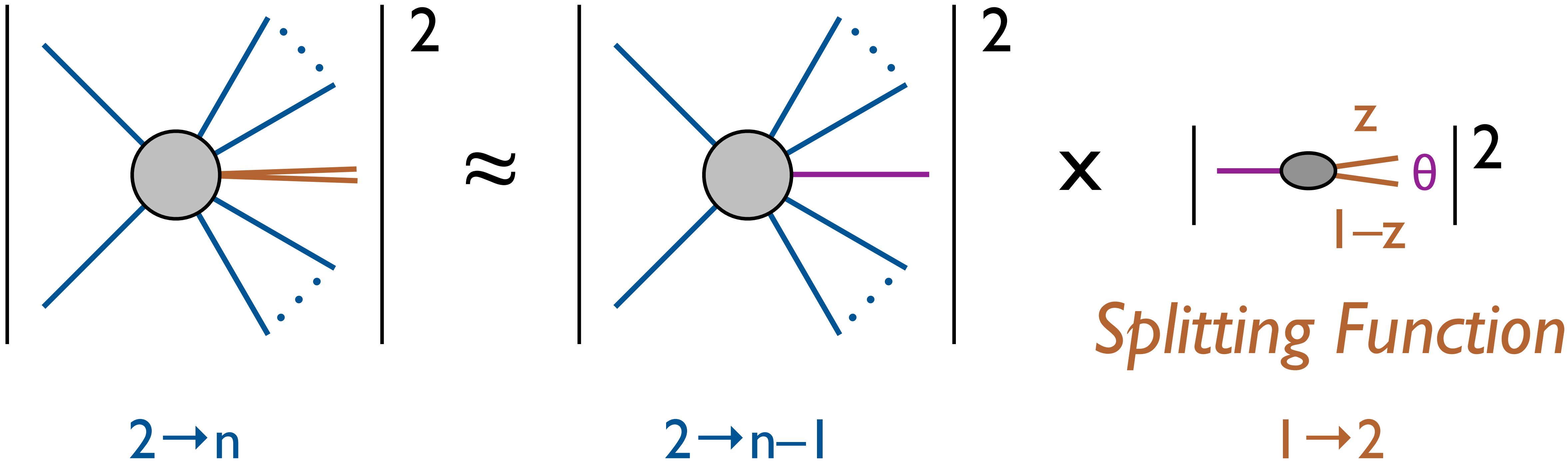
Probing the Core of QCD

Jesse Thaler

Boost 2015, Chicago — August 10, 2015

Textbook QCD: Universal Collinear Limit



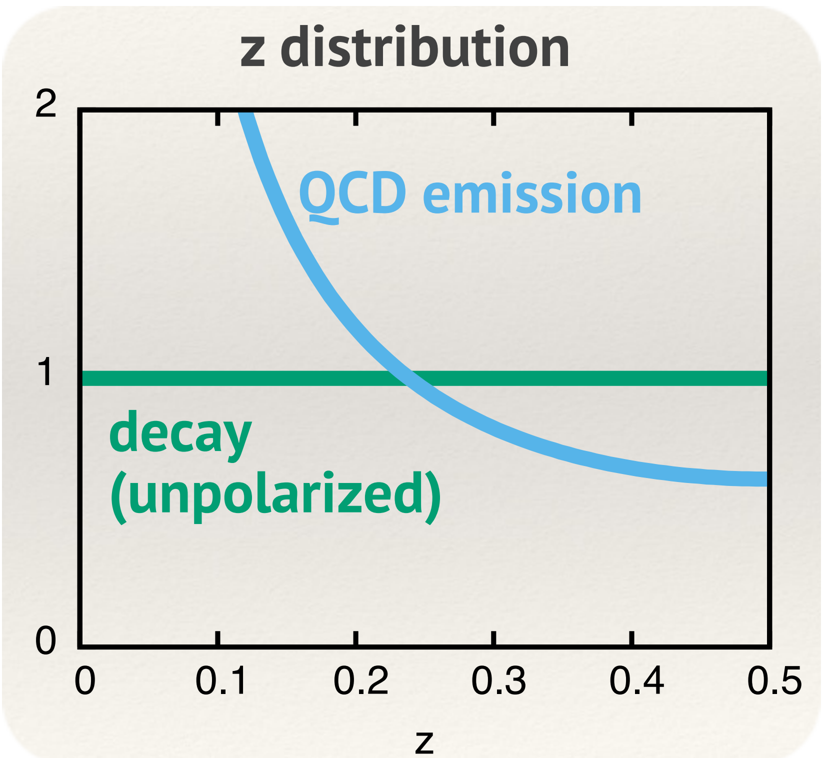
$$\int \frac{d\theta}{\theta} \, dz \, P(z)$$

Collinear singularity   Soft singularity

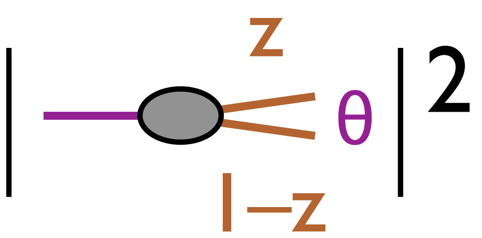
$$P(z) \simeq \frac{1}{z}$$

The Core of QCD

Basis for parton shower MC generators,
PDF evolution, NLO subtractions,
k_t clustering, jet substructure intuition…



[From Gavin's FCC talk, March 2015]



Splitting Function

1→2

$$\int \frac{\mathrm{d}\theta}{\theta}\, \mathrm{d}z\, P(z)$$

Collinear singularity   Soft singularity

$$P(z) \simeq \frac{1}{z}$$

Measurable? Calculable?

↳ IRC Unsafe

Today:

Jet substructure to probe universal singularity structure of gauge theories (e.g. QCD)

Ingredients:

Sudakov Safety

[Andrew Larkoski, JDT, 1307.1699; my talk at Boost 2013]

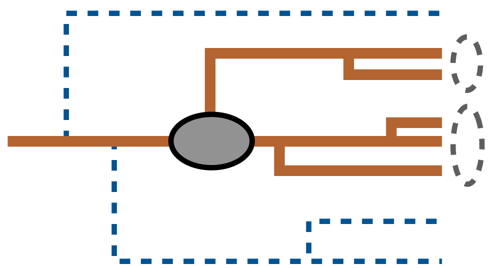
Soft Drop

[Andrew Larkoski, Simone Marzani, Gregory Soyez, JDT, 1402.2657; Simone's talk at Boost 2014]

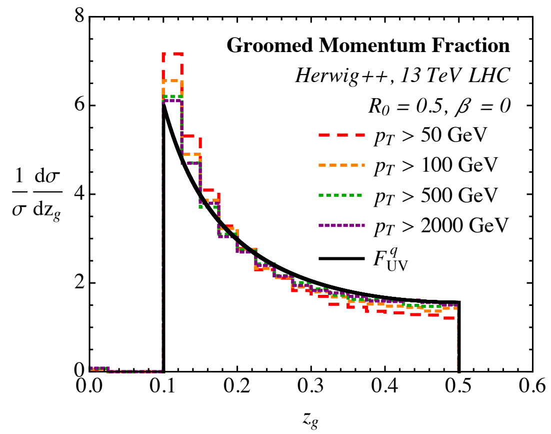
Standard Candles

[Andrew Larkoski, Simone Marzani, JDT, 1502.01719]

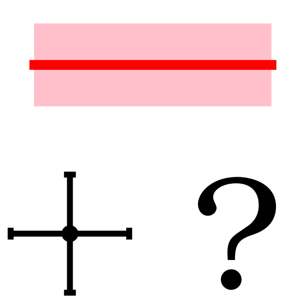
Outline



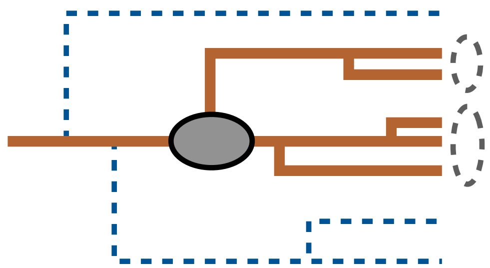
From Soft Drop to Splitting Functions



From Sudakov Safety to Standard Candles



From Theory to Experiment



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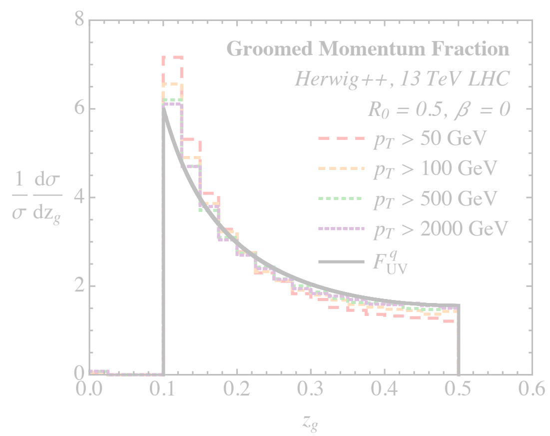
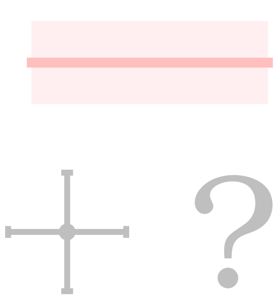
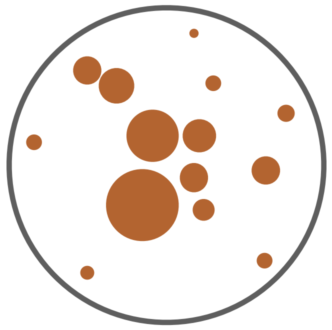


From Sudakov Safety to Standard Candles

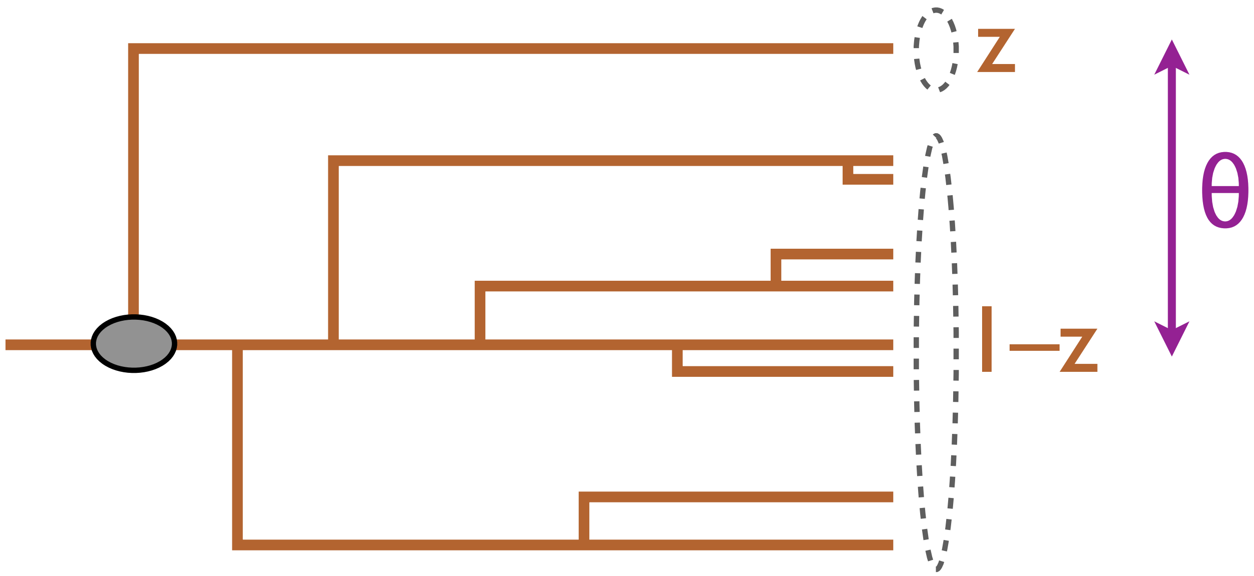


From Theory to Experiment

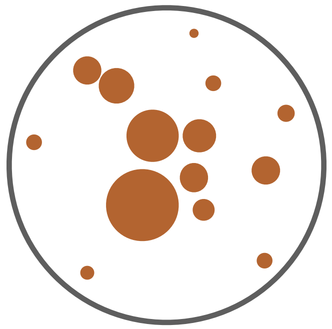
Measure Universal Singularity?



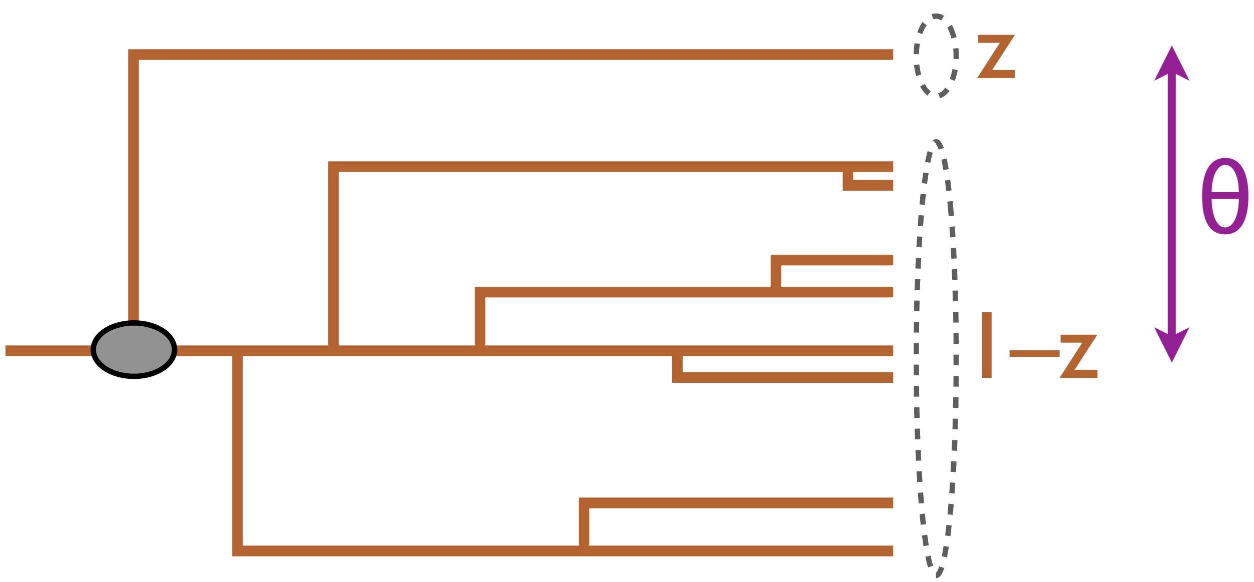
Angular-ordered tree (C/A)…



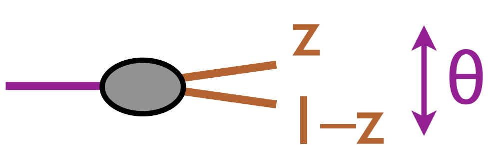
Measure Universal Singularity?



Angular-ordered tree (C/A)...



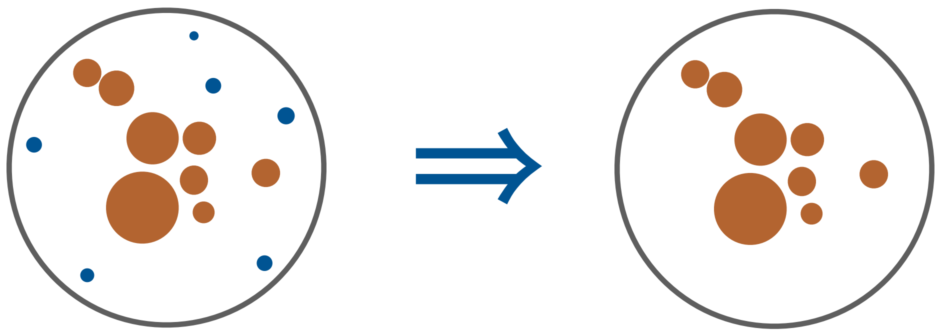
...gives splitting function?



$$\int \frac{d\theta}{\theta}\, dz\, P(z)$$

z IRC Unsafe

Measure Universal Singularity?

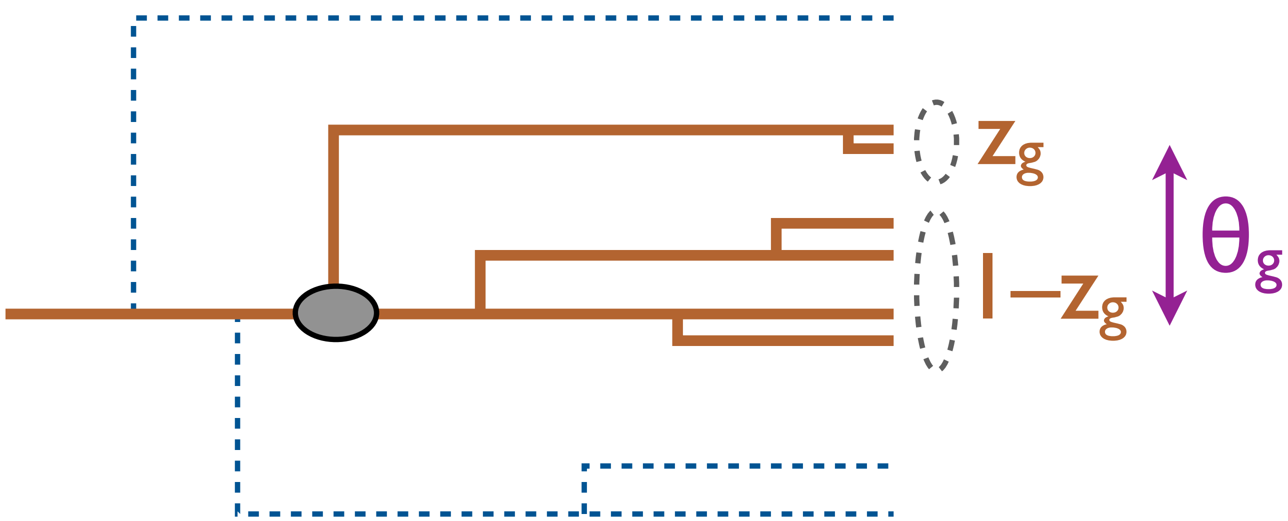


Soft Drop (β = 0, aka mMDT)

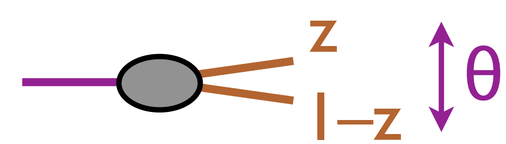
$$z > z_{\mathrm{cut}}$$

↑ energy threshold

Groomed angular-ordered tree…



…gives splitting function?

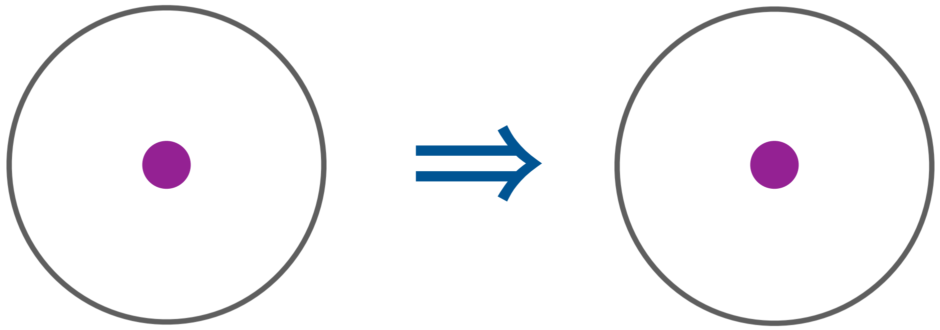


$$\int \frac{d\theta}{\theta}\, dz\, P(z)$$

z_g — IR Safe, C Unsafe

[Larkoski, Marzani, Soyez, JDT, 1402.2657]
[see also Butterworth, Davison, Rubin, Salam, 0802.2470; Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Measure Universal Singularity?



Soft Drop (β = 0, aka mMDT)

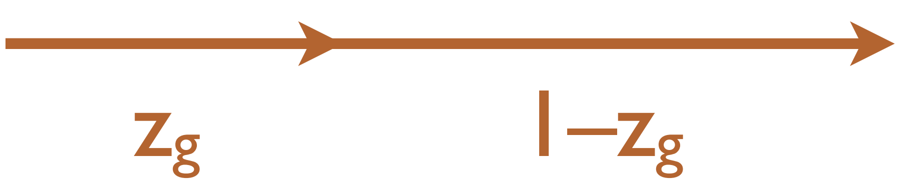
$$z > z_{\mathrm{cut}}$$

↑ energy threshold

One prong jet…

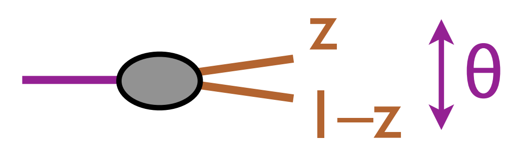
$\theta_g = 0$

vs.



$\theta_g = 0$

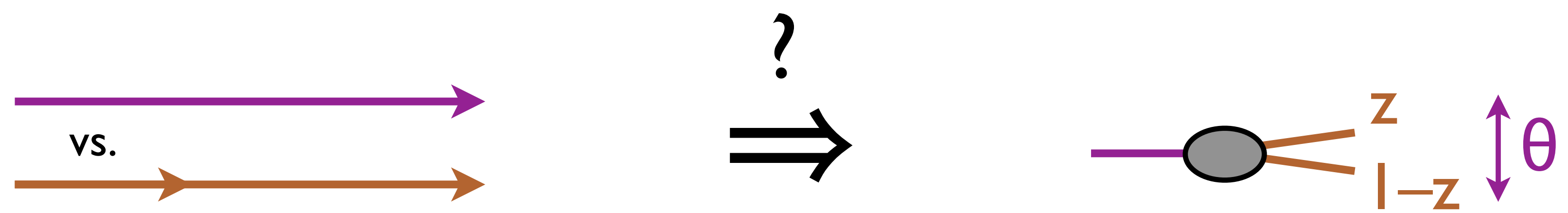
…gives splitting function?



$$\int \frac{d\theta}{\theta}\, dz\, P(z)$$

z_g	IR Safe C Unsafe

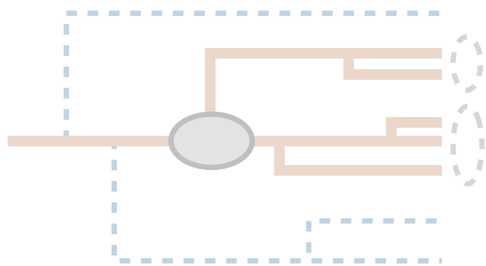
[Larkoski, Marzani, Soyez, JDT, 1402.2657]
[see also Butterworth, Davison, Rubin, Salam, 0802.2470; Dasgupta, Fregoso, Marzani, Salam, 1307.0007]



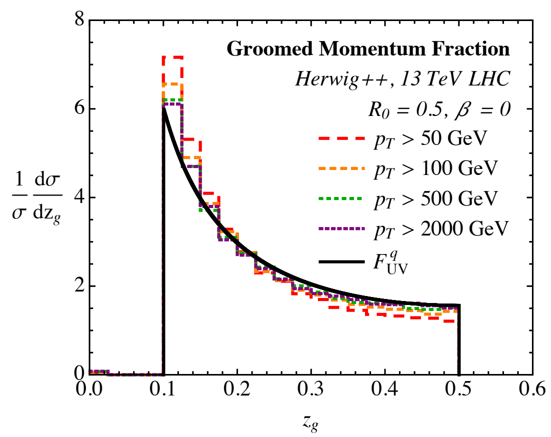
z_g	IR Safe C Unsafe

How to calculate from first principles?

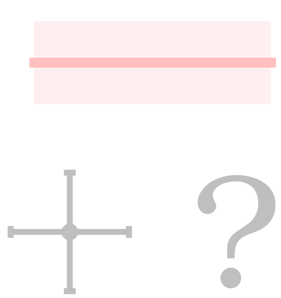
(see backup for how our elders addressed this in 1978)



From Soft Drop to Splitting Functions



From Sudakov Safety to Standard Candles



From Theory to Experiment

1. Use Sudakov Form Factors

Measure jet mass?

z_g	IR Safe C Unsafe	$z_g^{m>0}$	IRC Safe

[Larkoski, JDT, 1307.1699]

1. Use Sudakov Form Factors

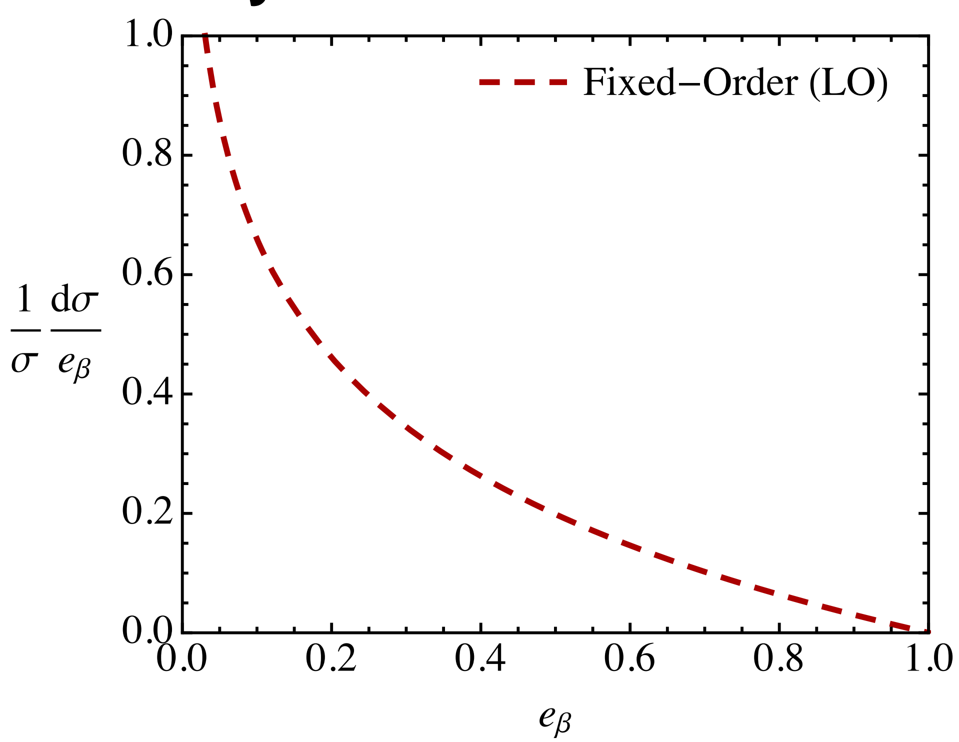
	Measure jet mass?		Jet mass never zero!
z_g IR Safe, C Unsafe	$z_g^{\,m>0}$ IRC Safe	$\Rightarrow$	z_g Sudakov Safe

[Larkoski, JDT, 1307.1699]

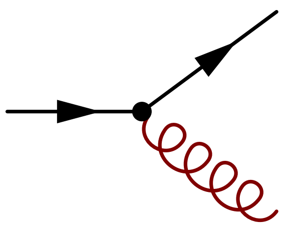
1. Use Sudakov Form Factors

	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 $O(\alpha_s)$



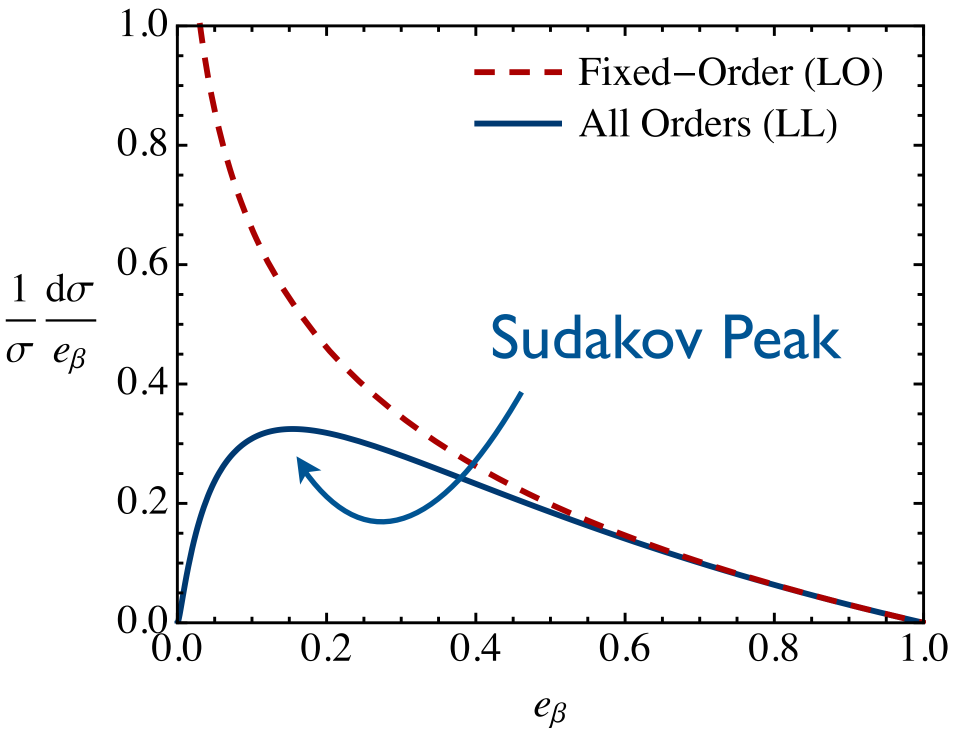
m=0 singular

[Larkoski, JDT, 1307.1699]

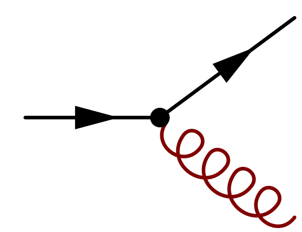
1. Use Sudakov Form Factors

	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 $O(\alpha_s)$

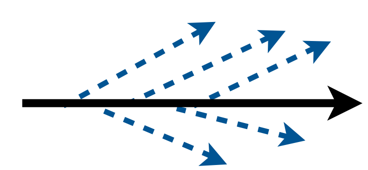


m=0 singular

vs.

All α_s Orders

(resummed logs)



m=0 suppressed

[Larkoski, JDT, 1307.1699]

1. Use Sudakov Form Factors

Unsafe
↓

Want: $$p(u) = \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}u}$$

[Larkoski, Marzani, JDT, 1502.01719]

1. Use Sudakov Form Factors

Unsafe

Want: $$p(u) = \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}u}$$

Calculable…

Need: $$p(u|s) = \frac{p(u,s)}{p(s)}$$

…with Safe companion

[Larkoski, Marzani, JDT, 1502.01719]

1. Use Sudakov Form Factors

Unsafe ↓

Want: $p(u) = \frac{1}{\sigma}\frac{d\sigma}{du}$

Calculable… ↓

Need: $p(u|s) = \frac{p(u,s)}{p(s)}$

↑ …with Safe companion

Sudakov Safe ↓

Insight: $p(u) = \int ds\, p(s)\, p(u|s)$

↑ Sudakov form factor (all orders in α_s)

↑ Perturbative (fixed order in α_s)

Suppresses isolated singularities… …at each perturbative order

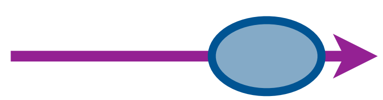
[Larkoski, Marzani, JDT, 1502.01719]

2. Use Fragmentation Functions

$\mathbf{z_g}$ IR Safe
C Unsafe

Absorb singularities
into universal function
(just like PDFs!)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} \simeq F(z_g)$$

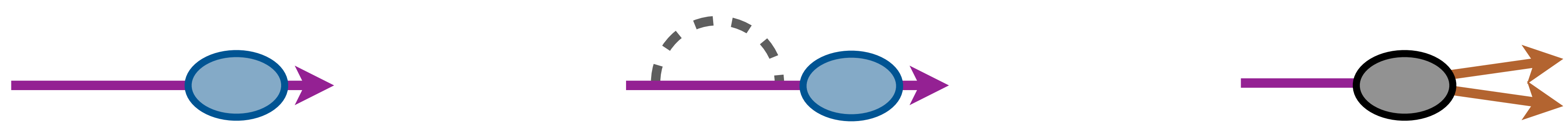


[Larkoski, Marzani, JDT, 1502.01719]

2. Use Fragmentation Functions

z_g IR Safe
C Unsafe ← Absorb singularities into universal function (just like PDFs!)

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

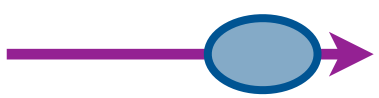
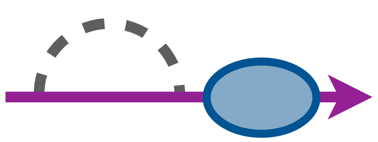
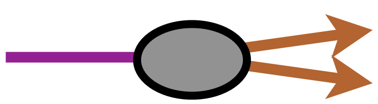


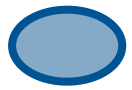
[Larkoski, Marzani, JDT, 1502.01719]

2. Use Fragmentation Functions

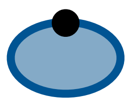
z_g
IR Safe
C Unsafe ← Absorb singularities into universal function (just like PDFs!)

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


$F(z_g)$

renormalize
$\Rightarrow$

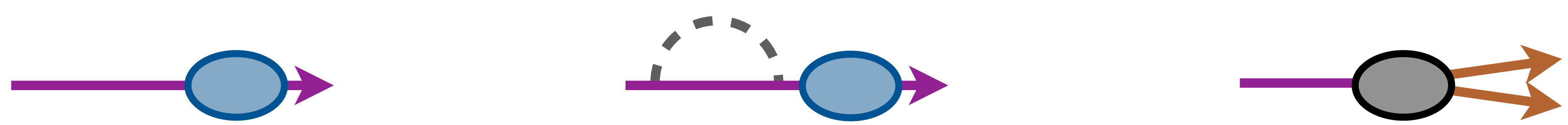

$F(z_g; \mu)$

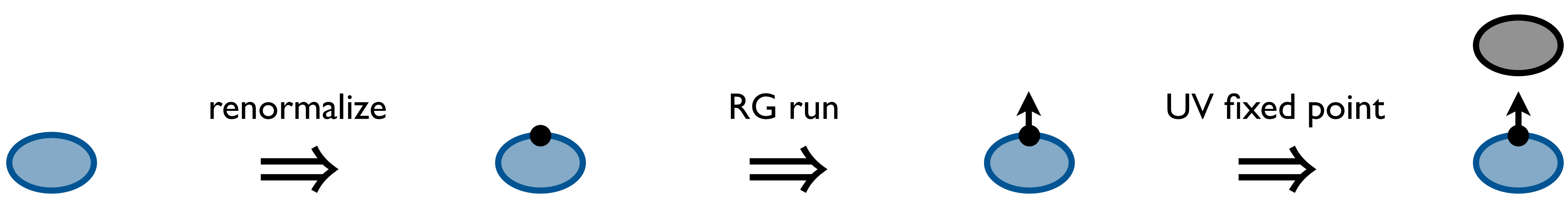
[Larkoski, Marzani, JDT, 1502.01719]

2. Use Fragmentation Functions

z_g — IR Safe / C Unsafe ← Absorb singularities into universal function (just like PDFs!)

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

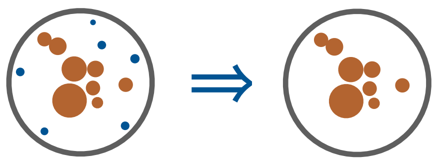




$F(z_g) \quad \Rightarrow \quad F(z_g;\mu) \quad \Rightarrow \quad d/d\mu \quad \Rightarrow \quad P(z_g)$

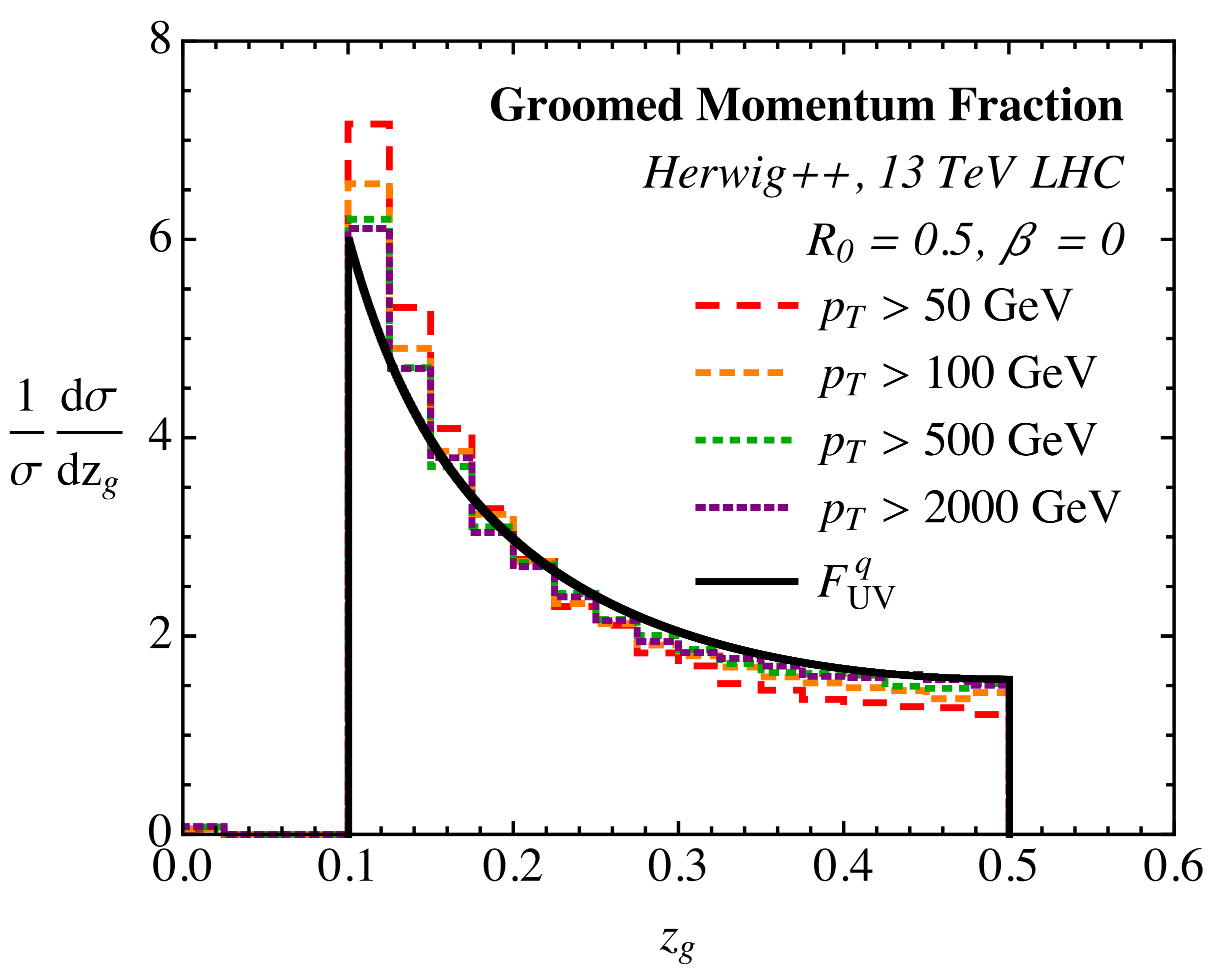
[Larkoski, Marzani, JDT, 1502.01719]

A Standard Candle for Jets

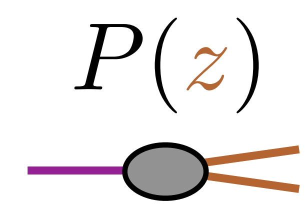


$z > z_{\mathrm{cut}}$

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



z_g ⇒

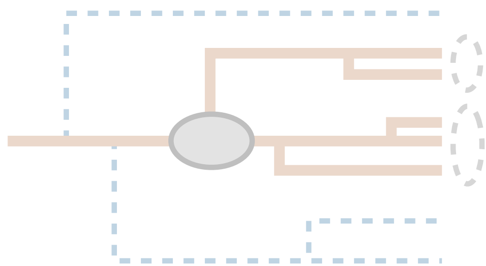


≈ independent of α_s (!)
≈ independent of jet p_T and radius
≈ same for quarks and gluons

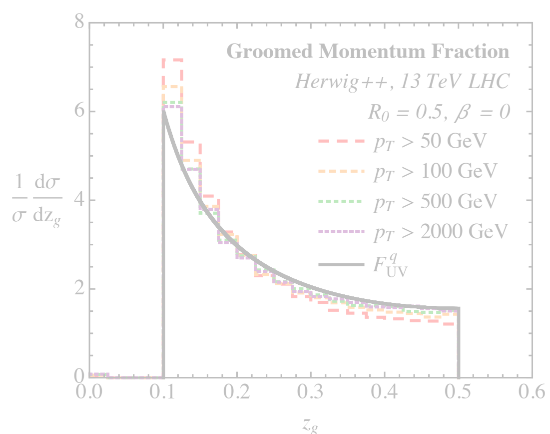
calculable deviations from universality

(see backup for $\beta \neq 0$)

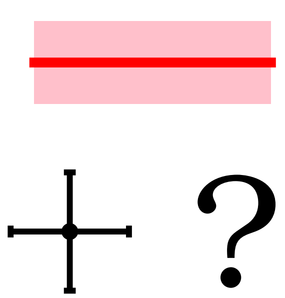
[Larkoski, Marzani, JDT, 1502.01719]



From Soft Drop to Splitting Functions

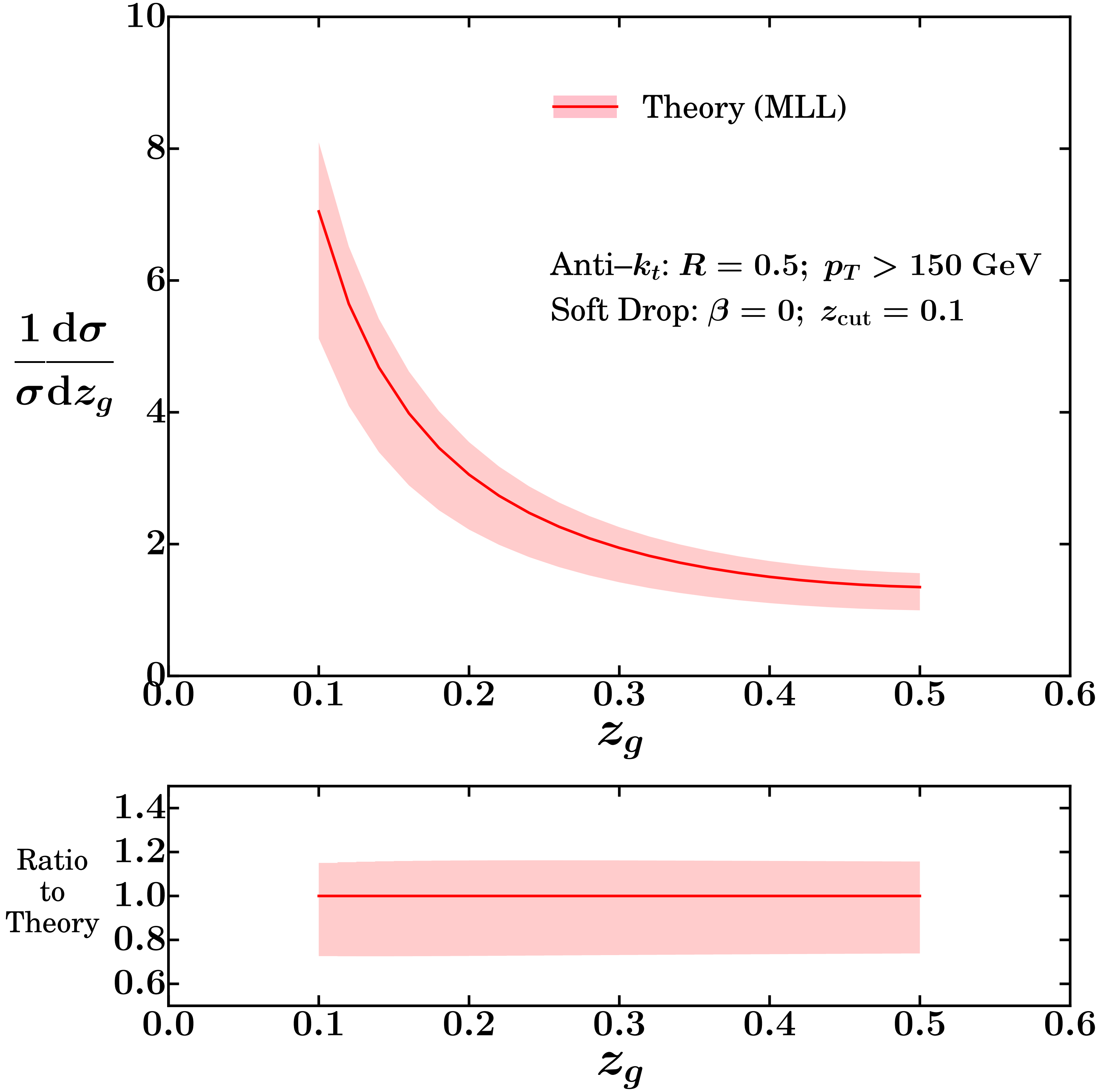


From Sudakov Safety to Standard Candles



From Theory to Experiment

Theory Calculation



$p_T > 150$ GeV
$z_{cut} = 0.1$

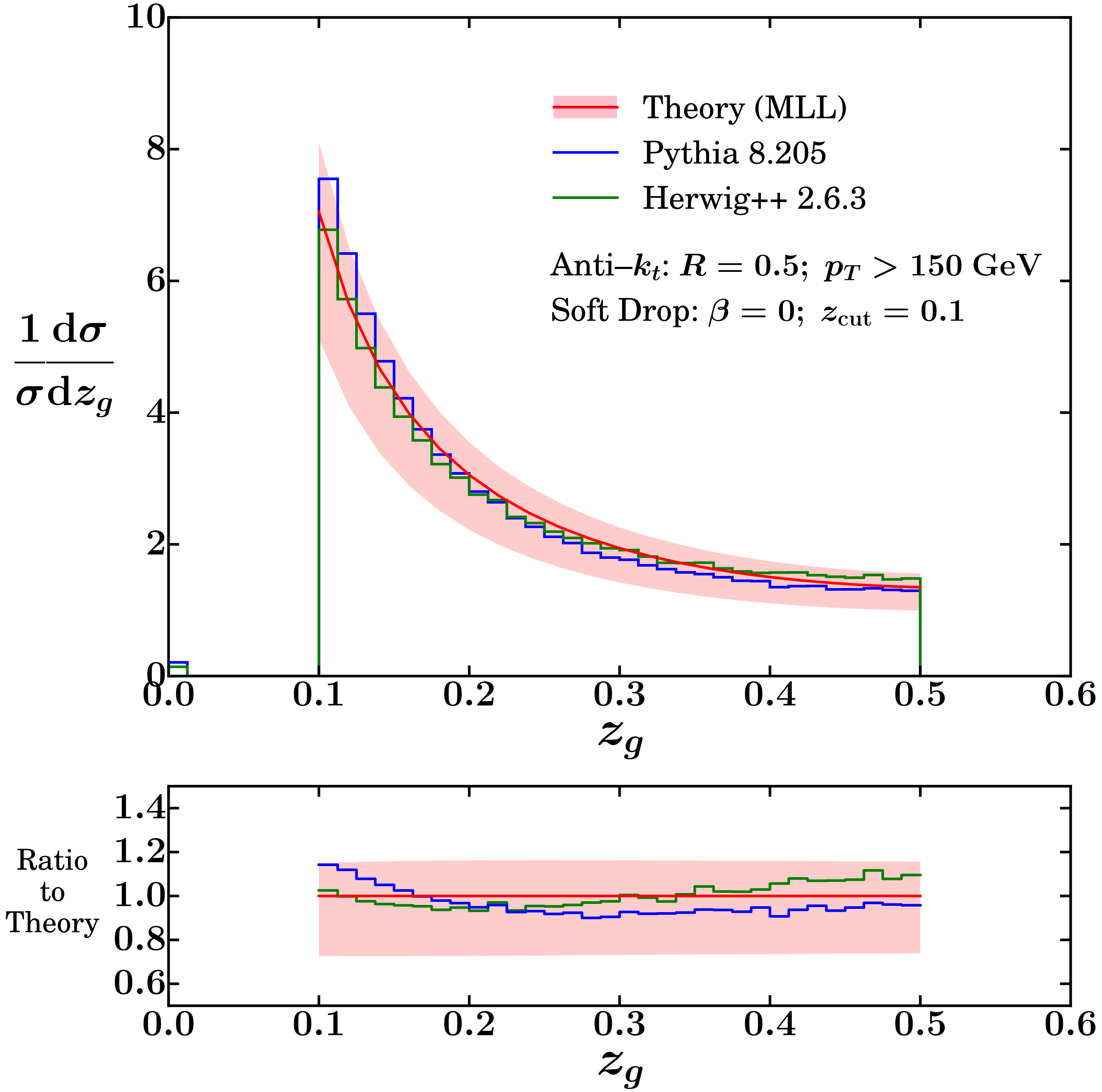
MLL:
leading log plus running coupling

Uncertainties from α_s scale variation and quark/gluon composition

(Likely an overestimate since normalization is not enforced and q/g composition is known)

[Thanks to Simone Marzani]

Parton Shower Simulation



$p_T > 150$ GeV
$z_{cut} = 0.1$

MC:
LO QCD dijets
out of the box

Particle level, default underlying event tune, no detector simulation

[Thanks to Andrew Larkoski, **Alexis Romero**]

Experimental Measurement

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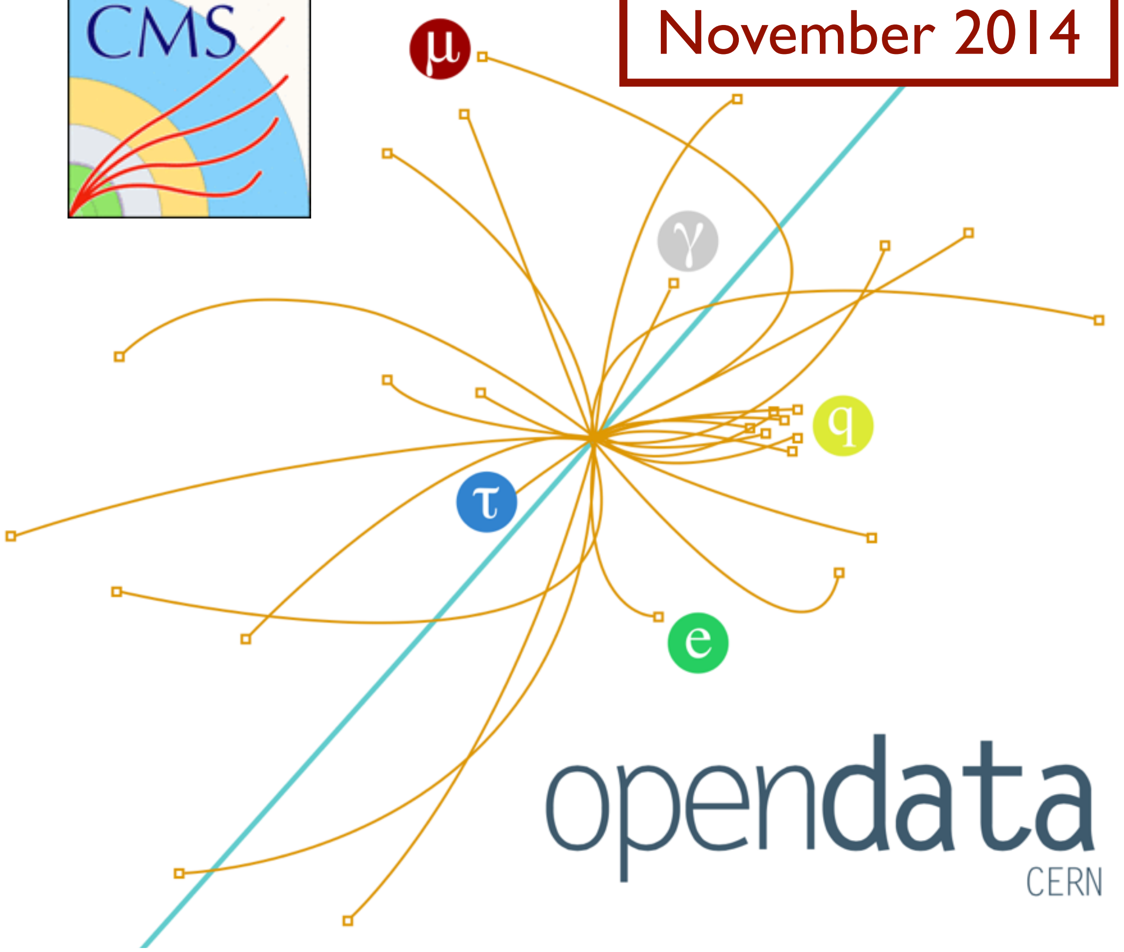
The Future is Open

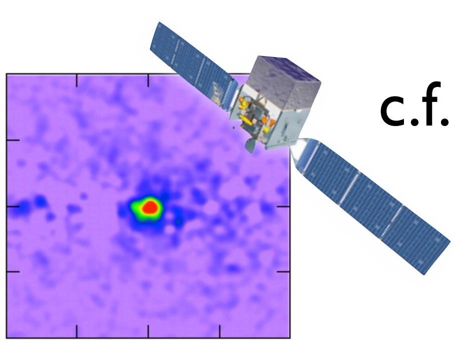
November 2014



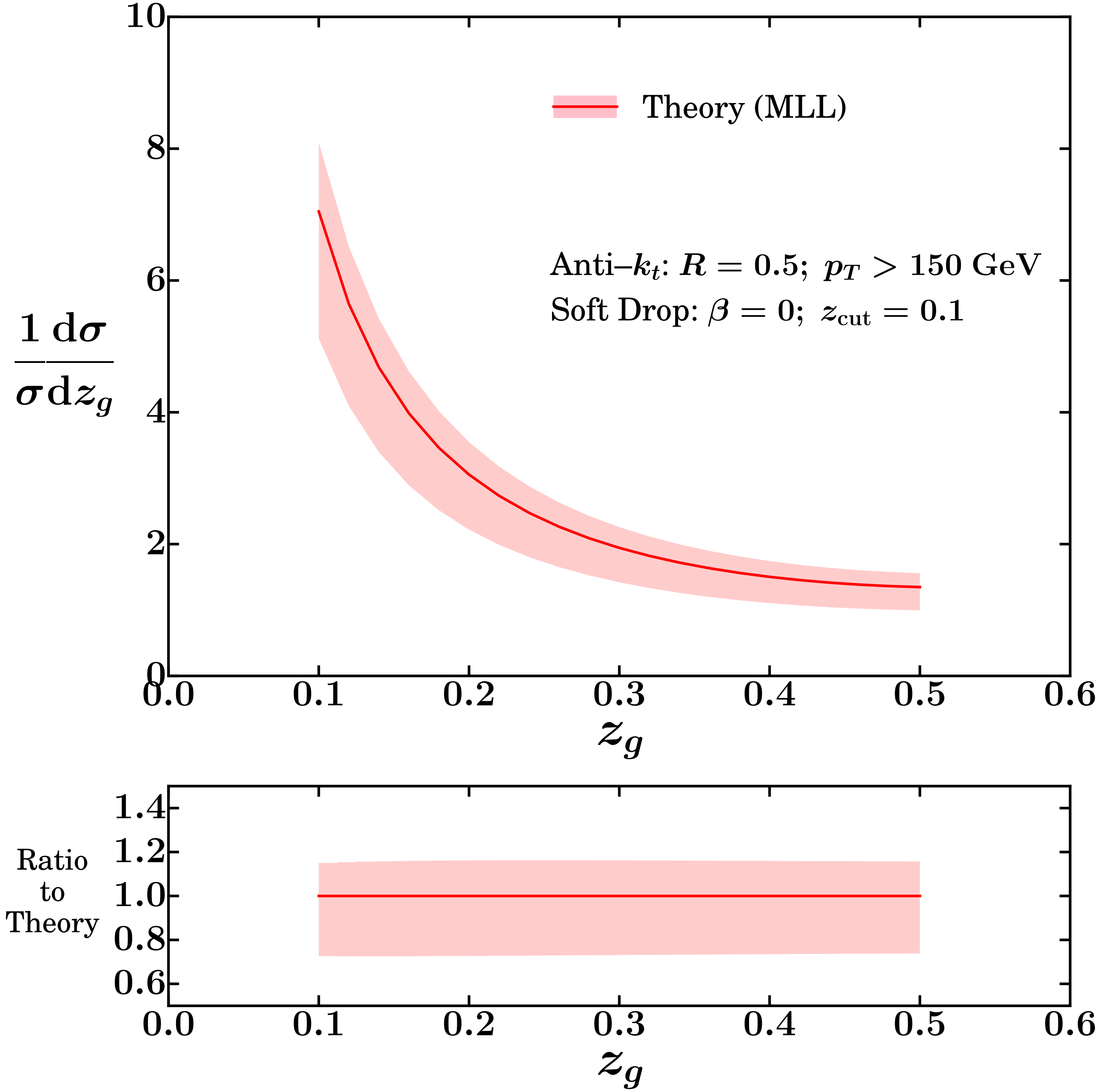
CMS 2010 Data:

≈200k events with hardest jet p_T>150 GeV, very low pileup

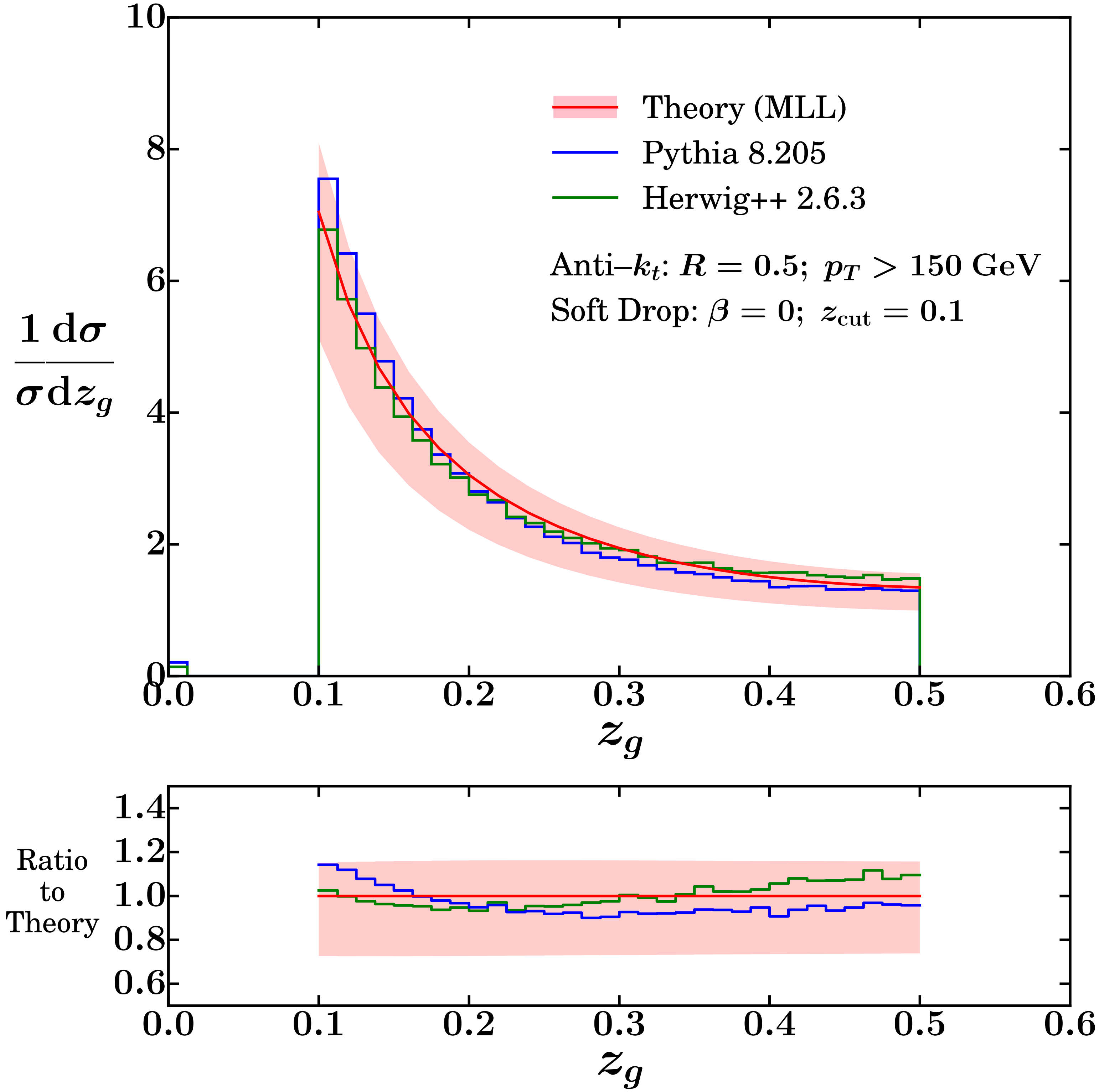
Accelerating science through (judicious) public data releases



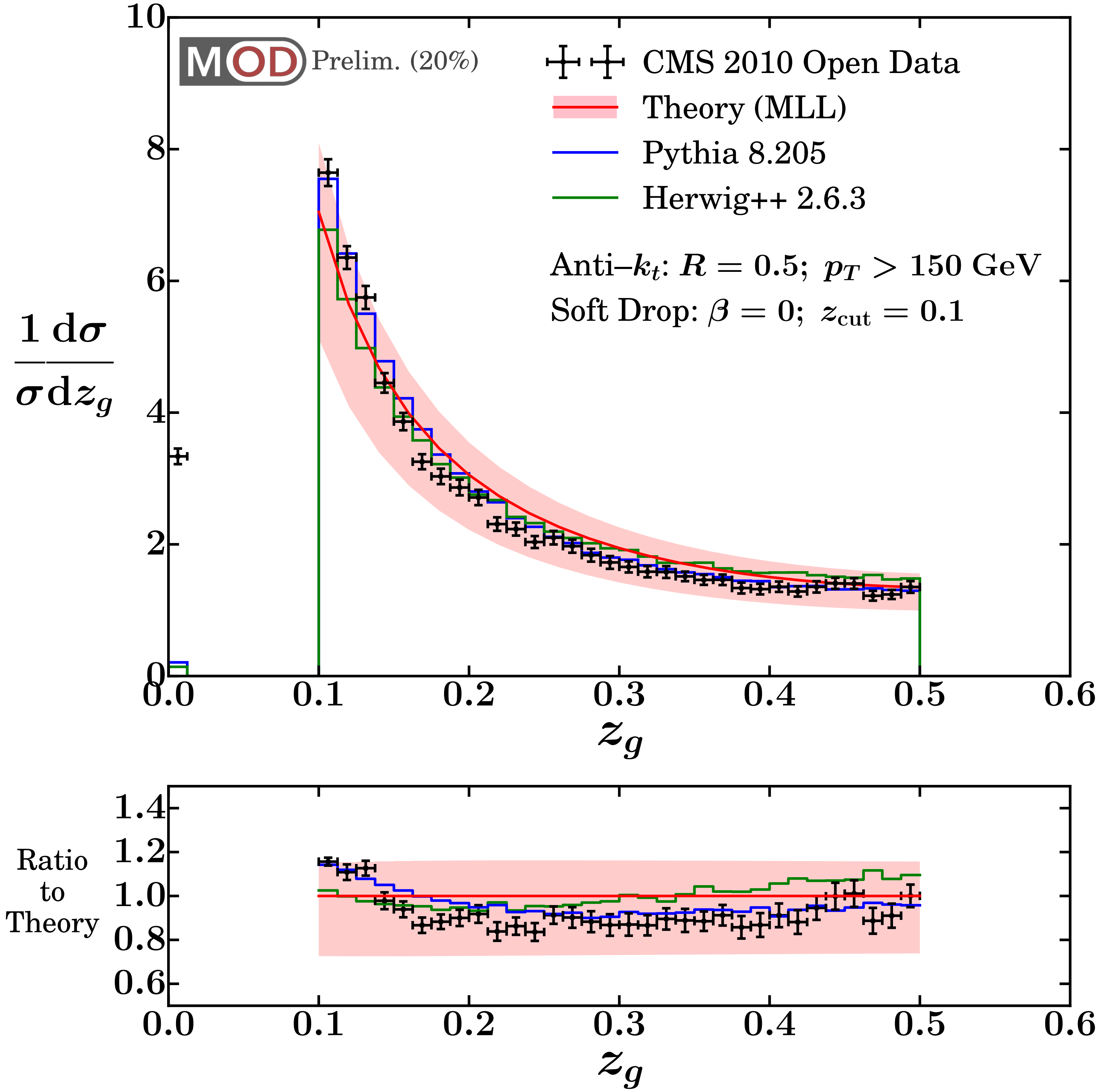
c.f. Fermi



Theory (MLL)
Anti–k_t: $R = 0.5$; $p_T > 150$ GeV
Soft Drop: $\beta = 0$; $z_{\rm cut} = 0.1$
$\frac{1}{\sigma}\frac{d\sigma}{dz_g}$
z_g
Ratio to Theory
0.0 0.1 0.2 0.3 0.4 0.5 0.6
0 2 4 6 8 10
0.6 0.8 1.0 1.2 1.4


Theory (MLL)
Pythia 8.205
Herwig++ 2.6.3
Anti–k_t: $R = 0.5$; $p_T > 150$ GeV
Soft Drop: $\beta = 0$; $z_{\rm cut} = 0.1$
$\frac{1}{\sigma}\frac{d\sigma}{dz_g}$
z_g
Ratio to Theory
0.0 0.1 0.2 0.3 0.4 0.5 0.6
0 2 4 6 8 10
0.6 0.8 1.0 1.2 1.4

Open Data Analysis



p_T > 150 GeV
z_{cut} = 0.1

CMS Open Data: Jet Primary Data Set with Particle Flow Candidates

Statistical uncertainties only, no unfolding, 58021 events

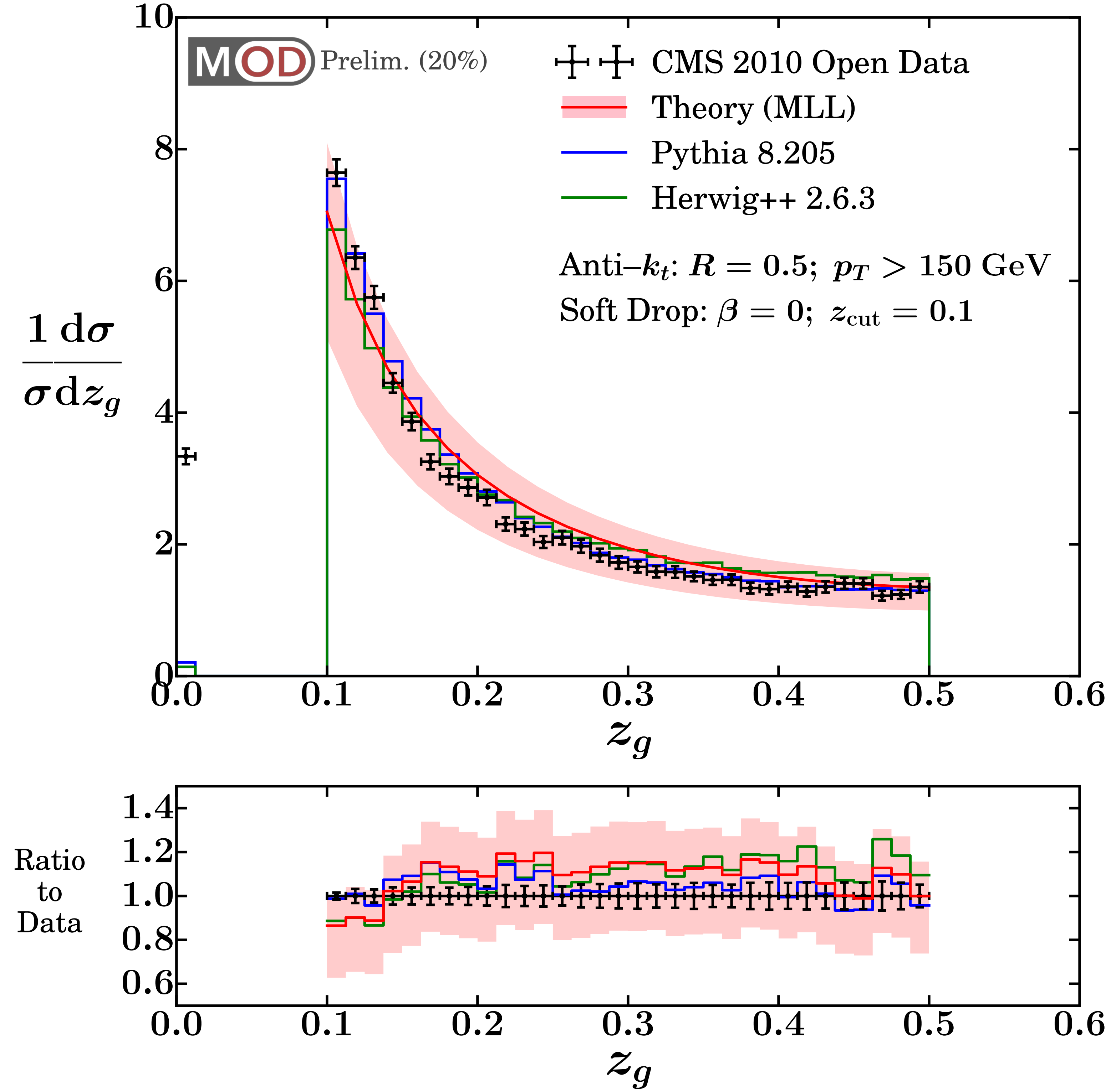
Using single jet triggers with ≈100% efficiency, AK5 jet energy corrections with area subtraction, no PFC corrections

AOD → MOD format (MIT Open Data project)

More plots in backup slides

[Thanks to Sal Rappoccio, **Aashish Tripathee**, Wei Xue]

Open Data Analysis



As nature intended:

$p_T > 150$ GeV
$z_{cut} = 0.1$

CMS Open Data: Jet Primary Data Set with Particle Flow Candidates

Statistical uncertainties only, no unfolding, 58021 events

Using single jet triggers with ≈100% efficiency, AK5 jet energy corrections with area subtraction, no PFC corrections

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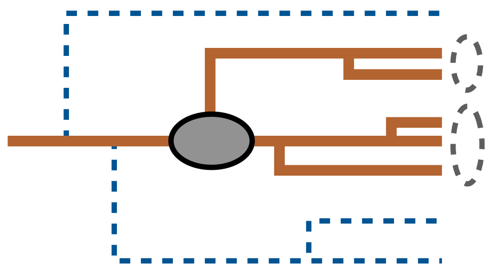
More plots in backup slides

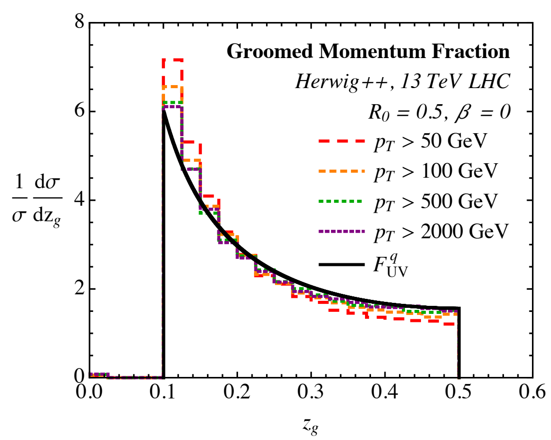
[Thanks to Sal Rappoccio, **Aashish Tripathee**, Wei Xue]

Summary



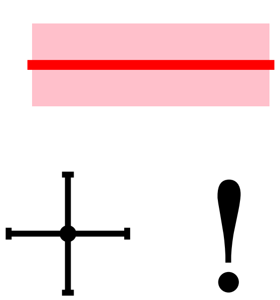
From Soft Drop to Splitting Functions

Jet grooming to expose two-prong energy sharing "z"
Makes concrete what we already intuit from jet substructure



From Sudakov Safety to Standard Candles

All orders in α_s yields new insights into QFT
New way to measure the universal singularity structure of QCD

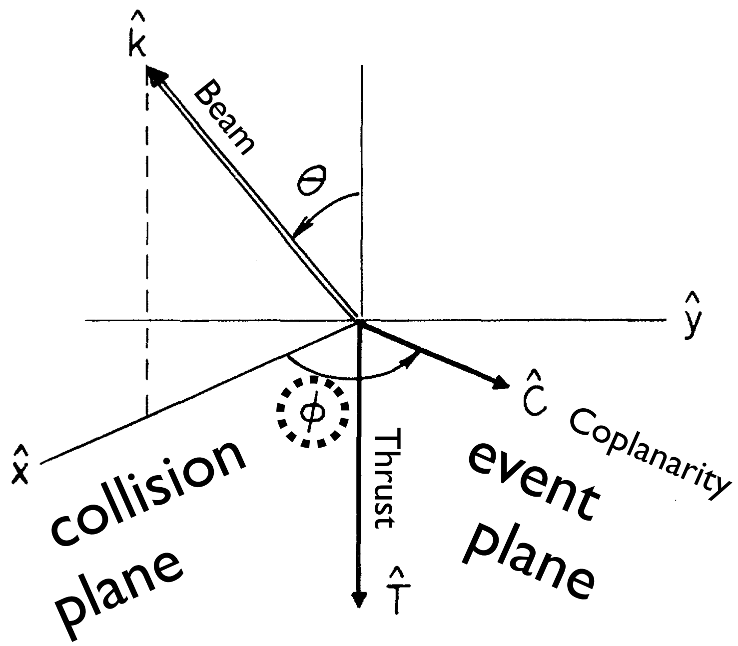


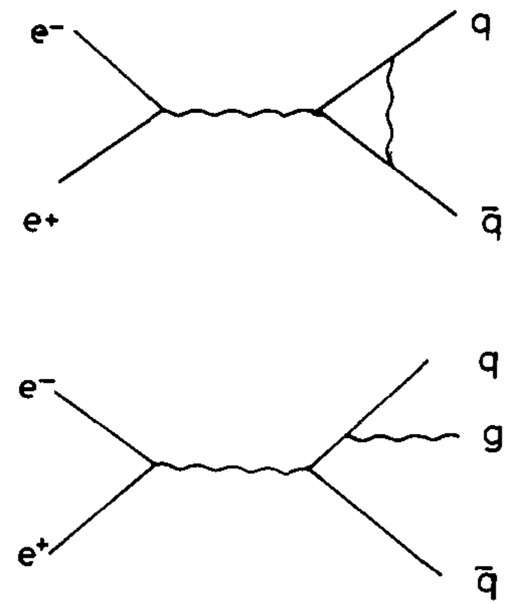
From Theory to Experiment

The future is now: idea + simulation + calculation + open data analysis
Can open data enhance theory/experiment interface?

Backup Slides

3. Learn from Our Elders





φ ambiguous

φ well-defined

Me: "φ is IRC unsafe"

My Elder: "We explicitly calculated dσ/dφ in 1978"

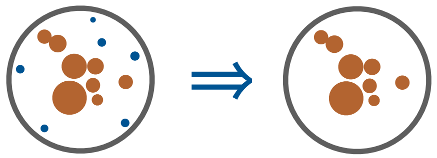
$$\frac{2\pi}{\sigma_0}\frac{d\sigma}{d\varphi} = 1 + O(\alpha_s(Q^2)) + \frac{\alpha_s(Q^2)}{\pi}\left(\frac{16}{3}\ln\frac{3}{2} - 2\right)\cos 2\varphi$$

↑ Born cross section despite ambiguity (!)

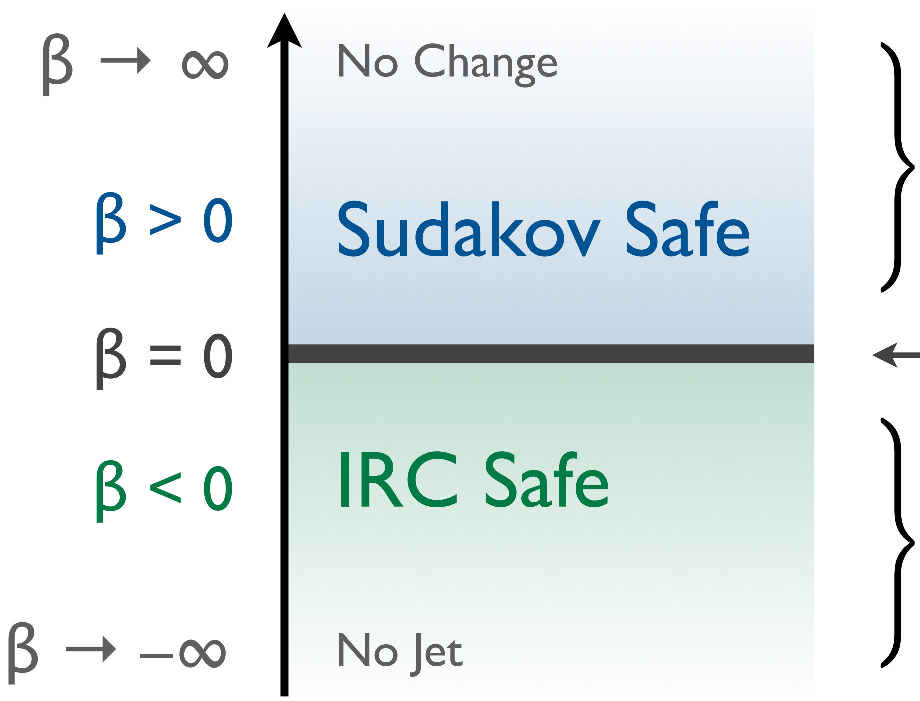
Lesson: Use IRC limit to resolve ambiguities

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

“Phase Diagram” for Observables



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



$$\sqrt{\frac{\alpha_s C_i}{\beta}}\,\overline{P}_i(z_g) + \ldots$$

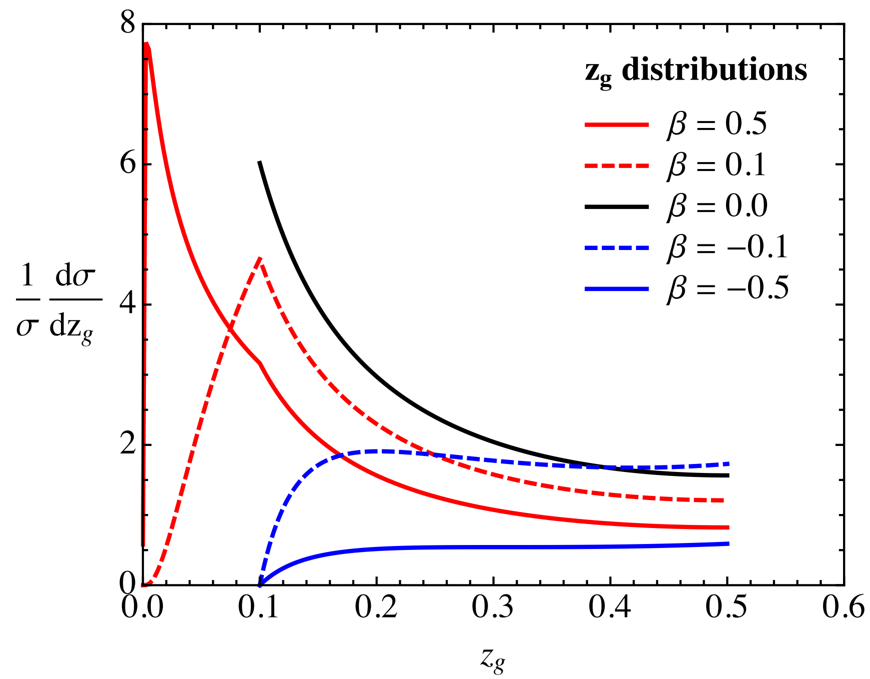
$$\frac{\overline{P}_i(z_g)}{\int_{z_{\rm cut}}^{1/2} dz\, \overline{P}_i(z)} + \ldots$$

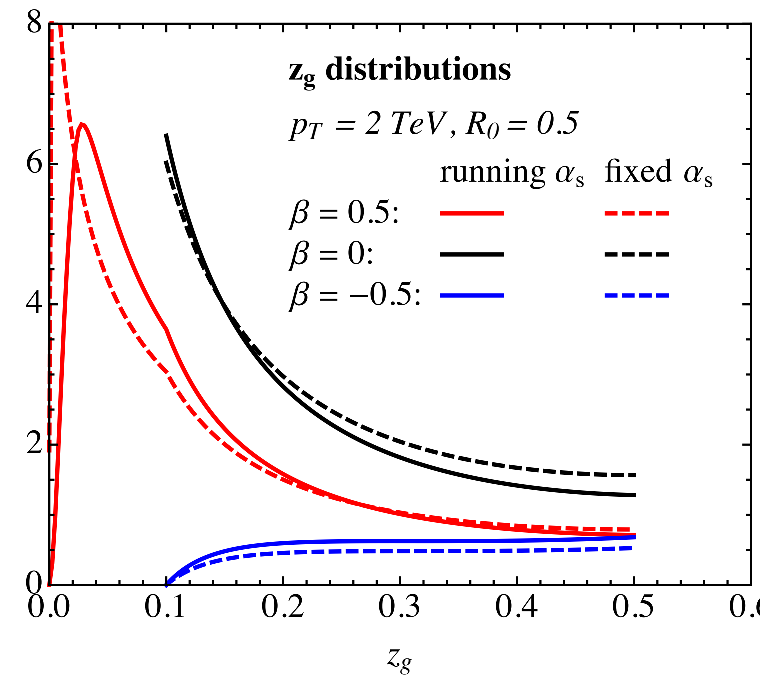
UV fixed point of RG evolution

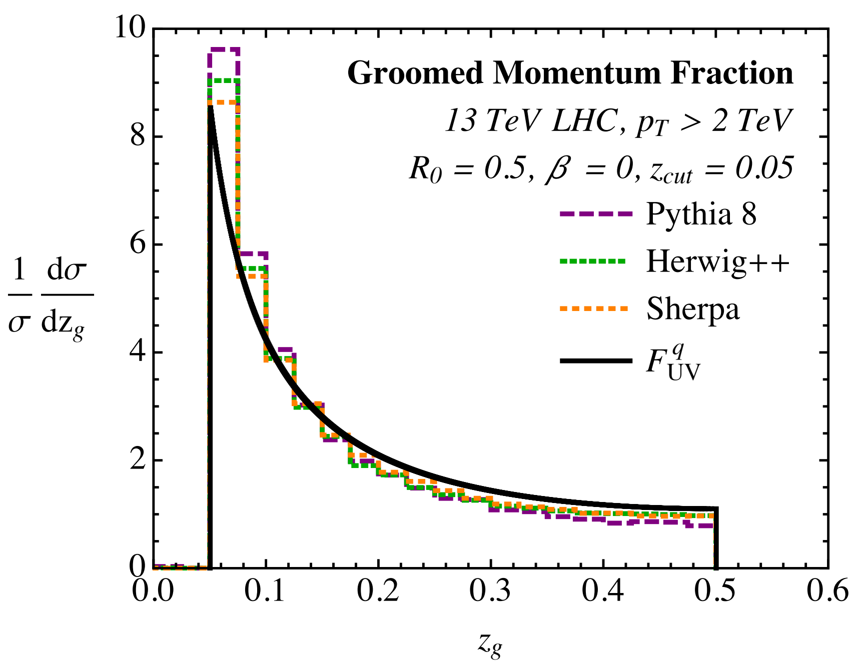
$$\frac{2\alpha_s C_i}{\pi|\beta|}\,\overline{P}_i(z_g)\log\frac{z_g}{z_{\rm cut}} + \ldots$$

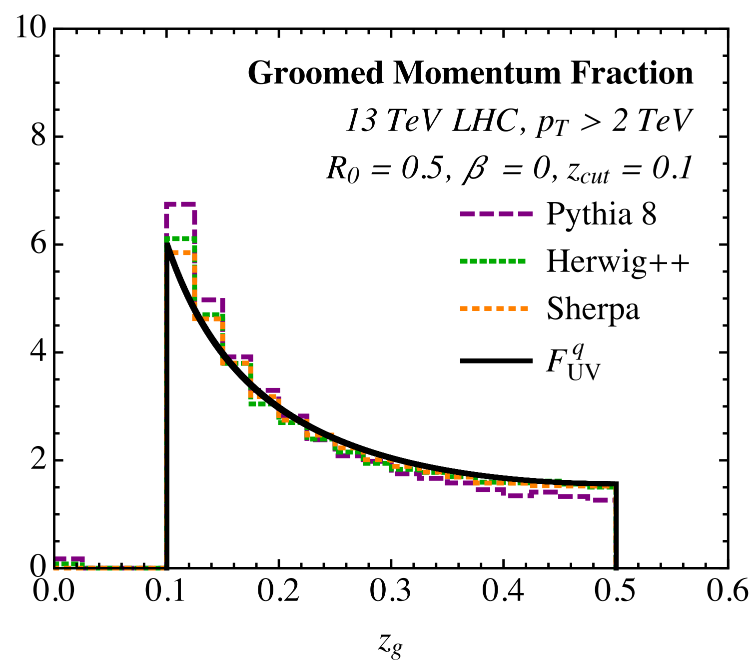
[Larkoski, Marzani, JDT, 1502.01719]

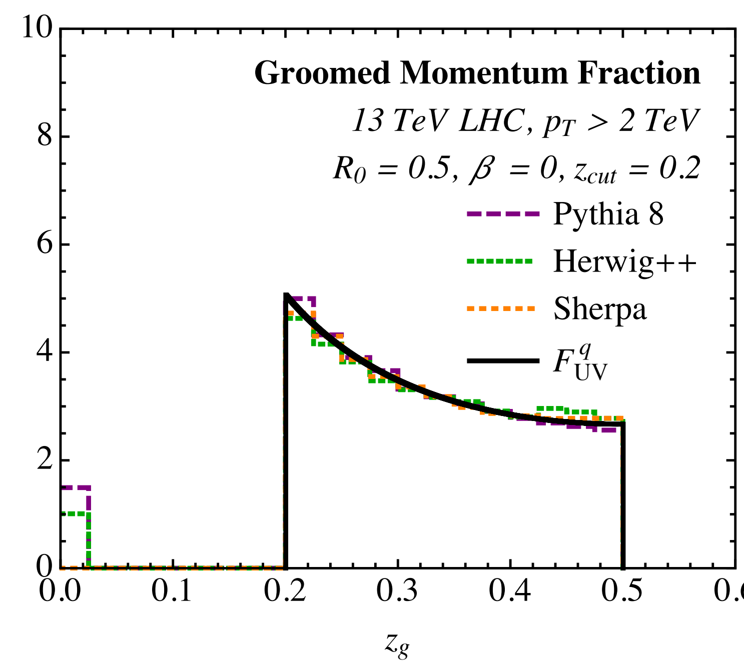
Additional z_g Theory Plots









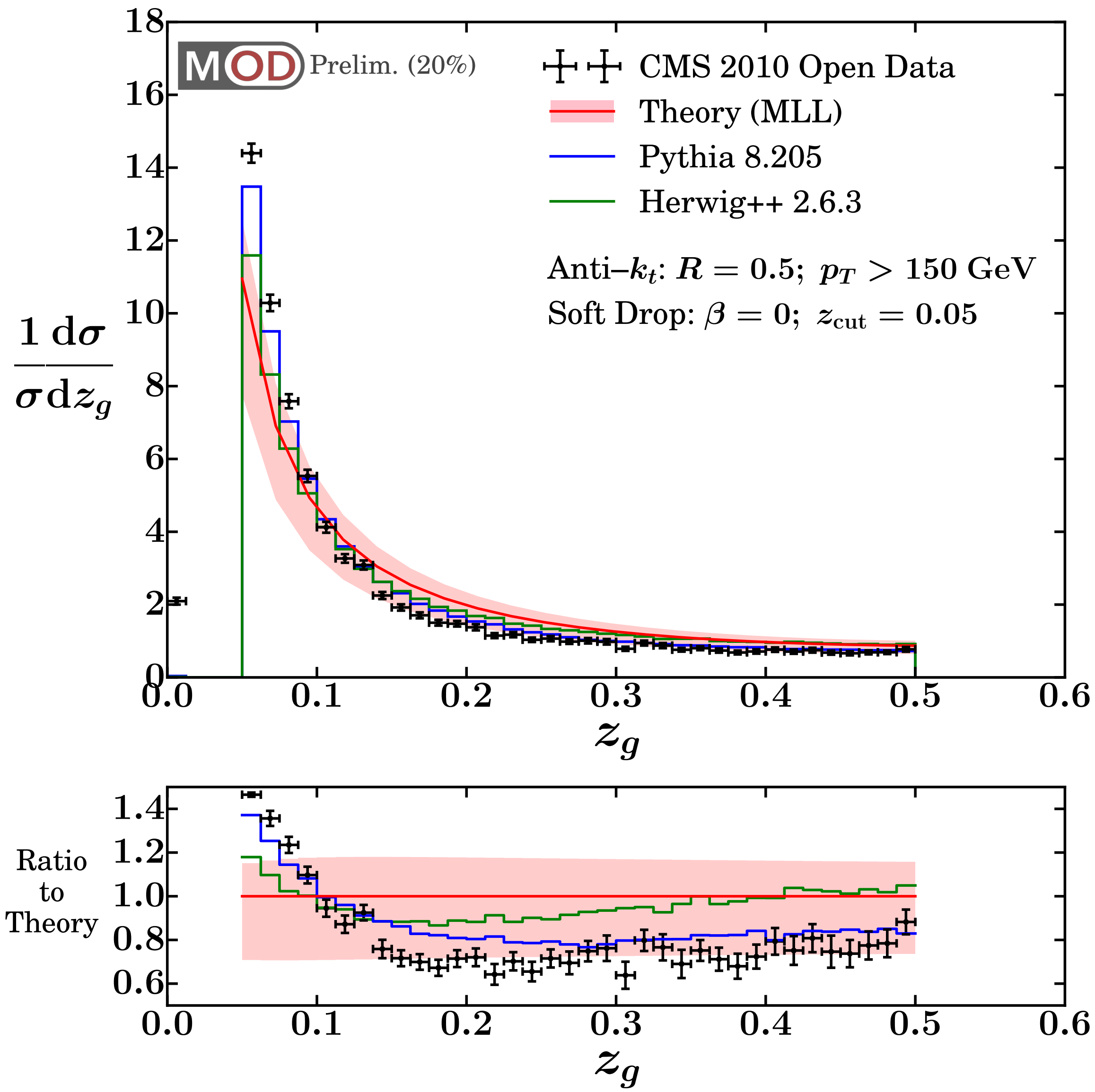


[Larkoski, Marzani, JDT, 1502.01719]

Additional z_{cut} Values

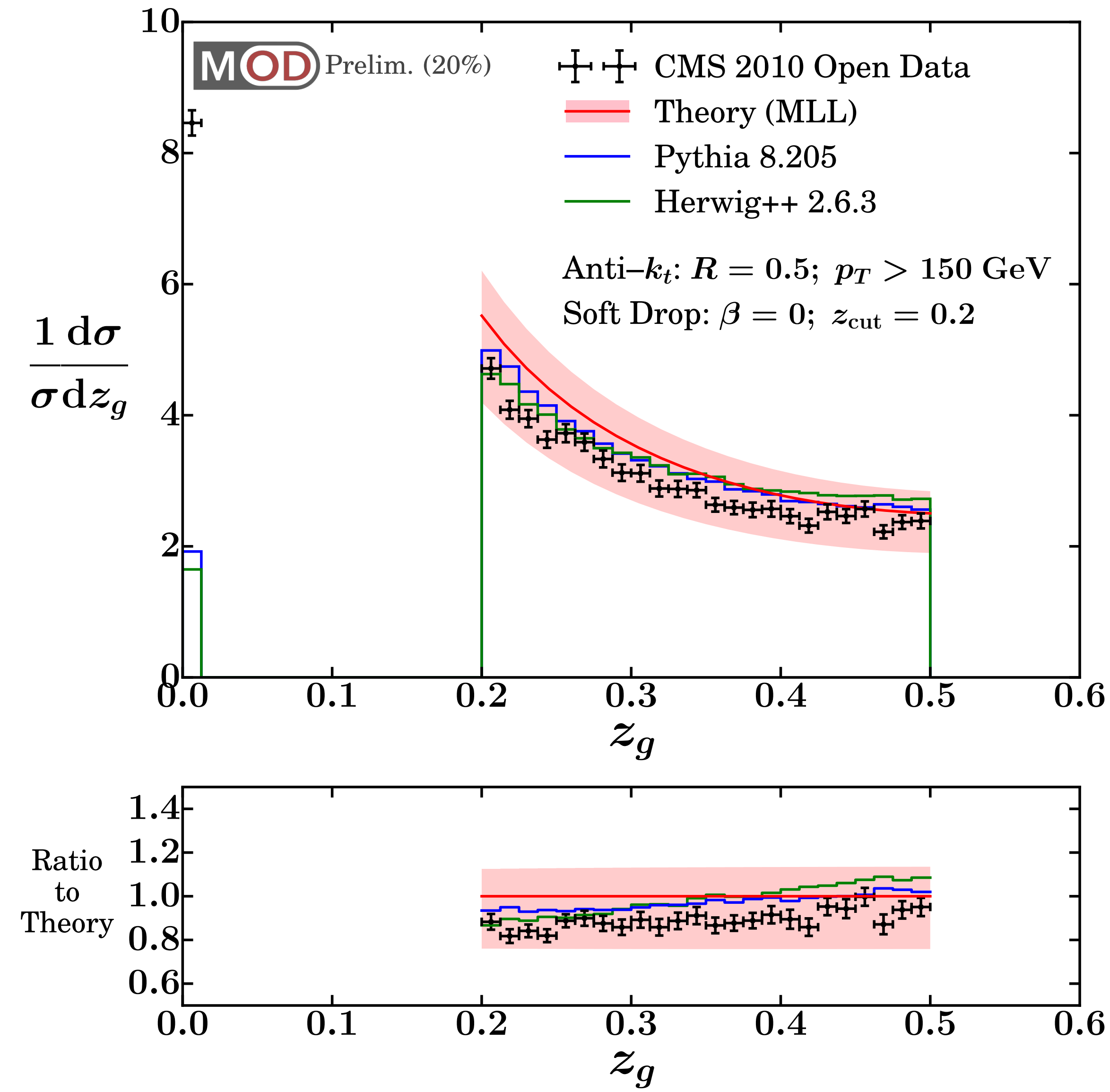
p_T > 150 GeV

z_{cut} = 0.05



58021 events

z_{cut} = 0.2



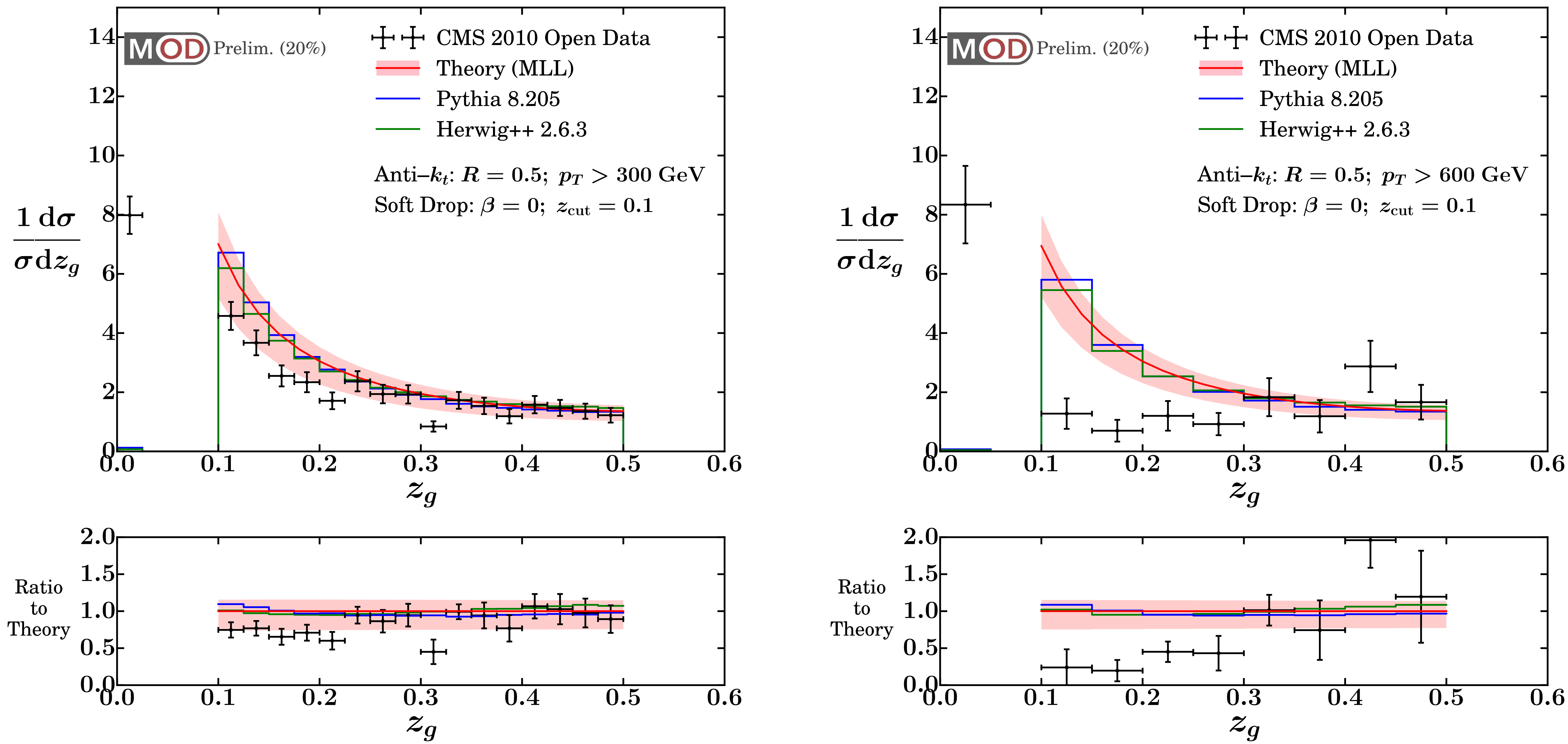
58021 events

Additional $p_{T\mathrm{cut}}$ Values

$z_{\mathrm{cut}} = 0.1$

$p_T > 300$ GeV

$p_T > 600$ GeV



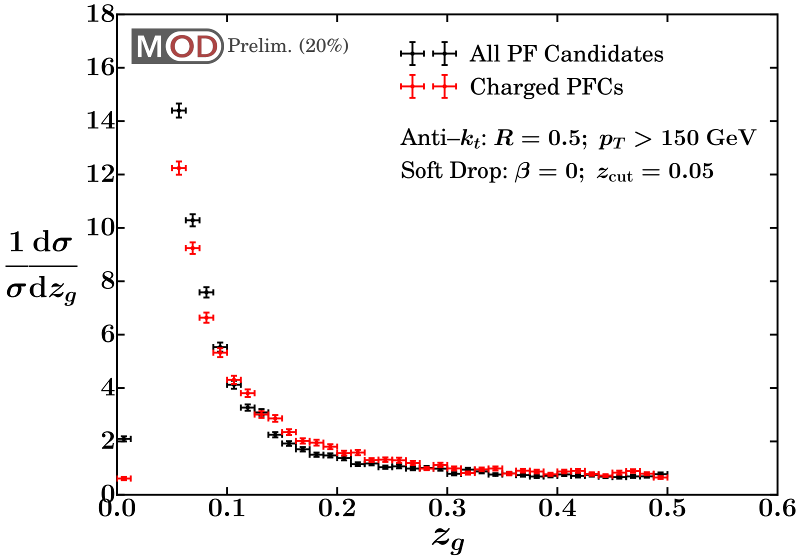
2316 events

323 events

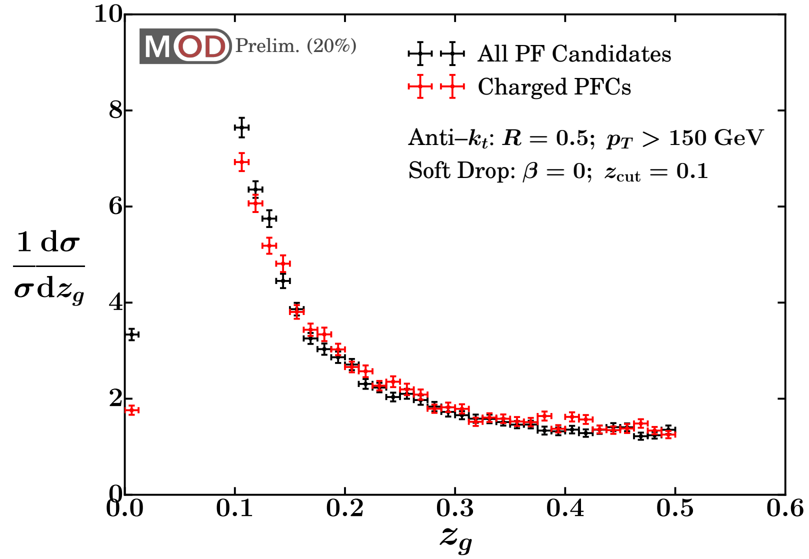
All Particles vs. Track Only

p_T > 150 GeV

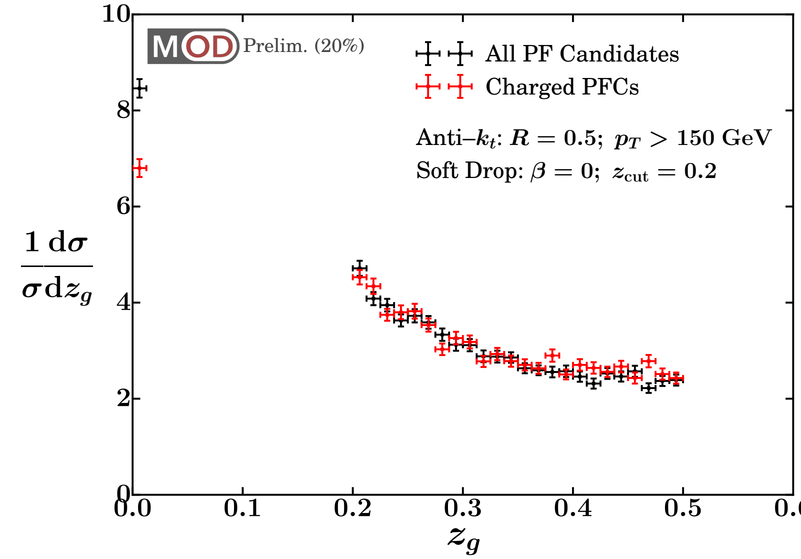
z_{cut} = 0.05



z_{cut} = 0.1

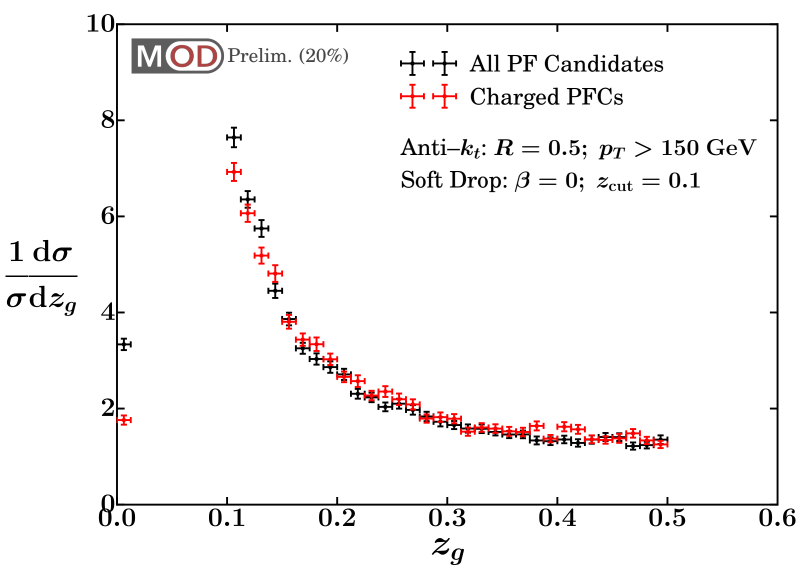


z_{cut} = 0.2

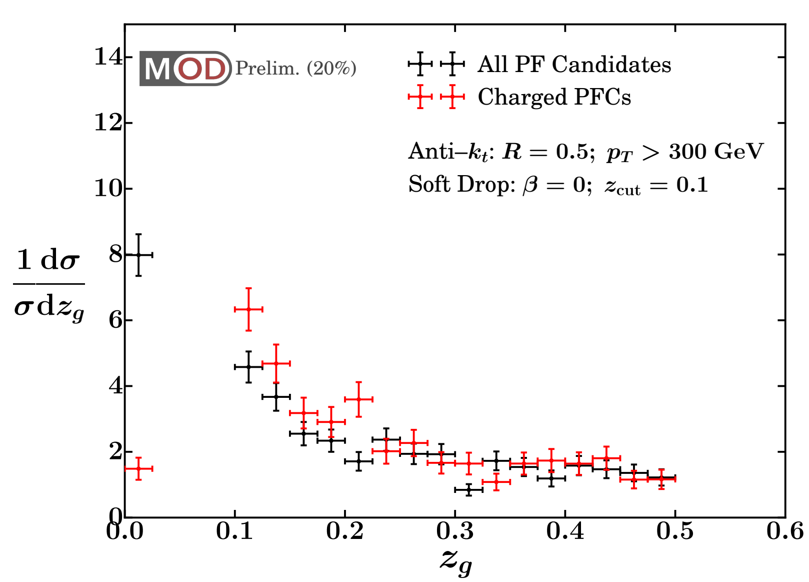


z_{cut} = 0.1

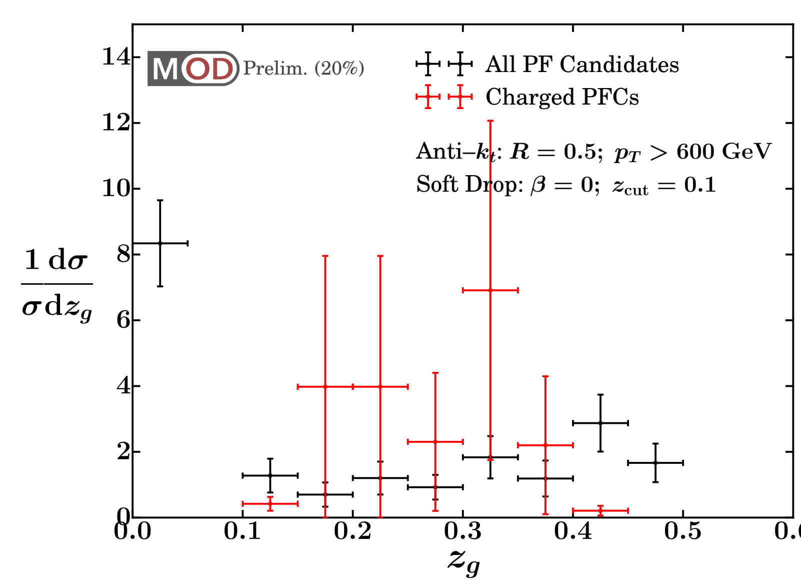
p_T > 150 GeV



p_T > 300 GeV



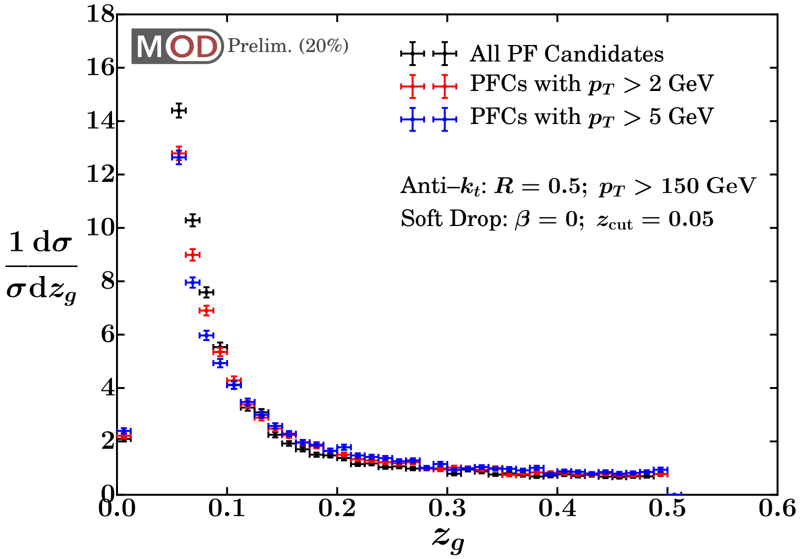
p_T > 600 GeV



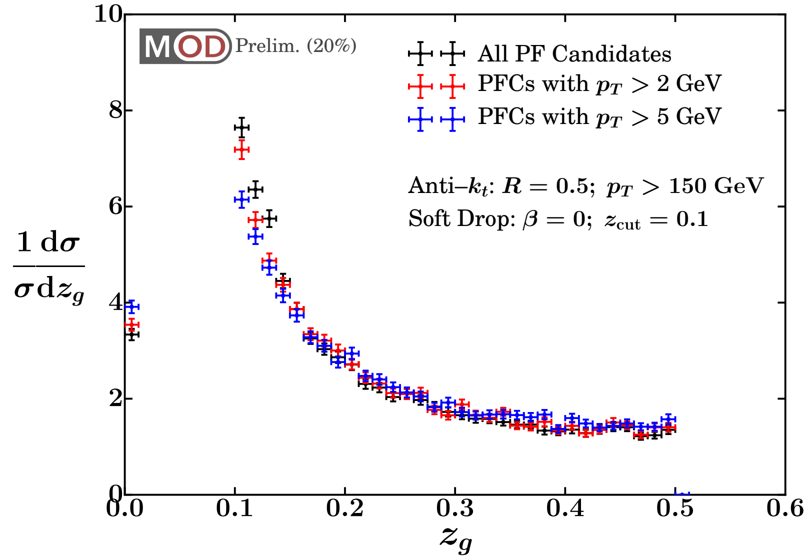
Applying Pseudo SoftKiller

p_T > 150 GeV

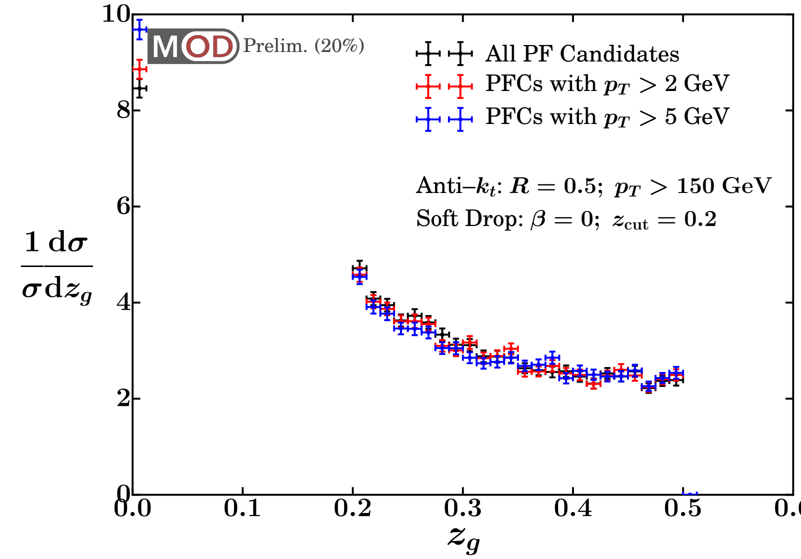
z_{cut} = 0.05



z_{cut} = 0.1

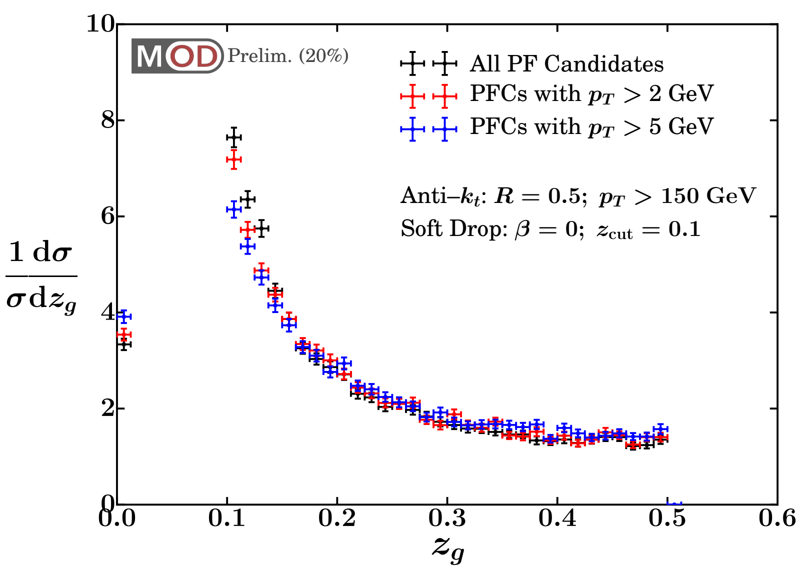


z_{cut} = 0.2

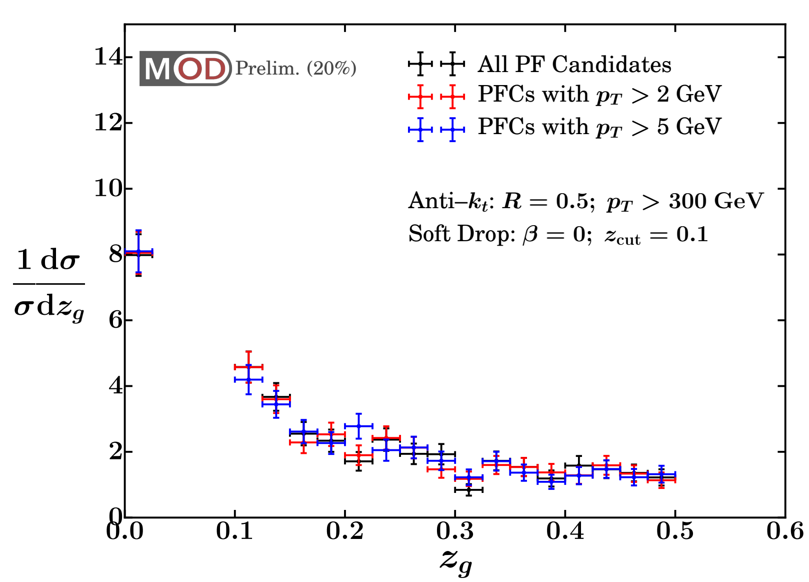


z_{cut} = 0.1

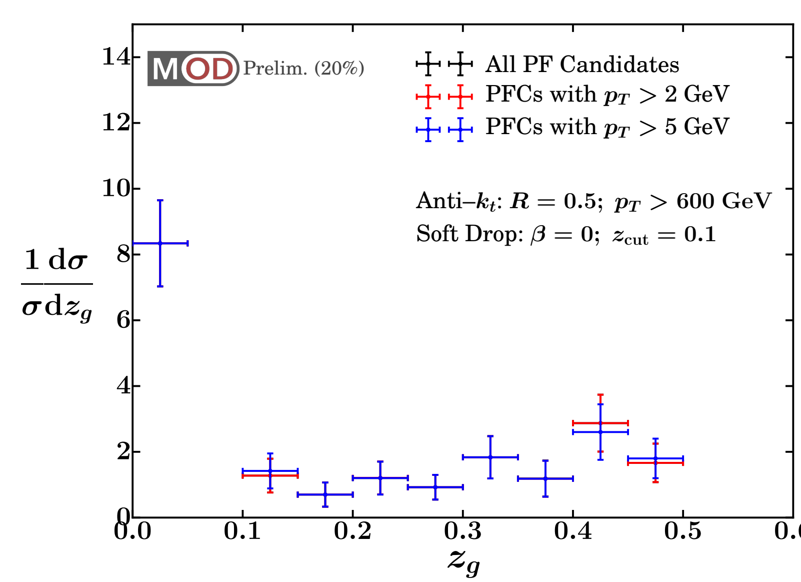
p_T > 150 GeV



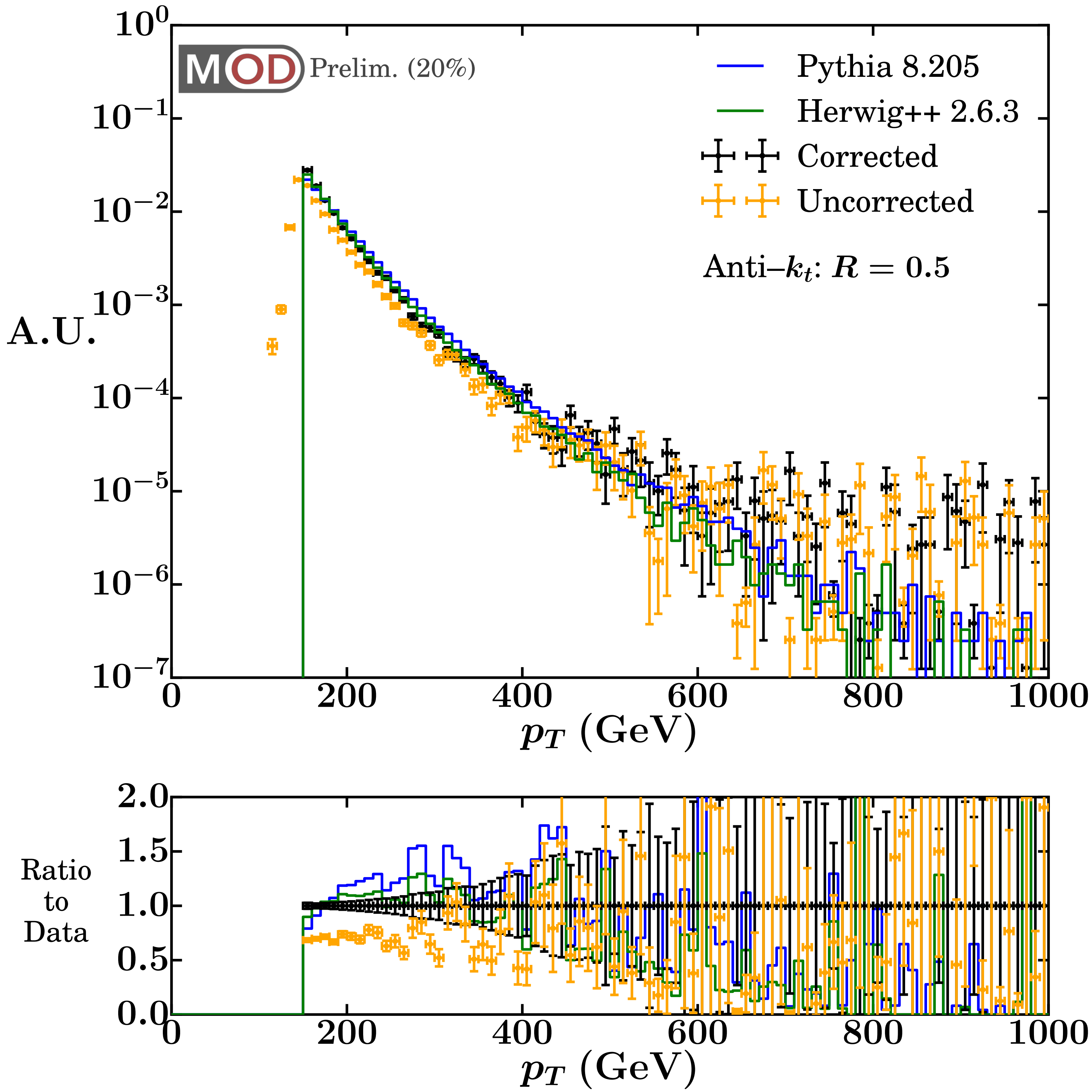
p_T > 300 GeV



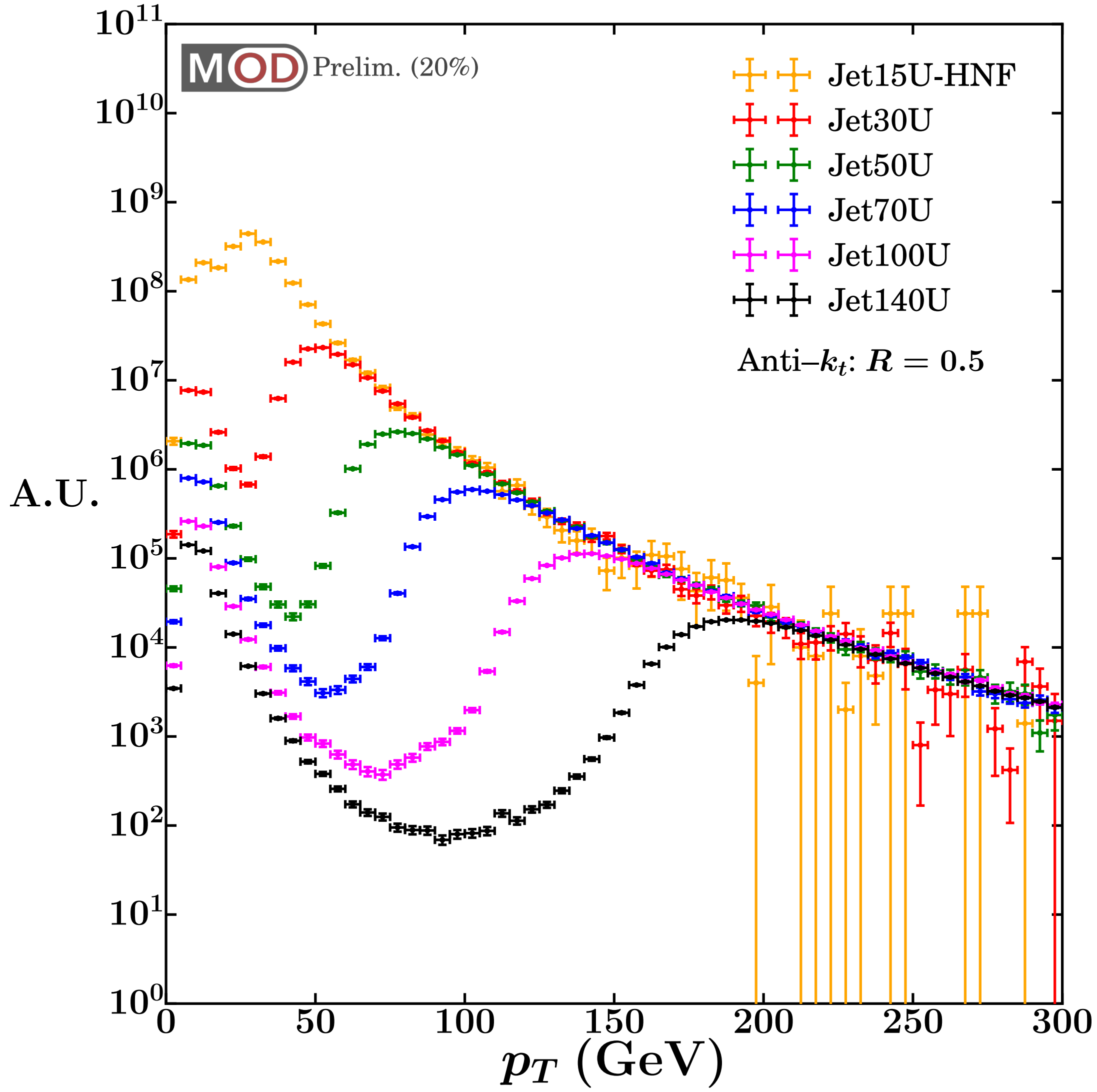
p_T > 600 GeV

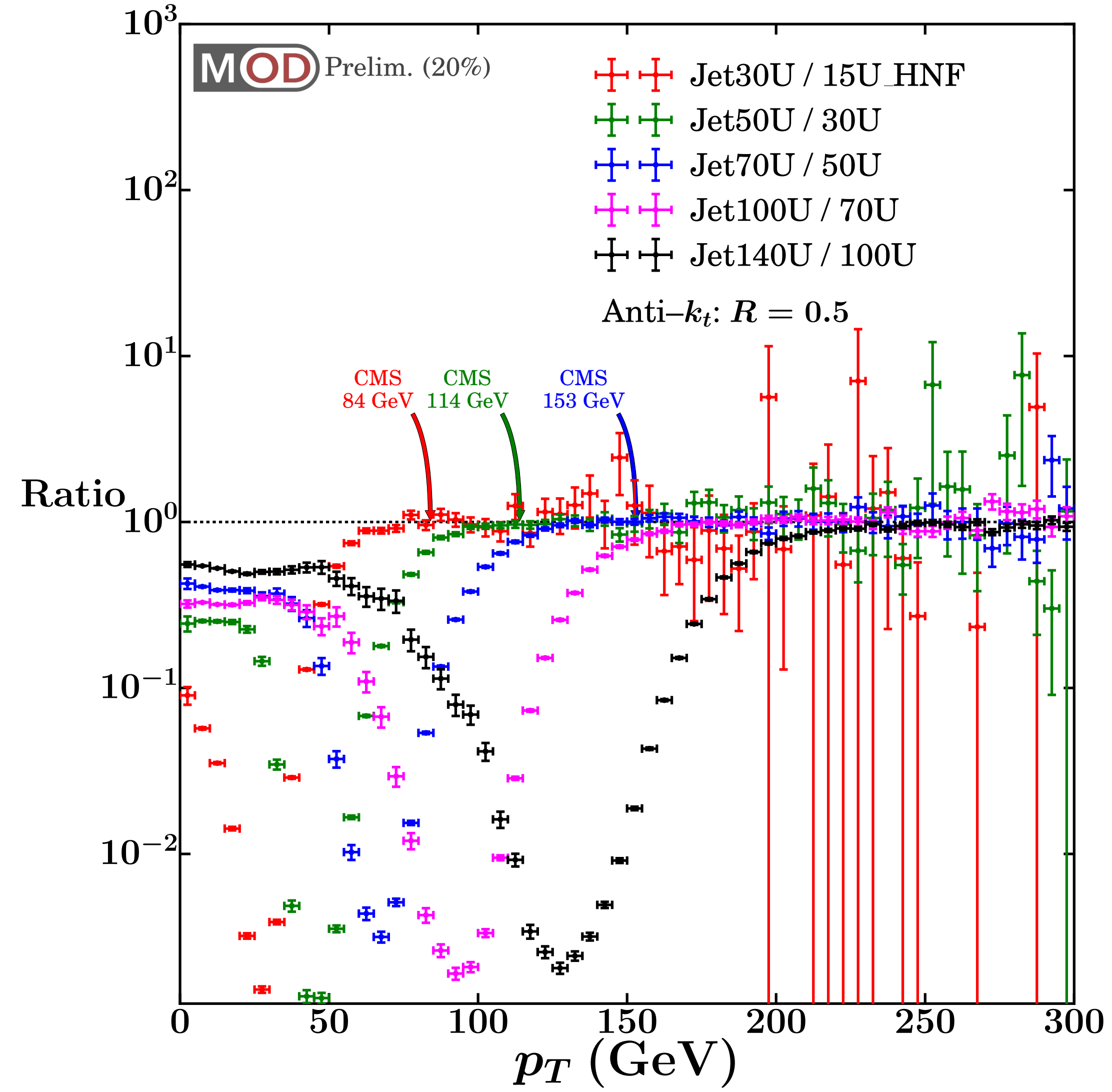


CMS Corrected Jet p_T Spectrum



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