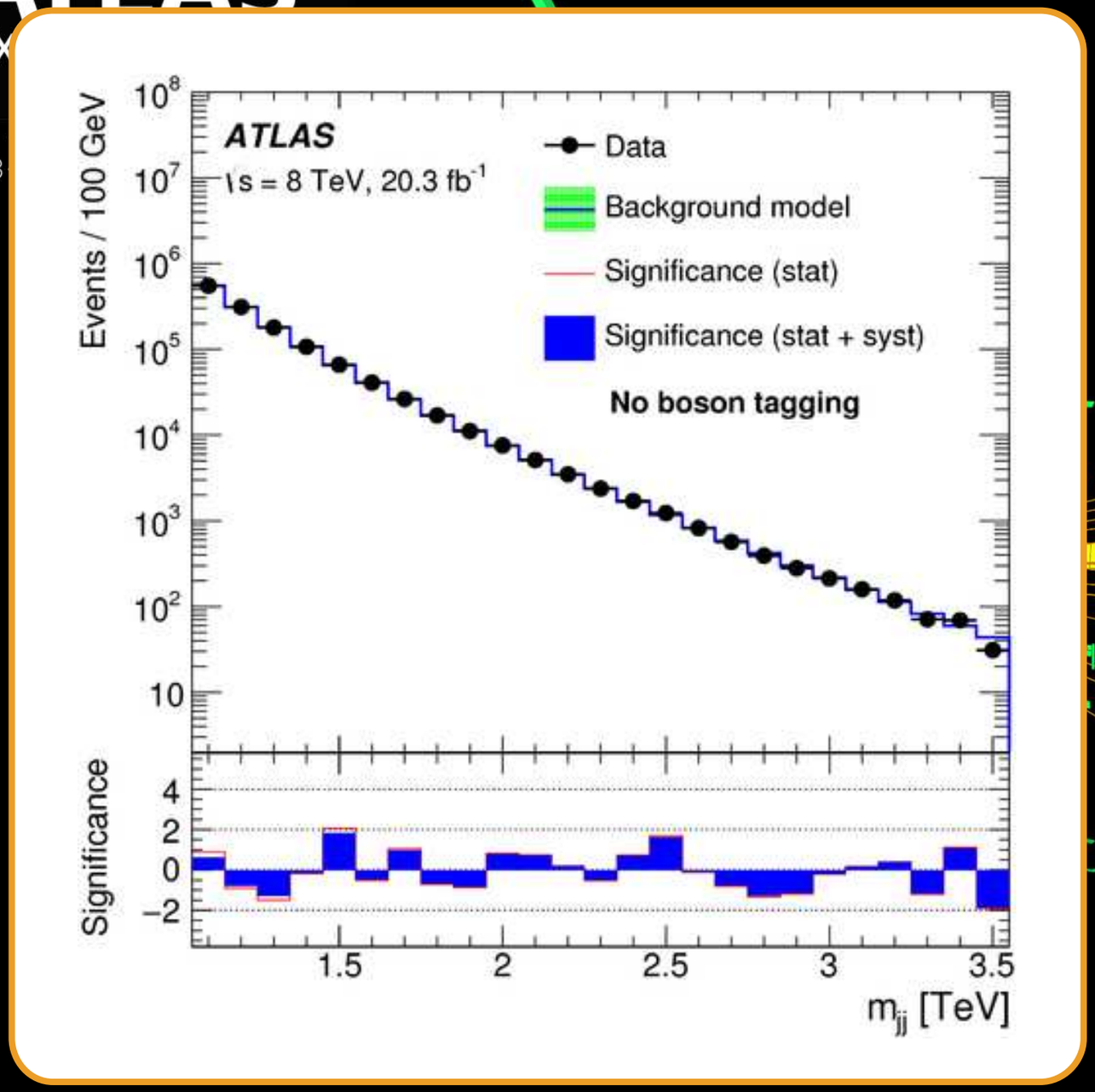
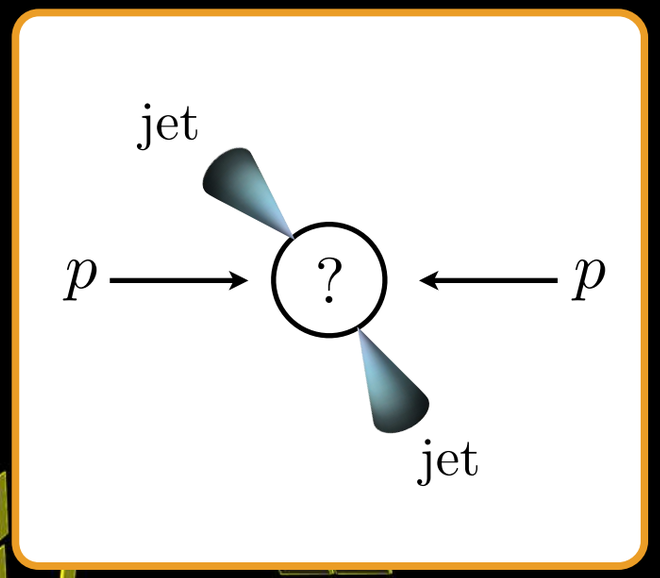
Probing the Core of QCD with Jet Substructure

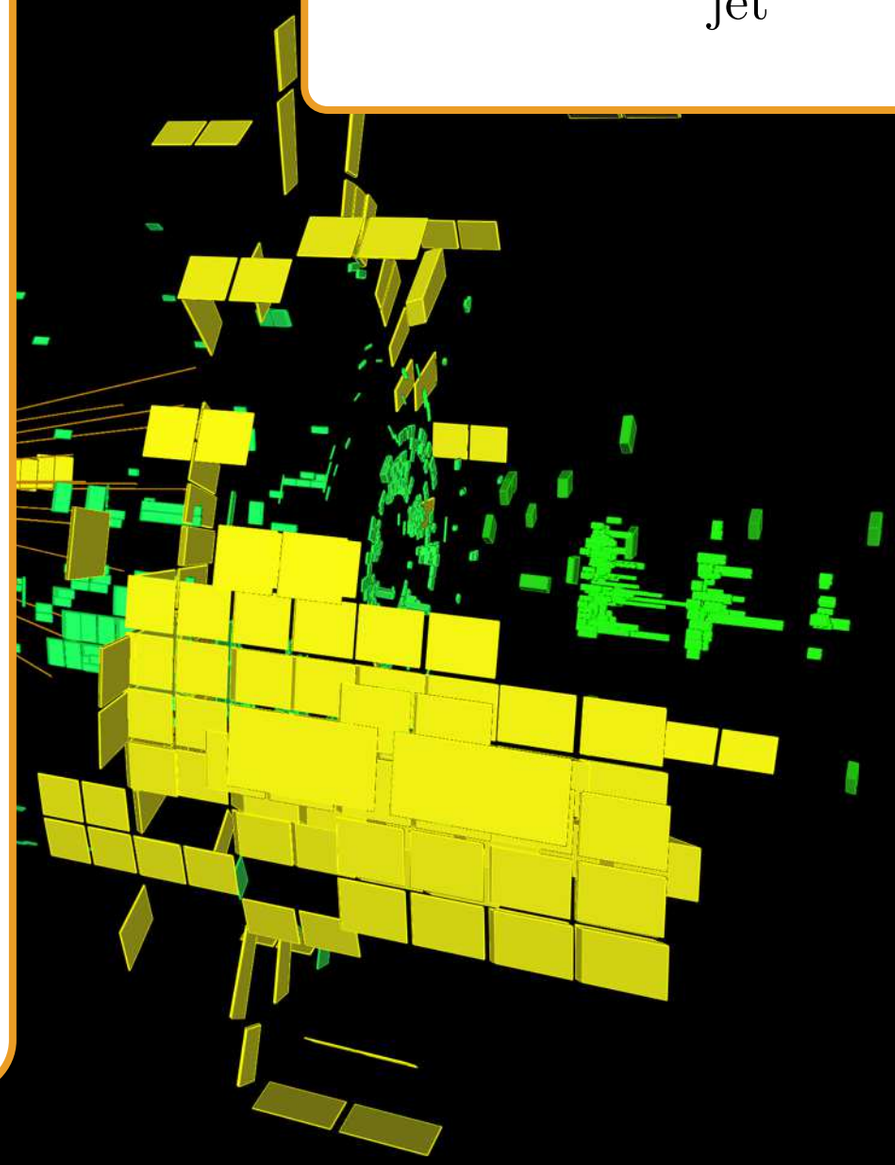
Jesse Thaler

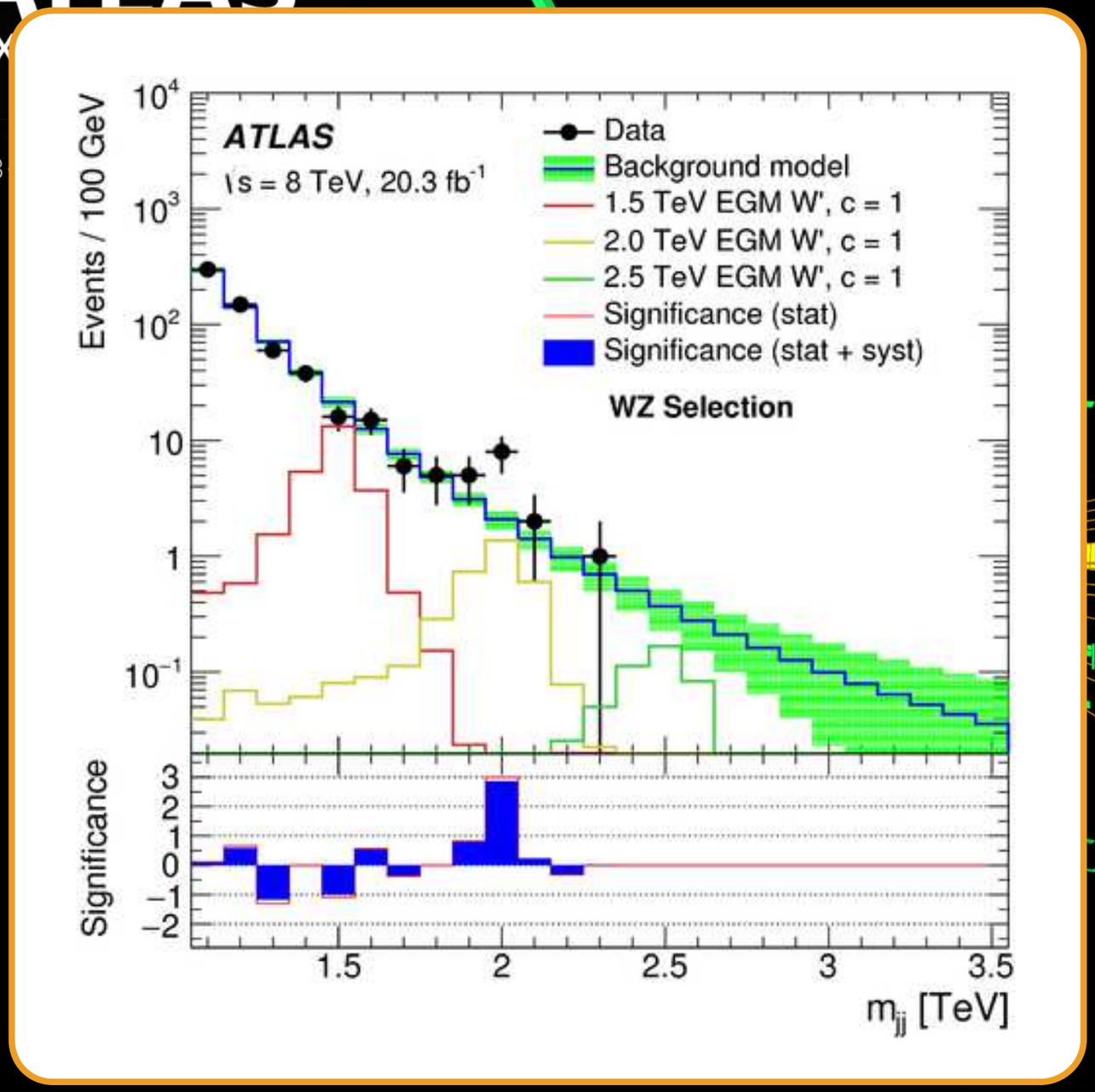
Fermilab Joint Experimental-Theoretical Physics Seminar — May 6, 2016

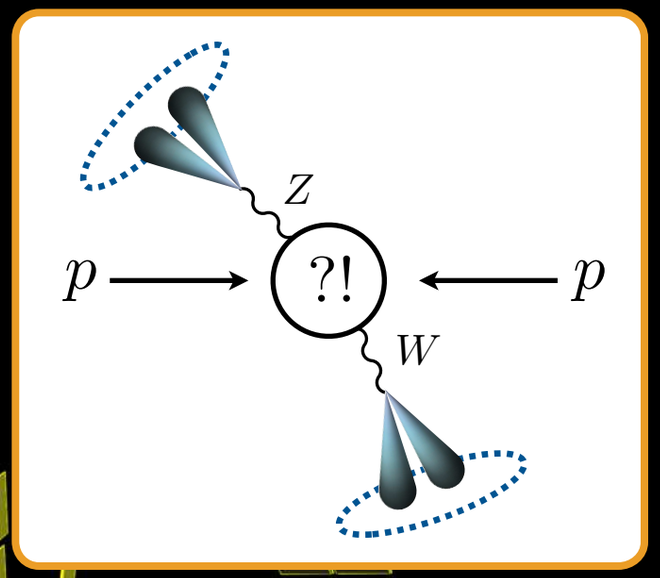
Event:
2015-08

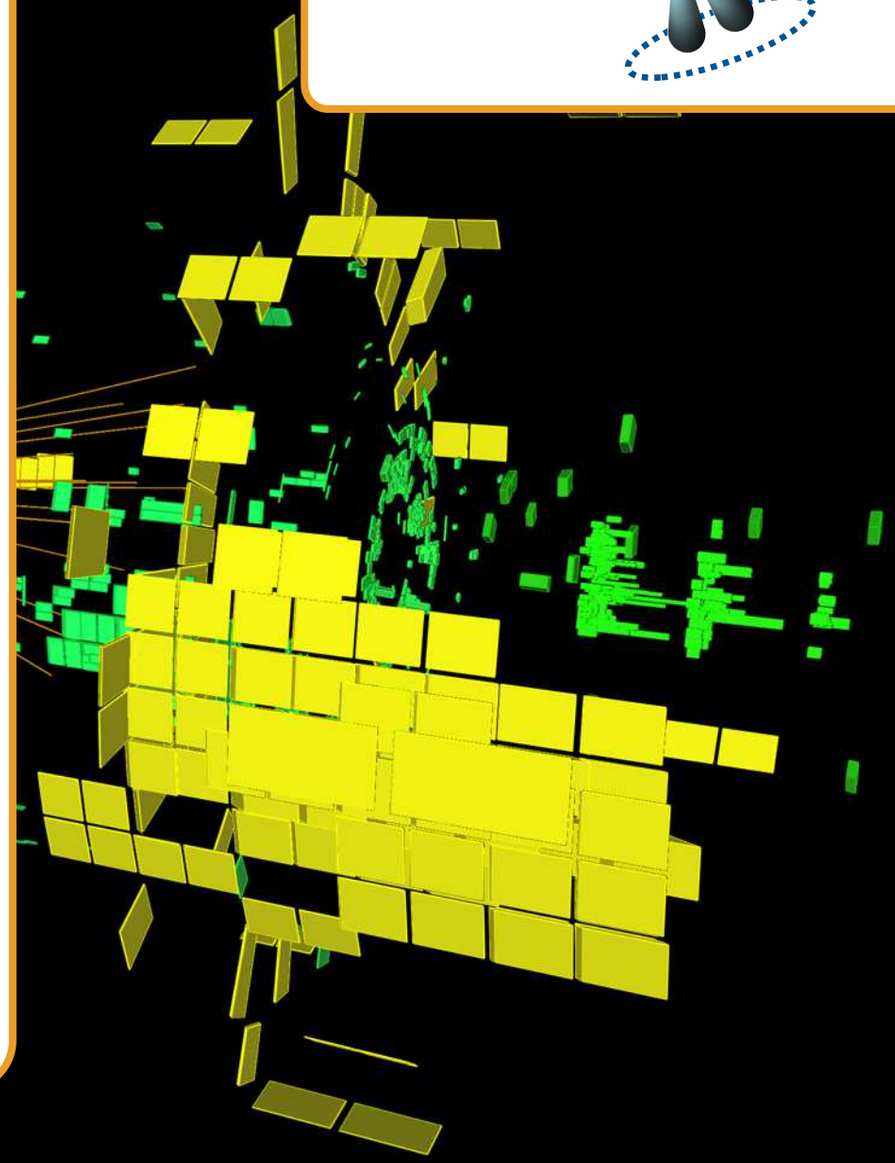


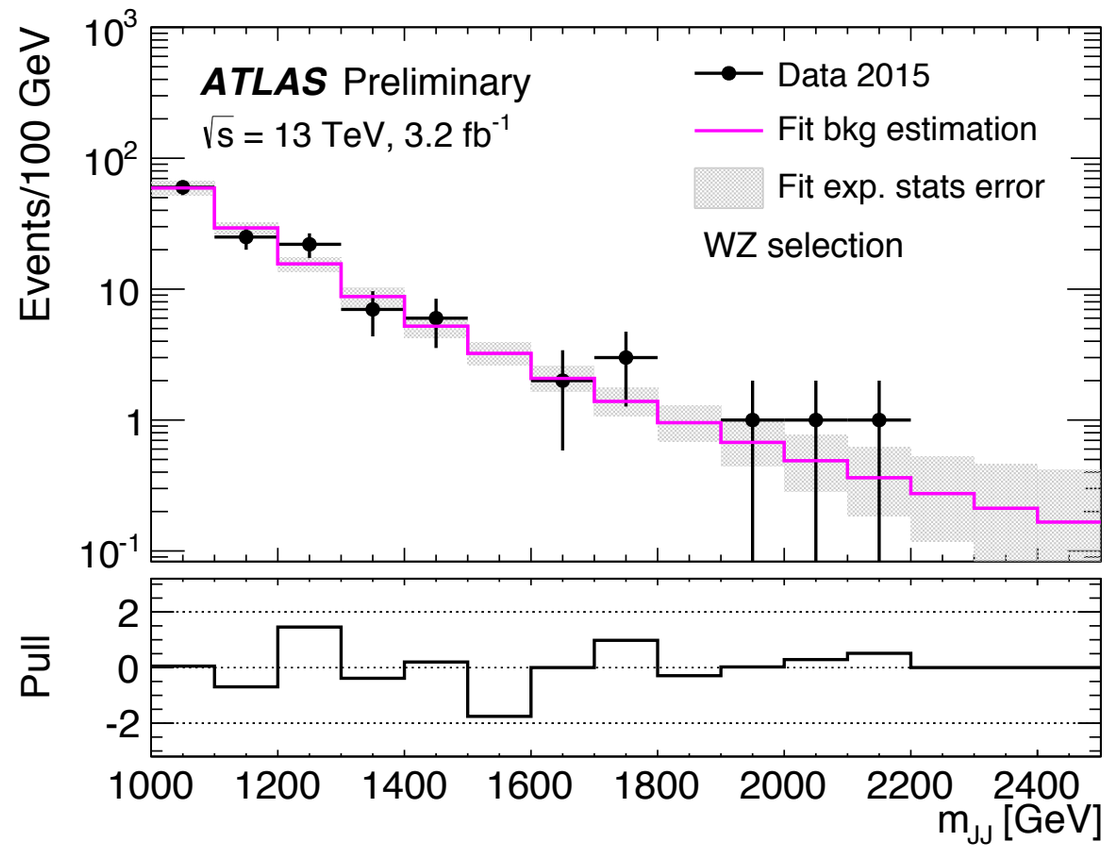




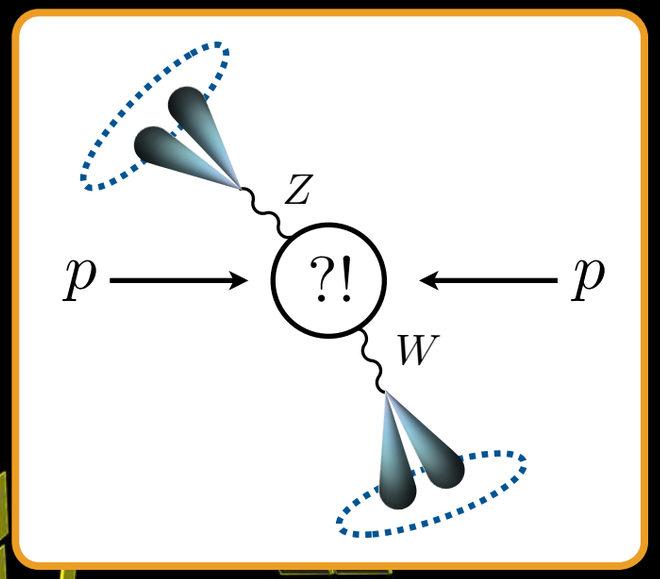

ATLAS
√s = 8 TeV, 20.3 fb⁻¹
Data
Background model
1.5 TeV EGM W', c = 1
2.0 TeV EGM W', c = 1
2.5 TeV EGM W', c = 1
Significance (stat)
Significance (stat + syst)
WZ Selection
Events / 100 GeV
Significance
m_jj [TeV]

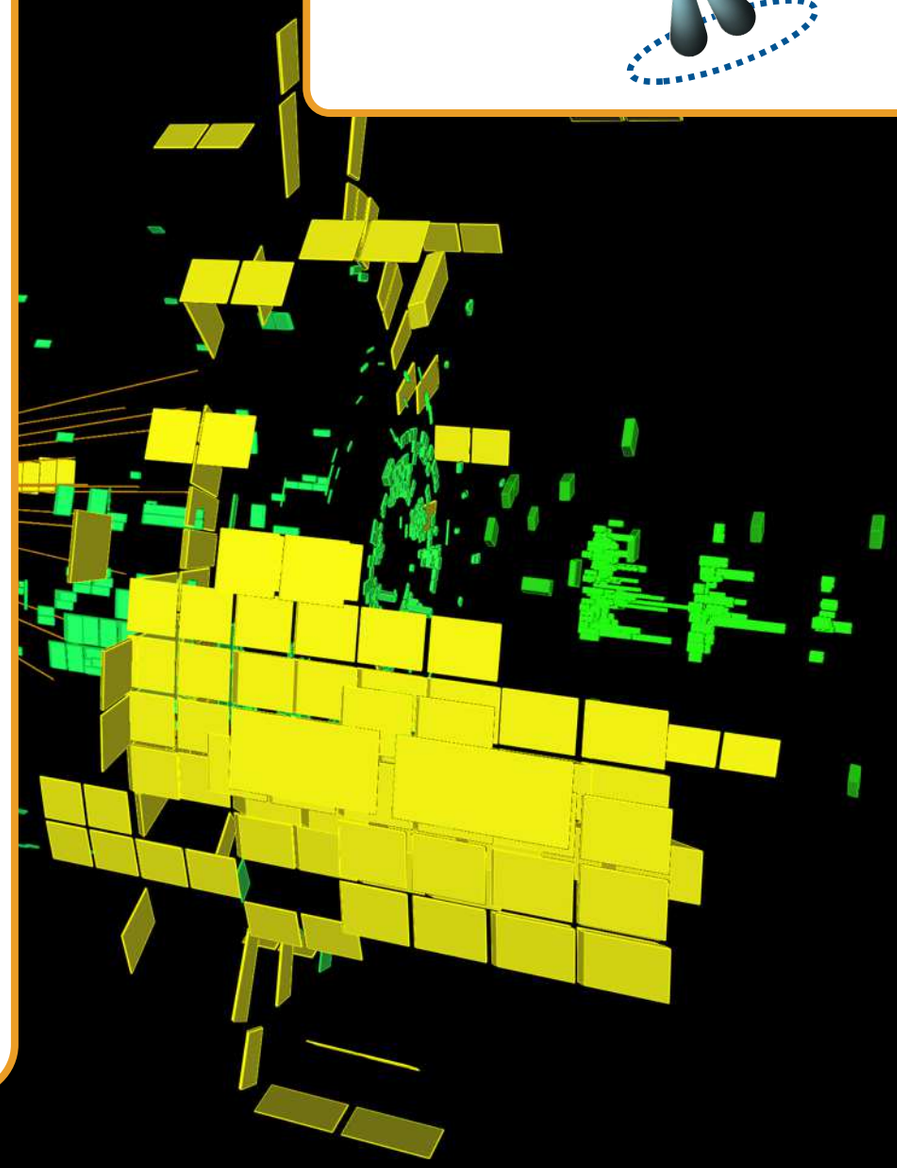

Z
p
?!
p
W



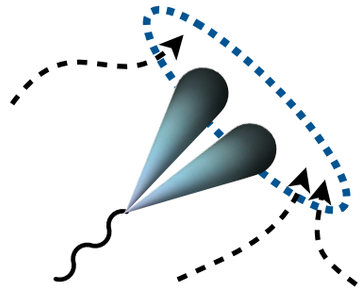


Bumps may come and go…

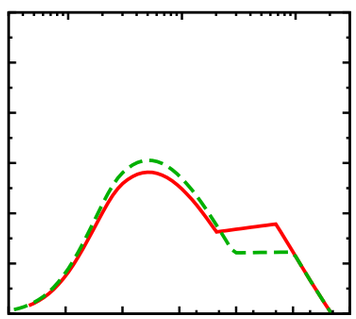




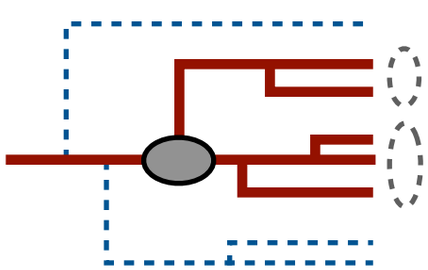
Outline



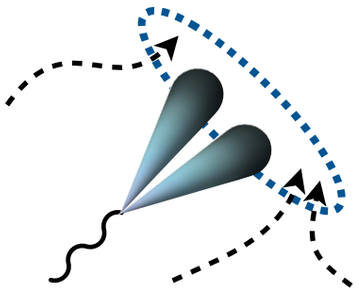
Giving New Physics a Boost



Substructure from First Principles



Probing the Core of QCD

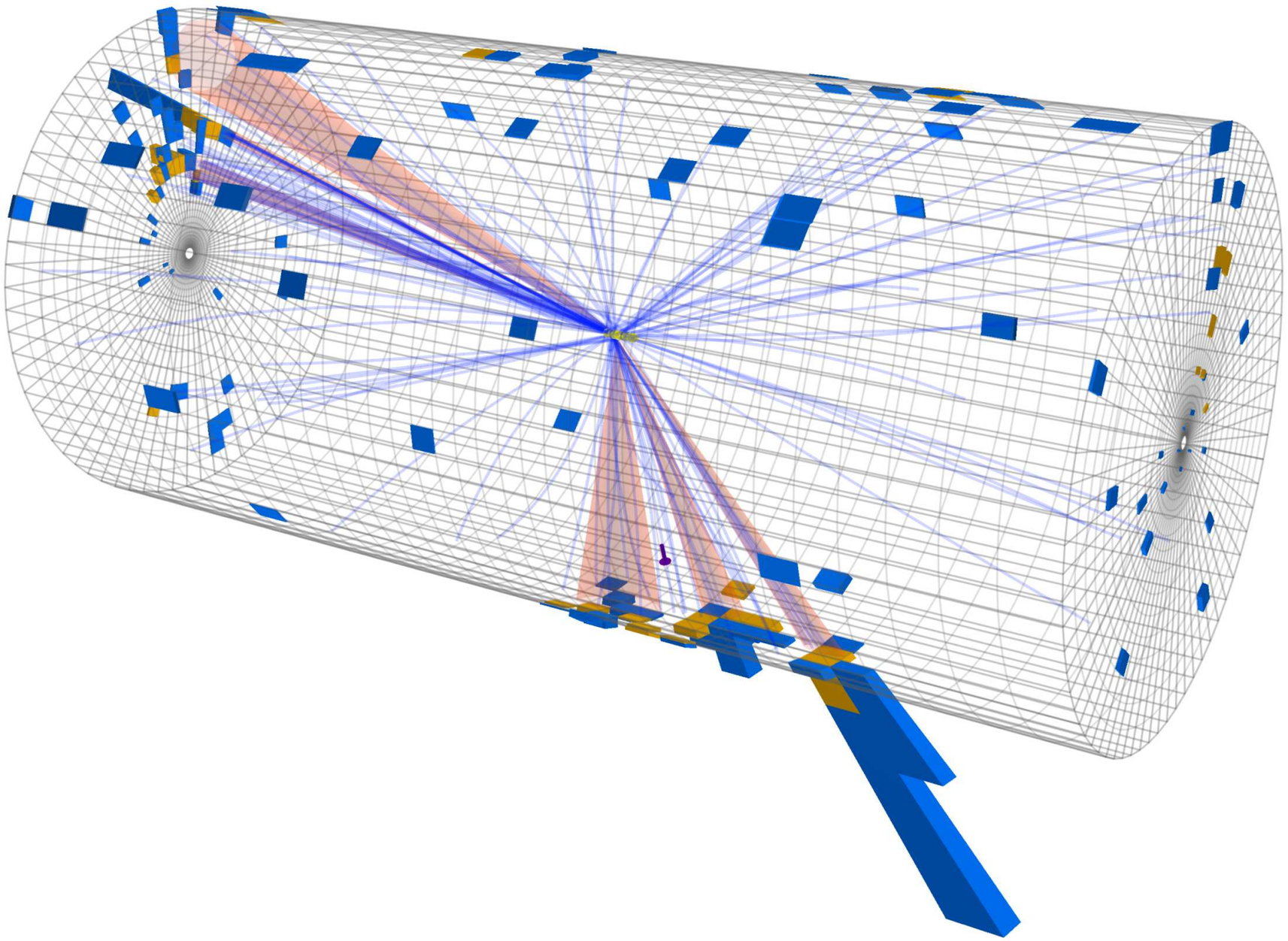


Giving New Physics a Boost

Substructure from First Principles

Probing the Core of QCD

CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253



[CMS, 1506.03062]
[using Kaplan, Rehermann, Schwartz, Tweedie, 0806.0848; using Ellis, Vermilion, Walsh, 0903.5081, 0912.0033]

CMS Experiment at LHC, CERN
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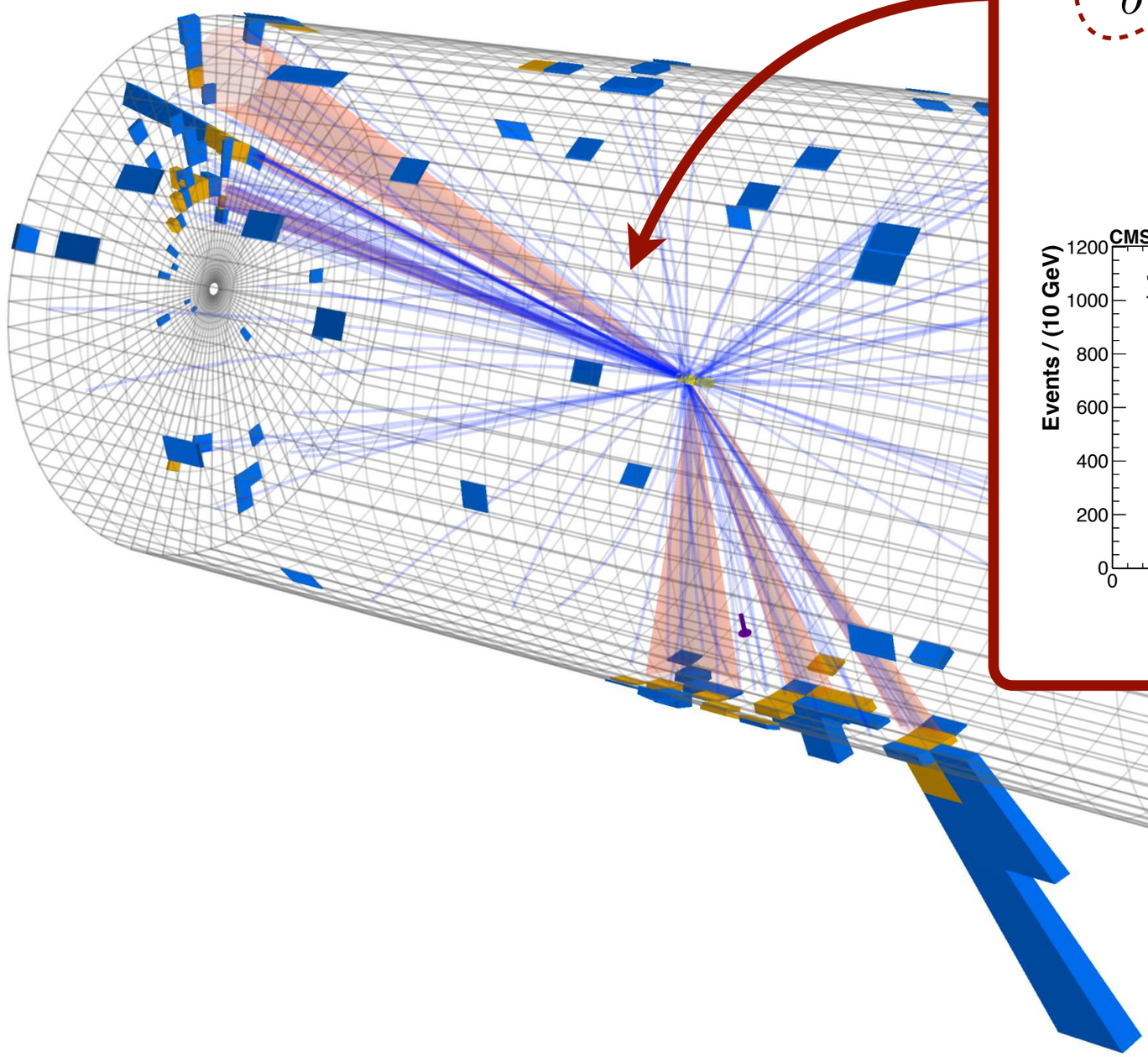
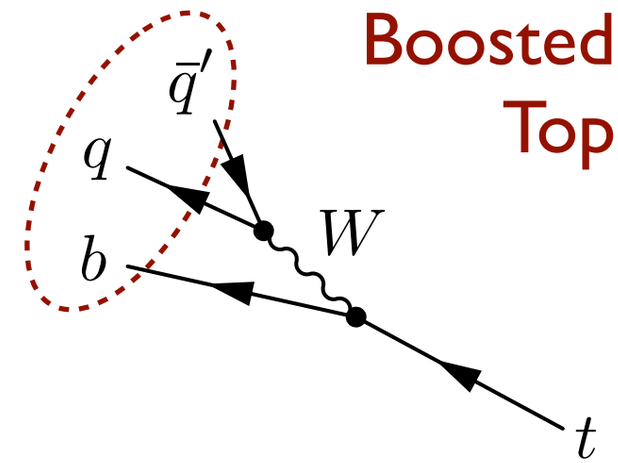
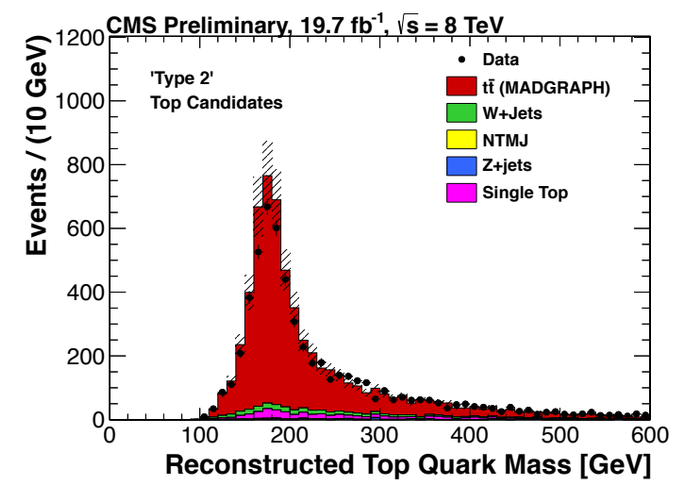


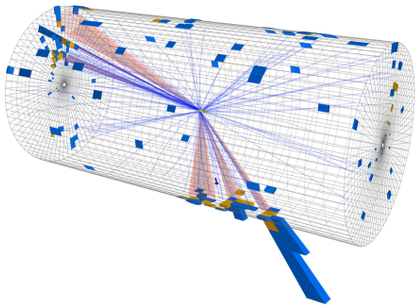
Boosted Top

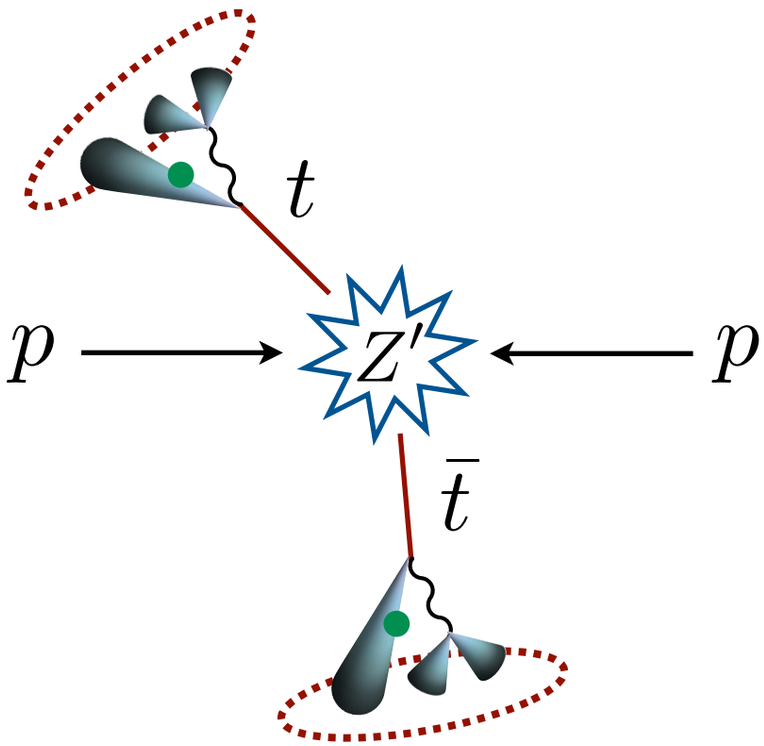


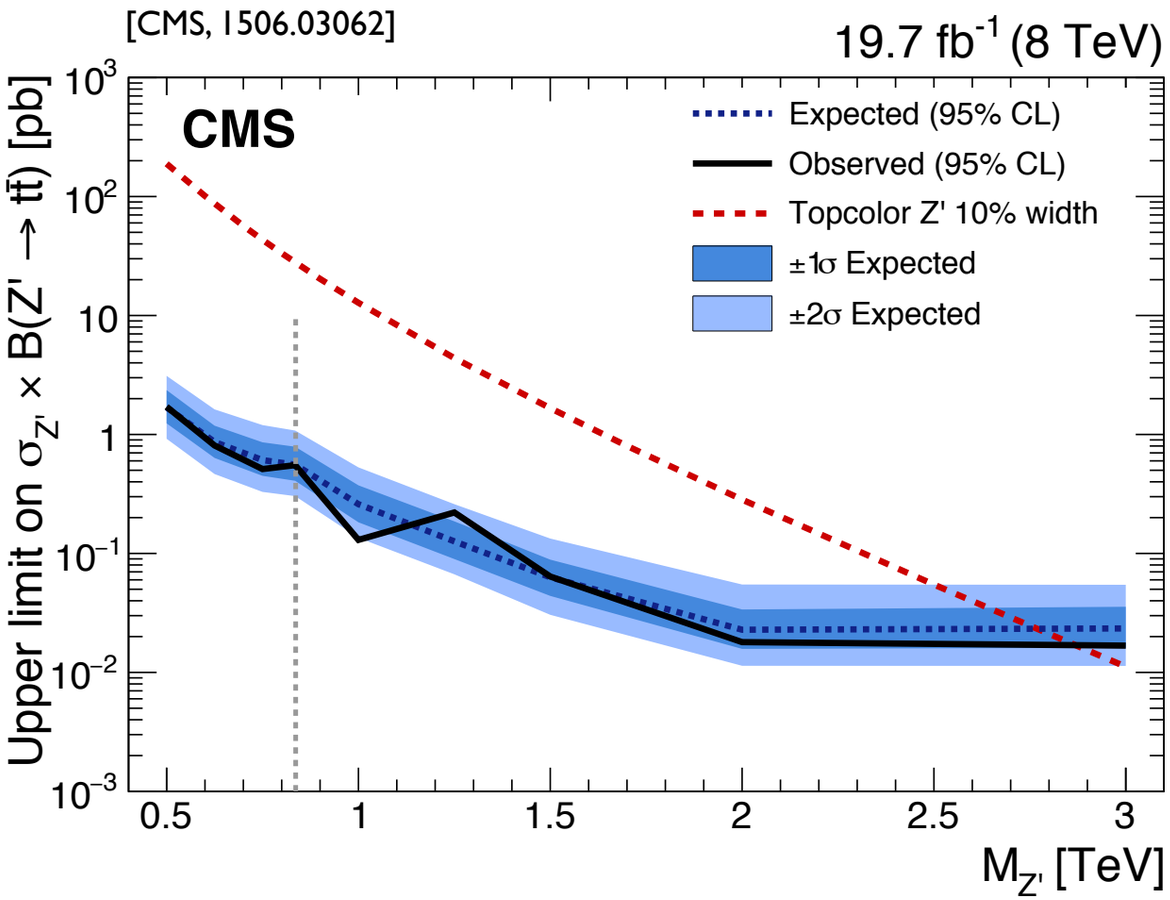


[CMS, 1506.03062]
[using Kaplan, Rehermann, Schwartz, Tweedie, 0806.0848; using Ellis, Vermilion, Walsh, 0903.5081, 0912.0033]

Welcome to the Boosted Regime

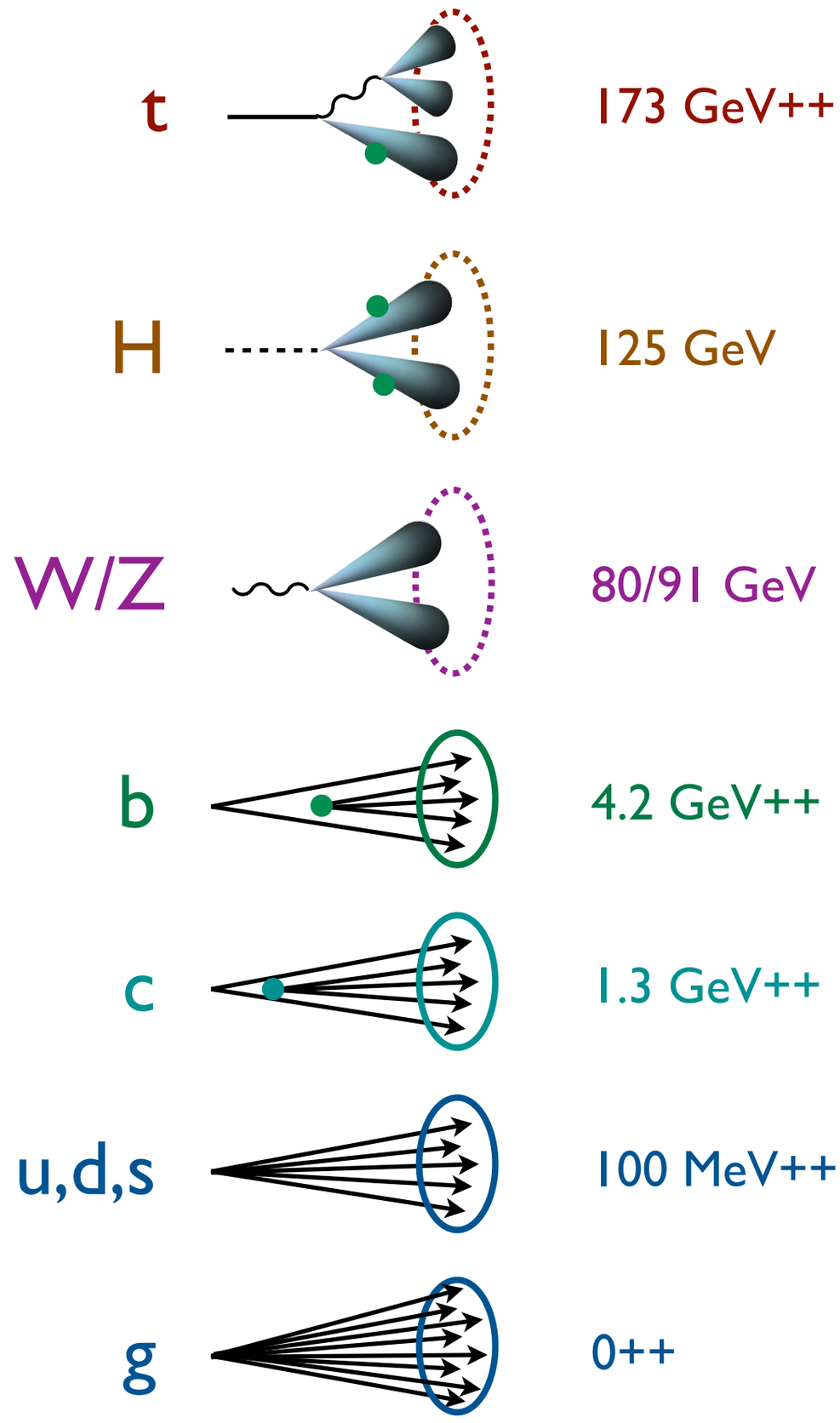






$$\Delta R \simeq \frac{2m_{\text{top}}}{p_T}$$

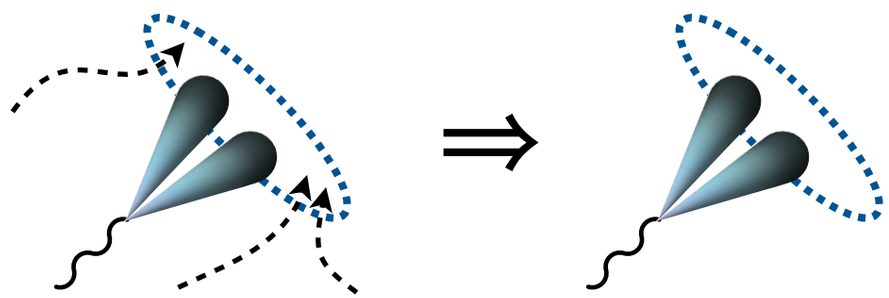
BOOST 2015
CHICAGO


t
173 GeV++
H
125 GeV
W/Z
80/91 GeV
b
4.2 GeV++
c
1.3 GeV++
u,d,s
100 MeV++
g
0++

Key Substructure Techniques

Jet Cleaning:

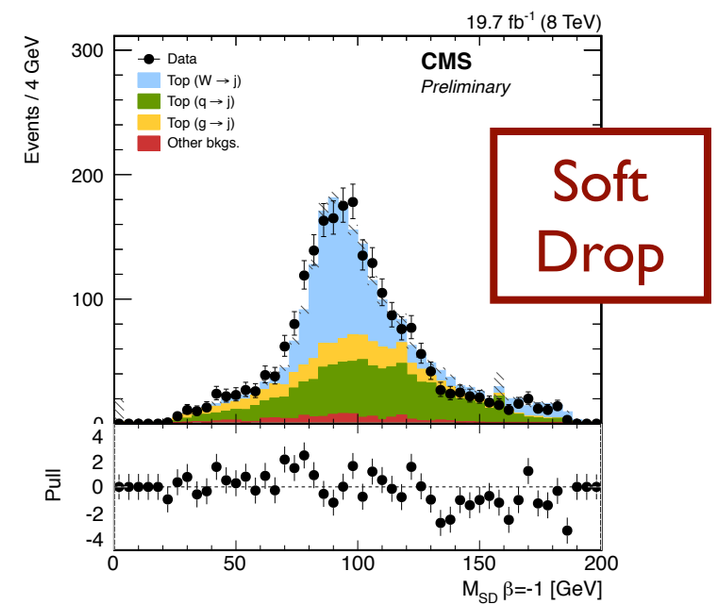
e.g. ISR/UE/pileup



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

W/Z-Tagging @ CMS

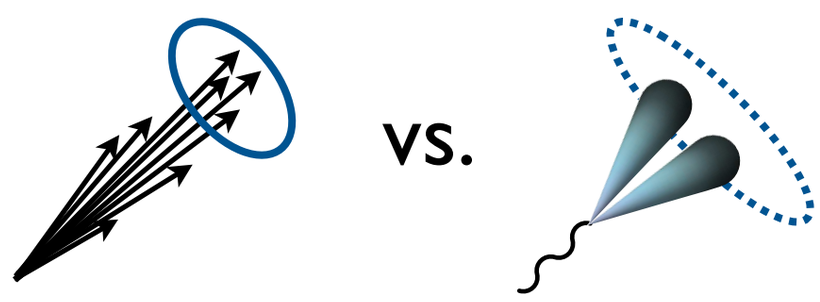
[JME-14-002, CMS-PAS-EXO-15-002]



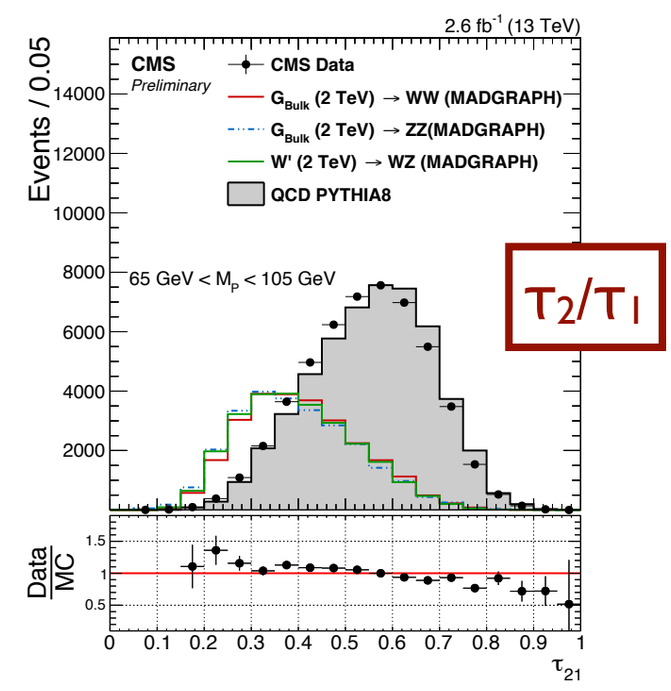
[using Larkoski, Marzani, Soyez, JDT, 1402.2657]

Discrimination:

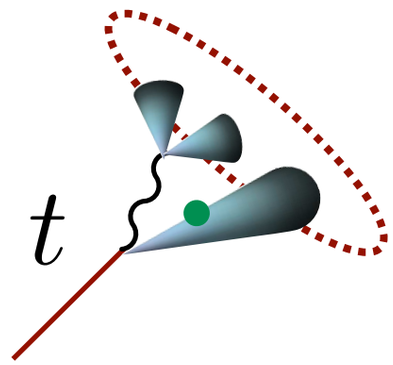
e.g. 1-prong vs. N-prong



[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, LHA, 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]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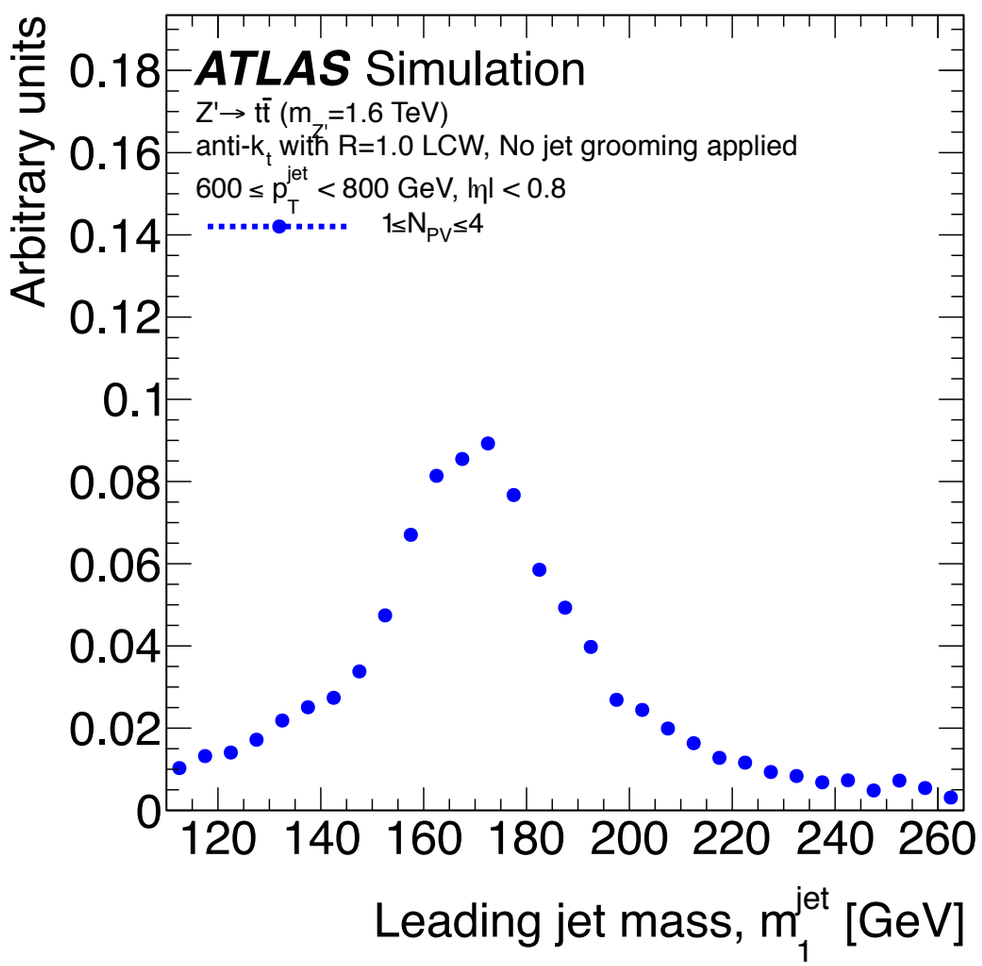
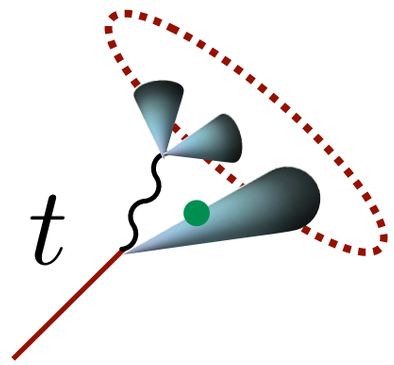

ATLAS Simulation
Z'→ tt̄ (m_Z'=1.6 TeV)
anti-k_t with R=1.0 LCW, No jet grooming applied
600 ≤ p_T^jet < 800 GeV, |η| < 0.8
1≤N_PV≤4
Arbitrary units
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
120
140
160
180
200
220
240
260
Leading jet mass, m_1^jet [GeV]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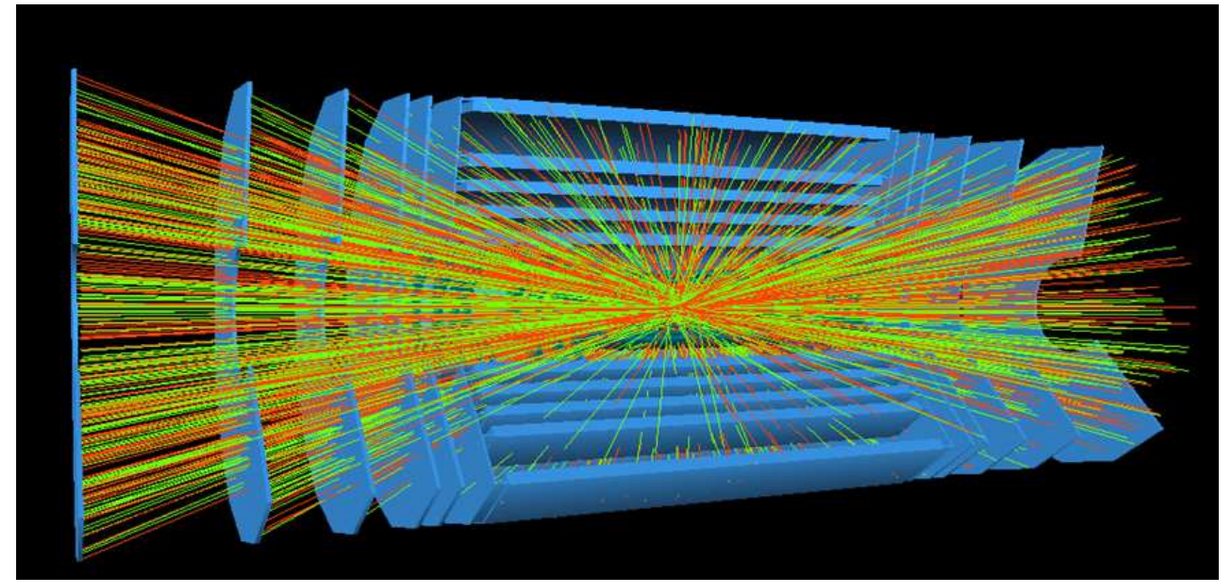
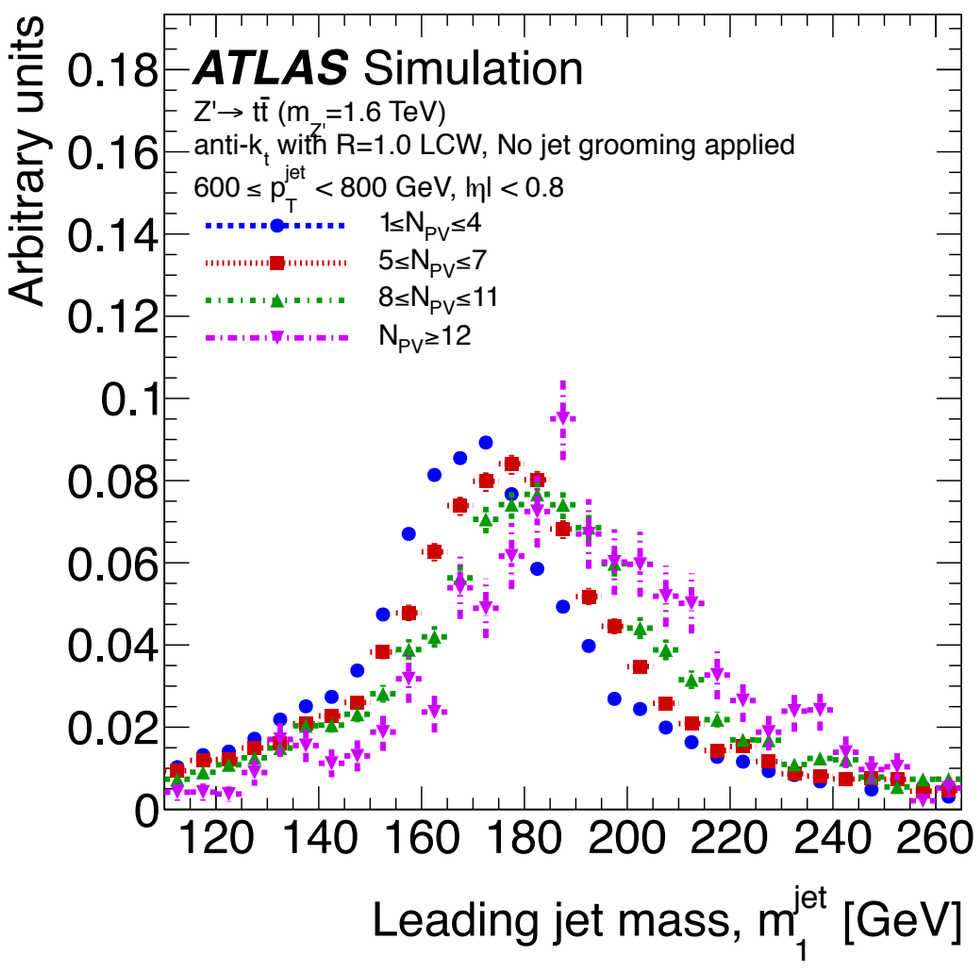
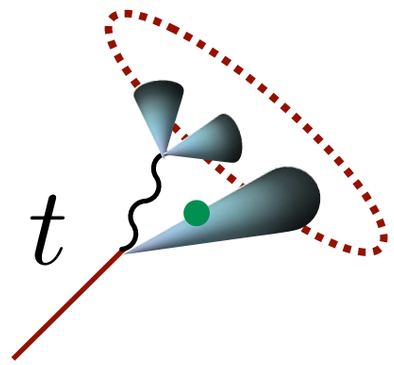



ATLAS Simulation
Z'→ tt̄ (m_Z'=1.6 TeV)
anti-k_t with R=1.0 LCW, No jet grooming applied
600 ≤ p_T^jet < 800 GeV, |η| < 0.8
1≤N_PV≤4
5≤N_PV≤7
8≤N_PV≤11
N_PV≥12
Arbitrary units
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
120
140
160
180
200
220
240
260
Leading jet mass, m_1^jet [GeV]



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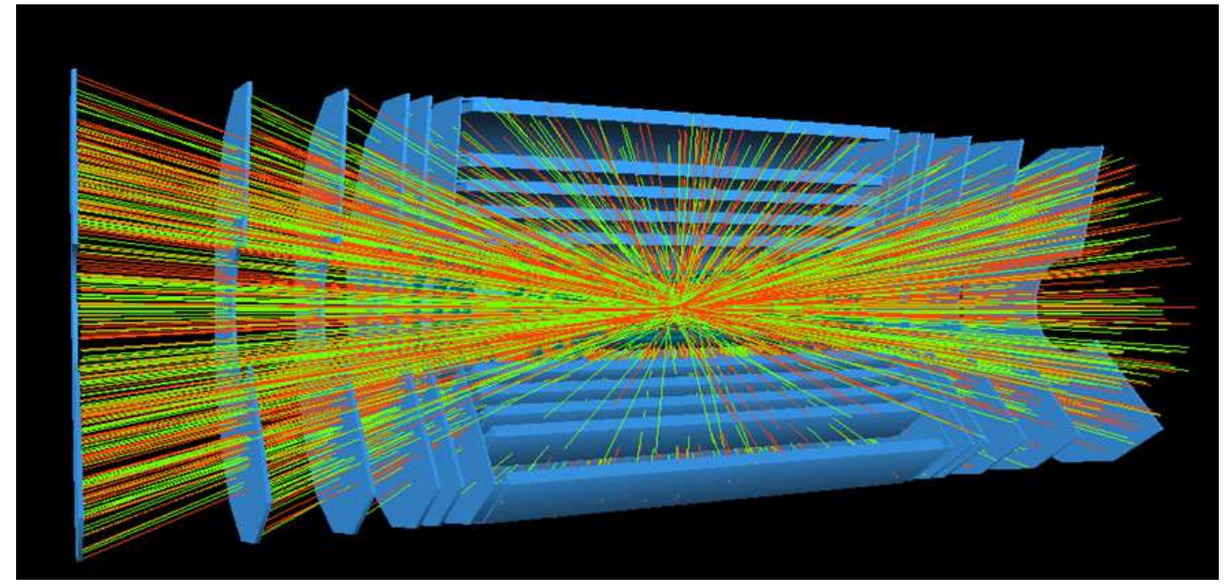

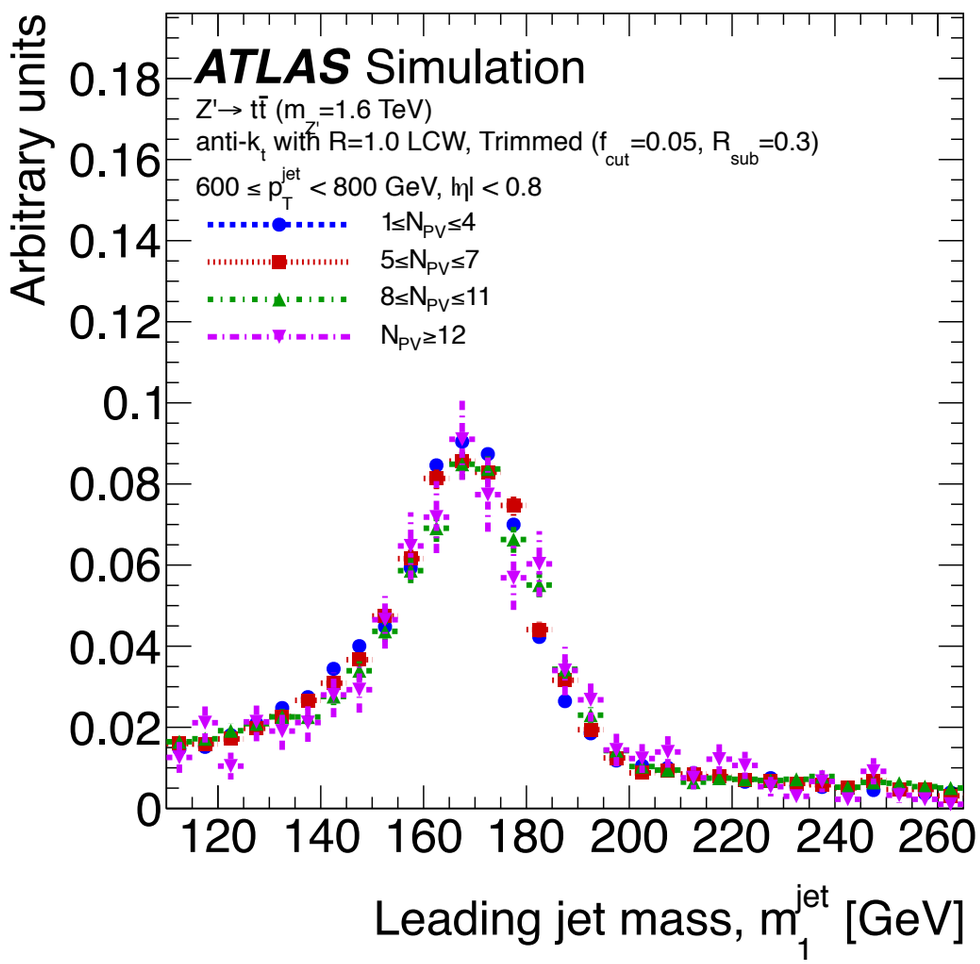

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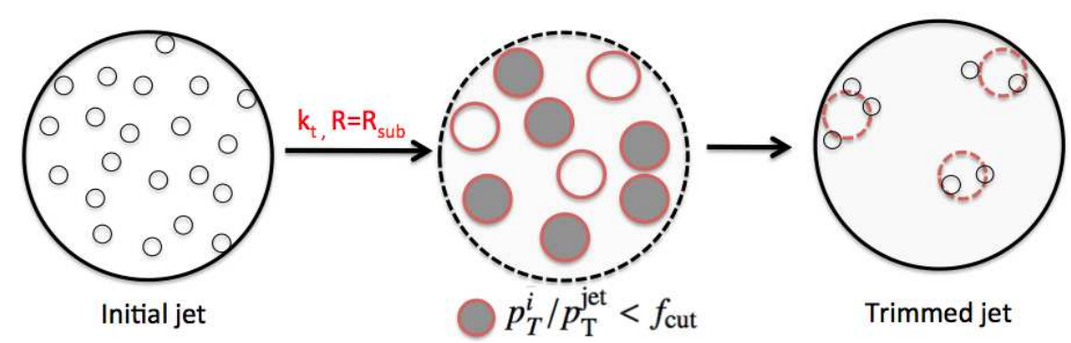
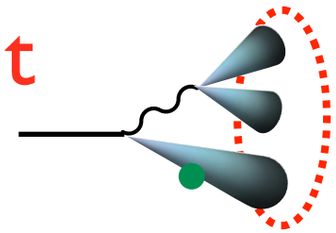
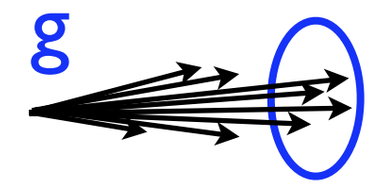
e.g. Jet Trimming

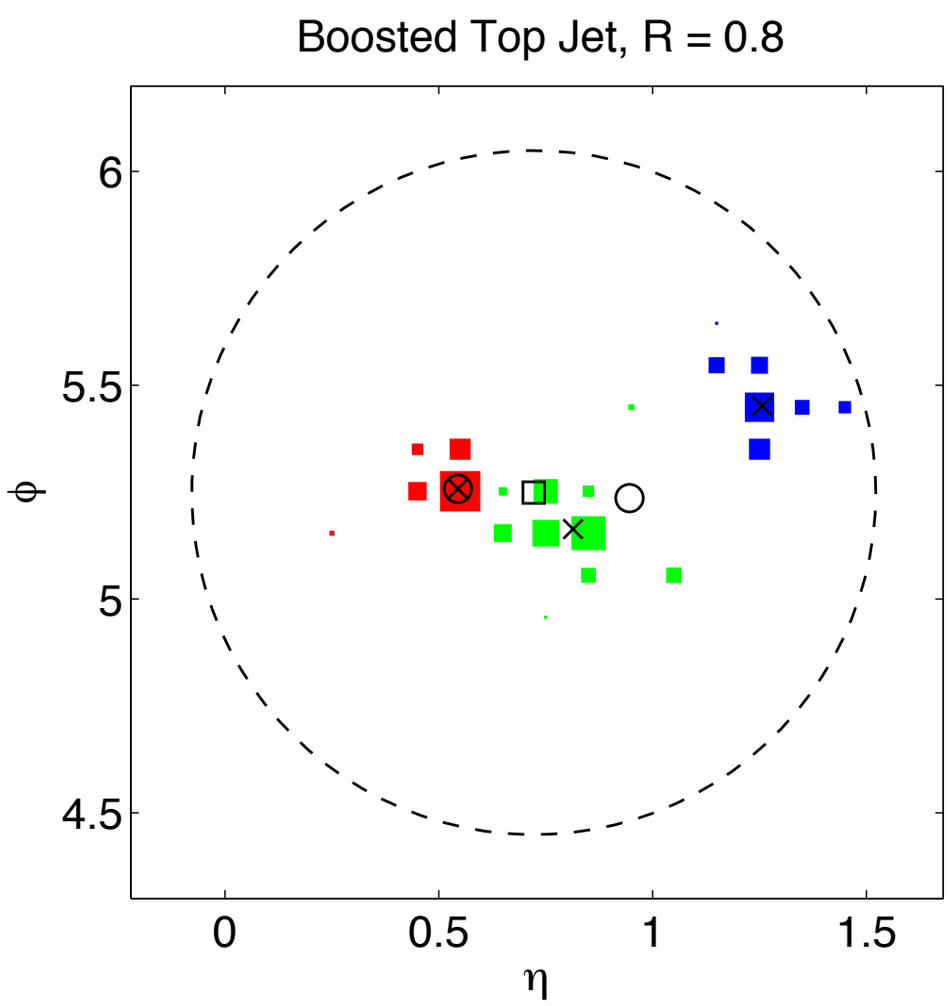


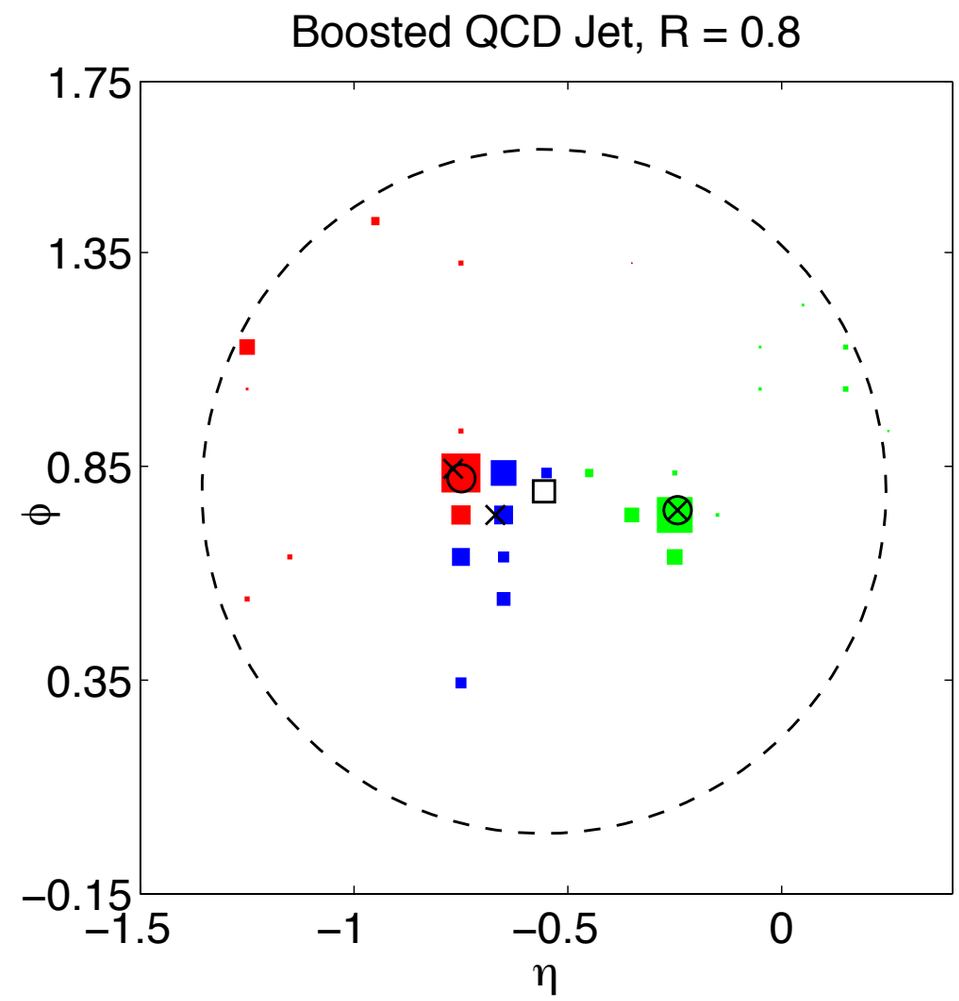
[ATLAS, 2012; using Krohn, JDT, Wang, 2009]



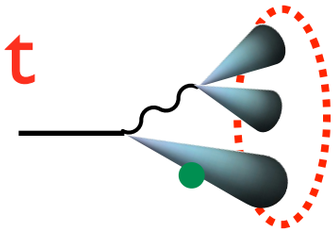
N-Prong vs. 1-Prong



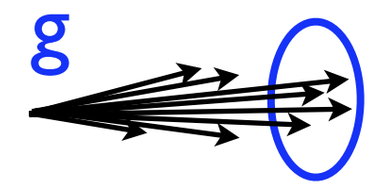


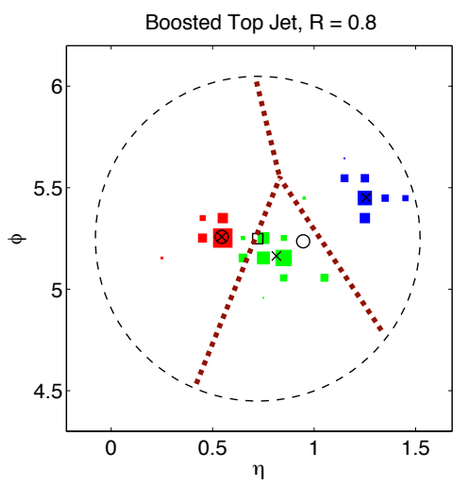


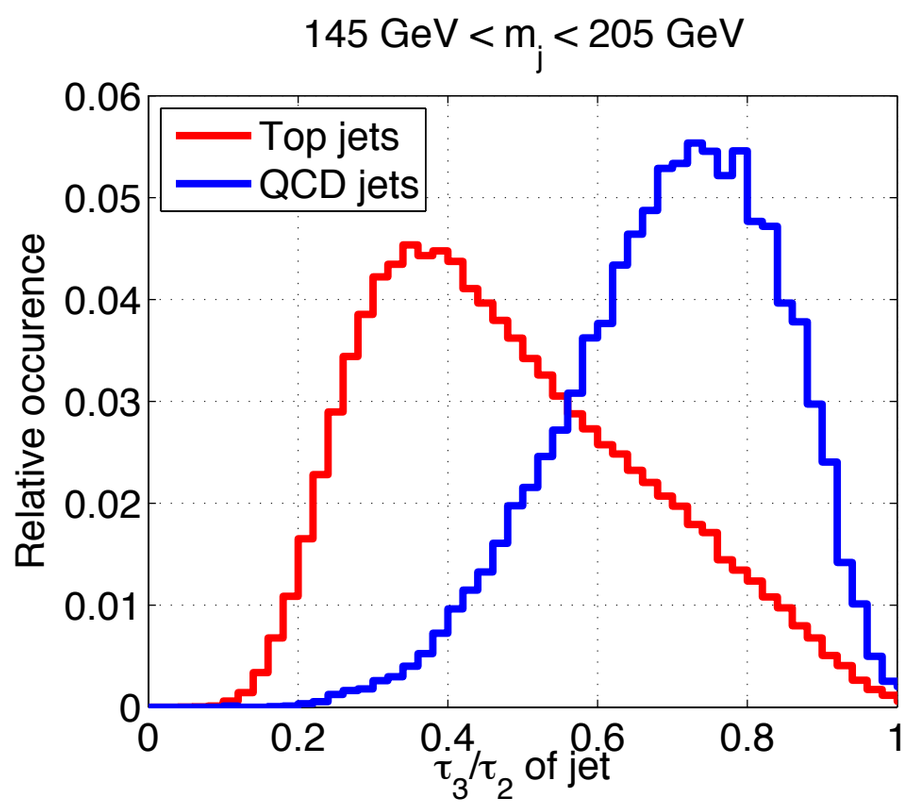
Both jets have m ≈ 170 GeV

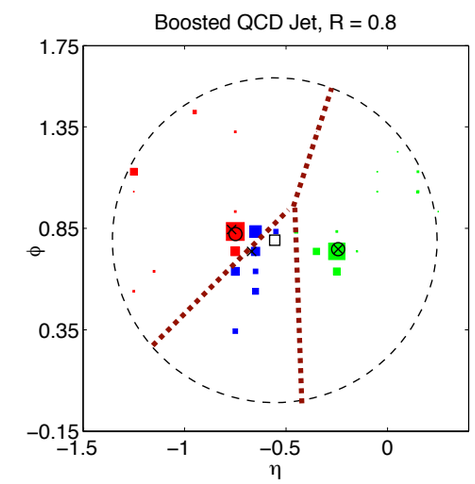


N-Prong vs. 1-Prong









$\boxed{\tau_3/\tau_2}$ $t \to bW$

$H \to b\bar{b}$

$\boxed{\tau_2/\tau_1}$ $Z \to q\bar{q}$

$W \to q\bar{q}'$

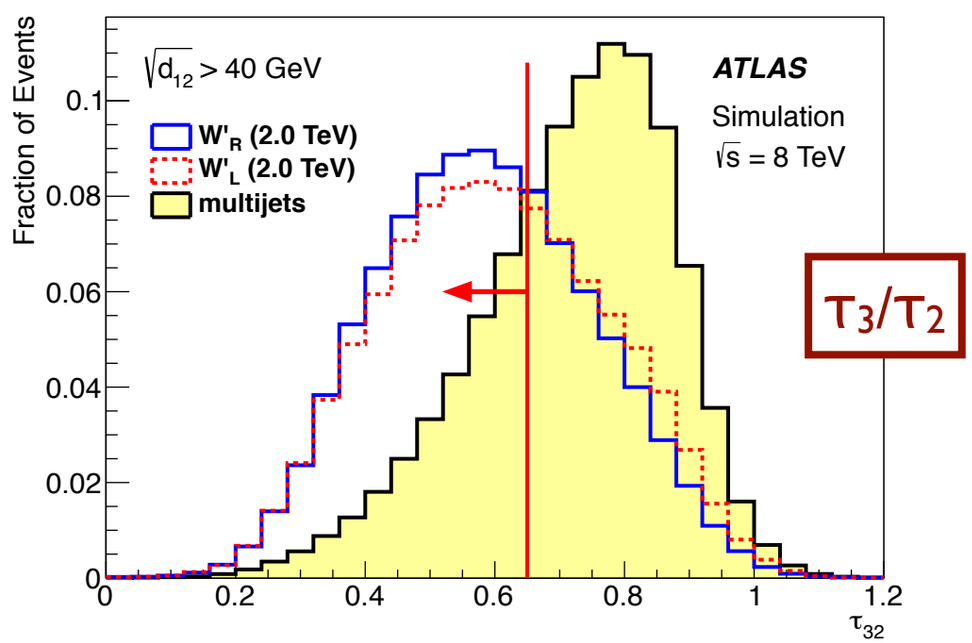
N-subjettiness IRC Safe

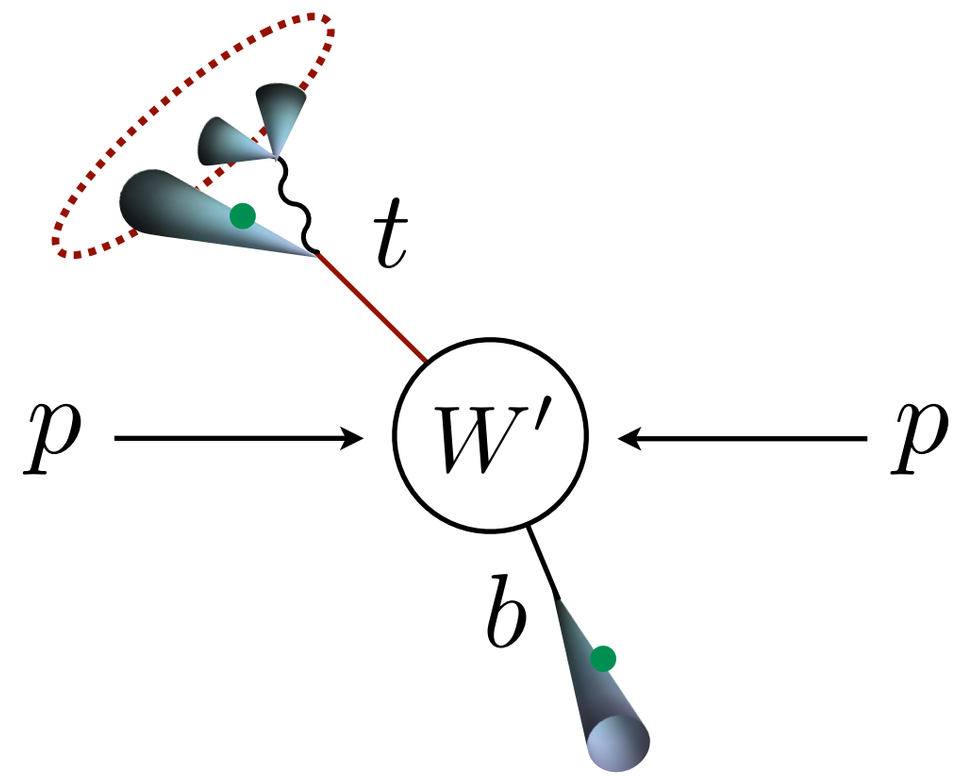
$$\tau_N = \sum_k p_{T,k} \min\{\Delta R_{k,1}, \Delta R_{k,2}, \ldots, \Delta R_{k,N}\}^{\beta}$$

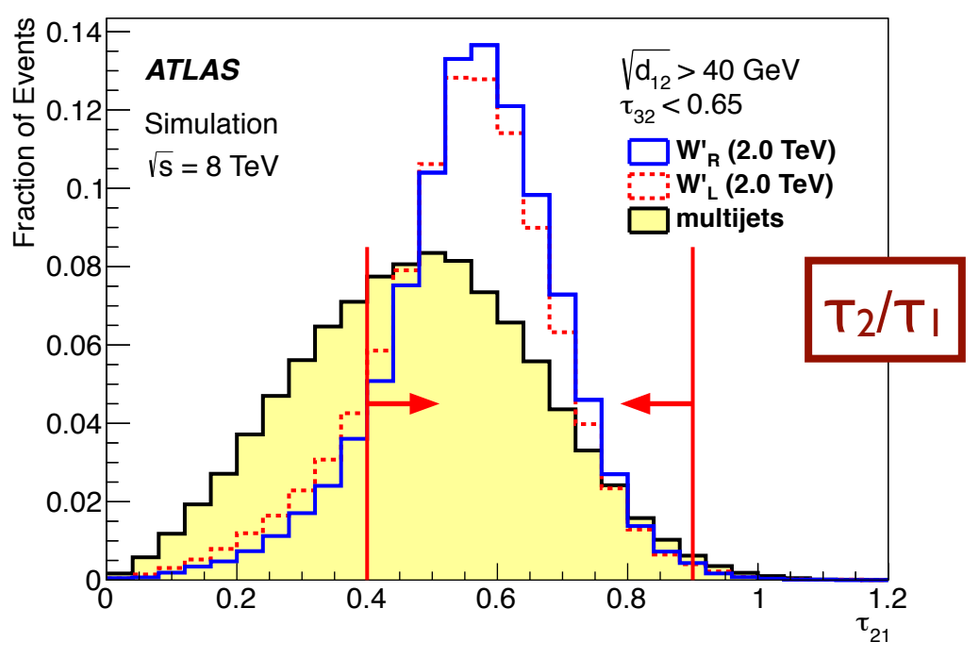
[JDT, Van Tilburg, 1011.2268, 1108.2701; see also Kim, 1011.1493]
[related work in Stewart, Tackmann, Waalewijn, 1004.2489; Larkoski, Salam, JDT, 1305.0007; Larkoski, Moult, Neill, 1409.6298]

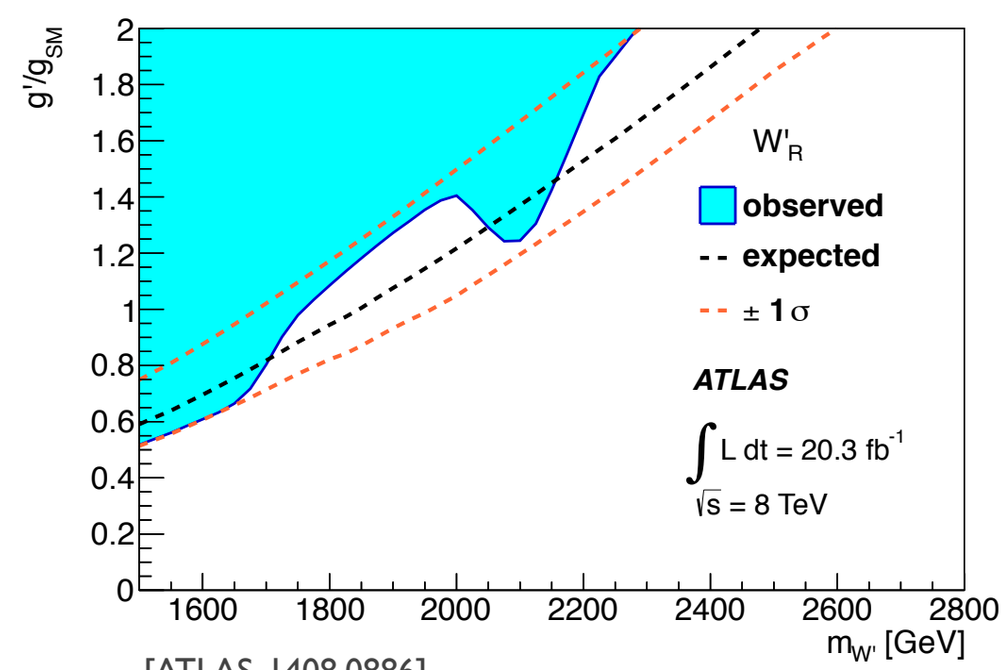
ATLAS: Heavy W Search

N-subjettiness + *B-tagging* + *Trimming*





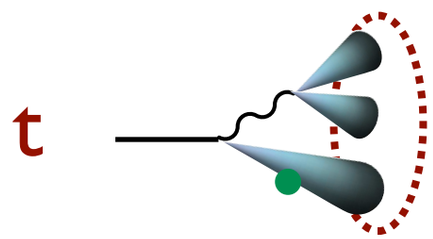




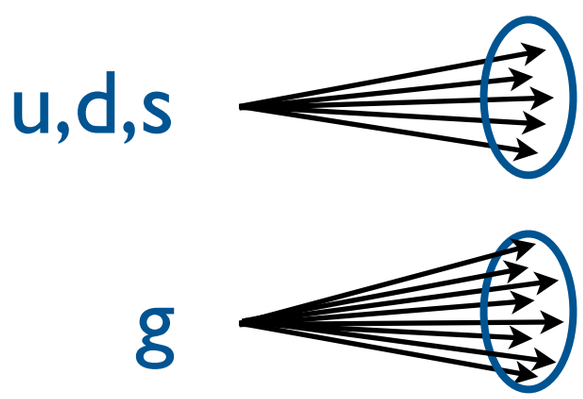
[ATLAS, 1408.0886]

SD = Shower Deconstruction

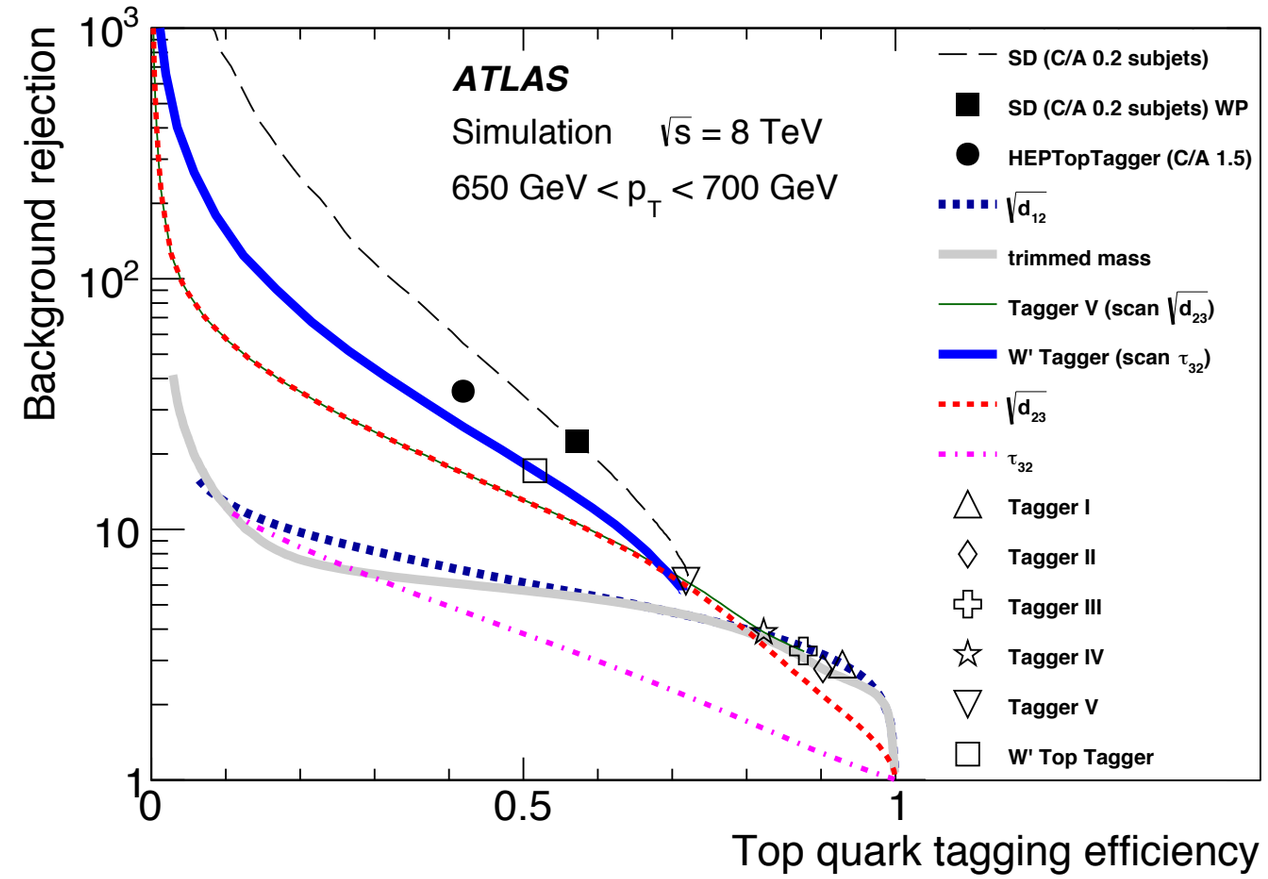
[Soper, Spannowsky, 1102.3480, 1211.3140]

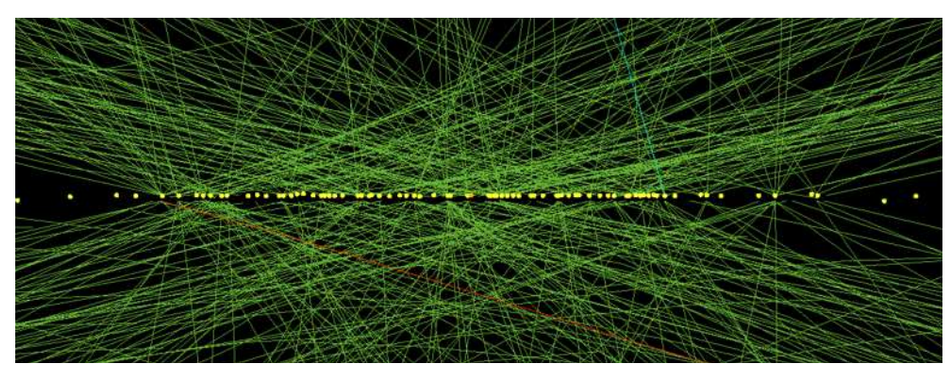


vs.



[ATLAS, 1603.03127]

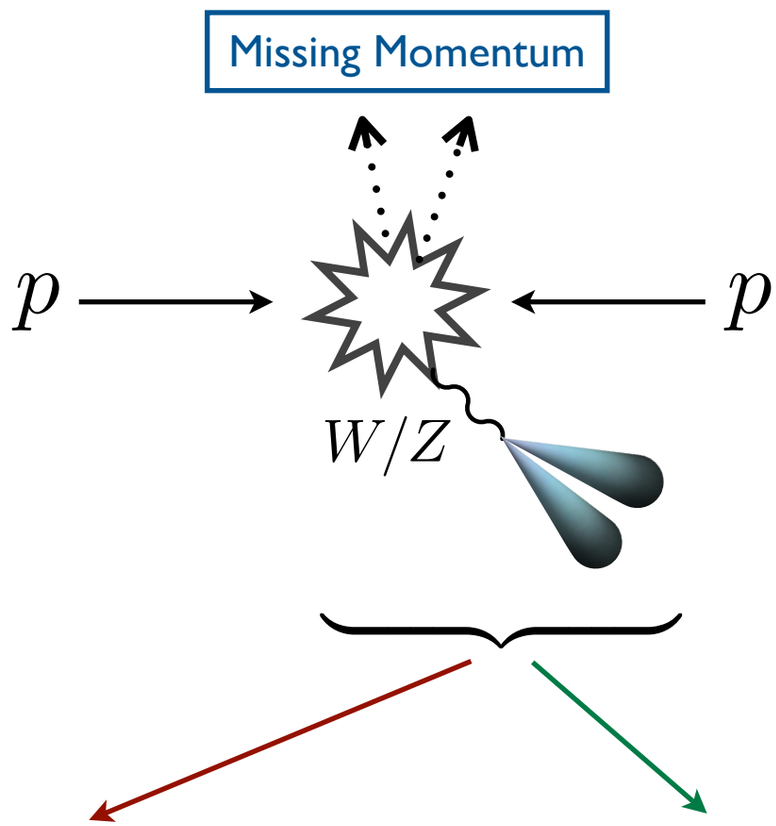




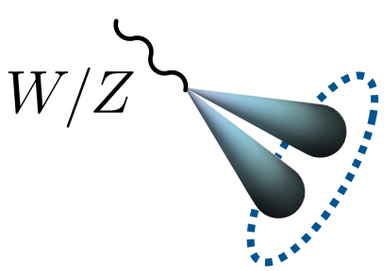
Performant even with pileup

CMS: Dark Matter Search

Hot Topic @ BOOST2015

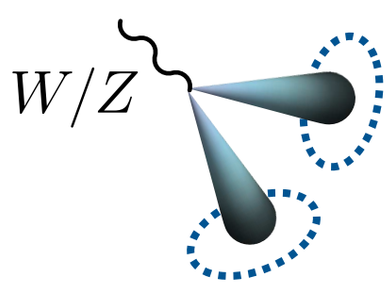


Boosted

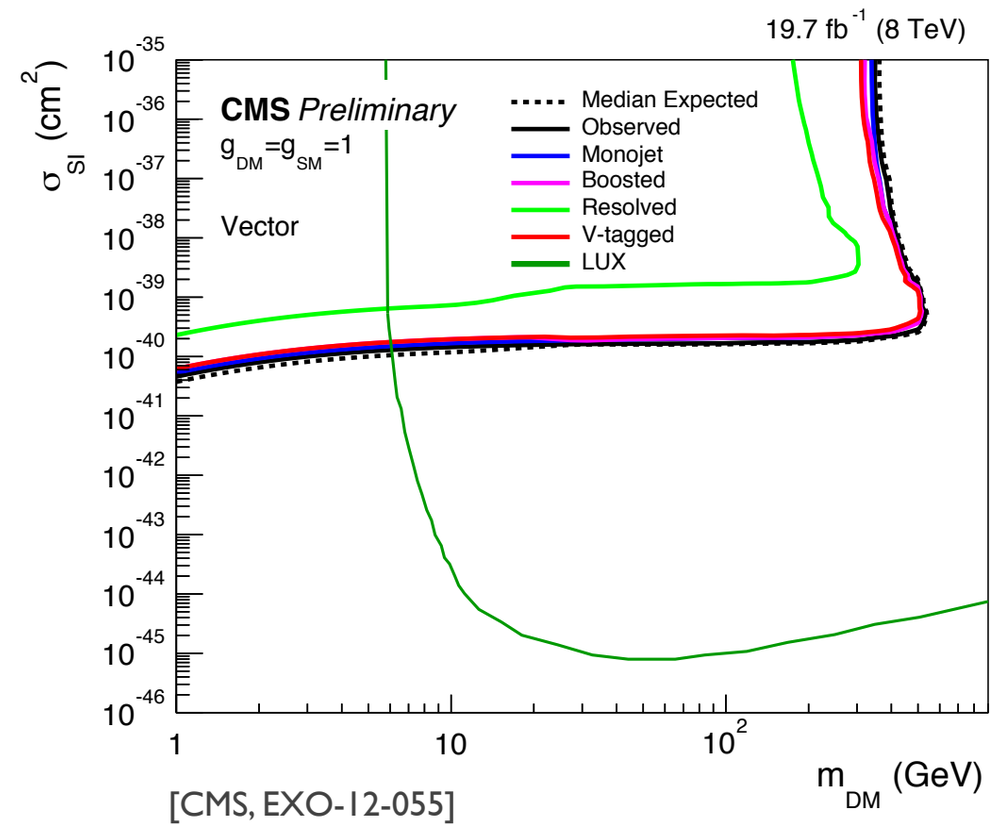


with Pruning
+ N-subjettiness

Resolved

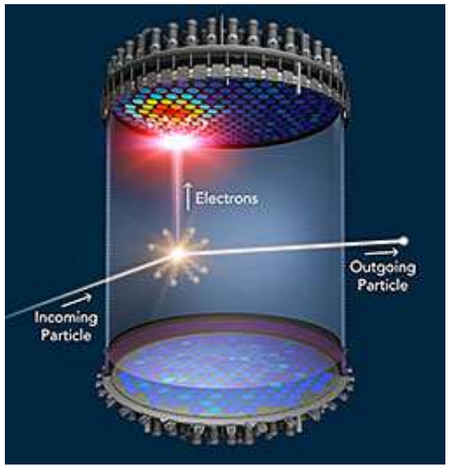


with Quark/Gluon
+ Color Flow
+ Mass Drop



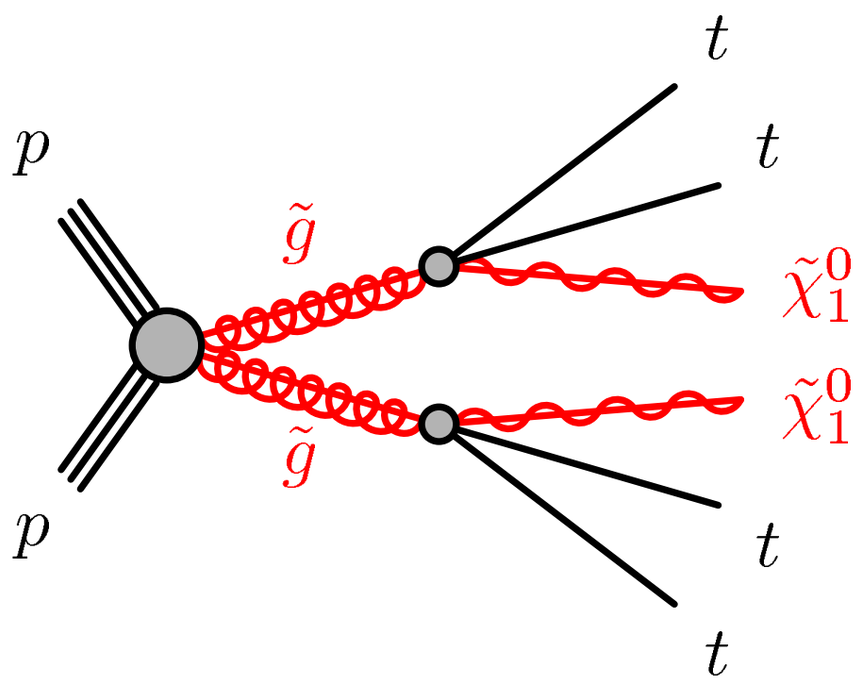
[CMS, EXO-12-055]

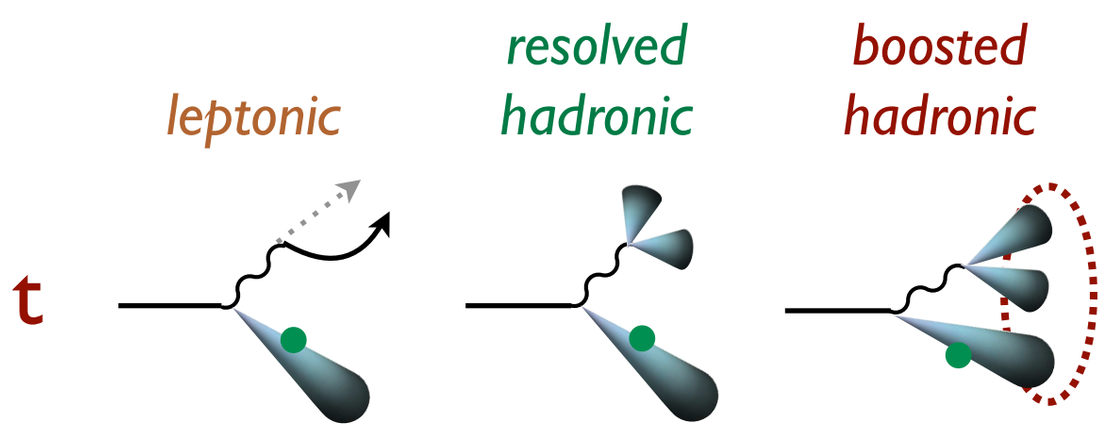
Complementary to direct dark matter searches

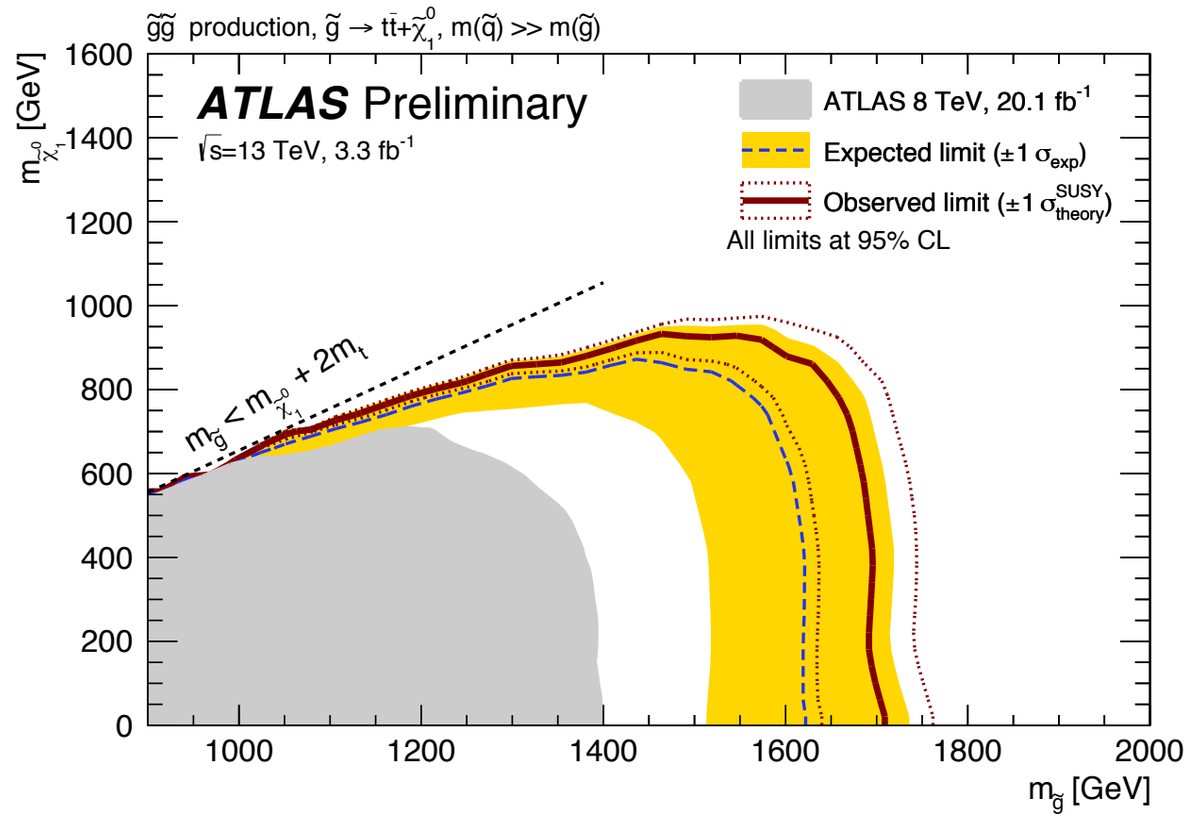


ATLAS: SUSY Search

Missing Momentum + *Leptons* + *B-tagging* + *Trimming* + …





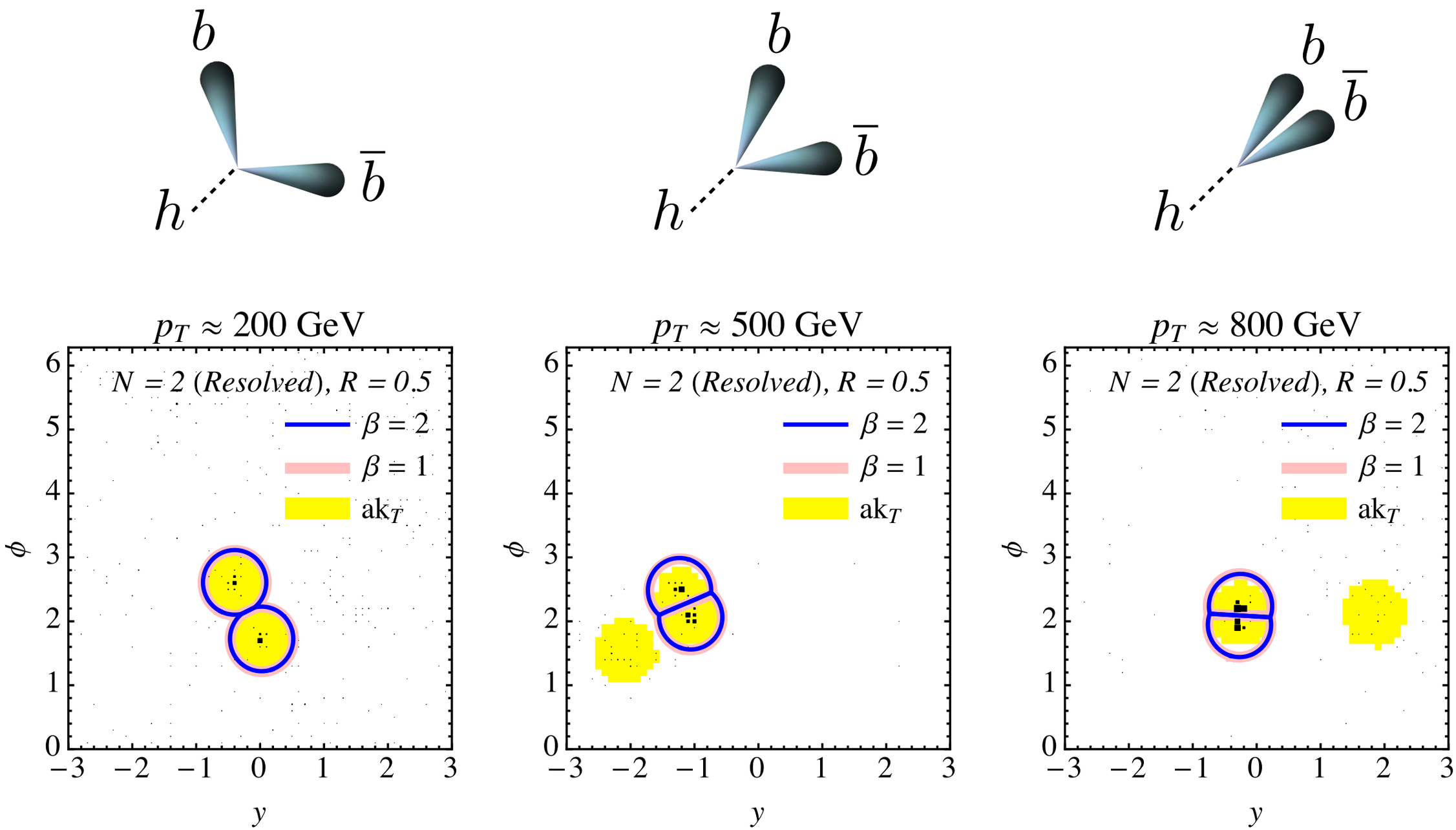


[ATLAS, CONF-2015-067]

Merging Resolved & Boosted?

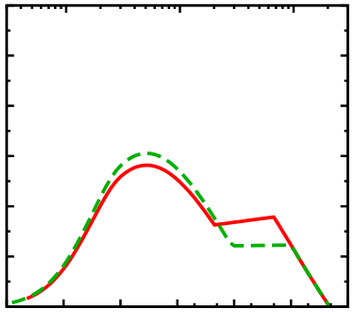
XCone for Higgs bosons

$$\Delta R \simeq \frac{2m_H}{p_T}$$



[inspired by Stewart, Tackmann, Waalewijn, 1004.2489; Stewart, Tackmann, JDT, Vermilion, Wilkason, 1508.01516; JDT, Wilkason, 1508.01518]

Giving New Physics a Boost

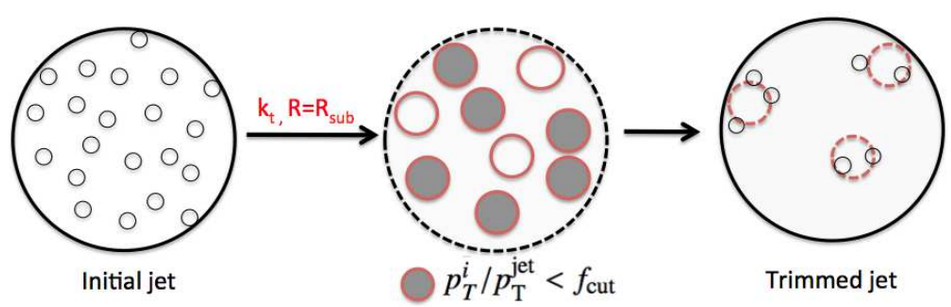


Substructure from First Principles

Probing the Core of QCD

Substructure from First Principles?

e.g. Jet Trimming

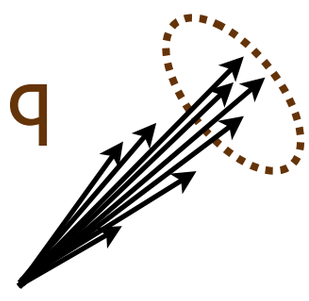


extensively used by ATLAS

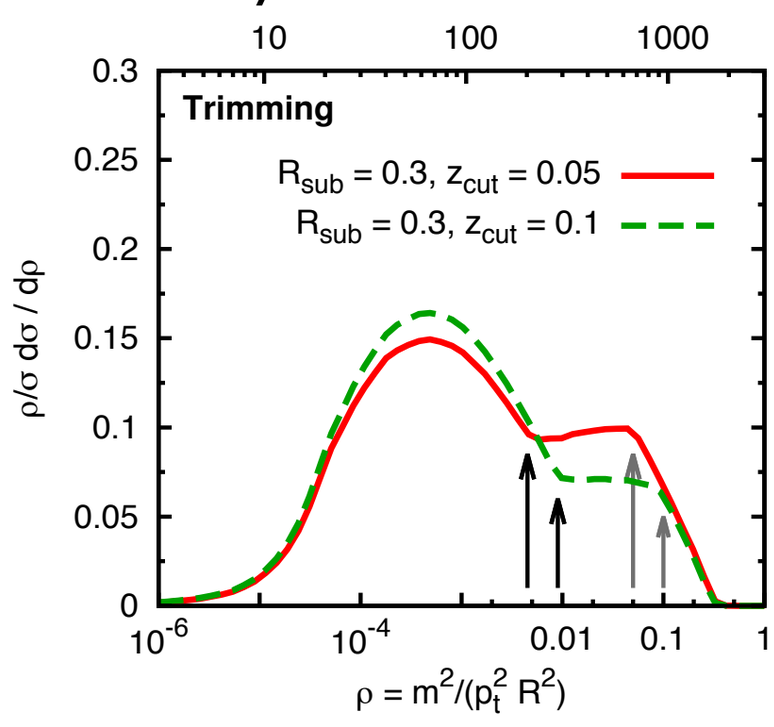
[Krohn, JDT, Wang, 0912.1342; diagram from ATLAS, 1306.4945]

Trimmed Jet Mass:

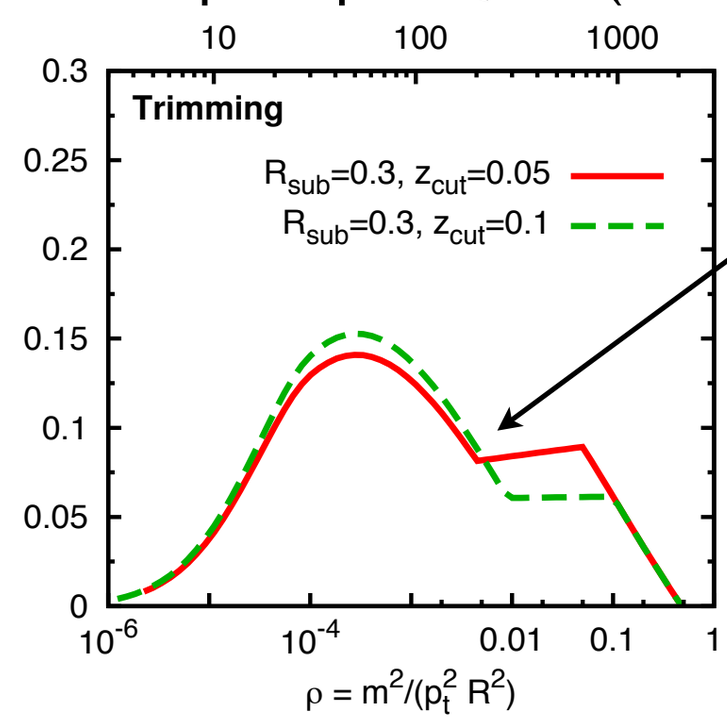
3 TeV quark jets



Pythia 6 Simulation



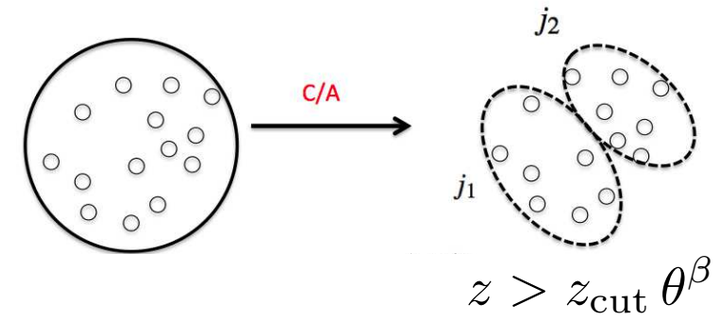
First-principles QCD (MLL)



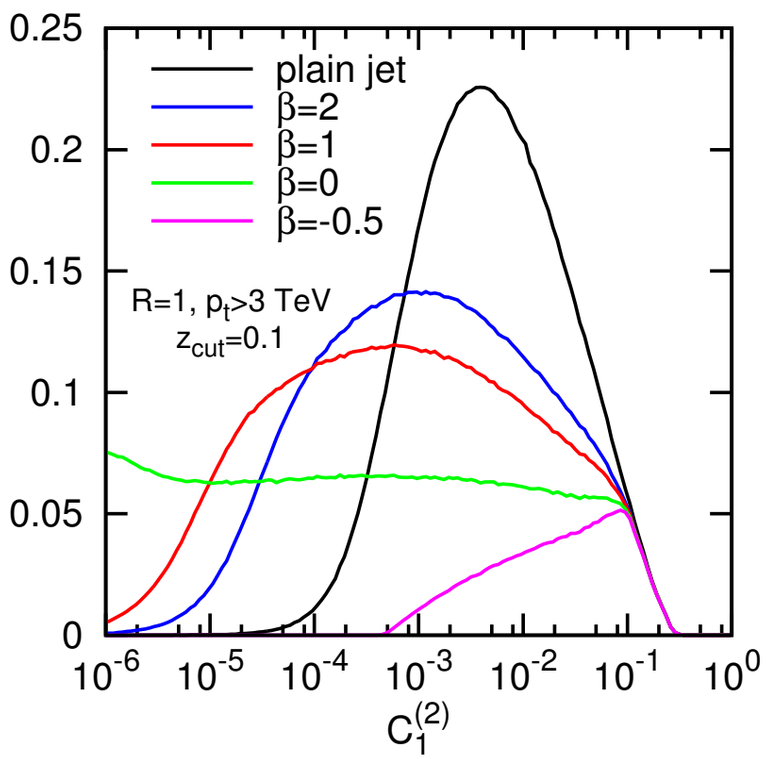
Analytically understand Sudakov peak, kink, and plateau

[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

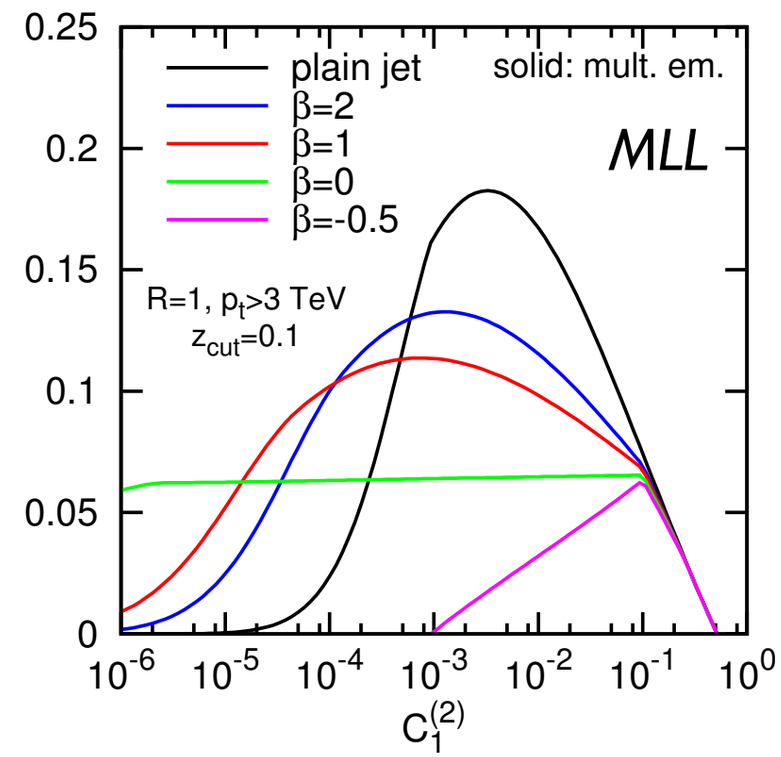
Soft-Dropped Jet Mass



Simulated LHC Data



First-principles QCD



More Grooming

Less Grooming

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

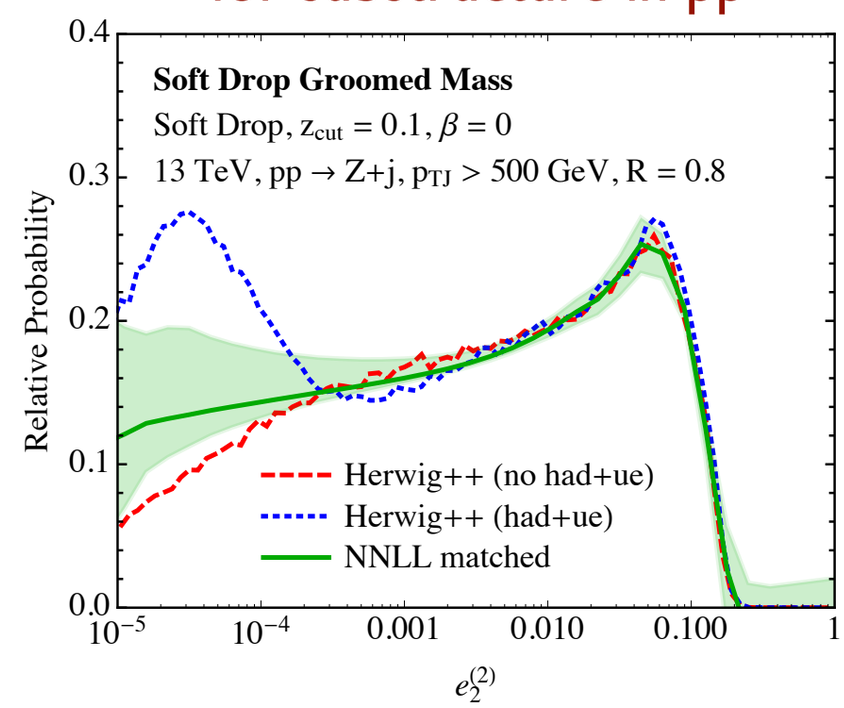
[Larkoski, Marzani, Soyez, JDT, 1402.2657]

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; Frye, Larkoski, Schwartz, Yan, 1603.06375, 1603.09338
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
Small R jets: Dasgupta, Dreyer, Salam, Soyez, 1411.5182, 1602.01110

First NNLL + $O(\alpha_s^2)$ calculation for substructure in pp



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

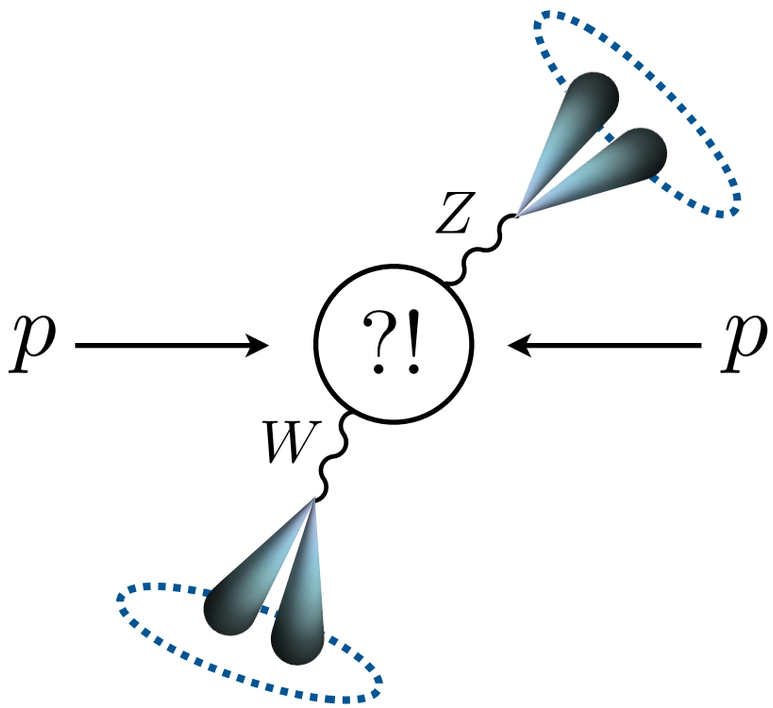
3-prong substructure:

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

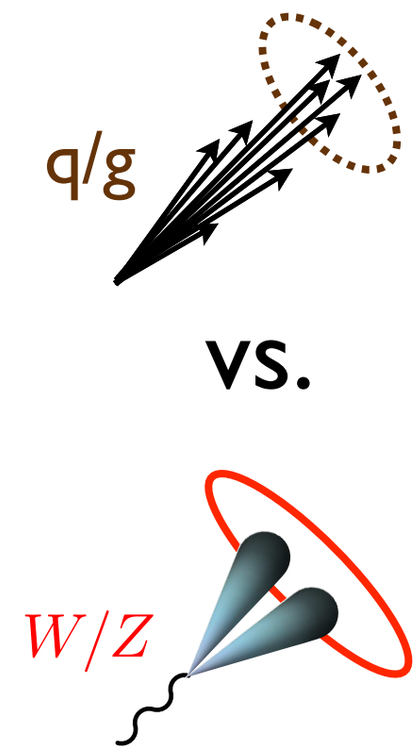
Non-perturbative substructure:

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)



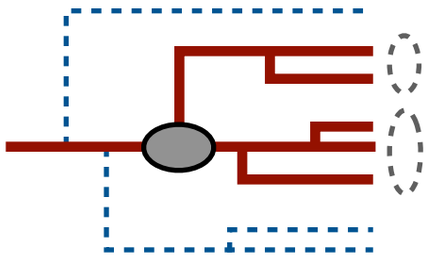
ATLAS Diboson Excess



Simple discriminant requires new calculational techniques

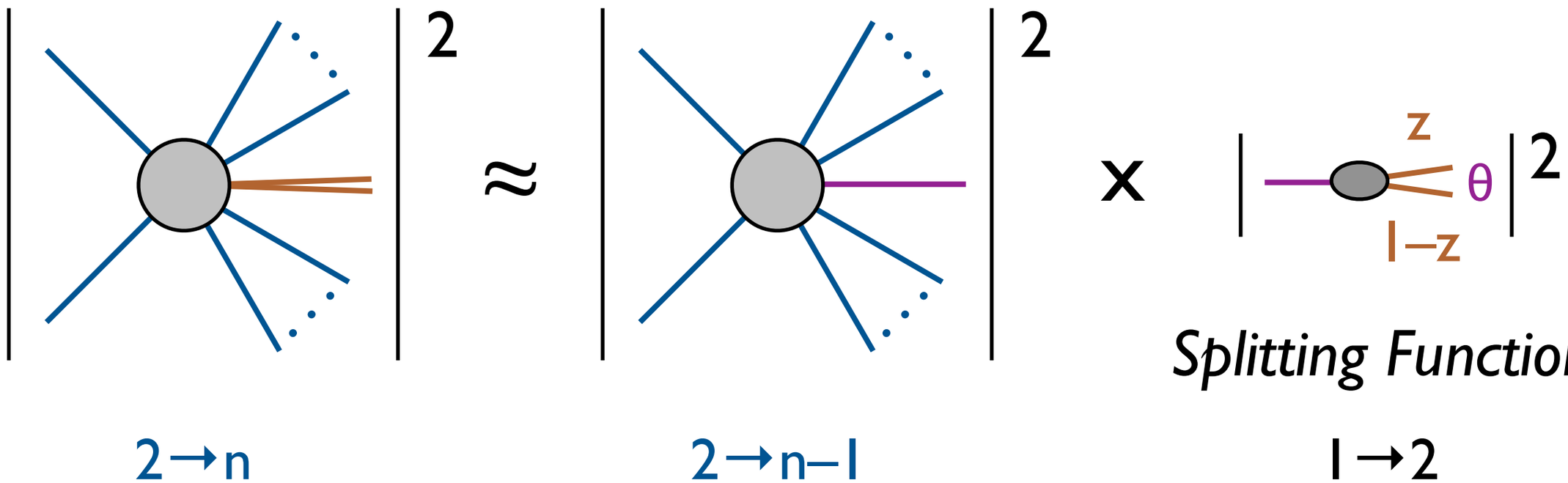
Giving New Physics a Boost

Substructure from First Principles



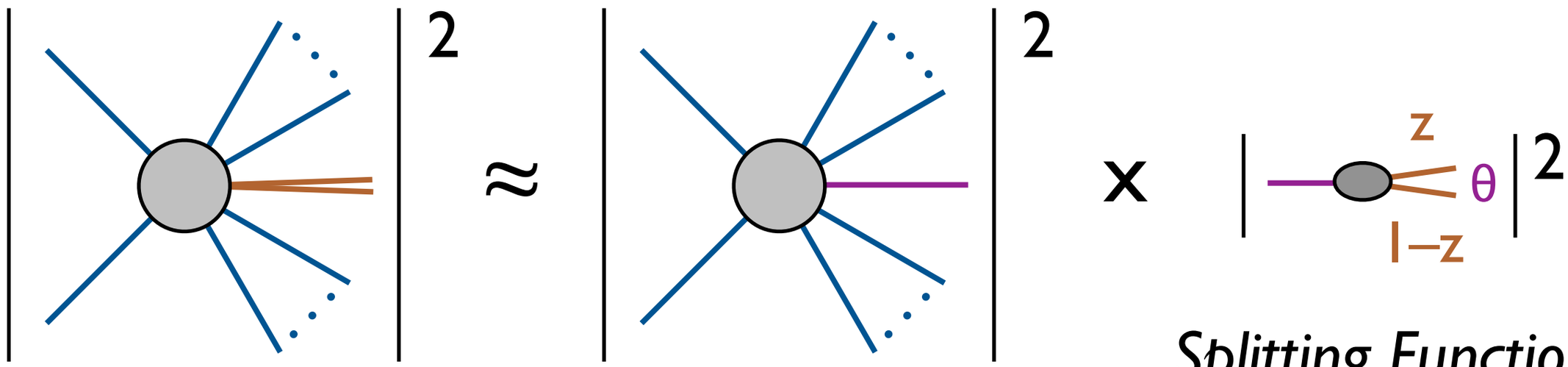
Probing the Core of QCD

Textbook QCD: Universal Collinear Limit



$$\mathrm{d}P_{i\to jk} = \underbrace{\frac{\mathrm{d}\theta}{\theta}}_{\text{Collinear singularity}} \mathrm{d}z \, \underbrace{P_{i\to jk}(z)}_{\text{Altarelli-Parisi splitting function}}$$

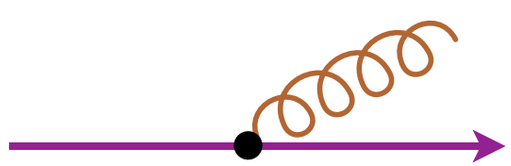
Textbook QCD: Universal Collinear Limit



Splitting Function

2→n 2→n−1 1→2

For this talk:



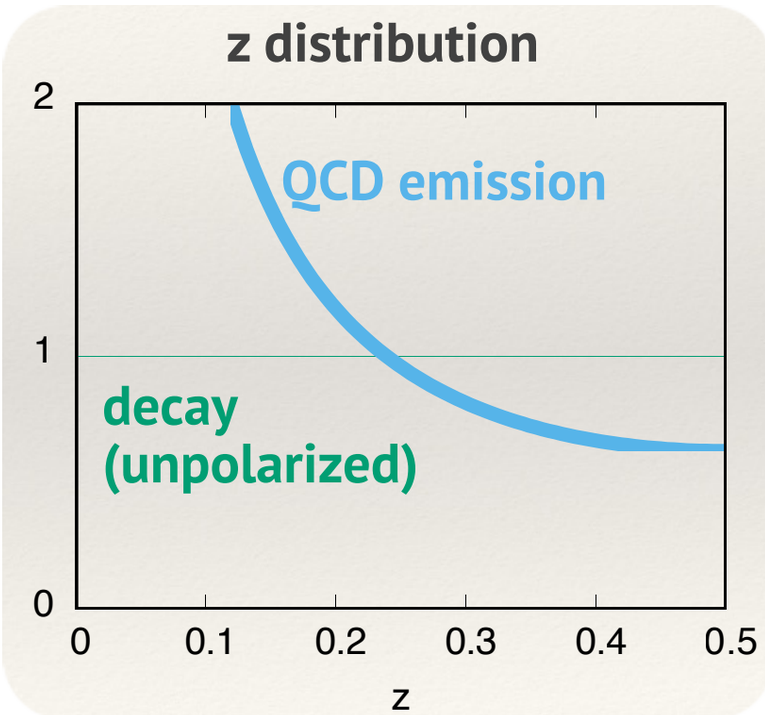
$C_q = 4/3$
$C_g = 3$

$$\mathrm{d}P_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \underbrace{\frac{\mathrm{d}\theta}{\theta}}_{\text{Collinear singularity}} \underbrace{\frac{\mathrm{d}z}{z}}_{\text{Soft singularity}}$$

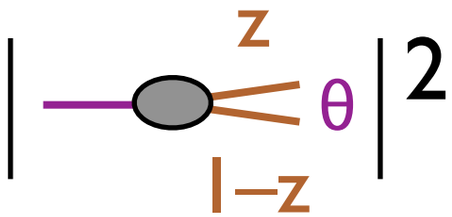
QCD Splitting Functions

Basis for DGLAP evolution of PDFs, parton shower generators, fixed-order subtractions, k_t jet clustering…

Jet Substructure Discrimination



[Gavin Salam FCC talk, March 2015]

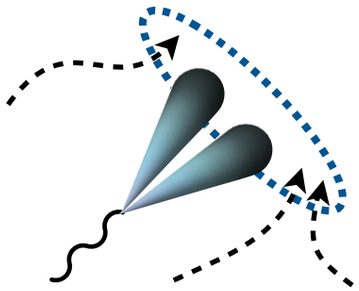


Splitting Function

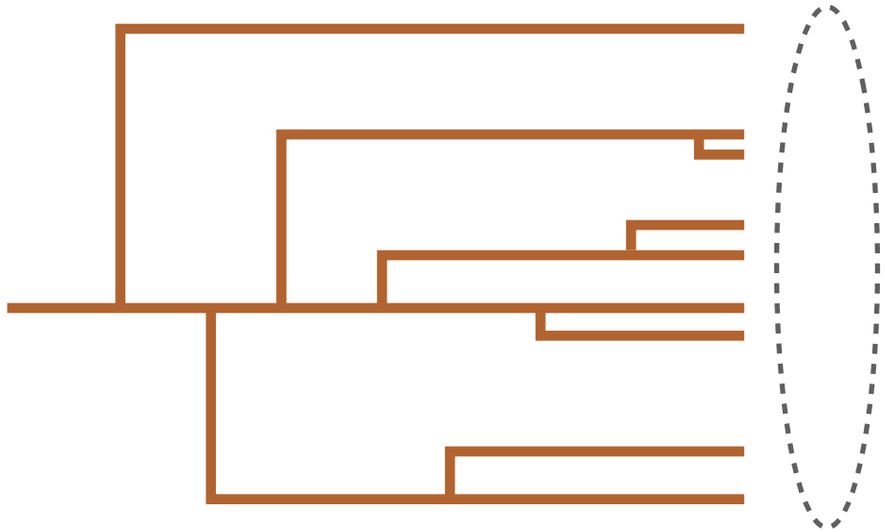
$1 \to 2$

$$\frac{2\alpha_s}{\pi} C_i \underbrace{\frac{d\theta}{\theta}}_{\text{Collinear singularity}} \underbrace{\frac{dz}{z}}_{\text{Soft singularity}}$$

ATLAS W/Z Tagging: BDRS

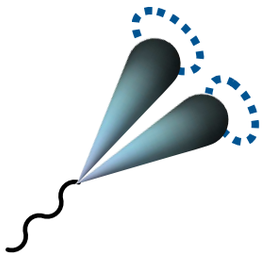


Angular-ordered clustering tree:

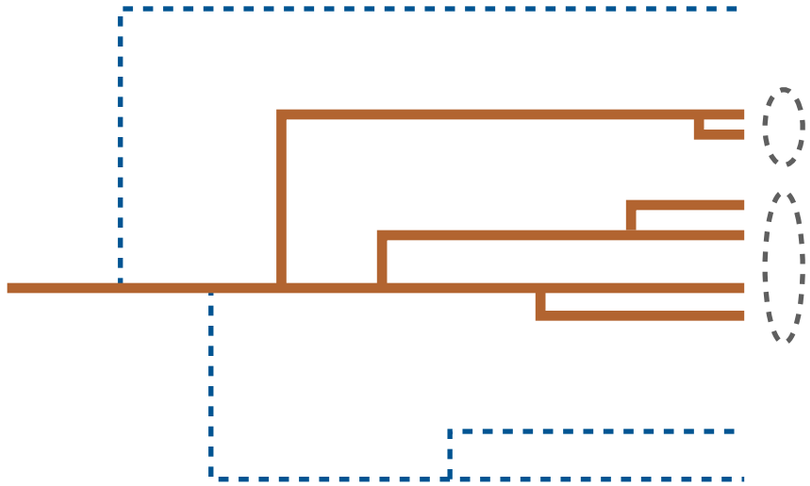


[Butterworth, Davison, Rubin, Salam, 0802.2470; see also Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

ATLAS W/Z Tagging: BDRS

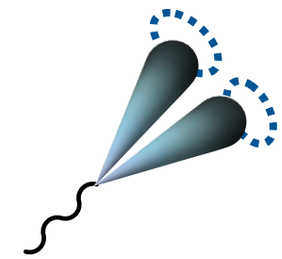


Groomed angular-ordered clustering tree:

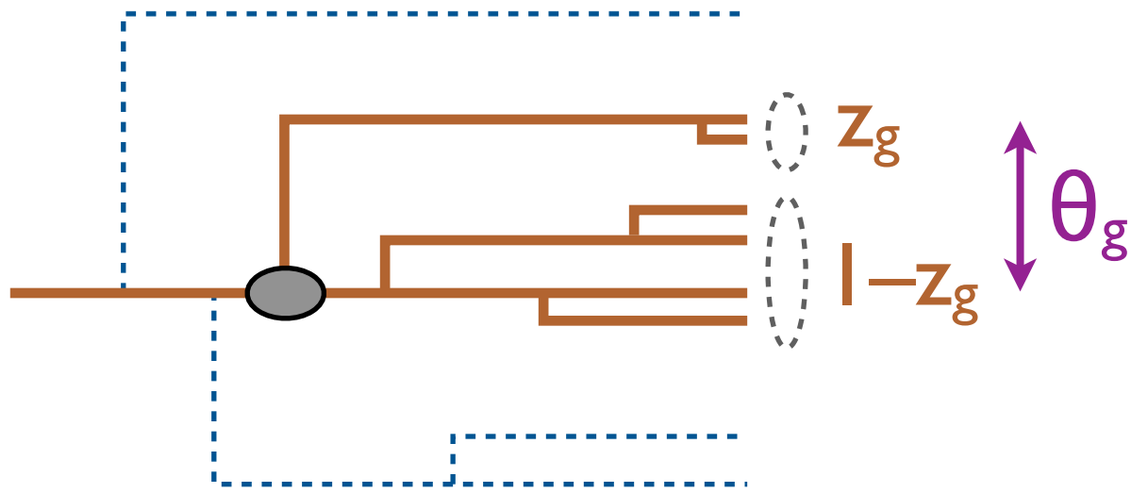


[Butterworth, Davison, Rubin, Salam, 0802.2470; see also Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

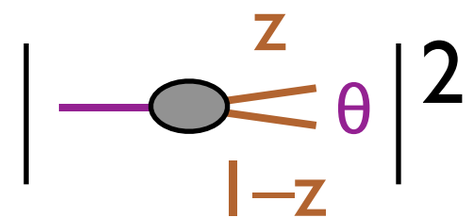
ATLAS W/Z Tagging: BDRS



Groomed angular-ordered clustering tree:



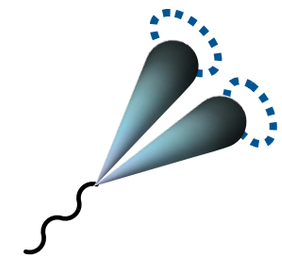
cf.



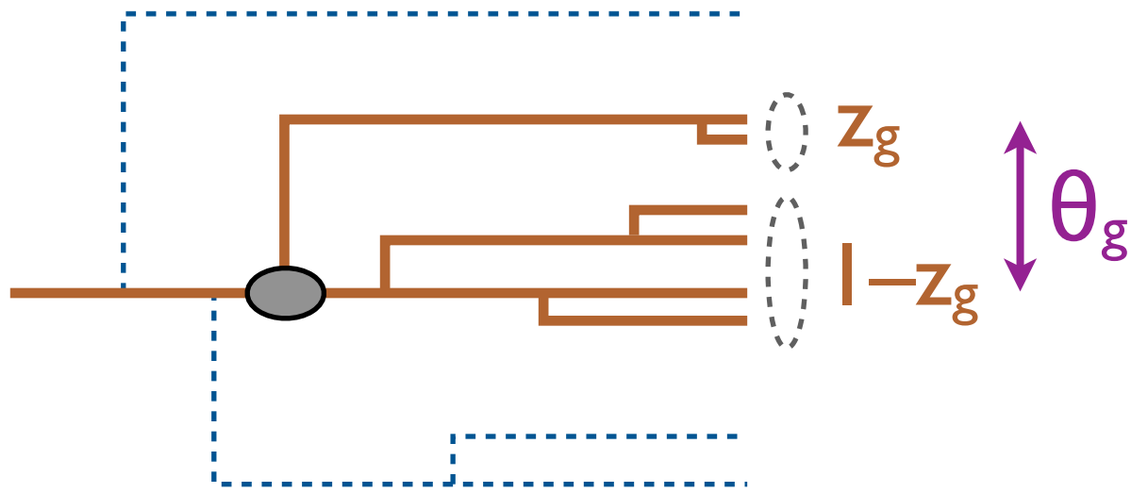
$$\frac{2\alpha_s C_i}{\pi}\,\frac{\mathrm{d}\theta}{\theta}\,\frac{\mathrm{d}z}{z}$$

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

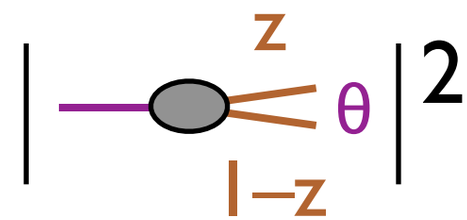
ATLAS W/Z Tagging: BDRS



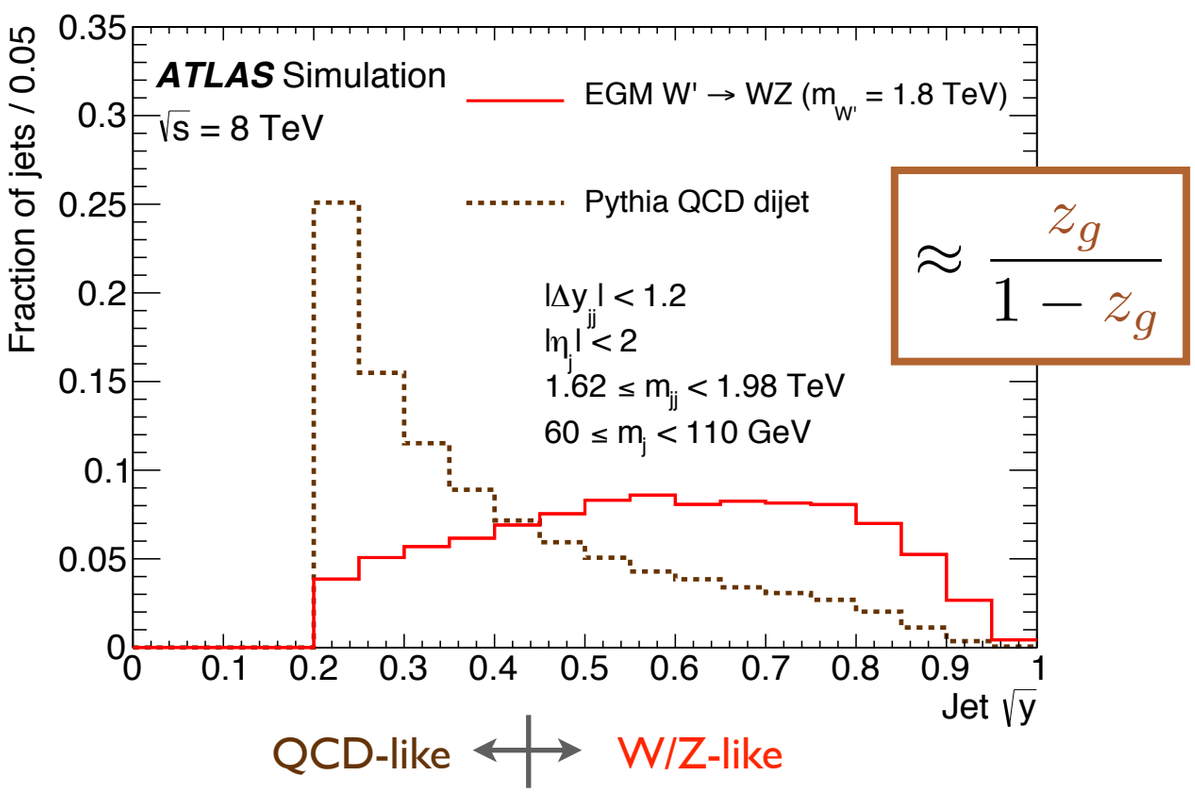
Groomed angular-ordered clustering tree:



cf.



$$\frac{2\alpha_s C_i}{\pi}\,\frac{\mathrm{d}\theta}{\theta}\,\frac{\mathrm{d}z}{z}$$

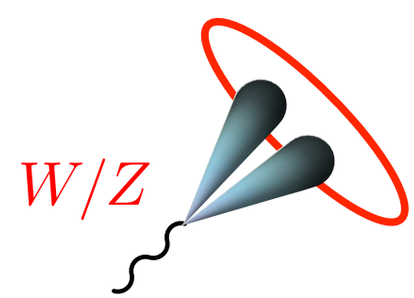


$$\approx \frac{z_g}{1-z_g}$$

QCD-like ⟷ W/Z-like

One soft subjet

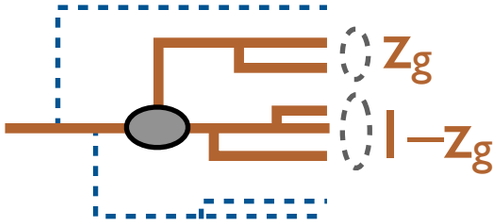
vs.



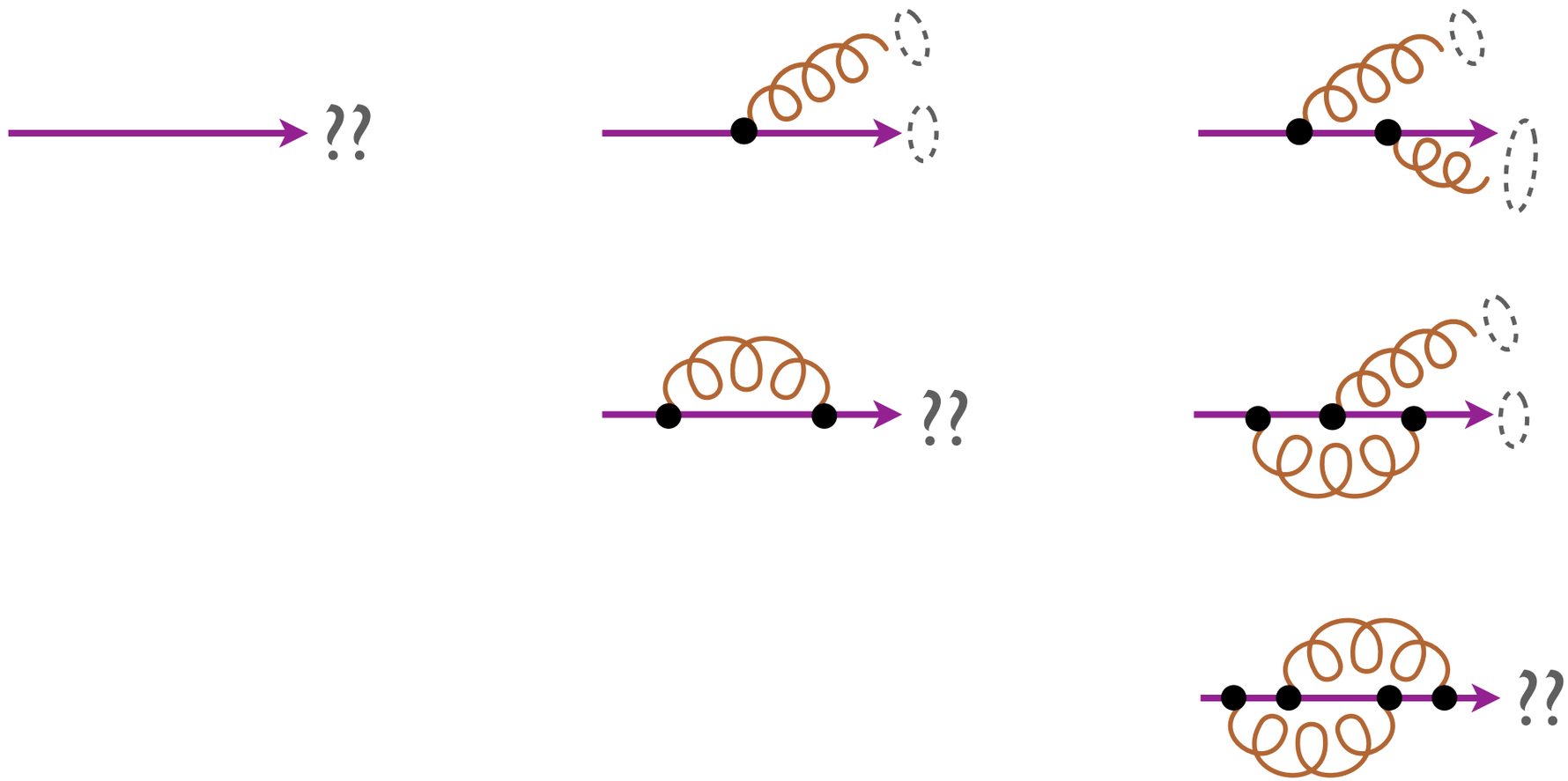
Balanced subjets

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

Calculating Momentum Balance?



$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} = \Big(\ \textit{undefined}\ \Big) + \alpha_s\Big(\ \textit{infinity}\ \Big) + \alpha_s^2\Big(\ \textit{infinity}^2\ \Big) + \ldots$$



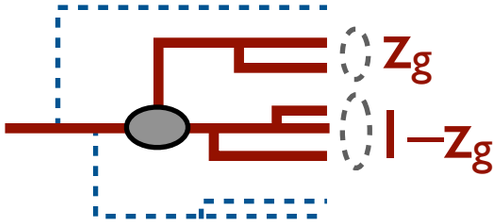
z_g

Collinear Unsafe*

Can't make prediction from perturbative QCD (?)

*unless you simultaneously restrict jet mass

The Puzzle

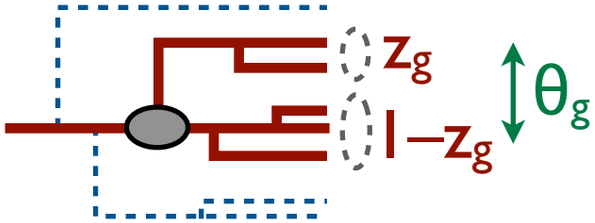


Collinear Unsafe

$$p(z_g)$$

z_g ??

The Puzzle



Collinear Unsafe

↓

$$p(z_g)$$

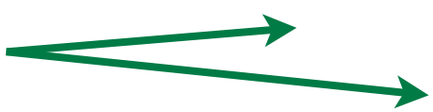
Calculable
order-by-order in α_s

↓

$$p(z_g|\theta_g)$$

z_g ??

vs.

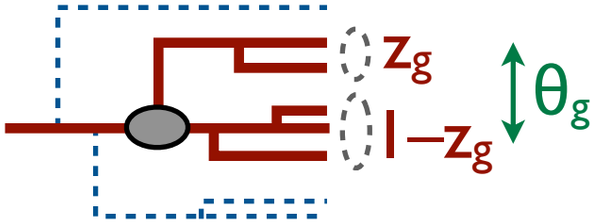


z_g

$1-z_g$

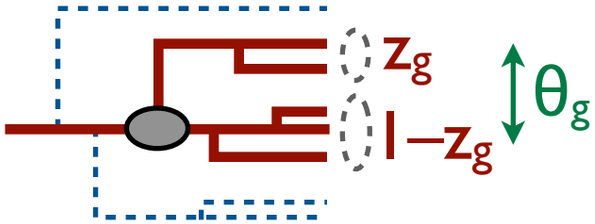
θ_g

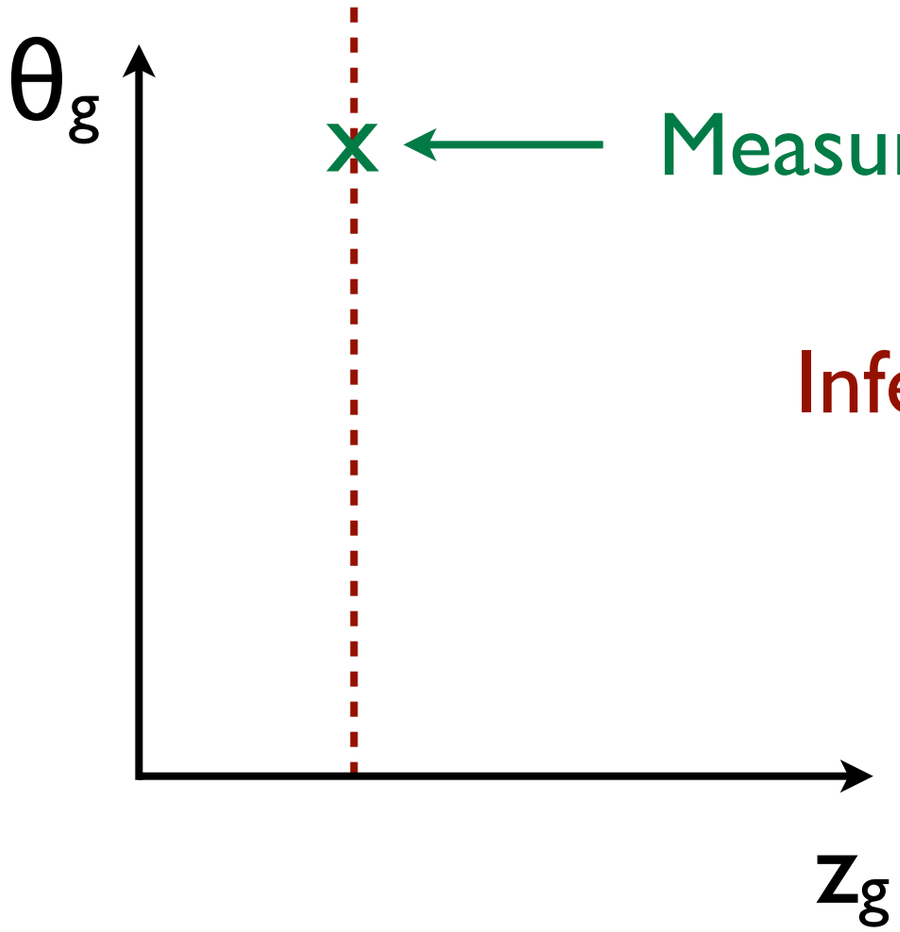
The Puzzle



$$p(z_g) \overset{?!}{=} \int \mathrm{d}\theta_g \, p(\theta_g) \, p(z_g|\theta_g)$$

2 Safe = 1 Unsafe?!

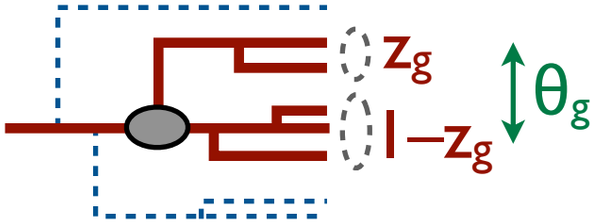


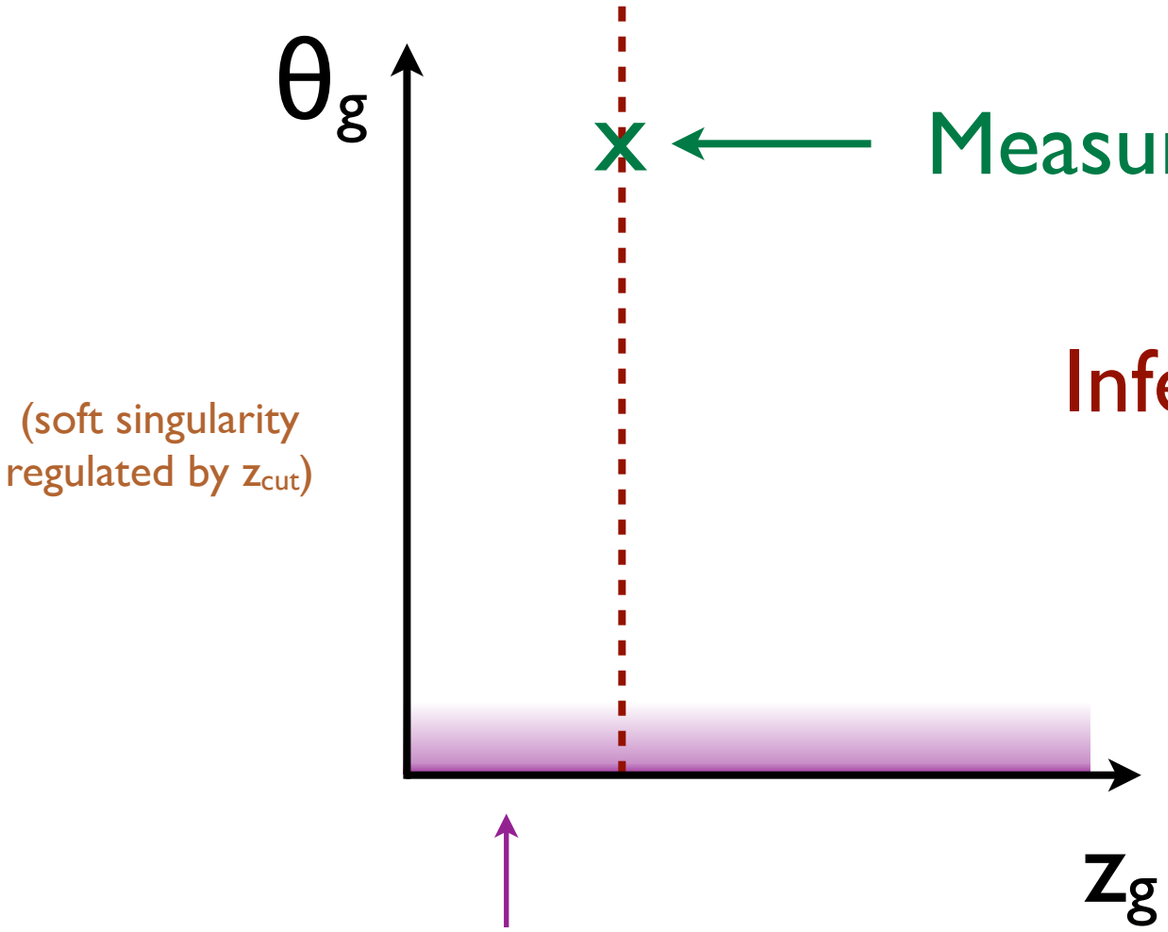


Measure: θ_g (IRC Safe)
z_g (IRC Safe if $\theta_g > 0$)

Infer: z_g (IRC Unsafe)

2 Safe = 1 Unsafe?!

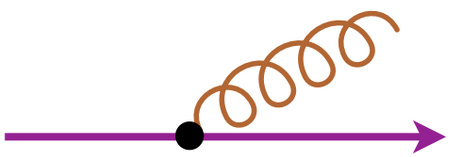




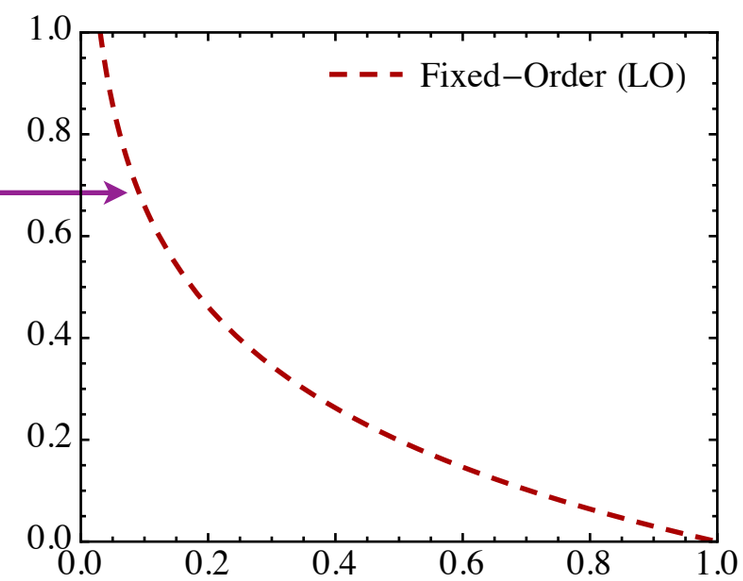
Measure: θ_g (IRC Safe)
z_g (IRC Safe if $\theta_g > 0$)

Infer: z_g (IRC Unsafe)

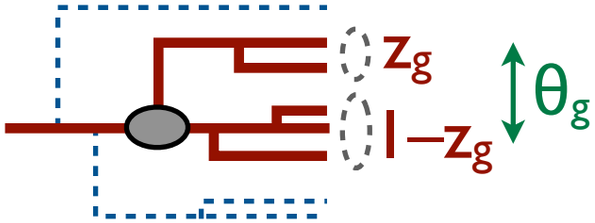
$$\frac{2\alpha_s C_i}{\pi}\,\frac{d\theta}{\theta}\,\frac{dz}{z}$$

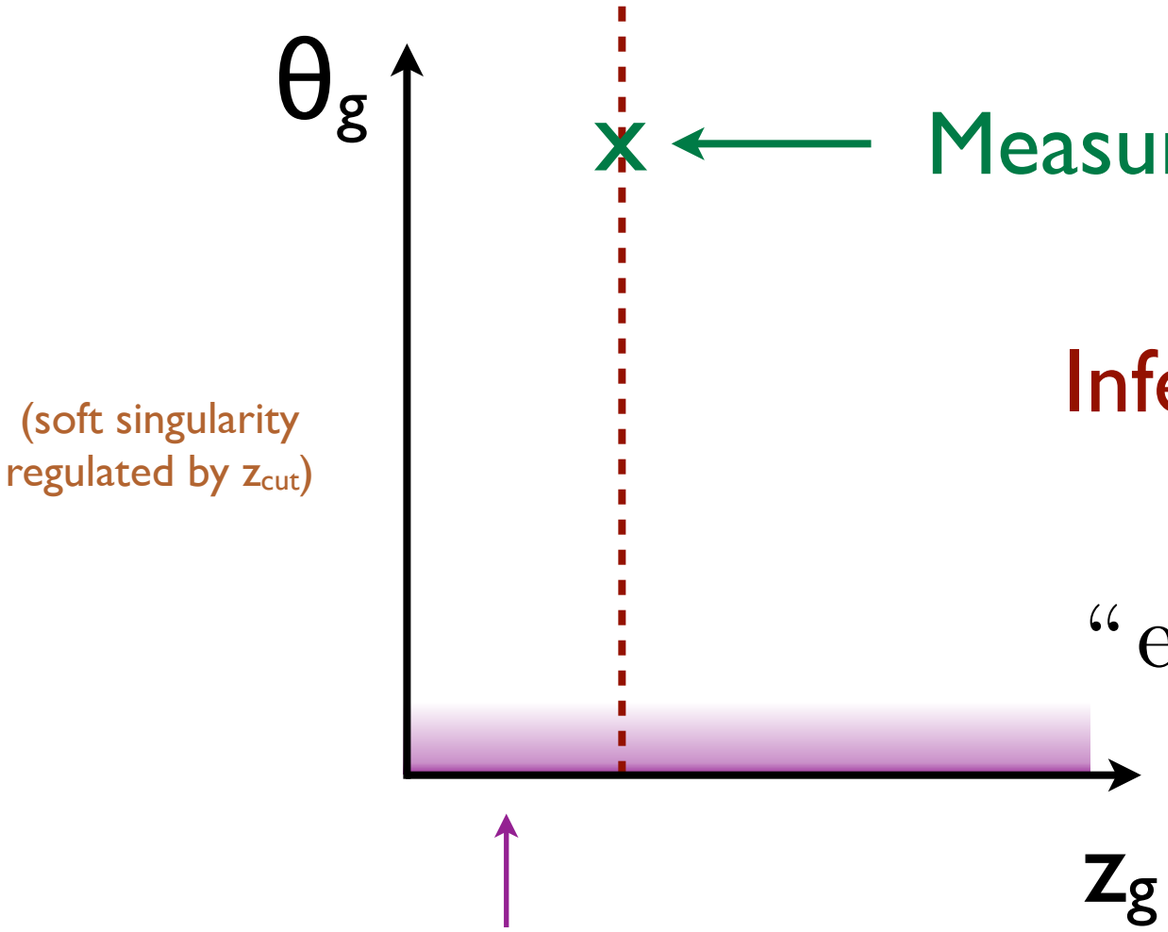


Collinear Singularity …



2 Safe = 1 Unsafe?!

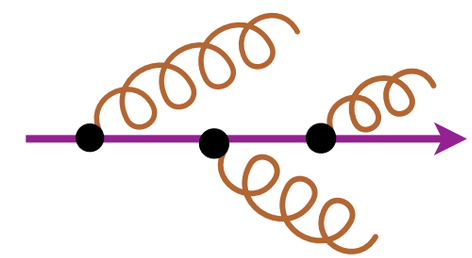




Measure: θ_g (IRC Safe)
z_g (IRC Safe if $\theta_g > 0$)

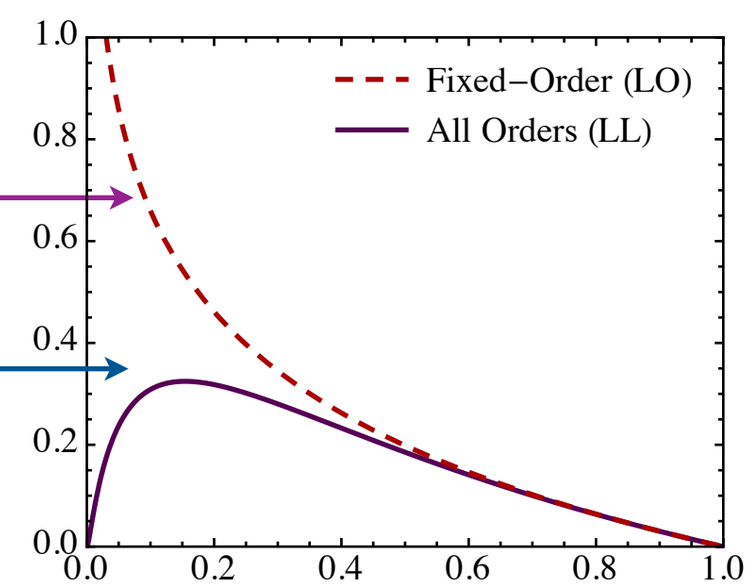
Infer: z_g (IRC Unsafe)

$$\text{“}\exp\left[\int \frac{2\alpha_s C_i}{\pi}\,\frac{d\theta}{\theta}\,\frac{dz}{z}\right]\text{”}$$



Collinear Singularity …

… Regulated by Sudakov Form Factor



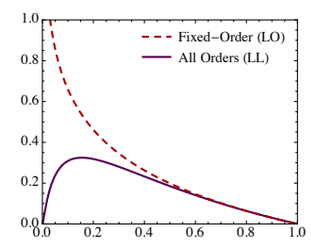
Introducing Sudakov Safety

"Sudakov Safe"

Calculable
order-by-order in α_s

$$p(z_g) = \int \mathrm{d}\theta_g \, p(\theta_g) \, p(z_g|\theta_g)$$

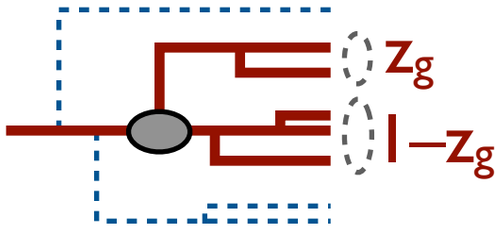
Form factor
suppresses singularities
at all orders in α_s



New calculational technique to extend validity of perturbative quantum field theory

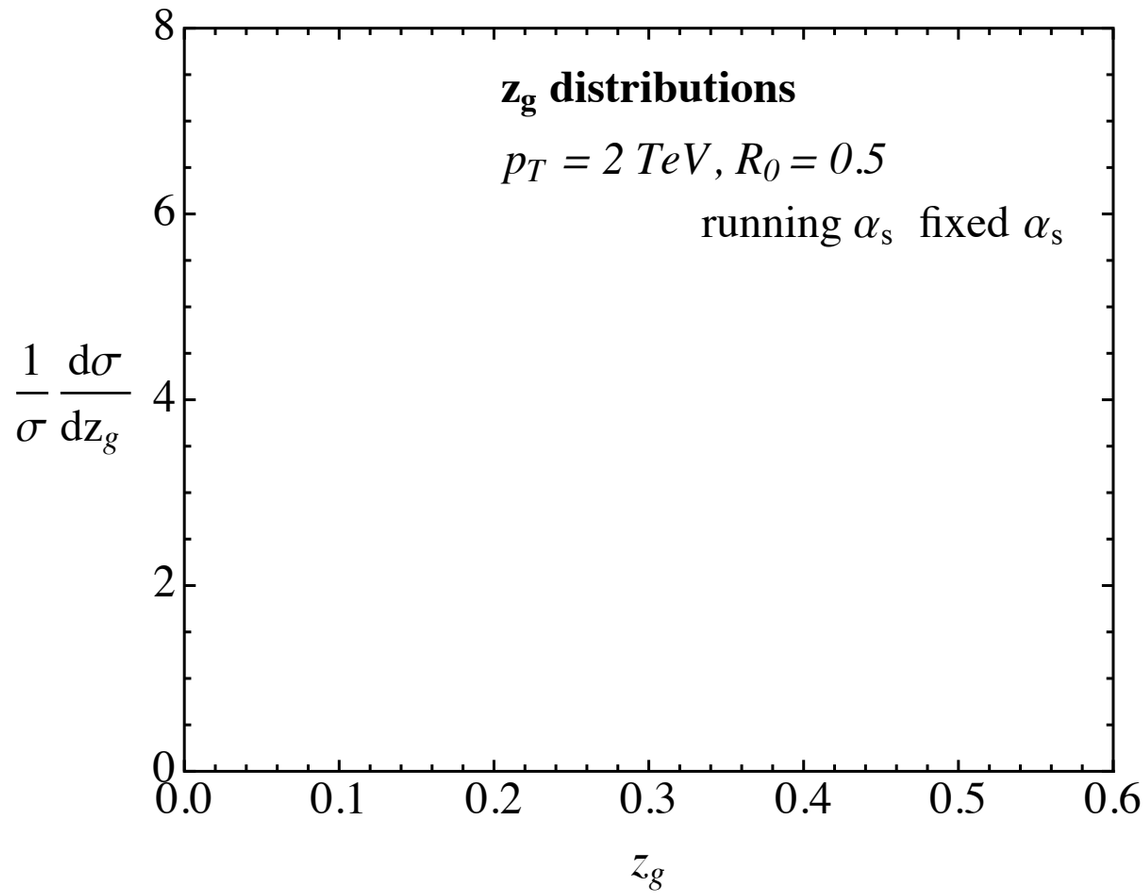
[Larkoski, JDT, 1307.1699; Larkoski, Marzani, JDT, 1502.01719]

Soft Drop



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

First-Principles QCD



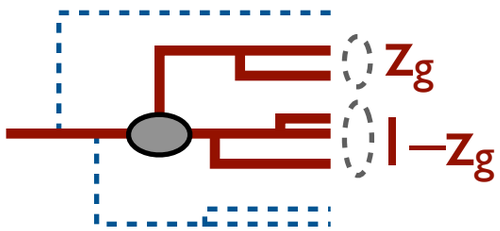
$C_q = 4/3$
$C_g = 3$

ATLAS 8 TeV
Diboson Search

More Grooming — Less Grooming

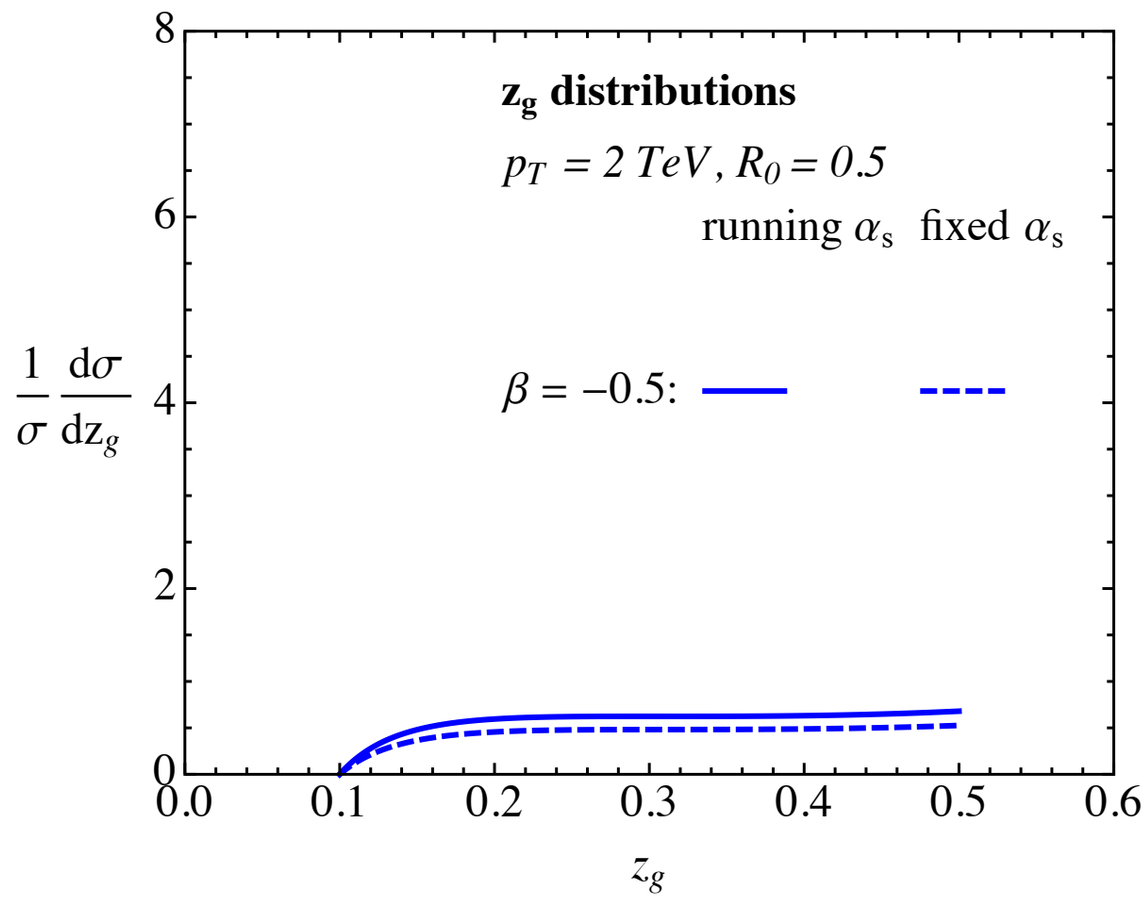
$\beta \to -\infty$ — $\beta < 0$ — $\beta = 0$ — $\beta > 0$ — $\beta \to \infty$

Soft Drop



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

First-Principles QCD



$C_q = 4/3$
$C_g = 3$

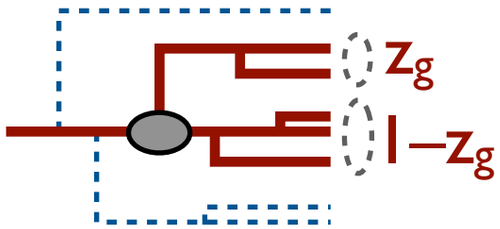
$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\,\frac{1}{z_g}\log\frac{z_g}{z_{\rm cut}}$$

More Grooming

Less Grooming

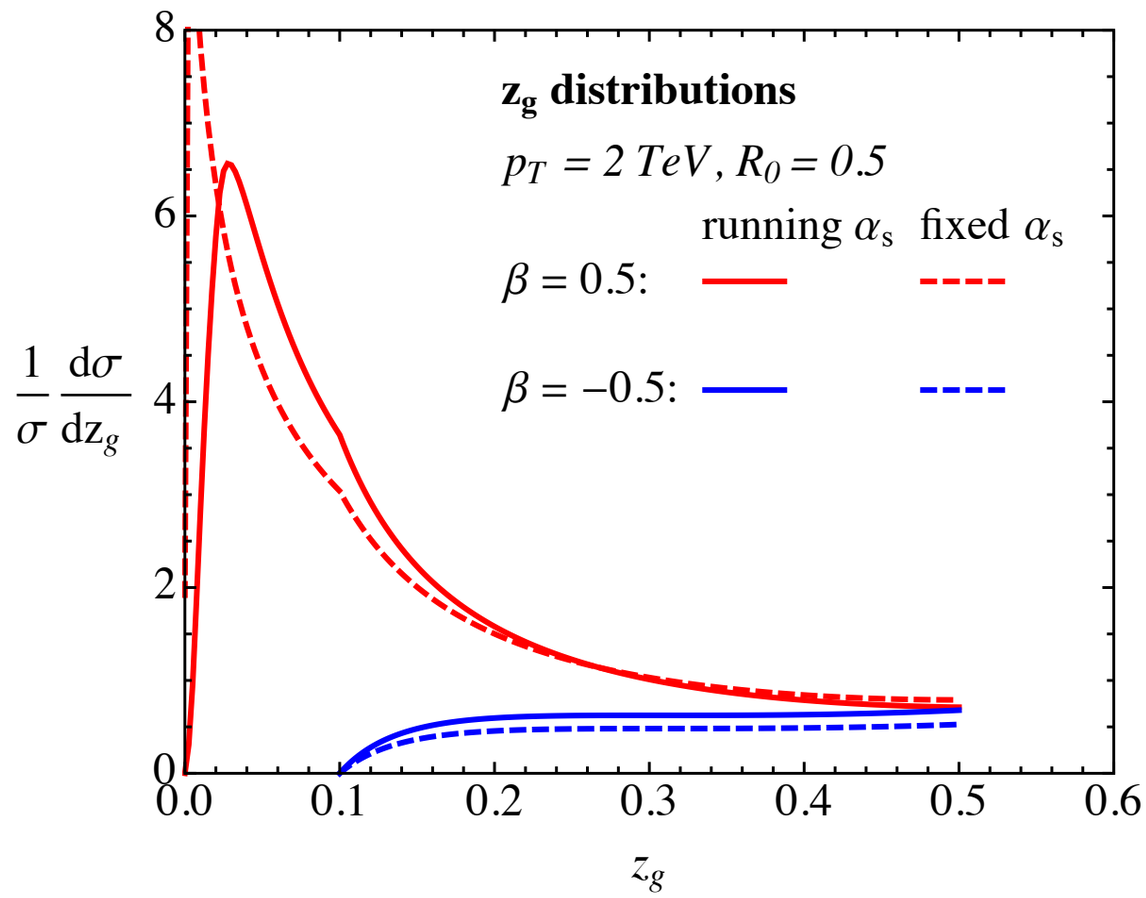
$\beta \to -\infty$ $\quad$ $\beta < 0$ $\quad$ $\beta = 0$ $\quad$ $\beta > 0$ $\quad$ $\beta \to \infty$

Soft Drop



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

First-Principles QCD



$C_q = 4/3$
$C_g = 3$

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

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

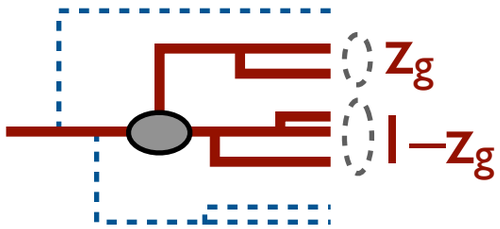
Beyond traditional perturbation theory (Sudakov safe)

More Grooming

Less Grooming

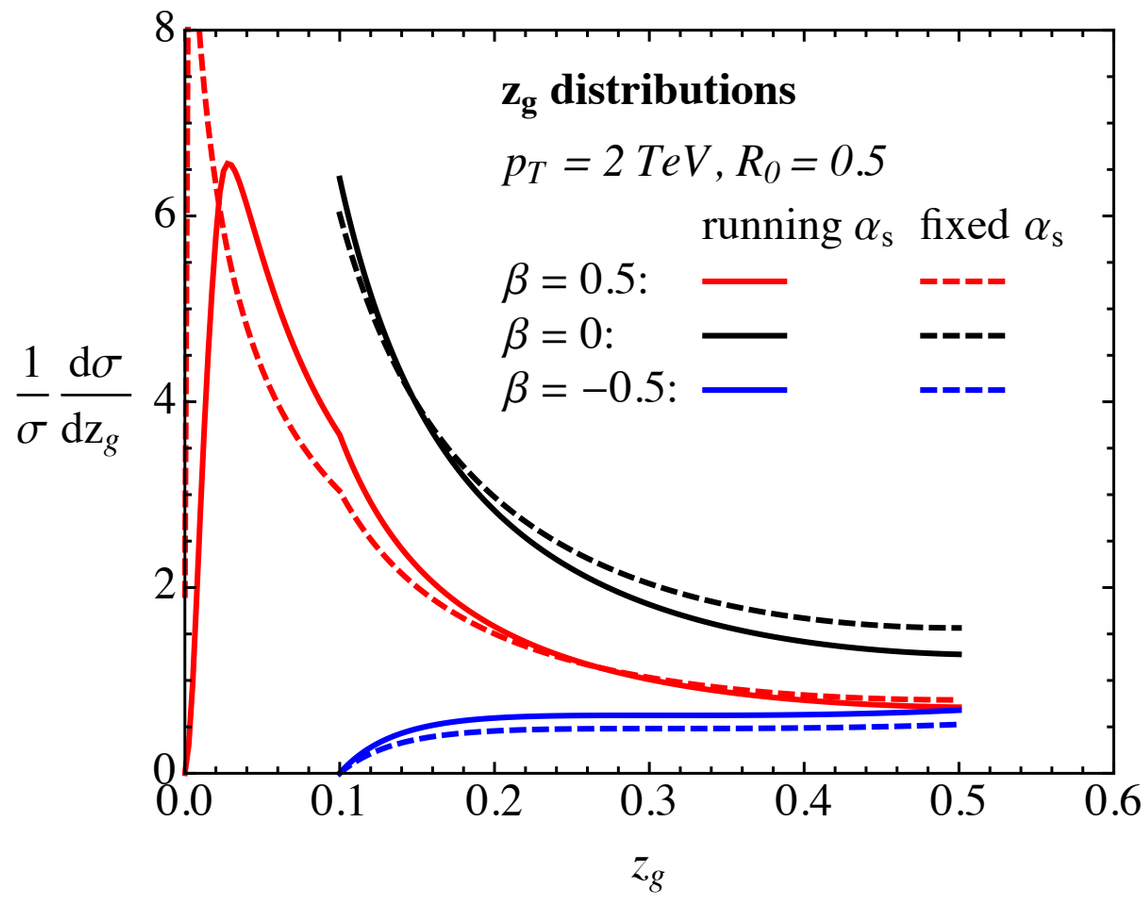
$\beta \to -\infty$ $\quad$ $\beta < 0$ $\quad$ $\beta = 0$ $\quad$ $\beta > 0$ $\quad$ $\beta \to \infty$

Soft Drop



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

First-Principles QCD



$C_q = 4/3$
$C_g = 3$

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

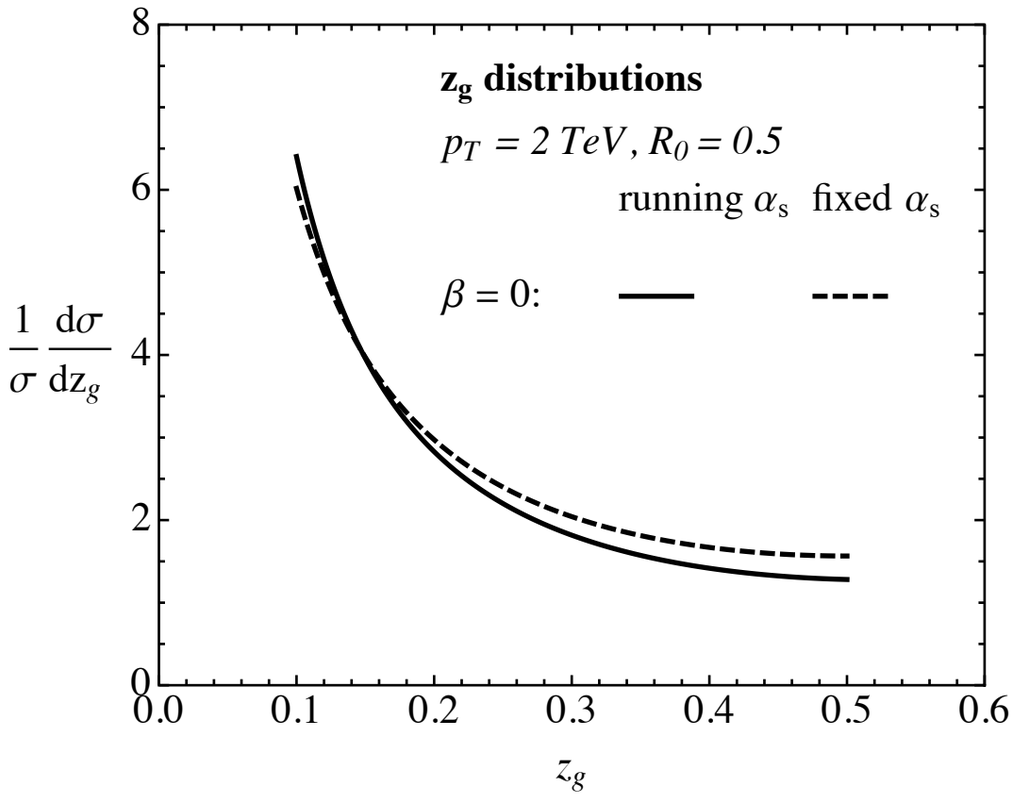
Beyond traditional perturbation theory (Sudakov safe)

More Grooming

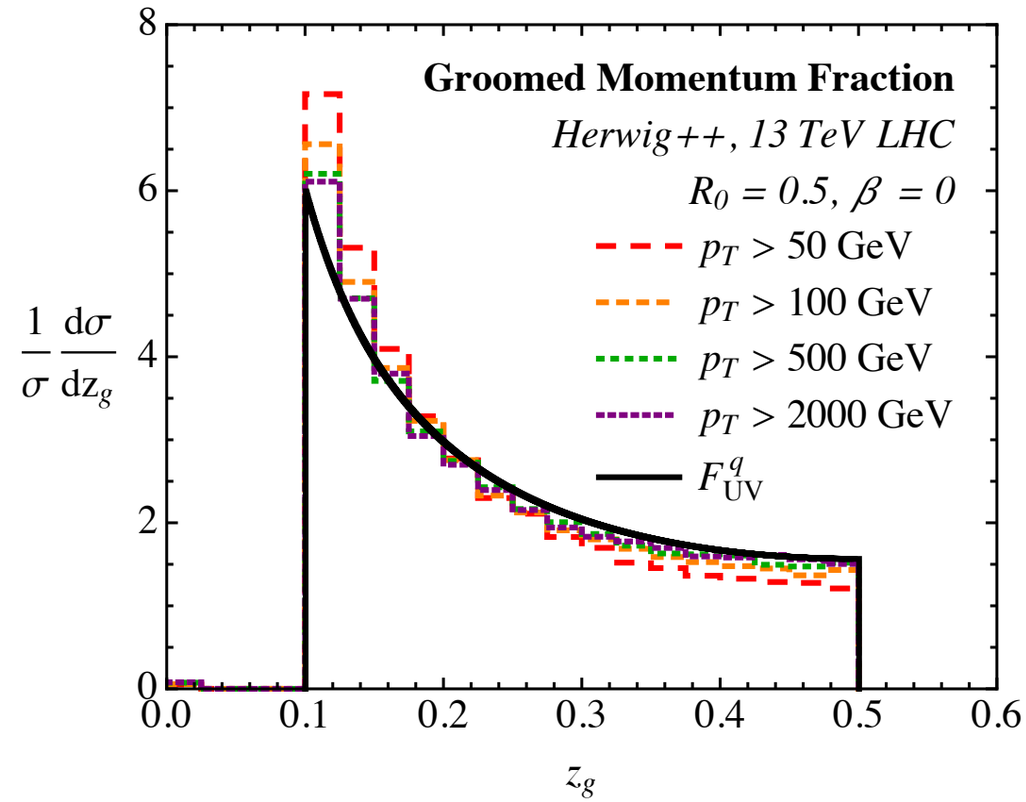
Less Grooming

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

First-Principles QCD



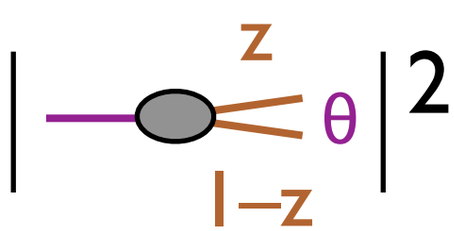
Simulated LHC Data



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

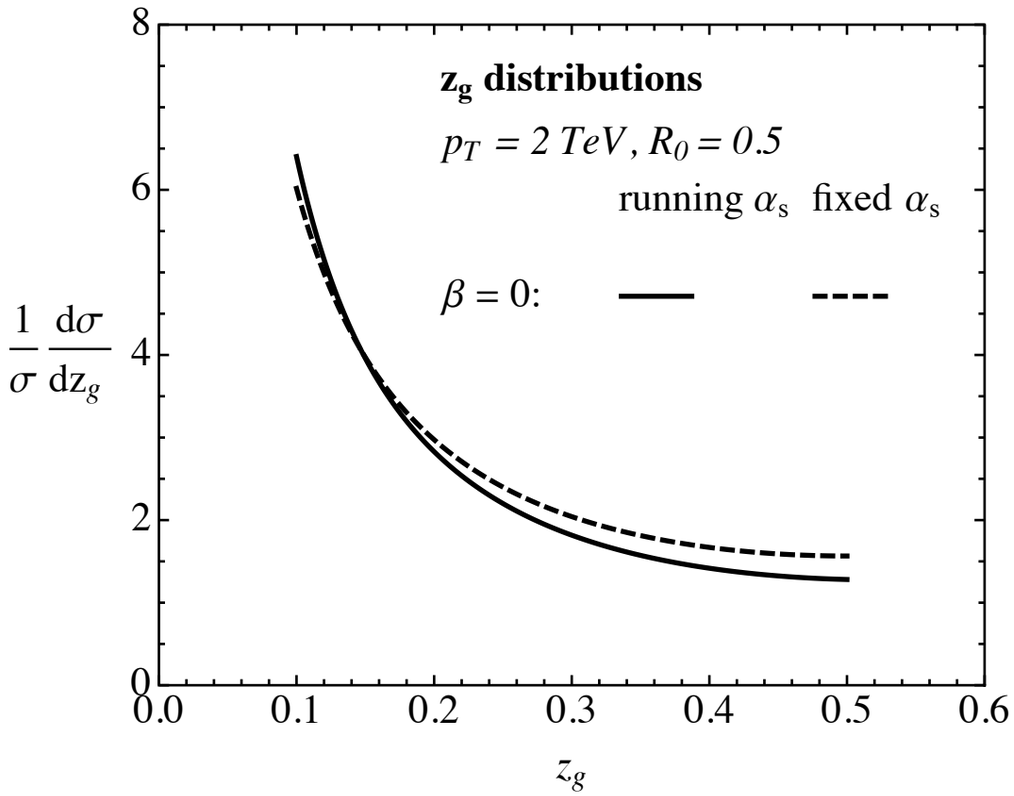
$$\mathrm{d}P_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}z}{z}$$

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

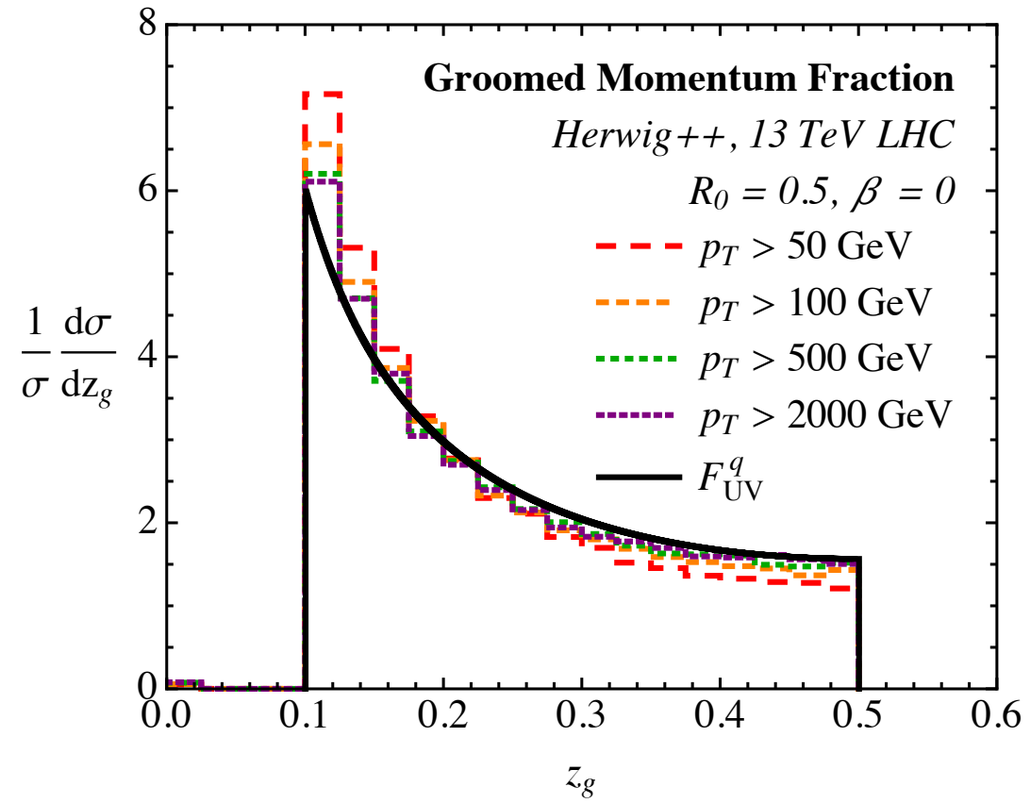
cf. 

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

First-Principles QCD

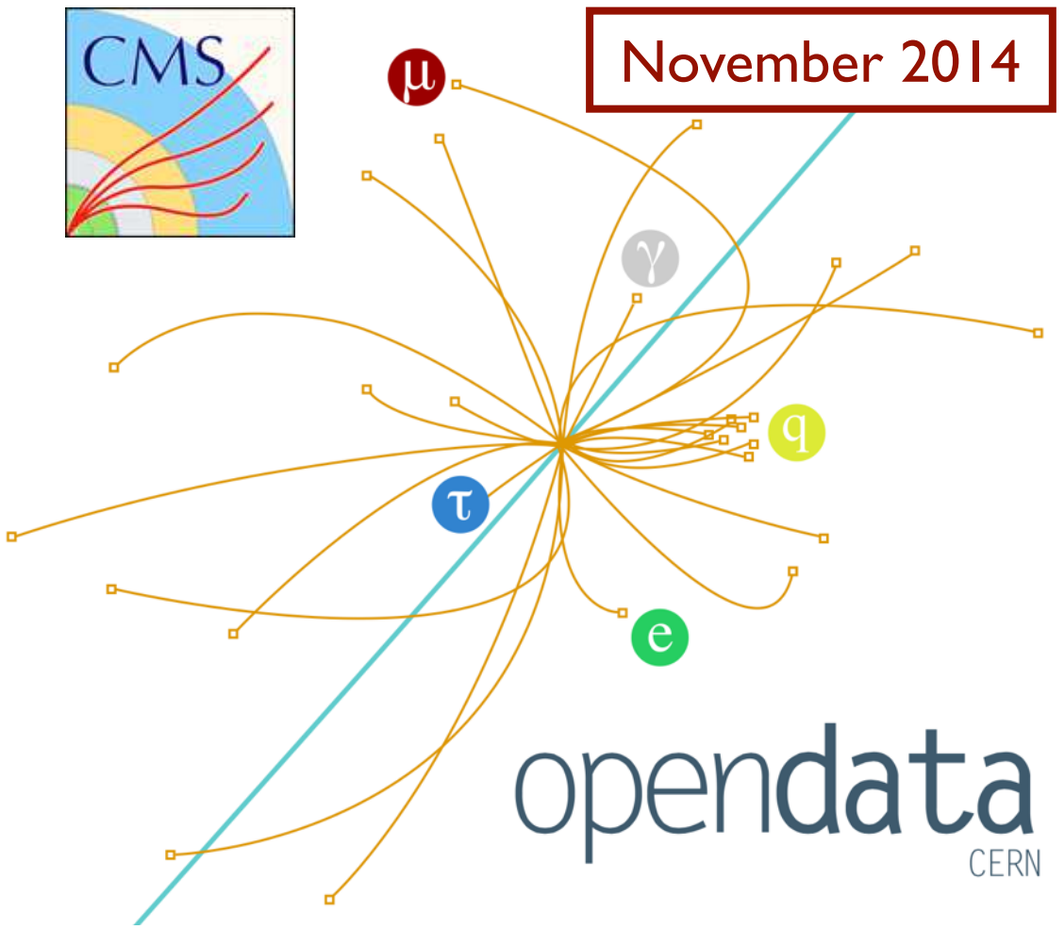


Simulated LHC Data



Actual LHC Data?

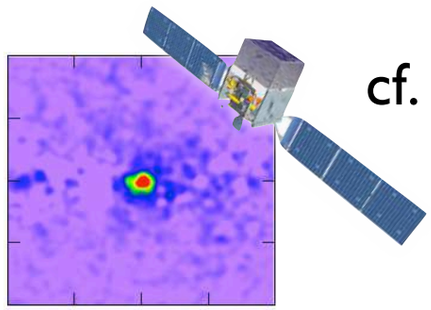
The Future is Open



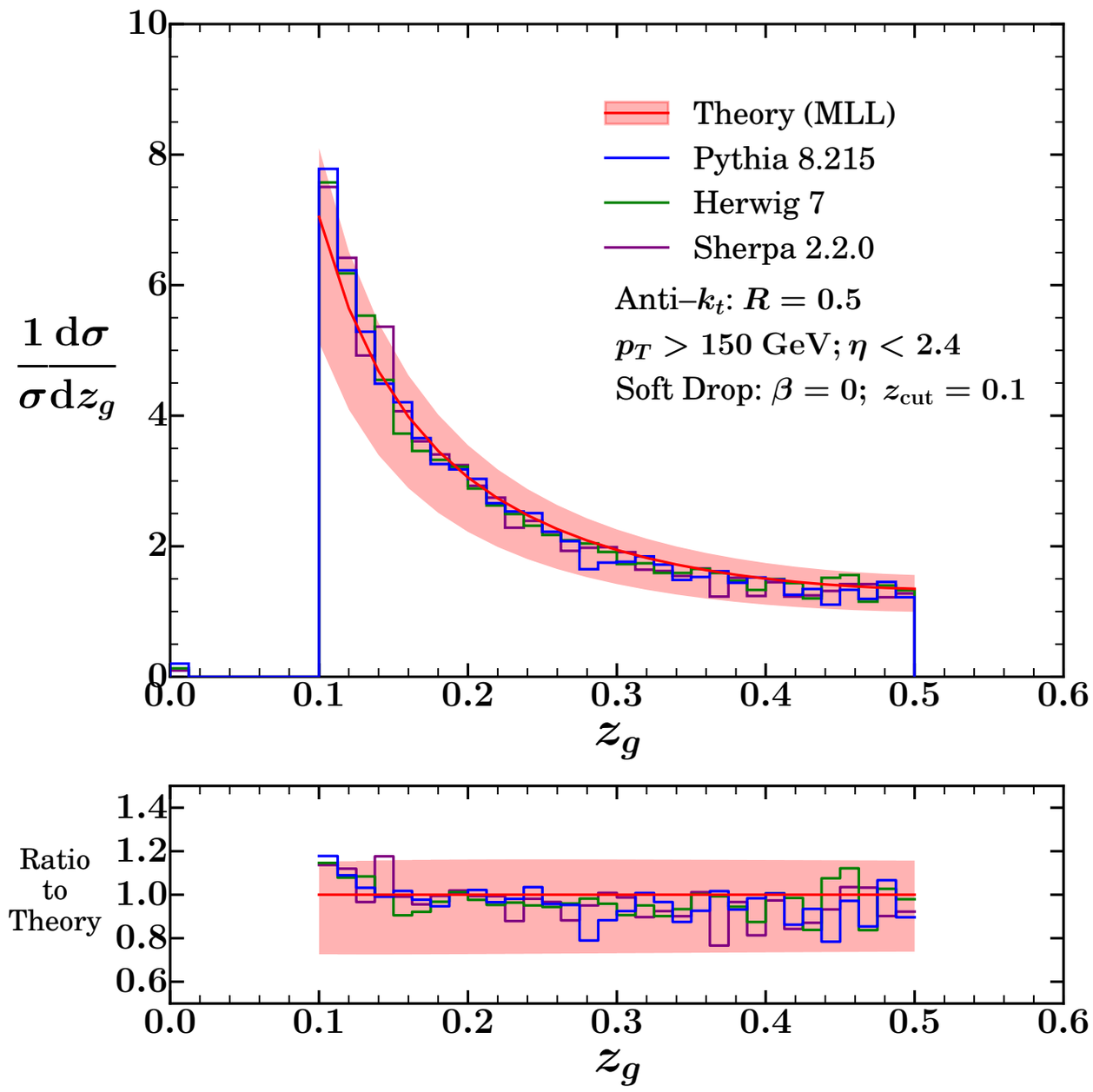
CMS 2010:

Unique data set
with very low pileup

Accelerating science
through public data



cf. Fermi

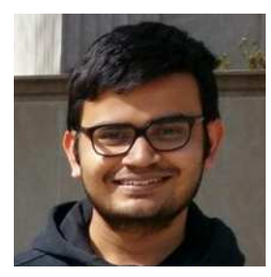


Andrew Larkoski

Simone Marzani

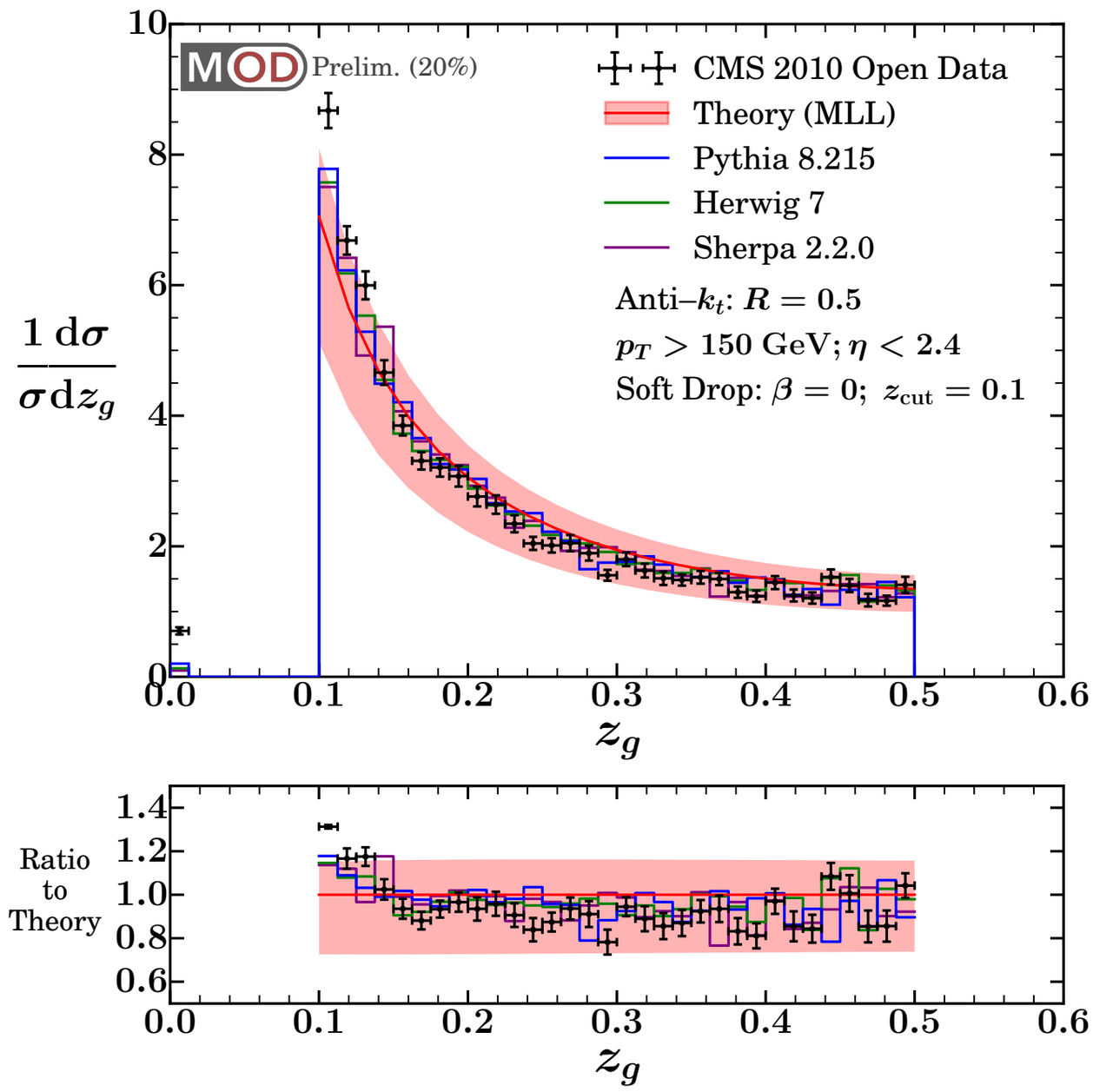
Alexis Romero

Aashish Tripathee



Wei Xue

CMS advice from Sal Rappoccio



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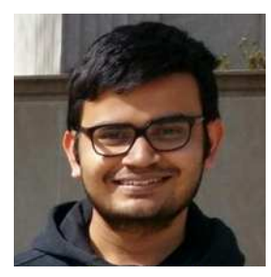
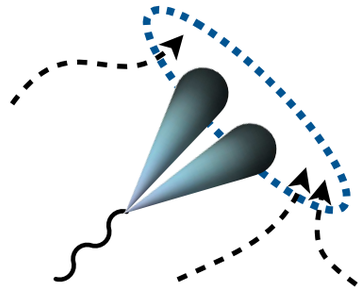


Wei Xue

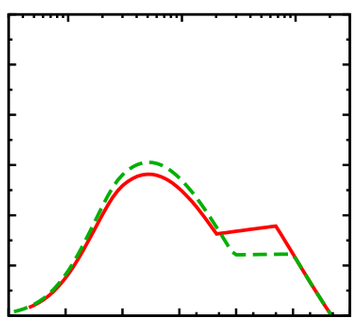
CMS advice from Sal Rappoccio

Summary



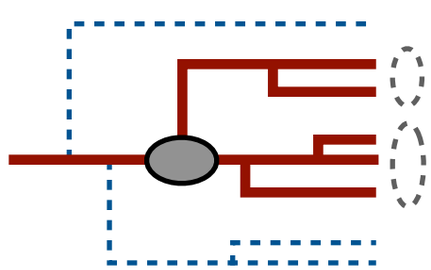
Giving New Physics a Boost

Exceptional LHC performance + (B)SM physics



Substructure from First Principles

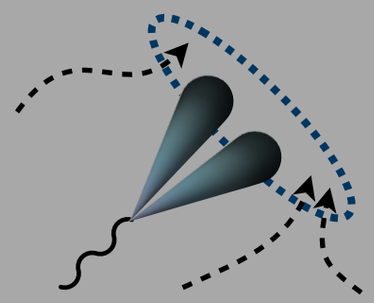
Growing catalog of observables, growing toolbox of approaches



Probing the Core of QCD

Accessing the universal singularity structure of gauge theories

Summary

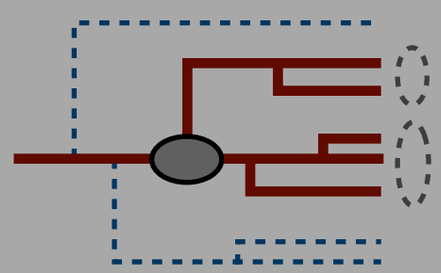


Giving New Physics a Boost

Exceptional LHC performance + (B)SM physics

Jet Substructure

Boosting the Search for New Phenomena
Pushing the Boundaries of Quantum Field Theory



Probing the Core of QCD

Accessing the universal singularity structure of gauge theories

July 18–22, 2016

Backup Slides

All observables are calculable,
but some observables are
more calculable than others.

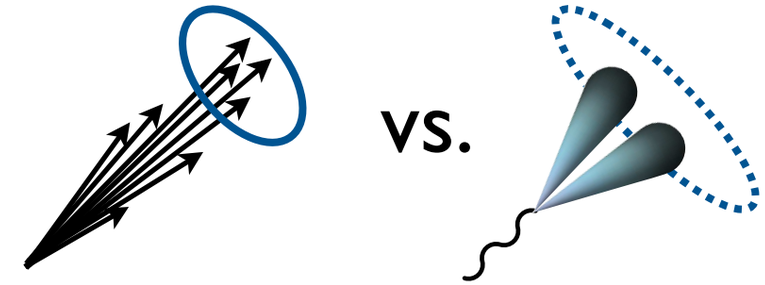
≈ George Orwell, *Animal Farm*

All IRC safe observables are alike;
each IRC unsafe observable
is unsafe in its own way.

≈ Leo Tolstoy, *Anna Karenina*

ATLAS W/Z Tagging: "R2 D_2"

R_{sub} = 0.2 trimming with D_2 tagging



Energy correlation functions:

$$e_2 = \sum_{i<j} z_i z_j R_{ij}$$

$$e_3 = \sum_{i<j<k} z_i z_j z_k R_{ij} R_{jk} R_{ki}$$

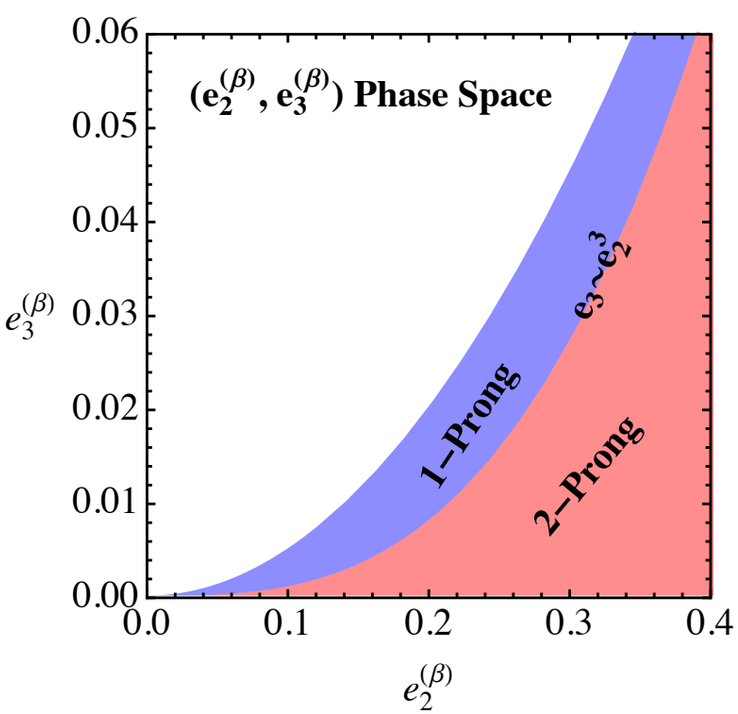
momentum fraction $z = p_T/p_{T\,jet}$

pair-wise angles

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

natural?

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



$\Rightarrow$

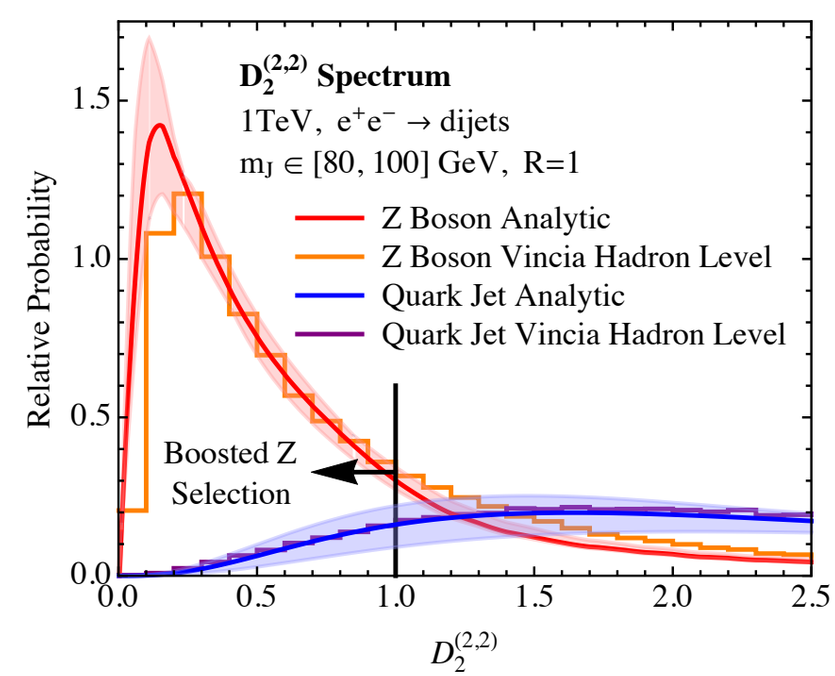
Theory insight:

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

key!

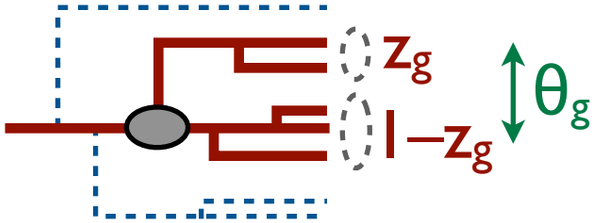
now ATLAS default

$\Rightarrow$



[Larkoski, Moult, Neill, 1409.6298,1507.03018]

1. Explicit Computation



Master Formula: $$p(z_g) = \int \mathrm{d}\theta_g \, p(\theta_g) \, p(z_g|\theta_g)$$

$$p(\theta_g) \simeq \frac{\mathrm{d}}{\mathrm{d}\theta_g} \exp\left[-\frac{\alpha_s C_i}{\pi}\left(\beta \log^2 \frac{1}{\theta_g} + 2 \log \frac{1}{\theta_g} \log \frac{1}{2\, z_{\mathrm{cut}}}\right)\right]$$

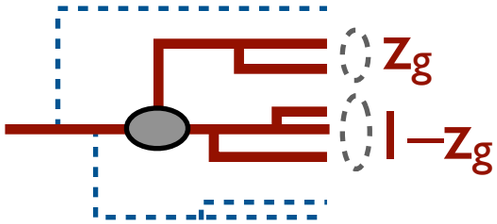
$$p(z_g|\theta_g) \simeq \frac{1}{\mathrm{norm}} \frac{1}{z_g} \Theta(z_g - z_{\mathrm{cut}} {\theta_g}^{\beta})$$

$$p(z_g) \simeq \sqrt{\frac{\alpha_s C_i}{\beta}} \frac{1}{z_g} \exp\left[\frac{\alpha_s C_i}{\pi\beta} \log^2 \frac{1}{2 z_{\mathrm{cut}}}\right] \mathrm{erfc}\left[\sqrt{\frac{\alpha_s C_i}{\pi\beta}} \log \frac{1}{\min[2 z_{\mathrm{cut}}, 2 z_g]}\right]$$

$$\Rightarrow \frac{1}{\mathrm{norm}} \frac{1}{z_g} \Theta(z_g - z_{\mathrm{cut}}) \quad (\beta = 0)$$

[Larkoski, Marzani, JDT, 1502.01719;
using Larkoski, JDT, 1307.1699; Larkoski, Marzani, Soyez, JDT, 1402.2657]

2. Renormalization Group Flow

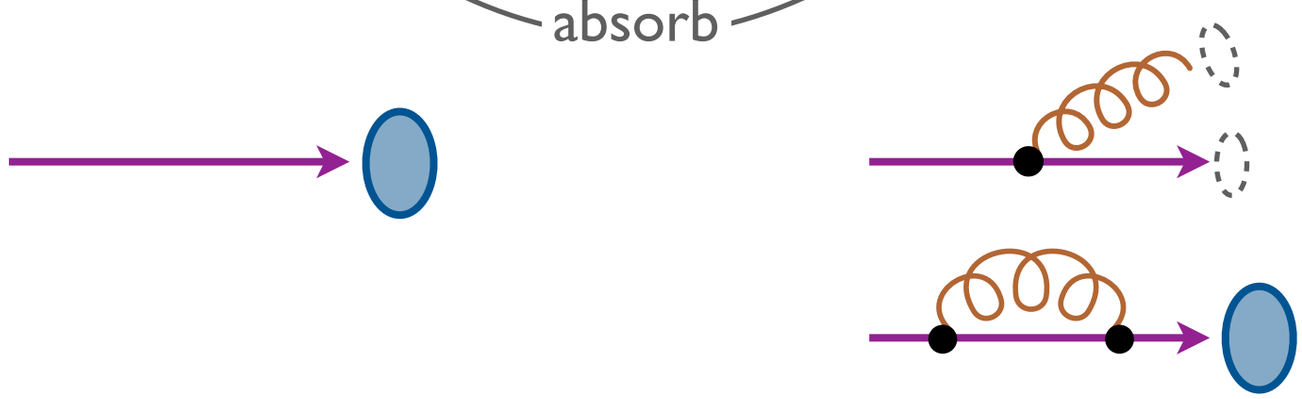


Collinear Unsafe?

Absorb singularities into universal nonperturbative function (cf. PDFs)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} = \Big(\text{fragmentation function}\Big) + \alpha_s\Big(\text{collinear singularities}\Big) + \mathcal{O}(\alpha_s^2)$$

absorb

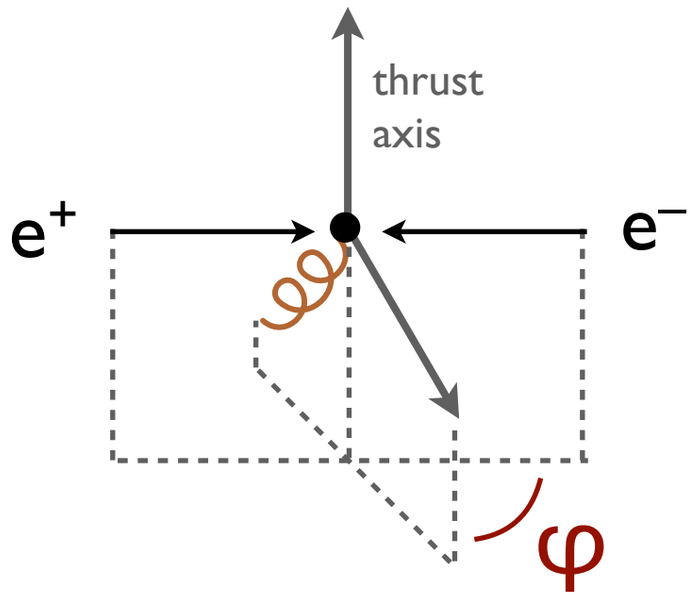


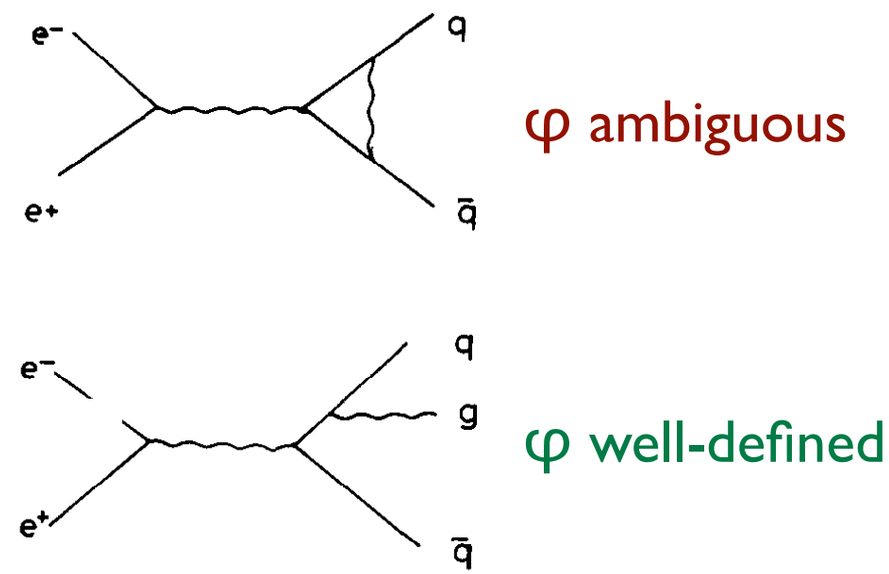
$$\mu\frac{\partial}{\partial\mu}F_i(z_g;\mu) \simeq \frac{\alpha_s C_i}{\pi}\Big(p(z_g) - F_i(z_g;\mu)\Big)$$

UV fixed point

[Larkoski, Marzani, JDT, 1502.01719]

3. Learn from our Elders





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

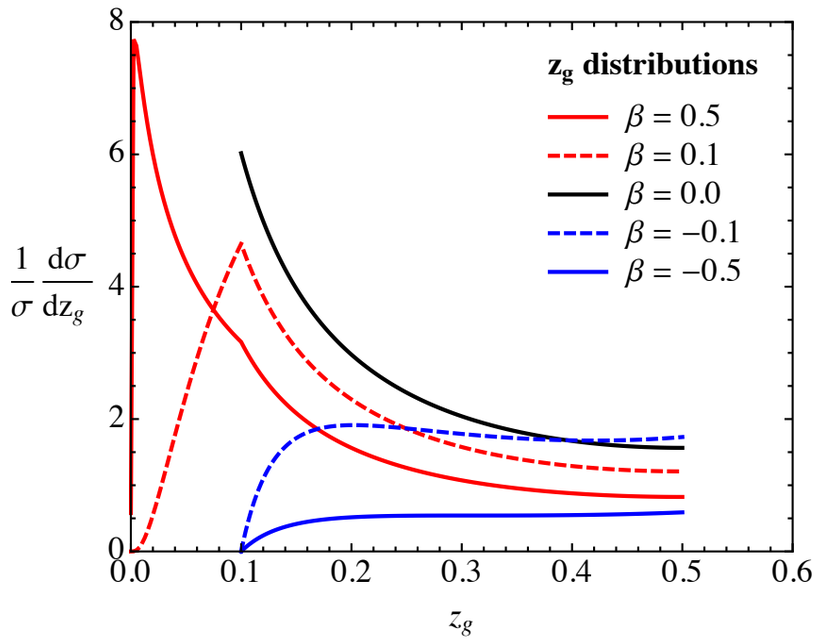
Born cross section despite ambiguity (!)

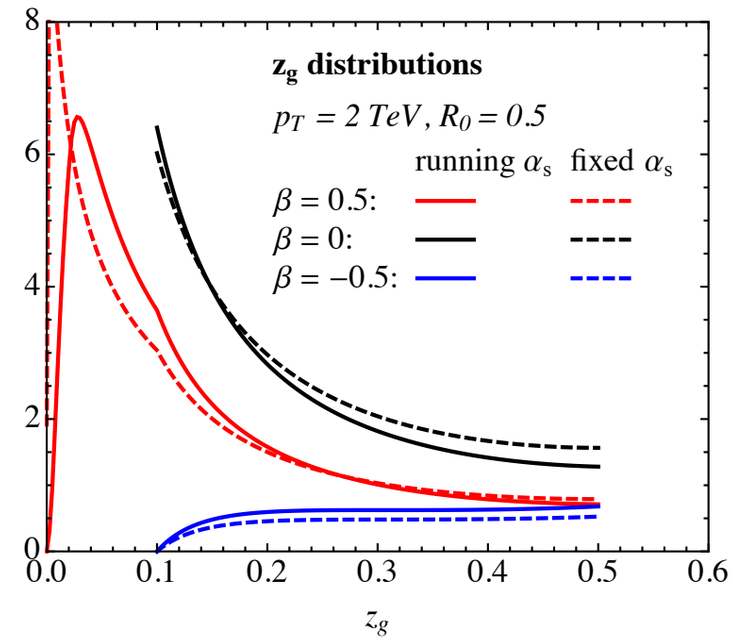
Exploits generalized notion of "observable"

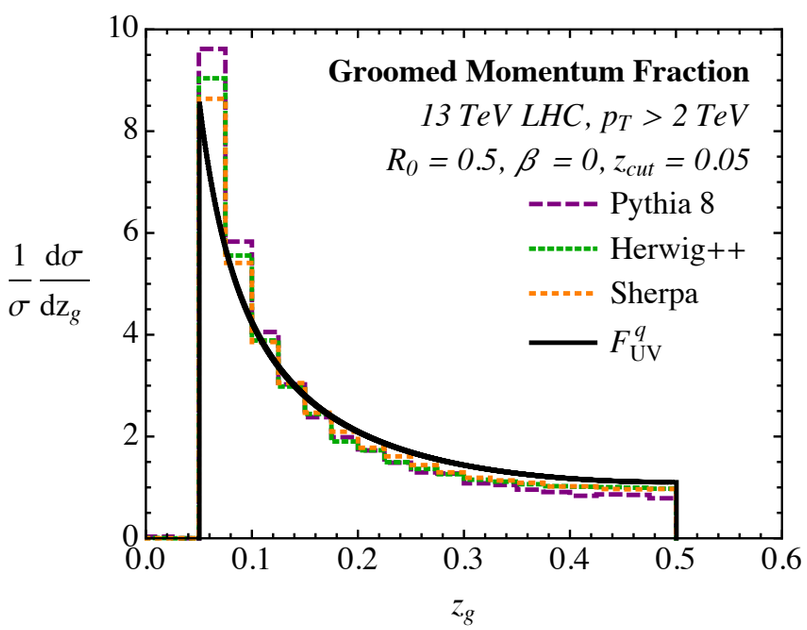
[Pi, Jaffe, Low, 1978; Kramer, Schierholz, Willrodt, 1978]

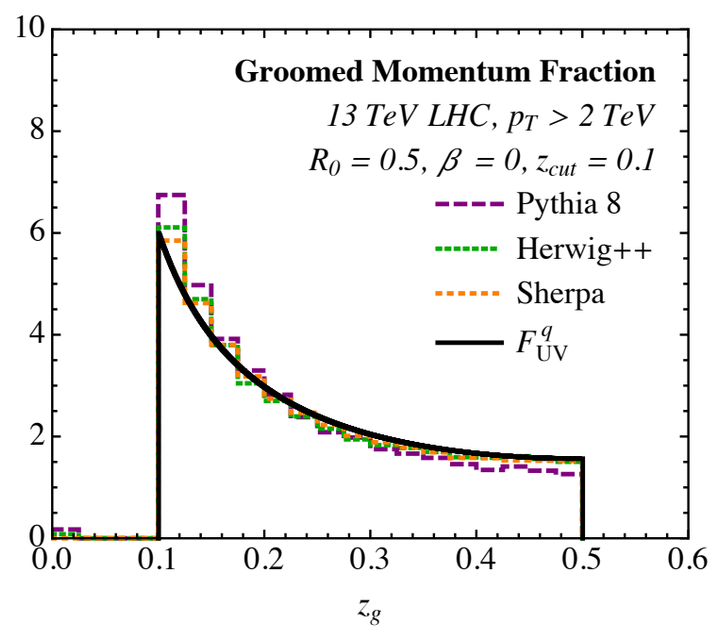
More About Open Data

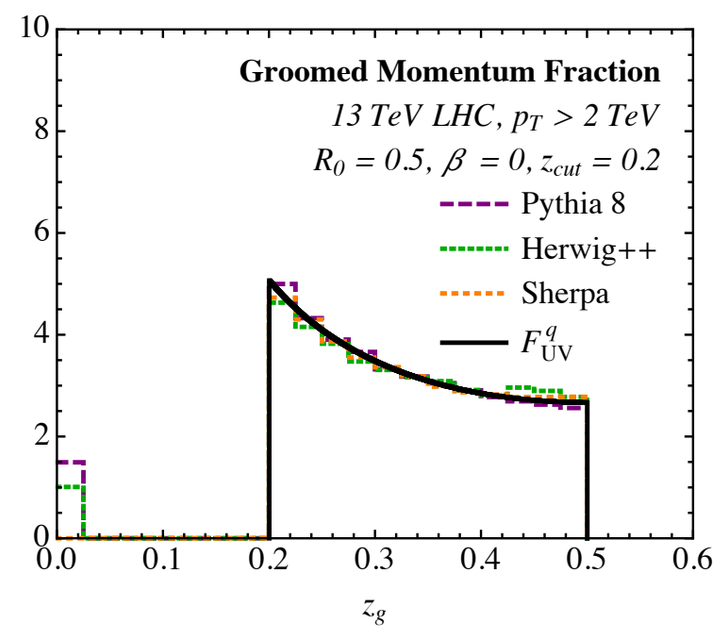
Additional z_g Theory Plots





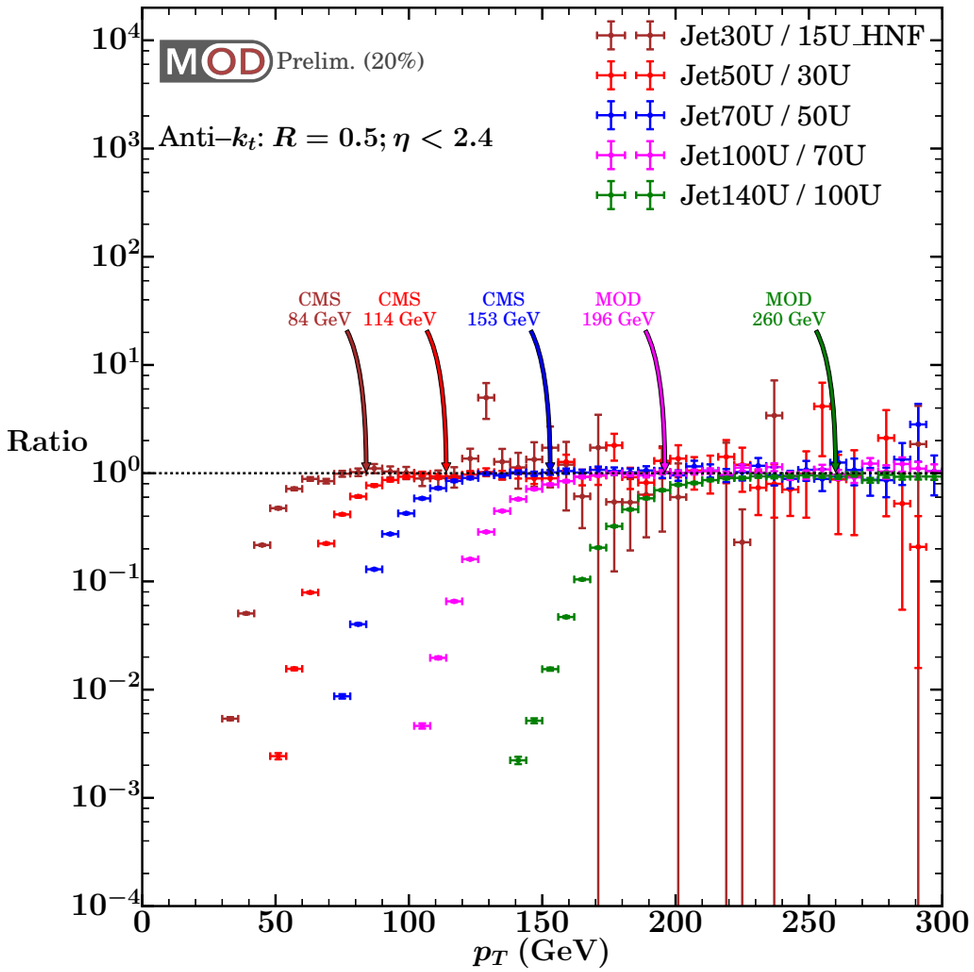


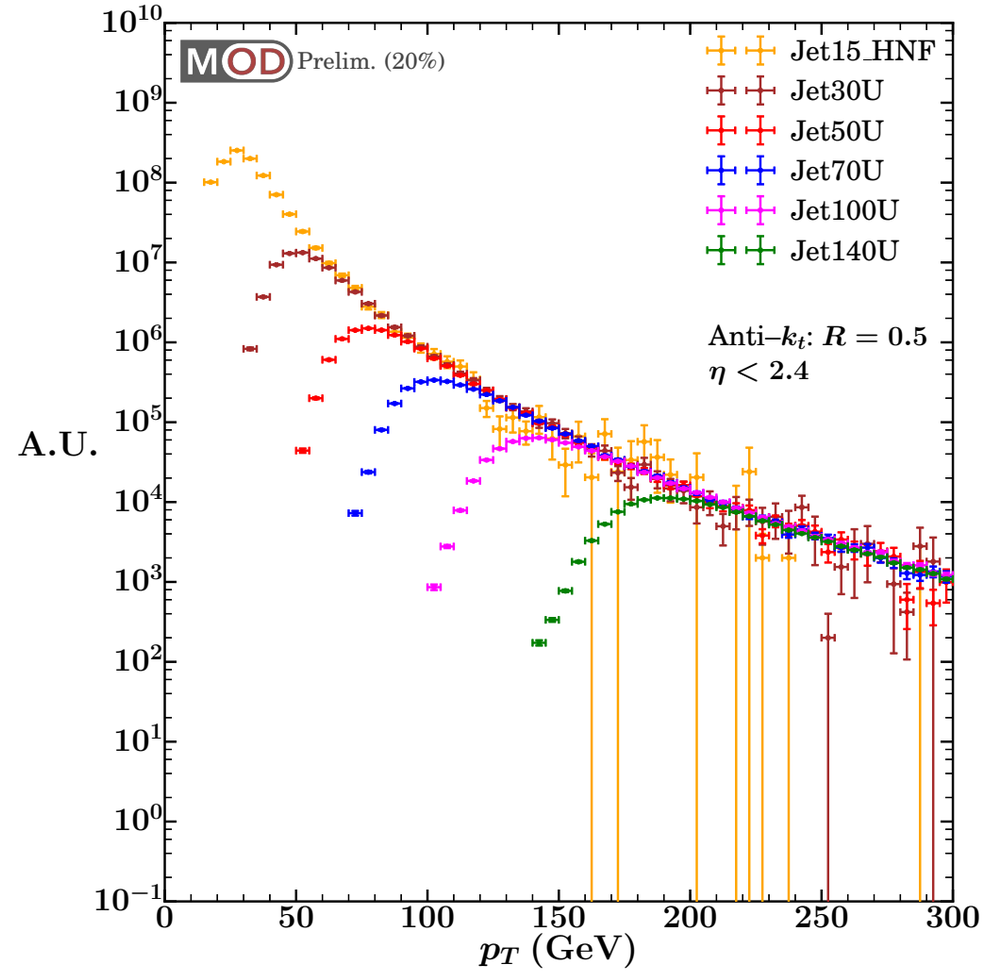




[Larkoski, Marzani, JDT, 1502.01719]

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
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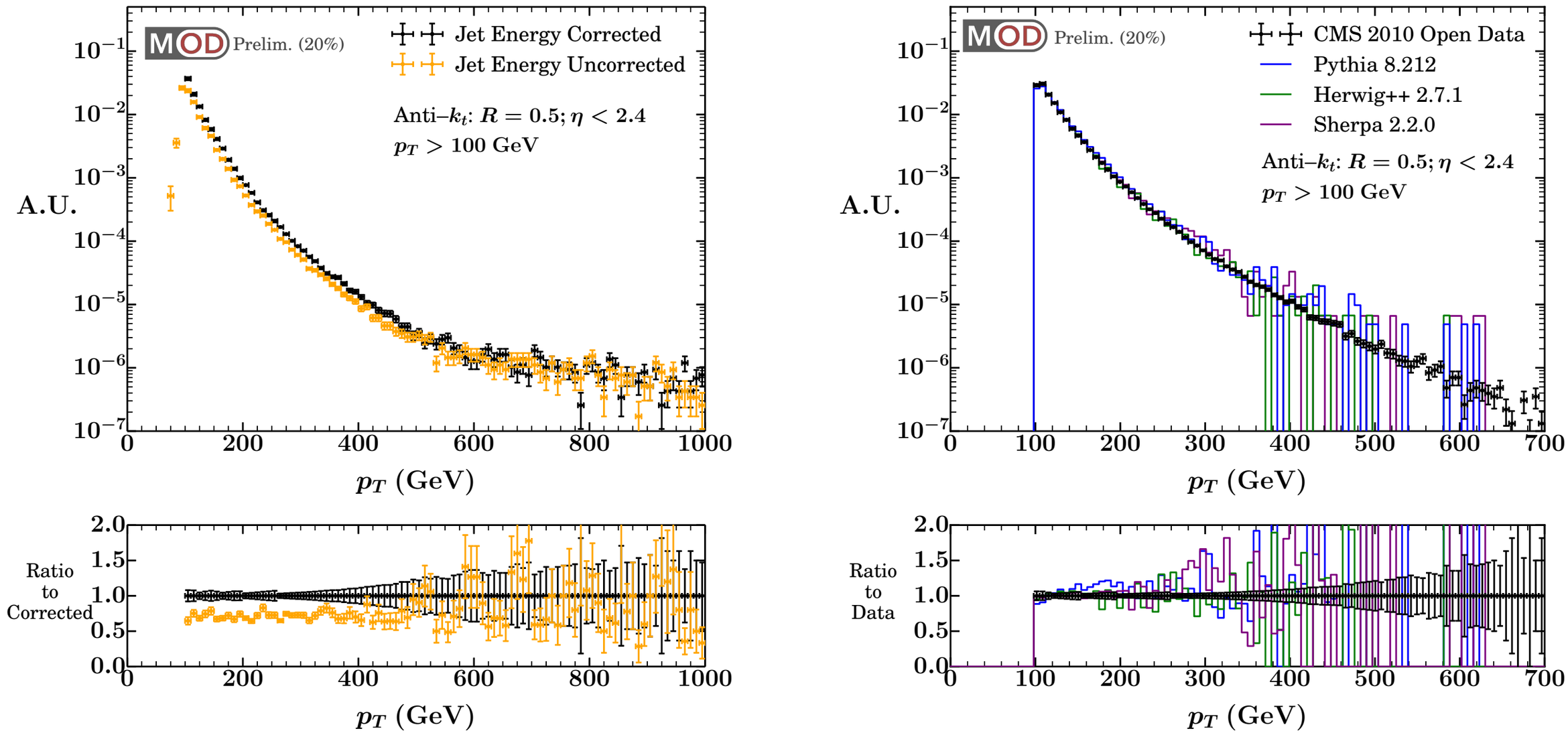
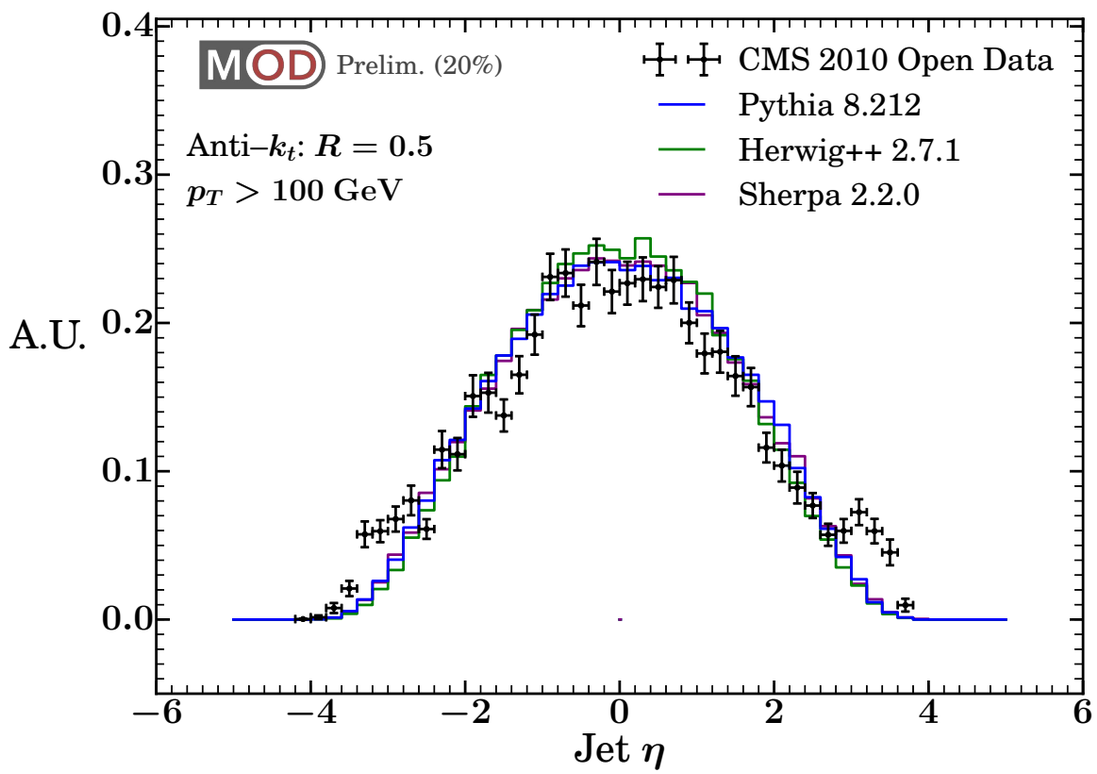
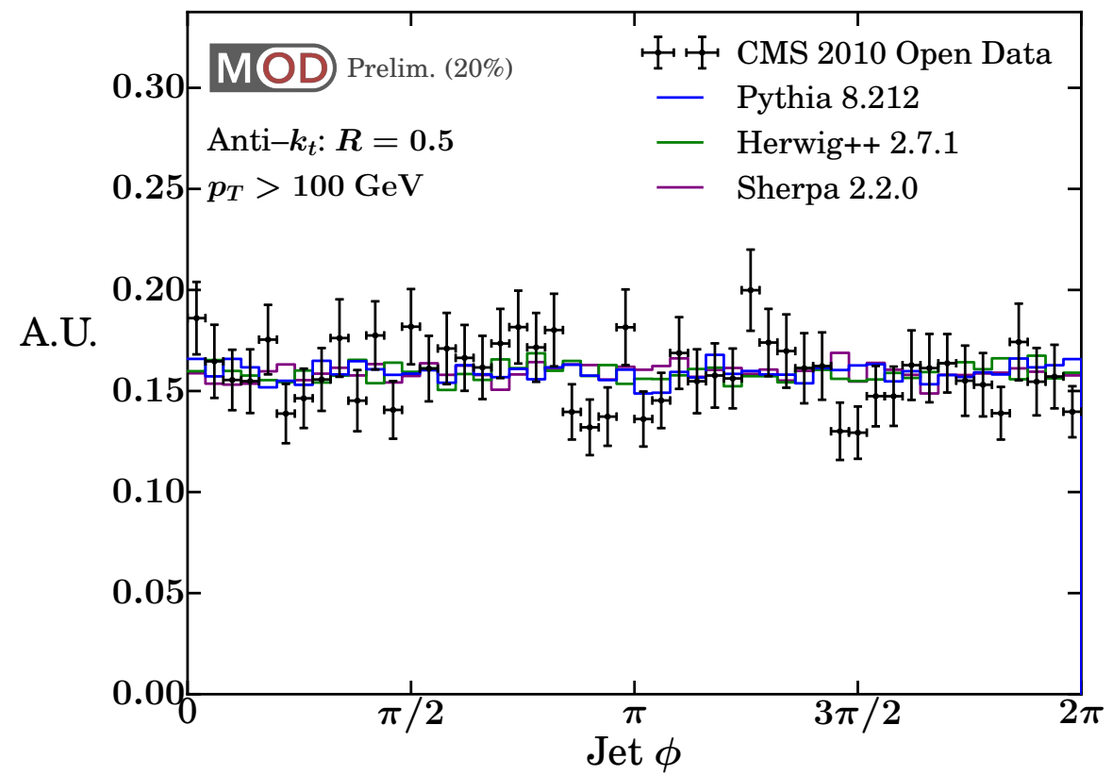
Corrected Jet p_T Spectrum

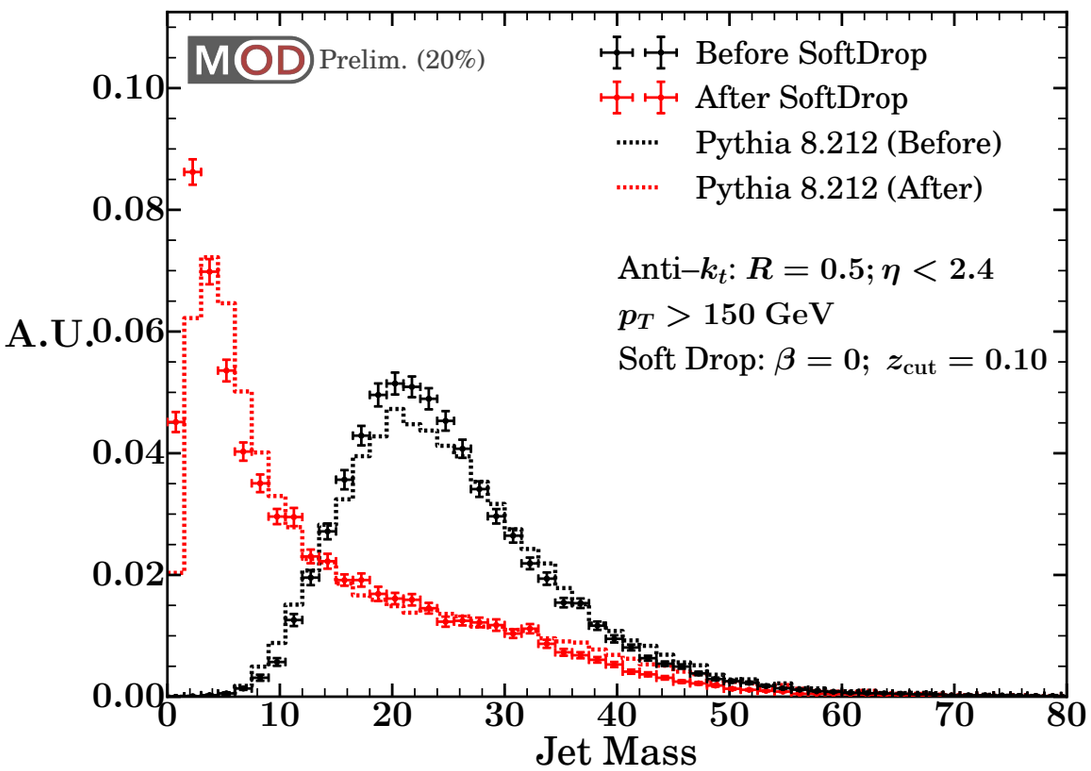


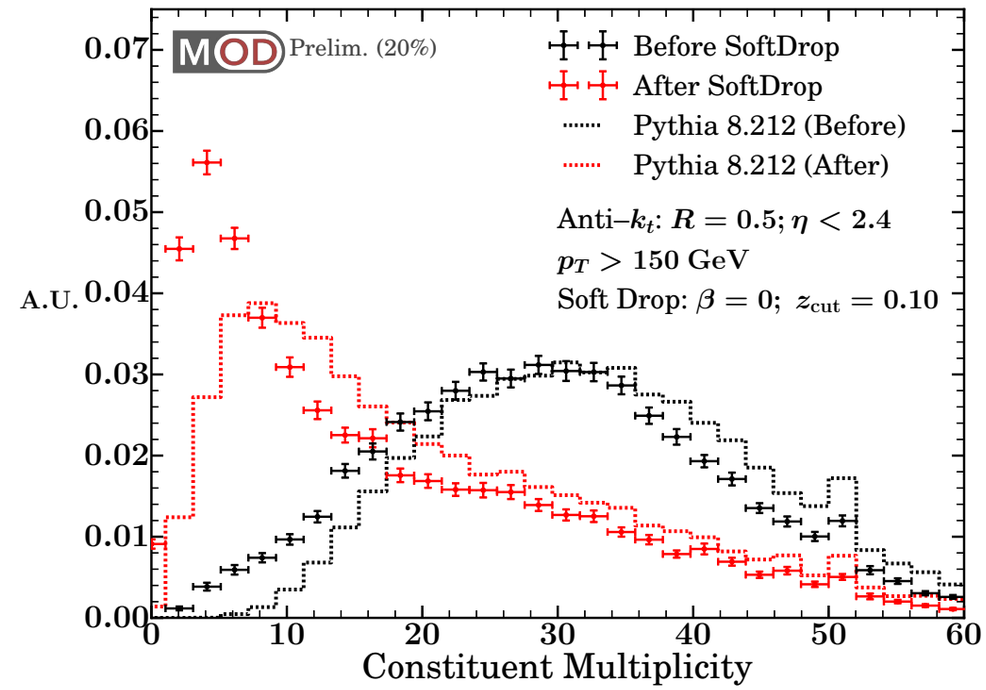
Jet Kinematics

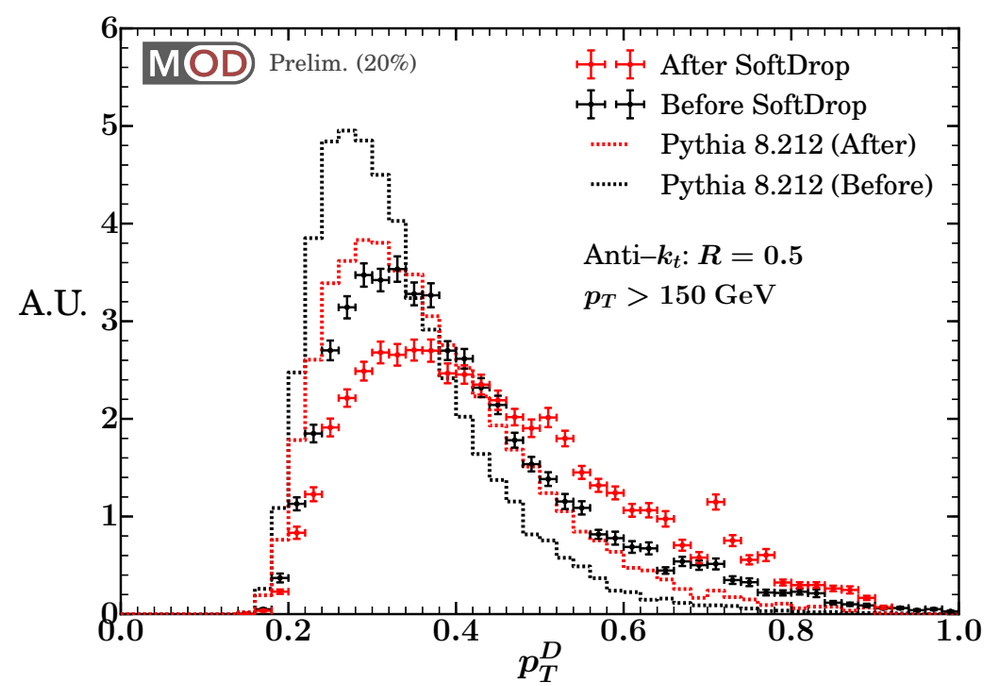




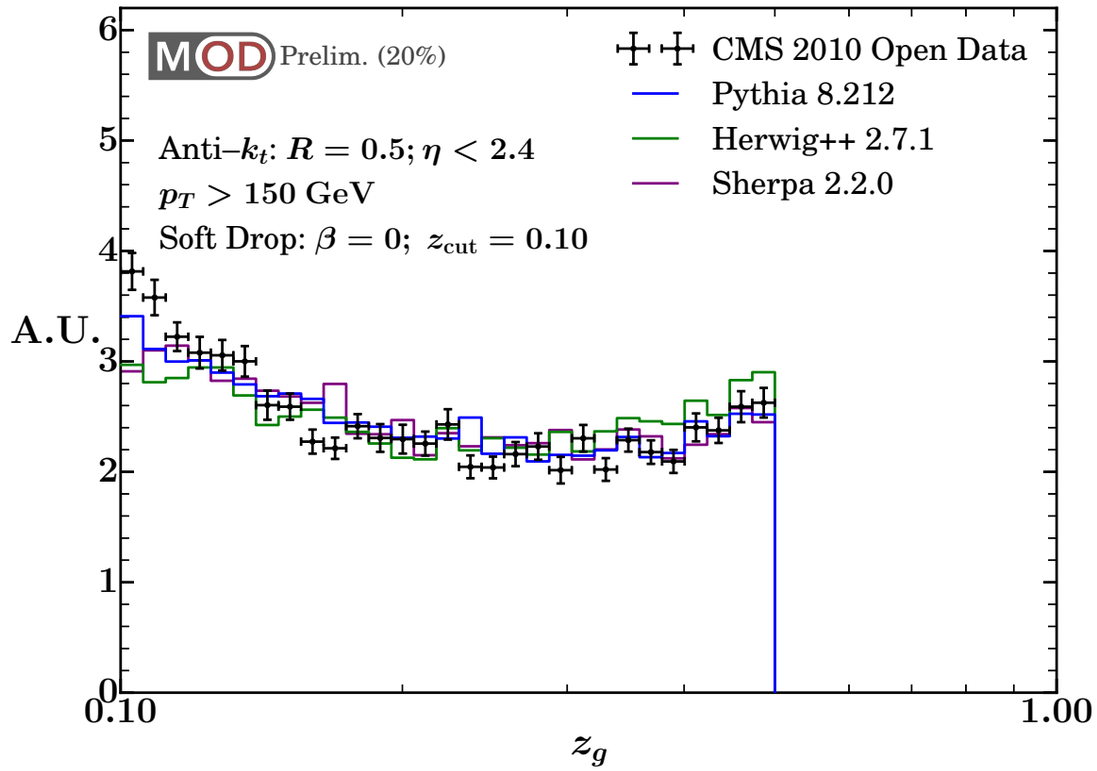
Simple Substructure

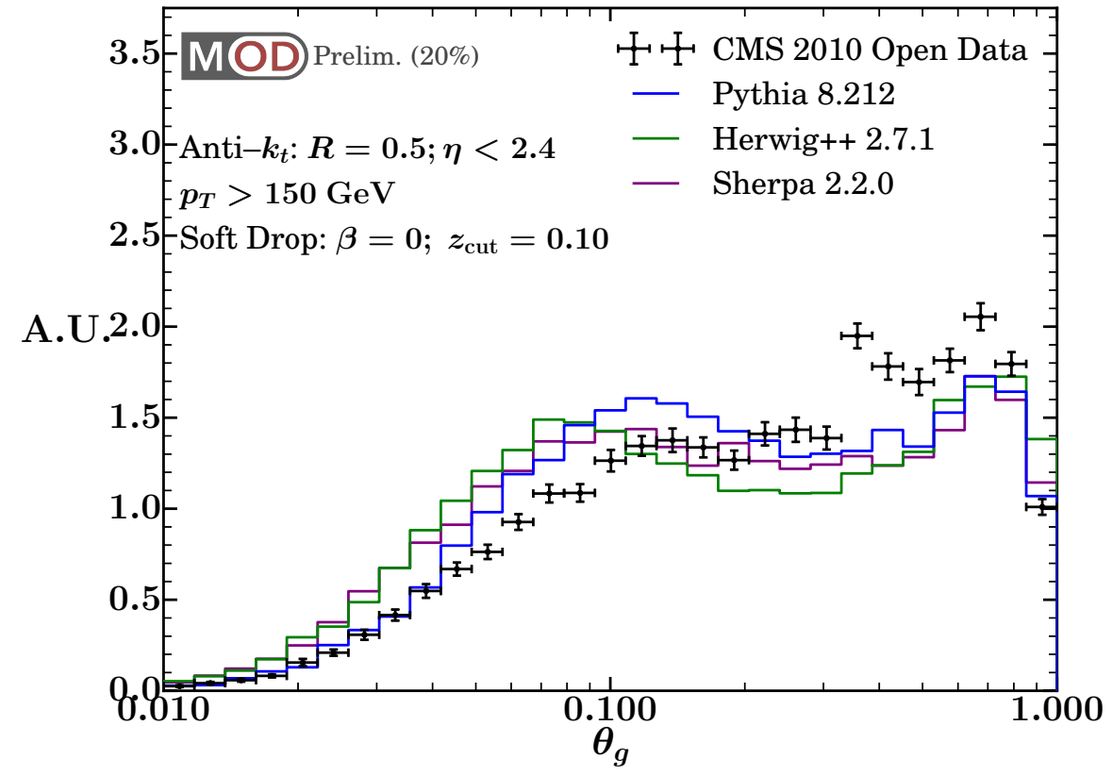


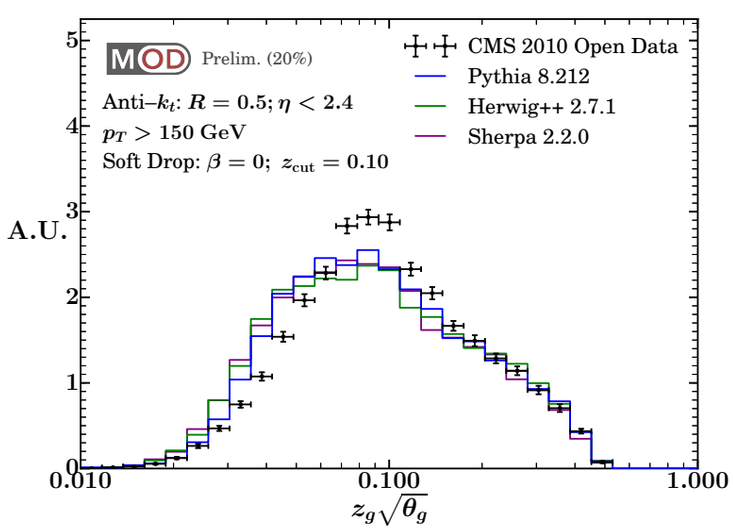


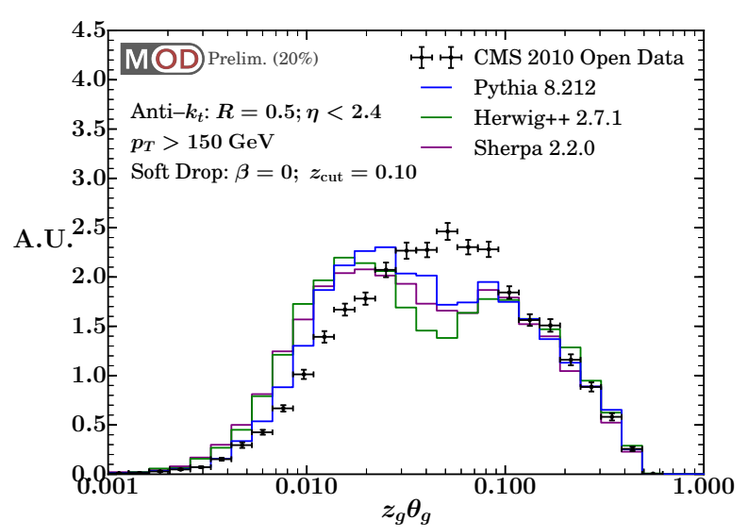


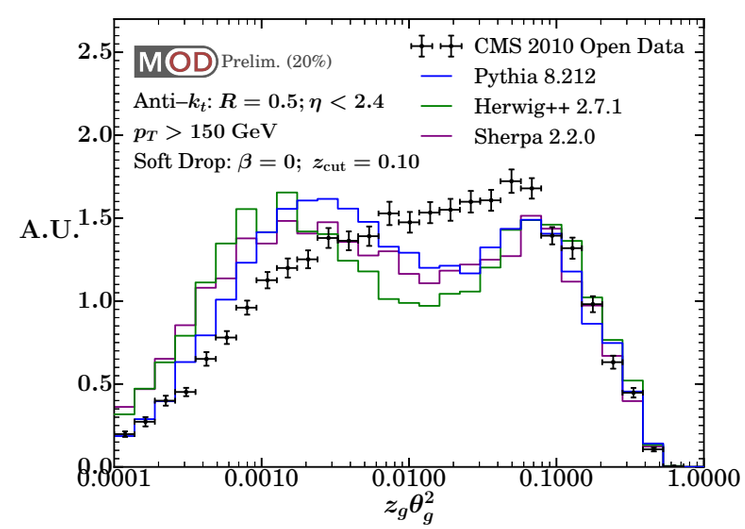
2-prong Substructure



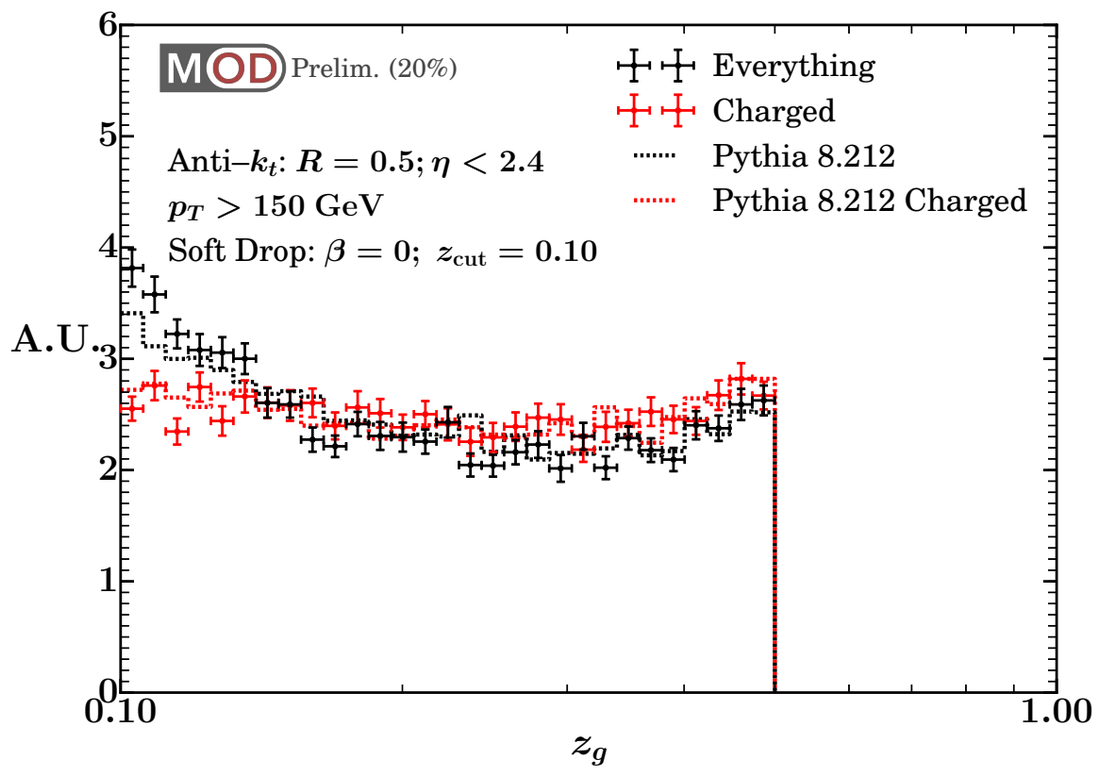


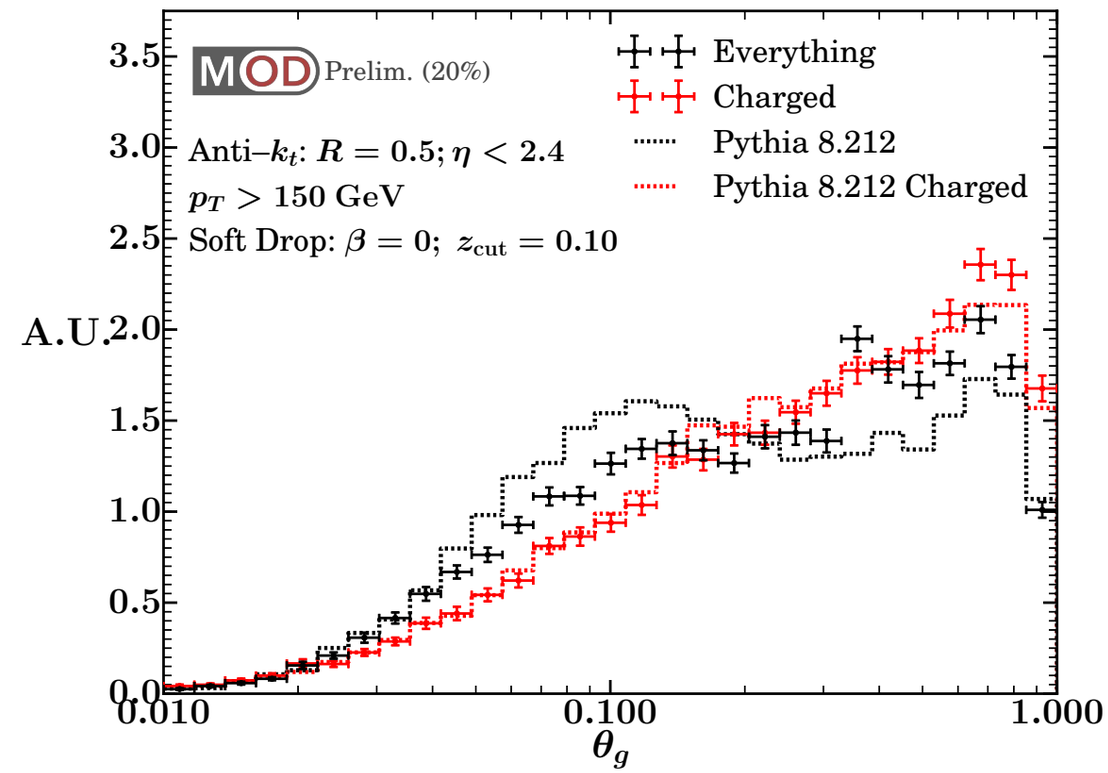


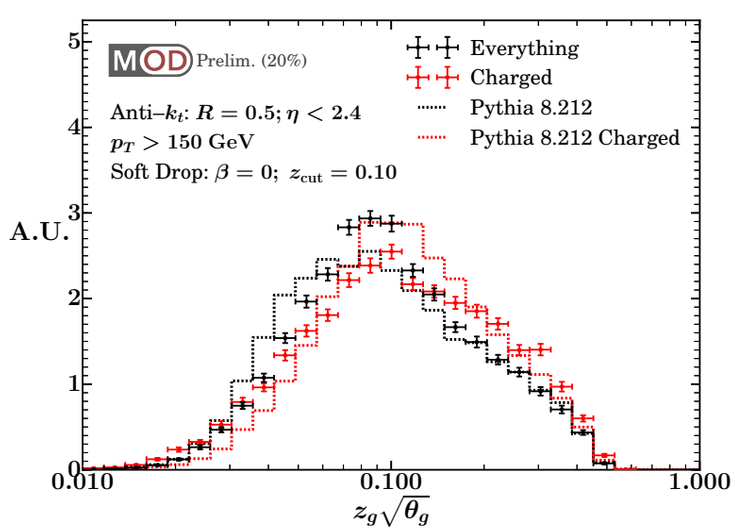


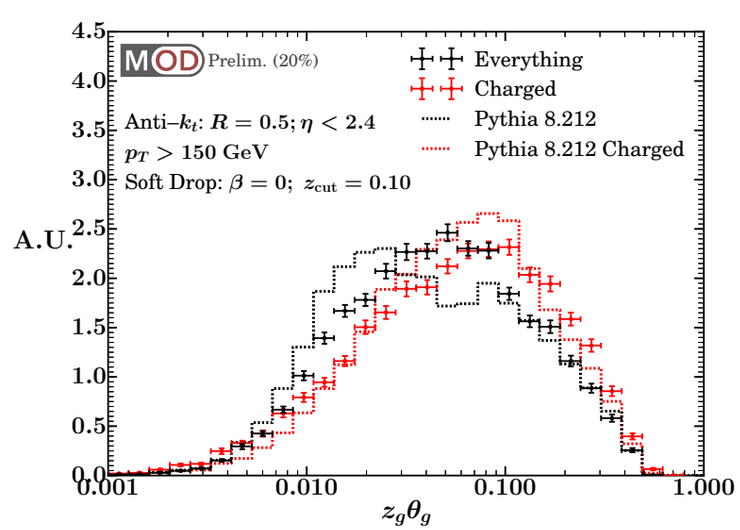


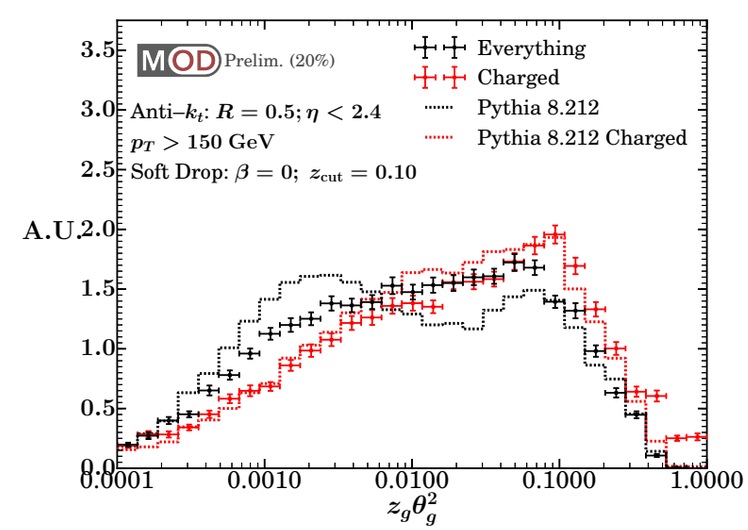
Track-Only Substructure



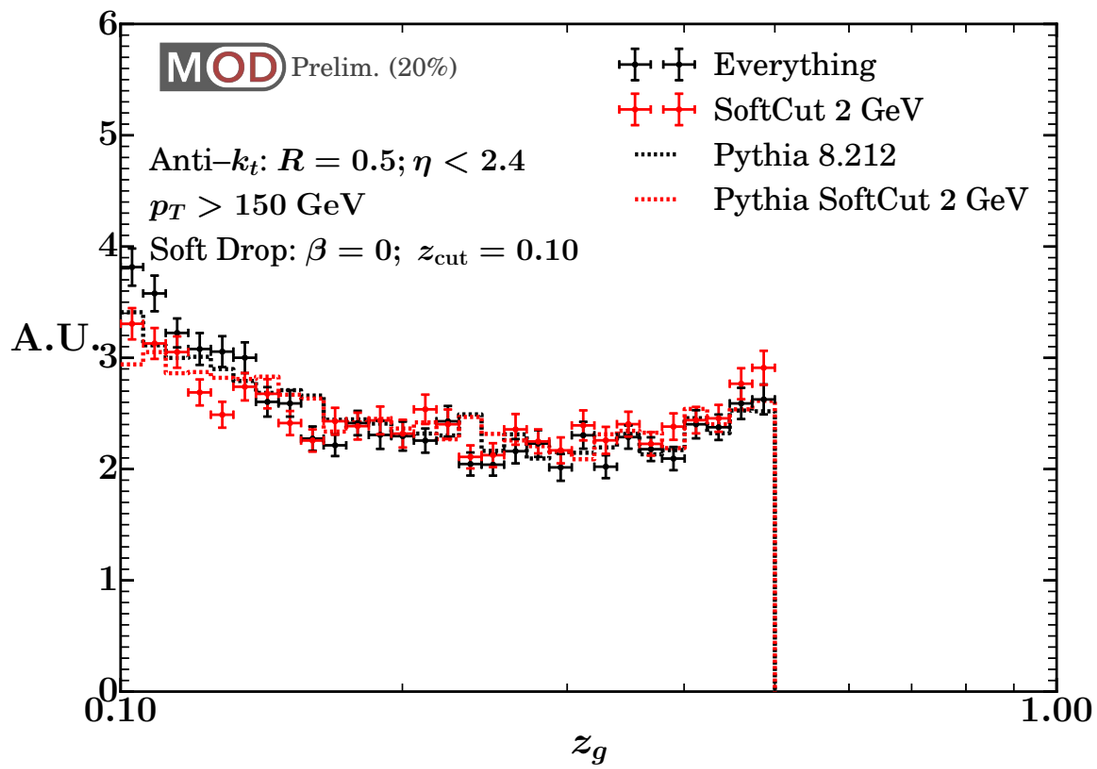


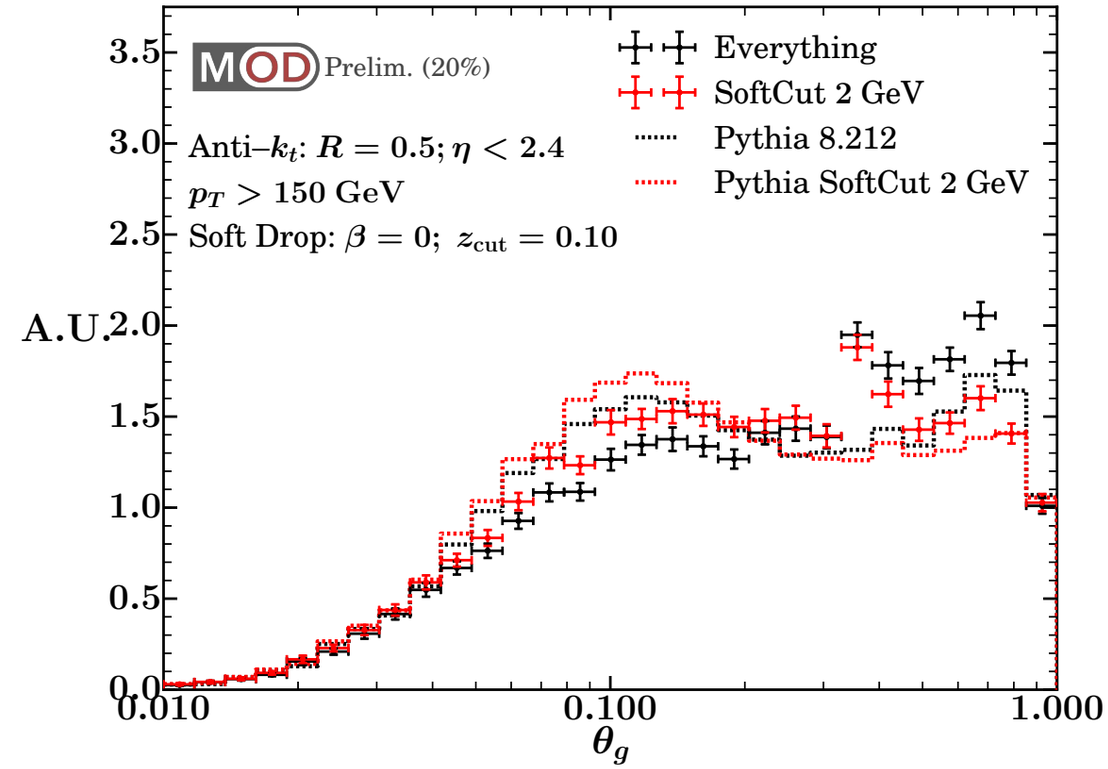


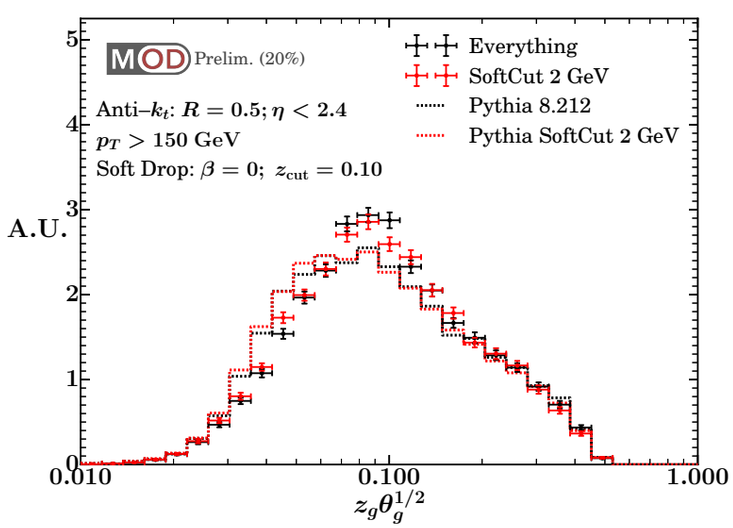


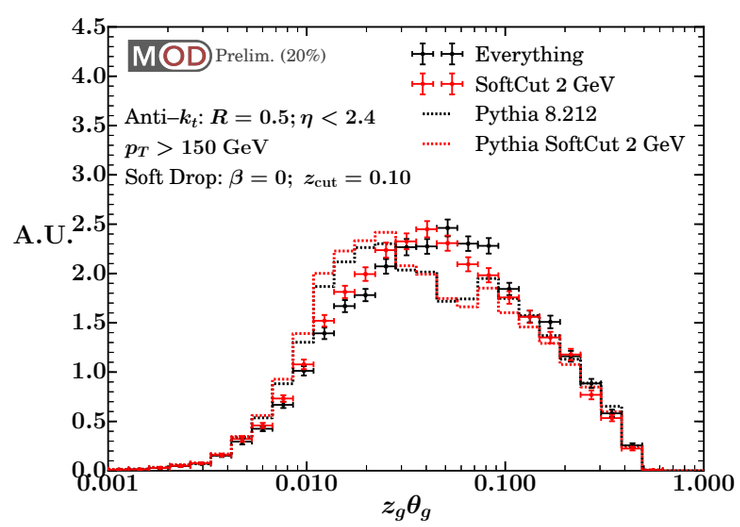


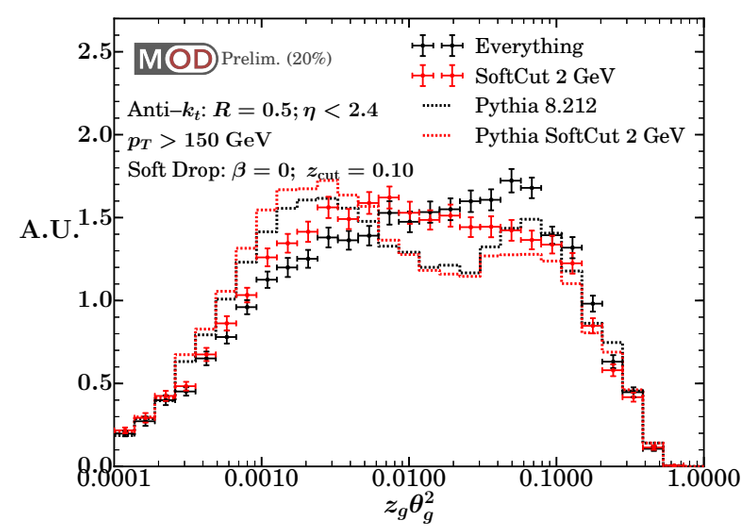
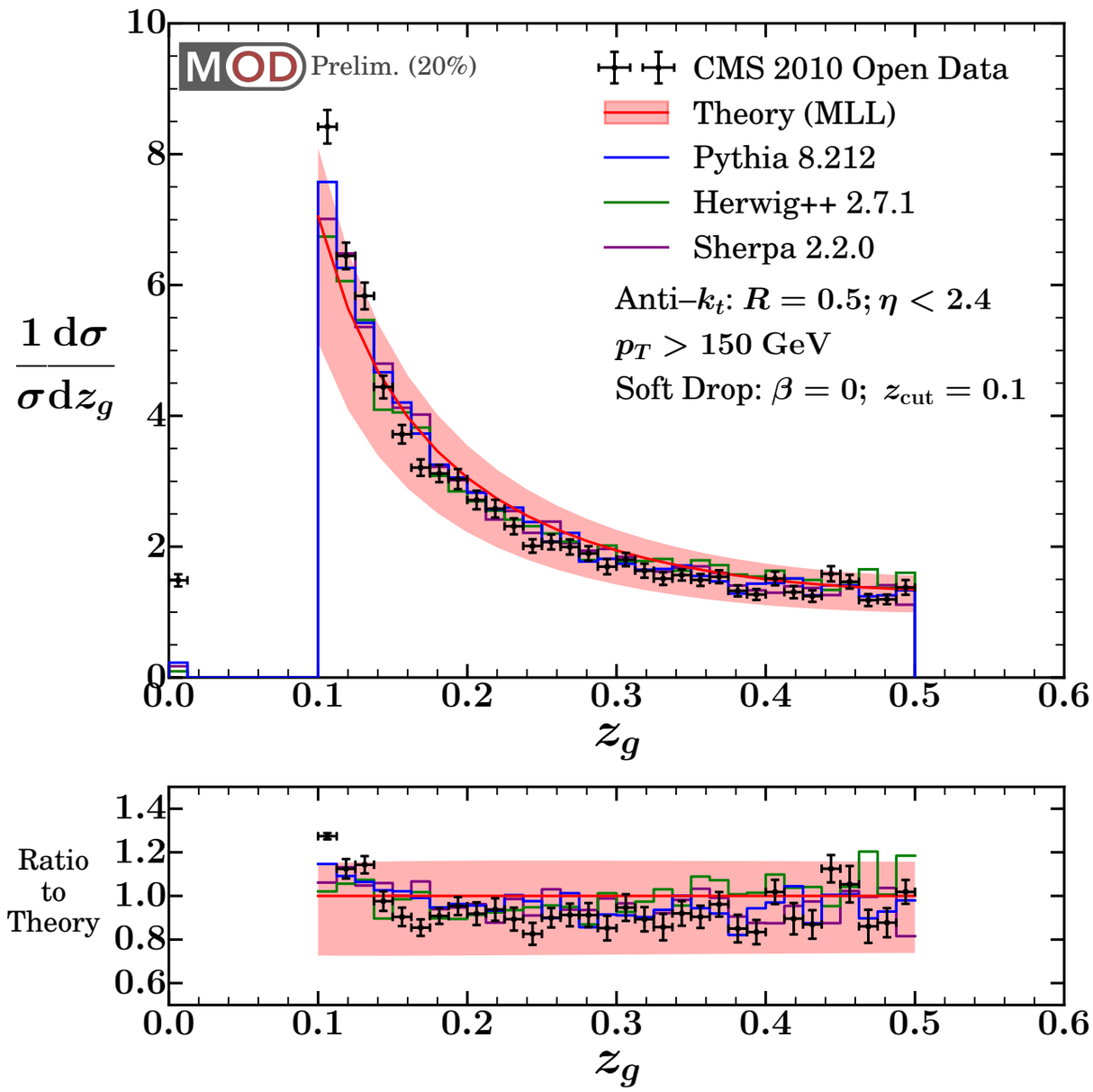
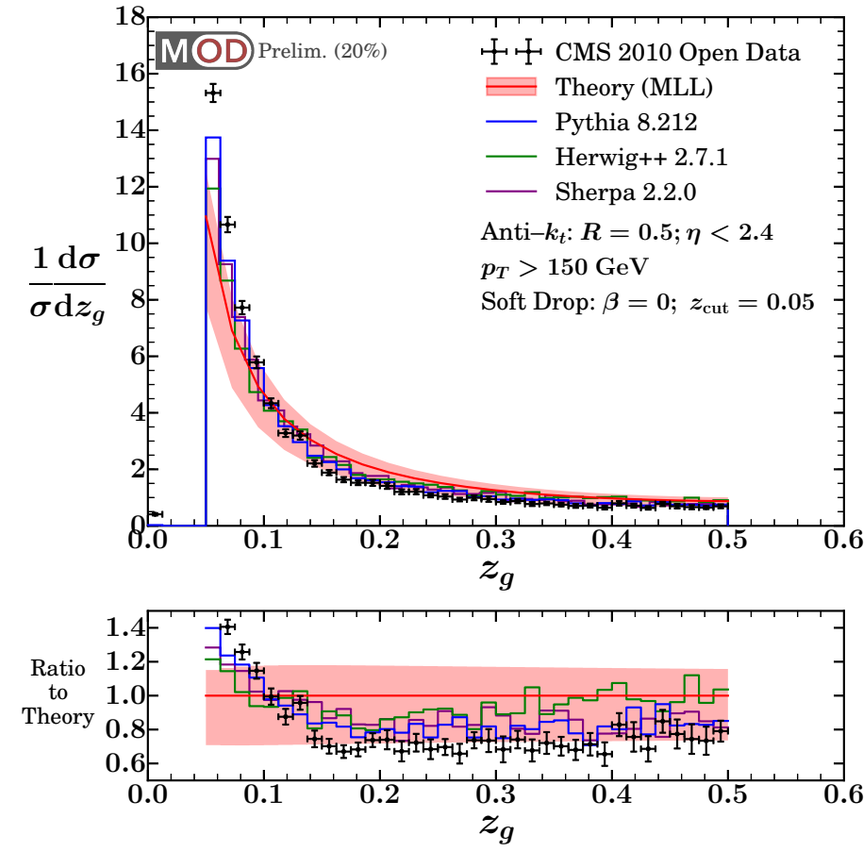
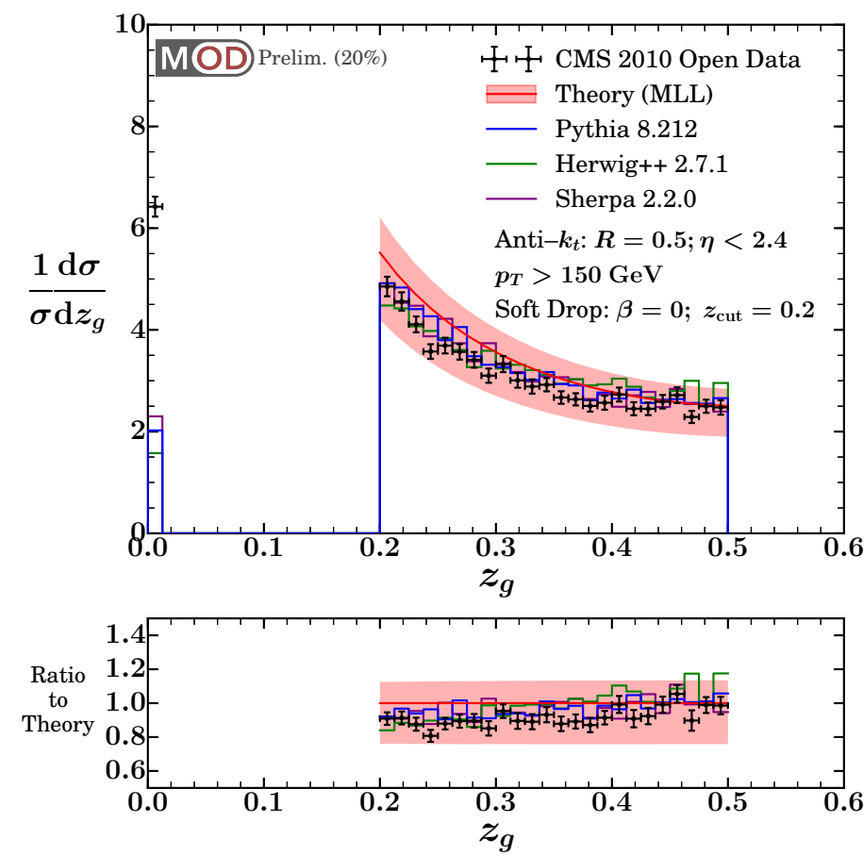
Soft-Killed Substructure











Changing z_{cut}