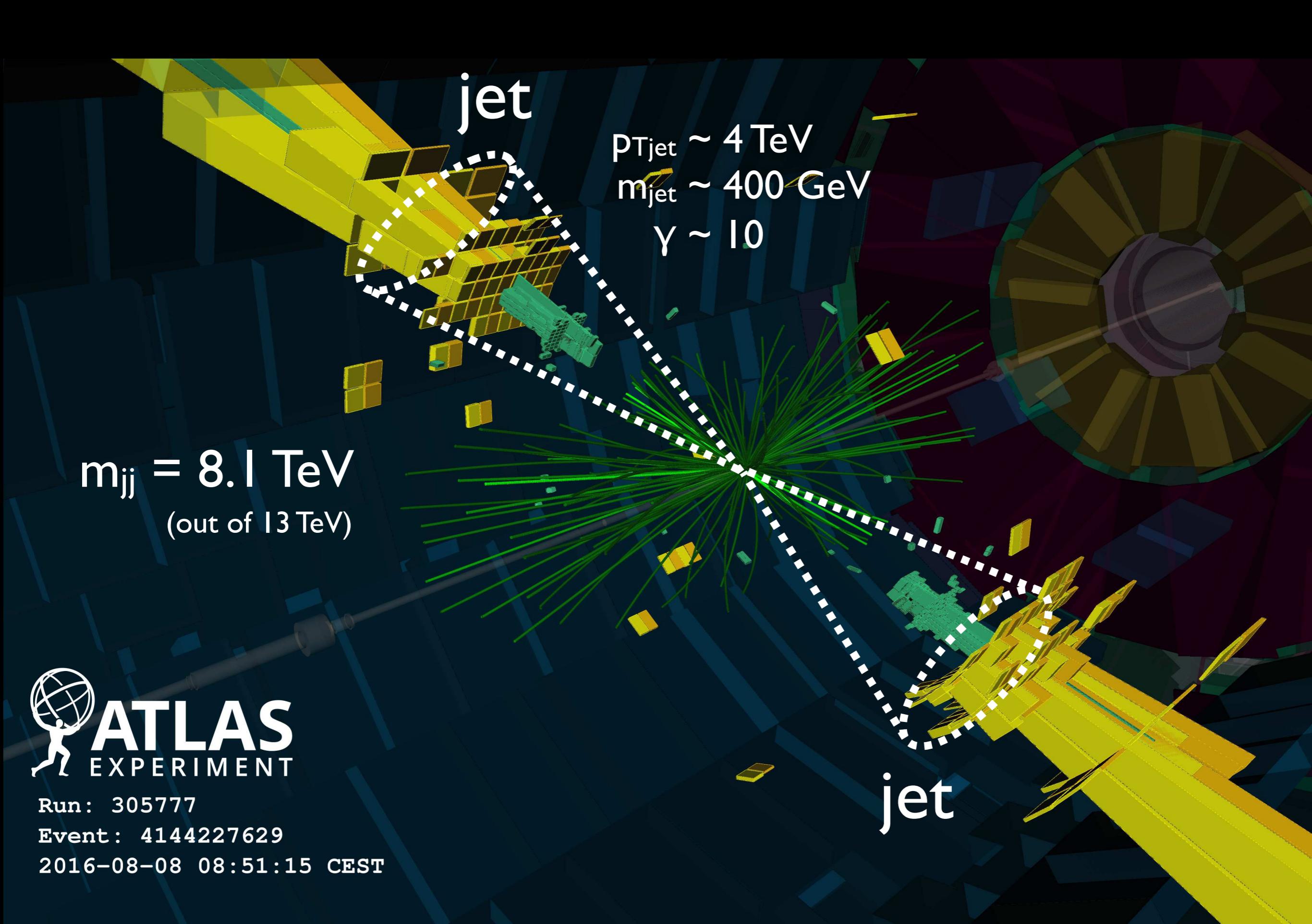


Towards Systematic Jet Dissection

Jesse Thaler



Nuclear Particle Astrophysics Seminar, Wright Laboratory, Yale — December 1, 2017



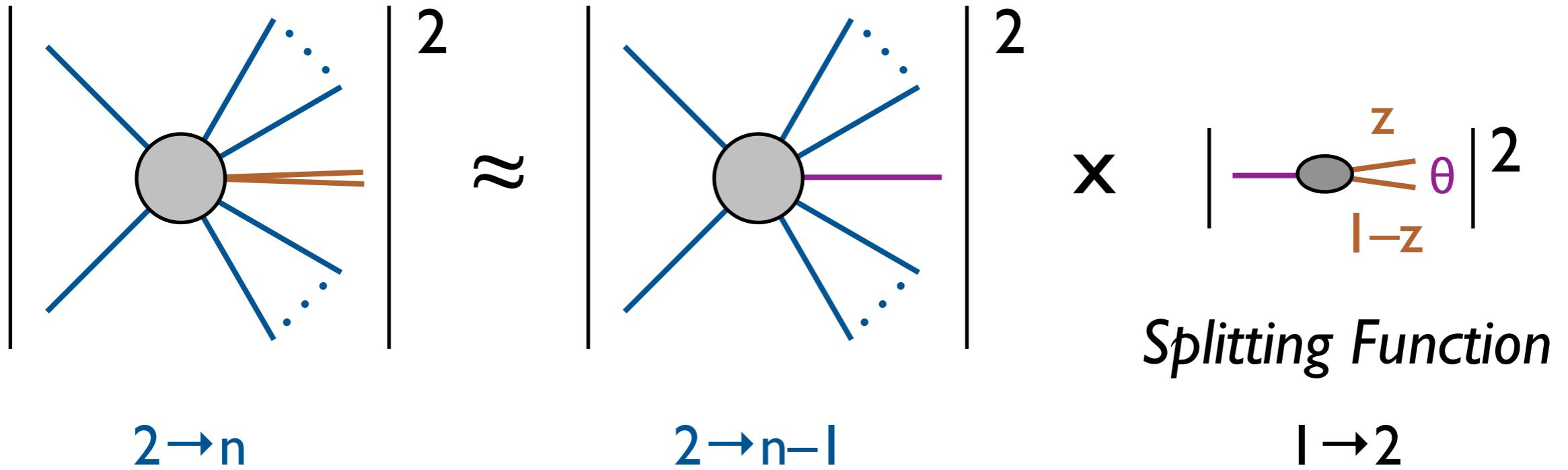
 **ATLAS**
EXPERIMENT

Run: 305777

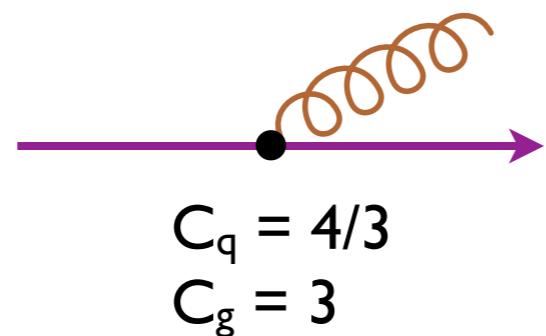
Event: 4144227629

2016-08-08 08:51:15 CEST

Why Jets? Collinear Dynamics of QCD



For this talk:

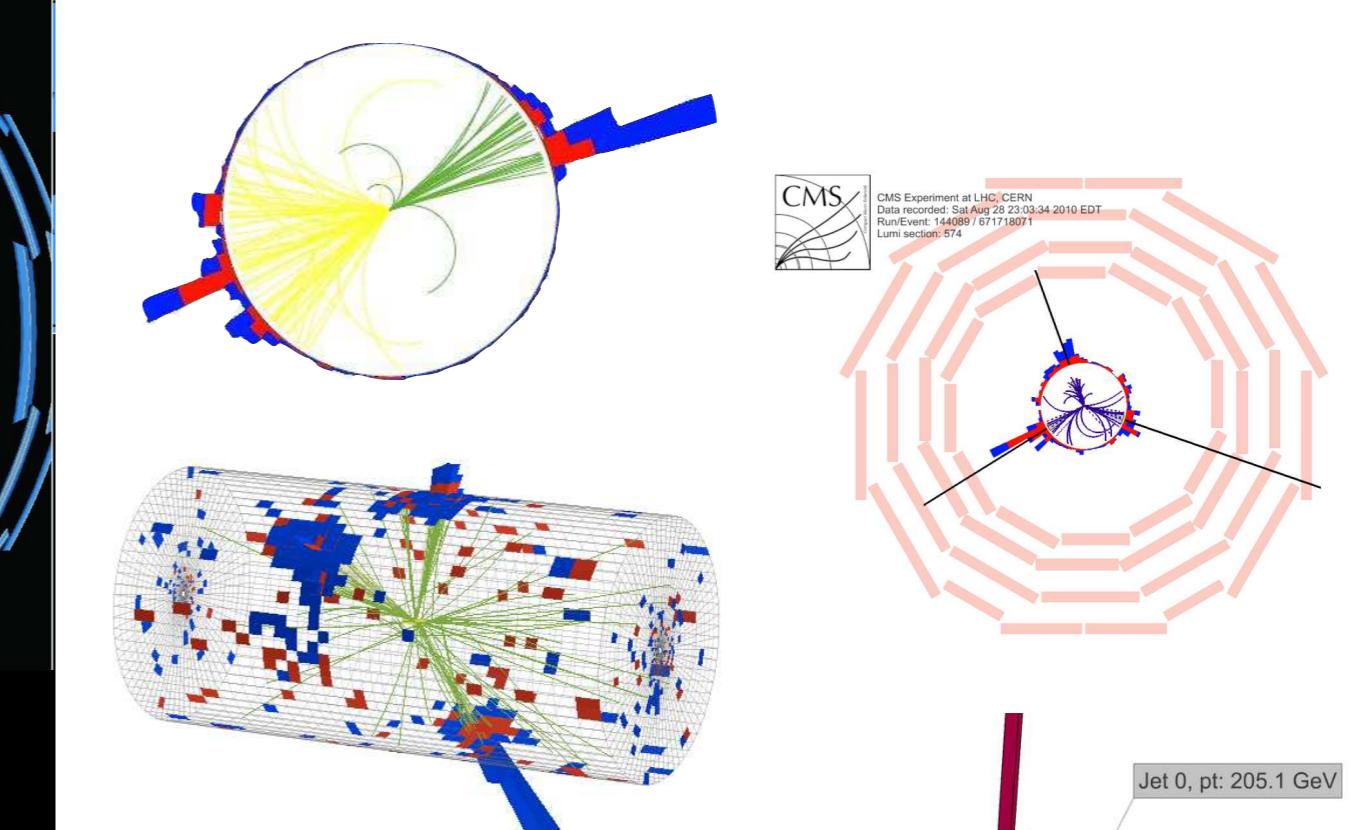
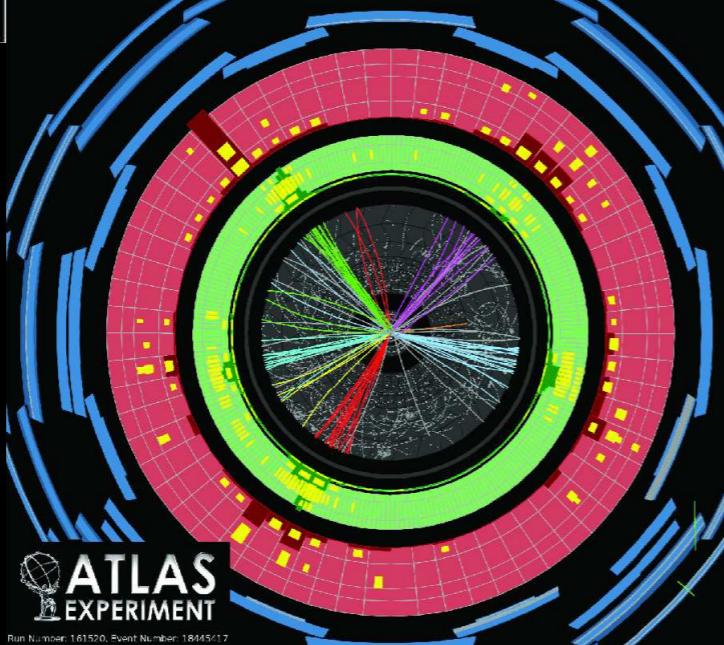
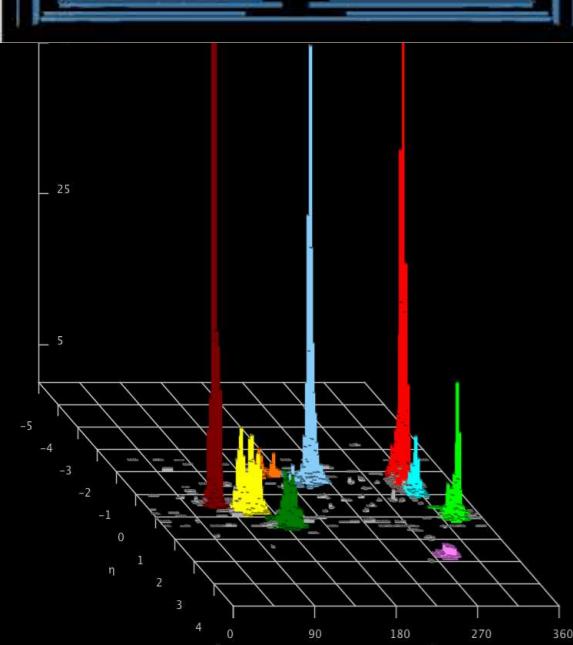
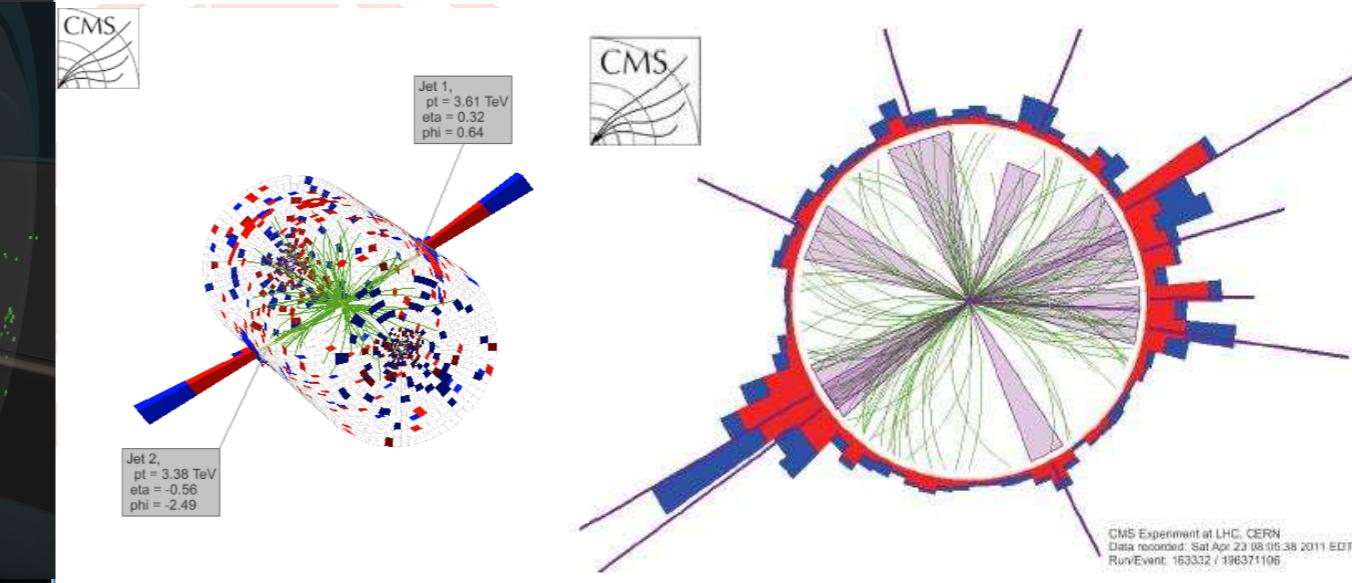
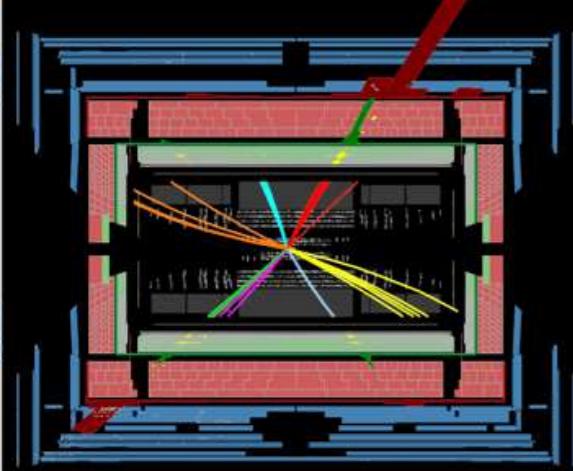


$$dP_{i \rightarrow ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

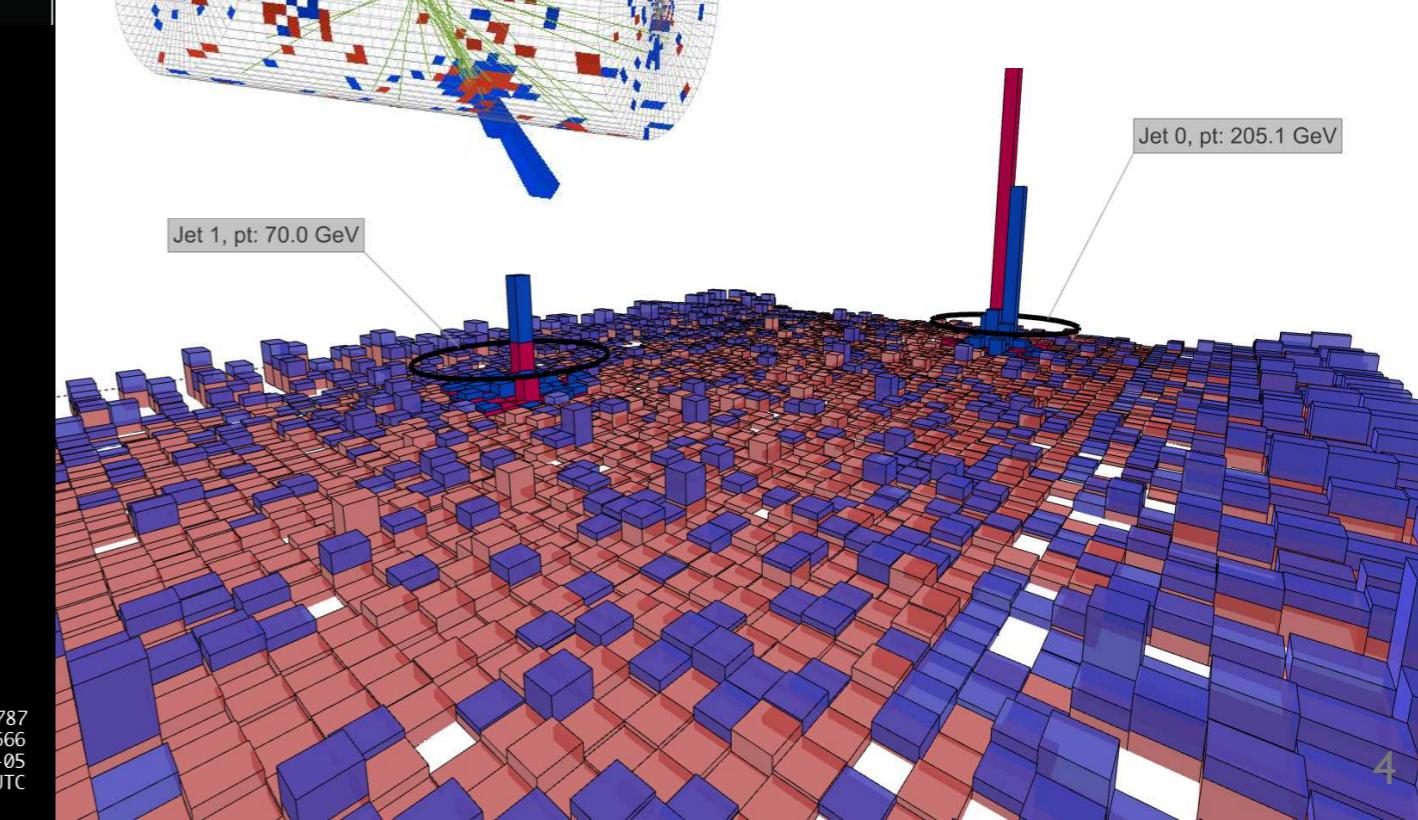
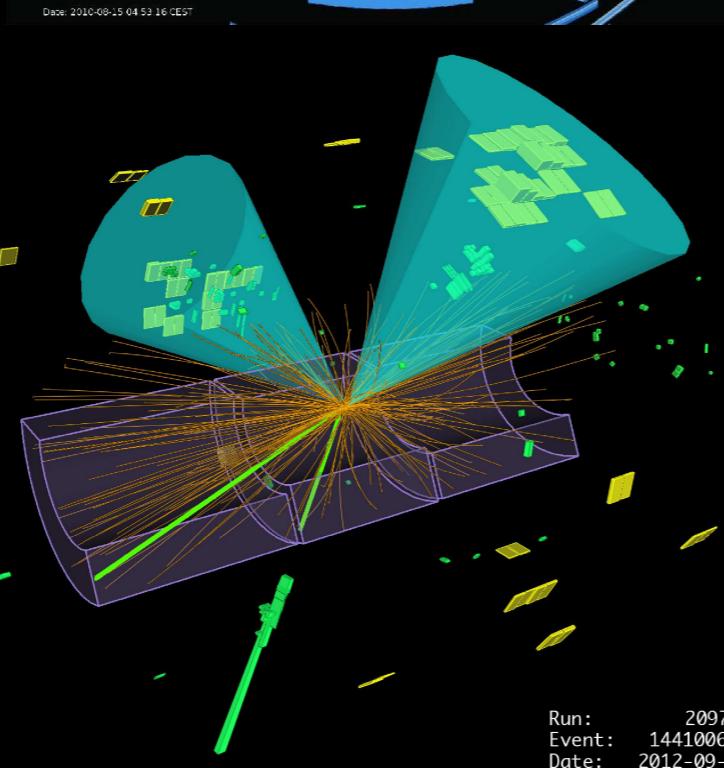
Collinear singularity Soft singularity

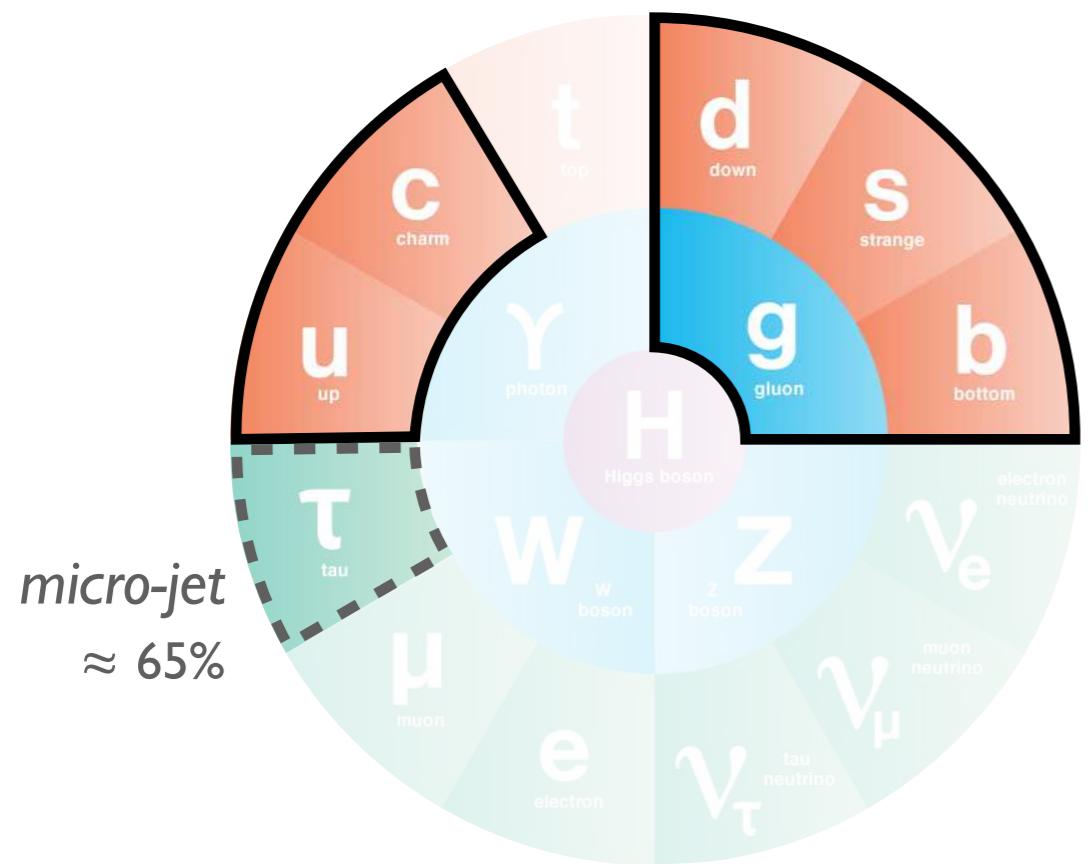
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Date: 2010-07-18 11:05:54 CEST

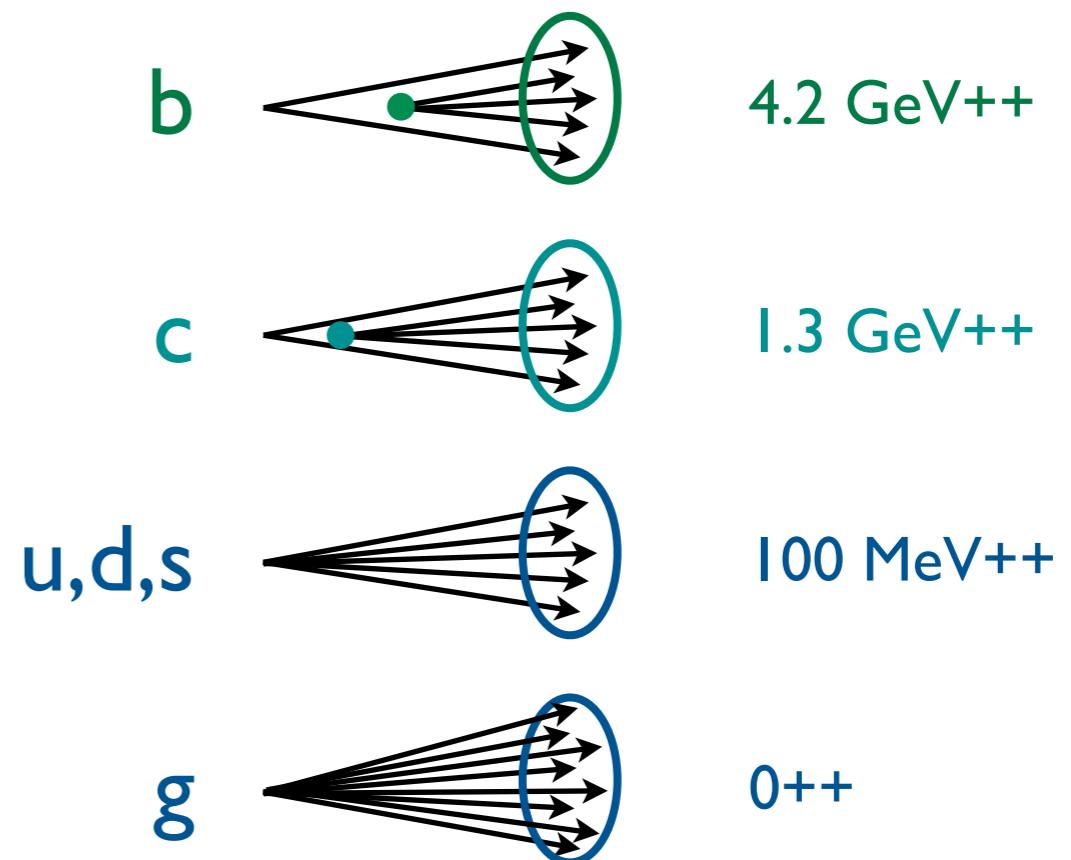


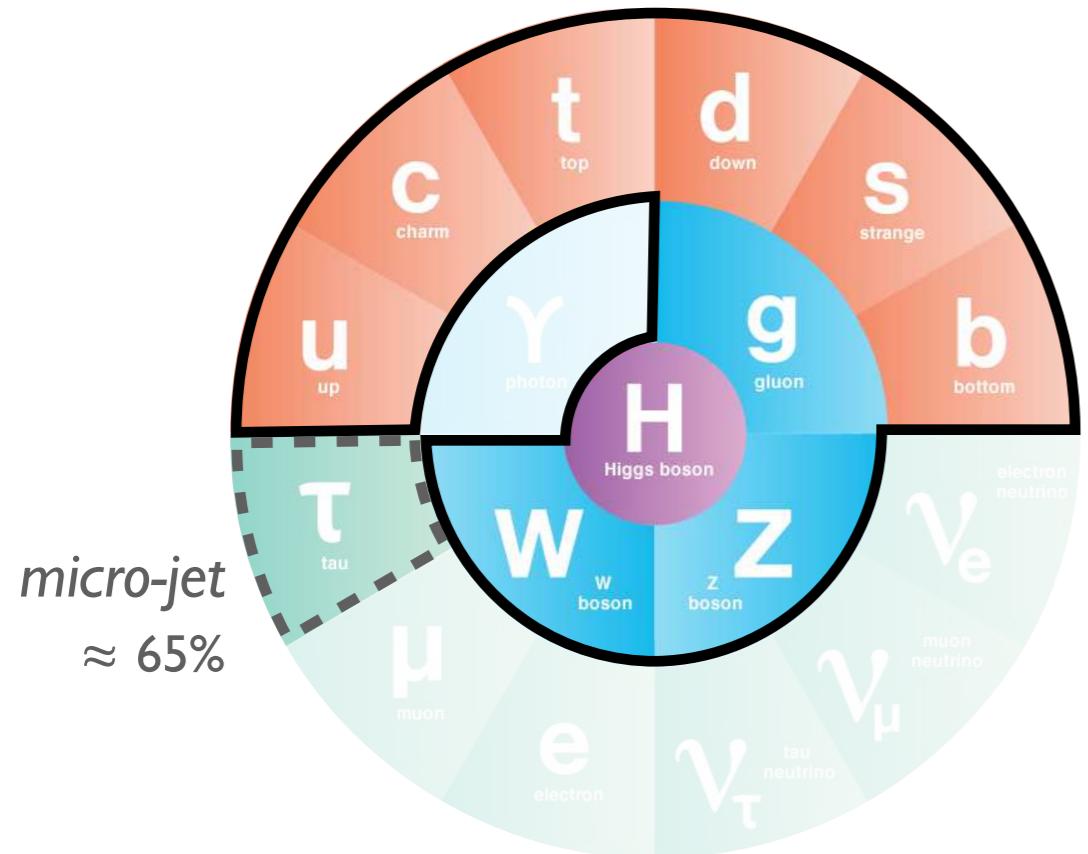
ATLAS
EXPERIMENT
<http://atlas.ch>



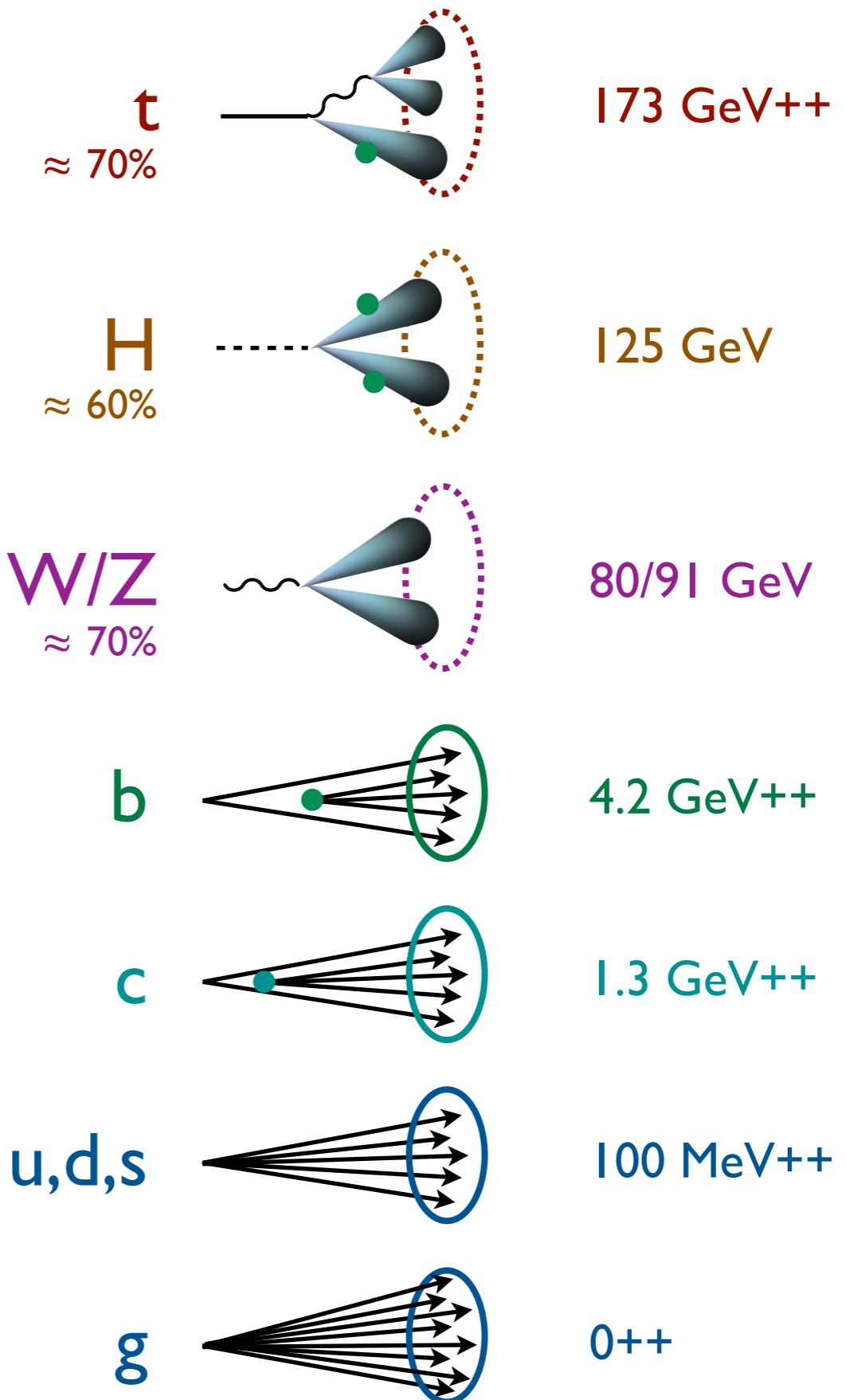


Jets from the Standard Model



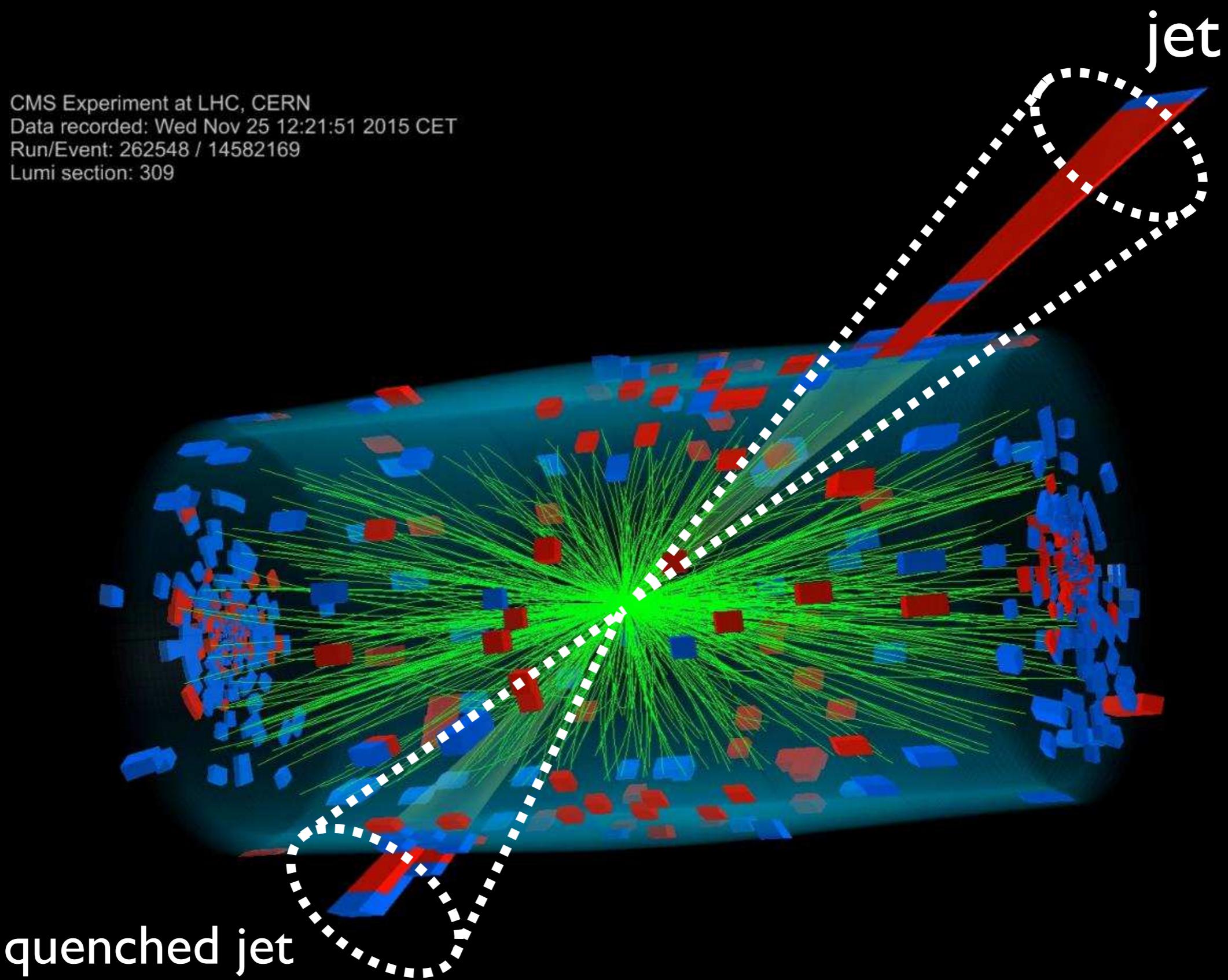


Jets from the Standard Model



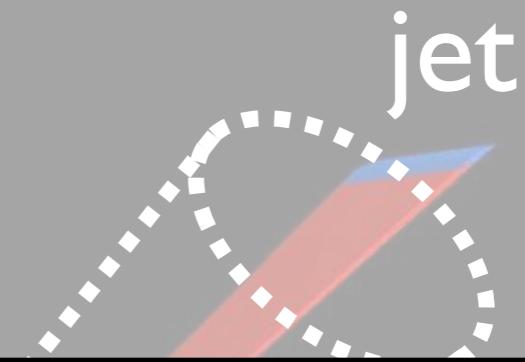


CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309





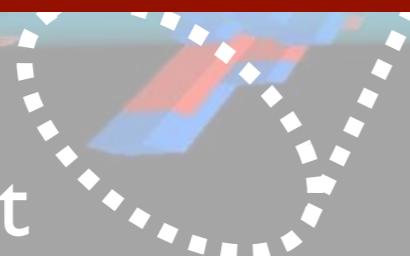
CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309



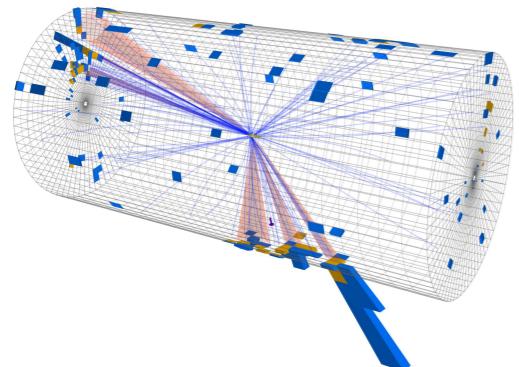
*Can we go beyond jet classification
to really understand jet dynamics?*

*Can we systematically measure the
substructure components of jets?*

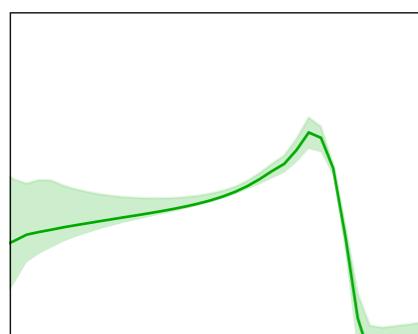
quenched jet



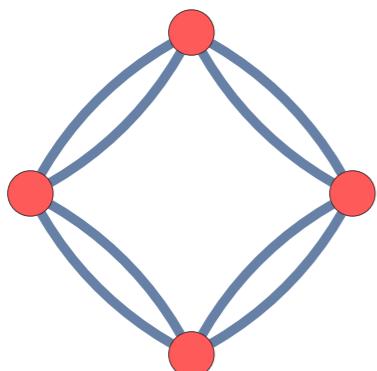
Outline



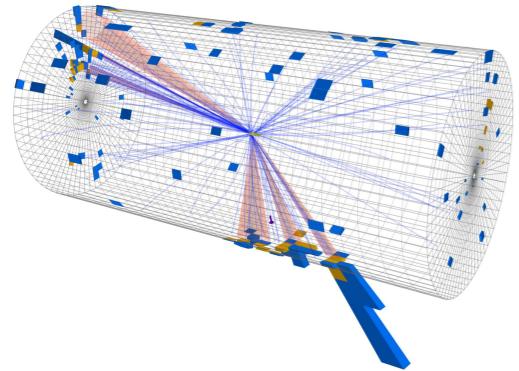
The Rise of Jet Substructure



The Importance of First Principles



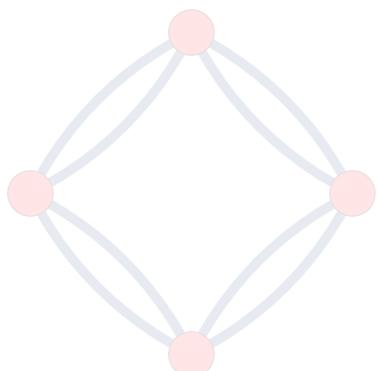
Towards a Systematic Expansion



The Rise of Jet Substructure



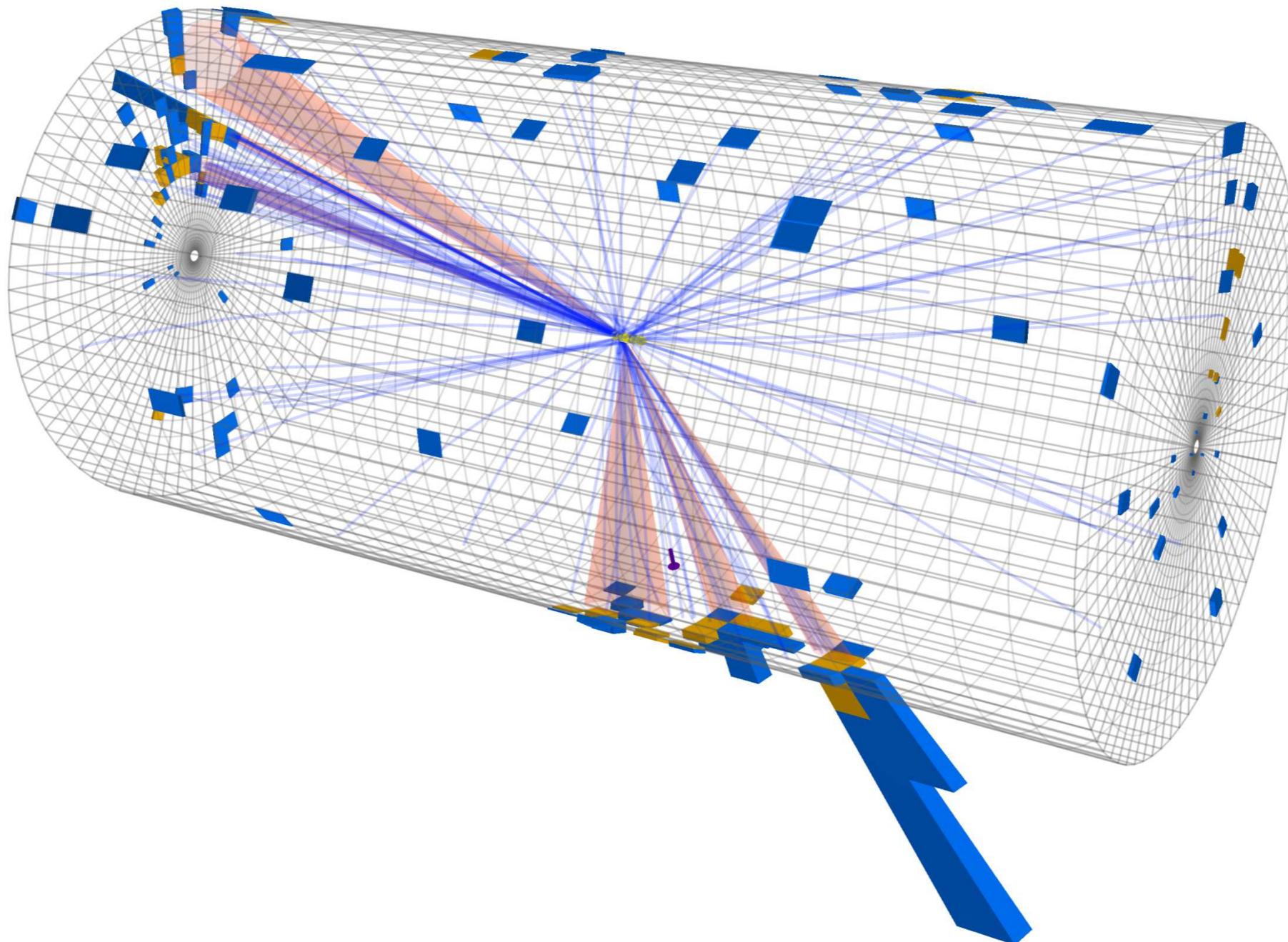
The Importance of First Principles



Towards a Systematic Expansion

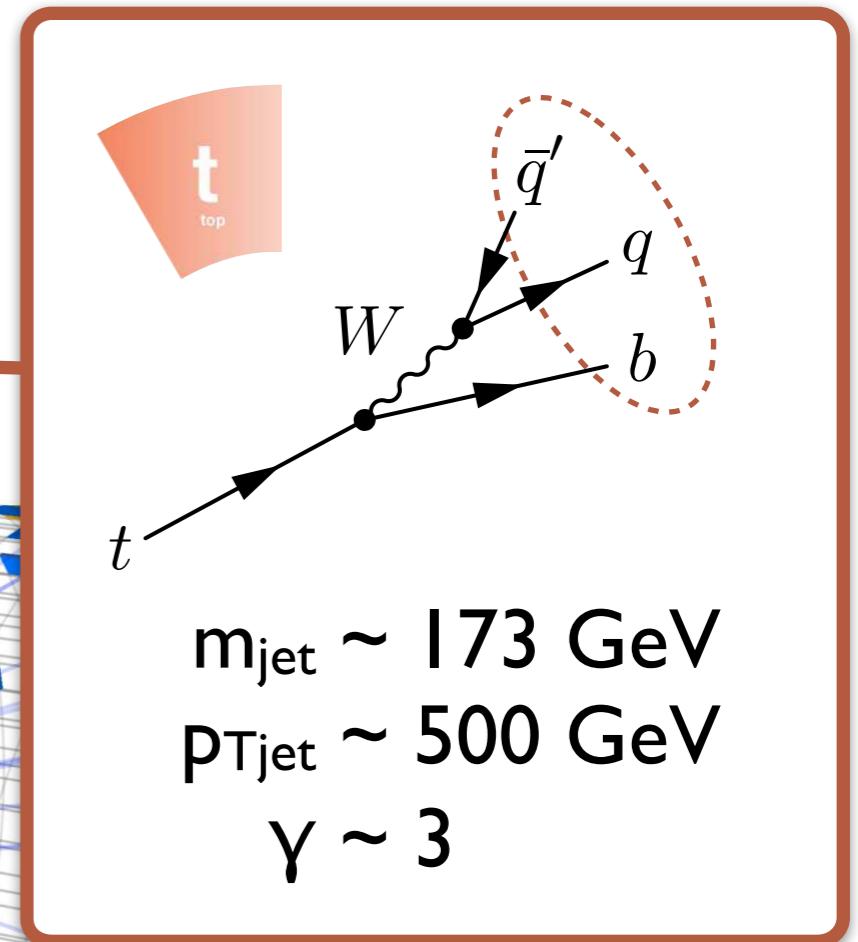
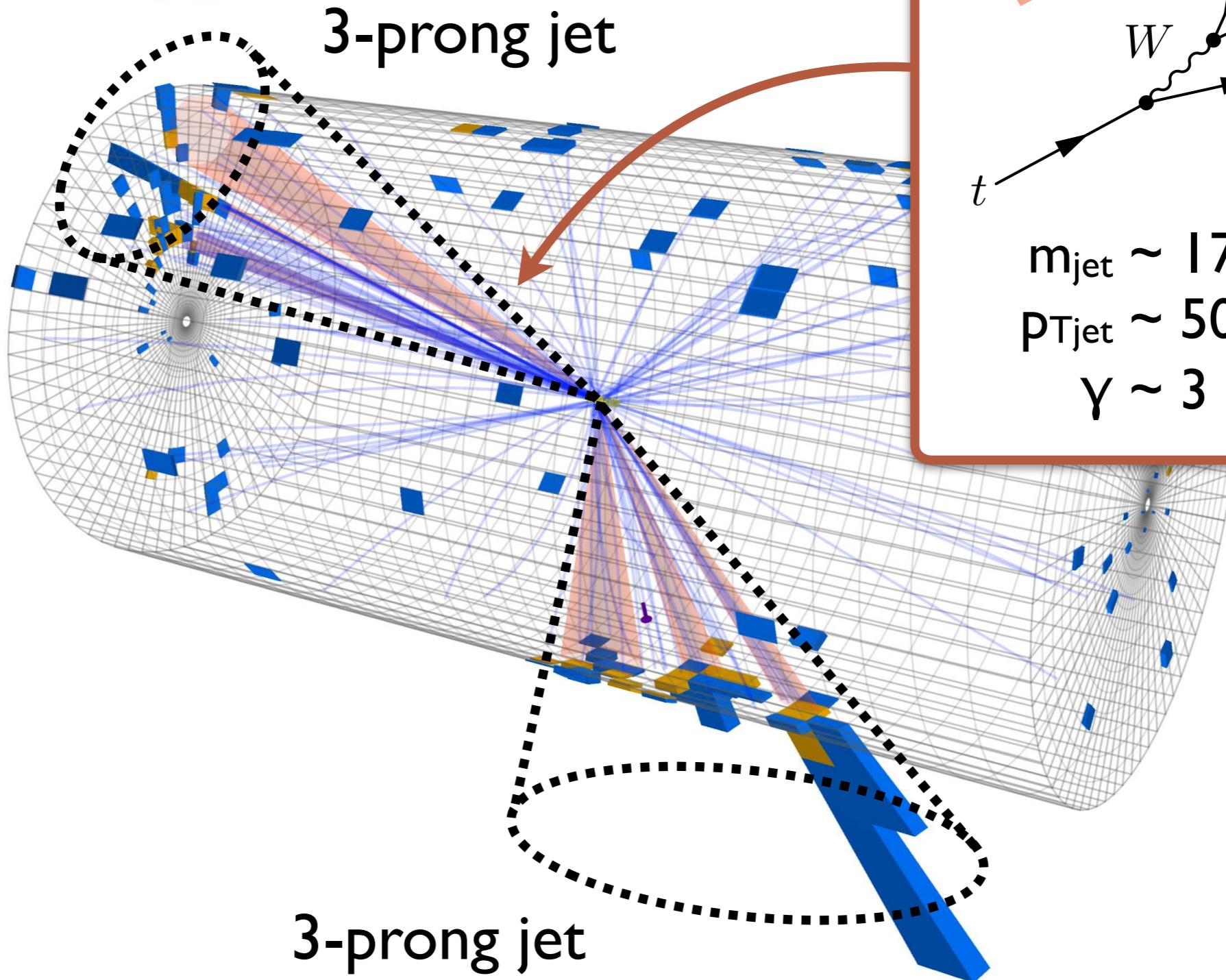


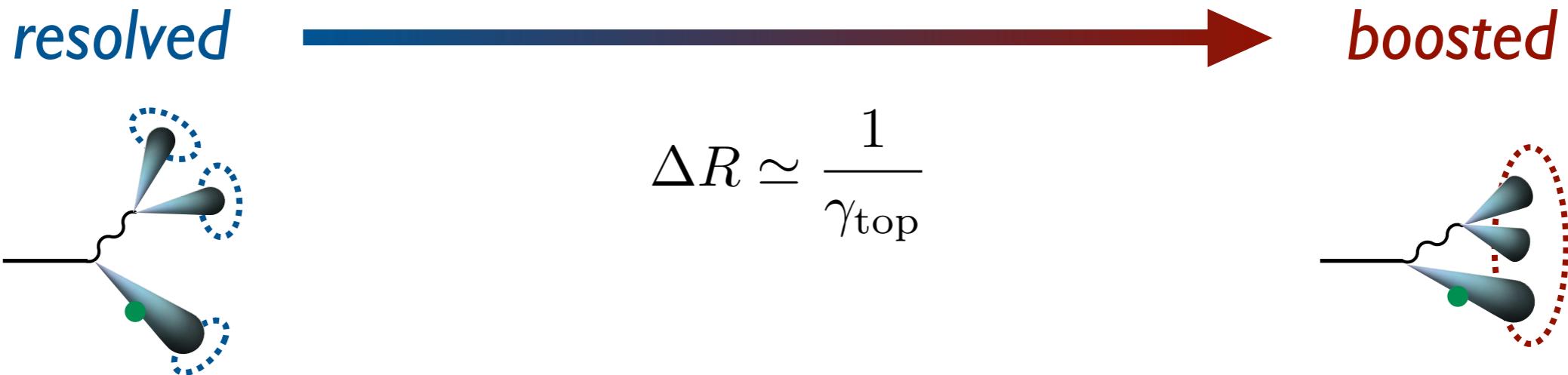
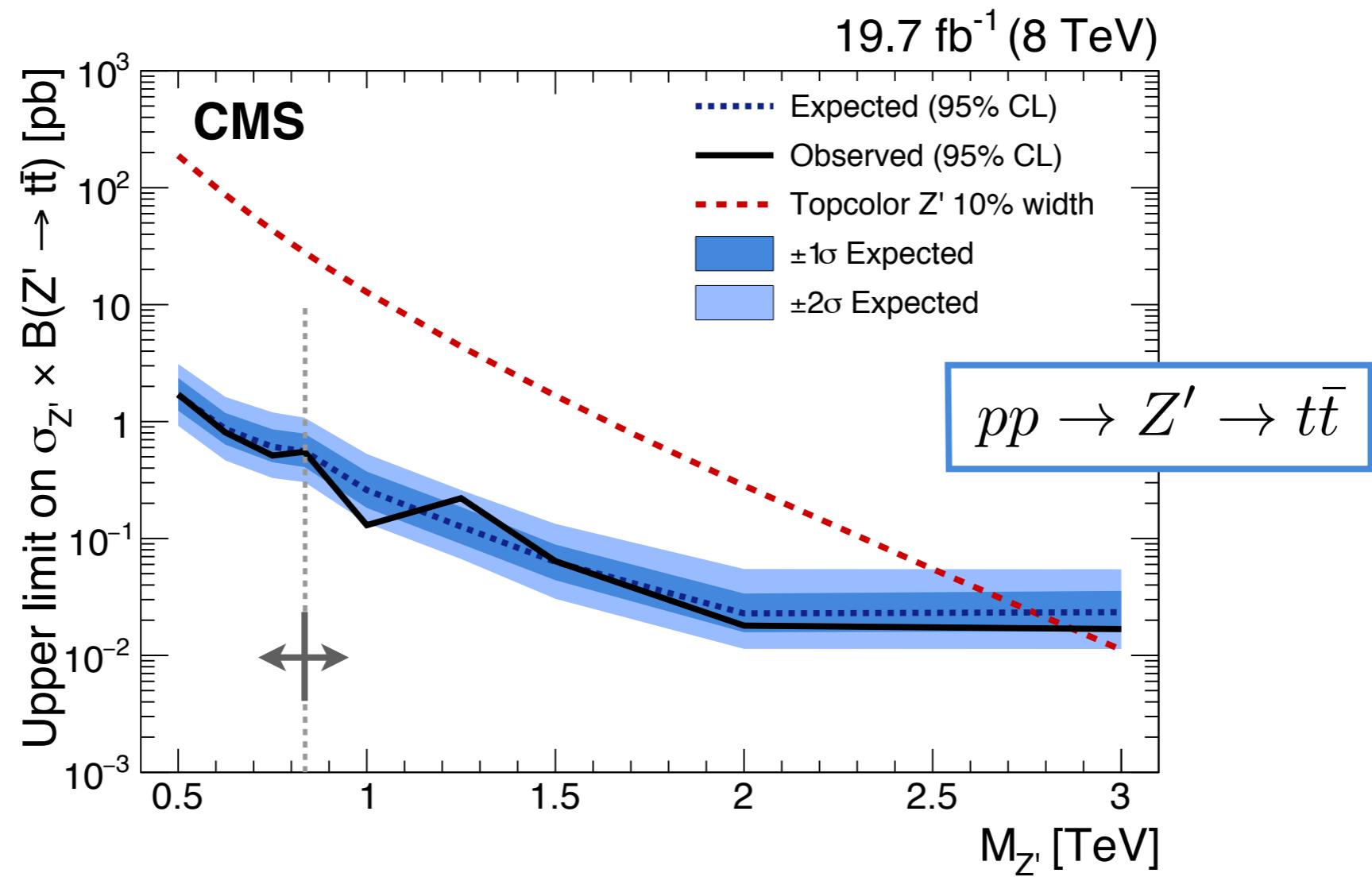
CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253





CMS 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

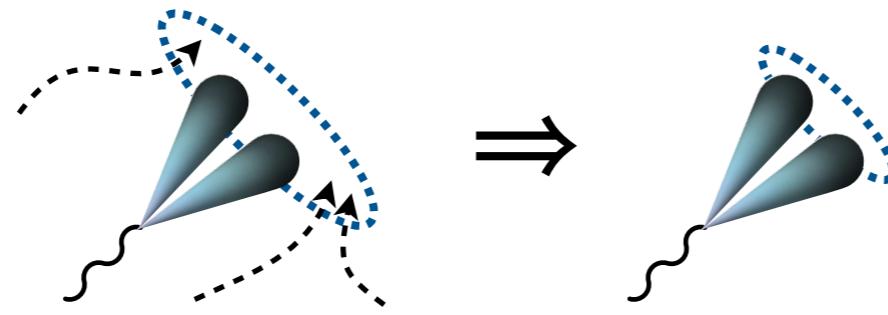




[CMS 2011, 2013, 2015; using Kaplan, Rehermann, Schwartz, Tweedie, 2008; Ellis, Vermilion, Walsh, 2009]

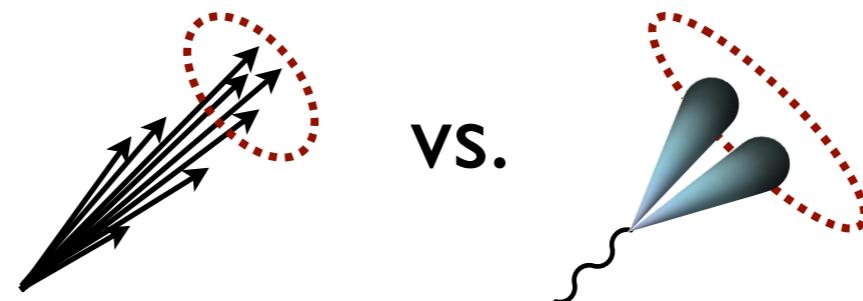
Key Substructure Techniques

Grooming: e.g. ISR/UE/pileup



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

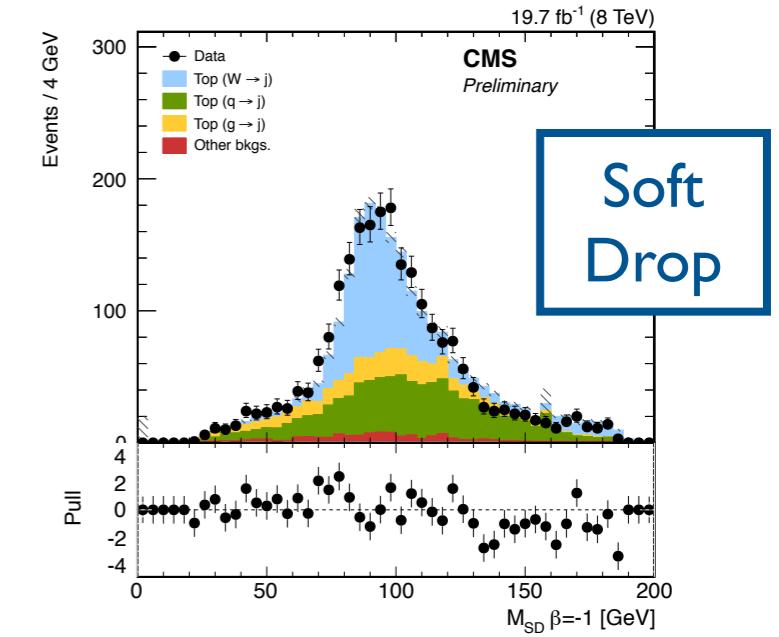
Discrimination: e.g. 1-prong vs. N-prong



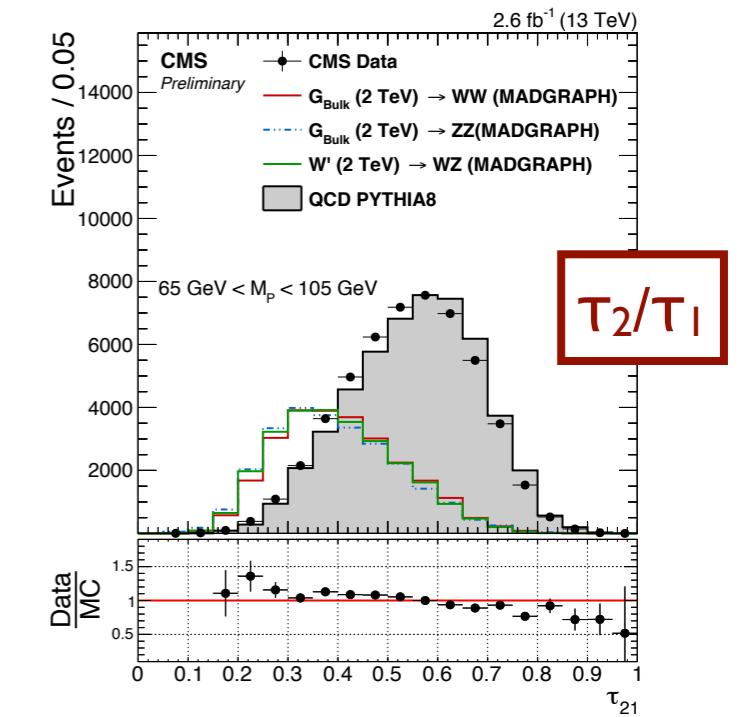
[p_T Balance, Y-splitter, Angularities, Planar Flow, N-subjettiness, Angular Structure Functions, Jet Charge, Jet Pull, Energy Correlation Functions, Dipolarity, p_T^D , Zernike Coefficients, LHA, Fox-Wolfram Moments, JHU/CMS Top Tagger, HEPTopTagger, Template Method, Shower Deconstruction, Subjet Counting,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

W/Z-Tagging @ CMS

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



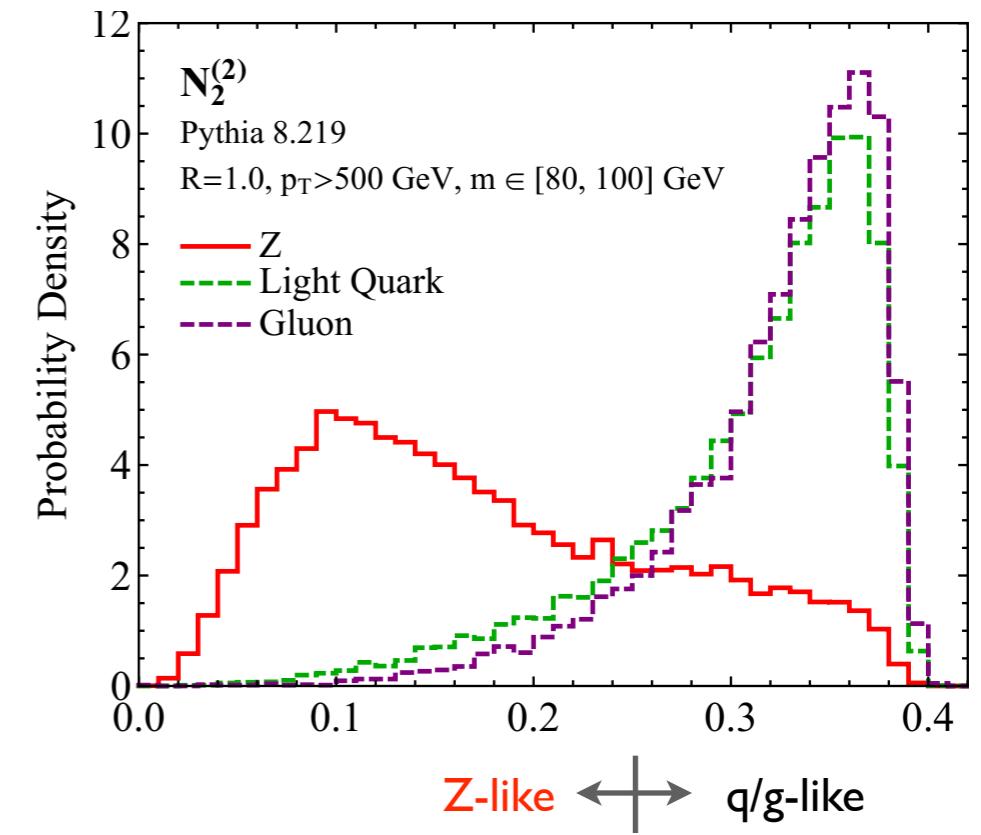
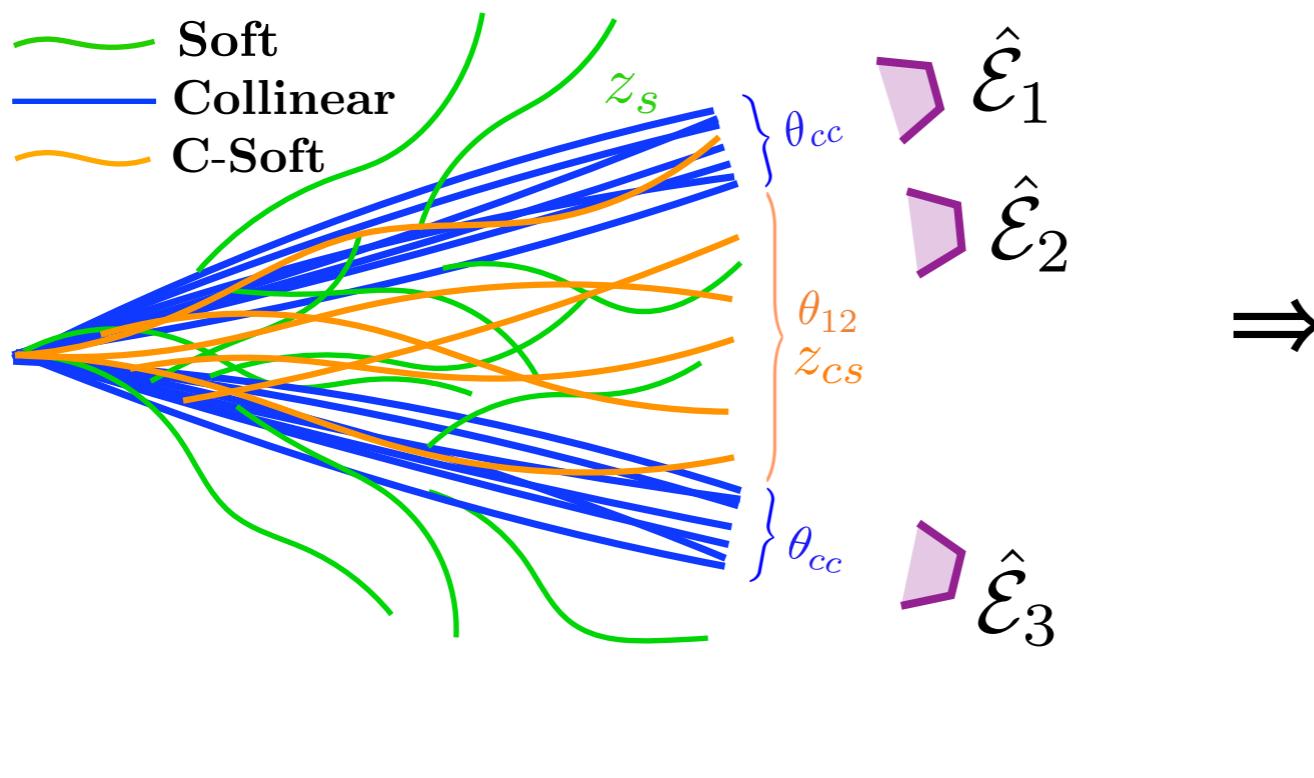
[using Larkoski, Marzani, Soyez, JDT, 1402.2657]



[using JDT, Van Tilburg, 1011.2268, 1108.2701]

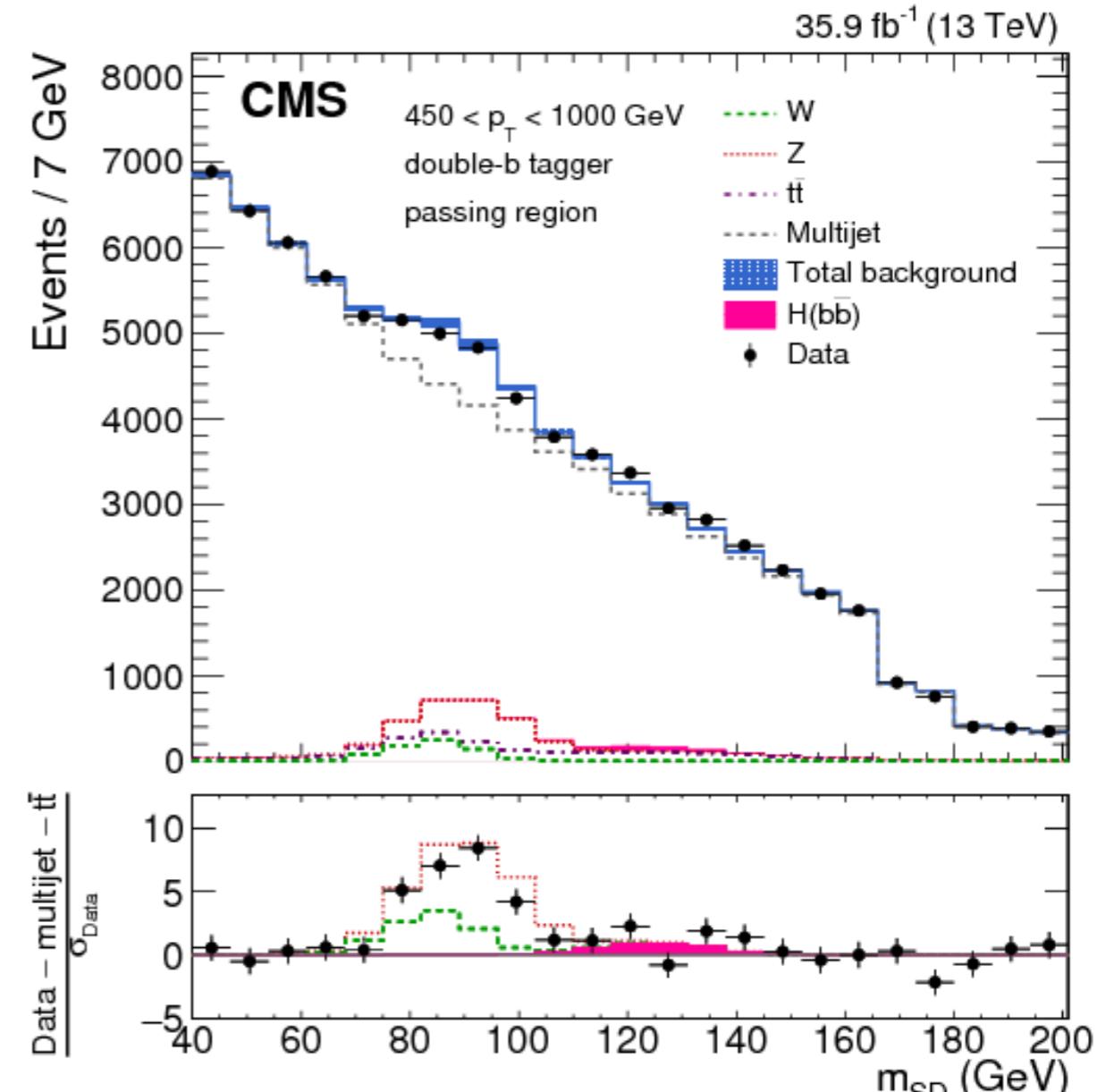
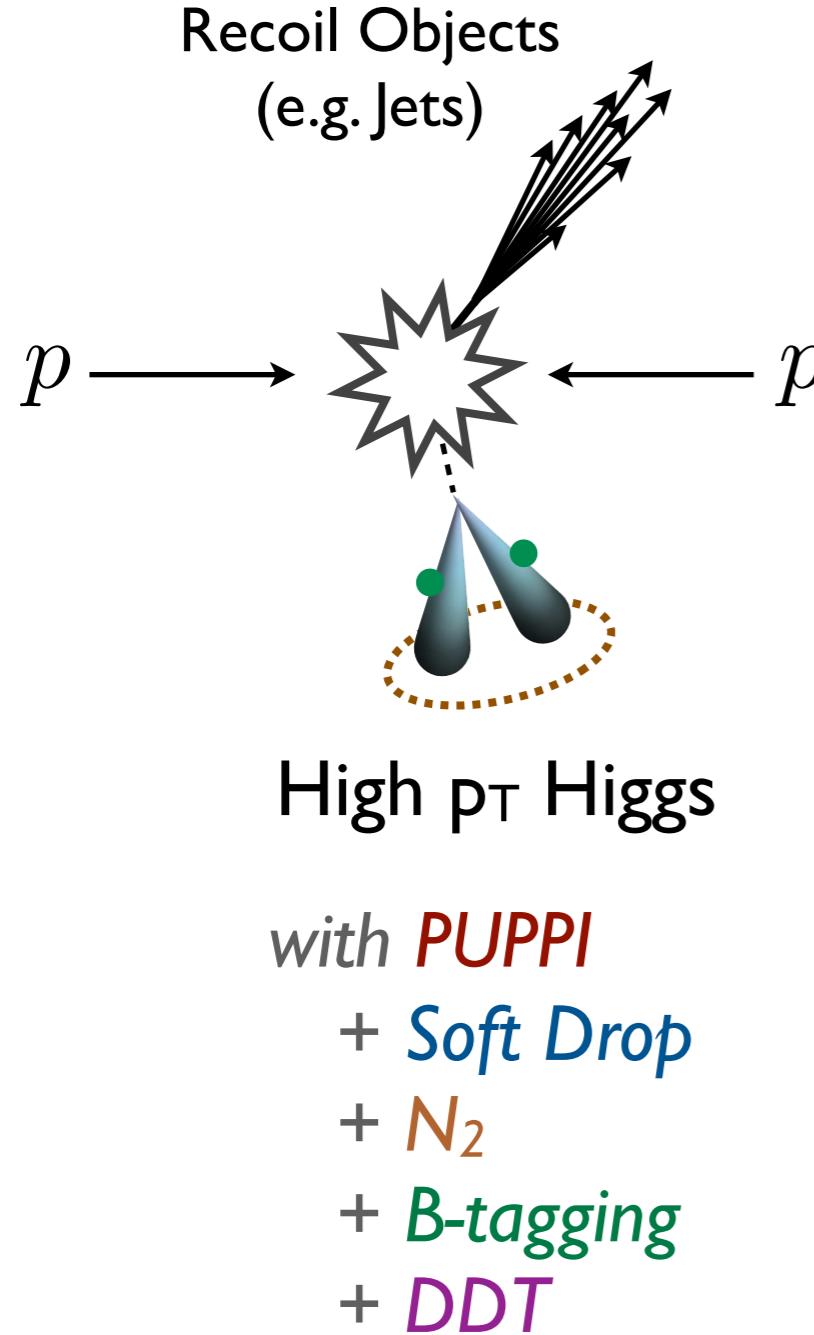
2-prong Discrimination with Energy Correlators

$$N_2 = \frac{\sum_{i < j < k} p_{Ti} p_{Tj} p_{Tk} \min \left\{ (R_{ij} R_{jk})^2, (R_{jk} R_{ki})^2, (R_{ki} R_{ij})^2 \right\}}{\left(\sum_{i < j} p_{Ti} p_{Tj} R_{ij}^2 \right)^2 / \sum_i p_{Ti}}$$



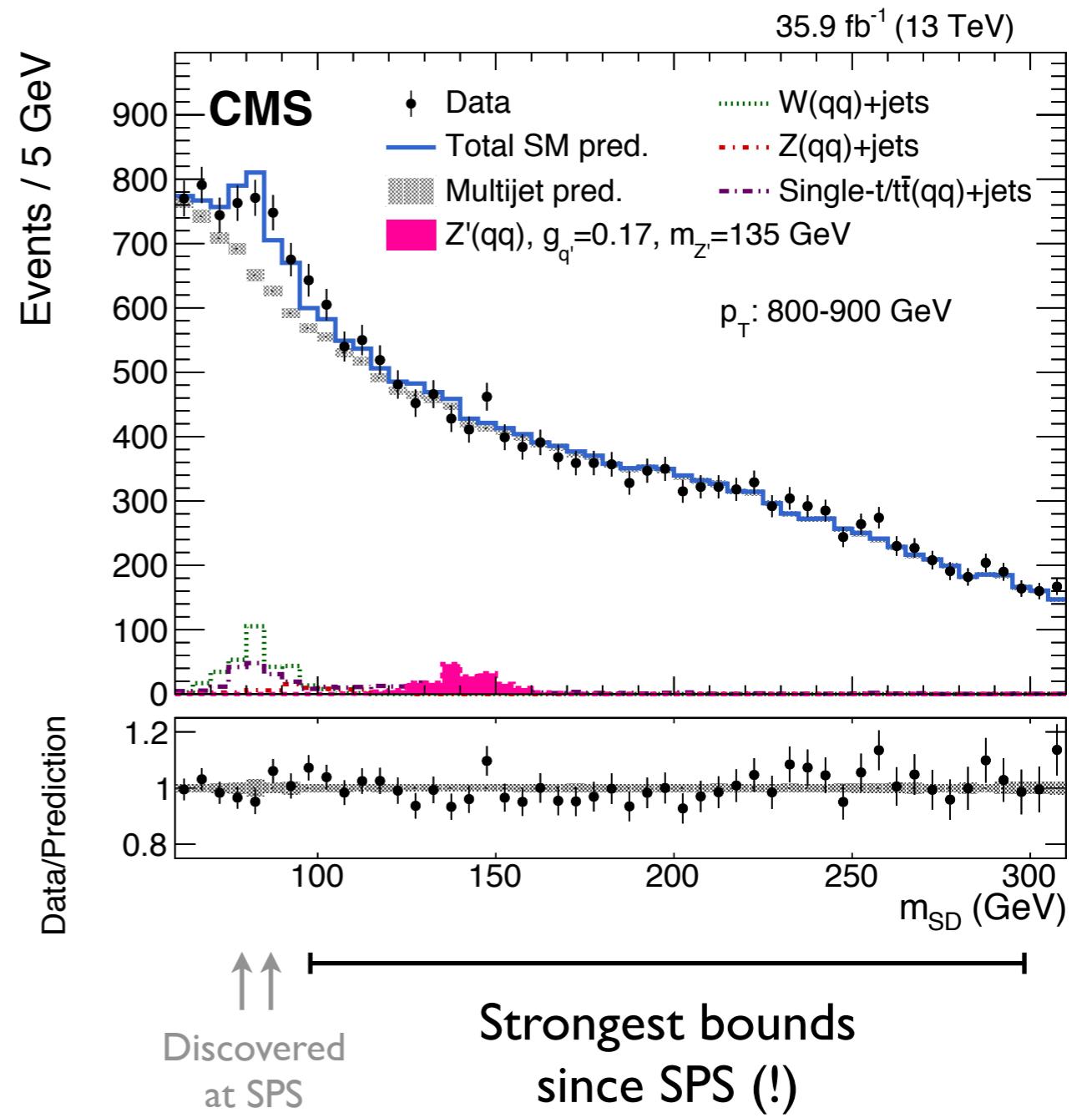
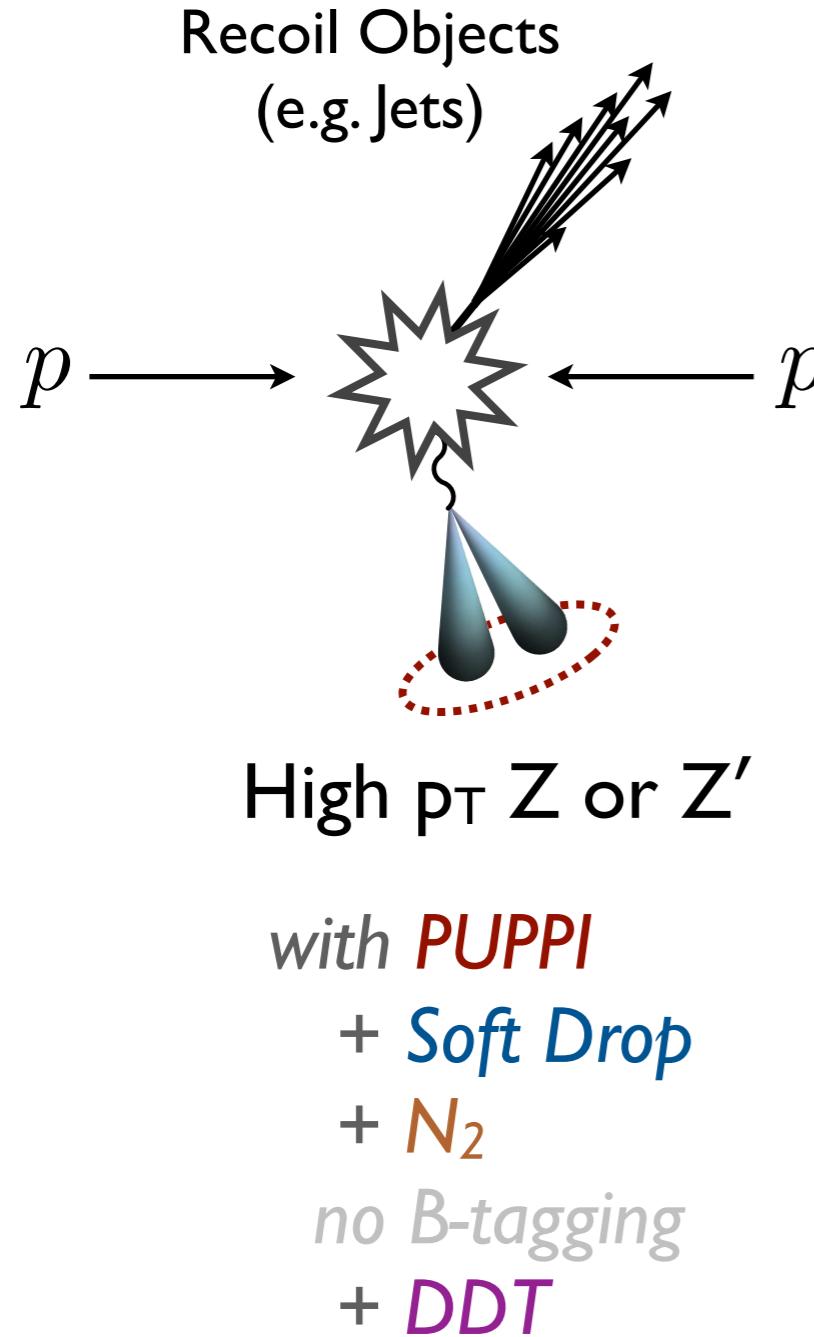
[Moult, Necib, JDT, 1609.07483; based on Larkoski, Salam, JDT, 1305.0007]

CMS: Boosted Higgs...

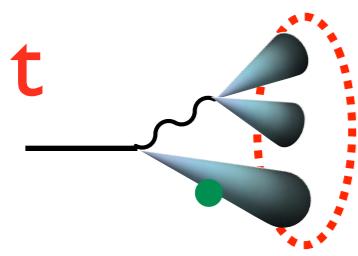


[CMS, 2017; using Bertolini, Harris, Low, Tran, 2014; Larkoski, Marzani, Soyez, JDT, 2014;
Moult, Necib, JDT, 2016; CMS, 2015; Dolen, Harris, Marzani, Rappoccio, Tran, 2016]

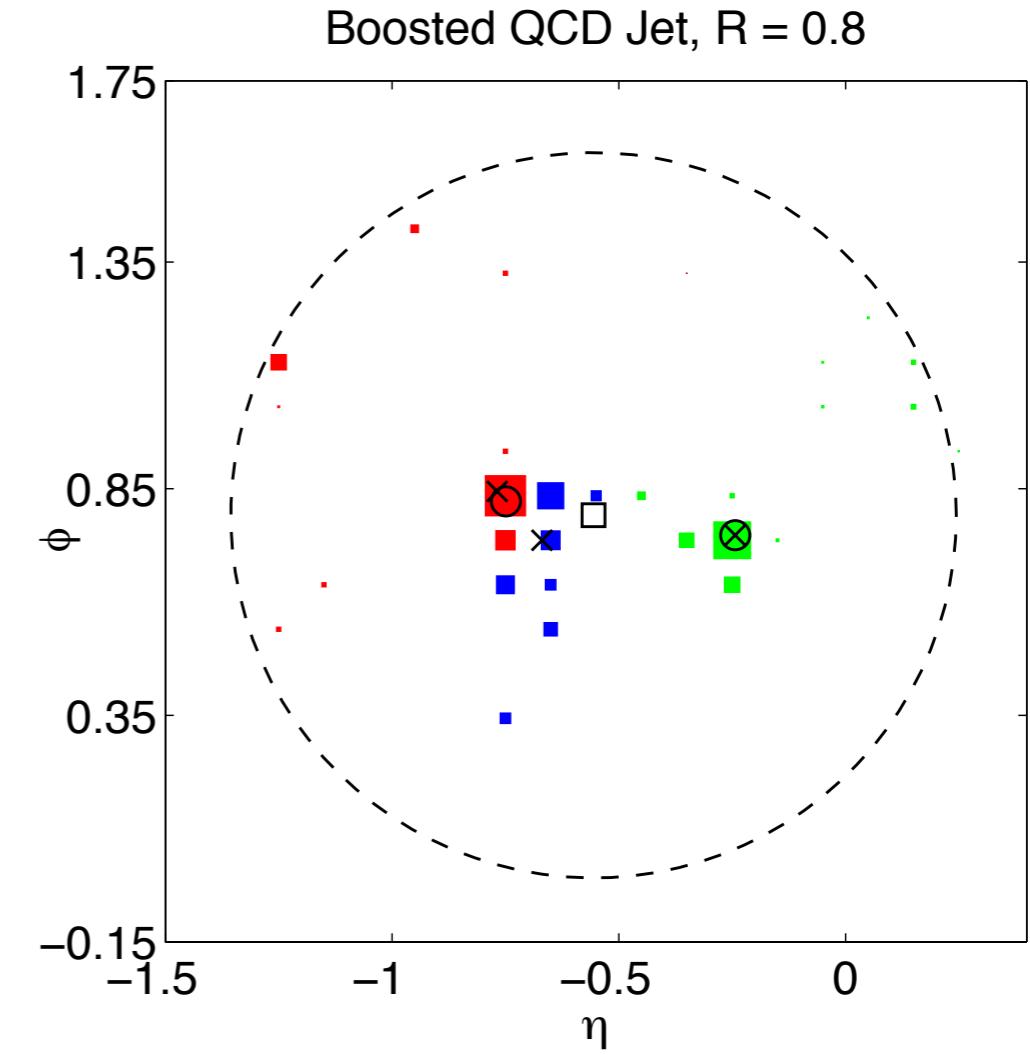
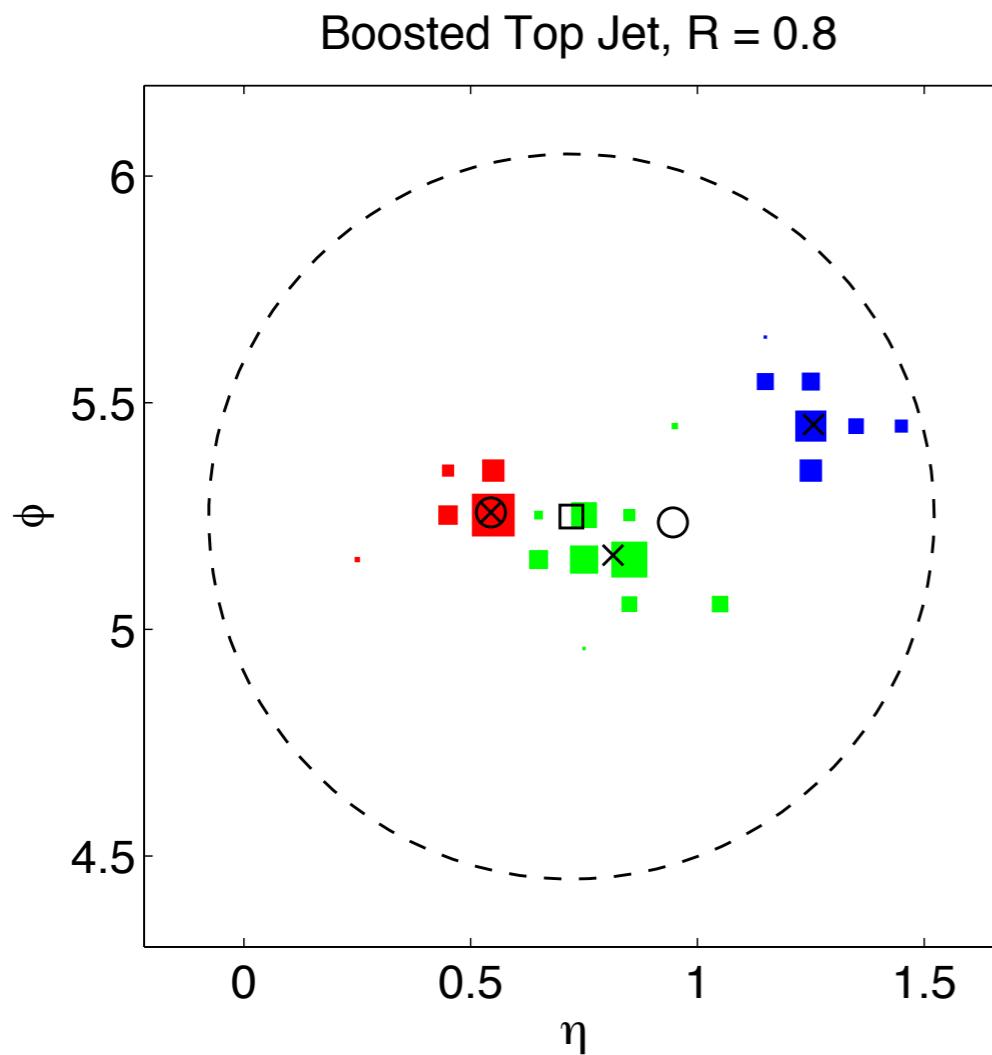
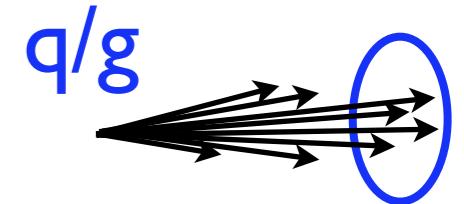
CMS: Boosted Higgs... & Beyond



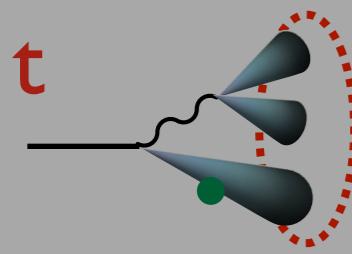
[CMS, 2017; using Bertolini, Harris, Low, Tran, 2014; Larkoski, Marzani, Soyez, JDT, 2014;
Moult, Necib, JDT, 2016; CMS, 2015; Dolen, Harris, Marzani, Rappoccio, Tran, 2016]



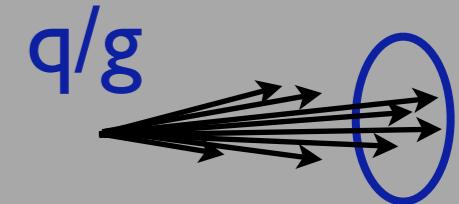
N-Prong vs. I-Prong



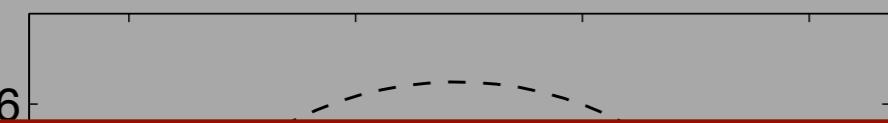
Both jets have $m \approx 173$ GeV



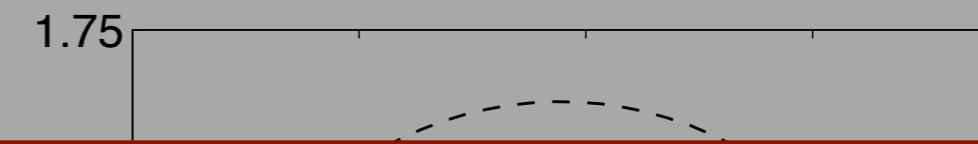
N-Prong vs. I-Prong



Boosted Top Jet, $R = 0.8$

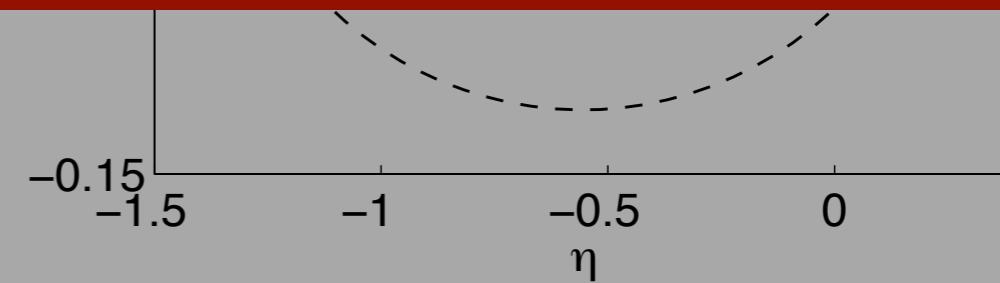
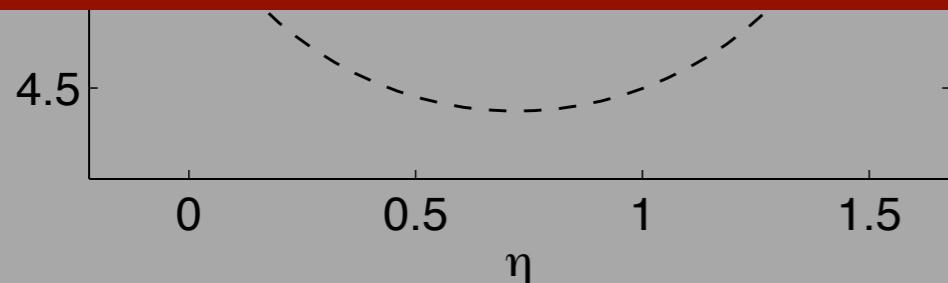


Boosted QCD Jet, $R = 0.8$

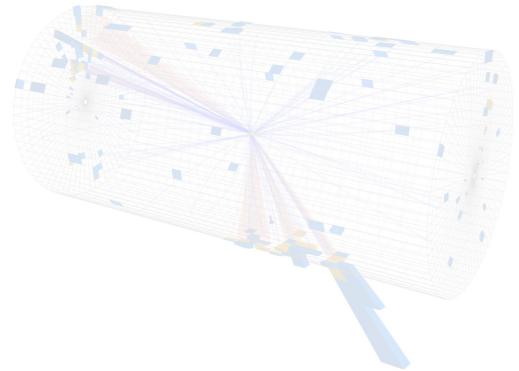


Classification by eye (or machine learning)

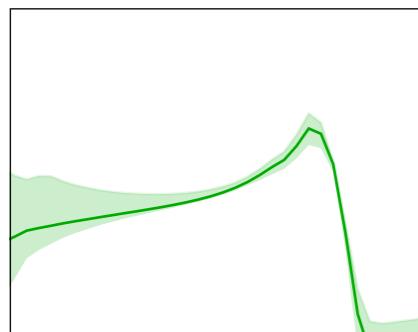
Still value to analytic substructure tools?



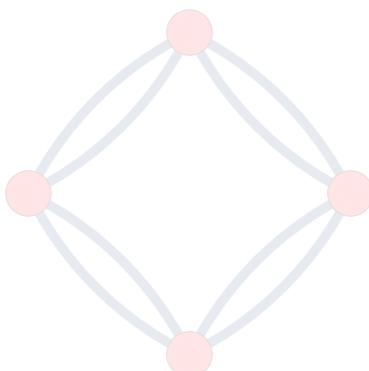
Both jets have $m \approx 173$ GeV



The Rise of Jet Substructure



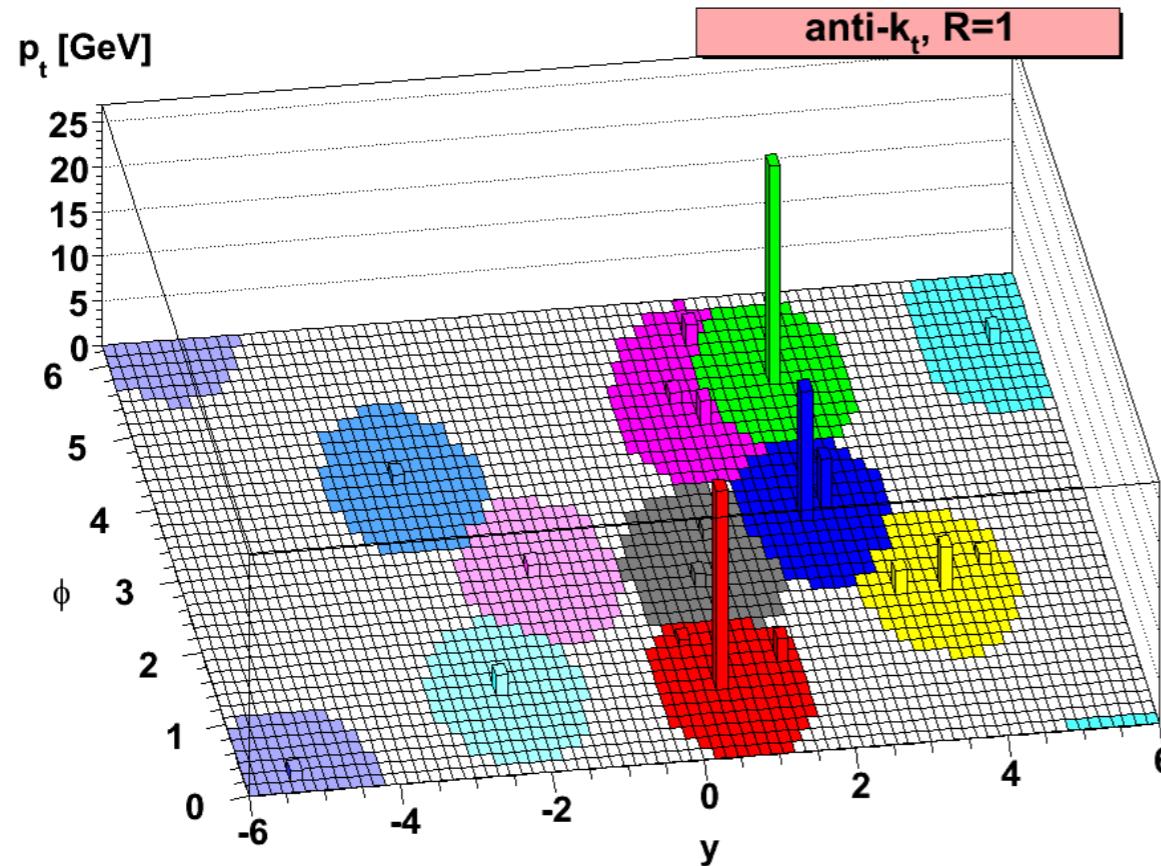
The Importance of First Principles



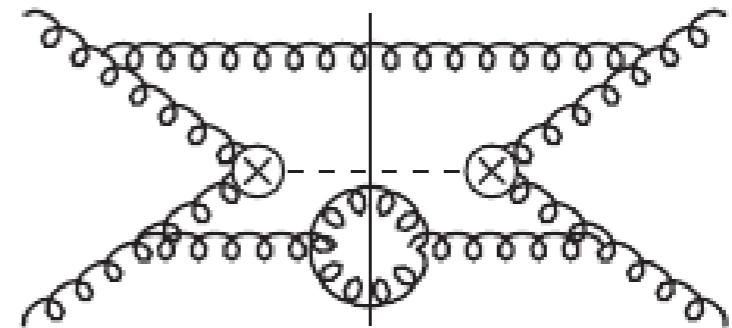
Towards a Systematic Expansion

QCD Renaissance

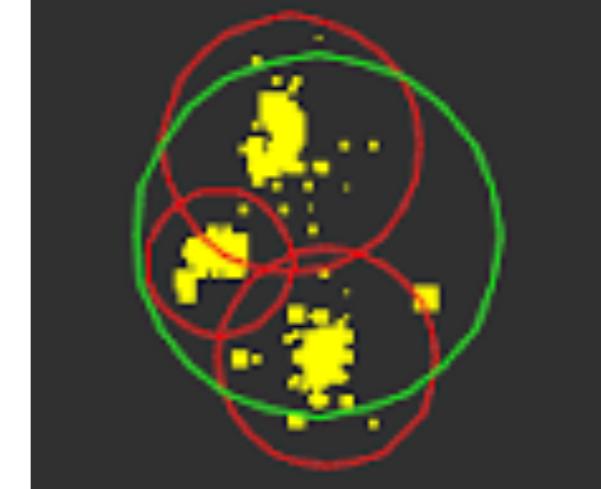
Theory c. 2008–present



New Jet Algorithms



Loop/Leg/Log Explosion



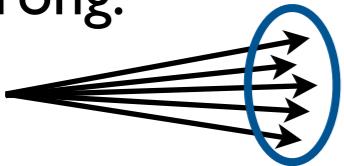
Jet Substructure

[Anti- k_T : Cacciari, Salam, Soyez, 2008; see also Delsart, 2006] [N³LO: Anastasiou, Duhr, Dulat, Herzog, Mistlberger, 2015]
[BDRS: Butterworth, Davison, Rubin, Salam, 2008; see also Seymour, 1991, 1994]

First-Principles Calculations

Comprehensive/ible Review:
Larkoski, Moult, Nachman, 1709.04464

1-prong:



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;
Marzani, Schunk, Soyez, 1704.02210

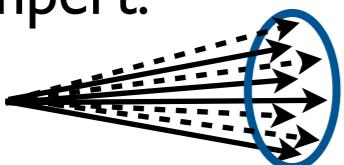
Double differential: Larkoski, JDT, 1307.1699; Larkoski, Moult, Neill, 1401.4458; Procura, Waalewijn, Zeune, 1410.6483

In heavy ions: Chien, Vitev, 1405.4293; Chien, 1411.0741

p_T balance: Larkoski, Marzani, JDT, 1502.01719; Chien, Vitev, 1608.07283

Small R jets: Dasgupta, Dreyer, Salam, Soyez, 1411.5182, 1602.01110

Nonpert:

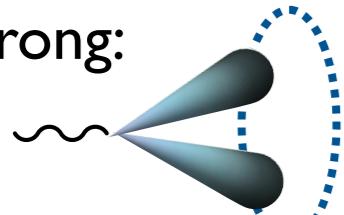


Jet charge: Krohn, Schwartz, Lin, Waalewijn, 1209.2421;
Waalewijn, 1209.3019

Track-only shapes: Chang, Procura, JDT, Waalewijn, 1303.6637, 1306.6630

Fractal observables: Elder, Procura, JDT, Waalewijn, Zhou, 1704.05456

2-prong:



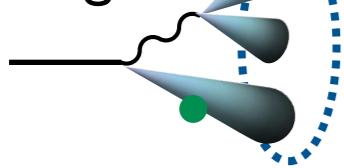
Signal grooming: Rubin, 1002.4557; Dasgupta, Powling, Siadmok, 1503.01088

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, 1708.06760;
Dasgupta, Schunk, Soyez, 1512.00516;
Dasgupta, Powling, Schunk, Soyez, 1609.07149

Decorrelation: Moult, Nachman, Neill, 1710.06859

3-prong:



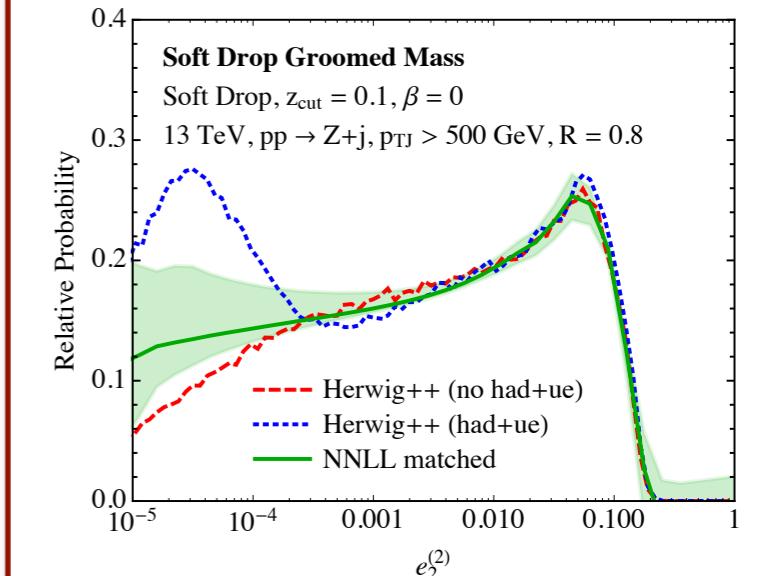
Planar flow: Field, Gur-Ari, Kosower, Mannelli, Perez, 1212.2106

Fractional jets: Bertolini, JDT, Walsh, 1501.01965

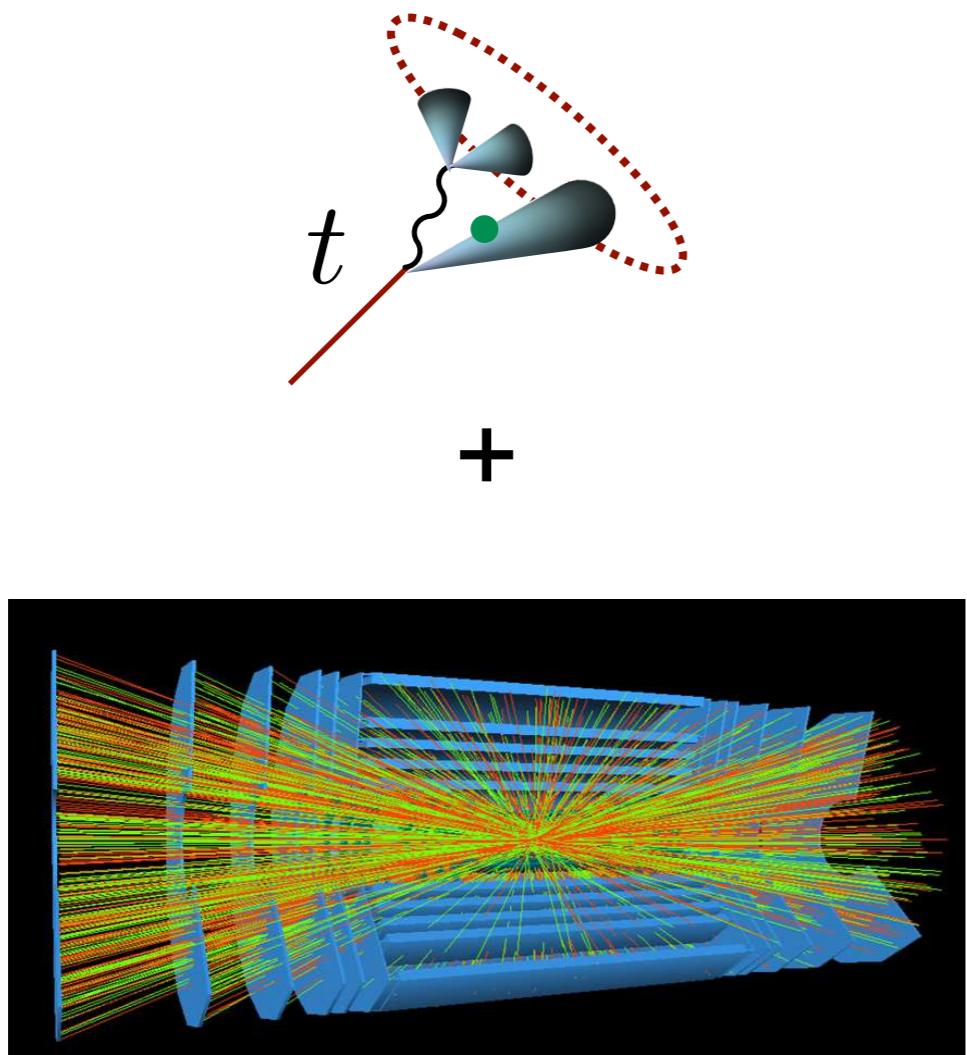
Power counting: Larkoski, Moult, Neill, 1411.0665

Top mass definition: Hoang, Mantry, Pathak, Stewart, 1708.02586

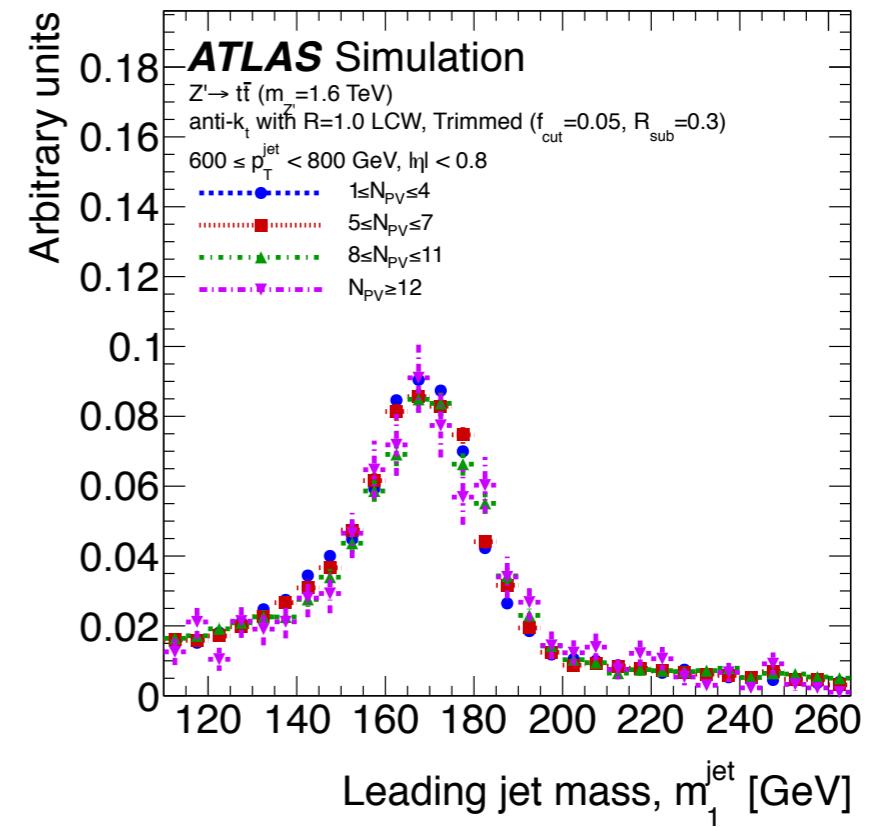
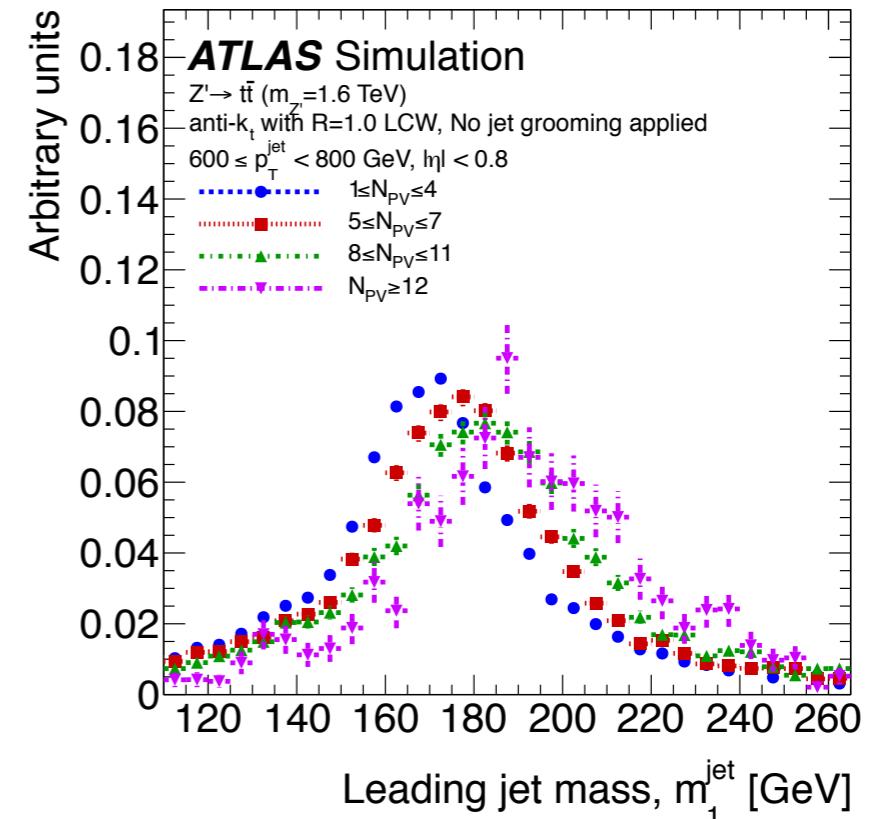
First NNLL + $O(\alpha_s^2)$ calculation
for substructure in $p\bar{p}$



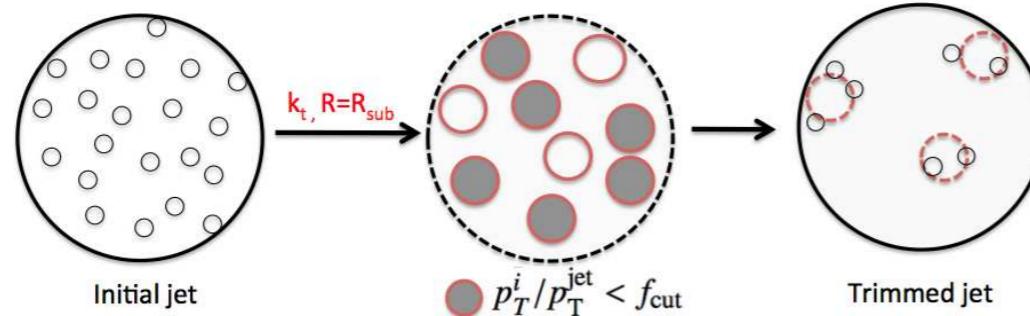
Combination of fixed-order, direct resummation, SCET, RG evolution,
and new techniques (e.g. Sudakov safety, multi-differential projections)



Jet Grooming



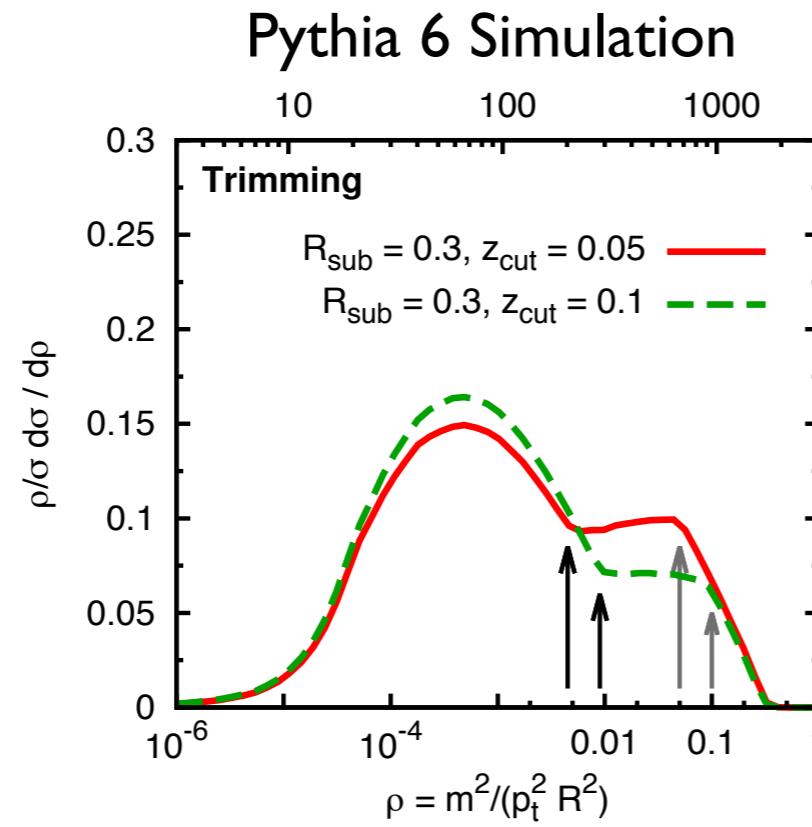
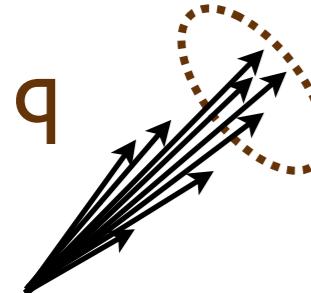
Trimming from First Principles?



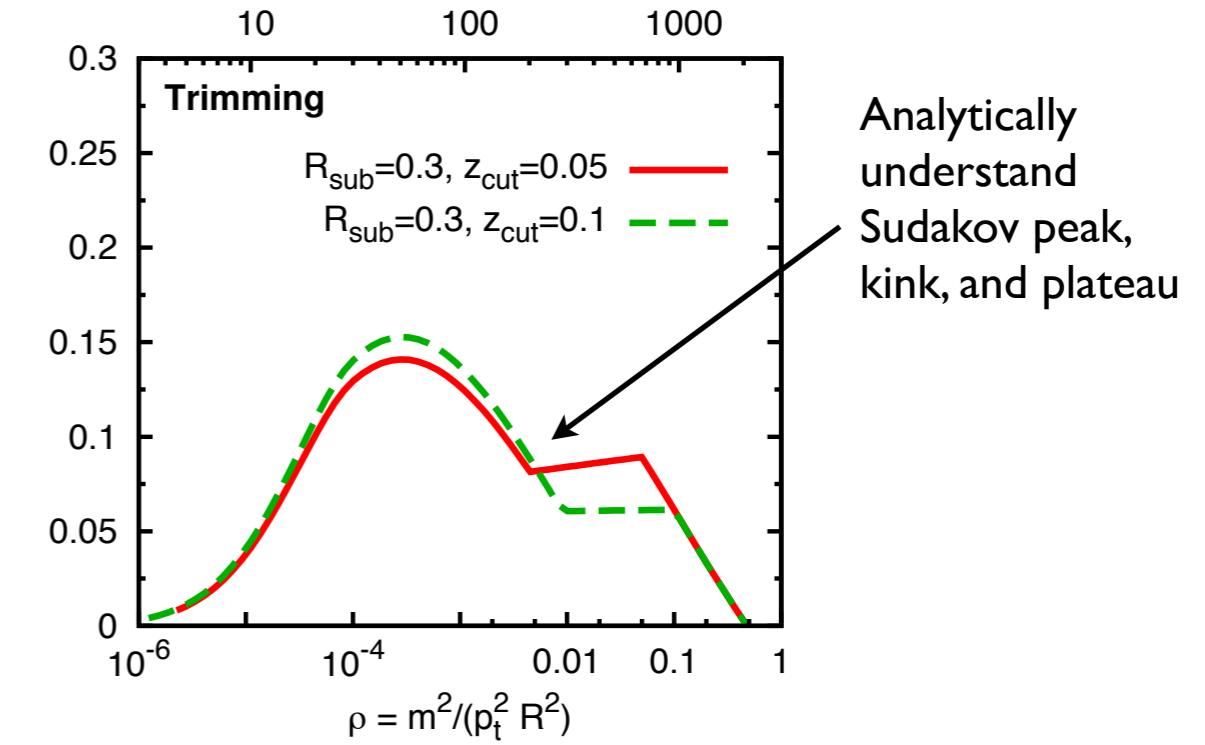
R_{sub} : subjet radius
 z_{cut} : fractional energy threshold

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

Trimmed
Jet Mass:
3 TeV quark jets



First-principles QCD (MLL)



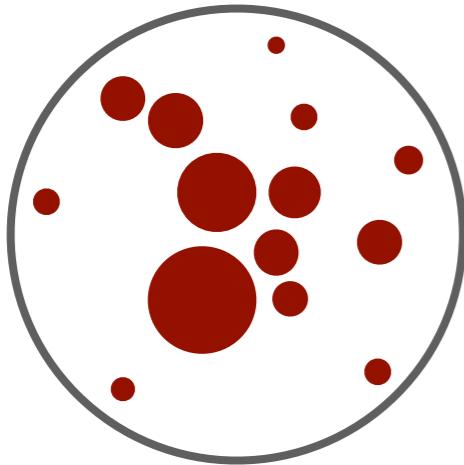
[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Soft Drop Declustering

Default for

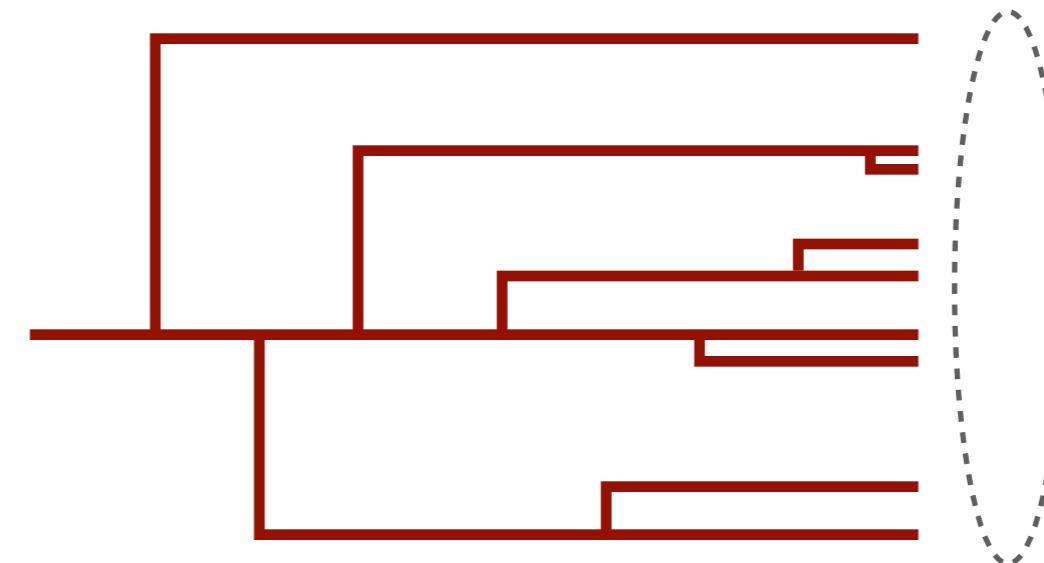


Original Jet



=

Clustering Tree



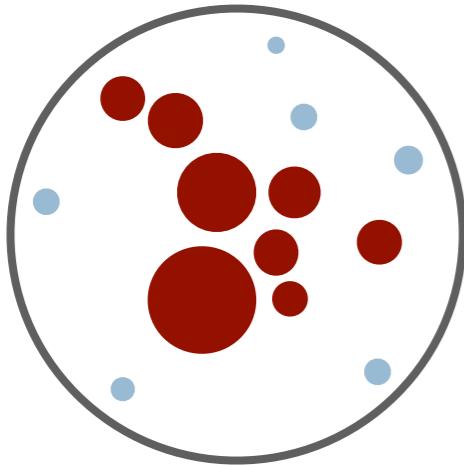
[Larkoski, Marzani, Soyez, JDT, 2014; see also Butterworth, Davison, Rubin, Salam, 2008; Dasgupta, Fregoso, Marzani, Salam/Powling, 2013]

Soft Drop Declustering

Default for

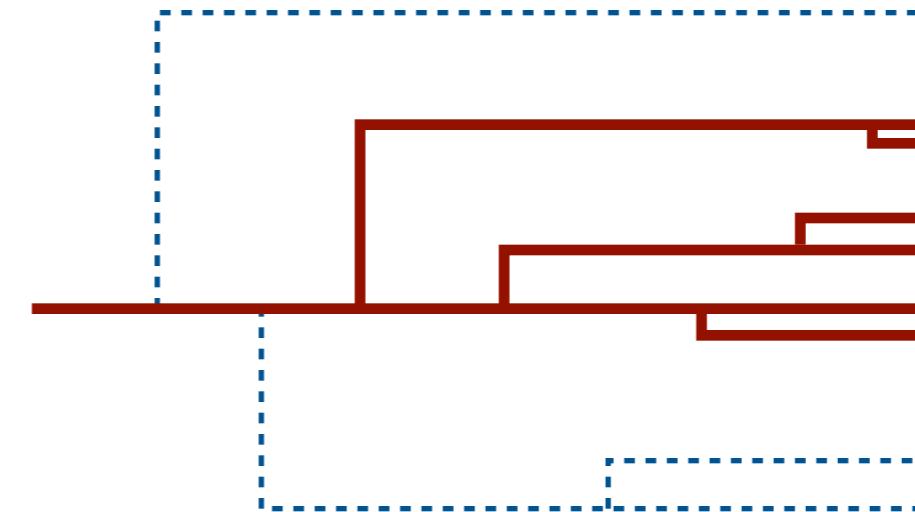


Groomed Jet



=

Groomed
Clustering Tree



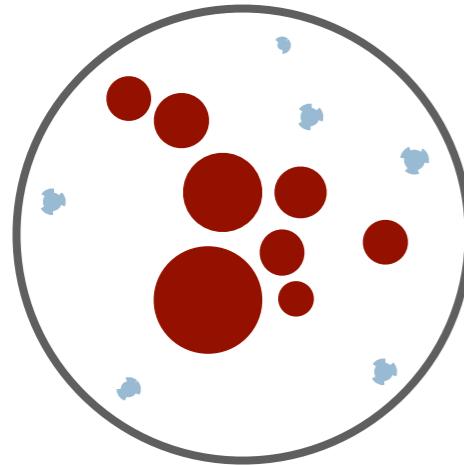
[Larkoski, Marzani, Soyez, JDT, 2014; see also Butterworth, Davison, Rubin, Salam, 2008; Dasgupta, Fregoso, Marzani, Salam/Powling, 2013]

Soft Drop Declustering

Default for

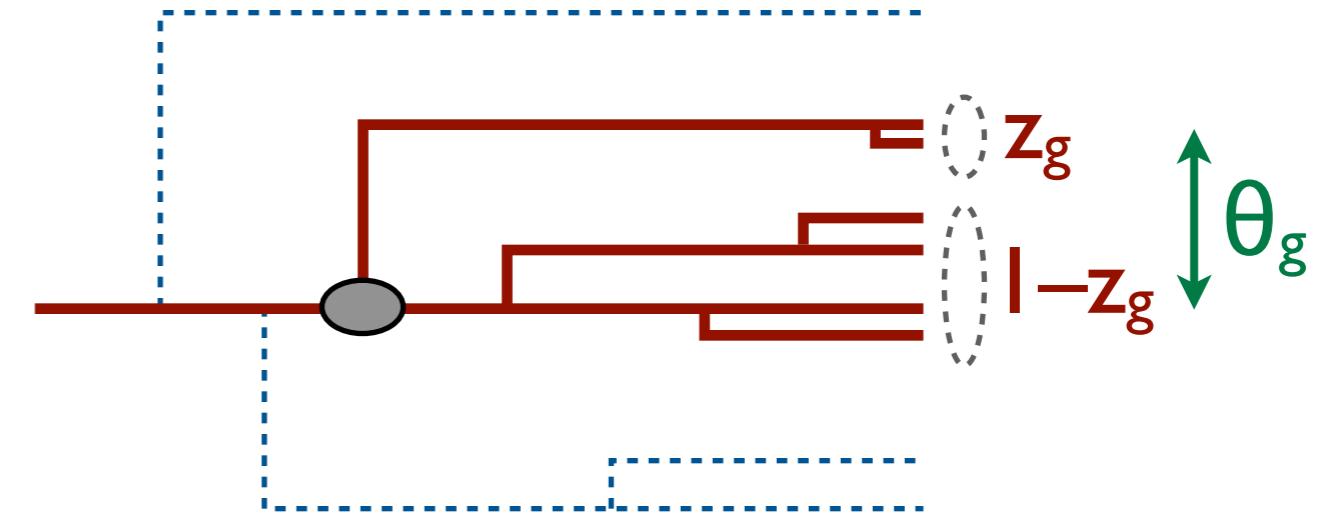


Groomed Jet



=

Groomed
Clustering Tree



$$z_g > z_{\text{cut}} \theta_g^\beta$$

More Grooming

aka $mMDT$

Less Grooming

$\beta \rightarrow -\infty$

$\beta < 0$

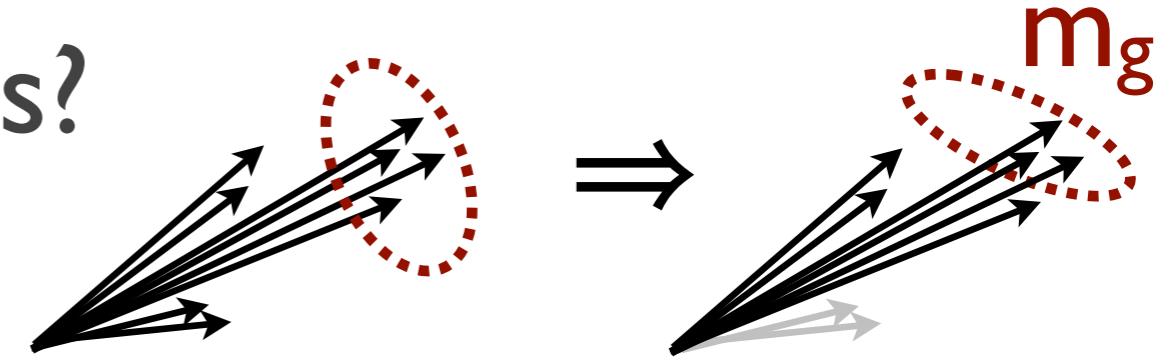
$\beta = 0$

$\beta > 0$

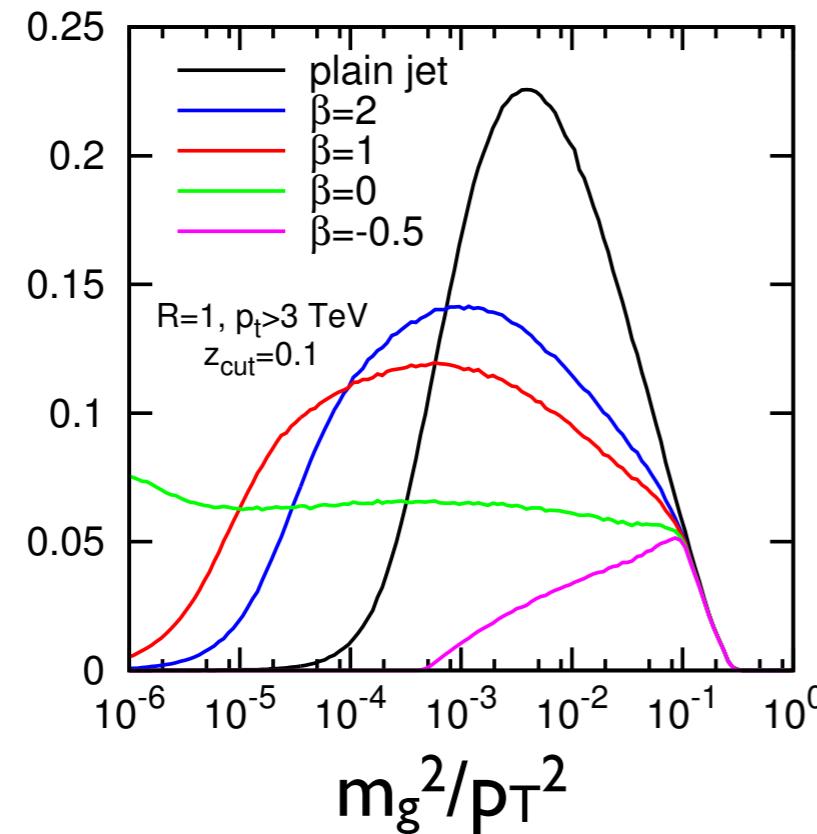
$\beta \rightarrow \infty$

[Larkoski, Marzani, Soyez, JDT, 2014; see also Butterworth, Davison, Rubin, Salam, 2008; Dasgupta, Fregoso, Marzani, Salam/Powling, 2013]

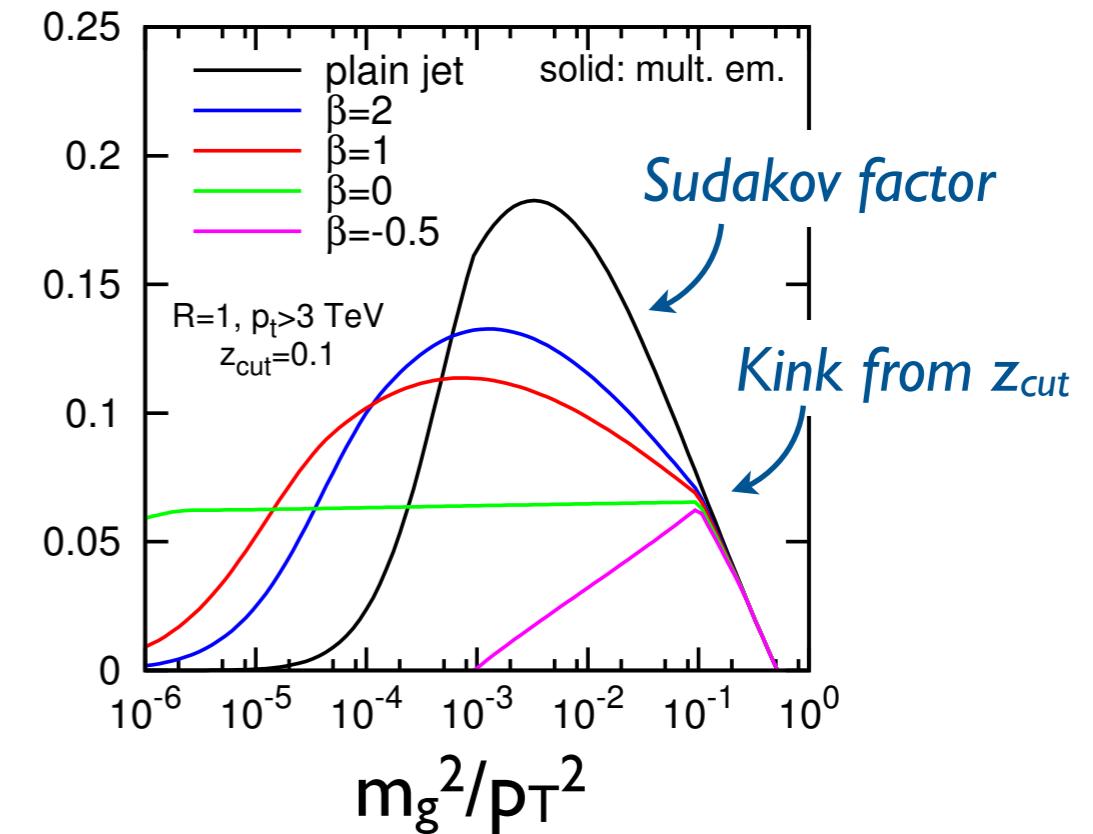
Calculating Groomed Mass?



Simulated LHC Data



First-principles QCD (MLL)



More Grooming

$\beta \rightarrow -\infty$

$\beta < 0$

$\beta = 0$

$\beta > 0$

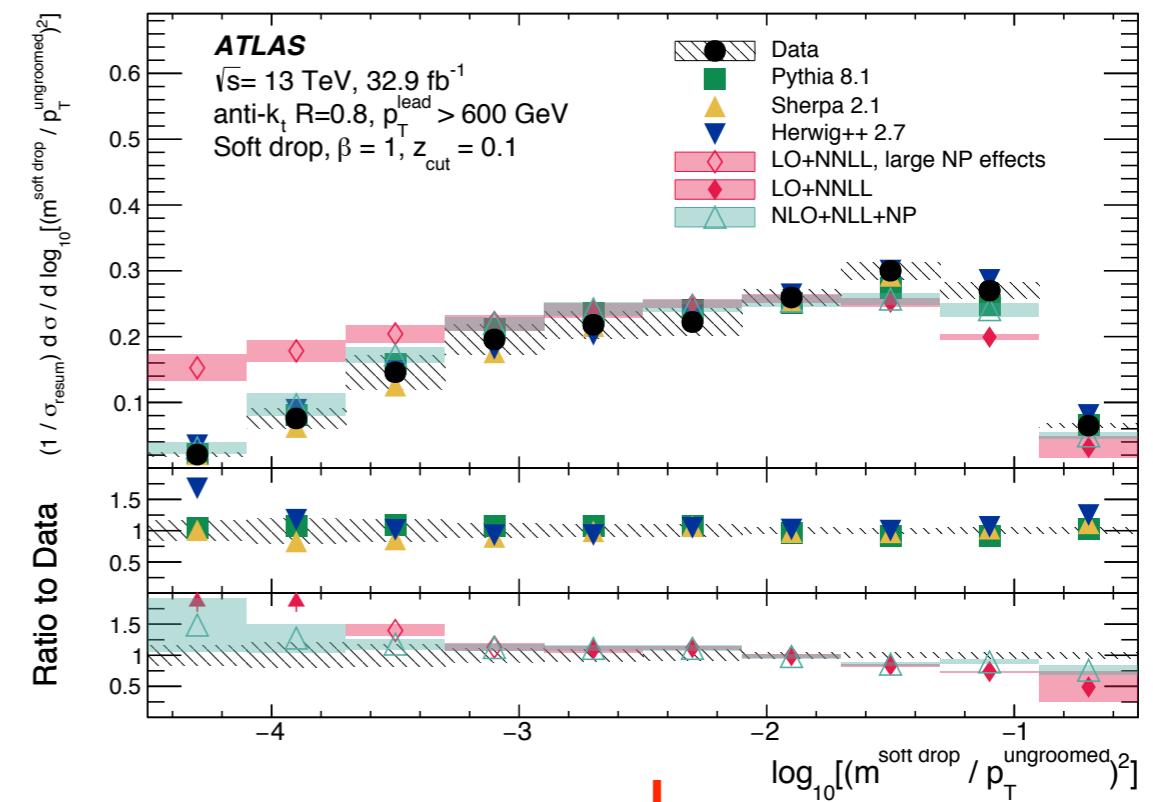
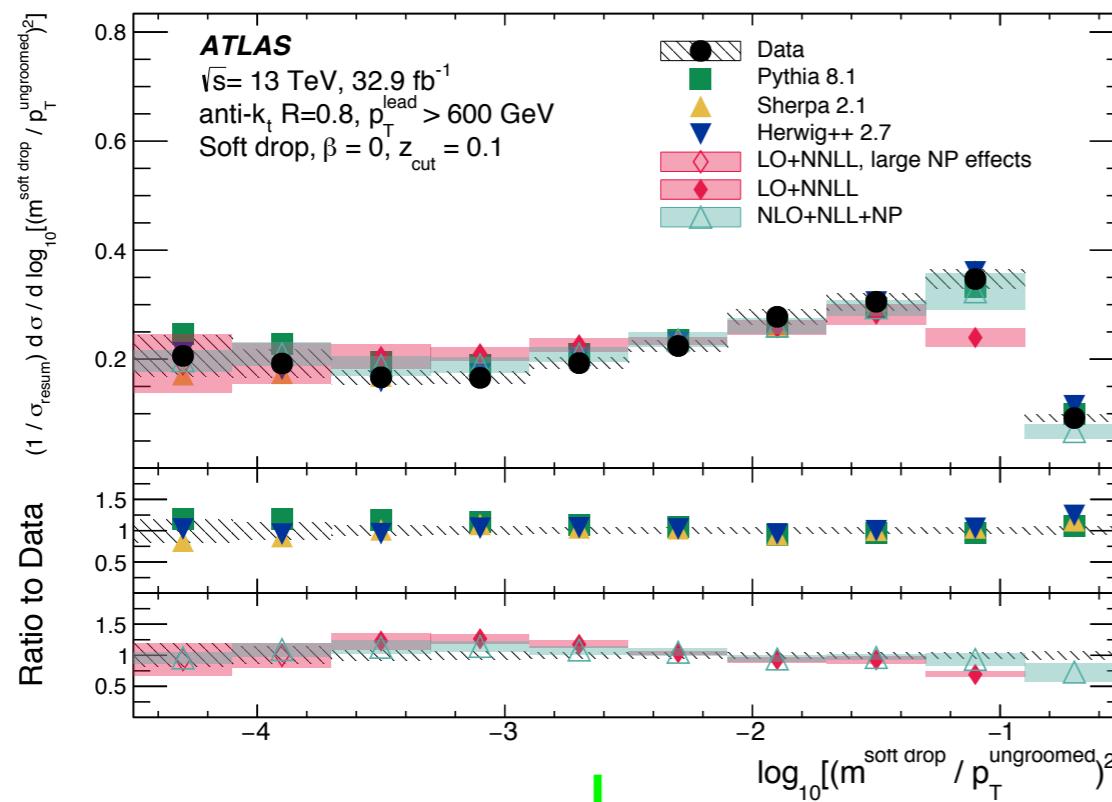
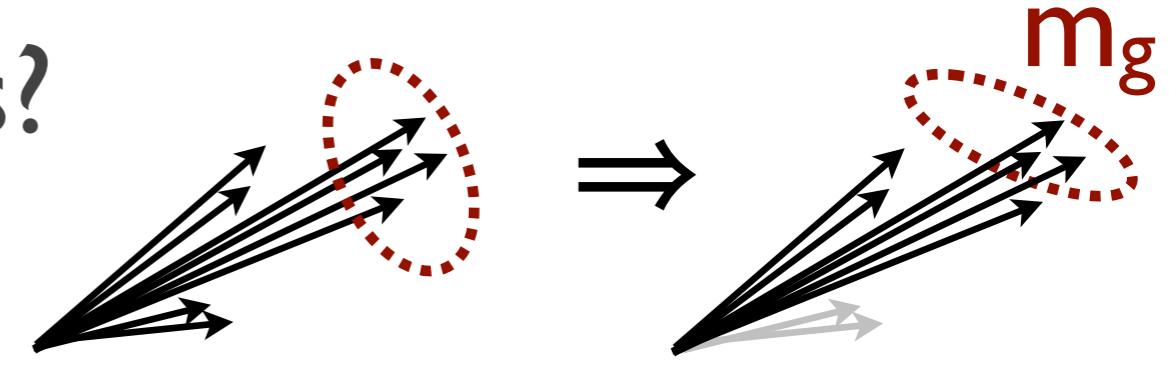
$\beta \rightarrow \infty$



[Larkoski, Marzani, Soyez, JDT, 1402.2657]

Measuring Groomed Mass?

Hot off the press from **ATLAS EXPERIMENT**



More Grooming

$\beta \rightarrow -\infty$

$\beta < 0$

$\beta = 0$

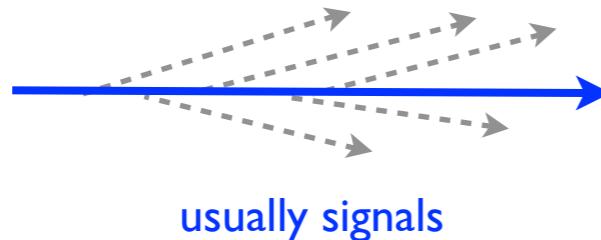
$\beta > 0$

$\beta \rightarrow \infty$

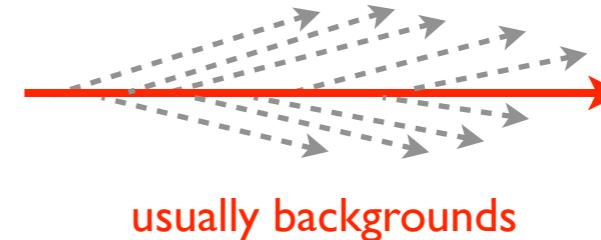
[ATLAS, 1711.08341; compared to Frye, Larkoski, Schwartz, Yan, 1603.06375, 1603.09338; Marzani, Schunk, Soyez, 1704.02210]

The Practical Value of First Principles

Quark: $C_F = 4/3$



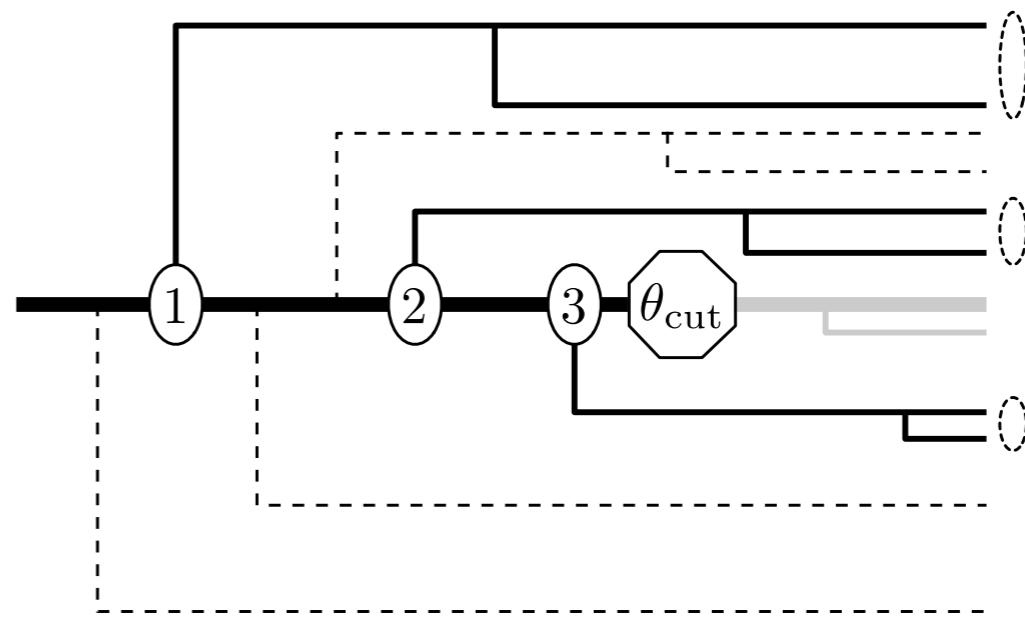
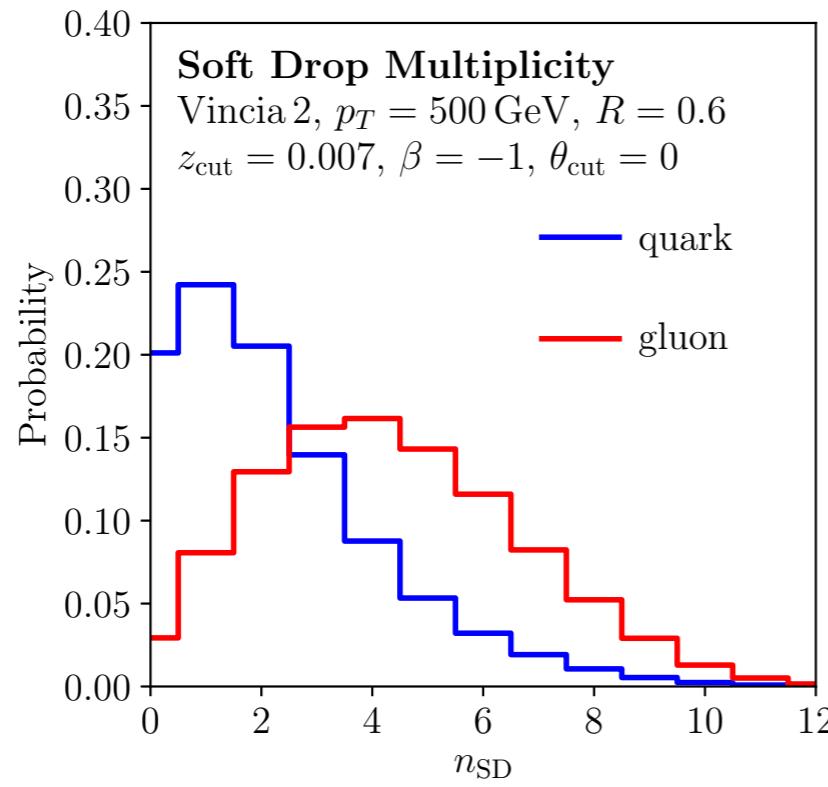
Gluon: $C_A = 3$



VS.

“Soft Drop Multiplicity” with $\beta = -1$

Provably optimal quark/gluon discriminant (at MLL accuracy)



[Frye, Larkoski, Thaler, Zhou, 1704.06266]

From this morning...

PRL 119, 132003 (2017)

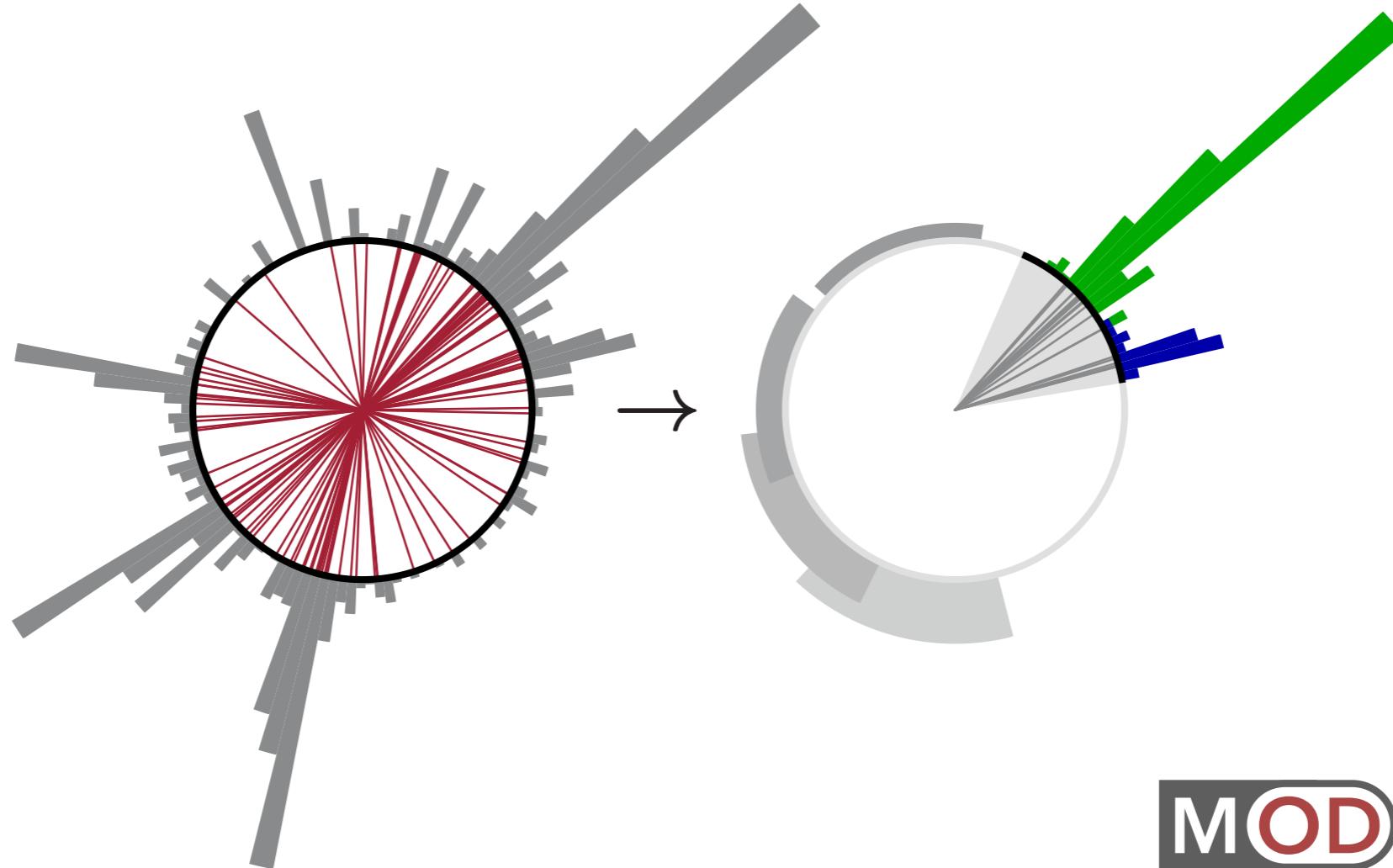
PHYSICAL REVIEW LETTERS

week ending
29 SEPTEMBER 2017

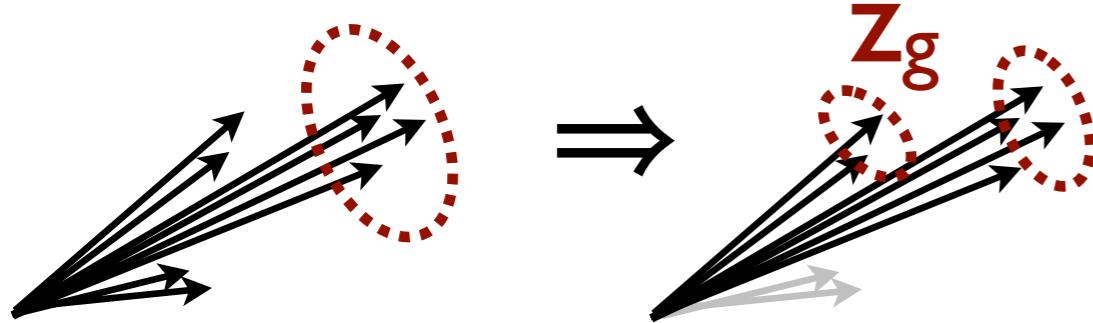


Exposing the QCD Splitting Function with CMS Open Data

Andrew Larkoski,^{1,*} Simone Marzani,^{2,†} Jesse Thaler,^{3,‡} Aashish Tripathee,^{3,§} and Wei Xue^{3,||}



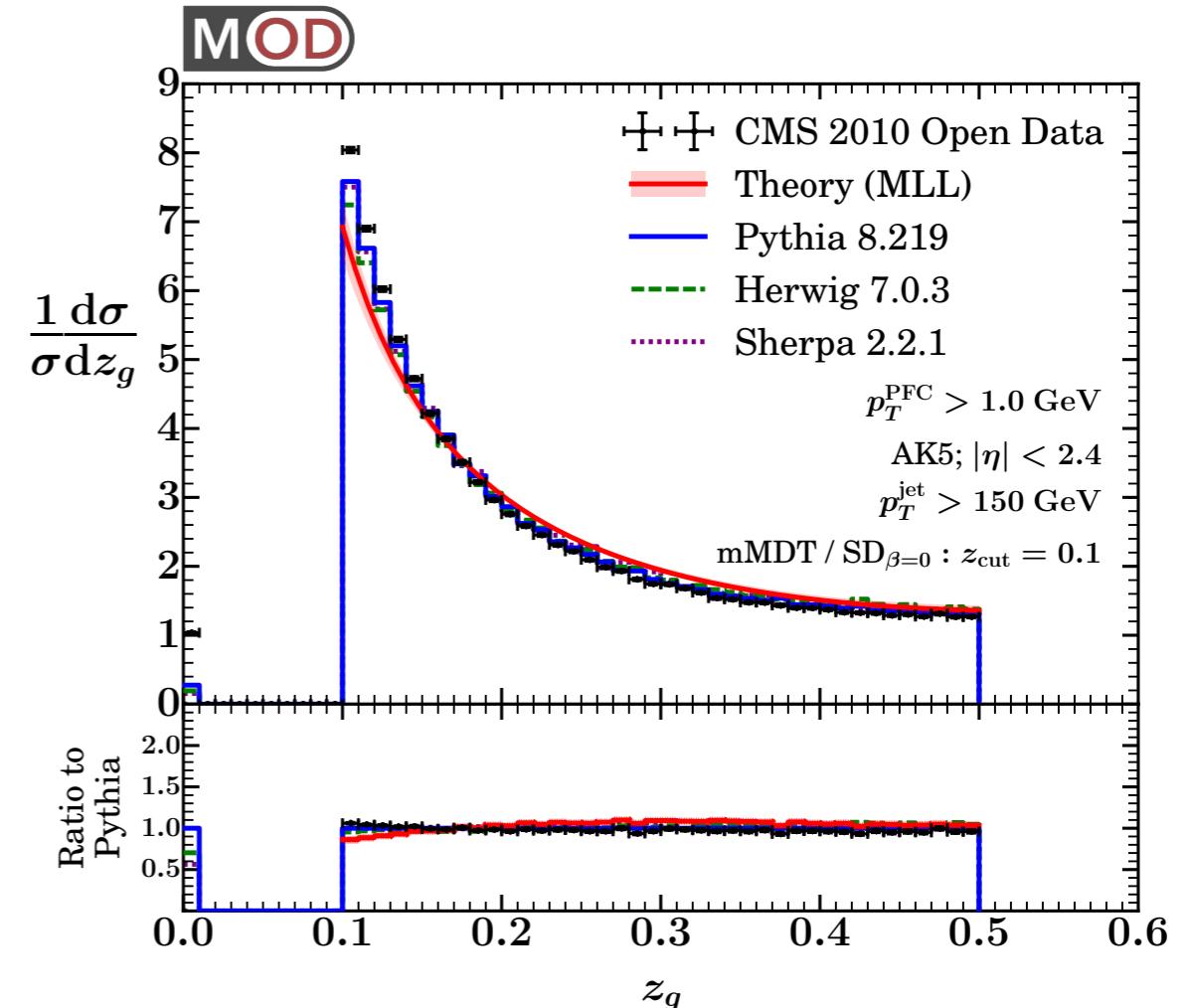
Grooming to Explore QCD...



A “standard candle”
from soft drop

$$dP_{i \rightarrow ig} \sim \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

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

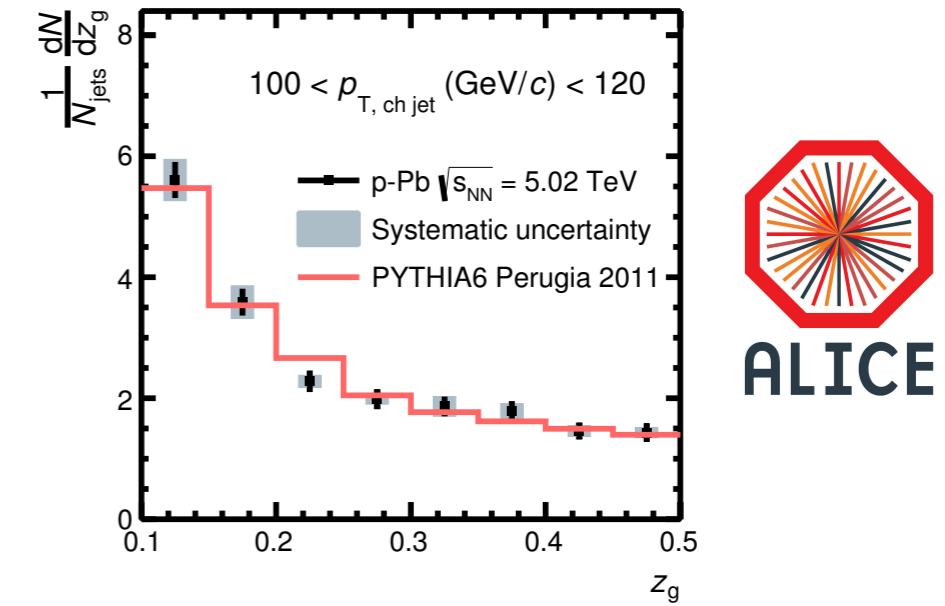
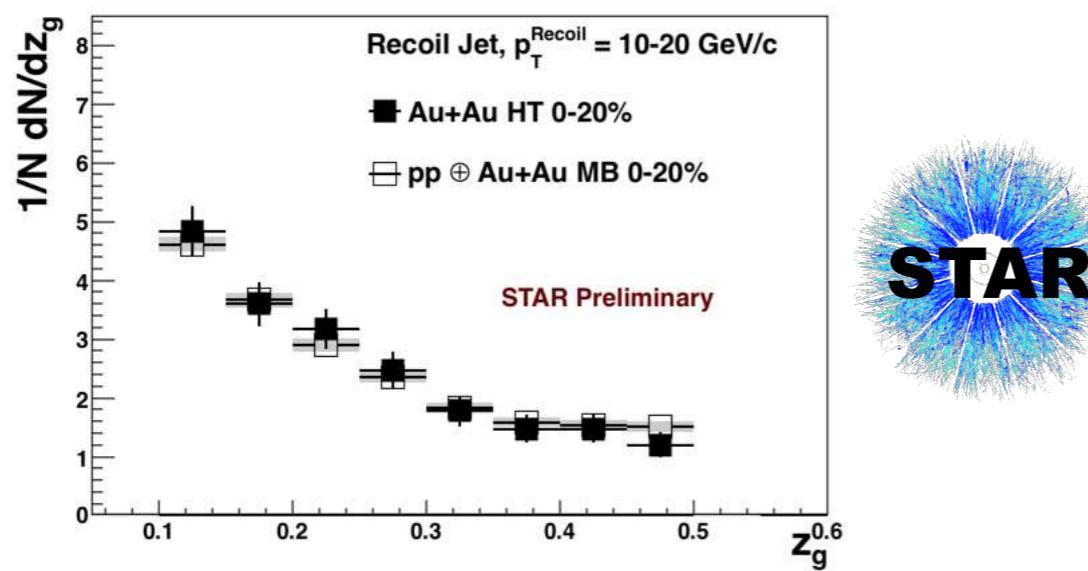
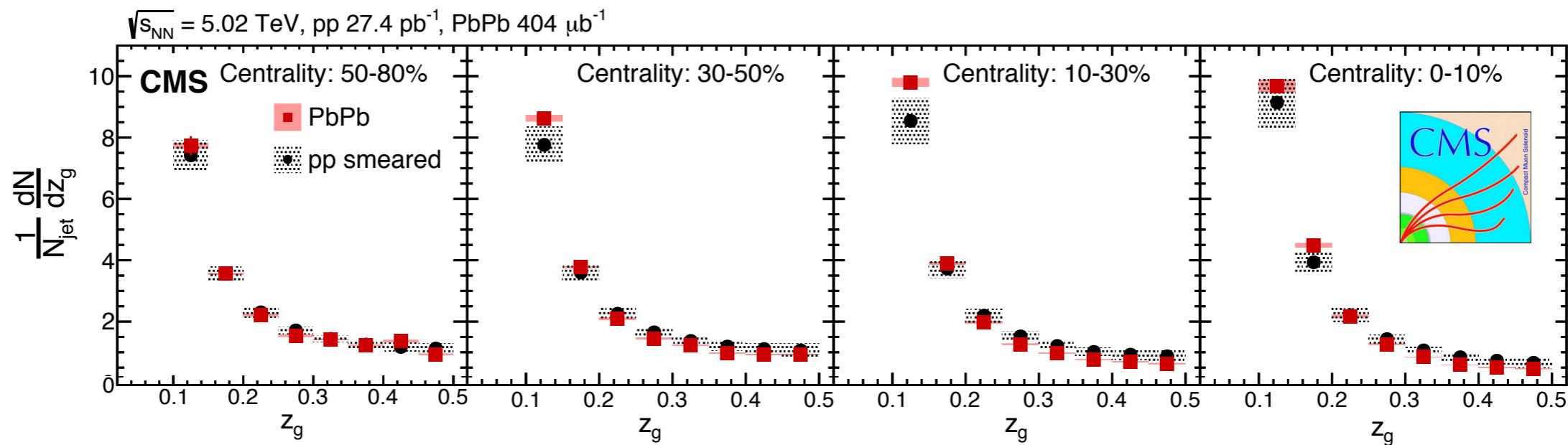


opendata
CERN

“Accelerating science
through public data”

[Larkoski, Marzani, JDT, I502.01719; using Larkoski, JDT, I307.1699]
[Larkoski, Marzani, Romero, Tripathi, Xue, JDT, I704.05066, I704.05842]

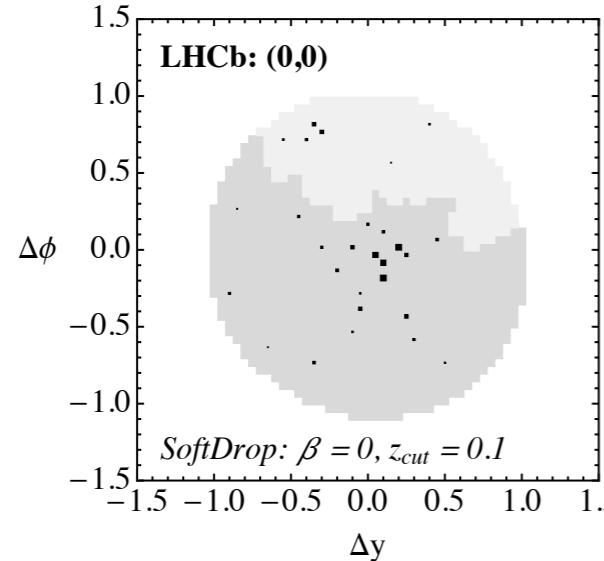
Grooming to Explore QCD... & the QGP



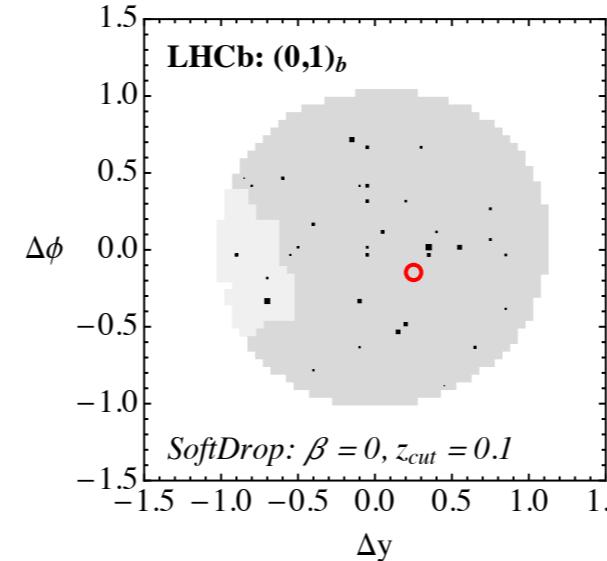
[CMS 1708.09429, STAR preliminary, ALICE preliminary]

Grooming to Explore QCD... & Heavy Flavor

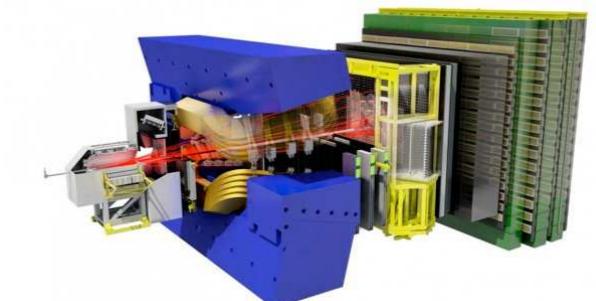
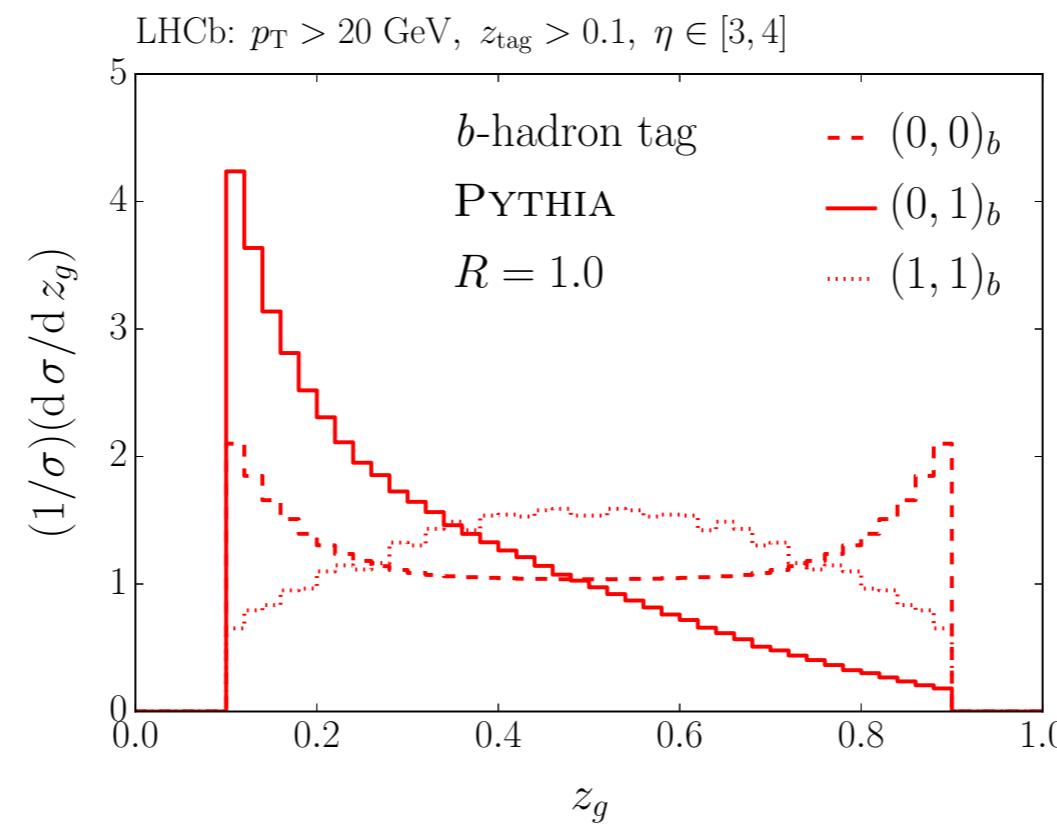
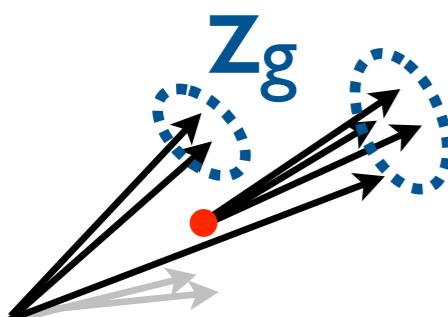
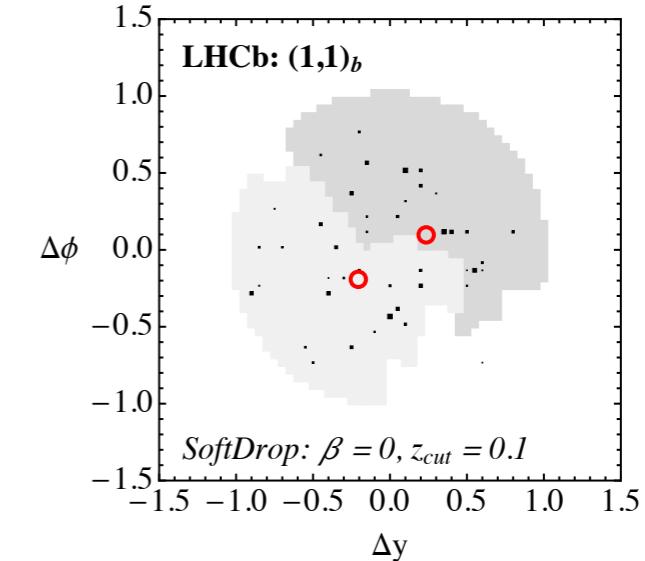
$g \rightarrow gg$



$b \rightarrow bg$



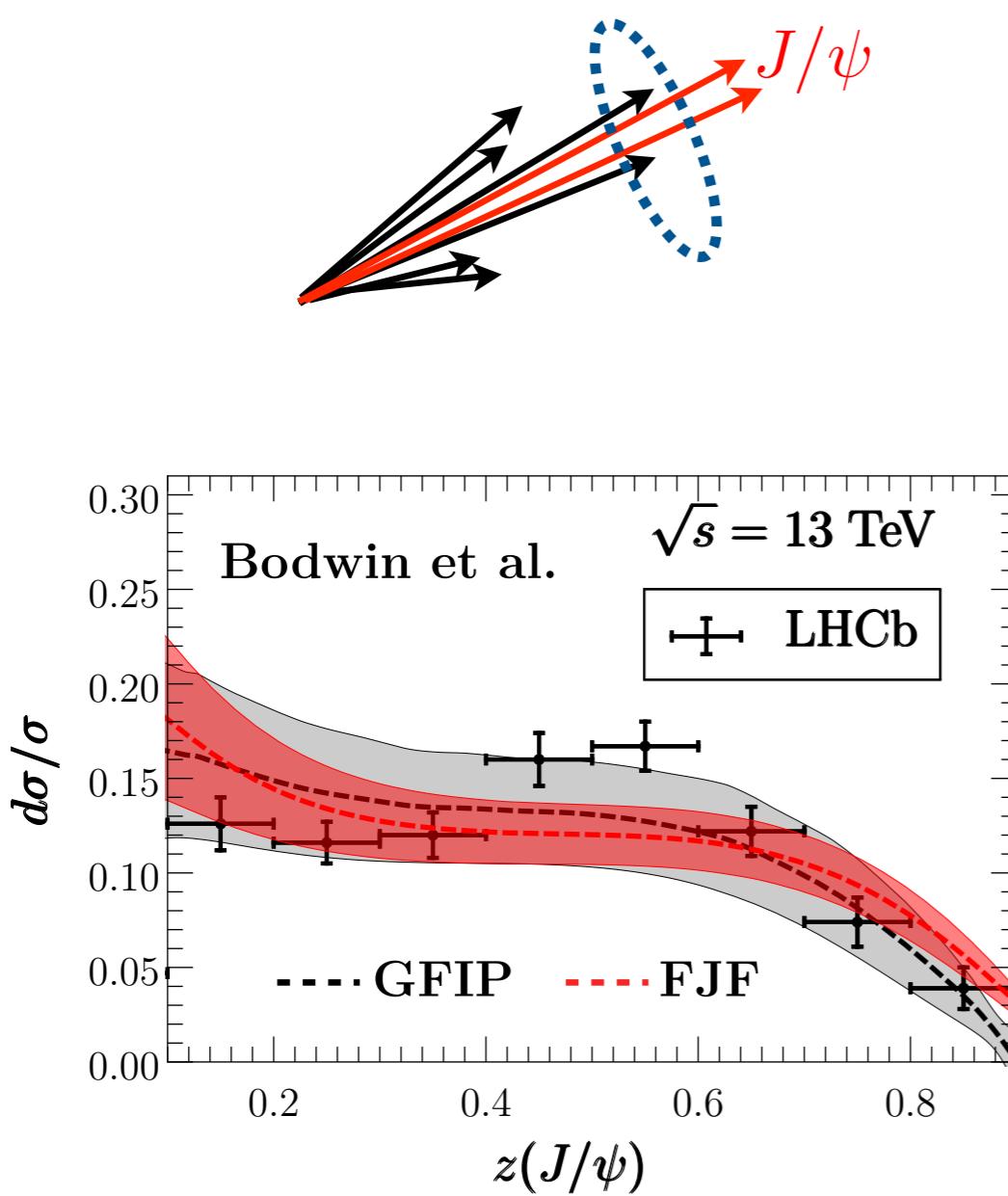
$g \rightarrow b\bar{b}$



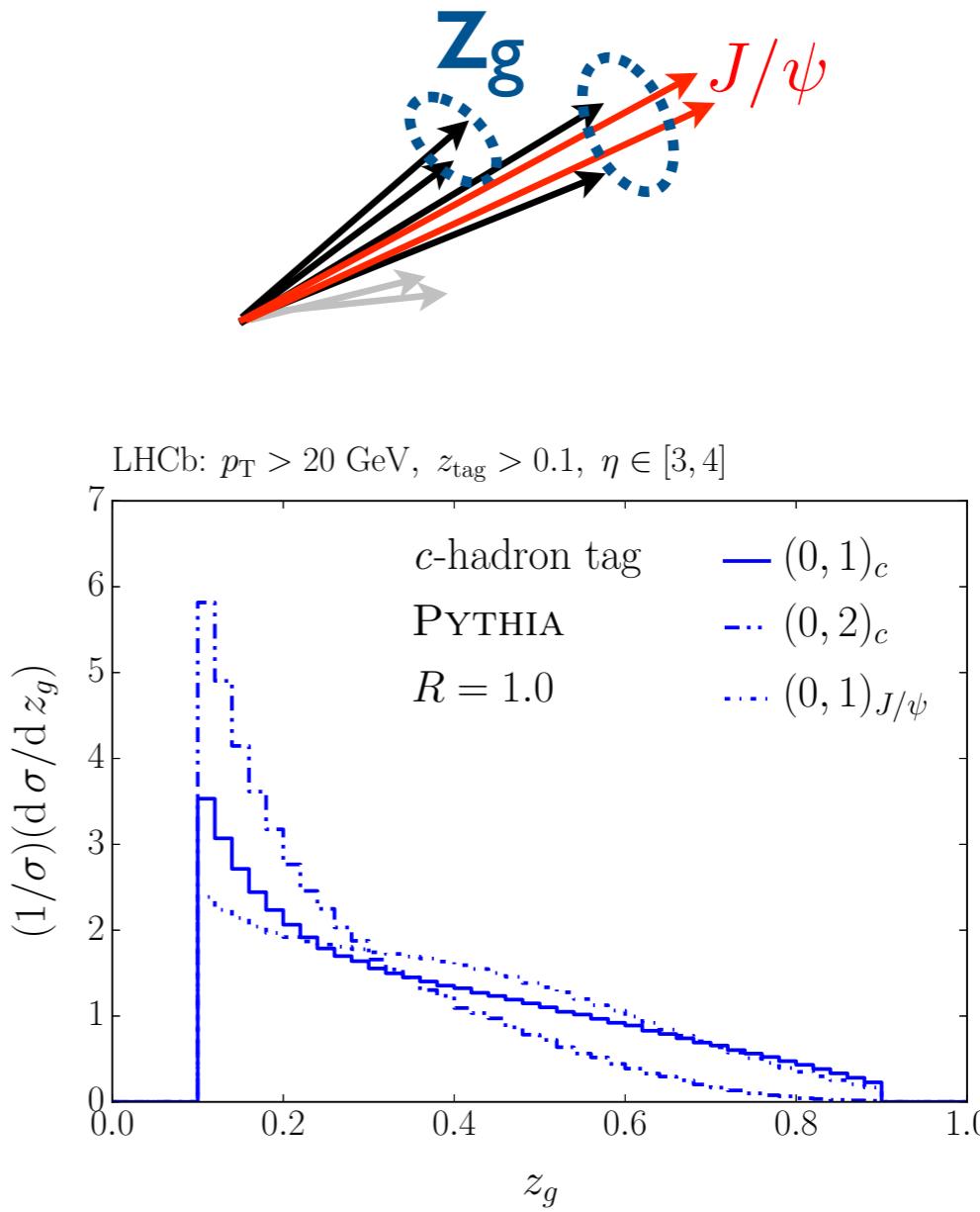
[Ilten, Rodd, JDT, Williams, I1702.02947]

Grooming to Explore QCD... & Onium Physics

Standard Fragmentation



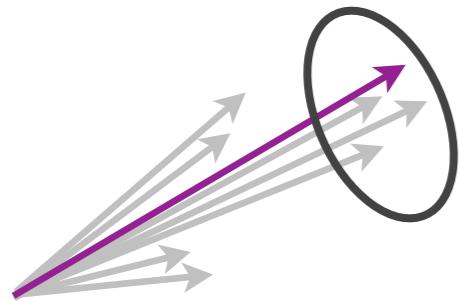
Tagged-Subjet Fragmentation



[Bain, Dai, Leibovich, Makris, Mehen, 1702.05525; Ilten, Rodd, JDT, Williams, 1702.02947]

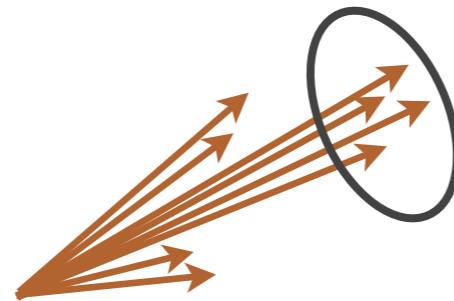
The Broader Lesson

Fragmentation Functions



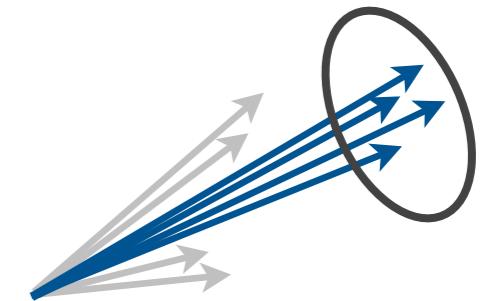
Single hadron

Classic Jet Shapes



All hadrons

Groomed Observables



Subset of hadrons

For another talk:

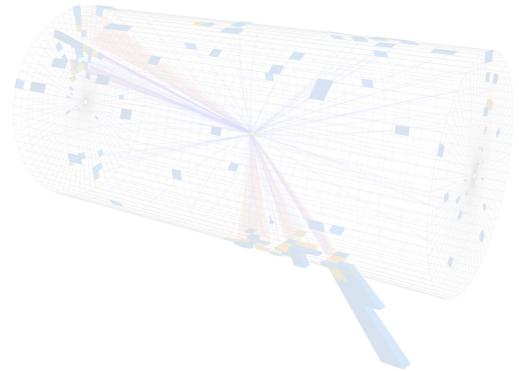
“Fractal Observables”

*Generalized fragmentation with
non-linear DGLAP evolution*

Examples: Jet charge, track fraction, p_T^D , $z \log z$, ...

[see also Waalewijn, I209.3019; Krohn, Lin, Schwartz, Waalewijn, I209.2421; Chang, Procura, JDT, Waalewijn, I303.6637, I306.6630; Larkoski, JDT, Waalewijn, I408.3122]

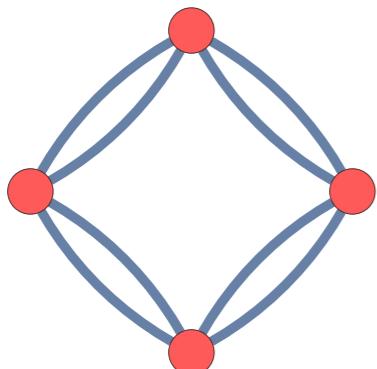
[Elder, Procura, JDT, Waalewijn, Zhou, I704.05456]



The Rise of Jet Substructure



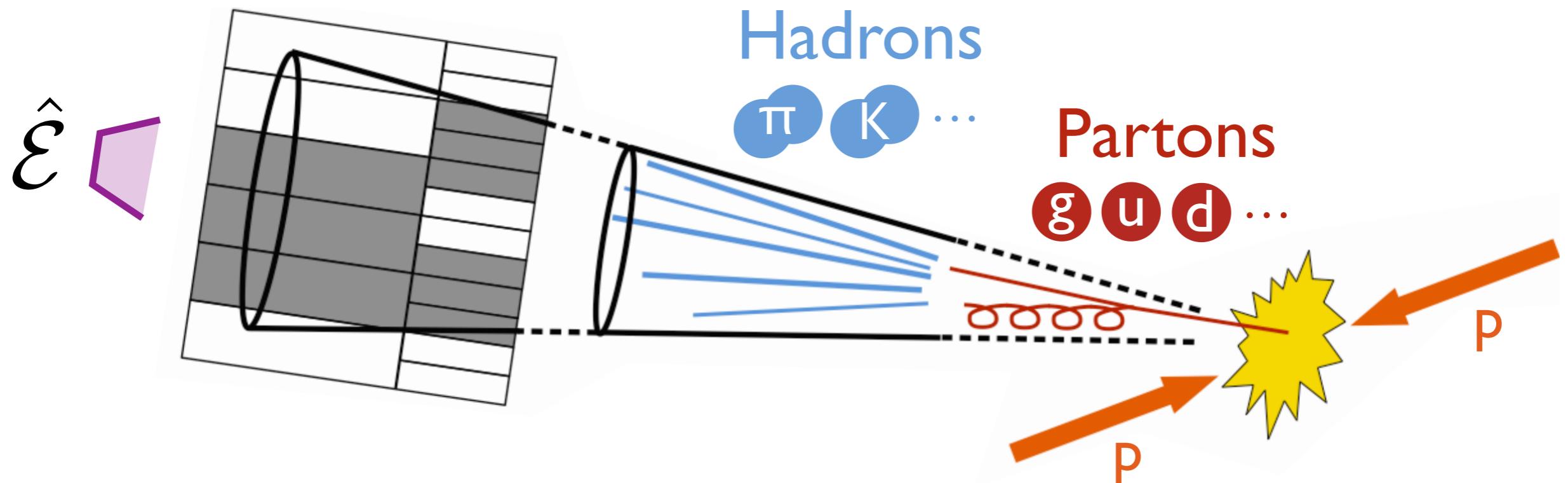
The Importance of First Principles



Towards a Systematic Expansion

Theory

Detection



theoretical
calculations
(energy flow)

reconstruction
 $\approx 1\text{-to-}1$ @ LHC
(e.g. particle flow)

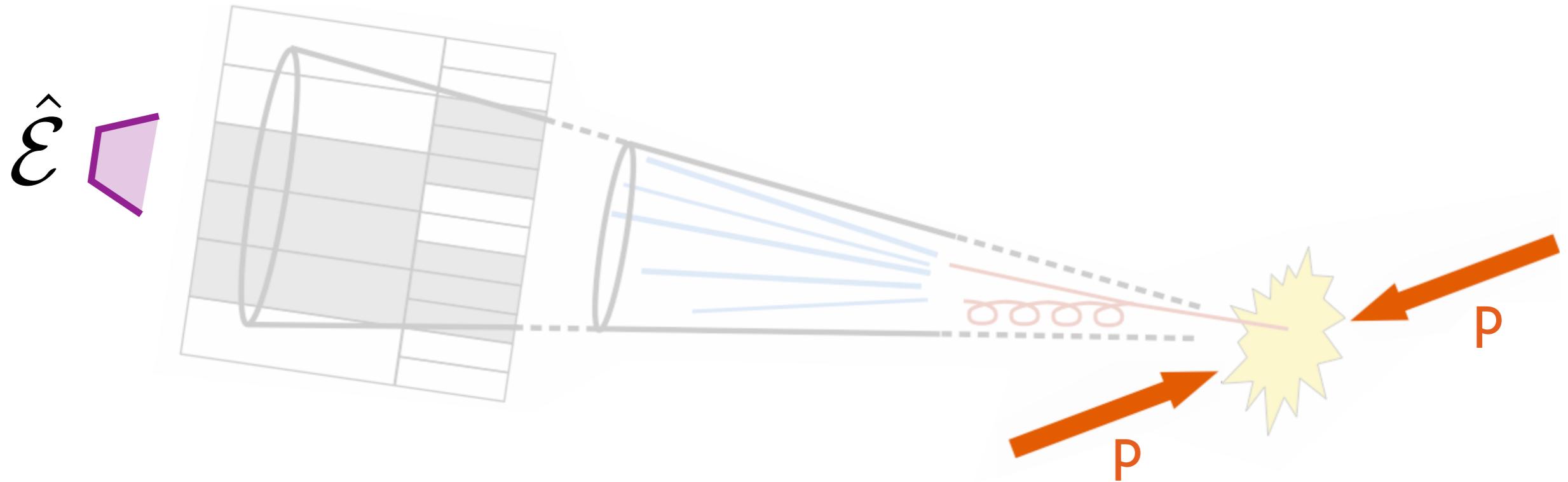
nonperturbative
confinement
(hadronization)

perturbative
gluonic radiation
(parton shower)

short-distance
collision
(hard scattering)

Layers of Jet Understanding

Back to Basics: What is a Measurement?



Stress-Energy
Flow Operator:

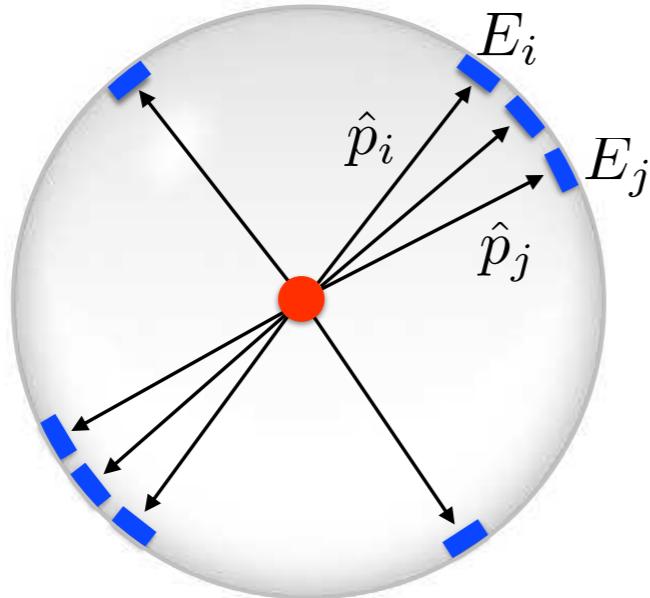
Also charge flow operators,
but not IRC safe

$$\hat{\mathcal{E}}(\theta, \phi, v) \simeq \lim_{t \rightarrow \infty} \hat{n}_i T^{0i}(t, vt\hat{n})$$

energy flowing to infinity
in a particular direction at a particular speed

[Sveshnikov, Tkachov, hep-ph/9512370; see also Mateu, Stewart, JDT, 1209.3781]

Back to Basics: What is a Measurement?



Energy Correlators:
Decomposition for any
IRC safe observable

$$F_N(\{p_i\}) = \sum_{i_1} \sum_{i_2} \dots \sum_{i_N} E_{i_1} E_{i_2} \dots E_{i_N} f_N(\hat{p}_{i_1}, \hat{p}_{i_2}, \dots, \hat{p}_{i_N})$$

All N-tuples

N Energies

Angular Weighting
(symmetric, ~~vanishes for $Q_{ij} \rightarrow 0$~~)
fake news

Completely general, but useful for jets?

[Tkachov, hep-ph/9601308]

1-point Correlator

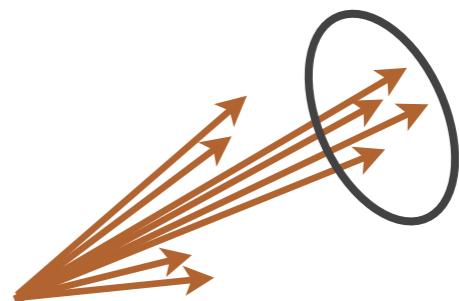
The most basic jet observable:

$$p_T^{\text{jet}} \simeq \sum_i p_{Ti}$$

Using dimensionless quantities

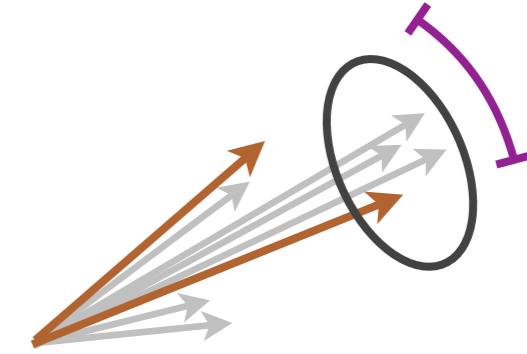
$$z_i \equiv \frac{p_{Ti}}{\sum_j p_{Tj}} \quad \theta_{ij} \equiv \Delta R_{ij}$$

1-point: $e_1 = \sum_i z_i = 1$

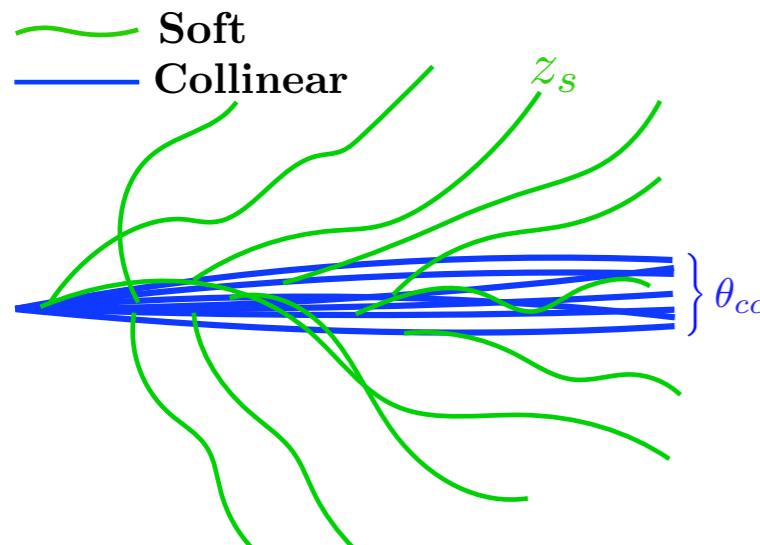


2-point Correlators

$$\text{2-point: } e_2^{(\beta)} = \sum_{i < j} z_i z_j \theta_{ij}^\beta$$



Similar information to jet mass



soft
dominated

equal
weight

collinear
dominated

$\beta = 2 \approx \text{thrust}$

a.k.a. m^2/p_T^2

$\beta = 1 \approx \text{width}$

a.k.a. broadening, girth

$\beta = 0.5 \approx \text{"Les Houches Angularity"}$

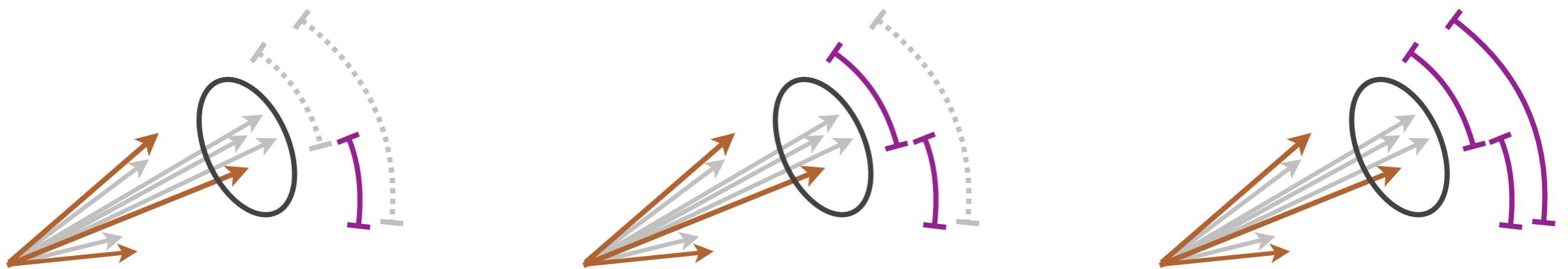
[see also Berger, Kucs, Sterman, hep-ph/0303051; Ellis, Vermilion, Walsh, Hornig, Lee, 1001.0014;
Larkoski, Salam, JDT, 1305.0007; Larkoski, Neill, JDT, 1401.2158; Larkoski, JDT, Waalewijn, 1408.3122;
Soyez, JDT, Freytsis, Gras, Kar, Lönnblad, Plätzer, Siódak, Skands, Soper, 1605.04692]

3-point Correlators

$${}_1e_3^{(\beta)} = \sum_{i < j < k} z_i z_j z_k \min\{\theta_{ij}, \theta_{jk}, \theta_{ki}\}^\beta$$

3-point: ${}_2e_3^{(\beta)} = \sum_{i < j < k} z_i z_j z_k \min\{\theta_{ij}\theta_{jk}, \theta_{jk}\theta_{ki}, \theta_{ki}\theta_{ij}\}^\beta$

$${}_3e_3^{(\beta)} = \sum_{i < j < k} z_i z_j z_k (\theta_{ij}\theta_{jk}\theta_{ki})^\beta$$

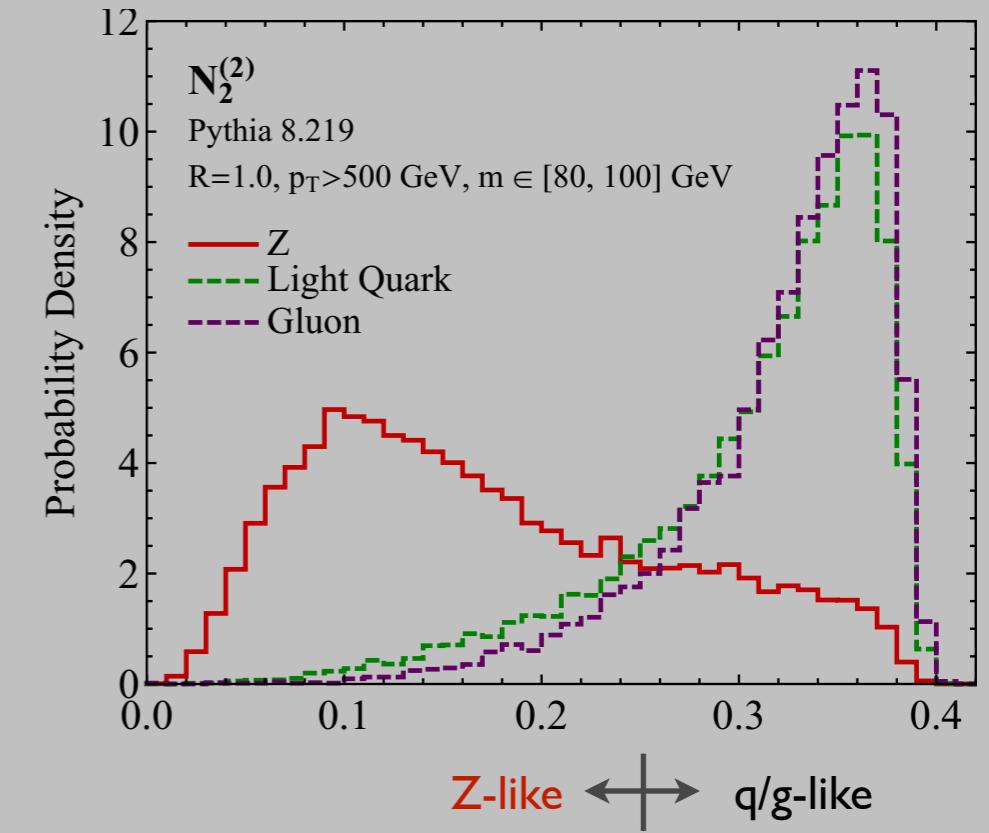
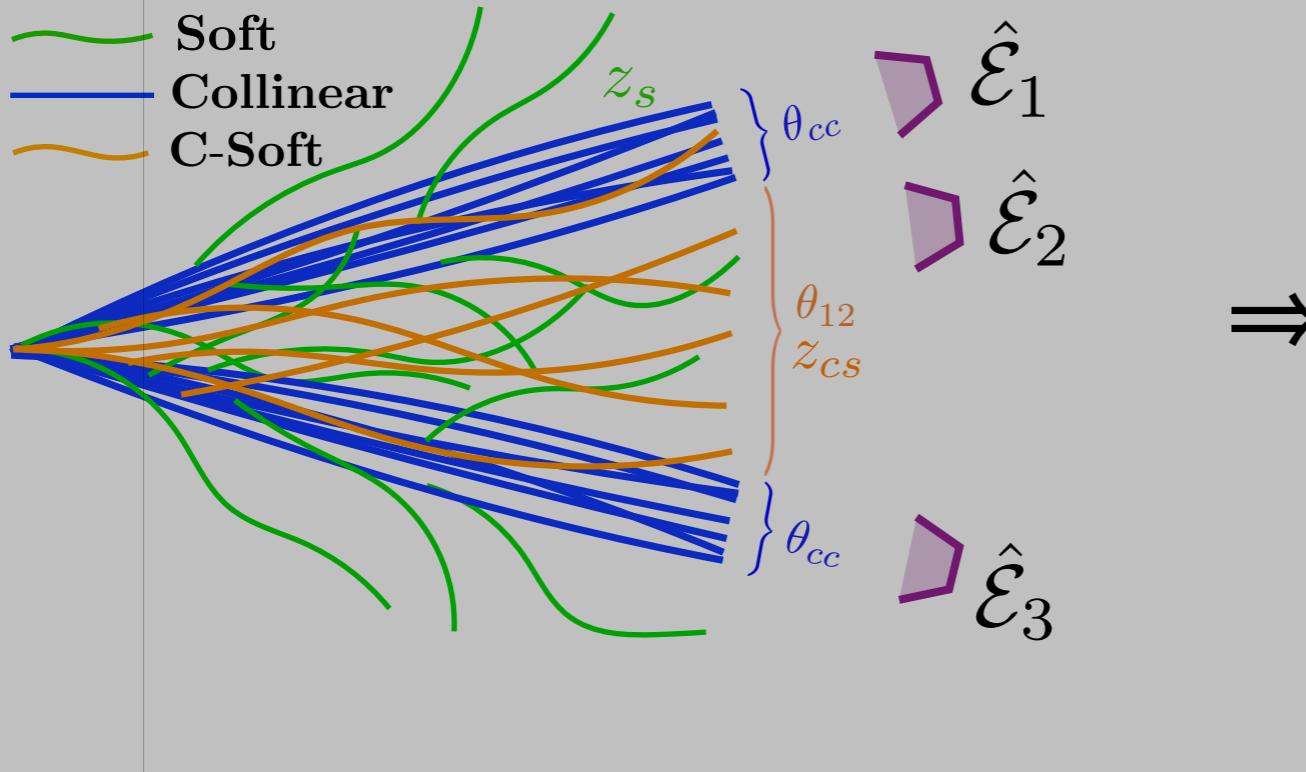


Probe of hierarchical jet substructure

[Moult, Necib, JDT, 1609.07483; see also Larkoski, Moult, Neill, 1409.6298]

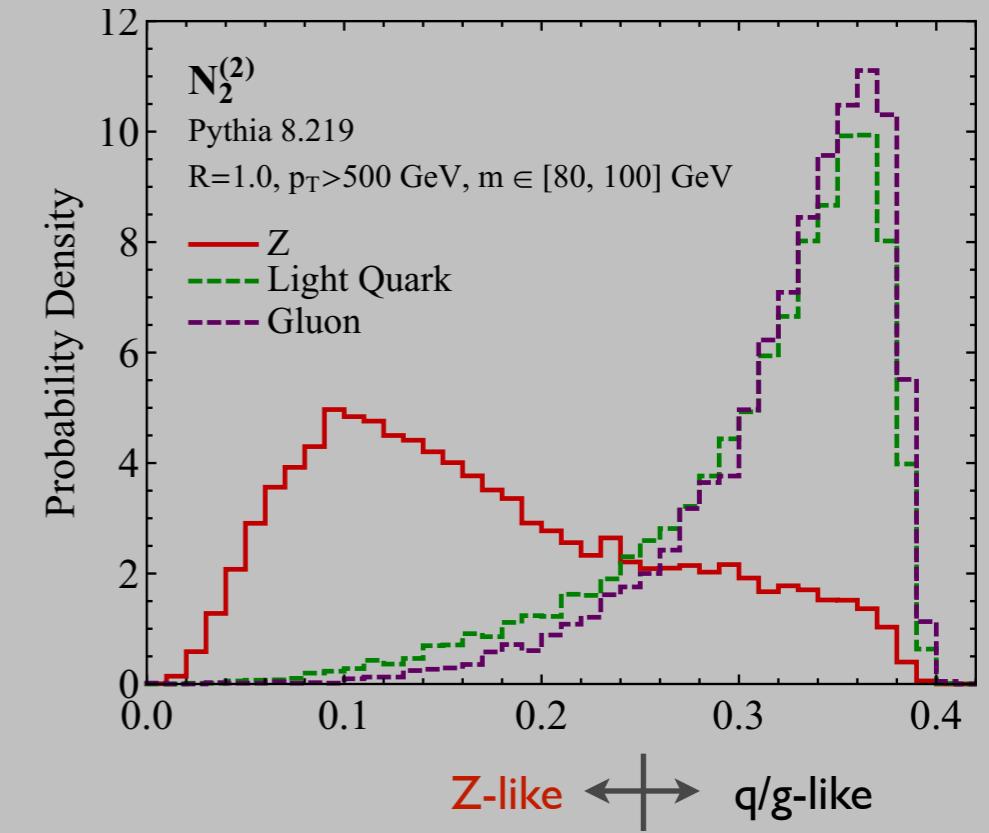
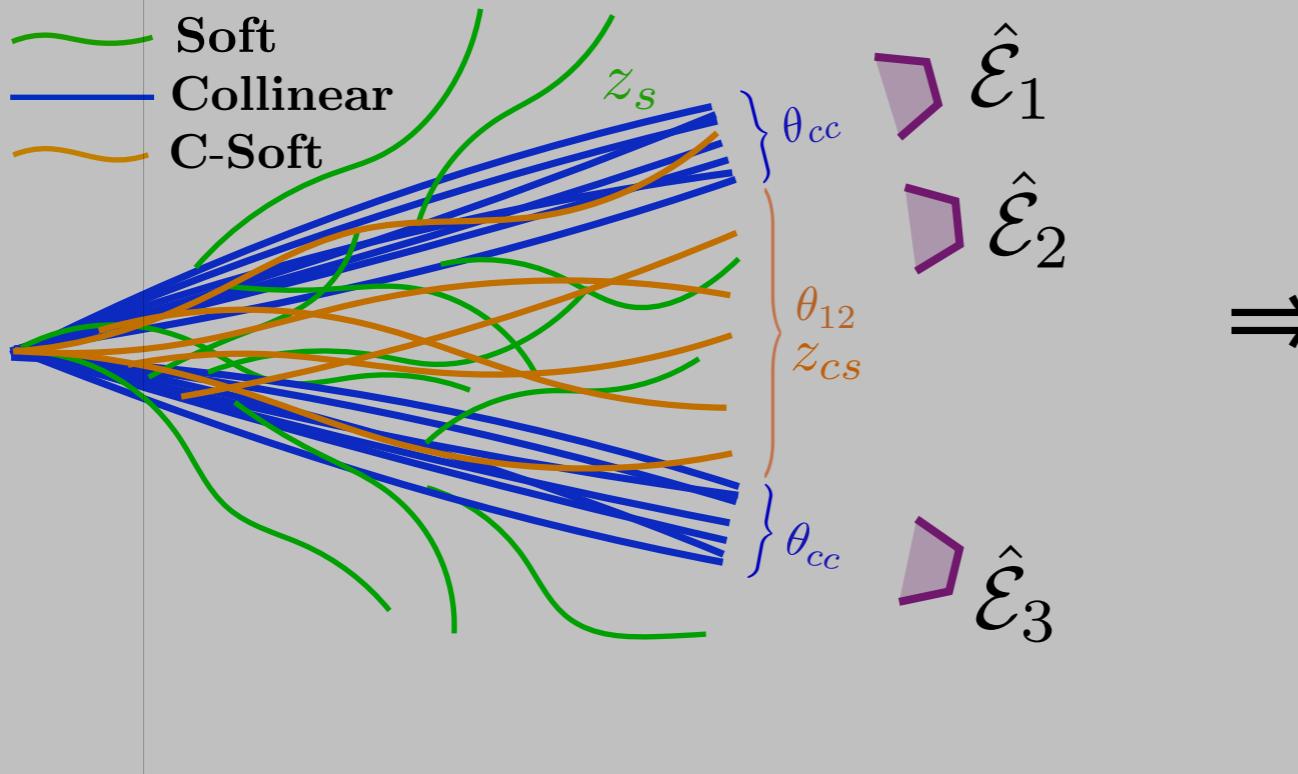
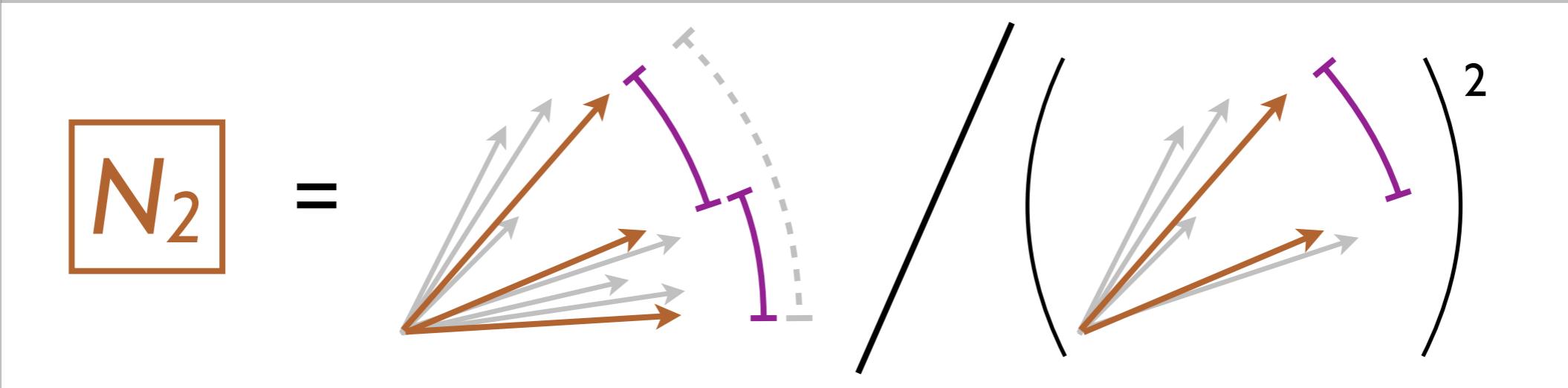
2-prong Discrimination with Energy Correlators

$$N_2 = \frac{\sum_{i < j < k} p_{Ti} p_{Tj} p_{Tk} \min \left\{ (R_{ij} R_{jk})^2, (R_{jk} R_{ki})^2, (R_{ki} R_{ij})^2 \right\}}{\left(\sum_{i < j} p_{Ti} p_{Tj} R_{ij}^2 \right)^2 / \sum_i p_{Ti}}$$



[Moult, Necib, JDT, 1609.07483; based on Larkoski, Salam, JDT, 1305.0007]

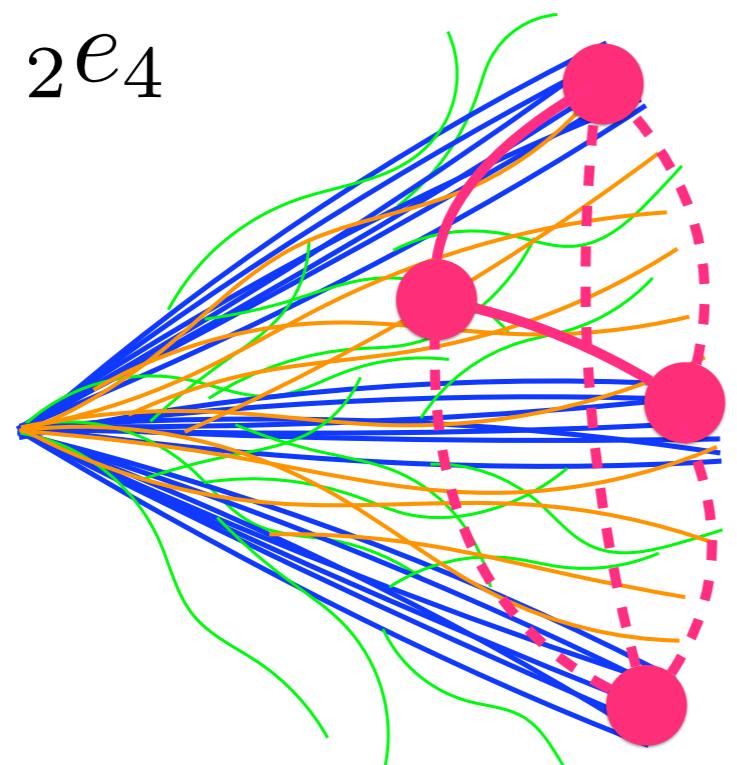
2-prong Discrimination with Energy Correlators



[Moult, Necib, JDT, 1609.07483; based on Larkoski, Salam, JDT, 1305.0007]

N-point Correlators

$$v e_n^{(\beta)} = \sum_{\text{all } n\text{-tuples}} (n \text{ energies}) (v \text{ smallest angles})^\beta$$



Systematic jet dissection (?)

$$n = 2, 3, 4, \dots$$

$$v = 1, 2, 3, \dots, n \text{ choose } 2$$

$$\beta = \dots, 0.5, 1, 2, \dots$$

collinear
dominated

soft
dominated

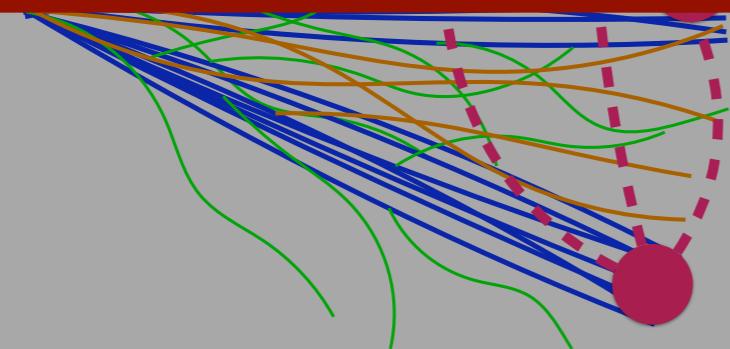
[Moult, Necib, JDT, 1609.07483]

N-point Correlators

$$v e_n^{(\beta)} = \sum_{\text{all } n\text{-tuples}} (n \text{ energies}) (\text{ } v \text{ smallest angles})^\beta$$

Not systematic enough!

Preliminary work with Patrick Komiske & Eric Metodiev



$v = 1, 2, 3, \dots, n$ CHOOSE \angle

$\beta = \dots, 0.5, 1, 2, \dots$

collinear
dominated

soft
dominated

[Moult, Necib, JDT, 1609.07483]

Introducing the Energy Flow Polynomials

Multigraph

$$\text{EFP}_G = \sum_{i_1=1}^M \cdots \sum_{i_N=1}^M z_{i_1} \cdots z_{i_N} \prod_{(k,\ell) \in G} \theta_{i_k i_\ell}$$

All N-tuples

N Energies

Polynomial in
Pairwise Angles

e.g.

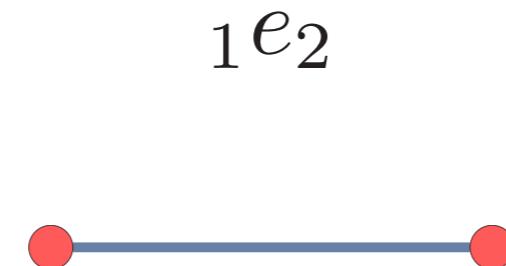
$$= \sum_{ijkl} z_i z_j z_k z_l \theta_{ij} \theta_{jk} \theta_{jl}^2 \theta_{kl}$$

A Linear Basis for Jet Substructure (!)

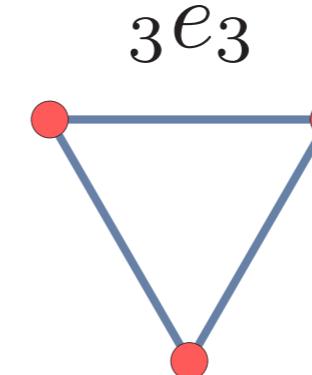
[Komiske, Metodiev, JDT, in progress]

Down the Rabbit Hole

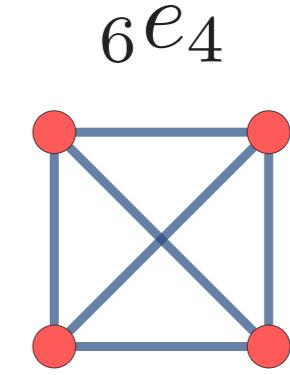
Known
Structures:



mass, width, LHA

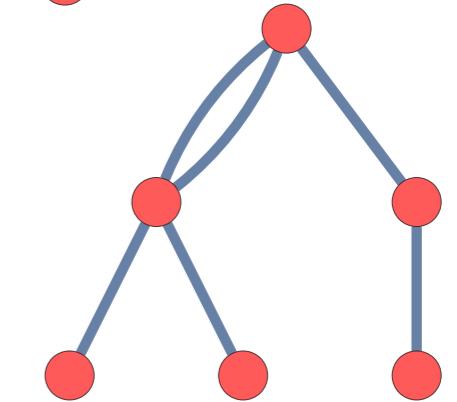
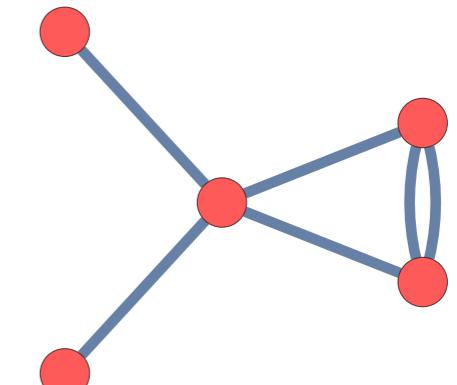
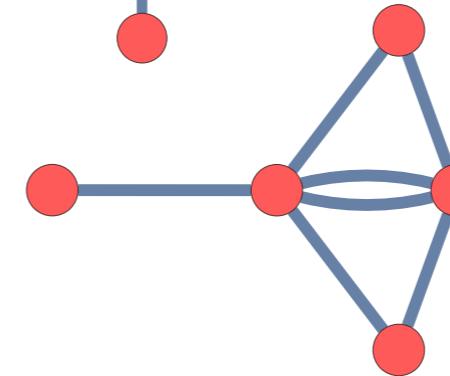
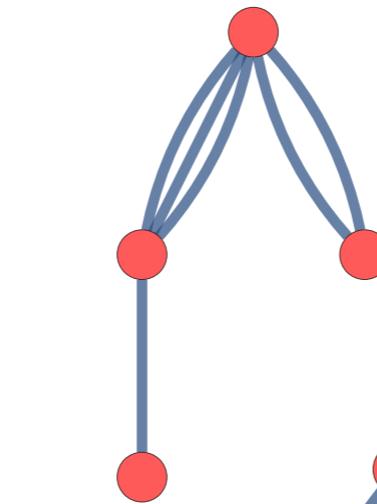
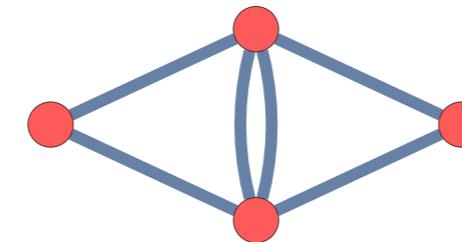
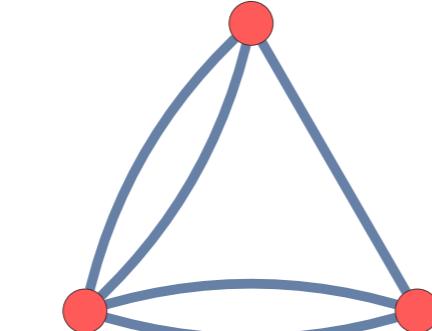


used in D_2

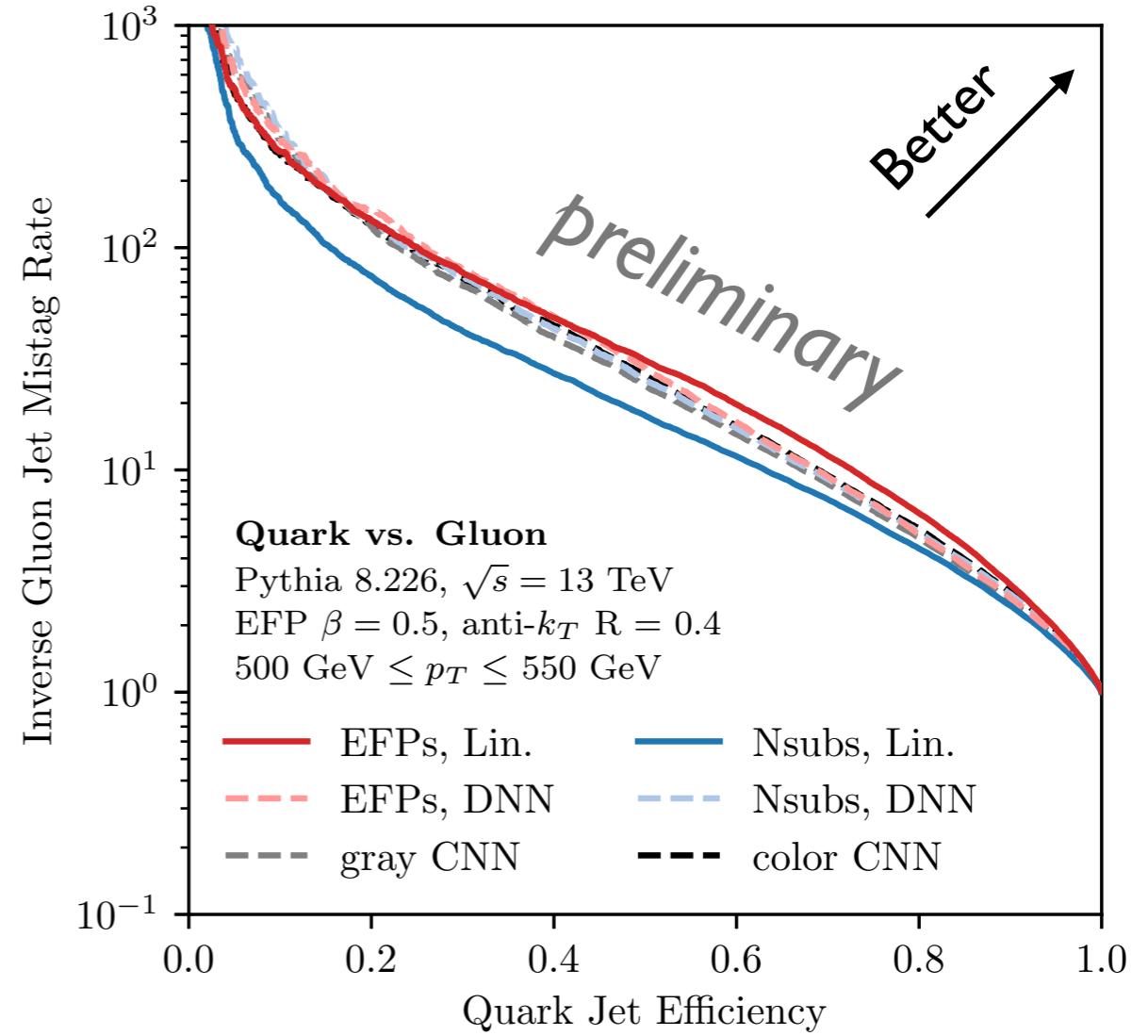
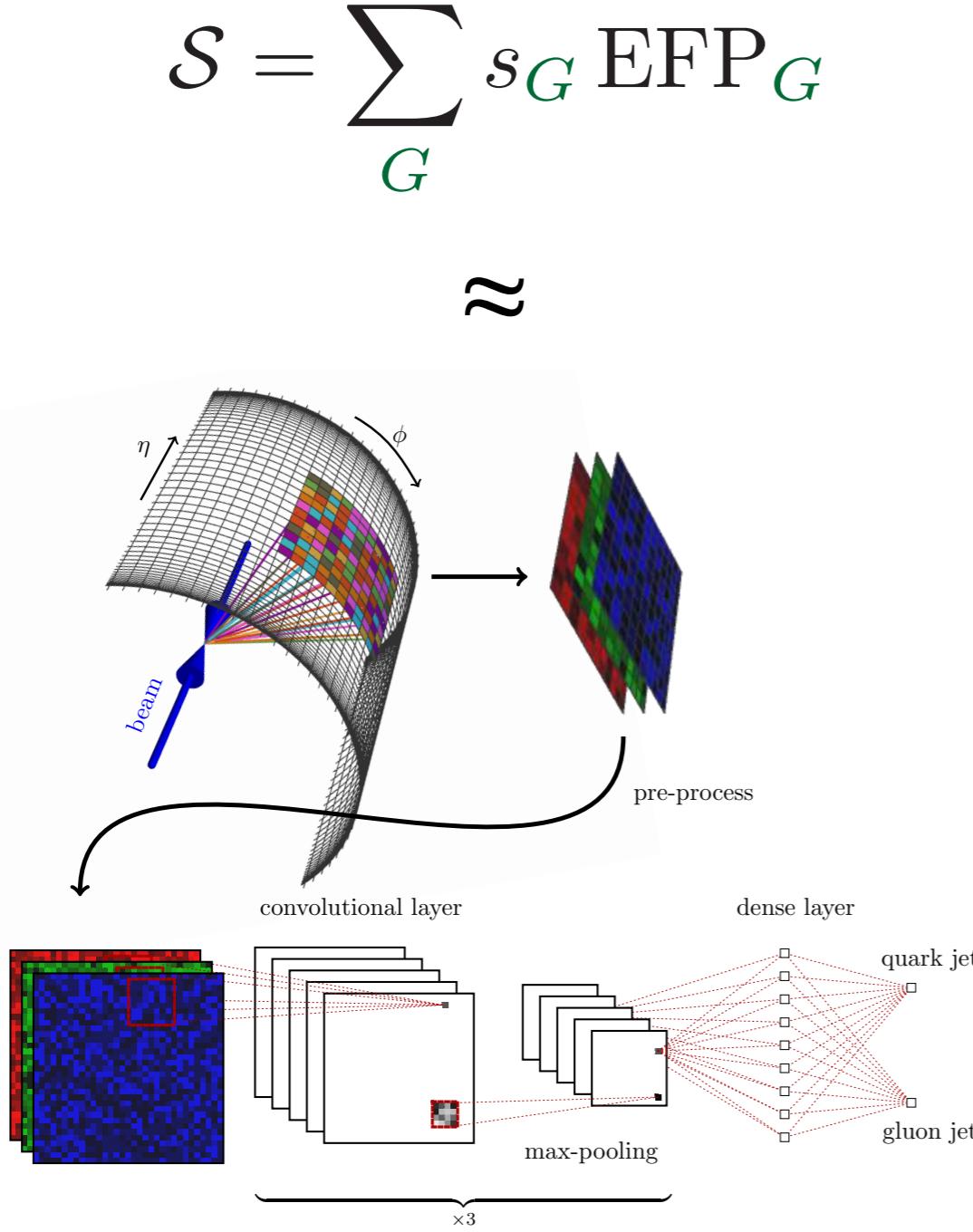


used in C_3

No Idea:



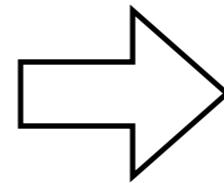
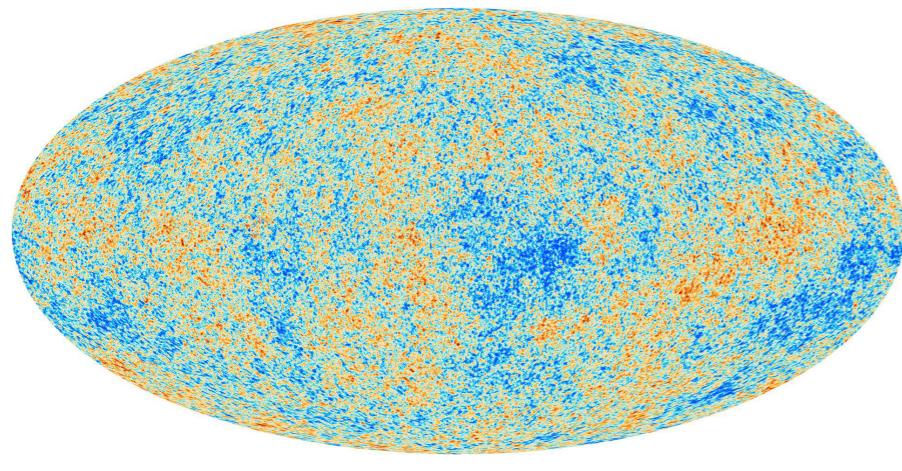
Deep Thinking meets Deep Learning



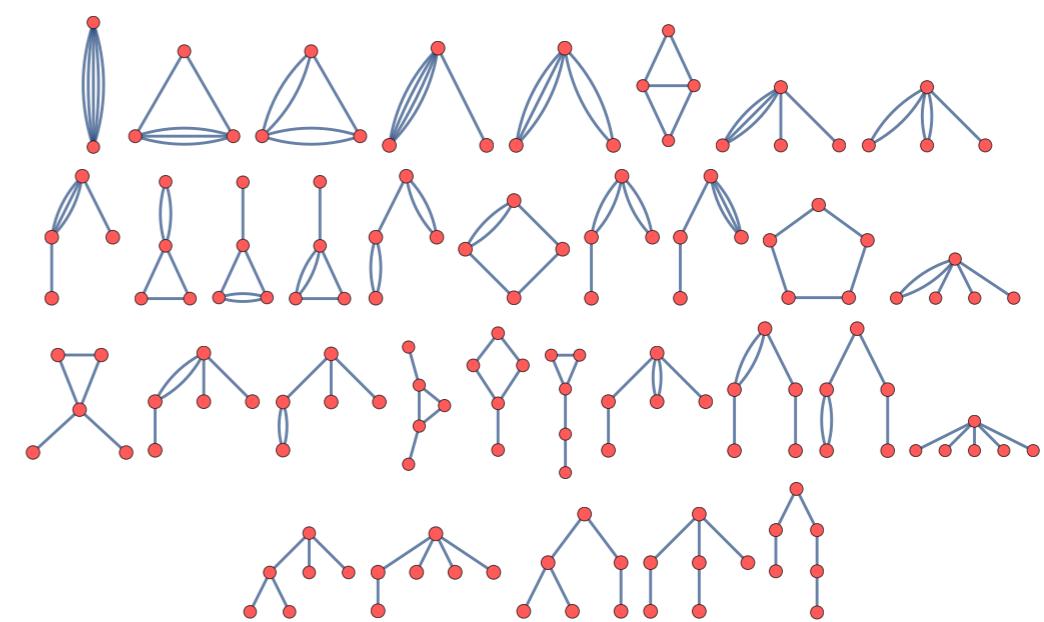
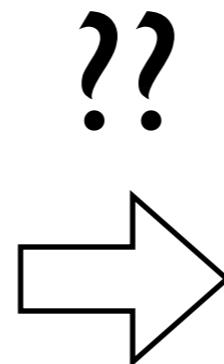
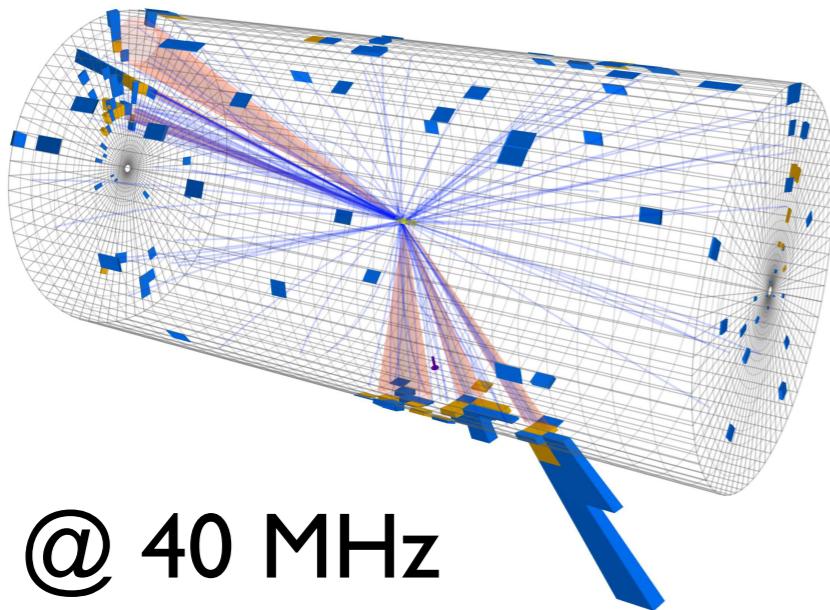
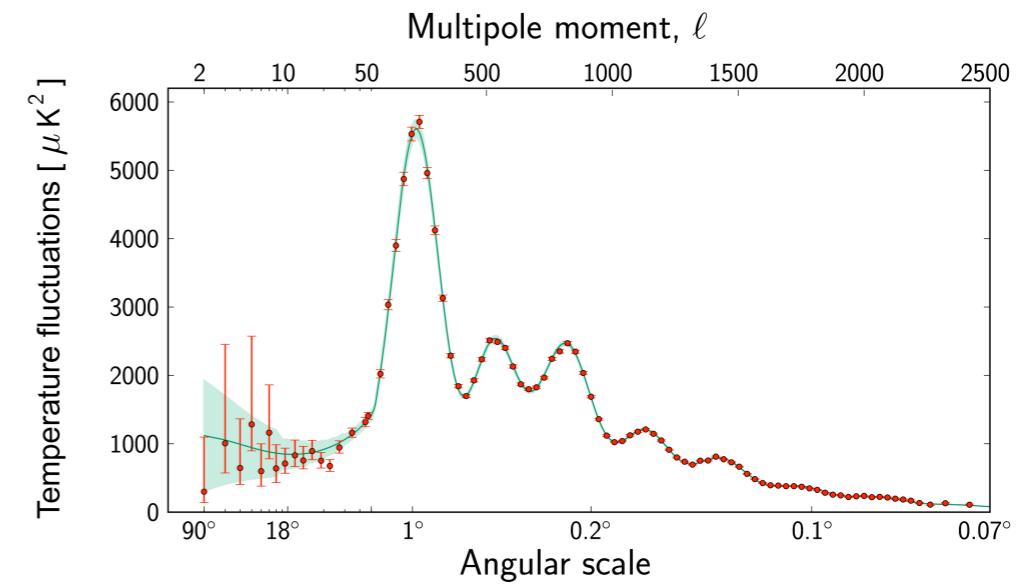
[Komiske, Metodiev, JDT, in progress; Komiske, Metodiev, Schwartz, 1612.01551]

The Missing Step

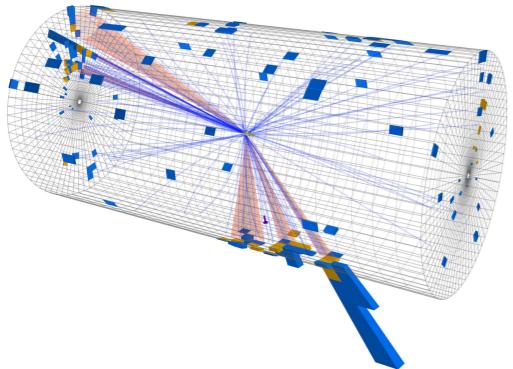
Position Space



Moment Space

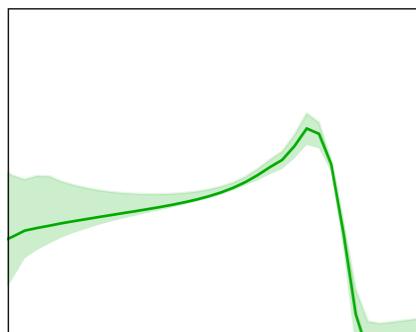


Summary



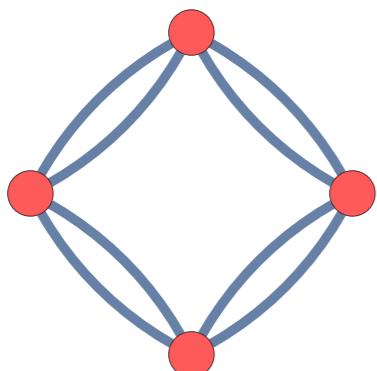
The Rise of Jet Substructure

From hadron-level jets to parton-level classification



The Importance of First Principles

QCD calculations motivate jet dissection strategies



Towards a Systematic Expansion

Energy flow observables as a basis for jet substructure