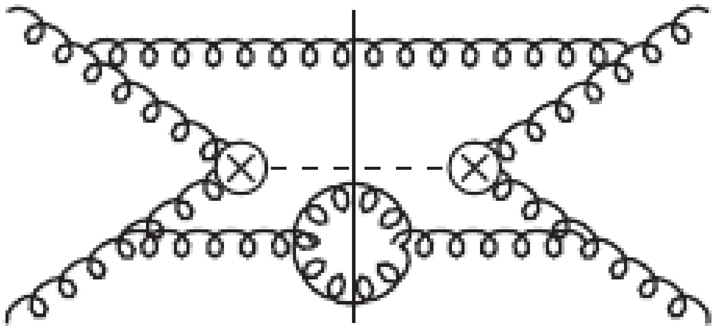
Aspects of Jets from First Principles

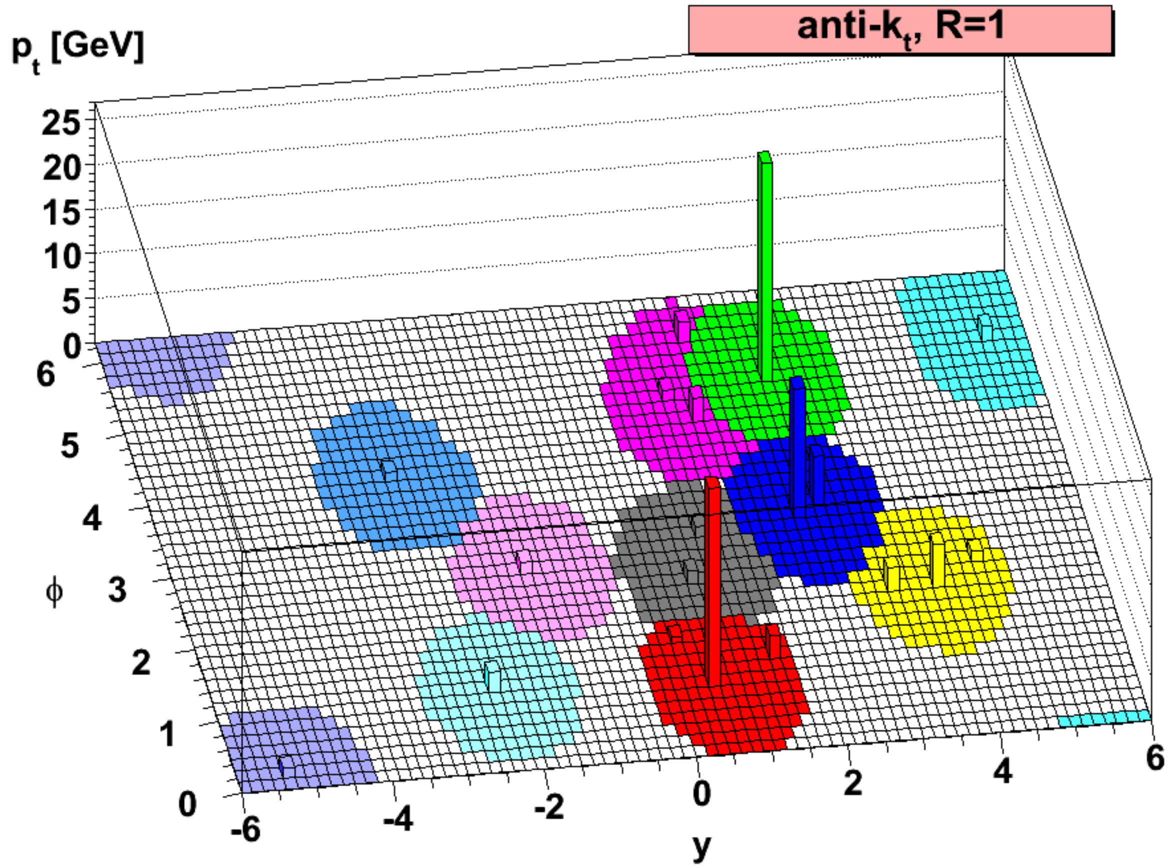
Jesse Thaler

Jets @ LHC, ICTS-TIFR, Bangalore — January 25, 2017

QCD Renaissance

Theory c. 2008–present





New Jet Algorithms

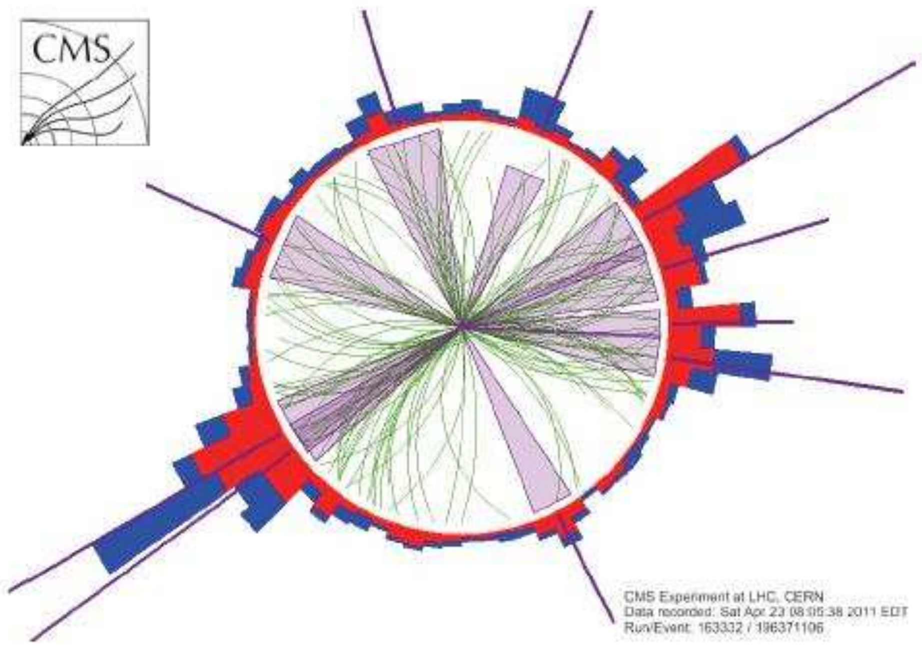
Jet Substructure

[Anti-k_T: Cacciari, Salam, Soyez, 2008; see also Delsart, 2006] [N^{3}LO: Anastasiou, Duhr, Dulat, Herzog, Mistlberger, 2015]
[BDRS: Butterworth, Davison, Rubin, Salam, 2008; see also Seymour, 1991, 1994]

What is a Jet?

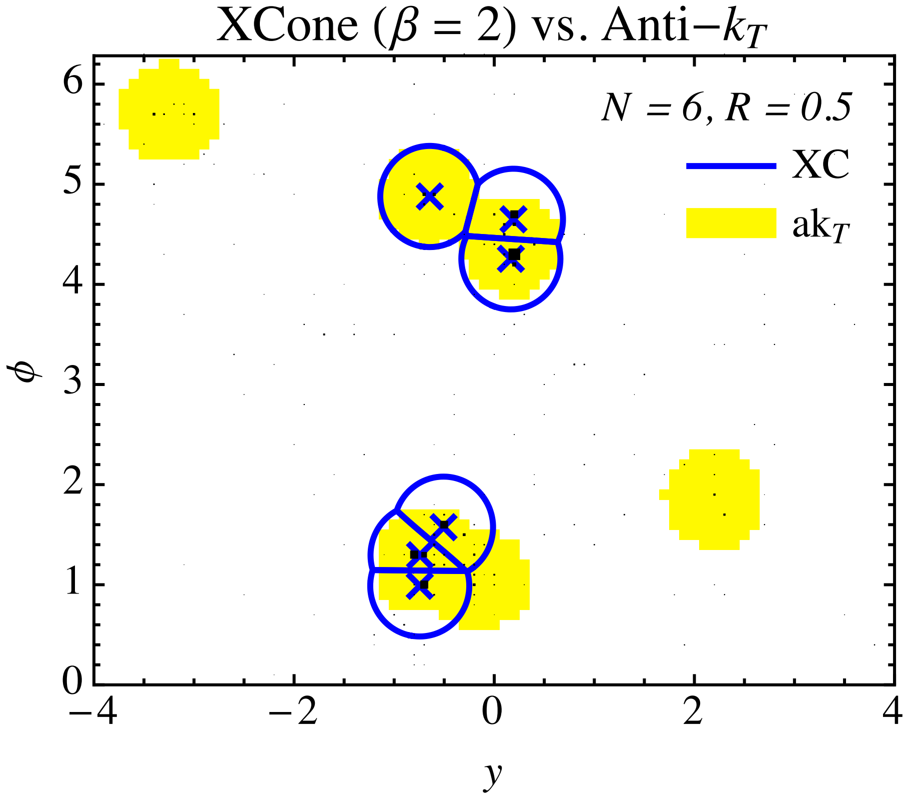
A physical phenomena:

Emergent feature of confining gauge theories

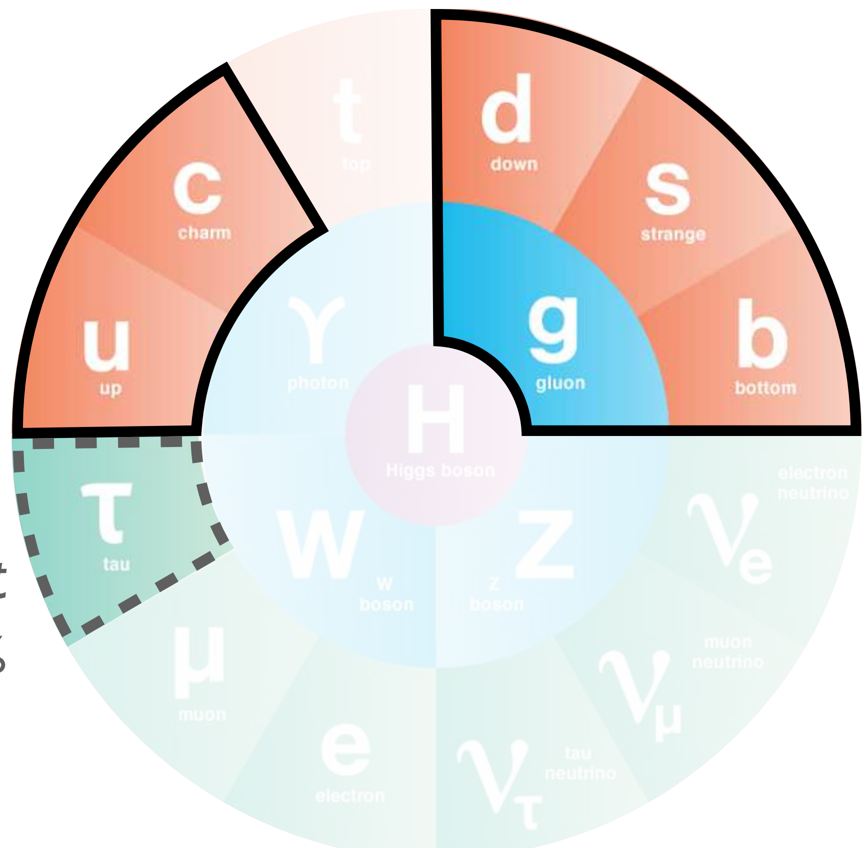


An analysis technique:

Method to interpret hadronic final states



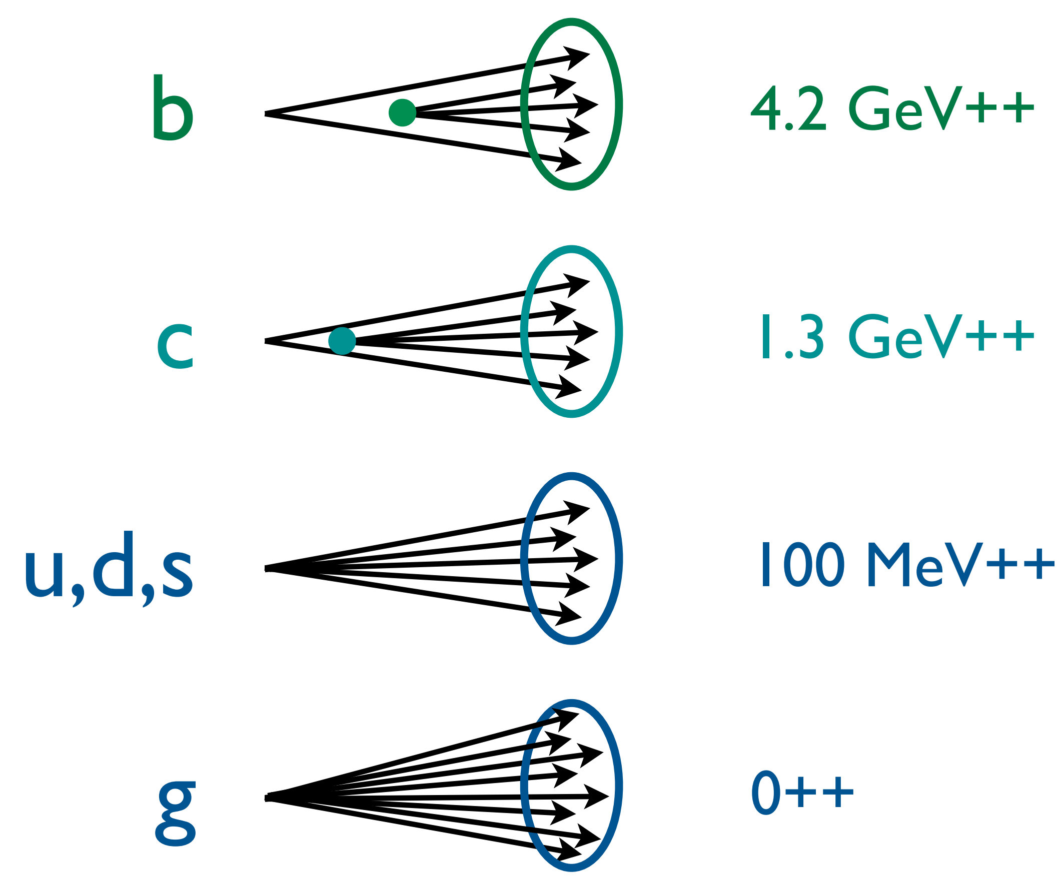
Freedom to use different analysis strategies for different physical questions

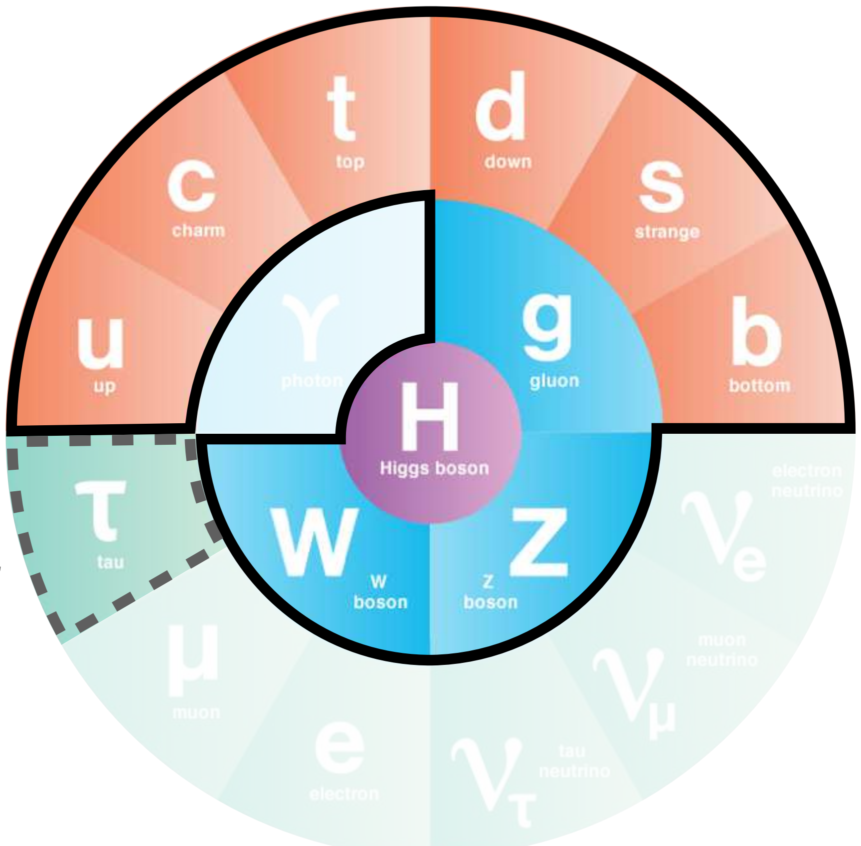


micro-jet
≈ 65%

Jets from the Standard Model

++ = plus gluonic radiation





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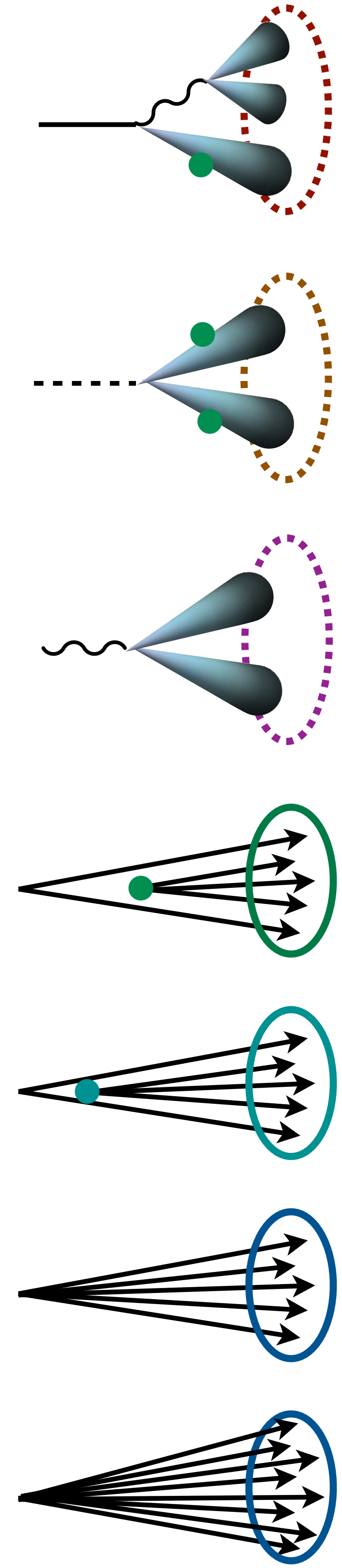


t ≈ 70% — 173 GeV++

H ≈ 60% — 125 GeV

W/Z ≈ 70% — 80/91 GeV

b — 4.2 GeV++

c — 1.3 GeV++

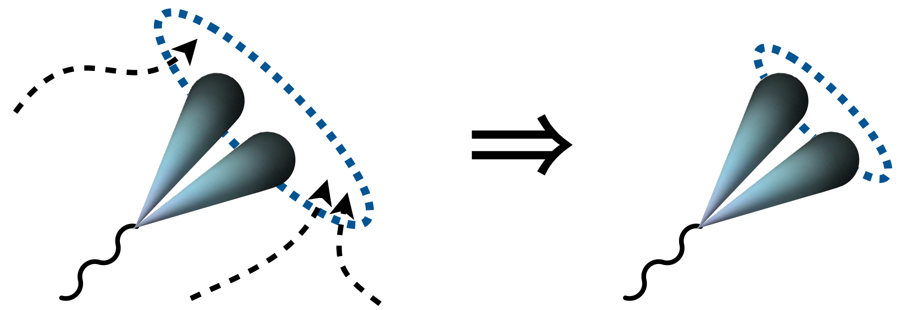
u,d,s — 100 MeV++

g — 0++

The Rise of Jet Substructure

Grooming:

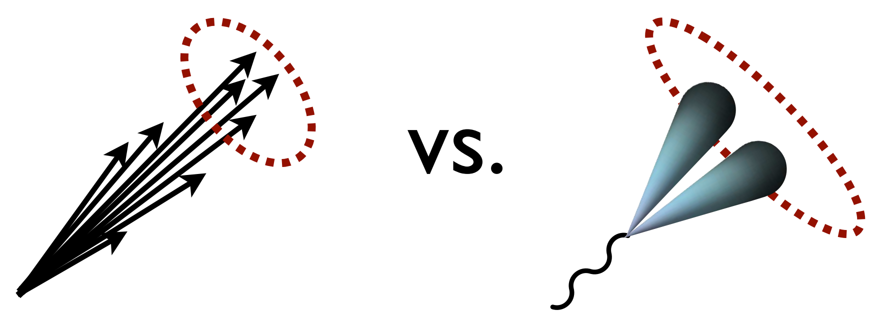
e.g. ISR/UE/pileup



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

Discrimination:

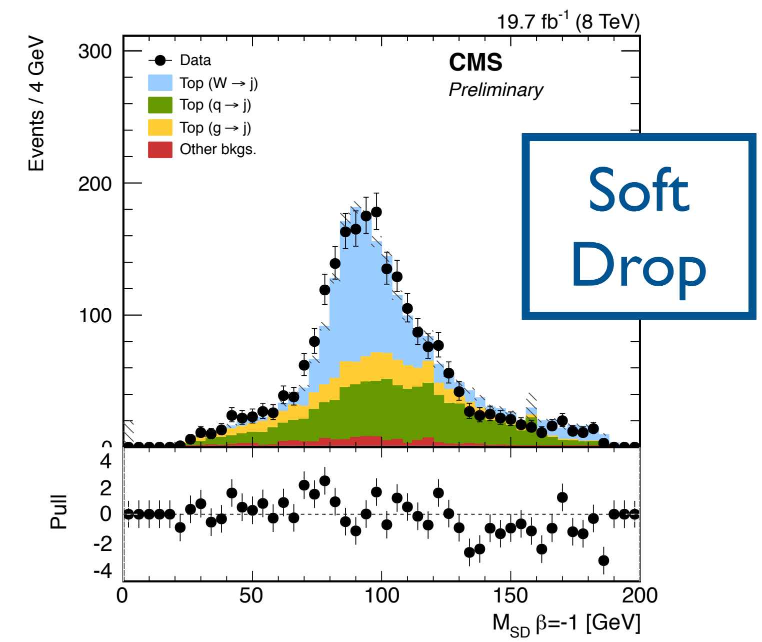
e.g. 1-prong vs. N-prong



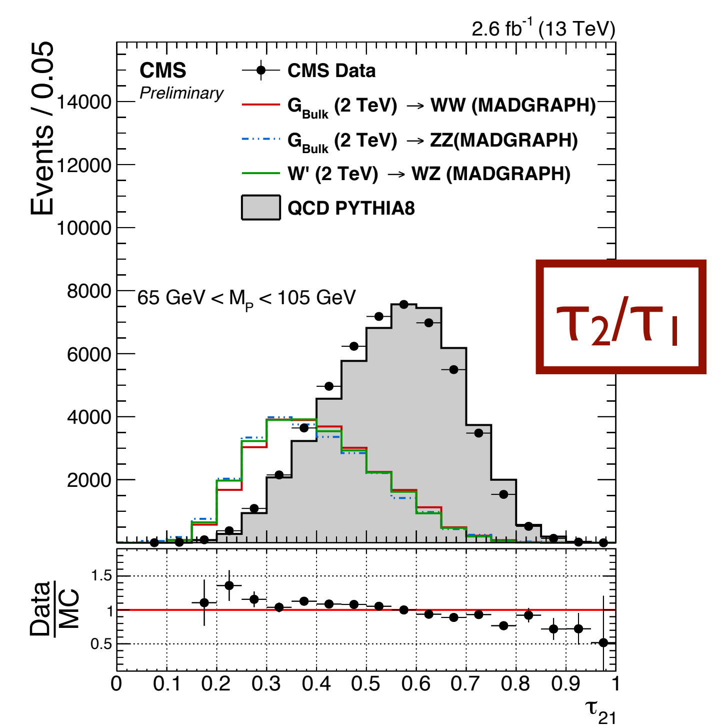
[p_T Balance, Y-splitter, Angularities, Planar Flow, N-subjettiness, Angular Structure Functions, Jet Charge, Jet Pull, Energy Correlation Functions, Dipolarity, p_T^D, Zernike Coefficients, LHA, Fox-Wolfram Moments, JHU/CMSTopTagger, HEPTopTagger, Template Method, Shower Deconstruction, Subjet Counting,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

W/Z-Tagging @ CMS

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

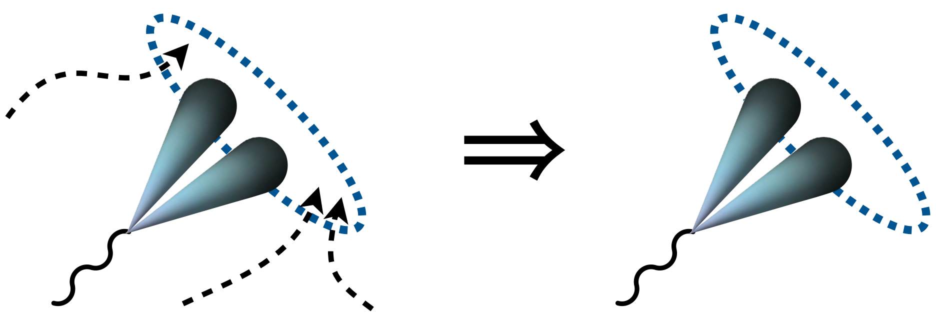


[using Larkoski, Marzani, Soyez, JDT, 1402.2657]



[using JDT, Van Tilburg, 1011.2268, 1108.2701]

W/Z Tagging in 2016

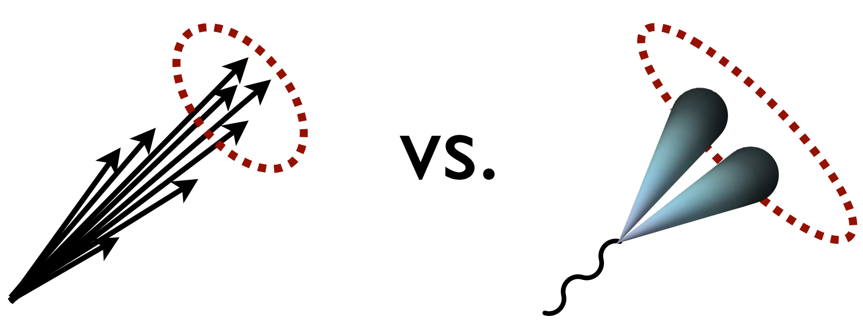


Soft Drop

[Larkoski, Marzani, Soyez, JDT, 2014;
see also Dasgupta, Fregoso, Marzani, Salam, 2013]

Trimming

[Krohn, JDT, Wang, 2009]



N-subjettiness

before grooming, after decorrelation

[JDT, Van Tilburg, 2010, 2011;
Dolen, Harris, Marzani, Rappoccio, Tran, 2016]

D_2

after grooming

[Larkoski, Moult, Neill, 2014;
based on Larkoski, Salam, JDT, 2013]

W/Z Tagging in 2016

Can we understand these choices from first principles QCD?

Can we construct improved algorithms for 2017?

CMS

ATLAS EXPERIMENT

Soft Drop

[Larkoski, Marzani, Soyez, JDT, 2014; see also Dasgupta, Fregoso, Marzani, Salam, 2013]

Trimming

[Krohn, JDT, Wang, 2009]

N-subjettiness

before grooming, after decorrelation

[JDT, Van Tilburg, 2010, 2011; Dolen, Harris, Marzani, Rappoccio, Tran, 2016]

D_2

after grooming

[Larkoski, Moult, Neill, 2014; based on Larkoski, Salam, JDT, 2013]

W/Z Tagging in 2016

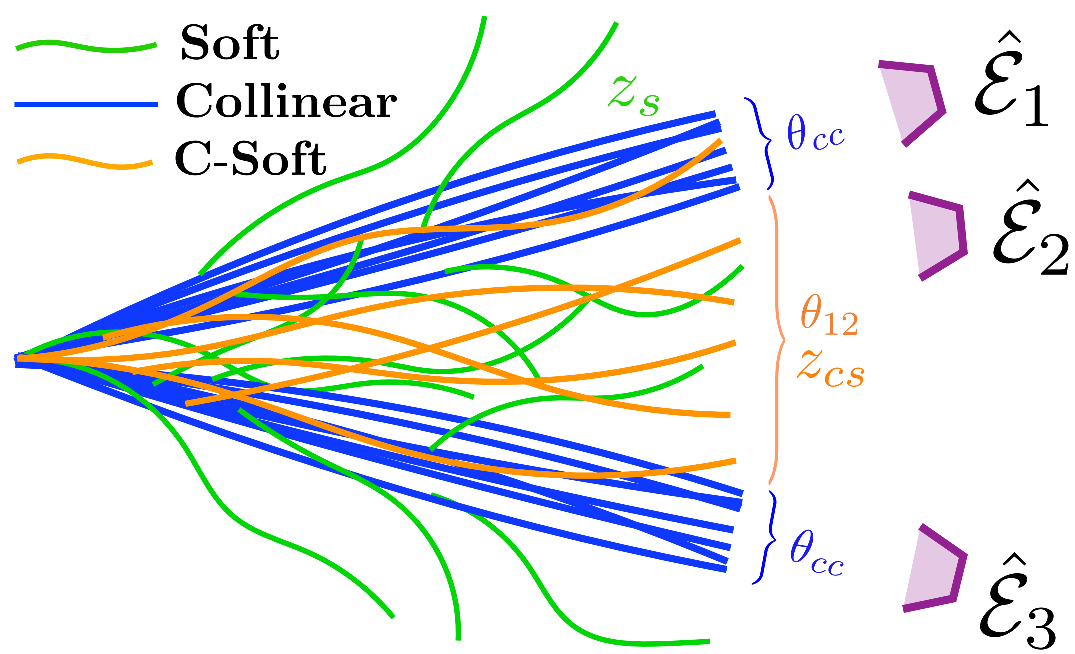
Can we understand these choices from first principles QCD?

Can we construct improved algorithms for 2017?

Yes! Key realization:
Discrimination different before/after grooming

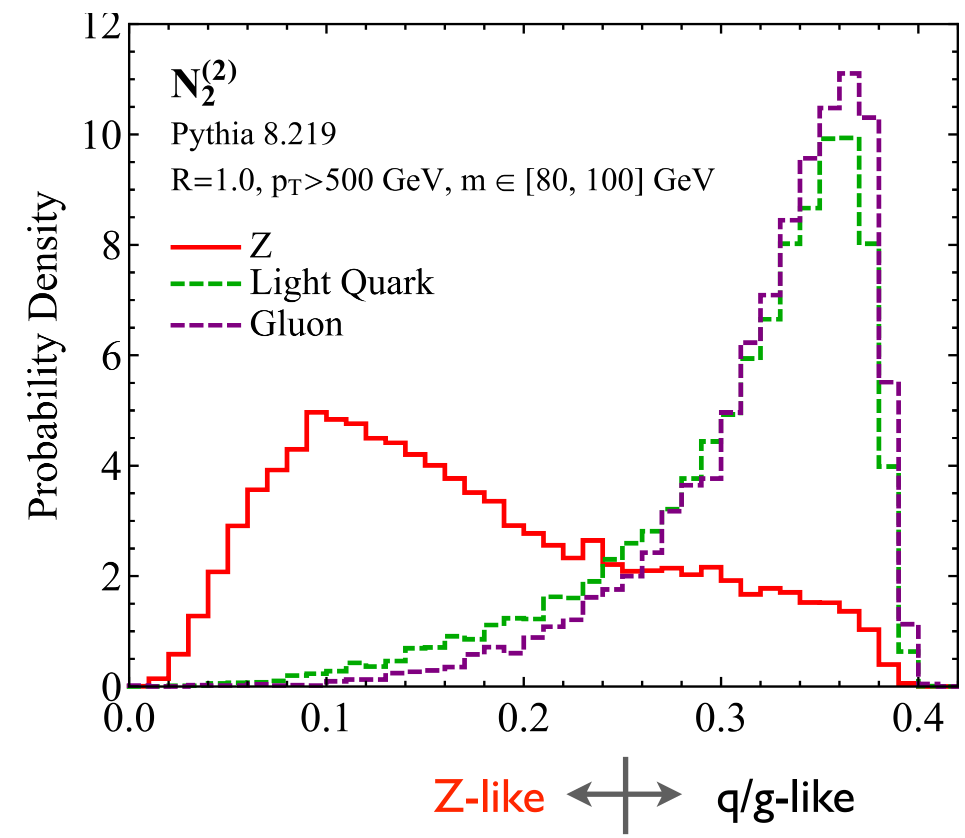
Yes!
Use power counting to design robust discriminants

Punchline: W/Z Tagging in 2017?



$\Rightarrow$

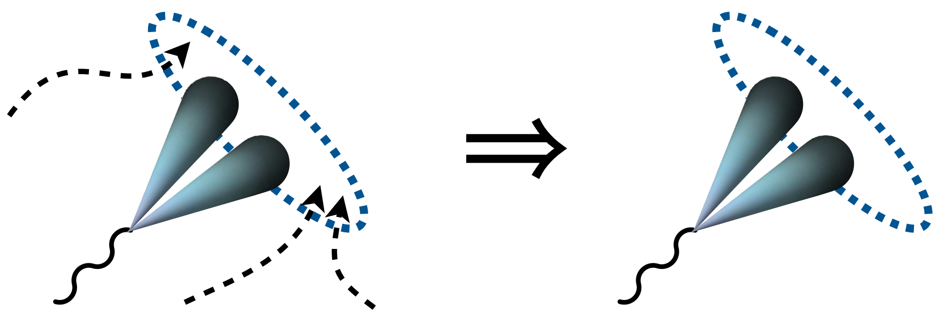
Stable & Performant



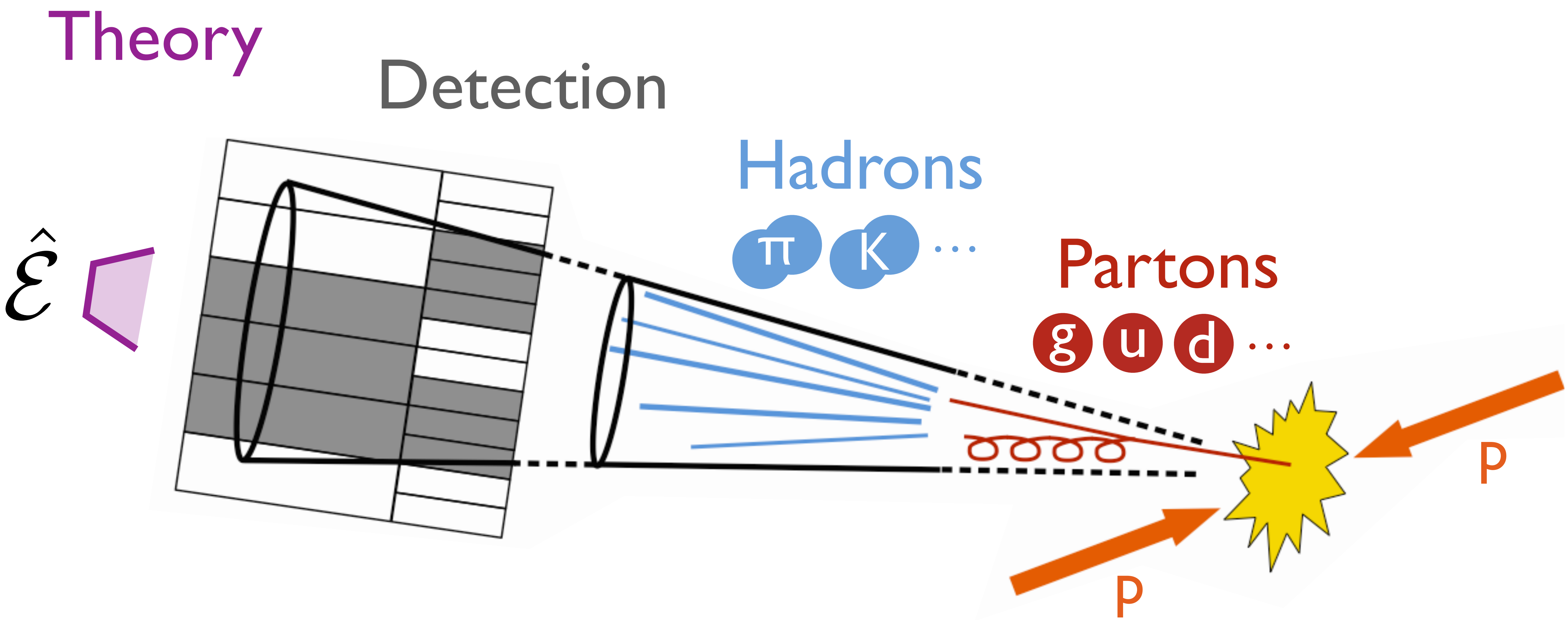
$$\boxed{N_2} = \frac{\sum_{i<j<k} p_{Ti}\, p_{Tj}\, p_{Tk} \min\left\{(R_{ij}R_{jk})^2, (R_{jk}R_{ki})^2, (R_{ki}R_{ij})^2\right\}}{\left(\sum_{i<j} p_{Ti}\, p_{Tj}\, R_{ij}^2\right)^2 \Big/ \sum_i p_{Ti}}$$

[Moult, Necib, JDT, 2016]

Grooming from First Principles



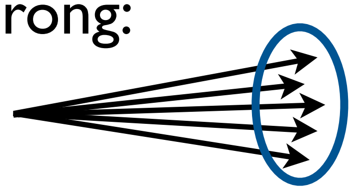
Layers of Jet Understanding



theoretical calculations (energy flow)	reconstruction ≈1-to-1 @ LHC (e.g. particle flow)	nonperturbative confinement (hadronization)	perturbative gluonic radiation (parton shower)	short-distance collision (hard scattering)

First-Principles Calculations

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

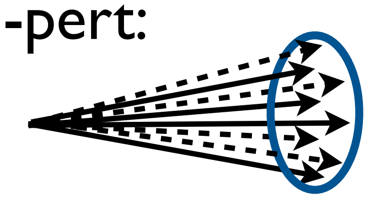
Double differential: Larkoski, JDT, 1307.1699; Larkoski, Moult, Neill, 1401.4458; Procura, Waalewijn, Zeune, 1410.6483

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

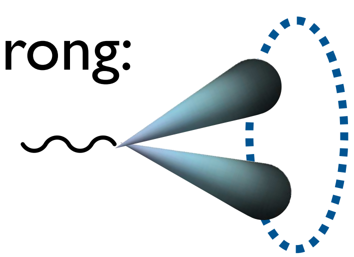
Non-pert:



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

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

2-prong:

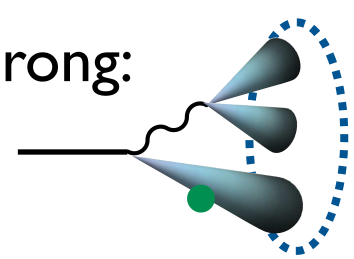


Signal grooming: Rubin, 1002.4557; Dasgupta, Powling, Siodmok, 1503.01088

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; Dasgupta, Powling, Schunk, Soyez, 1609.07149

3-prong:

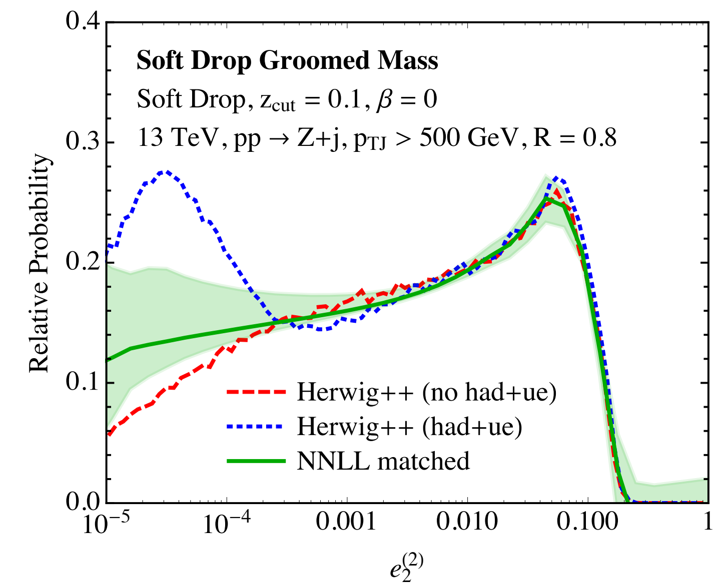


Planar flow: Field, Gur-Ari, Kosower, Mannelli, Perez, 1212.2106

Fractional jets: Bertolini, JDT, Walsh, 1501.01965

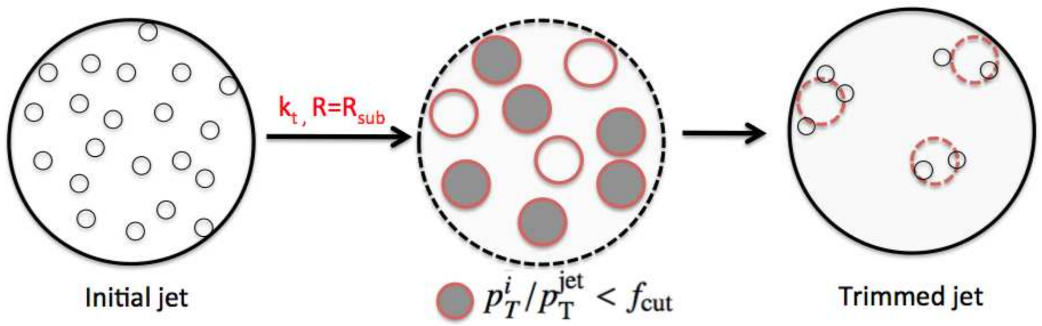
Power counting: Larkoski, Moult, Neill, 1411.0665

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



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

Trimming from First Principles?



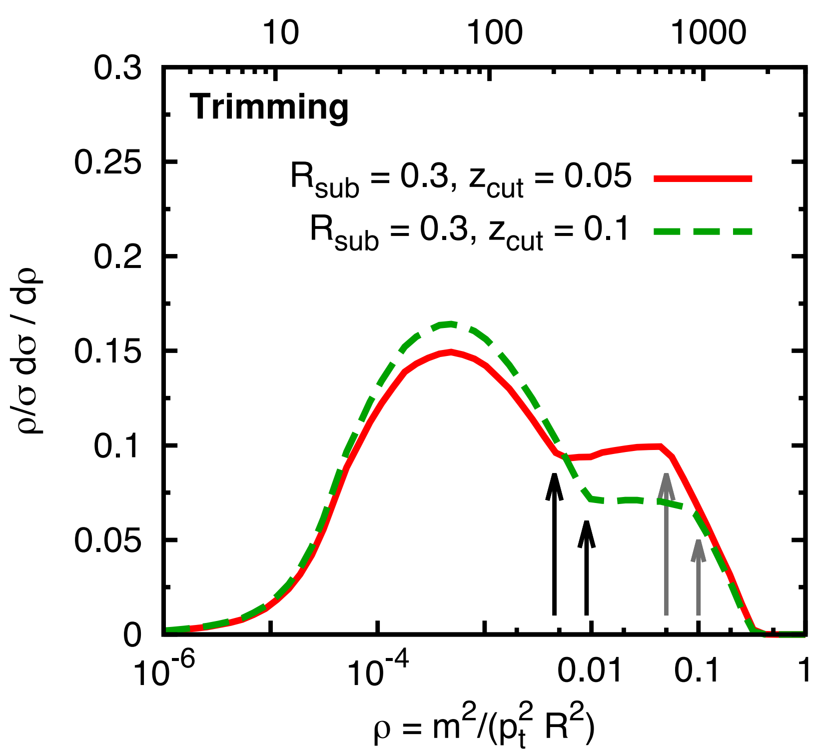
R_{sub}: subjet radius
z_{cut}: fractional energy threshold

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

Trimmed Jet Mass:

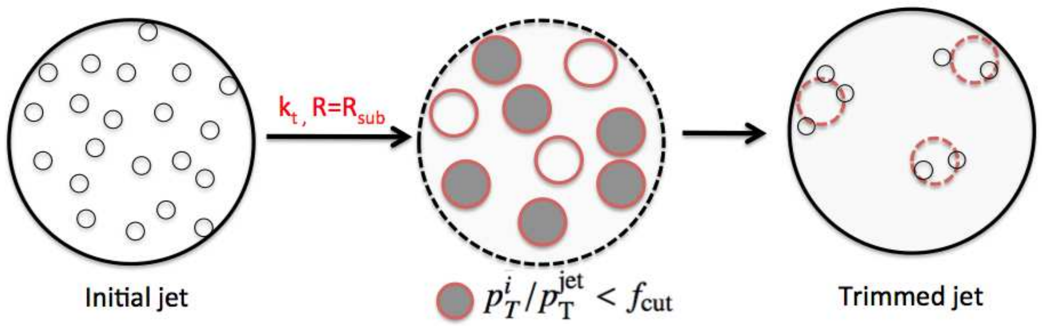
3 TeV quark jets

Pythia 6 Simulation



[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Trimming from First Principles?



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

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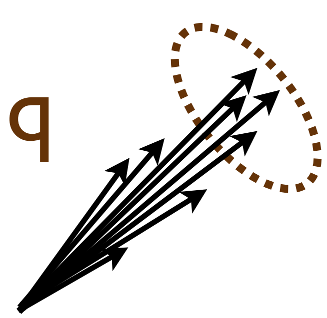
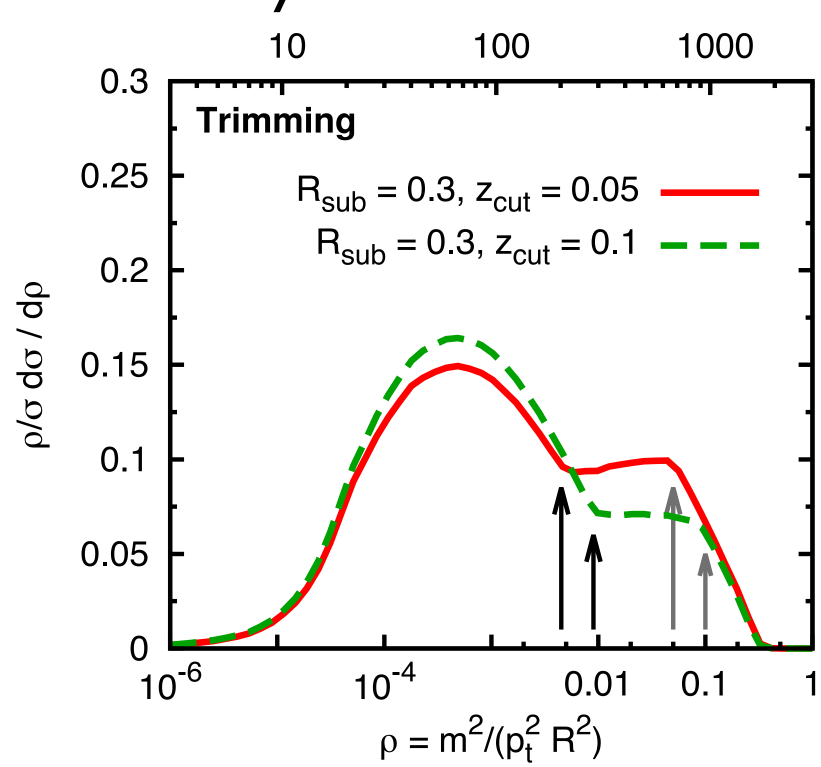
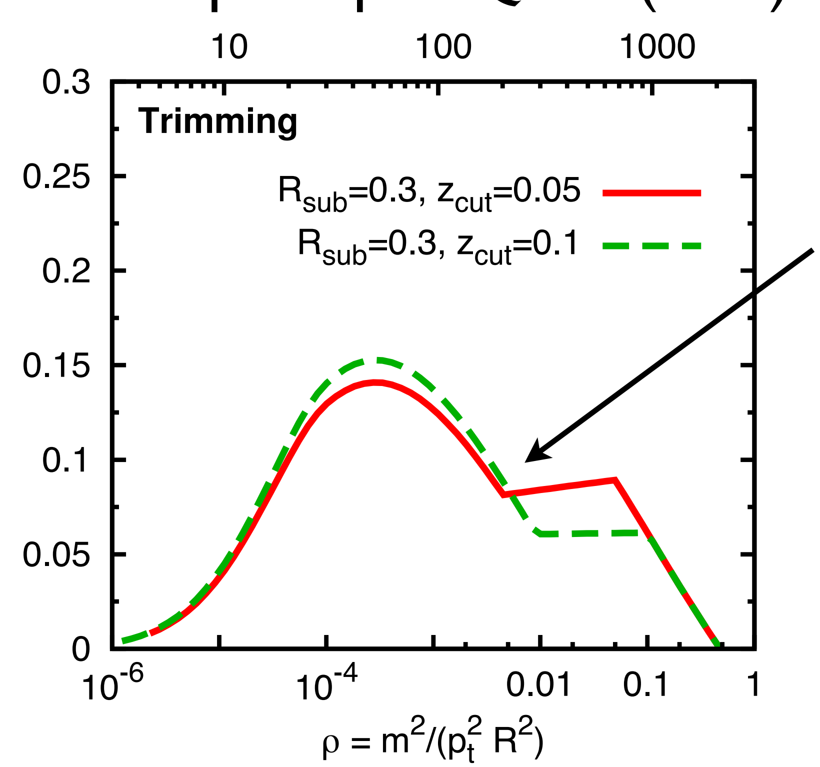


Pythia 6 Simulation



First-principles QCD (MLL)

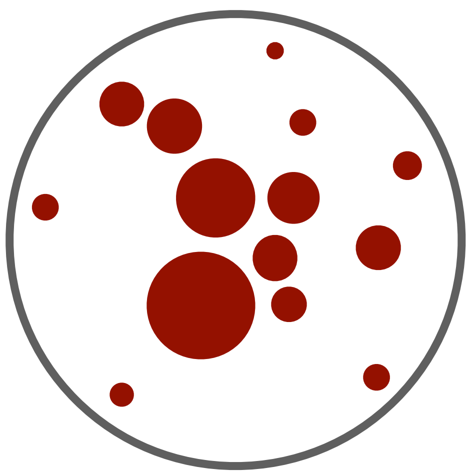


Analytically understand Sudakov peak, kink, and plateau

[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Soft Drop Declustering

Original Jet



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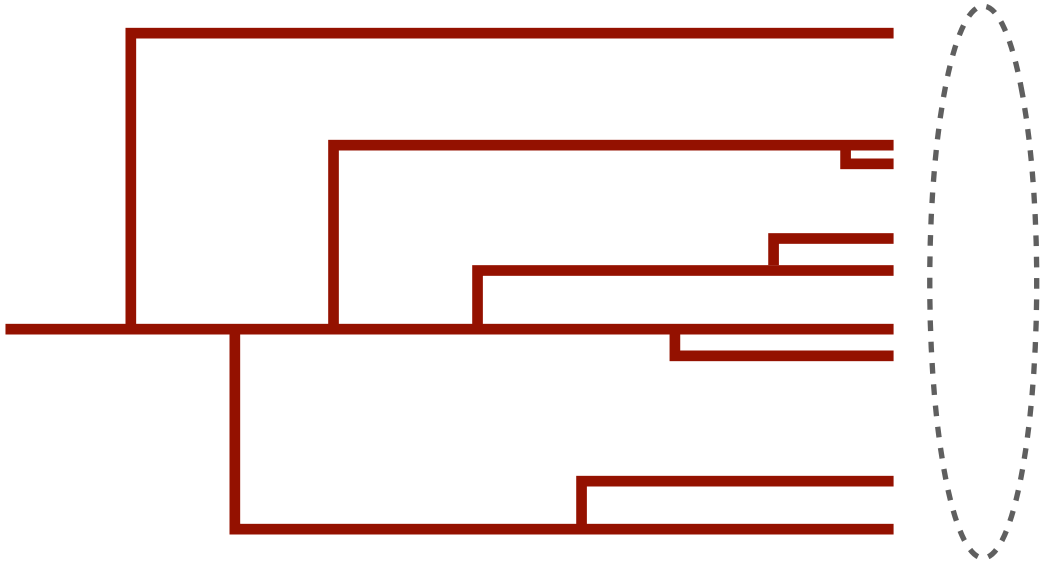
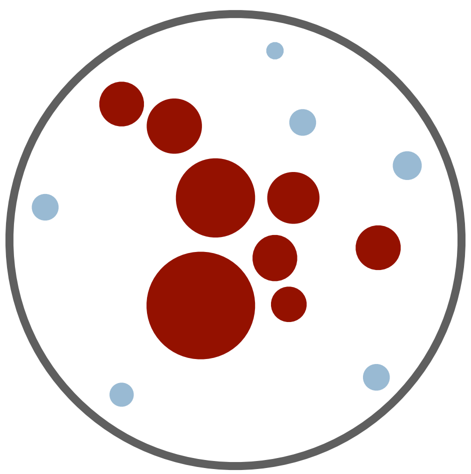
Clustering Tree



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

Soft Drop Declustering

Groomed Jet



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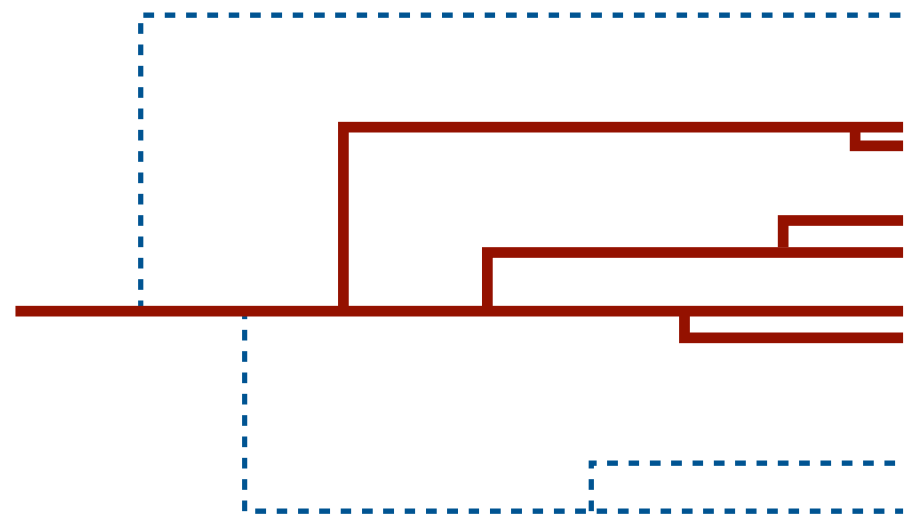
Groomed Clustering Tree



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Soft Drop Declustering

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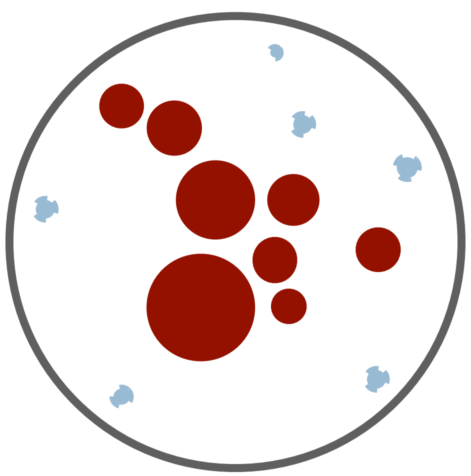

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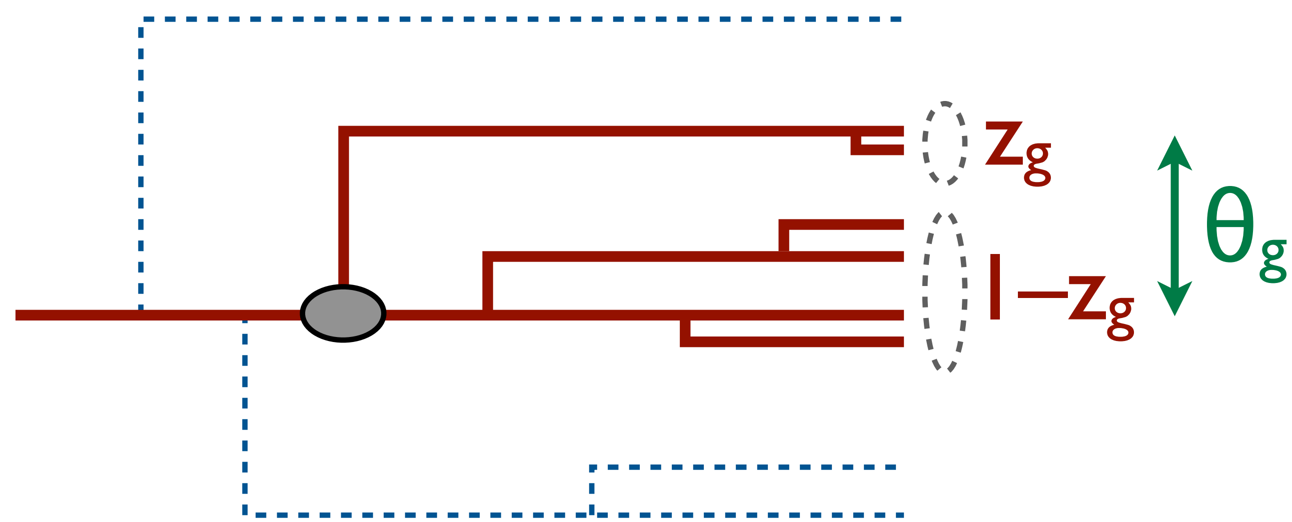
Groomed Clustering Tree



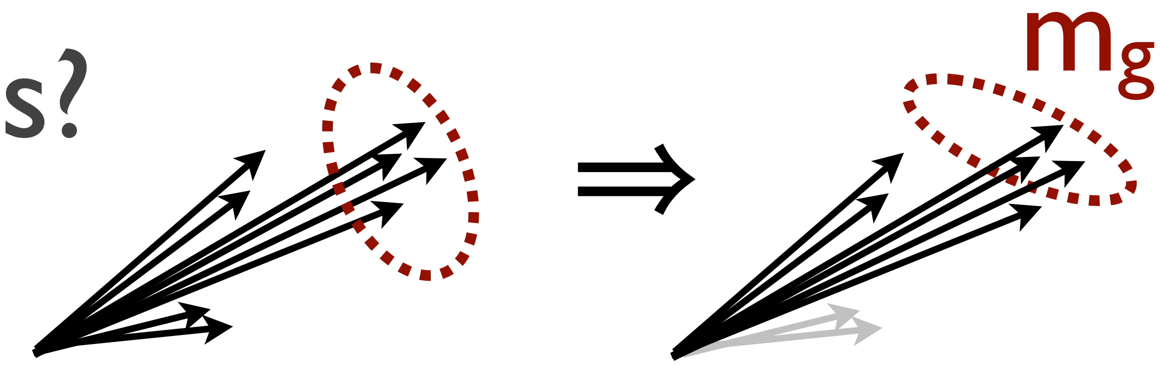
$$z_g > z_{cut}\, \theta_g^{\beta}$$

More Grooming — Less Grooming

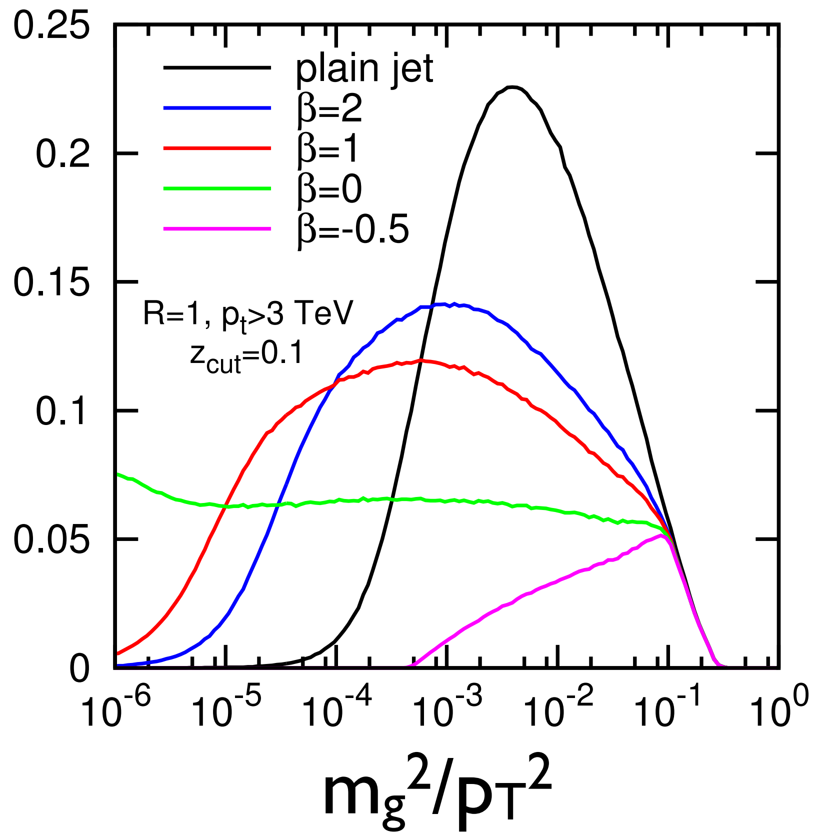
$\beta \to -\infty$ | $\beta < 0$ | $\beta = 0$ | $\beta > 0$ | $\beta \to \infty$

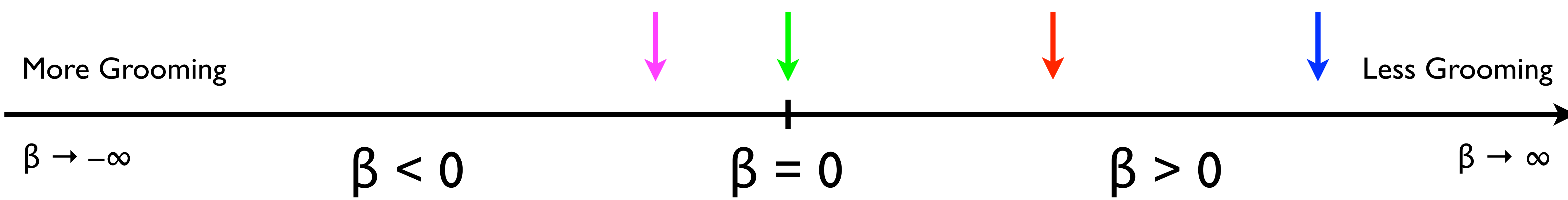
[Larkoski, Marzani, Soyez, JDT, 2014; see also Butterworth, Davison, Rubin, Salam, 2008; Dasgupta, Fregoso, Marzani, Salam/Powling, 2013]

Calculating Groomed Mass?



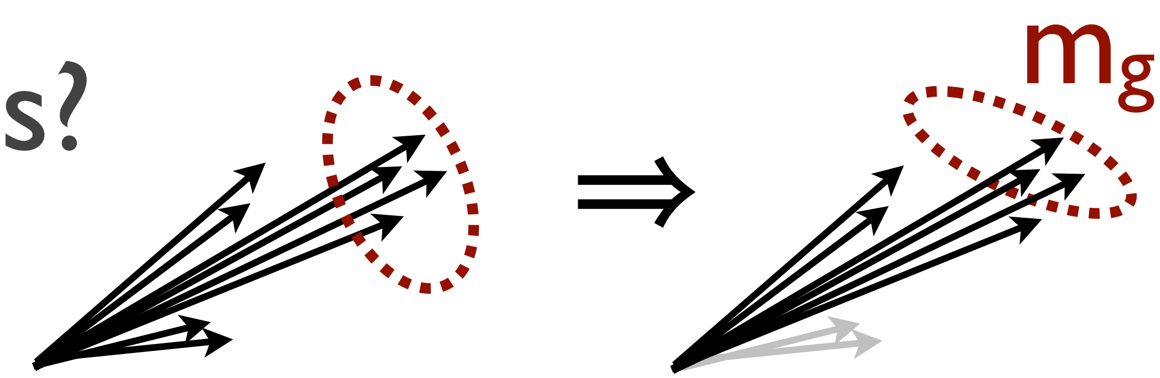
Simulated LHC Data





[Larkoski, Marzani, Soyez, JDT, 2014]

Calculating Groomed Mass?



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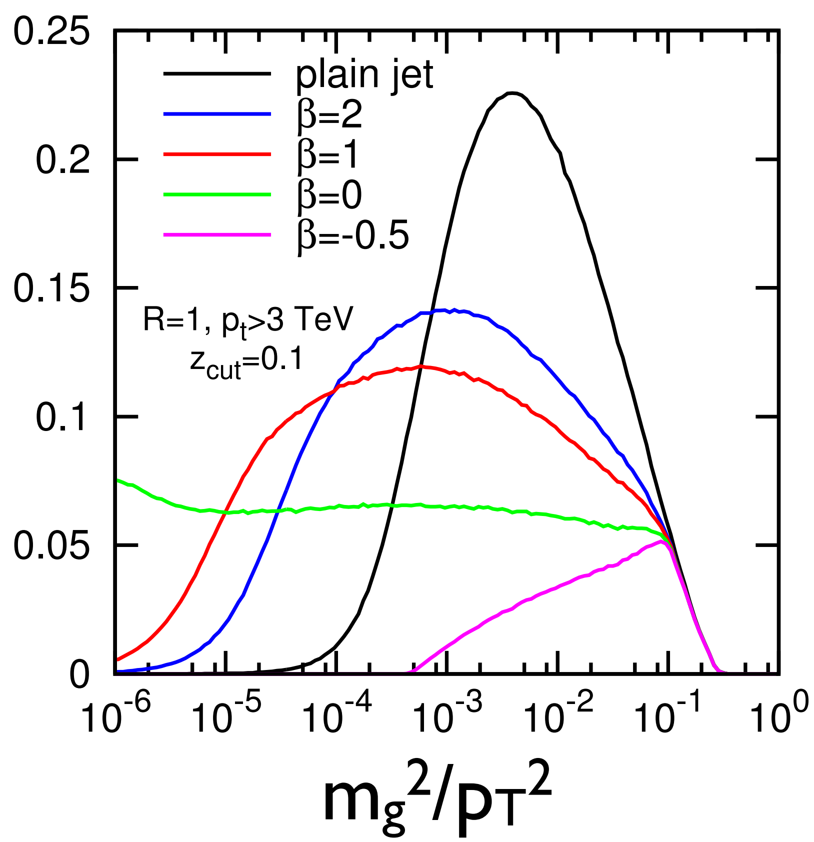
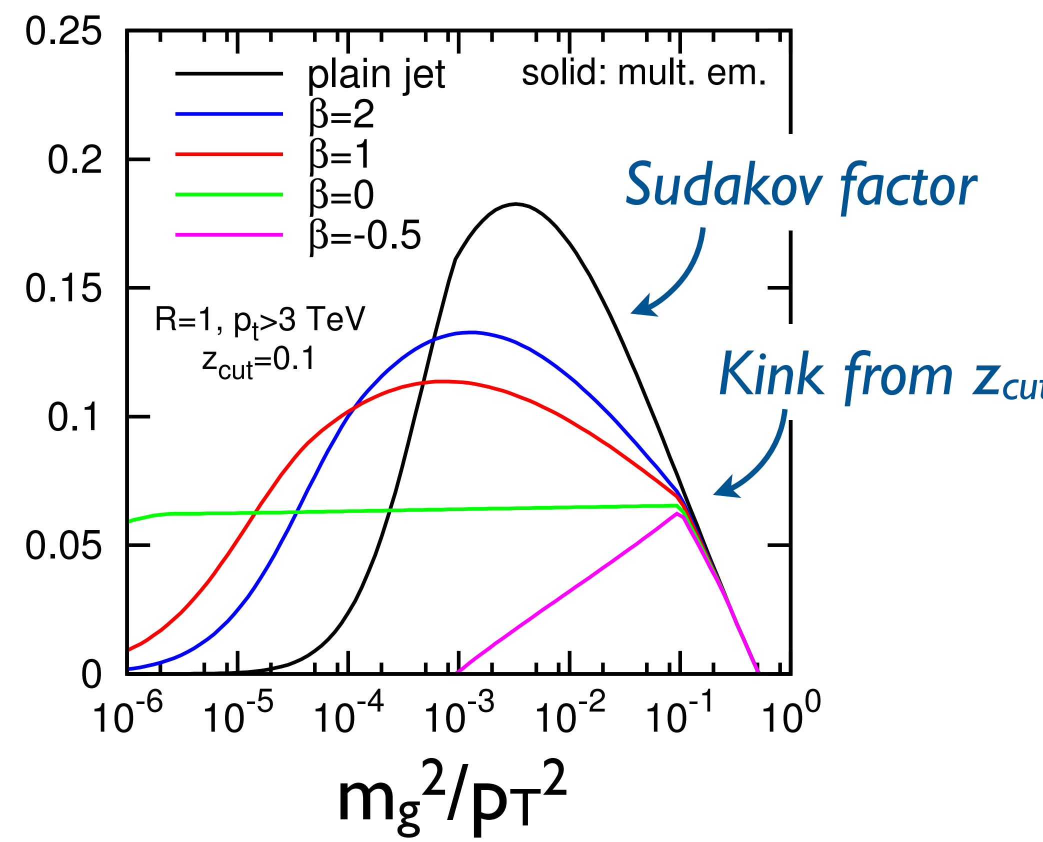
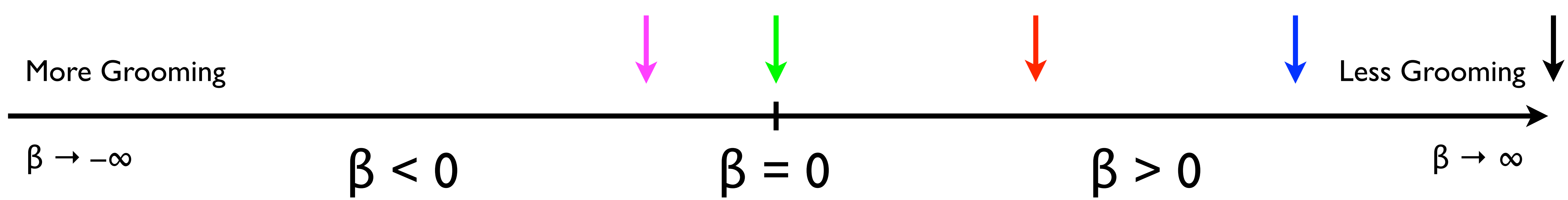
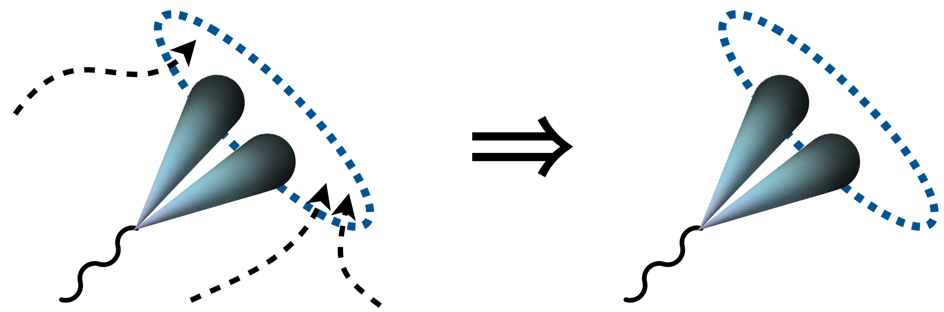


First-principles QCD (MLL)

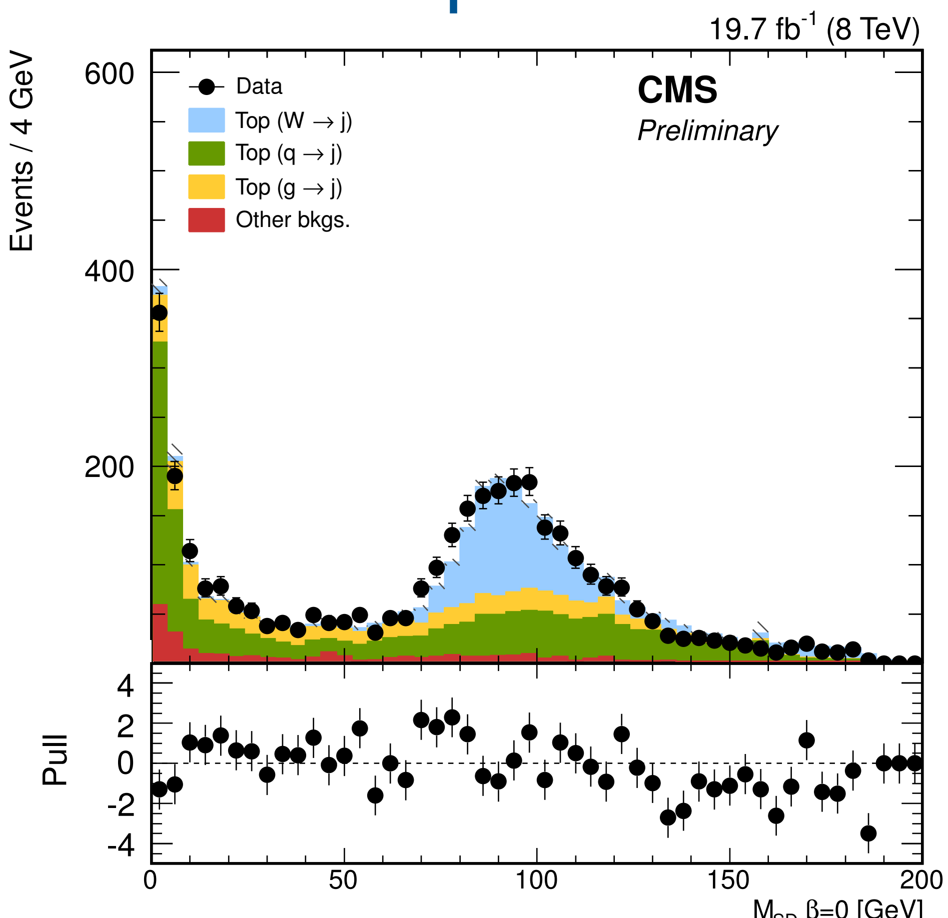




[Larkoski, Marzani, Soyez, JDT, 2014]

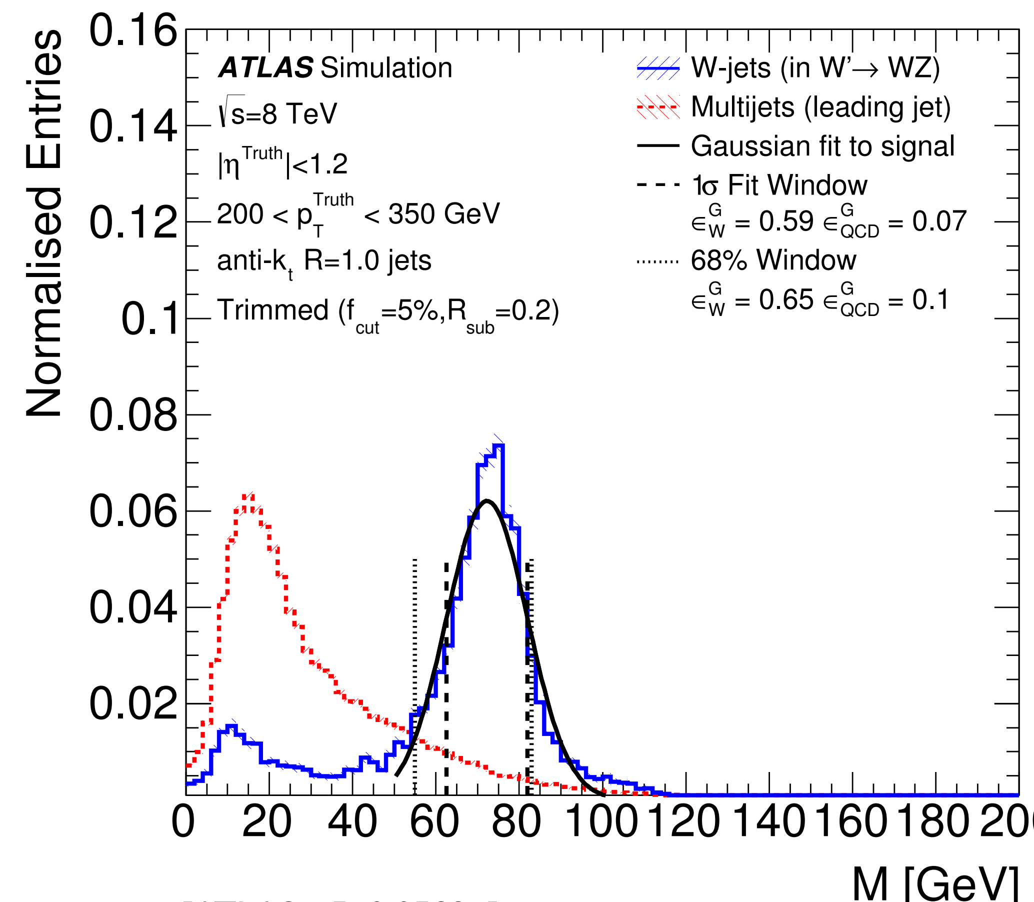


Soft Drop



[CMS, JME-14-002]

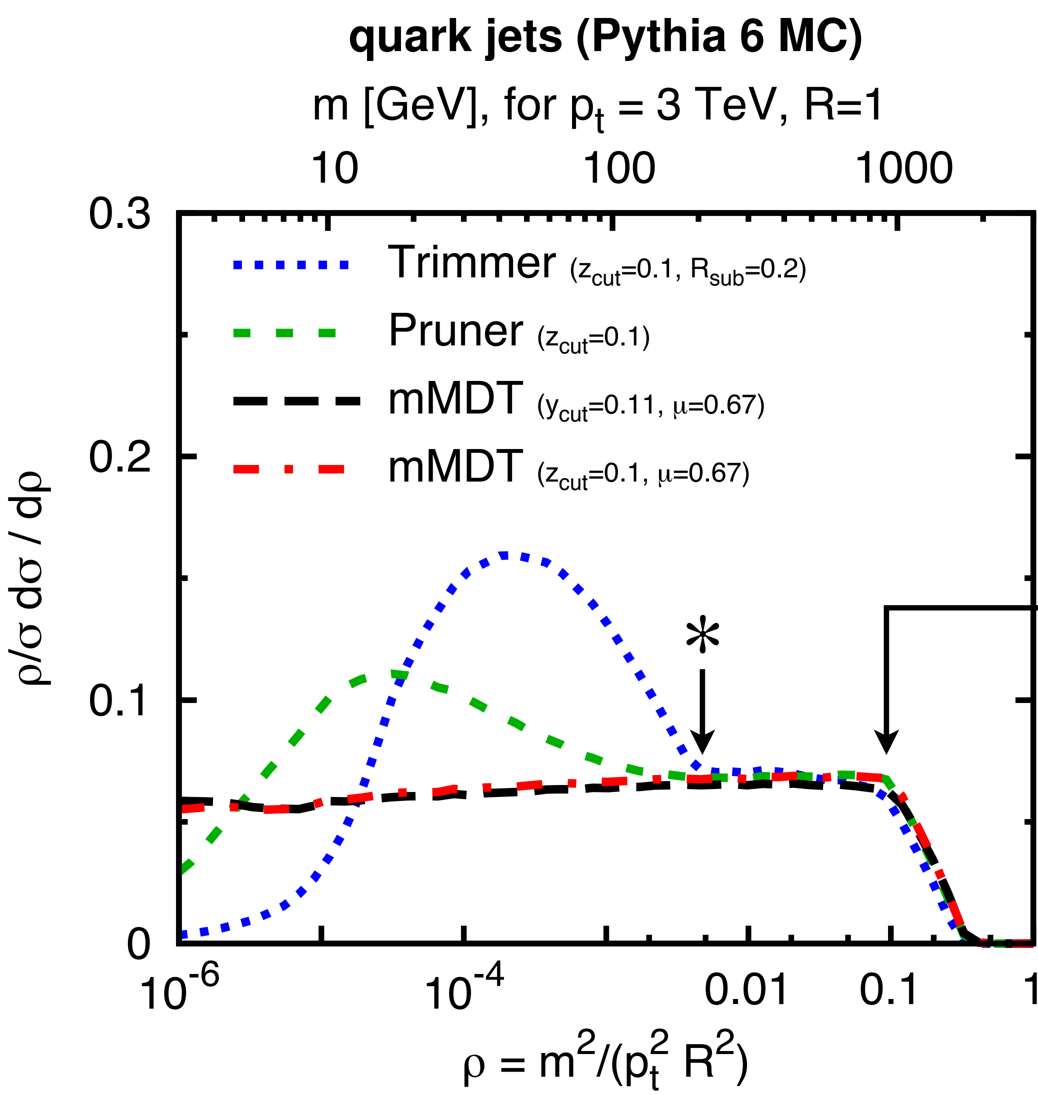
Trimming



[ATLAS, 1510.05821]

Both grooming strategies give good signal isolation

Scorecard



[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Soft Drop ✓

Soft drop with β = 0
= mMDT with μ = 1

Trimming ✓*

Both have primary kink at

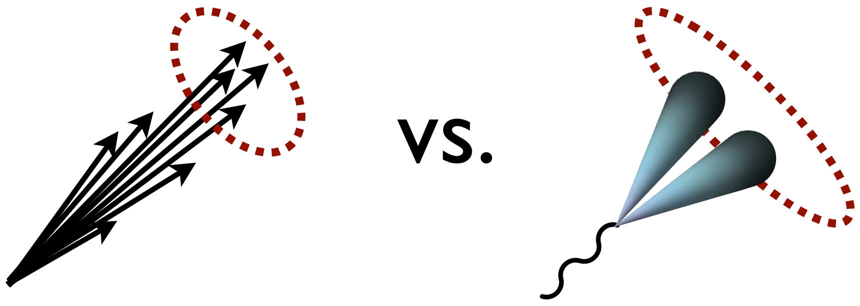
$$m \simeq p_T R \sqrt{z_{\rm cut}}$$

* Trimming has secondary kink at

$$m \simeq p_T R_{\rm sub} \sqrt{z_{\rm cut}}$$

(Pruning also has similar behavior)

Discrimination from First Principles



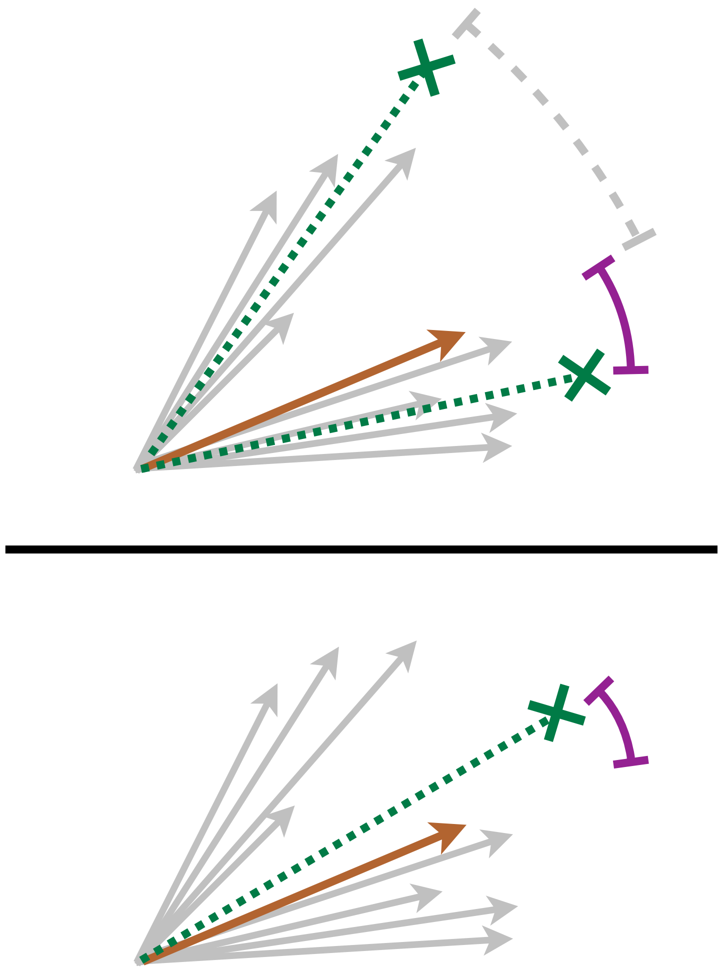
(aka Axes or Axes-Free?)

Discrimination with Axes

Dimensionless kinematics: $z_i \equiv \frac{p_{Ti}}{\sum_j p_{Tj}}$ $\theta_{ij} \equiv \Delta R_{ij}$

N-subjettiness

$$\frac{\tau_2}{\tau_1} = \frac{\sum_k z_k \min\{\theta_{k1}, \theta_{k2}\}^\beta}{\sum_k z_k \, \theta_{k1}{}^\beta} =$$



Requires a definition of subjet axes
(i.e. minimizing over all axes possibilities)

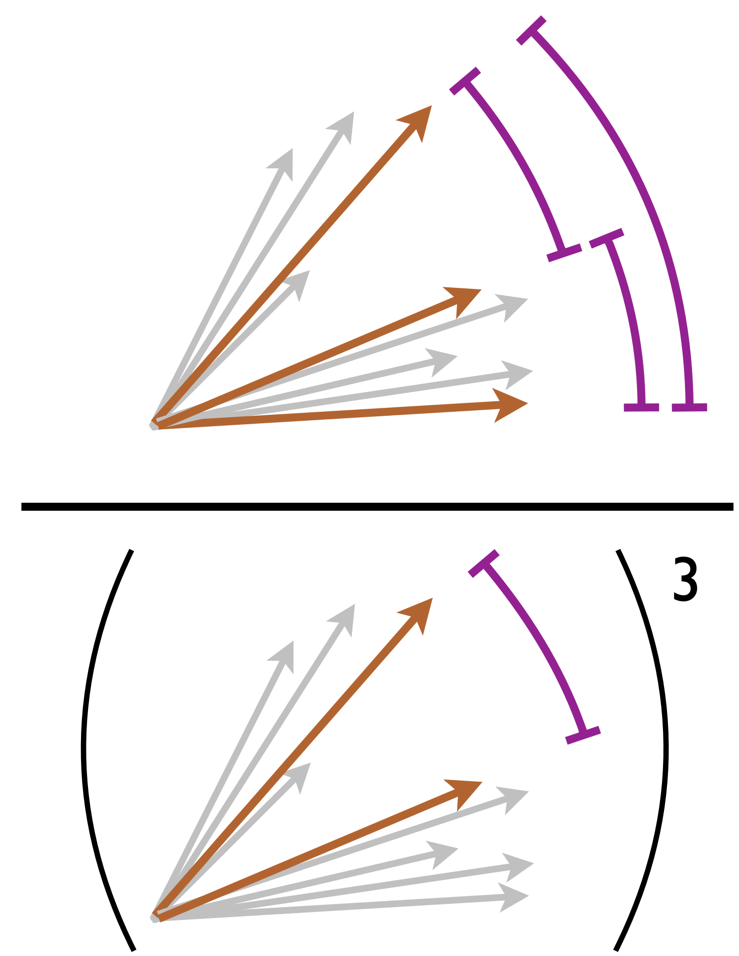
[JDT, Van Tilburg, 1011.2268, 1108.2701; see also Kim, 1011.1493]
[related work in Stewart, Tackmann, Waalewijn, 1004.2489]

Discrimination without Axes

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

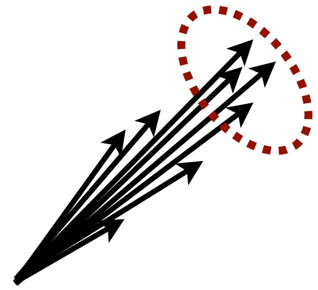
Energy Correlation Functions

$$D_2 = \frac{e_3}{(e_2)^3} = \frac{\sum_{i<j<k} z_i z_j z_k \left(\theta_{ij}\theta_{jk}\theta_{ki}\right)^\beta}{\left(\sum_{i<j} z_i z_j \, \theta_{ij}{}^\beta\right)^3} =$$

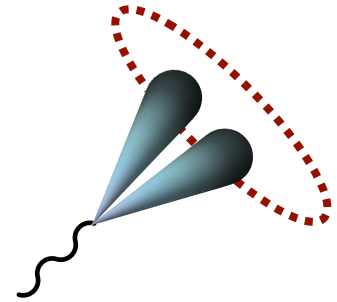


Axes-free probe for substructure;
not immediately obvious how it works

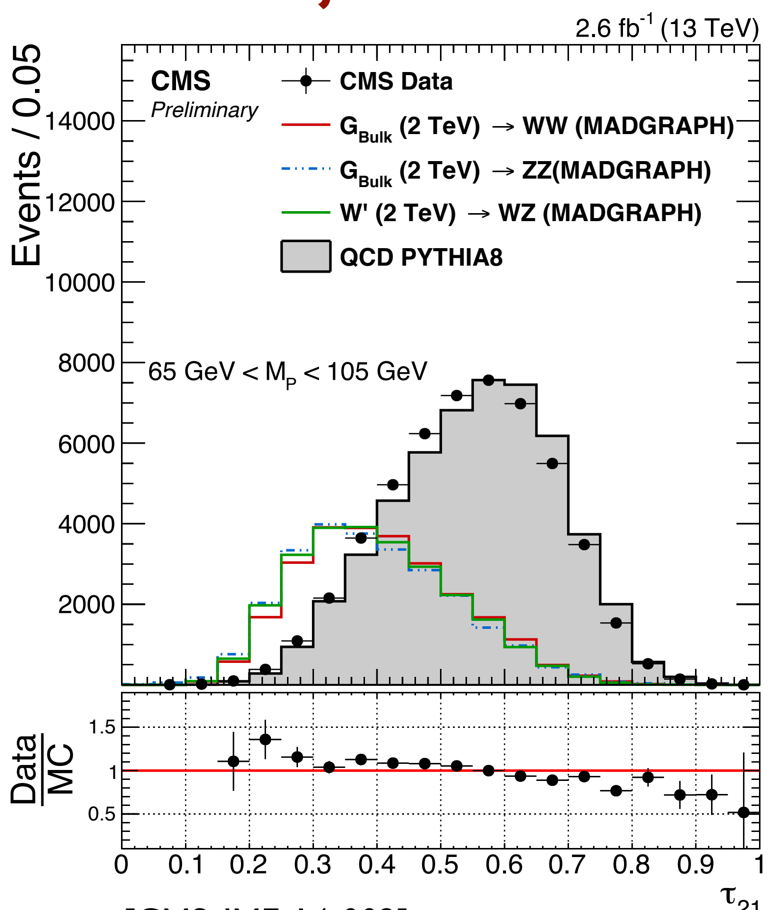
[Larkoski, Salam, JDT, 1305.0007; Larkoski, Moult, Neill, 1409.6298, 1507.03018; see also Banfi, Salam, Zanderighi, hep-ph/0407286; Jankowiak, Larkoski, 1104.1646]



vs.

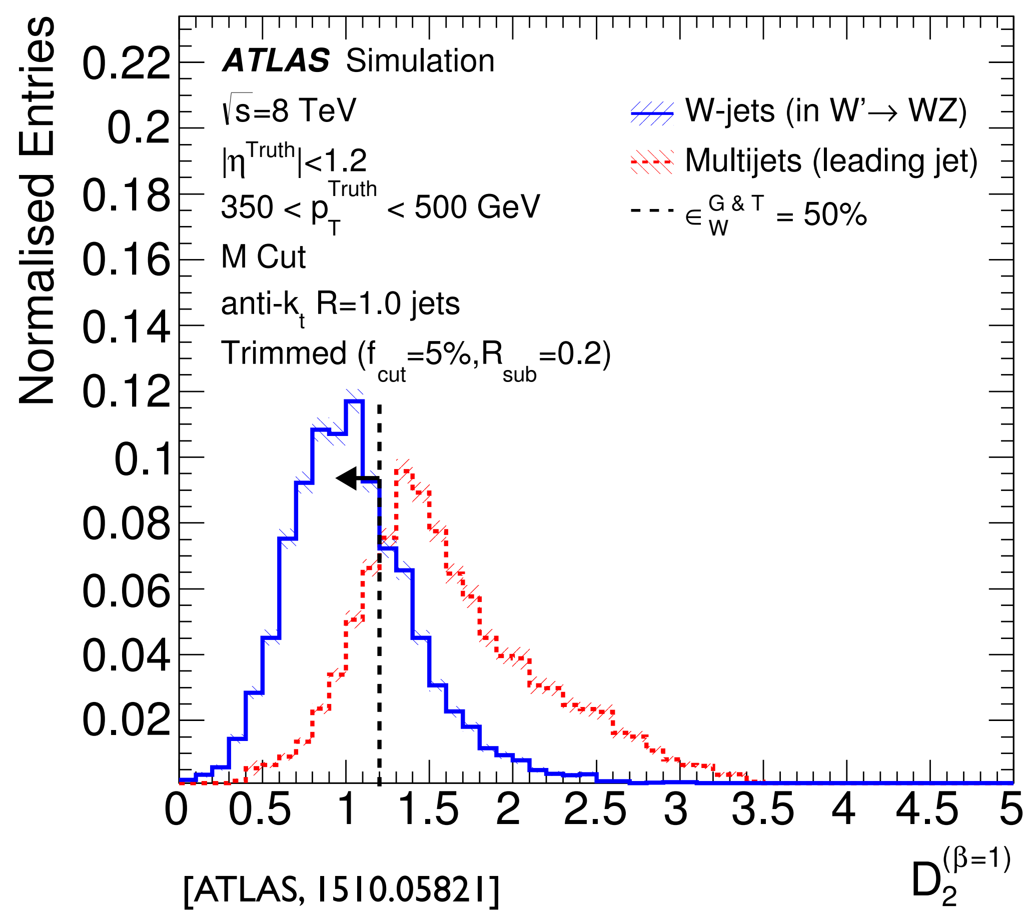


N-subjettiness



[CMS, JME-14-002]

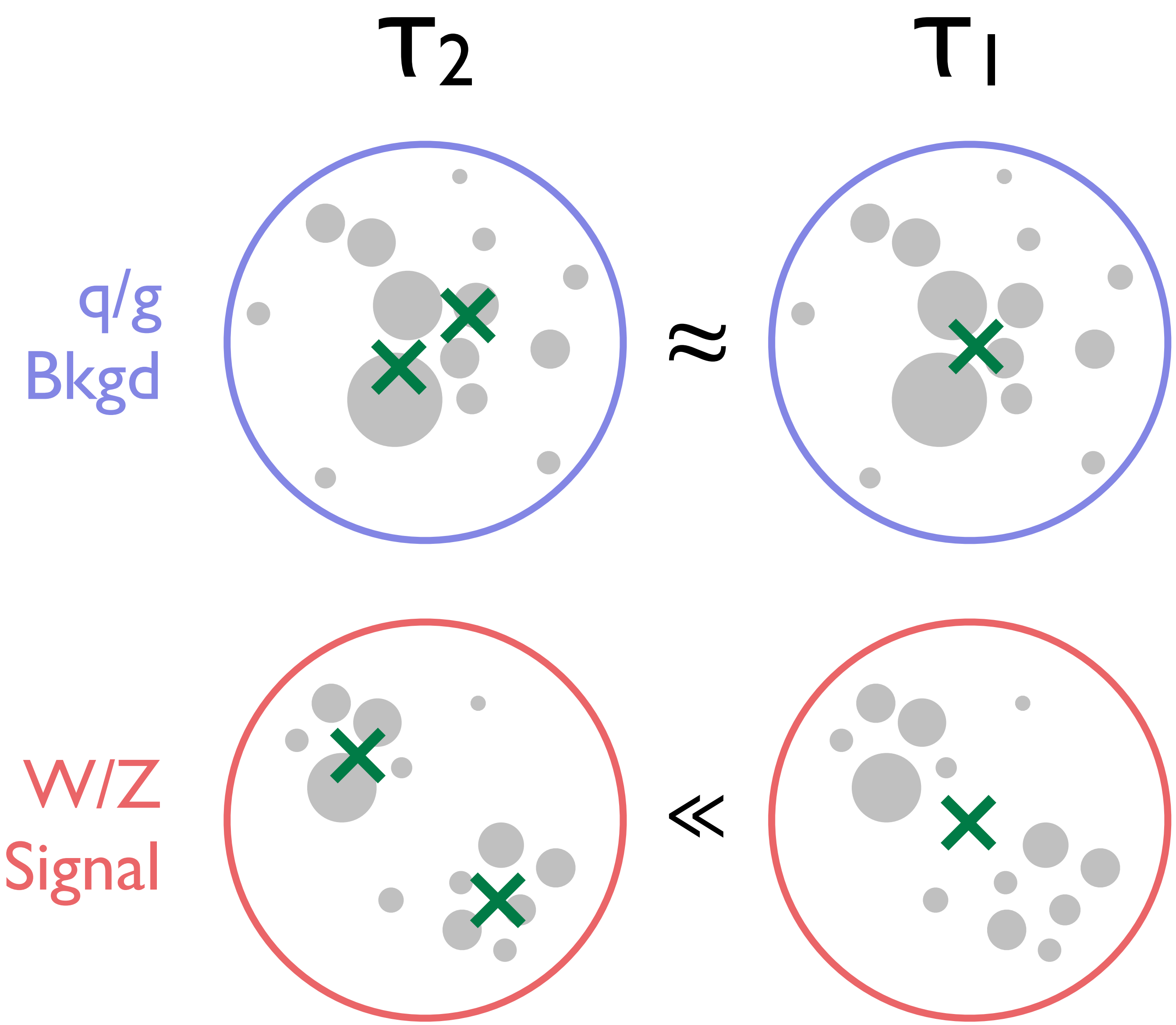
Energy Correlator: D_2

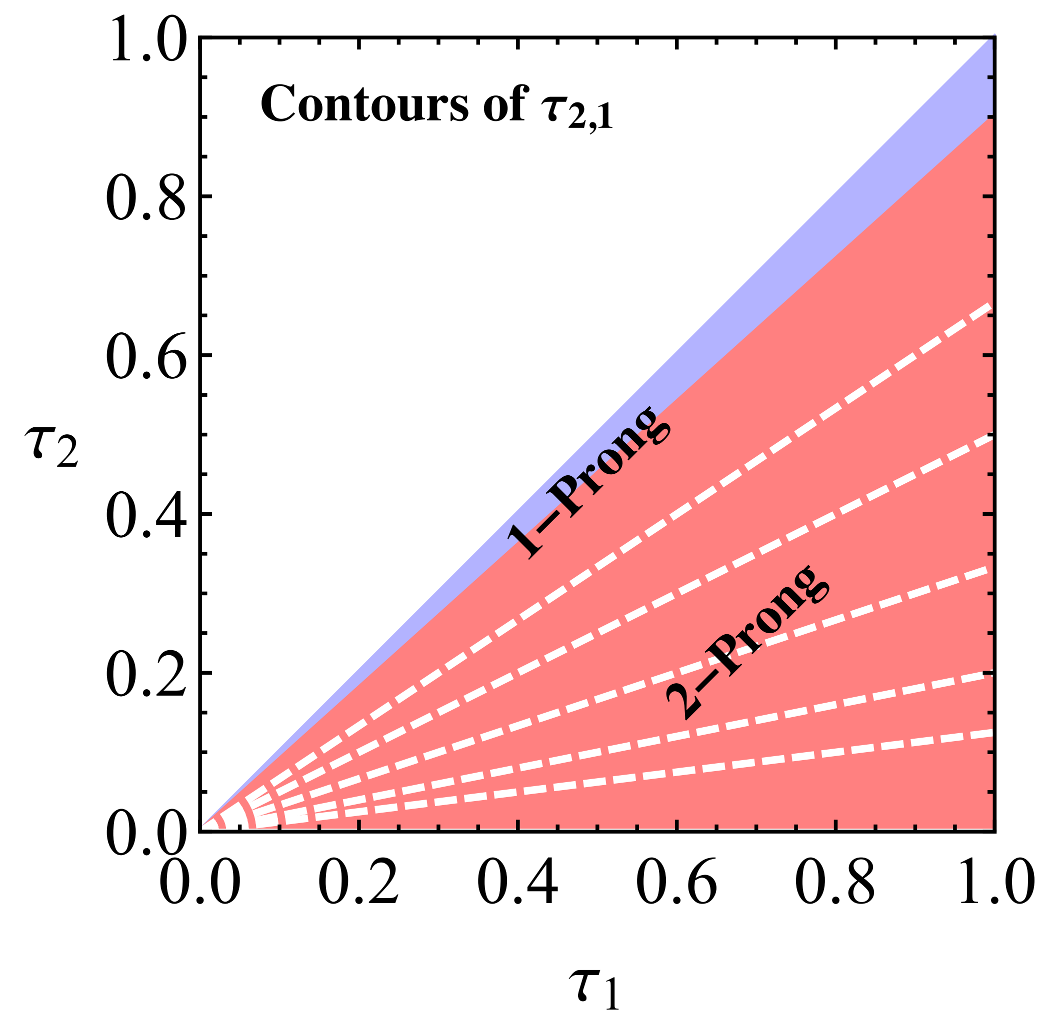


[ATLAS, 1510.05821]

Can we understand this behavior from first principles?

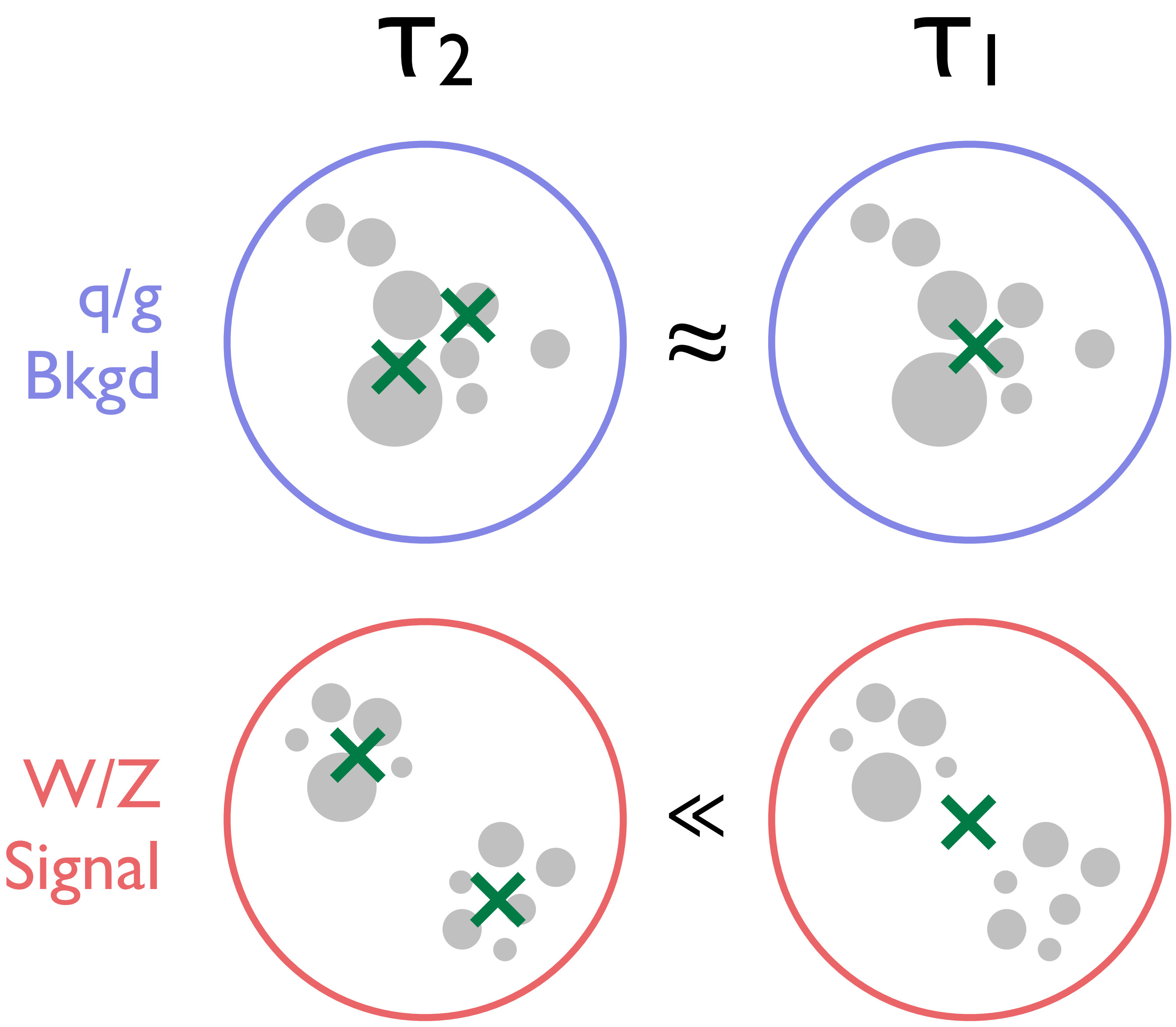
N-subjettiness Behavior

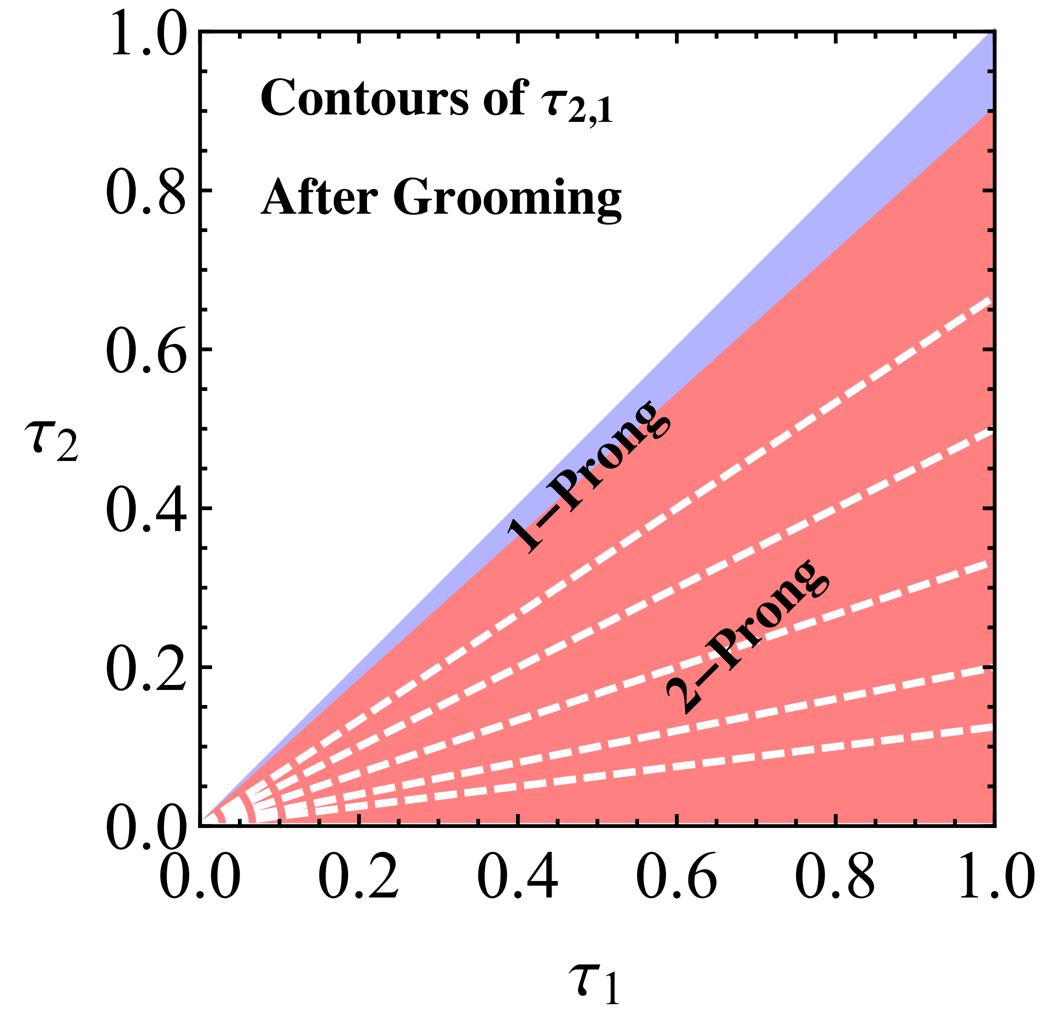




Parametric separation between 1 and 2 prong jets

N-subjettiness Behavior with Grooming





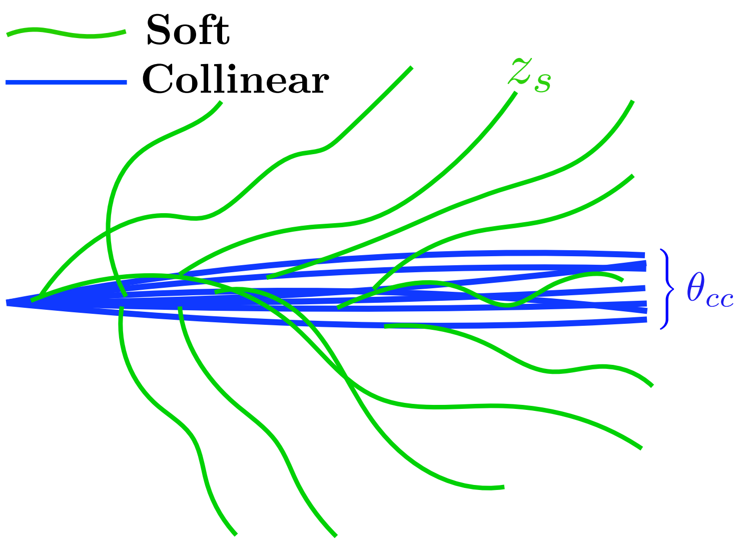
Parametric separation between 1 and 2 prong jets even after removing soft peripheral radiation

Scorecard

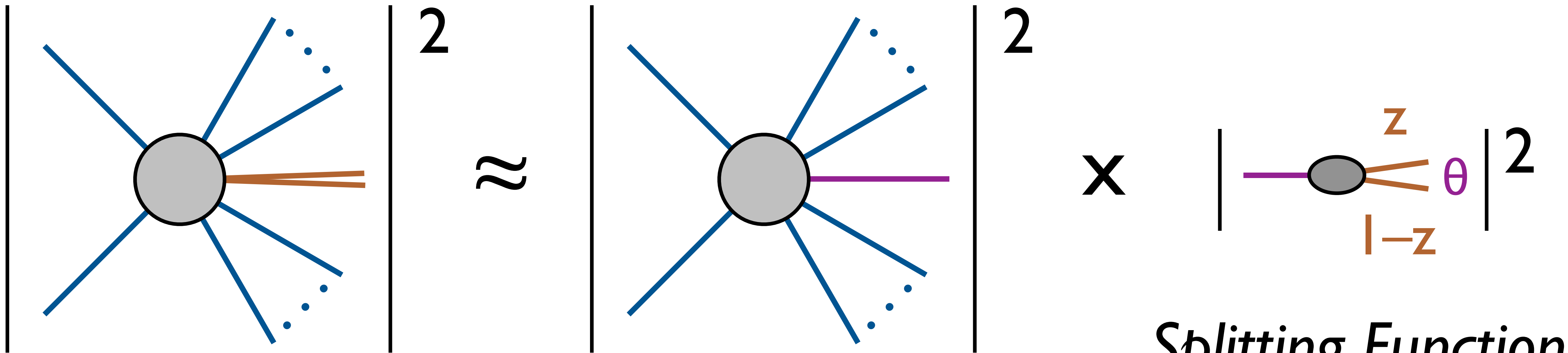
	CMS	ATLAS EXPERIMENT
	Soft Drop	*Trimming*
	✓	✓*
	N-subjettiness before grooming	D_2 after grooming
	✓	☐*
	(also works after grooming)	

Not just good discrimination, but stability to choice of cuts

The Power of Power Counting



Textbook QCD



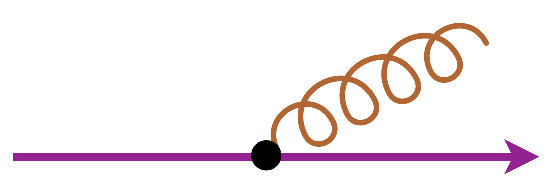
Splitting Function

2→n

2→n−1

1→2

At leading log order:



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

See end of talk for quark/gluon tagging

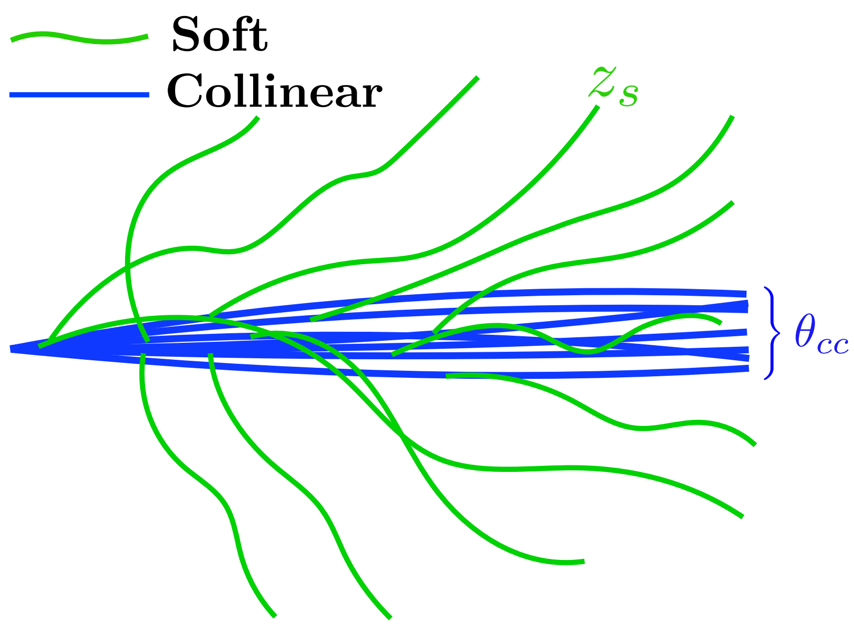
$$dP_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

Collinear singularity

Soft singularity

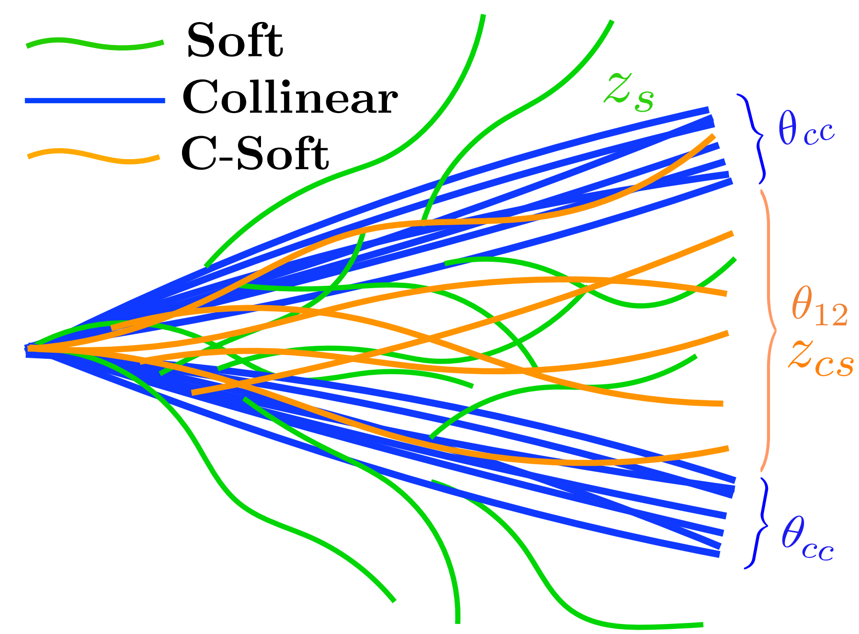
Power Counting Modes

1-prong background (quark or gluon)



	C	S
energies	1	z_s
	CC	SX
angles	θ_{cc}	1

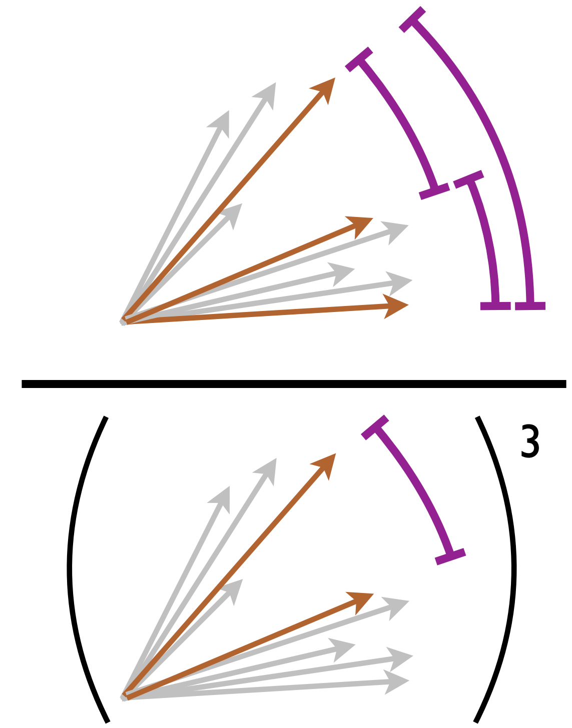
2-prong signal (W or Z)



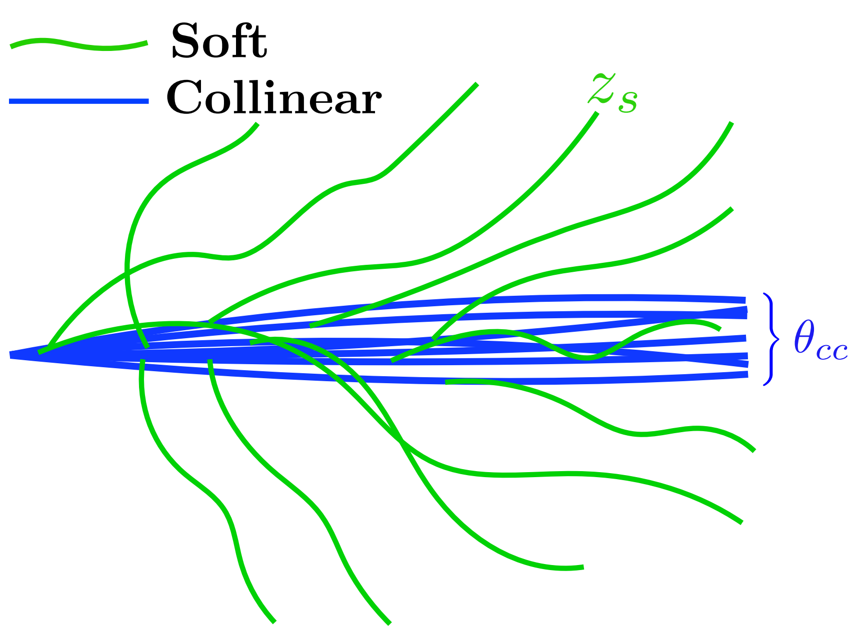
	C	C_S	S
energies	1	z_{cs}	z_s
	CC	C_1C_2 or CC_S	SX
angles	θ_{cc}	θ_{12}	1

Power Counting D2: Background

$$D_2 = \frac{e_3}{(e_2)^3} = \frac{\sum_{i<j<k} z_i z_j z_k \left(\theta_{ij}\theta_{jk}\theta_{ki}\right)^\beta}{\left(\sum_{i<j} z_i z_j \, \theta_{ij}{}^\beta\right)^3} =$$



Setting β = 1



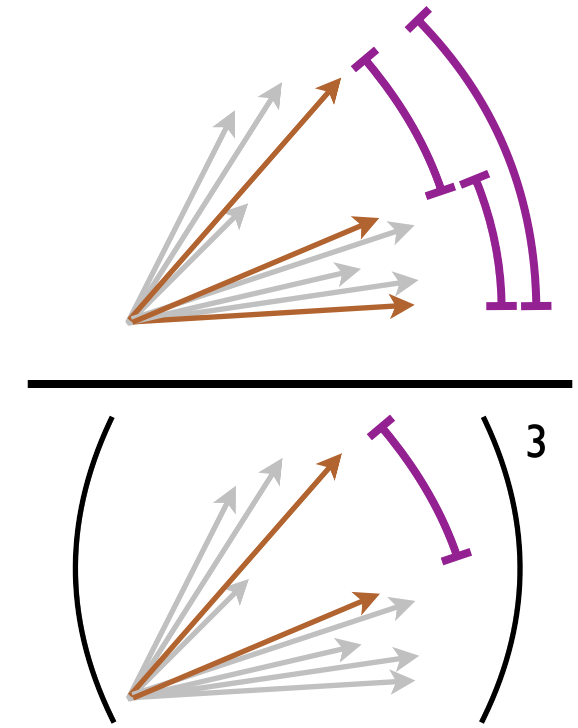
CCC CCS CSS

$$\simeq \frac{\theta_{cc}{}^3 + \theta_{cc} z_s + z_s{}^2}{\left(\theta_{cc} + z_s\right)^3}$$

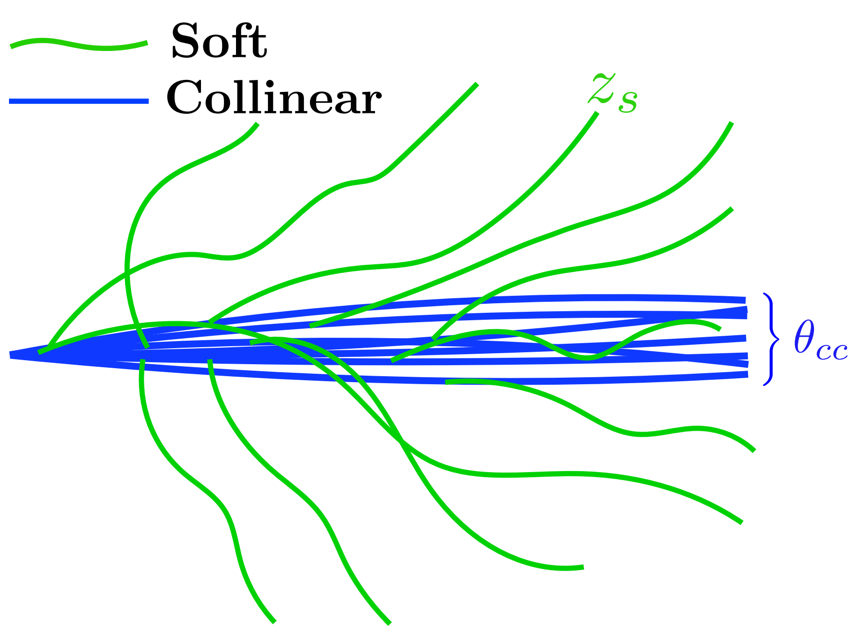
CC CS

Power Counting D_2: Background

$$D_2 = \frac{e_3}{(e_2)^3} = \frac{\sum_{i<j<k} z_i z_j z_k \left(\theta_{ij}\theta_{jk}\theta_{ki}\right)^\beta}{\left(\sum_{i<j} z_i z_j \, \theta_{ij}{}^\beta\right)^3} =$$



Setting β = 1



CCC CCS CSS

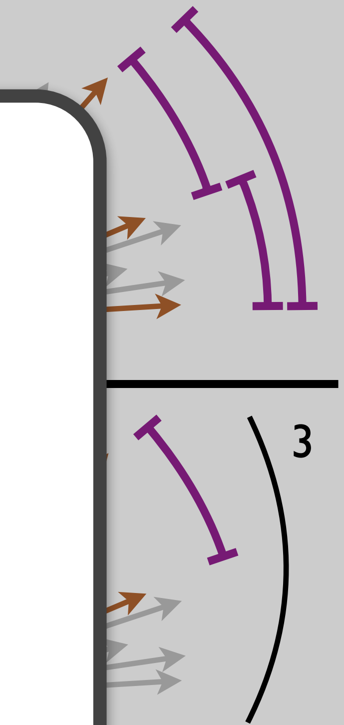
$$\simeq \frac{\theta_{cc}{}^3 + \theta_{cc} z_s + z_s{}^2}{\left(\theta_{cc} + z_s\right)^3} \Rightarrow \frac{1}{z_s} \simeq \frac{p_T}{m}$$

CC CS

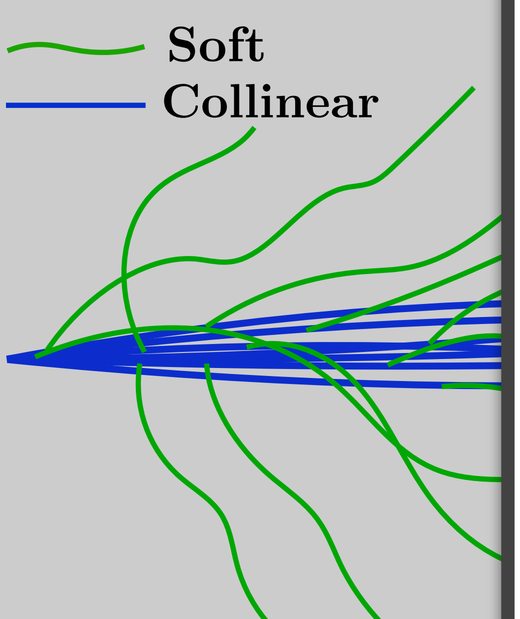
if soft dominates

Power Counting D2: Background

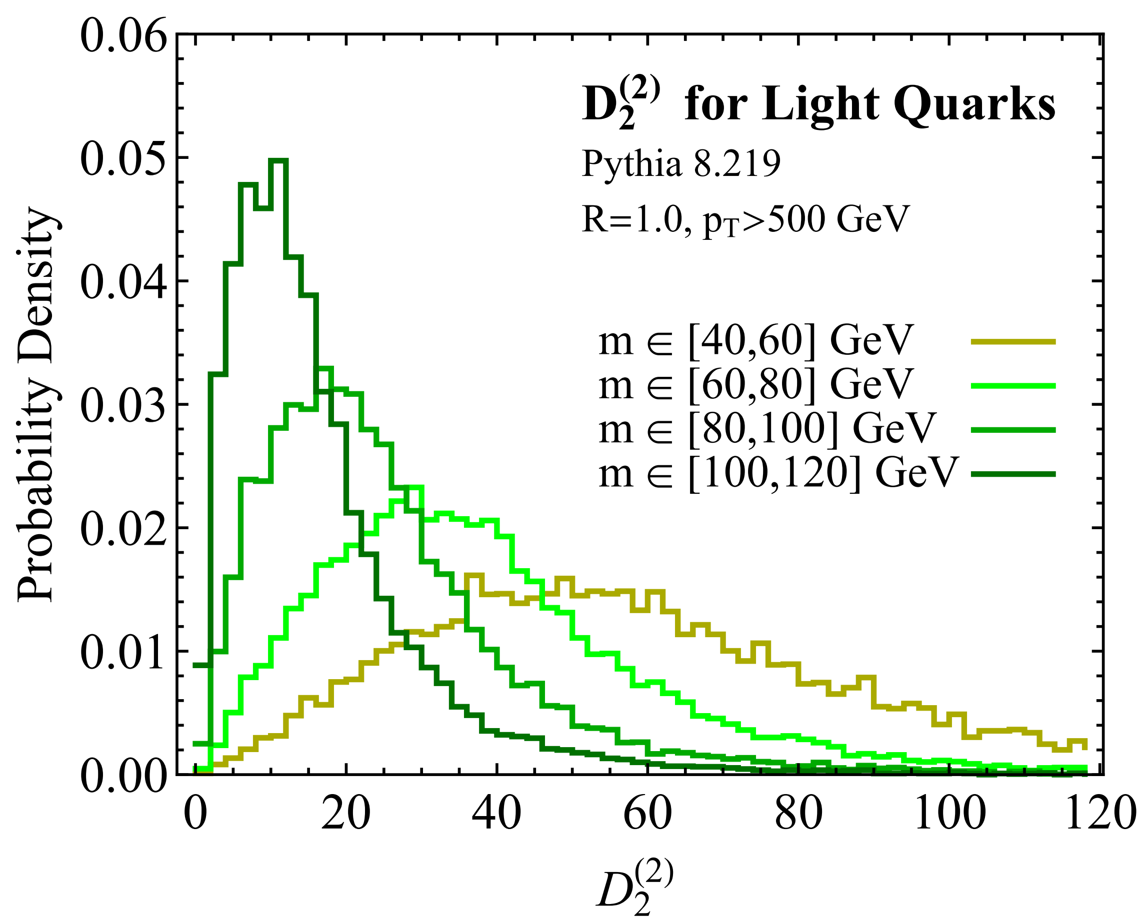
$D_2 = \frac{\ldots}{(\ldots}$



Setting β



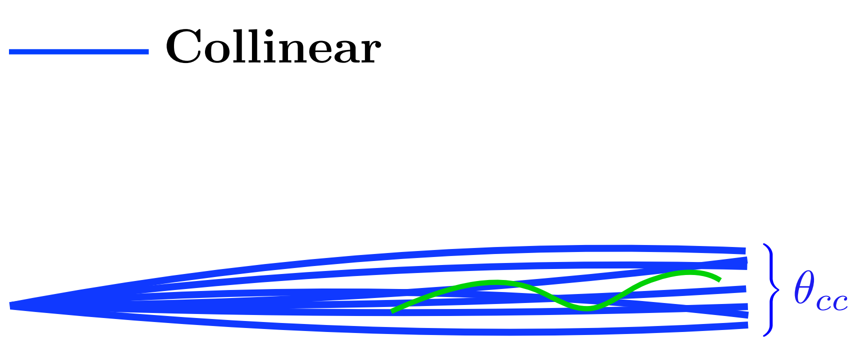
Without grooming, D2 unstable to mass cut (hard to do sideband analysis)

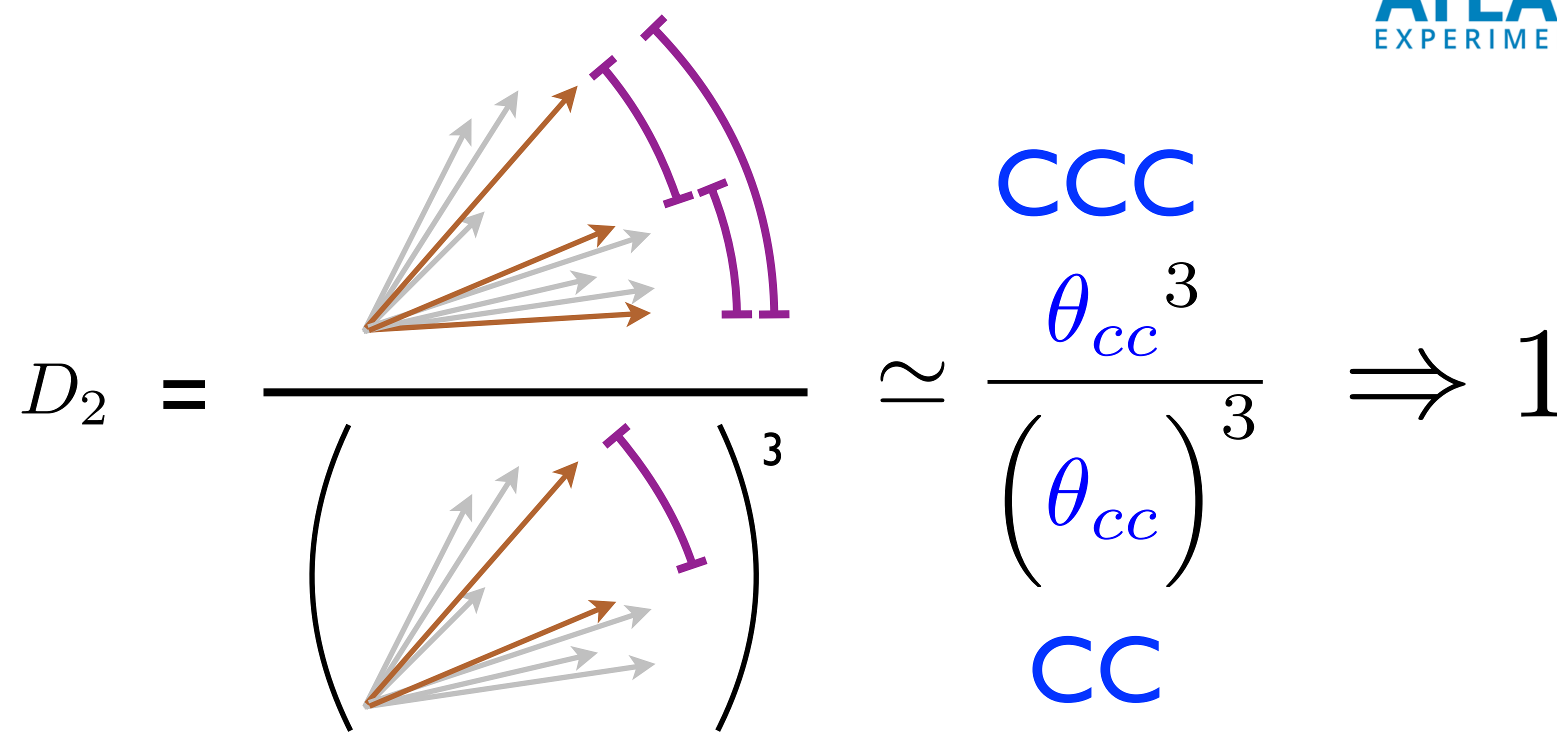


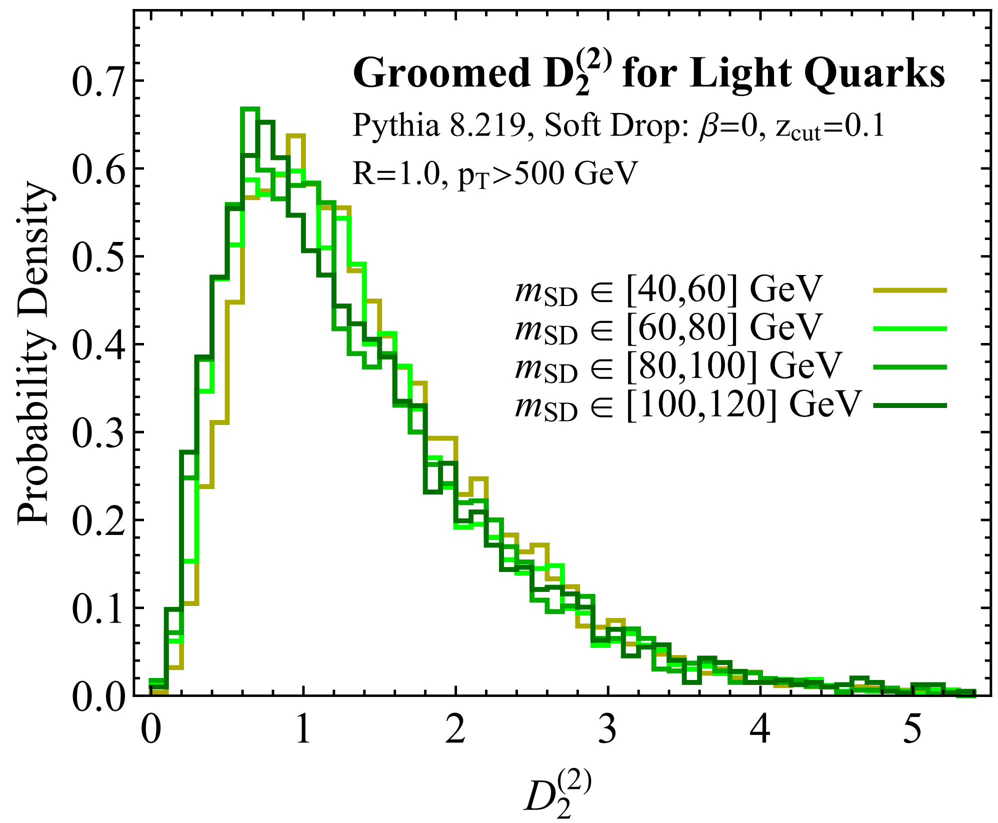
$$\frac{1}{z_s} \simeq \frac{p_T}{m}$$

if soft dominates

Background after Grooming

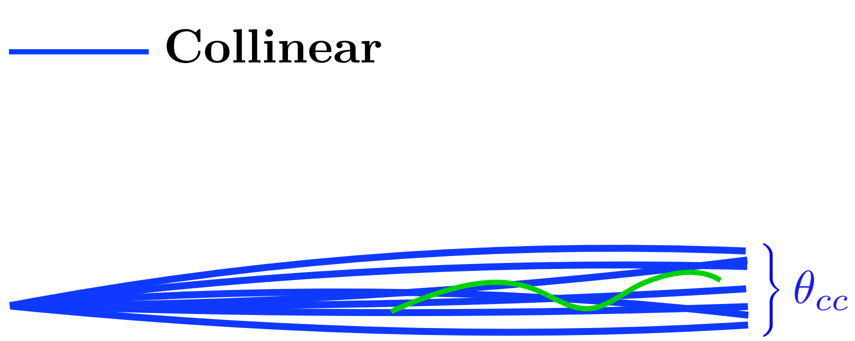




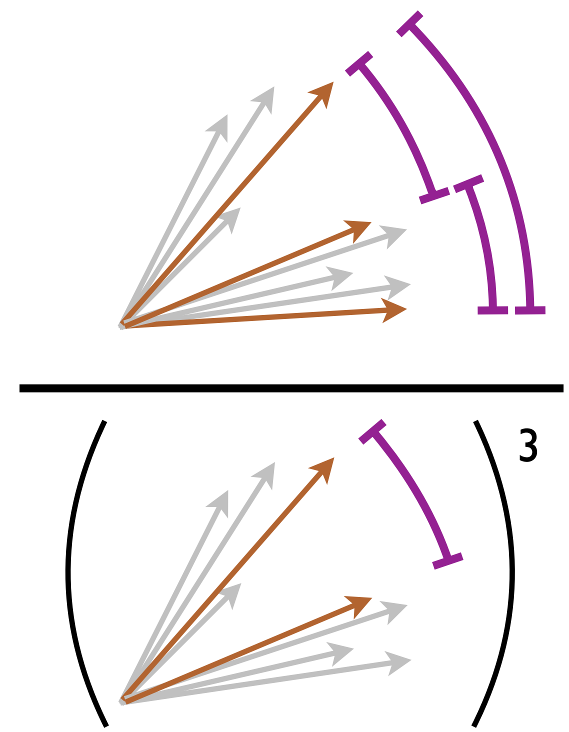


After grooming,
D_2 background distribution
is parametrically stable

Signal/Background Separation



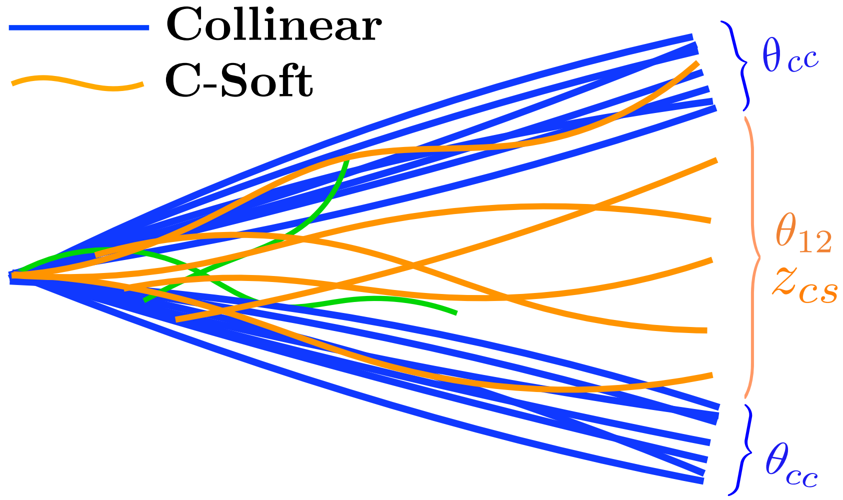
D_2 =



CCC

$$\simeq \frac{{\theta_{cc}}^3}{\left(\theta_{cc}\right)^3} \Rightarrow 1$$

CC



C₁C₂Cs   C₁C₂C

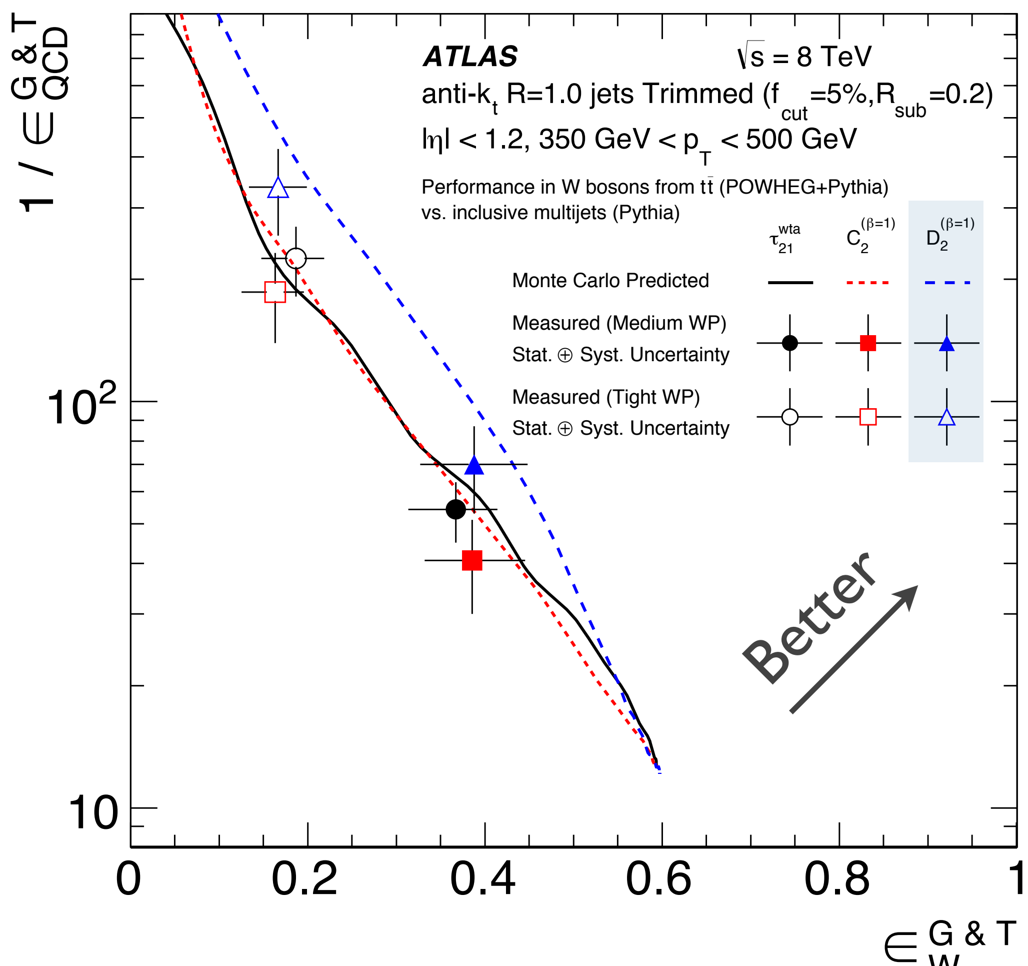
$$D_2 \simeq \frac{\theta_{12}^3 z_{cs} + \theta_{12}^2 \theta_{cc}}{\left(\theta_{12}\right)^3} \ll 1$$

C₁C₂

Signal parametrically distinct

Scorecard

ATLAS "R2D2" Tagger

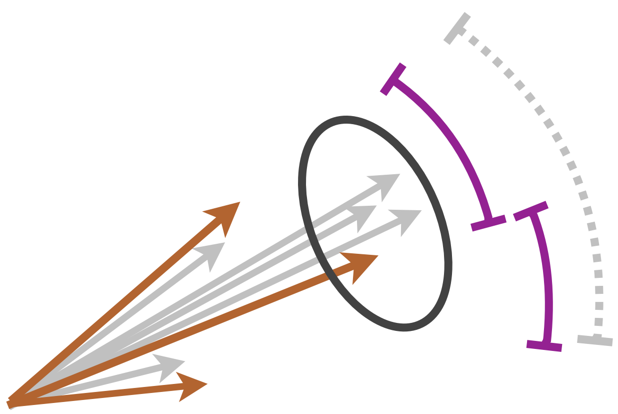


[ATLAS, 1510.05821]

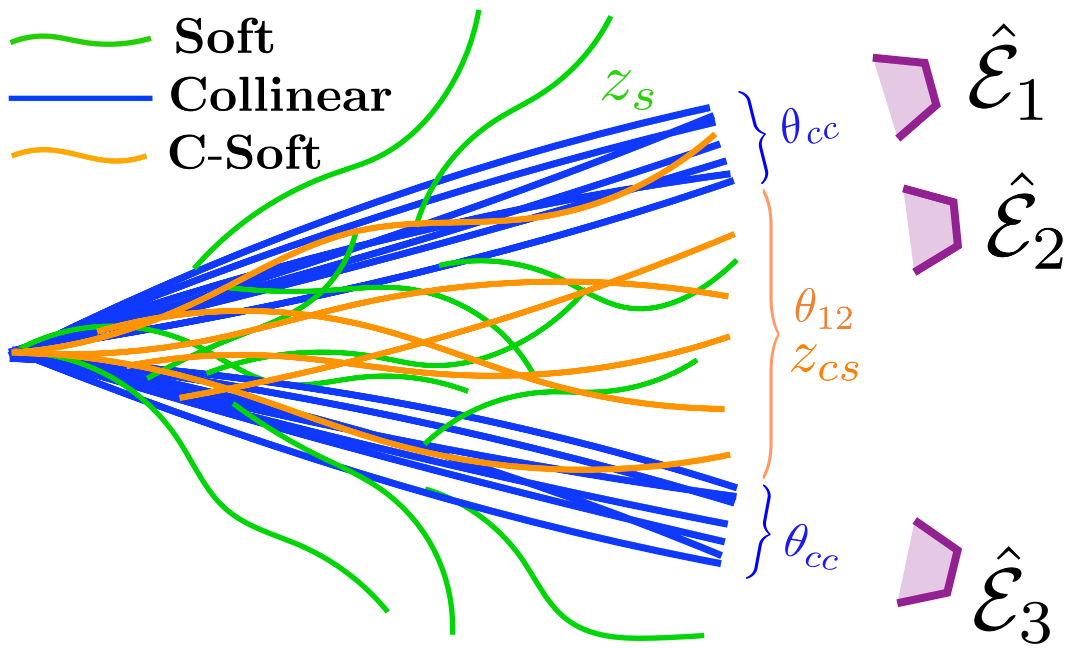
CMS	ATLAS EXPERIMENT
Soft Drop	*Trimming*
✓	✓*
N-subjettiness	*D_2*
before grooming	*after grooming*
✓	✓*
(also works after grooming)	*unstable before grooming

Theoretically sound W/Z tagging strategies for the LHC

A New Angle on Jet Substructure

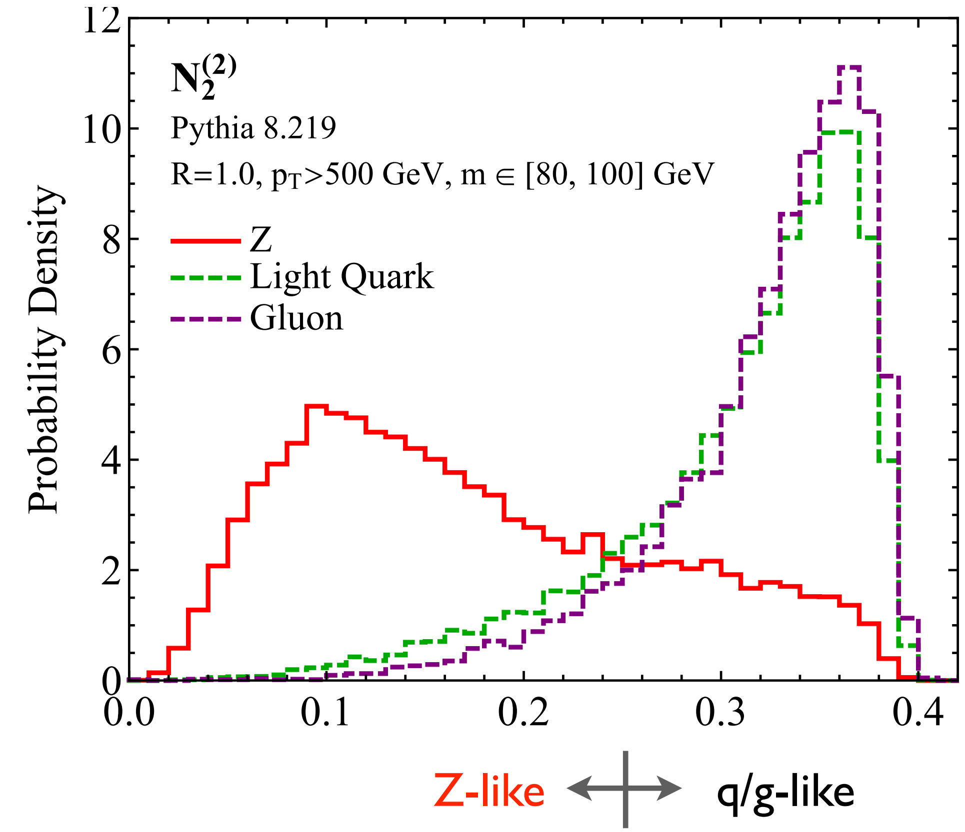


Punchline: W/Z Tagging in 2017?



$\Rightarrow$

Stable & Performant



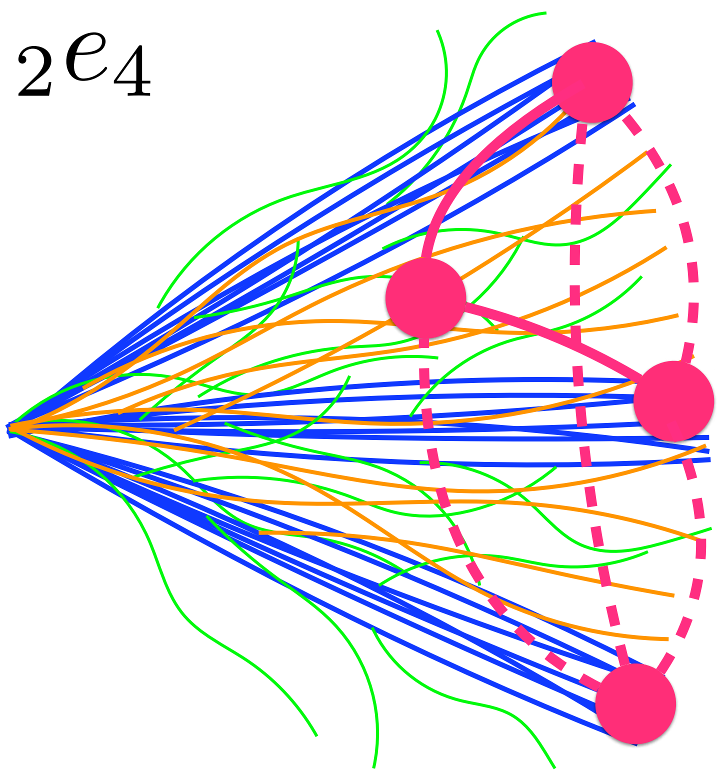
$$\boxed{N_2} = \frac{\displaystyle\sum_{i<j<k} p_{Ti}\, p_{Tj}\, p_{Tk} \min\left\{(R_{ij}R_{jk})^2, (R_{jk}R_{ki})^2, (R_{ki}R_{ij})^2\right\}}{\left(\displaystyle\sum_{i<j} p_{Ti}\, p_{Tj}\, R_{ij}^2\right)^2 \Big/ \displaystyle\sum_i p_{Ti}}$$

[Moult, Necib, JDT, 2016]

A New Angle on Energy Correlators

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

$_2e_4$



Systematic jet dissection

n = 2, 3, 4, …

v = 1, 2, 3, …, n choose 2

β = …, 0.5, 1, 2, …

collinear dominated

soft dominated

[Moult, Necib, JDT, 1609.07483]

3-point Correlators

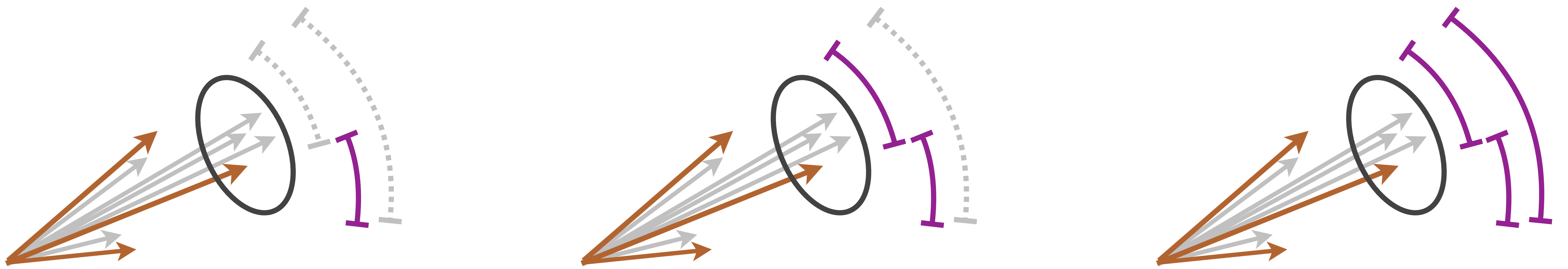
3-point:

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

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

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

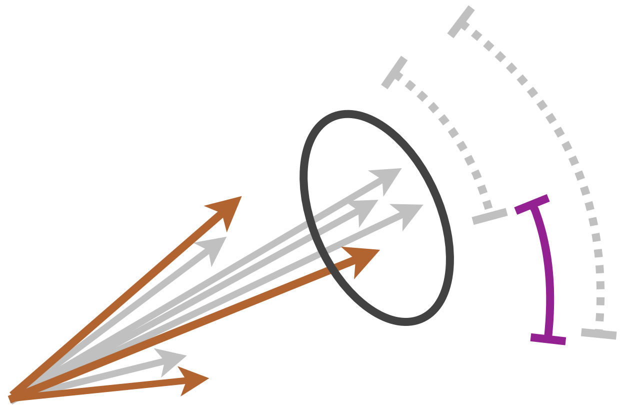
used for D_2



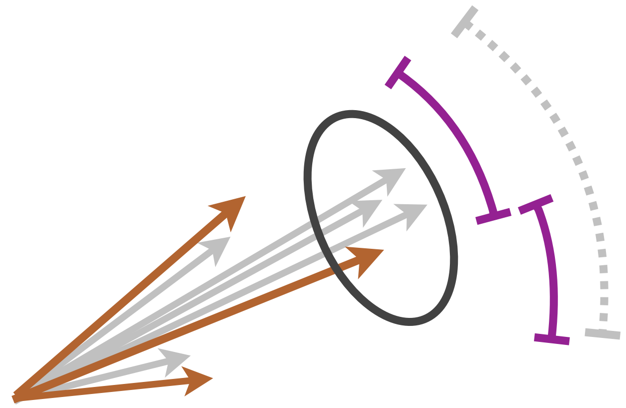
Probe of hierarchical jet substructure

[Moult, Necib, JDT, 1609.07483]

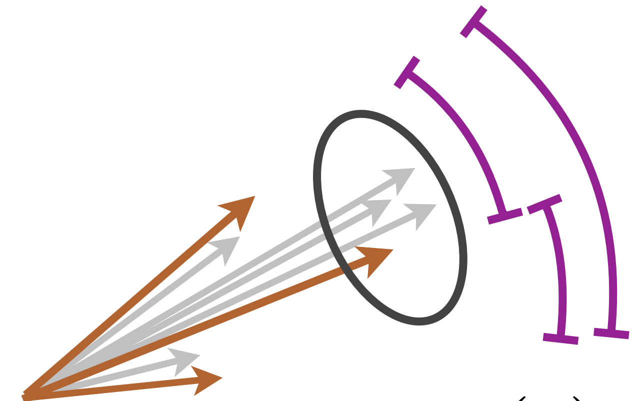
New Boosted W/Z Discriminants



$$M_2 = \frac{{}_1e_3}{{}_1e_2}$$



$$N_2 = \frac{{}_2e_3}{({}_1e_2)^2}$$



$$D_2^{(1,2)} = \frac{{}_3e_3^{(1)}}{\left({}_1e_2^{(2)}\right)^{\frac{3}{2}}}$$

Rule of thumb: boost invariance along jet axis

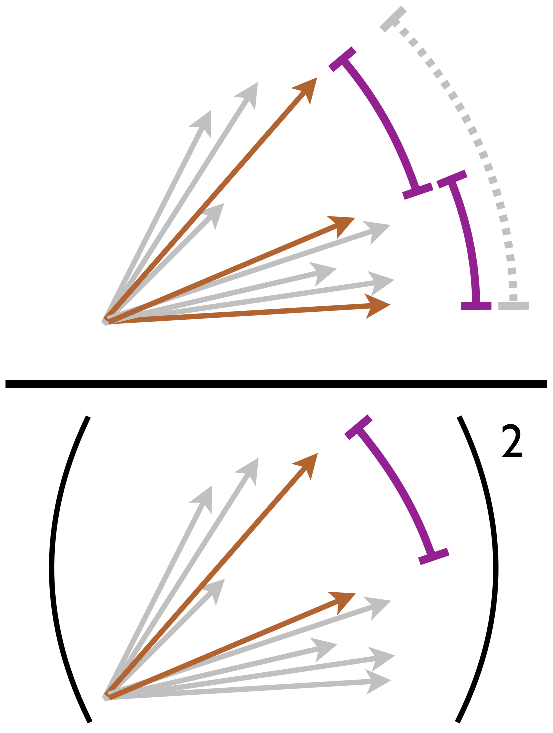
$$z_i \to z_i \quad \theta_{ij} \to \gamma^{-1}\theta_{ij}$$

(i.e. same angular scaling in numerator and denominator)

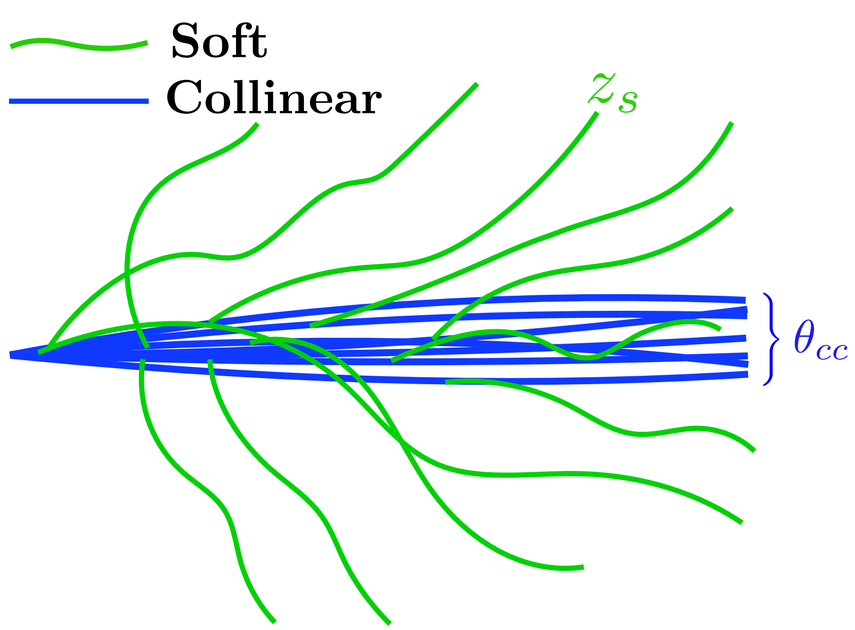
See also N_3 in the case of boosted top quarks

Power Counting N_2: Background

$$N_2 = \frac{{}_2e_3}{(e_2)^2} = \frac{\sum_{i<j<k} z_i z_j z_k \min\{\theta_{ij}\theta_{jk}, \theta_{jk}\theta_{ki}, \theta_{ki}\theta_{ij}\}^\beta}{\left(\sum_{i<j} z_i z_j \, \theta_{ij}{}^\beta\right)^2} =$$



Setting β = 1



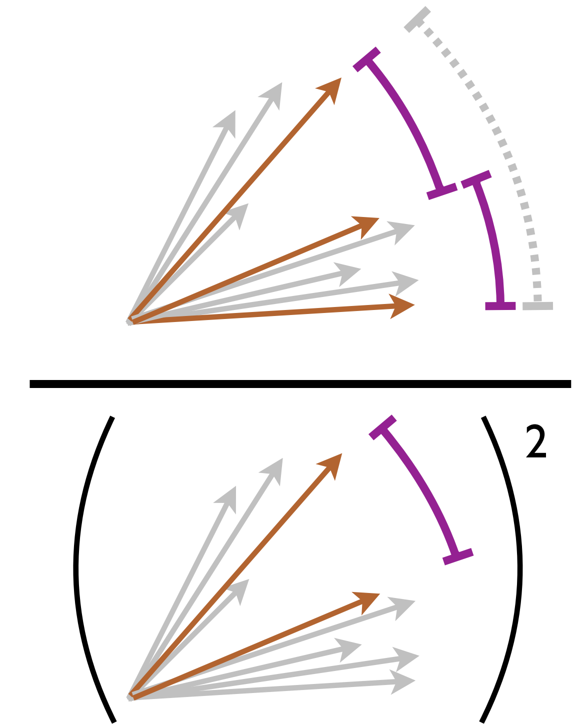
CCC CCS CSS

$$\simeq \frac{\theta_{cc}{}^2 + \theta_{cc} z_s + z_s{}^2}{\left(\theta_{cc} + z_s\right)^2}$$

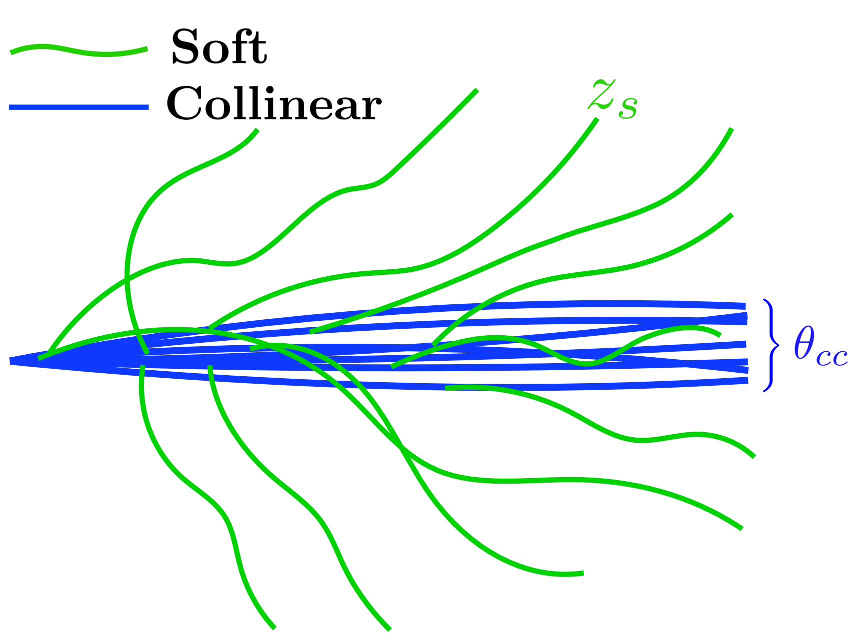
CC CS

Power Counting N_2: Background

$$N_2 = \frac{{}_2e_3}{(e_2)^2} = \frac{\sum_{i<j<k} z_i z_j z_k \min\{\theta_{ij}\theta_{jk}, \theta_{jk}\theta_{ki}, \theta_{ki}\theta_{ij}\}^\beta}{\left(\sum_{i<j} z_i z_j \, \theta_{ij}{}^\beta\right)^2} =$$



Setting β = 1



CCC CCS CSS

$$\simeq \frac{\theta_{cc}{}^2 + \theta_{cc} z_s + z_s{}^2}{\left(\theta_{cc} + z_s\right)^2} \Rightarrow 1$$

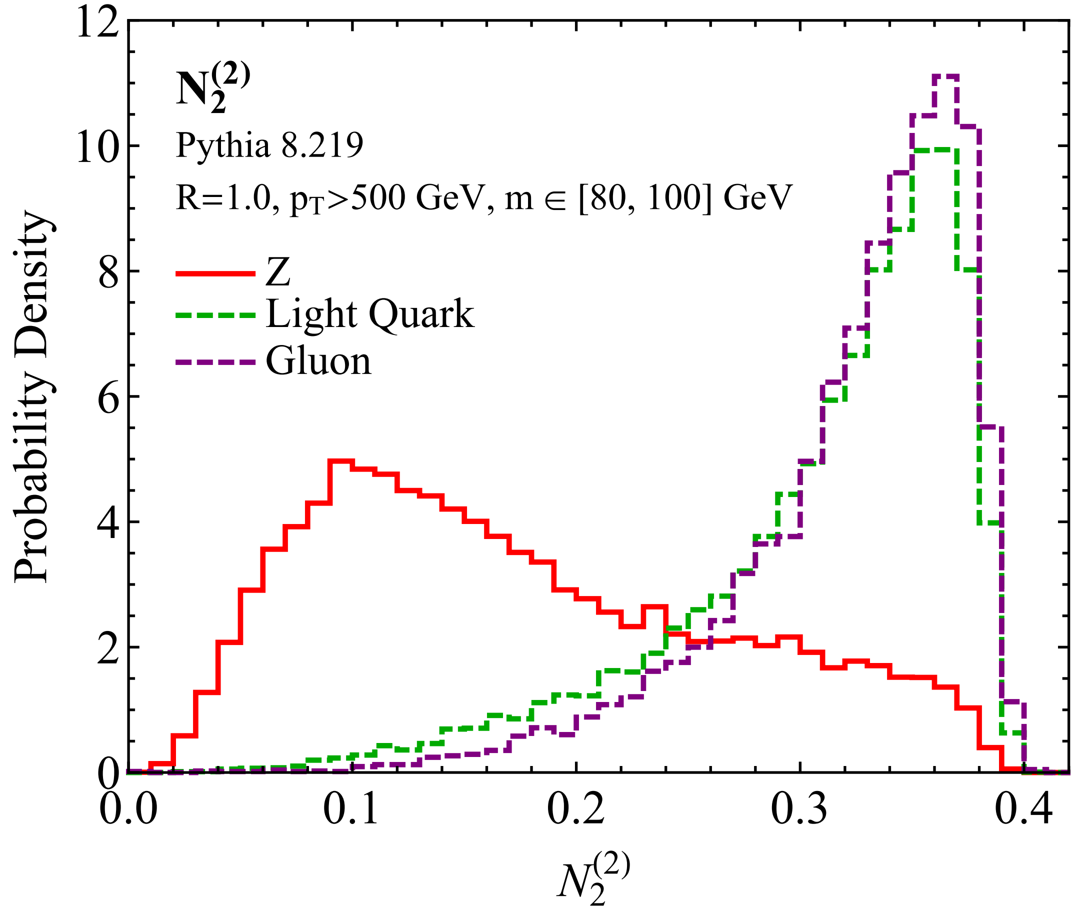
CC CS

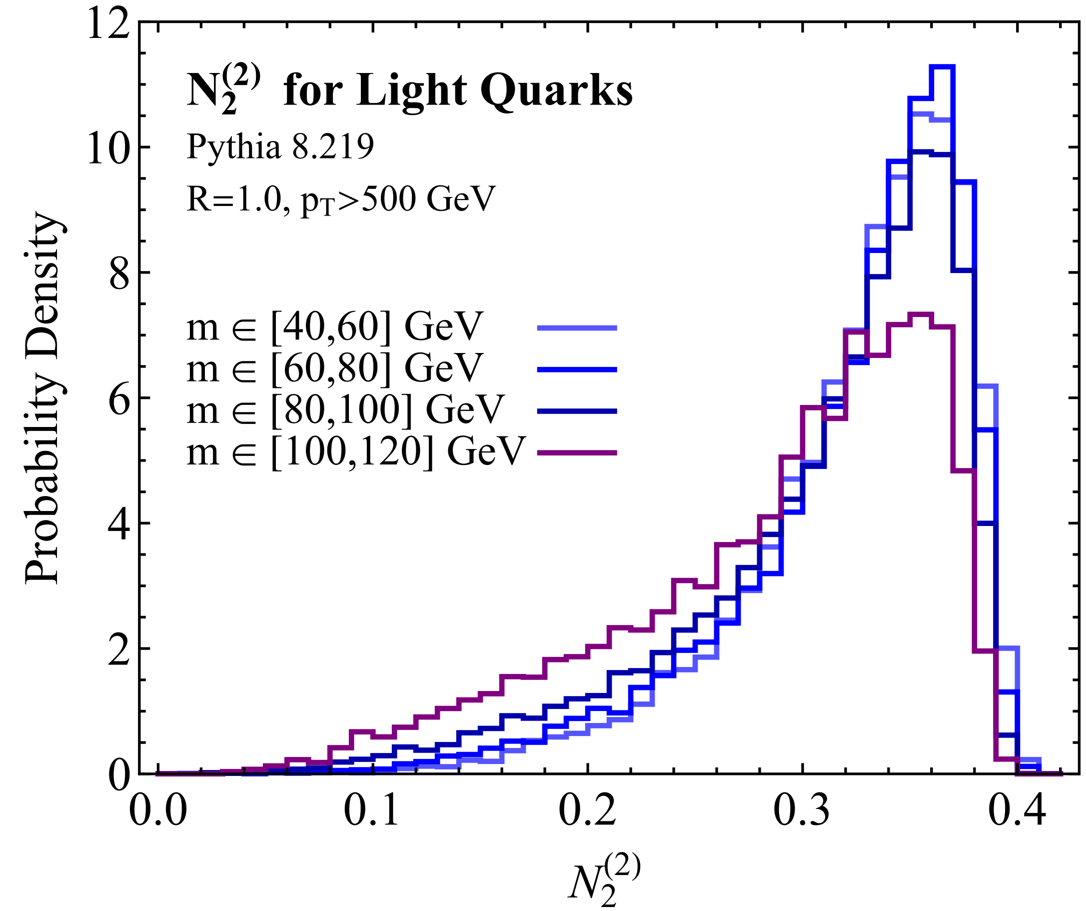
Parametrically stable in both soft and collinear regimes

N_2: Before Grooming

Derived using EFT power counting for both…

Performance & *Robustness*



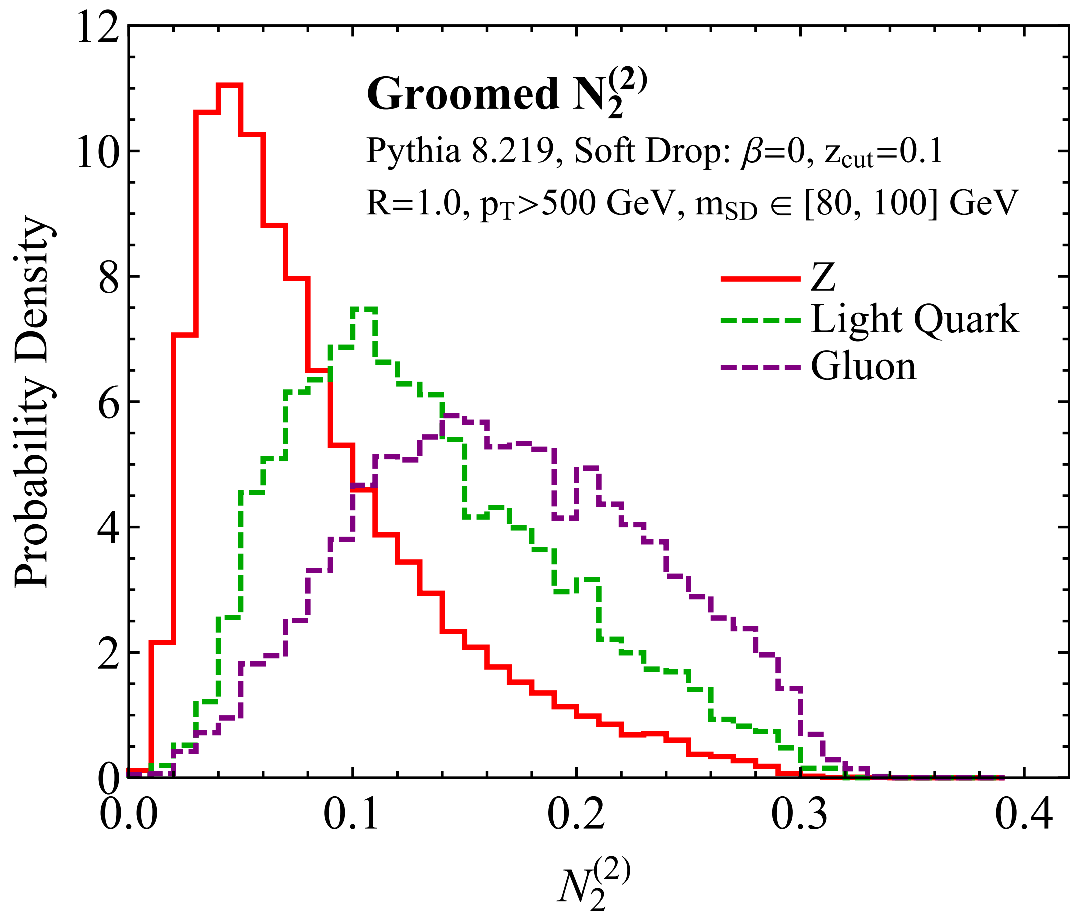


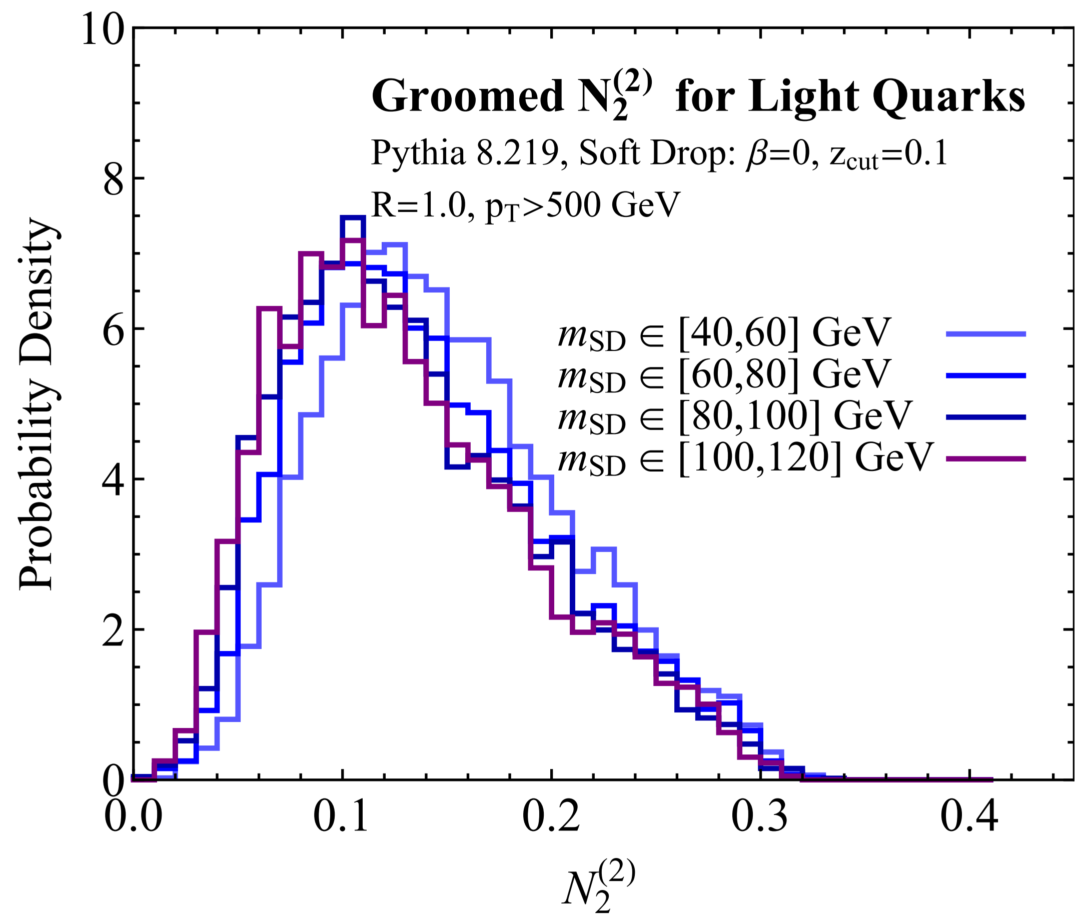
[Moult, Necib, JDT, 1609.07483]

N_2: After Grooming

Derived using EFT power counting for both…

Performance & *Robustness*





[Moult, Necib, JDT, 1609.07483]

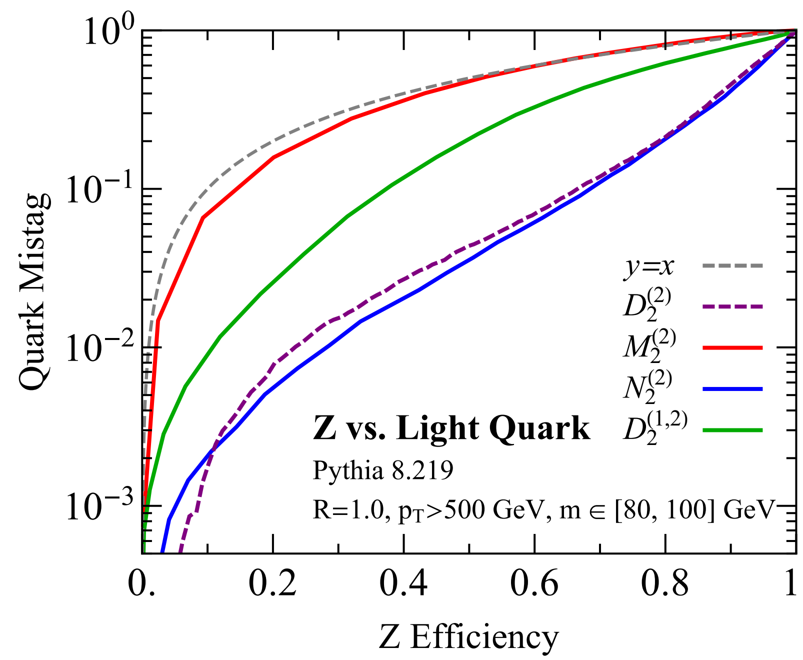
Performance Follows Power Counting

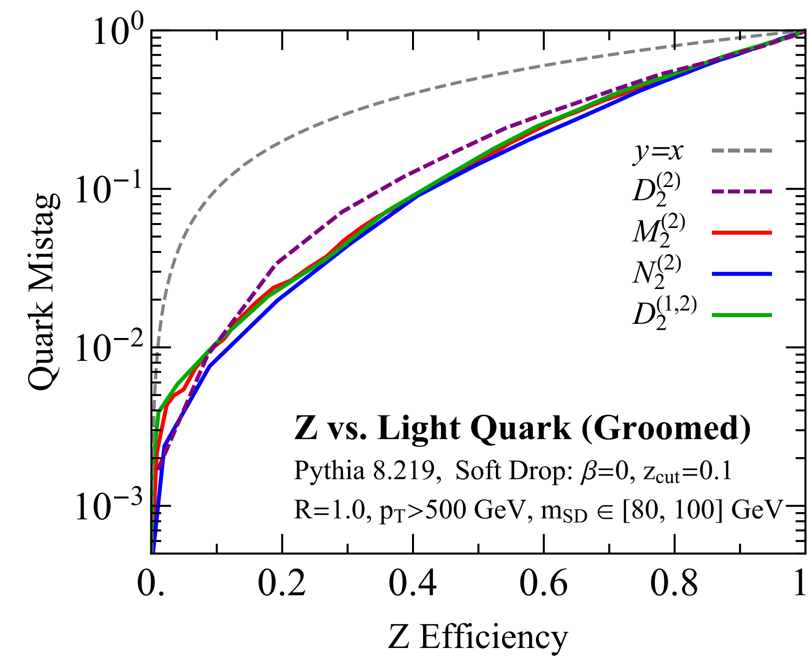
Better

Before Grooming

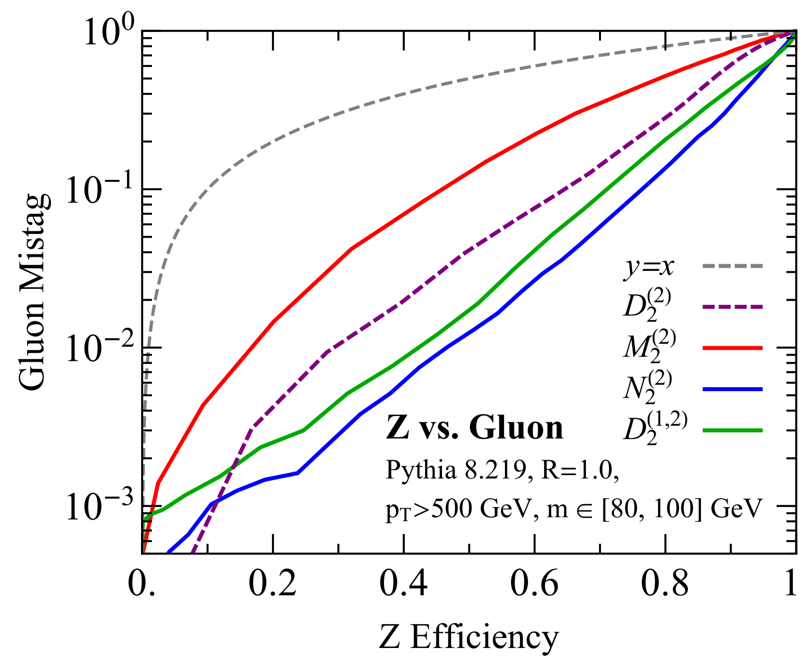
After Grooming

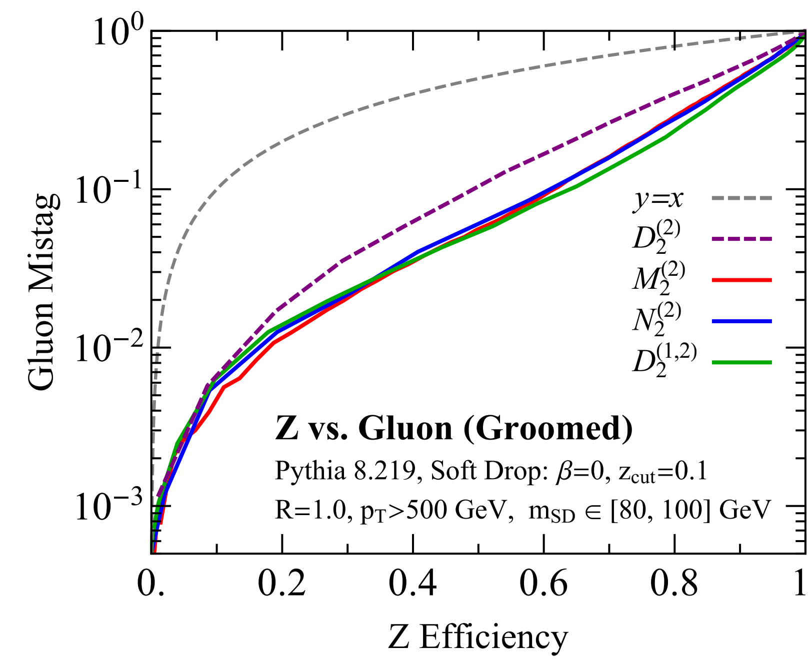
Z vs. q





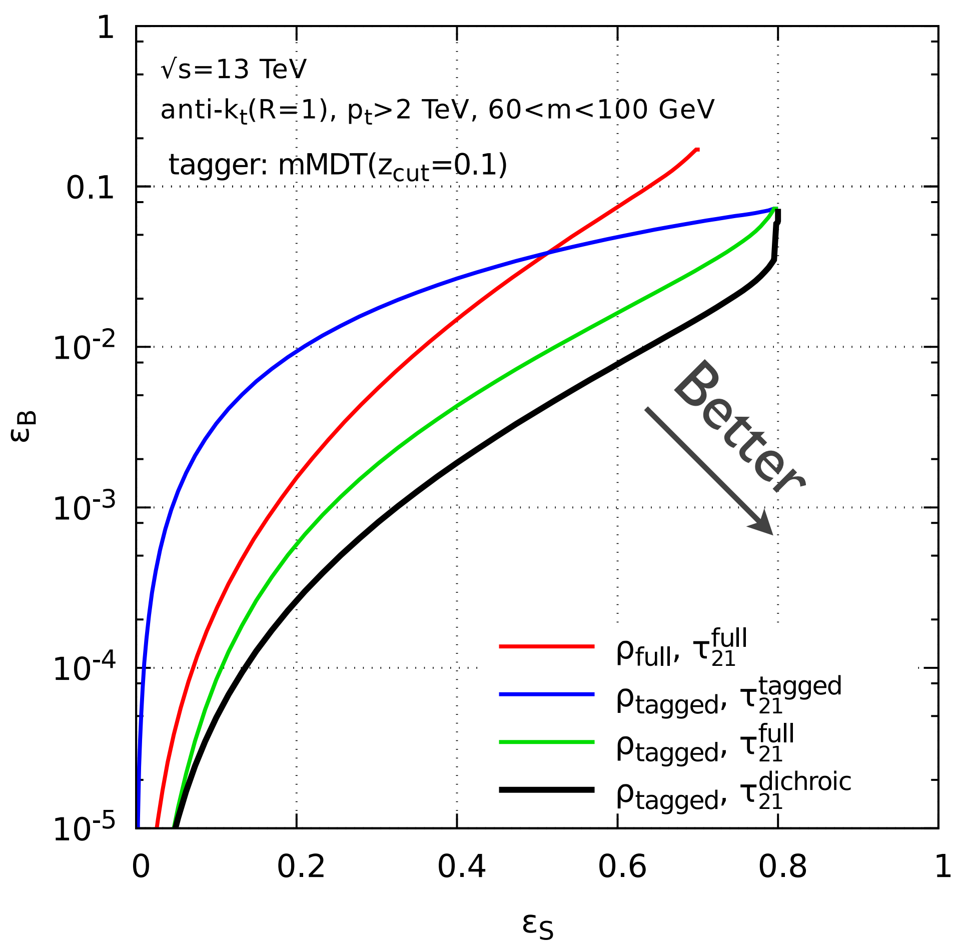
Z vs. g





(Note, groomed mass gives x3-5 better background rejection by itself)

More Grooming/Discrimination Interplay



no grooming

(N.B. for this talk, tagged ⇒ groomed)

groomed mass
groomed τ_2/τ_1

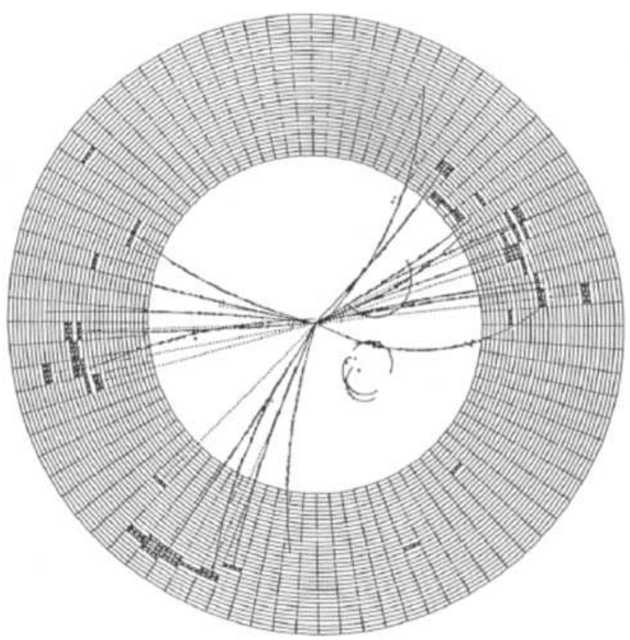
groomed mass
ungroomed τ_2/τ_1 ←

groomed mass
"dichroic" τ_2/τ_1 $= \dfrac{\textbf{ungroomed } \tau_2}{\textbf{groomed } \tau_1}$

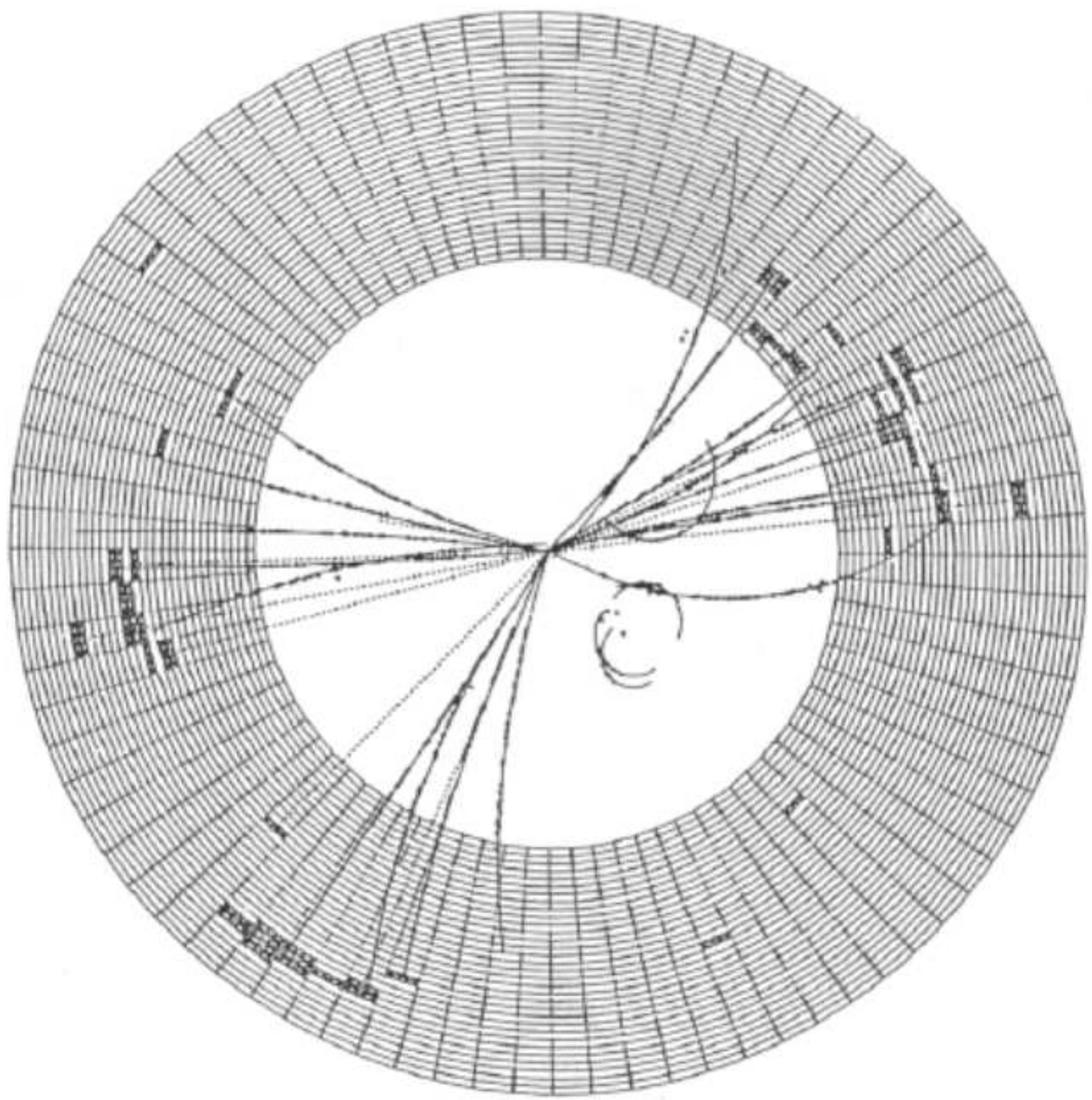
Analytic calculations to identify optimal use of substructure information

[Salam, Schunk, Soyez, 1612.03917]

Back to the Future: Quarks vs. Gluons



Quark vs. Gluon?



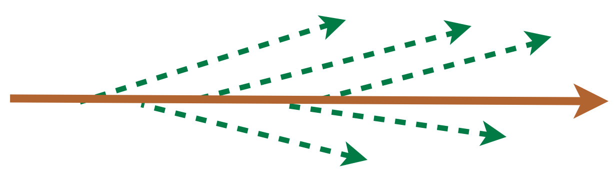
$$e^+e^- \to q\bar{q}g$$

[JADE,1979]

Cartoon:

Quark: $C_F = 4/3$

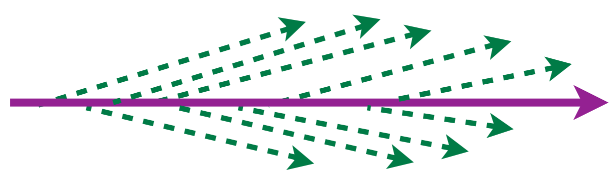
usually signals



vs.

Gluon: $C_A = 3$

usually backgrounds

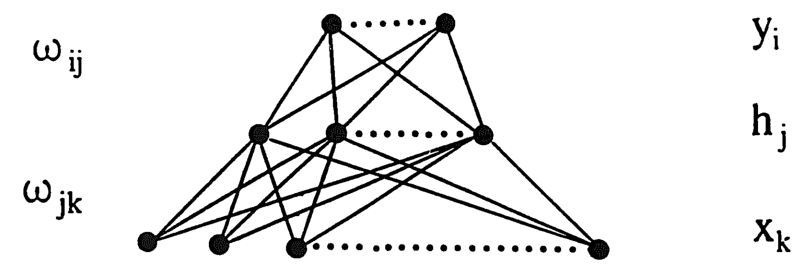


$$\text{gluon mistag} \simeq \left(\text{quark efficiency}\right)^{C_A/C_F}$$

barely improves $S/\sqrt{B}$

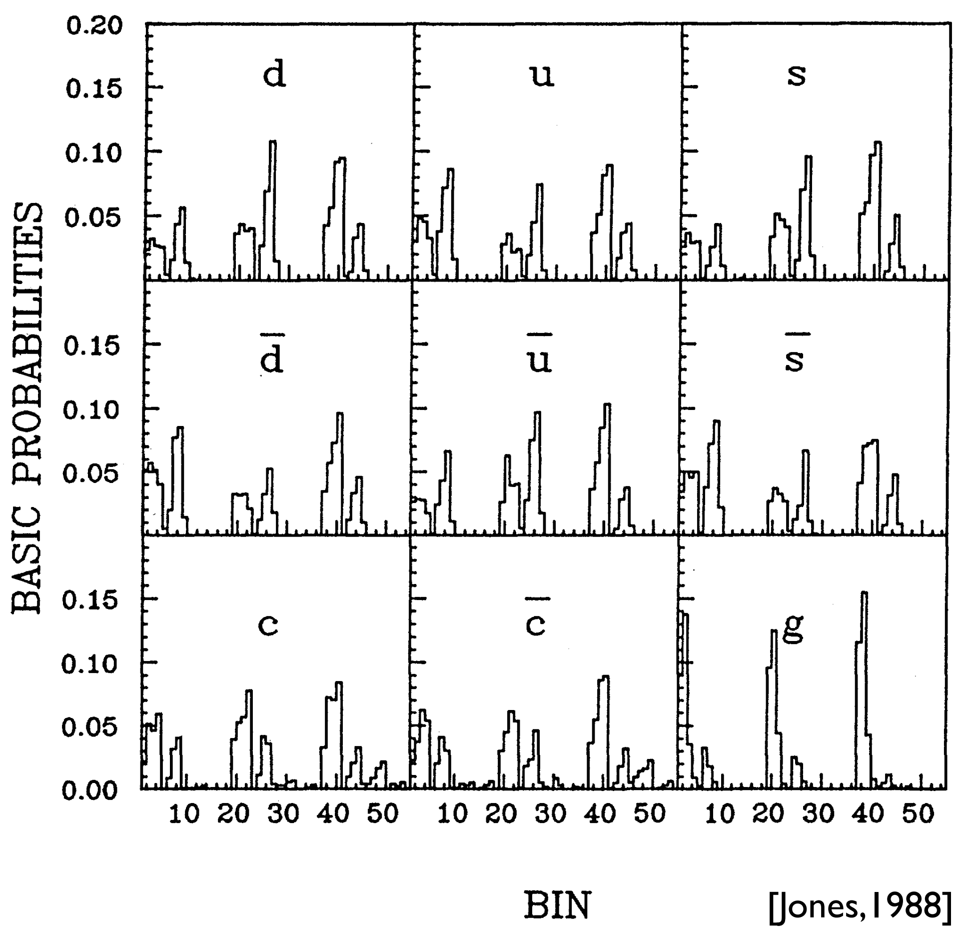
An Old Idea…

Neural Network Classification



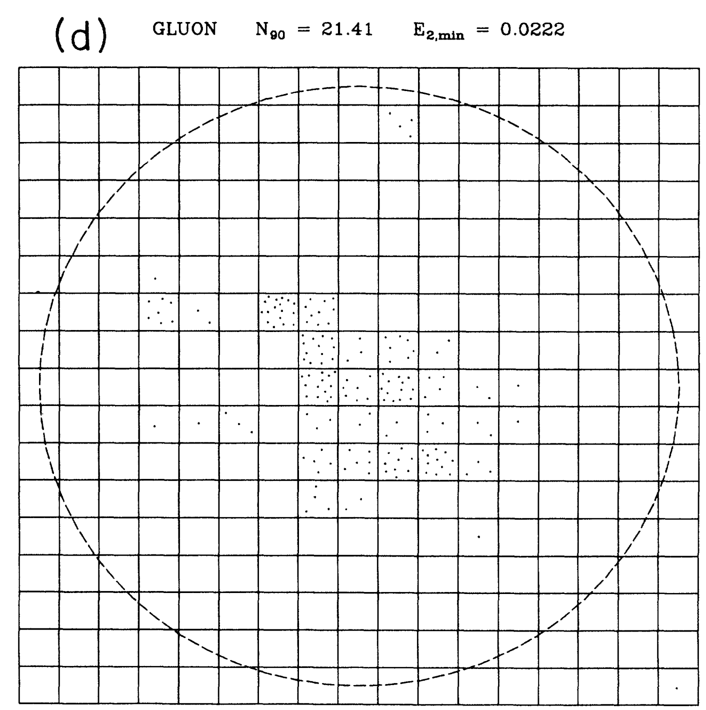
[Lönnblad, Peterson, Rögnvaldsson, 1991]

Binned hadron flavor/kinematics



[Jones,1988]

N_{90} = Cell count for 90% of jet p_T

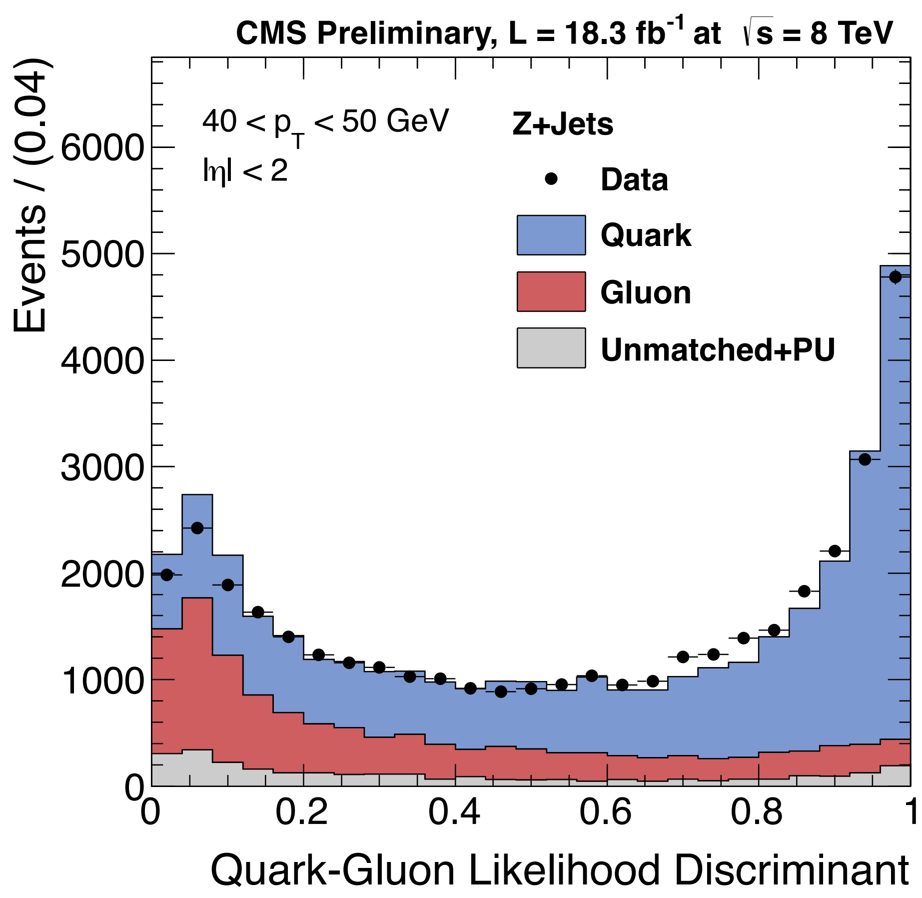


[Pumplin, 1991]

[see also Nilles, Streng, 1981; Fodor, 1990; …]

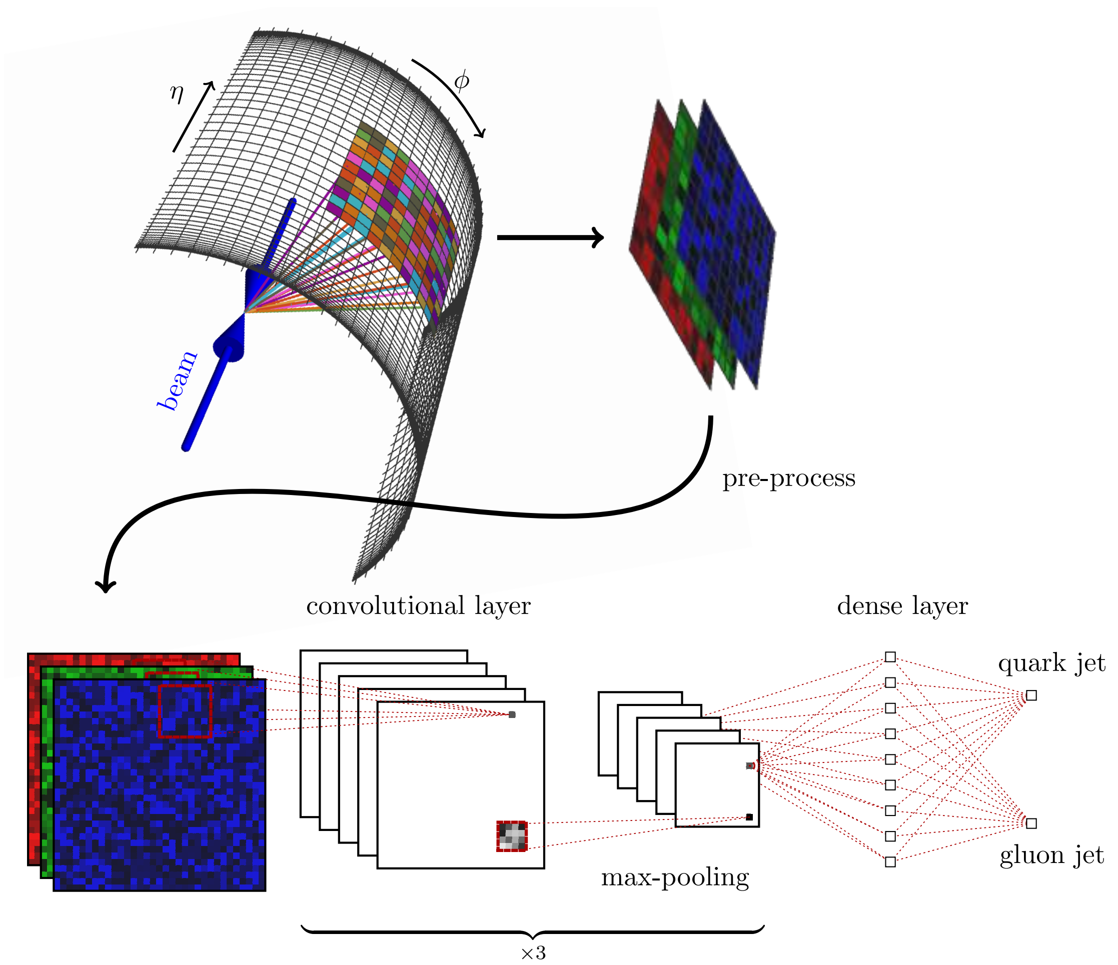
…with Renewed LHC Interest

Three Observable Discriminant
(n_{had}, $p_T{}^D$, σ_2)



[CMS, JME-13-002]

Convolutional ("Deep") Network
($p_T{}^{charged}$, $p_T{}^{neutral}$, $n_{charged}$)

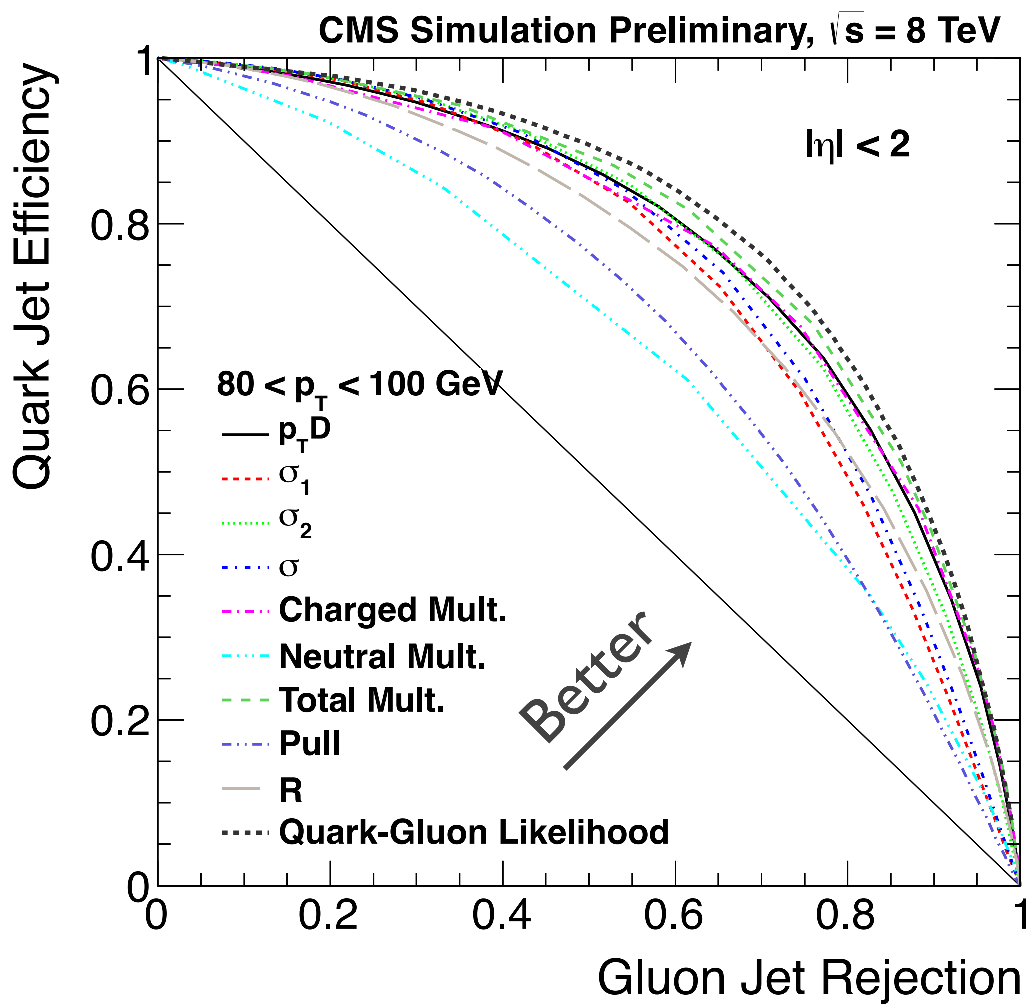


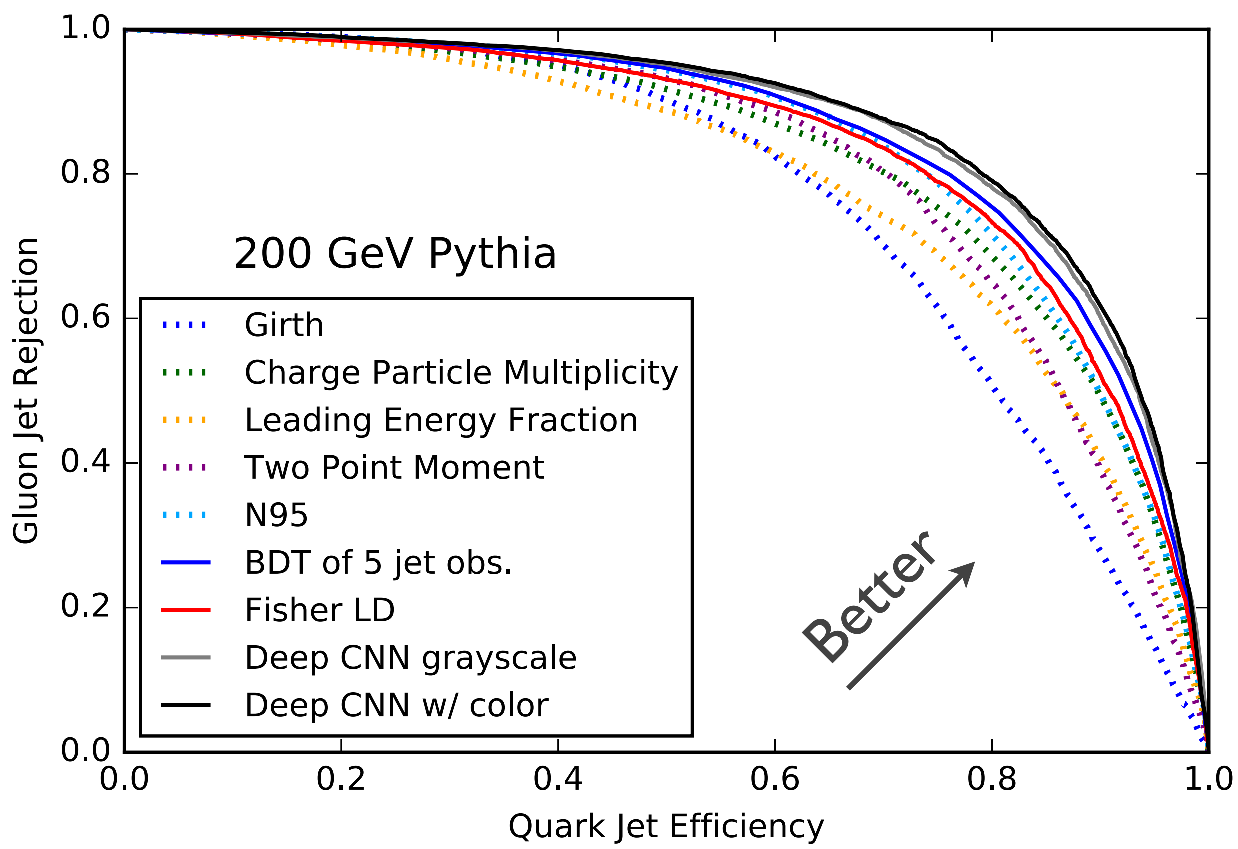
[Komiske, Metodiev, Schwartz, 1612.01551]

[see also Gallicchio, Schwartz, 1106.3076, 1211.7038; Krohn, Schwartz, Lin, Waalewijn, 1209.2421;
Larkoski, Salam, JDT, 1305.0007; Larkoski, JDT, Waalewijn, 1408.3122; Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, Webber, 1501.04794]

…with Renewed LHC Interest

Performance gains from multivariate information

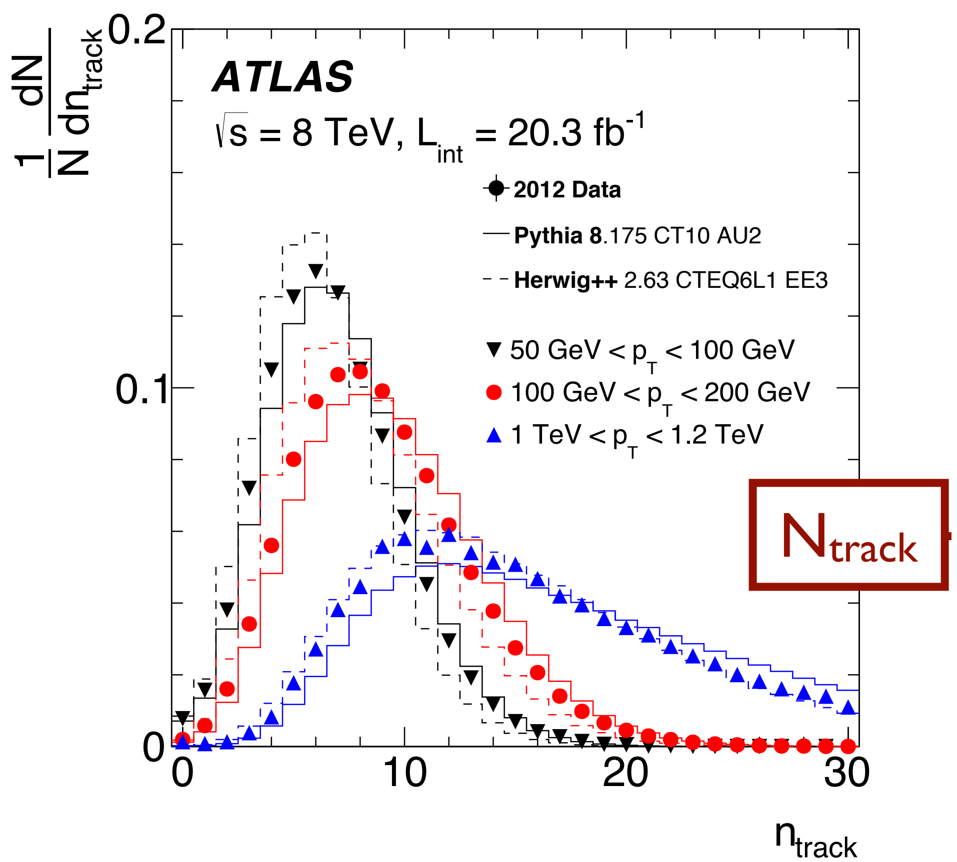




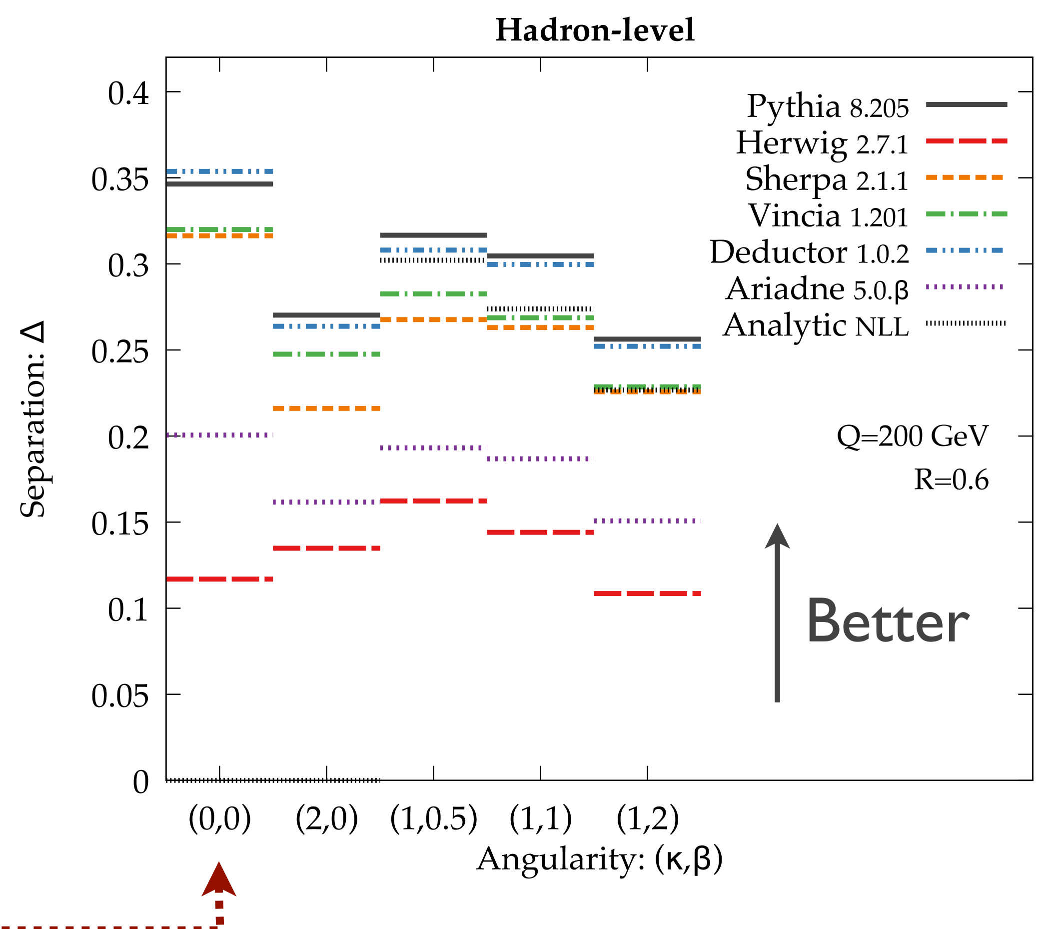
[see also Gallicchio, Schwartz, 1106.3076, 1211.7038; Krohn, Schwartz, Lin, Waalewijn, 1209.2421; Larkoski, Salam, JDT, 1305.0007; Larkoski, JDT, Waalewijn, 1408.3122; Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, Webber, 1501.04794]

Challenge: Theoretical Uncertainties

“Pythia/Herwig Sandwich”



Classifier Separation

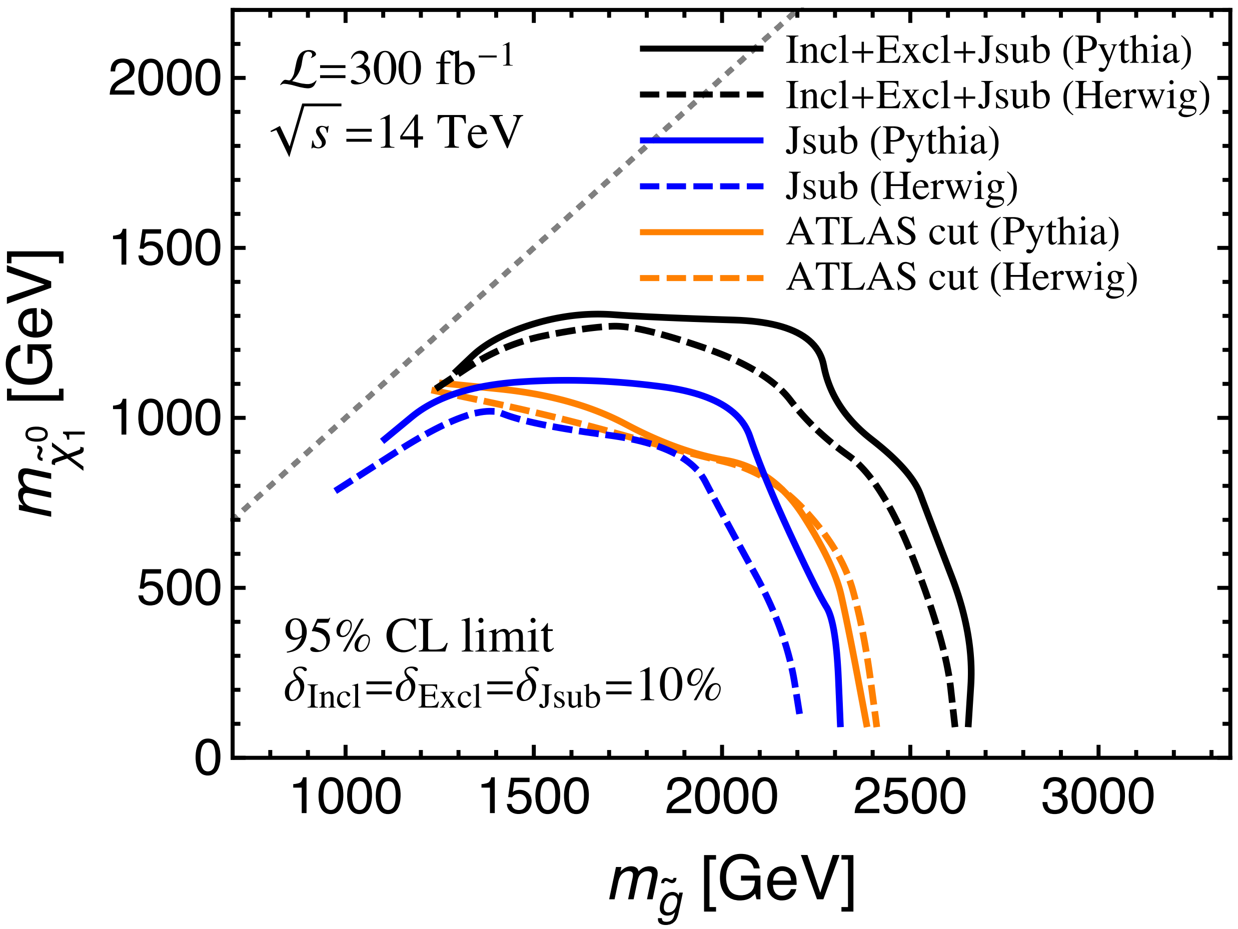


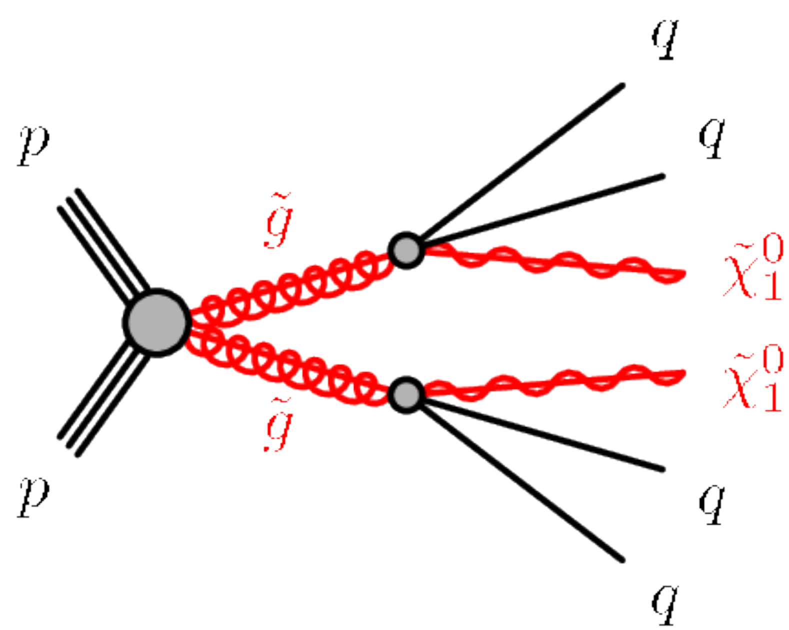
Small uncertainties in distributions yield large uncertainties in discrimination power

[ATLAS, 1602.00988]
[Soyez, JDT, Freytsis, Gras, Kar, Lönnblad, Plätzer, Siodmok, Skands, Soper, 1605.04692]

Challenge: Theoretical Uncertainties

Opportunity: New Physics Applications



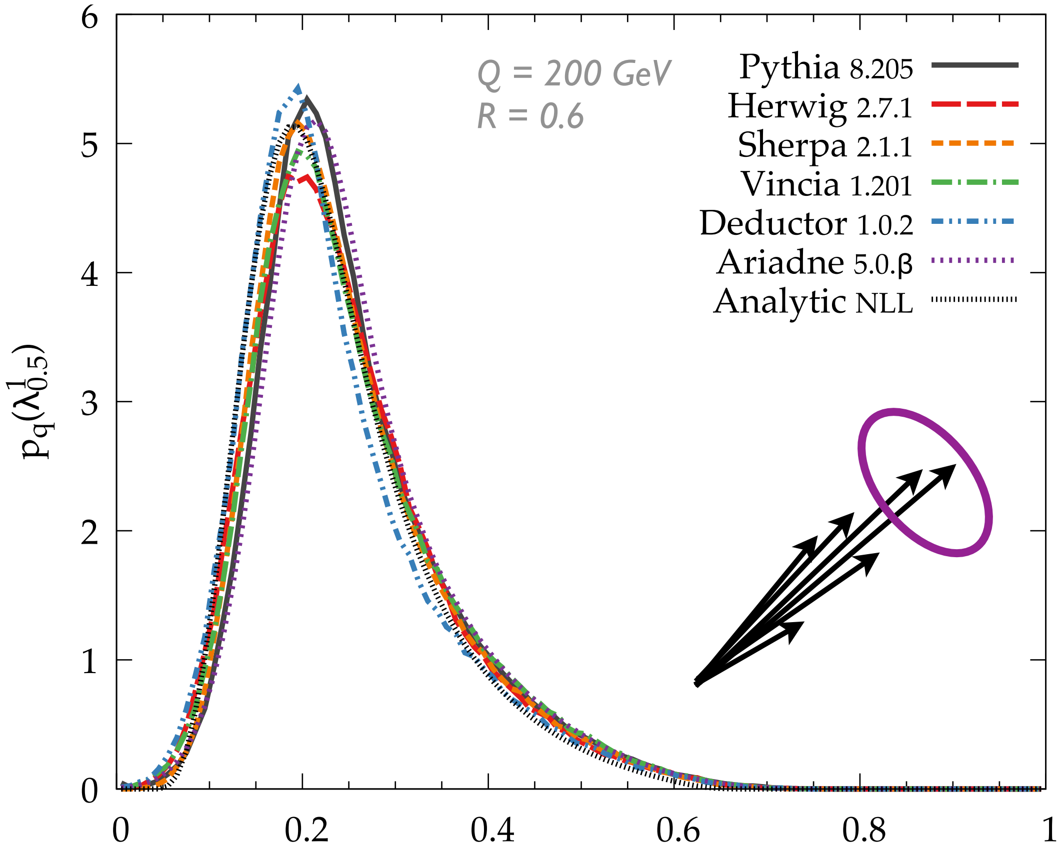


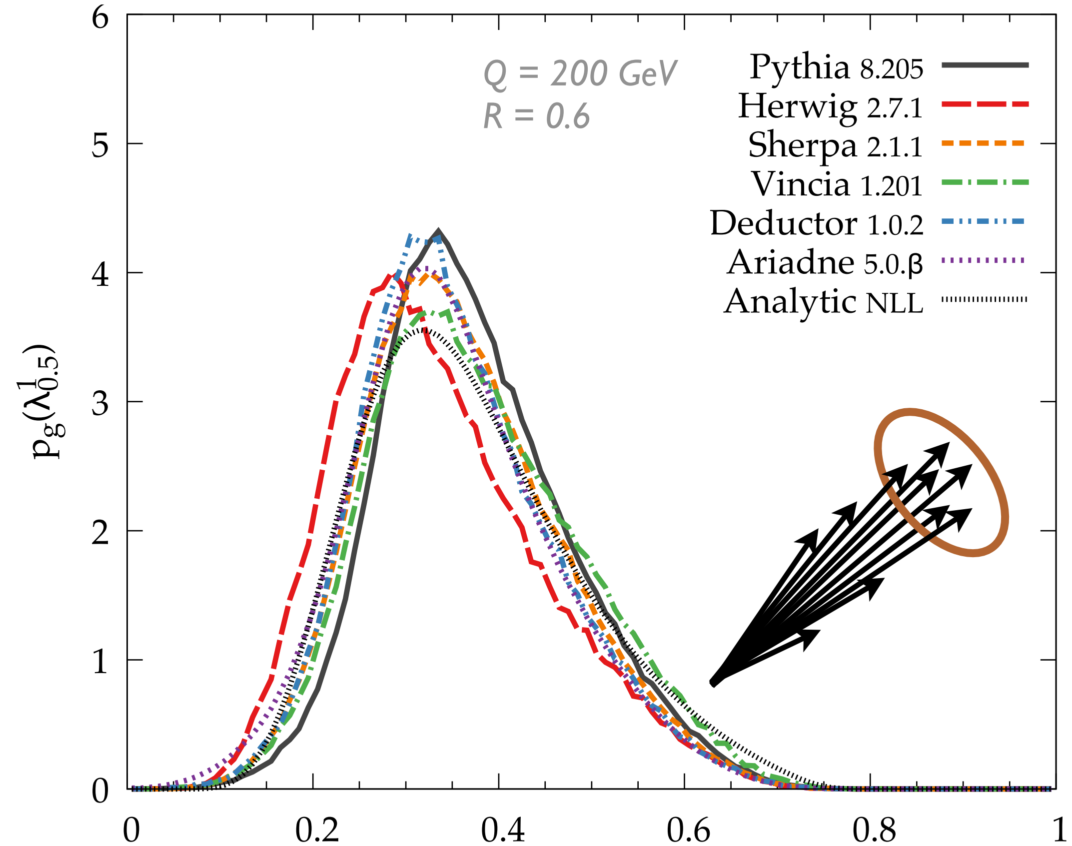
[Bhattacherjee, Mukhopadhyay, Nojiri, Sakakie, Webber, 1609.08781]

[ATLAS, 1602.00988]
[Soyez, JDT, Freytsis, Gras, Kar, Lönnblad, Plätzer, Siodmok, Skands, Soper, 1605.04692]

Key Task for Jet Substructure

$e^+e^- \to$ quarks ($C_F = 4/3$) *vs.* $e^+e^- \to$ gluons ($C_A = 3$)





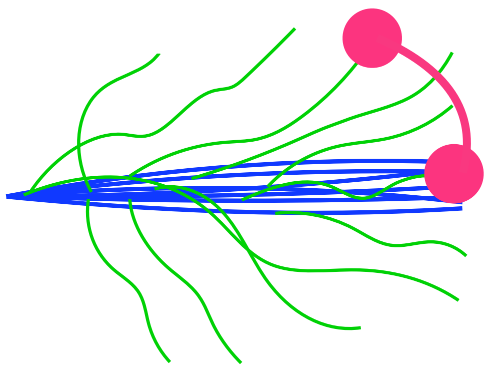
$$\mathrm{LHA} = \sum_i z_i \sqrt{\theta_i}$$

Well-constrained by LEP measurements

Needs more input from experiment (and theory)

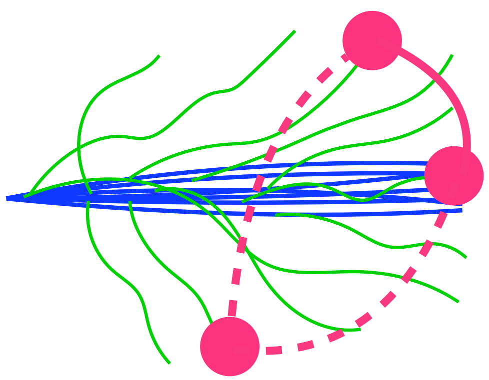
[Soyez, JDT, Freytsis, Gras, Kar, Lönnblad, Plätzer, Siodmok, Skands, Soper, 1605.04692]

The Next Frontier: Information Beyond C_A/C_F

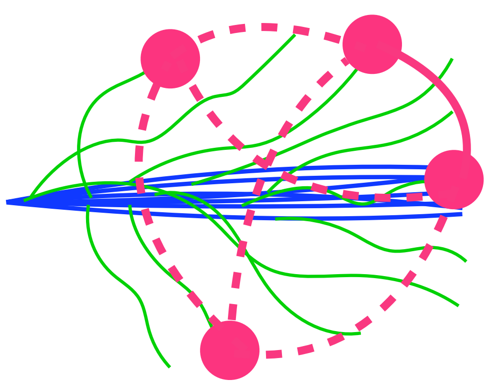


$$U_1 = \frac{\sum_{i<j} p_{Ti}\, p_{Tj}\, {R_{ij}}^{\beta}}{\left(\sum_i p_{Ti}\right)^2}$$

← Typical Quark/Gluon Discriminants



$$U_2 = \frac{\sum_{i<j<k} p_{Ti}\, p_{Tj}\, p_{Tk} \min\{R_{ij}, R_{jk}, R_{ki}\}^{\beta}}{\left(\sum_i p_{Ti}\right)^3}$$



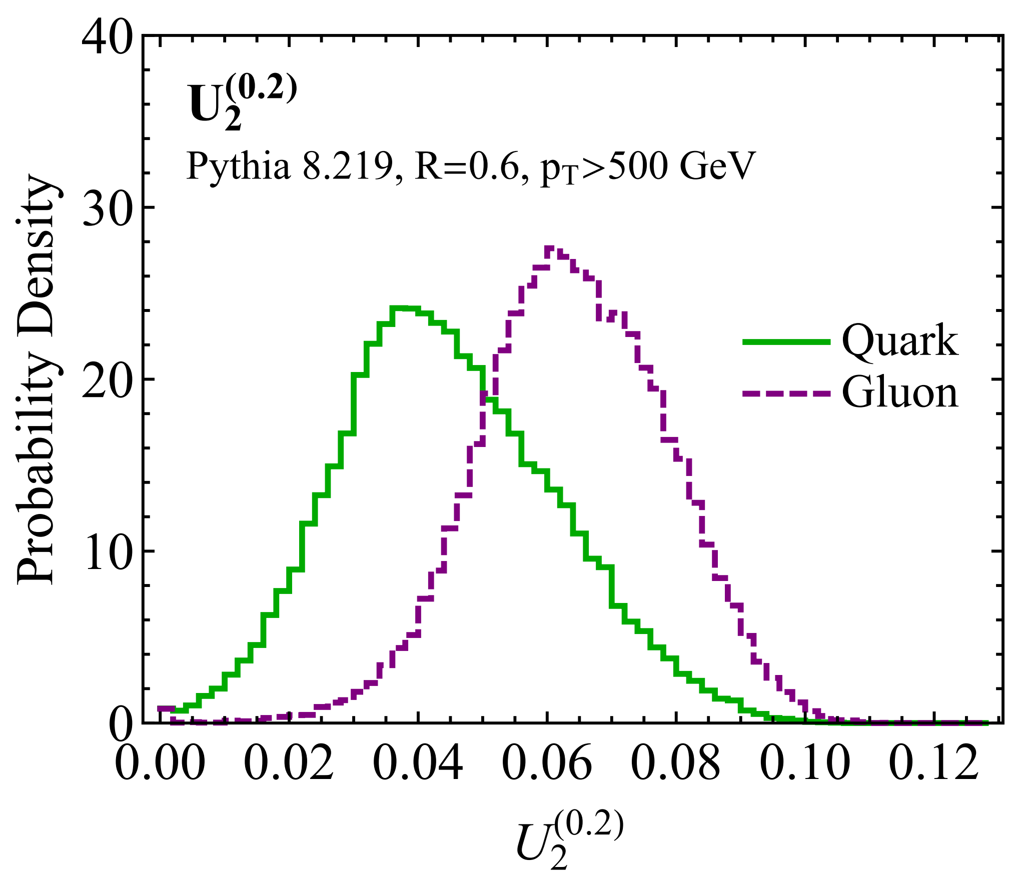
$$U_3 = \frac{\sum_{i<j<k<\ell} p_{Ti}\, p_{Tj}\, p_{Tk}\, p_{T\ell} \min\{R_{ij}, R_{jk}, R_{k\ell}, R_{ik}, R_{j\ell}, R_{i\ell}\}^{\beta}}{\left(\sum_i p_{Ti}\right)^4}$$

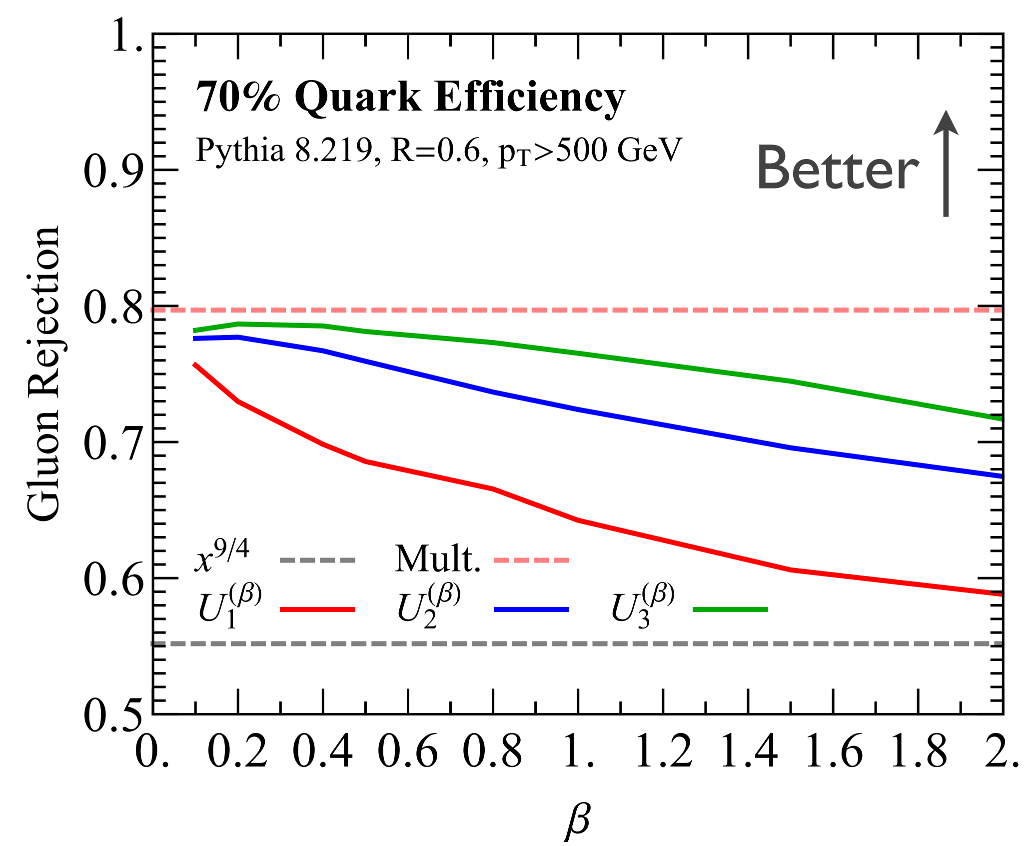
"Deep Learning" inspires "Deep Thinking"

[Moult, Necib, JDT, 1609.07483]

The Next Frontier: Information Beyond C_A/C_F

Derived using EFT power counting to probe perturbative multi-point soft-gluon phase space

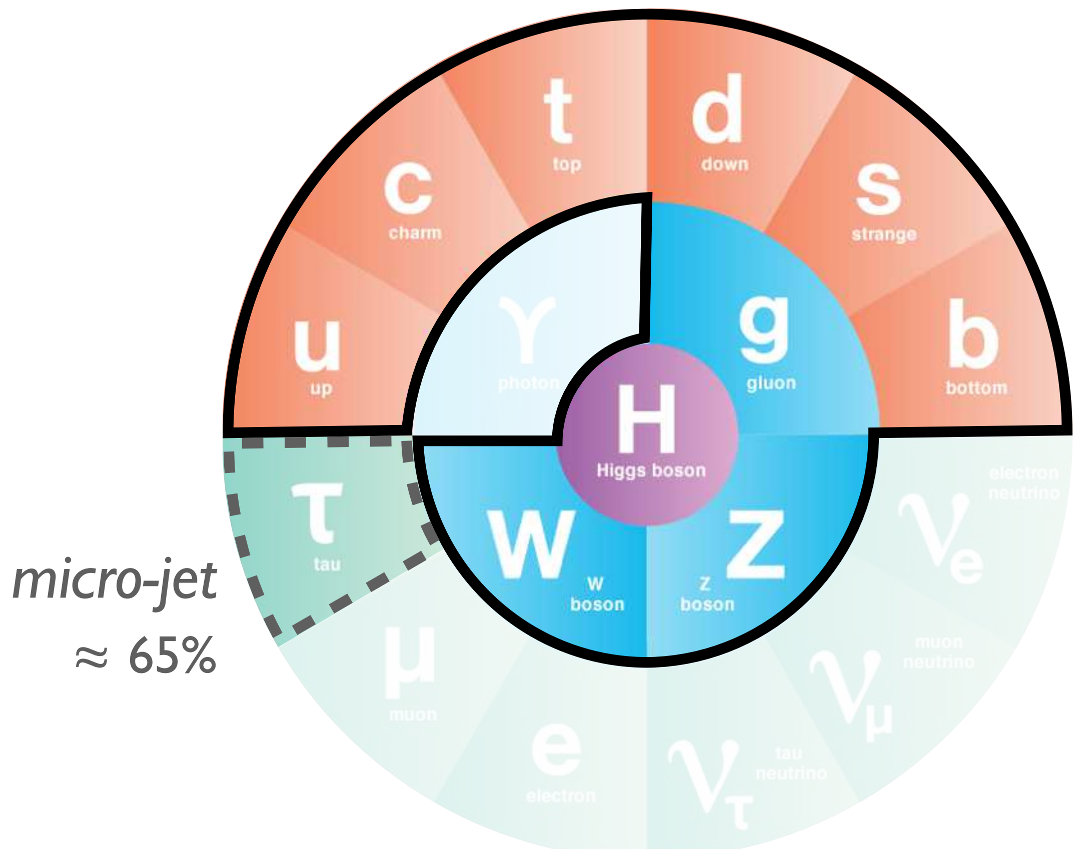


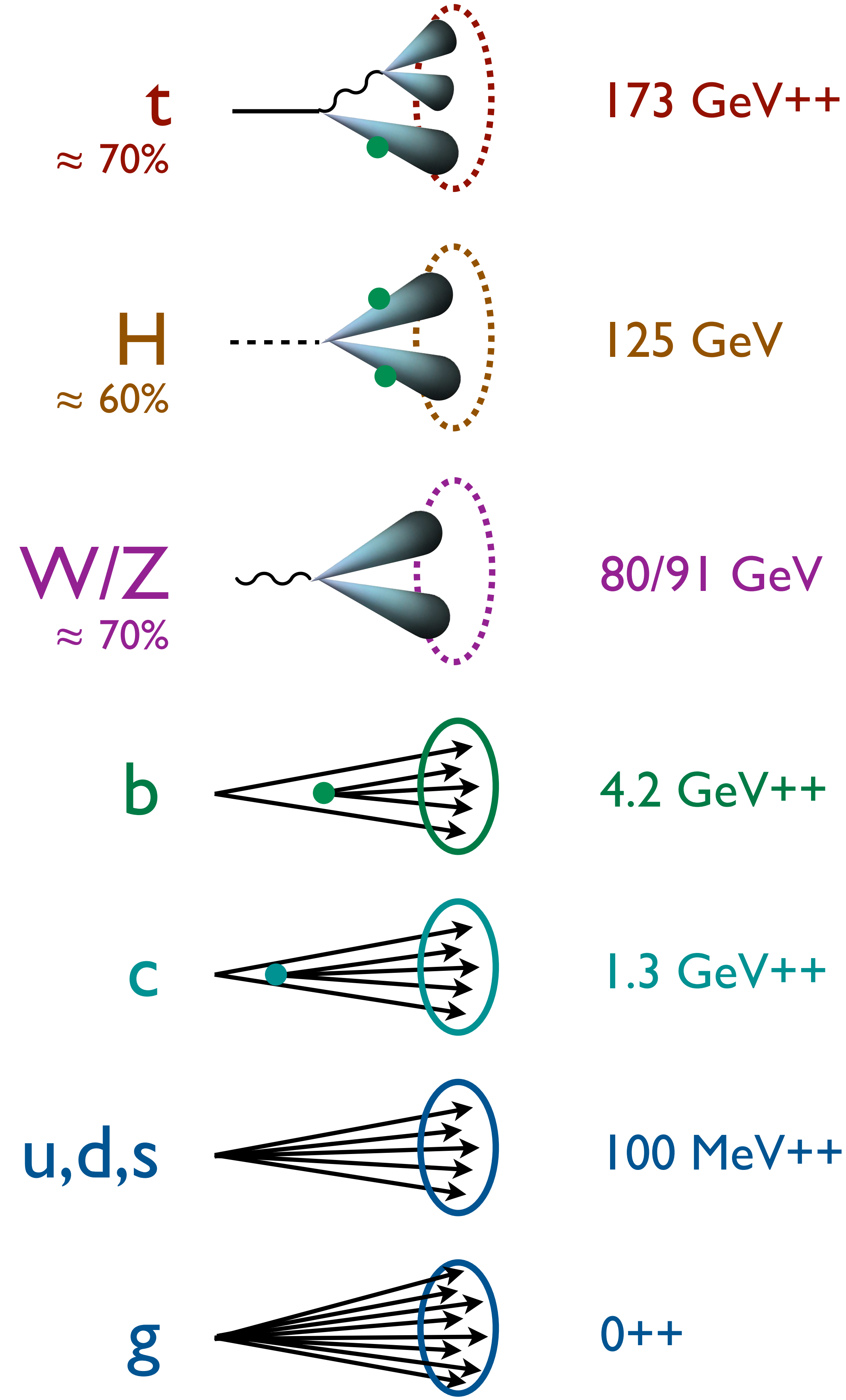


"Deep Learning" inspires "Deep Thinking"

[Moult, Necib, JDT, 1609.07483]

Jet Substructure in 2017





Goal: Systematic Jet Classification from First Principles