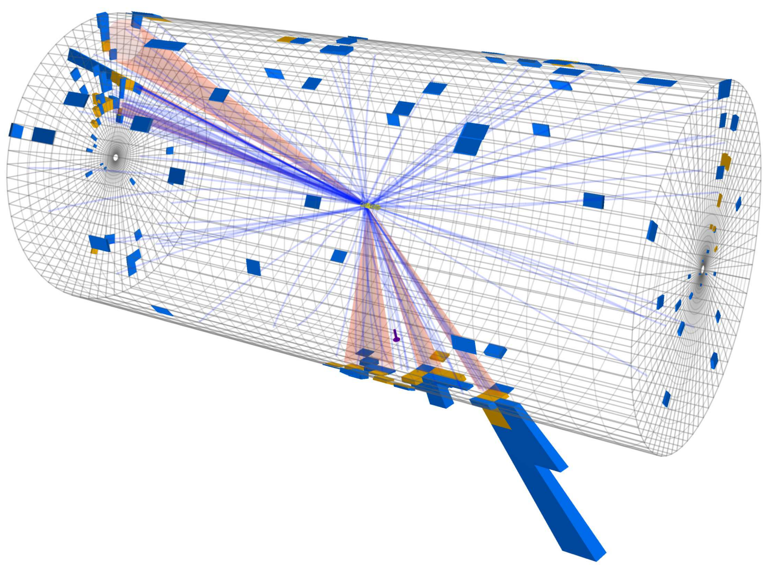
A New Angle on Jet Substructure

Jesse Thaler

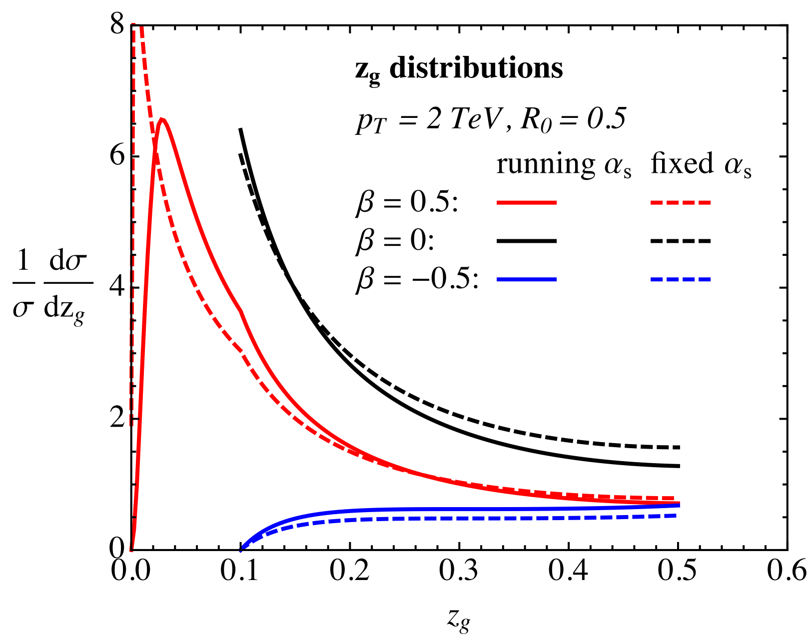
Kavli IPMU — January 13, 2017

Jet Substructure



Boosting the Search for New Phenomena

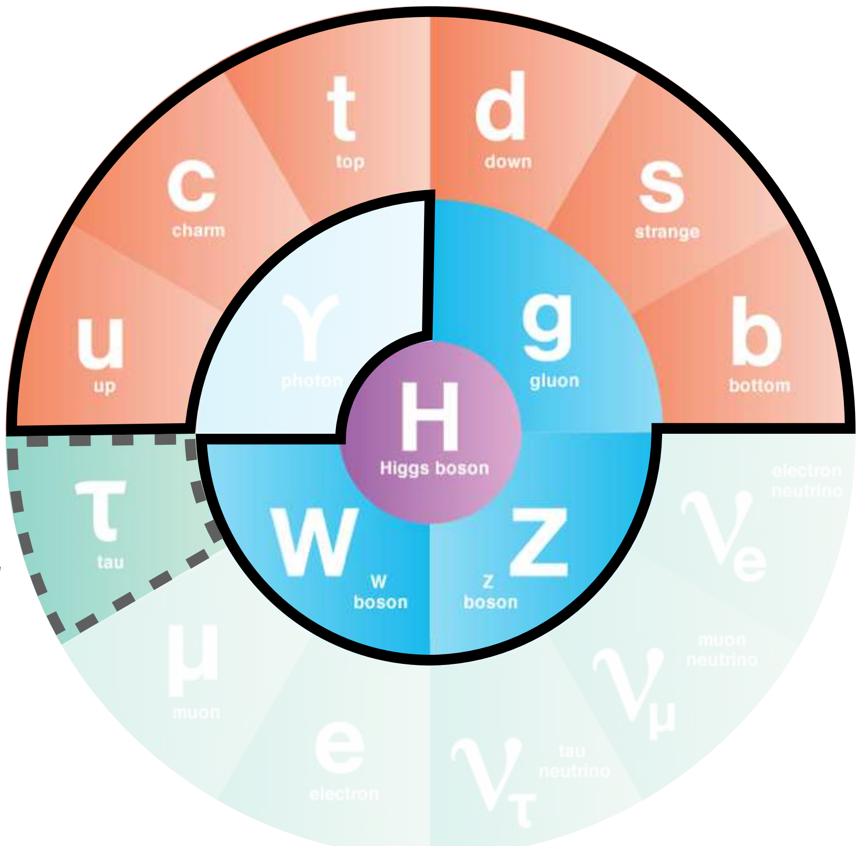
[Thursday & **Today**]



Pushing the Boundaries of Quantum Field Theory

[Next Monday & Tuesday]

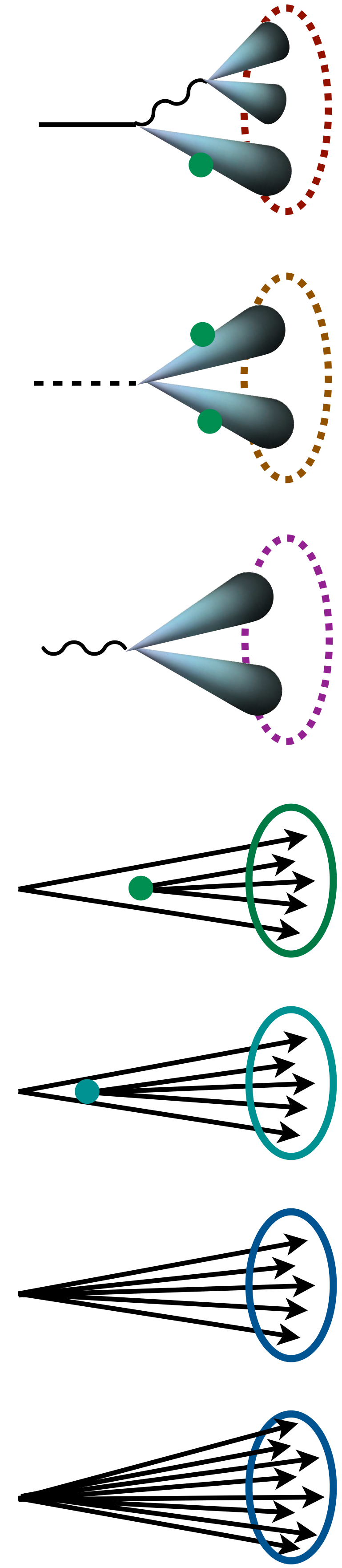
Last Time



micro-jet
≈ 65%

Jets from the Standard Model

++ = plus gluonic radiation

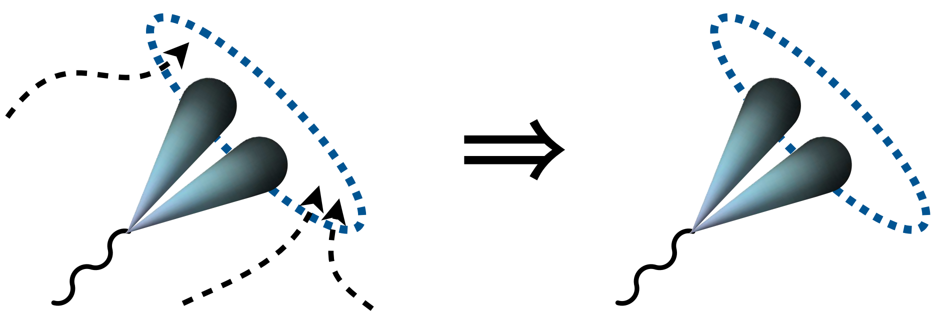


t ≈ 70%	173 GeV++
H ≈ 60%	125 GeV
W/Z ≈ 70%	80/91 GeV
b	4.2 GeV++
c	1.3 GeV++
u,d,s	100 MeV++
g	0++

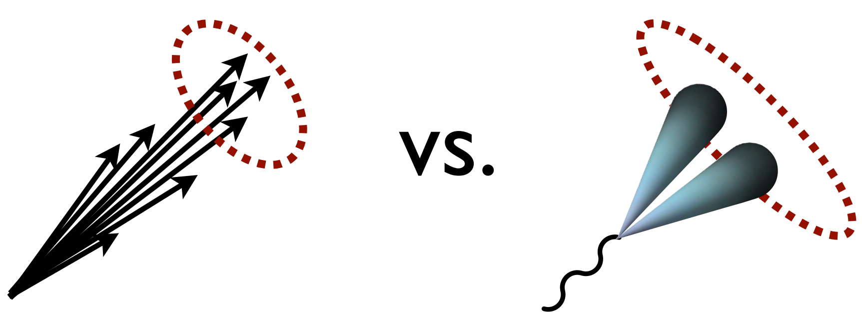
Last Time

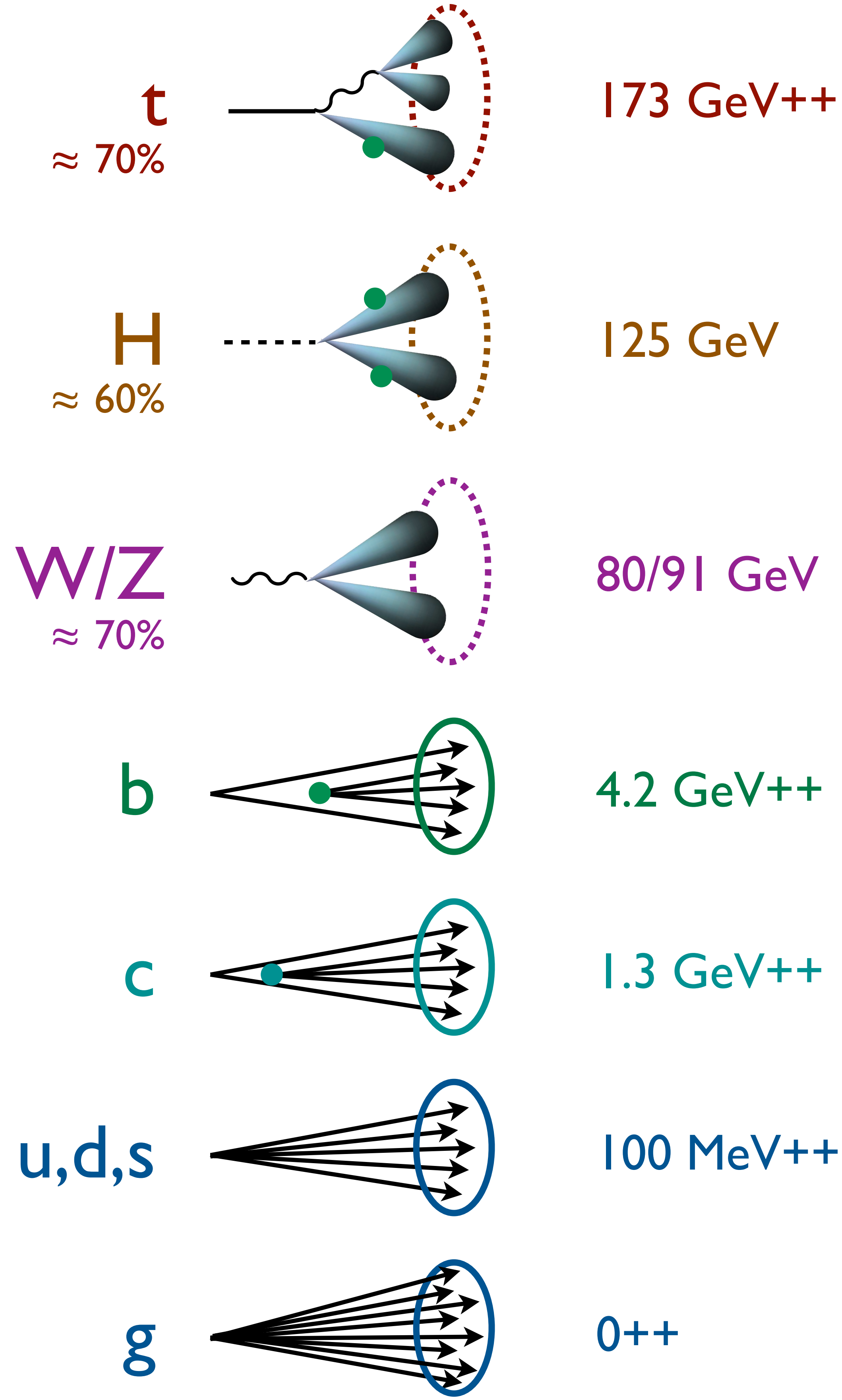
Substructure Toolbox:

Jet Grooming



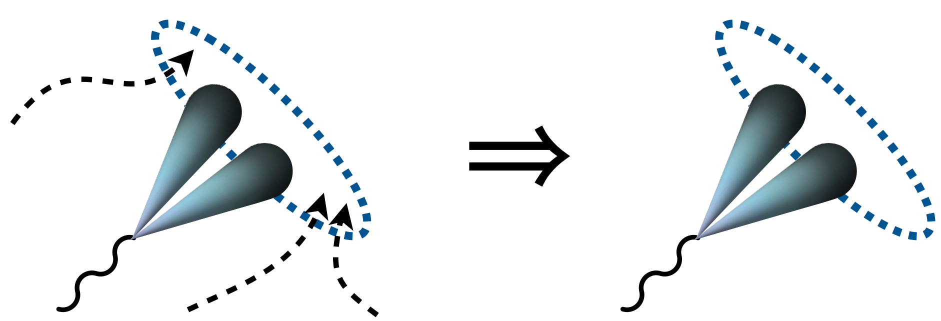
Jet Discrimination





W/Z Tagging in 2016

CMS | ATLAS EXPERIMENT

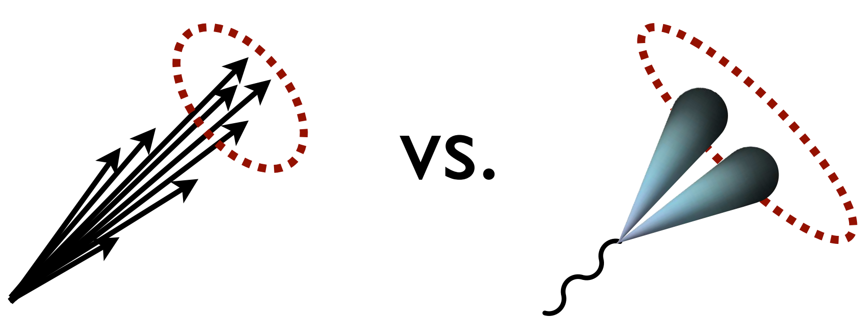


Soft Drop

[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?

CMS

ATLAS EXPERIMENT

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[Larkoski, Marzani, Soyez, JDT, 2014;
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W/Z Tagging in 2016

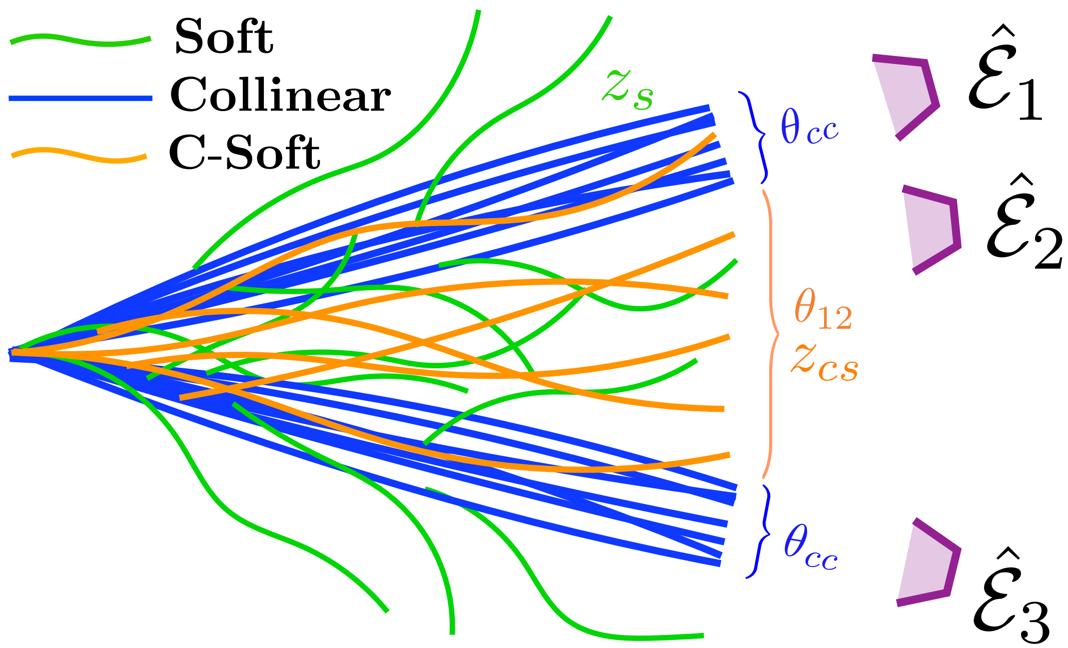
Can we understand these choices from first principles QCD?

Can we construct improved algorithms for 2017?

Yes! Key realization:
Discrimination different before/after grooming

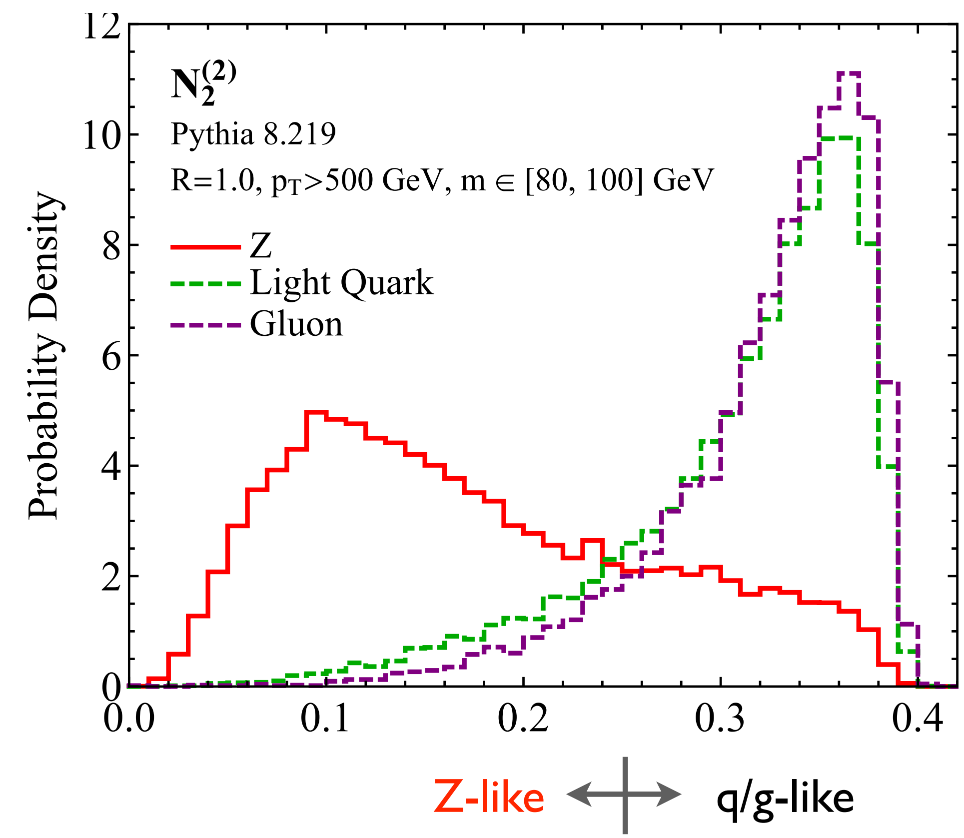
Yes!
Systematic basis for jet substructure observables

Punchline: W/Z Tagging in 2017?



$\Rightarrow$

Stable & Performant



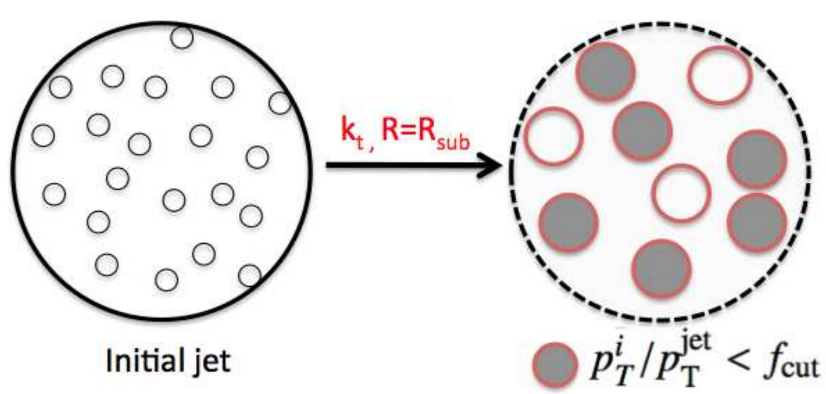
$$\boxed{N_2} = \frac{\displaystyle\sum_{i<j<k} p_{Ti}\, p_{Tj}\, p_{Tk} \min\left\{(R_{ij}R_{jk})^2, (R_{jk}R_{ki})^2, (R_{ki}R_{ij})^2\right\}}{\left(\displaystyle\sum_{i<j} p_{Ti}\, p_{Tj}\, R_{ij}^2\right)^2 \Bigg/ \displaystyle\sum_i p_{Ti}}$$

[Moult, Necib, JDT, 2016]

Grooming From First Principles

[More details on Monday]

Trimming from First Principles?

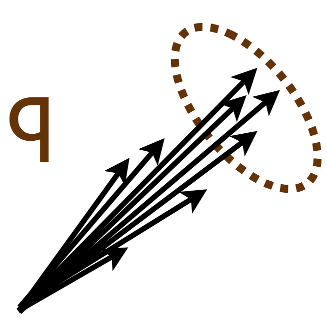


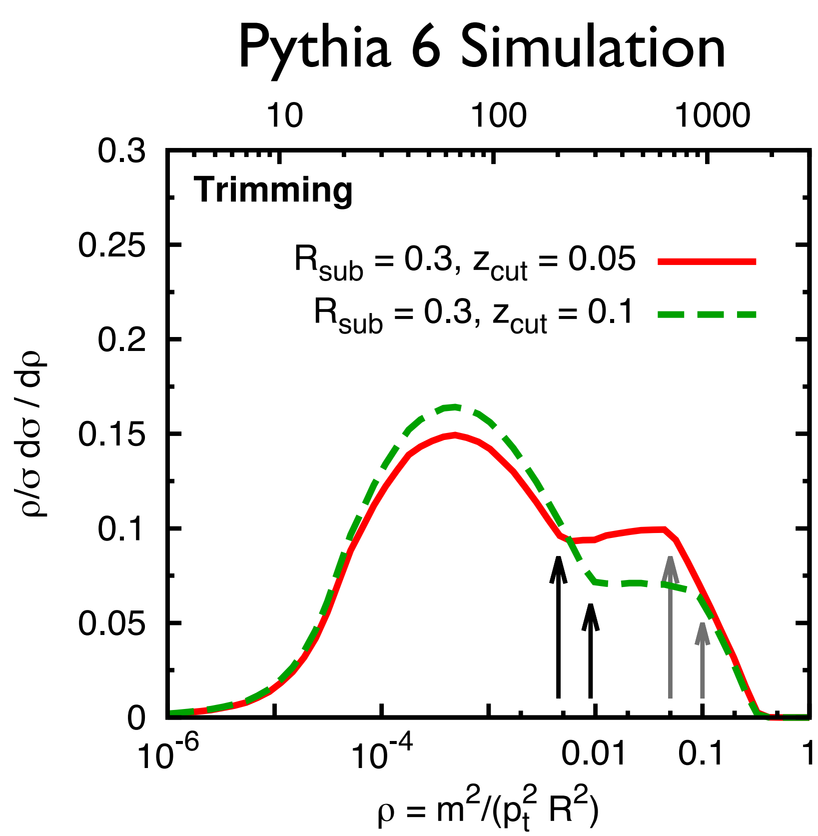
extensively used by ATLAS

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

Trimmed Jet Mass:

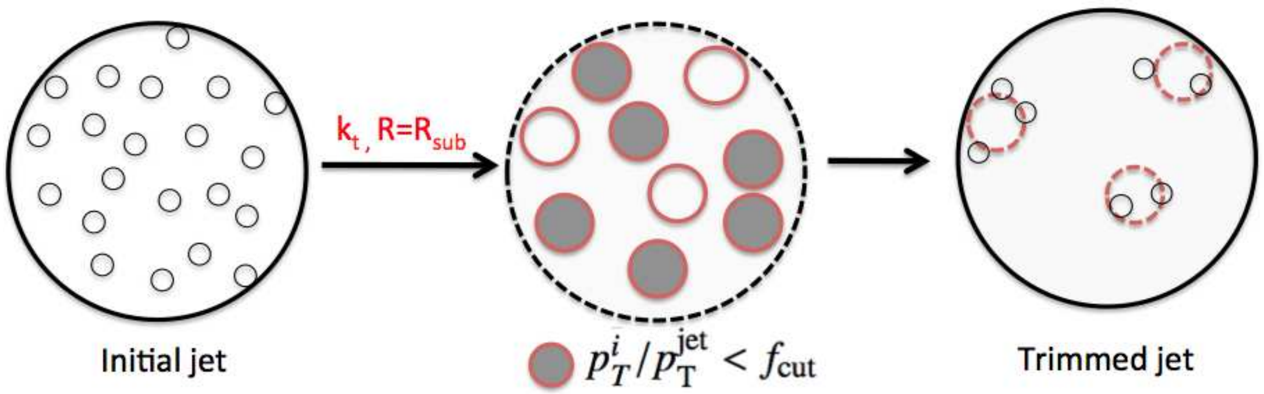
3 TeV quark jets





[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Trimming from First Principles?



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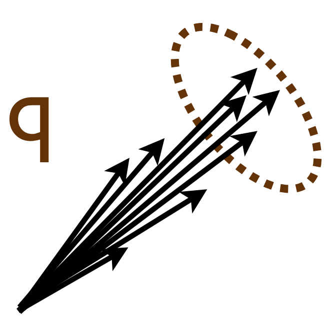
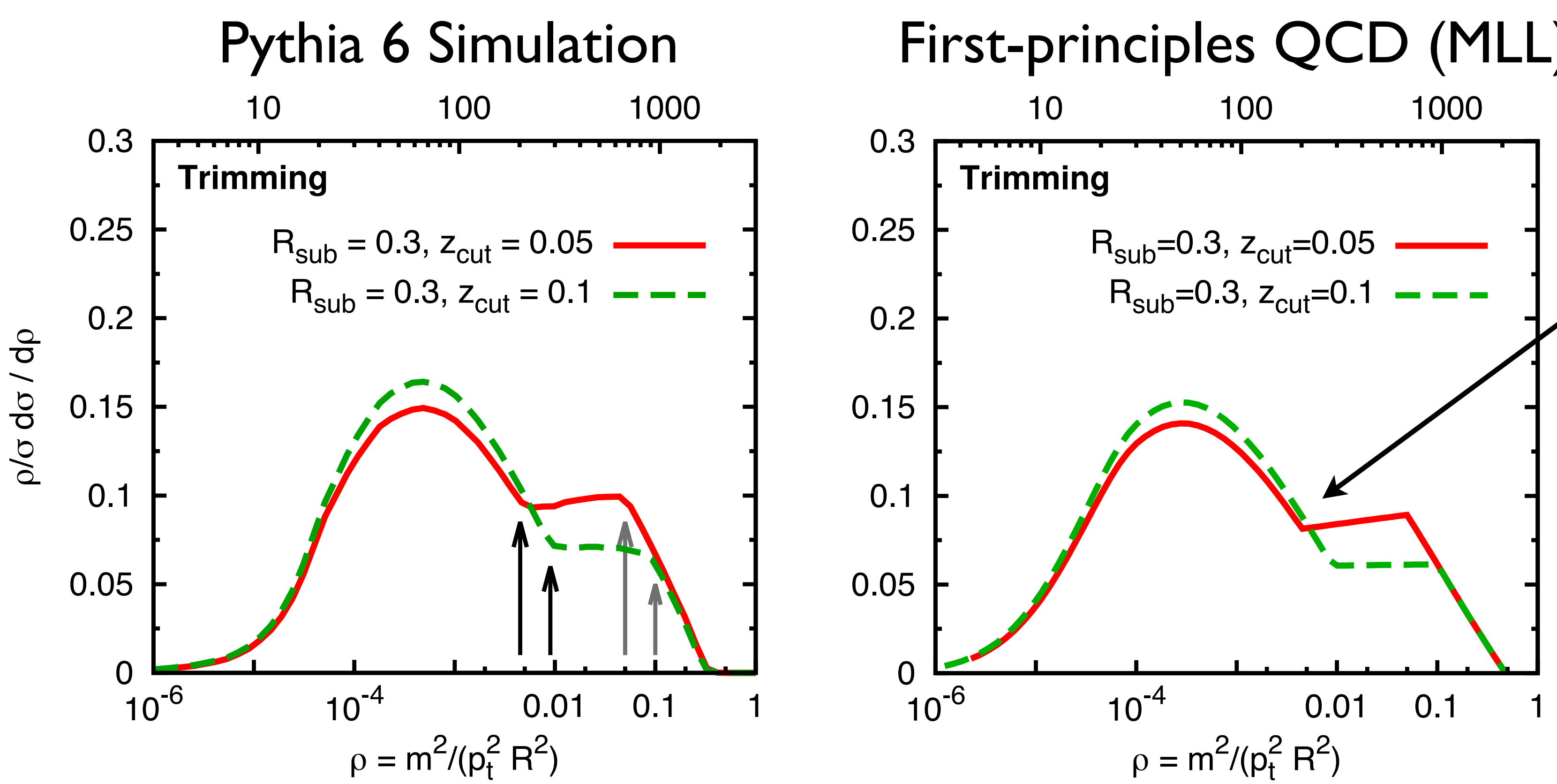
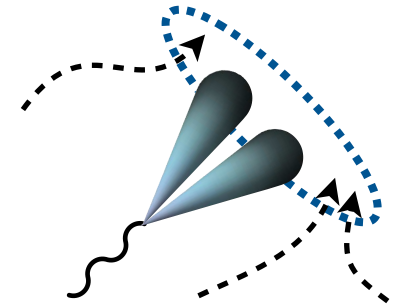




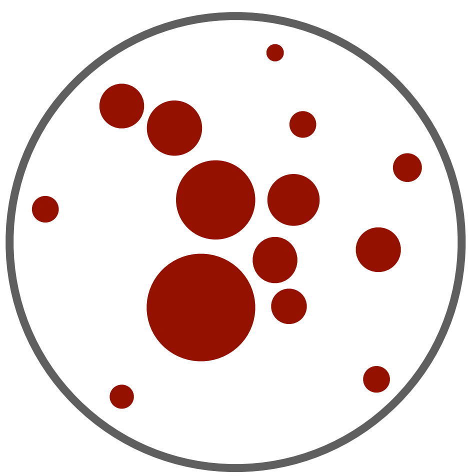
Analytically understand Sudakov peak, kink, and plateau

[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Soft Drop Declustering



Original Jet



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

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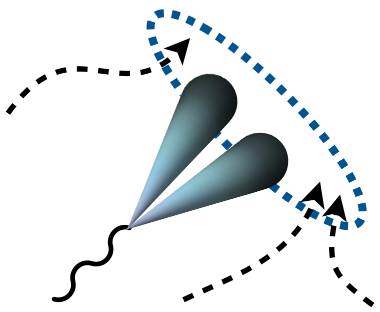
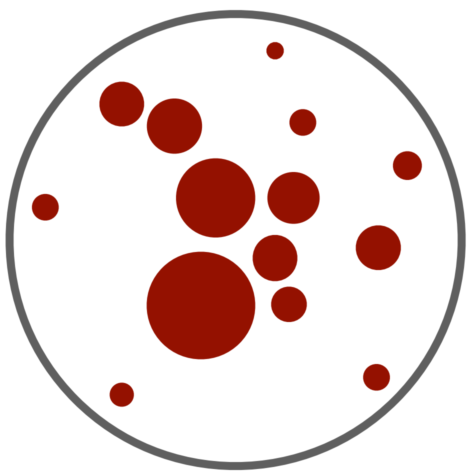


Original Jet



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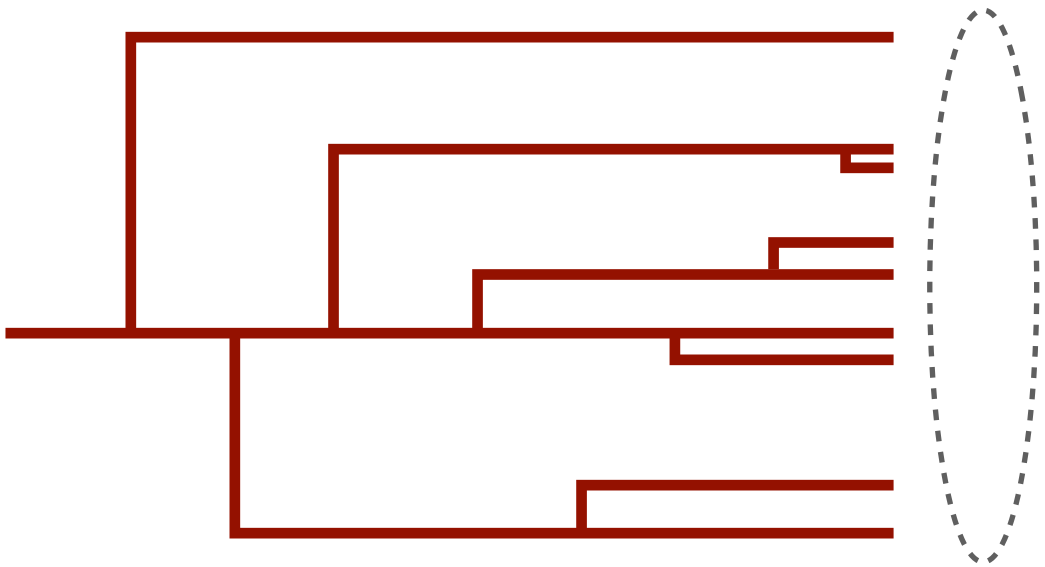
Clustering Tree



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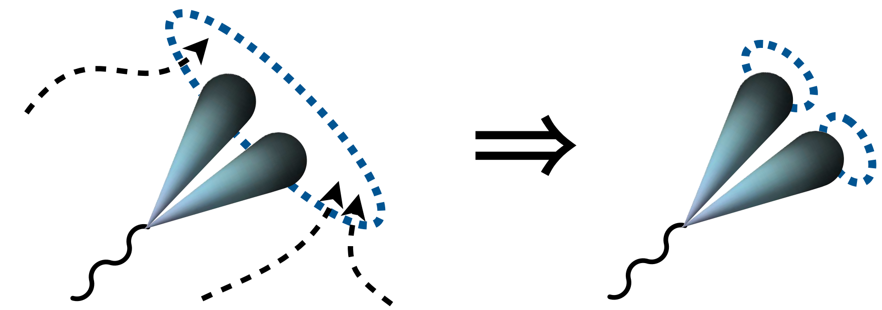
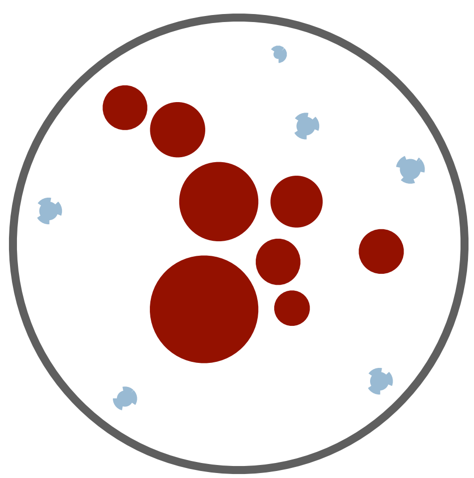


Groomed Jet



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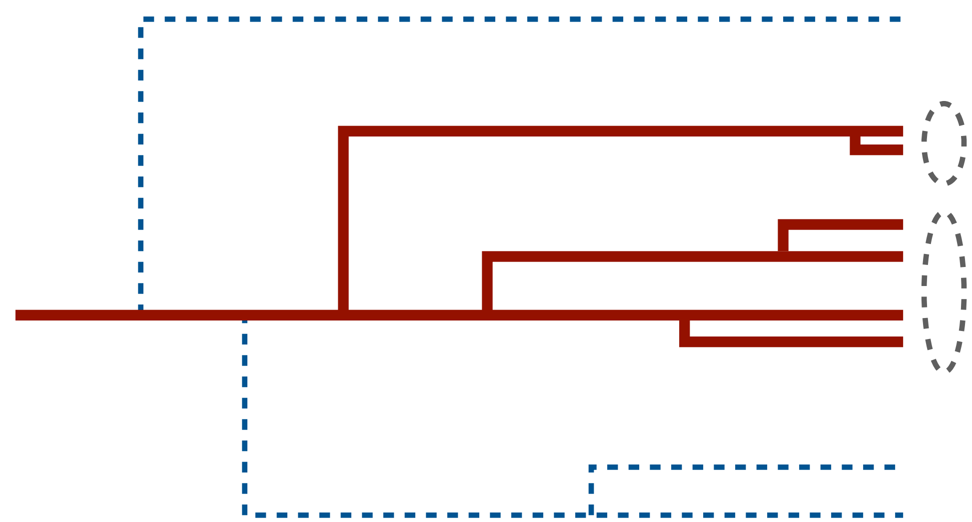
Groomed
Clustering Tree



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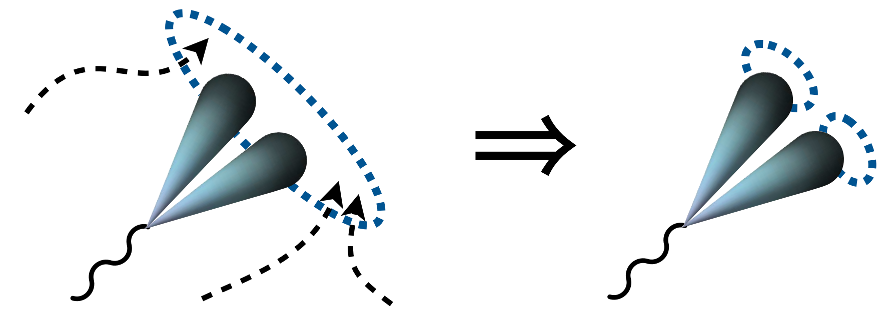

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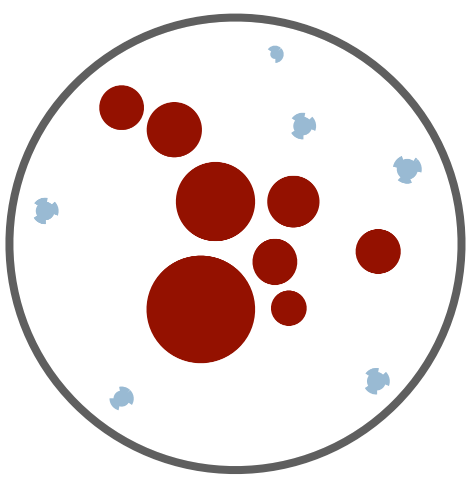

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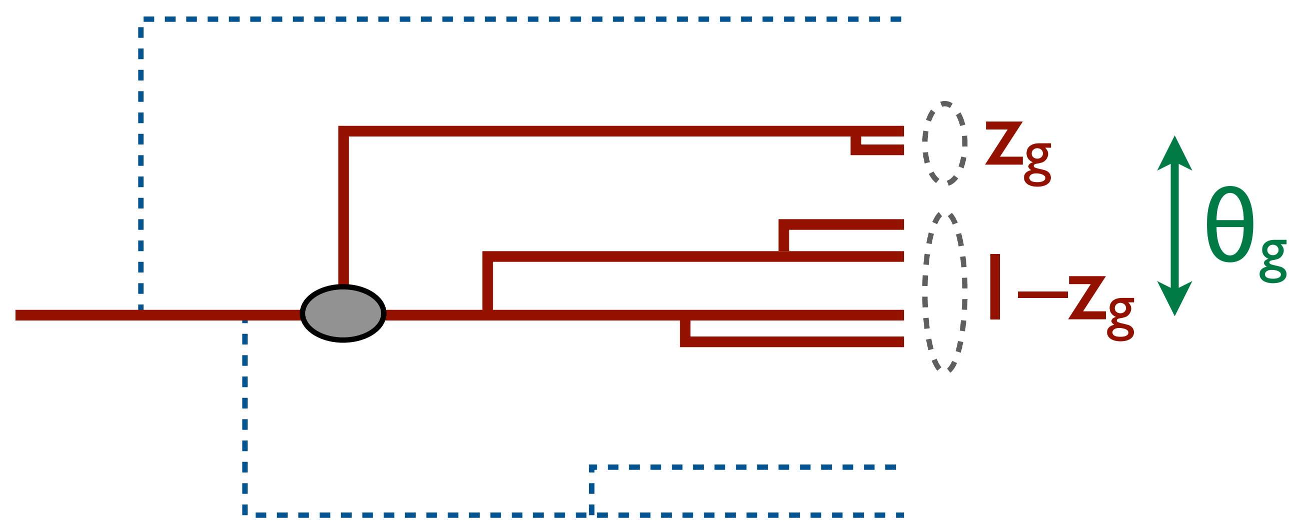
Groomed Clustering Tree

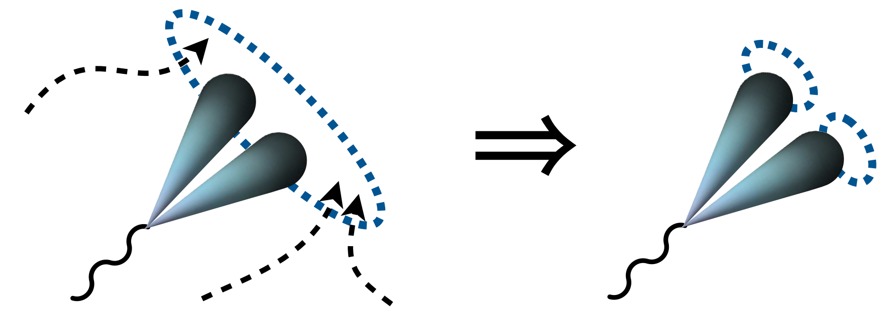


$$z_g > z_{cut}\,\theta_g^{\beta}$$

[We'll study z_g next Tuesday]

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

Soft Drop Declustering



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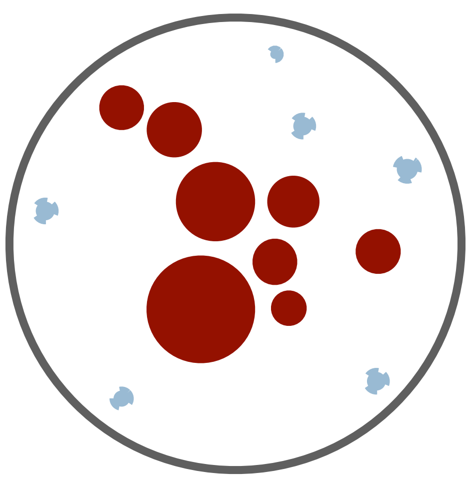

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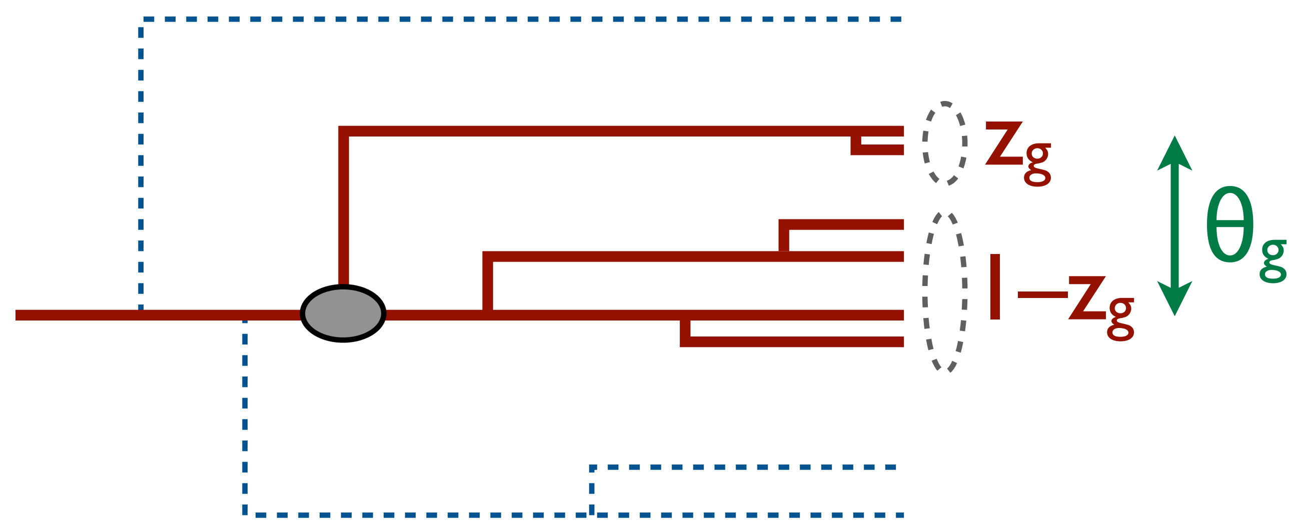


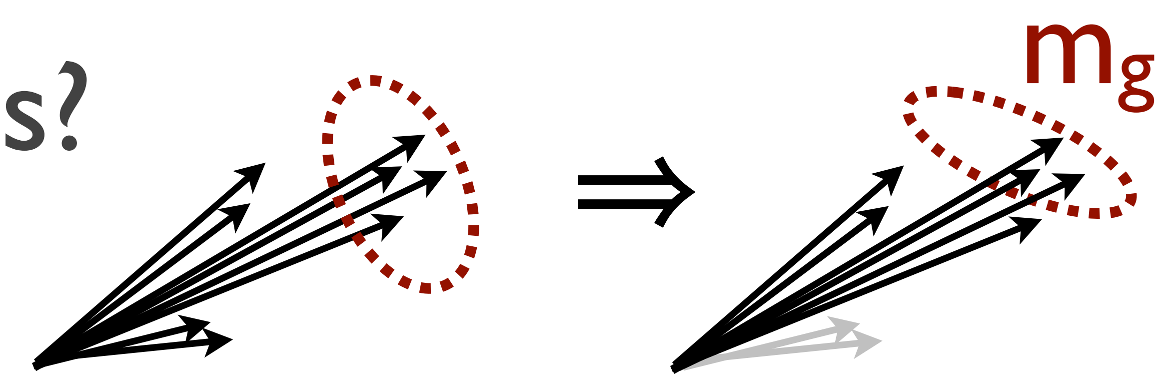
$$z_g > z_{cut}\,\theta_g^{\beta}$$

[We'll study z_g next Tuesday]

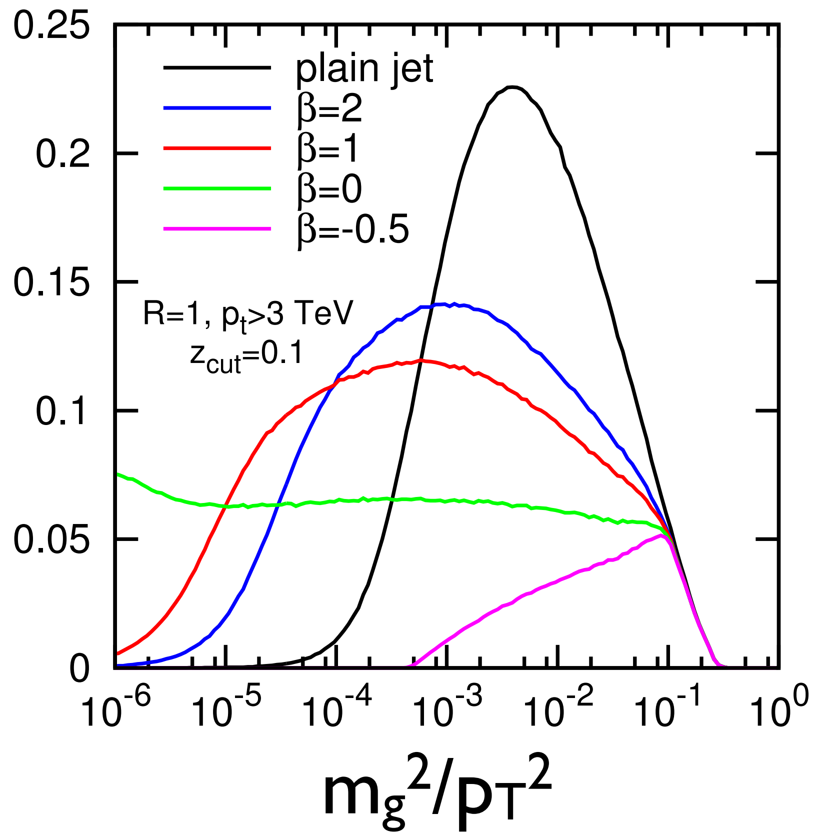
More Grooming | Less Grooming

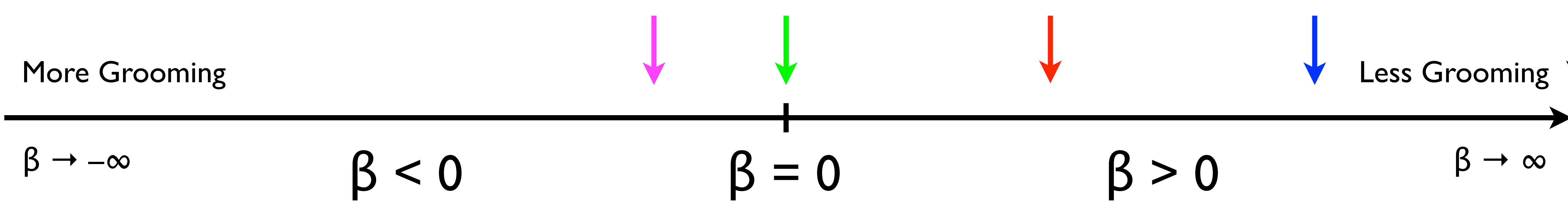
$\beta \to -\infty$ | $\beta < 0$ | $\beta = 0$ | $\beta > 0$ | $\beta \to \infty$

Calculating Groomed Mass?



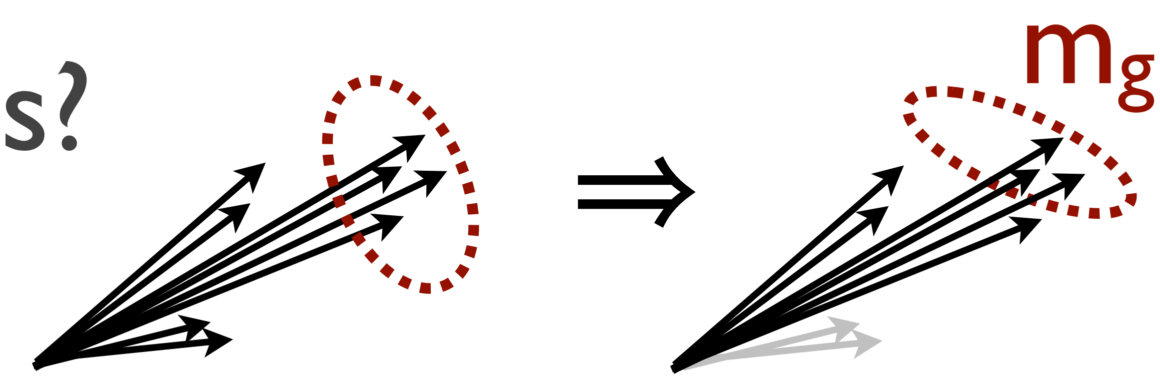
Simulated LHC Data





[Larkoski, Marzani, Soyez, JDT, 2014]

Calculating Groomed Mass?



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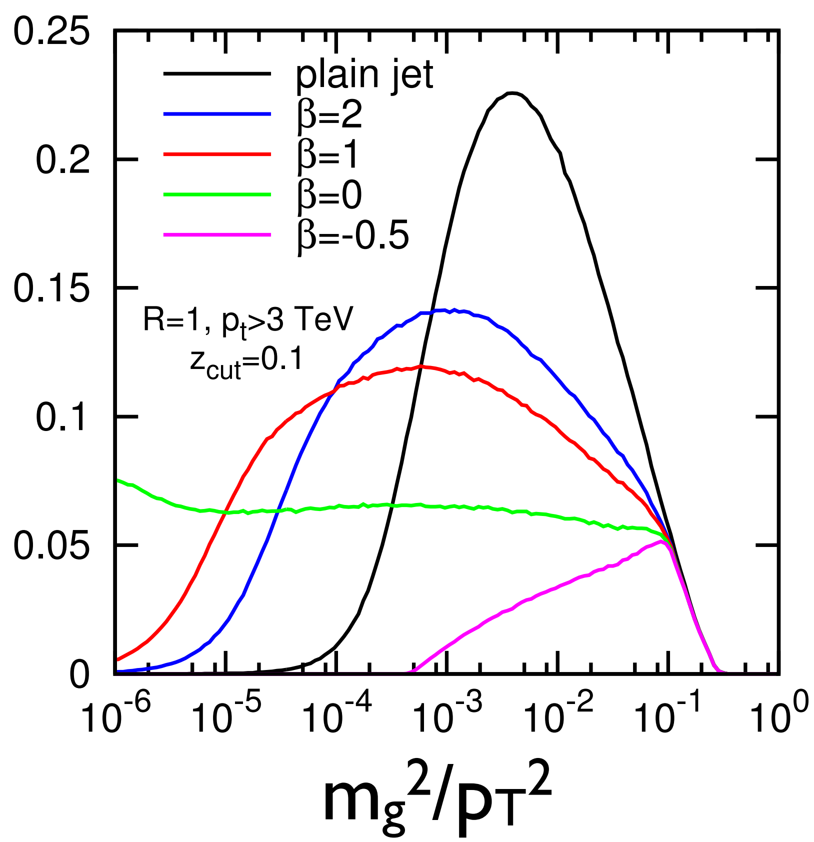
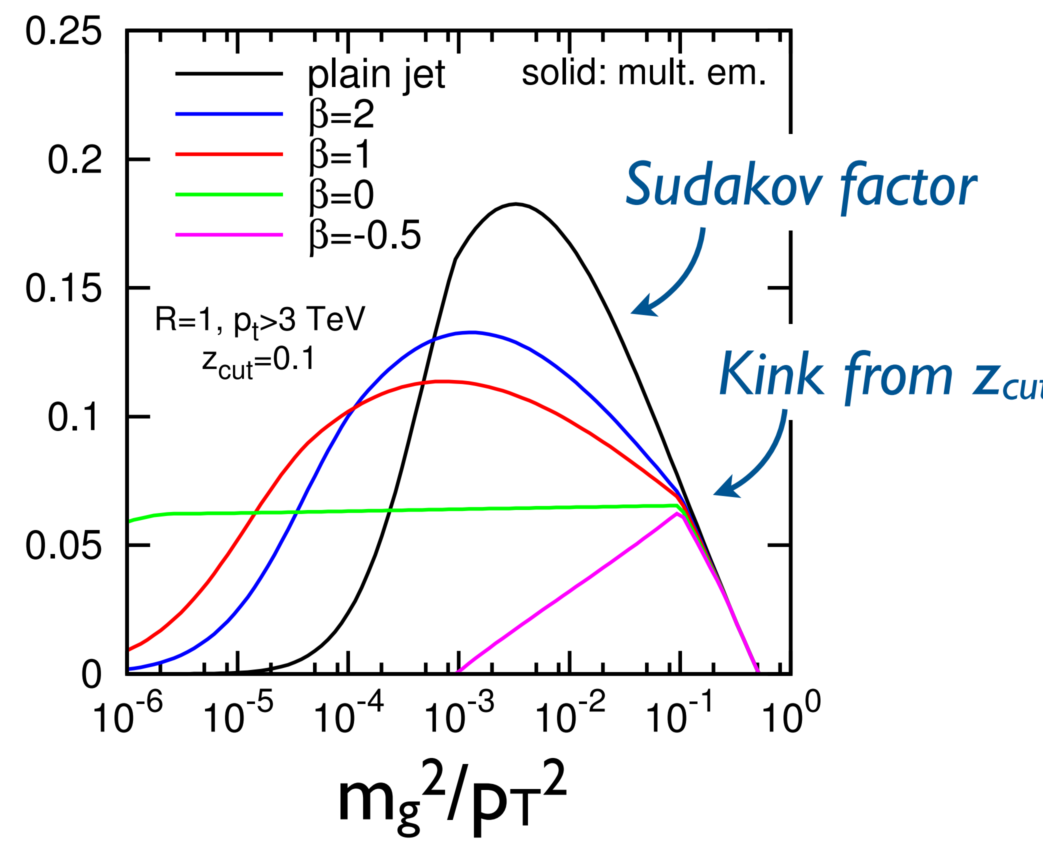
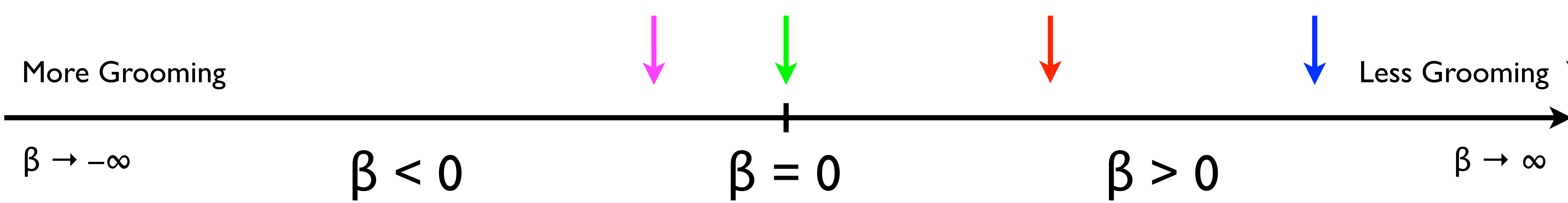


First-principles QCD (MLL)





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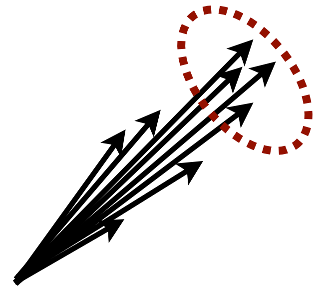
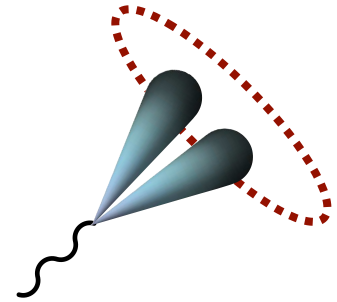
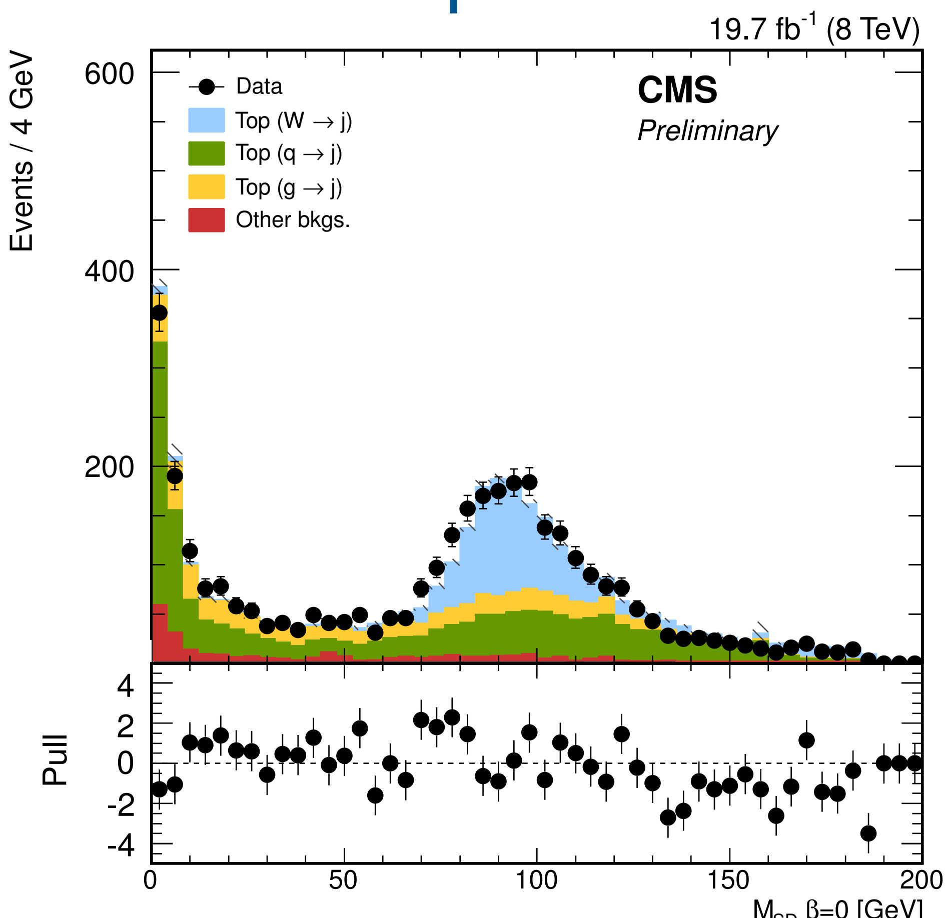


vs.

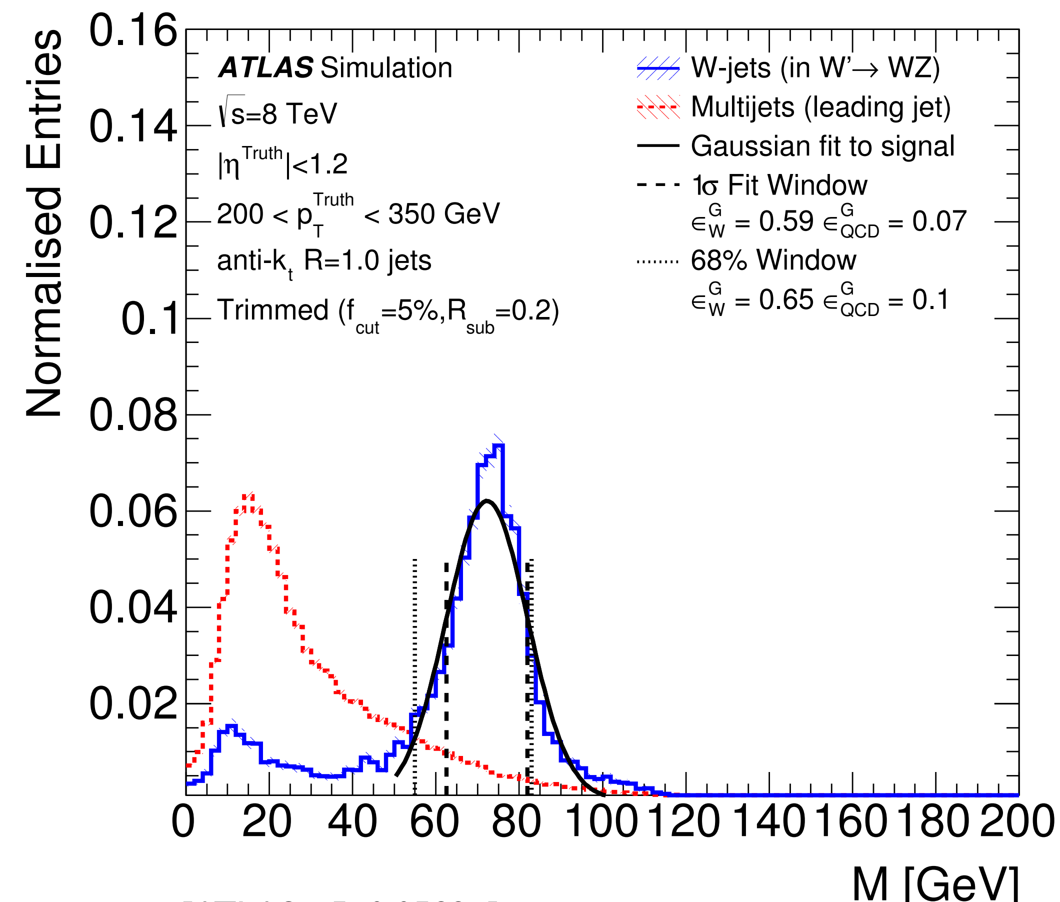


Soft Drop



[CMS, JME-14-002]

Trimming



[ATLAS, 1510.05821]

Both grooming strategies give good signal isolation

Scorecard

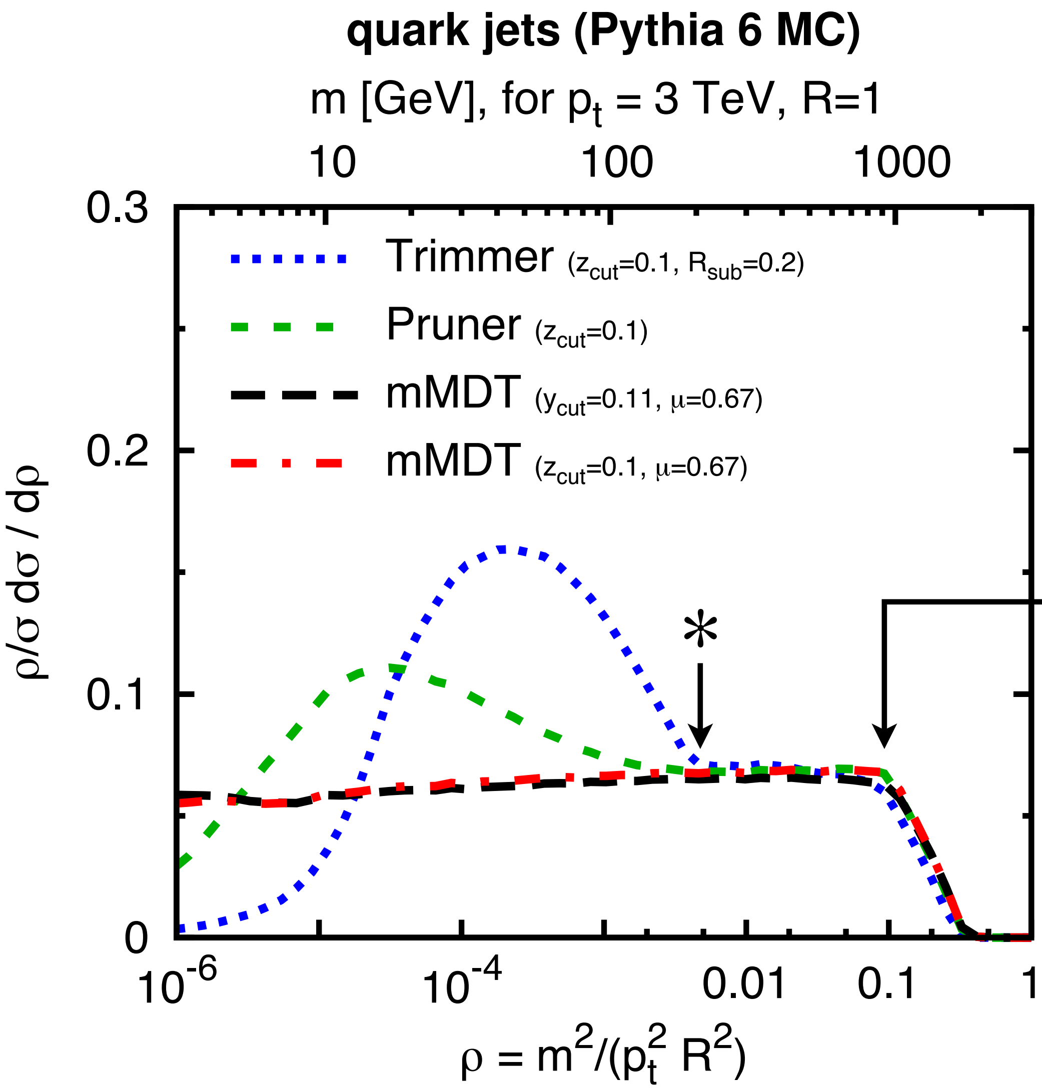
Soft Drop

✓

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

Trimming

✓*



[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

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)

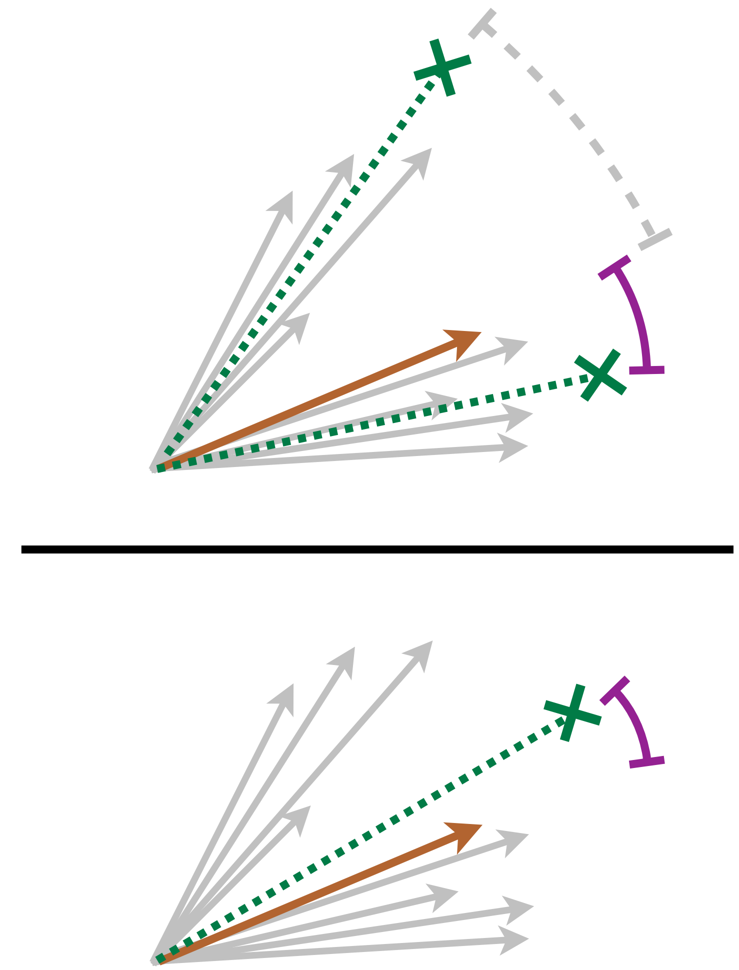
Axes or Axes-Free?

Discrimination with Axes

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

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)

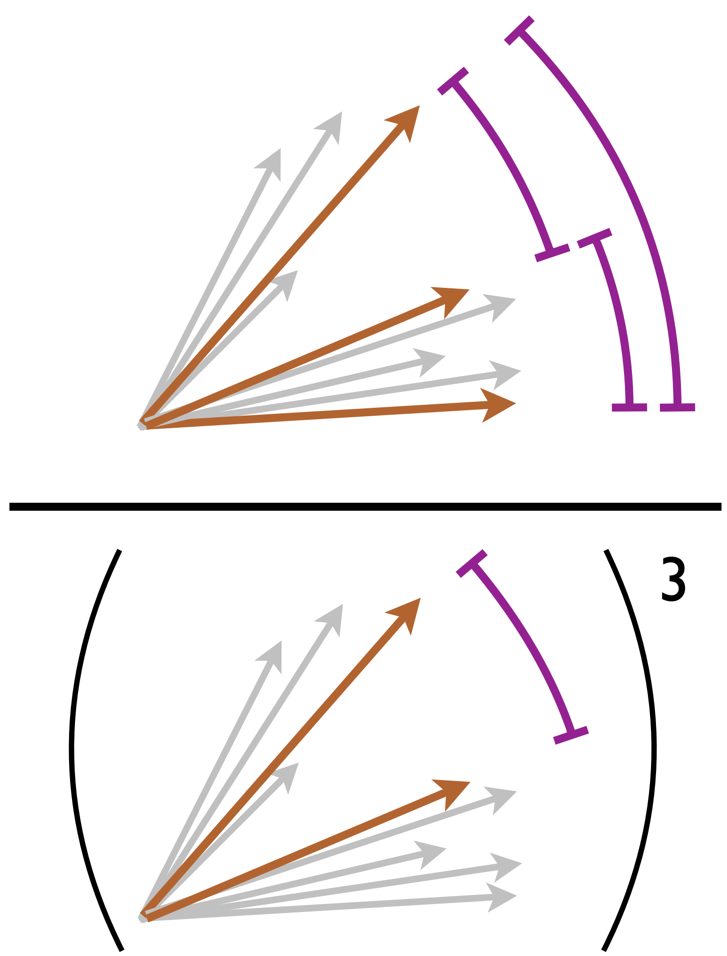
[JDT, Van Tilburg, 1011.2268, 1108.2701; see also Kim, 1011.1493]
[related work in Stewart, Tackmann, Waalewijn, 1004.2489]

Discrimination without Axes

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

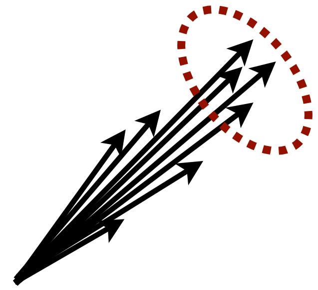
Energy Correlation Functions

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



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]



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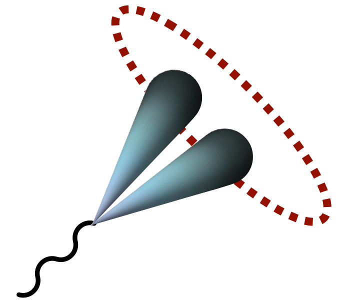
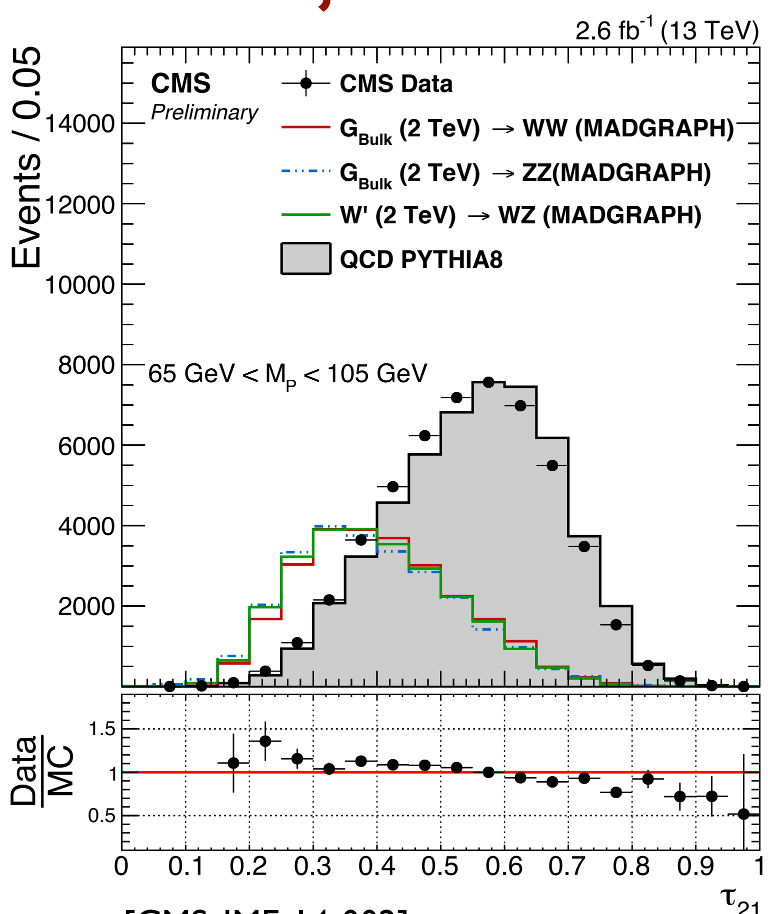
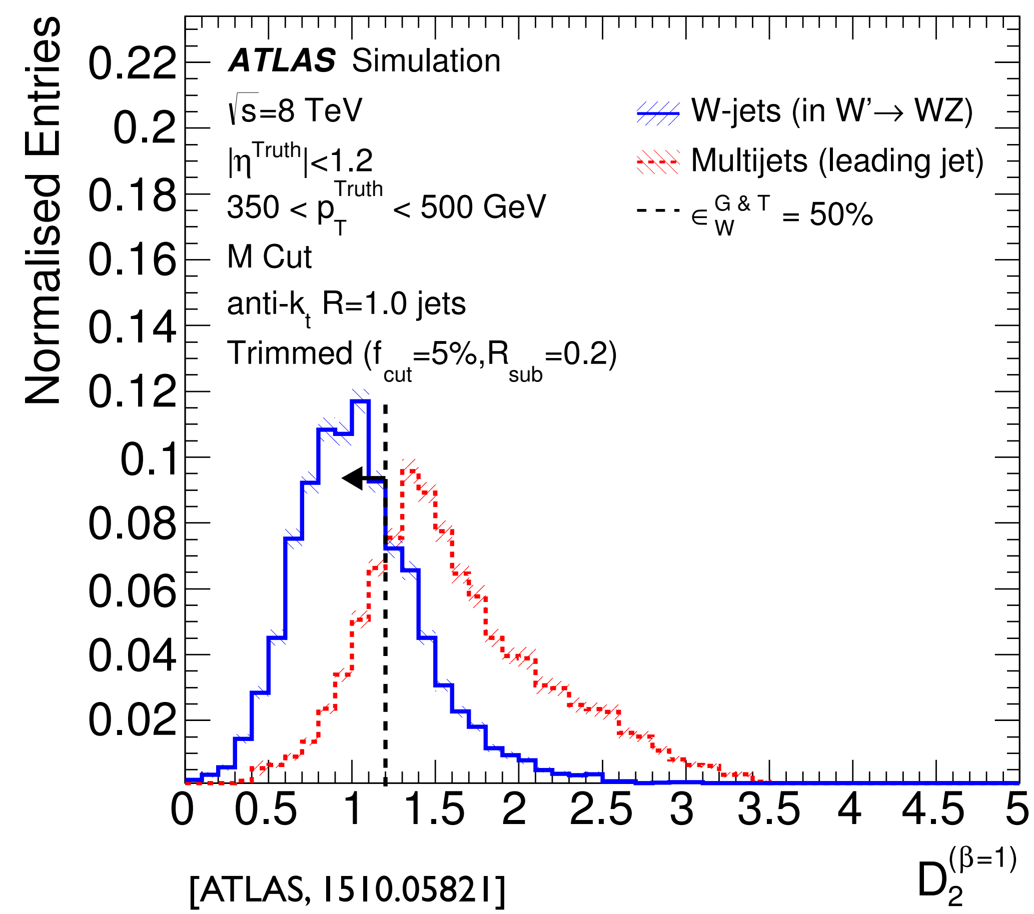


N-subjettiness



[CMS, JME-14-002]

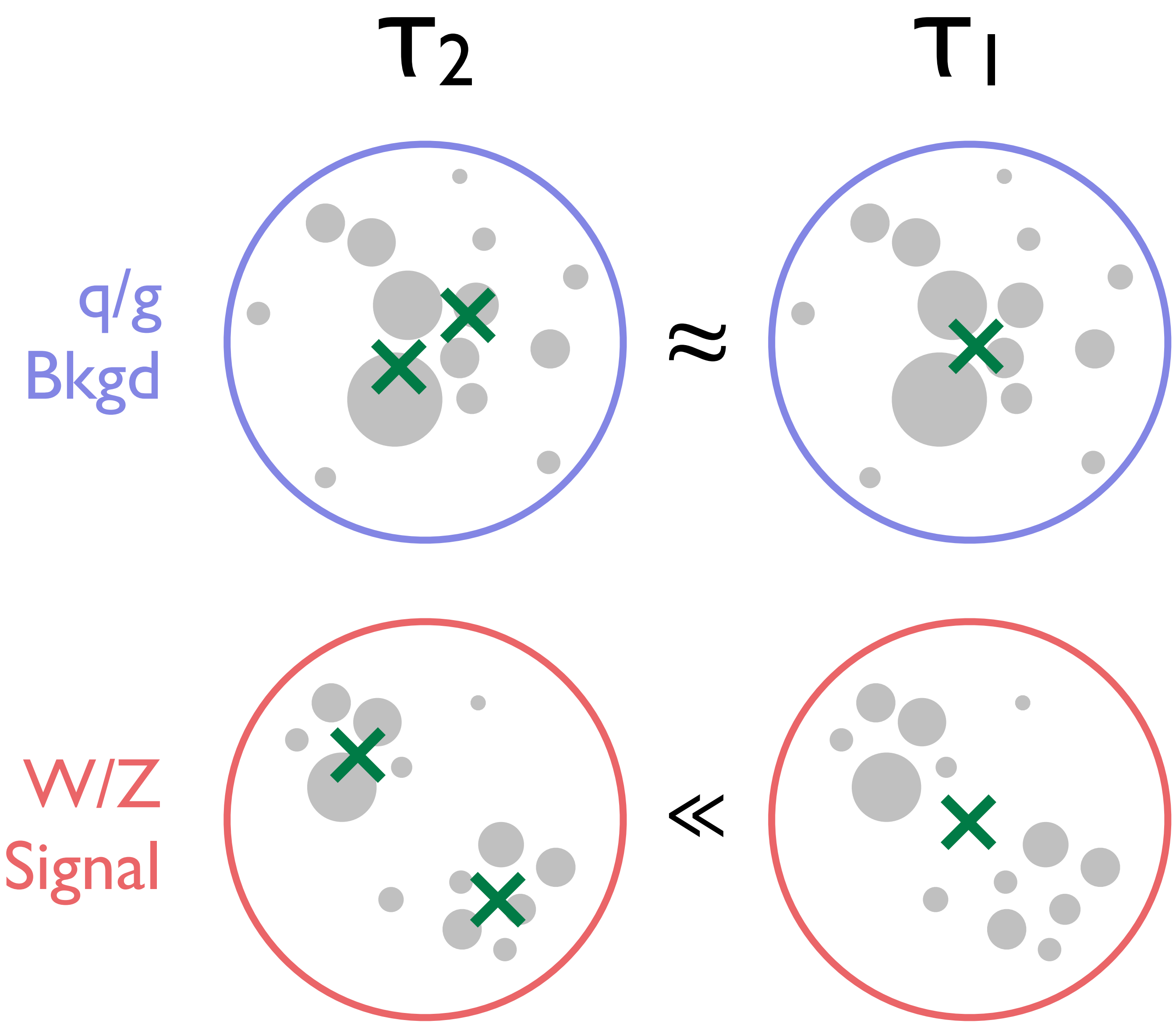
Energy Correlator: D_2

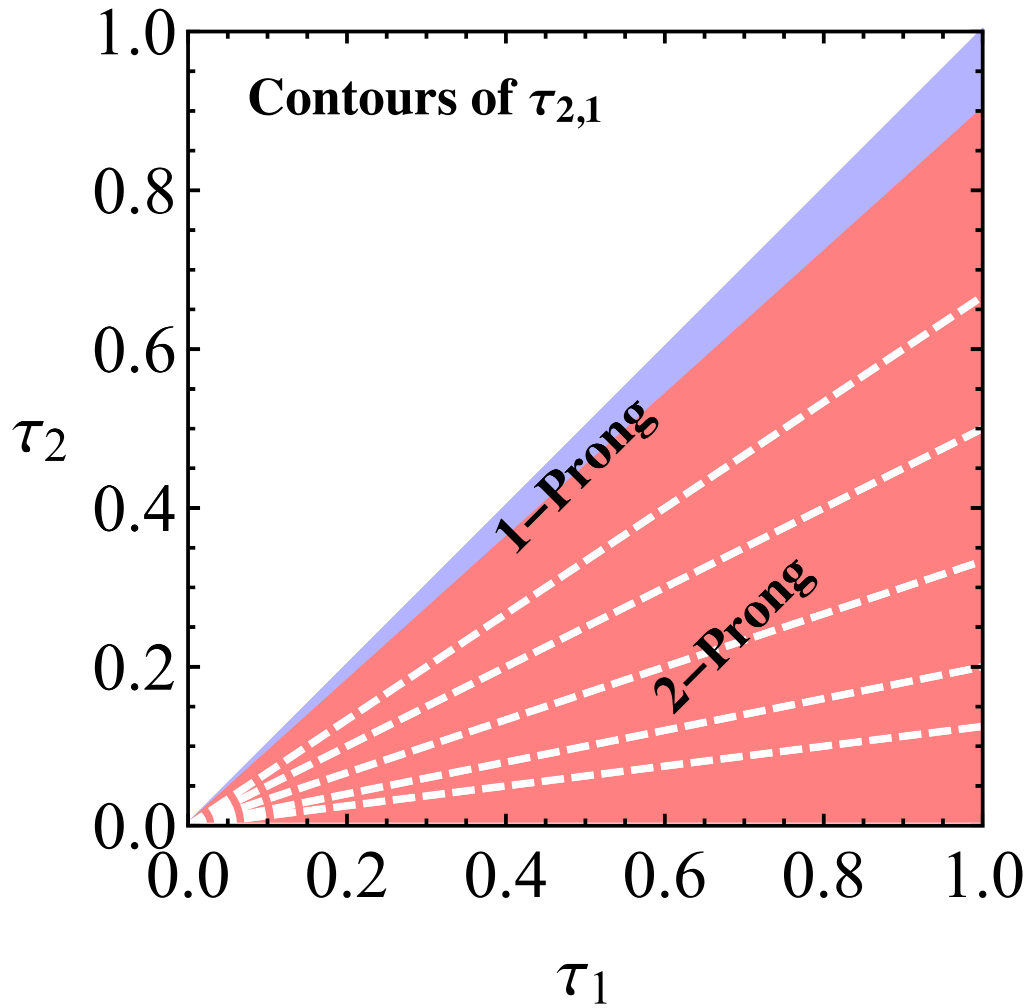


[ATLAS, 1510.05821]

Can we understand this behavior from first principles?

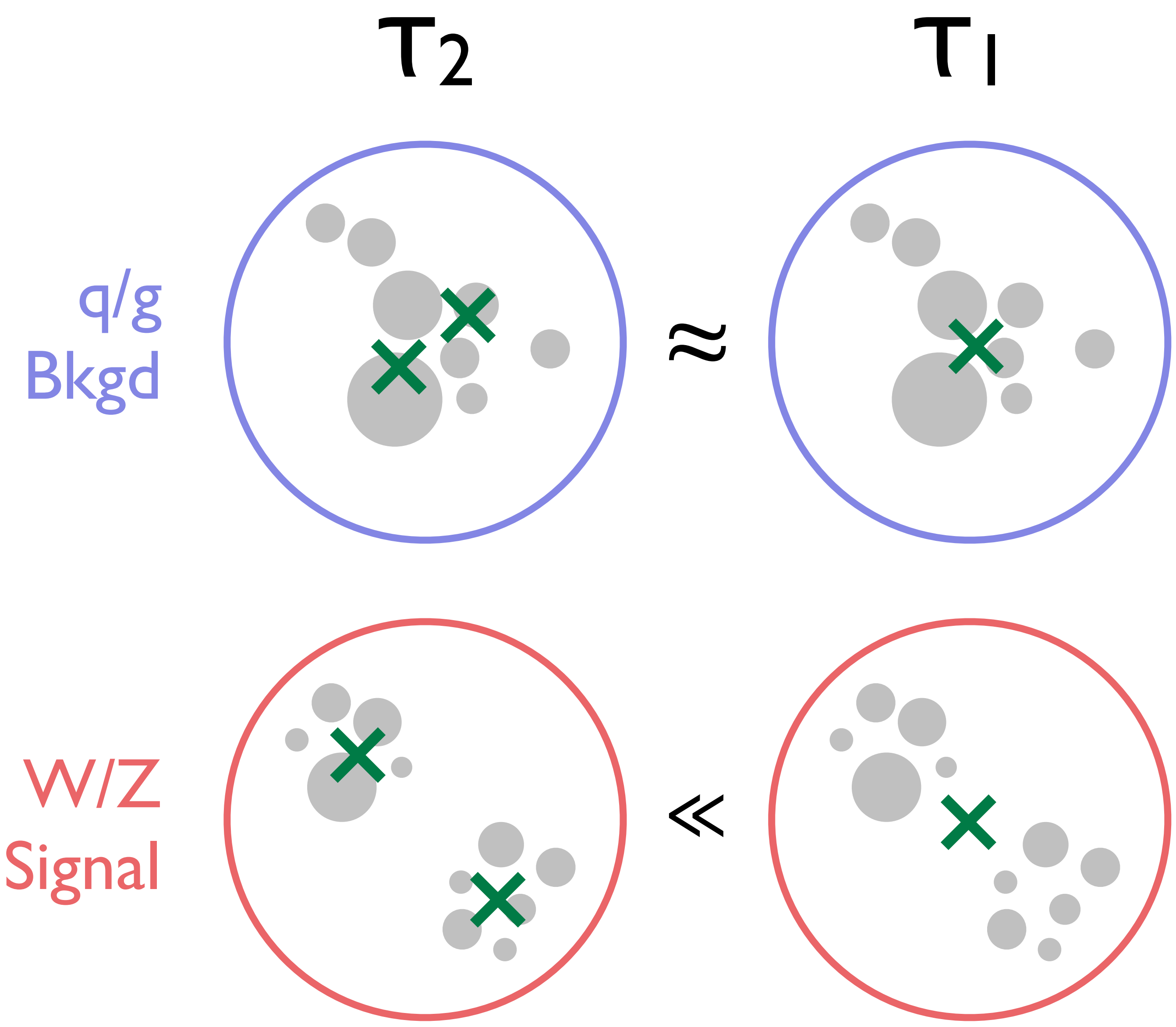
N-subjettiness Behavior

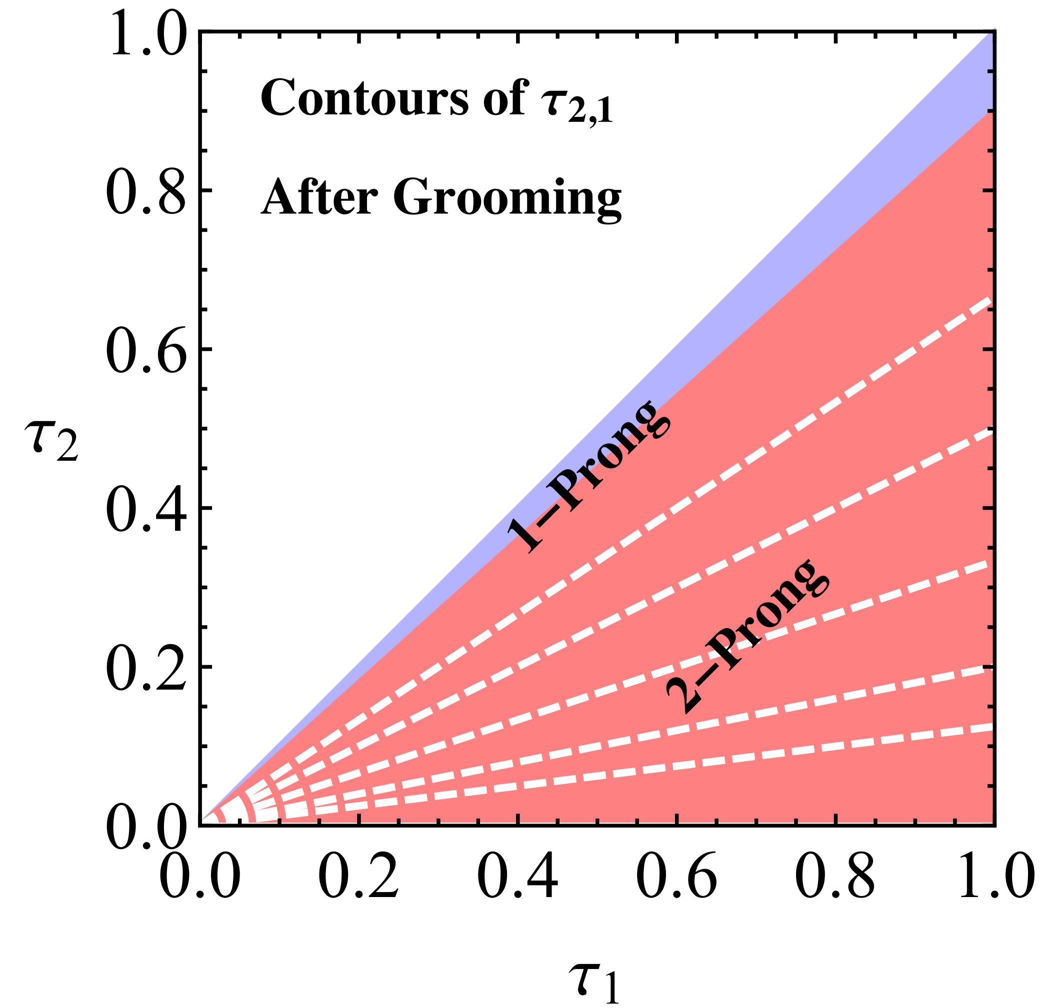




Parametric separation between 1 and 2 prong jets

N-subjettiness Behavior with Grooming





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

Scorecard

Soft Drop

✓

Trimming

✓*

N-subjettiness

before grooming

✓

(also works
after grooming)

D_2

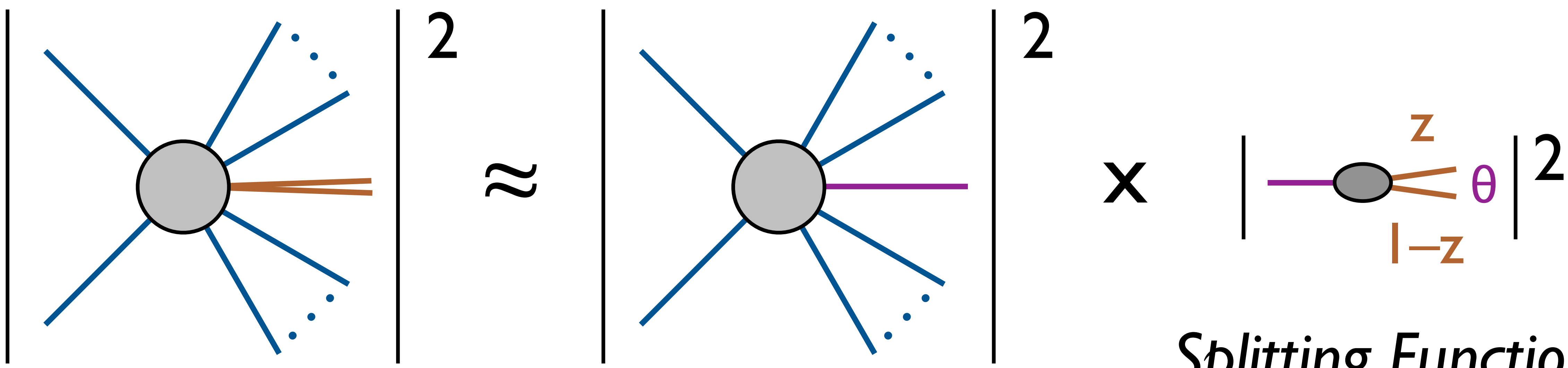
after grooming

☐*

Not just good discrimination,
but stability to choice of cuts

The Power of Power Counting

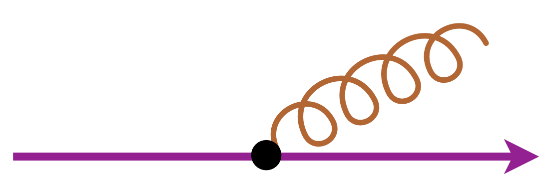
Textbook QCD



Splitting Function

$2 \to n$ $\qquad$ $2 \to n-1$ $\qquad$ $1 \to 2$

At leading log order:



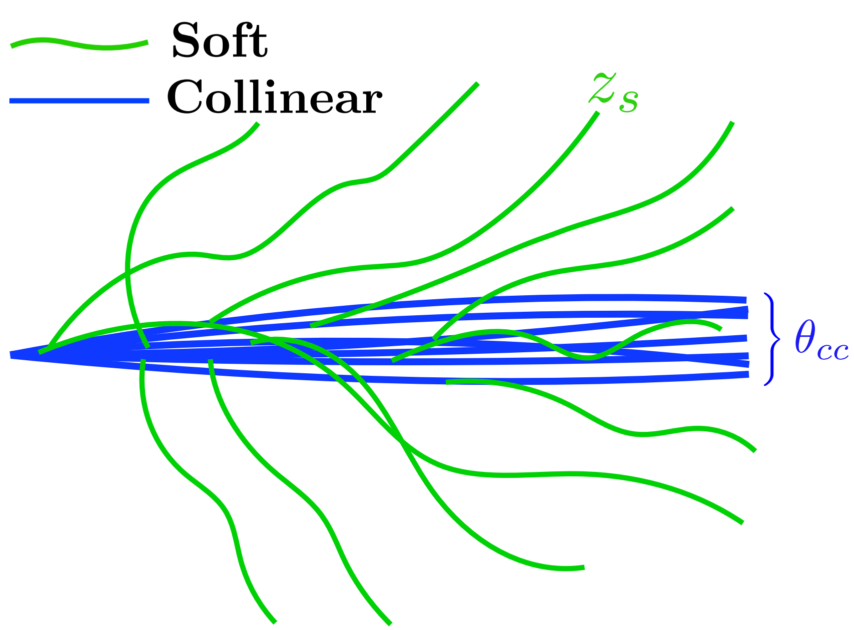
$C_q = 4/3$
$C_g = 3$

See end of talk for quark/gluon tagging

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

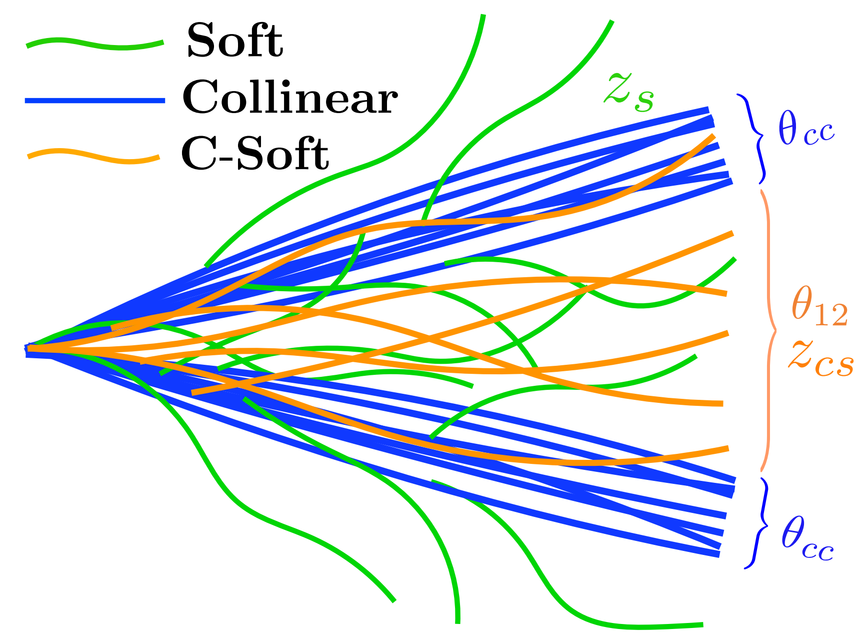
Power Counting Modes

1-prong background (quark or gluon)



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

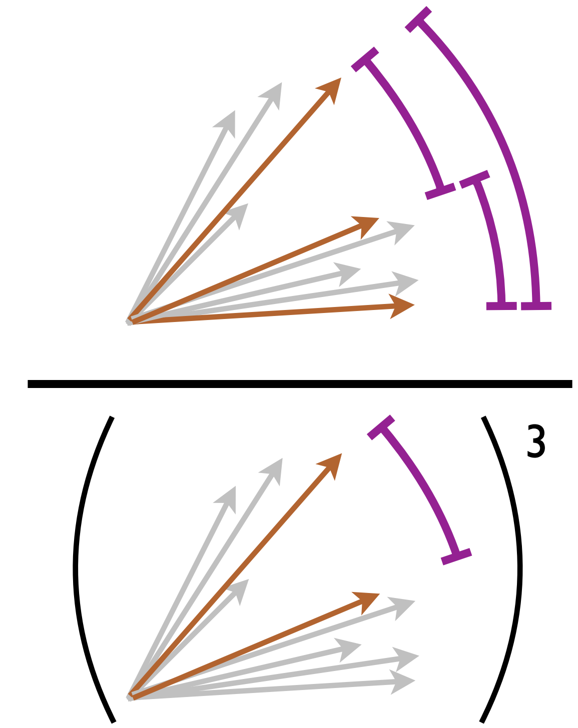
2-prong signal (W or Z)



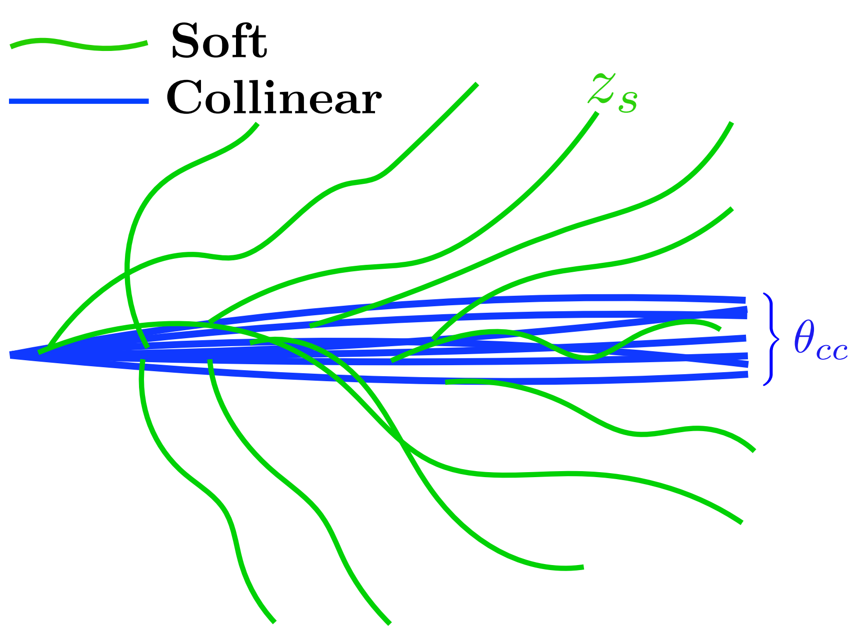
	C	C_S	S
energies	1	z_{cs}	z_s
	CC	C_1C_2 or CC_S	SX
angles	θ_{cc}	θ_{12}	1

Power Counting D_2: Background

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



Setting β = 1



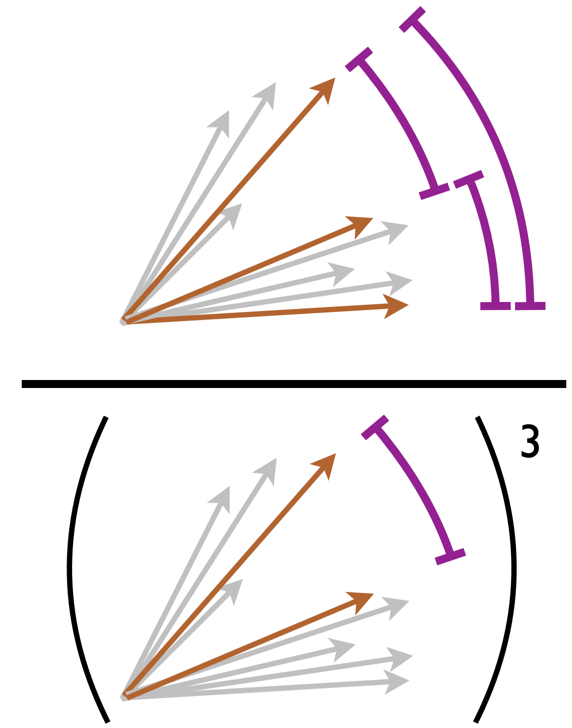
CCC CCS CSS

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

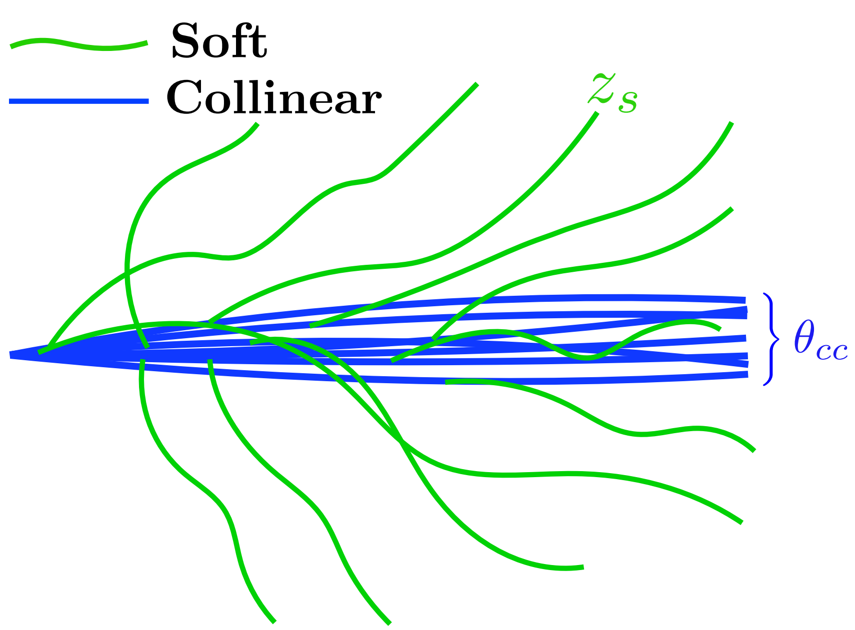
CC CS

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

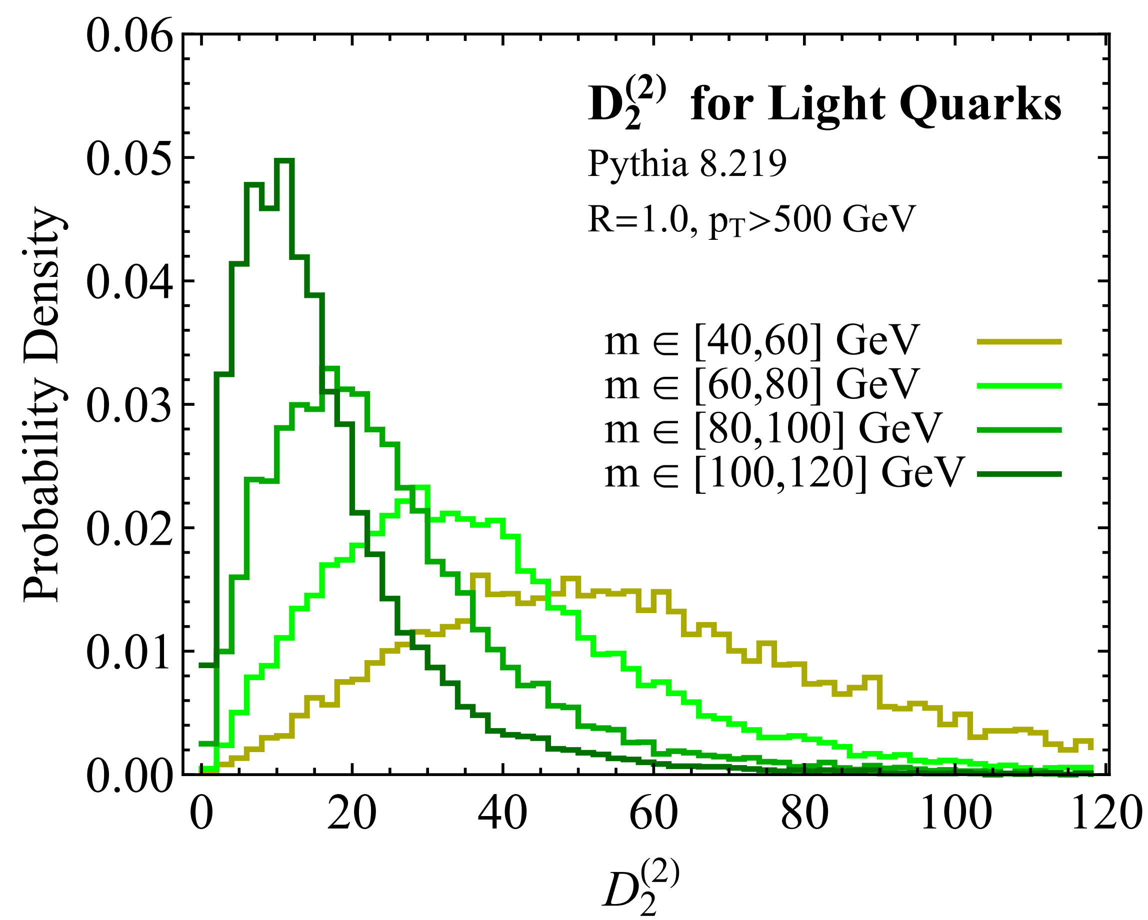
if soft dominates

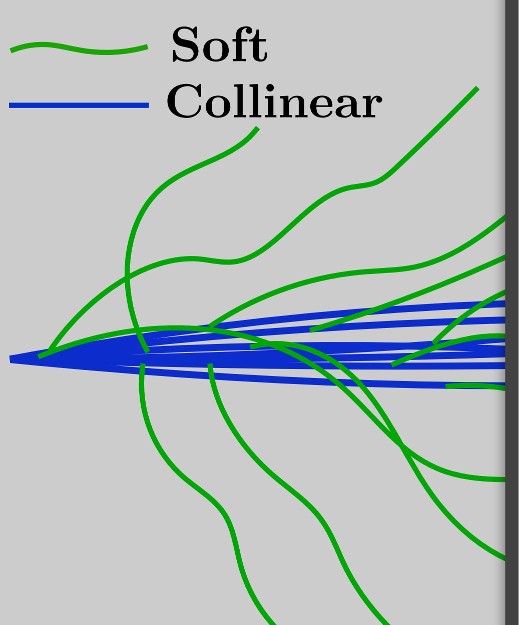
Power Counting D2: Background

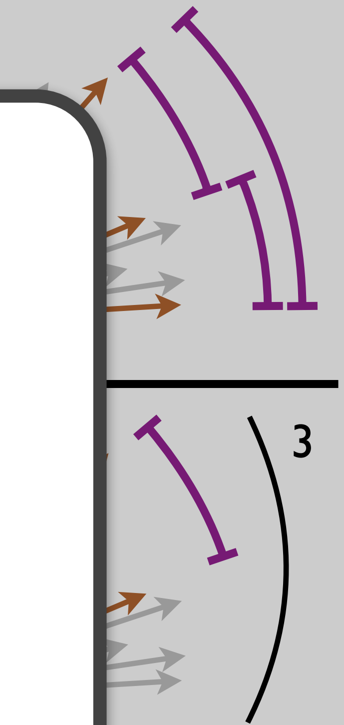
$D_2 =$

Setting

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



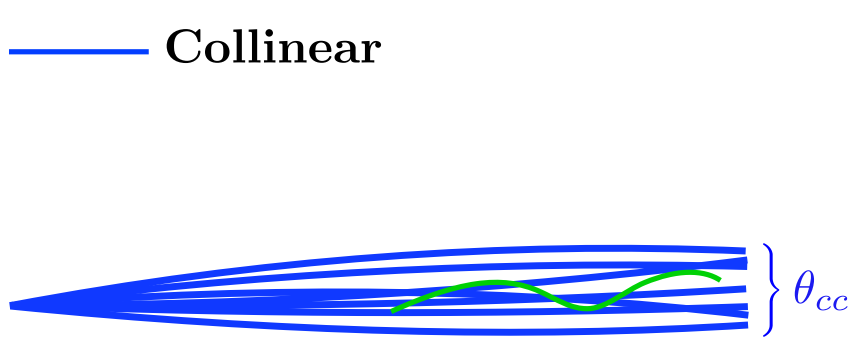




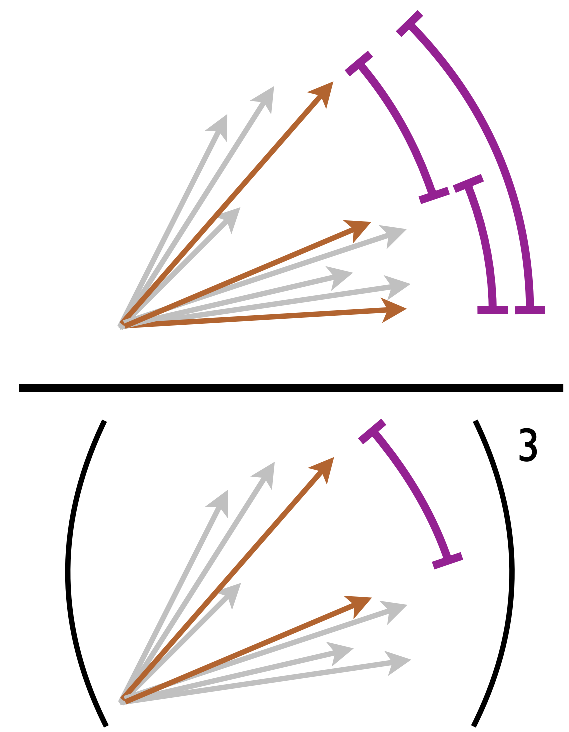
$$\frac{1}{z_s} \simeq \frac{p_T}{m}$$

if soft dominates

Background after Grooming



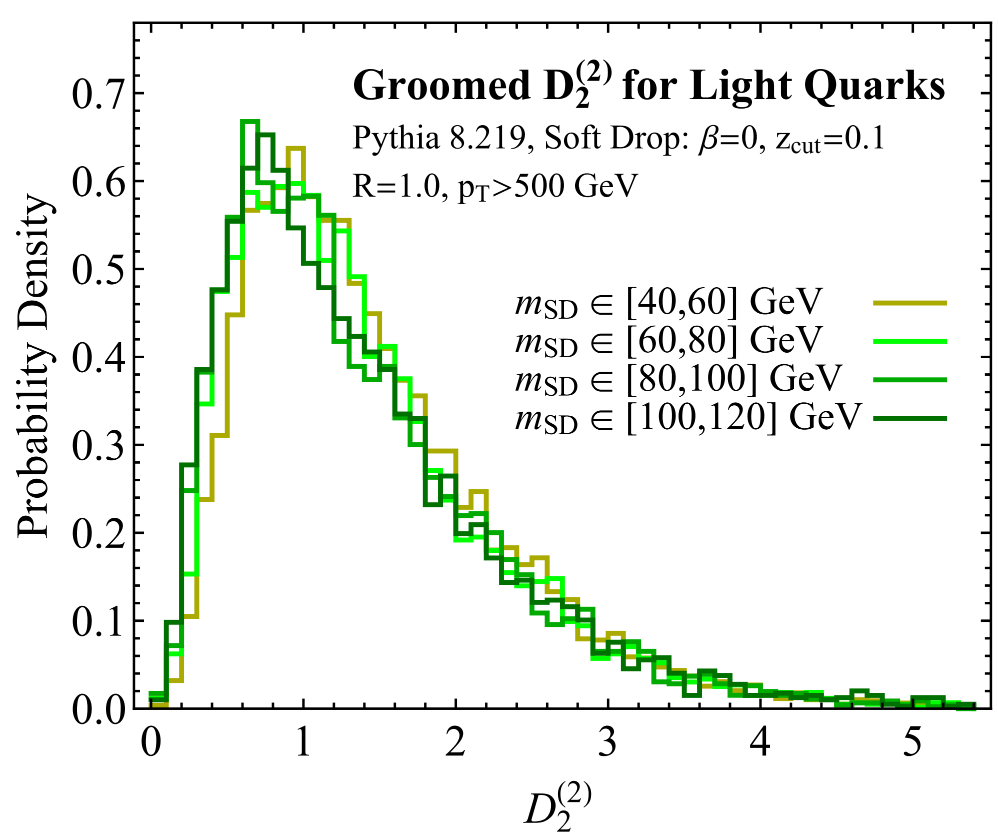
D_2 =



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

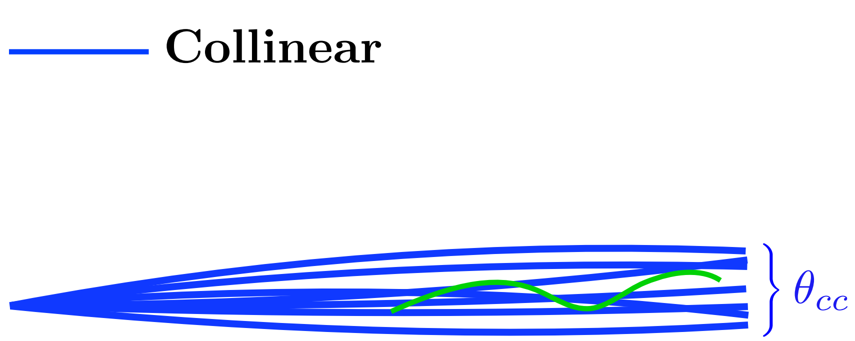
CCC

CC

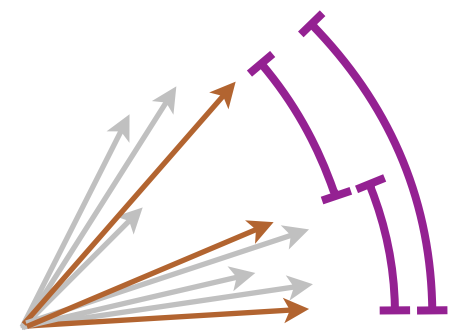


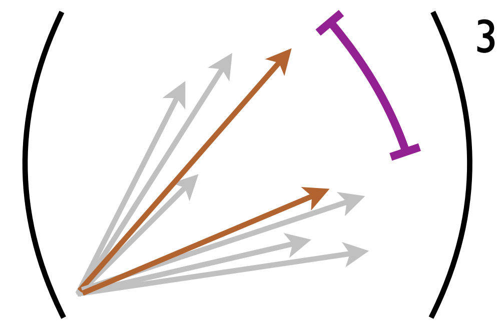
After grooming,
D_2 background distribution
is parametrically stable

Signal/Background Separation



$D_2 =$



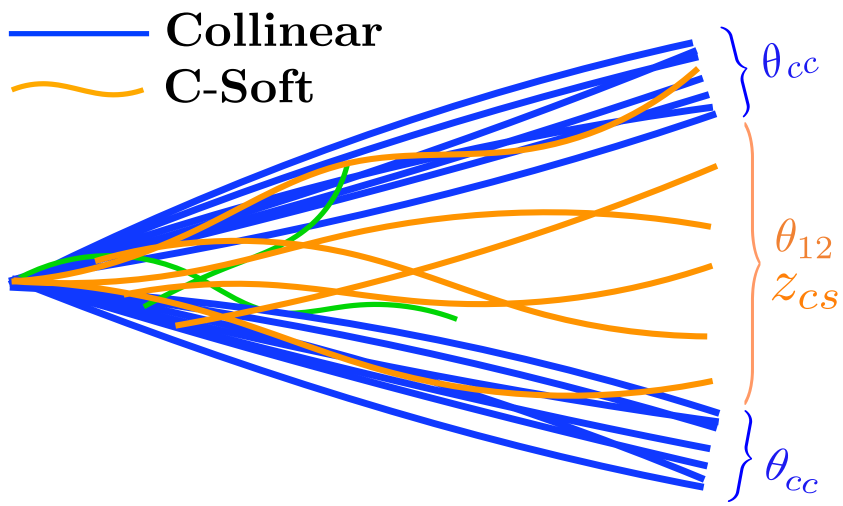


^{3}

CCC

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

CC



$C_1C_2C_S$ C_1C_2C

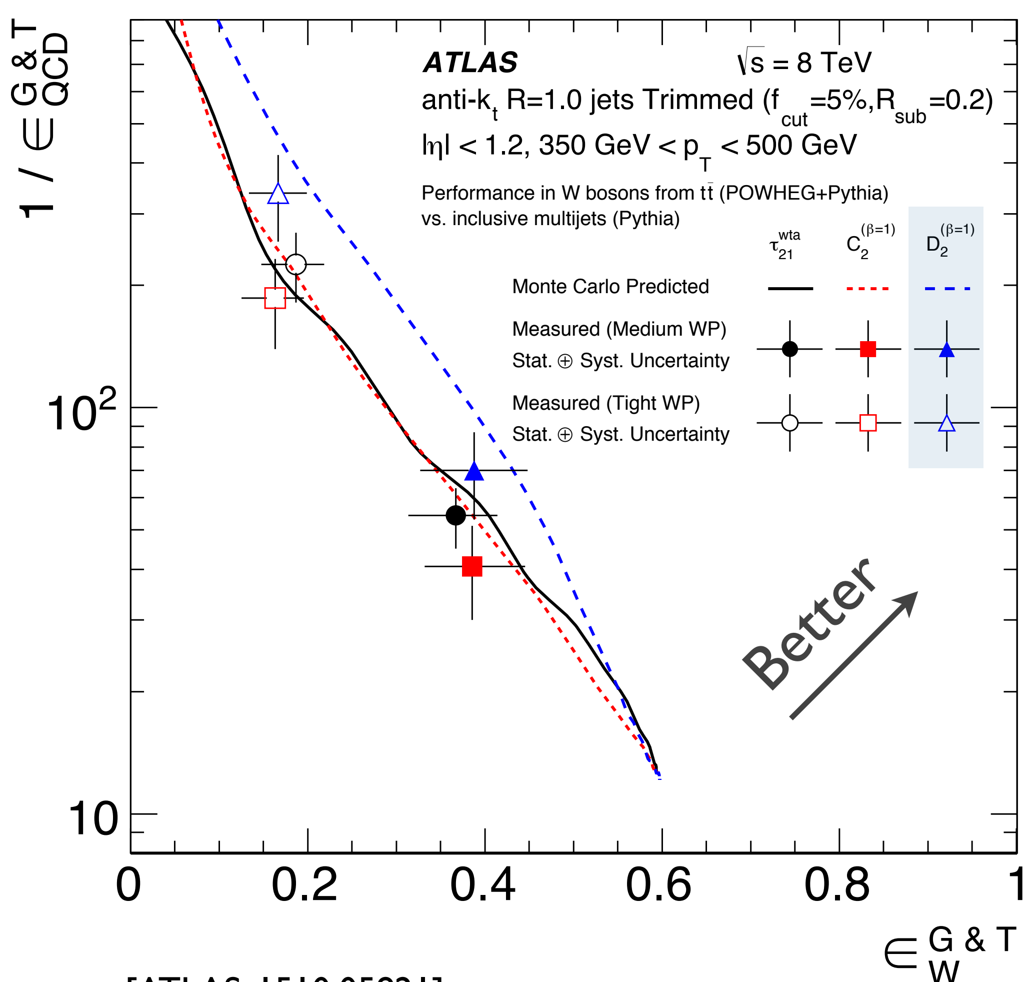
$$D_2 \simeq \frac{\theta_{12}^3 z_{cs} + \theta_{12}^2 \theta_{cc}}{\left(\theta_{12}\right)^3} \ll 1$$

C_1C_2

Signal parametrically distinct

Scorecard

ATLAS "R2D2" Tagger



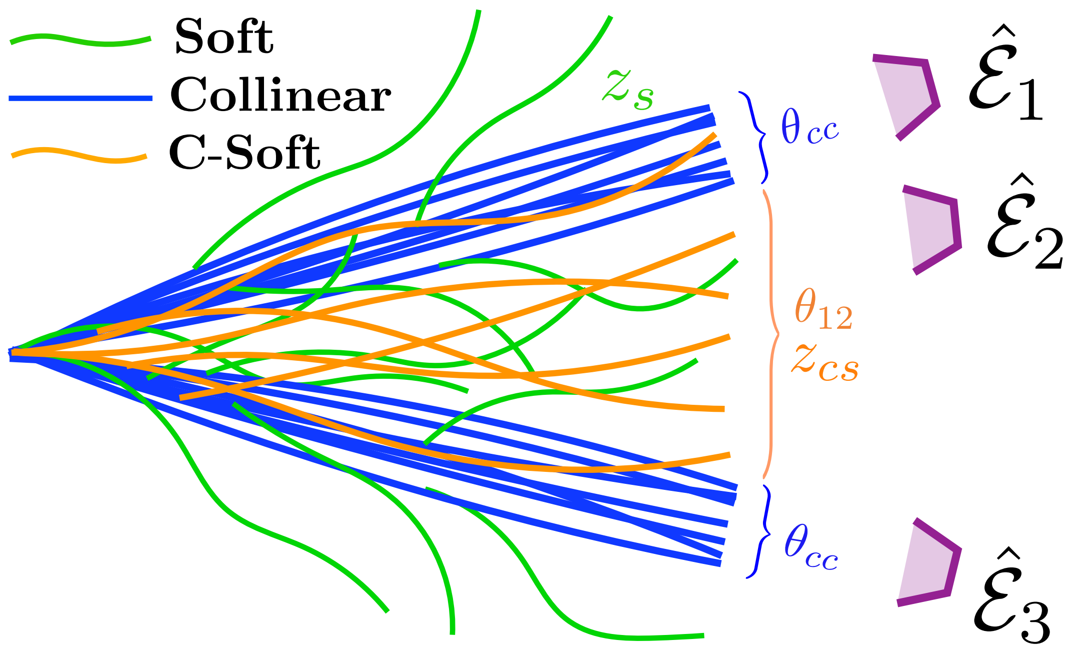
[ATLAS, 1510.05821]

	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

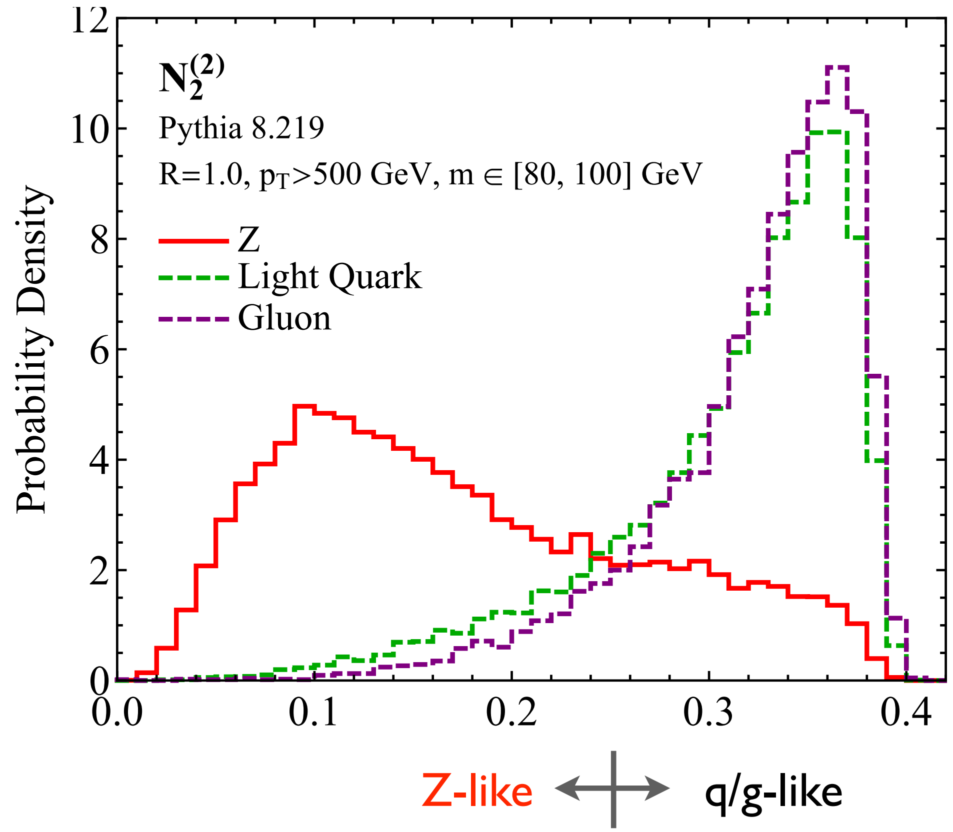
Systematic Catalog of Axes-Free Observables

Punchline: W/Z Tagging in 2017?



$\Rightarrow$

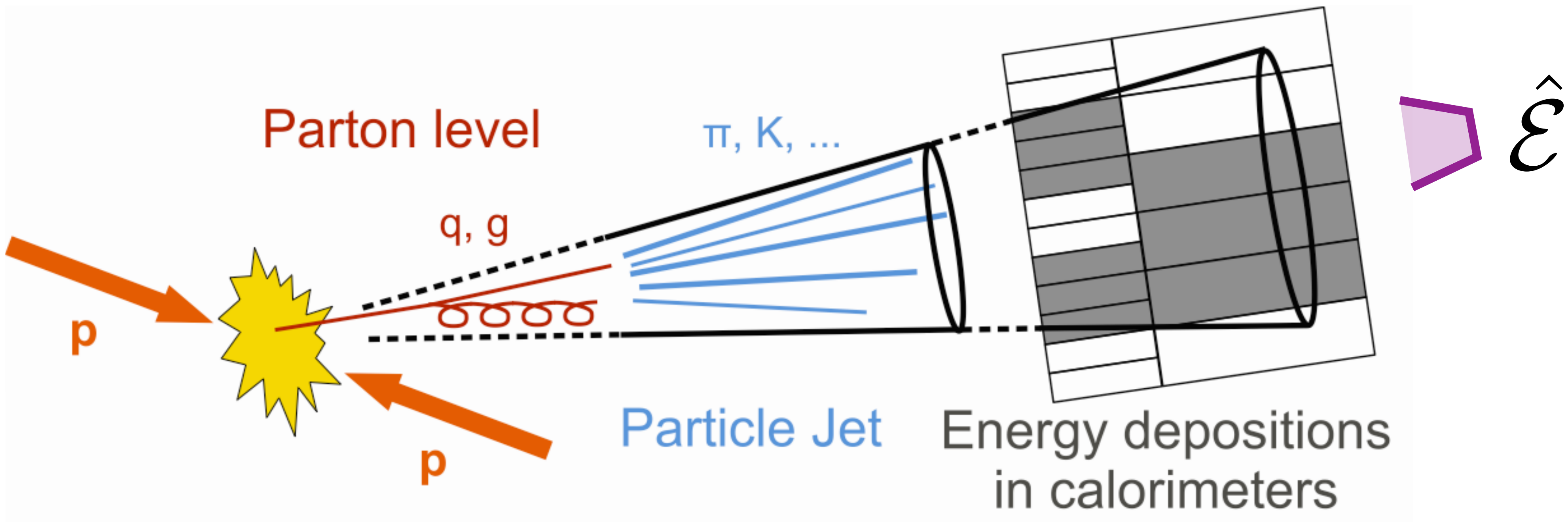
Stable & Performant



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

[Moult, Necib, JDT, 2016]

Back to Basics: What is a Measurement?



Stress-Energy Flow Operator:

energy flowing to infinity

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

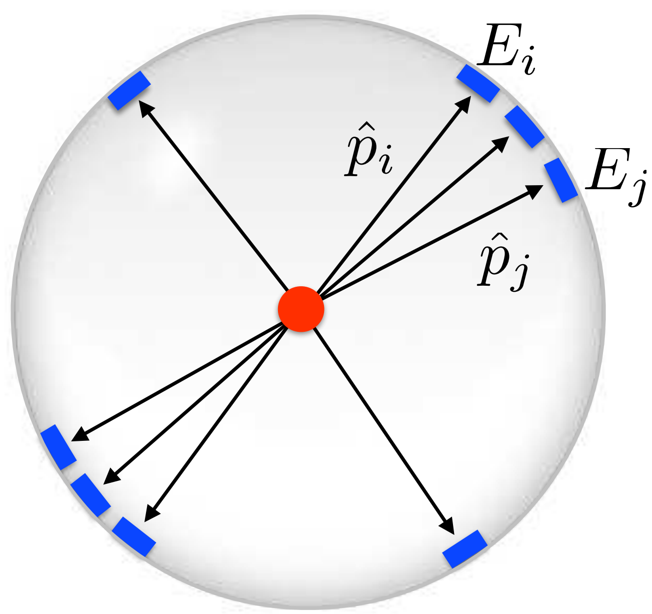
in a particular direction

at a particular speed

Also charge flow operators, but not IRC safe

[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

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

All N-tuples — N Energies — Angular Weighting

(symmetric, vanishes for $\theta_{ij} \to 0$)

Completely general, but useful for jets?

[Tkachov, hep-ph/9601308]

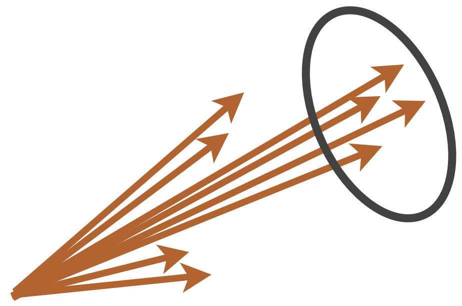
1-point Correlator

The most basic jet observable: $$p_T^{\text{jet}} \simeq \sum_i p_{Ti}$$

Using dimensionless quantities

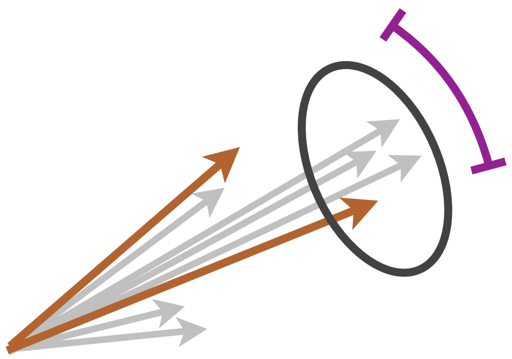
$$z_i \equiv \frac{p_{Ti}}{\sum_j p_{Tj}} \qquad \theta_{ij} \equiv \Delta R_{ij}$$

1-point: $$\boxed{e_1 = \sum_i z_i = 1}$$

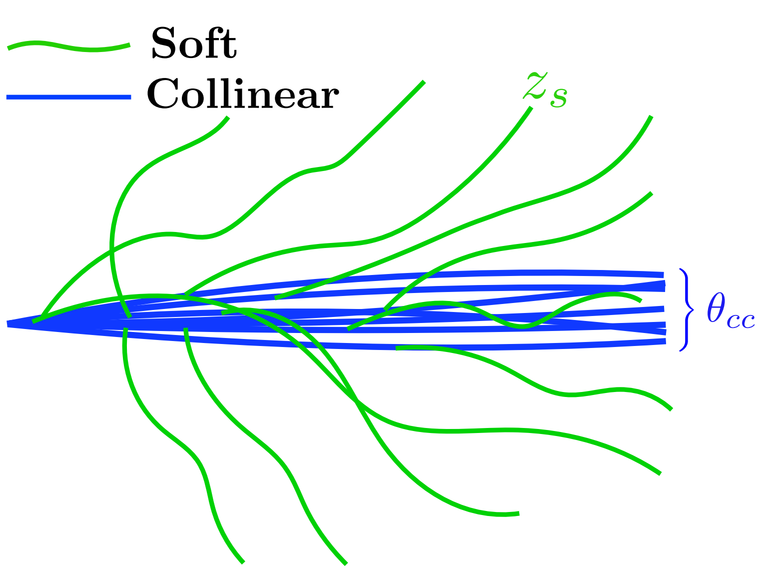


2-point Correlators

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



Similar information to jet mass



soft dominated	$\beta = 2$	$\approx$	thrust	*a.k.a.* m^2/p_T^2
equal weight	$\beta = 1$	$\approx$	width	*a.k.a. broadening, girth*
collinear dominated	$\beta = 0.5$	$\approx$	"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, Siodmok, Skands, Soper, 1605.04692]

3-point Correlators

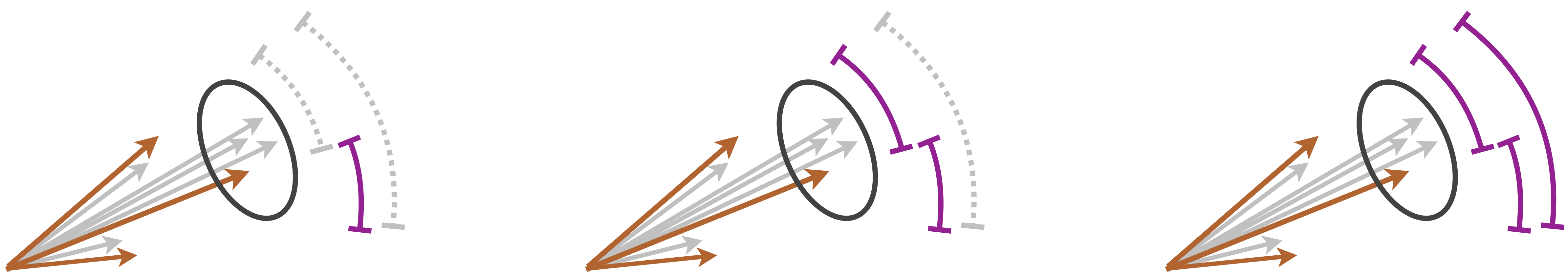
3-point:

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

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

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

used for D_2



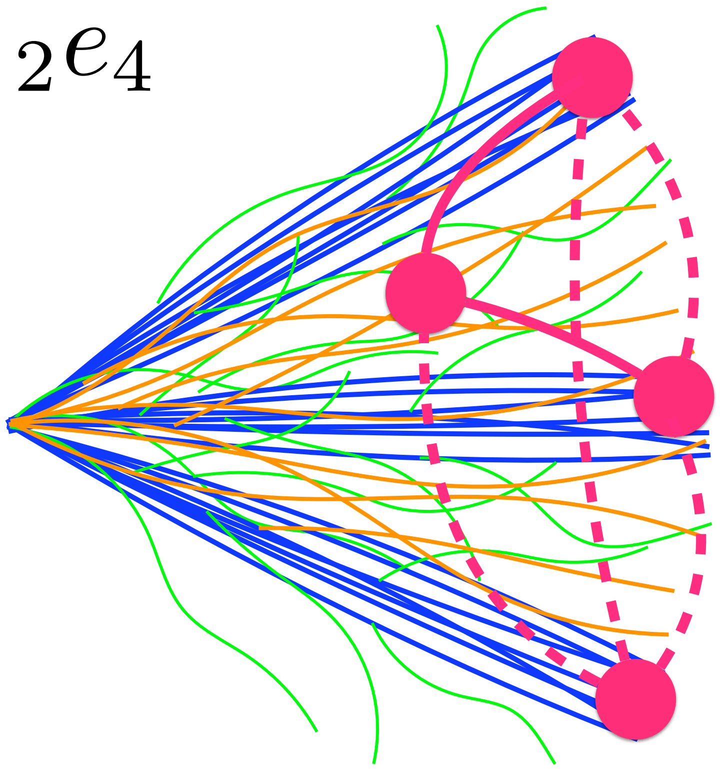
Probe of hierarchical jet substructure

[Moult, Necib, JDT, 1609.07483]

N-point 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, . . .

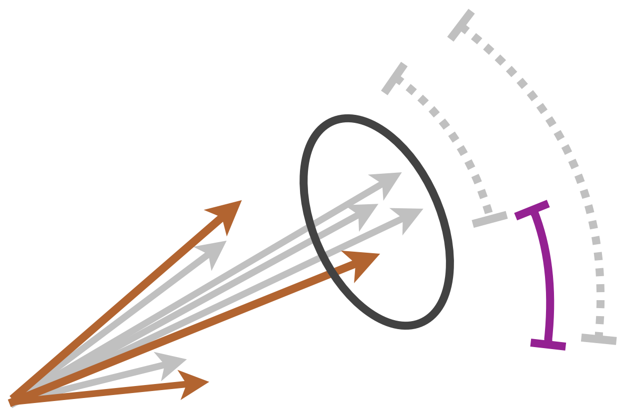
collinear dominated

soft dominated

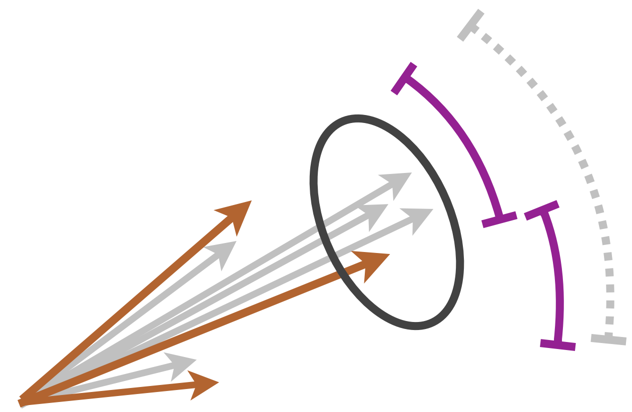
[Moult, Necib, JDT, 1609.07483]

New Discriminants

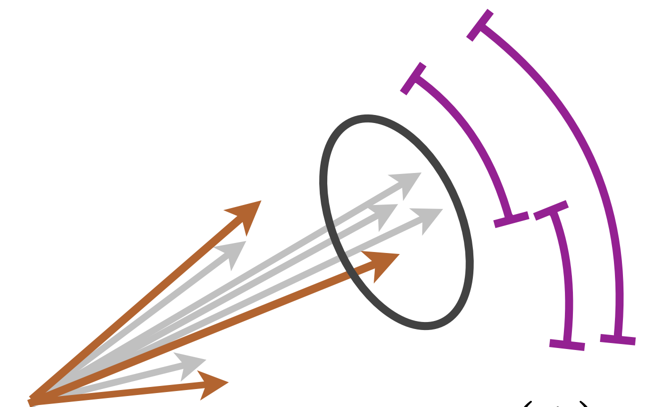
New Boosted W/Z Discriminants



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



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



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

Rule of thumb: boost invariance along jet axis

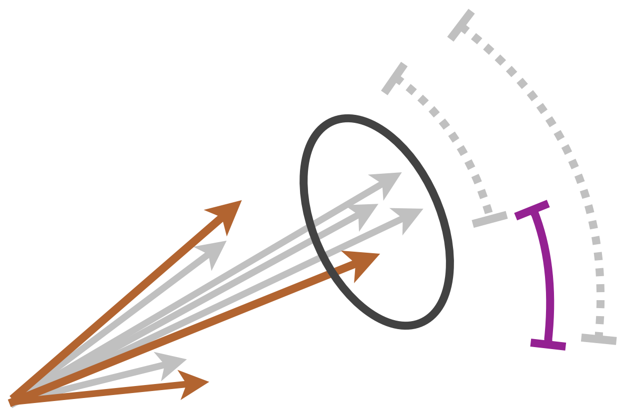
$$z_i \to z_i \qquad \theta_{ij} \to \gamma^{-1}\theta_{ij}$$

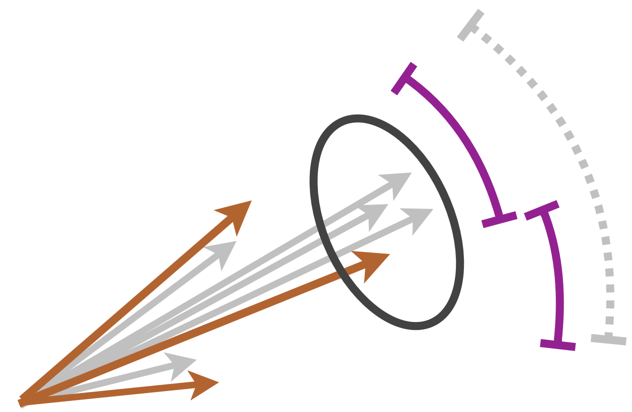
(i.e. same angular scaling in numerator and denominator)

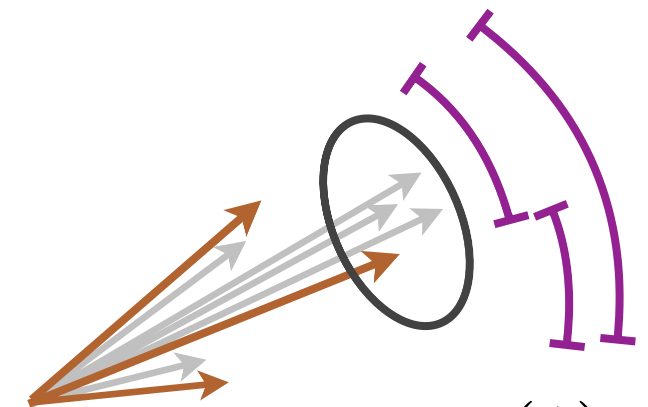
Lesson: Signal robust to grooming, but background can change when soft modes removed

[Moult, Necib, JDT, 1609.07483]

W/Z Tagging before Grooming



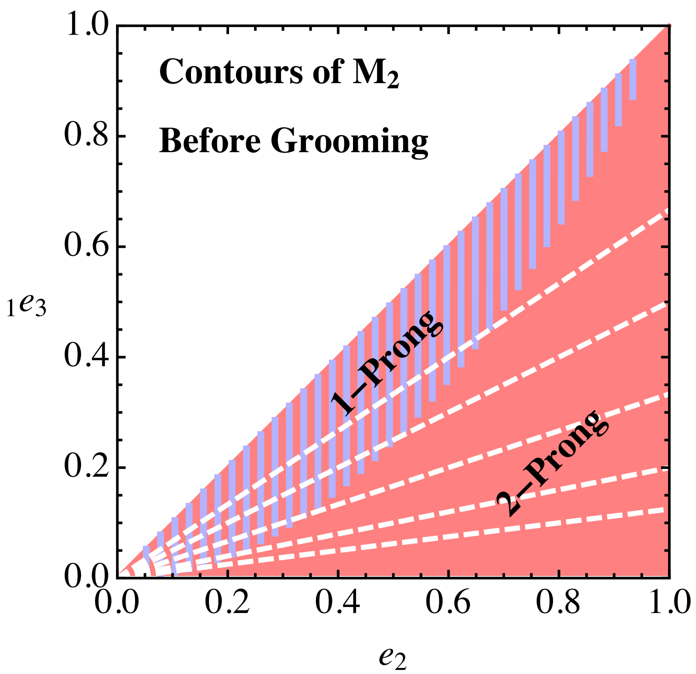




$$M_2 = \frac{{}_1e_3}{{}_1e_2}$$

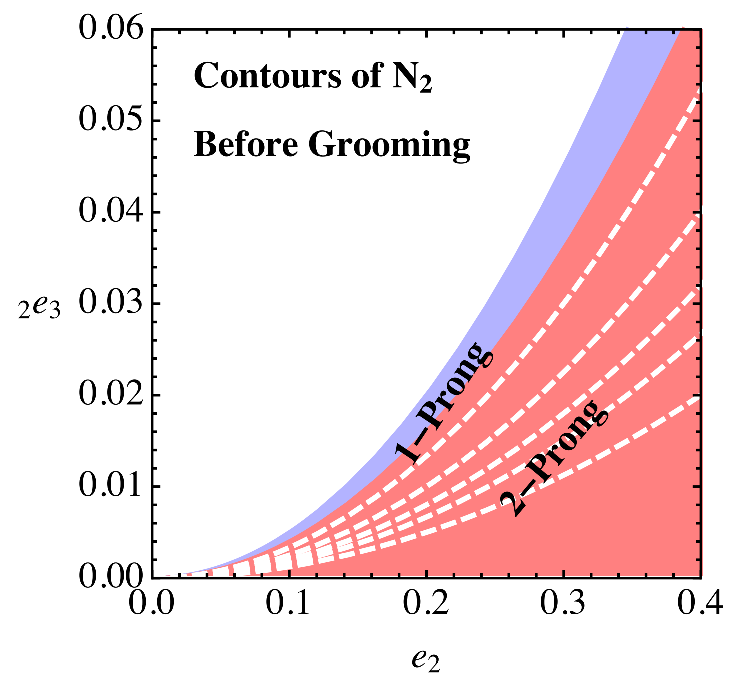
$$N_2 = \frac{{}_2e_3}{({}_1e_2)^2}$$

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

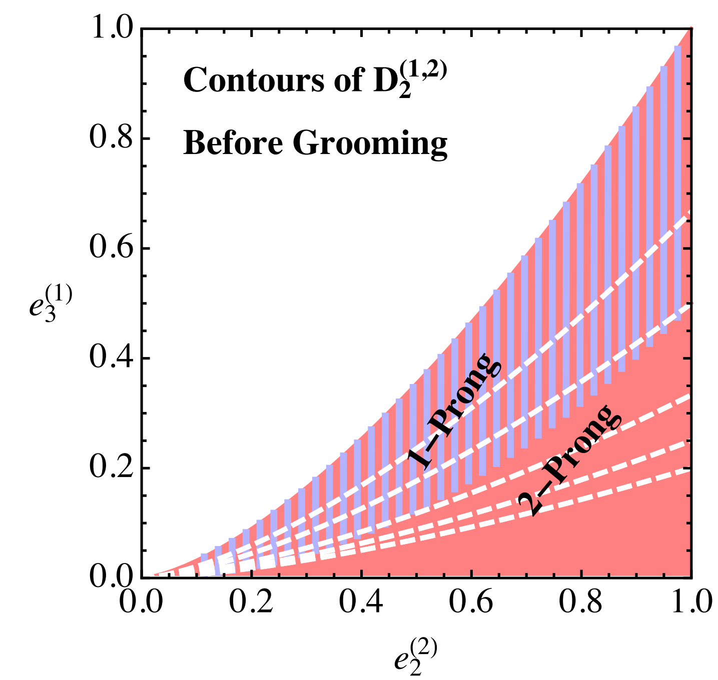


✗

(B overlaps S)



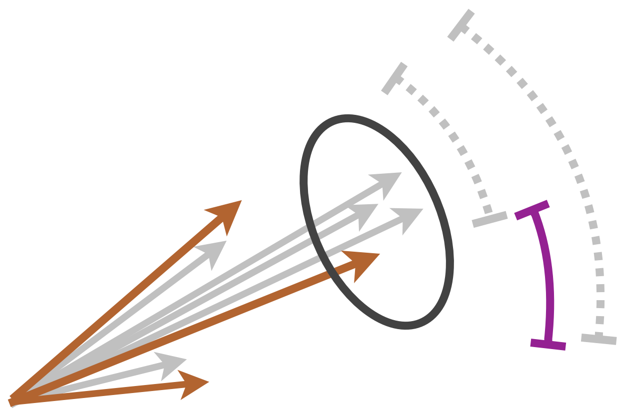
✓

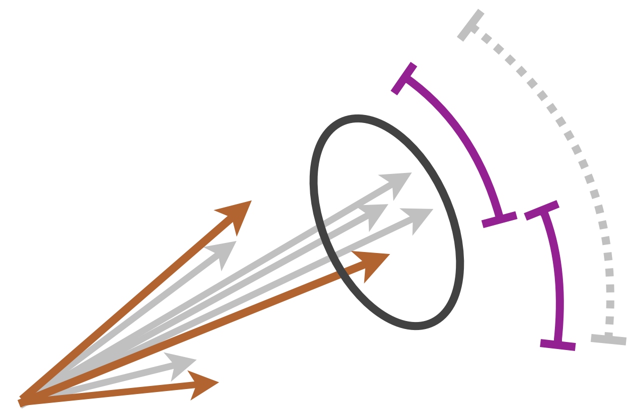


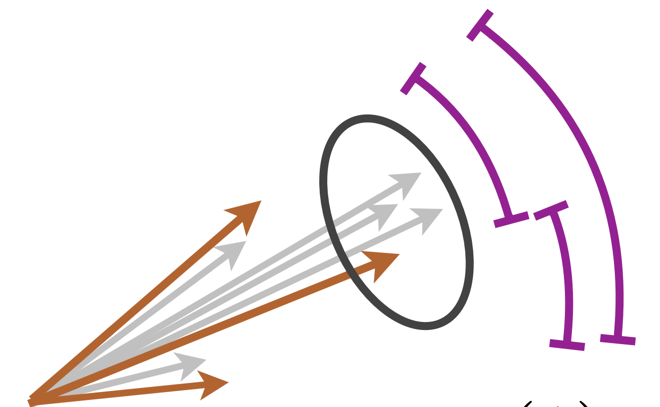
✗

(B overlaps S)

W/Z Tagging after Grooming



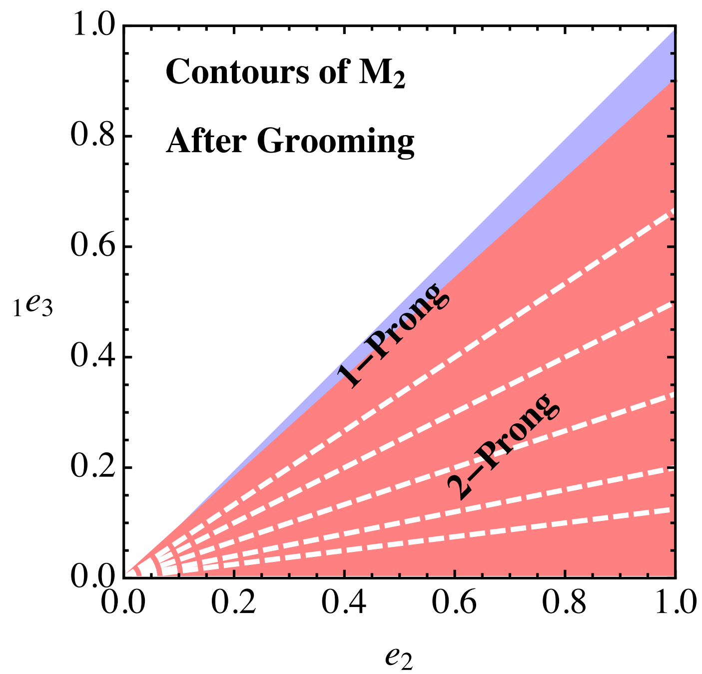


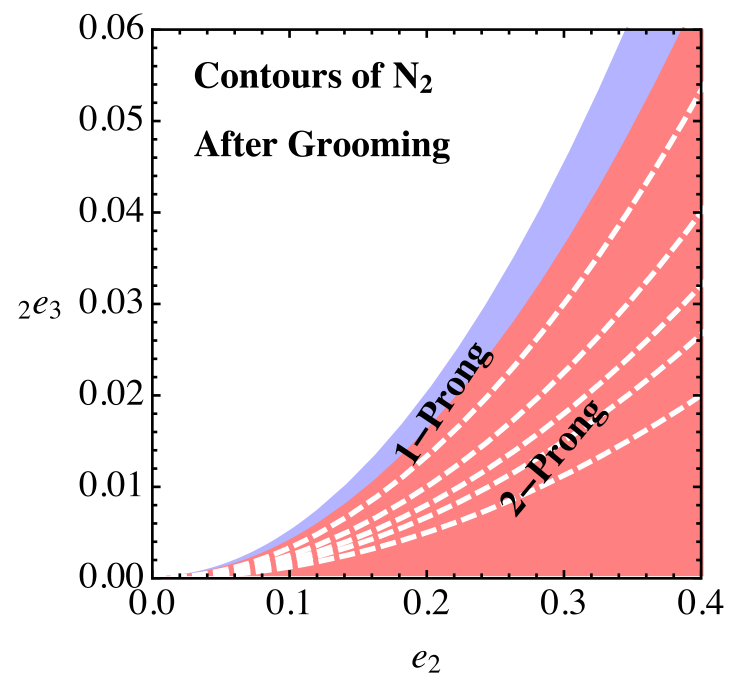


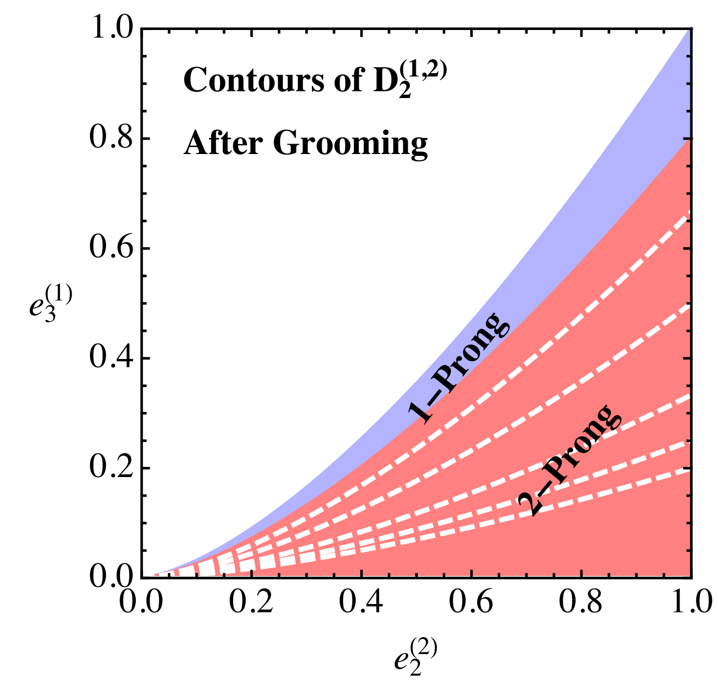
$$M_2 = \frac{{}_1e_3}{{}_1e_2}$$

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

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







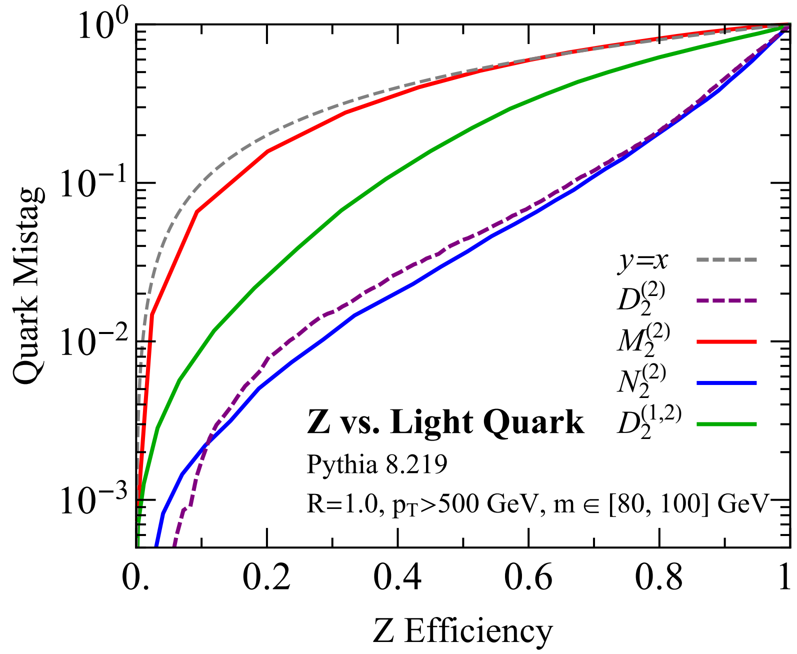
✓ ✓ ✓

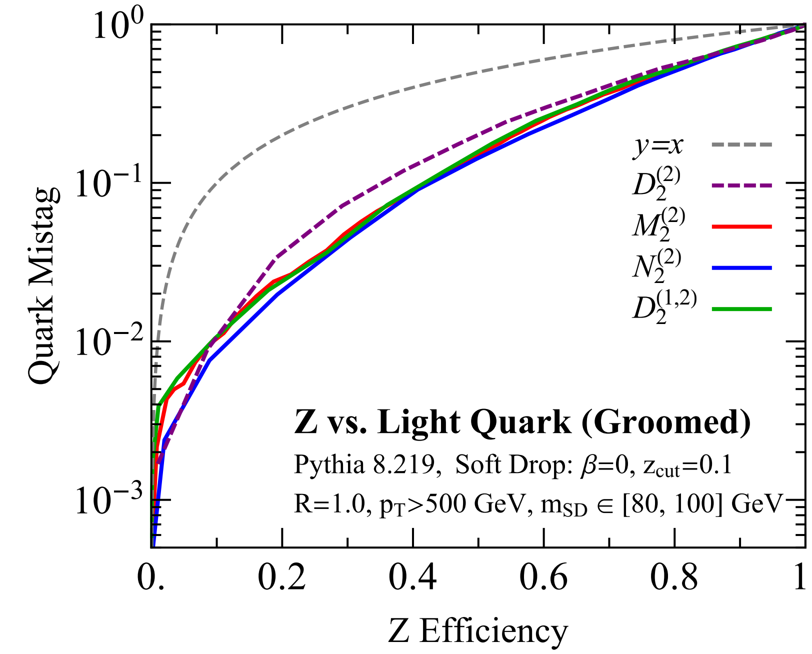
Performance Follows Power Counting

Better

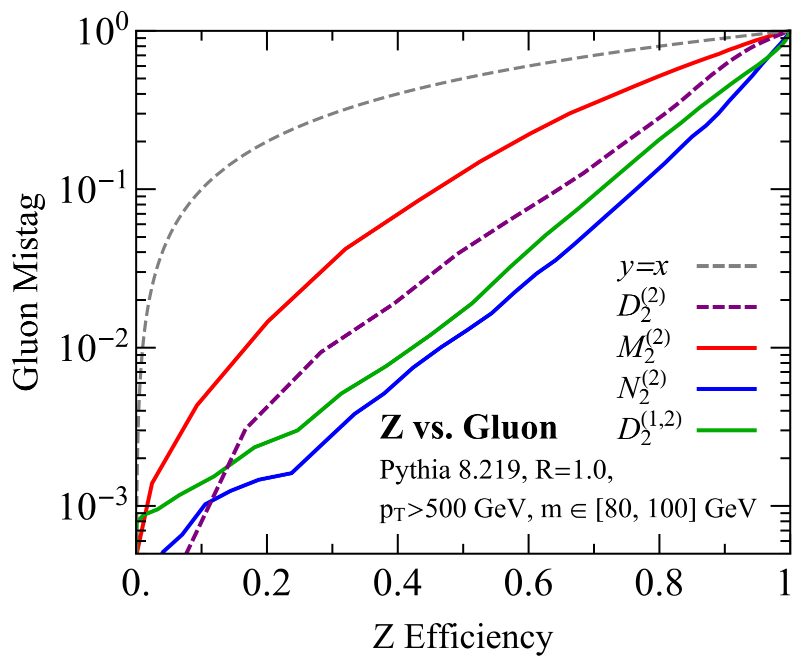
Before Grooming | After Grooming

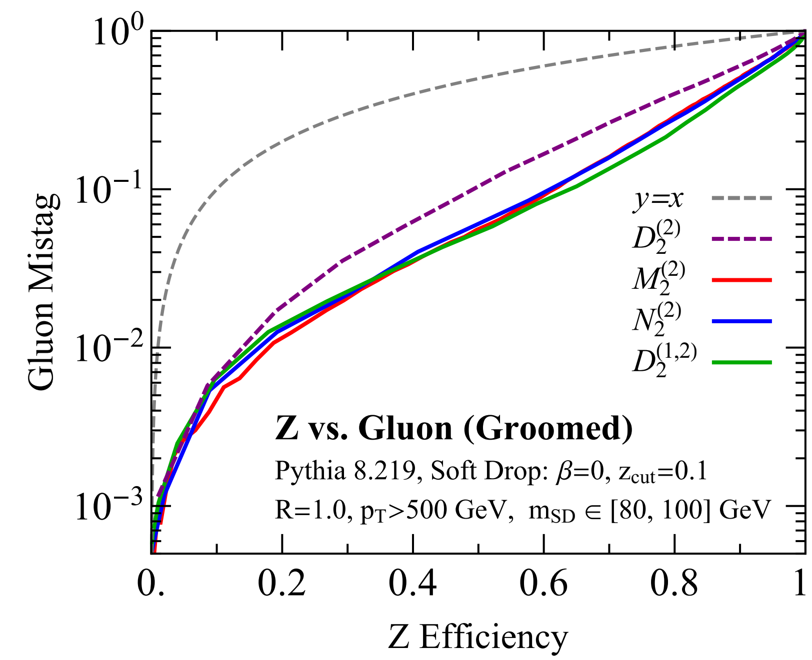
Z vs. q





Z vs. g

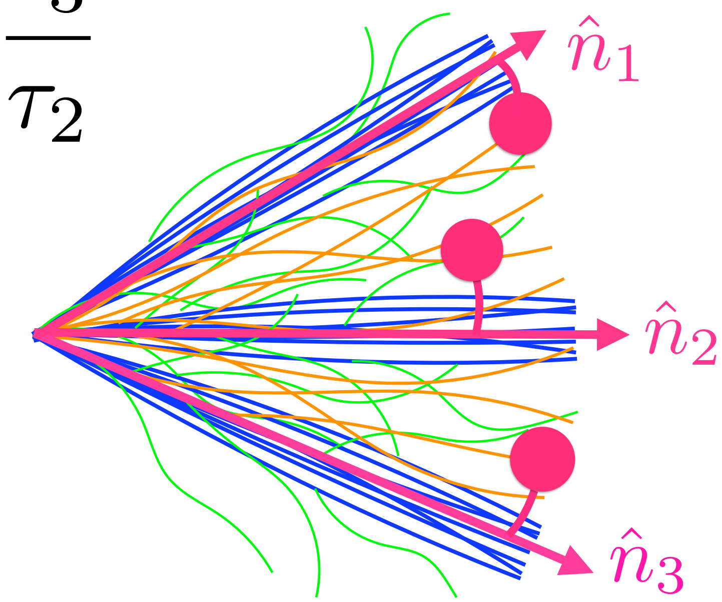




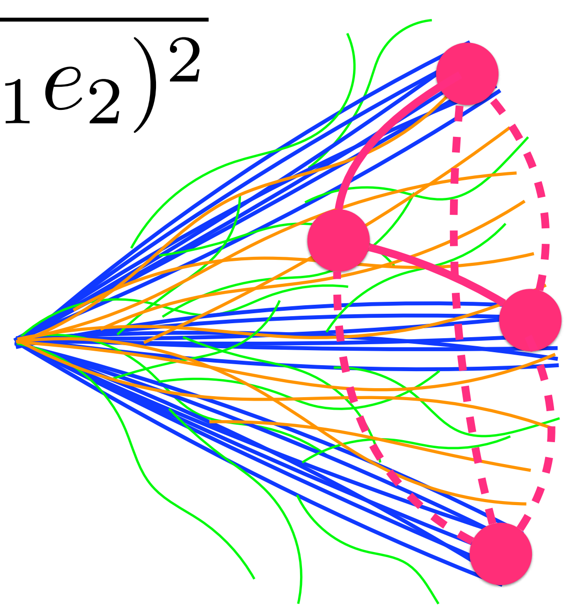
(Note, groomed mass gives x3-5 better background rejection by itself)

Boosted Top Discrimination

$$\tau_{3,2} = \frac{\tau_3}{\tau_2}$$

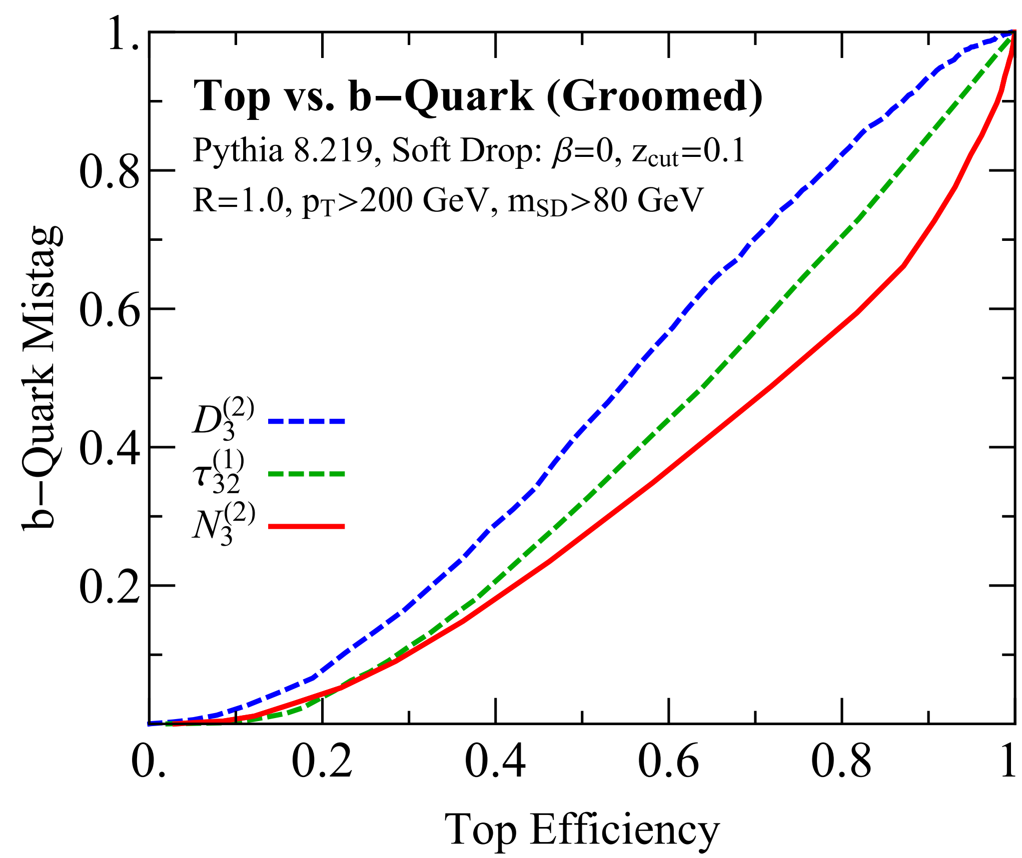


$$N_3 = \frac{{}_2e_4}{({}_1e_2)^2}$$



Axes vs. axes-free?

After grooming,
identical power counting,
similar performance

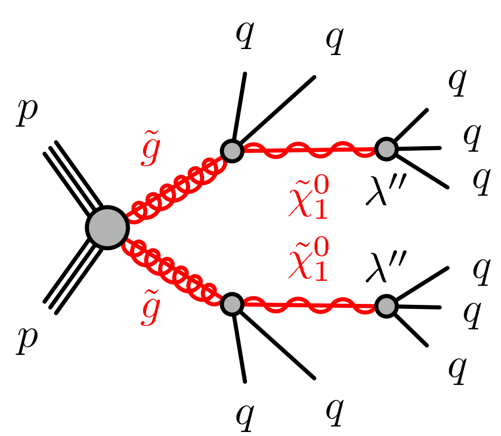


[Moult, Necib, JDT, 1609.07483]

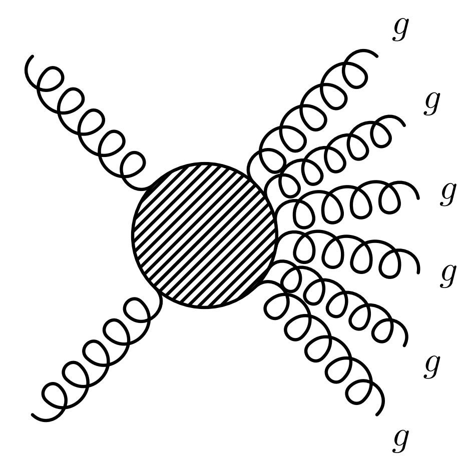
The Next Frontier

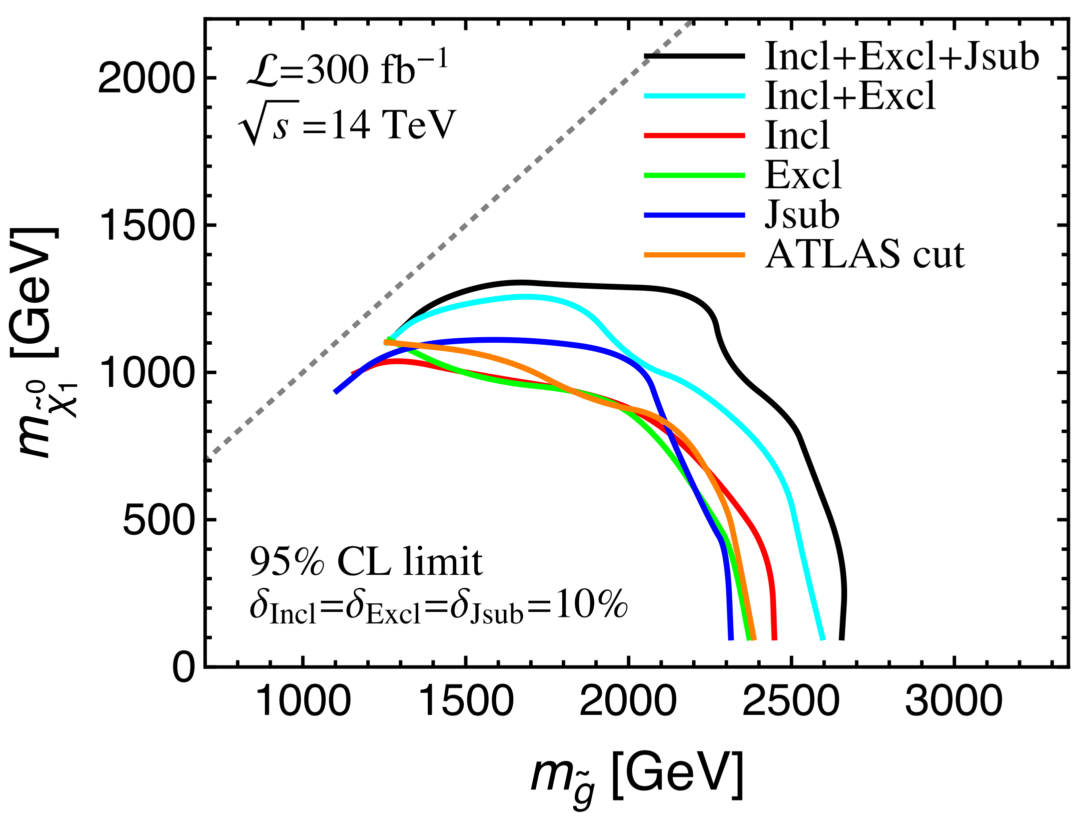
Quark/Gluon Tagging for New Physics

Signals ⇒ quark-enriched



Backgrounds ⇒ gluon-enriched



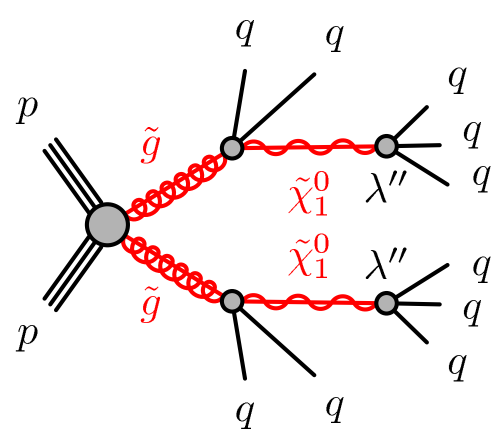


Promising performance in SUSY searches…

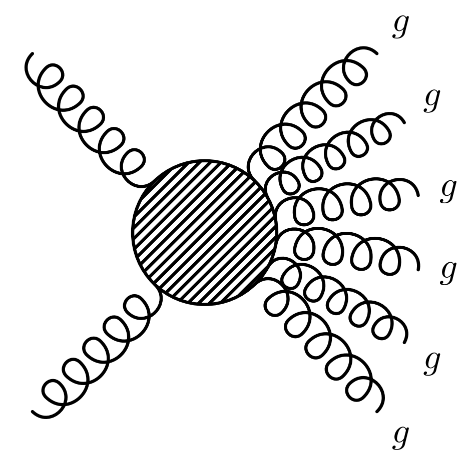
[Bhattacherjee, Mukhopadhyay, Nojiri, Sakakie, Webber, 1609.08781]

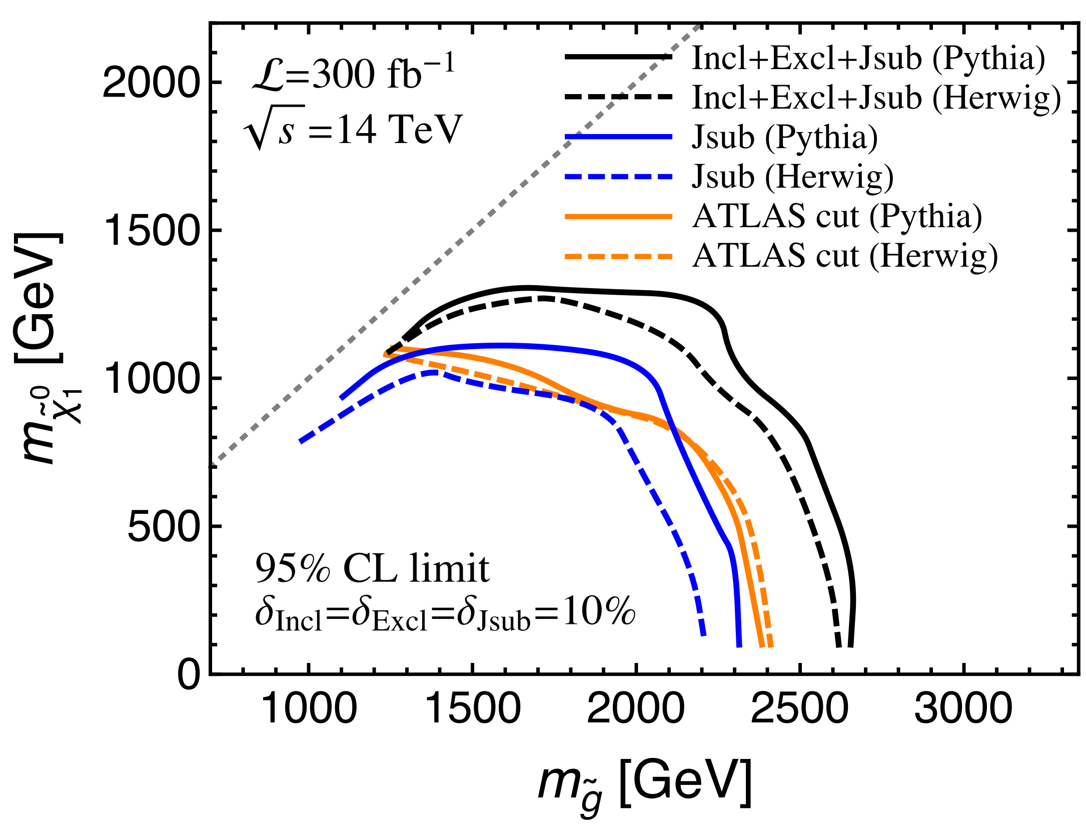
Quark/Gluon Tagging for New Physics

Signals ⇒ quark-enriched



Backgrounds ⇒ gluon-enriched





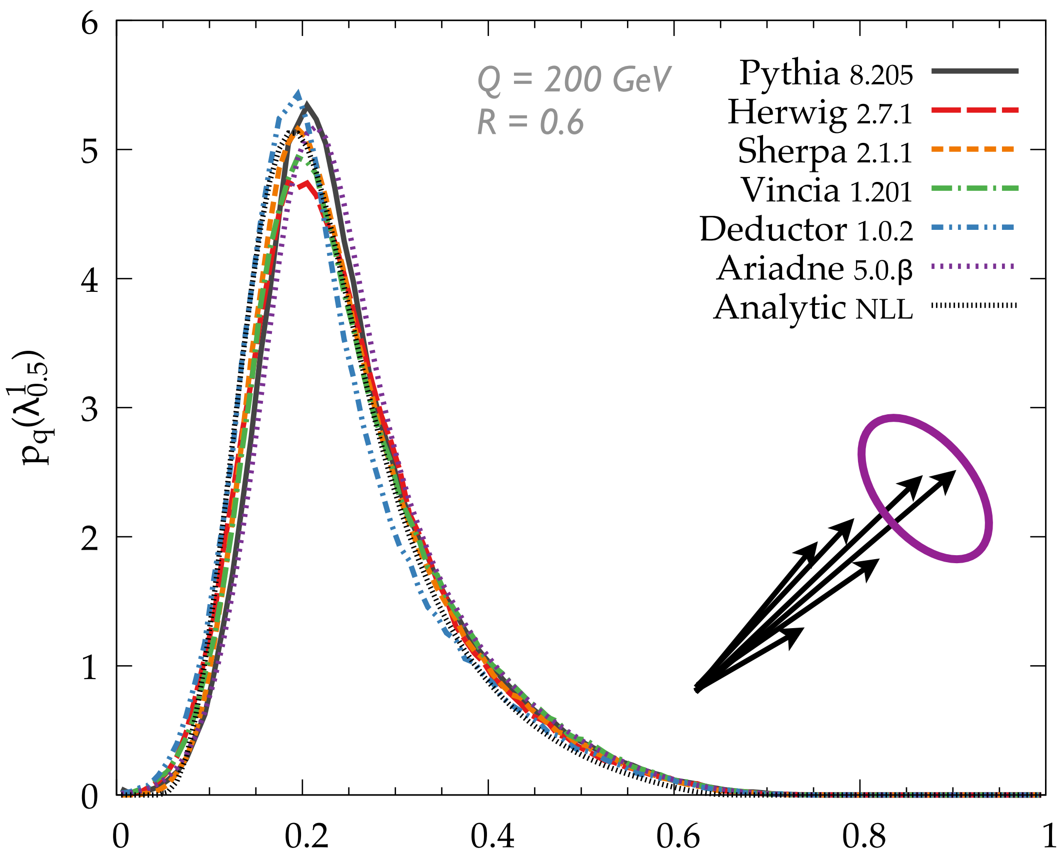
Promising performance in SUSY searches…

…but considerable theoretical uncertainties

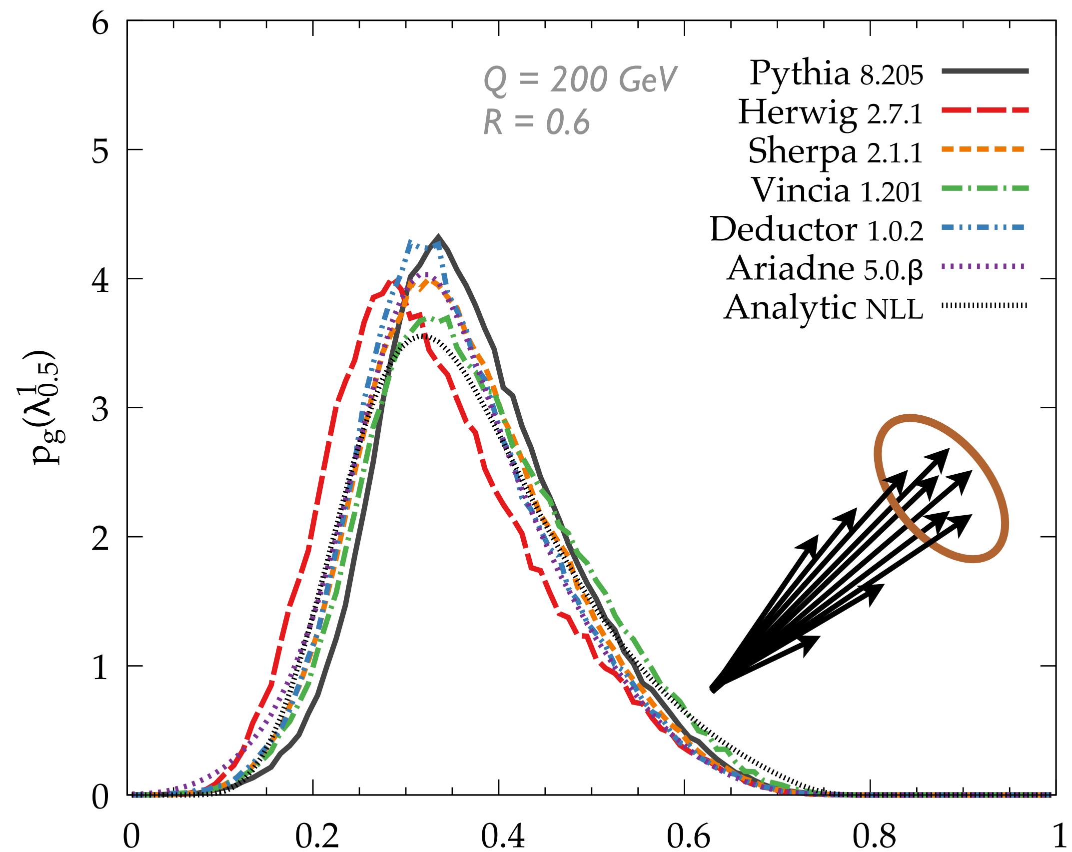
[Bhattacherjee, Mukhopadhyay, Nojiri, Sakakie, Webber, 1609.08781]

Key Task for Jet Substructure

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



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



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

Well-constrained by LEP measurements

Needs more input from experiment (and theory)

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

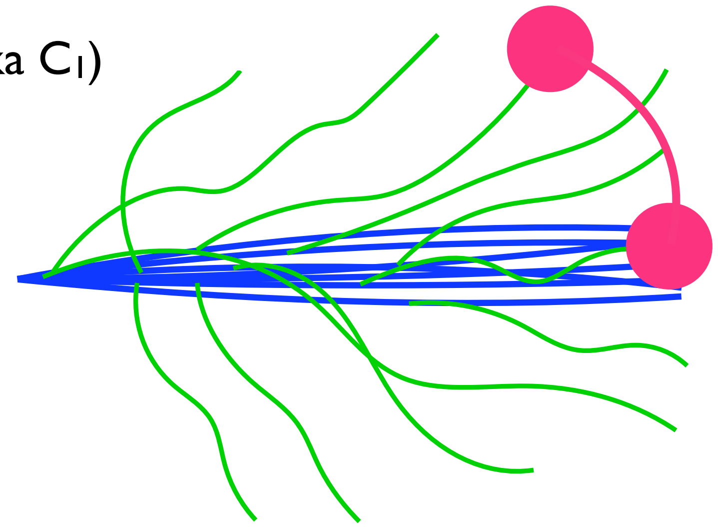
Higher-Point Quark/Gluon Discriminants

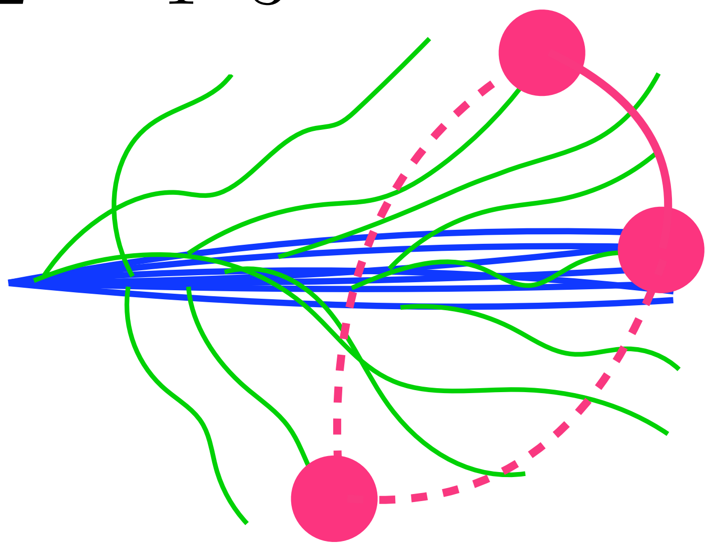
$U_1 = {}_1e_2$

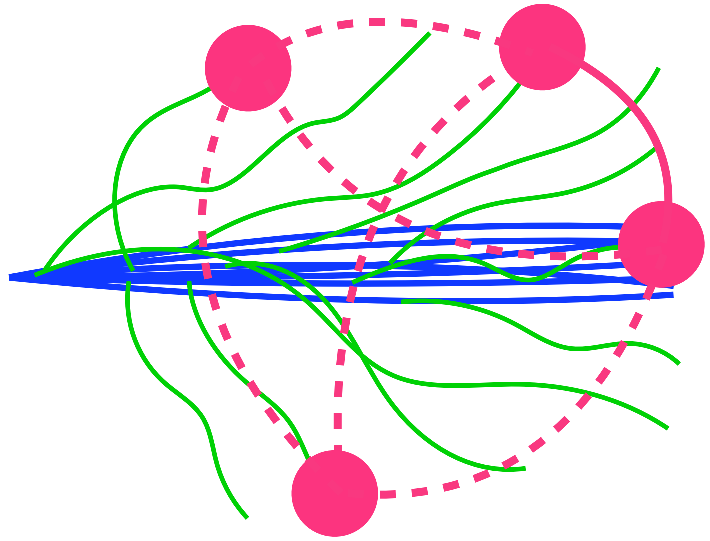
(aka C_1)

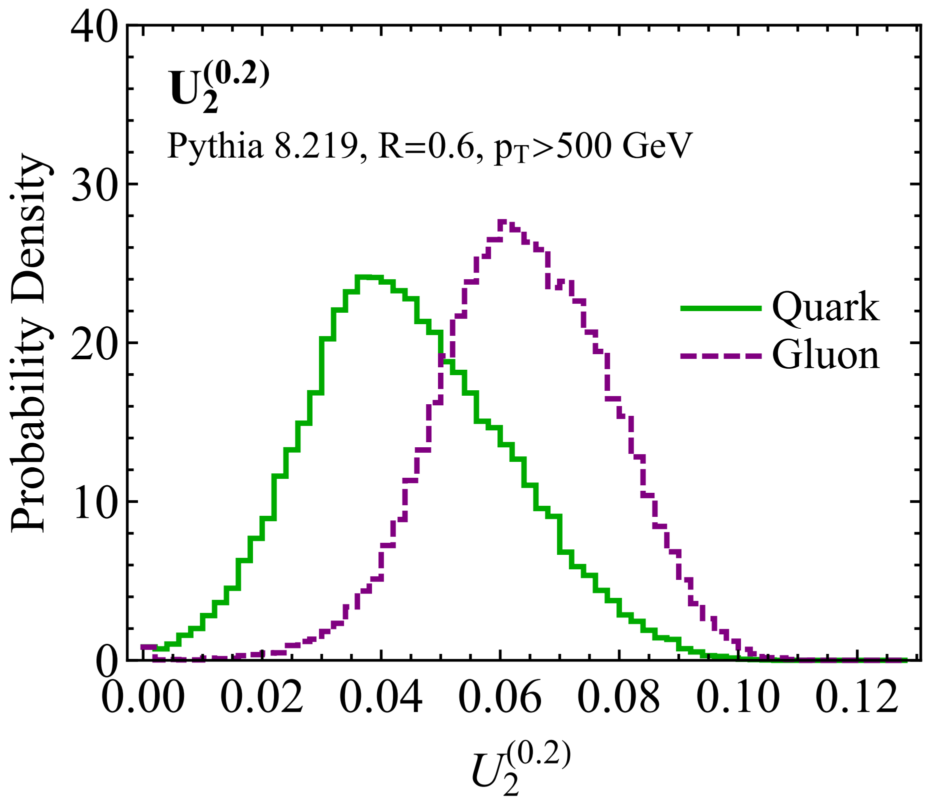
$U_2 = {}_1e_3$

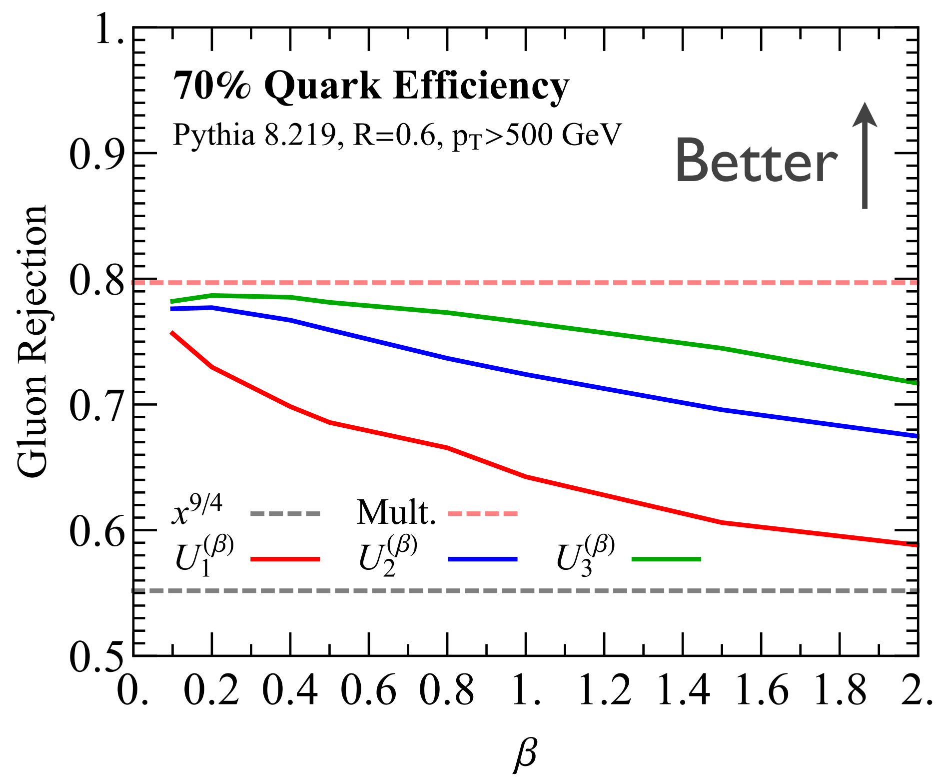
$U_3 = {}_1e_4$





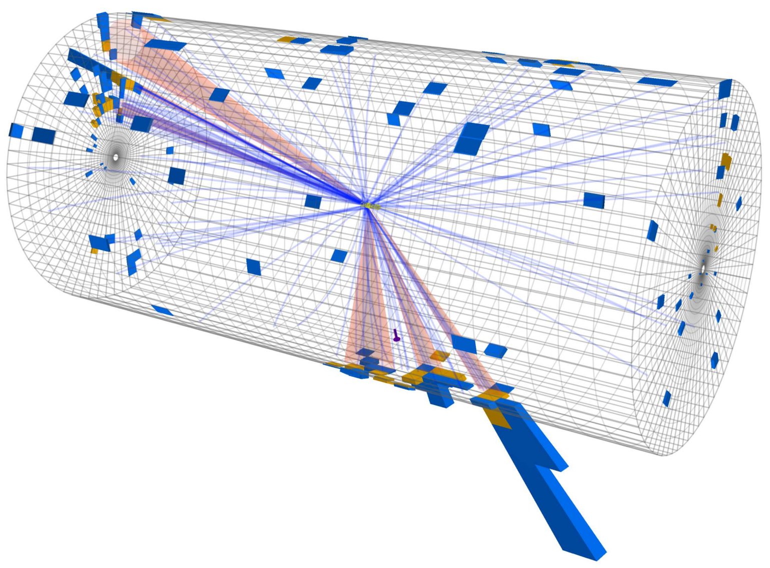






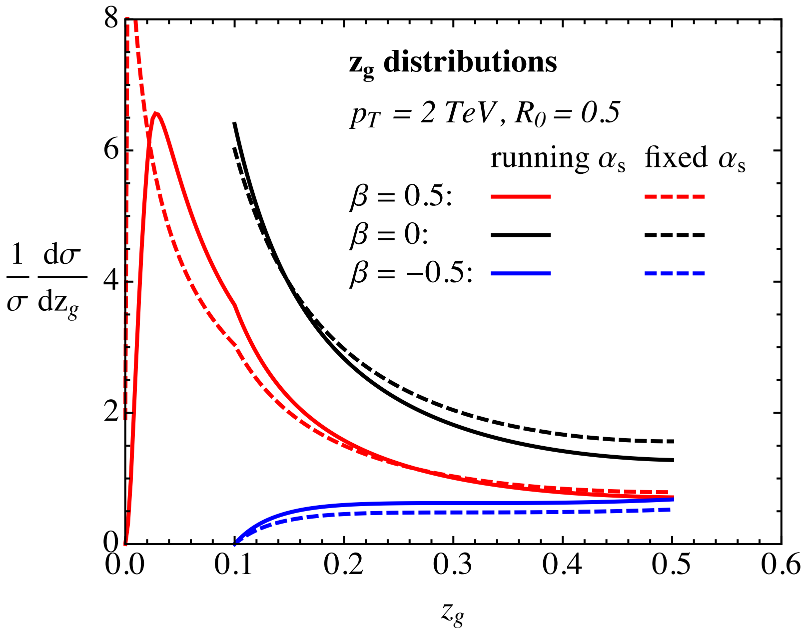
[Moult, Necib, JDT, 1609.07483]

Jet Substructure



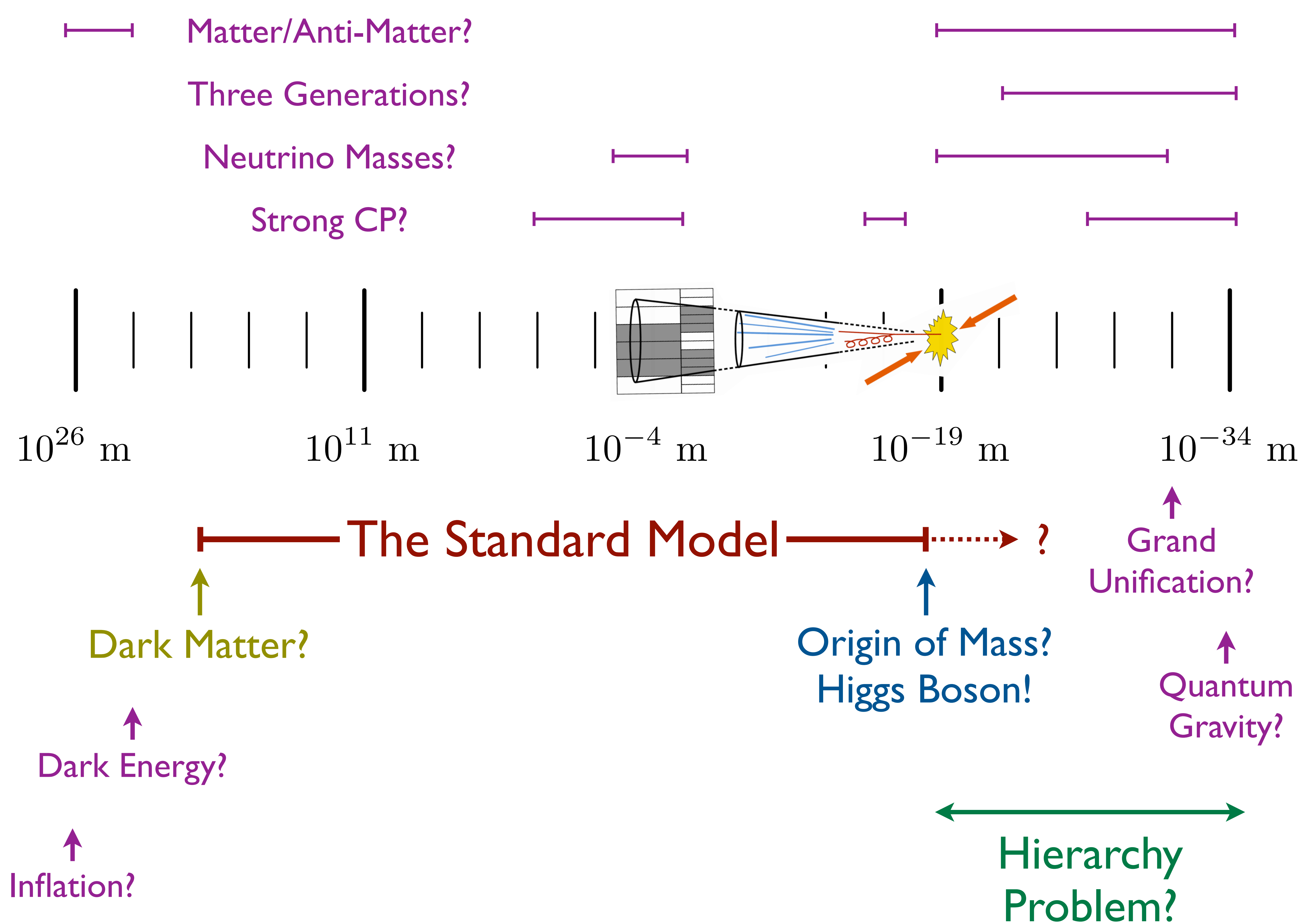
Boosting the Search for New Phenomena

[Thursday & **Today**]

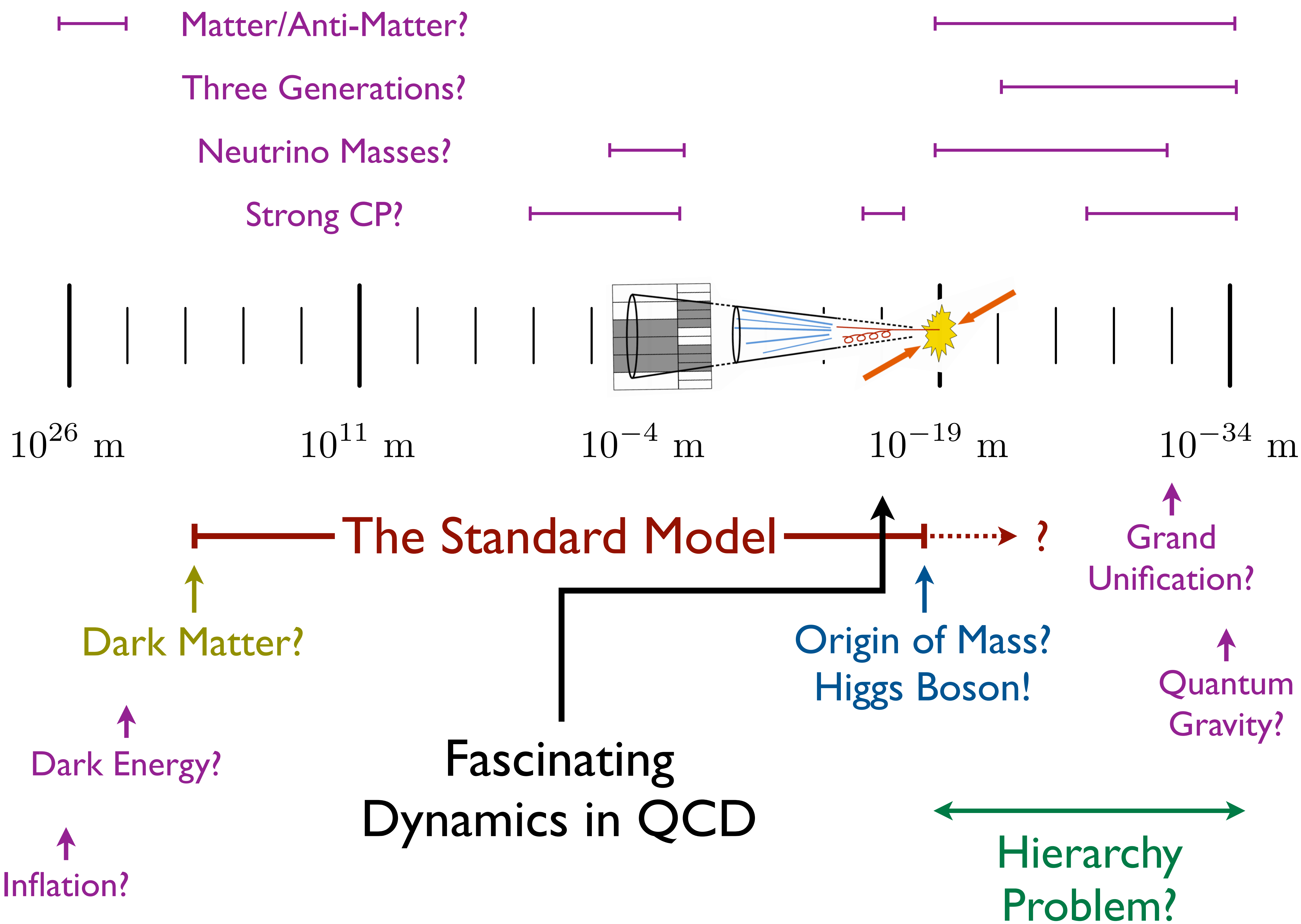


Pushing the Boundaries of Quantum Field Theory

[Next Monday & Tuesday]



Matter/Anti-Matter?
Three Generations?
Neutrino Masses?
Strong CP?
10^{26} m
10^{11} m
10^{-4} m
10^{-19} m
10^{-34} m
The Standard Model
?
Grand Unification?
Dark Matter?
Origin of Mass? Higgs Boson!
Quantum Gravity?
Dark Energy?
Inflation?
Hierarchy Problem?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