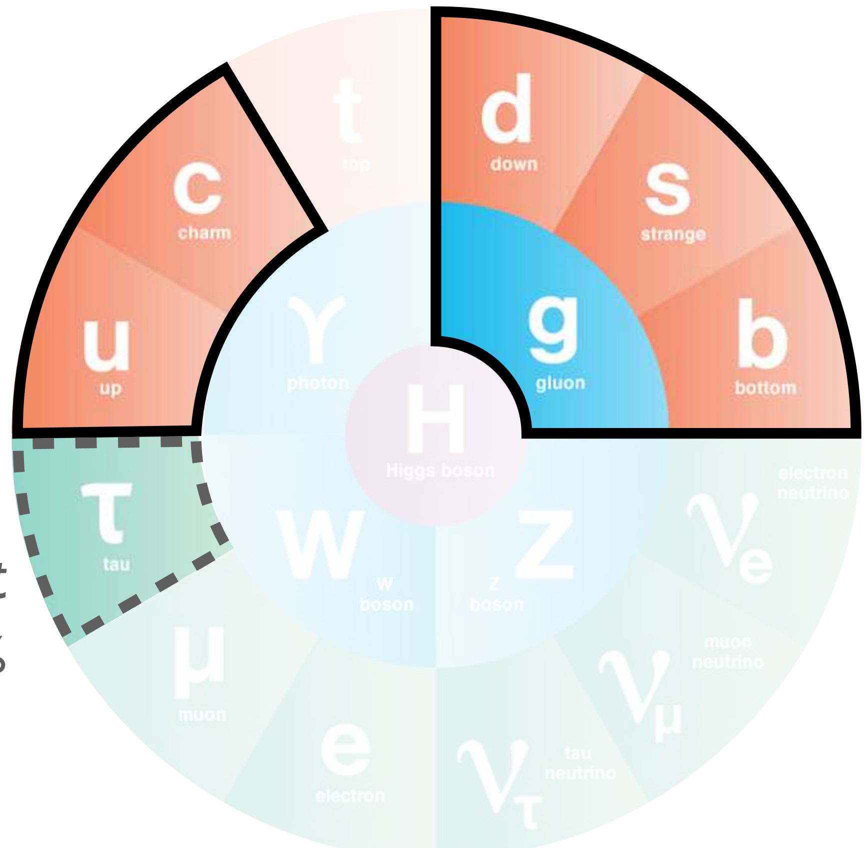
Recent Progress in Jet Physics

Jesse Thaler

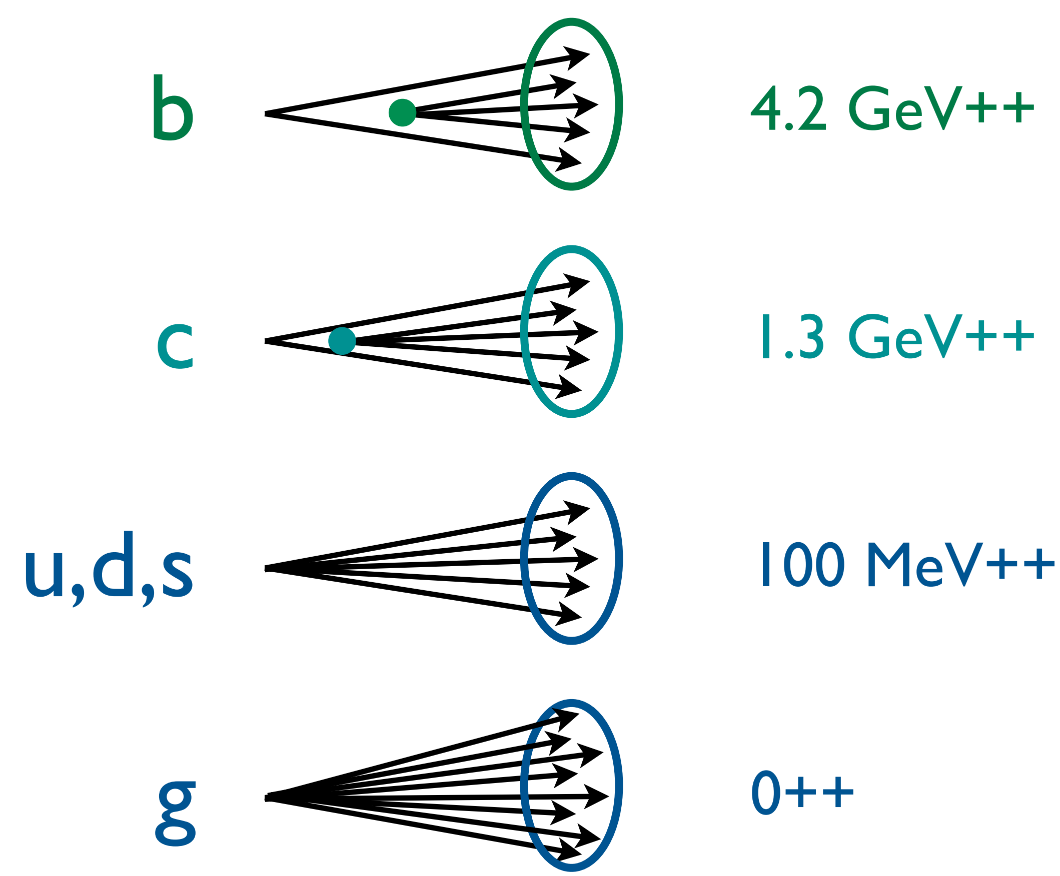
From the LHC to Dark Matter and Beyond, Aspen Center for Physics — March 24, 2017

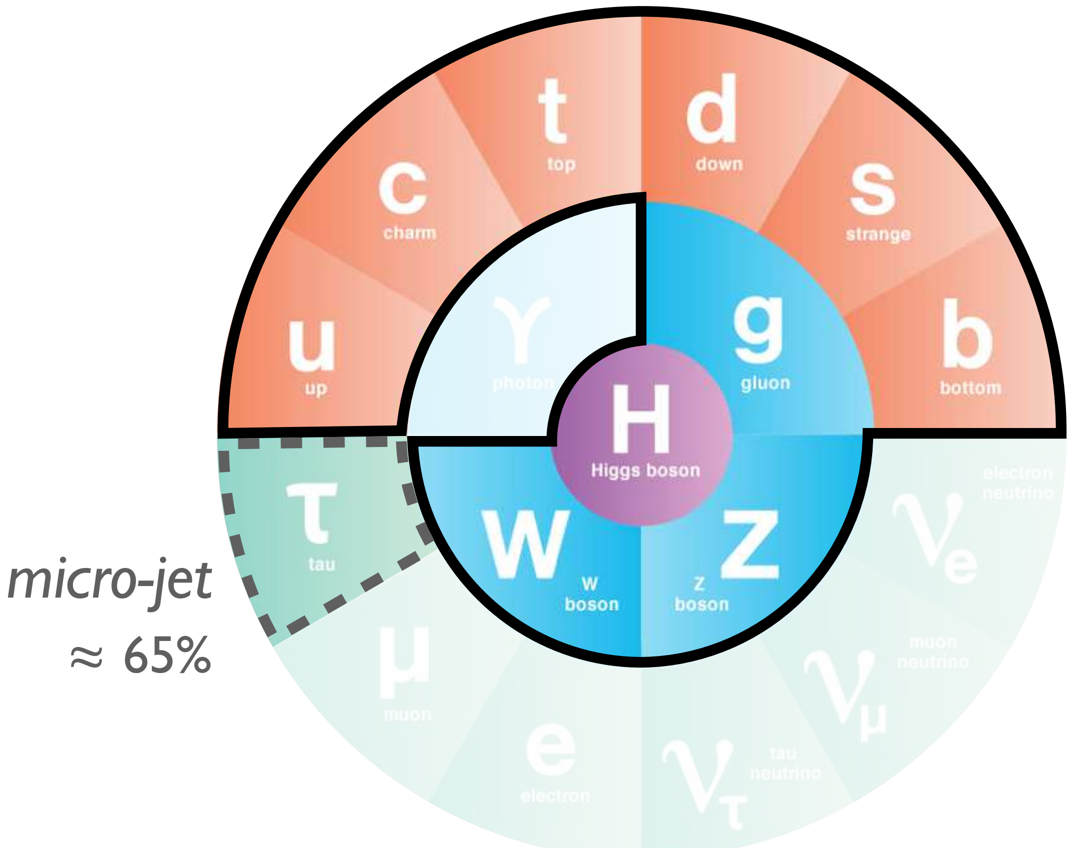


micro-jet
≈ 65%

Jets from the Standard Model

++ = plus gluonic radiation





Jets from the Standard Model

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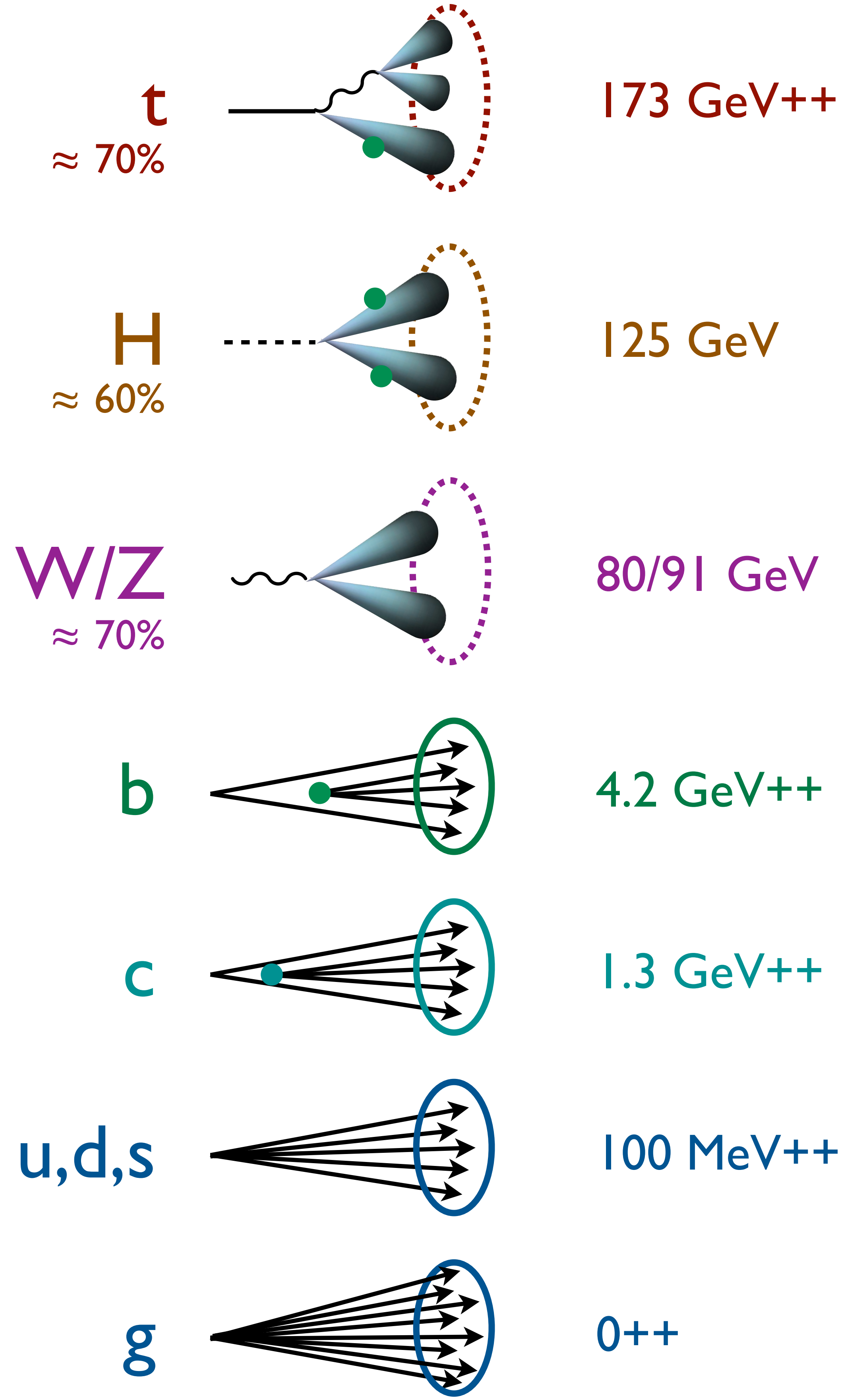
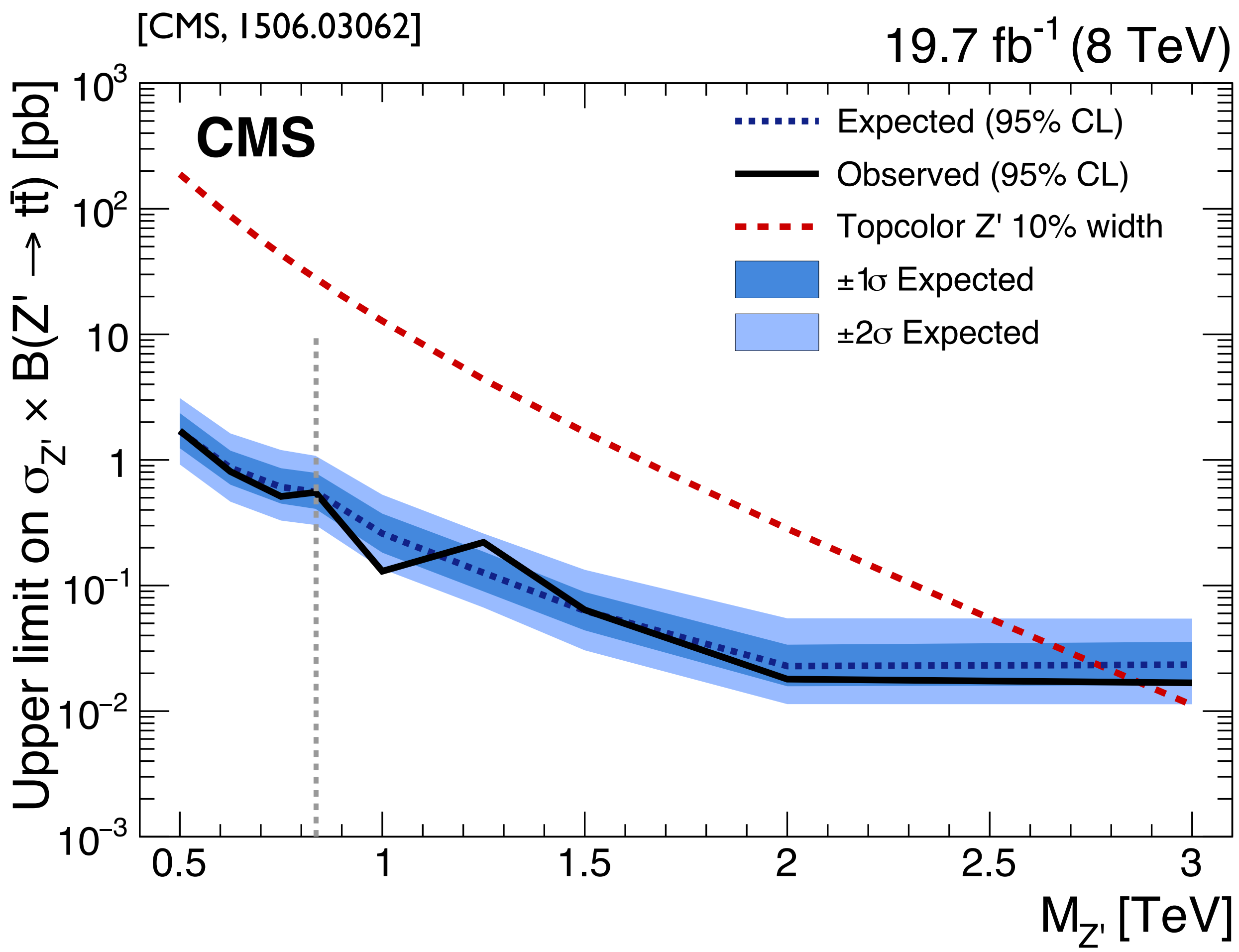
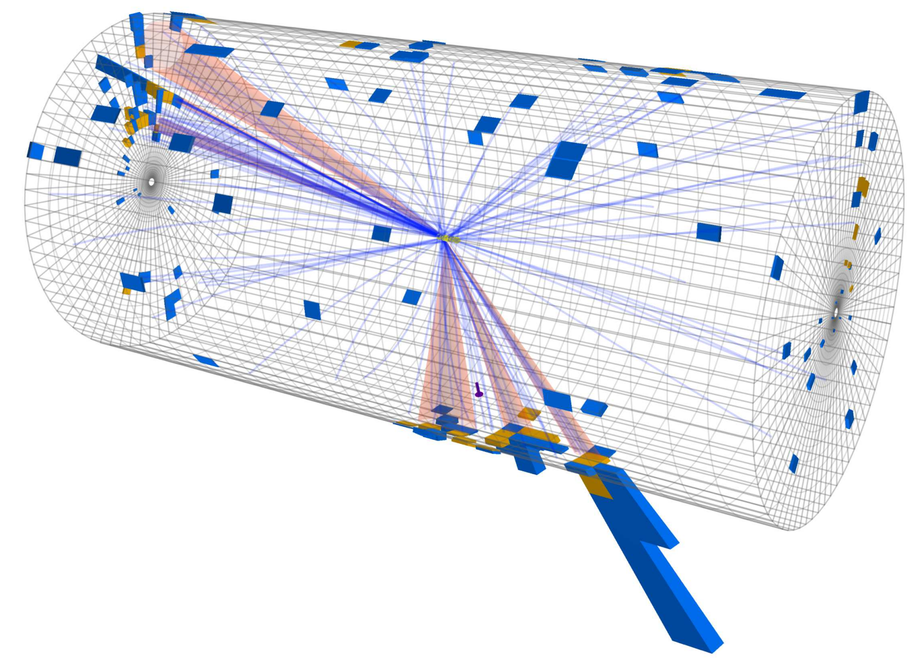
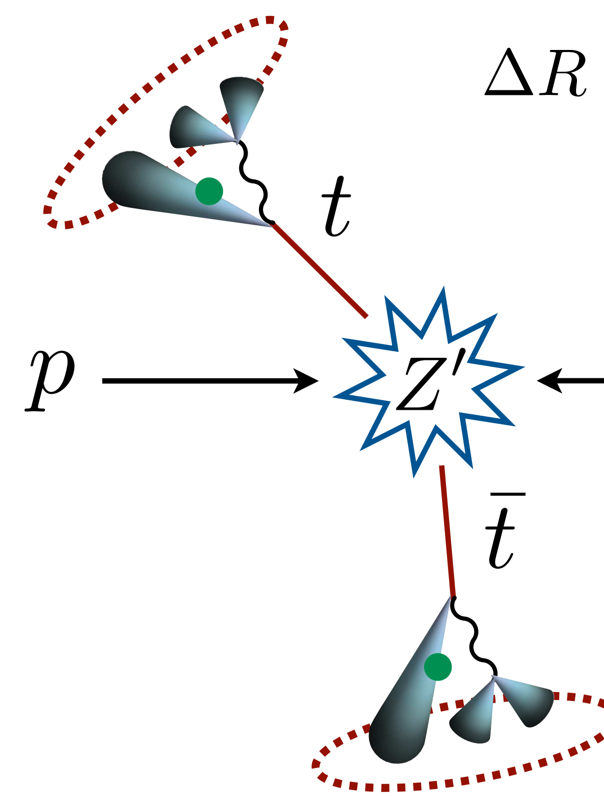


The Boosted Regime







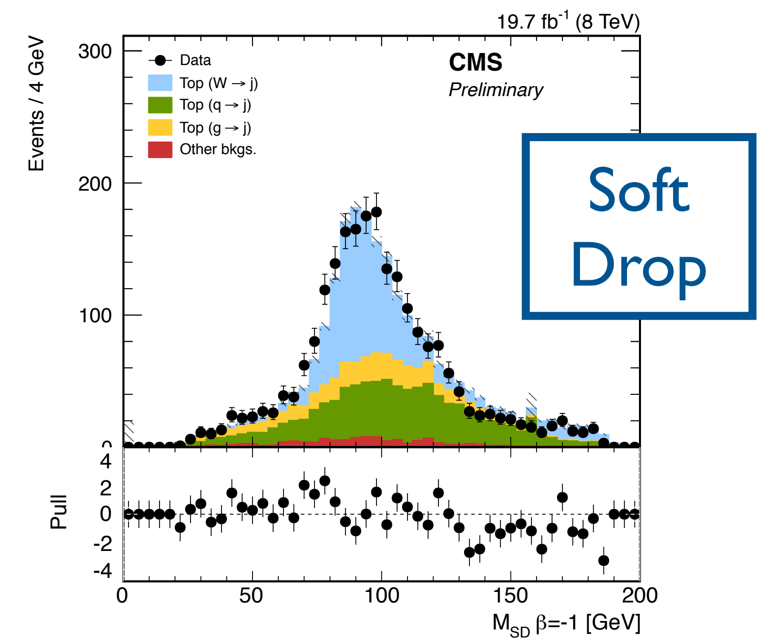
$$\Delta R \simeq \frac{m_{\rm top}}{m_{Z'}}$$

See new results from Eva (CMS) and Francesco (ATLAS)!

Key Substructure Techniques

W/Z-Tagging @ CMS

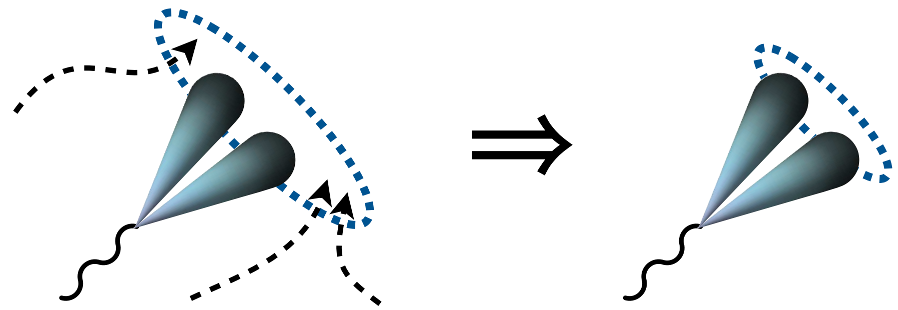
[JME-14-002, CMS-PAS-EXO-15-002]



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

Grooming:

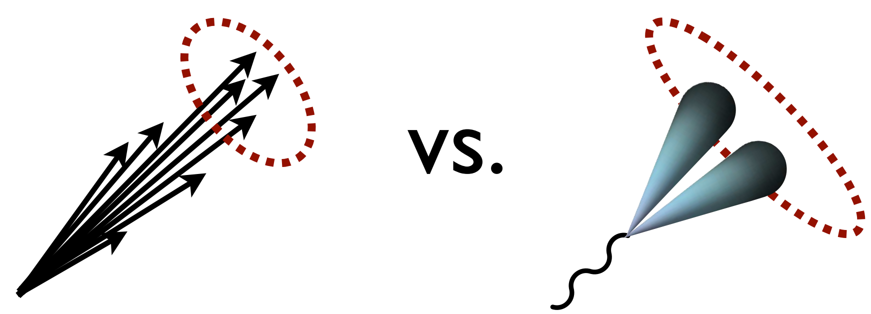
e.g. ISR/UE/pileup



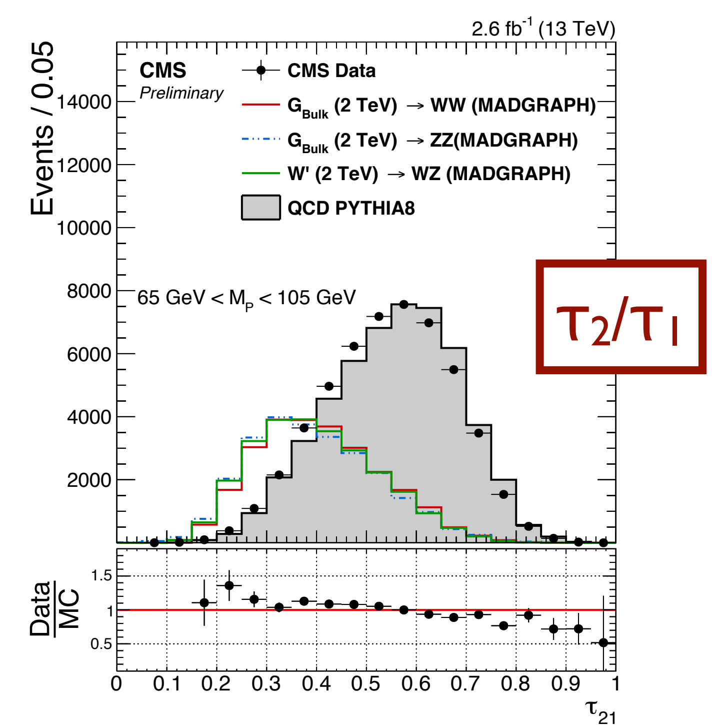
[Mass Drop/Filtering, Trimming, Pruning, Soft Drop, Jet Reclustering…;
for pileup: Area Subtraction, Jet Cleansing, SoftKiller, PUPPI, Constituent Subtraction…]

Discrimination:

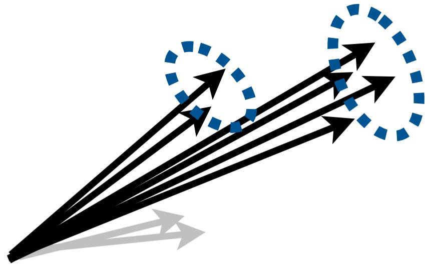
e.g. 1-prong vs. N-prong



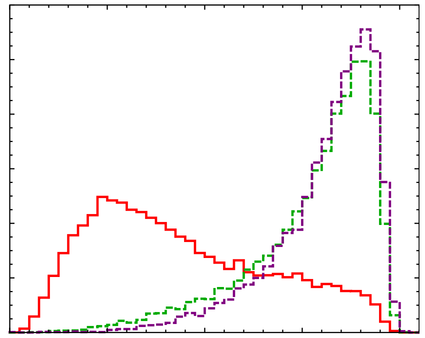
[p_T Balance, Y-splitter, Angularities, Planar Flow, N-subjettiness, Angular Structure Functions, Jet Charge, Jet Pull, Energy Correlation Functions, Dipolarity, p_T^D, Zernike Coefficients, LHA, Fox-Wolfram Moments, JHU/CMSTopTagger, HEPTopTagger, Template Method, Shower Deconstruction, Subjet Counting,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



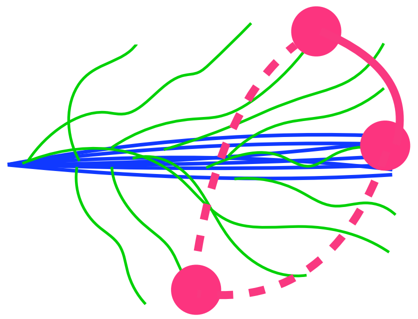
[using JDT, Van Tilburg, 1011.2268, 1108.2701]



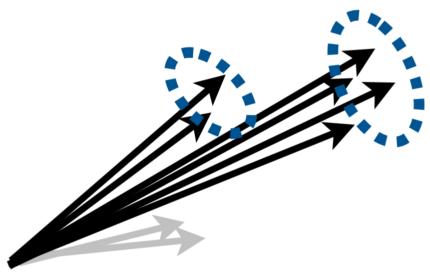
Insights from Jet Grooming



Performance meets Robustness



(Comments about the Future)

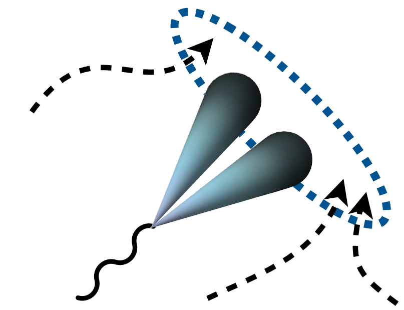


Insights from Jet Grooming

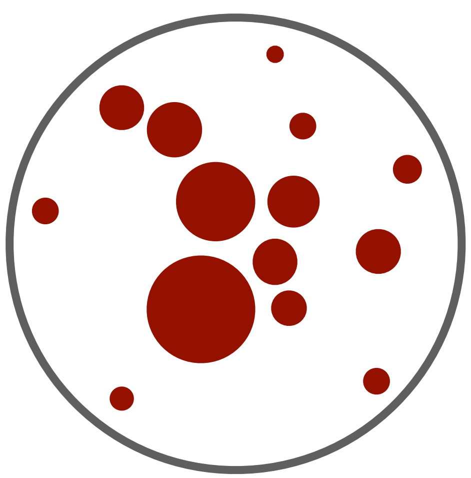
Performance meets Robustness

(Comments about the Future)

Soft Drop Declustering



Original Jet



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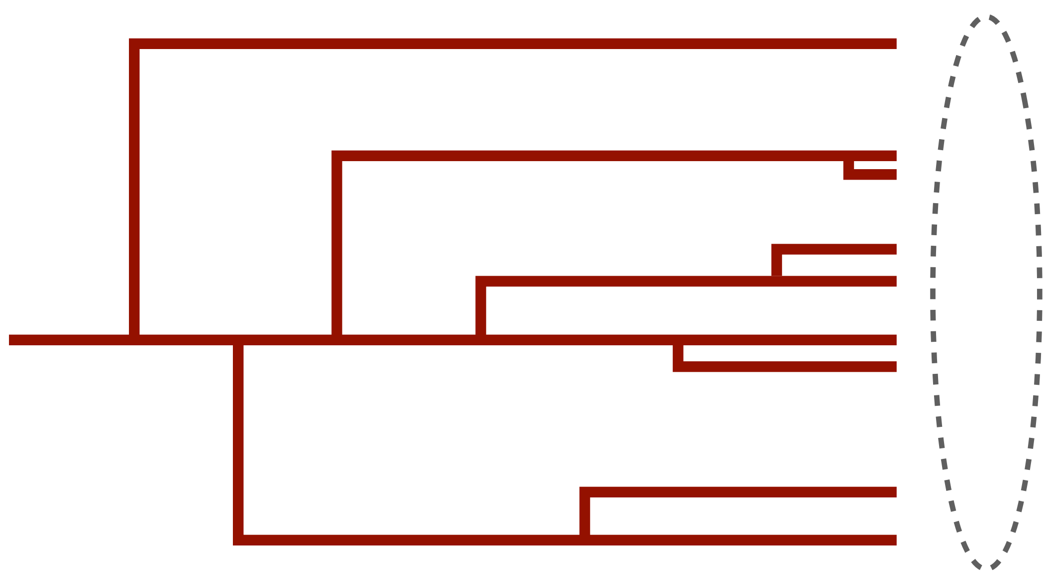
Clustering Tree

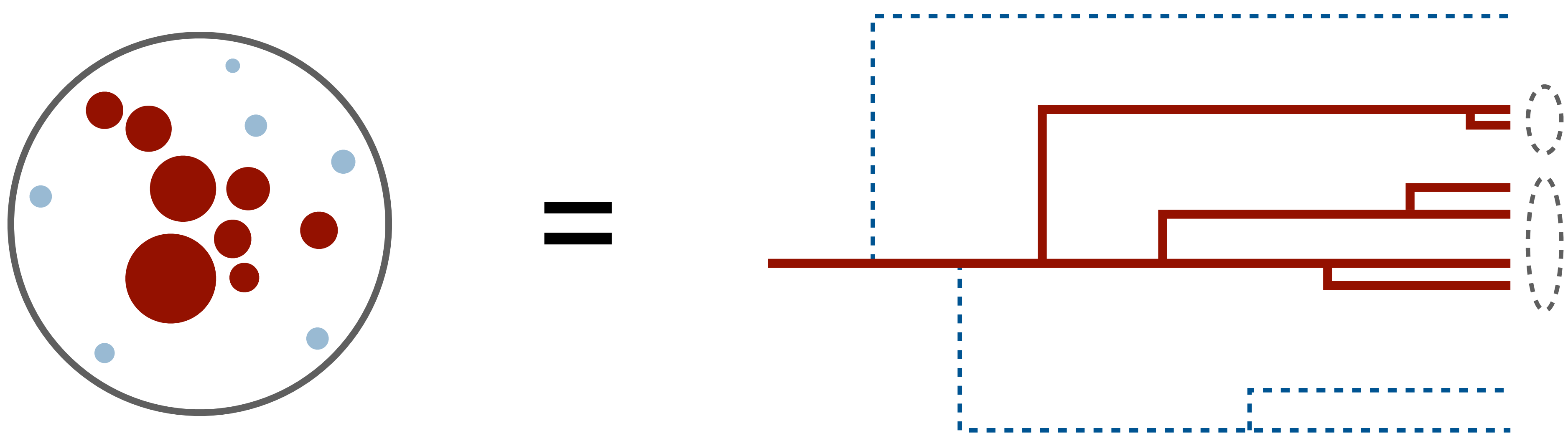


[Larkoski, Marzani, Soyez, JDT, 2014; see also Butterworth, Davison, Rubin, Salam, 2008; Dasgupta, Fregoso, Marzani, Salam/Powling, 2013]

Soft Drop Declustering

Groomed Jet

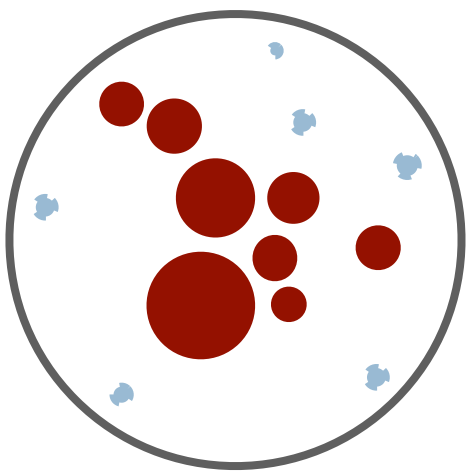
Groomed
Clustering Tree



[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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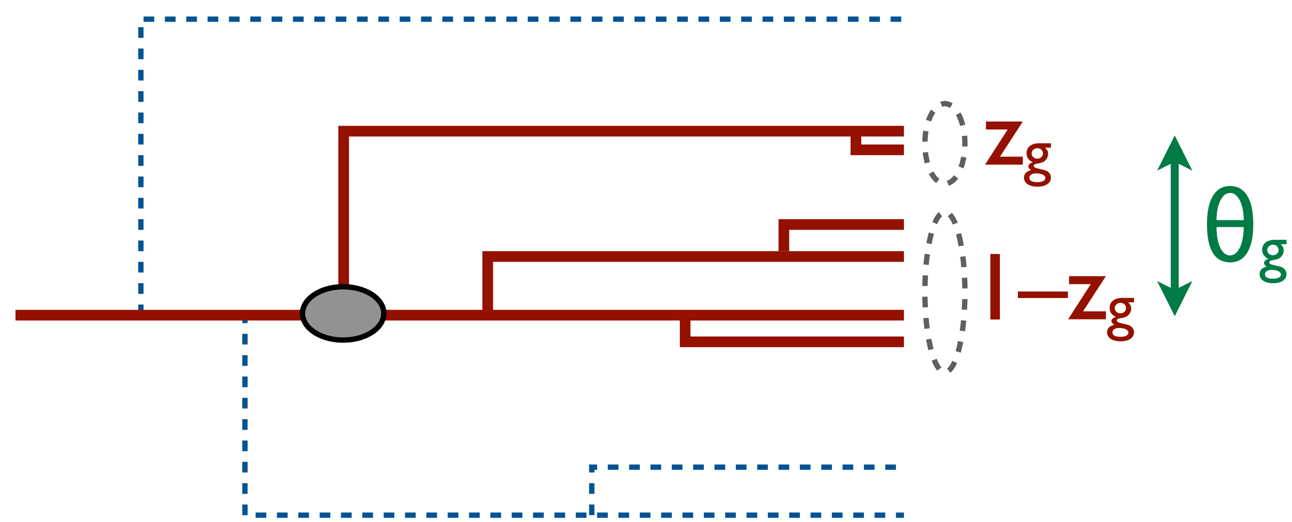
Groomed Clustering Tree

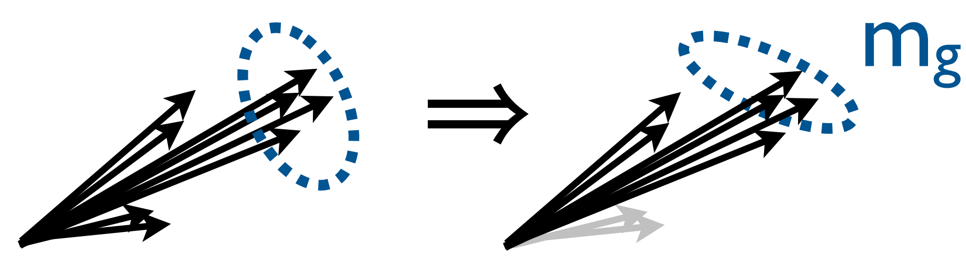


$$z_g > z_{cut}\,\theta_g^{\beta}$$

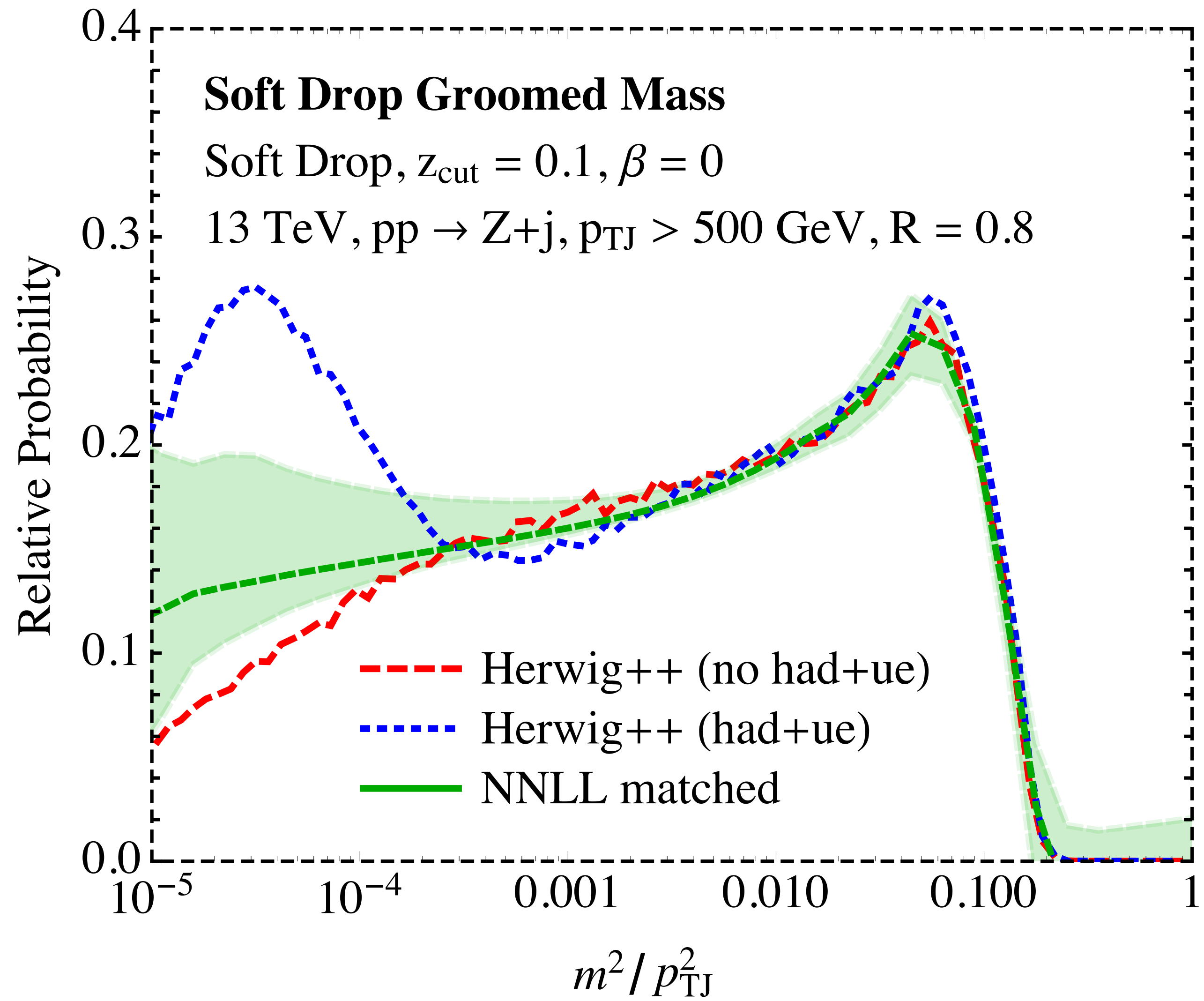
$\beta = 0$: mMDT

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

Soft Drop Jet Mass



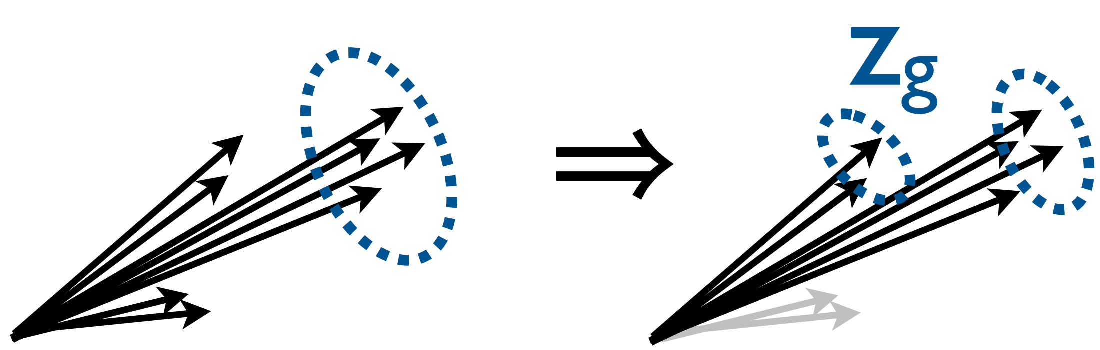
First NNLL + $O(\alpha_s^2)$ result for substructure in pp (!)



Grooming *simplifies* structure of calculation

[Frye, Larkoski, Schwartz, Yan, 1603.06375, 1603.09338]

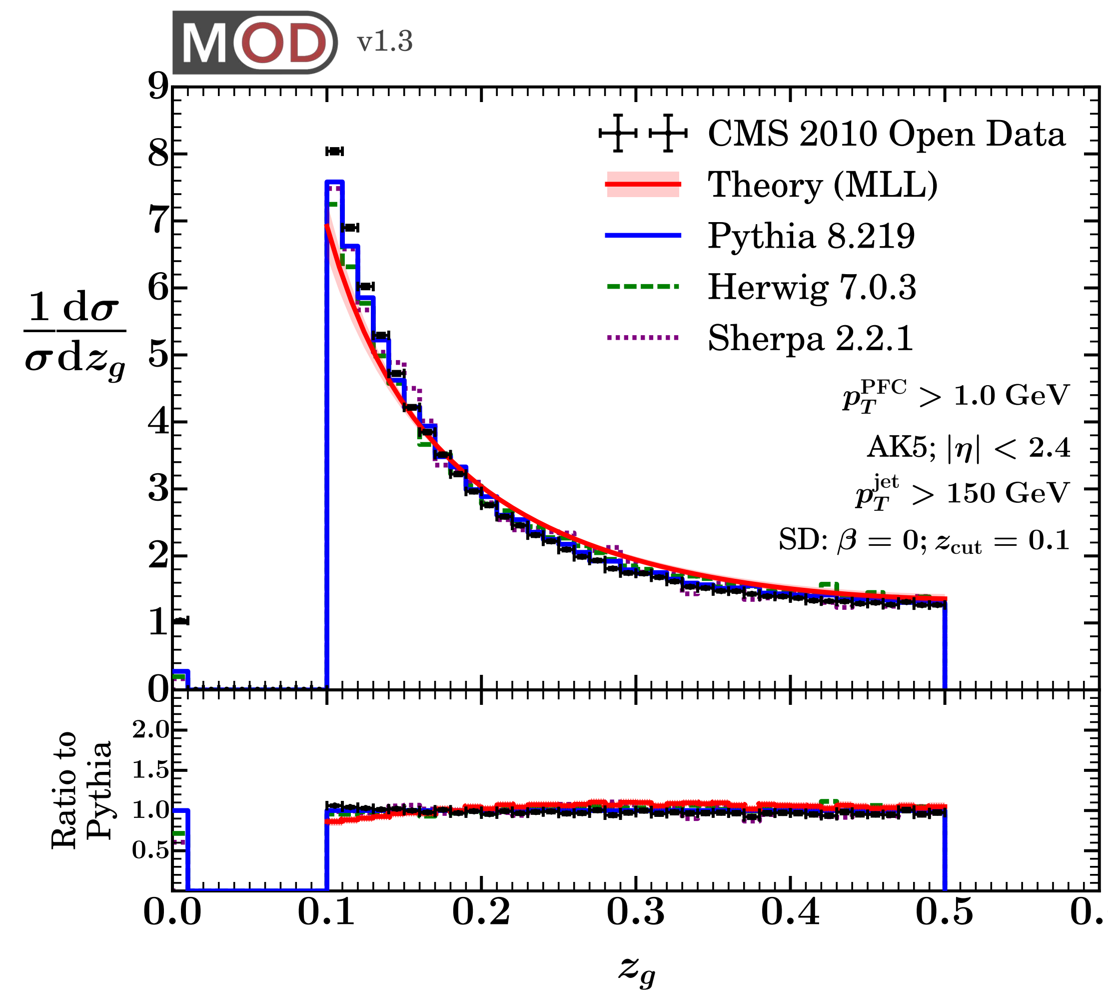
From Aspen 2016: Grooming to Explore QCD



A “standard candle” from soft drop

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

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



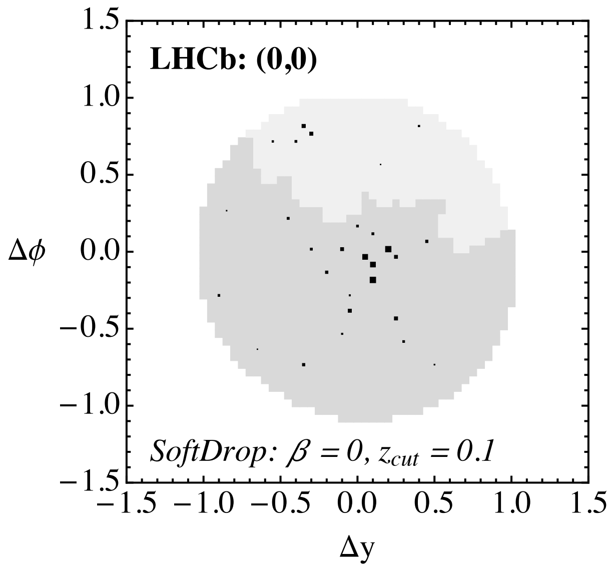
opendata CERN

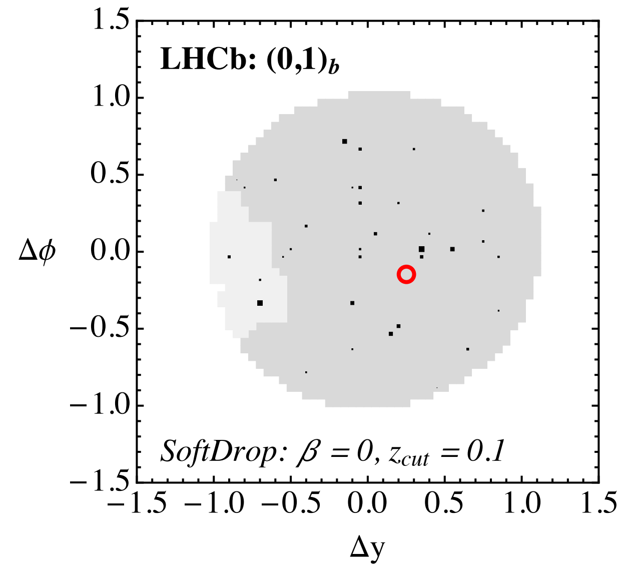
“Accelerating science through public data”

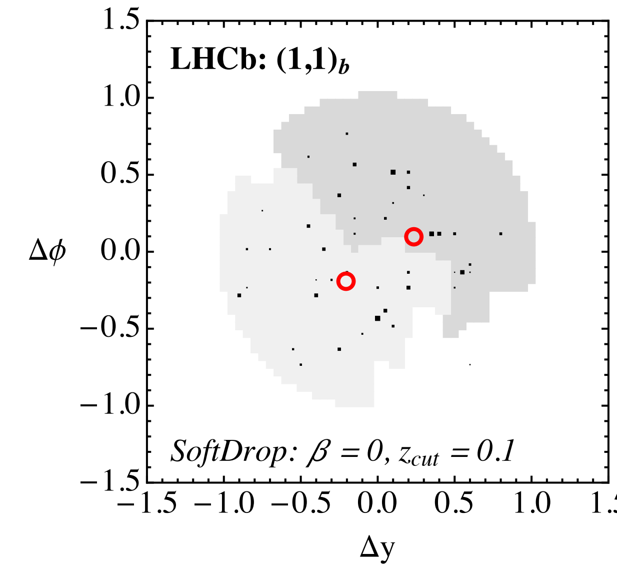
[Larkoski, Marzani, JDT, 1502.01719; using Larkoski, JDT, 1307.1699]
[Tripathee, Xue, Larkoski, Marzani, JDT, in progress;
see also CMS-PAS-HIN-16-006, STAR Hard Probes 2016]

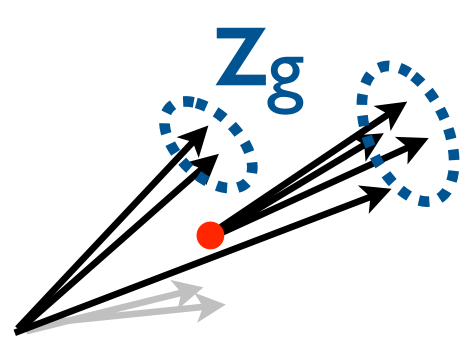
Grooming for Heavy Flavor

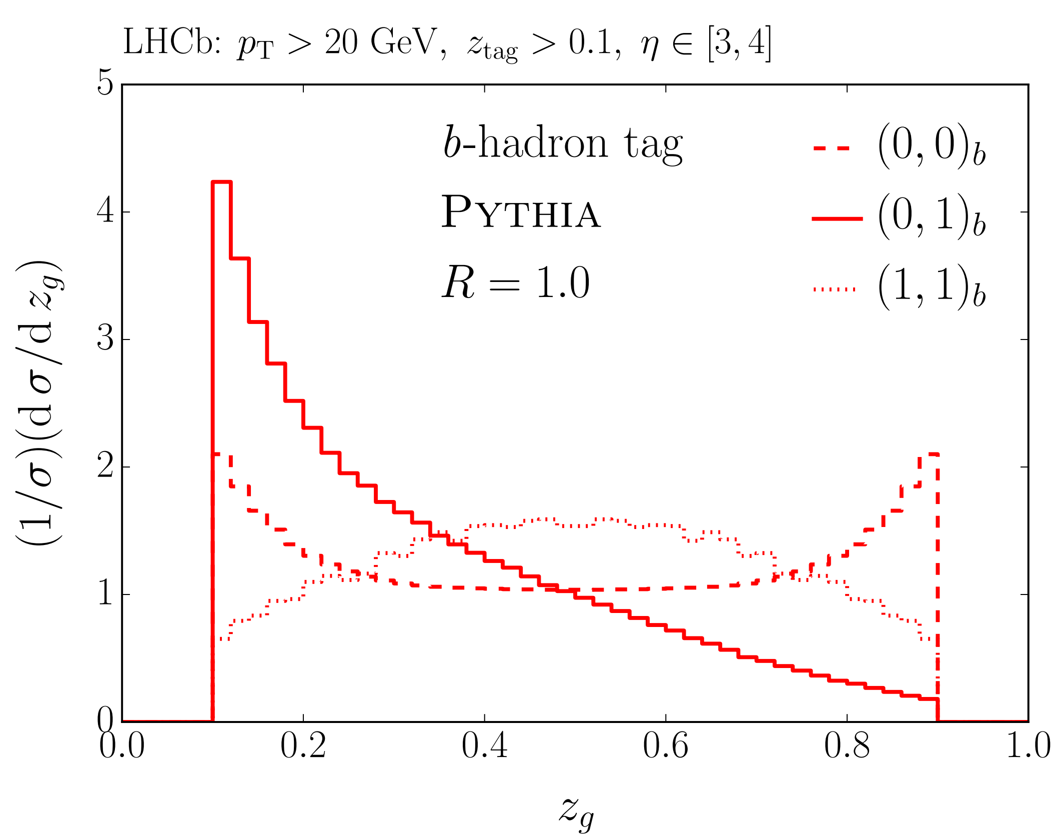
$g \to gg$ $\qquad$ $b \to bg$ $\qquad$ $g \to b\bar{b}$

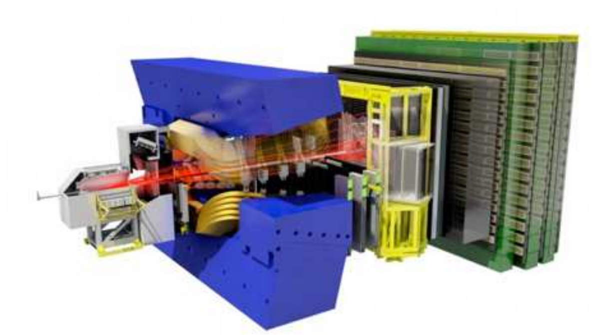








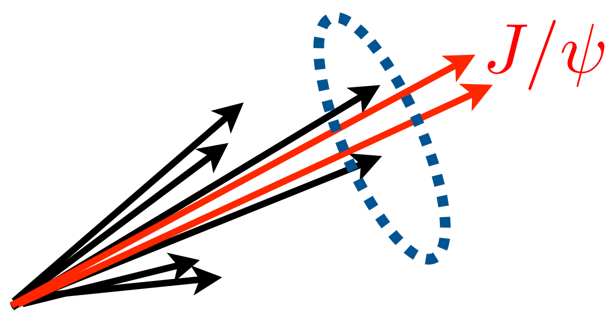


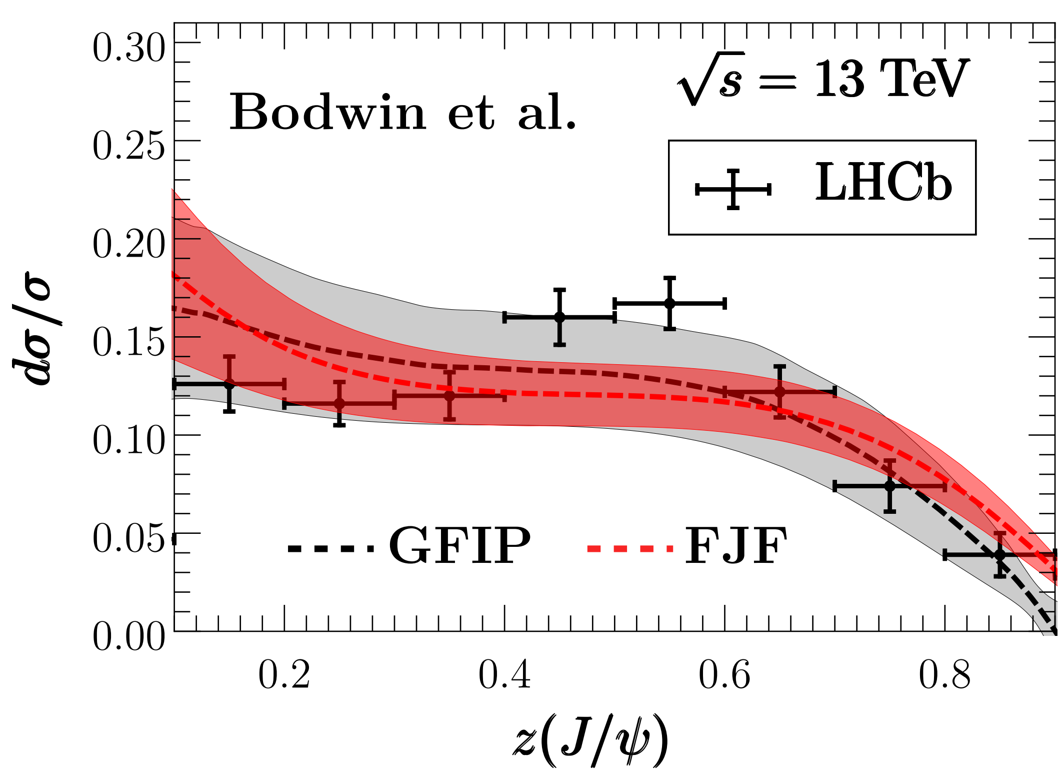


[Ilten, Rodd, JDT, Williams, 1702.02947]

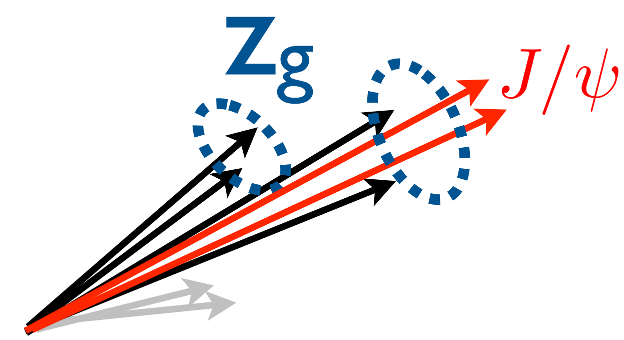
Grooming for Onium Physics

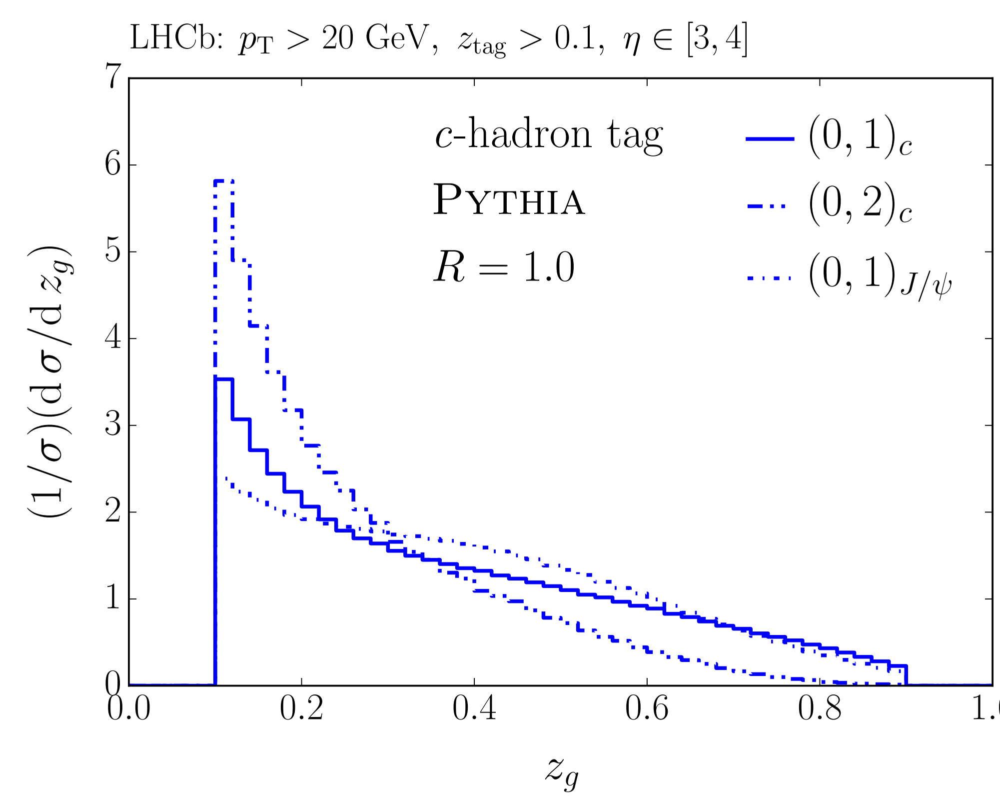
Standard Fragmentation





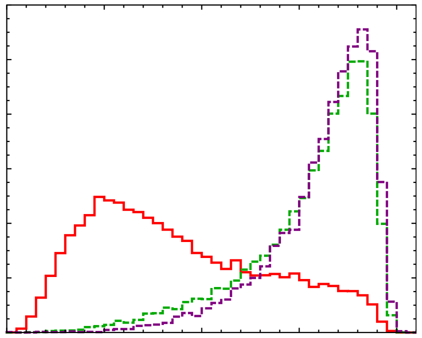
Tagged-Subjet Fragmentation





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

Insights from Jet Grooming



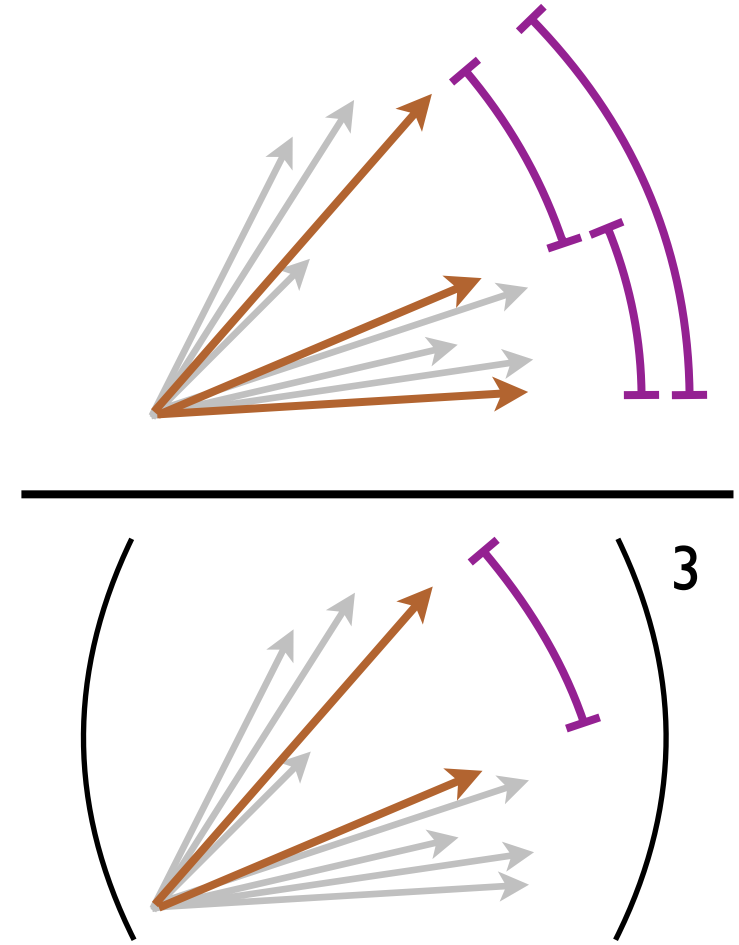
Performance meets Robustness

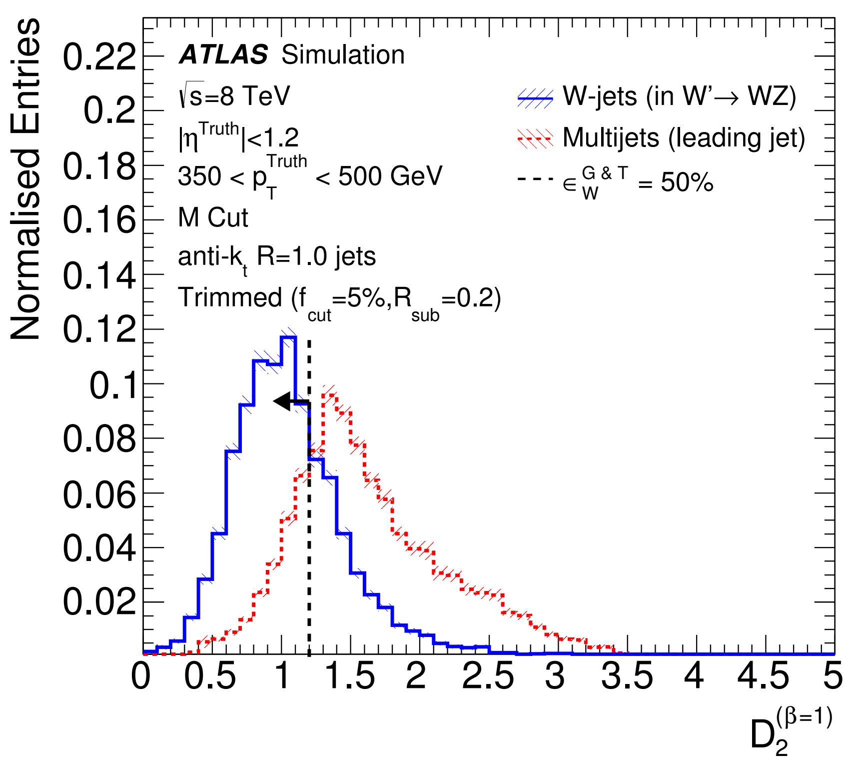
(Comments about the Future)

From Aspen 2016: D_2

$$D_2 = \frac{\displaystyle\sum_{i<j<k} p_{Ti}\, p_{Tj}\, p_{Tk}\, (R_{ij} R_{jk} R_{ki})^{\beta}}{\left(\displaystyle\sum_{i<j} p_{Ti}\, p_{Tj}\, R_{ij}{}^{\beta}\right)^3 \Big/ \left(\displaystyle\sum_{i} p_{Ti}\right)^3}$$

=



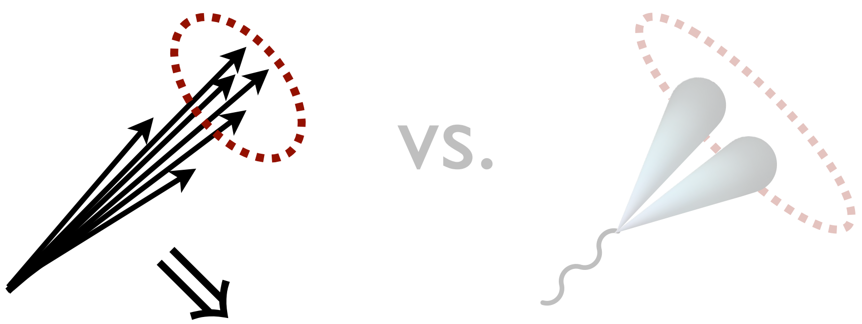


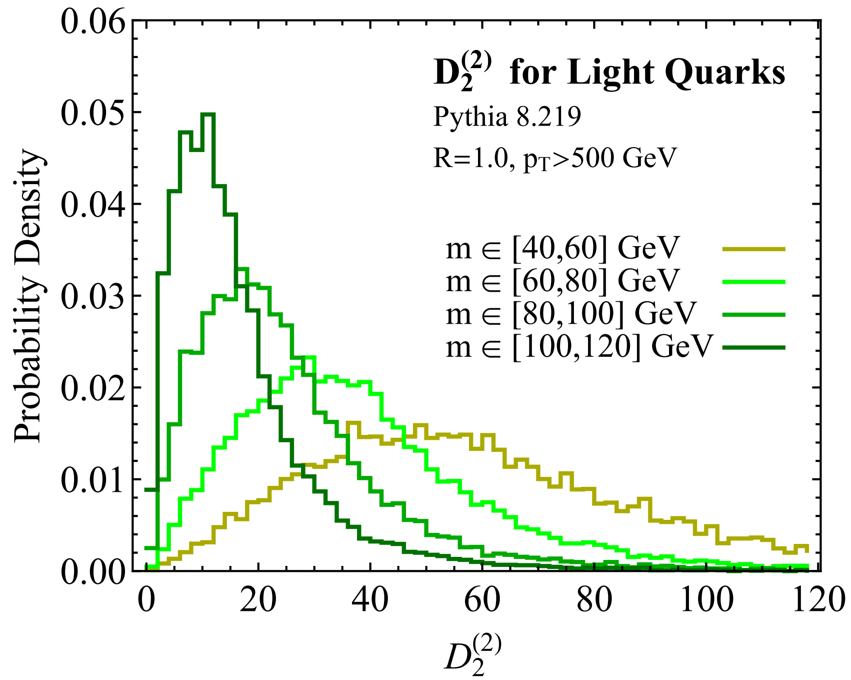
Derived for 2-prong W/Z tagging using EFT power counting

Used in ATLAS "R2D2" Tagger

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

Robustness of D_2?





Background highly sensitive to mass cut

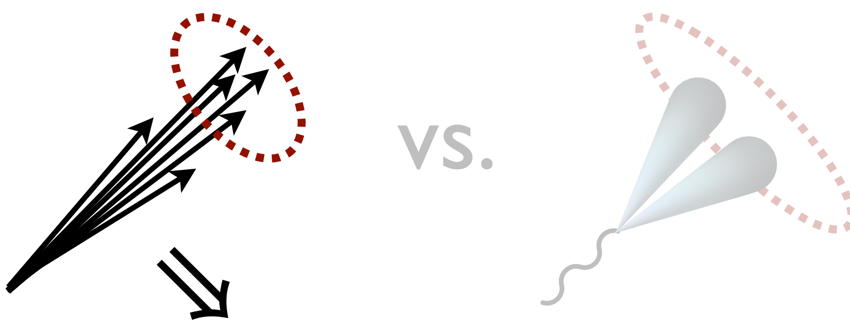
$$D_2^{\max} \sim \frac{p_{TJ}^2}{m_J^2}$$

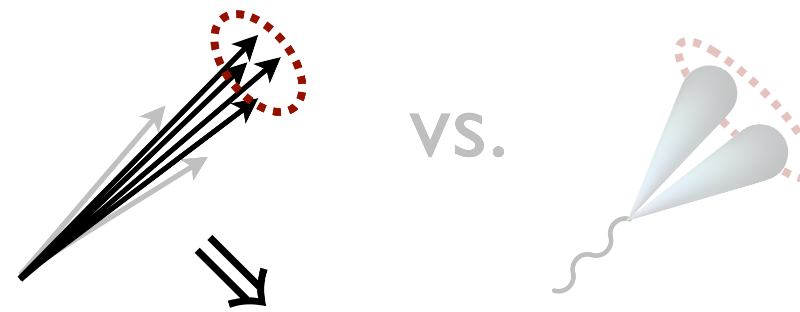
Difficult to use sideband control regions

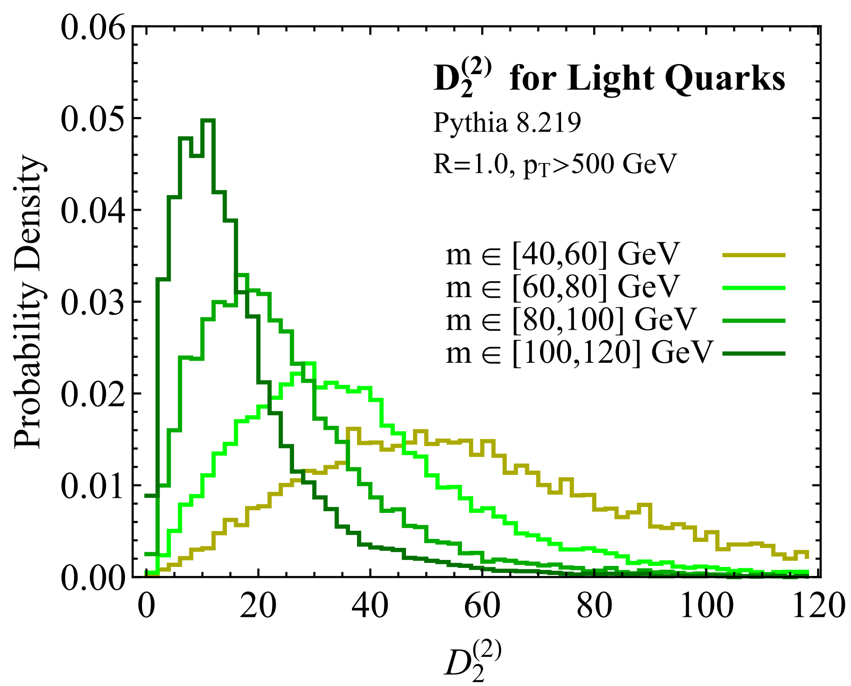
[Moult, Necib, JDT, 1609.07483]

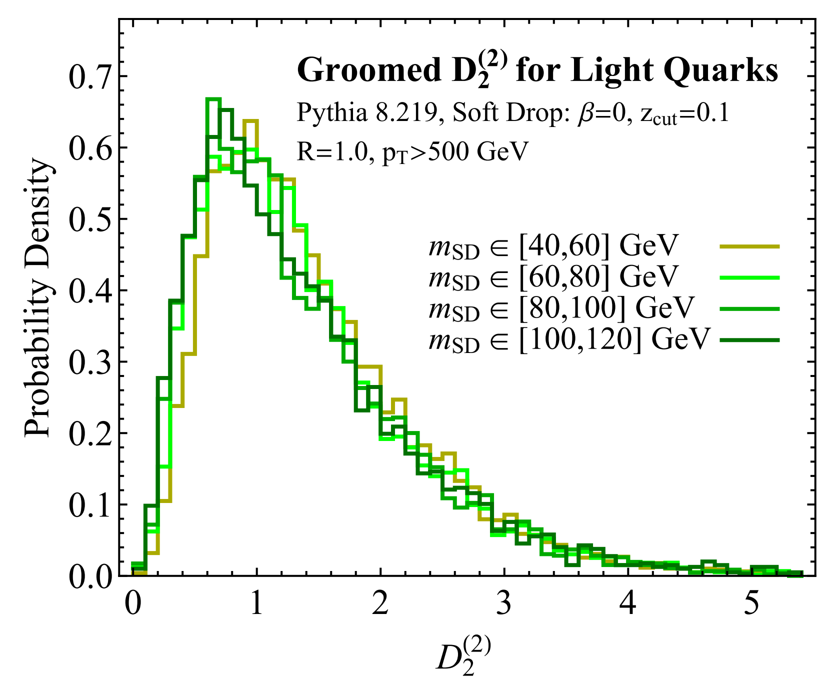
Robustness of D_2?

After grooming









Background highly sensitive to mass cut

$$D_2^{\max} \sim \frac{p_{TJ}^2}{m_J^2}$$

Difficult to use sideband control regions

Remarkably stable distributions

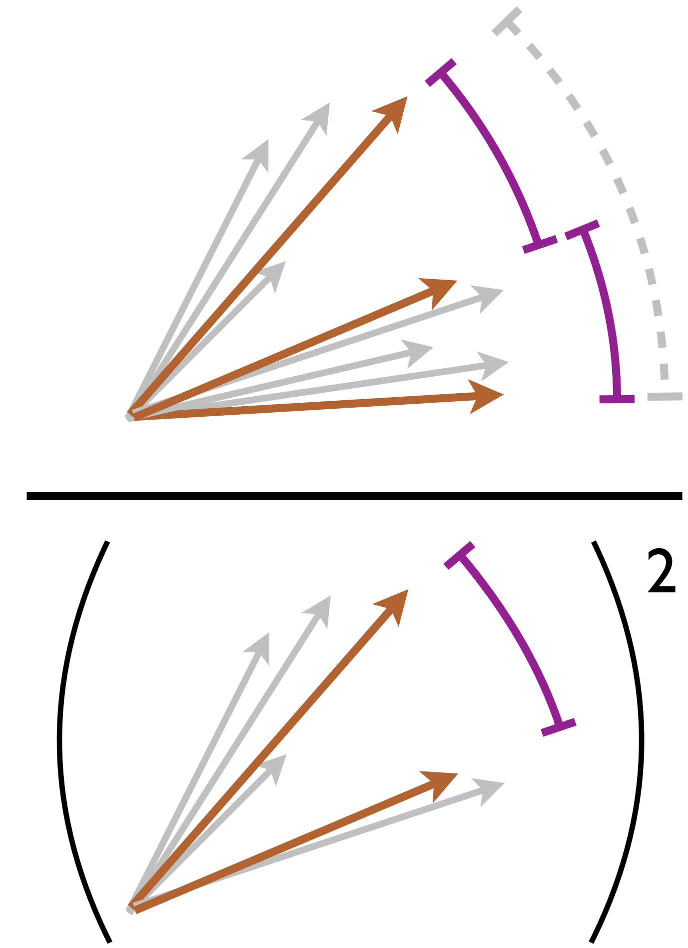
$$D_2^{\max} \sim \text{const}$$

Explains ATLAS strategy of
R2 (trimming) + D2 (discrimination)

[Moult, Necib, JDT, 1609.07483]

N_2: A New Angle on Energy Correlators

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



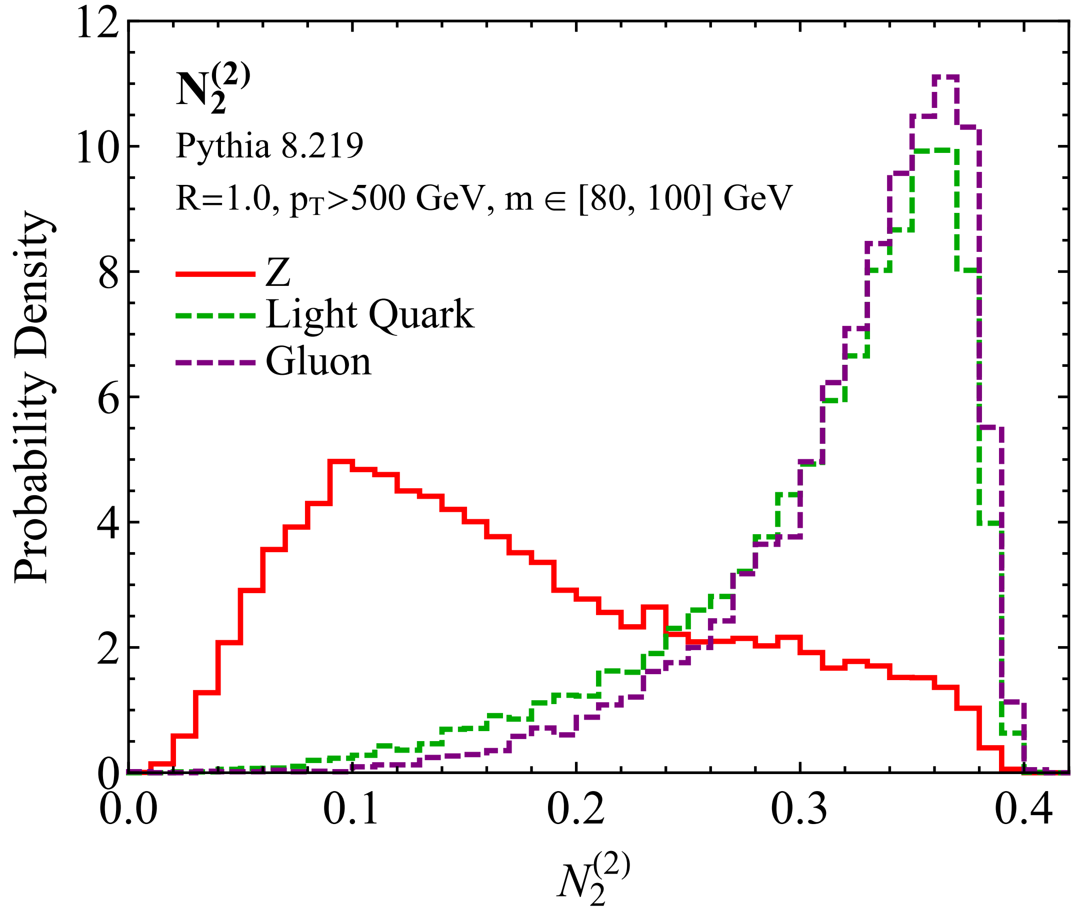
Not the most obvious substructure discriminant
Kind of a hybrid of D_2 and N-subjettiness (hence the name)

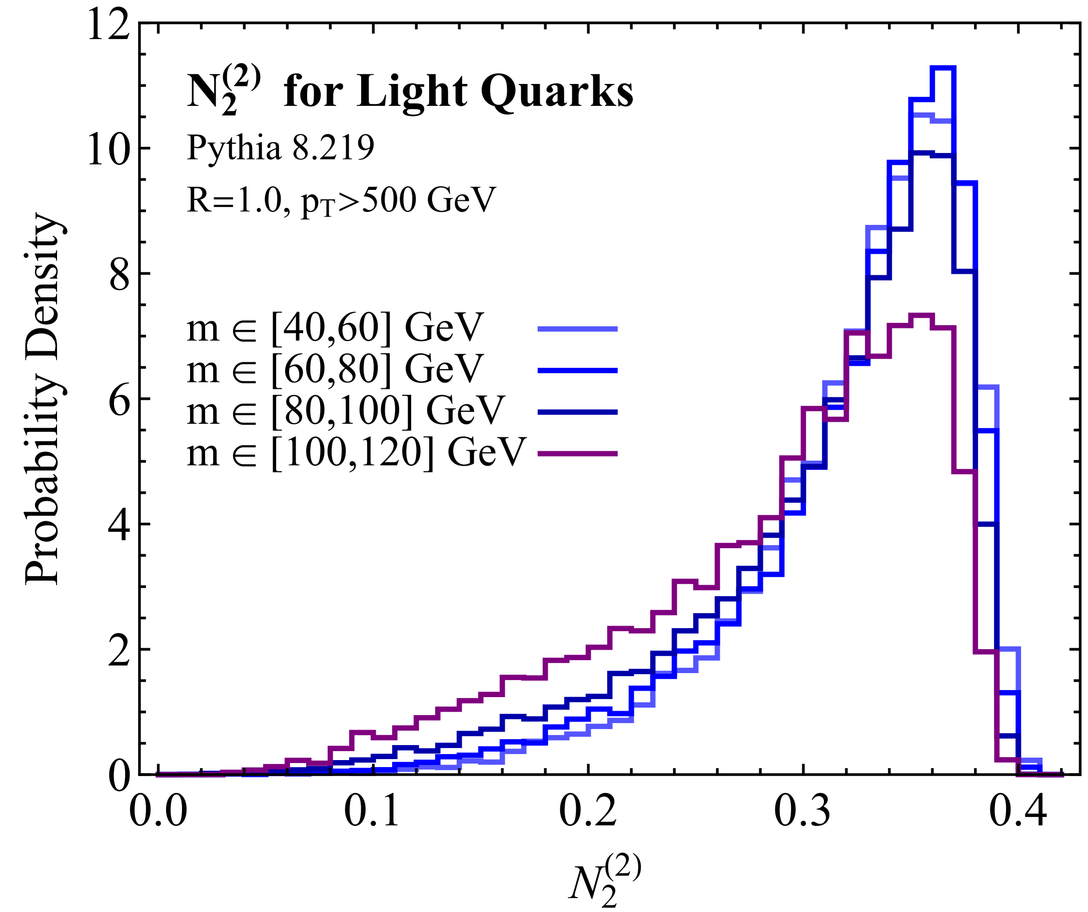
[Moult, Necib, JDT, 1609.07483]

N_2: A New Angle on Energy Correlators

Derived using EFT power counting for both…

Performance & *Robustness*

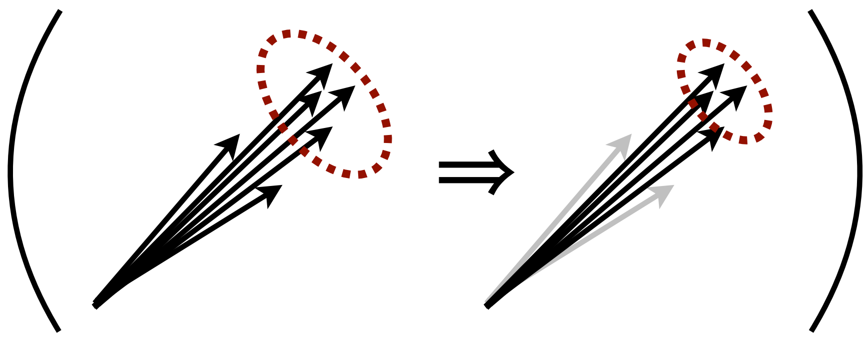




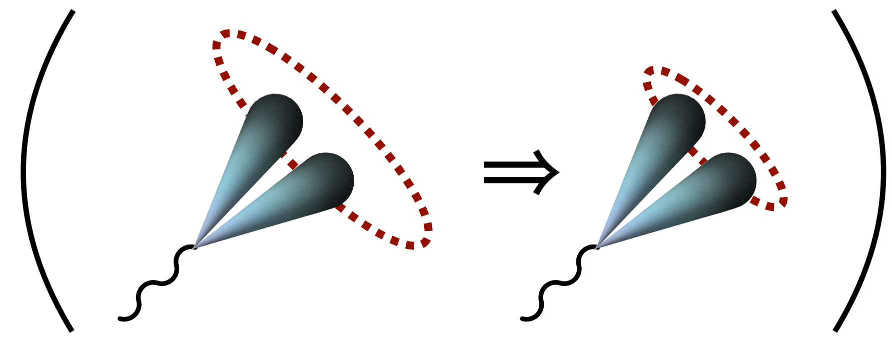
(with and without grooming)

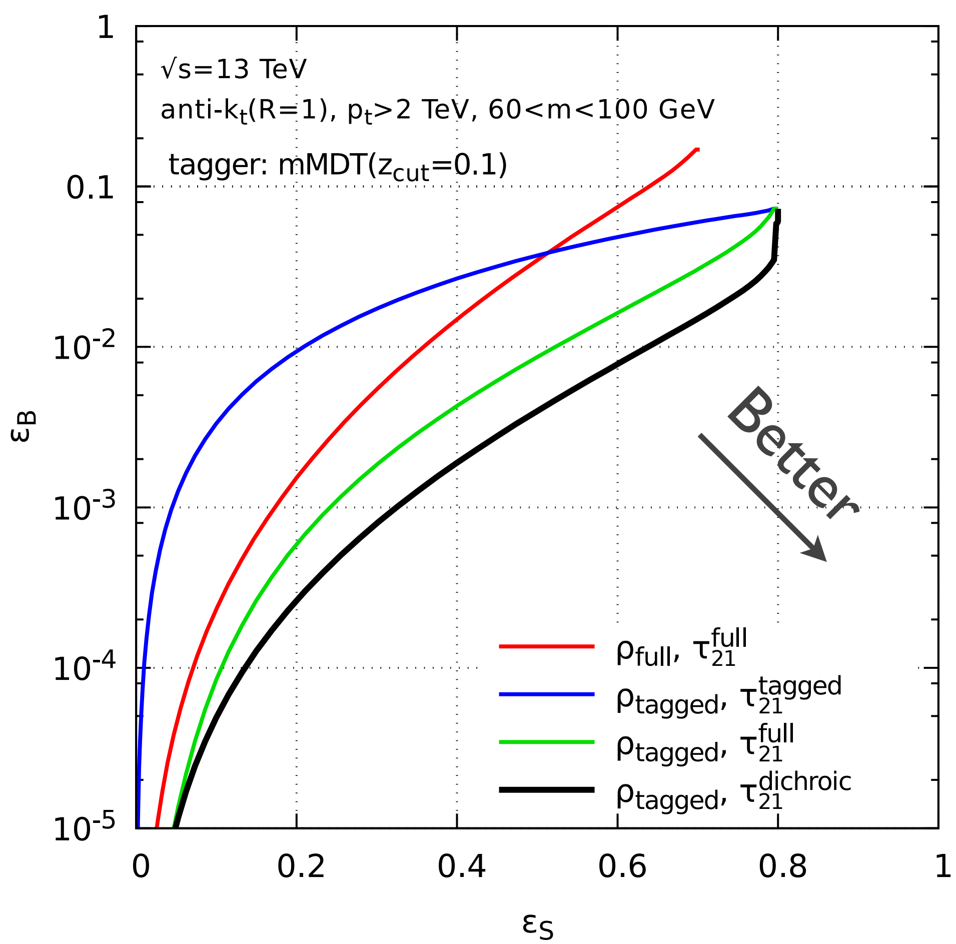
[Moult, Necib, JDT, 1609.07483]

Grooming/Discrimination Interplay



vs.





no grooming

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

groomed mass
groomed τ_2/τ_1

groomed mass
ungroomed τ_2/τ_1 ←

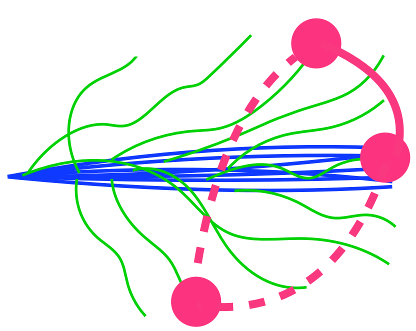
groomed mass
"dichroic" τ_2/τ_1 $= \dfrac{\textbf{ungroomed } \tau_2}{\textbf{groomed } \tau_1}$

Analytic calculations to identify optimal use of substructure information

[Salam, Schunk, Soyez, 1612.03917]

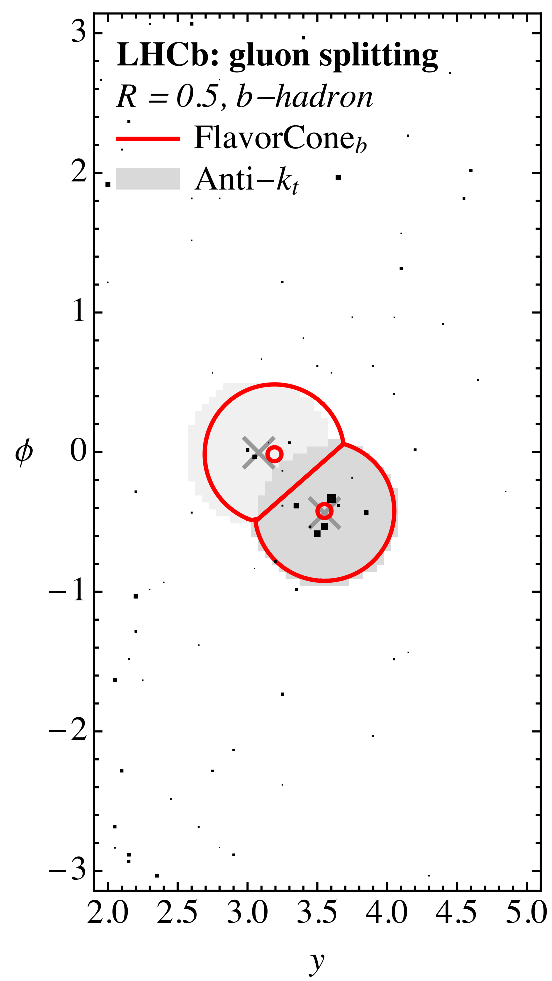
Insights from Jet Grooming

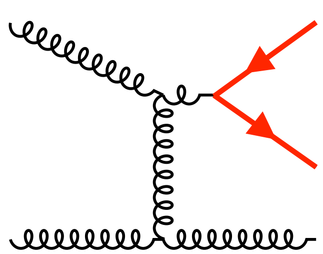
Performance meets Robustness



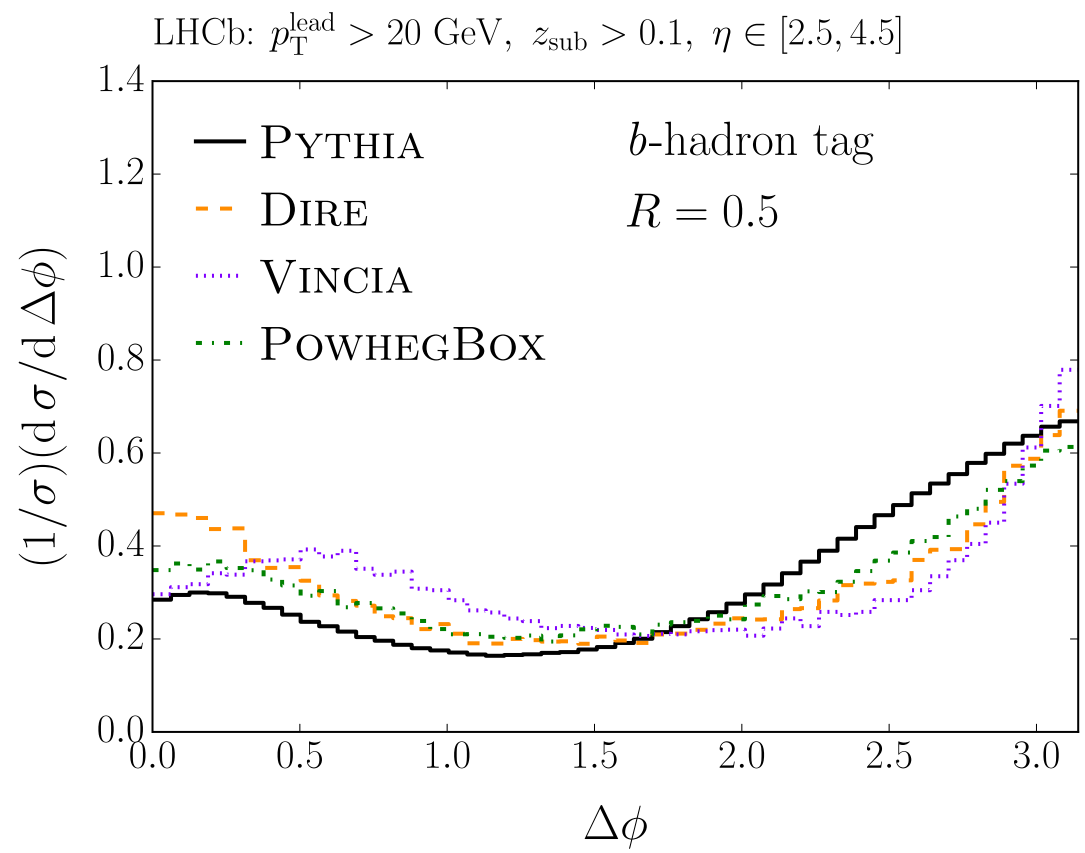
(Comments about the Future)

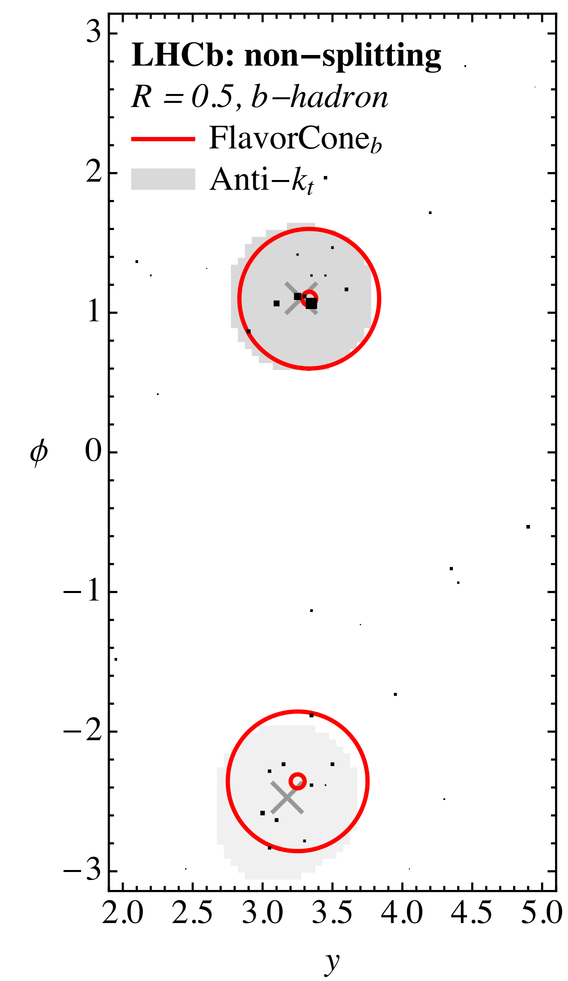
Opportunity: Application-Specific Jet Strategies

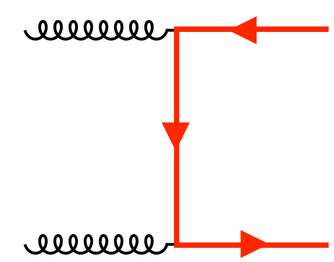




e.g. FlavorCone







$g \to b\bar{b}$

hard b

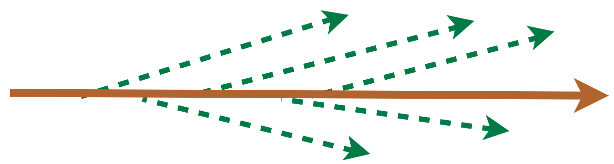
[Ilten, Rodd, JDT, Williams, 1702.02947]

Opportunity: Machine Learning

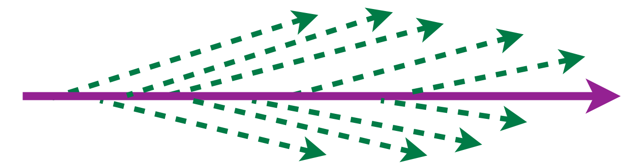
Quark: C_F = 4/3

Gluon: C_A = 3

e.g.



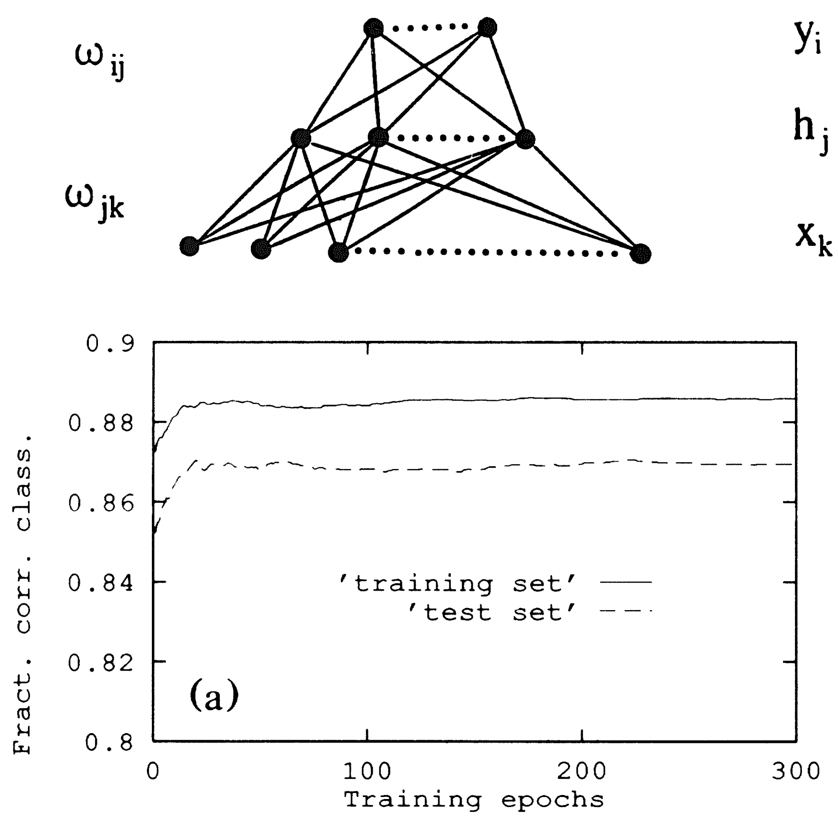
vs.



usually signals

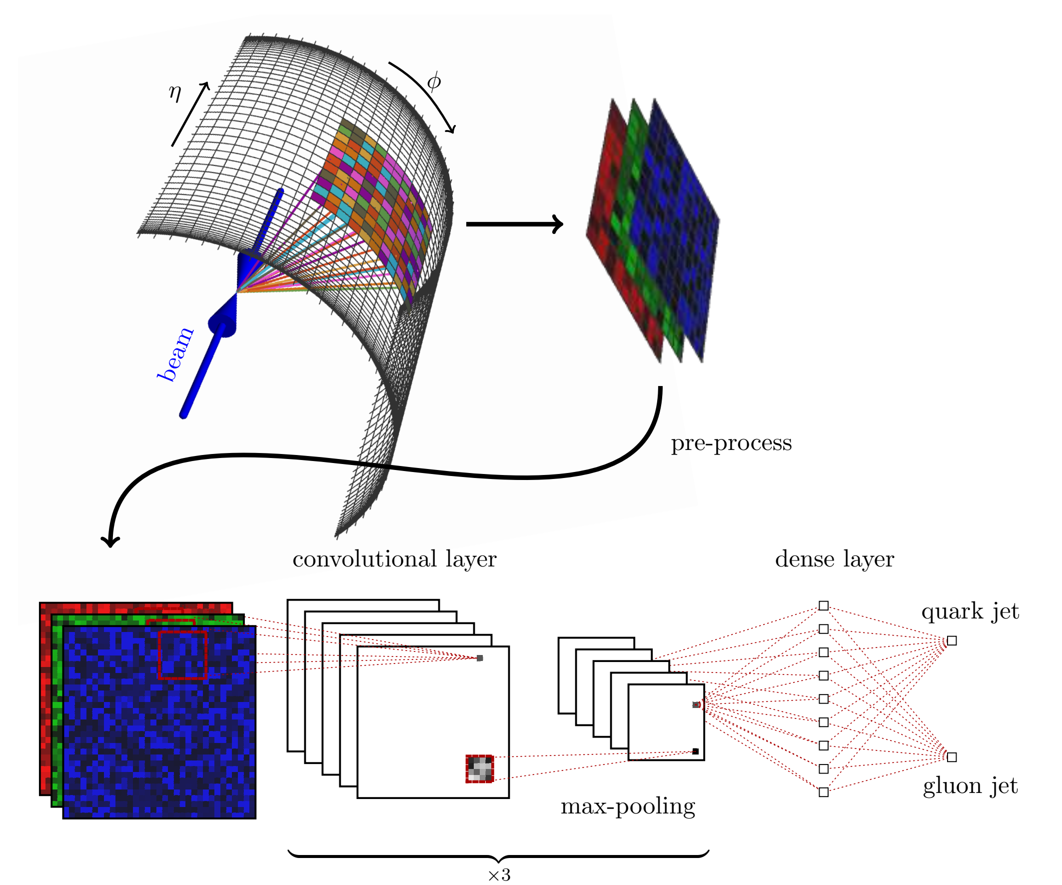
usually backgrounds

From Shallow Networks…



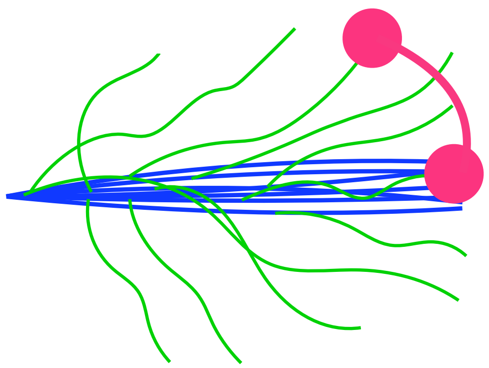
[Lönnblad, Peterson, Rögnvaldsson, 1991]

…to "Deep" Networks



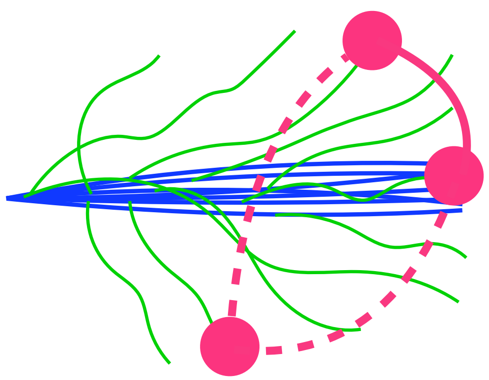
[Komiske, Metodiev, Schwartz, 1612.01551]

Continued Importance of First-Principles QCD

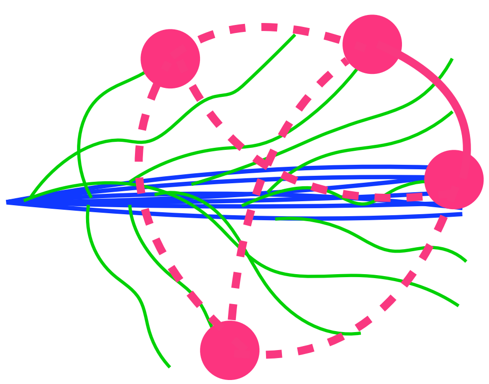


$$U_1 = \frac{\sum\limits_{i<j} p_{Ti}\, p_{Tj}\, R_{ij}{}^{\beta}}{\left(\sum\limits_i p_{Ti}\right)^2}$$

$\longleftarrow$ Typical Quark/Gluon Discriminants



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



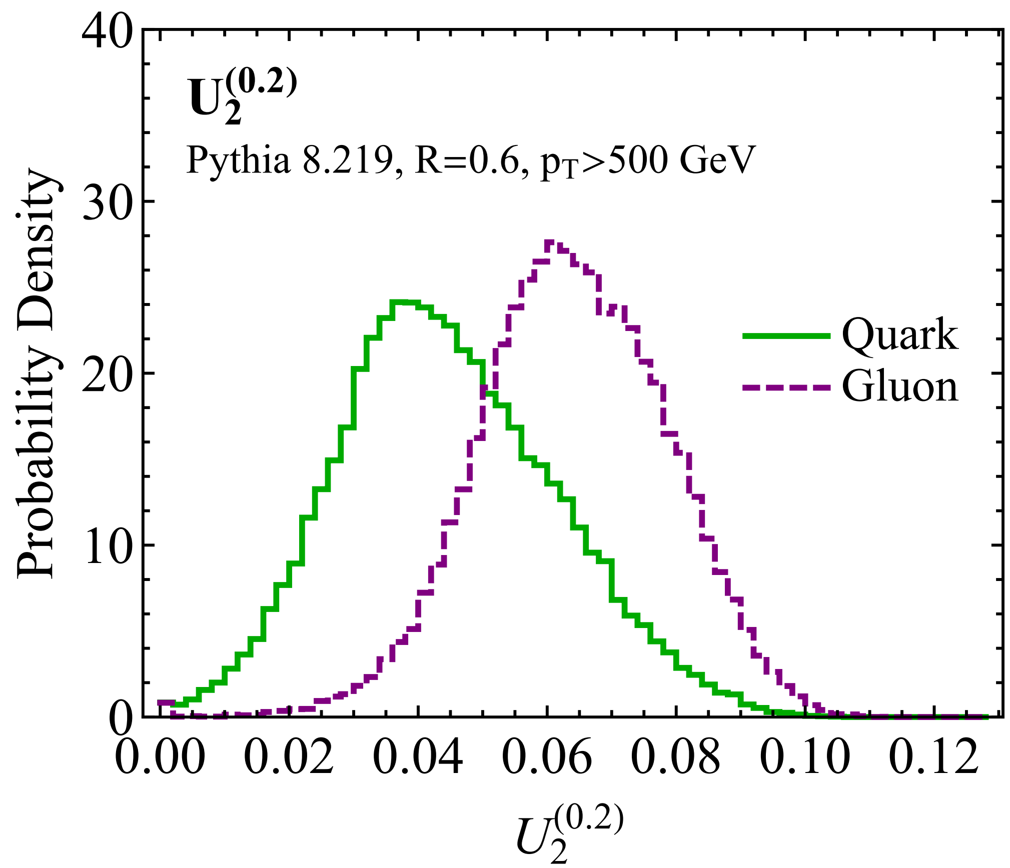
$$U_3 = \frac{\sum\limits_{i<j<k<\ell} p_{Ti}\, p_{Tj}\, p_{Tk}\, p_{T\ell} \min\{R_{ij}, R_{jk}, R_{k\ell}, R_{ik}, R_{j\ell}, R_{i\ell}\}^{\beta}}{\left(\sum\limits_i p_{Ti}\right)^4}$$

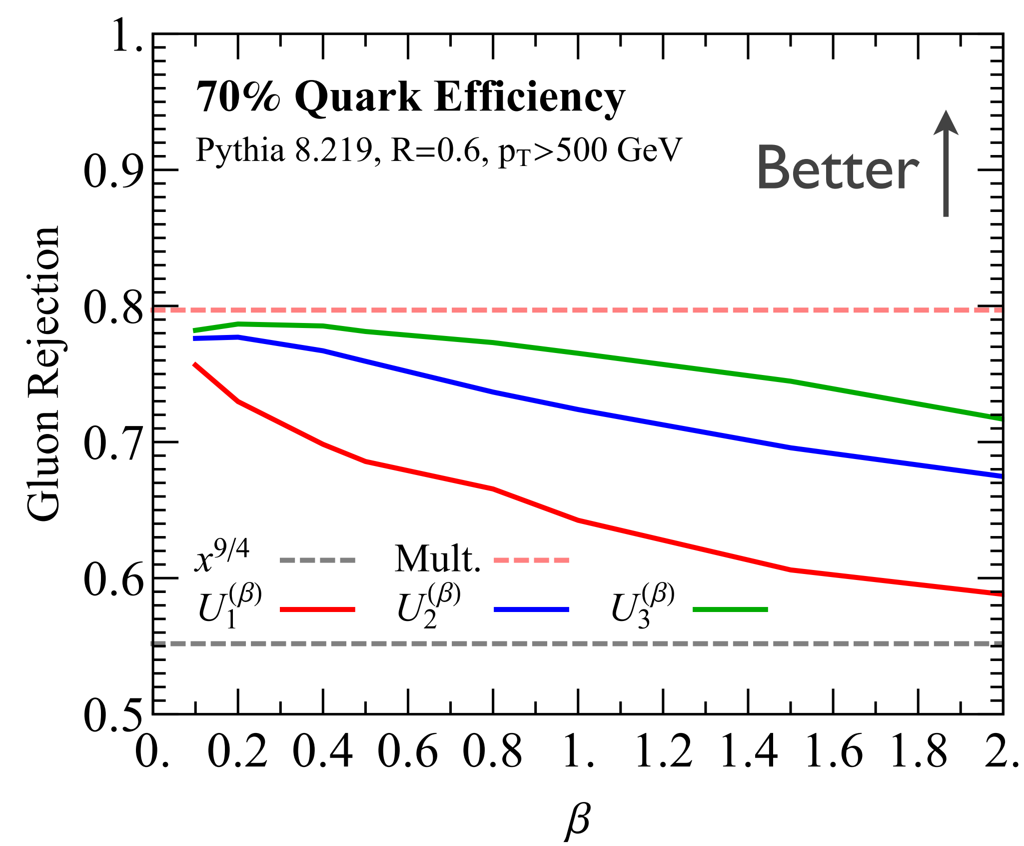
"Deep Learning" inspires "Deep Thinking"

[Moult, Necib, JDT, 1609.07483]

Continued Importance of First-Principles QCD

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

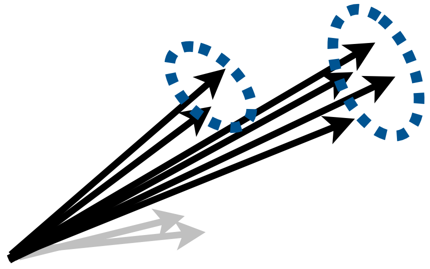




"Deep Learning" inspires "Deep Thinking"

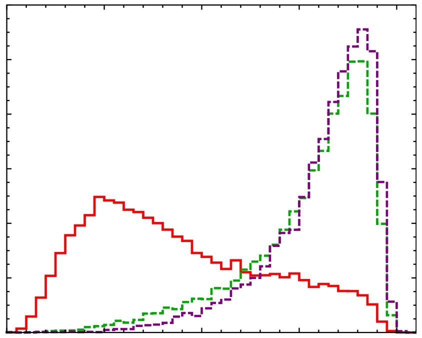
[Moult, Necib, JDT, 1609.07483]

Summary



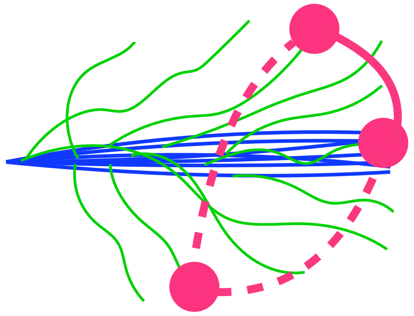
Insights from Jet Grooming

Active jet manipulation to probe new structures in QCD



Performance meets Robustness

Power counting to achieve improved, robust techniques



(Comments about the Future)

Complementarity between automated and customized strategies