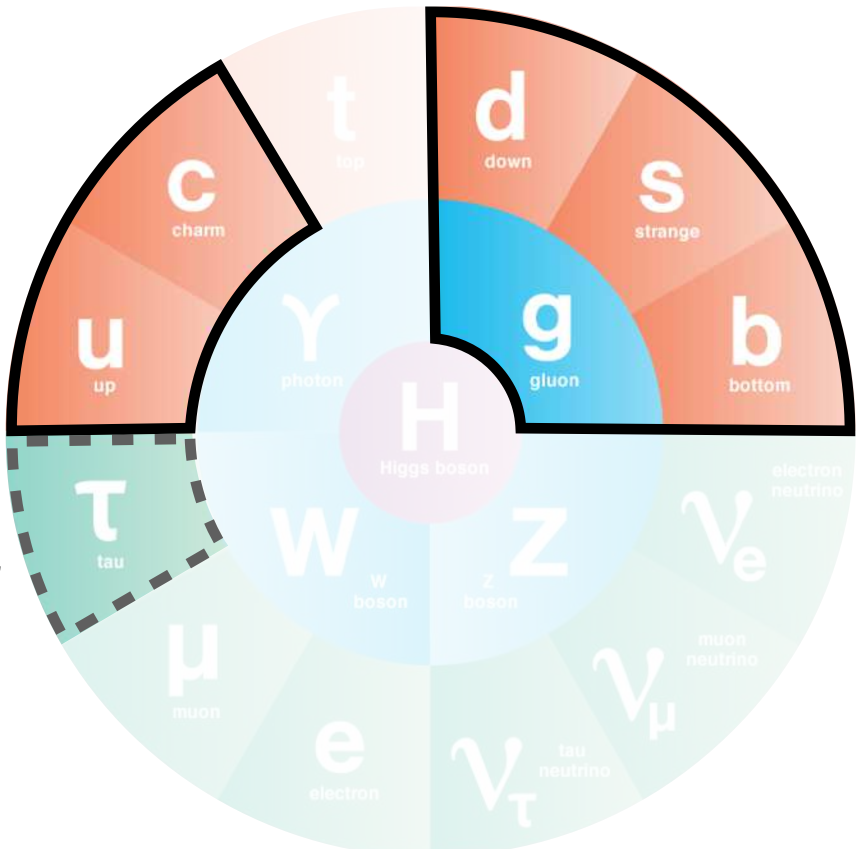
Using Jets and QCD to Boost the Search for New Physics

Jesse Thaler

MIT

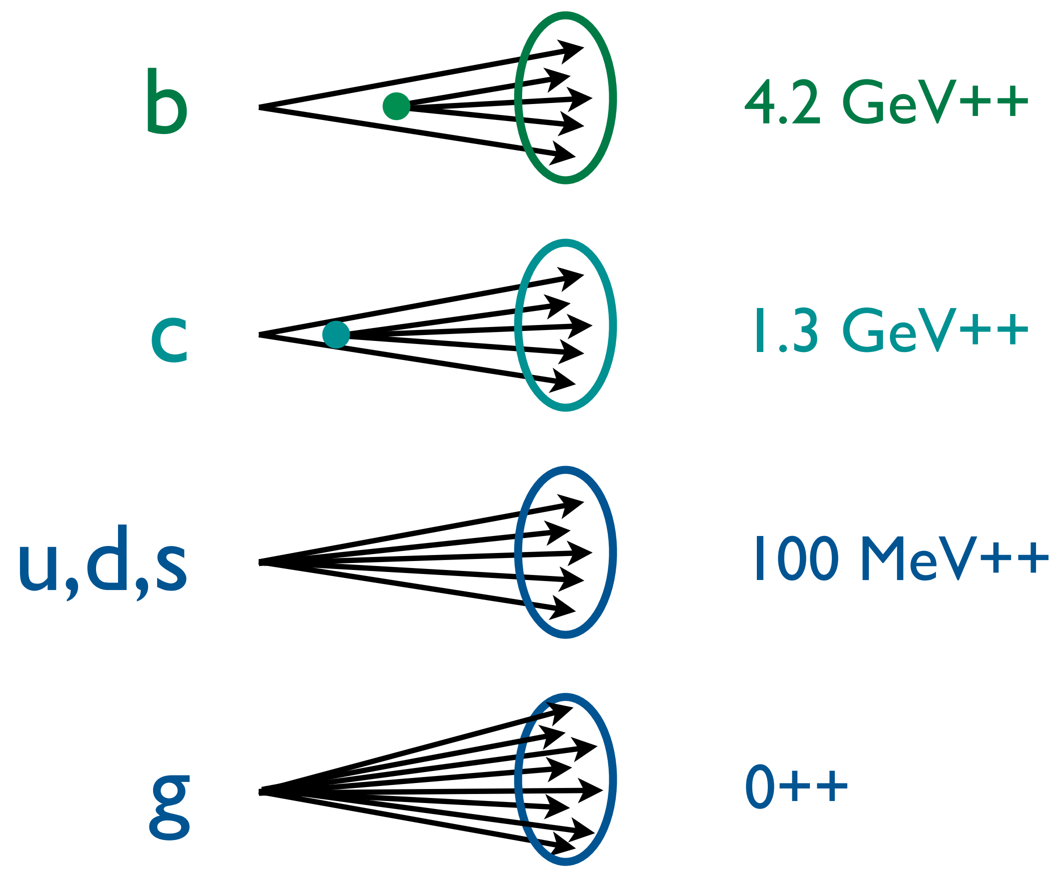
Physics in LHC and the Early Universe, University of Tokyo — January 10, 2017

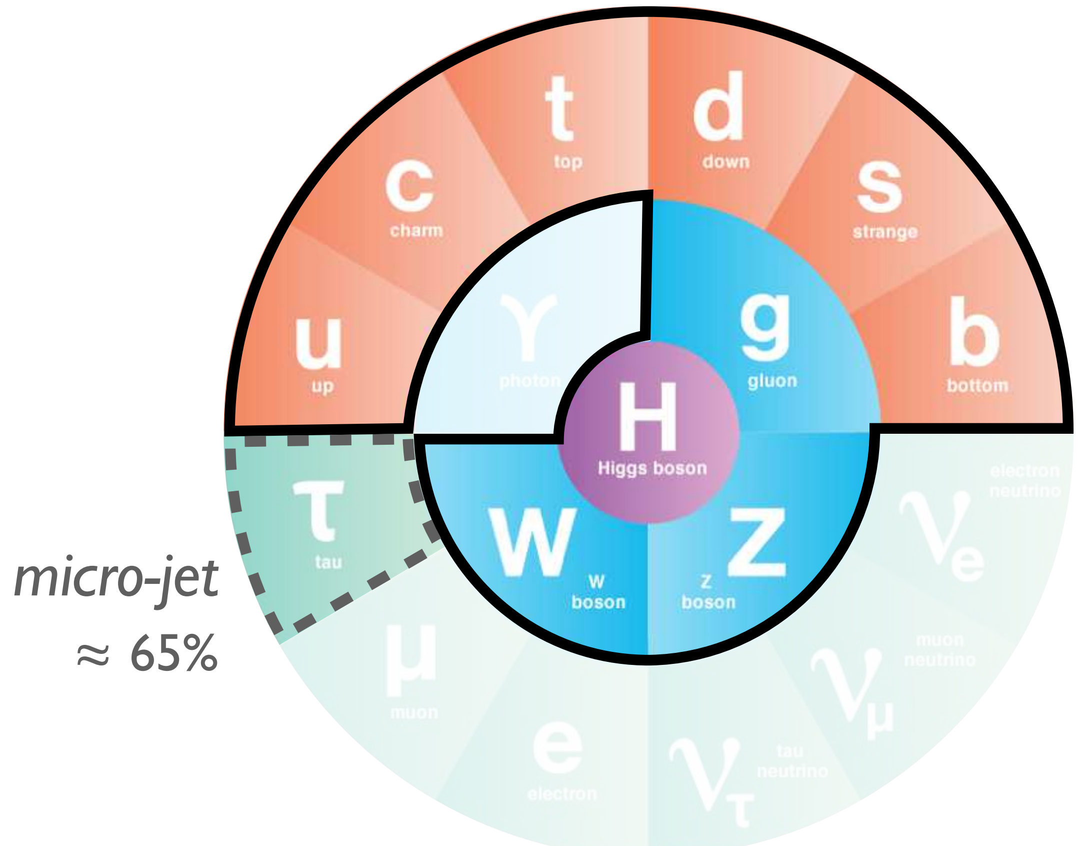
micro-jet
≈ 65%



Jets from the Standard Model

++ = plus gluonic radiation





Jets from the Standard Model

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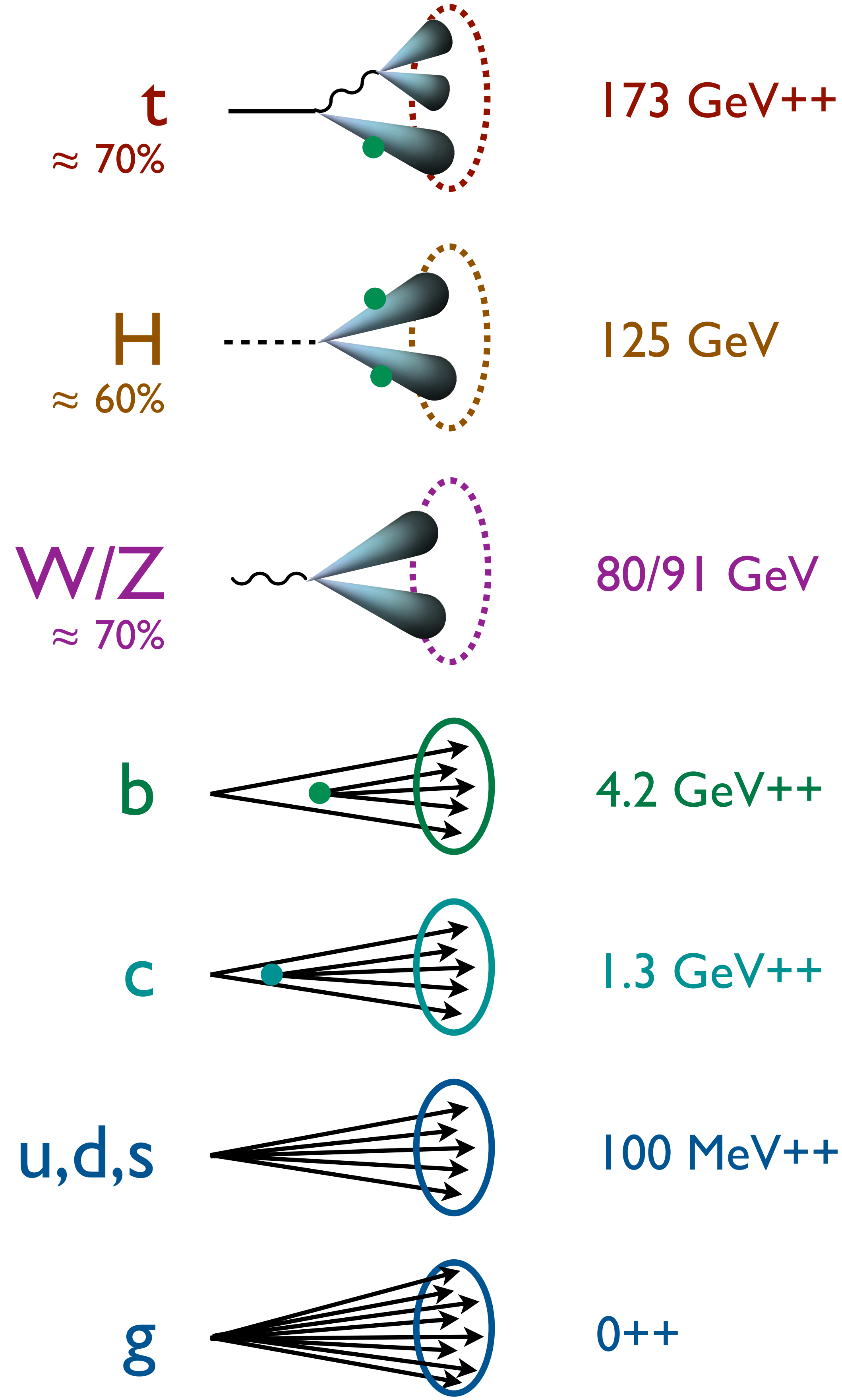
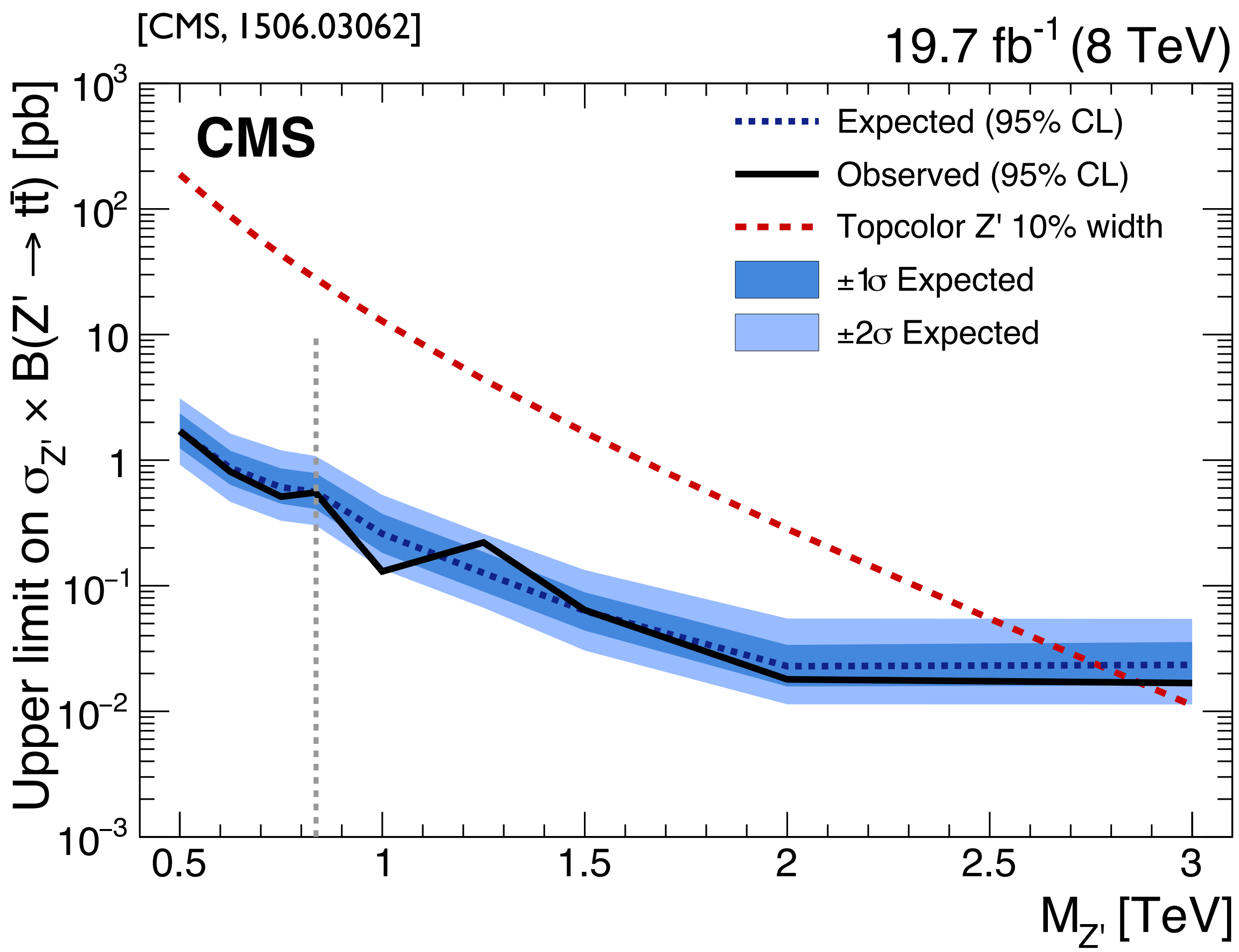
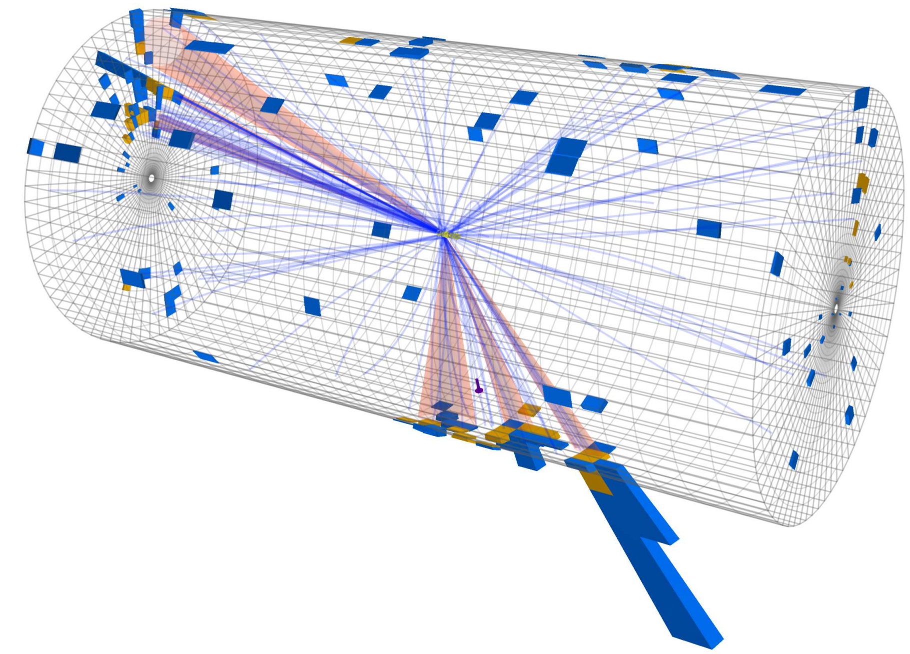
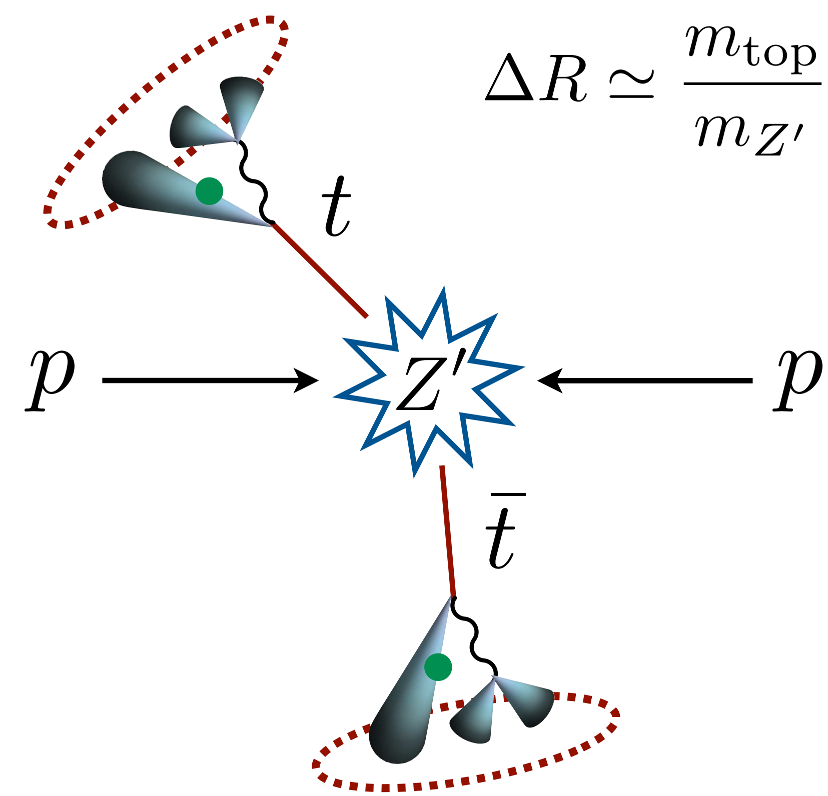


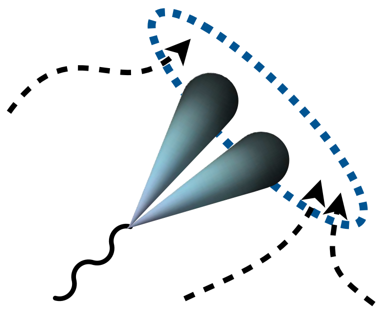
The Boosted Regime



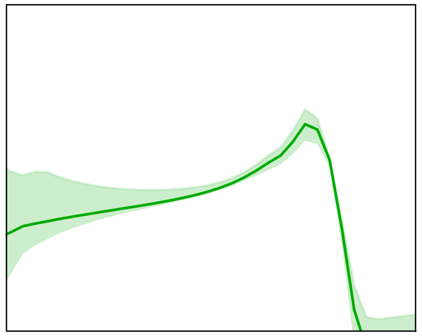




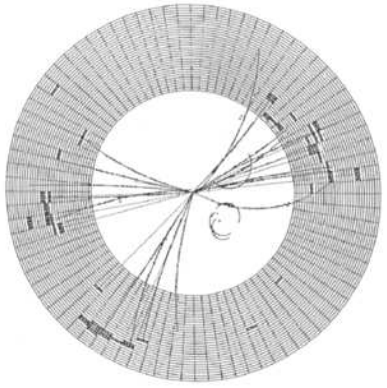
Outline



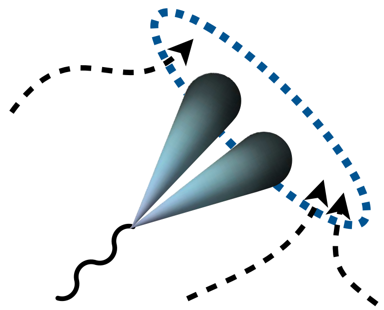
New Physics in the Boosted Regime



Theoretical Advances in Jet Substructure



Back to the Future: Quarks vs. Gluons



New Physics in the Boosted Regime

Theoretical Advances in Jet Substructure

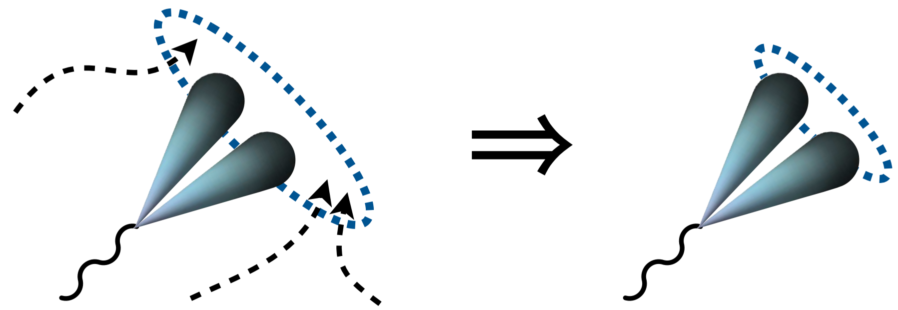
Back to the Future: Quarks vs. Gluons

	ICHEP2016CHICAGO	ATLAS EXPERIMENT	CMS
New Results (includes performance studies)		≈ 67	≈ 79
Using Jets		≈ 31	≈ 54
Using Substructure		≈ 10	≈ 12

Key Substructure Techniques

Grooming:

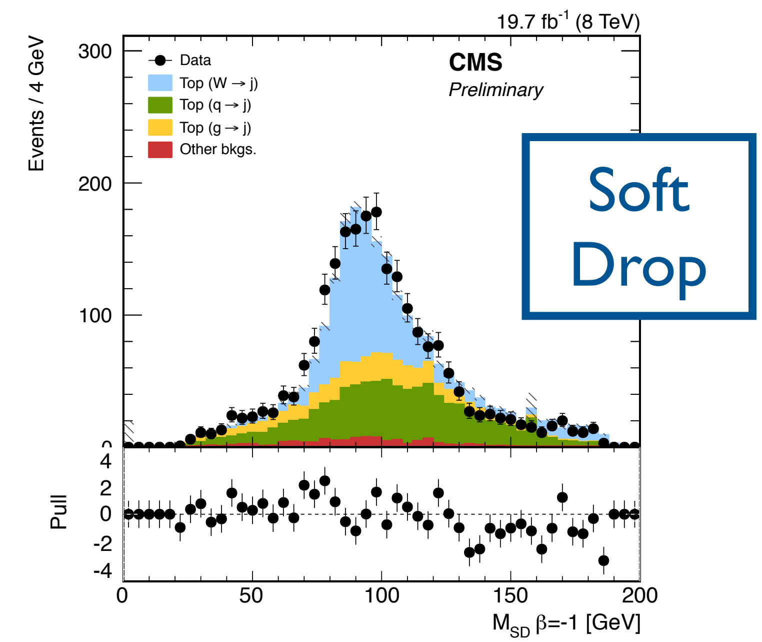
e.g. ISR/UE/pileup



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

W/Z-Tagging @ CMS

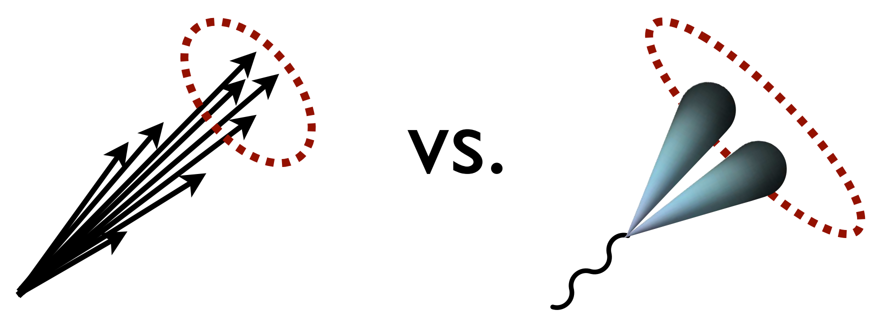
[JME-14-002, CMS-PAS-EXO-15-002]



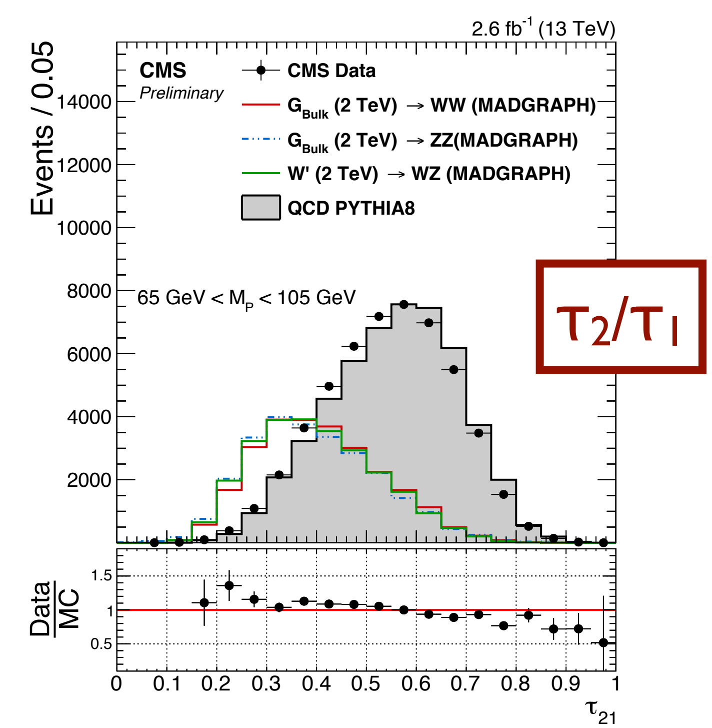
[using Larkoski, Marzani, Soyez, JDT, 1402.2657]

Discrimination:

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



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



[using JDT, Van Tilburg, 1011.2268, 1108.2701]

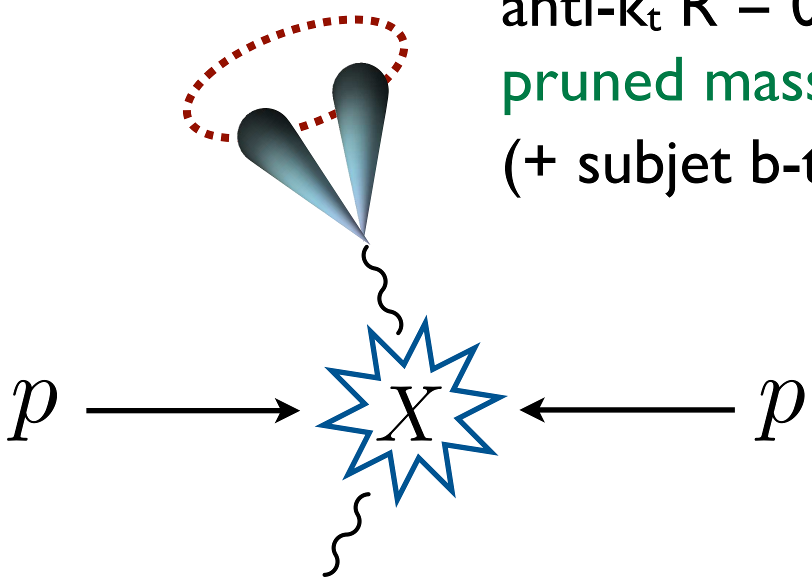
CMS: Zγ Resonance Search

Z candidate

anti-k_t R = 0.8, p_T > 200 GeV

pruned mass ∈ [75,105] GeV

(+ subjet b-tagging for Z → bb)



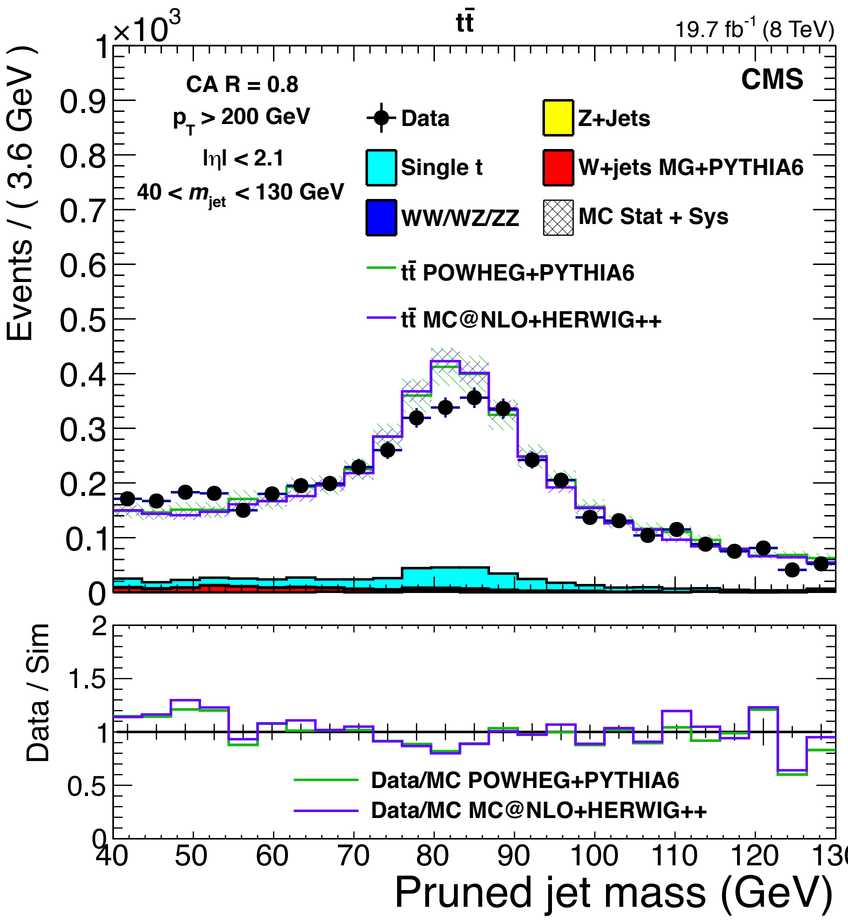
γ candidate

p_T > min[180 GeV, 0.34 $M_{j\gamma}$]

$R_{j\gamma}$ > 1.1

~ 20% signal efficiency
(vs. ~5% for e/μ)

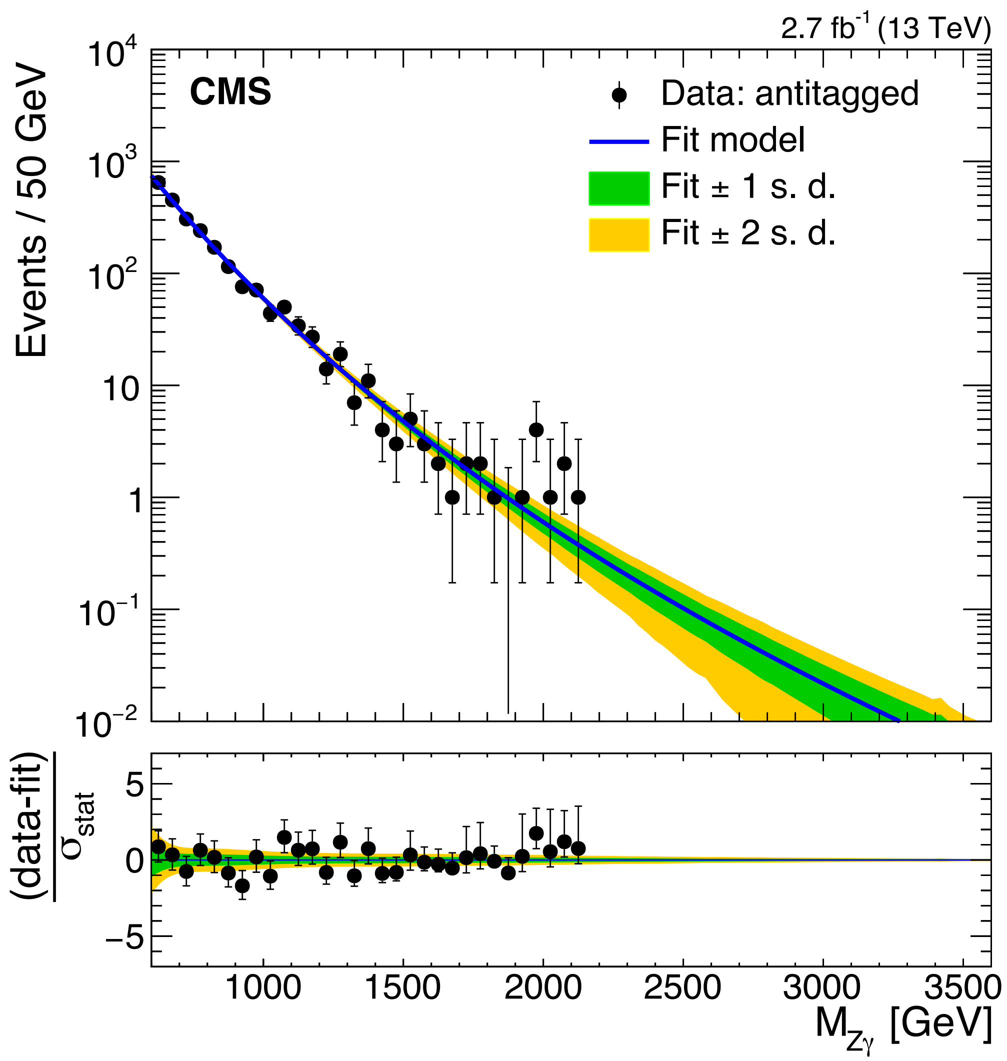
Top control sample
(with W candidates)

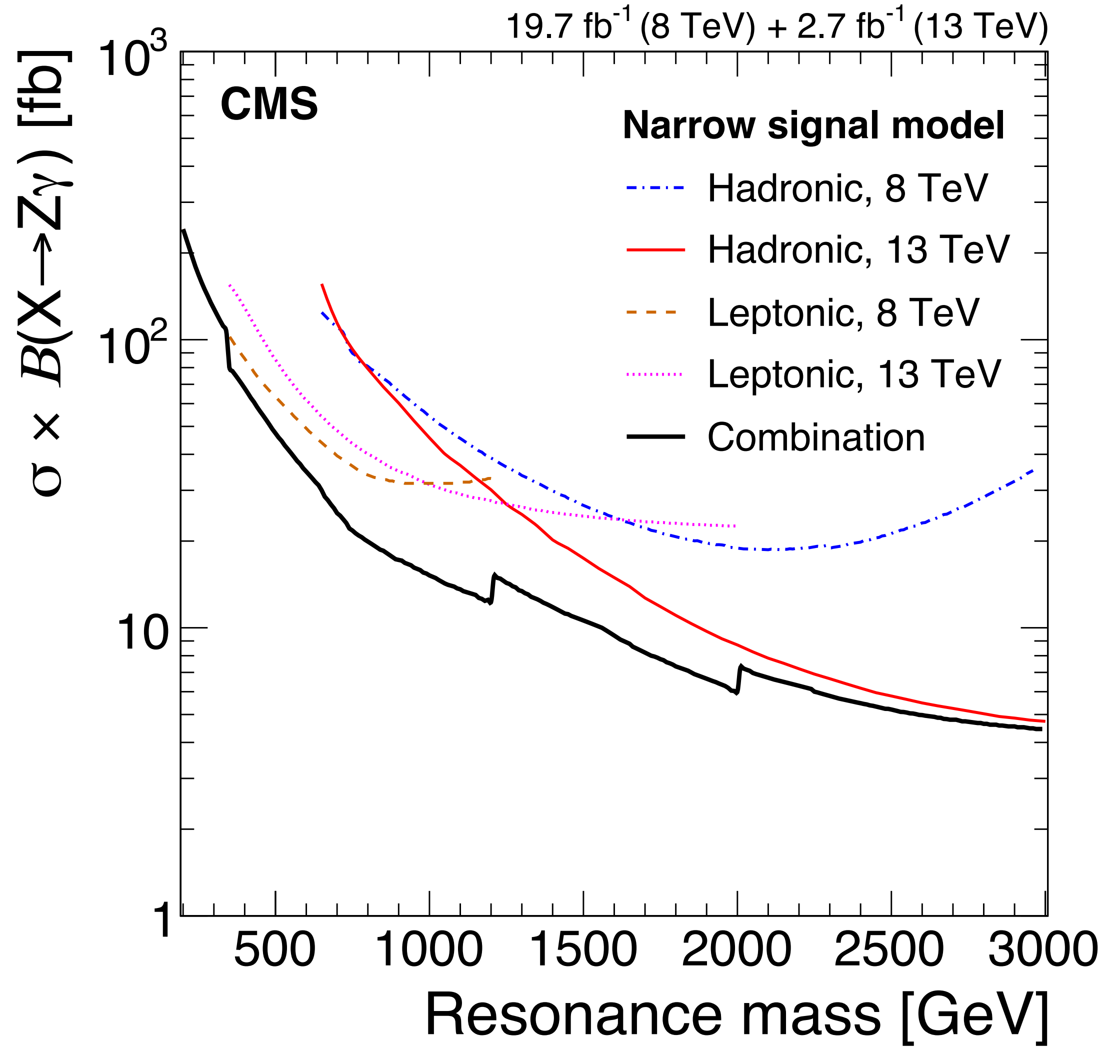


Z window

[CMS, 1410.4227, 1612.09516]
[using Ellis, Vermilion, Walsh, 0903.5081, 0912.0033]

CMS: Zγ Resonance Search

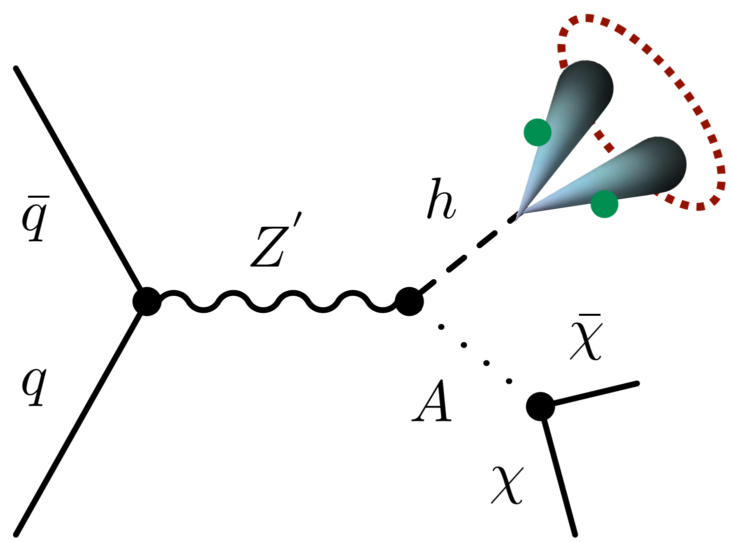




Hadronic Z channel dominates for $M_X > 1.2$ TeV

[CMS, 1410.4227, 1612.09516]
[using Ellis, Vermilion, Walsh, 0903.5081, 0912.0033]

ATLAS: Dark Matter plus Higgs Search



H candidate

anti-k_t R = 1.0, p_T > 250 GeV

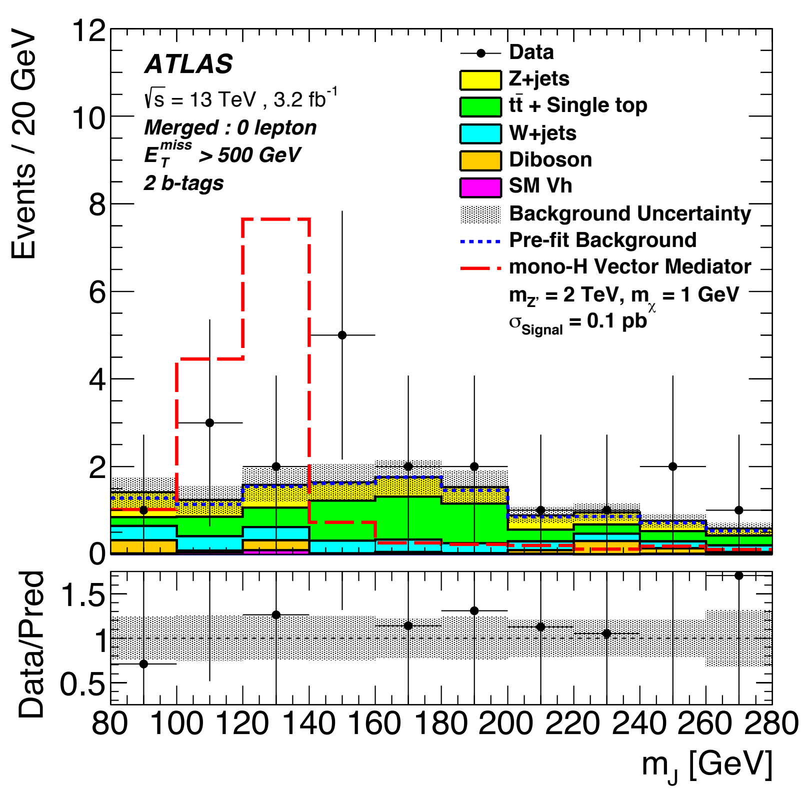
trimmed jet mass as discriminant

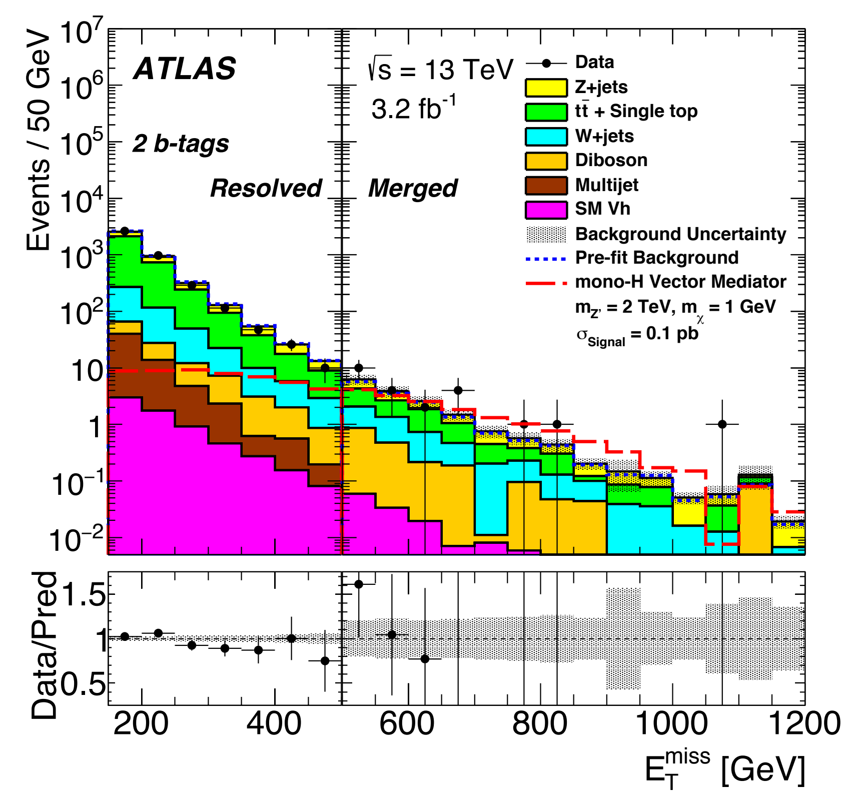
double b-tagging via R = 0.2 track jets

Missing Energy

E_T > 500 GeV in merged analysis

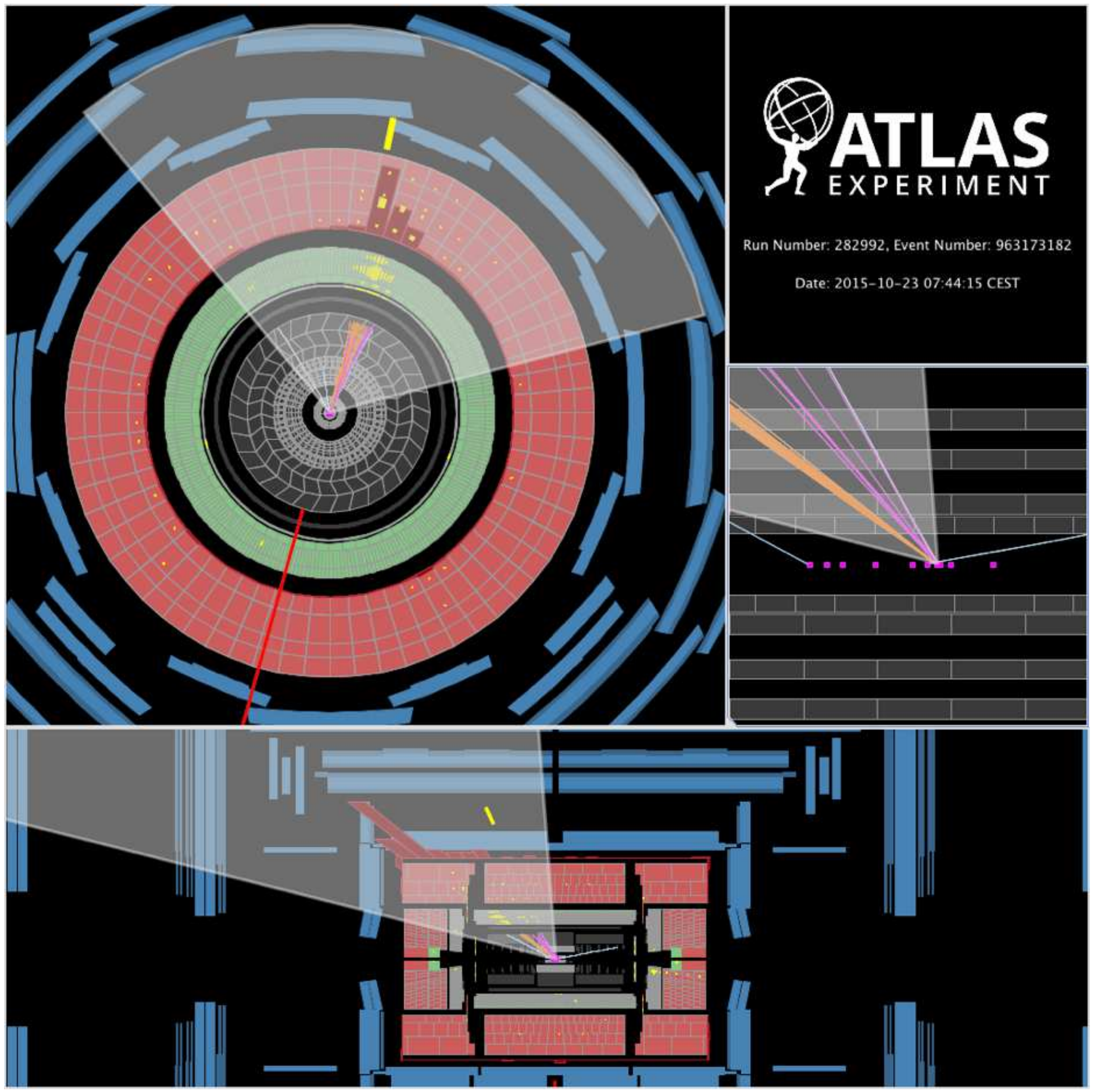
(+ separate resolved analysis)

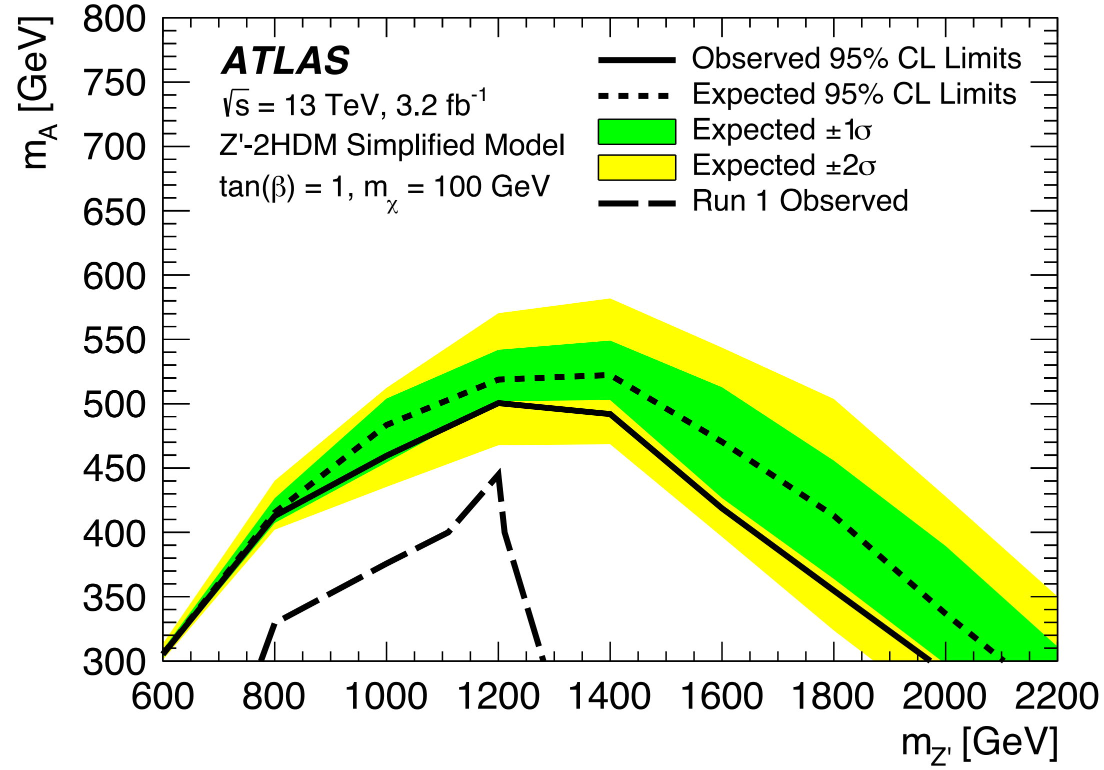




[ATLAS, 1609.04572; using Krohn, JDT, Wang, 0912.1342]

ATLAS: Dark Matter plus Higgs Search

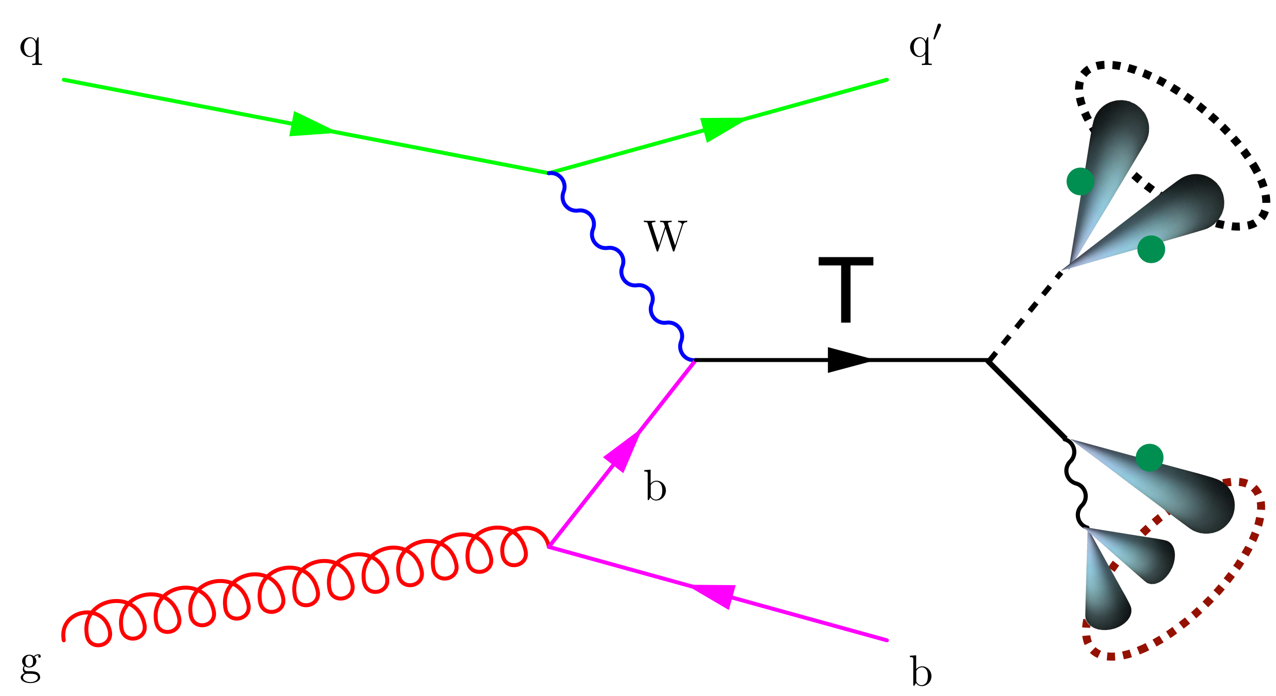




Boosted regime essential to explore heavy mediator masses

[ATLAS, 1609.04572; using Krohn, JDT, Wang, 0912.1342]

CMS: Vector-like Quark Search



H candidate

anti-k_t R = 0.8, p_T > 300 GeV

τ_2/τ_1 cut

pruned mass ∈ [105,135] GeV

double subjet b-tagging

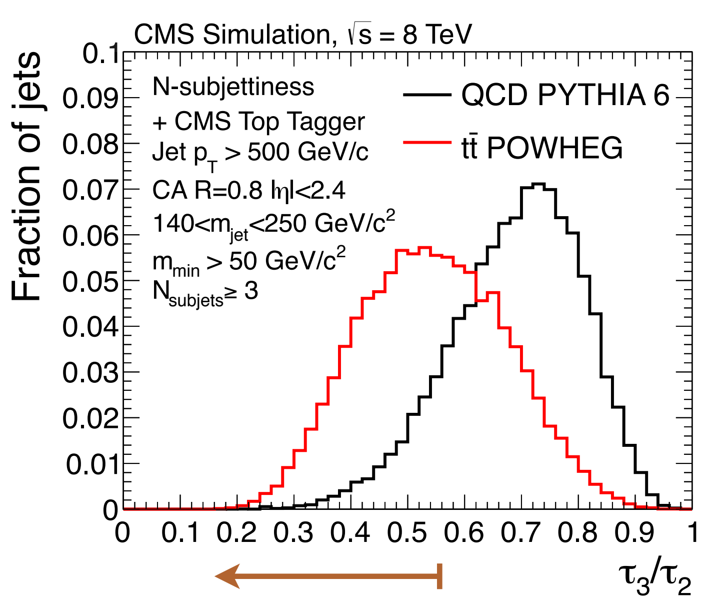
top candidate

anti-k_t R = 0.8, p_T > 400 GeV

τ_3/τ_2 cut

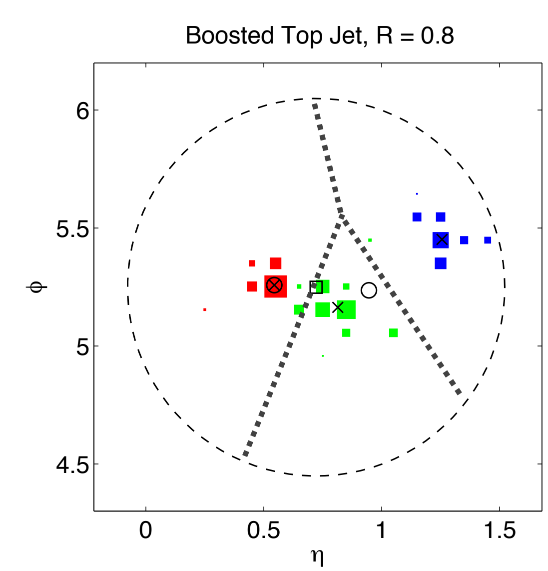
soft drop mass ∈ [110,210] GeV

single subjet b-tagging



N-subjettiness Ratios

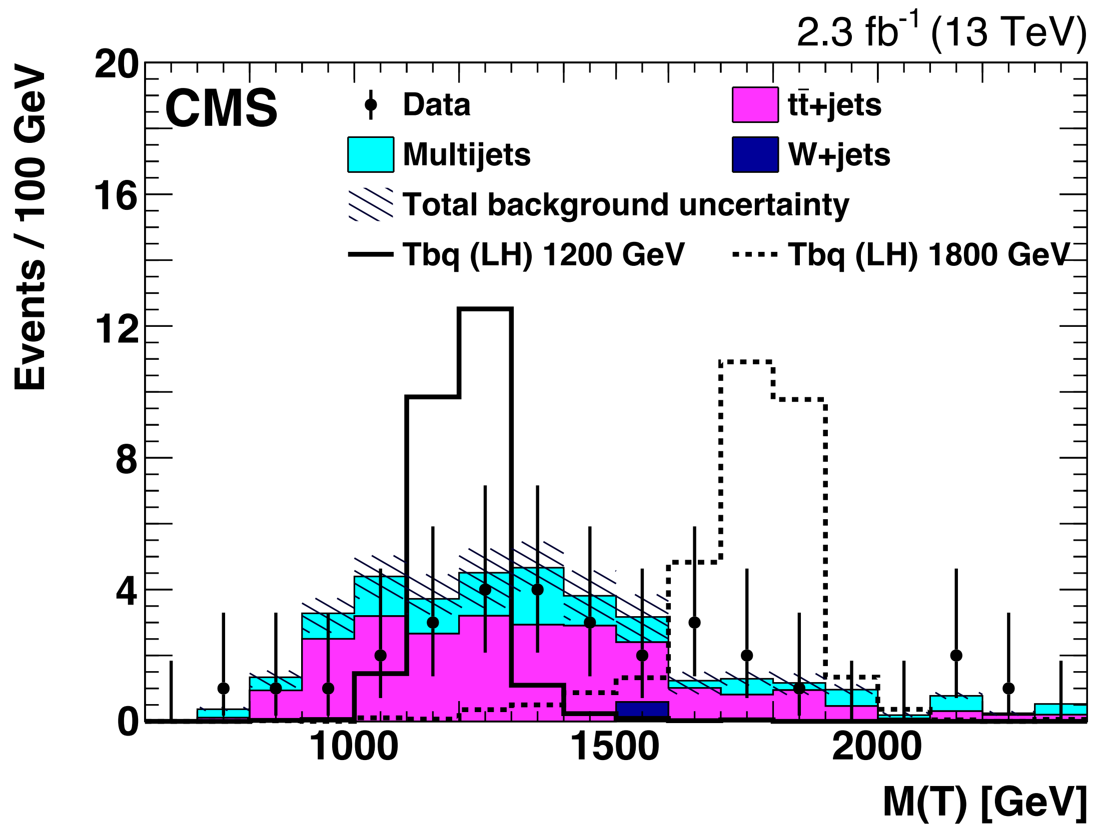
$$\frac{\tau_3}{\tau_2} = \frac{\sum_i p_{Ti} \min\{R_{i1}, R_{i2}, R_{i3}\}^\beta}{\sum_i p_{Ti} \min\{R_{i1}, R_{i2}\}^\beta}$$

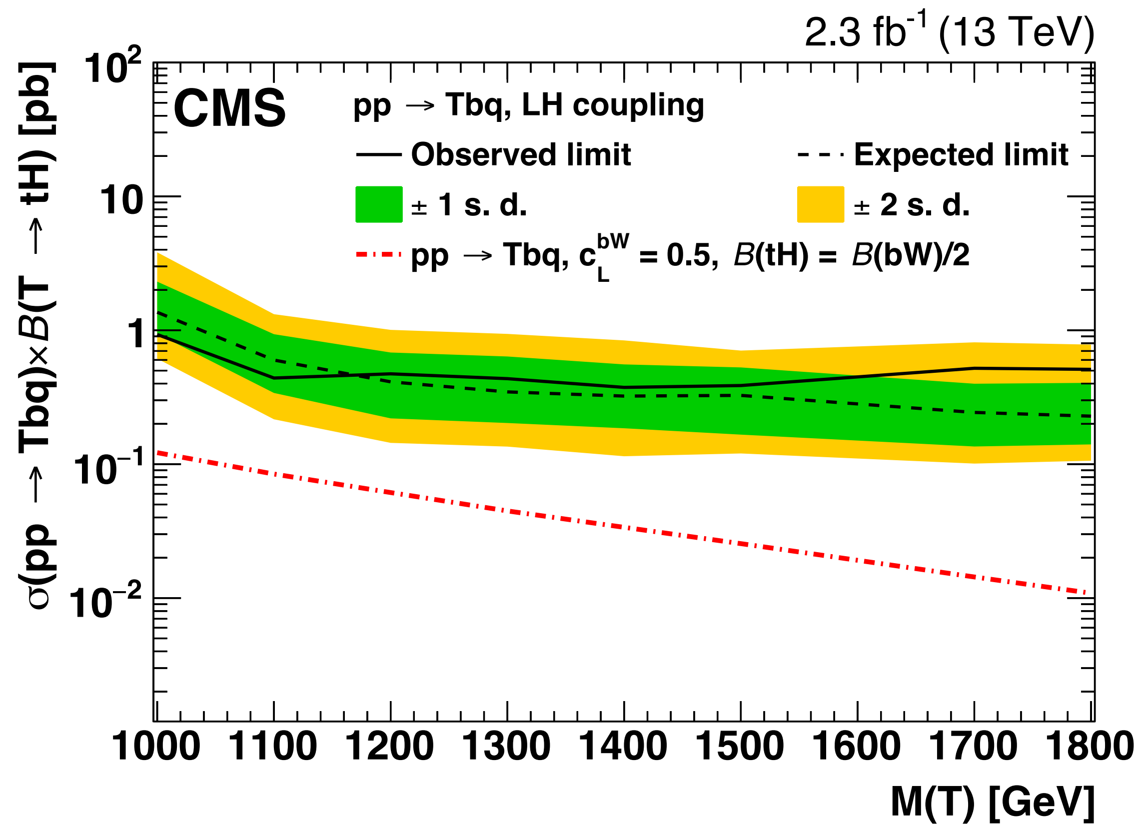


[CMS, 1612.05336, JME-13-007]

[using JDT, Van Tilburg, 1011.2268, 1108.2701; Ellis, Vermilion, Walsh, 0903.5081, 0912.0033; Larkoski, Marzani, Soyez, JDT, 1402.2657]

CMS: Vector-like Quark Search

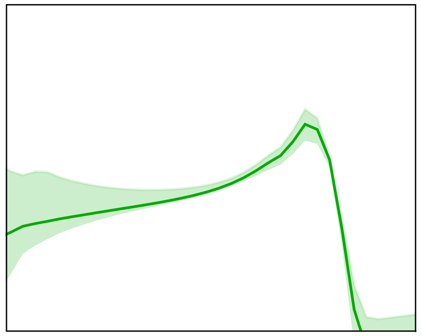




Jet substructure techniques well-suited to intricate final states with extreme kinematics

[CMS, 1612.05336, JME-13-007]
[using JDT, Van Tilburg, 1011.2268, 1108.2701; Ellis, Vermilion, Walsh, 0903.5081, 0912.0033; Larkoski, Marzani, Soyez, JDT, 1402.2657]

New Physics in the Boosted Regime

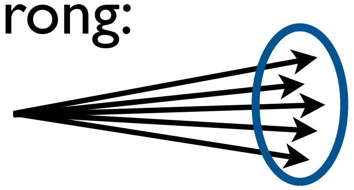


Theoretical Advances in Jet Substructure

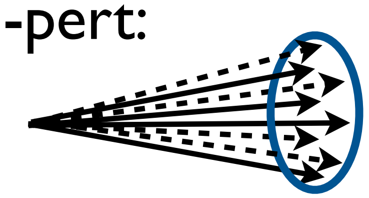
Back to the Future: Quarks vs. Gluons

First-Principles QCD Calculations

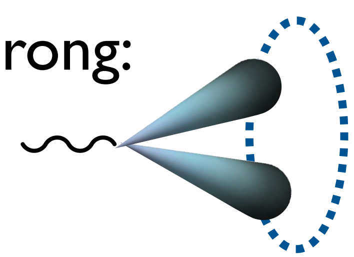
1-prong:



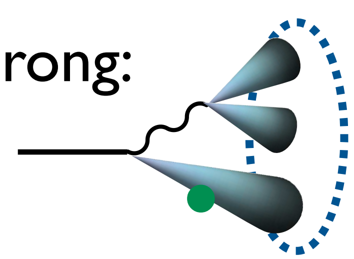
Non-pert:



2-prong:



3-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

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

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

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; Salam, Schunk, Soyez, 1612.03917

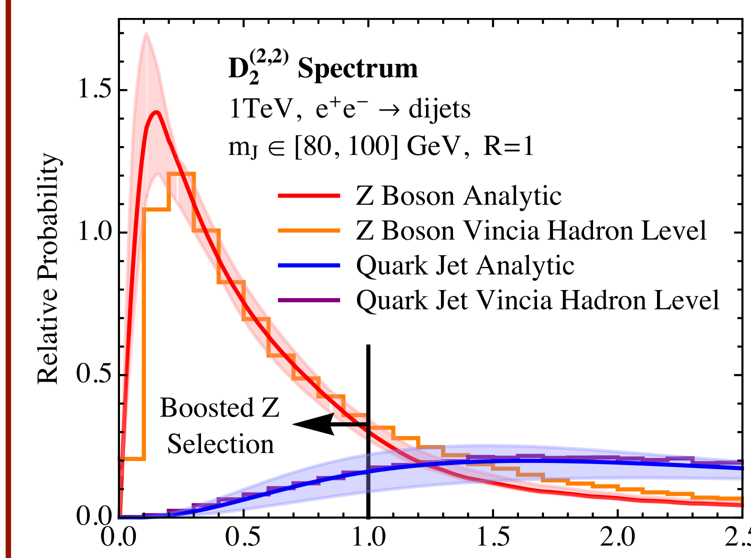
Separation power: Larkoski, Moult, Neill, 1409.6298, 1507.03018; Dasgupta, Schunk, Soyez, 1512.00516; Dasgupta, Powling, Schunk, Soyez, 1609.07149

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

Fractional jets: Bertolini, JDT, Walsh, 1501.01965

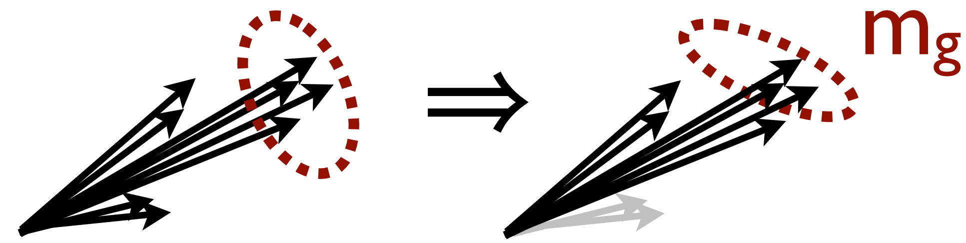
Power counting: Larkoski, Moult, Neill, 1411.0665

First precision prediction of 2-prong discrimination power

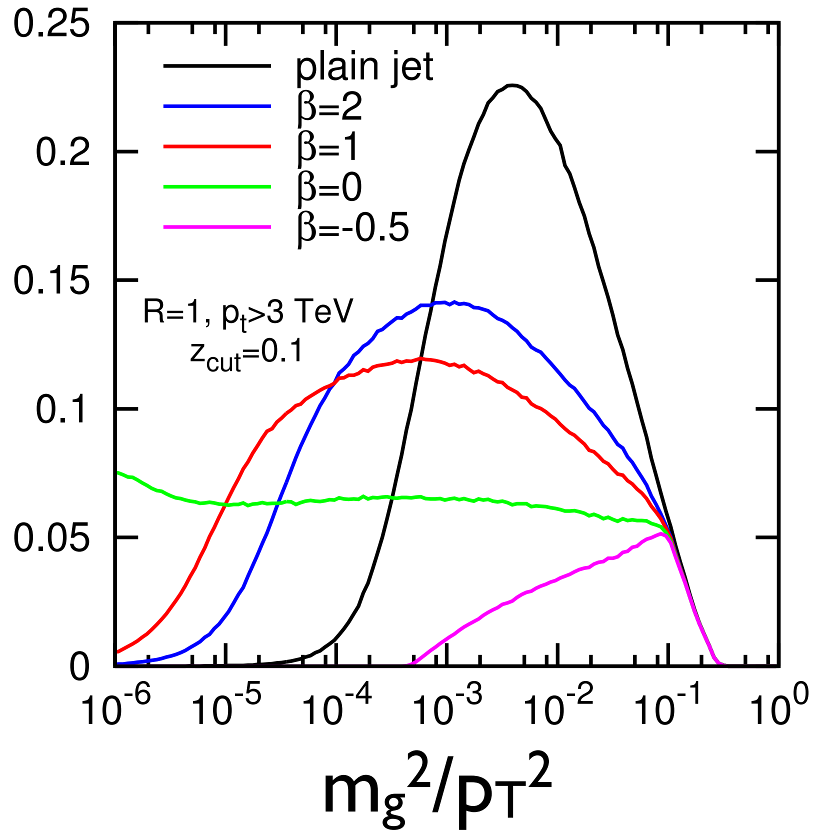


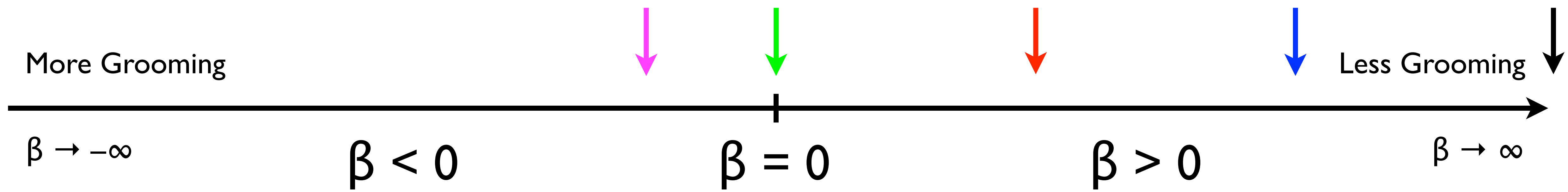
Combination of fixed-order, direct resummation, SCET, RG evolution, and new techniques (e.g. Sudakov safety, multi-differential projections)

Soft-dropped Mass?



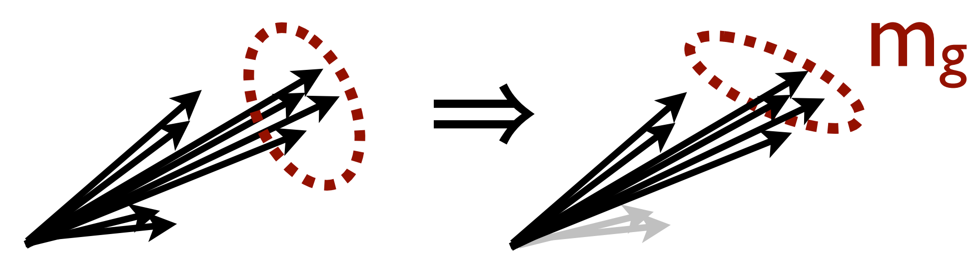
Simulated LHC Data



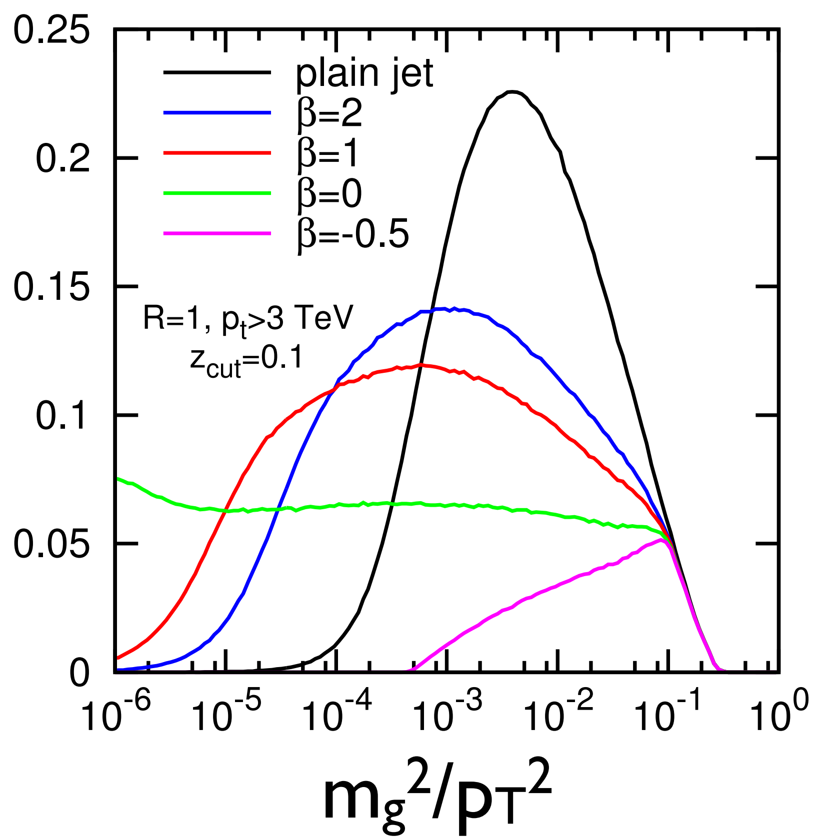


[Larkoski, Marzani, Soyez, JDT, 1402.2657; see also Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

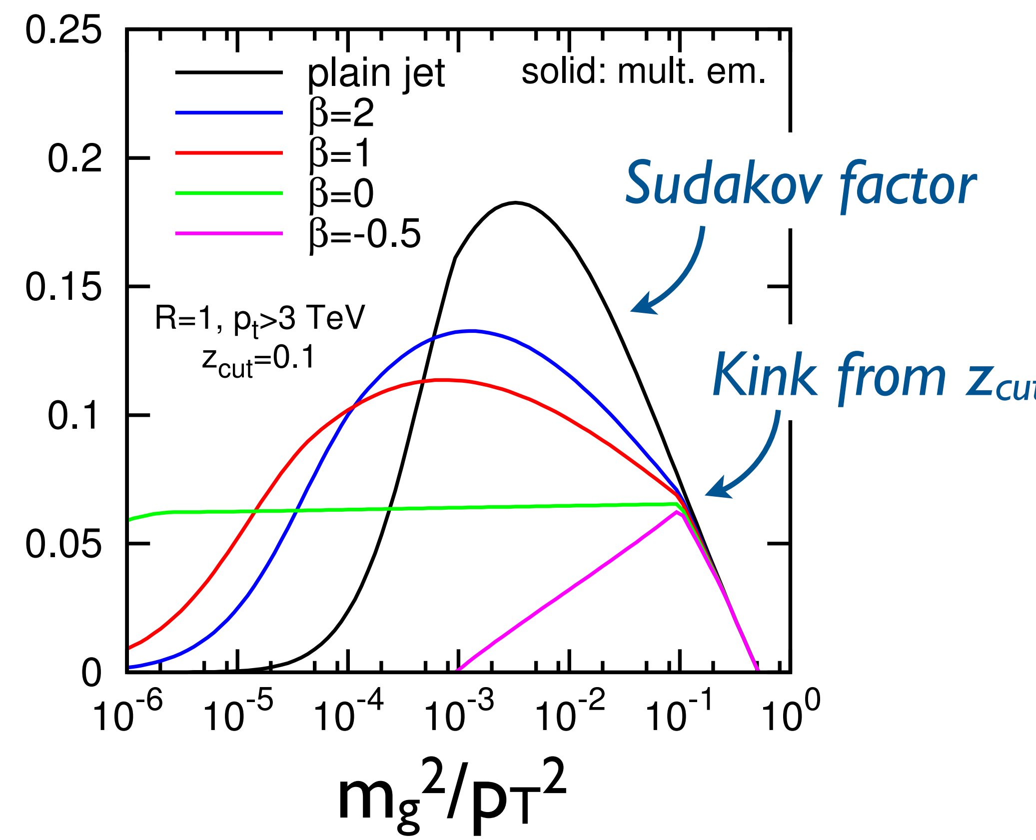
Soft-dropped Mass?

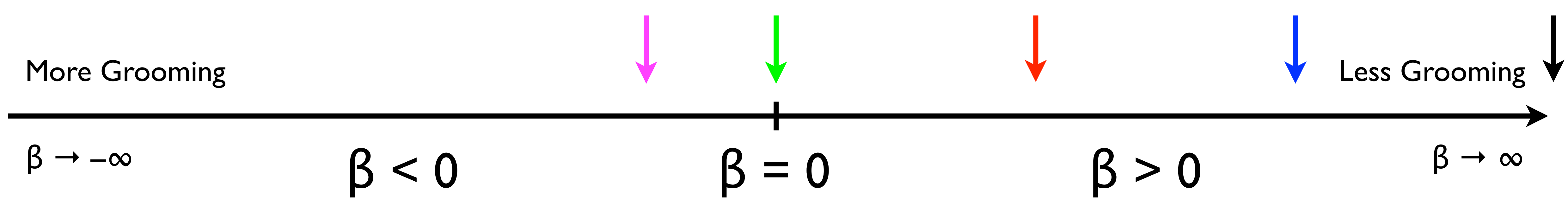


Simulated LHC Data



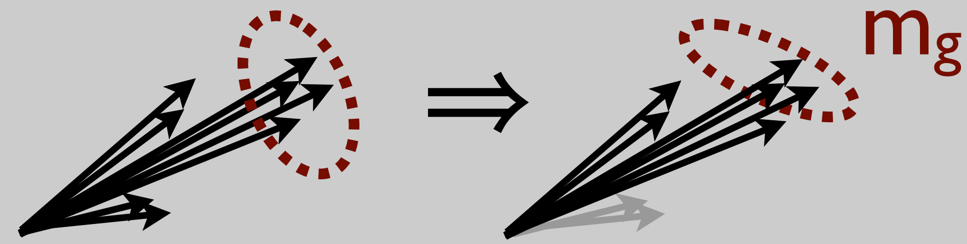
First-principles QCD (MLL)



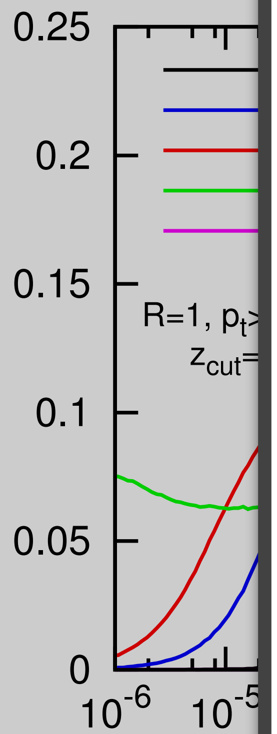


[Larkoski, Marzani, Soyez, JDT, 1402.2657; see also Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

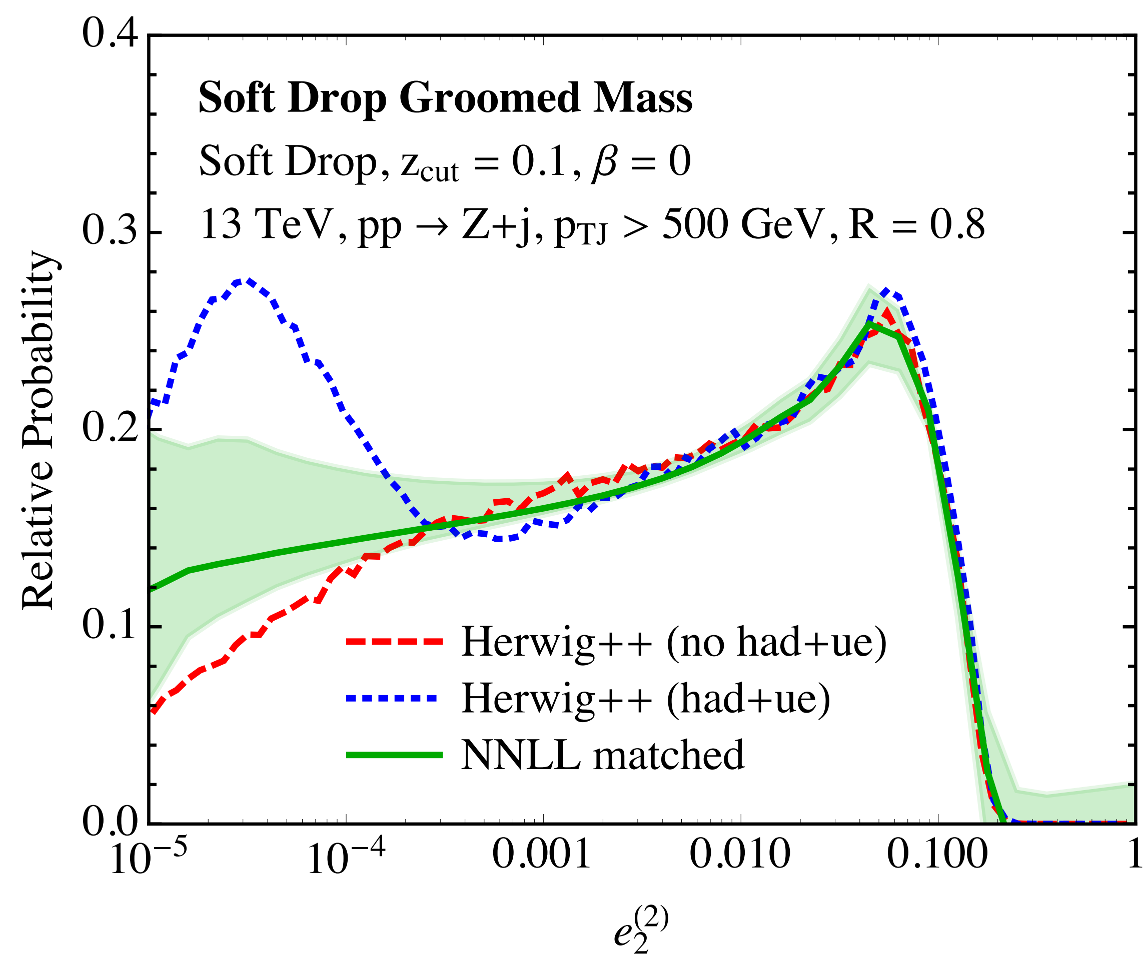
Soft-dropped Mass?

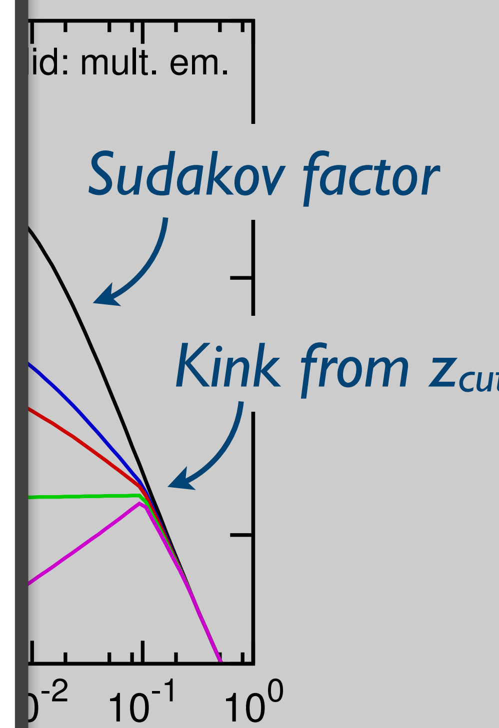


Simu… …CD (MLL)



First NNLL + O(α_s^2) calculation for substructure in pp (!)





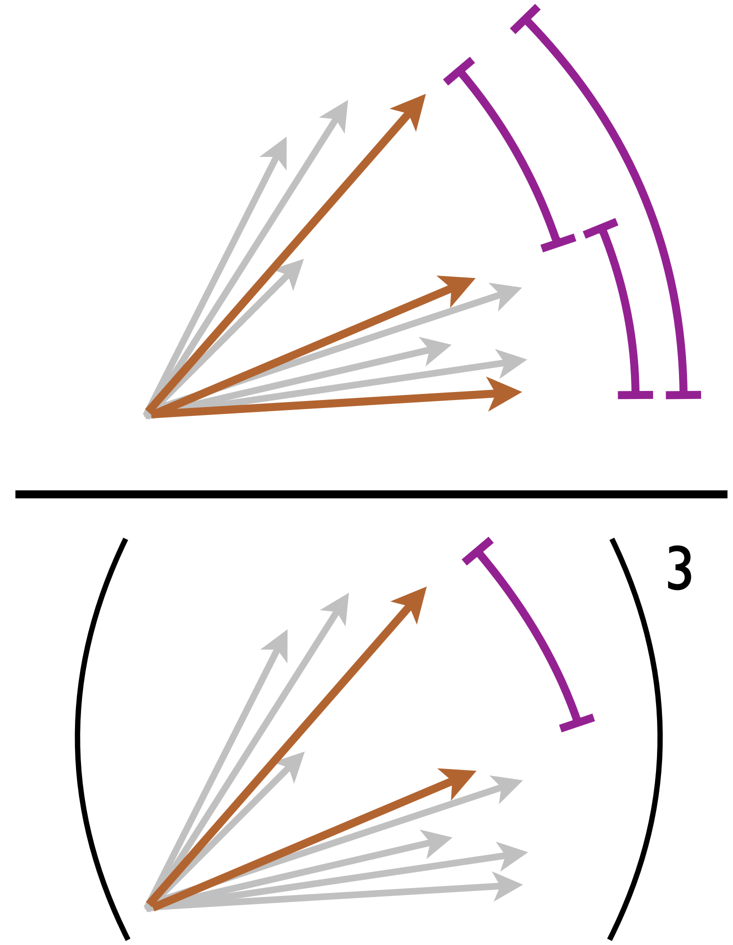
More Grooming — Less Grooming

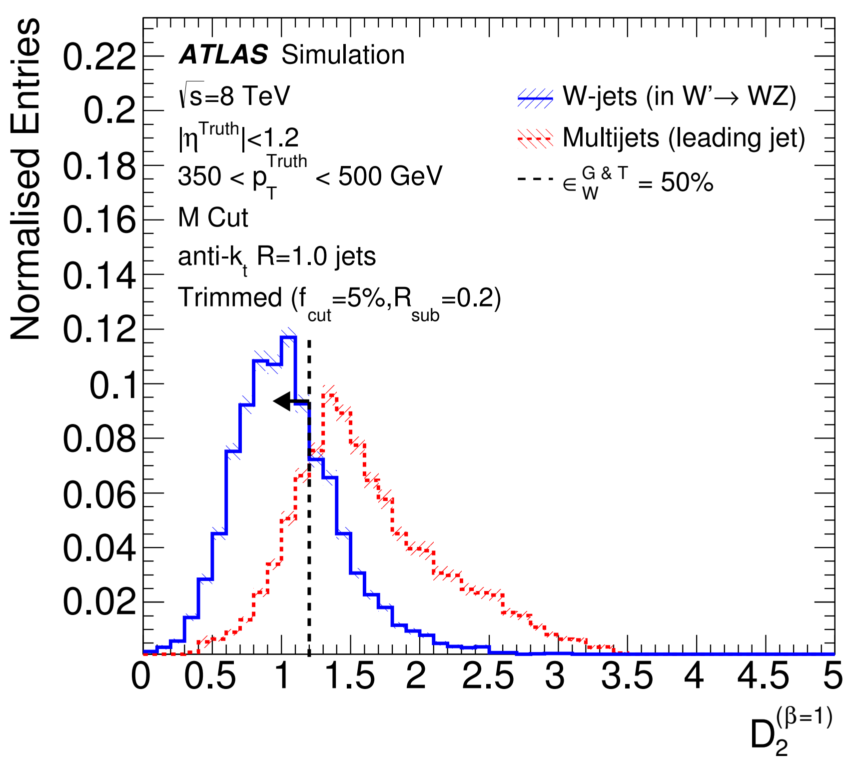
$\beta \to -\infty$ — $\beta \to \infty$

[Larkoski, Marzani, Soyez, JDT, 1402.2657; see also Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

D2: Energy Correlation Functions

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



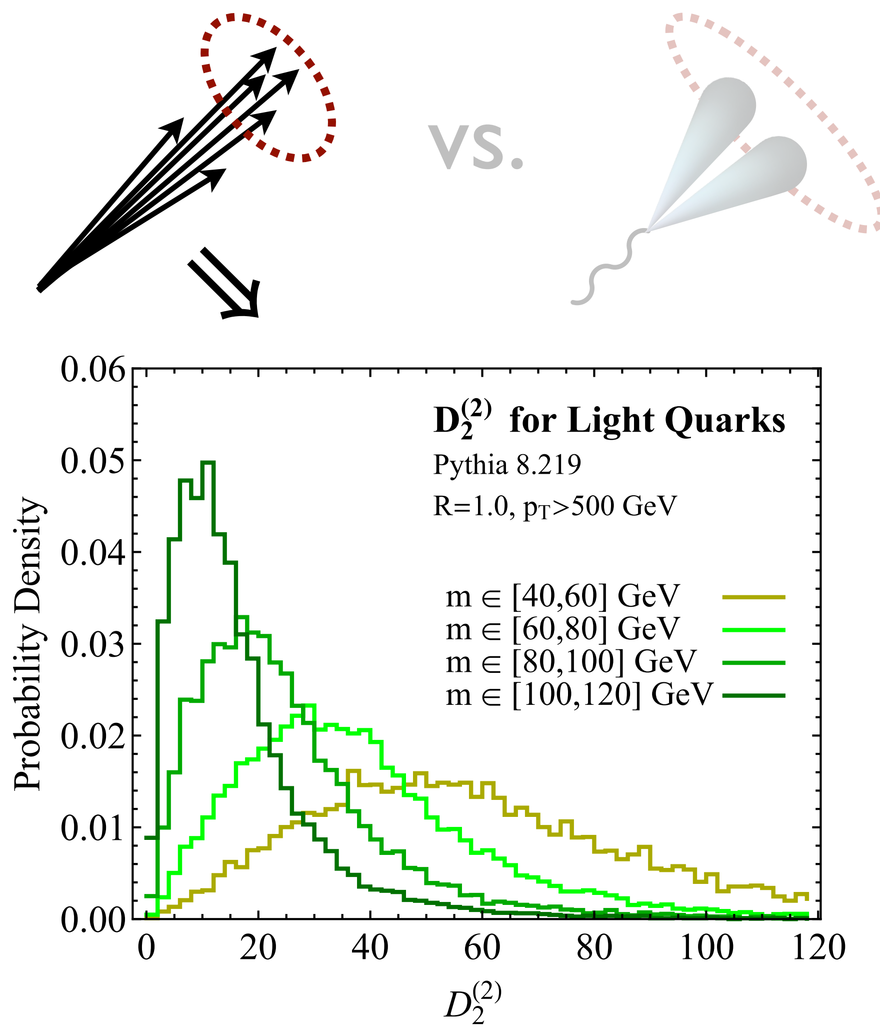


Derived for 2-prong W/Z tagging using EFT power counting

Used in ATLAS "R2D2" Tagger

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

Robustness of D_2?



Background highly sensitive to mass cut

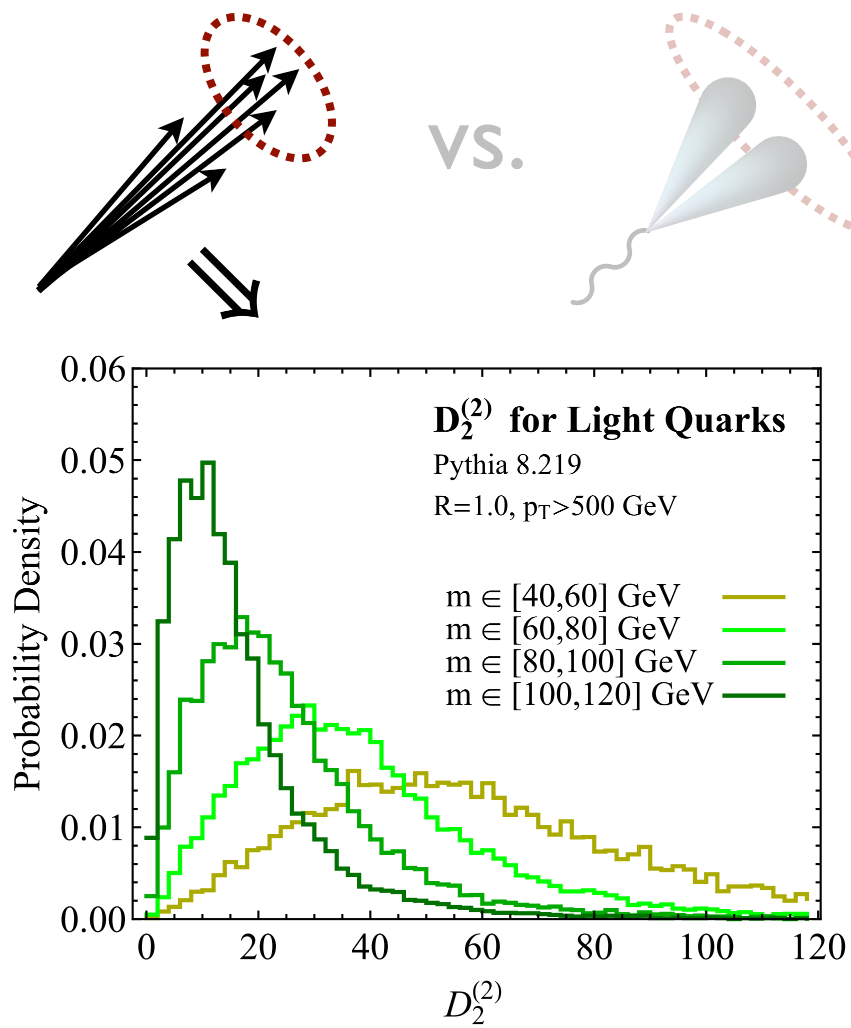
$$D_2^{\max} \sim \frac{p_{TJ}^2}{m_J^2}$$

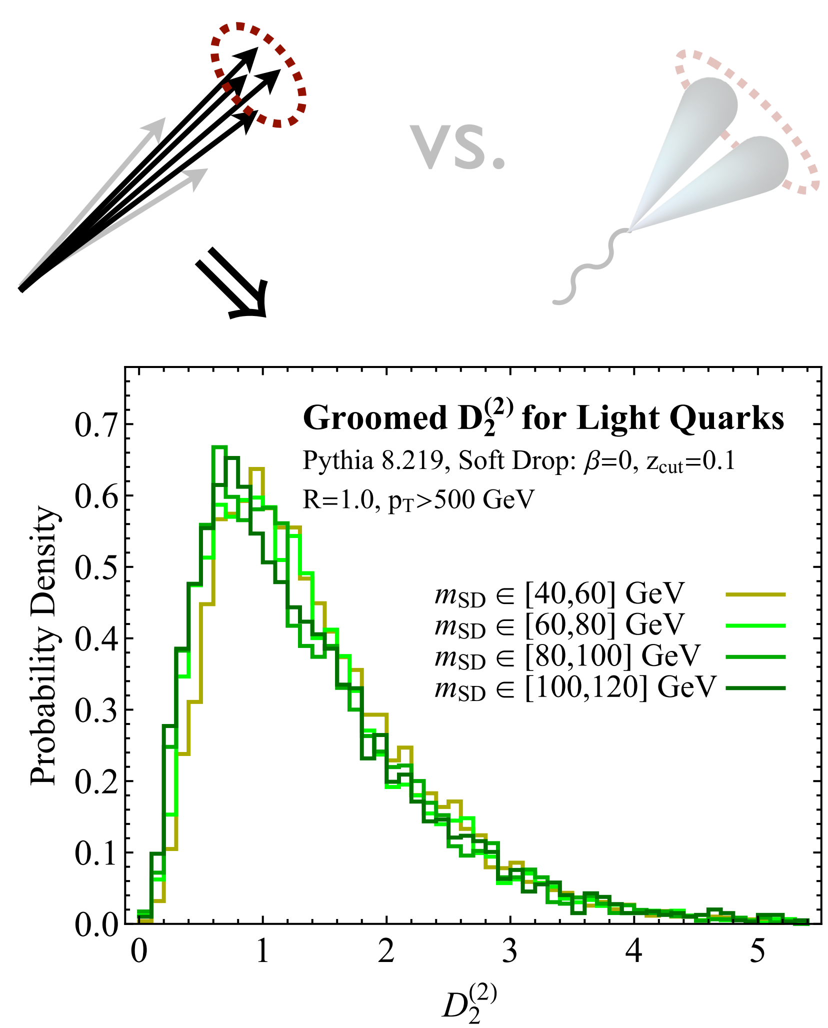
Difficult to use sideband control regions

[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

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

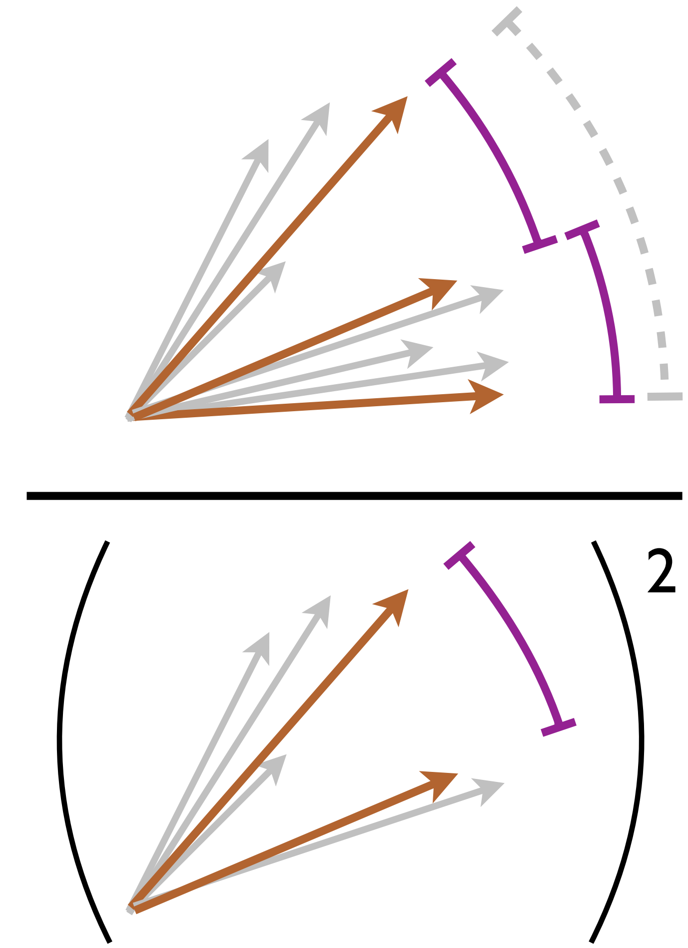
Explains ATLAS strategy of
R2 (trimming) + D2 (discrimination)

[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

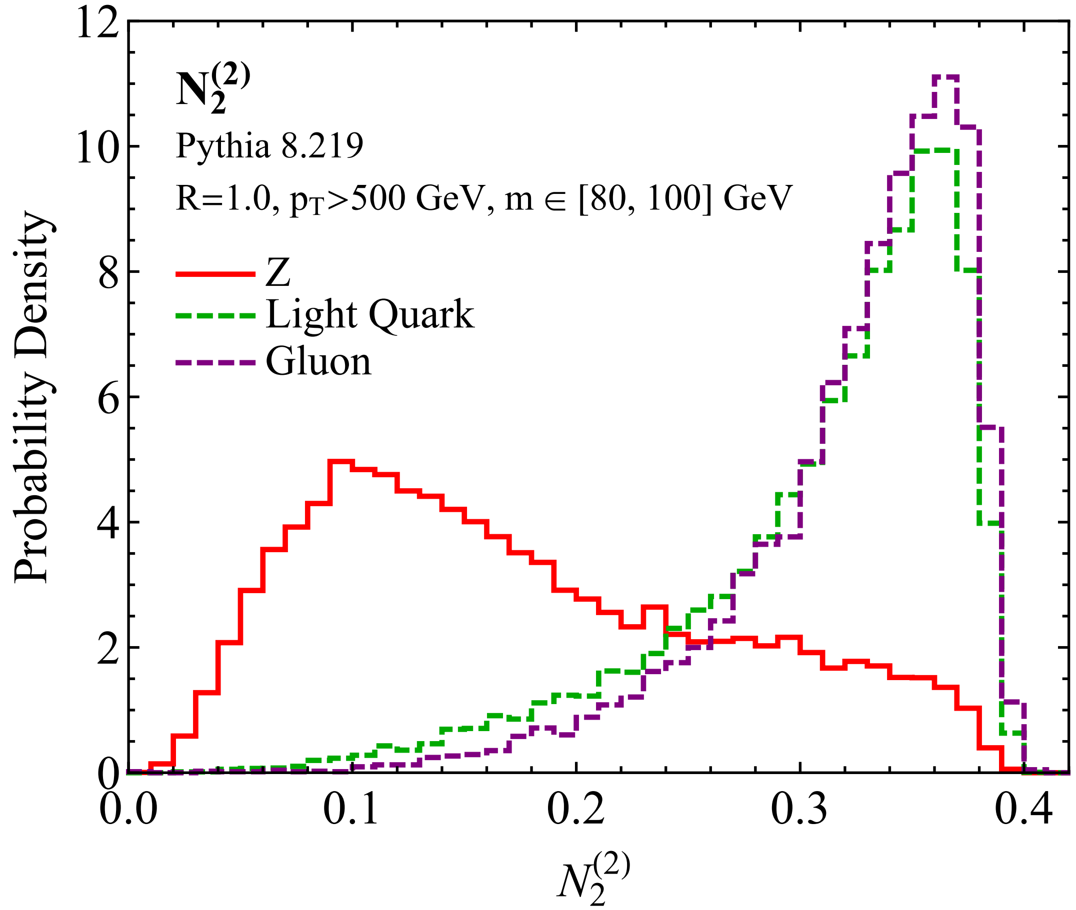
Kind of a hybrid of D_2 and N-subjettiness (hence the name)

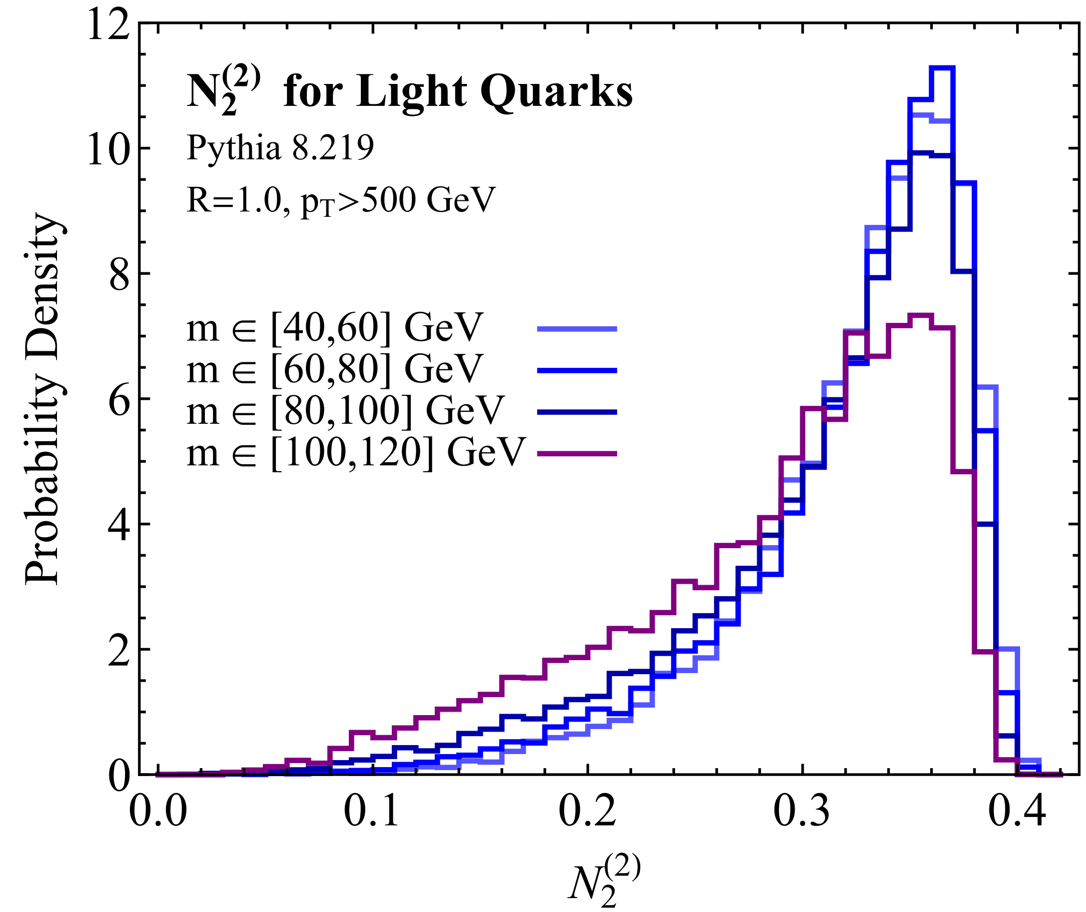
[Moult, Necib, JDT, 1609.07483]

N_2: A New Angle on Energy Correlators

Derived using EFT power counting for both…

Performance & *Robustness*

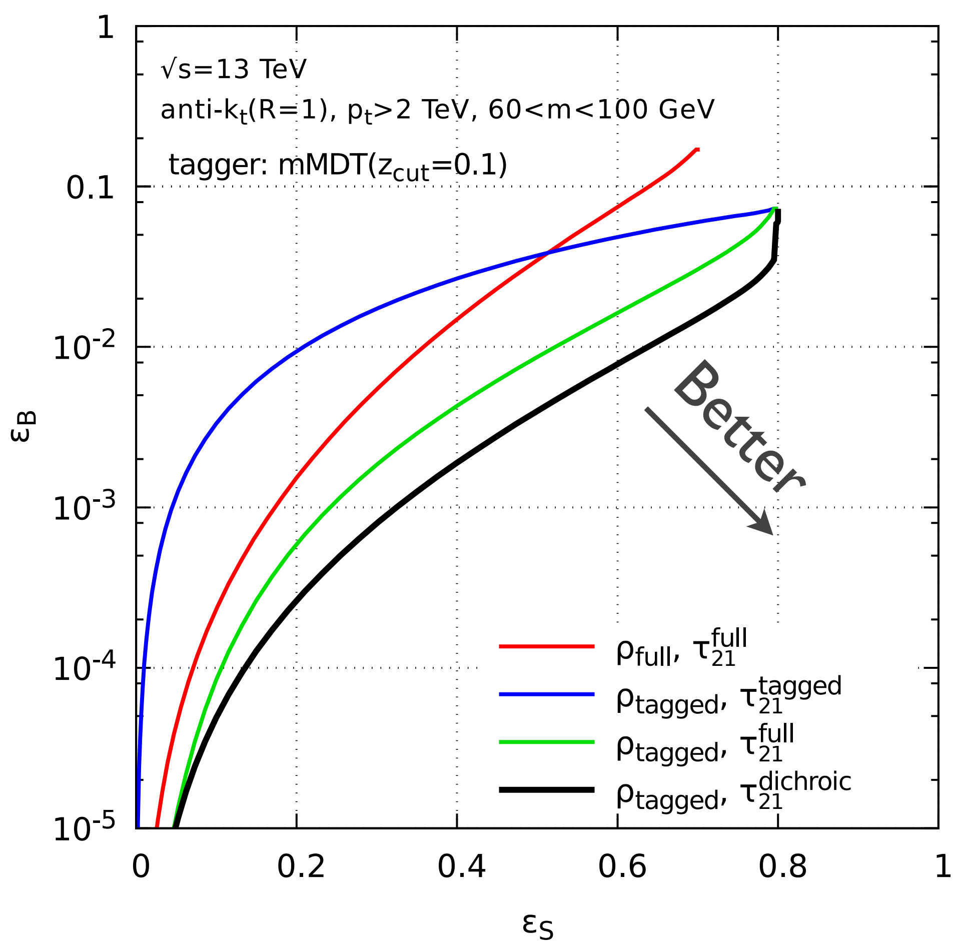




(with and without grooming)

[Moult, Necib, JDT, 1609.07483]

Grooming/Discrimination Interplay



no grooming

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

groomed mass
groomed τ_2/τ_1

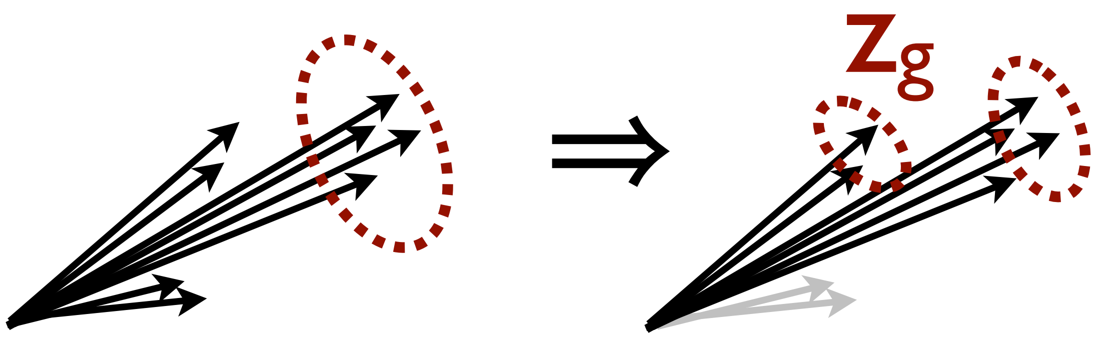
groomed mass
ungroomed τ_2/τ_1

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

Analytic calculations to identify optimal use of substructure information

[Salam, Schunk, Soyez, 1612.03917]

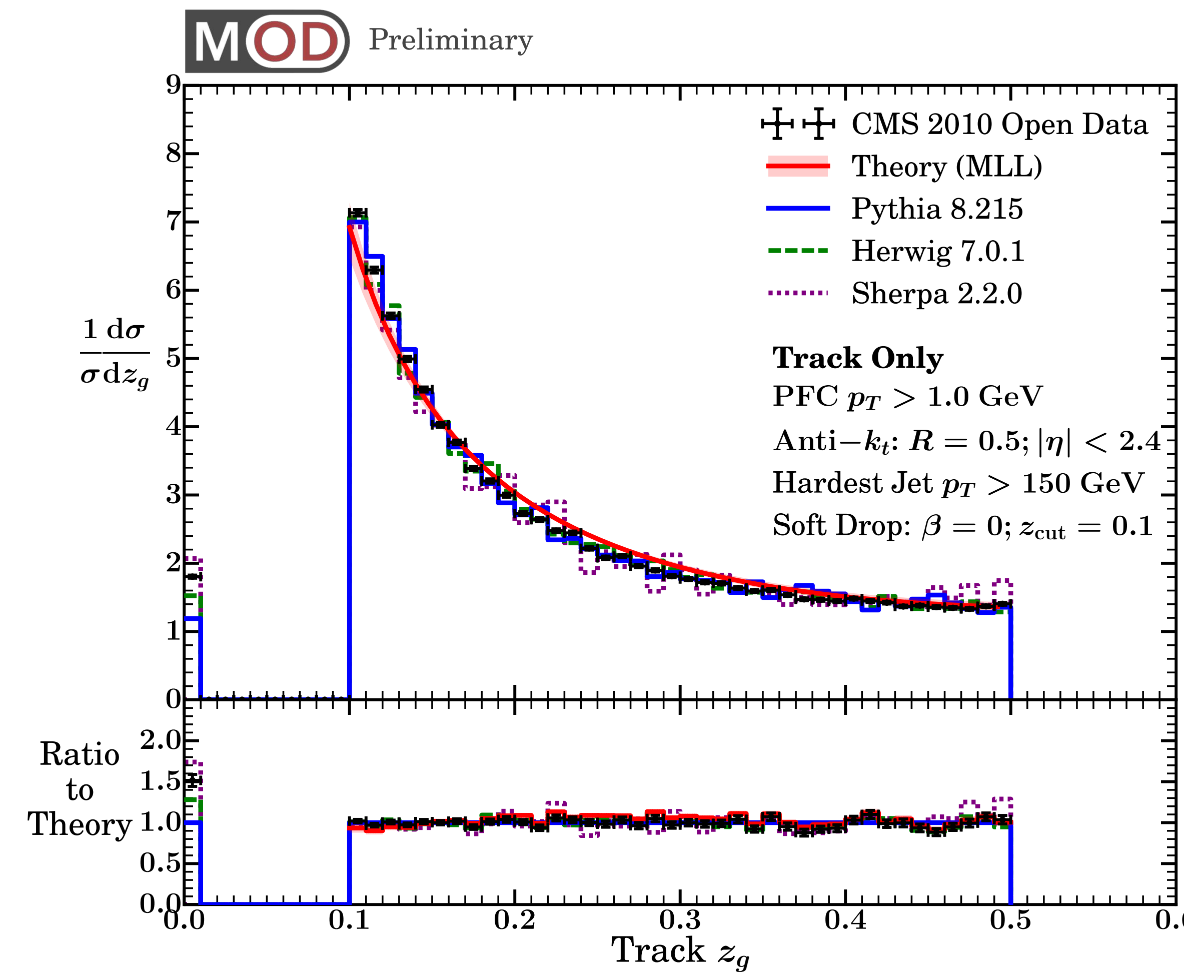
Grooming to Explore QCD



A "standard candle"
from soft drop

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

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



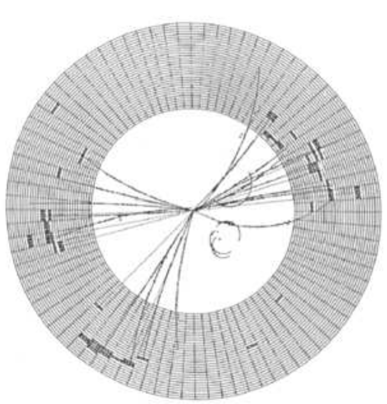
CMS opendata CERN

"Accelerating science through public data"

[Larkoski, Marzani, JDT, 1502.01719; using Larkoski, JDT, 1307.1699]
[Larkoski, Marzani, Romero, Tripathee, Xue, JDT, in progress]

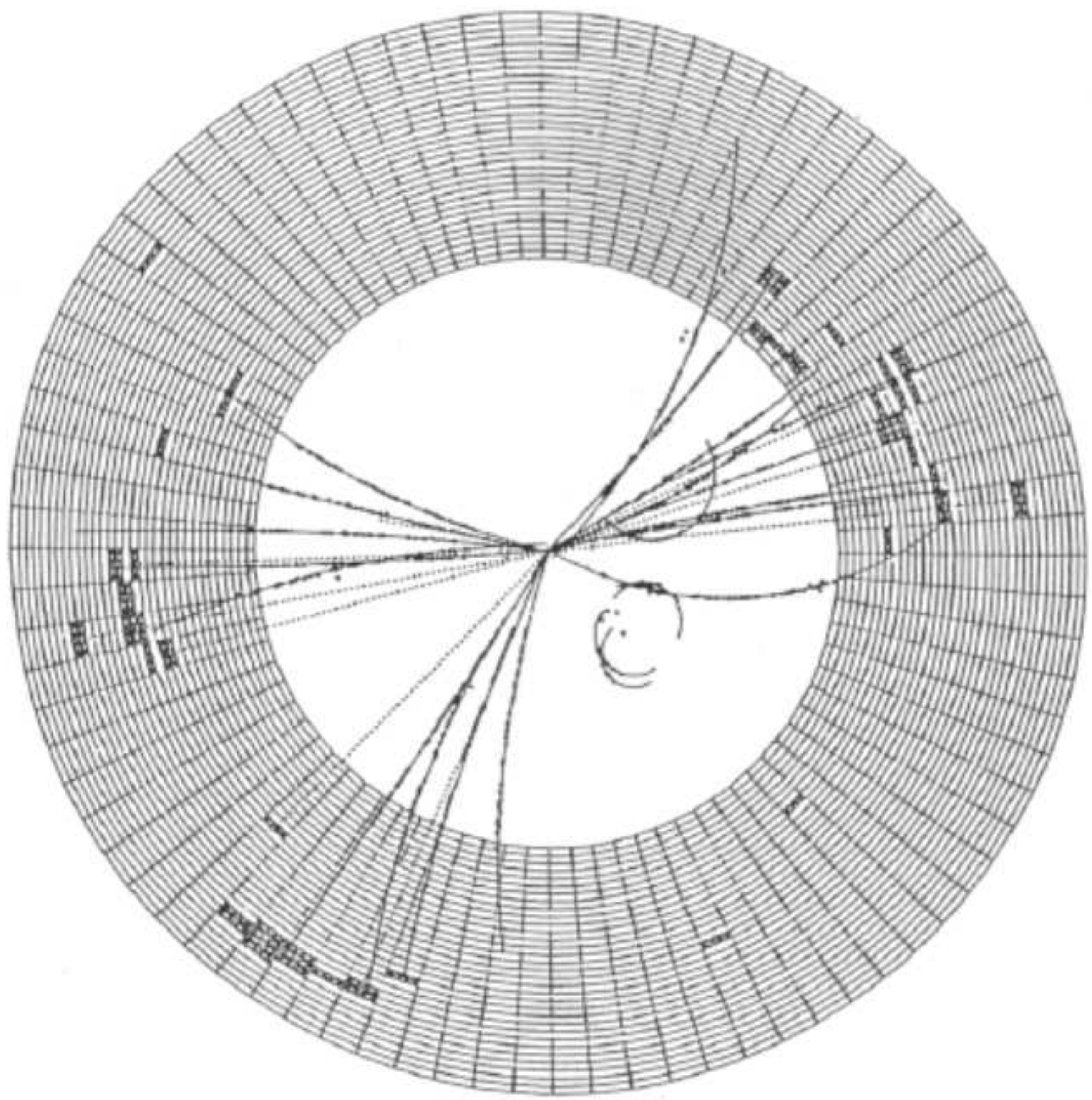
New Physics in the Boosted Regime

Theoretical Advances in Jet Substructure



Back to the Future: Quarks vs. Gluons

Quark vs. Gluon?



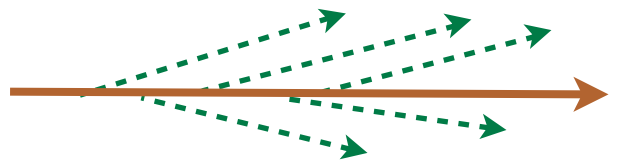
$$e^+e^- \to q\bar{q}g$$

[JADE,1979]

Cartoon:

Quark: $C_F = 4/3$

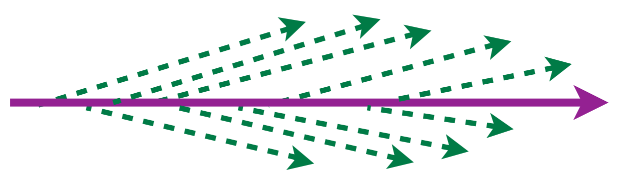
usually signals



vs.

Gluon: $C_A = 3$

usually backgrounds

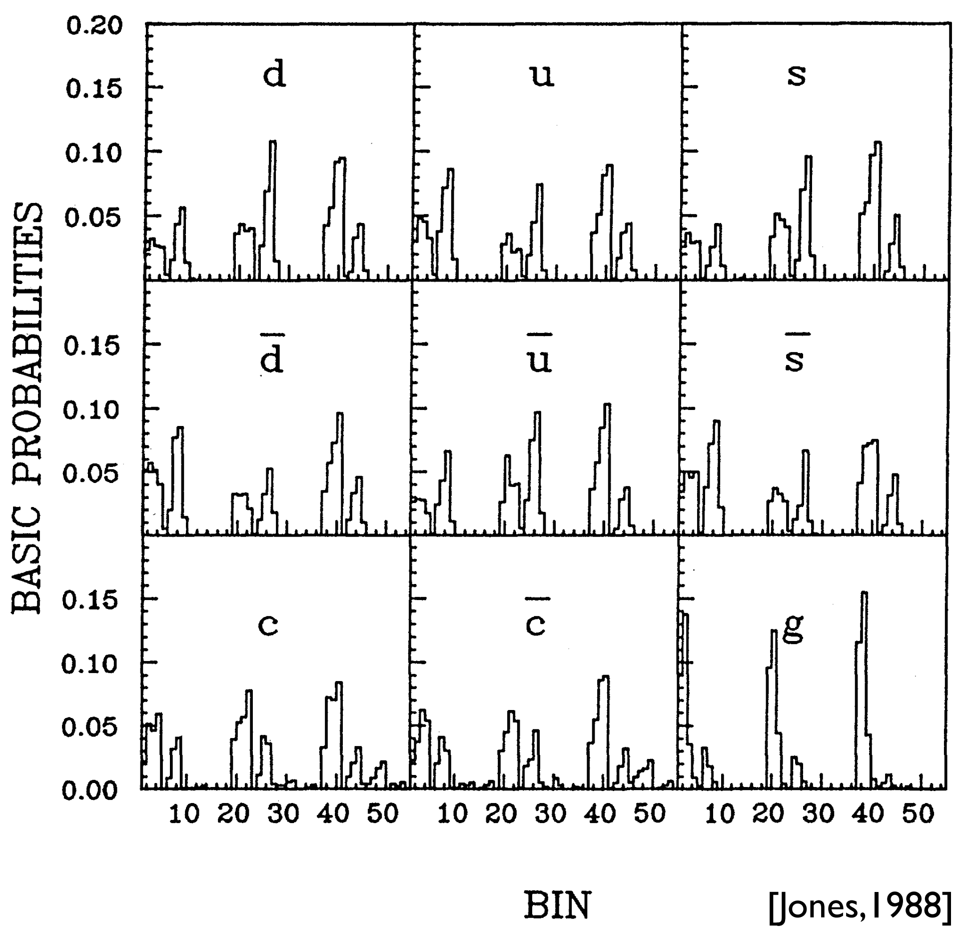


$$\text{gluon mistag} \simeq \left(\text{quark efficiency}\right)^{C_A/C_F}$$

barely improves $S/\sqrt{B}$

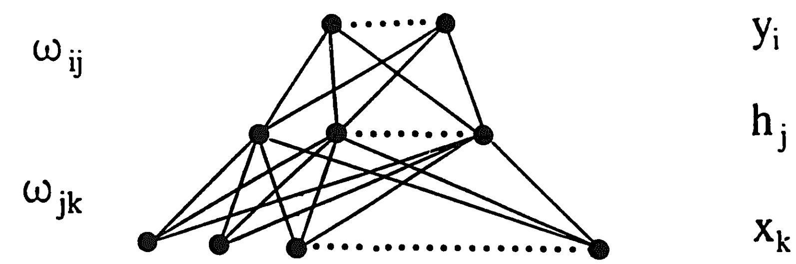
An Old Idea…

Binned hadron flavor/kinematics



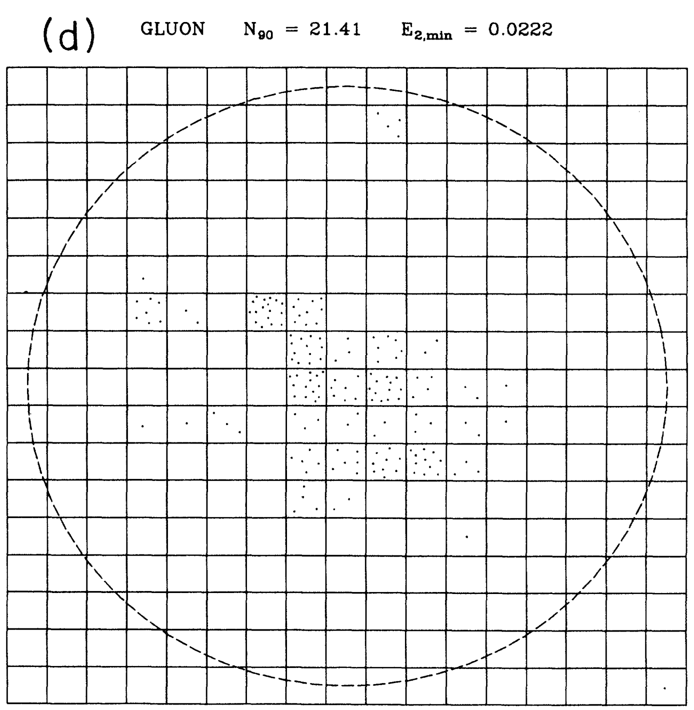
[Jones,1988]

Neural Network Classification



[Lönnblad, Peterson, Rögnvaldsson, 1991]

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

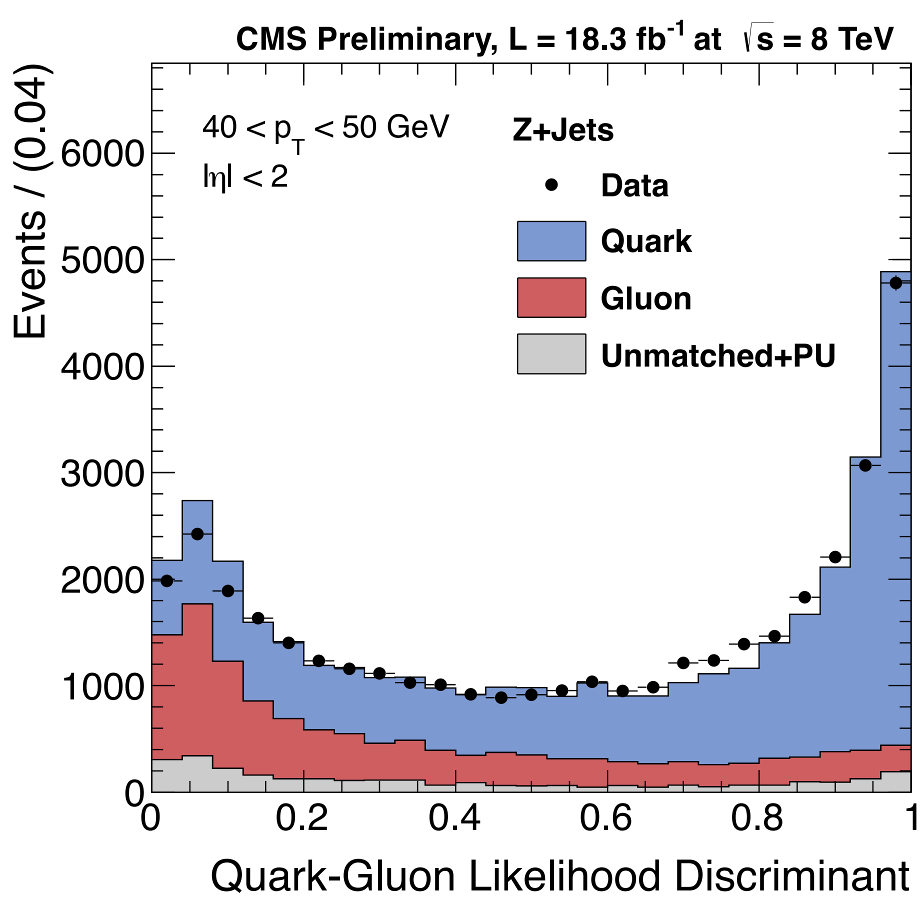


[Pumplin, 1991]

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

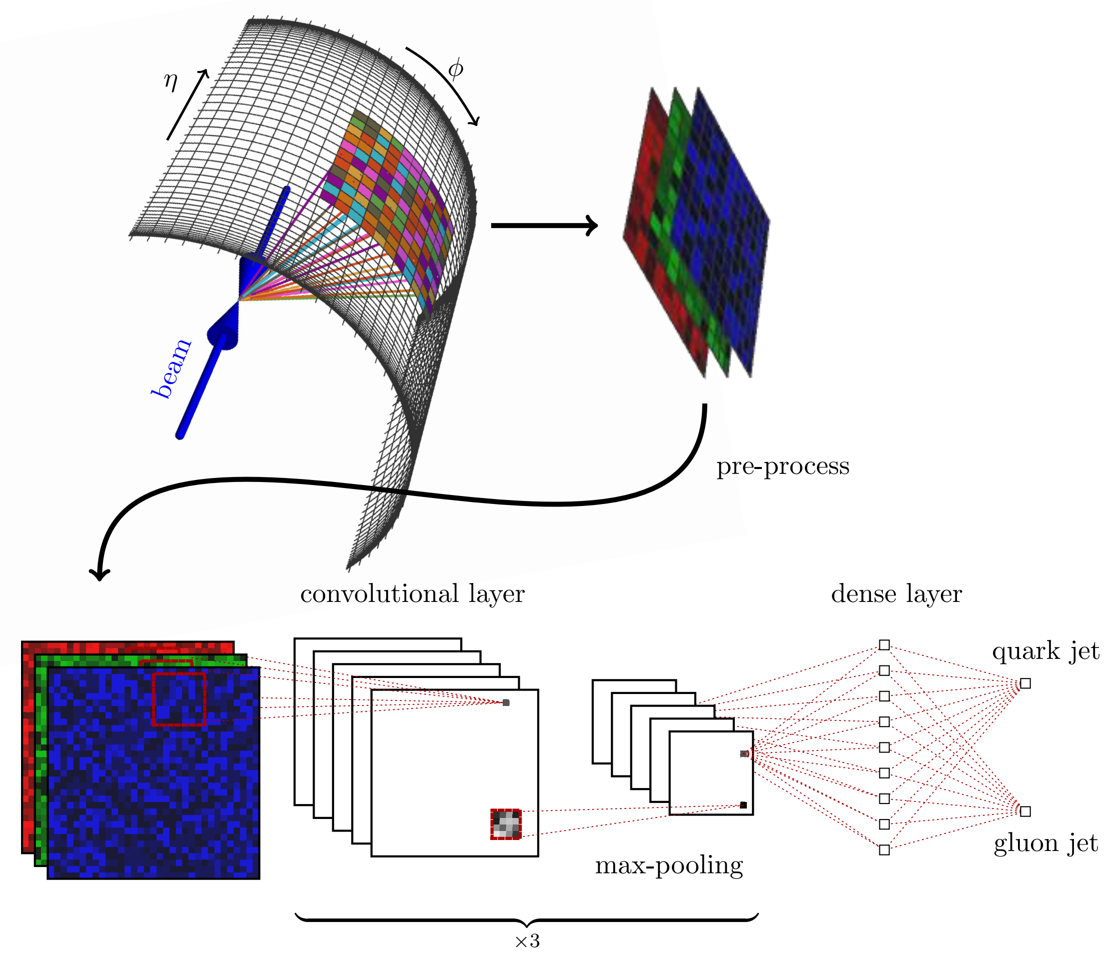
…with Renewed LHC Interest

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



[CMS, JME-13-002]

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

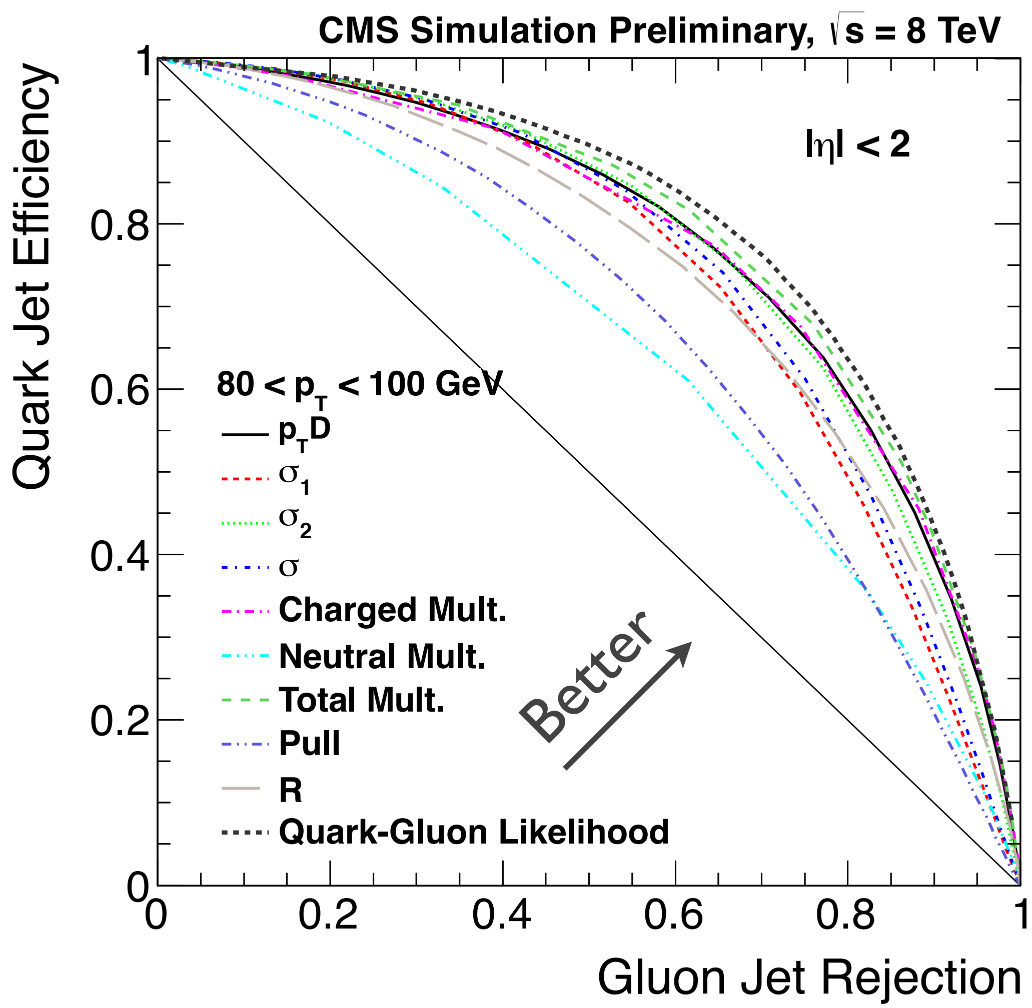


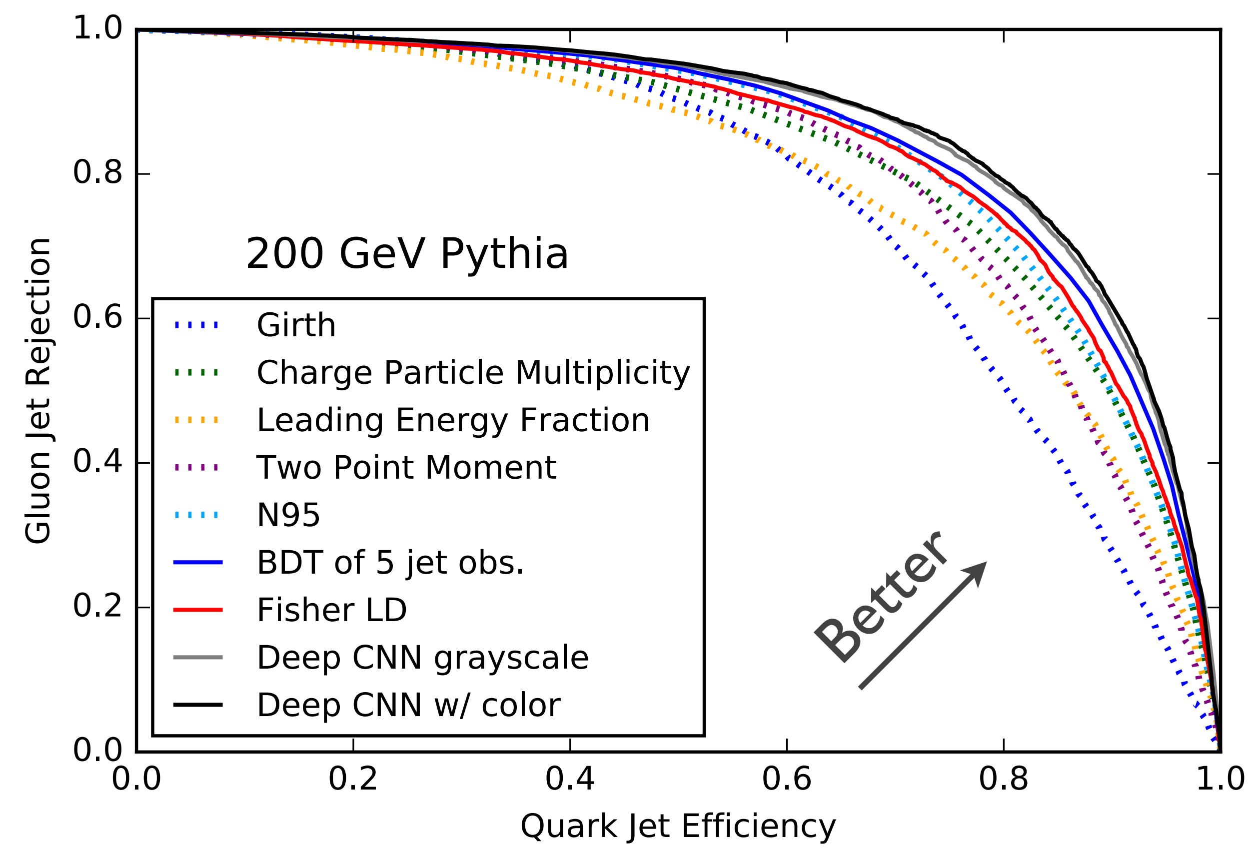
[Komiske, Metodiev, Schwartz, 1612.01551]

[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

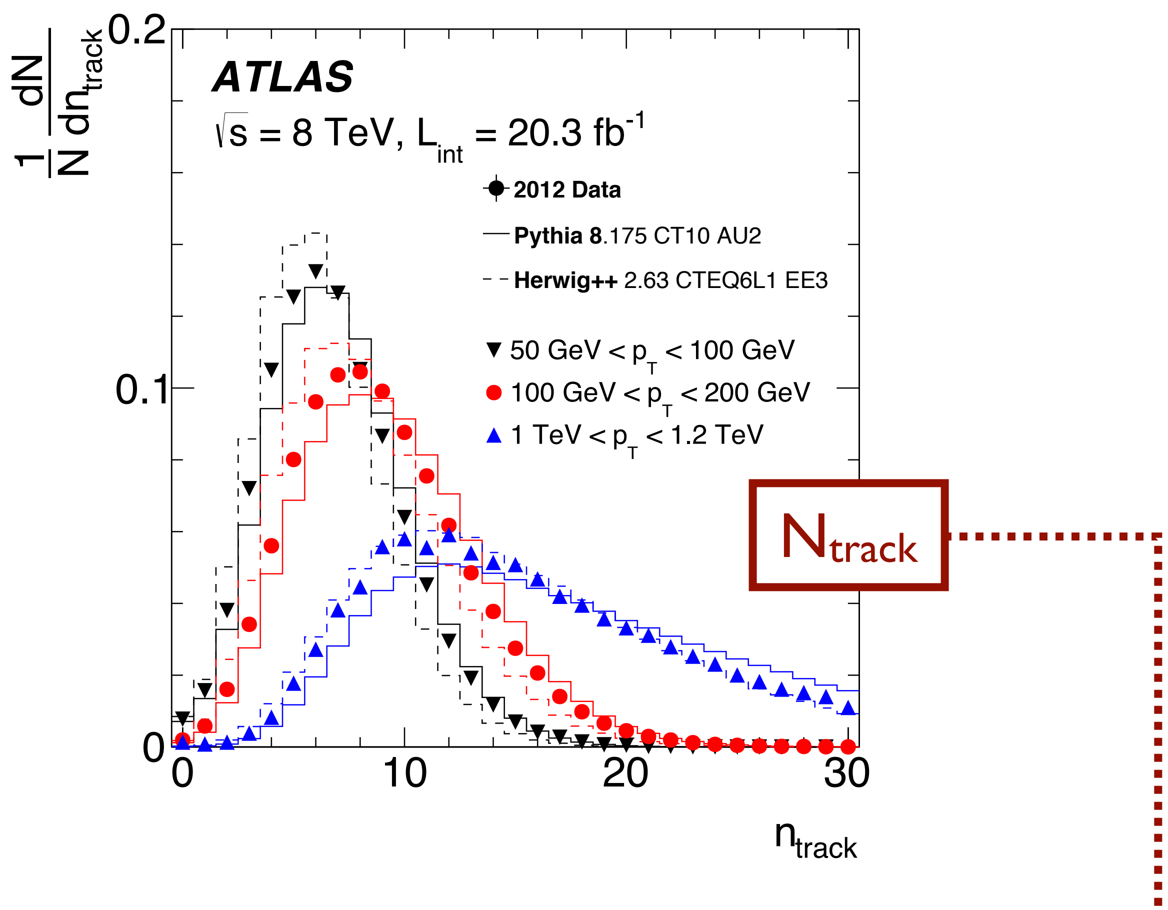




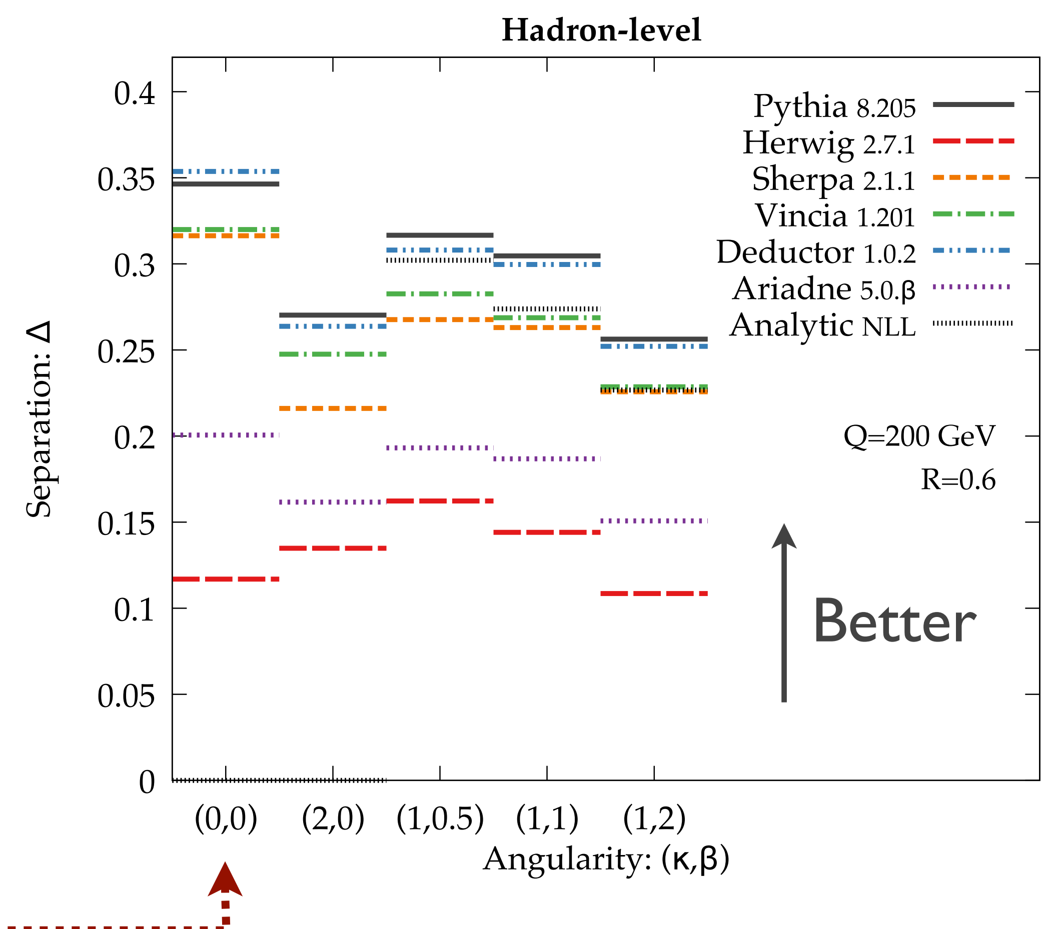
[see also Gallicchio, Schwartz, 1106.3076, 1211.7038; Krohn, Schwartz, Lin, Waalewijn, 1209.2421; Larkoski, Salam, JDT, 1305.0007; Larkoski, JDT, Waalewijn, 1408.3122; Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, Webber, 1501.04794]

Challenge: Theoretical Uncertainties

"Pythia/Herwig Sandwich"



Classifier Separation

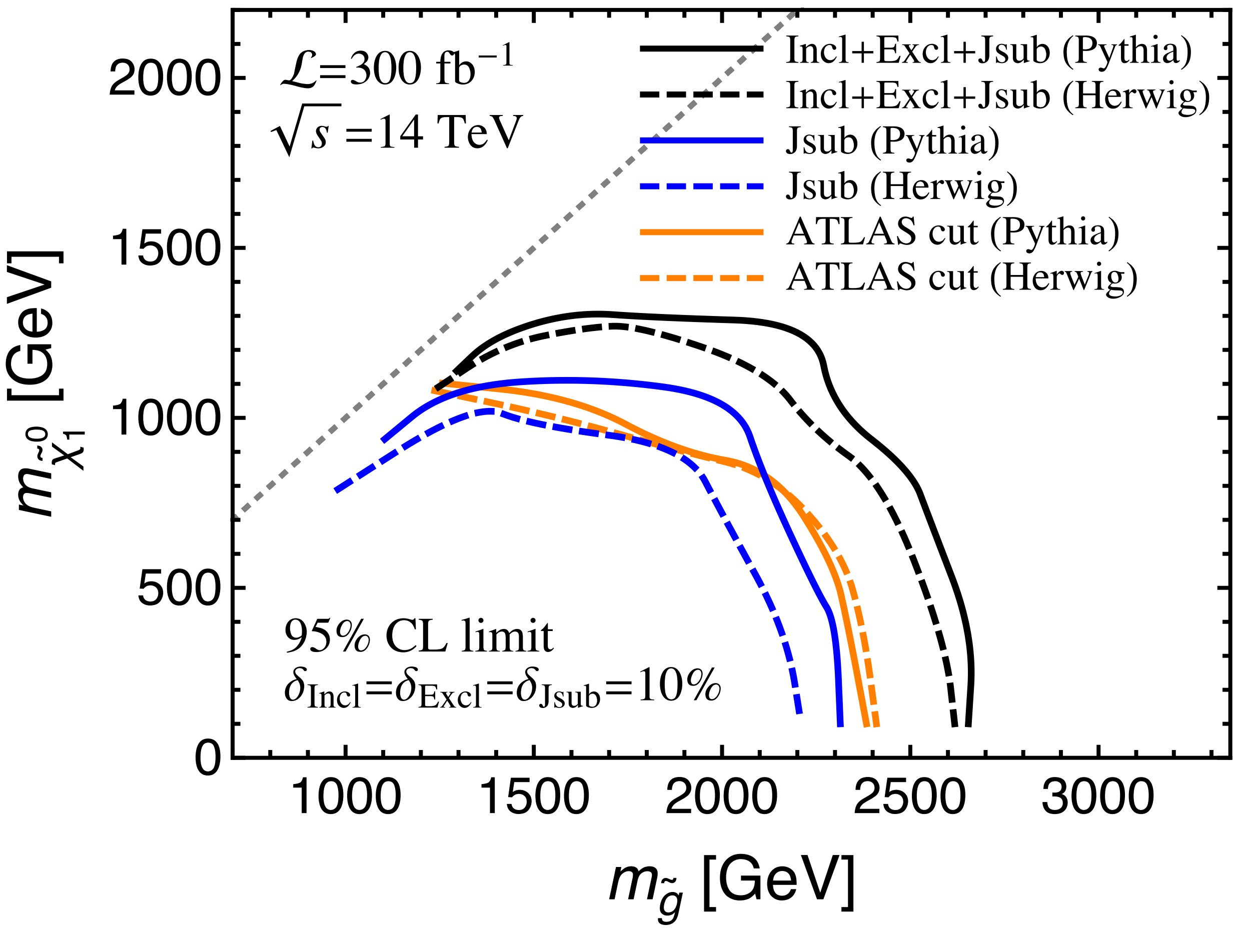


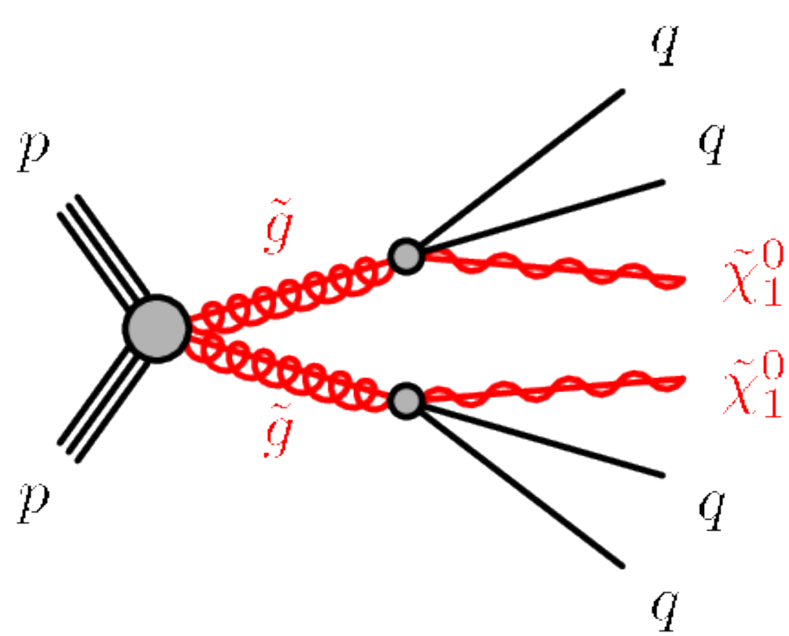
Small uncertainties in distributions yield
large uncertainties in discrimination power

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

Challenge: Theoretical Uncertainties

Opportunity: New Physics Applications

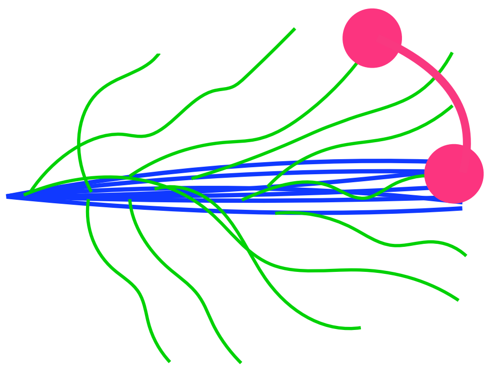




[Bhattacherjee, Mukhopadhyay, Nojiri, Sakakie, Webber, 1609.08781]

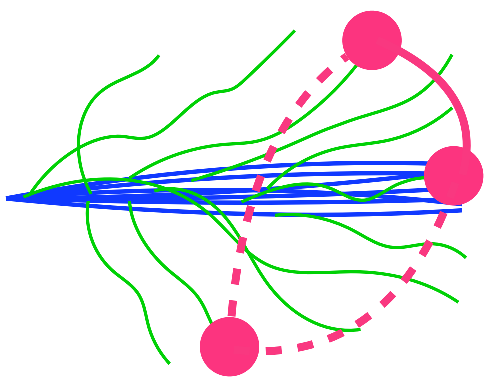
[ATLAS, 1602.00988]
[Soyez, JDT, Freytsis, Gras, Kar, Lönnblad, Plätzer, Siodmok, Skands, Soper, 1605.04692]

The Next Frontier: Information Beyond C_A/C_F

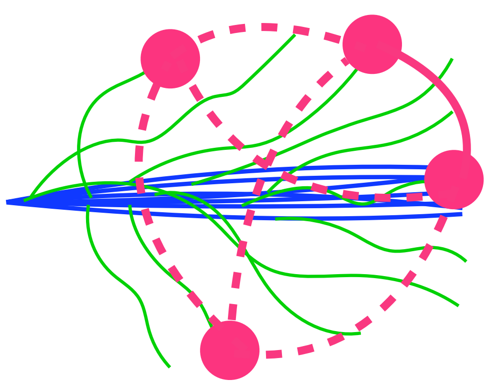


$$U_1 = \frac{\sum_{i<j} p_{Ti}\, p_{Tj}\, R_{ij}{}^{\beta}}{\left(\sum_i p_{Ti}\right)^2}$$

⟵ Typical Quark/Gluon Discriminants



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



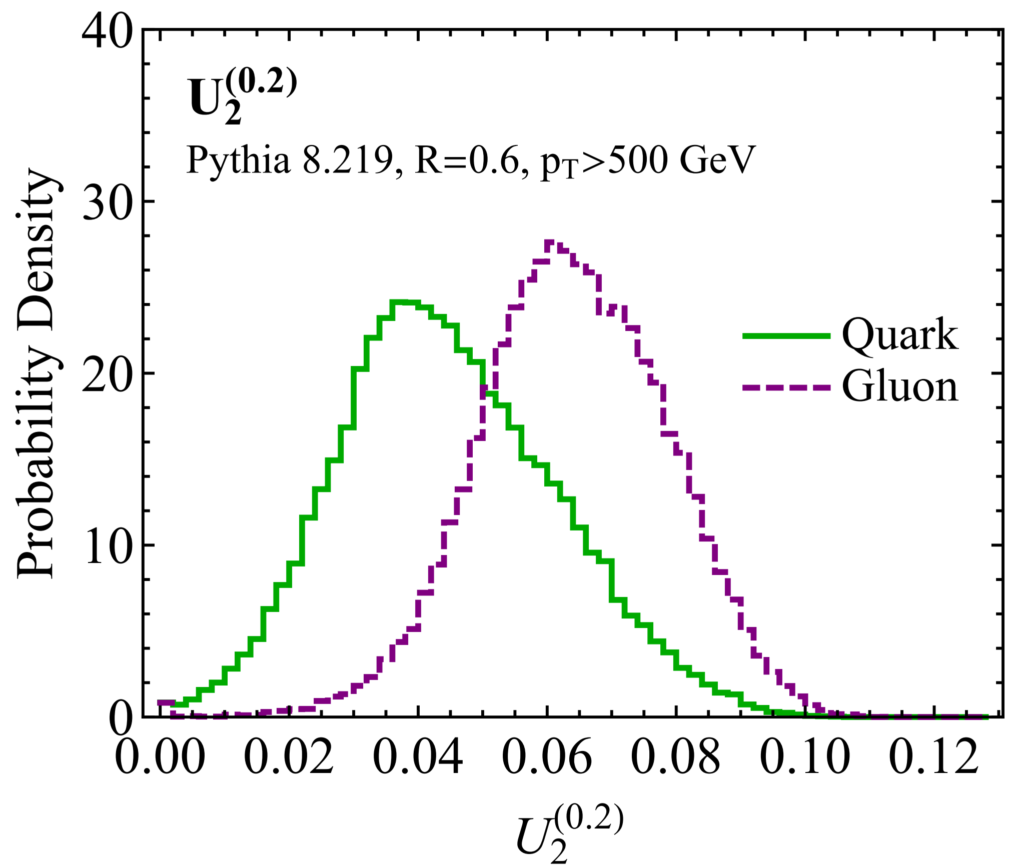
$$U_3 = \frac{\sum_{i<j<k<\ell} p_{Ti}\, p_{Tj}\, p_{Tk}\, p_{T\ell} \min\{R_{ij}, R_{jk}, R_{k\ell}, R_{ik}, R_{j\ell}, R_{i\ell}\}^{\beta}}{\left(\sum_i p_{Ti}\right)^4}$$

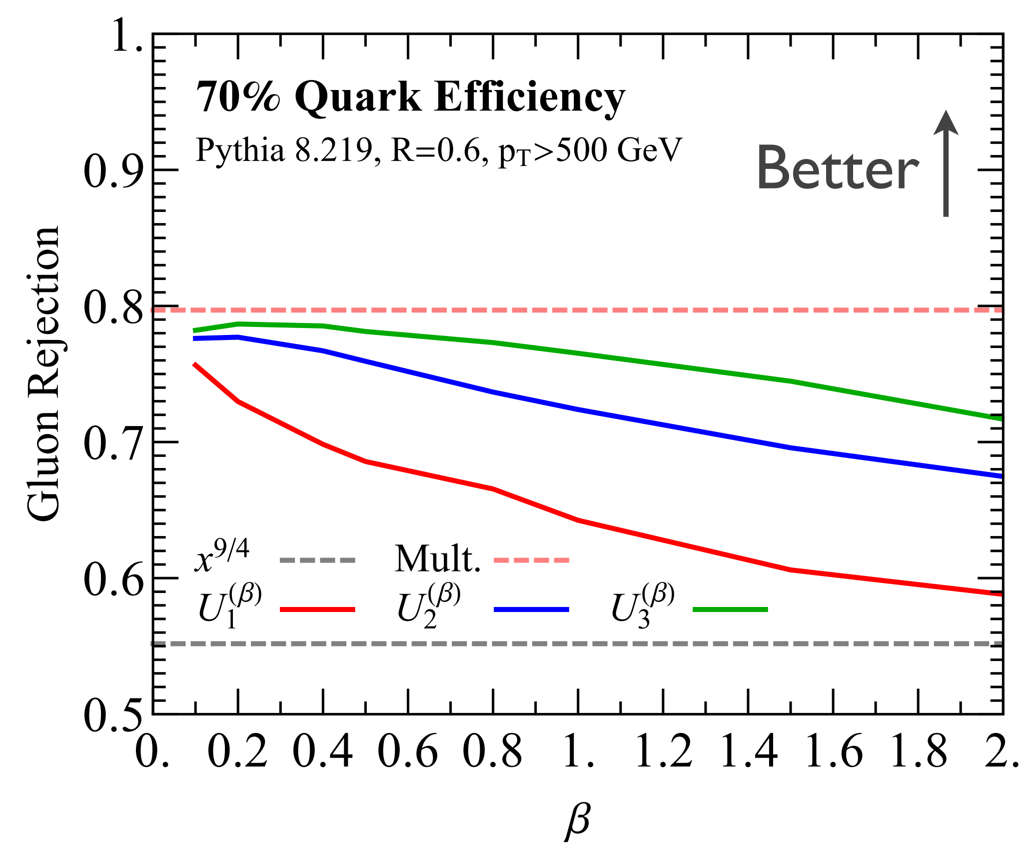
"Deep Learning" inspires "Deep Thinking"

[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

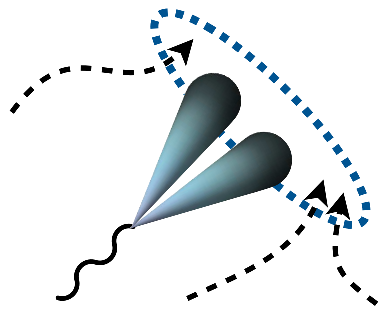




"Deep Learning" inspires "Deep Thinking"

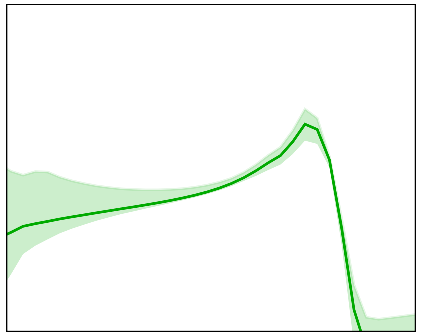
[Moult, Necib, JDT, 1609.07483]

Using Jets & QCD for BSM



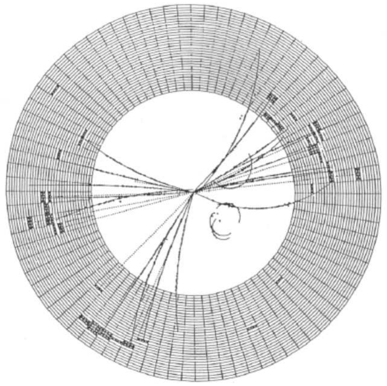
New Physics in the Boosted Regime

Wide range of searches capitalizing on jet substructure



Theoretical Advances in Jet Substructure

Precision calculations inspire improved, robust techniques



Back to the Future: Quarks vs. Gluons

Using detailed radiation patterns to enhance new physics searches