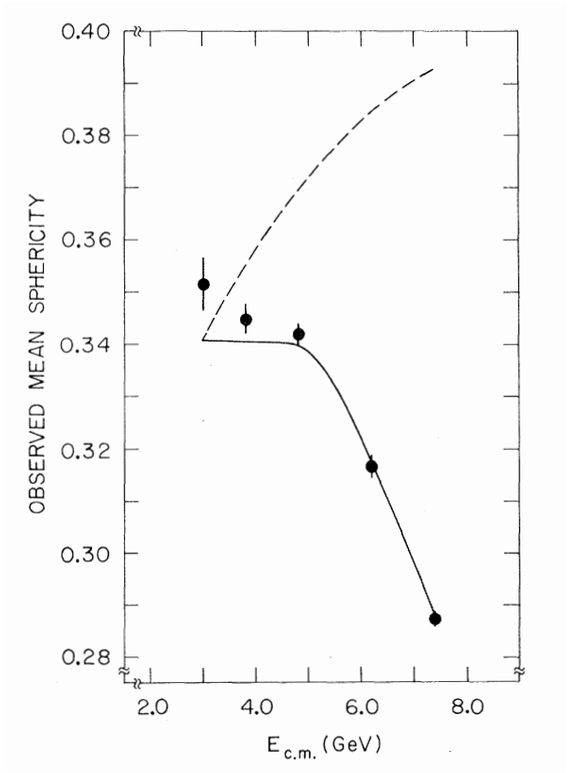
Jet Studies for Les Houches

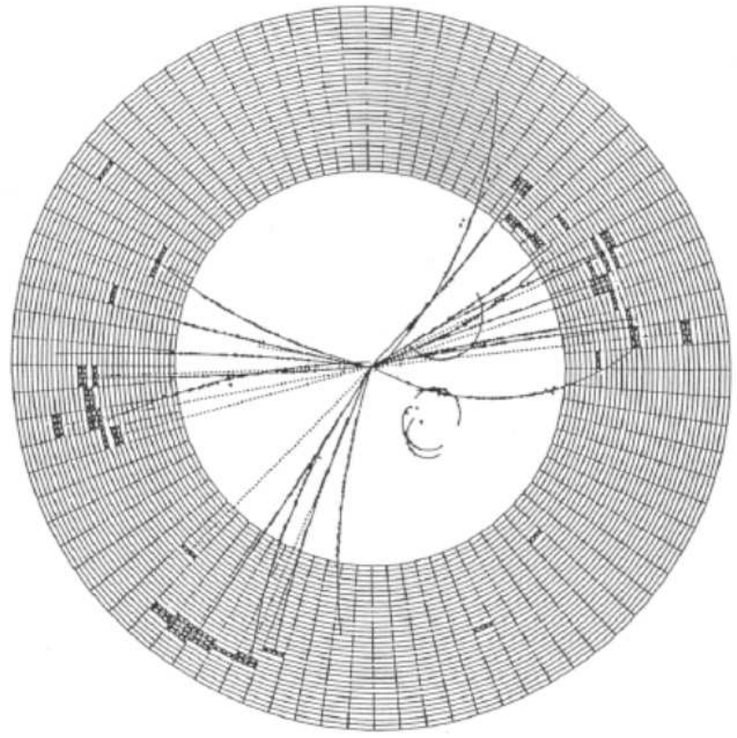
Jesse Thaler

Les Houches Workshop — June 6, 2017

Over Four Decades of Jets and QCD!



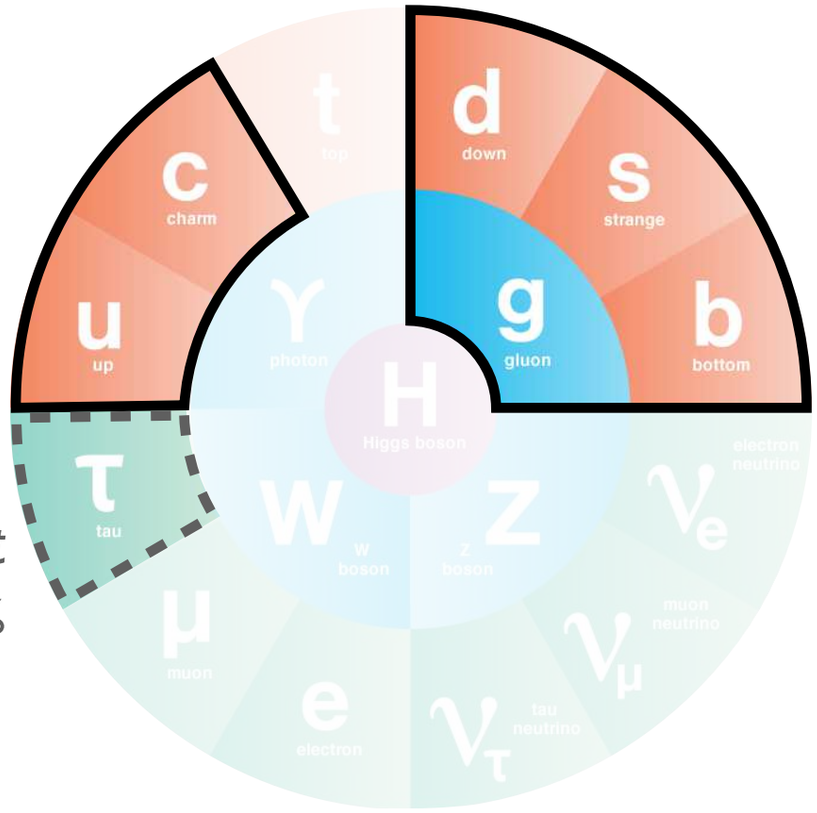
[Hanson, et al., 1975]



[JADE, 1979]

Question to Les Houches royalty:

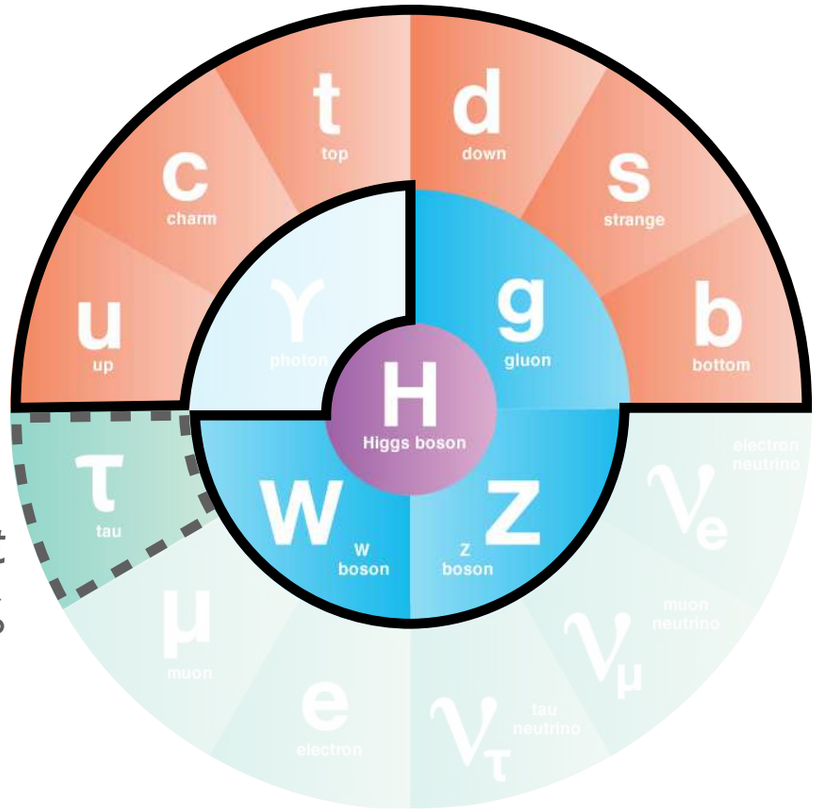
First dedicated jet session at LH 2007 (Salam/Wobisch)?
First official "jet convener" at LH 2011 (Soyez)?



micro-jet
≈ 65%

Jets from the Standard Model

++ = plus gluonic radiation



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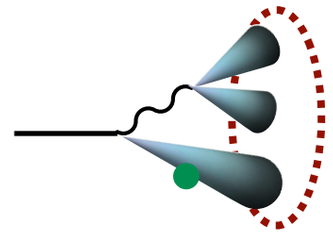
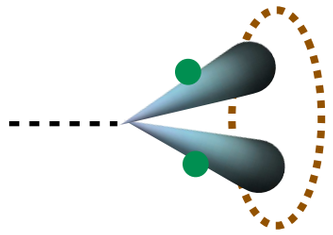


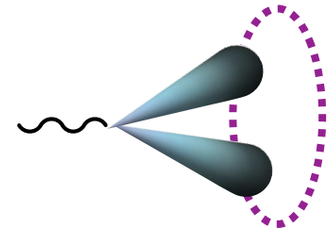
t
≈ 70%

173 GeV++



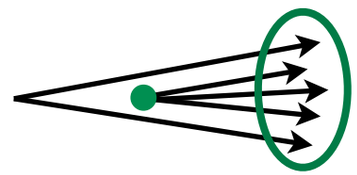
H
≈ 60%

125 GeV



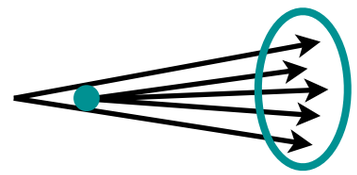
W/Z
≈ 70%

80/91 GeV



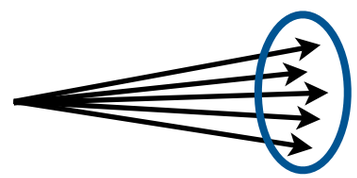
b

4.2 GeV++



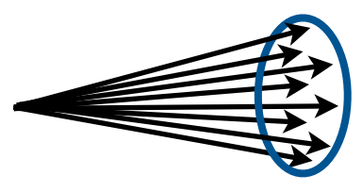
c

1.3 GeV++



u,d,s

100 MeV++

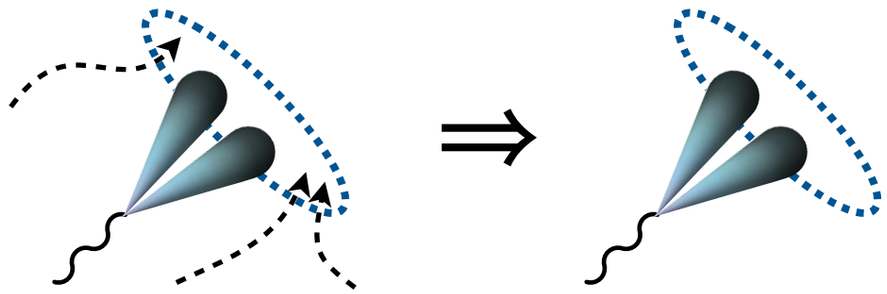


g

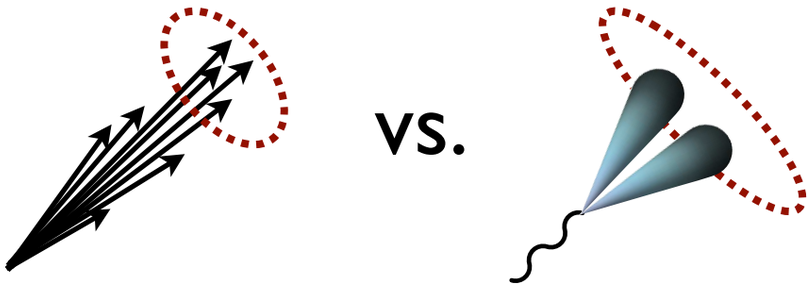
0++

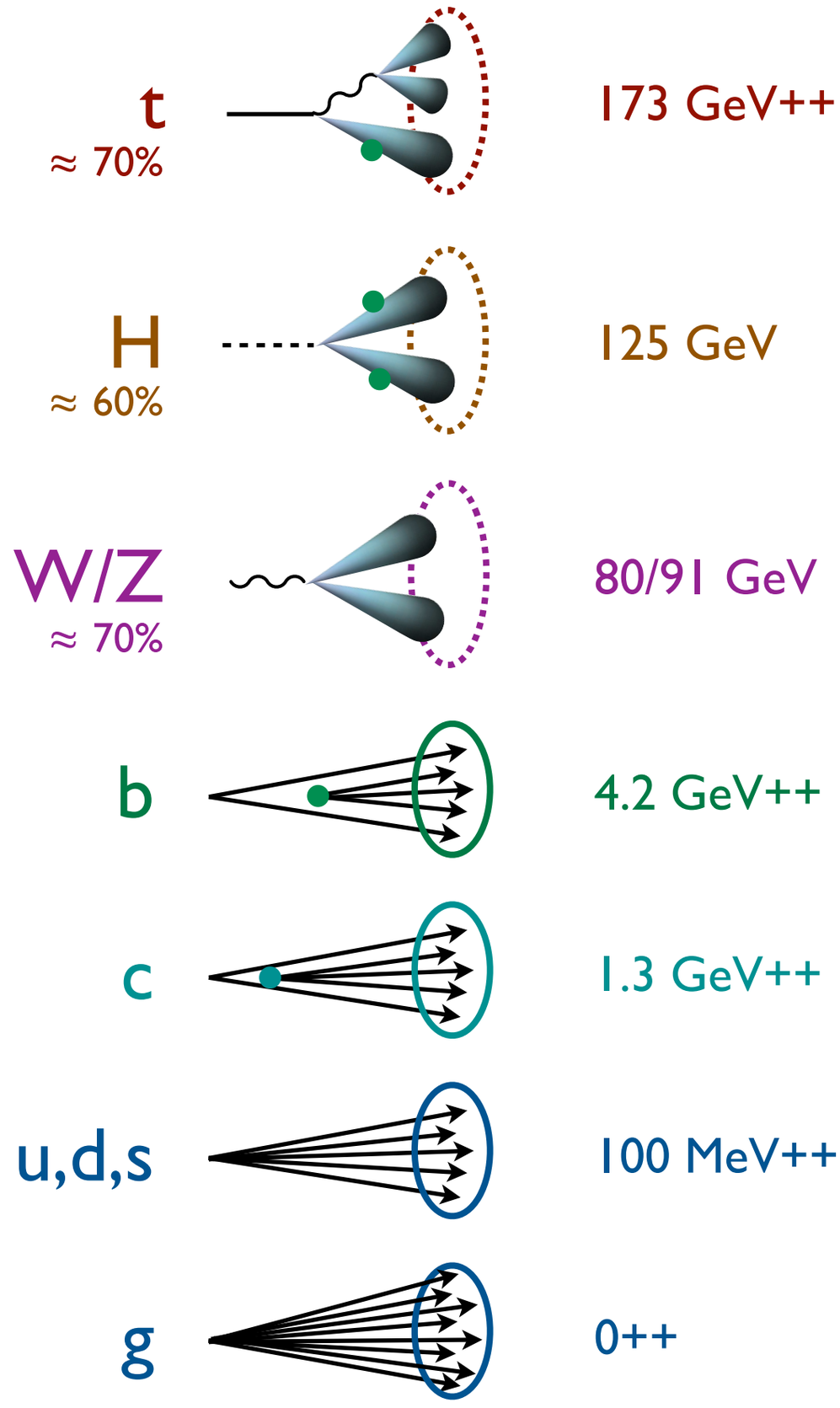
Substructure Toolbox:

Jet Grooming

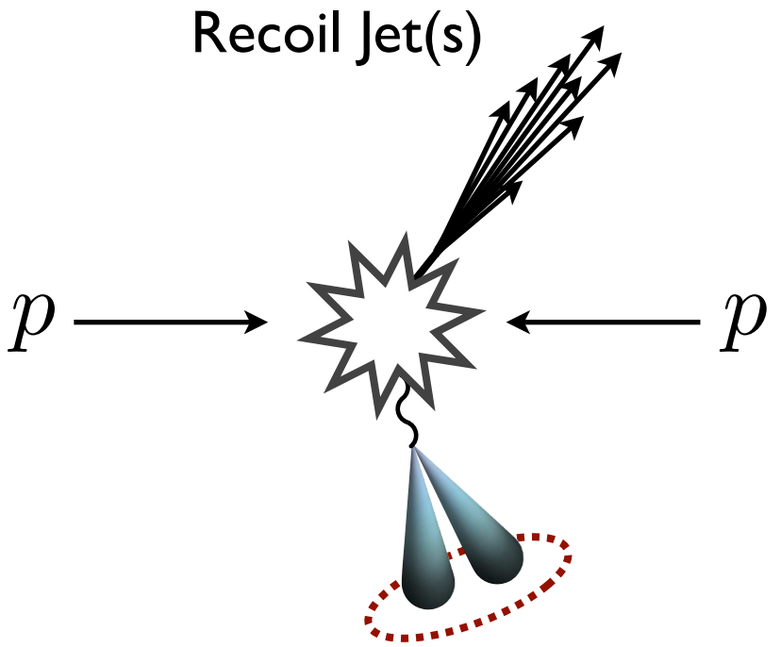


Jet Discrimination



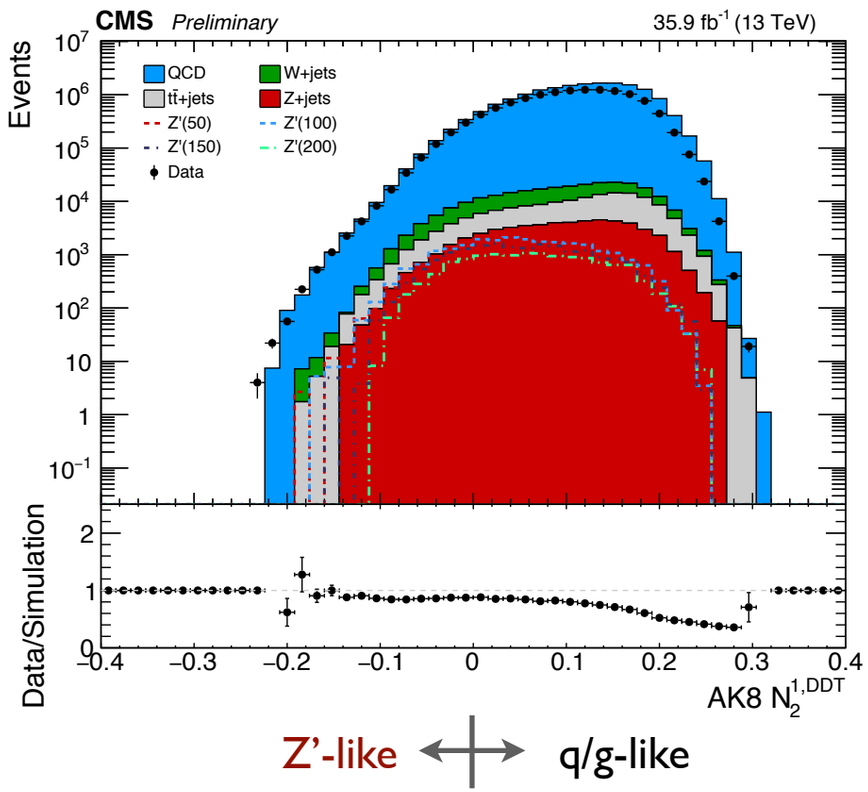


E.g. CMS Boosted Z' Search

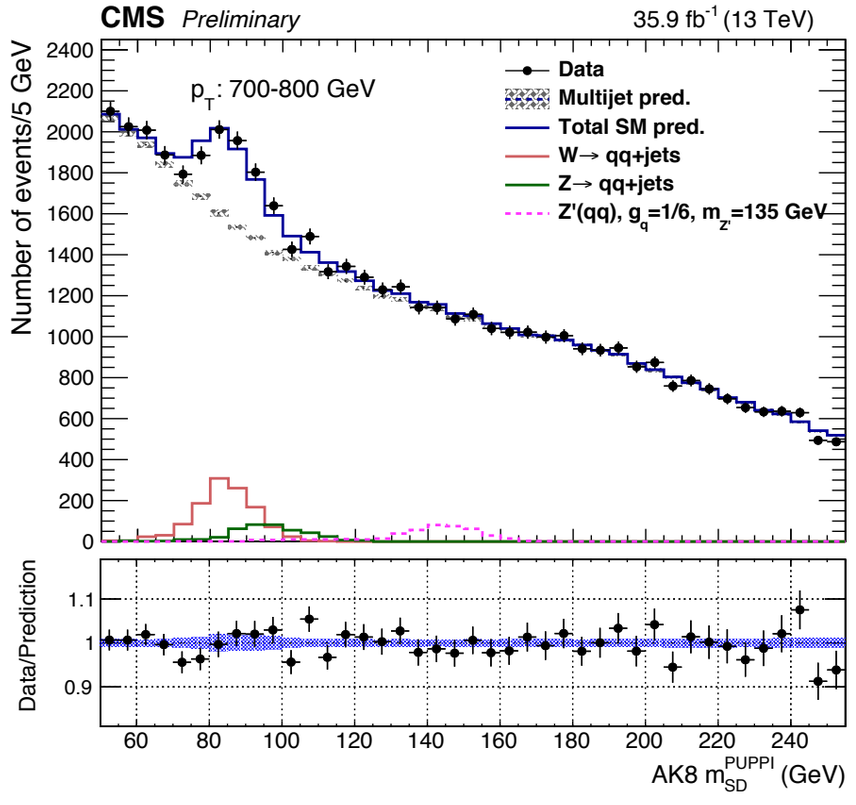


Z or Z' ?

with N_2 + Decorrelation
+ Soft Drop + PUPPI

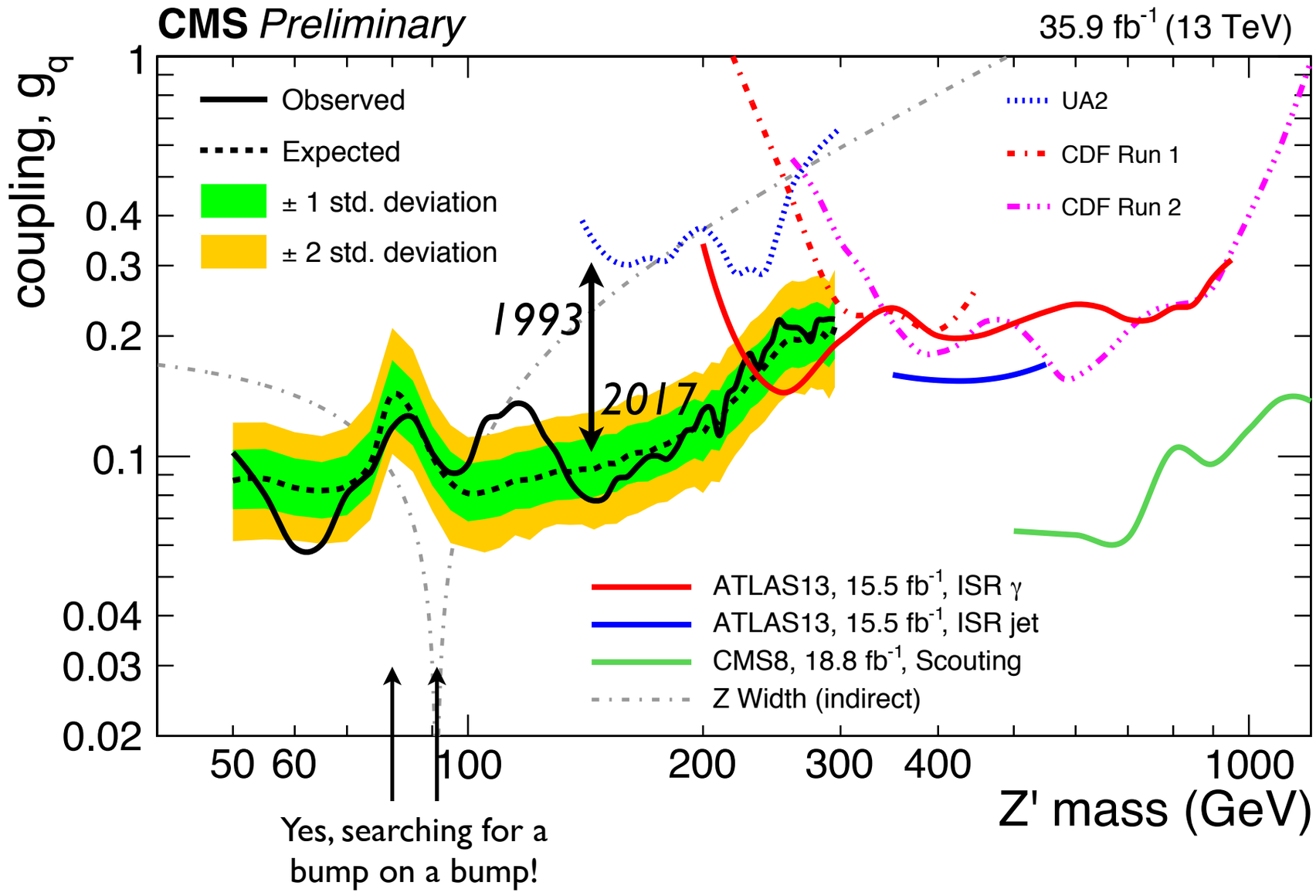


Z'-like ⟷ q/g-like



[CMS PAS EXO-17-001;
using Moult, Necib, JDT, 1609.07483; Dolen, Harris, Marzani, Rappoccio, Tran, 1603.00027; Larkoski, Marzani, Soyez, JDT, 1402.2657; Bertolini, Harris, Low, Tran, 1407.6013]

Back to the Future



Jet Physics = Innovative Approaches to Hadronic Final States

[CMS PAS EXO-17-001]

Back to Les Houches 2015

Report of the Les Houches Quark/Gluon Subgroup

Jesse Thaler

= Jets are Les H.

on behalf of Andy Buckley, Jon Butterworth, Mario Campanelli, Marat Freytsis, Peter Loch, Philippe Gras, Deepak Kar, Simon Plätzer, Andrzej Siodmok, Peter Skands, Dave Soper, Gregory Soyez, Frank Tackmann

Les Houches Workshop — June 10, 2015

Hunting the White Whale: Quarks vs. Gluons

Cartoon:

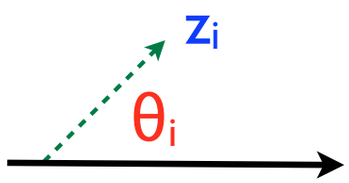
Quark: $C_F = 4/3$ vs. Gluon: $C_A = 3$

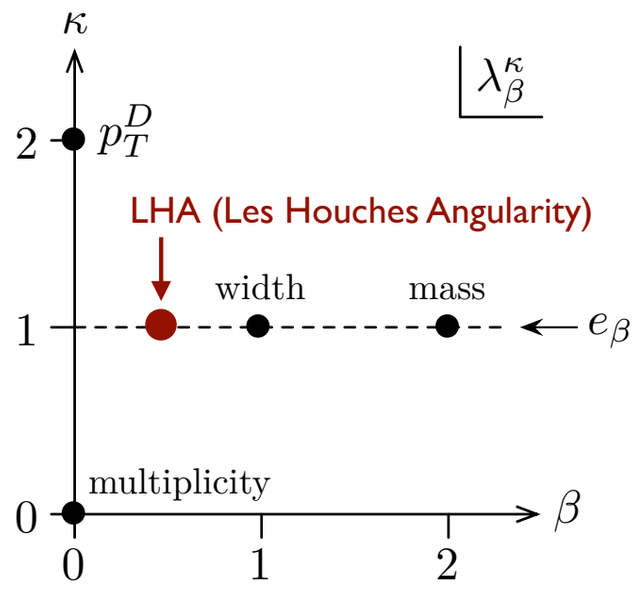
Probe radiation pattern with e.g. Generalized Angularities

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta$$

momentum fraction

angle to recoil-free axis





[Larkoski, JDT, Waalewijn, 1408.3122]
[based on Berger, Kucs, Sterman, hep-ph/0303051; Ellis, Vermilion, Walsh, Hornig, Lee, 1001.0014]
[see also Larkoski, Salam, JDT, 1305.0007; Larkoski, Neill, JDT, 1401.2158]
[For a more complete catalog, see Gallicchio, Schwartz, 1106.3076, 1211.7038]

white whale

Something you obsess over to the **point** that it nearly or completely destroys you. An obsession that becomes your ultimate goal in life; **one** that your life **now** completely encircles and defines you.

High Energy Physics - Phenomenology

Systematics of quark/gluon tagging

Philippe Gras, Stefan Hoeche, Deepak Kar, Andrew Larkoski, Leif Lönnblad, Simon Plätzer, Andrzej Siódmok, Peter Skands, Gregory Soyez, Jesse Thaler

(Submitted on 12 Apr 2017)

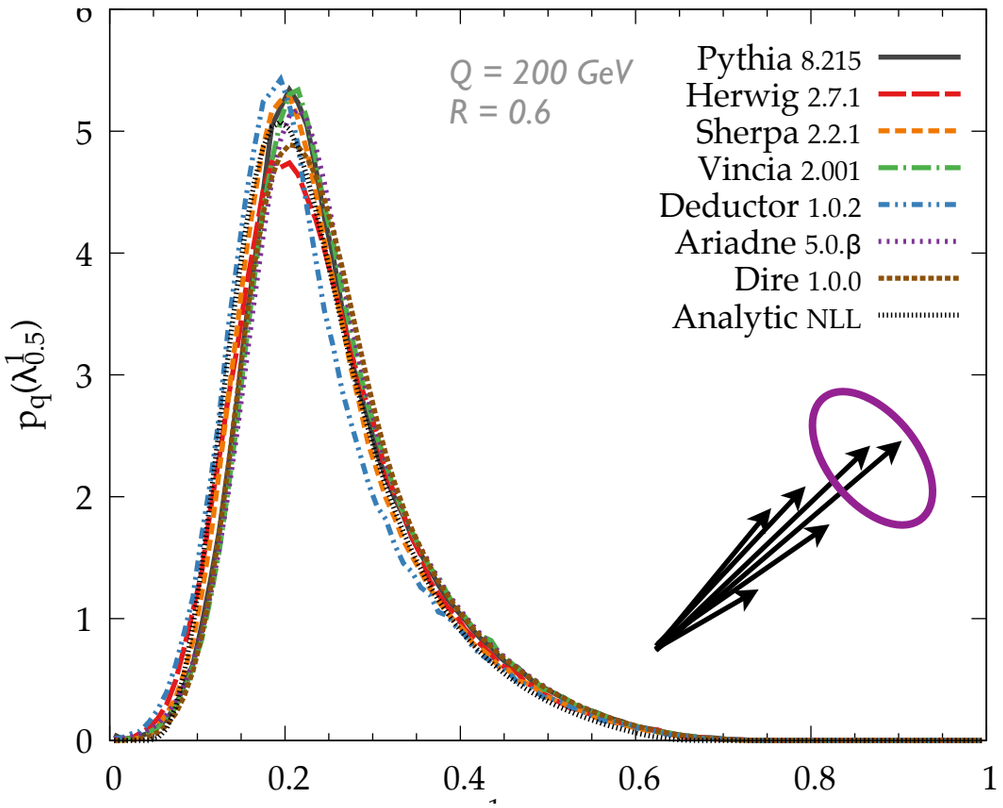
By measuring the substructure of a jet, one can assign it a "quark" or "gluon" tag. In the eikonal (double-logarithmic) limit, quark/gluon discrimination is determined solely by the color factor of the initiating parton (C_F versus C_A). In this paper, we confront the challenges faced when going beyond this leading-order understanding, using both parton-shower generators and first-principles calculations to assess the impact of higher-order perturbative and nonperturbative physics. Working in the idealized context of electron-positron collisions, where one can define a proxy for quark and gluon jets based on the Lorentz structure of the production vertex, we find a fascinating interplay between perturbative shower effects and nonperturbative hadronization effects. Turning to proton-proton collisions, we highlight a core set of measurements that would constrain current uncertainties in quark/gluon tagging and improve the overall modeling of jets at the Large Hadron Collider.

Comments: 50 pages, 20 figures, extended version of the Les Houches 2015 study from 1605.04692
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)
Report number: MIT--CTP 4885, CoEPP-MN-17-2, MCNET-17-04
Cite as: **arXiv:1704.03878 [hep-ph]**
(or **arXiv:1704.03878v1 [hep-ph]** for this version)

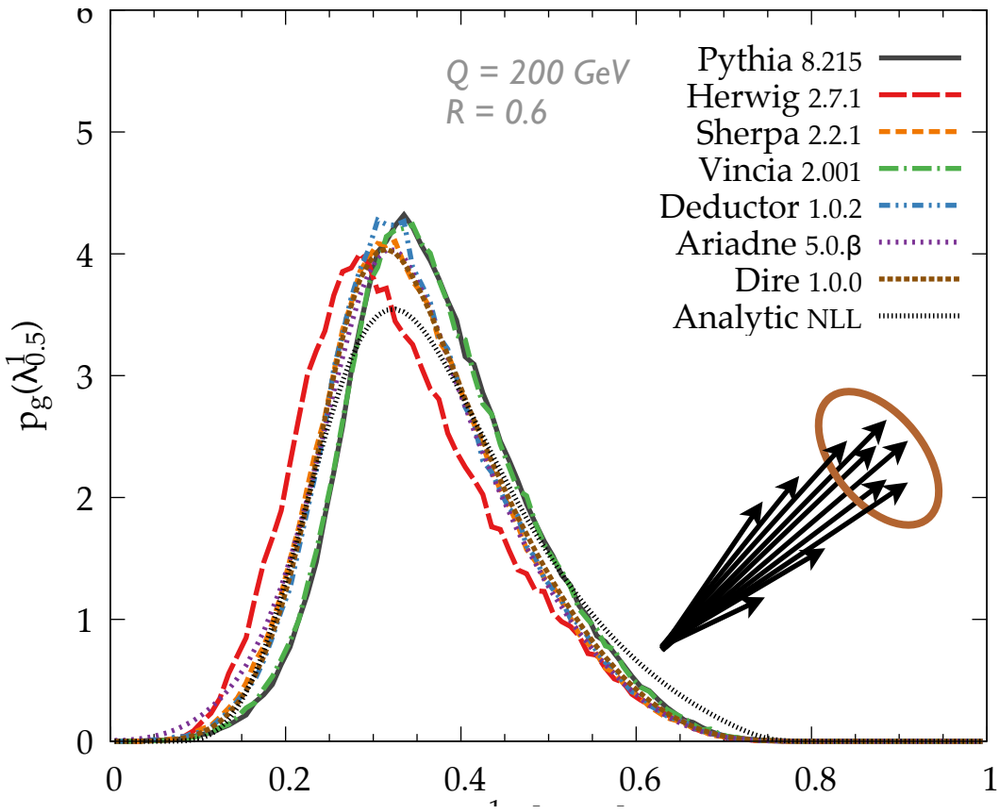
Coming soon to JHEP!

Idealized Quark/Gluon Distributions

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



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



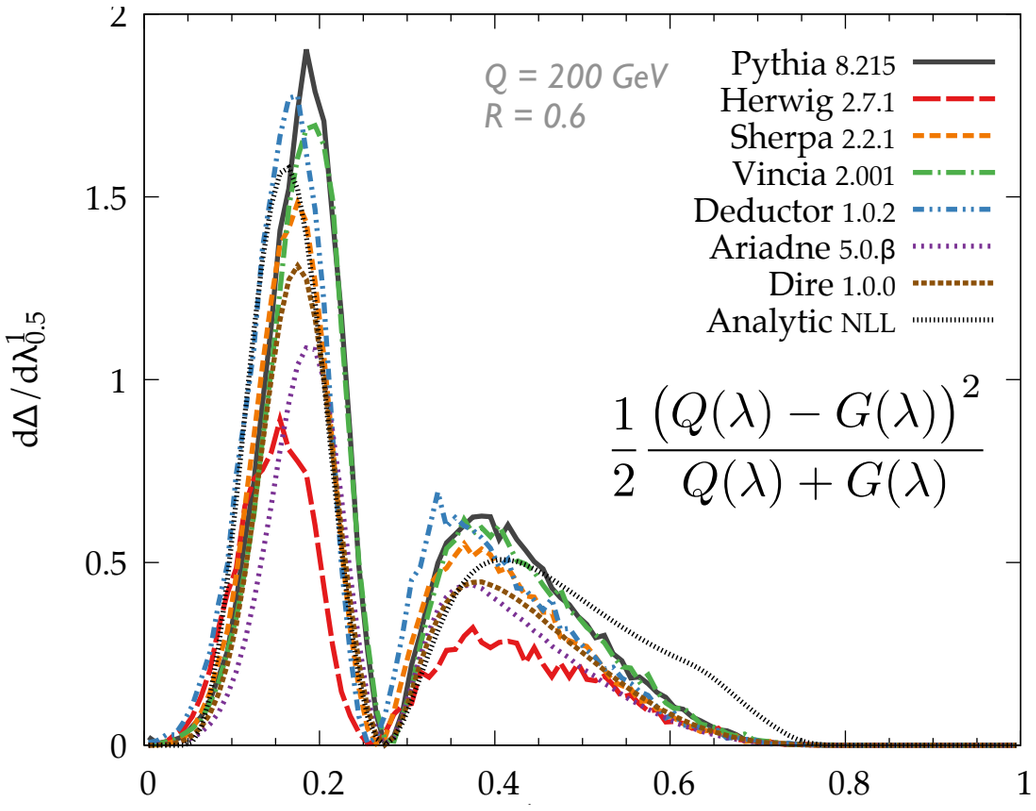
$$\text{LHA} = \sum_i z_i \sqrt{\theta_i}$$

Large variations for gluon jets (not tuned to LEP)

[Gras, Hoeche, Kar, Larkoski, Lönnblad, Plätzer, Siódmok, Skands, Soyez, JDT, 1704.03878; based on Soyez, JDT, Freytsis, Gras, Kar, Lönnblad, Plätzer, Siodmok, Skands, Soper, 1605.04692]

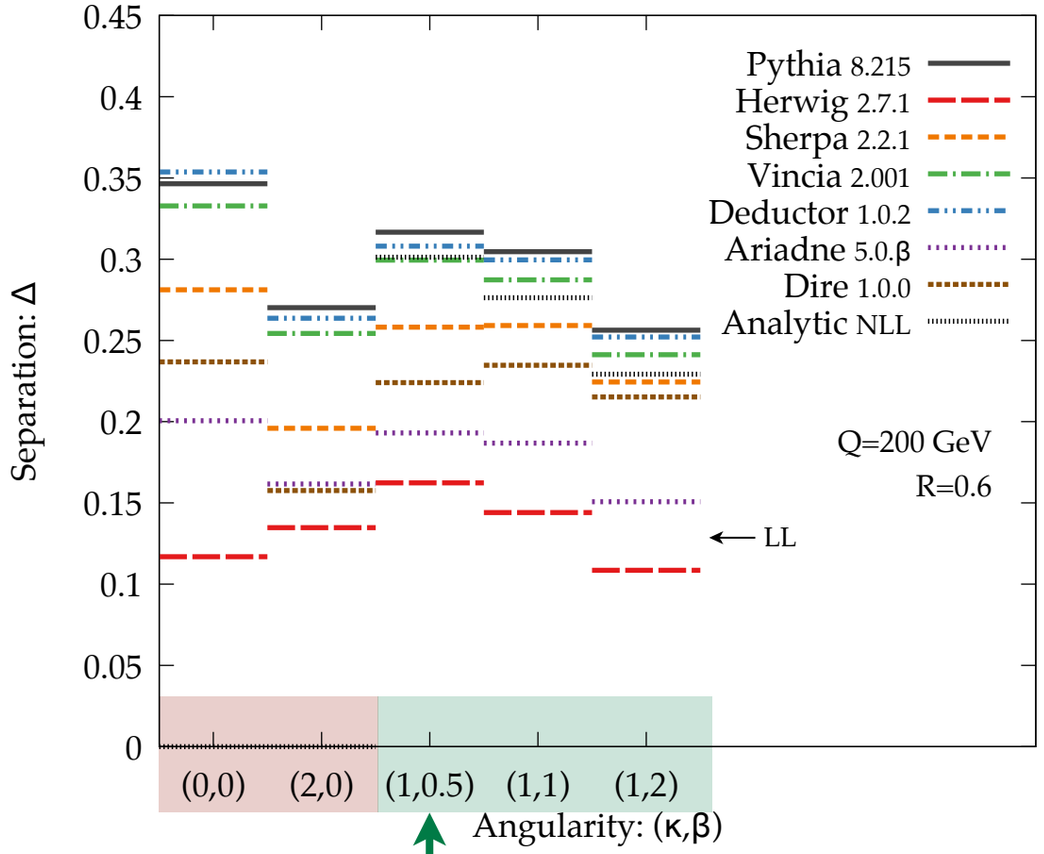
Impact on Quark/Gluon Separation

Differential



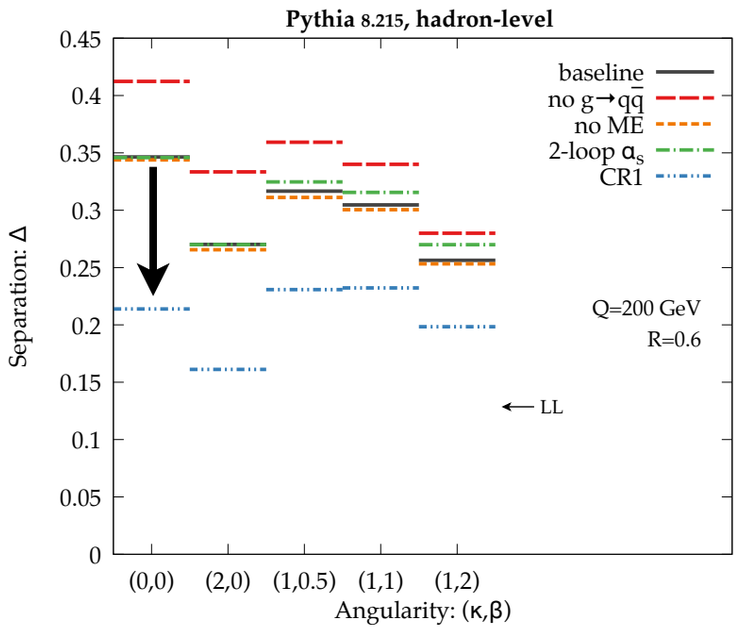
$$\text{LHA} = \sum_i z_i \sqrt{\theta_i}$$

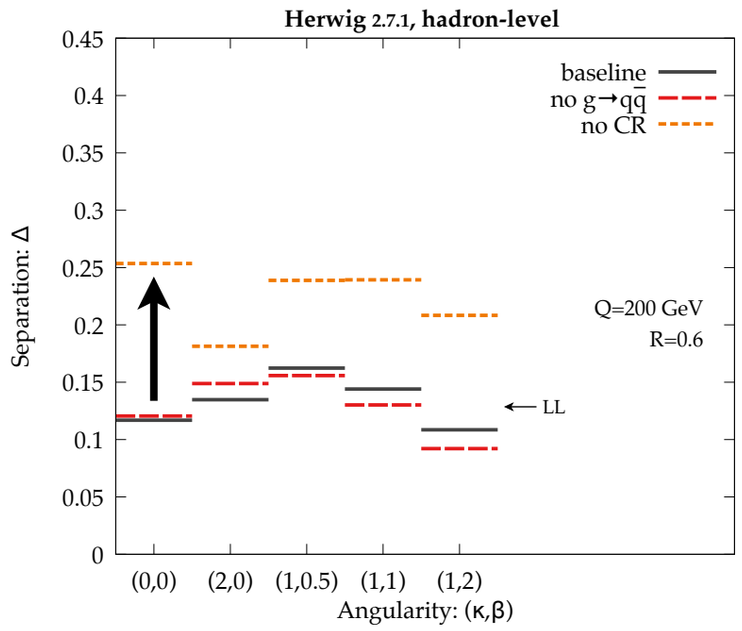
Integrated Values

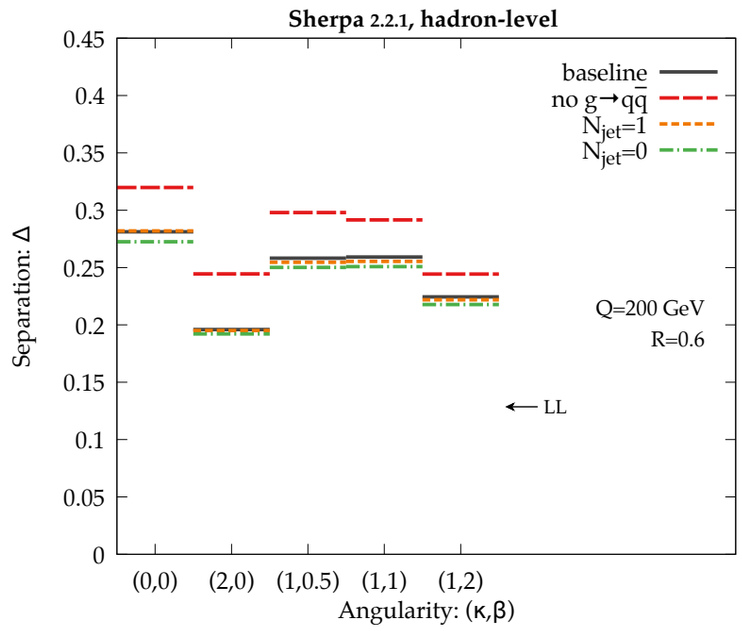


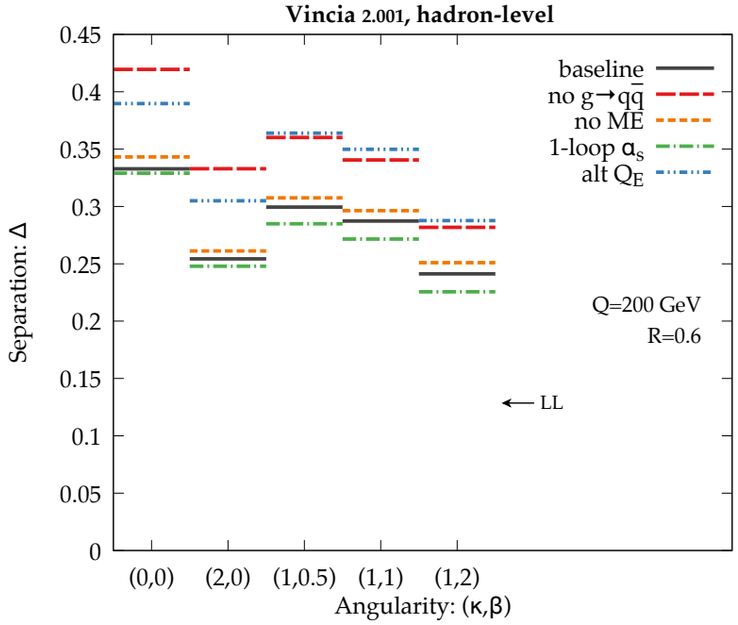
Affects both IRC unsafe and IRC safe observables

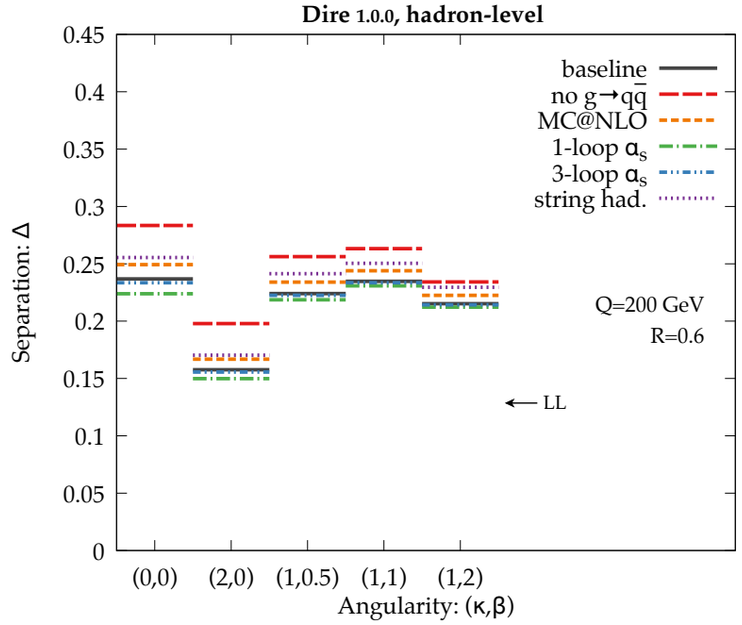
Testing Shower Variants

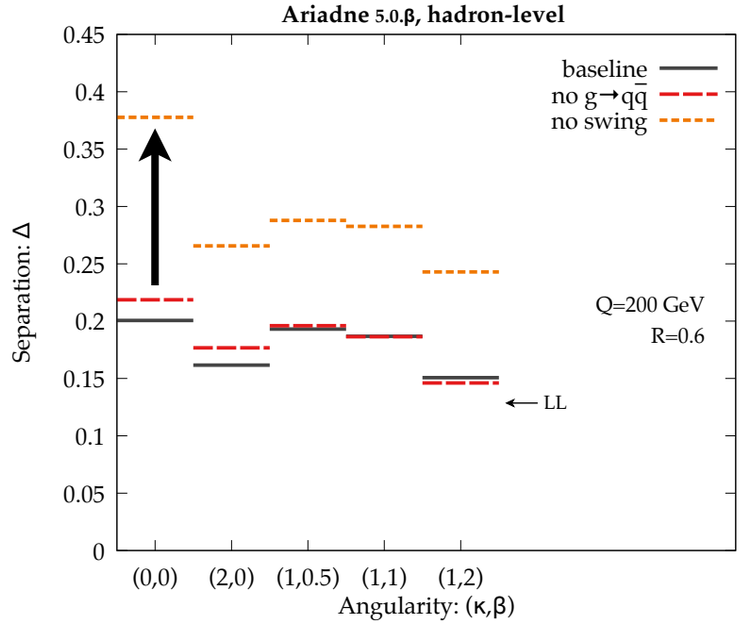






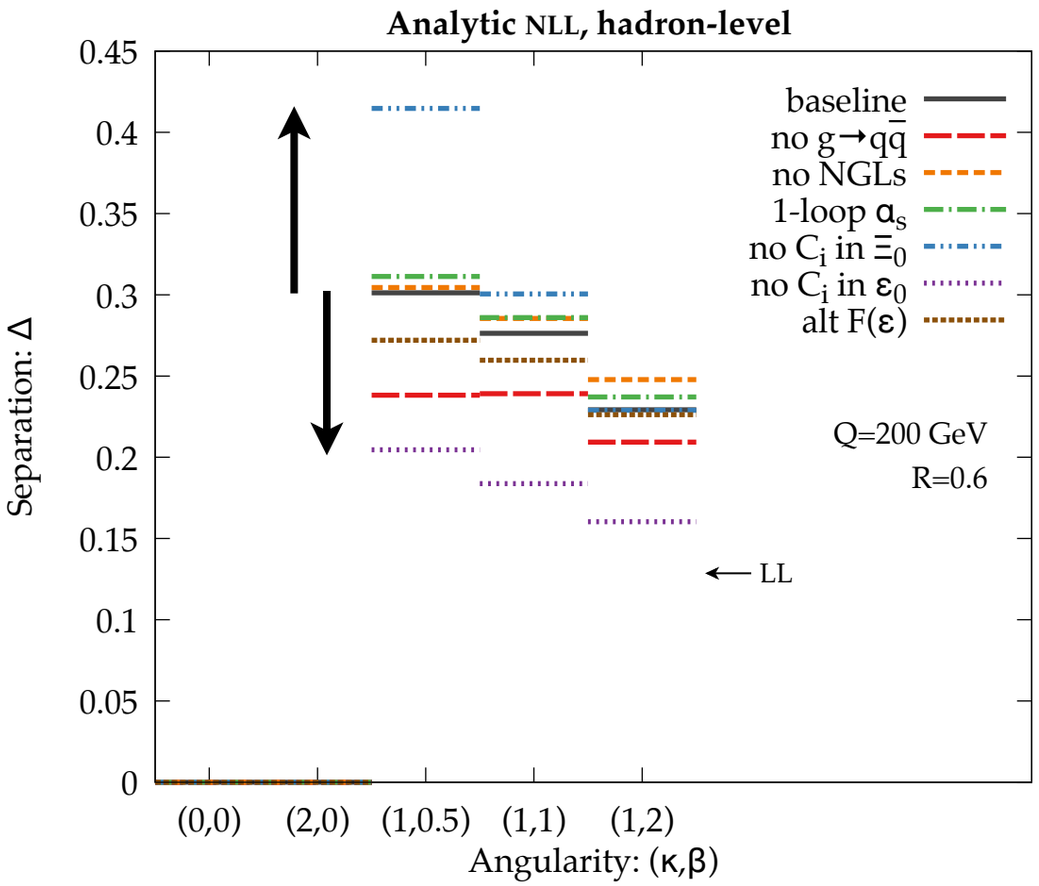






Large impact from color reconnection

NLL Resummation plus NP Correction



NLL with Non-Global Logs

$$\Sigma(e_\beta) = \frac{e^{-\gamma_E R'(e_\beta)}}{\Gamma\left(1+R'(e_\beta)\right)}\, e^{-R(e_\beta)}\, e^{-f_{\mathrm{NGL}}(e_\beta)}$$

Shift from NP Shape Function

$$F(\epsilon) = \frac{\pi\epsilon}{2\epsilon_0^2}\exp\left[-\frac{\pi}{4}\frac{\epsilon^2}{\epsilon_0^2}\right]$$

$$\epsilon_0 = \frac{1}{\beta-1}\frac{\Omega_0}{R\,E_J}\left(1-\left(\frac{\Xi_0}{R\,E_J}\right)^{\beta-1}\right)$$

$$\frac{\Omega_0^g}{\Omega_0^q} = \frac{\Xi_0^g}{\Xi_0^q} = \frac{C_A}{C_F}$$

Default: Full Casimir Scaling
↑: No Casimir Scaling for Ξ_0
↓: No Casimir Scaling for Ω_0 or Ξ_0

Convolution (Simplified)

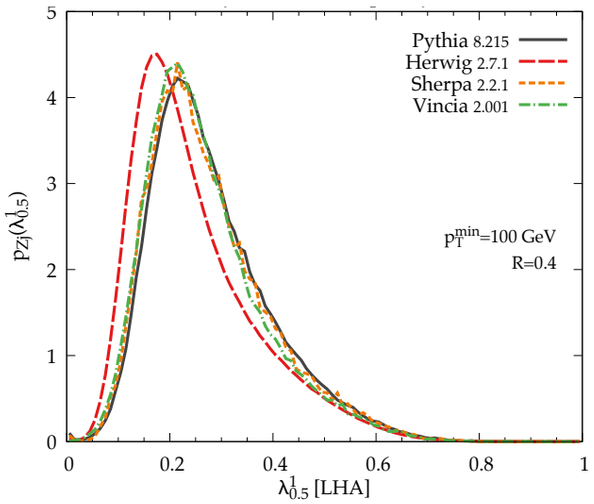
$$\frac{\mathrm{d}\sigma}{\mathrm{d}e_\beta} = \int \mathrm{d}\hat{e}_\beta\,\mathrm{d}\epsilon\,\hat{\sigma}(\hat{e}_\beta)\,F(\epsilon)\,\delta\left(e_\beta-\hat{e}_\beta-\epsilon\right)$$

Large impact from nonperturbative assumptions

Differences Persist at LHC

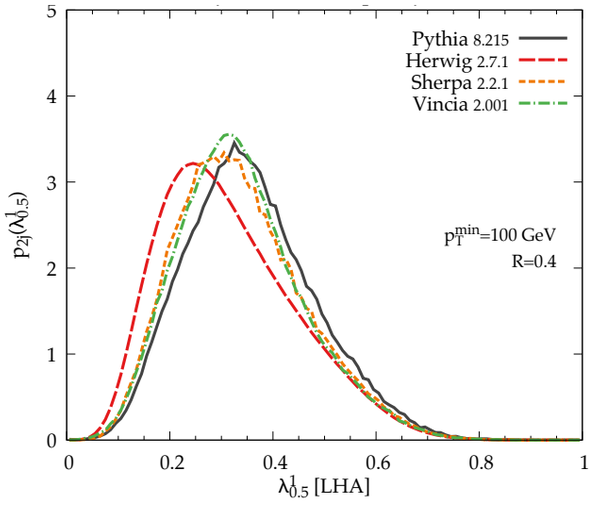
pp → Z + jet

85% quarks @ 100 GeV

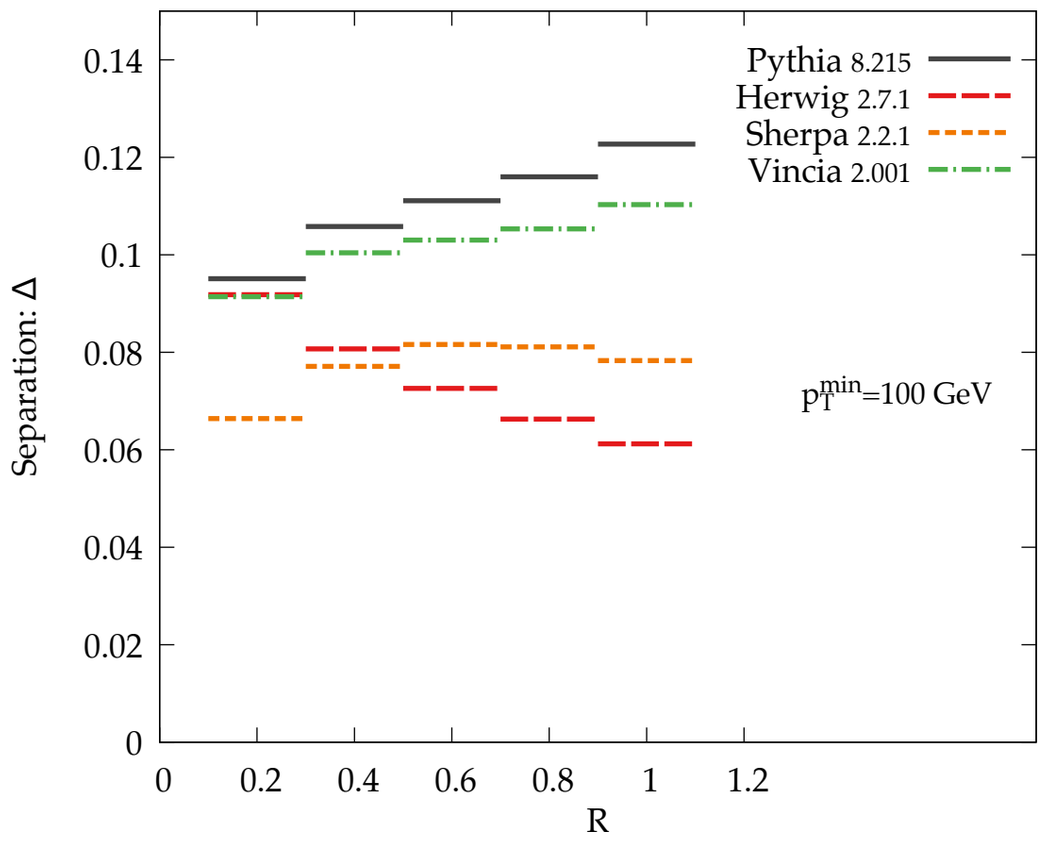


pp → dijet

75% gluons @ 100 GeV



Varying Jet Radius



LHC sensitive to jet radiation patterns (esp. gluons)

Recommendations

Scrutinize aspects of final-state parton shower

Gluon splitting to quark/antiquark
Color reconnection models
Default choice of α_s

New tuning/measurement campaigns

LEP: Tune to existing $e^+e^- \to b\,\bar{b}\,g$ measurements
LEP: Measure Les Houches Angularity (LHA, $\beta = 1/2$)
LHC: Differential studies in multiple channels at multiple p_T and R

Further analytic studies

Pursue (N)NLL + (N)NLO calculations
First-principles understanding of NP corrections?

[Gras, Hoeche, Kar, Larkoski, Lönnblad, Plätzer, Siódmok, Skands, Soyez, JDT, 1704.03878; based on Soyez, JDT, Freytsis, Gras, Kar, Lönnblad, Plätzer, Siodmok, Skands, Soper, 1605.04692]

Action Items for LH 2017

Overlap with other working groups

Develop concrete plan for LHC (and LEP) jet shape measurements and parton shower tuning (see backup)

Assess matching/merging uncertainties and impact on jet substructure methods (and vice versa)

Identify new uses for quark/gluon tagging, (e.g. improved PDF extraction?)

Beyond quark/gluon discrimination, correct modeling of jet radiation will benefit many LHC studies

Further Goals for Les Houches 2017

Two Broad Themes

From the wiki and pre-LH discussions

Precision Jet Substructure Calculations

Improved control with jet grooming (e.g. top mass, α_s extraction)
Quantifying impact of soft QCD effects (underlying event and hadronization)
Charmonium polarization puzzle in identified jets
Heavy ion physics: jet shapes in medium, probe QGP with boosted objects
…

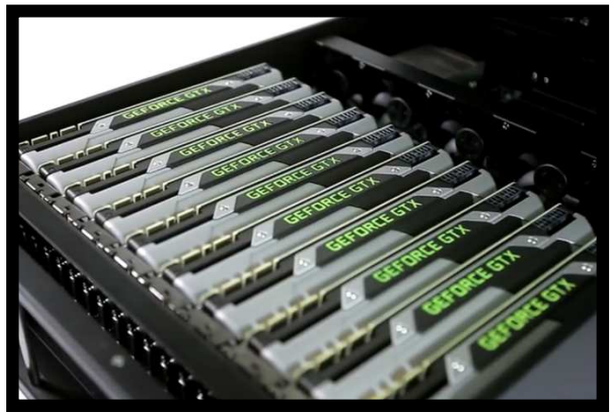
Advanced Tagging Strategies

Interplay of jet radius, jet discriminants, and jet grooming (e.g. dichroic)
Exploiting charm/bottom tags (e.g. gluon splitting to heavy flavor)
More refined tagging categories (e.g. longitudinal vs. transverse W/Z bosons)
Machine learning: multi-category classification, physics-inspired network design
…

Many points of contact with other working groups

Deep Thinking meets Deep Learning

Starting from well-defined physics goal…



Blackboards, Coffee,
Mountains, Inspiration

$\Leftrightarrow$

Construct Explicit
Optimization Problem

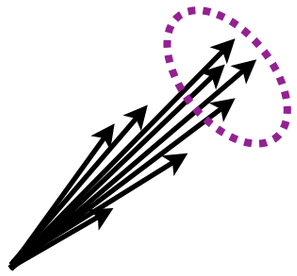
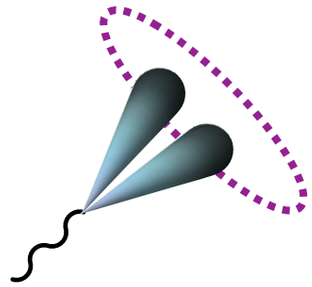
$\Downarrow$

Validation in
Simulation/Data/Calculations

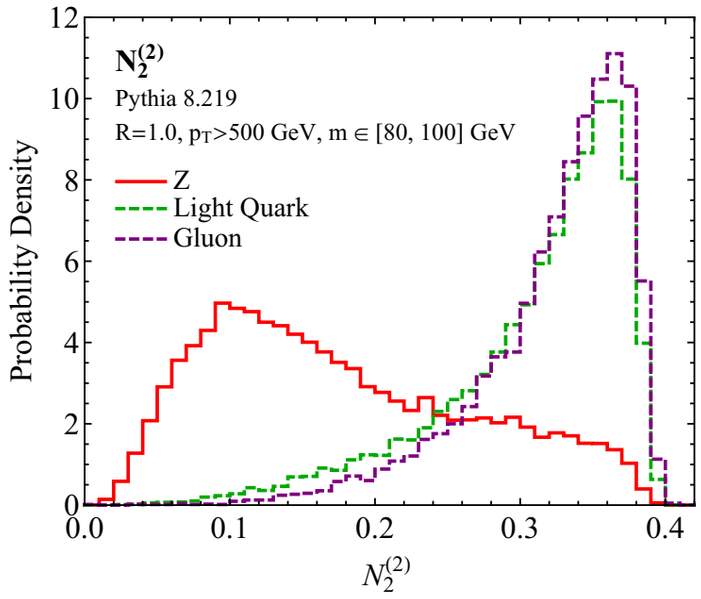
$\Downarrow$

Training in
Simulation/Data

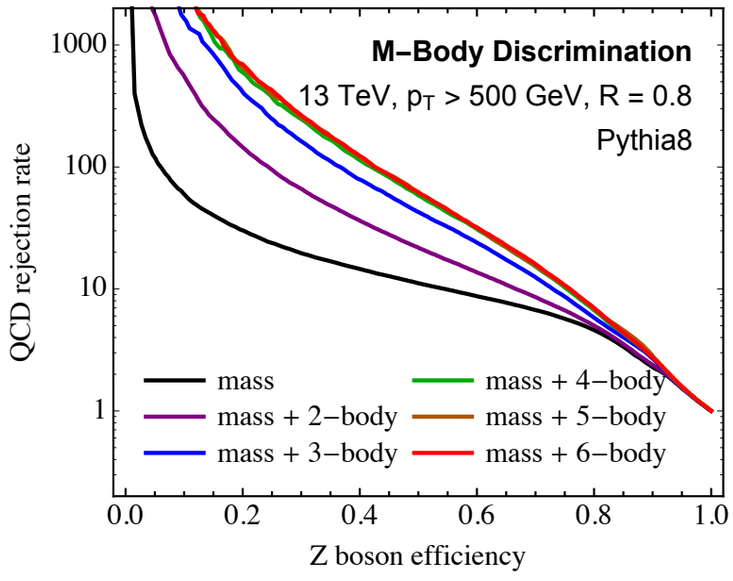
Deep Thinking meets Deep Learning

e.g. q/g  vs.  W/Z

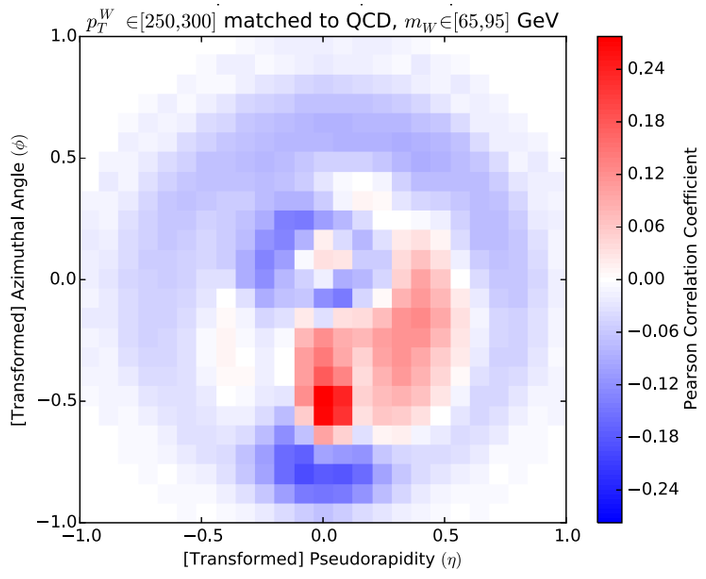
Energy Correlators from Power Counting



Dense Network of N-subjettiness Values



Convolutional Neural Network



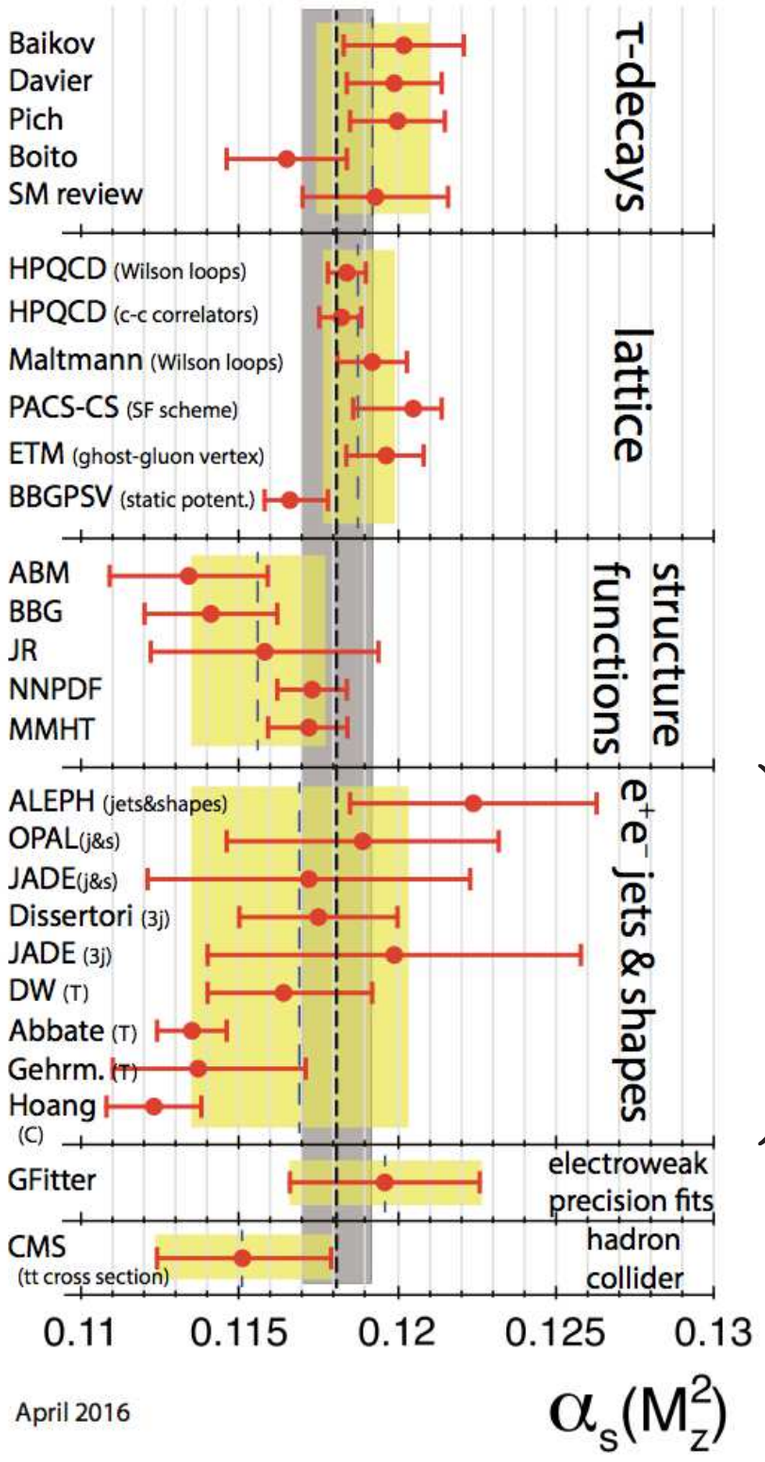
Continuum of approaches, ripe for cross fertilization
Optimize for performance and robustness (and calculability)

[e.g. Moult, Necib, JDT, 1609.07483; Datta, Larkoski, 1704.08249; de Oliveira, Kagan, Mackey, Nachman, Schwartzman, 1511.05190]

My goal for Les Houches:

Hunting the next white whale for jet physics

Extracting Strong Coupling Constant



Determine α_s from LHC jet substructure?

Clarify role of jet grooming for precision studies?

Highlight ways to control soft QCD corrections?

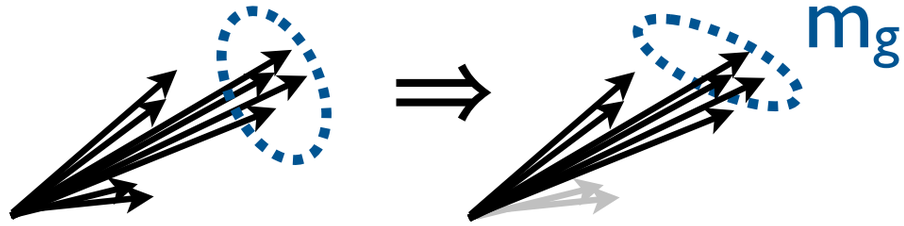
Inform strategies used at lepton colliders?

Ignite progress in (N)NLO substructure?

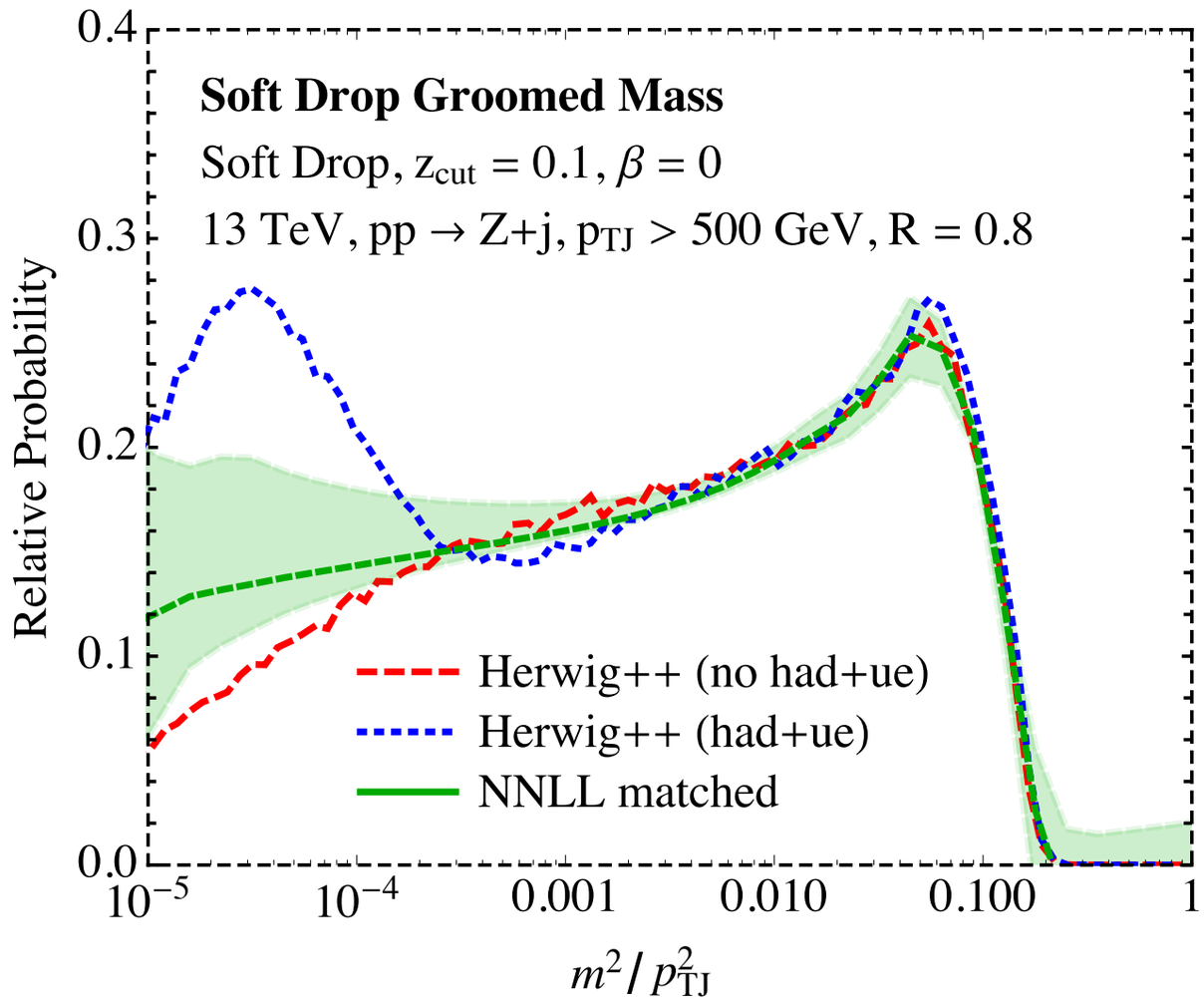
↳ Needed to get in the PDG!

Proof of Concept

Soft-dropped jet mass



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

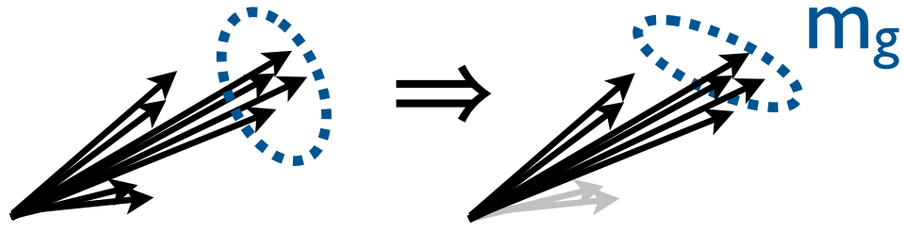


Grooming *simplifies* structure of calculation, *reduces* NP effects

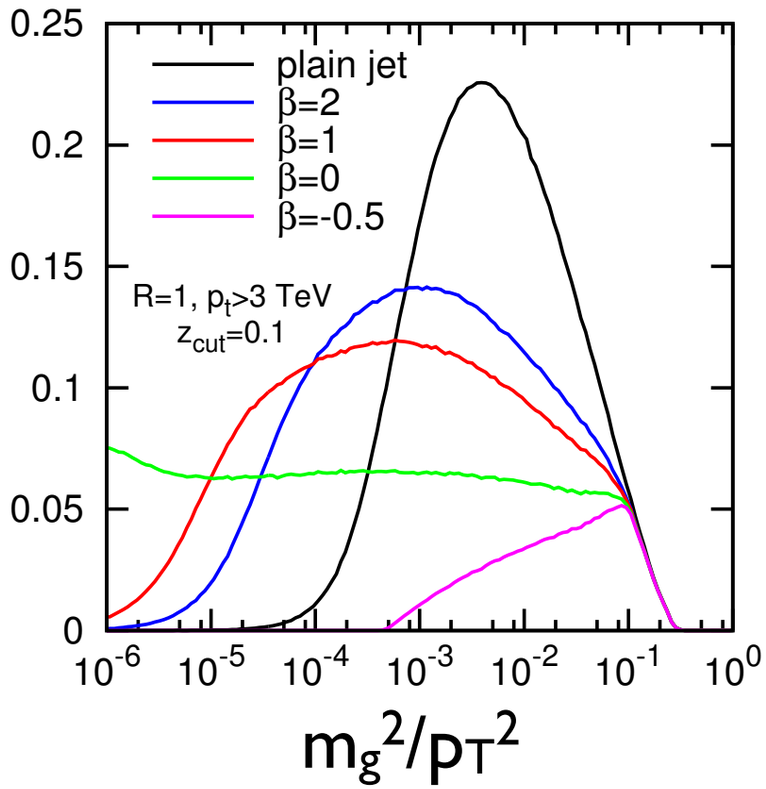
[Frye, Larkoski, Schwartz, Yan, 1603.06375, 1603.09338; see also Marzani, Schunk, Soyez, 1704.02210]

Systematic Strategy for α_s?

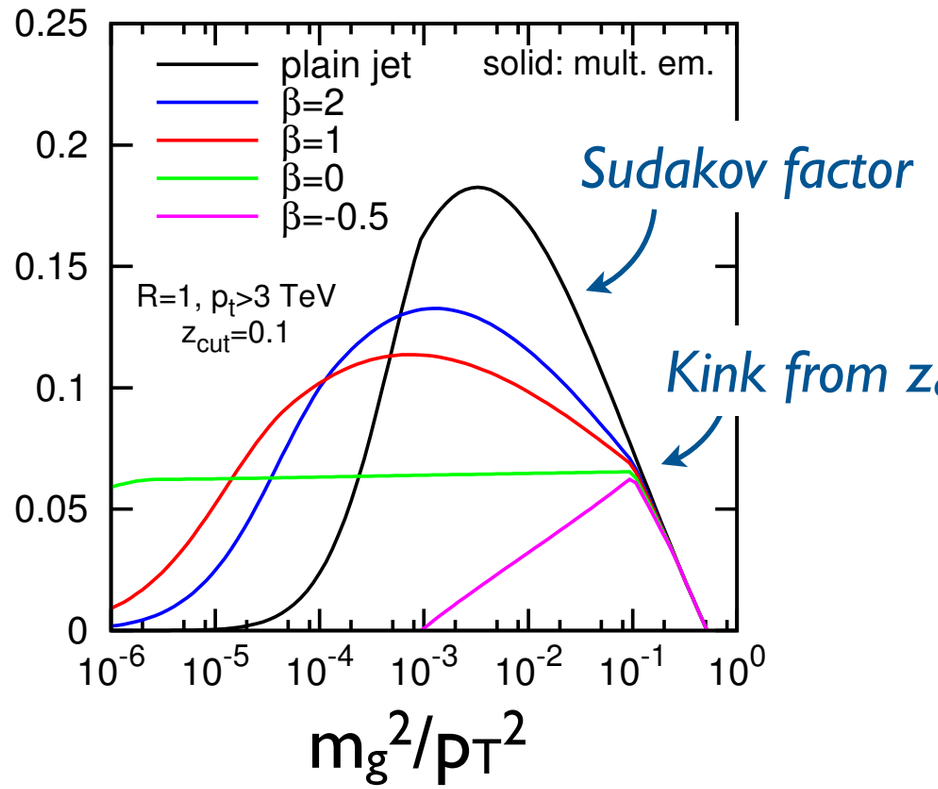
Scanning soft-drop variants?

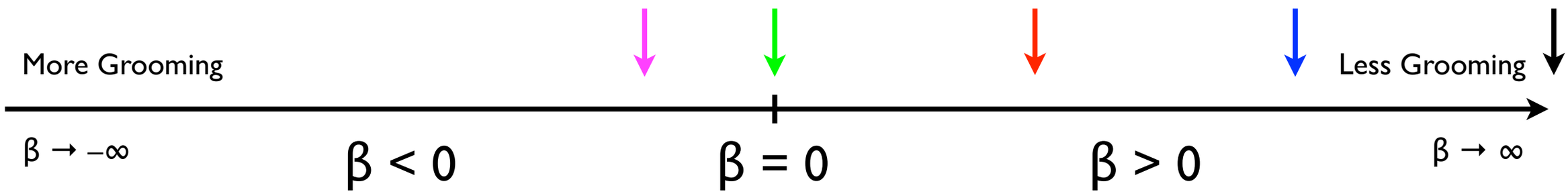


Pythia 8



NLL Resummation



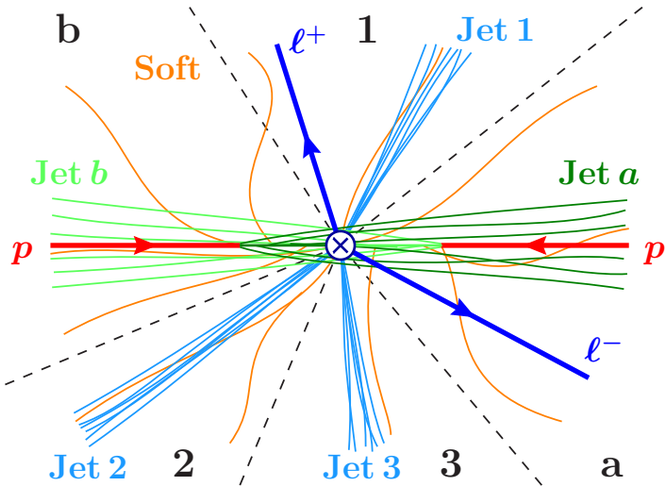


[Larkoski, Marzani, Soyez, JDT, 1402.2657; see also Butterworth, Davison, Rubin, Salam, 0802.2470; Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

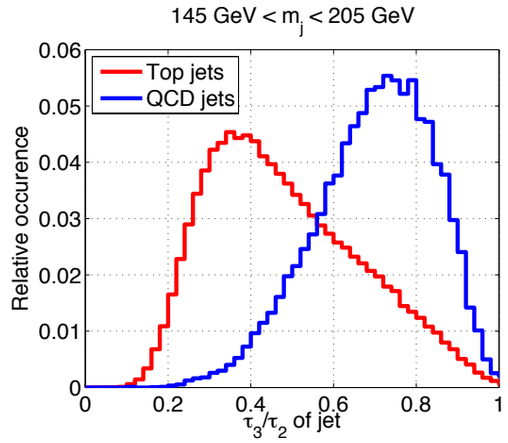
Benefits of Cross-pollination

wide-angle ⇔ boosted regimes

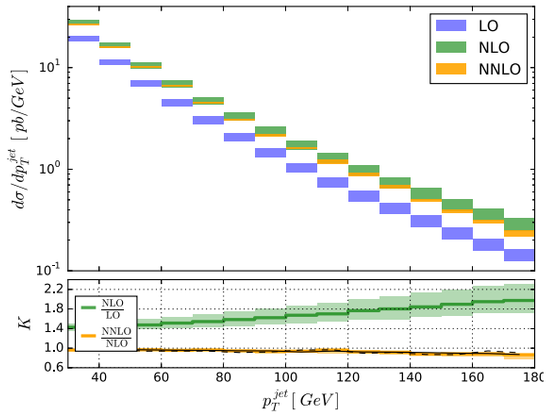
N-jettiness



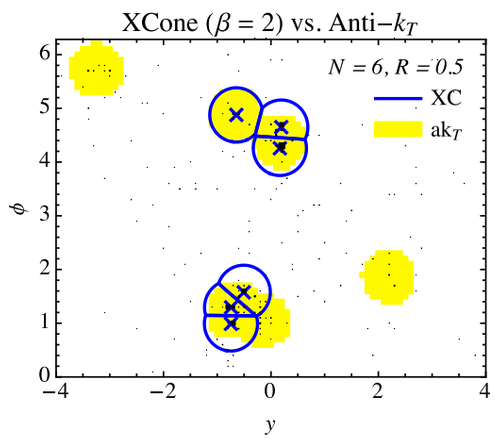
for jet vetos



N-subjettiness for boosted objects



N-jettiness for NNLO calculations



XCone for exclusive cone jets

[Stewart, Tackmann, Waalewijn, 1004.2489; Kim, 1011.1493; JDT, Van Tilburg, 1011.2268, 1108.2701; Boughezal, Focke, Liu, Petriello, 1504.02131; Gaunt, Stahlhofen, Tackmann, Walsh, 1505.04794; Stewart, Tackmann, JDT, Vermilion, Wilkason, 1508.01516; JDT, Wilkason, 1508.01518]

Jet Studies for Les Houches

2015:

Pursuing white whale of quark/gluon discrimination

reveals (non)perturbative uncertainties in jet radiation

2017:

Pursuing _____

(topic of interest to jet physics community)

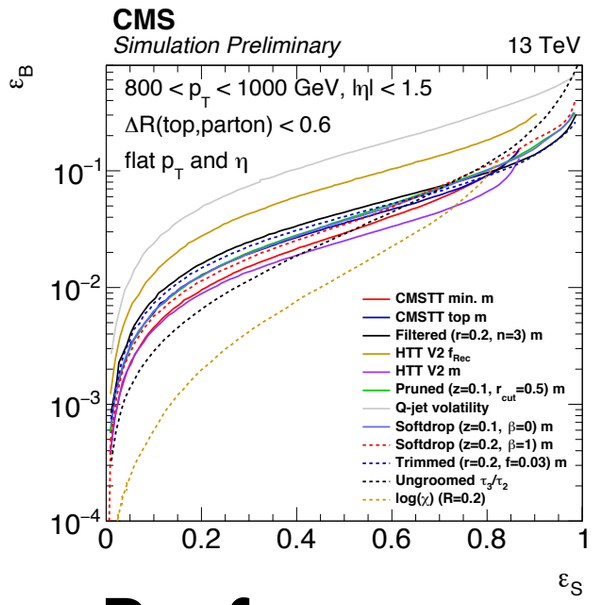
reveals _____

(insights with broader implications for QCD and beyond)

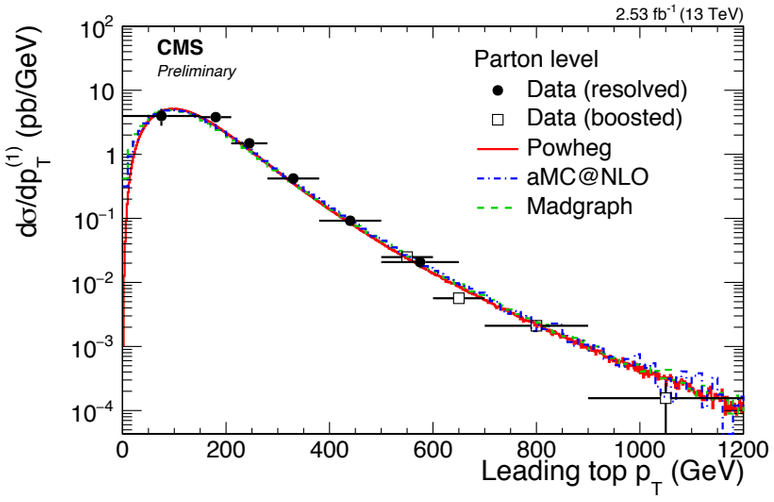
Looking forward to a fun, productive workshop!

Backup Slides

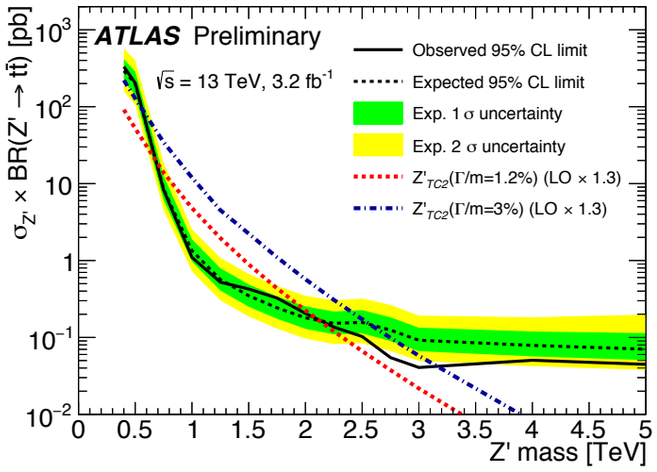
Innovative Approaches to Hadronic Final States



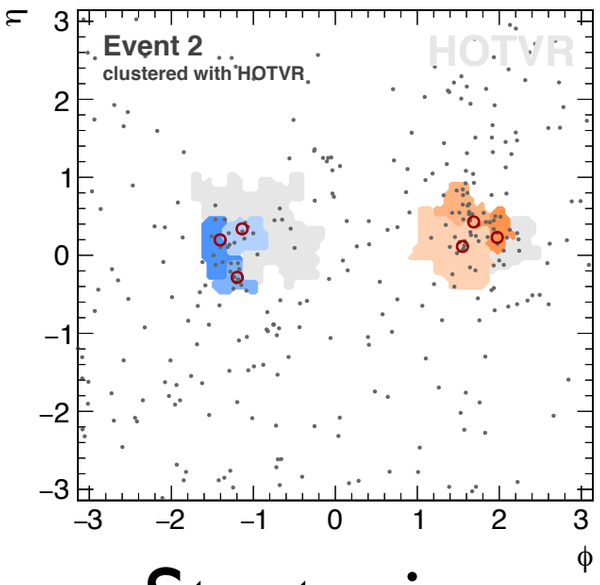
Performance



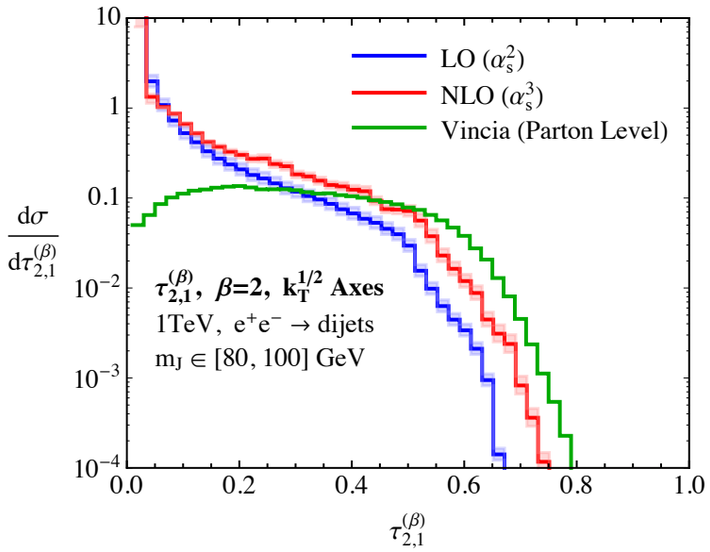
Measurements



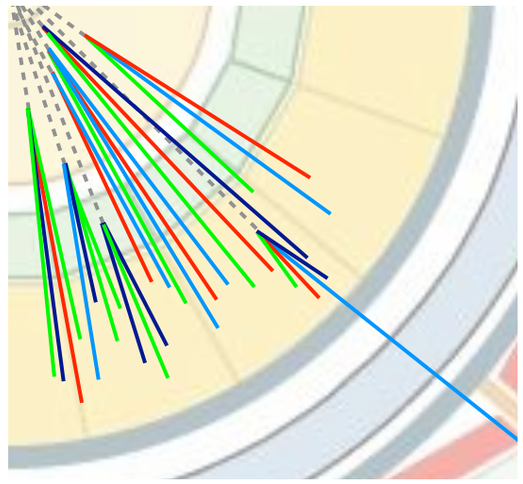
Searches



Strategies



Calculations

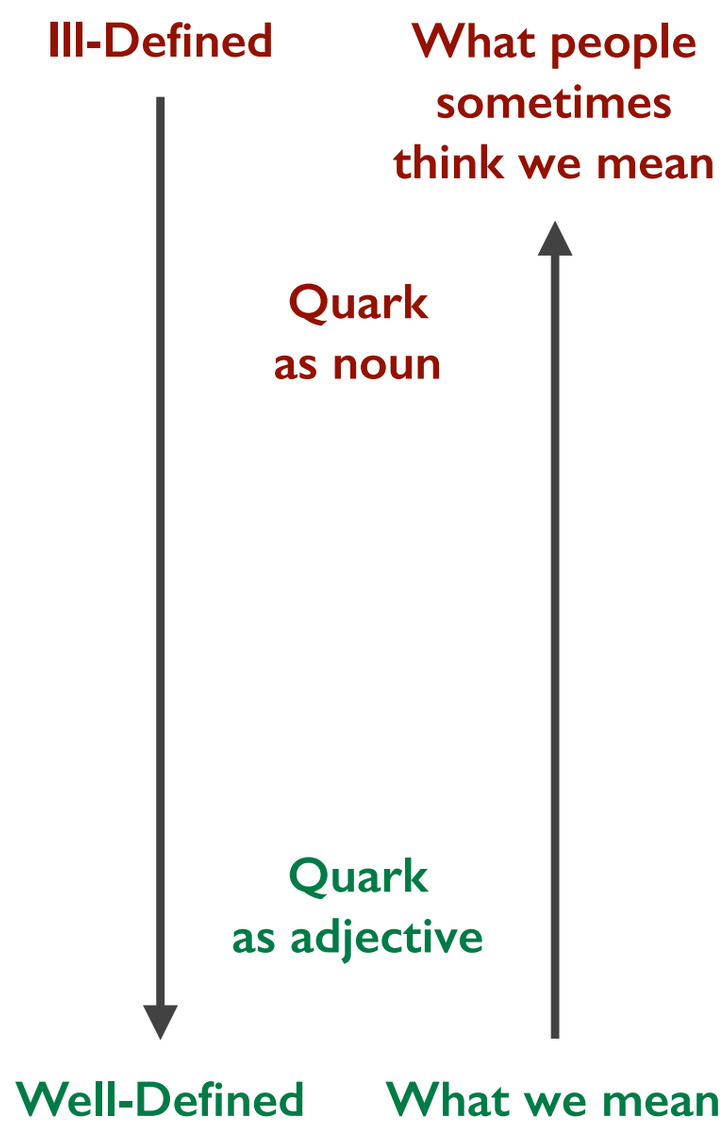


Scenarios

[e.g. CMS-PAS-JME-15-002; CMS-PAS-TOP-16-013; ATLAS-CONF-2016-014]
[e.g. Lapsien, Kogler, Haller, 1606.04961; Larkoski, Moult, 1510.08459; Schwaller, Stolarski, Weiler, 1502.05409]

What is a Quark Jet?

From lunch/dinner discussions



A quark parton

A Born-level quark parton

The initiating quark parton in a final state shower

An eikonal line with baryon number 1/3 and carrying triplet color charge

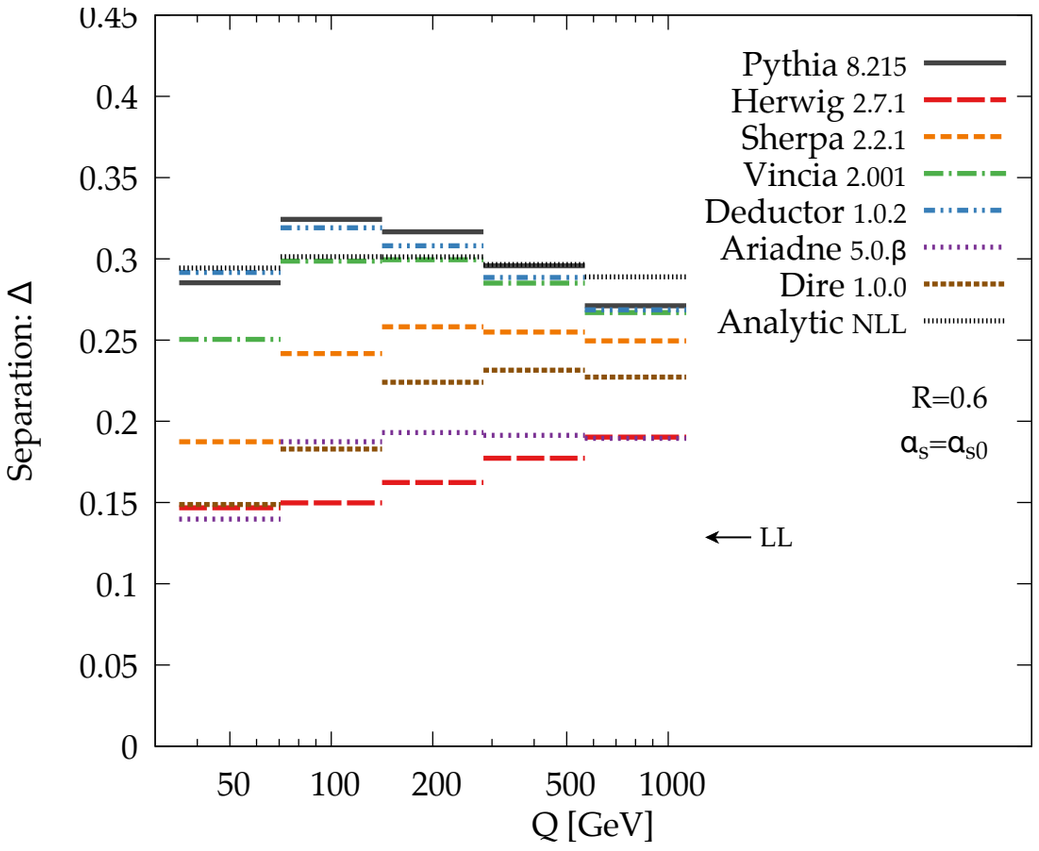
A quark operator appearing in a hard matrix element in the context of a factorization theorem

A parton-level jet object that has been quark-tagged using a soft-safe flavored jet algorithm (automatically collinear safe if you sum constituent flavors)

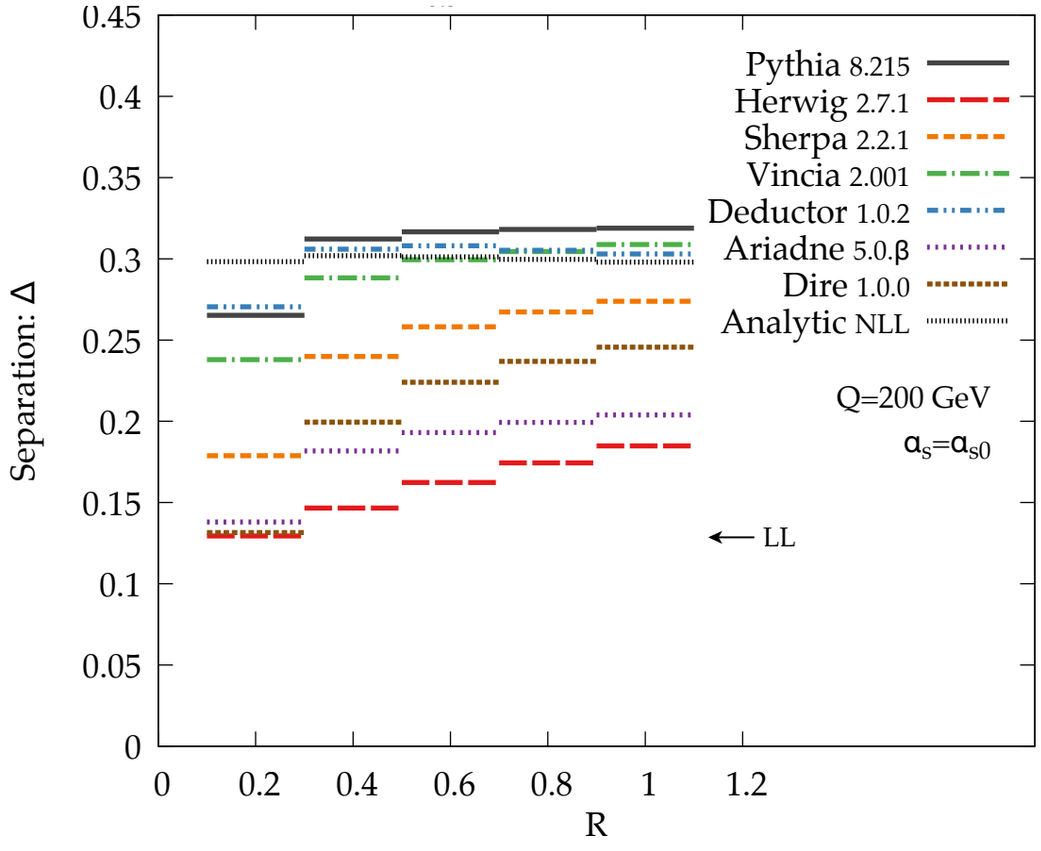
A phase space region (as defined by an unambiguous hadronic fiducial cross section measurement) that yields an enriched sample of quarks (as interpreted by some suitable, though fundamentally ambiguous, criterion)

Systematic Differences between Generators

Varying Collision Energy



Varying Jet Radius



Differences in both absolute and relative trends

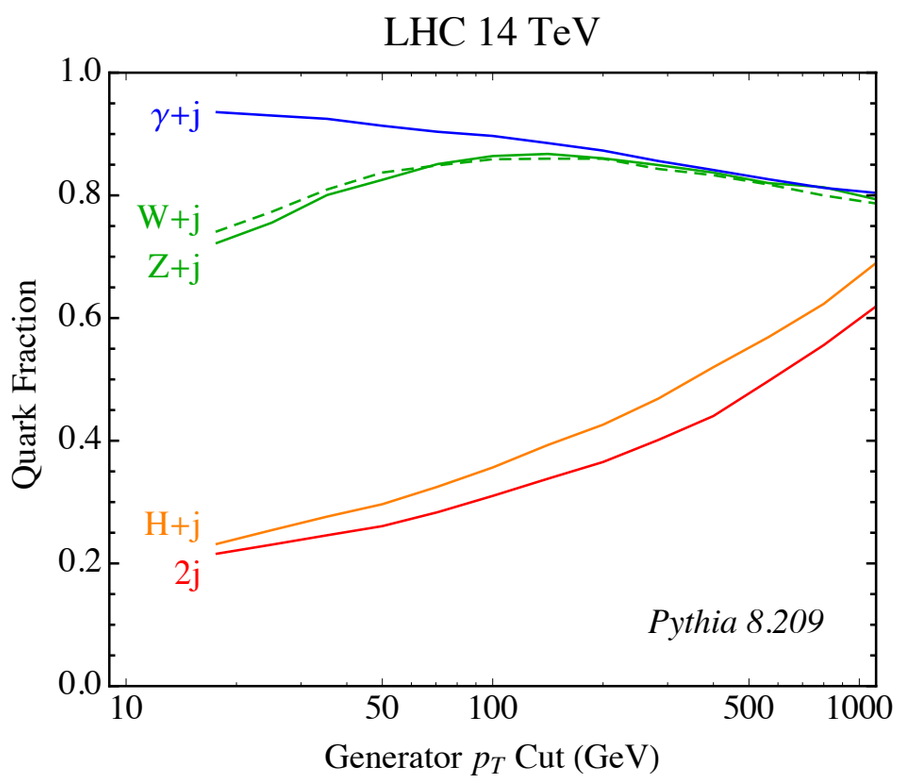
Proposed Systematic LHC Study

Strategy: (Over)constrain final-state parton shower

Observables: multiplicity, p_T^D, LHA, width, thrust, …

Samples: V + jet = quark-enriched
vs. dijet = gluon-enriched
(No need to diagonalize?)

Variations: Multiple jet p_T ranges
Multiple jet radii
e.g. R = 0.2, 0.4, 0.6, 0.8, 1.0
With & without grooming
e.g. mMDT (soft drop β=0, z_{cut}=0.1)



Key task for jet physics community
In principle, benefits every LHC measurement