Jet Physics at the LHC

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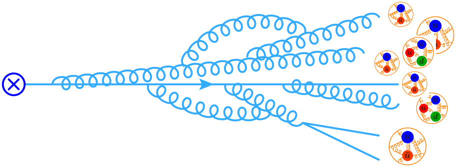
Introduction.

Why Jets?

QCD doesn’t let us observe quarks and gluons directly, only jets of hadrons



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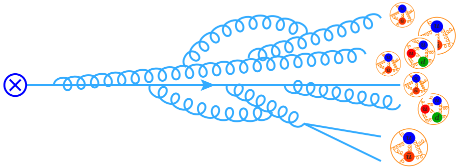
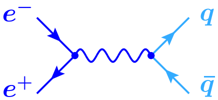
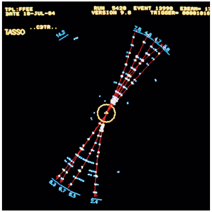
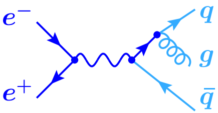


Jets tell us the QCD final state of the hard interaction process

- 36 years ago:





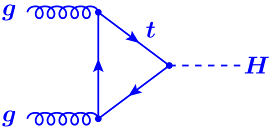


- Today: Essentially the same (just a bit more complicated ...)

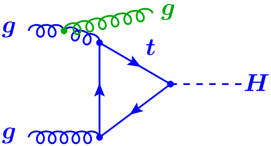
Executive Summary of Higgs Production.

$\sim 2/3$ of Higgs bosons are produced at low p_T

0 jets

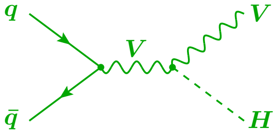


0-1 jets

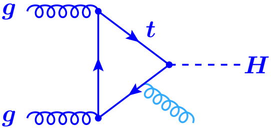


$\sim 1/3$ of Higgs bosons have sizeable p_T

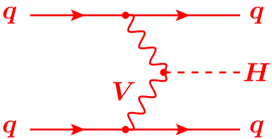
0 (normal) jets



1 jet



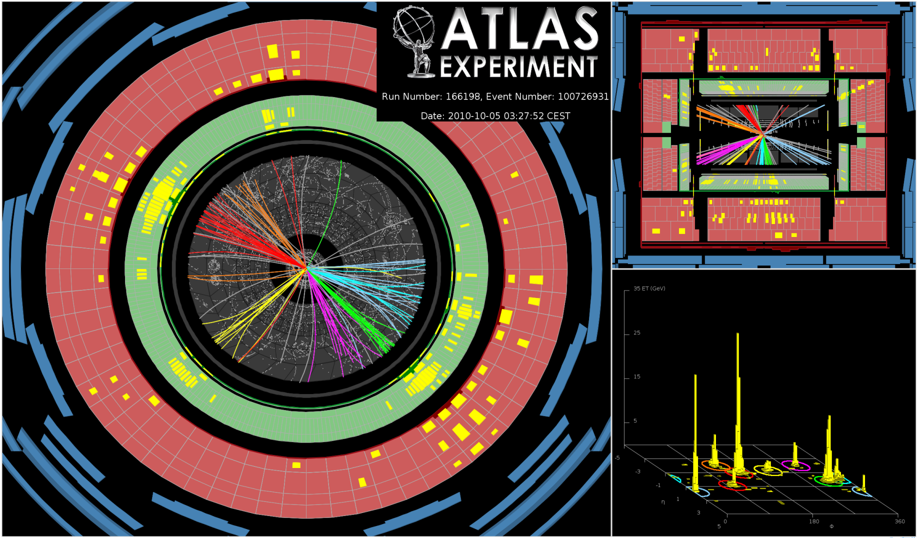
2 (quark) jets



- Kinematics and number of jets distinguishes different Higgs processes
- Discriminates against different backgrounds (e.g. in $H \to WW, \tau\tau, b\bar{b}$)

Why Else Jets?

Jets are Ubiquitous



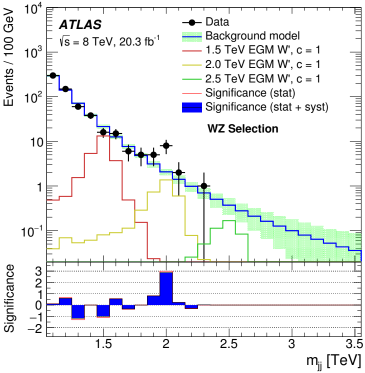
Why Else Jets?

Jets are essential also in EW final states

Recall $$\mathrm{BR}(W \to q\bar{q}') = 67\%$$

$$\mathrm{BR}(Z \to q\bar{q}) = 70\%$$

- Diboson excess is in dijet mass spectrum of two *filtered W/Z-tagged jets*
  [ATLAS 1506.00962]



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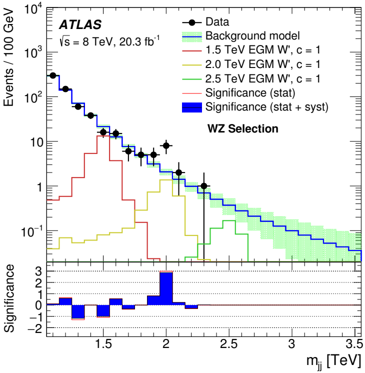
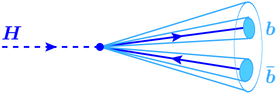


- Diboson excess is in dijet mass spectrum of two *filtered W/Z-tagged jets*

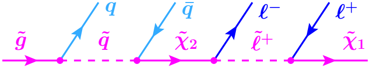
  [ATLAS 1506.00962]

Search strategies increasingly rely on exploiting jet substructure

- Boosted decays: top-jets, W/Z-jets, Higgs-jets



- Distinguish quark jets (from BSM cascades) from gluon jets (QCD backgrounds)



- Jet mass, shape, charge, tracks, ...

Outline.

I can only cover a few selected topics:

- Higgs and jets
- Jet hierarchies
- New jet algorithm: XCone
- Quark-gluon separation

QCD corrections in jet processes are typically sizeable

- (N)NLO calculations are often necessary $\rightarrow$ see Giulia Zanderighi's talk

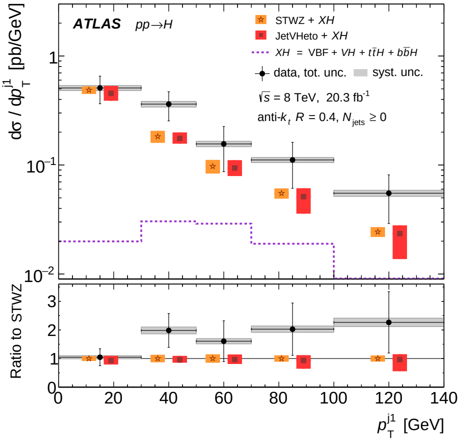
Jets involve multiple physical scales

- Fixed-order perturbation theory is often not enough
- Require understanding all-order structure, resummation, hadronic effects, ...

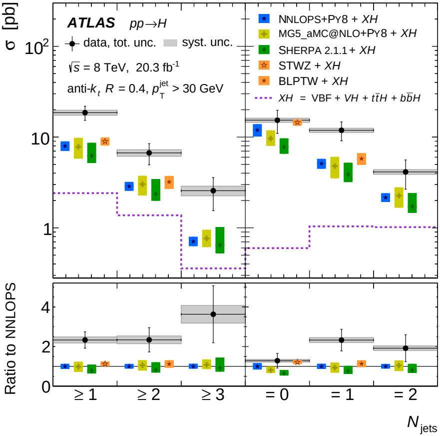
Higgs + Jets

Differential Higgs+Jets Measurements.

$\mathrm{d}\sigma/\mathrm{d}p_T^{\mathrm{jet}}$



$\sigma(N\text{jets})$



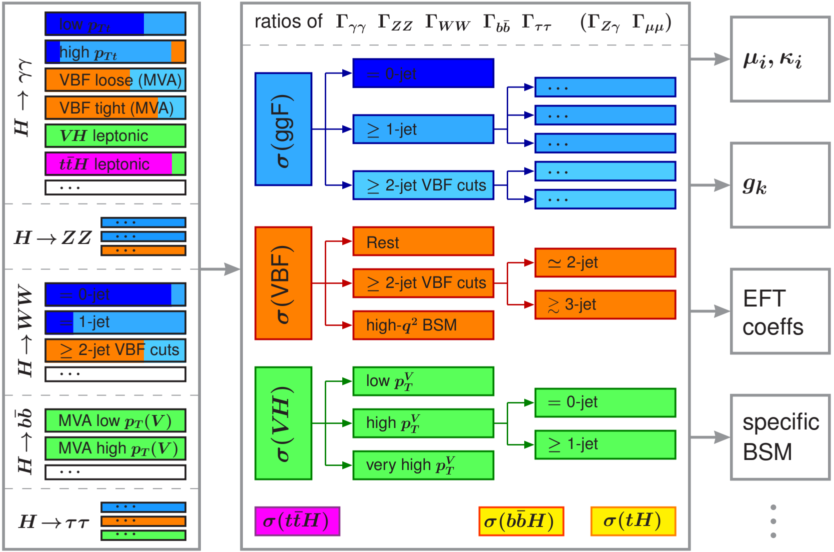
Combined high-resolution $H \to \gamma\gamma$ and $H \to 4\ell$ [ATLAS arXiv:1504.05833]

- Still statistics limited, but theory uncertainties will become relevant with $\sim$20 times more statistics ($\sim$ end of Run2)

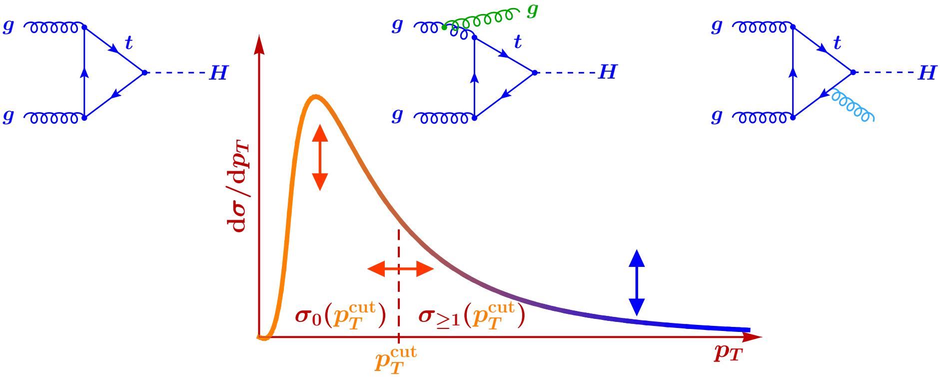
Higgs Simplified Cross Sections.

[Les Houches & LHC Higgs WG2]

- Production cross sections split into kinematic bins → most involve jets



Jet Binning.



Spectrum describes transition between 0-jet and ≥ 1-jet regions

- Need consistent treatment of theory uncertainties across entire spectrum
  - *quite nontrivial* because it requires nontrivial correlations (simple factor-2-scale-variation-recipes are not good enough)
  - Understood much better by now, but still open issues to figure out
- Complete description from combining resummation+fixed order

Rapidity-Weighted Jet Bins.

[Gangal, Stahlhofen, FT]

Generalize $p_T^{\rm jet}$ by defining

$$\mathcal{T}_{fj} = p_{Tj}\, f(y_j)$$

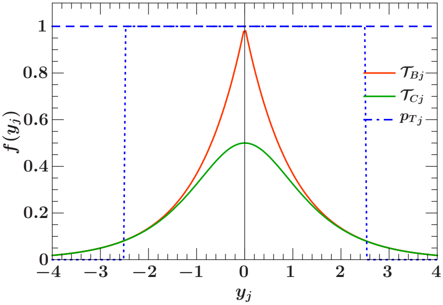
$$\mathcal{T}_f^{\rm jet} = \max_{j \in J(R)} \mathcal{T}_{fj}$$

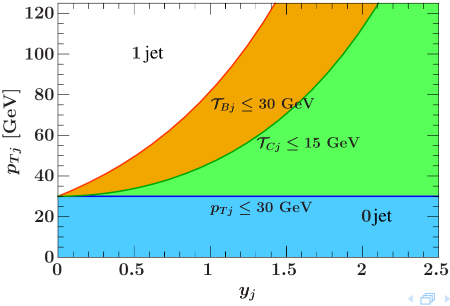
- Can choose different rapidity weighting functions such that $\mathcal{T}_f^{\rm jet}$
  - can be resummed
  - is insensitive to forward rapidities
- Count jets according to $\mathcal{T}_{fj}$

0 jets: $\sigma_0(\mathcal{T}_f^{\rm jet} < \mathcal{T}^{\rm cut})$

≥ 1 jets: $\sigma_{\geq 1}(\mathcal{T}_f^{\rm jet} > \mathcal{T}^{\rm cut})$

$\Rightarrow$ Provides different slicing through jet phase space

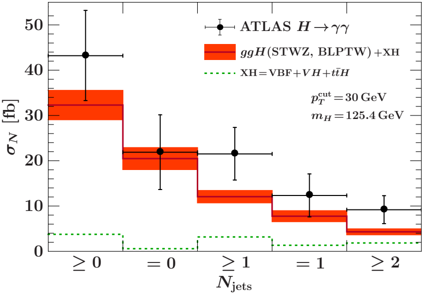




Resolving Jet Bins.

(only using $H \to \gamma\gamma$ here)

Pretend uncertainties are much smaller and we want to resolve the “excess”



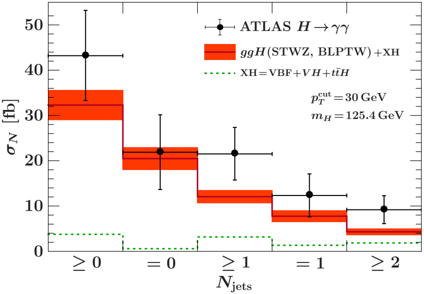
Resolving Jet Bins.

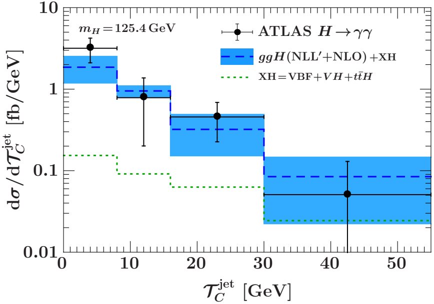
(only using $H \to \gamma\gamma$ here)

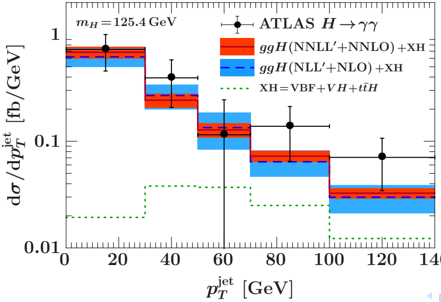
Pretend uncertainties are much smaller and we want to resolve the "excess"

- Different slices of jet phase space adds nontrivial information
- One might conclude that "excess" sits at higher $p_T^{\rm jet}$ at more forward rapidities

$\Rightarrow$ Ultimately measure double-differential in $p_T^{\rm jet} - \mathcal{T}_f^{\rm jet}$







Jet Hierarchies.

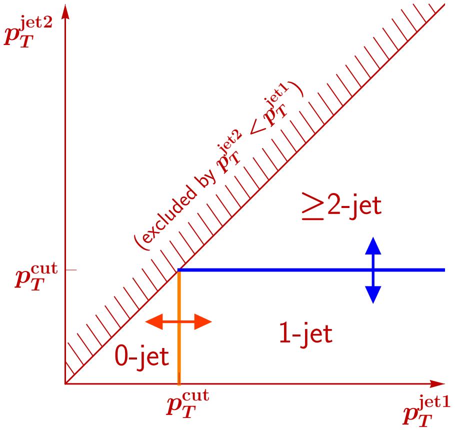
In More Dimensions and with More Jets...

... it quickly gets more complicated

Multiscale problem

$$\cdots \lesssim p_T^{\mathrm{jet2}} \lesssim p_T^{\mathrm{jet1}} \lesssim Q$$

- Different multiple hierarchies possible
- Resummation often limited to LL (parton shower)
  - $p_T^{\mathrm{cut}} \ll p_T^{\mathrm{jet1}} \sim m_H$ limit is known at NLL′ [Liu, Petriello]



Need to better understand distribution and correlations

- between different kinematic variables
- across different jet multiplicities

$\Rightarrow$ Increasingly important as we probe higher and higher scales (and in particular if we find new heavy particles)

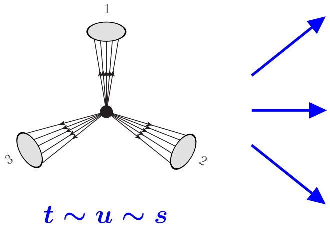
Jet Hierarchies.

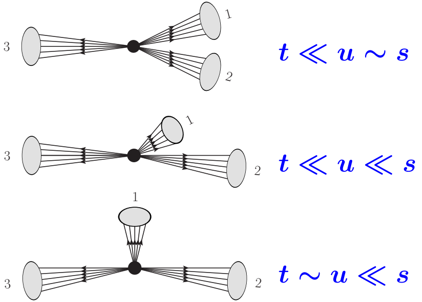
SCET$_+$: Extension of SCET to treat additional (emerging) scale hierarchies beyond standard SCET

[Bauer, FT, Walsh, Zuberi ’11]
[Procura, Waalewijn, Zeune ’14]
[Larkoski, Moult, Neill ’15]
[Pietrulewicz, FT, Waalewijn (prep.)]

- Adds two types of intermediate modes
  - collinear-soft: soft mode arising from a collinear sector
  - soft-collinear: collinear mode arising from a soft sector
  - Relative scaling and interactions depend on specific observable

⇒ Resummation of hierarchies in hard jet kinematics





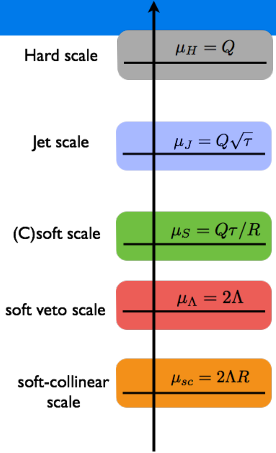
⇒ Resummation of double-differential spectra → talk by Lisa Zeune

Jet Rates and Nonglobal Logarithms.

Thrust with cone jets [Chien, Hornig, Lee 1509.04287]

$$2(\Lambda/Q)R^2 \sim \tau \ll R^2 \ll 1$$

- With SCET$_+$ can resum $\ln\tau$ and also $\ln R$
- For $\tau \sim R^2$ resum all global $\ln R$ in total jet rate
  - But not appearing non-global logs of Λ/Q



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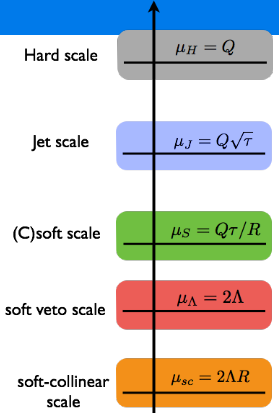
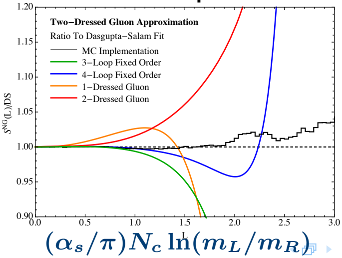


"Resum" nonglobal logs by explicitly resolving and summing infinite set of emissions

- Resolved soft subjets → "dressed gluons"
  [Larkoski, Moult, Neill 1501.04596, 1508.07568]
  - Infinite sum reproduces BMS equation
    [Dasgupta, Salam; Banfi, Marchesini, Smye]
  - Instead: Expand in number of dressed gluons
    → Systematic reorganization of pert. series
- Renormalize "Color-density matrix"
  [Caron-Huot 1501.03754]
- Renormalize matrix of bare emissions
  [Becher, Neubert, Rothen Shao 1508.06645]

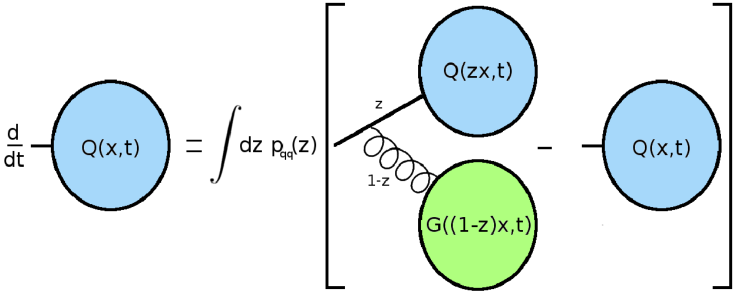


Phenomenology of Small-R Jets.

[Dasgupta, Dreyer, Salam, Soyez, Cacciari]

Jet algorithms induce logarithms $\sim \alpha_s \ln R$

- Use a generating functional formalism to numerically resum leading $(\alpha_s \ln R)^n$ terms (LL_R)



  - Exploits angular ordering, evolution variable $t \sim (\alpha_s/2\pi) \ln(R_0^2/R^2)$

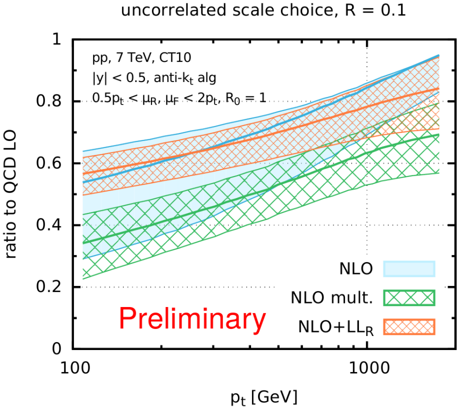
- Studied several jet observables, including jet trimming and filtering
  - Trimming is particularly sensitive to small-R effects

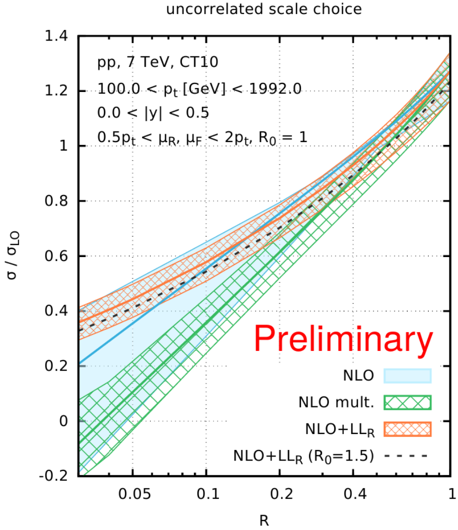
Phenomenology of Small-R Jets.

[plots stolen from F. Dreyer's BOOST 2015 talk]

Inclusive jet spectrum

- LL_R has noticeable effect for $R \lesssim 0.4$





Theory for Jet Substructure.

Jet substructure methods

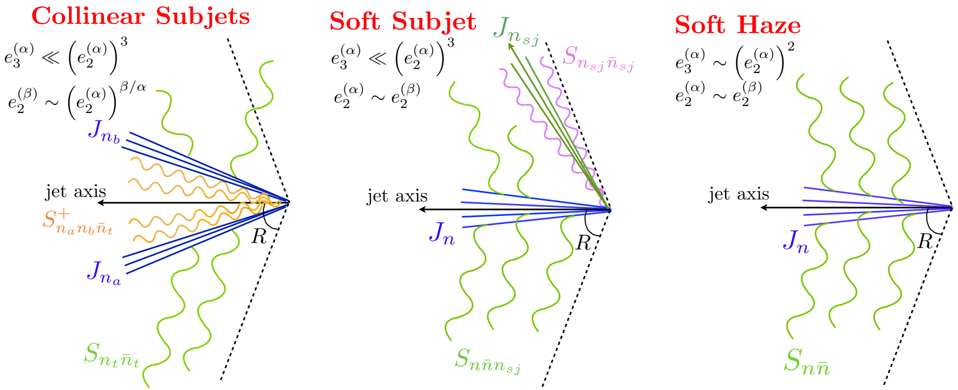
- Typically involve complex algorithms and cuts, very sensitive to resummation and nonperturbative effects
  - Vast majority of studies and applications heavily rely (necessarily) on parton shower Monte Carlos
- In past few years focus increased on gaining a better analytic and systematic understanding in two important and complementary ways [many groups/authors ...]
  - Better analytic understanding, tools, calculations
  - Instead of optimizing solely for performance, also taking theory controlability into account in designing new algorithms and methods

Analytic Boosted Boson Discrimination.

[Larkoski, Moult, Neill]

First factorization and analytic resummation of a 2-prong variable $\boldsymbol{D_2}$
(similar to $\mathbf{2}$-subjettiness but based on energy correlation functions)

- For boosted boson signal and QCD background (latter is the hard part)
- Use SCET_+ to resum and combine different subjet limits



Analytic Boosted Boson Discrimination.

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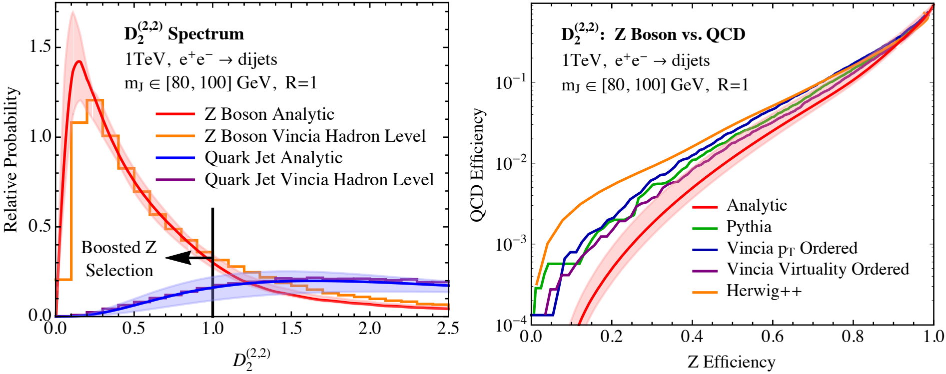


- Region relevant for discrimination is very sensitive to hadronization
  - Described by nonperturbative soft function with field-theoretic definition
  - Good description with single-parameter shape function
- Should be possible to extend to other substructure observables and pp collisions

XCone.

Substructure without substructure

XCone: An eXclusive Cone-Jet Algorithm.

[Stewart, FT, Thaler, Vermilion, Wilkason]

Basic construction

- Start from standard N-jettiness

$$\widetilde{\mathcal{T}}_N(\{n_k\}) = \sum_i \min\{\rho_{\rm jet}(p_i, n_1), \ldots, \rho_{\rm jet}(p_i, n_N), \rho_{\rm beam}(p_i)\}$$

  - Given N jet axes $\{n_k\}$, partitions event into N jet regions and beam region
  - Shape and size of jet regions depend on $\rho_{\rm jet}$ and $\rho_{\rm beam}$ measures (New XCone measure yields conical jets and maintains theory control)

- Minimize over all jet axes

$$\mathcal{T}_N = \min_{n_1, n_2, \ldots, n_N} \widetilde{\mathcal{T}}_N(\{n_k\})$$

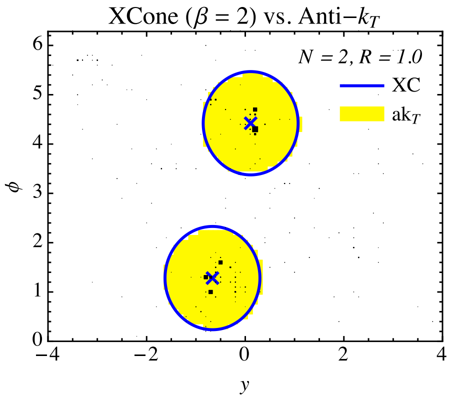
  - Finding exact global minimum is computationally expensive
  - Finding approximate (local) minimum is sufficient and inexpensive

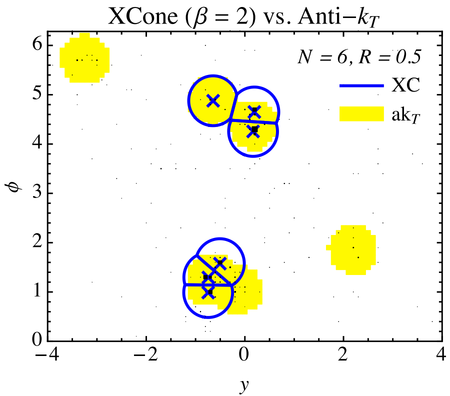
Key features

- Exclusive: Returns preselected number of jets
  - Yields best interpretation of the event in terms of the signal one is looking for
  - Final $\mathcal{T}_N$ value provides additional quality measure for free
- Smoothly transitions between well-separated and boosted regimes

Comparison to anti-k_T

Boosted $t\bar{t} \rightarrow$ hadrons event (from BOOST 2010 sample)





Well-separated jets

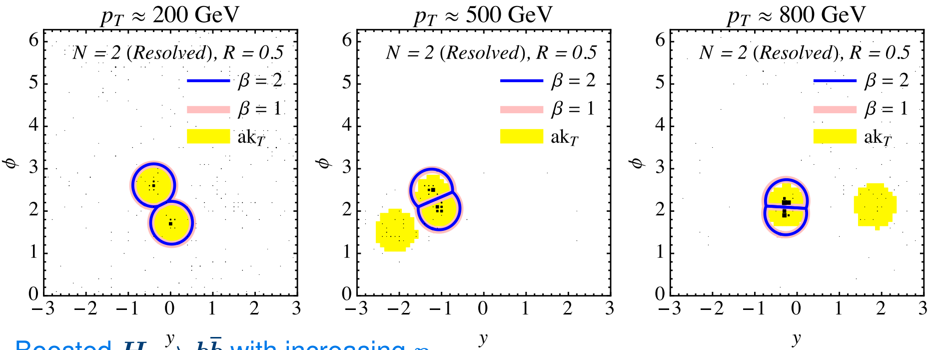
- XCone jets practically the same as leading anti-k_T jets

Adjacent/overlapping jets

- anti-kT merges signal jets, picks up ISR, FSR jets
- XCone still finds jets, dynamically split by nearest-neighbor

Case Study: Boosted Higgs Reconstruction.

[Thaler, Wilkason]



Boosted $H \to b\bar{b}$ with increasing p_T

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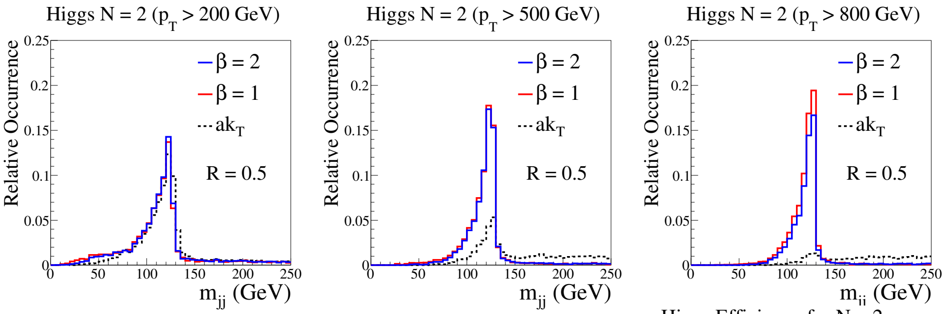
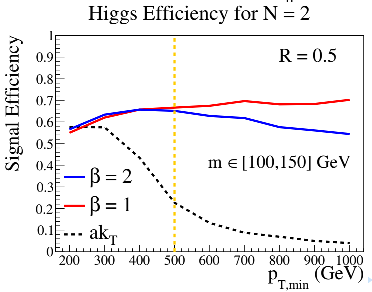


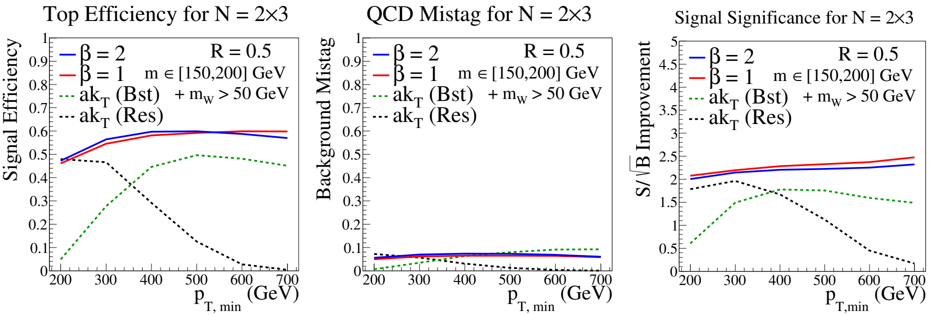
Boosted $H \to b\bar{b}$ with increasing p_T

- XCone provides stable performance across kinematic regimes
  - Effectively provides automatic transition from 2-jettiness to 2-subjettiness
  - Further improvements possible, e.g. with explicit ISR veto



Case Study: Boosted Top Reconstruction.

Classic example of jet substructure: $pp \to t\bar{t} \to WWb\bar{b} \to q\bar{q}q\bar{q}b\bar{b}$



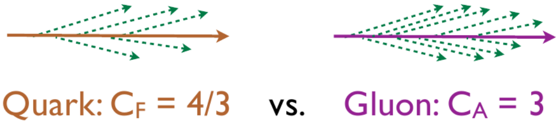
- Use XCone with $N = 2 \times 3$ $(R_2 \gg 1, R_3 = 0.5)$
- Compare to
  - "Resolved": 2 k_T jets $(R \gg 1)$ with 3 anti-k_T subjets
  - "Boosted": 2 anti-k_T jets $(R = 1.0)$ with 3 k_T subjets

⇒ Better performance across all p_T

Quark-Gluon Discrimination.

a.k.a. Hunting the White Whale of Jet Substructure

Quark-Gluon Discrimination.



- QCD background jets from ISR and FSR are dominantly "gluon-jets"
- Signal jets are dominantly "quark-jets"
  - Color singlets couple to quarks only

$\Rightarrow$ Would be powerful discriminator if it could be exploited

- See b-tagging
- Long history, but still (almost embarassingly) not well under control
- Initiated a comprehensive study at Les Houches this year

What is a Quark Jet?

From lunch/dinner discussions

[stolen from Jesse Thaler, Les Houches]

Ill-Defined

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)

Well-Defined

What is a Quark Jet?

From lunch/dinner discussions

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Ill-Defined

What people sometimes think we mean

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)

Well-Defined

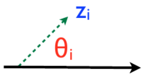
What we mean

Les Houches Quark/Gluon Performance Study.

[Les Houches q/g subgroup]

Compare $e^+e^- \to u\bar{u}$ ("quark-tagged") to $e^+e^- \to gg$ ("gluon-tagged")

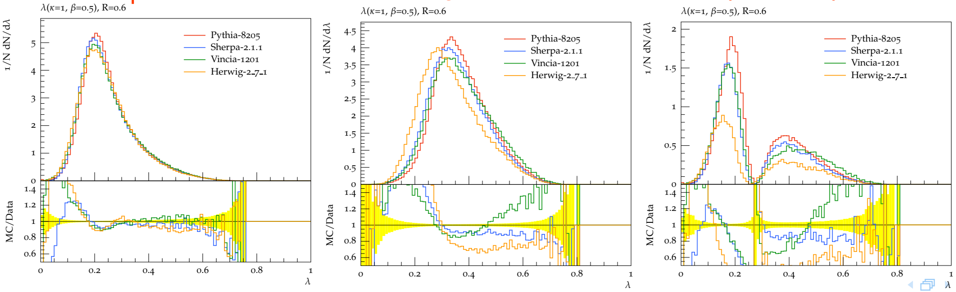
- Generalized jet angularities: $\lambda_\beta^\kappa = \sum_{i\in\mathrm{jet}} z_i^\kappa \theta_i^\beta$



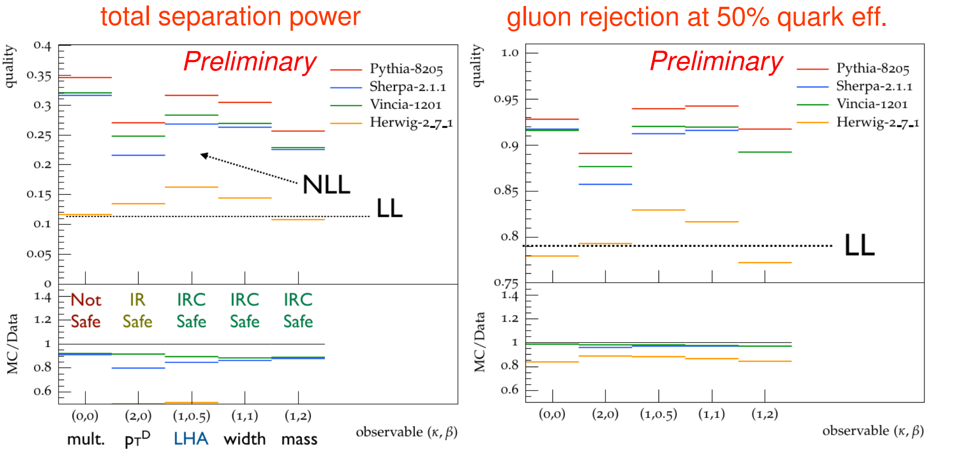
- Separation power: $$\frac{1}{2}\frac{[S(\lambda)-B(\lambda)]^2}{S(\lambda)+B(\lambda)}$$

"Les Houches Angularity" $\lambda(\kappa=1,\beta=0.5)$, $R=0.6$, $Q=200\,\mathrm{GeV}$

quarks gluons separation power



Quark/Gluon Performance: Some Lessons Learned.



- Improving quark/gluon robustness seems synonymous with controlling final state shower uncertainties (LEP measured quark not gluon event shapes)
- Hadronization can be important, even for IRC safe angularities

⇒ Comparison to analytic predictions, uncertainties, stay tuned ...

Summary.

Jets are our window onto the hard interaction

- Jets inevitably involve nontrivial QCD corrections and several physical scales
  - Fixed-order calculations are often necessary but seldom sufficient
- As experimental analyses are getting more sophisticated they make more detailed use of jets
  - More differential, more exclusive binning, more detailed substructure, ...
  - Important to keep theory under control
- Calculations and methods are constantly being refined and developed
  - But there are also many open issues

Many things I have not covered (apologies ...)

$\rightarrow$ See e.g. many interesting talks at BOOST 2015