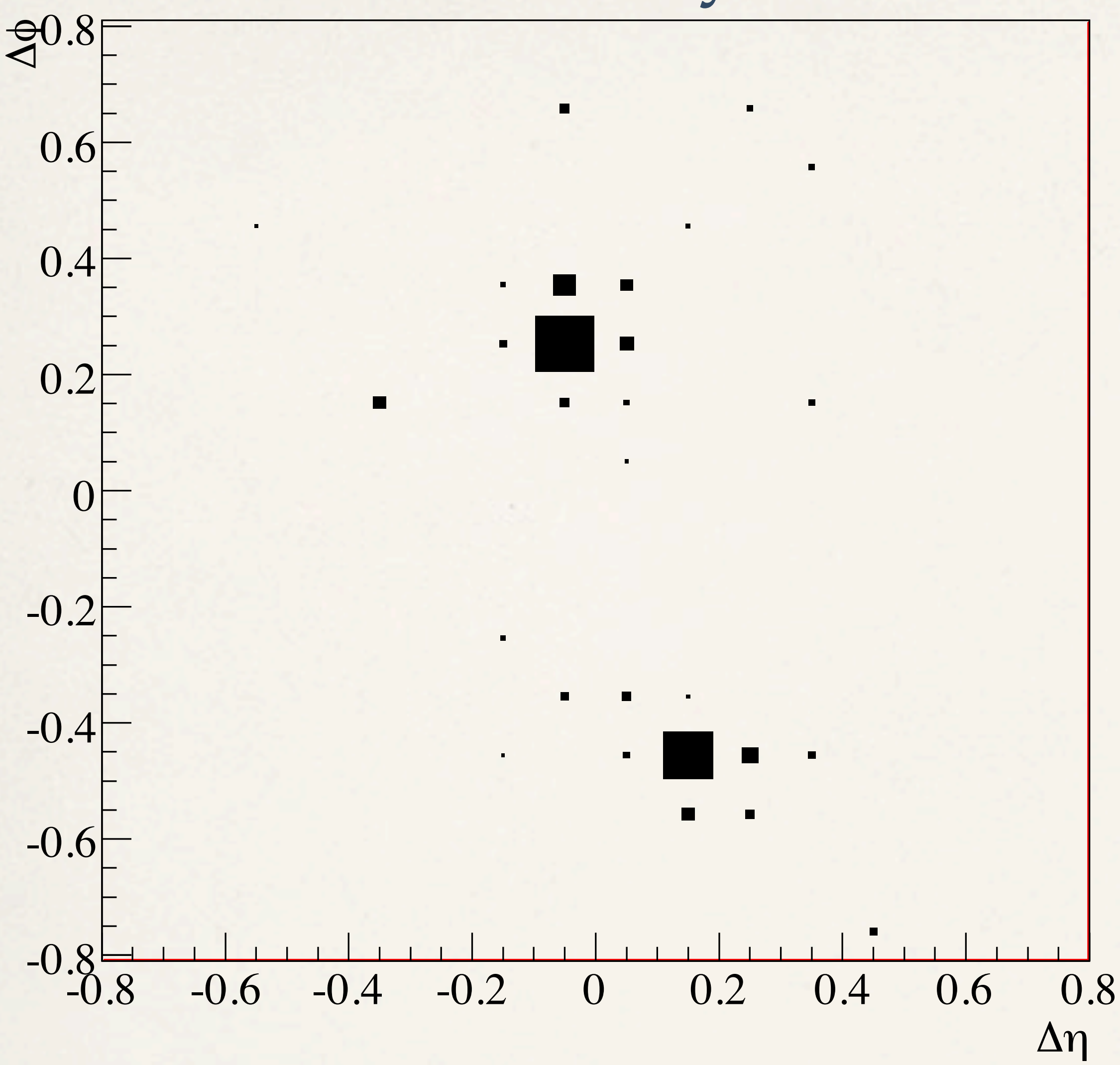
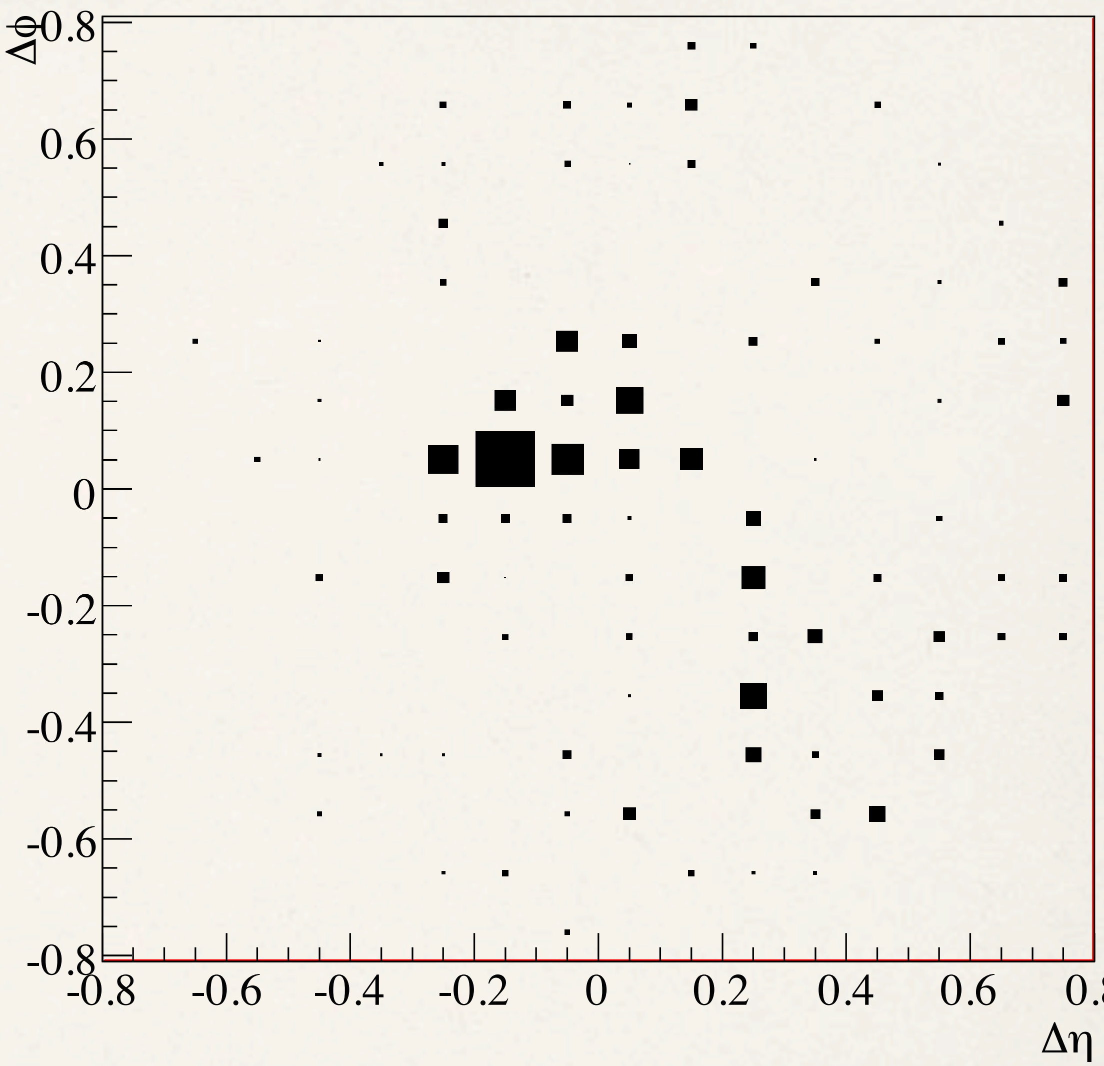
Boosted Heavy Particle



QCD Jet



Boosted Heavy Objects

David Krohn (Harvard)

Upcoming Jet Conference

- Boost 2011, Princeton [5/23-5/27]

Goal: Study jets from boosted heavy objects, as well as exotic jets (lepton jets, etc.).

http://boost2011.org

Outline

- Introduction to Boosted Heavy Objects
- Recent results
- Conclusion & Outlook

Takeaway

- At the LHC, sometimes heavy particles (e.g. W/Z/t/h) are so energetic their decay products are resolved in a single jet.
  - The resulting jets are very different from the jets formed from the showering of light partons
- By looking inside such a jet we can try to recover some of the original heavy particle's properties (identity, polarization, color structure, etc).
- Remarkably, not only can we recover information on the jet's properties, but in some cases by looking in the boosted region we can actually do better than conventional analyses.

Introduction

Kinematics of Boosted Particles

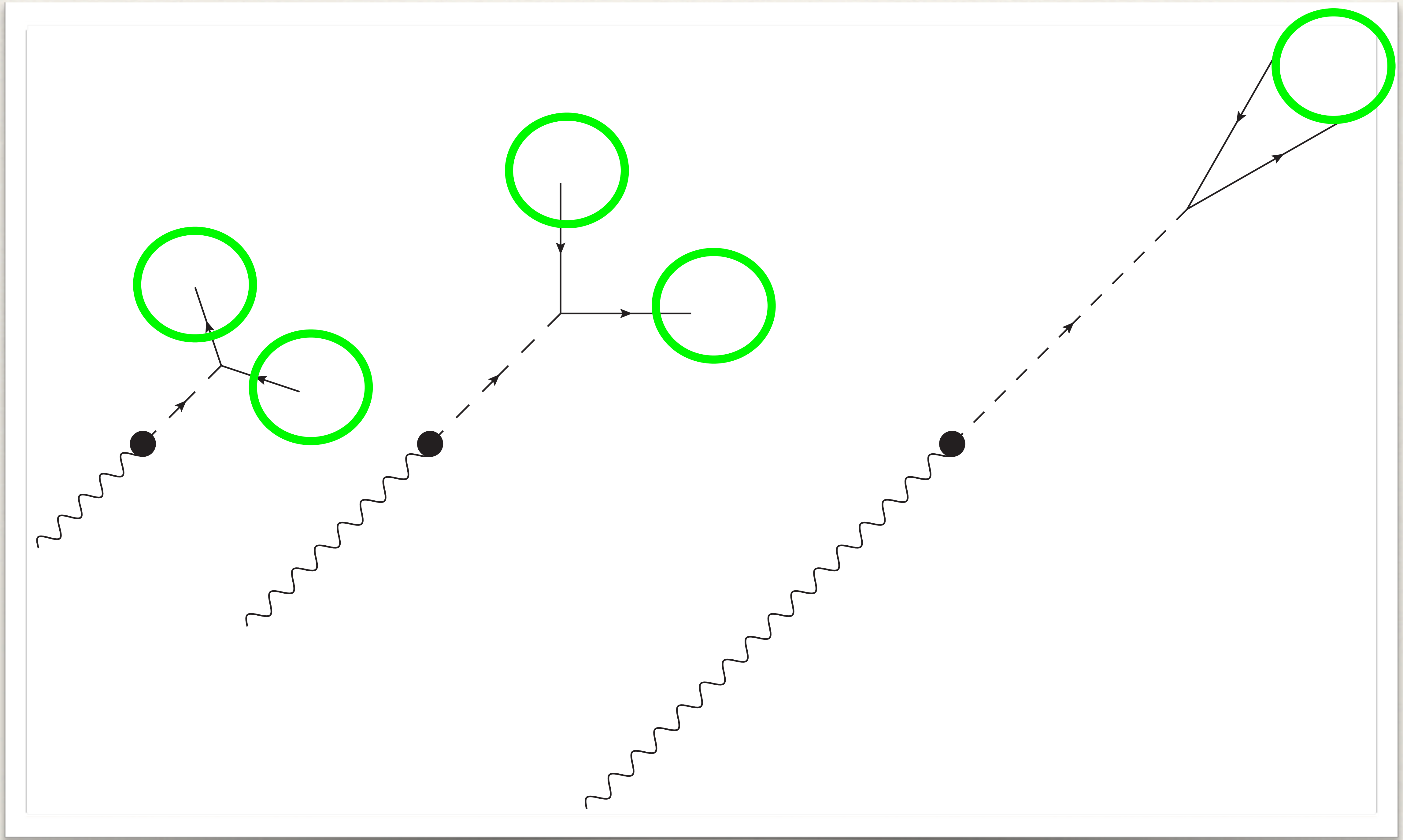
- The cone containing the decay products of a particle scales as

$$R \sim \frac{2m_X}{p_T}$$

- At LHC energies, even the heaviest particles we know of (Top, W, Z, Higgs) can become collimated (roughly $R < 1$).

- When this happens we say that they're "boosted".

- So we find that EW scale particles are clustered as a single jet as soon as their p_T exceeds a few hundred GeV.



Here one can see the effect - as we boost more and more (i.e. go to higher pT), the particles become more collimated.

What can we say about these jets?

- Internally, QCD jets look really different than the jets of boosted heavy objects.

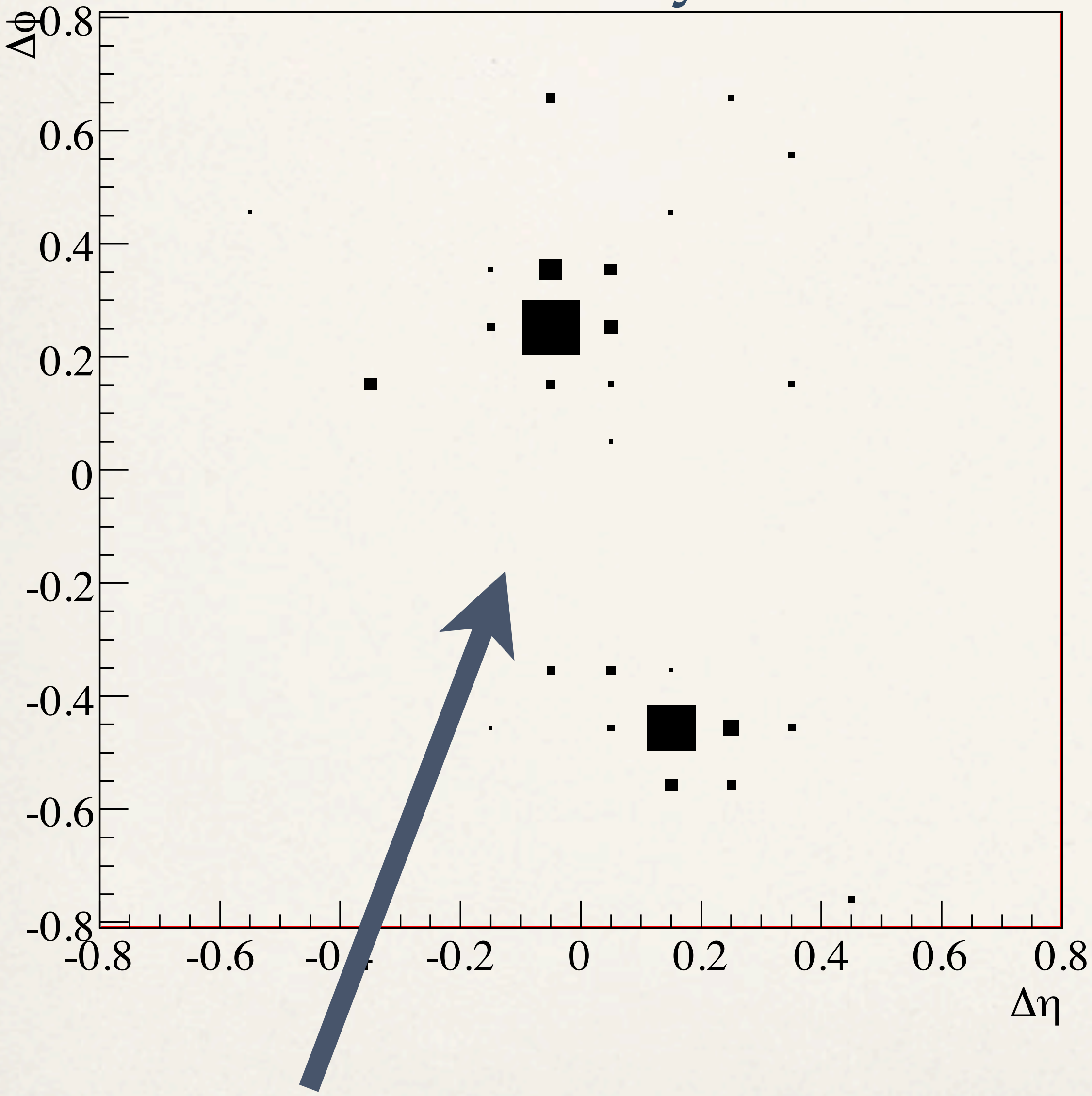
- If we start with a high energy gluon/quark, it wants to emit soft/collinear gluons:

$$P_{q\to qg}(z) = C_F \frac{1+z^2}{1-z},$$
$$P_{g\to gg}(z) = C_A\left[\frac{1-z}{z} + \frac{z}{1-z} + z(1-z)\right]$$
$$P_{g\to q\bar{q}}(z) = T_R\left[z^2 + (1-z)^2\right],$$

Here P(z) measures how much a particle wants to emit another with energy fraction “z” (Altarelli-Parisi splitting fcns.).

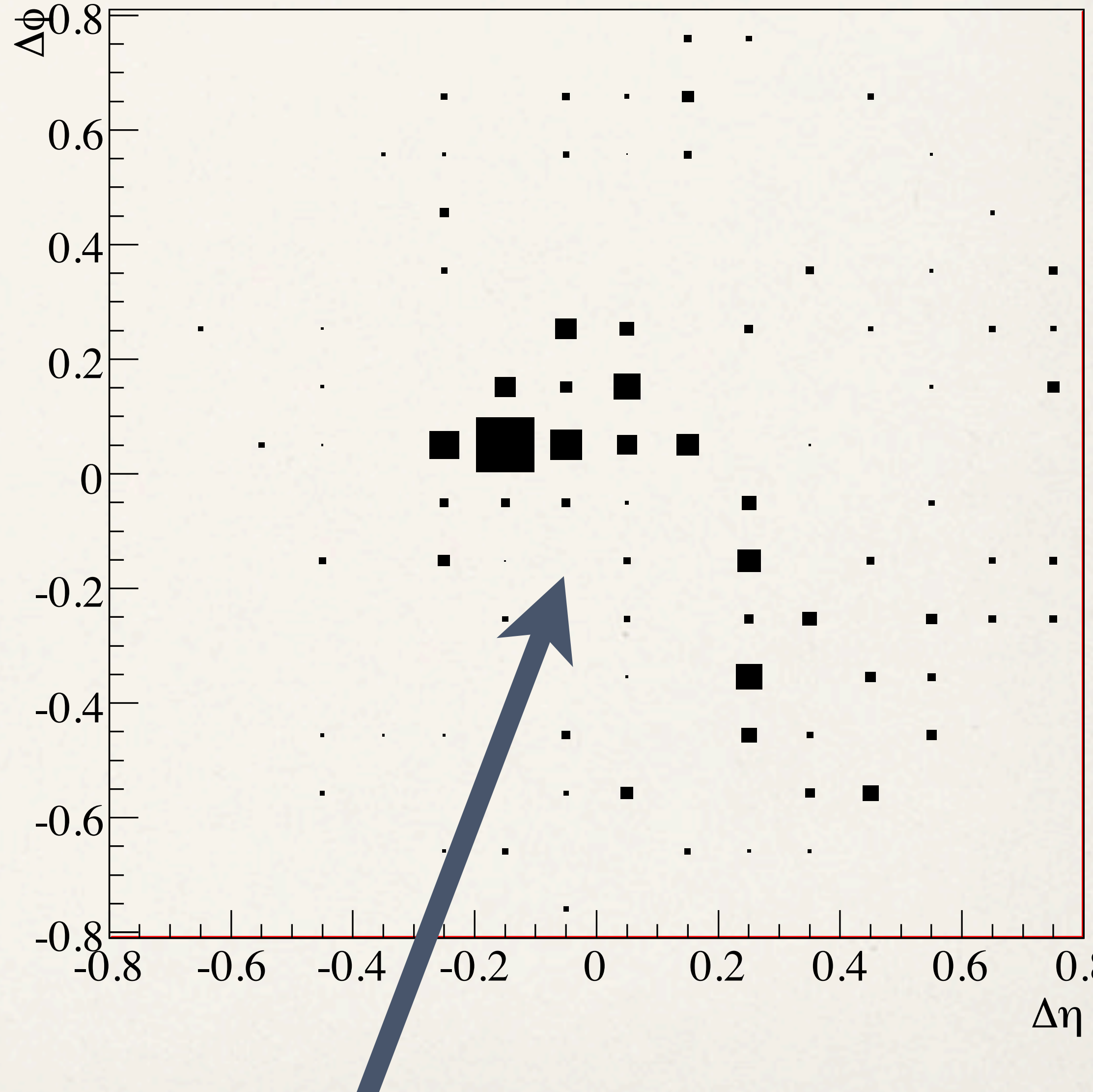
- In contrast, a high energy heavy particle (W/Z/t/h) just decays - it has no singularity.

Boosted Heavy Particle



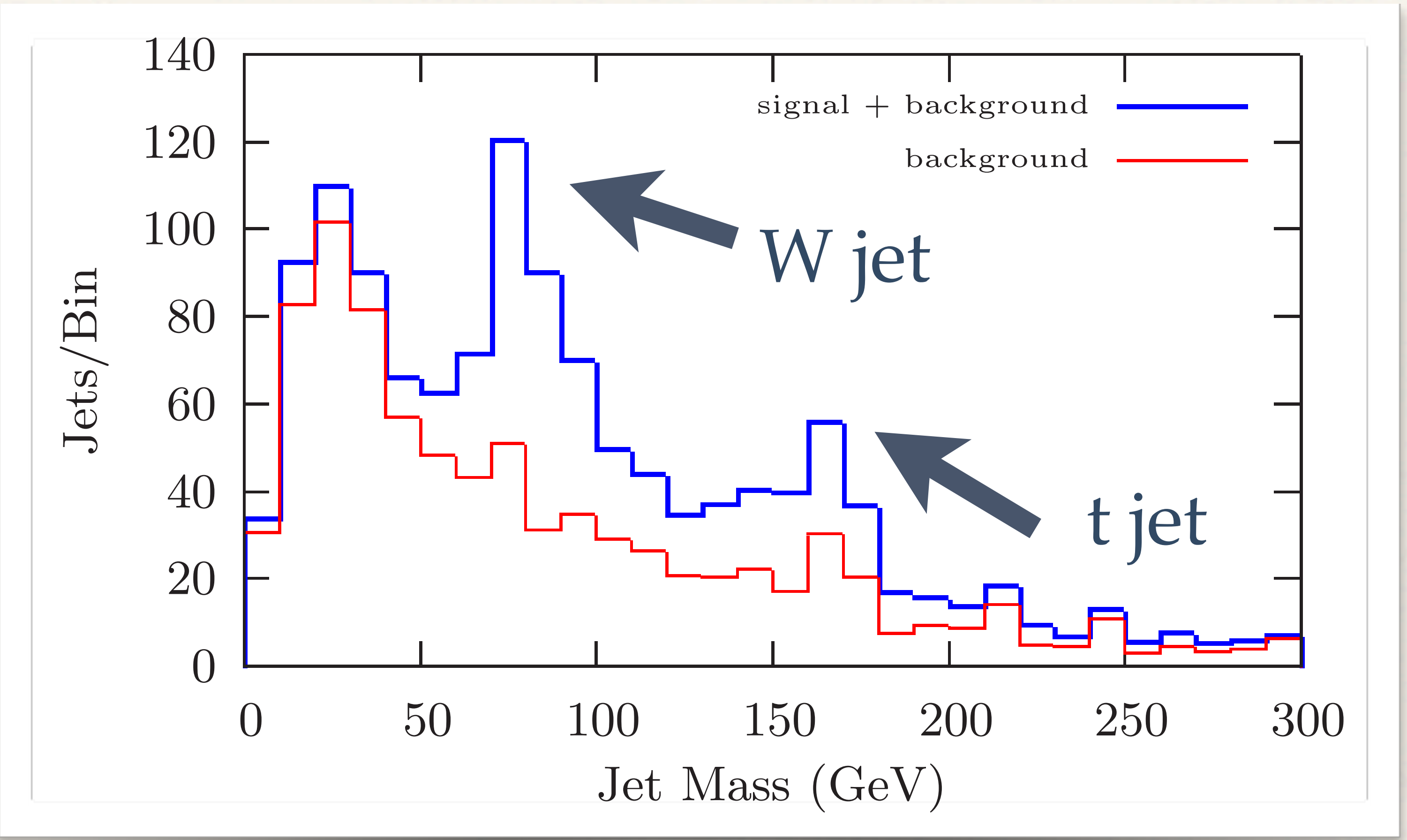
Hard splitting, energy shared equally

QCD Jet



Softer splittings. Unequal sharing of energy (note only one hard center)

- Moreover, QCD jets have a continuum mass distribution, while the jets of boosted heavy particles have a fixed mass.



- These will form our main tools as we study the jets of boosted objects:

  1. Jet internal radiation distribution

  2. Jet mass

Figure: Skiba, Tucker-Smith, [hep-ph/0701247]

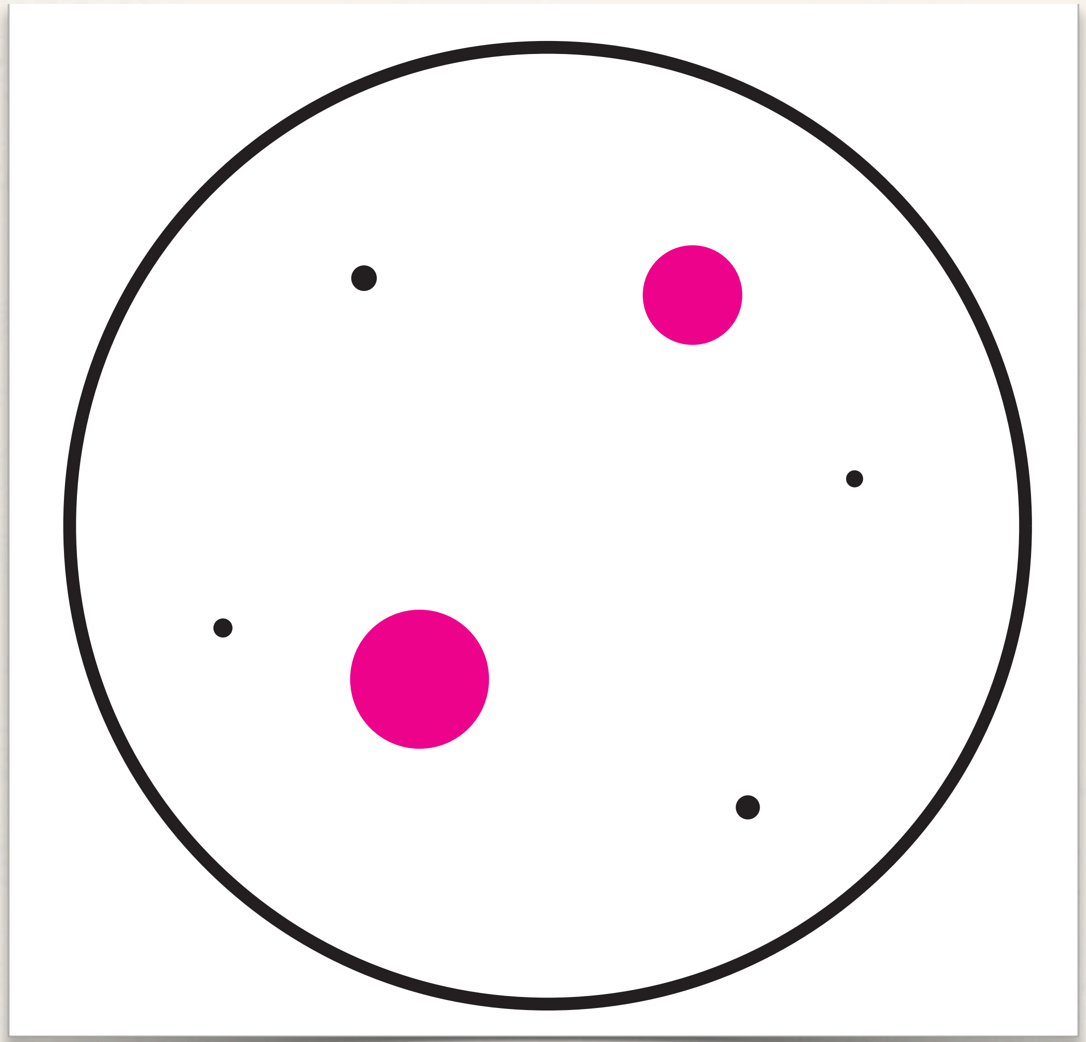
(1) Internal Radiation Distribution

- We can quantify the difference in appearance between QCD jets and the jets of boosted heavy particles.
  - Boosted objects tend to have a many hard prongs
  - QCD jets tend to have one central hard core
- Lots of jet shapes have been proposed. For instance (many more..):
  - Angularity: Almeida, Lee, Perez, Sterman, Sung, Virzi [0807.0234]
    - Measures how pencil-like/pancake-like a jet is
  - N-Subjettiness: Kim [1011.1493], Thaler, Van Tilburg [1011.2268]
    - How `N-prong like' does a jet look?

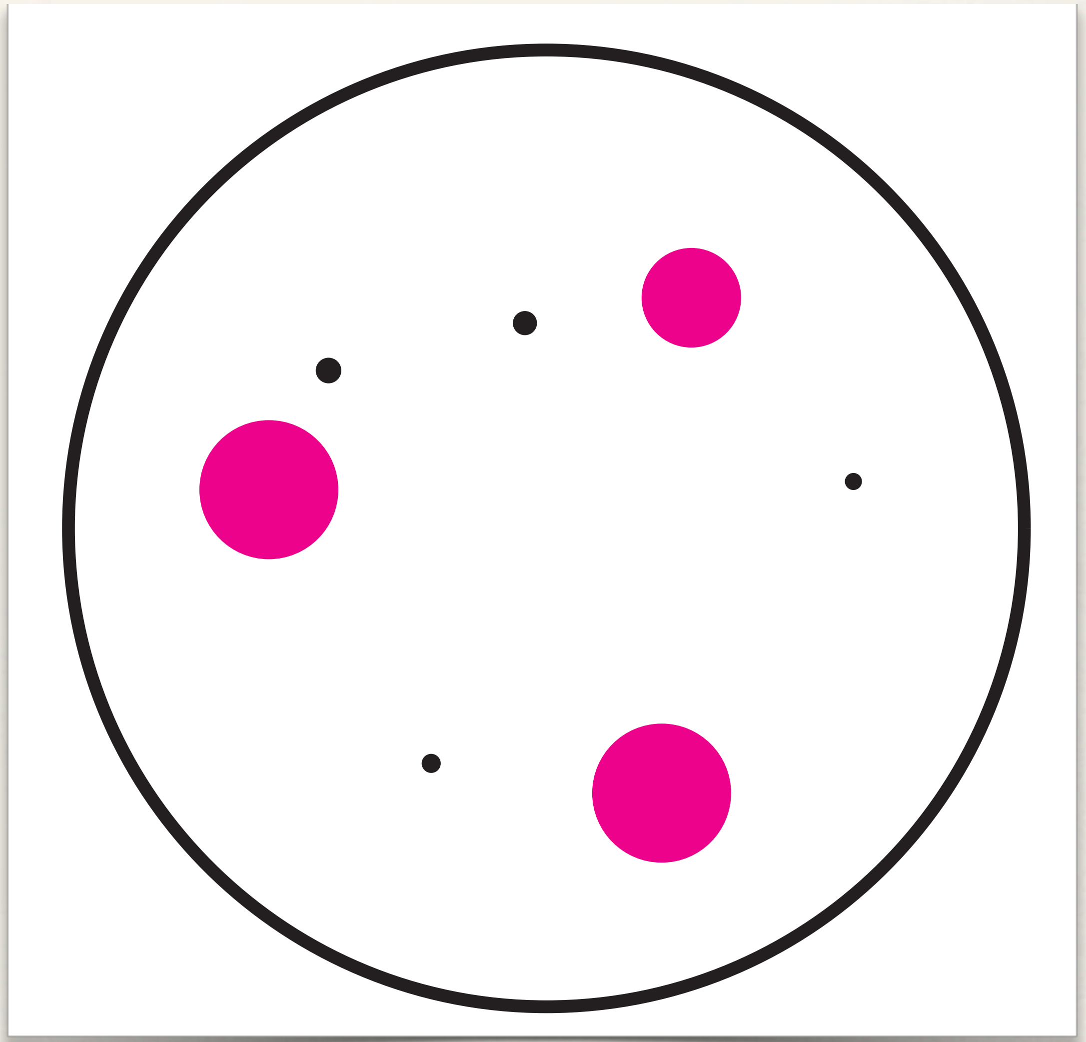
Example: Planar Flow

See Almeida, Lee, Perez, Sterman, Sung, Virzi [0807.0234] and Thaler, Wang [0806.0023]

QCD-like



Top-like



$$I_w^{kl} = \sum_i E_i \frac{p_{i,k}}{E_i} \frac{p_{i,l}}{E_i}$$

λ=Eigenvalues of I

$$\mathrm{Pf} = \frac{4\lambda_1\lambda_2}{(\lambda_1+\lambda_2)^2}$$

(2) Jet Mass

- A lot of work on boosted objects has gone into into improving jet mass reconstruction (i.e. *Jet Topiary*).
- These aim to discard `contamination'
- Techniques on the market:
  - Filtering [Butterworth, Davison, Rubin, Salam: 0802.2470]
  - Pruning [Ellis, Vermillion, Walsh: 0903.5081,0912.0033]
  - Trimming [DK, Thaler, Wang: 0912.1342]

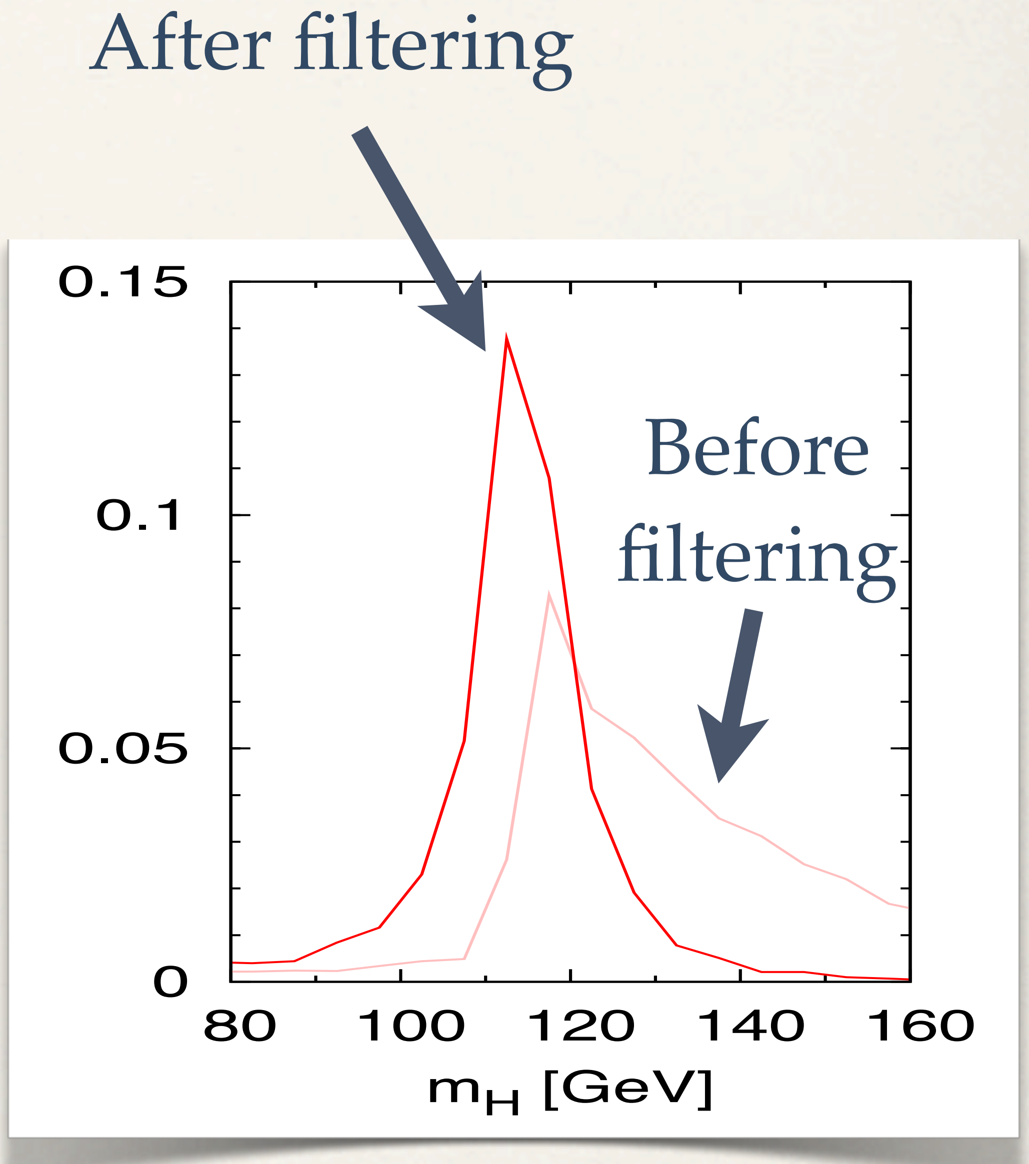
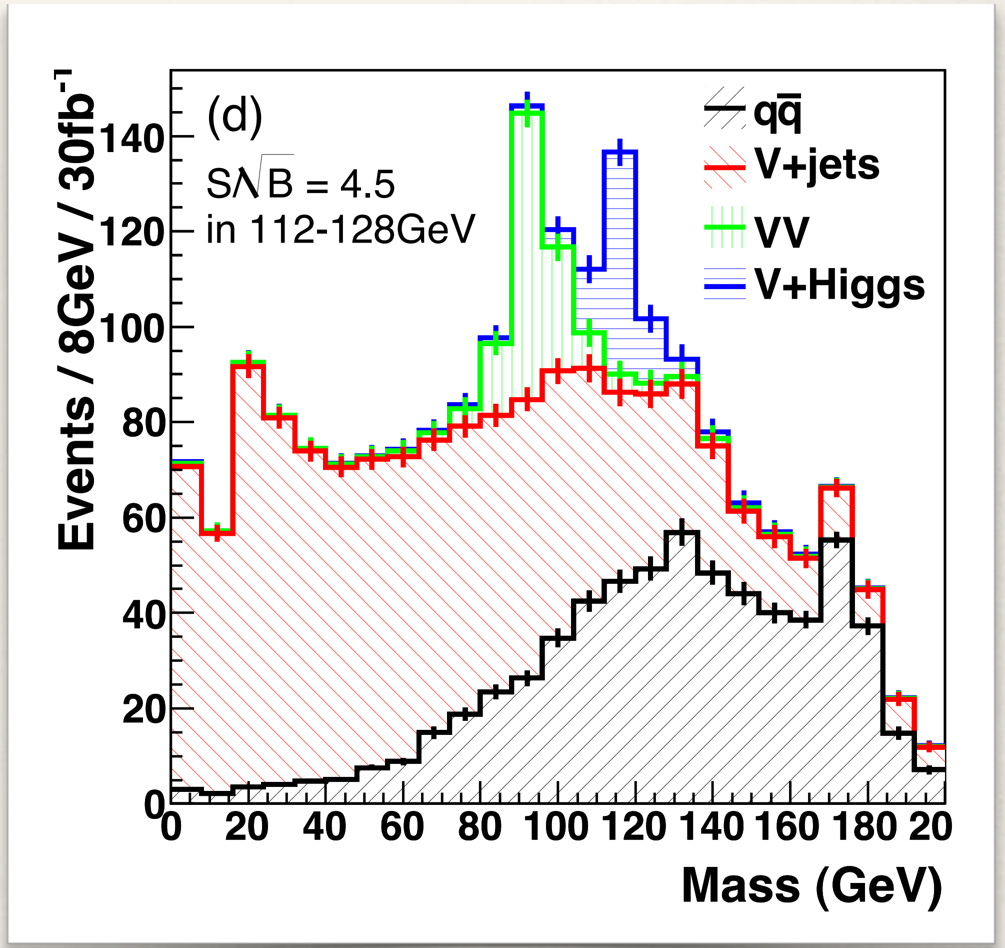


Figure: http://www.lpthe.jussieu.fr/~salam/talks/repo/2009-Princeton-BoostedHiggs.pdf

Recent Results

Higgs

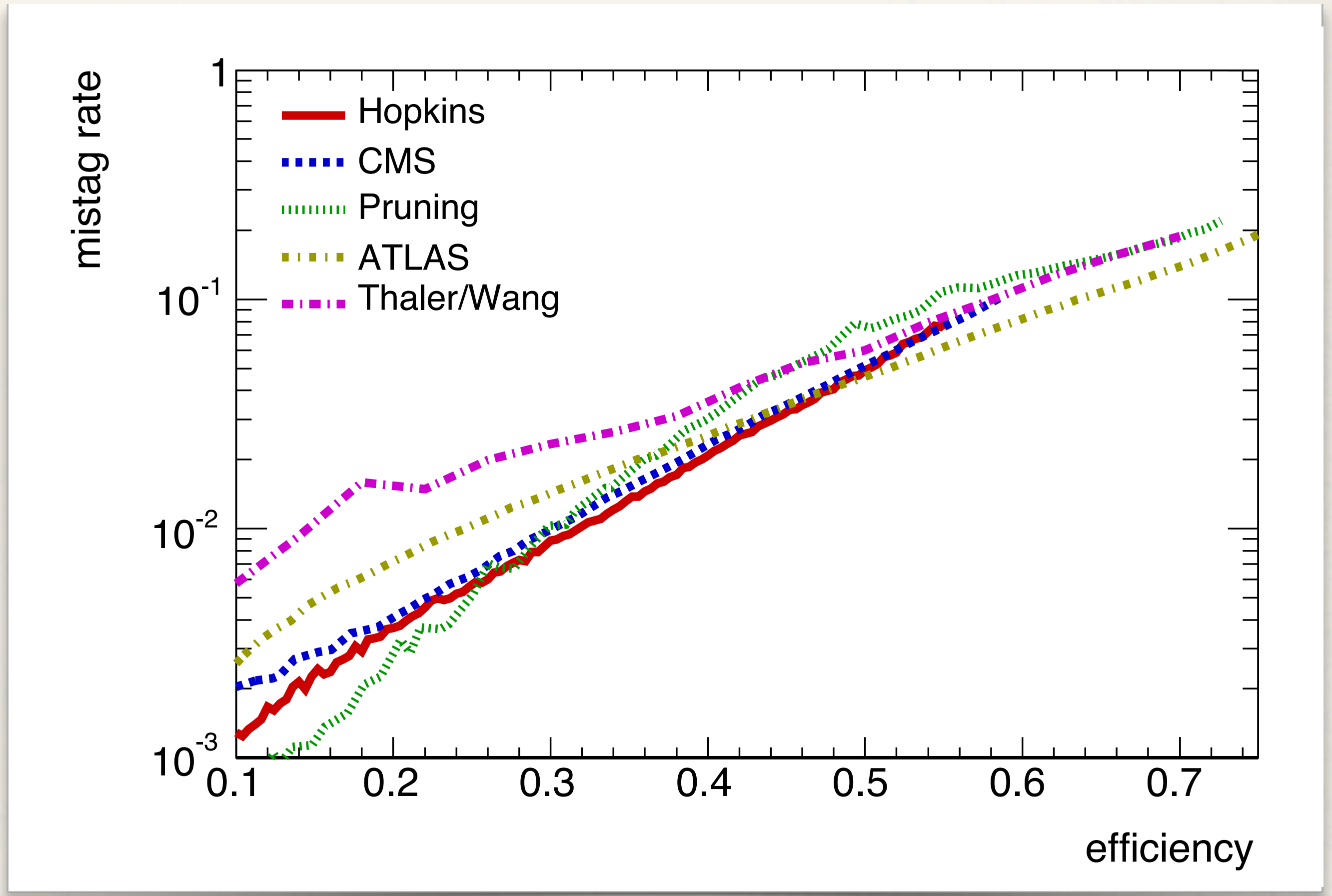
- One can look for boosted Higgses in Z/W+H with H->bb : Butterworth, Davison, Rubin, Salam [0802.2470]
  - 4.5 σ in 30 fb-1
- Another possibility is ttH: Plehn, Salam, Spannowsky [0910.5472]
  - Analysis uses `fat' jets (R=1.5)
  - Useful algorithm for finding mildly boosted tops.
    - `HEP' tagger (Heidelberg, Eugene, Paris)



Source: 0802.2470

Tops

- Top tagging is now a well studied topic
- Many established tagging techniques:
  - Kaplan, Rehermann, Schwartz, Tweedie [0806.0848]
  - Thaler, Wang [0806.0023]
  - Almeida, Lee, Perez, Sterman, Sung, Virzi [0807.0234]

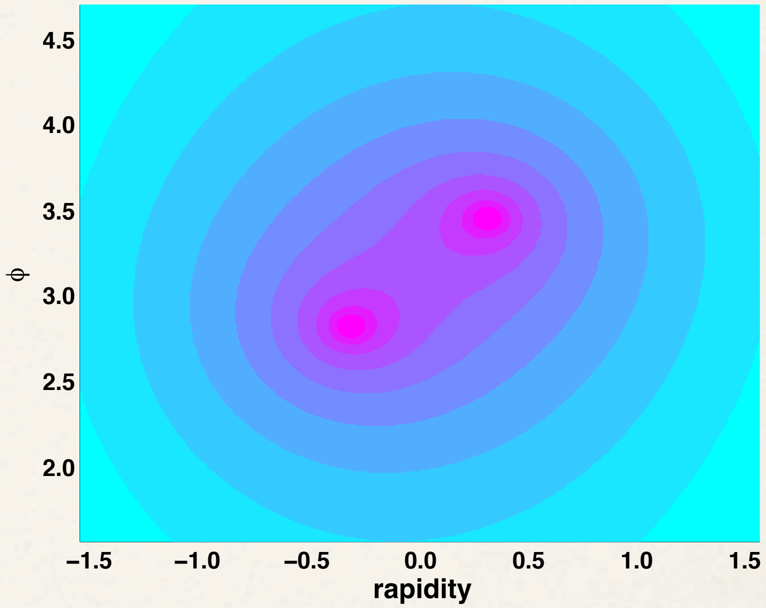


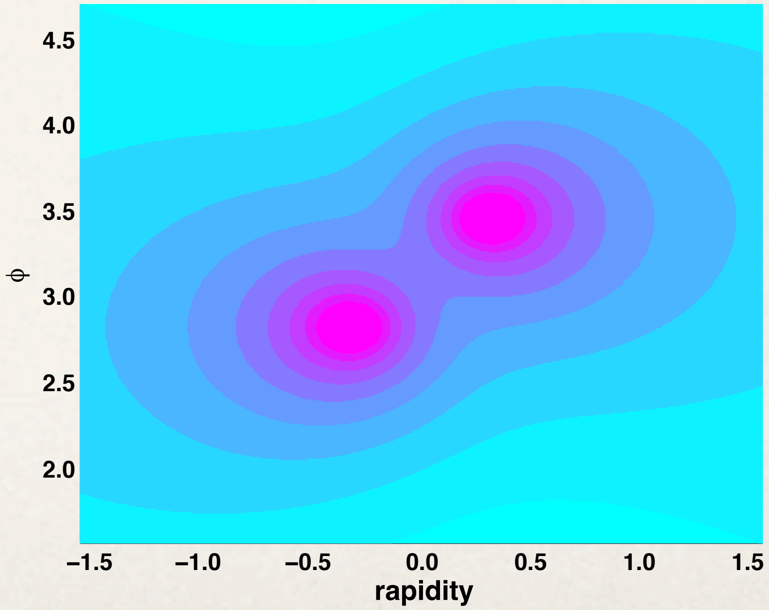
Roughly comparable efficiencies

Figure source: 1012.5412

Ever more sophisticated techniques

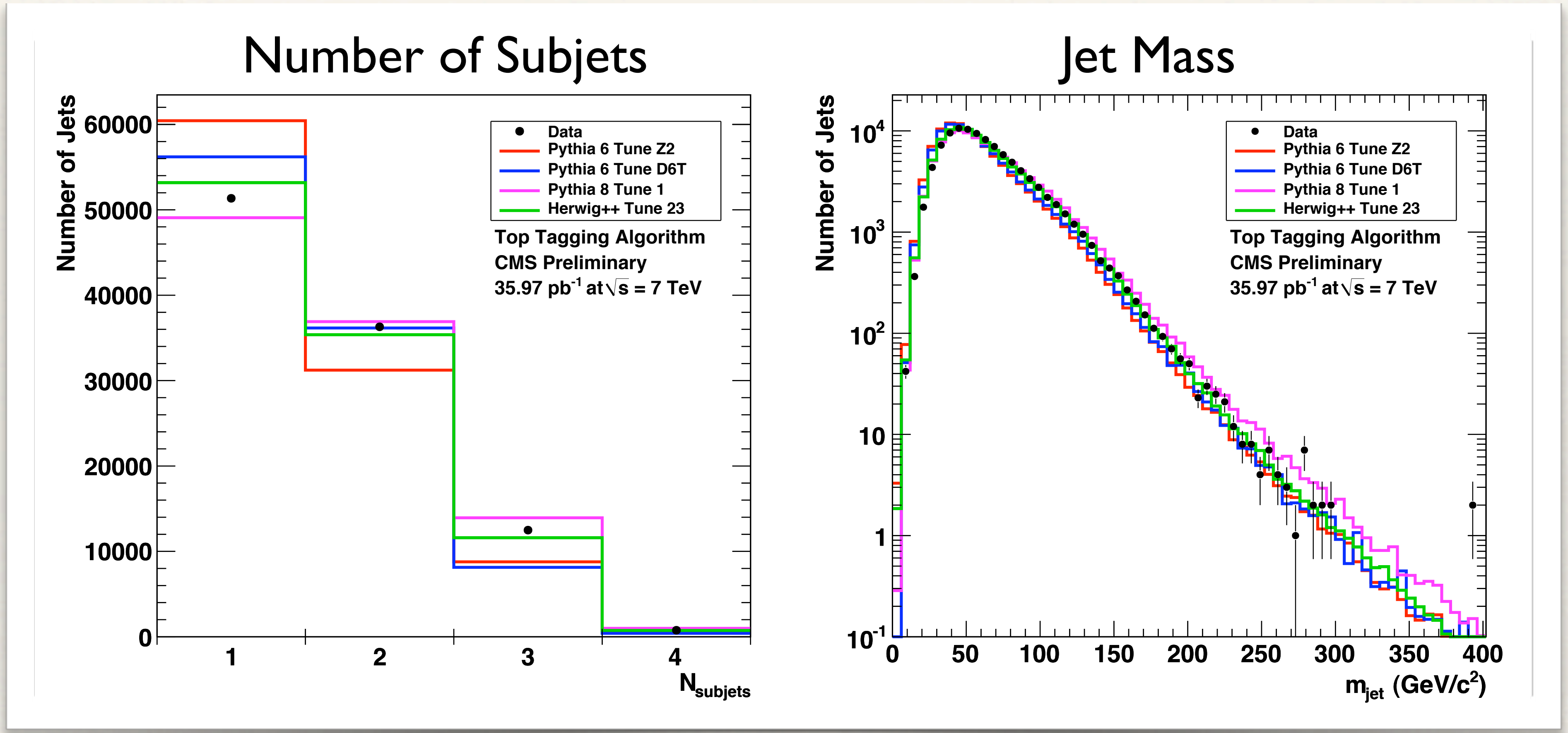
- Measure hadronic top polarization: DK, Shelton, Wang [0909.3855]
- Measure fit to radiation profile: Almeida, Lee, Perez, Sterman, Sung [1006.2035]
- Top identification taking into account color singlet nature of W: Hook, Jankowiak, Wacker [1102.1012]





Source: 1102.1012

- LHC experiments are going to use these techniques
- Validation has started using QCD data.
- MC and experiment agree well:



- Herwig++ seems to show the best agreement

Source: http://www.physics.uoregon.edu/~soper/Jets2011/Dolen.pdf

W/Z

- Measure W polarization in vector boston fusion to distinguish anomalous Higgs couplings: DK, Han, Wang, Zhu [0911.3656]
- Multivariate methods sensitive to radiation pattern: Cut, Han, Schwartz [1012.2077]
- Applications to Z′ physics: Katz, Son, Tweedie [1010.5253]

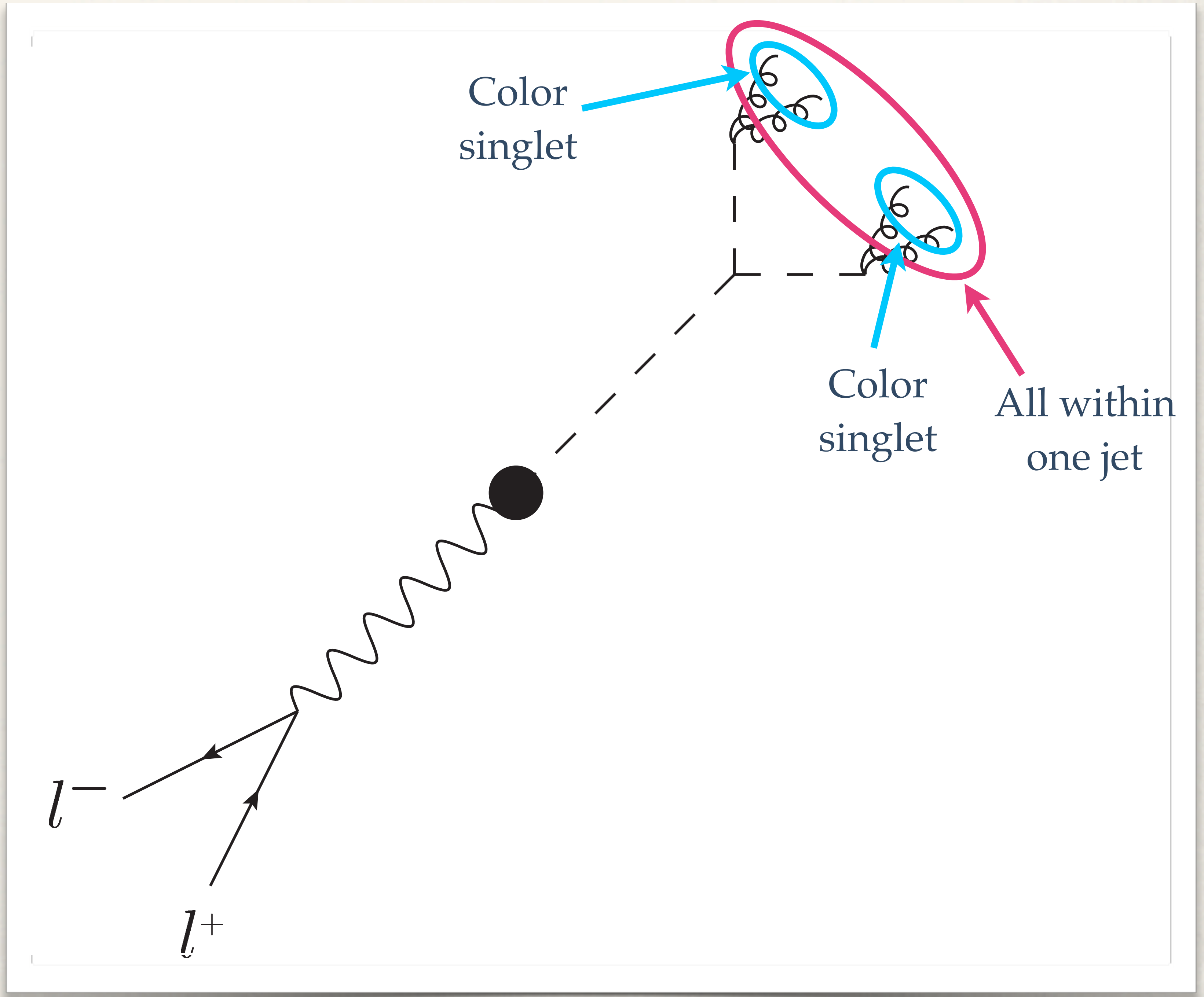
Applications in BSM Physics

Significant Benefits Using Substructure

- TeV scale BSM physics coupling to EW scale particles -> boosted objects!
- BSM events are complicated - jet substructure aids in reconstruction (HEP tagger)
- Substructure can resolve color structure - useful for exotic decays.

Qualitatively New Measurements

- In `Buried Higgs' models the Higgs decays to two scalars, which subsequently decay to gluons
- h>2a>4g
- Substructure methods can look for color singlet nature of scalar: see details in [1006.1650]



- Some examples (incomplete list):
  - Neutralino decays: Butterworth, Ellis, Raklev, Salam [0906.0728]
  - SUSY Higgses (often result from SUSY cascade decays):
    - Kribs, Martin, Roy, Spannowsky [0912.4731,1006.1656]
  - Exotic Higgses:
    - Chen, Nojiri, Sreethawong: [1006.1151]
    - Falkowski, DK, Shelton, Thalapillil, Wang [1006.1650]
    - Bellazzini, Csaki, Hubisz, Shao [1012.1316]
  - Boosted gluinos from heavy squarks: Fan, DK, Mosteiro, Thalapillil, Wang [1102.0302]

Conclusions

- At the LHC, particles with EW scale masses are often so energetic (i.e. boosted) their decay products are lumped together into a single jet.
- By looking at the radiation inside jets we find we can identify these particles and learn about their properties (e.g. polarization).
    - This leads to a marked improvement in discover reach.
- Techniques already undergoing validation with LHC data. Promising results!
- See the proceedings of Boost 2010 [1012.5412] for more discussion.

http://boost2011.org