Boosted Jets

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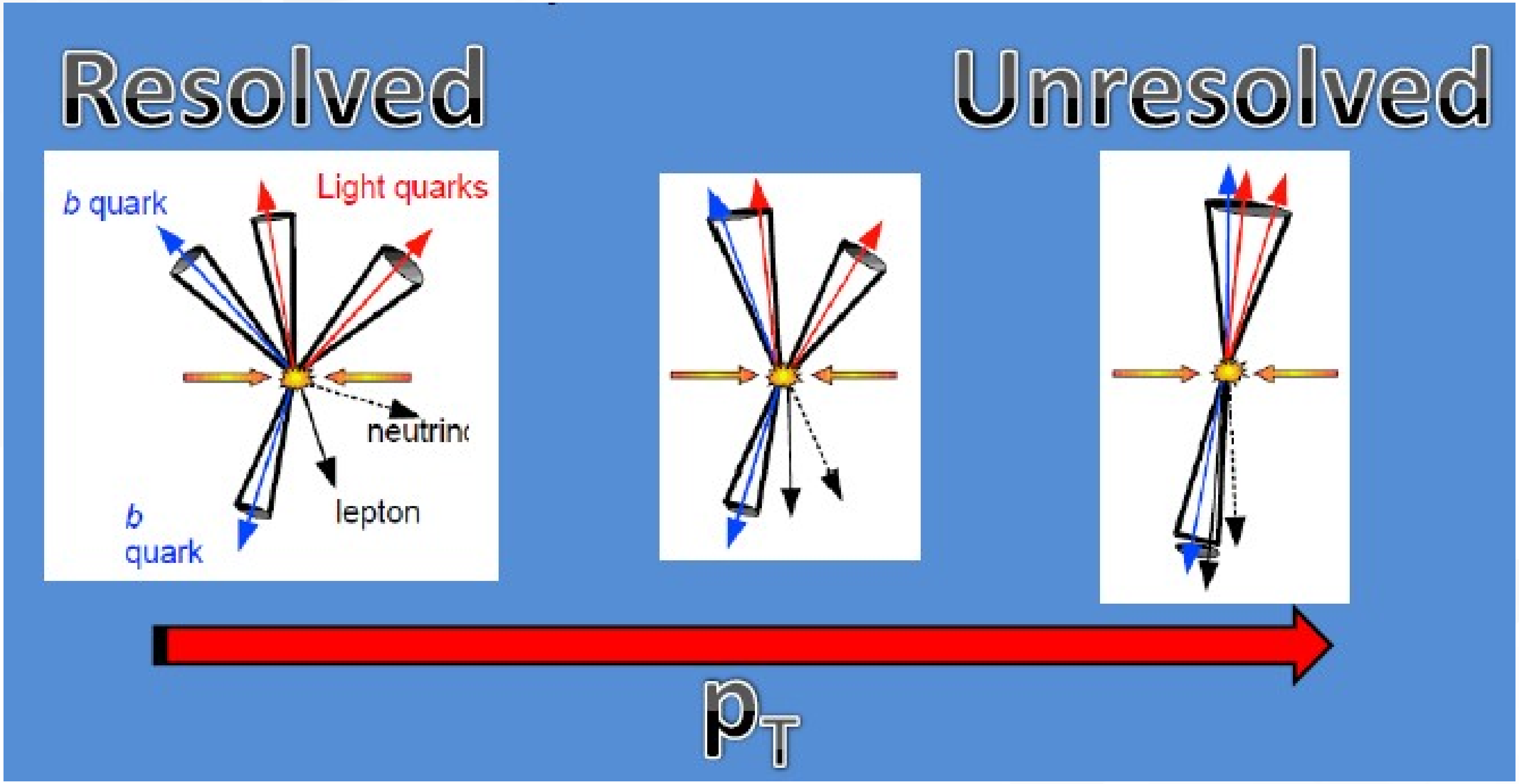
- 24th Rencontres de Blois
- Château Royal de Blois, May 27-June 1 2012

Motivation

- A very heavy object (e.g. Z', KK gluons) decays to something lighter (t,W/Z,H,...), which is then given a boost
- A massive particle (t,W/Z,H,...) recoils against other energetic objects, so it's produced with high transverse momentum
- Jets with high transverse momentum and high mass are a playground for testing perturbative QCD

Why substructure?



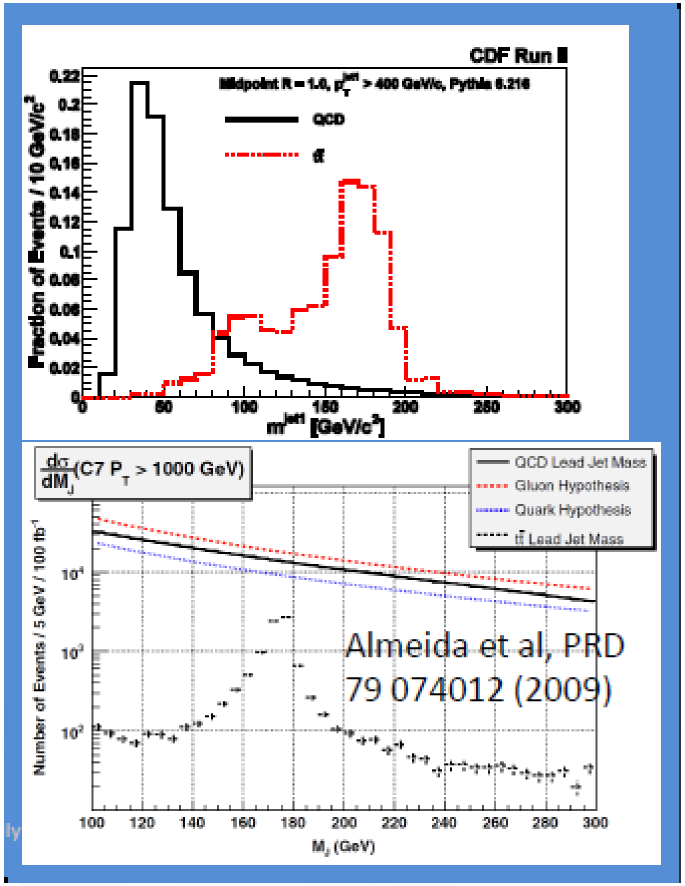
At high enough pT, their decay products will appear as heavy, collimated jets

But... QCD is our enemy

- The signal is not easily separated from the background
- Even such exotic states will coexist with substantial tail of the mass distribution of light parton QCD jets.

$$\frac{1}{\sigma}\frac{d\sigma}{dM^2} \sim \frac{1}{M^2}\frac{\alpha_s C_i}{\pi}\left(\ln\frac{R^2 p_t^2}{M^2} + \mathcal{O}(1)\right)$$

- Thus, it will generaly be necessary to use jet substructure systematically to identify the states that initiated the jets



Background rejection, basic approaches

Not an exhaustive list

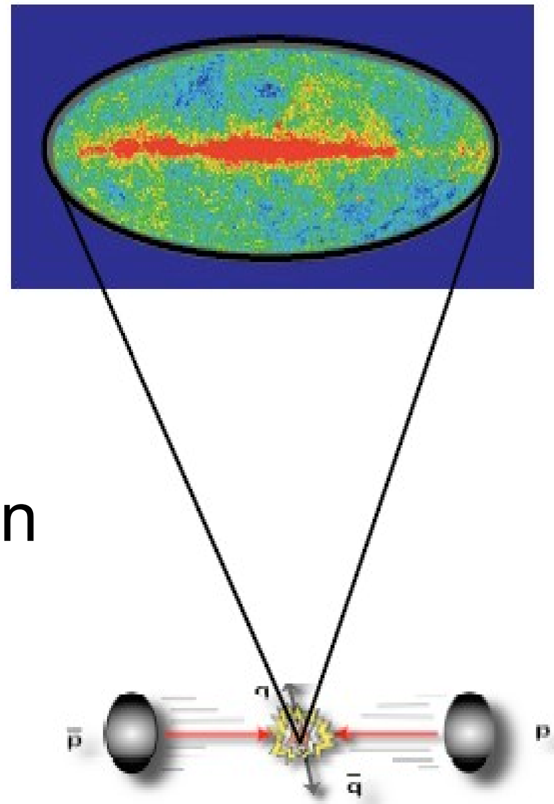
- Filtering
  - Butterworth, Cox, Forshaw;
  - Thaler, Wang;
  - Kaplan, Rehermann, Schwartz, Tweedie;...
  - Butterworth, Davison, Rubin, Salam;
  - Plehn, Salam, Spannowsky;
  - Ellis, Vermilion, Walsh;
  - Krohn, Thaler,Wang;...
- Jet shapes

  Almeida, Lee, Perez, Sterman, Sung, Virzi
  Gur-Ari,Papucci, Perez; Kim, Thaler & Van Tilberg, ...
- Template function

  Almeida, Lee, GP, Sterman & Sung (10).

Need to understand the energy flow inside jet

- Find observable correlated with parton shower and hadronization
- Jet cross sections are naturally described in terms of correlation functions of energy flow
- Energy flow is also a natural language for the description of jet substructure



- IR-safe observables sensitive to the distribution of energy within the jets
- Today's examples
  - Jet shapes
  - Template functions

(All-purpose taggers; More amenable to pQCD calculations, weak jet finder dependence)

Jet shape: Angularity

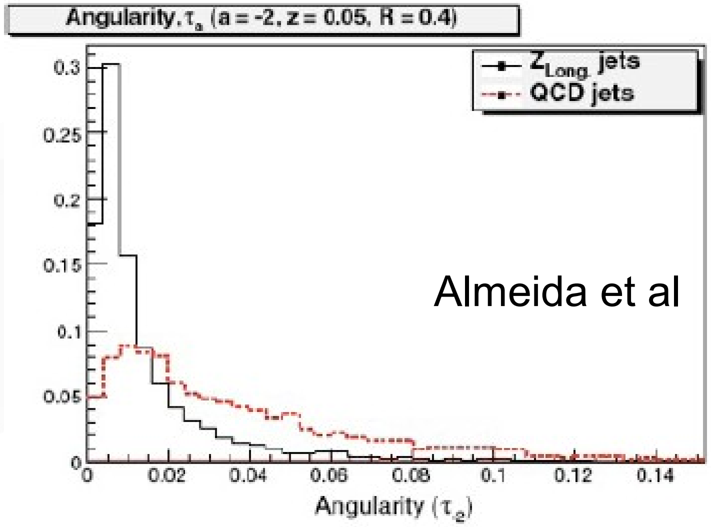
Angularity distinguishes between QCD jets and other two-body decays.

$$\tau_a(R, p_T) = \frac{1}{m_J} \sum_{i \in jet} \omega_i \sin^a \theta_i \left[1 - \cos\theta_i\right]^{1-a}$$

- ωi component's energy
- θi angle w.r.t. the jet axis
- a≤2 ensures IR safety, we use a=-2

- QCD $$\frac{d^2\sigma}{dm_J^2 d\theta} \propto \alpha_s \frac{C_F}{m_J^2} \frac{1}{\theta}\bigg|_{R>\theta>\frac{m_J}{E_J}}$$

- Higgs $$\frac{d^2\sigma}{dm_J^2 d\theta} \propto \delta(m_J^2 - m_H^2) \frac{1}{\theta^3}\bigg|_{R>\theta>\frac{m_J}{E_J}}$$



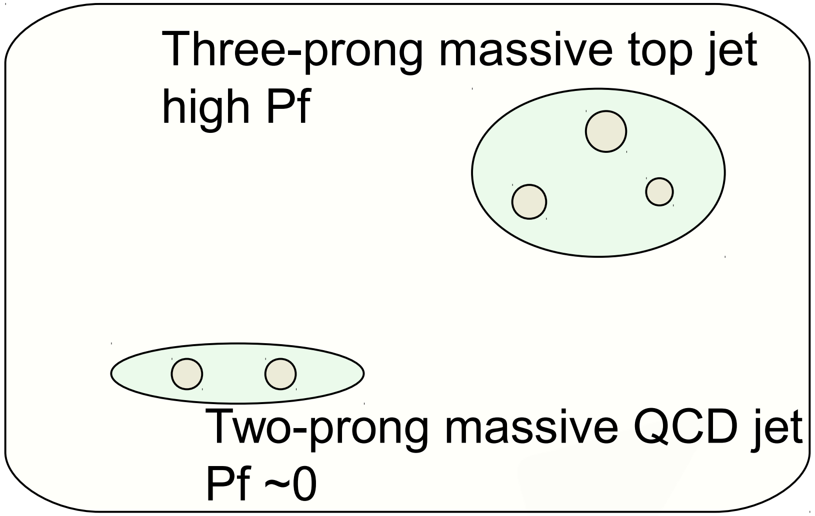
Almeida et al

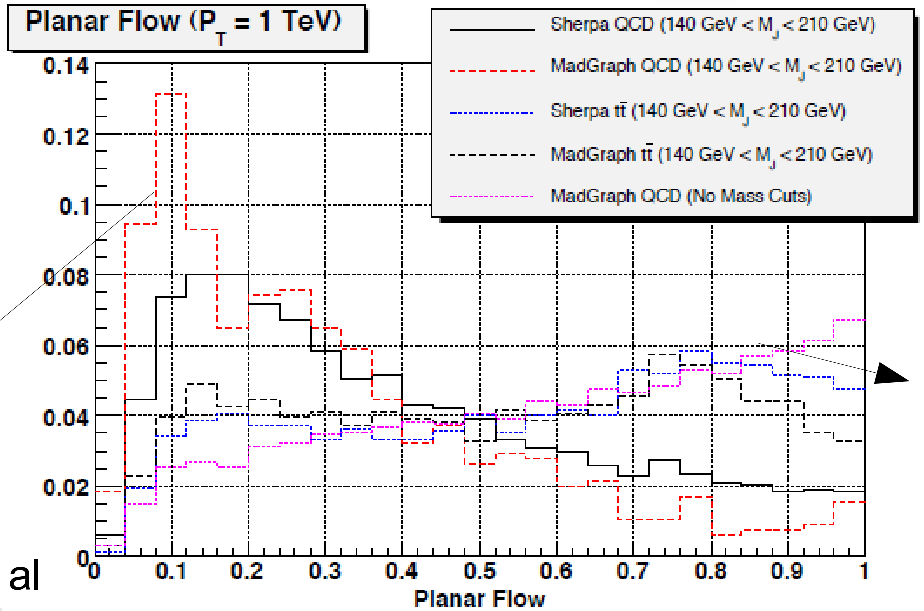
Jet shape: Planar flow

- IR-safe jet shape that distinguishes planar from linear configurations
- Vanishes for linear shapes and approaches unity for isotropic depositions of energy

$$I_\omega^{kl} = \frac{1}{m_J} \sum_i \omega_i \frac{p_{i,k}}{\omega_i} \frac{p_{i,l}}{\omega_i}$$

$$\mathrm{Pf} = \frac{4 \det I_\omega}{(\mathrm{tr} I_\omega)^2}$$





Almeida et al

Template Overlap Method

L. Almeida, S. Lee, G. Perez,
G. Sterman, & I. Sung '10

- Functional measure for the quantitative comparison of the energy flow of observed jets at high-pT with the flow of selected sets (the templates) of partonic states

$$\langle j|f\rangle = \mathscr{F}\left[\frac{dE(j)}{d\Omega}, \frac{dE(f)}{d\Omega}\right]$$

- Our templates will be sets of partonic momenta $f = \{p_1, p_2, \ldots, p_n\}$

$$\sum_{i=1}^{N} p_i = P, \; P^2 = M^2$$

- For a given jet j, we determine the template state f[j] for which the measure is maximized:

$$Ov(j,f) = \max_{\{f\}} \mathcal{F}(j,f)$$

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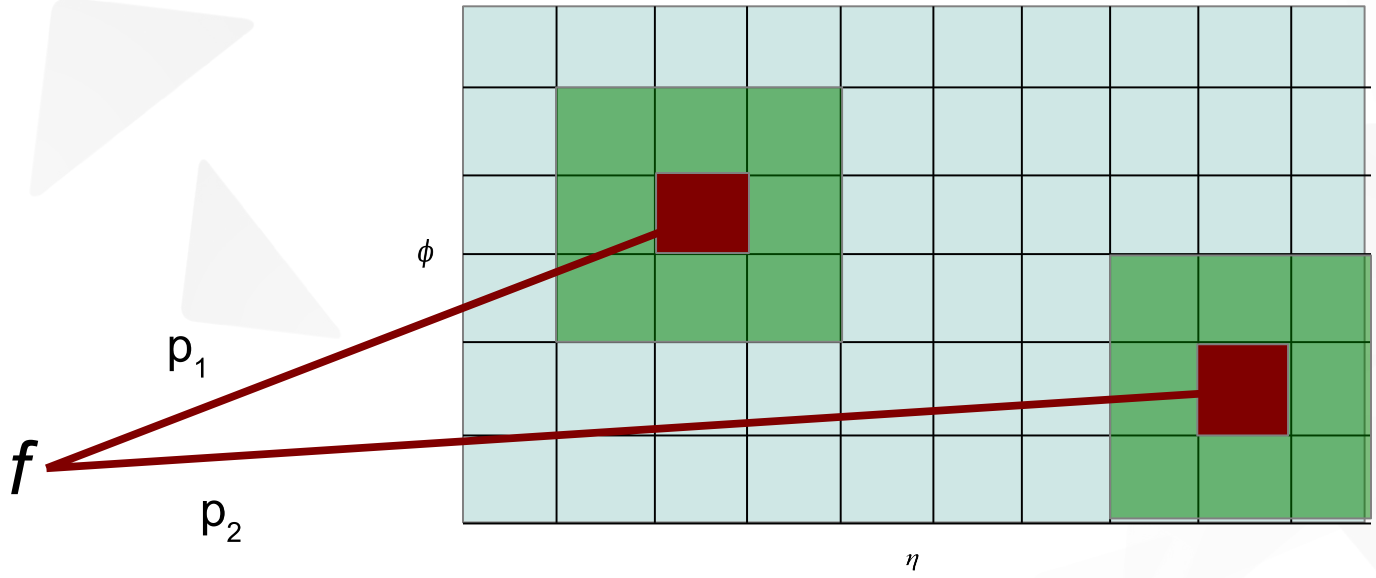
Example

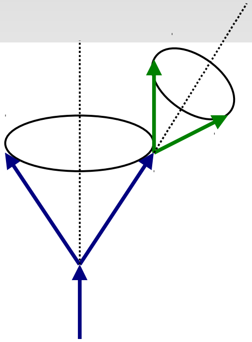
- We compute the overlap between data state j and N-body template f from the sum of the energy in the nine cells of state j surrounding and including the cells of template f

$$Ov_N(j,f) = \max_{\tau_N^{(R)}} \exp\left[-\sum_{a=1}^{N} \frac{1}{2\sigma_a^2} \left(\sum_{k=i_a-1}^{i_a+1} \sum_{l=j_a-1}^{j_a+1} E(k,l) - E(i_a, j_a)^{(f)} \right)^2 \right]$$



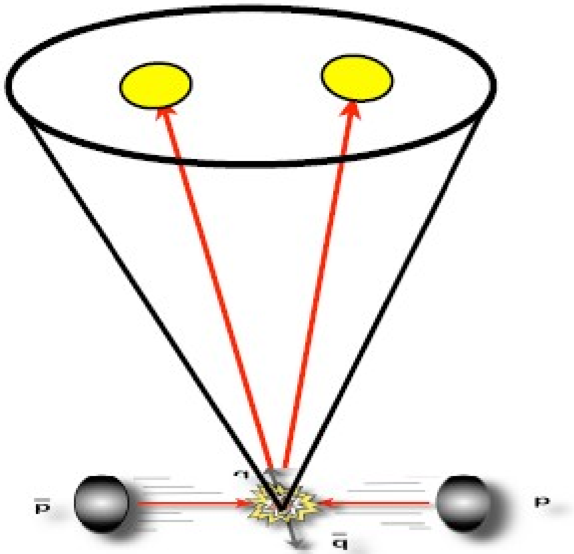
Three-Particle Templates and Top Decay

- At LO, top decay has a simple three-body kinematics

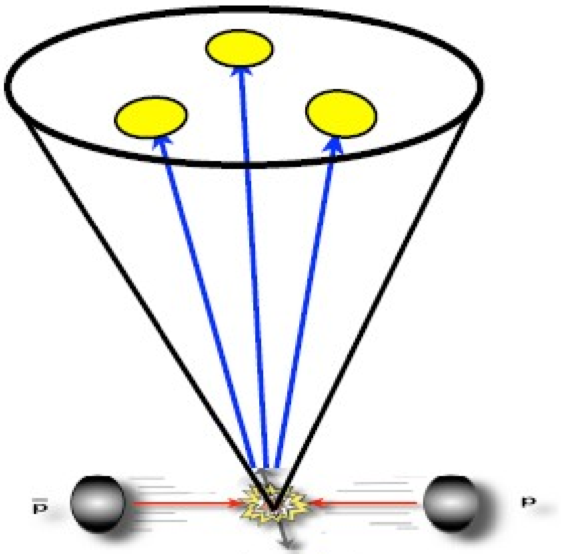


$$t \to b + W \to b + q + \bar{q}. \quad \text{with} \quad (p_q + p_{\bar{q}})^2 = M_W^2$$

- While we expect high mass, QCD jets have a two-subjet topology



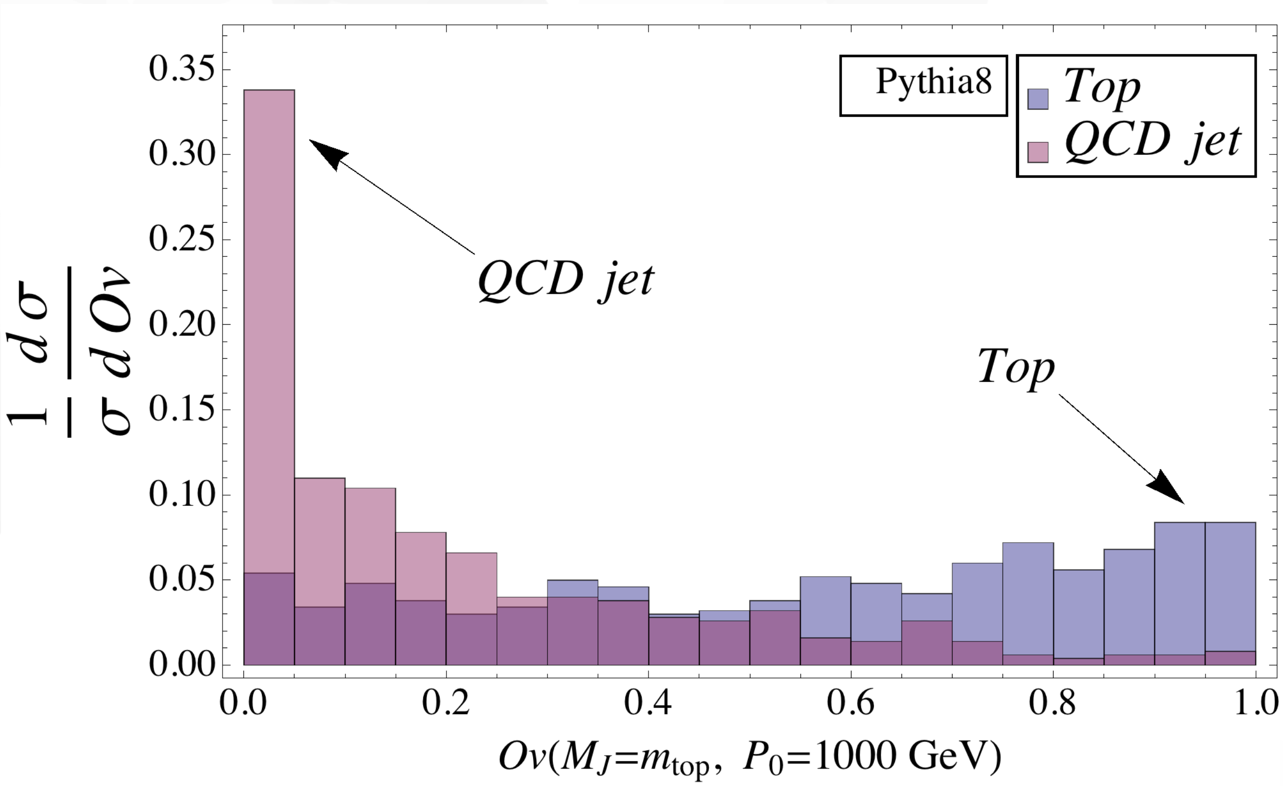
QCD massive jet



top jet

Three-Particle Templates and Top Decay

L. Almeida, S. Lee, G. Perez,
G. Sterman, & I. Sung '10



Jet mass and pT:

$160\ \text{GeV} < m_J < 190\ \text{GeV}$,

$950\ \text{GeV} < E_J < 1050\ \text{GeV}$

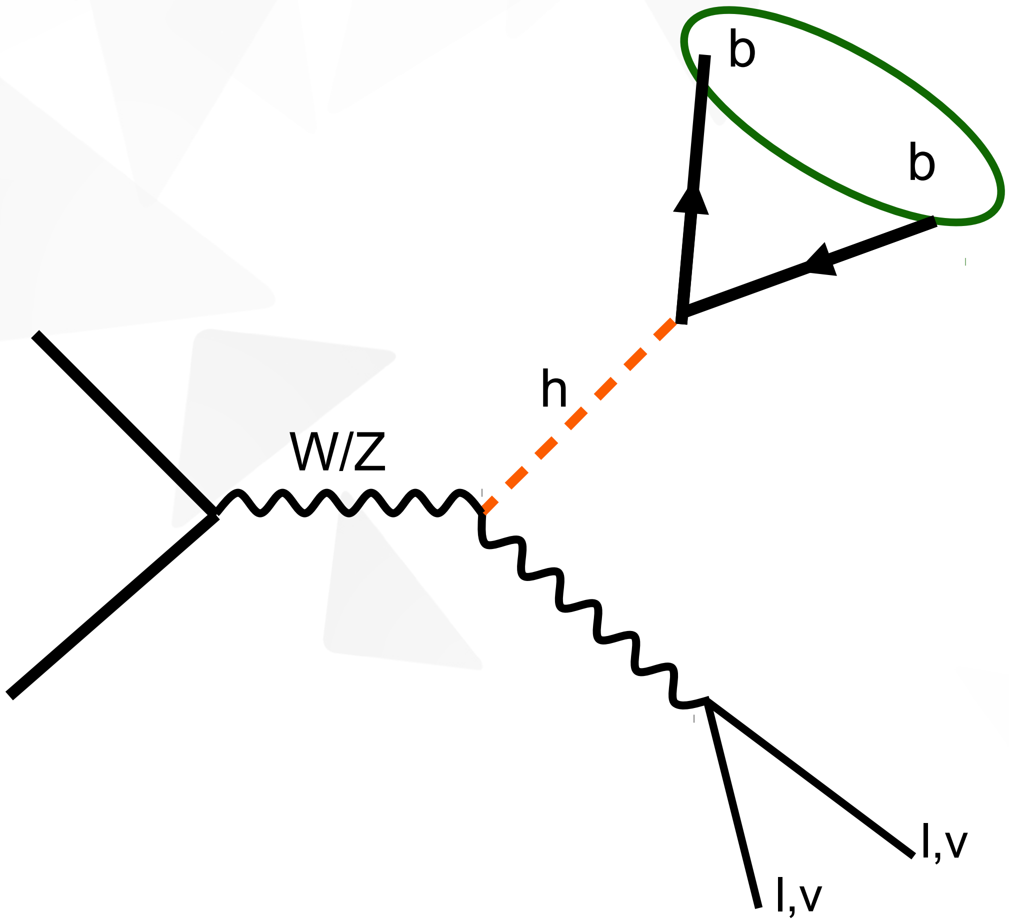
Jets found with anti-kt algorithms D=0.5

Can be combined with Planar flow to distinghuish between many three-jet events with large overlap.

Search For Boosted Higgs

Butterworth, Davison, Rubin, Salam (2008)

- Look for associated WH and ZH production
- Use the leptonic decay mode of the W/Z to suppress QCD bkg



$$h \to b\bar{b}$$

$$\Delta R \sim 2m_H/p_T$$

$$p_T^j = 200\,\mathrm{GeV}$$

$$\Rightarrow \Delta R \sim 1.2$$

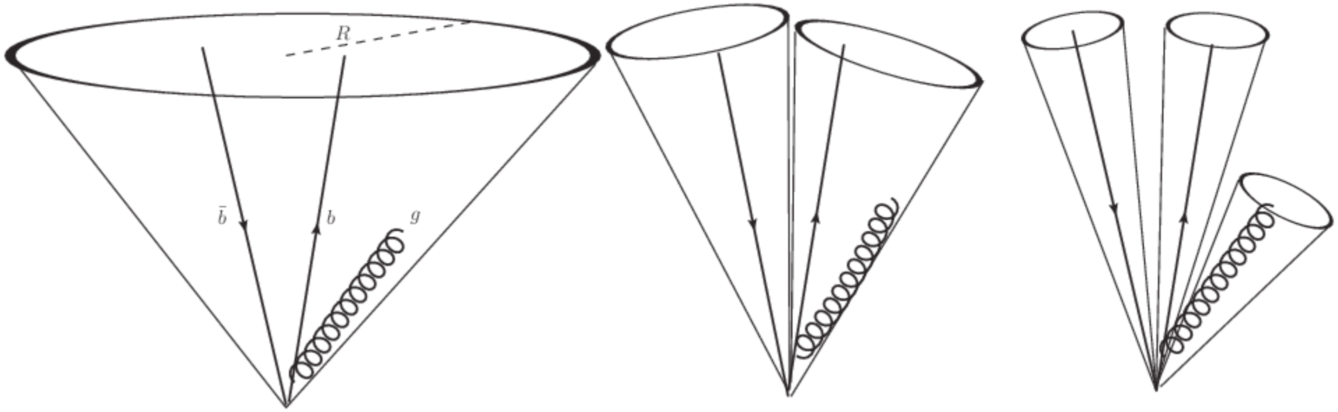
Typical jet size

$$\Delta R \sim 1.2$$

First look at the overlap observables

L. Almeida, O. Erdogan, JJ, S. Lee, G. Perez, & G. Sterman (1112:1957)

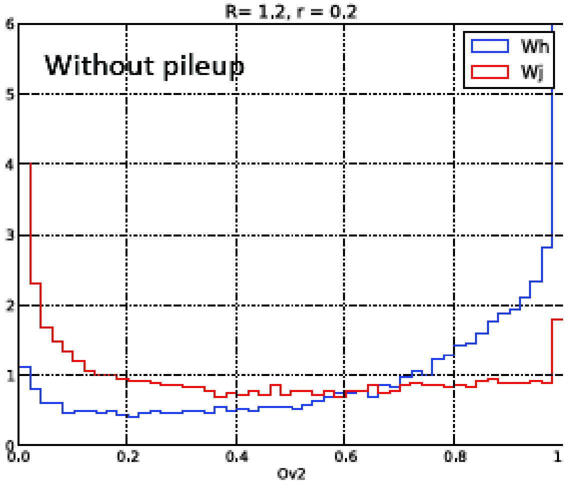
M. Backovic, JJ, G. Perez and J. Winter, in preparation.



$$|f\rangle = |h\rangle^{(\mathrm{LO})} = |p_1, p_2\rangle$$

$$|f\rangle = |h\rangle^{(\mathrm{NLO})} = |p_1, p_2, p_3\rangle$$

$p_T \sim 200\,\mathrm{GeV}$



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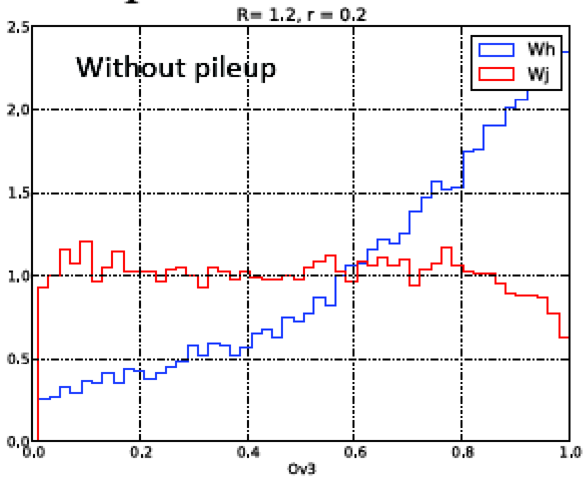
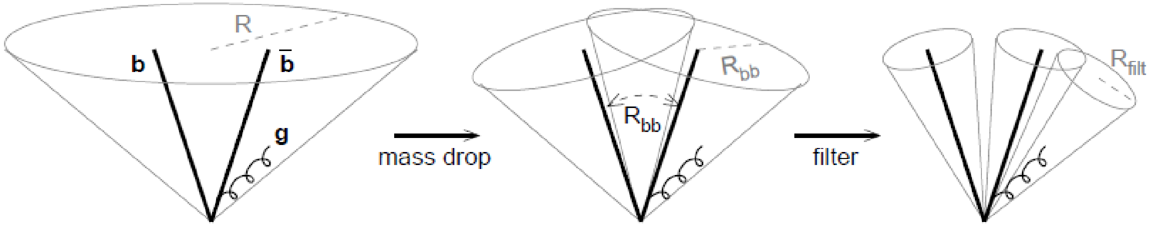


Can use best matched template to compute other shapes: angularities, Pf,...

Other approaches: Grooming ideas, hybrid shapes

- Filtering (Butterworth, Davison, Rubin, Salam)
  - Split jets into two subjets with significantly lower mass and filter with smaller cone to eliminate UE/pileups



- Pruning (Ellis, Vermilion, Walsh)
  - Jet is reclustered to ignore the junk
- Trimming (Krohn, Thaler, Wang)
  - Remove regions of the jet with low energy density
- N-subjettiness, dipolarity
  - Hybrid jet shapes, which describe the energy flow of a jet with respect to candidate subjet axes (determined using filtering)
  - above

Conclusions

- Plenty of ideas for background rejection and understanding jets in a new kinematic regime: very active field
- Jet shapes and Template functions are more amenable for pQCD calculation
- The method seems robust against pileup effects: incoherent stuff does not affect spiky hard part of signal
- Perform a complete VH $H \rightarrow bb$ analysis
  - Refine the selection, include also b-tagging
  - Estimate the background
  - ATLAS affiliated Template Overlap "Task Force" formed at the Weizmann Institute.

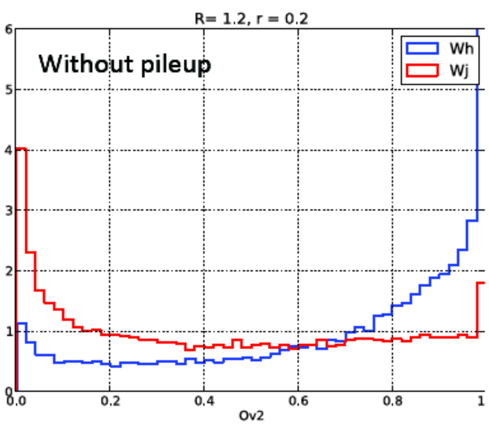
Stay tuned...

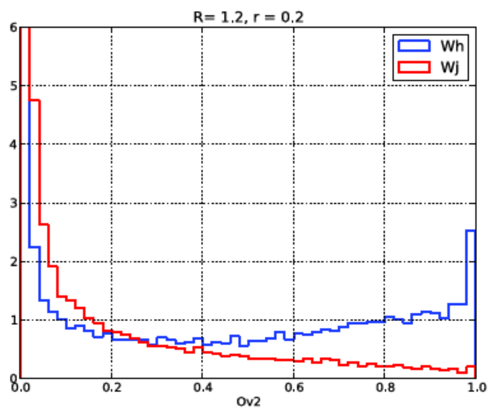
Thanks!

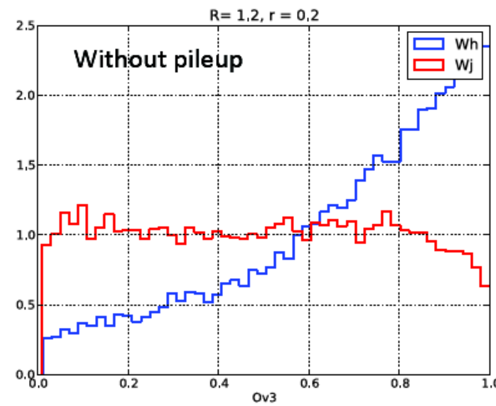
Pileup effects

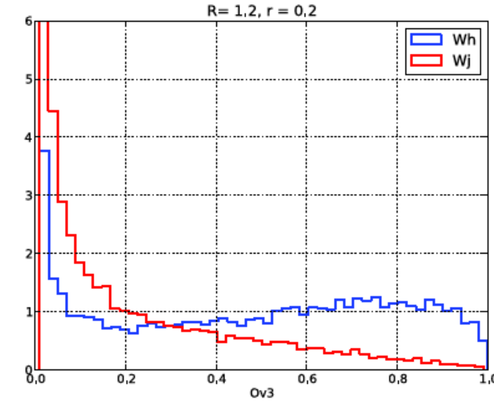
Two-Body Overlap w/pileup

Three-Body Overlap w/pileup









Pileup

Pileup

As expected, pileup pushes both distributions towards lower values of maximum overlap.

Pythia8, 2.5 Low pileup

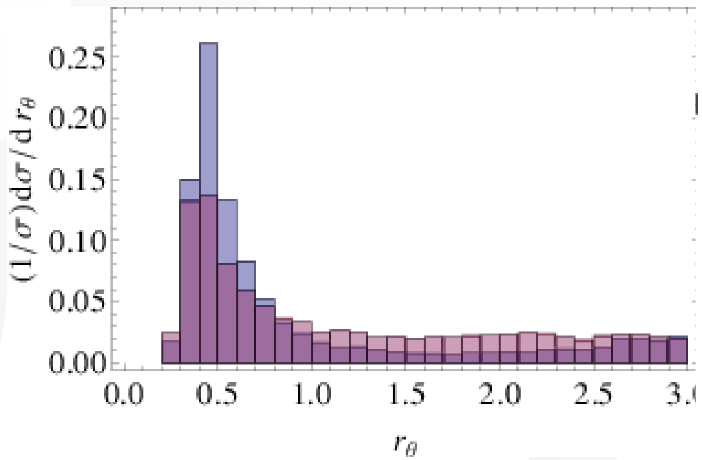
- Pile up yields lots of soft incoherent deposition
- Does not affect the spiky hard part of the signal

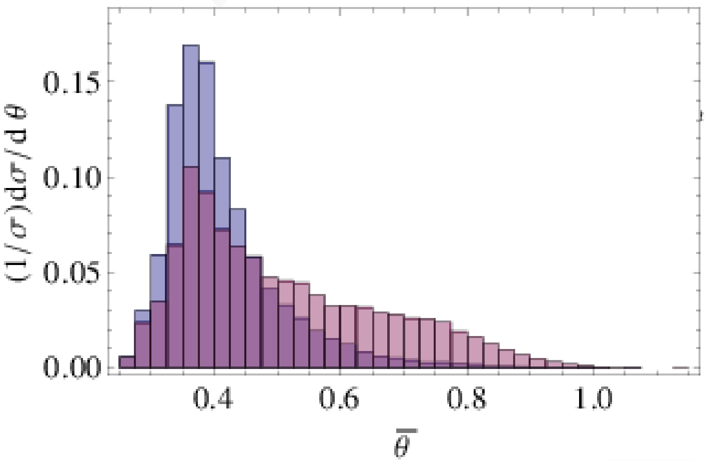
Best matched template dist.

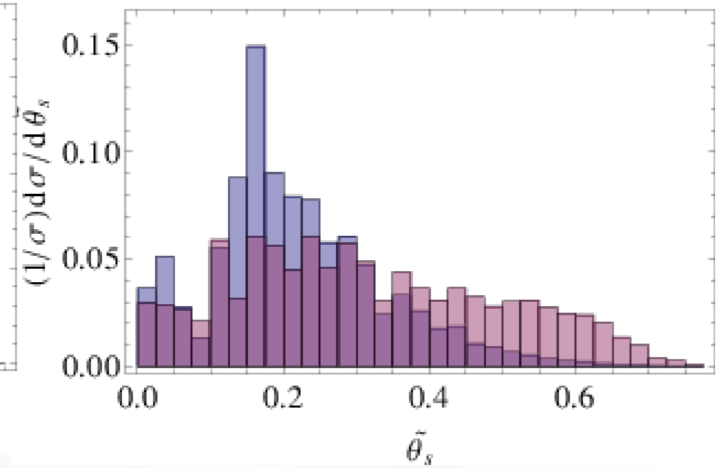
- We can analyze angular distributions of template partons

Max. Ov: *f*[*j*]

Kinematical variables |*f*> ⟷ Jets |*j*>





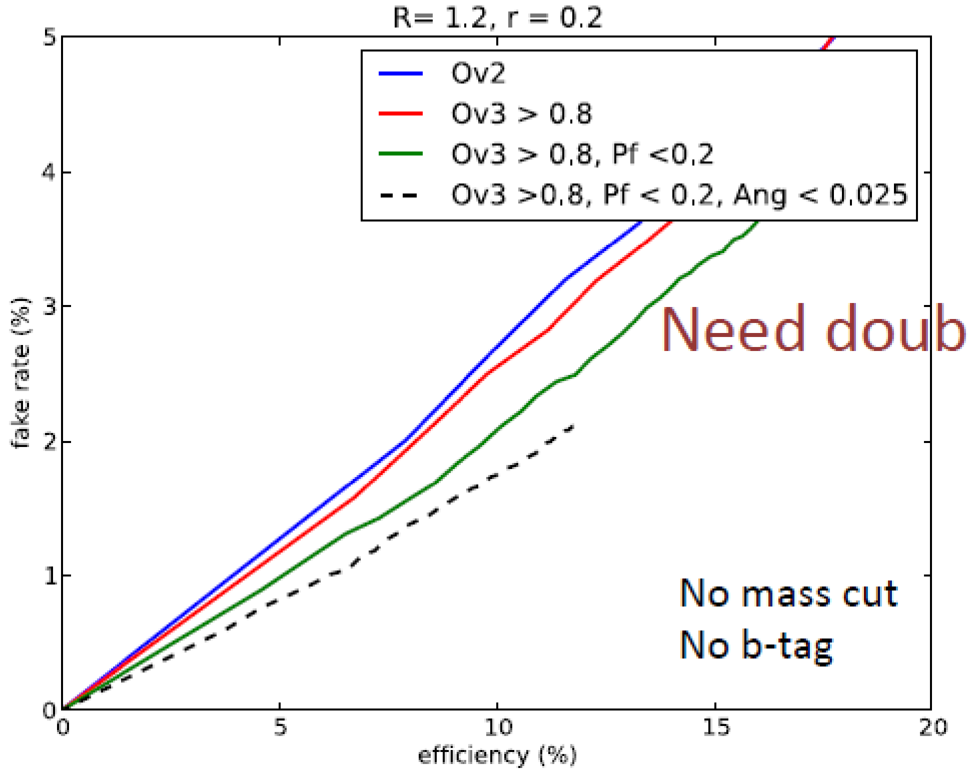


$$r_\theta = \min\{\theta_{13}/\theta_{12}, \theta_{23}/\theta_{12}\}$$

$$\bar{\theta} = \sum_i \sin\theta_{iJ}$$

$$\theta_s = \min\{\theta_{iJ}\}$$

Rejection power before pileup



For 10 % efficiency rejection
Factor of ~ 5.

Total rejection factor:

Need double b tag

	15	-	*mass cut*
x	40	-	*b-tagging*
x	5	-	*template+pf*

= 3000

Not using other variables such as partonic angle, angularity or planar-flow ...