Analytic control of jet substructure

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Based on a paper with Gregory Soyez and Mirinal Dasgupta
arXiv:1512.00516, to appear on JHEP

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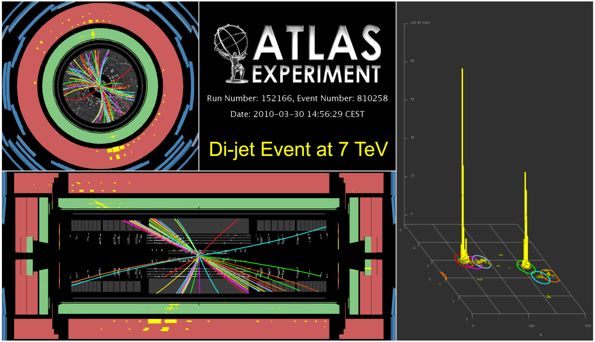
Outline

1. Introduction: jets at the LHC
2. Jet substructure: looking inside the jet
3. Control of jet substructure: an analytical understanding
4. Conclusion and prospectives

Outline

Introduction

- QCD partons produced in collisions cannot be directly observed;
- Due to QCD collinear divergence, their final state are complex collimated structures called *jets*;

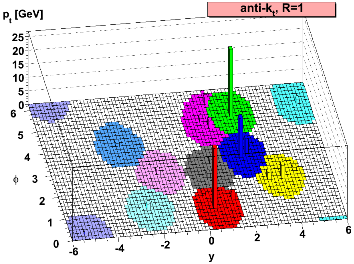


ATLAS collaboration

- Jets are used very frequently in LHC analyses.

Definition of jet

- A *jet definition* is how one clusters particles into jets;
- Composed of a *clustering algorithm* (e.g. anti-k_t) and its *parameters* (e.g. the jet radius R);

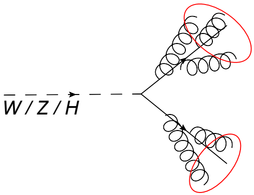


M. Cacciari, G. P. Salam and G. Soyez (2008)

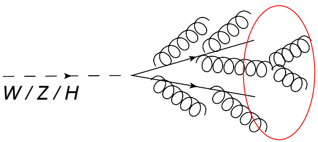
Outline

Boosted heavy particles

- At the LHC $\rightarrow$ boosted heavy particles ($p_t \gg m$)
  $\rightarrow$ decay in very collimated final states
  $\rightarrow$ clustered into a single jet



$p_t \lesssim m$

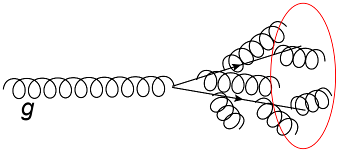


$p_t \gg m$

- Characteristic opening angle of the jet is $\theta \propto \dfrac{m}{p_t}$.

QCD background

- Jets originated by partons (g or q) are collimated for any p_t;



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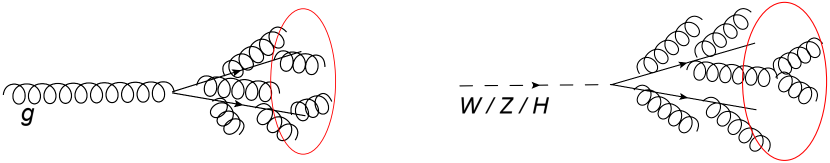
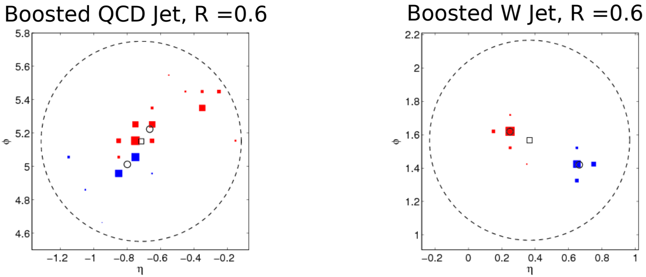


- How to discriminate QCD jets from $Z/W/H \to \textit{hadrons}$ jets?

Jet substructure

- In order to identify a jet we need to access the *jet substructure* $\rightarrow$ to look inside the jet;



J. Thaler and K. V. Tilburg (2010)

- Different techniques are available:
  1. Find hard cores (1 for QCD, 2 for bosons);
  2. Constrain the soft gluon radiation.

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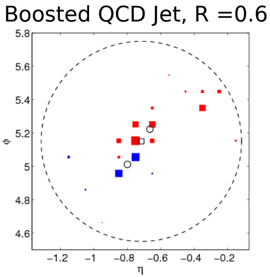
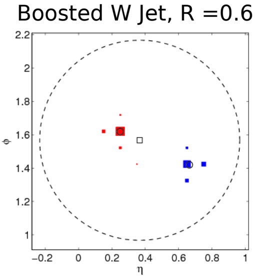




J. Thaler and K. V. Tilburg (2010)

- Different techniques are available:
  1. Find hard cores (1 for QCD, 2 for bosons);
  2. Constrain the soft gluon radiation. $\leftarrow$ focus of this talk

See e.g. M.Dasgupta, A. Fregoso, S. Marzani and G.Salam (1307.0007) for similar study in core finders.

Jet shapes

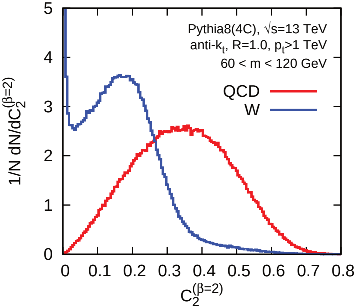
- Jet-shapes: observables which are functions of the jet constituents $v(p_1^\mu, p_2^\mu, ..., p_n^\mu) \rightarrow$ measure the radiation within the jet;

- **Energy correlation**

$$C_2 = e_3/(e_2)^2,$$

$$e_2 = \frac{1}{p_t^2 R^2} \sum_{i<j\in jet} p_{t,i} p_{t,j} \theta_{ij}^2,$$

$$e_3 = \frac{1}{p_t^3 R^6} \sum_{i<j<k\in jet} p_{t,i} p_{t,j} p_{t,k} \theta_{ij}^2 \theta_{ik}^2 \theta_{jk}^2.$$



Jet shapes

- **N-subjettiness** with axes $a_1, ..., a_N$

$$\tau_{21} = \frac{\tau_2}{\tau_1}, \qquad \tau_N = \frac{1}{p_{t,jet} R^2} \sum_{i \in jet} p_{t,i} \min_{a_i \ldots a_N} (\theta^2_{ia_1}, ..., \theta^2_{ia_N}).$$

- **Mass-drop** with subjets j_1 and j_2

$$\mu_p^2 = \max(m_{j1}^2, m_{j2}^2)/m_j^2.$$

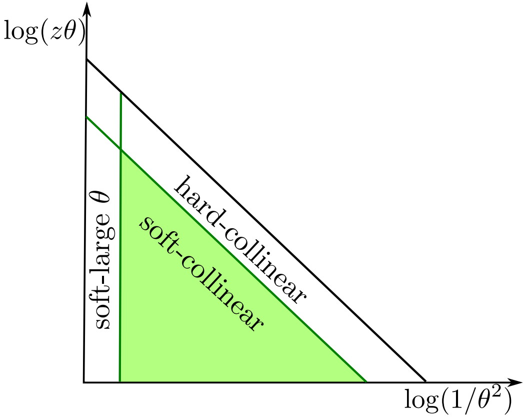
Outline

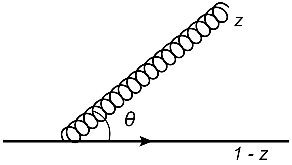
Control of jet substructure

- Understand differences/similarities from a *first-principle analytical study*;
- Compute physical quantities (cross-section, efficiency curves) with a cut v_{cut} on jet shape;
- We assume $v_{cut} \ll 1$.

Lund diagrams

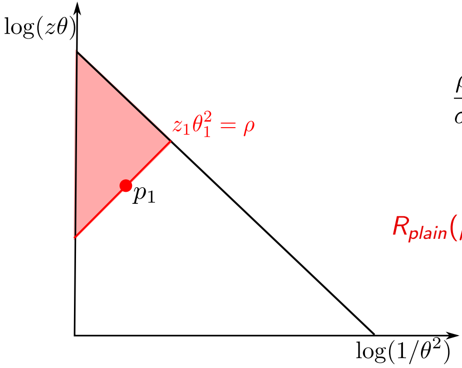
- Lund diagram: graphical representation of emissions in $z\theta$ vs. $1/\theta^2$.





Structure of the results (QCD background)

- We consider *boosted jets* of a *given mass*, $\rho = m^2/p_t^2 R^2 \ll 1$;
- Approximation: emissions are strongly ordered in mass and angle;
- Independent emissions $\rightarrow$ constraints as an exponential factor.

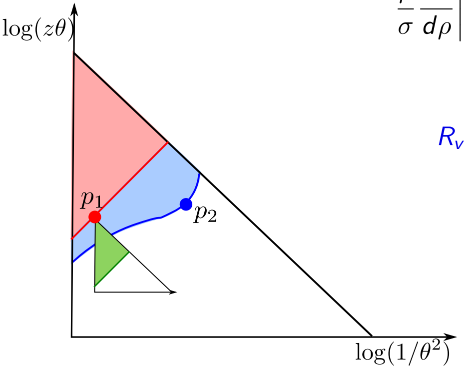


$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho} = \int_\rho^1 dz_1 P_i(z_1)\frac{\alpha_s}{2\pi} e^{-R_{plain}(\rho)}$$

$$R_{plain}(\rho) = \int_0^1 \frac{d\theta^2}{\theta^2}\int_0^1 dz P_i(z)\frac{\alpha_s}{2\pi}\Theta(z\theta^2 > \rho)$$

Structure of the results (QCD background)

- For a jet of a given mass + a cut in the jet shape v_{cut}:



$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}\bigg|_{<v} = \int_\rho^1 dz_1 P(z_1)\frac{\alpha_s}{2\pi} e^{-R_{plain}(\rho) - R_v(\rho, z_1)}$$

$$R_v(\rho, z_1) = \int_0^1 \frac{d\theta_2^2}{\theta_2^2}\int_0^1 dz_2 P_i(z_2)\frac{\alpha_s}{2\pi} \times\Theta(v > v_{cut})\Theta(z_2\theta_2^2 < \rho) + \int_0^1 \frac{d\theta_{12}^2}{\theta_{12}^2}\int_0^1 dz_2 P_g(z_2)\frac{\alpha_s}{2\pi} \times\Theta(v^{sec} > v_{cut})$$

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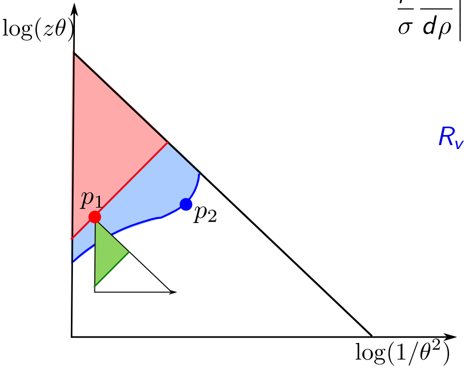

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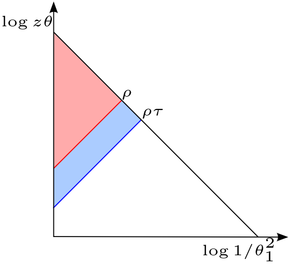
Now all we need is to find $v(\rho, z_1, z_2, \theta_2)$.

Results (QCD background)

N-subjettiness



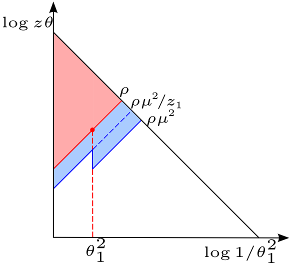
$$R_\tau(z_1) =$$

$$\frac{\alpha_s C_R}{2\pi}\left[\frac{L_\tau^2}{2} + L_\rho L_\tau\right]$$

$$+\frac{\alpha_s C_A}{2\pi}\frac{L_\tau^2}{2}$$

$$L_X = \log(1/X)$$

Mass drop



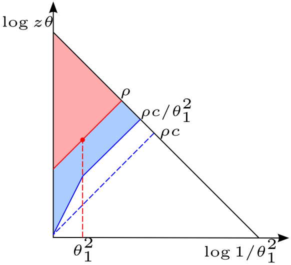
$$R_{\mu^2_{1/2}}(z_1) =$$

$$\frac{\alpha_s C_R}{2\pi}\left[\frac{L_\mu^2}{2} + L_\rho L_\mu\right]$$

$$-\frac{\alpha_s C_R}{2\pi}\frac{L_1}{2}(L_\rho - L_1)$$

$$+\frac{\alpha_s C_A}{2\pi}\frac{(L_\mu - L_1)^2}{2}$$

Energy correlation



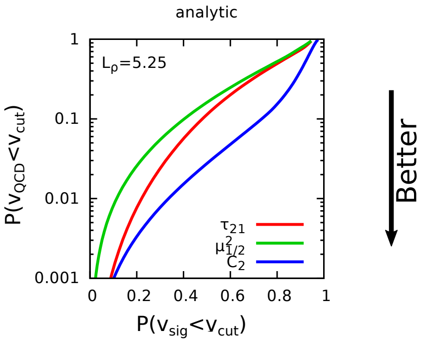
$$R_{C^2}(z_1) =$$

$$\frac{\alpha_s C_R}{2\pi}\left[\frac{L_e^2}{2} + (L_e - L_\rho + L_1)L_1\right]$$

$$+\frac{\alpha_s C_A}{2\pi}\frac{1}{2}(L_e - L_\rho + L_1)^2$$

ROC curves

- Probability that $v_{QCD} < v_{cut}$ vs. probability that $v_{sig} < v_{cut}$;
- C_2 is the most efficient, and τ_{21} more efficient than μ^2 (more delicate call).



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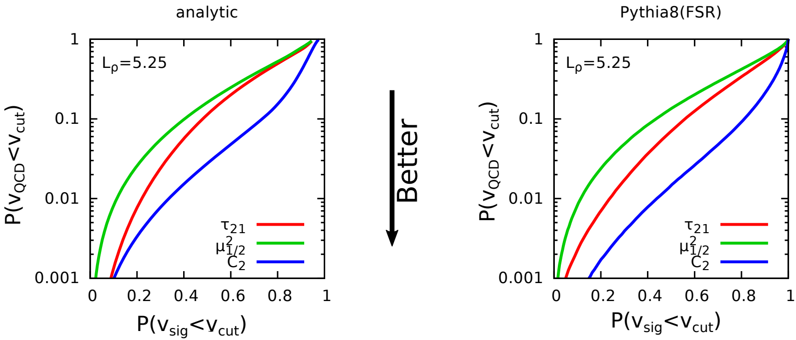
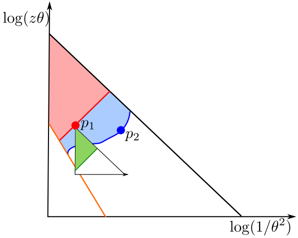


- Good description of the order between shapes.

Outline

Conclusion

- Good **qualitative description** of the shapes.
- **Efficiency** of the shapes: $C_2 > \tau_{21} \gtrsim \mu^2$.
- **Next steps**
  - Higher accuracy;
  - Add grooming;
  - Different jet shapes;
  - 3-pronged jet shapes;
  - Calculations for $v \sim 1$.

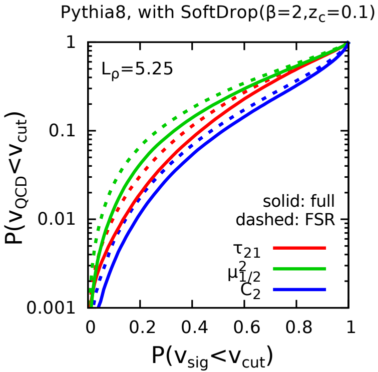


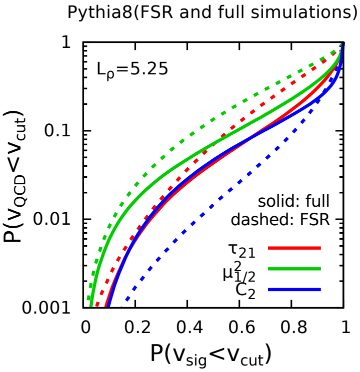
Backup Slides

Generalized k_t algorithm

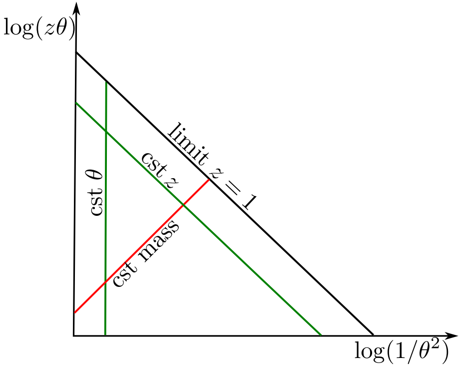
- Depends on a parameter p;
- Cluster partons by smallest distance $d_{ij} = \min(z_i^{2p}, z_j^{2p})\theta_{ij}^2$;
- Particular cases:
  - p=0: C/A algorithm, angular ordered;
  - p=-1: anti-k_t algorithm;
  - p=1/2: similar to mass measure.

Non-perturbative effects



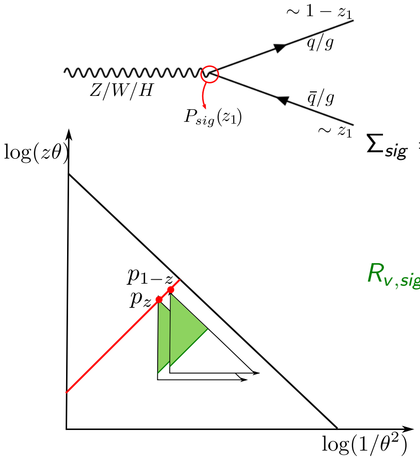


More on Lund diagram



Structure of the results (Signal)

- Decay of a boosted object into a pair $q\bar{q}$ or gg.
- For a signal jet (fixed mass always) + a cut in the shape v:



$$\Sigma_{sig} = \int_{\rho}^{1} dz_1 P_{sig}(z_1) e^{-R_{v,sig}(z_1,\rho) - R_{v,sig}(1-z_1,\rho)}$$

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