Jet substructure

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DESY

SM@LHC
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Motivation

- LHC plays a major role in particle physics today and it may be the key to probe beyond Standard Model theories.
- Unprecedented situation: production of heavy particles (W, Z and Higgs boson, top quark) with high momentum ($p_T \gg m$).

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  $\rightarrow$ **boosted regime** $\rightarrow$ **substructure techniques**

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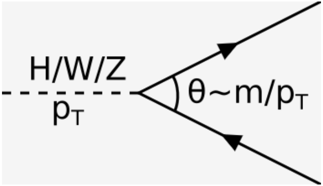
- Unprecedented situation: production of heavy particles (W, Z and Higgs boson, top quark) with high momentum ($p_T \gg m$).

  $\rightarrow$ **boosted regime** $\rightarrow$ **substructure techniques**
- Jet substructure also reduce **non-perturbative effects**
  e.g. hadronization effects, UE contamination

Boosted heavy particles

Boosted Z, W, H



- Boosted particles ($p_T \gg m$) :
  $\rightarrow$decay in collimated final states ($\theta \sim m/p_T$)
  $\rightarrow$ **clustered in a single jet.**

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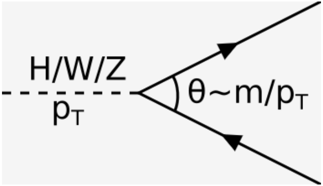
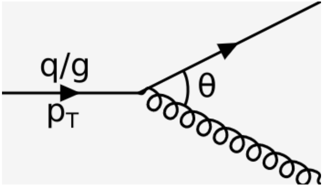


Standard QCD jet



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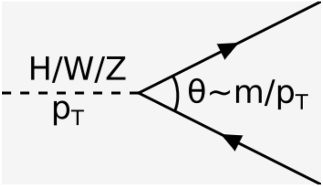
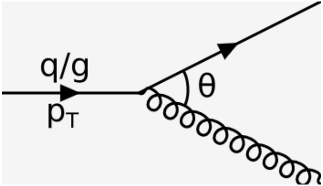


Signal

Standard QCD jet



Background

- Boosted particles ($p_T \gg m$) :
  $\rightarrow$decay in collimated final states ($\theta \sim m/p_{\mathrm{T}}$)
  $\rightarrow$ **clustered in a single jet.**
- **How to discriminate between QCD jets and Z/W/H jets?**

Jet Substructure

- Use **jet substructure** techniques
  $\rightarrow$ look at dynamics inside the jet;

- Different techniques are available:

Shapes constrain soft gluon radiation, signal is colorless and has different radiation pattern than QCD jets;
e.g. Energy correlation, N-subjettiness.

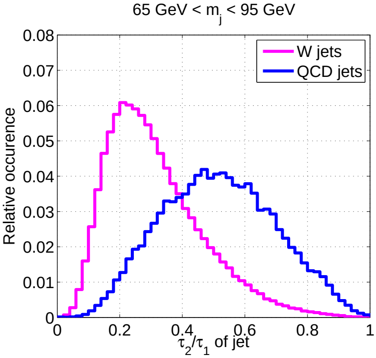
Prong Finders find hard prongs in the jets, usually signal has 2 symmetric prongs and QCD background has only 1;
e.g. modified MassDrop, Y-splitter.

Groomers clean soft and large angle radiation, often dominated by non-perturbative effects
e.g. modified MassDrop, SoftDrop

Example : N-subjettiness

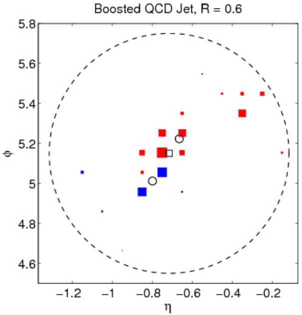
- Measures radiation around 2 (pre-determined) axis.
  Thaler, Tilburg (2010)

$$\tau_{21} = \tau_2/\tau_1,$$
$$\tau_N = \frac{1}{p_{t,jet} R^\beta} \sum_{i \in jet} p_{t,i} \min_{a_i \dots a_N} (\theta^\beta_{ia_1}, \dots, \theta^\beta_{ia_N}).$$

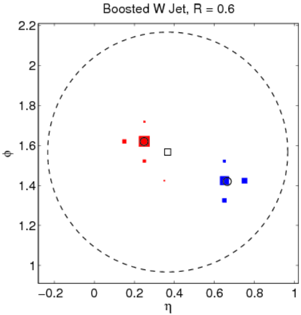


Example : N-subjettiness

QCD background



W boson signal



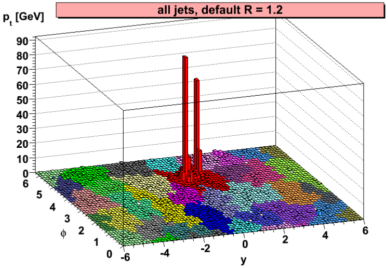
- Background has a more “diffuse” radiation pattern;
- 1 prong vs. 2 prong structure.

Example : (modified) Mass Drop Tagger

- Removes **soft and large-angle radiation**;

  Butterworth, Davison, Rubin, Salam (2008)

  Dasgupta, Fregoso, Marzani, Salam (2013)



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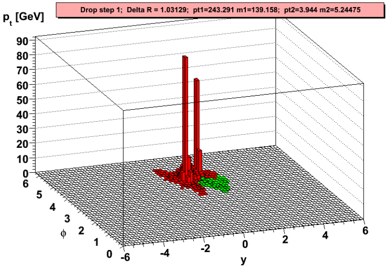
1. Break jet into two $j \rightarrow j_1 + j_2$;
   using C/A algorithm
2. Check condition
   $\min(p_{T,1}, p_{T2})/(p_{T,1} + p_{T,2}) > z_{cut}$;



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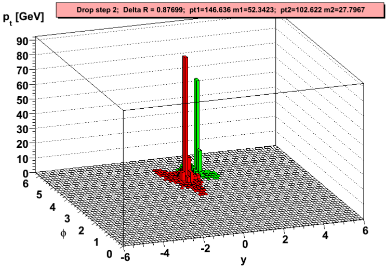
3. If fails, removes the subjet with lower p_T.



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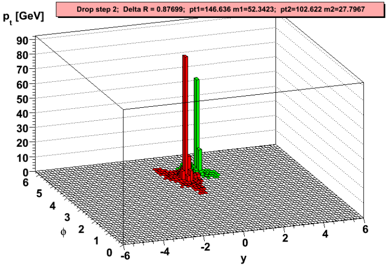
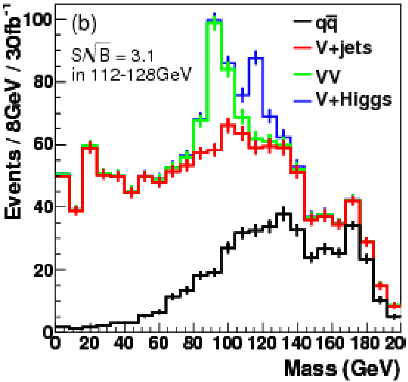
4. If passes, stop recursion;



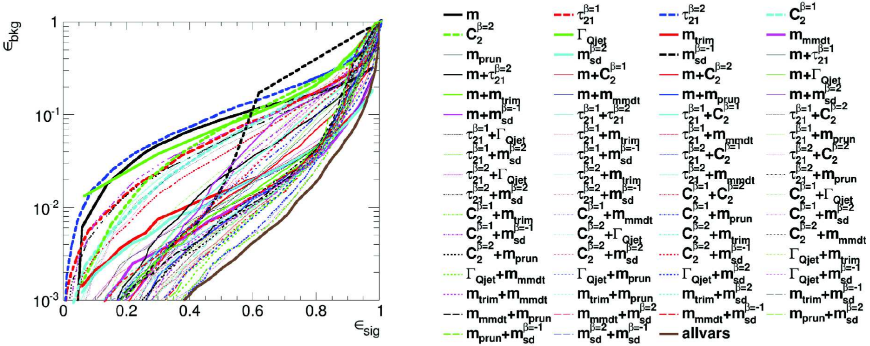
mMDT is equivalent to SoftDrop wiht $\beta = 0$

Example : (modified) Mass Drop Tagger

- Signal and background for a 115 GeV SM Higgs.



- Parton shower Monte Carlo generators are very useful tools, but numerically costly and the physical message is not always clear.



Plot : Grogory Soyez

- Example: ROC curves for different jet substructure methods

A case for analytical approach

- We can acquire **insight from analytical expressions**
  $\rightarrow$ Better understand a phenomenon
  $\rightarrow$ Develop better tools (*e.g.* boson and top taggers)

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- Compute robust **uncertainty bands**
  $\rightarrow$ Correct assessment of the higher orders corrections we are neglecting

Some recent developments

- Improvements to the **fitting of the strong coupling**
  Baron, Marzani, Theeuwes (2018)
  Les Houches 2017 SM Working Group
- **Generalizations of energy-correlation functions**
  Moult, Necib,Thaler (2016)
- Observables **decorrelated from jet masses**
  Dolen, Harris, Marzani, Rappocio, Tran (2016)
  Moult, Nachman, Neil (2017)
- **Dichroic observables** for 2-prong tagging
- Precision calculations in **groomed jet mass**
- Advances in **machine learning techniques**
  See Larkoski, Moult, Nachman (2017) for an overview

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Dichroic Jet Shapes

- Explore the interplay between **groomers / prong finders** and **jet shapes**;
- Example : N-subjetiness Salam, LS, Soyez (2016)
  Usual τ_{21} measures

$$\tau_{21} = \frac{\tau_2(\text{mMDT})}{\tau_1(\text{mMDT})} \quad \text{or} \quad \frac{\tau_2(\text{SD})}{\tau_1(\text{SD})} \quad \text{or} \quad \frac{\tau_2(\text{plain})}{\tau_1(\text{plain})}$$

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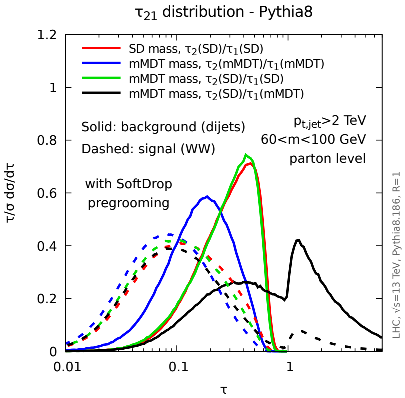
- **Dichroic** : different subjets for numerator / denominator in τ_{21} ratios;

$$\boxed{\tau_{21}^{\text{dichroic}} \equiv \frac{\tau_2^{\text{full / SD}}}{\tau_1^{\text{tagged}}}}$$

- τ_2 on large jet $\rightarrow$ sensitivity to diffent color structures
- τ_1 on small jet $\rightarrow$ only sensitive to the invariant mass
  $\rightarrow$ smaller influence of non-perturbative effects.

Dichroic Jet Shapes

- Dichroic version has better separation between signal and background



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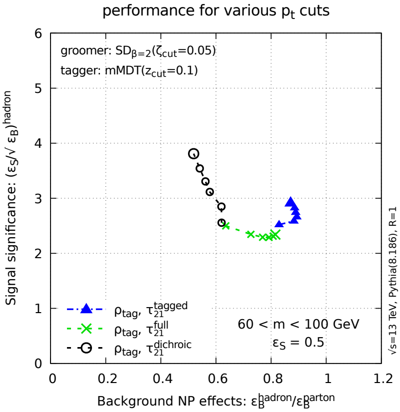

- Dichroic τ_{21} variation
  $\rightarrow$ increase in discriminating power;

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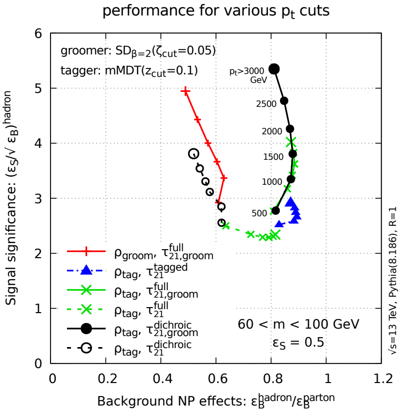
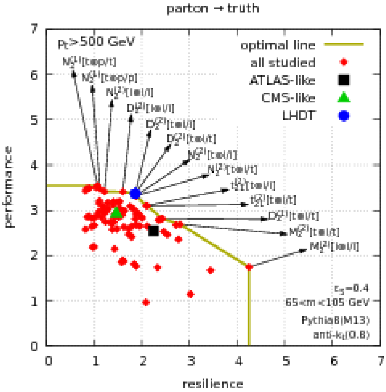


- Dichroic τ_{21} variation
  $\rightarrow$ increase in discriminating power;
- With pre-grooming step
  $\rightarrow$ reduction of NP effects and still has a better performance;
- Performance gain increases as p_t increases.

Dichroic Jet Shapes

- Comparison between a variety of jet shapes

  Les Houches 2017 SM Working Group



- Dichroic version of observables show **good performance** with relatively **low sensitivity to non-perturbative effects**

Groomed jet mass

- Connection between measurements and calculations
  For experimental aspects see Jennifer ROLOFF talk later today
- **Jet mass** is one of the simplest observables
- **Grooming** eliminates part of UE contamination
- We studied modified MassDrop Tagger and SoftDrop

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- **Jet mass** is one of the simplest observables
- **Grooming** eliminates part of UE contamination
- We studied modified MassDrop Tagger and SoftDrop
- For **boosted jets** $p_T \gg m \to \rho \equiv m/(p_T R) \ll 1$
  $\to$ log enhancements $\alpha_s^n \log^{2n}(1/\rho)$

Needs to be resummed at all orders

Groomed jet mass

- Various interesting QCD structures emerging
  - For mMDT it becomes $[\alpha_s f(z_{\text{cut}}) \log(1/\rho)]^n$ at leading-log
  - Finite z_{cut} introduce a flavour changing matrix structure

- Compare with experiment $\rightarrow$ needs a matching procedure:

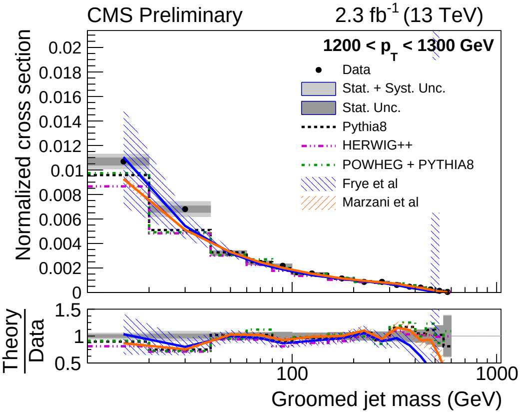
$$\underbrace{N^k LL}_{\text{small } \rho} + \underbrace{N^m LO}_{\text{large } \rho}$$

Small ρ $\rightarrow$ **resummation** of large logarithms
Large ρ $\rightarrow$ **fixed-order** (exact at $\mathcal{O}(\alpha_s^m)$)

- Calculations done with different theoretical approaches
  - NLL + NLO for $z_{\text{cut}} \ll 1$ — Frye, Larkoski, Schwartz, Yan (2016)
  - LL + NLO for all z_{cut} — Marzani, Soyez, LS (2017)

Groomed jet mass

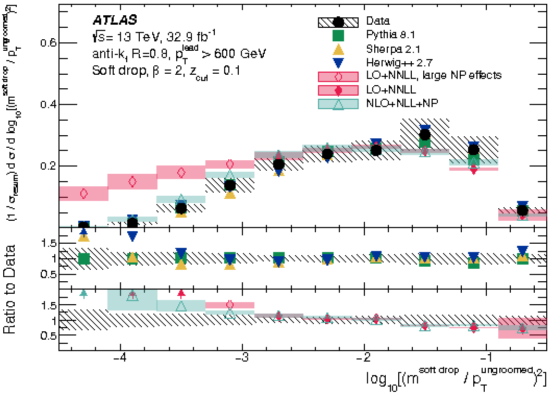
- Comparison with CMS measurements using mMDT



CMS-PAS-SMP-16-010

Groomed jet mass

- Comparison with ATLAS measurements using SoftDrop ($\beta > 0$)



CERN-EP-2017-231

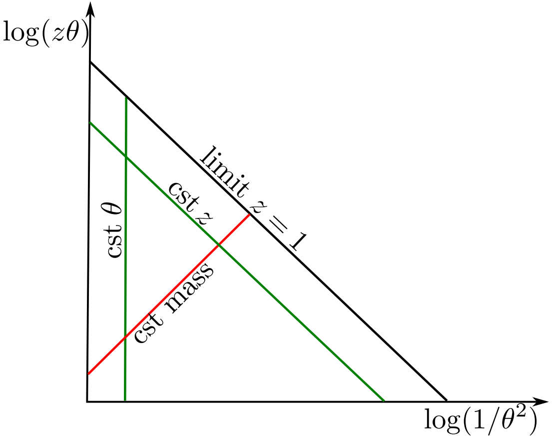
Conclusion

- Jet substructure has many applications in particle physics today
- Very active community, both in experiment and theory
- Analytical studies:
  1. Better insight of existing tools
  2. Development of new tools
  3. Higher accuracy results
  4. Robust uncertainty bands
- Increasing role as LHC reaches higher energy scales

Backup slides

Lund diagrams

- Lund diagram : graphical representation of the results in $z\theta$ (transverse momentum) vs. $1/\theta^2$ (emission angle) coordinates.



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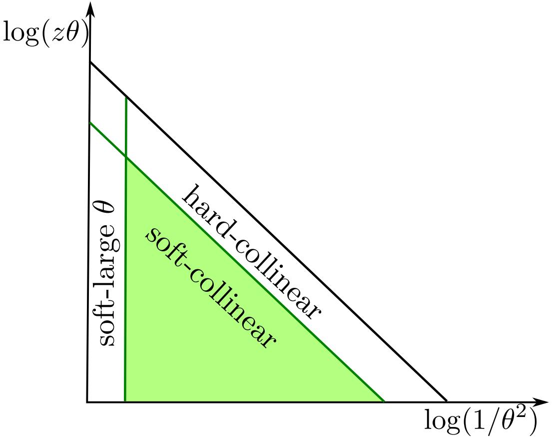
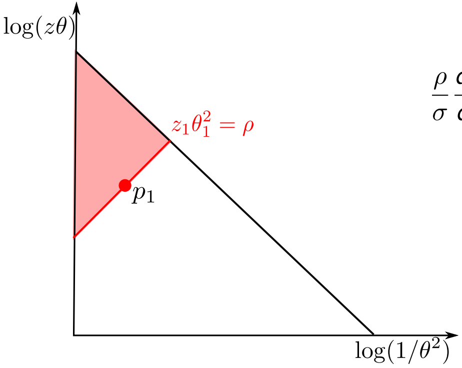


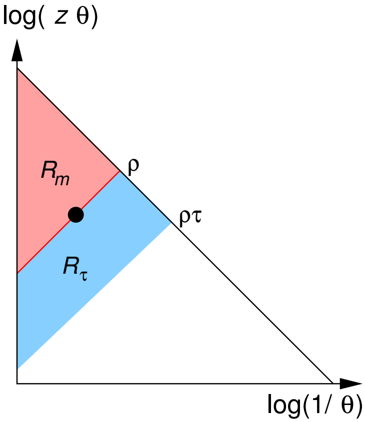
Calculations



$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho} \sim \frac{C_F\alpha_s}{2\pi} R'_{\mathrm{plain}}(\rho)\exp(-R_{\mathrm{plain}}(\rho))$$

$$R_{plain}(\rho) \sim \frac{C_F\alpha_s}{2\pi}\int_0^1 \log(1/\rho)^2$$

Lund diagram for τ_{21}



- Jet mass with cut on τ_{21}

$$\frac{\rho}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\rho}\bigg|_{<v} = R'_m \exp\left(-R_{m+\tau}\right)$$

	R'_m	$R_{m+\tau}$	NP
full	large	large	large

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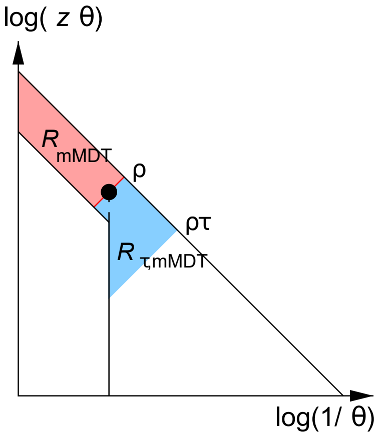

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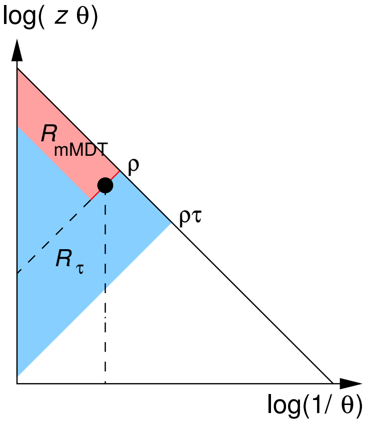

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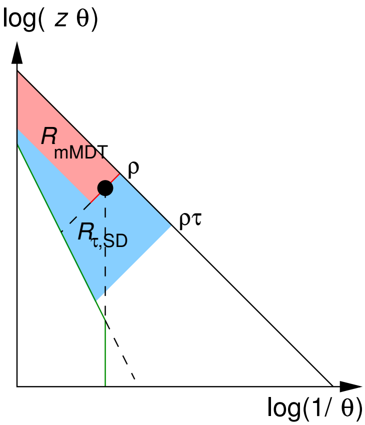

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dichroic + SD	small	large	small

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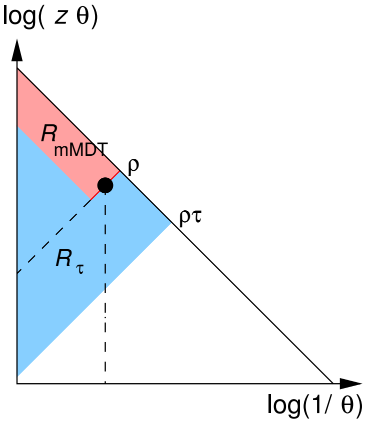

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$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}\bigg|^{\mathrm{LL}}_{\tau_{21}^{\mathrm{dichroic}}} \overset{\mathrm{f.c.}}{=} \frac{C_F\alpha_s}{\pi}\log\frac{1}{y} \times \exp\left[-\frac{C_F\alpha_s}{2\pi}\log^2\frac{1}{\tau\rho}\right]$$