Jet substructure

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GDR QCD
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Motivation

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

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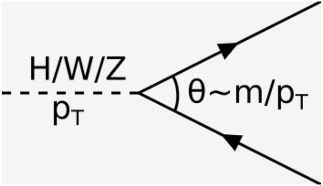
  $\rightarrow$ concentrate on EW bosons in this talk

Boosted heavy particles

Boosted Z, W, H



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  $\rightarrow$decay in collimated final states ($\theta \sim m/p_{\mathrm{T}}$)
  $\rightarrow$ clustered in a single jet.

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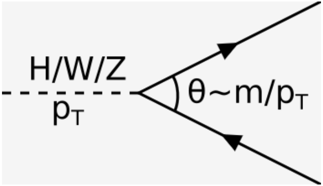
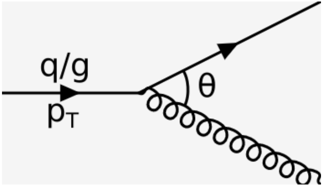


Standard QCD jet



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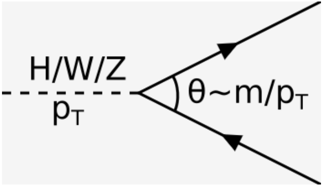
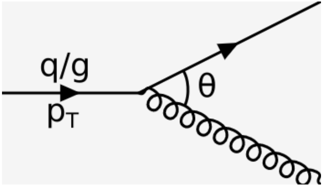


Signal

Standard QCD jet



Background

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

Jet Substructure

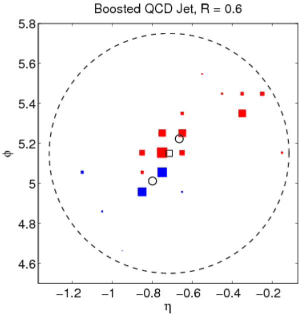
- Use jet substructure techniques
  $\rightarrow$ look at dynamics inside the jet;
- Different techniques are available:

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

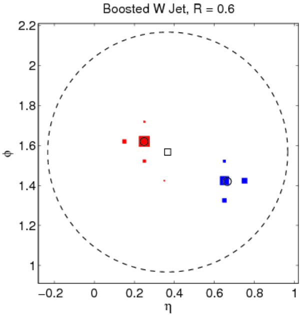
Taggers find hard prongs in the jets, usually signal has 2 symmetric prongs and QCD background has only 1;
e.g. modified Mass Drop, SoftDrop.

Jet substructure

QCD background



W boson signal



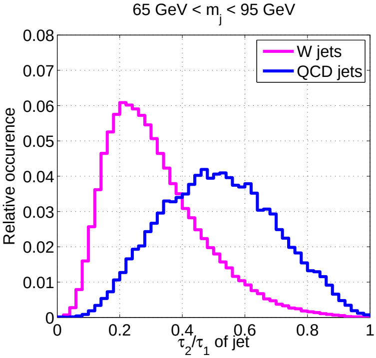
- Background has a more "diffuse" radiation pattern;
- 1 prong vs. 2 prong structure.

Example : N-subjettiness

- Measures radiation around 2 (pre-determined) axis.

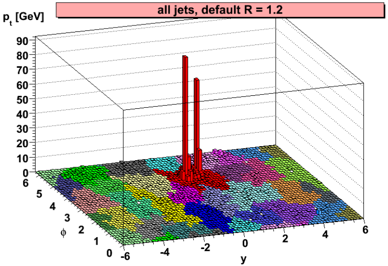
  J. Thaler, K. V. Tilburg (2010)

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



Example : (modified) Mass Drop Tagger

- Removes soft and large-angle radiation;
  J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam (2008)
  M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam (2013)



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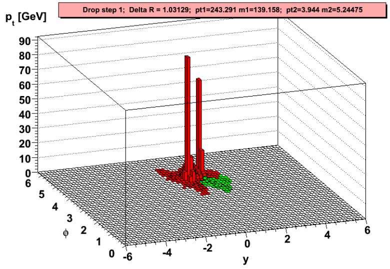
1. Break jet into two $j \to j_1 + j_2$;
   [using C/A algorithm]
2. Check condition
   $\min(p_{T,1}, p_{T2})/(p_{T,1} + p_{T,2}) > z_{cut}$;



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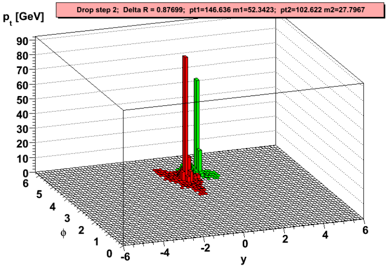

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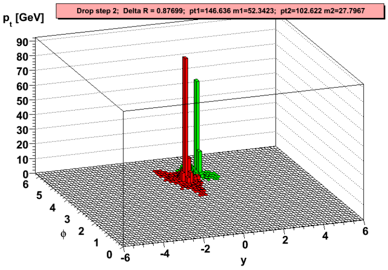
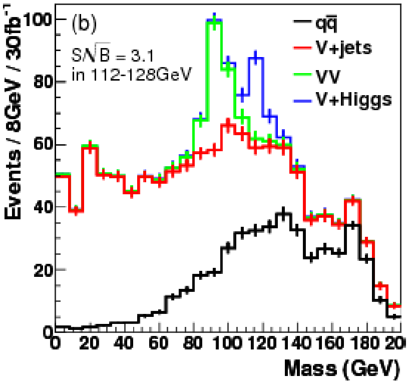
3. If fails, removes the subjet with lower p_T.
4. If passes, stop recursion;

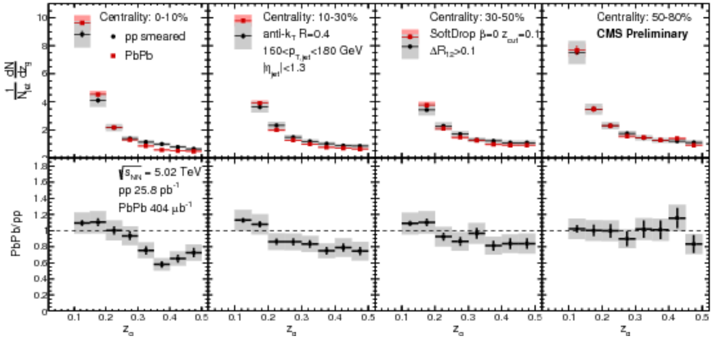


Example : (modified) Mass Drop Tagger

- Signal and background for a 115 GeV SM Higgs.

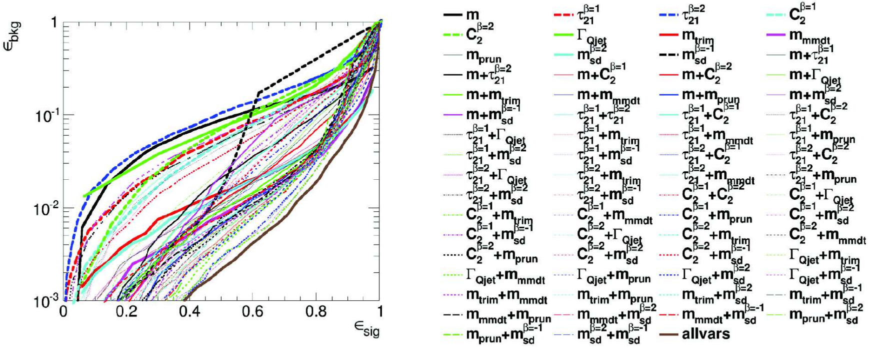


- Jet substructure techniques used in CMS and ATLAS analyses;
  CMS collaboration (2016) – [CMS PAS HIN-16-006]
- Momentum shearing between 2 leading subjets:
  $z_g = \min(p_{T,1}, p_{T2})/(p_{T,1} + p_{T,2})$;
- z_g distribution measures the *splitting function*.



A case for analytical approach

- Monte Carlo generators are powerful tools;
- But we can loose understanding of physics.



Boost2013 Proceedings

Some recent developments

- Jet substructure from first principles:
  1. Understand why some methods are more performant than others;
  2. Use insight to develop new methods;
  3. Find optimal parameters;
  4. Provide precise calculations with genuine theoretical incertitudes.

- Examples:

  Improved N-subjettiness : combination of shapes and taggers
  $\rightarrow$ increase performance.

  Mass distribution with mMDT : matched precision calculation.

Improving N-subjettiness

- Usual: measure mMDT mass + a cut on

$$\frac{\tau_2(\text{mMDT})}{\tau_1(\text{mMDT})} \quad \text{or} \quad \frac{\tau_2(\text{plain})}{\tau_1(\text{plain})}$$

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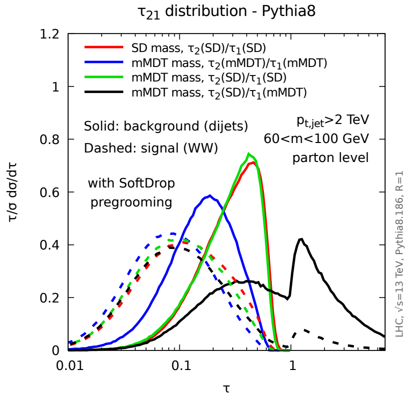
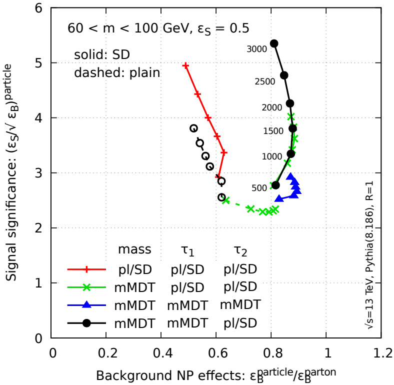
- Performance gain;
- Limited sensitivity to model-dependent non-perturbative effects;
- Calculable from first principles;

- Comparison to Monte Carlo generator.





G. P. Salam, G. Soyez, L. S. (in progress)

Reaching higher precisions

- For boosted jets $p_T \gg m \to \rho \equiv m/(p_T R) \ll 1$
  $\to$ log enhacements $\alpha_s^n \log^{2n}(1/\rho)$

  Needs to be resummed at all orders.

- For mMDT it becomes $[\alpha_s f(z_{cut}) \log(1/\rho)]^n$ at leading-log;

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

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

  Small $\rho \to$ resummation
  Large $\rho \to$ fixed-order (exact)

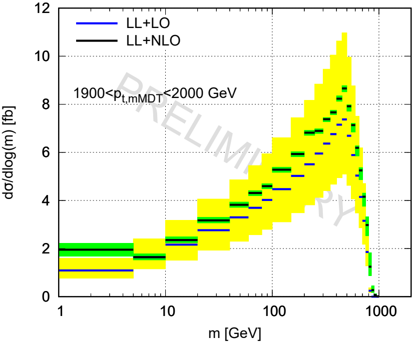
Reaching higher precisions

- NLL + NLO for $z_{\rm cut} \ll 1$ (for $p_{\rm t,jet}$)
  C. Frye, A. J. Larkoski, M. D. Schwartz, K. Yan (2016)

- LL + NLO for all $z_{\rm cut}$ (for $p_{\rm t,jet}$ and $p_{\rm t,mMDT}$)
  S. Marzani, G. Soyez, L. S. (in progress)

- Comparison to CMS : complications from $p_{\rm t,mMDT}$ (ill-defined at fixed order);

- Various interesting QCD structures emerging.



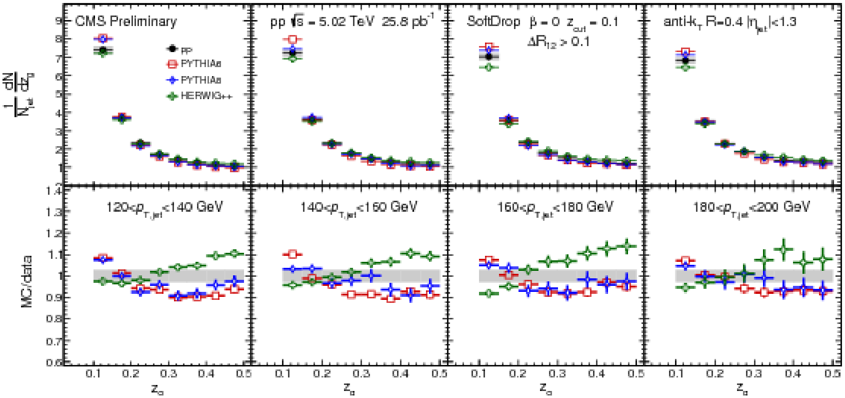
Conclusion

- Jet substructure has many applications in particle physics today;
- Analytical studies:
  1. Development of new tools;
  2. Comparison with experiments (uncertainties);
- Increasing role as LHC reaches higher energy scales.

Backup slides

Application: Splitting function in pp and PbPb collisions

Comparison to MC simulations.



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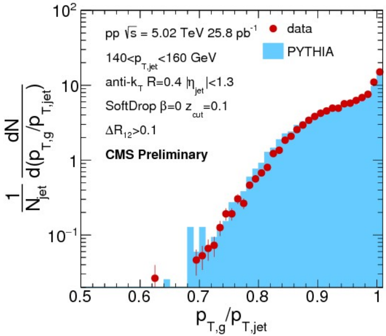
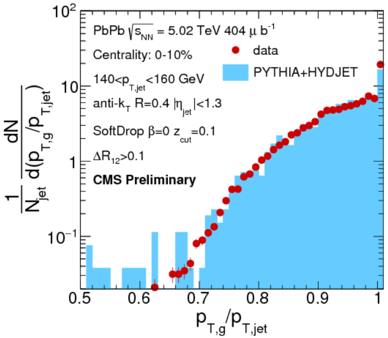
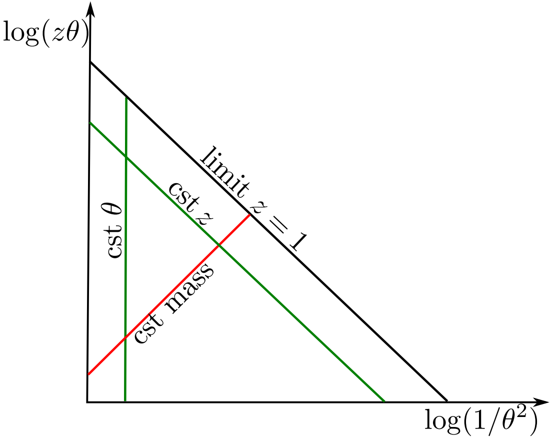




Lund diagrams

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



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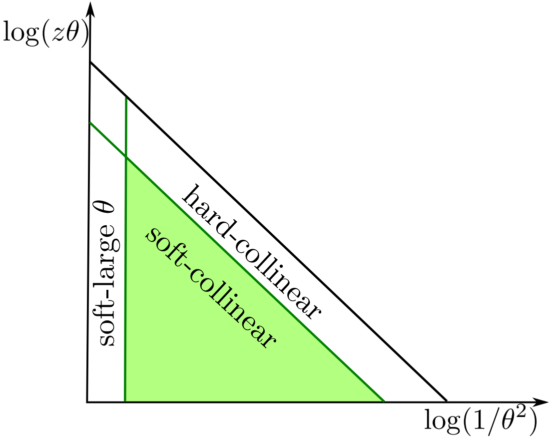
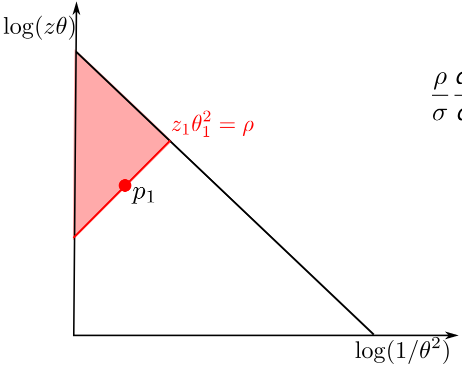


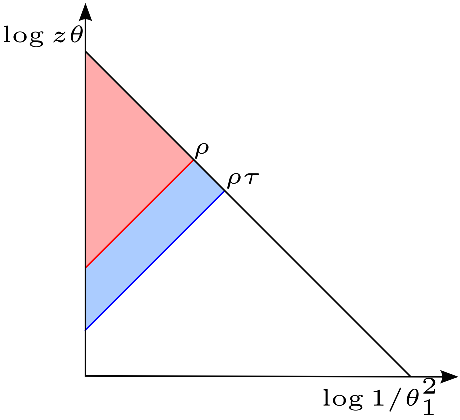
Calculations



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

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

Calculations



$$\left.\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}\right|_{<v} = R'_\tau \exp(R_\tau)$$

$$R_\tau(z_1) \sim \frac{\alpha_s C_R}{2\pi} \log\left(\frac{1}{\rho\tau}\right)^2$$

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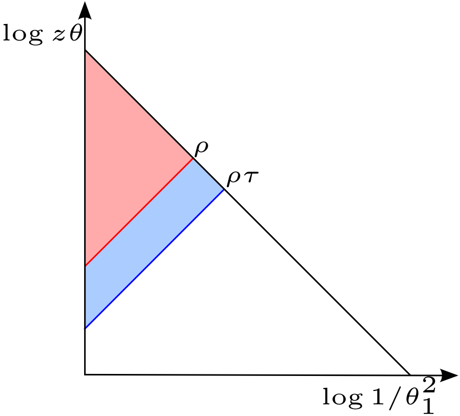

$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}\bigg|_{<v} = R'_{\mathrm{mMDT}}\exp(R_{\mathrm{mMDT}})$$

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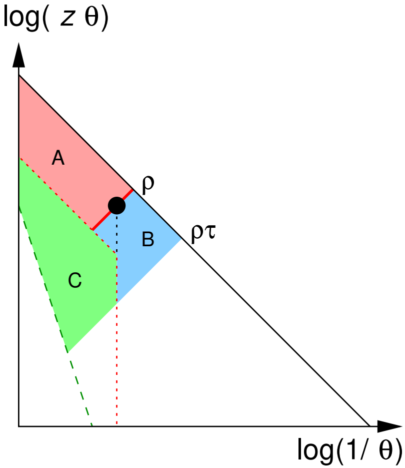

$$\tau_{21} = \frac{\tau_2(SD)}{\tau_1(mMDT)}$$

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