New ideas for Jet Substructure

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DESY

B2G Spring Workshop
Open Session – May 23, 2018

Jet Substructure

- **Jet substructure** techniques play a major role in LHC physics
  Boosted regime $\rightarrow$ 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. Y-splitter.

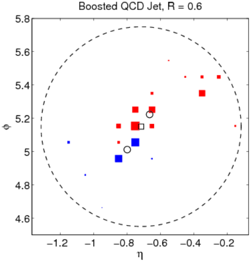
Groomers clean soft and large angle radiation, often dominated by non-perturbative effects
e.g. modified MassDrop, Soft Drop

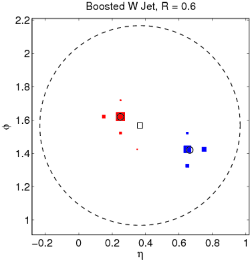
Example : N-subjettiness

- Measures **radiation around N (pre-determined) axis**
  Thaler, Tilburg (2010)

$$\tau_N = \frac{1}{R^\beta} \sum_{i \in jet} z_i \min_{a_i \dots a_N} (\theta_{ia_1}^\beta, \dots, \theta_{ia_N}^\beta),$$
$$\theta_{ij}^2 = \Delta\phi_{ij}^2 + \Delta y_{ij}^2, \qquad z_i = p_{t,i}/p_{t,jet}$$

- Use the ratios $\tau_{21} = \tau_2/\tau_1$ or $\tau_{32} = \tau_3/\tau_2$ to find multi-prong jets





Example : Energy correlation functions

- Basis of observables usend to probe multi-pronged jets
  Larkoski, Salam, Thaler (2013)

$$
\begin{aligned}
e_2^{(\beta)} &= \sum_{1\leq i<j\leq n_J} z_i z_j \theta_{ij}^{\beta} \\
e_3^{(\beta)} &= \sum_{1\leq i<j<k\leq n_J} z_i z_j z_k \theta_{ij}^{\beta}\theta_{ik}^{\beta}\theta_{jk}^{\beta}
\end{aligned}
$$

- Used to **2-pronged boson discrimination** (like Z/W/H)

$$
C_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^2}, \quad \text{or} \quad D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}
$$

- Or **top quark discrimination**

$$
C_3^{(\beta)} = \frac{e_4^{(\beta)} e_2^{(\beta)}}{(e_3^{(\beta)})^2}
$$

Example : Soft Drop and modified MassDrop Tagger

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

  Butterworth, Davison, Rubin, Salam (2008)

  Dasgupta, Fregoso, Marzani, Salam (2013)

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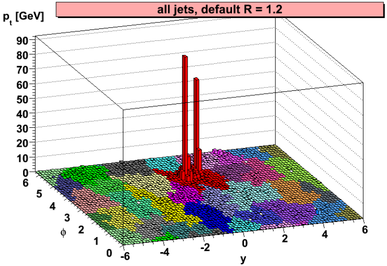

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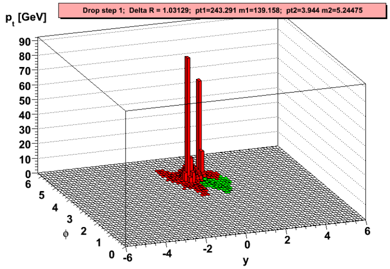
1. Break jet into two $j \to j_1 + j_2$;
   using C/A algorithm
2. Check condition
   $\frac{\min(p_{T,1}, p_{T2})}{(p_{T,1}+p_{T,2})} > z_{\text{cut}} \left(\frac{\theta_{12}}{R}\right)^{\beta}$;



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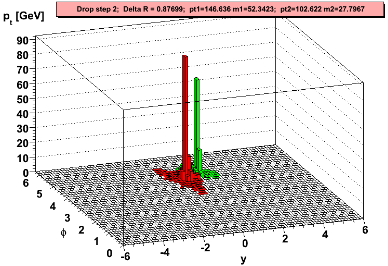
3. If fails, removes the subjet with lower p_T.



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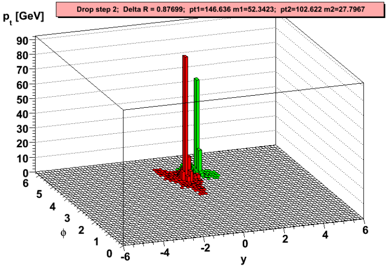
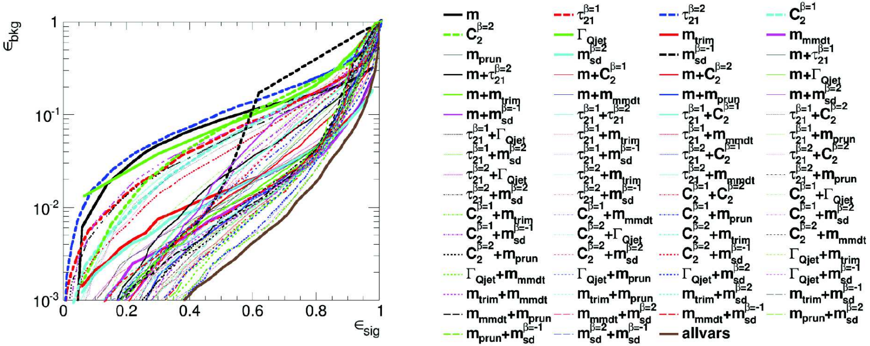
4. If passes, stop recursion;



mMDT is equivalent to Soft Drop wiht $\beta = 0$

A case for analytical approach

- 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

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  $\rightarrow$ Better understand a phenomenon
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  $\rightarrow$ Results are systematically improvable

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

Some recent developments

- Development of **new jet substructure tools**
  - Generalizations of energy-correlation functions
  - Dichroic observables
  - Recursive Soft Drop
  - Observables decorrelated from jet masses

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  - Dichroic observables
  - Recursive Soft Drop
  - Observables decorrelated from jet masses
- **Precision calculations** in groomed jet mass
- Studies on **fitting of the strong coupling**
- Advances in machine learning techniques
  See Larkoski, Moult, Nachman (2017) for an overview

New angles on energy correlation functions

Moult, Necib, Thaler (2016)

- Generalization of the energy correlation functions

$$_v e_n^{(\beta)} = \sum_{1 \leq i_1 < \cdots < i_n \leq n_J} z_{i_1} \ldots z_{i_n} \prod_{m=1}^{v} \overset{(m)}{\min_{s<t \in \{i_1 \ldots i_n\}}} \{\theta_{st}^{\beta}\}$$

- In particular, defined the series
  - M_i : identify jets with hard prongs, effective for groomed jets

$$M_i^{(\beta)} = \frac{{}_1 e_{i+1}^{(\beta)}}{{}_1 e_i^{(\beta)}}$$

  - N_i : mimics the behavior of N-subjettiness, no need for pre-defined axes

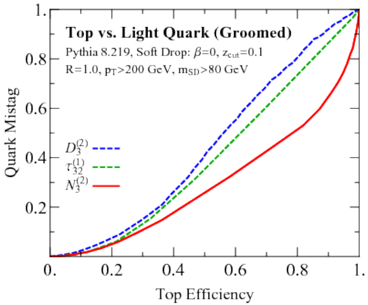
$$N_i^{(\beta)} = \frac{{}_2 e_{i+1}^{(\beta)}}{({}_1 e_i^{(\beta)})^2}$$

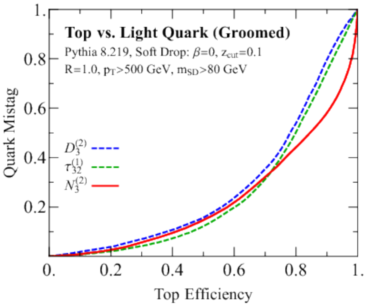
  - U_i : probe multiple emissions within 1-pronged jets

$$U_i^{(\beta)} = {}_1 e_{i+1}^{(\beta)}$$

Top Tagging N_3

- Use the variable $N_3 = {}_2e_4^{(\beta)}/({}_1e^{(\beta)})^2 \sim \tau_3/\tau_2$ (for groomed jets only)

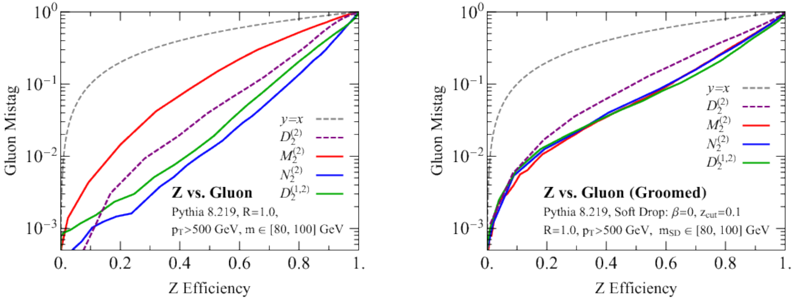




- **Improved performance**, specially for higher significance efficiency

2-prong tagging : N_2, M_2 and $D_2^{(\alpha,\beta)}$

- Observables proposed: $N_2 = {}_1e_3^{(\beta)}/{}_1e_2^{(\beta)}$, $M_2 = {}_2e_3^{(\beta)}/({}_1e_2^{(\beta)})^2$ and $D_2^{(\alpha,\beta)} = {}_3e_3^{(\alpha)}/({}_1e_2^{(\beta)})^{\frac{3\alpha}{\beta}}$
- Grooming matters, it can change considerably ROC curves

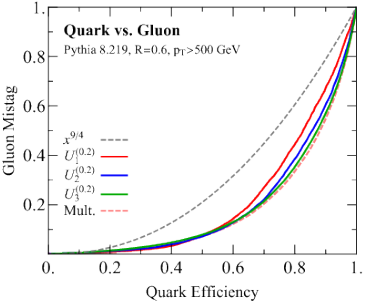


- These shapes **perform slightly better** than standard $D_2^{(2)}$

  (see paper for stability study in MC)

Quark / gluon discrimination: U_i

- Proposed the variable $U_i = {}_1e_{i+1}^{(\beta)}$
- Case $U_1 = C_1$ is the standard quark/gluon discrimination variable



- Increasing $i \rightarrow$ **increases performance** (but the effect saturates)

Dichroic Jet Shapes

Salam, LS, Soyez (2016)

- Explore the interplay between **groomers / prong finders** and **jet shapes**;
- Example : N-subjetiness
  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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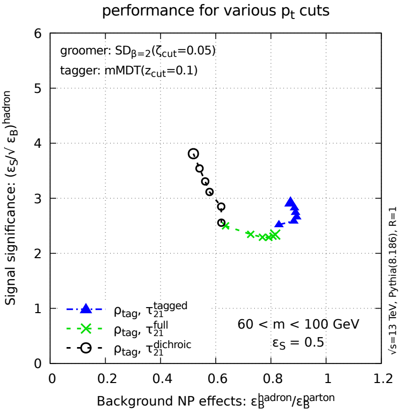
- **Dichroic** : different subjets for numerator / denominator in τ_{21} ratios;

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

- 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 τ_{21} variation
  $\rightarrow$ **increases discriminating power**

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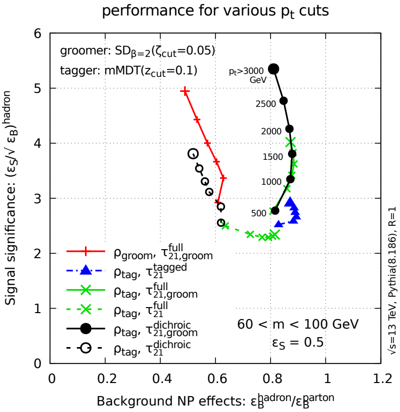
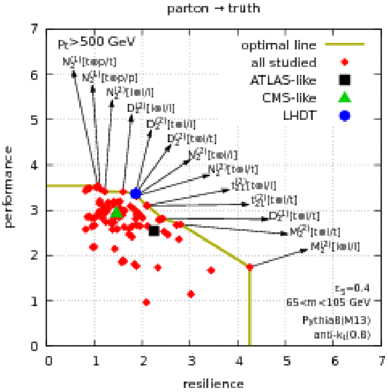


- Dichroic τ_{21} variation
  $\rightarrow$ **increases discriminating power**
- With pre-grooming step
  $\rightarrow$ **reduction of NP effects** and still has a **better performance**
- Performance gain increases as p_t increases

Dichroic Jet Shapes

- Comparison between a variety of jet shapes
  Les Houches 2017 SM Working Group



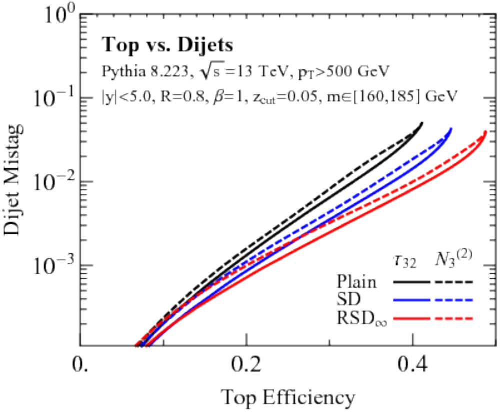
- Dichroic version of observables show **good performance** with relatively **low sensitivity to non-perturbative effects**

Recursive Soft Drop

Dreyer, Necib, Soyez, Thaler (2018)

- Generalized version of Soft Drop algorithm
- Recursive Soft Drop algorithm:
  1. Uncluster the jet into 2 subjets $j \to j_1 + j_2$
  2. Check the Soft Drop condition $\frac{\min(p_{t1}, p_{t2})}{p_{t1}+p_{t2}} > z_{\text{cut}} \Delta R_{12}^{\beta}$
  3. Keep both subjets if condition is met, eliminate softer subjet if it is not
  4. **Iterate process until SD condition is met N times**, or until all particles are recursed through
- For $N = 1$, we recover the original Soft Drop

- Example : boosted top tagging
- Increases mass resolution and **improves tagging performance** (when combined to others jet shapes)



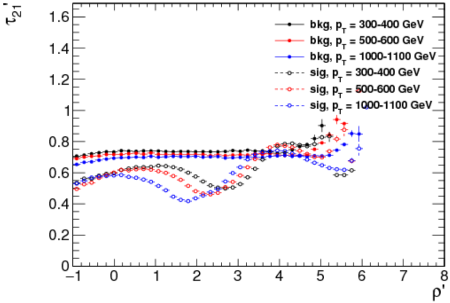
DDT : Designing Decorrelated Taggers

Dolen, Harris, Marzani, Rappocio, Tran (2016)

- Observables are modified to **reduce mass correlations**
  → practical advantages for the experimental measures

- Redefine the following quantities:

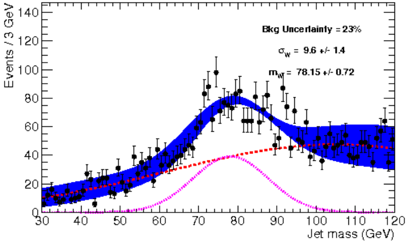
$$\rho = \log\left(\frac{m^2}{p_t^2}\right) \to \rho' = \log\left(\frac{m^2}{p_t \mu}\right), \quad \tau_{21} = \frac{\tau_2}{\tau_1} \to \tau'_{21} = \frac{\tau_2}{\tau_1} - M * \rho'$$

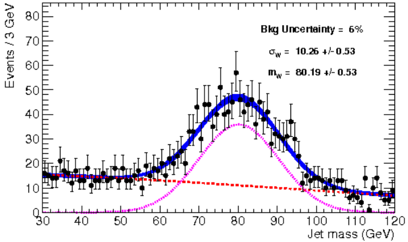


Case study : Diboson background estimate

- Both selections with same background efficiency

  Blue band is the background + signal fit





Cuts are $\tau_{21} < 0.45$ in left and $\tau'_{21} < 0.6$ in right

- We see a considerable **reduction of uncertainty bands**

Analytical approach to decorrelated observables

Moult, Nachman, Neil (2017)

- Convoluted SubStructure approach : use **theoretical knowledge** over observables to decorralate them and the jet mass
- Can be seen as a generalized systematical approach to DDT
- Derivate a function F_{CSS} (see systematical derivation in the paper)

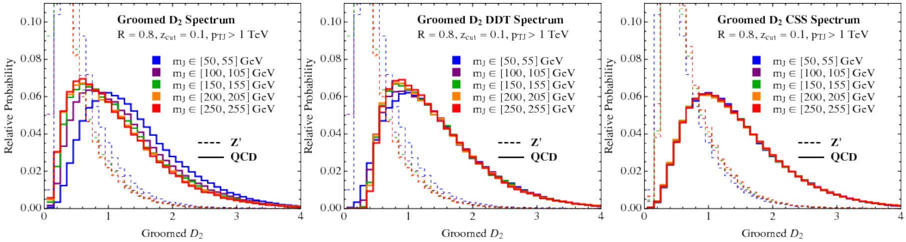
$$\frac{d\sigma^{\text{CSS}}}{dD_2} = \int_0^\infty F_{\text{CSS}}(\epsilon)\frac{d\sigma}{dD_2}(D_2 - \epsilon)$$

- F_{CSS} contains both perturbative and non-perturbative information

$$F_{\text{CSS}} = F_{\text{NP}}^{-1} \otimes F_{\text{P}} \otimes F_{\text{NP}}$$

Case study : $Z' \to q\bar{q}$

- D_2 groomed distribution for signal jets (dashed) and QCD background



- QCD background becomes decorrelated from jet mass

Groomed jet mass

- Connection between measurements and calculations
- **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:

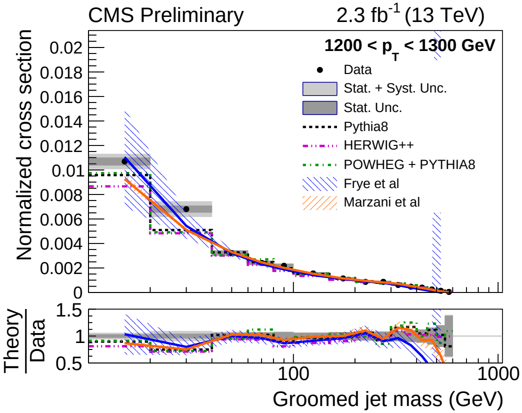
$$\underbrace{N^kLL}_{\text{small } \rho} + \underbrace{N^mLO}_{\text{large } \rho}$$

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 + LO for $z_{\text{cut}} \ll 1$ — *Frye, Larkoski, Schwartz, Yan (2016)*
  - LL + NLO for all z_{cut} — *Marzani, Soyez, LS (2017)*
  - Inclusive jets version — *Kang, Lee, Liu, Ringer (2018)*

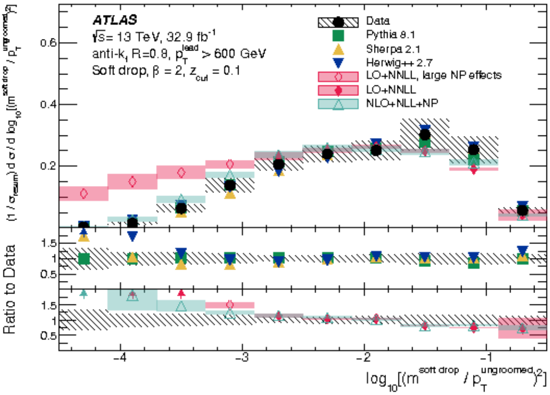
Groomed jet mass

- Comparison with CMS measurements using mMDT



CMS-PAS-SMP-16-010

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



CERN-EP-2017-231

Fitting of strong coupling

Les Houches 2017 SM Working Group

- Possibility of using jet observables at the LHC to do a α_s fitting
- Use of **grooming techniques** to remove undesired NP effects
- **Developments in jet shapes calculations** (now up to NNLL)
- Recent feasibility study using groomed jet mass as an example
  - With currently achievable theoretical and experimental uncertainties a α_s extraction at 10% level is realistic
  - Optimistic about how developments on both sides can improve this precision

See also : use of groomed tools to improve α_s fitting obtained with e^+e^- collisions
Baron, Marzani, Theeuwes (2018), or Theeuwe's Talk at SCET18

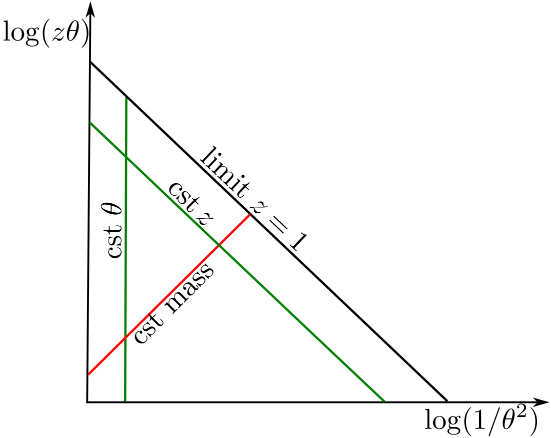
Conclusion

- Jet substructure domain has a 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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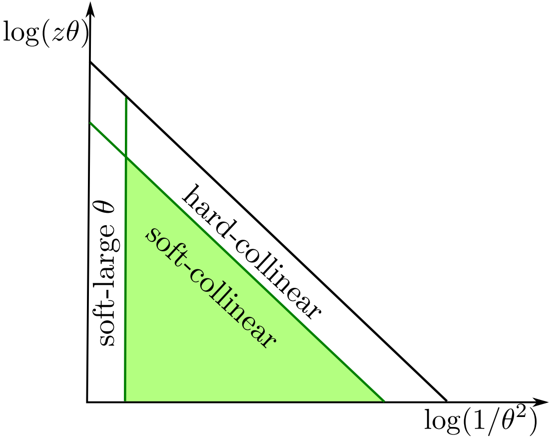
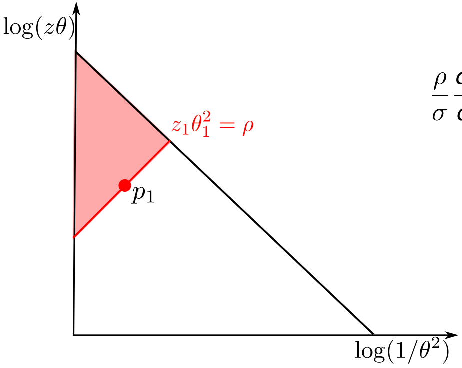


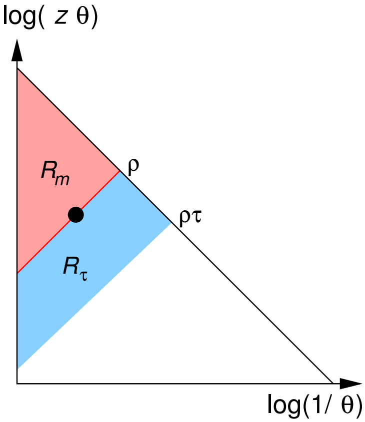
Calculations



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

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

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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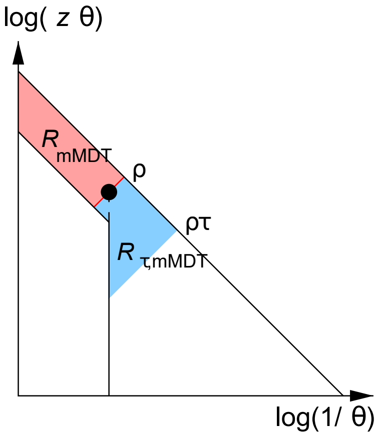

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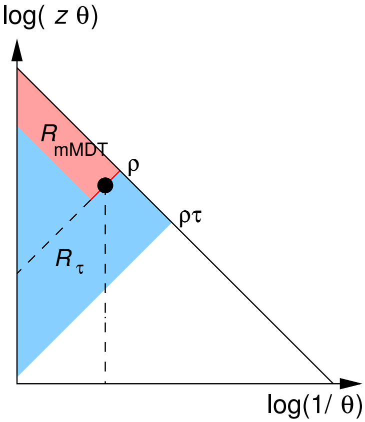

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dichroic	small	large	large

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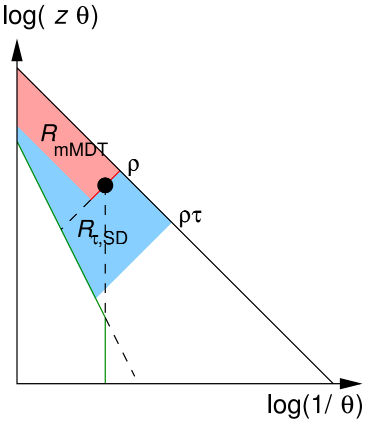

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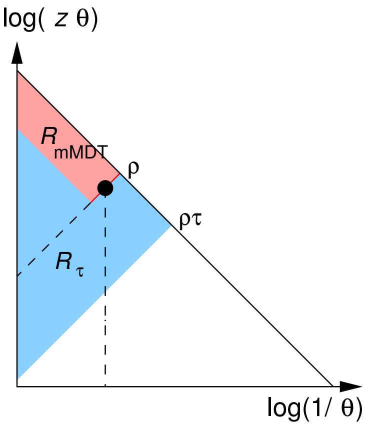
dichroic	small	large	large
dichroic + SD	small	large	small



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dichroic	small	large	large
dichroic + SD	small	large	small

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