Dependence of Z+multi-jet events on the merging scale in TMD multi-jet merging

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TMD multi-jet merging for Z+jets

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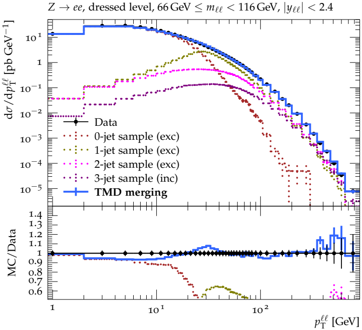
TMD multi-jet merging method

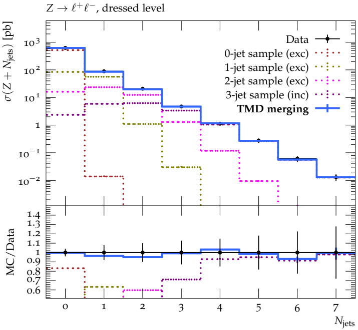
- Include higher order matrix element contributions; hard emissions
- Combining ME with Parton Branching TMDs and TMD ISR within CASCADE3 Baranov S., AMvK, et al. [Eur.Phys.J.C 81 (2021) 5, 425]

Z + 0,1,2,3 jets at $\sqrt{s} = 8$ TeV, $m_{ll} \simeq m_Z$
merged with
Parton Branching TMD and $E_{\perp,\text{clus}} = 23$ GeV

Z boson p_T spectrum



Jet multiplicity spectrum



Motivation for high DY mass studies

- TMD merging predictions accurate up to high jet p_T and large N_{jets} due to properly combining matrix element and parton showers
- Combination depends on merging parameters:

$$R_{\text{clus}},\ E_{\perp,\text{clus}},\ \eta_{max,\text{clus}}$$

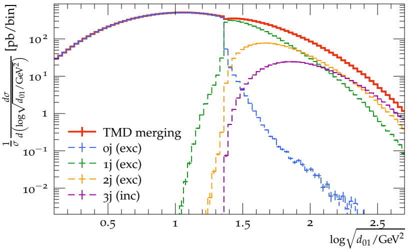
- The merging scale $E_{\perp,\text{clus}}$ separates hard radiation from soft radiation.
  Hard radiation should come from the matrix element: $p_T > E_{\perp,\text{clus}}$
  Soft radiation should come from the parton shower: $p_T < E_{\perp,\text{clus}}$
- Does this methodology still work when we move away from the Z mass and to events with a very different hard scale?
- Interesting question in its own right and from experimental point of view; measurements of Z + jets starting to be performed e.g. by *CMS collaboration* in [Eur.Phys.J.C 83 (2023) 7, 628]

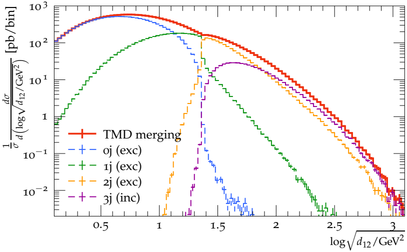
Test of merging algorithm: **Differential jet rates (DJRs)** d_{ij}

$d_{i,(i+1)}$ contains the squared energy scale at which an i-jet configuration is resolved in an $(i+1)$-jet configuration

The **smoothness** of DJRs is a strong indication of the efficiency and accuracy of the merging algorithm.

Z+jets @$\sqrt{s} = 13$ TeV with $m_{ll} \simeq m_Z$ and $E_{\perp,\text{clus}} = 23$ GeV
k_T jet algorithm





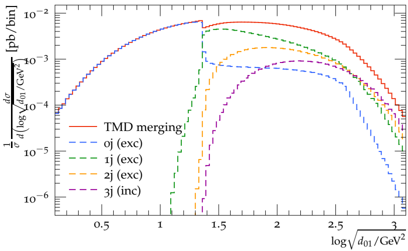
Generate DY hard scattering events with high di-lepton mass with MadGraph5:

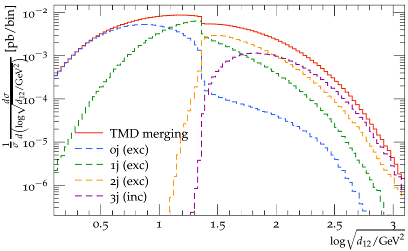
$$m_{ll} = 800 \text{ GeV}$$

TMD PDFs + TMD shower + TMD merging with Cascade3

Calculated DJRs show **large discontinuities** when

$$E_{\perp,\text{clus}} \equiv \mu_m = 23\text{GeV}$$



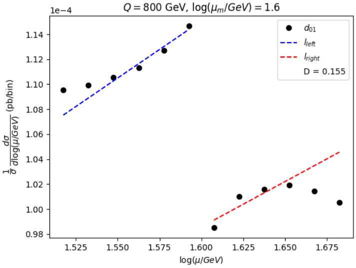


Definition of smoothness in DJR

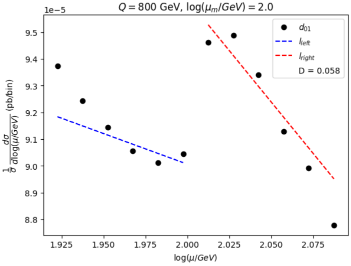
- Zoom on merging scale region in d_{01}
- Fit tangent lines to both sides of the discontinuity: $l = a \log(\sqrt{d_{ij}}) + b$
  - 0th-order discontinuity equals: $l_{left}(\mu_m) - l_{right}(\mu_m)$
  - 1st-order discontinuity includes slope: $a_{left}\delta - a_{right}\delta$
- Result is the following quantification of discontinuity:

$$D(Q, \mu_m) = \frac{|L_l(\mu_m) - L_r(\mu_m)|}{(L_l(\mu_m) + L_r(\mu_m))/2}$$

with $L_i(\mu) = l_i(\mu) + a_i \cdot \delta$.



$m_{ll}^{\min} = 800$ GeV, $\mu_m = 40$ GeV



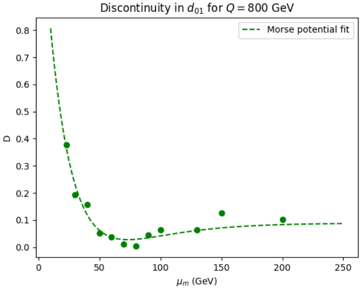
$m_{ll}^{\min} = 800$ GeV, $\mu_m = 100$ GeV

Smoothness distribution from d_{01} analysis

- Distribution of discontinuity D versus the merging scale μ_m values
- Minimum discontinuity reflects **the merging scale that works well** $\mu_m^{(0)}$

Morse potential

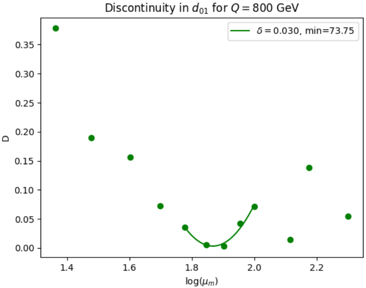
$$D_{fit} = a\left(e^{-2b(\mu_m - c)} - 2e^{-b(\mu_m - c)}\right) + d$$



Linear scale

Parabola

$$D_{fit} = a(\log_{10}(\mu_m))^2 + b\log_{10}(\mu_m) + c$$



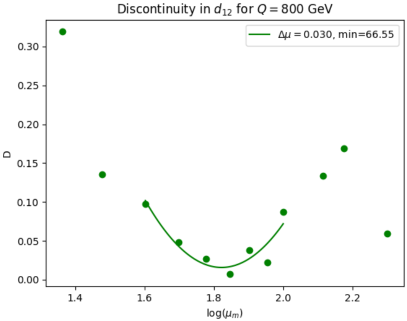
Logarithmic scale

- Shape of this distribution is "Morse potential"-like (nuclear physics)
- **Use polynomial fit through points near the minimum**

Smoothness distribution from d_{12} analysis

- Move to higher order DJR: d_{12}
- Observe similar behavior of discontinuities

$$D_{fit} = a(\log(\mu_m))^2 + b\log(\mu_m) + c$$



- Log scale, smoothest DJR at $\mu_m \sim 10^{1.85} \simeq 70$ GeV

Theoretical uncertainties

Which sources of uncertainty on $\mu_m^{(0)}$? Two uncertainty sources at DJR level:

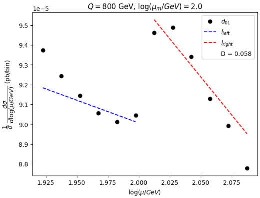
- Statistical: Monte Carlo errors calculated by varying DJR using σ_{MC}; tiny variations, $\leq 0.5\%$
- Systematic: bin size of DJR $\delta = \Delta \log(\sqrt{d_{ij}/\mathrm{GeV}^2})$

Bin size uncertainties

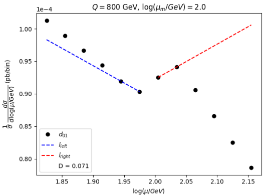
- Vary bin size δ by adding bins of DJR to have $\delta \in \{0.015, 0.030, 0.045\}$
- Tangent line fitted only through a few data points:
  - $\delta = 0.015$: fit of $l(\mu)$ through 4 data points
  - $\delta = 0.030$: fit of $l(\mu)$ through 2 data points
  - $\delta = 0.045$: fit of $l(\mu)$ through 2 data points

Example d_{01} for $m_{ll} = 800$ GeV, $\mu_m = 100$ GeV

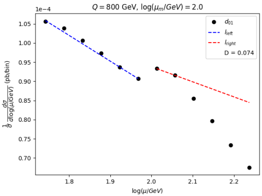
$\delta = 0.015$



$\delta = 0.030$

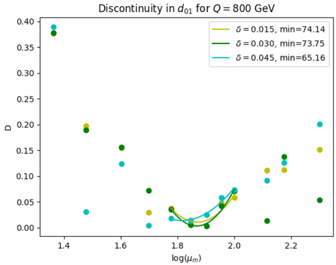


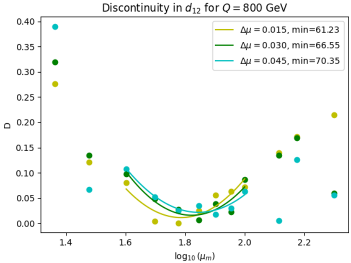
$\delta = 0.045$



Systematic uncertainties

Three distributions D for the same hard scale Q for d_{01} (left) and d_{12} (right):





- Shape of discontinuity most pronounced near minimum
- Bin size uncertainty calculated by:

$$\sigma_{bin.} = \frac{1}{2}\left(\max_k \mu_{m,k}^{(0)} - \min_k \mu_{m,k}^{(0)}\right) \tag{1}$$

A second source of systematic uncertainty: number of data points used for fitting D.

This error is circumvented!

$\Rightarrow$ pick data close to the minimum and use χ^2 for goodness of fit.

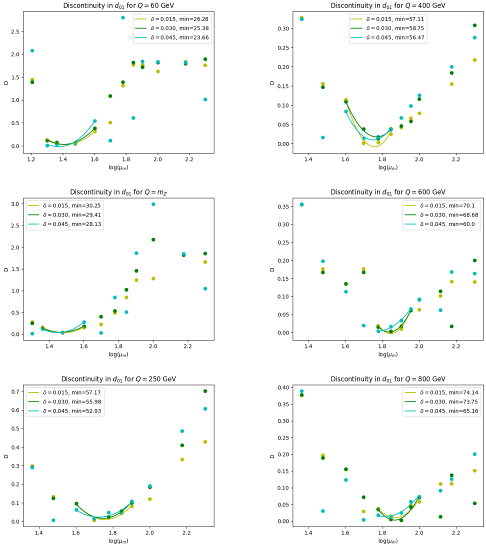
Multiple DY mass windows

Six sets of hard scattering events (LHE) with hard scales $Q = m_{ll}$:

- $Q = 60$ GeV:
  $m_{ll}^{\text{min}} = 58$ GeV, $m_{ll}^{\text{max}} = 62$ GeV
- $Q \simeq m_Z$:
  $m_{ll}^{\text{min}} = 40$ GeV
- $Q = 250, 400, 600, 800$ GeV:
  $m_{ll}^{\text{min}} = Q$

- Shape of discontinuity distributions for various masses is similar!
- **Remarkable observation**: minimum $\mu_m^{(0)}$ shifts with the increase of the hard scale!

Same features at higher order DJR d_{12}



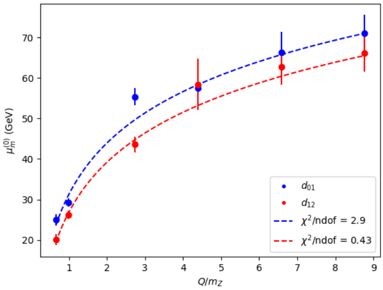
Final results

- Plot results for merging scales $\mu_m^{(0)}$ versus the hard scale Q with $\sigma = \sqrt{\sigma_{bin}^2 + \sigma_{stat}^2}$.
- Data from d_{01} and d_{12} follow similar pattern

Find the functional form of $\mu_m^{(0)}(Q)$:

- Ansatz; logarithmic behavior with off-set
- Z boson mass used in ansatz to fix the units
- Leaves two free parameters to fit

$$\mu_m^{(0)} = m_Z \left(a + b \ln \left(\frac{m_{ll}}{m_Z} \right) \right)$$



Fits result in

$$\mu_m^{(0)}(m_{ll}) = m_Z \left(0.34 + 0.20 \ln \left(\frac{m_{ll}}{m_Z} \right) \right) \quad \text{for } d_{01}$$

$$\mu_m^{(0)}(m_{ll}) = m_Z \left(0.29 + 0.20 \ln \left(\frac{m_{ll}}{m_Z} \right) \right) \quad \text{for } d_{12}$$

Note that $\mu_m^{(0)} \simeq m_Z/3$ in case $m_{ll} = m_Z$

Outlook & summary

- Studies on differential jet rates of Z + jets in TMD merging
- A **measure for smoothness** D is defined which includes two orders of discontinuity: the zeroth and first order.
- Jet merging is studied for varying di-lepton masses from 60 GeV up to 800 GeV
- Systematic (bin size) and statistical (Monte Carlo) uncertainties are included
- An expression for the merging scale dependence on the DY mass is found corresponding to results from both analyses of d_{01} as d_{12}:

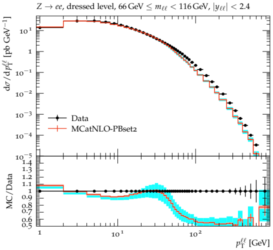
$$E^{(0)}_{\perp,\text{clus}}(m_{ll}) = \mu^{(0)}_m(m_{ll}) = m_Z\left[0.3 + 0.2\ln\left(\frac{m_{ll}}{m_Z}\right)\right]$$

Backup

Combining PB with higher orders

Matching TMD and NLO

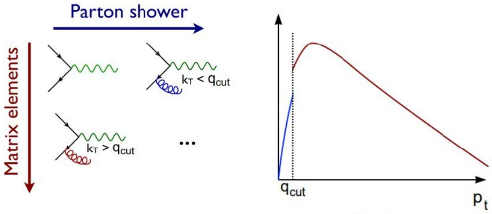
- Match with MC@NLO procedure, subtraction terms HERWIG6
- Intermediate p_T region described
- Deficit at large p_T



Multi-jet merging at TMD level New!

- Include higher fixed-order calculations: **multi-jets**
- Make ME exclusive by Sudakov suppression
- Avoid double counting between initial state TMD evolution & hard emissions

figure by A. Bermudez Martinez $\rightarrow$



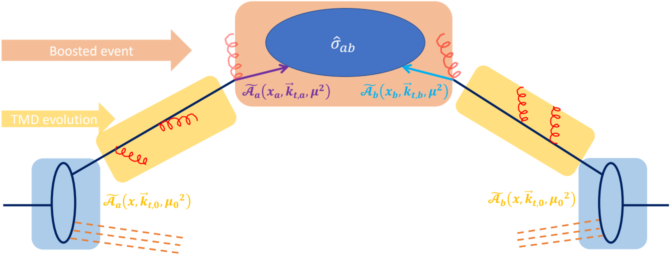
- 1[st] emission PS: $\mathcal{R}^{PS}(p_t^2) \times \exp\left[-\int_{p_t^2} dp_t'^2 \frac{\mathcal{R}^{PS}(p_t'^2)}{\mathcal{B}}\right]$
- 1[st] emission ME: $\mathcal{R}(p_t^2) \longrightarrow \mathcal{R}(p_t^2)\times\exp\left[-\int_{p_t^2} dp_t'^2 \frac{\mathcal{R}^{PS}(p_t'^2)}{\mathcal{B}}\right]$

TMD merging

A. Bermudez Martinez, F. Hautmann, M.L. Mangano Phys.Lett.B 822 (2021) 136700

TMD multi-jet merging method

1. Evaluate n-jet matrix elements: $\hat{\sigma}_{ab}$
2. Reweight the strong coupling
3. Apply forward PB-TMD evolution with condition: $|k_t|^2 \leq \mu_{min}^2$
4. Shower the events using the backward PB evolution
5. Apply MLM[1] prescription between boosted events and the showered events



[1] Other merging prescriptions can potentially also be used