Jet mass distributions with grooming

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1704.02210 and 1712.05105
Marzani, LS, Soyez

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Why jet substructure?

- 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, H and top) with high momentum ($p_t \gg m$)

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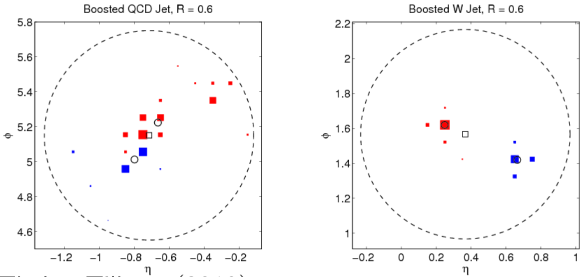
- Unprecedented situation: production of heavy particles (W, Z, H and top) with high momentum ($p_t \gg m$)
  $\rightarrow$ **boosted regime** $\rightarrow$ **substructure techniques**
  $\rightarrow$ look at **dynamics inside the jet**;



Thaler, Tilburg (2010)

Jet Substructure

- Different techniques are available:

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

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

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Soft Drop (and modified MassDrop Tagger)

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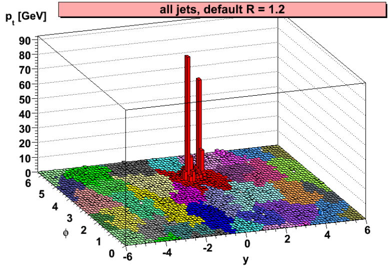

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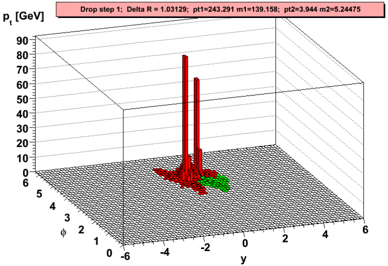
1. Break jet into two $j \to j_1 + j_2$
   using C/A algorithm
2. Check condition
   $\frac{\min(p_{t,1}, p_{t,2})}{(p_{t,1}+p_{t,2})} > z_{\text{cut}} \left(\frac{\theta_{12}}{R}\right)^{\beta}$



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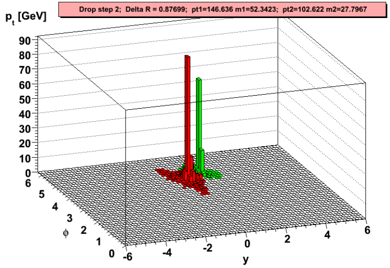

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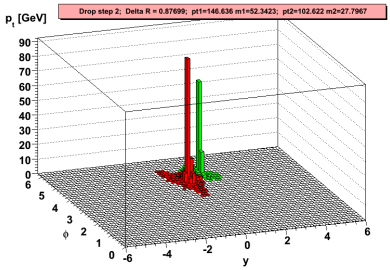
3. If fails, removes the subjet with lower p_t
4. If passes, stop recursion



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

Jet mass with grooming

- Jet substructures techniques are now fundamental ingredients in experimental analysis
- Connection between what can be **measured** and what can be **calculated**

  Frye, Larkoski, Schwartz, and Yan, 2016
  CMS-PAS-SMP-16-010 and CERN-EP-2017-231

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  CMS-PAS-SMP-16-010 and CERN-EP-2017-231
- **Jet mass** is one of the simplest observables

$$m^2 = \left(\sum_{i \in jet} p_{t,i} \right)^2$$

- **Grooming** eliminates part of UE contamination

  → we use modified MassDrop Tagger and Soft Drop

Our accuracy for mMDT

- Our accuracy → **LL matched with NLO** (FLSY is NLL+LO)

$$\sigma \overset{\mathrm{FO}}{=} \sigma_{\mathrm{LO}} + \alpha_s \delta_{\mathrm{NLO}} + \dots$$
$$\overset{\mathrm{LL}}{=} \sigma_{\mathrm{LL}} \simeq \sigma_{\mathrm{LL,LO}} + \alpha_s \delta_{\mathrm{LL,NLO}} + \dots$$

- For mMDT leading contribution is **single-log**

$$\sigma_{\mathrm{LL}} \ni \alpha_s^n \log(p_t/m)^n f_n(z_{\mathrm{cut}})$$

→ includes α_s up to 1-loop and hard-collinear emissions.

- Consider finite z_{cut} contributions;
  → effects are small for the parameters used in measures
- Two options for p_t bins:
  1. Ungroomed momentum $p_{t,\mathrm{jet}}$ preferred version
  2. Groomed momentum $p_{t,\mathrm{mMDT}}$ collinear unsafe

Structure of LL calculation

- Resummation in the **boosted regime**, consider the variable

$$\rho = \frac{m^2}{p_{t,\text{jet}}^2 R^2} \ll 1.$$

- In practice, we want a results for each mass bin

$$\frac{\Delta\sigma}{\Delta m}(m_1, m_2; z_{\text{cut}}, p_{t1}, p_{t2}) = \frac{1}{m_2 - m_1} \int_{p_{t1}}^{p_{t2}} dp_t \frac{d\sigma^{\text{inclu}}}{dp_t} \Sigma(m; z_{\text{cut}}, p_t) \Big|_{m_1}^{m_2}.$$

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- Finite z_{cut} contributions have a **nontrivial flavor structure**

$$\Sigma(m; z_{\text{cut}}, p_t) = \exp\begin{pmatrix} -R_q - R_{q\to g} & R_{g\to q} \\ R_{q\to g} & -R_g - R_{g\to q}\end{pmatrix}\begin{pmatrix} f_q \\ f_g \end{pmatrix},$$

R_x are single-log Sudakov corresponding to different decay channels

Fixed order calculation

- **Fixed order** (NLO) valid in $\rho \sim 1$ region
- Used NLOJet++ with the parton distribution set CT14
- Cluster jets with anti-k_t implemented in FastJet
- Use mMDT implemented in fjcontrib

Matching

- "Naive" multiplicative matching :

$$\sigma_{\mathrm{NLO+LL,naive}} = \sigma_{\mathrm{LL}}\ \sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LL,NLO}},$$

  Problem : $\rightarrow \sigma_{\mathrm{(LL,)NLO}}$ may turn negative at small ρ.

- Our alternative multiplicative matching

$$\sigma_{\mathrm{NLO+LL}} = \sigma_{\mathrm{LL}} \left[\frac{\sigma_{\mathrm{LO}}}{\sigma_{\mathrm{LL,LO}}} + \alpha_s \left(\frac{\delta_{\mathrm{NLO}}}{\sigma_{\mathrm{LL,LO}}} - \sigma_{\mathrm{LO}} \frac{\delta_{\mathrm{LL,NLO}}}{{\sigma_{\mathrm{LL,LO}}}^2} \right) \right].$$

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- LL endpoint matched to NLO

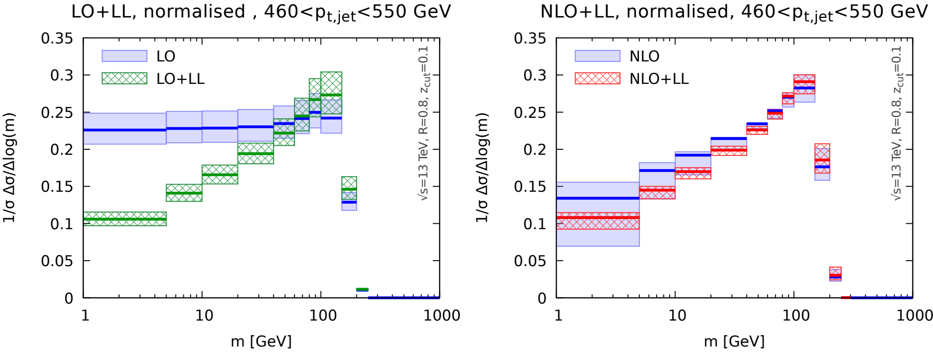
$$\log\left(\frac{1}{\rho}\right) \rightarrow \log\left(\frac{1}{\rho} - \frac{1}{\rho_{\mathrm{max},i}} + e^{-B_q}\right),$$

  where $\rho_{\mathrm{max,NLO}} = 0.44974$, for $R = 0.8$.

- Normalization to (N)LO x-section.

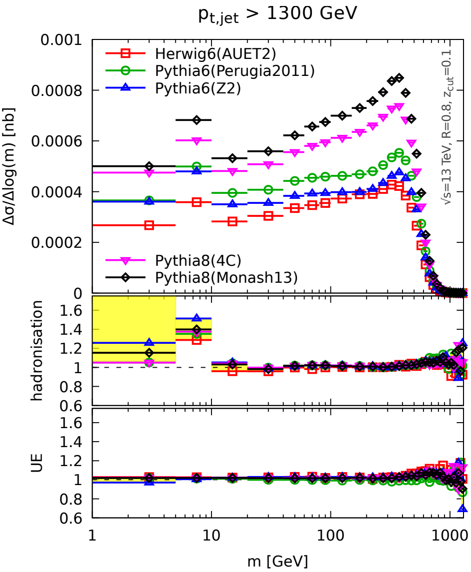
Perturbative results

- Obtain uncertainties by varying all perturbative scales



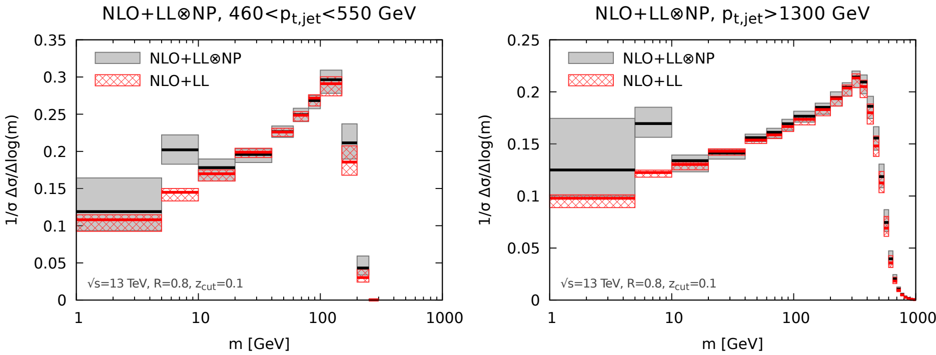
- Going from LO $\rightarrow$ NLO has large impact in uncertainties;
- NLO has smaller effects from resummation.

Non-perturbative corrections



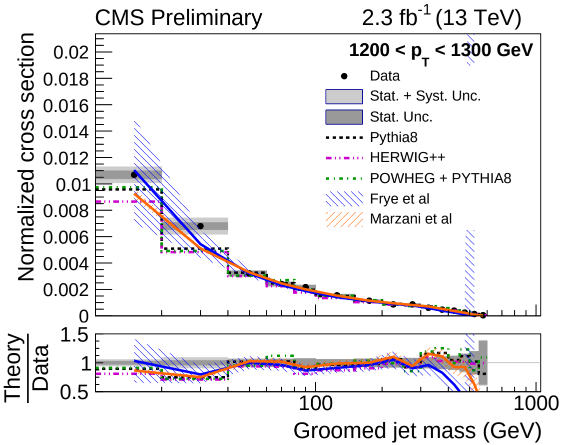
- Extract NP corrections from different generators and tunes;
- Average of corrections as a multiplicative factor;
- Envelope as uncertainty;
- Added quadratically to perturbative uncertainty.

Final results LL + NLO



- Relatively **small NP corrections** above $m = 10\text{GeV}$.

Comparison to experiment



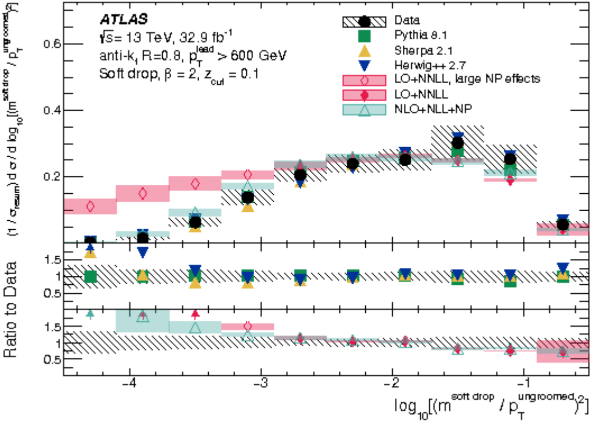
- Good agreement with experimental measurements.

  Plot from CMS-PAS-SMP-16-010

Our accuracy – extended to SD ($\beta > 0$)

- Leading contribution now is **double-logarithm**
- Our accuracy is **NLL + NLO**
  $\rightarrow$ includes α_s up to 2-loops (CMW scheme) and multiple emissions
- Finite z_{cut} contributions are power corrections
- Matching requires flavor separation of σ_{jet} at LO and NLO, and of $d\sigma/dm$ at LO
- Multiplicative matching has flaws
  $\rightarrow$ we are using the envelope of log-R and R scheme
  Banfi, Salam and Zanderighi (2010)

Comparison to experiment



- Good agreement with experimental measurements.
  Plot from CERN-EP-2017-231

Conclusion

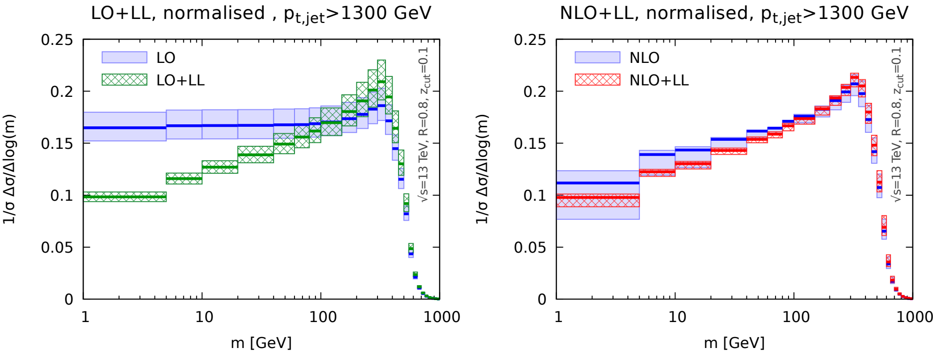
- Jet substructure is a very active field, both in theory and experiment
- Predictions can be **successfully compared to measurement**
- Finite z_{cut} contributions are small for $z_{cut} = 0.1$, although they formally start at LL
- Going to NLO decreases uncertainties considerably and increases agreement at small mass
- Future :
  1. (N)NLL accuracy;
  2. Study other observables.

Backup slides

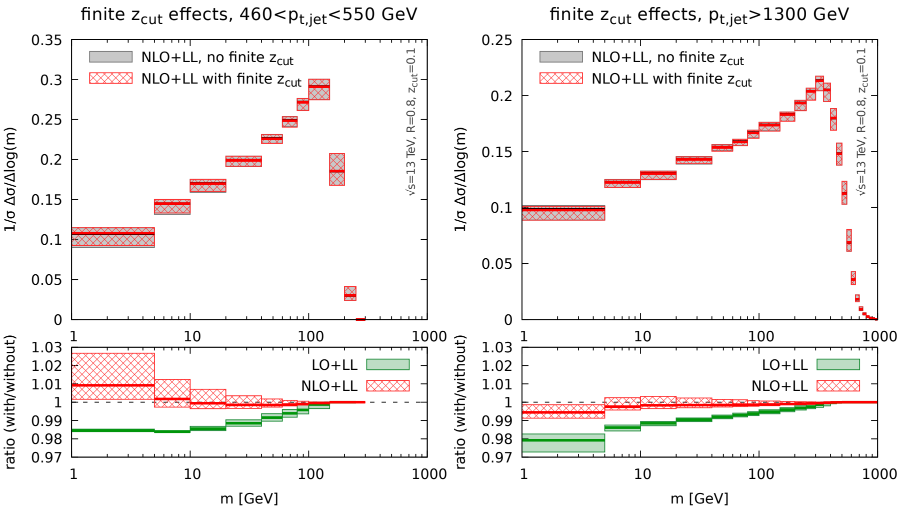
Perturbative uncertainties

- Vary μ_R and μ_F (7-point scale variation) around $p_{t,\mathrm{jet}}R$;
  Cacciari, Frixione, Mangano, Nason, and Ridolf, 2004
- Vary μ_Q around $p_{t,\mathrm{jet}}R$;
- (Optional) Vary matching scheme (use also R and logR) (minor effects);
- Vary α_s freezing scale (minor effects).

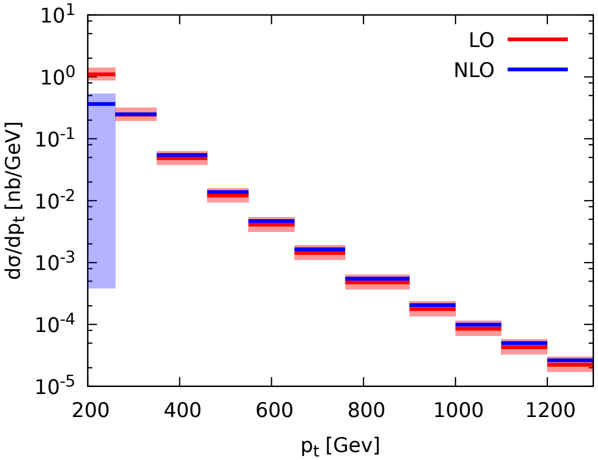
Perturbative results at $p_t > 1300\text{GeV}$



Impact of finite z_{cut} effects



Instability of NLO contribution



Resummed results $p_{t,\text{jet}}$ case

$$R_q = C_F \int_0^1 \frac{d\theta^2}{\theta^2} \int_0^1 dz\ p_{gq}(z) \frac{\alpha_s}{\pi} \Theta\left(z_{\text{cut}} < z < 1 - z_{\text{cut}}\right) \Theta(z\theta^2 > \rho),$$

$$R_g = C_A \int_0^1 \frac{d\theta^2}{\theta^2} \int_0^1 dz\ p_{xg}(z) \frac{\alpha_s}{\pi} \Theta\left(z_{\text{cut}} < z < 1 - z_{\text{cut}}\right) \Theta(z\theta^2 > \rho),$$

$$R_{q\to g} = C_F \int_0^1 \frac{d\theta^2}{\theta^2} \int_0^1 dz\ p_{gq}(z) \frac{\alpha_s}{\pi} \Theta\left(1 - z < z_{\text{cut}}\right) \Theta(z\theta^2 > \rho),$$

$$R_{g\to q} = T_R n_f \int_0^1 \frac{d\theta^2}{\theta^2} \int_0^1 dz\ p_{qg}(z) \frac{\alpha_s}{\pi} \left[\Theta\left(1 - z < z_{\text{cut}}\right) + \Theta\left(z < z_{\text{cut}}\right)\right] \Theta(z\theta^2 > \rho).$$

Resummed results $p_{t,\mathrm{jet}}$ case

$$
\begin{aligned}
R_q &= C_F \mathcal{R}_q(\rho; z_{\mathrm{cut}})\,\Theta(\rho < e^{B_q}) + C_F\,\mathcal{I}(\rho; z_{\mathrm{cut}})\,\pi_q(z_{\mathrm{cut}})\,\Theta(\rho < z_{\mathrm{cut}}),\\
R_g &= C_A \mathcal{R}_g(\rho; z_{\mathrm{cut}})\,\Theta(\rho < e^{B_g}) + C_A\,\mathcal{I}(\rho; z_{\mathrm{cut}})\,\pi_g(z_{\mathrm{cut}})\,\Theta(\rho < z_{\mathrm{cut}}),\\
R_{q\to g} &= C_F\,\mathcal{I}(\rho; z_{\mathrm{cut}})\,\pi_{q\to g}(z_{\mathrm{cut}})\,\Theta(\rho < z_{\mathrm{cut}}),\\
R_{q\to g} &= n_f\,T_R\,\mathcal{I}(\rho; z_{\mathrm{cut}})\,\pi_{g\to q}(z_{\mathrm{cut}})\,\Theta(\rho < z_{\mathrm{cut}}),
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{R}_i(\rho; z_{\mathrm{cut}}) = \frac{1}{2\pi\alpha_s\beta_0^2}\Big[&W\big(1 + 2\alpha_s\beta_0 B_i\big) - W\big(1 + 2\alpha_s\beta_0 \log(z_m)\big)\\
&+ 2W\big(1 + \alpha_s\beta_0 \log(\rho z_m)\big) - 2W\big(1 + \alpha_s\beta_0(\log(\rho) + B_i)\big)\Big],
\end{aligned}
$$

$$
\mathcal{I}(\rho; z_{\mathrm{cut}}) = \int_\rho^{z_{\mathrm{cut}}} \frac{dx}{x}\frac{\alpha_s(x p_t R)}{\pi} = \frac{1}{\pi\beta_0}\log\left(\frac{1 + \alpha_s\beta_0 \log(z_{\mathrm{cut}})}{1 + \alpha_s\beta_0 \log(\rho)}\right),
$$

with $W(x) = x\log(x)$, $z_m = \max(z_{\mathrm{cut}}, \rho)$, $B_q = -\frac{3}{4}$,

Resummed results $p_{t,\text{jet}}$ case

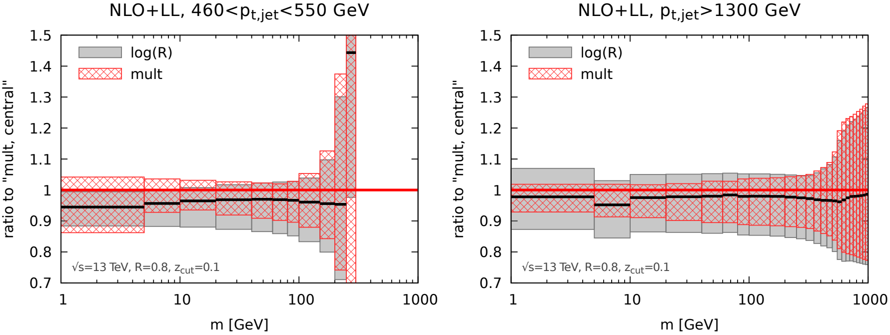
$$\pi_q(z_{\text{cut}}) = \log(1 - z_{\text{cut}}) + \frac{3z_{\text{cut}}}{2},$$

$$\pi_g(z_{\text{cut}}) = \log(1 - z_{\text{cut}}) + 2z_{\text{cut}} - \frac{z_{\text{cut}}^2}{2} + \frac{z_{\text{cut}}^3}{3} - \frac{n_f T_R}{C_A}\left(z_{\text{cut}} - z_{\text{cut}}^2 + \frac{2z_{\text{cut}}^3}{3}\right),$$

$$\pi_{q\to g}(z_{\text{cut}}) = -\log(1 - z_{\text{cut}}) - \frac{z_{\text{cut}}}{2} - \frac{z_{\text{cut}}^2}{4},$$

$$\pi_{g\to q}(z_{\text{cut}}) = z_{\text{cut}} - z_{\text{cut}}^2 + \frac{2z_{\text{cut}}^3}{3}.$$

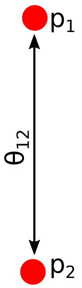
$p_{t,\mathrm{jet}}$ option : matching options

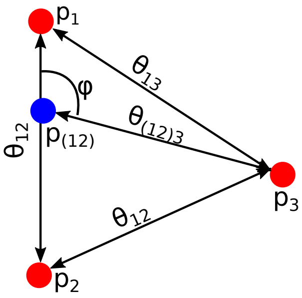


$$\Sigma^{\text{log-}R}_{\text{NLO+LL}} = \Sigma_{\text{LL}} \exp\left[\alpha_s\left(\Sigma^{(1)} - \Sigma^{(1)}_{\text{LL}}\right) + \alpha_s^2\left(\Sigma^{(2)} - \Sigma^{(2)}_{\text{LL}}\right) - \frac{\alpha_s^2}{2}\left({\Sigma^{(1)}}^2 - {\Sigma^{(1)}_{\text{LL}}}^2\right)\right].$$

Endpoint ρ_{max}

Determine $\rho_{\text{max}} \to$ find configurations with maximal mass for LO (left) and NLO (right).





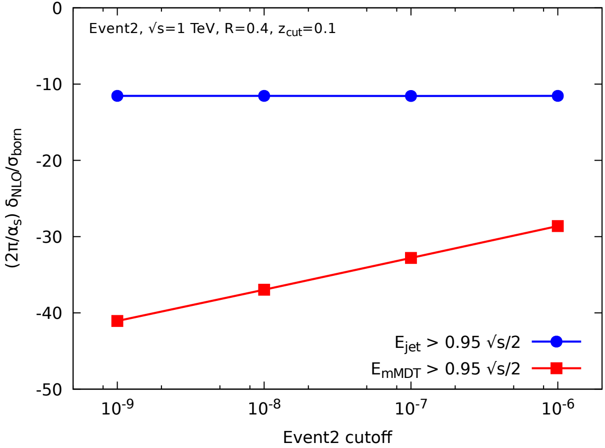
Back to $\beta = 0$ case.

What happens if we consider $p_{t,\text{mMDT}}$ bins instead of $p_{t,\text{jet}}$ bins ?

Collinear unsafety

- $\frac{d\sigma}{dp_{t,\text{mMDT}}}$ is collinear unsafe, but remains Sudakov safe;
- Example : bin [1000 : 1100]GeV, jet at $p_{t,\text{jet}} = 1010$GeV
  Emission of a parton at 20GeV
  $\rightarrow$ if real $\rightarrow$ $p_{t,\text{mMDT}} = 990$GeV $\rightarrow$ not in bin
  $\rightarrow$ if virtual $\rightarrow$ $p_{t,\text{mMDT}} = 1010$GeV $\rightarrow$ in bin
- No constraints over emission angle $\rightarrow$ collinear divergence;
- For a fixed mass $\rho \propto \theta$, mass naturally cuts the angle
  $\rightarrow$ finite, but comes with LL contributions.

Collinear unsafety $p_{t,\text{mMDT}}$ case



Fixed-order structure $p_{t,\mathrm{mMDT}}$ case

$$\rho \frac{d\sigma^{\mathrm{LL,NLO},C_F^2 a}}{d\rho} = \int_{p_{t1}}^{p_{t2}} dp_{t,\mathrm{jet}}\, \sigma_q(p_{t,\mathrm{jet}}) R_q' \Big[- R_q - R_{q\to g} \Big]$$

$$- \int_{p_{t1}}^{\min\left[p_{t2}, \frac{p_{t1}}{1-z_{\mathrm{cut}}}\right]} dp_{t,\mathrm{jet}}\, \sigma_q(p_{t,\mathrm{jet}})\; R_q'$$

$$\times\; \frac{\alpha_s C_F}{\pi} \log\frac{1}{\rho} \int_{1-\frac{p_{t1}}{p_{t,\mathrm{jet}}}}^{z_{\mathrm{cut}}} dz_1\, p_{gq}(z_1)$$

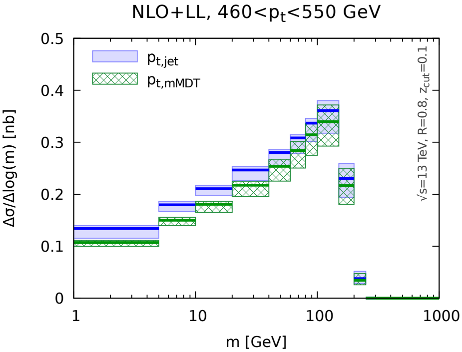
Resummation at LL for $p_{t,\mathrm{mMDT}}$ variant

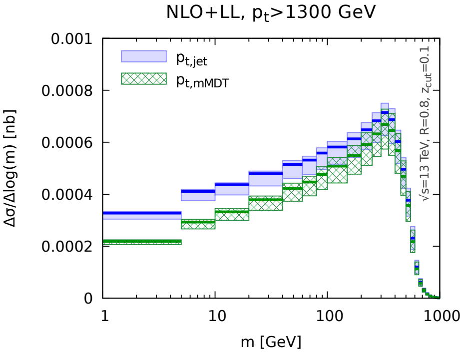
- Generating functional approach
  (for $x > z_{\mathrm{cut}}$ and for quarks)

$$\frac{d}{dt}Q(x,t) = 2C_F \int_0^1 dz\, p_{gq}(z)\left[Q\left((1-z)x\right)\Theta\left(z < \frac{1}{2}\right) + G\left(zx\right)\Theta\left(z > \frac{1}{2}\right) - Q(x,t)\right].$$

M. Dasgupta, F. Dreyer, G. P. Salam, and G. Soyez, 2014 and 2016

Comparison $p_{t,\text{jet}}$ vs. $p_{t,\text{mMDT}}$





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