# Jet mass distributions with grooming

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*Based on arXiv:1704.0221 with S. Marzani and G. Soyez, to appear in JHEP.*

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# Motivation

- Connection between what can be measured and what can be calculated;
  See also: Frye, Larkoski, Schwartz, and Yan, 2016
  CMS-PAS-SMP-16-010 and upcoming ATLAS measurements
- Jet mass is one of the simplest observables;
- Grooming eliminates part of UE contamination;
- We use modified MassDrop Tagger and SoftDrop.

# Cuts for dijets events

| CMS |
|---|
| anti-$k_t$, $R = 0.8$ <br> $p_{t,\mathrm{lead}}, p_{t,\mathrm{sublead}} > 200$ GeV <br> $\|y\| < 2.4$ <br> $p_{t,\mathrm{lead}} < (1.3/0.7) p_{t,\mathrm{sublead}}$ <br> $\Delta\phi_{lead,sub} > \pi/2$ |
| mMDT ($\beta = 0$), $z_{\mathrm{cut}} = 0.1$ |

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| $\Delta\phi_{lead,sub} > \pi/2$ |
| mMDT ($\beta = 0$), $z_{\mathrm{cut}} = 0.1$ |

Watch out : $p_{t,\mathrm{sublead}}$ cut results in large NLO corrections
$\rightarrow$ Instability in the first $p_t$ bin.

# Our accuracy for mMDT

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

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

- For mMDT leading contribution is single-log

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

→ includes $\alpha_s$ up to 1-loop and hard-collinear emissions.
(Our log counting is equivalent to FLSY's NLL)

- Consider finite $z_{\text{cut}}$ contributions; (not in FLSY)
- Two options for $p_t$ bins:
  1. Ungroomed momentum $p_{t,\text{jet}}$ preferred version
  2. Groomed momentum $p_{t,\text{mMDT}}$ 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 $z_{\text{cut}}$ contributions have a nontrivial flavor structure

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

- $R_x$ are single-log Sudakov corresponding to different decays.

# 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 :

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

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

- 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

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

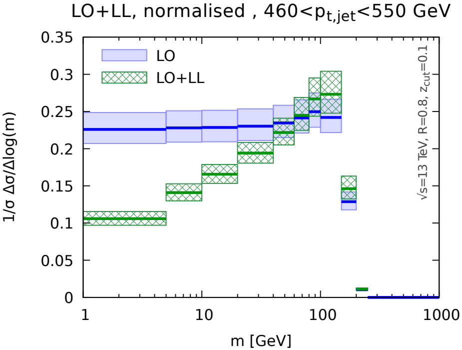
  where $\rho_{\mathrm{max,NLO}} = 0.44974$, for $R = 0.8$.

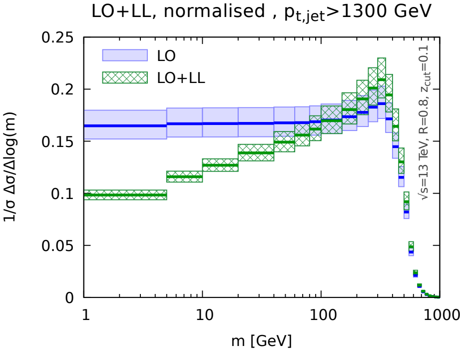
- Normalization to (N)LO x-section.

# Uncertainties

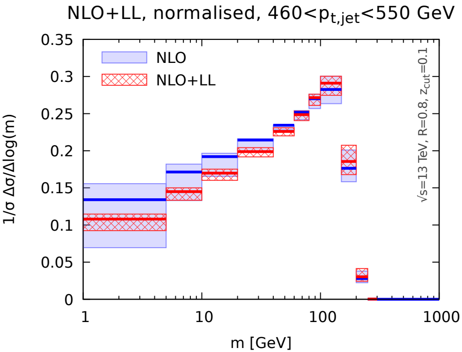
- Vary $\mu_R$ and $\mu_F$ (7-point scale variation) around $p_{t,\text{jet}}R$;
  Cacciari, Frixione, Mangano, Nason, and Ridolf, 2004
- Vary $\mu_Q$ around $p_{t,\text{jet}}R$;
- (Optional) Vary matching scheme (use also R and logR) (minor effects);
- Vary $\alpha_s$ freezing scale (minor effects).

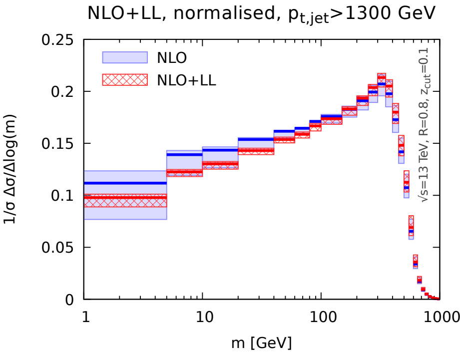
# Perturbative results at LO + LL



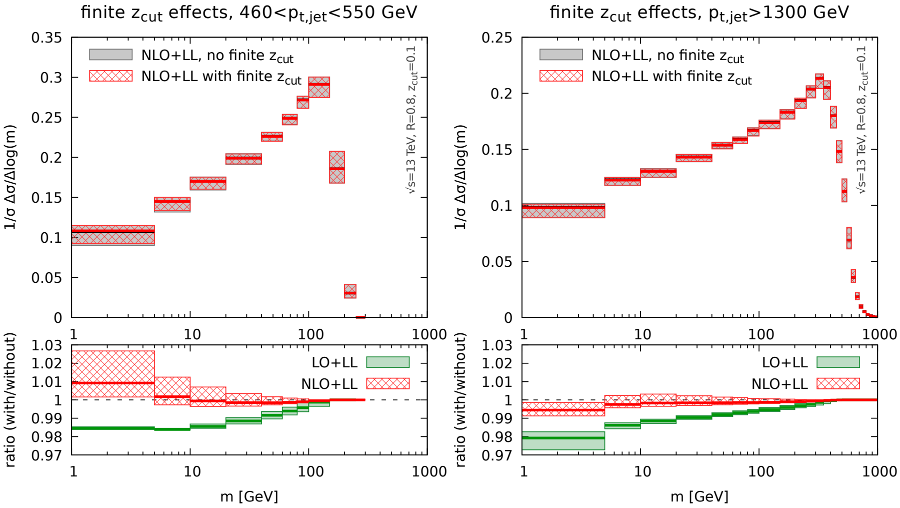
# Perturbative results at NLO + LL



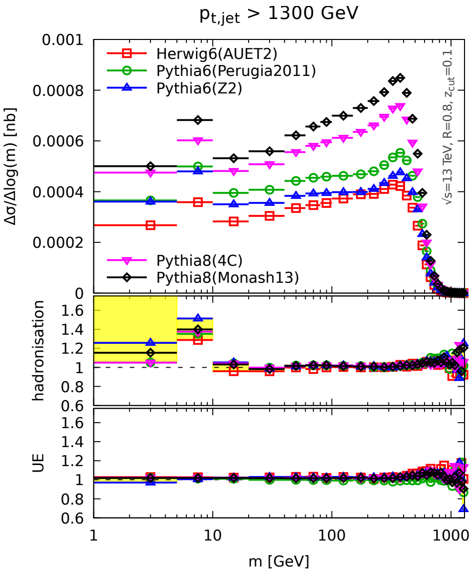

- Going from LO → NLO has large impact in uncertainties;
- Smaller effects from resummation.

# Impact of finite $z_{cut}$ effects



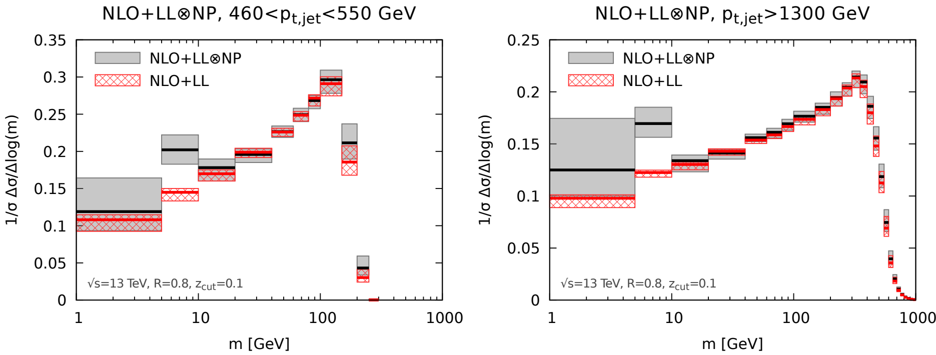

- For the $p_{t,\text{jet}}$ option, finite $z_{\text{cut}}$ effects are small.

# Non-perturbative corrections



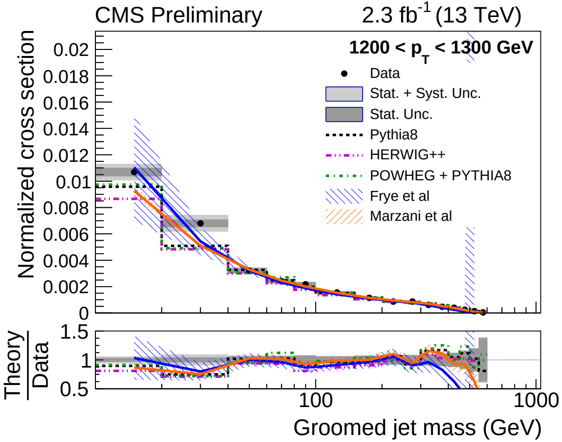

- Extract NP corrections from different generators and tunes;
- Average of corrections as a multiplicative factor;
- Envelope as uncertainty;
- Added quadratically to perturbative uncertainty.

# Final results LL + NLO




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

# Comparison to experiment



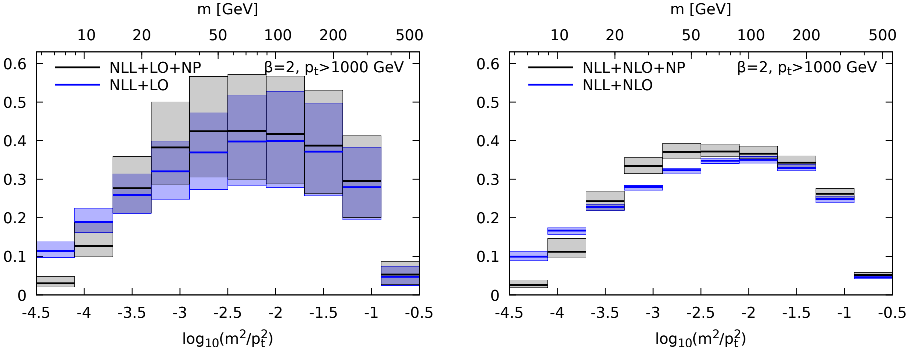

- Good agreement with experimental measurements.

  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
  → includes $\alpha_s$ up to 2-loops (CMW scheme) and multiple emissions;
- Finite $z_{\text{cut}}$ contributions are power corrections;
- Matching requires flavor separation of $\sigma_{jet}$ at LO and NLO, and of $d\sigma/dm$ at LO;
- Multiplicative matching has flaws
  → we are using the envelope of log-R and R scheme.
  Banfi, Salam and Zanderighi, 2010

# Final results NLL + (N)LO




- Uncertainty decreases when going LO $\rightarrow$ NLO.
- NP effects increase for large $\beta$.

Back to $\beta = 0$ case.

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.

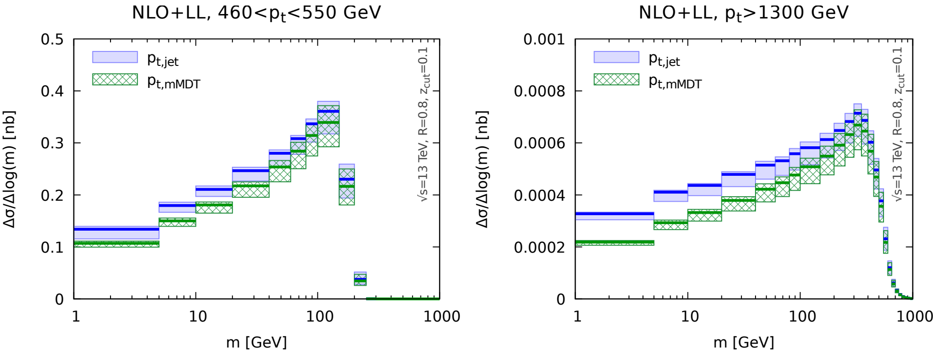
# Resummation at LL for $p_{t,\mathrm{mMDT}}$ variant

- Complex structure $\rightarrow$ resummed numerically;
- Generating functional approach
  (for $x > z_{\text{cut}}$ and for quarks)

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

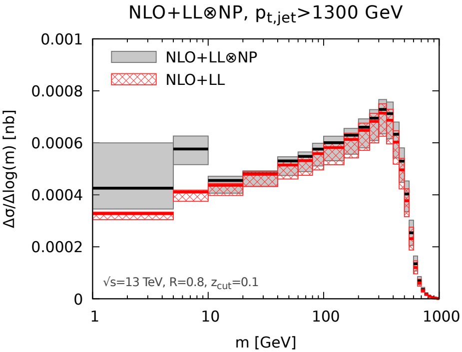
M. Dasgupta, F. Dreyer, G. P. Salam, and G. Soyez, 2014 and 2016

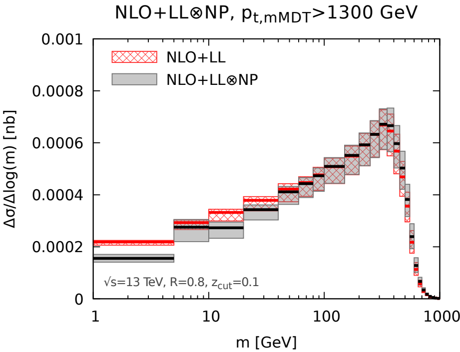
# Comparison $p_{t,\text{jet}}$ vs. $p_{t,\text{mMDT}}$




- Delicate normalization $\rightarrow$ we present x-sections;
- Sizable pure finite $z_{\text{cut}}$ effects.

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




- $p_{t,\text{mMDT}}$ is slightly more resilient against NP effects;
- Theoretically difficult to extend to higher orders;
- We encourage the use of $p_{t,\text{jet}}$, but $p_{t,\text{mMDT}}$ still an interesting option.

# Conclusion

- Finite $z_{\text{cut}}$ contributions are small for $z_{\text{cut}} = 0.1$, 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

# Reminder of grooming process

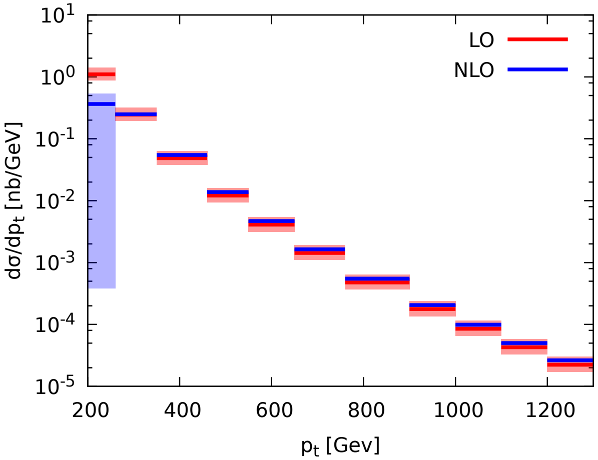
The SoftDrop procedure take a jet with momentum $p_{t,\text{jet}}$ and radius $R$. Re-cluster it using the C/A algorithm. Follow the recursion:

1. it de-clusters the jet into 2 subjets $j \to j_1 + j_2$;
2. it checks the condition

$$\frac{\min(p_{t1}, p_{t2})}{p_{t1} + p_{t2}} > z_{\text{cut}} \left(\frac{\theta_{12}}{R}\right)^{\beta} ;$$

3. if the jet passes the condition, the recursion stops; if not the softer subjet is removed and the algorithms goes back to step 1 with the hardest of the two subjets.

# 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 $p_{t,\text{jet}}$ case

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

$$
\begin{aligned}
\mathcal{R}_i(\rho; z_{\text{cut}}) &= \frac{1}{2\pi\alpha_s\beta_0^2}\Big[W\big(1+2\alpha_s\beta_0 B_i\big) - W\big(1+2\alpha_s\beta_0\log(z_m)\big)\\
&\qquad + 2W\big(1+\alpha_s\beta_0\log(\rho z_m)\big) - 2W\big(1+\alpha_s\beta_0(\log(\rho)+B_i)\big)\Big],\\
\mathcal{I}(\rho; z_{\text{cut}}) &= \int_\rho^{z_{\text{cut}}}\frac{dx}{x}\frac{\alpha_s(xp_tR)}{\pi} = \frac{1}{\pi\beta_0}\log\left(\frac{1+\alpha_s\beta_0\log(z_{\text{cut}})}{1+\alpha_s\beta_0\log(\rho)}\right),
\end{aligned}
$$

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

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

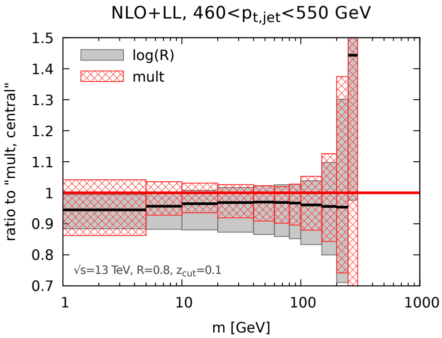
$$\pi_q(z_{\text{cut}}) = \log(1 - z_{\text{cut}}) + \frac{3z_{\text{cut}}}{2},$$

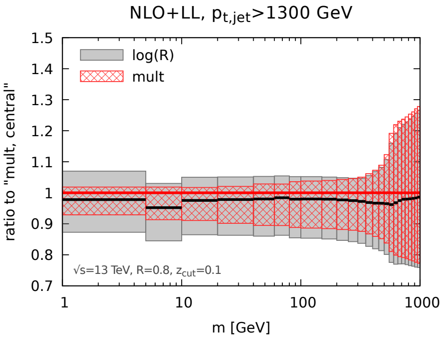
$$\pi_g(z_{\text{cut}}) = \log(1 - z_{\text{cut}}) + 2z_{\text{cut}} - \frac{z_{\text{cut}}^2}{2} + \frac{z_{\text{cut}}^3}{3} - \frac{n_f T_R}{C_A}\left(z_{\text{cut}} - z_{\text{cut}}^2 + \frac{2z_{\text{cut}}^3}{3}\right),$$

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

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

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

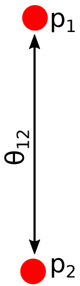


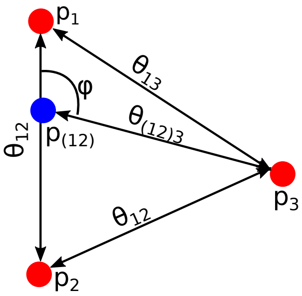




$$\Sigma^{\text{log-}R}_{\text{NLO+LL}} = \Sigma_{\text{LL}} \exp\left[\alpha_s\left(\Sigma^{(1)} - \Sigma^{(1)}_{\text{LL}}\right) + \alpha_s^2\left(\Sigma^{(2)} - \Sigma^{(2)}_{\text{LL}}\right) - \frac{\alpha_s^2}{2}\left(\Sigma^{(1)^2} - \Sigma^{(1)^2}_{\text{LL}}\right)\right].$$

# Endpoint $\rho_{\max}$

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



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

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

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

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

# Collinear unsafety $p_{t,\mathrm{mMDT}}$ case