Matching NNLO Calculations and Parton Showers.

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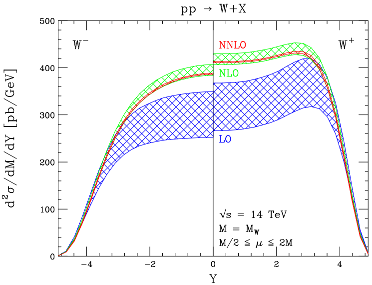
20 January 2014

Frontiers in Particle Physics: From Dark Matter to the LHC and Beyond

arXiv:1311.0286 SA, C. Bauer, C. Berggren, F. Tackmann, J. Walsh, S. Zuberi

Why higher-order calculations?

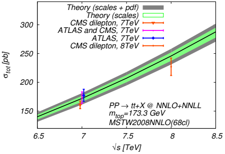
- NLO is the first order in which rates and associated theoretical uncertainties are reliably predicted.
- NNLO gives non-negligible contributions in several cases (eg. $gg \to H \approx 30\%$).
- Theoretical uncertainties further reduced by including NNLO corrections. For few % precision, NNLO is required.



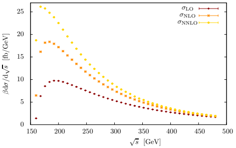
[Anastasiou et al., hep-ph/0312266]

- Shapes are generically better described increasing the parton multiplicity: new channels at NLO, and NNLO, larger K-factors and noticeable shape distorsions.
- Recent progresses in subtraction methods allowed to address several important processes at NNLO: $Z, W, H, \gamma\gamma, Z\gamma, HH, t\bar{t}, Hj, jj \ldots$

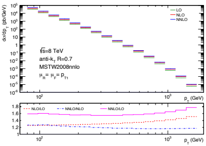
[Czackon et al., 1303.6254]



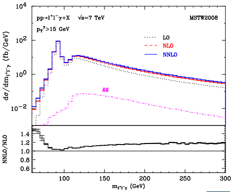
[Boughezal et al., 1302.6216]



[Currie et al., 1310.3993]



[Grazzini et al., 1309.7000]



Problems with higher-order perturbative calculations

- Fixed-order results are only at the parton level. No immediate way to estimate detector effects. Singular regions are poorly described.
- Resummation improve sing. region but requires to define the observable in advance, no fully-exclusive events.
- Beyond LO, perturbative calculations are plagued by IR divergencies, that only disappear after properly combining real emission contributions with virtual corrections.
- At fully exclusive level, this requires the introduction of subtraction counterterms to regulate the divergencies in 4D

$$\sigma^{\mathrm{NLO}}(X) = \int \mathrm{d}\Phi_N \left(B_N(\Phi_N) + {V_N}^C(\Phi_N)\right) M_X(\Phi_N)$$
$$+ \int \mathrm{d}\Phi_{N+1} \left\{ B_{N+1}(\Phi_{N+1})\, M_X(\Phi_{N+1}) - \sum_m C^m_{N+1}(\Phi_{N+1})\, M_X[\hat{\Phi}^m_N(\Phi_{N+1})] \right\}$$

- B_{N+1} and C^m_{N+1} are correlated unphysical "events", separately IR-divergent:
  - large positive and negative weights
  - correlations must be propagated to shower/detector
  - no reasonable way of unweighting

IR-safe definitions of events beyond LO

- Goal is to generate "physical events" , i.e. to each event can be assigned a IR-finite cross section $\mathrm{d}\sigma^{\mathrm{MC}}$.
- Introduction of a resolution parameter $\mathcal{T}_N$, $\mathcal{T}_N \to 0$ in the IR region. Emissions below $\mathcal{T}_N^{\mathrm{cut}}$ are unresolved (i.e. integrated over).
- M-parton events are really N-jet events (no jet-algo), fully differential in Φ_N
  - Price to pay: power corrections in $\mathcal{T}_N^{\mathrm{cut}}$ due to projection, vanish for IR-safe observables as $\mathcal{T}_N^{\mathrm{cut}} \to 0$
- Iterating the procedure, the phase space is sliced into jet-bins

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Inclusive Φ_N

$$\frac{\mathrm{d}\sigma^{\mathrm{MC}}_{\geq N}}{\mathrm{d}\Phi_N}$$

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Exclusive Φ_N

$$\frac{\mathrm{d}\sigma_N^{\mathrm{MC}}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}})$$

Inclusive Φ_{N+1}

$$\frac{\mathrm{d}\sigma_{\geq N+1}^{\mathrm{MC}}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}})$$

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$$\frac{\mathrm{d}\sigma_{N+1}^{\mathrm{MC}}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}}; \mathcal{T}_{N+1}^{\mathrm{cut}})$$

Inclusive Φ_{N+2}

$$\frac{\mathrm{d}\sigma_{\geq N+2}^{\mathrm{MC}}}{\mathrm{d}\Phi_{N+2}} \begin{pmatrix} \mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}}, \\ \mathcal{T}_{N+1} > \mathcal{T}_{N+1}^{\mathrm{cut}} \end{pmatrix}$$

IR-safe definitions of events beyond LO

- Goal is to generate "physical events" , i.e. to each event can be assigned a IR-finite cross section $\mathrm{d}\sigma^{\mathrm{MC}}$.
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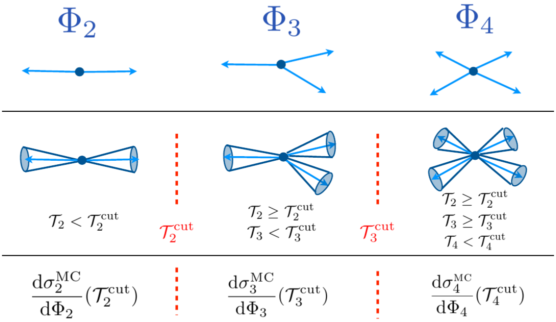
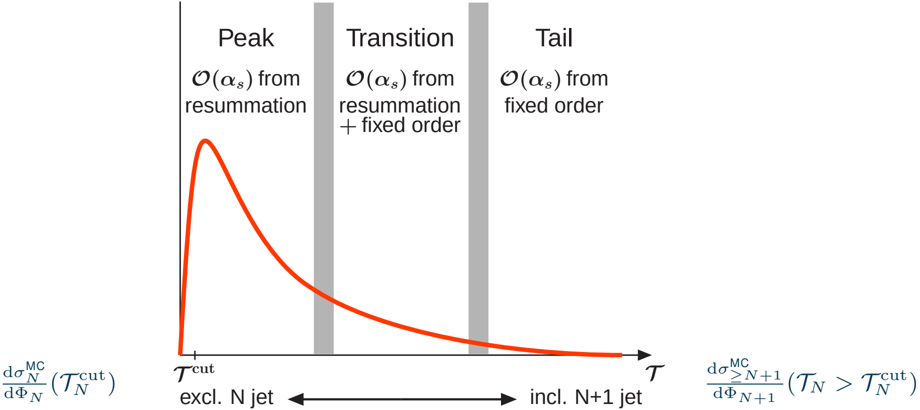


Which $d\sigma_N^{\text{MC}}/d\Phi_N(\mathcal{T}_N^{\text{cut}})$ and $d\sigma_{\geq N+1}^{\text{MC}}/d\Phi_{N+1}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}})$ to use ?

- Jet-resolution parameter $\mathcal{T}$, e.g. p_T^{N+1} for $N+1$ jets, or p_T^H in $gg \to H$.

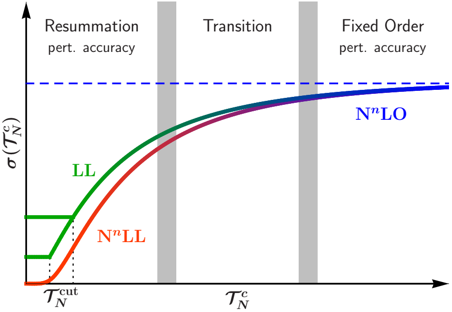


- At LL one counts $\alpha_s \ln^2(\mathcal{T}_N/Q) \sim 1$ and $\alpha_s \ln^2(\mathcal{T}_N^{\text{cut}}/Q) \sim 1$ with Q hard
- Combining FO+LL achieves LL accuracy where F0 is invalid and maintain FO where LL is unimportant

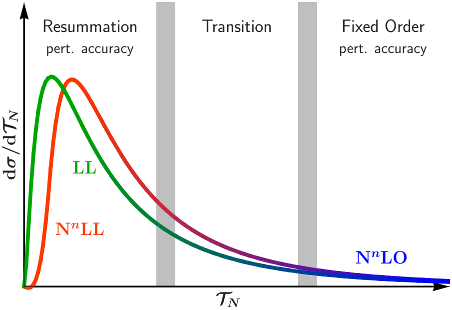
Which $\mathrm{d}\sigma_N^{\mathrm{MC}}/\mathrm{d}\Phi_N(\mathcal{T}_N^{\mathrm{cut}})$ and $\mathrm{d}\sigma_{\geq N+1}^{\mathrm{MC}}/\mathrm{d}\Phi_{N+1}(\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}})$ to use ?

- For both cumulant and spectrum perturbative accuracy driven by $\mathcal{T}$.

Cumulant: $\mathrm{d}\sigma_N^{\mathrm{MC}}/\mathrm{d}\Phi_N(\mathcal{T}_N^{\mathrm{cut}})$



Spectrum: $\frac{\mathrm{d}\sigma_{\geq N+1}^{\mathrm{MC}}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}})$



- Further condition: consistency between $\mathrm{d}\sigma^{\mathrm{MC}}$'s is required to push $\mathcal{T}_N^{\mathrm{cut}}$ dependence to high-enough order

$$\frac{\mathrm{d}}{\mathrm{d}\mathcal{T}_N^{\mathrm{cut}}}\left[\frac{\mathrm{d}\sigma_N^{\mathrm{MC}}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}})\right]_{\mathcal{T}_N^{\mathrm{cut}}=\mathcal{T}_N} = \int \frac{\mathrm{d}\Phi_{N+1}}{\mathrm{d}\Phi_N}\,\delta[\mathcal{T}_N - \mathcal{T}_N(\Phi_{N+1})]\,\frac{\mathrm{d}\sigma_{\geq N+1}^{\mathrm{MC}}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}})$$

i.e. spectrum is total derivative of the cumulant

POWHEG and MC@NLO : the NLO+LL case

- Standard NLO+PS tools used by experimental collaborations
- Same basic formula correct to $(\text{NLO+LL})_N$ and $(\text{LO+LL})_{N+1}$:

$$\frac{d\sigma_N^{\text{MC}}}{d\Phi_N}(\mathcal{T}_N^{\text{cut}}) = \underbrace{\frac{d\sigma_{\geq N}^{S}}{d\Phi_N}\Delta_N(\Phi_N;\mathcal{T}_N^{\text{cut}})}_{\text{resummed}} + \underbrace{\frac{d\sigma_N^{B-S}}{d\Phi_N}(\mathcal{T}_N^{\text{cut}})}_{\text{FO matching}},$$

$$\frac{d\sigma_{\geq N+1}^{\text{MC}}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}}) = \sum_m \left\{ \frac{d\sigma_{\geq N}^{S}}{d\Phi_N}\bigg|_{\hat{\Phi}_N} \frac{S_{N+1}(\Phi_{N+1})}{B_N(\hat{\Phi}_N)} \Delta_N(\hat{\Phi}_N;\mathcal{T}_N)\,\theta(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}}) \right\}_m + \frac{d\sigma_{\geq N+1}^{B-S}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}})$$

- Difference in choice of splitting functions S_{N+1} entering the Sudakov:

MC@NLO

$S_{N+1} \approx G \times \mathbf{PS}_{n+1} + (1-G) \times C_{n+1}$

- If $\mathbf{PS}_{n+1}$ doesn't have full IR sing. of B_{N+1}, leftover $\mathcal{T}_N^{\text{cut}}$ dependence
- Spectrum is not quite total derivative of the cumulant.
- Numerical effects neglible.

POWHEG

$S_{N+1} \approx B_{N+1} \times F$

- Resummation can be turned off $F \to 0$ in hard regions.
- Spectrum is total derivative of the cumulant by construction.

Combining fully exclusive NNLO with LL resummation.

- Recipe and ingredients given in [1311.0286] : $\frac{d\sigma^{\text{MC}}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}})$

$$\frac{d\sigma^{\text{MC}}_N}{d\Phi_N}(\mathcal{T}_N^{\text{cut}}), \quad \overbrace{\frac{d\sigma^{\text{MC}}_{N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}}; \mathcal{T}_{N+1}^{\text{cut}}), \quad \frac{d\sigma^{\text{MC}}_{\geq N+2}}{d\Phi_{N+2}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}}, \mathcal{T}_{N+1} > \mathcal{T}_{N+1}^{\text{cut}})}$$

- Exclusive N-jet cross section

$$\frac{d\sigma^{\text{MC}}_N}{d\Phi_N}(\mathcal{T}_N^{\text{cut}}) = \underbrace{\frac{d\sigma^{C}_{\geq N}}{d\Phi_N}\Delta_N(\Phi_N; \mathcal{T}_N^{\text{cut}})}_{\text{resummed}} + \underbrace{\frac{d\sigma^{C-S}_N}{d\Phi_N}(\mathcal{T}_N^{\text{cut}})}_{\text{FO singular matching}} + \underbrace{\frac{d\sigma^{B-C}_N}{d\Phi_N}(\mathcal{T}_N^{\text{cut}})}_{\text{FO nonsingular matching}}$$

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  - Singular part of NNLO cross-section, contains all $\log(\mathcal{T}_N^{\text{cut}})$

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  - Singular part of NNLO cross-section, contains all $\log(\mathcal{T}_N^{\mathrm{cut}})$
  - Sudakov factor, provides (at least) LL resummation of $\mathcal{T}_N^{\mathrm{cut}}$

$$\Delta_N(\Phi_N; \mathcal{T}_N^{\mathrm{cut}}) = \exp\left\{-\int \frac{d\Phi_{N+1}}{d\Phi_N}\,\frac{S_{N+1}(\Phi_{N+1})}{B_N(\hat{\Phi}_N)}\,\theta[\mathcal{T}_N(\Phi_{N+1}) > \mathcal{T}_N^{\mathrm{cut}}]\right\}$$

Combining fully exclusive NNLO with LL resummation.

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$$\overbrace{\frac{d\sigma^{\text{MC}}_{N}}{d\Phi_N}(\mathcal{T}_N^{\text{cut}}), \quad \frac{d\sigma^{\text{MC}}_{N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}}; \mathcal{T}_{N+1}^{\text{cut}}), \quad \frac{d\sigma^{\text{MC}}_{\geq N+2}}{d\Phi_{N+2}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}}, \mathcal{T}_{N+1} > \mathcal{T}_{N+1}^{\text{cut}})}^{\frac{d\sigma^{\text{MC}}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}})}$$

- Exclusive N-jet cross section

$$\frac{d\sigma^{\text{MC}}_{N}}{d\Phi_N}(\mathcal{T}_N^{\text{cut}}) = \underbrace{\frac{d\sigma^{C}_{\geq N}}{d\Phi_N}\Delta_N(\Phi_N; \mathcal{T}_N^{\text{cut}})}_{\text{resummed}} + \underbrace{\frac{d\sigma^{C-S}_{N}}{d\Phi_N}(\mathcal{T}_N^{\text{cut}})}_{\text{FO singular matching}} + \underbrace{\frac{d\sigma^{B-C}_{N}}{d\Phi_N}(\mathcal{T}_N^{\text{cut}})}_{\text{FO nonsingular matching}}$$

- Singular part of NNLO cross-section, contains all $\log(\mathcal{T}_N^{\text{cut}})$
- Sudakov factor, provides LL resummation of $\mathcal{T}_N^{\text{cut}}$
- Corrects singular $\mathcal{T}_N^{\text{cut}}$ dependence from Sudakov expansion.

Combining fully exclusive NNLO with LL resummation.

- Recipe and ingredients given in [1311.0286] :

$$\frac{d\sigma^{\text{MC}}_{N}}{d\Phi_N}(\mathcal{T}_N^{\text{cut}}), \quad \underbrace{\frac{d\sigma^{\text{MC}}_{N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}}; \mathcal{T}_{N+1}^{\text{cut}}), \quad \frac{d\sigma^{\text{MC}}_{\geq N+2}}{d\Phi_{N+2}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}}, \mathcal{T}_{N+1} > \mathcal{T}_{N+1}^{\text{cut}})}_{\frac{d\sigma^{\text{MC}}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}})}$$

- Exclusive N-jet cross section

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  - Sudakov factor, provides LL resummation of $\mathcal{T}_N^{\text{cut}}$
  - Corrects singular $\mathcal{T}_N^{\text{cut}}$ dependence from Sudakov expansion.
  - Corrects the finite terms to the exact inclusive cross section.

Combining fully exclusive NNLO with LL resummation.

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$$\frac{\mathrm{d}\sigma^{\mathrm{MC}}_{\geq N+1}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}})$$

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- Exclusive N-jet cross section (NNLO+LL)

$$\frac{\mathrm{d}\sigma^{\mathrm{MC}}_{N}}{\mathrm{d}\Phi_{N}}(\mathcal{T}_N^{\mathrm{cut}}) = \underbrace{\frac{\mathrm{d}\sigma^{C}_{\geq N}}{\mathrm{d}\Phi_{N}}\,\Delta_N(\Phi_N; \mathcal{T}_N^{\mathrm{cut}})}_{\text{resummed}} + \underbrace{\frac{\mathrm{d}\sigma^{C-S}_{N}}{\mathrm{d}\Phi_{N}}(\mathcal{T}_N^{\mathrm{cut}})}_{\text{FO singular matching}} + \underbrace{\frac{\mathrm{d}\sigma^{B-C}_{N}}{\mathrm{d}\Phi_{N}}(\mathcal{T}_N^{\mathrm{cut}})}_{\text{FO nonsingular matching}}$$

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- Inclusive N+1-jet cross section (NLO+LL)

$$\frac{d\sigma^{\text{MC}}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}}) = \frac{d\sigma^{C}_{\geq N}}{d\Phi_N}\bigg|_{\Phi_N = \hat{\Phi}_N} \frac{S_{N+1}(\Phi_{N+1})}{B_N(\hat{\Phi}_N)} \Delta_N(\hat{\Phi}_N; \mathcal{T}_N)\, \theta(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}})$$
$$+ \frac{d\sigma^{C-S}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}}) + \frac{d\sigma^{B-C}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}})$$

Combining fully exclusive NNLO with LL resummation.

- Recipe and ingredients given in [1311.0286] : $\frac{d\sigma^{\text{MC}}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}})$

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$$\frac{d\sigma^{\text{MC}}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}}) = \left.\frac{d\sigma^{C}_{\geq N}}{d\Phi_{N}}\right|_{\Phi_N = \hat{\Phi}_N} \frac{S_{N+1}(\Phi_{N+1})}{B_N(\hat{\Phi}_N)}\,\Delta_N(\hat{\Phi}_N; \mathcal{T}_N)\,\theta(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}})$$
$$+ \frac{d\sigma^{C-S}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}}) + \frac{d\sigma^{B-C}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\text{cut}})$$

- Inclusive N-jet cross-section correct by construction, since they are related by exact derivative.

Combining fully exclusive NNLO with LL resummation.

- Split up inclusive N+1-jet cross section using resolution scale $\mathcal{T}_{N+1}^{\rm cut}$
- Exclusive N+1-jet cross section (NLO+LL)

$$\frac{d\sigma^{\rm MC}_{N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\rm cut}; \mathcal{T}_{N+1}^{\rm cut}) = \underbrace{\frac{d\sigma'^{C}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\rm cut})\, \Delta_{N+1}(\Phi_{N+1}; \mathcal{T}_{N+1}^{\rm cut})}_{\text{resummed}}$$
$$+ \Bigg(\underbrace{\frac{d\sigma^{C-S}_{N+1}}{d\Phi_{N+1}}}_{\text{FO singular matching}} + \underbrace{\frac{d\sigma^{B-C}_{N+1}}{d\Phi_{N+1}}}_{\text{FO nonsing. matching}}\Bigg)(\mathcal{T}_N > \mathcal{T}_N^{\rm cut}; \mathcal{T}_{N+1}^{\rm cut})$$

- Inclusive N+2-jet cross section (LO+LL)

$$\frac{d\sigma^{\rm MC}_{\geq N+2}}{d\Phi_{N+2}}(\mathcal{T}_N > \mathcal{T}_N^{\rm cut}, \mathcal{T}_{N+1} > \mathcal{T}_{N+1}^{\rm cut}) = \frac{d\sigma'^{C}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\rm cut})\Big|_{\Phi_{N+1}=\hat{\Phi}_{N+1}}$$
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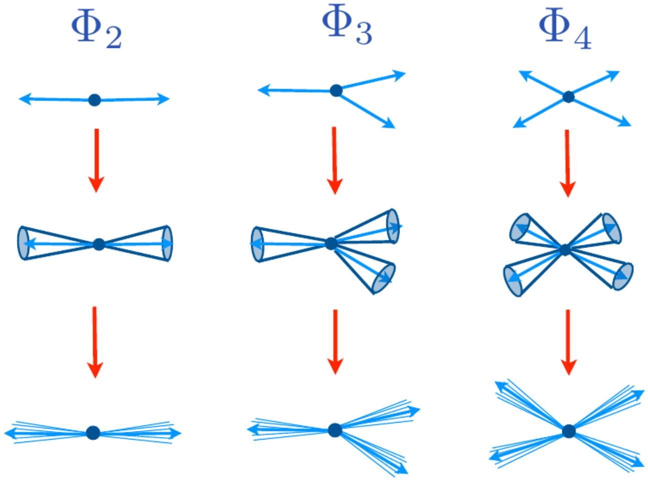
$$+ \Bigg(\frac{d\sigma^{C-S}_{\geq N+2}}{d\Phi_{N+2}} + \frac{d\sigma^{B-C}_{\geq N+2}}{d\Phi_{N+2}}\Bigg)(\mathcal{T}_N > \mathcal{T}_N^{\rm cut}, \mathcal{T}_{N+1} > \mathcal{T}_{N+1}^{\rm cut})$$

Adding the parton shower.

- Use the NNLO+LL fully-exclusive results $d\sigma_N^{\text{MC}}, d\sigma_{N+1}^{\text{MC}}, d\sigma_{>N+2}^{\text{MC}}$ as event weights and their kinematics as starting point for showering.

- Create phase space for jet event
- Calculate cross section and assign to partonic event
- Let parton shower fill jets with radiation



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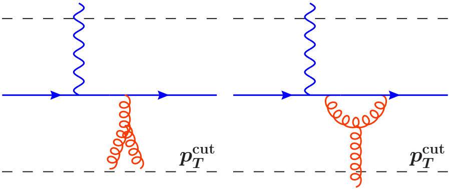
- Caveat: when showering the NNLO N-jet bin care must be taken.
  - Single parton variables not IR-safe at NNLO
  - Conditions above could be applied after showering as a global veto



Comparison with existing approaches: GENEVA

- GENEVA combines higher logarithimc accuracy with parton shower

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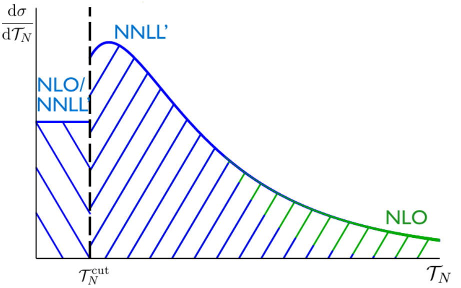

- Inclusive cross section NNLL' + NLO
- Perturbative $\mathcal{O}(\alpha_s)$ everywhere
- Logarithms of merging scale ($\mathcal{T}_N^{\rm cut}$) cancel at NNLL' by construction: merging of 2 NLOs is a by-product
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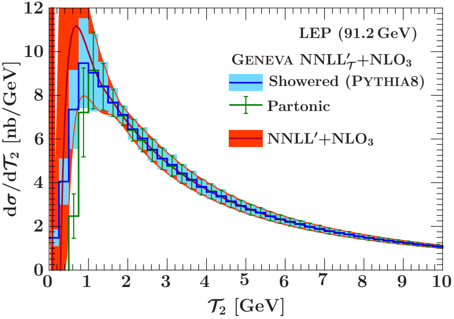

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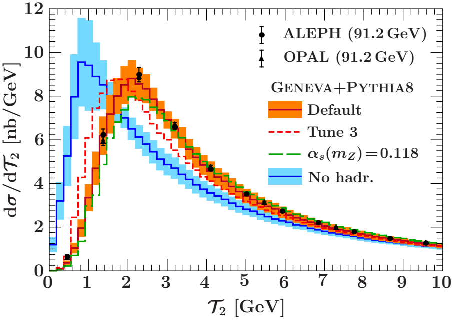

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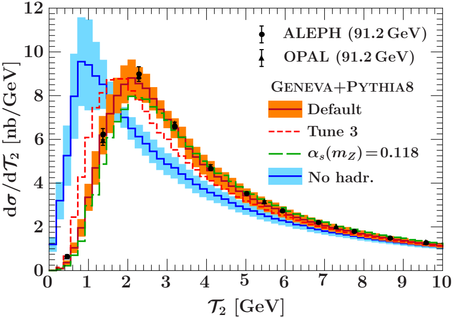

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- If NNLL' is available, NNLO singular contributions are already included

✓ $\frac{d\sigma^C_{\geq N}}{d\Phi_N}\Delta_N(\Phi_N;\mathcal{T}_N^{\rm cut}) \to \frac{d\sigma_N^{\rm resummed}}{d\Phi_N}(\mathcal{T}_N^{\rm cut})$ ✓ $\frac{d\sigma_N^{C-S}}{d\Phi_N}(\mathcal{T}_N^{\rm cut}) = 0$

✗ $\frac{d\sigma_N^{B-C}}{d\Phi_N}(\mathcal{T}_N^{\rm cut}) \to \frac{d\sigma_N^{\rm nonsingular}}{d\Phi_N}(\mathcal{T}_N^{\rm cut})$ not full NNLO non-sing. (power corrections)

- Bottom-line: NNLO+LL log accuracy can be easily extended.

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- Achieves NLO merging without merging scale (H+0 jets is never present)
- For simple processes (e.g. $gg \to H$), using HNNLO [Catani et al. 0801.3232] for event-by-event reweighting results in a NNLO+PS [Hamilton,Nason,Re,Zanderighi 1309.0017]

$$\mathcal{W}(y) = \frac{\left(\frac{d\sigma}{dy}\right)_{\mathrm{HNNLO}}}{\left(\frac{d\sigma}{dy}\right)_{\mathrm{HJ-MiNLO}}} = \frac{c_2\alpha_{\mathrm{S}}^2 + c_3\alpha_{\mathrm{S}}^3 + c_4\alpha_{\mathrm{S}}^4}{c_2\alpha_{\mathrm{S}}^2 + c_3\alpha_{\mathrm{S}}^3 + c_4'\alpha_{\mathrm{S}}^4 + \dots} = 1 + \frac{c_4 - c_4'}{c_2}\alpha_{\mathrm{S}}^2 + \dots$$

- Integrates back to the total NNLO cross-section
- NLO accuracy of Hj not spoiled
- Need to reweight after generation

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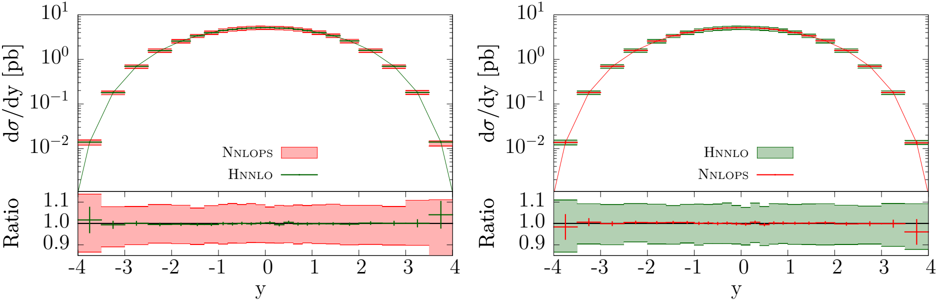

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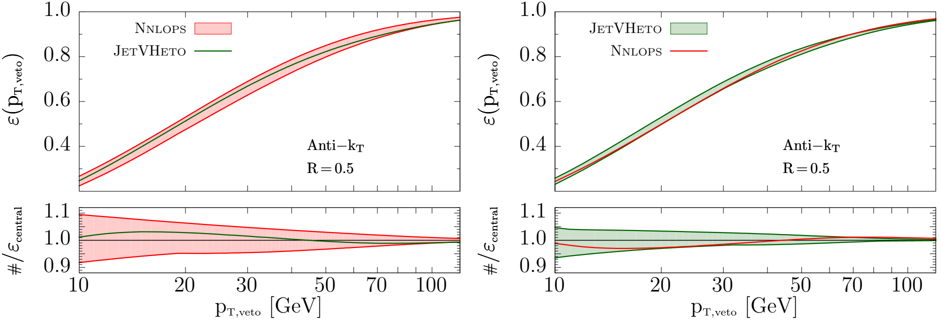

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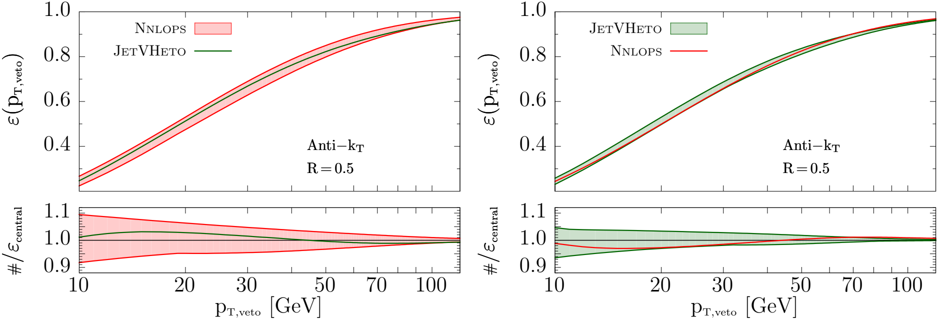

- MiNLO NNLO+PS formula re-derived as a special case of our framework
- Specific choice of splitting functions brings two advantanges: [1311.0286]

✓ No need to know NLL resummation to reach NNLO

✓ No need to reweight after generation

Conclusions and outlook

- Provided theoretical framework for NNLO+LL+PS:
  - IR-safe, jet-like definitions of events are the basis for event generation with higher accuracy.
  - Provided formulas for jet cross section at the necessary accuracy in both fixed order (NNLO_N,NLO_{N+1},LO_{N+2}) and resummation regions (LL).
  - When resummation accuracy does not match fixed-order, enforced correlation between jet bins (spectrum is derivative of cumulant).
  - Resummation accuracy can be improved if desired.
- POWHEG, MC@NLO, GENEVA and MiNLO-NNLOPS are special limits

Outlook:

- Implementation feasibility supported by comparison with existing NNLO+PS approach.
- Several possibilities for implementation laid out in [1311.0286] , investigating which one is more efficient or better for incorporating existing NNLO calculations with little effort.
- Framework not limited to NNLO, can be extended to higher-order, when available. Details to be worked out.

Thank you for your attention!

BACKUP

Perturbative accuracy

	$\mathcal{T}_N^{\rm eff} \sim Q$ (fixed order)	$\mathcal{T}_N^{\rm eff} \ll Q$ (resummation)
	N-jet observables	
LO_N	$1 + \mathcal{O}(\alpha_s)$	$\mathcal{O}(1)$
NLO_N	$1 + \alpha_s + \mathcal{O}(\alpha_s^2)$	$\mathcal{O}(1)$
NNLO_N	$1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)$	$\mathcal{O}(1)$
LO_N+LL	$1 + \mathcal{O}(\alpha_s)$	$1 + \mathcal{O}\left(\alpha_s^{1/2}\right)$
$\mathrm{LO}_{N,N+1}$+LL	$1 + \mathcal{O}(\alpha_s) + \mathcal{O}_{\rm cut}(\alpha_s^{\geq 1})$	$1 + \mathcal{O}\left(\alpha_s^{1/2}\right)$
NLO_N+LL	$1 + \alpha_s + \mathcal{O}(\alpha_s^2) + \mathcal{O}_{\rm cut}(\alpha_s^{\geq 2})$	$1 + \mathcal{O}\left(\alpha_s^{1/2}\right)$
$\mathrm{NLO}_{N,N+1}$+LL	$1 + \alpha_s + \mathcal{O}(\alpha_s^2) + \mathcal{O}_{\rm cut}(\alpha_s^{\geq 2})$	$1 + \mathcal{O}\left(\alpha_s^{1/2}\right)$
NNLO_N+LL	$1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3) + \mathcal{O}_{\rm cut}(\alpha_s^{\geq 3})$	$1 + \mathcal{O}\left(\alpha_s^{1/2}\right)$
	$(N+1)$-jet observables	
LO_N	$\times$	$\times$
NLO_N	$1 + \mathcal{O}(\alpha_s)$	$\mathcal{O}(1)$
NNLO_N	$1 + \alpha_s + \mathcal{O}(\alpha_s^2)$	$\mathcal{O}(1)$
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Merging NLO Shower Monte Carlo samples

- When merging NLO_N and NLO_{N+1} samples separated by a $\mathcal{T}_{\rm cut}$ cut, the unphysical dependence manifests itself in $\sigma^{\rm tot}$ as $\log(\mathcal{T}_{\rm cut}/Q)$.

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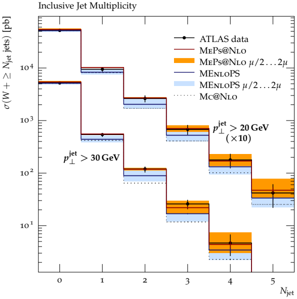
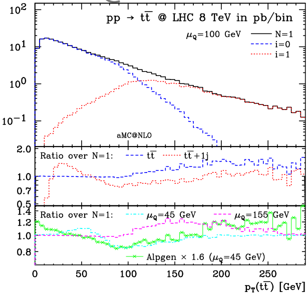
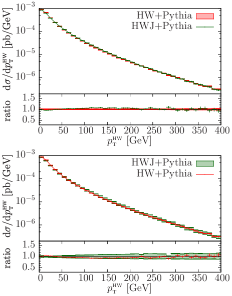
SHERPA



MC@NLO/FxFx



MiNLO



GENEVA Master Formula

arXiv:1211.7049

- Introduce an unphysical infrared regulator $\mathcal{T}^{\text{cut}}$ and separate inclusive and exclusive regions: $\mathcal{T}^{\text{cut}}$ dependence drops out to the order we are working.

$$\sigma_{\geq N} = \int \mathrm{d}\Phi_N \, \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_N}(\mathcal{T}^{\text{cut}}) + \int \mathrm{d}\Phi_{N+1} \, \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}) \, \theta(\mathcal{T} > \mathcal{T}^{\text{cut}})$$

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- Spectrum: $\mathcal{T}$ distribution of inclusive $N+1$-jets sample above $\mathcal{T}^{\rm cut}$

$$\frac{d\sigma}{d\Phi_{N+1}}(\mathcal{T}) = \frac{d\sigma^{\rm FO}}{d\Phi_{N+1}}(\mathcal{T}) \left[\frac{d\sigma^{\rm resum}}{d\Phi_N d\mathcal{T}} \Big/ \frac{d\sigma^{\rm resum}}{d\Phi_N \, d\mathcal{T}}\Big|_{\rm FO}\right]$$

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- Spectrum: $\mathcal{T}$ distribution of inclusive $N+1$-jets sample above $\mathcal{T}^{\rm cut}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}) = \frac{\mathrm{d}\sigma^{\rm FO}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}) \left[\frac{\mathrm{d}\sigma^{\rm resum}}{\mathrm{d}\Phi_N \mathrm{d}\mathcal{T}} \bigg/ \frac{\mathrm{d}\sigma^{\rm resum}}{\mathrm{d}\Phi_N \, \mathrm{d}\mathcal{T}}\bigg|_{\rm FO}\right]$$

- Correctly reproduces the expected limits for $\mathcal{T} \to 0$ and $\mathcal{T} \sim Q$.

GENEVA Master Formula

arXiv:1211.7049

- Introduce an unphysical infrared regulator $\mathcal{T}^{\rm cut}$ and separate inclusive and exclusive regions: $\mathcal{T}^{\rm cut}$ dependence drops out to the order we are working.

$$\sigma_{\geq N} = \int d\Phi_N \frac{d\sigma}{d\Phi_N}(\mathcal{T}^{\rm cut}) + \int d\Phi_{N+1} \frac{d\sigma}{d\Phi_{N+1}}(\mathcal{T})\, \theta(\mathcal{T} > \mathcal{T}^{\rm cut})$$

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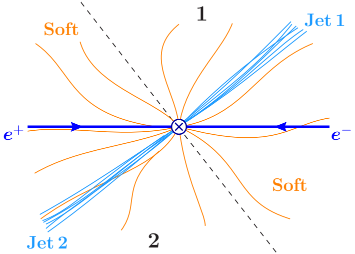
- Correctly reproduces the expected limits for $\mathcal{T} \to 0$ and $\mathcal{T} \sim Q$.

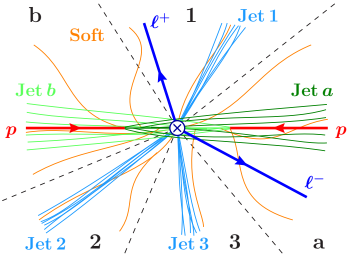
- MonteCarlo's perspective: increases SMC resummation while including multiple NLO.
- Resummation's perspective: takes the resummation of $\mathcal{T}$ and produces fully differential results.

N-Jettiness as jet-resolution variable

- Use N-jettiness as resolution parameter. Global physical observable with straightforward definitions for hadronic colliders, in terms of beams $q_{a,b}$ and jet-directions q_j

$$\mathcal{T}_N = \frac{2}{Q}\sum_k \min\{q_1\cdot p_k, \ldots, q_N\cdot p_k\} \Rightarrow \mathcal{T}_N = \frac{2}{Q}\sum_k \min\{q_a\cdot p_k, q_b\cdot p_k, q_1\cdot p_k, \ldots, q_N\cdot p_k\}$$



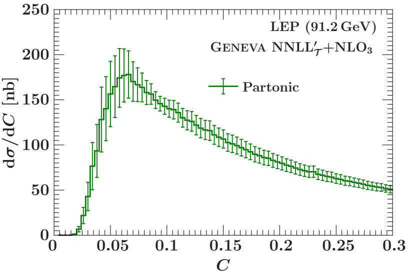


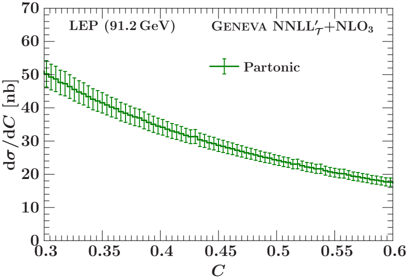
- N-jettiness has good factorization properties, IR safe and resummable at all orders. Resummation known at NNLL for any N [Stewart et al. 1004.2489, 1102.4344]
- $\mathcal{T}_N \to 0$ for N pencil-like jets, $\mathcal{T}_N \gg 0$ spherical limit.
- $\mathcal{T}_N < \mathcal{T}_N^{\rm cut}$ acts as jet-veto, e.g. CJV $\mathcal{T}_0 = \frac{2}{Q}\sum_k \min\{q_a\cdot p_k, q_b\cdot p_k\} < \mathcal{T}_0^{\rm cut}$

Predictive power for other observables

- After showering we are formally limited by shower resummation for generic observables $\mathcal{O} \neq \mathcal{T}$. Naively, (N)LL is expected.
- What is the perturbative accuracy we obtain for other $\mathcal{O}$?

- C-parameter – perturbative structure very similar to $\mathcal{T}_2$





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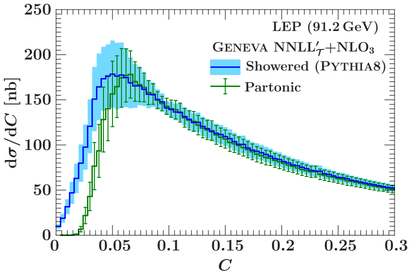

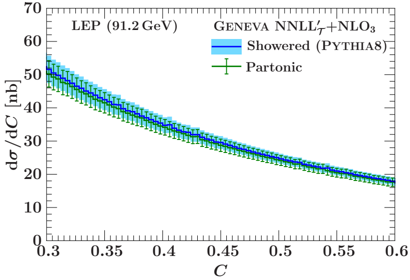

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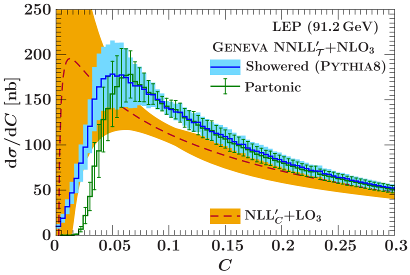

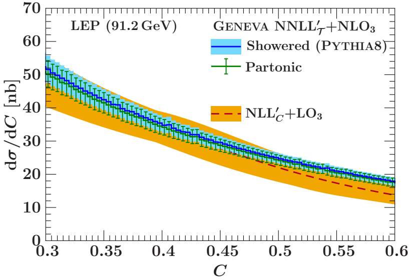

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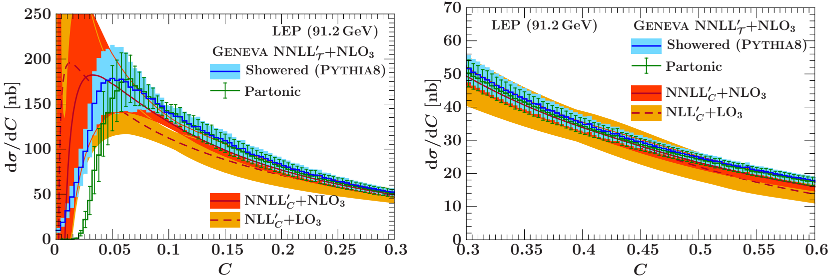

- Good agreement in central values and scale uncertainties envelopes at NNLL, also for observables with a very different resummation structure.
- NNLL resummation allows to push $\mathcal{T}_2^{\rm cut}$ to very small values, effectively replacing the shower evolution.

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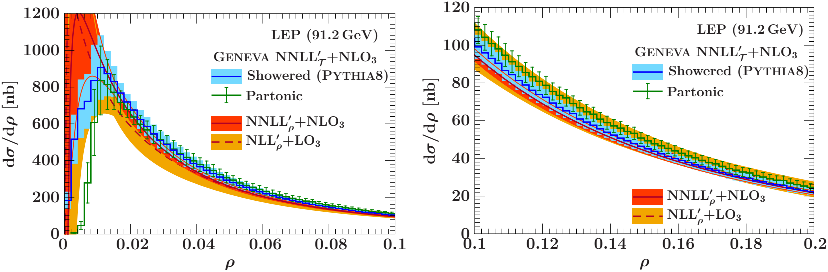
- After showering we are formally limited by shower resummation for generic observables $\mathcal{O} \neq \mathcal{T}$. Naively, (N)LL is expected.
- What is the perturbative accuracy we obtain for other $\mathcal{O}$?
- Heavy jet mass – perturbative structure partially related to $\mathcal{T}_2$



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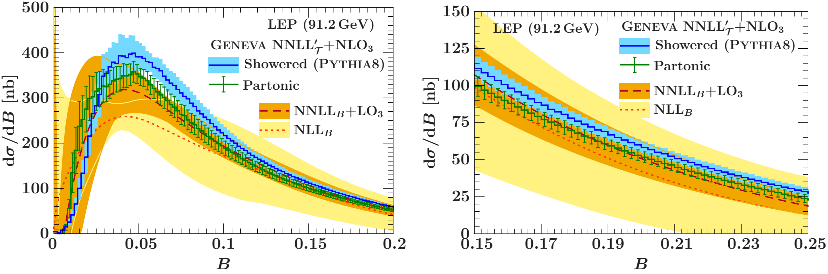
- After showering we are formally limited by shower resummation for generic observables $\mathcal{O} \neq \mathcal{T}$. Naively, (N)LL is expected.
- What is the perturbative accuracy we obtain for other $\mathcal{O}$?

- Jet Broadening – perturbative structure completely different from $\mathcal{T}_2$



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