Matching NNLO calculations with parton showers in GENEVA

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Particle and Astro-Particle Physics Seminar

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SA, C. Bauer, C. Berggren, A. Hornig, F. Tackmann, C. Vermilion, J. Walsh, S. Zuberi JHEP09(2013)120

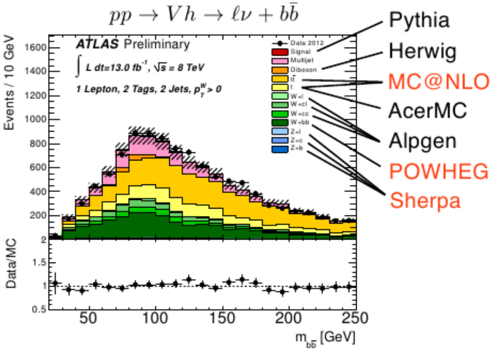
SA, C. Bauer, C. Berggren, F. Tackmann, J. Walsh, S. Zuberi JHEP06(2014)089

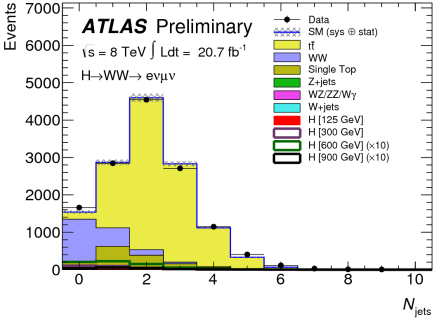
SA, C. Bauer, F. Tackmann, J. Walsh (in preparation)

Introduction

Motivations

- Monte Carlo event generators play a key role in HEP, from discovery to precision measurements

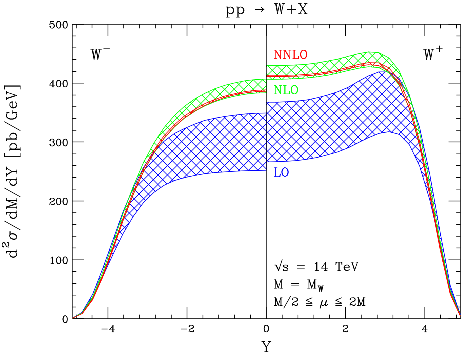




- Sometimes they are the only tool to make theoretical predictions talk to data
- For higher accuracy, event generators should include the best theory predictions

Motivations

- NLO is the first order in which rates and associated theoretical uncertainties are reliably predicted.
- NNLO gives non-negligible contributions in several cases (eg. $gg \to H \approx 30\%$).
- Shapes are generically better described increasing the parton multiplicity: new channels at NLO, and NNLO, larger K-factors and noticeable shape distorsions.
- Theoretical uncertainties further reduced by including NNLO corrections. For few % precision, NNLO is required.
- Remarkable new results for N3LO total ggH cross section! [Anastasiou et al., 1503.06056]
- When comparing with data, precision still limited by Monte Carlo used. Only very limited set of inclusive quantities can be directly compared.

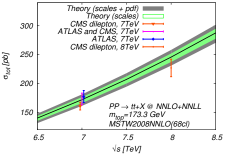


[Anastasiou et al., hep-ph/0312266]

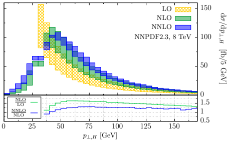
NNLO calculations: subtraction methods

- Recent progresses in subtraction methods allowed to address several important processes at NNLO. Different subtractions method employed..

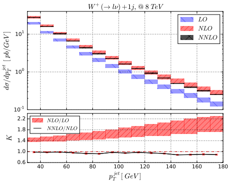
[Czackon et al., 1303.6254]



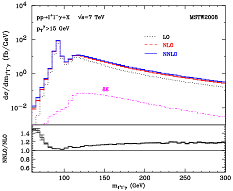
[Boughezal et al., 1504.07922]



[Boughezal et al., 1504.02131]



[Grazzini et al., 1309.7000]

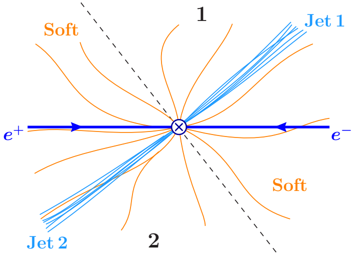


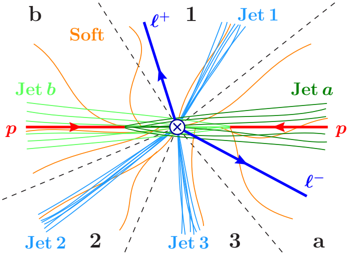
- STRIPPER [1005.0274, 1101.0642]. Extension of FKS method, disentangling singularities in each sector. Highly local subtractions. Applied to $t\bar{t}$ production. Similar method applied to $H + j$,single-top, top-decay [1504.07922, 1404.7116, 1301.7133]
- Democratic-recoil local subtraction method by "Trocsany et al." Not all integrated counterterms available yet. Recently applied to $H \to b\bar{b}$ [1501.07226]
- ANTENNA subtractions. Uses approximation of matrix elements to remove singularities. Less local , averaged over azimuth. Applied to $pp \to jj$ [1312.5608]
- $\boldsymbol{q_T}$-subtractions. Applied to several colorless system $H, V, \gamma\gamma, V\gamma, VV, HH, VH$ [0903.2120, 1002.3112, 1110.2375,1309.7000]. Also applicable to $t\bar{t}$.
- N-Jettiness subtractions . . .

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 in SCET [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 $\mathcal{T}_0 = \frac{2}{Q}\sum_k \min\{q_a \cdot p_k, q_b \cdot p_k\} < \mathcal{T}_0^{\rm cut}$

N-jettiness subtractions

- Basic idea very much resemble q_T-subtraction. Divide phase space into NNLO$_N$ and NLO$_{N+1}$, only apply extra subtraction to NNLO$_N$.
- N-jettiness more powerful than q_T of the colorless system (or massive colored system). Any number of massless leg could in principle be dealt with.
- Simplest approach is to just use slicing. This amounts to approximate the α_S^2 terms by their singular counterpart, neglecting α_S^2 non-singular
- First example of N-jettiness like slicing $\tau = (p_b + p_X)^2/m_t^2$ in top-decay Gao et al. [1210.2808]
- 1-jettiness slicing recently applied to $W+1$-jet and $H+1$-jet production. Boughezal et al. [1504.02131, 1505.03893] .
- Proper subtraction requires instead to use the singular to regulate the (integrated) divergencies left over by the NLO subtraction (as done in q_T-subtraction).

$$
\begin{aligned}
\sigma(X) &= \sigma^{\rm s}(X, \mathcal{T}_{\rm off}) + \int_{\mathcal{T}_\delta} \mathrm{d}\mathcal{T}_N \left[\frac{\mathrm{d}\sigma(X)}{\mathrm{d}\mathcal{T}_N} - \frac{\mathrm{d}\sigma^{\rm s}(X)}{\mathrm{d}\mathcal{T}_N}\, \theta(\mathcal{T}_N < \mathcal{T}_{\rm off}) \right] + \mathcal{O}\left(\delta_{\rm IR}\right) \\
&= \sigma^{\rm s}(X, \mathcal{T}_{\rm off}) + \int_{\mathcal{T}_\delta}^{\mathcal{T}_{\rm off}} \mathrm{d}\mathcal{T}_N \, \frac{\mathrm{d}\sigma^{\rm nons}(X)}{\mathrm{d}\mathcal{T}_N} + \int_{\mathcal{T}_{\rm off}} \frac{\mathrm{d}\sigma(X)}{\mathrm{d}\mathcal{T}_N} + \mathcal{O}\left(\delta_{\rm IR}\right) .
\end{aligned}
$$

- Method used in GENEVA for NNLO results SA et al. [1311.0286] .
- General method formalized in Gaunt et al. [1505.04794] . Also discussed how to make the subtraction more differential for better numerical stability.

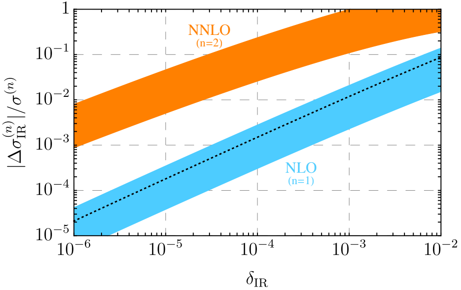
N-jettiness subtractions

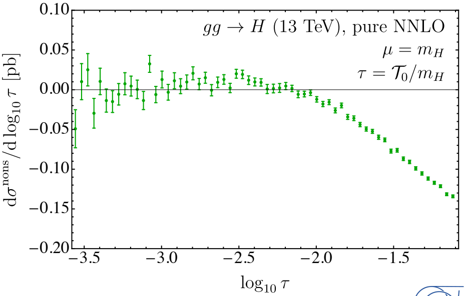
- The error can be estimated considering dominant missing non-singulars at $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$ go as

$$\Delta\sigma^{(1)}(\delta_{IR})/\sigma^{(1)} \approx c\,\delta_{IR}\log\delta_{IR}$$

$$\Delta\sigma^{(2)}(\delta_{IR})/\sigma^{(2)} \approx c\,\delta_{IR}\log^3\delta_{IR}$$

- When $\sigma^{(2)}$ is small, a larger $\Delta\sigma^{(2)}(\delta_{IR})$ could be tolerated.
- In any case, the correct behaviour of the non-singular towards zero should always be checked.
- This results from very delicate cancellations between 2 divergent quantities $\sigma(\tau) - \sigma^{\text{sing.}}(\tau)$, so their ratio going to 1 does not necessarily imply $\sigma^{\text{non-sing.}}(\tau)$ being zero.





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 improves sing. region but requires the definition of the observable beforehand, no fully-exclusive events.

Beyond LO, perturbative results are plagued by IR divergencies, that only disappear after properly combining real emission contributions with virtual correction:

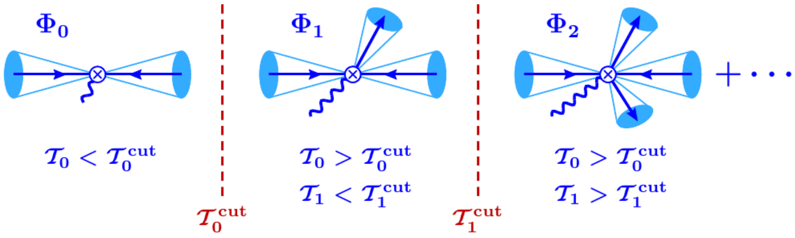
- At fully exclusive level, this requires the introduction of subtraction counterterms to regulate the divergencies in 4D

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

- 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
  - ✗ very difficult to unweight

Recipe for an IR-safe definitions of events beyond LO

- Only generate "physical events", i.e. events to which one can assign an IR-finite cross section $\mathrm{d}\sigma^{\mathrm{MC}}$.
- Introduce 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) and the kinematic considered is the one of the event before the emission.
- An M-parton event is thus really defined as an N-jet event, $N \leq M$, fully differential in Φ_N (standard "jet-algo" not needed)
  - Price to pay: power corrections in $\mathcal{T}_N^{\mathrm{cut}}$ due to PS projection.
  - Advantage: 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 N-jet bin

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

$\mathcal{T}_0^{\rm cut}$ $\mathcal{T}_1 < \mathcal{T}_1$ $\mathcal{T}_1^{\rm cut}$ $\mathcal{T}_1 > \mathcal{T}_1$

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Exclusive N-jet bin

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

Inclusive $(N+1)$-jet bin

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

$\mathcal{T}_0^{\mathrm{cut}}$ $\mathcal{T}_1 < \mathcal{T}_1$ $\mathcal{T}_1^{\mathrm{cut}}$ $\mathcal{T}_1 > \mathcal{T}_1$

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Exclusive N-jet bin

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

Excl. $(N+1)$-jet

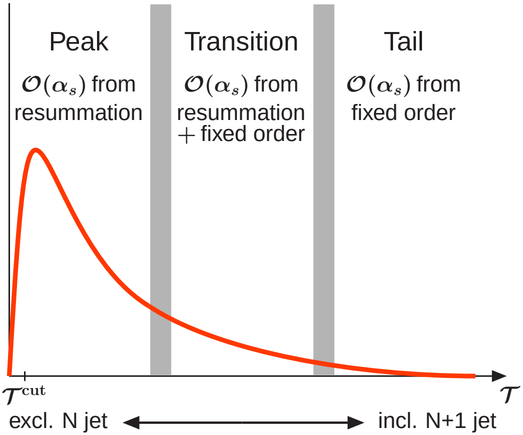
$$\frac{\mathrm{d}\sigma_{N+1}^{\mathrm{MC}}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}};\ \mathcal{T}_{N+1}^{\mathrm{cut}})$$

Inclusive $(N+2)$-jet bin

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

$\mathcal{T}_0^{\mathrm{cut}}$ $\mathcal{T}_1^{\mathrm{cut}}$

Perturbative accuracy



- Fixed NLO$_{N+1}$ (MCFM,BH,...) is insufficient outside FO region
- Lowest accuracy across the whole spectrum in MEPS: CKKW, MLM
- Standard NLO+PS (POWHEG, MC@NLO) improve total rate, not spectrum

Perturbative accuracy

(Notation: $\tau = \mathcal{T}/Q$, $L = \ln\tau$, $L_{\rm cut} = \ln\tau^{\rm cut}$)

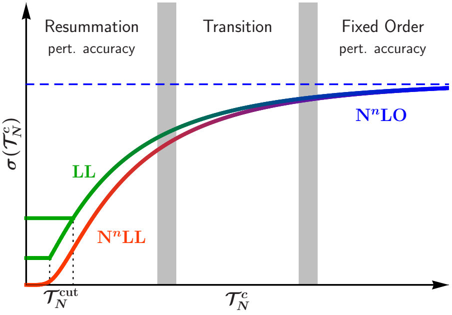
$$
\begin{array}{lllllll}
 & \mathrm{LL}_\sigma & \mathrm{NLL}_\sigma & \mathrm{NLL}'_\sigma & \mathrm{NNLL}_\sigma & & \\
\dfrac{\sigma(\tau^{\rm cut})}{\sigma_B} = & 1 & & & & & \mathrm{LO_N} \\
+\ \alpha_s\big[& \frac{c_{11}}{2}L^2_{\rm cut} & +\, c_{10}L_{\rm cut} & +\ c_{1,-1} & + & F_1(\tau^{\rm cut})\big] & \mathrm{NLO_N} \\
+\ \alpha_s^2\big[& \vdots & +\ \vdots & +\ \vdots & +\ \vdots & &
\end{array}
$$

$$
\begin{array}{lllllll}
\dfrac{1}{\sigma_B}\dfrac{d\sigma}{d\tau} = \alpha_s/\tau\big[& c_{11}L & +\ c_{10} & + & & \tau f_1(\tau)\big] & \mathrm{LO_{N+1}} \\
+\,\alpha_s^2/\tau\big[& c_{23}L^3 & +\ c_{22}L^2 & +\ c_{21}L & +\ c_{20} & +\ \tau f_2(\tau)\big] & \mathrm{NLO_{N+1}} \\
+\,\alpha_s^3/\tau\big[& \vdots & +\ \vdots & +\ \vdots & +\ \vdots & &
\end{array}
$$

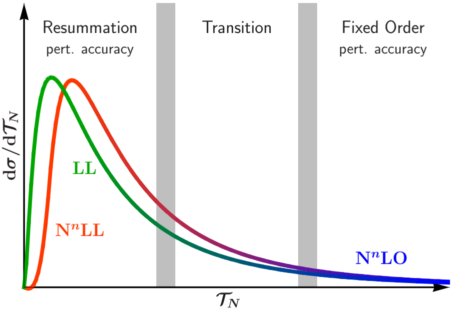
- Lowest pert. accuracy everywhere requires NLL$_{\mathcal{T}}$ + LO$_{N+1}$
  - NLL because $\alpha_{\rm s}(\alpha_{\rm s}^n L^{2n}) \approx \alpha_{\rm s}$ in the peak.
- Next-to-Lowest pert. accuracy everywhere requires NNLL$_{\mathcal{T}}$ + NLO$_{N+1}$

Relation between cumulant and spectrum

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



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



- Consistency between $\mathrm{d}\sigma_N^{\mathrm{MC}}, \mathrm{d}\sigma_{N+1}^{\mathrm{MC}}, \ldots$ is required to push $\mathcal{T}_N^{\mathrm{cut}}$ dependence to high-enough order to ensure spectrum is total derivative of the cumulant

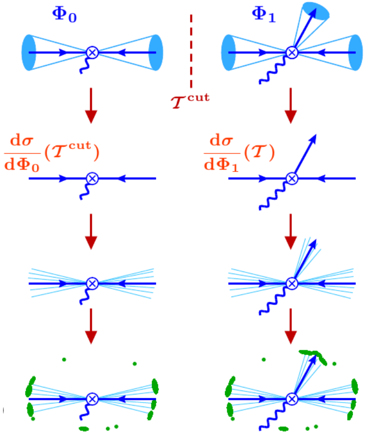
$$\frac{\mathrm{d}}{\mathrm{d}\mathcal{T}_N^{\mathrm{cut}}}\left[\frac{\mathrm{d}\sigma_N^{\mathrm{MC}}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}})\right]_{\mathcal{T}_N^{\mathrm{cut}}=\mathcal{T}_N} = \int \frac{\mathrm{d}\Phi_{N+1}}{\mathrm{d}\Phi_N}\,\delta[\mathcal{T}_N - \mathcal{T}_N(\Phi_{N+1})]\,\frac{\mathrm{d}\sigma_{\geq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

- If this is not satisfied, claimed accuracy might be spoiled by log of $\mathcal{T}_N^{\mathrm{cut}}$.

GENEVA: quick overview

Combines 3 key ingredients in a single framework:

1. Fully Exclusive NLO Calculations
   - NLO_N, NLO_{N+1}, ...
2. Higher-order Resummation (using SCET, but not limited to it)
   - $\text{LL}_\mathcal{O}$, $\text{NLL}_\mathcal{O}$, $\text{NLL'}_\mathcal{O}$, $\text{NNLL}_\mathcal{O}$ ...
3. Parton Shower and Hadronization
   - Pythia8, Herwig++, ...



GENEVA guiding principle

Give a coherent description at the **Next-to-Lowest perturbative accuracy** in both fixed-order perturbation theory and logarithmic resummation, including **event-by-event theoretical uncertainties**, and combine it with parton shower and hadronization.

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.

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

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- Cumulant: $\mathcal{T}$ integral over exclusive N-jets bin up to $\mathcal{T}^{\mathrm{cut}}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_N}(\mathcal{T}^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_N}(\mathcal{T}^{\mathrm{cut}}) + \left[\frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi_N}(\mathcal{T}^{\mathrm{cut}}) - \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_N}(\mathcal{T}^{\mathrm{cut}}) \bigg|_{\mathrm{FO}} \right]$$

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

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

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

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

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

- Cumulant: $\mathcal{T}$ integral over exclusive N-jets bin up to $\mathcal{T}^{\mathrm{cut}}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_N}(\mathcal{T}^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_N}(\mathcal{T}^{\mathrm{cut}}) + \left[\frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi_N}(\mathcal{T}^{\mathrm{cut}}) - \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_N}(\mathcal{T}^{\mathrm{cut}}) \bigg|_{\mathrm{FO}} \right]$$

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

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

- Correctly reproduces the expected limits for $\mathcal{T} \to 0$ and $\mathcal{T} \sim Q$.
- Additive approach in spectrum better suited for Monte Carlo programs.

Additive matching

- Theoretically, both the multiplicative and additive approach are valid, the difference being higher order terms present in the multiplicative approach.

$$\frac{d\sigma}{d\Phi_{N+1}}(\mathcal{T}) = \frac{d\sigma^{NNLL'}}{d\Phi_N d\mathcal{T}} \left[\frac{d\sigma^{NLO1}}{d\Phi_{N+1}} \Big/ \frac{d\sigma^{NNLL'}}{d\Phi_N\, d\mathcal{T}}\Big|_{NLO1} \right]$$

$$\frac{d\sigma}{d\Phi_{N+1}}(\mathcal{T}) = \left[\frac{d\sigma^{NNLL'}}{d\Phi_N d\mathcal{T}} - \frac{d\sigma^{NNLL'}}{d\Phi_N\, d\mathcal{T}}\Big|_{NLO1} \right] + \frac{d\sigma^{NLO1}}{d\Phi_{N+1}}$$

- However, one must be careful these higher order terms do not spoil the accuracy after integration of the spectrum against the cumulant.

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

Example: $\alpha_S \mathcal{T}_0^{\rm cut} \log\left(\mathcal{T}_0^{\rm cut}\right) * \alpha_s^2 \log(\mathcal{T}_0^{\rm cut})^4 \approx \alpha_S \mathcal{T}_0^{\rm cut} \log\left(\mathcal{T}_0^{\rm cut}\right) * 1$

- Additive approach requires instead resummed and resummed expanded to be made more differential.

$$\frac{d\sigma^{NNLL'}}{d\Phi_N d\mathcal{T}} \quad \Longrightarrow \quad \frac{d\sigma^{NNLL'}}{d\Phi_{N+1}} \equiv \frac{d\sigma^{NNLL'}}{d\Phi_N d\mathcal{T}} P(z, \varphi)$$

- Using splitting-function $P(z, \varphi)$ that integrates to 1 for each $\mathcal{T}$, automatically preserving $\mathcal{T}$ distribution at given log accuracy .

First application: $e^+e^- \to$ jets

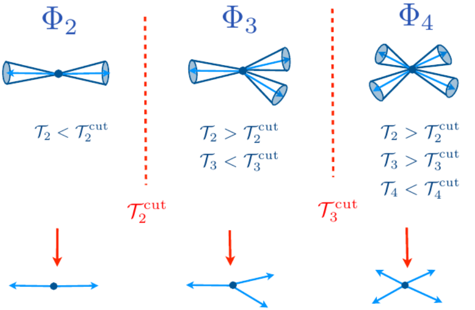
- ✓ Simpler process to test our construction.
- ✓ Thrust spectrum known to $\mathrm{N^3LL'}_{\mathcal{T}}$+ $\mathrm{NNLO_3}$.
- ✓ Several $\mathbf{2}$-jet shapes known to $\mathrm{NNLL}_{\mathcal{O}}$+$\mathrm{NNLO_3}$.
- ✓ LEP data available for validation.

- Use 2- and 3-jettiness.

$$\mathcal{T}_2 = E_{\rm cm}\left(1 - \max_{\hat{n}} \frac{\sum_k |\hat{n}\cdot\vec{p}_k|}{\sum_k |\vec{p}_k|}\right)$$
$$= E_{\rm cm}(1-T)$$

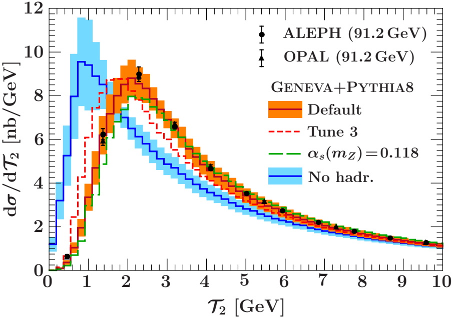
- Opportunely partitioning the phase-space

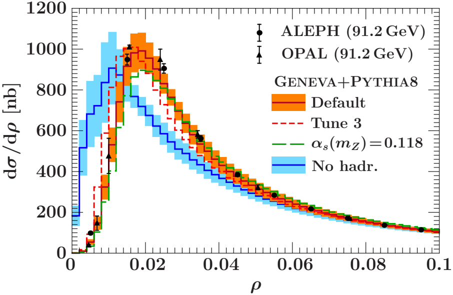
- Perturbatively calculating NLO/Resumm. jet-cross sections.

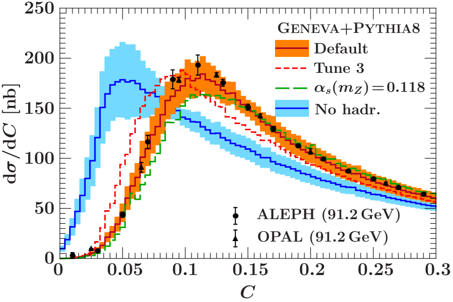


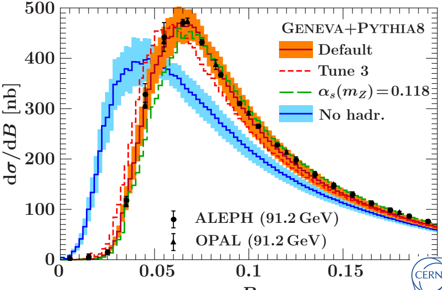
$$\underbrace{\frac{d\sigma}{d\Phi_2}(\mathcal{T}_2^{\rm cut})}_{\mathrm{NNLL'}_{\mathcal{T}_2}} \quad \underbrace{\frac{d\sigma}{d\Phi_3}(\mathcal{T}_2, \mathcal{T}_3^{\rm cut}) + \frac{d\sigma}{d\Phi_4}(\mathcal{T}_2, \mathcal{T}_3)}_{\mathrm{NNLL'}_{\mathcal{T}_2}+\mathrm{NLO_3}}$$

Results for $e^+e^- \to$ jets and comparison with LEP data







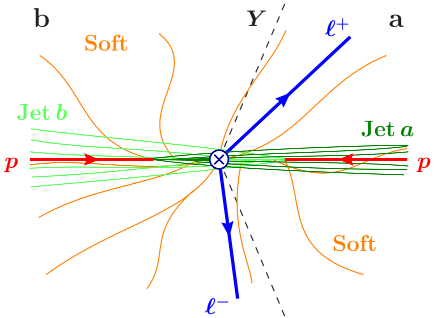


Hadronic collisions: $pp \to (Z \to \ell^+\ell^-)$ + jets

- To extend GENEVA approach to Drell-Yan we need :
  - A factorizable and resummable resolution parameter: Beam Thrust $\mathcal{T}_0 = \sum_i p_{T,i} e^{-|\eta_i - y_V|}$. Resummation known to NNLL

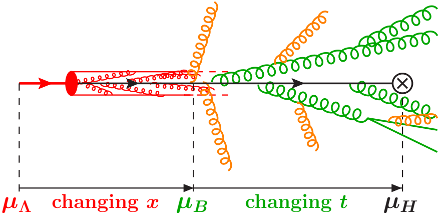
$$\frac{d\sigma^s}{dx_a dx_b\, d\mathcal{T}_B} = \sigma_B \cdot H(\mu_H) \otimes U_H(\mu_H, \mu) \cdot B(x_a, \mu_{B_a}) \otimes U_B(\mu_{B_a}, \mu) \otimes B(x_b, \mu_{B_b}) \otimes U_B(\mu_{B_b}, \mu) \otimes S(\mathcal{T}_B, \mu_S) \otimes U_S(\mu_S, \mu)$$

  - We use NNLL Soft $\mathbf{S}$, Beam $\mathbf{B}$ and Hard $\mathbf{H}$ functions. Evolution kernels $\mathbf{U}$ are obtained by RGE running at NNLL in SCET.



- Beam Functions convolutions with PDFs
- Preserving Beam Thrust and full V kinematics in $V+1 \to V+2$
- Efficient Pythia8 showering without changing $\mathcal{T}_0$ for ISR
- Proper framework to deal with MPI
- Re-tuning of GENEVA+PYTHIA ...

Beam Functions



- Beam functions are perturbative objects, connected to PDF via OPE in SCET

$$B_i(t, x; \mu_B) = \sum_k \int_x^1 \frac{\mathrm{d}\xi}{\xi} \mathcal{I}_{ik}\Big(t, \frac{x}{\xi}; \mu_B\Big) f_k(\xi; \mu_B)$$

- Calculating these integral on-the-fly is computationally intensive
- We have prepared interpolation grids for all convolutions, will distribute them independently from GENEVA
- These grids are essentially LHAPDF6 grids, we use the LHAPDF6 log-bicubic interpolator to get the values on-the-fly

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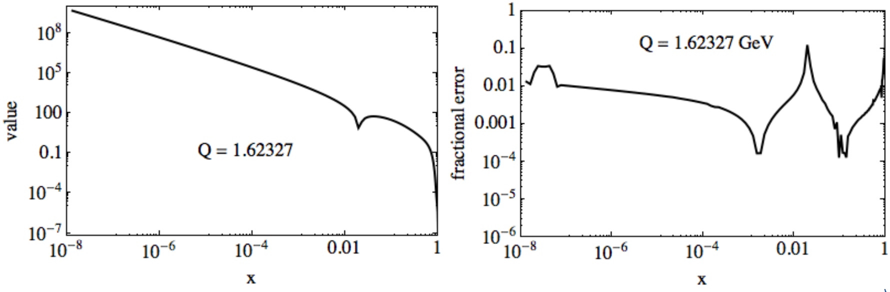
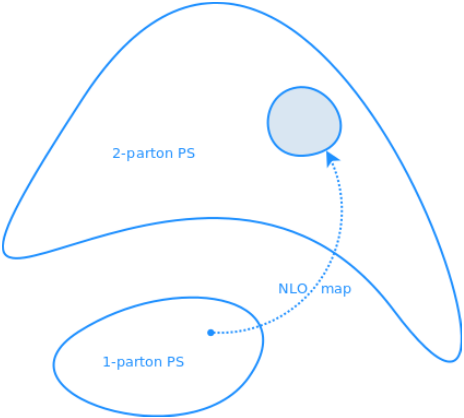
- These grids are essentially LHAPDF6 grids, we use the LHAPDF6 log-bicubic interpolator to get the values on-the-fly
- Results have been validated against direct integration, e.g. CT10NNLO $P_{gg} \otimes g$



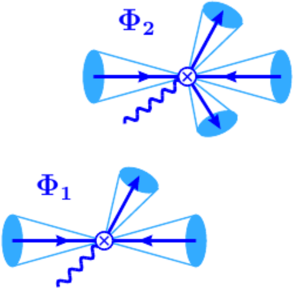
Preserving the $\mathcal{T}_0$ value in $V+1 \to V+2$ partons splittings

$$\frac{d\sigma^{\rm NLO}}{d\Phi_1}(\mathcal{T}_0) = [B_1(\Phi_1) + V_1(\Phi_1)]\,\delta(\mathcal{T}(\Phi_1) - \mathcal{T}_0) + \int \frac{d\Phi_2}{d\Phi_1} B_2(\Phi_2)\,\delta\left(\mathcal{T}(\Phi_1(\Phi_2)) - \mathcal{T}_0\right)$$

- When calculating NLO_1 we must preserve $d\Phi_1$. Cannot re-use existing calculations.
- Real emissions must preserve both $d^4q\,\delta(q^2 - M^2_{\ell^+\ell^-})$ and $\mathcal{T}_0 \equiv \bar{p}_{T,1}e^{-|y_V - \bar{\eta}_1|} = p_{T,1}e^{-|y_V - \eta_1|} + p_{T,2}e^{-|y_V - \eta_2|}$.

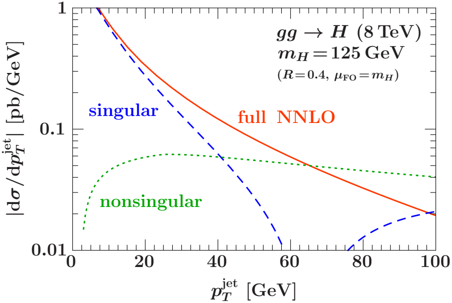


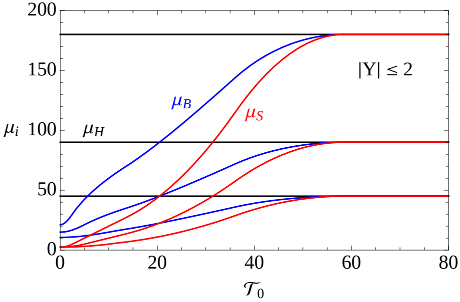
- Standard FKS or CS don't do this. They are design to preserve other quantities. We had to design our own map

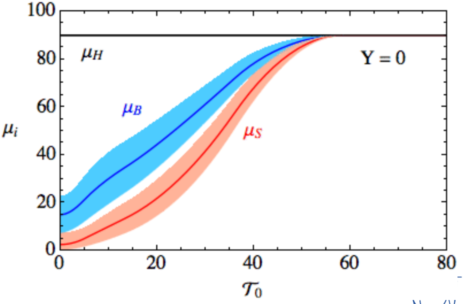


Scale profiles and theoretical uncertainties

- Theoretical uncertainties in resum. are evaluated by independently varying each μ. Final results are added in quadrature
- Range of variations is tuned to turn off the resummation before the nonsingular dominates (Y_V-dependent) and to respect SCET scaling $\mu_H \gtrsim \mu_B \gtrsim \mu_S$
- FO unc. are usual $\{2\mu_H, \mu_H/2\}$ variations. Added linearly.

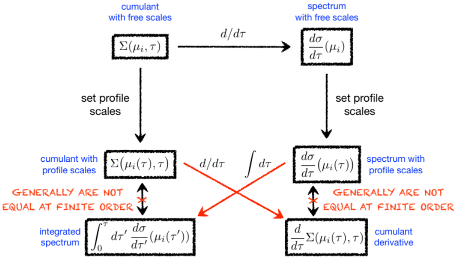




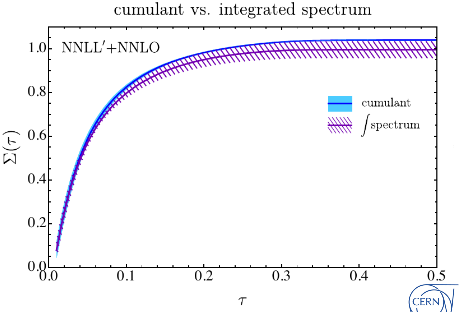


Preserving the total cross-section

- Different advantages in resumming the cumulant (better cross-section and correlated unc.) or the spectrum (better unc. in transition and better point-by-point unc.)
- The two approaches only agree at all order. When the series is truncated results are incompatible.
- Similar problem in preserving total xsec in matched QCD resummation solved with ad-hoc smoother
- Here simpler solution: add higher-order term to the spectrum such that integral get closer to cumulant. Add the exact higher-order difference to restore it completely.
- Correlations now enforced by hand, automatic method to select profile scale enforcing correlations under study.



[slide from J. Walsh]



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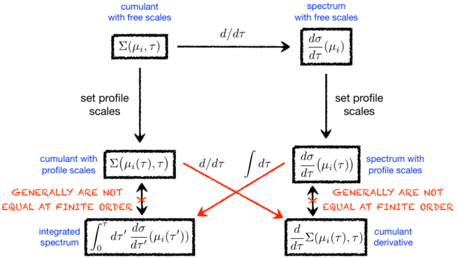

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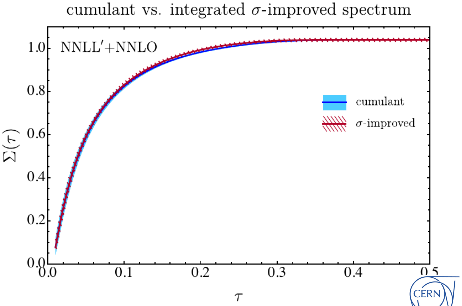

NNLO Shower Monte Carlo

Combining fully exclusive NNLO with LL resummation.

- We have worked out analytically the ingredients (and the recipe) needed to achieve NNLO accuracy in LL accurate SMC. [1311.0286]

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

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

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

- Exclusive N-jet cross section

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

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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 $\log(\mathcal{T}_N^{\text{cut}})$
  - Sudakov factor, provides (at least) LL resummation of $\mathcal{T}_N^{\text{cut}}$

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

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

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- 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.
- Corrects the finite terms to the exact inclusive cross section.

Combining fully exclusive NNLO with LL resummation.

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

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

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

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

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

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

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

Combining fully exclusive NNLO with LL resummation.

- We have worked out analytically the ingredients (and the recipe) needed to achieve NNLO accuracy in LL accurate SMC. [1311.0286]

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

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

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

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

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

- 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 $\mathcal{T}_{N+1}^{\mathrm{cut}}$
- Exclusive N+1-jet cross section (NLO+LL)

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

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

$$\frac{d\sigma^{\mathrm{MC}}_{\geq N+2}}{d\Phi_{N+2}}(\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}}, \mathcal{T}_{N+1} > \mathcal{T}_{N+1}^{\mathrm{cut}}) = \frac{d\sigma'^{C}_{\geq N+1}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}})\Big|_{\Phi_{N+1}=\hat{\Phi}_{N+1}}$$
$$\times \frac{S_{N+2}(\Phi_{N+2})}{B_{N+1}(\hat{\Phi}_{N+1})}\, \Delta_{N+1}(\hat{\Phi}_{N+1}; \mathcal{T}_{N+1})\, \theta(\mathcal{T}_{N+1} > \mathcal{T}_{N+1}^{\mathrm{cut}})$$
$$+ \left(\frac{d\sigma^{C-S}_{\geq N+2}}{d\Phi_{N+2}} + \frac{d\sigma^{B-C}_{\geq N+2}}{d\Phi_{N+2}}\right)(\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}}, \mathcal{T}_{N+1} > \mathcal{T}_{N+1}^{\mathrm{cut}})$$

Adding the parton shower.

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

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- Three conditions have to be satisfied for the shower matching:

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- Conditions above also ensure double-counting is avoided.

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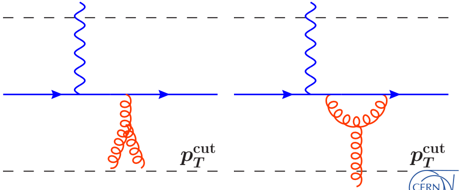
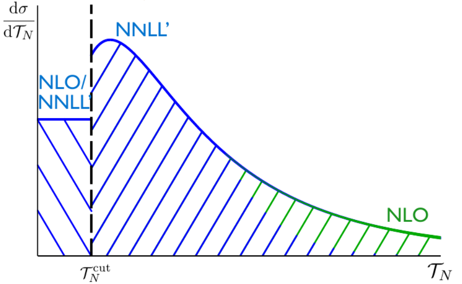
- Conditions above also ensure double-counting is avoided.

- 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



NNLO+PS in GENEVA

- What do we need need to make a NNLO+PS out of GENEVA ?



- Inclusive cross section NNLL' + NLO accurate
- 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

- Starting from NNLL' resummation, NNLO singular is automatically included

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

✗ $\frac{d\sigma_N^{B-C}}{d\Phi_N}(\mathcal{T}_N^{\rm cut}) \to \frac{d\sigma_N^{\rm nonsingular}}{d\Phi_N}(\mathcal{T}_N^{\rm cut})$ suppressed by powers of $\mathcal{T}_N^{\rm cut}$

- Only non-singular power-supressed contribution stemming from RV and RR are missing. Their effect can be made negligible by lowering $\mathcal{T}_N^{\rm cut}$.
- Adding the NNLO non-singular terms back to 0-jet bin allows to raise $\mathcal{T}_N^{\rm cut}$ to more moderate values.

Including $\mathcal{T}_1$ resummation

- Including also the separation between exclusive 1-jet and inclusive 2-jets using $\mathcal{T}_1^{\rm cut}$

$$
\begin{aligned}
\frac{d\sigma_0^{\rm MC}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) &= \frac{d\sigma_0^{\rm resum}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) + \frac{d\sigma_0^{\rm nons}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) \,, \\
\frac{d\sigma_1^{\rm MC}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut}) &= \frac{d\sigma_1^{\rm resum}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut}) + \frac{d\sigma_1^{\rm nons}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut}) \,, \\
\frac{d\sigma_{\geq 2}^{\rm MC}}{d\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}, \mathcal{T}_1 > \mathcal{T}_1^{\rm cut}) &= \frac{d\sigma_{\geq 2}^{\rm resum}}{d\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})\, \theta(\mathcal{T}_1 > \mathcal{T}_1^{\rm cut}) \\
&\quad + \frac{d\sigma_{\geq 2}^{\rm nons}}{d\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}, \mathcal{T}_1 > \mathcal{T}_1^{\rm cut}) \,.
\end{aligned}
$$

- We also perform a Sudakov-like (N)LL resummation of $\mathcal{T}_1^{\rm cut}$ to obtain a sensible separation between 1 and 2 jets, always enforcing unitarity

$$
\begin{aligned}
\frac{d\sigma_1^{\rm resum}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut}) &= \frac{d\sigma_{\geq 1}^{C}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})\, U_1(\Phi_1, \mathcal{T}_1^{\rm cut}) \,, \\
\frac{d\sigma_{\geq 2}^{\rm resum}}{d\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}) &= \frac{d\sigma_{\geq 1}^{C}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})\, U_1'(\Phi_1, \mathcal{T}_1)\Big|_{\Phi_1 = \Phi_1^{\mathcal{T}}(\Phi_2)} \mathcal{P}(\Phi_2) \,,
\end{aligned}
$$

Including $\mathcal{T}_1$ resummation

- One still has the freedom to choose what gets exponentianted by the U_1 Sudakov

$$\frac{d\sigma^{C}_{\geq 1}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}) = \frac{d\sigma^{\rm resum}_{\geq 1}}{d\Phi_1}\,\theta(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}) + \left[\frac{d\sigma^{C}_{\geq 1}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})\right]_{\rm NLO_1} - \frac{d\sigma^{\rm s}_{\geq 1}}{d\Phi_1}\,\theta(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})\,,$$

$$\left[\frac{d\sigma^{C}_{\geq 1}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})\right]_{\rm NLO_1} = (B_1 + V_1)(\Phi_1)\,\theta(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}) + \int \frac{d\Phi_2}{d\tilde{\Phi}_1}\,C_2(\Phi_2)\,\theta(\tilde{\mathcal{T}}_0 > \mathcal{T}_0^{\rm cut})\,.$$

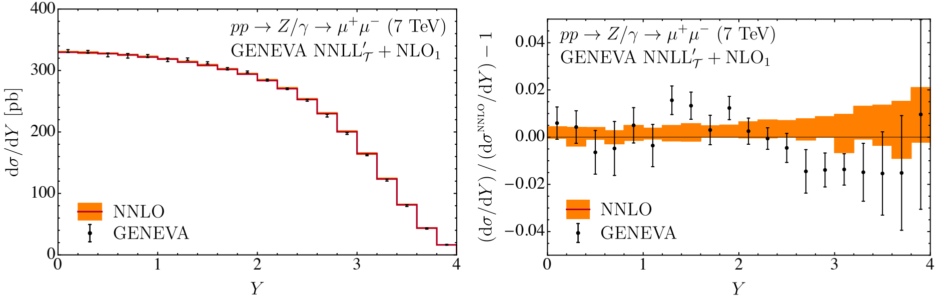
- The complement gets automatically taken care of by the non-singular contributions

$$\frac{d\sigma^{\rm nons}_{1}}{d\Phi_1}(\mathcal{T}_1^{\rm cut}) = \int d\Phi_2 \left[\frac{B_2(\Phi_2)}{d\Phi_1^{\mathcal{T}}}\,\theta(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})\theta(\mathcal{T}_1 < \mathcal{T}_1^{\rm cut}) - \frac{C_2(\Phi_2)}{d\tilde{\Phi}_1}\theta(\tilde{\mathcal{T}}_0 > \mathcal{T}_0^{\rm cut})\right] - B_1(\Phi_1)\,U_1^{(1)}(\Phi_1, \mathcal{T}_1^{\rm cut})\,,$$

$$\frac{d\sigma^{\rm nons}_{\geq 2}}{d\Phi_2}(\mathcal{T}_1 > \mathcal{T}_1^{\rm cut}) = \Big\{B_2(\Phi_2)\,[1 - \Theta^{\mathcal{T}}(\Phi_2)\,\theta(\mathcal{T}_1 < \mathcal{T}_1^{\rm cut})] - B_1(\Phi_1^{\mathcal{T}})\,U_1^{(1)\prime}(\Phi_1^{\mathcal{T}}, \mathcal{T}_1)\,\mathcal{P}(\Phi_2)\,\theta(\mathcal{T}_1 > \mathcal{T}_1^{\rm cut})\Big\}\theta(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})\,.$$

NNLO validation

- NNLO xsec and inclusive distributions validated against DYNNLO. Also checked against VRAP



- Comparison for 7 TeV LHC, $\mathcal{T}_0^{\mathrm{cut}} = 1$. Very good agreement for NNLO quantities, both central scale and variations.
- Non-trivial correlations for outer scales, ad-hoc procedure to ensure exact reproducibility of fixed-order variations.

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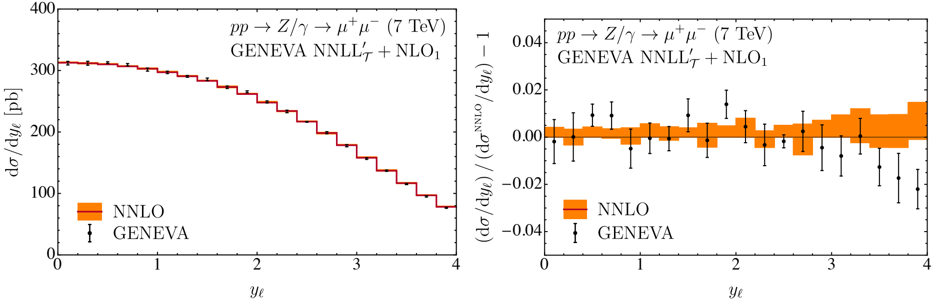

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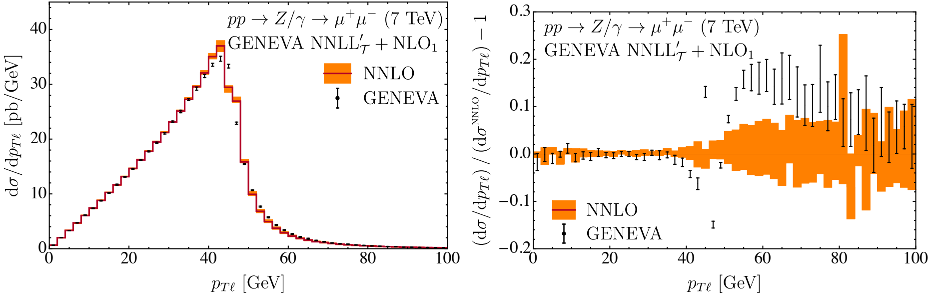

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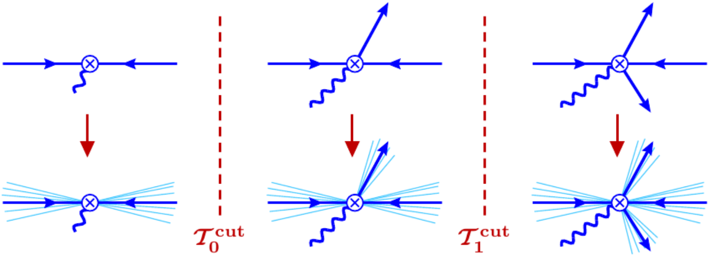
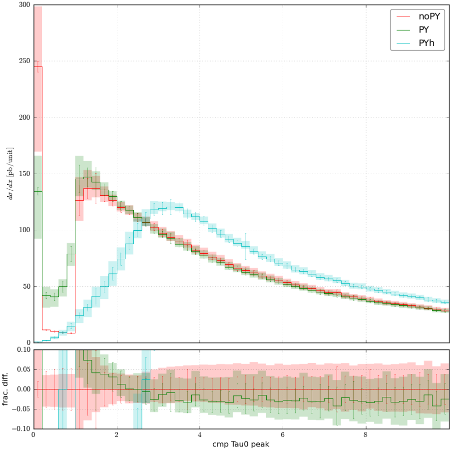
Showering and Hadronization



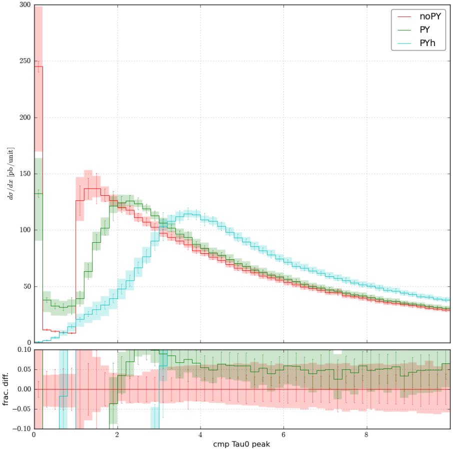
- Push $\mathcal{T}_0^{\text{cut}}$ towards zero allows to replace as much of the shower as possible with GENEVA higher logarithmic resummation.
- However, ultimately non-perturbative effects have to take over.
- Shower fills in $\mathcal{T}_0 < \mathcal{T}_0^{\text{cut}}$ from 0-jet events and $\mathcal{T}_1 < \mathcal{T}_1^{\text{cut}}$ from 1-jet ones. Small spill-over parameter $\lambda > \frac{\left|\mathcal{T}_0^{GE+PY} - \mathcal{T}_0^{GE}\right|}{\mathcal{T}_0^{GE}}$.
- Internal shower machinery untouched. Running shower repeatedly until conditions are met. Clever choice of starting scale makes showering quite efficient.

Showering and hadronization

$\mathcal{T}_0-$ constrained

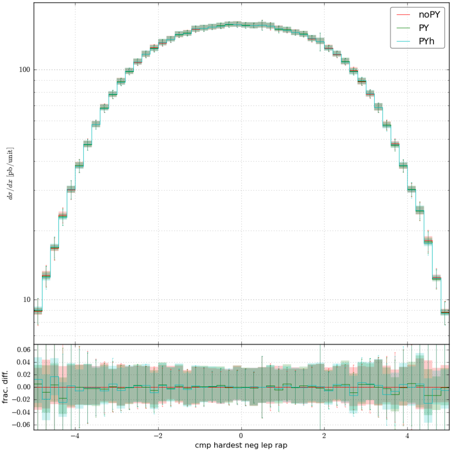


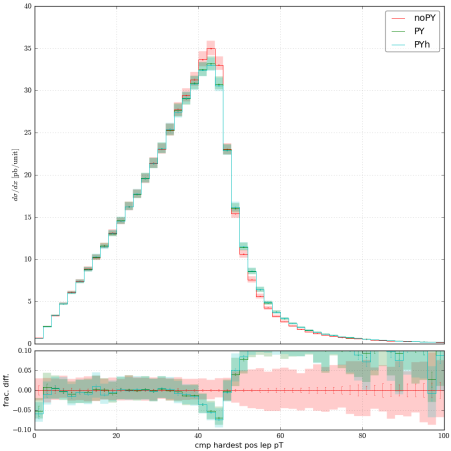
$\mathcal{T}_0-$ unconstrained



- Hadronization completely unconstrained and left to Pythia.
- As expected, $\mathcal{O}(1)$ shift in peak region. At larger $\mathcal{T}_0$ it only reduces to power corrections
- At small $\mathcal{T}_0$, important to constrain the shower even in presence of $\mathcal{T}_1$ resummation (only up to $\mathcal{T}_0/2$)

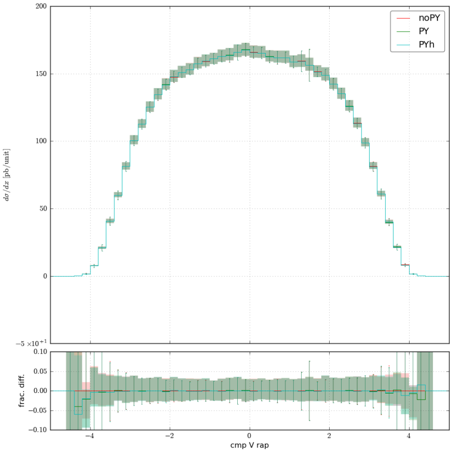
Showering and hadronization

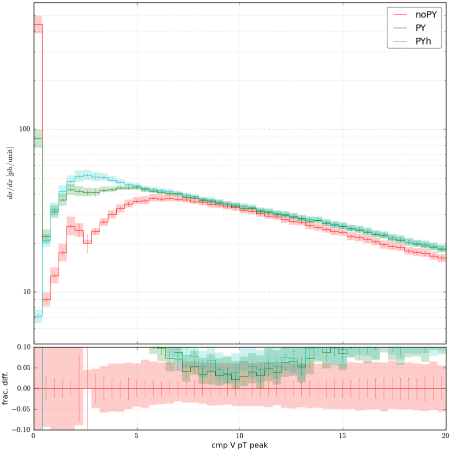




- Inclusive quantities not modified
- PYTHIA 8 tuning to data includes tuning of the shower parameters → replacing PYTHIA by GENEVA showering could imply re-tuning is necessary

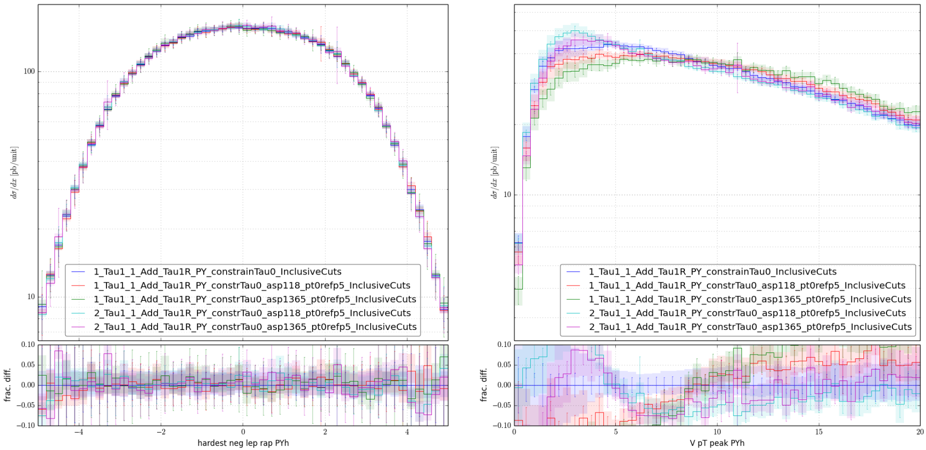
Showering and hadronization





- PYTHIA8 includes variations of perturbative parameters into tunes.
- Some distributions particularly sensitive to PYTHIA8 choices.

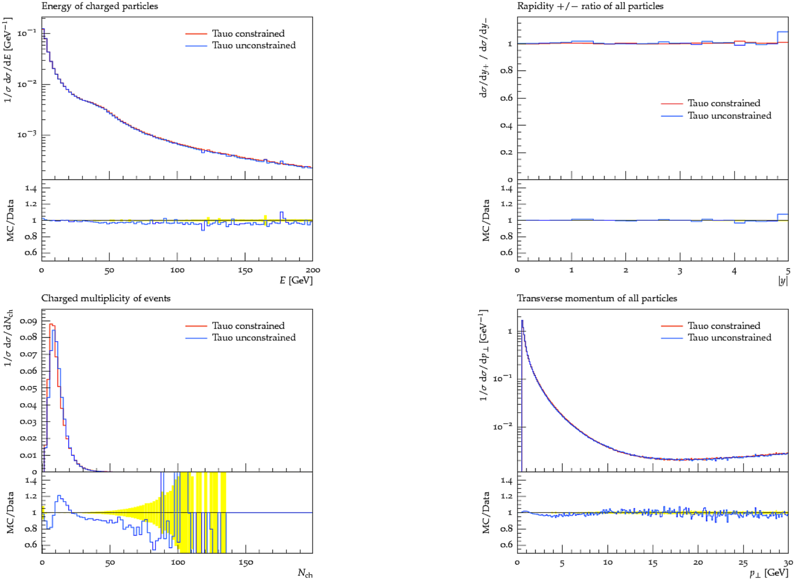
Showering and hadronization



- First study to determine freedom in selection of particular PYTHIA8 parameters governing the shower, like $p_{T_0}^{\mathrm{ref}}$ or $\alpha_s(M_Z)$
- Adopted approach much more conservative than standard ranges suggested in PYTHIA manual.
- Leaving only true non-perturbative effects to further tuning.

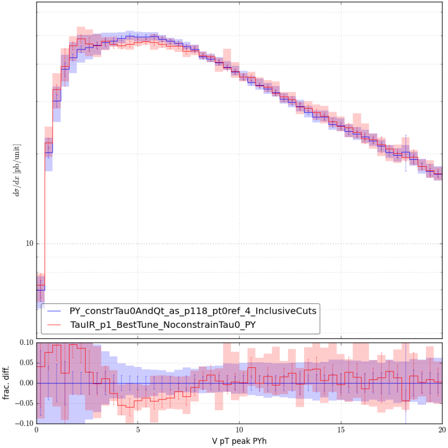
Showering and Hadronization

- How much is $\mathcal{T}_0$ constrain affecting the shower ?



Showering and Hadronization

- How can we relax the $\mathcal{T}_0$ constrain ? We need the shower to fill the phase space that we consider unresolved. This specifically depends on the map we have used in the calculation. Pythia uses a very different map. So the idea is to do the first $1 \to 2$ splitting ourselves with out $\mathcal{T}_0$-preserving map and using a LL $\Delta(\mathcal{T}1)$ Sudakov . PYTHIA will then start after our first emission.
- Preliminary results seem to go in the right direction. More careful investigation is ongoing.
- Ideally one could use a NLL $\Delta(\mathcal{T}1)$ or use POWHEG/MC@NLO method to do this splitting with higher accuracy.



Predictions for other observables : q_T and ϕ^*

- Comparison with DYqT Bozzi et al. arXiv:1007.2351 and BDMT results Banfi et al. arXiv:1205.4760
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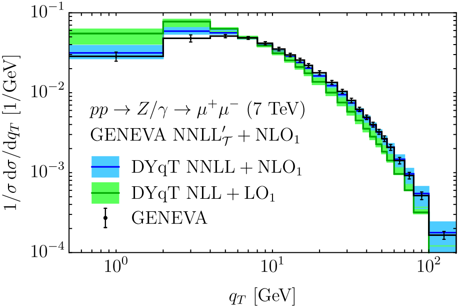
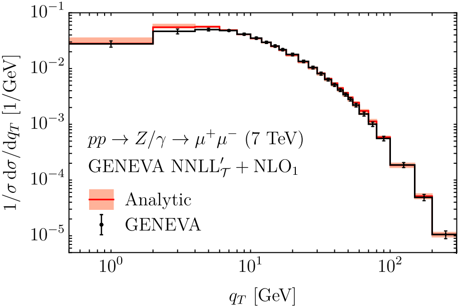
- Analytic predictions formally higher log accuracy than GENEVA
- PYTHIA8 provides non-perturbative hadronization corrections





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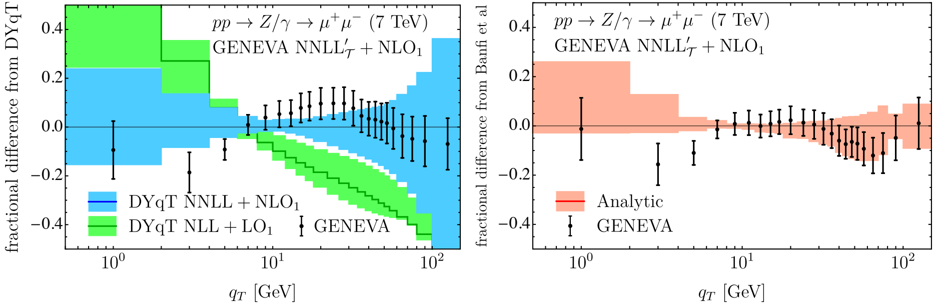

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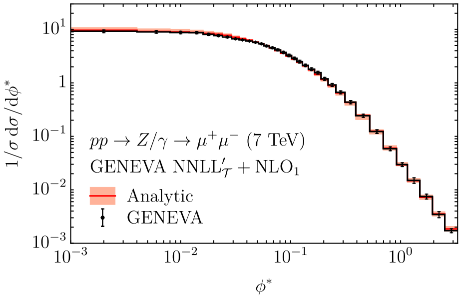

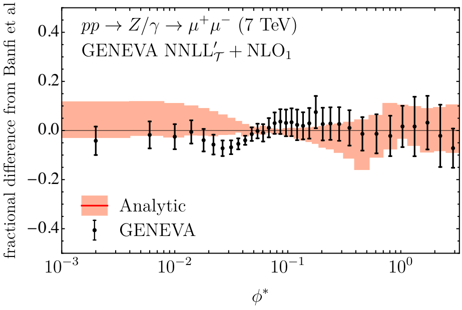

- ϕ^* strongly correlated to q_T , $\phi^* = \tan\left(\frac{\pi-\Delta\phi}{2}\right)\sin\theta^* \approx \left|\sum_i \frac{k_{T,i}}{Q}\sin\phi_i\right|$

Predictions for other observables : jet-veto acceptance

- Comparison with JetVHeto results Banfi et al. arXiv:1308.4634
- Analytic predictions at NNLL formally higher log accuracy than GENEVA
- Must reduce to total xsec in the tail. Small differences due to different hard-scale and NWA.
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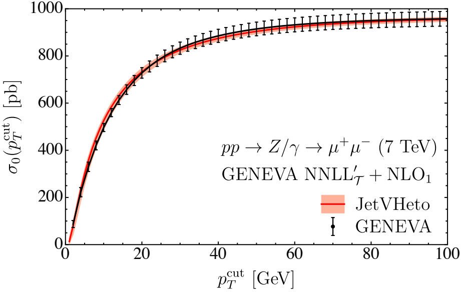
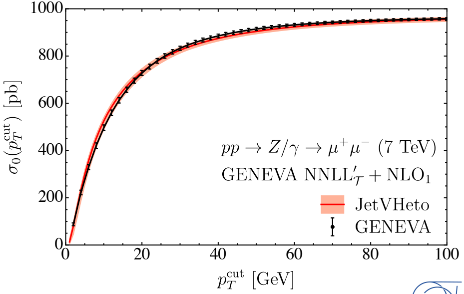
uncorrelated variations



correlated variations



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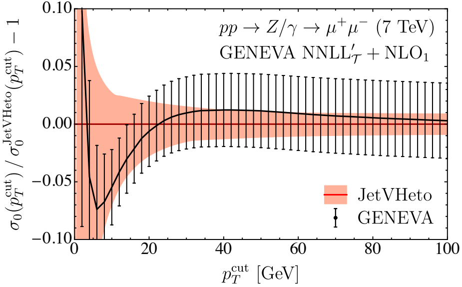

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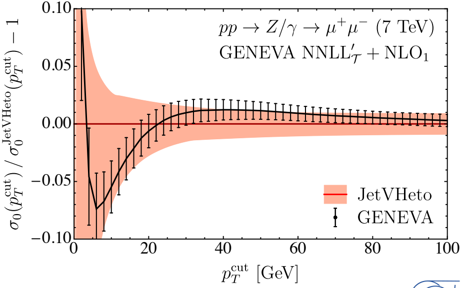

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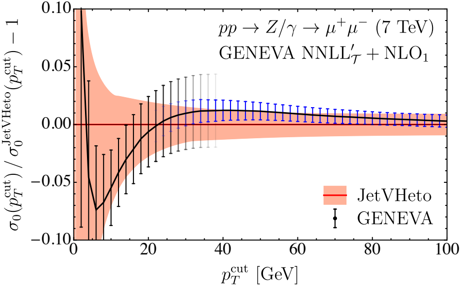
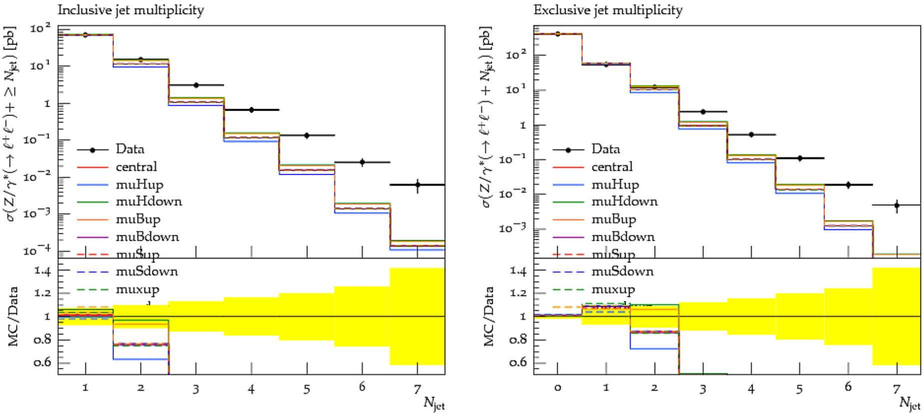


- Testing new profile scales that correctly capture the right uncertainty. see J. Walsh talk at SCET '15

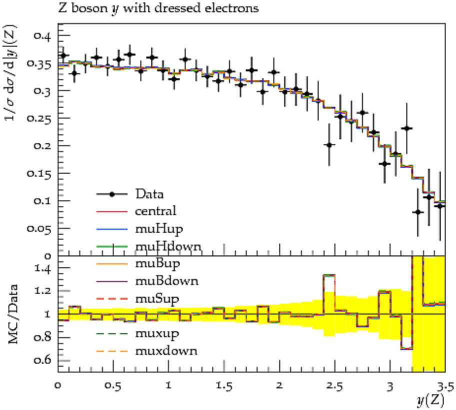
Comparisons with data

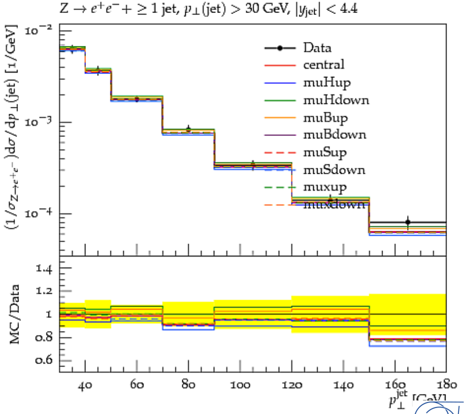


- First preliminary results for 7 TeV LHC .
- Results consistent with NNLO_0 MC expectations
- Higher multiplicities could be improved at LO with standard CKKW /MLM approaches
- Provided sufficent resummation available for $\mathcal{T}_N$ further NLO matrix elements could be included.

Comparisons with data

- Preliminary comparisons. All scale variations show to provide breakdown on uncertainties.
- More accurate uncertainty requires the envelope of resummation scales added in quadrature to hard scale variations.
- For inclusive quantities, fixed order scale variations including correlations provide the best estimate of theory uncertainty





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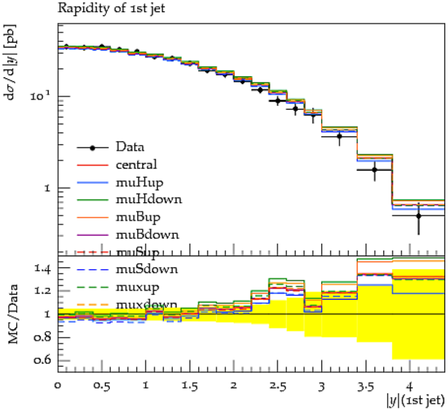

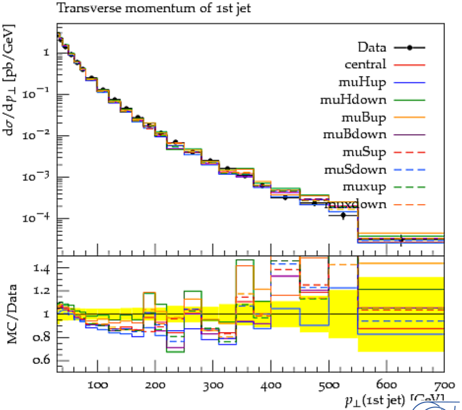

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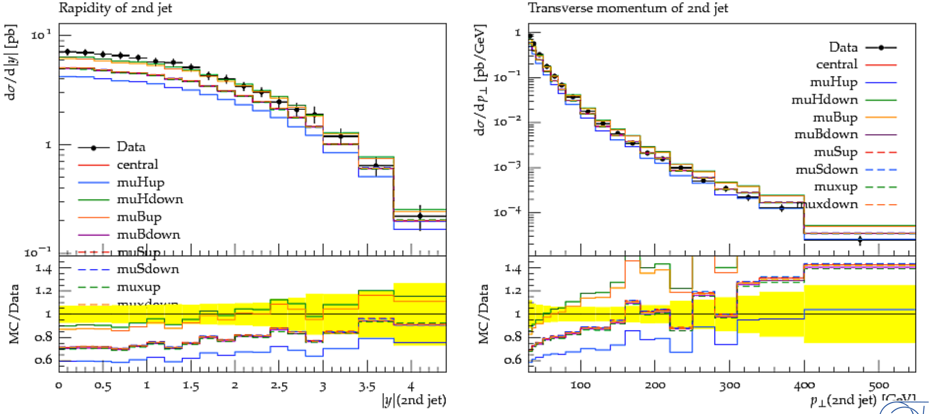

Comparisons with $Z/\gamma^* p_T$ LHC 7 TeV data

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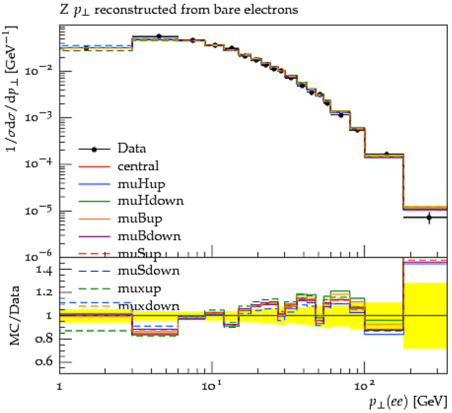
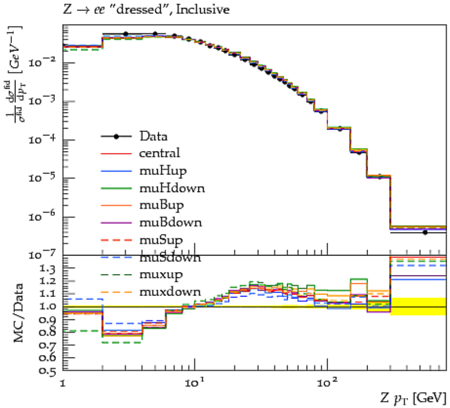
ATLAS 2011



ATLAS 2014



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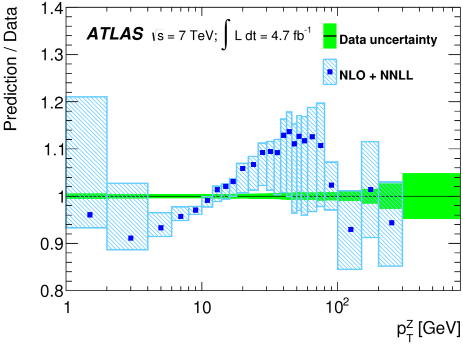

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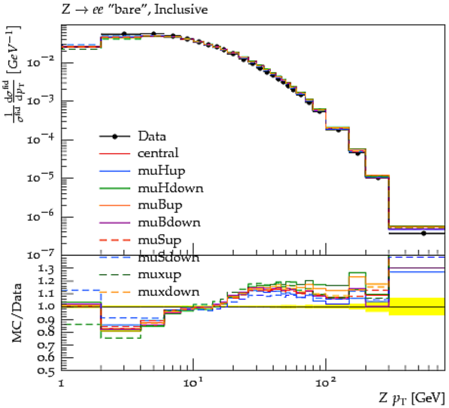

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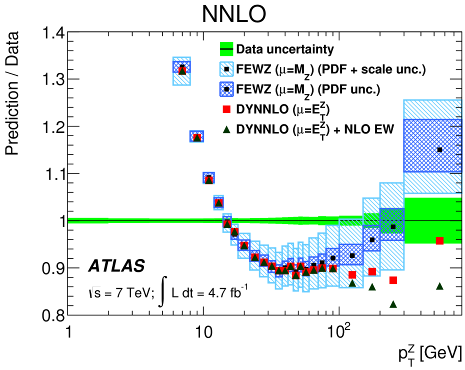

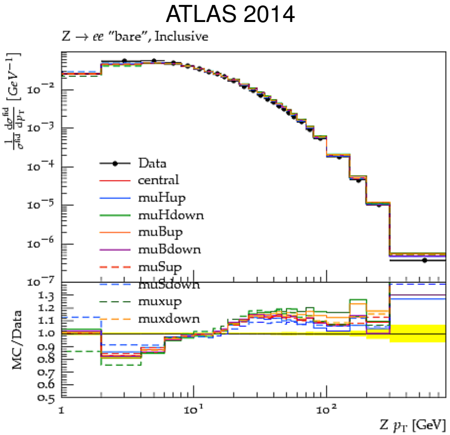

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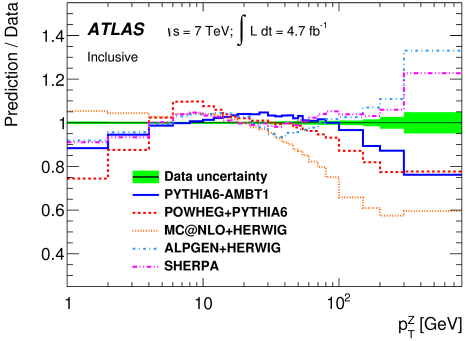
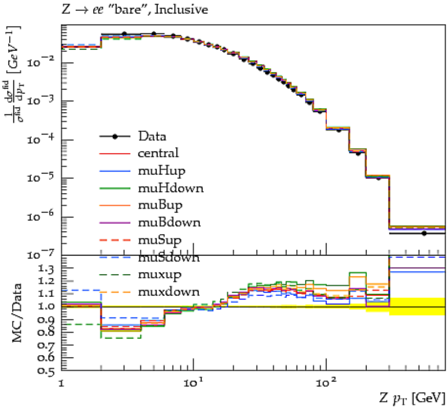


ATLAS 2014



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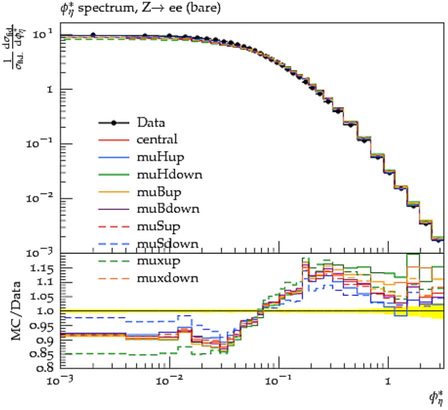
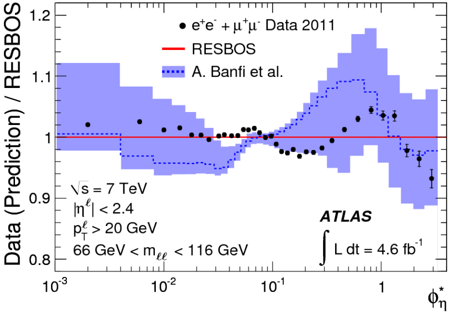
ATLAS 2012



BDMT / RESBOS



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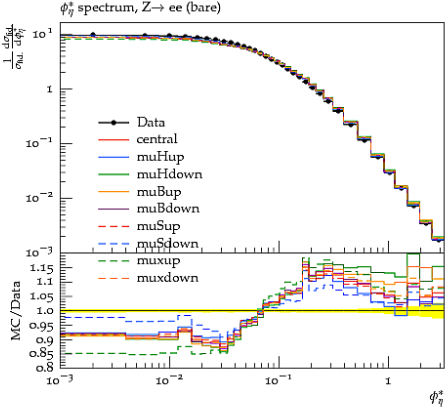

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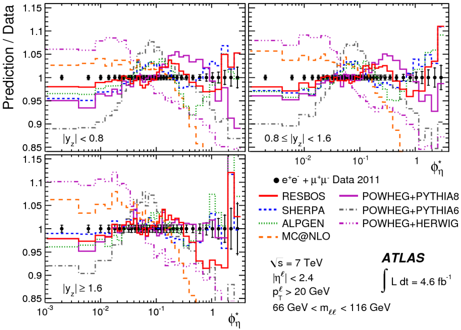

Conclusions and outlook

GENEVA is NNLO event generator that can be interfaced with shower/hadronization.

- Based on IR-safe, jet-like definitions of events.
- Uses a physics observable, N-jettiness, factorizable and whose resummation is known to NNLL as jet resolution parameter. e^+e^- and Drell-Yan results extremely encouraging.
- Worked out theoretical framework for NNLO+PS: given 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). Discussed shower matching.
- POWHEG, MC@NLO, GENEVA and MiNLO-NNLOPS re-derived as special limits. GENEVA also immediately follows, imposing NNLL' accuracy .
- Good agreement with analytical calculation / tools and with LHC data.

Future directions:

- Adding more jets, e.g. $pp \to V + 0, 1, 2$ and validation with LHC data.
- Next process is $gg \to H + 0, 1, 2$ jets.
- Investigate resummation of different resolution parameters / double resummation
- Study interface to other SMC: `HERWIG++`, `SHERPA` ...
- Comprehensive tuning program of GENEVA + SMC.

Thank you for your attention!

Backup

Comparison with existing approaches: MiNLO NNLO+PS.

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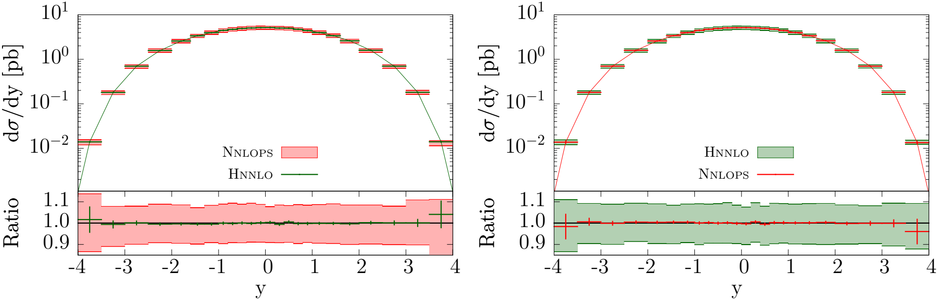
- For simple processes (e.g. $gg \to H$), using HNNLO [Catani et al. 0801.3232] for event-by-event reweighting results in a NNLO+PS [Hamilton,Nason,Re,Zanderighi 1309.0017]

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

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

Comparison with existing approaches: MiNLO NNLO+PS.

- Hj-MiNLO NNLO+PS results [Hamilton,Nason,Re,Zanderighi 1309.0017]



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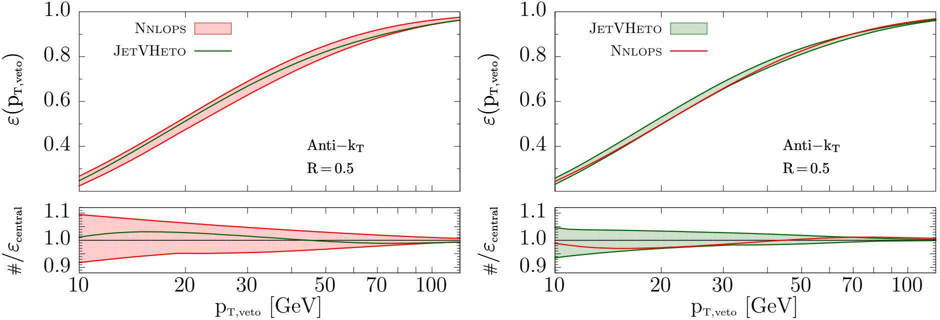

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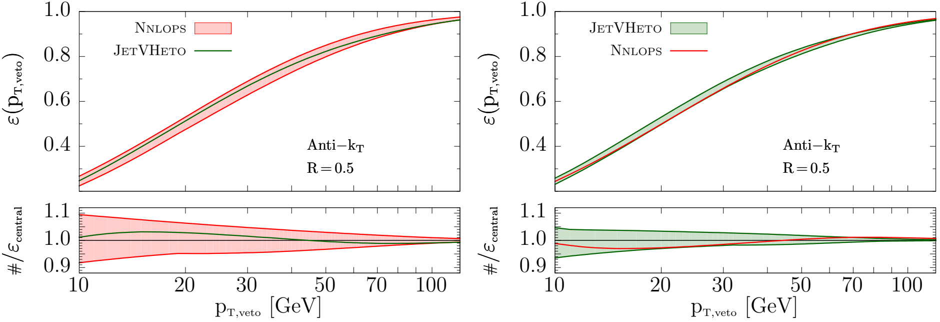
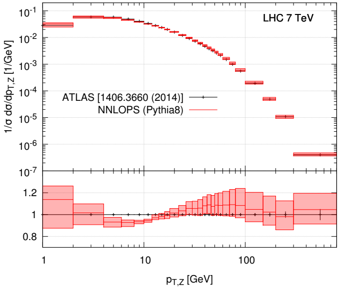
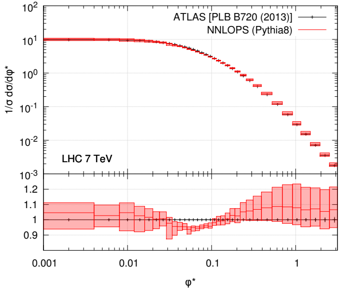


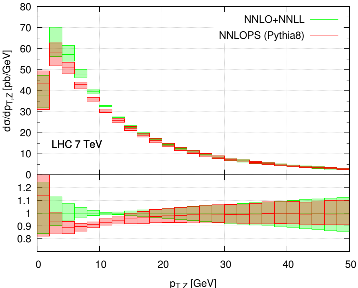
- We have re-derived MiNLO NNLO+PS formula as a check of our framework. It follows directly with a specific choice of splitting functions.
- Alternative choice of splitting functions proposed in [1311.0286] has pros and cons:
  - ✓ No need to know NLL resummation for NNLO+PS
  - ✓ No need to reweight after generation
  - ✗ Can't just simply run NNLO code as is . . .

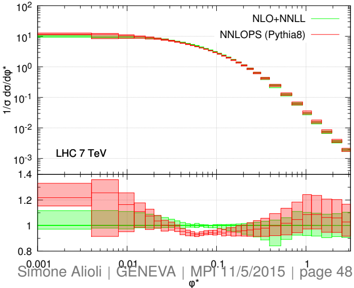
Comparison with existing approaches: MiNLO NNLO+PS.

- Also available for Z production [Karlberg et al. 1407.2949]

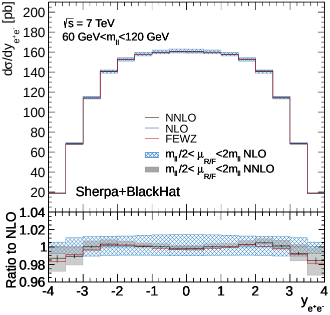


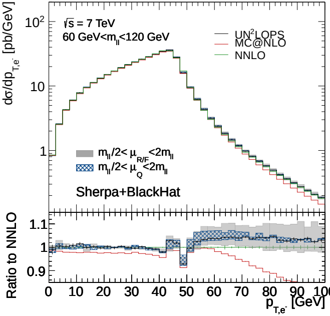


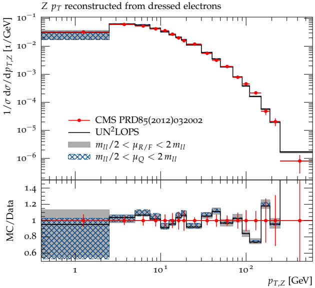




Comparison with existing approaches: UNNLOPS.







- Recent results from SHERPA+BlackHat [1405.3607]
- Uses q_T-subtraction for zero jet bin (phase-space slicing)
- NNLO accuracy is maintained via UNNLOPS approach, basically enforcing spectrum is derivative of the cumulant via unitarity