The GENEVA Monte Carlo framework

Improving Shower Monte Carlo's with resummation

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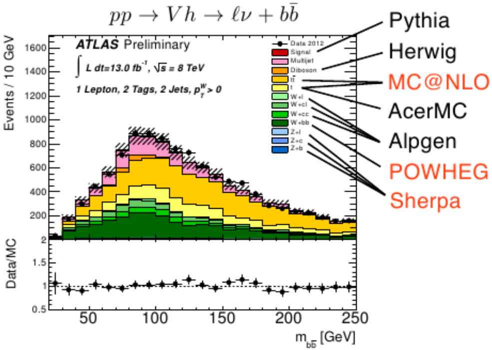
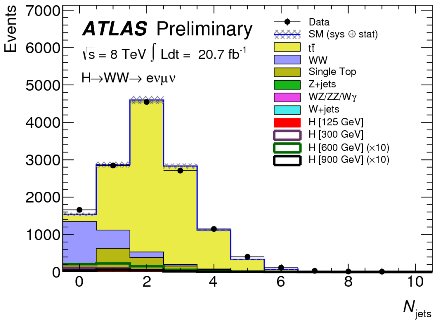
SA, C. Bauer, C. Berggren, A. Hornig, F. Tackmann, C. Vermilion, J. Walsh, S. Zuberi JHEP09(2013)120
SA, C. Bauer, C. Berggren, F. Tackmann, J. Walsh, S. Zuberi JHEP06(2014)089
SA, C. Bauer, C. Berggren, F. Tackmann, J. Walsh, Phys.Rev. D92 (2015) 9
SA, C. Bauer, F. Tackmann, S. Guns, Eur.Phys.J. C76 (2016) 614

Motivations

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





- Often the only tools to make theoretical predictions talk to data.
- For high accuracy, event generators should include the best theory predictions.

Introduction

GENEVA combines the 3 theoretical tools we use for QCD predictions into a single framework:

1) Fully differential fixed-order calculations
- up to NNLO via N-jettiness subtraction

2) Higher-logarithmic resummation
- up to NNLL$'$ via SCET (but not limited to it)

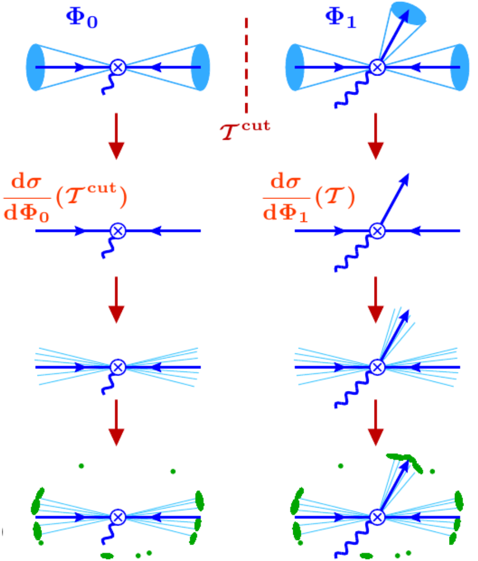
3) Parton showering, hadronization and MPI
- recycling standard SMC (currently using PYTHIA8)

Resulting Monte Carlo event generator has many advantages:

- consistently improves perturbative accuracy away from FO regions
- provides event-by-event systematic estimate of theoretical perturbative uncertainties and correlations
- gives a direct interface to SMC hadronization, MPI modeling and detector simulations.

Building GENEVA in 4 steps

1. Design IR-finite definition of events, based on resolution parameters $\mathcal{T}_N^{\mathrm{cut}}$.
2. Associate differential cross-sections to events such that inclusive jet bins are (N)NLO accurate and jet resolution is resummed at NNLL'$_{\mathcal{T}}$
3. Shower events imposing conditions to avoid spoiling higher order logarithmic accuracy reached at step 2
4. Hadronize, add multi-parton interactions (MPI) and decay without further restrictions



Step 1: Slice up the phase-space

The problem

✓ Fixed-order gives high precision for inclusive quantities.

✗ Only at parton level, no immediate way to estimate detector effects.

✗ Singular regions poorly described.

✓ Resummation improves singular regions.

✗ Requires observable definition beforehand.

✗ No fully-exclusive events.

Beyond LO, perturbative results are plagued by IR divergencies.
Only disappear after combining real emission with virtual correction:

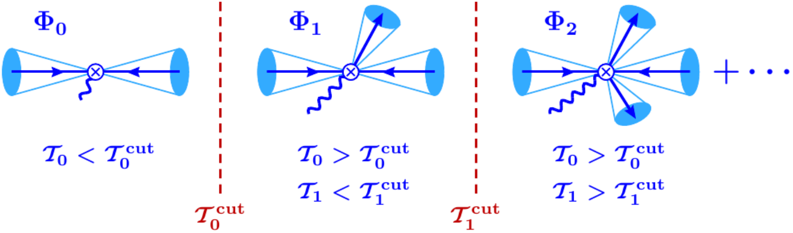
- At fully exclusive level, require introduction of subtraction counterterms to regulate the divergencies in 4D

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

- 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
  - ✗ impossible to fully 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 sensible 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

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

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Exclusive N-jet bin

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

Inclusive $(N+1)$-jet bin

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

$\mathcal{T}_1 < \mathcal{T}_1$ $\mathcal{T}_1 > \mathcal{T}_1$

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

Recipe for an IR-safe definitions of events beyond LO

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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

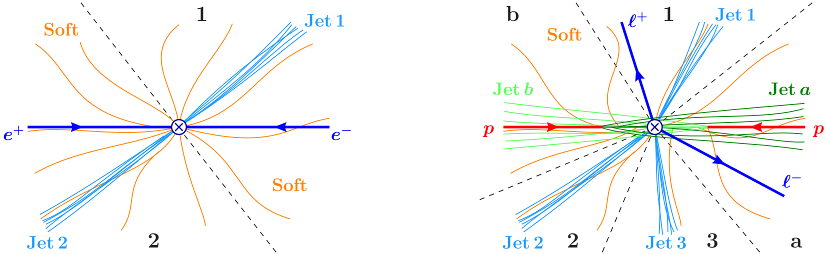
$$\frac{\mathrm{d}\sigma_{\geq N+2}^{\mathrm{MC}}}{\mathrm{d}\Phi_{N+2}}(\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}}, \mathcal{T}_{N+1} > \mathcal{T}_{N+1}^{\mathrm{cut}})$$

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

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

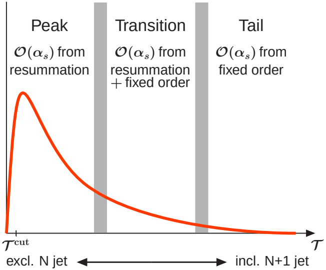
$$\mathcal{T}_N = \frac{2}{Q}\sum_k \min\{q_1 \cdot p_k, \ldots, q_N \cdot p_k\} \;\Rightarrow\; \mathcal{T}_N = \frac{2}{Q}\sum_k \min\{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \ldots, q_N \cdot p_k\}$$



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

Step 2: Construct NNLO+NNLL' cross sections

Perturbative accuracy required



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

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

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

- Lowest order accuracy across the whole spectrum in MEPS: CKKW, MLM
- Standard NLO+PS only improve total rate, not spectrum.
- GENEVA includes up to NNLL'$_{\mathcal{T}}$ + NNLO$_N$, meaning the two-loop virtuals $\sim \alpha_s^2\delta(\mathcal{T})$ are properly included and spread to non-zero $\mathcal{T}$ values as dictated by resummation.

Combining resummation with fixed-order in GENEVA

- For Drell-Yan at NNLO need to provide partonic formulae for up to 2 extra partons.
- $0-$jet exclusive cross section

$$\frac{\mathrm{d}\sigma_0^{\mathsf{MC}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma_0^{\mathrm{resum}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma_0^{\mathrm{sing\,match}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma_0^{\mathrm{nons}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$$

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$$\begin{aligned}\frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \int_0^{\mathcal{T}_0^{\mathrm{cut}}} \mathrm{d}\mathcal{T}_0 \, \sum_{ij} \frac{\mathrm{d}\sigma_{ij}^B}{\mathrm{d}\Phi_0} H_{ij}(Q^2, \mu_H)\, U_H(\mu_H, \mu) \\ \times \left[B_i(x_a, \mu_B) \otimes U_B(\mu_B, \mu)\right] \times \left[B_j(x_b, \mu_B) \otimes U_B(\mu_B, \mu)\right] \\ \otimes \left[S(\mu_S) \otimes U_S(\mu_S, \mu)\right],\end{aligned}$$

- SCET factorization: hard, beam and soft function depend on a single scale. No large logarithms present when scales are at their characteristic values:

$$\mu_H = Q, \quad \mu_B = \sqrt{Q\mathcal{T}_0}, \quad \mu_S = \mathcal{T}_0$$

- Resummation performed via RGE evolution factors U to a common scale μ.

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$$\frac{\mathrm{d}\sigma_0^{\mathrm{sing\ match}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = 0$$

- At NNLL' all singular contributions to $\mathcal{O}\left(\alpha_s^2\right)$ already included in $\frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$ by definition. Singular matching vanishes.
- Two-loop virtual corrections properly spread to nonzero $\mathcal{T}_0$ as resummation dictates.

Combining resummation with fixed-order in GENEVA

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$$\frac{d\sigma_0^{\mathrm{MC}}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{d\sigma^{\mathrm{NNLL}'}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \frac{d\sigma_0^{\mathrm{nons}}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$$

$$\frac{d\sigma_0^{\mathrm{nons}}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{d\sigma_0^{\mathrm{NNLO}_0}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) - \left[\frac{d\sigma^{\mathrm{NNLL}'}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})\right]_{\mathrm{NNLO}_0}$$

- Nonsingular matching constrained by requirement of NNLO_0 accuracy.

Combining resummation with fixed-order in GENEVA

- For Drell-Yan at NNLO need to provide partonic formulae for up to 2 extra partons.
- $0-$jet exclusive cross section

$$\frac{d\sigma_0^{\mathsf{MC}}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) = \frac{d\sigma^{\rm NNLL'}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) + \frac{d\sigma_0^{\rm NNLO_0}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) - \left[\frac{d\sigma^{\rm NNLL'}}{d\Phi_0}(\mathcal{T}_0^{\rm cut})\right]_{\rm NNLO_0}$$

Combining resummation with fixed-order in GENEVA

- For Drell-Yan at NNLO need to provide partonic formulae for up to 2 extra partons.
- $1-$jet inclusive cross section

$$
\begin{aligned}
\frac{\mathrm{d}\sigma^{\mathsf{MC}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{resum}}_{\geq 1}}{\mathrm{d}\Phi_1}\,\theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma^{\mathrm{sing\,match}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) \\
+ \frac{\mathrm{d}\sigma^{\mathrm{nons}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})
\end{aligned}
$$

Combining resummation with fixed-order in GENEVA

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$$\frac{\mathrm{d}\sigma^{\mathsf{MC}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{resum}}_{\geq 1}}{\mathrm{d}\Phi_1}\,\theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma^{\mathrm{sing\,match}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$
$$+ \frac{\mathrm{d}\sigma^{\mathrm{nons}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

$$\frac{\mathrm{d}\sigma^{\mathrm{resum}}_{\geq 1}}{\mathrm{d}\Phi_1} = \frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0\mathrm{d}\mathcal{T}_0}\,\mathcal{P}(\Phi_1)$$

- Resummed formula only differential in $\Phi_0, \mathcal{T}_0$. Need to make it differential in 2 more variables, e.g. energy ratio $z = E_M/E_S$ and azimuthal angle ϕ
- We use a normalized splitting probability to make the resummation differential in Φ_1.

$$\mathcal{P}(\Phi_1) = \frac{p_{\mathrm{sp}}(z,\phi)}{\sum_{\mathrm{sp}}\int_{z_{\min}(\mathcal{T}_0)}^{z_{\max}(\mathcal{T}_0)}\mathrm{d}z\mathrm{d}\phi\, p_{\mathrm{sp}}(z,\phi)}\,\frac{\mathrm{d}\Phi_0\mathrm{d}\mathcal{T}_0\mathrm{d}z\mathrm{d}\phi}{\mathrm{d}\Phi_1}, \qquad \int\frac{\mathrm{d}\Phi_1}{\mathrm{d}\Phi_0\mathrm{d}\mathcal{T}_0}\,\mathcal{P}(\Phi_1) = 1$$

- p_{sp} are based on AP splittings for FSR, weighted by PDF ratio for ISR.

Combining resummation with fixed-order in GENEVA

- For Drell-Yan at NNLO need to provide partonic formulae for up to 2 extra partons.
- $1-$jet inclusive cross section

$$\frac{d\sigma^{\mathrm{MC}}_{\geq 1}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{d\sigma^{\mathrm{NNLL}'}}{d\Phi_0 d\mathcal{T}_0}\,\mathcal{P}(\Phi_1) + \frac{d\sigma^{\mathrm{nons}}_{\geq 1}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

$$\frac{d\sigma^{\mathrm{nons}}_{\geq 1}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{d\sigma^{\mathrm{NLO}_1}_{\geq 1}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) - \left[\frac{d\sigma^{\mathrm{NNLL}'}}{d\Phi_0 d\mathcal{T}_0}\,\mathcal{P}(\Phi_1)\right]_{\mathrm{NLO}_1} \theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

- Singular matching vanishes again at NNLL’
- Nonsingular matching fixed by NLO_1 requirement

Combining resummation with fixed-order in GENEVA

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Combining resummation with fixed-order in GENEVA

- For Drell-Yan at NNLO need to provide partonic formulae for up to 2 extra partons.
- We also perform the NLL resummation of $\mathcal{T}_1^{\rm cut}$ to obtain a sensible separation between 1 and 2 jets, always enforcing unitarity.

$$U_1(\Phi_1, \mathcal{T}_1^{\rm cut}) = \frac{U}{\Gamma\left(1 + 2(2C_F + C_A)\left[\eta_\Gamma^{\rm NLL}(\mu_S, \mu_H) - \eta_\Gamma^{\rm NLL}(\mu_J, \mu_H)\right]\right)}$$

$$\begin{aligned}
\ln U =& 2(2C_F + C_A)\left[2K_\Gamma^{\rm NLL}(\mu_J, \mu_H) - K_\Gamma^{\rm NLL}(\mu_S, \mu_H)\right] \\
&+ 2C_F\left[-\eta_\Gamma^{\rm NLL}(\mu_J, \mu_H)\ln\left(\frac{w_q w_{\bar q}}{\mu_H^2}\right) + \eta_\Gamma^{\rm NLL}(\mu_S, \mu_H)\ln\left(\frac{w_q w_{\bar q}}{s_{q\bar q}}\right)\right] \\
&+ C_A\left[-\eta_\Gamma^{\rm NLL}(\mu_J, \mu_H)\ln\left(\frac{w_g^2}{\mu_H^2}\right) + \eta_\Gamma^{\rm NLL}(\mu_S, \mu_H)\ln\left(\frac{w_g^2 s_{q\bar q}}{s_{qg} s_{\bar q g}}\right)\right] \\
&+ K_\gamma^{\rm NLL}(\mu_J, \mu_H) - 2\gamma_{\rm E}(2C_F + C_A)\left[\eta_\Gamma^{\rm NLL}(\mu_S, \mu_H) - \eta_\Gamma^{\rm NLL}(\mu_J, \mu_H)\right].
\end{aligned}$$

Combining resummation with fixed-order in GENEVA

- For Drell-Yan at NNLO need to provide partonic formulae for up to 2 extra partons.
- We also perform the NLL resummation of $\mathcal{T}_1^{\rm cut}$ to obtain a sensible separation between 1 and 2 jets, always enforcing unitarity.
- Results in lengthier expressions. Need to include both the $\mathcal{T}_0$ and $\mathcal{T}_1$ resummations. See arXiv: 1508.01475 and arXiv: 1605.07192 for derivation.

$$\frac{d\sigma_1^{\rm MC}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut}) = \frac{d\sigma_1^{\rm resum}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut}) + \frac{d\sigma_1^{\rm match}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut})$$

$$\frac{d\sigma_{\geq 2}^{\rm MC}}{d\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}, \mathcal{T}_1 > \mathcal{T}_1^{\rm cut}) = \frac{d\sigma_{\geq 2}^{\rm resum}}{d\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})\, \theta(\mathcal{T}_1 > \mathcal{T}_1^{\rm cut}) + \frac{d\sigma_{\geq 2}^{\rm match}}{d\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}, \mathcal{T}_1 > \mathcal{T}_1^{\rm cut})$$

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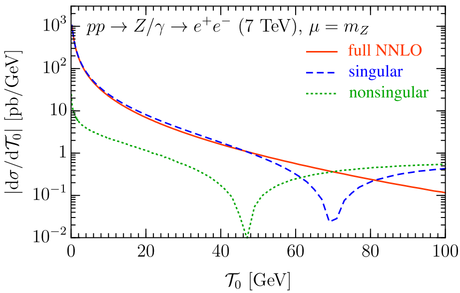
$$\frac{d\sigma_1^{\rm resum}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut}) = \frac{d\sigma_{\geq 1}^C}{d\Phi_1} U_1(\Phi_1, \mathcal{T}_1^{\rm cut})\, \theta(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})$$

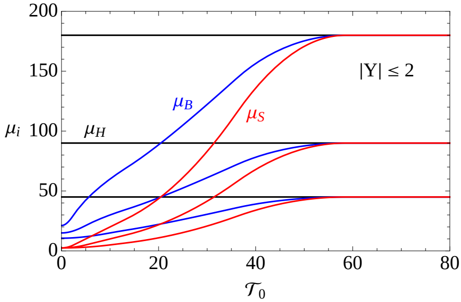
$$\frac{d\sigma_{\geq 2}^{\rm resum}}{d\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}) = \frac{d\sigma_{\geq 1}^C}{d\Phi_1} U_1'(\Phi_1, \mathcal{T}_1)\, \theta(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})\Big|_{\Phi_1 = \Phi_1^{\mathcal{T}}(\Phi_2)} \mathcal{P}(\Phi_2)\, \theta(\mathcal{T}_1 > \mathcal{T}_1^{\rm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

$$\frac{d\sigma_{\geq 1}^C}{d\Phi_1} = \frac{d\sigma_{\geq 1}^{\rm resum}}{d\Phi_1} + (B_1 + V_1^C)(\Phi_1) - \left[\frac{d\sigma_{\geq 1}^{\rm resum}}{d\Phi_1}\right]_{\rm NLO_1}$$

- The fully differential $\mathcal{T}_0$ information is contained trough $\frac{d\sigma_{\geq 1}^{\rm resum}}{d\Phi_1}$

Scale profiles and theoretical uncertainties





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

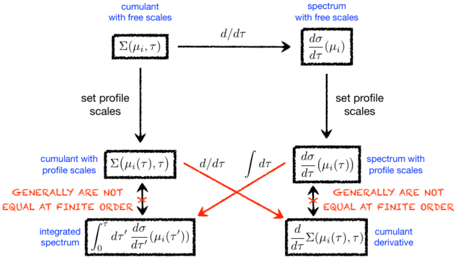
$$\mu_H = \mu_{\rm FO} = M_{\ell^+\ell^-}\,,$$
$$\mu_S(\mathcal{T}_0) = \mu_{\rm FO}\, f_{\rm run}(\mathcal{T}_0/Q)\,,$$
$$\mu_B(\mathcal{T}_0) = \mu_{\rm FO}\sqrt{f_{\rm run}(\mathcal{T}_0/Q)}$$

- $f_{\rm run}(x)$ common profile function: strict canonical scaling $x \to 0$ and switches off resummation $x \sim 1$

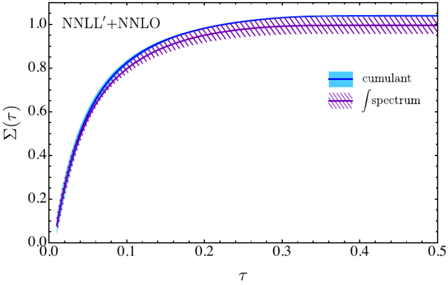
Scale profiles that preserve the total cross-section

- Different advantages in resumming the cumulant (better cross-section and correlated unc.) or the spectrum (better profiles in trans and tail region and better point-by-point unc.)
- The two approaches only agree at all order. Numerical differences when truncating are a problem for NNLO precision.
- Enforcing equivalence by taking derivative or integrating results in unreliable uncertainties.
- Similar problem in preserving total xsec in matched QCD resummation solved with ad-hoc smoother.
- We add higher-order term to the spectrum such that the total NNLO XS is preserved.
- Correlations now enforced by hand for up/down scales, new automatic method to select profile scale recently proposed

arXiv: 1701.07919



cumulant vs. integrated spectrum



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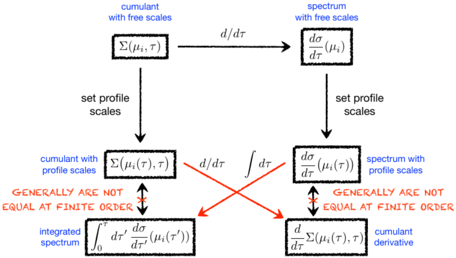
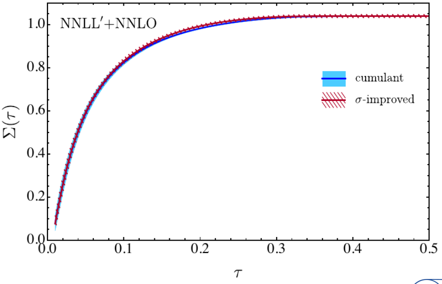


cumulant vs. integrated σ-improved spectrum



NNLO accuracy in GENEVA

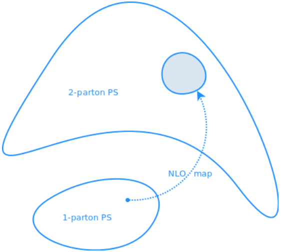
- Resum. expanded result in $\mathrm{d}\sigma^{\mathrm{nons}}_{\geq 1}/\mathrm{d}\Phi_1$ acts as a differential NNLO $\mathcal{T}_0$-subtraction

$$\frac{\mathrm{d}\sigma^{\mathrm{NLO}_1}_{\geq 1}}{\mathrm{d}\Phi_1} - \left[\frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0 \mathrm{d}\mathcal{T}_0} \mathcal{P}(\Phi_1)\right]_{\mathrm{NLO}_1}$$

- Nonlocal cancellation in Φ_1, after averaging over $\mathrm{d}\Phi_1/\mathrm{d}\Phi_0\mathrm{d}\mathcal{T}_0$ gives finite result.
- To be local in $\mathcal{T}_0$ has to reproduce the right singular $\mathcal{T}_0$-dependence when projected onto $\mathrm{d}\mathcal{T}_0\mathrm{d}\Phi_0$.

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

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



- Standard FKS or CS map don't preserve $\mathcal{T}_0$. They are designed to preserve other quantities. We had to design our own map.

- This map makes $\mathcal{T}_0$-subtraction local in $\mathcal{T}_0$. Better numerical convergence. Still averaged over $\mathrm{d}\Omega_2$

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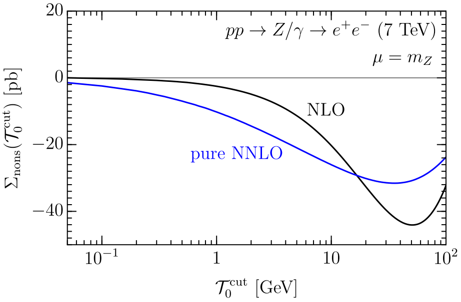
$$\frac{\mathrm{d}\sigma^{\mathrm{nons}}_0}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \left[\alpha_s f_1(\mathcal{T}_0^{\mathrm{cut}}, \Phi_0) + \alpha_s^2 f_2(\mathcal{T}_0^{\mathrm{cut}}, \Phi_0)\right]\mathcal{T}_0^{\mathrm{cut}}$$

$$\Sigma_{\mathrm{nons}}(\mathcal{T}_0^{\mathrm{cut}}) = \int \mathrm{d}\Phi_0 \frac{\mathrm{d}\sigma^{\mathrm{nons}}_0}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$$



- At $\mathcal{T}_0^{\mathrm{cut}} = 1\,\mathrm{GeV}$ gives $\sim 1\%$ xsec. Small but not negligible, can be lowered further. Tradeoff with speed/stability.
- $f_1(\Phi_0, \mathcal{T}_0^{\mathrm{cut}})$ included exactly by doing NLO$_0$ on-the-fly.
- For pure NNLO$_0$, we currently neglect the Φ_0 dependence below $\mathcal{T}_0^{\mathrm{cut}}$ and include total integral via simple rescaling of $\mathrm{d}\sigma_0^{\mathrm{MC}}/\mathrm{d}\Phi_0(\mathcal{T}_0^{\mathrm{cut}})$.

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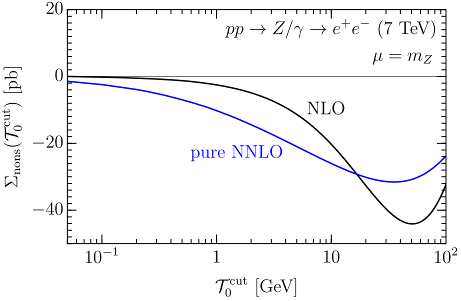

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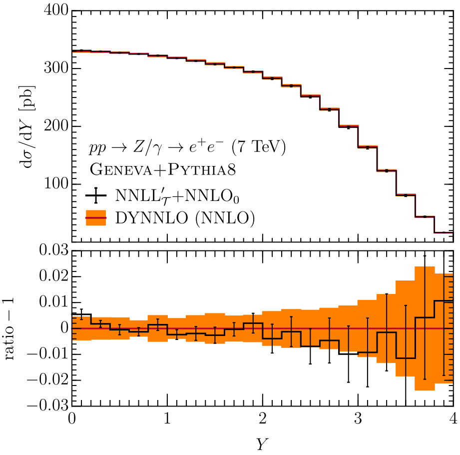
- $f_1(\Phi_0, \mathcal{T}_0^{\mathrm{cut}})$ included exactly by doing NLO_0 on-the-fly.
- Leading-power nonsingular recently calculated arXiV:1612.00450,1612.02911. Inclusion under study.

NNLO validation

- NNLO xsec and inclusive distributions validated against DYNNLO.
  Catani, Grazzini et al. [[hep-ph/0703012, 0903.2120]
  Also checked against VRAP.
  Anastasiou, Dixon et al. [hep-ph/0312266]
- Comparison for 7 TeV LHC, $\mathcal{T}_0^{\mathrm{cut}} = 1$. Very good agreement for NNLO quantities, both central scale and variations.
- Only scale variations shown as error bands, statistical fluctuations show up at large rapidities.
- Non-trivial correlations for outer scales, ad-hoc procedure to ensure exact reproducibility of fixed-order variations.



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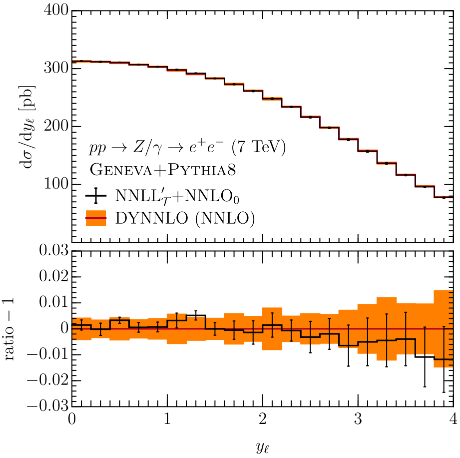

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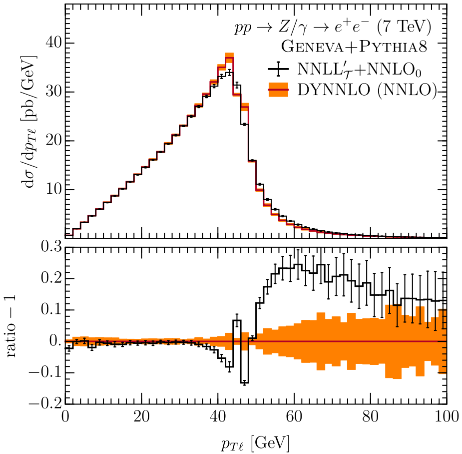
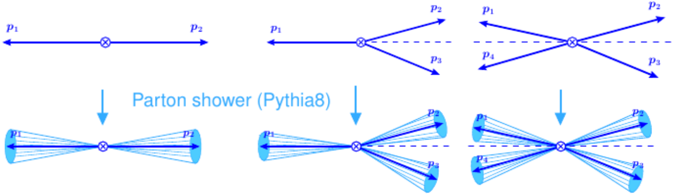


- True NNLO only for $p_{T\ell} < m_{\ell^+\ell^-}/2$. Around $m_{\ell^+\ell^-}/2$ very sensitive to Sudakov shoulder logarithms. GENEVA resumes some of these logs.
- $p_{T\ell} > m_{\ell^+\ell^-}/2$ only NLO. GENEVA results higher than NLO due to spillovers from below $m_{\ell^+\ell^-}/2$ caused by resumm. Converges back to NLO at higher $p_{T\ell}$

Step 3: Interface to the parton shower

Adding the parton shower.

- Purpose of the parton shower is to make the partonic calculation differential in the higher multiplicities.
- Can be viewed as filling the $0-$ and $1-$jet exclusive bins with radiations and adding more to the inclusive $2-$jet bin



- Not allowed to affect jet xsec at accuracy reached at partonic level.
- $\mathcal{T}_k^{\mathrm{cut}}$ constraints must be respected.

$$\theta_{\mathcal{T}_N}(\Phi_M) \equiv \theta[\mathcal{T}_N(\Phi_M) < \mathcal{T}_N^{\mathrm{cut}}], \quad \theta_{\mathrm{map}}(\Phi_N;\Phi_{N+1}) \equiv [\Phi_{N+1} \text{ projects onto } \Phi_N]$$

	Φ_0	Φ_1	Φ_2	Φ_N
$\mathrm{d}\sigma_0^{\mathrm{MC}}/\mathrm{d}\Phi_0$	All	$\theta_{\mathcal{T}_0}(\Phi_1)$ and $\theta_{\mathrm{map}}(\Phi_0;\Phi_1)$	$\theta_{\mathcal{T}_0}(\Phi_2)$	$\theta_{\mathcal{T}_0}(\Phi_N)$
$\mathrm{d}\sigma_1^{\mathrm{MC}}/\mathrm{d}\Phi_1$	–	$\overline{\theta}_{\mathcal{T}_0}(\Phi_1)$ or $\overline{\theta}_{\mathrm{map}}(\Phi_1)$	$\overline{\theta}_{\mathcal{T}_0}(\Phi_2)$ and $\theta_{\mathcal{T}_1}(\Phi_2)$ and $\theta_{\mathrm{map}}(\Phi_1;\Phi_2)$	$\overline{\theta}_{\mathcal{T}_0}(\Phi_N)$ and $\theta_{\mathcal{T}_1}(\Phi_N)$
$\mathrm{d}\sigma_{\geq 2}^{\mathrm{MC}}/\mathrm{d}\Phi_2$	–	–	$\overline{\theta}_{\mathcal{T}_0}(\Phi_2)$ and $\left[\overline{\theta}_{\mathcal{T}_1}(\Phi_2) \text{ or } \overline{\theta}_{\mathrm{map}}(\Phi_2)\right]$	$\overline{\theta}_{\mathcal{T}_0}(\Phi_N)$ and $\overline{\theta}_{\mathcal{T}_1}(\Phi_N)$

Adding the parton shower.

- If shower ordered in N-jettiness, $\mathcal{T}_k^{\rm cut}$ constraints are enough.
- For different ordering variable (i.e. any real shower), $\mathcal{T}_k^{\rm cut}$ constraints need to be imposed on hardest radiation (largest jet resolution scale), rather than the first.
- Impose the first emission has the largest jet resolution scale, by using an NLL Sudakov and the $\mathcal{T}_k$-preserving map.

$$\frac{\mathrm{d}\sigma^{\rm MC}_{N\to N}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\rm cut};\Lambda_N) = \frac{\mathrm{d}\sigma^{\rm MC}_{N}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\rm cut})\,U_N(\mathcal{T}_N^{\rm cut},\Lambda_N)$$

$$\frac{\mathrm{d}\sigma^{\rm MC}_{N\to N+1}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_N > \Lambda_N, \mathcal{T}_N^{\rm cut}) = \frac{\mathrm{d}}{\mathrm{d}\mathcal{T}_N}\left[\frac{\mathrm{d}\sigma^{\rm MC}_{N\to N}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\rm cut};\mathcal{T}_N)\right]\mathcal{P}(\Phi_{N+1}) \times\theta(\mathcal{T}_N^{\rm cut} > \mathcal{T}_N > \Lambda_N)$$

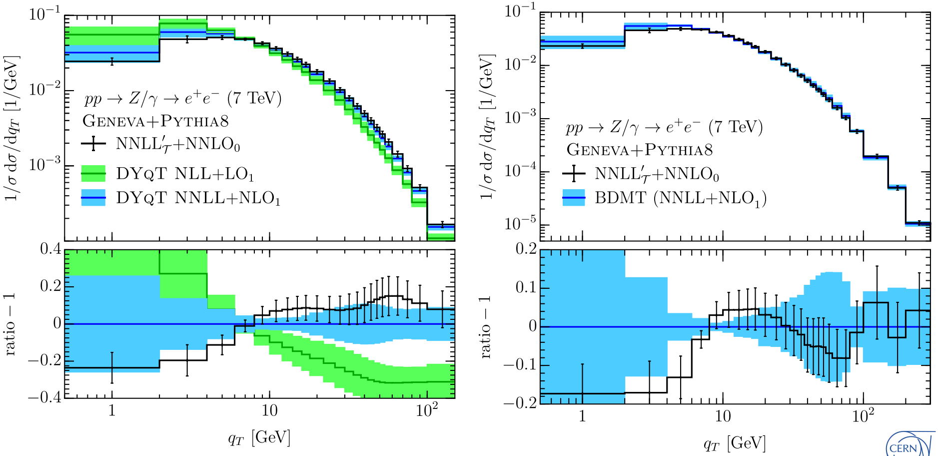
- Λ_N is shower cutoff, much lower than $\mathcal{T}_N^{\rm cut}$.

Showering setting starting scales $\mathcal{T}_k^{\rm cut}$ does not spoil NNLL'+NNLO accuracy:

- Φ_0 events only constrained by normalization, shape given by PYTHIA
- Φ_1 events vanish for $\Lambda_1 \lesssim 100$ MeV (sub per mille of total xsec).
- Φ_2 events: PYTHIA showering can be shown to shift $\mathcal{T}_0$ distribution at the same $\alpha_s^3/\mathcal{T}_0$ order of the dominant term beyond NNLL'. Beyond claimed 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
- Inclusive cuts for DYqT, ATLAS cuts for BDMT. Each normalized to own XS.
- Analytic NNLL predictions formally higher log accuracy than GENEVA
- PYTHIA8 provides non-perturbative hadronization corrections



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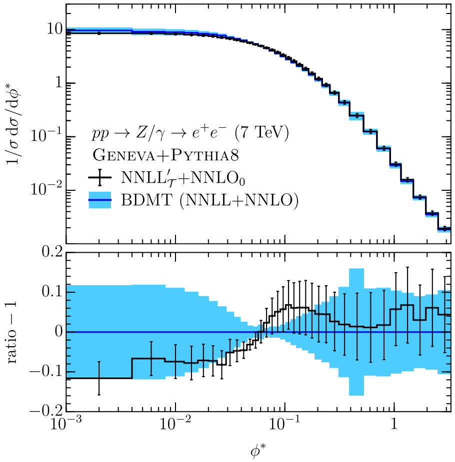


- ϕ^* strongly correlated to q_T

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

- Very low end highly sensitive to non-pertub. effects, k_{T} smearing.
- Smaller unc. in GENEVA there not necessarily an indication of higher precision.
- No sistematic tuning attempt, nor inclusion of shower uncert. yet.

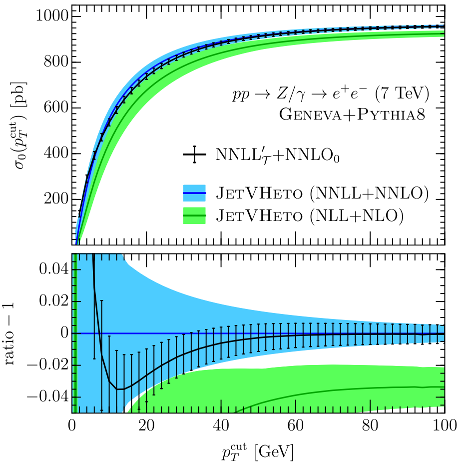
Predictions for other observables : jet-veto acceptance

- Comparison with JetVHeto

Banfi et al. 1308.4634

- Analytic predictions at NNLL formally higher log accuracy than GENEVA
- Correctly gets total xsec in the tail.
- Non-trivial propagation of spectrum uncertainties to cumulant result. Neglecting correlations yield much larger uncertainties.
- Imposing total XS hard variations only results in smaller uncertainties in peak region.
- Solution is to pick profiles that correctly capture the right uncertainty (currently under investigation).

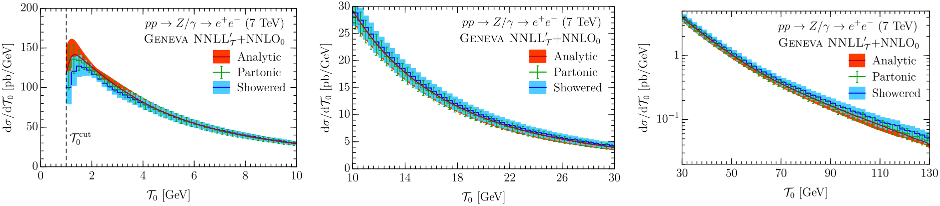
arXiv:1701.07919



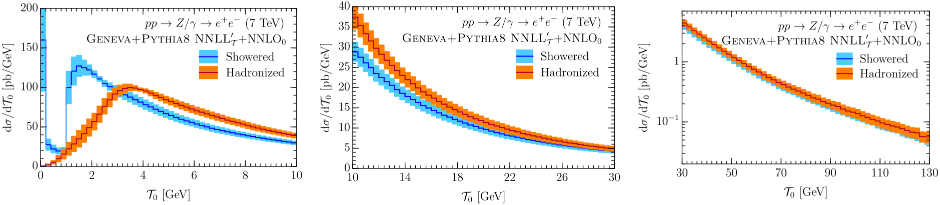
Step 4: Add hadronization and MPI

Hadronization corrections to the beam-thrust spectrum.

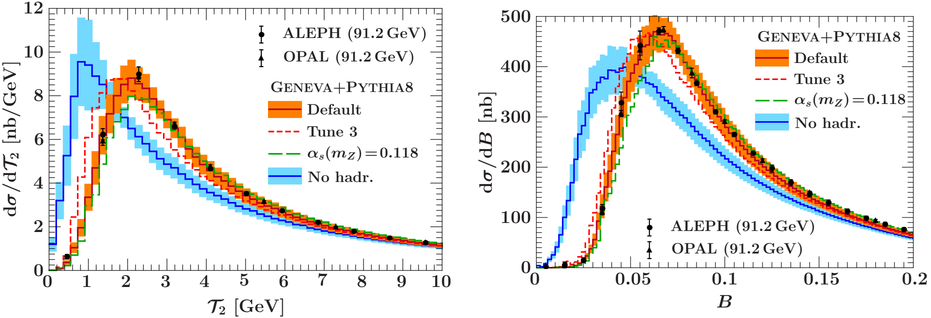
- Hadronization is left totally unconstrained by the GENEVA-PYTHIA interface
- After showering level only small changes within pert. uncertainties.



- After hadronization $\mathcal{O}(1)$ shift in peak, tail unchanged: as predicted by factorization.



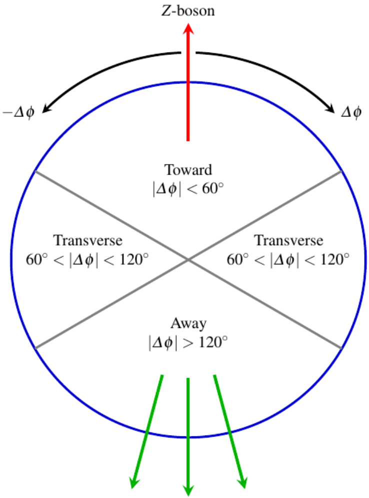
Hadronization effects for e^+e^-



- ✓ Excellent agreement with LEP measurements
- ✓ Directly uses PYTHIA8 hadronization model to include nonperturbative corrections.

MPI and underlying-event sensitive observables

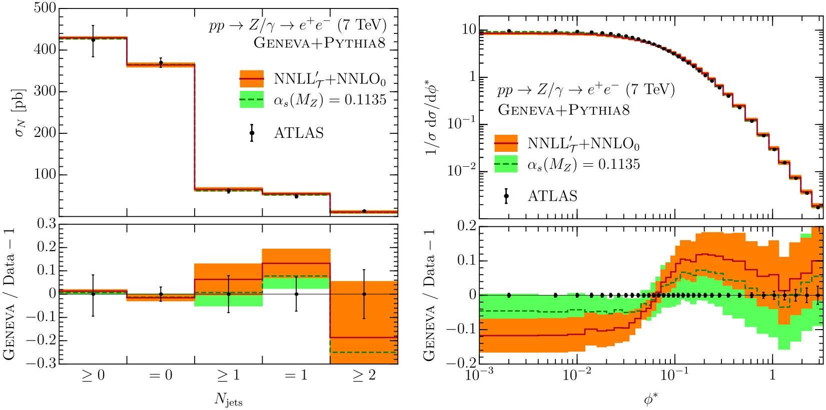
- Underlying event is used to characterize the physics not arising from the primary interaction
- Can receive contributions from small and large energy scales, including multiple parton interactions (MPI)
- Experimentally, studied by looking at the transverse region.
- But higher order effects also often produce big changes in the transverse regions.
- Correct modeling needs accurate description of hard interaction as well as MPI and non perturbative physics.



- Addition of MPI to GENEVA not straightforward, due to PYTHIA8 interleaved evolution.
  Shower constraints only applied to particle arising from primary hard interaction. Secondary interactions unconstrained.

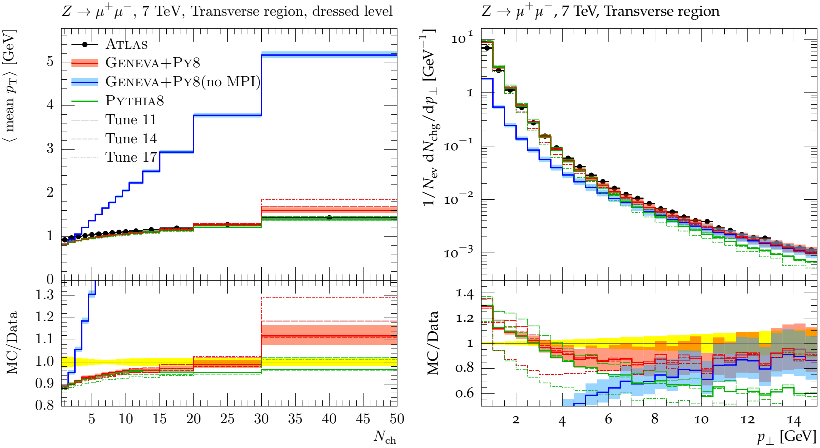
Results and comparisons with data

Comparisons with data



- Used RIVET [Buckley et al. 1003.0694] analyses to ensure full compliance with exp. selection.
- Also showing results for $\alpha_s(M_Z) = 0.1135$ in GENEVA perturbative calculation.
- Good agreement for both inclusive and exclusive jet cross sections.
- Given agreement with NNLO, Z rapidity distributions mostly driven by PDF used (CT10nnlo), same deviations observed in ATLAS and LHCb papers.

Comparisons with underlying event measurements



- Both ATLAS and CMS presented studies of UE-sensitive observables in DY [Eur. Phys. J. C (2014), Eur. Phys. J. C 72 (2012)].
- GENEVA without MPI completely wrong. GENEVA with MPI as good as PYTHIA8 at low transverse momenta. Validates interface with the shower is not spoiling PYTHIA8
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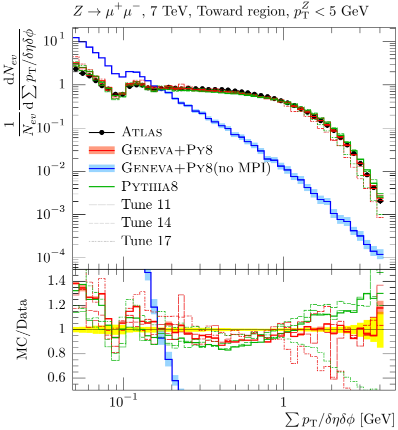

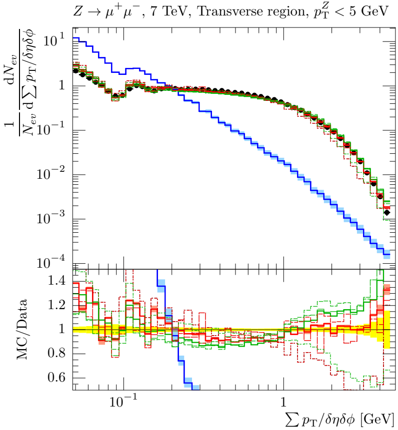

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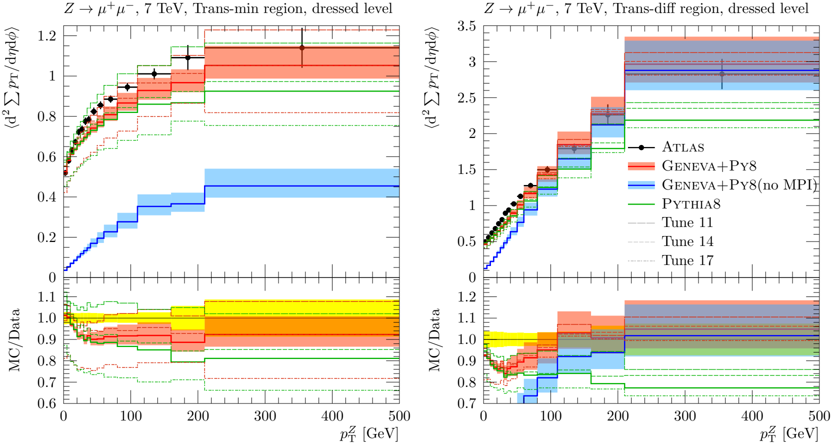

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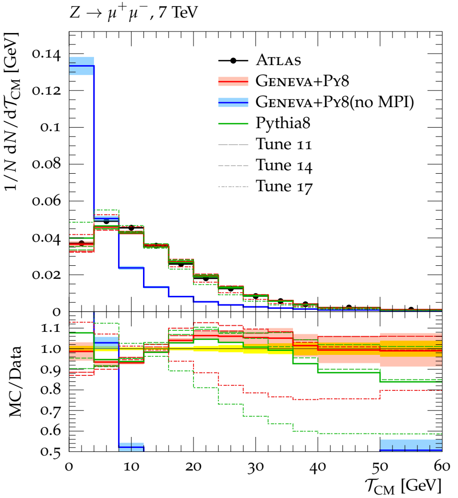
Comparisons with event-shape measurements

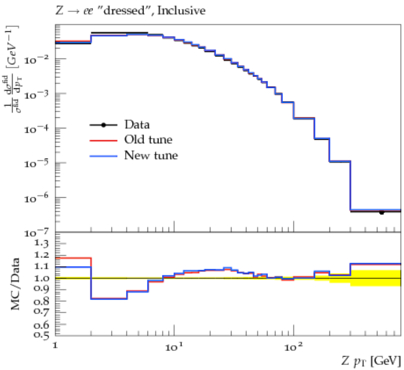
- ATLAS measurements of event-shapes [arXiv:1602.08980] includes Beam-Thrust $\mathcal{T}_{CM}$
- Not exactly the same resolution parameter we are resumming but resummation closely related (only differ in Y_V dependence). Upon integration overe Y_V and matching to FO, distributions found to be nearly identical.
- Main issue in tuning UE is that many observables are sensitive to both perturbative and nonperturbative physics (cfr. trans-min / trans-diff)
- Starting from a distribution which is know perturbatively very well, one gets a much better handle to tune MPI and nonperturbative physics.

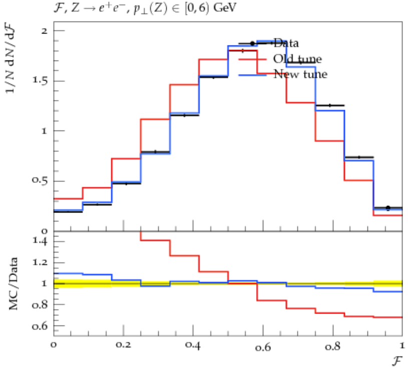


Tuning MPI and nonperturbative parameters

Ongoing GENEVA+PYTHIA8 tuning with Professor2 (with L. Gellersen)

- Using Drell-Yan data + MPI, both CMS and ATLAS Rivet analyses.
- Only 2 values of $\alpha_s(M_z)$ explored so far, 0.118 and 0.1135. Shower keeps same.
- 5 tuning parameters considered: $p_{T,0}^{\mathrm{ref,ISR}}$, intrinsic k_T for ISR, $\alpha_s^{\mathrm{MPI}}(M_Z)$, $p_{T,0}^{\mathrm{ref,MPI}}$ for MPI and color-reconnection range.
- Preliminary results:





Towards a public code release

- We have been working toward an user-friendly release for several of the past months
- We are now close to this goal.
- As most NNLO codes, GENEVA needs reasonable parallelization and runtime to produce accurate results.
  - Setup stage is particularly non-trivial, due to parallal grid adaptation and constraints on the resummation to preserve the total xsec.
  - Example runtime for 1 per mille stat accuracy in total xsec is 2-3 hours running on 120 cores (but also produces events and plots)
- Set-up a Python interface that help the user to run GENEVA on several systems (own laptop, NERSC clusters, LXPLUS cluster)
- Alternatively, it can just provide the list of commands to be run and their grouping, to extend it to other systems.
- Revamped the GENEVA options to only expose to the user a reasonable subset of options (with some backdoors for savvy users)
- Provided static interfaces to PYTHIA8, to allow for immediate delivery of GENEVA into experimental collaboration's toolchains, using default PYTHIA8 installations.

Running

- All stages of running can be accessed and managed through the Python interface

```
✔ alioli@woland:~/GENEVA/geneva/bin/python [release-RC1| …81]> ./geneva -h
usage: geneva [-h] {setup,run,reweight,analyze_lhef,shower,rivet} ...

Run the Geneva event generator

positional arguments:
  {setup,run,reweight,analyze_lhef,shower,rivet}
                        Available stages:
    setup               Sets up Geneva to start generating events
    run                 Runs the main Calculation
    reweight            Reweights the LHEF events
    analyze_lhef        Analyze the LHEF events
    shower              Shower LHEF events using Pythia8
    rivet               Analyze (compressed) HepMC files using Rivet

optional arguments:
  -h, --help            show this help message and exit
```

- Main inputs are GENEVA and PYTHIA8 option cards

```
✔ alioli@woland:~/GENEVA/geneva/bin/python [release-RC1| …81]> ./geneva setup -h
usage: geneva setup [-h] [--startSeed SEED] [--numRuns N] [--mpi] [--dryRun]
                    [--extraOptions OPT]
                    optionFile

Sets up Geneva to start generating events

positional arguments:
  optionFile          the Geneva option file

optional arguments:
  -h, --help          show this help message and exit
  --startSeed SEED    first random number seed [1]
  --numRuns N         the number of runs
  --mpi               parallelize runs with MPI [NO]
  --dryRun            print the commands without executing them [NO]
  --extraOptions OPT  extra options (only for power-users)
```

```
✔ alioli@woland:~/GENEVA/geneva/bin/python [release-RC1| …81]> ./geneva shower -h
usage: geneva shower [-h] [--startSeed SEED] [--numRuns N] [--mpi] [--dryRun]
                     [--noHepMC] [--noLhefOptionsCheck]
                     [--overwriteFileStem NEW_FILESTEM] [--maxTime MAXTIME]
                     [--numEvents NUMEVENTS]
                     optionFile pythiaOptionFile

Shower LHEF events using Pythia8

positional arguments:
  optionFile          the Geneva option file
  pythiaOptionFile    pythia8 input card

optional arguments:
  -h, --help          show this help message and exit
  --startSeed SEED    first random number seed [1]
  --numRuns N         the number of runs
  --mpi               parallelize runs with MPI [NO]
  --dryRun            print the commands without executing them [NO]
  --noHepMC           suppress hepmc output [NO]
```

GENEVA's input card

```
#-------------------------------
# Global run options
#-------------------------------

global:
   process: pp_V
   run_name: "myFirstRun"
   num_events: 1000
   max_time: 60

input_output:
   verbosity: info
   output_path: "./"

event_generation:
   sampling: Adaptive
   unweighting:
      partial_relative: 30
      estimate_precision: 0.1
   random:
      seed: 1

event_analysis:
   analyzer: DrellYan
```

- YAML options: easy to parse by both humans and computers

```
#-----------------------------------------
# Process
#-----------------------------------------

process:
   pp_V:
      initial_state:
         beams: pp
         Ecm: 13000
         pdf_provider:
            LHAPDF:
               set: "PDF4LHC15_nnlo_100"
      final_state:
         boson_type: Z
         boson_mass: 91.1876
         boson_width: 2.4952
         decay: e+e-
      calculation: SCETppV012
      phase_space: PP2BosonJets
      matrix_element_provider: OpenLoops
```

GENEVA's input card

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# Global run options
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   process: pp_V
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   random:
      seed: 1

event_analysis:
   analyzer: DrellYan
```

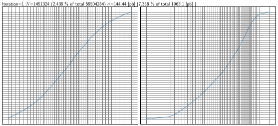
- YAML options: easy to parse by both humans and computers

```
#----------------------------------------
# Calculation
#----------------------------------------

calculation:
   SCETppV012:
      precision: NNLO+NNLL0+NLL1
      scale_settings:
         fixed_order:
#              fixed: 91.1876
            dynamic: TransverseMass
      couplings:
         alpha_s: fromPDF
#         alpha_s:
#              scale: 91.1876
#              value: 0.118
         alpha_em:
            scale: 91.1876
            value: 7.556383906173868E-03
         GF: 1.16639E-05
         sin2W: 0.2226459
```

Results at different stages:

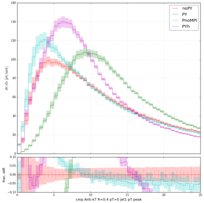
setup Integration grids, splitting function grids, xsec files, etc.



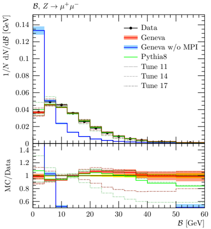
run LHEF event files

```
<event>
6 10006 -2.7706143547e+03 3.7377166023e+00 -1.0000000000e+00 -1.0000000000e+00
  1  -1    0    0  506    0 0.0000000000000000e+00 0.0000000000000000e+00 1.1618
 -1  -1    0    0    0  502 0.0000000000000000e+00 0.0000000000000000e+00 -2.031
-13   1    1    2    0    0 3.8009313823604494e+01 2.2071448444533097e+01 4.6363
 13   1    1    2    0    0 -4.0639739427329552e+01 -2.2146817566638056e+01 5.91
 21   1    1    2  505  502 -1.0798415519664145e-01 -1.0284843446143794e+00 3.93
 21   1    1    2  506  505 2.7384097589216974e+00 1.1038534667193394e+00 1.0058
 #pdf 1  -1 0.1787484980292695 0.0003125410921325 1.0000000000000000 1.00000000
<weights> -2.7706143547e+03 -2.0954201596e+03 -3.5182907785e+03 -2.9394922042e+
7e+03 -2.7706143547e+03 -2.0950507344e+03 -3.5232530892e+03 </weights>
</event>
```

shower Pythia8 output, compressed HEPMC and XML analysis files



rivet Rivet output



Summary and Outlook

GENEVA is the first complete matching of NNLO+NNLL$'$+PS.

- Higher-order resummation of N-jettiness resolution parameter provides a natural link between NNLO and PS.
- Provides theoretical perturbative uncertainties coming from both fixed-order and resummation on a event-by-event basis.

Current status:

- $pp \to \gamma^*/Z \to \ell^+\ell^-$ is completed. It achieves:
  - NNLO+NNLL' accuracy for $0/1$-jet resolution $\mathcal{T}_0$
  - NLO+NLL accuracy for $1/2$-jet resolution $\mathcal{T}_1$
  - Interface to 8 shower+hadronization and MPI

Outlook:

- Public code release soon
- $pp \to W$ at same precision in the pipeline
- Finish up dedicated GENEVA+PYTHIA8 tune
- Other processes (Higgs, VV, HH, etc.) will follow.

Thank you for your attention!

Backup

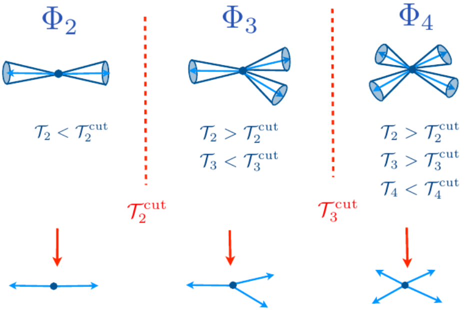
First application: $e^+e^- \to$ jets

- ✓ Simpler process to test our construction.
- ✓ Thrust spectrum known to N³LL'$_{\mathcal{T}}$+ NNLO$_3$.
- ✓ Several 2-jet shapes known to NNLL$_{\mathcal{O}}$+NNLO$_3$.
- ✓ LEP data available for validation.

- Use 2- and 3-jettiness.

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

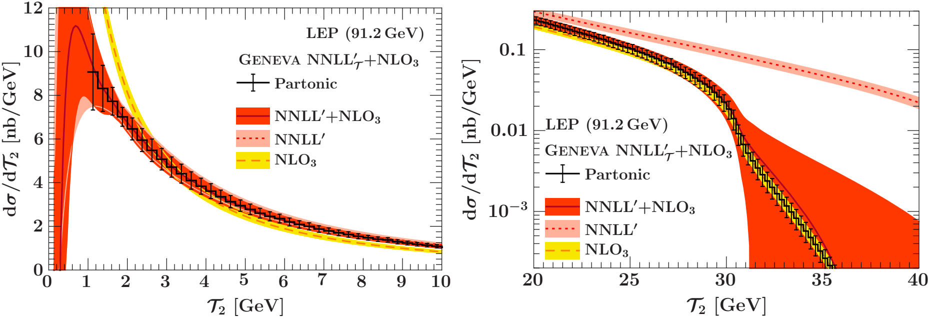
- Opportunely partitioning the phase-space
- Perturbatively calculating NLO/Resumm. jet-cross sections.



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

Resummation of $\mathcal{T}_2$

- GENEVA precisely reproduces full NNLL'+NLO3 analytic result : simply getting out what we put in!



- Error bars are always theory uncertainties, obtained via scale variations. Statistical uncertainties negligible and not shown.
- Resummation unc. obtained via quadrature sum of single scale variations (μ_S, μ_J) inside profile scale bands plus direct sum of FO uncertainties (μ_H).
- GENEVA $\mathcal{T}_2^{\text{cut}} = 1$ GeV above
- Theoretical uncertainties agree across most of the spectrum, differences after kinematic 3-body endpoint consequence of different matching procedure (multiplicative vs. additive).

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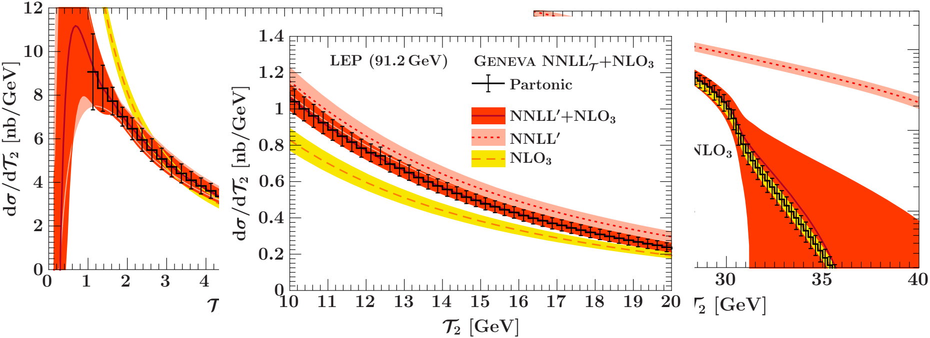

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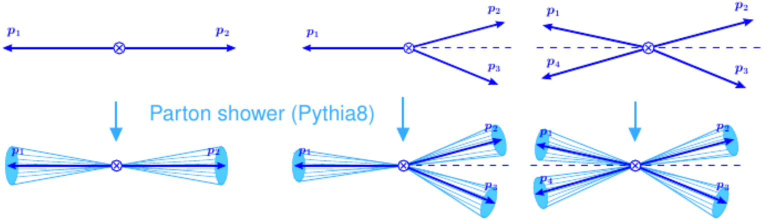
Interface with the parton shower

- The shower must not be allowed to spoil NNLL'$_{\mathcal{T}}$ accuracy of GENEVA, but only used to fill out jets.



- $\mathcal{T}_2$ spectrum for 3 and 4-parton events constrained by higher-order resummation. Only allow small variations $\Delta\mathcal{T}_2 < \mathcal{T}_2^{\text{cut}}(1+\epsilon)$.
- 2-parton events must remain in 2-jets bin, up to small corrections
- Similarly for $\mathcal{T}_3(\Phi_4)$ spectrum and 3-jets bin. Proxy for $\mathcal{T}$-ordered PS.
- Shower unconstrained in the far tail at the moment, since only LO$_4$ there.

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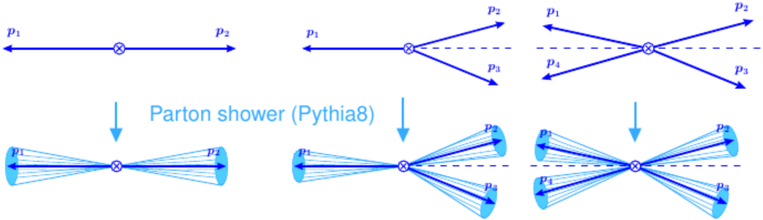

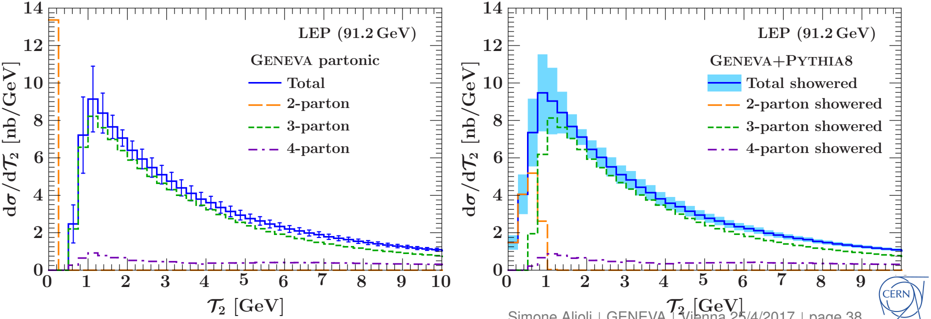

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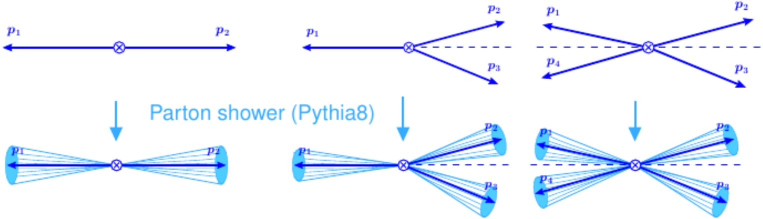
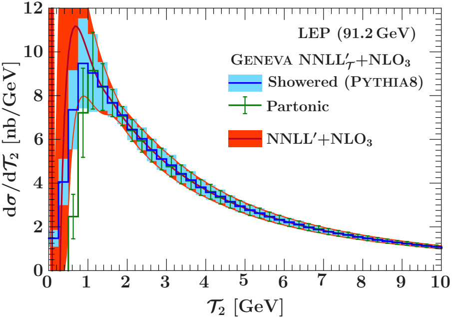
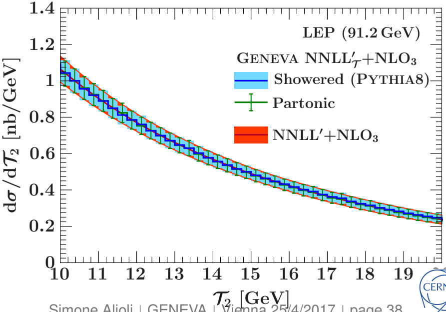
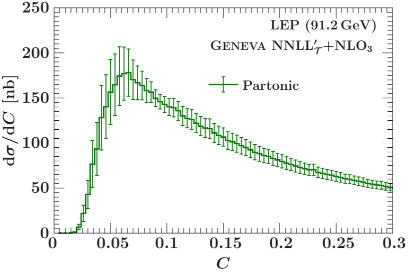


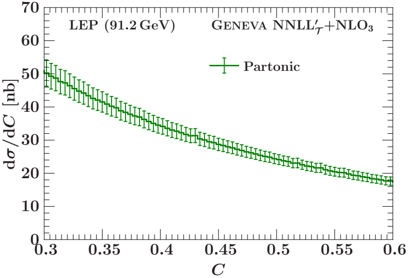




Accuracy of observables different from resolution parameter

- After showering we are formally limited by shower resummation for generic observables $\mathcal{O} \neq \mathcal{T}_{\in}$. 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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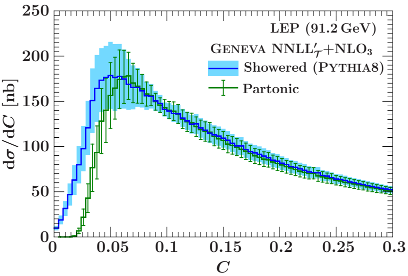

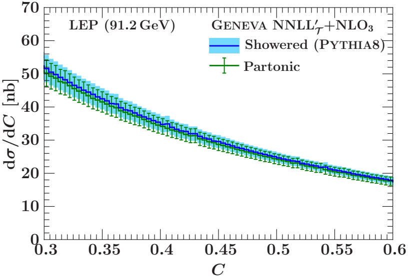

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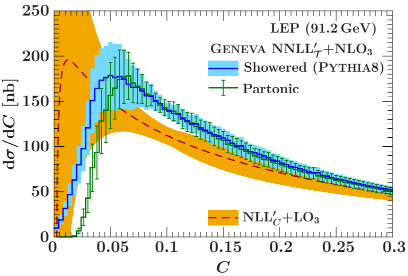

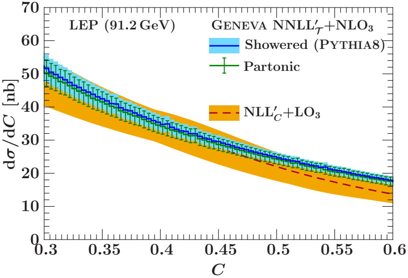

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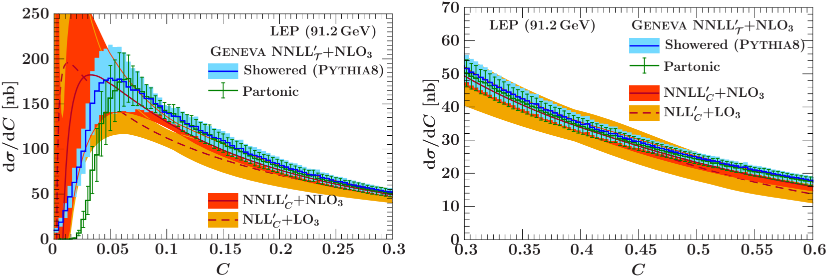
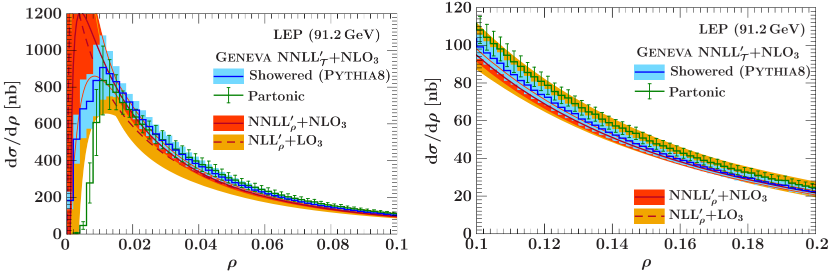


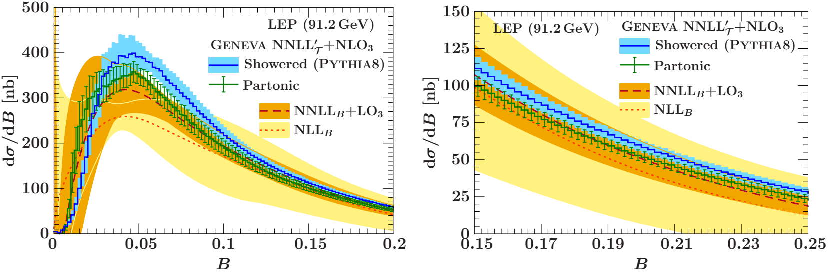
Accuracy of observables different from resolution parameter

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



Accuracy of observables different from resolution parameter

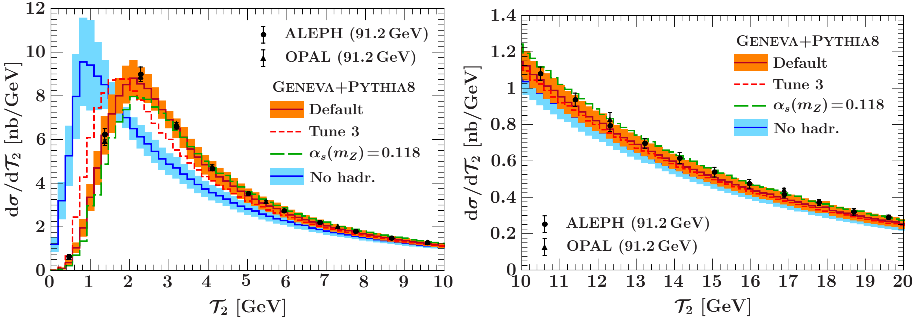
- After showering we are formally limited by shower resummation for generic observables $\mathcal{O} \neq \mathcal{T}_\in$. Naively, (N)LL is expected.
- What is the perturbative accuracy we obtain for other $\mathcal{O}$?
- Jet Broadening – perturbative structure completely different from $\mathcal{T}_2$



- 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.
- Ultimately, we rely on Pythia8 hadronization model for non-pert. physics

Hadronization and comparison with LEP data.

- Two-jettiness $= E_{\rm cm}(1 - T)$



- Hadronization (non-perturbative effect) is unconstrained.
- No ad-hoc tune yet, default Pythia8 Tune1 with $\alpha_s(mZ) = \mathbf{0.1135}$ from τ fits.

[Abbate et al. 1006.3080]

- Large shift due to hadronization, $\mathcal{O}(1)$, in the peak.
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Hadronization and comparison with LEP data.

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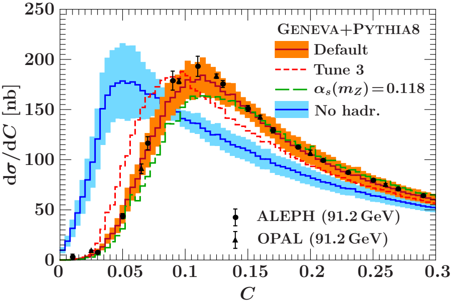

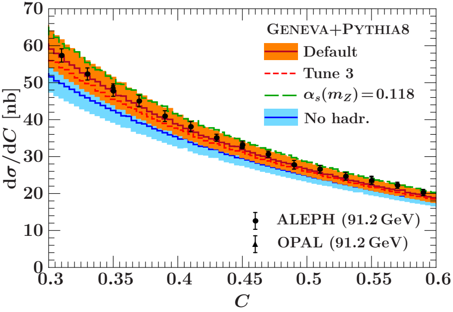

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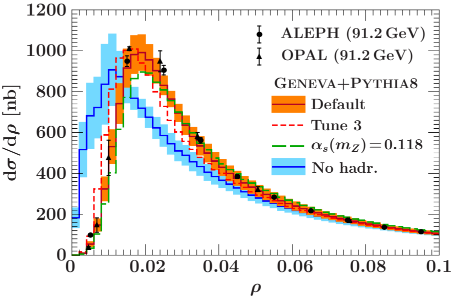

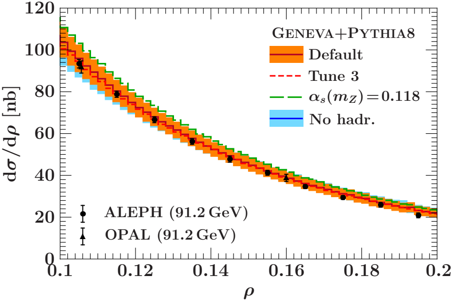

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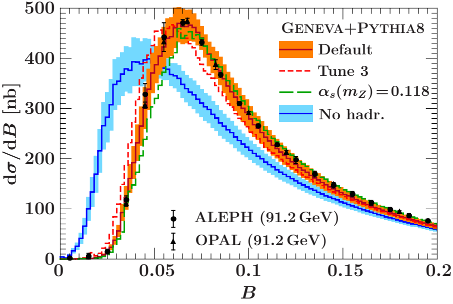

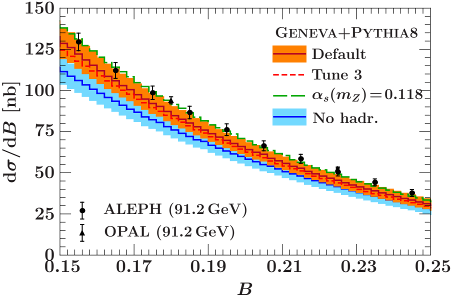

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- NLO accuracy for inclusive sample not achieved in MiNLO v1
  - The reason is that resumming $q_{T\mathrm{cut}}$ with LL Sudakov generates terms $\mathcal{O}(\alpha_{\mathrm{s}}^{1.5})$
- By carefully comparing with NNLL resummation and including missing terms (B_2) in MiNLO Sudakovs, NLO accuracy for inclusive sample can be restored $\to$ MiNLO v2 . [Hamilton et al. 1212.4504]

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- MiNLO v1 is CKKW-inspired recipe to set *a priori* the scales of a NLO calculation involving multiple scales. [Hamilton et al. 1206.3572]
- Like CKKW, it also includes LL Sudakovs factors, that regulate IR divergencies (e.g. H+1 jets finite $p_{\mathrm{T}}^{j} \to 0$)
- NLO accuracy for inclusive sample not achieved in MiNLO v1
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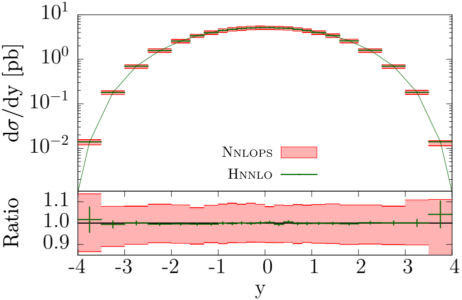
- For simple processes (e.g. $gg \to H$), using HNNLO [Catani et al. 0801.3232] for event-by-event reweighting results in a NNLO+PS [Hamilton,Nason,Re,Zanderighi 1309.0017]

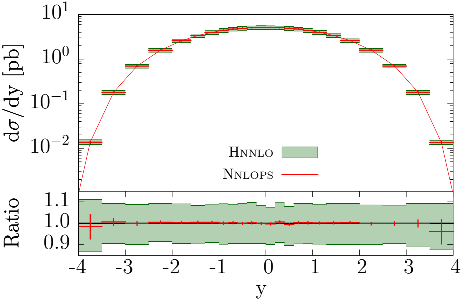
$$\mathcal{W}(y) = \frac{\left(\frac{d\sigma}{dy}\right)_{\mathrm{HNNLO}}}{\left(\frac{d\sigma}{dy}\right)_{\mathrm{HJ-MiNLO}}} = \frac{c_2\alpha_{\mathrm{S}}^2 + c_3\alpha_{\mathrm{S}}^3 + c_4\alpha_{\mathrm{S}}^4}{c_2\alpha_{\mathrm{S}}^2 + c_3\alpha_{\mathrm{S}}^3 + c_4'\alpha_{\mathrm{S}}^4 + \ldots}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

- 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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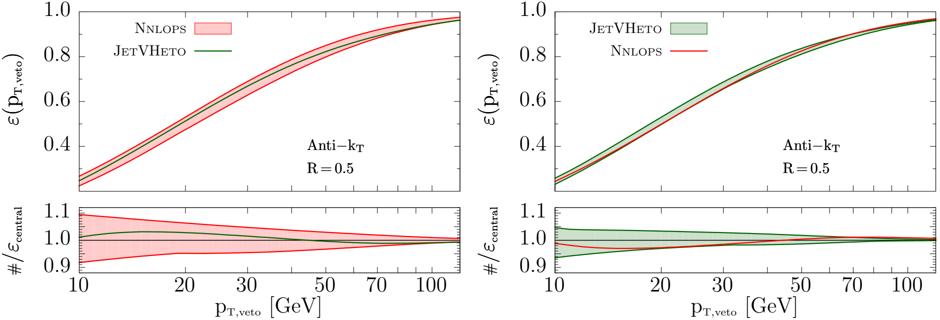

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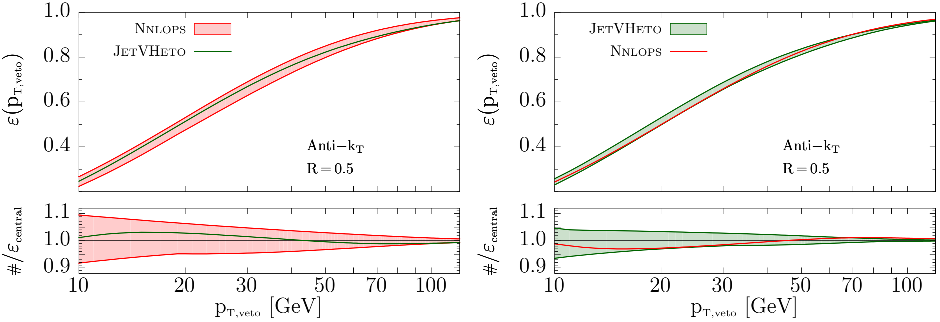
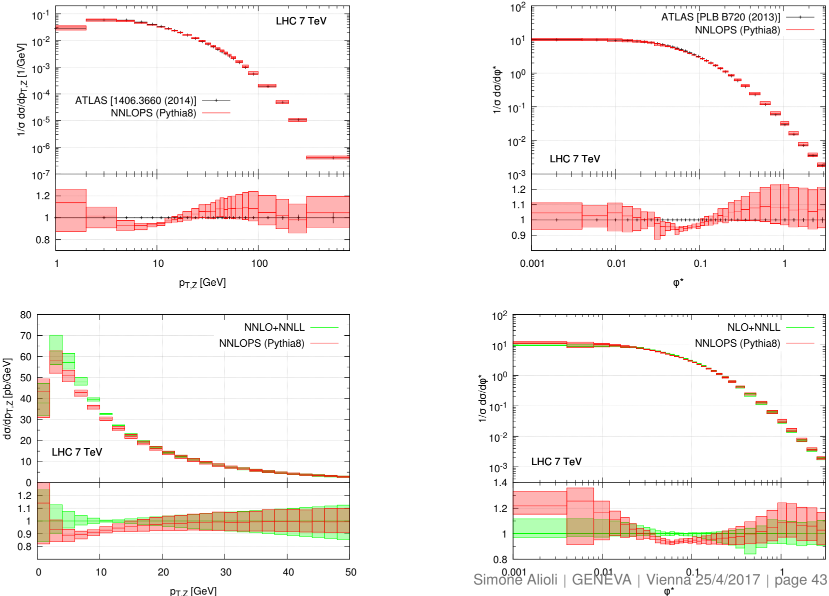


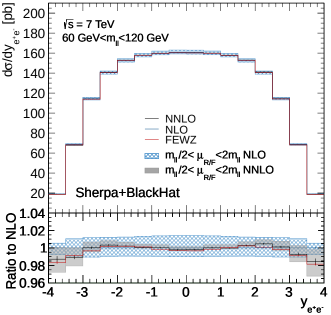
- We have re-derived MiNLO NNLO+PS formula as a check of our framework. It follows directly with a specific choice of splitting functions.
- Alternative choice of splitting functions proposed in [1311.0286] has pros and cons:
  - ✓ No need to know NLL resummation for NNLO+PS
  - ✓ No need to reweight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

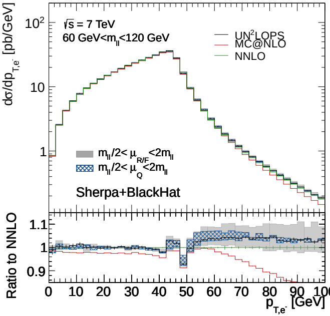
Comparison with existing approaches: MiNLO NNLO+PS.

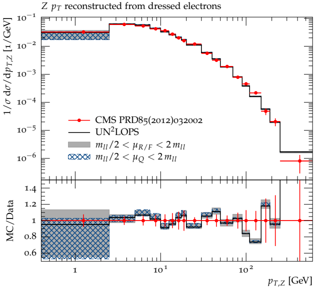
- Also available for Z production [Karlberg et al. 1407.2949]



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