Drell-Yan production at NNLO+NNLL'+PS in GENEVA

Improving shower Monte Carlo event generators with higher-order analytical resummation.

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Future challenges for precision QCD

IPPP - Durham
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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, arXiv:1605.07192

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

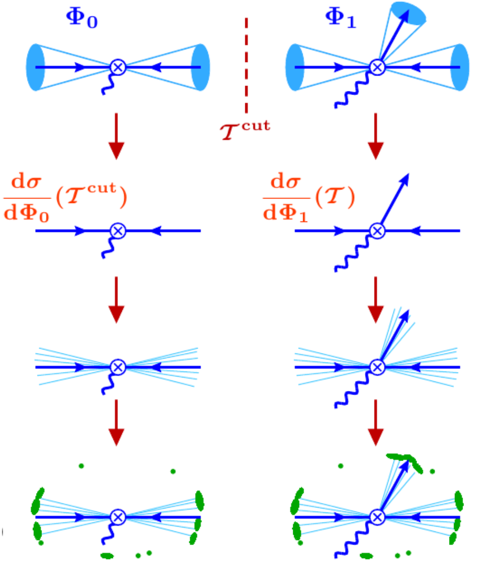
- recycling standard SMC (currently using PYTHIA8)

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

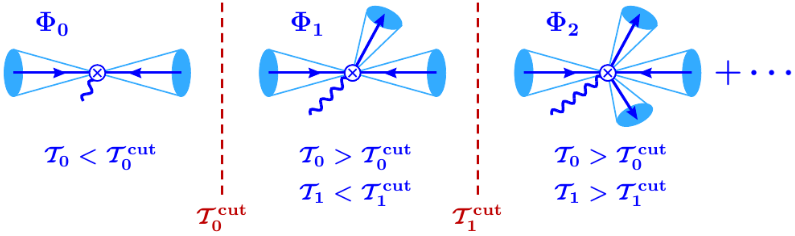
1. Design IR-finite definition of events, based on resolution parameters $\mathcal{T}_N^{\mathrm{cut}}$.
2. Associate differential cross-sections to events such that inclusive jet bins are (N)NLO accurate and jet resolution is resummed at NNLL'$_{\mathcal{T}}$
3. Shower events imposing conditions to 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

IR-safe definitions of events beyond LO

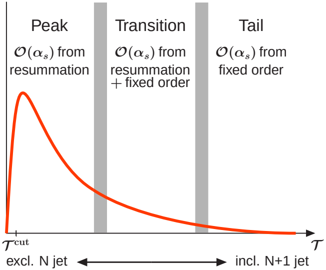
- Only generate "physical events", i.e. events to which one can assign an IR-finite physically-sensible cross section $\mathrm{d}\sigma^{\mathrm{MC}}$.



- 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.
- N-jettiness resolution parameters
  $\mathcal{T}_N \to 0$ for N pencil-like jets (IR limit), $\mathcal{T}_N \gg 0$ is spherical limit.
- 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]

Step 2: Construct NNLO+NNLL’ cross sections

Perturbative accuracy required



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

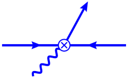
$$
\begin{array}{rcccccccc}
 & & \text{LL}_\sigma & & \text{NLL}_\sigma & & \text{NLL}'_\sigma & & \text{NNLL}_\sigma \\
\dfrac{\sigma(\tau^{\rm cut})}{\sigma_B} = & & 1 & & & & & & \\
+ & \alpha_s [& \frac{c_{11}}{2} L^2_{\rm cut} & + & c_{10} L_{\rm cut} & + & c_{1,-1} & + & F_1(\tau^{\rm cut})] \\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

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

- 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 fixed-order and resummation in GENEVA

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



$$\frac{\mathrm{d}\boldsymbol{\sigma}_{\geq 1}^{\mathrm{MC}}}{\mathrm{d}\boldsymbol{\Phi}_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\boldsymbol{\sigma}_0^{\mathrm{NNLL}'}}{\mathrm{d}\boldsymbol{\Phi}_0 \mathrm{d}\mathcal{T}_0}\theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})\mathcal{P}(\boldsymbol{\Phi}_1) + \frac{\mathrm{d}\boldsymbol{\sigma}_{\geq 1}^{\mathrm{nons}}}{\mathrm{d}\boldsymbol{\Phi}_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

$$\begin{aligned}\frac{\mathrm{d}\sigma_0^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \int_0^{\mathcal{T}_0^{\mathrm{cut}}} \mathrm{d}\mathcal{T}_0 \; \sum_{ij} \frac{\mathrm{d}\sigma_{ij}^B}{\mathrm{d}\Phi_0} H_{ij}(Q^2, \mu_H)\, U_H(\mu_H, \mu) \\ \times \left[B_i(x_a, \mu_B) \otimes U_B(\mu_B, \mu)\right] \times \left[B_j(x_b, \mu_B) \otimes U_B(\mu_B, \mu)\right] \\ \otimes \left[S(\mu_S) \otimes U_S(\mu_S, \mu)\right],\end{aligned}$$

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

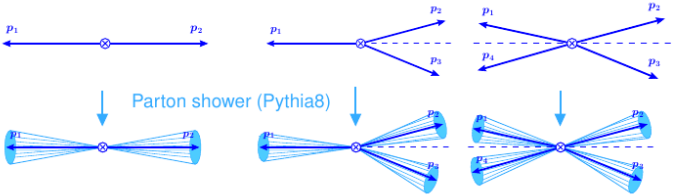
$$\mu_H = Q, \quad \mu_B = \sqrt{Q\mathcal{T}_0}, \quad \mu_S = \mathcal{T}_0$$

- Resummation performed via RGE evolution factors U to a common scale μ.
- Non-singular corrections fixed by matching conditions.

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.
- $\mathcal{T}_k^{\rm cut}$ constraints must be respected.

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

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

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

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

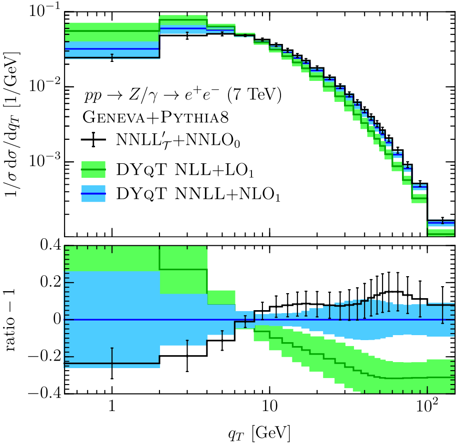
- Λ_N is shower cutoff, much lower than $\mathcal{T}_N^{\rm cut}$.

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, φ^* and jet-veto

- Comparison with DYqT Bozzi et al. arXiv:1007.2351 and BDMT results Banfi et al. arXiv:1205.4760
- Comparison with JetVHeto Banfi et al. 1308.4634
- Analytic NNLL predictions formally higher log accuracy than GENEVA
- Non-perturbative hadronization corrections provided by PYTHIA8
- Non-trivial propagation of spectrum uncertainties to cumulant result.



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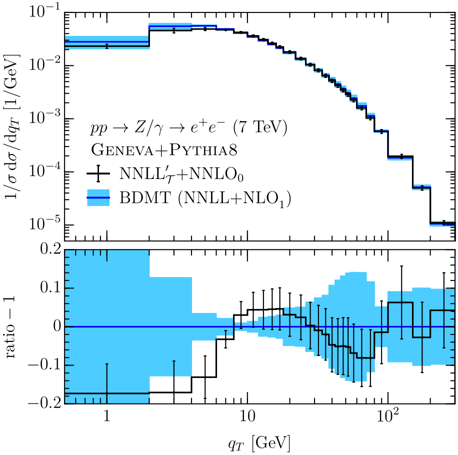

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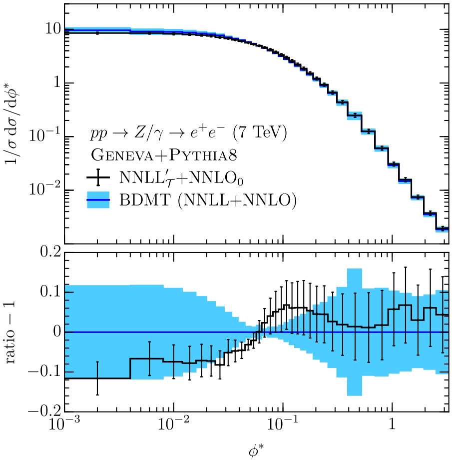

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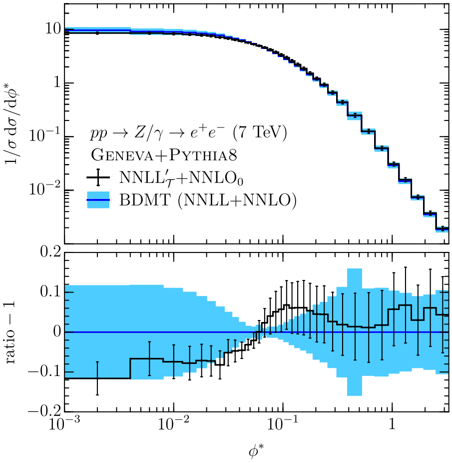
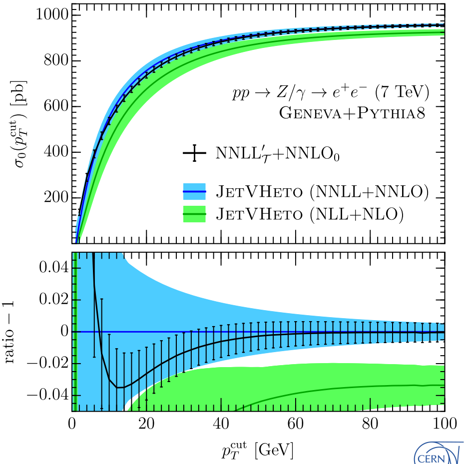
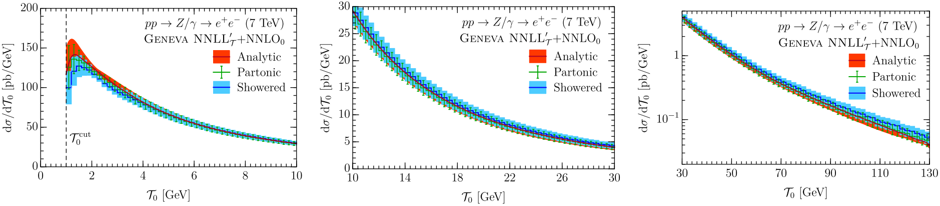




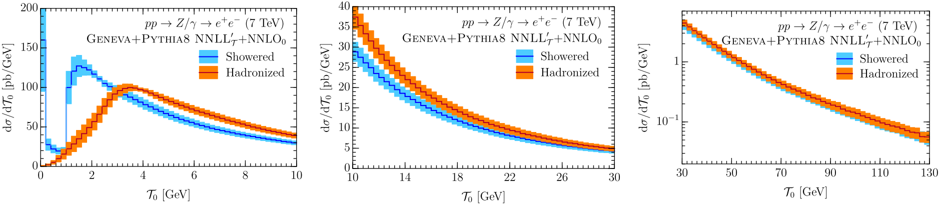
Step 4: Add hadronization and MPI

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.



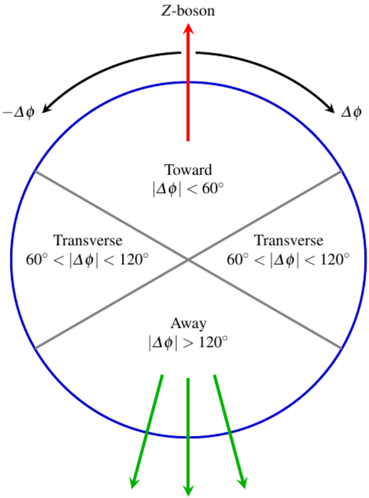
- After hadronization $\mathcal{O}(1)$ shift in peak, tail unchanged: as predicted by factorization.



- Benefit of GENEVA is to obtain nonperturb. corrections directly from PYTHIA8

MPI and underlying-event sensitive observables

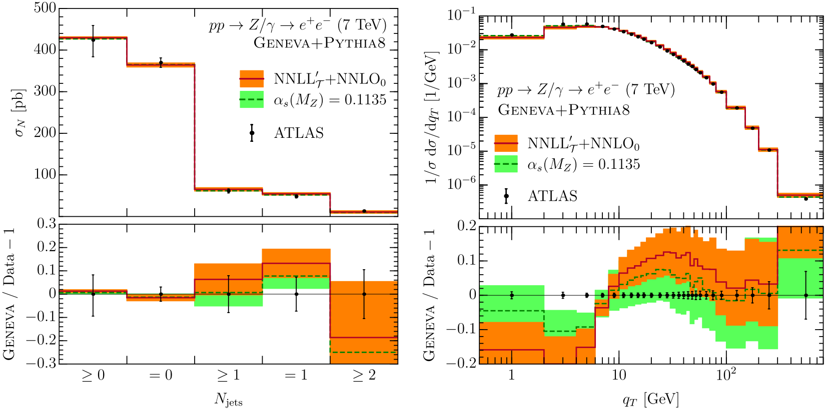
- Underlying event is used to characterize the physics not arising from the primary interaction
- Can receive contributions from small and large energy scales, including multiple parton interactions (MPI)
- Experimentally, studied by looking at the transverse region.
- But higher order effects also often 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.

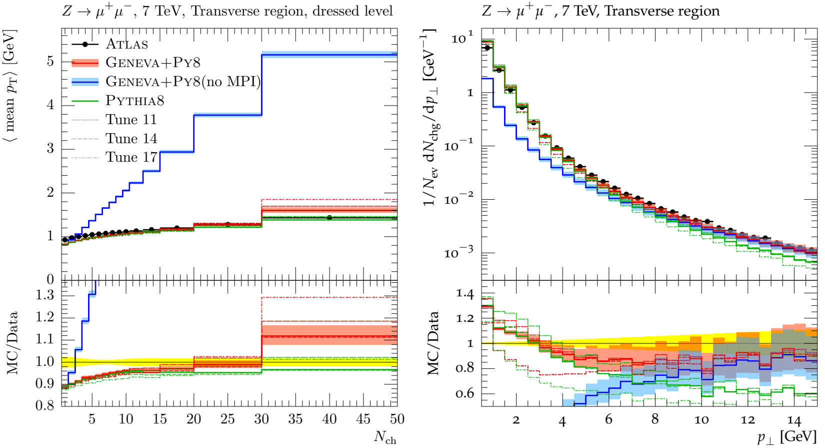
Results and comparisons with data

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. Better agreement with $\alpha_s(M_Z) = 0.1135$ for resummation-sensitive quantities.

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
- Higher-accuracy in GENEVA yields better predictions for increasing Z hardness

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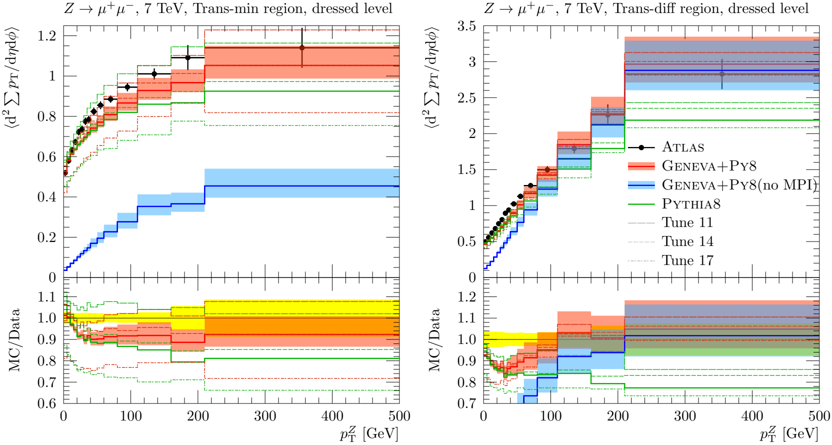

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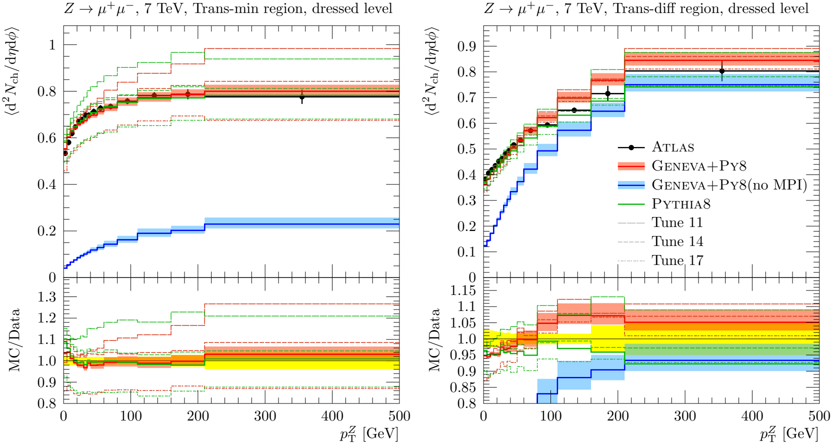

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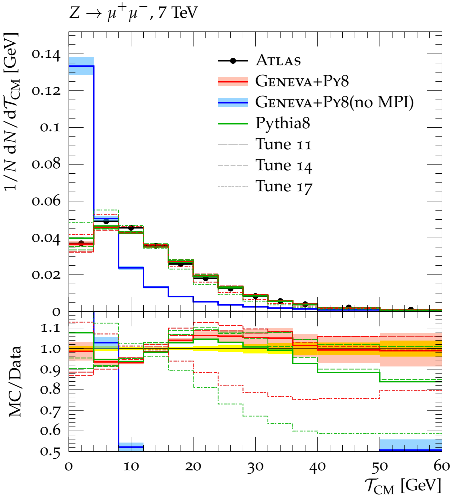
Comparisons with event-shape measurements

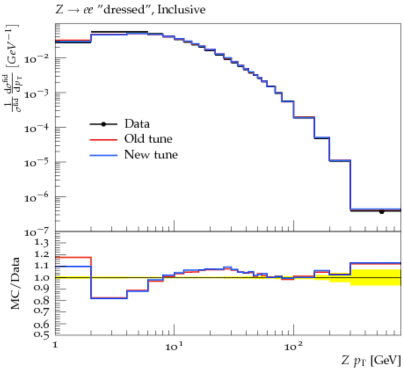
- ATLAS measurements of event-shapes [arXiv:1602.08980] includes Beam-Thrust $\mathcal{T}_{CM}$
- Not exactly the same resolution parameter we are resumming but resummation closely related (only differ in Y_V dependence). Upon integration overe Y_V and matching to FO, distributions found to be nearly 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.

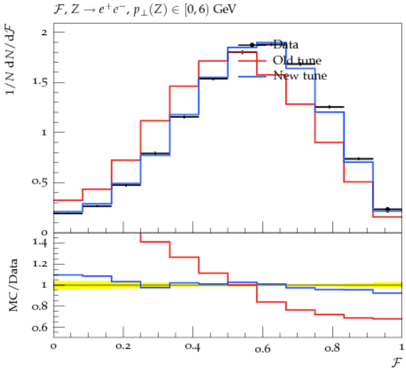


Re-tuning MPI and nonperturbative parameters

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

- Using Drell-Yan data + MPI, both CMS and ATLAS Rivet analyses.
- 2 values of $\alpha_s(M_z)$ explored, 0.118 and 0.1135. Much less freedom given the starting higher accuracy.
- 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.
- Very preliminary results:





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

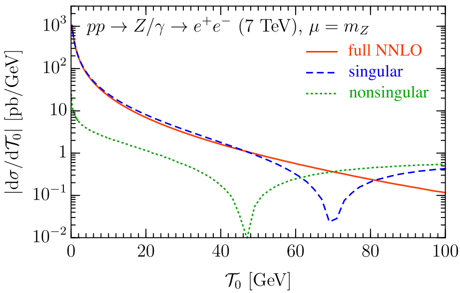
Outlook:

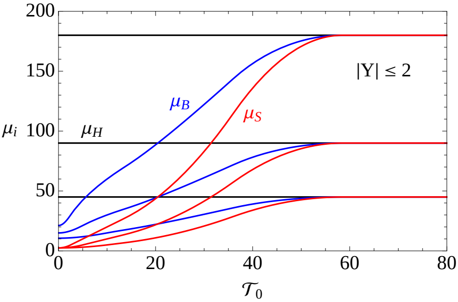
- Public code release
- $pp \to W$ at same precision in the pipeline (likely in first release!)
- Finish up dedicated GENEVA+PYTHIA8 tune
- Other processes (Higgs, VV, HH, etc.) will follow.

Thank you for your attention!

Backup

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 $x \sim 1$

NNLO accuracy in GENEVA

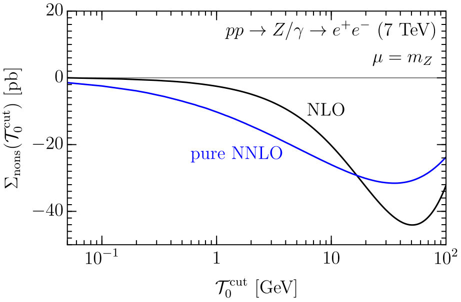
- Resum. expanded result in $\mathrm{d}\sigma_{\geq 1}^{\mathrm{nons}}/\mathrm{d}\Phi_1$ acts as a differential NNLO $\mathcal{T}_0$-subtraction

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

- 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 $\mathrm{d}\mathcal{T}_0\mathrm{d}\Phi_0$.

$$\frac{\mathrm{d}\sigma_0^{\mathrm{nons}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \left[\alpha_s f_1(\mathcal{T}_0^{\mathrm{cut}}, \Phi_0) + \alpha_s^2 f_2(\mathcal{T}_0^{\mathrm{cut}}, \Phi_0)\right]\mathcal{T}_0^{\mathrm{cut}}$$

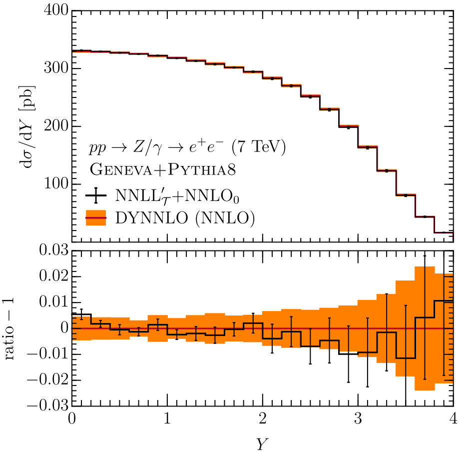
$$\Sigma_{\mathrm{nons}}(\mathcal{T}_0^{\mathrm{cut}}) = \int \mathrm{d}\Phi_0 \frac{\mathrm{d}\sigma_0^{\mathrm{nons}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$$



- 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 $\mathrm{d}\sigma_0^{\mathrm{MC}}/\mathrm{d}\Phi_0(\mathcal{T}_0^{\mathrm{cut}})$.

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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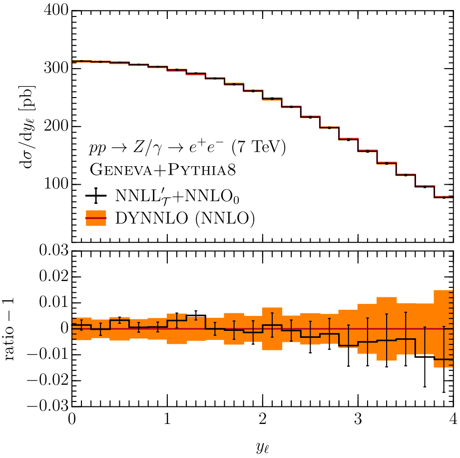
- Non-trivial correlations for outer scales, ad-hoc procedure to ensure exact reproducibility of fixed-order variations.



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, $\mathcal{T}_0^{\rm cut} = 1$. Very good agreement for NNLO quantities, both central scale and variations.
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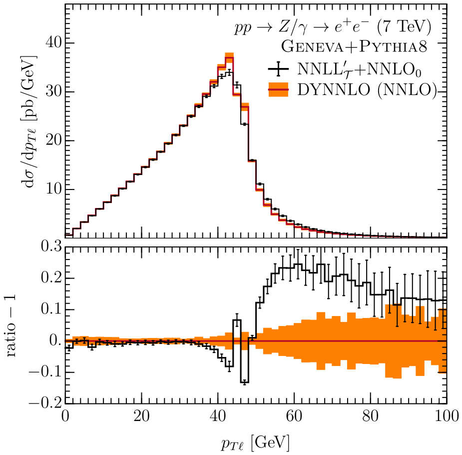

- True NNLO only for $p_{T\ell} < m_{\ell^+\ell^-}/2$. Around $m_{\ell^+\ell^-}/2$ very sensitive to Sudakov shoulder logarithms. GENEVA resumes some of these logs.
- $p_{T\ell} > m_{\ell^+\ell^-}/2$ only NLO. GENEVA results higher than NLO due to spillovers from below $m_{\ell^+\ell^-}/2$ caused by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