Progress with GENEVA

Simone Alioli

ATLAS-CMS Monte Carlo Workshop

CERN - Geneva
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http://geneva.physics.lbl.gov

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

Introduction

GENEVA is Monte Carlo event generator combining 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

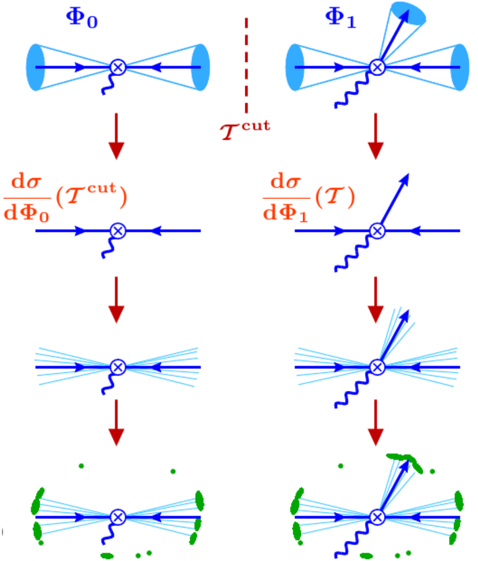
- recycling standard SMC (currently using PYTHIA8)

This provides many advantages:

- consistently improves accuracy of perturbative predictions 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.

GENEVA in a nutshell: Drell-Yan production

1. Design IR-finite definition of events, based on resolution parameters $\mathcal{T}_0^{\mathrm{cut}}$.
2. Associate differential cross-sections to events such that 0-jet events are (N)NLO accurate and $\mathcal{T}_0$ is resummed at NNLL' accuracy
3. Shower events imposing conditions to avoid spoiling NNLL' accuracy reached at step 2
4. Hadronize, add multi-parton interactions (MPI) and decay without further restrictions

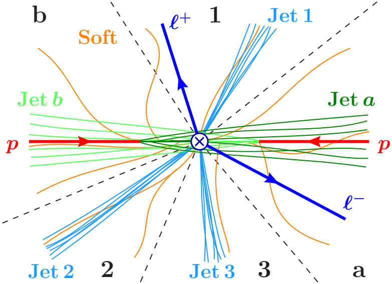


N-jettiness as jet-resolution variable

- GENEVA for Drell-Yan production uses $0-$ and $1-$jettiness as resolution parameter.

- N-jettiness $\mathcal{T}_N$ is a global physical observable with straightforward definition in terms of beams $q_{a,b}$ and jet directions q_j

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



- Important features:
  - $\mathcal{T}_N \to 0$ for N pencil-like jets, $\mathcal{T}_N \gg 0$ in case of hard emission(s).
  - Requiring $\mathcal{T}_N < \mathcal{T}_N^{\text{cut}}$ restricts the jet activity
  - 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]

IR-safe definition of events beyond LO

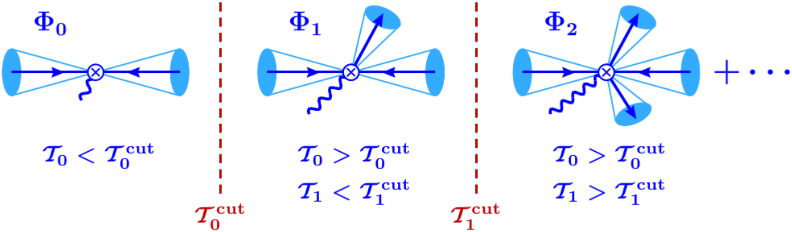
Using 0- and 1-jettiness an IR safe definition of Drell-Yan events with any number of extra emissions can be devised:

- Emissions below $\mathcal{T}_N^{\rm cut}$ are unresolved (i.e. integrated over) and the kinematic considered is the one of the event before the extra emission(s).
- Emissions above $\mathcal{T}_N^{\rm cut}$ are retained and the kinematics is fully specified.

An M-parton event is interpreted as an N-jet event, $N \leq M$, fully differential in Φ_N, without using a standard “jet-algo”

- Price to pay: power corrections in $\mathcal{T}_N^{\rm cut}$ due to PS projection.
- Advantage: vanish for IR-safe observables as $\mathcal{T}_N^{\rm cut} \to 0$

Iterating the procedure, the phase space is sliced into jet-bins



Combining resummation with fixed-order in GENEVA

For Drell-Yan at NNLO provide partonic formulae for up to 2 extra partons.

Combining resummation with fixed-order in GENEVA

For Drell-Yan at NNLO provide partonic formulae for up to 2 extra partons.

- $0-$jet exclusive cross section

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

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

- 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.
- At NNLL' all singular contributions to $\mathcal{O}\left(\alpha_s^2\right)$ already included by definition.
- Two-loop virtual corrections properly spread to nonzero $\mathcal{T}_0$ by resummation.

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

- Nonsingular matching constrained by requirement of NNLO_0 accuracy.
- $\mathrm{d}\sigma_0^{\mathrm{nons}}/\mathrm{d}\Phi_0$ acts as a local 0-jettiness NNLO subtraction

Combining resummation with fixed-order in GENEVA

For Drell-Yan at NNLO provide partonic formulae for up to 2 extra partons.

- $1-$jet inclusive cross section

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

Combining resummation with fixed-order in GENEVA

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

- 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.
- All singular $\mathcal{O}(\alpha_s^2)$ terms again included at NNLL' by definition.

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

- Nonsingular matching fixed by NLO_1 requirement

Combining resummation with fixed-order in GENEVA

For Drell-Yan at NNLO provide partonic formulae for up to 2 extra partons.

- $1-$jet inclusive cross section
- The separation between 1 and 2 jets is determined by the NLL resummation of $\mathcal{T}_1^{\mathrm{cut}}$
  - 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.

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

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

$$\frac{\mathrm{d}\sigma_{\geq 1}^{C}}{\mathrm{d}\Phi_1} = \frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_1} + (B_1 + V_1^C)(\Phi_1) - \left[\frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_1}\right]_{\mathrm{NLO}_1}$$

- The fully differential $\mathcal{T}_0$ information is contained trough $\frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_1}$

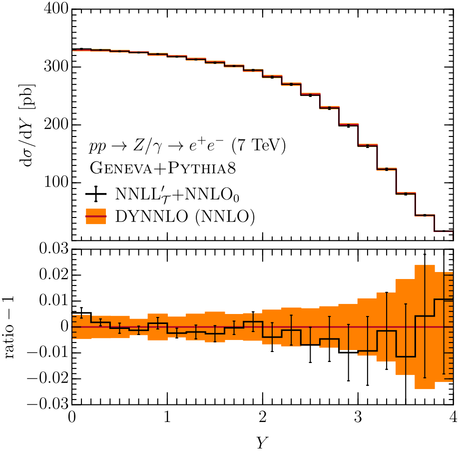
NNLO validation

- 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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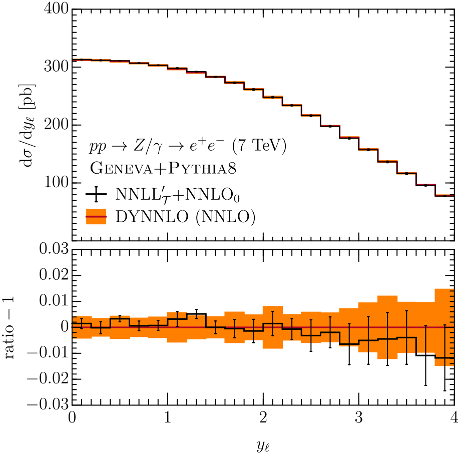

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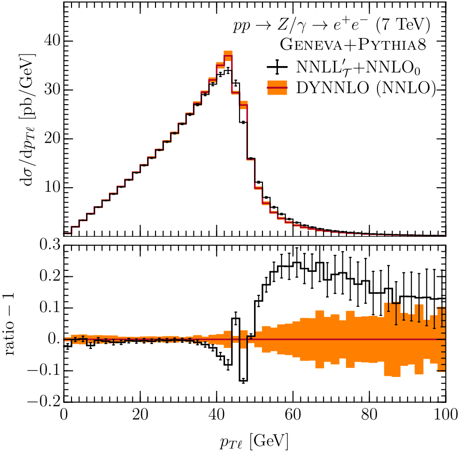
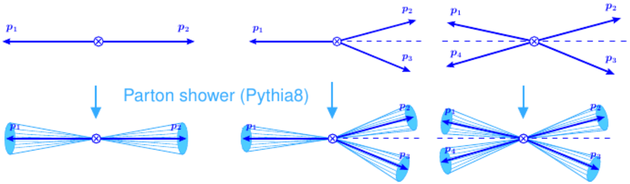


- True NNLO only for $p_{T\ell} < m_{\ell^+\ell^-}/2$. Around $m_{\ell^+\ell^-}/2$ very sensitive to Sudakov shoulder logarithms. GENEVA resumes some of these logs.
- $p_{T\ell} > m_{\ell^+\ell^-}/2$ only NLO. GENEVA results higher than NLO due to spillovers from below $m_{\ell^+\ell^-}/2$ caused by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

Adding the parton shower.

- Purpose of the parton shower is to fill the $0-$ and $1-$jet exclusive bins with radiation and add more emissions to the inclusive $2-$jet bin



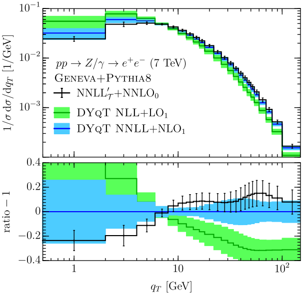
- Not allowed to change accuracy reached at partonic level.
- If shower ordered in N-jettiness setting starting scales is enough.
- For different ordering variable (i.e. any real shower), jet-boundaries constraints $\mathcal{T}_k^{\rm cut}$ need to be imposed on hardest radiation (largest jet resolution scale)
- Impose the first emission has the largest jet resolution scale, by performing a splitting by hand using a NLL $\mathcal{T}_1$ Sudakov and the $\mathcal{T}_0$-preserving map.

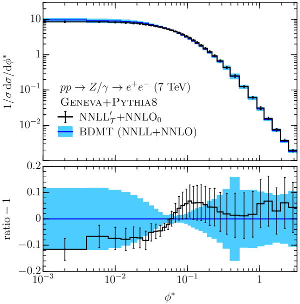
Showering setting starting scales $\mathcal{T}_k^{\rm cut}$ does not spoil NNLL'+NNLO accuracy:

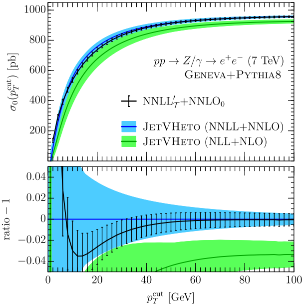
- Φ_0 events only constrained by normalization, shape given by PYTHIA
- Φ_1 events vanish forced to vanish by splitting down to $\Lambda_1 \lesssim 100$ MeV.
- Φ_2 events: PYTHIA showering can be shown to shift $\mathcal{T}_0$ distribution at the same $\alpha_s^3/\mathcal{T}_0$ order of the dominant 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 , BDMT Banfi et al. arXiv:1205.4760 and JetVHeto Banfi et al. 1308.4634
- Analytic NNLL predictions formally higher log accuracy than GENEVA
- PYTHIA8 provides non-perturbative hadronization corrections



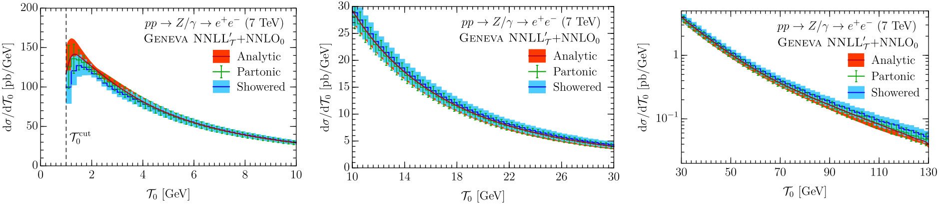




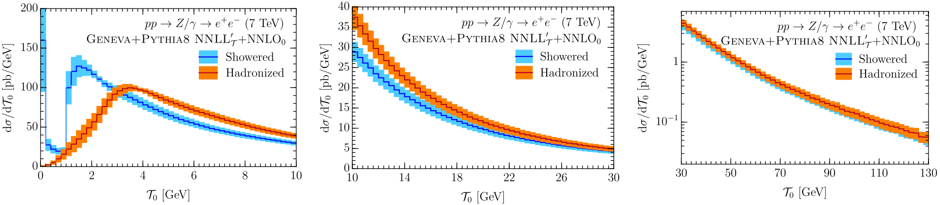
- Very low end highly sensitive to non-pertub. effects, $k_{\rm T}$ smearing.
- Smaller unc. in GENEVA there not necessarily an indication of higher precision.
- No sistematic tuning attempt, nor inclusion of shower uncertainties yet.

Adding hadronization and MPI

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

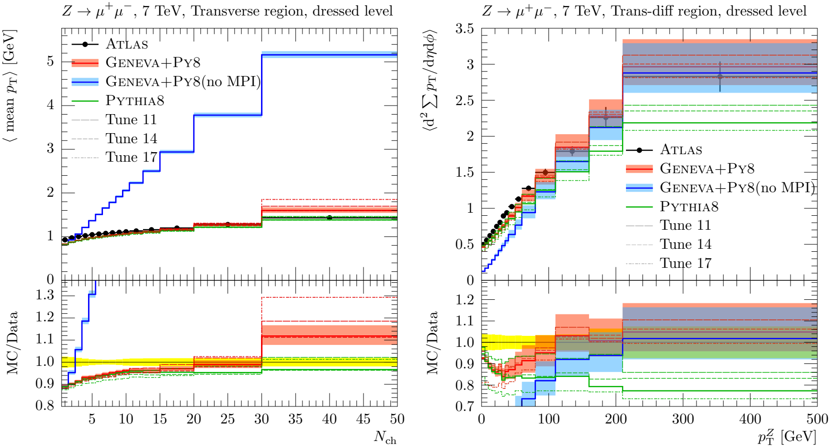


- After hadronization $\mathcal{O}(1)$ shift in peak, tail unchanged: as predicted by factorization.



- Addition of MPI complicated by PYTHIA8 interleaved evolution. Shower constraints only applied to particle arising from primary hard interaction. Secondary interactions unconstrained.

Comparisons with underlying event measurements



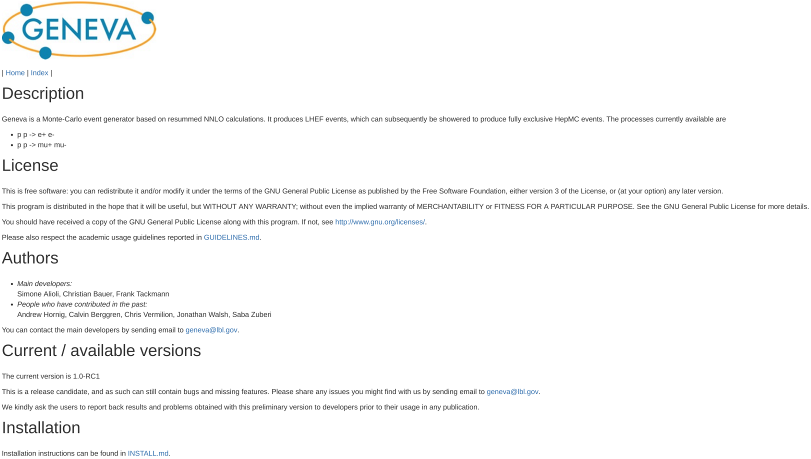
- Both ATLAS and CMS presented studies of UE-sensitive observables in DY

[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

Public code release candidate http://geneva.physics.lbl.gov

- The first release candidate version 1.0-RC1 is publicly available as of Today. Downloadable from DESY git repo or LBNL mirror.



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Description

Geneva is a Monte-Carlo event generator based on resummed NNLO calculations. It produces LHEF events, which can subsequently be showered to produce fully exclusive HepMC events. The processes currently available are

- p p -> e+ e-
- p p -> mu+ mu-

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Authors

- *Main developers:*
  Simone Alioli, Christian Bauer, Frank Tackmann
- *People who have contributed in the past:*
  Andrew Hornig, Calvin Berggren, Chris Vermilion, Jonathan Walsh, Saba Zuberi

You can contact the main developers by sending email to geneva@lbl.gov.

Current / available versions

The current version is 1.0-RC1

This is a release candidate, and as such can still contain bugs and missing features. Please share any issues you might find with us by sending email to geneva@lbl.gov.

We kindly ask the users to report back results and problems obtained with this preliminary version to developers prior to their usage in any publication.

Installation

Installation instructions can be found in INSTALL.md.

- Please report back results and issues at geneva@lbl.gov.
  In return we offer support and advice.

Installation and running

- Installation
  - Instructions in `INSTALL.md` (also online). Needed external packages are either found by CMake or can be specified when in non-standard locations.
  - In extreme cases, CMake can download, compile and install the required external packages.
  - Static PYTHIA8 interface allow to use default PYTHIA8 installations (e.g. from experiments SW frameworks).

- Running
  - User guide available in `doc/UserGuide.md`

- As most NNLO codes, GENEVA needs reasonable parallelization and runtime to produce accurate results.
- We recommend running production runs on medium-size clusters.
- Example runtime for producing events with 1 per mille stat. accuracy in total xsec is 2-3 hours running on 120 cores

- Python interface to steer the running on several systems.
- Running is best organized into 4 separate stages: setup, generate, reweight and shower
- All stages of running can be accessed and managed through the Python interface

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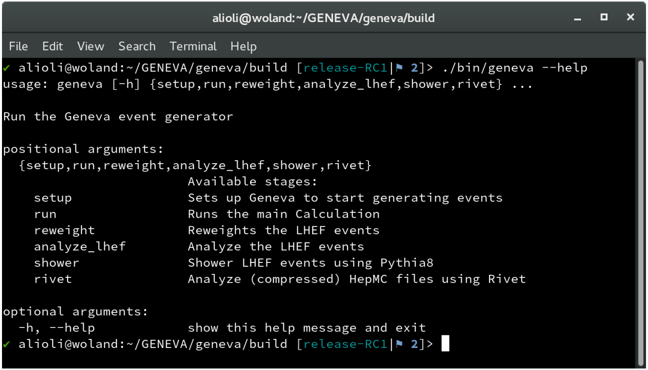
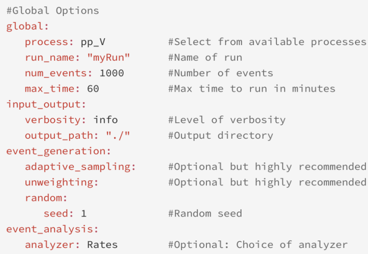


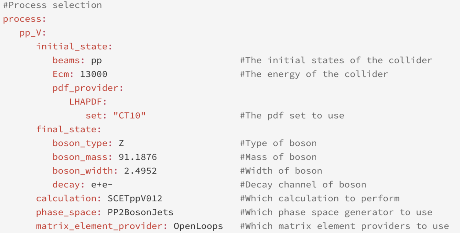
```
✓ alioli@woland:~/GENEVA/geneva/build [release-RC1|⚑ 2]> ./bin/geneva --help
usage: geneva [-h] {setup,run,reweight,analyze_lhef,shower,rivet} ...

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
✓ alioli@woland:~/GENEVA/geneva/build [release-RC1|⚑ 2]> 
```

Options documentation and tutorial

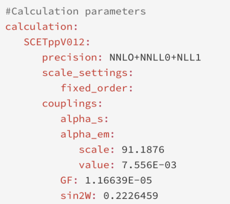
- GENEVA options documented in `doc/OptionsFile.md`
- Needed inputs files are GENEVA (YAML) and PYTHIA8 default option cards.



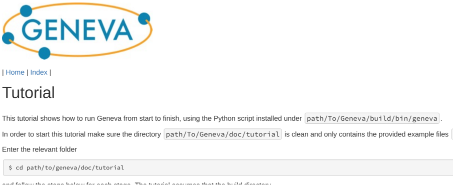
```
#Global Options
global:
   process: pp_V             #Select from available processes
   run_name: "myRun"         #Name of run
   num_events: 1000          #Number of events
   max_time: 60              #Max time to run in minutes
input_output:
   verbosity: info           #Level of verbosity
   output_path: "./"         #Output directory
event_generation:
   adaptive_sampling:        #Optional but highly recommended
   unweighting:              #Optional but highly recommended
   random:
      seed: 1                #Random seed
event_analysis:
   analyzer: Rates           #Optional: Choice of analyzer
```



```
#Process selection
process:
   pp_V:
      initial_state:
         beams: pp                                  #The initial states of the collider
         Ecm: 13000                                 #The energy of the collider
         pdf_provider:
            LHAPDF:
               set: "CT10"                          #The pdf set to use
      final_state:
         boson_type: Z                              #Type of boson
         boson_mass: 91.1876                        #Mass of boson
         boson_width: 2.4952                        #Width of boson
         decay: e+e-                                #Decay channel of boson
      calculation: SCETppV012                       #Which calculation to perform
      phase_space: PP2BosonJets                     #Which phase space generator to use
      matrix_element_provider: OpenLoops            #Which matrix element providers to use
```



```
#Calculation parameters
calculation:
   SCETppV012:
      precision: NNLO+NNLL0+NLL1
      scale_settings:
         fixed_order:
      couplings:
         alpha_s:
         alpha_em:
            scale: 91.1876
            value: 7.556E-03
         GF: 1.16639E-05
         sin2W: 0.2226459
```



Tutorial

This tutorial shows how to run Geneva from start to finish, using the Python script installed under `path/To/Geneva/build/bin/geneva`.

In order to start this tutorial make sure the directory `path/To/Geneva/doc/tutorial` is clean and only contains the provided example files

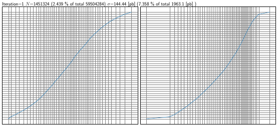
Enter the relevant folder

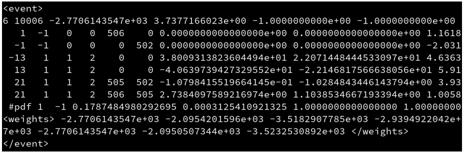
```
$ cd path/to/geneva/doc/tutorial
```

- Complete tutorial to run GENEVA start to finish is available in `doc/tutorial/Tutorial.md`.

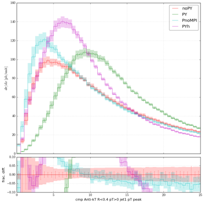
Results and outputs at different stages

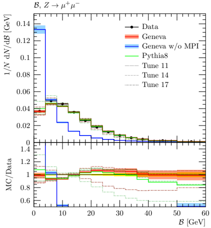
setup	Integration grids, splitting function grids, xsec files, etc.
run	LHEF event files
shower	Pythia8 output and compressed HepMC files. Optionally, internal analyzer files.
rivet	Rivet output





```
<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>
```





Summary and Outlook

GENEVA is the first complete matching of NNLO$_0$+NNLL$'_{\mathcal{T}_0}$+PS.

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

Current status:

- Public release candidate `1.0-RC1`, including $pp \to \gamma^*/Z \to \ell^+\ell^-$ DOWNLOAD
  - NNLO$_0$+NNLL'$_{\mathcal{T}_0}$ accuracy for $0/1$-jet resolution
  - NLO$_1$+NLL$_{\mathcal{T}_1}$ accuracy for $1/2$-jet resolution
  - LO$_2$+PS for 2 or more jets
  - Interface to PYTHIA8 shower+hadronization and MPI

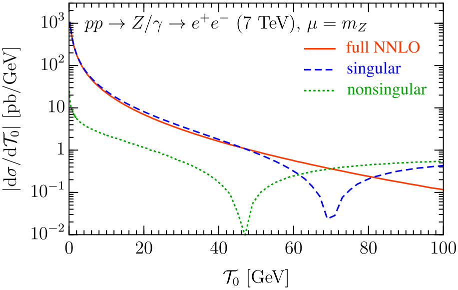
Outlook:

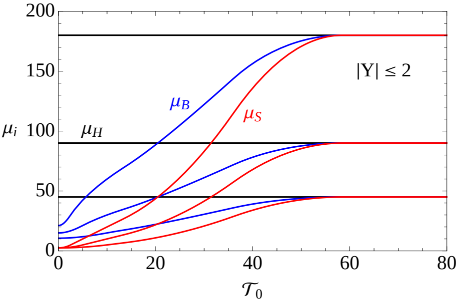
- $pp \to W$ at same precision in the pipeline
- Other processes (Higgs, VV, HH, etc.) will follow.
- Dedicated GENEVA+PYTHIA8 tune

Thank you for your attention and enjoy running GENEVA!

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.

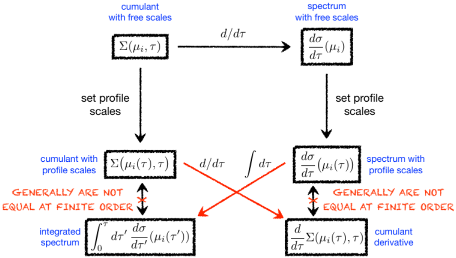
$$\mu_H = \mu_{\rm FO} = M_{\ell^+\ell^-}\,,$$
$$\mu_S(\mathcal{T}_0) = \mu_{\rm FO}\, f_{\rm run}(\mathcal{T}_0/Q)\,,$$
$$\mu_B(\mathcal{T}_0) = \mu_{\rm FO}\sqrt{f_{\rm run}(\mathcal{T}_0/Q)}$$

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

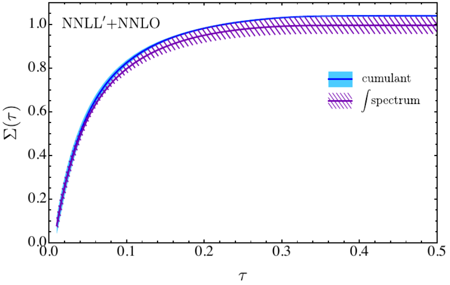
Scale profiles that preserve the total cross-section

- 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



Scale profiles that preserve the total cross-section

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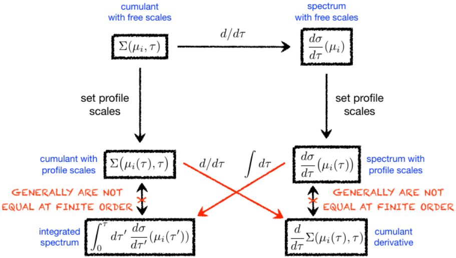


cumulant with free scales

$\Sigma(\mu_i,\tau)$

$d/d\tau$

spectrum with free scales

$\frac{d\sigma}{d\tau}(\mu_i)$

set profile scales

set profile scales

cumulant with profile scales

$\Sigma(\mu_i(\tau),\tau)$

$d/d\tau$

$\int d\tau$

$\frac{d\sigma}{d\tau}(\mu_i(\tau))$

spectrum with profile scales

GENERALLY ARE NOT EQUAL AT FINITE ORDER

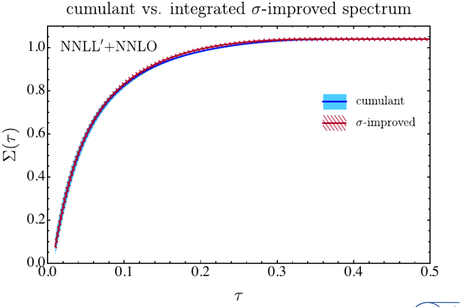
GENERALLY ARE NOT EQUAL AT FINITE ORDER

integrated spectrum

$\int_0^\tau d\tau' \frac{d\sigma}{d\tau'}(\mu_i(\tau'))$

$\frac{d}{d\tau}\Sigma(\mu_i(\tau),\tau)$

cumulant derivative



NNLO accuracy in GENEVA

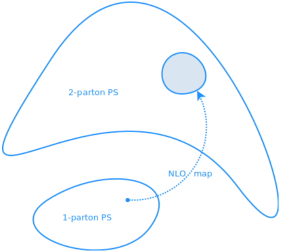
- Resum. expanded result in $\mathrm{d}\sigma^{\mathrm{nons}}_{\geq 1}/\mathrm{d}\Phi_1$ acts as a differential NNLO $\mathcal{T}_0$-subtraction

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

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

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

- 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 $\mathrm{d}\Omega_2$

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

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

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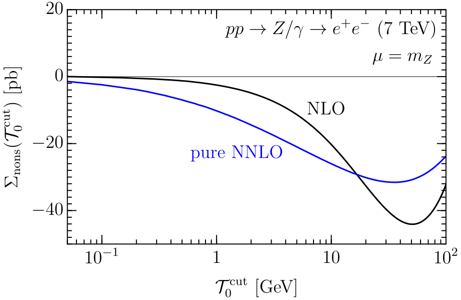
- To be local in $\mathcal{T}_0$ has to reproduce the right singular $\mathcal{T}_0$-dependence when projected onto $\mathrm{d}\mathcal{T}_0\mathrm{d}\Phi_0$.

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

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



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

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

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

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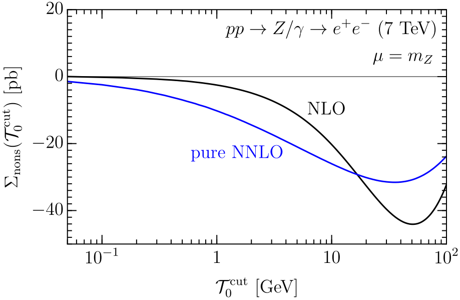
$$\frac{\mathrm{d}\sigma^{\mathrm{nons}}_0}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \big[\alpha_{\mathrm{s}} f_1(\mathcal{T}_0^{\mathrm{cut}},\Phi_0) + \alpha_{\mathrm{s}}^2 f_2(\mathcal{T}_0^{\mathrm{cut}},\Phi_0)\big]\,\mathcal{T}_0^{\mathrm{cut}}$$

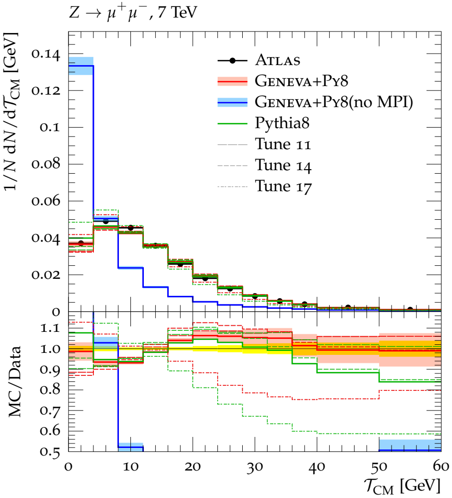
$$\Sigma_{\mathrm{nons}}(\mathcal{T}_0^{\mathrm{cut}}) = \int \mathrm{d}\Phi_0\,\frac{\mathrm{d}\sigma^{\mathrm{nons}}_0}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$$



- 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.
- Leading-power nonsingular recently calculated arXiv:1612.00450,1612.02911. Inclusion under study.

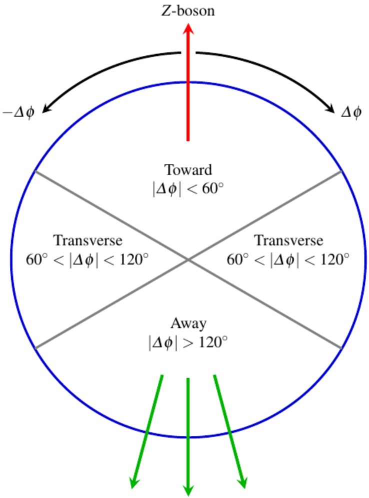
Comparisons with event-shape measurements

- 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.



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.



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: