Drell-Yan Production at NNLO+NNLL′+PS in GENEVA

Frank Tackmann

Deutsches Elektronen-Synchrotron

LHC Physics Discussion
DESY, July 4, 2016

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

S. Alioli, C. Bauer, C. Berggren, A. Hornig, FT, C. Vermilion, J. Walsh, S. Zuberi [JHEP09 (2013) 120]

S. Alioli, C. Bauer, C. Berggren, FT, J. Walsh [PRD92 (2015), 094020]

S. Alioli, C. Bauer, S. Guns, FT [arXiv:1605.07192]

Overview.

GENEVA consistently combines 3 ingredients

1. Fully differential fixed-order calculations
   - up to NNLO (based on N-jettiness subtractions)
2. Higher-order resummation
   - up to NNLL′ using SCET formalism (but not restricted to it)
3. Parton showering and hadronization to "fill out" jets
   - using standard shower MC (currently PYTHIA8)

⇒ NNLO+NNLL′+PS Monte Carlo

Overview.

GENEVA consistently combines 3 ingredients

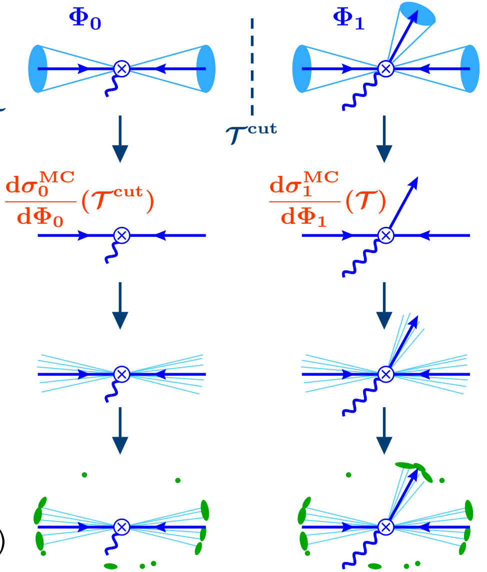
1. Fully differential fixed-order calculations
   - up to NNLO (based on N-jettiness subtractions)
2. Higher-order resummation
   - up to NNLL′ using SCET formalism (but not restricted to it)
3. Parton showering and hadronization to “fill out” jets
   - using standard shower MC (currently PYTHIA8)

⇒ NNLO+NNLL′+PS Monte Carlo

Higher-order resummation

- Provides a natural link between NNLO and PS
- Is key to consistently improve perturbative accuracy outside FO region
- Allows to systematically estimating perturbative uncertainties and correlations (on event-by-event basis)

GENEVA in a Nut Shell.



GENEVA

1. Physical (IR-finite, all-order) definition of events using suitable jet resolution variable $\mathcal{T}$
2. Construct resummed+FO matched MC cross sections at NNLL$'_{\mathcal{T}}$+NNLO

GENEVA–PYTHIA8 interface

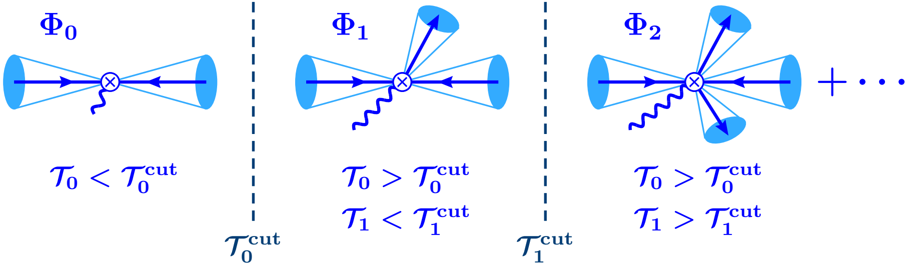
3. Let shower fill out jets with radiation

PYTHIA8

4. Hadronization
5. Additional soft interactions (MPI)

Step 1: Define Physical Events.

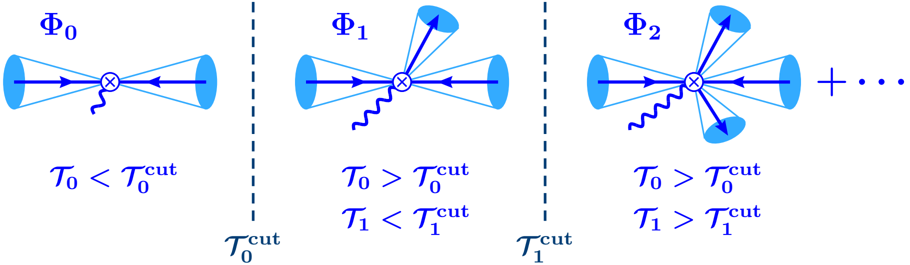
Jet resolution variable $\mathcal{T}$ characterizes the scale of additional emission(s)
(analogous to evolution variable in PS, merging scale/variable in other approaches)



- N-parton event represents an IR-finite physical (idealized) N-jet cross section fully-differential in Φ_N
  - Emissions below $\mathcal{T}_N^{\mathrm{cut}}$ are unresolved (integrated over) and projected onto $\mathcal{T}_{M<N}$ spectra (which are part of Φ_N)
  - In the end take $\mathcal{T}_N^{\mathrm{cut}} \to 0$ (up to small IR cutoff Λ_N)

Step 1: Define Physical Events.

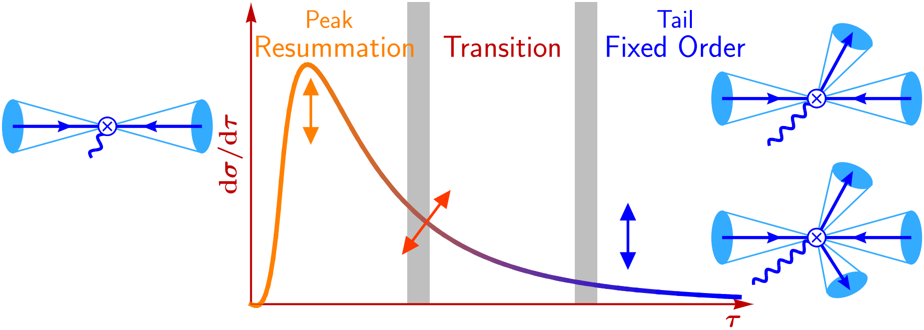
Jet resolution variable $\mathcal{T}$ characterizes the scale of additional emission(s)
(analogous to evolution variable in PS, merging scale/variable in other approaches)



We currently use N-jettiness $\mathcal{T} \equiv \mathcal{T}_N$ [Stewart, FT, Waaelwijn '09, '10]

- Scales with $p^+ = E - |\vec{p}|$ of emissions (virtuality-like)
  - $e^+e^- \to 2/3$ jets: $\mathcal{T} \equiv \mathcal{T}_2$ is equivalent to thrust
  - $pp \to V + 0/1$ jets: $\mathcal{T} \equiv \mathcal{T}_0$ is equivalent to beam thrust
- Factorization and up to NNLL′ resummation in principle known for any N

Step 2: Jet Resolution Spectrum.

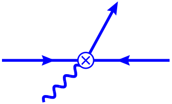


There are no strict boundaries $\rightarrow$ $\mathcal{T}$ spectrum describes transition between 0-jet and ≥ 1-jet regions

- Need consistent treatment of theory uncertainties across entire spectrum
  - *quite nontrivial* because it requires nontrivial correlations (simple factor-2-scale-variation-recipes are not good enough)
- Complete description requires consistent matching of resummation+fixed order
  - Well understood for single-differential spectra to NNLL′+NNLO

Step 2: Combining Resummation and FO.

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



$$\frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{MC}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma_0^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0 \mathrm{d}\mathcal{T}_0}\theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})\mathcal{P}(\Phi_1) + \frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{nons}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

Construct partonic MC cross sections that are fully-differential in Φ_N and reproduce NNLL′+NNLO$_0$ $\mathcal{T}_0$ spectrum

- NNLL′ resummation contains full $\mathcal{O}(\alpha_s^2)$ singular contributions
  - Proper distribution of 2-loop virtuals as dictated by NNLL′ resummation
- Nonsingular corrections are fixed by matching to NNLO$_0$ and NLO$_1$
  - Implementation of differential N-jettiness subtractions

Interlude: Resummation for $\mathcal{T}_0$

Beam thrust/0-jettiness factorization in SCET [Stewart, FT, Waalewijn '09]

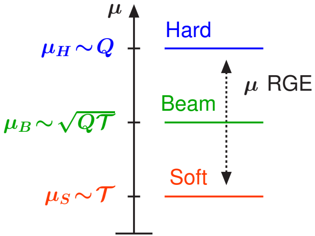
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}_0} = H_{ij}(\mu) \int \mathrm{d}t_a \mathrm{d}t_b \, B_i(t_a, \mu) B_j(t_b, \mu) \, S_{ij}\Big(\mathcal{T}_0 - \frac{t_a + t_b}{Q}, \mu\Big)$$

Logarithms are split apart and resummed using RGE

$$\ln^2 \frac{\mathcal{T}_0}{Q} = 2 \ln^2 \frac{Q}{\mu} - \ln^2 \frac{\mathcal{T}_0 Q}{\mu^2} + 2 \ln^2 \frac{\mathcal{T}_0}{\mu}$$

$\Rightarrow$ Always resums ratios of hard, beam, soft scales

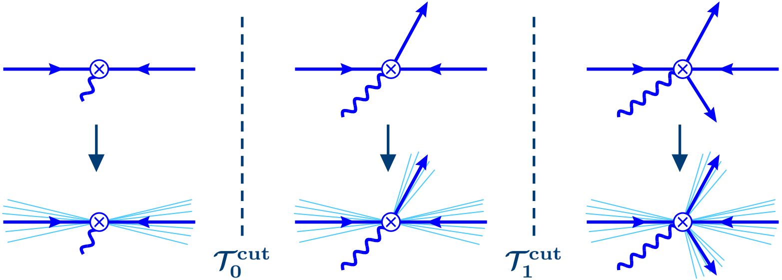
$\mu_H \simeq Q, \quad \mu_B \simeq \sqrt{\mathcal{T}_0 Q}, \quad \mu_S \simeq \mathcal{T}_0$



Resummation is controlled by using $\mathcal{T}_0$-dependent profile scales $\mu_i(\mathcal{T}_0)$
[Ligeti, FT, Stewart '08; Abbate et al. '10; Berger et al. '10; Gangal, Stahlhofen, FT '14]

- Can identify and estimate different sources of perturbative uncertainties using appropriate profile scale variations
- Evaluating MC cross sections for all sets of profile scales gives different weights for each event providing event-by-event pert. uncertainties

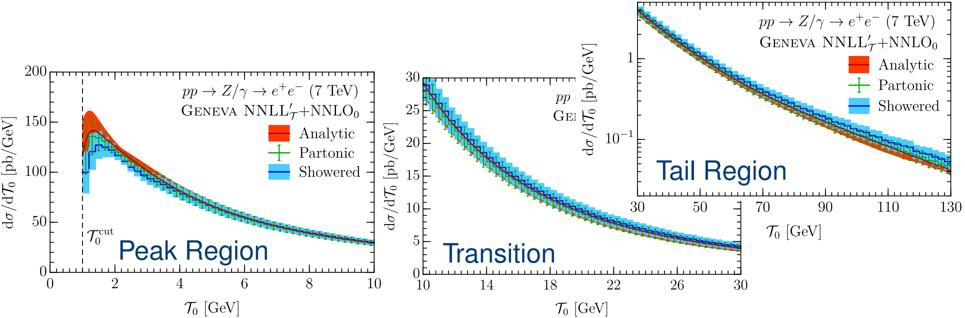
Step 3: Attaching the Parton Shower.



Since the parton shower generates perturbative emissions it should

- fill jets with radiation, i.e., provide unresolved emissions that have been integrated over and projected onto partonic events
- not change resummed jet cross sections
  - Additional showering must not change the jet Φ_N kinematics, in particular $\mathcal{T}_0$, of an event (up to small power corrections)
  - Achieved by taking $\mathcal{T}_{0,1}^{\rm cut}$ as small as possible, first shower emission of Φ_1 events done by GENEVA using $\mathcal{T}_0$-preserving phase-space map
  - Inclusive Φ_2 events further showered by PYTHIA8

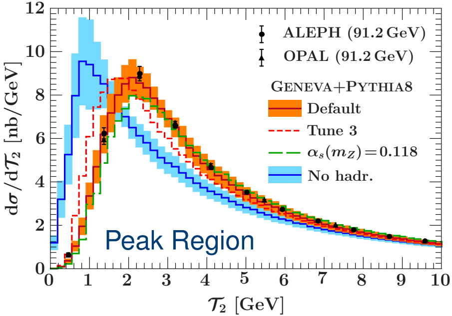
Step 3: Attaching the Parton Shower.

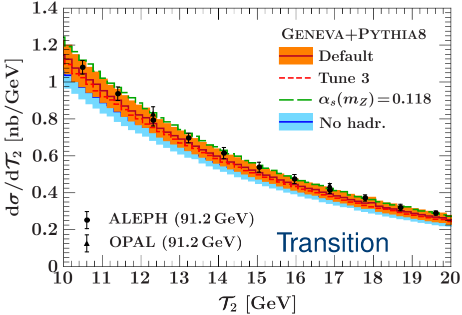


Since the parton shower generates perturbative emissions it should

- fill jets with radiation, i.e., provide unresolved emissions that have been integrated over and projected onto partonic events
- not change resummed jet cross sections
  - Additional showering must not change the jet Φ_N kinematics, in particular $\mathcal{T}_0$, of an event (up to small power corrections)
  - Achieved by taking $\mathcal{T}_{0,1}^{\mathrm{cut}}$ as small as possible, first shower emission of Φ_1 events done by GENEVA using $\mathcal{T}_0$-preserving phase-space map
  - Inclusive Φ_2 events further showered by PYTHIA8

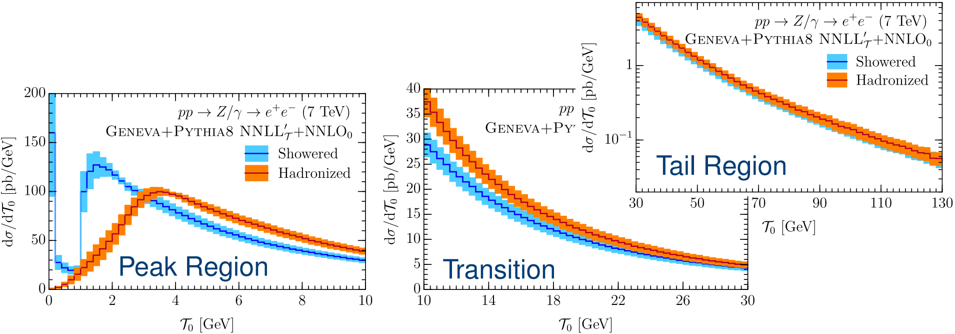
Step 4: Hadronization.





PYTHIA8 hadronization is unconstrained

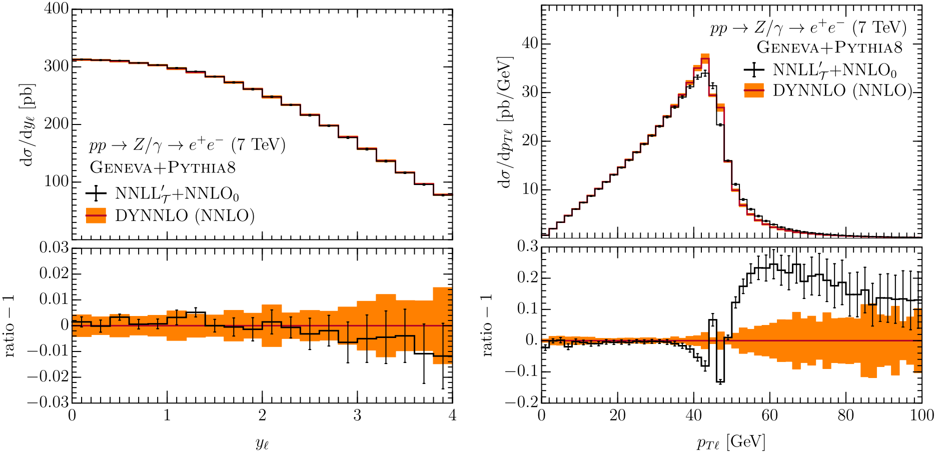
- Observed to behave as expected from field theory and factorization
  - $\mathcal{O}(1)$ effect in nonperturbative peak region at very small $\mathcal{T}$
  - power-suppressed effect at larger $\mathcal{T}$
- With enough pert. information included, tuning becomes equivalent to extracting nonperturbative inputs from data (i.e. what it really should be)
- Can directly utilize PYTHIA8's nonperturbative model together with higher-order resummed calculation



PYTHIA8 hadronization is unconstrained

- Observed to behave as expected from field theory and factorization
  - $\mathcal{O}(1)$ effect in nonperturbative peak region at very small $\mathcal{T}$
  - power-suppressed effect at larger $\mathcal{T}$
- With enough pert. information included, tuning becomes equivalent to extracting nonperturbative inputs from data (i.e. what it really should be)
- Can directly utilize PYTHIA8's nonperturbative model together with higher-order resummed calculation

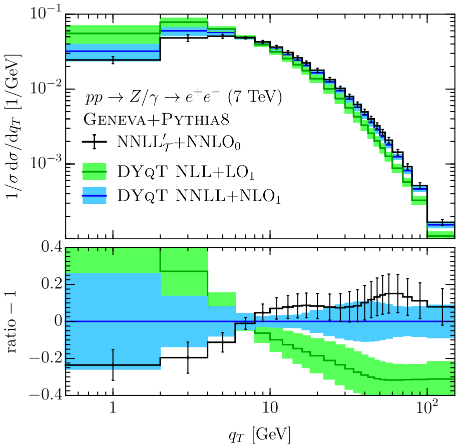
Other observables: FO.



- Validation against DYNNLO [Catani, Grazzini et al. '07, '09]
- True NNLO only for $p_{T\ell} < m_Z/2$, $\gtrsim m_Z/2$ sensitive to resummation effects due to Sudakov shoulder

Other observables: q_T and ϕ^*.

Compare to analytic resummed predictions from DYqT [Bozzi et al., '09, '11]
(each normalized to own total cross section)

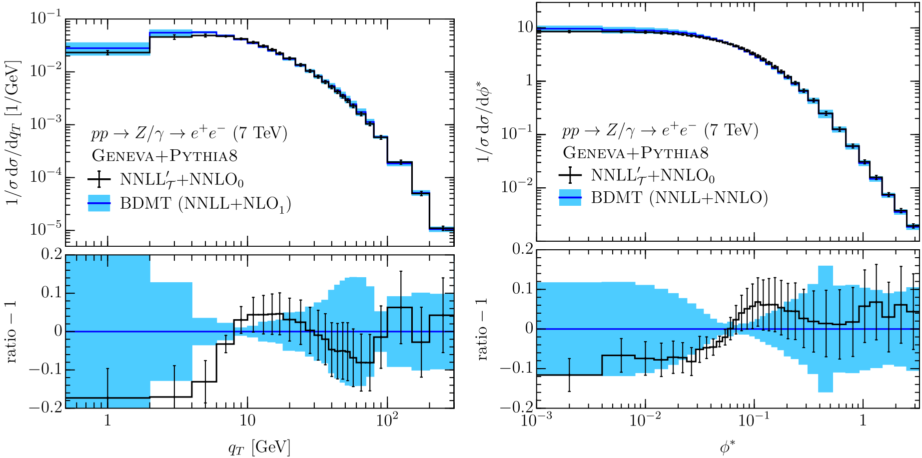


- GENEVA does not have formal NNLL′ accuracy for variables other than $\mathcal{T}_0$ itself
- Pert. improvement still clearly translates to other observables due to fully exclusive description
  - Was also observed for e^+e^-
  - Relies on NLL $\mathcal{T}_1$ resummation and PYTHIA8 showering
  - Smaller GENEVA uncertainties at very small q_T do not imply higher accuracy but are due to lack of uncertainties in $\mathcal{T}_1$ resummation and shower interface

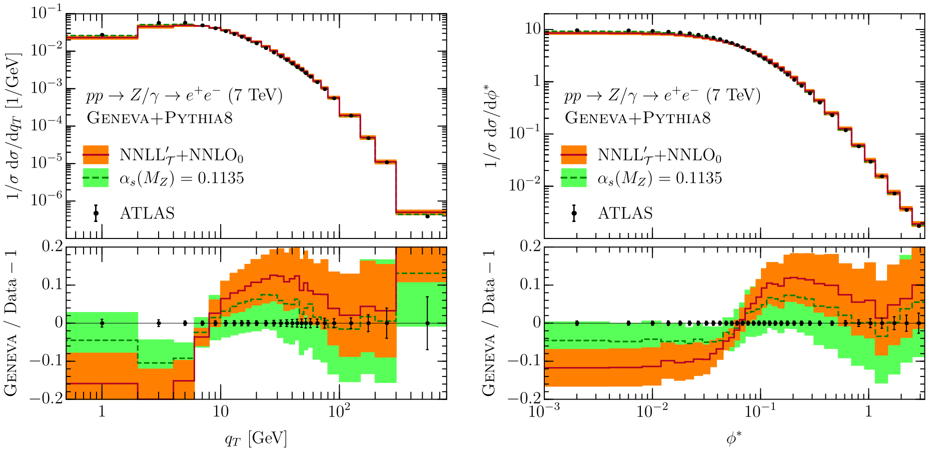
Other observables: q_T and ϕ^*.

Compare to analytic resummed predictions from BDMT [Banfi et al., '12]

(each normalized to own total cross section)

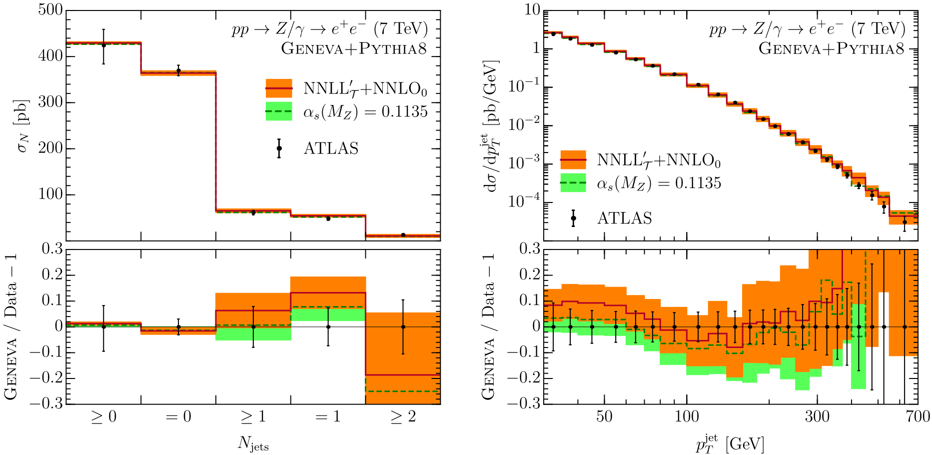


Comparison to Data.



- Essentially out-of-the-box results, no attempt at systematic tuning
  - We do observe reduced sensitivity to PYTHIA8 parameters (as it should be)
- Noticeably better agreement for lower $\alpha_s(M_Z)$
  - Same as seen in e^+e^- with higher-order resummation and hadronization

Comparison to Data.

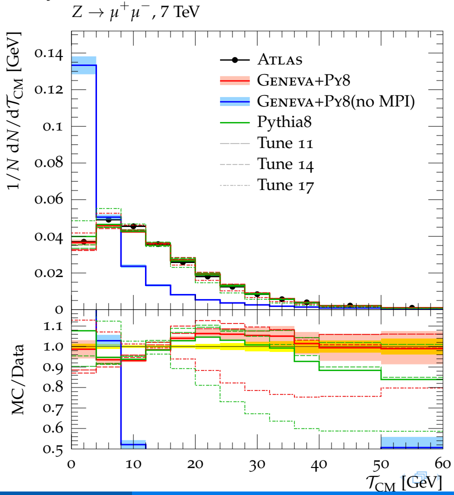


- Essentially out-of-the-box results, no attempt at systematic tuning
  - We do observe reduced sensitivity to PYTHIA8 parameters (as it should be)
- Noticeably better agreement for lower $\alpha_s(M_Z)$
  - Same as seen in e^+e^- with higher-order resummation and hadronization

Step 5: Adding MPI.

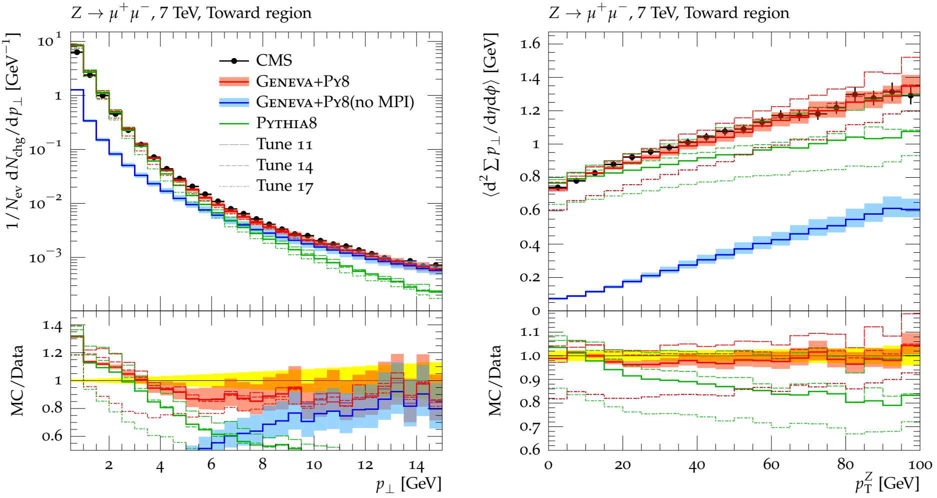
Discussion so far was for the primary hard collision

- Addition of MPI is slightly nontrivial due to PYTHIA8 interleaved evolution
  - Shower conditions are applied to all particles identified as arising from primary hard interaction, while secondary interactions are unconstrained (requires to turn off rescattering)



- Beam thrust/0-jettiness potentially very useful for tuning MPI models
  - Primary perturbative effects are known precisely
  - Should allow to fully disentangle MPI contributions from primary soft ISR
- There has been significant progress on field-theoretic description of MPI
  - Can imagine including this in perturbative input which would then place constraint on MPI model

Traditional UE Measurements in DY.



- Overall GENEVA +PYTHIA8 agrees well PYTHIA8 in low-p_T regions
  - Confirms that PYTHIA8 shower and MPI are not being spoiled by GENEVA
- Clear improvements observed toward larger transverse momenta

Summary and Outlook.

First complete matching of NNLO+NNLL′+PS

- Higher-order resummation of jet resolution variable provides a natural link between NNLO and PS
- Provides systematic estimate of both resummation and FO perturbative uncertainties on event-by-event basis

Current status

- $pp \to \gamma/Z$ is completed
  - NNLL′+NNLO$_0$ for $0/1$-jet resolution $\mathcal{T}_0$
  - NLL+NLO$_1$ for $1/2$-jet resolution $\mathcal{T}_1$
  - Interface to PYTHIA8 shower+hadronization and MPI

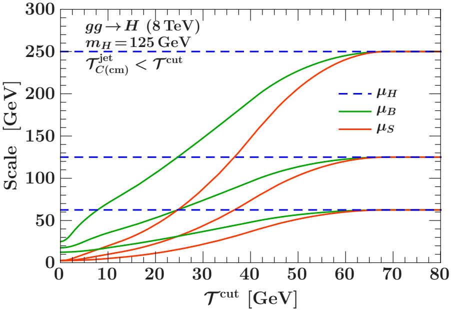
Plans for immediate future

- Currently working on public release
  - Spending significant effort to make the code easy to use as well as easy to extend, stay tuned ...
- $pp \to W$ at same precision is in the pipeline (likely to be part of release)
- Dedicated PYTHIA8 tune for GENEVA
- Further improve and study perturbative inputs and accuracy

Backup Slides

Uncertainties from Profile Scale Variations.

(Illustration for $gg \to H$ at $m_H = 125\,\mathrm{GeV}$)

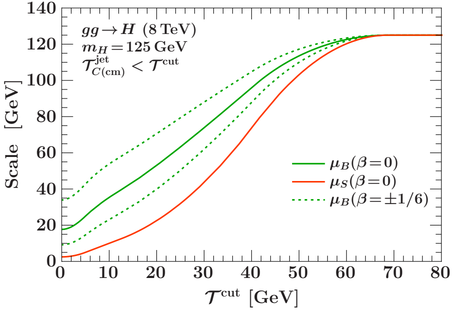


$\Delta_{\mu i}$: Collective overall scale variation

- Leaves all scale ratios and resummed logs invariant and thus corresponds to overall FO uncertainty (within resummed prediction)
- Reproduces usual FO scale variation in inclusive cross section

Uncertainties from Profile Scale Variations.

(Illustration for $gg \to H$ at $m_H = 125\,\mathrm{GeV}$)



Δ_{resum}: Resummation scale variations

- Envelope of separately varying all profile scales for fixed μ_H, μ_{FO} (within canonical constraints), total of six independent variations
- Directly probes size of logs and uncertainties in resummed log series
- Vanishes at large $\mathcal{T}$ as resummation turns off

Perturbative Accuracy.

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

	LL_σ	NLL_σ	NLL'_σ	NNLL_σ		
$\frac{\sigma(\tau^{\rm cut})}{\sigma_B} =$	1					LO_N
$+\ \alpha_s[$	$\frac{c_{11}}{2}L^2_{\rm cut}$	$+\ c_{10}L_{\rm cut}$	$+\ c_{1,-1}$	$+$	$F_1(\tau^{\rm cut})]$	NLO_N
$+\ \alpha_s^2[$	$\vdots$	$+\ \vdots$	$+\ \vdots$	$+\ \vdots$		
$\frac{1}{\sigma_B}\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = \alpha_s/\tau[$	$c_{11}L$	$+\ c_{10}$	$+$		$\tau f_1(\tau)]$	$\text{LO}_\text{N+1}$
$+\ \alpha_s^2/\tau[$	$c_{23}L^3$	$+\ c_{22}L^2$	$+\ c_{21}L$	$+\ c_{20}$	$+\ \tau f_2(\tau)]$	$\text{NLO}_\text{N+1}$
$+\ \alpha_s^3/\tau[$	$\vdots$	$+\ \vdots$	$+\ \vdots$	$+\ \vdots$		

Lowest perturbative accuracy at all $\mathcal{T}$ requires (N)LL_σ+$\text{LO}_\text{N+1}$

→ Provided by ME/PS: CKKW, MLM (except PS might not get full NLL_σ)

→ LO_N is naturally part of LL_σ and so automatically included

Perturbative Accuracy.

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

$$
\begin{array}{rcccccl}
 & \text{LL}_\sigma & \text{NLL}_\sigma & \text{NLL}'_\sigma & \text{NNLL}_\sigma & & \\
\dfrac{\sigma(\tau^{\mathrm{cut}})}{\sigma_B} = & 1 & & & & & \text{LO}_\text{N} \\
+ \alpha_s \big[& \frac{c_{11}}{2} L_{\mathrm{cut}}^2 & + c_{10} L_{\mathrm{cut}} & + c_{1,-1} & + & F_1(\tau^{\mathrm{cut}}) \big] & \text{NLO}_\text{N} \\
+ \alpha_s^2 \big[& \vdots & + \vdots & + \vdots & + \vdots & & \\
\dfrac{1}{\sigma_B}\dfrac{\mathrm{d}\sigma}{\mathrm{d}\tau} = \alpha_s/\tau \big[& c_{11} L & + c_{10} & + & & \tau f_1(\tau) \big] & \text{LO}_{\text{N+1}} \\
+ \alpha_s^2/\tau \big[& c_{23} L^3 & + c_{22} L^2 & + c_{21} L & + c_{20} & + \tau f_2(\tau) \big] & \text{NLO}_{\text{N+1}} \\
+ \alpha_s^3/\tau \big[& \vdots & + \vdots & + \vdots & + \vdots & &
\end{array}
$$

NLO+PS matching (MC@NLO, POWHEG) adds full NLO_N to $\sigma(\tau^{\mathrm{cut}})$

→ Improves accuracy for $\sigma(\tau^{\mathrm{cut}} \sim 1)$ to NLO

→ Does *not* improve accuracy of spectrum

Perturbative Accuracy.

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

	LL$_\sigma$	NLL$_\sigma$	NLL$'_\sigma$	NNLL$_\sigma$		
$\dfrac{\sigma(\tau^{\mathrm{cut}})}{\sigma_B} =$	1					LO$_\mathrm{N}$
$+\ \alpha_s\big[$	$\frac{c_{11}}{2}L^2_{\mathrm{cut}}$	$+\ c_{10}L_{\mathrm{cut}}$	$+\ c_{1,-1}$	$+$	$F_1(\tau^{\mathrm{cut}})\big]$	NLO$_\mathrm{N}$
$+\ \alpha_s^2\big[$	$\vdots$	$+\ \vdots$	$+\ \vdots$	$+\ \vdots$		
$\dfrac{1}{\sigma_B}\dfrac{d\sigma}{d\tau} = \alpha_s/\tau\big[$	$c_{11}L$	$+\ c_{10}$	$+$		$\tau f_1(\tau)\big]$	LO$_{\mathrm{N+1}}$
$+\ \alpha_s^2/\tau\big[$	$c_{23}L^3$	$+\ c_{22}L^2$	$+\ c_{21}L$	$+\ c_{20}$	$+\ \tau f_2(\tau)\big]$	NLO$_{\mathrm{N+1}}$
$+\ \alpha_s^3/\tau\big[$	$\vdots$	$+\ \vdots$	$+\ \vdots$	$+\ \vdots$		

Relative $\mathcal{O}(\alpha_s)$ accuracy at all $\mathcal{T}$ requires NNLL$_\sigma$+NLO$_{\mathrm{N+1}}$

$\rightarrow$ NLO$_\mathrm{N}$ is now naturally part of NLL$'_\sigma$ and automatically included

$\rightarrow$ similarly NNLO$_\mathrm{N}$ is naturally part of NNLL$'_\sigma$

Resummation Order Counting.

Resummation is really performed in the exponent of the cross section with counting $\alpha_s L \sim 1$

$$\sigma \sim \left[1 + \alpha_s + \alpha_s^2 + \cdots\right] \exp\left[\sum_n \alpha_s^n L^{n+1} (1 + \alpha_s + \alpha_s^2 + \cdots)\right]$$

$$\sim \quad \text{LL} + \text{NLL} + \text{NNLL} + \cdots$$

Default conventions:

	Fixed-order corrections		Resummation input		
	singular	nonsingular	γ_x	Γ_{cusp}	β
NLL	1	-	1-loop	2-loop	2-loop
NLL′+NLO	α_s	α_s	1-loop	2-loop	2-loop
NNLL′+NNLO	α_s^2	α_s^2	2-loop	3-loop	3-loop