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

Frank Tackmann

Deutsches Elektronen-Synchrotron

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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

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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

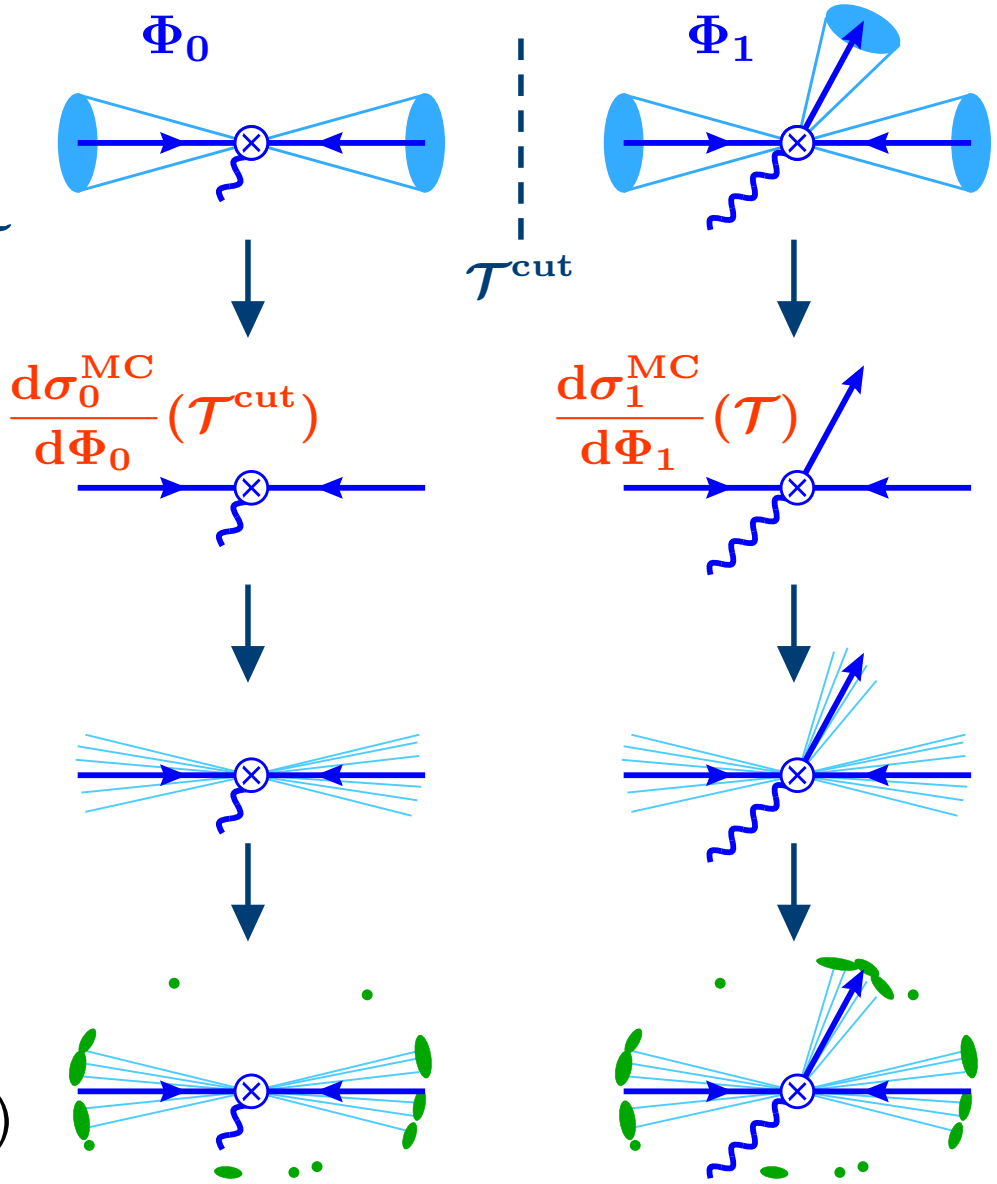
1. Physical (IR-finite, all-order) definition of events using suitable jet resolution variable $\mathcal{T}$
2. Construct resummed+FO matched MC cross sections at NNLL$'_{\mathcal{T}}$+NNLO

GENEVA–PYTHIA8 interface

3. Let shower fill out jets with radiation

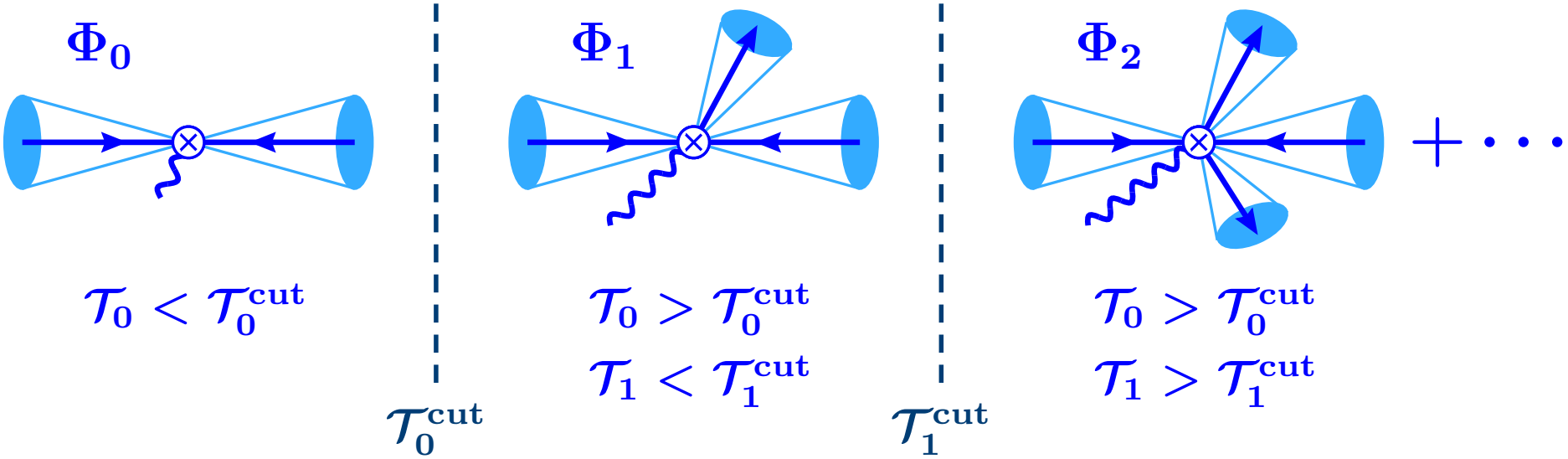
PYTHIA8

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 $\mathcal{T}_N^{\rm cut}$ are unresolved (integrated over) and projected onto $\mathcal{T}_{M<N}$ spectra (which are part of Φ_N)
  - In the end take $\mathcal{T}_N^{\rm cut} \to 0$ (up to small IR cutoff Λ_N)

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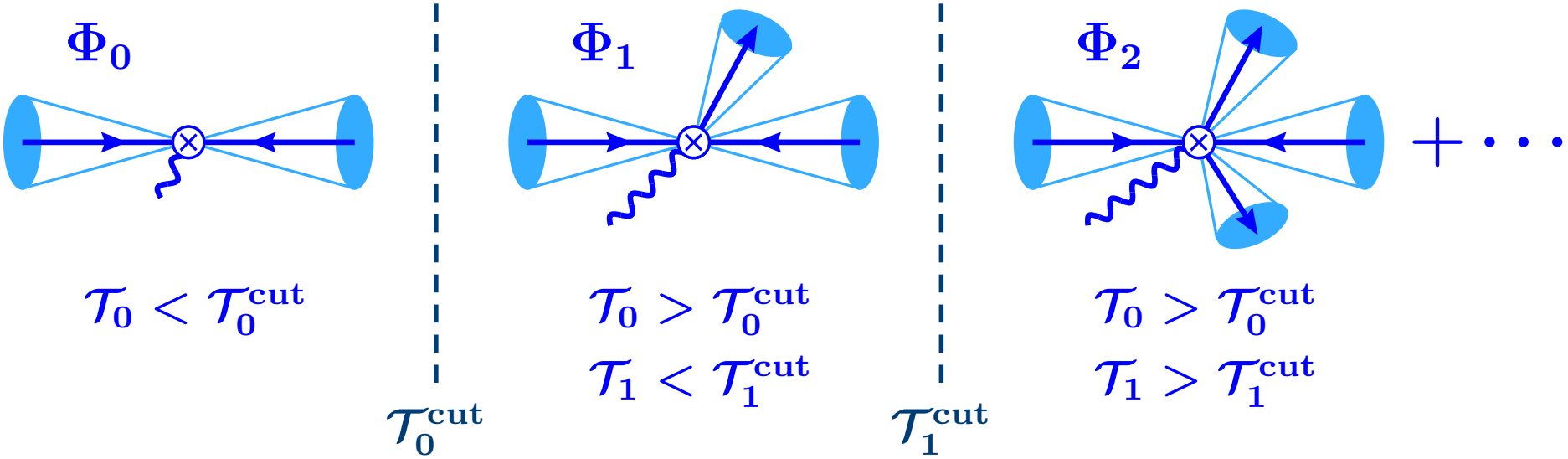
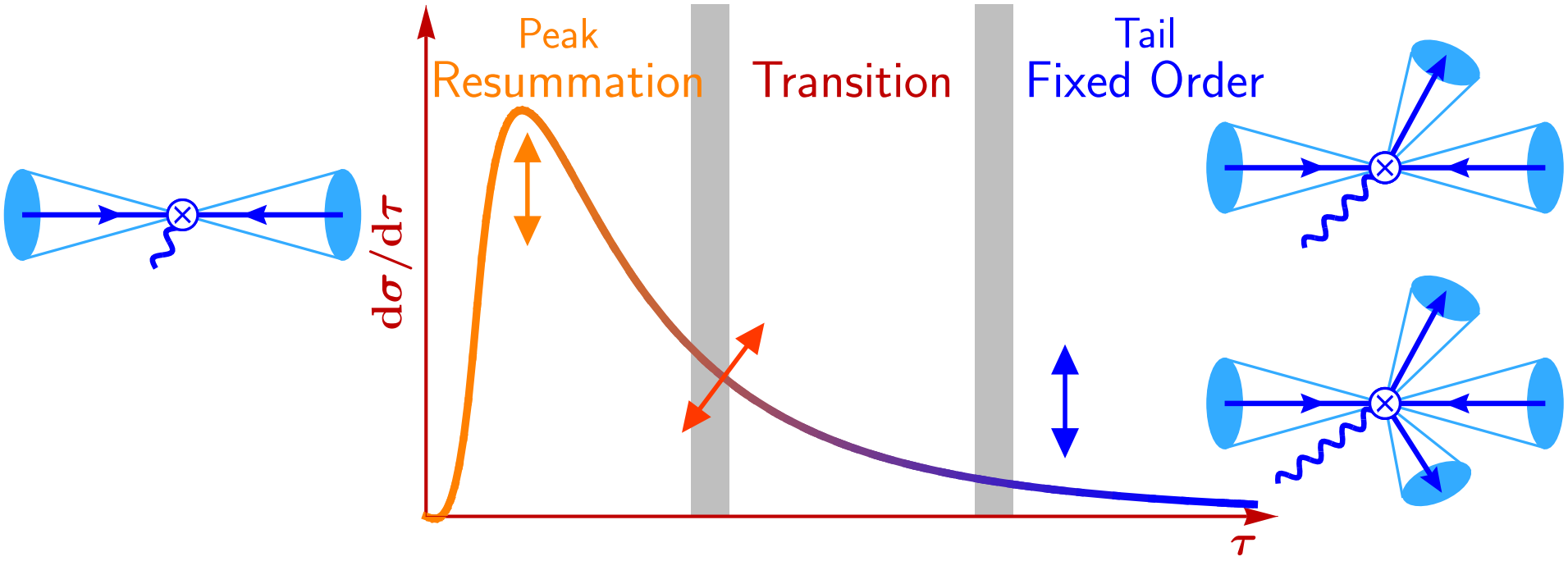


We currently use N-jettiness $\mathcal{T} \equiv \mathcal{T}_N$ [Stewart, FT, Waaelwijn '09, '10]

- 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.

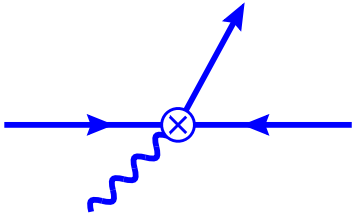


There are no strict boundaries $\rightarrow$ $\mathcal{T}$ spectrum describes transition between 0-jet and $\geq$ 1-jet regions

- 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

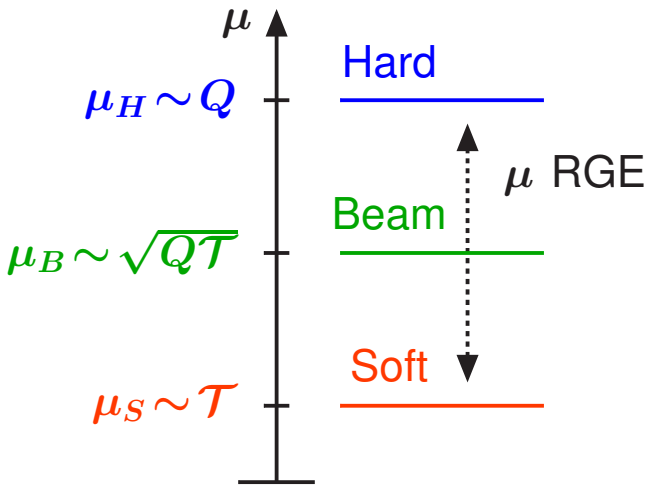
Interlude: Resummation for $\mathcal{T}_0$.

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

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

Logarithms are split apart and resummed using RGE

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



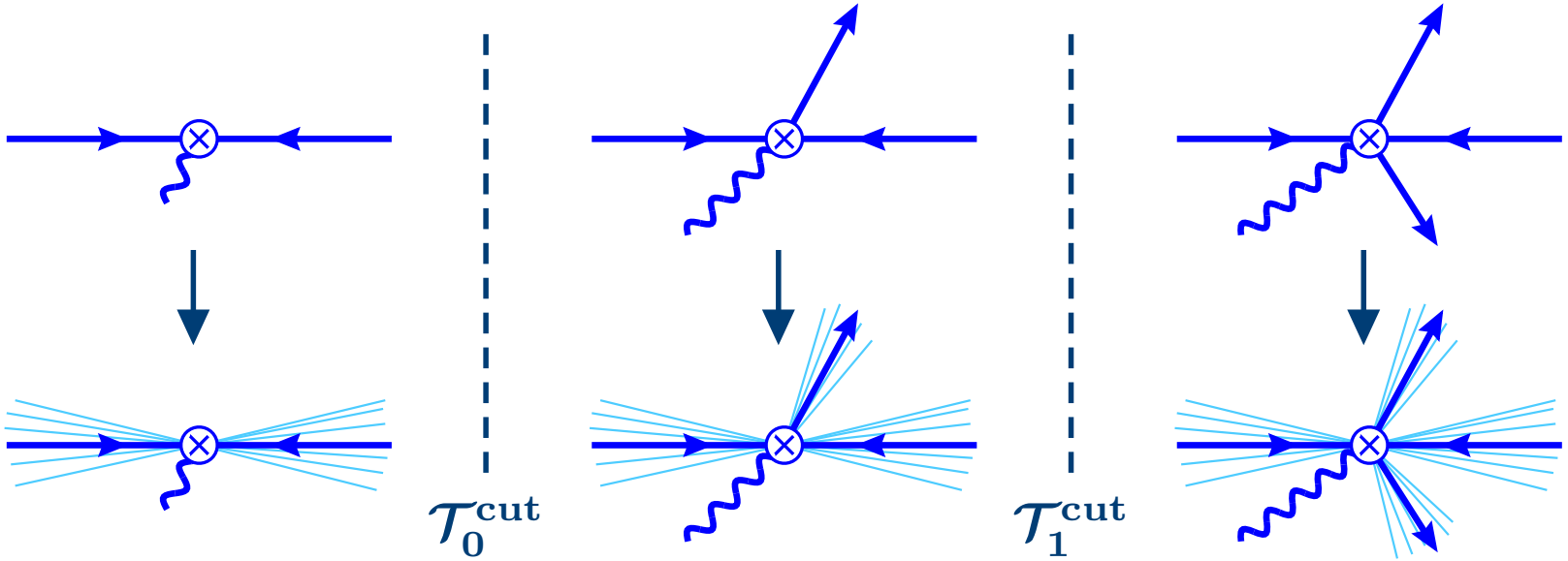
$\Rightarrow$ Always resums ratios of hard, beam, soft scales

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

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 $\mathcal{T}_{0,1}^{\mathrm{cut}}$ 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

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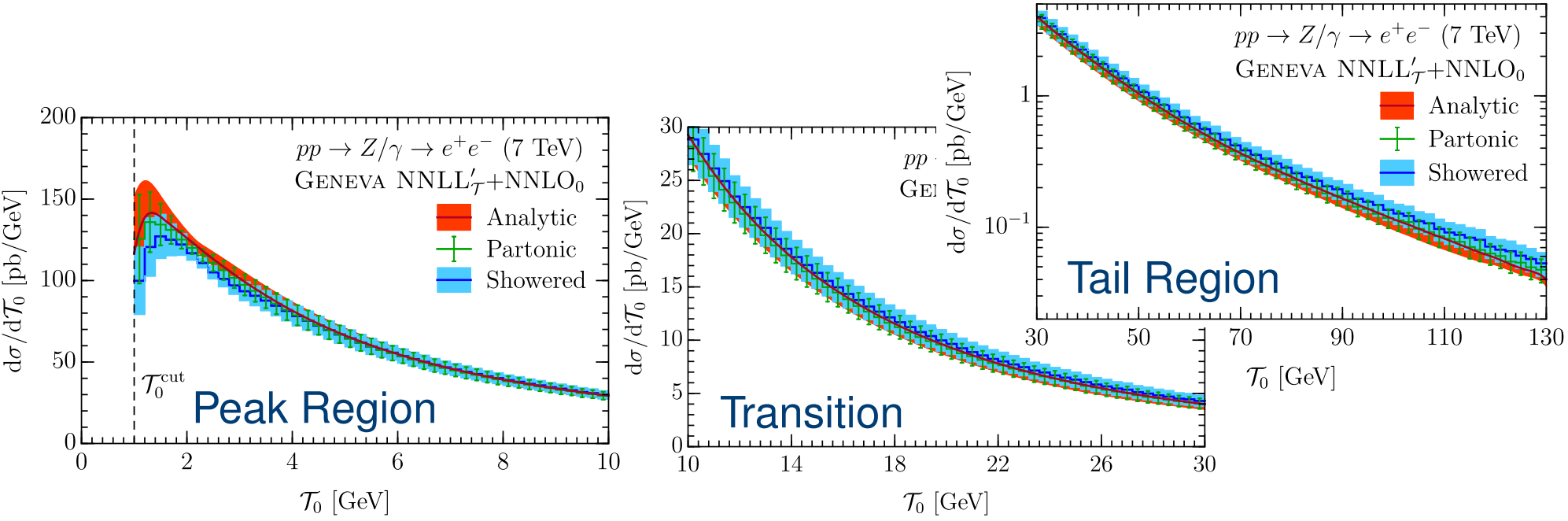

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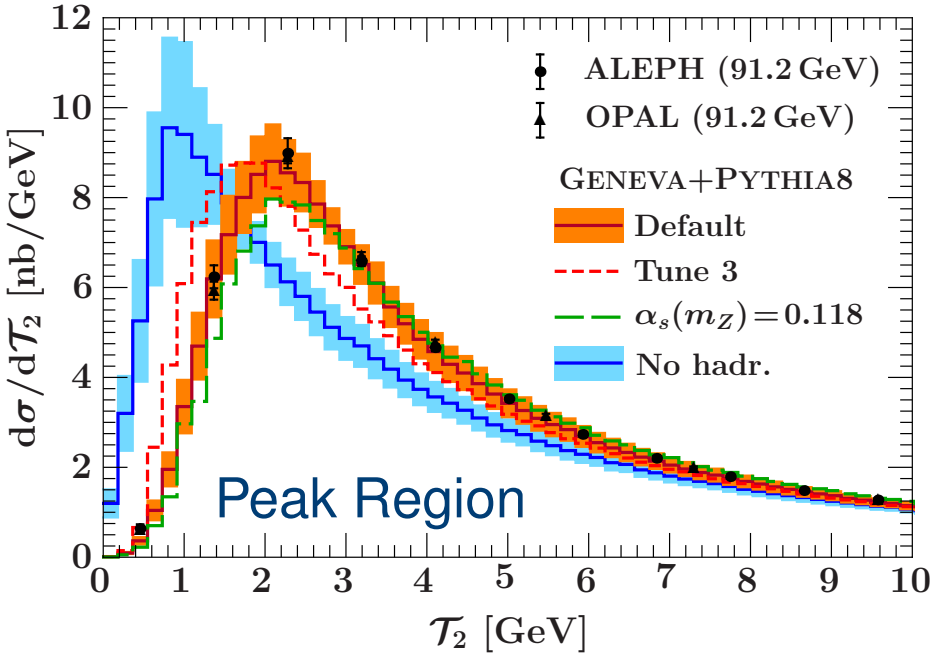

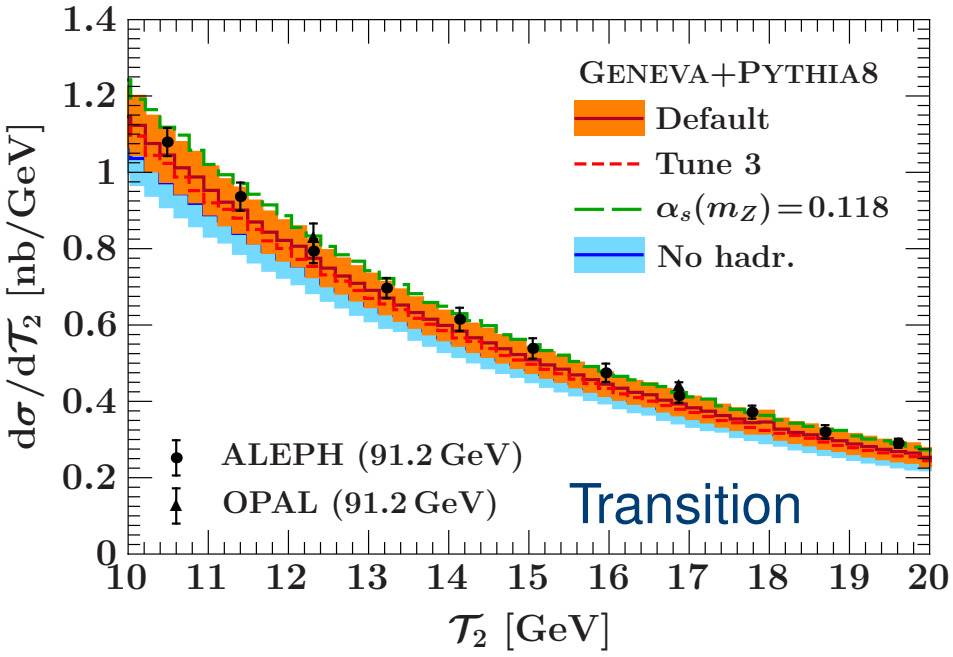

PYTHIA8 hadronization is unconstrained

- 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

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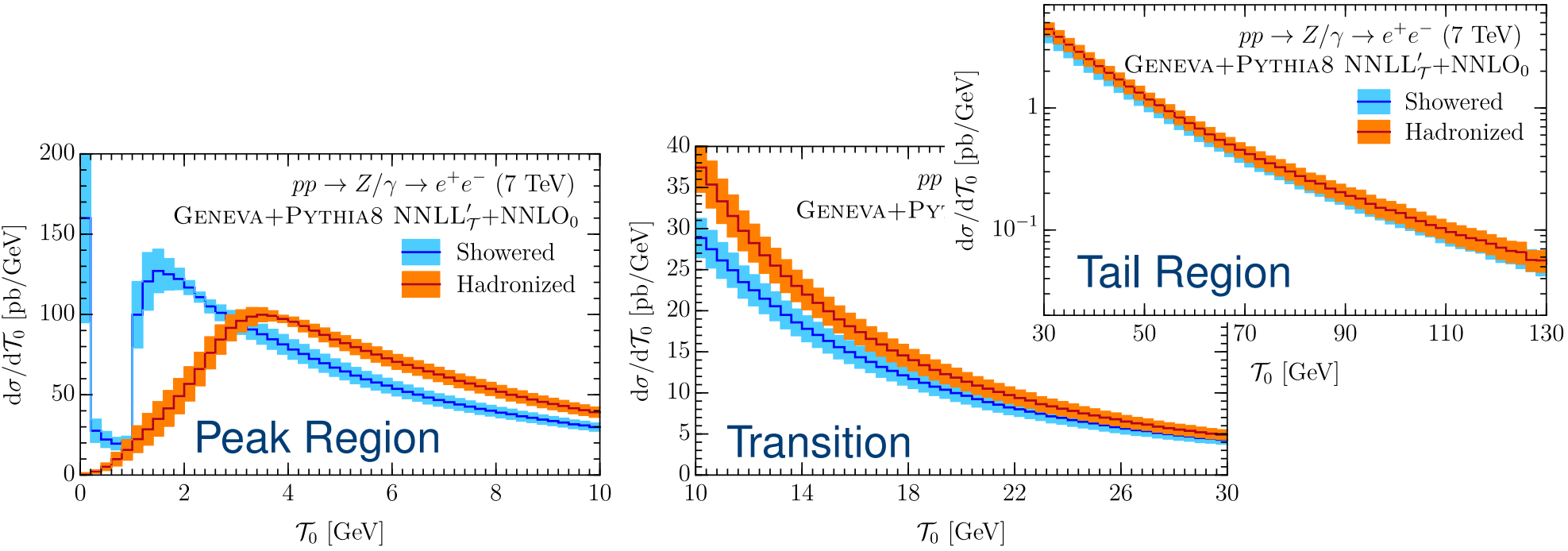

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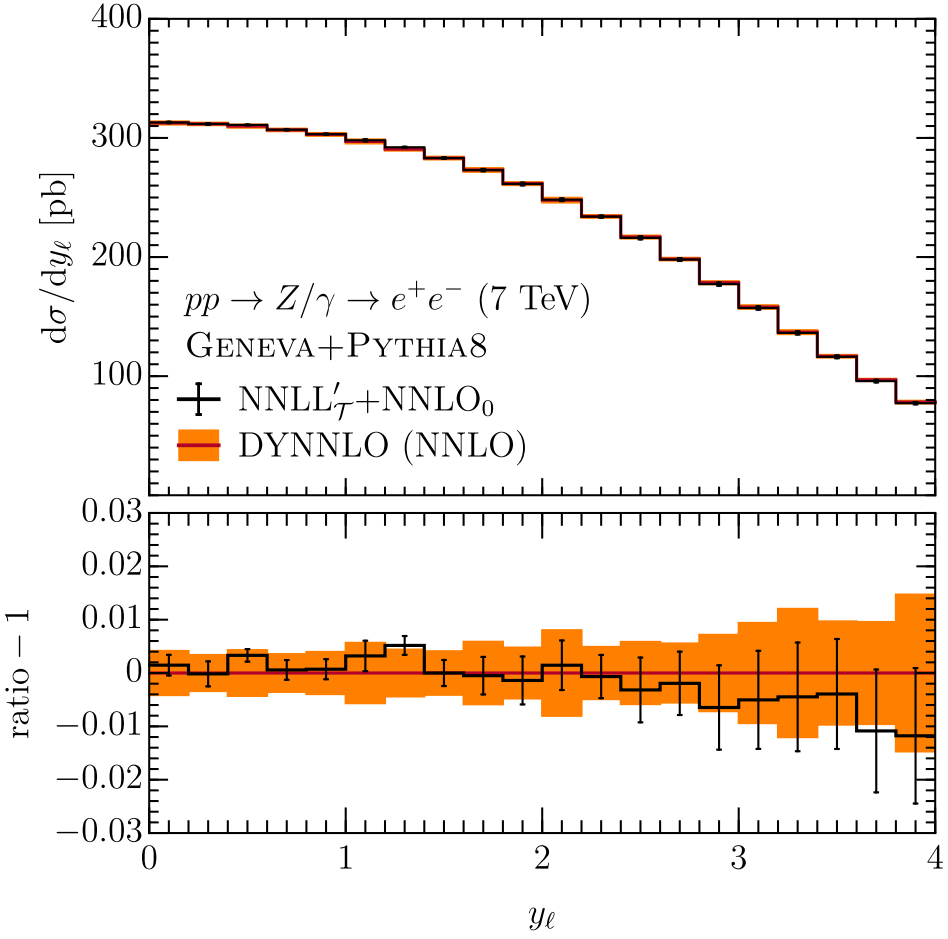
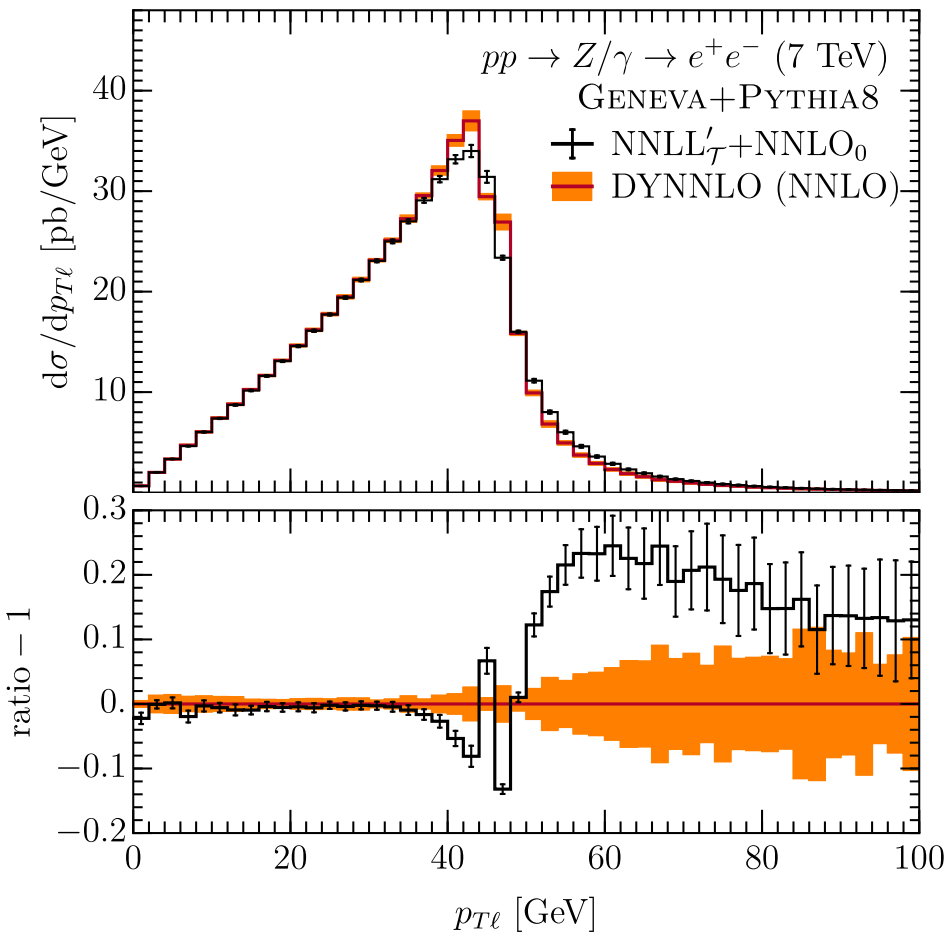
Other observables: FO.

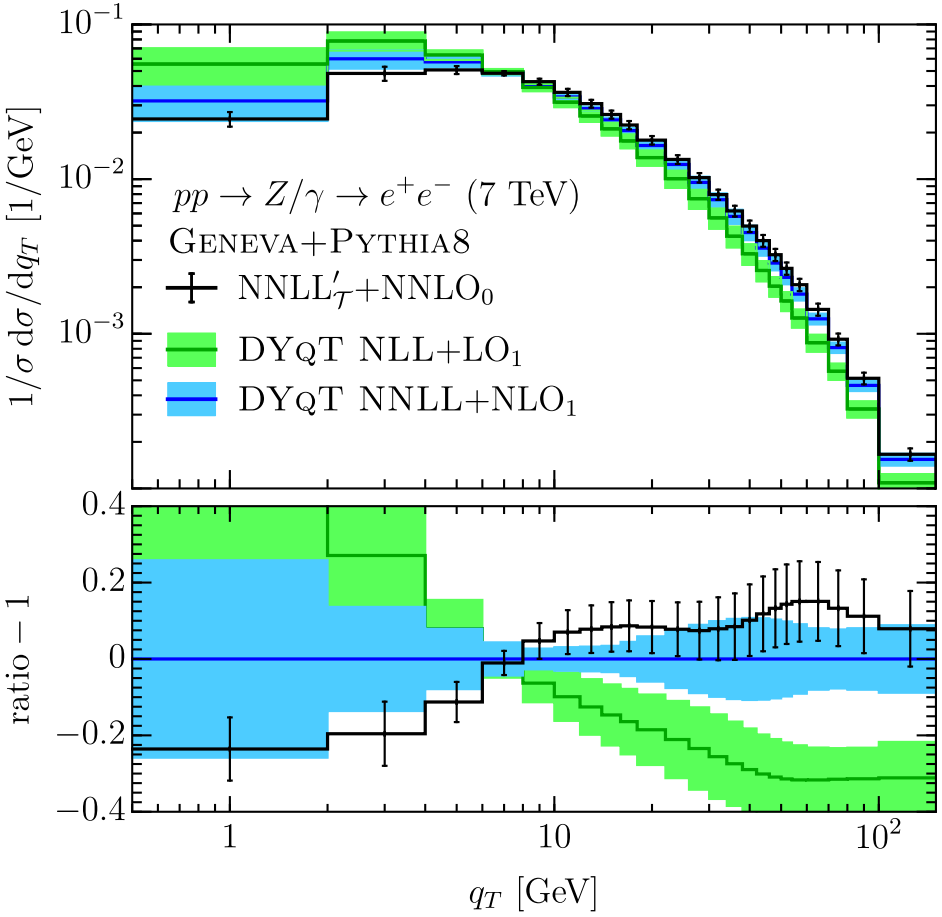




- Validation against DYNNLO [Catani, Grazzini et al. '07, '09]
- True NNLO only for $p_{T\ell} < m_Z/2$, $\gtrsim m_Z/2$ sensitive to resummation effects due to Sudakov shoulder

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]
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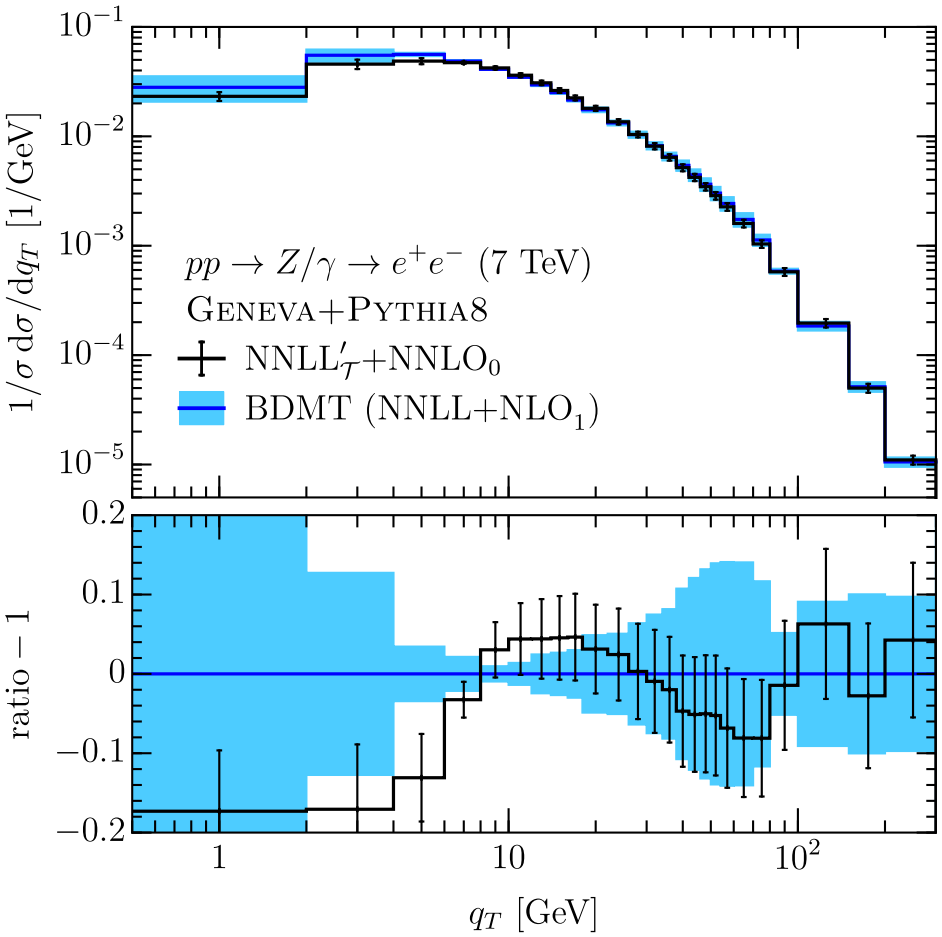
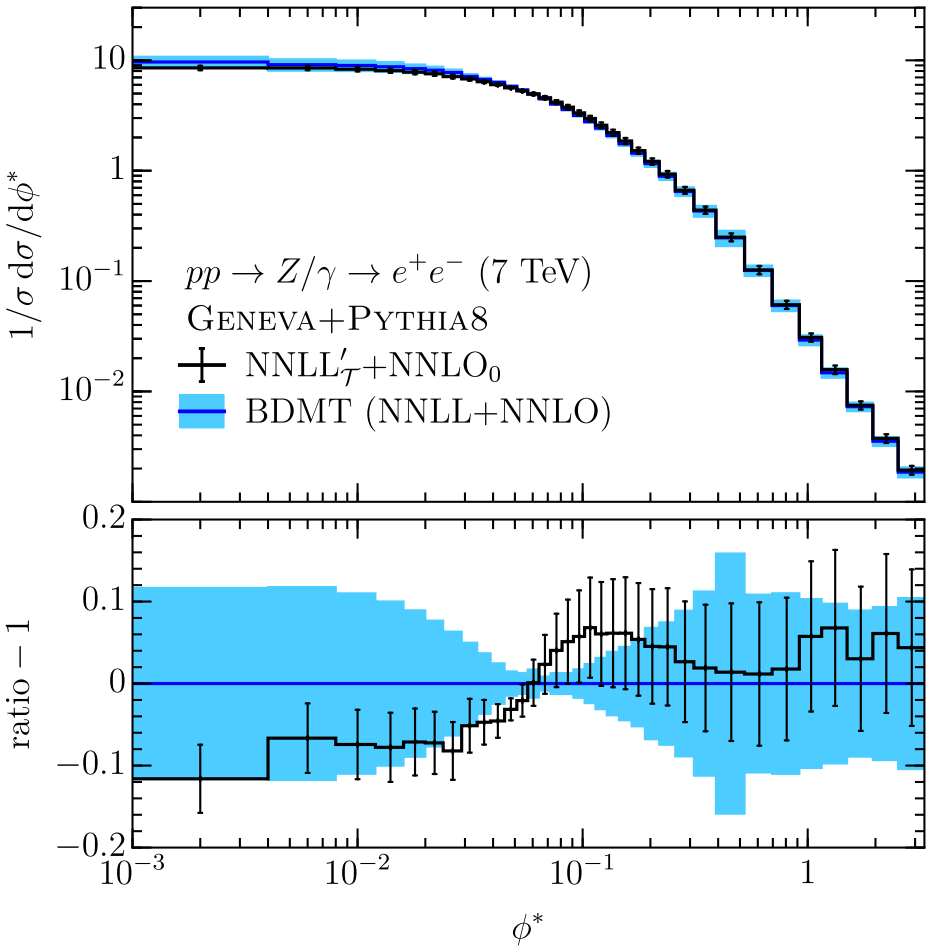
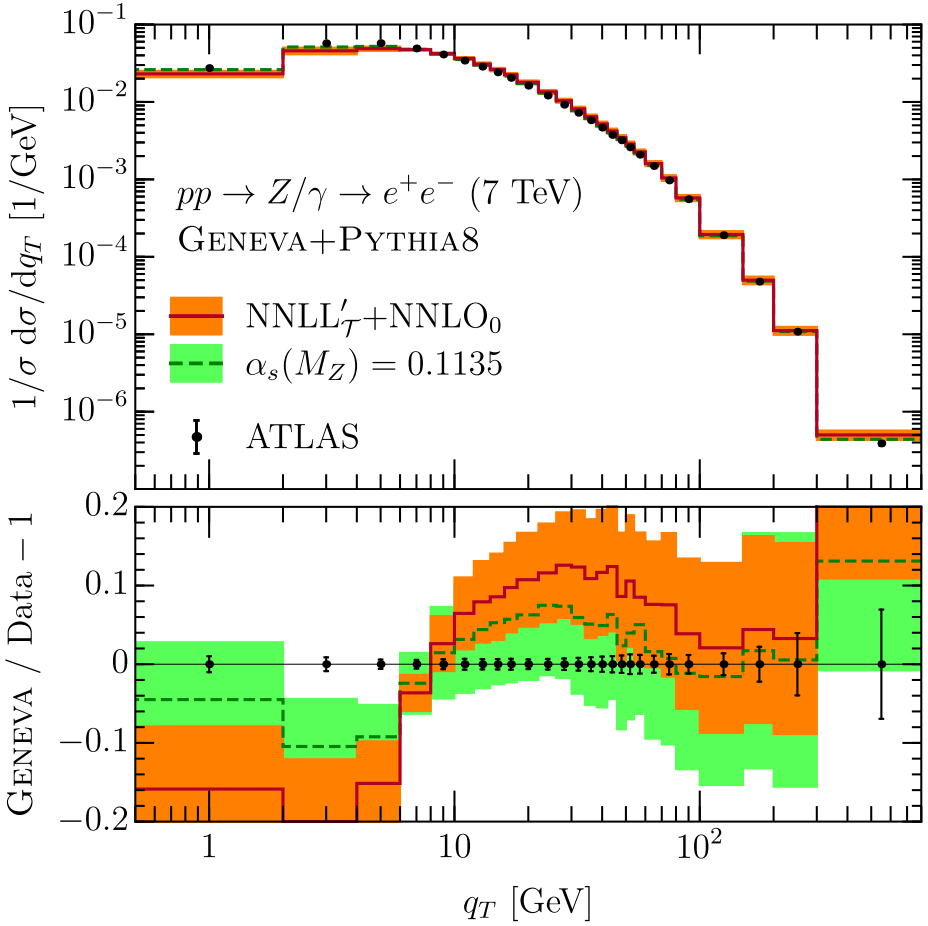
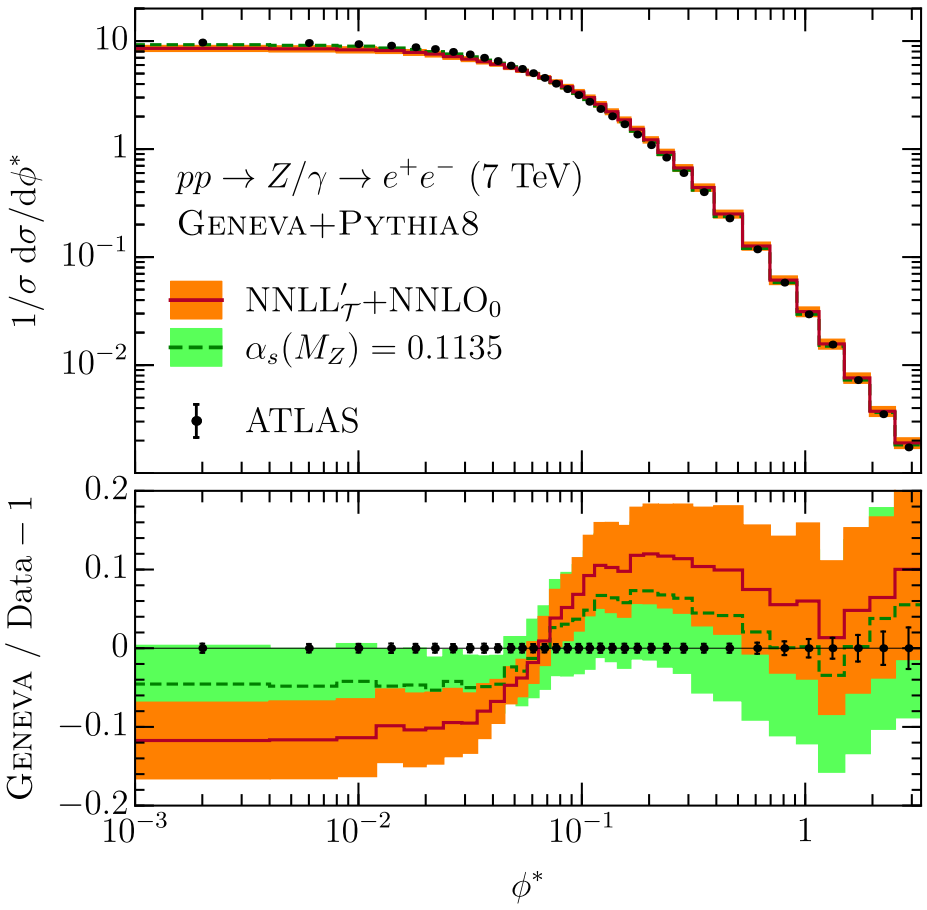




Comparison to Data.





- 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

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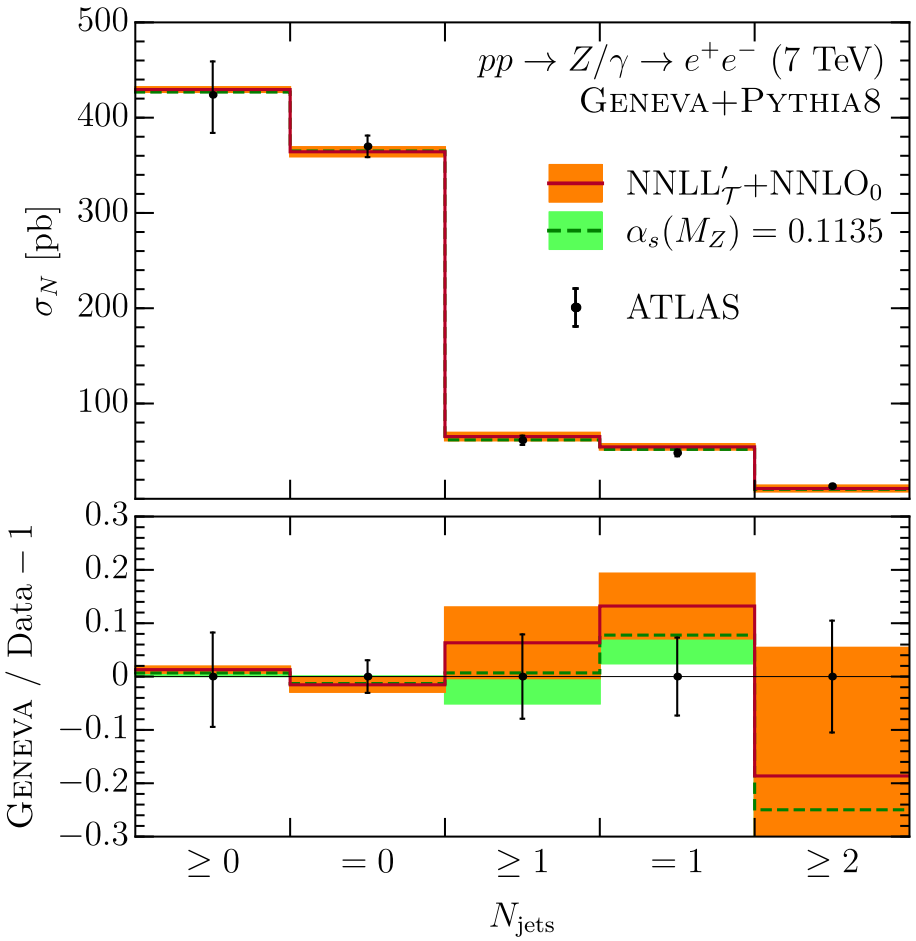

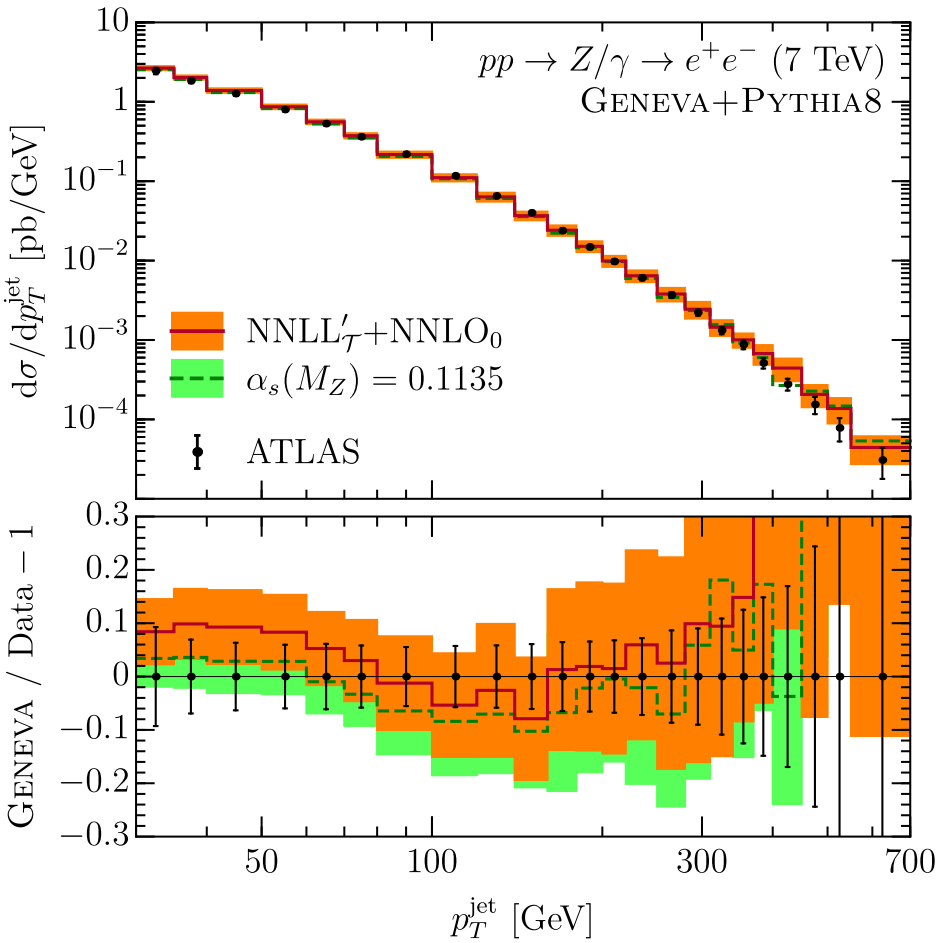

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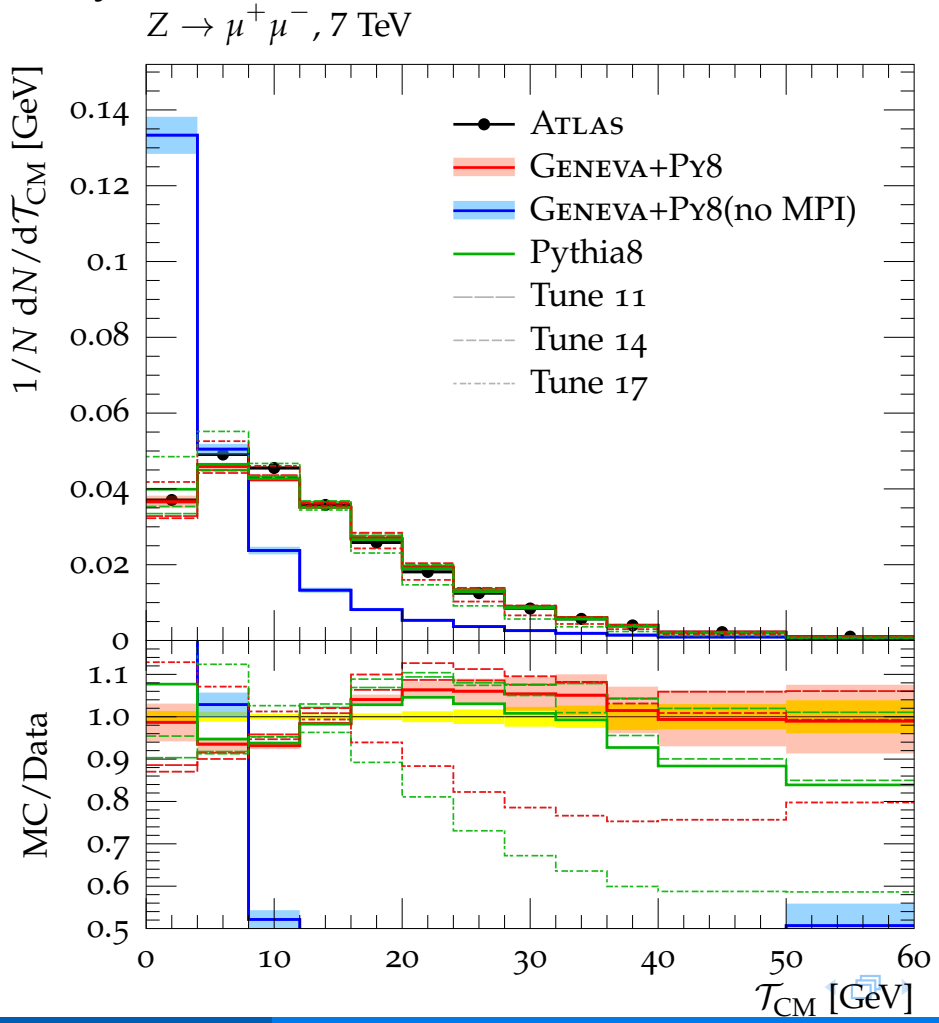
Step 5: Adding MPI.

Discussion so far was for the primary hard collision

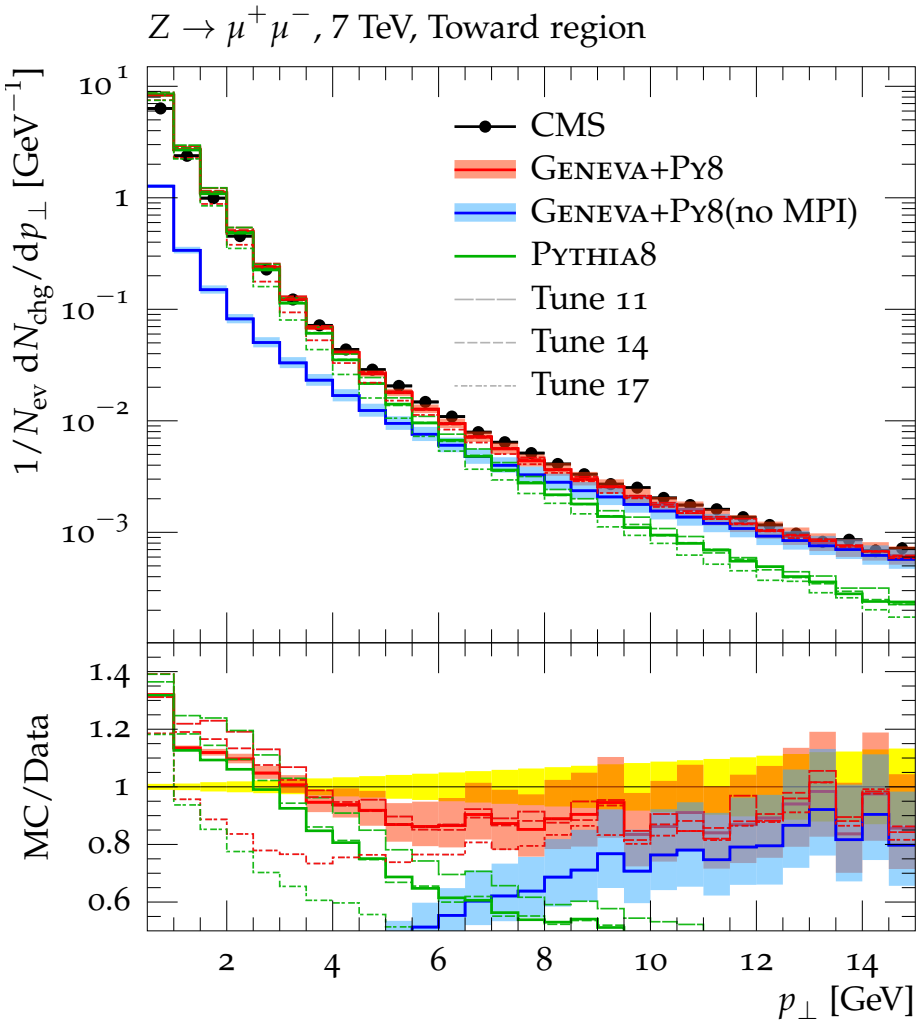
- Addition of MPI is slightly nontrivial due to PYTHIA8 interleaved evolution
  - Shower conditions are applied to all particles identified as arising from primary hard interaction, while secondary interactions are unconstrained (requires to turn off rescattering)

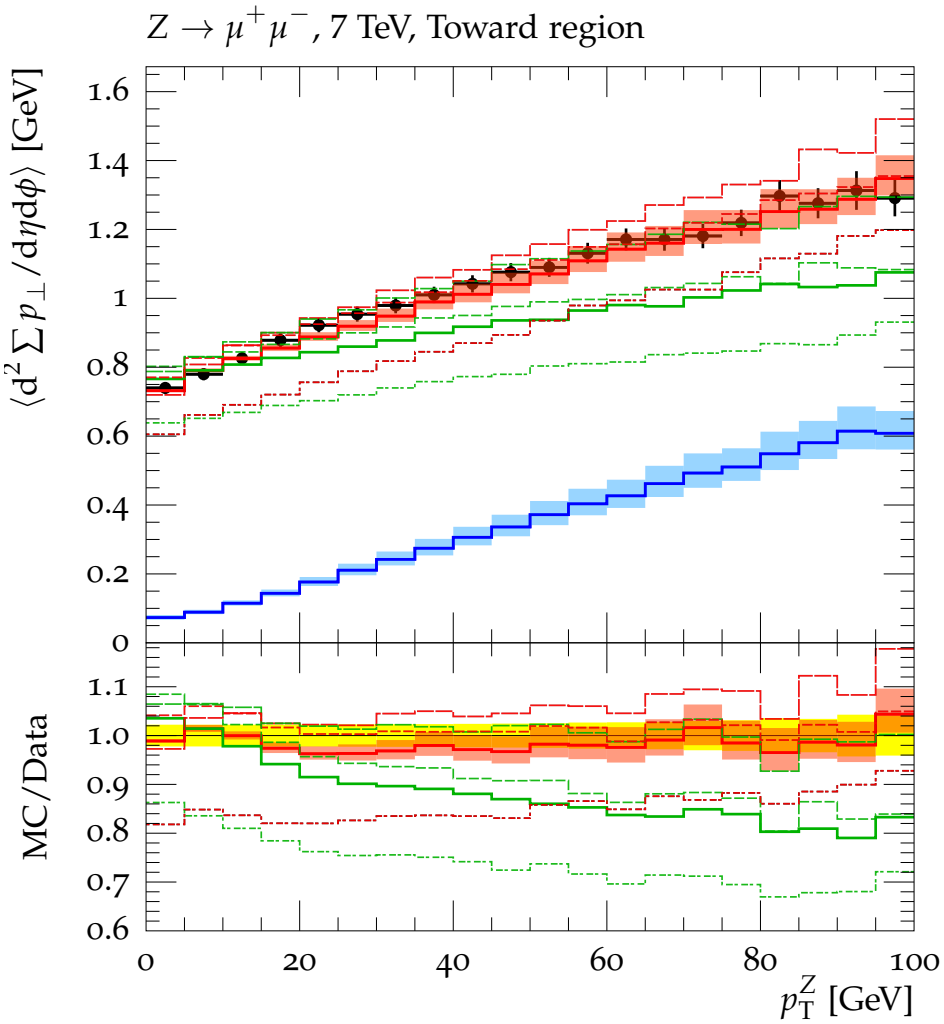
- Beam thrust/0-jettiness potentially very useful for tuning MPI models
  - Primary perturbative effects are known precisely
  - Should allow to fully disentangle MPI contributions from primary soft ISR

- 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

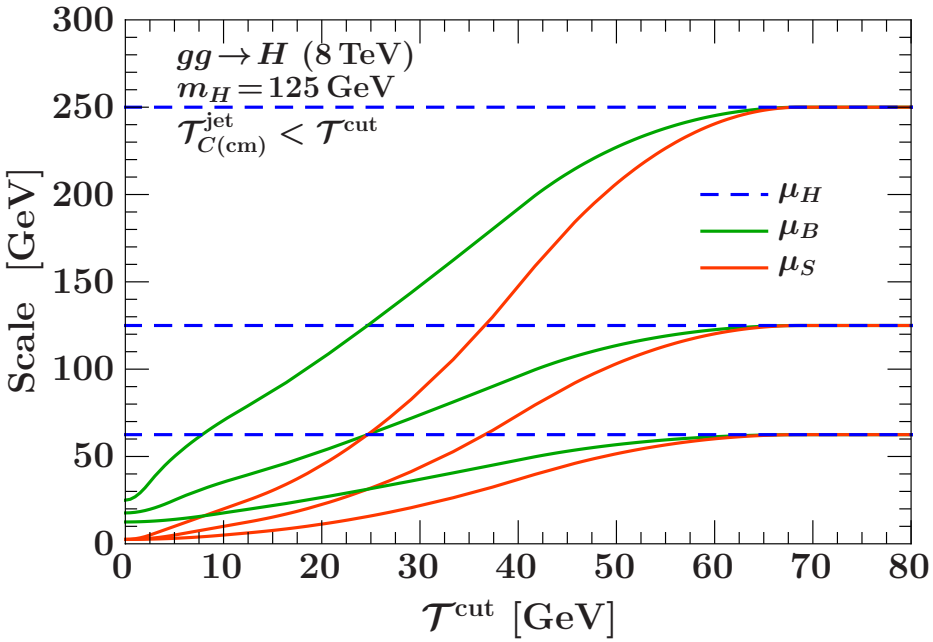
Plans for immediate future

- 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.

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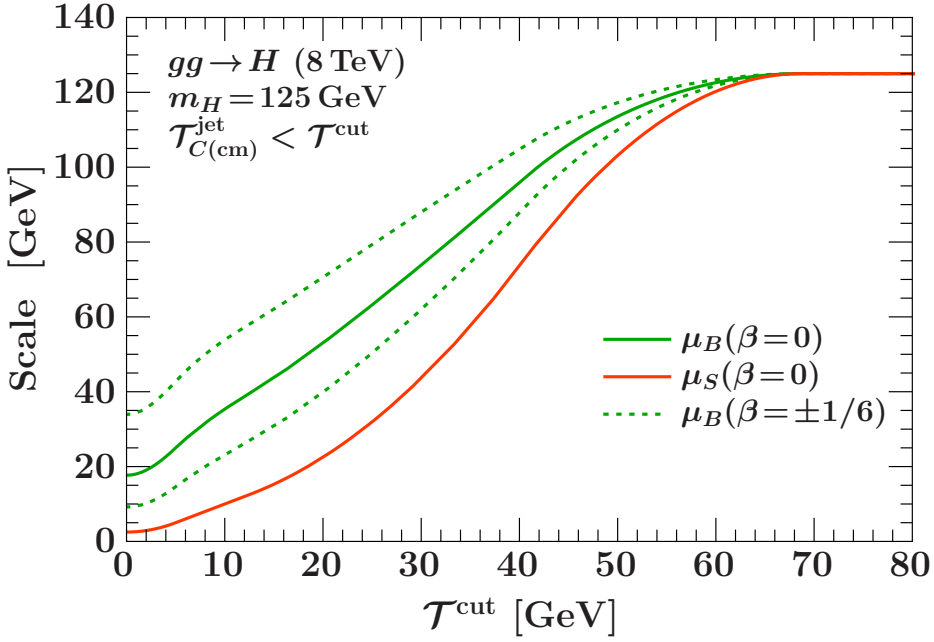

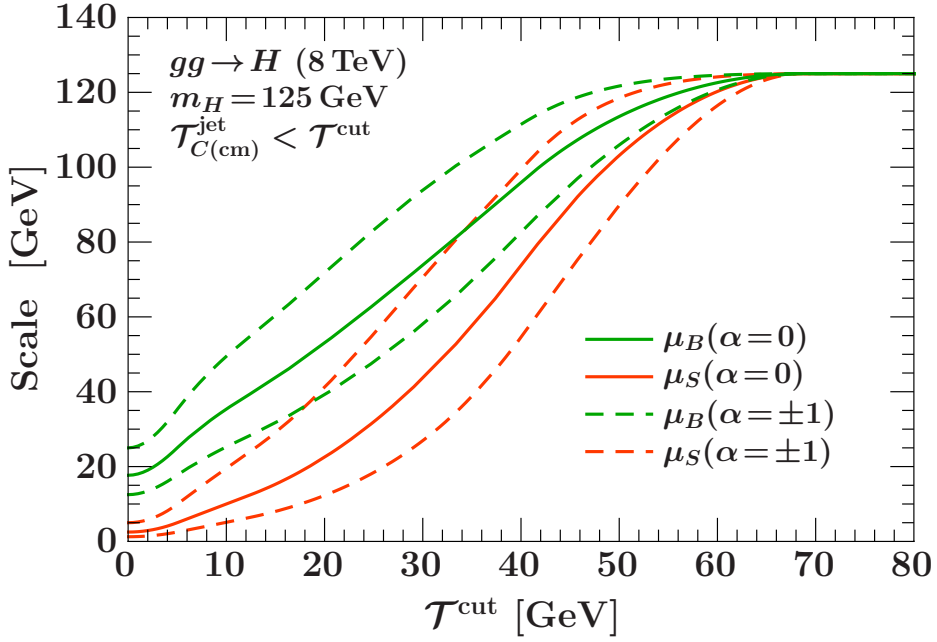

Δ_{resum}: Resummation scale variations

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

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

Lowest perturbative accuracy at all $\mathcal{T}$ requires (N)LL_σ+$\mathrm{LO_{N+1}}$

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

→ $\mathrm{LO_N}$ is naturally part of LL_σ and so automatically included

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+ & \alpha_s^3/\tau\Big[& \vdots & + & \vdots & + & \vdots & + & \vdots &
\end{array}
$$

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

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

→ Does *not* improve accuracy of spectrum

Perturbative Accuracy.

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 & + & \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] & \mathrm{NLO_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] & \mathrm{LO_{N+1}} \\
 & + & \alpha_s^2/\tau\Big[\ c_{23}L^3 & + & c_{22}L^2 & + & c_{21}L & + & c_{20} & + \ \tau f_2(\tau)\Big] & \mathrm{NLO_{N+1}} \\
 & + & \alpha_s^3/\tau\Big[\ \vdots & + & \vdots & + & \vdots & + & \vdots & &
\end{array}
$$

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

→ $\mathrm{NLO_N}$ is now naturally part of NLL'_σ and automatically included

→ similarly $\mathrm{NNLO_N}$ is naturally part of NNLL'_σ

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