Higer Orders in Parton Showers

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Heavy Flavour Production at the LHC (IPPP 2017)

Reminder: How parton showers work

- parton showers are approximations, based on

  leading colour, leading logarithmic accuracy, spin-average
- parametric accuracy by comparing Sudakov form factors:

$$\Delta = \exp\left\{-\int\frac{\mathrm{d}k_\perp^2}{k_\perp^2}\left[A\log\frac{k_\perp^2}{Q^2}+B\right]\right\},$$

  where A and B can be expanded in $\alpha_S(k_\perp^2)$
- Q_T resummation includes $A_{1,2,3}$ and $B_{1,2}$

  (transverse momentum of Higgs boson etc.)
- showers usually include terms $A_{1,2}$ and B_1

  A = cusp terms ("soft emissions"), $B\sim$ anomalous dimensions γ

Matching at NLO and NNLO

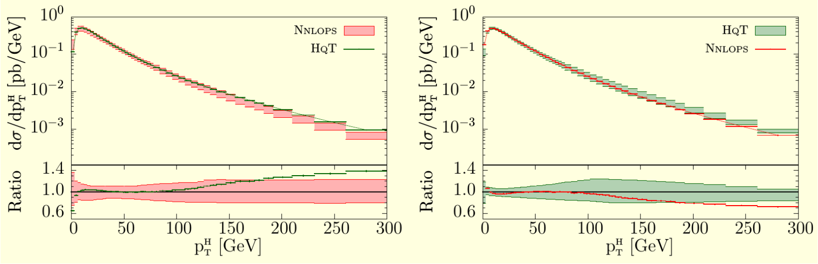
- avoid double-counting of emissions
- two schemes at NLO: MC@NLO and POWHEG
  - mismatches of K factors in transition to hard jet region
  - MC@NLO: $\longrightarrow$ visible structures, especially in $gg \to H$
  - POWHEG: $\longrightarrow$ high tails, cured by h dampening factor
  - well-established and well-known methods

(no need to discuss them any further)

- two schemes at NNLO: MINLO & UN^{2}LOPS (singlets S only)
  - different basic ideas
  - MINLO: $S + j$ at NLO with $p_T^{(S)} \to 0$ and capture divergences by reweighting internal line with analytic Sudakov, NNLO accuracy ensured by reweighting with full NNLO calculation for S production
  - UN^{2}LOPS identifies and subtracts and adds parton shower terms at FO from $S + j$ contributions, maintaining unitarity
  - available for two simple processes only: DY and $gg \to H$

NNLOPs for H production: MINLO

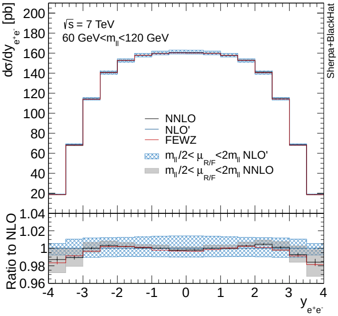
K. Hamilton, P. Nason, E. Re & G. Zanderighi, JHEP 1310

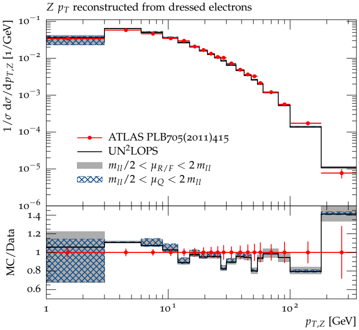


- also available for $Z/W/VH$ production

NNLOPs for Z production: UN^{2}LOPs

S. Hoche, Y. Li, & S. Prestel, Phys.Rev.D90 & D91





- also available for H production

A new shower implementation in DIRE

(S.Höche & S.Prestel, Eur.Phys.J. C75 (2015) 461)

- evolution and splitting parameter $((ij) + k \to i + j + k)$:

$$\kappa^2_{j,ik} = \frac{4(p_i p_j)(p_j p_k)}{Q^4} \quad \text{and} \quad z_j = \frac{2(p_j p_k)}{Q^2} .$$

- splitting functions including IR regularisation

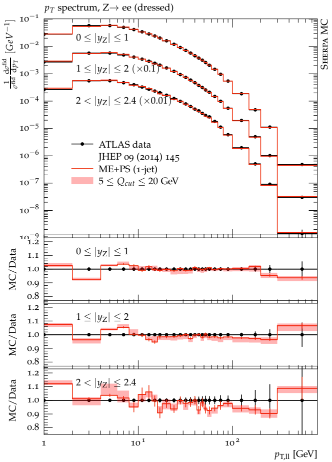
(a la Curci, Furmanski & Petronzio, Nucl.Phys. B175 (1980) 27-92)

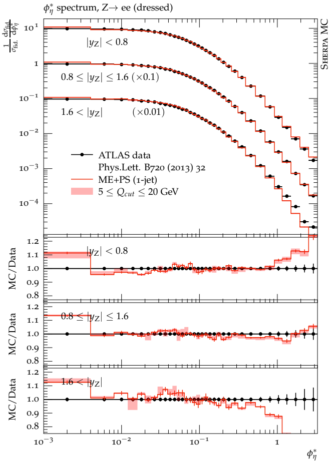
$$\begin{aligned}
P^{(0)}_{qq}(z,\kappa^2) &= 2C_F\left[\frac{1-z}{(1-z)^2+\kappa^2} - \frac{1+z}{2}\right] , \\
P^{(0)}_{qg}(z,\kappa^2) &= 2C_F\left[\frac{z}{z^2+\kappa^2} - \frac{2-z}{2}\right] , \\
P^{s(0)}_{gg}(z,\kappa^2) &= 2C_A\left[\frac{1-z}{(1-z)^2+\kappa^2} - 1 + \frac{z(1-z)}{2}\right] , \\
P^{(0)}_{gq}(z,\kappa^2) &= T_R\left[z^2+(1-z)^2\right]
\end{aligned}$$

- renormalisation/factorisation scale given by $\mu = \kappa^2 Q^2$
- combine gluon splitting from two splitting functions with different spectators k $\to$ accounts for different colour flows

LO results for Drell-Yan

(example of accuracy in description of standard precision observable)





Including NLO splitting kernels

(Hoeche, FK & Prestel, 1705.00982, and Hoeche & Prestel, 1705.00742)

- expand splitting kernels as

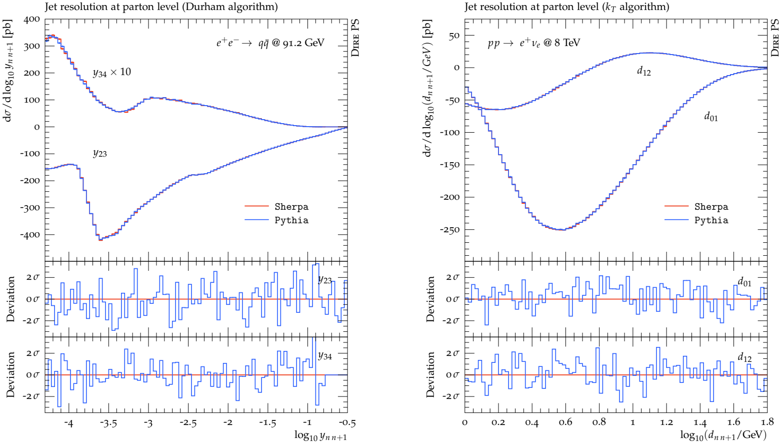
$$P(z,\,\kappa^2) \,=\, P^{(0)}(z,\,\kappa^2) + \frac{\alpha_S}{2\pi}\,P^{(1)}(z,\,\kappa^2)$$

- aim: reproduce DGLAP evolution at NLO

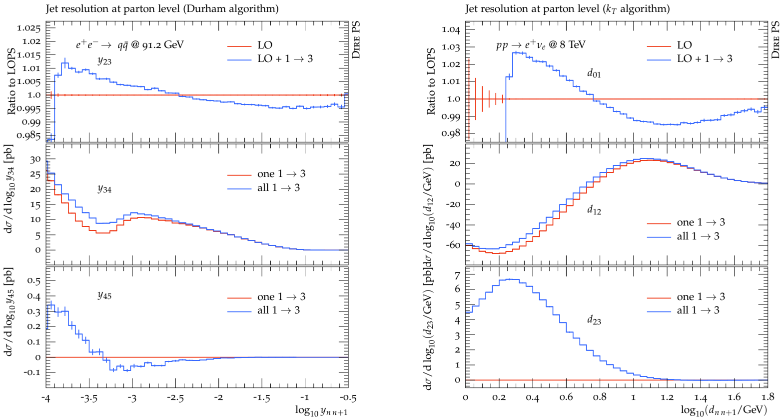
  include all NLO splitting kernels

- three categories of terms in $P^{(1)}$:
  - cusp (universal soft-enhanced correction) (already included in original showers)
  - corrections to $1 \to 2$
  - new flavour structures (e.g. $q \to q'$), identified as $1 \to 3$
- new paradigm: two independent implementations

Validation of 1 → 3 splittings

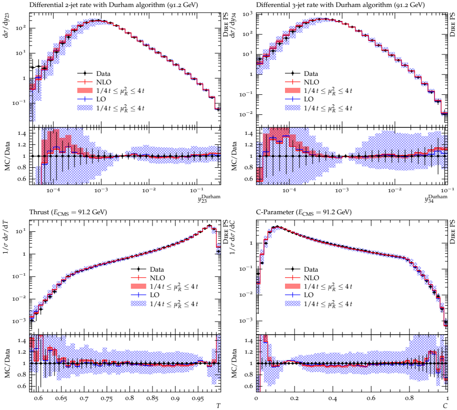


Impact of 1 → 3 splittings



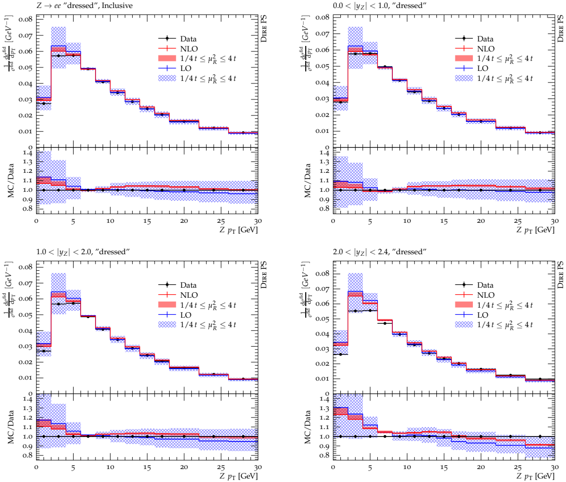
Physical results: $e^-e^+ \to$ hadrons

(Hoeche, FK & Prestel, 1705.00982)

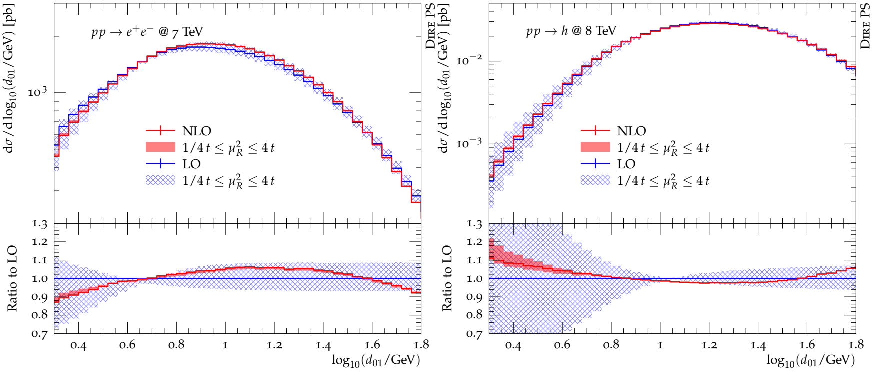


Physical results: DY at LHC

(untuned showers vs. 7 TeV ATLAS data)

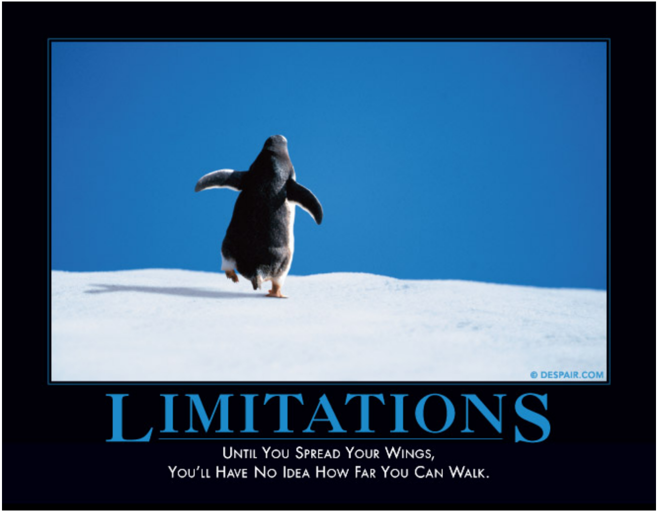


Physical results: differential jet rates at LHC



Summary

- implemented NLO DGLAP kernels into two independent showers
  will allow cross checks/validation of NP effects
- cross-validated implementations PYTHIA $\longleftrightarrow$ SHERPA
- matching to NNLO/multijet merging at NLO ongoing work
- extension to include loop-corrections to $1 to 2$ straightforward
  will allow to use triple-collinear splitting functions throughout
- future plans: soft-gluon emissions and non-trivial colour correlations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LIMITATIONS
Until You Spread Your Wings,
You'll Have No Idea How Far You Can Walk.