NNLOPS for Drell-Yan production

Emanuele Re

Rudolf Peierls Centre for Theoretical Physics,
University of Oxford

EW precision physics at the LHC

CERN, 30 June 2014

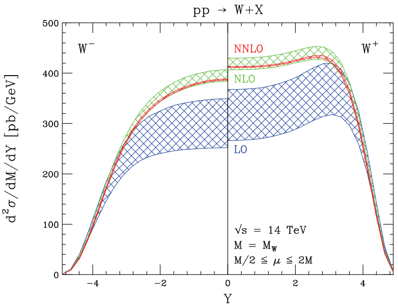
Outline

- brief motivation
- description of the method
- results:
  - validation
  - comparison with data (and available analytic resummation)
- conclusions

Why going NNLO?

- sometimes NLO not enough:
  - large NLO/LO "K-factor"
    [as in Higgs Physics]
  - very high precision needed
    [PDF extraction / W-mass measurement / luminosity monitoring, ...]

  $\Rightarrow$ NNLO



[Anastasiou et al., '03]

- NNLO is the frontier:
  first $2 \to 2$ NNLO computations in 2012-13 !

- here focus on Drell-Yan

☞ aim: build an event generator that is NNLO accurate (NNLOPS)

- the approach presented here was used for Higgs production
- we are currently finalising results for neutral & charged Drell-Yan
  [Karlberg,Re,Zanderighi '14 (WIP)]

V+j @ NLOPS

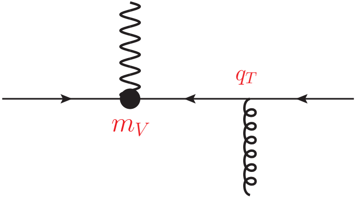
1. V+j @ NLO, V+jj @ LO $\Rightarrow$ use V+j @ NLOPS (POWHEG)

$$d\sigma_{\mathrm{POWHEG}} = d\Phi_n\, \bar{B}_{\mathrm{NLO}}(\Phi_n) \left\{ \Delta(\Phi_n; k_{\mathrm{T}}^{\min}) + \Delta(\Phi_n; k_{\mathrm{T}}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)}\, d\Phi_r \right\}$$

1. V+j @ NLO, V+jj @ LO $\Rightarrow$ use V+j @ NLOPS (POWHEG)

$$d\sigma_{\rm POWHEG} = d\Phi_n\, \bar{B}_{\rm NLO}(\Phi_n) \left\{ \Delta(\Phi_n; k_{\rm T}^{\rm min}) + \Delta(\Phi_n; k_{\rm T}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)}\, d\Phi_r \right\}$$

$$\bar{B}_{\rm NLO}(\boldsymbol{\Phi}_n)\, d\boldsymbol{\Phi}_n = \alpha_{\rm S}(\mu_R) \Big[B + \alpha_{\rm S}^{\rm (NLO)} V(\mu_R) + \alpha_{\rm S}^{\rm (NLO)} \int d\Phi_{\rm r} R \Big]\, d\boldsymbol{\Phi}_n$$

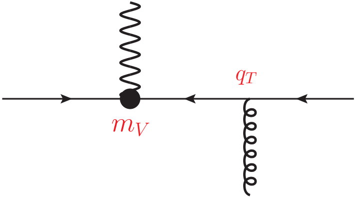


V+j is a 2-scales problem ($\rightarrow$ choice of μ not unique)

1. V+j @ NLO, V+jj @ LO $\Rightarrow$ use V+j @ NLOPS (POWHEG)

$$d\sigma_{\rm POWHEG} = d\Phi_n\, \bar{B}_{\rm NLO}(\Phi_n) \left\{ \Delta(\Phi_n; k_{\rm T}^{\rm min}) + \Delta(\Phi_n; k_{\rm T}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)}\, d\Phi_r \right\}$$

$$\bar{B}_{\rm NLO}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n = \alpha_{\rm S}(\mu_R) \Big[B + \alpha_{\rm S}^{\rm (NLO)} V(\mu_R) + \alpha_{\rm S}^{\rm (NLO)} \int d\Phi_{\rm r} R \Big]\, d\mathbf{\Phi}_n$$



V+j is a 2-scales problem ($\rightarrow$ choice of μ not unique)

☞ want to reach NNLO accuracy for *e.g.* $y_V, \eta_\ell, k_{{\rm T},\ell} (< M_V/2)$, *i.e.* when fully inclusive over QCD radiation

- need to allow the 1st jet to become unresolved
- the above approach needs to be modified: as it stands, $\bar{B}_{\rm NLO}(\Phi_n)$ is not finite when $q_T \rightarrow 0$!

2. integrate over phase space regions where V is produced with arbitrarily soft/collinear jet (i.e. finite results when integrating over all q_T spectrum)

MiNLO: Multiscale Improved NLO [Hamilton,Nason,Zanderighi, 1206.3572]

- original goal: method to a-priori choose scales in multijet NLO computation (where hierarchy among scales can spoil accuracy since resummation of logs is missing)
- how: correct weights of different NLO terms with CKKW-inspired approach:

MiNLO

2. integrate over phase space regions where V is produced with arbitrarily soft/collinear jet (i.e. finite results when integrating over all q_T spectrum)

MiNLO: Multiscale Improved NLO [Hamilton,Nason,Zanderighi, 1206.3572]

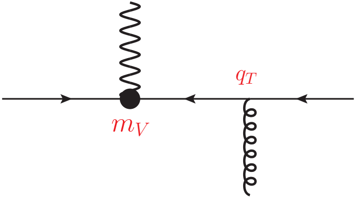
- original goal: method to a-priori choose scales in multijet NLO computation (where hierarchy among scales can spoil accuracy since resummation of logs is missing)
- how: correct weights of different NLO terms with CKKW-inspired approach:
  - for all PS points, build the "more-likely" shower history that would have produced it (can be done by clustering kinematics with k_T-algo)
  - correct original NLO including α_S couplings evaluated at nodal scales and Sudakov FFs
  - make sure that NLO accuracy is not spoiled !

2. integrate over phase space regions where V is produced with arbitrarily soft/collinear jet (i.e. finite results when integrating over all q_T spectrum)

MiNLO: Multiscale Improved NLO [Hamilton,Nason,Zanderighi, 1206.3572]

- original goal: method to a-priori choose scales in multijet NLO computation (where hierarchy among scales can spoil accuracy since resummation of logs is missing)
- how: correct weights of different NLO terms with CKKW-inspired approach:

$$\bar{B}_{\text{NLO}} = \alpha_{\text{S}}(\mu_R)\Big[B + \alpha_{\text{S}}^{(\text{NLO})} V(\mu_R) + \alpha_{\text{S}}^{(\text{NLO})} \int d\Phi_{\text{r}} R\Big]$$



MiNLO

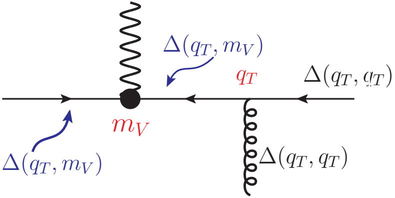
2. integrate over phase space regions where V is produced with arbitrarily soft/collinear jet (i.e. finite results when integrating over all q_T spectrum)

MiNLO: Multiscale Improved NLO [Hamilton,Nason,Zanderighi, 1206.3572]

- original goal: method to a-priori choose scales in multijet NLO computation (where hierarchy among scales can spoil accuracy since resummation of logs is missing)
- how: correct weights of different NLO terms with CKKW-inspired approach:

$$\bar{B}_{\rm NLO} = \alpha_{\rm S}(\mu_R)\Big[B + \alpha_{\rm S}^{\rm (NLO)} V(\mu_R) + \alpha_{\rm S}^{\rm (NLO)} \int d\Phi_{\rm r} R\Big]$$

$$\bar{B}_{\rm MiNLO} = \alpha_{\rm S}(q_T)\Delta_q^2(q_T, m_V)\Big[B\left(1 - 2\Delta_q^{(1)}(q_T, m_V)\right) + \alpha_{\rm S}^{\rm (NLO)}\, V(\bar{\mu}_R) + \alpha_{\rm S}^{\rm (NLO)} \int d\Phi_{\rm r} R\Big]$$



- $\bar{\mu}_R = q_T$
- $\log \Delta_{\rm f}(q_T, m_V) = -\int_{q_T^2}^{m_V^2} \frac{dq^2}{q^2} \frac{\alpha_{\rm S}(q^2)}{2\pi}\left[A_f \log\frac{m_V^2}{q^2} + B_f\right]$
- $\Delta_{\rm f}^{(1)}(q_T, m_V) = -\frac{\alpha_{\rm S}^{\rm (NLO)}}{2\pi}\left[\frac{1}{2} A_{1,{\rm f}} \log^2\frac{m_V^2}{q_T^2} + B_{1,{\rm f}} \log\frac{m_V^2}{q_T^2}\right]$
- $\mu_F = q_T$

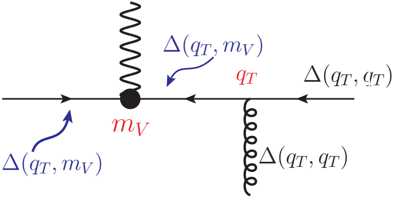
2. integrate over phase space regions where V is produced with arbitrarily soft/collinear jet (i.e. finite results when integrating over all q_T spectrum)

MiNLO: Multiscale Improved NLO [Hamilton,Nason,Zanderighi, 1206.3572]

- original goal: method to a-priori choose scales in multijet NLO computation (where hierarchy among scales can spoil accuracy since resummation of logs is missing)
- how: correct weights of different NLO terms with CKKW-inspired approach:

$$\bar{B}_{\mathrm{NLO}} = \alpha_{\mathrm{S}}(\mu_R)\Big[B + \alpha_{\mathrm{S}}^{(\mathrm{NLO})} V(\mu_R) + \alpha_{\mathrm{S}}^{(\mathrm{NLO})} \int d\Phi_{\mathrm{r}} R\Big]$$

$$\bar{B}_{\mathrm{MiNLO}} = \alpha_{\mathrm{S}}(q_T)\Delta_q^2(q_T, m_V)\Big[B\left(1 - 2\Delta_q^{(1)}(q_T, m_V)\right) + \alpha_{\mathrm{S}}^{(\mathrm{NLO})} V(\bar{\mu}_R) + \alpha_{\mathrm{S}}^{(\mathrm{NLO})} \int d\Phi_{\mathrm{r}} R\Big]$$



☞ Sudakov FF included on V+j Born kinematics

- VJ−MiNLO yields finite results also when 1st jet is unresolved ($q_T \to 0$)
- $\bar{B}_{\mathrm{MiNLO}}$ ideal to extend validity of V+j POWHEG

- after further refinements (in particular include B_2 coefficient in MiNLO Sudakov), one can prove that `VJ-MiNLO` differential cross section $d\sigma_{\mathrm{VJ-MiNLO}}$ is NLO accurate when fully inclusive over QCD emissions [Hamilton,Nason,Oleari,Zanderighi '13]

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{NNLO}}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{VJ-MiNLO}}} = \frac{c_0 + c_1\alpha_{\mathrm{S}} + c_2\alpha_{\mathrm{S}}^2}{c_0 + c_1\alpha_{\mathrm{S}} + d_2\alpha_{\mathrm{S}}^2} \simeq 1 + \frac{c_2 - d_2}{c_0}\alpha_{\mathrm{S}}^2 + \mathcal{O}(\alpha_{\mathrm{S}}^3)$$

- reweighting each "MiNLO-generated" event (from LH file) with this factor, we get NNLO+PS

  - clear for fully-inclusive oservables (Φ_B)

  - "$\alpha_{\mathrm{S}} + \alpha_{\mathrm{S}}^2$" accuracy of `VJ-MiNLO` in 1-jet region not spoiled, because $W(\Phi_B) = 1 + \mathcal{O}(\alpha_{\mathrm{S}}^2)$

- for Higgs production, the function W was simply a function of y_H:

$$W(\Phi_B) \to W(y) = \frac{\left(\frac{d\sigma}{dy}\right)_{\mathrm{NNLO}}}{\left(\frac{d\sigma}{dy}\right)_{\mathrm{VJ-MiNLO}}} = \frac{c_0\alpha_{\mathrm{S}}^2 + c_1\alpha_{\mathrm{S}}^3 + c_2\alpha_{\mathrm{S}}^4}{c_0\alpha_{\mathrm{S}}^2 + c_1\alpha_{\mathrm{S}}^3 + d_2\alpha_{\mathrm{S}}^4} \simeq 1 + \frac{c_2 - d_2}{c_0}\alpha_{\mathrm{S}}^2 + \mathcal{O}(\alpha_{\mathrm{S}}^3)$$

NNLO+PS II

- For Drell-Yan, needs to use variables specifing the Born process $pp \to \ell\bar{\ell}$
  $\hookrightarrow$ also need variable to take into account spin-correlation in vector-boson decay products
- we need a 3-d differential distribution, and there is some freedom in choosing the 3 variables
  $\hookrightarrow$ Useful to make choices such that bins in multidimensional distribution are $\sim$ uniformly populatad
- we have chosen:
  - V-boson rapidity: y_V
  - variable for dilepton invariant mass: $\arctan((m_{\ell\ell}^2 - M_V^2)/(\Gamma_V M_V))$
  - angle between electron and beam in frame where $p_V^z = 0$

- For Drell-Yan, needs to use variables specifing the Born process $pp \to \ell\bar{\ell}$
  $\hookrightarrow$ also need variable to take into account spin-correlation in vector-boson decay products
- we need a 3-d differential distribution, and there is some freedom in choosing the 3 variables
  $\hookrightarrow$ Useful to make choices such that bins in multidimensional distribution are $\sim$ uniformly populatad
- we have chosen:
  - V-boson rapidity: y_V
  - variable for dilepton invariant mass: $\arctan((m_{\ell\ell}^2 - M_V^2)/(\Gamma_V M_V))$
  - angle between electron and beam in frame where $p_V^z = 0$

- Variants for W are possible:

$$W(\Phi_B, p_T) = h(p_T)\frac{\int d\sigma_A^{\mathrm{NNLO}}\delta(\Phi_B - \Phi_B(\mathbf{\Phi}))}{\int d\sigma_A^{\mathrm{MiNLO}}\delta(\Phi_B - \Phi_B(\mathbf{\Phi}))} + (1 - h(p_T))$$

$$d\sigma_A = d\sigma\ h(p_T), \qquad d\sigma_B = d\sigma\ (1 - h(p_T)), \qquad h = \frac{(\beta m_V)^2}{(\beta m_V)^2 + p_T^2}$$

- $h(p_T)$ controls where the NNLO/NLO K-factor is distributed
  (in the high-k_{T} region, there is no improvement in including it)

- β cannot be too small, otherwise resummation spoiled

NNLO+PS III

In 1309.0017, and for DY too, we use

$$W(\Phi_B, p_T) = h(p_T)\frac{\int d\sigma^{\rm NNLO}\delta(\Phi_B - \Phi_B(\mathbf{\Phi})) - \int d\sigma_B^{\rm MiNLO}\delta(\Phi_B - \Phi_B(\mathbf{\Phi}))}{\int d\sigma_A^{\rm MiNLO}\delta(\Phi_B - \Phi_B(\mathbf{\Phi}))} + (1 - h(p_T))$$

$$d\sigma_A = d\sigma\ h(p_T), \qquad d\sigma_B = d\sigma\ (1 - h(p_T)), \qquad h = \frac{(\beta m_V)^2}{(\beta m_V)^2 + p_T^2}$$

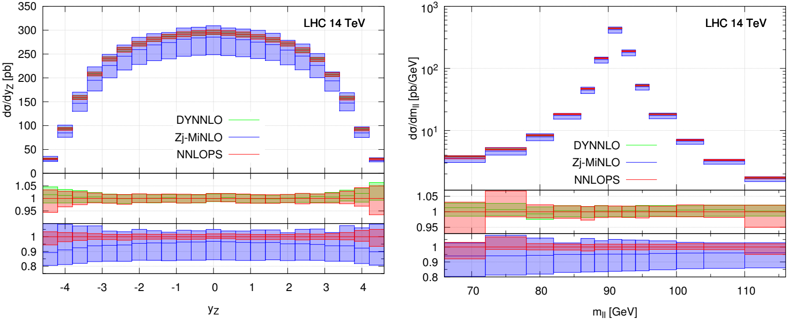
- one gets exactly $(d\sigma/d\Phi_B)_{\rm NNLO}$ (no α_S^3 terms)
- we used $h(p_T^{j_1})$, and $\beta = 1$

---

inputs for following plots:

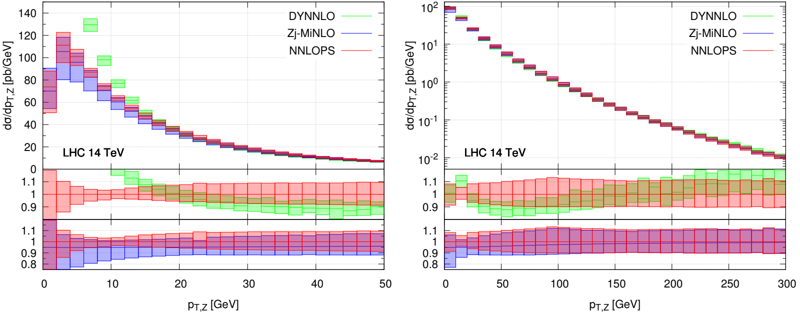
- scale choices: NNLO input with $\mu = m_V$, VJ-MiNLO has its own scale
- PDF: everywhere MSTW2008 NNLO
- NNLO from DYNNLO [Catani,Cieri,Ferrera et al.]
  (3pts scale variation, but 7pts in pure NNLO plots)
- MiNLO: 7pts scale variation (using POWHEG BOX-V2 machinery)
- events reweighted at the LH level: 21-pts scale variation $(7_{\rm Mi} \times 3_{\rm NN})$

Validation results: Z, PS level (I) Preliminary



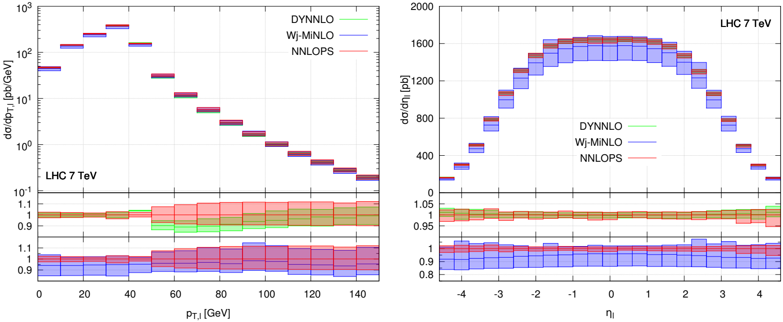
- $(7_{\rm Mi} \times 3_{\rm NN})$ pts scale var. in NNLOPS, 7pts in NNLO
- agreement with DYNNLO
- scale uncertainty reduction wrt ZJ-MiNLO

Validation results: Z, PS level (II) — Preliminary

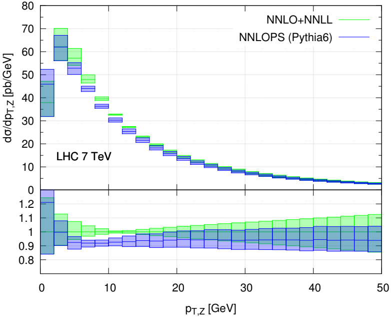


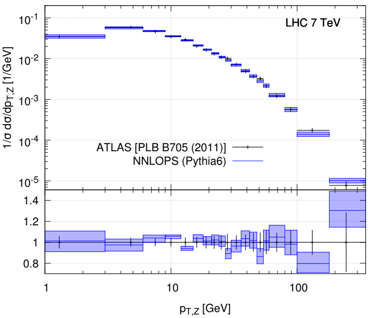
- NNLOPS: smooth behaviour at small k_{T}, where NNLO diverges
- at high p_T, all computations are comparable (band size similar)
- at very high p_T, `DYNNLO` and `ZJ-MiNLO` (and hence NNLOPS) use different scales !
- NNLO envelope shrinks at ~ 10 GeV; NNLOPS inherits it
  - uncertainties become in fact larger when NP-effects included
  - see also comparison with resummation

 Preliminary



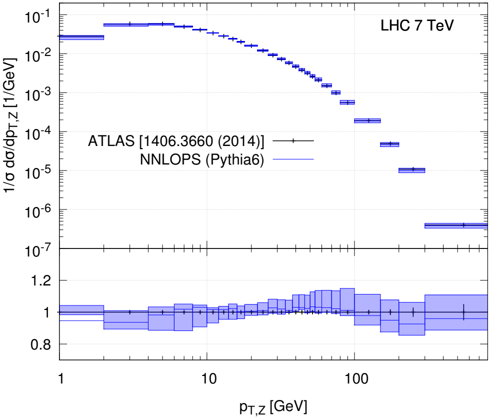
- not the observables we are using to do the NNLO reweighting
- we see exactly what we expect: $p_{T,\ell}$ has NNLO uncertainty if $p_T < M_W/2$, NLO if $p_T > M_W/2$, η_ℓ is NNLO everywhere
- smooth behaviour when close to Jacobian peak and thin binning
- just above peak, DYNNLO uses M_W, WJ-MiNLO uses $p_{T,W}$ and here $0 \lesssim p_{T,W} \lesssim M_W$





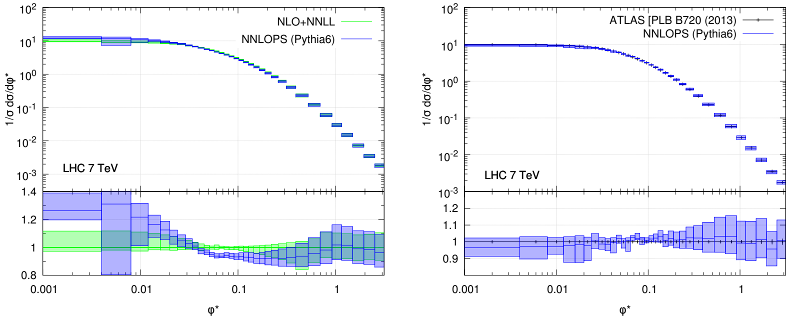
- resummation from DyQT [Bozzi,Catani,Ferrera, et al]
- good agreement with data (PS+hadronisation+MPI)
- agreement with resummation good (PS only), but not perfect
  - formal accuracy not exactly the same
  - shrinking of bands makes it looking perhaps worse than what it is...

Vector boson p_T (new-released data!) Preliminary



ϕ^*: resummation and data

Preliminary

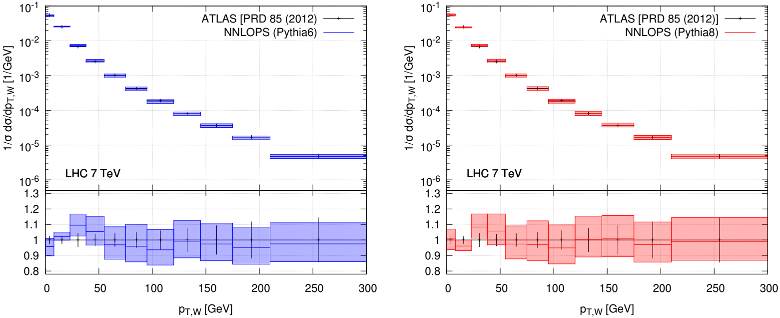


$$\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sin\theta^*$$

- θ^* is the scattering angle of the electron with respect to the beam, in Z boson rest frame
- ATLAS uses slightly different definition $\cos\theta^* = \tanh((y_{l^-} - y_{l^+})/2)$

- comparison with resummation [Banfi et al.] not very good at small ϕ^*
- non-perturbative effect seem important here, and indeed agreement with data is much better
- NP-effects observed here have same pattern as those discussed in Banfi et al. [1102.3594]

Vector boson p_T: data comparison for $p_{T,W}$ Preliminary



- data comparison both with `Pythia6` and `Pythia8`

Few technical details

- we use as input distributions from `DYNNLO`
- `POWHEG+MiNLO` events generation is highly parallelizable: grids (30 cores) + generating 20M events (+ reweighting to have 7-pts scale uncertainty) (400 cores): ~ 2 days
- "`MiNLO-to-NNLO`" rescaling takes few hours (for all 20M events)
- showering (+ hadronisation + MPI): ~ 2 M events/day (on 1 core)

Conclusions

- shown results for Drell-Yan at NNLOPS
- precision and theoretical uncertrainties match NNLO where they have to
- resummation effects important when close to Sudakov regions
  - agreement with data very good
  - with resummation good agreement, but not always as good as one would have hoped (especially for ϕ^*)
- paper will be out soon, and code will follow soon afterwards
  - we will release full code, but also prepare files for W function for LHC 7,8,13,14 TeV

- looking forward for interesting phenomenology (for instance W-mass measurement, interplay with EW effects,...)
- at this level of precision, a dedicated tune is probably needed to have as much consistency as possible everywhere

Conclusions

- shown results for Drell-Yan at NNLOPS
- precision and theoretical uncertrainties match NNLO where they have to
- resummation effects important when close to Sudakov regions
  - agreement with data very good
  - with resummation good agreement, but not always as good as one would have hoped (especially for ϕ^*)
- paper will be out soon, and code will follow soon afterwards
  - we will release full code, but also prepare files for W function for LHC 7,8,13,14 TeV

- looking forward for interesting phenomenology (for instance W-mass measurement, interplay with EW effects,...)
- at this level of precision, a dedicated tune is probably needed to have as much consistency as possible everywhere

Thank you for your attention!