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NNLO and parton shower predictions for Higgs production in the WW decay channel

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Introduction

- results of Higgs searches (especially exclusion limits) depend heavily on the knowledge of the expected Higgs event rate
  - example: CDF $H \rightarrow WW + 0$ *jets* analysis
    - experimental uncertainty: ~ 10 %
    - theoretical uncertainty: ~ 12 %

      on the expected signal rate [arXiv:0808.0534]
- very precise predictions for the inclusive (and partially exclusive) cross-sections (at NNLO and beyond) are available since a while
- combining them with parton shower Monte Carlos, the CDF/D0 searches claim 95% CL exclusion of a 170 GeV standard model Higgs

  [CDF and D0 collaborations, arXiv:0808.0534]

- higher order corrections for Higgs production are
  1. large (σ(NNLO)/σ(LO) ~ 2)
  2. phase-space region dependent, i.e. different after the application of experimental cuts
- we want to understand them (and thus the expected Higgs event rate) after the application of such selection cuts
- to do this we
  1. use a fully exclusive program to compute the cross-section at NNLO after the application of such cuts
  2. compare the results to parton shower MC event generators
- we do this focusing on the most promising discovery channel $H \rightarrow WW \rightarrow l\,\nu\,l\,\nu$ and a Higgs mass of 165 GeV

Example: Cut based analysis at LHC

- strategy: apply cuts on the final state phase-space to increase signal over background ratio
- typical cuts involve restrictions on
  1. the transverse angle φ_{ll} between the charged leptons
     - effective against WW continuum, ttbar ...
  2. the invariant mass m_{ll} of the lepton pair
     - effective against Drell-Yan, WZ, ...
  3. the missing transverse energy E_T^{miss}
     - effective against Drell-Yan, ZZ, ...
  4. the hadronic activity (jet-veto) in the final state
     - effective against ttbar, W + jets
  5. the transverse momentum of the harder lepton p_T^{max}

[M. Dittmar, H. Dreiner, PRD 55:167-172, 1997]

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Fully differential cross-section at NNLO

- starting point is the sector-decomposition program FEHiP, that allows to compute the NNLO Higgs cross-section in a fully differential way
  [C. Anastasiou, K. Melnikov, F. Petriello, Nucl.Phys.B 724, 2005]
- we add the full $H \rightarrow WW \rightarrow l\nu l\nu$ decay to the program and apply the selection cuts
- due to the severity of the cuts we had to restructure the numerical integration strategy
  - instead of sampling all the sectors simultaneously, we integrate them separately and sum up the results for the final number
- similar results have been obtained with a different program HNNLO, that uses a subtraction technique
  [M. Grazzini, JHEP0802:043, 2008]

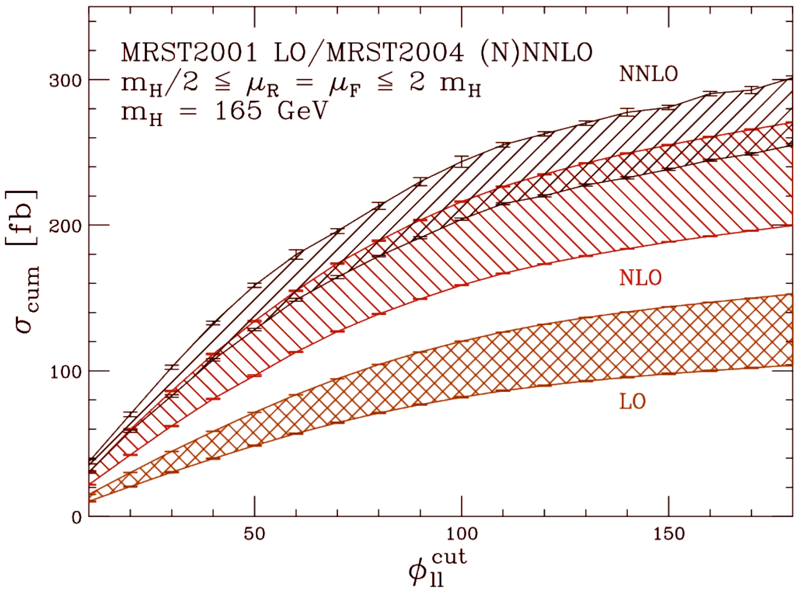
- to understand the effect of each cut on the higher order corrections we define the cumulative cross-section as

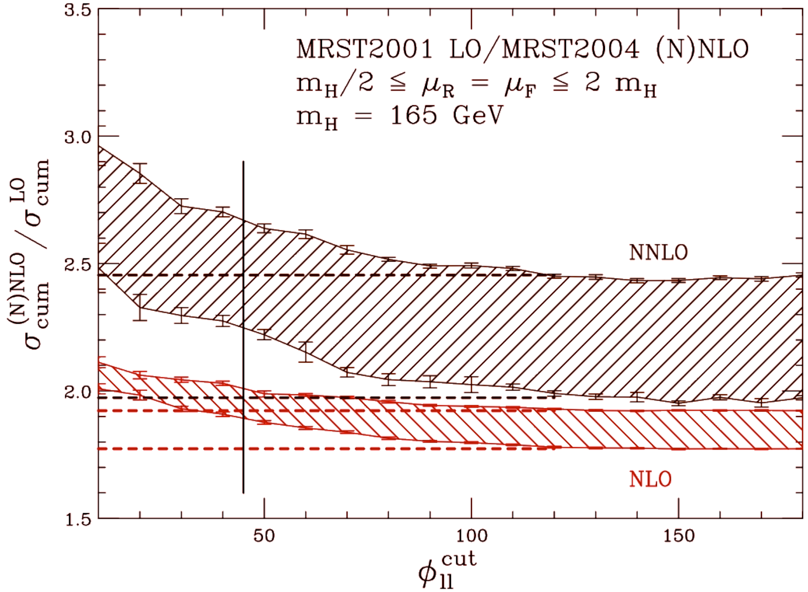
$$\sigma_{\mathrm{cum}}(X^{\mathrm{cut}}) = \int_0^{X^{\mathrm{cut}}} \frac{d\sigma}{dX} dX$$

- where X denotes one of the cut variables and X^{cut} a specific value for this cut
- and we study these distributions for each of the mentioned variables under the variation of the renormalization and factorization scales

Transverse Angle between Leptons

- reject events where the angle in the transverse plane between the charged leptons is larger then some cut-off φ_{ll}^{cut}

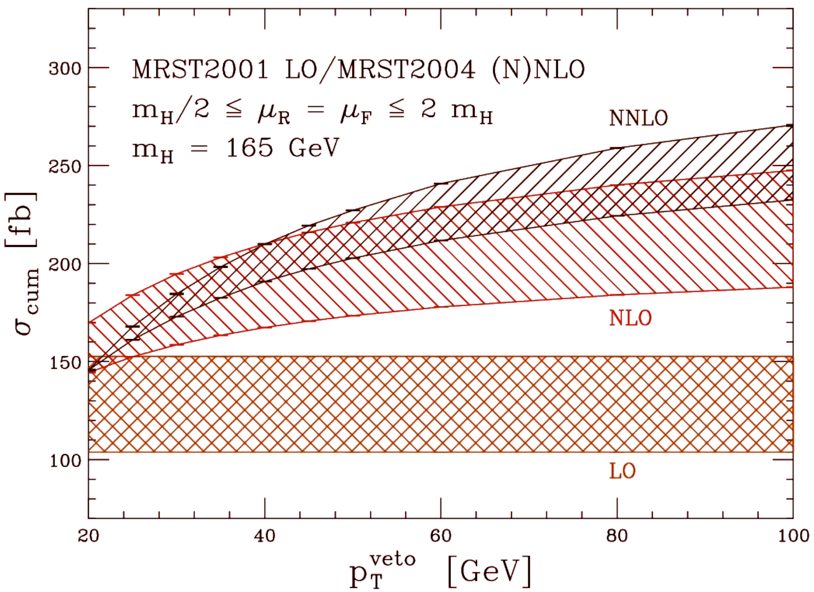


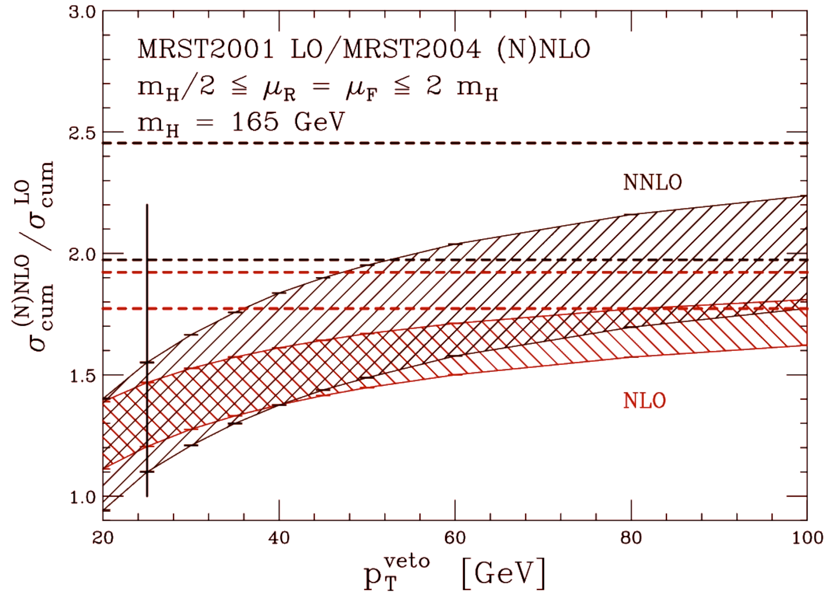


- the solid line on the right denotes a typical value of 45°
- the corrections increase when lowering the cut value on the lepton angle

Jet-Veto

- reject events containing jets in the central detector region ($|\eta| < 2.5$) above some cut-off p_T^{veto}





- jet-veto has no impact at LO (no partons in final state)
- jet-veto at NLO corresponds to cut on Higgs transverse momentum
- K-factors ($\sigma^{(N)NLO}/\sigma^{LO}$) depend heavily on cut-value!

Cross-Section after all cuts

- other variables have each a distinct behavior
  [C. Anastasiou et al., JHEP0709:018, 2007]
- cross-sections after the application of all cuts

$\sigma(\mathrm{fb})$	LO	NLO	NNLO
$\mu = \frac{M_h}{2}$	21.002 ± 0.021	22.47 ± 0.11	18.45 ± 0.54
$\mu = M_h$	17.413 ± 0.017	21.07 ± 0.11	18.75 ± 0.37
$\mu = 2M_h$	14.529 ± 0.014	19.50 ± 0.10	19.01 ± 0.27

- (N)NLO corrections are at the order of 1
  - depending on scale choice even < 1
  - inclusive corrections predict an increase by a factor of 2
- very small scale variation after cuts are applied

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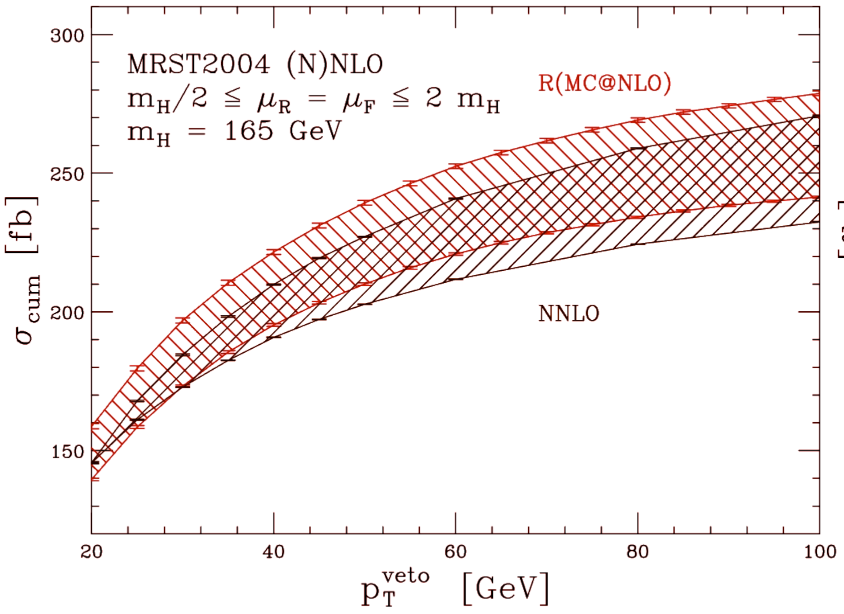
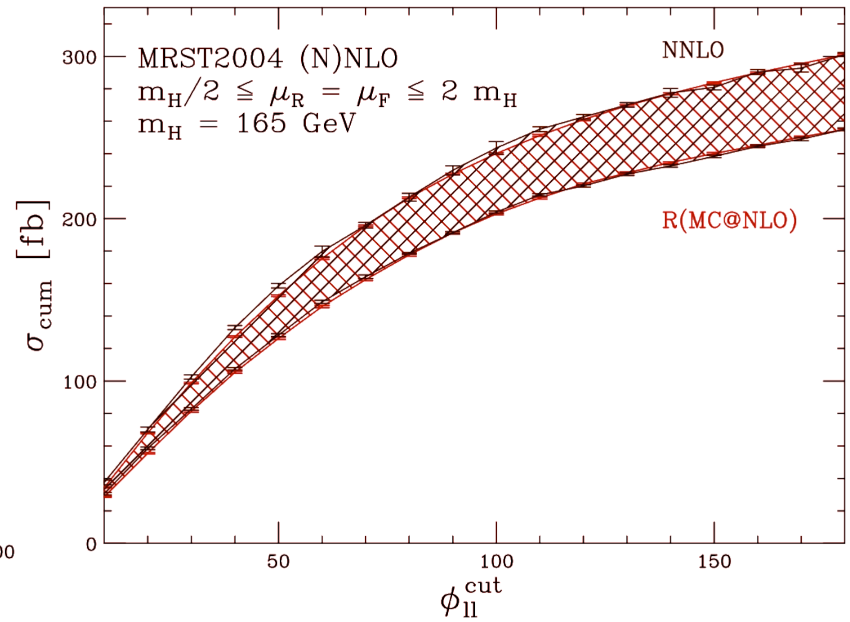
Comparison to MC@NLO

- for the process simulation in experimental studies event generators are needed
  - the events can be passed to detector simulation software
- we compare our NNLO results to the program MC@NLO, that incorporates NLO matrix elements with the parton shower of HERWIG
  [S. Frixione, B. Webber, JHEP0206:029, 2002]
  [G. Corcella et al. JHEP0101:010, 2001]
- a good agreement would give confidence that
  1. the effects of multiple soft and collinear radiation beyond NNLO can be neglected for such a study
  2. the main NNLO effects are captured in MC@NLO, thus it can be used for a reliable simulation

Cut variables: NNLO vs MC@NLO





- jet-veto: especially in the region of the envisaged cut (25 GeV) excellent agreement
- angular cut: 'perfect' agreement
- all other variables agree also 'perfectly'

  [Anastasiou et al. JHEP0803:017,2008]

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Signal Cross-Section: NNLO vs. MC@NLO

σ_{acc} [fb]	$\mu = \frac{m_{\mathrm{H}}}{2}$		$\mu = 2\, m_{\mathrm{H}}$	
jet algorithm	SISCone	k_{T}	SISCone	k_{T}
LO	21.00 ± 0.02		14.53 ± 0.01	
HERWIG	11.16 ± 0.04	11.59 ± 0.04	7.60 ± 0.03	7.89 ± 0.03
NLO	22.40 ± 0.06		19.52 ± 0.05	
MC@NLO	17.42 ± 0.08	18.42 ± 0.08	13.60 ± 0.06	14.39 ± 0.06
R^{NLO}(HERWIG)	19.79 ± 0.07	20.56 ± 0.07	14.61 ± 0.05	15.17 ± 0.05
NNLO	18.84 ± 0.59	18.45 ± 0.54	18.76 ± 0.31	19.01 ± 0.27
R^{NNLO}(MC@NLO)	19.33 ± 0.09	20.43 ± 0.09	17.24 ± 0.07	18.24 ± 0.07
R^{NNLO}(HERWIG)	22.02 ± 0.08	22.88 ± 0.08	18.65 ± 0.07	19.38 ± 0.07

- failure to agree at LO/NLO, due to the ‘poor’ hadronic structure
- very good agreement at NNLO ⇒ very accurate prediction

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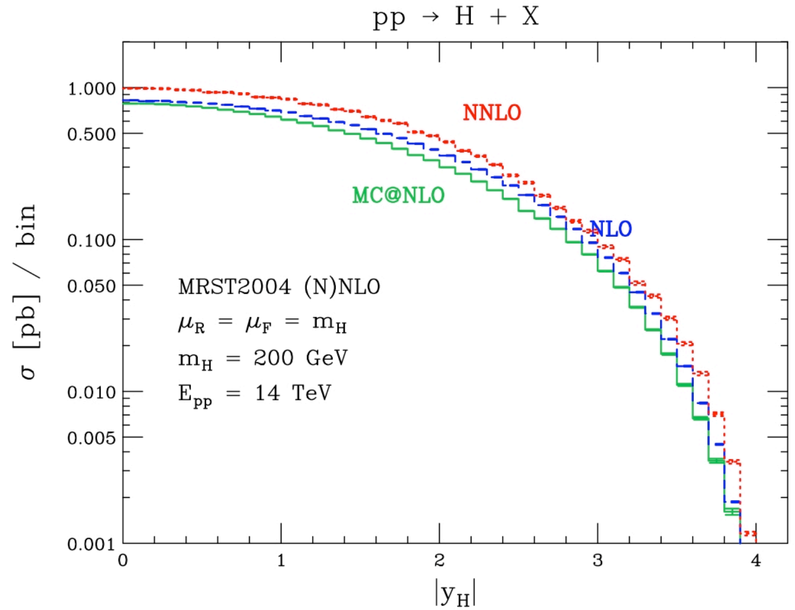
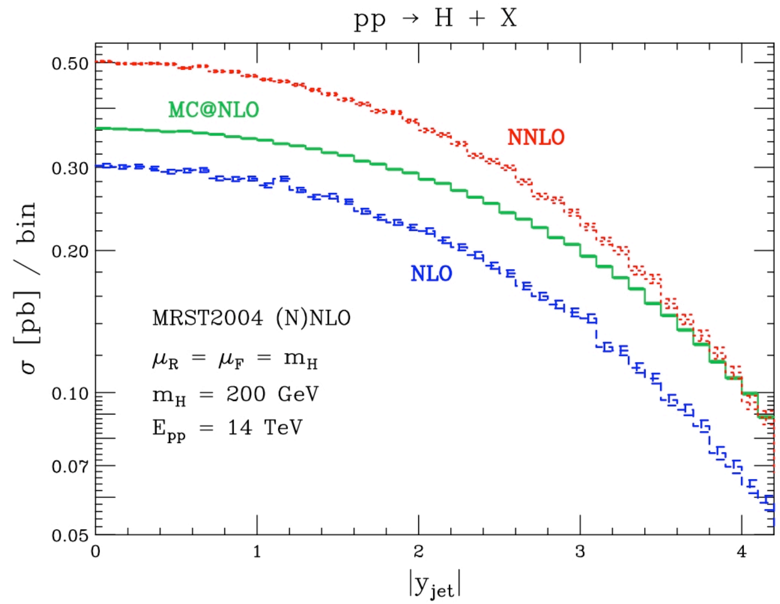
More sophisticated techniques

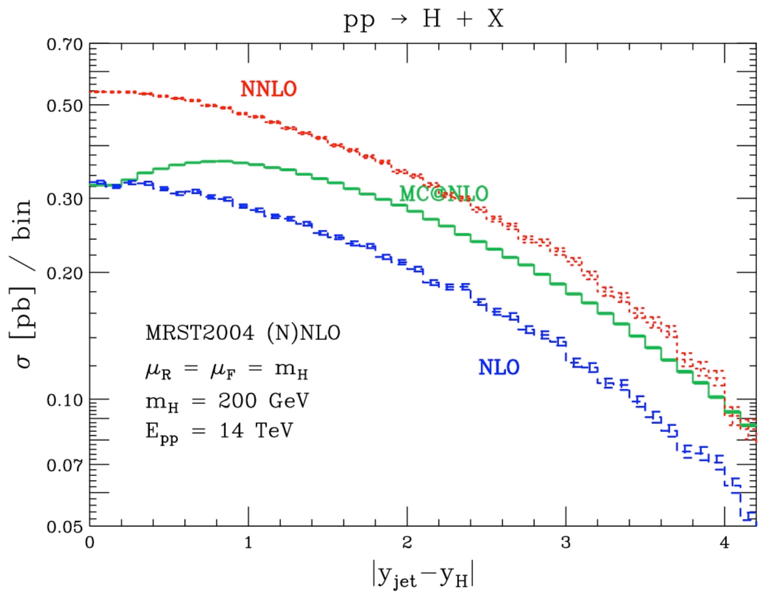
- the cut based analysis, though ‘easy’ to understand does not guarantee for the best performance
- to increase the analysis sensitivity more complex techniques are needed and already in use
  - artificial neural networks (ANN)
  - boosted decision trees, etc
- such analyses typically take distributions of kinematic variables as input
- to validate these distributions against a high precision calculation, our tool should be able to compute such distributions (histograms) effectively
- in addition it would be nice to being able to compute e.g. an ANN output distribution at fixed NNLO

Histograms in FEHiP

- usually, to compute histograms with programs relying on sector-decomposition, each bin of each histogram has to be computed separately
  - in contrast to programs like HNNLO
- this leads to long computing times
- this short-coming can be overcome by a ‘clever’ structuring of the code
- we have applied this strategy to the program FEHiP and are thus able to compute any number of histograms in one running procedure
- as a first application we compute the rapidity of the Higgs and the leading jet, as well as their difference at NNLO with a fine binning







- the fine binning and the excellent accuracy allow for a much better/faster comparison of e.g. MC@NLO spectra to fixed NNLO spectra

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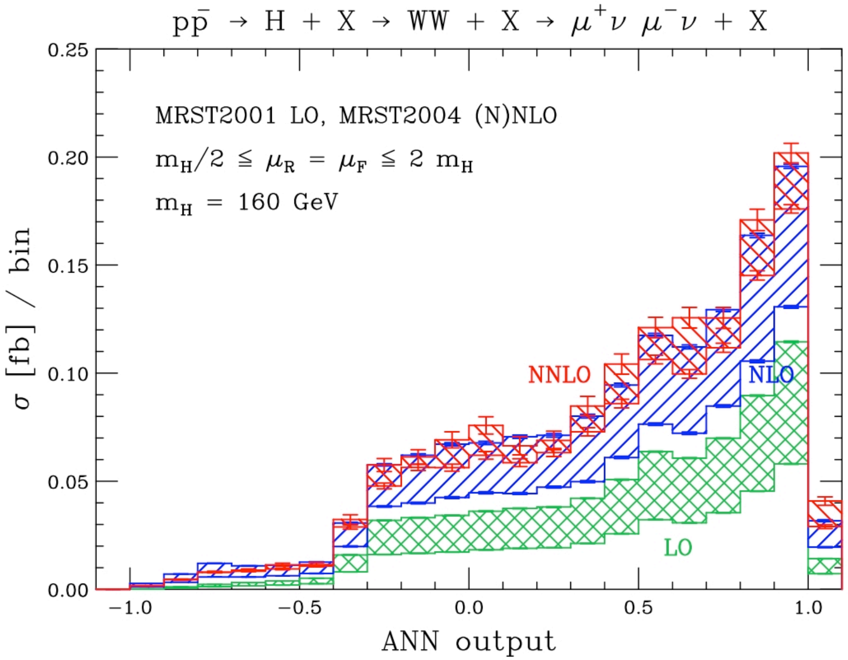
ANN at NNLO: Tevatron example

- as a final application we want to compute the distribution of a ANN outcome, as it is used by the Tevatron collaborations, at NNLO
- we use the TMVA root package and train the network with samples for Higgs (160 GeV), WW and ttbar processes generated with PYTHIA 8
- to these events we apply a pre-selection
  - muon trigger requirements and isolation
  - minimal transverse momenta for the leptons
  - cuts on invariant mass and missing transverse momentum
  - no more than 1 jet harder than 15 GeV
- the input variables to the ANN are:
  - p_T of the leptons, the invariant mass, the angle φ_{ll} and the missing transverse energy



- K-factor after pre-selection:
  - σ(NNLO)/σ(LO) ~ 1.9
- K-factor in last two bins:
  1. σ(NNLO)/σ(LO) ~ 2.9
  2. σ(NNLO)/σ(LO) ~ 1.8

⇒ the ANN is more ‘discriminating’ at NNLO

- ongoing study:
  - run for better precision
  - compare to parton shower MC
- to my knowledge: first time ANN output has been computed at fixed order beyond LO

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Conclusions

- we achieved a fully differential calculation and understanding of the QCD corrections up to NNLO for the possible discovery channel $H \to WW$
- the corrections are significant and have to be taken into account for an accurate cross-section prediction
- there are tools that allow for the computation of
  1. cross-sections after experimental cuts up to NNLO
  2. distributions of any kinematic variables after such cuts (input to multi-variate analyses (MVA), e.g ANN)
  3. distributions of the output variables of such MVAs
- the tools can in principle be extended to take into account lepton reconstruction efficiencies, jet energy scales etc.
- scale variation and higher order effects can be studied in detail to allow for an accurate estimation of the theoretical uncertainty on the expected signal event rate
- a version of FEHiP including all these features should be available soon

BACKUP SLIDES