WW production at NNLO+PS

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CERN & LAPTh Annecy

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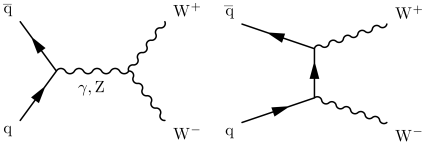
*ongoing work with M. Wiesemann and G. Zanderighi

introduction and outline



- vector boson pair production
  - access to anomalous gauge couplings.
  - background for several searches, for instance $H \to WW$.

- as shown in previous talk, the current experimental precision already demands for predictions that go beyond NLO(+PS) accuracy.
- NNLO corrections are certainly needed, and resummation too, in corners of phase-space.

- this talk: matching NNLO and PS for $pp \to W^+W^-$, using **MiNLO** and **MATRIX**

(a) method: (improved) MiNLO

(b) NNLO input: MATRIX

(c) results [preliminary]

[the literature on VV production is vast, so I will refrain from trying to summarize it]

Multiscale Improved NLO

[Hamilton,Nason,Zanderighi '12]

- original goal: method to a-priori choose scales in multijet NLO computation
- non-trivial task: hierarchy among scales can spoil accuracy (large logs can appear, without being resummed)
- how: correct weights of different NLO terms with CKKW-inspired approach (without spoiling formal NLO accuracy)

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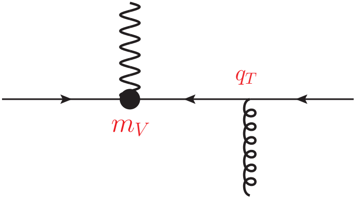

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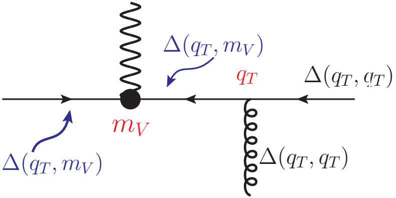

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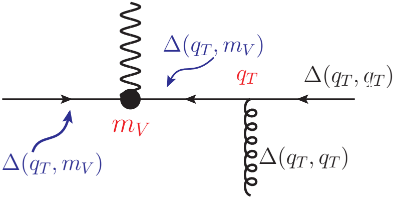

- $\bar{\mu}_R = q_T$
- $\log \Delta_{\mathrm{f}}(q_T, m_V) = -\int_{q_T^2}^{m_V^2} \frac{dq^2}{q^2} \frac{\alpha_{\mathrm{S}}(q^2)}{2\pi}\left[A_f \log \frac{m_V^2}{q^2} + B_f\right]$
- $\Delta_{\mathrm{f}}^{(1)}(q_T, m_V) = -\frac{\alpha_{\mathrm{S}}}{2\pi}\left[\frac{1}{2}A_{1,\mathrm{f}} \log^2 \frac{m_V^2}{q_T^2}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

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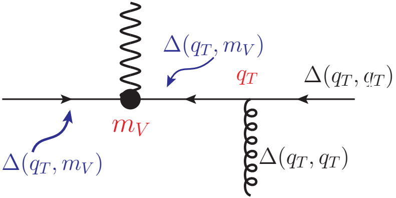

☞ Sudakov FF included on V+j Born kinematics

- MiNLO-improved VJ yields finite results also when 1st jet is unresolved ($q_T \to 0$)
- $\bar{B}_{\mathrm{MiNLO}}$ allows extending the validity of VJ−POWHEG [called "VJ-MiNLO" hereafter]

MiNLO′

- formal accuracy of VJ-MiNLO for inclusive observables carefully investigated.

  [Hamilton et al. 1212.4504]

- possible to improve VJ-MiNLO such that inclusive NLO is recovered (NLO$^{(0)}$), without spoiling NLO accuracy of V+j (NLO$^{(1)}$):

  MiNLO′ : NLO+PS merging, without merging scale

- accurate control of subleading small-p_T logarithms is needed:
  - include B_2 (NNLL) coefficient in MiNLO-Sudakov.
  - set scales in R, V and subtraction terms equal to q_T (boson transverse momentum).
  - without the above requirements, spurious $\alpha_S^{3/2}$ terms show up in $\sigma_{\rm NLO}^{(0)}$ upon integration over q_T.

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  - without the above requirements, spurious $\alpha_S^{3/2}$ terms show up in $\sigma_{\mathrm{NLO}}^{(0)}$ upon integration over q_T.
- for color-singlet production X, the above procedure is general, and (almost) process independent.

	X (inclusive)	X+j (inclusive)	X+2j (inclusive)
✓ X-XJ @ NLOPS	NLO	NLO	LO
X @ NNLOPS	NNLO	NLO	LO

- a generalization of the MiNLO′ approach for processes with jets at LO has also been proposed (but here we are not using it). [Frederix,Hamilton '15]

MiNLO′ : from Drell-Yan to WW

A MiNLO′ generator that merges WW and WW + 1 jet at NLO+PS
was obtained a while ago: [Hamilton,Melia,Monni,ER,Zanderighi '16]

- POWHEG WWJ generator obtained ex-novo using interfaces to Madgraph and Gosam 2.0
[Campbell et al. 1202.547; Luisoni et al. 1306.2542; Cullen et al. 1404.7096]

- starting from the Drell-Yan case, we extracted the $B_2^{\text{(WW)}}$ term from the virtual ($V^{\text{(WW)}}$) and Born ($B^{\text{(WW)}}$) contributions of $pp \to WW$.

  - for Drell-Yan, $V^{\text{(V)}}$ and $B^{\text{(V)}}$ are proportional, hence $B_2^{\text{(V)}}$ is just a number.
  - in $pp \to WW$, this is no longer true: $B_2^{\text{(WW)}} = B_2^{\text{(WW)}}(\Phi_{WW})$:
    - for $q\bar{q}$-initiated color singlet production, B_2 has the form

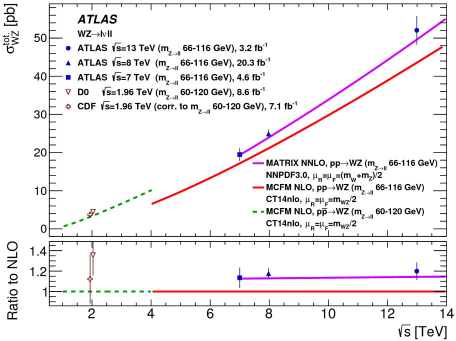
$$B_2 = -2\gamma^{(2)} + \beta_0 C_F \zeta_2 + 2(2C_F)^2\zeta_3 + \beta_0 H_1(\Phi)$$

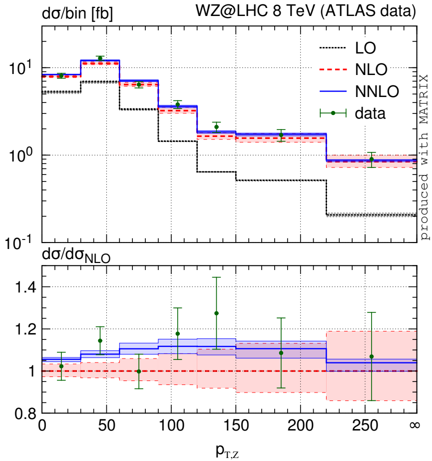
- $H_1(\Phi)$ (process-dependent part of B_2) extracted on an event-by-event basis:
projection of Φ_{WWJ} onto Φ_{WW}, used FKS ISR mapping (smooth collinear limit).

- for validation and results, see paper from '16.

importance of NNLO for diboson production

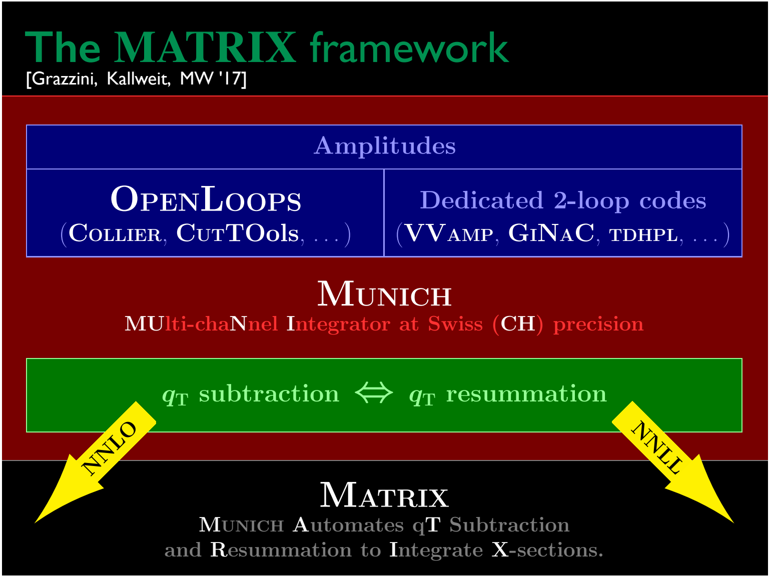
...clear example where plots speak for themselves...





► NNLO results in these plots: MATRIX

[Grazzini,Kallweit,Wiesemann -'17]



[slide from talk by M. Wiesemann, CERN, Feb '18]

- q_T *-subtraction* formalism, in a nutshell [Catani,Grazzini '07]

$$\mathrm{d}\sigma^{\mathrm{F}}_{\mathrm{(N)NLO}} = \mathcal{H}^{\mathrm{F}}_{\mathrm{(N)NLO}} \otimes \mathrm{d}\sigma^{\mathrm{F}}_{\mathrm{LO}} + \left[\mathrm{d}\sigma^{\mathrm{F+jet}}_{\mathrm{(N)LO}} - \mathrm{d}\sigma^{\mathrm{CT}}_{\mathrm{(N)NLO}}\right]$$

  - subtraction term known from resummation, and process independent (apart from LO dependence).
  - hard-collinear function: can be extracted from 2-loops amplitudes.
  - so far, extensively used for color-singlet production at NNLO.

MATRIX

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- as shown next, for NNLOPS, one needs

$$\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{NNLO}} \leftarrow \text{fully differential in the Born phase space}$$

- we used MATRIX:

  2-loops amplitudes from VVAMP [Gehrmann et al. '15]
  tree-level and 1-loop from OPENLOOPS [Cascioli et al. '11]
  see also: [Grazzini,Kallweit,Pozzorini,Rathlev,Wiesemann '16]

- we have NOT included the gg loop-induced channel
  - it's about 30% of the NNLO correction.

NNLO+PS for color-singlet production

- starting from a `MiNLO'` generator, it's possible to match a PS simulation to NNLO.
- `XJ-MiNLO'` (+`POWHEG`) generator gives X-XJ @ NLOPS:

	X (inclusive)	X+j (inclusive)	X+2j (inclusive)
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- reweighting (differential on Φ_B) of "MiNLO-generated" events:

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{NNLO}}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{XJ-MiNLO'}}}$$

  - by construction NNLO accuracy on inclusive observables; [✓]
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of XJ−MiNLO in 1-jet region; [ ]

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  - notice: formally works because no spurious $\mathcal{O}(\alpha_S^{1.5})$ terms in X-XJ @ NLOPS (relative to σ_X).

WW at NNLO+PS, in practice

- $pp \to e^- \bar{\nu}_e \mu^+ \nu_\mu$: Φ_B is 9-dimensional [impossible]
- choose variables, drop dependence upon (ℓ, ν_ℓ) invariant masses (fairly flat)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_B} = \frac{\mathrm{d}^9\sigma}{\mathrm{d}p_{T,W^-}\,\mathrm{d}y_{WW}\,\mathrm{d}\Delta y_{W^+W^-}\,\mathrm{dcos}\,\theta^{\mathrm{CS}}_{W^+}\,\mathrm{d}\phi^{\mathrm{CS}}_{W^+}\,\mathrm{dcos}\,\theta^{\mathrm{CS}}_{W^-}\,\mathrm{d}\phi^{\mathrm{CS}}_{W^-}\,\cancel{\mathrm{d}m_{W^+}}\,\cancel{\mathrm{d}m_{W^-}}}$$

- use "Collins-Soper" angles for both W decays

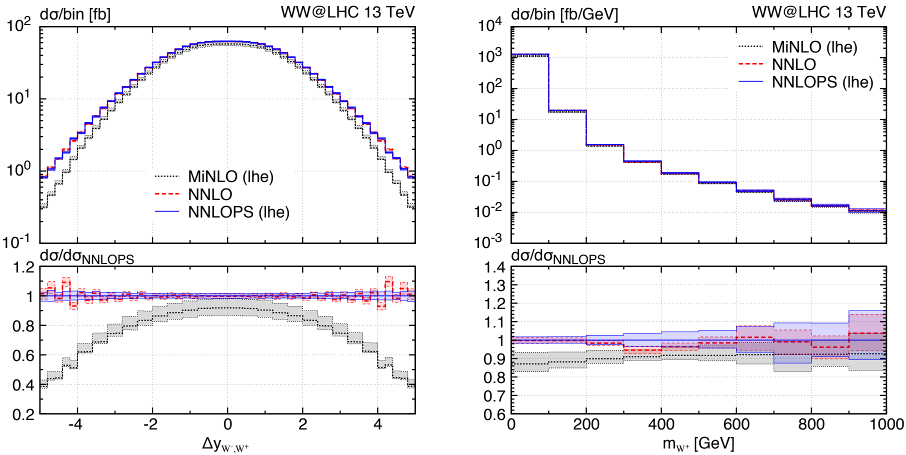
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_B} = \frac{9}{256\pi^2} \sum_{i=0}^{8} \sum_{j=0}^{8} AB_{ij}\, f_i(\theta^{\mathrm{CS}}_{W^-}, \phi^{\mathrm{CS}}_{W^-})\, f_j(\theta^{\mathrm{CS}}_{W^+}, \phi^{\mathrm{CS}}_{W^+})$$

$$AB_{ij} = AB_{ij}(p_{T,W^-}, y_{WW}, \Delta y_{W^+W^-})$$

- final complexity: 81 triple-differential distributions at NNLO [doable]

WW at NNLO+PS: validation

[ER,Wiesemann,Zanderighi, preliminary]



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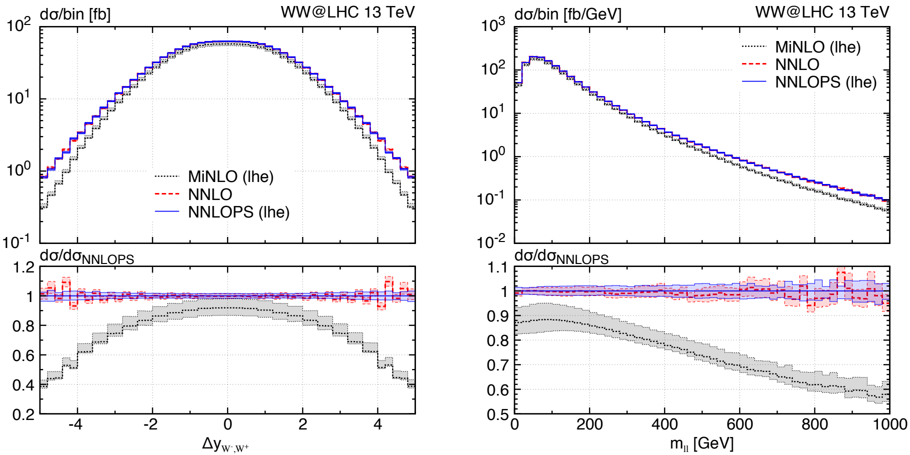
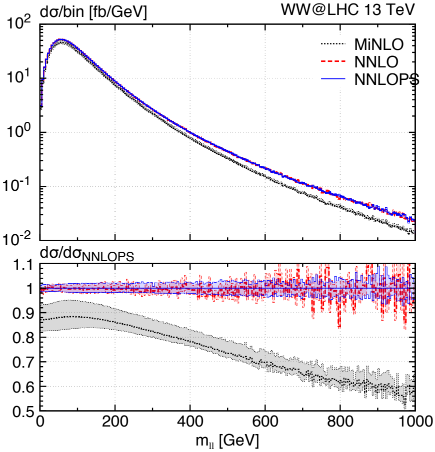
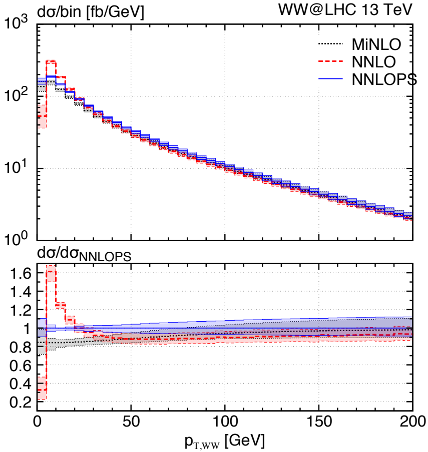


- m_W distribution well reproduced also off from peak.
- validated also other "Born" observables, as well as angular dependence (Collins-Soper angles) [not shown].

WW at NNLO+PS: results

[ER,Wiesemann,Zanderighi, preliminary]

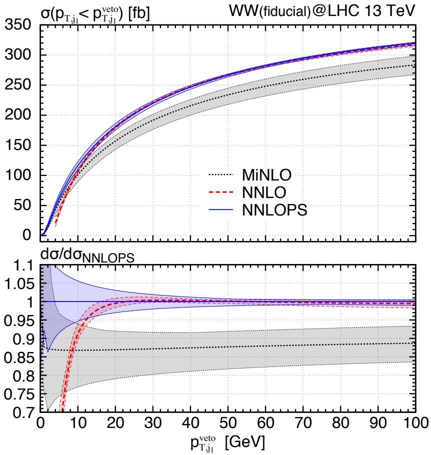




- expected patterns in inclusive and exclusive observables.
- the jet-vetoed cross-section is particularly important (e.g. for Higgs studies, but also to just measure WW production).

WW at NNLO+PS: results

[ER,Wiesemann,Zanderighi, preliminary]



- jet-veto cross section.
- fiducial cuts almost identical to ATLAS analysis [1702.04519]
- in ATLAS paper, jet-veto at 25/30 GeV.

conclusion and outlook

- ongoing remarkable progress of NNLO computations: try to match them with parton showers.
- for color-singlet-production, **POWHEG+MiNLO** allows to do that.

  [other methods are possible]
- shown for the first time (preliminary) results for WW production at NNLO+PS ($pp \to e^- \bar{\nu}_e \mu^+ \nu_\mu$).
- Next steps:
  - finish paper, release code;
  - other diboson processes...;
  - loop-induced gluonic channels; available at NLO+PS [Alioli et al. '16]
  - find more efficient method;

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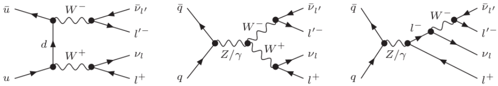
Thanks for your attention!

Extra slides

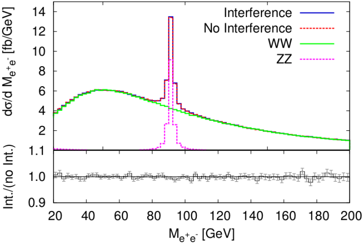
$\texttt{WWJ-MiNLO'}$: technical details and choices

- All off-shell and single-resonant diagrams included. Full matrix-element with leptonic decays.



- worked in the 4F scheme: no interference with Wt and $t\bar{t}$.
- for same-family leptons, "$Z(\to \ell\bar{\ell})Z(\to \nu_\ell\bar{\nu}_\ell)$" not included:

  - will be part of ZZ generator ;
  - interference between WW and ZZ shown to be extremely small ; [Melia et al. 1107.5051]



- option to include/exclude fermionic loop corrections (at most 1-2% difference in tails, x2 difference in speed).

NNLOPS: technical details

- Variants for reweighting $W(\Phi_B)$ are also possible:

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

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

- freedom to distribute "NNLO/NLO K-factor" only over medium-small p_T region
  - $h(p_T)$ controls where the NNLO/NLO K-factor is distributed
    (in the high-p_T region, there is no improvement in including it)
  - β cannot be too small, otherwise resummation spoiled:
    for Higgs, chosen $\beta = 1/2$; for DY, HW, WW, $\beta = 1$

- in practice, we used

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

  - one gets exactly $(d\sigma/d\Phi_B)_{\rm NNLOPS} = (d\sigma/d\Phi_B)_{\rm NNLO}$
  - chosen $h(p_T^{j_1})$