Latest developments in the simulation of final states involving top-pair and heavy bosons

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LAPTh Annecy

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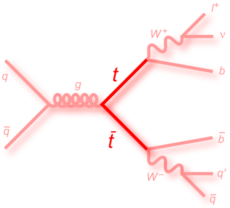
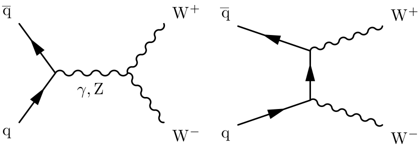
Plan of the talk

1. top-pair production

   - recent progress in the simulation of fully differential $pp \to W^+W^-b\bar{b}$ at NLO+PS





2. vector boson pair production

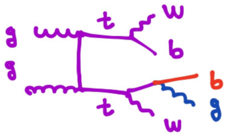
   - NLO+PS merging of $pp \to WW$ and $pp \to WWj$ using `MiNLO`

- throughout the talk, W bosons are understood to be offshell and decay products fully included
- I will just focus on QCD aspects of MC simulations (no EW)

1. top-pair production

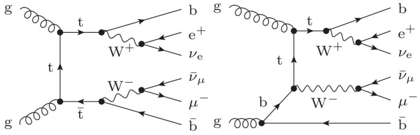
$pp \to W^+W^-b\bar{b}$ at the LHC

★ measurement of the top-mass: at the LHC likely to be achieved from combination of different strategies: total x-section, $t\bar{t}$ + jet, leptonic spectra, $b\ell$ endpoint and distribution,...
[see *e.g.* TOP LHC Working Group]



- some techniques rely on looking into the kinematics of visible particles from top-decay
- important that simulations are as accurate as possible, and associated uncertainties are quantified

★ $t\bar{t}$ vs. tW: by including decays with massive b, unified treatment of $t\bar{t}$ and tW:



- " $t\bar{t}$ " $\to WWbb$: 2 resolved b-jets
- " Wt " $\to WWb$: veto on second b-jet
- arbitrary cuts on the other objects

★ jet-vetoes: used in many searches where $t\bar{t}$ is a background (*e.g.* $H \to W^+W^-$):

- vetoes can also act on decay products (*e.g.* b-jet veto)

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important to have a fully-consistent NLO+PS simulation of $W^+W^-b\bar{b}$

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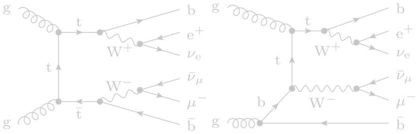

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$pp \to W^+W^-b\bar{b}$ at the LHC: what is known

- at fixed order a lot is known (and automated):
  - QCD NLO in production and decay, narrow-width approximation
    [Bernreuther et al],[Melnikov,Schulze],[Campbell,Ellis]
    - known also in presence of 1, 2 and 3 extra jets [Dittmaier et al, Bevilacqua et al] [Hoeche, Maierhoefer, et al '16]
  - fully exclusive NLO, massless b-quarks [Denner et al],[Bevilacqua et al],[Heinrich et al]
  - fully exclusive NLO, massive b-quarks [Frederix '13],[Cascioli,Kallweit, et al '13]
    - known also in presence of 1 extra jet [Bevilacqua et al '15]
- `POWHEG` and `MC@NLO` are well established
- a `POWHEG` implemenation for the full final state (5FS) was already attempted
  [Garzelli,Kardos,Trocsanyi '14]

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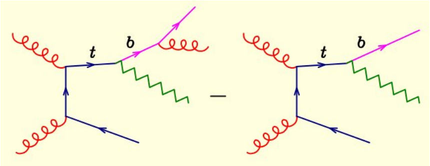
- a fully-consistent NLO+PS simulation of $W^+W^-b\bar{b}$, with exact decays at NLO and offshellness effects (no approximations), was obtained in `POWHEG` only few weeks ago!

- similar effort is ongoing also within the `MC@NLO` scheme [Frederix et al '16]

in the following: issues and solutions thereof

towards $WWbb$ at NLO+PS

1. problem already present at NLO: commonly-used subtraction schemes don't preserve top virtuality between real emission terms and their counterterms



- top-quark virtuality displaced by amount m_{bg}^2/E_b
- IR cancellation spoiled while approaching IR limit (when bgW is on-shell, the counterterm goes off-shell)

2. at NLO+PS, further problems:

$$d\sigma = d\Phi_{\rm rad}\bar{B}(\Phi_B)\frac{R(\Phi_B,\Phi_{\rm rad})}{B(\Phi_B)}\exp\left[-\int\frac{R(\Phi_B,\Phi_{\rm rad})}{B(\Phi_B)}d\Phi_{\rm rad}\right]$$

$\Phi_B \to (\Phi_B, \Phi_{\rm rad})$ mapping doesn't preserve virtuality, therefore R/B can become large also far from collinear singularity, but it shouldn't

- expect shape distorsions of b-jet distributions

3. `POWHEG` radiation should have a well-defined resonance assignment, otherwise the shower will not preserve invariant masses, distorting the BW shape.

- need to define a resonance history. However a full $WWbb$ computation contains non-doubly-resonant terms, interferences,...

towards $WWbb$ at NLO+PS

Some of these issues were addressed at the end of 2014, using matrix elements in the narrow-width approximation: [Campbell,Ellis,Nason,ER '14]

- in narrow-width limit, NLO corrections in production and decay factorize
  - real (and virtual) corrections can be separated between production and decay
  - if radiation comes from a resonance decay, Φ_B constructed in the resonance frame: top-virtuality is preserved (both at NLO and when generating the POWHEG first emission) [✓]
  - unique resonance history (no ambiguity): radiation either from production, or from decay [✓]
- finite-width effects included approximately, by rescaling with exact LO matrix elements
  - generic (offshell) phase-space + projection onto on-shell zero-width phase-space
  - reweighting using LO exact results (finite width, non-double-resonant diagrams,...) [✓]

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- "multiplicative POWHEG": keep multiple emissions before showering [☜]
  - by default POWHEG is additive: keeps only the hardest emission
  - for heavy-pair production and decay, emissions from decay are rarely the hardest. Hence, with default POWHEG, they would be mostly generated by the shower
  - keep hard radiation and the emissions from all decaying resonances, then merge them into a single radiation phase space with several radiated partons, up to one for each resonance

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$$d\sigma = \bar{B}(\Phi_{\rm B})\, d\Phi_{\rm B} \left[\Delta(q_{\rm cut}) + \sum_{\alpha} \Delta(k_T^\alpha) \frac{R_\alpha(\Phi_\alpha(\Phi_{\rm B}, \Phi_{\rm rad}))}{B(\Phi_{\rm B})}\, d\Phi_{\rm rad} \right]$$

$$\Rightarrow \quad d\sigma = \bar{B}(\Phi_{\rm B})\, d\Phi_{\rm B} \prod_{\alpha=\alpha_b,\alpha_{\bar{b}},\alpha_{\rm ISR}} \left[\Delta_\alpha(q_{\rm cut}) + \Delta_\alpha(k_T^\alpha) \frac{R_\alpha(\Phi_\alpha(\Phi_{\rm B}, \Phi^\alpha_{\rm rad}))}{B(\Phi_{\rm B})}\, d\Phi^\alpha_{\rm rad} \right]$$

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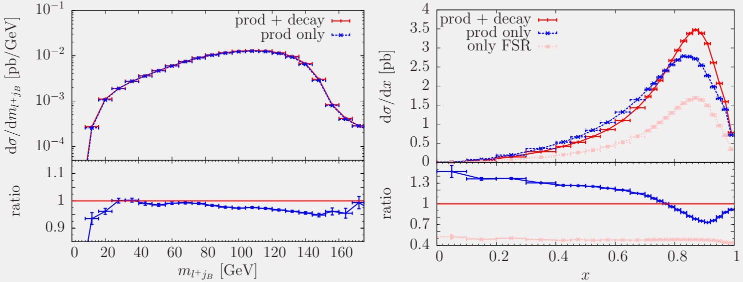

- left: 5% effects on $m_{\ell j_b}$ distribution
- right: fragmentation function ($x = E_B/E_{B,max}$)

$WWbb$ at NLO+PS

- recently a general solution was proposed: [Jezo,Nason '15]
  tested for single-top + framework ("`POWHEG-BOX-RES`")
- method refined and applied to the $WWbb$ case: [Jezo,Lindert,Nason,Oleari,Pozzorini '16]
  (important by-product: general interface `POWHEG-BOX + OpenLoops`)

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1. complete matrix elements for $W^+W^-b\bar{b}$ final state are used, no approximations
2. need to project each partonic subprocess onto all possible "resonance histories":
   - projectors: built by combining terms like $\dfrac{M_i^4}{(s_i - M_i^2)^2 + \Gamma_i^2 M_i^2}$
   - each contribution should be dominated by a single resonance history:

     $$B_{f_b} = \Pi_{f_b} B_{F_b} \qquad B_{F_b} = \sum_{f_b \in T(F_b)} B_{f_b}$$

   - for real contributions, split also according to compatible FKS regions:
     - only pair or partons "belonging" to the same resonance are "allowed" to become collinear
     - a term R_{α_r} is dominant if the collinear partons of region α_r have the smallest k_T, and the corresponding resonance history is the closest to its mass shell.
3. by doing so, each term is attributed to an unique resonance history
   - virtuality-preserving mappings between Φ_B and $(\Phi_B, \Phi_{\text{rad}})$ can be used
   - (& other technical subtleties that I won't discuss...)

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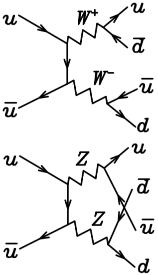

$$P_b^1 = \frac{M_W^4}{(s_{34} - M_W^2)^2 + \Gamma_W^2 M_W^2} \times \frac{M_W^4}{(s_{56} - M_W^2)^2 + \Gamma_W^2 M_W^2}$$

$$P_b^2 = \frac{M_Z^4}{(s_{35} - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \times \frac{M_Z^4}{(s_{46} - M_Z^2)^2 + \Gamma_Z^2 M_Z^2}$$

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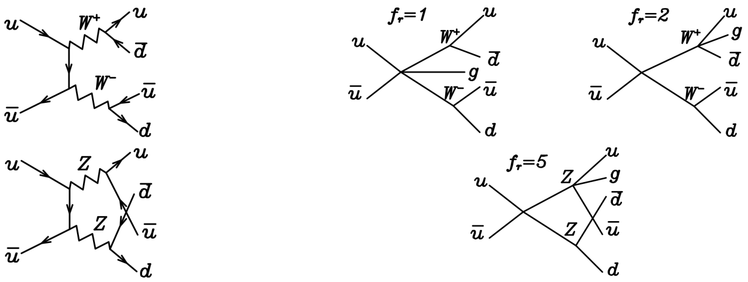

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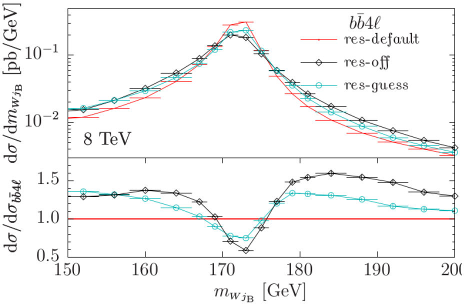
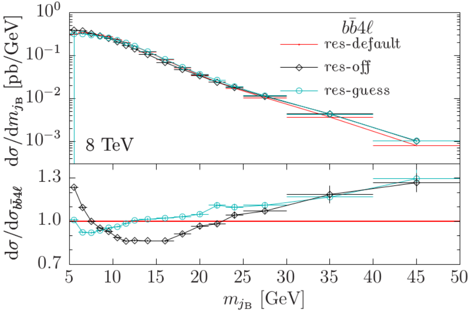
$WWbb$ at NLO+PS: results I

[Jezo,Lindert,Nason,Oleari,Pozzorini '16]

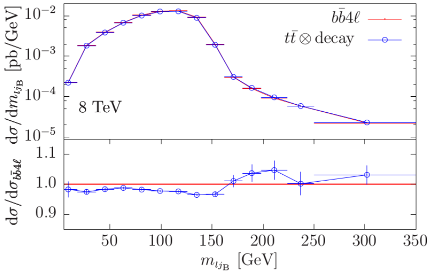


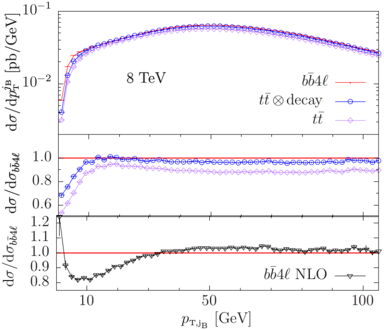


- no cuts.
- "res-default": resonance-aware, "res-off": not-resonance-aware, "res-guess": guess resonance history a posteriori, using event kinematics
- left: important effects both from information made available to parton-showering, but also from generating radiation using resonance history
- right: less radiation close to B in "res-off". Distorsion of b-jet mass ("expected" to be at $m^2 \approx E_b\Gamma_t$, *i.e.* $m_j \simeq 8$ GeV)

$WWbb$ at NLO+PS: results II

[Jezo,Lindert,Nason,Oleari,Pozzorini '16]





- "tt⊗decay": based on narrow-width [Campbell,Ellis,Nason,ER '14]
- left: $t\bar{t}$ cuts. Very good agreement: serves also as a validation, since one result supports the choices made to obtain the other.
- right: no cuts. Clearly shows the "Wt" contribution, particularly relevant at small transverse momenta.

2. vector boson pair production

W-pair production

★ WW as signal and background:

- interesting on its own: access to anomalous gauge couplings
- it's a background for several searches, for instance $H \to WW$

- as for top-pair, lot of progress has been done on the theory side (part of which will be presented tomorrow)
  - WW + 1, 2 and 3 extra jets [Campbell et al '07,Campbell,Miller,Robens '15],[Melia et al '11] [Febres Cordero,Hofmann,Ita '16]
  - gluon-induced, now also at NLO [Caola et al '16]
  - NNLO QCD [Grazzini et al '16]
- in `Sherpa` and `MG5_aMC@NLO`, NLO+PS merging available (using the `MEPS@NLO` and "FxFx" schemes, respectively)
- recent results also in `Herwig++` [Bellm et al '16]

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rest of the talk: NLO+PS merging of WW and WW+1 jet using `MiNLO`

[Hamilton,Melia,Monni,ER,Zanderighi '16]

MiNLO [in 1 slide]

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)
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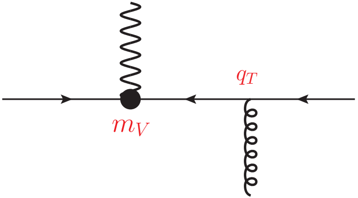

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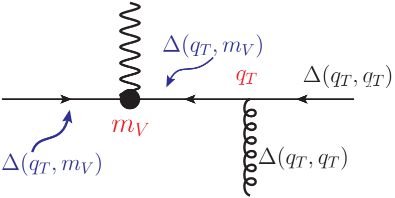

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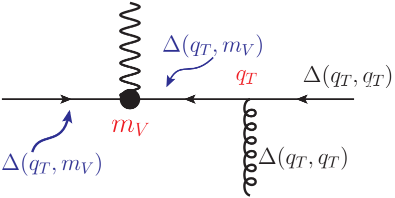

- $\bar{\mu}_R = q_T$
- $\log \Delta_{\mathrm{f}}(q_T, m_V) = -\int_{q_T^2}^{m_V^2} \frac{dq^2}{q^2} \frac{\alpha_{\mathrm{S}}(q^2)}{2\pi}\left[A_f \log\frac{m_V^2}{q^2} + B_f\right]$
- $\Delta_{\mathrm{f}}^{(1)}(q_T, m_V) = -\frac{\alpha_{\mathrm{S}}}{2\pi}\left[\frac{1}{2} A_{1,\mathrm{f}} \log^2\frac{m_V^2}{q_T^2}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

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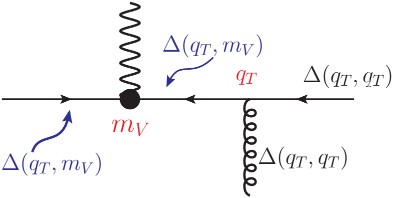

☞ Sudakov FF included on $V+j$ Born kinematics

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

“Improved” MiNLO: from Drell-Yan to WW

- formal accuracy of VJ−MiNLO for inclusive observables carefully investigated
  [Hamilton et al., 1212.4504]
- shown that it's possible to improve VJ−MiNLO such that inclusive NLO is recovered (NLO$^{(0)}$), without spoiling NLO accuracy of $V+j$ (NLO$^{(1)}$):

  NLO+PS merging

- accurate control of subleading small-p_T logarithms is needed.
  In particular, need to include the B_2 (NNLL) coefficient in MiNLO-Sudakov.

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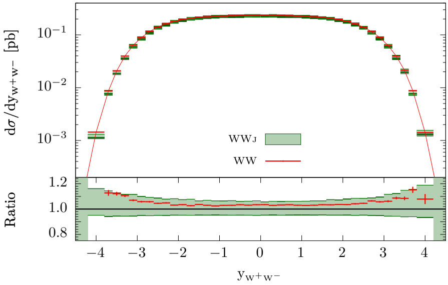
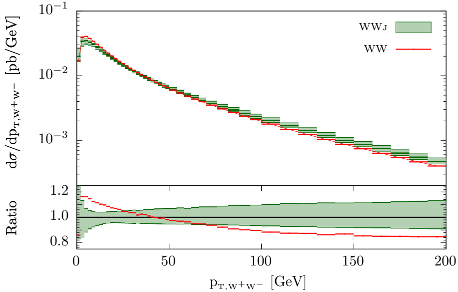
In 1606.07062 we presented a `MiNLO'` generator for WW and WW + 1 jet:

- `POWHEG` WWJ generator obtained using interfaces to `Madgraph` and `Gosam`
- starting from the Drell-Yan case, we extracted the B_2 term from the virtual (V) and Born (B) contributions of $pp \to WW$
- for Drell-Yan, V and B are proportional, hence B_2 is just a number
- in $pp \to WW$, this is no longer true: $B_2 = B_2(\Phi_{WW})$
- process-dependent part of B_2 extracted on an event-by-event basis

WWJ−MiNLO′ : results I

[Hamilton,Melia,Monni,ER,Zanderighi '16]

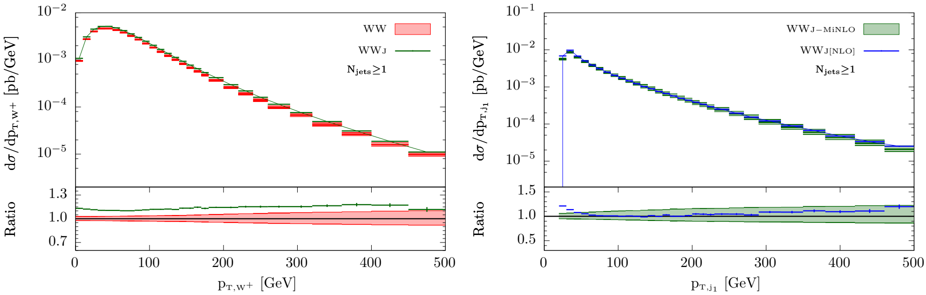




- total cross-section agrees at the level of 4% (although MiNLO uncertainty bands are wider than the WW ones)
- part of the shape difference in y_{WW} is correlated with the differences in the $p_{T,WW}$ spectrum

WWJ−MiNLO′ : results II

[Hamilton,Melia,Monni,ER,Zanderighi '16]



- cuts: $N_j \geq 1$
- left: effect of NLO corrections
- right: plot shows that MiNLO mantains the formal NLO accuracy in the “1-jet” region
- small differences can be explained by Sudakov effects, and use of different scale choices

conclusions

- important progress in the simulation of fully differential top-pair production at NLO+PS
- measuring the top mass, or dealing with the separation between $t\bar{t}$ and Wt production, have been two recurring themes over the past few years:
  - it's now possible to perform a number of studies and experimental analysis with more accurate NLO+PS tools
- I've also presented one recent non-trivial application of the "improved" MiNLO method to an electroweak process:
  - one obvious avenue to be explored is NNLOPS simulations for $2 \to 2$ processes
  - another is related to the results of [Frederix,Hamilton '15]

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Thank you for your attention!