Status of POWHEG and MiNLO

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Outline

- status of the `POWHEG BOX` repository
- NLO+PS: status and recent developments [SM and BSM]
- MiNLO and NNLOPS [more details in K. Hamilton's talk tomorrow]
- short update on facilities for users

POWHEG BOX

Current status of repository:

- **POWHEG BOX**:
  - since revision 2801, common files mirrored in separate repository:

  `svn://powhegbox.mib.infn.it/trunk/POWHEG-BOX-NoUserProcesses`

  user processes: `svn://powhegbox.mib.infn.it/trunk/POWHEG-BOX/XXX`

- **POWHEG BOX V2**:
  - MiNLO/MiNLO' merging
  - facility for QED/EW corrections
  - scales and PDF reweighting on LHE file

  `svn://powhegbox.mib.infn.it/trunk/POWHEG-BOX-V2`

  user processes: `svn://powhegbox.mib.infn.it/trunk/User-Processes-V2/XXX`

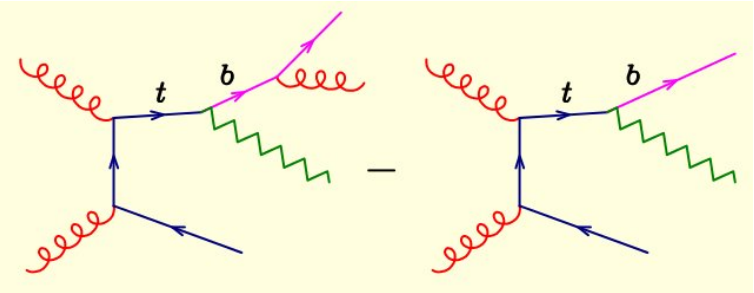
- **POWHEG BOX RES**:
  - can deal with intermediate resonances

  `svn://powhegbox.mib.infn.it/trunk/POWHEG-BOX-RES`

  user processes: `svn://powhegbox.mib.infn.it/trunk/User-Processes-RES/XXX`

NLO+PS & intermediate resonances

The problem, in a nutshell:



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

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

- Issues first addressed, for $pp \to b\bar{b} + 4$ leptons production, in the narrow-width approximation [Campbell,Ellis,Nason,ER '14]
- `POWHEG BOX RES`: general solution and new framework [Jezo,Nason '15]
  - applied to 4F t-channel single-top and $pp \to b\bar{b} + 4$ leptons (full exact NLO)
    [Jezo,Nason '15; Jezo,Lindert,Nason,Oleari,Pozzorini '16]

intermediate resonances in NLO+PS w/ POWHEG

1. complete matrix elements for $W^+W^-b\bar{b}$: need to project each partonic subprocess onto all possible "resonance histories":
   - each contribution should be dominated by a single resonance history:

$$B = \sum_{f_b} B_{f_b}, \quad \text{where} \quad B_{f_b} \equiv \frac{P^{f_b}(\Phi_B)}{\sum_{f'_b} P^{f'_b}(\Phi_B)} B(\Phi_B)$$

$P^{f_b}(\Phi_B)$ (products of) Breit-Wigner functions $\Leftrightarrow$ resonance history f_b

   - for real contributions, split also according to compatible FKS regions:

$$R = \sum_{\alpha_r} R_{\alpha_r}, \quad \text{where} \quad R_{\alpha_r} = \frac{P^{f_r} d^{-1}(\alpha_r)}{\sum_{f'_r}(P^{f'_r} \sum_{\alpha'_r} d^{-1}(\alpha'_r))} R$$

$d_{\alpha_r} \to 0$ when approaching FKS region α_r

   - 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.

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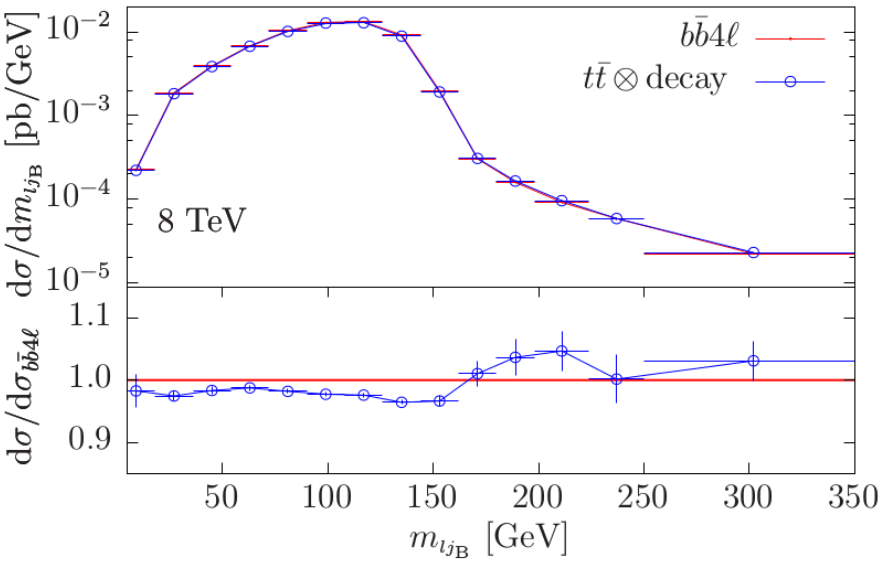
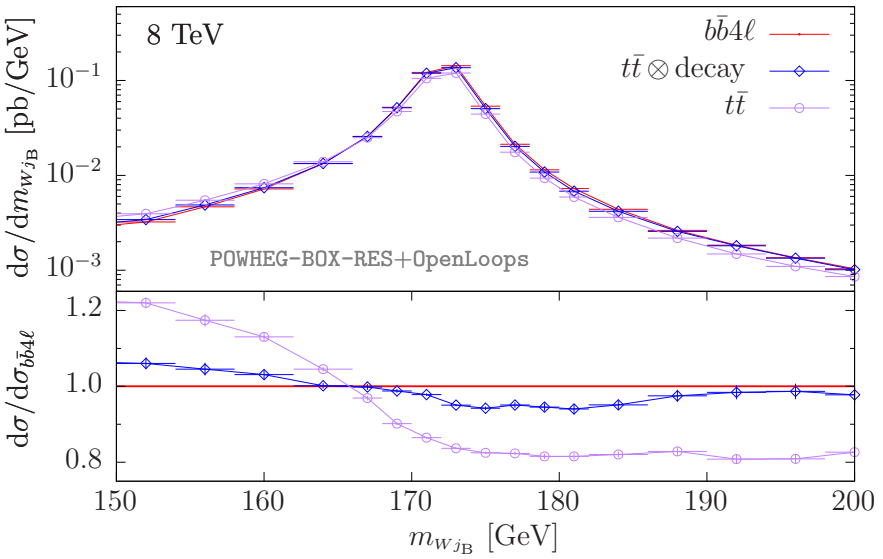
2. each term (Born-like and real) is attributed to an unique resonance history
   - virtuality-preserving mappings between Φ_B and $(\Phi_B, \Phi_{\text{rad}})$ can be used
   - `POWHEG` radiation(s) can now be assigned to a resonance
   - (& other technical but crucial subtleties...)

intermediate resonances in NLO+PS w/ POWHEG

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

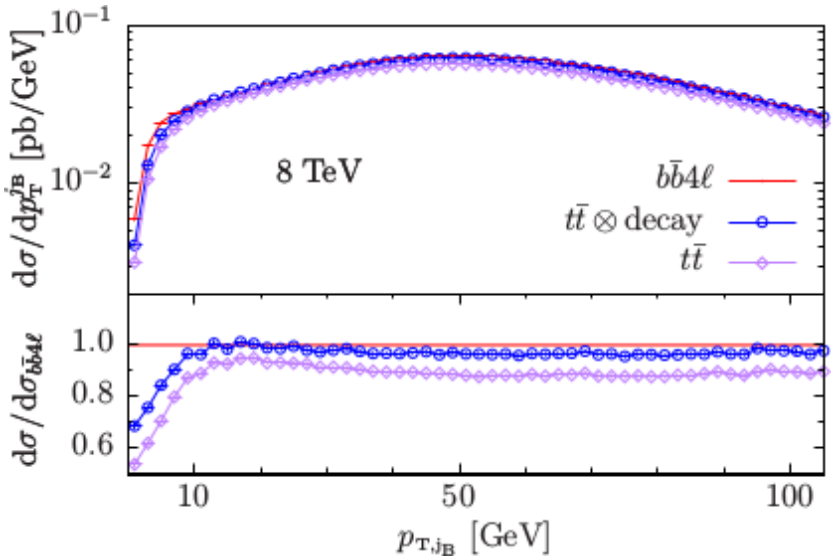




- "tt⊗decay": based on narrow-width [Campbell,Ellis,Nason,ER '14]
- left: $t\bar{t}$ cuts. Very good agreement: serves also as a validation, since one result supports the choices made to obtain the other.
- right: bigger differences with original $t\bar{t}$.

intermediate resonances in NLO+PS w/ POWHEG

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



- "tt⊗decay": based on narrow-width [Campbell,Ellis,Nason,ER '14]
- no cuts. Clearly shows the "Wt" contribution, particularly relevant at small transverse momenta.

intermediate resonances in NLO+PS w/ POWHEG

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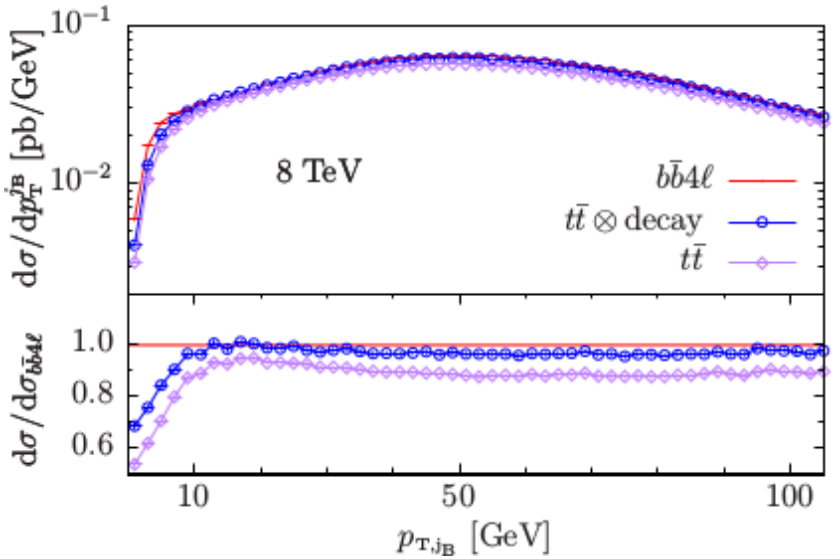

- "tt⊗decay": based on narrow-width [Campbell,Ellis,Nason,ER '14]
- no cuts. Clearly shows the "Wt" contribution, particularly relevant at small transverse momenta.
- ongoing pheno study on top mass extraction [Ferrario-Ravasio,Jezo,Nason,Oleari; in progress]

Multiple radiation scheme

feature introduced in `POWHEG BOX V2`, for `ttb_NLO_dec`;
present also in `POWHEG BOX RES`

- keep multiple emissions before showering

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- 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

Multiple radiation scheme

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- keep multiple emissions before showering

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

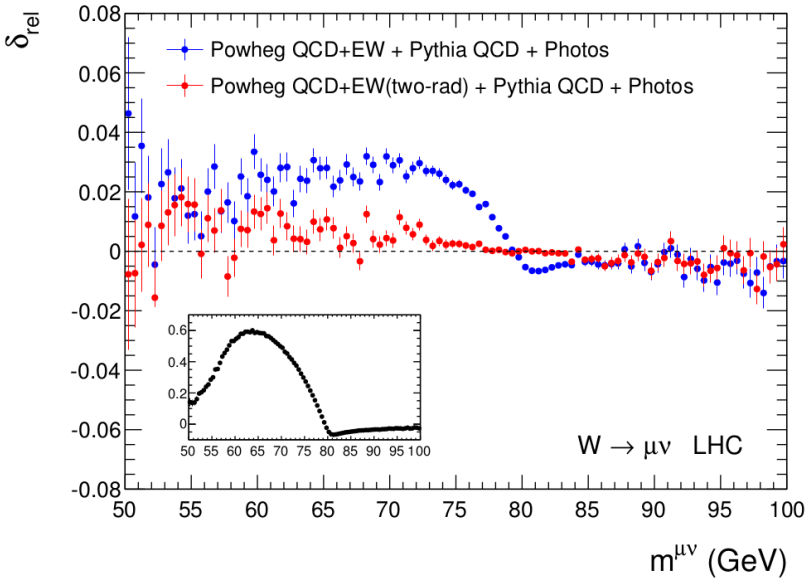
$$\Rightarrow \quad \mathrm{d}\sigma = \bar{B}(\Phi_{\mathrm{B}})\,\mathrm{d}\Phi_{\mathrm{B}}\prod_{\alpha=\alpha_b,\alpha_{\bar{b}},\alpha_{\mathrm{ISR}}}\left[\Delta_\alpha(q_{\mathrm{cut}}) + \Delta_\alpha(k_T^{\alpha})\frac{R_\alpha(\Phi_\alpha(\Phi_{\mathrm{B}},\Phi_{\mathrm{rad}}^{\alpha}))}{B(\Phi_{\mathrm{B}})}\,\mathrm{d}\Phi_{\mathrm{rad}}^{\alpha}\ri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

- in the above case, the interface to parton shower becomes more complicated.
  - for results in published results, brute-force approach (iterate shower untill all veto conditions respected)
  - more recently: `PowhegHooksBB4L.h`, `Pythia8` UserHook, dedicated for vetoes in presence of resonance decays adapted from `PowhegHooks` [Jezo,Seidel,Nachman; April '17]

Multiple radiation scheme

- This scheme has also been implemented to improve the QCD+EW NLO+PS programs `W_ew-BMNNP` and `Z_ew-BMNNPV`. Therein, option was dubbed `two-rad`.
- used for phenomenological study on M_W measurement

[Carloni Calame,Chiesa,Martinez,et al. '16]



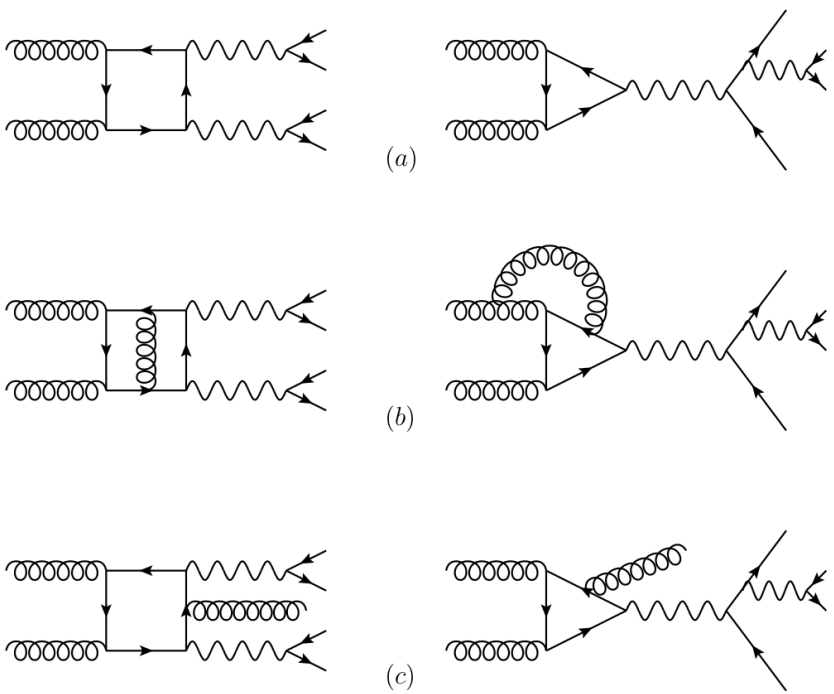
	$pp \to W^+$, $\sqrt{s} = 14$ TeV Templates accuracy: NLO-QCD+QCD$_{PS}$ Pseudodata accuracy	QED FSR	M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	p_T^ℓ	$W^+ \to e^+\nu$(dres) M_T	p_T^ℓ
1	NLO-QCD+(QCD+QED)$_{PS}$	Pythia	-95.2±0.6	-400±3	-38.0±0.6	-149±2
2	NLO-QCD+(QCD+QED)$_{PS}$	Photos	-88.0±0.6	-368±2	-38.4±0.6	-150±3
3	NLO-(QCD+EW)+(QCD+QED)$_{PS}$`two-rad`	Pythia	-89.0±0.6	-371±3	-38.8±0.6	-157±3
4	NLO-(QCD+EW)+(QCD+QED)$_{PS}$`two-rad`	Photos	-88.6±0.6	-370±3	-39.2±0.6	-159±2
5	NLO-(QCD+EW)+(QCD+QED)$_{PS}$	Pythia	-101.8±0.4	-423±2	-45.0±0.6	-179±2
6	NLO-(QCD+EW)+(QCD+QED)$_{PS}$	Photos	-94.2±0.6	-392±2	-45.2±0.6	-181±2

- plot: normalized to NLOPS for only QCD; effects also on transverse mass
- table shows that previous version had problems:
  - line 5,6: dependence on the model that describes QED FSR was not reduced after matching with an exact NLO EW calculation
  - line 3,4: matching shows improvement

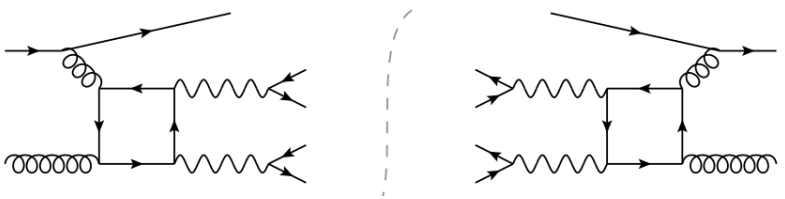
$gg \to ZZ$

[Alioli,Caola,Luisoni,Rontsch '16]

- Diboson processes start with quarks-only initial states at LO: $q\bar{q} \to VV$
- gg-induced ($WW, ZZ, \gamma Z, \gamma\gamma$): start at NNLO, but important (large gluon flux)
- NLO corrections are only a part of the N3LO corrections



- virtual corrections: 2-loop amplitudes!
  - not reliable when radiation harder than m_t, as only massless internal lines
- quark-initiated loop-squared known, gauge invariant, but not included

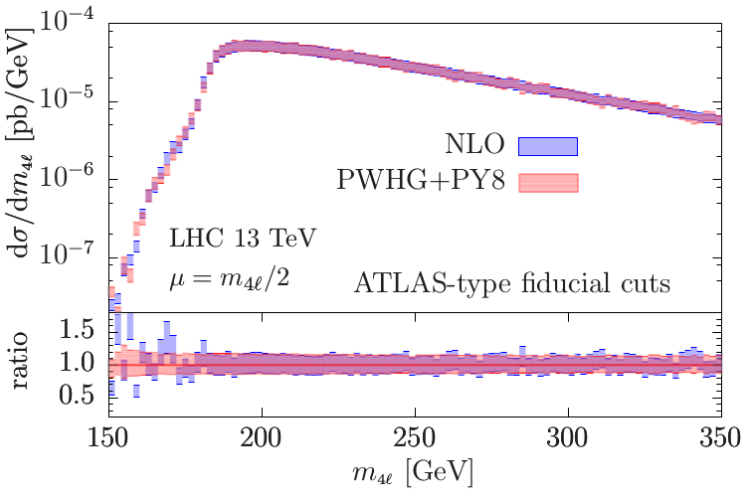


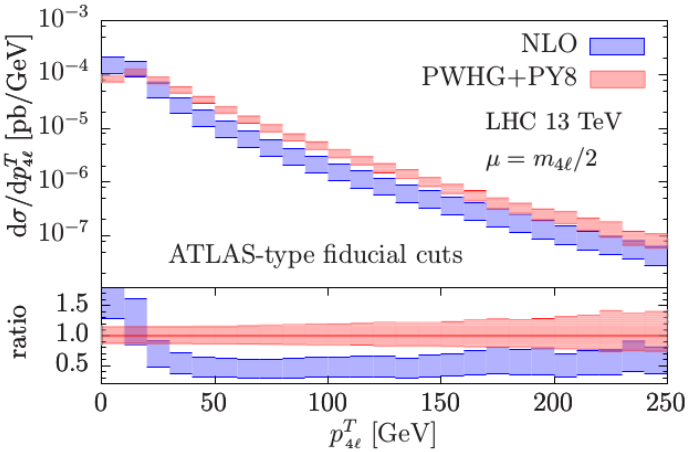
- B and R: in-house routines, 2-loops from [Gehrmann,von Manteuffel,Tancredi, '15 '15]

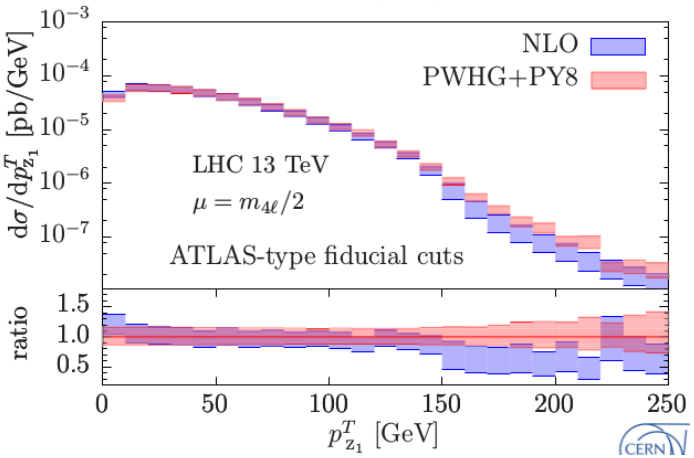
Implemented $gg \to ZZ \to e^+e^-\mu^+\mu^-$ at NLO+PS in V2

$gg \to ZZ$

$\Delta R_{\ell\ell} > 0.2$,
$p_\ell^T > 7$ GeV, $\quad 80$ GeV $< m_{4\ell} < 350$ GeV
$|\eta_\ell| > 2.7$. $\quad 66$ GeV $< m_{\ell\ell} < 160$ GeV.







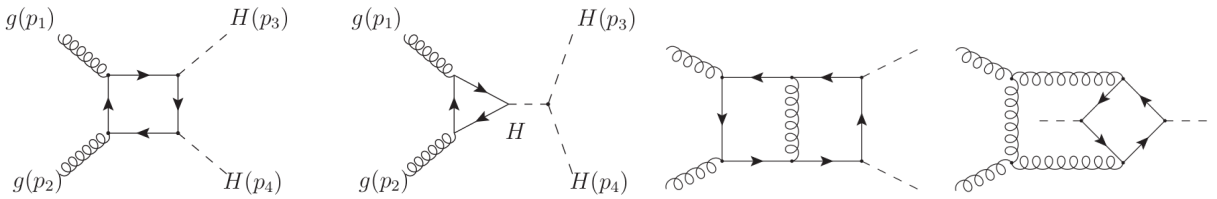
- for inclusive observables, excellent agreement NLO vs NLO+PS
- Shower effect on $p_{T,ZZ}$ due to recoil from all emitted particles:
  - slight unbalance can give large effects (even when `hdamp`= 150 GeV)
  - roughly compatible inside large LO bands

- outlook: $gg \to 4\ell$ (identical lepton interferences), investigate loop-squared quark-initiated

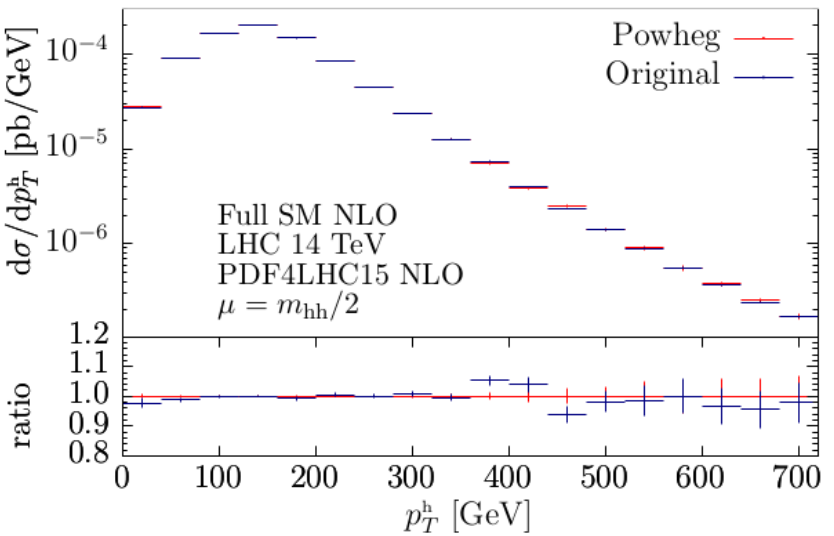
HH production with exact m_t

[Heinrich,Jones,Kerner,Luisoni,Vryonidou '17]

- relevant for studies of HHH coupling
- exact NLO computation by [Borowka,Greiner,Heinrich, et al. '16]:
  - very difficult, as some 2-loops integrals are not known analytically



- 2-loop: too slow for direct interface to an NLOPS code
- interpolation grid in (transformed) $(\hat{s}, \hat{t})$
- plot on the right: validation



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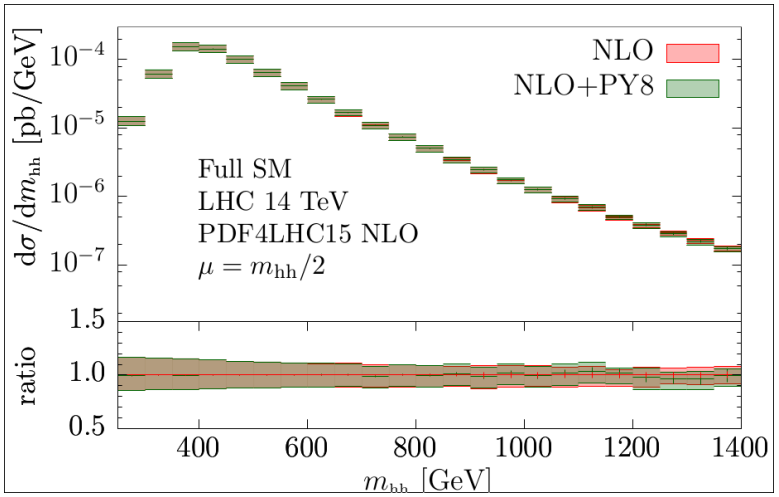
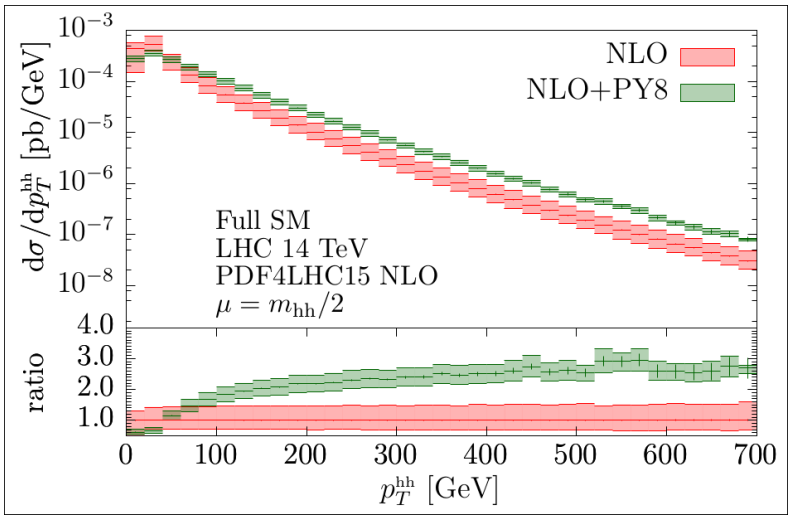
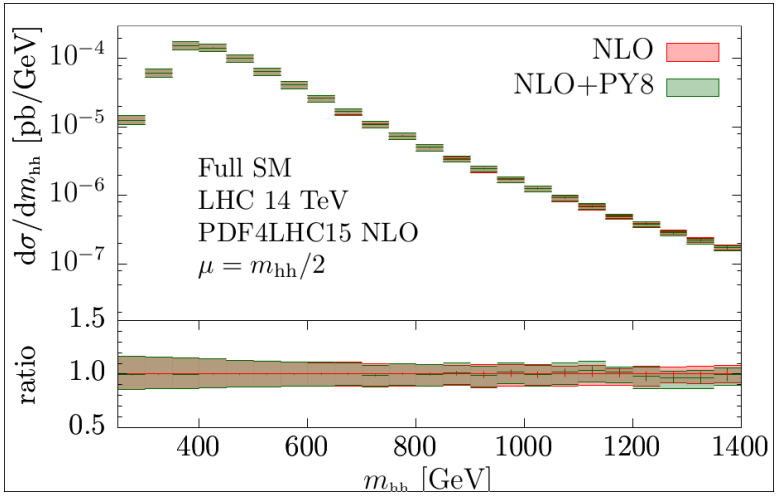
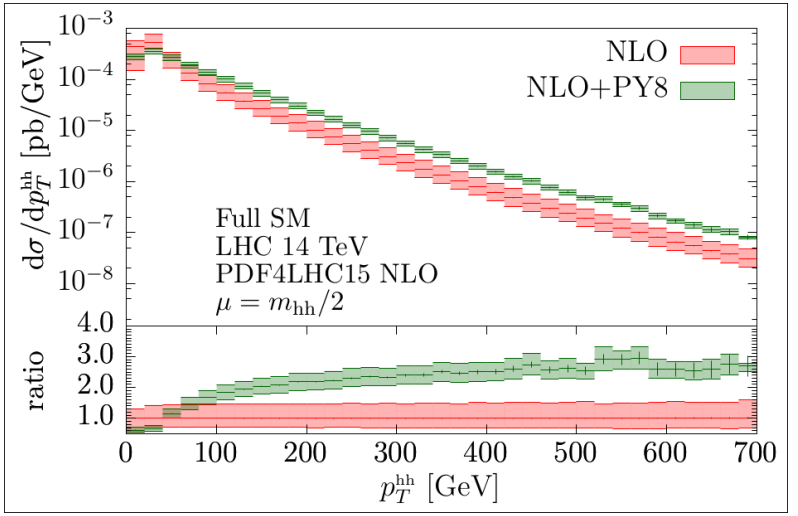




- for fully-inclusive NLO observables, shower plays essentially no role, as expected.
- enhancement of $p_{T,hh}$ tail wrt NLO result; this also has a (smaller) impact on observables like $p_{T,h}$ (due to recoil effects).

HH production with exact m_t





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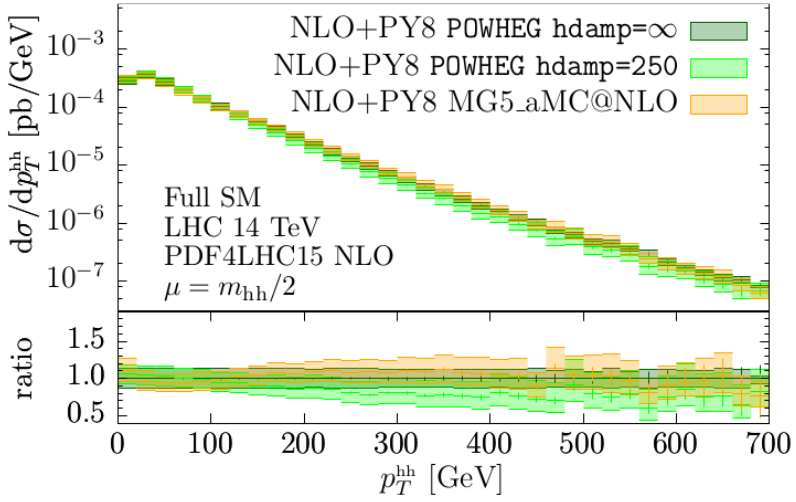
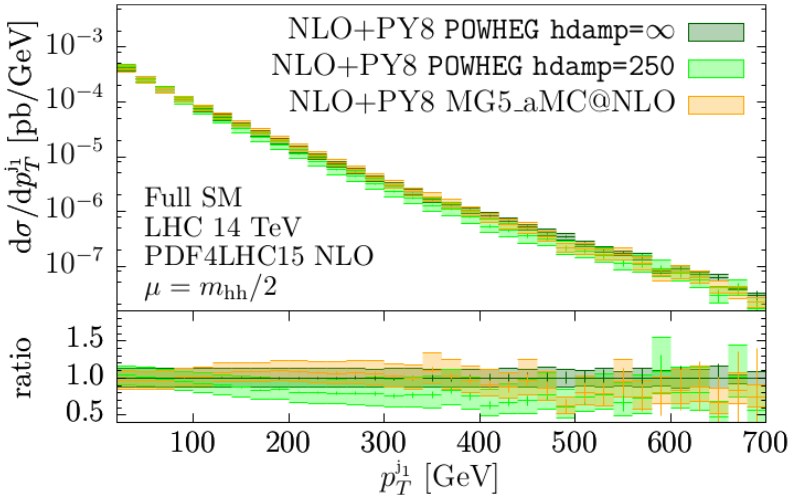




- `hdamp`: NLO+PS $p_{T,hh}$ tail gets closer to fixed-order (formally LO)
- uncertainty due to matching: detailed comparison with `MG5_aMC@NLO`

BSM in POWHEG and other recent results

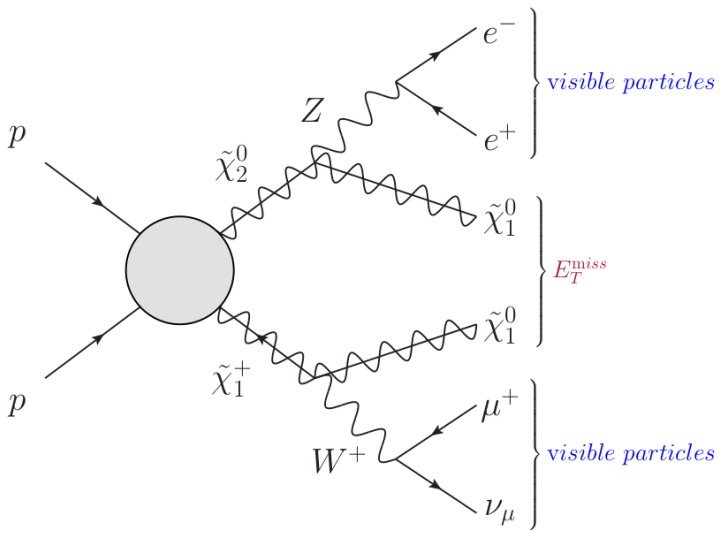
- although there isn't an effort aiming at complete automation, a few BSM processes are available:
  - Scalar and Pseudoscalar Higgs production in gluon fusion in the MSSM and 2HDM [Bagnaschi,Degrassi,Slavich,Vicini]
  - Charged Higgs+top quark* [Klasen,Kovarik,Nason,Weydert '12]
  - Dark-Matter + Monojet [Haisch,Kahlhoefer,ER '13]
  - Squark production and decay [Gavin,Hangst,Krämer,Mühlleitner,Pellen,Popenda,Spira '13 '14]
  - Slepton pair, slepton pair + 1 jet [Jäger,von Manteuffel,Thier '12 '14]
  - Higgs production in association with a vector boson at NLO QCD including SM EFT effects [Mimasu,Sanz,Williams '15]
  - Electroweakino pair production at the LHC: NLO SUSY-QCD corrections and parton-shower effects [Baglio,Jäger,Kesenheimer '16]

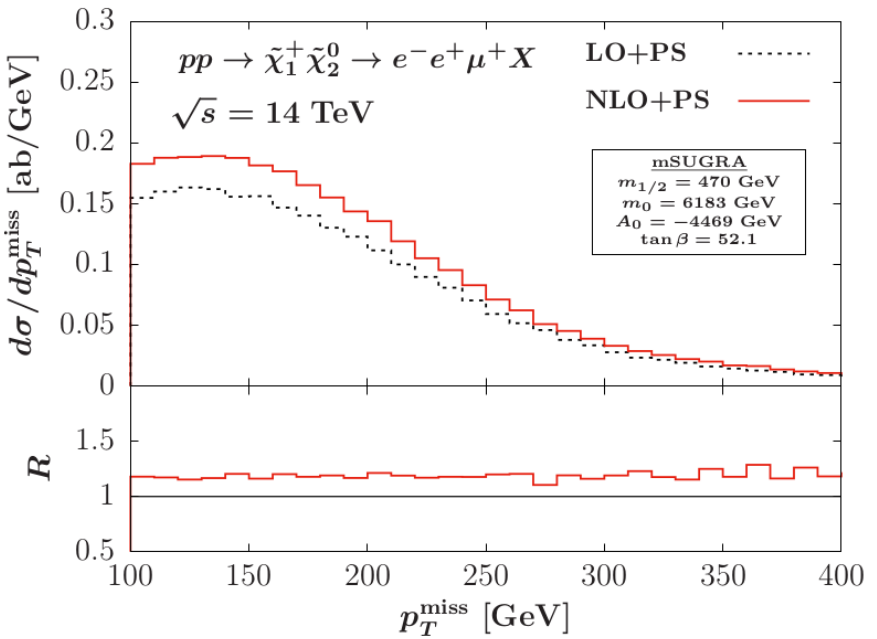
  - Higgs+diboson* [Baglio '15 '16]

Electroweakino pair production at the LHC

[Baglio,Jäger,Kesenheimer '16]

- DM as decay remnant of main production process, *i.e.* production of partner particles which then decay into LSP.
  - neutralino+chargino: $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^+$, tag on missing E_T + visible SM particles

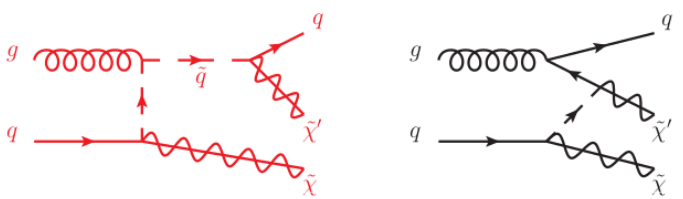




Spectrum used

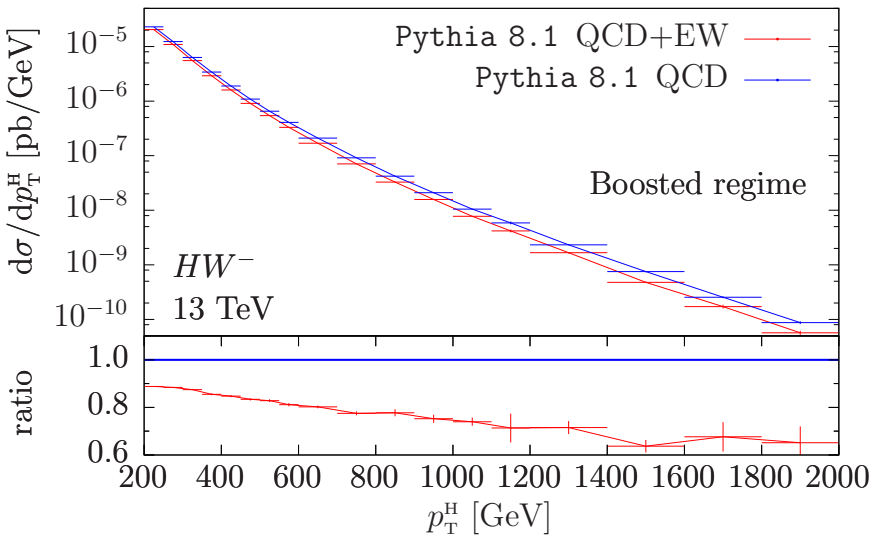
$m_{\tilde{\chi}_1^0} = 207$ GeV, $m_{\tilde{\chi}_2^0} = 405.9$ GeV, $m_{\tilde{\chi}_1^\pm} = 405.8$ GeV

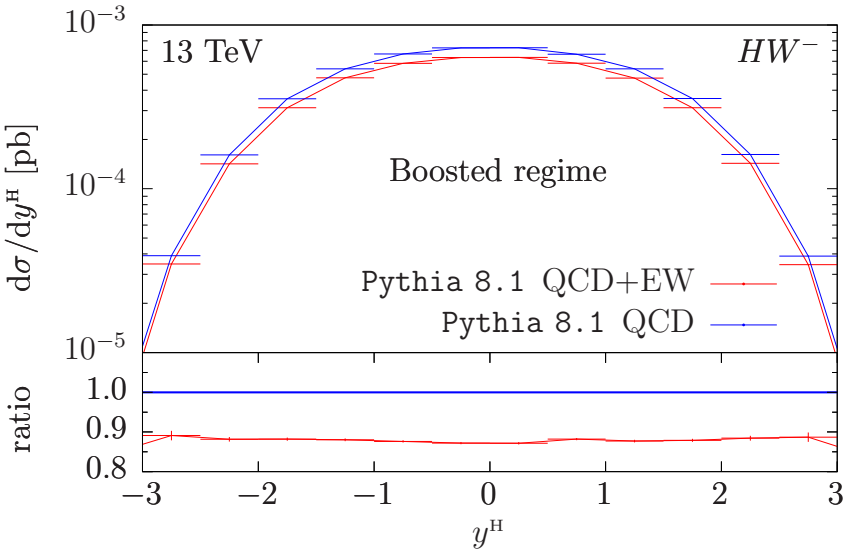
- on-shell subtraction terms:



some work in progress: NLO QCD+NLO EW

- QCD + EW corrections for HV and HV+jet [Granata,Lindert,Oleari,Pozzorini; in progress]





  - will be made available in `RES` framework

- QCD + EW corrections to V+j [Pavia group; in progress]

POWHEG+MiNLO merging

Multiscale Improved NLO [Hamilton,Nason,Oleari,Zanderighi, '12, '12]

- a-priori scale choice in multijet NLO computation
- correct weights of different NLO terms with CKKW-inspired approach (keeping NLO)
- from $X + n$ jets at NLO+PS, can get finite results also for $X + (n-1)$, $X + (n-2)$,... jets
  $\Rightarrow$ it is a merging, without an external merging scale (just 1 event sample)
- formal accuracy of lower multiplicity fully understood for $V + 0, 1$ jet merging [MiNLO']
- formalism also extended for higher multiplicity [Frederix,Hamilton '15]

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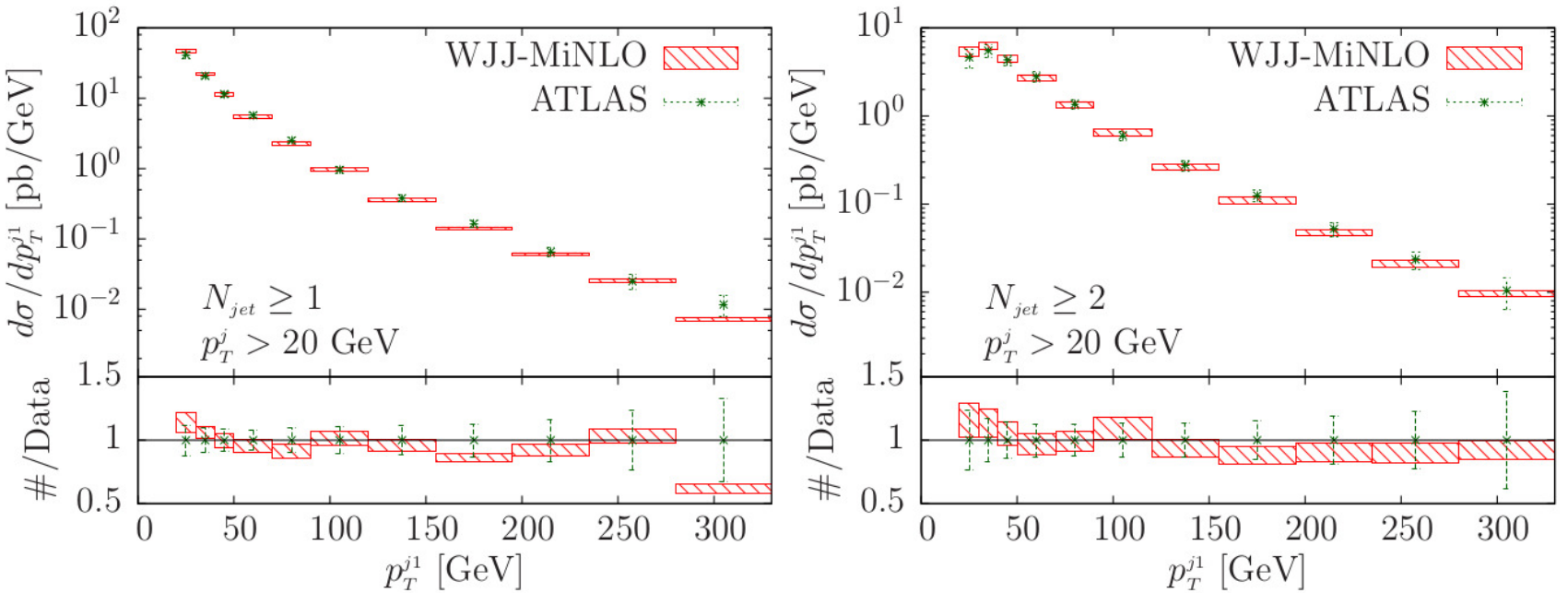
- V + 0,1,2 jets

[Campbell,Ellis,Nason,Zanderighi, '13]



- works clearly well also for 0- and 1-jet region

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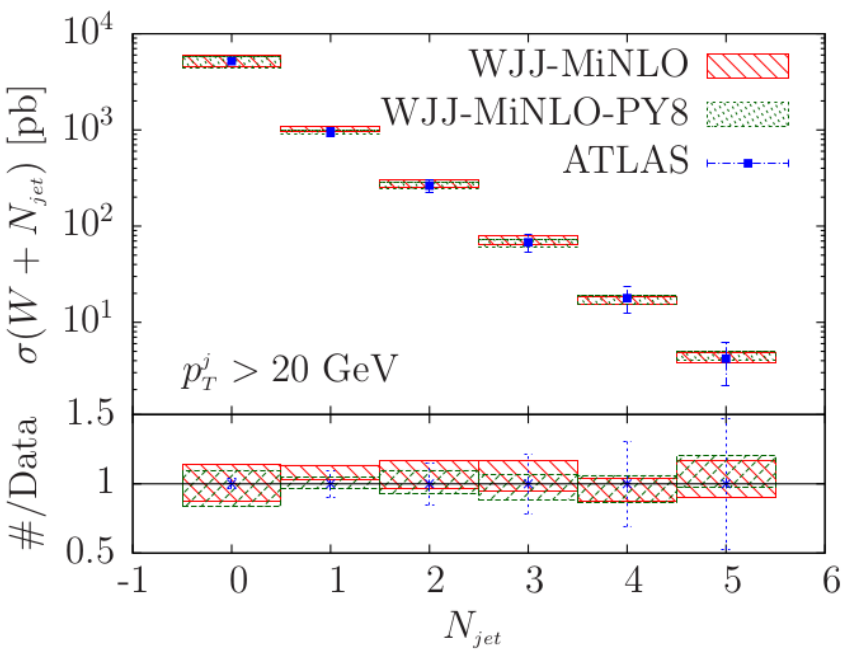
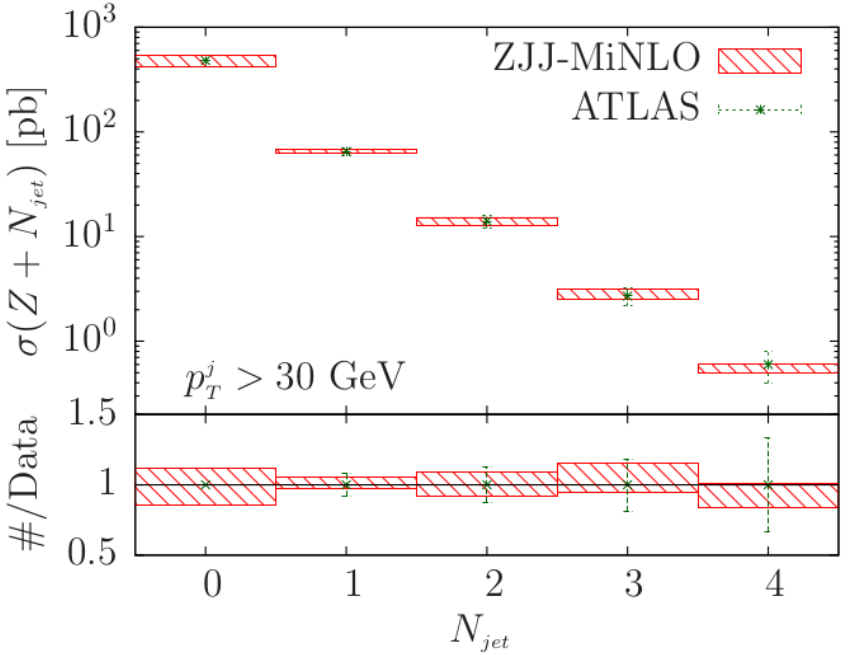
  $\Rightarrow$ it is a merging, without an external merging scale (just 1 event sample)
- formal accuracy of lower multiplicity fully understood for $V + 0, 1$ jet merging [MiNLO']
- formalism also extended for higher multiplicity [Frederix,Hamilton '15]

- V + 0,1,2 jets

[Campbell,Ellis,Nason,Zanderighi, '13]





- works clearly well also for 0- and 1-jet region

POWHEG+MiNLO merging

MiNLO

- H + 0,1,2 jets [Hamilton,Nason,Zanderighi '12]
- V + 0,1,2 jets [Hamilton,Nason,Zanderighi '12]
- JJ + JJJ [Kardos,Nason,Oleari '14]
- $Wb\bar{b}$ + 0,1 jets [Luisoni,Oleari,Tramontano '15]

MiNLO′ for "color singlet (X) + 1 j" processes

- inclusive NLO can be recovered (NLO$^{(0)}$), without spoiling NLO accuracy of X+j (NLO$^{(1)}$):

  NLO+PS merging, without merging scale

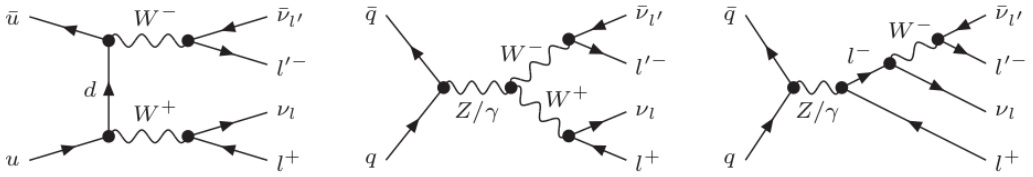
- accurate control of subleading small-p_T logarithms is needed (e.g. B_2 (NNLL))
  - H + 0,1 jet [Hamilton,Nason,Oleari,Zanderighi '12]
  - V + 0,1 jet [Hamilton,Nason,Oleari,Zanderighi '12]
  - HV + 0,1 jet [Luisoni,Nason,Oleari,Tramontano '13]
  - W^+W^- + 0,1 jet [Hamilton,Melia,Monni,ER,Zanderighi '16]
  - H + 0,1,2 jets [Frederix,Hamilton '15]

$\Rightarrow$ more details: K. Hamilton's talk tomorrow

MiNLO': from Drell-Yan to WW

1606.07062: `MiNLO'` generator that merges WW and WW + 1 jet at NLO+PS:

- 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]
  - 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
- 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: $B_2 = B_2(\Phi_{WW})$

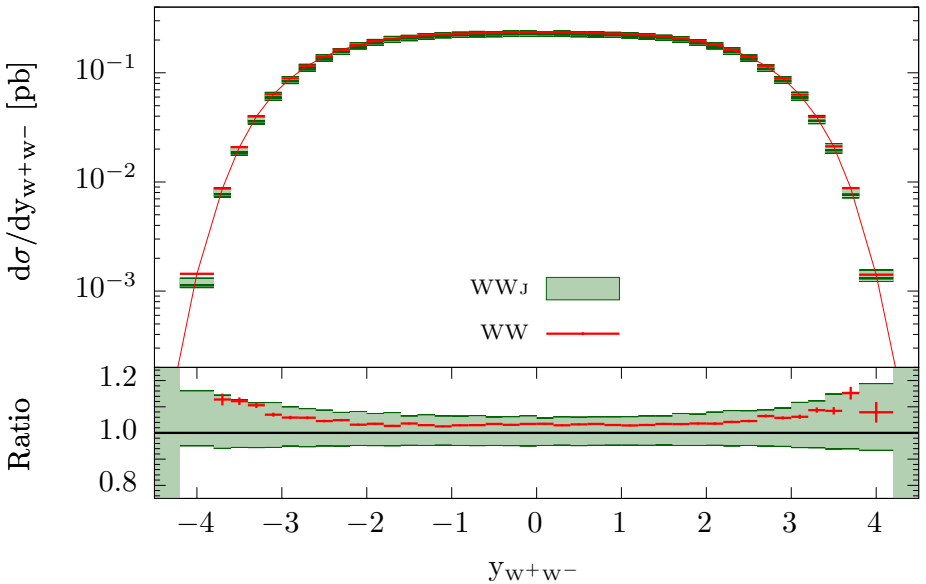
$$B_2 = -2\gamma^{(2)} + \bar{\beta}_0 C_F \zeta_2 + 2\left(2C_F\right)^2 \zeta_3 + \bar{\beta}_0 H_1(\Phi)$$
$$B_2 \to B_2 - \bar{\beta}_0 H_1^{(\mathrm{DY})} + \bar{\beta}_0 H_1^{(\mathrm{WW})}(\Phi)$$

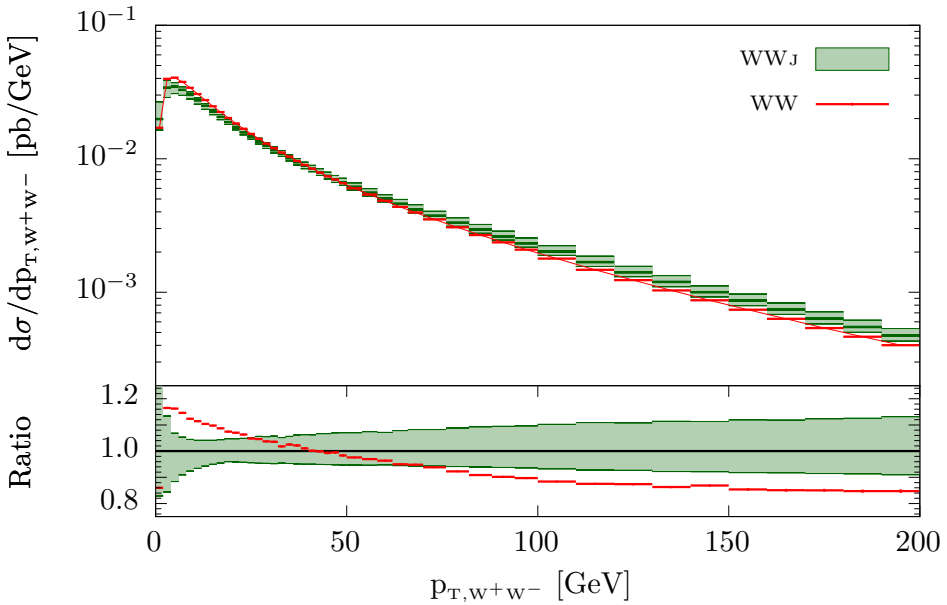
- process-dependent part of B_2 extracted on an event-by-event basis:
  projection of Φ_{WWJ} onto Φ_{WW}, used FKS ISR mapping (smooth collinear limit)

WWJ-MiNLO′ : results I

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

WW generator vs. WWJ-MiNLO generator



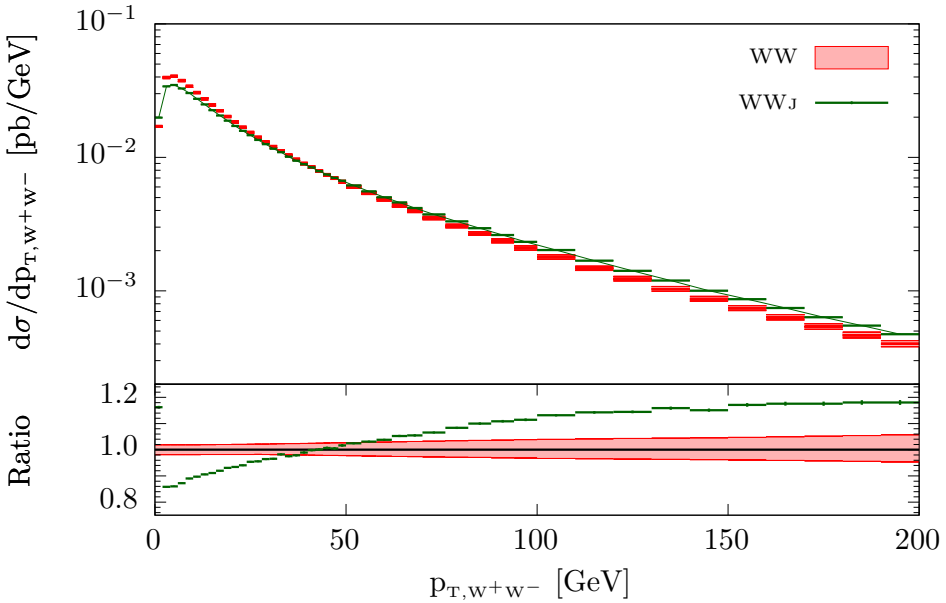


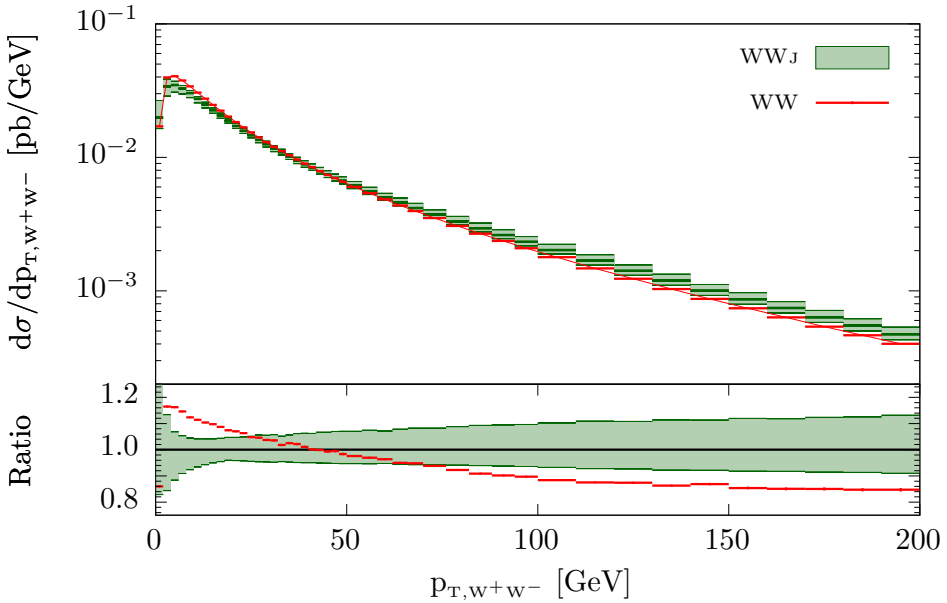
- total cross-section agrees at the level of 4% (although MiNLO uncertainty bands are wider than the WW ones)
- part of the shape difference in y_{WW} is correlated with the differences in the $p_{T,WW}$ spectrum

WWJ-MiNLO′ : results II

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

WW generator vs. WWJ-MiNLO generator

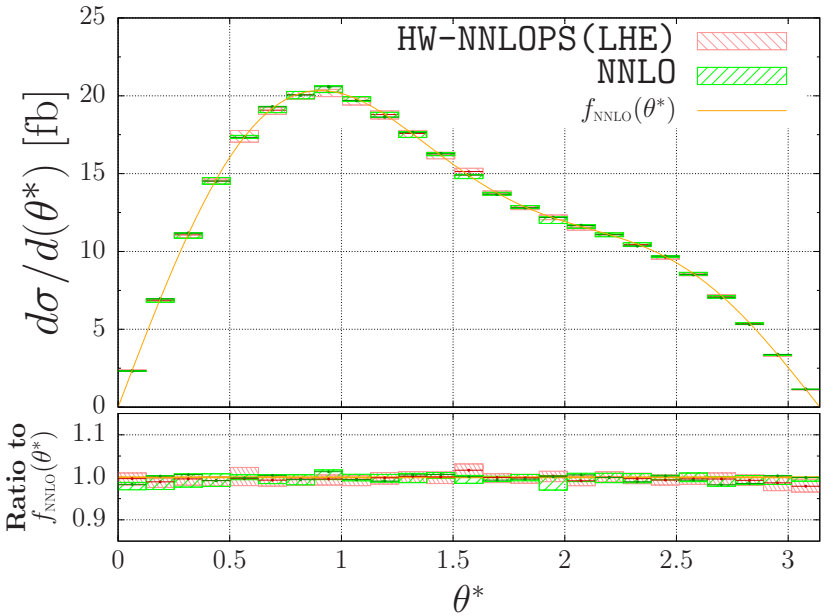


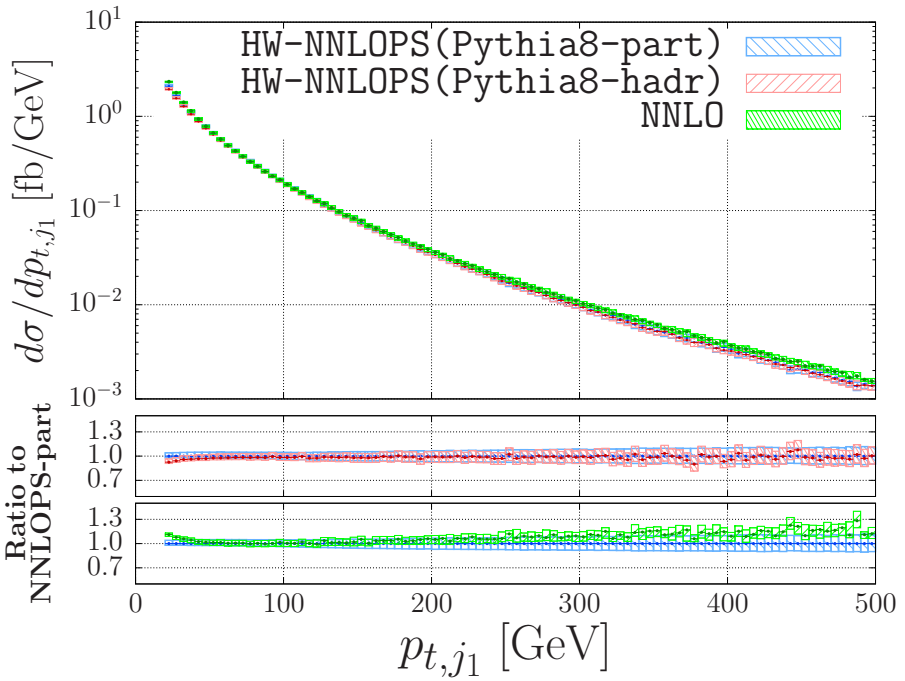


- NLO corrections sizeable in the spectrum
- small p_T region: different terms in the two approaches.
  Moreover, at small p_T, there is also a non-zero contribution from the 2 emissions matrix element (which is missing in the WW case)
- underestimated WW uncertainty band

NNLO+PS from POWHEG+MiNLO'

- by means of a reweighting (differential on Φ_B) of "MiNLO-generated" events, one can achieve NNLO accuracy on fully inclusive observables:
- latest application: WH @ NNLOPS [Astill,Bizon,Zanderighi,ER '16]





- left plot: angular dependence in slice of y_{HW}
- right plot: hardest-jet spectrum
- outlook: include $H \to b\bar{b}$ decay, w/ NLO QCD corretions

update on facilities for users

- machinery to write multiple weights during a single reweighting, as well as to use zipped .lhe files [POWHEG-BOX-V2/Docs/README.Compression-And-Weights]
- interfaces to `Madgraph` and `GoSam` were already available. Now possible also to link to `Openloops`.
- there exists an “experimental” tool to reweight the hardest emission weight in POWHEG (V2); could be useful for W mass studies

[Nason,Vicini, ’15: POWHEG-BOX-V2/Docs/README.fullreweight]

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Thank you for your attention!