Off-shell $W^+W^-b\bar{b}$ production

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HF production at the LHC, IPPP Durham, 6 September 2017

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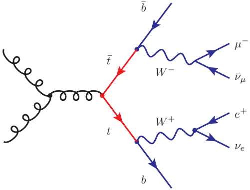
$t\bar{t}$ production and decay

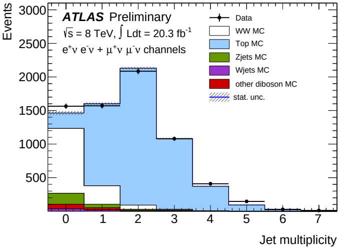
Vast $t\bar{t}$ physics program at LHC (~ 900 pb at 14 TeV)

- precision SM tests and measurements (m_t, PDFs)
- leading background to leptons + jets + missing E_T
  discovery signatures (top partners, $H \to W^+W^-$, ...)
- $\sim$30 years of precision calculations: NLO+NNLL QCD, NLO EW, NNLO QCD (mostly $t\bar{t}$ production...)



Full description of $t\bar{t}$ production *and* decay crucial for any experimental measurement

- cut efficiency
- jet vetoes for $t\bar{t}$ bckg. to $H \to WW$ and Wt
- m_t measurements, ...

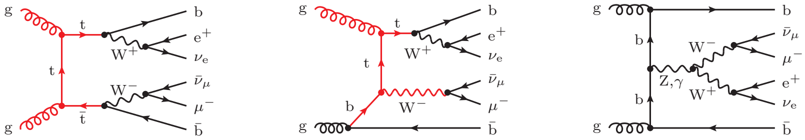


Outline

1. $pp \to W^+W^-b\bar{b}$ at NLO
2. NLO+PS matching with Powheg-RES method
3. Predictions for $t\bar{t}$ observables (Powheg-RES+Pythia8)

$pp \to W^+W^-b\bar{b}$ at NLO QCD

Representative doubly- ($t\bar{t}$ like) singly- (tW like) and non-resonant (WW like) trees



NLO $t\bar{t}$ production×decay in NWA [Bernreuther et al. '04; Melnikov, Schulze '09]

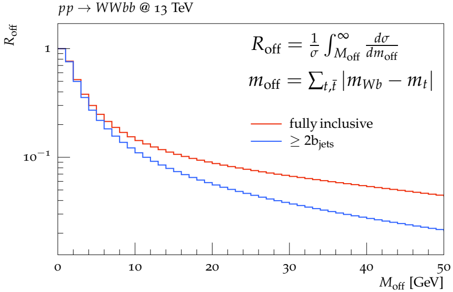
$$\lim_{\Gamma_t \to 0} \left| \frac{1}{p_t^2 - m_t^2 + \mathrm{i}\Gamma_t m_t} \right|^2 = \frac{\pi}{\Gamma_t m_t} \delta(p_t^2 - m_t^2)$$

and simple factorisation at NLO

Full calculations of $pp \to W^+W^-b\bar{b}$ [Denner et al. '10; Bevilacqua et al. '10; Heinrich et al. '13; Cascioli et al '13; Frederix'13] **and $WWb\bar{b}j$** [Bevilacqua et al,'15–'16]

- $t\bar{t}$ production *and* decays at NLO with off-shell effects
- $t\bar{t} + Wt$ and non-resonant channels with interference at NLO
- also 0- and 1-jet bins with $m_b > 0$ [Cascioli,Kallweit,Maierhöfer,S.P. '13; Frederix'13]

Finite-width corrections wrt NWA



10% of $\sigma_{t\bar{t}}$ with off-shellness > 10 GeV

- deviations from NWA can be significant, depending on the observable

Finite-width effects

- *inclusive* $t\bar{t}$ observables (2 b-jets) receive only order $\Gamma_t/m_t \simeq \alpha \simeq 10^{-2}$ corrections
- sizable effects in 0- and 1-jet bins

$W^+W^-b\bar{b}$ cross section in jet bins

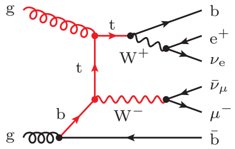
- first $t\bar{t}+tW$ NLO predictions for $n_{\text{jet}} = 0, 1$
- crucial for suppression of $t\bar{t}$ backgrounds

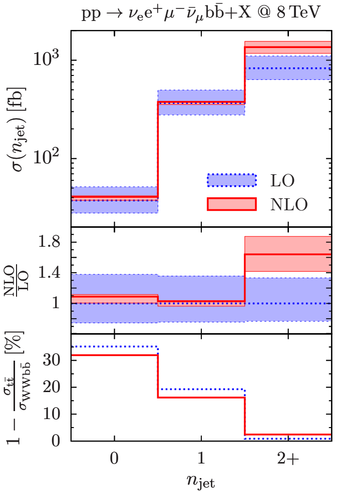
Excellent convergence for $n_{\text{jet}} = 0, 1$

- small NLO correction and reduction of scale uncertainty from 40% to less than 10%

$\mathcal{O}(\Gamma_t/m_t)$ effects (driven by Wt production)

- **strong enhancement in 0/1-jet bins!** (up to 30%)





$\Rightarrow$ $W^+W^-b\bar{b}$ description needed and reliable

NLO(LO) 4F NNPDFSs, $p_{\text{T},j} = 30\,\text{GeV}$

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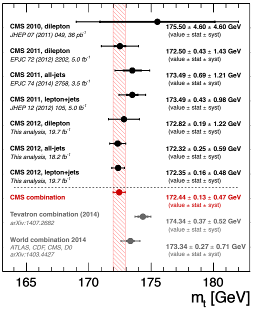
Motivation: precision m_t determination



Direct and indirect m_t determinations

- $\Delta m_t^{(\mathrm{exp})} \sim 0.5\,\mathrm{GeV}$ but spread around 2 GeV
- EW precision fit ($m_t = 177 \pm 2.1$ GeV)
  1.6σ above world average

Kinematic m_t^{pole} determinations

- excellent experimental systematics
- require accurate theory understanding of
  $m_t^{\overline{\mathrm{MS}}} \quad \leftrightarrow \quad m_t^{\mathrm{pole}} \quad \leftrightarrow$ observables

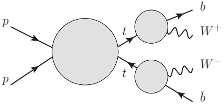
Non-perturbative (renormalon) ambiguity in $m_t^{\overline{\mathrm{MS}}} \leftrightarrow m_t^{\mathrm{pole}}$

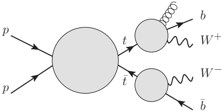
- intrinsic $\mathcal{O}(\Lambda_{\mathrm{QCD}})$ ambiguity of pole mass small wrt m_t accuracy at LHC:
  $\Delta m_t^{\mathrm{pole}} \sim 110\,$MeV [Beneke et al, 1605.03609]

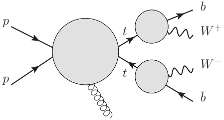
Monte Carlo simulations with higher-order $pp \to WWb\bar{b}$ matrix elements

- well defined m_t^{pole} input (no MC mass!)
- systematic precision improvements in $m_t^{\mathrm{pole}} \leftrightarrow$ observables

NLO+PS matching for $pp \to W^+W^-b\bar{b}$







Standard Powheg method

$$\frac{d\sigma}{d\Phi_B} = \underbrace{\left[B(\Phi_B) + V(\Phi_B) + \sum_\alpha \int R_\alpha(\Phi_R^\alpha)\, d\Phi_{rad}\right]}_{\bar{B}(\Phi_B)} \underbrace{\left[\Delta(q_{cut}) + \sum_\alpha \Delta(k_T^\alpha) \frac{R_\alpha(\Phi_R^\alpha)}{B(\Phi_B)}\, d\Phi_{rad}\right]}_{\text{1st emission}}$$

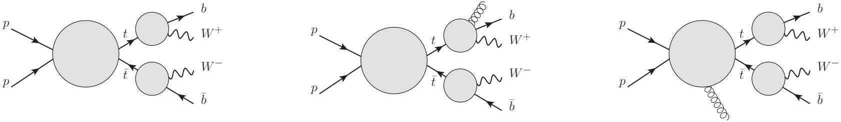
- NLO accuracy based on factorisation of soft/collinear radiation with $k_T \ll Q_{hard}$

$$R(\Phi_R^\alpha) \to B(\Phi_B) \otimes K(\Phi_{rad})$$

and smoothness of hard subprocess wrt recoil from soft/collinear radiation

Sharp resonances with $\Gamma_t \ll k_T$ lead to unphysical effects

- recoil implemented in standard $\Phi_B \to \Phi_R^\alpha$ mappings induces unphysical distortions of Breit-Wigner shape and fake effects of order $\alpha_S^2 \frac{m_t^2}{\Gamma_t^2} \sim 1$
- for example $\delta(p_t^2 - m_t^2)$ distribution not respected in $\Gamma_t \to 0$ limit



Mismatch between resonances in Φ_{B} and $\Phi_{\mathrm{R}}(\Phi_{\mathrm{B}}, \Phi_{\mathrm{rad}})$ phase space

$$\frac{m_t^4}{\left[M_{Wbg}^2(\Phi_{\mathrm{R}}) - m_t^2\right]^2 + \Gamma_t^2 m_t^2} - \frac{m_t^4}{[M_{Wb}^2(\Phi_{\mathrm{B}}) - m_t^2]^2 + \Gamma_t^2 m_t^2}\bigg|_{M_{Wb}(\Phi_{\mathrm{B}})=m_t}$$

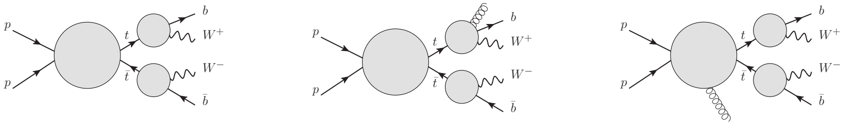
$$= \frac{m_t^4}{\left[M_{Wbg}^2(\Phi_{\mathrm{R}}) - m_t^2\right]^2 + \Gamma_t^2 m_t^2} - \frac{m_t^2}{\Gamma_t^2} = -\frac{m_t^2}{\Gamma_t^2} \frac{\left[M_{Wbg}^2(\Phi_{\mathrm{R}}) - m_t^2\right]^2}{\left[M_{Wbg}^2(\Phi_{\mathrm{R}}) - m_t^2\right]^2 + \Gamma_t^2 m_t^2}$$

- cancels only in soft/collinear limits, where $M_{Wbg}(\Phi_{\mathrm{R}}) \to M_{Wb}(\Phi_{\mathrm{B}})$

$\Rightarrow$ unphysical $\mathcal{O}\left(\alpha_S^2 \frac{m_t^2}{\Gamma_t^2}\right) = \mathcal{O}(1)$ distortions of top line shape in resonance region

$\Rightarrow$ highly inefficient integration and event generation

Resonance aware Powheg matching [Jezo and Nason, 1509.09071]



Unphysical $\mathcal{O}\left(\alpha_S^2 \frac{m_t^2}{\Gamma_t^2}\right)$ effects avoided requiring consistent $\Gamma_t \to 0$ behaviour

(A) all-order factorisation of top production$\times$decay

(B) top on-shellness ($p_t^2 = m_t^2$)

Powheg-RES implementation

- probabilistic assignment of radiation to top production or decays ("resonance history") with correct $\Gamma_t \to 0$ limit (dictated by $p_t^2 = m_t^2$)
- modify $\Phi_\mathrm{B} \to \Phi_\mathrm{R}^\alpha$ mappings, subtraction terms and showering such as to preserve resonance virtualities (M_{Wb} or M_{Wbg} according to "resonance history")

$\Rightarrow$ consistent and efficient $\Gamma_t > 0$ continuation of NWA based on full $WWbb$ MEs

see analogous approach in MC@NLO [Frederix et al, 1603.01178]

POWHEGBOX-RES+OPENLOOPS $b\bar{b}4\ell$ generator

[Jezo, Lindert, Nason, Oleari, S.P., 1607.04538] http://powhegbox.mib.infn.it

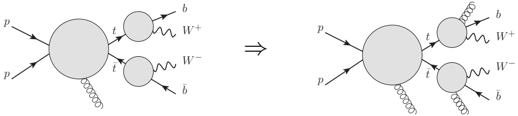
Some key features

- dilepton process $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ including $t\bar{t}+tW$ and interference
- applicable to observables with unresolved b quarks (jet vetoes) thanks to $m_b > 0$
- interference between radiation from top production *and* decay
- quantum corrections to top propagators $\Rightarrow$ well defined $M_t^{(\mathrm{OS})}$

Multi-radiation scheme based on [Campbell, Ellis, Nason, Re '15]

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

$\Rightarrow$ triple radiation from $t\bar{t}$ production *and* decays at NLO based on full $WWbb$ MEs



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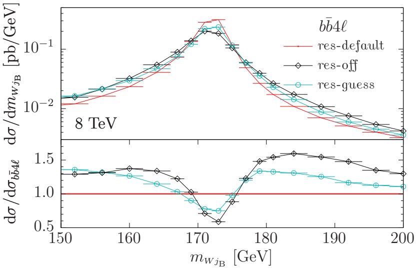
Resonance aware vs resonance blind matching

res-default: resonance-aware throughout

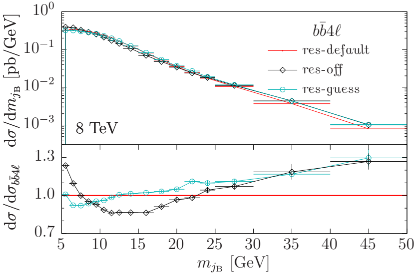
res-off: resonance-blind throughout

res-guess: resonance-blind 1st emission + resonance-aware shower (kinematic guess)

Reconstructed top mass



b-jet mass



Effects of naive (resonant-blind) matching of $WWbb$ MEs

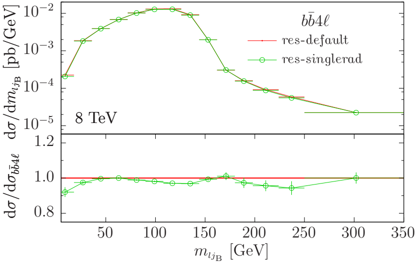
- unphysical smearing of top resonance and distortion of b-jet shape
- can be avoided only with rigorous treatment of 1st emission and shower

Multiple vs single NLO radiation

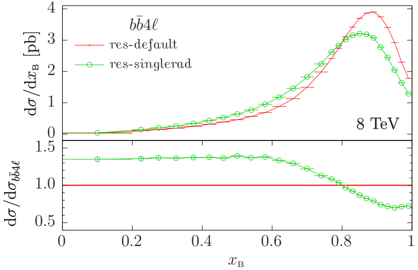
res-default: triple NLO radiation from $t\bar{t}$ production and decays (based on bb4l MEs)

res-singlerad: single NLO radiation (most likely from $t\bar{t}$ production)

b-jet–lepton mass



B-hadron fragmentation function



Radiation from top decays mostly from PY8 in *res-singlerad*

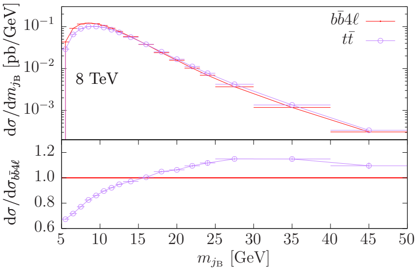
- minor impact on observables defined in terms of b-jets
- significant effects on b-jet substructure (e.g. softer x_B spectrum)
- despites ME corrections in PY8

$b\bar{b}4\ell$ vs $t\bar{t}$ Powheg generator (hvq)

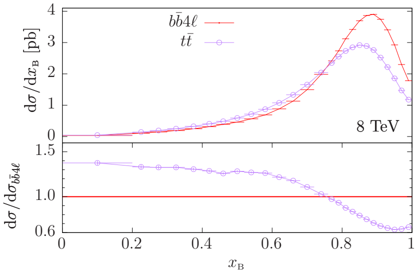
$b\bar{b}4\ell$: NLO+PS $e^+\mu^-\nu_e\bar{\nu}_\mu b\bar{b}$ [Jezo et al, 1607.04538]

$t\bar{t}$: NLO+PS $t\bar{t}$ with LO+PS decays [Frixione, Nason, Ridolfi, '07]

b-jet mass



B-hadron fragmentation function



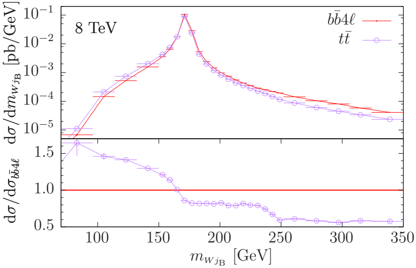
Significant effects in b-jet properties

- bb4l predicts narrower/lighter b-jets and harder x_B
- can be attributed to reduced radiation from b-quarks due to NLO top decays
- similar to *res-default* vs *res-singlerad* difference

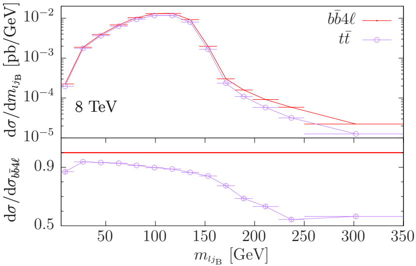
$b\bar{b}4\ell$: NLO+PS $e^+\mu^-\nu_e\bar{\nu}_\mu b\bar{b}$ [Jezo et al, 1607.04538]

$t\bar{t}$: NLO+PS $t\bar{t}$ with LO+PS decays [Frixione, Nason, Ridolfi, '07]

Reconstructed top mass



b-jet–lepton mass



Significant effects for m_t determination

- 10–30% asymmetric shape corrections to top resonance and $M_{\ell j_B}$ endpoint
- average $M_{W j_B}$ roughly 0.5 GeV higher * (within ± 30 GeV around m_t) in $b\bar{b}4\ell$
- can be due to NLO radiation in decays, off-shell effects, Wt production

* studies on implications for m_t determinations ongoing [talk by T.Jezo at QCD@LHC 2017]

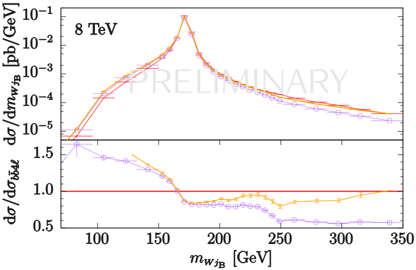
Comparing against $t\bar{t} + Wt$ combination

$b\bar{b}4\ell$: NLO+PS $e^+\mu^-\nu_e\bar{\nu}_\mu b\bar{b}$ [Jezo et al, 1607.04538]

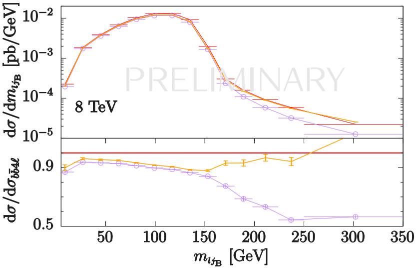
$t\bar{t}$: NLO+PS $t\bar{t}$ with LO+PS decays [Frixione, Nason, Ridolfi, '07]

$t\bar{t} + Wt$: NLO+PS $t\bar{t}$ (`hvq`) and Wt (`ST_wtch_DR`) with LO+PS decays [Re '10]

Reconstructed top mass



b-jet–lepton mass



Adding $t\bar{t} + Wt$ contributions

- improves agreement with $b\bar{b}4\ell$, especially for endpoint of $M_{\ell j_b}$
- $t\bar{t} + tW$ depends on prescription (DR or DS) to remove overlap at NLO

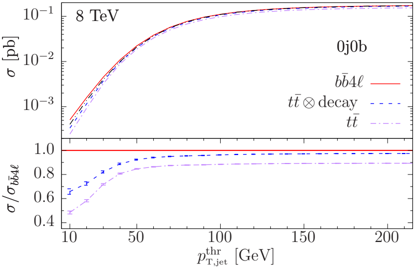
Wt enriched observables (jet-vetoed cross sections)

$b\bar{b}4\ell$: NLO+PS $e^+\mu^-\nu_e\bar{\nu}_\mu b\bar{b}$ [Jezo et al, 1607.04538]

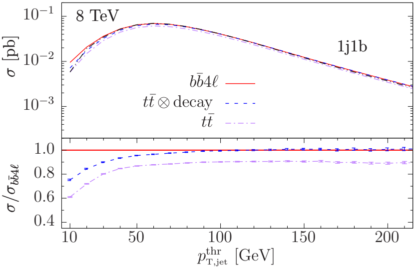
$t\bar{t}$: NLO+PS $t\bar{t}$ with LO+PS decays [Frixione, Nason, Ridolfi, '07]

$t\bar{t}\otimes$decay: NLO+PS $t\bar{t}\times$decays & LO $WWbb$ reweighting [Campbell, Ellis, Nason, Re '14]

$n_\mathrm{j} = n_\mathrm{b} = 0$



$n_\mathrm{j} = n_\mathrm{b} = 1$



Exclusive cross sections with n_j jets and n_b b-jets above p_T^{thr}

- inclusive regime (large p_T^{thr}): LO reweighting can account for Wt part (10%)
- Wt enriched regions (small p_T^{thr}): full $W^+W^-b\bar{b}$ at NLO needed (for correct radiation pattern of events with low-p_T b-jets)

$\Rightarrow$ relevant for Wt measurements

Summary and Conclusions

WWbb vs standard $t\bar{t}$ prod$\times$ decay

- NLO decays with exact spin correlations and off-shell effects
- $t\bar{t} + Wt$ with interference at NLO
- quantum description of QCD radiation (production-decay interference)
- quantum description of top-resonance and top mass

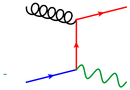
$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ generator based on Powheg-RES+OpenLoops

- resonance-aware method to respect key theory properties of resonances
- multiple radiation scheme: triple NLO radiation from production *and* decays
- potentially large $\mathcal{O}\left(\Gamma_t/m_t\right)$ effects at large p_T, large MET, Wt-enriched regions, b-jet substructure, reconstructed top mass, ...
- especially relevant for interpretation of kinematic m_t measurements (ongoing studies)

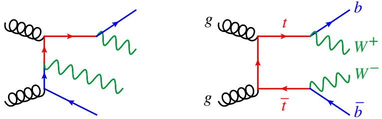
Backup slides

Wt production in the 5F scheme [Demartin et al, 1607.05862]

tW at LO



NLO b-bremsstrahlung (tWb) with decay

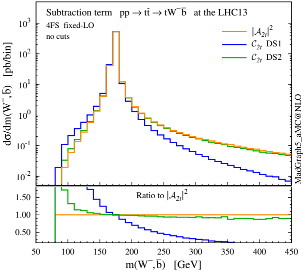


Subtraction of $t\bar{t}$ and $t\bar{t}$–tW interference crucial

- $\sigma_{t\bar{t}}/\sigma_{tW} \sim 10$ enhances interference and requires *accurate* $t\bar{t}$ subtraction!
- standard (DR1, DS1) and modified (DR2,DS2) prescriptions

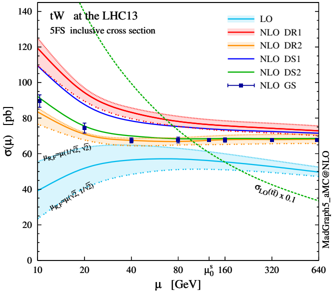
scheme	$2\mathrm{Re}(\mathcal{A}_{1t}\mathcal{A}_{2t})$	$\lvert\mathcal{A}_{2t}\rvert^2$
DR1	subtracted	subtracted
DR2	included	subtracted
DS1	included	CT subtraction
DS2	included	improved CT subtraction

differences reflect interference and uncertainties

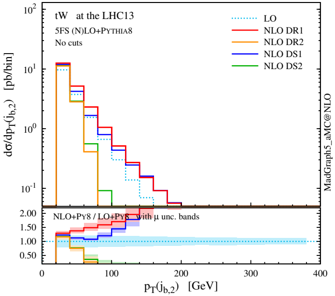


$pp \to tW$ in 5F scheme at 13 TeV [Demartin et al, 1607.05862]

σ_{tot}



2nd b-jet pT



Inclusive cross sections: $t\bar{t}$-tW interference amounts to -13%

- standard subtractions (DR1, DS1) inconsistent with rigorous approach (**GS**)
- modified subtractions (DR2, DS2) more consistent

Distributions interference can grow and lead to negative cross section at high b-jet p_T

tW **fiducial cuts** ($n_{b-\text{jets}} = 1$): $\sigma_{t\bar{t}}/\sigma_{tW}$ reduced to ~ 2 and interference suppressed

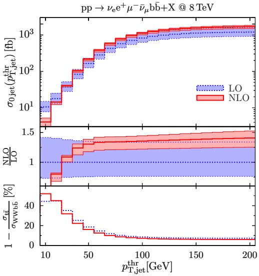
$\Rightarrow$ more meaningful and accurate separation of tW from $t\bar{t}$

$WWb\bar{b}$ cross section in jet bins [Cascioli, Maierhöfer,Kallweit, S.P. ’13]

Jet-Veto and Binning Effects

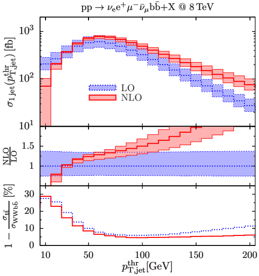
0-jet bin vs p_{T}-veto

- smooth inclusive limit at large p_{T} and very strong p_{T} sensitivity below $50\,\mathrm{GeV}$:
  - FtW effects increase up to 50%
  - K-factor falls very fast
- at low p_{T} IR singularity calls for NLO+PS matching
- typical veto $p_{\mathrm{T}} \sim 30\,\mathrm{GeV}$ yields 98% suppression and still decent NLO stability ($K \sim 1$)

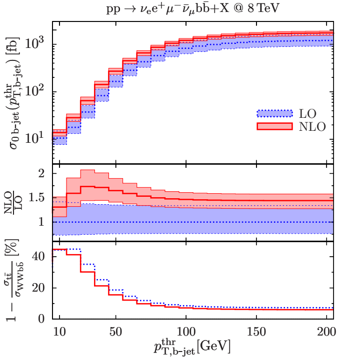


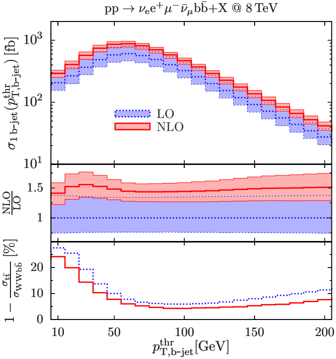
1-jet bin vs p_{T} threshold

- low p_{T} behaviour driven by veto on 2nd jet and analogous to 0-jet case
- high p_{T} region driven by 1st jet and NLO radiation dominates over b-jets from $W^+W^-b\bar{b}$



$WWbb$ cross section in b-jet bins [Cascioli, Maierhöfer, Kallweit, S.P. '13

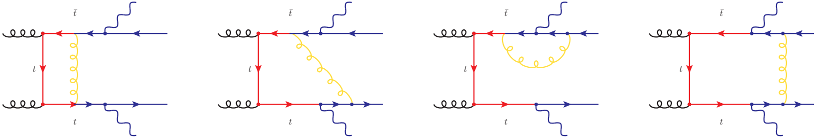




- NLO radiation doesn't change b-jet multiplicity ⇒ rather stable K-factor and uncertainties
- single-top and off-shell effects still enhanced at small b-jet p_T

In general: nontrivial interplay of NLO and off-shell/single-top effects

Examples of factorisable and non-factorisable 1-loop diagrams

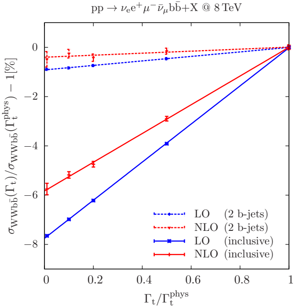


Separation of narrow- and finite-top-width parts

- via numerical $\Gamma_t \to 0$ extrapolation

$$\lim_{\xi_t \to 0} \mathrm{d}\sigma_{W^+W^-b\bar{b}}(\xi_t \Gamma_t) = \xi_t^{-2} \left[\mathrm{d}\sigma_{t\bar{t}} + \xi_t\, \mathrm{d}\sigma_{\mathrm{FtW}}\right]$$

$\Rightarrow$ permille-level convergence demonstrates nontrivial cancellation of soft-gluon $\ln(\Gamma_t/m_t)$ singularities



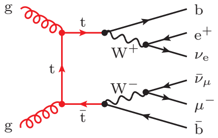
$\sigma_{t\bar{t}} =$ on-shell $t\bar{t}$ production $\times$ decay

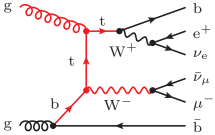
$\sigma_{\mathrm{FtW}} = \mathcal{O}(\Gamma_t/m_t)$ effects dominated by Wt + interference + off-shell $t\bar{t}$ + ...

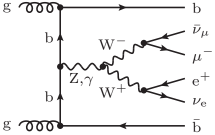
$=$ 6–8% of $\sigma_{\mathrm{inclusive}}$ (cf. sub-percent effect with $t\bar{t}$ cuts!)

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ at NLO EW [Denner and Pellen '16]

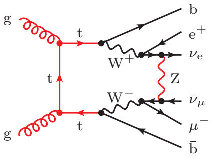
Representative doubly- ($t\bar{t}$ like) singly- (tW like) and non-resonant (WW like) trees







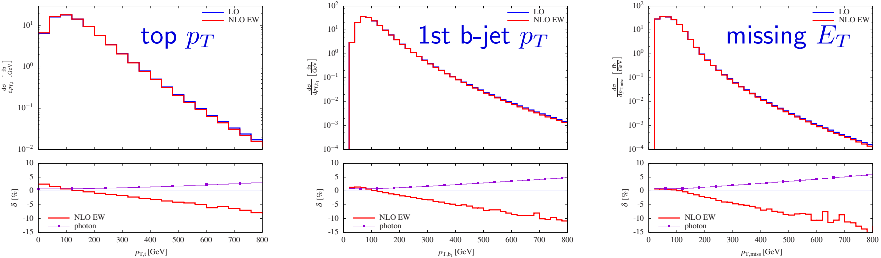
Exact $2 \to 6$ NLO EW calculation



- fully differential 6-particle final state
- NLO EW top decays
- off-shell $t\bar{t} + Wt$ + non-resonant contributions

Applicable only with $t\bar{t}$ type cuts ($m_b = 0 \Rightarrow$ no unresolved b-quarks)

- 2 b-jets ($p_T > 25\,$GeV, $|\eta| < 2.5$)
- 2 charged leptons ($p_T > 20\,$GeV, $|\eta| < 2.5$) and missing $E_T > 20\,$GeV



NLO EW corrections

- up to -10-15% at $p_T \sim 800$ GeV
- qualitatively consistent with [Pagani et al '16] for reconstructed top p_T

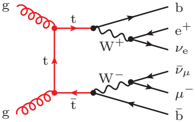
γ-induced contributions (γg at LO and γq at NLO EW included)

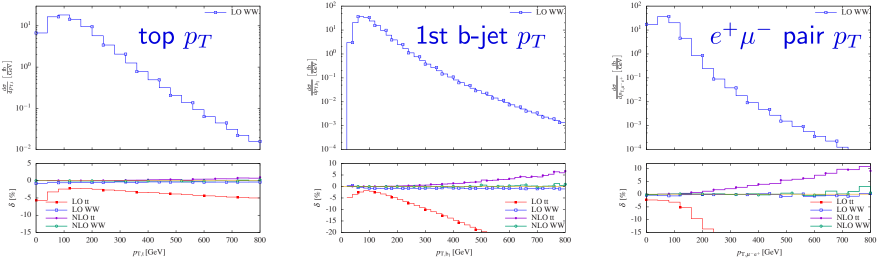
- 5–6% at $p_T \sim 800$ GeV
- smaller wrt [Pagani et al '16] due to fixed $\mu_F = m_t$

Exact $pp \to b\bar{b} + 4\ell$ vs double-pole approximation

Double-pole approximation (similar to $t\bar{t}$ MC generators!)

- on-shell $t\bar{t} \to b\bar{b} + 4\ell$ matrix elements
- approx. off-shell effects via $1/[(p^2 - m_t^2)^2 + \Gamma_t^2 m_t^2]$ distributions





Genuine off-shell and Wt effects (see deviations wrt LO $t\bar{t}$)

- $+3\%$ for σ_{tot} and $+5\%$ in tail of reconstructed top p_T
- beyond 20–30% in p_T-tails of individual top-decay products

$\Rightarrow$ **NLO EW and $\mathcal{O}(\Gamma_t/m_t)$ effects mandatory for precision at high p_T**