Issues on Wt definition and ttbar/single-top/WbWb separation

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based on work with: T. Gehrmann, M. Grazzini, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi

Phys. Rev. Lett. 113 (2014) 21, 212001 [arXiv:1408.5243 [hep-ph]]

and with: F. Cascioli, P. Maierhöfer and S. Pozzorini

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Outline

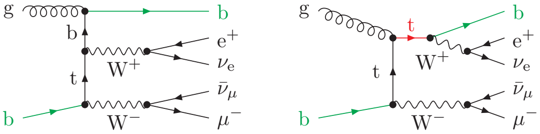
1. Introduction
   - Definition of WW cross section without top contamination
   - Extrapolation in top width to isolate WW contributions

2. WWbb – a unified description of ttbar, single-top and WbWb production
   - Full description vs. narrow-width approximation
   - Extrapolation in top width to separate WWbb contributions
   - Exclusive (b)jet bins and differential cross sections at NLO QCD

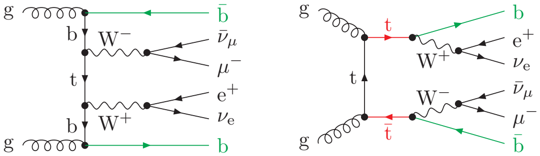
3. Conclusions

Definition of top-contamination free WW cross section

- Non-trivial in 5FNS (massless b's $\rightarrow$ WW and $\mathrm{WWb\bar{b}}$ connected by IR structure)
  - Single-top production enters at NLO.



  - Top-pair production enters at NNLO.



$\hookrightarrow$ Huge "higher-order corrections" result from top-resonance contamination in 5FNS (cross-section enhancement of 30%/400% at NLO/NNLO for $\sqrt{s} = 8$ TeV).

- Straightforward in 4FNS (massive b's $\rightarrow$ $\mathrm{WWb\bar{b}}$ finite and can be split off)

Extrapolation in top width to isolate WW contributions

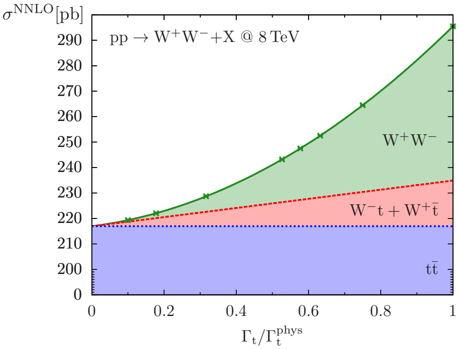
Γ_t-dependence of NNLO cross section can be used to isolate the different processes (other methods like "diagram removal", "diagram subtraction", ... not discussed here)

- Exploit the Γ_t dependence of the genuine WW, tW, and $\mathrm{t\bar{t}}$ contributions,

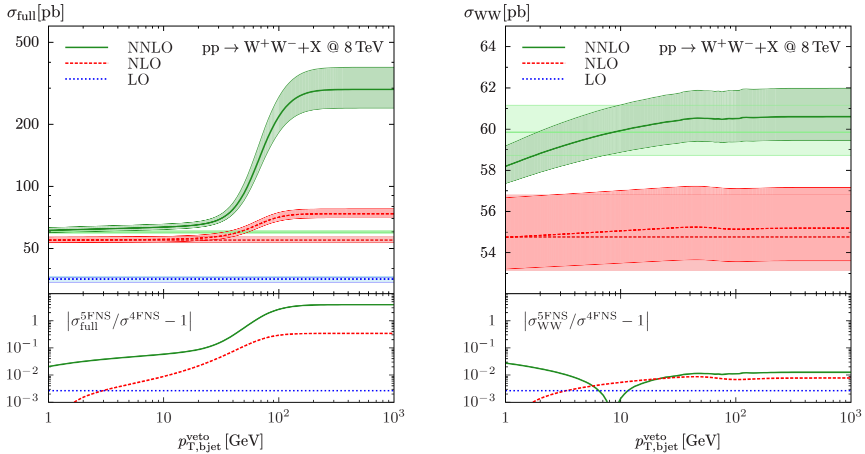
$$\sigma_{\mathrm{WW}} \propto 1, \quad \sigma_{\mathrm{tW}} \propto 1/\Gamma_t, \quad \sigma_{\mathrm{t\bar{t}}} \propto 1/\Gamma_t^2,$$

  and treat Γ_t as technical parameter to approach the $\Gamma_t \to 0$ limit.

↪ Parabolic fit of the $(\Gamma_t/\Gamma_t^{\mathrm{phys}})^2$-rescaled cross section delivers σ_{WW}, σ_{tW}, $\sigma_{\mathrm{t\bar{t}}}$.



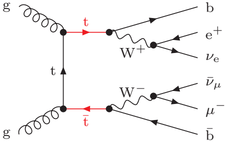
Comparison between 4FNS and 5FNS WW cross sections



- About 15% of enhancement remain at NNLO for "physical" $p_{\mathrm{T,bjet}}^{\mathrm{veto}} \approx 30\,\mathrm{GeV}$.
- The limit $p_{\mathrm{T,bjet}}^{\mathrm{veto}} \to 0\,\mathrm{GeV}$ cannot be directly accessed (Infrared divergent in 5FNS).
- Extrapolation gives ≈ 1-2% agreement between 4FNS and 5FNS for $p_{\mathrm{T,bjet}}^{\mathrm{veto}} \to \infty$.

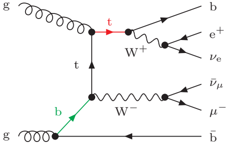
Full $W^+W^-b\bar{b}$ description vs narrow-width approximation in LO

Doubly-resonant diagrams



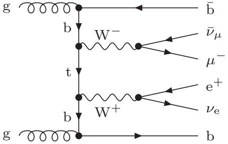
$t\bar{t}$

Singly-resonant diagrams



Wt

Non-resonant diagrams



WbWb

$t\bar{t}$ in narrow-width approximation

- only DR channels in narrow-width limit

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

- Wt and WbWb are completely split off.

Finite-top-width contributions to $WWb\bar{b}$

- off-shell corrections to DR channels
  $\hookrightarrow$ $\mathcal{O}(\Gamma_t/m_t)$ corrections to inclusive $t\bar{t}$
- SR+NR channels and interferences
  $\hookrightarrow$ Divergences appear for $p_{T,b} \to 0$ if $m_b = 0$

Finite bottom masses in $WWb\bar{b}$

- Complete phase-space accessible, also $p_{T,b} \to 0$ where Wt and WbWb are enhanced.
- Unified description of $t\bar{t}$, Wt, and WbWb with all off-shell effects and interferences!

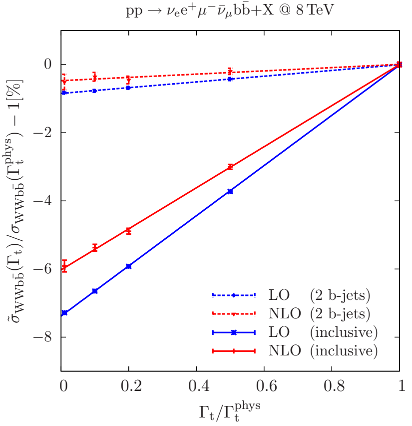
Assessment of finite-top-width effects in inclusive WWbb

Assessment of finite-width effects $\tilde{\sigma}(\Gamma_t^{\text{phys.}}) - \tilde{\sigma}(0)$

- Numerical extrapolation $\Gamma_t \to 0$ is performed using rescaled values $\Gamma_t = \xi \Gamma_t^{\text{phys.}}$ and rescaled cross sections $\tilde{\sigma}(\Gamma_t) = (\Gamma_t/\Gamma_t^{\text{phys.}})^2 \sigma(\Gamma_t)$.

Cancellation of soft-gluon $\ln(\Gamma_t/m_t)$ singularities

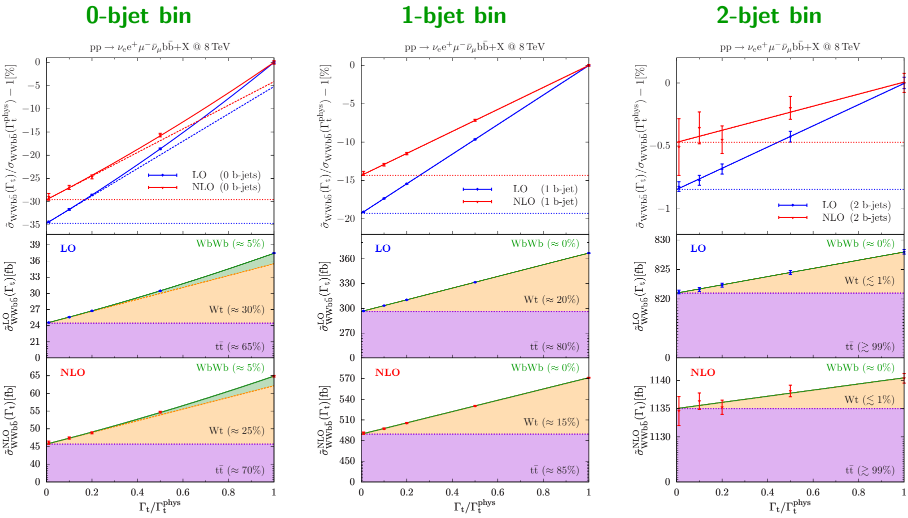
- Dipole-subtracted virtual and real parts diverge logarithmically when $\Gamma_t \to 0$.
- Linear convergence of $\tilde{\sigma}(\Gamma_t^{\text{phys.}}) \to \tilde{\sigma}(0)$ (non-resonant WbWb tiny) provides non-trivial consistency and stability check.



2-bjet bin: Small $\mathcal{O}(\Gamma_t/m_t) \simeq 0.8\%$ effects
$\hookrightarrow$ essentially $t\bar{t}$, as in $m_b = 0$ case.

inclusive: 10 times larger finite-top-width effects
$\hookrightarrow$ Wt dominated.

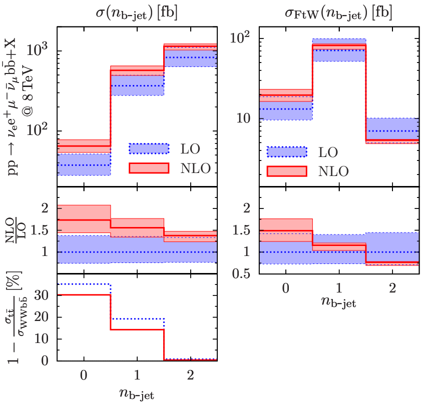
Separation of WWbb cross section in b-jet bins (p_T threshold 30 GeV)



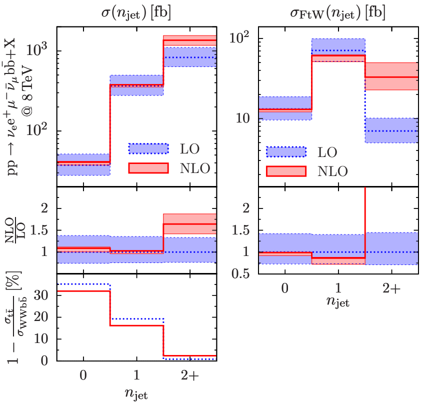
- Finite-top-width effects (Wt and WbWb) significantly enhanced in lower bjet bins.
- Non-resonant WbWb can only be identified in 0-bjet bin (too small elsewhere).

WWbb predictions in exclusive (b)jet bins (p_{T} threshold 30 GeV)

$\sigma_{\mathrm{WWb\bar{b}}}$ - multiplicity of bjets



$\sigma_{\mathrm{WWb\bar{b}}}$ - multiplicity of jets

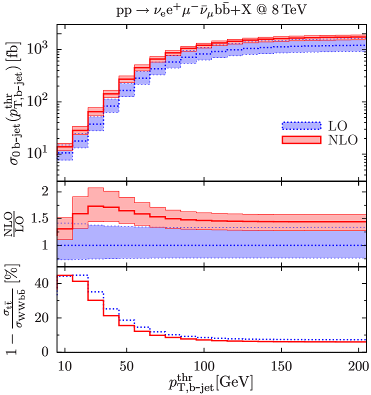


Moderate size of NLO corrections (particularly for the finite-top-width contributions) guaranteed by dynamic scale $\mu_{\mathrm{WWb\bar{b}}}$ dedicated to ($\mathrm{t\bar{t}}$ + Wt + WbWb) situation.

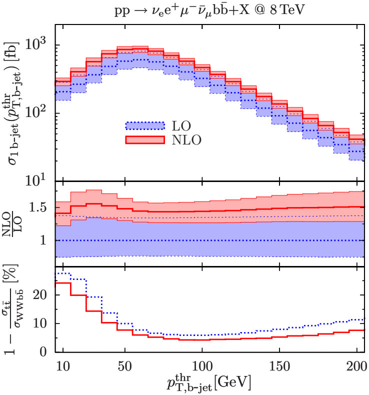
↪ $\mu_{\mathrm{WWb\bar{b}}}$ interpolates between the typical scales $E_{\mathrm{T,t/\bar{t}}}$ and $E_{\mathrm{T,b/\bar{b}}}$ for each event, based on the kinematics of $\mathrm{W^+b/W^-\bar{b}}$ subconfigurations.

Multiplicity of bjets in dependence of jet-p_T threshold

0-bjet exclusive cross section



1-bjet exclusive cross section

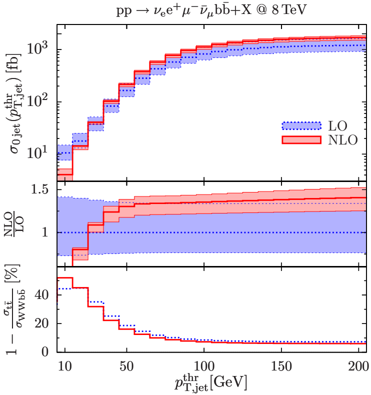


- saturates the integrated cross section for high p_T thresholds.
- gets largest contribution at a threshold $p_T \approx 60$ *GeV*.

Results are perturbatively quite stable in the relevant range of jet-p_T thresholds.
$\hookrightarrow$ At $p_T \approx 30\,\text{GeV}$ (typical veto range), both NLO and $t\bar{t}/Wt$ ratio non-trivial.

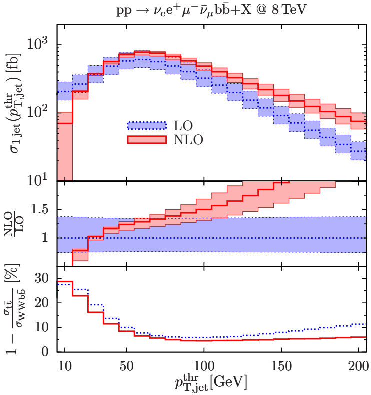
Multiplicity of jets in dependence of jet-p_{T} threshold

0-jet exclusive cross section



- saturates the integrated cross section for high p_{T} thresholds.

1-jet exclusive cross section



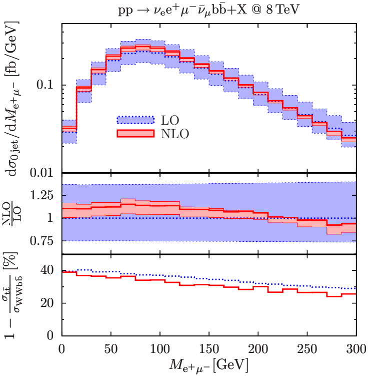
- is dominated by LO-like contributions in the high-p_{T} region.

For low jet-p_{T} threshold ($p_{\mathrm{T}} \lesssim 20\,\mathrm{GeV}$), perturbative stability breaks down.

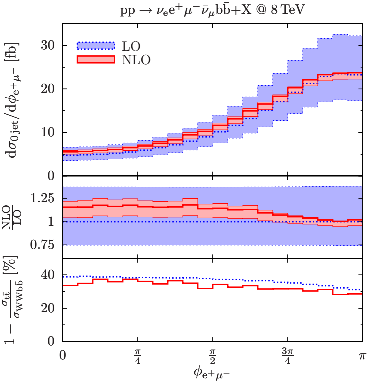
$\hookrightarrow$ Parton shower is needed to restore perturbative stability for very low jet-p_{T} threshold.

0-jet-bin distributions for $\mathrm{H} \to \mathrm{WW}$ analysis (p_T threshold 30 GeV)

Invariant mass of the lepton pair



Azimuthal angle between the leptons



Top-induced background for $\mathrm{H} \to \mathrm{WW}$ analysis $\to$ precise description needed.

- Significant finite-top-width effects up to 40% with $\sim$ 10% phase-space dependence.
- Small NLO corrections and significant reduction of scale variations to about 10%.

$\hookrightarrow$ Further evidence for stability of the perturbative description.

Conclusions

- **Underlying calculations performed within widely automated frameworks**
  - NLO QCD $\mathbf{WWb\bar{b}}$ calculation: MUNICH + OPENLOOPS (using COLLIER)
  - NNLO QCD $\mathbf{WW}$ calculation: MATRIX (MUNICH + q_T subtraction) + OPENLOOPS (using COLLIER and CUTTOOLS) + two-loop WW amplitudes.
- **Definition of top-contamination free WW cross section at NNLO**
  - 4-flavour scheme: straightforward, as $\mathrm{WWb\bar{b}}$ can be split off.
  - 5-flavour scheme: Overlap with Wt and $\mathrm{t\bar{t}}$ at higher orders unavoidable.
    ↪ Contributions can be separated by top-width extrapolation procedure.
- **NLO QCD calculation for $\mathbf{WWb\bar{b}}$ production in 4FNS ($\mathbf{m_b > 0}$)**
  - Complete phase-space covered, in particular the low-$p_{\mathrm{T,b}}$ region, where Wt and WbWb are enhanced, can be addressed.
  - Simultaneous treatment of $\mathrm{t\bar{t}}$, Wt, and WbWb, including off-shell effects, non-resonant backgrounds and interferences.
  - Extrapolation procedure can be applied to separate the contributions.
  - Exclusive jet-multiplicity dependent cross sections accessible.
    ↪ non-trivial effects from NLO and interplay of $\mathrm{t\bar{t}}$, Wt, and WbWb.

Backup

Backup slides

Setup and input parameters in $\mathrm{WWb\bar{b}}$

Particle masses and widths

$$
\begin{aligned}
m_{\mathrm{b}} &= 4.75\,\mathrm{GeV} \\
m_{\mathrm{t}} &= 173.2\,\mathrm{GeV} & \Gamma_{\mathrm{t,LO}} &= 1.47451\,\mathrm{GeV} & \Gamma_{\mathrm{t,NLO}} &= 1.34264\,\mathrm{GeV} \\
M_{\mathrm{W}} &= 80.385\,\mathrm{GeV} & & & \Gamma_{\mathrm{W,NLO}} &= 2.09530\,\mathrm{GeV} \\
M_{\mathrm{Z}} &= 91.1876\,\mathrm{GeV} & & & \Gamma_{\mathrm{Z,NLO}} &= 2.50479\,\mathrm{GeV} \\
M_{\mathrm{H}} &= 126\,\mathrm{GeV} & \Gamma_{\mathrm{H}} &= 4.21 \times 10^{-3}\,\mathrm{GeV}
\end{aligned}
$$

G_μ-scheme couplings $\cos^2\theta_{\mathrm{w}} = \dfrac{M_{\mathrm{W}}^2 - \mathrm{i}\Gamma_{\mathrm{W}} M_{\mathrm{W}}}{M_{\mathrm{Z}}^2 - \mathrm{i}\Gamma_{\mathrm{Z}} M_{\mathrm{Z}}}$, $\alpha = \sqrt{2} G_\mu M_{\mathrm{W}}^2 (1 - M_{\mathrm{W}}^2/M_{\mathrm{Z}}^2)/\pi$

$$G_\mu = 1.16637 \times 10^{-5}\,\mathrm{GeV}^{-2}$$

PDFs and α_{S} 4-flavour NNPDF at LO and NLO with 4-flavour running of α_{S}; independent variations $1/2 \leq \mu_{\mathrm{R}}/\mu_0 \leq 2$ and $1/2 \leq \mu_{\mathrm{F}}/\mu_0 \leq 2$.

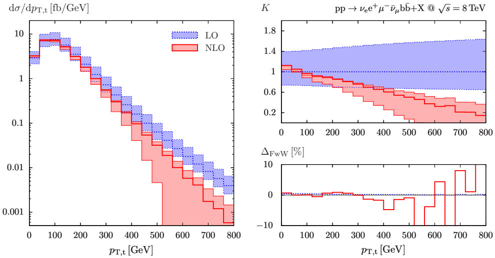
Cuts only on leptons: $|\eta_l| < 2.5$, $p_{\mathrm{T},l} > 20\,\mathrm{GeV}$, $p_{\mathrm{T,miss}} > 20\,\mathrm{GeV}$

Anti-k_{T} Jet Algorithm

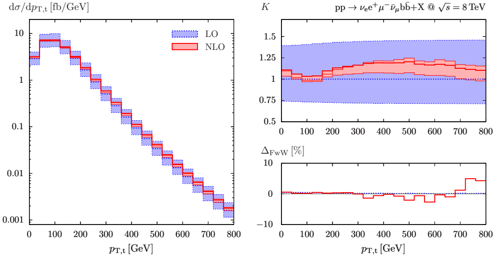
- Separation of (b)jets with $\sqrt{\Delta\phi^2 + \Delta y^2} > R = 0.4$.
- No "IR-safe" recombination of $\mathrm{b\bar{b}}$ applied ($m_{\mathrm{b}} > 0$).
- (b)jets are defined by $|\eta_{j/\mathrm{b}}| < 2.5$, $p_{\mathrm{T},j/\mathrm{b}} > 30\,\mathrm{GeV}$.

Adequate scale choice for $W^+W^-b\bar{b}$ dedicated to $t\bar{t}$ production

Fixed scale $\mu_{R/F} = m_t/2$: [Denner/Dittmaier/SK/Pozzorini '12]



Dynamic scale $\mu_{R/F} = \overline{E}_{T,t}/2$: [Denner/Dittmaier/SK/Pozzorini '12]



Fixed scale too low in high-p_T tails of produced particles

- LO overestimates cross section,
- NLO calculation gets perturbatively unstable.

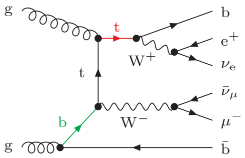
$\Rightarrow$ **Introduction of dynamic scale**

- which coincides with fixed scale if $p_{T,t} \to 0$,
- which adapts to the higher scattering energy in high-$p_{T,t}$ regions.

$\Rightarrow$ **Use average over t and $\bar{t}$ transverse energies:**

$$\overline{E}_{T,t}^2 = \sqrt{m_t^2 + p_{T,t}^2} \times \sqrt{m_t^2 + p_{T,\bar{t}}^2}$$

Scale choice for simultaneous description of $\mathrm{t\bar{t}}$ and Wt



Dynamic scale $\overline{E}_{\mathrm{T,t}}$ is motivated from the $\mathrm{t\bar{t}}$ side only.

↪ Scale overestimates natural scale for Wt-like events, particularly due to $g \to \mathrm{b\bar{b}}$ splitting.

⇒ **Introduction of a new dynamic scale to interpolate between $\mathrm{t\bar{t}}$ and Wt production (multi-scale problem)**

- which coincides with the dynamic scale $\overline{E}_{\mathrm{T,t}}$ for $\mathrm{t\bar{t}}$-like events,
- which takes into account the $g \to \mathrm{b\bar{b}}$ splitting for Wt-like events.

Ansatz: $\mu_{\mathrm{IS}}^2 = E_{\mathrm{Wb}} \times E_{\mathrm{W\bar{b}}}$ with

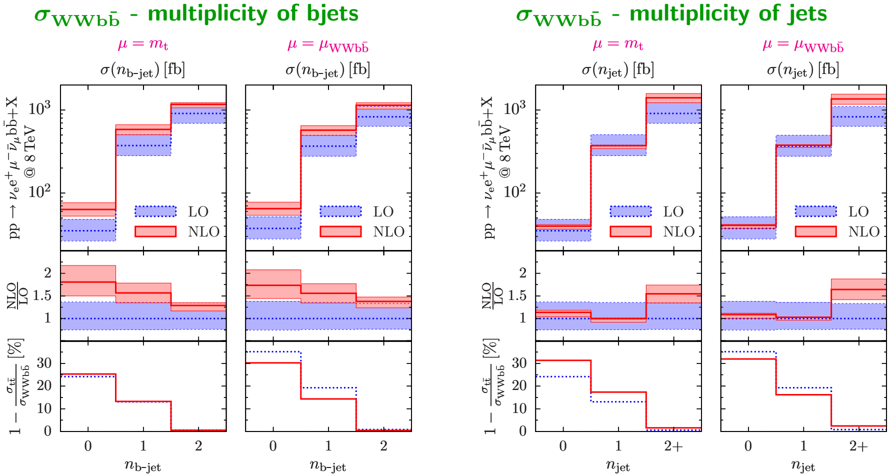
$$E_{\mathrm{Wb}} = P(t)E_{\mathrm{T,t}} + P(b)E_{\mathrm{T,b}} \;,$$
$$E_{\mathrm{W\bar{b}}} = P(\bar{t})E_{\mathrm{T,\bar{t}}} + P(\bar{b})E_{\mathrm{T,\bar{b}}} \;.$$

$P(t/\bar{t})$ and $P(b/\bar{b})$ stand for probability estimates of the $\mathrm{W^+b/W^-\bar{b}}$ configurations in the respective event to be "top-like" or "bottom-like":

$$P(t) \propto \chi(t) = \frac{m_\mathrm{t}^4}{(p_\mathrm{t}^2 - m_\mathrm{t}^2)^2 + \Gamma_\mathrm{t}^2 m_\mathrm{t}^2} \quad \text{and} \quad P(b) \propto \chi(b) = \frac{m_\mathrm{t}^2}{E_{\mathrm{T,b}}^2} \,.$$

↪ Normalization of "top-like" and "bottom-like" probabilities ($P(t) + P(b) = 1$) and an iterative procedure performed at LO fix the weighting between $P(t)$ and $P(b)$.

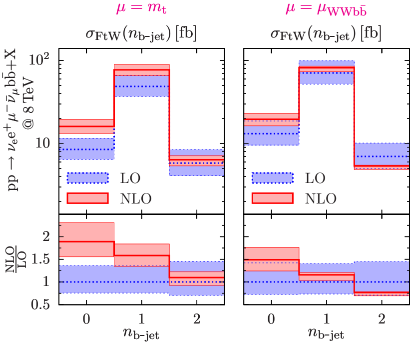
WWbb predictions in exclusive (b)jet bins



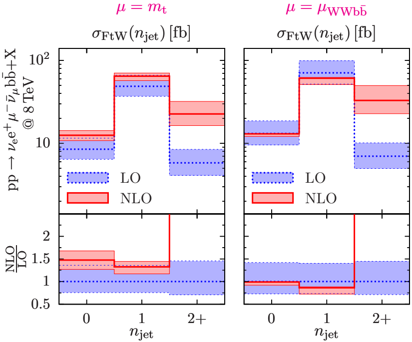
- Enhanced finite-top-width effects in 0- and 1-(b)jet bins (up to ~ 30%)
  ↪ Importance of unified $t\bar{t}$ and Wt description!
- Perturbative benefit from $\mu_{\mathrm{WWb\bar{b}}}$ is widely washed out by dominating $t\bar{t}$ contribution.

Finite-top-width contribution: (exclusive) multiplicity of (b)jets

$\sigma^{\mathrm{FtW}}_{\mathrm{WWb\bar{b}}}$ - multiplicity of bjets



$\sigma^{\mathrm{FtW}}_{\mathrm{WWb\bar{b}}}$ - multiplicity of jets



- Both the size of NLO corrections and the residual scale uncertainties are reduced by the dynamic scale choice $\mu = \mu_{\mathrm{WWb\bar{b}}}$.
- Similar reduction as in the b-jet case due to $\mu = \mu_{\mathrm{WWb\bar{b}}}$ (2+-jet bin anyway dominated by $\mathrm{t\bar{t}}$ contribution).

$\hookrightarrow$ Perturbative stability seems to be improved by the dynamic scale choice $\mu = \mu_{\mathrm{WWb\bar{b}}}$.