A unified NLO description of top-pair and associated Wt production

Stefan Kallweit[1]

based on work with F. Cascioli, P. Maierhöfer and S. Pozzorini

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[1]University of Zurich

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MIAPP summer institute “Challenges, Innovations and Developments in Precision Calculations for the LHC” at TU Munich

Universität Zürich UZH

Outline

1. Introduction
    - Full description vs. narrow-width approximation
    - Motivation for WWbb — with massive bottom quarks
2. Technical aspects of the NLO QCD calculation
    - NLO QCD calculation with OpenLoops/Collier/CDST dipoles
    - Phase-space integration by multi-channel approach
3. Numerical Results for the 8TeV LHC
    - Adequate scale choice for WWbb
    - 0-, 1-, and 2-jet cross sections at NLO QCD
    - Differential cross sections at NLO QCD
4. Conclusions

Precise predictions for hadronic $\mathrm{t\bar{t}}$ production (and decay)

NLO QCD corrections

Beenakker, Dawson, Ellis, Frixione, Kuijf, Meng, Nason, van Neerven, Schuler, Smith

Electroweak NLO corrections

Beenakker, Bernreuther, Denner, Fücker, Hollik, Kao, Kollar, Kühn, Ladinsky, Mertig, Moretti, Nolten, Ross, Sack, Scharf, Si, Uwer, Wackeroth, Yuan

From LL to NNLL resummations

Ahrens, Beneke, Berger, Bonciani, Cacciari, Catani, Contopanagos, Czakon, Falgari, Ferroglia, Frixione, Kidonakis, Kiyo, Klein, Laenen, Mangano, Mitov, Moch, Nason, Neubert, Pecjak, Piclum, Ridolfi, Schwinn, Sterman, Ubiali, Uwer, Vogt, Yan, Yang

Towards full NNLO predictions

Abelof, Anastasiou, Aybat, Baernreuther, Bonciani, Czakon, Dittmaier, Ferroglia, Gehrmann, Gerhmann–De Ridder, Kniehl, Körner, Langenfeld, Maierhöfer, Maitre, Merebashvili, Mitov, Moch, Pozzorini, Ritzmann, Rogal, Studerus, von Manteuffel, Uwer, Vogt, Weinzierl

NNLO QCD $\mathrm{t\bar{t}}$ production

Czakon, Fiedler, Mitov, Rojo

NLO QCD $\mathrm{t\bar{t}}$ production $\otimes$ decay in spin-correlated narrow-width approximation

Bernreuther, Brandenburg, Melnikov, Schulze, Si, Uwer

NLO QCD $\mathrm{W^+W^-b\bar{b}}$ production with massless bottom quarks (with leptonic W decays)

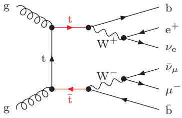
Bevilacqua, Czakon, Denner, Dittmaier, van Hameren, Heinrich, Kallweit, Maier, Nisius, Papadopoulos, Pozzorini, Schlenk, Worek, Winter

NLO QCD $\mathrm{W^+W^-b\bar{b}}$ production with massive bottom quarks (with leptonic W decays)

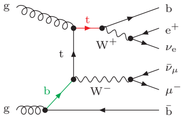
Cascioli, Frederix, Kallweit, Maierhöfer, Pozzorini

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

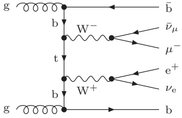
Doubly-resonant ($\mathrm{t\bar{t}}$-like) diagrams (DR)



Singly-resonant (Wt-like) diagrams (SR)



Non-resonant diagrams (NR)



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

- only DR channels
- narrow-width limit of Breit-Wigner top resonances

$$\lim_{\Gamma_\mathrm{t}\to 0}\left|\frac{1}{p_\mathrm{t}^2-m_\mathrm{t}^2+\mathrm{i}\Gamma_\mathrm{t}m_\mathrm{t}}\right|^2=\frac{\pi}{\Gamma_\mathrm{t}m_\mathrm{t}}\,\delta(p_\mathrm{t}^2-m_\mathrm{t}^2)$$

Finite-width contributions to $\mathrm{W^+W^-b\bar{b}}$

- off-shell corrections to DR channels
- SR+NR channels and interferences
  ↪ Divergences appear for $p_{\mathrm{T,b}}\to 0$ if $m_\mathrm{b}=0$
- $\mathcal{O}(\Gamma_\mathrm{t}/m_\mathrm{t})$ corrections to inclusive $\mathrm{t\bar{t}}$ observables

Finite bottom masses in $\mathrm{W^+W^-b\bar{b}}$

- phase-space regions with unresolved b-jets accessible
  ↪ huge finite-top-width corrections from Wt
- $\mathrm{W^+W^-b\bar{b}}$ describes both $\mathrm{t\bar{t}}$ and Wt with all off-shell effects and interferences in a unified way!

Relevance of $\mathrm{W^+W^-b\bar{b}}$ production at NLO QCD — with $m_\mathrm{b} > 0$

Full description of $\mathrm{t\bar{t}}$ production $\otimes$ decays

- off-shell top quark and non-doubly-resonant background
  $\hookrightarrow$ huge effects from regions with unresolved b-jets (where Wt is enhanced!)
- leptonic W decays taken into account (actually full four-lepton final states)

Relevance for many BSM searches

- typical discovery signature: leptons + jets + missing E_T (SUSY, . . .)
- heavy resonances decaying into $\mathrm{t\bar{t}}$ in various BSM scenarios

Importance as background to SM processes
(especially if jet vetoes are required!)

- $pp \to \mathrm{WH}(\to \mathrm{b\bar{b}}) + X$ (if one of the W-decay leptons is invisible)
- $pp \to \mathrm{H}(\to \mathrm{WW}) + \mathrm{2jets} + X$ in VBF (particular relevance of the high-$\Delta\eta_\mathrm{jj}$ region)
- $pp \to \mathrm{H} \to \mathrm{WW} + X$ (particular relevance of the 0-jet and 1-jet bins)

$\hookrightarrow$ Consistent treatment of $\mathrm{t\bar{t}}$, Wt backgrounds and interferences needed.

Technical realization of the NLO QCD calculation

Treatment of unstable particles via complex-mass scheme

(introduced at NLO for $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to 4f$ [Denner/Dittmaier/Roth/Wieders '05])

- Γ is absorbed into the renormalised pole mass: $M^2 \to \mu^2 = M^2 - \mathrm{i}M\Gamma$
- on-shell renormalisation on complex propagator pole: $\hat{\Sigma}(p^2) = 0$ at $p^2 = \mu^2$

Calculation of top-quark width

- Consistent treatment in amplitude and parameters crucial (to avoid fake effects)
- top width calculated with off-shell W and finite bottom mass [Jezabek/Kühn '89, Czarnecki '90, Campbell/Ellis '12]

Scattering amplitudes with OpenLoops [Cascioli/Maierhöfer/Pozzorini '11]

- tree, one-loop and real-emission amplitudes (including colour/helicity correlations)
- fully automated for NLO QCD for any SM process
- compact and fast numerical code

Tensor reduction by means of the Collier library [Denner/Dittmaier/Hofer]

- numerically stable Denner–Dittmaier reduction methods [Denner/Dittmaier '02&'05]
- scalar integrals with complex masses [Denner/Dittmaier '10]

Mediation of IR divergences between Born- and real-emission phase-spaces

- dipole subtraction for massless and massive particles [Catani/Dittmaier/Seymour/Troscanyi '02]

Numerical realization of the calculation

Fully automated NLO QCD Monte Carlo framework (implementation in C++) [SK]

- Phase-space integration by multi-channel Monte Carlo techniques
  - Automatized generation of mappings for arbitrary partonic processes
  - Additional Monte Carlo channels based on dipole kinematics (improvement of convergence, particularly in multi-resonance processes)

↪ Fast and stable numeric calculation of cross sections and distributions

- Additional features of the integrator
  - Code generation for arbitrary Standard Model process (including automatic bookkeeping of all required partonic channels)
  - Automatic generation of OpenLoops interface
  - Automatic selection and construction of massless and massive dipoles
  - Simultaneous calculations for different scale choices and variations
- Applicability to NNLO calculations proven (via q_T subtraction)
  [Grazzini/SK/Rathlev/Torre '13, Cascioli, Gehrmann, Grazzini, SK, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14]
- Extension to NLO EW calculations straightforward

↪ All ingredients well tested in various multi-particle processes!

Setup and input parameters

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 $1/2 \le \mu_{\mathrm{R}}/\mu_0 \le 2$ and $1/2 \le \mu_{\mathrm{F}}/\mu_0 \le 2$.

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

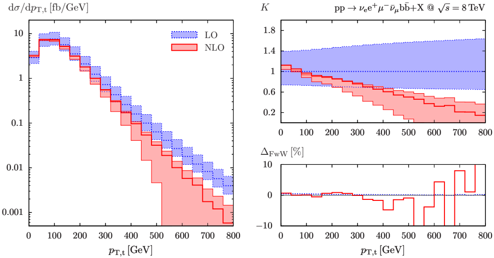
Anti-k$_{\mathrm{T}}$ Jet Algorithm

- 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 $\mathrm{W^+W^-b\bar{b}}$ dedicated to $\mathrm{t\bar{t}}$ production

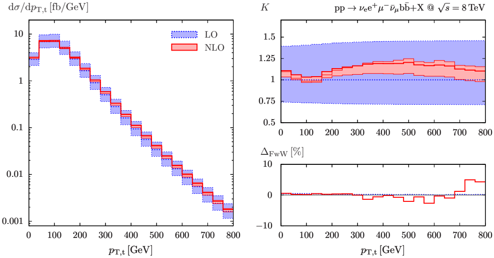
Fixed scale $\mu_{\mathrm{R/F}} = m_{\mathrm{t}}/2$:

[Denner/Dittmaier/SK/Pozzorini '12]



Dynamic scale $\mu_{\mathrm{R/F}} = \mu_{\mathrm{t\bar{t}}}/2$:

[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.

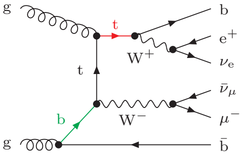
⇒ **Introduction of dynamic scale**

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

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

$$\mu^2_{\mathrm{t\bar{t}}} = \sqrt{m^2_{\mathrm{t}} + p^2_{\mathrm{T,t}}} \times \sqrt{m^2_{\mathrm{t}} + p^2_{\mathrm{T,\bar{t}}}}$$

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



Dynamic scale $\mu_{\mathrm{t\bar{t}}}$ 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 $\mu_{\mathrm{t\bar{t}}}$ for $\mathrm{t\bar{t}}$-like events,
- which takes into account the $g \to \mathrm{b\bar{b}}$ splitting for Wt-like events.

Ansatz: $\mu^2_{\mathrm{WWb\bar{b}}} = E_{\mathrm{Wb}} \times E_{\mathrm{W\bar{b}}}$ 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":

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

↪ 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 $P(b)$.

Off-shell and not doubly-resonant contributions to σ_{incl}

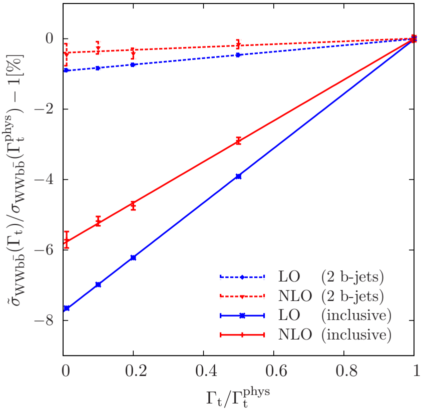
Assessment of finite-width effects $\sigma(\Gamma_t) - \sigma(0)$

- Numerical extrapolation to $\Gamma_t \to 0$ is performed using five rescaled values $\Gamma_t = \xi\Gamma_t^{\mathrm{phys.}}$ with $0.01 \le \xi \le 1$.

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 $\sigma(\Gamma_t) \to \sigma(0)$ provides non-trivial consistency and stability check.

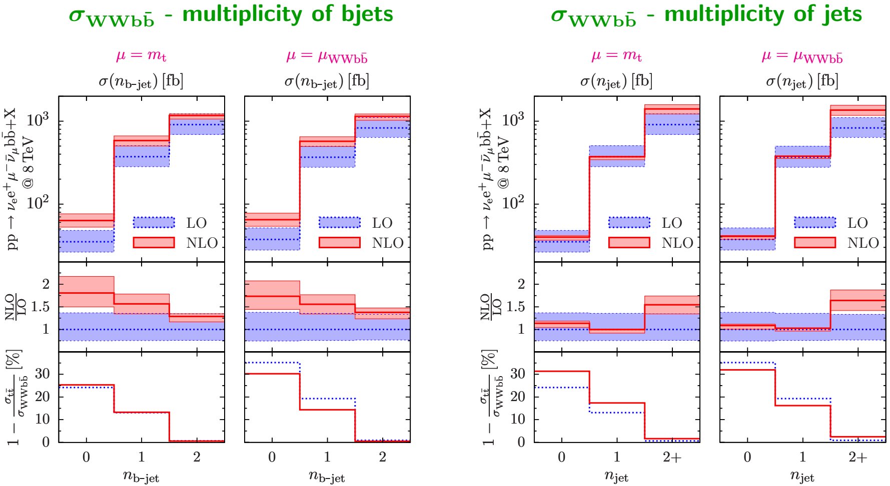
$\mathrm{pp} \to \nu_e e^+ \mu^- \bar{\nu}_\mu b\bar{b} + X$ @ 8 TeV



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

inclusive: 10 times larger finite-top-width effects
↪ Wt dominated.

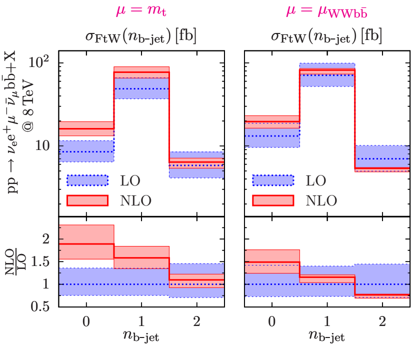
First WWbb predictions in (exclusive) 0- and 1-(b)jet bins



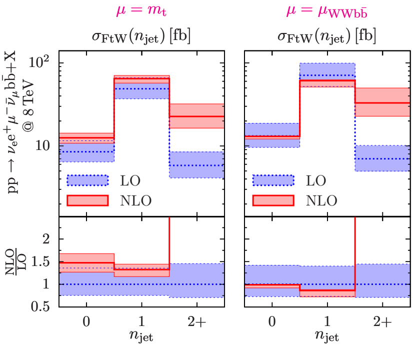
- Enhanced finite-top-width effects in 0- and 1-(b)jet bins (up to $\sim 30\%$)
  $\hookrightarrow$ Importance of unified $\mathrm{t\bar{t}}$ and Wt description!
- Perturbative benefit from $\mu_{\mathrm{WWb\bar{b}}}$ is widely washed out by dominating $\mathrm{t\bar{t}}$ contribution.

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

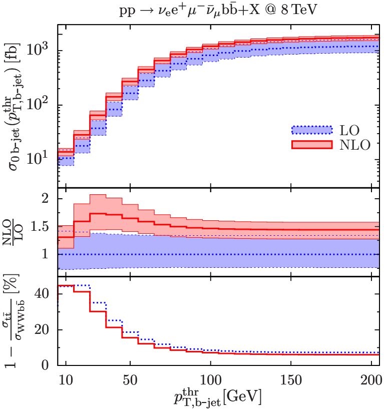


- Both the size of NLO corrections and the residual scale uncertainties are reduced by the dynamic scale choice $\mu = \mu_{\mathrm{WWb\bar{b}}}$.
- Similar reduction as in the b-jet case due to $\mu = \mu_{\mathrm{WWb\bar{b}}}$ (2+-jet bin anyway dominated by $t\bar{t}$ contribution).

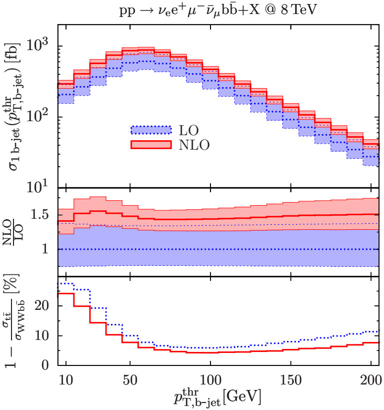
↪ Perturbative stability seems to be improved by the dynamic scale choice $\mu = \mu_{\mathrm{WWb\bar{b}}}$.

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

0-bjet exclusive cross section



1-bjet exclusive cross section

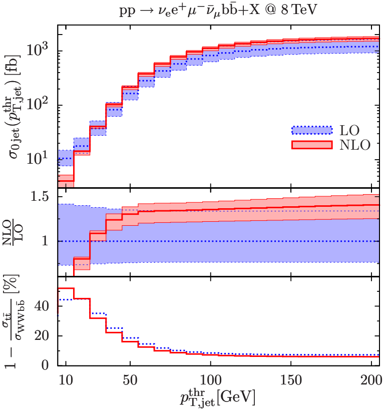


- saturates the integrated cross section for high p_{T} thresholds.
- gets largest contribution at a threshold $p_{\mathrm{T}} \approx 60\ GeV$.

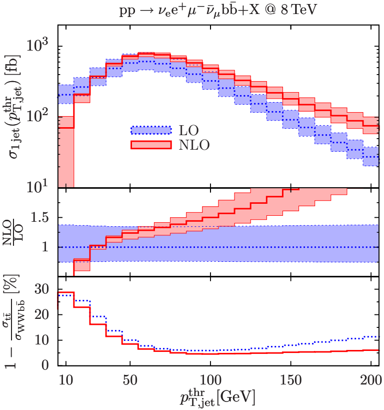
Results are perturbatively quite stable in the relevant range of jet-p_{T} thresholds.
$\hookrightarrow$ At $p_{\mathrm{T}} \approx 30\,\mathrm{GeV}$ (typical veto range), both NLO and $\mathrm{t\bar{t}/Wt}$ ratio non-trivial.

Multiplicity of jets in dependence of jet-p_T threshold

0-jet exclusive cross section



1-jet exclusive cross section

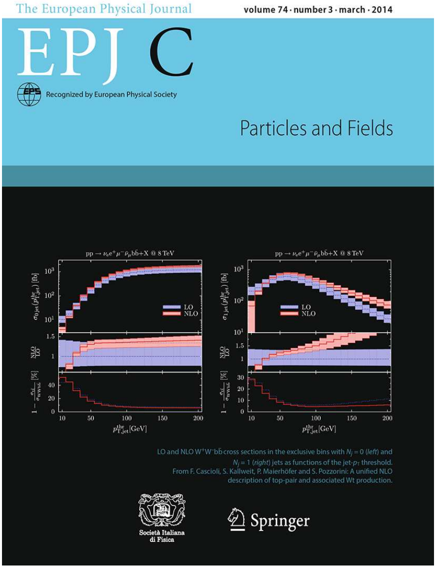


- saturates the integrated cross section for high p_T thresholds.
- is dominated by LO-like contributions in the high-p_T region.

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

$\hookrightarrow$ Parton shower is needed to restore perturbative stability for very low jet-p_T threshold.

Multiplicity of jets in dependence of jet-p_T threshold



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Particles and Fields

LO and NLO $W^+W^-b\bar{b}$ cross sections in the exclusive bins with $N_j = 0$ (*left*) and $N_j = 1$ (*right*) jets as functions of the jet-p_T threshold.
From F. Cascioli, S. Kallweit, P. Maierhöfer and S. Pozzorini: A unified NLO description of top-pair and associated Wt production.

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In the relevant range of jet-p_T thresholds ($p_\mathrm{T} \approx 30\,\mathrm{GeV}$),

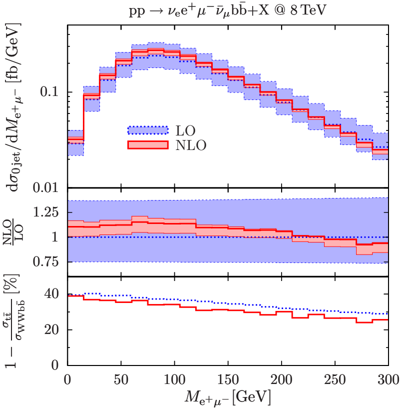
- the size of NLO corrections is strongly jet-p_T-threshold dependent,
- the off-shell contributions are sizable.

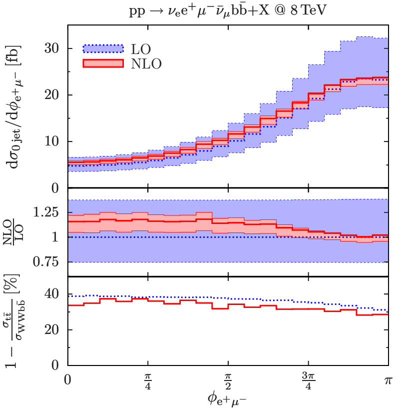
$\hookrightarrow$ A combined description of $\mathrm{t\bar{t}}$ and Wt at NLO QCD is highly motivated.

[EPJ C volume 74 number 3 March 2014]

0-jet-bin distributions for $\mathrm{H} \to \mathrm{WW}$ analysis

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%.

↪ Further evidence for stability of the perturbative description.

Conclusions

NLO QCD calculation for $\mathrm{W}^+\mathrm{W}^-\mathrm{b}\bar{\mathrm{b}}$ production with $m_\mathrm{b} > 0$

- Precise unified description of $\mathrm{t}\bar{\mathrm{t}}$ and Wt (with full leptonic decays) in the 4F scheme, including off-shell effects, non-resonant backgrounds and interferences
- Suggestion for an adequate scale choice to interpolate between $\mathrm{t}\bar{\mathrm{t}}$ and Wt
- **New results with $m_\mathrm{b} > 0$**
  - Full b-quark phase-space coverage
    $\hookrightarrow$ no cuts needed for IR-safety reasons
  - Exclusive jet-multiplicity dependent cross sections accessible
    $\hookrightarrow$ non-trivial effects from NLO and interplay of $\mathrm{t}\bar{\mathrm{t}}$ and Wt
  - 0- and 1-(b)jet-bin exclusive distributions
    $\hookrightarrow$ Scale variations significantly reduced at NLO QCD
  - Sizable finite-top-width effects
    $\hookrightarrow$ 6% for inclusive $\sigma_{\mathrm{WWb}\bar{\mathrm{b}}}$, up to 40% in 0-jet bin!

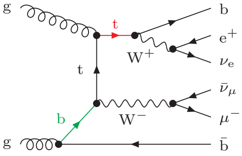
Outlook

- More dedicated analysis of the $\mathrm{W}^+\mathrm{W}^-\mathrm{b}\bar{\mathrm{b}}$ background to relevant signal processes
- Analysis of impact on m_t measurement
- Combination with parton shower to improve stability in low-p_T region

Backup

Backup slides

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



Dynamic scale $\mu_{\mathrm{t\bar{t}}}$ 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 $\mu_{\mathrm{t\bar{t}}}$ for $\mathrm{t\bar{t}}$-like events,
- which takes into account the $g \to \mathrm{b\bar{b}}$ splitting for Wt-like events.

Ansatz: $\mu^2_{\mathrm{WWb\bar{b}}} = E_{\mathrm{Wb}} \times E_{\mathrm{W\bar{b}}}$ 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":

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

$$P(t) + P(b) = 1 \quad \Rightarrow \quad P(\mathrm{t}) = \frac{R\chi(\mathrm{t})}{\chi(\mathrm{b}) + R\chi(\mathrm{t})} \quad \text{and} \quad P(\mathrm{b}) = \frac{\chi(\mathrm{b})}{\chi(\mathrm{b}) + R\chi(\mathrm{t})} \; .$$

Iterative procedure to determine new dynamic scale choice

The parameter R is determined in an iterative procedure to fulfill the condition:

$$\int \mathrm{d}\sigma^{\mathrm{FtW}}_{\mathrm{WWb\bar{b}}}(R) \overset{!}{=} \int \mathrm{d}\Phi \, [1 - P_{\mathrm{t}}(\Phi) P_{\bar{\mathrm{t}}}(\Phi)] \, (R) \, \frac{\mathrm{d}\sigma_{\mathrm{WWb\bar{b}}}(R)}{\mathrm{d}\Phi} \, , \tag{1}$$

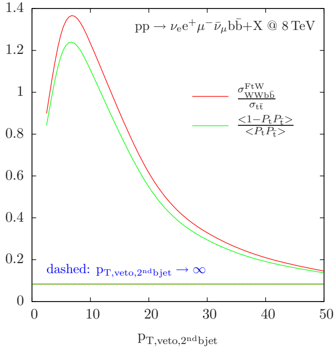
where $\sigma^{\mathrm{FtW}}_{\mathrm{WWb\bar{b}}} = \sigma_{\mathrm{WWb\bar{b}}} - \sigma_{\mathrm{t\bar{t}}}$ with $\sigma_{\mathrm{t\bar{t}}}$ defined as the narrow-width limit of $\sigma_{\mathrm{WWb\bar{b}}}$.

Iterative procedure (fully inclusive, LO)

- Start with $R \to \infty$ (dynamic $\mathrm{t\bar{t}}$ scale $\mu_{\mathrm{t\bar{t}}}$).
- Perform iteration step at $\mu_{\mathrm{WWb\bar{b}}}(R)$:
  - Calculate $\sigma^{\mathrm{FtW}}_{\mathrm{WWb\bar{b}}}$ at $\mu_{\mathrm{WWb\bar{b}}}(R)$.
  - Scan $< [1 - P_{\mathrm{t}}(\Phi) P_{\bar{\mathrm{t}}}(\Phi)] \, (R) >$ over R at the same scale $\mu_{\mathrm{WWb\bar{b}}}(R)$.

  ↪ (1) fixes R for next iteration step.
- Fast convergence delivers $\mu_{\mathrm{WWb\bar{b}}}(R)$.

Validation of final $\mu_{\mathrm{WWb\bar{b}}}(R)$:



↪ accurate description of FtW content of differential $\mathrm{WWb\bar{b}}$ cross section.