NLO QCD corrections to $W^+W^-b\bar{b}$ production with massive bottoms

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based on work with F. Cascioli, P. Maierhöfer and S. Pozzorini
(in preparation)

and with A. Denner, S. Dittmaier and S. Pozzorini
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Outline

1. Introduction
   - Motivation
   - Full description vs. narrow-width approximation
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
   - Integrated 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

Anastasiou, Aybat, Baernreuther, Bonciani, Czakon, Dittmaier, Ferroglia, Gehrmann, Gerhmann–De Ridder, Kniehl, Körner, Langenfeld, Maitre, Merebashvili, Mitov, Moch, 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$\times$decay in spin-correlated narrow-width approximation

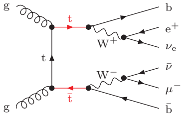
Bernreuther, Brandenburg, Melnikov, Schulze, Si, Uwer

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

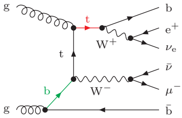
Bevilacqua, Czakon, Denner, Dittmaier, van Hameren, Kallweit, Papadopoulos, Pozzorini, Worek

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

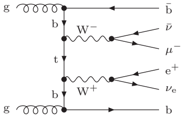
Doubly-resonant ($t\bar{t}$-like) diagrams (DR)



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



Non-resonant diagrams (NR)



$t\bar{t}$ in narrow-Width Approximation

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

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

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

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

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

- low $p_{T,b}$ (tW-relevant) region can be accessed.
- $W^+W^-b\bar{b}$ describes both $t\bar{t}$ and tW 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-resonant background (including tW)
- leptonic W decays taken into account (actually full four-lepton final states)

Huge $\mathrm{t\bar{t}}$ samples at hadron colliders

- LHC at 7...14 TeV: $1.5 \ldots 9 \times 10^5$ events per $\mathrm{fb}^{-1} \Rightarrow \frac{\delta\sigma}{\sigma} = \mathrm{few}\,\%$
- improved top-mass measurements with $\delta m_\mathrm{t}^\mathrm{exp} \sim 1\,\mathrm{GeV}$

Relevance for BSM discoveries

- 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

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

$\hookrightarrow$ Consistent treatment of $\mathrm{t\bar{t}}$, tW 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 (no 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 [SK]
(implementation in C++)

- 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 (based on q_{T} subtraction)!
  (cf. Dirk Rathlev's talk on $\mathrm{Z}\gamma$ production)

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

Setup and input parameters

Particle masses and widths

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

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

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

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

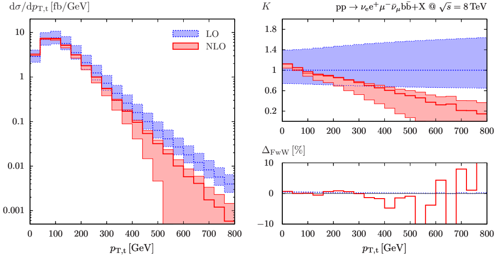
Anti-$k_{\rm T}$ Jet Algorithm (b)jets with $\sqrt{\Delta\phi^2 + \Delta y^2} > R = 0.5$

Cuts

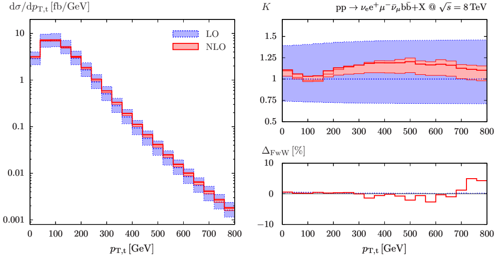
leptons:	$\lvert\eta_l\rvert \le 2.5$	$p_{{\rm T},l} > 20\,{\rm GeV}$	$p_{\rm T,miss} > 20\,{\rm GeV}$
b-jets:	$\lvert\eta_{\rm b}\rvert \le 4.5$	but no cut on $p_{\rm T,b}$ required	

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]



Dyn. 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**

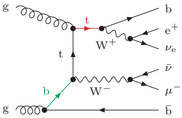
- which coincides with fixed scale if $p_{T,t} \to 0$,
- which adapts to the higher scattering energy in high-$p_{T,t}$ regions.

$\Rightarrow$ **Use averaged transverse energy**

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

Scale choice for simultaneously describing $\mathrm{t\bar{t}}$ and tW

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



↪ Scale overestimates natural scale for single-top-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 tW)**

- 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 tW-like events.

Ansatz: $\mu_{\mathrm{IS}} = \sqrt{E_{\mathrm{Wb}} \times E_{\mathrm{W\bar{b}}}}$ with $E_{\mathrm{Wb}} = P(t)E_{\mathrm{T,t}} + P(b)E_{\mathrm{T,b}}$

$P(t)$ and $P(b)$ stand for the probabilities of the Wb configurations in an event to be "top-like" or "bottom-like":

$$P(t) \propto X(t) = \frac{1}{(p_{\mathrm{t}}^2 - m_{\mathrm{t}}^2)^2 + \Gamma_{\mathrm{t}}^2 m_{\mathrm{t}}^2} \quad \text{and} \quad P(b) \propto X(b) = \frac{1}{E_{\mathrm{T,b}}^2}.$$

$$P(t) + P(b) = 1 \quad \Rightarrow \quad P(\mathrm{t}) = \frac{RX(\mathrm{t})}{X(\mathrm{b}) + RX(\mathrm{t})} \quad \text{and} \quad P(\mathrm{b}) = \frac{X(\mathrm{b})}{X(\mathrm{b}) + RX(\mathrm{t})}.$$

Iterative procedure to determine new dynamic scale choice

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

$$\frac{\sigma_{\mathrm{tW}}}{\sigma_{\mathrm{t\bar{t}}}} := \frac{\sigma_{\mathrm{WWb\bar{b}}} - \sigma_{\mathrm{t\bar{t}}}}{\sigma_{\mathrm{t\bar{t}}}} \stackrel{!}{=} \frac{< P(\mathrm{t})P(\bar{\mathrm{b}}) > + < P(\mathrm{b})P(\bar{\mathrm{t}}) >}{< P(\mathrm{t})P(\bar{\mathrm{t}}) >}, \qquad (1)$$

$\sigma_{\mathrm{t\bar{t}}}$ is the narrow-width limit of $\sigma_{\mathrm{WWb\bar{b}}}$.

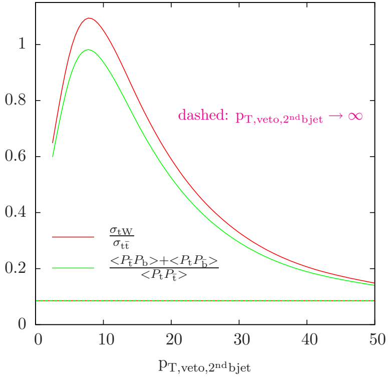
The expectation values $< \ldots >$ are defined as $< A >= \int d\sigma A / \int d\sigma$.

Iterative procedure (fully inclusive, LO)

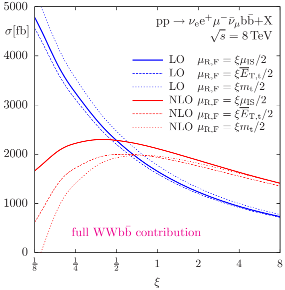
- Start with $R \to \infty$ (dynamic $\mathrm{t\bar{t}}$ scale $\overline{E}_{T,\mathrm{t}}/2$).
- Perform iteration step at $\mu_{\mathrm{IS}}(R)$:
  - calculate $\frac{\sigma_{\mathrm{tW}}}{\sigma_{\mathrm{t\bar{t}}}}$ at $\mu_{\mathrm{IS}}(R)$.
  - scan $\frac{<P(\mathrm{t})P(\bar{\mathrm{b}})>+<P(\mathrm{b})P(\bar{\mathrm{t}})>}{<P(\mathrm{t})P(\bar{\mathrm{t}})>}(R)$ at $\mu_{\mathrm{IS}}(R)$ over relevant range of R values.

  $\hookrightarrow$ (1) fixes R for next iteration step.
- Fast convergence delivers $\mu_{\mathrm{IS}}(R)$.

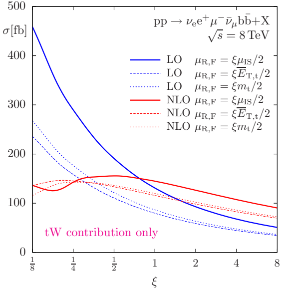
Test of final $\mu_{\mathrm{IS}}(R)$:



Scale variation and K factors with different scale choices



$\sigma_{\mathrm{WWb\bar{b}}}$ [fb]	LO	NLO	$K = \frac{NLO}{LO}$
$\mu = m_\mathrm{t}$	1316.7[2]	1816[2]	1.38
$\mu = m_\mathrm{t}/2$	1777.3[2]	1962[2]	1.10
$\mu = \overline{E}_{\mathrm{T,t}}/2$	1604.1[2]	1938[2]	1.21
$\mu = \mu_{\mathrm{IS}}/2$	1655.4[2]	2115[2]	1.28



σ_{tW} [fb]	LO	NLO	$K = \frac{NLO}{LO}$
$\mu = m_\mathrm{t}$	63.4[2]	103[3]	1.63[5]
$\mu = m_\mathrm{t}/2$	86.6[3]	121[2]	1.40[3]
$\mu = \overline{E}_{\mathrm{T,t}}/2$	79.6[3]	117[3]	1.47[4]
$\mu = \mu_{\mathrm{IS}}/2$	131.2[3]	147[3]	1.12[3]

↪ better perturbative convergence of σ_{tW} with new interpolating scale $\mu = \mu_{\mathrm{IS}}/2$
(thanks to absorbtion of running-α_s effects in LO).

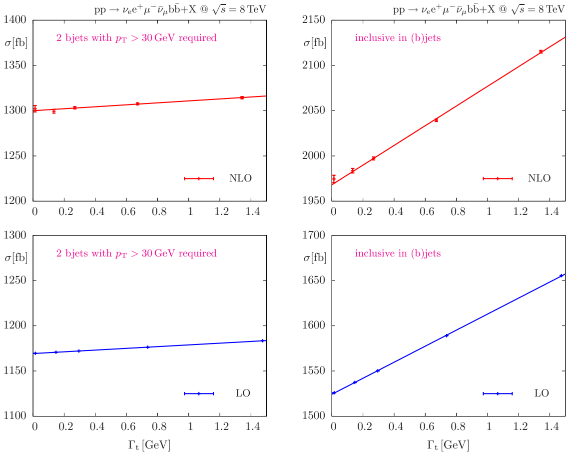
Off-shell and not doubly-resonant contributions to σ_{incl}

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

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

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

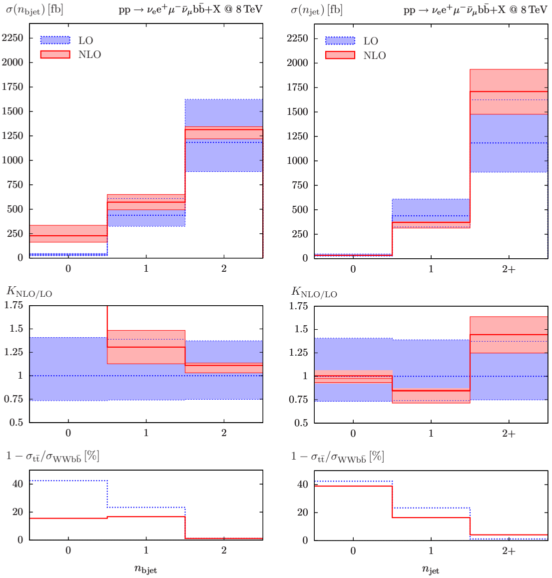
- Dipole-subtracted virtual and real parts diverge logarithmically when $\Gamma_t \to 0$.
- Linear convergence of $\sigma(\Gamma_t) \to \sigma(0)$ provides non-trivial consistency and stability check.



Off-shell $t\bar{t}$ contribution of $+1.2\%$ (LO) and $+1.1[2]\%$ (NLO) in the 2-bjet bin ($\mathcal{O}(\Gamma_t/m_t) \simeq 0.8\%$).

Off-shell $t\bar{t}$ contribution of $+8.6\%$ (LO) and $+7.5[2]\%$ (NLO) if inclusive in bjets (tW dominated).

Multiplicity of (b)jets with $p_{\mathrm{T}} \geq 30\,\mathrm{GeV}$



First "off-shell" insights into **exclusive 0- and 1-(b)jet bins** of the combined process $t\bar{t} + tW$

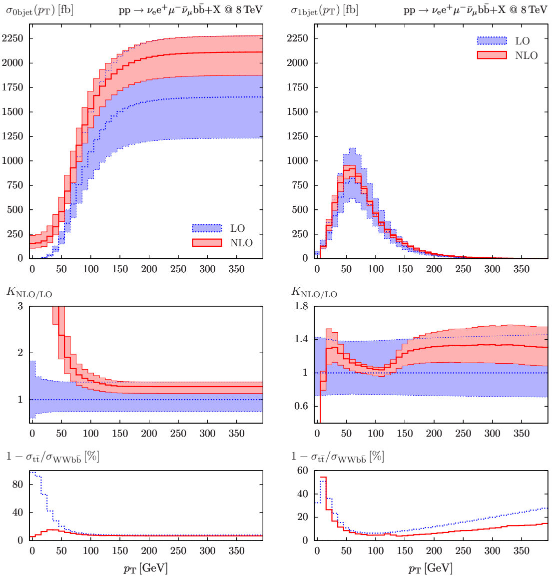
bjet multiplicity

- large K factors in 0-bjet and 1-bjet bins due to light-jet emission,
- tW contribution to 0-bjet and 1-bjet bins reduced at NLO.

(generic) jet multiplicity

- reduced K factors in the lower jet-multiplicity bins,
- relative contribution from tW stays quite constant when going from LO to NLO.

Multiplicity of bjets in dependence of jet-p_T threshold



0-bjet exclusive cross section

- for high p_T, 0-bjet bin saturates the integrated cross section,
- for low p_T, LO dominance of tW disappears at NLO.

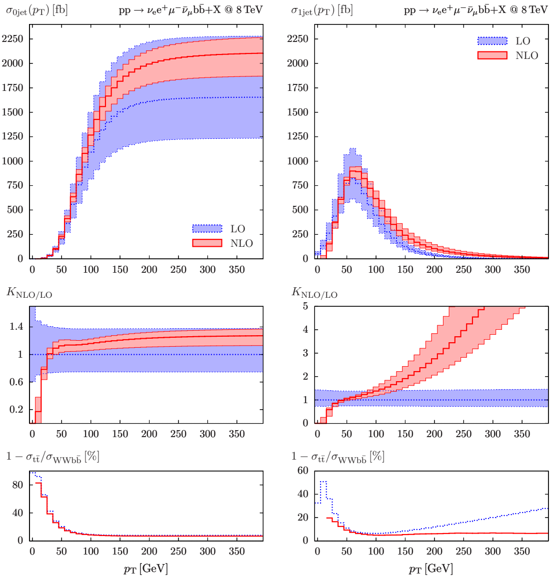
1-bjet exclusive cross section

- gets largest contribution at $p_T \approx 60$ *GeV*,
- shows instabilities for low jet-p_T threshold ($p_T \lesssim 10\,\mathrm{GeV}$).

$\hookrightarrow$ At $p_T \approx 30\,\mathrm{GeV}$ (typical veto range), both NLO and $t\bar{t}/tW$ ratio non-trivial.

$\hookrightarrow$ Huge NLO requires log p_T resummation via parton shower.

Multiplicity of jets in dependence of jet-p_T threshold



0-jet exclusive cross section

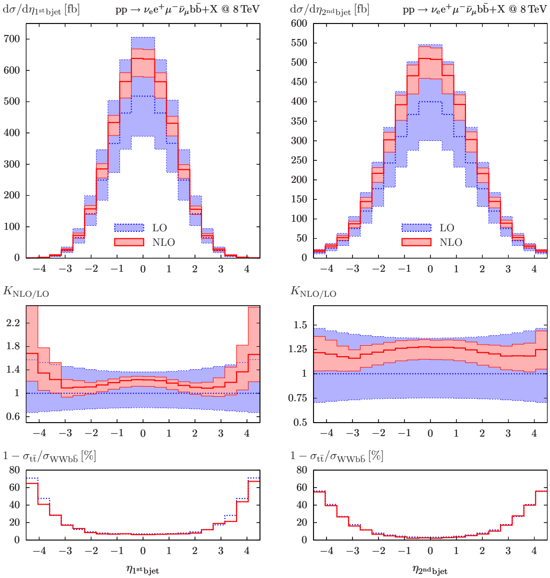
- $\mathrm{tW} - \mathrm{t\bar{t}}$ ratio remains very stable from LO to NLO,
- for low jet-p_T threshold ($p_T \lesssim 20\,\mathrm{GeV}$), perturbative stability breaks down.

1-jet exclusive cross section

- gets largest contribution at $p_T \approx 60\ GeV$.
- unstable at low jet-p_T threshold ($p_T \lesssim 20\,\mathrm{GeV}$),
- high-p_T region dominated by LO-like contributions.

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

Pseudo-rapidity distribution of (sub-)leading bjet



Central detector region

- relatively flat K factors,
- dominated by $t\bar{t}$ events.

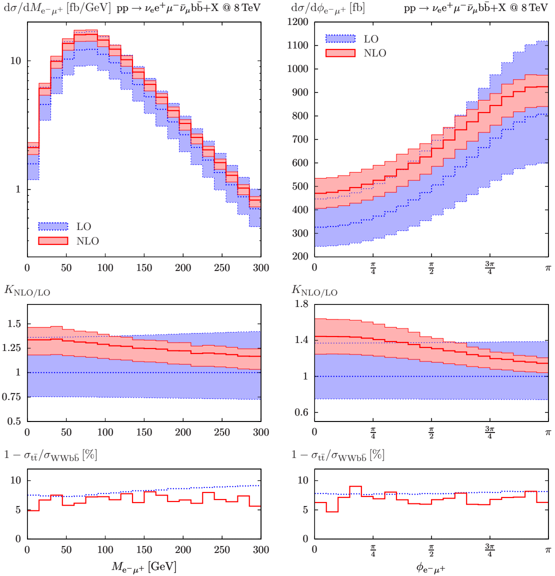
Forward/backward region

$\hookrightarrow$ collinear emission of b-quarks

- large off-shell contribution (dominated by tW) in the region $|\eta_{bjet}| \geq 2.5$,
- also K factors non-trivial in this region.

$\hookrightarrow$ Interesting combined $t\bar{t} + tW$ background to VBF $H \to (WW)$ production.

Sample leptonic distributions



Invariant mass of leptons

important for $\mathrm{H} \to \mathrm{WW}$ analysis

- relatively stable K factor,
- off-shell (and thus tW) contribution essentially independent of $m_{e^-\mu^+}$.

Azimuthal angle of leptons

important for $\mathrm{H} \to \mathrm{WW}$ analysis

- H-signal prefers low azimuthal angle due to spin correlations,
- NLO corrections enhance background at low $\phi_{e^-\mu^+}$,
- off-shell contribution essentially independent of $\phi_{e^-\mu^+}$.

Conclusions

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

- precise description of $\mathrm{t\bar{t}}$ and tW (with full leptonic decays)
- including off-shell effects, non-resonant backgrounds and interferences
- suggestion for an adequate scale choice to interpolate between $\mathrm{t\bar{t}}$ and tW

- **New results with $m_\mathrm{b} > 0$**
  - full b-quark phase-space coverage (no cuts need for IR-safety reasons)
  - exclusive jet-multiplicity dependent cross sections:
    non-trivial effects from NLO and interplay of $\mathrm{t\bar{t}}$ and tW

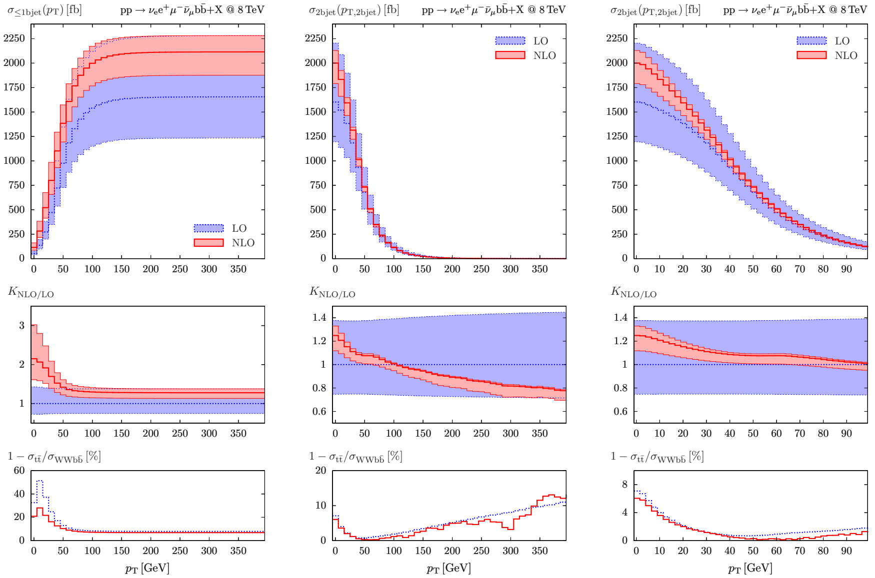
Outlook:

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

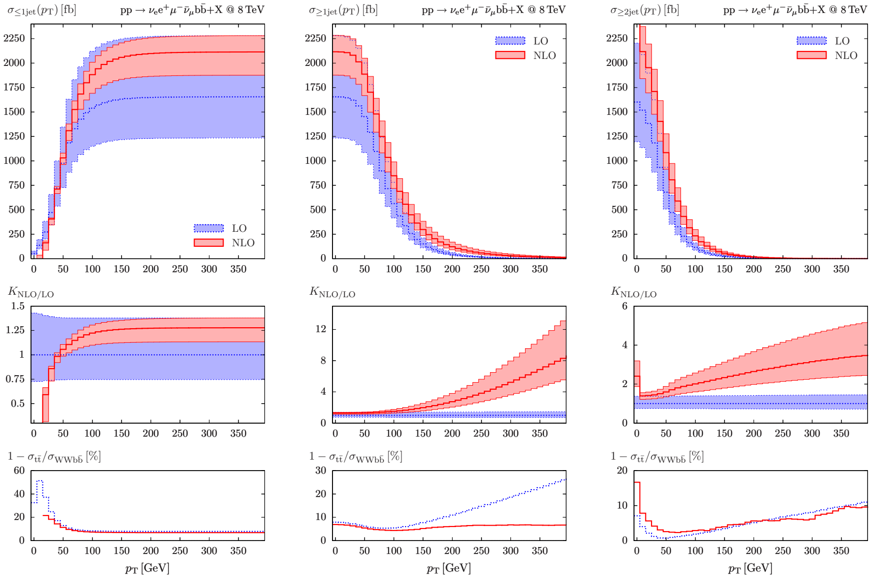
Backup

Backup slides

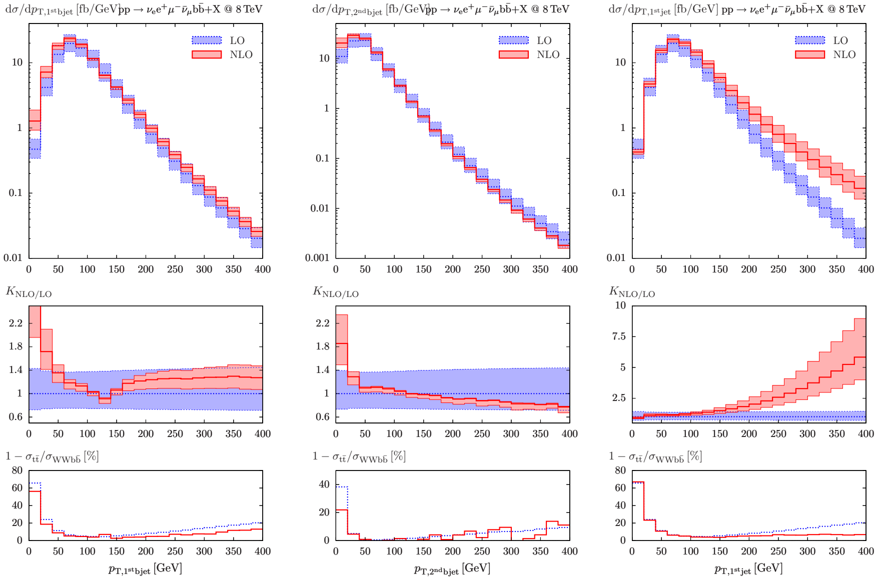
Multiplicity of bjets in dependence of jet-defining p_T



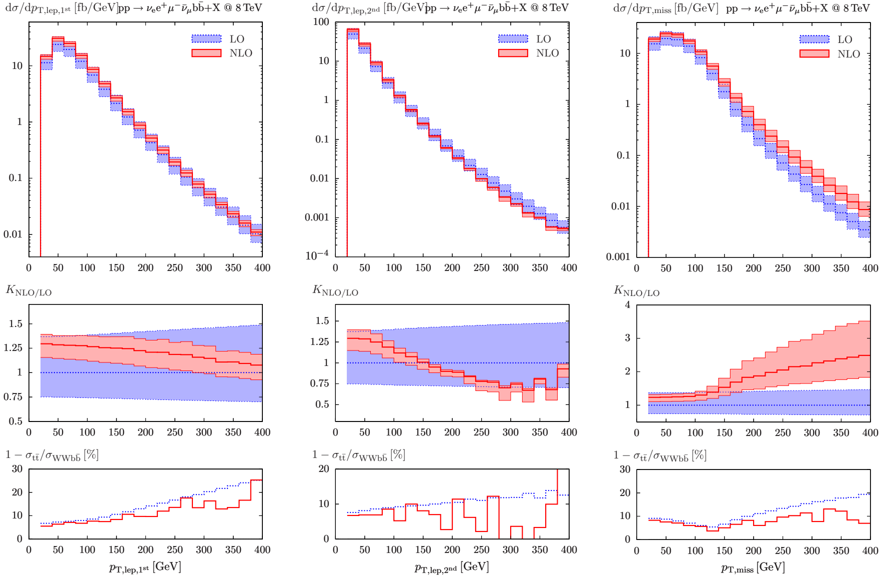
Multiplicity of jets in dependence of jet-defining p_T



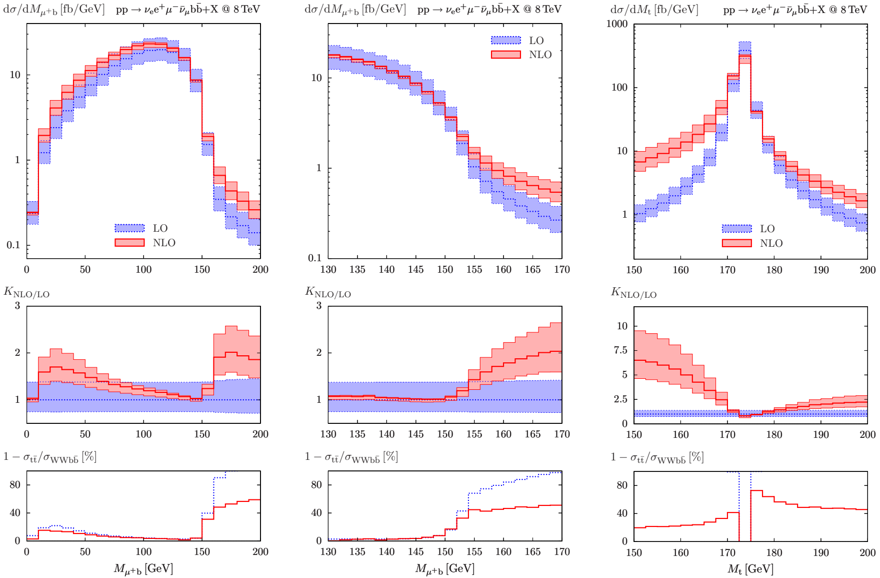
Further distributions



Further distributions



Further distributions



Further distributions