Latest developments on $Wb\bar{W}\bar{b}$ production at hadron colliders

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Why are we interested in $WbW\bar{b}$ predictions.

In the experiment we do not measure tops. We only have a handle on their decay products.
$WbW\bar{b}$ is therefore the more realistic final state if you are interested in $t\bar{t}$ production.

$\sim$ quantum mechanical versus semi-classical treatment $\sim$

- important contributions to Wt and WW final states (tricky to disentangle at higher orders)
- important background to BSM searches and SM measurements
  (e.g. population of N-jet bins in WW production)
- at current precision, we start worrying about
  offshell effects, non-factorizable corrections, b-mass dependence etc.
- expect small ($\mathcal{O}(\Gamma_t/m_t)$) effects (wrt NWA) for inclusive $t\bar{t}$ observables
  $\rightarrow$ similar statements for more exclusive phase spaces?

Outline.

$WbW\bar{b}$ calculations and impact on phenomenology – a recap

New calculations at fixed order

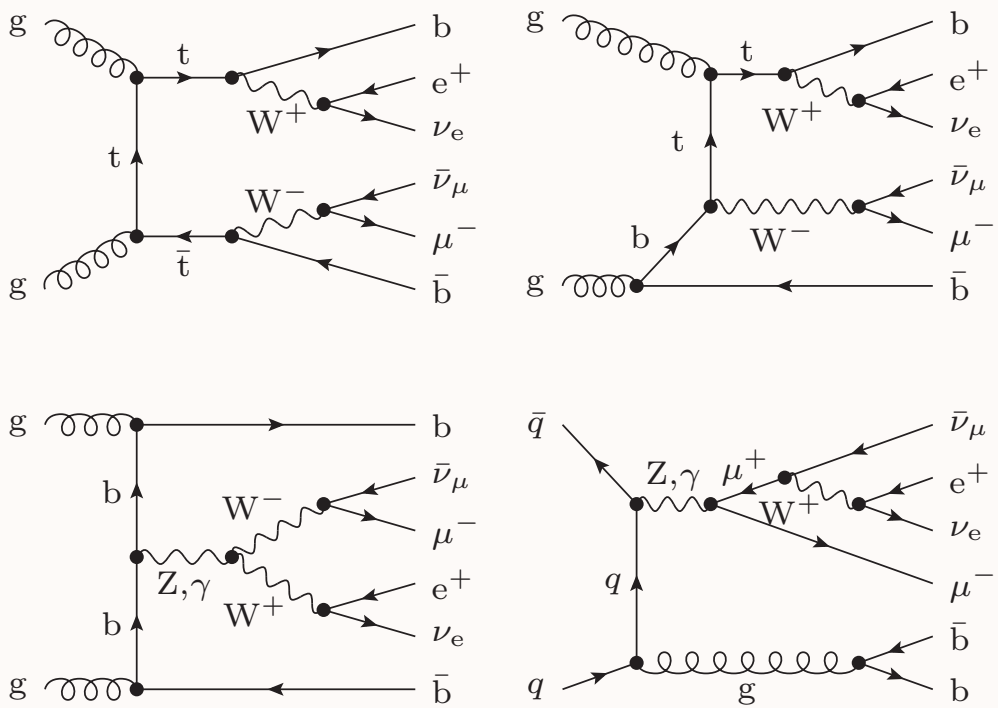
Recent developments in NLO+PS matched simulations for $WbW\bar{b}$

Summary

Disclaimer: content based on personal selection, my apologies to underrepresented and unmentioned efforts.

$WWb\bar{b}$ production at NLO in QCD

➡ ***Some introductory remarks on $WWb\bar{b}$ production at NLO in QCD.***

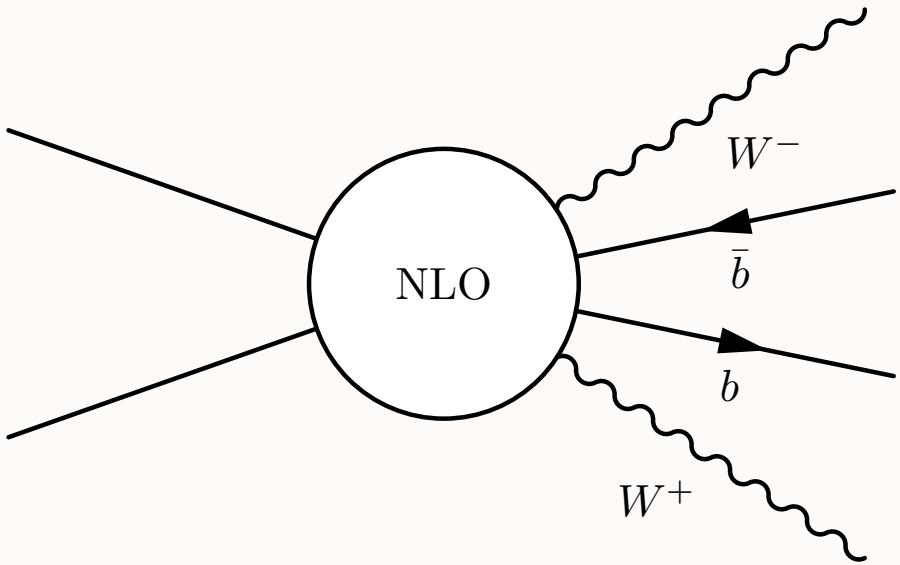


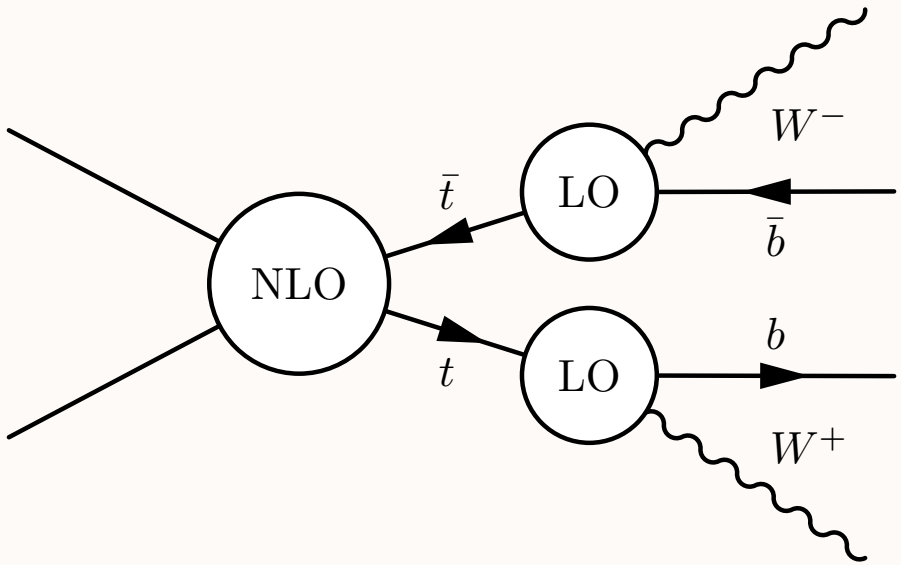
- full NLO treatment includes double-, single- and non-resonant contributions
  (DR – $t\bar{t}$-like) (SR – Wt-like) (NR – VV-like)
- complex-mass scheme
- finite top-quark and W width effects
  (offshell DR, SR, NR and interferences)
- first done in massless b-quark approximation
  ($\longrightarrow$ requires two hard b-jets)
  ($\longrightarrow$ $WWb\bar{b}$ in 5-flavour scheme)
  [Denner et al. arXiv:1012.3975, arXiv:1207.5018]
  [Bevilacqua et al. arXiv:1012.4230]

- earlier done in NWA ($\Gamma_t \longrightarrow 0$ limit) where production and decay factorize (neglected contributions are suppressed by powers of $\Gamma_t/m_t \lesssim 1\%$)
  [Bernreuther, Brandenburg, Si, Uwer, arXiv:hep-ph/0403035]
  [Melnikov, Schulze, arXiv:0907.3090]

$$\lim_{\Gamma_t/m_t \to 0} \frac{1}{(p_t^2 - m_t^2)^2 + m_t^2\,\Gamma_t^2} = \frac{\pi}{m_t\,\Gamma_t}\,\delta(p_t^2 - m_t^2)$$

Full versus factorized approach





full ($WWb\bar{b}$)

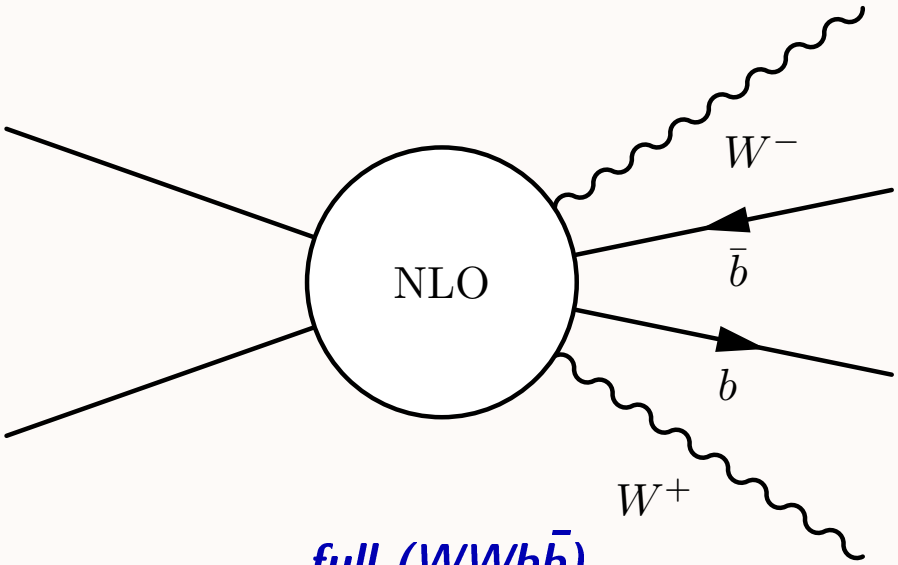
- full NLO description of the $WWb\bar{b}$ final state ($2 \to 4$ processes)
- accounts for non-resonant/non-factorizing contributions, includes NLO effects in top quark decays

factorized ($t\bar{t}$)

- NLO $t\bar{t}$ production ($2 \to 2$ processes) with LO decays attached and spin correlations preserved
- standard description for the NLO core in NLO+PS matching

- Use these calculations for pure parton level analyses, i.e. m_t is not a MC mass here, it is the pole mass.

Full calculation versus NWA



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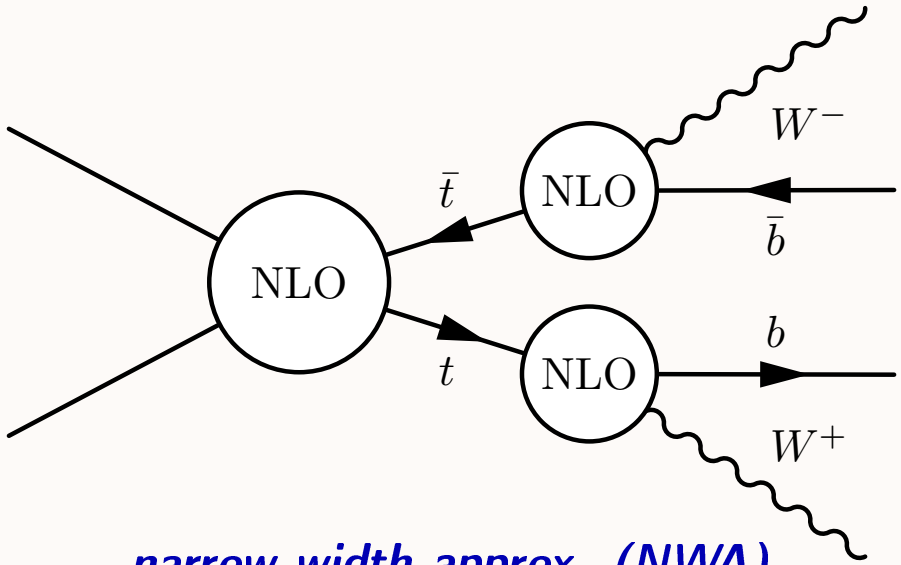


narrow width approx. (NWA)

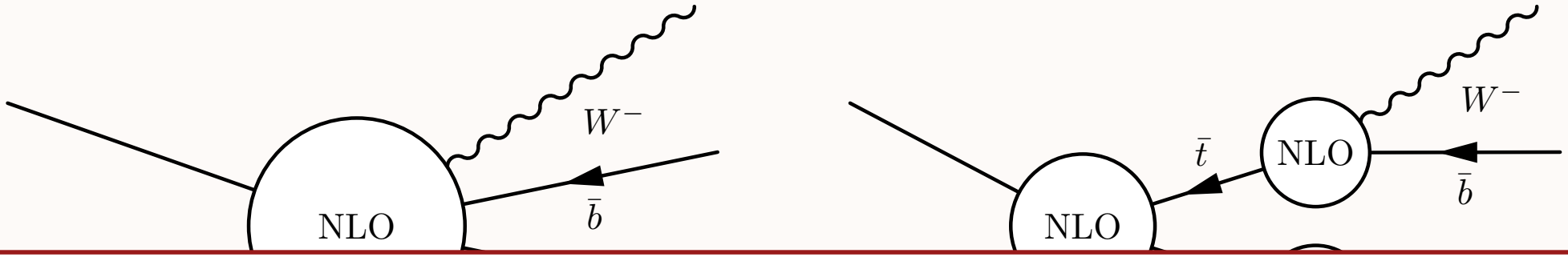
- full NLO description of the $WWb\bar{b}$ final state ($2 \to 4$ processes)
- non-resonant/-factorizing contributions (quantum interferences)
- NLO effects in top quark decays

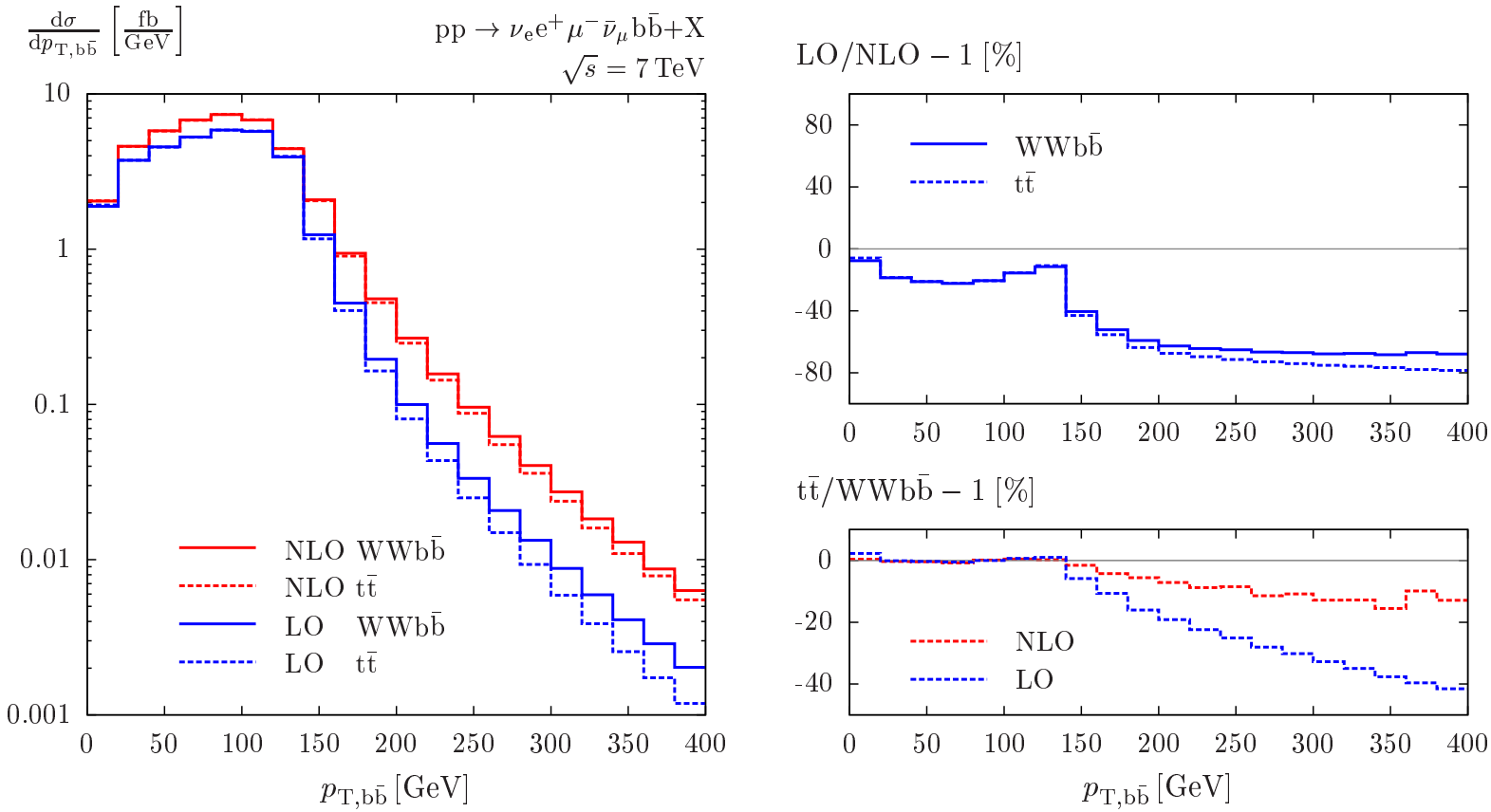
- full NLO NWA treatment of $t\bar{t}$ production and top quark decays preserving spin correlations (Factorization: Prod $\otimes$ Dec)
- only DR contributions survive in $\Gamma_t \to 0$ limit (onshell tops)
- NLO effects in top quark decays

- Comparison between both calculations (in the $\ell\ell$ channel) to investigate finite top-quark width effects.
  - No more than 1% deviations for inclusive cross sections (with experimental cuts).
  - Effects can be (significantly) larger in differential distributions.

$\Rightarrow$ [Denner, Dittmaier, Kallweit, Pozzorini, Schulze, LesHouches2011, arXiv:1203.6803]

Full calculation versus NWA





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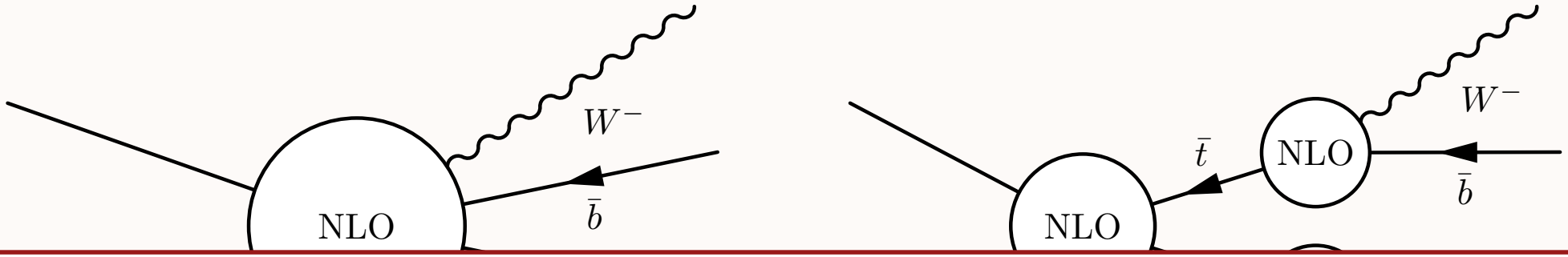

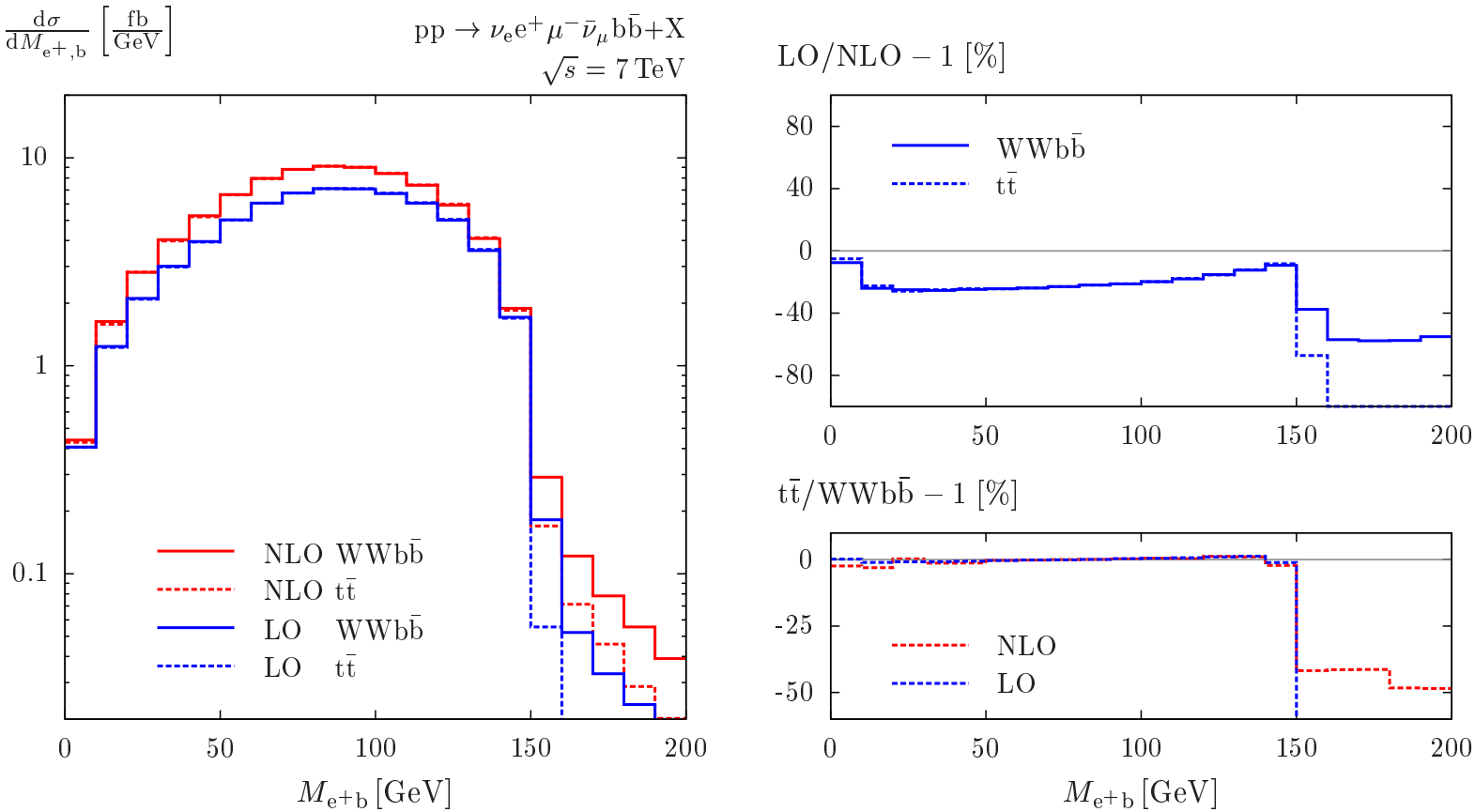

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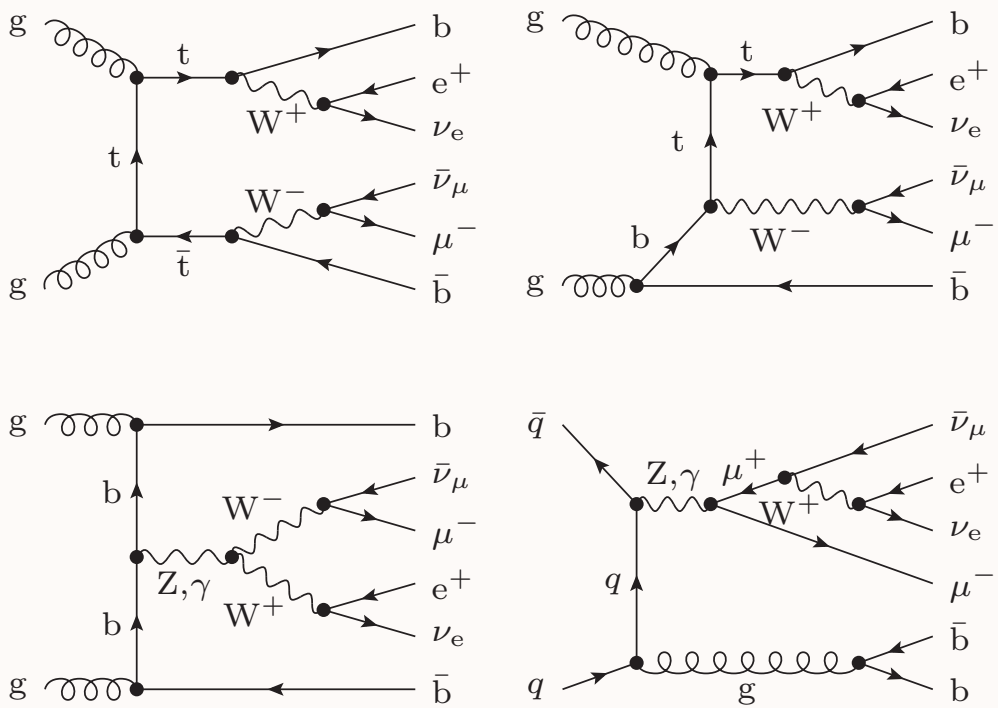
$WWb\bar{b}$ production at NLO: massive b-quarks

➡ ***New development: bottom quark mass included in the calculation.***



- full NLO treatment includes double-, single- and non-resonant contributions
- complex-mass scheme
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  [Bernreuther et al. arXiv:hep-ph/0403035]
  [Melnikov, Schulze, arXiv:0907.3090]

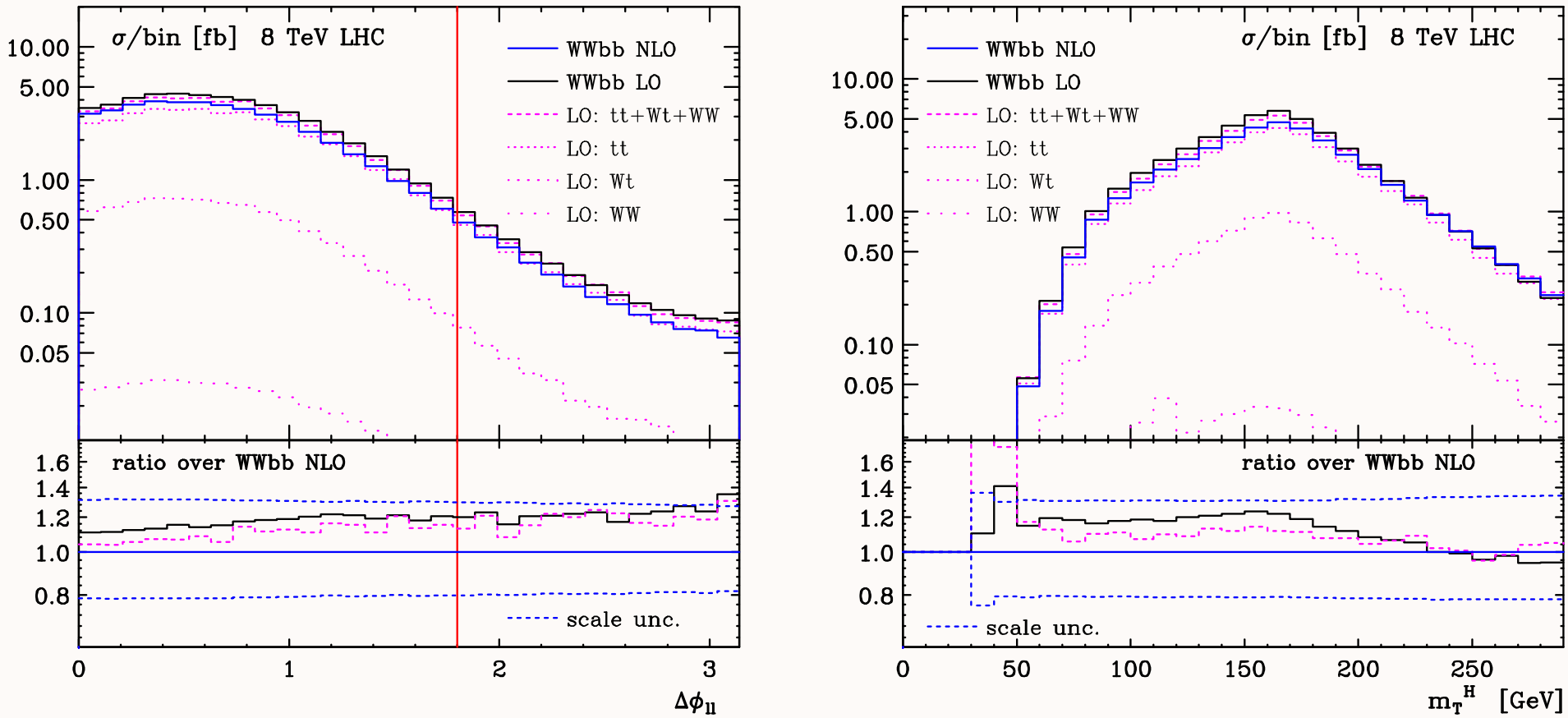
- off-shell and single-top contributions more important in phase-space regions with unresolved b-quarks
- only accessible in calculations with massive b-quarks in the 4-flavour (4F) scheme
- in the 4F, fully differential NLO description of both FS b-jets $\longrightarrow$ permits application of jet vetoes
- $\longrightarrow$ gauge-invariant separation of narrow-top-width contribution and finite-width remainder

- results provided recently by two groups:
  [Frederix, arXiv:1311.4893] [Cascioli, Kallweit, Maierhöfer, Pozzorini, arXiv:1312.0546]

$WWb\bar{b}$ production at NLO

➡ ***Calculation performed within MadGraph5_aMC@NLO framework.*** [FREDERIX, ARXIV:1311.4893]

- top-quark induced backgrounds in $h \to WW^{(*)} \to ll\nu\nu$ channel at 8 TeV LHC $(\mu_{\mathrm{R,F}} = \hat{H}_T/2)$
- "Higgs measurement" cuts in one-jet bin motivated by ATLAS analysis



- (left) azimuthal angle separation between leptons, (right) Higgs boson transverse mass
  Higgs boson topology cuts: $m_{ll} < 50$ GeV and $|\Delta\phi_{ll}| < 1.8$

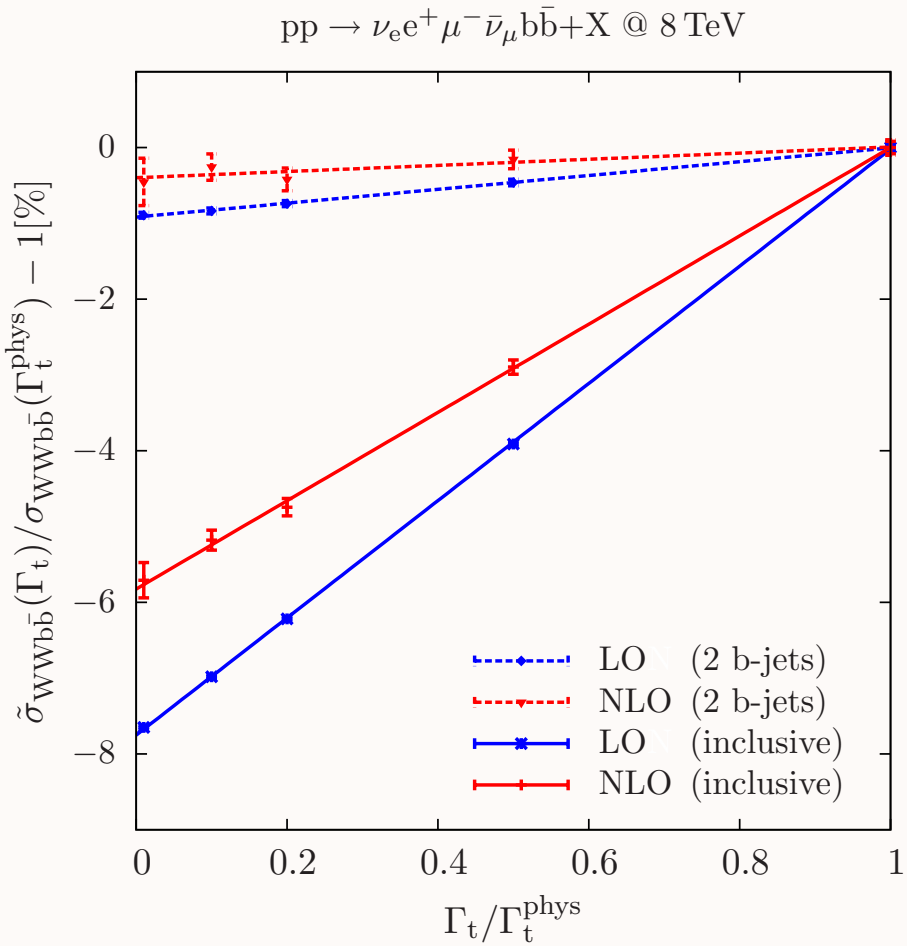
$WWb\bar{b}$ production at NLO

➡ ***OpenLoops + Collier + New in-house NLO MC framework.*** [Cascioli et al. arXiv:1312.0546] [Kallweit]

- 4F scheme enables gauge-invariant $t\bar{t}$/non-$t\bar{t}$ separation instead of ill-defined $t\bar{t}$/Wt separation in 5F
- dynamical scale interpolating between $t\bar{t}$ ($\mu^2_{t\bar{t}} = E_{T,t}E_{T,\bar{t}}$) and single-$t$ ($\mu^2_{tW^-} = E_{T,t}E_{T,\bar{b}}$) ...
- ... to account for multiscale problem

numerical NWA

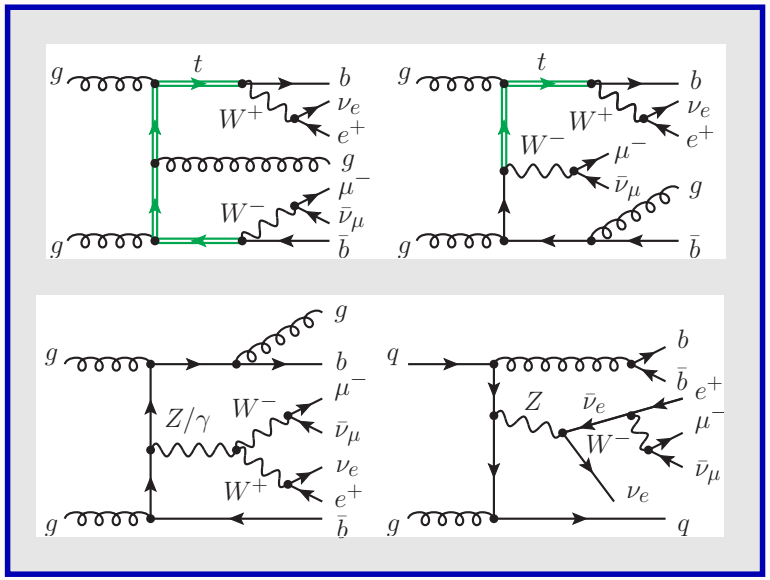
$$d\sigma_{t\bar{t}} = \lim_{\Gamma_t \to 0} \left(\frac{\Gamma_t}{\Gamma_t^{\text{phys}}} \right)^2 d\sigma_{WWb\bar{b}}(\Gamma_t)$$



- numerical extrapolation to $\Gamma_t \to 0$: Wt contribution dominates finite top-quark width remainder

$WWb\bar{b} + j$ production at NLO in QCD

[Bevilacqua, Hartanto, Kraus, Worek, arXiv:1509.09242]



NLO corrections to $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j$ with the Helac-NLO MC

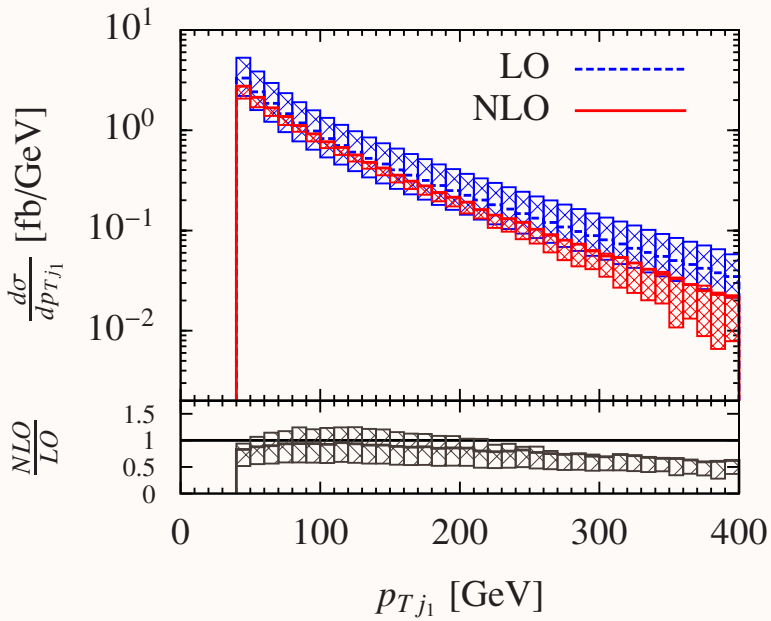
- fully realistic final state for $t\bar{t}$ production with a final state jet in hadronic collisions (2nd example of $2 \to 5$ beyond NWA)
- including finite W width, offshell and non-resonant effects
- reduction of scale dependence by factor 3 (at least), size of top quark offshell effects below 2%

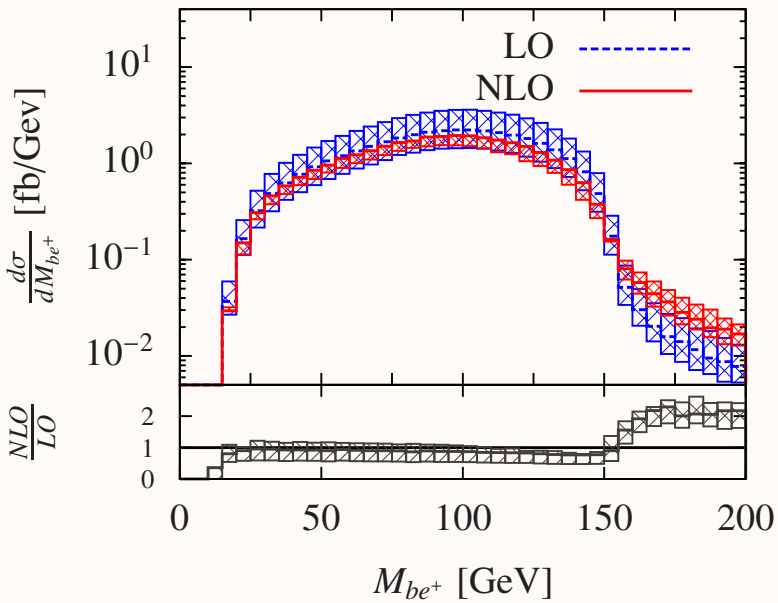
$\Rightarrow$ LHC 8 TeV results for total xsec (13% lower than LO!!) and some key distributions, hardest light jet p_T (center), minimal inv. mass of e^+ and b jet (right)

$$\sigma^{\rm LO}_{\rm Helac\text{-}Nlo} = 183.1\,^{+112.2\,(61\%)}_{-64.2\,(35\%)}\ \text{fb}\,,$$

$$\sigma^{\rm NLO}_{\rm Helac\text{-}Nlo} = 159.7\,^{-33.1\,(21\%)}_{-7.9\,(\ 5\%)}\ \text{fb}\,.$$

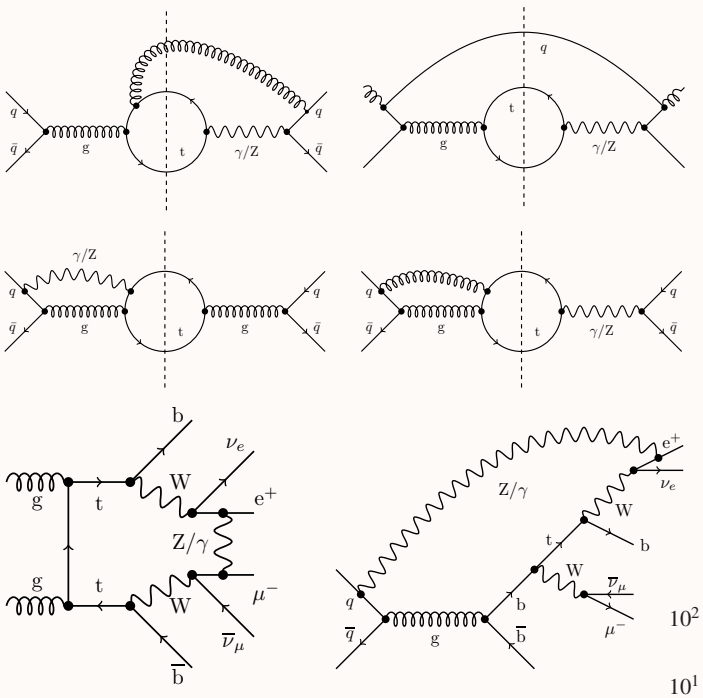
$p_{T\ell} > 30$ GeV, $p_{Tj} > 40$ GeV,
$p_T^{\rm miss} > 40$ GeV, $\Delta R_{jj} > 0.5$,
$\Delta R_{\ell\ell} > 0.4$, $\Delta R_{\ell j} > 0.4$,
$|y_\ell| < 2.5$, $|y_j| < 2.5$,





$WWb\bar{b}$ production at NLO EW

[Denner, Pellen , arXiv:1607.05571], [Denner, Feger, arXiv:1506.07448]
[Basso, Dittmaier, Huss, Oggero, arXiv:1507.04676]

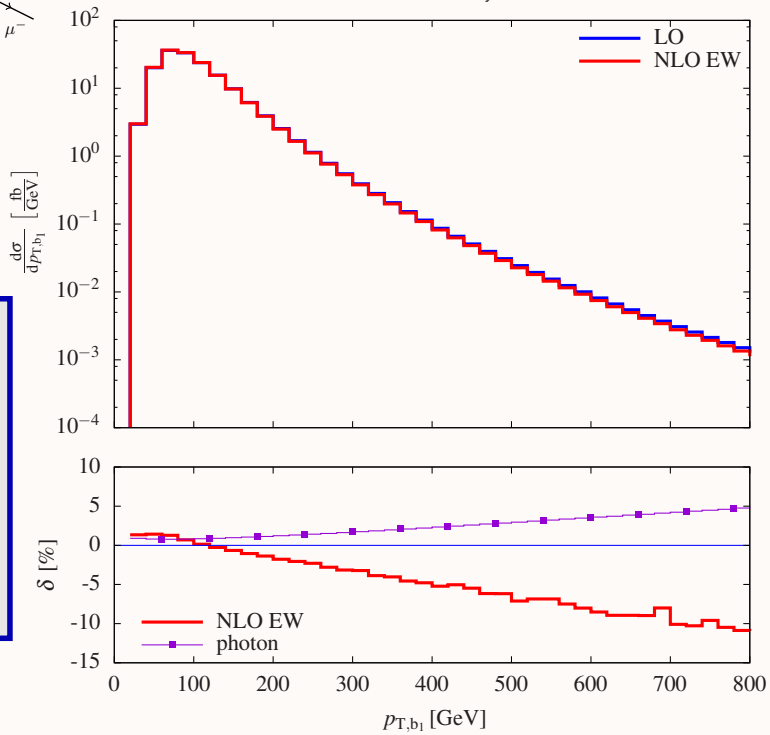


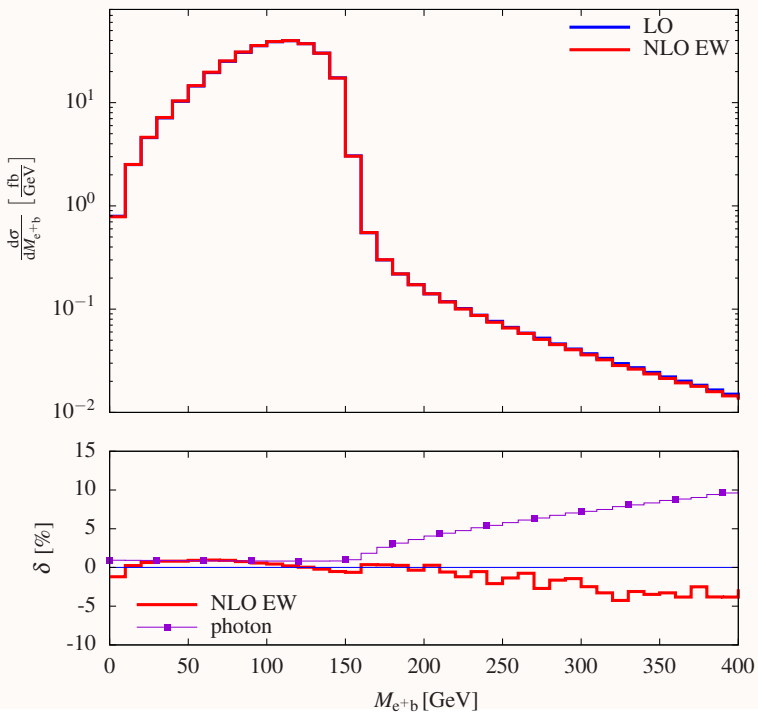
NLO EW corrections to $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ with MoCaNLO (PS), Recola (ME), Collier (1L-lib)

- includes all $\mathcal{O}(\alpha_s^2\alpha^5)$ corrections with offshell, non-resonant, and interference effects for $2 \to 6$ phase space
- photon-induced γg contributions of $\mathcal{O}(\alpha_s\alpha^5)$ given for reference; DPA for W bosons works very well but not for t quarks
- uses techniques developed for $WWb\bar{b} + H$ at NLO in QCD (see 1506.07448) and top width from Basso et al.

$\Rightarrow$ LHC 13 TeV results

Ch.	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO\ EW}$ [fb]	δ [%]
gg	2824.2(2)	2834.2(3)	0.35
$q\bar{q}$	375.29(1)	377.18(6)	0.50
$gq(/\bar{q})$		0.259(4)	
γg		27.930(1)	
pp	3199.5(2)	3211.7(3)	0.38



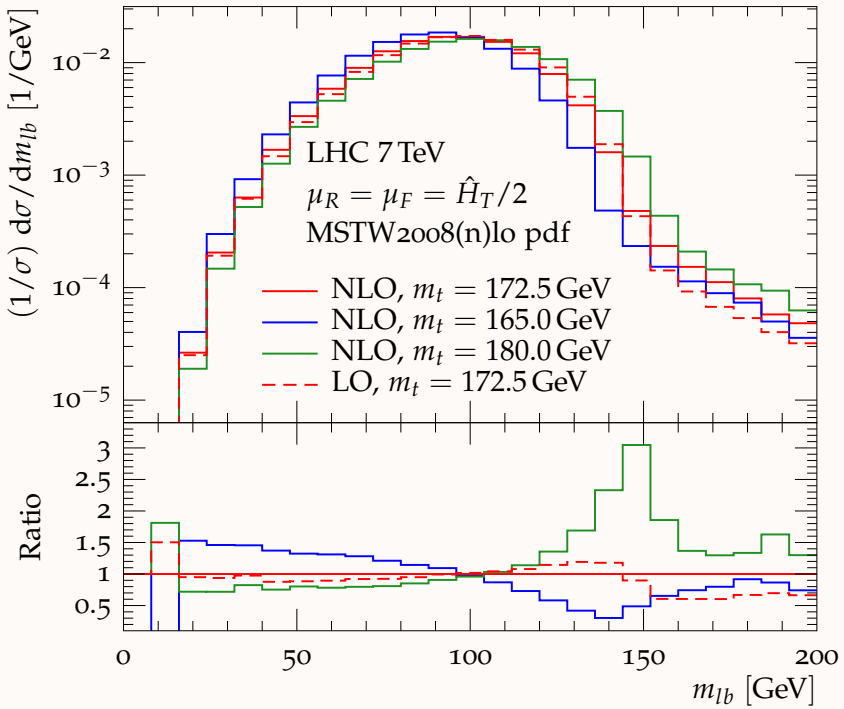


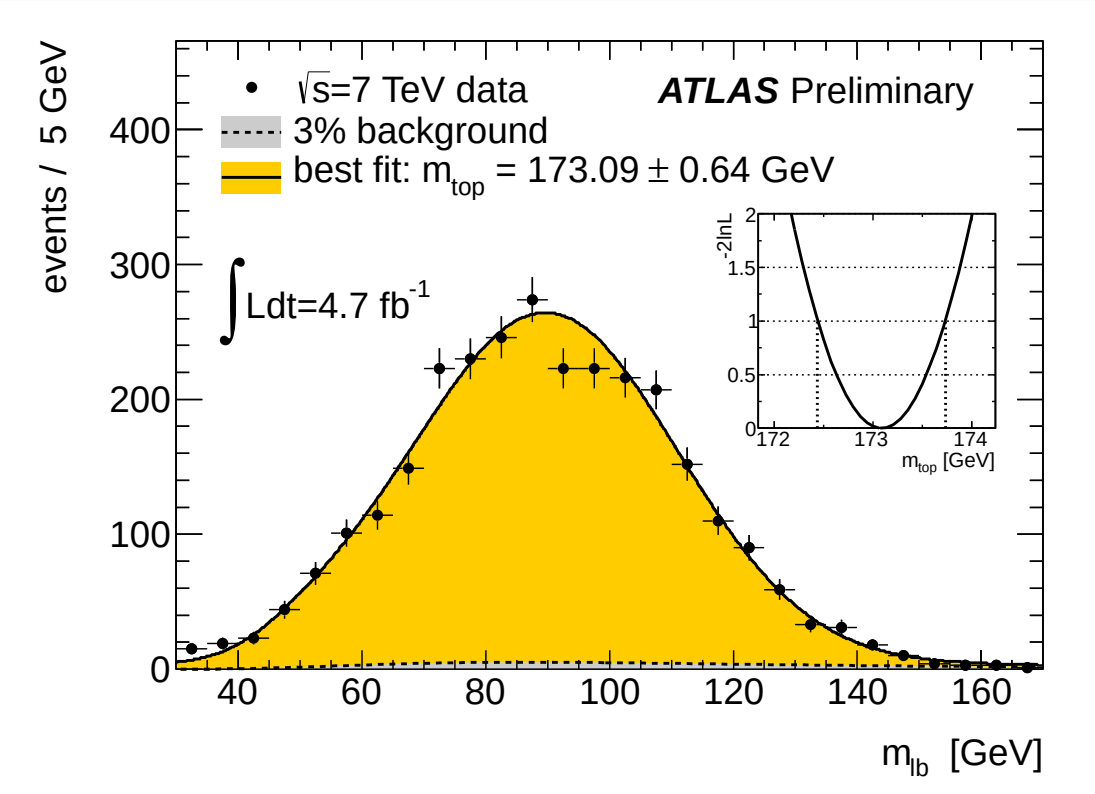
Top quark mass determination using the m_{lb} method

Parametrize "your" theory (m_{lb} predictions).

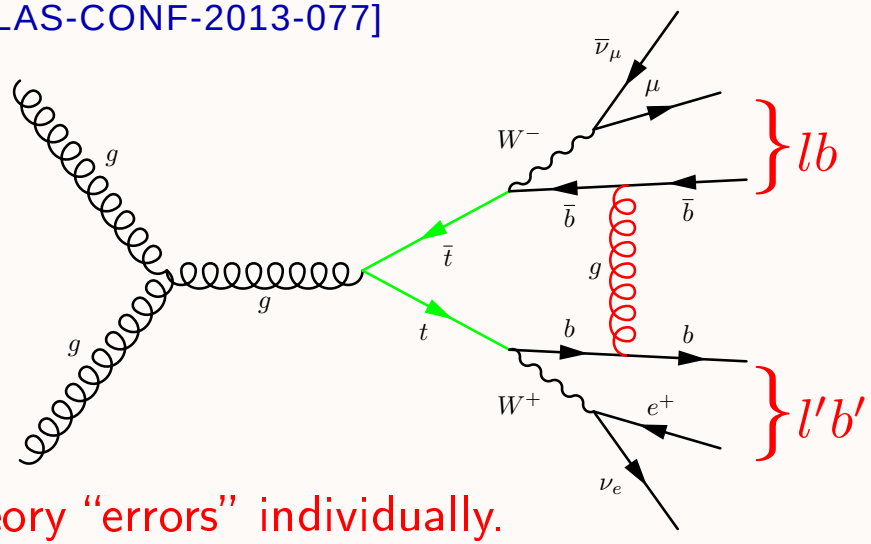
- Full QCD NLO prediction for $W^+W^-b\bar{b}$ in dilepton channel: m_{lb} distribution is sensitive to top quark mass.
- ATLAS uses one-dim. template method to determine m_t. Theory uncertainty has been estimated to 0.8 GeV.

→ Verify size of th. uncertainties using more advanced calc's!





[ATLAS-CONF-2013-077]

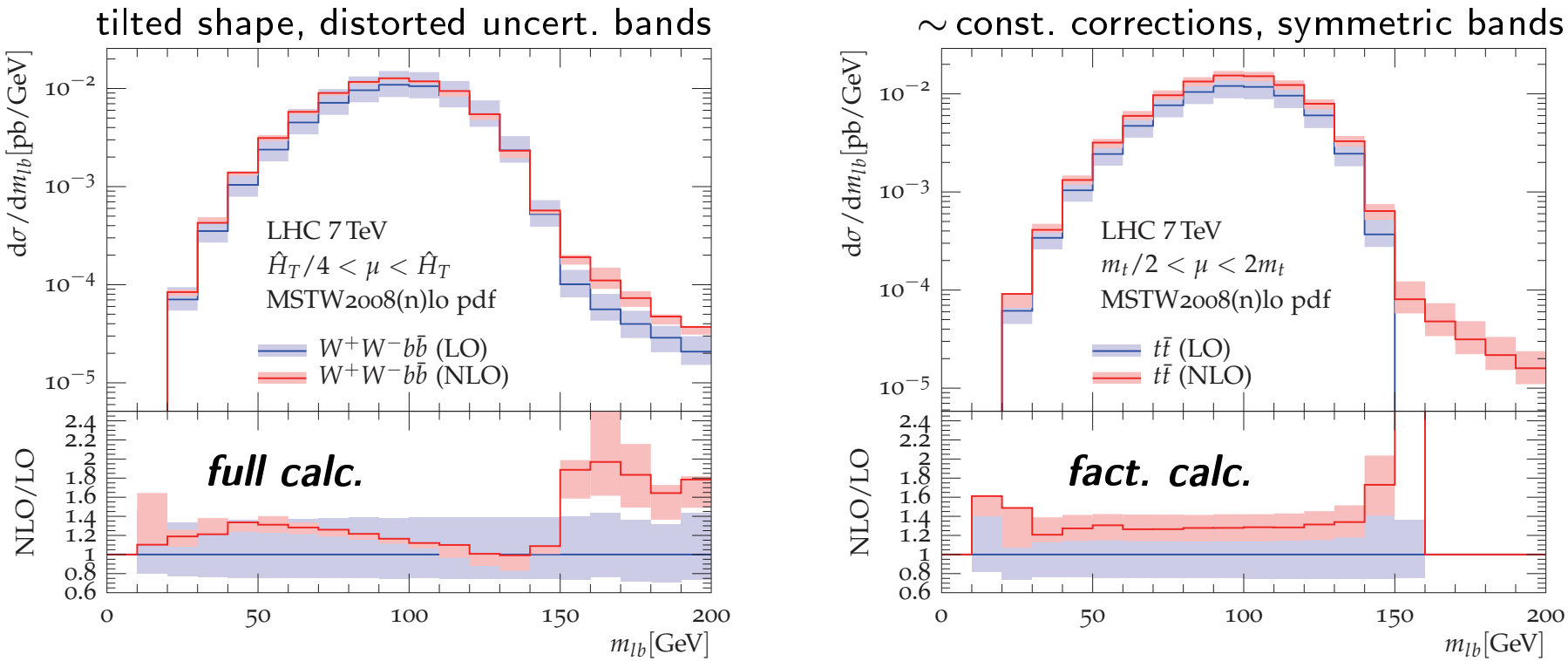


➡ Use pseudo-data to study different types of theory "errors" individually.

The m_{lb} distribution at NLO and scale variations

➡ ***Parton-level NLO calculations for $W^+W^-b\bar{b}$ based on GoSam+Sherpa framework.***

(full & factorized calc., 5-flavour scheme, massless b-quarks, two resonant W decaying leptonically @ LO)

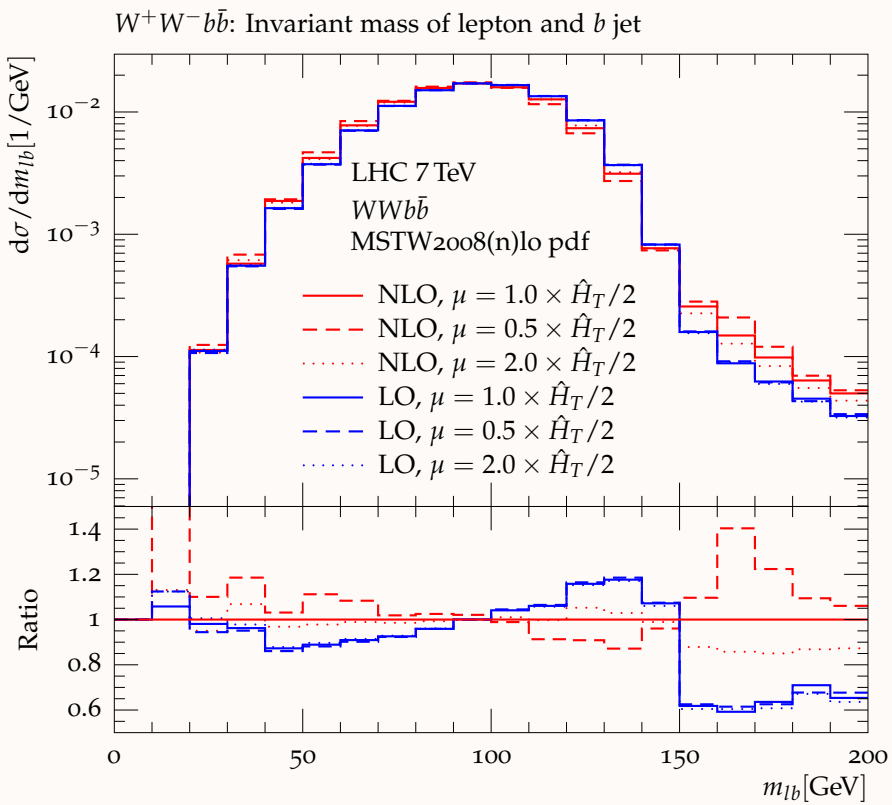


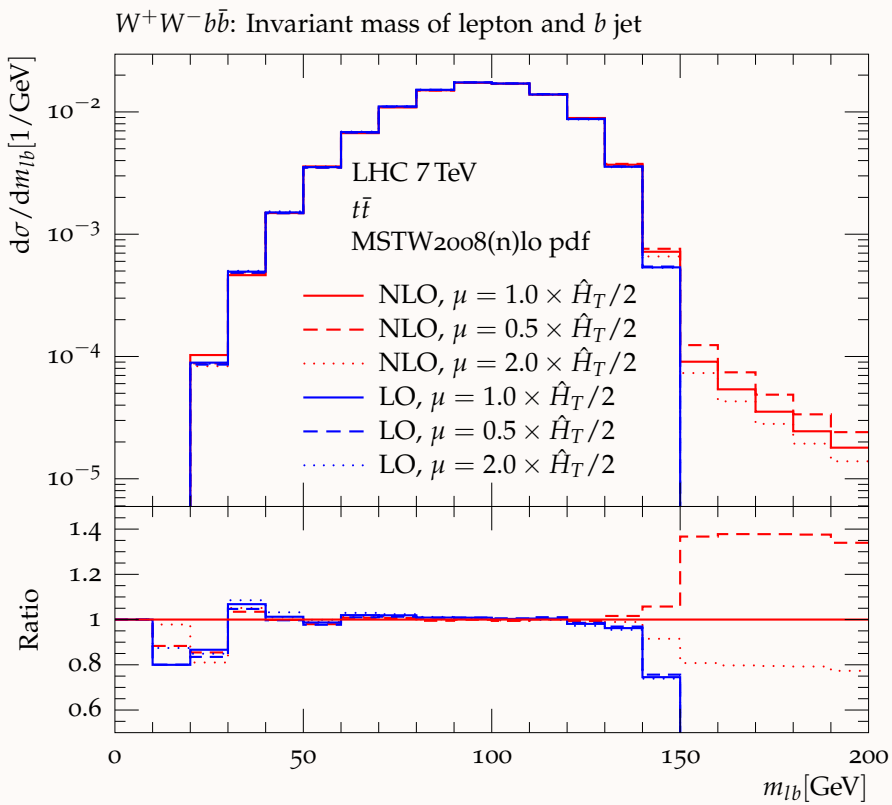
- Important NLO corrections to the shape of m_{lb}
- Values of m_{lb} larger than $\sqrt{m_t^2 - m_W^2}$ are kinematically forbidden in narrow width approximation at LO

• follow ATLAS strategy: use charged-lepton b-jet pairing minimizing sum of both m_{lb} and average.

Normalized m_{lb}: scale versus m_t variation

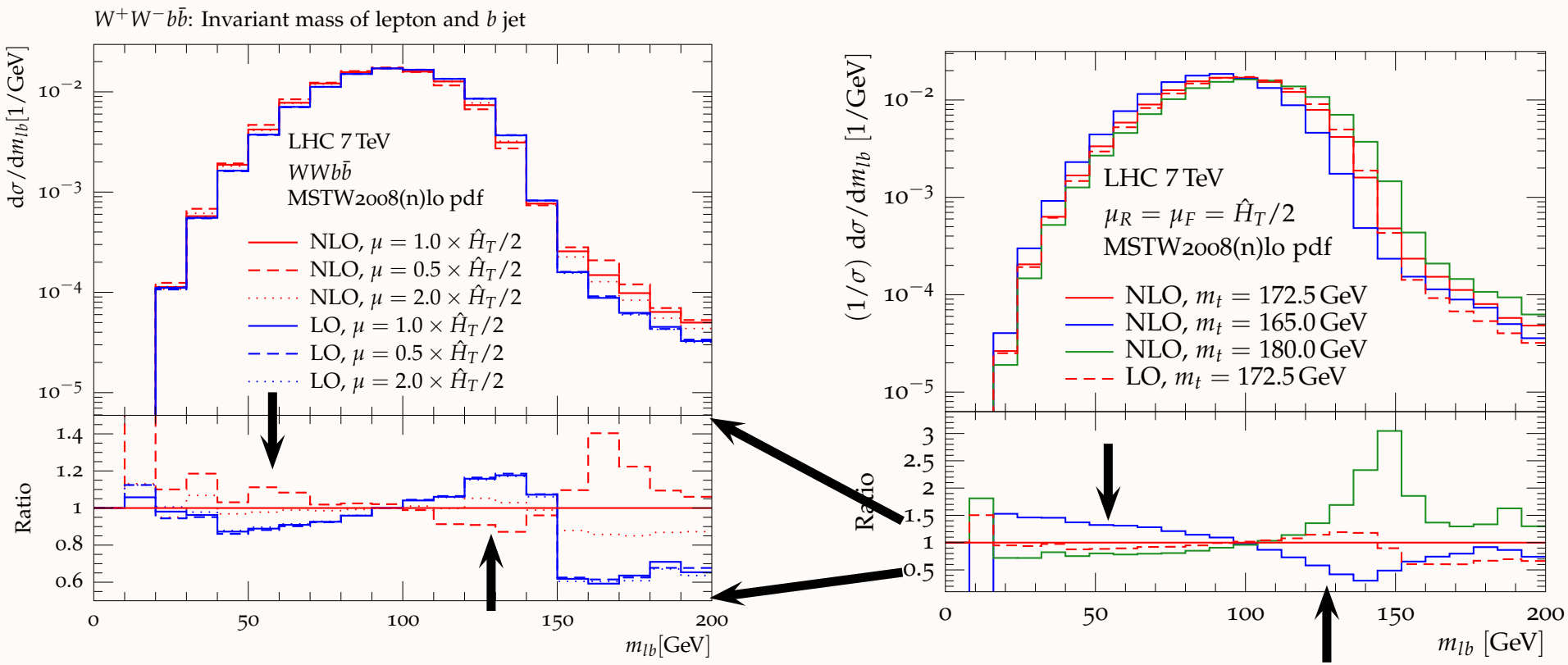
- shape modifications resulting from variation of scales by factors of two
- left panel, for the full approach → visible
- right panel, for the factorized approach → only in tails





Normalized m_{lb}: scale versus m_t variation

- shape modifications resulting from variation of scales by factors of two
- left panel, for the full approach $\longrightarrow$ visible
- right panel, shape changes due to m_t variation @ NLO (m_t variation @ LO very similar!)



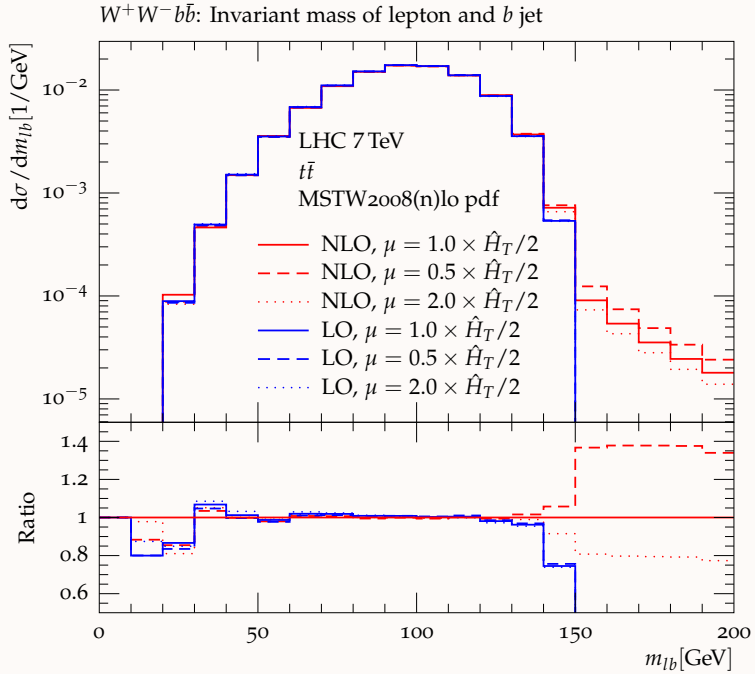
- scale factor variation mimics shape changes as induced by different m_t values $\longrightarrow$ uncertainty
- @NLO: scale down corresponds to lower mass
- fit mass and scale simultaneously, but would resulting choice work for other distributions (eg. $m_{t\bar{t}}$)?

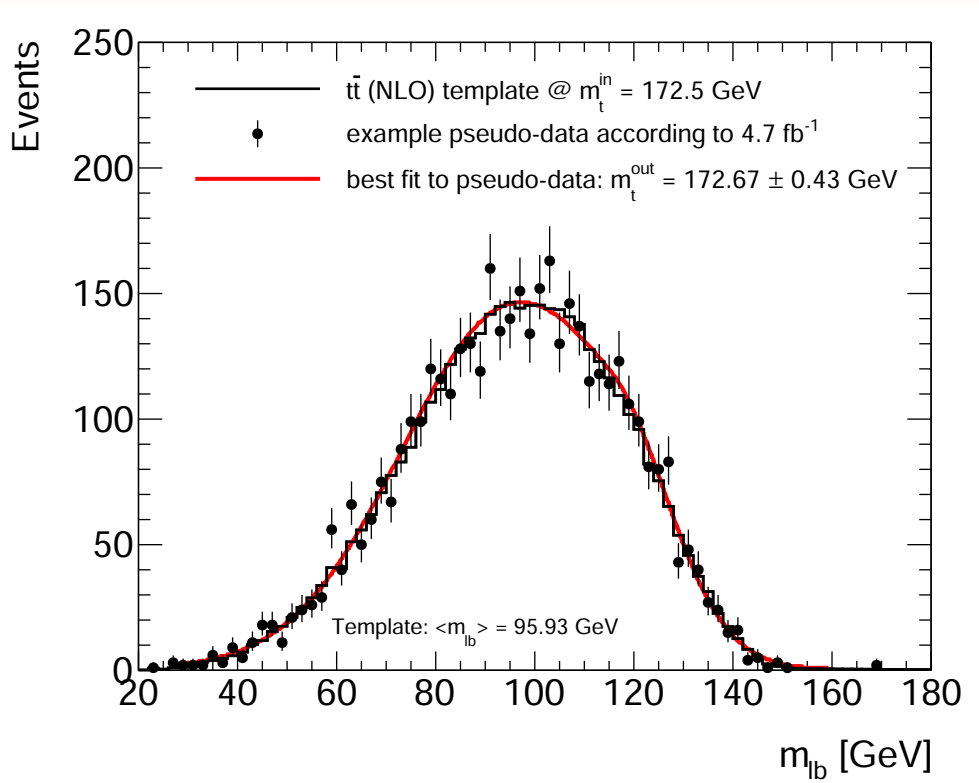
Scale uncertainties and the m_{lb} method

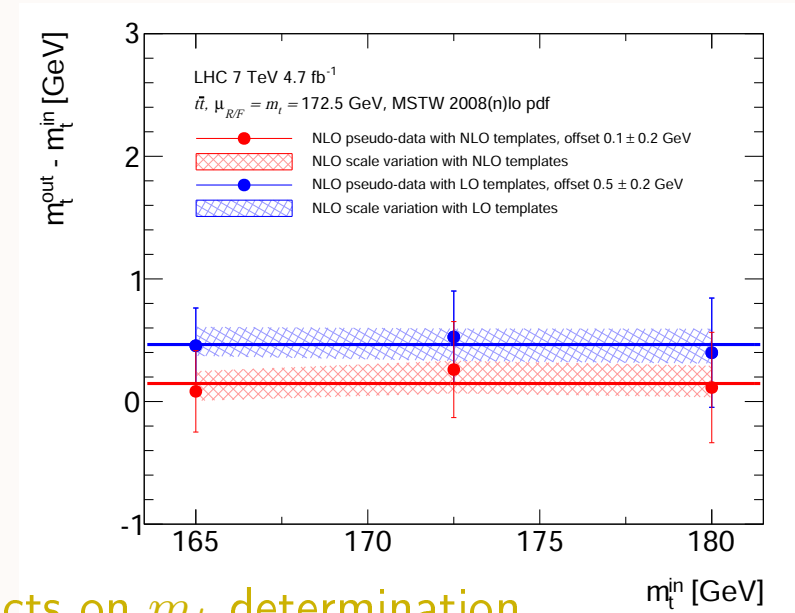
[Heinrich, Maier, Nisius, Schlenk, Winter, arXiv:1312.6659]

Single out effect of NLO scale uncertainties on top mass.

- Use m_{lb} method in a parton-level analysis where we assume that data follows factorized QCD NLO prediction for $t\bar{t}$ with subsequent dilepton decays at LO [pseudo-data].
- Apply/test against the theories given by default scale choice NLO and LO predictions (templates) [hypotheses].







➡ Based on NLO $t\bar{t}$ + LO decays, only small effects on m_t determination.

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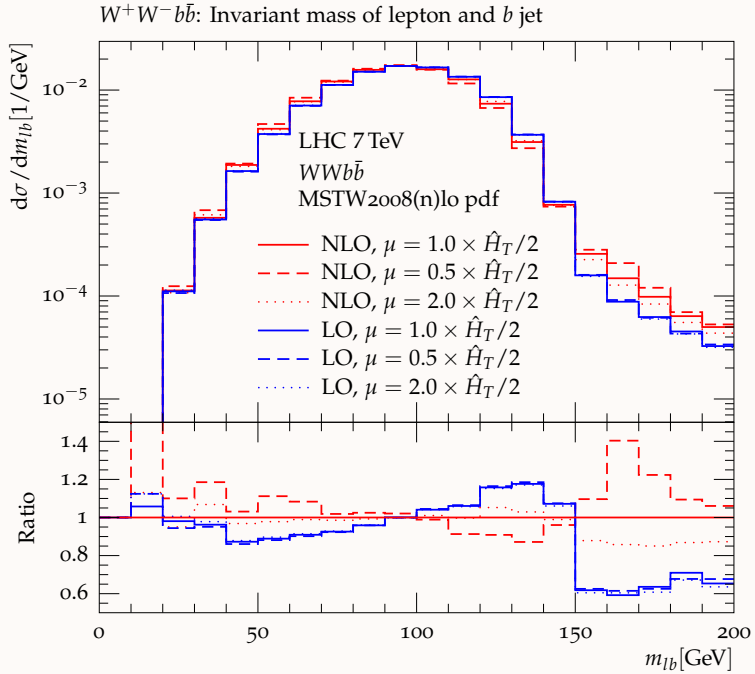
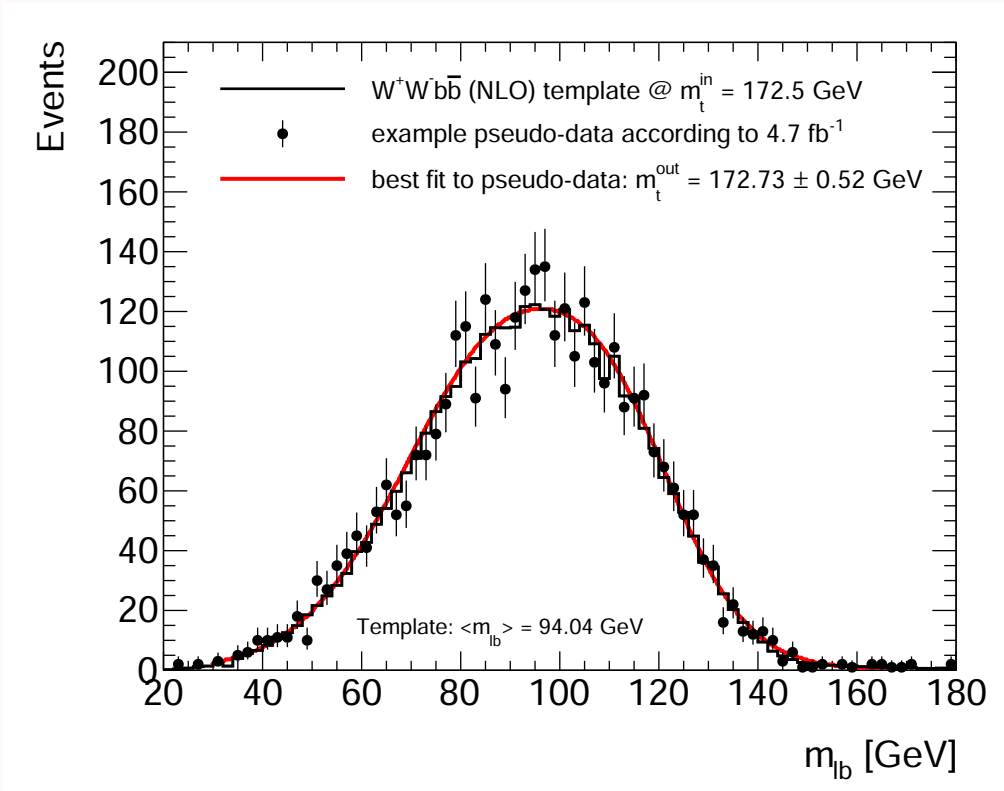
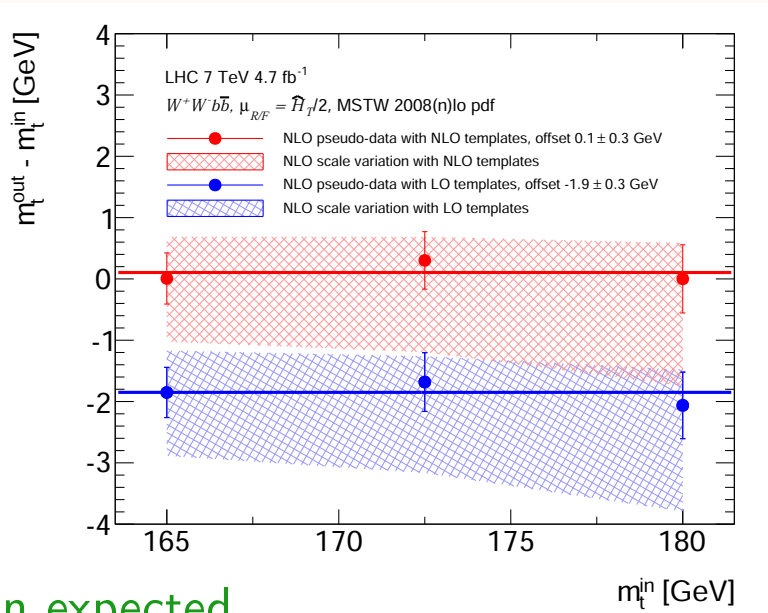


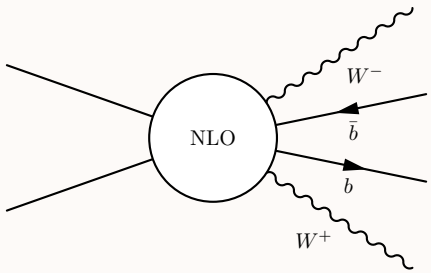


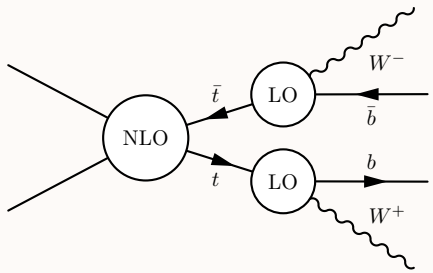


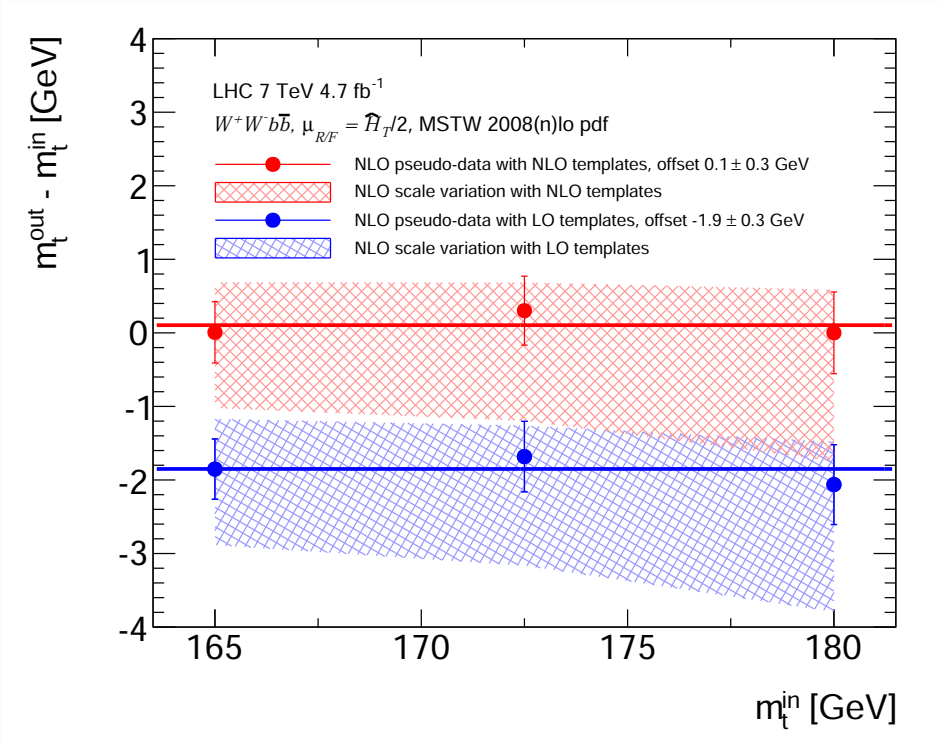
➡ Impacts top quark mass determination more than expected.

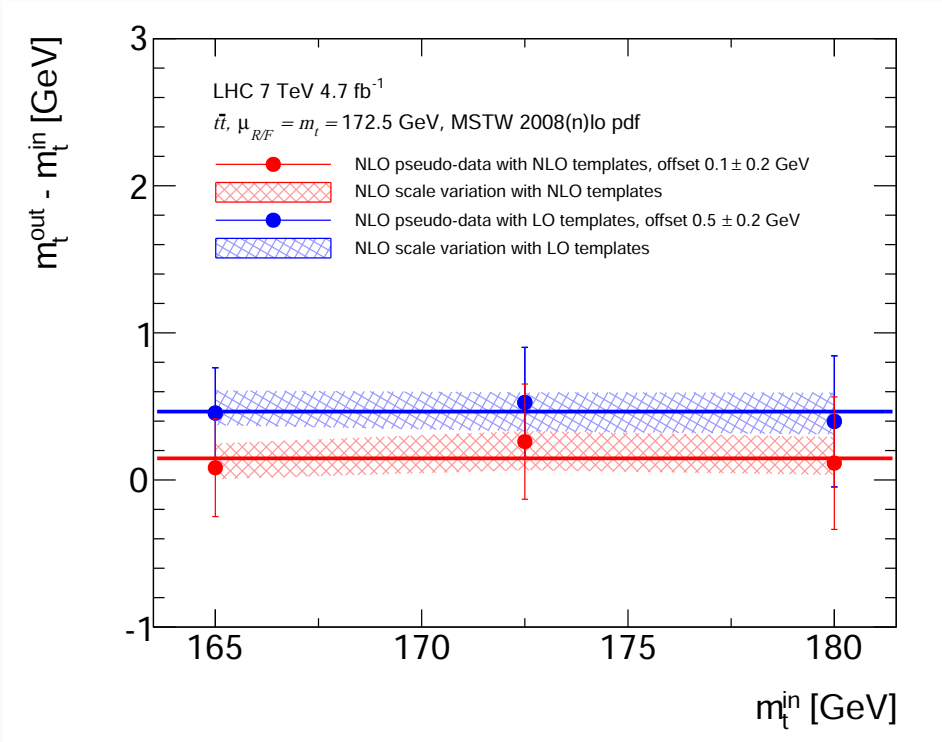
Summary

➡ ***Full (left) vs factorized (right) NLO calculation: results for mass shifts.***





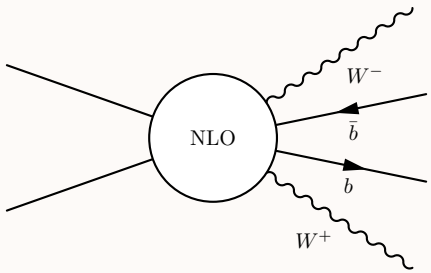


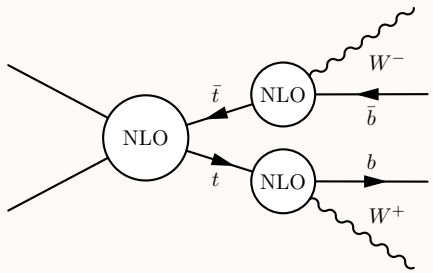


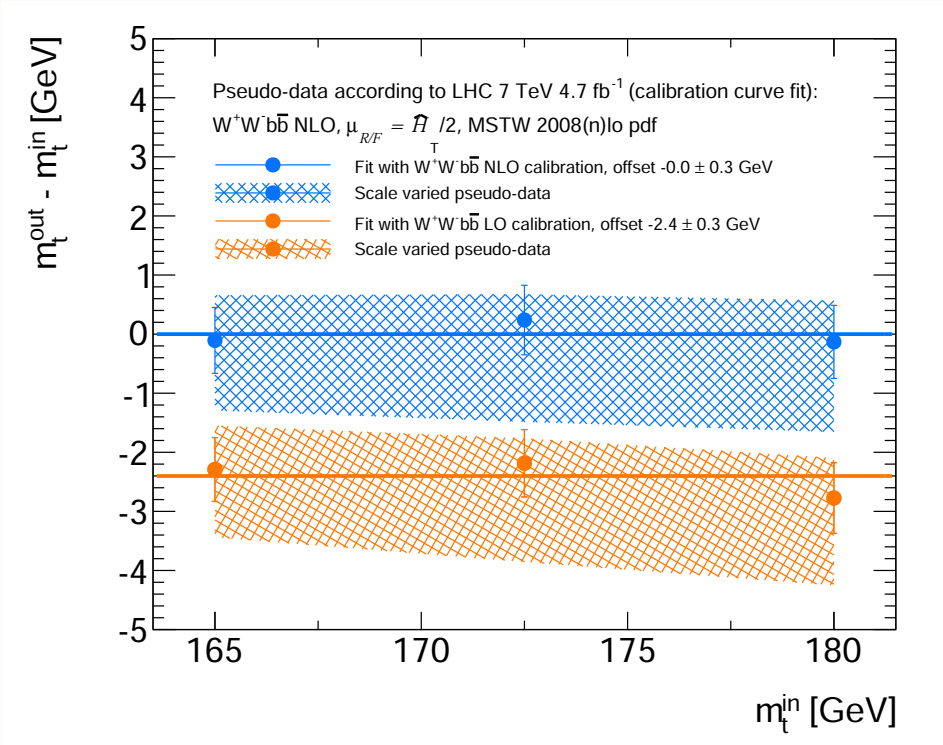
- larger shift btwn NLO & LO description ($\sim 1.9\,\mathrm{GeV}$) as compared to factorized approach ($\sim 0.5\,\mathrm{GeV}$)
- significantly larger uncertainties from scale variations for full approach ($^{+0.6}_{-1.0}\,\mathrm{GeV}$ vs $\pm 0.2\,\mathrm{GeV}$)

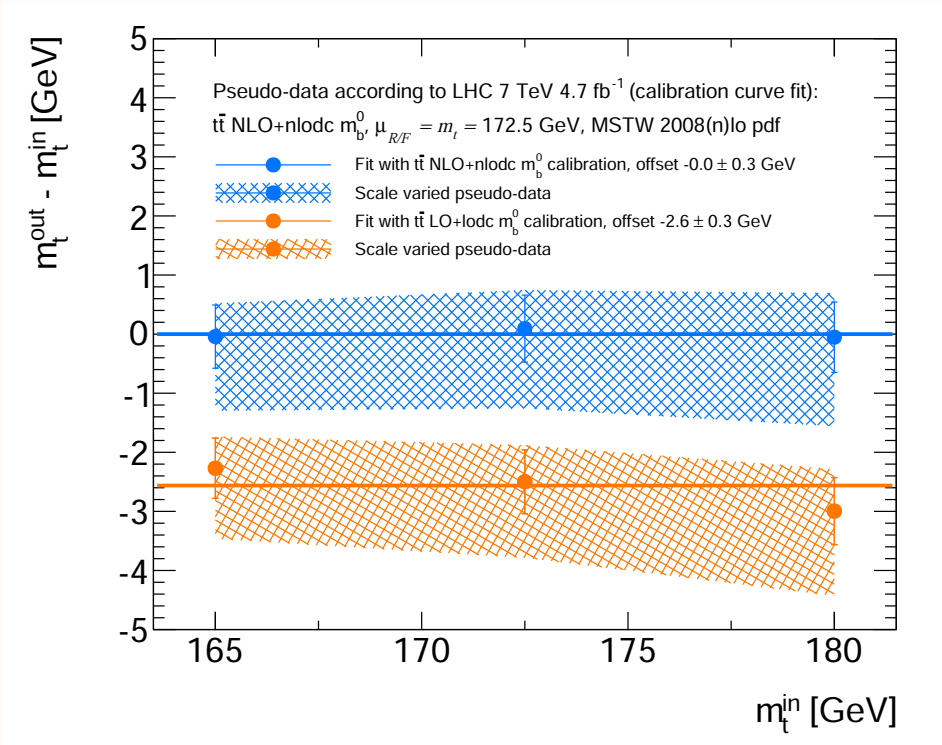
Preliminary result

➡ ***Full (left) vs NWA (right) NLO calculation.***







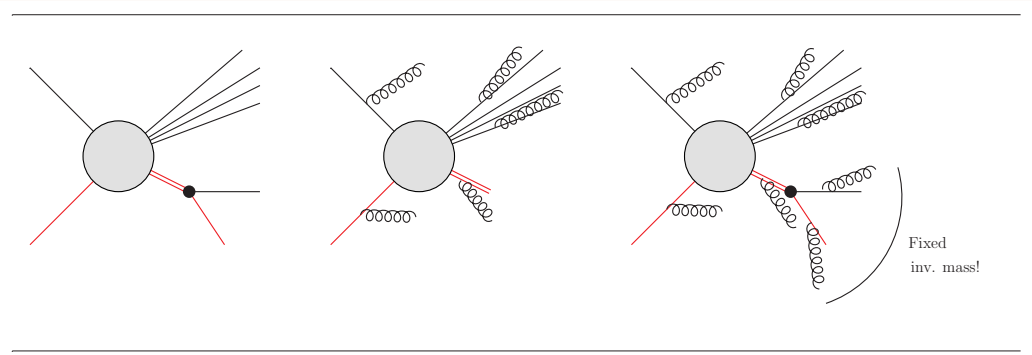


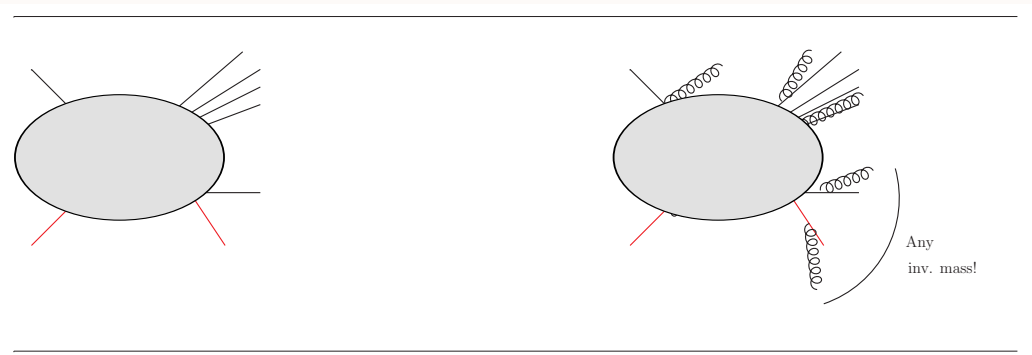
- PRELIMINARY RESULTS based on calibration curve fit

Combination with parton showers.

What about NLO+PS matching for WWb$\bar{b}$?

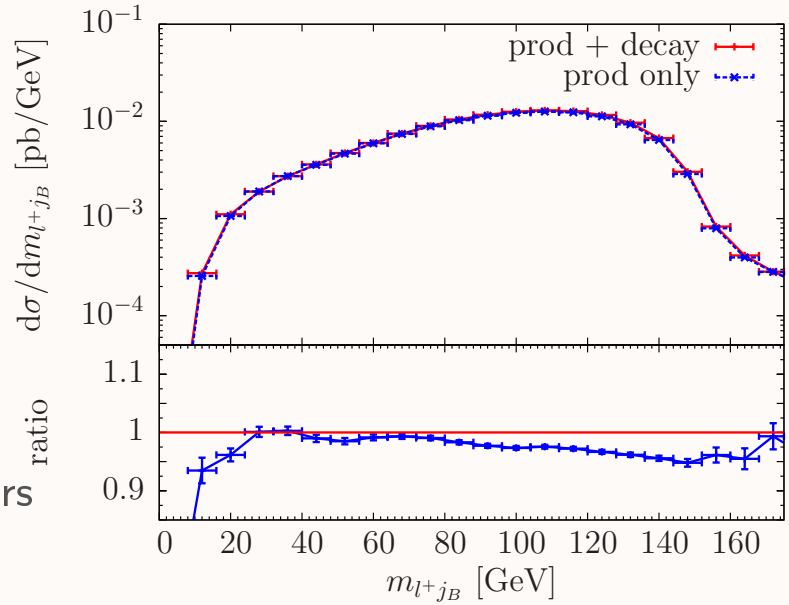
- ... to obtain more realistic, i.e. hadron level final states.
- first attempt and results using PowHel [Garzelli, Kardos, Trocsanyi, arXiv:1405.5859]
- however, the issue of intermediate resonances has not been addressed. (Without a proper treatment of intermediate resonances, parton shower effects will distort the (NLO-accurate) Breit–Wigner shape.)





Recent developments towards a consistent treatment:

- consistent NLO+PS in the narrow-width limit [Campbell, Ellis, Nason, Re, arXiv:1412.1828]
- resonance-aware subtraction and matching in Powheg [Jezo, Nason, arXiv:1509.09071]
  each xsec component (B, V, R) separated into their dominant resonance histories
  subtr. procedure preserves offshellness of resonant $\hat{s}$-propagators
  resonance info on fs particles communicated to shower.



NLO+PS generator for $WWb\bar{b}$ production

[Jezo, Lindert, Nason, Oleari, Pozzorini, arXiv:1607.04538], [Jezo, Nason, arXiv:1509.09071]
[20] [Frixione, Nason, Ridolfi, arXiv:0707.3088], [35] [Campbell, Ellis, Nason, Re, arXiv:1412.1828]

Significant theoretical improvements:

NLO MEs for $pp \to \ell^+\nu_\ell l^-\bar{\nu}_l b\bar{b}$ (i.e. up to $\mathcal{O}(\alpha_s^3\alpha^4)$) in the 4FNS can be matched to parton shower using information about resonance histories and the resonance-aware subtraction and matching method of Powheg.

label	$t\bar{t}$	$t\bar{t} \otimes$ decay	$b\bar{b}4\ell$
generator	`hvq` [20]	`ttb_NLO_dec` [35]	`bb4l`
framework	`POWHEG-BOX`	`POWHEG-BOX-V2`	`POWHEG-BOX-RES`
NLO matrix elements	$t\bar{t}$	$t(\to \ell^+\nu_\ell b)\,\bar{t}(\to l^-\bar{\nu}_l\bar{b})$	$\ell^+\nu_\ell\, l^-\bar{\nu}_l\, b\,\bar{b}$
decay accuracy	LO+PS	NLO+PS	NLO+PS
NLO radiation	single	multiple	multiple
spin correlations	approx.	exact	exact
off-shell $t\bar{t}$ effects	BW smearing	LO $b\bar{b}4\ell$ reweighting	exact
Wt & non-resonant effects	no	LO $b\bar{b}4\ell$ reweighting	exact
b-quark massive	yes	yes	yes

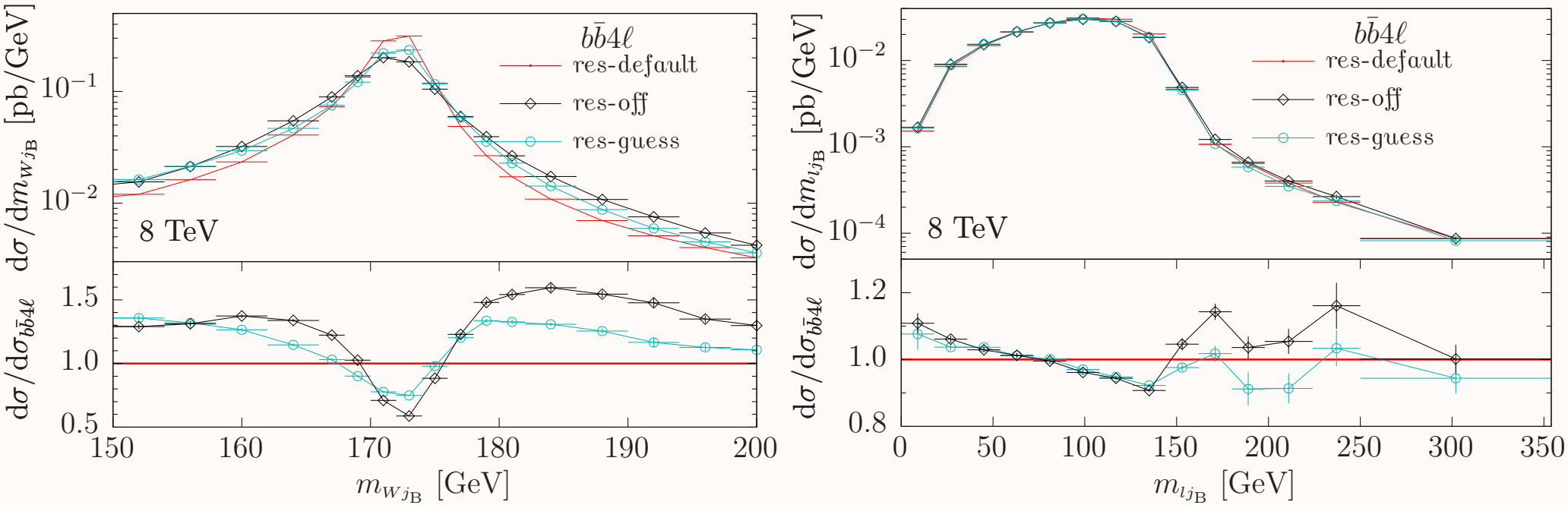
Physics features combined for the 1st time in one generator dubbed `bb4l` (`POWHEG-BOX-RES` framework with `OpenLoops` interface matched to `Pythia8`)

- consistent NLO+PS treatment of t resonances, including quantum corrections to t propagators and offshell t decay chains
- exact spin correlations at NLO, interference between NLO radiation from top production and decays, full NLO accuracy in $t\bar{t}$ production and decays
- unified treatment of $t\bar{t}$ and Wt production with interference at NLO
- improved modelling of b quark kinematics owing to b quark mass effects
- access to phase-space regions with unresolved b quarks and/or jet vetoes

NLO+PS generator for $WWb\bar{b}$ production

[Jezo, Lindert, Nason, Oleari, Pozzorini, arXiv:1607.04538]

➡ comparison of resonance-aware with resonance-unaware, traditional $(res - off)$, and resonance kinematic-guess based predictions $(res - guess)$:
the traditional approach gives wider mass peaks as it does not preserve the virtuality of top resonances, neither in Powheg nor in the shower.

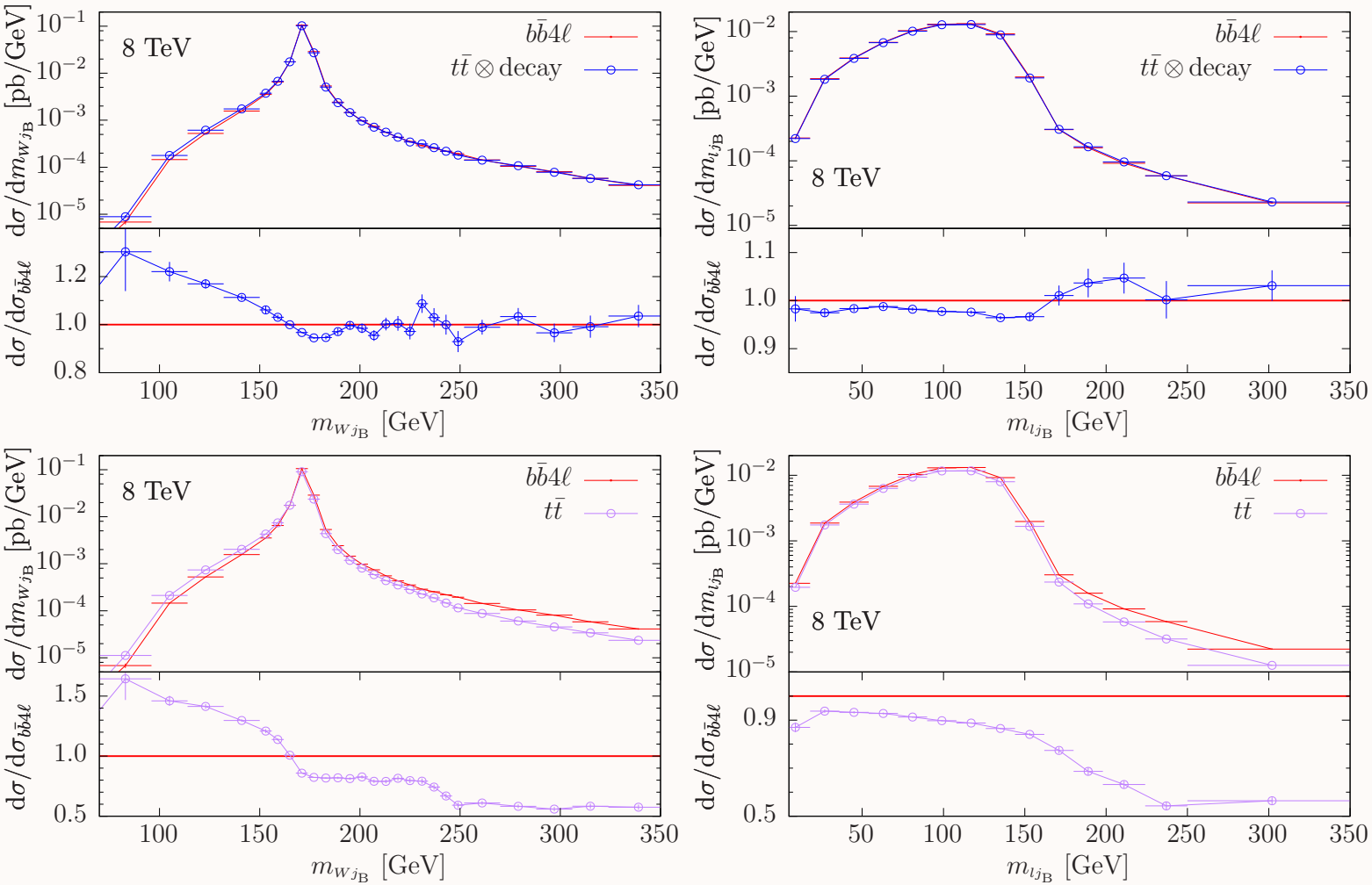


- j_B is b jet containing hardest B hadron, W reco. via corresponding offshell $\ell\nu$ pair in hard ME
- t reconstruction via charge and b flavour information at MC truth level

NLO+PS generator for $WWb\bar{b}$ production

[Jezo, Lindert, Nason, Oleari, Pozzorini, arXiv:1607.04538]

➡ comparison of the predictions of the new generator, standard Powheg (lower row) and that obtained from operating in narrow-width limit (upper row) including offshellenss and interference effects in an approximate way.



- j_B is b jet containing hardest B hadron, W reco. via corresponding offshell $\ell\nu$ pair in hard ME
- t reconstruction via charge and b flavour information at MC truth level

Summary.

Cutting edge parton-level calculations of NLO QCD corrections to $WWb\bar{b}$ production are available, using modern NLO tools (MG5_aMCNLO, OpenLoops+Powheg, OpenLoops+Sherpa, GoSam+Sherpa, Helac-NLO/PowHel).
Realistic, many body final states!!

Comparison with NWA approaches & standard Monte Carlos helps disentangle effects beyond the factorization and assess their relevance for phenomenology (on the inclusive level approximations work well, but differential distributions have to be checked as well).

The 4-flavour scheme calculations (treating b-quarks as massive partons) give us new insight to the validation of "top-induced" backgrounds.

Recent developments in matching $WWb\bar{b}$ to parton showers led to first NLO+PS generator combining POWHEG-BOX-RES with OpenLoops and Pythia8. Strategy is based on resonant-aware subtraction & matching as implemented in Powheg framework.

The end. (:o) Thank You.