NLO QCD corrections to WWb$\bar{\text{b}}$

"And how they may impact the determination of the top quark mass parameter using the m_{lb} method".

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NLO QCD corrections to $WWb\bar{b}$ production and their impact on top quark mass measurements

[Top LHC WG Meeting – CERN]

Jan Winter *

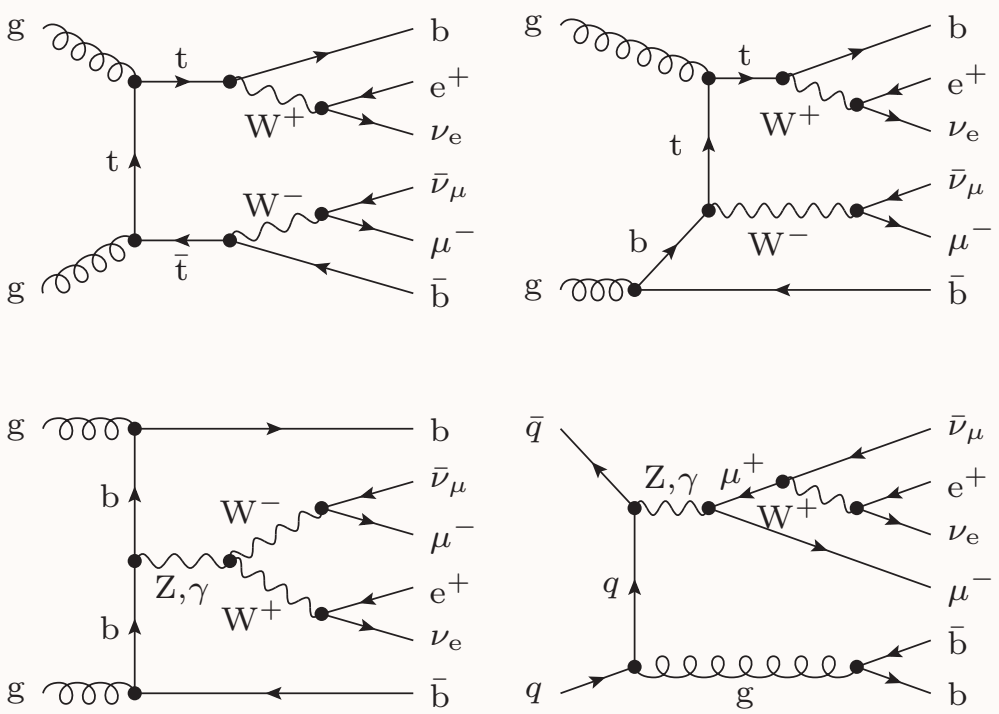
– MPP Munich, Germany –

- ***Based on work presented in arXiv:1312.6659.***
- *$WWb\bar{b}$ calculations at QCD NLO.*
- *Top quark mass determination and scale uncertainties.*
- *Summary & conclusions.*
- *Open questions, suggestions and discussion.*

* Work in collaboration with G. Heinrich, A. Maier, R. Nisius and J. Schlenk

$WWb\bar{b}$ production at NLO

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



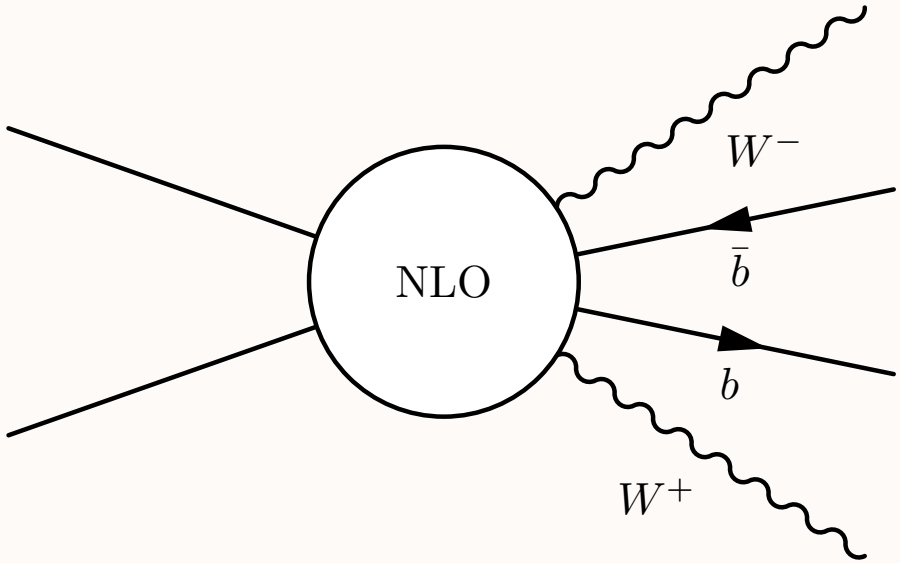
- full NLO treatment includes double-, single- and non-resonant contributions
- complex-mass scheme
- finite top-quark and W width effects
- first done in massless b-quark approximation
  [Denner et al. arXiv:1012.3975, arXiv:1207.5018]
  [Bevilacqua et al. arXiv:1012.4230]
- earlier done in NWA where production and decay factorize (neglected contributions are suppressed by powers of $\Gamma_t/m_t \lesssim 1\%$)
  [Melnikov, Schulze, arXiv:0907.3090]

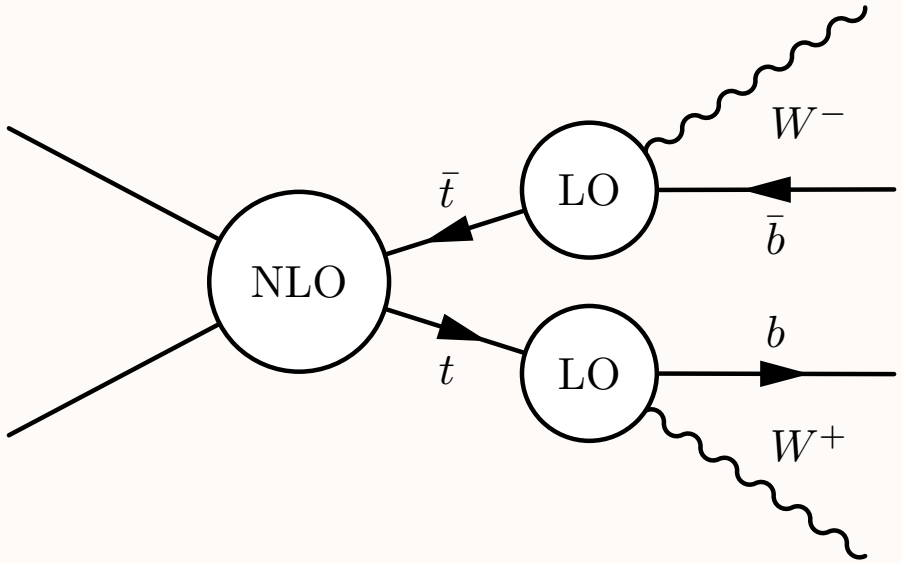
➡ *Our parton level calculations ...*

- use the GoSam+Sherpa combined generator package (current versions, GoSam 2.0 and Sherpa 2.1).
- Sherpa for calculating Born, real corrections and infrared subtractions [Gleisberg et al, arXiv:0811.4622]
- GoSam for calculating virtual corrections [Cullen, vanDeurzen, Greiner, Heinrich et al, arXiv:1404.7096]
- 5-flavour scheme, massless b-quarks, two resonant W decaying leptonically @ LO respecting spin correlations

$\Rightarrow$ [Heinrich, Maier, Nisius, Schlenk, Winter, arXiv:1312.6659]

Full versus factorized approach





full ($WWb\bar{b}$)

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

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

- Calculations used for pure parton level analyses, i.e. m_t is not a MC mass; we use a pole mass.

Top quark mass (parameter) determination from the shape of the invariant mass distribution of the charged lepton and b-jet in $WW b\bar{b}$ production (dilepton channel).

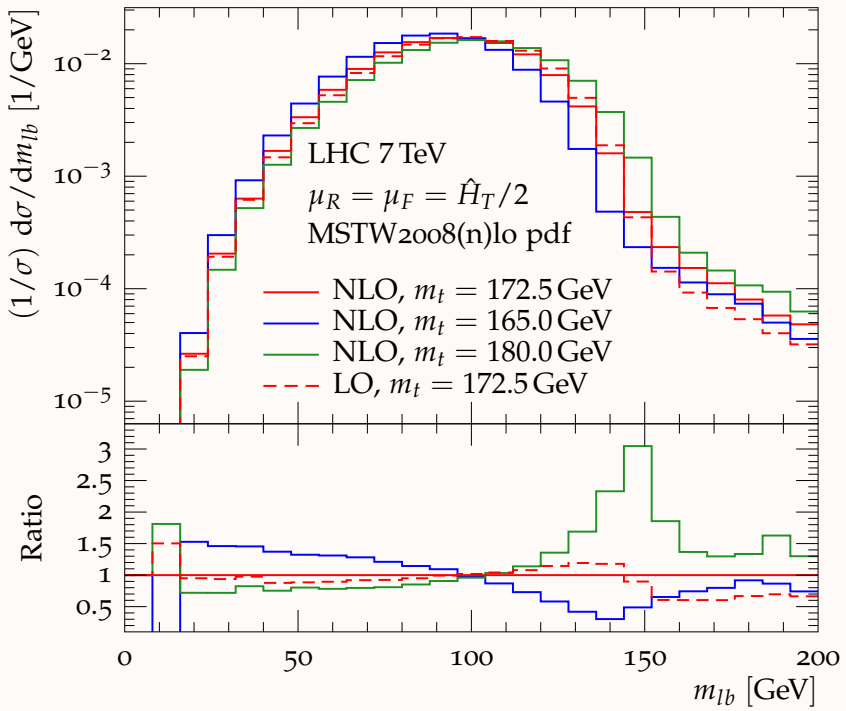
Invariant mass of b-jet and charged lepton

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

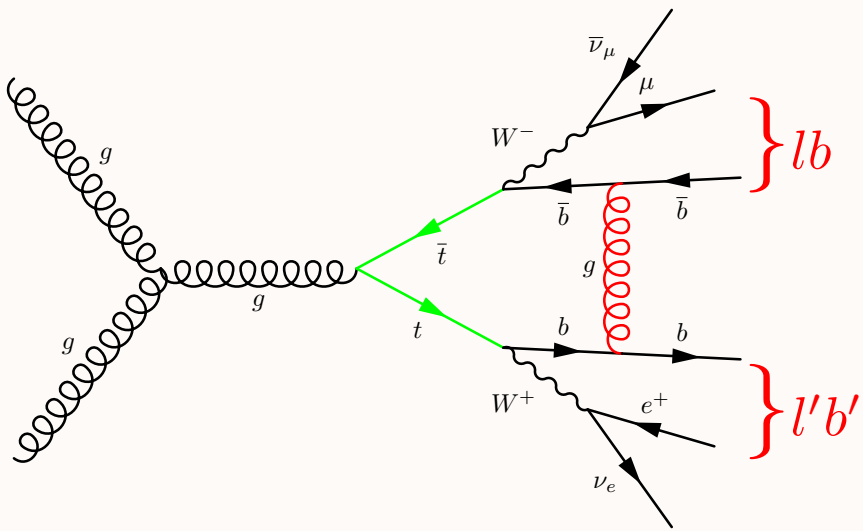
(full & factorized calc., 5-flavour scheme, massless b-quarks, two resonant W decaying leptonically @ LO)

- Definition: $m^2_{lb} = (p_{b\text{-jet}} + p_l)^2$ (and criteria to deal with combinatorial problem)
- The m_{lb} distribution is sensitive to varying the top quark mass → NLO calculations for different m_t.
- Analysis and kinematical requirements according to ATLAS measurement as described in [ATLAS-CONF-2013-077]; in particular: use lepton b-jet pairing minimizing sum of both m_{lb} and average

→ Suitable observable for template fit to precisely measure the top quark mass.



← shape predictions from full QCD NLO WWb$\bar{\text{b}}$

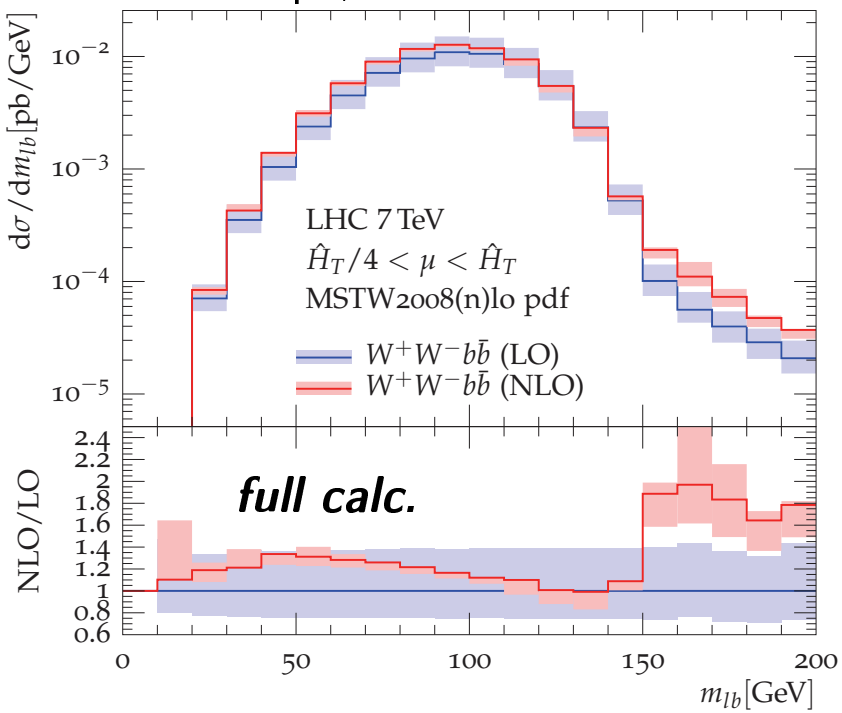


The m_{lb} distribution at NLO and scale variations

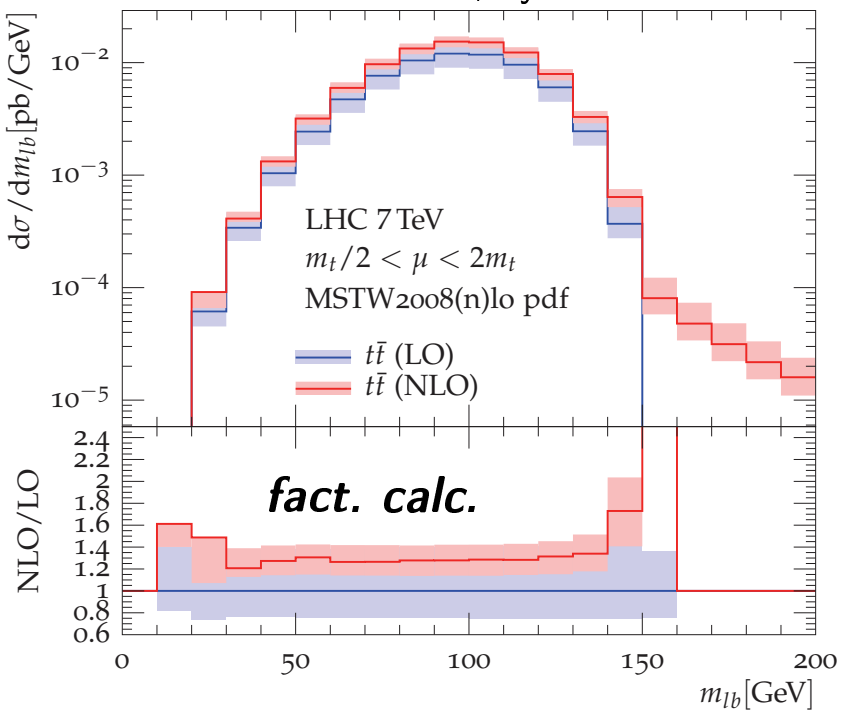
➡ ***Parton-level NLO calculations for $W^+W^-b\bar{b}$ based on GoSam+Sherpa framework.***

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

tilted shape, distorted uncert. bands



∼const. corrections, symmetric bands



- 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.

Note on the inclusive cross section

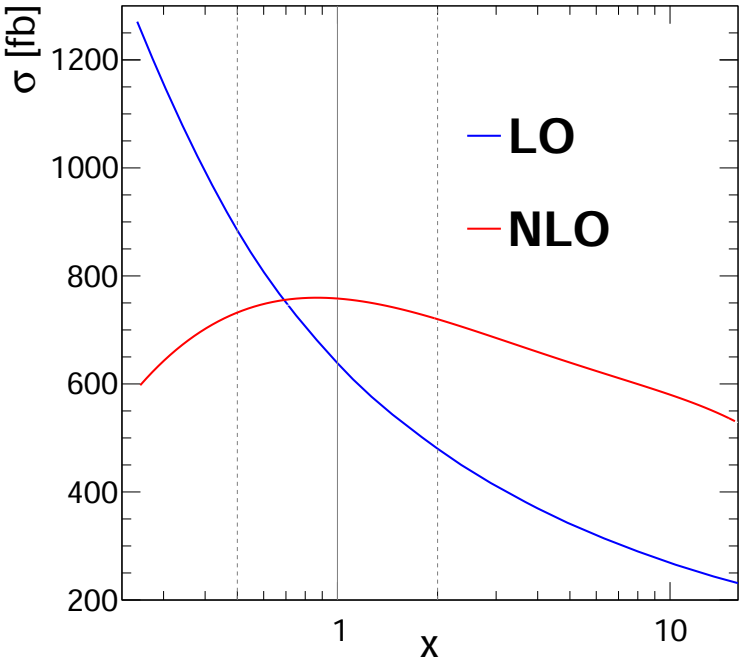
[From J. Schlenk]

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

Renormalization and Factorization scale:

$$\mu = \frac{\hat{H}_T}{2} = \frac{1}{2}\sum_i p_{T,i}$$

Scalar sum over transverse momenta of all final state particles



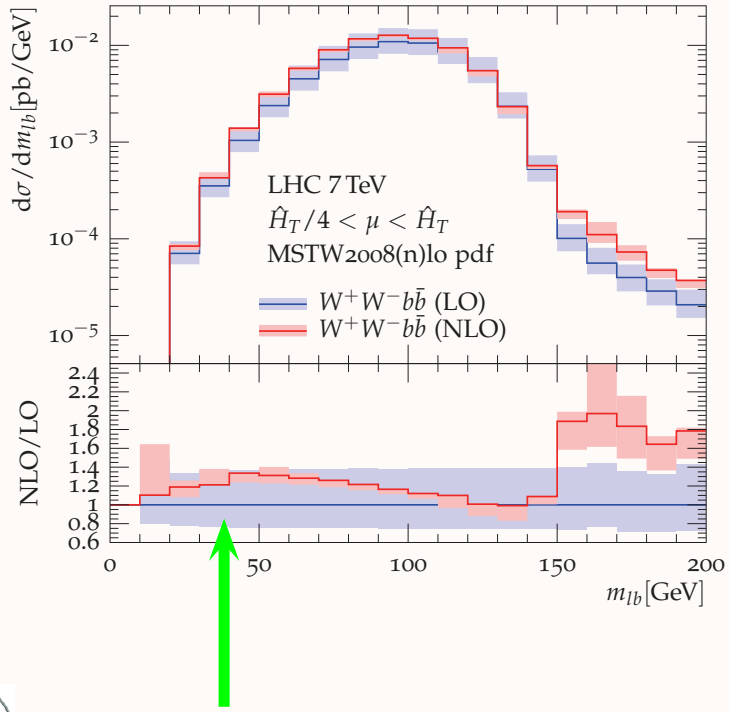
$$x = \frac{\mu}{\hat{H}_T/2}$$

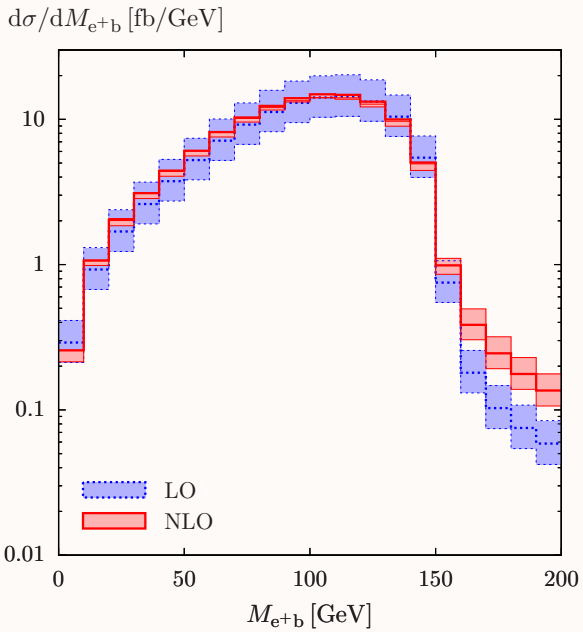
Qualitative comparison of m_{lb} predictions

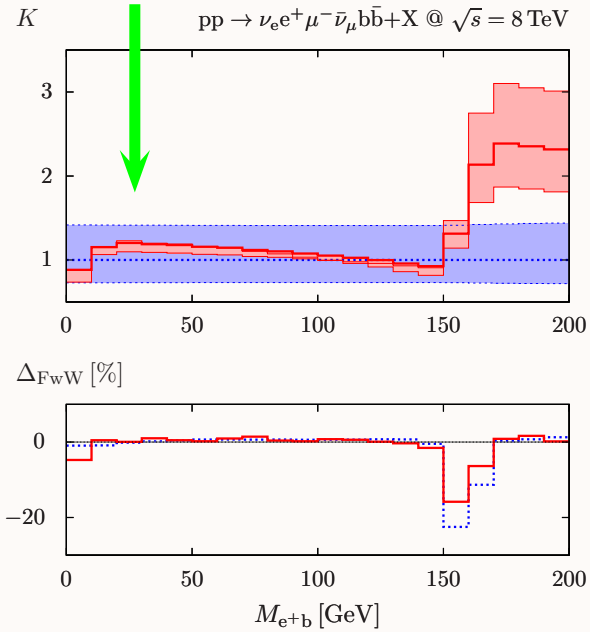
[Denner, Dittmaier, Kallweit, Pozzorini, arXiv:1207.5018]

➡ ***WWbb̄: NLO corrections strongly affect the shape of m_{lb}***

- similar features → agreement on qualitative level only, noting the differences however:
- different LHC energies & kinematical constraints (cuts), slightly different observable (a truth m_{lb})
- different dynamical scale choice (transverse mass of tops)
- non-resonant and off-shell effects due to finite W boson width
- different treatment of b-quark initial states ....

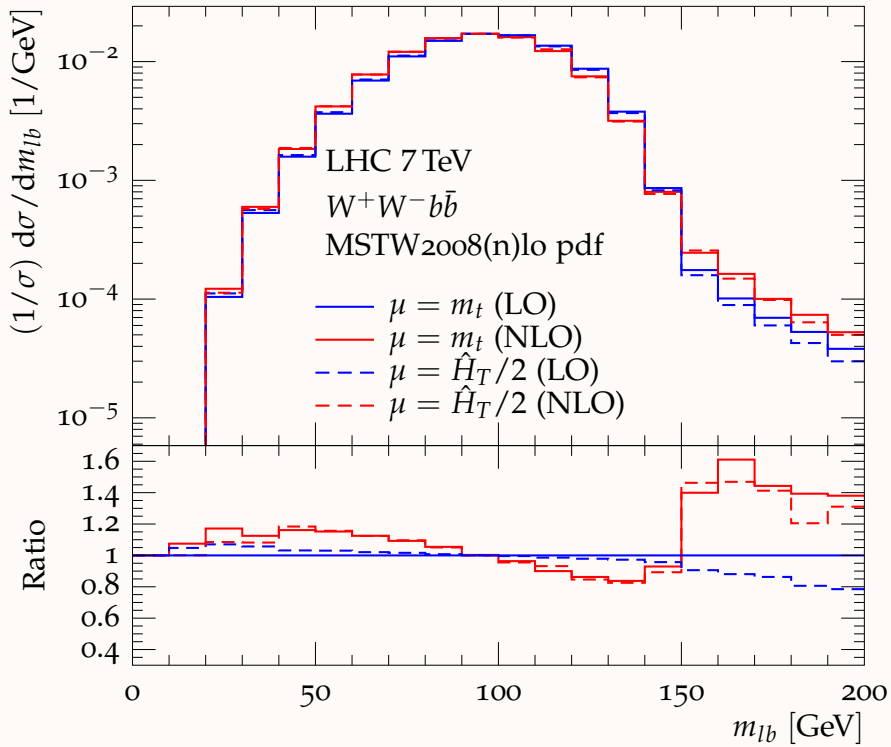


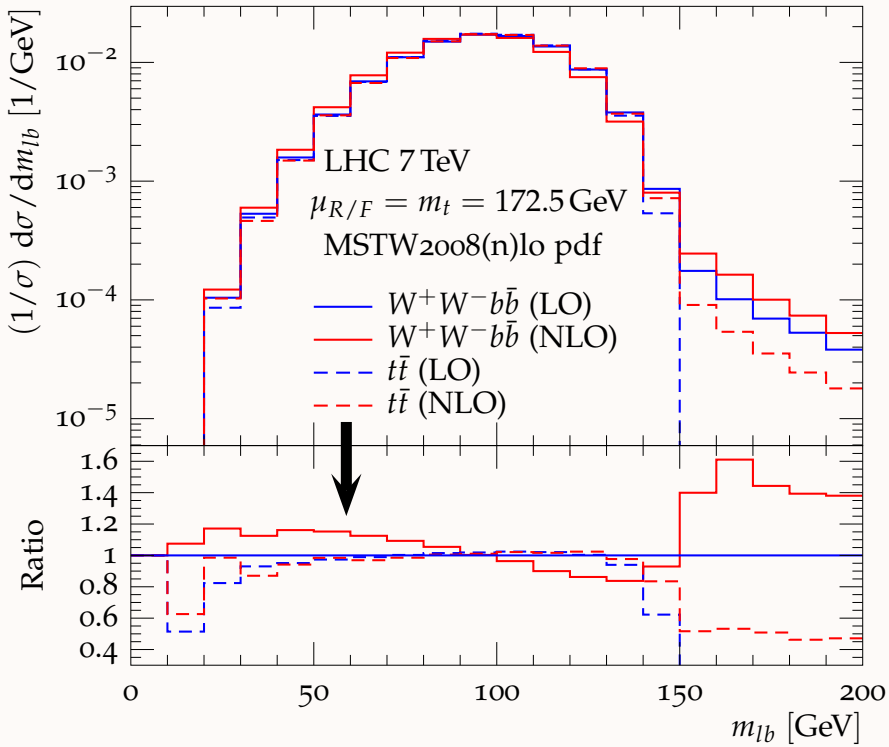




Normalized m_{lb}: shape comparisons & cross-checks

- analysis strongly driven by shape of the distribution (rate comes in only through number of events passing acceptance/analysis cuts)

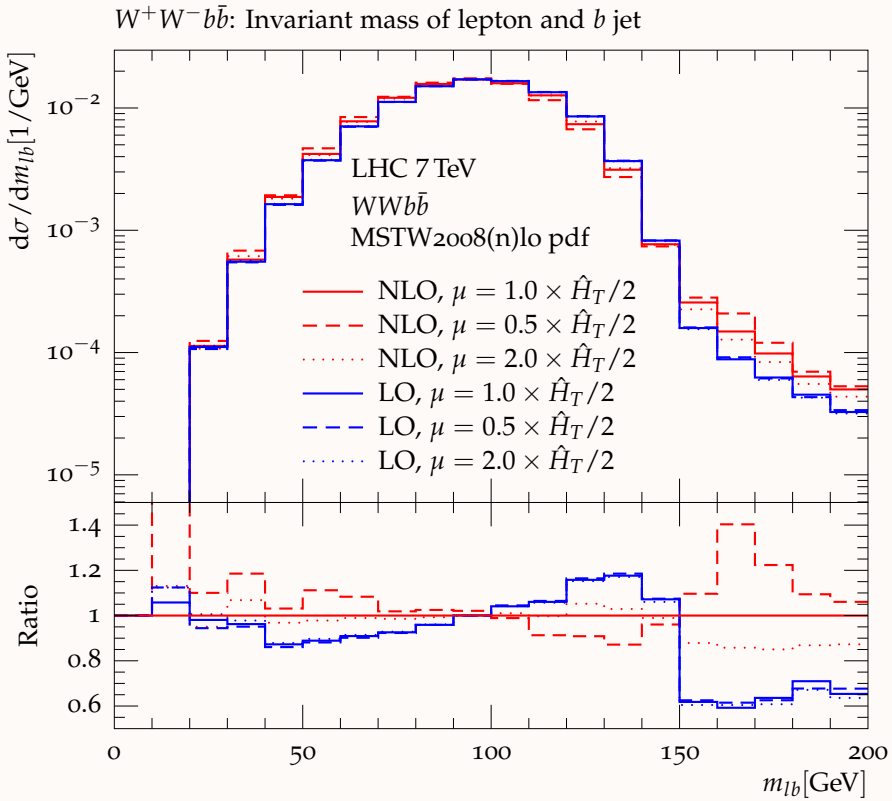


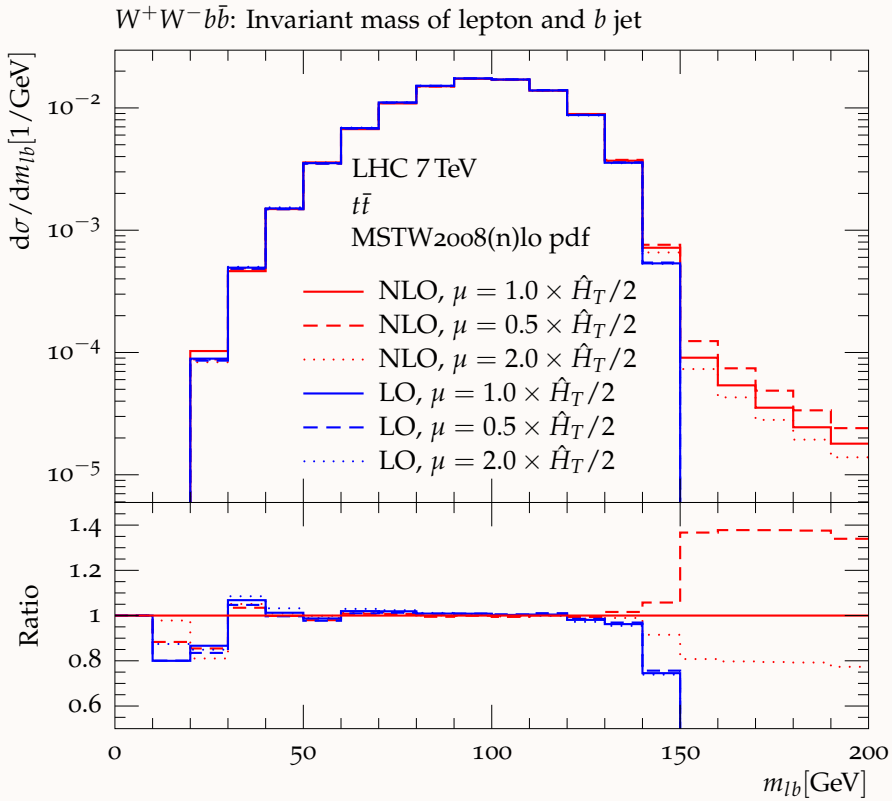


- left: small effect of different scale choices on normalized distributions
- right: for full NLO WWbb̄, shape change is drastic while shapes of others are similar

Normalized m_{lb}: scale versus m_t variation

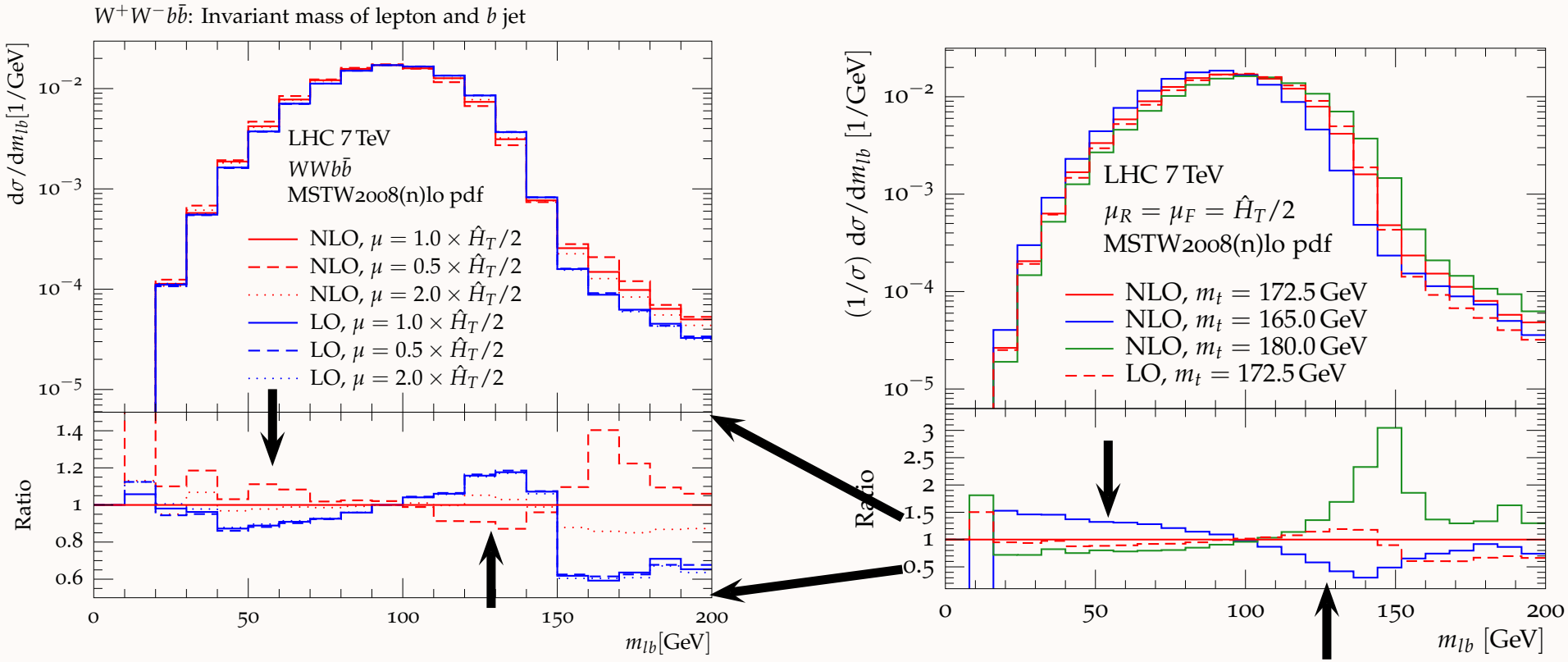
- shape modifications as a result of varying scales by factors of two
- left panel, for the full approach → visible
- right panel, for the factorized approach → only in tails





Normalized m_{lb}: scale versus m_t variation

- shape modifications as a result of varying scales by factors of two
- left panel, for the full approach $\longrightarrow$ visible



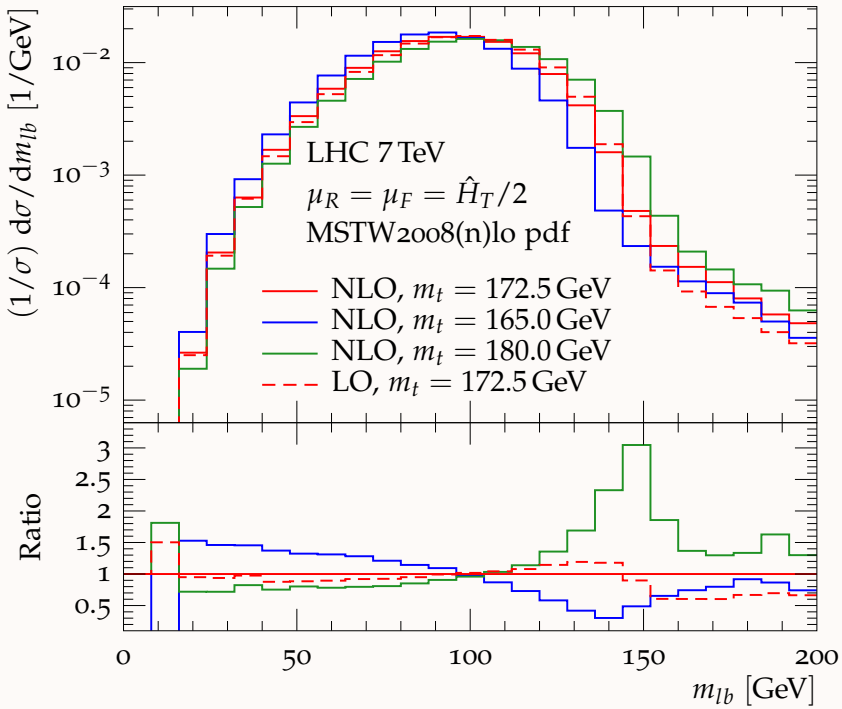
- scale factor variation mimics shape changes as induced by different m_t values $\longrightarrow$ uncertainty
- @NLO: scale down corresponds to lower mass
- fit mass and scale simultaneously, but would resulting choice work for other distributions (eg. $m_{t\bar{t}}$)?

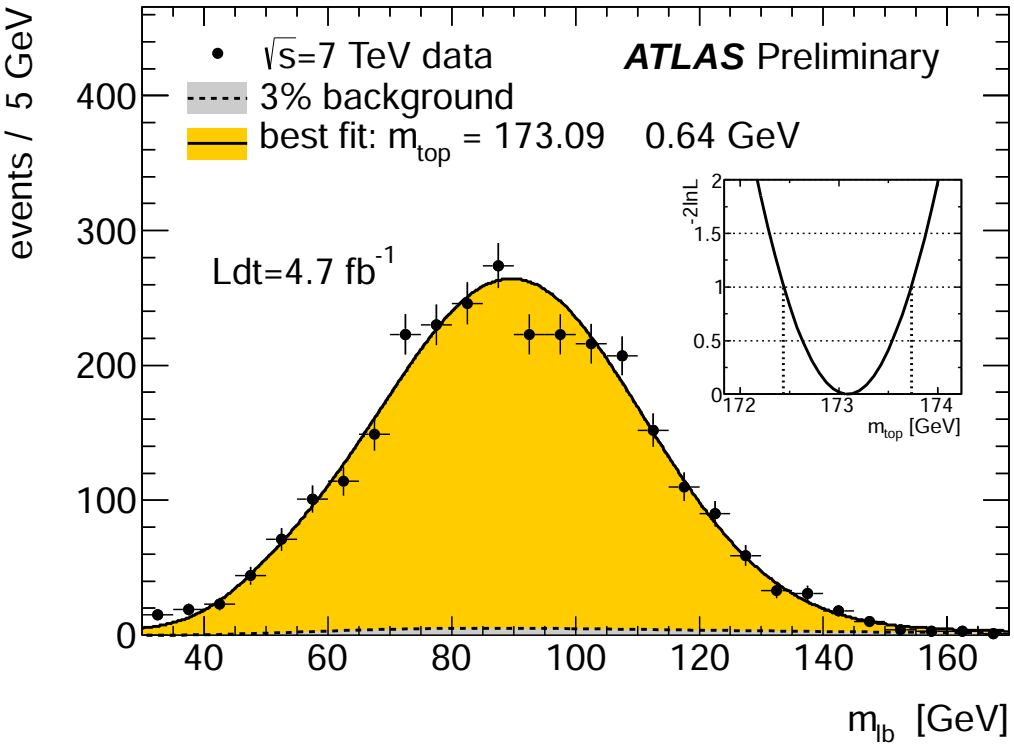
Top quark mass determination using the m_{lb} method

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

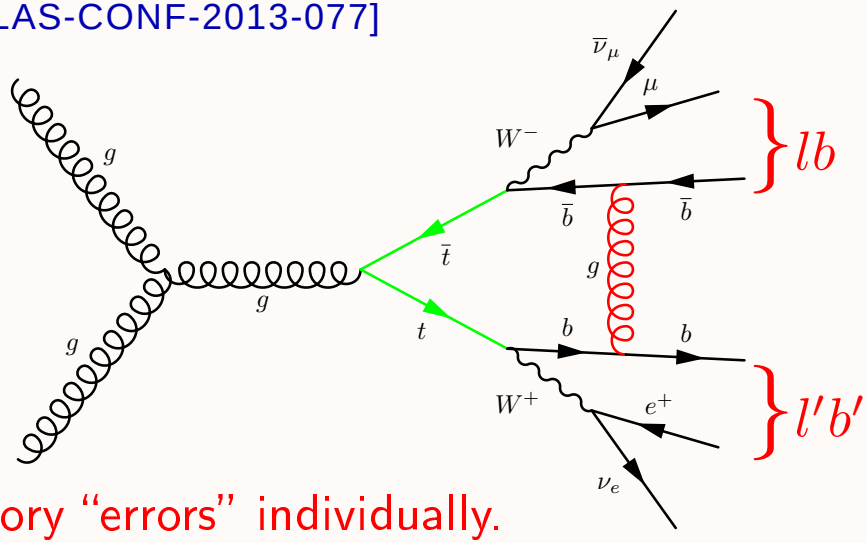
- Full QCD NLO prediction for $W^+W^-b\bar{b}$ in dilepton channel: m_{lb} distribution is sensitive to top quark mass.
- ATLAS uses one-dim. template method to determine m_t. Theory uncertainty has been estimated to 0.8 GeV.

$\rightarrow$ Verify size of th. uncertainties using more advanced calc's!





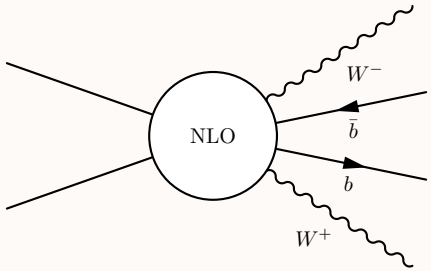
[ATLAS-CONF-2013-077]

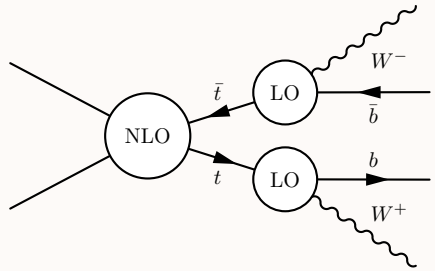


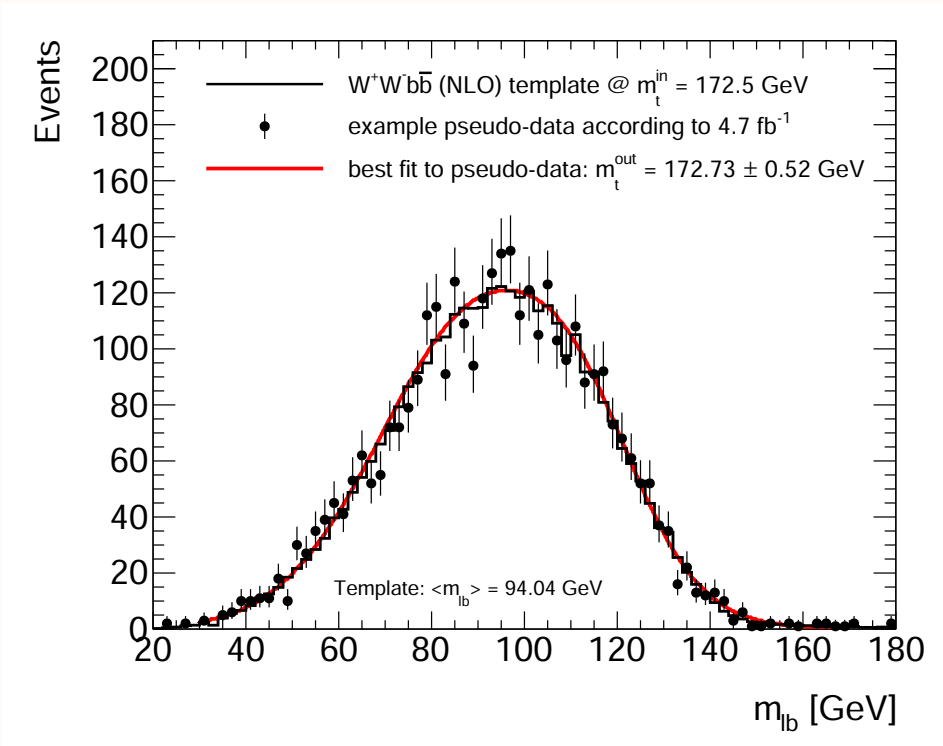
➡ Use pseudo-data to study different types of theory "errors" individually.

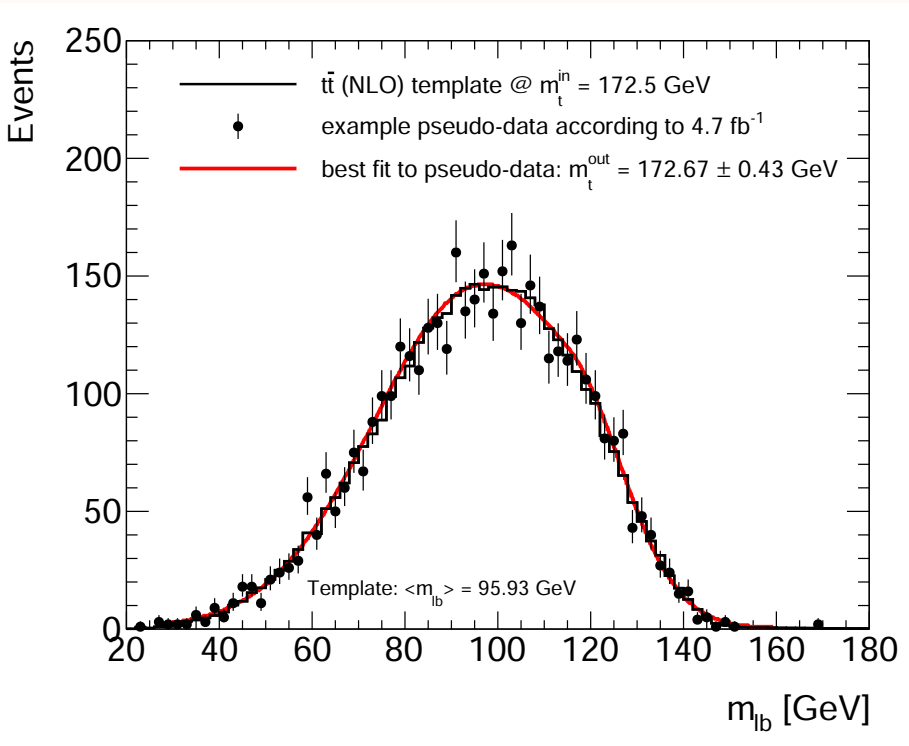
NLO templates vs pseudo-data

➡ ***Representative examples for full (left) and factorized (right) NLO calculation.***









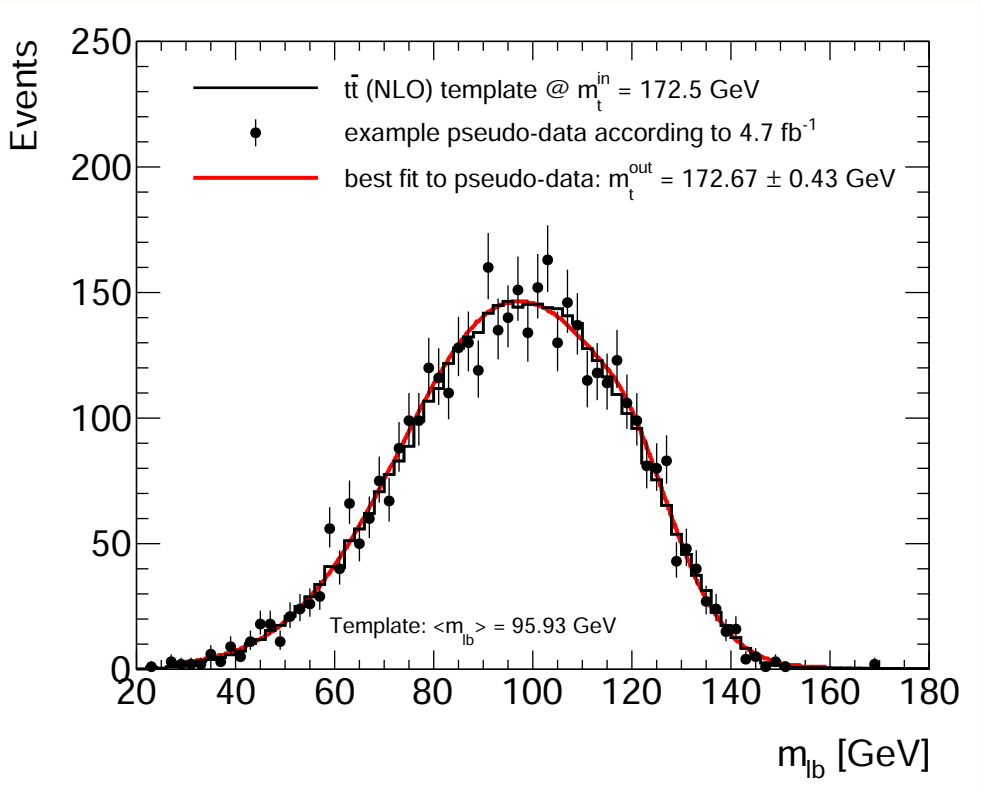
- pseudo-data (black points) are generated from the NLO distributions (black histograms) at m_t^{in}
- fit with NLO templates (parametrization) gives $m_t^{\mathrm{out}} \rightarrow$ best fit to pseudo-data (red line)

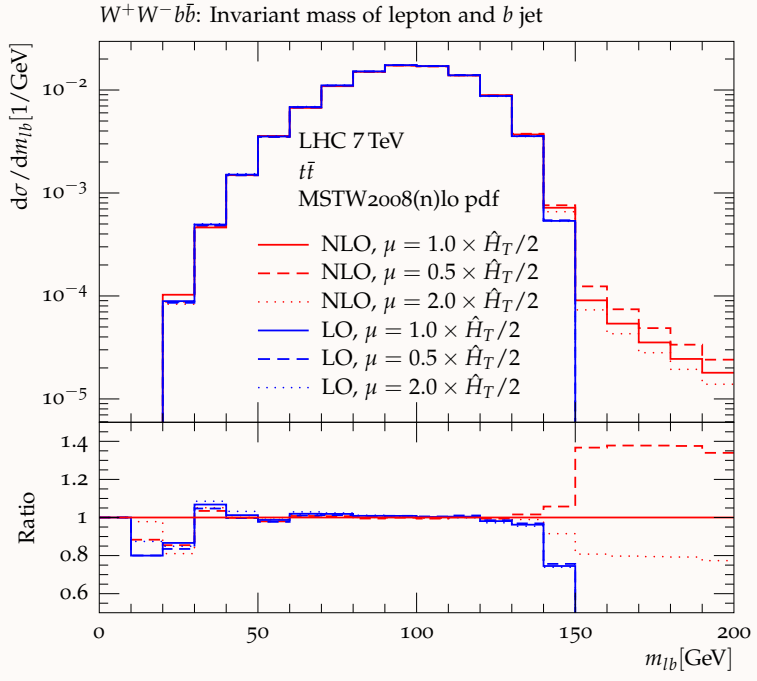
Scale uncertainties and the m_{lb} method

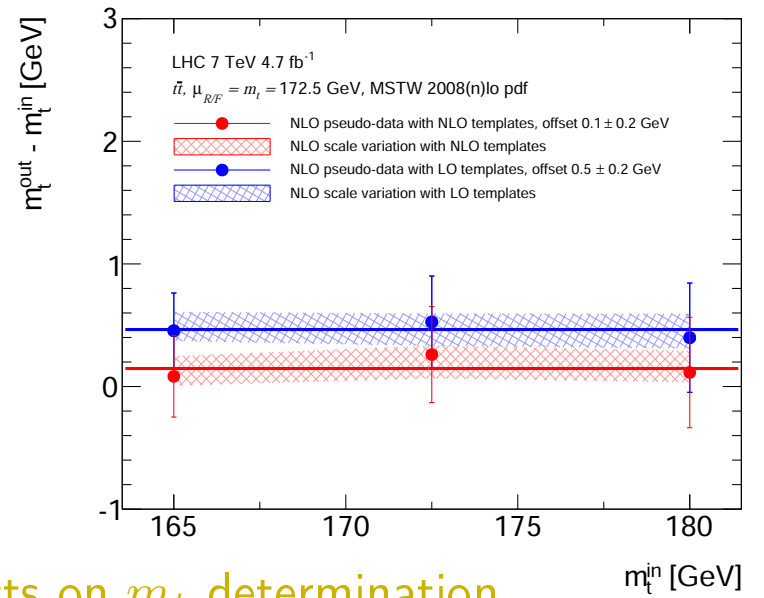
[Heinrich, Maier, Nisius, Schlenk, Winter, arXiv:1312.6659]

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].







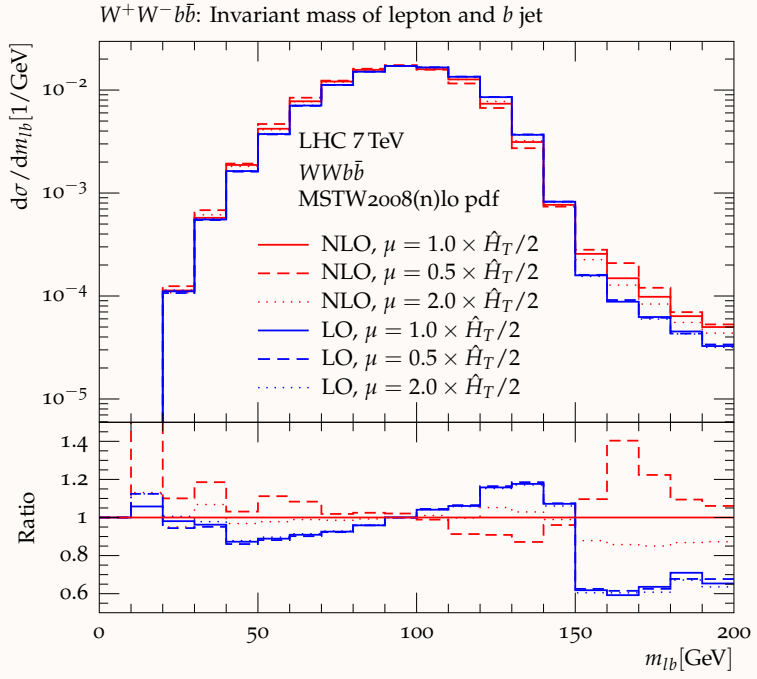
➡ Based on NLO $t\bar{t}$ + LO decays, only small effects on m_t determination.

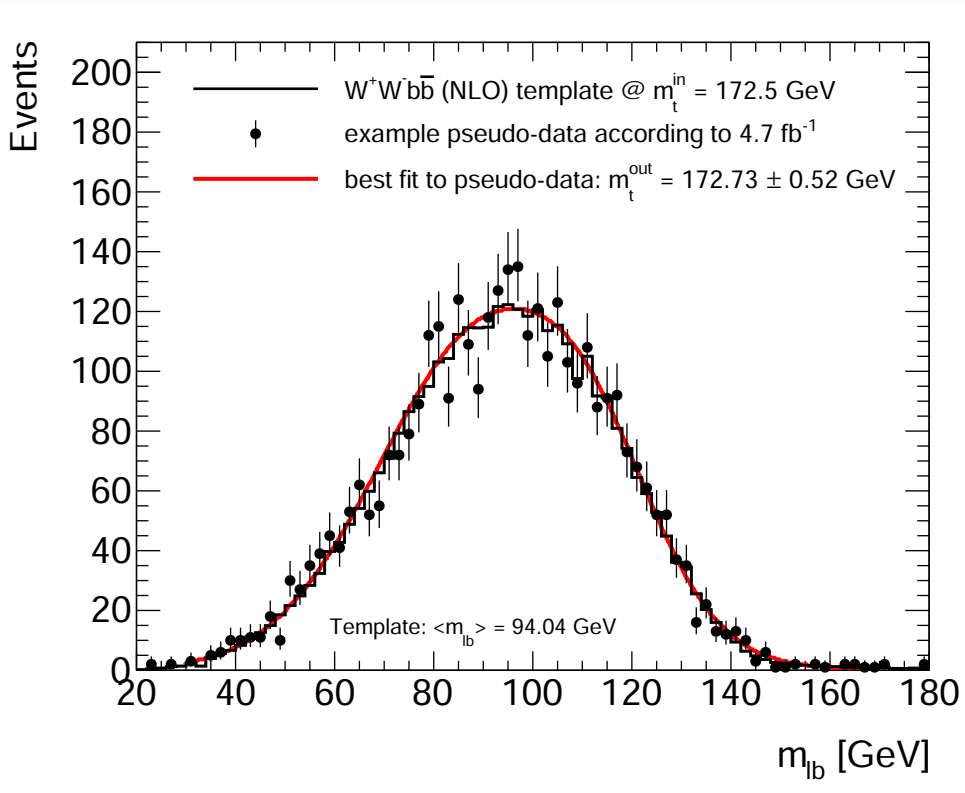
Scale uncertainties and the m_{lb} method

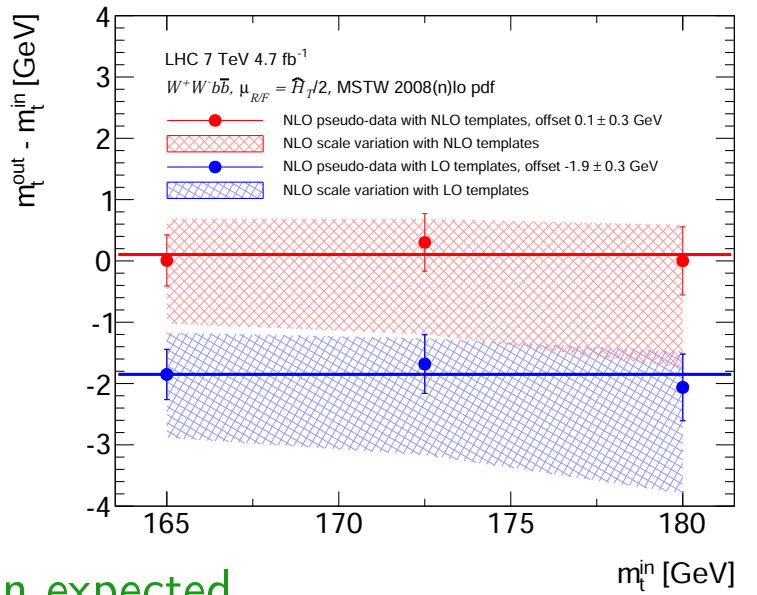
[Heinrich, Maier, Nisius, Schlenk, Winter, arXiv:1312.6659]

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 full QCD NLO prediction for dileptonic $W^+W^-b\bar{b}$ [pseudo-data].
- Apply/test against the theories given by default scale choice NLO and LO predictions (templates) [hypotheses].



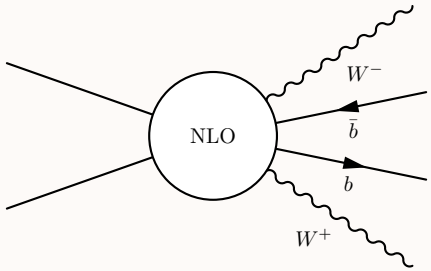


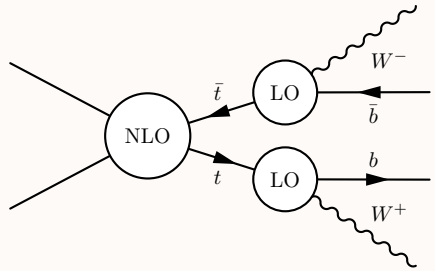


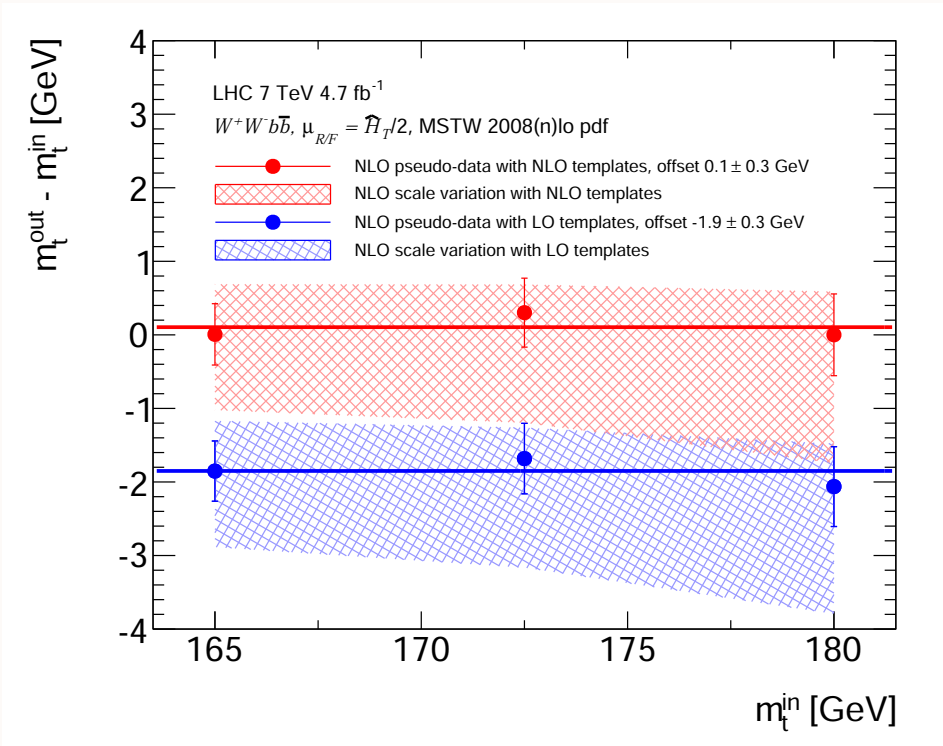
➡ Impacts top quark mass determination more than expected.

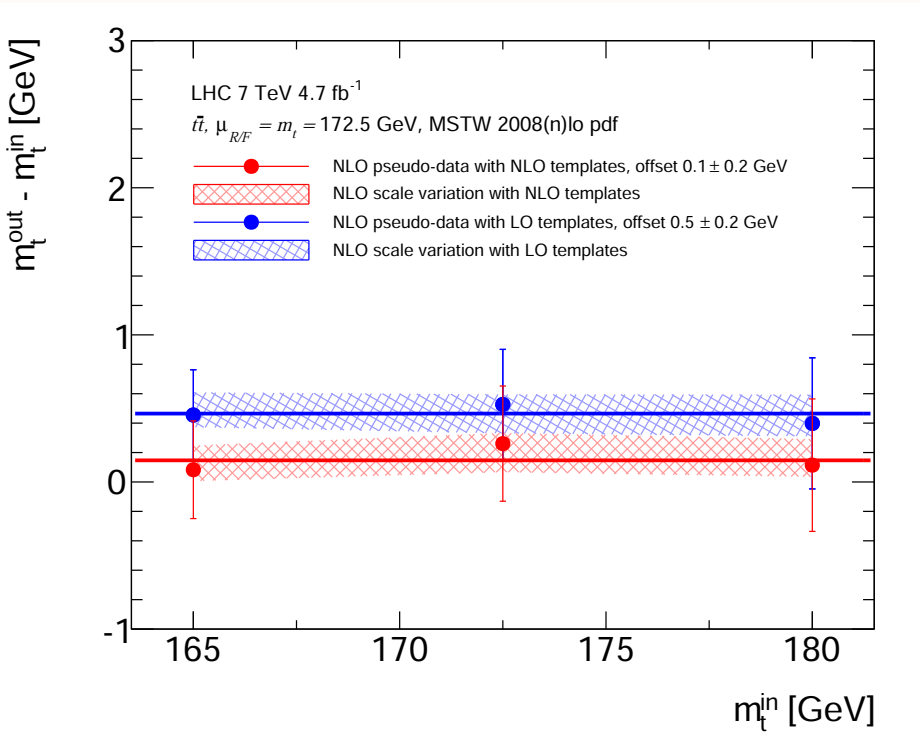
Summary

➡ ***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 $\pm 0.2\,\mathrm{GeV}$)

Summary.

Calculation of the NLO QCD corrections to WWbb̄ production using the parton level combined event generator GoSam+Sherpa.

NLO effects studied in the context of the top quark mass measurement based on the m_{lb} template method (well defined framework for our pure parton level analysis).

Shape uncertainties from scale variations of the full NLO QCD corrections to $WWb\bar{b}$ production result in larger theory errors on the top quark mass determination than expected.

Discussion, preliminary results & questions.

Validation ongoing to disentangle effects from radiative corrections in decay, non-resonant contributions and finite-width treatment (NLO in “decay” seems crucial).

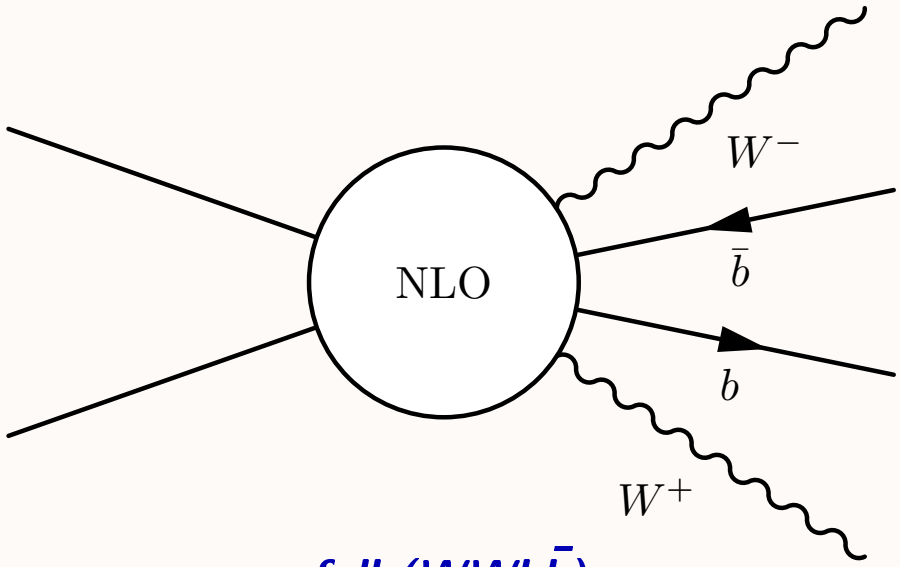
Parton shower and hadronization effects? Hadron-level predictions wanted.

Phase-space regions and/or observables less affected by scale uncertainties (or, on the contrary, where they dominate over m_t dependence to fix scale with data).

Using improved calculations, what are the effects on other top quark mass analyses?

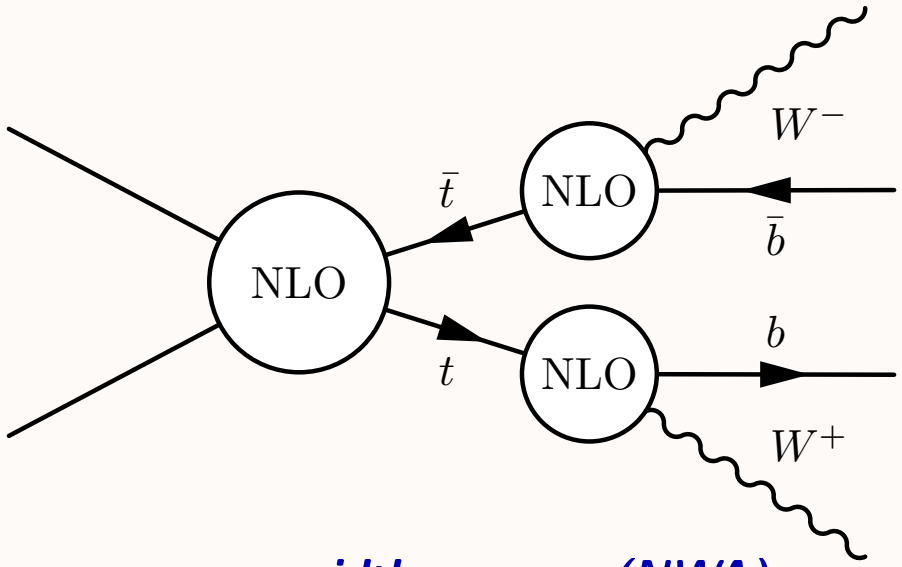
Radiation in the decay

[Biswas, Melnikov, Schulze, arXiv:1006.0910]



full ($WWb\bar{b}$)

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



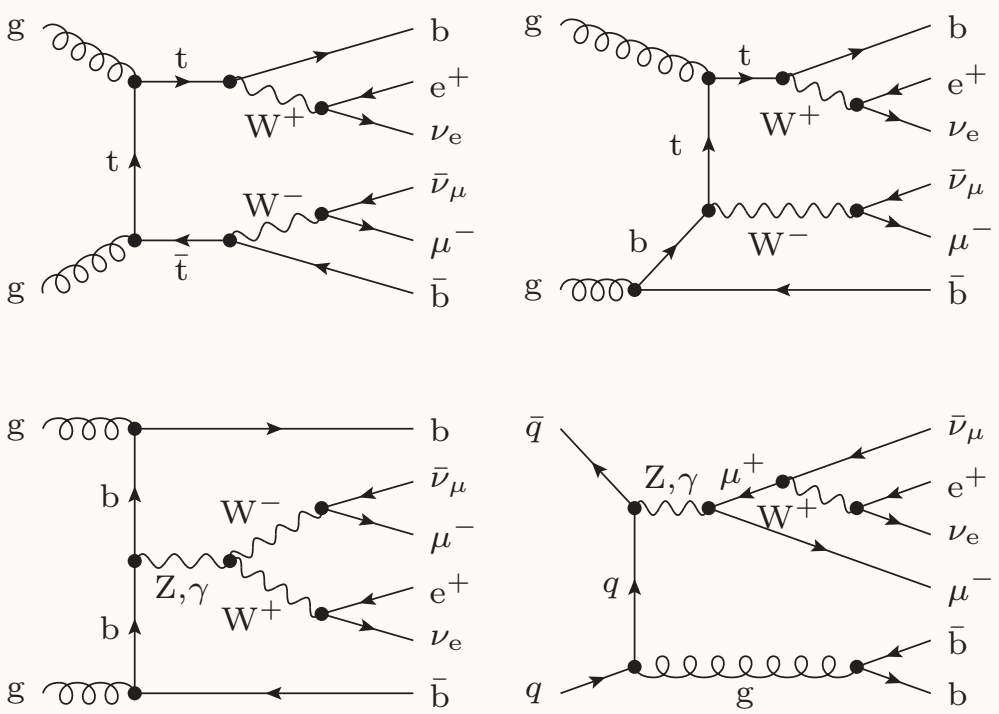
narrow width approx. (NWA)

- full NLO NWA treatment of $t\bar{t}$ production and top quark decays preserving spin correlations

- comparison will help disentangle effects from NLO decays and non-resonant contributions
- choose different scales in the production and decay ... becomes testable
- to what extent are radiative decay corrections well modelled by shower in NLO+PS (how do we assess the uncertainties related to these shower emissions)
- also in reference, an estimator related to m_t obtained from moment of $m_{lb} \to$ experimental alternative?

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

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



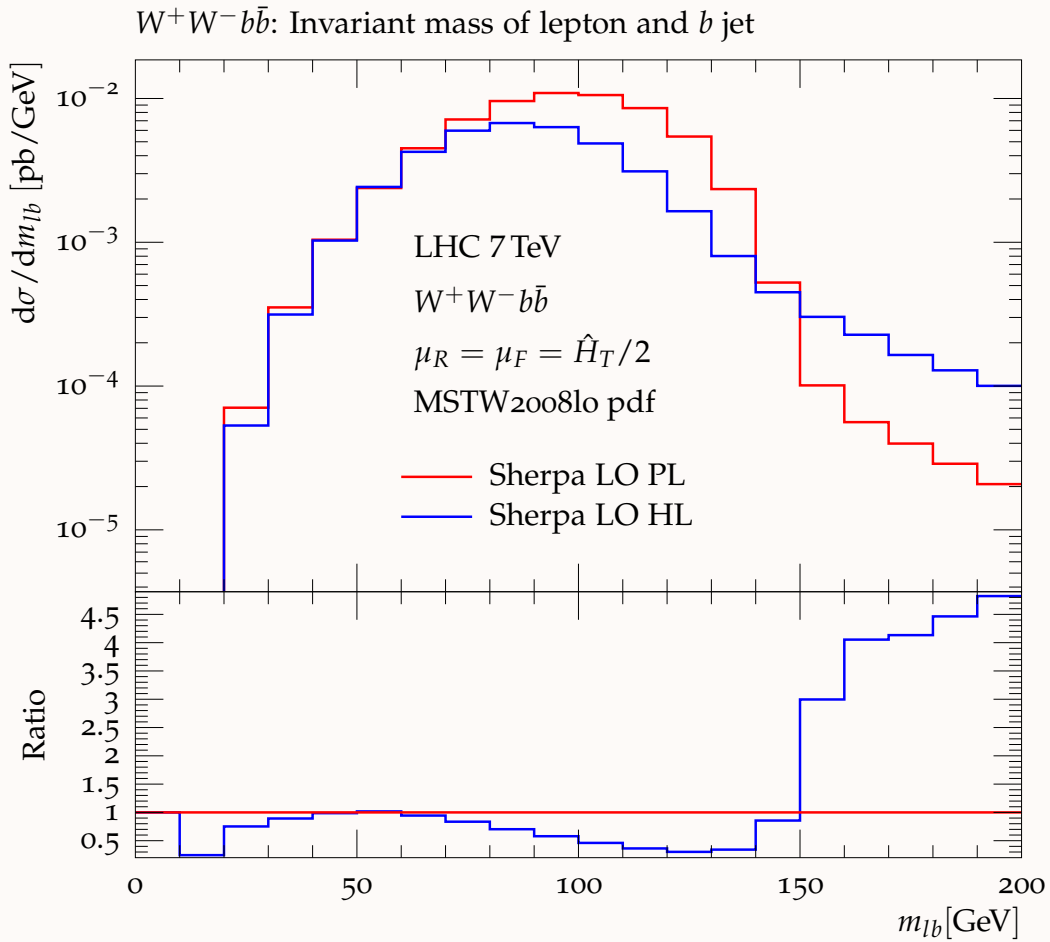
- full NLO treatment includes double-, single- and non-resonant contributions
- complex-mass scheme
- finite top-quark and W width effects
- first done in massless b-quark approximation
  [Denner et al. arXiv:1012.3975, arXiv:1207.5018]
  [Bevilacqua et al. arXiv:1012.4230]
- earlier done in NWA where production and decay factorize (neglected contributions are suppressed by powers of $\Gamma_t/m_t \lesssim 1\%$)
  [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 → permits application of jet vetoes
- → 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]

What to expect from showering and hadronization?

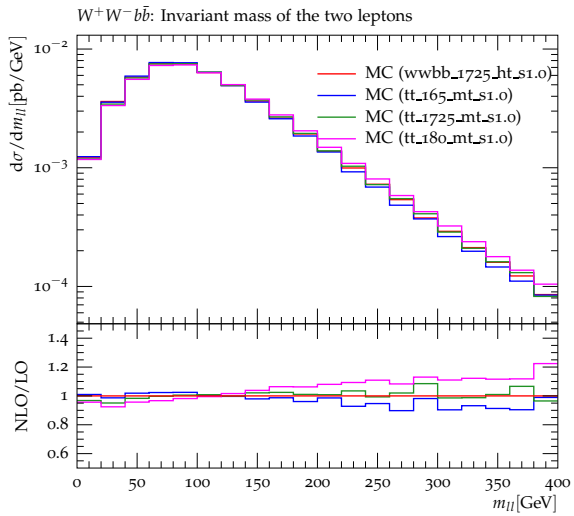
- only PRELIMINARY result
- transition region between peak and tail washed out



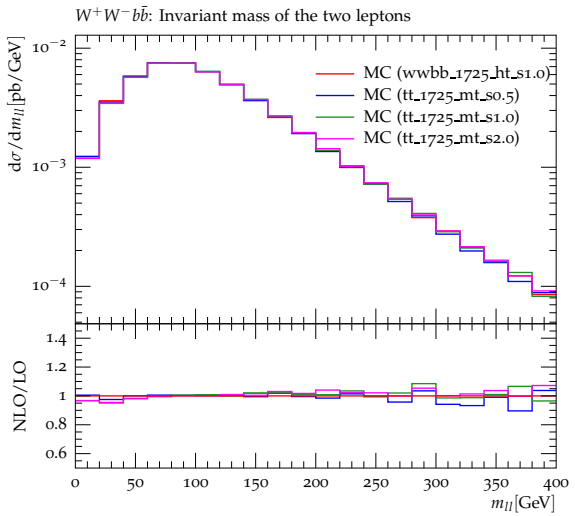
Other observables?

- less sensitive to m_t, but "cleaner" observable $\rightarrow$ better systematics?
- pay-off comes with more data ...

m_{ll}

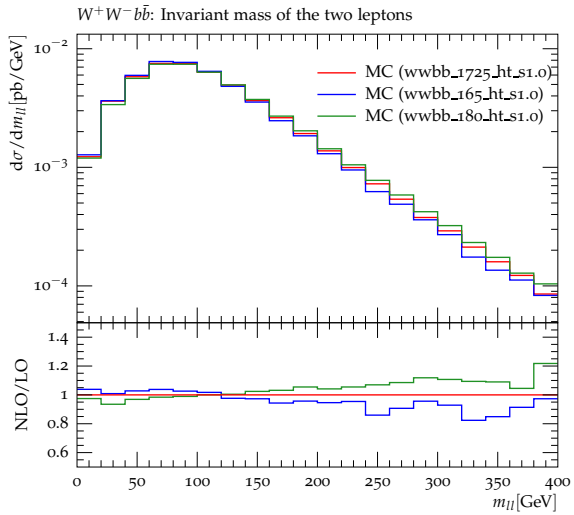


fact.

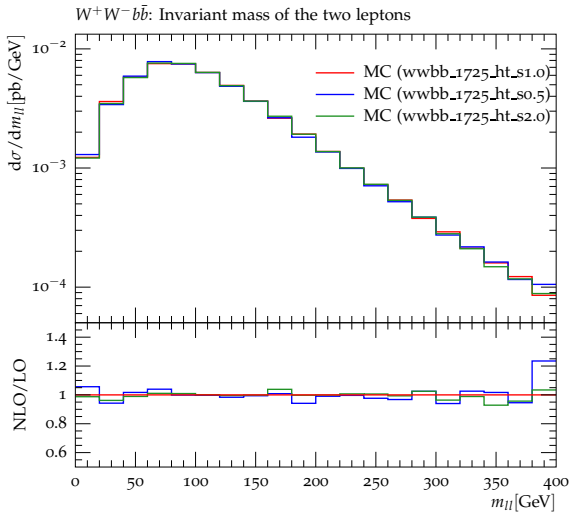


m_t variation

scale variation



full



The end.