$\mathrm{WbW\bar{b}}$ at NLO

"NLO QCD corrections to $\mathrm{WbW\bar{b}}$ production: new developments and new issues".

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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?

(see Frank Krauss' and Fabrizio Caola's talks given earlier today)

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

[TOP2014 – sunny Cannes Mandelieu]

Jan Winter

– MPP Munich, Germany –

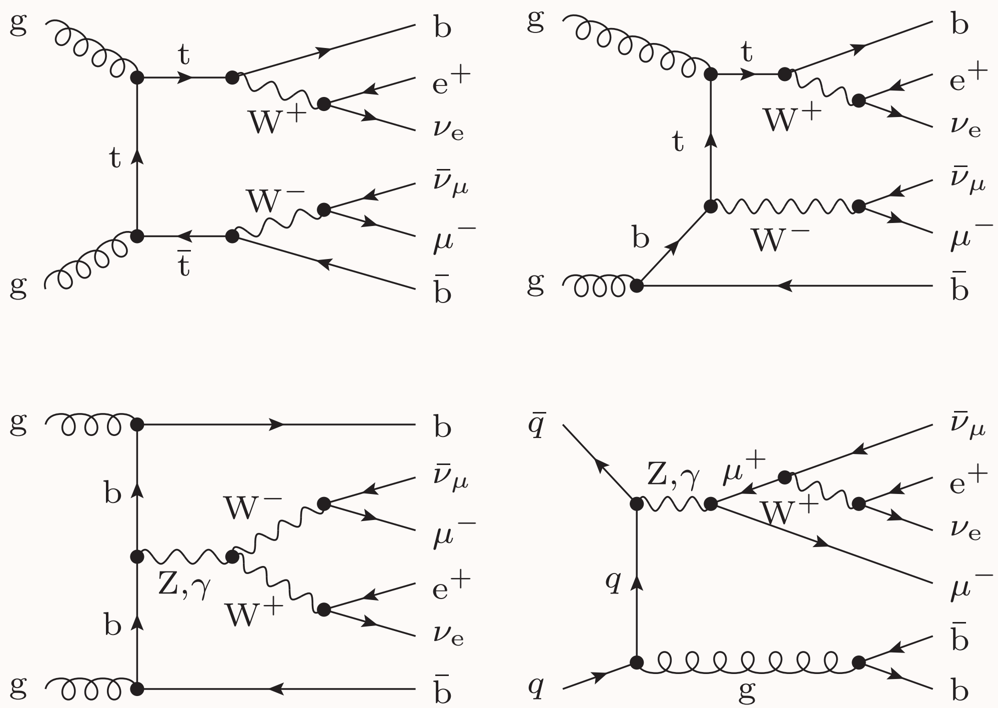
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

➡ *Discussion of several recent results.*

- *$WWb\bar{b}$ at NLO in QCD – general remarks.*
- *Finite b-quark masses – $WWb\bar{b}$ in the 4-flavour scheme.*
- *Predicting the M(lb) distribution and consequences.*
- *Summary & conclusions.*

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

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

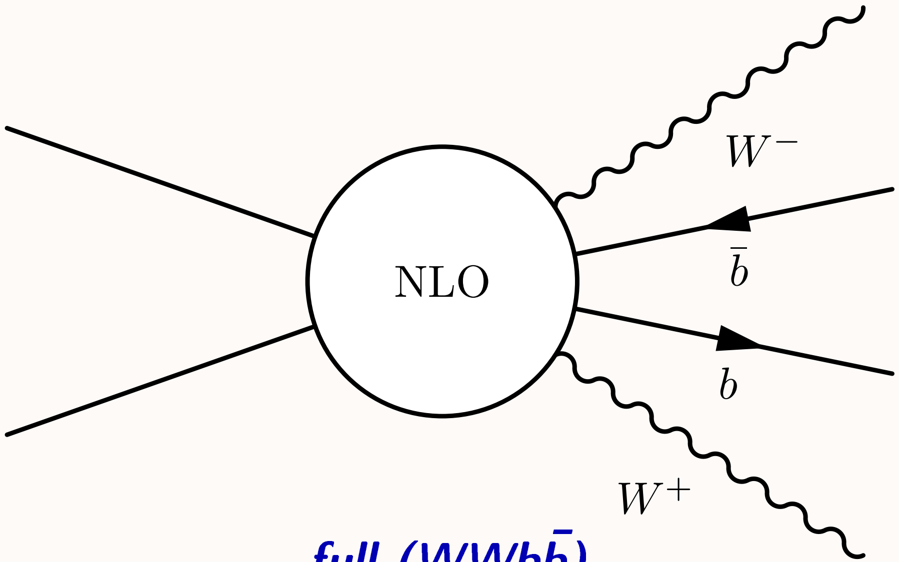


- full NLO treatment includes double-, single- and non-resonant contributions (DR – $t\bar{t}$-like) (SR – Wt-like) (NR – VV-like)
- complex-mass scheme
- finite top-quark and W width effects (offshell DR, SR, NR and interferences)
- first done in massless b-quark approximation
  (→ requires two hard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

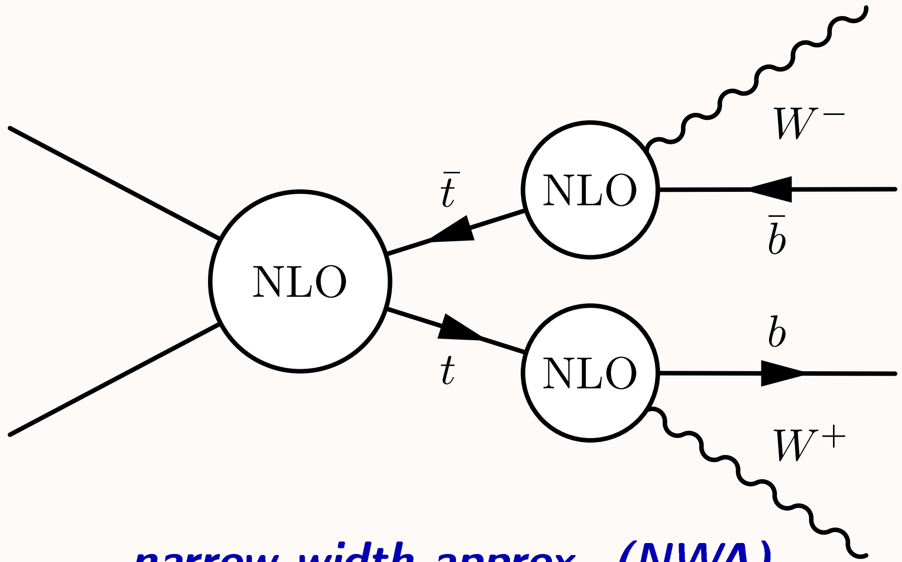
- earlier done in NWA ($\Gamma_t \to 0$ limit) where production and decay factorize (neglected contributions are suppressed by powers of $\Gamma_t/m_t \lesssim 1\%$)
  [Bernreuther, Brandenburg, Si, Uwer, arXiv:hep-ph/0403035]
  [Melnikov, Schulze, arXiv:0907.3090]

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

Full calculation versus NWA



full ($WWb\bar{b}$)



narrow width approx. (NWA)

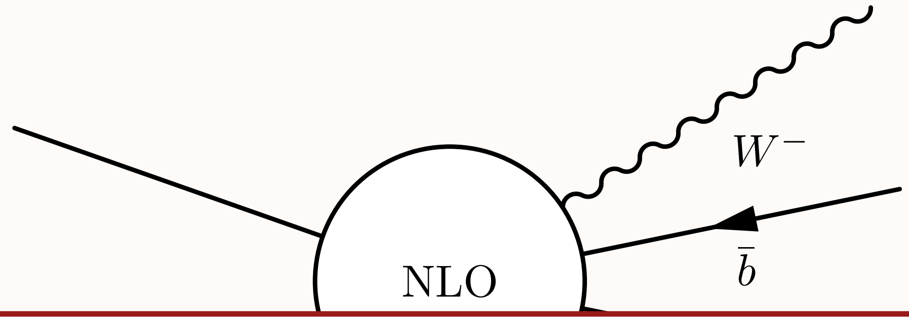
- full NLO description of the $WWb\bar{b}$ final state ($2 \to 4$ processes)
- non-resonant/-factorizing contributions (quantum interferences)
- NLO effects in top quark decays

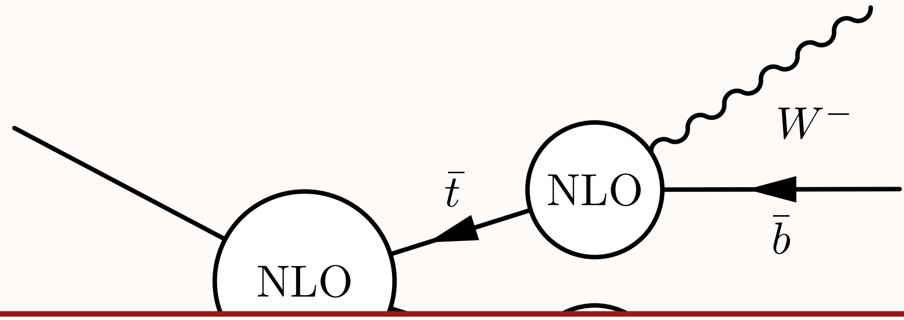
- full NLO NWA treatment of $t\bar{t}$ production and top quark decays preserving spin correlations (Factorization: Prod $\otimes$ Dec)
- only DR contributions survive in $\Gamma_t \to 0$ limit (onshell tops)
- NLO effects in top quark decays

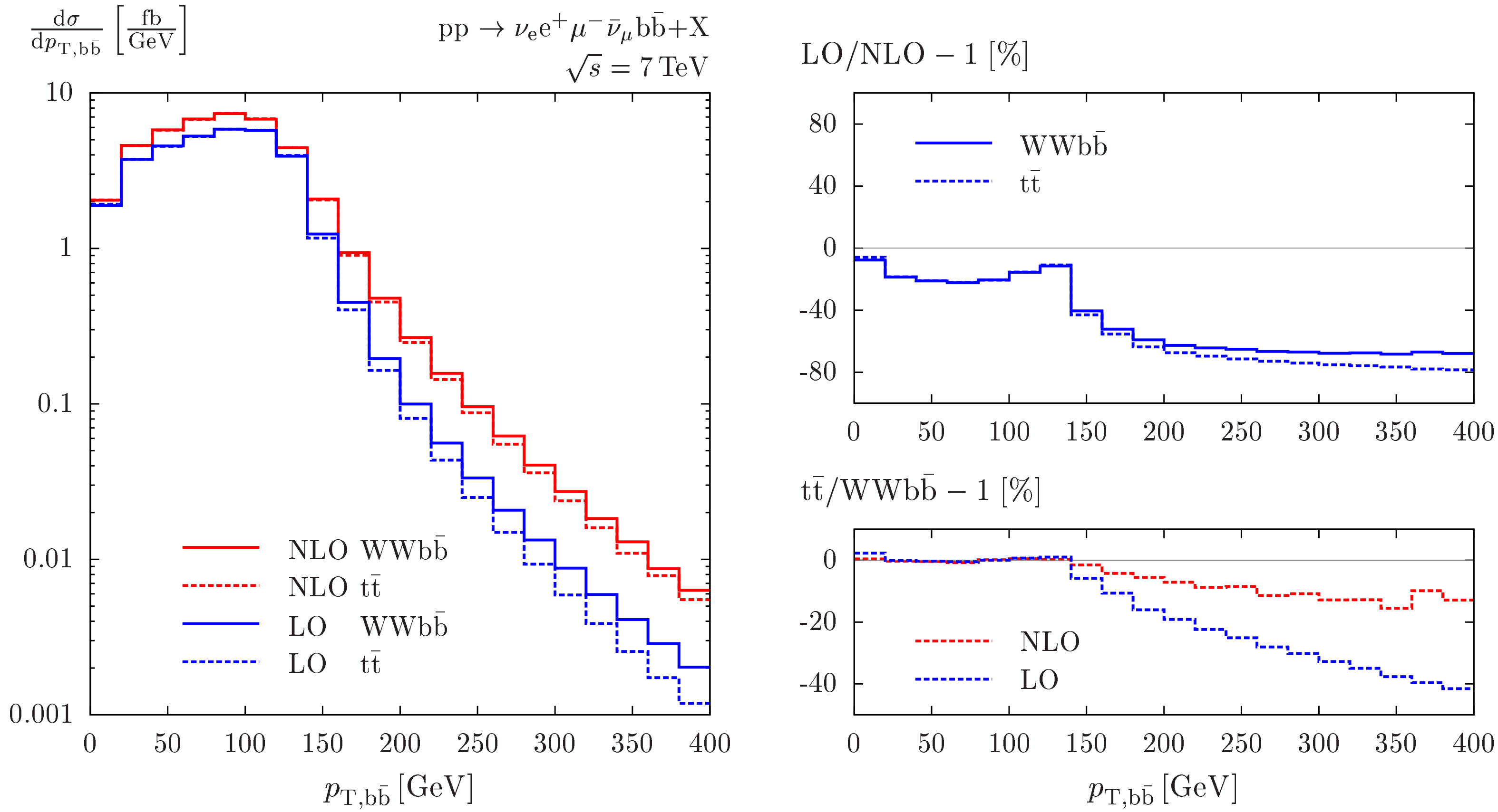
- Comparison between both calculations (in the $\ell\ell$ channel) to investigate finite top-quark width effects.
  - No more than 1% deviations for inclusive cross sections (with experimental cuts).
  - Effects can be (significantly) larger in differential distributions.

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

Full calculation versus NWA







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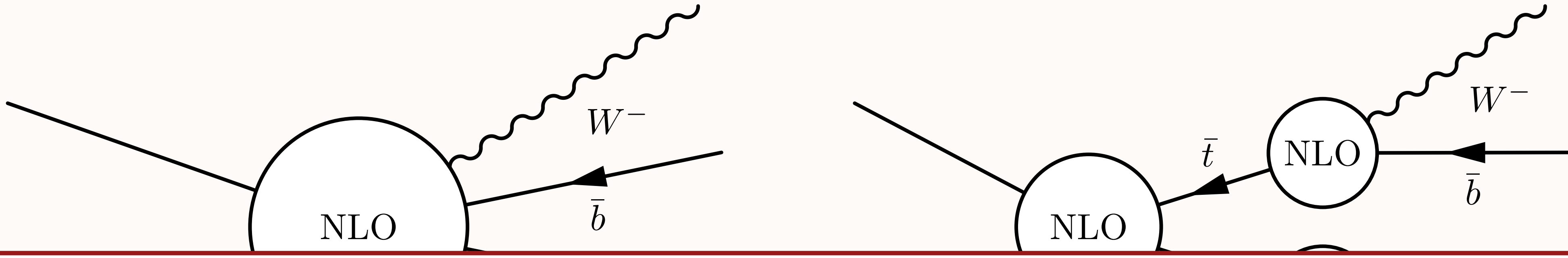
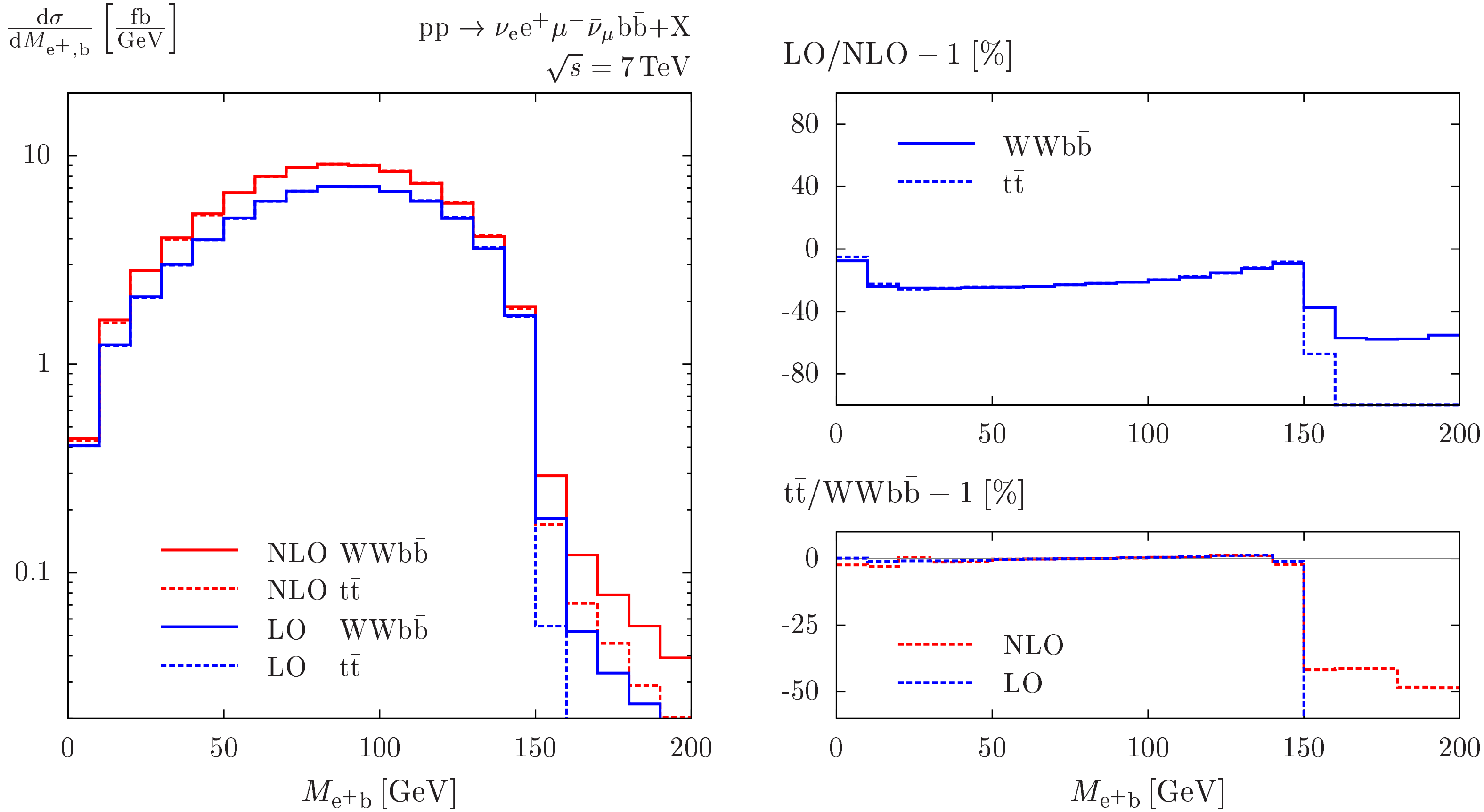
Full calculation versus NWA





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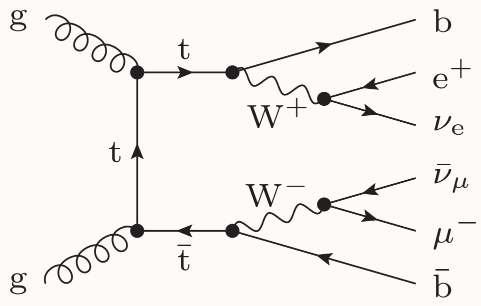
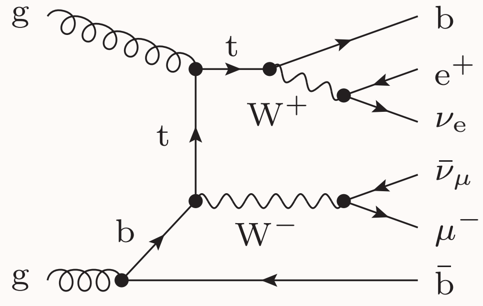
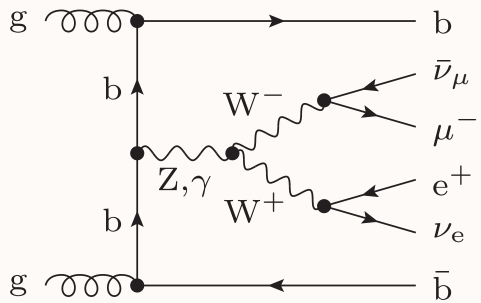
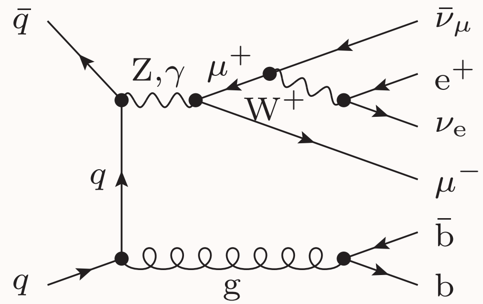
$WWb\bar{b}$ production at NLO: massive b-quarks

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









- full NLO treatment includes double-, single- and non-resonant contributions
- complex-mass scheme
- finite top-quark and W width effects
- first done in massless b-quark approximation
  [Denner et al. arXiv:1012.3975, arXiv:1207.5018]
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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 $\rightarrow$ permits application of jet vetoes
- $\rightarrow$ gauge-invariant separation of narrow-top-width contribution and finite-width remainder

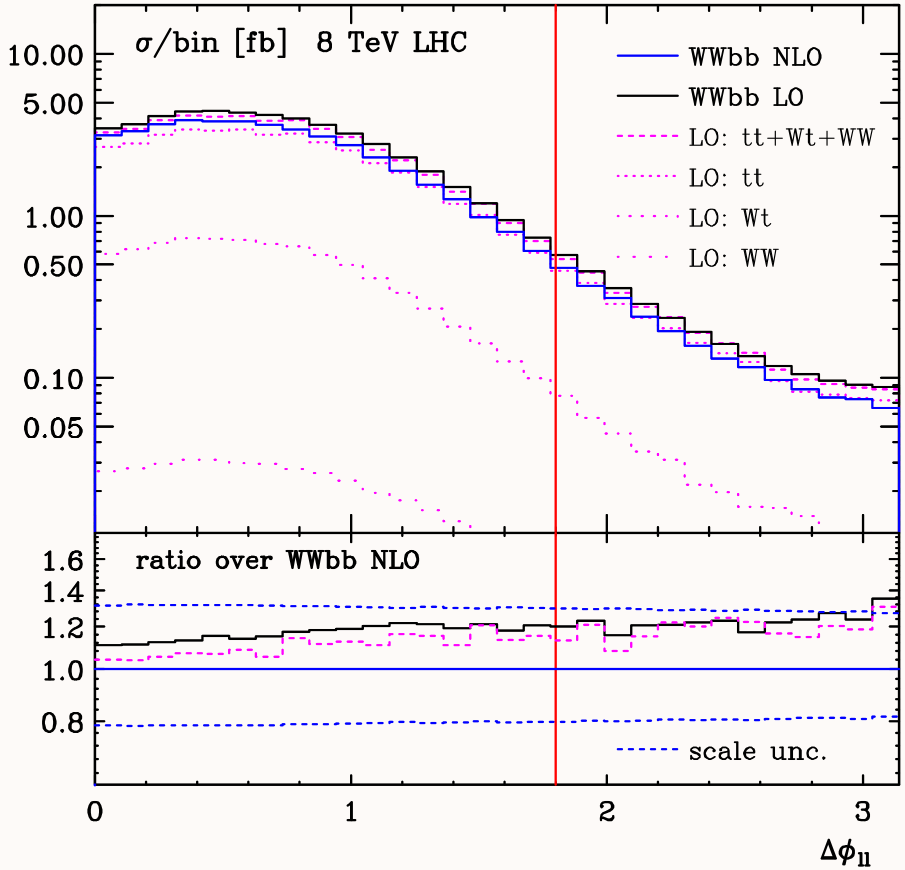
- results provided recently by two groups:

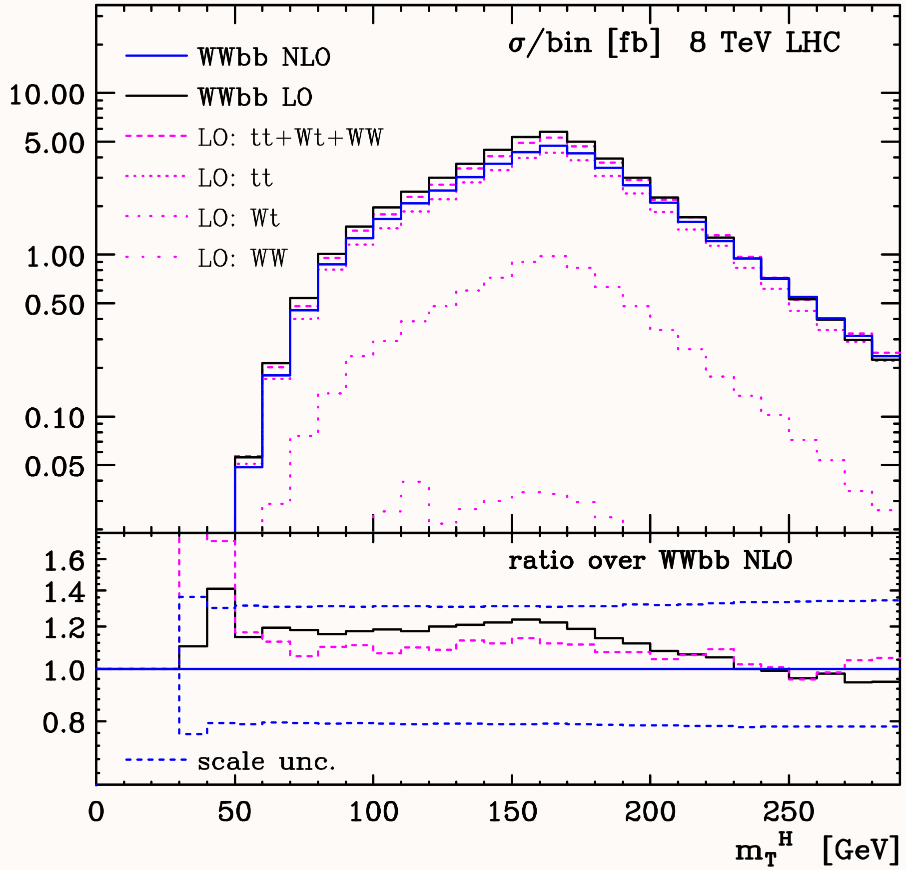
  [Frederix, arXiv:1311.4893] [Cascioli, Kallweit, Maierhöfer, Pozzorini, arXiv:1312.0546]

$WWb\bar{b}$ 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 $|\Delta\phi_{ll}| < 1.8$

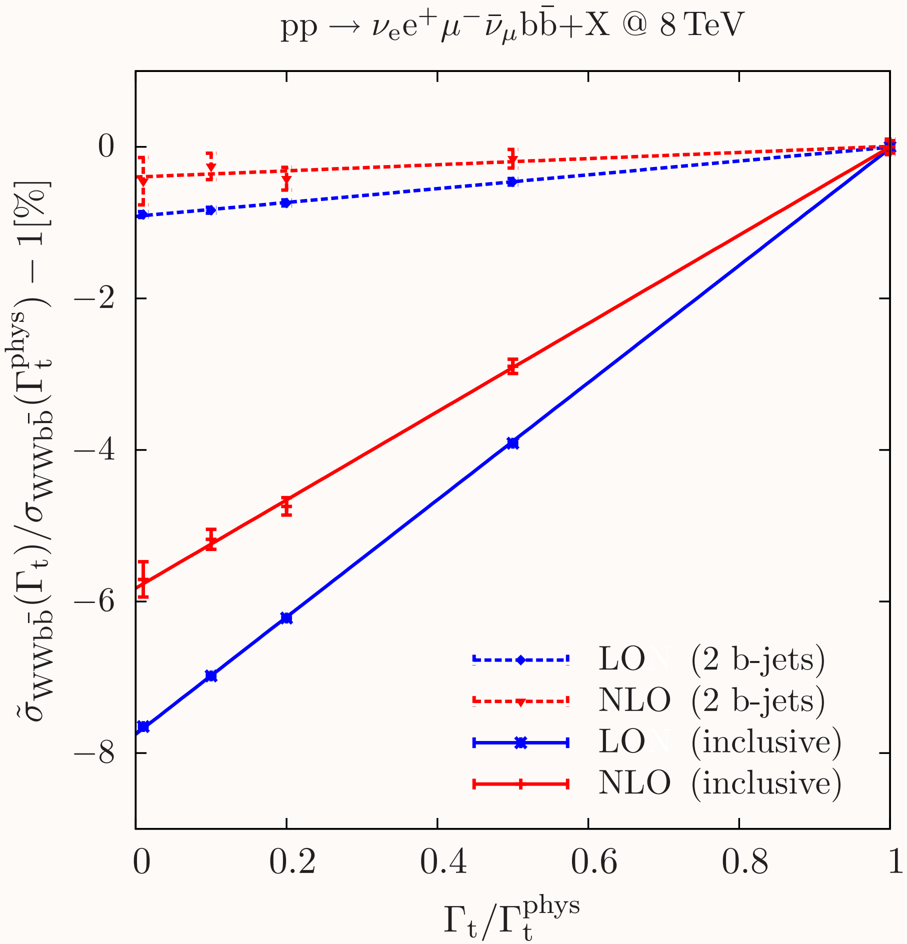
$WWb\bar{b}$ production at NLO

➡ ***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

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

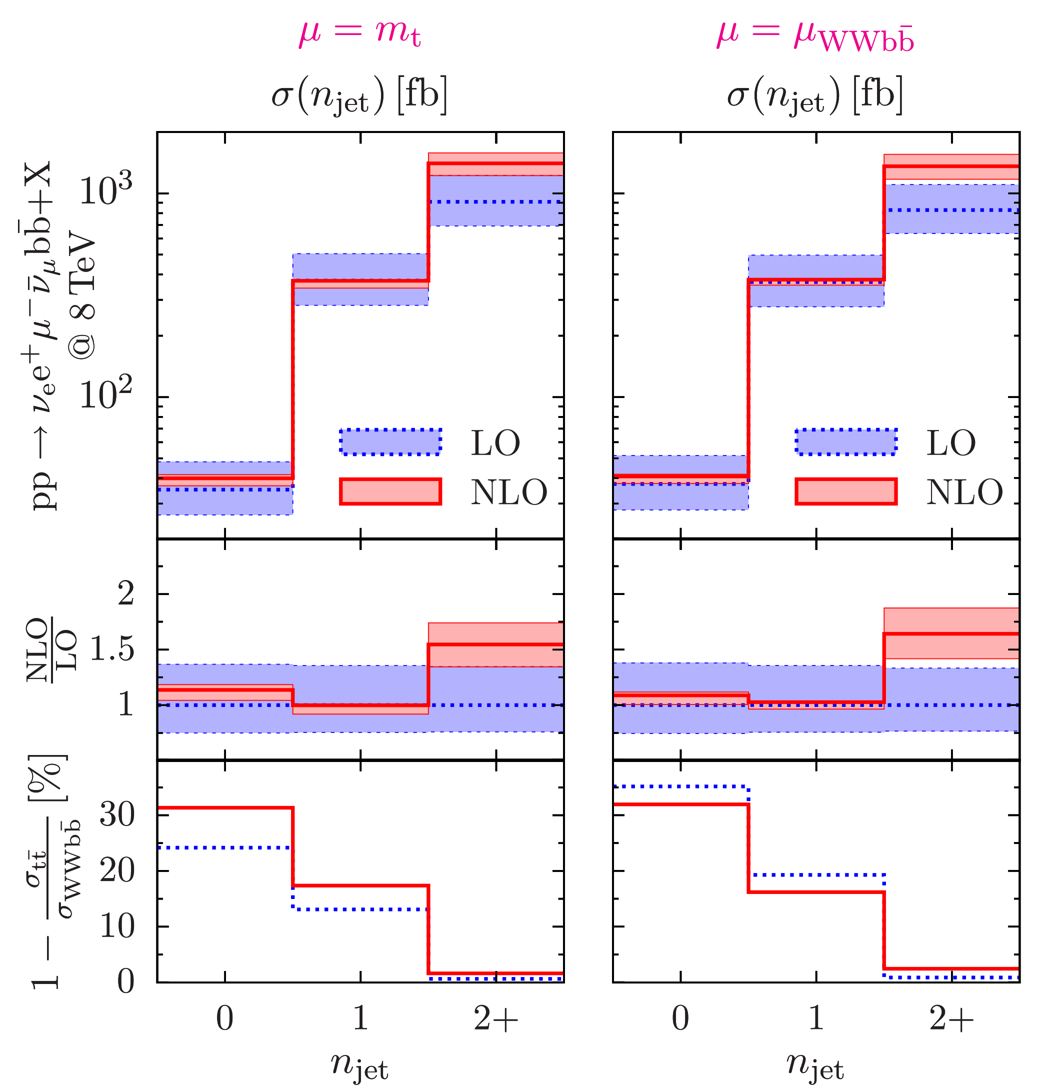


- numerical extrapolation to $\Gamma_t \to 0$: Wt contribution dominates finite top-quark width remainder

$WWb\bar{b}$ production at NLO

➡ ***OpenLoops + Collier + New in-house NLO MC framework.*** [CASCIOLI ET AL. ARXIV:1312.0546] [KALLWEIT]

- Controlling the $t\bar{t}$ background in WW – NLO and finite top quark width effects in jet bins
- dynamical scale interpolating between $t\bar{t}$ ($\mu^2_{t\bar{t}} = E_{T,t}E_{T,\bar{t}}$) and single-$t$ ($\mu^2_{tW^-} = E_{T,t}E_{T,\bar{b}}$)



- very interesting application of finite b-mass calculation
- the 40% inclusive NLO correction is driven by the large two-jet bin correction
- strongly enhanced finite top quark width effects in zero- and one-jet bins

$WWb\bar{b}$ production at NLO

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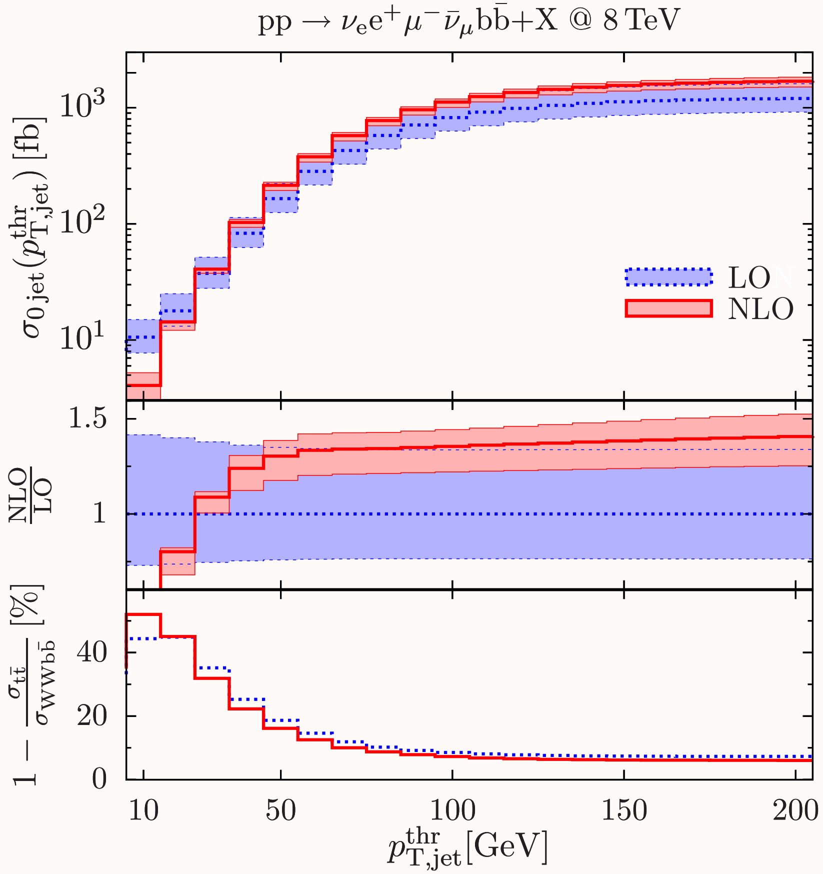
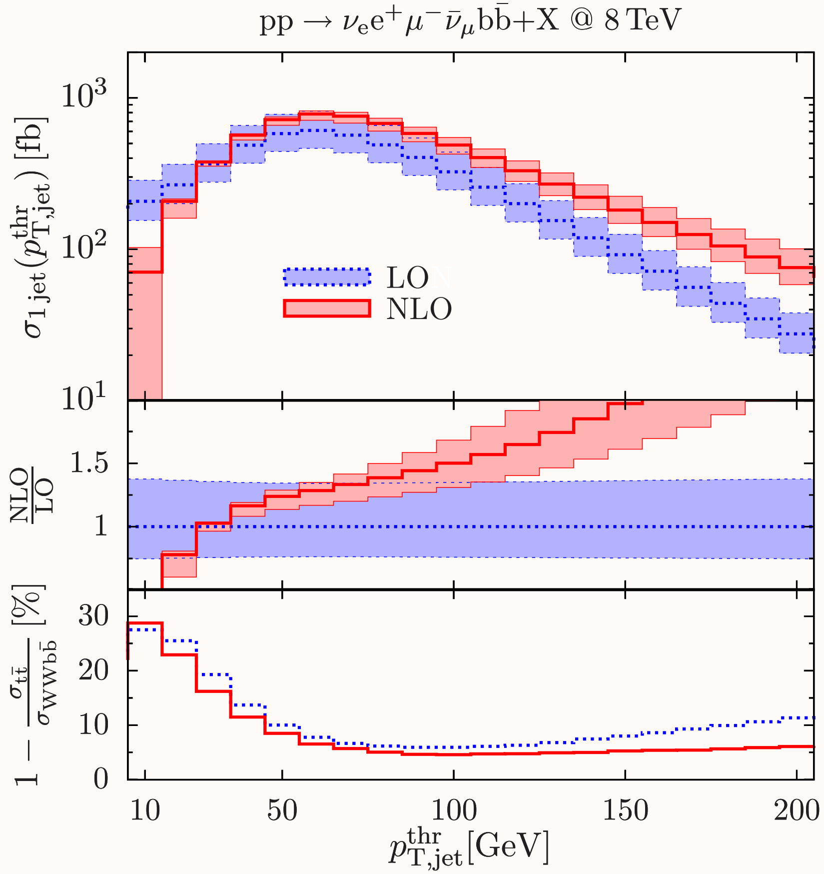
- xsec scale uncertainties of $10-15\%$ (similar for $\mu_0 = m_t$), 6% due to finite-t-width corrections





- cross section in exclusive zero- and one-jet bins as a function of jet p_T threshold

$WWb\bar{b}$ production at NLO

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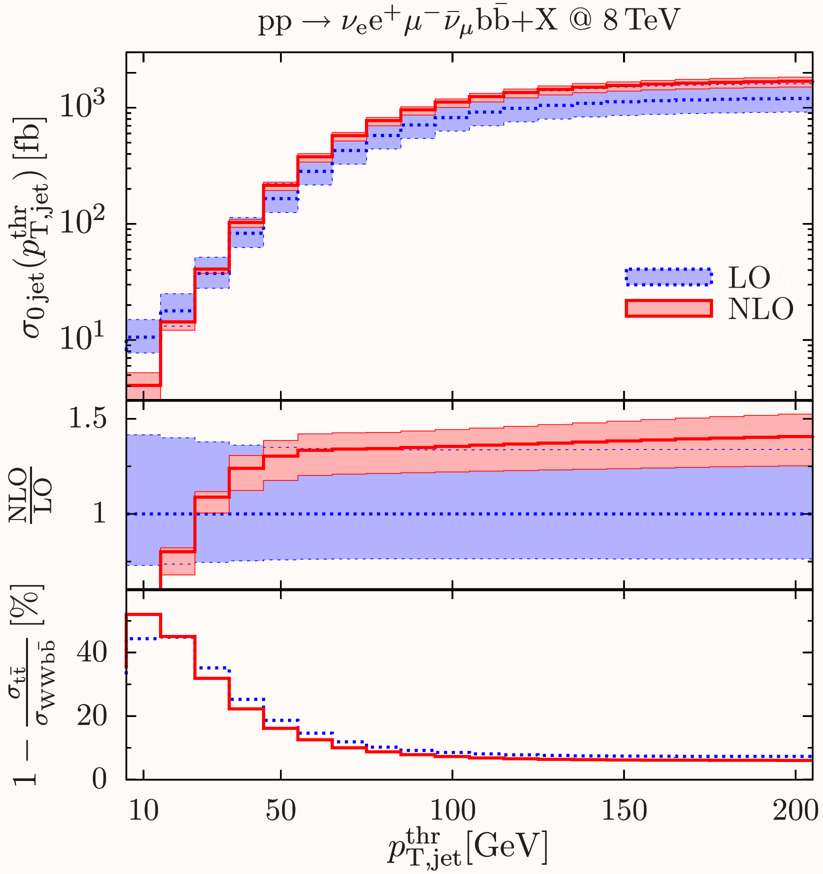
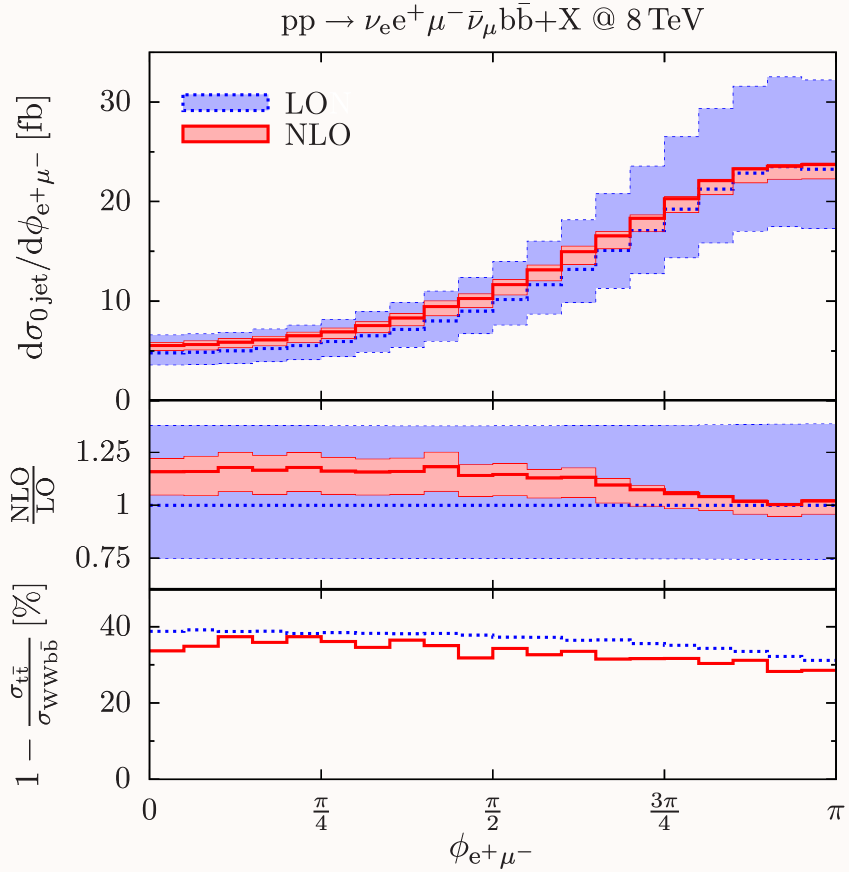




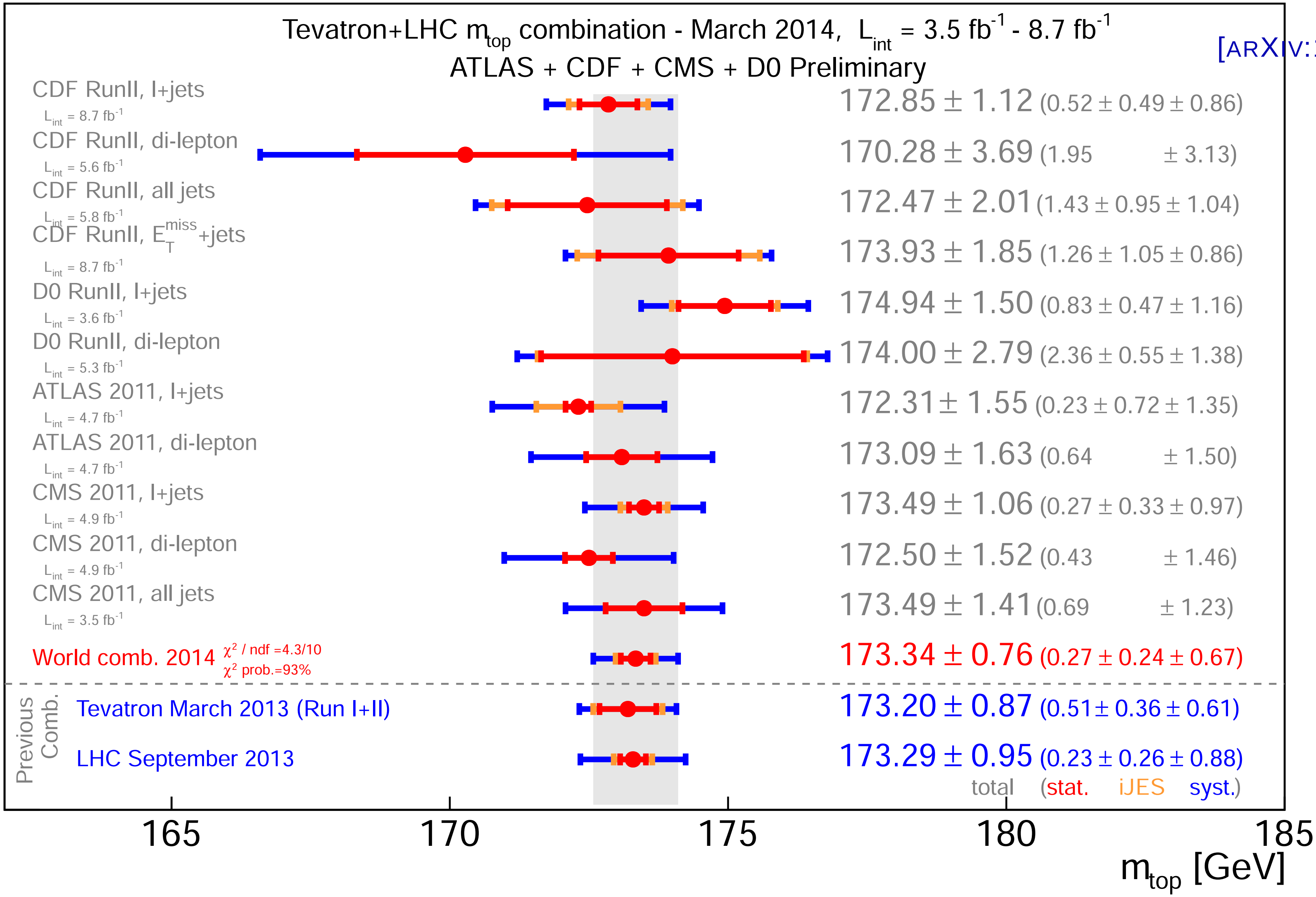
- cross section in exclusive zero- and one-jet bins as a function of jet p_T threshold
- (right) azimuthal angle between leptons (0-jet), finite-t-width effects increase with harsher vetoes

Top quark mass measurements

- first LHC+Tevatron result; total uncertainty on top quark mass < 1 GeV for combinations.

Rich and active experimental program (various complementary techniques).

[ARXIV:1403.4427]



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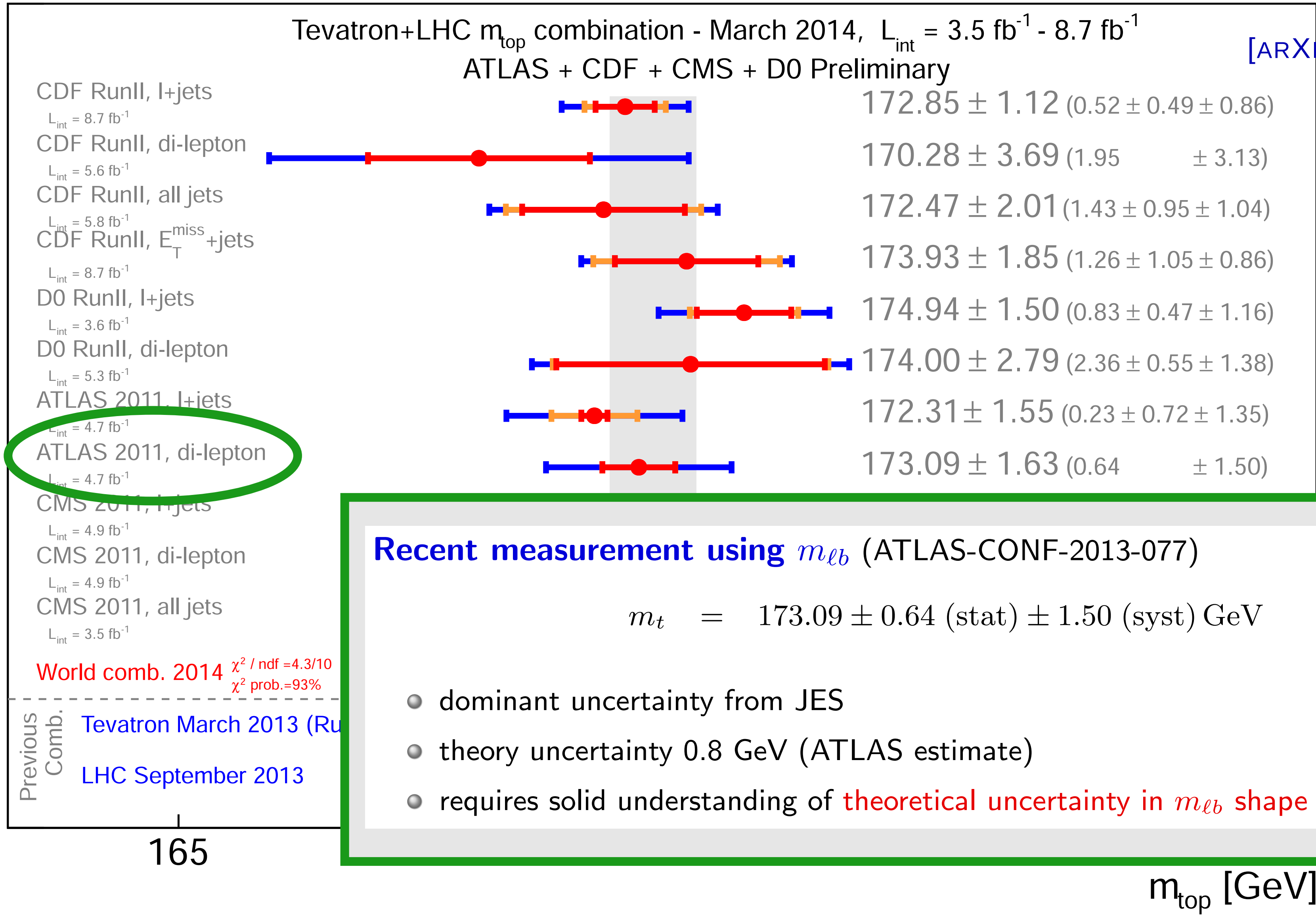


Recent measurement using $m_{\ell b}$ (ATLAS-CONF-2013-077)

$$m_t \quad = \quad 173.09 \pm 0.64\ (\mathrm{stat}) \pm 1.50\ (\mathrm{syst})\ \mathrm{GeV}$$

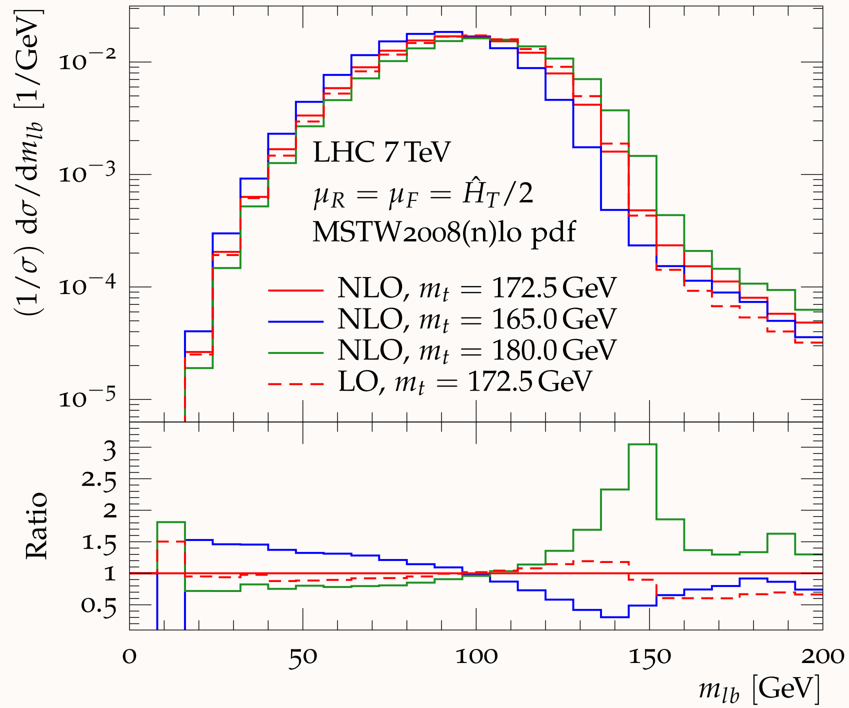
- dominant uncertainty from JES
- theory uncertainty 0.8 GeV (ATLAS estimate)
- requires solid understanding of theoretical uncertainty in $m_{\ell b}$ shape

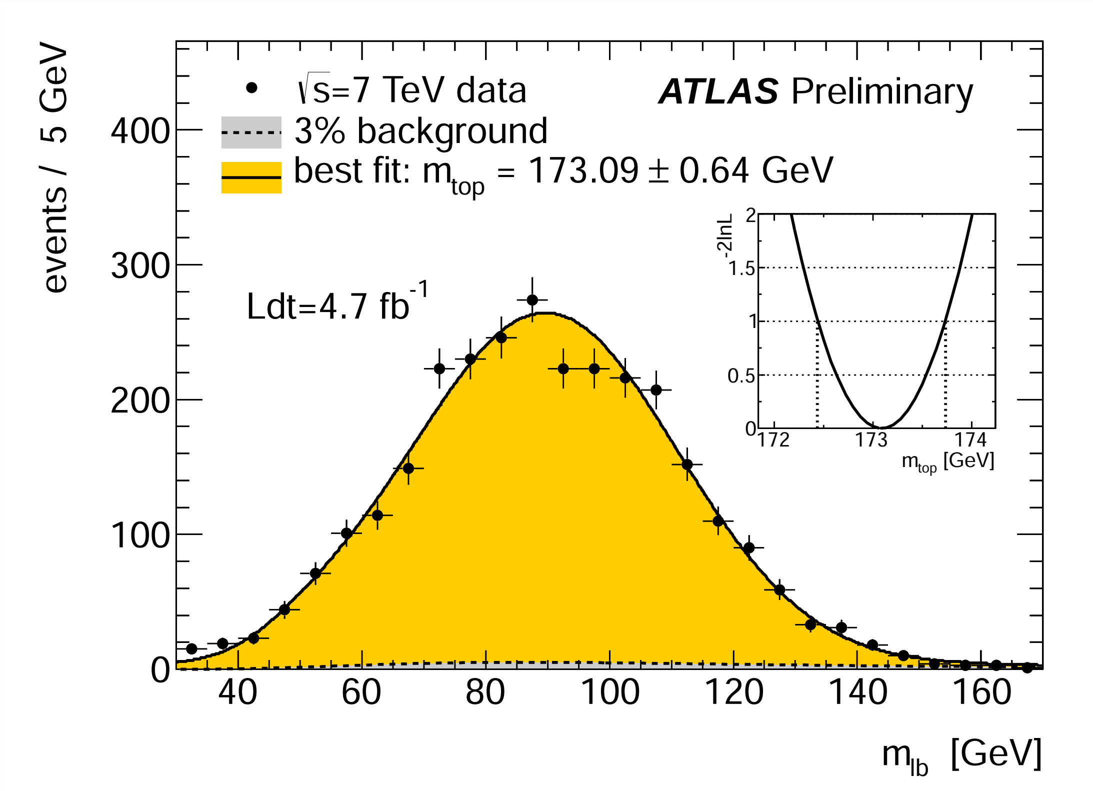
Top quark mass determination using the m_{lb} method

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

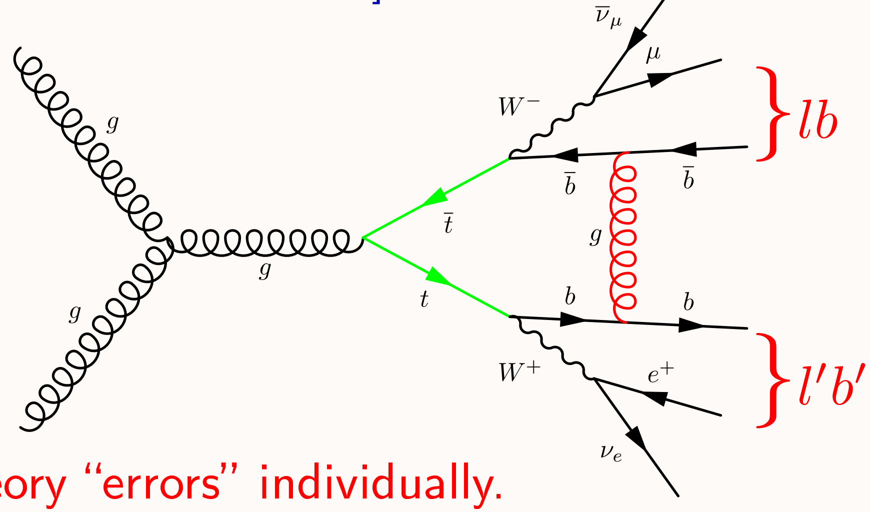
- Full QCD NLO prediction for $W^+W^-b\bar{b}$ in dilepton channel: m_{lb} distribution is sensitive to top quark mass.
- ATLAS uses one-dim. template method to determine m_t. Theory uncertainty has been estimated to 0.8 GeV.

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



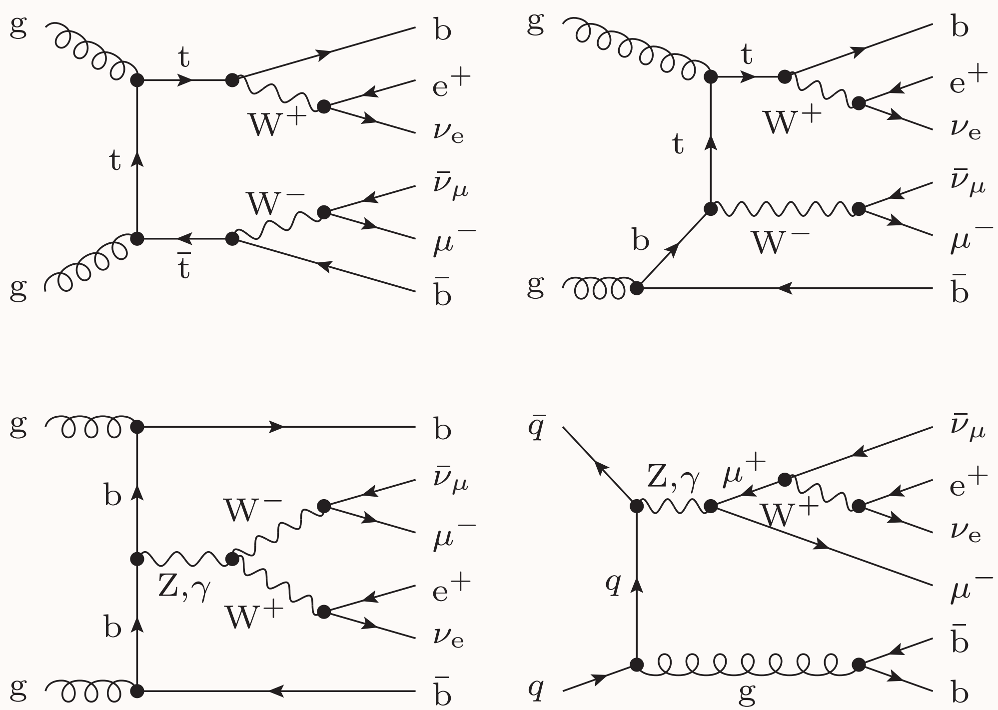


[ATLAS-CONF-2013-077]



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

$WWb\bar{b}$ production at NLO



- 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 $\Gamma_t/m_t \lesssim 1\%$)

  [Bernreuther et al. arXiv:hep-ph/0403035]

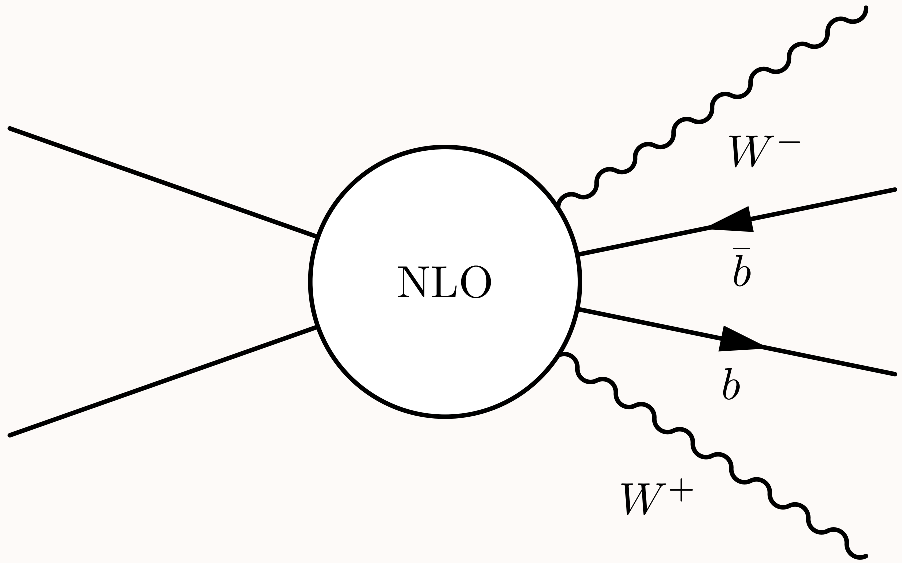
  [Melnikov, Schulze, arXiv:0907.3090]

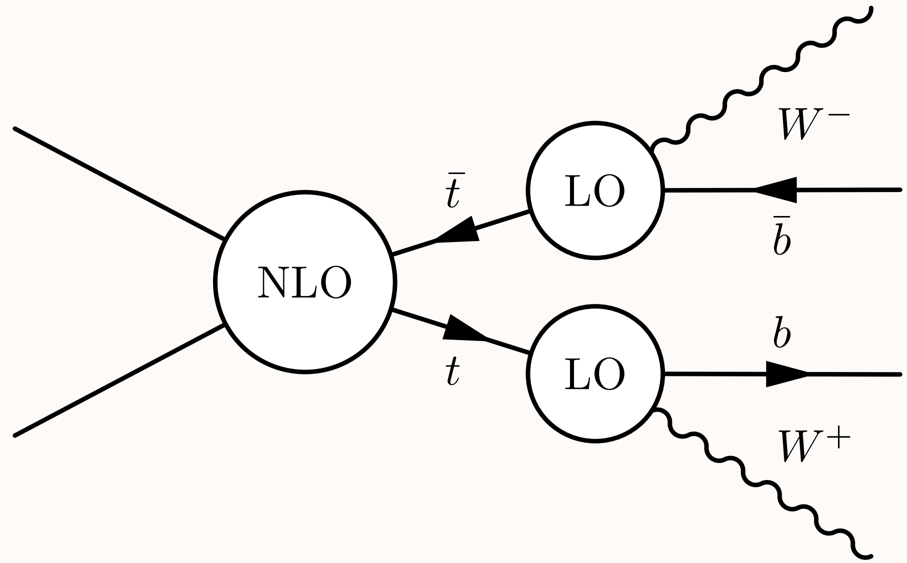
➡ ***Our parton level calculations ...***

- 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 ($2 \longrightarrow 4$ processes)
- accounts for non-resonant/non-factorizing contributions, includes NLO effects in top quark decays

factorized ($t\bar{t}$)

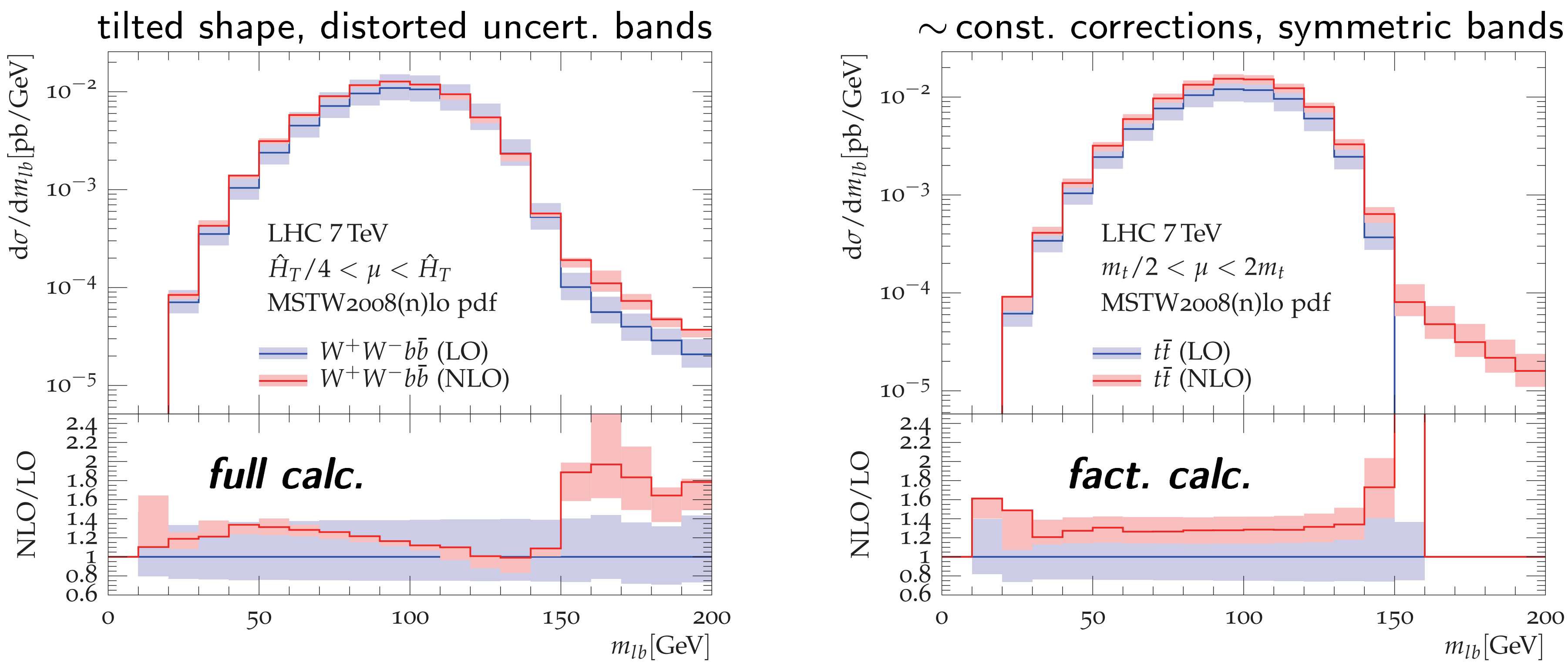
- NLO $t\bar{t}$ production ($2 \longrightarrow 2$ processes) with LO decays attached and spin correlations preserved
- standard description for the NLO core in NLO+PS matching

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

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

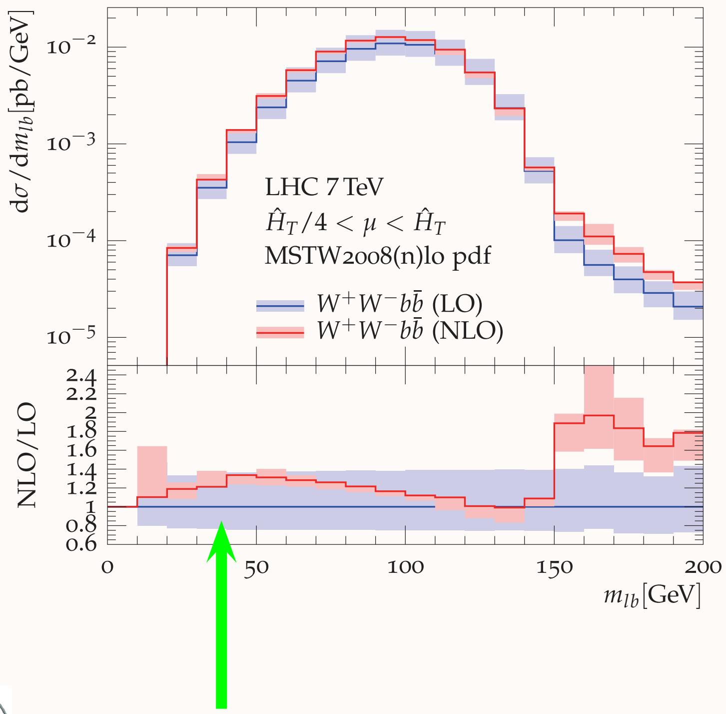
• follow ATLAS strategy: use charged-lepton b-jet pairing minimizing sum of both m_{lb} and average.

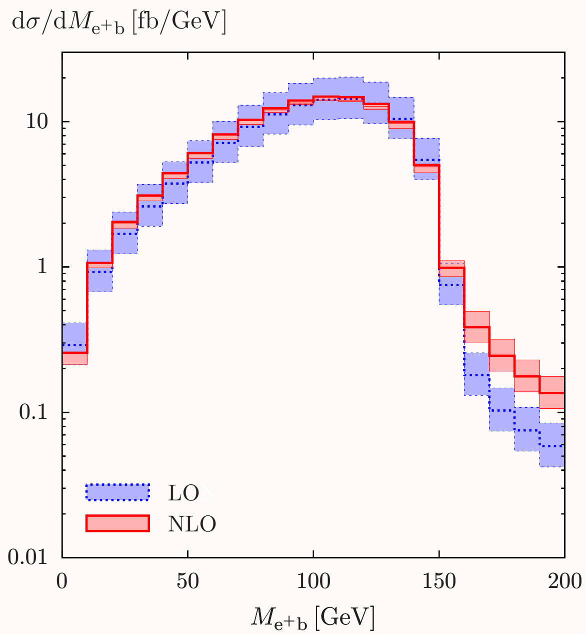
Qualitative comparison of m_{lb} predictions

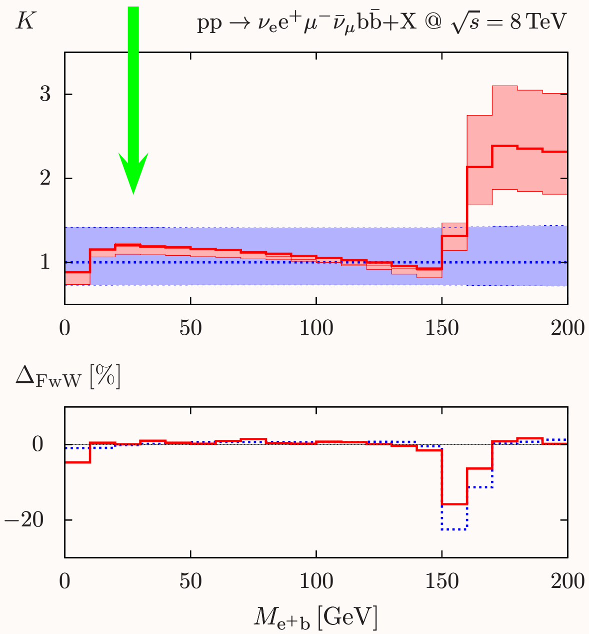
[DENNER, DITTMAIER, KALLWEIT, POZZORINI, ARXIV:1207.5018]

➡ ***$WWb\bar{b}$: 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 ....

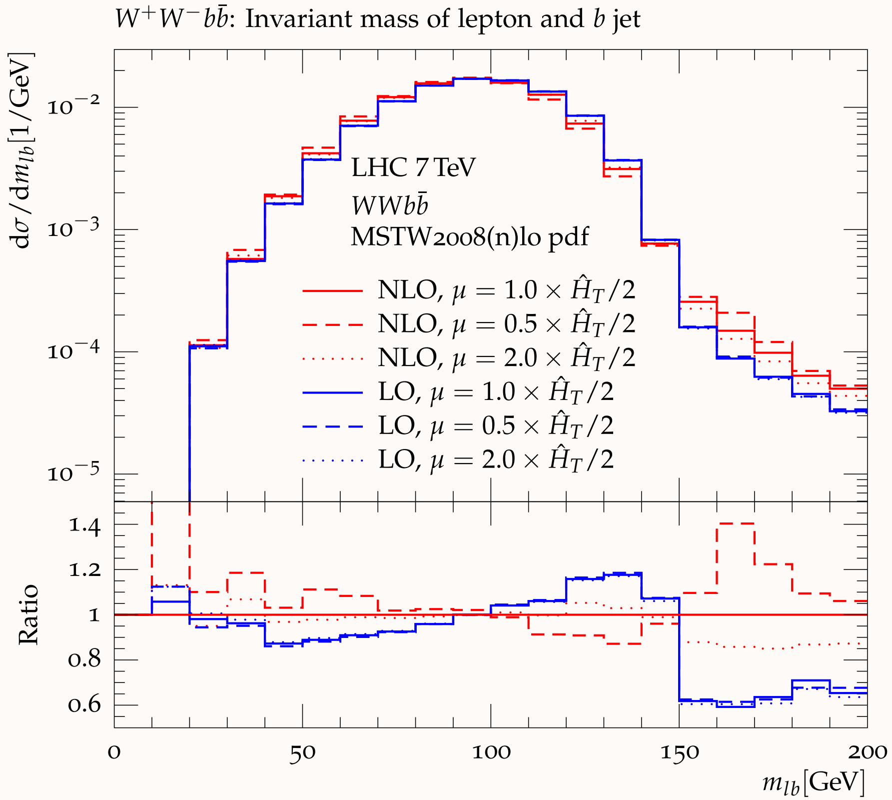


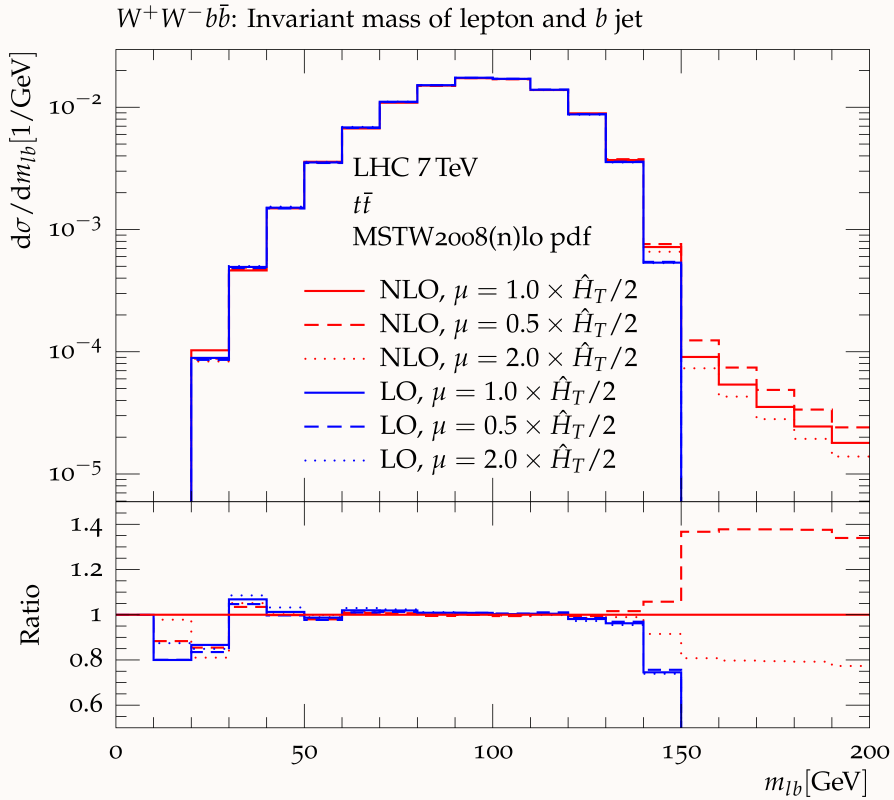




Normalized m_{lb}: scale versus m_t variation

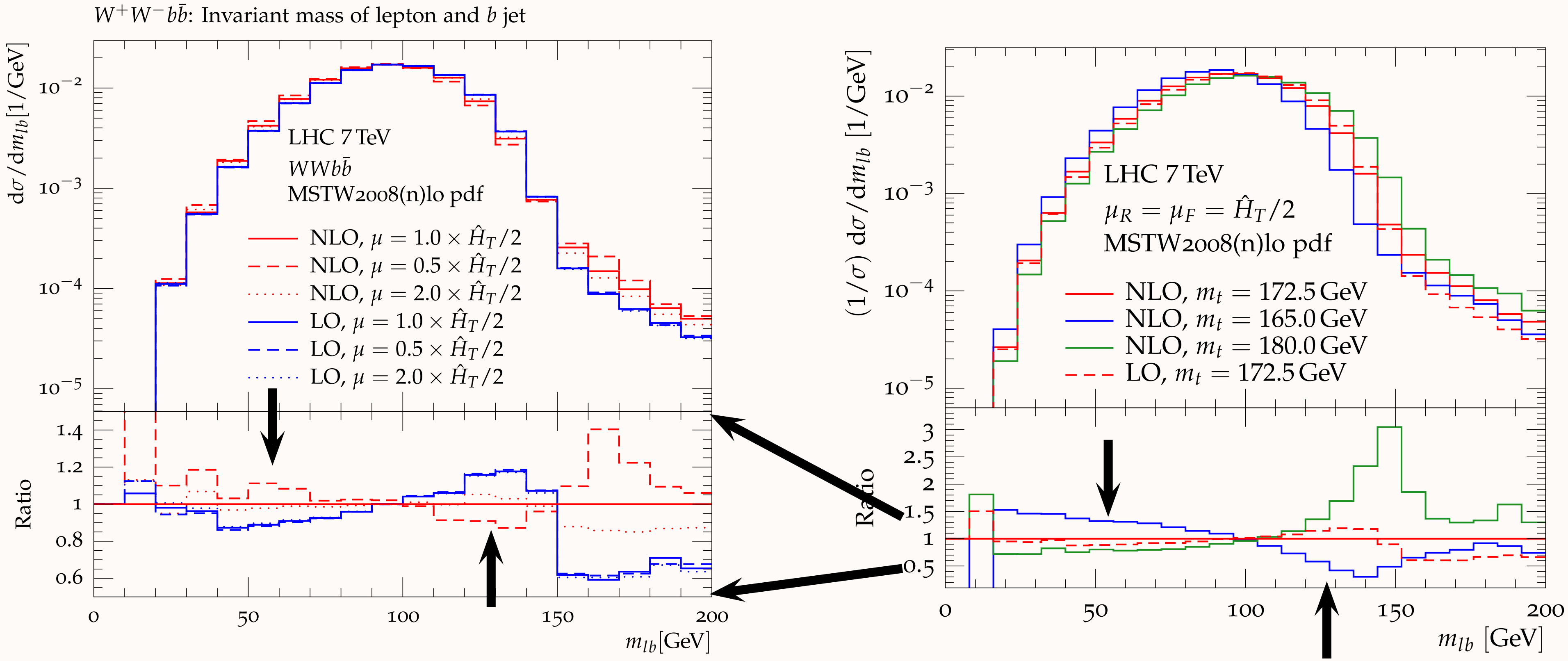
- shape modifications resulting from variation of scales by factors of two
- left panel, for the full approach $\longrightarrow$ visible
- right panel, for the factorized approach $\longrightarrow$ only in tails





Normalized m_{lb}: scale versus m_t variation

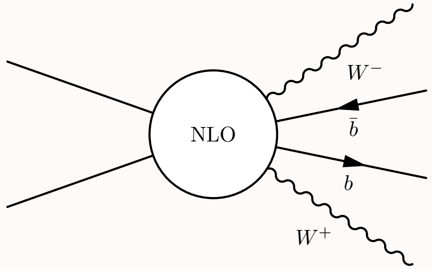
- shape modifications resulting from variation of scales by factors of two
- left panel, for the full approach → visible
- right panel, shape changes due to m_t variation @ NLO (m_t variation @ LO very similar!)

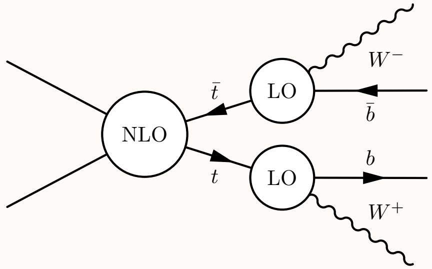


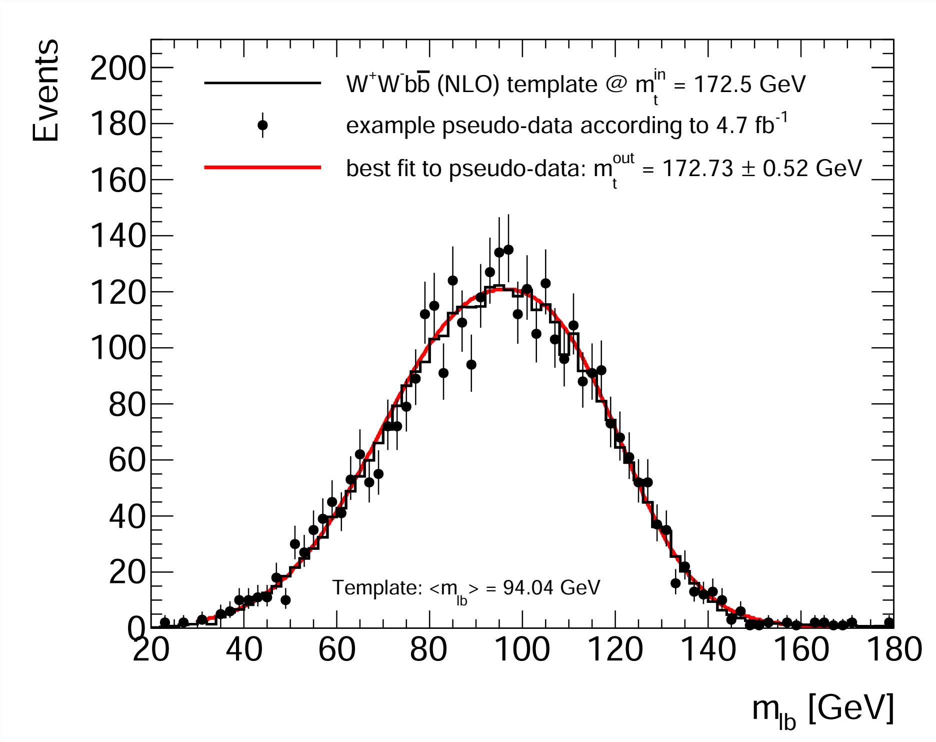
- scale factor variation mimics shape changes as induced by different m_t values → uncertainty
- @NLO: scale down corresponds to lower mass
- fit mass and scale simultaneously, but would resulting choice work for other distributions (eg. $m_{t\bar{t}}$)?

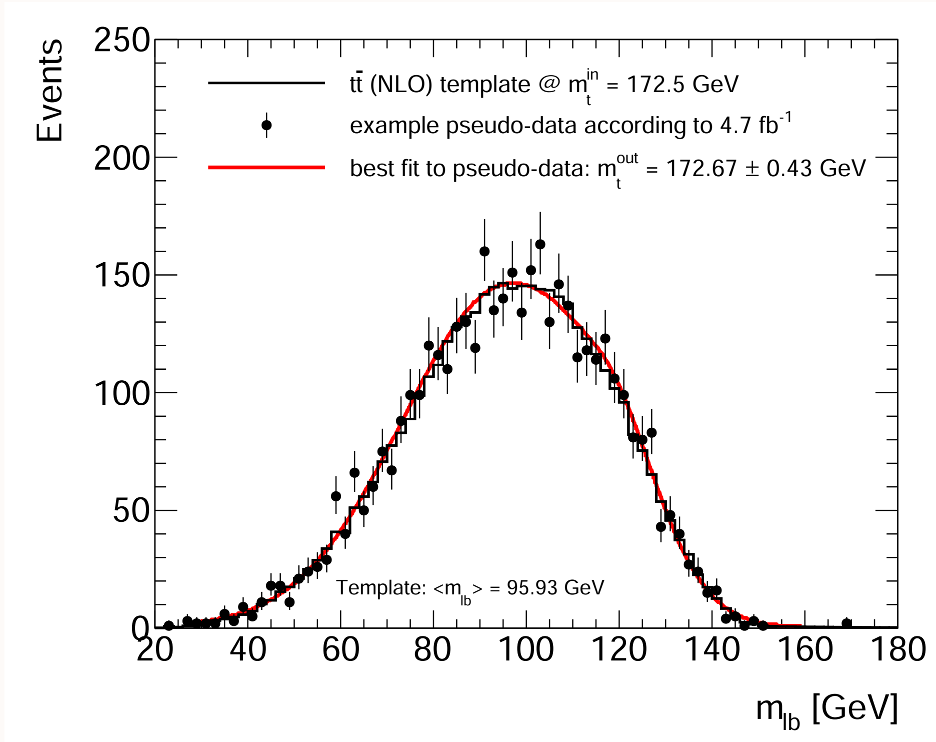
NLO templates vs pseudo-data

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





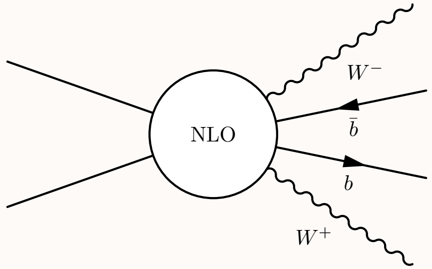


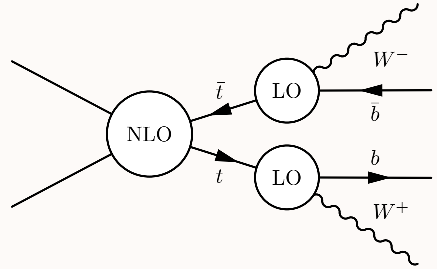


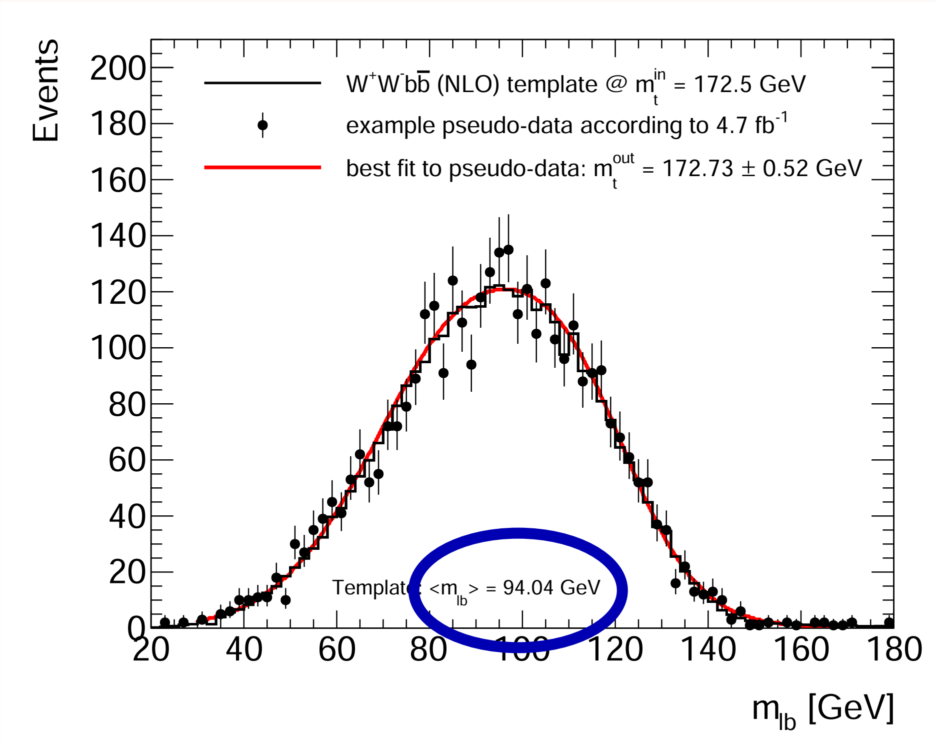
- pseudo-data (black points) are generated from the NLO distributions (black histograms) at $m_t^{\rm in}$
- fit with NLO templates (parametrization) gives $m_t^{\rm out}$ $\rightarrow$ best fit to pseudo-data (red line)

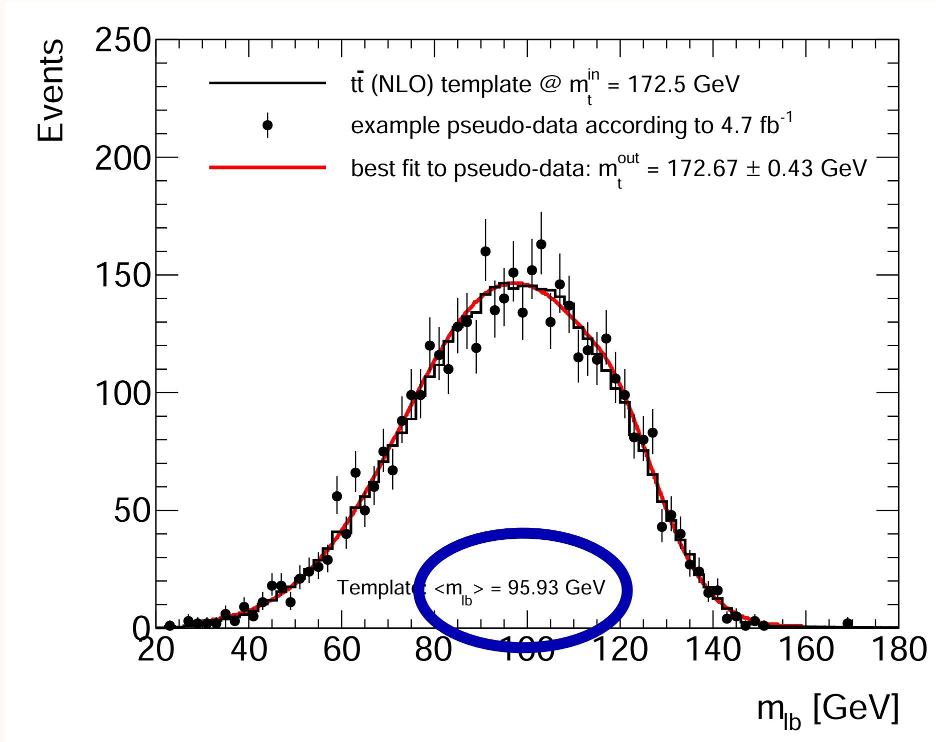
NLO templates vs pseudo-data

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









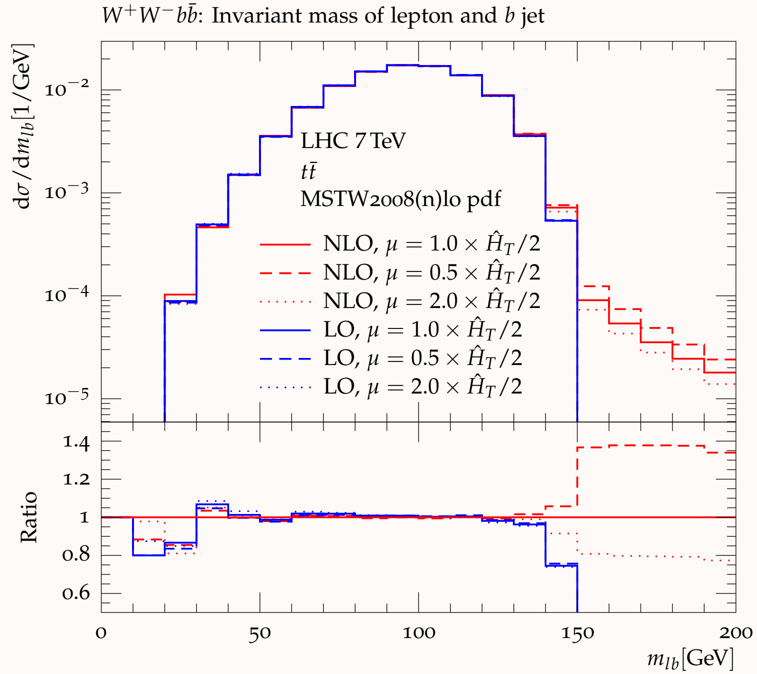
- pseudo-data (black points) are generated from the NLO distributions (black histograms) at m_t^{in}
- fit with NLO templates (parametrization) gives m_t^{out} $\rightarrow$ best fit to pseudo-data (red line)

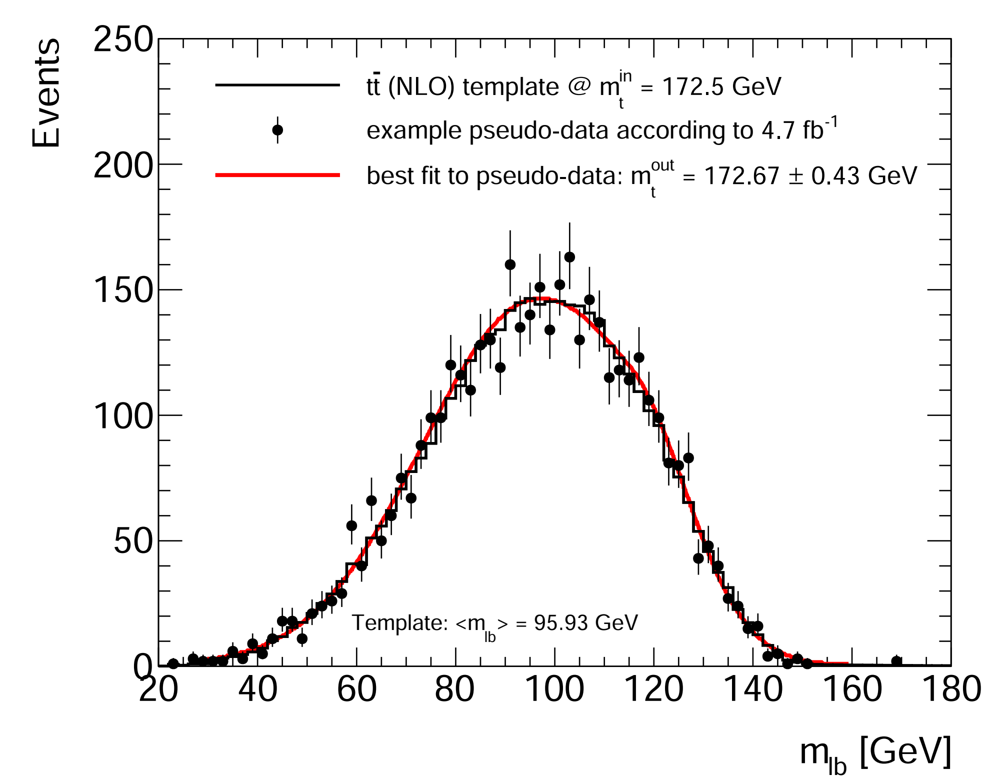
Scale uncertainties and the m_{lb} method

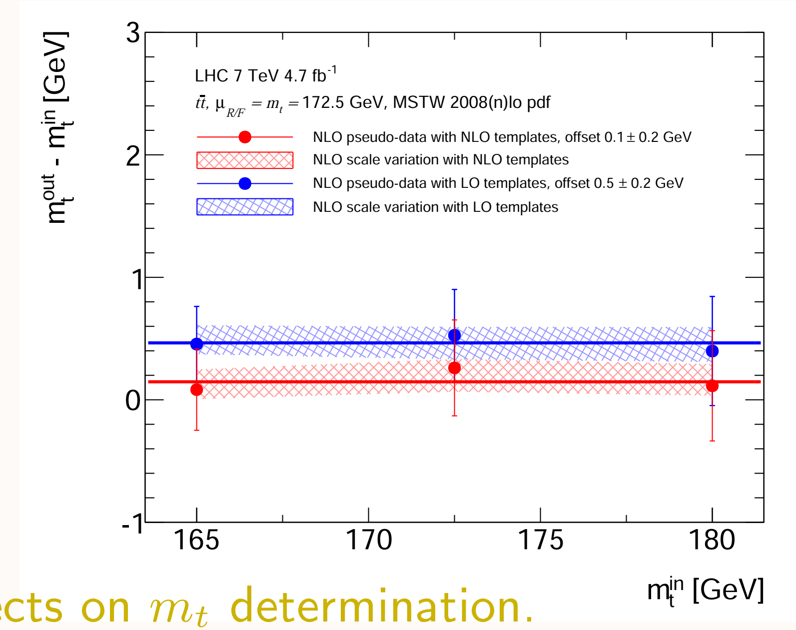
[HEINRICH, MAIER, NISIUS, SCHLENK, WINTER, ARXIV:1312.6659]

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].







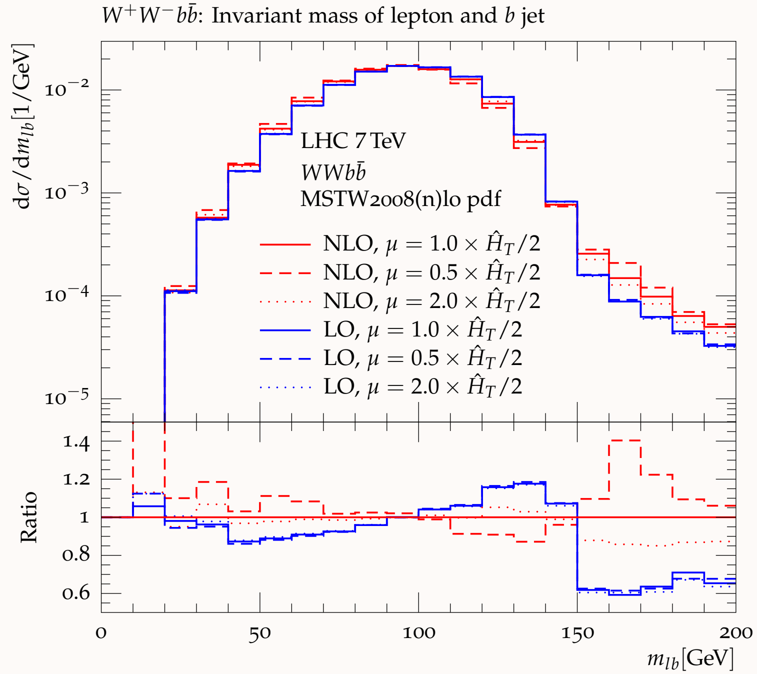
➡ Based on NLO $t\bar{t}$ + LO decays, only small effects on m_t determination.

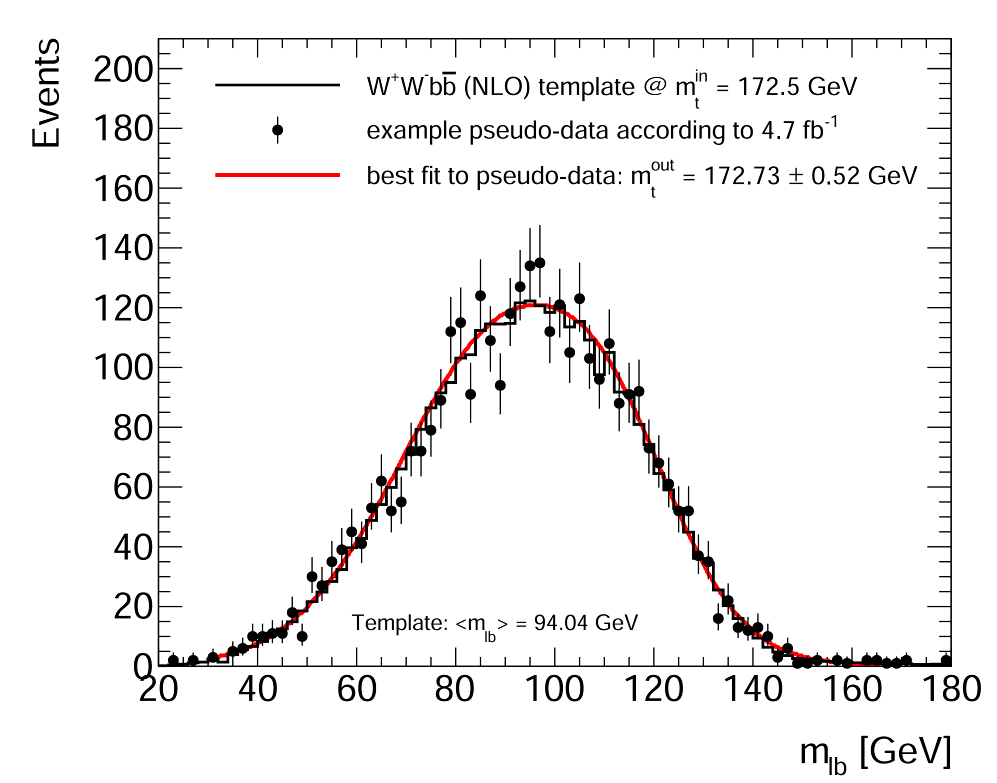
Scale uncertainties and the m_{lb} method

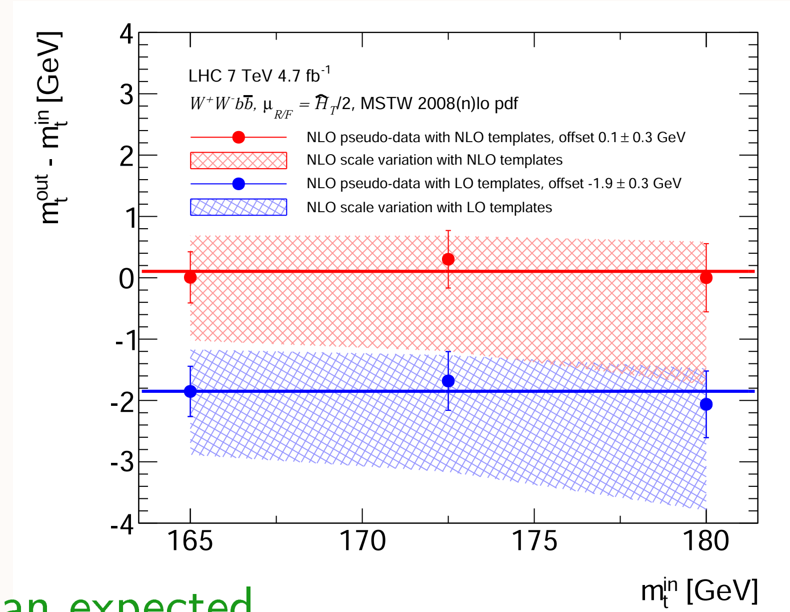
[HEINRICH, MAIER, NISIUS, SCHLENK, WINTER, ARXIV:1312.6659]

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].



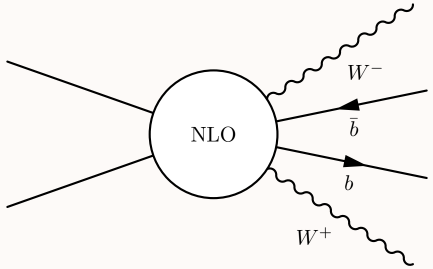


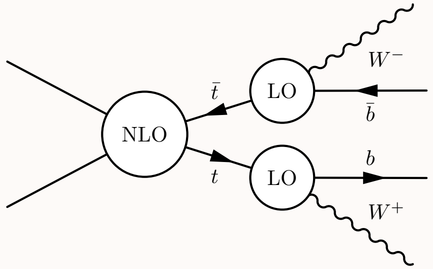


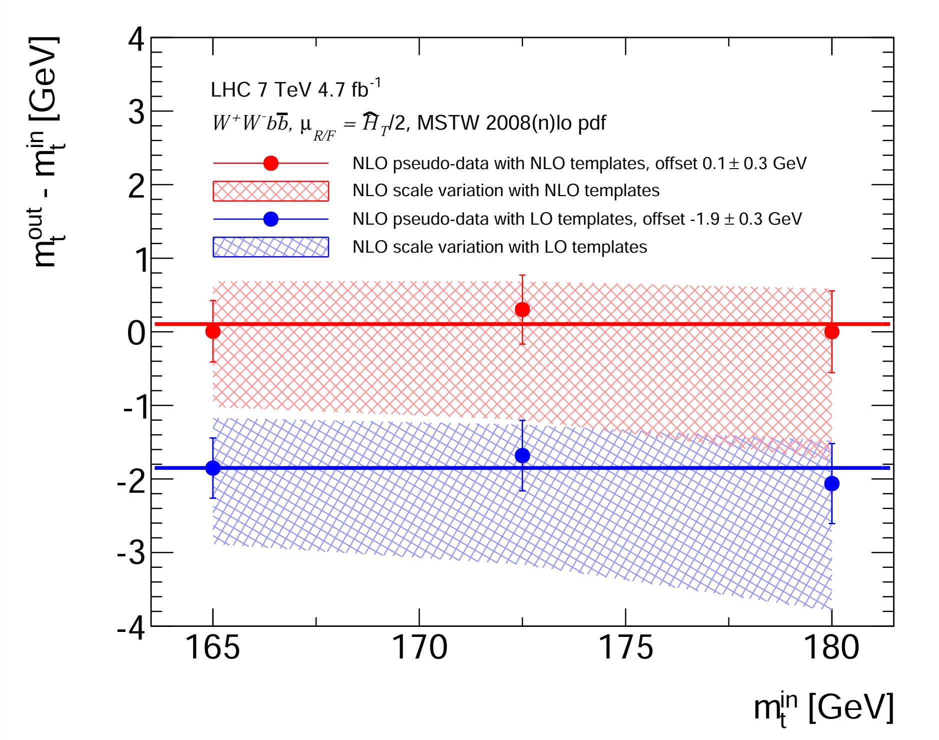
→ Impacts top quark mass determination more than expected.

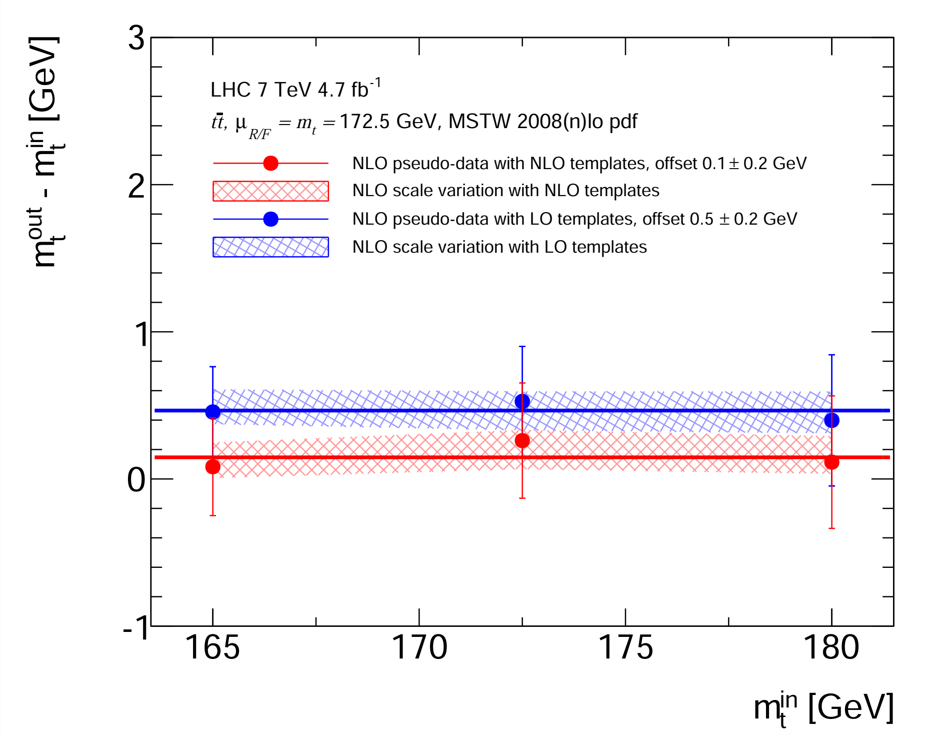
Summary

➡ ***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 $\pm 0.2\,\mathrm{GeV}$)

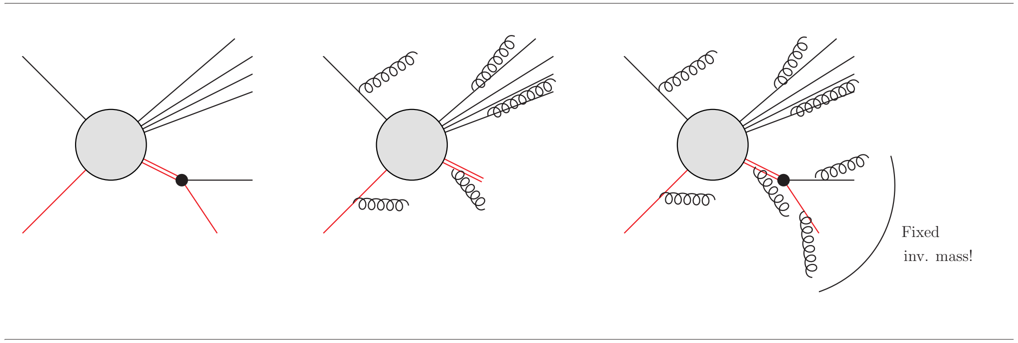
Further remarks.

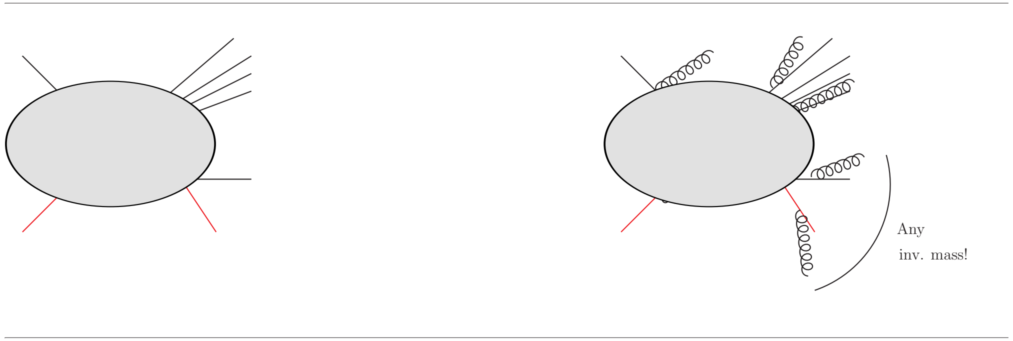
What about variables other than m_{lb} ?

- recent study concerning the prospects to determine m_t from leptonic observables (dilepton channel) [FRIXIONE, MITOV, ARXIV:1407.2763]
- proposal to exploit the top quark mass dependence of the shape of the $t\bar{t}$+1-jet invariant mass [ALIOLI, FERNANDEZ, FUSTER, IRLES, MOCH, UWER, VOS, ARXIV:1303.6415]
- ...

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. This is an open issue to the MC community. (Without a proper treatment of intermediate resonances, parton shower effects will distort the (NLO-accurate) Breit–Wigner shape.)





Summary.

Cutting edge parton-level calculations of NLO QCD corrections to $WWb\bar{b}$ production are available, using modern NLO tools (MG5_aMCNLO, 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, ...).

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

NLO effects were also studied in the context of the top quark mass measurement based on the m_{lb} template method (well defined framework also for a 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 this top quark mass determination than expected.

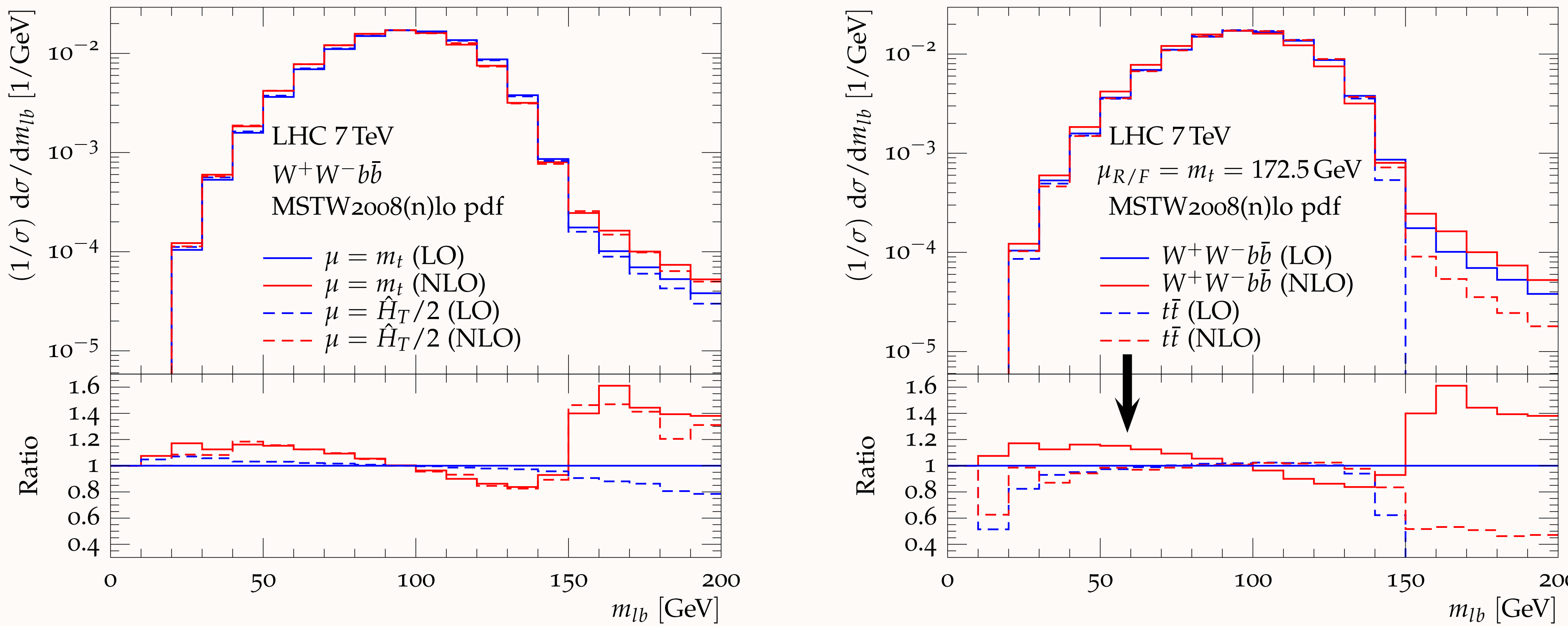
Validation ongoing ... e.g. to separate effects from radiative corrections in decay and finite-width contributions (NLO in the "decay" seems crucial).


Thank You.

Extra notes.

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

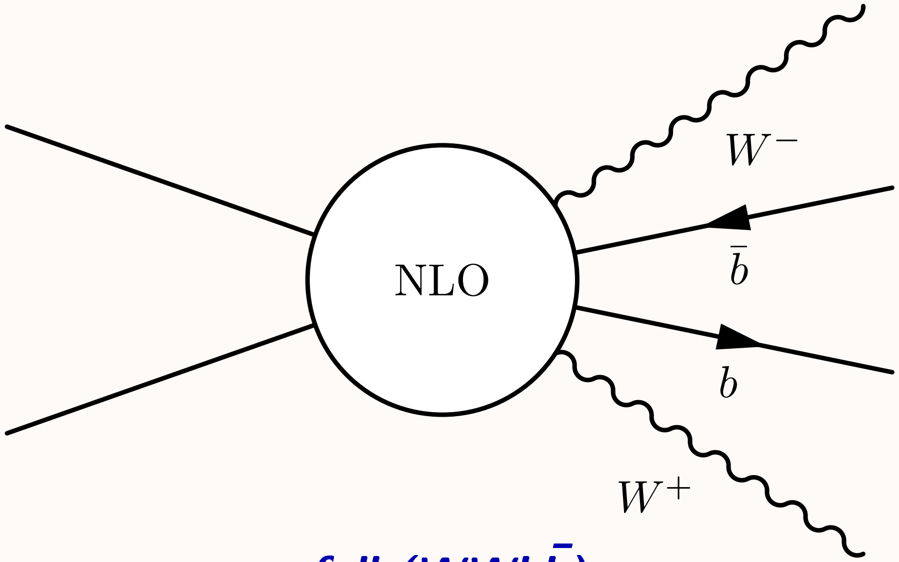
- analysis strongly driven by shape of the distribution (rate comes in only through number of events passing acceptance/analysis cuts)



- left: small effect of different scale choices on normalized distributions
- right: for full NLO WWb$\bar{\text{b}}$, shape change is drastic while shapes of others are similar

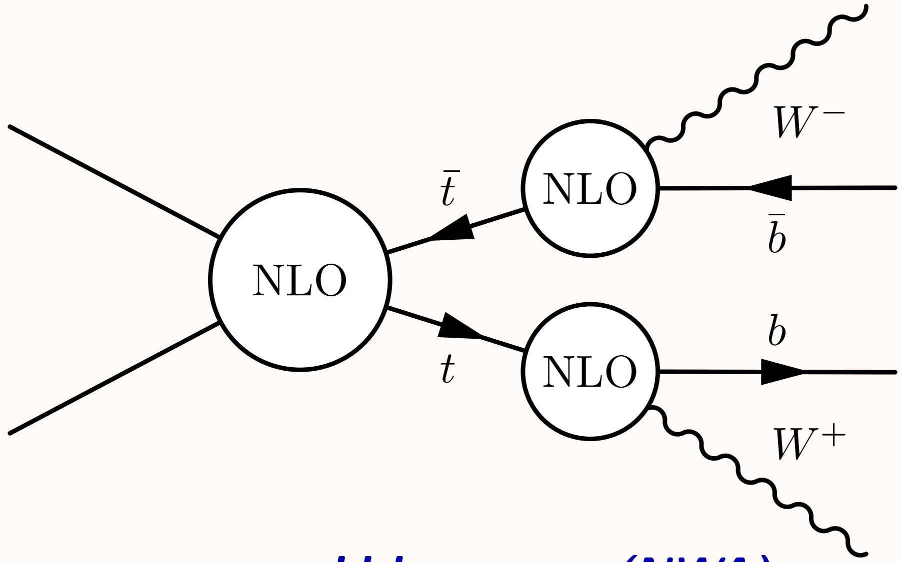
Radiation in the decay

[Biswas, Melnikov, Schulze, arXiv:1006.0910]



full ($WWb\bar{b}$)

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



narrow width approx. (NWA)

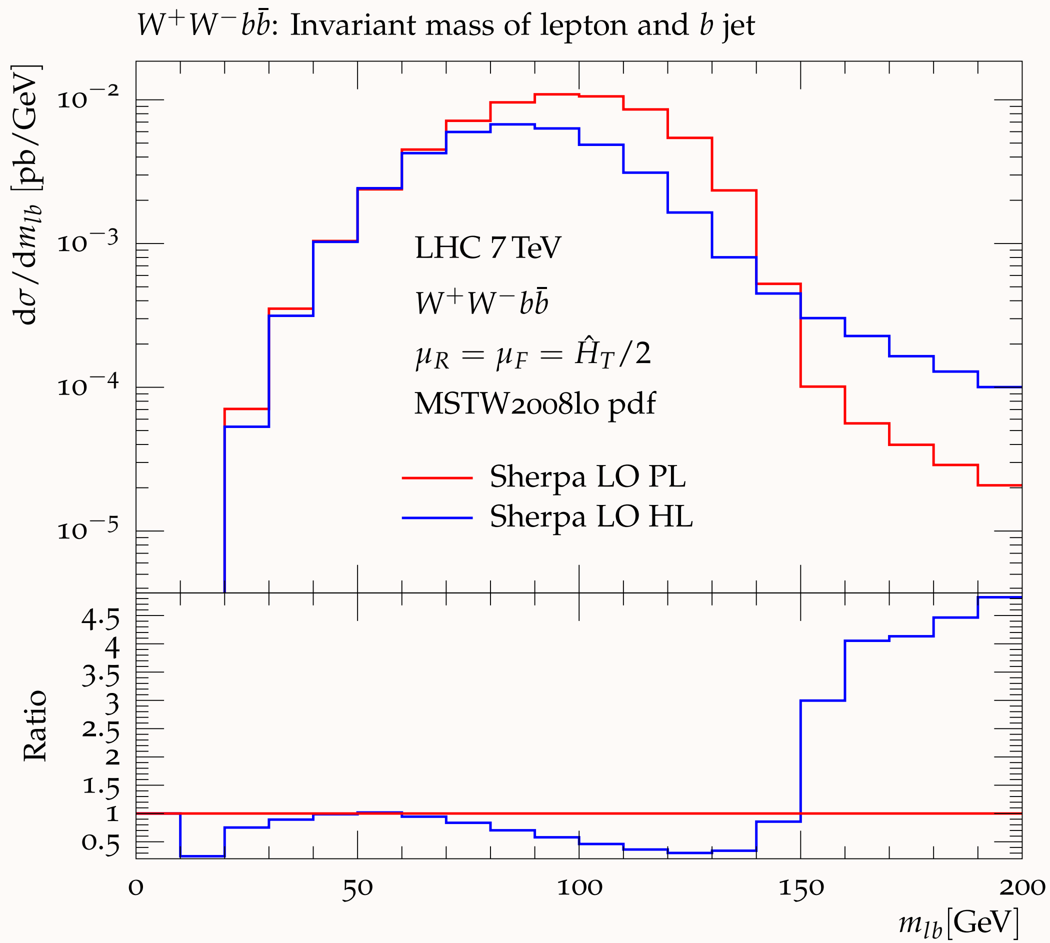
- full NLO NWA treatment of $t\bar{t}$ production and top quark decays preserving spin correlations

- comparison will help disentangle effects from NLO decays and non-resonant/-factorizing 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?

What to expect from showering and hadronization?

- Only PRELIMINARY result / illustration. Observation on a qualitative level:

- transition region between peak and tail gets washed out, mainly by parton showering (PS)
- also peak position shifts to the left
- further amplified by hadronization (HAD)



- PS + HAD reduce the top mass sensitivity of m_{lb}

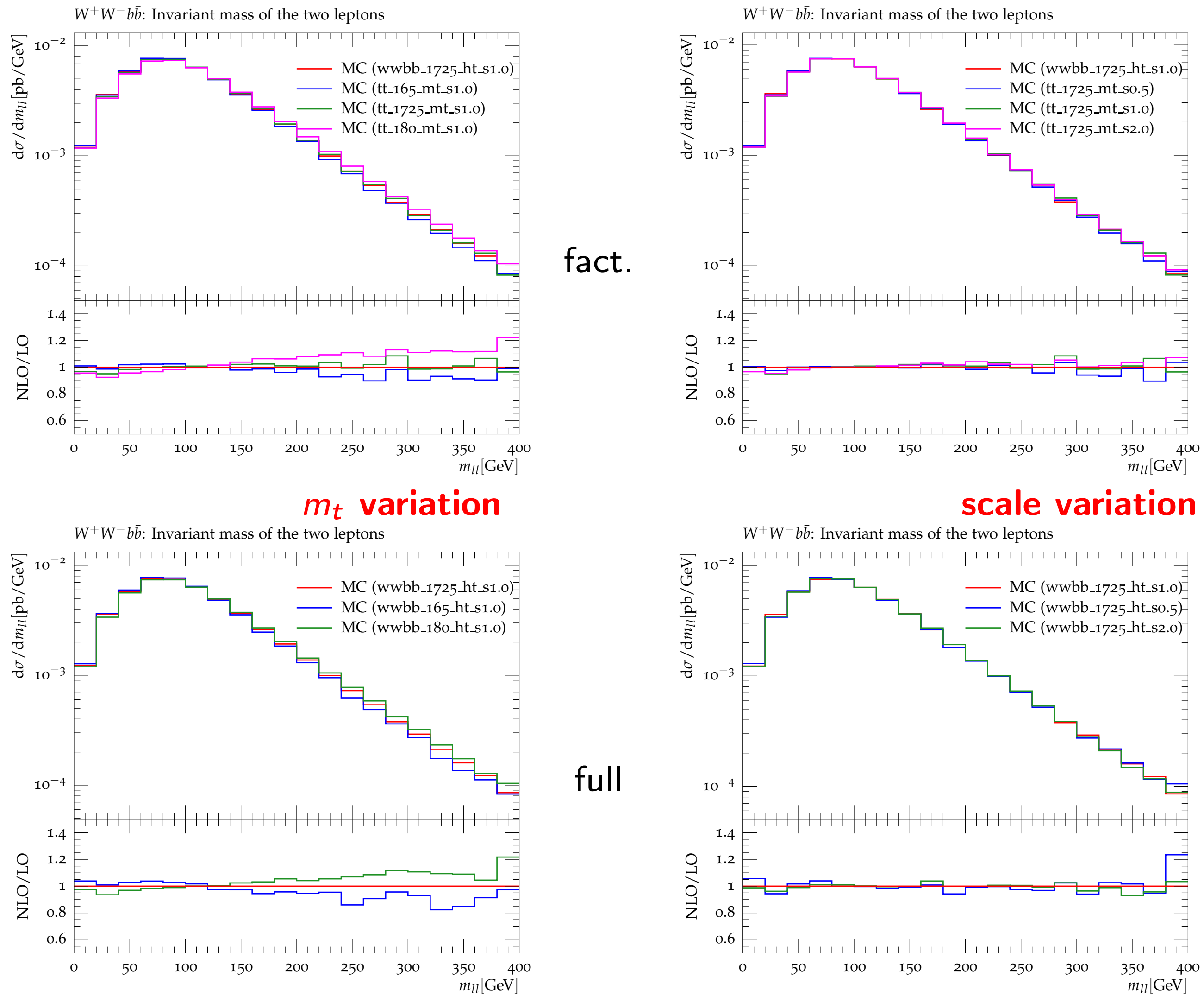
  (cannot be neglected but is not dramatic either)

Other observables?

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

m_{ll}

- m_{ll} is an observable almost free of PS + HAD corrections



m_t variation

scale variation