NLO and off-shell effects in top quark mass determinations

Theorist of the month seminar at DESY Hamburg.

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Work in collaboration with Gudrun Heinrich, Andreas Maier, Richard Nisius, Johannes Schlenk, Markus Schulze and Ludovic Scyboz.

Mass of the top quark.

Importance of knowing this Standard Model parameter precisely:

- close link to Higgs physics because of largest Yukawa coupling
- Higgs potential and SM vacuum stability critically depend on this value
- processes involving top quarks used for SM precision tests and constraining PDFs
- many important backgrounds in new physics searches contain large portion of top quark physics

Measurements to extract this parameter are complicated:

- top quark production leads to complex hadronic & leptonic final states often plus additional jets
- top hadrons do not exist: top quarks decay before they can hadronize
- challenging environment: many effects and subtle theoretical issues need be understood

(top quark reconstruction, higher-orders, off-shell effects, interferences, colour reconnections, IR renormalon, Monte Carlo mass versus pole mass etc)

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 $\sim$

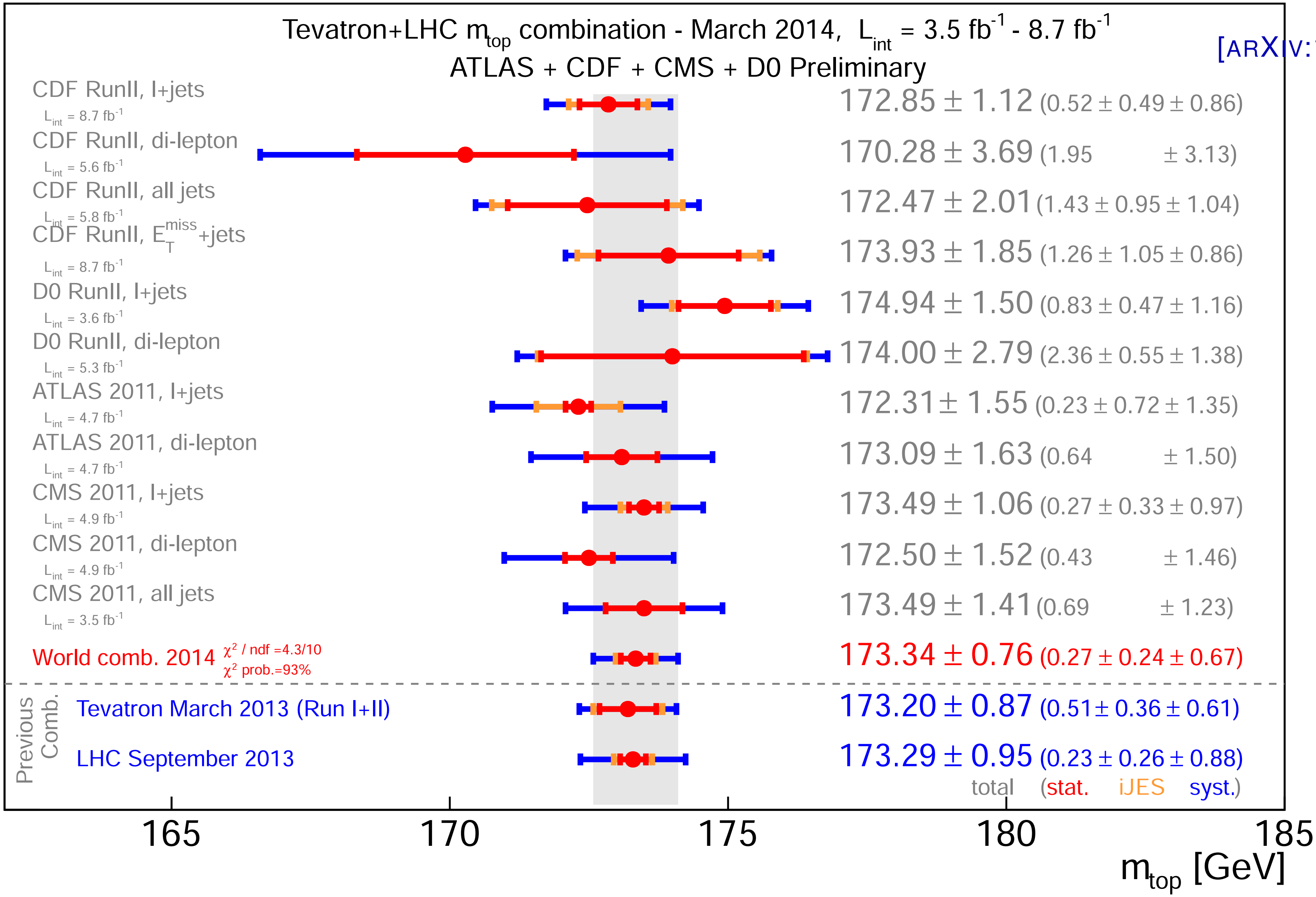
- important contributions to Wt and WW final states (tricky to disentangle at higher orders)
- important background to BSM searches and SM measurements (e.g. population of N-jet bins in WW production)
- at current precision, we start worrying about offshell effects, non-factorizable corrections, b-mass 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?

Top quark mass measurements, March 2014

- 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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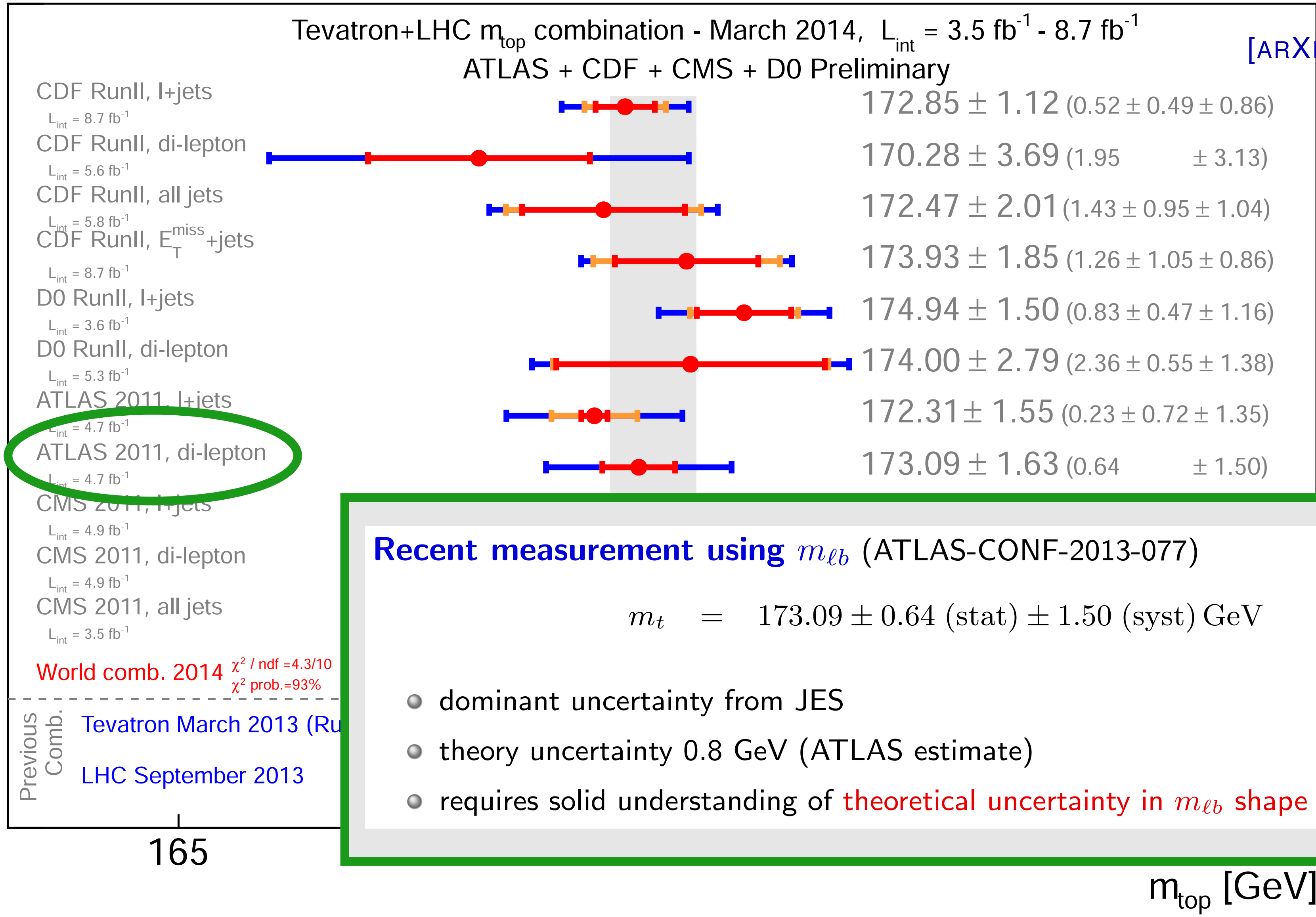


Recent measurement using $m_{\ell b}$ (ATLAS-CONF-2013-077)

$$m_t = 173.09 \pm 0.64\,(\text{stat}) \pm 1.50\,(\text{syst})\,\text{GeV}$$

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

Outline.

Current experimental status

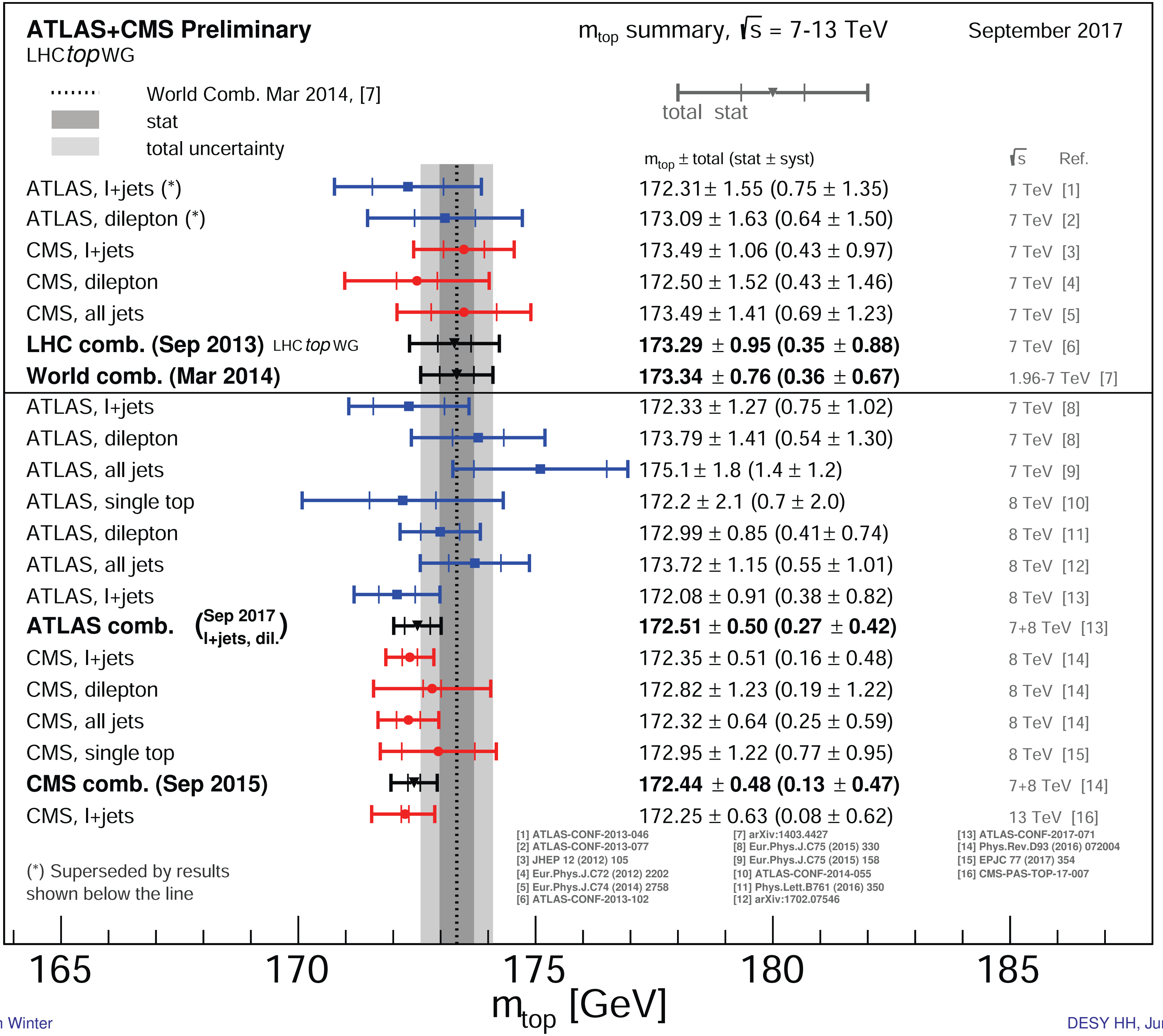
Template method for top quark mass sensitive observables &
Earlier results for LHC 7 TeV

New studies for LHC 13 TeV

$WbW\bar{b}$ calculations – quick recap

(Snippet of recent literature review)

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

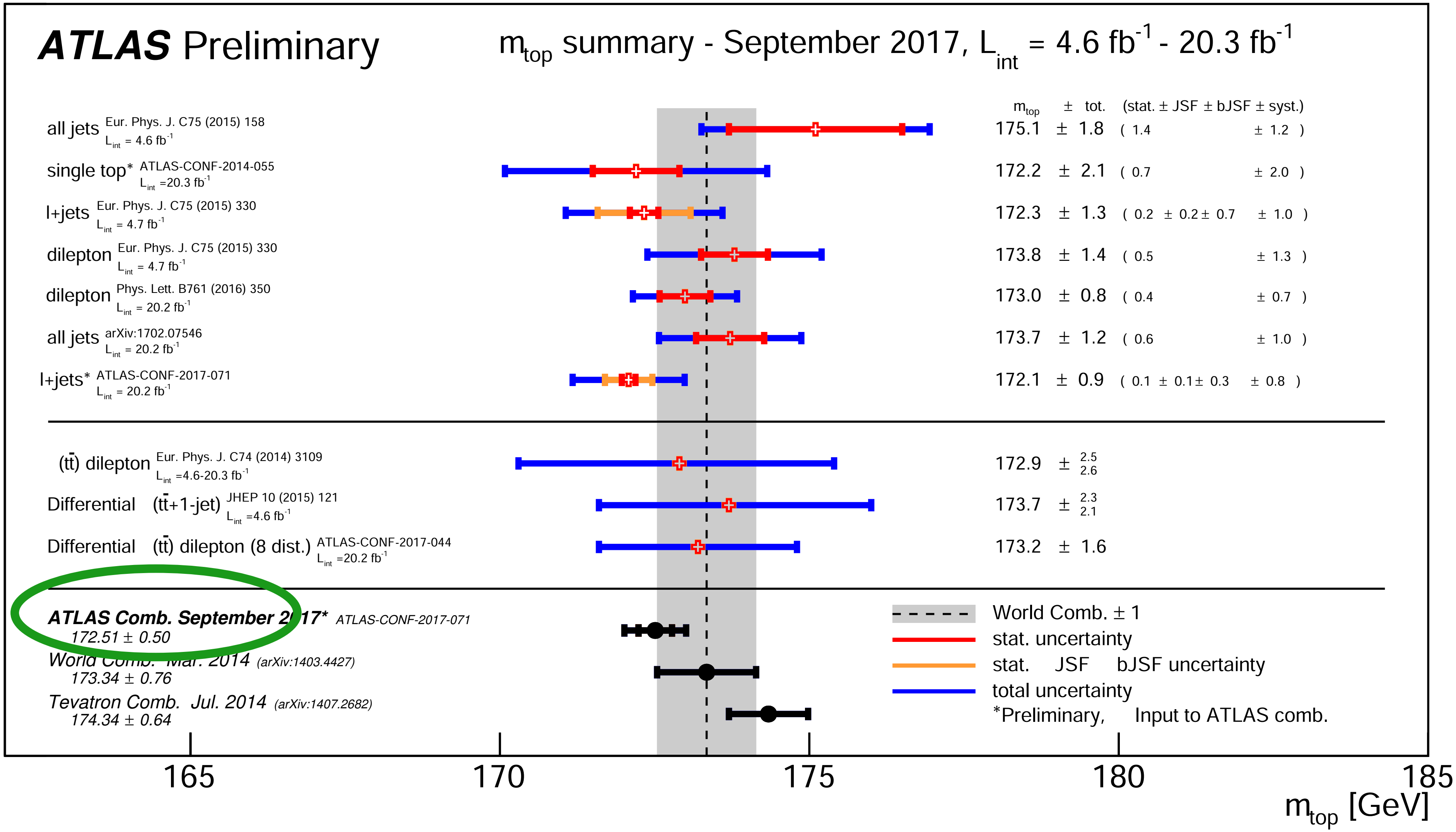

ATLAS+CMS Preliminary
LHCtopWG
m_top summary, √s = 7-13 TeV
September 2017
World Comb. Mar 2014, [7]
stat
total uncertainty
total stat
m_top ± total (stat ± syst)
√s Ref.
ATLAS, l+jets (*) 172.31± 1.55 (0.75 ± 1.35) 7 TeV [1]
ATLAS, dilepton (*) 173.09 ± 1.63 (0.64 ± 1.50) 7 TeV [2]
CMS, l+jets 173.49 ± 1.06 (0.43 ± 0.97) 7 TeV [3]
CMS, dilepton 172.50 ± 1.52 (0.43 ± 1.46) 7 TeV [4]
CMS, all jets 173.49 ± 1.41 (0.69 ± 1.23) 7 TeV [5]
LHC comb. (Sep 2013) LHCtopWG 173.29 ± 0.95 (0.35 ± 0.88) 7 TeV [6]
World comb. (Mar 2014) 173.34 ± 0.76 (0.36 ± 0.67) 1.96-7 TeV [7]
ATLAS, l+jets 172.33 ± 1.27 (0.75 ± 1.02) 7 TeV [8]
ATLAS, dilepton 173.79 ± 1.41 (0.54 ± 1.30) 7 TeV [8]
ATLAS, all jets 175.1± 1.8 (1.4 ± 1.2) 7 TeV [9]
ATLAS, single top 172.2 ± 2.1 (0.7 ± 2.0) 8 TeV [10]
ATLAS, dilepton 172.99 ± 0.85 (0.41± 0.74) 8 TeV [11]
ATLAS, all jets 173.72 ± 1.15 (0.55 ± 1.01) 8 TeV [12]
ATLAS, l+jets 172.08 ± 0.91 (0.38 ± 0.82) 8 TeV [13]
ATLAS comb. (Sep 2017 l+jets, dil.) 172.51 ± 0.50 (0.27 ± 0.42) 7+8 TeV [13]
CMS, l+jets 172.35 ± 0.51 (0.16 ± 0.48) 8 TeV [14]
CMS, dilepton 172.82 ± 1.23 (0.19 ± 1.22) 8 TeV [14]
CMS, all jets 172.32 ± 0.64 (0.25 ± 0.59) 8 TeV [14]
CMS, single top 172.95 ± 1.22 (0.77 ± 0.95) 8 TeV [15]
CMS comb. (Sep 2015) 172.44 ± 0.48 (0.13 ± 0.47) 7+8 TeV [14]
CMS, l+jets 172.25 ± 0.63 (0.08 ± 0.62) 13 TeV [16]
(*) Superseded by results shown below the line
[1] ATLAS-CONF-2013-046
[2] ATLAS-CONF-2013-077
[3] JHEP 12 (2012) 105
[4] Eur.Phys.J.C72 (2012) 2202
[5] Eur.Phys.J.C74 (2014) 2758
[6] ATLAS-CONF-2013-102
[7] arXiv:1403.4427
[8] Eur.Phys.J.C75 (2015) 330
[9] Eur.Phys.J.C75 (2015) 158
[10] ATLAS-CONF-2014-055
[11] Phys.Lett.B761 (2016) 350
[12] arXiv:1702.07546
[13] ATLAS-CONF-2017-071
[14] Phys.Rev.D93 (2016) 072004
[15] EPJC 77 (2017) 354
[16] CMS-PAS-TOP-17-007
165
170
175
180
185
m_top [GeV]

Current experimental status, September 2017

- first ATLAS combination result giving total uncertainty on top quark mass $\approx \frac{1}{2}$ GeV.

Dilepton channel results:

7 TeV: [Eur. Phys. J. C **75** (2015) no.7, 330; arXiv:1503.05427]
8 TeV: [Phys. Lett. B **761** (2016) 350; arXiv:1606.02179]

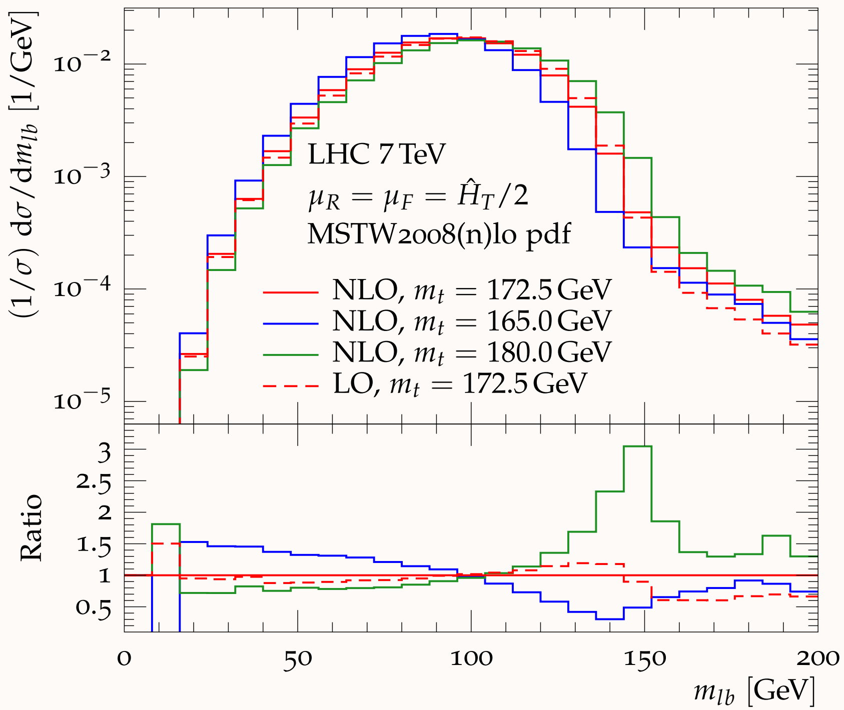


Top quark mass (parameter) determination from the shape of the invariant mass distribution of the charged lepton and b-jet in the dilepton channel at the LHC.

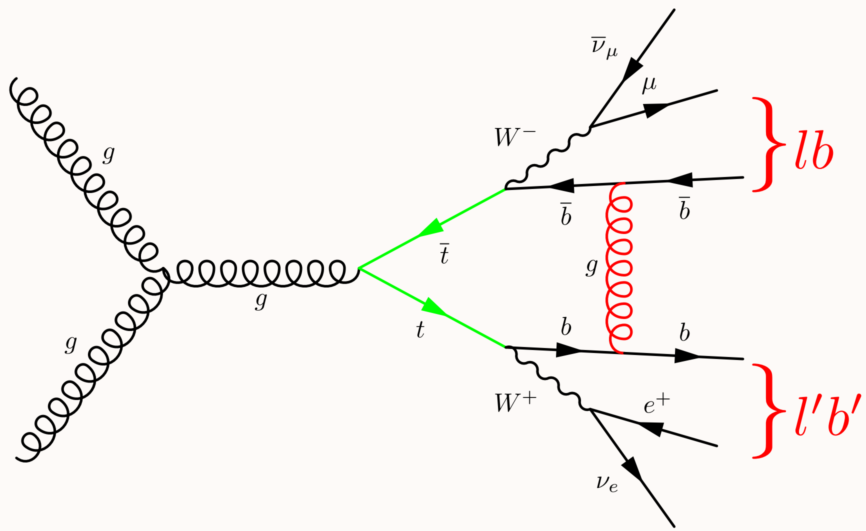
Invariant mass of b-jet and charged lepton

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

$\rightarrow$ Suitable observable for template fit to precisely measure the (MC) top quark mass.



$\leftarrow$ shape predictions from full QCD NLO WWb$\bar{b}$ from GoSam+Sherpa

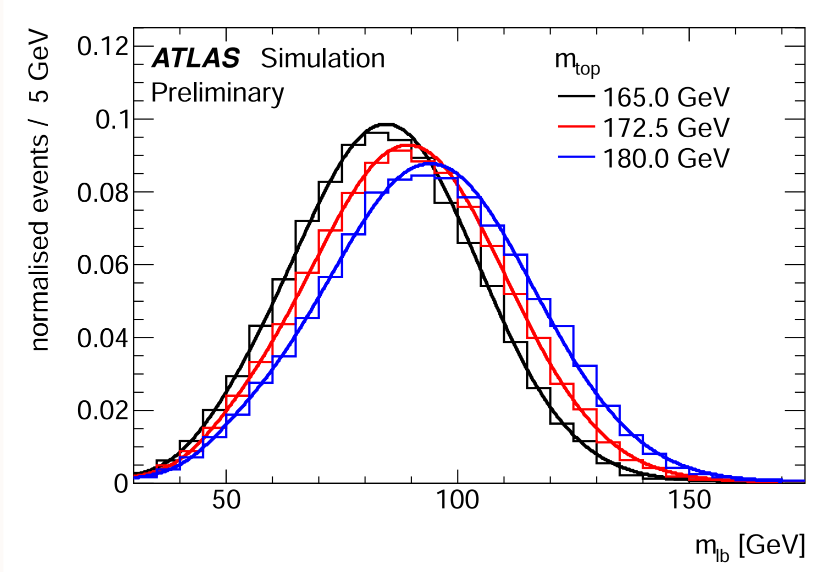


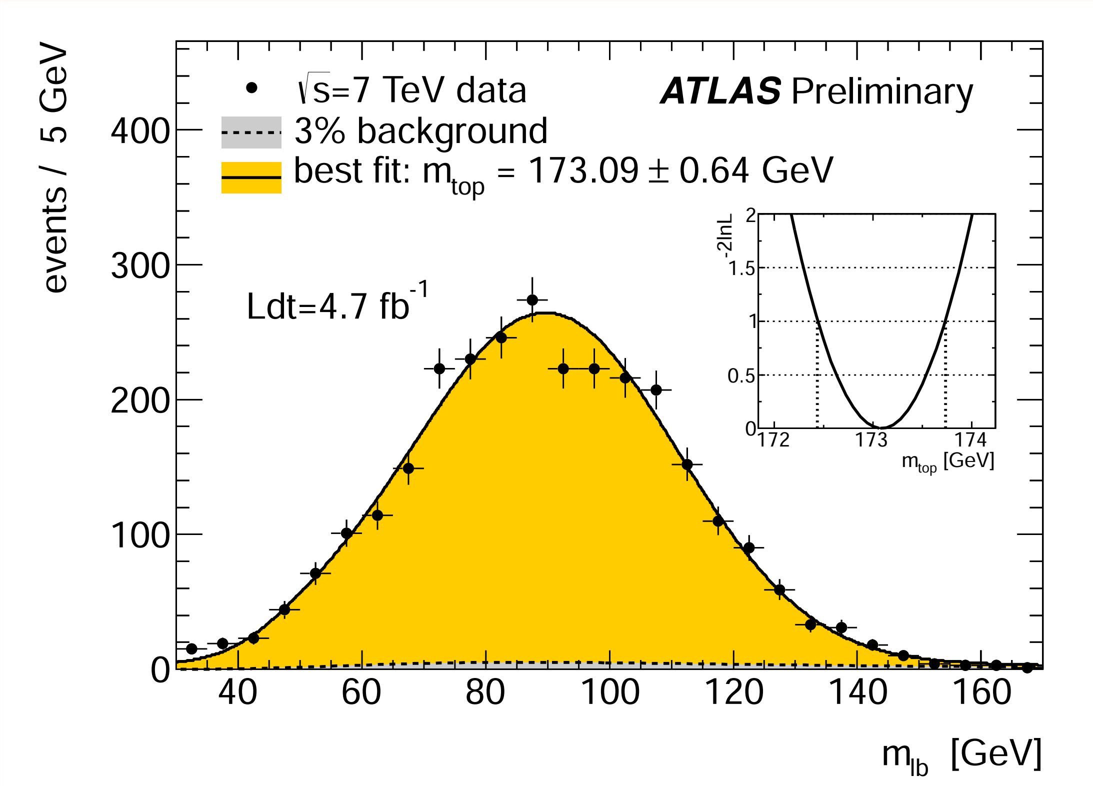
Top quark mass determination using the m_{lb} method

Parametrize "your" theory (provide m_{lb} predictions incl. as many physics effects as possible).

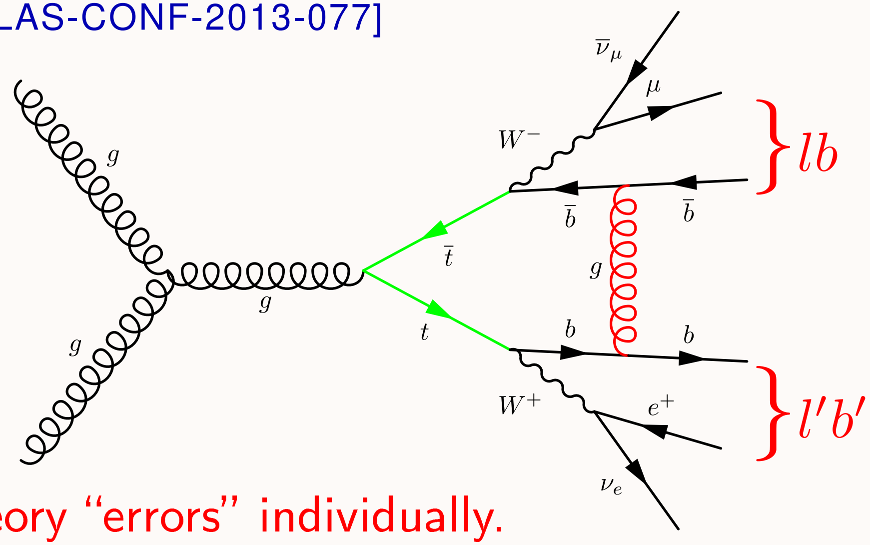
- Already at LO NWA or LO $W^+W^-b\bar{b}$ in dilepton channel: m_{lb} distribution is sensitive to top quark mass.
- ATLAS uses one-dim. template method to determine m_t. Theory uncertainty had been estimated to 0.8 GeV at 7 TeV.

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





[ATLAS-CONF-2013-077]

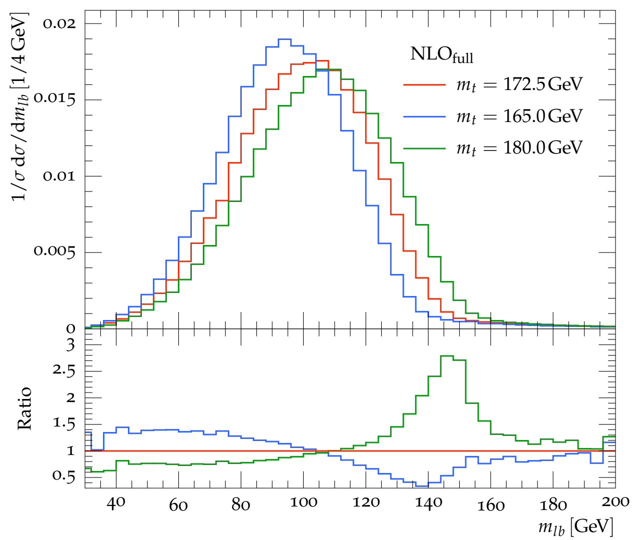


→ Use pseudo-data to study different types of theory "errors" individually.

Calibration of template fit function

- 1. Choose distributions sensitive to the top-quark mass
- 2. Generate distributions for different input m_t^{in}:

  $m_t^{in} \in [165.0, 172.5, 180.0]$ GeV



- 3. Calibrate the fit function
  - Choose appropriate fit functions
  - Verify, then impose linear dependence of function parameters on m_t
  - Fix the parameters by a simultaneous fit to all distributions
  - Top-quark mass m_t left as a floating parameter

$\rightsquigarrow$ **"calibration"**

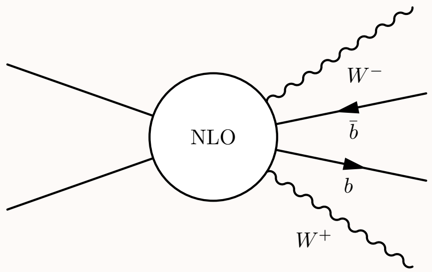
- From a given underlying theory prediction, draw a number of events corresponding to a target luminosity.

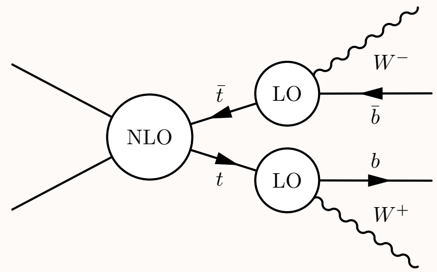
$\Rightarrow$ ***"pseudo-data"***

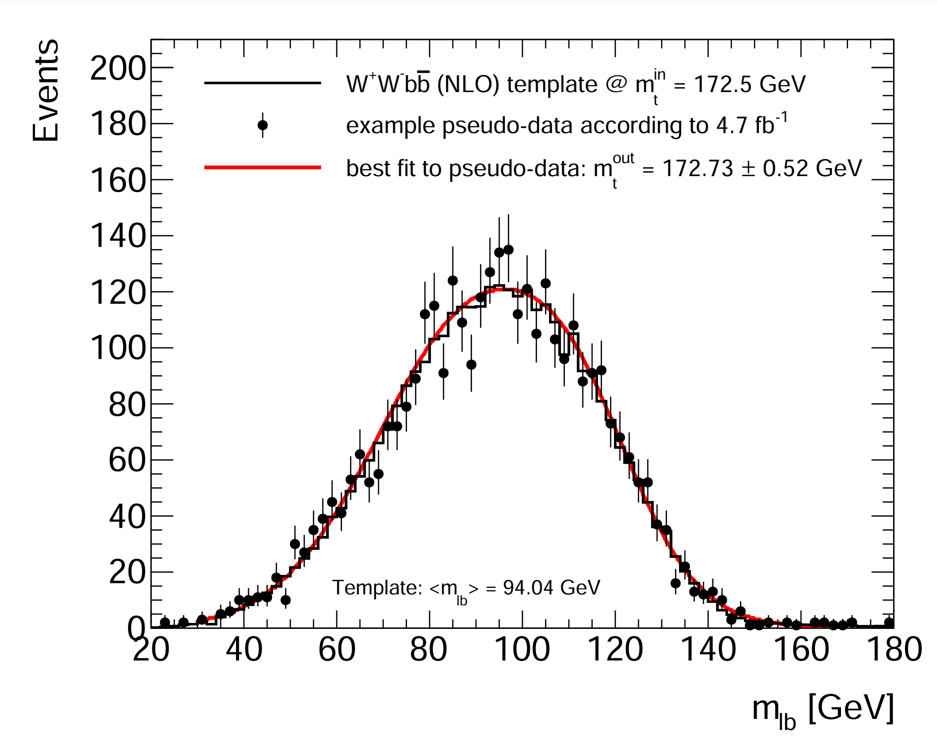
- Fit the pseudo-data with the calibration function $\longrightarrow m_t^{out}$

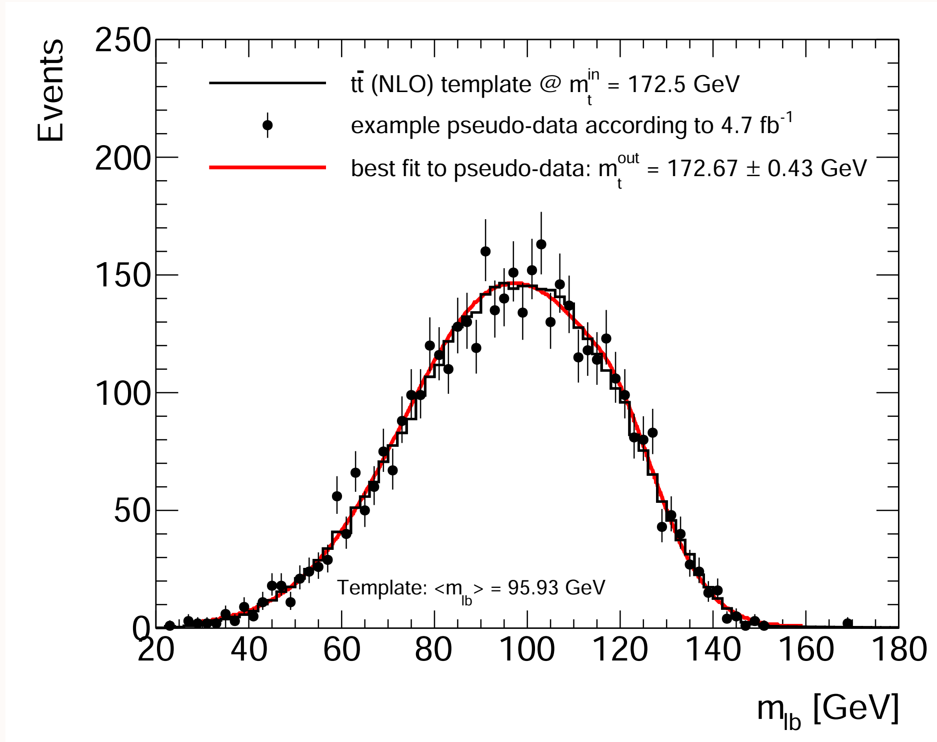
NLO templates vs pseudo-data (same model)

➡ ***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)

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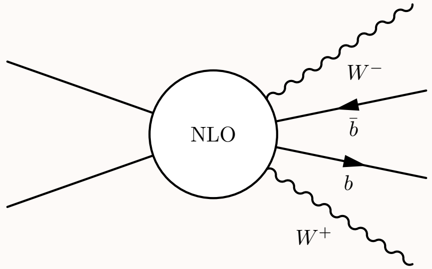

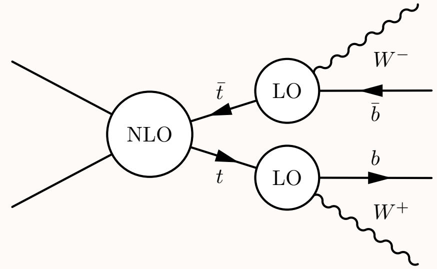

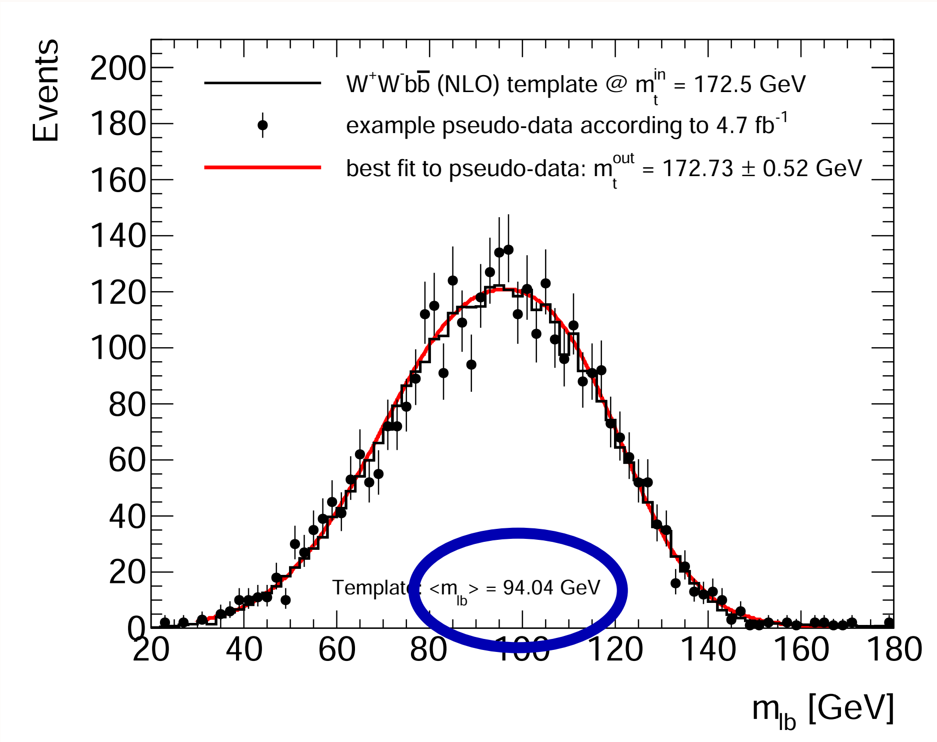

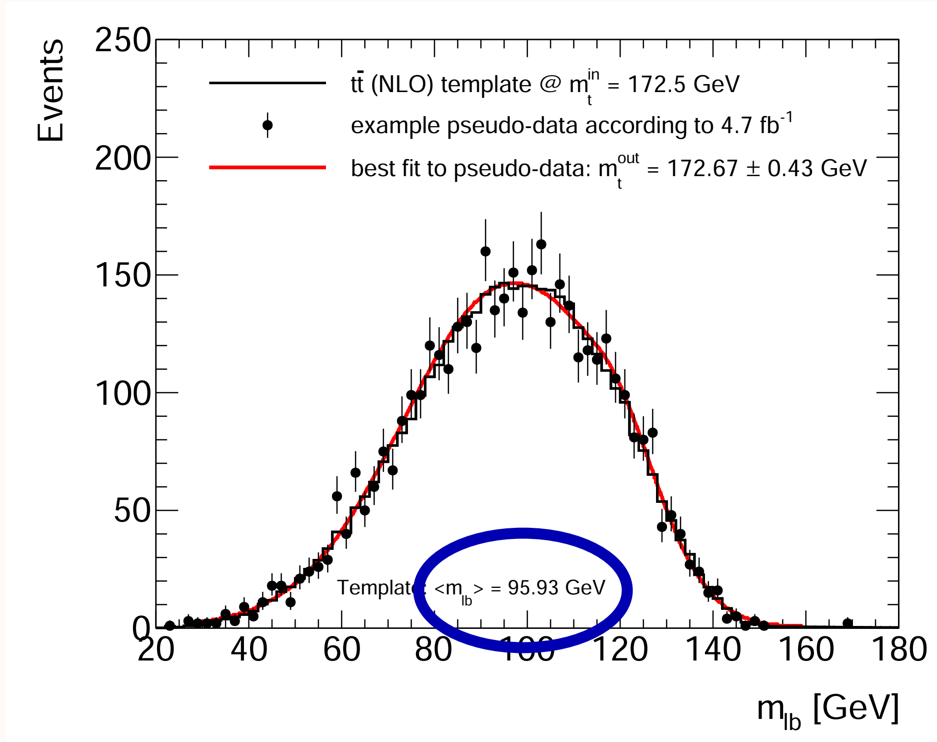

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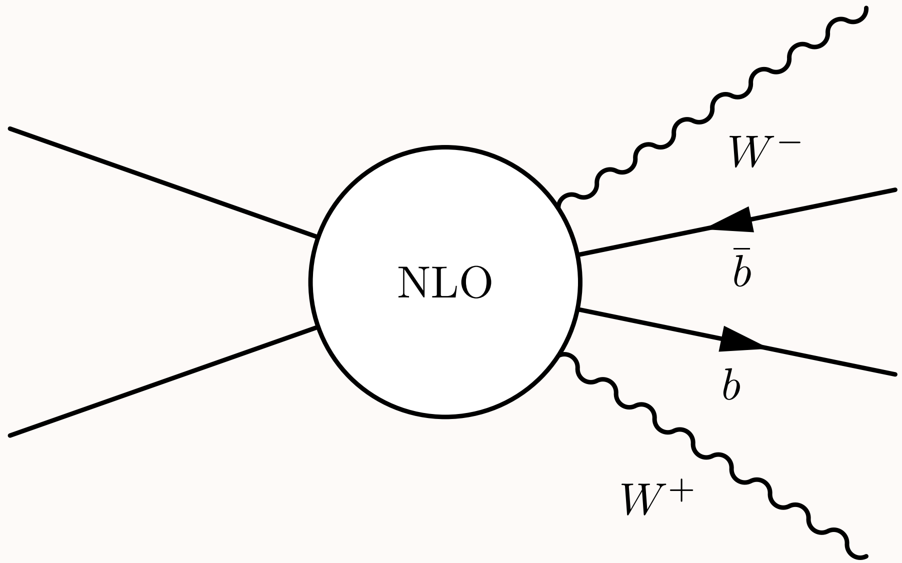
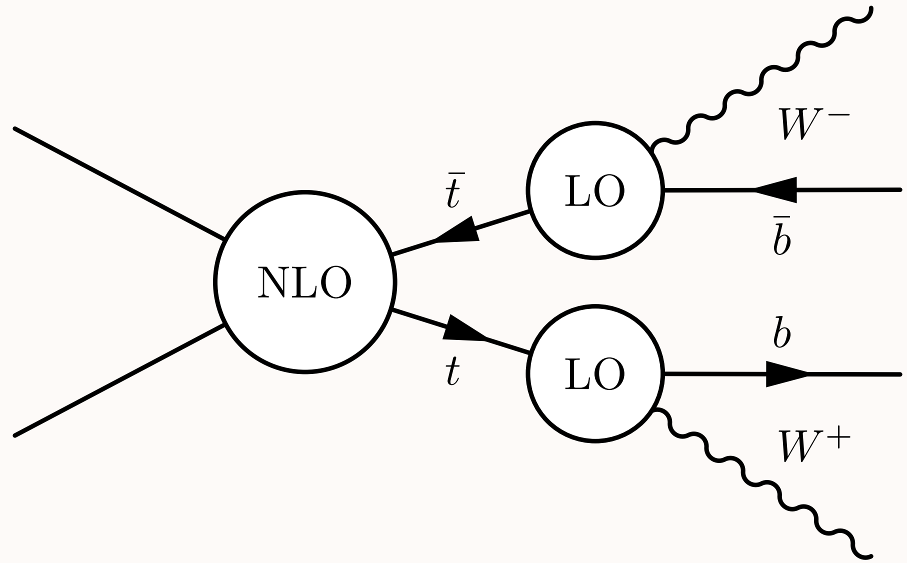
Full versus factorized approach





full ($WWb\bar{b}$)

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

factorized ($t\bar{t}$)

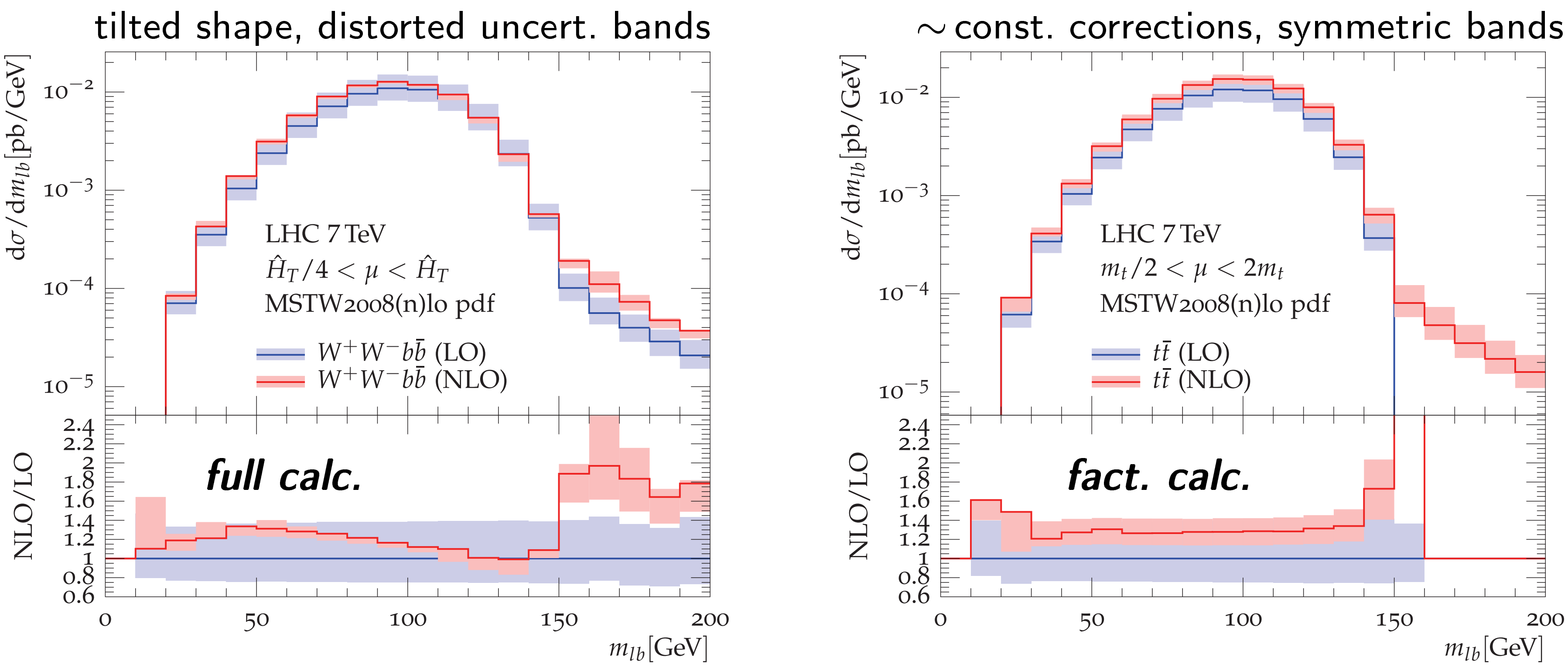
- NLO $t\bar{t}$ production ($2 \rightarrow 2$ processes) with LO decays attached and spin correlations preserved
- standard description for the NLO core in NLO+PS matching

(Use these calculations for pure parton level analyses, i.e. m_t is no 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

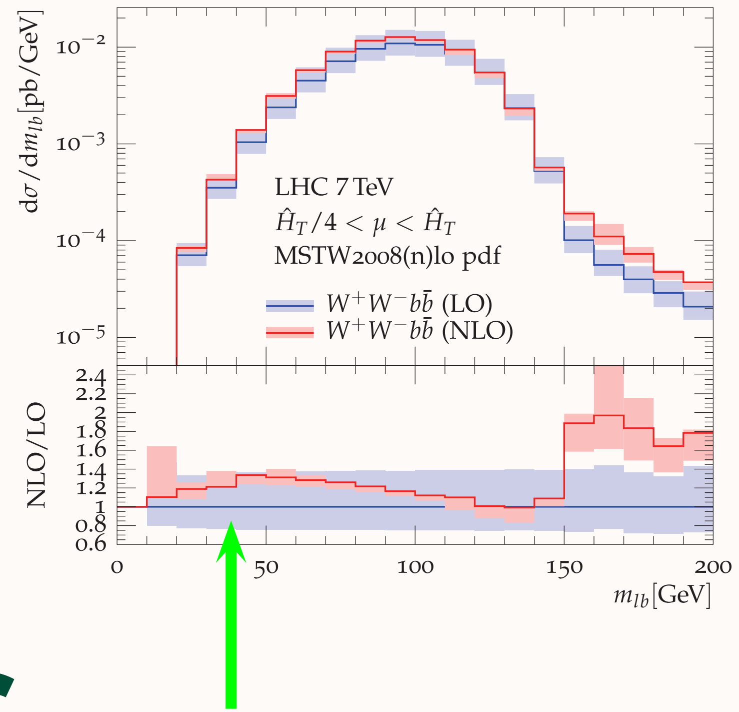
• follow ATLAS strategy: use charged-lepton b-jet pairing minimizing sum of both m_{lb} and average.

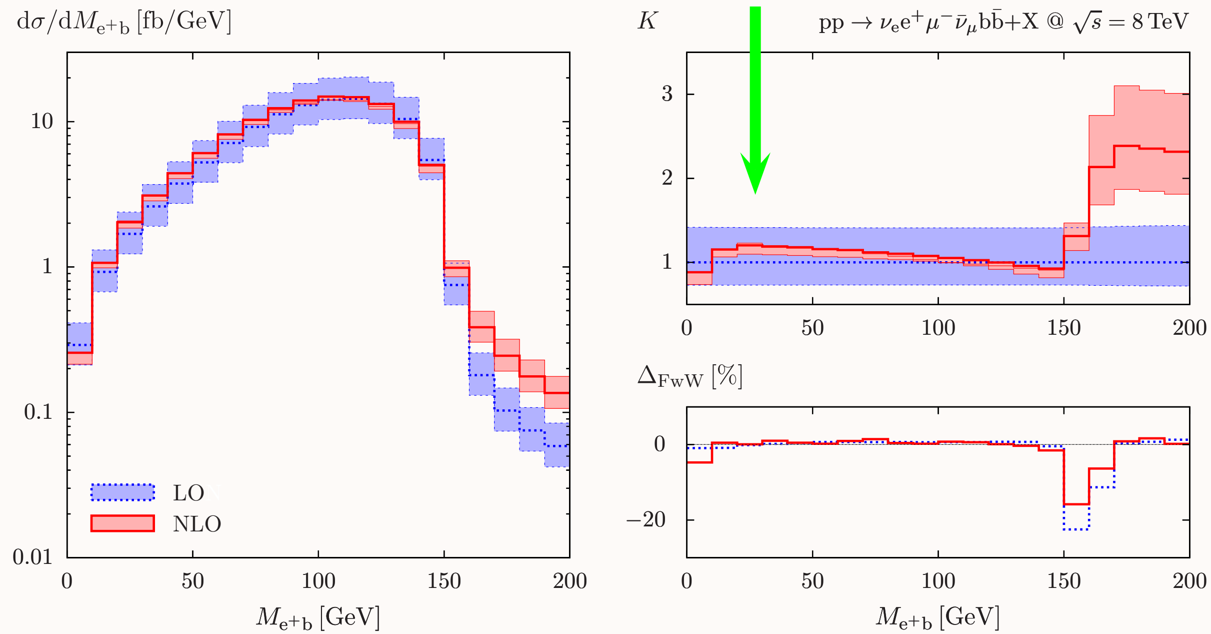
Qualitative comparison of m_{lb} predictions

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

➡ ***$WWb\bar{b}$: NLO corrections strongly affect the shape of m_{lb}***

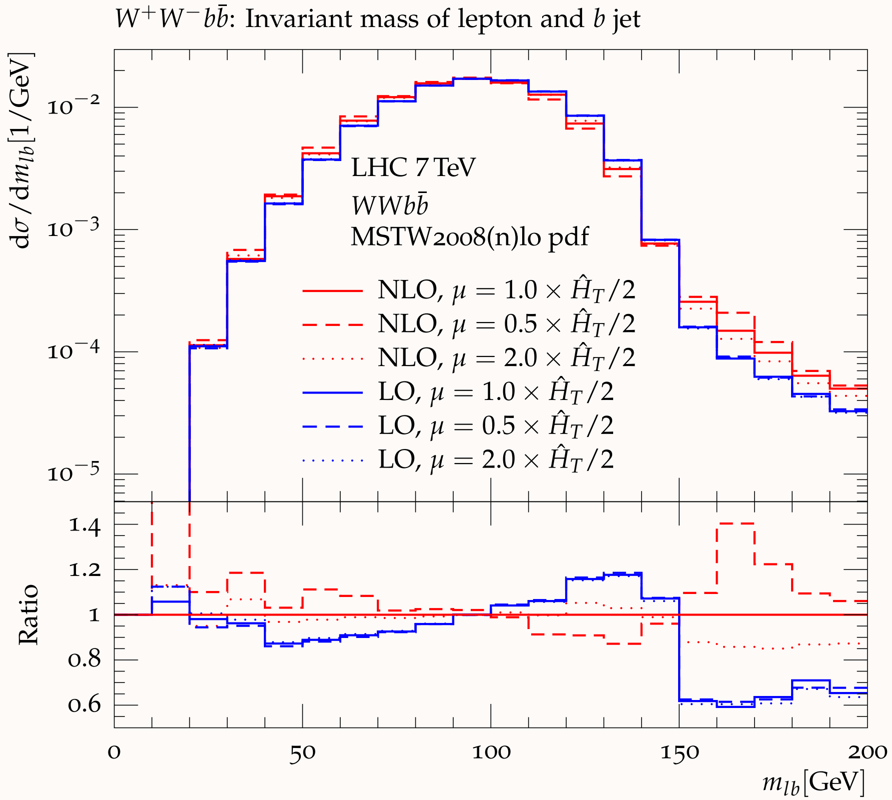
- similar features → agreement on qualitative level only, noting the differences however:
- different LHC energies & kinematical constraints (cuts), slightly different observable (a truth m_{lb})
- different dynamical scale choice (transverse mass of tops)
- non-resonant and off-shell effects due to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

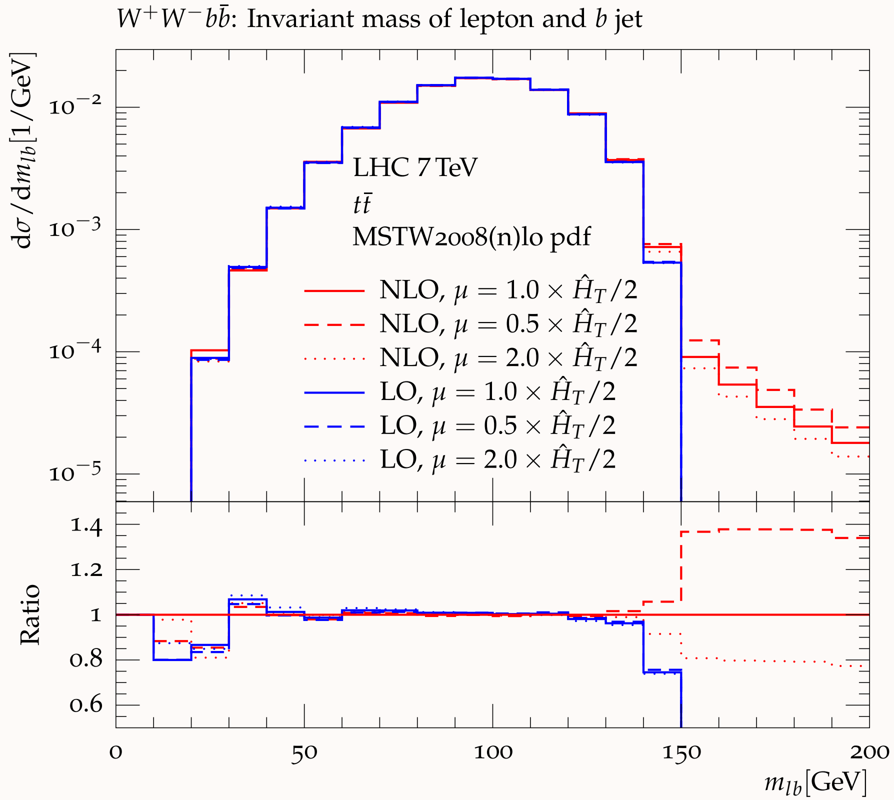




Normalized m_{lb}: scale versus m_t variation

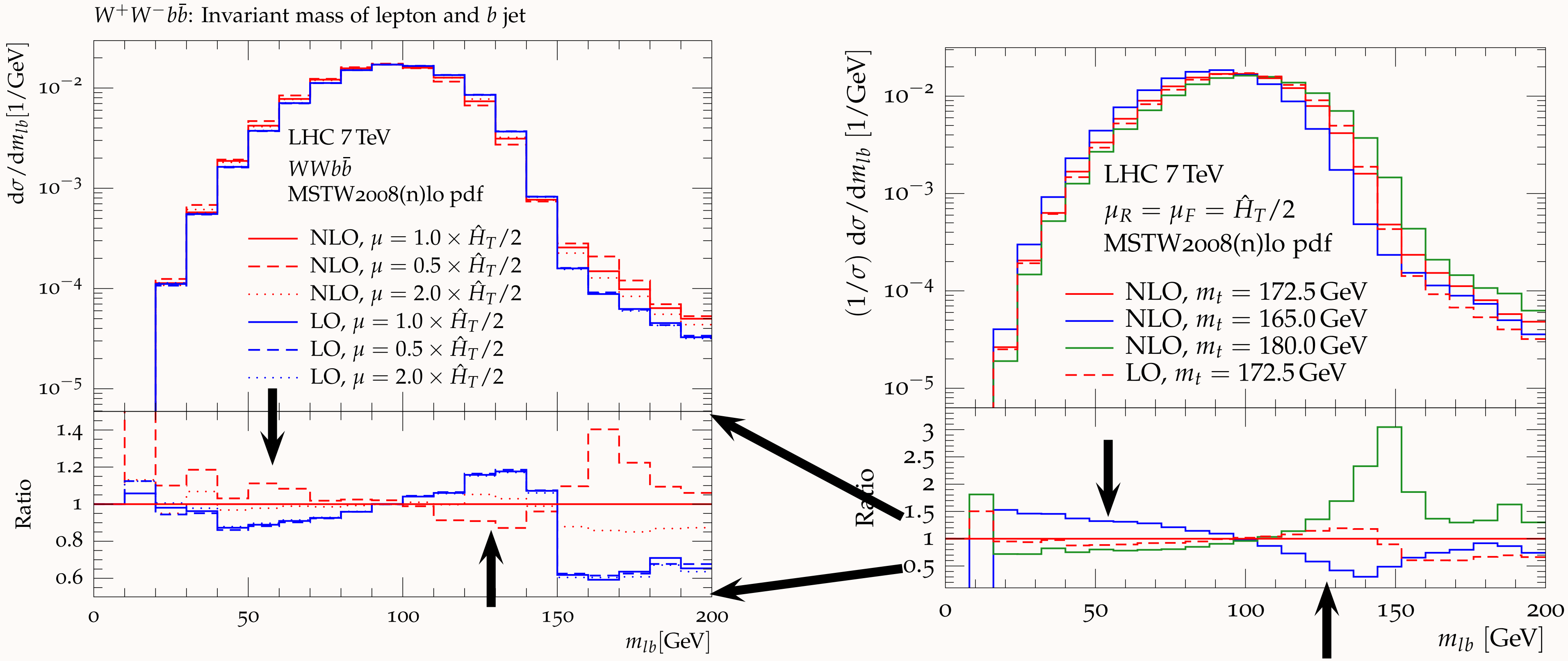
- shape modifications resulting from variation of scales by factors of two
- left panel, for the full approach $\longrightarrow$ visible
- right panel, for the factorized approach $\longrightarrow$ only in tails





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!)

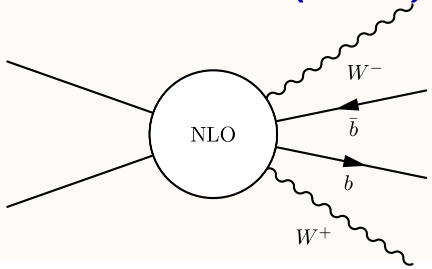


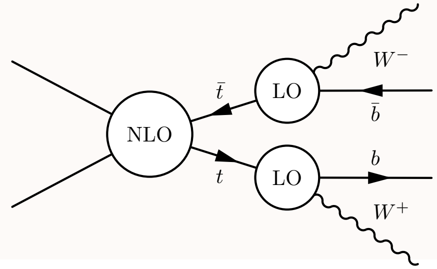
- scale factor variation mimics shape changes as induced by different m_t values → uncertainty
- @NLO: scale down corresponds to lower mass
- fit mass and scale simultaneously, but would resulting choice work for other distributions (eg. $m_{t\bar{t}}$)?

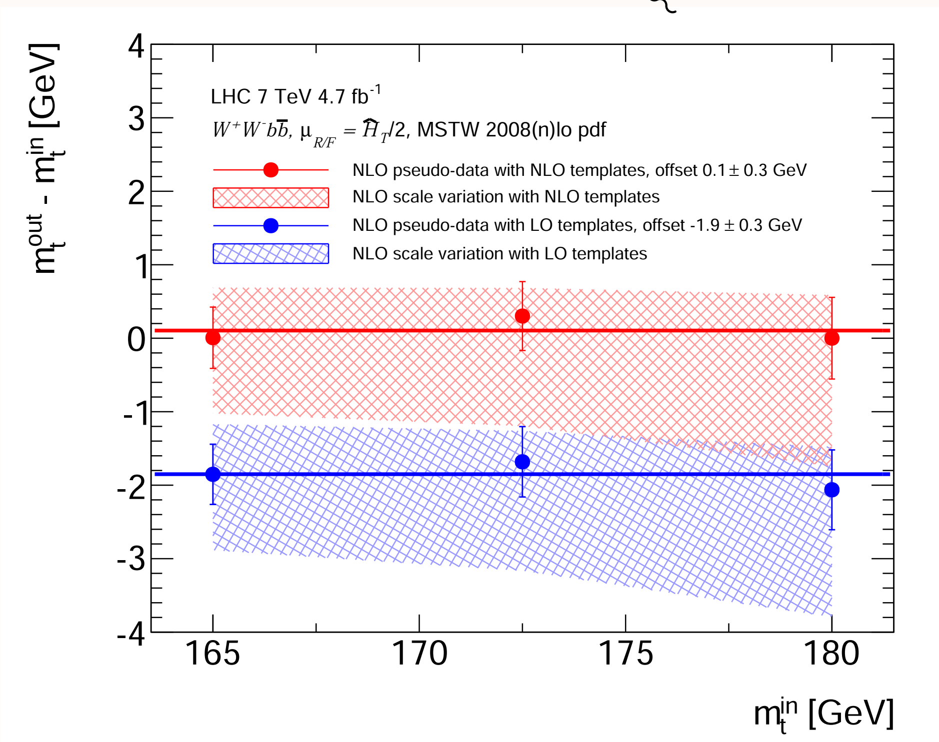
NLO templates vs pseudo-data (different models)

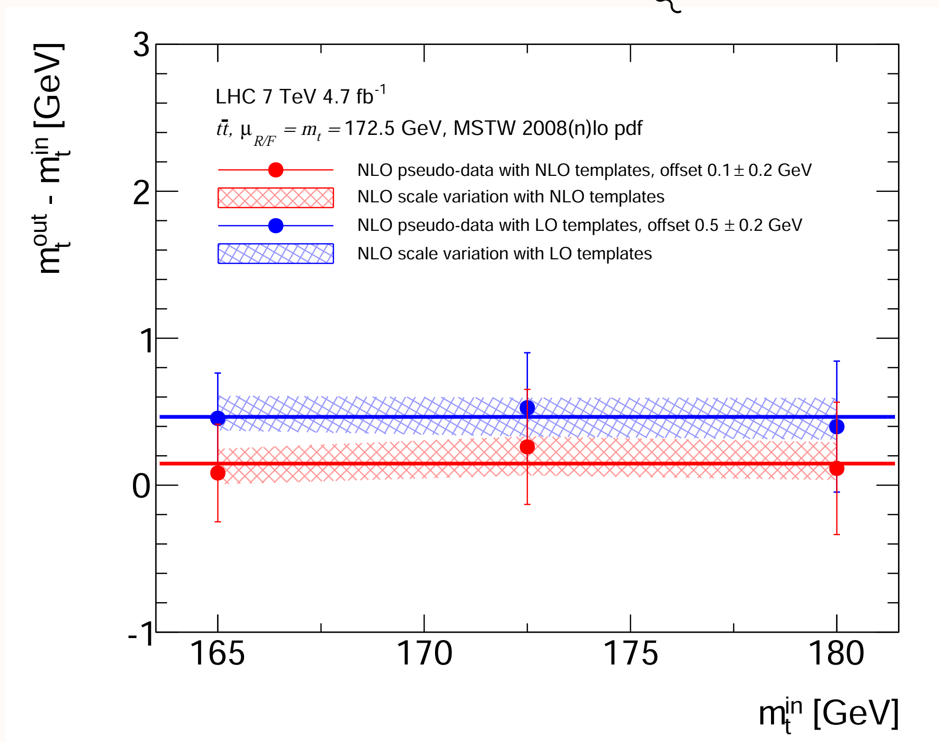
[Heinrich, Maier, Nisius, Schlenk, Winter, arXiv:1312.6659]

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









Use m_{lb} method in parton-level analysis assuming that data follows full / factorized theory [pseudo-data].
Test against the templates given by default scale choice NLO and LO theories [hypotheses].

- 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 $\pm 0.2\,\mathrm{GeV}$)

Motivation for new studies.

(- mostly emerging from the open questions after the earlier studies.)

Larger scale uncertainties driven by radiative corrections in decays, or non-resonant/non-factorizing contributions?

Parton shower effects? To what extent are radiative decay corrections well modelled by shower in NLO+PS?

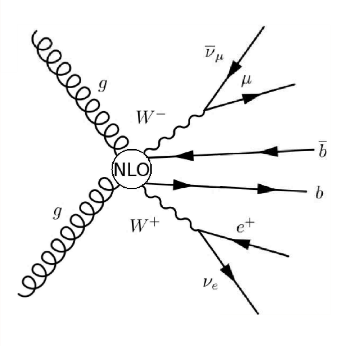
-> Include more calculations.

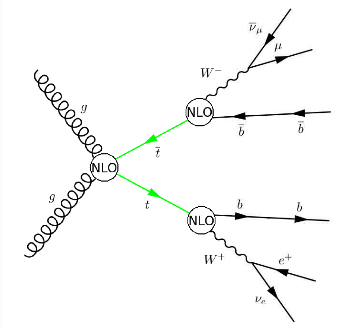
Observables with reduced scale dependence, and good top quark mass sensitivity?

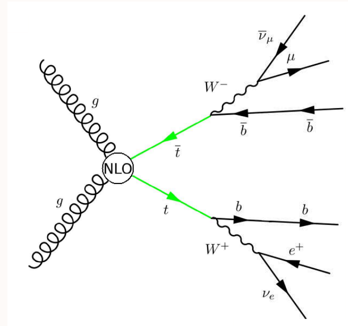
-> Study other observables/analysers than m_lb.

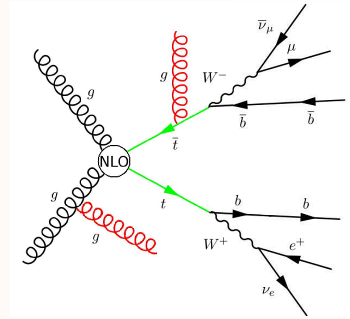
Different experimental setup:
LHC Run 2: higher center-of-mass energy, more luminosity, 'more gluons'

Active field of research (Nason et al, Bevilacqua et al, Hoang et al, Denner et al, ...)









Calculations used in the new studies.

$\mathrm{NLO_{full}}$: full QCD NLO corrections to WbWb̄ production with leptonic W decays

$\mathrm{NLO_{NWA}^{NLOdec}}$: NLO $t\bar{t}$ production and NLO decays in narrow-width approximation

$\mathrm{NLO_{NWA}^{LOdec}}$: NLO $t\bar{t}$ production and LO decays in narrow-width approximation

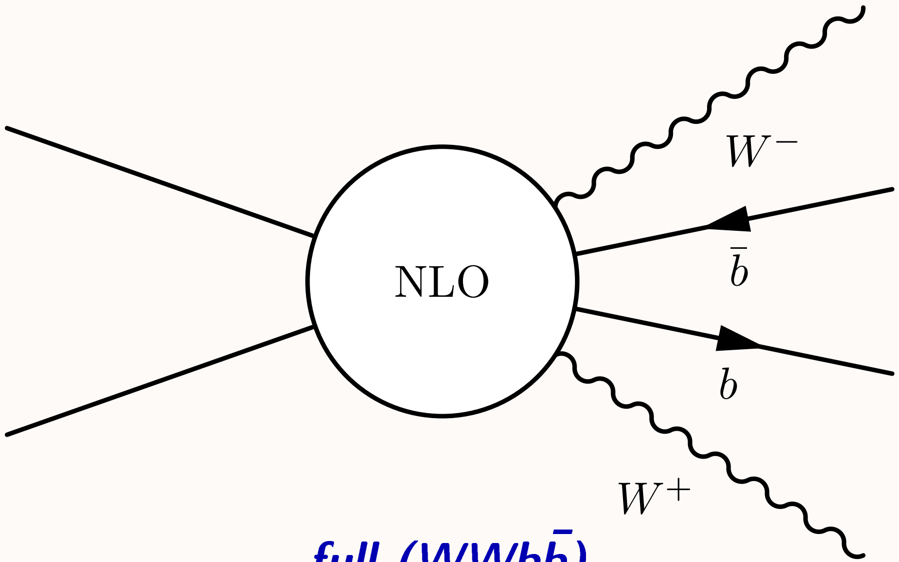
$\mathrm{NLO_{PS}}$: NLO $t\bar{t}$ production plus parton shower and decays via parton showering

Also available here: associated LO calculations: $\mathrm{LO_{full}}$, $\mathrm{LO_{NWA}^{LOdec}}$, $\mathrm{LO_{PS}}$

note NWA theory state-of-the-art: $\mathrm{NNLO_{NWA} + NLO_{EW}}$, $\mathrm{NNLOdec}$

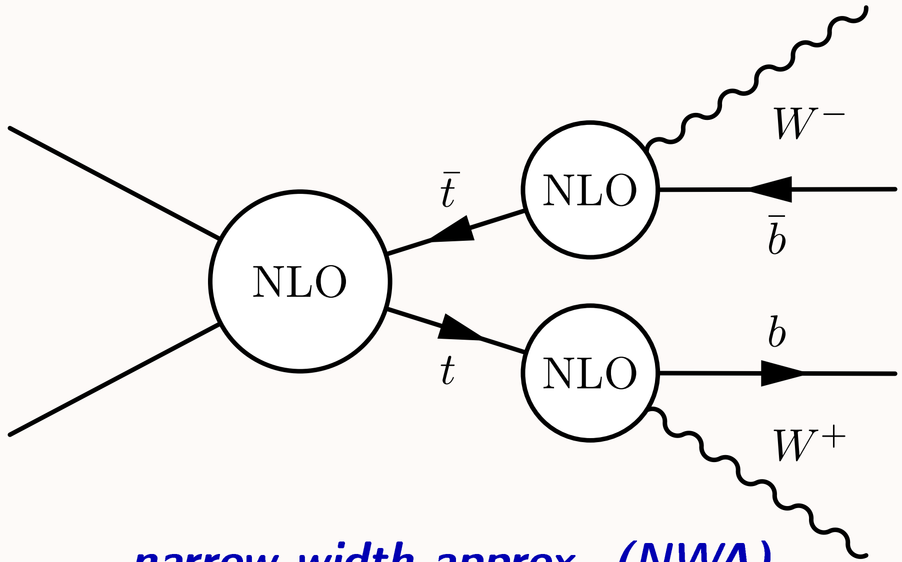
note shower state-of-the-art: $\mathrm{NLO_{full} + PS}$ -> see T. Jezo's talk.

Full calculation versus NWA



full ($WWb\bar{b}$)

- 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

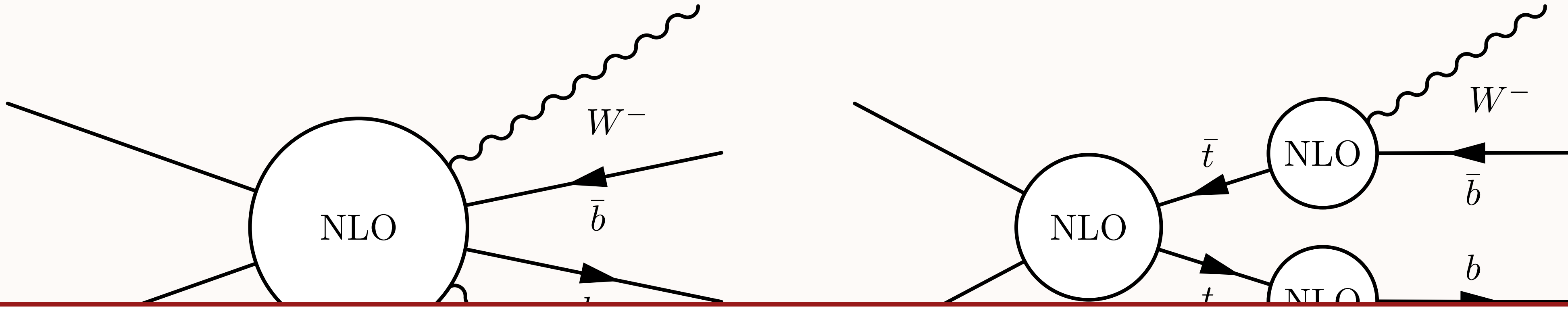


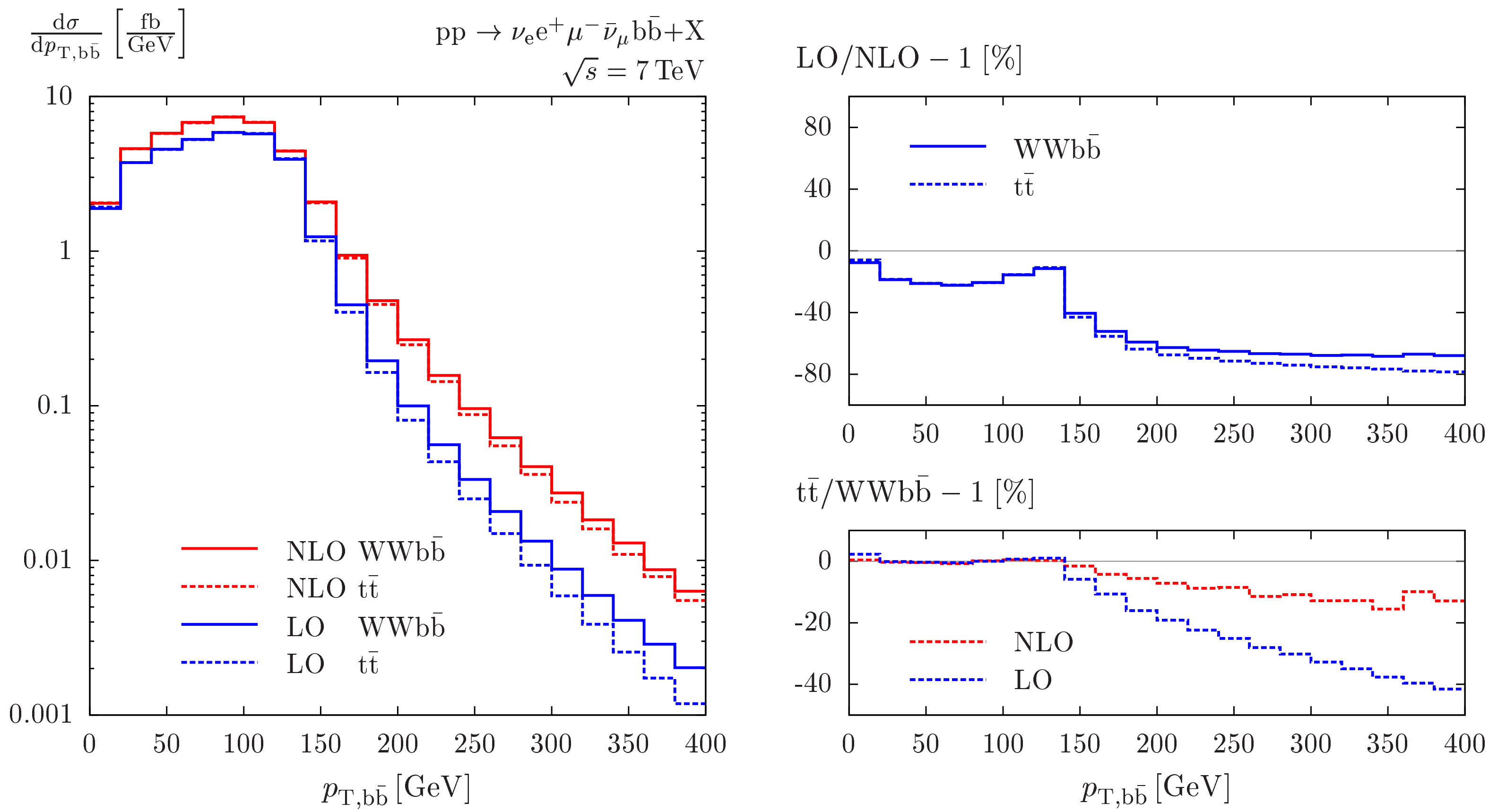
narrow width approx. (NWA)

- 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

- $\ell\ell$ channel comparison: [Denner, Dittmaier, Kallweit, Pozzorini, Schulze, LesHouches2011, arXiv:1203.6803]
  - no more than 1% deviations for inclusive cross sections (with experimental cuts), but effects can be (significantly) larger in differential distributions.
- Here, comparison will help disentangle effects from NLO decays and non-resonant/-factorizing contributions.

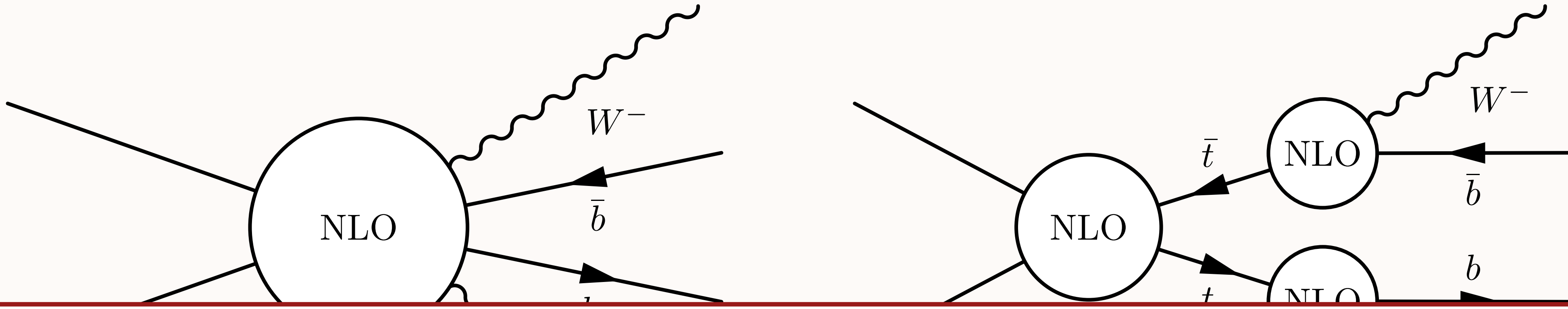
Full calculation versus NWA

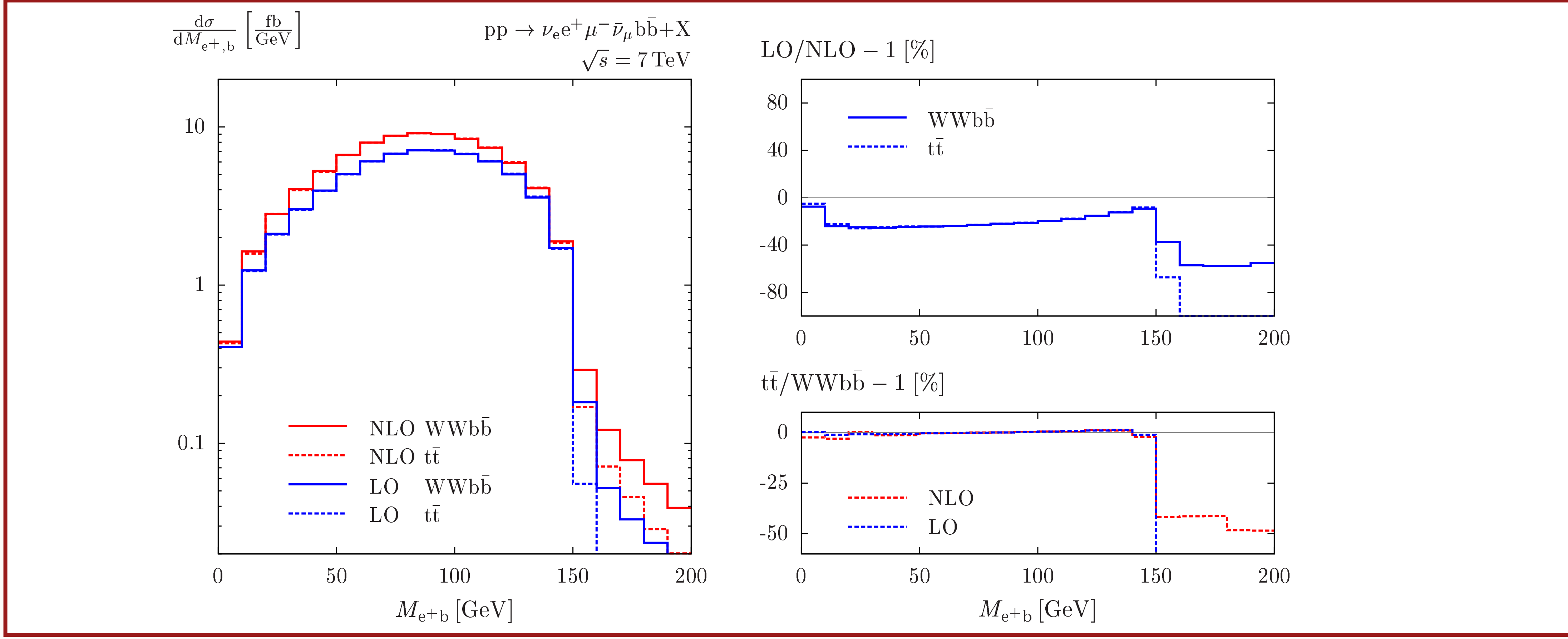




- Here, comparison will help disentangle effects from NLO decays and non-resonant/-factorizing contributions.

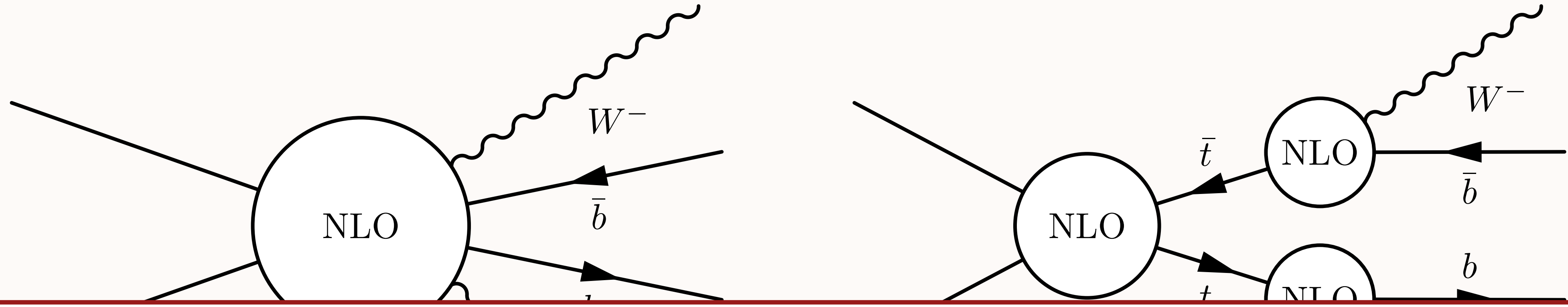
Full calculation versus NWA





- Here, comparison will help disentangle effects from NLO decays and non-resonant/-factorizing contributions.

Full calculation versus NWA



➡ ***Remark: state-of-the-art NNLO NWA.***

- On-shell $t\bar{t}$ NNLO QCD corrections to differential distributions, NLO EW corrections

  [Czakon, Heymes, Mitov '15], [Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro '17],[Hollik, Pagani '11], [Kühn, Scharf, Uwer '13]

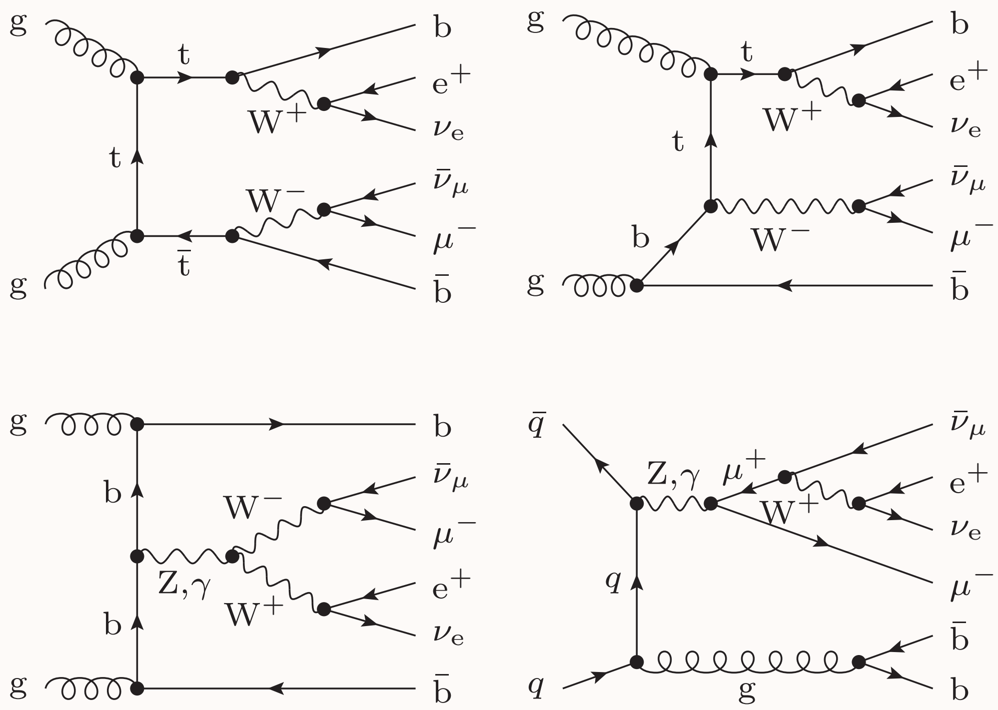
- Top decay: NNLO+NNLL QCD corrections

  [Beneke, Falgari, Klein, Schwinn '11], [Cacciari, Czakon, Mangano, Mitov, Nason '11], [Pecjak, Scott, Wang, Yang '16], [Ferroglia, Marzani, Pecjak, Yang '13], [Broggio, Papanastasiou, Signer '14], [Kidonakis '15], [Gao, Papanastasiou '17]

- Here, comparison will help disentangle effects from NLO decays and non-resonant/-factorizing contributions.

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

➡ ***Going beyond $t\bar{t}$ production to include offshell, non-factorizing and b-mass effects.***

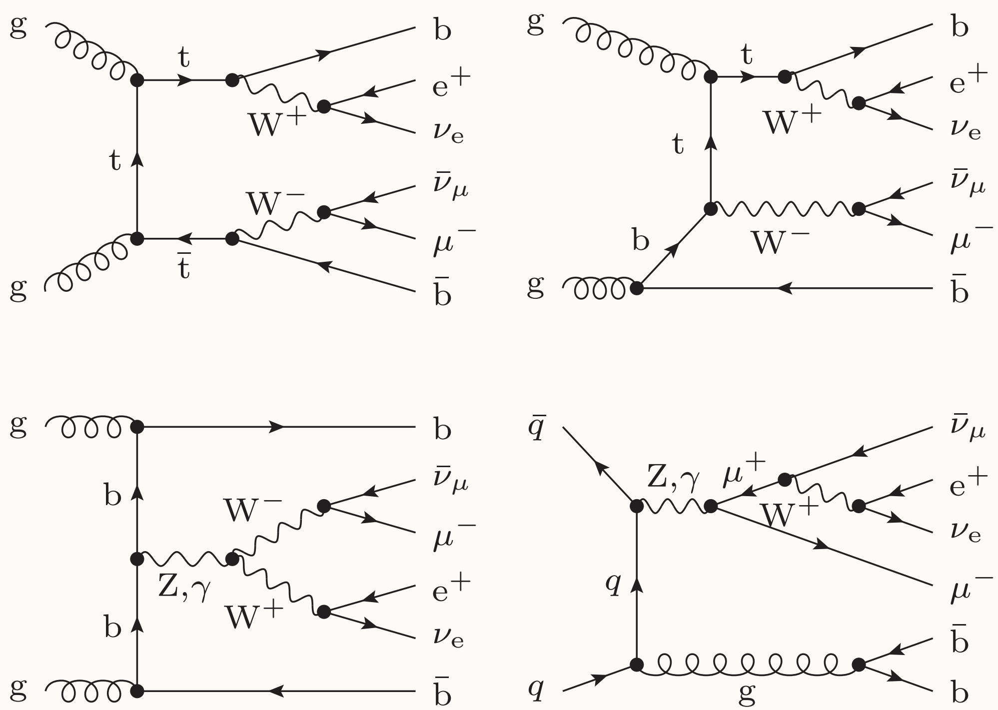


- full NLO treatment includes double-, single- and non-resonant contributions (DR – $t\bar{t}$-like) (SR – Wt-like) (NR – VV-like)
- complex-mass scheme
- finite top-quark and W width effects (offshell DR, SR, NR and interferences)
- first done in massless b-quark approximation (→ requires two hard b-jets) (→ $WWb\bar{b}$ in 5-flavour scheme)
  [Denner et al. arXiv:1012.3975, arXiv:1207.5018]
  [Bevilacqua et al. arXiv:1012.4230]
  [Heinrich et al. arXiv:1312.6659
- also available in 4-flavour scheme
  [Frederix, arXiv:1311.4893] [Cascioli, Kallweit, Maierhöfer, Pozzorini, arXiv:1312.0546]

- 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]
  [Biswas, Melnikov, Schulze, arXiv:1006.0910]

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

$WWb\bar{b}$ 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 2.2.3).
- 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]

Other observables

Top-quark mass $m_t^{(\mathrm{MC})}$ extracted from fitting $\frac{d\sigma}{d\Omega}(m_t^{\mathrm{MC}})$

- Differential distributions particularly sensitive to m_t:
  - $m_{\ell b}^2 = (p_\ell + p_b)^2$
  - $m_{T2}^2 = \min_{\mathbf{p}_T^{\nu_1} + \mathbf{p}_T^{\nu_2} = \mathbf{p}_T^{miss}} \left[\max \left\{ m_T^2 \left(\mathbf{p}_T^{(\ell b)_1}, \mathbf{p}_T^{\nu_1} \right), m_T^2 \left(\mathbf{p}_T^{(\ell b)_2}, \mathbf{p}_T^{\nu_2} \right) \right\} \right]$
  - $E_T^{\Delta R} = \frac{1}{2} \left(E_T^{\ell_1} \Delta R(\ell_1, b_1) + E_T^{\ell_2} \Delta R(\ell_2, b_2) \right)$
  - $m_{\ell\ell}^2 = (p_{\ell_1} + p_{\ell_2})^2$

where we choose the lepton-b-jet pairing (ℓ^+, b), (ℓ^-, b') minimizing $m_{\ell^+ b} + m_{\ell^- b'}$.

- Top quark mass sensitivity for $m_{\ell b}$ and m_{T2} is similar while it is lower for the other two variables.

- $\sqrt{s} = 13$ TeV
- PDF4LHC15_nlo_30_pdfas
- Fastjet anti-k_T algorithm with $R = 0.4$
- EW parameters:

$$\Gamma_t^{\mathrm{LO}} = 1.4806\,\mathrm{GeV} \qquad \Gamma_t^{\mathrm{NLO}} = 1.3535\,\mathrm{GeV},$$
$$\Gamma_W^{\mathrm{LO}} = 2.0454\,\mathrm{GeV} \qquad \Gamma_W^{\mathrm{NLO}} = 2.1155\,\mathrm{GeV},$$
$$\Gamma_Z = 2.4952\,\mathrm{GeV}$$

$$G_\mu = 1.16637 \cdot 10^{-5}\,\mathrm{GeV}^{-2}$$

$$M_W = 80.3850\,\mathrm{GeV} \qquad M_Z = 91.1876\,\mathrm{GeV}$$

- 5FNS (massless b's)

For the $\mathrm{NLO_{full}}$, $\mathrm{NLO_{NWA}^{LOdec}}$, $\mathrm{NLO_{PS}}$ calculations:

- Sherpa 2.2.3 interfaced to GoSam OLP

→ ***Calculational/experimental setup.***

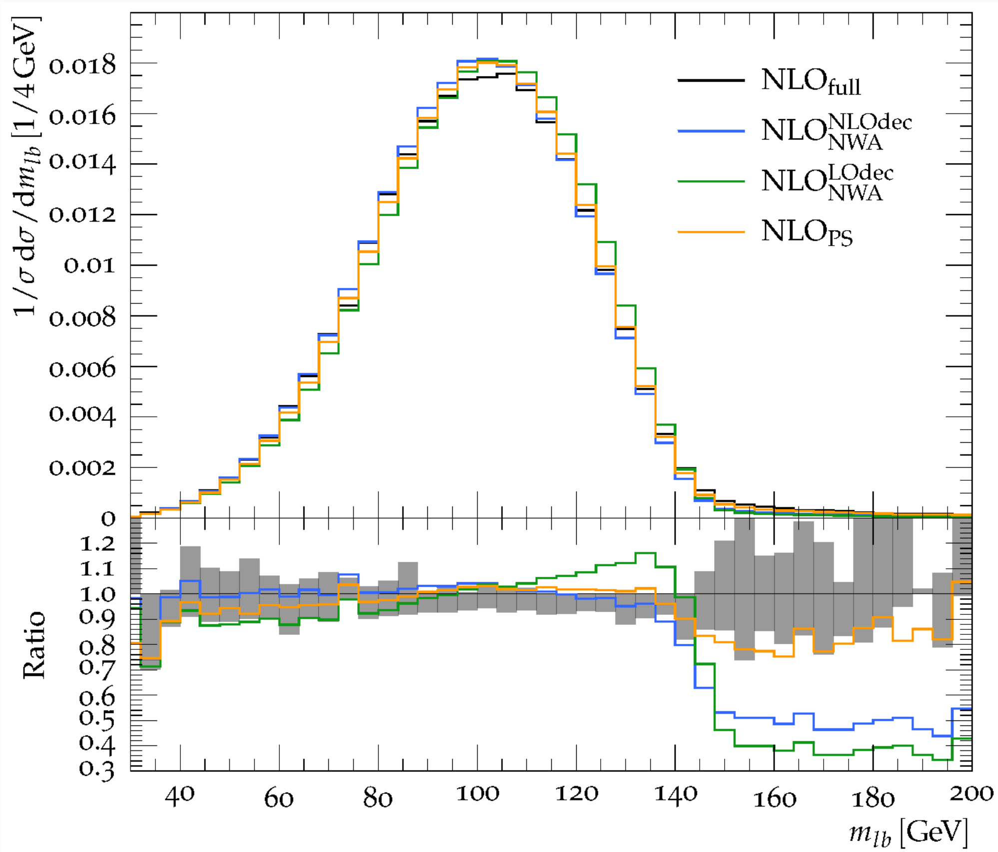
- Exactly two b-tagged jets with
  - $p_T^{\mathrm{jet}} > 25$ GeV and $|\eta^{\mathrm{jet}}| < 2.5$
- Exactly two oppositely charged leptons with
  - $p_T^\mu > 28$ GeV, $|\eta^\mu| < 2.5$
  - $p_T^e > 28$ GeV,$|\eta^e| < 2.47$ with the exclusion of $1.37 < |\eta^e| < 1.52$
  - $\Delta_R(\ell, \mathrm{jets}) > 0.4$
- $p_T^{\ell b} > 120$ GeV

Dilepton final states at NLO

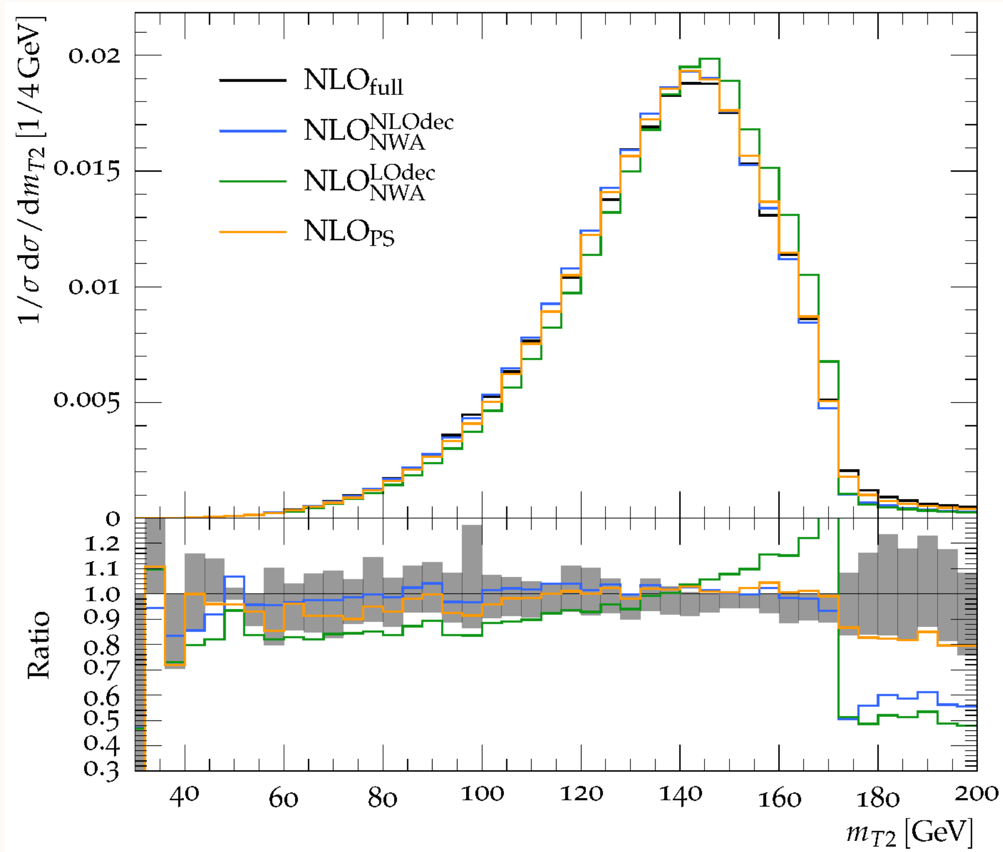
[Heinrich et al, arXiv:1709.08615]

➡ ***Comparison of different theory predictions for analyser shape observables at LHC 13 TeV.***

- m_{lb} analyser



- m_{T2} analyser



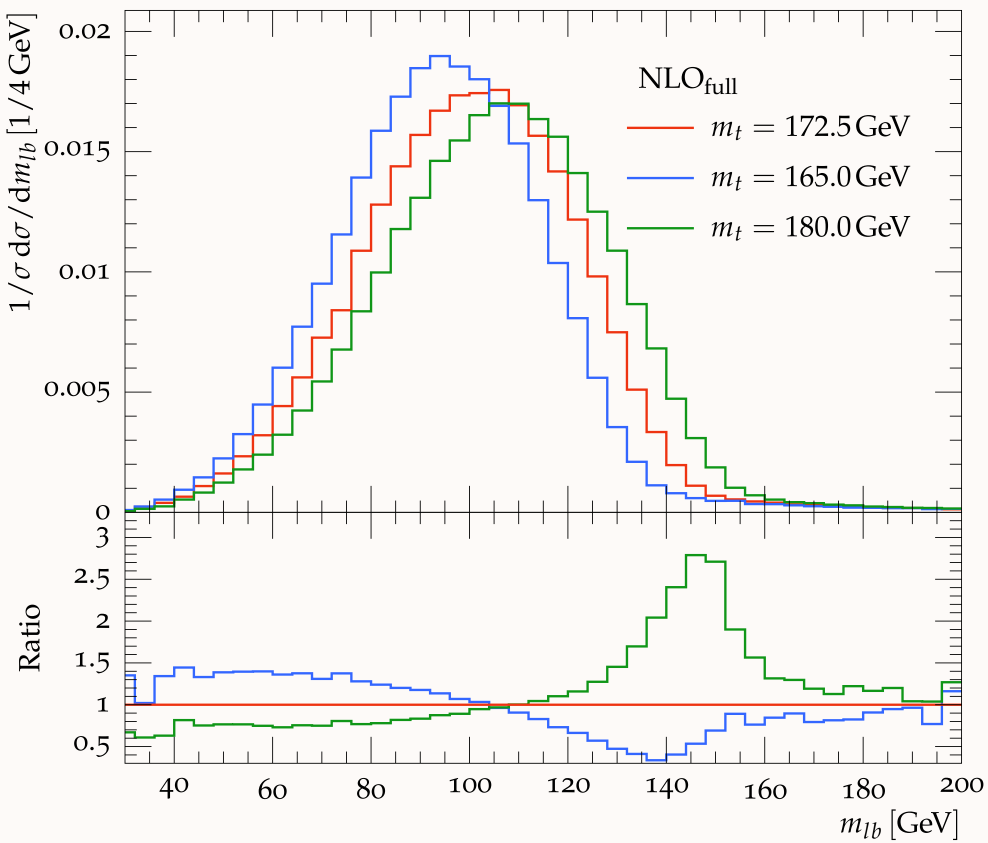
- scale uncertainty band for full NLO calculation included in ratio plot
- top quark mass sensitive observables with ‘reasonable’ theory uncertainties

Top quark mass variation

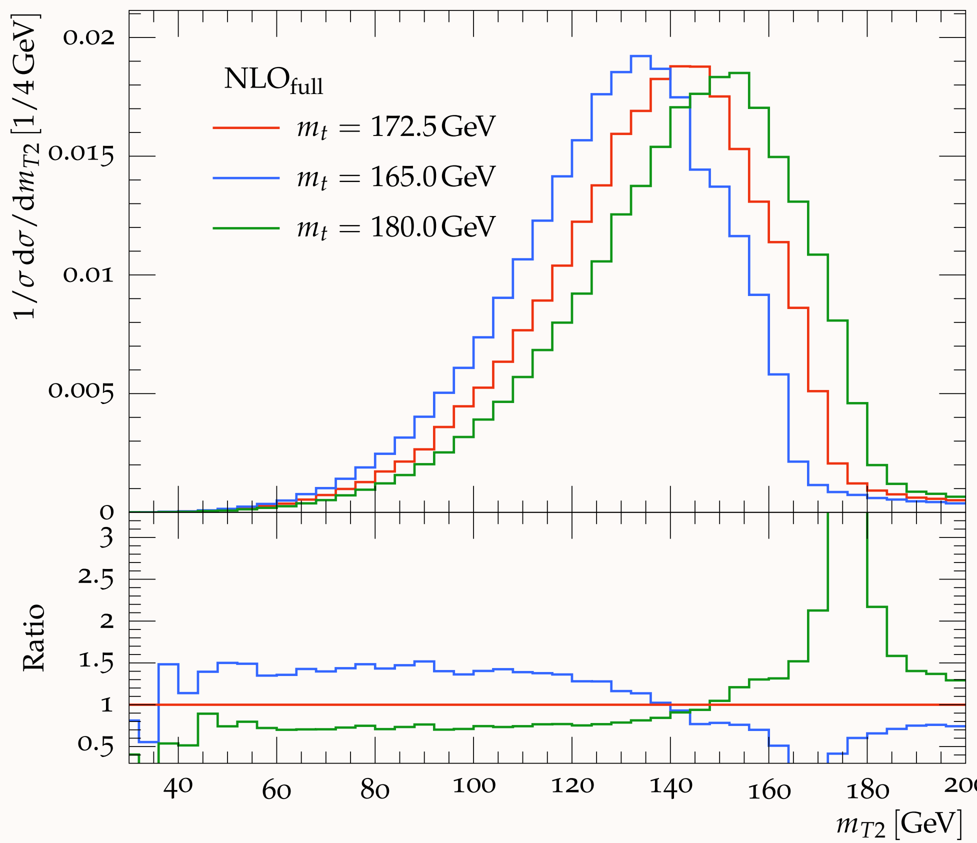
[HEINRICH ET AL, ARXIV:1709.08615]

➡ ***Shape comparison of full NLO predictions for analyser shape observables at LHC 13 TeV.***

- m_{lb} analyser



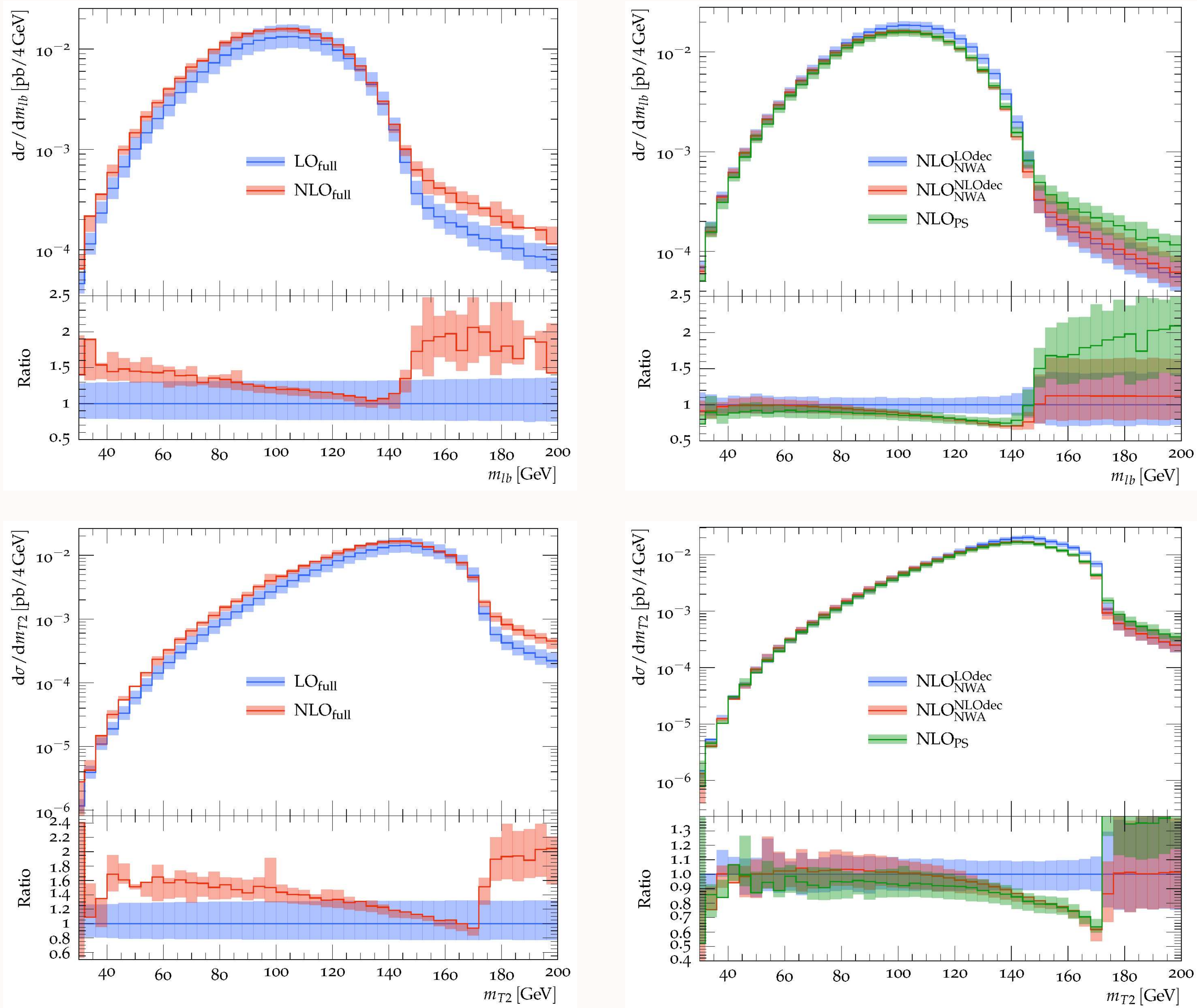
- m_{T2} analyser



- harder shapes for increasing top quark masses
- top quark mass sensitive observables with ‘reasonable’ theory uncertainties

Scale dependence

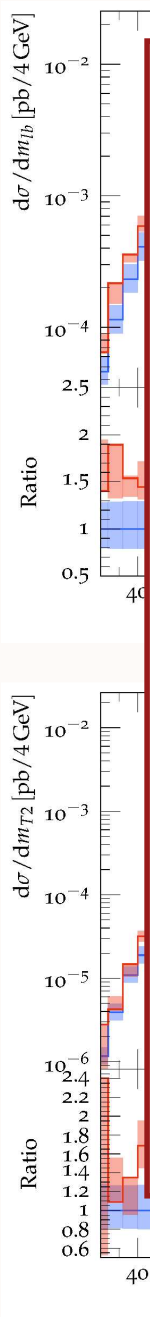
[HEINRICH ET AL, ARXIV:1709.08615]



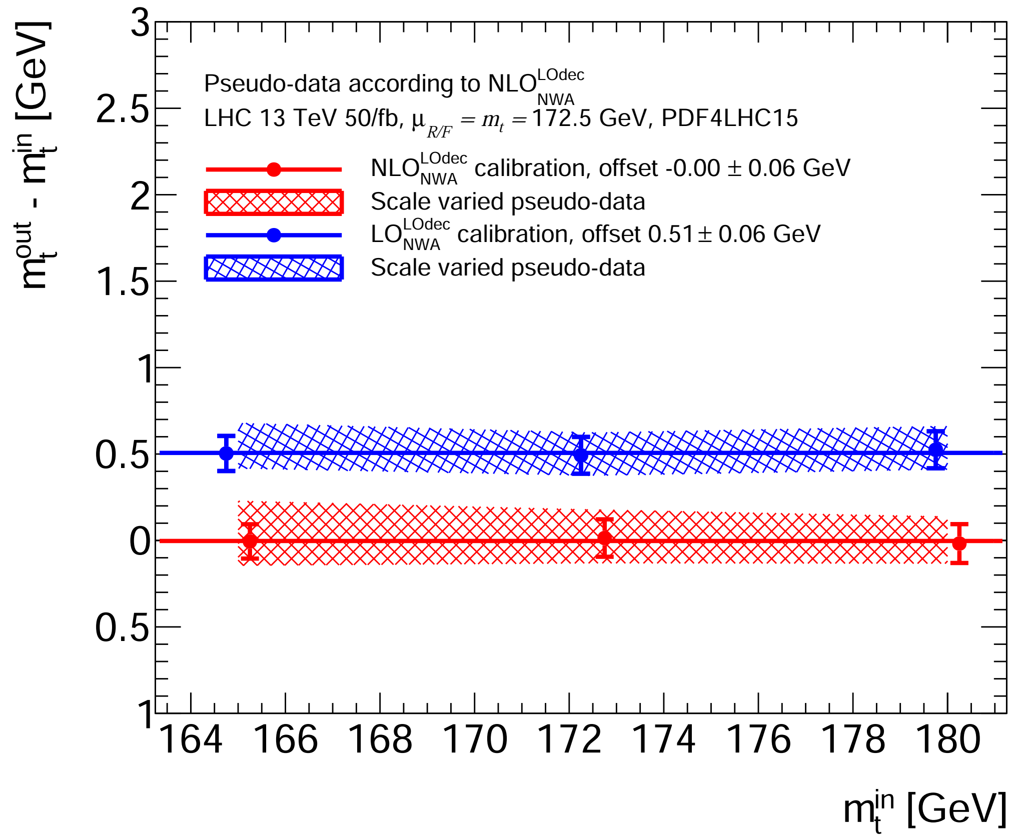
- m_{lb} analyser
- m_{T2} analyser

Scale dependence

[HEINRICH ET AL, ARXIV:1709.08615]



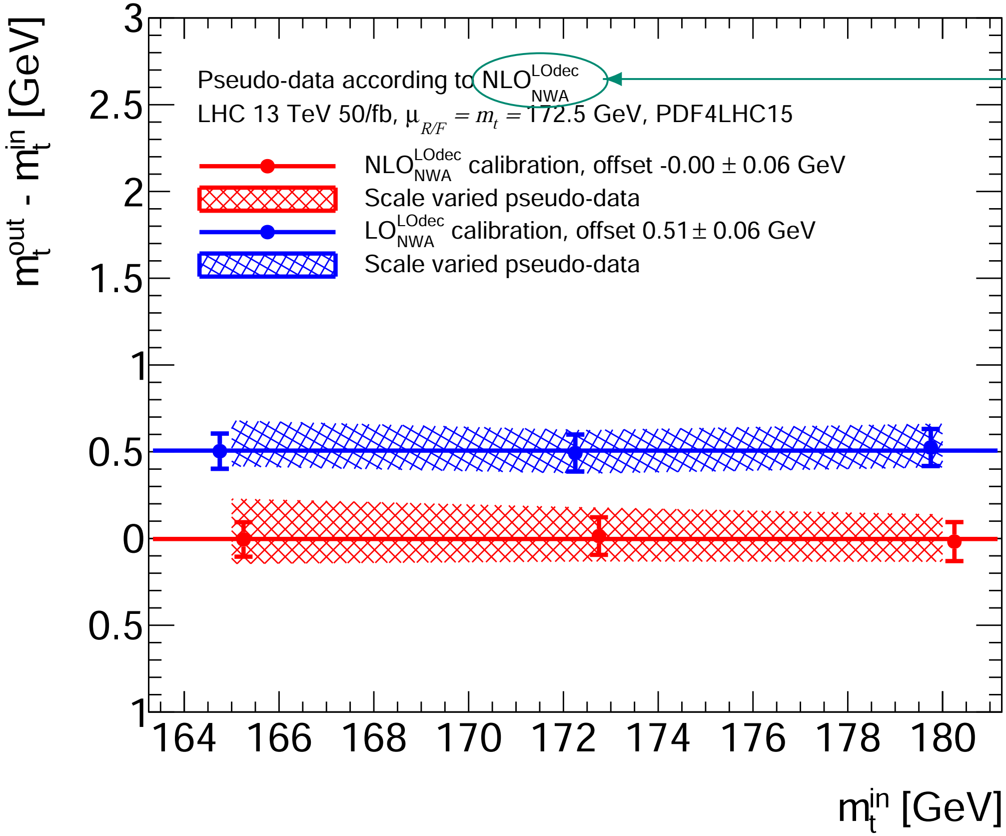
➡ ***How to read the mass offset plots:***



Scale dependence

[HEINRICH ET AL, ARXIV:1709.08615]

➡ *How to read the mass offset plots:*

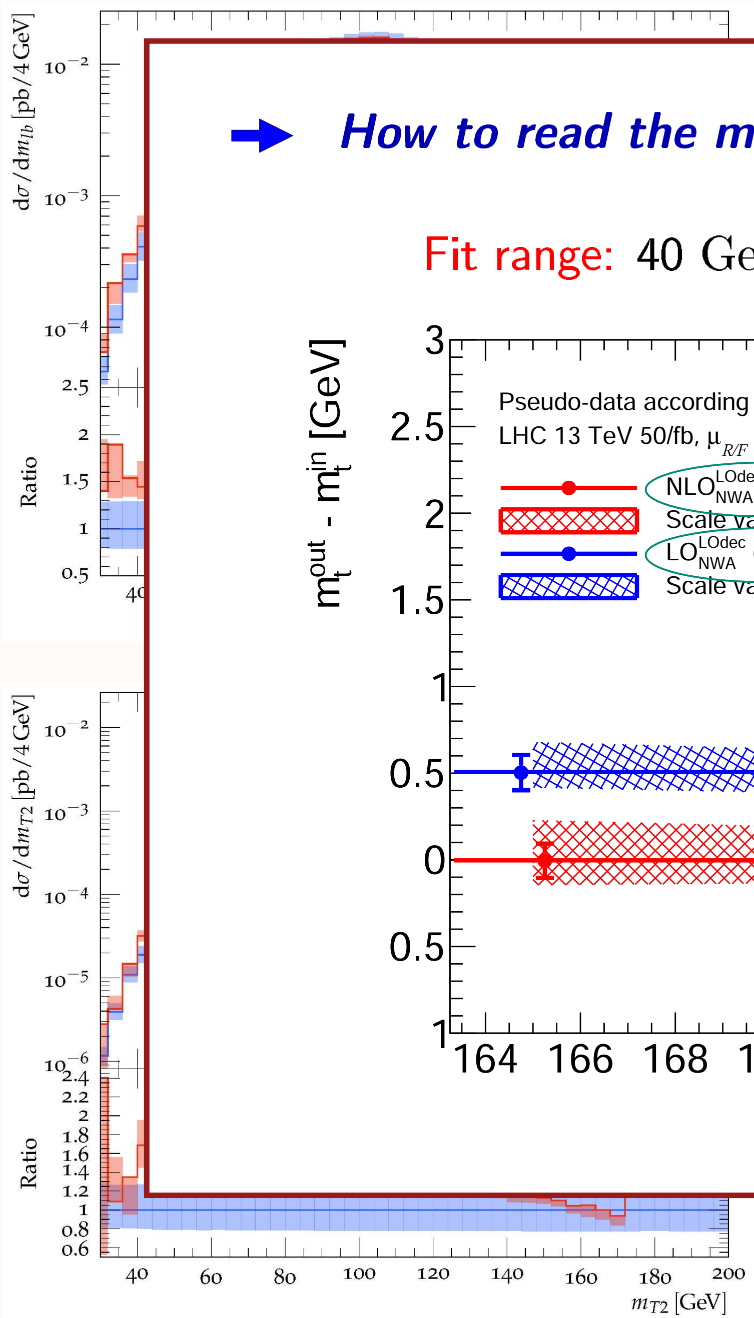


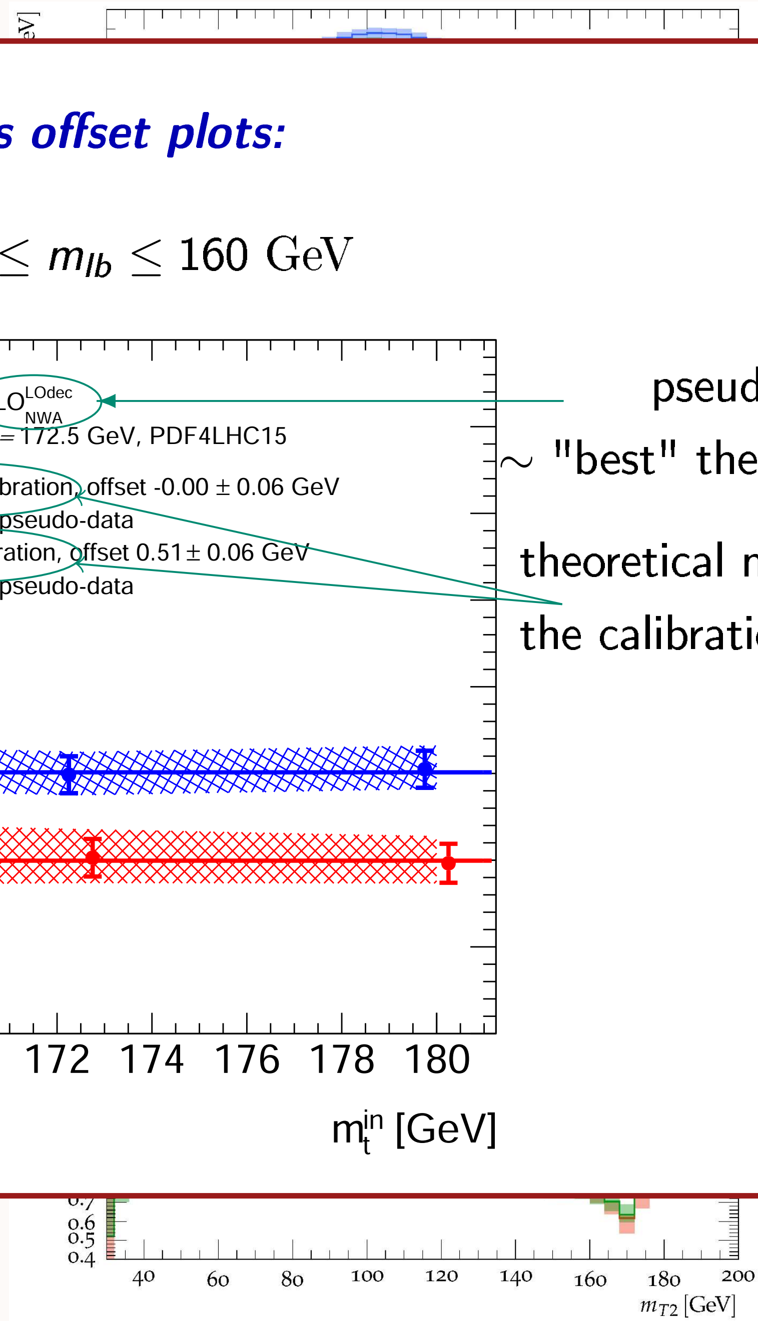
pseudo-data set

∼ "best" theoretical model

Scale dependence

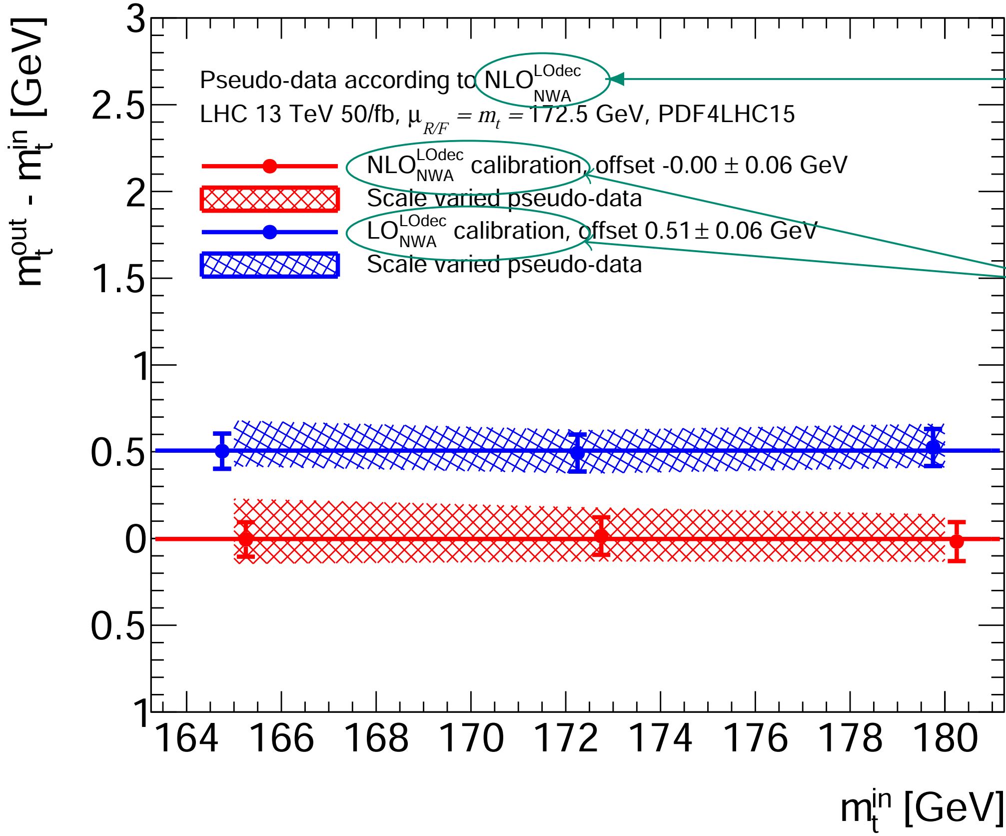
[HEINRICH ET AL, ARXIV:1709.08615]





➡ *How to read the mass offset plots:*

Fit range: $40\ \text{GeV} \leq m_{lb} \leq 160\ \text{GeV}$



pseudo-data set

∼ "best" theoretical model

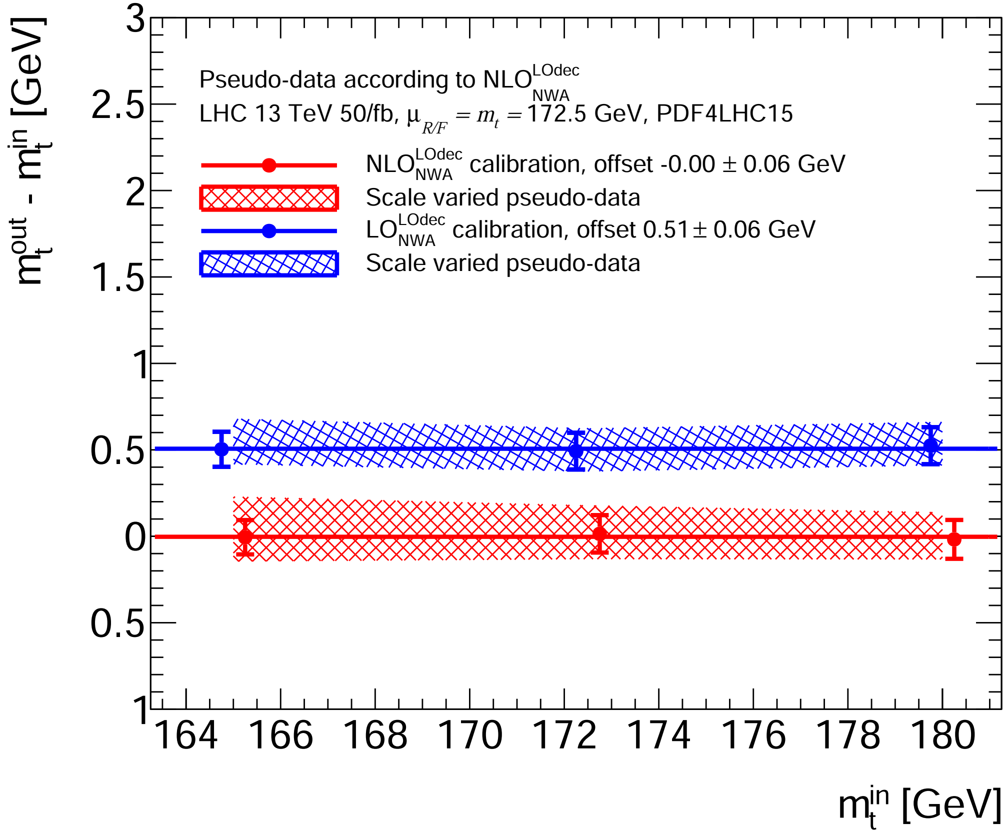
theoretical model used for the calibration fit function

Scale dependence

[HEINRICH ET AL, ARXIV:1709.08615]

How to read the mass offset plots:

Fit range: 40 GeV $\leq m_{lb} \leq$ 160 GeV



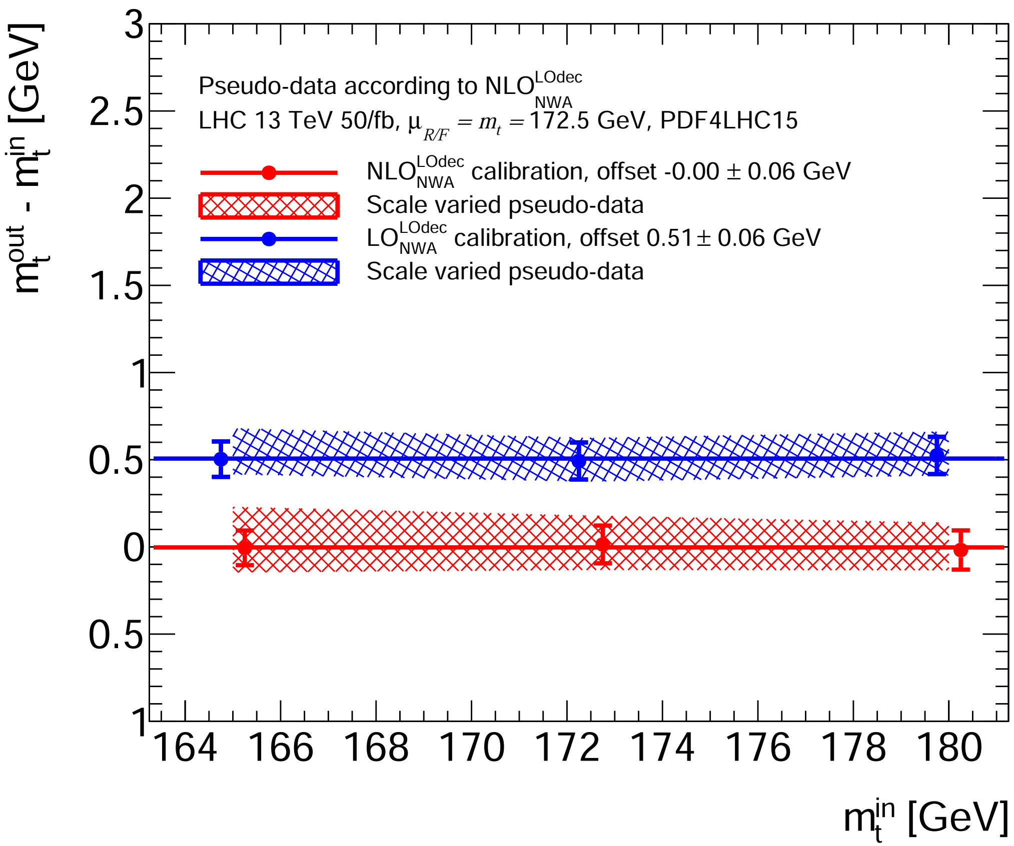
points : fitted difference with stat. uncertainties

Scale dependence

[HEINRICH ET AL, ARXIV:1709.08615]

How to read the mass offset plots:

Fit range: 40 GeV $\leq m_{lb} \leq$ 160 GeV

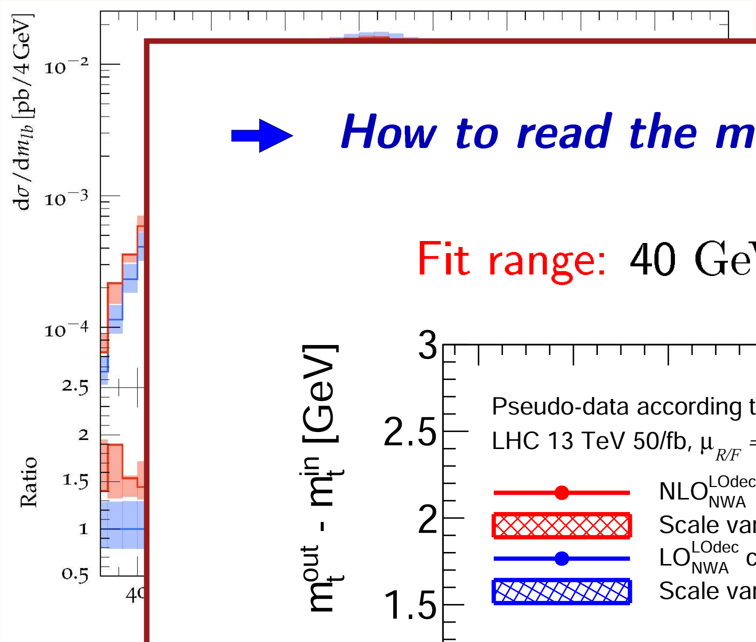


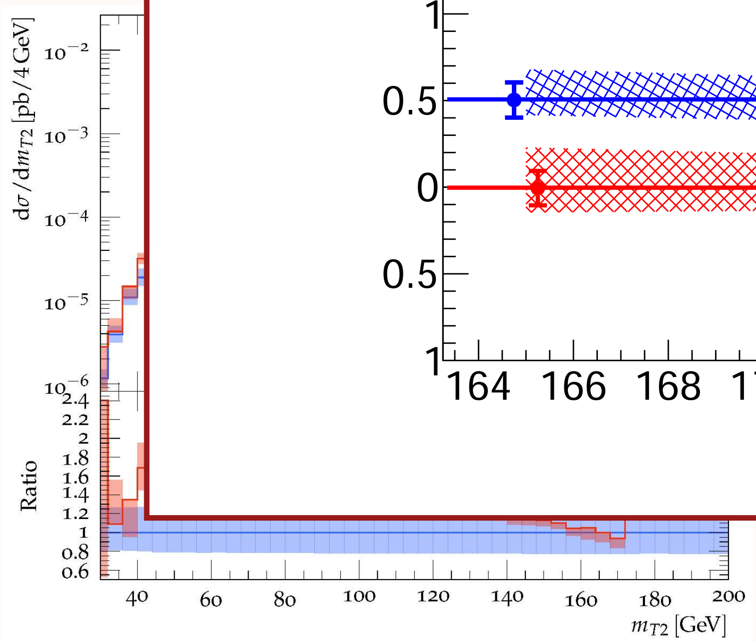
points : fitted difference with stat. uncertainties

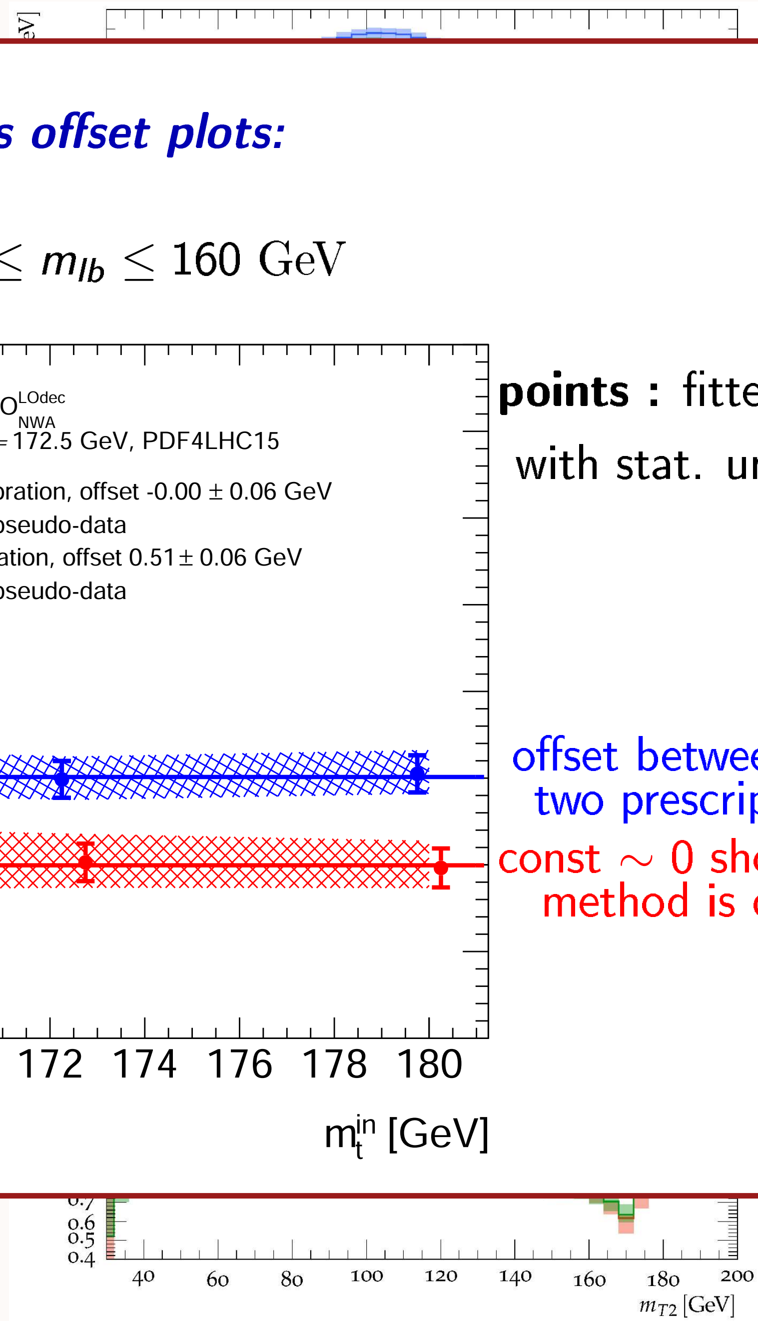
const ~ 0 shows the method is closed

Scale dependence

[Heinrich et al, arXiv:1709.08615]

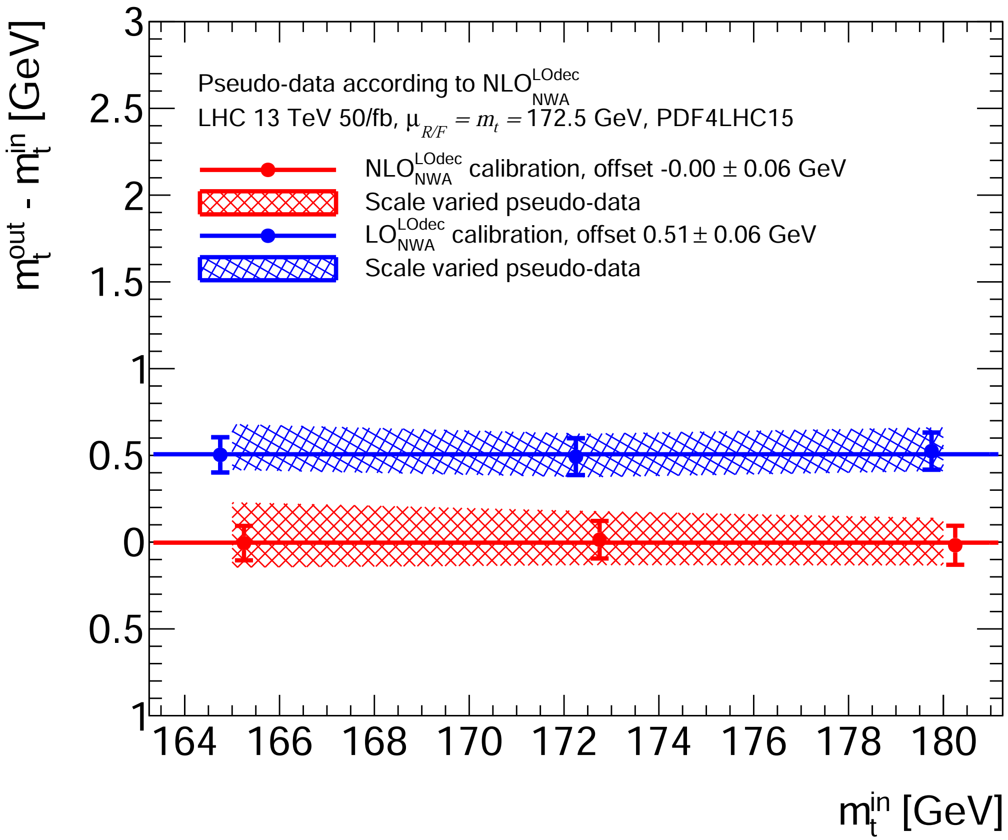






➡ ***How to read the mass offset plots:***

Fit range: $40\ \mathrm{GeV} \leq m_{lb} \leq 160\ \mathrm{GeV}$



points : fitted difference with stat. uncertainties

offset between the two prescriptions

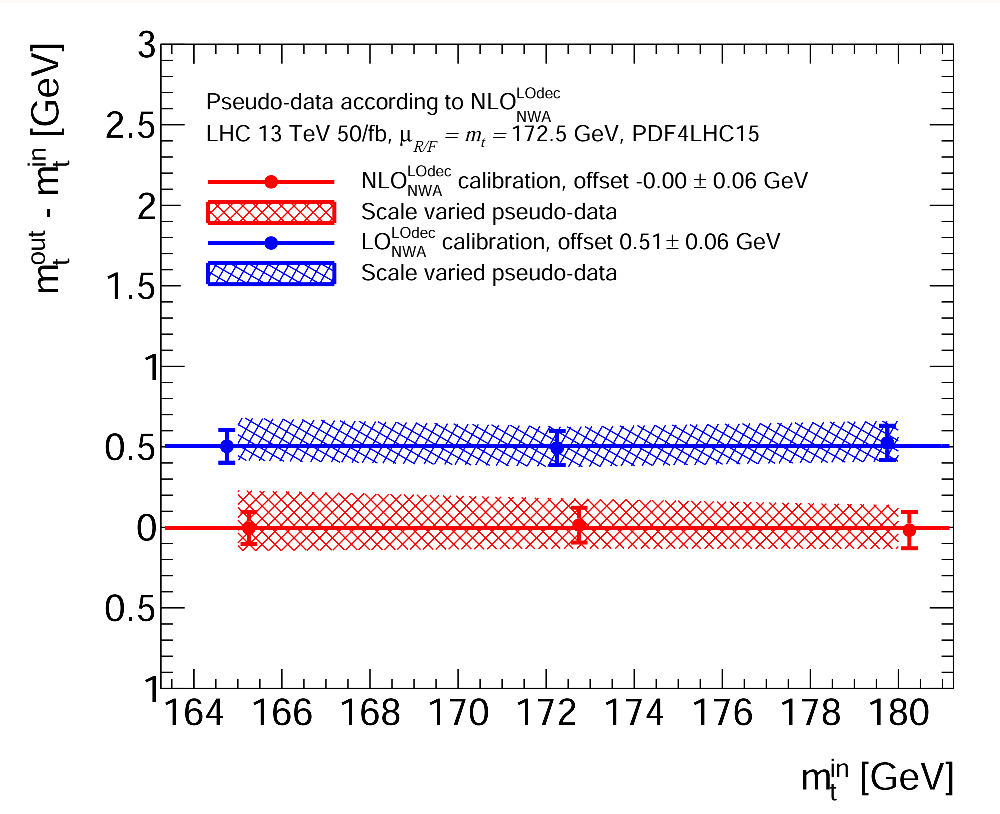
const $\sim$ 0 shows the method is closed

Fit results for m_{lb}

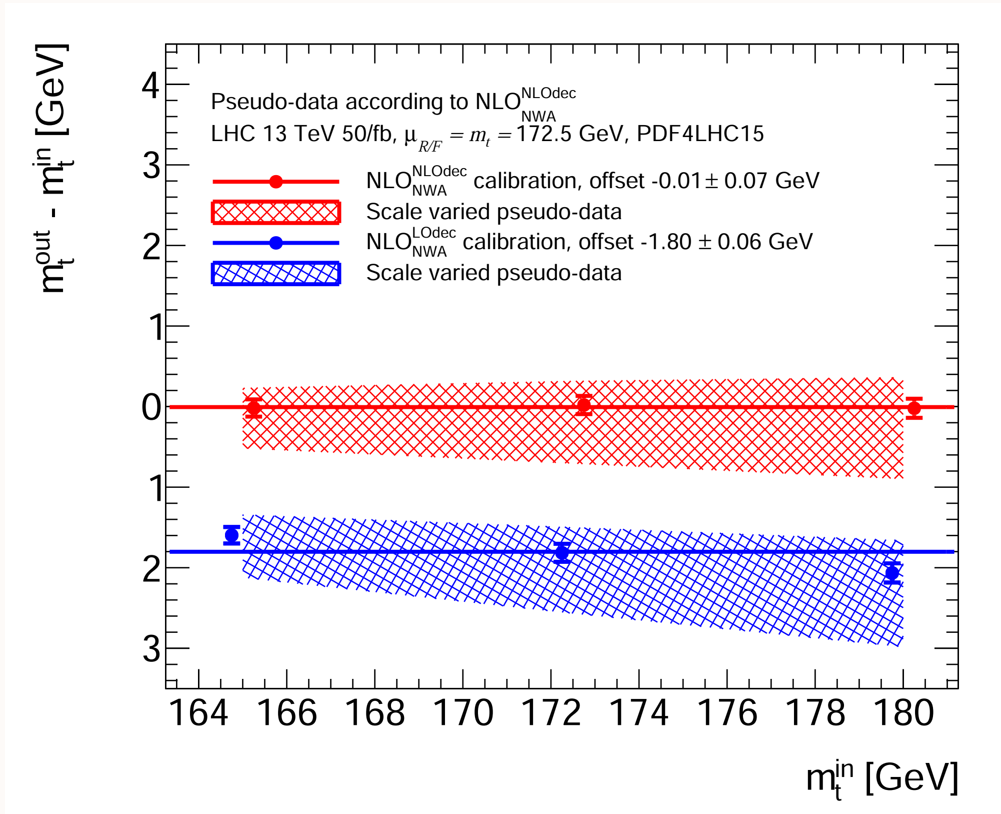
[Heinrich et al, arXiv:1709.08615]

➡ ***Changing the order of perturbation theory in production or decay only.***

- NLO NWA vs LO NWA using LOdec



- NLO NWA NLOdec vs LOdec



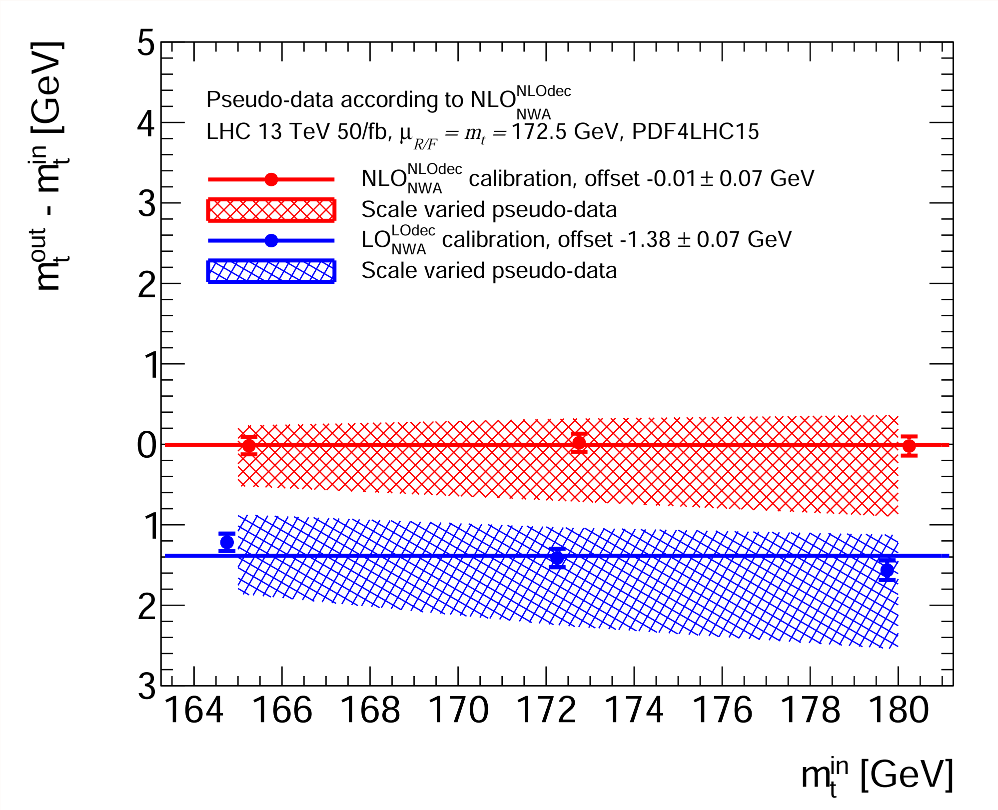
- NLO description of the top quark decay makes a large difference
- much larger mass shifts and much larger uncertainties on mass determination due to scale variations

Fit results for m_{lb}

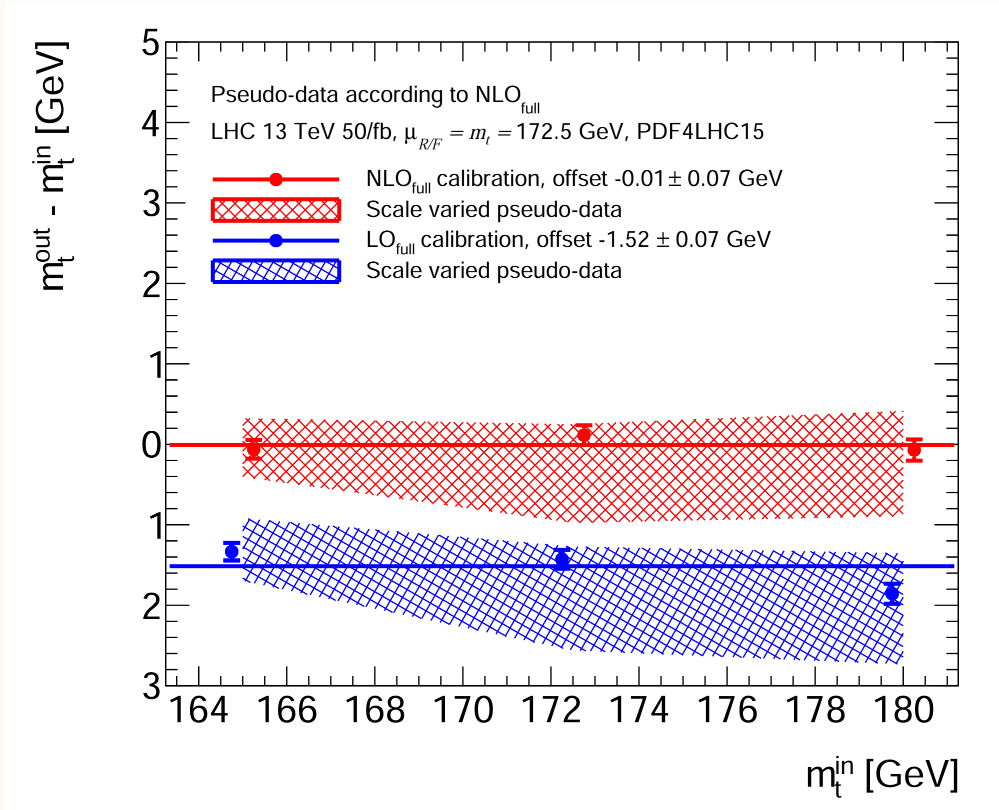
[HEINRICH ET AL, ARXIV:1709.08615]

➡ ***Changing the order of perturbation theory in both production and decay.***

- NLO NWA NLOdec vs LO NWA LOdec



- NLO full vs LO full



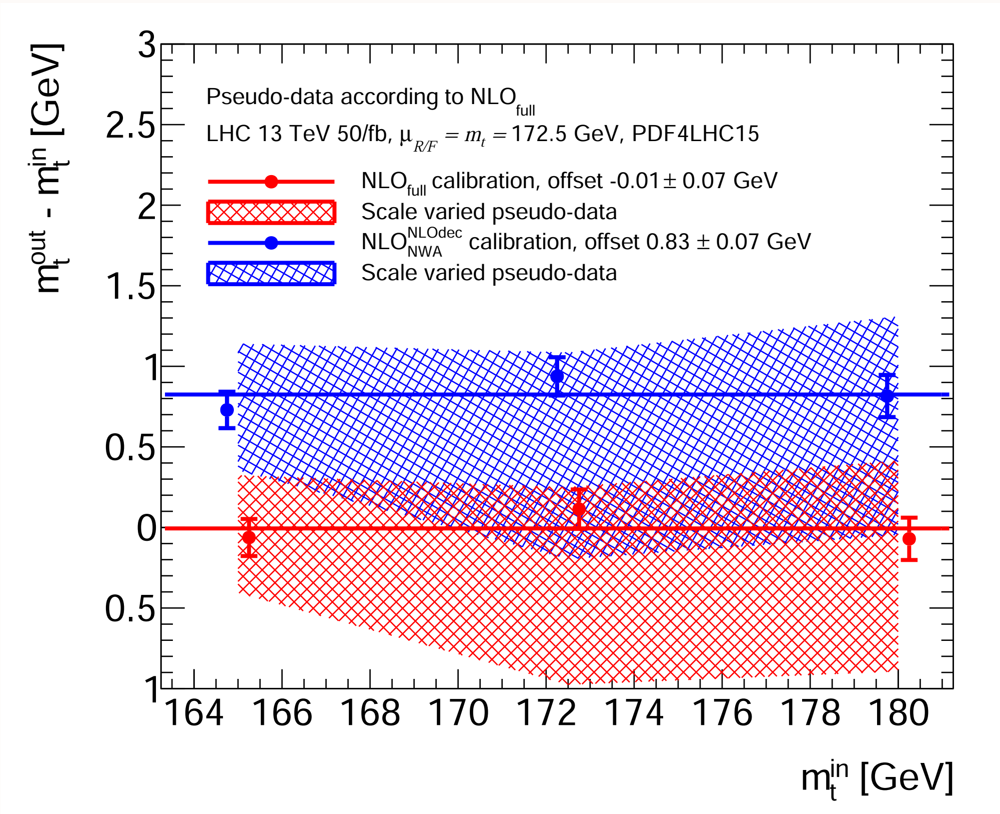
- similar magnitude of mass shift
- similar size of scale uncertainties on mass determination

Fit results for m_{lb}

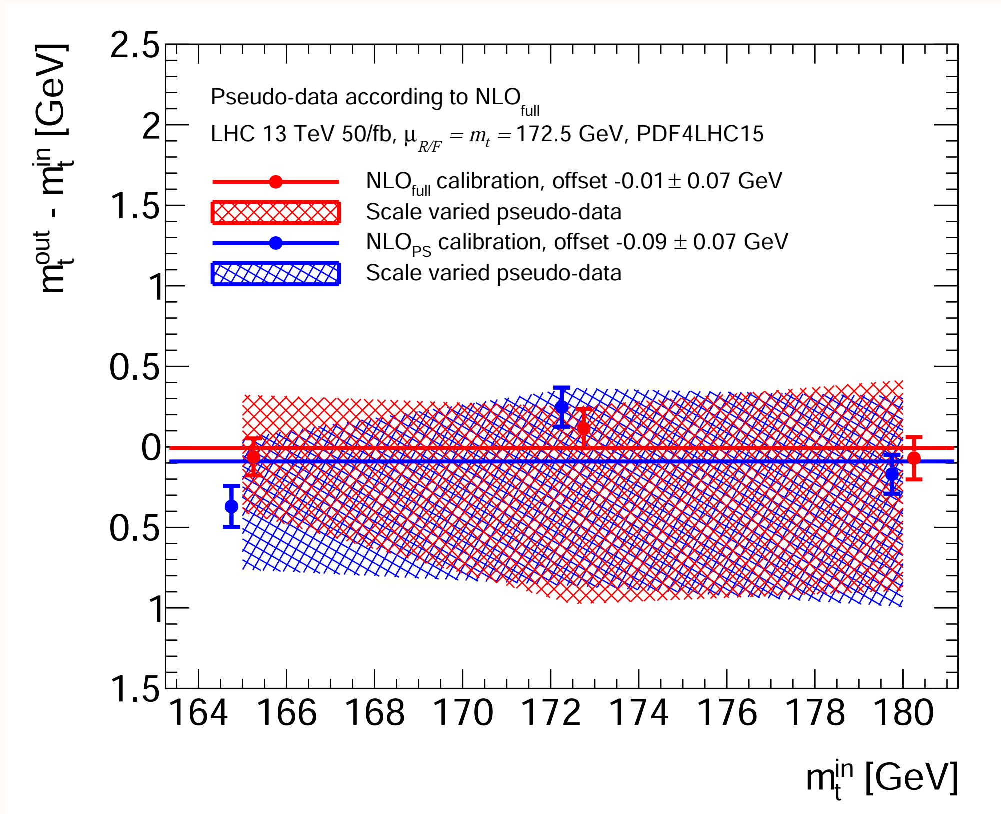
[Heinrich et al, arXiv:1709.08615]

➡ ***Comparing full with NWA calculations.***

- NLO full vs NLO NWA NLOdec



- NLO full vs NLO+PS



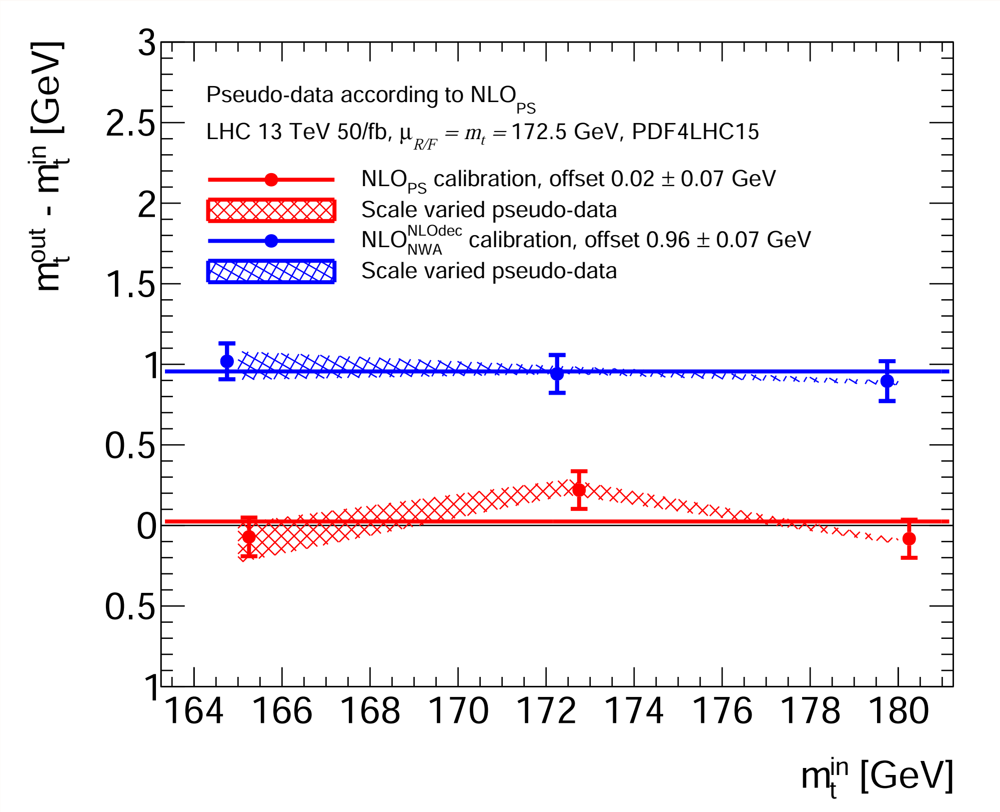
- NLO full vs NLO NWA produces mass shift of the order of 0.8 GeV
- nearly zero mass shift between NLO full and NLO+PS is accidental (agreement despite different physics content)

Fit results for m_{lb}

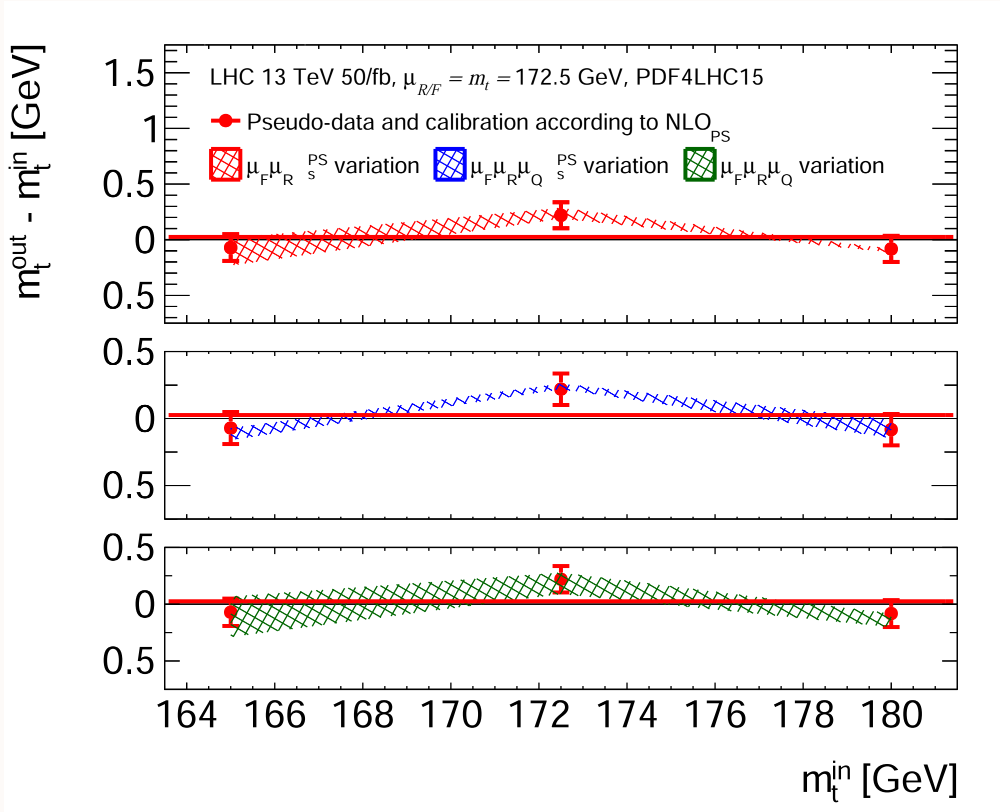
[Heinrich et al, arXiv:1709.08615]

➡ ***Comparing NLO+PS matching with the NLO NWA approach.***

- NLO+PS vs NLO NWA NLOdec



- NLO+PS variation schemes



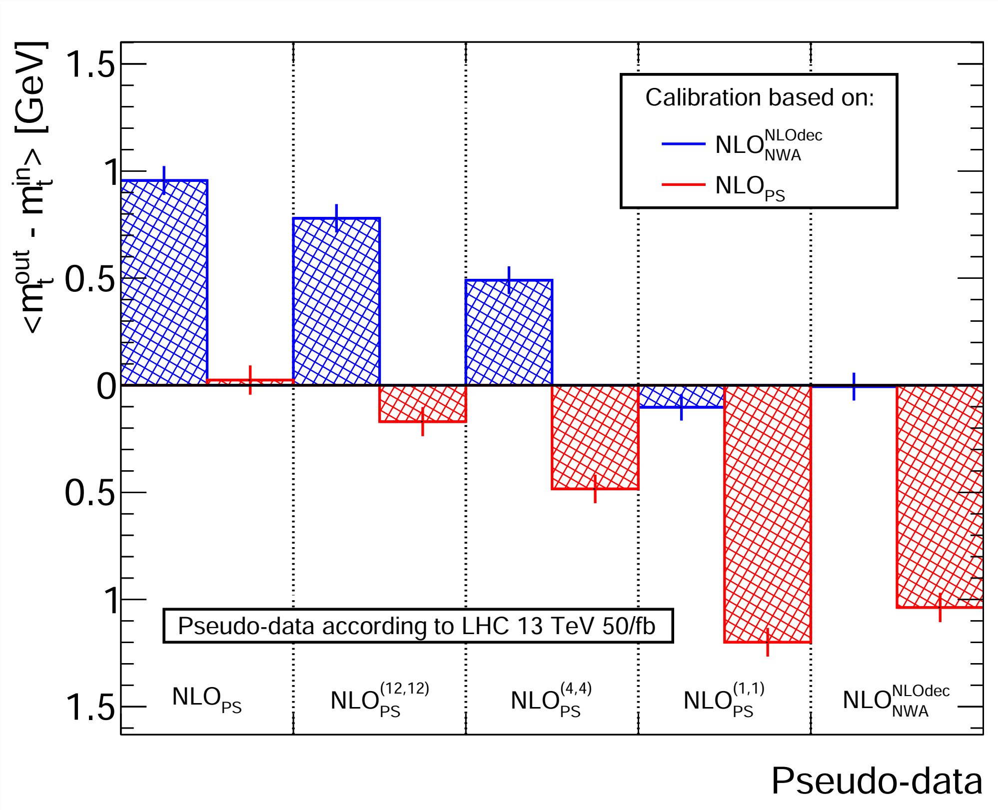
- further investigation needed to understand source of largish $\mathcal{O}(1\ \mathrm{GeV})$ mass shift (resummation effect or ME corrections)
- rhs plot: different schemes of assessing the theory uncertainties of the NLO+PS shape predictions

Fit results for m_{lb}

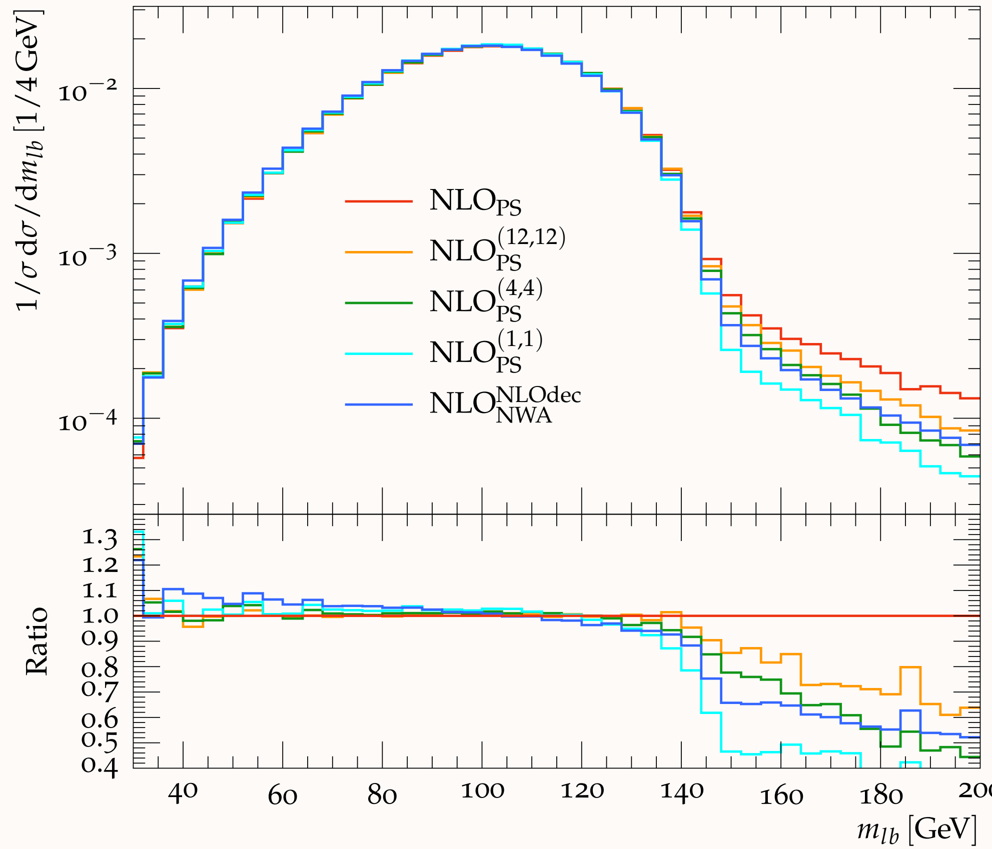
[Heinrich et al, arXiv:1709.08615]

➡ ***Estimating the impact of resummation effects.***

- NLO+PS vs NLO NWA NLOdec
  restricted showering



- associated m_{lb} distributions



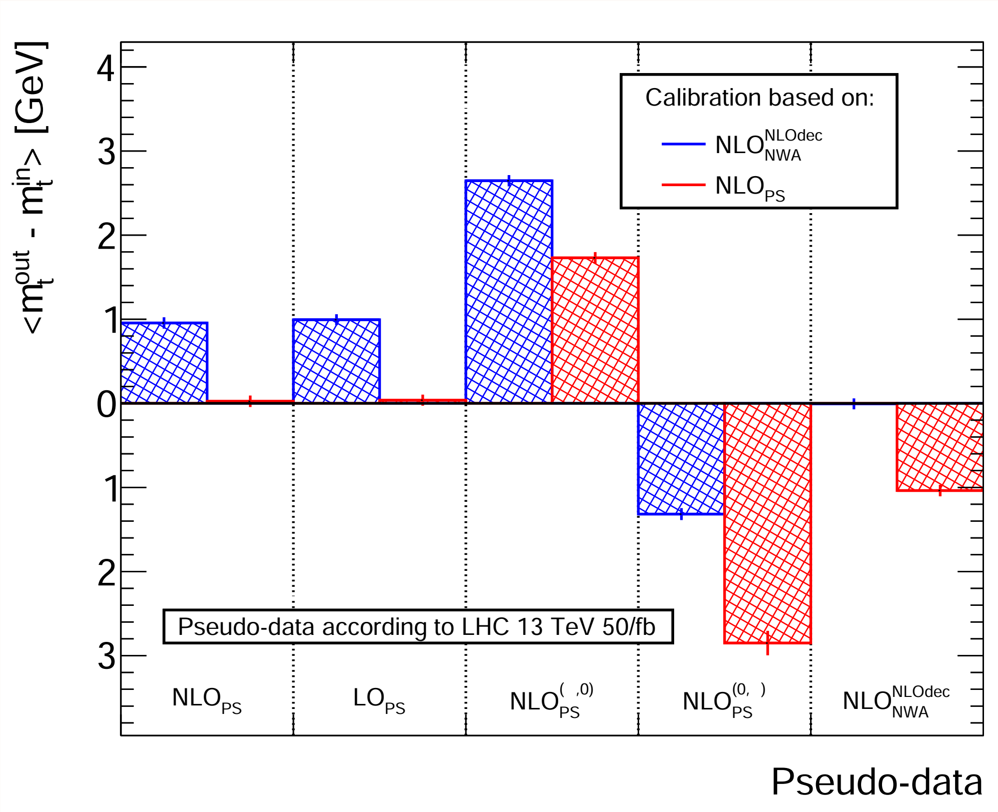
- our studies suggest that most of the mass shift between NLO NWA and NLO+PS emerge due to resummation effects (fixed-order vs fully evolved radiation pattern)

Fit results for m_{lb}

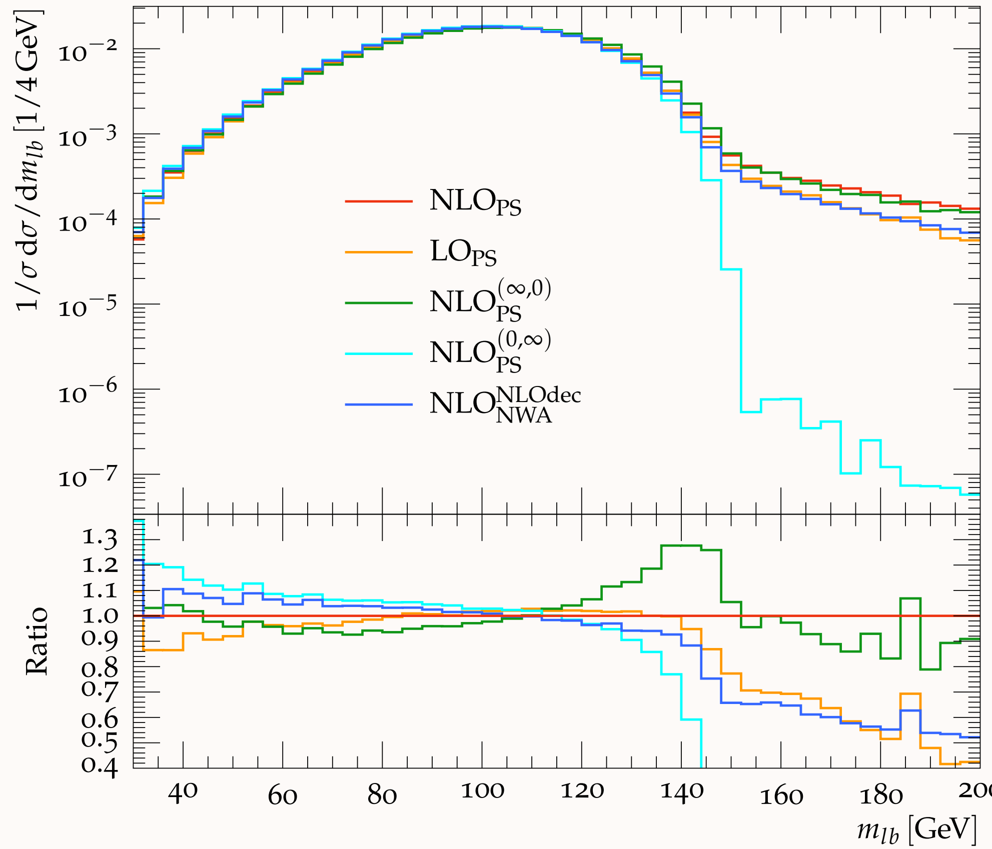
[Heinrich et al, arXiv:1709.08615]

➡ ***Effects of dissecting the radiation pattern in other ways.***

- NLO+PS vs NLO NWA NLOdec
  pure LO, production & decay showers



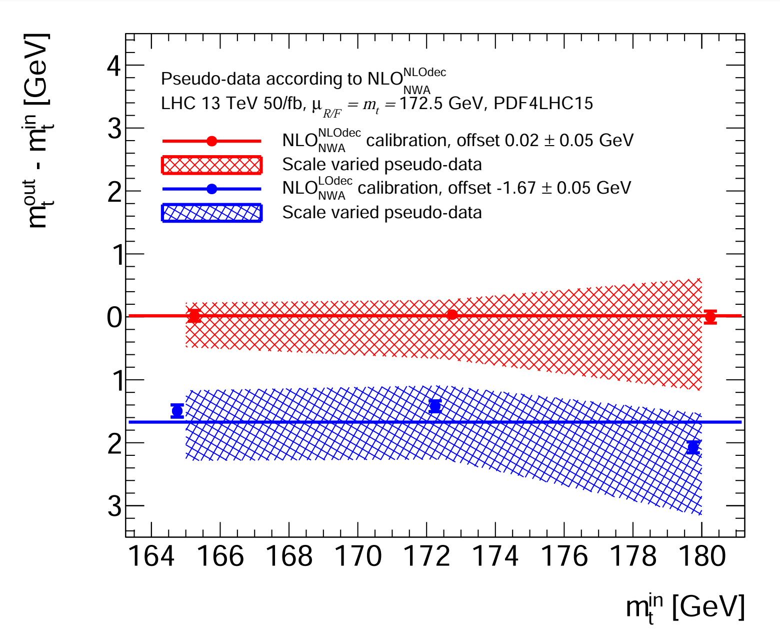
- associated m_{lb} distributions

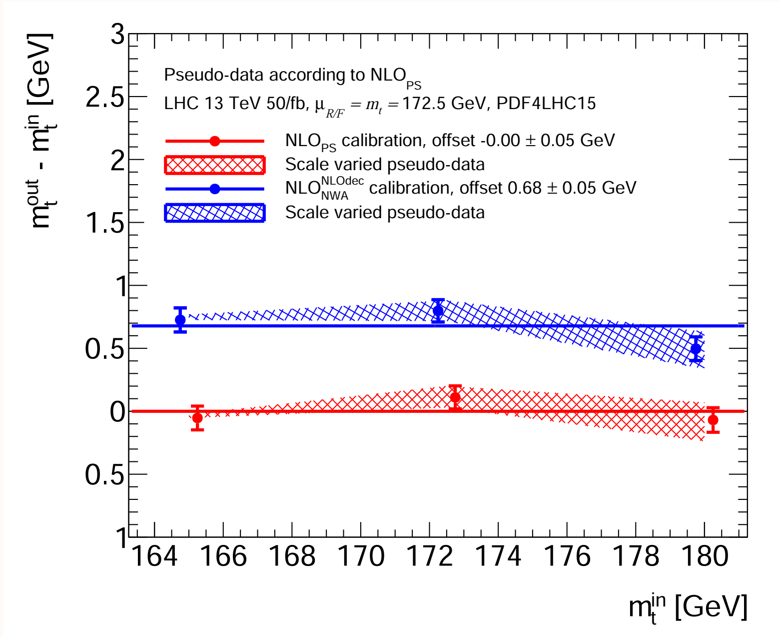


- similarity of NLO+PS & LO+PS because the same resummation corrections are applied in both showers
- large mass shifts for both pure prod. and decay showers (ISR for former / FSR for latter pull fits towards larger / smaller m_t); blue offsets: bin1 ≈ bin3 + bin4 ⇒ generation-level factorization survives

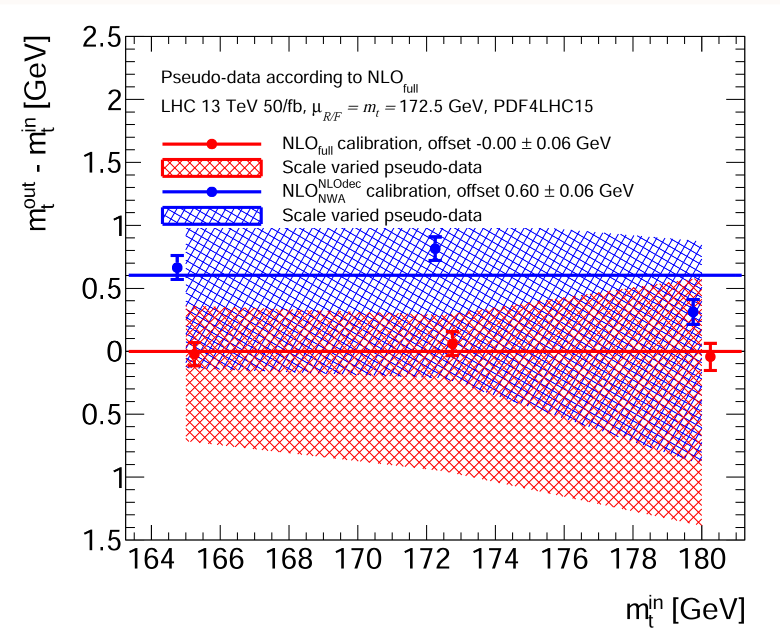
Fit results for m_{T2}

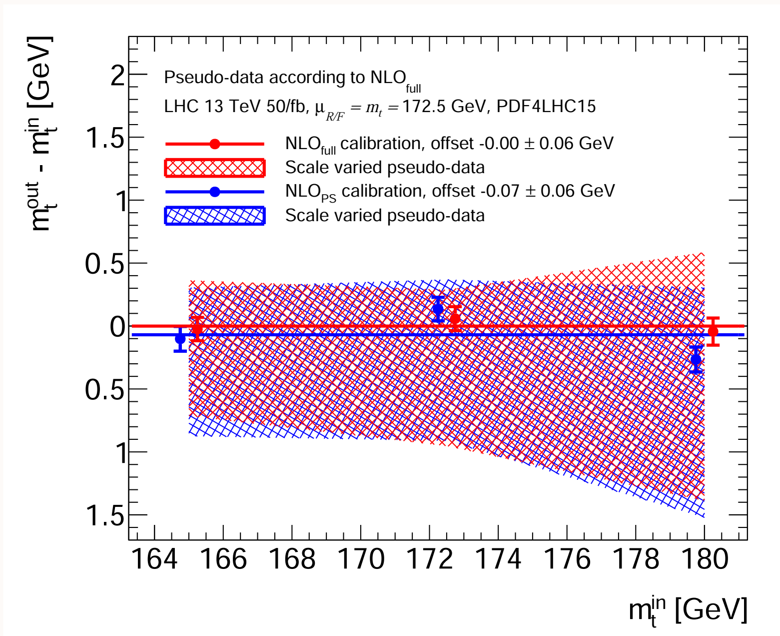
[Heinrich et al, arXiv:1709.08615]





- ◁ radiation in decay
- ▷ resummation effects





- ◁ NLO full vs NWA
- ▷ NLO full vs NLO+PS

Snippet list of recent literature.

Nason et al. group

(1509.09071, 1607.04538, 1711.06281, 1801.03944)

resonance-aware subtraction and NLO+PS matching and the $b\bar{b}4l$ generator, theoretical study comparing NLO+PS generator of increasing accuracy

Bevilacqua et al. group

(1509.09242, 1609.01659, 1710.07515)

comprehensive study of the $t\bar{t}j$ final state including off-shell, non-resonant effects and its prospects for top quark mass extractions

Denner et al. group

(1607.05571, 1711.10359)

NLO EW corrections to dilepton final state and NLO QCD corrections to lepton+jets final state

Hoang et al. group

(1608.01318, 1704.01580)

discussing/quantifying the relation of the Monte Carlo generator mass with a short-distance mass, the MSR mass

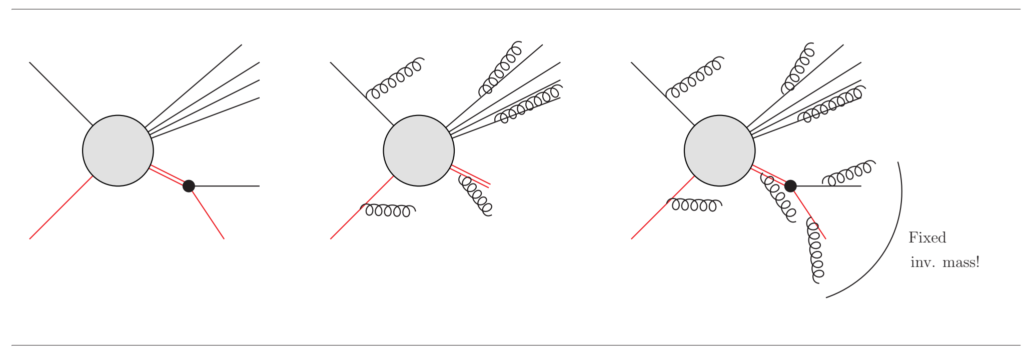
Disclaimer: this is a personal selection which by no means is intended to be complete.

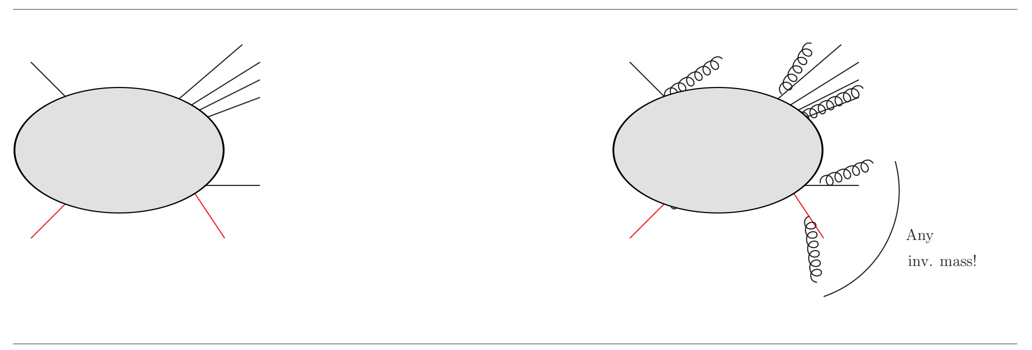
$WbW\bar{b}$ combined with parton showering.

Combination with parton showers.

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

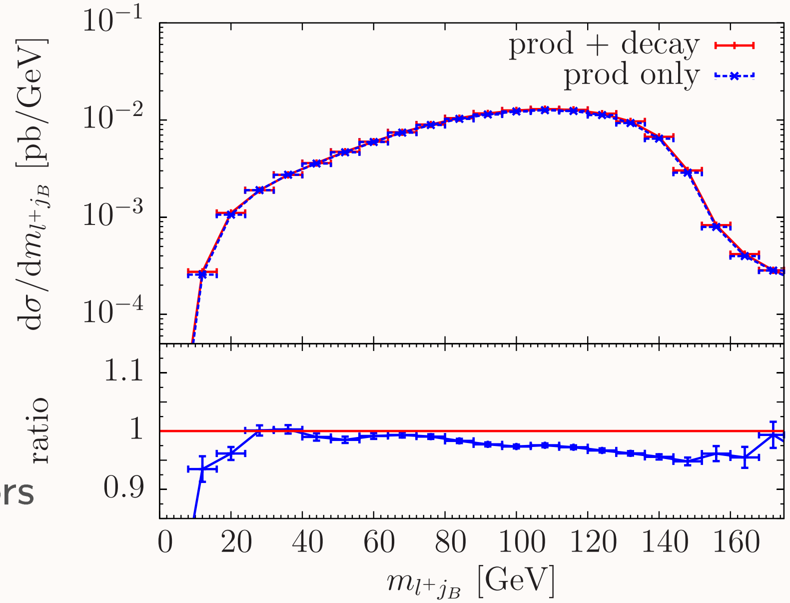
- ... to obtain more realistic, i.e. hadron level final states.
- first attempt and results using PowHel [Garzelli, Kardos, Trocsanyi, arXiv:1405.5859]
- however, the issue of intermediate resonances has not been addressed. (Without a proper treatment of intermediate resonances, parton shower effects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

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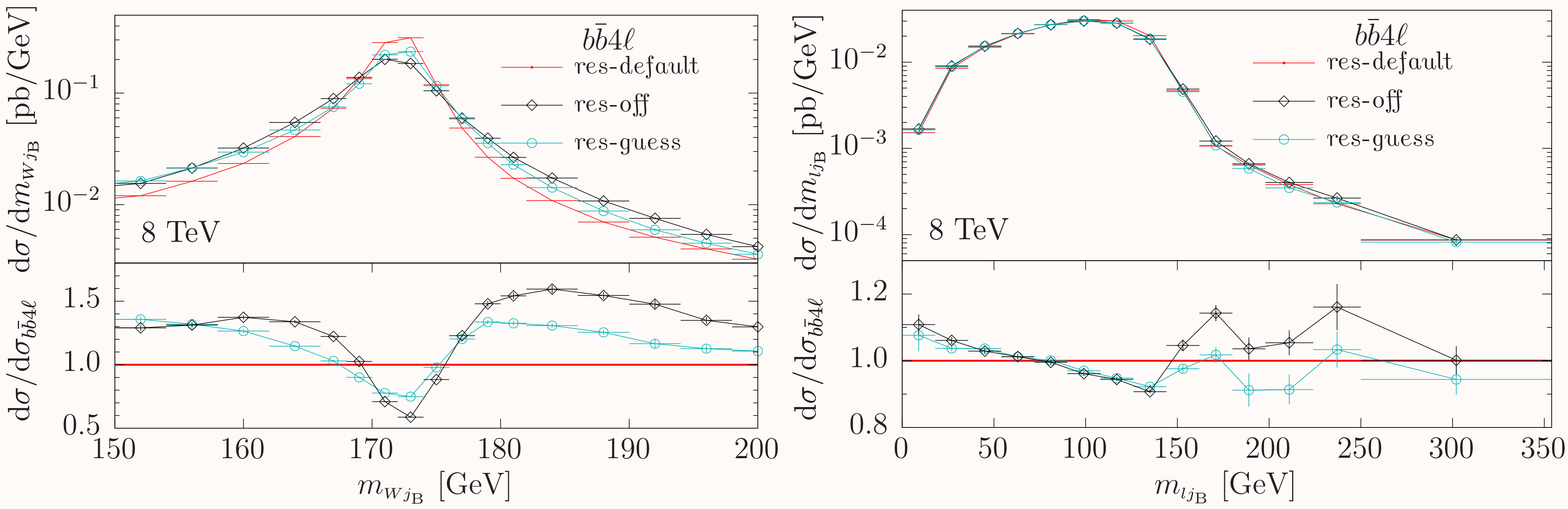
[JEZO, LINDERT, NASON, OLEARI, POZZORINI, ARXIV:1607.04538]

➡ 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

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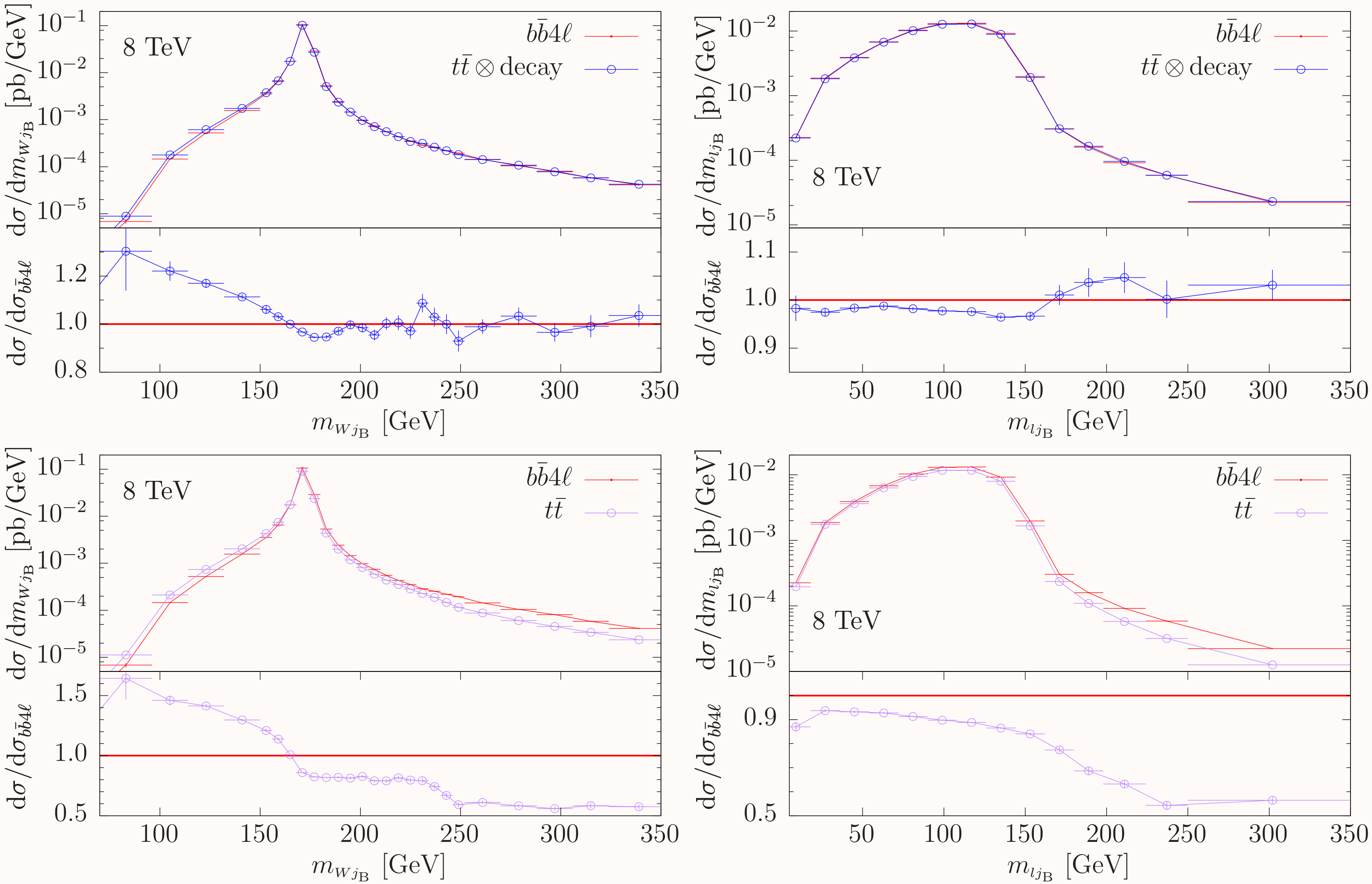
➡ comparison of the predictions of the new generator, standard Powheg (lower row) and that obtained from operating in narrow-width limit (upper row) including offshellenss and interference effects in an approximate way.



- 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 / Outlook.

Studied variety of relevant theoretical descriptions and top quark mass sensitive observables (for a well-defined framework in the context of a dilepton analysis).

Prospects for top quark mass extraction are best for observables m_lb and m_T2. The details of the theoretical descriptions matter for the (quality of the) extraction, much more than finding the optimal choice for the fit range.

Confirmed: large effect of radiative corrections in the top quark decay increases the theoretical uncertainties of the extraction. Still: non-factorizing/non-resonant contributions lead to mass shift of the order of 1 GeV between full calculation and NWA at NLO.

NLO matched parton shower gives surprisingly small mass shift compared to full NLO calculation (agreement by chance –> different physics effects, similar pheno impact) while the associated theoretical uncertainties very likely are underestimated. The offset compared to NLO NWA is larger than expected, again of the order of 1 GeV. Restricted-shower studies indicate that the resummation corrections included by the full showers lead to effects on the m_t determination that can be as large as 1 GeV. Fixed-order results can be expected to change accordingly once parton showering is included but their non-uniform scale dependence will likely survive.

Desired: comparison to NNLO production plus NNLO decay; comparison to real data; estimation of hadronization & detector effects in same framework; dedicated (maybe larger-scale) comparison between different parton shower (matched) approaches as useful exercise to assess related uncertainties on broader, more global scale.

The end. (:o) Thank You.