

# NLO electroweak corrections to off-shell top-antitop production with leptonic decays at the LHC

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In collaboration with: Ansgar Denner

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Zurich, Switzerland

28<sup>th</sup> October 2015



# Outline

- 1 Presentation of the Calculation
- 2 Numerical results
- 3 Comparison to Double-Pole Approximations
- 4 Conclusion

# Outlook

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- The top quark is the heaviest particle in the SM
  - Window to new physics [Frederix, Maltoni; 0712.2355], [Backović, MP et al.; 1508.05327], [Arina, MP et al.; 1605.09242], [Hespel et al.; 1606.04149]
  - Study of top quarks production very important at LHC

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  - Study of top quarks production very important at LHC
- Need for precise predictions for  $t\bar{t}$  production:
  - NLO QCD [Melnikov, Schulze; 0907.3090], [Bevilacqua et al.; 1012.4230], [Denner et al.; 1207.5018], [Frederix; 1311.4893], [Campbell et al.; 1204.1513, 1608.03356], ...
  - NLO EW [Bernreuther et al.; hep-ph/0610335, 0804.1237, 0808.1142], [Kühn et al.; hep-ph/0508092, hep-ph/0610335], [Hollik, Kollar; 0708.1697], [Pagani et al.; 1606.01915]
  - NNLO QCD [Czakon et al.; 1303.6254, 1601.05375, 1606.03350]
  - Resummation [Beneke et al.; 0907.1443], [Czakon et al.; 0907.1790], [Ahrens et al.; 1003.5827], [Kidonakis; 0903.2561, 1009.4935]
  - NLO QCD matched to PS [Frixione et al.; hep-ph/0305252, 0707.3088], [Höhe et al.; 1402.6293], [Garzelli et al.; 1405.5859], [Campbell et al.; 1412.1828], [Ježo et al.; 1607.04538]

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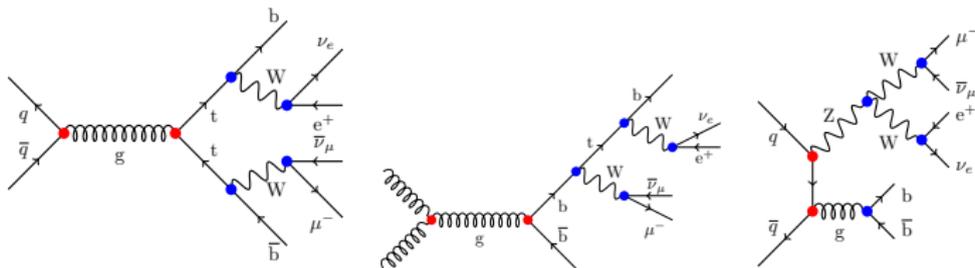
→ All the EW calculations have been done for on-shell top quarks

→ Calculation the NLO EW corrections to off-shell  $t\bar{t}$  production:

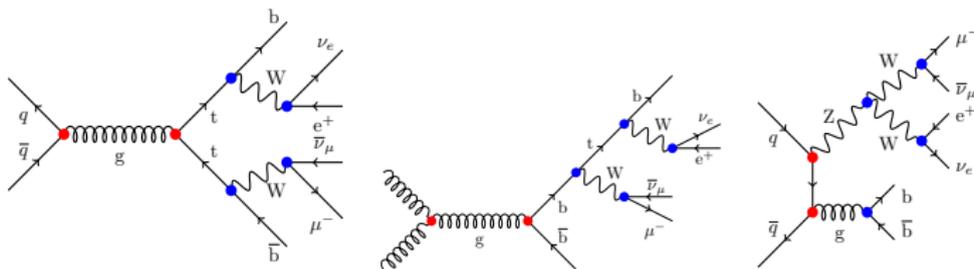
$$pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b}$$

- Off-shell, non-resonant, and interference effects
  - Realistic final state
- EW corrections can be large in certain phase space regions
  - Sudakov logarithms
- Theoretical and numerical challenge to consider  $2 \rightarrow 6$  process
  - Up to 6 external charged particles and 4 intermediate resonances

→ The LO is defined at order  $\mathcal{O}(\alpha_s^2 \alpha^4)$

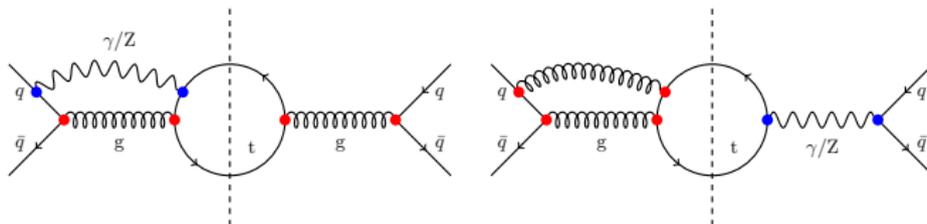


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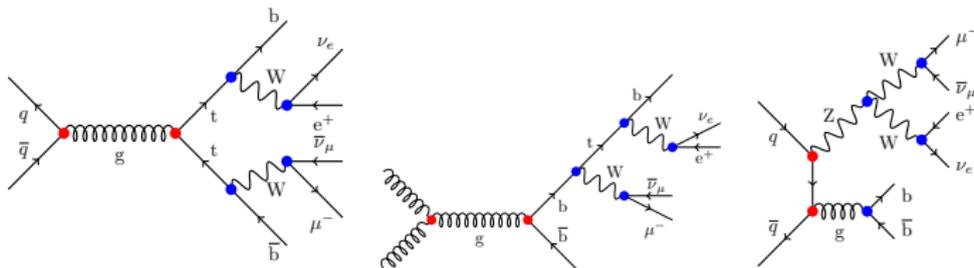


→ NLO EW corrections are of order  $\mathcal{O}(\alpha_s^2 \alpha^5)$

→ Interference of EW and QCD processes

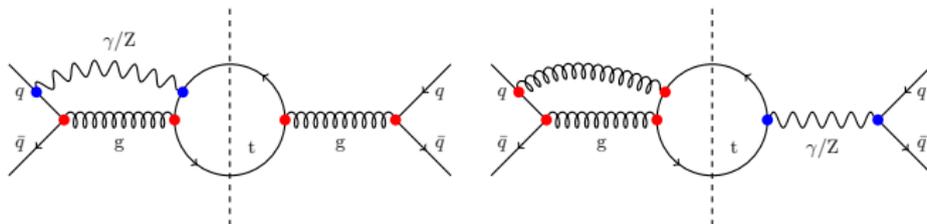


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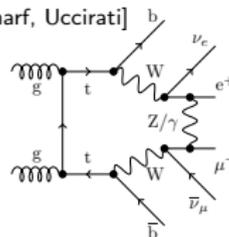
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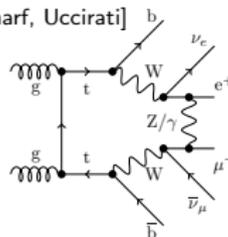


→ QCD corrections of photon induced  $\mathcal{O}(\alpha_s \alpha^6)$  (neglected here)

- Virtual corrections: RECOLA [Actis, Denner, Hofer, Lang, Scharf, Uccirati]
- Dipole subtraction scheme [Catani, Seymour], [Dittmaier]
- Complex mass-scheme [Denner et al.]
- In-house Monte Carlo - MoCANLO [Feger]

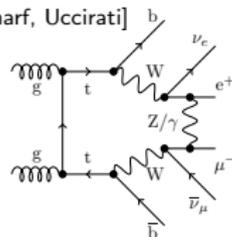


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Predictions for  $\sqrt{s} = 13\text{TeV}$  at the LHC

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## Predictions for $\sqrt{s} = 13\text{TeV}$ at the LHC

- NNPDF23\_nlo\_as\_0119\_qed [NNPDF Collaboration]
- with massless bottom quarks and bottom-quark PDF neglected
- Cuts:

$$\text{b jets: } p_{T,b} > 25 \text{ GeV}, \quad |y_b| < 2.5$$

$$\text{charged lepton: } p_{T,\ell} > 20 \text{ GeV}, \quad |y_\ell| < 2.5$$

$$\text{missing transverse momentum: } p_{T,\text{miss}} > 20 \text{ GeV}$$

$$\text{b-jet-b-jet distance: } \Delta R_{bb} > 0.4$$

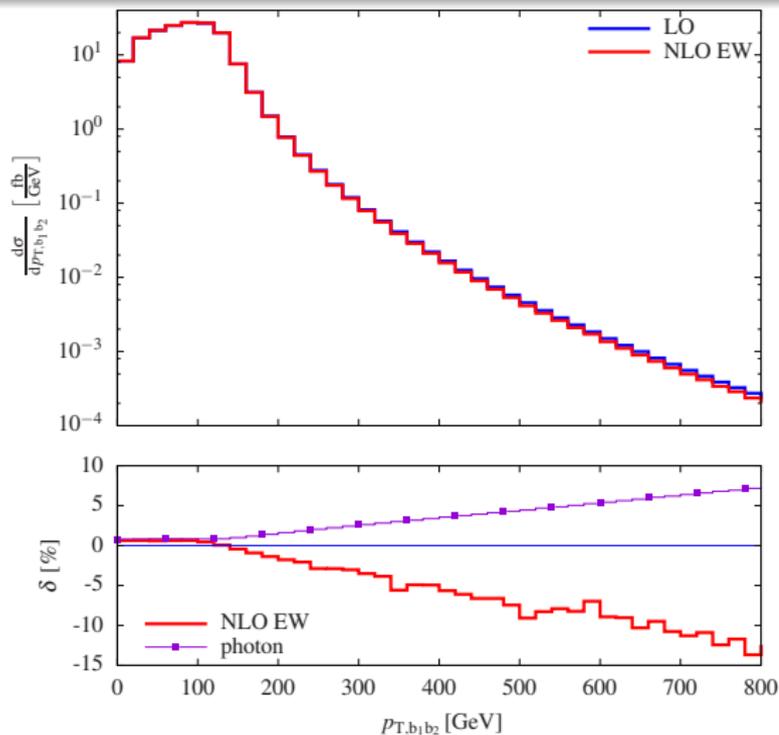
- anti- $k_T$  jet algorithm [Cacciari, Salam, Soyez]

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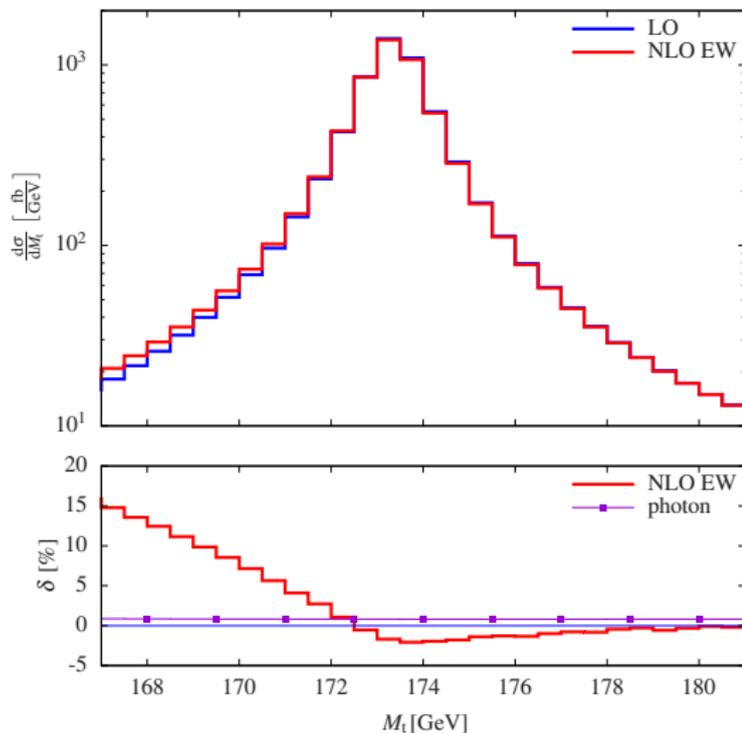
Ch.	$\sigma_{\text{LO}}$ [fb]	$\sigma_{\text{NLO EW}}$ [fb]	$\delta$ [%]
gg	2824.2(2)	2834.2(3)	0.35
$q\bar{q}$	375.29(1)	377.18(6)	0.50
$gq(/q)$		0.259(4)	
$\gamma g$		27.930(1)	
pp	3199.5(2)	3211.7(3)	0.38

- Cross section dominated by the gg channel
- $\gamma g$  channel around 1% (not included in the NLO definition)
- Small positive EW corrections
  - Negative corrections for on-shell top quarks ( $\sim -1.5\%$ ) (due to the choice of the top width)



→ Sudakov logarithms →  $-15\%$

→ Important photon contributions →  $+6\%$  [Pagani, Tsinikos, Zaro; 1606.01915]



→ Radiative tail due to non-reconstructed photons

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→ Double-Pole Approximation (DPA):

- Accounts for off-shell effects
  - Resonant propagator fully included / Full phase space
- Expansion about the resonance poles
- Applied only to the virtual corrections
  - Accounts for non-factorisable corrections

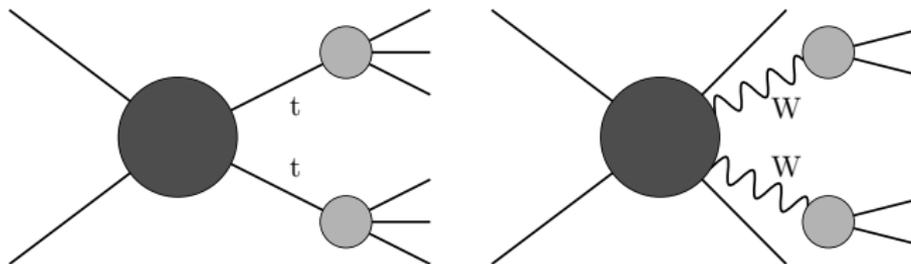
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→ Two DPAs considered: **tt** and **WW**



Ch.	$\sigma_{\text{LO}}^{\text{WW DPA}}$ [fb]	$\delta_{\text{LO}}^{\text{WW DPA}}$ [%]	$\sigma_{\text{LO}}^{\text{tt DPA}}$ [fb]	$\delta_{\text{LO}}^{\text{tt DPA}}$ [%]
gg	2808.4(6)	-0.56	2738.8(2)	-3.0
$q\bar{q}$	372.90(1)	-0.64	368.82(1)	-2.2
pp	3181.3(5)	-0.57	3107.6(2)	-2.9

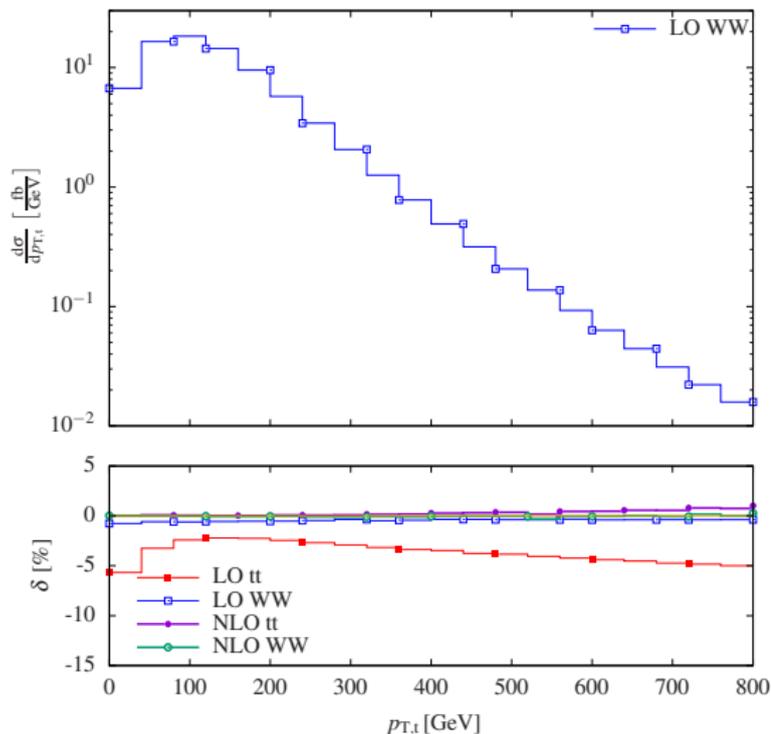
→ At LO, WW DPA is better than the tt DPA

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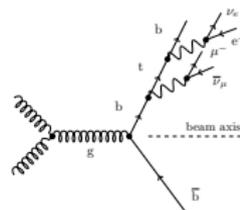
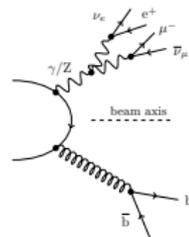
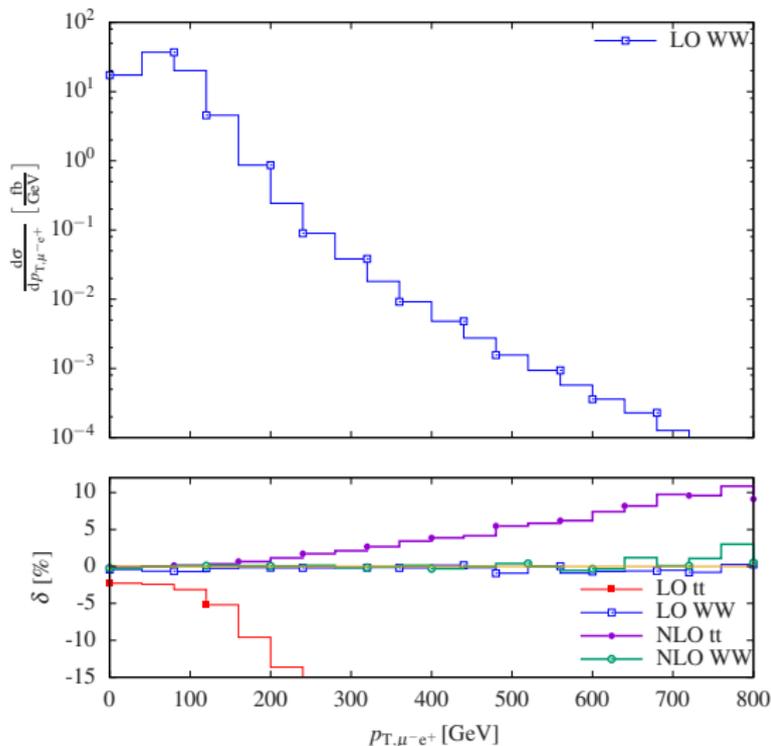
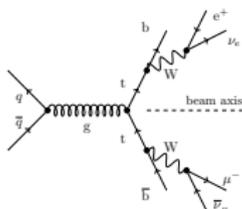
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Ch.	$\sigma_{\text{NLO EW}}^{\text{WW DPA}}$ [fb]	$\delta_{\text{NLO EW}}^{\text{WW DPA}}$ [%]	$\sigma_{\text{NLO EW}}^{\text{tt DPA}}$ [fb]	$\delta_{\text{NLO EW}}^{\text{tt DPA}}$ [%]
gg	2832.9(2)	-0.046	2836.5(2)	+0.082
$q\bar{q}$	377.36(8)	0.047	377.23(5)	+0.013
pp	3210.5(2)	-0.037	3214.0(2)	+0.072

→ At NLO, both DPAs are equally good



→ Both DPAs work well for top dominated observables



→ tt DPA is failing due to 0/1-top resonance contributions

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## Summary

- First NLO EW calculation of the full off-shell  $t\bar{t}$  production
- EW corrections can reach 15%
- Only the full calculation is reliable for arbitrary distributions

**These corrections are particularly relevant for ...  
... SM measurements as well as BSM searches**

→ For more details please look at:

**[arXiv:1607.05571]**

## Back-up slides

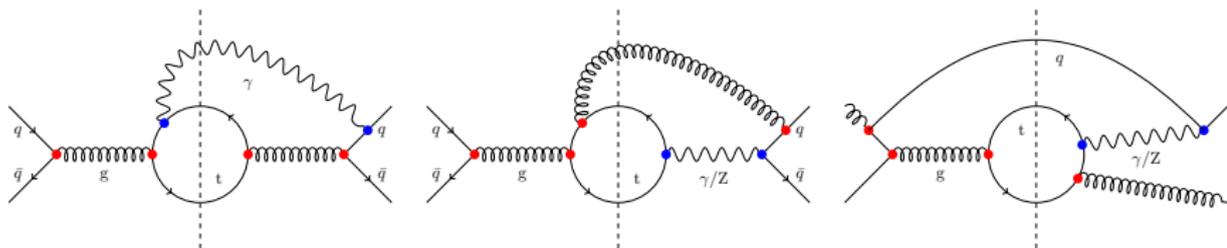
# BACK-UP

# Validation

- Three-level matrix elements: `MADGRAPH5_AMC@NLO` [Alwall et al.; 1405.0301]
- One-loop matrix elements:
  - DPAs (the DPA implementation being checked for DY and di-boson)
  - Check of a Ward identity in `RECOLA`
  - Two libraries in `COLLIER` [Denner, Dittmaier, Hofer; 1407.0087, 1604.06792]
- IR-subtraction/finiteness:
  - Variation of  $\alpha$  parameter [Nagy, Troscanyi; hep-ph/9806317]
  - Variation of technical cuts
  - Variation of IR-scale
- Born hadronic cross sections: `MADGRAPH5_AMC@NLO`

# Real radiations

→ Photon radiation / Gluon radiation /  $gq(/\bar{q})$  channel



- Factorisable corrections

$$\mathcal{M}_{\text{virt, fact, PA}} = \sum_{\lambda_1, \dots, \lambda_r} \left( \prod_{i=1}^r \frac{1}{K_i} \right) \left[ \mathcal{M}_{\text{virt}}^{I \rightarrow N, \bar{R}} \prod_{j=1}^r \mathcal{M}_{\text{LO}}^{j \rightarrow R_j} \right. \\ \left. + \mathcal{M}_{\text{LO}}^{I \rightarrow N, \bar{R}} \sum_{k=1}^r \mathcal{M}_{\text{virt}}^{k \rightarrow R_k} \prod_{j \neq k}^r \mathcal{M}_{\text{LO}}^{j \rightarrow R_j} \right] \left\{ \bar{k}_l^2 \rightarrow \hat{\bar{k}}_l^2 = M_l^2 \right\}_{l \in \bar{R}}$$

- Non-factorisable corrections:

$$2\text{Re} \{ \mathcal{M}_{\text{LO, PA}}^* \mathcal{M}_{\text{virt, nfact, PA}} \} = |\mathcal{M}_{\text{LO, PA}}|^2 \delta_{\text{nfact}}$$

- On-shell projection
- DPA applied to virtual corrections and  $I$ -operator
- Full Born and Real contributions:

# Inputs

- For the fixed renormalisation and factorisation scale  $\mu_{\text{fix}} = m_t$ :

$$\alpha_s(\mu_{\text{fix}}) = 0.1084656 \dots$$

- $G_\mu$  scheme:

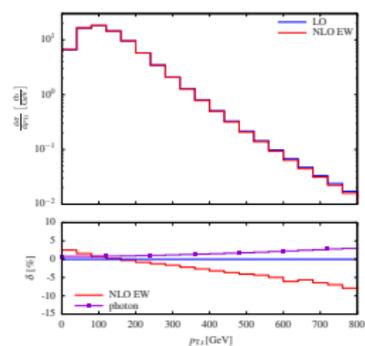
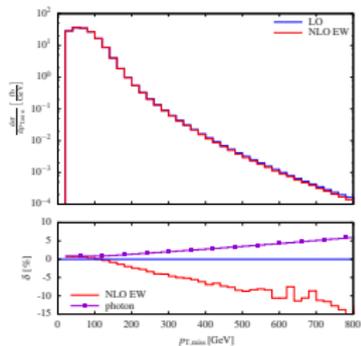
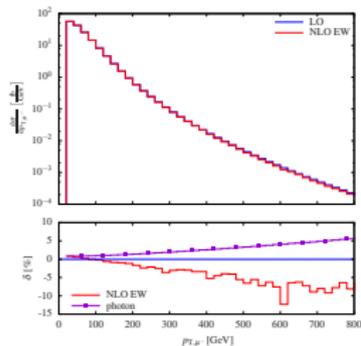
$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left( 1 - \frac{M_W^2}{M_Z^2} \right) \quad \text{with} \quad G_\mu = 1.16637 \times 10^{-5} \text{ GeV}^2$$

- Inputs:

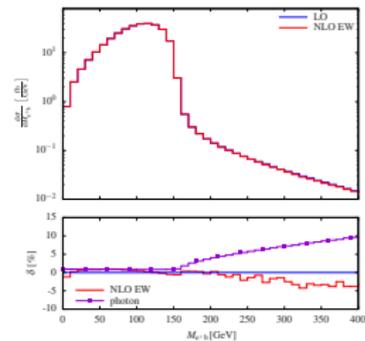
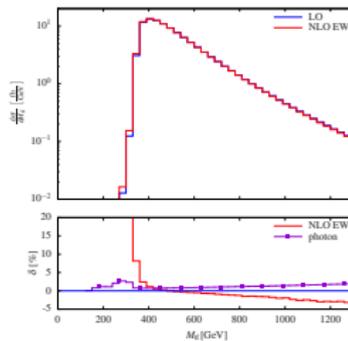
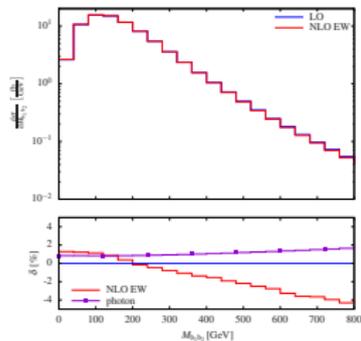
$$\begin{aligned} m_t &= 173.34 \text{ GeV}, & \Gamma_t &= 1.36918 \dots \text{ GeV} \\ M_Z^{\text{OS}} &= 91.1876 \text{ GeV}, & \Gamma_Z^{\text{OS}} &= 2.4952 \text{ GeV} \\ M_W^{\text{OS}} &= 80.385 \text{ GeV}, & \Gamma_W^{\text{OS}} &= 2.085 \text{ GeV} \\ M_H &= 125.9 \text{ GeV} \end{aligned}$$

→ Top width at NLO EW and QCD [Basso, Dittmaier, Huss, Oggero; 1507.04676]

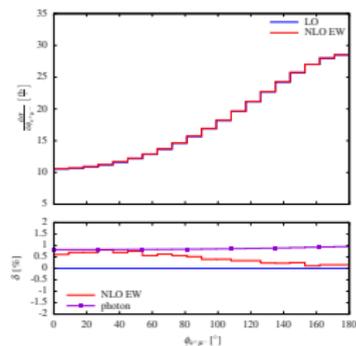
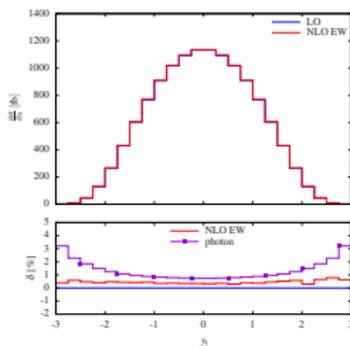
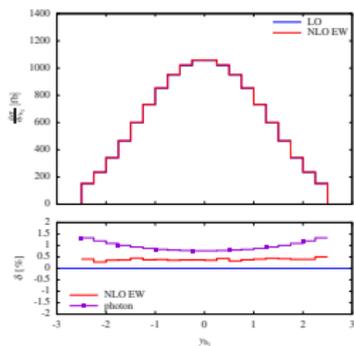
# Distributions full (1)



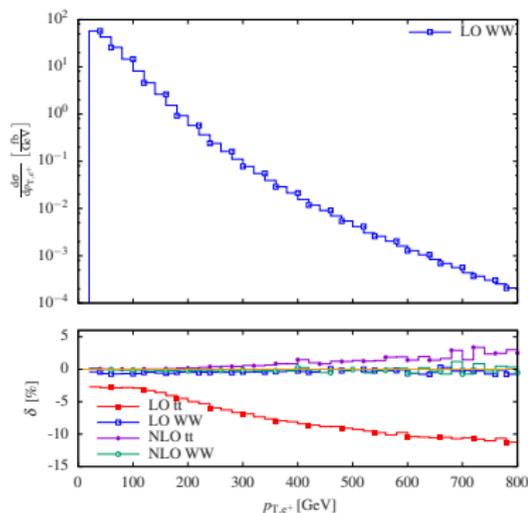
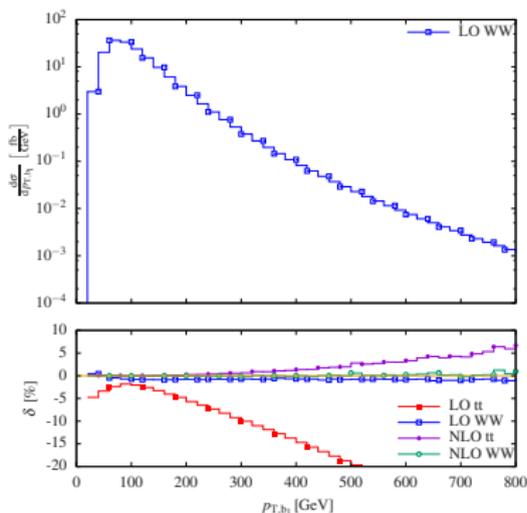
# Distributions full (2)



# Distributions full (3)



# DPA distributions (1)



# DPA distributions (2)

